Gravitational Wave and Multimessenger Astronomy

765. WE-Heraeus-Seminar

25 - 28 April 2022

hybrid

at the Physikzentrum Bad Honnef, Germany

WILHELM UND ELSE HERAEUS-STIFTUNG

Introduction

The Wilhelm und Else Heraeus-Stiftung is a private foundation that supports research and education in science with an emphasis on physics. It is recognized as Germany's most important private institution funding physics. Some of the activities of the foundation are carried out in close cooperation with the German Physical Society (Deutsche Physikalische Gesellschaft). For detailed information see https://www.we-heraeus-stiftung.de

Aims and scope of the 765. WE-Heraeus-Seminar:

After decades of designing, building and improving the most sensitive laser interferometers on Earth, the first direct detection of gravitational waves from a binary black hole merger in 2015 heralded the beginning of a new era of astronomy. Six years later, more than 50 gravitational-wave observations of binary black holes and binary neutron stars have been reported, and the focus has shifted – from proving that gravitational waves exist and can be detected, to advancing our understanding of the composition and evolution of the Universe.

Gravitational waves are the only way to access the dark side of the Universe that is invisible to other instruments. The large number and properties of the detected black hole binaries already challenge our understanding of their formation. Furthermore, other cataclysmic events like the merger of neutron stars emit gravitational waves and other "messengers," such as electromagnetic radiation and neutrinos. In this new era of multimessenger astronomy, all information must be combined to unravel more secrets of the expanding Universe, matter at extreme densities, gamma-ray bursts and much more.

This workshop will bring together pioneers and experts of this new era and a new generation of astronomers who will use all available tools to advance the field in the future. Introductory talks will not only summarize the status quo, but also look into the future of instrumental developments, data analysis, astronomy and astrophysics. In addition, tutorials will offer hands-on experience with these new types of data and software, and participants will have ample opportunity to discuss the future of a field that has just begun.

Scientific Organizers:

Prof. Michèle Heurs	Leibniz Universität Hannover, Germany E-mail: michele.heurs@aei.uni-hannover.de
Dr. Frank Ohme	MPI für Gravitationsphysik, Hannover, Germany E-mail: frank.ohme@aei.mpg.de

Introduction

Administrative Organization:

Dr. Stefan Jorda Elisabeth Nowotka	Wilhelm und Else Heraeus-Stiftung Postfach 15 53 63405 Hanau, Germany Phone +49 6181 92325-12 Fax +49 6181 92325-15 E-mail nowotka@we-heraeus-stiftung.de Internet: www.we-heraeus-stiftung.de

Venue:

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Registration:

Elisabeth Nowotka (WE Heraeus Foundation)
at the Physikzentrum, reception office
Sunday (17:00 h – 21:00 h) and Monday
morning

Program

Sunday, 24 April 2022

17:00 – 20:00	Registration	
18:00	*BUFFET SUPPER and informal get-together*	

Monday, 25 April 2022

08:00	*BREAKFAST*	
08:45 – 09:00	Scientific organizers	**Welcome words**
09:00 – 09:45	Stefan Hild	**The Einstein telescope**
09:45 – 10:30	Tim Dietrich	**Interpreting the nuclear physics - multi-messenger astrophysics picture drawn by neutron star mergers**
10:30 – 11:00	*COFFEE BREAK*	
11:00 – 11:45	Harald Lück	**Surpassing the standard quantum limit of interferometry**
11:45 – 12:30	Moritz Mehmet	**Squeezed states of light and their application in gravitational wave detectors**
12:30 – 12:40	**Conference Photo** (in the front of the lecture hall)	
12:40	*LUNCH*	

Program

Monday, 25 April 2022

14:30 – 15:00	**Sparkler talks poster session I**	
15:00 – 16:00	**Poster session I**	
16:00 – 16:30	*COFFEE BREAK*	
16:30 – 17:15	Nial Tanvir	**Strategies and prospects for electromagnetic observations of gravitational wave sources**
17:15 – 18:00	Jennifer Barnes	**Electromagnetic counterparts to compact object mergers**
18:30	*DINNER*	
20:30	Bernard Schutz	**Does GW astronomy have a long term future?**

Program

Tuesday, 26 April 2022

08:00	*BREAKFAST*	
09:00 – 09:45	Anna Franckowiak	**Multi-messenger astronomy with high-energy neutrinos**
09:45 – 10:30	Christian Stegmann	**Multi-messenger astronomy with gamma-rays**
10:30 – 11:00	*COFFEE BREAK*	
11:00 – 11:45	Alex Nitz	**Detection of gravitational waves from compact-binary mergers**
11:45 – 12:30	Vivien Raymond	**Perspectives for astrophysical inference with gravitational waves**
12:30	*LUNCH*	
14:30 – 15:00	**Sparkler talks poster session II**	
15:00 – 16:00	**Poster session II** and *COFFEE*	
16:00 – 16:45	Mansi Kasliwal	**Multi-messenger astrophysics**
16:45 – 17:30	Maya Fishbach	**Black hole astrophysics with gravitational-wave populations**
17:30 – 17:45	Stefan Jorda	**About the WE-Heraeus-Foundation**
18:30	*DINNER*	

Program

Wednesday, 27 April 2022

08:00	*BREAKFAST*	
09:00 – 09:45	Alex Nitz	**Basics of gravitational-wave data analysis with PyCBC**
09:45 – 10:30	Vivien Raymond	**tba**
10:30 – 11:00	*COFFEE BREAK*	
11:00 – 11:45	Guido Müller	**LISA**
11:45 – 12:30	Bangalore Sathyaprakash	**Listening to the universe with the next generation of ground-based gravitational-wave detectors**
12:30	*LUNCH*	
14:00 – 18:00	**Excursion**	
18:30	*HERAEUS DINNER* *(social event with cold & warm buffet with complimentary drinks)*	

Program

Thursday, 28 April 2022

08:00	*BREAKFAST*	
09:00 – 09:45	Andreas Freise	**Einstein telescope instrument design and commissioning: a short tutorial on simulation tools**
09:45 – 10:30	Jakob Nordin	**AMPEL: Connecting theoretical models with multi-messenger data streams**
10:30 – 11:00	*COFFEE BREAK*	
11:00 – 11:45	Stefanie Kroker	**Nanophotonics for future gravitational wave detectors**
11:45 – 12:30	Scientific organizers	**Conclusion**
12:30	*LUNCH*	

End of the seminar and departure

NO DINNER for participants leaving on Friday morning

Posters

Posters for session I

Haakon Andresen	**Gravitational waves from core-collapse supernovae**
Jordan Barber	**Primordial binaries in dense stellar clusters**
Sumedha Biswas	**Preparing for Gaia and BlackGEM searches for electromagnetic counterparts during O4**
Angela Borchers	**Assessing gravitational waveform accuracy with the kick velocity**
Patrick Bourg	**Simple, efficient method of calculating the Detweiler-Whiting singular field**
Floor Broekgaarden	**Impact of massive binary star and cosmic evolution on gravitational wave observations II: Double compact object rates and properties**
Srija Chakraborty	**Exploring SMBH progenitors with LISA**
Debatri Chattopadhyay	**Modelling the formation of the first two neutron star-black hole mergers, GW200105 and GW200115: metallicity, chirp masses and merger remnant spins**
Martyna Chruslinska	**Gravitational wave sources care about metallicity dependent cosmic star formation history**
Marco Dall'Amico	**Never two without three: binary black hole mergers via three-body interactions**
Thomas Dent	**Gravitational wave astrophysics of stellar-mass remnants: the population view**
Michael Ebersold	**Leveraging gravitational-wave memory to distinguish neutron star - black hole binaries from black hole binaries**
Cecilio García Quirós	**IMRPhenomXE: Towards computationally efficient eccentric waveform models**

Posters for session I

Sebastián Gomez Lopez	**Identifying basic properties of postmerger BNS GW signals with simplified templates**
Julian Gurs	**Coherent and squeezed light at 2128 nm for future gravitational-wave observatories**
Thomas Huber	**A novel particle detector for monitoring the Cosmic Ray flux at advVirgo**
Nived Johny	**Negative-mass oscillator for coherent quantum noise cancellation**
Robert Joppe	**Test setup for cryogenic sensors and actuators working towards the Einstein Telescope**
Wolfgang Kastaun	**Visualizing neutron star merger remnants**
Tanazza Khanam	**Post-merger gravitational wave searches using the cross-correlation algorithm**
Kaveh Kooshk	**Coincident detection of cherenkov photons from electrons for medical applications**
Mikhail Korobko	**Compensating decoherence of squeezed light in cavity-enhanced quantum metrology**
Roman Kossak	**Opto-mechanics in coherent quantum noise cancellation**
Nina Kunert	**Quantifying modeling uncertainties when combining multiple gravitational-wave detections from binary neutron star sources**
Konstantin Leyde	**Current and future constraints on cosmology and modified gravitational-wave friction from binary black holes**
David Maksimović	**Novel approaches in multimessenger observation of core-collapse supernovae**

Posters for session I

Praveen Manoharan	**Finding universal relations using statistical data analysis**
Maite Mateu-Lucena	**Machine learning applications to modelling compact binary waveforms**
Sarah Mechbal	**Correlations of astrophysical neutrinos with physical properties of active galactic nuclei cores**
Luana Michela Modafferi	**Searching for long-duration transient gravitational waves from glitching pulsars using convolutional neural networks**
Joan Moragues Roca	**Prospects for detecting long-duration transient gravitational waves from glitching pulsars with current and future detectors**
Tista Mukherjee	**Multi-messenger studies with gravitational waves and neutrinos**
Krishnendu Nderi Varium	**Interplay of spin-precession and higher harmonics in the parameter estimation of binary black holes**
Anna Neuweiler	**Studying kilonova properties through long-term numerical-relativity simulations**

Posters for session II

Martin Obergaulinger	**Engines of magneto-rotational supernovae and their multi-messenger signals**
Anastasiia Omeliukh	**Understanding the multi-wavelength variabilty of TeV blazar VER J0521+211 with high-energy particle interactions**
Terri Pearce	**Development of a polarisation phase camera**
Maria de Lluc Planas Llompart	**Toward calibrating precessing fourth generation phenomenological waveform models to numerical relativity**
Suvrat Rao	**Detecting millihertz gravitational waves using circular particle accelerators**
Patrick Reichherzer	**GW follow-up campaigns in conjunction with Astro-COLIBRI**
Philip Relton	**The identification and separation of time-overlapping gravitational-wave transients**
Simeon Reusch	**Neutrinos from tidal disruption and accretion events**
Lea Richtmann	**Experimental testbed for quantum machine learning algorithms**
Jonas Rittmeyer	**Gentle loss measurement: Probing samples with quantum squeezed vacuum**
Qazal Rokn	**Generation of squeezed states of light for gravitational wave detectors**
Roxana Rosca-Mead	**Core collapse in scalar-tensor theory with massive fields**

Posters for session II

Philip Rühl	**Follow-up search for ultra-high-energy photons from gravitational wave sources with the Pierre Auger Observatory**
Hannes Rüter	**Gravitational waves from hyperbolic-like encounters of black holes**
Anuradha Samajdar	**Detecting binary neutron star systems with the thirdgeneration era: the challenge and benefits**
Marlin Schäfer	**MLGWSC-1: The first Gravitational-Wave Search Mock Data Challenge**
Federico Schianchi	**Implementation of first-order multipolar radiation transport in numerical relativity code BAM**
Md Arif Shaikh	**Surrogate and hybrid models of eccentric waveforms using numerical relativity**
Ayatri Singha	**Improving sky localization of the network of gravitational-wave detectors using the signal-independent null stream of Einstein telescope.**
Jakob Stegmann	**Binary black hole mergers from merged stars in the galactic field**
Nils Sültmann	**Bimodal local readout for back-action evasion**
Max Trevor	**Incorporating information from LIGO data quality streams into the PyCBC search for gravitational waves**
Ada Uminska	**Dimensional stability verification of the LISA telescope**
Andrei Utina	**ETpathfinder: a cryogenic testbed for interferometric gravitational-wave detectors**
Zeb Van Ranst	**A novel speedmeter concept for next-generation gravitational wave detectors**

Posters for session II

Vijay Varma	**Evidence of large recoil velocity from a black hole merger signal**
Paritosh Verma	**Probing gravitational waves from pulsars in Brans-Dicke theory**
Sander Vermeulen	**Direct limits for scalar field dark matter from a gravitational wave detector**
Verónica Villa-Ortega	**Rapid online estimation of astrophysical source category and compact binary parameters**
Andrea Virtuoso	**Frequency-dependent effects in the localization of GW events**
Alexander Weaver	**TTL Expansions for LISA as polynomials in zernike contributions to the outgoing beam wavefront**
Kyle Willetts	**Real-time parameter estimation of un-modelled gravitational wave transients using machine learning**
Vojtech Witzany	**Quasi-periodic oscillations in tidal disruption events as markers of multimessenger sources?**

Abstracts of Talks

(in alphabetical order)

Electromagnetic Counterparts to Compact Object Mergers

Jennifer Barnes[1]

[1]*Kavli Institute for Theoretical Physics, Kohn Hall, University of California at Santa Barbara, Santa Barbara, CA, 93106 USA*

Observations of merging compact object binaries represent an opportunity to make progress on many pressing questions in astrophysics, including the architecture of neutron stars, the formation and evolution of relativistic jets, and the origin of heavy elements produced by rapid neutron capture nucleosynthesis. The electromagnetic emission powered by the radioactive decay of the unstable nuclei produced in the merger—known as a kilonova—can provide unique insights into to merger-driven mass ejection and element synthesis. Indeed, analysis of the kilonova that accompanied the first gravitational wave-detected neutron star merger, GW170817, offered an amazingly detailed picture of the outflows that produced it, demonstrating the value of electromagnetic observations for the study of compact binary mergers. I will give an overview of the developments in theory that underpinned this analysis, and discuss the key questions and uncertainties that continue to challenge our efforts to fully understand these exotic transients.

