Hundred Years of Gauge Theory

678. WE-Heraeus-Seminar

July 30 – August 3, 2018
at the Physikzentrum Bad Honnef/Germany

WILHELM UND ELSE
HERAEUS-STIFTUNG

Subject to alterations!

Introduction

The Wilhelm and Else Heraeus Foundation (Wilhelm und Else Heraeus-Stiftung) is a private foundation which supports research and education in science, especially in physics. A major activity is the organization of seminars. To German physicists the foundation is recognized as the most important private funding institution in their fields. Some activities of the foundation are carried out in cooperation with the German Physical Society (Deutsche Physikalische Gesellschaft).

Scope of the 678. WE-Heraeus-Seminar:

In the Centenary of the publication of Hermann Weyl's masterpiece Raum-Zeit-Materie, this workshop aims at stimulating the reflection upon the origin and development of gauge theory and its scientific and philosophical importance. Taking into account one of the central concepts of Weyl's work, symmetry, this workshop sheds light on several aspects of Weyl's work and gauge theory and connects theoretical physics with other fields. Plenary lectures will be given by theoretical and experimental physicists, mathematicians, historians, and philosophers of science. This approach will allow detailed and broader discussions on questions such as

- Which role does Weyl's Raum-Zeit-Materie play in the research fields of gauge theory and gravity?
- Which role did Weyl's ideas play and still play in the philosophy of science?
- Can gravitation and quantum theory be consistently unified?
- How well is gauge theory experimentally tested?
- Which is the role that gauge theory play for the relation of mathematics to physics?

Scientific Organizers:

Prof. Dr. Claus Kiefer	University of Cologne, GERMANY Institute of Theoretical Physics E-mail kiefer@thp.uni-koeln.de
Dr. Silvia De Bianchi	Autonomous University of Barcelona, SPAIN Department of Philosophy and & Centre for the History of Science E-mail silvia.debianchi@uab.cat

Introduction

Administrative Organization:

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Registration:

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

Door Code:

(Key symbol button) 2 6 7 8 #
For entering the Physikzentrum
during the whole seminar

Program

Program

Sunday, July 29, 2018

17:00 – 21:00	Registration	
from 18:30	*BUFFET SUPPER / Informal get together*	

Monday, July 30, 2018

08:00	BREAKFAST	
08:45 – 09:00	Scientific organizers	**Opening and welcome**
09:00 – 10:00	Gerardus ' t Hooft	**Past and future of gauge theory**
10:00 – 11:00	Christof Wetterich	**Scale symmetry in particle physics and cosmology**
11:00 – 11:30	COFFEE BREAK	
11:30 – 12:30	Friedrich Hehl	**The conserved energy-momentum current of matter as the basis for the gauge theory of gravitation**
12:30	**Conference Photo** (in front of the historical building)	
12:45	LUNCH	

Program

Monday, July 30, 2018

14:30 – 15:30	Norbert Straumann	**Hermann Weyl's space-time geometry and the origin of gauge theory 100 years ago**
15:30 – 16:30	Erhard Scholz	**Gauging the spacetime metric - looking back and forth a century later**
16:30 – 17:00	*COFFEE BREAK*	
17:00 – 17:15	Stefan Jorda	**About the Wilhelm and Else Heraeus-Foundation**
17:15 – 18:15	**Poster flash presentations**	
19:00	*DINNER*	

Program

Tuesday, July 31, 2018

08:00	*BREAKFAST*	
09:00 – 10:00	Alexander Blum	**The early history of the connection between gauge theory and renormalizability**
10:00 – 11:00	Jeremy Butterfield / Sebastian De Haro	**On gauge, symmetry and duality**
11:00 – 11:30	*COFFEE BREAK*	
11:30 – 12:30	Dennis Dieks	**Hermann Weyl and objectivity (and gauge)**
12:45	*LUNCH*	
14:30 – 15:30	Gabriel Catren	**Steps towards an ontological interpretation of gauge symmetries**
15:30 – 16:30	Thomas Ryckman	**Weyl, gauge invariance and symbolic construction from the 'purely infinitesimal'**
16:30 – 17:00	*COFFEE BREAK*	
17:00 – 18:00	Dennis Lehmkuhl	**Geodesics in general relativity and in Weyl geometry**
18:00 – 19:00	**Poster session I**	
19:00	*DINNER*	

Program

Wednesday, August 1, 2018

08:00	*BREAKFAST*	
09:00 – 10:00	Thomas Schücker	**The gauge theoretical underpinnings of general relativity**
10:00 – 11:00	Silvia De Bianchi	**Weyl's Raum-Zeit-Materie and the Philosophy of Science**
11:00 – 11:30	*COFFEE BREAK*	
11:30 – 12:30	Hans-Peter Nilles	**Gauge symmetries and CP-violation**
12:45	*LUNCH*	
14:30 – 18:30	**Excursion** (boat trip to Linz on the river Rhine)	
19:00	*DINNER*	

Program

Thursday, August 2, 2018

08:00	*BREAKFAST*	
09:00 – 10:00	Johanna Stachel	**Experimental tests of gauge theories: The QCD phase diagram at high temperature**
10:00 – 11:00	Laura Covi	**Gauge fields in cosmology**
11:00 – 11:30	COFFEE BREAK	
11:30 – 12:30	Christian Steinwachs	**Higgs field in cosmology**
12:45	*LUNCH*	
14:30 – 15:30	Francesca Vidotto	**Loop quantum gravity: A general-covariant lattice gauge theory**
15:30 – 16:30	Elise Crull	**Neo-Kantian quantum gravity**
16:30 – 17:00	COFFEE BREAK	
17:00 – 18:00	Claus Kiefer	**Space, time, matter in quantum gravity**
18:00 – 19:00	**Poster session II**	
19:00	*HERAEUS DINNER* at the Physikzentrum (cold & warm buffet, free beverages)	

Program

Friday, August 3, 2018

08:00	BREAKFAST	
09:00 – 11:00	**Podium discussion**	
11:00 – 11:30	COFFEE BREAK	
11:30 – 12:30	Scientific organizers	**Poster awards, summary and closing remarks**
12:45	LUNCH	

End of the seminar and FAREWELL COFFEE **/ Departure**

Please note that there will be **no** dinner at the Physikzentrum on Friday evening for participants leaving the next morning.

