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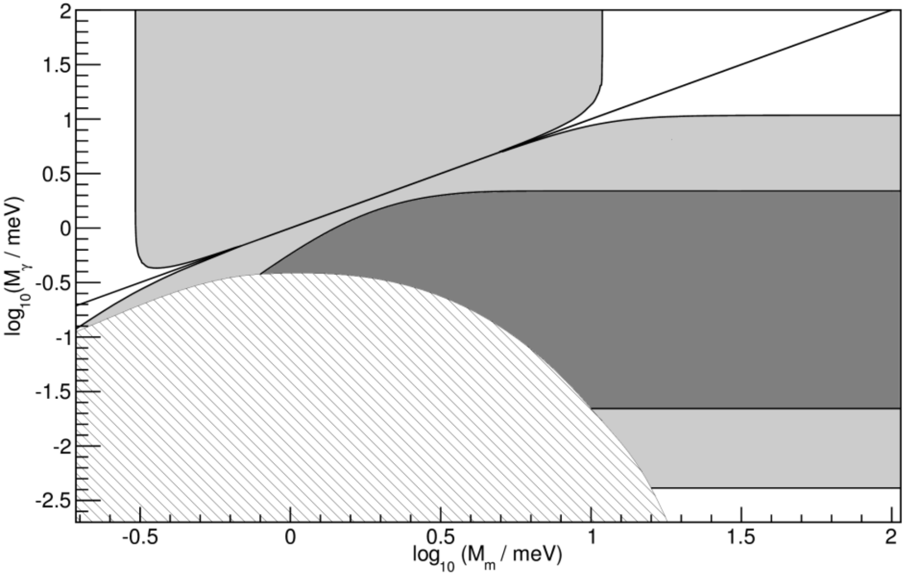

Exclusion plot for masses of matter and radiation in a cosmology with a disformally coupled dark energy field.
Courtesy: J. Morrice

See http://gp.iop.org for more details

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Welcome from the Chair

Dear Colleagues,

Ca 2015 will be 100 years since the birth of the General Relativity. In November 1915 Einstein completed the final version of his new theory of gravity. Ca 2016 will be the centenary year of Einstein's another landmark paper in which he predicted the existence of gravitational waves. The International Society for General Relativity and Gravitation has declared 25 November 2015 as Einstein Centenary Day. The Society will promote public outreach events to celebrate the Centenary throughout the world. The year 2015 is being proposed as the International Year of Light, which is highly relevant to gravitational-wave detection using laser interferometry.

The physics community in the UK has played a pivotal role in furthering the experimental and theoretical aspects of Einstein's theory, starting from Eddington's solar eclipse expedition to Hawking's black hole evaporation and the ongoing experimental and theoretical effort to detect gravitational waves. It is, therefore, natural that the UK should play a major role in celebrating the Centenary. I hope that Relativity Groups around the UK will help celebrate the centenary by organizing events at local societies and science centres. The Gravitational Physics Group welcomes your ideas for what sort of events can be organised to commemorate the centenary.

The next BritGrav meeting will be held during 31 March-1 April at Cambridge. Please note the dates and encourage your students and postdoctoral fellows to present their work at BritGrav.

Our topical meeting this year focussed on the Kerr solution. The aim of the meeting was to showcase and celebrate the study of black holes, 50 years after Roy Kerr published his now seminal work on the gravitational field of a spinning mass. We are seeking topics for our next topical meeting to be held in September 2014 and welcome your ideas.

The Group invites nominations for this year's student thesis prize, which will close on 6th January 2014. Candidates should complete an application form available from the Group's web pages and submit it with an electronic copy of their thesis to our secretary Timothy Clifton (t.clifton@qmul.ac.uk)..

Greetings and best wishes for the coming year,

B.S. Sathyaprakash
Cardiff University
Chair, IOP Gravitational Physics Group

Events

Young Theorists' Forum 2012
Rafael Maldonado

December 2012 saw the fifth edition of the Young Theorists' Forum (YTF), an annual event which has proven to remain popular among doctoral students in theoretical high energy physics from around the UK. The conference took the form of a two day meeting following on from the Annual Theory Meeting, and held between Durham University's Department of Mathematical Sciences and Institute of Particle Physics Phenomenology. Students were invited to give one of 37 short (15-30 minute) talks about their research in one of the following sessions: Gravity, Cosmology, Solitons, QCD & Lattice, BSM Physics, Gauge/Gravity Duality, Particle Phenomenology, and Amplitudes & String Pheno. Sessions were interspersed with tea and coffee breaks, giving the 80 attendees from 14 British universities the opportunity to discuss their research and forge future collaboration.

The highlight of the forum was the plenary talk given by Luis Fernando Alday, entitled "Local and non-local observables in maximally supersymmetric Yang-Mills", to which senior members of the Durham particle physics community were invited. The talk was followed by an informal pizza evening, the format of which was ideally suited to encourage lively discussion between the particpants. A summary of the event, along with abstracts of the talks, can be found at the conference webpage: www.cpt.dur.ac.uk/Workshops/YTF2012. Preparation for this year's Forum (18-19 December) is currently underway. The organisers are grateful of funding received from the IOP through the Gravitational Physics, Mathematical & Theoretical Physics, and High Energy Particle Physics Groups, as well as to SUPA and Durham University.

BritGrav 13
Elizabeth Winstanley & Sam Dolan

The 13th British Gravity (BritGrav) Meeting was held on Wednesday 3rd and Thursday 4th April 2013 in the School of Mathematics and Statistics at the University of Sheffield. The meeting had 67 participants and 33 speakers – a bumper year! The meeting covered a wide range of topics, including black holes, neutron stars, numerical relativity, cosmology, exact solutions, quantum field theory in curved spacetimes, gravitational self force, and gravitational wave detection.

BritGrav is aimed particularly at young researchers, providing a forum in which to showcase new work and initiate collaborations. As has become traditional, the meeting consisted of rapid-fire 15-minute presentations, with short questions afterwards. Ph.D students were encouraged to describe their recent work. It was generally agreed that the standard of presentations was very high.

The Best Student Talk prize, awarded by Classical and Quantum Gravity, went to Jack Morrice, a Ph.D student at Sheffield, for his talk on "Constraints on disformal couplings from the CMB temperature evolution". We are grateful to the panel of judges (Sathya, Jorma and Ian) for their careful deliberations.

This meeting was kindly sponsored by the Gravitational Physics Group, and the journal Classical and Quantum Gravity. The meeting would not have been possible without their financial support. We are grateful also for local support from students and staff in Sheffield. Next year's meeting will be held in Cambridge, and is being organised by Priscilla Canizares and Jonathan Gair. Look out for their updates!