Interpreting the nuclear physics - multi-messenger astrophysics picture drawn by neutron star mergers

T.Dietrich[1,2], M. Bulla[3] ,M. W. Coughlin[4], Ingo Tews[5], P.T.H.Pang[6,7], S. Huth[8,9], A. Le Fèvre[10], A. Schwenk[8,9,11], W. Trautmann[10], K.Agarwal[12], C. Van Den Broeck[6,7], J. Heinzel[4,13,14], L. Issa[3,15],S. Antier[16], G.Ashton[17]

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Our knowledge about dense matter explored in the cores of neutron stars remains limited. Fortunately, the detection of gravitational waves emitted from the merger of neutron stars and the corresponding electromagnetic signals allow us to place constraints on the properties of matter at supranuclear densities.
In this talk, we will combine information from the gravitational-wave signals GW170817 and GW190425, the electromagnetic counterparts AT2017gfo and GRB170817A, with the information provided by NICER and radio pulsar observations to derive new constraints on the neutron-star equation of state and the Hubble constant. In addition to astrophysical observations, extreme densities are probed in terrestrial experiments. We will combine our multi-messenger information with studies from heavy-ion collisions of gold nuclei at relativistic energies with microscopic nuclear theory calculations. Our findings show that constraints from heavy-ion collision experiments show a remarkable consistency with multi-messenger observations and provide complementary information on nuclear matter at intermediate densities.

References

[1] T. Dietrich et al., Science 370 (2020) 6523, 1450-1453
[2] S. Huth et al., arXiv: 2107.06229 [nucl-th]
[3] G. Ashton & T. Dietrich, 2111.09214 [gr-qc]

Black Hole Astrophysics with Gravitational-Wave Populations

M. Fishbach[1]

[1]Center for Interdisciplinary Exploration and Research in Astrophysics (CIERA), Northwestern University, 1800 Sherman Ave, Evanston, IL 60201, USA

LIGO and Virgo have observed around 70 mergers of black holes, including black holes in neutron star- black hole systems. I will describe the properties of the binary black hole population, including the mass distribution, the spin distribution, and evolution with redshift. The population distributions encode astrophysical lessons about how, where and when black holes are made. I will discuss some of these lessons, including understanding the pair-instability mass gap in light of massive black hole observations, resolving the transition between neutron star and black hole masses, and inferring the time delays that black holes experience between formation and merger. Several mysteries remain about the origins of these black holes, and I will discuss what we expect to learn from future observations.

References

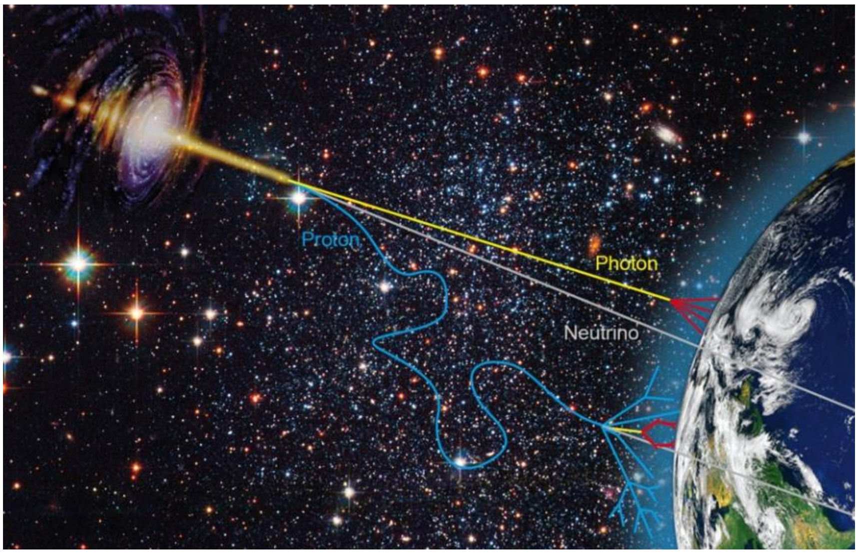
1. Ye, C., Fishbach, M., arXiv:2202.05164 (2022)
2. LIGO-Virgo-Kagra Collaboration, arXiv:2111.03634 (2021)
3. Farah, A. M., Fishbach, M., Essick, R., Holz, D. E., Galaudage, S., arXiv:2111.03498 (2021)
4. Fishbach, M., Kalogera, V., The Astrophysical Journal Letters **914**, L30
5. LIGO-Virgo-Kagra Collaboration, The Astrophysical Journal Letters **913**, L7 (2021)

Multi-messenger Astronomy with High-energy Neutrinos

A. Franckowiak[1]

[1] Ruhr-University Bochum, 44780 Bochum, Germany

Cosmic rays are charged particles (mainly protons) that bombard the Earth from all directions reaching energies up to 10 million times what can be archived by the most powerful man-made accelerator, the LHC. Their origin is difficult to trace, because cosmic rays are deflected by magnetic fields on their journey from their source to Earth. However, cosmic rays produce gamma-ray photons and neutrinos in interactions with matter and photon fields in or close to their source. Being neutral those secondary particles can travel undeflected and ultimately point back to the source. While gamma rays are not solely produced in interactions of cosmic ray protons, neutrinos provide a smoking-gun signature for acceleration of protons or heavier nuclei (see [1] for a recent review).
At the same time, unfortunately, neutrinos are difficult to detect and giant detector volumes are required. The first breakthrough in high-energy neutrino astronomy was the discovery of a diffuse flux of cosmic neutrinos by the cubic-kilometer-sized IceCube detector located at the South Pole in 2013 [2].
I will present the ongoing search for the origin of those neutrinos using multi-messenger studies and discuss promising candidate sources including the close-by galaxy NGC 1068 [3], an active galactic nuclei with a relativistic jet of ionized matter pointing in our direction (TXS 0506+056) [4], and AT2019dsg, a supermassive black hole shredding a star [5].



References

[1] M. Ahlers and F. Halzen, Progress in particle and nuclear physics, **102**, 73, 2018
[2] M.G. Aartsen et al., Science **342**, 6161, 2013
[3] M.G. Aartsen et al., PRL **124**, 051103, 2020
[4] M.G. Aartsen et al., Science **361**, 2018
[5] R. Stein et al., Nature Astronomy **5**, 510-518, 2021

Einstein Telescope instrument design and commissioning: a short tutorial on simulation tools

A. Freise[1]

[1]Nikhef, Science Park 105, 1098 XG Amsterdam, and Vrije Universiteit Amsterdam De Boelelaan 1085, NL-1081 HV Amsterdam, The Netherlands

Interferometric gravitational-wave detectors are highly complex instruments that consist of several closely coupled subsystems, such as seismic isolation systems, coupled optical resonators, and many layers of control systems. Each subsystem represents years of development and requires detailed knowledge to understand. In order to predict or analyse the behaviour of the full, coupled system we use powerful simulation software [1]. I will introduce some of important software tools, with a particular focus on our own simulation software package FINESSE [2,3]. The session will include a tutorial on how to use the software on your own laptop, either during or after the session.

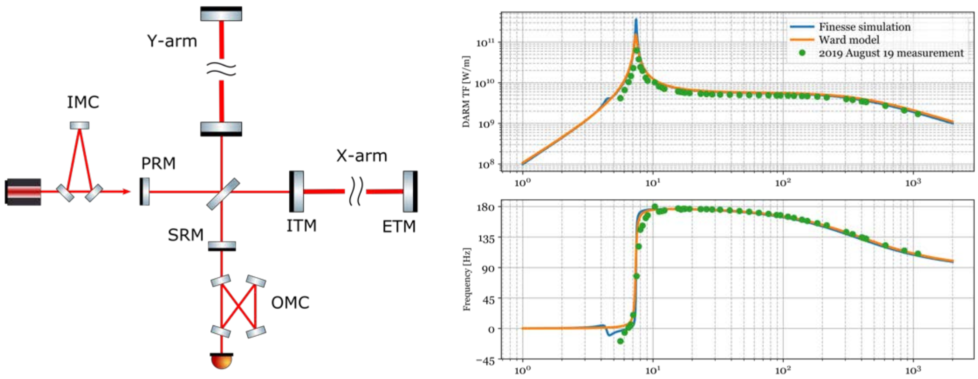


Figure 1: Finesse example, modelling and measuring the signal response of Advanced LIGO by Craig Cahillane, 2019. A sketch of the Advanced LIGO optical setup is shown on the left. The plot on the right shows the signal response to differential arm modulation.

References

[1] D. Brown and A. Freise: 'Simulation methods for advanced interferometers' in 'Advanced Interferometric Gravitational-Wave Detectors', World Scientific (2019)

[2] D. Brown, P. Jones, S. Rowlinson, S. Leavey, A.C. Green, D. Töyrä and A. Freise, 'Pykat: Python package for modelling precision optical interferometers', SoftwareX, 12, 100613 (2020)

[3] A. Freise, D. Brown et al., 'FINESSE 3', alpha release available at https://anaconda.org/conda-forge/finesse (2021)

The Einstein Telescope

S. Hild[1,2]

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[2] *Nikhef, Amsterdam, The Netherlands*

Building on the recent discoveries by LIGO and Virgo of gravitational waves from compact binary systems, a new class of gravitational wave observatories, the Einstein Telescope in Europe [1] and Cosmic Explorer [2] in the US, are being proposed to fully open up our observational capacity of the gravitational wave universe. This talk will give an overview of the ET design and its capabilities. In addition challenges and R&D opportunities related to new technologies are discussed.

References

[1] www.et-gw.eu
[2] cosmicexplorer.org

Nanophotonics for future gravitational wave detectors

Johannes Dickmann[1,2,3], Steffen Sauer[1,2], Liam Shelling Neto[1,2] and Stefanie Kroker[1,2,3]

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[3] Physikalisch-Technische Bundesanstalt, Braunschweig, Germany

Photonic nanomaterials provide a fascinating platform to tailor light fields in virtually arbitrary manner [1]. Amongst others, the spatial distribution of light can be controlled down to scales of a few tens of nm. This spatial control of light fields provides the possibility to reduce thermal noise of optical components in gravitational wave detectors and other high-precision optical devices. Here, particularly cavity components like input test masses and end test masses play a crucial role limiting the sensitivity of today's detectors [2,3].

Deliberately designed near-field distributions in highly reflective metasurfaces
can reduce the contribution of these optical components and thereby providing a sensitivity enhancement of a factor of about 10 [2-5]. This would give access to a plenty of yet undiscovered phenomena in our universe.

In this contribution, we give an overview on the development and possibilities of metamaterials for applications in future gravitational wave detectors. We explain important physical phenomena of light-matter interaction and illustrate the role of material properties in these experiments.

References

[1] A. S. Solntsev, G. S. Agarwal, Y. S. Kivshar, Nature Photonics 15 (2021)
[2] B. Sathyaprakash et al., Class. Quantum Grav. 124013 (2012)
[3] D. G. Matei et al., Phys. Rev. Lett. 118 (2017)
[4] J. Dickmann, S. Kroker, Physical Review D 98 (2018)
[5] S. Kroker, J. Dickmann, C. B. Rojas Hurtado, D. Heinert, R. Nawrodt, Y. Levin, S. P. Vyatchanin, Physical Review D 96 (2017)

Surpassing the Standard Quantum Limit of interferometry

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The sensitivity of interferometric gravitational wave detectors is limited by the quantum noise of the laser light, which is present in both amplitude and phase. It is possible to reduce either noise component at the expense of the other. Still, the achievable minimum of the total quantum noise is limited by the so-called standard quantum limit of interferometry in conventional setups. This limitation can be circumvented by generating and exploiting correlations between the two noise components. The presentation will give an intuitive explanation of the effects and techniques to overcome the SQL in third-generation gravitational wave detectors.

Squeezed states of light and their application in gravitational wave detectors

M. Mehmet[1,2]

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[2]*Leibniz Universität Hannover, Institut für Gravitationsphysik, Callinstr.38, 30167 Hannover, Germany*

Quantum engineering of non-classical light is of fundamental as well as applied interest. In particular, squeezed and entangled states of light enable fundamental research in quantum physics, e.g. on the famous Einstein-Podolsky-Rosen paradox and they allow for quantum enhanced metrology, most prominently demonstrated by providing a means to increase the astrophysical reach of current and future gravitational wave detectors.