Posters

Posters

1.	Tomasz Andrzejewski	**Kinematical Lie algebras in 2+1 dimensions**
2.	Aroonkumar Beesham	**Influence of Hermann Weyl on general relativity and cosmology**
3.	David Benisty	**Energy transfer from space-time into matter and a bouncing inflation from Covariant Canonical Gauge theory of Gravity**
4.	Jens Boos	**Algebraic superenergy in Poincaré gauge gravity**
5.	Kaća Bradonjić	**On the distinction between physical and mathematical symmetries of spacetime**
6.	Marco de Cesare	**Noncommutative gauge theory of gravity with self-dual variables**
7.	Elena De Paoli	**A gauge-invariant symplectic potential for tetrad general relativity**
8.	Maaneli Derakhshani	**Unimodular bohmian gravity**
9.	Rasmus Jaksland	**A preference for gauge theory (over gravity)**
10.	Iarley Lobo	**Experimental constraints on the second clock effect**
11.	Colin MacLaurin	**Gauge freedom and black holes**
12.	Edgardo José Marbello Santrich	**Flavour changing neutral currents mediated by scalars in a 3-4-1 model**
13.	Pierre Martin-Dussaud	**A black-to-white hole spacetime**
14.	Salvador Robles-Perez	**Third quantization: A complete analogy with a quantum field theory**
15.	Carlos Romero	**Weyl's unified field theory and non-locality**
16.	Fabio Scardigli	**Generalized uncertainty principle parameter from quantum corrections to the Newtonian potential**
17.	Tim Schmitz	**Singularity avoidance of the quantum LTB model for gravitational collapse**
18.	Luca Smaldone	**Energy-time uncertainty principle and neutrino oscillations in quantum field theory**
19.	Roberto Tanzi	**Quantum electrodynamics with area-metric deviations from a metric**

Abstracts of Lectures

(in chronological order)

Past and future of gauge theory

Gerard 't Hooft

Institute of Theoretical Physics, Princetonplein 5, 3584 CC Utrecht, the Netherlands

When a particle model is renormalizable this implies that interactions can be calculated quite accurately as soon as the interaction strengths are sufficiently weak. The complete set of interaction models with such properties can be identified by extensive use of the gauge principle.

The most general structure for such models was subsequently established; in flat Minkowski space-time, they are based on fundamental particles with spin values 0, 1/2 or 1. The resulting theories have rich topological structures and scale dependences.

If we switch on gravity, space and time are no longer flat, and fundamental particles with spin 2 may appear, the gravitons. In this case, also space-time will have intricate topological features, induced by gravitational collapse. The fundamental questions to be addressed in the near future are speculated on.

Scale symmetry in particle physics and cosmology

Christof Wetterich

Universität Heidelberg, Institut für Theoretische Physik,
Heidelberg/Germany

Already in the early years of general relativity Weyl has discussed gravitational theories with scale invariance. While quantum effects generically violate scale symmetry, they can also generate scale symmetry at fixed points for the running couplings. This quantum scale symmetry near the ultraviolet fixed point is a general feature for quantum gravity described as a renormalizable quantum field theory by asymptotic safety. It is the origin of the almost scale invariant spectrum of primordial fluctuations in cosmology. Spontaneously broken scale symmetry produces a massive particle spectrum and a massless scalar Goldstone boson. The pseudo-goldstone boson of approximate scale symmetry may be responsible for dynamical dark energy.

The conserved energy-momentum current of matter as the basis for the gauge theory of gravitation

Friedrich W. Hehl

Institute for Theoretical Physics, University of Cologne, 50923 Köln, Germany

According to Yang and Mills (1954), "Conservation of Isotopic Spin and Isotopic Gauge Invariance" are the starting point for the setting up a hypothetical SU(2) gauge theory of strong interaction. The conserved isospin current, via the reciprocal of the Noether theorem, yields a rigid ('global') SU(2)-invariance. Insisting, as Yang and Mills did, that a rigid symmetry is inconsistent with field-theoretical ideas, the SU(2)-invariance is postulated to be valid *locally*. This enforces to introduce a compensating (or gauge) field B which uphold the SU(2)-invariance even under these generalized local transformations. The curl of B turns out to be the field strength of the emerging gauge field.

The analogous procedure for the conserved electric current and its associated U(1)-invariance of the Dirac equation was already executed by Weyl in 1929.

For gravity, a similar procedure, was basically performed by Sciama and Kibble in 1960/61, with Utiyama as a forerunner (1956). It can be formulated as follows: In Newtonian gravity, mass is the source of gravity and—in its quasi field-theoretical formulation—the mass density. Mass is conserved in Newtonian gravity. In special relativity, the mass density is superseded by the *energy-momentum* current of matter and the conservation of mass by the conservation of energy-momentum. Thus, the conserved energy-momentum current of matter in special relativity is doubtlessly the starting point for a gauge theory of gravity. Rigid translational invariance is made *local* at the price of introducing 4 translational gauge potentials (the coframe ϑ) which compensate the violation of the rigid invariance. The curl of ϑ corresponds to the gravitational field strength.

Since the translation group in special relativity is a subgroup of the Poincaré group, the symmetry group of special relativity, one has to straightforwardly extend the gauging of the translations to the gauging of full Poincaré transformations thereby also including the conservation law of the *angular momentum* current. The emerging Poincaré gauge theory of gravity, starting from the Sciama-Kibble theory of 1960/61, will be shortly reviewed.

M. Blagojević, F. W. Hehl (eds.), *Gauge Theories of Gravitation: A Reader with Commentaries* (Imperial College Press, London, 2013).

M. Blagojević, B. Cvetković, General Poincaré gauge theory: Hamiltonian structure and particle spectrum, arXiv:1804.05556 (2018).

J. Boos, F. W. Hehl, Gravity-induced four-fermion contact interaction implies...gauge bosons, Int. J. Theor. Phys. **56**, no. 3, 751 (2017), arXiv:1606.09273.

M. Chaichian, N. F. Nelipa, *Introduction to Gauge Field Theories* (Springer, Berlin, 1984).

Y. Itin, Energy momentum current for coframe gravity, Class. Quant. Grav. **19**, 173 (2002), arXiv:gr-qc/0111036.

Y. Itin, Y. N. Obukhov, J. Boos, F. W. Hehl, Premetric teleparallel theory of gravity and its local and linear constitutive law, to be submitted to EPJC (2018).

