THE STRUCTURE OF GRAVITY AND SPACE-TIME

International Workshop

6-7 February 2014

Lady Margaret Hall, Oxford, UK

Part of the 'Establishing the Philosophy of Cosmology' project

The aim of this workshop is to review the state of the art of different models of gravity and to engage a debate on fundamental questions on the nature of gravity and the nature of space-time. Preference will be given to ample open discussion and to exploration of new territories.

We will focus on a few metric and fundamental theories of space-time and gravity, to discuss what the theoretical-philosophical inputs and phenomenological outputs are for each, and what we empirically can and currently do know about them.

What are the similarities and differences? What scales enter? Are they 'natural'? Interrelated? What limits do current observations place? What are the future experimental prospects? What theoretical and technical improvement is needed? What are the philosophical implications?

Some aspects we will consider are not limited to

i) Horizons
ii) Lorentz violation
iii) Equivalence principle
iv) Entropy - thermodynamics
v) Gravitational collapse, black holes
vi) Lensing
vii) Gravitational waves, inflation
viii) Thermal/temporal evolution of the Universe, geometrodynamics, causal structure

Participation is by invitation only, and the number of participants will be limited to approximately 40 people.

The participants come from a wide range of backgrounds, and we will accordingly aim for inclusiveness in terms of content level, yet encourage necessary technical detail as appropriate.

Organisers: Joe Silk (Oxford), Simon Saunders (Oxford), Martin Sahlen (Oxford), Khalil Chamcham (Oxford), David Sloan (Cambridge)

WEDNESDAY 5 FEBRUARY

18.00 Welcome reception: Denys Wilkinson Building, Keble Road, Level 5. Free evening.

THURSDAY 6 FEBRUARY

INTRODUCTION

9.00 Welcome: J. Silk (Oxford) [Chair: B. Pitts]

9.15 G. Ellis (Cape Town): Fundamental questions on the nature of gravity and the nature of space-time

METRIC THEORIES

Bimetric gravity, massive gravity, galileons

10.00 F. Hassan (Stockholm): An overview of bimetric theory

10.45 Coffee [Chair: J. Barrow]

11.10 E. Gumrukcuoglu (Nottingham): Stability issues in massive gravity cosmology

11.40 K. Koyama (Portsmouth): The Vainshtein mechanism

12.10 Discussion: B. Pitts (Cambridge), speakers, Y. Akrami, J. Barrow, J. Enander, B. Li, J. Noller, O. Pooley, M. Sahlén, A. Schmidt-May, D. Spolyar, H. Winther.

12.55 Lunch

Horava-Lifshitz, TeVeS, Horndeski gravity [Chair: TBC]

14.20 T. Sotiriou (Nottingham): Horava gravity, a brief review

14.50 C. Skordis (Nottingham and Cyprus): TBC

15.20 Coffee [Chair: TBC]

15.45 E. Barausse (Paris): Astrophysical consequences of Lorentz violations in gravity

16.15 H. Brown (Oxford): What TeVeS tells us about General Relativity

16.30 Discussion: P. Ferreira (Oxford), speakers, T. Baker, D. Lehmkuhl, J. Miller, S. Saunders.

17.15 Close

19.30 Conference dinner: Christ Church College, McKenna Room (drinks at 7.30pm, dinner served at 8pm)

Dinner speech by J. Silk (Oxford): Gravity works … or does it?

FRIDAY 7 FEBRUARY – FUNDAMENTAL THEORIES

09.30 D. Tong (Cambridge): Some Comments on Quantum Gravity [Chair: B. Sundborg]

'Fundamental length' gravity: Quantum gravity approaches

10.15 J. Barrett (Nottingham): The Planck scale

10.45 A. Barrau (Grenoble): Loop Quantum Cosmology

11.15 Coffee [Chair: L. Mersini-Houghton]

11.40 S. Hossenfelder (NORDITA): Planck Scale Phenomenology

12.10 Discussion: A. Barrau (Grenoble), speakers, D. Sloan, B. Sundborg.

12.55 Lunch

'Fundamental dof' gravity: Strings and space-time structure

14.20 D. Tong (Cambridge): What is String Theory [Chair: J. Barbour]

14.50 B. Sundborg (Stockholm): Space from boundary?

15.20 Coffee [Chair: TBC]

15.45 L. Mersini-Houghton (UNC Chapel Hill): Inflation, Eternal Inflation and the Landscape

16.15 J. Barbour (Oxford): Gravity as Shape Evolution

16.30 Discussion: D. Sloan (Cambridge), speakers, G. Ellis, K. Chamcham, J. Conlon, F. Mercati.

17.15 Summary talk: O. Pooley (Oxford)

17.45 Closing open discussion: M. Sahlén (Oxford) + all

> "Can we further constrain philosophical choice on the nature of gravity and space-time by i) theoretical progress, ii) observation, iii) philosophical elucidation, in the foreseeable future? What problems may appear? How to invest our time?"

