# Testing General Relativity with Astrophysical Observations – Program

**MONDAY, JANUARY 6 – (Venue: Yerby Conference Center - note special venue!)**

**Present and future experimental tests of GR**

**8:30am–8:50am: Welcome** from the organizers

**8:50am–9:40am** Cliff Burgess (McMaster/Perimeter Institute)
*Effective field theories and modified gravity: A bad cop wrapped in a wet blanket standing in a cold shower*
**9:40-10:30** Norbert Wex (MPI, Bonn)
*Tests of gravity from radio pulsars*
**10:30-10:50** Coffee break
**10:50-11:40** Pedro Ferreira (Oxford)
*Testing general relativity with cosmology*
**11:40-12:30** Nicolas Yunes (Montana State)
*Gravitational wave tests of general relativity*
**2:00pm** Bangalore Sathyaprakash (Cardiff)
*[Discussion] Testing strong field gravity: Expectations from ground- and space-based gravitational-wave detectors*

**TUESDAY, JANUARY 7 – (Venue: Student Union)**

**Systematic errors in GR; data analysis issues**

**8:30-9:10** Chris Van den Broeck (Nikhef)
*Testing the strong-field dynamics of general relativity with gravitational wave signals from coalescing compact binaries. I. Basic framework.*
**9:10-10:00** Tjonnie Li (Caltech)
*Testing the strong-field dynamics of general relativity with gravitational wave signals from coalescing compact binaries. II. The TIGER data analysis pipeline.*
**10:00-10:20** Coffee break
**10:20-11:10** Richard OShaughnessy (Milwaukee)
*Disentangling astrophysics from gravity*
**11:10-12:00** Tyson Littenberg (Northwestern)
*Evidence you can trust through detailed modeling of GW data*
**2:00pm** Neil Cornish (Montana State)
*[Discussion]*

**WEDNESDAY, JANUARY 8 – (Venue: Student Union)**

**Overview of alternative theories**

**8:30-9:20** Antonio De Felice (Kyoto)
*Review of modified gravity models*
**9:20-10:10** Andrew Matas (Case Western Reserve University)
*Observational tests of massive gravity and galileons*
**10:10-10:30** Coffee break
**10:30-11:20** Michael Horbatsch (Mississippi)
*Scalar-tensor gravity*

**11:20-12:10** Enrico Barausse (IAP, Paris)
*Astrophysical consequences of Lorentz violations in gravity*
**12:10-1:00** Flavio de Sousa Coelho (Aveiro)
*n-DBI gravity*
**2:30pm** Leo Stein (Cornell)
*[Discussion]*

**THURSDAY, JANUARY 9 – (Venue: Student Union)**

**Compact objects in alternative theories**

**8:30-9:10** Vitor Cardoso (Lisbon)
*Precision gravitational-wave astrophysics*
**9:10-9:50** Kostas Kokkotas (Tübingen)
*Rotating relativistic stars: Equilibrium configurations and instabilities*
**9:50-10:30** Hajime Sotani (Kyoto)
*Stellar oscillations in scalar-tensor theory*
**10:30-10:50** Coffee break
**10:50-11:30** Kent Yagi (Montana State)
*Strong-field Tests of gravity with universal relations in neutron stars and quark stars*
**11:30-12:10** Ryan Lang (Florida)
*Compact binaries in scalar-tensor gravity: Equations of motion and tensor gravitational waves to high post-Newtonian order*
**2:00pm** Paolo Pani (Lisbon)
*[Discussion] Parametrizing compact objects in modified gravity: where do we stand?*

**FRIDAY, JANUARY 10 – (Venue: Student Union)**

**Numerical simulations and strong-field dynamics**

**8:30-9:10** Ulrich Sperhake (Cambridge)
*Black-hole binary inspiral and merger in scalar-tensor theory of gravity*
**9:10-9:50** Pablo Laguna (Georgia Tech)
*Merger of binary black holes in scalar-tensor theories of gravity*
**9:50-10:10** Coffee break
**10:10-11:00** Helvi Witek (Cambridge)
*Black holes as observatories for beyond-standard model physics*
**11:00-11:40** Hirotada Okawa (Lisbon)
*Collapse of self-interacting fundamental fields in asymptotically flat spacetimes*
**1:00pm** Pablo Laguna, Ulrich Sperhake
*[Discussion]*

# ABSTRACTS

## MONDAY, JANUARY 6

**Cliff Burgess**
*Effective Field Theories and Modified Gravity: A Bad Cop wrapped in a Wet Blanket standing in a Cold Shower*

We live at a time of contradictory messages about how successfully we understand gravity. General Relativity seems to work very well in the Earths immediate neighborhood, but arguments abound that it needs modification at very small and/or very large distances. This talk tries to put this discussion into the broader context of similar situations in other areas of physics, and summarizes some of the lessons which our good understanding of gravity in the solar system has for proponents for its modification over very long and very short distances. The main mes- sage is that effective theories, in the technical sense of effective, provide the natural (and arguably only known) precise language for testing proposals, making them also effective in the colloquial sense.

