Scientific Program: Abstracts

21st Midwest Relativity Meeting
Departments of Physics and Astronomy
University of Illinois at Urbana-Champaign
November 4–5, 2011

Friday, November 4

Section I: Black Holes/Cosmology

8:50am **Membrane paradigm and η/s: Gauss-Bonnet gravity**
Arif Mohd (*University of Mississippi*), Ted Jacobson (*University of Maryland*), Sudipta Sarkar (*Institute of Mathematical Sciences, Chennai, India*)

We describe the construction of membrane paradigm in Einstein-Gauss-Bonnet gravity. For perturbations around the static black backgrounds, the membrane stress-energy tensor is shown to be that of a viscous fluid. We calculate the ratio of viscosity to entropy density of this membrane-fluid. The ratio can be interpreted as the one for the dual CFT in the long wavelength hydrodynamic limit.

9:02am **Stability of black holes and black branes**
Robert Wald, (*University of Chicago*), Stefan Hollands (*University of Cardiff*)

I describe very recent work with Stefan Hollands establishing that linearized stability of black holes and black branes with respect to axisymmetric perturbations is equivalent to the positivity of canonical energy (in a particular gauge) for all perturbations with vanishing linearized ADM mass and angular momentum. For black branes, we further show that linearized stability can hold only if "thermodynamic stability" holds, as conjectured by Gubser and Mitra. Furthermore, for a family of black holes or black branes, we show that linearized stability is equivalent to the satisfaction of a local Penrose inequality, as recently suggested by Figueras, Murata, and Reall.

9:14am **Wick rotation and thermal states in static spacetimes**
Ko Sanders (*University of Chicago*)

In a large class of static, globally hyperbolic spacetimes we show that the thermal equilibrium states of a massive, scalar quantum field can be obtained from a Wick rotation. For this we complexify the Killing time parameter and then compactify the imaginary axis. On the Riemannian manifold so obtained we choose a suitable Euclidean Green's function and indicate how it can be analytically continued back to the original spacetime, yielding the two-point distribution for the thermal equilibrium state. (If time permits we indicate the consequences of this analysis for Hartle-Hawking type states across a bifurcate Killing horizon.)

9:26am **Measure and probability in cosmology**
Joshua Schiffrin, Robert Wald (*University of Chicago*)

General relativity has a phase space formulation, which formally provides a canonical (Liouville) measure on the space of solutions. The restriction of this measure to the space of FLRW universes (minisuperspace), known as the Gibbons-Hawking-Stewart (GHS) measure, has been used by various authors to make arguments about the likelihood of inflation. We argue that truncating the degrees of freedom by restricting the measure to minisuperspace could potentially give very different answers to questions of probability, as compared with merely restricting the measure to the space of nearly-FLRW universes. We therefore calculate how the GHS measure is modified when the effects of inhomogeneities are taken into account. We further argue that one must justify interpreting the canonical measure as a probability distribution, and that the justifications used in usual statistical mechanics do not apply in cosmology.

9:38am **Newtonian and relativistic cosmologies**
Stephen Green, Robert Wald (*University of Chicago*)

Cosmological N-body simulations are now being performed using Newtonian gravity in boxes which are significantly larger than the Hubble radius. While it is well known that a uniformly expanding ball of dust in Newtonian gravity is described by the Friedmann equations, it is not obvious that Newtonian gravity can provide a good description of an inhomogeneous cosmology. Even in the marginally bound / spatially flat case, where a correspondence continues to hold in linearized perturbation theory, it is still not obvious that Newtonian gravity can provide a good global description when there is significant non-linearity at small scales. We have recently developed a perturbative framework (PRD83 084020, 2011) which allows for such non-linearity at small scales, but retains a linearized description at large scales, and is thus particularly well-suited to treating this issue. This framework includes an ordering scheme by which one can determine the degree to which a metric and matter distribution solve the Einstein equation. In this paper we provide a mapping which takes a Newtonian dust cosmological solution into a corresponding general relativistic spacetime with dust matter, and we provide criteria by which one can determine the extent to which a Newtonian simulation yields a good approximation to a solution to Einstein's equation.

9:50am **How extreme are extreme black holes?**
David Garfinkle (*Oakland University*)

The inner horizons of black holes are known to become singular. But in the limit of extremality, outer and inner horizons coincide. So is the outer horizon of an extreme black hole singular? This talk will show how this question can be answered for the case of a charged black hole produced by the collapse of a thin shell.

10:02am **Exploring the global structure of the Curzon-Chazy metric by analyzing the Weyl scalar**

Majd Abdelqader, Kayll Lake (*Queen's University*)

The global structure of many exact solutions, such as the Curzon-Chazy (CC hereafter) metric, and the singularities they contain are still inadequately explored because of the complexity of the resulting geodesics. The standard analysis of the geodesics in the CC metric indicates a sole ring-like singularity at the origin, which seems to be naked because the apparent lack of horizons. Alternatively, analyzing the CC metric using a new proposed method, which focuses on the Weyl invariant and its gradient field, reveals a richer structure that cannot be readily seen by only looking at geodesics. We confirm the established result that the source of the CC spacetime is a ring, but more importantly the new analysis method reveals the contribution of self interaction as infinitely thin disk in the plane of the ring, making the general relativistic ring qualitatively different from a Newtonian one.

10:14am **Intrinsic and extrinsic geometries of a tidally deformed black hole**

Eric Poisson, Ian Vega, Ryan Massey (*University of Guelph*)

A description of the event horizon of a perturbed Schwarzschild black hole is provided in terms of the intrinsic and extrinsic geometries of the null hypersurface. This description relies on a Gauss-Codazzi theory of null hypersurfaces embedded in spacetime, which extends the standard theory of spacelike and timelike hypersurfaces involving the first and second fundamental forms. We show that the intrinsic geometry of the event horizon is invariant under a reparameterization of the null generators, and that the extrinsic geometry depends on the parameterization. Stated differently, we show that while the extrinsic geometry depends on the choice of gauge, the intrinsic geometry is gauge invariant. We apply the formalism to solutions to the vacuum field equations that describe a tidally deformed black hole. In a first instance we consider a slowly-varying, quadrupolar tidal field imposed on the black hole, and in a second instance we examine the tide raised during a close parabolic encounter between the black hole and a small orbiting body.

10:26am **Emergence of a thin shell structure during gravitational collapse in isotropic coordinates**

Hugues Beauchesne, Ariel Edery (*Bishop's University*)

We observe the emergence of a thin shell structure during the gravitational collapse of matter in isotropic coordinates. The spacetime separates into three distinct regions: a static Schwarzschild region outside the shell, a collapsing Friedmann-Robertson-Walker universe inside the shell and the formation of a thin shell of matter in the vicinity of the event horizon. We show that the ADM mass originates from the shell region and that the stress-energy tensor tends to zero everywhere except near the event horizon. The extrinsic curvature has a jump discontinuity across the event horizon in accordance with the presence of a thin shell. The Kretschmann and Ricci scalars are plotted as probes of the collapsing interior of the black hole. We also show that the results remain qualitatively the same in the presence of charge.

10:38am **Black holes with only one Killing field in arbitrary odd dimension**
Sean Stotyn (*University of Waterloo*)

There is a well-known theorem in general relativity which states that any stationary solution to the Einstein equations must also be axisymmetric and, as a consequence, such solutions possess at least two Killing symmetries. In this talk I will discuss a new class of asymptotically AdS black holes with scalar hair that possess only one Killing vector, which is tangent to the generators of the horizon. These black hole solutions are neither static nor axisymmetric and are the end result of a super-radiant instability of the Myers-Perry-AdS class of black holes with a single rotation parameter, at least for low energies and angular momenta.

Section II: Numerical Relativity

11:15am **Parameter space dependence of junk radiation in binary black hole simulations**
Nick Tacik (*University of Toronto*), Harald Pfeiffer (*CITA*)

At early times in binary black hole simulations, spurious "junk" radiation is emitted. I will discuss work that quantifies how the amount of junk radiation scales with the spins of the black holes, and their initial separation, and how the amount of junk radiation compares for conformally flat initial data and superposed Kerr-Schild initial data.