Y. N. Obukhov, Poincaré gauge gravity:..., Int. J. Geom. Meth. Mod. Phys. **3**, 95 (2006), arXiv:gr-qc/0601090. Y. N. Obukhov, Poincaré gauge gravity:..., arXiv:1805.07385.

Hermann Weyl's Space-Time Geometry and the Origin of Gauge Theory 100 Years ago

Norbert Straumann
Physik-Institut
University of Zürich, Switzerland

One of the major developments of twentieth century physics has been the gradual recognition that a common feature of the known fundamental interactions is their gauge structure. In this talk the early history of gauge theory is reviewed, emphasizing especially Weyl's seminal contributions of 1918 and 1929.

Gauging the spacetime metric -- looking back and forth a century later

Erhard Scholz[1]

[1]*Department of Math., University of Wuppertal, Germany*
[2]*Interdisciplinary Center for Hist. and Phil. of Science, Wuppertal*

H. Weyl's proposal of 1918 for generalizing Riemannian geometry by local scale gauge (Weyl geometry) was motivated by mathematical, philosophical and physical considerations. It led to his well known idea of a geometrically unified field theory of electromagnetism and gravity. After getting disillusioned with this interpretation and the convincing alternative translation of the gauge idea to the phase of wave functions and spinor fields in quantum mechanics in the later 1920s, he no longer considered the original gauge idea as of physical import ("mathematical" versus "physical" automorphisms).

About the middle of the last century the question of conformal and/or local scale gauge transformation were reconsidered independently in high energy physics (Bopp, Wess, et al.) and gravitation theory (Jordan, Fierz, Brans, Dicke). In this context Weyl geometry attracted new interest among different groups of physicists (Omote/Utiyama/Kugo, Dirac/Canuto/Maeder, Ehlers/Pirani/Schild and others), often by hypothesizing a new scalar field linked to gravity and/or high energy physics. Although not crowned by immediate success this "retake" of Weyl geometrical methods seems to live on a century after Weyl's first proposal of his basic geometrical structure.

There even seem to be present questions of physics for which the Weyl geometric perspective might still be valuable. Weyl's idea of a "natural" (scale) gauge appears in a new light, if the Higgs field and an additional (Weyl geometric) scalar field are coupled by a common biquadratic potential (Shaposhnikov et al.). And why shouldn't it be worthwhile to look at the present, MOND inspired, modified gravity theories from the point of view of Weylian scale covariance?

References

[1] E. Scholz. "The unexpected resurgence of Weyl gometry in late 20-th century physics". In D. Rowe; T. Sauer, S. Walter (eds.): *Beyond Einstein. Perspectives on Geometry, Gravitation and Cosmology*. Springer 2018 (in print) arXiv:1703.03187

The early history of the connection between gauge theory and renormalizability

Alexander Blum[1]

[1]*Max Planck Institute for the History of Science, Berlin, Germany*

Already in the 1930s, before the development of renormalization theory, physicists realized that two kinds of quantum field theories could be distinguished, depending on the structure of the divergences appearing in perturbation theory. Around 1950, this distinction was recast as that between renormalizable and non-renormalizable theories. While this distinction was easy to draw for theories involving only scalar fields and Dirac spinors, it was far more difficulty for theories involving higher-spin fields. In the course of the 1950s, the existence of conserved currents and ultimately gauge invariance came to play an important role in this distinction, arguably contributing to the central status nowadays afforded to gauge theories. In my talk, I will trace this historical development, placing special emphasis on the changing criteria for distinguishing the two kinds of field theories, as well as on the changing physical interpretations of these criteria.

On gauge, symmetry and duality

J. Butterfield[1] and S. De Haro[1,2]

[1] *Trinity College, University of Cambridge, UK*
[2] *University of Amsterdam, The Netherlands*

This talk (presented by both authors) will relate the topic of gauge, to dualities and equivalence of physical theories. All three topics have recently been popular in the philosophy of science. We will begin by reporting our own account of duality. Namely: a duality is (roughly speaking): an isomorphism of two models, that are both representations of a common core theory. We will then relate this account to various recent proposals about gauge and to theoretical equivalence. We will mention several examples, but focus on bosonization.

References

[1] S. De Haro and J Butterfield ,'A Schema for Duality, Illustrated by Bosonization',
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[2] J Butterfield ,'On Dualities and Equivalences Between Physical Theories', Forthcoming in *Philosophy Beyond Spacetime*, ed. B. Le Bihan, N. Huggett and C. Wuthrich (OUP 2018). 54 pages; http://philsci-archive.pitt.edu/14736/ ; https://arxiv.org/abs/1806.01505 (2018)

[3] S. De Haro, 'Spacetime and Physical Equivalence'. Forthcoming in one of two edited volumes Space and Time after Quantum Gravity by N. Huggett and C. Wüthrich (Eds.), Cambridge University Press (2018). http://philsci-archive.pitt.edu/13243/

Hermann Weyl and Objectivity (and Gauge)

Dennis Dieks

History and Philosophy of Science, Utrecht University, The Netherlands

Hermann Weyl's approach to science was quite distinctive: as he himself wrote, it was the combination of philosophy, mathematics and physics that was dearest to his heart and to which he devoted most effort. Many of his physics publications accordingly contain parts of a philosophical nature. In particular, the relation between the subjective and the objective, and the role of "intuition" were life-long concerns for Weyl. As we shall argue, attention for these philosophical concerns makes some of his physics ideas better understandable. In the talk we will discuss a number of Weyl's central philosophical conceptions and illustrate how these shine through in his technical physics work. In particular, we will pay attention to notions relating to his introduction of gauge theories.

Steps Towards an Ontological Interpretation of Gauge Symmetries

G. Catren

[1]*Laboratoire SPHERE – Science, Philosophie, Histoire, UMR 7219, Université Paris Diderot – CNRS, Paris.*

We shall address the problem of understanding the ontological and/or epistemic underpinnings of gauge symmetries by placing gauge theories in a broader historical constellation of philosophical and mathematical problems going from Leibniz's reflections on the notions of *identity* and *indiscernibility* to the far-reaching reconceptualization of statements of the form *a=b* developed in the framework of category theory.