Almost 40 years after squeezed vacuum states of light were proposed to improve the sensitivity of interferometric gravitational wave (GW) detectors [1], both the Advanced Virgo detector and the Advanced LIGO detectors have been operating with a quantum enhanced sensitivity during their third joint observation run O3 [2,3] from April 2019 to March 2020. Many years of experimental research focusing on developing the necessary concepts and technologies for the generation and application of squeezed light had been necessary to turn the conceptual idea of a non-classical sensitivity enhancement into a key technology which is now included in the baseline designs of all future earthbound GW interferometers.

In my talk I will introduce the basic concepts of squeezed light generation and detection as well as their application in GW detectors. Furthermore, I will present our work on the design and construction of the squeezed light source for the Advanced Virgo GW detector [4] and its integration on-site in Cascina, Italy, which was carried out in cooperation with the Virgo collaboration.

References

[1] Caves, C.M. Quantum-mechanical noise in an interferometer. Phys. Rev. D **23**, 1693–1708 (1981).

[2] Acernese, F., et al. Increasing the Astrophysical Reach of the Advanced Virgo Detector via the Application of Squeezed Vacuum States of Light. Phys. Rev. Lett. **123**, 231108 (2019).

[3] Tse, M., et al. Quantum-Enhanced Advanced LIGO Detectors in the Era of Gravitational-Wave Astronomy. Phys. Rev. Lett. **123**, 231107 (2019).

[4] Mehmet, M. and Vahlbruch, H. The Squeezed Light Source for the Advanced Virgo Detector in the Observation Run O3. Galaxies **8**, 79 (2020).

LISA

G. Mueller[1]

[1]University of Florida, Gainesville, FL, U.S.A.

Gravitational waves (GW) from sources involving black holes beyond a few thousand solar masses have frequencies below the reach of ground-based observatories. The study of these sub-Hz to uHz signals require space-based observatories with arm lengths somewhat comparable to the wavelengths of the detected GW. The Laser Interferometer Space Antenna (LISA) is the most advanced of these future projects [1]. It is optimized for a frequency band centered around a few mHz or the frequency band in which systems involving 10^4 to 10^7 solar mass black holes generate GW. The ESA-led mission consists of three spacecrafts in an almost equilateral triangle with 2.5 Gm arm lengths or 8.3 s light travel times between the spacecrafts.

LISA uses two free falling gold platinum cubes per spacecraft to map out the wiggles in the curvature of spacetime caused by GW along the line of sight to one of the other spacecrafts. The positions of these test masses within their host spacecrafts are measured using capacitive sensors and corrected using electro-static actuators along all non-sensitive degrees of freedom. Along the interferometer axis, the host spacecraft is steered around both test masses keeping them centered inside their housings. These drag free gravitational reference sensors have been successfully tested in space by the LISA Pathfinder mission [2].

The distances between these test masses will be measured using optical heterodyne interferometry. This technique is reminiscent of Doppler ranging using active transponders instead of a simple reflections. However, the required sensitivity goes many orders of magnitude beyond what has been achieved before. The cancellation of laser frequency noise and of clock noise using time delay interferometry or the subtraction of apparent length changes caused by spacecraft jitter are examples of many technologies which have been demonstrated in some representative setting but still need to be successfully employed by LISA itself.

However, LISA is only the beginning of exploring the universe using sub-Hz GWs. Future missions — often based on LISA principles — target other frequencies and require to continuously improve these technologies [3]. I will try to give an overview of the status and future avenues for improvements of these critical technologies.

References

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2. M. Armano et al., LISA Pathfinder, arXiv:1903.08924
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Basics of Gravitational-wave Data Analysis with PyCBC

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In this hands-on tutorial, we'll get experience using the basic techniques of gravitational-wave data analysis used to identify signals. This tutorial covers essential signal processing, fourier transforms, power spectral density estimation, and matched filtering using the PyCBC python library. Participants will be challenged to identify gravitational-wave signals in mock data sets.

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AMPEL: Connecting Theoretical Models with Multi-Messenger Data Streams

J. Nordin[1]

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AMPEL is a modular software framework designed to allow multi-messenger models to be exposed to complex sets of input data-streams.[1] Such tools become essential if we wish to make use of the full capabilities of upcoming astronomical facilities: we will have access to multiple data streams, each of which delivers alerts at a higher rate and where each alert contains more detailed data compared with what is currently available.

In this tutorial we walk through the sample case of how a model for the merger of two neutron stars, and the resulting kilonova, can be (i.) shaped into a model suitable for real-time usage and distribution, (ii.) locally tested based on sample data, (iii.) used to examine archive LIGO/Virgo/ZTF data for potential counterparts and (iv.) submitted for real-time exposure to future GW triggers. We will also comment on the importance of provenance and collaborative software development in the emerging world of large collaborations and once-in-a-lifetime combinations of time-domain sources.

AMPEL has already helped change real-time astronomy in terms of (e.g.) finding Tidal Disruption Events [2], looking for potential counterparts of GW triggers [3], and connecting extragalactic neutrinos with source classes [4]. Finally, we will outline how AMPEL in the coming years will make data from (among others) the Rubin Observatory, IceCube, CTA and GW detectors available for community access.

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Perspectives for Astrophysical Inference with Gravitational Waves

V. Raymond[1]

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We are now firmly in the era of gravitational-wave astronomy as a successful, discovery-rich observational science. One of the most important keys to opening this new window on the Universe is the astrophysical inference of the sources of gravitational waves. Parameter estimates and signal model comparisons are among the most sought-after results in the field in order to fulfill its most ambitious promises. Those include studying the distribution and history of invisible compact objects, measuring the equation of state of matter at the ultimate density, or testing General Relativity.

In this introductory talk I will summarize some of the techniques used in the characterization of gravitational-wave sources. I will also discuss some of the future perspectives of astrophysical inference with gravitational waves; some of the many challenges ahead and some of the even more numerous opportunities in the future of the field.

Listening to the Universe with the Next Generation of Ground-Based Gravitational-Wave Detectors

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Abstract: LIGO and Virgo have made phenomenal new discoveries that are already making waves in a range of fields from fundamental physics to cosmology. This talk will highlight the science impact of the discoveries so far and the potential of future detectors. Planned upgrades of LIGO and Virgo will discover events from new corners of the parameter space. The next generation of ground-based detectors will observe coalescences of black holes and neutron stars throughout the cosmos, thousands of them with exceptional fidelity. This talk will also discuss how such observatories would make it possible to address unsolved problems in numerous areas of physics and astronomy, from Cosmology to Beyond the Standard Model of particle physics, and how they could provide insights into workings of strongly gravitating systems, astrophysics of compact objects and the nature of dense matter. It is inevitable that observatories of such depth and finesse will make new discoveries inaccessible to other windows of observation.

Does GW Astronomy have a long term future?

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[2] *Albert Einstein Institute, Potsdam, Germany*

The remarkable achievements of LIGO and Virgo since 2015 are set, not just to continue, but to accelerate for most of the current decade, thanks to the addition of KAGRA and LIGO-India and to hardware upgrades already funded. Moreover, we can confidently expect that LISA will be launched in the mid-2030s. Our success so far has also led to widespread confidence that the next generation of ground-based detectors (ET and CE) will begin operation with some overlap with LISA and continue much longer. But a reading of the long and often difficult history of our field before 2015 might suggest that this confidence could turn out to be misplaced. I will attempt to draw some lessons from our past that might be worth paying attention to as we begin to lay the foundations of our long-term future.

Strategies and prospects for electromagnetic observations of gravitational wave sources

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Merging compact binaries that involve neutron stars are intense sources of gravitational waves (GW) that can be detected by current generation detectors to distances of several hundred Mpc[1]. In at least some cases produce kilonova explosions, and launch outflows leading to short-duration gamma-ray bursts. Thus, the combination of electromagnetic and GW observations of these events shed light on the nucleosynthesis of heavy elements, the acceleration and shocking of ultra-relativistic jets, and questions of fundamental physics. Although important breakthroughs have been made in the last decade[2,3], realising the promise of this new field in coming years remains challenging both in terms of the observational difficulties and theoretical interpretation. I will review these efforts and requirements in the context of the likely evolution of gravitational wave detector capabilities in the coming years and decades.

References

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[2] N. Tanvir et al., Nature **500**, 547 (2013)
[3] B. Abbott et al., Astrophysical Journal **848**, L12 (2017)

Abstracts of Posters

(in alphabetical order)

Gravitational Waves from Core-collapse Supernovae

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Core-collapse supernovae are among the brightest transients known to astrophysicists, but traditional optical observations provide little insight into the mechanism driving the explosions of massive stars. Gravitational waves, on the other hand, are excellent probes of the physical processes taking place in the cores of exploding stars. I will summarize our current, theoretical, understanding of the gravitational radiation emitted by core-collapse supernovae and highlight interesting problems that still exist.

Primordial Binaries in Dense Stellar Clusters

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Most stellar progenitors of black holes are found in binaries. My work focuses on the formation of black hole binary mergers in dense star clusters; in particular, I study the effect of primordial binaries on the secular evolution of the cluster and the resulting population of merging black hole binaries. Here I will present results from two distinct types of models. First, an isolated binary formation model using the rapid binary population synthesis code COMPAS. Second, a dynamical model using the N-body code PeTar which models a star cluster, taking into account both dynamical interactions as well as stellar evolution. We find that the initial binary fraction among black hole progenitors is an important parameter to consider for globular cluster models and has a significant effect on the resulting population of merging black hole binaries.

Preparing for Gaia and BlackGEM Searches for Electromagnetic Counterparts during O4

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Motivated by the recent developments in the field of multimessenger astronomy and the expected commencement of LIGO/Virgo's next observing run (O4) later this year, ESA's Gaia satellite and the three dedicated telescopes of BlackGEM (Chile) will be contributing to the electromagnetic (EM) follow-up of gravitational wave (GW) events. This will be the first time Gaia contributes to the search for EM counterparts of GW events, and a new alerts stream called GaiaX [1] has been introduced to do the same. On the other hand, BlackGEM has been specifically designed to optically follow-up GW events, and will be operational in time for O4.

Ahead of O4, an experiment was executed to test the various transient detection pipelines related to both these missions, in Sep-Oct 2021. Since BlackGEM was not yet operational at the time, MeerLICHT (South Africa), an operational prototype of BlackGEM, was used to take contemporaneous observations with Gaia. We then analysed the data to understand and test the detection algorithms of both, before the start of O4. In this poster, I will explain the current status of our work and how Gaia and BlackGEM will contribute to the search for EM counterparts to GW events during O4.

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Assessing gravitational waveform accuracy with the kick velocity

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Gravitational waveform models need to be accurate enough to make unbiased interpretations of the observed gravitational-wave events. The accuracy of gravitational-wave models of compact binaries has traditionally been addressed through the mismatch error between the model and numerical-relativity simulations. Here we propose the use of a more sensitive and complementary tool to investigate the performance of waveform models: the estimate of the kick velocity. The prediction of the kick velocity is highly sensitive to the intrinsic inaccuracies of gravitational-wave models. In addition, the estimate involves the description of the gravitational-wave signal during the strongly relativistic and highly dynamic merger regime, the region where the largest modelling errors may appear in the models. In this work, we investigate the accuracy of four state-of-the-art waveform models of binary black holes using the kick velocity. We find that the SEOBNRv4HM_ROM, IMRPhenomHM, IMRPhenomXHM and NRHybSur3dq8 models, used in current gravitational-wave studies, are not consistent in their kick predictions. Our results provide new insights on waveform modelling errors and support the use of the kick estimate to evaluate waveform accuracy. Besides, we discuss how numerical-relativity estimates of the kick velocity could be used to calibrate current gravitational-wave models further, proposing the first steps towards kick-based gravitational-wave tuning.

Simple, efficient method of calculating the Detweiler-Whiting singular field

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For a toy scalar-field model, we compute analytically the singular field via a novel method to 12th order in radius to the particle. To demonstrate the method, we fix the scalar particle on a circular orbit in Schwarzschild space-time. The singular field is computed without the need to invoke Green's functions, as is done traditionally. We show that our method is both conceptually more natural and efficient in computing the puncture field at very high order.

