

Physics of the Cosmos Program Analysis Group (PhysPAG) Report on Flagship Mission Concepts to Study for the 2020 Decadal Survey

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Physics of the Cosmos Executive Committee

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1. Joint PAG Statement

This is a joint summary of the reports from the three Astrophysics Program Analysis Groups (PAGs) in response to the charge given to the PAG Executive Committees by the Astrophysics Division Director, Paul Hertz, in the white paper "Planning for the 2020 Decadal Survey", issued January 4, 2015. This joint executive summary is common to all three PAG reports, and contains points of consensus across all three PAGs, achieved through extensive discussion and vetting within and between our respective communities. Additional information and findings specific to the individual PAG activities related to this charge are reported separately in the remainder of the individual reports. These additional findings are not necessarily in contradiction to material in the other reports, but rather generally focus on findings specific to the individual PAGs.

The PAGs concur that all four large mission concepts identified in the white paper as candidates for mission concept maturation prior to the 2020 Decadal Survey should be studied in detail. These include the Far-IR Surveyor, the Habitable-Exoplanet Imaging Mission, the UV/Optical/IR Surveyor, and the X-ray Surveyor. Other flagship mission concepts were considered, but none achieved sufficiently broad community support to be elevated to the level of these four primary candidate missions.

This finding is predicated upon assumptions outlined in the white paper and subsequent charge, namely that 1) major development of future large flagship missions under consideration are to follow the implementation phases of the James Webb Space Telescope (JWST) and the Wide-Field InfraRed Survey Telescope (WFIRST); 2) NASA will partner with the European Space Agency on its L3 Gravitational Wave Surveyor, participate in preparatory studies leading to this observatory, and conduct the necessary technology development and other activities leading to the L3 mission, including preparations that will be needed for the 2020 decadal review; and 3) that the Inflation Probe be classified as a probe-class mission to be developed according to the technology and mission planning recommendations in the 2010 Decadal Survey report. Physics of the Cosmos PAG (PhysPAG) sought input on the mission size category for this mission and finds that it is appropriately classified as a Probe-class mission. If these key assumptions were to change, this PAG finding would need to be re-evaluated in light of the changes.

The PAGs find that there is strong community support for the second phase of this activity - maturation of the four proposed mission concept studies. The PAGs believe that these concept studies should be conducted by scientists and technical experts assigned to the respective Science and Technology Definition Teams (STDTs). The PAGs find that the community is concerned about the composition of these STDTs and that there is strong consensus that all of the STDTs contain broad and interdisciplinary representation of the science community. The PAGs also find that the community expects cross-STDT cooperation and exchange of information whenever possible to facilitate the sharing of expertise, especially in the case of the UVOIR Surveyor and the Habitable-Exoplanet Imaging Mission, which share some

science goals and technological needs. The PAGs concur that a free and open process should be used to competitively select the STDTs.

Finally, the PAGs find that there is community support for a line of probe-class missions within the Astrophysics Division mission portfolio. The PAGs would be willing to collect further input on probe missions from the community as a following strategic planning charge if asked to do so by the Astrophysics Division Director.

2. Summary of PhysPAG Findings

To address the charge on flagship missions given to the PAGs by Paul Hertz (http://science.nasa.gov/media/medialibrary/2015/01/28/White_Paper_-_Planning_for_the_2020_Decadal_Survey_-_signed.pdf), the PhysPAG collected community input through conference and town hall sessions, and PhysPAG SIG splinter meetings and described in the Appendix.

2a. Findings on Flagship Missions

The findings of the PhysPAG agree with those of the joint PAG statement given in § 1. These flagship missions offer exciting opportunities for astrophysics, including scientific themes of particular interest to the Physics of the Cosmos community. Beyond these universal joint findings, the PhysPAG separately finds the following:

- 1) *The ESA L3 gravitational wave mission is compelling and we look forward to seeing this mission being fully prepared for the US 2020 Decadal review.*

Appropriate developments are described in § 2c and the revolutionary science enabled by this mission is described in § 4a.

