Abstracts

Of papers submitted for presentation at the international workshop:
"From Quantum to Cosmos - III: Space-Based Research in Fundamental Physics for the Next Decade,"
July 6-10, 2008 at the Airlie Center, Virginia, USA, http://physics.jpl.nasa.gov/Q2C3/

1. **Abazajian, Kevork**, University of Maryland
   Detecting the Dark Matter in the X-ray
   Indications of potential deviations in small scale structure hint that the dark matter particle mass could be light and in the keV mass range, as a particle of the form of a sterile neutrino. It's decay is two body and produces a line in the X-ray, which could be detected in current or future X-ray observatories. Different production mechanisms predict varying amounts of this signature X-ray decay photon. I review these production mechanisms and their relation to what can be detected in the X-ray. I also review complementary constraints from cosmological structure formation.

2. **Adler, Stephen L.**, IAS, Princeton U
   Can the flyby anomaly be attributed to earth-bound dark matter?
   We make preliminary estimates to assess whether the recently reported flyby anomaly can be attributed to dark matter interactions. We consider both elastic and exothermic inelastic scattering from dark matter constituents; for isotropic dark matter velocity distributions, the former decrease, while the latter increase, the final flyby velocity. Since the observed flyby velocity anomaly shows examples with both positive and negative signs, a two-component model is indicated, involving both elastic and inelastic scatterers with differing spatial distributions. The magnitude of the observed anomalies requires dark matter densities many orders of magnitude greater than the galactic halo density. Such a large density could result from an accumulation cascade, in which the solar system-bound dark matter density is much higher than the galactic halo density, and the earth-bound density is much higher than the solar system-bound density. Constraints on this picture are discussed.

3. **Amelino-Camelia, Giovanni**, U of Rome La Sapienza
   Planck-scale physics in space
   I argue that a special role in planning fundamental-physics studies in space could be played by the young field of "quantum-gravity phenomenology". In part this is already implemented in considering GLAST-type or EUSO-type studies, but much more is possible. The fact that quantum-gravity phenomenology has a target scale, the Planck scale, often translates in target sensitivities for certain measurements, such as some atom-interferometry measurements. When we can argue that the target sensitivity can only be achieved in a space environment the science case is correspondingly strengthened.

4. **Angonin Marie-Christine**, SYRTE Observatoire de Paris
   The SAGAS Project
   We summarize the scientific and technological aspects of the SAGAS (Search for Anomalous Gravitation using Atomic Sensors) project, submitted to ESA in June 2007 in response to the Cosmic Vision 2015-2025 call for proposals. The proposed mission aims at flying highly sensitive atomic sensors (optical clock, cold atom accelerometer, and optical link) on a Solar System escape trajectory in the 2020 to 2030 time-frame. SAGAS has numerous science objectives in fundamental physics and Solar System science, for example numerous tests of general relativity and the exploration of the Kuiper belt. The combination of highly sensitive atomic sensors and of the laser link well adapted for large distances will allow measurements with unprecedented accuracy and on scales never reached before. We present the proposed mission in some detail, with particular emphasis on the science goals and associated measurements and technologies.

5. **Asmar, Sami** (JPL) **and Luciano Iess** (Univ. Rome)
   Instrumentation for Tests of General Relativity By the BepiColombo Mission
   Testing the theory of general relativity is one of the science objectives of ESA's BepiColombo mission to Mercury. This objective that can be achieved using Radio Science instrumentation traditionally used for planetary and solar system exploration, but augmented with to meet more stringent requirements. The mission's Mercury Orbiter Radio-science Experiment (MORE) team will carry out high precision tests of relativistic gravity in an ideal laboratory, the gravitational field of the Sun. Range and range-rate

measurements from radio-tracking the spacecraft in orbit around Mercury will lead to precise determination of perturbations in the global orbital solutions. This will, in turn, lead to significantly improved measurement of post-Newtonian parameters. Experimental limitations of microwave systems used for these tests, including attitude motion and non-gravitational accelerations of the spacecraft, propagation noise, and mechanical noise of ground antenna. In order to achieve the scientific objectives and fundamental physics, suitable radio frequency instrumentation for the Doppler and ranging observables for the spacecraft as well as ground stations have been designed. This paper will describe the instrumentation and calibration methods including new proposed development for ranging with the Deep Space Network to achieve target ranging accuracy of ~20 cm.

6. **Bailey, Quentin, G.,** Embry-Riddle Aeronautical University
Gravitational experiments testing Lorentz symmetry
Recently, growing efforts have been devoted to precision tests of the principle of Lorentz symmetry, one of the cornerstones of modern fundamental physics. The primary motivation is to uncover possible experimental clues coming from a long-sought after fundamental theory that combines General Relativity and the Standard Model of particle physics. The theoretical framework called the Standard-Model Extension (SME) offers a comprehensive description of possible Lorentz violations, and has been used in many experiments to date. In a recent work, laboratory and space-based gravitational experiments have been identified that could probe coefficients controlling the degree of Lorentz violation in the gravitational sector of the SME. In this talk, I will discuss the theory behind these tests, including some recent results in lunar laser ranging and atom interferometry.

7. **Bender, Peter L.** (JILA, Univ. of Colorado), **Neil Ashby** (Univ. of Colorado and NIST), **Rita Dolesi, Stefano Vitale** and **William J. Weber** (Dept. of Physics, Univ. of Trento)
Measurement of the Gravitational Time Delay from L-1
An attractive approach for accurately determining the gravitational time delay due to the Sun involves measurements between carefully isolated test masses in two different spacecraft. If one spacecraft is at the L-1 point [1], a convenient choice for the orbit of the other one is a 1.5 year period elliptical orbit, like that chosen for the proposed LATOR mission. The primary challenge for such a mission appears to be keeping the disturbances acting on the test masses very low over a period of roughly 20 days. Devices called Gravitational Reference Sensors which will protect freely moving test masses inside them to well below the required level out to periods of 10,000 seconds or longer are being developed for use in the LISA gravitational wave mission. The main development of such devices was carried out at the University of Trento, based on earlier work at ONERA. They will be tested in the LISA Pathfinder mission, planned by ESA for flight in 2010. The requirements to extend the performance to longer times are mainly thermal, and will be discussed. The measurement of the round trip travel time between the spacecraft would be done by using Ka-band modulation on laser beams. The main clock on the L-1 spacecraft could be a cooled-atom Cs or Rb hyperfine clock, possibly with daily drift monitoring by comparison with ground clocks. An accuracy goal of 1 or 2×10^{-8} for determining the PPN parameter gamma seems reasonable.

[1] N. Ashby and P. L. Bender, "Measurement of the Shapiro Time Delay between Drag-Free Spacecraft", in Lasers, Clocks and Drag-Free Control, Astrophysics and Space Science Library, Vol. 349, Eds. H. Dittus, C. Laemmerzahl, and S. G. Turyshev (Springer, 2008), pp. 219-230.

8. **Bertolami, Orfeu,** Instituto Superior Técnico, Lisbon, Portugal
The coupling of dark energy with Standard Model states
We study the coupling of dark energy to the Higgs field and to neutrinos. In the first case, we find that an interesting cosmological solution includes the unification of dark energy and dark matter. For neutrinos, we develop a perturbative approach which allows considering viable varying mass neutrinos models coupled to quintessence.

9. **Binetruy Pierre,** *APC, University Paris Diderot*
European roadmap for fundamental physics in space
I will describe the effort presently undertaken by the Fundamental Physics Advisory Group (FPAG) of ESA to conduct a European roadmap for fundamental physics in space.

10. **Bouyer, Philippe,** Laboratoire Charles Fabry de l'Institut d'Optique

ICE : Towards a UFF test with ultra cold atoms in microgravity

We present our progress on developing atom-interferometric inertial sensors in microgravity. In addition, we propose a scheme for testing the Universality of Free Fall (UFF) with a freely-falling atom interferometer.

Atom-interferometric inertial sensors rival in accuracy and precision state-of-the-art conventional sensors. Moreover, the quantity they measure directly relates to inertial effects on well-controlled weakly-interacting Dirac particles, and it thus of interest for tests of gravitational theories. Their current precision is limited by the scaling factor of the interferometer, scaling up with the available atomic free-fall time, and technical noise, mainly due to vibrations of apparatus.

We present progress on transportable atom-interferometry apparatuses that can be used on an airplane, in ballistic flights, to perform measurements in microgravity. Low-frequency acceleration noise in the airplane reference frame is compatible with 4s-free-fall measurements for a 1m displacement of the experiment. A novel laser source using standard fibered telecom components and frequency doubling to rubidium wavelength (780nm) allows for compact and transportable laser sources suitable for laser cooling and coherent manipulation of atoms in a noisy environment. A cold-atom apparatus for coherent-splitting of laser-cooled rubidium clouds has been tested to produce a magneto-optical trap during a flight campaign last year.

We detail a protocol to perform tests of the UFF with the freely-falling interferometer. We address the problem of acceleration noise that also plagues ground-based interferometers by using phase-locked measurements for both species to measure directly the differential acceleration, rejecting common-mode noise. We show that the use of a Bayesian estimator rejects the remaining phase-noise, due to a vernier effect between the two species, and can correlate measurements between different free falls, removing the need to scan an interferometric fringe. Taking in account the most relevant sources of noise, we predict a precision of $\triangle a/a$.