Quantum Fields, Gravity and Information

David Bruschi, Nicolai Friis, Antony Lee & Sara Tavares

The meeting ‘Quantum Fields, Gravity and Information’ (QFGI) took place between the 3rd and 5th of April 2013 in the newly refurbished Highfield House, University of Nottingham. This was the first postgraduate meeting within the growing community of relativistic quantum information ever to occur. We brought together experts and new researchers in gravity, information science and quantum theory.

A total of 34 delegates, 23 of which from all around the UK, were selected along with our four invited speakers. Together with the organisers and volunteers the conference had a total of 43 guests. The four keynote speakers – Dr I. Fuentes, Dr E. Livine, Prof T. Ralph and Prof B. Coecke – delivered well-paced and well-structured introductory lectures on their topic of expertise. These lectures were greatly appreciated by the delegates and stimulated numerous questions and discussions.

Traditionally in conferences oral presentations are immediately followed by questions from the audience. Instead of taking this typical approach, we grouped the talks into small sessions with a common theme. Each of the sessions was then followed by questions for all speakers. The allocation of sessions followed the spirit of the introductory lectures. Therefore, ‘Relativistic quantum information’ was the first day’s main theme, ‘Quantum information and higher mathematical structures’ and ‘Quantum optics in spacetime’ those of the second and ‘Foundations, quantum field theory and quantum gravity’ the last day’s topic. The standard of contributed talks was very high. The decision to award the conference prize for the best talk not to one, but two delegates, Hal Haggard (Marseille) and Michael Skotiniotis (Innsbruck), substantiates this claim, which is further supported by the interest and questions attracted by all presentations.

As envisioned by the organisers, the poster session differed from the norm. A total of eight posters were displayed which means all participants had an average of fifteen minutes to observe each poster and talk to its author. Moreover, the session was held on the first day – the day with the highest attendance – and not cornered to lunch or break hours. Our judging panel had a very hard time in concerting their opinions, evidence of the high quality of work on display. The prize was awarded to Jack Binysh and Felix Pollock from Oxford, who presented their work jointly.

We are pleased to confirm our workshop exceeded all expectations. Its scientific objectives were accomplished amidst an unparalleled ambience celebrated by all participants. The IOP's generous contribution to our project was used in full. As anticipated, the funds were spent on accommodation and subsistence of the delegates. We have to emphasise that both the IOP's willingness to supply its grant upfront and its openness in discussing the conditions of the support greatly benefited budget planning. There is no question that without the IOP's generous support our meeting would not have been as wide reaching or impactful.

COSMO 2013

Paul Shellard, Daniel Baumann & James Parke

The seventeenth edition of COSMO, the annual International Conference on Particle Physics and Cosmology, was held at the Centre for Theoretical Cosmology, Cambridge, UK in the week of September 2-6, 2013. The conference attracted the world's leading researchers and had more than 200 participants. The IOP Gravitational Physics Group was one of the institutions providing funding for the conference.

The COSMO series is one of the major venues of interaction between cosmologists and particle physicists. This year's was a particularly exciting conference, 2013 being the year of the first release of cosmological results from the Planck satellite experiment. We now have the most detailed map ever created of the cosmic microwave background radiation. A whole day was dedicated to the implications of these results for cosmology; a highlight of the conference was a lively discussion between David Spergel, representing WMAP, and George Efstathiou and Jean-Loup Puget from the Planck Science Team.

COSMO 2013 had an excellent line-up of plenary speakers and parallel talks across a broad range of timely subject areas. The discovery of the Higgs-like boson has been a milestone in the history of particle physics. COSMO 2013 featured a talk from the CMS Collaboration reviewing the status of the LHC experiment. There were also theory talks discussing the implications of the LHC results for both particle physics and cosmology, and contributions in particle astrophysics such as talks on dark matter, neutrinos and axions. A day was devoted to discussing the prospects for large-scale structure observations, and the latest results from the SDSS Collaboration were also presented. All the plenary talks were recorded on video and are available online at:

http://www.ctc.cam.ac.uk/activities/cosmo2013/programme.php

The conference also featured a large public symposium with talks by Stephen Hawking, Brian Cox and Andrew Liddle. More than 500 people attended these lectures, and a much larger audience watched the live webcast, see:

http://www.ctc.cam.ac.uk/activities/lectures.php

The Gruber Cosmology Prize was also awarded at COSMO to Professors Slava Mukhanov and Alexei Starobinsky in recognition of their contributions to inflationary universe theory.

Prizes

2013 GPG Thesis Prize

Cesar Simon Lopez-Monsalvo produced his PhD thesis on the subject of covariant thermodynamics and relativity at the University of Southampton. We, the judging committee, found that this thesis not only contributed significantly to the state-of-the-art in the field, but that it did so in a way that brought the subject to life. We found the thesis to be very well written, and to display originality and character. In the end the decision of the committee was unanimous in recommending Dr. Lopez-Monsalvo as the winner of the Institute of Physics Group Thesis Prize 2012. We heartily congratulate him on his achievement, and wish him all the best for the future.

Contributed Articles

Cosmologies of point masses

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If a prize existed for minimal-effort achievement by a single scientific field, relativistic cosmology would be the favorite. The development of the completely homogeneous and isotropic class of cosmologies (also known as the Friedmann-Lemaître-Robertson-Walker class, from here on FLRW) was so straightforward that it could be carried out in the very early days of general relativity, its predictions predating many of the observational discoveries that have have occurred since, such as the existence of an isotropic microwave radiation and the chemical composition of the universe. In addition to the many technical insights that keep making the news, the discovery that the universe is not static is truly one of the broadest cultural paradigm shifts of the twentieth century. Few sciences have been able to achieve so much with such a little investment.

The FLRW framework is so successful that further progress in modeling relativistic effects in the large-scale universe lost steam very early on. Yet, on many levels the observable universe looks remarkably different from a homogeneous and isotropic space filled with a perfect fluid, as assumed in the FLRW case: for one, most of its observable mass lies in isolated objects arranged in non-trivial large-scale structures, interspersed with large voids. From a formal standpoint, it is also interesting to ask about the properties of General Relativity solutions in compact spaces with periodic boundary conditions, as classical studies in general relativity have concentrated on *asymptotically-flat* spacetimes, i.e. gravitational fields of central objects surrounded by vacuum, and relatively few general results exist in other cases. In later years, even the lack of observational need for beyond-FLRW models has been rediscussed, as observations raise questions that it may not be possible to answer otherwise.

Attempts to study cosmological models with small-scale inhomogeneities have now existed for some time, and can be roughly categorized into general formalisms [1,2] and exact solutions [3]. The first ones are, in principle, powerful frameworks, but it is not straightforward to extract observational predictions without simplifying assumptions. In the second ones, one has full control over all the details from the beginning, but can only analyze relatively simple spacetimes with no claim for even qualitative realism. As I will illustrate below, a third road, based on full-3D, relativistic numerical simulations of arbitrary spacetimes, can provide just the right complement to the existing methods.