Impact of Massive Binary Star and Cosmic Evolution on Gravitational Wave Observations II: Double Compact Object Rates and Properties

Floor S. Broekgaarden,[1] Edo Berger,[1] Simon Stevenson,[2,3] Stephen Justham,[4,5,6,7] Ilya Mandel,[8,3,9] Martyna Chruślińska,[7,10] Lieke A. C. van Son,[1,6,7] Tom Wagg,[11,1,7] Alejandro Vigna-Gómez,[12,13] Selma E. de Mink,[7,6,1] Debatri Chattopadhyay,[2,3] Coenraad J. Neijssel[9]

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Making the most of the rapidly increasing population of gravitational-wave detections of black hole (BH) and neutron star (NS) mergers requires comparing observations with population synthesis predictions. In this work we investigate the combined impact from the key uncertainties in population synthesis modelling of the isolated binary evolution channel: the physical processes in massive binary-star evolution and the star formation history as a function of metallicity, Z, and redshift z, S (Z, z). Considering these uncertainties we create 560 different publicly available model realizations and calculate the rate and distribution characteristics of detectable BHBH, BHNS, and NSNS mergers. We find that our stellar evolution and S (Z, z) variations can impact the predicted intrinsic and detectable merger rates by factors 100–10 000. We find that BHBH rates are dominantly impacted by S (Z, z) variations, NSNS rates by stellar evolution variations and BHNS rates by both. We then consider the combined impact from all uncertainties considered in this work on the detectable mass distribution shapes (chirp mass, individual masses and mass ratio). We find that the BHNS mass distributions are predominantly impacted by massive binary-star evolution changes. For BHBH and NSNS we find that both uncertainties are important. We also find that the shape of the delay time and birth metallicity distributions are typically dominated by the choice of S (Z, z) for BHBH, BHNS and NSNS. Our work demonstrates that it is essential to consider a wide range of allowed models to study double compact object merger rates and properties. Conversely, larger observed samples could allow us to decipher currently unconstrained stages of stellar and binary evolution.

Exploring SMBH progenitors with LISA

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We study hydrodynamical simulations of galaxy formation, based on the GADGET-3 code, and investigate supermassive black hole(SMBH) binaries coalescence at $5.5<z<12$ and the expected gravitational waves (GW) emitted from the binary mergers for different AGN feedback models. . We consider the cases of AGN fiducial feedback where the feedback energy is thermal, as well as kinetic feedback. We further consider the case in which no AGN feedback is implemented in the simulation. We compare the merger rate for different feedback scenario and various chirp mass ranges and compare our results with contemporary literature. For each model, we estimate the expected characteristic strain of GW emitted by SMBH binary mergers, the time to coalesce, and the expected number of resolved events and compare our predictions with the LISA sensitivity and resolution.
We further investigate the host galaxy properties for the events detectable by LISA and make predictions of the electromagnetic counterparts expected events to be detected by other EM instruments operating along the proposed operational time of LISA and present a panoramic view of merger events through different detectors.

Modelling the formation of the first two neutron star-black hole mergers, GW200105 and GW200115: metallicity, chirp masses and merger remnant spins

Debatri Chattopadhyay[1,2,3], Simon Stevenson[2,3], Floor Broekgaarden[4], Fabio Antonini[1], and Krzysztof Belczynski[5]

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Abstract

The two neutron star-black hole mergers (GW200105 and GW200115) observed in gravitational waves by advanced LIGO and Virgo, mark the first ever discovery of such binaries in nature. We study these two neutron star-black hole systems through isolated binary evolution, using a grid of population synthesis models. Using both mass and spin observations (chirp mass, effective spin and remnant spin) of the binaries, we probe their different possible formation channels in different metallicity environments. Our models only support LIGO data when assuming the black hole is non spinning. Our results show a strong preference that GW200105 and GW200115 formed from stars with sub-solar metallicities $Z \lesssim 0.005$. Only two metal-rich ($Z = 0.02$) models are in agreement with GW200115. We also find that chirp mass and remnant spins jointly aid in constraining the models, whilst the effective spin parameter does not add any further information.

Gravitational wave sources care about metallicity dependent cosmic star formation history

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How exactly nature turns massive stars into close black hole and neutron star binaries (double compact objects - DCO) that can be observed with gravitational waves (GW) - remains an open question with many possible answers.
One of the challenges with finding a meaningful answer to this question is that it has to be considered in the context of chemically evolving Universe. We show that the properties of the populations of DCO mergers are sensitive to the metallicity dependent cosmic star formation history [1].
We develop a framework to empirically characterise this quantity [2]. To build our observation-based model, we assemble and combine a large set of literature results describing the properties of star forming galaxies. In a series of papers, we quantify the uncertainty of our result due to factors such as: the ambiguous absolute metallicity scale and metallicity evolution at high redshift, poorly constrained properties of the low mass/faint galaxies, IMF variations or contribution of starbursts [2][3][4].
We show that current uncertainty of the metallicity-dependent cosmic star formation history severely limits our ability to use gravitational wave observations to constrain the origin of the detected sources. At the same time, our results indicate that constraints that will be obtained with future GW observations are invaluable to understand the fate of galaxies across cosmic time.

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Università degli Studi di Padova

March 25, 2022

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TITLE:

Never two without three: binary black hole mergers via three-body interactions

ABSTRACT:

Since the first detection of gravitational waves in 2015, the population of compact binary objects has grown year after year, counting now more than 60 confirmed binary black hole mergers detected with ground-based interferometers. With such a rapidly increasing population, more and more questions are arising. First, the detection of some systems with primary black hole mass inside the pair-instability mass gap seems to suggest the existence of a pathway to produce massive black holes inside this deserted mass range, between ~ 50 to 100 solar masses. Second, the spin magnitudes derived from gravitational wave signals favor low-spin black holes, in strong contradiction with the population of black holes observed in X-ray binaries. Finally, several systems seem to present misaligned spins at the moment of the merger, with a consequent precession effect in the final moments of the binary.

In my poster, I show how three-body encounters between a binary and a single black hole may represent a way out to solve this black hole population puzzle. Three-body interactions are the most frequent kind of dynamical encounters that can take place between black holes inside crowded stellar environments. Starting from the results of my N-body simulations, I present how these interactions differently affect the black hole population of young, globular, and nuclear star clusters and what is their role in the formation of binary black hole mergers. The mass, spin, and eccentricity of the black hole binaries are strongly influenced by these interactions and by the hosting environment. Different properties may therefore be used as fingerprints to derive the birthplace of these mergers from the observations, and thus to solve these still-open questions.

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Black hole mergers via three-body interactions in young, globular and nuclear star clusters, Dall'Amico et al., in prep.

Gravitational wave astrophysics of stellar-mass remnants: the population view

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After the first three observing runs of the advanced gravitational-wave detector network, the detected signals – from merging binary neutron star, binary black hole and mixed binary sources – have raised more puzzles and unanswered questions than they have answered. Both the mass and spin distributions of black holes differ strongly from those previously seen in X-ray systems, while also not following expectations from stellar evolution and supernova models. The mass distribution of neutron stars in merging binaries is also broader than that seen in galactic binaries. In order to clarify and motivate investigation of possible formation channels that may have led to these features, a statistical analysis of the observed systems including effects from selection (Malmquist bias), source parameter uncertainties, and finite (small) event counts is required. I will present results of such population analyses using data from the LIGO-Virgo network [1], addressing questions such as the evidence for features in the remnant mass distribution beyond power law behaviour [2], and the magnitude and (lack of) alignment of black hole spins, which will ultimately help to disentangle the binary formation paths.

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Leveraging gravitational-wave memory to distinguish neutron star - black hole binaries from black hole binaries

M. Ebersold[1], S. Tiwari[1] and E. Hamilton[1]

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To confidently distinguish a neutron star - black hole binary (NSBH) from a black hole binary (BBH) by means of their gravitational-wave (GW) signal, one needs to measure tidal effects. These are encoded in the phasing of the signal and in the case of tidal disruption an abrupt cutoff of the signal amplitude occurs. We show that tidal effects are also captured by the nonlinear memory of the GW signal. Although small in amplitude, nonlinear memory is present at low frequency in contrast to the oscillatory GW signal. By adding memory to the NSBH and BBH waveform models we show how it aids in distinguishing these systems. We discuss the recently detected events of interest by LIGO-Virgo and provide the future prospects for the third generation detectors where memory can play a crucial role in inferring the nature of the coalescence from its GW signal alone.

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IMRPhenomXE: Towards computationally efficient eccentric waveform models

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Waveform models are an essential tool to extract physical information from the gravitational wave signals registered in our detectors. They provide theoretical predictions for the full solution of Einstein's equations, the more accurate they are, the more insight we gain of the emitting source. With the increasing sensitivity of the detectors, not only the models need to become more accurate and include all kinds of physical effects, but they also need to be computationally efficient to cope with the increasing number of GW events. Here we present one first step within the IMRPhenomX family of waveform models to include the effect of small eccentricities in binary black hole systems. This first model will set the cornerstone for future eccentric models that will include further physical effects like subdominant harmonics and precession.

Identifying basic properties of postmerger BNS GW signals with simplified templates

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The Gravitational wave postmerger signal produced by the coalescence of a BNS system carries information about the hypermassive or supramassive NS remnant dynamics. It is a unique tool to test the validity of several existing models that intend to describe the equation of state of extreme matter. Its complex morphology requires a large parameter space to fully describe it, making parameter estimation a computationally expensive task.

This work investigates how much SNR one can recover from the postmerger BNS GW signal by using the matched filtering algorithm and considering: A simple finite monochromatic template model with 2 degrees of freedom: frequency, and duration; A set of 164 numerical relativity waveforms from the CoRe BNS catalog, and several detector noise spectral densities.

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Coherent and squeezed light at 2128 nm for future gravitational-wave observatories

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Current gravitational-wave observatories use intense coherent laser light and squeezed light at the wavelength of 1064 nm. The observatory noise is dominated by coating thermal noise in the mid-range of the detection spectrum and by quantum noise at high frequencies. Changing the laser wavelength from 1064 nm to around 2 µm would allow the usage of crystalline silicon test masses and coatings with reduced thermal noise. Here, we report the detection of (7.2 ± 0.2) dB squeezing at 2128 nm at MHz frequencies [1]. Different from the established approach [2,3], no second harmonic generation is required because the pump light is provided by a nonplanar ring oscillator (NPRO) at 1064 nm. Stable intense light at 2128 nm was produced by a home-built degenerate optical oscillator (DOPO) with an external conversion efficiency of greater 88 % at a 1064nm pump power of 52 mW in periodically-poled potassium titanyl phosphate [4].

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A novel particle detector for monitoring the Cosmic Ray flux at advVirgo

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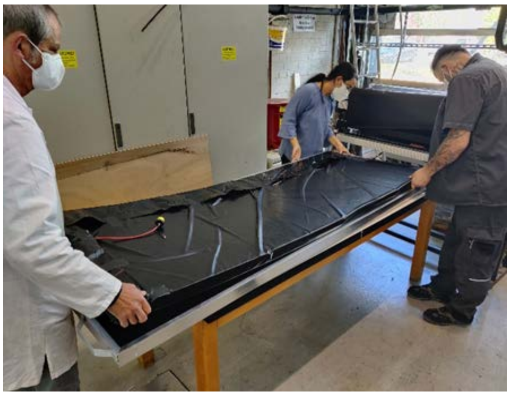
Single muons from extensive air-showers, originated in the interaction between cosmic rays and the Earth’s atmosphere, can propagate into low noise facilities, like underground research laboratories or gravitational wave detectors, and can contribute to the noise level of the experiments. The goal is to investigate and veto these possible systematic effects by single muons on the mirrors and the entire interferometer, and by that, to improve the overall sensitivity of the instrument.

For this purpose, a monitoring system based on a network of scintillators is in development. The scintillation detectors presented here are readout with Silicon Photomultipliers (SiPMs) and are based on detectors developed for the surface instrumentation of the IceCube Neutrino Observatory.

These R&D detectors can be seen as a blueprint for monitoring instruments of next-generation gravitational wave experiments, such as the planned Einstein Telescope. The contribution includes R&D ideas towards an appropriate data acquisition (DAQ) system for the distributed network of scintillators, developing a real time monitoring data stream for the Einstein-Telescope and as well as the handling of the measurement data and its analysis.



Negative-mass oscillator for coherent quantum noise cancellation

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Gravitational-wave detectors in the current state are still subject to numerous noise sources, limiting the measuring capabilities due to the unfavorable signal-to-noise ratio. A cap to these measurements is the standard quantum limit (SQL), which is defined by quantum shot noise (SN) and the quantum backaction (QBA) noise due to radiation pressure. Our solution to the confinement by the SQL is based on the coherent quantum noise cancellation (CQNC) scheme as in [1]. As opposed to the integrated system in [1], we show how a simpler cascaded system that includes two subsystems achieves the same. The first subsystem is an optomechanical positive-mass oscillator which achieves a QBA noise-limited light field. In this poster, the second subsystem is explained. This is an 'effective negative mass oscillator (eNMO)' which is an all-optical system consisting of a beam-splitter (BS) and down-conversion (DC) process. The combination of these ideally should result in evading the back-action noise. The eNMO is characterized and optimally matched to the optomechanical system [2].

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Test setup for cryogenic sensors and actuators working towards the Einstein Telescope

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The Einstein Telescope will be the first gravitational wave detector of the third generation. The sensitivity goal, especially in the low frequency region, will be achieved among other improvements by cooling the main parts of the interferometer. The required electronic components, sensors and actuators needed for mirror alignment and active dampening of suspension resonances have to perform at cryogenic temperatures.

In this poster we will present our work on electronics and mechanics within the E-TEST project. Furthermore the performance of our cryogenic UHV test setup will be explicated.