**Norbert Wex**
*Tests of gravity from radio pulsars*

The discovery of the first binary pulsar by Russell Hulse and Joseph Taylor in the summer of 1974 initiated a completely new field for testing relativistic gravity. For the first time the back reaction of gravitational wave emission on the binary motion could be studied, which gave the first evidence for the existence of gravitational waves as predicted by Einstein's general relativity. Furthermore, the Hulse-Taylor pulsar provided the first test bed for the gravitational interaction of strongly self-gravitating bodies.

To date there are a number of radio pulsars known, which can be utilized for precision test of gravity. Depending on their orbital properties and their companion, these pulsars provide tests for various different aspects of gravity. Besides tests of specific theories, like general relativity or scalar-tensor gravity, there are pulsars that allow for generic constraints on deviations of gravity from general relativity in the quasi-stationary strong-field regime and in the generation of gravitational waves.

In my talk I give an introduction to gravity tests with radio pulsars, and highlight some of the most important results. In addition, I give a brief outlook into the future of this exciting field of experimental gravity.

**Pedro Ferreira**
*Testing General Relativity with Cosmology*

With the successes of observational cosmology, a new window has opened up on to gravitational physics. By carefuly measuring the morphology and growth of structure in the Universe it may be possible to constrain general relativity on a completely new range of scales. It also allows us to explore a plethora of modified gravity theories that have emerged as an attempt to explain the observational evidence for dark energy. I will discuss the challenges and approaches which are being taken in this new field.

**Nicolas Yunes**

*Gravitational Wave Tests of General Relativity*

With the imminent detection of gravitational waves by ground-based interferometers, such as LIGO, VIRGO and TAMA, pulsar timing observations, and proposed space-borne detectors, such as LISA, we must ask ourselves: how much do we trust general relativity? The confirmation of general relativity through Solar System experiments and binary pulsar observations has proved its validity in the weak-field, where velocities are small and gravity is weak, but no such tests exist in the strong, dynamical regime, precisely the regime of most interest to gravitational wave observations. Unfortunately, because of their inherent feebleness, the extraction of gravitational waves from detector noise relies heavily on the technique of matched filtering, where one constructs waveform filters or templates to clean the data. Currently, all such waveforms are constructed with the implicit assumption that general relativity is correct both in the weak and strong, dynamical regimes. Such an assumption constitutes a fundamental bias that could introduce a systematic error in the detection and parameter estimation of signals, and in turn lead to a mischaracterization of the universe through incorrect inferences about source event rates and populations. In this talk, I will define this bias, explain its possible consequences and propose a remedy through a new scheme: the parameterized post-Einsteinian framework. In this framework one enhances GR waveforms via the inclusion of post-Einsteinian parameters that both interpolate between general relativity and well-motivated alternative theories, but also extrapolate to unknown theories, following sound theoretical principles, such as consistency with conservation laws and symmetries. The parametrized post-Einsteinian framework should allow matched filtered data to select a specific set of post-Einsteinian parameters without a priori assuming the validity of the former, thus allowing the data to either verify general relativity or point to possible dynamical strong-field deviations.

**Bangalore Sathyaprakash**

*Testing Strong Field Gravity: Expectations from Ground- and Space-Based GW Detectors*

Interferometric detectors and pulsar timing arrays will observe systems under the influence of strong field gravity and offer a unique tool for testing General Relativity and its alternatives. However, owing to the complexity of the gravitational wave signal will pose challenges that will not be easy to tackle. At the same time, the complexity of the waveforms will also mean it will be an unprecedented opportunity to test strong field dynamics. What then can we expect from upcoming ground-based and planned underground and space-based detectors? This will be the topic of my review.