Mass, not matter

In 1957, Lindquist and Wheeler proposed an interesting sort of inhomogeneous cosmology: one in which matter is replaced by a collection of black holes [4]. This results in the tremendous simplification that the stress-energy tensor is zero everywhere, at all times, and no hydrodynamical treatment (relativistic or otherwise) is required. The rules to assemble such structures in general relativity were, however, not investigated. At first, the black-hole lattices were obtained by simply gluing several Schwarzschild solutions to each other, each of them at the center of a cell of one of the tessellations of the 3-sphere. The scaling of lengths in this model was then imposed to be that of the corresponding homogeneous model. In 2009, the same procedure was repeated by Clifton and Ferreira for flat and negatively-curved spaces [5]. In all these studies, however, the focus was to study the optical properties of an approximate model, rather than obtain a global solution of Einstein's equation.

In principle, building exact, multi-black-hole solutions of Einstein's equation is a complex task, entailing the solution of a system of coupled, elliptic, partial differential equations (the Einstein constraints) to obtain the gravitational field configuration at an instant of time, and then evolving this configuration using the hyperbolic part of Einstein's equation. It turns out, however, that in at least one case it is possible to construct a constant-time hypersurface of a multi-black-hole spacetime with no recourse to numerics altogether [6][7]. This special case can be best understood in the 3+1 formulation of general relativity, which I will introduce next.

The 3+1 formulation and numerical relativity

Finding solutions to Einstein's equation does not necessarily entail assumptions of symmetry. One can construct general-relativistic spacetimes in full generality by resorting to numerical methods: first, a coordinate basis is chosen and Einstein's equation is turned into a coupled system of partial differential equations; second, the elliptic part of this system is solved to obtain the three-dimensional metric tensor and its first time derivative on a spacelike 3-surface; and finally, these data are evolved in time using the hyperbolic part of the system, thus obtaining the time development of the initial data for (in principle) as long as desired. Hydrodynamical equation for the stress-energy tensor would typically be evolved alongside.

The field responsible for this studies is called, unsurprisingly, numerical relativity, and has vast applications to problems where symmetry assumptions cannot be applied: among all, compact objects as sources of gravitational radiation [8]. The same techniques can of course be applied to generate spacetimes of all sorts; in particular, they can help build truly 3D cosmological initial data and follow its development over time [9]. The actual feasibility of this scheme depends, however, on many factors, including the detail required in the initial data and the equation of state of the matter included in the stress-energy tensor. With current technology, realistic representations of the observable universe in full general relativity are obviously intractable.

The first two steps towards the numerical solution of Einstein's equation consist of introducing a coordinate basis (and in particular, a time direction along which the evolution is to occur), and then discretizing the equation, i.e. expressing the solution formally in terms of a finite number of its "modes", so that the system of partial differential equations turns into an algebraic system that is straightforward to solve on a computer.

The first step is referred to as a *3+1 decomposition*, and it often proceeds along the lines of the Arnowitt-Deser-Misner formalism (or a closely-related modification) [10], so that the system of equations to solve reads:

$$R + K^2 - K_{ab}K^{ab} = 16\pi\rho \tag{1}$$

$$D_b K_a^b - D_a K = 8\pi j_a \tag{2}$$

$$\mathcal{L}_t \gamma_{ab} = -2\alpha K_{ab} + \mathcal{L}_\beta \gamma_{ab} \tag{3}$$

$$\mathcal{L}_t K_{ab} = -D_a D_b \alpha + \alpha(R_{ab} - 2K_{ac}K_b^c + KK_{ab}) - \alpha 8\pi\left(S_{ab} - \frac{1}{2}\gamma_{ab}(S-\rho)\right) + \mathcal{L}_\beta K_{ab} \tag{4}$$

for the spatial metric $\gamma_{ab}$and its first time derivative, the extrinsic curvature K_{ab} (for details, see [10]). Whilst the details of the above equations can vary depending on the formulation, the important fact is that Einstein's equation turns into a system of ten partial differential equations: the first four are elliptic equations (just like Poisson's equation in Newtonian gravity), and constrain the components of the metric tensor on a 3-surface of equal time; the remaining six are hyperbolic, and prescribe how these equal-time data evolve from one 3-surface to the following. In other words, the first set of equations has to be taken into account when setting initial data for the second set, as the metric tensor will have to satisfy (1) and (2) in order to represent a legitimate gravitational-field configuration that can be evolved with (3) and (4).

It is relatively straightforward to turn these equations into an algebraic system that can be solved numerically. A popular route is the method of finite differences, by which all the fields are described through their value at some representative points, chosen judiciously to cover all the relevant part of the spacetime and to resolve the small-scale details at a satisfactory level. Over the past decade, this strategy has enabled researchers to carry out long-lived simulations of compact objects and gravitational waves, and has been consolidated into an open-source community code that can be readily adopted and extended [11].

Periodic spaces and the Einstein constraints

In Newtonian gravity, periodic solutions do not exist: Poisson's equation with periodic boundary conditions only has solutions for matter density profiles that integrate to zero over a periodic cell, which is unphysical. One could ask whether the same holds for general relativity.

It indeed turns out that swapping Dirichlet boundary conditions for periodic boundary conditions changes the problem significantly: expressing (1) in the Lichnerowicz-York form [12]

$$\tilde{\Delta}\psi - \frac{\tilde{R}}{8}\psi - \frac{K^2}{12}\psi^5 + \frac{1}{8}\tilde{A}_{ij}\tilde{A}^{ij}\psi^{-7} = -2\pi G\psi^5\rho \tag{5}$$

for the metric conformal factor ψ, the Einstein constraint system now has solutions only for free data that satisfy an integrability condition given by

$$\int_D \left(\frac{\tilde{R}}{8}\psi + \frac{1}{12}K^2\psi^5 - \frac{1}{8}\psi^{-7}\tilde{A}^{ij}\tilde{A}_{ij}\right)\sqrt{\tilde{\gamma}}d^3x = 2\pi G\left(\int_D \rho\psi^5\sqrt{\tilde{\gamma}}\,d^3x + \sum_{i=1}^{N} m_i\right) \tag{6}$$

which is only satisfied for certain values of R, K, A_{ij}, ρ and m_i. In other words, the system becomes *singular*, admitting solutions only for particular values of its coefficients (in particular, this restriction implies that periodic black hole solutions with both zero spatial curvature and zero trace of the extrinsic curvature cannot exist)[14].