Visualizing Neutron Star Merger Remnants

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Abstract

Numerical simulations of binary neutron star mergers have made a lot of progress. They enable us to predict many important observables such as the gravitational wave signal, the properties of dynamically ejected matter, and the formation of a black hole. However, such simulations are very expensive. In order to interpret observational data from multi-messenger gravitational wave astronomy, we still need methods to predict quickly the observable outcome for given parameters. Constructing predictive models requires a good understanding. Therefore, postprocessing and visualization of raw numerical simulation data becomes increasingly important. This is a nontrivial task that requires combining existing software with custom developments. Here, we show an example postprocessing chain that turns raw data into 3D raytraced images and movies that visualize important aspects of neutron star merger remnants.

Post-merger gravitational wave searches using the Cross-Correlation Algorithm

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After the multi-messenger detection of the binary neutron star merger GW170817, associated with gamma-ray burst (GRB) 170817a, one big open question left is the nature of the compact remnant which acts as a central engine for the GRB. In the context of cosmological GRBs, it has been suggested that X-ray afterglows showing light curve plateaus at timescales of order ~10^2- 10^4 s since the GRB/merger could harbor a long-lived central engine, such as a long-lived highly magnetized NS (magnetar). Newly born magnetars have also been proposed as potential gravitational wave (GW) sources. Motivated by these considerations, we present first results from a new GW data analysis method (the Cross Correlation Algorithm - CoCoA) targeting long-lived GWs from magnetars formed in binary NS mergers associated with GRBs. We show how our search method improves substantially on previously published results for post-merger GW searches in GW170817, but requires a more restrictive hypothesis on the GW signal properties. We conclude by discussing the prospects for these types of searches in future runs of the LIGO detectors.

Coincident Detection of Cherenkov Photons from Electrons for Medical Applications

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The need for medical imaging devices capable of detecting high energy photons prompts research into new detection methods such as Compton camera in nuclear medicine. A new detection method for Compton electrons using Cherenkov radiation is proposed in this work as a proof of principle. Electrons from beta minus decay of Strontium 90/Yttrium 90 with energies up to 2.28 MeV are used. They are directed through a vacuum channel within which an EM field from an electromagnet allows only a specific energy to reach a collimator at the end of the path. After the collimator, the energy spread of the electrons is less than 6% around the nominal energy which can vary between 0.5 and 2.28 MeV. The electrons subsequently reach a radiator material (PMMA) and produce Cherenkov photons, which are detected via a 8x8 Silicon-Photomultiplier array with 64 readout channels. For each electron, the Cherenkov photons are collected within a time-window of 100 ns. The spatial distribution of the Cherenkov photons and their total number are recorded and will be investigated as a function of electron energy, and the results will be compared with theoretical data.

Compensating decoherence of squeezed light in cavity-enhanced quantum metrology

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Quantum states of light are being more commonly used to increase the sensitivity of various sensors. They allow to reach high sensitivity without using significant light power, and thus find application in various fields, from biological sensing to gravitational-wave detection. At the same time, these states are very fragile, and even a small amount of decoherence can significantly reduce their benefit. While modern metrological devices benefit from the best optical components, they are never devoid of some loss, which leads to decoherence. For example, this limits benefit from using quantum-squeezed light for enhancing the sensitivity of cavity-enhanced detectors, such as gravitational-wave detectors. We propose a new approach that allows to compensate part of quantum decoherence, thus increasing the sensitivity beyond the previously established decoherence-induced quantum limit [1]. To achieve this, we use an optimally tuned quantum squeezer placed directly inside the detector cavity [2]. This squeezer operates to restore the externally injected squeezing or to amplify the signal, depending on the level of loss. It can be flexibly tuned to the optimal operation [3, 4]. We present the first experimental combination of intra-cavity and externally injected squeezing used to enhance detector's sensitivity. We demonstrate for the first time how optimal tuning allows to compensate quantum decoherence. Finally, we derive the new decoherence-induced quantum limit. Based on this approach, we develop the quantum expander for the detection bandwidth of GW detectors, which allows to significantly increase the sensitivity at high frequencies [3, 4].

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Opto-mechanics in coherent quantum noise cancellation

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Gravitational wave detectors in the current state are still subject to numerous noise sources, limiting the measuring capabilities due to the unfavorable signal to noise ratio.
A cap to these measurements is the standard quantum limit (SQL), which is defined by quantum shot noise and the quantum back action (QBA) noise, due to radiation pressure. Our solution to the confinement by the SQL is based on the coherent quantum noise cancellation scheme proposed by Tsang and Caves [1].
Our approach utilizes a cascaded all optical setup, with an opto-mechanical oscillator (OMO) and an effective negative mass oscillator [2] (eNMO), consisting of a beam-splitter (BS) and down-conversion (DC) process. This eNMO interacts with the opto-mechanically generated QBA noise limited light field and therefore cancels it.
In this poster, we present the opto-mechanical side of the coherent quantum noise cancellation (CQNC) scheme to elaborate on the opto-mechanical coupling and under which conditions it is achieved.
For the interaction/coupling between photons of the light-field and phonons of a micro-mechanical oscillator to be satisfying for CQNC, cryogenic conditions and ultra-high vacuum are needed.
To enhance the otherwise weak coupling of the micro-mechanical oscillator (100nm thick silicon nitride membrane), it is used as part of an optical cavity. Furthermore we analyse the characterization and the parameter matching of this positive mass oscillator and modify it, to satisfy the CQNC requirements.

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Quantifying modeling uncertainties when combining multiple gravitational-wave detections from binary neutron star sources

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With the increasing sensitivity of gravitational-wave detectors, we expect to observe multiple binary neutron-star systems through gravitational waves in the near future.
The combined analysis of these gravitational-wave signals offers the possibility to constrain the neutron-star radius and the equation of state of dense nuclear matter with unprecedented accuracy. However, it is crucial to ensure that uncertainties inherent in the gravitational-wave models will not lead to systematic biases when information from multiple detections are combined. To quantify waveform systematics, we perform an extensive simulation campaign of binary neutron-star sources and analyze them with a set of four different waveform models.
For our analysis with 38 simulations, we find that statistical uncertainties in the neutron-star radius decrease to ±250m (2\% at 90\% credible interval) but that systematic differences between currently employed waveform models can be twice as large. Hence, it will be essential to ensure that systematic biases will not become dominant in inferences of the neutron-star equation of state when capitalizing on future developments.

Current and future constraints on cosmology and modified gravitational-wave friction from binary black holes

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Gravitational wave (GW) standard sirens are well-established probes with which one can measure cosmological parameters, and are complementary to other probes like the cosmic microwave background or supernovae standard candles. Here we focus on dark GW sirens, specifically binary black holes (BBHs) for which there is only GW data. We rely on the assumption of a source mass model for the BBH distribution, and we consider four models that are representative of the BBH population observed so far. In addition to inferring cosmological and mass model parameters, we use dark sirens to test modified gravity theories. These theories often predict a different GW propagation, leading to a changed GW luminosity distance which in some cases can be parametrized by variables Ξ_0 and n. General relativity (GR) corresponds to $\Xi_0 = 1$. We perform a joint estimate of the population parameters governing mass, redshift, cosmology, and GW propagation. We use data from the third LIGO-Virgo-KAGRA observation run (O3) and find — for the four mass models and three signal-to-noise cutoffs — that GR is consistently the preferred model to describe all observed BBH GW signals to date. Furthermore, all modified gravity parameters have posteriors that are compatible with the values predicted by GR at the $90\,\%$ confidence interval. We then focus on future observation runs O4 and O5. We show that there are strong correlations between cosmological, astrophysical and modified gravity parameters. If GR is the correct theory of gravity, and assuming narrow priors on the cosmological parameters, we recover the modified gravity parameter $\Xi_0 = 1.47^{+0.92}_{-0.57}$ with O4, and $\Xi_0 = 1.08^{+0.27}_{-0.16}$ with O4 and O5. If, however, Nature follows a modified gravity model with $\Xi_0 = 1.8$ and $n = 1.91$, we exclude GR at the 1.7 σ level with O4 and at the $2.3\,\sigma$ level with O4 and O5 combined.

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Novel approaches in multimessenger observation of core-collapse supernovae

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This contribution presents a novel machine learning approach in the field of multimessenger astronomy by investigating possible correlation between features in gravitational waves (GW) and neutrino signals originating from core collapse supernovae (CCSN). Overarching phenomena during the explosion process can be so better understood, such as the suspected standing accretion shock instability (SASI) or oscillation modes of the newly formed proto-neutron star. Applying machine learning on combined GW- and neutrino-detector outputs from simulated CCSN can enable us a potential reconstruction of these crucial moments and more parameters such as the shock radius during the explosion.

Finding Universal Relations using Statistical Data Analysis

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The successful detection of gravitational waves from binary neutron star (BNS) mergers through the LIGO-VIRGO detectors has opened a new avenue into probing and understanding the structure of neutron stars and will hopefully allow us to eventually uncover their true equation of state (EoS).
Important tools for this task are EoS independent - or *(approximately) universal* - relations that allow for the inference of neutron star bulk parameters through information extracted from gravitational waves. Inspired by early work on such universal relations for single neutron stars, the last five years have also given rise to universal relations for binary neutron stars (BNS): they relate features of the pre-merger neutron stars to the early and late post-merger remnant.

Following our own recent work on universal relations for BNS using perturbative calculations [1], we found that the traditional method of relying on physical intuition to find universal relations might not always uncover all possible or the best universal relations for a given scenario. Instead, with the increasing number of features and amount of data that simulations are able to produce, an automated approach fueled by statistical data analysis might yield better results in finding highly correlated features, and the best functional form to relate them with.
With this poster, we present our ongoing work in investigating the application of statistical data analysis methods from both bi- and multivariate statistics to find suitable sets of neutron star features that can be leveraged for accurate and EoS independent relations. To this end, we analyze the statistical power of various correlation measures such as Distance Correlation and Mutual Information in identifying suitable pairs of features. We also evaluate the accuracy of relations produced by methods of multiple regression such as Principal Component Regression to assess their suitability for producing universal relations with multiple independent variables.
Our preliminary results support this approach through, both, the successful reconstruction of already known universal relations, as well as the extraction of entirely novel relations.

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Machine learning applications to modelling compact binary waveforms

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Machine learning methods are rapidly becoming more important in gravitational wave science, to distinguish signals from noise, for parameter estimation, and to model the signals across high dimensional parameter spaces [1]. In this work we investigate the use of machine learning as a way of fitting the coefficients in phenomenological waveform models across the parameter space, focusing on the parameter space of precessing black hole binaries. We first train an aligned spin and then a precessing deep learning model with numerical relativity (NR) simulations from the SXS catalog [2] in order to predict the remnant quantities of the source. We add analytical knowledge to our training dataset in the extreme mass ratio regime and physical boundaries in our predictions, and discuss the application to other quantities.

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Correlations of astrophysical neutrinos with physical properties of Active Galactic Nuclei cores

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The source of the majority of the high-energy astrophysical neutrinos observed by IceCube remains unknown. Several studies lead us to think that the core of Active Galactic Nuclei (AGN) can produce high energy neutrinos in the accretion disk, via the acceleration of cosmic rays. A recent stacking analysis[1] has shown a 2.6σ correlation between the neutrino signal and an infrared (IR) selected sample of ~32,000 AGN sources using 8 years of IceCube data. We propose to further this analysis by characterising the physical properties of the AGN sources in the catalogue. To do so, we train a neural network on a set of SDSS observed AGN sources, completed by the SPIDERS programme[2]. This catalogue of over 7000 sources combines multi-wavelength (X-ray, IR, optical) with spectroscopic observations, providing estimates of black hole masses, bolometric luminosities, and Eddington luminosities and ratios. We show results of results of the predictive power of the neural network and its future usage in order to for the neutrino signal strength dependence on the central black hole mass and Eddington ratio of the AGN cores.

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Searching for long-duration transient gravitational waves from glitching pulsars using Convolutional Neural Networks

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Pulsars are spinning neutron stars which emit an electromagnetic beam. We expect pulsars to slowly decrease their rotational frequency due to the radiation emission. However, sudden increases of the rotational frequency have been observed from different pulsars. These events are called "glitches", and are followed by a relaxation phase with timescales from days to months. Gravitational-wave (GW) emission may follow these peculiar events, including long-duration transient continuous waves (tCWs) lasting hours to months. These are modeled similarly to continuous waves but are limited in time. Previous studies have searched for tCWs from glitching pulsars with matched filtering techniques and by computing a detection statistic, the F-statistic, maximized over a set of transient parameters like the duration and start time of the potential signals [1-2]. This method is very sensitive, but the computational costs can easily increase when widening the frequency and spindown search bands and the duration of the potential signals.
In order to reduce computational and human effort, we present a procedure for detecting potential tCWs using Convolutional Neural Networks (CNNs). CNNs have proven to be valid networks for detecting various CW signals, but have never been tested on tCWs from glitching pulsars. For our initial configuration, we train the CNN on F-statistic "atoms", i.e. quantities computed during the matched filtering step from signal/noise data. This still constrains the frequency evolution of the signal to be CW-like, but already allows for flexible amplitude evolution and significant speed-up compared to the traditional method. In the future, we also plan to implement a second CNN with input the frequency-time maps, which in this case can search for unmodeled tCWs both in frequency and amplitude evolution, which we expect to be a further improvement to the speed and performance of the search.