11:27am **Compact binaries in gaseous environments**
Stu Shapiro, Zachariah Etienne, Brian Farris, Yuk Tung Liu, Vasileios Paschalidis (*University of Illinois*)

Numerical relativity is a vital tool for simulating the inspiral and merger of compact binaries. For compact binaries involving matter, the equations of relativistic MHD and radiative transport must be evolved together with Einstein's field equations. The simultaneous detection of electromagnetic and gravitational wave signals from such systems is a real possibility. Recent work at Illinois involving the mergers of binary black hole-neutron stars and binary black holes in circumbinary disks will be previewed in this talk with movie highlights.

11:39am **Improved EM gauge condition for GRMHD simulations with AMR**

Yuk Tung Liu, Zachariah Etienne, Vasileios Paschalidis, Stuart Shapiro (*University of Illinois*)

We recently developed a new GRMHD code with AMR that evolves the electromagnetic (EM) vector potential A_i instead of the magnetic fields directly. Evolving A_i enables one to use any interpolation scheme on refinement level boundaries and still guarantee that the magnetic field remains divergenceless. As in classical EM, a gauge choice must be made when evolving A_i, and we originally chose a straightforward "algebraic" gauge condition to simplify the A_i evolution equation. However, magnetized black hole-neutron star (BHNS) simulations in this gauge exhibit unphysical behavior, including the spurious appearance of strong magnetic fields on refinement level boundaries. This spurious behavior is exacerbated when matter crosses refinement boundaries during tidal disruption of the NS. We demonstrate via an eigenvalue analysis and a numerical study that zero-speed modes in the algebraic gauge, coupled with the frequency filtering that occurs on refinement level boundaries, are responsible for the creation of spurious magnetic fields. We show that the EM Lorenz gauge exhibits no zero-speed modes, and as a consequence, spurious magnetic effects are quickly propagated away, allowing for long-term, stable magnetized BHNS evolutions.

11:51am **Simulations of magnetized BHNS in full GR**

Zachariah Etienne, Yuk Tung Liu, Vasileios Paschalidis, Stuart Shapiro (*University of Illinois*)

As a neutron star (NS) is ripped apart by black hole (BH) tidal fields at the end of a BH–NS binary inspiral, its magnetic field will be stretched and amplified. If sufficiently strong, these magnetic fields may impact the gravitational waveforms, merger evolution and mass of the remnant disk. Formation of highly-collimated magnetic field lines in the remnant disk+spinning BH system may launch relativistic jets, providing the engine for a short-hard GRB. We analyze this scenario through fully general relativistic, magnetohydrodynamic (GRMHD) BH–NS simulations from inspiral through merger and disk formation. Different seed magnetic field configurations and strengths are chosen, starting with both nonspinning and moderately-spinning (a_{BH}/M=0.75) BHs aligned with the orbital angular momentum. Only extremely strong ($\sim 10^{17}$G) initial magnetic fields in the NS significantly influence merger dynamics, enhancing the remnant disk mass by 100% and 40% in the nonspinning and spinning BH cases, respectively. However, we find that detecting the effects even of strong magnetic fields may be challenging for Advanced LIGO. While there is no evidence of outflows during the preliminary simulations we have explored, longer disk evolutions, improved resolution and different field topologies will be required to more thoroughly assess the plausibility of BHNS binaries as short-hard GRB progenitors.

12:03pm Black hole-neutron star mergers for $10M_\odot$ black holes

Francois Foucart (*CITA*), M.D. Duez (*Washington State University*), L.E. Kidder (*Cornell University*), M.A. Scheel, B. Szilagyi (*Caltech*), S.A. Teukolsky (*Cornell University*)

General relativistic simulations of black hole-neutron star mergers have currently been limited to low-mass black holes ($M_{\rm BH} \leq 7M_\odot$), even though population synthesis models indicate that a majority of mergers might involve more massive black holes ($M_{\rm BH} \geq 10M_\odot$). We present general relativistic simulations of black hole-neutron star mergers with $M_{\rm BH} \sim 10M_\odot$. For high mass black holes, tidal effects are significantly less likely to cause the neutron star to be disrupted before reaching the location of the innermost stable circular orbit. The formation of heavy accretion disks, a fairly common outcome for BHNS mergers with lower mass black holes, is only possible if the spin of the black hole is large ($a_{\rm BH}/M_{\rm BH} \geq 0.7 - 0.9$). We discuss variations in the qualitative features of the mergers as we modify the spin of the black hole, and derive constraints on the ability of BHNS mergers to power short-gamma ray bursts.

12:15pm The merger of binary white dwarf-neutron stars: simulations in full GR

Vasileios Paschalidis, Yuk Tung Liu, Zachariah Etienne, Stuart Shapiro (*University of Illinois*)

Using the pseudo-white dwarf (pWD) approximation we perform fully general relativistic hydrodynamic simulations of binary white dwarf-neutron star (WDNS) late inspiral and merger. The initial binary is in a circular orbit at the Roche critical separation. The goal is to determine the ultimate fate of such systems. We focus on binaries whose total mass exceeds the maximum mass ($M_{\rm max}$) a cold, degenerate equation of state can support against gravitational collapse. Our simulations of a pWDNS system with a 0.98-solar-mass WD and a 1.4-solar-mass NS show that the merger remnant is a spinning Thorne-Zytkow-like Object (TZlO) surrounded by a massive disk. The final total rest mass exceeds $M_{\rm max}$, but the remnant does not collapse promptly. To assess whether the object will ultimately collapse after cooling, we introduce radiative thermal cooling. When we cool the spinning TZlO, the remnant does not collapse, demonstrating that differential rotational support is sufficient to prevent collapse. Given that the final total mass exceeds $M_{\rm max}$, magnetic fields and/or viscosity may redistribute angular momentum and ultimately lead to delayed collapse to a BH. We infer that the merger of realistic massive WDNS binaries likely will lead to the formation of spinning TZlOs that undergo delayed collapse.

12:27pm IMEX evolutions of black hole spacetimes
Harald Pfeiffer (*CITA*), Stephen Lau (*UNM Albuquerque*), Geoffrey Lovelace (*Cornell*)

Numerical simulations of binary black holes are computationally expensive, especially for binaries with high mass ratios or with rapidly spinning constituent holes. One reason for the high expense is the Courant limit imposed by explicit time-steppers. This talk introduces implicit-explicit (IMEX) time-stepping methods. As a first step toward IMEX evolution of a full binary-black-hole spacetime, we develop an IMEX algorithm of the generalized harmonic formulation of the Einstein equations and use this algorithm to evolve stationary and perturbed single-black-hole spacetimes. Numerical experiments explore the stability and computational efficiency of our method.

12:39pm Black hole kicks, antikicks, and plunges
Richard Price (*Univ. Texas at Brownsville*), Gaurav Khanna (*UMass Dartmouth*), Scott A. Hughes (*MIT*)

Black hole inspiral consists of the well-understood epochs of quasicircular orbits and quasinormal ringing, and the ill-understood plunge that connects them. A study of the gravitational wave patterns of this transition has given a much improved understanding of kicks and antikicks, and suggests the direction for a more general understanding of the dynamics of this epoch.

12:51pm Highly precessing binary black holes using the dual frame system
Serguei Ossokine, Harald Pfeiffer (*CITA*), Lawrence Kidder (*Caltech*)

In this talk I will describe a new approach to implement part of the dual-frame coordinate system by Scheel et al that employs quaternions. This new technique allows one to explore highly precessing binary black hole systems using the Spectral Einstein Code developed by Caltech, Cornell and CITA.