This is not unlike other eigenvalue problems in physics where the eigenvalue spectrum becomes discrete once periodic boundaries are imposed, and it poses additional constraints on the allowed free data; additionally, these conditions cannot be established at the start, but have to be enforced iteratively during the solution process. One thus has to approach the (Einstein) constraint surface in the solution space, whilst at the same time keeping on the (integral) constraint surface. This type of optimization problem is sometimes referred to as a *doubly-constrained* problem, and depending on the shape of the constraint surfaces in the solution space, can pose challenges to solution algorithms that focus on the two constraints in a decoupled way. For a complex problem as the Einstein constraint system in periodic spaces, it is in practice quite complicated to explore the shape of the constraint surfaces and establish whether there is a real danger for non-convergent behavior; I have empirically observed, however, that a multigrid algorithm for the constraint system coupled to a variable resetting yields fast and reasonable convergence [13].

Notice that the equations corresponding to the momentum constraint do not yield any such integral condition [13].

Types of periodic black-hole solutions

From the integral condition for the Hamiltonian constraint, one deduces that this equation only has solutions when the spatial curvature R is positive or the trace of the extrinsic curvature K is non-zero (or both are non-zero and such that (6) is respected). Given that the extrinsic curvature represents the time derivative of the spatial metric, this is reminiscent of the FLRW class where only the positively curved models admit an instant of time symmetry.

The simplest black-hole-lattice initial data can then be classified into two categories: models with positive conformal curvature at their instant of time symmetry, and expanding (or contracting) conformally-flat models. It is now easy to see how one can obtain an analytic expression for the instantaneous configuration of the gravitational field of many black holes in a special case: the idea is to exploit the linearity of the constraint system in the positive-curvature case with no extrinsic curvature; if a black-hole solution can be found, arbitrary multiple-black-hole configurations can be created with a simple superposition. A black hole with $R > 0$, it turns out, is given simply by

$$\psi(\lambda) = \frac{A}{\sin \lambda/2} \tag{7}$$

where A is a measure of the black-hole mass and λ is one of the coordinates on the 3-sphere. Any superposition of terms like (7) yields a valid instantaneous configuration for a system of black holes. If one is interested in arrangements that are periodic in all three spatial dimensions, however, the black hole locations have to coincide with the centers of one of the six regular tessellations of the three-sphere.

Since the extrinsic curvature is identically zero in this case, the configuration is instantaneously time-symmetric. The parallel with the inversion point in closed FLRW models is evident. Notice that numerics are still needed to obtain the full time development of these initial data [14]; a number of properties can however be extracted analytically by studying the initial data [6,7,14], or following the evolution of a set of special curves in these spacetimes [15].

One can, for instance, investigate the relationship between some suitably-defined density and curvature in the initial data, and compare it to the FLRW class. The results is that in the FLRW class, the same amount of curvature requires a larger total mass; in other words, the gravitational effect of black-hole mass is fairly larger than that of homogeneous, pressure-free matter, likely due to non-linear amplification [14]. This statement can also be cast in terms of the mass-to-scale relationship: homogeneous universes are smaller than the same-mass black-hole lattices [7].

Naturally, one of the quantities of major interest is the scaling of lengths over time. One can, for instance, choose the distance between neighboring black-hole horizons, or the proper length of the edge of a lattice cell, and track it during the evolution to see how it compares to the FLRW class (which curves to track and where the comparison to FLRW makes sense is an interesting question on its own). In [14], these quantities were derived using direct 3D numerical simulation for about one third of the FLRW recollapse time; in [15], the same observables were shown to obey ordinary differential equations that could be evolved for as long as desired. The results agree where they overlap: the edge length of these lattices behaves initially very close to FLRW; the results in [15], however, show that the behaviour diverges significantly from FLRW after about half of the FLRW recollapse time, leading to negative values of the deceleration parameter. Other curves have even more contrasting evolutions, and start shedding light into the ultimate fate of these recollapsing cosmologies.

Another class of black-hole lattices is obtained by choosing zero conformal Ricci curvature, but a non-zero extrinsic curvature. In this case, the initial data will be conformally flat (just like the Schwarzschild solution), but the extrinsic curvature will need to be always non-zero, and the constraint system will cease to be linear, requiring numerical solution.

One suggestion for a possible conformally-flat lattice has been put forward by Yoo et al. in 2012, based on a matched extrinsic curvature profile that respected some of the properties of the Schwarzschild solution near the black holes, and reduced to a constant FLRW-like expansion away from them [16]. This initial-data set has been further reproduced in [13], and evolved in time in [17] and [18]. Here again, the evolution of the cell-edge length proves to stay close to the FLRW solution at leading order, but features a number of higher-order departures that include oscillations in the edge lengths and, consequently, in the effective density and pressure of these models. One can also quantify the mass dressing effect discovered in the 3-sphere models, finding that in this case it has opposite sign with respect to the 3-sphere case. The ambiguity in the initial-data construction, however, opens up the possibility that these lattices could be constructed in a cleaner, oscillation-free way, and that the observed phenomenology might be not that fundamental after all. A summary of the current numerical results is given in Figure 1.

It is instructive to compare these results to the complementary, perturbative approach of Bruneton and Larena [19,20], who construct a lattice cosmology with equally spaced masses, exact to linear order in the mass-over-spacing parameter. The resulting evolution is kinematically identical to FLRW dust cosmologies, but the observables can differ significantly from their FLRW counterparts if the compactness parameter of the sources is too high. This suggests two points: that the non-FLRW effects observed in black hole lattices

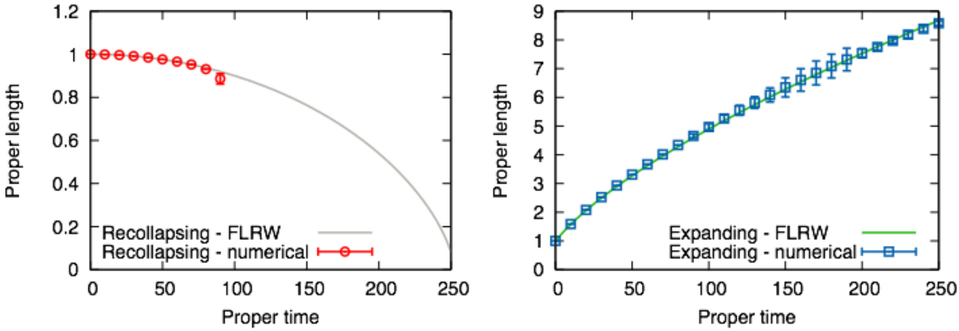

Figure 1: Length scaling in the recollapsing and expanding black-hole solutions, contrasted to the corresponding FLRW models (for details, see [14] and [18]). The left panel is to be compared to Figure 7 in [15].

are truly higher-order effects that should disappear as the mass-over-spacing parameter goes to zero (a conclusion that has also emerged recently in a non-perturbative approach [21]), and that the study of light propagation in these spacetimes is likely to hold some surprises. A better grasp on the art and science of constructing black-hole lattice will definitely require more work.

Acknowledgement
My work on black-hole lattices has been carried out in collaboration with Mikołaj Korzyński.

