Astrophysical Windows on Dark Matter

British-German WE-Heraeus-Seminar

03 - 05 November 2021
The Royal Society, London

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

<u>Aims and scope of the British-German WE-Heraeus-Seminar:</u>

Dark matter makes up most of the gravitating mass in the Universe and is responsible for the growth of cosmic structure. Multiple lines of evidence, most notably the properties of the cosmic microwave background radiation, indicate that the dark matter is an elementary particle made in the early phases of the Big Bang, which is different from ordinary (or baryonic) matter. Searches for these particles have been ongoing for 35 years. They can take three forms: (i) direct detection; (ii) indirect detection of the products of dark matter particle decay or annihilation and (iii) production in particle accelerators. Although there are claims that the dark matter has been indirectly detected, there is no consensus on this so far.

While only detection or production of dark matter will conclusively establish its properties, various astrophysical phenomena can provide strong hints about its nature. The purpose of this workshop is to explore these astrophysical windows on dark matter. It will focus on both on the key astronomical observables that might reveal the identity of the dark matter and also on how astrophysical constraints may inform experimental searches for dark matter.

Introduction

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Program

British-German WE-Heraeus-Seminar "Astrophysical Windows on Dark Matter"
Royal Society, Kohn Centre, London (3-5 November, 2021)

Wednesday, 3 November 2021 (GMT)

Session 1. Chair – Carlos Frenk		
9:15 – 9:30	Carlos Frenk/ Jürgen Mlynek/ Stefan Jorda	**Welcome / About the Wilhelm and Else Heraeus-Foundation**
9:30 – 10:15	Gianfranco Bertone	**A New Era in the Quest for Dark Matter**
10:15 – 11:00	Chris McCabe	**Astrophysical Constraints on Dark Matter Detection**
11:00 – 11:30	*COFFEE*	
11:30 – 12:15	Francesca Calore	**Astrophysical Inputs and Current Constraints from Indirect Dark Matter Detection**
12:15 – 1:00	Tracy Slatyer	**The Gamma-Ray Excess from the Galactic Centre**
12:55 – 2:00	*LUNCH*	
Session 2. Chair – Anne Green		
2:00 – 2:20	Katie Mack	**Dark Matter Annihilation and the First Structures**
2:20 – 2:50	Alexander Murphy	**Recent Results and the Future of Direct Searches for Particle Dark Matter**
2:50 – 3:30	Andrew Robertson	**Self-Interacting Dark Matter**
3:30 – 4:00	*COFFEE*	
4:00 – 4:45	Alexey Boyarsky	**Warm Dark Matter**
4:45 – 5:30	Elisa Ferreira	**Fuzzy Dark Matter**
5:30 – 5:50	Francesca Chadha-Day	**Astrophysical Windows on the String Axiverse**
5:50 – 6:10	Dan Hooper	**Dark Radiation and Superheavy Dark Matter from Hawking Evaporation of Primordial Black Holes**

British-German WE-Heraeus-Seminar "Astrophysical Windows on Dark Matter"
Royal Society, Kohn Centre, London
Thursday, 4 November 2021 (GMT)