11. **Buchman, Sasha,** Stanford University

STAR Space Time Asymmetry Research

Stanford University and NASA Ames Research Center propose a SMEX MO: Space Time Asymmetry Research (STAR). We will use precision molecular iodine stabilized Nd:YAG laser interferometers to search for small deviations from Lorentz Invariance, a cornerstone of relativity and particle physics and thus our understanding of the Universe. A Lorentz violation would have profound implications for cosmology and particle physics. An improved null result will constrain theories attempting to unite particle physics and gravity.

Science Objectives:

• Measure the absolute anisotropy of the velocity of light to 10^{-18} (100-fold improvement)

• Derive the Michelson-Morley coefficient to 10^{-12} (100-fold improvement)

• Derive the Kennedy-Thorndyke coefficient to $7x10^{-10}$ (400-fold improvement)

• Derive the coefficients of Lorentz violation in the Standard Model Extension, in the range $7x10^{-18}$ to 10^{-14} (50 to 500-fold improvement)

The instrument uses advanced technology with most components functional on other space missions, TRL-9, and with no components below TRL-6. The spacecraft is a standard bus development by Ames, to fly as a secondary payload in an 850 km orbit for a one-year mission. Other orbit options are possible. This project will demonstrate the feasibility of advanced science projects on small satellites for around $35M and with moderate mission durations.

12. **Byer, Robert,** Stanford University

Advances in LISA technology

The LISA mission requires drag free formation flying with a precision of 30pm over a separation distance of 5 million km or 15 light seconds. We have completed a trade study of dual and single proof masses, both cubic and spherical. The study is informed by experiments in the laboratory on the elements of a Modular Grvitational Reference Sensor (MGRS) that uses optical sensing, a wide gap separation of the proof mass, grating-based all reflective beam splitters and interferometers and two step interferometery. Also investigated are proof mass inertial properties such as location of the center of mass to 100nm, and moment of inertia measurements. Algorithms have been developed and tested that enable the on-orbit sensing of the center of mass of a spinning sphere to be acquired in less than 30 seconds and the determination of higher order spherical harmonics, spin rate, and center of mass to the precision required to meet LISA requirements.

13. **Cadez, Andrej,** University in Ljubljana, Slovenia
Tidal potential energy release before plunging into a black hole
It will be shown that large amounts of energy can be released before plunging into a black hole if tides can exponentially be raised on the infalling object. Conditions necessary to raise exponential tides and orbital evolution leading to such conditions will be discussed. The light curve signature and characteristic time scales of such possible astrophysical events will also be discussed.

14. **Carpenter, Brad,** NASA Headquarters
The ISS National Laboratory and the Future of Research in Space.
As NASA begins to lay the foundation for an era of human exploration of the Moon and Mars with the start of a new launch system and a new crew vehicle, the importance of low Earth orbit, and especially existing orbital assets like the International Space Station, in the future of space exploration needs to be kept in mind. For even as bold new missions to establish outposts first on the Moon and eventually on Mars are on our horizon, low Earth orbit will remain our first and most accessible destination in space. Low earth orbit will provide the widest opportunity to test concepts for extending human presence and enlarging the sphere of human activities in space. In designating the U.S. assets of the ISS as a National Laboratory, the 2005 NASA Authorization Act to a major step toward opening low Earth orbit to a broader community of users. The Act specifically calls on NASA to take steps to increase the utilization of the ISS by other Federal entities and the private sector. This talk will describe the policy background for the ISS National Laboratory, and the status of some of NASA's efforts to accommodate research projects of several major Federal agencies and companies in the private sector.

15. **Chakrabarty, Deepto**, (MIT), **Paul S. Ray** (NRL), **Tod E. Strohmayer** (NASA/GSFC), for the AXTAR Collaboration
Determining the Equation of State of Ultradense Matter with the Advanced X-ray Timing Array (AXTAR)
The Advanced X-ray Timing Array (AXTAR) is an X-ray observatory mission concept that combines very large collecting area, broadband spectral coverage, high time resolution, highly flexible scheduling, and an ability to respond promptly to time-critical targets of opportunity. It is optimized for submillisecond timing of bright
Galactic X-ray sources in order to study phenomena at the natural time scales of neutron star surfaces and black hole event horizons, thus probing the physics of ultradense matter, strongly curved spacetimes, and intense magnetic fields. In particular, AXTAR will determine the equation of state of ultradense matter by obtaining precise radius measurements for an ensemble of neutron stars. AXTAR's main instrument, the Large Area Timing Array (LATA), is a collimated, thick Si pixel detector with 2-50 keV coverage and 8 m2 collecting area. For timing observations of accreting neutron stars and black holes, AXTAR provides at least an order of magnitude improvement in sensitivity over both the Rossi X-ray Timing Explorer (RXTE) and the planned Constellation-X mission. A sensitive Sky Monitor acts as a trigger for pointed LATA observations of X-ray transients and also provides continuous monitoring of the X-ray sky with 20 times the sensitivity of the RXTE monitor and a source localization accuracy of 1 arcmin. The baseline mission concept builds on detector and electronics technology previously developed for other applications with support from NASA, DOE, DARPA, and DHS, and thus offers high scientific impact at moderate, known cost and minimal technical risk.

16. **Chui, Talso C. P.,** Jet Propulsion Laboratory, California Institute of Technology
Seismic Search for Strange Quark Nuggets and/or other Unknown Massive Particles - a Secondary Science Objective for Lunar Exploration
As part of the lunar exploration program, the International Lunar Network Mission is being planned to place a suite of science instruments, including seismometers, throughout the surface of the Moon. The primarily objective of these instruments is to conduct lunar science studies. But, as a secondary objective, a network of sensitive seismometers can be used to search for rare astrophysical impact events due to the postulated strange quark nuggets and/or other unknown massive particles. These particles could interact, in various degrees, with ordinary matter, and some of them could produce detectable seismic signals. The seismically quiet lunar environment would allow the Moon to be used as a low noise detector of large cross sectional area for these types of impact events. During the Apollo program, a rare and unusual type of seismic event was detected, which was subsequently called the shallow moonquake. The waves from shallow moonquakes have much larger high frequency components than other types of moonquakes. Recently Frohlich and Nakamura [Icarus, 185, 21-28, 2006] reported that out of 28 of such events observed, 23 of them occurred when the lunar nearside was in the general direction of the Virgo constellation, leading them to postulate a possible

extra-solar-system origin. I will review these results and discuss the new parameter space to be explored by a lunar seismic search for strange quark nuggets. I will also review the current status of a funded effort to develop a seismometer which would be 100 times more sensitive than the current state of the art.

17. Ciufolini, Ignazio, Universita' del Salento and INFN, Lecce, Italy, A.Paolozzi, Sapienza, Universita' di Roma and INFN, Roma, Italy. E. C. Pavlis, University of Maryland and R. A. Matzner, University of Texas, Austin.

A heritage of John Archibald Wheeler: the accurate measurement of dragging of inertial frames using the LAGEOS satellites and the forthcoming LARES satellite

A long time ago, John Archibald Wheeler introduced one of us (I.C.) to the fascinating problems of the origin of inertia and dragging of inertial frames in gravitational physics and General Relativity. Another time he showed to I.C. a puzzling paper on the tiny and then mysterious and anomalous decrease of the LAGEOS semimajor axis. Later on, together with Richard Matzner, he supported very strongly I.C.'s proposal for a new laser ranged satellite to measure frame-dragging called, in 1984, LAGEOS 3, which evolved into LARES, the Italian Space Agency (ASI) mission approved last February.

Here, we first describe the past and present accurate measurements of the Lense-Thirring effect, a frame-dragging effect, obtained by I.C. and Erricos Pavlis, with the laser ranged satellites LAGEOS (NASA) and LAGEOS 2 (NASA and ASI), thanks to the latest Earth gravity field models obtained using the GRACE mission (NASA and DLR). We then describe the new generation laser ranged satellite mission LARES of ASI which is planned to be launched in 2009 using the new European Space Agency launcher VEGA built by ELV (AVIO and ASI). LARES, together with the two LAGEOS satellites, will provide a very accurate measurement of Lense-Thirring effect and frame-dragging as predicted by Einstein's theory of General Relativity.

18. Cutler, Curt , J., Jet Propulsion Laboratory, California Institute of Technology

LISA and Fundamental Physics

The Laser Interferometer Space Antenna (LISA) is a planned ESA-NASA mission to measure gravitational waves from space. LISA is both an astronomy mission and a fundamental physics mission. This talk will briefly review the fundamental physics reach of LISA. LISA observations of merging supermassive black holes and of inspirals of stellar-mass black holes into supermassive black holes will both allow precision tests of general relativity in the ultra-strong field regime. Additionally LISA has several potential gravitational-wave sources from the early universe, including cosmic (super-)strings or a strongly first-order electroweak phase transition. Any such discovery of gravitational waves from the early universe would likely have important implications for fundamental physics.

19. D'Ambrosio, Erika, Istituto Nazionale di Fisica Nucleare, Florence, Italy

Quantum superposition of test-masses to probe general relativity

The need for new physics that recent discoveries have initiated, is complemented by a lack of full understanding and applications of present theories and models, especially in general relativity. Even a familiar concept such as the Newtonian center-of-mass has no unambiguous definition, beyond classical mechanics. While searching for the evidence of a variety of modern theories of gravity, the real breakthrough quantum science and technology can provide for, is testing the predictions of "current" theories. Controlled and well-characterized collections of laser-cooled atoms are, in this respect, the ideal probe. Of foremost and fundamental interest, the interaction of matter and gravity is a standing problem that still awaits an unequivocal mathematical description, also for the non relativistic case, that is when the coupling is represented by means of an "external field". This is a theoretical issue at the intersection of quantum mechanics and metric theory that indicates a persisting inability of correctly analyzing even simple situations. The result is a number of definitions of the quantum phase variation and a more recent discussion on the translational invariance of its description. We illustrate the benefits and the importance of quantum technology based tests: first of all, the degree of manipulation of cold atoms has achieved the required accuracy for establishing unprecedented high-precision measurements of absolute gravity. Further improvement can be obtained by increasing the observation cycle and this can most probably be accomplished only in a space-based environment. We anticipate that significant investigations are needed in order to attenuate and possibly neutralize the most relevant noise sources and that all inertial terms, as determined by the reference frames involved, must be accurately accounted for and their effects identified in the data. The sensational advantages we envision concern the implementation of orthogonally-oriented detectors, which in a stable and quiescent environment, would enable scientists to discriminate gravitational waves from unpolarized perturbations.