18.15 End

Participants

Yashar	Akrami	Oslo
Tessa	Baker	Oxford
Julian	Barbour	Oxford
Enrico	Barausse	Paris
Aurelien	Barrau	Grenoble
John	Barrett	Nottingham
John	Barrow: Thurs only	Cambridge
Noah	Brosch	Tel Aviv
Harvey	Brown	Oxford
Clare	Burrage: Friday only	Nottingham
Khalil	Chamcham	Oxford
Joe	Conlon	Oxford
George	Ellis	Cape Town
Jonas	Enander	Stockholm
Pedro	Ferreira	Oxford
Emir	Gumrukcuoglu	Nottingham
Fawad	Hassan	Stockholm
Sabine	Hossenfelder	NORDITA
Kazuya	Koyama	Portsmouth
Dennis	Lehmkuhl	Oxford
Baojiu	Li	Durham
Flavio	Mercati	Perimeter Institute
Laura	Mersini-Houghton	UNC Chapel Hill / Cambridge
John	Miller	Oxford
Johannes	Noller	Oxford
Brian	Pitts	Cambridge
Oliver	Pooley	Oxford
Martin	Sahlén	Oxford
Simon	Saunders	Oxford
Angnis	Schmidt-May	Stockholm
Joe	Silk	Oxford
Constantinos	Skordis	Nottingham and Cyprus
David	Sloan	Cambridge
Adam	Solomon	Cambridge
Thomas	Sotiriou	Nottingham
Douglas	Spolyar	Amsterdam
Bo	Sundborg	Stockholm
David	Tong	Cambridge
Hans	Winther	Oxford
*********	**********	**********
Ashling	Morris	Admin
Christoper	Doogue	Admin
Marianne	Freiberger	Journalist (Cambridge)
Journalist	New Scientist	TBC

Abstracts

E. Barausse: Astrophysical consequences of Lorentz violations in gravity
Einstein-aether theory and Horava gravity violate Lorentz invariance in the gravitational sector by introducing a dynamical unit timelike vector (the "aether") that defines a preferred time direction at each spacetime point. I will show that the strong equivalence principle does not hold in these theories, which allows constraints to be placed on the aether's couplings using observations of binary pulsars. I will also discuss how the notion of a black hole gets modified in these theories due to the possible presence of aether modes propagating at velocities different than the speed of light.

J. Barbour: Gravity as Shape Evolution
In my brief talk, I will show that in the case of a spatially closed universe interesting features of gravitational dynamics emerge when it is studied as the evolution of the shape of the universe. As in York's work on the initial-value problem, a unique notion of universal simultaneity and a distinguished monotonic time variable can be defined. In the limit of the Newtonian N-body problem there is a surprising sense in which an arrow of time defined by growth of complexity and information is generated dynamically in all solutions. My collaborator Flavio Mercati will mention further features of the shape-dynamic treatment of gravity in the discussion group on fundamental degrees of freedom.

A. Barrau: Loop Quantum Cosmology
I will briefly present the groundings of Loop Quantum Gravity as a tentative background-independent and non-perturbative quantization of General relativity and its application to Loop Quantum Cosmology. Then, I will focus on the main results and predictions: the replacement of the Big Bang by a Big Bounce, the high probability for inflation to occur, and most importantly possible footprints in the Cosmological Microwave Background.

J. Barrett: The Planck scale
I will review the arguments that suggest there must be new physics at or before the Planck scale. Various approaches to modelling the Planck scale will be surveyed, with brief remarks about their achievements and drawbacks.

H. Brown: What TeVeS tells us about General Relativity
Studying the dynamical structure of TeVeS reinforces the lesson that in any metric theory of gravity, the local validity of special relativity, and hence the expected behaviour of rods and clocks, depends crucially on how the relevant matter fields couple to (one of) the metric(s). In general relativity, this lesson is sometimes overlooked.