Session 3. Chair – Andrew Robertson		
9:30 – 10:15	Catherine Heymans	**Weak Gravitational Lensing as a Probe of Dark Matter**
10:15 – 11:00	Simona Vegetti	**Strong Gravitational Lensing as a Probe of Dark Matter**
11:00 – 11:30	*COFFEE*	
11:30 – 12:15	Denis Erkal	**Dark Matter Halo Detection from Gaps in Tidal Streams**
12:15 – 12:35	James Nightingale	**Constraining the Dark Matter Particle with Strong Gravitational Lensing**
12:35 – 12:55	Devon Powell	**Visibility-Space Model Comparison for Global VLBI Observation of Strongly Lensed Quasar MG J0751+2716**
12:55 – 2:00	*LUNCH*	
Session 4. Chair – Volker Springel		
2:00 – 2:45	Simon White	**The Smallest Dark Matter Halos and their Annihilation Radiation**
2:45 – 3:05	Martin Haehnelt	**Constraining the Nature of Dark Matter Using the Lyman-Alpha Forest**
3:05 – 3:25	Malcolm Fairbairn	**Searching for Lumpy and Clumpy Dark Matter**
3:25 – 4:00	*COFFEE*	
4:00 – 4:45	Andrew Pontzen	**The Core-Cusp Controversy: Theory and Observations**
4:45 – 5:05	Kyle Oman	**Baryon-Induced Dark Matter Cores Struggle to Explain the Diversity of Dwarf Galaxy Rotation Curves**
5:05 – 5:25	Francesca Fragkoudi	**On the Tension between Bar Dynamics and the LCDM Cosmological Paradigm**
5:25 – 6:10 Discussion	Mark Lovell, Giulia Despali, Nicola Amorisco	**What Is the Best Probe for Dark Subhalos: Lensing, Gaps or Something Else?**

British-German WE-Heraeus-Seminar "Astrophysical Windows on Dark Matter"
Royal Society, Kohn Centre, London

Friday, 5 November 2021 (GMT)

Session 5. Chair – Anna Genina		
9:30 – 10:15	Alejandro Benitez-Llambay	**Baryon Deficient Galaxies - Dark Galaxies as a Probe of Dark Matter**
10:15 – 11:00	Till Sawala	**Lessons About Dark Matter from Satellite Galaxies**
11:00 – 11:30	*COFFEE*	
11:30 – 12:15	Noam Libeskind	**Cosmography of the Local Universe**
12:15 – 1:00	Matthias Steinmetz	**Dark Matter Structure in the Milky Way after Gaia**
1:00– 1:55	*LUNCH*	
Session 6. Chair – Simon White		
1:55 – 2:15	Bradley Kavanagh	**Detecting and Measuring Dark Matter around Black Holes with Gravitational Waves**
2:15 – 3:00 Discussion	Justin Read, Azi Fattahi, Anna Genina	**Dwarf Galaxies as Probes of Dark Matter**
3:00 – 3:15	*COFFEE*	
3:15 – 4:00 Discussion	Sownak Bose, Louie Strigari, Alex Murphy	**How Will We Convince the World that We've Detected the Dark Matter (if We Do)?**
4:00		**End of the Seminar**

Abstracts of Lectures

(in alphabetical order)

Dark and late-forming galaxies: probing ΛCDM at the edge of galaxy formation

A. Benítez-Llambay[1]

[1]University of Milano-Bicocca, Milano, Italy.

The fact that 85% of the matter in the Universe is dark constitutes the cornerstone of the leading cosmological model and the galaxy formation theory. Although the predictions of this Cold-Dark-Matter (CDM) paradigm have been successfully tested against the distribution of bright galaxies, the comparison between the model and observations of faint galaxies has proven to be challenging. This is due to both theoretical and observational uncertainties.

In this talk, I will discuss theoretical predictions of the CDM model that can be tested observationally. In particular, I will explain what determines the time-dependent critical dark matter (DM) halo mass below which galaxies do not form, and I will argue that the interplay between the growth history of dark matter halos and the existence of this critical mass implies that in CDM: 1) there must be a population of starless halos inhabiting DM halos in with masses M_{vir}<$5x10^9$ $M_\odot$(so-called RELHICs) that contain gas in hydrostatic equilibrium that is dense enough to recombine and emit radiation in 21 cm [1]; 2) there must be a small population of late-forming dwarfs that underwent their formation after redshift z=3 [2]. The majority of these galaxies have stellar masses comparable to the extremely old ultrafaint dwarfs (stellar masses < 10^5 $M_\odot$), and inhabit DM halos that span the narrow range in halo mass $3x10^9 < M_{vir} / M_\odot < 10^{10}$ [2]; 3) as a corollary, I will argue that the great majority of luminous galaxies in CDM are expected to be quite old [3].