- 2) *We agree with the assumption given in the charge that the Inflation Probe mission should be planned as probe-class. Recent studies of comparable implementations in Europe (CORE+) and Japan (LITEBIRD) broadly correspond to the NASA probe cost category. Furthermore a spectro-polarimetric implementation with low spatial resolution (PIXIE) was proposed as a MIDEEX mission. We note that a more definitive statement about the cost of a NASA mission requires a dedicated study, which will be necessary for the 2020 Decadal Review, and which may help better define the parameters of a probe mission category or categories.*

Issues for planning for the inflation probe are discussed in § 2d and its science is described in § 4b.

- 3) *We assume that the ESA L2 ATHENA mission will progress with NASA participation to a stage of development such that it will not be reviewed by the 2020 Decadal Review. If this is not the case, then we urge NASA, in coordination with ESA, to make appropriate preparations for presenting ATHENA to the 2020 Decadal Review.*

- 4) *The flagship mission studies should fulfill scientific objectives broadly, to the extent possible. We encourage the STDTs to build upon these PCOS themes in planning the scientific capabilities when developing the flagship missions.*

We have described scientific themes of particular interest to the PCOS community in § 3.

- 5) *For possible future development of probe missions, we note the historical success of the NASA Explorer mission line of completed missions, and its strong support in the scientific community. We anticipate that the scientific community will benefit from NASA guidance in defining the probe-class mission category or categories as part of the process of developing probe missions for the 2020 Decadal Review.*

Issues discussed in the community for planning for probes are discussed in § 2e and examples of potential PCOS science that can be accomplished as probe missions are discussed in § 5.

2b. Preparing the L3 Gravitational-Wave Mission for the 2020 Decadal

With a long history of strong science recommendations, LISA is the highest ranked large mission of the Astrophysics Division after WFIRST. Changes in the budgetary landscape have meant that NASA has been unable to initiate a new start for LISA in the 2010 decade, and financial support for LISA has fallen significantly below that recommended in the 2010 Decadal report. Following the termination of the joint NASA-ESA LISA project, ESA decided to pursue a similar mission with the selection of the "Gravitational Universe" theme for the L3 launch opportunity in the Cosmic Visions program.

The Astrophysics Division white paper "Planning for the 2020 Decadal Survey" mentions plans for independent NASA studies and technology development activities in this decade that will lead toward realization of a Gravitational Wave Surveyor through U.S. participation in ESA's L3 "Gravitational Universe" mission. The GW community endorses these plans for NASA investment in a LISA-like mission, acknowledging that a NASA partnership in L3 represents an important opportunity. The community feels strongly (and unanimously) that a viable partnership with ESA needs immediate action from NASA.

While it is crucial to closely engage in ESA's LISA Pathfinder mission and L3 technology preparation in pursuit of a vigorous U.S. role, realization of NASA participation in such a Gravitational Wave Surveyor mission will also require a strong recommendation in the 2020 Decadal Survey. The next decadal committee will be able to draw on materials prepared for the previous decadal survey, and the results of ESA-led activities. But further study is required to assess new developments in science and technology that impact the science case, cost, risks and technical readiness, particularly in relation to the U.S. role in L3. The goals of such a study should encompass the following:

1. Evaluate all technologies needed to realize the gravitational wave mission architecture guided by ESA's and NASA's latest studies and define the combinations of technologies that are compatible with the needs and capabilities of the space agencies involved.
2. Define a range of options for various potential NASA contributions to the L3 mission. The study should evaluate a set of perhaps three or four options which span a large range of potential NASA contributions to evaluate their science return, cost and risk.
3. Assess the science cases for U.S. participation options, and update the science case for LISA based on knowledge gained since the preparation for the 2010 Decadal Survey.
4. Assess the size and scope of the U.S. LISA Science Team and needs for a U.S. Data Center to support the L3 collaboration in science, technology, and data analysis.

2c. Preparing the Inflation Probe Mission for the 2020 Decadal

The Inflation Probe requires appropriate NASA investment as well as continued scientific and technical leadership by the U.S. scientific community. The 2010 Decadal Survey provides guidance to NASA regarding technologies required to develop the next generation orbital mission, referred to as the Inflation Probe. This mission was identified as a strategic astrophysics objective in the 2014 Roadmap and as a science goal in the 2010 Decadal Survey. The Decadal Survey called for a robust technology development program in preparation for the mission as well as a mid-decade review of the science and technology requirements to support these objectives. In particular, the decadal committee identified systems for detecting the polarization of the CMB as a high-priority science need for mid-term technology investments, and recommended an augmentation of support to ramp up toward the end of the decade. This plan builds upon the field's long and successful history of demonstrating new technologies in ground-based and sub-orbital experiments.