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Disformal couplings and cosmology

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In upgrading the cosmological constant to a dynamical field, dark energy inherits myriad extra structure from the arsenal of general effective field theory. Along with vast freedoms in the form its Lagrangian can take, it can now also couple to other fields [1,2]. A lesson well taught by the physics of fundamental particles is that nature will in general do as it pleases, unless some symmetry forbids it; if there exist plausible degrees of freedom open to the dark energy field – such as couplings to matter or gravity – why would they not be exploited? The unconventional type of coupling between dark energy and matter known as disformal coupling is gaining popularity in the literature, partly because we have no known theoretical mechanism to suppress it, and too it is well motivated by fundamental constructions like warped branes and massive gravitons [3,4].

Disformal couplings of a dark energy scalar field to matter are notoriously elusive. By their nature they hide well from ground based experiments and their effects are negligible on static spherically symmetric objects like planets. They are not well constrained [5]. Issues of coincidence and fine-tuning plaguing the dark energy paradigm could potentially be alleviated by these couplings to matter - as exit strategies from scaling solutions. In this article I'll discuss how disformal terms arise from considerations of a generalised gravitational coupling between dark energy and matter, and then describe how we have recently shown these couplings to be not so elusive after all. They can in fact leave signatures, not locally in the solar system but globally, on the Cosmic Microwave Background [6].

There are many ways a scalar, φ, can couple to matter, either directly in the Lagrangian, for example to electromagnetism $\mathcal{L} \supset A(\varphi)F^{\mu\nu}F_{\mu\nu}$ [2], or indirectly, through the metric. This gravitational coupling could be of the field to the Ricci scalar, R, $\mathcal{L} \supset B(\varphi)R$. Such is the gauge freedom of gravitationally coupled scalar-tensor theories that both the spin-0 and spin-2 fields can always be redefined to simplify the action. The Einstein frame of a scalar-tensor theory corresponds to the set of field definitions that reduce the gravitational part to general relativity, but now the redefined scalar, ϕ, appears explicitly in the invariant volume element of the matter sector, i.e. $\mathcal{L} \supset \sqrt{-\left|C(\phi)g_{\mu\nu}\right|}\mathcal{L}_m$; the scalar is now said to be directly coupled gravitationally to matter. It is with respect to this Einstein frame that disformal couplings are so defined.

But of course if this scalar is coupled, this raises the obvious problem of enhanced detection. If matter produces not only a metric field profile, but a scalar one too, why is this additional force not manifest on the dynamics of the nearby stars and planets? If we want to selectively modify gravitation theory over cosmic distances, but not on much smaller ones like that of the solar system (where general relativity stands infallibly), we need a mechanism to suppress these modifications in regions where we know their presence is clearly not being felt; we need to selectively screen them. Like coupling, there are many ways to screen a field, each with its own degree of arbitrariness. Two notable mechanisms often invoked to screen conformal couplings (i.e. $B(\varphi)R$, $C(\phi)g_{\mu\nu}$ as described above) are the Chameleon and Symmetron [7,8]. In the former, the scalar field's mass is made to increase in high density areas, thus rendering this new force too short-ranged. In the later, the coupling is assumed due to some broken symmetry that is restored in high density regions. One of the most attractive features of disformally coupled scalar fields, though, is that they are not sourced by static spherical objects like planets, and so disformal terms naturally hide from local gravity tests.

Now, we can best understand how these unconventional couplings might arise by asking: what is the most general gravitational coupling possible in a scalar-tensor theory? Jacob Bekenstein asked this question from the point of view of the Einstein frame in a very elegant way [9]. Considering the action

$$\mathcal{S} = \frac{1}{2}\int d^4x\sqrt{-g}\left(R - \mathcal{L}_\phi\right) - \int d^4\, x\sqrt{-\tilde{g}}\mathcal{L}_m$$

at face value as a theory of two geometries, that of the gravity sector, $g_{\mu\nu}$, and of the matter sector, $\tilde{g}_{\mu\nu}$, he restated the problem as: what is the most general transformation between these two geometries that observation will allow? The idea of gravitational coupling becomes one of metric transformations. The language of gravitational couplings and metric transformations can then be used interchangeably. This transformation he argued must respect causality, and for the new metric, $\tilde{g}_{\mu\nu}$, it must always be possible to locally map to flat Minkowski spacetime, as particle accelerators have shown that on very small scales, the geometry of nature is – to a very high degree of precision – that of a flat Lorentzian manifold.

Given the addition of a single scalar degree of freedom, the most general transformation between metrics physically permissible, Bekenstein demonstrated, was both a conformal plus what he christened a disformal one

$$\tilde{g}_{\mu\nu} = C(\phi, X)g_{\mu\nu} + D(\phi, X)\phi_{,\mu}\phi_{,\nu}$$

where $X = \frac{1}{2}\partial_\mu\phi\partial^\mu\phi$, the field's kinetic energy. Each of these terms has a clear geometric interpretation. A conformal transformation, $C(\phi, X)$, of the metric locally stretches the matter geometry equally in all directions while a disformal one locally distorts spacetime in the direction of the gradient of the scalar field at that point. This usually entails a distortion of casual structure, while under conformal transformations, the shape of light cones is preserved. In this generalised model, general relativity now represents a point in the parameter space where $C = 1$ and $D = 0$. What symmetry principle restricts the true theory of gravity from straying away from this special place?

With no such principle in hand, we decided to investigate whether such a coupling could leave any observational traces (see [10] for closely related work). Any realistic cosmological model that hopes to mimic our observable universe requires at least two separate species: pressure-less matter, (baryonic and Dark), and relativistic radiation (CMB). This corresponds to at least two fluids. What if each fluid were to reside in its own distinct disformal geometry? We considered a cosmology with both a matter and radiation fluid, each one disformally coupled to the scalar, but with different strengths in general, allowing ϕ to play the role of a dark energy field whose potential drives the late-time expansion of the universe. For the matter and radiation geometries respectively then, we isolated disformal effects, setting $C_m = C_\gamma = 1$ and D_m, D_γ to constant energy scales M_m^{-4}, M_γ^{-4}. Such couplings, we found, lead to distortions in both the CMB spectrum today and in the cosmic evolution of its temperature with redshift, as measured by a matter observer living in the matter geometry. These CMB properties have been well measured [11-13], which allowed us to place constraints on the $M_m \times M_\gamma$ parameter space as shown in Figure 1.