# TUESDAY, JANUARY 7

**Chris Van den Broeck**

*Testing the strong-field dynamics of general relativity with gravitational wave signals from coalescing compact binaries. I. Basic framework.*

Coalescences of binary neutron stars and/or black holes are amongst the most likely gravitational-wave signals to be observed in ground based interferometric detectors. Apart from the astrophysical importance of their detection, they will also provide us with our very first empirical access to the genuinely strong-field dynamics of General Relativity (GR). We present a new framework based on Bayesian model selection aimed at detecting deviations from GR, subject to the constraints of the Advanced Virgo and LIGO detectors. The method tests the consistency of coefficients appearing in the waveform with the predictions made by GR, without relying on any specific alternative theory of gravity. The framework is suitable for low signal-to-noise ratio events through the construction of multiple subtests, most of which involve only a limited number of coefficients. It also naturally allows for the combination of information from multiple sources to increase one's confidence in GR or a violation thereof. We expect it to be capable of finding a wide range of possible deviations from GR, including ones which in principle cannot be accommodated by the model waveforms, on condition that the induced change in phase at frequencies where the detectors are the most sensitive is comparable to the effect of a few percent change in one or more of the low-order post-Newtonian phase coefficients. In principle the framework can be used with any GR waveform approximant, with arbitrary parameterized deformations, to serve as model waveforms. In order to illustrate the workings of the method, we perform a range of numerical experiments in which simulated gravitational waves modeled in the restricted post-Newtonian, stationary phase approximation are added to Gaussian and stationary noise that follows the expected Advanced LIGO/Virgo noise curves.

**Tjonnie Li**

*Testing the strong-field dynamics of general relativity with gravitational wave signals from coalescing compact binaries. II. The TIGER data analysis pipeline.*

We present a data analysis pipeline called TIGER (Test Infrastructure for GEneral Relativity), which is designed to utilize detections of compact binary coalescences to test GR in the strong-field regime. TIGER is a model-independent test of GR itself, in that it is not necessary to compare with any specific alternative theory. It performs Bayesian inference on two hypotheses: the GR hypothesis $H_{\rm GR}$, and $H_{\rm modGR}$, which states that one or more of the post-Newtonian coefficients in the waveform are not as predicted by GR. By the use of multiple sub-hypotheses of $H_{\rm modGR}$, in each of which a different number of parameterized deformations of the GR phase are allowed, an arbitrarily large number of 'testing parameters' can be used without having to worry about a model being insufficiently parsimonious if the true number of extra parameters is in fact small. TIGER is well-suited to the regime where most sources have low signal-to-noise ratios, again through the use of these sub-hypotheses. Information from multiple sources can trivially be combined, leading to a stronger test. We focus on binary neutron star coalescences, for which sufficiently accurate waveform models are available that can be generated fast enough on a computer to be fit for use in Bayesian inference. We show that the pipeline is robust against a number of fundamental, astrophysical, and instrumental effects, such as differences between waveform approximants, a limited number of post-Newtonian phase contributions being known, the effects of neutron star spins and tidal deformability on the orbital motion, instrumental calibration errors, and non-stationarities in the data.

**Richard O'Shaughnessy**
*Disentangling astrophysics from gravity*

The gravitational wave signal from each merging compact binary encodes information about both the strong-field theory of gravity and the astrophysical properties of the source. Generic astrophysical sources have extra degrees of freedom (e.g., precession, tides, eccentricity), adding complexity and even degrees of freedom to outgoing radiation. In this talk, I first broadly review astrophysical formation scenarios, describing astrophysical systematics which could complicate high-precision tests of gravity. As a concrete illustration, I describe measurements and astrophysics of precessing binaries, at low and high mass.

**Tyson Littenberg**
*Evidence you can trust through detailed modeling of GW data*

Quantitatively testing General Relativity with Gravitational Waves amounts to comparing different models of the data and deciding which, if any, are preferred. The comparison is done using Bayesian inference algorithms which output the evidence for each model under consideration.

The evidence itself is a conditional probability that depends on all of our assumptions about the data, including our model for the signal as well as both the instrument noise and response to incoming gravitational waves.

When trying to make definitive statements about the validity of GR, potentially a small effect on the gravitational wave signal, we have to be sure that misguided assumptions do not masquerade as new physics. Modelling errors, regarding the signal or the noise, will introduce systematic biases into our analysis which could manifest itself in parameters used to measure departures from GR. If these systematic errors are comparable to, or larger than, the inherent statistical error in our measurement our test is suspect.

To combat this potential source of confusion, alongside continued developments in waveform modeling, work has begun in earnest to understand the impact of callibration errors and to improve our model for the LIGO/Virgo noise.

Together, these modifications allow us to boost the dependebility of our analysis methods for detecting, or ruling out, modified theories of gravity. In this talk I will highlight some of the key assumptions we feel are the least well founded, discuss what has been done already to mitigate their impacts, and discuss our strategy going forward to deal with this issue more completely.