The consensus view of the U.S. community is that the appropriate class for the Inflation Probe CMB polarization surveyor is a probe class mission, which should be studied for presentation to the 2020 Decadal Review. It will be important in conjunction with this study to remain cognizant of related developments toward a space-based CMB polarization observations including the status of the JAXA and NASA MO Litebird, NASA Midex, and ESA M-class mission studies.

In preparation for the Inflation Probe, investments should be made to update designs and cost-estimates for a probe-class mission in advance of the 2020 Decadal Review to refine the detailed mission specifications. Realizing the robust and increasing support for technology development called out in the 2010 Decadal Report will be also be essential. Finally, in addition to the complementary ground-based technology development and observations, the balloon-borne program, also explicitly endorsed by the 2010 Decadal Review, must continue in order to access frequency

bands not available from the ground and to complete the advancement of mission-critical technologies to the final stage.

Finally, we note that a segment of the CMB community has been advocating for a new ground-based CMB polarization program called S4. We feel S4 is naturally complementary with the Inflation Probe, as ground-based experiments are required for measuring fine angular scales, while a satellite offers unsurpassed measurements of large angular scales with complete spectral coverage for comprehensive foreground removal. NASA planning should be coordinated with these efforts to maximize the natural synergies between ground-based and space-based observations. The overlap in objectives provide a natural opportunity to enhance the science returns from both in terms of challenges such as control systematic errors, foreground component separation, and cross-calibration. Technological synergies with S4 should also be actively investigated and leveraged for the Inflation Probe.

2d. Importance of Probe-Class Missions

Our outreach for flagship mission planning uncovered strong interest in probe missions in the scientific community. We understand that NASA may develop probe missions for the 2020 Decadal following the current charge on flagship missions. Therefore we summarize the input we received while avoiding interpretation, in the hope that these community reactions will help NASA's planning process.

- Enthusiasm for developing probe missions as a vital component for planning the next decade was widespread and strongly expressed. The community finds both the cost and schedule of probe missions attractive. Compared to the price and development time for a flagship, several probe missions could be flown in a decade, leading to rapid science return across a broad scientific spectrum. This higher rate of missions may offer scientific synergies, such as multi-wavelength observational capability.
- Many in the community are interested in developing specific probe missions, and a number of new probe-class concepts were brought before the PhysPAG. These generally cover new scientific territory outside of the reach of foreseeable flagship missions. We give a generalized list of these new mission concepts from the input we received in § 5.
- Many in the community stressed the importance of the cost and schedule discipline of the NASA Explorer program, which has returned excellent science while carefully managing costs. These proponents reason that Explorer missions are less susceptible to the large and unfortunate cost, scope and schedule growth encountered in recent flagship missions. This group advocates for an expansion of the Explorer program to larger mission categories, and that developing the parameters of a category (or categories) of larger competed Explorers is as important as defining particular scientific concepts.

- Some pointed out that Explorer missions are not currently integrated into the strategic scientific planning process, in that they follow an open proposal process outside of the scientific investigations directed by the Decadal Review. Others noted that the planetary community has incorporated a degree of strategic planning for their larger competed Discovery and New Frontiers missions in their most recent decadal review.

As a follow-on to the flagship mission charge, the PhysPAG would look forward to assisting NASA in planning how probe missions are developed for the 2020 Decadal Review. While it seems that developing specific point designs would be appropriate, it may be useful to first clearly define the parameters of a competed probe-class mission category (or categories). These preparations should be planned to give the 2020 Decadal Review sufficient information to evaluate 1) whether probe missions follow the flagship model or are managed as cost-capped competed missions, and 2) what balance between flagship and probe missions is optimal for the next decade.