Weyl, gauge invariance and symbolic construction from the 'purely infinitesimal'

Thomas Ryckman
Stanford University, Stanford, CA, USA

I present an overview of how a non-naturalistic metaphysics of transcendental subjectivity proved an extremely fruitful heuristic in two of Weyl's central achievements, in the origin of the idea of "gauge invariance" in the 1918 "purely infinitesimal geometry", and in his purely mathematical turn to Lie theory in 1925-6 (on representations of semisimple Lie groups and Lie algebras). The two are not unrelated: Weyl would coin the term "Lie algebra" for the infinitesimal structure of a Lie group; he also showed in 1923 that this infinitesimal structure is a linear vector space, a concept itself first defined by Weyl in 1913. In this guise, Lie algebras (their representations) play an important role in contemporary gauge theories. I argue that both achievements are motivated by Weyl's injunction (derived from Riemann and Lie) to comprehend the world (via "symbolic construction") from its behavior in the infinitely small. The metaphysics of transcendental subjectivity evidentially privileges linear relations within the tangent space T_P and leads to constitution of the idea of *objectivity-as-invariance*. I suggest this may shed light on the redundancy of description in gauge theories, considered by some as the most important contemporary problem of philosophy of physics.

Geodesics in General Relativity and in Weyl Geometry

Dennis Lehmkuhl

Caltech, Einstein Papers Project
Pasadena, USA

In 1918, Hermann Weyl and Albert Einstein exchanged more than a dozen letters comparing general relativity (GR) with Weyl's unified field theory. The latter is based on a generalisation of pseudo-Riemannian geometry that we now call Weyl geometry. One of the most interesting aspects of this correspondence is the discussion of the motion of test particles in GR and in Weyl's theory. I will first outline the different positions advocated by Weyl and Einstein and the arguments they name in their favour. In the 1920s, Einstein and Weyl then independently argued that the geodesic motion of test particles in GR could be derived rather than assumed. In 1975, Geroch and Jang provided a new type of proof for such a `geodesic theorem'. I will argue that the Geroch-Jang theorem can be generalised to Weyl geometry if the latter is decoupled from the project of a unified field theory, and that it can then shed new light on the positions advocated by Einstein and Weyl in the 1910s and 1920s. (This is joint work with Erhard Scholz.)

The gauge theoretical underpinnings of general relativity

T. Schücker

Centre de Physique Théorique, Marseille, France

The gauge theoretical formulation of general relativity is presented. We are only concerned with local intrinsic geometry, i.e. our space-time is an open subset of a four-dimensional real vector space. Then the gauge group is the set of differentiable maps from this open subset into the general linear group or into the Lorentz group or into its spin cover.

Weyl's *Raum-Zeit-Materie* and the Philosophy of Science

S. De Bianchi[12]

[1]*Department of Philosophy, UAB, Bellaterra, Barcelona, Spain*
[2] *CEHIC, UAB, Bellaterra, Barcelona Spain*

In 1918, Hermann Weyl published the first edition of his masterpiece *Raum-Zeit-Materie.* The book constituted one of the most inspiring texts for early debates on gauge theory and a fascinating interpretation of Einstein's relativity. It generated debates among physicists and most importantly inspired philosophers in generating interpretations of the new physics. In this contribution, I shall outline the main consequences generated by Weyl's work in the 1920s and its impact on philosophy. I shall then highlight central aspects of Weyl's work that are influential in current philosophy and in philosophy of science in particular. Finally, I shall draw attention to relevant concepts elaborated by Weyl that can open new pathways of interaction between philosophy, mathematics and physics in the 21st century.

Gauge symmetries and CP-violation

Hans Peter Nilles

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Nussallee 12, 53115 Bonn, Germany

CP plays a crucial role in quantum field theory and elementary particle physics. While C (charge conjugation) and P (parity) are strongly violated in weak interactions, CP-violation is quite small. In cosmological considerations, CP-violation is an important ingredient for baryogenesis (the mechanism to explain the asymmetry of matter and antimatter in our universe). What is the origin of the CP-symmetry and its violation? Is there a connection to gauge symmetries? A first encounter with gauge symmetries reveals some problems. The SU(3) gauge symmetry of strong interactions (quantum chromodynamics) leads to a sizable CP-violation through nonperturbative effects: this is the so-called strong CP-problem. There have been various attempts to solve this problem (including the axion solution). Theoretical arguments, on the other hand, argue that CP itself is a (discrete) gauge symmetry. Examples of such symmetries have been identified in string theory. We present such examples and discuss the phenomenological consequences.

Experimental Tests of Gauge Theories: the QCD Phase Diagram at High Temperature

J. Stachel[1]

[1]Physikalisches Institut, Univ. Heidelberg, Heidelberg, Germany

Shortly after QCD was formulated as a field theory with asymptotic freedom by Gross, Politzer and Wilczek in 1972, it was conjectured by Cabibbo and Parisi and by Collins and Perry in 1975 that at high temperature and/or high density strongly interacting matter should exist in a different form compared to the hadronic matter we know at zero temperature. Confinement should be lifted and chiral symmetry, spontaneously broken in hadronic matter, should be restored. The according state of matter was named quark-gluon plasma. Since the 1980ies, using lattice QCD (lQCD), the equation of state of strongly interacting matter and thus the QCD phase diagram were computed with increasing accuracy, by now including various quark flavors with realistic masses and fermion actions and extrapolating to the chiral limit and to the continuum. The most recent results on the high temperature phase structure of QCD will be shown.

Starting at about the same time, the experimental exploration of the QCD phase diagram started first with fixed target collisions of heavy ions and, from 2000 on, with a collider program, at RHIC and since 2010 at the LHC. This talk will summarize the information we have gathered on the QCD phase diagram from the experimental programs. Yields of various identified hadrons and (anti-)nuclei allow to delineate the phase boundary experimentally and to compare to the lQCD results. Fluctuations of observables linked to conserved quantum numbers (like baryon number) are studied to associate possible non-Poissonian fluctuations to critical or pseudo-critical behavior. State-of-the-art lQCD calculations suggest that such behavior could be observed. Various observables in the sector of quarkonia, suggested early on as probes of deconfinement, give now a rather clear confirmation of deconfinement, although with an interesting twist.