# WEDNESDAY, JANUARY 8

**Antonio de Felice**
*Review of modified gravity models*

**Andrew Matas**
*Observational tests of Massive Gravity and Galileons*

Massive gravity is a model of gravity that is modified in the infrared by the presence of an explicit mass term for the graviton. In massive gravity there are 5 polarization states, appropriate for a massive spin 2 field. I will introduce these theories, and show that Vainshtein mechanism is a crucial aspect of the phenomenology. The Vainshtein mechanism requires us to work with a different toolbox than is used in General Relativity, because it is relies on non-linear effects not present in standard GR that are important even at the lowest orders in perturbation theory. I will then discuss existing and future observational constraints on these theories coming from solar system tests, cosmology, and binary pulsars.

**Michael Horbatsch**
*Scalar-Tensor Gravity*

I will present an overview of scalar-tensor gravity, focusing on the Brans-Dicke model and its natural generalizations that include quadratic scalar-matter coupling, multiple scalars, and massive scalars. I will discuss constraints from solar system experiments, constraints from binary pulsar timing, and prospective constraints from future gravitational wave detection. I will discuss the recent analytical and numerical work on the two-compact-body problem, and remaining open questions.

**Enrico 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 presence of aether modes propagating at velocities different from the speed of light.

**Flávio de Sousa Coelho**
*$n$-DBI Gravity*

$n$-DBI gravity is a modification of General Relativity which breaks Lorentz invariance by the explicit introduction of a unit time-like vector field $n$. This breaking of general diffeomorphism invariance down to the subgroup of foliation-preserving diffeomorphisms gives rise to an extra (scalar) degree of freedom. It was first motivated by the Dirac-Born-Infeld-type conformal scalar theory that it yields for a conformally flat (Friedmann-Robertson-Walker) universe, in which the presence of radiation automatically produces an epoch of accelerated expansion, thereby providing an alternative to inflaton-driven inflation. In this talk we shall go through the key results of this theory and discuss current (and future) challenges. Topics include: action and field equations, exact solutions and black holes, scalar mode dynamics, post-Newtonian expansion and cosmological perturbations.

# THURSDAY, JANUARY 9

**Vitor Cardoso**
*Precision gravitational-wave astrophysics*

Gravitational-wave (GW) astronomy will open a new window into the heart of compact objects such as neutron stars and black holes (BHs). It is often stated that large signal-to-noise detections of ringdown or inspiral waveforms can provide estimates of BH mass and spin to fractions of a percent level, as well as tests of General Relativity. These expectations usually neglect realistic astrophysical environments in which compact objects live. With the advent of GW astronomy, "dirtiness" effects for the GW signal will eventually have to be *quantified*. Here we present a wide survey of the corrections due to environmental effects in two situations of great interest for GW astronomy: the ringdown emission of massive BHs and the two-body inspiral in the extreme-mass ratio limit. We take into account various effects such as: electric charge, magnetic fields, cosmological evolution, deviations from General Relativity, and the effects related to various forms of matter such as disks and halos.

Our analysis predicts the existence of resonances dictated by the external mass distribution, which dominate the very late-time behavior of merger waveforms. The mode structure can drastically differ from the vacuum case, yet the BH response to external perturbations is unchanged at the relevant time scales. Although the vacuum Schwarzschild resonances are no longer quasinormal modes of the system, they still dominate the response at intermediate times. Our results strongly suggest that both parametrized and ringdown searches should include at least two-mode templates.

Finally, we derive simple estimates for various environmental effects in the inspiralling of extreme-mass-ratio black hole binaries. We show that accretion generically dominates over self-force effects for thin disks, whereas it can be safely neglected for thick-disk environments as those that are more relevant for eLISA. Dirtiness effects are (typically) negligible for detection, but they might be important for parameter estimation. Finally, we discuss how our ignorance of matter surrounding compact objects implies intrinsic limits on the ability of constraining strong-field deviations from Einstein's theory.

**Kostas Kokkotas**
*Rotating Relativistic Stars: Equilibrium Configurations and Instabilities*

We will present recent results on the construction of equilibrium configurations for fast rotating stars in scalar-tensor theory of gravity and the possibility of setting observational constraints. We will also present new results on the effect of rotation on the I-Q relations. Finally, we will discuss the rotational instabilities and their critical points of excitation based on general relativistic calculations.