20. **Danzmann, Karsten,** AEI Hannover
LISA: Listening to the Universe with Gravitational Waves
LISA is a joint ESA/NASA space mission to launch in 2018 a laser interferometric gravitational wave detector comprising 3 satellites at the corners of a triangle with 5 million kilometer arms. It will hear gravitational wave signals from supermassive black holes in the complete universe. Merging black holes are standard sirens and, combined with redshift determination after host identification, LISA will also give us the expansion history of the universe.

21. **Dremer, Charles**, US Naval Research Laboratory
Science with GLAST
The successful launch of the Gamma ray Large Area Space Telescope, GLAST, on June 11, 2008, opens a new era in gamma-ray astronomy. First results will be released after August 9th following the 60-day checkout period. In anticipation of this release, we present an overview of GLAST, its capabilities, and its science. GLAST will be important for many fields of astronomy--e.g., supernovae, cosmic rays, pulsars, pulsar wind nebulae, galactic structure, diffuse backgrounds, unidentified sources, dark matter, etc. This talk will focus on the use of GLAST for extragalactic black-hole astronomy, tying the anticipated GLAST results to discoveries in high-energy neutrino and charged particle astronomy.

22. **Diddams, Scott A.**, **D. Braje, M. Kirchner, T. Fortier** (NIST), S**. Osterman, C. Froning** (CASA, Univ. of Colorado), **A. Bartels, D. Heinecke** (Univ. Konstanz)
Combing through space: Precision Optical Frequencies for Astronomy
Optical frequency combs based on femtosecond mode-locked lasers have proven to be invaluable tools for the development and comparison of emerging optical clocks, providing accuracy to 17+ digits. However, for some applications in astronomy a frequency comb with one-millionth this accuracy but with modes sufficiently spaced to be resolved by a high-resolution (R>50 000) grating spectrometer could usher in a revolution in high precision astronomical spectroscopy. The laser physics and optics required for a broad bandwidth mode-locked laser comb make the large mode spacing a challenging requirement, but the scientific payoff could be significant. A comb-calibrated astronomical spectrograph could lead to improved searches for extrasolar planets and the variation of fundamental constants, as well as a direct measurement of the rate of expansion of the universe. We will discuss several techniques for the generation of atomically-referenced optical frequency combs that have mode-spacing on the order of 10-20 GHz. These include direct generation with passively mode-locked lasers as well as optical filtering of a higher-density frequency comb. The prospects of deploying such frequency combs to astronomical instruments on earth and in space will be considered.

23. **Duncan, Robert V.**, University of New Mexico and Caltech
Cosmology Model Tests Using Quantum Fluids
Measurements of thermal properties associated with spontaneous symmetry breaking at the superfluid transition in 4He have been made with a precision approaching one part in ten billion, using a new class of thermometry and recent advances in experimental control. These results depend very strongly upon the level that the system is driven away from equilibrium when the spontaneous symmetry breaking occurs, suggesting that the application of equilibrium critical phenomena to this problem in cosmology is inadequate. Measurements of dynamic critical phenomena near this superfluid transition in a weightless laboratory will provide physical insight into how long-range matter-wave coherence is lost while being driven far from equilibrium. These dynamical effects generally decrease the importance of critical fluctuations at the transition, and they create new phenomenology that is not observed in static measurements. These effects have been predicted theoretically, and comparison to the limited data that is available in an Earth-based laboratory show general agreement, but with some surprising differences. Other effects, such as an acoustic analogy to Hawking radiation, have been predicted, and these tiny effects may be observable in a weightless laboratory. Finally, the new level of experimental control that has been developed to conduct these measurements may be used to develop a new blackbody radiation temperature reference that is more stable than the predicted drift rate of the CMB temperature. While it is unlikely that this will lead to a direct measurement of the CMB temperature drift due to foreground source instability, it does promise to provide a

new method of ultra-stable baseline radiometry for future CMB measurements. Much of the experimental work referred to above has been supported by NASA and conducted at UNM, Caltech, and JPL.

24. **Easther, Richard**, Yale University
Gravitational Waves and the End of Inflation
I will discuss the production of gravitational radiation during the transition between accelerated growth and "regular'' expansion that marks the end of the inflationary era and explain how some well-studied mechanisms for this transition generate a significant gravitational wave background. This signal is distinct from the generic inflationary gravitational wave background, and represents a largely unexplored window into the inflationary epoch. I will discuss the scaling properties of this signal, its relationship to other possible inflationary observables, and its potential for detection by future gravitational wave experiments.

25. **Ertmer, Wolfgang**, Leibiz Universitaet Hannover, Institute for Quantum Optics
Quantum Sensors on Ground and in Space
Microgravity is expected to be a decisive condition for the next leap in tests in fun-damental physics of gravity, relativity, and theories beyond the standard model. Promising techniques for fundamental test in the quantum domain are matter-wave sensors based on cold atoms or atom lasers, which use atoms as unperturbed mi-croscopic test bodies for measuring inertial forces or as frequency references. Micro-gravity is of high relevance for matter-wave interferometers and experiments with quantum matter, like Bose-Einstein-condensates or degenerate Fermi-gases, as it permits the extension of an unperturbed free fall of these test particles (wave pack-ets) in a low-noise environment. First steps towards ransportable atom interferometer as well as towards an experi-mental realization of a Space atom laser are being undertaken within the QUANTUS project (QUANTen Gase Unter Schwerelosigkeit). A mobile platform for microgravity experiments with quantum matter in the drop tower and during parabolic flights as part of a DLR pilot project is being developed.

26. **Finn, Lee Samuel**, Penn State
LISA: A Space-Based Gravitational Wave Probe of Fundamental Physics
Einstein's general relativity has survived all challenges in the regime of weak fields, or strong but stationary fields. In none of these tests does gravity really take center-stage: i.e., play a leading, let alone solo, role in Nature's pageant. Nature abounds with examples of such phenomena - the coalescence of two supermassive black holes following, e.g., the major merger of their parent galaxies, is a principal example. In such an event, the role of matter, and even the potential of the rest of the galaxy, pales to insignificance when compared to the dynamics of the spacetime as the black holes dance about each other and finally merge. These mergers are, in theory, the most powerful and energetic phenomena that we know of in the universe: general relativity predicts that the coalescence of a binary black hole system consisting of two billion solar mass black holes releases upwards of 10^{62} ergs over the course of a 10^{5} seconds, dwarfing the output of the most energetic gamma-ray burst. All this energy is radiated in gravitational waves, which are presently invisible to us. LISA - the Laser Interferometer Space Antenna - is an ambitious project that will enable the direct detection of the gravitational wave signal from these and similar cosmic events involving strong and dynamical gravitational fields. Its sensitivity will allow precision tests of general relativity in that sector where the theory comes into its own: i.e., strong and dynamical fields. In this presentation I will describe LISA and the exploration of the fundamental physics and astrophysics that its successful completion will enable.

27. **Fischbach, Ephraim and J.H. Jenkins**, Physics Department Purdue University
Possible Detection of Neutrinos from a Solar Flare
We report the possible detection of neutrinos from the solar flare of 13 December 2006, whose x-rays were first recorded at 02:37 UT (21:37 EST on 12 December). Our detector was a 1 ?Ci sample of 54Mn, whose decay rate exhibited a dip coincident in time with spikes in both the x-ray and proton fluxes recorded by the GOES-10 and 11 satellites. A secondary peak in the x-ray and proton fluxes on 17 December at 12:40 EST was also accompanied by a coincident dip in the 54Mn decay rate. These observations provide a mechanism to account for the recent claims of several groups to have detected correlations between nuclear decay rates and solar activity.

28. **Flambaum, Victor**, University of New South Wales
Variation of fundamental constants from Big Bang to atomic clocks: theory and observations

Theories unifying gravity with other interactions suggest temporal and spatial variation of the fundamental "constants" in expanding Universe. The spatial variation can explain fine tuning of the fundamental constants which allows humans (and any life) to appear. We appeared in the area of the Universe where the values of the fundamental constants are consistent with our existence.

I present a review of works devoted to the variation of the fine structure constant alpha, strong interaction and fundamental masses (Higgs vacuum). There are some hints for the variation in quasar absorption spectra and Big Bang nucleosynthesis data.

A very promising method to search for the variation consists in comparison of different atomic clocks. Huge enhancement of the variation effects happens in transitions between very close atomic, nuclear and molecular energy levels. Large enhancement also happens in nuclear, atomic and molecular collisions near resonances.

How changing physical constants may occur? Light scalar fields very naturally appear in modern cosmological models, affecting parameters of the Standard Model (e.g. alpha). Cosmological variations of these scalar fields should occur because of drastic changes of matter composition in Universe: the latest such event is rather recent (about 5 billion years ago), from matter to dark energy domination. Massive bodies can also affect physical constants. The strongest limits are obtained from the measurements of dependence of atomic frequencies on the distance from the Sun (the distance varies due to the ellipticity of the Earth's orbit).