I will argue that RELHICs could be detected soon with current and upcoming ground-based radio facilities, such as MeerKAT and SKA. On the other hand, I will show that the scarcity of expected bright late-forming dwarfs in LCDM makes it unlikely that these objects have been already identified in our Universe. I anticipate that future surveys with the Vera Rubin Telescope, which will allow the detection of ultrafaint dwarfs beyond our Local Group, will be decisive to test this particular prediction.

References

[1] Benítez-Llambay A et al. (2017)

[2] Benítez-Llambay A & Frenk (2020)

[3] Benítez-Llambay A & Fumagalli (2021)

Dark matter, black holes, and gravitational waves

G. Bertone[1]

[1]*University of Amsterdam*

The interplay between dark matter and black holes remains largely unexplored. Dark matter can in principle be *made of* black holes, as long as these are *primordial*, i.e. they are formed in the very early universe. Dark matter can also accumulate *around* black holes, and modify the rich phenomenology exhibited by these objects. After a brief overview of the status of dark matter searches [1], I will discuss the prospects for detecting primordial black holes or robustly ruling them out as dark matter candidates (e.g. [2]). I will then discuss the prospects for characterizing and identifying dark matter using gravitational waves, covering a wide range of dark matter candidate types and signals [3,4].

References

[1] G. Bertone, T. Tait, *Nature* 562 (2018) 7725, 51-56
[2] G. Bertone et al. *Phys.Rev.D* 100 (2019) 12, 123013
[3] G. Bertone et al. *SciPost Phys.Core* 3 (2020)
[4] A. Coogan, G. Bertone, et al. arXiv: 2108.04154

Warm Dark Matter

Alexey Boyarsky

Leiden University, the Netherlands

Dark matter is one of the major puzzles in today physics. Insights about its nature will greatly affect the future of both astrophysics and cosmology and of particle physics. The so-called warm dark matter is an interesting scenario from this point of view. I will review warm dark matter from particle physics point of view and its relation to the feebly interacting particles as well as its current observational status and will discuss what can be expected in the near future.

Astrophysical Inputs for and Current Constraints from Indirect Dark Matter Detection

F. Calore[1]

Laboratoire d'Annecy-le-Vieux de Physique Théorique, CNRS, Annecy, France

Unveiling the nature of dark matter is one of the major endeavors of our century. The search for dark matter is developed across multiple channels and with different techniques.

In particular, indirect searches aims at disentangling dark matter signal above the largely dominant astrophysical background in the flux of cosmic particles, such as charged cosmic rays and gamma rays. Limits on the dark matter parameters space, and even more detection of tentative signals, crucially depends on our understanding of the astrophysical background. I will discuss what are the main astrophysical ingredients of relevance for dark matter indirect detection and how those impacts the current limits on dark matter particle models.

I will finally provide some prospects for future observations.

Astrophysical Windows on the String Axiverse

Francesca Chadha-Day

Durham University, UK

String theory models generically lead to a large number of axion-like particles (ALPs), known as the string axiverse. As well as the QCD axion providing a solution to the strong CP problem, axions and ALPs can act as Dark Matter. I will discuss the possible astrophysical signatures of the string axiverse, and how the phenomenology of many ALP systems differs from that of a single ALP or axion.