There are two standout features of this plot. First is that the excluded regions are bounded from two sides. This is simply because a disformal coupling to matter has a damping effect on the ϕ field. We are faced with a trade-off: couple the field too weakly, and any disformal effects on matter are suppressed; couple the field too strongly, and the matter has a damping back-reaction on the field: if the field's evolution is suppressed, so then are its derivatives, along with all disformal effects. Second, the straight line is a guide to the eye to show that when the species are coupled with the same strength, our observable signatures vanish. We understand this arises from the matter and radiation geometries coinciding; our constraint methods are probes of the discrepancy between the two geometries. Notice though that for the light grey regions, this discrepancy need

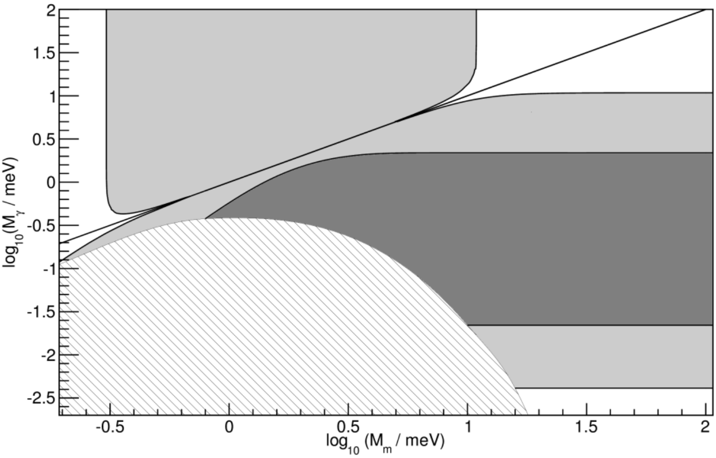

Figure 1: Bounds on the $M_m \times M_\gamma$ parameter space from measured properties of the CMB: The dark grey region is excluded above a 68%CL by measurements of the evolution of the CMB temperature [11-13]. The light grey regions are excluded by published limits on the CMB's departure from a perfect blackbody due to disformal effects [11] and the dashed region outlines where we could not obtain numerical solutions. The model constrained here was a canonical dark energy field in a shallow potential: $V(\phi) = V_0 e^{-\phi}$.

not be big at all. We could perhaps imagine such a difference coming from quantum corrections of ϕ couplings to the various matter species. Note also, there is always a finite (though negligibly small) space between the straight line and the edges of the light grey exclusion zones. The straight line and the exclusion zones never overlap.

So it seems that dynamical alternatives to a cosmological constant present a promising way to bridge the gap between fundamental constructs like extra dimensions and dark energy measurement. And if we do, we open a pandora's box of complicated structure, like couplings that – ignorant of the high energy behaviour of a dynamical dark energy theory – we cannot lightly cast aside. In particular for disformal terms in the metric of a modified gravity theory, we have no viable way of theoretically suppressing them via symmetries, which well warrants their study in such models. As well as emerging independently from theories of matter on curved branes or massive gravity, disformal couplings are also interesting phenomenologically. They are capable of providing exit strategies from tracking solutions, as shown by Zumalacarregui *et al.* [14], without the need of screening. And though they are unlikely to be observed on sub solar system scales, we have demonstrated that they can in fact leave a visible imprint: on the largest cosmic ones.

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Black holes as observatories for beyond-Standard Model physics

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It has recently been realized that astrophysical black holes (BHs) might serve as detectors for fundamental fields predicted in beyond-standard models (SMs) including, e.g., the "axiverse" scenario [1] or extensions of general relativity (GR) such as scalar – tensor theories [2,3]. This exciting application of BH phenomenology is facilitated by the vastly improving field of "precision BH physics" [1,2,4] together with the fact that BHs are extremely simple objects which are fully characterized by their mass, angular momentum and electric charge. Nowadays, there is compelling observational evidence for the existence of supermassive BHs (with $10^6 M_\odot \lesssim M \lesssim 10^9 M_\odot$) at the centre of most galaxies which, simultaneously, are expected to host a large number of stellar-mass BH systems (with $3M_\odot \lesssim M \lesssim 30M_\odot$) [5]. Recently, there has been tremendous progress in observing BHs in the electromagnetic spectrum: X-ray spectroscopy probes the accretion of matter discs surrounding BHs and, thus, allows for accurate estimates of the BH spin [4], while observations in the infrared and radio frequency band gives access to the region close the BH's horizon within few Schwarzschild radii [6]. These electromagnetic observations are expected to be complemented with detections in the gravitational wave (GW) channel within the next decades using GW interferometers [3,7], such as the advanced LIGO/ VIRGO detector network [8] that should be up and running in 2015, the KAGRA observatory which is currently under construction [9], third generation ground-based GW detectors such as the Einstein Telescope [10], or space-based operations along the lines of the (e)LISA mission [5].

The mechanism enabling us to exploit astrophysical BHs as laboratories for beyond-SM (particle) physics is the so-called "BH-bomb" or "superradiant (SR) instability" [11-13]. Exemplary, consider a wave scattering off a Kerr BH with mass M and spin a/M. The energy-momentum flux into the horizon can be negative if the wave's frequency satisfies

$$0 \leq \omega_R \leq m\Omega_H = m\frac{a}{2Mr_+} = \omega_C \qquad (1)$$

where we denote the azimuthal "quantum" number m, the angular velocity of the BH horizon Ω_H and its radius $r_+ = M\left(1+\sqrt{1-(a/M)^2}\right)$. The SR condition (1) implies that parts of the energy and angular momentum can be extracted from a BH while the field gets amplified. This has some far reaching implications [2] and,

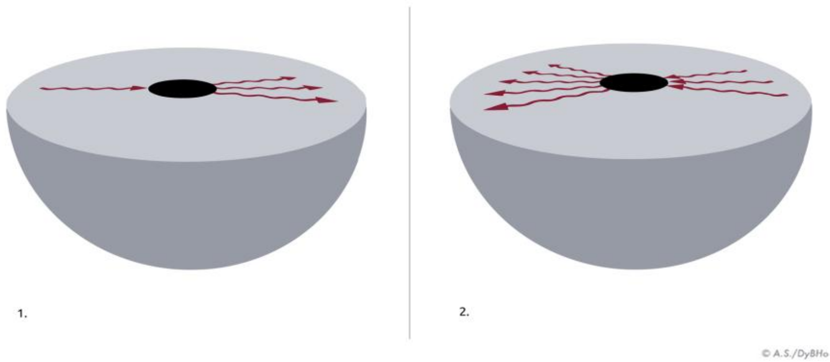

Figure 1: Illustration of the "BH bomb" configuration. A low frequency wave packet satisfying Eq. (1) is superradiantly amplified during the scattering off a rotating BH. Because of the presence of a perfectly reflecting mirror, these waves are trapped inside the system and will grow without bound, thus triggering the SR instability. Taken from Ref. [2].

here, I will put the spotlight on the gedankenexperiment first brought forward by Zel'dovich and Press & Teukolsky [11]: Imagine the system being enclosed by a perfectly reflecting cavity as illustrated in Fig. A, thus confining the field in the vicinity of the BH. Then, a wave satisfying Eq. (1) will grow without bound upon subsequent reflections at the “mirror” and scatterings off the BH. The thus induced energy cascade will eventually trigger the system to become unstable. Illustratively, this instability has been termed “BH bomb” [11]. One natural realization of this setup are asymptotically anti-de Sitter (AdS) spacetimes [12], that play an important role in high-energy physics and, in particular, in the gauge/gravity duality.