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Prospects for detecting long-duration transient gravitational waves from glitching pulsars with current and future detectors

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Continuous waves (CWs) are a particular kind of gravitational waves (GWs) not detected yet, with typically much lower amplitudes than transient GWs but long-lasting. Many neutron stars emit electromagnetic radiation while they rotate at a nearly fixed frequency: this is what we know as pulsars. Even though pulsars slow down while they lose energy, they can suffer glitches: spontaneous increases of their rotational frequency which can also lead to the emission of long-duration transient GWs with intermediate characteristics between CWs and traditional transients.

Different studies have shown that an increase in the sensitivity of GW detectors is indispensable for measuring new types of GWs. Existing ground-based detectors are currently being improved for the next observation run (O4) and a new generation of detectors will be built, like the Einstein Telescope, which will improve sensitivity by an order of magnitude and also open up lower frequencies for observation.

We present detection prospects for glitching pulsars by comparing data of known pulsars with the sensitivity of different future detectors. First we review methods to perform a post-glitch GW search. Then, the central part consists of reanalyzing the ATNF pulsar catalog together with the ATNF and Jodrell glitch catalogs to extrapolate to the detectability of future glitches. In particular, we perform a specific prediction for Crab-like and Vela-like pulsars: from the setup of our O3 matched-filter analysis, we can determine a realistic sensitivity for future searches (how deep we could dig below detector noise curves). Comparing the maximum strain of an emitted GW -from the maximum energy release by a particular source- with the expected sensitivity curve we can see how likely we are to detect long-duration transient GW signals from glitching pulsars in the future.

Multi-messenger Studies with Gravitational Waves and Neutrinos

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IceCube is a neutrino observatory located in Antarctica. Since its discovery of a high-energy neutrino (IC170922A) from the blazar TXS0506+056 in 2017, neutrino astronomy has been established as a viable option to probe the high-energy Universe. Neutrinos can carry undistorted information about their respective astrophysical sources, thus can serve as a cosmic ‘messenger’ to us. There are other potential messengers as well, e.g. gravitational waves (GW) and cosmic rays other than the traditional photons of various wavelengths. Combining interesting signals of such messengers available from different observatories leads us towards multi-messenger searches, allowing us to address many of the so far unanswered questions about the fundamentals of this Universe, such as the origin of ultra-high-energy cosmic ray sources. So far, we have the knowledge of detecting electromagnetic signal in multiple wavelengths, spatially and temporally correlated with GW and high-energy neutrinos, as two separate events. However, there is still a missing link as we have not been able to correlate GW with neutrino signals. The aim of my work is to contribute in this aspect, searching for LIGO-Virgo detected GW counterparts of neutrino events detected by IceCube, including low-energy neutrinos as well as sub-threshold GW events in our analysis. The corresponding work plan will be discussed in this presentation.

Interplay of spin-precession and higher harmonics in the parameter estimation of binary black holes

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Gravitational-wave (GW) signals from coalescing compact binaries carry enormous information about the source dynamics and are an excellent tool to probe unknown astrophysics and fundamental physics. Though the updated catalog of compact binary signals reports evidence for slowly spinning systems and unequal mass binaries, the data so far cannot provide convincing proof of strongly precessing binaries. Here, we use the GW inference library parallel Bilby to compare the performance of two waveform models for measuring spin-induced orbital precession. One of the waveform models incorporates both spin-precession effects and sub-dominant harmonics. The other model accounts for precession but only includes the leading harmonic. By simulating signals with varying mass ratios and spins, we find that the waveform model with sub-dominant harmonics enables us to infer the presence of precession in most cases accurately. In contrast, the dominant model often fails to extract enough information to measure precession. In particular, it cannot distinguish a face-on highly precessing binary from a slowly precessing binary system irrespective of the binary's mass ratio. As expected, we see a significant improvement in measuring precession for edge-on binaries. Other intrinsic parameters also become better constrained, indicating that precession effects help break the correlations between mass and spin parameters. However, the precession measurements are prior dominated for equal-mass binaries with face-on orientation, even if we employ waveform model including subdominant harmonics. In this case, doubling the signal-to-noise ratio does not help to reduce these prior induced biases. As we expect detections of highly spinning binary signals with misaligned spin orientations in the future, simulation studies like ours are crucial for understanding the prospects and limitations of GW parameter inferences.

Studying kilonova properties through long-term numerical-relativity simulations

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Numerical-relativity simulations are essential for studying binary neutron star mergers and interpreting observational data. In fact, numerical-relativity data can be used as an input for radiative transfer simulations to model kilonova light curves. While most radiative transfer codes assume homologous expansion of the outward flowing material, this condition is not met in most numerical-relativity simulations due to the high computational costs required for long-term evolutions. We plan to enable such long-term simulations of the ejecta to verify when the ejecta starts to expand homologous and to what extent this assumption could have biased previous studies.

For this purpose, we have to modify our grid structure during the numerical-relativity simulation to enable a faster computation of the outward flowing material after the merger. In addition, the size of the grid has to be increased to allow the outflowing material to be tracked over a longer period. To probe our new method, two systems with different equations of state are simulated at different resolutions until the homologous expansion stage is reached. The results are then used to calculate the light curves with a radiative transfer code and to analyze the kilonova properties.

Engines of magneto-rotational supernovae and their multi-messenger signals

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Core-collapse supernova form a diverse class of explosions produced at the end of the lives of massive stars. Studying these events is heavily dependent on supercomputing due to the complexity of the turbulent flows and the neutrino transport in dense matter. Our three-dimensional models including all relevant physics and covering long simulation times demonstrate how the subset of progenitors with strong magnetic fields and high rotational energies can be responsible for producing particularly high explosion energies and for playing an important role in the chemical enrichment of early galaxies with heavy elements in ways that are not accessible to ordinary, primarily neutrino-driven explosions. In addition, these explosions emit strong gravitational-wave signals and neutrinos. A combination of observations possible with future detectors and numerical models will give important information about the physics of the explosions and the properties of the compact central remnants.

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Understanding the multi-wavelength variabilty of TeV blazar VER J0521+211 with high-energy particle interactions

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In spring 2020, the MAGIC collaboration detected photons with energies above 200 GeV from the source VER J0521+211 which provides evidence of efficient particle acceleration in a relativistic jet. The monitoring of the source's short-term variability in very-high-energy gamma rays is complemented by simultaneous data from other observatories in radio, optical, X-ray, and GeV gamma rays. We perform multi-wavelength modeling of this source with a fully self-consistent one-zone leptohadronic model to explain four different multi-wavelength data sets. While the radio and optical fluxes seem to originate from electron synchrotron emission, in this model the gamma-ray fluxes are well explained by electromagnetic cascades induced by proton interactions.

Development of a Polarisation Phase Camera

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Sapphire and silicon mirrors are used in cryogenic detectors to reduce thermal noise but are predicted to be birefringent. Due to the structure of these materials, the refractive index is not constant throughout and converts some of the pure polarisation that enters into an unwanted one. Everything in a gravitational wave detector is designed to work for a single polarisation, therefore any unwanted varieties will spoil the sensitivity and degrade the length control signals. Indirect effects of birefringence can be observed, primarily as optical losses, but an optical sensor has been proposed for direct observation[1]. By adapting a phase camera to see the amplitude and phase of both S and P polarisations separately, a birefringence map can be built in order to characterise its effects in an interferometer. In this poster, the polarisation phase camera development is reported.

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Toward calibrating precessing fourth generation phenomenological waveform models to numerical relativity

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The increase in sensitivity and detector upgrades planned in the coming years will challenge waveform models and demand considerable improvements in accuracy, parameter space coverage, and computational efficiency. Binary systems of black holes in general relativity span a parameter space of 9 intrinsic parameters: two spin vectors, the mass ratio and two parameters associated with eccentricity. When the black hole spins are misaligned with the orbital angular momentum, the spins and orbital plane perform a precessing motion that leads to a complex modulation, especially for the amplitude of the signal. This phenomenon can be modelled using an approximate map between precessing signals in a co-precessing non-inertial frame and aligned-spin signals, which is referred to as the "twisting-up approximation". The current (fourth) generation of phenomenological waveform models, IMRPhenomX [1] and IMRPhenomT [2] use this approach directly, without calibrating precession information to numerical relativity. To further improve the accuracy of waveform models, it is necessary to only use the twisting-up procedure as a framework where unknown pieces of information are calibrated to numerical relativity simulations. A first step has been taken recently by the Cardiff group, extending the frequency domain IMRPhenomD model [3]. This poster shows the preliminary steps to perform a numerical calibration of the ringdown in the time domain. We used 1400 SXS precessing simulations to compute direct fits of the quasi-normal mode emission during the ringdown and investigated the incorporation of extreme mass ratio precessing waveforms [4-5] and the Surrogate models [6-7] to our calibration dataset.

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Detecting millihertz gravitational waves using circular particle accelerators

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We simulate the response of a Storage Ring Gravitational-wave Observatory (SRGO) to astrophysical gravitational waves (GWs), numerically obtaining its sensitivity curve, observational range, and parameter degeneracies. We also generate synthetic noisy data and use Markov Chain Monte Carlo (MCMC) methods to do GW parameter estimation. In particular, we focus on the sky-localization of the GW source, showing that a single SRGO detector can localize the source in the sky using Earth's rotation. We study the sky-localization area as a function of noise, no. of data points, observing time, source parameters, etc. and discuss the implications of using SRGO for detecting millihertz (mHz) GWs.

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GW follow-up campaigns in conjunction with Astro-COLIBRI

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The advances in the multi-messenger approach are driven by improved real-time alert and follow-up systems as well as next-generation instruments dedicated to the study of the most violent phenomena in the universe. Studying these extreme, flaring events in the multi-messenger approach requires real-time and, to a substantial extent, fully automated communication between telescopes. Furthermore, large uncertainties in the sky localization of current GW observatories impose challenges for searching for multi-messenger and electromagnetic counterparts and associated sources.

Astro-COLIBRI [1] is a novel tool that we developed to facilitate follow-up campaigns. It evaluates alerts of transient observations in real-time, filters them by user-specified criteria, and puts them into their multi-messenger context. For example, when gravitational waves are detected, users are informed in real-time and access extensive information about the event via the app or the interactive website. In addition to displaying the event on a sky map together with other events and sources in the relevant phase space, Astro-COLIBRI provides custom-generated links to other services and websites that provide additional information.

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The Identification and Separation of Time-Overlapping Gravitational-Wave Transients

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With every new observing run of gravitational-wave interferometers comes a sensitivity increase and a corresponding increase in the rate of observed astrophysical signals. There will come a point towards the end of the current generation of interferometers at which the signal rate is so high that transient gravitational waves may occasionally overlap. Current signal detection and parameter estimation techniques rely on many assumptions about the data they study. A significant assumption is that there is only one signal present in the data.

Our analysis has shown that current parameter estimation techniques will successfully recover a set of parameters for overlapping transient signals, but that this is biased away from the true parameters of either signal[1]. It is only apparent when the signals merge at similar times and have similar signal-to-noise ratios. Therefore, it is likely that time-overlapping transients will be miscategorised as single events. Here we present an injection study using both modelled and weakly-modelled transient search pipelines that attempts to identify if time-overlapping signals will be found. We also propose methods as to how time-overlapping transients can be identified and, potentially, separated into individual signals for analysis.

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Neutrinos from tidal disruption and accretion events

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Since the discovery of cosmic rays, their origin has been a mystery, as they are deflected by magnetic fields on their way through the universe. High-energy neutrinos could come to the rescue, as they are most likely produced in the very same sources as cosmic rays and travel on straight paths pointing back directly to their origin.

However, the directional uncertainties of the neutrino detections pose a challenge for identifying their sources. Tidal disruption events (TDEs) have long been proposed as sources of high-energy cosmic neutrinos. In these events, a star approaches a supermassive black hole too close for its own good, as it gets torn apart by tidal forces. About half of the star's shredded remains then fall toward the black hole and form an accretion disk around it, strongly emitting in the optical/UV and/or the X-ray wavelength bands for months.

In 2019, following up on the IceCube high-energy neutrino IC191001, we found the TDE AT2019dsg to be located within the 90% uncertainty region of the neutrino. It had a redshift of z=0.051, rendering it quite close compared to the full Zwicky Transient Facility (ZTF) TDE sample.

On my poster I present AT2019fdr, an exceptionally luminous TDE candidate, coincident with another high-energy neutrino detected by IceCube (IC200530A). It was further away than AT2019dsg (z=0.266), but of comparable apparent brightness. Its high bolometric luminosity renders it one of the most energetic transients ever discovered. I present observations that further support a TDE origin of this flare. These include a bright dust echo and soft late-time X-ray emission. The probability of finding two such bright events in neutrino follow-up by chance is just 0.034%. Furthermore, we have evaluated several models for neutrino production and can show that AT2019fdr is capable of producing the observed high-energy neutrino. I also show further evidence on accretion events accompanied by luminous dust echoes being connected to high-energy neutrinos, as we have found another accretion event with such a signature coincident with a high-energy neutrino (AT2019aalc). These findings reinforce the case for TDEs as neutrino sources.