Probing the nature of dark matter with stellar streams

D. Erkal[1]

[1]*Department of Physics, University of Surrey, Guildford, GU2 7XH*

Despite a substantial effort, dark matter has continued to prove elusive to direct and indirect detection. It is possible that dark matter has no interaction with the visible sector and that we will only be able to probe it through its gravitational interactions. In this vein, stellar streams are currently providing some of the tightest constraints on the microscopic nature of dark matter. These streams form as globular clusters or dwarf galaxies tidally disrupt in the presence of our Galaxy. The stars in these streams roughly follow the same orbit and hence they are very sensitive to perturbations which only affect a portion of the stream. In particular, they can probe the small-scale granularity and large-scale time-dependent distribution of dark matter. I will discuss our recent efforts to measure this granularity and the resulting constraints on the mass of dark matter particle assuming either a thermal relic or fuzzy dark matter. Next, I will show that these stellar streams can be used to measure the dynamical response of the dark matter in the Milky Way to the recent accretion of the Large Magellanic Cloud (a ~1:6 merger). This merger is believed to be substantially distorting the dark matter in both systems. Measuring these time-dependent distortions will give us a new window into the nature of dark matter since alternative dark matter models (i.e. SIDM, fuzzy DM) respond differently. I will end with a discussion of the remaining hurdles we must clear to make this measurement.

Searching for Lumpy and Clumpy Dark Matter

Malcolm Fairbairn

King's College London, UK

The Lumpiness and Clumpiness of Dark Matter can tell us many things about its particle nature. We will discuss results on how different dark matter particles can give rise to different characteristic signals in astronomical observations. In particular we will look at how axion dark matter has a rich particle phenomenology on small scales which can be probed through gravitational lensing and through non-linear effects such as the decay into photons, both of which can be observed cosmologically.

Fuzzy Dark Matter

Elisa Ferreira

Max Planck Institute for Astrophysics, Garching, Germany

University of São Paulo, São Paulo, Brazil

Among the many possible candidates for the nature of dark matter, one of the most well-motivated class of models and leading candidate is the ultra-light dark matter. This class represents the lightest possible dark matter candidates and exhibits a wave-like behavior on galactic scales. This leads to a rich phenomenology on small scales that can potentially not only reconcile the CDM picture with the small-scale behavior of dark matter, but offer us the unique possibility to probe their distinctive predictions, and imprints that can reveal clues about the internal properties of dark matter. In this talk, I will review this class of models, describing and classifying the different constructions and their phenomenology. I will give special attention to the fuzzy dark matter, which is the simplest and most studied of these models. Given their vast cosmological and astrophysical effects on observables, I will describe the ongoing advances in constraining these models using current gravitational tests and highlight the strong constraining power of small-scale astrophysical observations. I will show the latest constraints and how with this we are narrowing down the mass range available for these models.

References

[1] Elisa G.M. Ferreira, Astron. Astrophys. Rev. 29, 1, 7 (2021)

[2] K. Hayashi, Elisa G.M. Ferreira, H. Y. J. Chan, Astrophys. J. Lett. 912 1, L3 (2021)

On the Tension between Bar Dynamics and the LCDM Cosmological Paradigm

Francesca Fragkoudi

European Southern Observatory, Garching, Germany

The formation and properties of stellar bars in spiral galaxies are both tightly linked to the properties of their dark matter halos. For example, it has been shown that dynamical friction induced by a massive dark matter halo will slow down the rotation speed of bars. While numerous observational studies have found that bars tend to rotate fast, numerical simulations within the LCDM framework tend to find that bars slow down excessively. This has given rise to an apparent tension between fast bars and the LCDM cosmological paradigm, which has been highlighted over the past years in the literature. I will present recent findings from cosmological simulations that help to shed light on this longstanding issue, and discuss this within the context of recent claims in the literature of a > 10sigma tension between fast bars and LCDM.

Direct Detection of Galactic WIMPs with Large Underground Experiments: the Next (Last?) Generation

C. Ghag[1]
[1]*University College London, London, UK*

Rare event searches that deploy xenon targets in deep underground laboratories have proven remarkably successful in their ability to be scaled up and probe unexplored electroweak parameter space in the search for WIMPs. The leading experiments, LZ [1] and XENONnT [2], will extend reach by another order of magnitude over the next 3 years. With data taking imminent, attention is turning to the necessary R&D towards construction of the next generation ('G3') global experiment, bringing together the international xenon community, for confirmation of any signal in LZ/XENONnT, an historic first discovery, or the ruling out of standard intermediate-mass WIMPs down to the irreducible background from coherently scattering astrophysical and atmospheric neutrinos. The scale of G3 will deliver unprecedented sensitivity not only to WIMPs, but also theoretically well-motivated alternative non-WIMP dark matter, BSM, and exotic neutrino physics. Now is the time to tune our R&D and technical design efforts for G3 to ensure coverage of the most promising models towards discovery.