In the present article I will focus on another natural setting: massive bosonic fields with mass $m_B = \hbar\mu$ surrounding BHs [15]. Then, the field potential creates a well with $V(r \to \infty) \to \mu$ at large distances and, thus, can effectively mimic a mirror. Consequently, low frequency fields with $\omega \lesssim \mu$ are confined around the BH. Studies involving massive scalar fields $\Phi \sim e^{-i\omega t}$ surrounding rotating BHs revealed the existence of two types of solutions [16]: (i) quasi-normal modes which are characterized by radiative boundary conditions at infinity and (ii) quasi-bound states which decay exponentially at infinity. The latter condition implies that the scalar field is trapped inside the potential well and is, therefore, subject to the SR instability. In both cases the field's frequency is complex and the growth or decay timescale $\tau = 1/\omega_I$ is dictated by the imaginary part of the frequency. The behavior of the system is regulated by the mass coupling[1]

$$\frac{r_h}{\lambda_C} \sim M\mu \equiv \frac{G}{\hbar c} M\mu = 7.45 \times 10^9 \left(\frac{M}{M_\odot}\right)\left(\frac{m_B}{(eV/c^2)}\right)$$

between the BH mass M and the mass $m_B = \mu\hbar$ of the field. This effect can play an important role when the Compton wavelength of the bosonic field is comparable to the typical size of the BH given by the radius of its horizon. For example, the SR instability for massive scalar fields is most prominent for its dipole mode and a mass coupling of $M\mu = 0.42$ around a highly spinning BH with $a/M = 0.99$ [16]. While the mechanism is highly suppressed for astrophysical BHs for which $3M_\odot \lesssim M \lesssim 10^9 M_\odot$ and SM particles because of their large mass coupling, the “magic” coupling can be realized if either (i) the BH mass is very small, as is the case for primordial BHs or (ii) the mass of the bosonic field is tiny. Indeed, recent investigations of the former case have been used to put new stringent constraints on the allowed mass range of primordial BHs [17].

1 Note, that in general I use natural units $G = c = \hbar = 1$. I have reinstalled them here only for clarity.

The second option involving ultra-light massive fields has gained a lot of interest since the proposal of the "axiverse" scenario [1]. Inspired by the QCD axion, Arvanitaki et al [1] suggested the existence of an entire landscape of ultra-light axion-like particles emerging in string theory compactifications. These bosonic degrees of freedom are expected to cover a mass range from $10^{-33}eV \lesssim m_B \lesssim 10^{-8}eV$. In particular, this includes the range $10^{-21}eV \lesssim m_B \lesssim 10^{-8}eV,$ for which $M\mu \sim \mathcal{O}(1)$ around astrophysical BHs and the "BH bomb" mechanism should become significant. From there it is but a small step to realize that observations of astrophysical BHs have the potential to provide new insight into extensions of the SM. The presence of such ultra-light bosonic fields around BHs induces some interesting features: The potential well caused by the mass term effectively confines the field in the vicinity of the BH and gives rise to long-lived quasi-bound states which have a hydrogen-like spectrum [16,18], thus creating a "gravitational atom". Depending on the interplay between the accretion and the SR amplification of low frequency fields the system might turn into a "GW pulsar" or yield gaps in the Regge plane, i.e., the mass-spin phase-space of BHs, if the extraction of their mass and angular momentum is dominant.

These potentially interesting phenomena have driven a revival of the "simplest" model consisting of a massive scalar field in the background of a rotating BH [16,19-22]. Although this setup provides an excellent toy model, the SR amplification for scalar waves scattering off Kerr BHs is at best about 0.04% [11]. This rate increases by orders of magnitude if we consider fields with non-zero spin. For example, low frequency vector-type waves are expected to be amplified by a factor up to 4% which rises up to 138% for spin-2 fields in the background of nearly extremal BHs [23].

Indeed, exploring Proca fields is more than a mere academic exercise and can find important applications in high energy physics: compactifications of string theory also predict the existence of massive, hidden $U(1)$ fields [24]. Due to the mass term, the theory is not gauge invariant anymore (in contrast to electromagnetism) and the Proca field can have three polarizations: one axial (or scalar) and two polar (or vector) modes. What masquerades as a straight-forward extension of the scalar field model is, in fact, a non-trivial task because the Proca equations in the background of a rotating BH appear to be non-separable. While analytic solutions are still available for a non-rotating BH background [25], the Kerr case could only be tackled in the small rotation approximation [18] or by performing numerical simulations of highly rotating BHs [21].

As suspected, the SR instability timescales induced by the presence of massive vector fields can be up to four orders of magnitude shorter than those of its scalar counterpart. To be concrete, the most significant growth rate of $M\omega_I = (5 \pm 1) \times 10^{-4}$ has been found for a Kerr BH with spin parameter $a/M = 0.99$ and a mass coupling $M\mu = 0.40$ [21]. This translates into an instability timescale of $\tau \sim 0.016\,(M/M_{\odot})s$. In Figure 2, I depict one of the most striking outcomes from investigations of the Proca field in slowly rotating BH backgrounds [18]. Here, the authors compared the timescale for the SR instability, which would cause a spin-down and mass-loss of a BH, with the Salpeter timescale necessary to spin-up a BH through astrophysical processes such as accretion or BH mergers. These considerations facilitate the drawing of exclusion plots in the BH Regge-plane, i.e., gaps in the mass-spin phase-space of BHs that should be present if the extraction of energy and angular momentum from the BH was effective. Figure 2 exemplarily shows the contours of exclusion regions due to the axial Proca field mode for various mass parameters [18]. BH candidates inside this region would be unstable against the "BH bomb" mechanism and should therefore not exist. Reversely, the observation of BHs inside these contour regions thus can be exploited to put constraints on the allowed mass range of fundamental fields. In fact, exactly this feature has been used to exclude massive U(1) fields in the range $10^{-20}eV \lesssim m_B \lesssim 10^{-17}eV$. as illustrated in Figure 2, which has been superposed with actual astrophysical measurements of BH spins using X-ray spectroscopy [26]. Assuming the possibility that the photon could be an ultra-light but massive, hidden U(1) field, these studies have put new stringent constraints on the photon mass of $m_\gamma < 10^{-20}eV$ [18].