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Experimental testbed for quantum machine learning algorithms

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In the framework of "Quantum Valley Lower Saxony", a new collaboration is currently working on quantum technologies, prominently amongst them the development of an ion-trapped based quantum computer, as well as on quantum machine learning (QML) techniques [1,2]. As a quantum computer itself is a quantum system, one idea is to test these algorithms on a quantum system which is already known. For this we will set up a non-classical light source (a two-mode "squeezer" [3]). It will provide sufficient degrees of freedom to test new complex algorithms. I am working on the theoretical understanding of these new techniques as well as on the implementation of QML algorithms on the quantum-optical experiment.

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Gentle loss measurement: Probing samples with quantum squeezed vacuum

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Squeezed states of light improve the sensitivity of sensors in gravitational wave detection, biology and biochemistry. By decreasing the uncertainty for the squeezed quadrature, this allows for more precise measurements without increasing the light power. Measurements of samples, that are fragile to high intensities of light like absorptive coatings or proteins, benefit from the higher sensitivity at lower intensity. However, for even more fragile samples this improvement might not be sufficient.

Here I present a measurement scheme that allows to probe such samples, measure the loss induced by them and calculate their thicknesses, with a light power at the order of vacuum fluctuation. By transmitting squeezed vacuum through membranes, I measure the optical loss in that path. With a comparison to a reference I extract the loss induced by the membranes. Considering the index of refraction of the membrane, I was able to compute the thickness from the measured loss.

This scheme provides an atypical use of squeezed light by using its sensitivity to optical loss rather than its ability to enhance the sensitivity of a signal-carrying light beam.

I demonstrate the feasibility of this scheme for silicon nitride membranes between 20nm and 100nm thickness by comparing the gentle measurement with squeezed light to a theoretical estimation and a classical transmission measurement. Based on the scheme shown here various measurements on highly photosensitive samples, that are derivable from the optical loss induction of the samples, like determining the thickness, are possible.

Generation of squeezed states of light for gravitational wave detectors

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1 Abstract

In this poster we present the experimental setup of a future project to be realized at the AEI, with the goal to improve the squeezing generation for gravitational wave detectors.To reach this goal we plan to replace the usual linear OPO (optical parametric oscillator) resonator to a doubly resonant bow-tie design, resonant for the signal (1064 nm) and the pump (532 nm) frequencies. The main advantage of this design is that back-scattered light coming from the Interferometer leaves the resonator in a different direction than the signal beam. Therefore, no Faraday isolator is required, which in theory will reduce the losses in the squeezed field. With this design we expect to increase our squeezing level.

Core collapse in scalar-tensor theory with massive fields

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Though General Relativity has been successfully tested so far, concepts such as dark matter and string theory suggest the need of modifying it. Scalar-tensor theory is one of the most popular alternatives discussed. The key reason for looking at the ones with massive fields is that they are far less constrained by binary pulsar observations, in contrast to the massless case [1]. We produce studies of stellar core collapse in spherical symmetry that were performed by adapting the numerical code GR1D [2] to the case of massive scalar-tensor gravity. We systematically explore the parameter space that characterizes the progenitor stars, the equation of state and the scalar-tensor theory of the core collapse events. The addition of a mass term allows, within present constraints, much stronger gravitational emission than in the massless case and the dispersion of the signal leads to a quasi-monochromatic signal potentially detectable by LIGO with existing analysis pipelines. We identify a very sharp boundary in the parameter space that separates events with strong gravitational-wave emission from those with negligible radiation.

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Follow-up Search for Ultra-High-Energy Photons from Gravitational Wave Sources with the Pierre Auger Observatory

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The field of multimessenger astronomy has become increasingly important during the past decade. Some astronomical objects have already been successfully observed in the light of multiple messenger signals, allowing for a much deeper understanding of their physical properties. The Pierre Auger Observatory has taken part in multimessenger astronomy with an exhaustive exploration of the ultra-high-energy (UHE) sky [1-3]. In this contribution, a first search for UHE photons from the sources of gravitational waves (GWs) is presented [4]. This study complements the dedicated search for UHE neutrinos, which has already been established at the Pierre Auger Observatory. While the Observatory has a much larger exposure to primary photons than to neutrinos, interactions with the cosmic background radiation fields are expected to attenuate any possible flux of UHE photons from distant sources. In addition, a non-negligible background of air shower events with hadronic origin makes an unambiguous identification of primary photons a challenging task. In the analysis presented here, a sophisticated selection strategy is applied to both GW sources and air shower events aiming to provide maximum sensitivity to a possible photon signal. At the same time, a window is kept open for hypothetical processes of new physics, which might allow for much larger interaction lengths of photons in the extragalactic medium. Preliminary results on the UHE photon fluence from a selection of GW sources, including the binary neutron star merger GW170817 are presented.

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Gravitational Waves from hyperbolic-like encounters of black holes

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We present results on the encounter of two black holes that are initially on a hyperbolic-like orbit simulated with the numerical relativity code SpEC [1,2].
We discuss the dynamical capture scenario as well as the scattering scenario, in which the black holes remain unbound during the encounter.
In dynamical captures the binary becomes bound due to the emission of gravitational waves, which poses a possible formation scenario of highly eccentric binary mergers.
We present the waveforms for both scenarios and discuss key features like the beaming of radiation and the memory effect.

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Detecting binary neutron star systems with the third-generation era: the challenge and benefits

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Future gravitational wave observatories will detect a large number of gravitational-wave signals, eventually leading to overlapping signals, especially in the case of Einstein Telescope (ET) and Cosmic Explorer (CE). In an ET-CE network and over the course of a year, we find that a binary neutron star (BNS) signal will typically have tens of overlapping BNS signals. Moreover, it will happen up to tens of thousands of times per year that two signals will have their end times within seconds of each other. We perform injection studies with overlapping signals from binary neutron star coalescences to understand the results with our current data analysis pipelines. Varying the signal-to-noise ratios, the durations of overlap, and the kinds of overlapping signals, we find that in most scenarios the intrinsic parameters can be recovered with negligible bias. Biases do occur for a quieter BNS signal overlapping with a long and louder BNS event when the merger times are sufficiently close. Our studies show where improvements are required to ensure reliable estimation of source parameters for all detected compact binary signals as we go from second-generation to third-generation detectors.
Finally, I will focus on additional information we can obtain from observing BNS signals with an ET-CE network. Quasi-universal relations between the tidal deformability and the quadrupole moment of neutron stars are predicted by theoretical computations. Using simulations of many highly spinning BNS sources, we find that a network of ET-CE detectors will allow finding possible deviations from predicted relations, and even extracting such relations, providing new tests of general relativity and nuclear physics predictions.

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MLGWSC-1: The first Gravitational-Wave Search Mock Data Challenge

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Gravitational wave detection algorithms are one core aspect to enable multi-messenger astronomy that includes information from gravitational radiation. In recent years machine learning has been explored as a new approach to creating these searches. However, a clear picture of the capabilities these machine learning based searches have is still missing. This is caused by different authors using different datasets and targeting different parameter spaces as well as deriving metrics which are hard to compare to traditional search pipelines. The MLGWSC-1 is an international mock data challenge for machine learning gravitational-wave search algorithms. It tries to enable comparisons between different approaches and search types by providing a common dataset and deriving sensitivity curves that can be compared to existing literature. Here we present the core concepts of the challenge as well as the methods we are using for evaluation.

Implementation of first-order multipolar radiation transport in Numerical Relativity code BAM

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Numerical-relativistic simulations of binary neutron star mergers are getting a key role in the Multimessenger Astronomy, e.g., for modeling electromagnetic emissions connected to those events. For an accurate description of electromagnetic counterparts, one needs to know the electron density of the matter ejected during and shortly after the merger. Inside this material, heavy elements are synthesized, and it is the origin of most of the thermal emissions observed from binary neutron star mergers. All these phenomena are highly dependent on weak interactions between baryons and neutrinos [5] [1].

Our work consists of implementing a code that tracks the propagation of such particles and their interaction with matter. It will be part of our numerical simulation code BAM. The aim is to get a more accurate estimate of the ejecta properties, mostly of electron fraction, but recent studies revealed that neutrino emission/absorption also influences the mass and velocity of the ejected material.

The scheme we are implementing is based on a first-order multipolar formalism (M1) expansion [8] [7] [4] [3] [6]. It consists of evolving the energy and momentum densities of neutrinos without solving a full and too computationally expensive diffusion equation. The advantage of the M1 formalism is twofold. First, it allows taking into account the possibility of neutrinos to be reabsorbed in a different point of the simulation domain after they are emitted, leading to a higher electron density of the ejecta, as opposite to leakage schemes that only accounts for emission. Second, it allows to model monodirectional beams of particles instead of a simple isotropic diffusion.

However, the M1 scheme does not allow to reproduce the energy spectrum of neutrinos since it only evolves energy-integrated quantities, leading to significant uncertainties on the interaction rates with matter. Moreover it fails in solving second or higher order multipoles in neutrino distribution, like in the case of two crossing beams. To address this issue, a more accurate scheme is needed in the future [2].

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Surrogate and hybrid models of eccentric waveforms using numerical relativity

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Surrogate models built using numerical relativity waveforms are fast and accurate methods to generate gravitational waveforms. In this work, we aim to develop a surrogate model for numerical relativity (NR) waveforms from eccentric unequal mass aligned spin binary black hole systems. To accomplish this we are currently simulating about 150 eccentric non spinning binary black hole systems with mass ratio ranging from 1 to 4 and eccentricity from 0 to about 0.2 and each simulation is about 10,000 M_{sun} long. Our goal is to use this surrogate model to further develop a hybrid Inspiral Merger Ringdown (IMR) waveform by hybridizing Effective One Body (EOB) eccentric waveform (for inspiral part) and eccentric surrogate waveforms (for merger ringdown part) over an appropriate time interval where both of these models could be assumed to be accurate. To do this, we develop a method to identify the initial eccentricity and frequency required to generate the EOB waveform for the inspiral part that would correspond to the same physical system as the given NR waveform. This method further requires a particular definition of eccentricity to be used such that we can compare the eccentricity in the EOB and the NR waveform in the hybridisation window and they should match to a very good accuracy. We use a definition of eccentricity that is entirely based on the given waveform data and uses the peaks and troughs in the frequency of the 22 mode. We find a way to make this definition work for very small eccentricities by using residual amplitude instead of frequency or amplitude to find the location of the peaks and troughs of the 22 mode frequency. Using our method we are able to construct hybrid waveforms that have L2 norm (a measure of mismatch between two waveforms) with original waveform below $\sim 10^{-4}$ over the range of considered eccentricities. We expect the L2 norm to be made even smaller with more rigorous (and hence time consuming) settings in our code. The final goal of our work is to use these hybrid IMR waveforms to build a surrogate model for eccentric IMR waveforms that would have significant applications in Gravitational Wave data analysis.

Improving the sky localization capabilities of a network of gravitational-wave-detectors based on the signal-independent null stream of the Einstein Telescope

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(Dated: February 21, 2022)

The gravitational-wave detectors of the third generation, like Einstein Telescope and Cosmic Explorer, will have greatly improved sensitivity as compared to the current detectors. The network of such detectors will therefore have 10 times greater reach and higher accuracy of the source's parameter estimation. In this article, we show that the source sky localization accuracy of the network of 3G detectors, which includes the three detectors of Einstein Telescope(ET) arranged in an equilateral triangle and Cosmic Explorer(CE) is greatly improved, when using the signal-independent null stream of ET. We demonstrate that the null stream that contains only the sum noise of the ET part of the network can be optimally subtracted from the combined network data stream thereby increasing its effective signal-to-noise ratio and thus facilitating more accurate estimation of the source location on the sky. For the network containing ET and CE, We have found an improvement factor greater than 2 in the area covered by 10%, 50% and 90% probable region for sky localisation of GW source.

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Binary black hole mergers from merged stars in the galactic field

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The majority of massive stars are found in close binaries which: (i) are prone to merge and (ii) are accompanied by another distant tertiary star (triples). Here, we study the evolution of the stellar post-merger binaries composed of the merger product and the tertiary companion. We find that post-merger binaries originating from compact stellar triples with outer semi-major axes $a_{out,init} \lesssim 10^1 - 10^2$ AU provide a new way to form binary black hole mergers in the galactic field. By means of a population synthesis, we estimate their contribution to the total black hole merger rate to be $\mathcal{R}(z=0) = 0.3 - 25.2$ $Gpc^{-3}yr^{-1}$. Merging binary black holes that form from stellar post-merger binaries have exceptionally low mass ratios. We identify a critical mass ratio $q \simeq 0.5$ below which they dominate the total black hole merger rate in the field. We show that after including their additional contribution, the mass ratio distribution of binary black hole mergers in the galactic field scenario is in better agreement with that inferred from gravitational wave detections.