29. **Flanagan, Eanna**, Cornell University
Difficulties inherent in terrestrial tests of post-Newtonian gravity
Future high precision technologies will allow highly accurate terrestrial measurements of gravitational acceleration, at the level of parts per 10^{15} or better. Since post-Newtonian corrections to the Earth's gravitational field are at the level of parts in 10^{9}, it has been suggested that terrestrial measurements of parameterized post-Newtonian parameters might be possible. We argue that, for general terrestrial experiments whose self-gravity is negligible and which measure static gravitational accelerations, it will not be possible to measure these parameters due to unavoidable systematic effects from local matter inhomogeneities. Space-based experiments can evade this problem.

30. **Gibble, Kurt**, **Stephen Gensemer, Russell Hart, Ross Martin, Xinye Xu**, and **Ronald Legere**, Penn State
Probing Ultra-Cold Atom-Atom Interactions with Atomic Clock Accuracy
We have demonstrated a new technique to very precisely probe ultra-cold atom-atom interactions. We juggle atoms in our cesium fountain clock by launching two laser-cooled clouds in rapid succession. The atoms in one cloud are prepared in a coherent superposition of the two clock states and the atoms in the other cloud are prepared in one of the F,mF ground states. When the two clouds collide, the clock states experience s-wave phase shifts as they scatter off of the atoms in the other cloud. By detecting only the scattered part of the clock atom's wavefunction, we unambiguously observe the differences of scattering phase shifts. These phase shifts are independent of the atomic density to lowest order, which enables measurements of scattering phase shifts with atomic clock accuracy. Recently, we have observed the changes in scattering phase shifts as inelastic scattering channels open and close. An ensemble of measurements will accurately test and constrain our knowledge of cesium-cesium interactions. With such knowledge, this technique can place stringent limits on the time variation of fundamental constants, such as the electron-proton mass ratio, by precisely probing scattering phase shifts near a Feshbach resonance.

31. **Gill, Patrick**, **Helen Margolis** and **Hugh Klein**, National Physical Laboratory, UK
Opportunities for space-based experiments using optical clock and comb technology
The rapid evolution of optical clocks over the last few years has been achieved in part due to the emergence of wide-span femto-second combs. These provide the clockwork necessary for high-accuracy optical clock comparison and the means for optical-to-microwave downconversion. Optical clock performance has now converged with the best microwave fountain clock capability, and in some cases, even surpassed it. Optical clock fractional stabilities and estimated fractional uncertainties reaching down to the few x 10^{-17} are now being demonstrated, and look to be capable of achieving 10^{-18} over the next few years.

With this dramatic improvement in performance comes the potential for optical clocks and combs to provide very high precision time and frequency instrumentation for incorporation into future space missions and experiments. These experiments cover a spectrum from fundamental science through to Earth observation and satellite navigation. The major benefits from improved space-based clock precision are most likely found within fundamental physics, where enhanced tests of general relativity and gravity exploration on a solar system scale can be postulated. Additionally, possibilities arise for orbiting master clocks in space, and their use for geodesy with high spatial resolution, and for high-accuracy remote comparison of high performance terrestrial clocks.

This presentation will review some of these space-based experiments, and point to the requisite technology developments needed for optical clocks to ensure technology readiness. These considerations have arisen through an ESA study into optical combs for space-borne metrology [1] and follow-on deliberation of critical clock technology aspects.

[1] Patrick Gill, Hugh Klein and Helen Margolis (National Physical Laboratory), Ronald Holzwarth, Marc Fischer and Theodor Haensch (Menlo Systems GmbH), Stephan Schiller (Heinrich-Heine Universitaet, Duesseldorf), Volker Klein (Kayser-Threde GmbH) ESTEC Contract 19595/06/NL/PM.

32. Gould, Harvey, Lawrence Berkeley National Lab (LBNL)
Electron Electric Dipole Moment Experiments in Space
Electron electric dipole moments (eEDM)s, large enough to be discovered by a new experiment are common predictions of Standard Model extensions including models of baryogenesis, dark matter, and neutrino mass. Observing an EDM is unequivocal proof of new physics. Laser-cooled cesium atom eEDM experiments, which share many of the features of Cs atomic clocks, may be done to greater sensitivity in micro-gravity than on Earth. We will discuss the advantages of microgravity eEDM experiments, progress in identifying and meeting some challenges of a space-based experiment, and results from a ground based proof-of-principle laser-cooled Cs fountain eEDM experiment.

33. Hahn, Inseob, JPL
Critical phenomena in microgravity
This review provides an overview of the progress in using the low-gravity environment of space to explore critical phenomena and test modern theoretical predictions. Gravity-induced variations in the hydrostatic pressure and the resulting density gradients adversely affect ground-based measurements near fluid critical points. Performing measurements in a low-gravity environment can significantly reduce these difficulties. A number of significant experiments have been performed in low-Earth orbit. We describe the scientific content of previously flown low-gravity investigations of critical phenomena as well as those in the development stage, and associated ground-based work.

34. Hemmati, Hamid, Slava G. Turyshev, Caltech/JPL
Planetary Precision Laser-Ranging and High-Rate Lasercom
Status of JPL's research activities on active laser-ranging at Lunar and Mars ranges will be discussed. Millimeter-scale ranging is aimed at for planetary ranges utilizing landers or orbiters. Will also review JPL's research activities on planetary laser communications, with the capability to provide science instruments with orders of magnitude higher data-rate downlink relative to convention technologies.

35. Hogan, Craig, U of Washington, Seattle
Measuring Indeterminacy of Quantum Geometry
Theory suggests that there is a minimum length or UV cutoff at the Planck length. This results in a precisely computable indeterminacy of spacetime analogous to a diffraction limit: two events have transverse positions with uncertainty given by the geometric mean of their separation and the Planck length. A new kind of universal "holographic noise" is predicted with zero parameters, in the form of spatial shear fluctuations with a power spectral density given by the Planck time. The noise is predicted to be measurable in interferometric gravitational-wave detectors.

36. Horowitz, Gary, UC Santa Barbara
The Remarkable Power of Einstein's Equation
We are used to the fact that Einstein's equation gives a beautiful geometric description of gravity that agrees with all available experimental results. However recently, through the gauge/gravity duality discovered in string theory, this same equation describes other areas of physics as well. This includes aspects of the quark-gluon plasma in QCD and aspects of condensed matter systems such as superconductivity. These surprising applications of Einstein's equation will be explained and illustrated with simple examples.

37. Holberg, Leo W., C.W. Oates, Z. Barber, N. Lemke, A. Ludlow, S.A. Diddams, T. Fortier, D. Braje, M. Kirchner, S. Meyer, Q. Quraishi, and S. Xiao, National Institute of Standards and Technology (NIST)
Optical Atomic Clocks: Ready for Space?
Optical atomic frequency standards ("clocks") are now working at unprecedented levels at several laboratories around the world. On short time scales they achieve fractional frequency instabilities of a few times 10E-15$\tau^{-1/2}$ (τ; in seconds), and many standards are projecting frequency reproducibilities in the low 10E-17 range. The systems are relatively new and the parameter space only partially explored and developed, so performance in the laboratory continues to improve rapidly. Even with the current performance such clocks in space could improve tests of Relativity by orders of magnitude and advance time/frequency transfer. However, the high performance optical atomic clocks are not ready for space and will not be ready for many years. (This even ignores the critical and difficult engineering challenges of shrinking size, weight, power, reducing complexity, and space-qualifying necessary components.) We are still missing two critical required technologies (1) appropriate laser systems and (2) time/frequency transfer methods that can support this level of clock performance through the atmosphere. If we seriously envisioned launching optical atomic clocks, at the current performance levels, into space at the 10-year vision horizon of Quantum-Cosmos-III then programs should start immediately investing significant resources and people-time to develop the required technologies. The lack of suitable lasers is the same problem that impedes the commercialization of any atomic clocks (microwave or optical) that require precisely controlled single-frequency lasers at the atomic transitions. Presently, there are no reliable sources of reliable lasers that meet the requirements of even ground-based applications of atomic clocks, much less missions to space. Except for direct optical fiber connections we are orders of magnitude away from having the technology required for time/frequency transfer at the clock performance levels. In our laboratory we are developing two promising neutral-atom optical atomic frequency standards (free falling laser-cooled Ca and an optical lattice clock based on Yb) as-well-as the frequency counters/dividers based on mode-locked lasers (Ti:sapphire, Yb:KYW and fiber lasers). We will discuss the current performance and make some projections about transportable optical atomic frequency standards.

38. Kasevich, Mark, Stanford University
Gravity wave detection using atom interferometry
TBD

39. Kitching, John, Edward, NIST
Chip-Scale Atomic Devices for Space
We describe recent work at NIST to develop compact low power instruments based on a combination of microfabrication techniques, diode laser technology and atomic spectroscopy. These instruments promise comparable performance to their larger counterparts but with a size and power dissipation each reduced by a factor of about 100. If space qualified, these instruments might be ideal for space missions where power and weight are critical. The design, fabrication and performance of MEMS-based atomic clocks, magnetometers and possibly gyroscopes will be discussed, as well as prospects for application to fundamental science in space.