**Hajime Sotani**
*Stellar oscillations in scalar-tensor theory*

Neutron stars are good candidates to probe the gravitational theory in the strong-field regime. In particular, the frequencies of stellar oscillations and/or emitted gravitational waves could bring us the imprints of gravitational theory. In this talk, we especially focus on the scalar-tensor theory of gravity and calculate the stellar oscillations, varying the stellar properties and coupling constant in the theory. Then, we discuss the possibility to distinguish the gravitational theory in the strong-field regime via the direct observations.

**Kent Yagi**

*Strong-field Tests of Gravity with Universal Relations in Neutron Stars and Quark Stars*

One of largest uncertainties in nuclear physics is the equation of state (EoS) in nuclear and supra-nuclear densities. Neutron-star (NS) and quark-star (QS) observables such as the mass and radius depend strongly on the EoS. We found universal relations among the moment-of-inertia, quadrupole moment and various tidal deformabilities of a slowly-rotating NS and QS that are almost EoS-independent. Such unexpected relations have several interesting applications and one of them is on the fundamental physic front, where any two independent measurements of the quantities allow for a model-independent and EoS-independent test of general relativity (GR). For example, if one could measure the NS moment-of-inertia to O(10)pulsar observations and a tidal deformability to O(60)future gravitational-wave observations, one could place a constraint on a parity-violating gravitational theory that is six orders of magnitude stronger than the current bound. I explain in detail how the universal relations can be used to test GR, and discuss possible extensions in this avenue.

**Ryan Lang**

*Compact binaries in scalar-tensor gravity: Equations of motion and tensor gravitational waves to high post-Newtonian order*

We present progress in calculating the gravitational wave emission from compact binary systems in a class of general massless scalar-tensor theories of gravity. The equations of motion are now known to 2.5 post-Newtonian (2.5PN) order, and the tensor gravitational waves are known to 2PN order. They are calculated by using a modified version of the DIRE (Direct Integration of the Relaxed Einstein equations) mechanism previously used for general relativistic binaries. The strong internal gravity of the bodies is taken into account by letting the mass of each body depend on the value of the scalar field. We find that the differences from general relativity can be characterized by a reasonably small number of parameters. For binary black holes, the equations of motion and gravitational waves are observationally identical to those in general relativity. For mixed neutron-star-black-hole systems, the deviations from general relativity depend on a single parameter which is a function of the scalar-tensor coupling constant and the sensitivity of the neutron stars mass to variations in the scalar field.

# FRIDAY, JANUARY 10

**Ulrich Sperhake**
*Black-hole binary inspiral and merger in scalar tensor theory of gravity*

This talk presents numerical simulations of an inspiraling black-hole binary in scalar tensor theory. The no-hair theorem is overcome in this setup through a scalar field gradient and choosing the orbital plane of the binary to be oriented along the gradient direction. The interaction of the black holes with the scalar field give rise to a radiative scalar dipole which oscillates at twice the orbital frequency.

**Pablo Laguna**
*Merger of Binary Black Holes in Scalar-Tensor Theories of Gravity*

I will present results from configurations of black hole binary mergers in scalar-tensor theories of gravity that show emission of gravitational waves which differs from the corresponding radiation in general relativity. Barring an external mechanism to induce dynamics in the scalar field, I will discuss how binary black holes in scalar-tensor gravity are observationally indistinguishable from their general relativistic counterparts.

**Helvi Witek**
*Black holes as observatories for beyond-standard model physics*

Black holes are key players in a wide range of fundamental physics including astrophysics as well as high energy physics. Crucial questions concern the stability properties of these fascinating objects with potentially important implications for the phase-space of solutions or the understanding of condensates in the vicinity of black holes. Of particular interest is the superradiant instability of Kerr BHs which arises naturally in aymptotically anti-de Sitter spacetimes or in the presence of massive fields surrounding the BH.

Here, I will focus on recent results of massive fields in BH backgrounds as well as first numerical simulations of the fully non-linear case. We have explored massive scalar fields surrounding Kerr BHs and we have found interesting signatures in the scalar and gravitational wave channel. The BH's response hints at superradiant effects at the non-linear level.

**Hirotada Okawa**
*Collapse of self-interacting fundamental fields in asymptotically flat spacetimes*

It was recently pointed out that anti-de Sitter(AdS) spacetime is unstable against gravitational collapse. The pertubation in AdS does not simply decay away and can be reflected by AdS boundary to nonlinearly interact with one another. Confinement would play an important role in the nonlinear, turbulent instability. On the other hand, massive fundamental fields can also provide low-frequency confinement. Thus, we revisit an old problem on collapse of massive fields and will show the collapse after successive reflections by the potential wall.