3. PCOS Science Themes in Flagship Missions

a. X-Ray Surveyor Mission

The NASA Astrophysics Roadmap “Enduring Quests, Daring Visions” finds that an X-ray Surveyor is required to address a variety of fundamental questions about cosmic astrophysics. The Roadmap characterizes the X-ray Surveyor as an X-ray telescope with ~ 3 square meters of collecting area and sub-arcsecond angular resolution, equipped with instruments delivering images and high resolution spectra (resolving power ~ 3000) over a broad spectral band (0.1 – 10 keV). Notional telescope and instrument parameters are listed in the Table of Flagship Mission parameters in § 2e.¹

The Roadmap discusses a large number of astrophysical problems that X-ray Surveyor could attack. These include, among others, the physics of stars of super-nuclear density; the nature of supernova-driven feedback mechanisms that affect the chemical composition and dynamics of galaxies; the history of supermassive black holes as encoded in the demographics of black hole spin; the behavior of matter accreting at black hole event horizons; and the mechanisms producing relativistic jets extending over millions of light years. Here we highlight several other compelling scientific drivers for X-ray Surveyor of relevance to the Physics of the Cosmos program and to broader astrophysics: the origin of the first supermassive black holes; the physics of feedback linking black holes to the galaxies and clusters that

¹ In response to the report of the 2010 Decadal Survey, NASA’s Astrophysics Division has stated its intention to participate in the development of the European Space Agency’s large ATHENA X-ray mission, and is now taking steps to do so. The X-ray Surveyor mission concept discussed here would provide an order of magnitude better angular resolution than ATHENA and would have high-resolution, soft X-ray spectroscopic capabilities that ATHENA lacks. These differences enable X-ray Surveyor to address very different science.

surround them; and the growth of cosmic structure and its influence on galaxy evolution.

The origin and growth of the first supermassive black holes. A driving science objective for X-ray Surveyor is to understand the origin and enigmatic growth of the first supermassive black holes, and to trace their co-evolution with their host galaxies. Black holes as large as $10^9 M_{\text{sun}}$ have evolved to be quasars by redshifts of 6 to 7 (as early as 0.75 Gyr after the Big Bang), but we do not know how black holes so massive came to exist so early in cosmic history. Nor do we understand the nature and mass of the seed black holes from which these supermassive objects must have grown. X-Ray Surveyor will detect the central black holes in the earliest galaxies detected by JWST at redshifts of ten and higher. It will reveal the physical processes by which these objects have grown by observing black holes in their youth, with sufficient sensitivity to detect seed black holes as small as $10^4 M_{\text{sun}}$ at $z=10$ (under the reasonable assumptions of Eddington-limited accretion, with 10% of bolometric luminosity in the hard band). More massive seeds will be detected even earlier in cosmic time. X-rays are optimal probes of these high-redshift, moderate-mass ($M < 10^6 M_{\text{sun}}$) seed black holes because the spectral peak of their emission shifts with decreasing mass to wavelengths short-ward of the UV, because X-rays penetrate host-galaxy dust that would obscure UV and optical emission, and because at $z \gtrsim 10$ the IR signatures of AGN activity are red-shifted out of the JWST band. This scientific objective is a key driver of X-Ray Surveyor’s angular resolution, which is crucial to its capability to study such faint objects. X-ray Surveyor’s source detection flux limit is almost 100 times fainter than ATHENA’s, as the latter is limited by source confusion (see Figure 1).