Section III: Gravitational Waves

2:23pm Beyond LISA: Science reach of the new ESA gravitational wave detector
Ryan Lang (*Washington University in St. Louis*), Neil Cornish (*Montana State University*), Emanuele Berti (*University of Mississippi*)

A joint project of NASA and the European Space Agency (ESA), the Laser Interferometer Space Antenna (LISA) was designed to measure gravitational waves (GWs) in space, away from the seismic noise of the Earth. Unfortunately, due to budgetary concerns, LISA has been scrapped, with NASA and ESA each pursuing their own individual space-based GW missions at lower cost. The cost savings are achieved by shortening the detector arm length or removing an arm altogether. We calculate the effect these changes have on the ESA mission's science return, specifically the ability to extract parameters of a massive black hole binary from its GW signal. We find that the loss of parameter estimation is mitigated if we include the previously neglected merger and ringdown phases in the waveform model.

2:35pm **Gravitational wave standard sirens**
Daniel Holz (*University of Chicago*)

Gravitational-wave standard sirens are one of the most exciting potential sources for the upcoming era of multi-messenger astronomy. We will discuss what they are, and what we may learn from them.

2:47pm **Luck favors the prepared mind: Gravitational wave astronomy**
Sam Finn (*Penn State*)

Few, if any, new observational modalities have been as eagerly anticipated as gravitational waves.In addition to observing phenomena, like black hole binary systems, that are invisible to electromagnetic telescopes or particle detectors, gravitational wave observations will pierce the veil of gas and dust that shrouds regions of strong gravity: e.g., the core of a collapsing star, or the center of our own galaxy.
Detection of gravitational waves, while necessary before gravitational waves can take their place as a tool of observational discovery, is not sufficient. Astronomy is an integrated science. The most accomplished carpenters are known not for the tools in their toolchest, but for their ability to use those tools together to create something new. So it is with astronomy: the value of gravitational wave observations will be realized only when what those observations reveal can be understood and used by the master craftsman to create a richer understanding of astronomical phenomena.
In this presentation we will review briefly examples of recent work at Penn State focusing on developing the tools and insights that will allow us to take the greatest and most rapid advantage of all that gravitational wave observations have to offer.

2:59pm **Radiation-gauge approach to self-force for circular orbits in Kerr**
John Friedman (*University of Wisconsin-Milwaukee*), Abhay Shah (*Weizmann Institute*) and Tobias Keidl (*University of Wisconsin-Washington County*)

The extreme-mass-ratio approximation is commonly used to find the radiation emitted by stellar-mass black holes orbiting galactic black holes. Accurate wave form computations require one to find a renormalized perturbed metric associated with a particle moving in a Kerr background and with the renormalized self-force. This talk reports the first computation of the change in the angular velocity of particle in circular orbit (involving the renormalized metric perturbation) and the current state of the self-force computation.

3:11pm **Development of a search for gravitational waves from spinning compact-object binaries with ground-based interferometers**

Diego Fazi (*Northwestern University and CIERA*)

The search for gravitational waves emitted by spinning compact-object binaries with ground based detectors poses a great data analysis challenge due to the high number of parameters necessary to describe these signals, which need to be searched over. Computational constraints currently limit the size of waveform template banks that can be used to filter year-long stretches of data; the large dimensionality of the parameter space associated with generic double-spin signals makes them unusable for an actual search, however single-spin templates can be deployed with reasonably small banks. We present a data analysis strategy which deploys physical templates to search for gravitational waves emitted by precessing binaries with only one significantly spinning component, we show its efficiency and we assess the feasibility of a search on LIGO/Virgo data.

3:23pm **Evidence for spin in compact binary coalescence: When can we trust it?**

Vivien Raymond, Ben Farr, Will Farr, Diego Fazi (*CIERA, Northwestern University*), John Veitch (*Cardiff University*), Ilya Mandel, Ben Aylott (*University of Birmingham*), Christian Rver (*Albert-Einstein-Institut, Max-Planck-Institut für Gravitationsphysik; Leibniz Universität Hannover*), Vicky Kalogera (*CIERA, Northwestern University*)

LIGO/Virgo will soon enter their advanced phases and, among the anticipated detections, compact binary coalescences are of special interest because these events are the most promising for extracting to extract astrophysical parameters of sources systems. In order to do so, spin effects in the parameter estimation analysis have to be included. Given the complexity inherent to the high dimensions and strong correlations of the spinning parameter space, one can ask what limits our ability to distinguish non-spinning versus spinning signals. One way to answer this question is to explore when a non-spinning signal becomes indistinguishable from a spinning signal. We use our Bayesian inference code to compute evidences for non-spinning and spinning models on various injections, and try to assess the location in parameter space where non-spinning signals can hide.

3:35pm **Detecting off-Kerr perturbations with intermediate mass ratio inspirals in the advanced LIGO era**

Carl Rodriguez (*Northwestern University*), Ilya Mandel (*University of Birmingham*), Jonathan R. Gair (*Cambridge University*)

The detection of gravitational waves from the inspiral of a neutron star or stellar-mass black hole into an intermediate-mass black hole (IMBH) promises an entirely new look at strong field gravitational physics. Gravitational waves from these intermediate mass ratio inspirals (IMRIs), systems with mass ratios from 10:1 to 100:1, may be detectable at rates of up to a few tens per year and will encode a signature of the central bodys spacetime. Direct observation of the spacetime will allow us to use the no-hair theorem of general relativity to determine if the IMBH is a Kerr black hole (or some more exotic object, e.g. boson star). Using modified post-Newtonian (pN) waveforms, we explore the prospects for constraining the central bodys mass quadrupole moment in Advanced LIGO. We use the Fisher information matrix to estimate the accuracy with which the parameters of the central body can be measured. We find that for some mass and spin combinations, the quadrupole moment can be measured to within a fraction of its Kerr value. Although an effective first pass, the Fisher matrix formalism becomes increasingly untrustworthy due to high parameter correlations in our IMRI mass regime. Additionally, we find that the results are heavily dependent on pN order, suggesting that more accurate waveforms will be needed to perform precision parameter estimation.

3:47pm **Stellar-mass black holes in star clusters: Implications for gravitational wave astronomy**

Meagan Morscher (*Northwestern University/CIERA*), Frederic A. Rasio (*Northwestern University/CIERA*)

Globular clusters with core-collapse times longer that the lifetime of the most massive stars are thought to produce many stellar-mass black holes (BH) and retain most of them initially. The dynamical evolution of stellar BHs in clusters is important for studies of merging BH-BH binaries, which will be detectable by future gravitational wave observatories. Since BHs are among the most massive objects in a cluster, they tend to sink to the center through two-body relaxation, forming a dense core in which BH-BH binaries can be formed, destroyed, and ejected. The fate of BHs in clusters, however, is still highly uncertain. Only recently have dynamics codes become powerful enough to simulate clusters with realistic N, full stellar mass spectra, and significant numbers of primordial binaries. Using a Monte Carlo method, we model realistic star clusters with stellar-mass BHs. We discuss the evolution of BH populations in clusters, as well as the implications for gravitational wave astronomy.

3:59pm **Re-purposed MCMC for low latency sky localization of gravitational wave sources**

Ben Farr, Vivien Raymond, Will Farr, Diego Fazi (*Northwestern University*), John Veitch (*Cardiff University*), Ilya Mandel, Ben Aylott (*University of Birmingham*), Christian Roever (*Max-Planck-Institut fur Gravitationsphysik*), Vicky Kalogera (*Northwestern University*)

The electromagnetic followup of a gravitational wave event would not only increase confidence in the first detection, but also allow us to extract substantially more astrophysical information from the source. For successful followup, sky position is needed as quickly and accurately as possible. This is typically done using triangulation methods, capable of producing results with very low-latency through a frequentist approach. We have re-purposed our Markov-Chain Monte Carlo parameter estimation code, designed to produce the full 15 parameter PDF for gravitational waves emitted by coalescing compact binary objects with spin, for the purpose of low latency sky localization. The limiting factor in the runtime of a full MCMC analysis is waveform generation, which can be mitigated by making fewer jumps in intrinsic parameters (e.g. masses, spins). By limiting the majority of jumps to extrinsic parameters only, waveforms can be recycled and reprojected for new extrinsic parameter values, drastically reducing the cost of waveform generation.