40. Koenig, Friedrich, Thomas G. Philbin, Christopher E. Kuklewicz, Scott Robertson, Stephen Hill, and Ulf Leonhardt, University of St. Andrews
Fiber-optical analogue of the event horizon
We present a realistic scheme for an artificial event horizon in optics with ultrashort pulses in microstructured fibers that can probe the quantum effects of horizons, particularly Hawking radiation. We demonstrate experimentally how this artificial event horizon causes frequency shifts in probe light [1]. Our idea is based on nonlinear optical pulses in fibers. A pulse modifies the refractive index (Kerr effect) and forms an effective medium, moving at the speed of light. Consider also continuous-wave probe light, slowly catching up with the pulse. On approach, the cross-Kerr effect slows the probe to the group velocity of the pulse. The pulse's trailing end corresponds to a white-hole horizon; an object that light cannot enter. The Doppler shift is blue-shifting the light in analogy to frequency shifts at gravitational black- and white holes. In our microstructured fiber the 800nm wavelength of our mode-locked Ti:Sapphire laser exhibits the same group velocity as probe waves near 1500nm. We observed wavelength shifts exceeding 10nm at the horizon. Imagine a quantum field of light in a moving medium. For ultraviolet modes the medium moves superluminally and they oscillate

with negative frequencies in the co-moving frame for positive frequencies in the lab frame, and vice versa. Quantum-mechanically, negative frequencies correspond to creation operators. The horizon creates photon pairs. This process is the optical analogue of Hawking radiation. In our case, the pairs are distinguishable by polarisation and frequency from the pulses. We estimate a Hawking temperature of 10^3K. The first demonstration of Hawking radiation seems tantalizingly close.

[1] Philbin T. G., Kuklewicz C., Robertson S., Hill S., Konig F., Leonhardt U., Science **319**, 1367-1370 (2008).

41. Kopeikin, Sergei, University of Missouri-Columbia

Gravitational Physics of Reference Frames and Ranging Measurements

We discuss gravitational physics of reference frames in the solar system and various possibilities to measure it with the increasing capabilities of space-flight technologies. We pay particular attention to the ranging delay measurements conducted in gravitational field of a moving gravitating body (Sun, planet) and the way how it affects the observed values of the PPN parameters - gamma and beta.

42. Kusenko, Alexander, University of California, Los Angeles

Dark matter research in space

I will review the prospects for discovering the nature of dark matter using the space-based instruments.

43. Laemmerzahl, Claus, ZARM, University of Bremen

TBD

TBD.

44. Lane, Benjamin (Draper Laboratory), **Slava G. Turyshev**, **Michael Shao** (Jet Propulsion Laboratory)

Beyond Einstein Advanced Coherent Optical Network (BEACON)

The primary mission objective of the Beyond Einstein Advanced Coherent Optical Network (BEACON) mission is a search for new physics beyond general relativity by measuring the curvature of relativistic space-time (as characterized by the Eddington parameter "gamma") with unprecedented precision. The gamma-parameter is the most fundamental relativistic gravity parameter and is a direct measure of the presence of new any physical interaction.

BEACON will achieve a gamma-parameter measurement accuracy of one part in a billion (a factor of 30,000 beyond the present best result, viz. the 2003 test involving the Cassini spacecraft.) To achieve such precision BEACON uses four identical spacecraft placed in 80,000 km co-planar circular orbits around the Earth. The spacecraft form a flexible trapezoidal formation arranged such that one of the inter-satellite lines of sight passes close to the limb of the Earth. All six inter-satellite distances are measured to nanometer precision using laser ranging transceivers; this redundant "truss" architecture allows one to measure the additional gravitational delay with high precision and eliminates the need for expensive drag-free satellites. In addition, by placing the formation in geocentric orbit (vs. heliocentric) it is possible to rely on augmented GPS signals to navigate the spacecraft to the required levels of precision, vastly simplifying the required instrumentation.

The BEACON concept represents a combination of high sensitivity and comparatively low mission risk and cost, achieved by reliance on existing technologies where possible (laser metrology systems from the Space Interferometry Mission and GPS positioning) and by remaining in geocentric orbit.

45. Lee, Mark, NASA Headquarters.

Fundamental Physics on Space Shuttle and ISS

A history of NASA Fundamental Physics Program on Space Shuttle and International Space Station will be presented.

46. Loewenstein, Michael (NASA/GSFC,UMDCP, CRESST), **Alexander Kusenko** (UCLA), and **Peter L. Biermann** (MPI, UA, UAH)

Search for Warm Dark Matter with Suzaku Observations of Dwarf Spheroidal Galaxies

We have observed the Ursa Minor and Draco dwarf spheroidal galaxies with the Suzaku X-ray observatory to search for X-ray spectral lines emitted by radiatively decaying warm dark matter in the form of sterile neutrinos. These dense, dark-matter-dominated systems are the strongest potential sources of line emission from radiatively decaying keV dark matter of any astrophysical object. The low-level, stable background of the Suzaku CCD detectors makes it the most sensitive instrument to-date for this purpose. At the very least, constraints that enter a significant new regime may be derived. In the best case, the long sought-after identity of dark matter will be discovered, pointing the way to physics beyond the Standard Model. We present upper limits based on our preliminary analysis, and summarize the prospects for sharpening these constraints or detecting a signal below the present limits.

47. **Majewski, Steven R.,** U of Virginia
Exploring Local Dark Matter with the Space Interferometry Mission
The concordance LCDM models for formation of structure in the Universe, while remarkably successful at describing observations of structure on large scales, continues to be challenged by observations on galaxy scales. Fortunately, CDM models and their various proposed alternatives make a rich variety of testable predictions that make the Local Group a key laboratory for exploring dark matter (DM) in this regime. Some of the most definitive tests of local DM require microarcsecond astrometry of faint sources, an astrometric regime that is a unique niche of the Space Interferometry Mission (SIM).

I will highlight several important and distinct contributions that can be made by SIM in the exploration of galaxy dynamics and DM on galaxy scales and that have cosmological consequences. Key areas of potential SIM exploration include (1) measuring the shape, orientation, density law and lumpiness of the dark halo of the Milky Way and other nearby galaxies, (2) determining the orbits of Galactic satellites, which may be representatives of late infall from the hierarchical formation of the Milky Way, (3) ascertaining the distribution of angular momentum and orbital anisotropy of stars and globular clusters in the outer Galactic halo, which hold clues to the early hierarchical formation of these systems, and (4) measuring the physical nature of dark matter by measuring the phase space density in the cores of nearby dSph galaxies.

48. **Mielke, Eckehard W.,** Universidad Autonoma Metropolitana, Mexico
Toroidal halos in a BEC type scalar model of dark matter
Coherent soliton type solutions of an axion-like scalar model with self-interaction are analyzed as a toy model of dark matter halos. For a ``nonlinear superposition" of round and flattened configurations we found ring-like substructures in the density profile without a central cusp similarly as has been inferred for our Galaxy from the observed excess of the diffuse component of cosmic gamma rays. Under a conformal mapping of the background metric, a modified curvature Lagrangian emerges which bifurcates into several *almost Einsteinian* spacetime domains, distinguished only by different *effective* gravitational strengths and cosmological constant. cf., Phys. Rev. D75, 043504 (2007).

49. **Moffat, John** and **Viktor T. Toth,** Perimeter Institute
Observationally verifiable predictions of modified gravity
Modified Gravity (MOG) offers a viable alternative to the Lambda-CDM model of cosmology and astrophysics without exotic dark matter. The theory has been used successfully to account for the rotation curves of galaxies, the mass profile of galaxy clusters, and gravitational lensing by the Bullet Cluster. The theory is also consistent with key cosmological observations, including the CMB, the luminosity-distance relationship of Type Ia supernovae, and the acoustical and galaxy mass power spectra. As modified gravity does not possess non-baryonic dark matter, the baryonic oscillations in the galaxy mass power spectrum are not dampened, and their signature should be clearly detectable by future galaxy survey observations. On the scale of the solar system, the theory predicts a Yukawa-type deviation from Einstein gravity that is below observational limits. However, another aspect of the theory is that it violates Birkhoff's theorem, and as a result, may account for the origin of inertia, while a small deviation from Newtonian theory is predicted at very low accelerations, which may be testable by space-based experiments.

50. **Murphy, Thomas W. Jr.,** (UCSD) and E.G. Adelberger (UW), J.B.R. Battat (Harvard), C.D. Hoyle (Humboldt State), E.L. Michelsen (UCSD), K. Nordtvedt (Northwest Analysis), C.W. Stubbs (Harvard), H.E. Swanson (UW)
APOLLO: A Comprehensive Test of Gravity via Lunar Laser Ranging
The fundamental incompatibility of quantum mechanics with general relativity together with our well-quantified ignorance of large-scale gravity (dark energy, dark matter) strongly suggests that we intensify our tests of gravity. APOLLO (the Apache Point Observatory Lunar Laser-ranging Operation) is a new project that will bring about order-of-magnitude improvements in testing several fundamental aspects of gravity. Using a 3.5 meter telescope to bounce laser pulses off of the retroreflector arrays left on the moon by the Apollo astronauts, APOLLO is capable of one-millimeter range-precision. By determining the exact shape of the lunar orbit, it will be possible to test the equivalence principle, the time-rate-of-change of the gravitational

constant, gravitomagnetism, geodetic precession, and the inverse-square law to at least ten times better precision than currently tested. Details of the technique, millimeter-scale challenges, and performance to date will be presented.