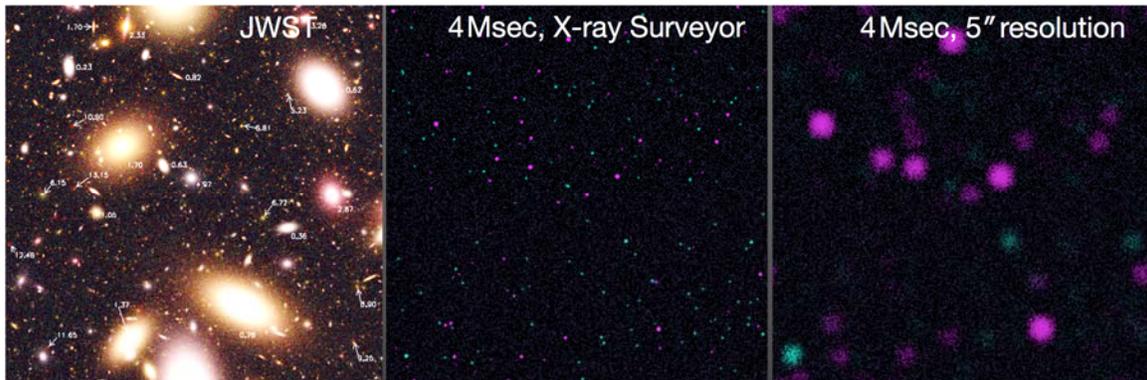


Figure 1 Simulated Deep Fields with JWST (left) and X-ray Surveyor (Center). Each is 2 arcmin on side. JWST detects $\sim 2 \times 10^6$ galaxies deg^{-2} . X-ray Surveyor resolves these without confusion (0.03 galaxies per $0.5''$ beam). A 4 Ms X-ray Surveyor exposure (same as the Chandra Deep Field) detects a $10^4 M_{\text{sun}}$ black hole at $z=10$ ($L_x 10^{41}$ erg s^{-1}). A telescope with the same area but $5''$ resolution (right) is confusion limited at this depth. AGN are shown in magenta; normal galaxies in green. [Gaskin, et al. 2015].

X-ray Surveyor will also probe the host galaxies of the $M \sim 10^9 M_{\text{sun}}$ black holes powering $z \sim 6-7$ Sloan quasars. These must be the most massive galaxies, and hence reside in the most massive dark matter halos ($M \sim 10^{12} M_{\text{sun}}$) to have collapsed by that epoch. The expected X-ray luminosity of the hot halo gas surrounding one of these galaxies is only a small fraction of the quasar’s, and X-ray Surveyor’s angular

resolution is necessary to separate quasar from halo emission, enabling measurement of the gas temperature and thereby halo mass.

The Physics of Feedback and Accretion in Galaxies and Clusters. X-ray Surveyor's capabilities are also driven by the need to understand the physics of galaxy assembly at more recent epochs. In Milky-Way sized galaxies, models predict that a substantial fraction (as much as 1/3) of the baryons reside in hot ($T \gtrsim 10^6$ K) gas extending far beyond the stellar component. These hot coronae must play a significant role in, and contain quantitative information about, the feedback processes that balance gravity and cooling to regulate gas accretion and, ultimately, star formation as galaxies evolve. At present our observational knowledge of these hot components of spiral galaxies is limited to a few nearby objects. X-ray Surveyor will characterize the quantity, composition and energy content of the hot gas in Milky-Way (and larger) sized galaxy coronae out to $z \sim 1$. Its angular resolution is crucial to its capability to map this emission while clearly distinguishing it from any central AGN and from unrelated background and foreground sources.

In the immediate vicinity of the AGN, high-resolution, time-resolved soft X-ray grating spectra will measure mass outflow rates in winds, providing quantitative information about the matter and energy injected by supermassive black holes into their host galaxies. X-ray Surveyor observations of spectral variability will also illuminate the physics of supermassive black hole accretion and jet formation, collimation and reacceleration.

X-ray Surveyor's spectral maps, with an unprecedented combination of spatial and spectral resolution, will yield new insight into cosmic plasma physics in a wide variety of astrophysical settings. Spectral images of galaxy clusters will reveal the kinematics and characterize the physical mechanisms responsible for the bubbles, ripples, and fronts detected by Chandra. These small-scale (few arcsecond) features must be resolved to understand turbulent heating, radiative cooling and matter flows, and plasma transport properties in clusters. X-ray Surveyor will resolve scales down to the Coulomb mean-free-path in cluster cool cores, providing quantitative physical understanding of the enormous cluster feedback loops that operate over length scales spanning more than ten orders of magnitude. In pulsar wind nebulae and supernovae remnants, X-ray Surveyor will enable high-statistics spectroscopy on fine spatial scales, contributing to our understanding of the energetic particle acceleration.