Gauge fields in cosmology

L. Covi[1]

[1]*Institute for theoretical physics, Georg-August Universität Göttingen, Göttingen, Germany*

We discuss a few cases in cosmology where the gauge fields and the gauge interactions play an important role, in particular:

- the Sommerfeld enhancement that can strongly modify the annihilation cross-section or even the elastic scattering among Dark Matter particles and the Standard Model or a Dark Sector and has been treated mostly at zero temperature [1], but here we discuss as well fine temperature effects [2,3];
- the issue of kinetic decoupling of Dark Matter, that can have consequences for structure formation and provide a solution for the small scale problems of the CDM model [4];
- inflation with a non-negligible interaction to gauge fields, like for example axion inflation, and their strong production during the inflationary phase [5];
- symmetry breaking and phase transitions, e.g. in the case of the electroweak theory, as epochs of strong deviation from thermal equilibrium, which can provide the conditions for baryogenesis or for the production of gravitational waves [6,7].

References

[1] M. Beneke, C. Hellmann and P. Ruiz-Femenia, JHEP {\bf 1505} (2015) 115, [arXiv:1411.6924 [hep-ph]].

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[5] N. Barnaby, E. Pajer and M. Peloso, Phys. Rev. D {\bf 85} (2012) 023525 [arXiv:1110.3327 [astro-ph.CO]].

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Higgs field in cosmology

Christian F. Steinwachs

Albert-Ludwigs-Universität, Freiburg, Germany

The accelerated expansion of the early universe is an integral part of modern cosmology and dynamically realized by the mechanism of inflation. The simplest theoretical description of the inflationary paradigm is based on the assumption of an additional propagating scalar degree of freedom which drives inflation – the inflaton. However, in most inflationary scalar-tensor models the fundamental nature of this hypothetical scalar field remains unexplained.

In the model of Higgs inflation, the inflaton is identified with the Standard Model Higgs boson. This provides a natural explanation for the nature of the inflaton and connects cosmology with elementary particle physics. A characteristic feature of this model is a non-minimal coupling of the Higgs boson to gravity. I present several phenomenological and fundamental aspects of this model. In particular, I discuss the similarity to geometrical f(R) models of inflation and the role of Weyl transformations of the metric field.

References

[1] M. S. Ruf, C. F. Steinwachs, Phys. Rev. D **97**, 044050 (2018)

[2] A. Yu. Kamenshchik, C. F. Steinwachs, Phys. Rev. D **91**, 084033 (2015)

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Loop Quantum Gravity: a general-covariant lattice gauge theory

F. Vidotto

University of the Basque County (UPV/EHU), Bilbao, Spain

The early development of the Loop approach to Quantum Gravity moved from a discretisation of classical General Relativity and used canonical-quantization methods. But support for the robustness of the resulting theory came from the convergence of different perspectives, in particular a more algebraic framework, very close to a standard gauge-theory construction, from which General Relativity emerges in the classical limit. This is especially clear within the covariant formulation of the dynamics of Loop Quantum Gravity.

The covariant dynamics, based on a path-integral quantization and broadly referred as spinfoam theory, defines transition amplitudes between quantum states of the geometry. The resulting amplitudes are 4-dimensional, Lorentzian, finite and they can accommodate the presence of the (positive) cosmological constant.

To understand states and amplitudes, it is useful to present them in analogy with the usual construction of lattice gauge theory. The resulting theory is a gauge theory whose gauge group is the Lorentz one. The Lorentz group, decomposed into its rotation and boost subgroups, colours the lattice structure. The lattice codes the bare structure of the quantum spacetime, given in terms of adjacency relations. The difference from conventional lattice Yang-Mills theory is that the geometry of the lattice is not defined a priori, but it rather determined by the quantum variables. The lattice is therefore naturally a coordinate-independent structure: this diff-invariance leads to crucial differences from the usual lattice theories in the way the continuous limit of the theory is recovered.

In the talk, I give a presentation of Loop Quantum Gravity that stresses the role of the fundamental gauge group and the invariant quantities in the construction of the theory. I highlight how a primitive notion of spacetime arises just considering the fundamental gauge and the lattice at the base of the theory. I describe the covariant dynamics, and I comment on how classical General Relativity is recovered in the classical limit.

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Neo-Kantian Quantum Gravity

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Belot and Earman [1] begin their paper titled "Pre-Socratic quantum gravity" with the following observation: "Physicists who work on canonical quantum gravity will sometimes remark that the general covariance of general relativity is responsible for many of the thorniest technical and conceptual problems in their field" (p. 213). In particular, physicists largely appreciate the fact that precisely how one interprets the physical content of a generally covariant or gauge invariant theory has nontrivial implications for new theories of quantum gravity.

In order to work out these consequences of interpretation, Belot and Earman explore two "pre-Socratic" views of time and change that capture (at least to some extent) the intuitions underlying traditional ontological views of spacetime itself. The first is the "Heraclitean" approach, wherein robust notions of time and change are maintained (associated with spacetime substantivalism, which insists upon intrinsic "this-ness" of spacetime points). The second is christened the "Parmenidean" approach, wherein notions of time and change are considered illusory (associated with spacetime relationalism, which denies any intrinsic "this-ness" to relata, according ontic privilege to relations instead).

While I agree with Belot and Earman's general philosophy of science point regarding the crucial interplay between content and method vis-à-vis theories of quantum gravity, I disagree with the particulars of their claim. The pre-Socratic approaches they describe are, I argue, individually insufficient and together inexhaustive. In this talk, I (i) underscore charges levied against the Heraclitean view, (ii) raise challenges against Belot and Earman's preferred Parmenidean view, and (iii) use these shortcomings to motivate a third perspective derived from Neo-Kantian scholarship. I suggest that certain insights articulated by the Neo-Kantians in their attempt to reconcile transcendental idealism with the new theories of *their* day – general relativity and non-relativistic quantum mechanics – carry over in interesting ways to the new theories of *our* day: canonical and covariant quantum gravity.

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Space, Time, Matter in Quantum Gravity

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The concepts of space, time, and matter are of central importance in any theory of the gravitational field. In my talk, I discuss the role that these concepts might play in quantum theories of gravity. I address all major approaches but will focus on the most conservative one, which is quantum geometrodynamics. We shall see that some, if not all, of these concepts will acquire a status different from the classical theory. In the spirit of Hermann Weyl, the concept of symmetry will play an essential role in these considerations.

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Abstracts of Posters

(in alphabetical order)

Kinematical Lie algebras in 2+1 dimensions

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We classify kinematical Lie algebras in dimension 2+1. This is approached via the classification of deformations of the static kinematical Lie algebra. In addition, we determine which kinematical Lie algebras admit invariant symmetric inner products.