Section IV: Field Theory/Compact Objects

4:36pm **Minimal length scale and its effect on Unruh radiation**

Patrick Myers, Demian Cho (*Kenyon College*)

The effect on the tunneling rate of a quantum particle moving across the Rindler horizon was calculated in the presence of a minimal length scale. This is a toy model for Hawking Radiation, where the Rindler space (the space of properly accelerating observers) horizon represents a black hole horizon, and tunneling particles represent the radiation. This form of calculating radiation in Rindler space recovers the same result for the temperature of thermal particles emitted from a black hole that was calculated by Hawking in 1974. Using a generalized form of the Heisenberg Uncertainty Principle to implement a minimal length scale, the change in this tunneling rate in Rindler space was calculated as a change to the imaginary action of a particle traveling through Rindler space. The final calculation yielded a change in the imaginary action relating to the square of the Planck length, the energy of the tunneling particle, and the acceleration of that particle. While the correction is small (the Planck length is on the order of 10-35m), it posits a correction nonetheless. Moreover, due to red shifting of waves near the horizon of a black hole it could produce more significant results for observers far from the horizon itself. Future work will include generalizing this to the full Schwarzschild metric, instead of a toy model, to provide a more formal setting for the tunneling.

4:48pm **Gravitationally stimulated creation of quanta**
Leonard Parker (*University of Wisconsin-Milwaukee*)

It is well known that the expansion of the universe creates quanta. However, it is not so well known that the expansion will also stimulate the creation of quanta if there already are quanta present when the expansion begins. I review the origin of this effect and the recent work done in collaboration with Ivan Agullo, in which we showed that this effect for inflation can lead to potentially observable non-gaussianities in the primordial spectrum of perturbations resulting from inflation. One can then hope to learn about the initial conditions at the beginning of inflation by observing the power spectra of perturbations of the Cosmic Microwave Background and of the Large Scale Structure.

5:00pm **Chameleon gravity and kinematics in the outer galaxy**
Razieh Pourhasan (*University of Waterloo*), Niayesh Afshordi (*Perimeter Institute for Theoretical Physics and University of Waterloo*), Robert B. Mann (*University of Waterloo*), Anne C. Davis (*Centre for Mathematical Sciences, Cambridge, UK*)

Light scalar fields are expected to arise in theories of high energy physics (such as string theory), and find phenomenological motivations in dark energy, dark matter, or neutrino physics. However, the coupling of light scalar fields to ordinary (or dark) matter is strongly constrained from laboratory, solar system, and astrophysical tests of fifth force. One way to evade these constraints in dense environments is through the chameleon mechanism, where the field's mass steeply increases with ambient density. Consequently, the chameleonic force is only sourced by a thin shell near the surface of dense objects, which significantly reduces its magnitude.
In this paper, we argue that thin-shell conditions are equivalent to "conducting" boundary conditions in electrostatics. As an application, we use the analogue of the method of images to calculate the back-reaction (or self-force) of an object around a spherical gravitational source. Using this method, we can explicitly compute the violation of equivalence principle in the outskirts of galactic haloes (assuming an NFW dark matter profile): Intermediate mass satellites can be slower than their larger/smaller counterparts by as much as 10% close to a thin shell.

5:12pm **The factor ordering problem in two-dimensional cosmologies**
Chris Creighton (*Wayne State University*), Rachel Maitra (*Albion College*)

General relativity can accurately describe then universe and the effects of gravity on the macroscale. However, there are points of singularity, such as the Big Bang, that operate at minute scales smaller than the Plank length. Events such as these need to be fused with quantum mechanics in order to explain the natures of the Big Band and black holes. When doing so in the 1+1 dimension FriedmannRobertsonWalker cosmology, we must quantize the Hamiltonian to obtain the Wheeler-DeWitt equation which gives rise to ambiguities in interpolating functions in the noncommutative factors that reduce to the same, classical model. Therefore, we set out to obtain the exact solution to the Wheeler-DeWitt equation and perform a unique analysis on this solution with varied factor orderings.

5:24pm **Alice falls into a black hole: Quantum correlations across the horizon.**
Eric Brown (*University of Waterloo*), Robert Mann (*University of Waterloo and Perimeter Institute of Theoretical Physics*)

In recent years there has been considerable interest in exploring concepts from quantum information theory in a relativistic setting, both special and general. This interest primarily started with the observation that the Unrue effect causes a degredation of quantum entanglement between two parties when one member is undergoing accelerated motion. This of course leads to similar effects near the horizon of a black hole. Fairly new onto the scene is the computation of quantum discord between such noninertial observers. Quantum discord is a measure of purely quantum correlations, and is not generally equal to entanglement entropy in the case of mixed states. After reviewing some of the aforementioned results I will present some new work on computing the quantum discord between parties near a black hole and show the presence of quantum correlations across the horizon.

5:36pm **Deformations of Lifshitz holography in higher dimensions**
Miok Park, Robert Mann (*University of Waterloo*)

$(n+1)$-dimensional Lifshitz spacetime is deformed by logarithmic expansions in the way to admit a marginally relevant mode in which z is restricted by $z = n - 1$. According to the holographic principle, the deformed spacetime is assumed to be dual to the quantum critical theories, and then thermodynamics of generic black holes in the bulk describe the field theory with a dynamically generated momentum scale Λ. This is a basically UV-expanded theory considered in higher dimensions of the Lifshitz holography from the previous studies done by others. By finding the proper counterterms, the renormalized action is obtained and by performing the numerical works, the free energy and energy density is expressed in terms of T/Λ^2.

5:48pm **Local space-time curvature effects on quantum orbital angular momentum**
Dinesh Singh, Nader Mobed (*University of Regina*)

This paper claims that local space-time curvature can non-trivially contribute to the properties of orbital angular momentum in quantum mechanics. Of key importance is the demonstration that an extended orbital angular momentum operator due to gravitation can identify the existence of orbital states with half-integer projection quantum numbers "m" along the axis of quantization, while still preserving integer-valued orbital quantum numbers "l" for a simply connected topology. The consequences of this possibility are explored in depth, noting that the half-integer "m" states vanish as required when the locally curved space-time reduces to flat space-time, fully recovering all established properties of orbital angular momentum in this limit. In particular, it is shown that a minimum orbital number of "$l = 2$" is necessary for the gravitational interaction to appear within this context, in perfect correspondence with the spin-2 nature of linearized general relativity.

6:00pm **Probing ultra-dense matter in neutron stars**

Simin Mahmoodifar, Mark Alford, Kai Schwenzer (*Washington University in St. Louis*)

Neutron stars are the only laboratory for studying cold ultra-dense matter. Since the density at the core of a neutron star is extremely high one could expect the existence of exotic matter such as degenerate quarks, boson condensate, ... etc. In this talk I will briefly review possible phases of ultra-dense matter and will explain how neutron stars' properties can be used as a probe of these phases. I will also present our results for the high amplitude bulk viscosity of dense matter and spin-down evolution of neutron stars.

6:12pm **Dark Matter distribution in the Schwarzschild geometry**

Laleh Sadeghian, Francesc Ferrer, Clifford M. Will (*Washington University in St. Louis*)

The cold dark matter at the galactic centre is redistributed by the presence of the central massive black hole. Using Newtonian calculations with relativistic factors inserted to mimic the effects of a black hole, Gondolo and Silk [1] showed that for cuspy halos responding to the adiabatic grown of a massive black hole, cold dark matter is accreted into a dense spike near the hole. We have calculated the same effect in a fully general relativistic formalism which leads to more realistic and reliable results near the massive black hole. The similarities and differences with the Gondolo-Silk results will be presented. We also discuss progress on generalizing these results to the rotating black hole case.