Galaxy Evolution and the Growth of Cosmic Structure: Just as galaxies co-evolve with the black holes they host, so also are they shaped by the growing cosmic structures enveloping them. With the formation of galaxy groups, galaxies experience more frequent mergers, and interact via ram pressure with the hot intragroup medium. These processes can in turn induce nuclear activity and modulate star formation. X-ray Surveyor will detect the first groups at redshifts as large as $z \sim 6$, and, crucially, will resolve AGN from the extended intragroup medium. It will detect and distinguish the thermal emission of intragroup plasma from (non-thermal) inverse Compton X-ray emission from radio jets.

X-ray Surveyor will open a new window onto the enrichment of the IGM, including the roles of different types of supernovae, and how winds and outflows

driven by supernovae and AGN helped seed the intergalactic medium with metals. Critically, it will track all of these processes from early times, through the peaks of cosmic star formation and AGN activity, to the present epoch, providing a comprehensive view of the physics linking black holes, galaxies and cosmic structure.

X-ray Surveyor will also reveal and study a substantial fraction of the as-yet unobserved, un-virialized baryons in the local Universe, and in so doing will trace the cosmic web of dark and baryonic matter linking galaxies, groups and clusters. Models predict that as much as half of the hot baryons in the cosmic web will be detectable *in emission* at X-ray Surveyor's surface brightness limit (about 1/30 that of Chandra's) in the 0.5-2 keV band even in the absence of significant metal enrichment. These images will trace density enhancements as low as $\rho_{\text{web}}/\rho_{\text{mean}} = 30$. If the web is enriched to the extent expected from simulations and suggested by currently available observations in cluster outskirts, X-ray Surveyor's high-resolution grating spectroscopy will detect the baryonic web in absorption spectra along many sightlines to background sources. These spectra will illuminate the history and physics of the web's baryons by diagnosing their composition, ionization state, temperature and kinematics.

b. Far-Infrared Surveyor Mission

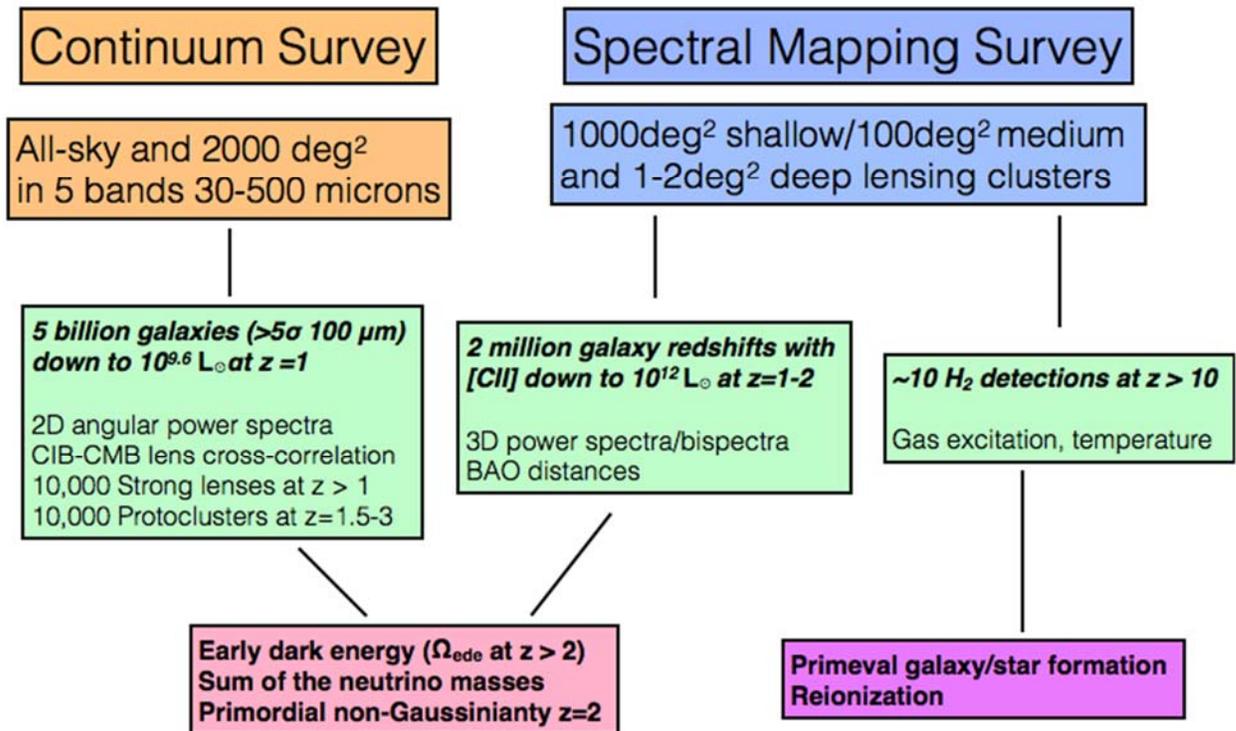
Star formation and black hole accretion are two of the most important processes that shape the evolution of the Universe, and they both occur embedded deeply within interstellar gas and dust. The Far-Infrared Surveyor probes these regions in distant galaxies with infrared lines and continuum at wavelengths > 30 microns. The FIR Surveyor can answer fundamental questions about growth and evolution of structure in the universe, as traced by dusty, star-forming galaxies, and thereby obtain clues to the nature of dark energy, measure certain cosmological parameters, test gravity at cosmological length scales, and study the non-Gaussianity of the density distribution. The key cosmological datasets from the Far-IR Surveyor will be 1) confusion-limited surveys in broad continuum bands over a few thousand square degrees to the whole sky, and 2) blind spectroscopic surveys covering tens to thousands square degrees with complete 3-D information provided by the bright far-IR emission lines of [CII] $158\mu\text{m}$, [OI] $63\mu\text{m}$ and [OIII] $52\mu\text{m}$ and $88\mu\text{m}$. The spectroscopic survey is particularly unique, and we anticipate 2 million galaxies to be detected blindly (automatically including redshifts) in this mode. Their clustering can be used to constrain cosmology, as is traditionally done in galaxy surveys.