References

[1] D. S. Akerib, et al., Phys. Rev. D **101**, 052002 (2020)
[2] E. Aprile, et al., JCAP **11**, 031 (2020)

Constraining the Nature of Dark Matter Using the Lyman-Alpha Forest

Martin G. Haehnelt

[1]*Institute of Astronomy and Kavli Institute for Cosmology, Cambridge, UK*

The Lyman-alpha forest is a sensitive probe of the properties of dark matter affecting the clustering of matter at small scales as well as the ionization and thermal history of the Intergalactic Medium. I describe the current status of disentangling these effects to obtain robust limits on warm and fuzzy dark matter.

References

[1] E. Boera et al., ApJ, **872,** 101 (2019)
[2] P. Gaikwad et al. 2020, MNRAS, **494**, 5091 (2020)
[3] V. Irsic et al, Phys. Rev. D., **96,** 023522 (2017)
[4] V. Irsic et al, in preparation (2021)
[5] M. Molaro et al., MNRAS, submitted, (2021), arxiv:2109.06897
[6] E. Puchwein et. al., in preparation (2021)
[7] K.K. Rogers, H.V. Peiris, Phys. Rev. Let., **126,** 1321 (2021)
[8] M. Viel et al. (2013), Phys. Rev. D, **88,** 043502 (2013)

Weak Gravitational Lensing as a probe of dark matter

Catherine Heymans [1,2]

[1]*University of Edinburgh, Scotland*
[2]*German Centre for Cosmological Lensing, Ruhr Universitat Bochum*

Observed images of distant galaxies appear to coherently align as a result of the distorted light paths induced by the curved space-time around foreground structures. By measuring these weakly gravitationally lensed shapes and distances to tens of millions of galaxies, we can infer the distribution of the total foreground matter irrespective of its dark or luminous nature. I will review the state-of-the-art large-scale structure maps of the Universe that have thrown the cosmology community into some state of turmoil: the dark matter clustering is found to be lower than expected given the cosmological model that describes Planck's exquisite observations of the cosmic microwave background. Do data challenges lie ahead, or is this new evidence for beyond-ΛCDM physics?

Dark Radiation and Superheavy Dark Matter from Hawking Evaporation of Primordial Black Holes

Dan Hooper

University of Chicago, USA

If even a relatively small number of black holes were created in the early universe, they will constitute an increasingly large fraction of the total energy density as space expands. It is thus well-motivated to consider scenarios in which the early universe included an era in which primordial black holes dominated the total energy density. Within this context, we consider Hawking radiation as a mechanism to produce both dark radiation and dark matter. If the early universe included a black hole dominated era, we find that Hawking radiation will produce dark radiation at a level of delta N_eff ~0.03-0.2 for each light and decoupled species of spin 0, 1/2, or 1. This range is well suited to relax the tension between late and early-time Hubble determinations, and is within the reach of upcoming CMB experiments. The dark matter could also originate as Hawking radiation in a black hole dominated early universe, although such dark matter candidates must be very heavy (m_DM > 10^11 GeV) if they are to avoid exceeding the measured abundance.

Detecting and Measuring Dark Matter around Black Holes with Gravitational Waves

Bradley Kavanagh

IFCA (CSIC-University of Cantabria), Santander, Spain

The observation of Gravitational Waves (GWs) has opened up a whole new avenue for constraining and detecting particle Dark Matter (DM). One of the most promising systems to study is the Intermediate Mass Ratio Inspiral (IMRI): a stellar-mass compact object such as a neutron star inspiraling towards an intermediate mass black hole, thousands of times more massive than the Sun. Sub-hertz GWs emitted during the inspiral should be detectable by future space-based observatories such as LISA. But the presence of DM in the system can have subtle dynamical effects on the inspiral, altering the waveform and hopefully allowing us to map out the DM distribution. I will discuss ongoing work to study these systems carefully and self-consistently, in order to determine whether such a signal can be detected and what we can learn about Dark Matter if it is.