Kinematical groups play a fundamental role in physics. Through these symmetry groups of space-times the basic invariances of the laws of physics can be implemented and through the Lie group of automorphisms we can describe the geometric models of the universe. For example, the Newtonian model of the universe is an affine bundle (with three-dimensional fibres to be interpreted as space) over an affine line (to be interpreted as time) and it has the galilean group as automorphisms, whose invariant notions are the time interval between events and the euclidean distance between simultaneous events. By contrast, Minkowski spacetime has the Poincare group as the group of automorphisms and the invariant notion is the proper distance (or, equivalently, the proper time), which defines a lorentzian metric. Both the galilean and Poincare groups are examples of kinematical Lie groups, whose Lie algebras (in dimension 2+1) are the subject of this paper.

A deformation theory approach is described in [1] with more details found in [2], [3] and [4]. Roughly speaking, deformations are continuous modifications of the structure constants of Lie algebras that lead to Lie algebras with more intricate Lie brackets. Deformations can be searched for systematically by computing Lie algebra cohomology groups.

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Influence of Hermann Weyl on General Relativity and Cosmology

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Hermann Weyl was one of the greatest mathematicians of the twentieth century and he made major contributions in the greatest number of different areas of mathematics. In 1913, he was a colleague at the Zurich Technische Hochschule, where he met a colleague, Einstein, who was working out the final details of his theory of general relativity. Needless to say, Weyl became captivated by the mathematics behind the theory. In 1917, Weyl gave a course of lectures on the teaching of general relativity through differential geometry. These lectures formed the basis of his now famous book *Raum-Zeit-Materie* (Space-time-matter) which first appeared in 1918 [1]. Subsequent editions followed in 1919, 1920 and 1923, showing the development of his ideas leading to the Weyl metrics and gauge field theory [2]. The Kerr-Newman, Schwarzschild and some classes of the Reissner-Nordstrom solutions belong to the Weyl class of metrics.

In this presentation, we focus upon the contributions made by Weyl towards general relativity. Weyl geometry is somewhat different from Riemannian geometry, and is invariant under gauge transformations. Canuto *et al* [3] developed a theory of gravitation based on Weyl geometry. The consequences of this theory for cosmology, and in particular for dark energy are explored in this framework. Some ideas of cosmography are used to shed more light on Weyl geometry. Zeyauddin and Rao [4] studied a Bianchi V cosmological model in the scale covariant theory by assuming a particular form for the deceleration parameter. We assume a particular form for the Hubble parameter [5-6], which allows for a transition from deceleration to the current accelerating phase. Properties of the model are discussed.

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Energy transfer from space-time into matter and a bouncing inflation from Covariant Canonical Gauge theory of Gravity

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Cosmological solutions for covariant canonical gauge theories of gravity are presented. The underlying covariant canonical transformation framework invokes a dynamical space-time Hamiltonian consisting of the Einstein-Hilbert term plus a quadratic Riemann tensor invariant with a fundamental dimensionless coupling constant g_1. A typical time scale related to this constant, \tau = \sqrt{8 \pi G g_1}, is characteristic for the type of cosmological solutions: for $t \ll \tau$ the quadratic term is dominant, the energy momentum tensor of matter is not covariant conserved, and we observe modified dynamics of matter and space-time. On the other hand, for $t \gg \tau$, the Einstein term dominates and the solution converges to classical cosmology. This is analyzed for different types of matter and dark energy with a constant equation of state. While for a radiation dominated universe solution the cosmology does not change, we find for a dark energy universe the well known de-Sitter space. However, we also identify a special bouncing solution (for k=0) which for large times approaches the de-Sitter space again. For a dust dominated universe (with no pressure) deviations are seen only in the early epoch. In late epoch the solution asymptotically behaves as the standard dust solution.

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Algebraic superenergy in Poincaré gauge gravity

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The Weyl tensor encodes the vacuum curvature in General Relativity. In gauge approaches to gravitation, such as Poincaré gauge gravity, this is no longer true since the field equations are modified. Introducing the Bel tensor as a particular square of the full Riemann tensor in the context of four-dimensional spacetimes with non-vanishing torsion, we first decompose this generalized Bel tensor irreducibly under the Lorentz group. Then, the completely symmetric and tracefree part constitutes the analogon of the Bel-Robinson tensor in General Relativity, and it gives rise to the notion of "algebraic superenergy." We demonstrate explicitly which curvature pieces appear in this tensor, leading in turn to a deeper understanding of the role of vacuum curvature in Poincare gauge gravity.

On the Distinction Between Physical and Mathematical Symmetries of Spacetime

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A careful analysis of the differences between the operationally-defined physical symmetries of spacetime and the purely mathematical coordinate symmetries of the differentiable manifold used to model spacetime shows that the diffeomorphism invariance overshoots the mark and that the largest symmetry group for physical spacetimes should be the unimodular group, a four-volume-preserving subgroup of the diffeomorphism group. Adopting the unimodular group leads to a framework for relativistic spacetime theories in terms of conformal and projective structures; such change in the framework has no consequences for the predictions of a theory because in the traditional framework the superfluous transformations are dealt away with by combining scalar and tensor densities so as to avoid the contributions to the scale-changing factors. However, unimodular framework simplifies the constructions of theories with explicit conformal invariance. After outlining the essential elements of the unimodular framework, with the emphasis on the conformal and projective structures, I present the formulation of both general relativity and Weyl's theory unifying general relativity and electromangetism in the unimodular framework.

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Noncommutative gauge theory of gravity with self-dual variables

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We build a noncommutative extension of Palatini-Holst theory on a twist-deformed spacetime, generalizing a model that has been previously proposed by Aschieri and Castellani. The twist deformation entails an enlargement of the gauge group, and leads to the introduction of new gravitational degrees of freedom. In particular, the tetrad degrees of freedom must be doubled, thus leading to a bitetrad theory of gravity. The model is shown to exhibit new duality symmetries.
The introduction of the Holst term leads to a dramatic simplification of the dynamics, which is achieved when the Barbero-Immirzi parameter takes the value $b=-i$, corresponding to a self-dual action. We study in detail the commutative limit of the model, focusing in particular on the role of torsion and non-metricity. The effects of spacetime noncommutativity are taken into account perturbatively, and are computed explicitly in a simple example. Connections with bimetric theories and the role of local conformal invariance in the commutative limit are also explored.