The FIR Surveyor survey complements Euclid and WFIRST by extending clustering measurements to early times. The FIR Surveyor dataset of 2 million galaxies is adequate to detect the baryon acoustic oscillation (BAOs) in 4-5 redshift bins between $z=1$ to 3.5 to a few percent accuracy. Euclid and WFIRST will perform BAO measurements using redshifts secured from grism spectra in the near-IR, primarily covering the $z=1-2$ with $\text{H}\alpha$ and, in the case of WFIRST, to z of 3 with [OIII]. In comparison to the FIR surveyor, Euclid will conduct a survey over 15,000 sq. degrees with a number density of about 0.4 galaxies per sq. arcmin, while WFIRST-AFTA will extend the depth down to the level of 3 galaxies per sq. arcmin over 2000 sq. degrees. The FIR Surveyor will reach a shallower depth at higher redshifts,

compensated by the higher bias factor of the dusty, star-forming galaxies at $z > 2$. Moreover, we expect the redshift distribution of the FIR Surveyor to peak at $z > 2$, maximizing its sensitivity to clustering measurements over the range $z = 2 - 3$ where WFIRST will be sub-optimal due to single-line line confusion associated with [OIII] emitters in 1.35-1.95 μm wavelength range of its grism.

Clustering measurements with the FIR Surveyor at z of 2-3 will bridge the gap between the distance to CMB and galaxy surveys. The 1-2% distance measurements in four broad z bins will provide an improved test of the evolution of the dark energy equation of state, $w(z)$, and a constraint on the early dark energy models that postulate a very low level of dark energy density that remains a constant at $z > 2$. The BAO-based distances correspond to a constraint on an early dark-energy component at $z > 2$ below 0.01. For comparison, the current constraint, with Planck CMB and CMB lensing is 0.06 (68% confidence level).

The Far-Infrared Surveyor Cosmology Roadmap



The 3D clustering from the FIR Surveyor, and intensity mapping in 3D spectral cubes that make use of all data not just high-significance line detections, also offers the potential to probe primordial non-Gaussianity with peak sensitivity at $z = 2 - 3$. The constraint comes from the fact that the galaxy bias on large scales has a correction arising from the non-Gaussianity parameter. This is best tested at very low redshifts but a measurement or even a constraint at $z > 2$ is helpful since surveys capable of studying this at high redshifts are currently limited. The expected depth of the FIR Surveyor dataset is such that we are able to constrain f_{nl} , the non-Gaussianity

parameter, down to a level of 9 (68% confidence). The combination of f_{nl} parameters measured with CMB at z of 1100, galaxy surveys at $z < 1$, with the FIR surveyor constraint at z of 2 to 3, will provide the redshift evolution of the non-Gaussianity and rule out extreme models that have significant redshift evolution over the cosmic epoch.