Cosmography of the Local Universe

Noam Libeskind
Leibniz Institute for Astrophysics Potsdam, Germany

Galaxies and dark matter are not distributed uniformly in the universe but instead forms a complicated multi scale network known as the cosmic web. The cosmic web may be segmented into various components that not only describe its morphology but also influence how matter moves and how galaxies assemble. In the current work I will describe the link between the large scale structure of the universe and the galaxies forming within it. Specifically I will tie the planes of satellite galaxies observed in the local universe to the principle directions of local expansion and compression. I will also show the first ever evidence that cosmic filaments spin, thereby demonstrating that angular momentum and vorticity can be generated on unprecedented scales.

Dark Matter Annihilation and the First Structures

Katie Mack

North Carolina State University, Raleigh, USA

As we search for the most distant galaxies in the universe with radio and infrared observations, we are in a position to explore the particle physics of dark matter — the possibility of annihilation, decay, or other particle interactions — through its effects on early stars and galaxies. I will discuss how dark matter annihilation can impact the formation of the first cosmic structures by altering the collapse of gaseous halos and how upcoming observations of the epoch of reionization and cosmic dawn can be used to constrain dark matter's particle properties and thermal history.

Impact of astrophysical inputs on direct searches for dark matter

C. O'Hare[1], C. McCabe[2], W. Evans[3]

[1]*School of Physics, The University of Sydney, New South Wales, Australia*
[2]*Department of Physics, King's College London, London, UK*
[3]*Institute of Astronomy, University of Cambridge, Cambridge, UK*

Predicting signals in experiments seeking to directly detect dark matter requires knowledge of several astrophysical inputs. The default parameterisation is encoded in the Standard Halo Model in which dark matter velocities are isotropic and follow a truncated Gaussian law. However, it is well known that deviations beyond the simplified Standard Halo Model are expected. Deviations could include a strongly radially anisotropic component associated with the 'Gaia Sausage', or substructure from other accretion events that have occurred during the history of the Milky Way.

In this talk, I will discuss the impact of changing these astrophysical inputs on the predictions for direct searches for dark matter. I will review the impact on a wide range of experimental techniques, including nuclear recoils, electron recoils, and searches for axion-like and ultra-light scalar dark matter. This work is based on the references below, as well as ongoing work in progress.

References

[1] C.A.J. O'Hare, C. McCabe, N.W. Evans, G. Myeong, V. Belokurov, Phys. Rev. D 98 (2018) 10, 103006
[2] N.W. Evans, C.A.J. O'Hare, C. McCabe, Phys. Rev. D 99 (2019) 2, 023012
[3] C.A.J. O'Hare, N.W. Evans, C. McCabe, G. Myeong, V. Belokurov, Phys. Rev. D 101 (2020) 2, 023006

Constraining the Dark Matter Particle With Strong Gravitational Lensing

James Nightingale

Durham University, UK

The dark matter (DM) particle forms the basis of the standard cosmological model, with the currently favored candidate cold dark matter (CDM) withstanding extensive observational tests on the Universe's largest scales for over thirty years. However, CDM remains largely untested on smaller scales, for example its prediction of ubiquitous clumps of DM with masses <10^9Msun, which do not form in alternative models of warm or self-interacting DM. Using galaxy-scale strong gravitational lenses, the presence (or lack thereof) of these DM clumps can be inferred by looking for distortions in the lensed source’s emission. I present results scanning for DM clumps in HST imaging of over 50 strong lenses, which include an independent reproduction of a previous detection found in the system SDSSJ0946+1006. I show that oversimplifications in the lens galaxy’s mass model produce false-positive detections of DM clumps and discuss strategies for mitigating this. Finally, to translate these results into constraints on the DM particle I show how properly accounting for scatter in the DM mass-concentration relation significantly improves our ability to distinguish between DM models, by making high concentration low mass DM halos (e.g. <10^9Msun) detectable.