A gauge-invariant symplectic potential for tetrad general relativity

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We identify a symplectic potential for general relativity in tetrad and connection variables that is fully gauge-invariant, using the freedom to add surface terms. When torsion vanishes, it does not lead to surface charges associated with the internal Lorentz transformations, and reduces exactly to the symplectic potential given by the Einstein-Hilbert action. In particular, it reproduces the Komar form when the variation is a Lie derivative, and the geometric expression in terms of extrinsic curvature and 2d corner data for a general variation.

As a direct application of this analysis we prove that the first law of black hole mechanics follows from the Noether identity associated with the covariant Lie derivative, and that it is independent of the ambiguities in the symplectic potential provided one takes into account the presence of non-trivial Lorentz charges that these ambiguities can introduce.

Unimodular Bohmian Gravity

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A Bohmian version of unimodular quantum gravity (unimodular Bohmian gravity) is proposed. It is shown that unimodular Bohmian gravity is free of the Problem of Time, the Hilbert Space Problem, and the Problem of "No Outside Observers". It is also argued that unimodular Bohmian gravity avoids the objections of Kuchar [1] against unimodular quantum gravity as proposed by Unruh and Wald [2] in the context of standard quantum theory. Accordingly, it is suggested that unimodular Bohmian gravity constitutes a formally consistent and possibly empirically viable theory of canonical quantum gravity.

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A Preference for Gauge Theory (over Gravity)

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What would be a truthful description of reality in a world where the AdS/CFT correspondence obtains? This paper explores physicists' replies to this question. The AdS/CFT correspondence is a duality – a pair of (apparently) different theories with same empirical content – between certain conformal quantum field theories and certain theories of gravity in anti-de Sitter background. The AdS/CFT correspondence offers a particularly interesting case study, since the dual theories are superficially significantly different; differing for instance in the number of spacetime dimensions. It is found that the AdS/CFT correspondence literature tends to express an ontological preference for the CFT side often accounting the AdS side as emerging from the CFT side (e.g. [1]-[3]). The paper identifies three reasons for this interesting preference for the CFT side among physicists:
1) The fact that we only have a non-perturbative formulation of the CFT side is taken to signify that only the CFT side is a full theory of a world where the AdS/CFT correspondence obtains [1]. We are not offered two dual theories and a choice between two possible worlds, but only one theory, one possible world and two representations in which to do perturbation theory (in different regimes). 2) A theory without local observables is regarded as unintelligible [4]. The AdS side lends its intelligibility – its notion of local observables – from the CFT side, which prioritizes the CFT side [5]. 3) In holography, there is a longstanding tradition for an ontological preference of the "hologram" (the two-dimensional boundary) over its "image" (the three-dimensional bulk). Since the AdS/CFT correspondence realizes holography, it is perhaps not surprising that the preference for the CFT (the boundary) side is (uncritically) continued.

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Experimental constraints on the second clock effect

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We set observational constraints on the second clock effect, predicted by Weyl unified field theory, by investigating recent data on the dilated lifetime of muons accelerated by a magnetic field. These data were obtained in an experiment carried out in CERN aiming at measuring the anomalous magnetic moment of the muon. In our analysis we employ the definition of invariant proper time proposed by V. Perlick, which seems to be the appropriate notion to be worked out in the context of Weyl space-time.

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Gauge freedom and black holes

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A common "gauge" choice in general relativity is the foliation of spacetime into hypersurfaces. One way this may be achieved is by taking the set of spatial hypersurfaces orthogonal to the worldlines of some given observer congruence. In this sense Schwarzschild-Droste coordinates correspond to static observers outside the horizon (these worldlines have r=const, and orthogonal hypersurfaces t=const), and "zero energy at infinity" observers inside the horizon (vice versa for r and t). The typical stated properties of a black hole are based on this foliation, at least outside the horizon, including the radial proper distance, simultaneity including "time at infinity", etc.

In contrast I present a foliation based on radially-moving freefalling observers, which is described using a generalisation of Gullstrand-Painleve coordinates. Since the spatial hypersurfaces are different, their properties are different including the proper distance, isometric embedding diagram, and simultaneity. My motivation is pedagogical, to emphasise gauge freedom and hence avoid "neo-Newtonian" misconceptions of black holes.

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Flavour changing neutral currents mediated by scalars in a 3-4-1 model

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In this work we have studied a Gauge Group (Su(3)c_x_SU(4)L_x_U(1)x). Some phenomena tha in standard Model occur in one loop, in this extension appear at tree level. Processes like neutral currents flavour changing are responsible for changes of flavour equals to two. Our interest are the neutral currents mediated by scalars. Seeking in the experimental data, we can fix the parameters and stablishing a energy range for it.

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A black-to-white hole spacetime

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Black holes have become common astrophysical objects, but general relativity does not answer all the questions about them. What happens ultimately to the in-falling matter? Is information lost after Hawking evaporation? There is no consensual answer to these questions yet.

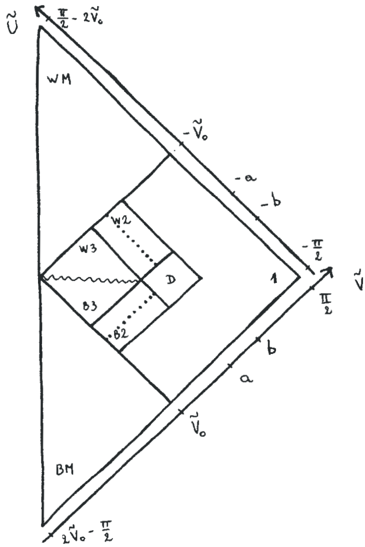

Figure 1. Penrose diagram of the black-to-white hole spacetime.

A scenario has recently raised interest: the possibility of a quantum tunnelling from a black hole to a white hole. This transition is allowed by general relativity provided that quantum theory permits a local violation of Einstein's equations. The hope is to compute the quantum probability for the process, using the spinfoam formalism of loop quantum gravity.

In our recent article [1], we present an improvement of the so-called 'firework metric' discovered by Rovelli and Haggard [2]. The total spacetime is represented on the Penrose diagram of Figure 1. Physically, this describes the fall and collapse of a thin null spherical shell of matter, which bounces at a minimal radius inside its Schwarzschild radius, and then expands forever. Interestingly, time-like and null geodesics are continuous through the singularity. Incidentally, we cure a pathology of the original firework metric (a conical singularity at the cusp point of the quantum region).