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Bimodal local readout for back-action evasion

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When detecting Gravitational waves we have to compensate for a huge range of noise sources. Some classical and some due to the quantum nature of light. Modern gravitational wave detectors use arm cavities to achieve higher sensitivity. However, the mirrors making up these cavities (the test-mass) can introduce significant noise. By motion along the optical axis, they introduce phase noise into the light. Radiation pressure due to light in the cavity can also excite the test-masses. The quantum mechanical nature of light means that this light pressure will vary. Future GW-detectors will go to even higher arm powers and reducing the radiation pressure noise can improve the detection efficiency. In this experiment, we show a bimodal local readout scheme for reducing noise due to ITM motion in post processing. We tested how an off resonant sideband can be used to readout the ITM motion independently of the channel containing GW-information. Using this data, we can subtract correlated noise. This can help with classical- as well as radiation pressure noise. Our results show how one could use existing sidebands in currently working gravitational wave detectors to reduce the noise due to the ITM motion.

Incorporating information from LIGO data quality streams into the PyCBC search for gravitational waves

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We introduce a method for incorporating data from LIGO auxiliary channels into the PyCBC offline search for gravitational waves. A variety of auxiliary data sources can be used, including seismic noise sensors, data quality flags and iDQ timeseries data. This additional data is correlated with the single detector trigger rate observed by PyCBC. The variation of the trigger rate with auxiliary channels is incorporated into a new statistic in order to decrease the significance of triggers during periods of high noise. We demonstrate that this time-dependent noise model increases the sensitive time-volume of PyCBC.

ETpathfinder: a cryogenic testbed for interferometric gravitational-wave detectors

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The third-generation of gravitational wave observatories, such as the Einstein Telescope, aim for an improvement factor in sensitivity of at least ten over a wide frequency range compared to the current advanced detectors. In order to inform the design of the third-generation detectors and to develop and qualify their subsystems, dedicated test laboratories are required. ETpathfinder is an ultra-low noise cryogenic facility with double interferometers of 10 m arm-length which can test full detector configurations compatible with the third-generation observatories. This poster highlights the core components of ETpathfinder and the design noise sensitivities for two interferometric configurations: 1550 nm laser wavelength at 18 K test mass temperature and 2090 nm at 123 K.

A novel speedmeter concept for next-generation gravitational wave detectors

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So far, Michelson interferometers have been proven extremely efficient in detecting gravitational waves at a large range of frequencies. Yet they are limited by a fundamental quantum uncertainty associated with the repeated measurement of the test mass positions. A well-known solution to work around these limitations in sensitivity is the concept of a speedmeter, which measures the relative velocity (or momentum) of the test masses instead of their position. If these velocity measurements are carried in a short enough time span, the measured quantity is an approximate constant of motion. This makes the momentum operators commute with themselves at different times, erasing the quantum uncertainties. However, the problem with earlier speedmeter setups is that they require more (coupled) cavities to be added to the already complex interferometers. This project aims to explore new speedmeter concepts that can be embedded in the trusted Michelson topology with limited additional components. There are two specific configurations that will be examined, the Einstein-Podolsky-Rosen (EPR) speedmeter and the polarization circulation (PC) speedmeter. In both cases, the differently polarized states are used to carry out a measurement of the test masses independently of each other. By combining the readouts of the two polarizations, one can produce a signal with a phase that is proportional to the velocity of the test mass. Given that the time between measurements is small enough. From an experimental point of view, one of the most crucial components in this setup is the central beamsplitter. Unlike a normal Michelson interferometer, the speedmeter configurations need a beamsplitter that splits both polarizations equally, while also ensuring that both polarizations remain in phase in each arm. Producing a beamsplitter coating that can do this is quite demanding, so the first step is to evaluate the performance of such a coating and confirm it is a viable option in terms of noise and control. If successful, a speedmeter configuration can boost the interferometer sensitivity significantly at the low-frequency side of the spectrum, possibly leading to detection rate improvements of the order 100 for binary systems with a total mass above 100 solar masses [1].

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Evidence of large recoil velocity from a black hole merger signal

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The final black hole left behind after a binary black hole merger can attain a recoil velocity, or a "kick", reaching values up to 5000 km/s. This phenomenon has important implications for gravitational wave astronomy, black hole formation scenarios, testing general relativity, and galaxy evolution. We consider the gravitational wave signal from the binary black hole merger GW200129_065458 (henceforth referred to as GW200129), which has been shown to exhibit strong evidence of orbital precession. Using numerical relativity surrogate models, we constrain the kick velocity of GW200129 to vf ~ 1542^{+747}_{-1098} km/s or vf ≳ 698 km/s (one-sided limit), at 90\% credibility. This marks the first identification of a large kick velocity for an individual gravitational wave event. Given the kick velocity of GW200129, we estimate that there is a less than 0.48% (7.7%) probability that the remnant black hole after the merger would be retained by globular (nuclear star) clusters. Finally, we show that kick effects are not expected to cause biases in ringdown tests of general relativity for this event, although this may change in the future with improved detectors.

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Probing gravitational waves from pulsars in Brans-Dicke theory

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I shall present the theoretical background for the data analysis of gravitational waves (GWs) from spinning neutron stars in Brans-Dicke (BD) theory. Einstein's general theory of relativity (GR) predicts only two tensor polarization states but a generic metric theory of gravity can also possess scalar and vector polarization states. The BD theory attempts to modify the GR by varying gravitational constant G, and it has three polarization states. The first two states are the same as in GR, and the third one is the scalar polarization. We derive the response of a laser interferometric detector to the GW signal from a spinning neutron star in BD theory. We obtain a statistic based on the maximum likelihood principle to identify the signal in BD theory in the detector's noise. This statistic generalizes the well known $\mathcal{F}$-statistic used in the case of GR. We perform Monte Carlo simulations in Gaussian noise to test the detectability of the signal and the accuracy of estimation of its parameters. We implemented our codes in the LVK pipeline to search for the dipole radiation in BD theory.

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Direct Limits for Scalar Field Dark Matter from a Gravitational Wave Detector

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We report on the first direct search for scalar field dark matter using a gravitational-wave detector. Scalar field dark matter is predicted to cause oscillations of fundamental constants, which in turn would drive oscillations of the size and index of refraction of the beamsplitter in an interferometer. This would thus produce an oscillatory signal in a gravitational-wave detector at a frequency set by the mass of the dark matter particle. We set new upper limits for the coupling constants of scalar field dark matter as a function of its mass, by excluding the presence of possible dark matter signals in data from the GEO600 interferometer. The new constraints improve upon bounds from previous direct searches by more than six orders of magnitude, and are in some cases more stringent than limits obtained in tests of the equivalence principle by up to four orders of magnitude. Our work demonstrates that scalar field dark matter can be probed or constrained with direct searches using gravitational-wave detectors, and highlights the potential of quantum-enhanced interferometry for dark matter detection.

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Rapid Online Estimation of Astrophysical Source Category and Compact Binary Parameters

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During the third observing run (O3) of the Advanced LIGO and Advanced Virgo detectors, dozens of candidate gravitational-wave (events have been catalogued. A challenge of this observing run has been the rapid identification and public dissemination of compact binary coalescence (CBC) signals, a task carried out by low-latency searches such as PyCBC Live [1,2]. During the later part of O3, we developed a method [3] of classifying CBC sources, via their probabilities of containing neutron star or black hole components, within PyCBC Live, in order to facilitate immediate follow-up observations by electromagnetic and neutrino observatories. This fast classification uses the chirp mass recovered by the search as input [Fig. 1], given the difficulty of measuring the mass ratio with high accuracy for lower-mass binaries. We also use a distance estimate derived from the search output to correct for the bias in chirp mass due to the cosmological redshift. We present results for simulated signals [Fig. 2], and for confirmed candidate events identified in low latency over O3.

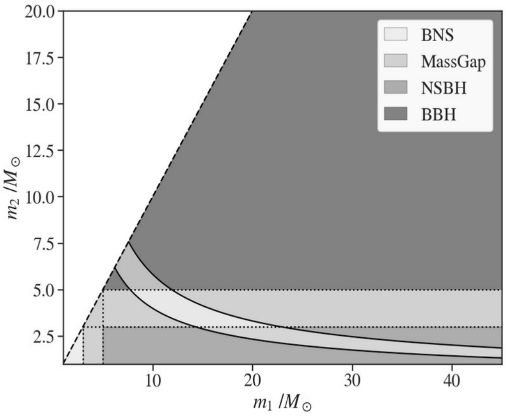

Figure 1: Chirp mass contour over the plane of component masses m1-m2 for GW190814 (source chirp mass estimate: 5.99 ± 0.60 M⊙).

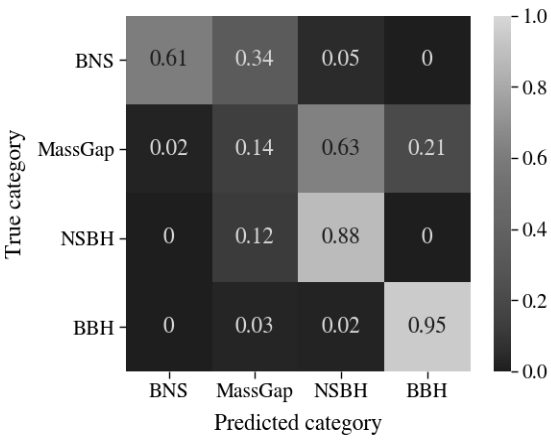

Figure 2: Confusion matrix comparing the true categories of the simulated signals versus the category found with highest probability in each event.

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Frequency-dependent effects in the localization of GW events

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In spite of the fact that interferometers detect gravitational waves (GWs) in a very complicated (and very clever) way, the final output (i.e. that used for data analysis, obtained after calibration and other processes) is up to now quite simple: the detected strain is linear in the two GW polarizations, which are multiplied by the corresponding antenna patterns, which describe the detector's response to each signal source location in the sky.

The usual antenna patterns do not take into account the transfer function of the interferometers, and as a result they are not frequency dependent: this is an approximation that works quite well as long at the signal frequencies are well below the LIGO - Virgo free spectral range (FSR) (for the LIGO detectors this frequency is about 37.5 Hz, and for Virgo 50 kHz).

Next generation detectors, such as Cosmic Explorer (CE) and the Einstein Telescope (ET), are expected to have far longer arms (40 km for CE, 10 for ET) so that phenomena associated with frequencies around 1000 Hz (as could be a signal from a core collapse supernova) are no longer so low with respect to the FSR of these detectors (3750 Hz for CE, 15000 Hz for ET).

This means that the transfer function must be taken into account and this produces a frequency dependence of the antenna patterns. However, while the frequency-domain version of the response function has been extensively explored, the time-domain version has not: this time dependence is described in this work.

Moreover, for a fixed frequency the frequency-dependent corrections depend on the source location as seen by each detector. This produces a frequency- and location-dependent systematics that must be taken into account.

In my work I explore all the implications of these corrections for sky localizations, trying to understand where we can apply the present methods and where we should take into account frequency-dependent effects: the final goal is to obtain a method that can give the best sky localization to share with non-GW observatories.

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TTL Expansions for LISA as Polynomials in Zernike Contributions to the Outgoing Beam Wavefront

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Wavefront Error (WFE) within the Laser Interferometer Space Antenna (LISA) transmit beams can lead to non-spherical wavefronts at receiving spacecrafts (SC). Such wavefront deformation may couple to transmit SC jitter, generating tilt-to-length (TTL) noise in signals. Decomposing initial WFE as a sum of Zernike polynomials, we've found maps allowing for the accurate recreation of TTL components as a polynomial in the Zernike decomposition coefficients. Such maps provide both fast and efficient modeling tools for the recreation of TTL coefficients for large scale simulations, and may be helpful in directing mirror manufacture to avoid the generation of WFE coupling most severely with SC jitter into length noise.

Real-Time Parameter Estimation of Un-modelled Gravitational Wave Transients Using Machine Learning.

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In this work, I present preliminary results from my research into machine learning for low latency parameter estimation and highlight MLy; a detection pipeline currently being developed at Cardiff University. Convolutional Neural Networks (CNNs) have proven to be useful in many areas of gravitational-wave (GW) science, including glitch rejection[1], noise reduction[2], detection and parameter estimation[3]. More recently, Skliris et al. showed the efficacy of CNNs for detecting un-modelled GWs[4]. Inspired by this recent progress, at Cardiff University we are building a detection pipeline for un-modelled transients. This pipeline will harness the benefits of deep learning. It is intended to run in the low-latency regime and provide alerts to the general astronomical community in the case of GW candidate events for multi-messenger follow-up searches.

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Quasi-periodic oscillations in tidal disruption events as markers of multimessenger sources?

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The tidal disruption event (TDE) ASASSN-14li exhibited an extremely loud quasi-periodic oscillation [1] that could have been sourced by a body perturbing the TDE accretion disk. This body could have been a remnant core of the tidally disrupted object, or a "zombie remnant" recoalesced from the debris. We show that if LISA had went online this year, ASASSN-14li would have possibly presented a formidable multimessenger source. Unfortunately, in a broad range of scenarios the body falls into the black hole well before LISA actually flies. Nevertheless, this example strongly motivates further searches for TDEs such as ASASSN-14li in the upcoming 12 years.

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