[1] P. Gondolo, J. Silk, Phys. Rev. Lett. 83, 1719-1722 (1999)

6:24pm **Faster or slower than Light? Constraining Lorentz violation with gravitational waves**

Saeed Mirshekari (*Washington University, St. Louis*), Nicolas Yunes (*Montana State University*), Clifford M. Will (*Washington University in St. Louis*)

Modified gravity theories generically predict a violation of Lorentz invariance, which leads to a modified dispersion relation for propagating modes of a massive graviton. We construct a generic dispersion relation that can reproduce a range of known Lorentz-violating predictions and investigate their impact on the propagation of gravitational waves. A modified dispersion relation forces different wavelengths of the gravitational wave train to travel at slightly different velocities, leading to a modified phase evolution observed at a gravitational-wave detector. We show how such corrections map to the waveform observable and the parameterized post-Einsteinian framework, proposed to model generic, model-independent deviations from General Relativity. Given a gravitational-wave detection, the lack of evidence for such corrections could then be used to place a constraint on Lorentz violation. The constraints we obtain are tightest for dispersion relations that scale with small power of the graviton's momentum and deteriorates for a steeper scaling.

Saturday, November 5

Section V: Numerical Relativity/Computational Astrophysics

8:40am **Stellar tidal encounters with a massive black hole**
Roseanne M. Cheng, Charles R. Evans (*University of North Carolina at Chapel Hill*)

We present a new numerical code constructed to obtain accurate simulations of encounters between a star and a massive black hole. The tidal interaction is modeled in a Fermi normal coordinate system that follows the average geodetic motion of the star and associated debris. The importance of higher-order terms in R_*/R_p in the relativistic treatment of the tidal field are discussed. The numerical method is applied to the regime of weak tidal interactions and initial results with second- and third-order tidal terms are presented. We assume Newtonian hydrodynamics and self-gravity for the star. The three-dimensional parallel code includes a PPMLR hydrodynamics module to treat the gas dynamics and a Fourier transform-based method to calculate the self-gravity. Results are given for polytropic stars with comparisons between simulations and predictions from the linear theory of tidal encounters. The computational limits of the method are discussed.

8:52am **Hang up gravitational recoils**
Carlos Lousto, Yosef Zlochower (*Rochester Institute of Technology*)

We revisit the scenario of the gravitational radiation recoil acquired by the final remnant of a black-hole-binary merger by studying a set of configurations that have components of the spin both aligned with the orbital angular momentum and in the orbital plane. We perform a series of 24 new full numerical simulations for equal-mass and equal-spin-magnitude binaries, but with different spin orientations.

9:04am **Solving black hole binary trumpet initial data with spectral methods**
Ian Ruchlin, Yosef Zlochower, Carlos Lousto (*Rochester Institute of Technology*)

A popular method for solving black hole initial data utilizes the puncture method. This allows us to solve the Hamiltonian constraint in the ADM Conformal Transverse Traceless formulation by writing the conformal factor as the sum of an analytical background term plus a correction. The background term aims to absorb singular quantities on the space-time, so that the correction term has a regular numerical solution. Black hole evolutions tend to approach a "trumpet" topology, which suggests that we use trumpet coordinates from the beginning. For any number of punctures, we can satisfy the momentum constraint with a linear superposition of the Schwarzschild extrinsic curvature and the Bowen-York momentum and spin solutions. These initial data can be solved using a single-domain spectral method. We consider second order analytical terms for the single black hole problem, as well as a black hole binary.

9:16am **Bridging the gap: Circumbinary MHD accretion in the post-Newtonian regime**

Scott Noble, Manuela Campanelli (*Rochester Institute of Technology*), Julian Krolik (*Johns Hopkins University*), Bruno Mundim, Hiroyuki Nakano (*Rochester Institute of Technology*), Nico Yunes (*Montana State University*), Yosef Zlochower (*Rochester Institute of Technology*)

Near synchronous detections of electromagnetic and gravitational wave events from supermassive black hole (BH) mergers would yield a new redshift-distance measurement, improved source localization and tighter constraints on source parameters (e.g., BH masses, BH spins, disk characteristics). Because of this potential and because it has only recently become possible to simulate a BH binary (BHB) merger, a surge of effort has begun to advance our theoretical understanding of these events. The oldest work on BHBs in gaseous environments has assumed that BHs to be at large separations, in the Newtonian regime of gravity, while also assuming that angular momentum transport occurs via a local kinematic viscosity. Recent work has included the merger proper and entailed evolving general relativistic (GR) hydrodynamics in a dynamic spacetime. Our work connects the two lines of research in order to provide more realistic initial conditions for the merger proper calculations, which have typically started from very small separations and ad hoc matter distributions. We further perform the calculation with magnetohydrodynamics (MHD) since the angular momentum is expected to be transported through the disk via the magnetorotational instability. In order to start from larger separations and evolve for many more binary orbits than previously performed in merger proper calculations, we use a post-Newtonian approximate for the spacetime dynamics. Our simulation demonstrates that MHD stresses are able to keep up with the shrinking binary and that real disks may not be left behind. We further demonstrate enhanced accretion rates through the gap over those from viscous hydrodynamic simulations.

9:28am **Binary black hole mergers in gaseous disks: Simulations in general relativity**

Brian Farris, Yuk Tung Liu, Stuart Shapiro (*University of Illinois*)

Binary black hole mergers in the presence of gaseous accretion flows are prime candidates for simultaneous observations of both gravitational waves and electromagnetic signals. We study such systems using our fully general relativistic hydrodynamics code, focusing on potentially observable electromagnetic signatures. We outline recent developments in our study, which explores the final stages of binary black hole mergers inside an adiabatic (except for shocks), disk-like accretion flow. We discuss the dynamical response of the disk to the inspiral and merger of the black holes, treating the optically thin electromagnetic radiation as a perturbation. We identify characteristic, observable changes in the electromagnetic luminosity during the merger.

9:40am **Tidal excitation of normal modes in eccentric binary neutron stars**
Roman Gold, (*FSU Jena and Princeton and University of Illinois*), Sebastiano Bernuzzi, Marcus Thierfelder, Bernd Bruegmann (*FSU Jena*), Frans Pretorius (*Princeton*)

Neutron star binaries offer a rich phenomenology in terms of gravitational waves and merger remnants. However, most general relativistic studies have been performed for nearly circular binaries, with the exception of head-on collisions. We present the first numerical relativity investigation of mergers of eccentric equal-mass neutron-star binaries that probes the regime between head-on and circular. In addition to gravitational waves generated by the orbital motion, we find that the signal also contains a strong component due to stellar oscillations (f-modes) induced by tidal forces, extending a classical result for Newtonian binaries. The merger can lead to rather massive disks on the order of 10% of the total initial mass.

9:52am **Electromagnetic radiation from compact binary mergers**
Carlos Palenzuela, Luis Lehner, (*Perimeter Institute & University of Guelph*), Steve Liebling (*LIU*), Chris Thompson (*CITA*), Dave Neilsen (*BYU*)

Mergers of compact binaries represent one of the most promising sources of gravitational waves, while that the presence of strong magnetic fields may offer the possibility of a characteristic electromagnetic signature that will allow for concurrent detection. In this talk I will present possible electromagnetic counterparts from binary black hole and neutron star mergers.

10:04am **Including realistic tidal deformations in binary-black-hole initial data**
Tony Chu (*CITA*)

A shortcoming of current binary-black-hole initial data is their contamination by spurious gravitational radiation that is not astrophysically relevant. This is a consequence of an oversimplified modeling of the binary's physics, which leads to an initially incorrect geometry that must relax during an evolution. This spurious radiation that is generated in the process limits the accuracy of the actual gravitational waveforms of interest. Several efforts to address this issue have made use of post-Newtonian results to include more realistic outgoing gravitational radiation content in the initial data, although they do not fully satisfy the Einstein constraint equations. In this talk I present a complimentary approach to include more realistic tidal deformations of the black holes in the initial data, but which does satisfy the constraints.