We are currently trying to describe a new asymmetric black-and-white hole scenario that would take into account Hawking evaporation, which would cure at the same time the instability of the current proposal.

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Third quantization: a complete analogy with a quantum field theory

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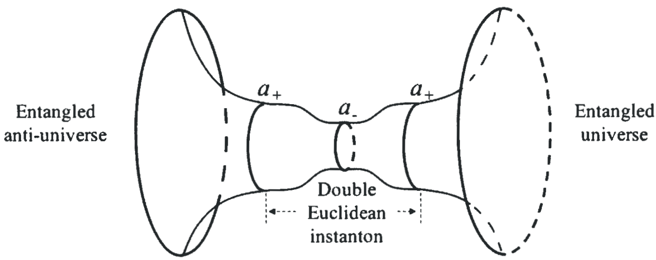
There is a formal analogy between the quantum description of the wave function of the universe in quantum cosmology and the formalism of a quantum field theory in a curved spacetime. It allows us to consider the creation of universes in entangled pairs as the most favored way in which the universes can be created, in a parallel way as particles are created in pairs in the context of a quantum field theory.



Taking further the analogy, the conservation of the total momentum conjugated to the configuration variables of the (mini)-superspace makes one of the universes to be the anti-universe of the other, restoring the primordial matter-antimatter asymmetry observed in the context of a single universe. Furthermore, the composite matter-antimatter state that propagates entangledly but separately in the two universes induces, when seen by internal observers that have no access to the field in the partner universe, a quasi-thermal state for the matter field that would produce a specific and distinguishable pattern in the spectrum of fluctuations of the early universe. That would make testable, at least in principle, the creation of universes in entangled pairs and, incidentally, the whole multiverse proposal.

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Weyl's unified field theory and non-locality

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Soon after the discovery of the general theory of relativity, H. Weyl attempted to extend Einstein's program of geometrization to include the electromagnetic field. His unified theory, however, encountered a strong objection raised by Einstein, who believed the theory would lead to a physical effect not yet observed (the so-called "second clock effect"). As far as we know, neither theoretical calculations nor any experimental attempt at measuring the magnitude of the predicted effect has been carried out up to now. The non-integrability of lengths present in Weyl space-time is the root of the already mentioned Einstein's objection. It has been argued recently that in order to discuss the existence of the second clock effect a new notion of proper time, consistent with Weyl's principle of gauge invariance is needed [1]. It happens to be that such a notion exists and was recently given by V. Perlick [2]. Rather surprisingly, Perlick's time, unlike the general relativistic time, leads to the second clock effect, and also to a kind of "non-local geometry", where geodesics must satisfy integro-differential equations [4].

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Generalized uncertainty principle parameter from quantum corrections to the Newtonian potential

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We compute for the first time the deformation parameter of the generalized uncertainty principle (GUP), by using a technique based on the leading quantum corrections to the Newtonian potential. The calculation gives, to first order, an unambiguous, specific numerical result. The physical meaning of this value is discussed, and compared with analogous previous results, and with known bounds on the GUP deformation parameter.

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Singularity Avoidance of the Quantum LTB Model for Gravitational Collapse

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In classical General Relativity, singularities signal a breakdown of the theory. One line of inquiry that can be followed to investigate whether quantum gravitational effects could resolve this peculiar behavior is to quantize classical models for gravitational collapse, for example the Lemaître-Tolman-Bondi (LTB) model, as will be done here.
An action for the outermost shell in the marginally bound LTB model for spherically symmetric, inhomogeneous dust collapse is derived starting from the Einstein-Hilbert action. The resulting Hamiltonian is then quantized, and the corresponding Schrödinger equation admits exact solutions. Because the dust naturally provides a preferred notion of time, one can construct a Hilbert space and impose unitary evolution in dust proper time on its elements. Wave functions then have the usual probability interpretation. Using this interpretation it can be shown that all wave packets, and even general linear superpositions of the stationary modes, contained in this Hilbert space avoid the classical singularity.
Furthermore, for a wave packet initially approximating the classical trajectory the collapse to a singularity is replaced by a bounce, effectively a transition from black to white hole.
Finally some implications of this bouncing behavior are discussed by constructing a semiclassical model for quantum corrected dust collapse: the nature of the horizon, the lifetime of the temporary 'gray' hole, and the effective pressure facilitating the bounce.

Energy-Time uncertainty principle and neutrino oscillations in quantum field theory

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Neutrino mixing and oscillations play a fundamental role in modern theoretical and experimental physics. To incorporate this phenomenon in the Standard Electroweak gauge theory, a non-trivial extension, including non-diagonal mass matrices, is required. In this case, only total flavor-charge [1] is conserved. However, at tree level, neutrinos are produced as exact eigenstates of the flavor charges [2]. These states were explicitly constructed in the context of field theoretical treatment of fermion mixing [3]. These were recognized not to be standard free asymptotic states, e.g., in Ref.[4]

In this work [5] we enforce this idea, studying energy-time uncertainty relation in the Mandelstam-Tamm form [6], due to the non commutativity of neutrino Hamiltonian with flavor charges. Our analysis shows the strong analogy among flavor neutrinos and unstable particles [7]. Although similar relations were obtained in Ref.[8], our treatment is consistent with quantum field theoretical treatment of neutrino mixing and not limited to the ultra-relativistic regime.

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Quantum electrodynamics with area-metric deviations from a metric

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The most general theory of electrodynamics with linear field equations introduces a new geometry, the area metric, that regulates the propagation of light rays and massive particles instead of the usual Lorentzian metric. In the majority of the experimental situations, the area metric is expected to be a small perturbation around a metric background. In this perturbative case, two interesting results can be achieved. First, the dynamics of the area metric can be found explicitly. Second, the relative quantum theory of electrodynamics can be shown to be renormalizable at every loop order in a gauge-invariant way and can be used to compute various fundamental processes.

I will show that, when one combines the results of quantum electrodynamics with the dynamics of an area-metric perturbation, the anomalous magnetic moment of the electron, the cross sections of Bhabha scattering, and the hyperfine splitting of the hydrogen pick up a dependence on the position. This way, measurements of the position dependence of these quantities provide a new channel to investigate area-metric deviations from a metric spacetime.

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Notes