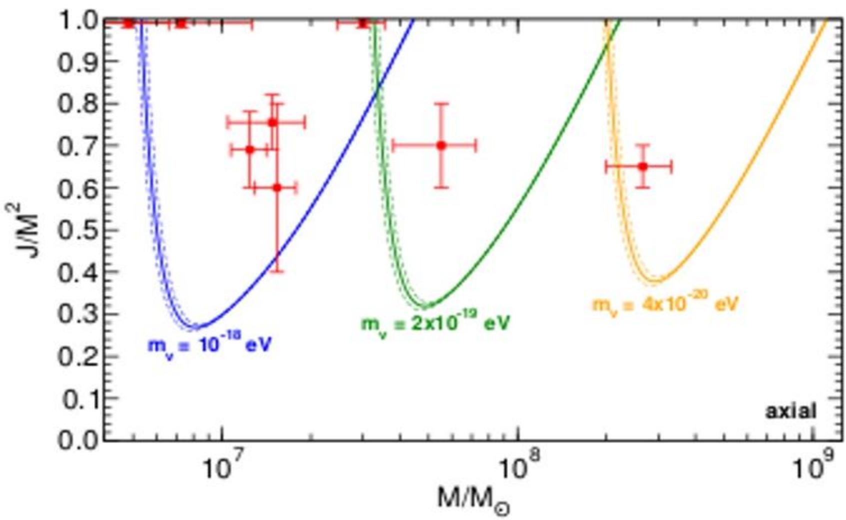

Figure 2: Contour plots in the mass-spin phase-space of BHs due to the SR instability of BHs against massive vector fields. Because of the measurement of BHs inside these contours, denoted by the dots, Proca fields with masses $10^{-20}eV \lesssim m_B \lesssim 10^{-17}eV$. are excluded. Figure taken from Ref. [18].

The realization that investigations of BH – massive field systems have the potential to uncover new physics by astronomical measurements has launched a plethora of studies concerning the "BH bomb" mechanism (see, e.g., Refs. [2] for recent reviews). Here, I point out some of the most appealing extensions as reference list for the interested reader: (i) massive spin-2 fields emerging as further natural extension of the SM or in the context of modified gravity theories [27]; (ii) 5-dimensional boosted black strings surrounded by massive scalars [28]; (iii) Proca fields in the background of Schwarzschild-Tangherlini BHs [29]; (iv) the stability of Kerr BHs in scalar - tensor theories [30]; (v) bosenova – like collapse appearing for a non-linear, self-interaction potential of (massive) scalar fields [20]; (vi) massive scalar fields in Reissner - Nordstrøm backgrounds, for which an additional confining mechanism is required to trigger the instability [14].

However, all these studies have assumed a fixed BH background. While this perturbative approach is valid as long as the amplitude of the field is small, it is doomed to fail eventually. Due to SR amplification, the energy of the field increases and its back-reaction onto the spacetime will become important. Then, the end-state of the SR instability could be either a true non-linear instability or yield some quasi-equilibrium situation. In a dynamical setting energy and angular momentum could be extracted from the BH such that the SR condition (1) is no longer satisfied and the system could be shifted into a stable regime. On the other

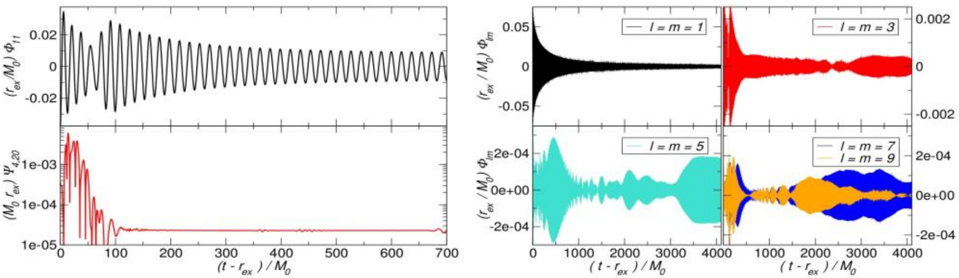

Figure 3: Illustration of non-linear evolutions of massive scalars fields in BH environments. Left: dominant scalar (top) and thus induced gravitational (bottom) waveforms for an initial Kerr BH with $\boldsymbol{a/M = 0.95}$ and a mass coupling $\boldsymbol{M\mu = 0.3}$; Right: Excitation of higher multipoles for an initial dipole scalar cloud around a non-rotating BH. Taken from Ref. [31].

hand, because accretion would feed the BH, thus again increasing its mass and spin there is the interesting possibility of a quasi-periodic behavior in which energy is transfered back and forth between the BH and its surrounding bosonic cloud. Furthermore, the interaction of a fundamental scalar field with a BH induces both scalar and gravitational radiation. This modification might serve as a smoking-gun effect for beyond-SM physics in the GW channel once we enter the stage of GW astronomy.

First steps towards exploring these interesting effects by performing fully non-linear evolutions of the Einstein – Klein – Gordon system are underway [31]. Here, I focus on the most tantalizing results concerning massive scalar shells with a dipole angular dependence around an initially Schwarzschild or highly spinning Kerr BH with $a/M = 0.95$. Animations of the scalar field evolution illustrating the process are available at Ref. [31]. The main features in both cases are similar: the scalar shell is (partly) accreted by the central BH, thus triggering the excitation of ringdown in both the scalar and gravitational wave channel as is shown in the left panel of Figure 3. The BH's response, however, strongly depends on the initial spin: the (initially) non-rotating BH devours the scalar field, thus gaining mass and spin. In other words, the state after the first interaction is a BH with a small, but non-vanishing spin. In case of the highly rotating BH, we observe a small decrease in both mass and spin for short periods of time. Interestingly, these hints of SR are compatible with induced, gravitational SR stimulated by the disturbance due to the scalar field. This short period is followed by a substantial increase of the BH's mass and a decrease of the dimensionless spin parameter, thus resulting in a moderately rotating BH.

This early, dramatic change in the configuration yielding a burst of radiation is succeeded by the formation of a scalar cloud, i.e., long-lived states of the massive field around the BH. The scalar cloud continues to leak into the BH, thereby stimulating a long-lived GW signal as can be seen at late times in the left panel of Figure 3.

A further interesting effect has been discovered in the higher multipoles: Although the initial configuration consisted of an almost pure dipole scalar field surrounding a non-rotating BH, we observe the excitation of higher multipoles as displayed in the right panel of Figure 3, where we also note a strong modulation due to beating effects [21]. Possible explanations for this effect include the nonlinear excitation of modes, mode mixing due to the small (but non-vanishing) spin of the originally non-rotating BH or it could even be an indication for gravitational turbulence recently discovered in the case of asymptotically AdS spacetimes [32], but now for asymptotically flat spacetimes. Further investigations are needed to get to the bottom of this exciting phenomenon.

Despite the “gold-rush” in studies concerning gravity coupled to fundamental fields, we have just scratched the surface and many interesting phenomena may still await us. The opportunity to gain insight into beyond SM physics – be it the possible existence of exotic, ultra-light particles, primordial BHs or modified gravity models – makes this an exciting playground for BH physics.

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