10:16am Spin-spin effects in models of binary black hole systems

Scott Hawley (*Belmont University*), Richard Matzner, (*University of Texas at Austin)*, Lindsey S. Thompson (*Belmont University*)

We have implemented a parallel multigrid solver, to solve the initial data problem for 3 + 1 General Relativity. This involves solution of elliptic equations derived from the Hamiltonian and the momentum constraints. We use the conformal transverse-traceless method of York and collaborators which consists of a conformal decomposition with a scalar that adjusts the metric, and a vector potential that adjusts the longitudinal components of the extrinsic curvature. The constraint equations are then solved for these quantities such that the complete solution fully satisfies the constraints. We apply this technique to compare with theoretical expectations for the spin-orientation- and separation-dependence in the case of spinning interacting (but not orbiting) black holes. We write out a formula for the effect of the spin-spin interaction which includes a result of Wald as well as additional effect due to the rotation of the mass quadrupole moment of a spinning black hole.

10:28am Slowly balding black holes

Maxim Lyutikov (*Purdue*), Jonathan McKinney (*UDM*)

The "no-hair" theorem is not applicable for black holes formed from collapse of a rotating neutron star or during a NS-NS merger. Rotating neutron stars can self-produce particles via vacuum breakdown forming a highly conducting plasma magnetosphere with magnetic field lines effectively "frozen-in" the star both before and during collapse. This introduces a topological constraint which prohibits the magnetic field from sliding off the newly-formed event horizon.

Section VI: Gravitational Waves/Neutron stars

11:05am Spin effects in the nonlinear gravitational-wave memory from inspiralling binaries

Marc Favata (*UWM/Caltech*), Xinyi Guo (*Pomona*)

The gravitational-wave memory effect is a time-varying but non-oscillatory contribution to the gravitational-wave amplitude. When a gravitational-wave with memory passes through an ideal detector, it will cause a permanent displacement of the test masses. The nonlinear form of the memory arises from the gravitational waves produced by previously emitted gravitational waves, and is present in virtually all gravitational-wave sources. It is also known to affect the gravitational-waveform at leading order despite the fact that it originates from higher-order interactions. Understanding the memory is important for building accurate knowledge of the gravitational-waveforms in order to probe the non-linearity of general relativity. Previous calculations of the memory have only considered non-spinning binaries. However, most compact binaries have spinning components; these spins will significantly modulate the gravitational-wave amplitude and phase. We studied the effect on the memory from the spin-orbit interaction and calculated the corrections to the memory waveform through 1.5 post-Newtonian (PN) order. We found that the spin correction starts to enter at 1PN order and can contribute a $\sim 20\%$ correction to the memory.

11:17am **Spectral representations of neutron star equations of state**
Lee Lindblom (*Caltech*)

I will discuss how neutron star equations of state can be accurately approximated using spectral expansions, and how these spectral approximations can be used as tools for determining the real physical neutron star equation of state.

11:29am **Detectability of equation of state parameters from black hole-neutron star inspiral**
Ben Lackey (*Univ. of Wisconsin-Milwaukee*), Koutarou Kyutoku, Masaru Shibata (*Kyoto University*), Patrick Brady, John Friedman, (*Univ. of Wisconsin-Milwaukee*)

Gravitational waves from black hole-neutron star binaries may provide an important source of information regarding the neutron star equation of state. In contrast to binary neutron star inspirals where finite size effects are observed from tidal interactions and post-merger oscillations, the main finite size effect in black hole-neutron star systems is tidal disruption of the neutron star and its effect on the black hole ringdown. We have performed approximately 100 black hole-neutron star simulations where two equation of state parameters, as well as the neutron star mass, mass ratio, and black hole spin, were systematically varied. Using these simulations, we discuss the accuracy to which equation of state parameters can be measured with Advanced LIGO and the proposed Einstein Telescope.

11:41am **Unique aspects of gravitational wave detection using radio pulsar timing techniques**
Fredrick Jenet (*University of Texas at Brownsville*)

Radio pulsar timing can be used to detect and study low frequency gravitational waves. The large separation between the Earth and the pulsar gives this type of detector certain features that are distinct from those of the more well known ground based and proposed space based detectors. This talk will review how to detect gravitational waves using pulsar timing techniques and discuss these unique features.

11:53pm **Detection methods for continuous gravitational waves using pulsar timing data**
Justin Ellis, Xavier Siemens (*University of Wisconsin-Milwaukee*), Fredrick Jenet, (*University of Texas at Brownsville*), Maura McLaughlin (*West Virginia University*)

Gravitational Waves (GWs) are tiny ripples in the fabric of space-time predicted by Einstein's General Relativity. Pulsar timing arrays (PTAs) are well poised to detect low frequency ($10^{-9} - 10^{-7}$ Hz) GWs in the near future. There has been a significant amount of research into the detection of a stochastic background of GWs from supermassive black hole binaries (SMBHBs). Recent work has shown that single continuous sources standing out above the background may be detectable by PTAs operating at a sensitivity sufficient to detect the stochastic background. The most likely sources of continuous GWs in the pulsar timing frequency band are extremely massive and/or nearby SMBHBs. In this poster we present detection strategies including various forms of matched filtering and power spectra addition. We will discuss the implementation of these methods into a fully functional data analysis pipeline that will be used both for detection and parameter estimation of signals in real pulsar timing data.

12:05pm Overlap reduction functions for pulsar timing arrays in alternative theories of gravity

Sydney J. Chamberlin, Xavier Siemens (*University of Wisconsin-Milwaukee*)

In the next decade gravitational waves could be detected using a pulsar timing array. In an effort to develop optimal detection strategies for stochastic backgrounds of gravitational waves in generic metric theories of gravity, we investigate the overlap reduction functions for these theories and discuss their features. We show that sensitivity increases for non-transverse gravitational waves and discuss the physical origin of this effect. We calculate the overlap reduction functions for the current NANOGrav Pulsar Timing Array (PTA) and show that the sensitivity to the vector and longitudinal modes can increase dramatically for pulsar pairs with small angular separations. For example, the J1853-J1857 pulsar pair, with an angular separation of ~ 3 degrees, is about 10^4 times more sensitive to the longitudinal component of the stochastic background, if it's present, than the transverse components.

12:17pm Using the measurability of spin in binary black hole systems to test cosmic censorship

Madeline Wade, Jolien Creighton (*University of Wisconsin-Milwaukee*)

Cosmic censorship prohibits naked singularities. For a Kerr black hole, the condition of cosmic censorship translates to a strict upper limit on the spin of a black hole ($|\boldsymbol{S}| \leq M^2$). For spins above this limit, the Kerr solution is a naked singularity. For a binary inspiral, the effects of the components spin can be seen in the phase of the gravitational waveform. The linear combination of component spins that appears at 1.5 post-Newtonian (PN) order in the phase of the waveform is defined as the dimensionless spin parameter β. Since there is a strict upper limit on the component spins in a binary black hole system, there is also a strict upper limit on the spin parameter β. A measurement of β in excess of this limit from gravitational wave observations of a binary inspiral could suggest a violation of cosmic censorship. Using a restricted SPA waveform and including terms up through 1.5PN in the phase, we have used the Fisher matrix approach to estimate the measurability of several parameters, including the dimensionless spin parameter β and the symmetric mass ratio η. From here we are able to create error ellipses in the η-β plane for a chosen value of β and chosen component masses. Even though η and β are known to be strongly correlated, which limits the ability to measure β alone, the physical constraint on η ($\eta \leq 1/4$) allows us to put a reasonable lower limit on the measurable value of β that violates the Kerr bound.

12:29pm **Continuous gravitational wave searches from galactic neutron stars in the advanced detector era**

Leslie Wade, Xavier Siemens, David Kaplan (*Univ. of Wisconsin-Milwaukee*,) Benjamin Knispel, Bruce Allen (*AEI-Hannover*)

We consider a simulated population of galactic neutron stars. The rotational frequency of each neutron star evolves through a combination of electromagnetic and gravitational wave emission. The magnetic field strength determines the dipolar emission, and the ellipticity (a measure of a neutron stars deformation) determines the gravitational wave emission. We find the gravitational wave amplitude emitted by each star in the population and probe the areas of magnetic field strength and ellipticity parameter space that would result in a detection by Advanced LIGO. We show that in the absence of a detection, for fixed ellipticity, we can set lower bounds on the magnetic fields of young neutron stars.