51. **Nobili, Anna M.**, Universita' di Pisa e INFN and for the GG Collaboration
"Galileo Galilei" (GG) to Test the Equivalence Principle in Space: Improvements with the Laboratory Prototype
The small satellite GG aims at testing the Equivalence Principle to 10^{-17} using a very sensitive fast rotating differential accelerometer at room temperature. A full scale laboratory prototype of the accelerometer named GGG-"GG on the Ground", with the same physical properties and the same transducer as the one to fly, allows us to perform long duration measurement runs similar to those to be performed in space. The major difficulties on the ground are motor/bearings noise and low frequency terrain tilts, both absent in the space experiment because the GG satellite is an isolated co-rotating system. We present the results and show that how GGG is currently limited by diurnal tilts through the temperature dependence of the sensor on which the tilt control loop is closed, even though diurnal temperature variations inside the vacuum chamber are limited to 20 millidegree. Thanks to funding from ASI (Agenzia Spaziale Italiana) and INFN (Istituto Nazionale di Fisica Nucleare) we are constructing an improved GGG accelerometer in a specifically designed chamber, incorporating passive reduction of terrain tilts and an even better thermal stability. Measurement runs with the new apparatus are expected for this fall.

52. **Numata, Kenji**, University of Maryland/NASA-GSFC
DECIGO : The Japanese Space Gravitational Wave Antenna
DECi-hertz Interferometer Gravitational wave Observatory (DECIGO) is a future Japanese space gravitational wave antenna. The goal of DECIGO is to detect gravitational waves from various kinds of sources, in particular the inflation of the universe, between 0.1 Hz and 10 Hz. DECIGO will consist of three drag-free spacecrafts, 1000 km apart from each other, whose relative displacements are measured by a Fabry-Perot Michelson interferometer. In order to test technologies required for DECIGO, demonstration mission is also planned as DECIGO pathfinder (DPF). DPF will be a small satellite, orbiting the earth along a sun-synchronous orbit. The conceptual design and current status of DECIGO and DPF will be reviewed in this talk.

53. **Overduin, James, C.W. Francis Everitt, John Mester**, and **Paul Worden**, Stanford University
The Science Case for STEP
STEP, the Satellite Test of the Equivalence Principle, will advance experimental limits on violations of Einstein's equivalence principle (EP) from their present sensitivity of 3 parts in 10^{13} to 1 part in 10^{18}. The experiment will perform multiple comparisons of the motions of four pairs of test masses of different compositions in an earth orbiting drag-free satellite. EP violations are predicted by many of the leading attempts at unified theories of fundamental interactions (e.g. string theory), as well as cosmological theories involving dynamical dark energy. Dimensional arguments suggest that these violations, if they exist, should be found in the range accessible by STEP. Discovery of a violation would constitute the discovery of a new force of nature and provide us with a critical signpost toward unification. A null result would be just as profound, because it would close off any possibility of a natural-strength coupling between standard-model fields and the new light degrees of freedom that nearly all such theories generically predict (e.g., dilatons, moduli, quintessence). STEP can be viewed as the intermediate-scale component of an integrated strategy for fundamental physics experiments that already includes particle accelerators (at the smallest scales) and supernova probes (at the largest). The former may find indirect evidence for new fields via their missing-energy signatures, and the latter may produce direct evidence through changes in cosmological equation of state – but only a gravitational experiment like STEP can go further and reveal how or whether such a field couples to the rest of the standard model. STEP is at once complementary to the other two kinds of tests, and a uniquely powerful probe of fundamental physics in its own right.

54. **Paik, Ho Jung, Lvyuan Chen** and **M. Vol Moody**, University of Maryland
SMART to Test the Equivalence Principle and the Inverse-Square Law
We propose to develop critical technologies and perform a design study for the SMART (Standard Model And Relativity Test) mission, which will test the Equivalence Principle (EP) to 10^{-18} and the gravitational inverse-square ($1/r^2$) law to 10^{-5} at 100-micrometer range.

Newton's $1/r^2$ law is a cornerstone of General Relativity. The theoretical rationale for testing Newton's law below 1 mm is compelling. The "strong CP problem" in the Standard Model of particle physics has led to the prediction of the "axion," which mediates a short-range mass-mass interaction and is a strong candidate for cold dark matter. Another impetus for testing the law of gravitation at short ranges comes from higher-dimensional string theories. A possibility that the law changes from $1/r^2$ as r goes below 0.1 mm has been suggested.

The EP is another cornerstone of General Relativity. Yet many models of the unified quantum theory of gravity, matter, and energy prefer a scalar-tensor theory and suggest a violation of this principle. In the string theory, the tensor gravitational field has two partners: a scalar field (dilaton) and an antisymmetric tensor field. They are coupled to the other fields with gravitational strength, but in ways generally violating EP. Many scalar and pseudo-scalar partners of the graviton may survive as massless particles in the four-dimensional low energy world.

To reach the sensitivities of SMART, superconducting accelerometer technology will be combined with advantages of the low-g environment of space. The experiment will be cooled to 1.5 K, which permits superconducting magnetic levitation, allowing very soft, low-loss suspension of the test masses. To minimize Newtonian errors, the $1/r^2$ law test employs a null Newtonian gravity source, a rotating circular disk with thin layers of materials of high density contrast. Unlike STEP, which utilizes test masses of cylindrical geometry, the SMART utilizes test masses of near spherical-shell geometry for the EP test. The spherical shell reduces higher multipole moments of the test masses and permits a simpler levitation and alignment scheme. The signals for both experiments are detected by superconducting differential accelerometers formed by pairs of levitated test masses.

55. Pickett, George, U of Lancaster, UK
Superfluid Helium-3: A Tabletop Universe
The wavefunction of superfluid 3He has a very similar broken symmetry-structure to that of the Universe after the transitions separating the strong, weak and E-M forces. The analogies are close enough that we can use the superfluid 3He condensate at very low temperatures (where there is no normal fluid) as a model system for studying a wide range of cosmological phenomena. We shall present the similarities between the superfluid and the Universe metric and illustrate the sort of experiments we can do by, among other things, looking first at quantized vortices in the superfluid as analogues of cosmic strings, and their production by the Kibble Zurek mechanism analogously to the similar postulated production of cosmic strings. Secondly, we will look at the phase interface between the two different phases of superfluid 3He (the A- and B-phases) which is the most coherent two-dimensional structure to which we have experimental access. This structure is our best current analog of a cosmological brane. We describe experiments where we annihilate two such "branes" and detect the topological defects left in the superfluid "metric" after the annihilation. Braneworld scenarios are so far removed from everyday intuition that analog laboratory experiments can provide valuable insight as well as validating those braneworld models which predict relic topological defects from brane annihilation.

56. Prestage, John, Sang Chung, Robert Thompson, Robert Tjoelker, Eric Burt, Meirong Tu, and Talso Chui, JPL
Developments in Compact Hg Microwave Ion Clocks for Fundamental Physics in Space
We have recently completed a small breadboard Hg Ion clock with frequency stability 10^{-15} at one-day averaging time interval using Hg trapping technology that delivers frequency stability into the low 10^{-16} range. When operated with a stable Local Oscillator, short-term stabilities ~$3x10^{-14}$/root tau can be generated that average down to low 10^{-16}.

A 1 kg engineering model clock physics package is currently being fabricated with short-term frequency stability competitive with ground based hydrogen masers and long-term stability 10-100 times better than current Rubidium space clocks. Challenges in miniaturizing the ultra-stable clock will be outlined.

Several novel features are developed for long term reliability including the first use of a sealed tube approach to the Ion-Clock vacuum system. Ion trapping architectures that increase clock short-term stability and also shorten the local oscillator frequency tracking response time will be described.

We will discuss a novel line acquisition method where signal measurements at 3 points on the curve are used to determine the line center, ion signal size and light level from the lamp. This also provides the means for reacquisition of frequency lock following a local oscillator frequency hop, with much less than a nanosecond timekeeping error.

We will also discuss novel microwave-rf transitions in Hg that may be very useful in reducing the level of magnetic shielding required for ultra stable operation.

57. Reynaud, Serge, Laboratoire Kastler Brossel, Paris
Testing general relativity in the solar system
Tests of gravity performed in the solar system show a good agreement with general relativity. The latter is however challenged by observations at larger, galactic and cosmic, scales which are presently cured by introducing dark matter or dark energy. A few measurements in the solar system, particularly the so-called Pioneer anomaly, might also be pointing at a modification of gravity law at ranges of the order of the size of the solar system. The current status of tests of general relativity in the outer solar system will be discussed.

58. Reynolds, Christopher S., University of Maryland
Black Hole Physics with Constellation-X
At the current time, observations in the X-ray band have provided the cleanest window on the behavior of matter very close (within a few gravitational radii) of astrophysical black holes. As well as detecting the highest gravitational redshifts to date, developments in both instrumentation and accretion theory are now allowing us to examine fundamental issues such as black hole spin. After briefly reviewing the current state-of-the-art, I will describe how the enormous improvement in collecting area and spectral resolution provided by Constellation-X will take these studies to the next level. Constellation-X will allow the measurement of the spins of hundreds of supermassive black holes, literally providing a new dimension against which models of black hole formation and growth can be tested. The connection between black hole spin and the presence of powerful jets will allow the first assessment of the role that spin-energy extraction plays in the Universe. Finally, I will describe how short time-scale spectral variability can be used to both examine the processes behind the enormous energy output associated with accretion disks, and search for (gross) deviations from General Relativity close to the event horizon.