Baryon-Induced Dark Matter Cores Struggle to Explain the Diversity of Dwarf Galaxy Rotation Curves

Kyle Oman

Durham University, UK

The 21-cm rotation curves of galaxies are well-established as kinematic tracers able to shed light on their dark matter content. The rotation curve shapes of dwarf galaxies are known to be quite diverse (at fixed maximum circular velocity), which implies at least one of: (i) the dark matter in these objects can be re-distributed due to properties of the dark matter, e.g. self-interacting dark matter; (ii) the dark matter can be re-distributed in the process of galaxy formation, e.g. by gravitational coupling to violent gas motions driven by supernova explosions; (iii) kinematic models of these objects suffer from non-negligible and systematic errors, e.g. due to un-modelled non-circular gas orbits in a geometrically thick disc. I will show that, when they are mock-observed and modeled, simulated galaxies containing dark matter cores (of the baryon-induced variety) exhibit secondary correlations in the parameters describing their rotation curves which run contrary to those observed. Galaxies hosting dark matter cusps instead more closely resemble the observed population.

The Core-Cusp Controversy: Theory and Observations

Andrew Pontzen[1]

[1]*University College London, WC1E 6BT, London, United Kingdom*

I will review the core-cusp controversy with an emphasis on the difficulties posed by baryonic physics. In the cold dark matter paradigm, all galaxies are predicted by numerical simulations to host a "cuspy" halo of dark matter with ever-increasing density towards the centre. However, starting in the 1990s, it became increasingly clear that many dwarf galaxies do not appear to play host to such cusps, with rotation curves instead pointing towards the existence of a constant-density "core". More indirect signs suggest that larger galaxies and clusters of galaxies may also host such dark matter cores. The physical interpretation of these observations has always been controversial, and remains so to this day. Attempts to explain them typically invoke either extensions to the cold dark matter paradigm (such as self-interacting or ultra-light dark matter models) or gravitational heating effects powered by galaxies themselves. I will review the observational evidence and discuss how this issue may eventually be laid to rest from a theoretical perspective.

A Visibility-Space Model Comparison for the Global VLBI Observation of the Strongly-Lensed Quasar MG J0751+2716

Devon Powell

Max Planck Institute for Astrophysics, Garching, Germany

Gravitational lensing by galactic potentials is a powerful tool with which to probe the abundance of low-mass dark matter structures in the universe. Dark matter substructures or line-of-sight haloes introduce small scale perturbations to the smooth lensing potential. By observing detections (or non-detections) of such low-mass perturbers in lensed systems, we can place constraints on the halo mass function and differentiate between different particle models for dark matter. High angular resolution observations can place the strongest constraints on the low end of the halo mass function.

In this talk, I will discuss the development of a Bayesian forward-modelling technique for simultaneously reconstructing the source brightness and the lens mass from VLBI observations. The fitting is done directly the native visibility space. Our method requires no pre-averaging or other data reduction steps prior to modelling, which sets it apart from previous approaches to this problem.

I will then present the results obtained from a global VLBI observation of the strongly-lensed quasar MG J0751+2716. This includes five different parametric forms for the lens mass, as well as the corresponding source reconstructions. The model comparison is done objectively via the Bayesian evidence. This is the first result of its kind on a high-resolution VLBI observation of a strong lens system, and it paves the way for detailed searches for substructure and line-of-sight perturbers.

Self-interacting dark matter

Andrew Robertson

Institute for Computational Cosmology, Durham University, South Road, Durham DH1 3LE, UK

I will review self-interacting dark matter, beginning with a brief discussion of the motivations for considering it as a dark matter candidate. I will then discuss how systems ranging from dwarf galaxies to galaxy clusters have been used to place constraints on the dark matter self-interaction cross-section.