12:41pm **Separating a stochastic gravitational wave background from instrument noise and the galactic white dwarf foreground**

Matt Adams, Neil Cornish (*Montana State University*)

Stochastic gravitational wave background signals of either astrophysical or cosmological origin could potentially be detected by the Laser Interferometer Space Antenna(LISA). The white dwarf binary foreground in our own Milky Way galaxy will likely overwhelm any extragalactic stochastic signals, so it must be separated out. In an earlier work we showed that instrument noise in LISA can be distinguished from a stochastic signal by exploiting the different transfer functions for each. We extend this work to account for the galactic foreground, which can be distinguished from an isotropic background using the modulation introduced into the galactic signal by LISAs orbital motion.

12:53pm **The spherically symmetric and static limit of multi-fluid compact stars**

Greg Comer (*Saint Louis University*)

A multi-fluid system has, in principle, N_c matter constituents and N_f independent flux four-velocities, where N_f is less than or equal to N_c. Starting with an action principle, we will show that the limit to spherically symmetric and static configurations of two-constituent, two-fluid compact stars ($N_c = N_f = 2$) is not the same as two-constituent, one-fluid stars ($N_c = 2$, $N_f = 1$). This is not a flaw in the formalism, but rather an illustration of how the underlying assumptions on the physical properties of the system leave their imprint even in equilibrium configurations.

Section VII: Black Holes/Cosmology II

2:30pm **Self-forced motion of a scalar particle around a Schwarzschild black hole**

Ian Vega (*University of Guelph*), Peter Diener (*LSU*), Barry Wardell (*Max-Planck-Institut fur Gravitationphysik*)

Motivated by the prospect of detecting low-frequency gravitational waves from the inspirals of compact objects onto massive black holes, much effort has gone into computing back-reacting self-forces and investigating their effects on the motion of a point mass in black hole spacetimes. However, none of the work done to date has been able to look at what happens when you evolve the field and particle self-consistently. With newly-developed code, we have been able to accomplish just this, for the case of a scalar charge. In this talk I present results from self-consistent simulations of the self-forced dynamics of a scalar charge in the vicinity of a Schwarzschild black hole. These self-consistent simulations are the first ever of its kind in the self-force community.

2:42pm **Eccentric orbits on a Schwarzschild background: Transforming from Regge-Wheeler to Lorenz gauge**

Seth Hopper (*Albert Einstein Institute*), Charles Evans (*University of North Carolina at Chapel Hill*)

We consider a small body (particle) in eccentric orbit about a Schwarzschild black hole. The particle induces a first-order perturbation to the gravitational field. We solve the first-order Einstein equations and obtain the metric perturbation in Regge-Wheeler gauge for a wide range of eccentricities. The ultimate goal is to use this solution to correct the particle's motion, driving it off the background geodesic as it spirals in toward the black hole. The preferred method of performing such a calculation requires the computation of the self-force in Lorenz gauge. To that end, we present work on transforming our solution to the Einstein equations from Regge-Wheeler to Lorenz gauge.

2:54pm **Static solutions of Einsteins equations with cylindrical symmetry**

Cynthia Trendafilova, Stephen A. Fulling (*Texas A&M University*)

In analogy with the standard derivation of the Schwarzschild solution, we find all static, cylindrically symmetric solutions of the Einstein field equations for vacuum. These include not only the well known cone solution, which is locally flat, but others in which the metric coefficients are powers of the radial coordinate and the space-time is curved. These solutions appear in the literature, but in different forms, corresponding to different definitions of the radial coordinate, and we examine the relationships between these forms. Because all the vacuum solutions are singular on the axis, we attempt to match them to "interior" solutions with nonvanishing energy density and pressure. In addition to the well known "cosmic string" solution joining on to the cone, we find some numerical solutions that join on to the other exterior solutions.

3:06pm **Quasi normal modes of black holes**
Sharmanthie Fernando (*Northern Kentucky University*)

I will talk about the perturbation of a spinning dilaton black hole in 2+1 dimensions by a massless scalar field. The wave equations of a massless scalar field is shown to be exactly solvable in terms of hypergeometric functions. The quasinormal frequencies are computed for slowly spinning black holes. I will discuss the stability of the black hole and the asymptotic form of the quasinormal frequencies.

3:18pm **Quantum cosmology and the factor ordering problem**
Rachel Maitra (*Albion College*)

Quantum cosmology proceeds by first imposing spatial symmetries within the theory of general relativity, then quantizing the resulting model with its fewer (for the most part finitely many) degrees of freedom. In this way, one gains an overall picture of the quantum behavior of spacetime as a guide to the difficult unsolved problem of quantizing full general relativity. However, the question remains whether features of the resulting quantized cosmology will accurately reflect quantized general relativity, or whether they may be artifacts of the imposed symmetries. To address this question, we investigate a quantization ambiguity which occurs both in quantum cosmology and in full quantum gravity. This ambiguity arises from the choice of ordering for non-commuting quantum observables. We present a series solution for the quantum cosmology wave function under a wide range of possible orderings, and discuss a means of determining which solution will most closely reflect the quantum theory of full general relativity.

3:30pm **Quantum states for fermions in Kerr**
Marc Casals (*Perimeter Institute for Theoretical Physics*), Sam Dolan (*University of Southampton*), Brien Nolan (*Dublin City University*), Adrian C. Ottewill (*University College Dublin*), Elizabeth Winstanley (*University of Sheffield*)

In the Schwarzschild spacetime it is possible to construct a quantum state which represents the black hole in thermal equilibrium with its own radiation, the so-called Hartle-Hawking state, and also a quantum state which is empty at radial infinity, the so-called Boulware state. It is known that equivalent states do not exist for bosons in the Kerr spacetime due to the property of superradiance. Fermions, however, do not exhibit superradiance, and so one may wonder whether a Hartle-Hawking-like state and a Boulware-like state can be constructed for fermions in Kerr. In this talk we will present work in progress that constructs candidates for such states for fermions and investigates their properties.

3:42pm **Holographic renormalization of asymptotically Lifshitz spacetimes**
Robert McNees (*Loyola University*), Robert B. Mann (*Univ. of Waterloo and Perimeter Institute*

A variational formulation is given for a theory of gravity coupled to a massive vector in four dimensions, with Asymptotically Lifshitz boundary conditions on the fields. For theories with critical exponent $z = 2$ we obtain a well-defined variational principle by explicitly constructing two actions with local boundary counterterms. As part of our analysis we obtain solutions of these theories on a neighborhood of spatial infinity, study the asymptotic symmetries, and consider different definitions of the boundary stress tensor and associated charges. A constraint on the boundary data for the fields figures prominently in one of our formulations, and in that case the only suitable definition of the boundary stress tensor is due to Hollands, Ishibashi, and Marolf. Their definition naturally emerges from our requirement of finiteness of the action under Hamilton-Jacobi variations of the fields. A second, more general variational principle also allows the Brown-York definition of a boundary stress tensor.

3:54pm **Instanton representation of Plebanski gravity: Gravitational coherent states**
Eyo Ita (*US Naval Academy*)

The instanton representation of Plebanski gravity (IRPG) is a reformulation of General Relativity, using new variables, for spacetimes of Petrov Types I, D and O. We perform a quantization of the IRPG restricted to the minisuperspace sector, and construct its Hilbert space of states both for zero and nonzero cosmological constant.