G. Ellis: Fundamental questions on the nature of gravity and the nature of space-time
Gravitational theories have to respect the special and general theories of relativity in appropriate limits, as well as the quantum field theory approach leading to the idea of gravitons. I will make the case that (a) space time must be discrete at the micro level, with a continuum view emerging via coarse graining; (b) holonomy is central to any foundational approach, inter alia because of the Aharanov-Bohm exeriments; (c) the true gravitational equations must be trace free, both to avoid the vacuum energy disaster and to respect the nature of gravitons; (d) this is related to many indications that gravity is essentially a conformal theory, with matter breaking the conformal symmetry; (e) at a fundamental level, the theory should probably be a relative theory, as initially pointed out by Weyl, but with outcomes depending on context, as pointed out by Mach; (f) at the emergent level, the focus should be on the Weyl tensor rather than the metric; (g) The past, present, and future are fundamentally different. Our theories must adequately take account both of the quantum measurement issue (`collapse of the wave function'), and the irreversible flow of time, as experienced in everyday physics, chemistry, and biology.

E. Gumrukcuoglu: Stability issues in massive gravity cosmology
The construction of a finite-range gravity theory has been one of the major challenges in classical field theory for the last 70 years. Generically, a massive gravity theory contains an extra degree in addition to the 5 polarizations of massive graviton, which turns out to be a ghost. In the last few years, a construction of nonlinear theory of massive gravity was introduced, where the residual ghost degree is successfully

eliminated. The theory allows for homogeneous and isotropic solutions with self-acceleration, which may potentially provide an alternative to dark energy. I will show that the self-accelerating solutions suffer from ghost instabilities, which show up at non-linear order. Building on this result, I will argue that, in order to construct an accurate cosmology in massive theories, one needs to either i) relax the background symmetry of the cosmology; ii) extend the theory with additional degrees of freedom. I will end with a brief discussion of some promising examples for both cases.

F. Hassan: An overview of bimetric theory
This talk will review the ghost-free bimetric theory as a theory of a single gravitational metric interacting with an extra dynamical spin-2 field, and its massive gravity as well as general relativity limits. I will also discuss some general features of the theory.

S. Hossenfelder: Planck Scale Phenomenology
I will talk about recent developments in the search for experimental signatures for quantum gravitational effects, most of which go back to the Planck scale playing the role of a fundamental length in one way or the other. Some of the topics that I will cover are the prospects of finding Planck scale effects in gamma ray bursts, in neutral Kaon oscillations, or with massive quantum oscillators. If time suffices, I might comment on Bekenstein's proposed table-top experiment.

K. Koyama: The Vainshtein mechanism
A modification to General Relativity generally introduces a new degree of freedom. For example, a massive spin-2 graviton has five degrees of freedom instead of two in a massless spin-2 graviton. The extra scalar degree of freedom mediates a fifth force, which is strongly constrained by solar system experiments. In massive gravity theories, this additional degree of freedom can be hidden by the so-called Vainshtein mechanism. Recently there has been significant progress in developing models that accommodate the Vainshtein mechanism without introducing pathology such as the Boulware-Deser ghost. These models are based on the idea of “Galileon”, a scalar field that involves an internal ``galilean'' invariance, under which the scalar field’s gradient shifts by a constant. In this talk, I introduce an effective theory that describes the Vainshtein mechanism and discuss the phenomenology of the Vainshtein mechanism.

L. Mersini-Houghton: Inflation, Eternal Inflation and the Landscape
I will discuss the role of homogeneity of spacetime on the measure for eternal inflation and show that the reproduction process of new bubble universes is finite. This new measure satisfies the fluctuation-dissipation theorem. I will then describe inconsistencies in the claim that eternal inflation bubbles populate the landscape by showing that the landscape solution is localized Anderson type wavefunctions. The conceptual and mathematical inconsistency of eternal inflation with the landscape multiverse and with the Many Worlds multiverse, as well as pathologies with its measure and predictability, may arise from the possibility that eternal inflation is not eternal after all.

C. Skordis: TBC

T. Sotiriou: Horava gravity, a brief review
I will give a brief overview of Horava gravity and its phenomenology. I will also discuss its relation with other theories, such as Einstein-aether theory and the Horndeski action.

B. Sundborg: Space from the boundary?
I will discuss the idea that space can be understood from its boundary. To approach this problem I first attempt to disentangle space and matter. It is not clear what fundamental degrees of freedom are, but for strings the problem can be addressed. Gauge theory is a possible answer in string theory and related quantum gravity theories: a boundary gauge theory encodes everything in certain spacetimes. I explore simple examples and mention puzzles concerning spaces without boundary or spacetimes with unsuitable boundaries (Minkowski).