59. Reasenberg, Robert D. and James D. Phillips, Smithsonian Astrophysical Observatory
A Sounding Rocket Test of the WEP
We are developing SR-POEM, a sounding-rocket variant of our laboratory-based principle of equivalence measurement (POEM). In SR-POEM, we perform the measurements while on the upper portion of the free-fall trajectory provided by a sounding rocket. At this high altitude at night, traveling at modest speed and well above the trace of atmosphere found at LEO, drag acceleration is suppressed below the acceleration caused by radiation pressure from a warm Earth. The instrument measures the motion of the four test mass assemblies (TMA) with respect to the freely falling payload. The goal for this experiment is an accuracy from a single flight of at least ~($\triangle g/g$) = 10^{-16}, a three order-of-magnitude improvement over the present best ground-based work. The experiment uses our picometer laser gauge (TFG) to compare the acceleration of two substances. The TFG is augmented to automatically adjust the incoming laser beam to meet the cavity condition as the TMA moves. The experiment has a total of four TMA so as to form a double-difference observable, uses a multi-channel capacitance gauge to measure secondary motions of the TMA, and inverts the orientation of the apparatus to reverse the WEP manifestation and thus allow the cancellation of systematic error. In this talk, we will describe the instrument and give the status of the project.

60. Russell, Neil, Northern Michigan University, Physics Dept
Constraining spacetime torsion
Torsion is an additional spacetime warping appearing in some alternative theories of gravity. I will discuss new and first constraints on 19 of the 24 torsion components, derived from precision experiments with dual masers and with spin-polarized matter.

61. Salamon, Michael, HASA Headquarters
Fundamental Physics at NASA
To set the stage for a discussion of fundamental physics at NASA, an up-to-date overview of missions and programs within NASA's Astrophysics is given along with current budgetary issues. The present state of fundamental physics missions and research in Astrophysics is then described, along with prospects for the

next decade. The role of the upcoming Astronomy and Astrophysics Decadal Survey with regard to fundamental physics will also be discussed.

62. **Salomon, Christophe** (Ecole Normale Supérieure) and **Luigi Cacciapuoti** (ESA)

Fundamental Physics with Space Clocks

We will present the status of the ACES mission of the European Space Agency scheduled for flight to the International Space Station at the end of 2012 [1]. In 2007-2008, all elements of the flight payload have successfully passed the Engineering Model tests. These include the cold atom clock PHARAO developed by CNES, the Space Hydrogen Maser developed by the Swiss Space Office, and the onboard frequency comparator and time transfer system developed by ESA. We will present the latest measurement results and flight model designs.

In a second part we will describe tests of fundamental physical laws using ultra-stable clocks in space and on the ground, that are planned for the ACES mission. By comparing clocks of different nature new limits are obtained for the time variation of the fundamental constants of physics such as the fine structure constant alpha and the ratio of electron to proton mass. The ability to compare microwave and optical clocks using the newly developed frequency comb technique opens a wide range of possibilities in clock comparisons. An improved test of general relativity will be performed, such as a measurement of Einstein's gravitational red-shift at the one part per million level. A new kind of relativistic geodesy based on the Einstein effect will provide information on the Earth geoïd. Finally prospects for laser cooled atomic clocks operating in the optical domain with frequency stability in the 10^{-18} range will be outlined.

References

[1] C. Salomon, L. Cacciapuotti, and N. Dimarcq, Int. Journ. Mod. Phys. D 16, 2511 (2007)..

63. **Sanders, Alvin J.**, Oak Ridge National Laboratory

Was Woit GNORW?

Various gravitational and cosmological measurements hold promise for tests of string theories (by which term we mean to include most extra-dimension models). Combinations of cosmological parameters, such $\dot{G}$, Ω_{JBD}, and the decceleration parameter q_0, may be able to provide tighter constraints, regarding which models are physically allowable, than would be possible with any single parameter. Carrying out such a program would probably require making new space-based measurements and combining the results with other existing cosmological data. Illustrative results are given. Such an approach would address some of the concerns of Peter Woit, who has prominently criticized string theories and theorists as having veered into pure mathematics and out of the realm of physics, most notably in his book "Not Even GNORW". If it is appropriate to read Woit's criticism as meaning that string theories are virtually untestable as well as untested, we respectfully dissent. Finally, we note that Project SEE (Satellite Energy Exchange) has in fact sponsored some research in tests of string-theory [1], which obtained useful constraints on PPN parameters using a specified class of extra-dimension models. Thus, future tighter limits on PPN parameters will vet these models for physical reality or lack thereof. This work was written up in NASA Fundamental Physics "Significant Events" [2].

[1] V.D. Ivashchuk, V.S. Manko, & V.N. Melnikov, "PPN Parameters for General Black Hole and Spherically Symmetric p-Brane Solutions", Gravitation & Cosmology v.6 No.3 (23), pp. 219-224 (2001).

[2] http://funphysics.jpl.nasa.gov/technical/library/sig-events-01/sig011214-science-b.html.

64. **Sahni, Varun**, Inter-University Centre for Astronomy and Astrophysics

An Artificial Planetary System in Space (APSIS) to probe modifications to the inverse square law and the possible existence of extra dimensions

A proposal is made to test Newton's inverse-square law using the periapsis shift of test masses (planets) in free fall within a spacecraft located at the Earth--Sun L2/L1 point. Such an Artificial Planetary System In Space (APSIS) will operate in a drag-free environment with controlled experimental conditions and minimal interference from terrestrial sources of contamination. The presence of extra dimensions could lead to modifications of the inverse square law of gravity on small scales. In such theories closed orbits would be absent and the quasi-elliptical orbit of two gravitationally bound test bodies (planets) would show a shift in its major axis (peripasis). Such a shift could provide a signature of extra dimensions and non-Einsteinian gravity. We demonstrate that APSIS can probe the presence of a "hidden" fifth dimension on the scale of a micron if the periapsis shift of a "planet" can be measured to sub-arc-second accuracy. The planets in APSIS will have small relative accelerations (~10^{-8} cm/sec^2) and could therefore be useful for testing the MOND hypothesis.

65. **Schleich, Wolfgang P.,** Institut für Quantenphysik, Universität Ulm
Fundamental physics in space
We briefly review our activities in the field of fundamental physics in space. In particular, we summarize ideas concerning the measurement of the rotation of the universe using interferometric methods. These ideas are stimulated by the model of the Goedel universe. Here we present simulations of the light propagation. Another topic will be the time evolution of a Bose Einstein condensate in microgravity. This work is closely connected to the experiments at the Bremen drop tower. In this context we speculate about the influence of the measurements in quantum mechanics for BECs of macroscopic size.

66. **Shao, Michael, Slava G. Turyshev** (Jet Propulsion Laboratory) **Benjamin Lane** (Draper Laboratory)
Technologies for Ultra Precise Distance and Angle Measurements in Space
Missions like LATOR and Beacon are tests of relativity that make use of over constrained geometries to measure deviations from Euclidean geometry. These missions require very precise, picometer level, measurement of distances from 100's of meters to ~a million meters. Laser heterodyn metrology is a standard method for measuring long distances with very high accuracy. Less discussed are the optical fiducials that define what the metrology is measuring. But if improperly designed or manufactured or improperly calibrated, systematic errors in the fiducials can be several orders of magnitude larger than the picometer accuracy needed in many such concepts. Many of the components for long distance metrology have been developed for other missions such as the Space Interferometry Mission; this talk discusses what has been done and what areas need further work.

67. **Shaya, Edward J.,** U of Maryland
Dark Matter on 1-5 Mpc Scales
TBD

68. **Shawhan, Peter S.**, U of Maryland, for the LIGO Scientific Collaboration
Gravitational Wave Detection from the Ground Up
Gravitational wave detectors in space will carry on the heritage of ground-based detectors, but with different science goals and technical challenges. I will describe the current status and future plans for the ground-based gravitational wave observatories. In particular, LIGO, Virgo, and GEO have reached astrophysically interesting sensitivity levels and have collected a significant amount of good data, which is currently being analyzed. "Enhanced" and "Advanced" detector upgrades are underway to increase the reach of LIGO and Virgo, with detection of gravitational wave signals expected to become routine in the middle of the next decade. I will also describe plans and ideas for the farther future.

69. **Strohmayer, Tod E.** (NASA/GSFC), for the Constellation-X Facility Science Team
Neutron Star Fundamental Physics with Constellation-X
Astrophysical observations of neutron stars provide a unique opportunity to probe the limits of physical theories, in particular, the equation of state of ultra-dense matter and the strong-field limit of relativistic gravity. Constellation-X is NASA's next facility-class X-ray observatory. It represents a factor of 100 increase in throughput over CHANDRA and XMM-Newton for high resolution X-ray spectroscopy in the 0.2 - 10 keV band. I will describe the contributions Con-X can make in studying the extreme physics at work in neutron stars. Con-X will make very deep searches for absorption lines from neutron star atmospheres. I will discuss how the detection of such lines can be used to measure the mass and radius of neutron stars, and thus constrain the dense matter equation of state. Measurement of pulse profiles from millisecond X-ray pulsars and X-ray burst oscillations will also provide mass - radius information. Measurement of rotationally broadened lines from neutron star surfaces could also provide a way to probe General Relativistic frame dragging.