4:06pm **Anisotropic evolution of 5D Friedmann-Robertson-Walker spacetime**
Chad Middleton (*Colorado Mesa University*), Ethan Stanley (*Purdue University*)

We examine the time evolution of the five-dimensional Einstein field equations subjected to a flat, anisotropic Robertson-Walker metric, where the 3D and higher-dimensional scale factors are allowed to dynamically evolve at different rates. By adopting equations of state relating the 3D and higher-dimensional pressures to the density, we obtain an exact expression relating the higher dimensional scale factor to a function of the 3D scale factor. This relation allows us to write the Friedmann-Robertson-Walker field equations exclusively in terms of the 3D scale factor, thus yielding a set of 4D effective Friedmann-Robertson-Walker field equations. We examine the effective field equations in the general case and obtain an exact expression relating a function of the 3D scale factor to the time. This expression involves a hypergeometric function and cannot, in general, be inverted to yield an analytical expression for the 3D scale factor as a function of time. When the hypergeometric function is expanded for small and large arguments, we obtain a generalized treatment of the dynamical compactification scenario of Mohammedi [Phys.Rev.D 65, 104018 (2002)] and the 5D vacuum solution of Chodos and Detweiler [Phys.Rev.D 21, 2167 (1980)], respectively. By expanding the hypergeometric function near a branch point, we obtain the perturbative solution for the 3D scale factor in the small time regime. This solution exhibits accelerated expansion, which, remarkably, is independent of the value of the 4D equation of state parameter w. This early-time epoch of accelerated expansion arises naturally out of the anisotropic evolution of 5D spacetime when the pressure in the extra dimension is negative and offers a possible alternative to scalar field inflationary theory.

4:18pm **Undergraduate studies of Oppenheimer Snyder collapse**
Brett Bolen, Eric Van Oever (*Grand Valley State University*)

Within general relativity, it is notoriously difficult to find analytical problems which undergraduates can perform meaningful research. I have begun a one year study with my co-author into the problem of gravitational collapse. I am finding that this problem is an excellent learning environment where the student can sharpen his tool belt for future research. I will conclude with some preliminary results of calculation of redshift from collapsing objects.

Section VIII: New Directions

4:55pm **Possible relationship between gravity, electromagnetic force and α**
Rickey Austin (*NC A&T*)

As an undergraduate student I have researched deriving the smallest possible black hole, without violating any known physical laws. The Schwarzschild Radius and the Uncertainty Principle were utilized in deriving this candidate. Upon analyzing the miniature black hole, a possible relation between gravitational force, electromagnetic force and α appeared. I will explain the path to this outcome, and what the possible relationship is in my talk.

5:07pm **Information-preserving black holes**
Wayne R Lundberg

Information-preserving black holes are constructed in AdS-2 geometry. When large numbers of quantum particles are superposed within the deep-deep throat of a finitary AdS space, an highly non-local scalar field forms. This extra field is interpreted in terms of string-theoretic symmetry about the Planck scale. As the I-P black hole grows and ages, the physical scale of the non-local field grows, to create a very macroscopic and uniform gravitational field. Indirect observation of such fields by GR lensing effects is discussed. Further, quanta preserved no longer experience temporal evolution. The potential for annihilation interaction with co-spatial matter also may be observed as small fractions of preserved matter experience Hawking radiation.

5:19pm **The horizon of the Universe may be similar to a black hole horizon, and may give rise to the mass cycles seen in particle physics**
Richard Kriske (*University of Minnesota*)

The Horizon of the Universe and that of a Black Hole are similar. If one looks at the Earth's Horizon objects in the distance not only grow smaller, but also lean backward, with the result being a convergence to a curved, well defined line. In the case of three space dimensions and one time dimension, the time dimension tilts backward with the result being a velocity and then an acceleration at the Horizon of a curved three space in 4 dimensional Space Time. To an observer far from the Horizon this looks like a Black Hole. Photons at the Horizon are Redshifted but can tunnel out like a Black Hole. They may have mass when they tunnel out as their time normal will be opposite that of the observer's normal. This backward normal is also seen on Earth, if someone from the far side of the Globe tunnels this direction he would be upside down. This author believes the upside down time-normal may generate mass, as it is an obvious mechanism in a Black-Hole as well. Although this is highly speculative, it could potentially be tested.

5:31pm **Ground-based experiments to test magnetic-type gravitational force**
Hui Peng (*Invenlux*)

Based on Maxwell-type Einstein equations of gravity, new effects and ground-based experiments to test these effects are proposed. Gyros with different rotating directions placed at the North Pole experience different forces of the magnetic-type gravitation due to the rotation of Earth. To test forces of gravito-magnetic field of Earth, these experiments can be done repeatedly in a laboratory with low cost, high accuracy and high sensitivity.

5:43pm **A Model of a simple, baryon-dominated universe that expands at an ever-increasing rate without relying on vacuum energy (Λ)**
Greg Proper

The prevailing view in modern cosmology is that the universe is comprised of immense quantities of exotic materials (i.e. Dark Matter and Dark Energy) that have yet to be positively identified. However, there is also a small group of scientists who believe that the answer to this dilemma is to be found in the modification of gravity (i.e. General Relativity). This short paper states that if we make the bold assumption that all objects/observers are comprised of sets of space-time coordinates that change (albeit slowly) as the universe ages, then three puzzles that currently confront cosmologists, astronomers and astro-physicists can easily be answered using relatively simple calculations. The condition necessary to explore this possibility can be obtained if one postulates that relativistic gravitational potential lessens (in absolute magnitude) everywhere as the universe ages (n). That is, the space-time metric $g_{\mu\nu}(x)$ becomes $g_{\mu\nu}(x, n)$. If gravity behaves in this manner, then it can be shown that it is the causitive agent of indeterminism in nature.

5:55pm **Derivation of $\Delta E = \Delta mc^2$: Revisited**
Ajay Sharma (*Fundamental Physics Society*)

Einstein's Sep. 1905 paper in which $\Delta L = \Delta mc^2$ (light energy-mass equation) is derived, is not completely studied; and is only valid under special conditions of involved parameters. Sometimes the derivation becomes invalid and $\Delta L = \Delta mc^2$ is not always obtained. The origin of $\Delta E = \Delta mc^2$ from $\Delta L = \Delta mc^2$ is completely speculative in nature without mathematical derivation. $\Delta E = \Delta mc^2$ is obtained from $\Delta L = \Delta mc^2$ by simply replacing L by E. $\Delta L = \Delta mc^2$ was initially derived for light energymass interconversion, then it was generalized for every energy $\Delta E = \Delta mc^2$. It is not justified logically and mathematically. The factor c^2 has been arbitrarily brought in picture by Einstein. As to obtain $L = \Delta mc^2$ Einstein retained term $v^2/2c^2$ (compared to unity) without giving numerical values to v. If the value of v is considered in typical classical region, 1cm/s say ($v^2/2c^2 = 5.5510^{-22}$ is negligible) then result is $M_b = M_a$. Thus conversion factor c^2 is arbitrarily brought in the picture as both the results i.e. $\Delta L = \Delta mc^2$ and $M_b = M_a$ are equally probable. Further, if body emits light energy, but measuring system is at rest ($v = 0$) even then Einstein's derivation is not applicable or valid and no result is obtained. If all values of parameters are taken in account then the same derivation also gives $L\Delta mc^2$ or $L = A\Delta mc^2$, where A is coefficient of proportionality. Thus the value of energy emitted varies with variables, thus result is not always $\Delta L = \Delta mc^2$. There are numerous values of coefficients of proportionality in the existing physics. The energy emitted can be less or more than emitted by L/c^2. Thus Einstein's derivation of $\Delta L = \Delta mc^2$ and speculation of $\Delta E = \Delta mc^2$ is not mathematically and logically consistent. Hence equation must be re-derived by other methods.

6:07pm **Special relativistic effects may impact the conditions necessary for an event horizon**
John Laubenstein

The predictions of General Relativity (GR) have been well tested, yet the precision needed to differentiate GR from other potential theories lies well beyond the level of precision available through current (and even proposed) experimentation. As such, any effort to differentiate theories must go beyond observation and be based on exact mathematical relationships. This paper explores the derivation of the Schwarzschild metric with a particular focus on the value of the metric in weak gravity where GR reduces to Newtonian gravity. Specifically, this paper explores the ramifications of including Special Relativistic (SR) effects into the weak field approximation used to derive the value of the parameter $1/S$ in the Schwarzschild metric. It can be shown that when SR effects are fully taken into account, including when $v \ll c$, that the conditions necessary to support the formation of the event horizon change. This paper explores whether these changes are significant enough to call into question the predictions of GR or whether they may be legitimately ignored as has been the past practice.