Lessons about Dark Matter from Satellite Galaxies

Till Sawala
University of Helsinki, Finland

The satellite galaxies of the Milky Way have presented some of the most stringent tests of the LCDM model, and of the general paradigm of galaxy formation inside dark matter haloes. I review progress towards resolving four of the Milky Way's cosmic puzzles and discuss how a combination of numerical simulations and observations have recently helped transform some of the previous discrepancies into successful model predictions. I also present a new perspective on the "plane of satellites problem".

The GeV Gamma Ray Excess in the Inner Milky Way

Prof. Tracy R Slatyer[1]

[1] *Center for Theoretical Physics, Massachusetts Institute of Technology, Cambridge, MA, USA*

Studies of public data from the Fermi Gamma-Ray Space Telescope have revealed a surprising excess of apparently diffuse gamma-ray emission in the region within 1.5 kiloparsecs of the Galactic Center. This excess has garnered great interest as a possible signal of either dark matter particles colliding and annihilating, or a previously undiscovered population of pulsars in the stellar bulge. Analyses of the photon statistics and morphology of the excess have been used to argue that the pulsar interpretation is strongly favored, but at least some of these claims appear to be highly sensitive to systematic effects. I will outline the history of our understanding of the excess and the arguments for various interpretations, describe the current status of the controversy and the implications of various hypotheses, and discuss future paths forward.

Constraints on the Mass of and the Mass Distribution in the Milky Way System Based on Gaia and Massive Spectroscopy

Matthias Steinmetz
Leibniz Institute for Astrophysics Potsdam, Germany

The Milky Way with its satellite system is a prime location to study gravitational effects caused by dark matter. However, the reliability of derived constraints on the mass distribution may be severely affected by non-equilibrium effects. Astrometric data as those provided by the Gaia satellite provides new insights into these effects in particular if combined with additional spectroscopic information from Multi-Object surveys and integral field units. I will present some recent results constraining the mass of and mass distribution in the Milky Way and some of its satellite galaxies.

Strong Gravitational Lensing as a Probe of Dark Matter

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The Cold Dark Matter model for structure formation is currently the most successful at reproducing many observations, but it remains largely untested in the non-linear sub-galactic regime. A clear prediction of this model is that a significant number of low-mass haloes should populate any galaxy and its line of sight. As most of these objects are expected to be completely dark, strong gravitational lensing provides a unique channel to detect them and determine the properties of dark matter by constraining the halo-mass function at the low-mass end.

In this talk, I will review the current status of this field and present the latest observational constraints on the halo mass function. I will then discuss the most significant challenges in successfully constraining the properties of dark matter with strong gravitational lensing and how upcoming observing facilities such as Euclid and the E-ELT will revolutionise this field.

The smallest dark matter halos and their annihilation radiation

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Small dark matter halos are often assumed to play a major role in astrophysical sources of annihilation radiation if the dark matter particle should turn out to be of a type (for example a WIMP) where annihilation occurs and leads directly or indirectly to photon emission. This role may either be through the detection of the halos of dwarf satellite galaxies of the Milky Way or through *boosting* of the total emission from larger mass halos (our own or those of other galaxies/clusters) by a very large population of very low-mass subhalos. Recent simulation work has for the first time allowed the structure of present-day low-mass halos to be studied across the full halo mass range expected in a Cold Dark Matter universe, and has also determined how this structure is modified by processes which affect their (initially) associated baryons. Low-mass halos turn out to have lower densities, concentrations and annihilation luminosities than assumed in almost all previous work, and these luminosities are reduced even further by baryonic effects. As a result, boost factors are expected to be small for halos of galactic scale or smaller, and the flux from the brightest substructure in our Milky Way's halo is expected to be lower than that from the inner regions of the Galaxy by about 3.5 orders of magnitude. As a result, it is unlikely that any emission will be detected from any small satellite before the Galactic Centre excess has been confirmed as annihilation radiation.