70. **Takahashi, Yoshiyuki,** The University of Alabama in Huntsville
Extreme Universe Space Observatory (EUSO) on board Japanese Experiment Module (JEM) of ISS and the quest of highest energy universe
Experiments The Extreme-Universe Space Observatory (EUSO) on Japanese Experiment Module (JEM) is an international mission on ISS, led by Japan Aerospace Exploration Agency (JAXA) to investigate the nature and origin of extremely-high-energy cosmic particles (EHECRs). This is the sole window on the extreme-energy

universe. JAXA has selected JEM-EUSO for Phase A/B study as one of two international mission candidates for installation on the JEM Exposure Facility by 2013. JEM-EUSO is designated to pioneer measurements of EHECR-induced extensive air showers (EAS) from space. As the detector, it uses the whole earth, observing from the International Space Station (ISS) where a remote sensor is located. The signal is fluorescent and Cherenkov light from the Extensive Air Showers (EAS). There may be significant sources of the highest energy particles near our galaxy within 50Mpc. Observable particles include baryons, gamma rays and neutrinos, all keep linear tracks to the origin at this energy, and qualified as the new messenger for astronomy. Sources could include the well-known brightest radio-galaxies (Centaur-A and Virgo M-87), or could be unknown objects. If many of the events do not point to any known objects, one may even question the validity of non-local relativity associated with external cosmological fields or other fundamental physics principles may be invoked. The observations to date may or may not be right, and the puzzle at the energy frontier of universe is awaiting more decisive explorations. This astronomical telescope is not directed toward the universe, but rather looks down toward the earth's surface. Whereas an ordinary astronomical observatory looks up at the universe from earth, JEM-EUSO observes the universe by looking toward the earth because the earth's atmosphere is the largest detector yet employed in our quest to understand the origins of these elusive particles coming from the universe. JEM-EUSO is a new type of astronomical observatory, namely, an "earth-observing" astronomical observatory.

71. **Tegmark, Max,** MIT
    Cosmology from space
    TBD

72. **Tino, Guglielmo M.,** Dipartimento di Fisica and LENS - Universita' di Firenze
    Precision Experiments on Gravity by Atom Interferometry
    Experiments we are performing using atom interferometry to determine the gravitational constant G [1] and test the Newtonian gravitational law at micrometric distances [2] will be presented. Other experiments in progress, planned or being considered using atom interferometers in ground laboratories [3] and in space [4] will be also discussed.
    References:

    [1]. G. Lamporesi, A. Bertoldi, L. Cacciapuoti, M. Prevedelli, G. M. Tino, *Phys. Rev. Lett*. **100**, 050801, (2008).
    [2]. G. Ferrari, N. Poli, F. Sorrentino, and G. M. Tino, *Phys. Rev. Lett*. **97**, 060402, (2006).
    [3]. M. de Angelis, A. Bertoldi, L. Cacciapuoti, A. Giorgini, G. Lamporesi, M. Prevedelli, G. Saccorotti, F. Sorrentino, G.M. Tino, to be published.
    [4]. G. M. Tino, L. Cacciapuoti, K. Bongs, Ch. J. Bordé, P. Bouyer, H. Dittus, W. Ertmer, A. Görlitz, M. Inguscio, A. Landragin, P. Lemonde, C. Lammerzahl, A. Peters, E. Rasel, J. Reichel, C. Salomon, S. Schiller, W. Schleich, K. Sengstock, U. Sterr, M. Wilkens, *Nuclear Physics B* (PS) **166**, 159, (2007).

73. **Thomsen, Jan, W.**, Andrew D. Ludlow, Gretchen K. Campbell, Sebastian Blatt, Michael J. Martin, Tanya Zelevinsky, Martin M. Boyd, and Yun Ye, JILA, NIST and University of Colorado
    High accuracy 87Sr atomic lattice clock for laboratory measurements of alpha variation
    High precision measurements in atomic and molecular systems have reached unprecedented accuracy owing to the state-of-the-art quantum control of both light and matter. We have recently completed an evaluation of the uncertainty of our 87Sr optical lattice clock at the $1x10^{-16}$ fractional level, surpassing the best current evaluations of Cs primary standards. By analyzing worldwide measurements of the absolute frequency of the clock transitions in Sr, we constrain temporal variations of fundamental physical constants as well as their possible couplings to the gravitational potential. We will report the latest results on our 87Sr optical atomic clock, as well as the use of the Sr system to constrain variations of the fine-structure constant.

74. **Vachaspati, Tanmay**, IAS, Princeton/CWRU, Cleveland
    Cosmic Magnetic Fields and Baryogenesis
    Sphaleron-mediated baryogenesis models imply a remarkable connection between primordial magnetic helicity and baryon number density. The observed baryon number density then implies a primordial magnetic field at the present epoch which can be of nano Gauss strength with coherence scale on the order of parsecs.

75. **Wandelt, Benjamin D.**, University of Illinois at Urbana-Champaign
    Fundamental Physics with Planck

Test…..

76. **Weber, William, J.,** Università di Trento and INFN
Ground testing of free-fall for LISA Pathfinder, LISA, and future space missions requiring high purity geodesic motion
Geodesic motion is a critical aspect of many ambitious fundamental physics experiments in space, including the LISA gravitational wave observatory, where the deviation from perfect free-fall must be limited to an acceleration noise below 3 10-15 m/s2/sqrt(Hz) (or 3 fm/s2/sqrt(Hz)) at frequencies at and below 1 mHz. In this talk, we report on laboratory investigations of the limits for achieving free-fall. Our discussion will focus on torsion pendulum small force measurements performed with prototype capacitive "gravitational reference" sensors for the LISA Pathfinder mission. Such tests have allowed us to place an upper limit of 100 fm/s2/sqrt(Hz) at 1 mHz on the stray acceleration caused by forces acting on the surfaces of the LISA PF and LISA test masses. We will present the key acceleration noise sources for LISA in light of the experimental data, and we will discuss how these studies – of a cubic, conducting LISA test mass inside a conducting electrostatic shield – can be applied to the general problem of placing objects into geodesic motion.

77. **Yu, Nan, John Dick, Meirong Tu, Kevin Birnbaum, and Dmitry Strekalov,** (JPL) and **Ertan Salik (**California State Polytechnic University, Pomona)
Coherent Optical Transponder at Femto-Watt Light Levels
We investigated two schemes for coherent optical transponder at extremely low light levels. Optical phase locking at femto-watt levels has been demonstrated and characterized. We will report the results of both Doppler and ranging experiments in the phase lock loop configuration. We also discuss an alternative "injection seeded" approach, and it's ranging experiments.

78. **Zharov, Vladimir E., M.V. Sazhin, K.V. Kuimov, V.N. Sementsov, O.S. Sazhina, and E.A. Rastorgueva** (Sternberg Astronomical Institute, Moscow, Russia)
Apparent motion of extragalactic radio sources
The XXVIth General Assembly of IAU formed a working group with a purpose to oversee the generation of the second realization of the ICRF from VLBI observations of extragalactic radio sources. The reference frame will apply state-of-the-art astronomical and geophysical models in the analysis of the entire relevant S/X bands astrometric and geodetic VLBI data set. The working group will ensure the selection of defining sources and the mitigation of source position variations and the consistency with the ITRF and the IERS EOP to improve the stability of the ICRF.

Here we propose the new method of selection of the reference sources or sources that should ideally show no variation of position. We use time series of coordinates of the sources obtained by different groups with different software tools to calculate parameters of stochastic sets. Among these parameters are coefficients of regression and degree of best fit polynomial. Our aim is to predict source coordinates variation and to calculate the confidence interval of it for 2025 year. This interval can be used as criteria for categorization of the sources.

Many extragalactic sources reveal both trends (linear, quadratic, etc) and short (from one to several years) periodic coordinates variation. For instance, the source 1044+719 shows both these phenomena. We discuss physical model of these variations. The model allows explaining apparent motion of the extragalactic sources (proper motion, acceleration, and short term variation of coordinates).

Main conclusion is: the new ICRF catalog has to contain both coordinates (right accession and declination) of the selected radio sources and parameters of their motions.

POSTERS:

1. **Dittus, Hansjoerg**, B. Rievers, C. Lämmerzahl, M. List, S. Bremer ZARM, University of Bremen
Heat dissipation and thermal models of satellites with drag-free attitude control
Heat dissipation onboard spacecraft leading to resulting accelerations need to be analyzed in detail. In particular, asymmetric heat dissipation disturbs spacecraft with highly precise attitude and orbit control as well as satellites in close formation flight as proposed for various fundamental physics space missions. We developed a method to calculate thermal forces with very high precision by means of Finite Element (FE)

modeling and ray-tracing algorithms. The elaborated method contains (i) the modeling of the spacecraft geometry in FE and the generation of a steady state temperature surface map and (ii) the computation of the resulting thermal force by ray-tracing. Results for some mission scenarios are presented.

2. **Sun, Ke-Xun Sun, Saps Buchman, Robert Byer, Dan DeBra, Graham Allen, John Conklin, John Goebel, Sei Higuchi, Nick Leindecker, Patrick Lu, Aaron Swank, Edgar Torres, Martin Trittler,** Stanford University
Modular Gravitational Reference Sensor (MGRS): A core fiduciary instrument for space gravitational science
The Modular Gravitational Reference Sensor (MGRS) is targeted as a next generation core instrument for space gravitational wave detection and an array of precision experiments in space. The MGRS by far is the only 3-dimensional gravitational reference sensor design, with redundant internal measurements to proof mass, and flexibility of configurable external measurements to remote spacecraft or ground stations.
We will give a balanced overview of the MGRS development at Stanford University. We will report progresses in system technologies, two layer sensing and control scheme, trade-off studies of GRS configurations, optical displacement and angle sensors, multiple optical sensor signal processing, diffractive optics, mass center determination, moment of inertial measurement, UV LED charge management, proof mass fabrication, thermal control and sensor development, differential optical shadow sensing, characterization for various proof mass shapes, alternative charge manage techniques, and potential tests using small satellites. MGRS will be a promising technology for future space gravitational sciences.