D. Tong (I): Some Comments on Quantum Gravity

I'll describe some basic features of quantum gravity without reference to any specific underlying theory. I'll try to stick to things that are uncontroversial. Which, given the subject matter, means that everyone in the audience will probably disagree with at least one thing I say.

D. Tong (II): What is String Theory

I'll give an overview of string theory. I'll focus on the perturbative string and try to explain some basic features such as where the extra dimensions come from and why strings can be viewed as a theory of gravity.

Ideas for Discussion Points

Bimetric gravity, massive gravity, galileons [B. Pitts]

Bimetric Gravity, Massive Gravity, Galileons and the Philosophy of Science: Mutual Illumination

I. Duhem-Quine Problem: When GR makes one infer dark matter & dark energy (surprising auxiliary hypotheses) to fit the data, should one believe in them or modify gravity?

A. Long-range difficulties for GR makes long-range modification natural to try.

B. Massive gravity the obvious place to start---expect to change only long-range behaviour, natural place in Wigner's mass-spin taxonomy, no extra fields, no unusual couplings.

II. Bayesianism: A logic for reasoning in shades of gray with theories and evidence.

A. *A priori* motivations:

1. Cox's theorem: logic in shades of gray must be probability calculus.

2. Dutch book theorems: degrees of belief that don't satisfy probability calculus guarantee loss.

B. Bayes' theorem: $P(T|E) = P(T) * P(E|T) / P(E)$.

1. Update degrees of belief when new evidence comes in, iteratively.

2. Principled combination of what one took oneself to know yesterday and what one learns today.

3. Seek optimal combination of prior plausibility (prior P(T)) and fit to data (likelihood $P(E|T)$).

C. Comparative testing: $P(E) = P(E|T)\,P(T) + P(E|T_2)\,P(T_2) + P(E|T_3)\,P(T_3)+....$

1. Approximate by thinking up high prior, high likelihood rivals T_2, T_3....

D. Priors P(T) partly subjective; seek evidence-driven convergence of opinion.

1. Acquainting each other with rival theories.

2. Their motivations---reflected in (high) priors $P(T_2)$.

3. Their data fit---reflected in likelihoods $P(E|T_2)$.

E. Convergence threatened if permanent underdetermination.

1. If massive gravity approximated GR arbitrarily well just as Proca does to Maxwell, could only put *bounds* on graviton mass.

III. Old high points worth recalling

A. 1965 Ogievetsky-Polubarinov: nonlinear spin 2-spin 0, nonlinear pure spin 2, though not appreciated even by them.

B. 1969 Freund-Maheshwari-Schonberg: universal coupling, sophisticated philosophy of geometry (conventionalism, constructivism).

IV. Gravity's crucial details: it's not just Proca all over again.

A. *c*. 1972: Pure spin 2 van Dam-Veltman-Zakharov discontinuity *vs*. spin 2-spin 0 instability, Boulware-Deser ghost makes linear pure spin 2 be nonlinear spin 2-spin 0, Vainshtein mechanism in embryo.

B. Today: Vainshtein mechanism, broadened universal coupling derivations, de Rham-Gabadadze-Tolley-Hassan-Rosen nonlinear pure spin 2, instabilities within pure spin 2, Deser-Waldron acausality worry, galileon generalization of Vainshtein mechanism.

V. Why philosophy needs particle physics, especially massive gravity.

A. Didn't discern threat of underdetermination, often overcommitted to GR or committed but for partly wrong reasons.

B. Didn't recognize serious epistemic possibility of violating Einstein's principles (general covariance, strong equivalence) with tiny plausible empirical tweak.

C. Massive gravity a serious option *for the particle physics-aware until 1972* (not 1921 as Schlick *vs*. Kant), reviving after 1999, serious since 2010.

D. Details can show massive gravity to be not just like Proca *conceptually*.

1. Subtle causality issue with two metrics, maybe need gauge freedom.

2. Do features of GR surprisingly reappear, hence robust?

VI. If and when dust settles, should have either serious rival(s) to GR, or much better reason to accept GR after seriously exploring alternatives.

Horava-Lifshitz, TeVeS, Horndeski gravity [P. Ferreira]

TBD

'Fundamental length' gravity: Quantum gravity approaches [A. Barrau]

Is there necessarily a fundamental length in quantum gravity?
Fundamental length and Lorentz invariance
How to make predictions and experimentally probe different scenarios?

'Fundamental dof' gravity: Strings and space-time structure [D. Sloan]

Quantum gravity and space from the boundary?
Do we need the boundary in string theory (or quantum gravity)? (Observables being S-matrix elements or boundary correlators.) Is that all there is?
Matter in space or space from matter?