Far-IR sources, with a redshift distribution that peaks at $z = 2 - 3$, are also useful for a cross-correlation studies. In particular dusty, star-forming galaxies trace the foreground dark matter potential that is responsible for lensing of the CMB. Studies so far focus on fields of order 100 sq. degrees, with SPT and POLARBEAR and Herschel maps (Holder et al. 2013; Ade et al. 2014). The FIR Surveyor will extend such studies to 1,000-10,000 sq. degrees and with CMB polarization B-mode lensing data coming from next-generation ground-based CMB-S4 experiments. The cross-correlation can be performed with either the far-IR galaxy locations, selected based on color and flux cuts, or with CIB intensity maps as a whole, again with some color based on the combined continuum maps. The redshift distribution for far-IR sources can be calibrated through the FIR Surveyor spectral surveys. The CMB-S lensing studies have the goal of measuring the sum of the neutrino masses down to the sub-0.05 eV level to distinguish between normal and inverted mass hierarchies for the neutrinos (Abazajian et al. 2015). The cross-correlation with an external tracer as proposed here also has the advantage that the impact of systematics can be reduced for the proposed measurement.

Moving beyond clustering, the FIR Surveyor is capable of providing an independent measure of cosmological parameters through two additional tracers of cosmology. First will be the large sample of bright gravitational lenses that it is expected at far-IR/sub-mm wavelengths. Unlike the case with Herschel that required significant ground-based follow-up, the FIR Surveyor will have the advantage that these lensing events will also have accompanying redshift measurements. And if the FIR wide area survey is conducted on a field such as WFIRST HLS with significant ancillary data we will also have redshifts for the foreground galaxies. The lensing rate, and the distribution of foreground lens and background source redshifts, are cosmology dependent. With a complete sample of lensing events, down to a fixed flux density, we are able to measure dark energy and other cosmological parameters (e.g., MERLIN radio lens survey with 11 radio lenses over 5000 snapshots; Chae et al. 2002). Finally, the statistics of proto-clusters of galaxies that will appear as star-forming galaxy clumps (e.g., Casey et al. 2015) will also trace the underlying cosmology. As current detections are limited to a few, they have not been discussed widely as cosmological probes in the same way galaxy clusters are used. We expect the FIR Surveyor will encourage the simulation and theory community to study the connection between cosmology and the statistics of proto-clusters so the expected data can lead to cosmological constraints.

Moving to the epoch of reionization and pre-reionization sources, the Far-Infrared Surveyor is capable of searching for the molecular hydrogen cooling in primordial halos that are sites of first stars in the universe. Such halos have virial temperatures below 10^4 K and molecular hydrogen is the only cooling mechanism. During reionization, H_2 due to turbulent energy dissipation in proto-galaxies could also be detected. These generally require deep observations of strongest lensing

clusters, similar to a Hubble Frontiers Fields program. From reionization, the strongest H₂ line is at 10 μm (Gong et al. 2012). With multiple lines detected, H₂ will allow a determination of mass, excitation, and total cooling power, key ingredients necessary to understand the conditions of primordial gas converting to stars in an extreme environment of the primordial universe.

c. UV/Optical/IR Surveyor Mission

The LUVOIR surveyor is a concept for an 8-meter to 16-meter UVOIR space observatory. LUVOIR will allow astronomers to answer fundamental questions at the forefront of modern astrophysics. We discuss here the relevance of the LUVOIR for the PhysPAG science by highlighting few particularly promising scientific opportunities.

Unraveling Galactic Dynamics with Proper Motions. The mysterious dark matter that dominates the mass of the Universe binds and organizes all large-scale cosmic structure, including galaxies that trace them. The nature of the dark matter remains unknown, and yet its gravitational influence on the dynamics of stars and galaxies is clear. The motions of stars on the sky (their proper motion) are sculpted by the underlying dark-matter-dominated gravitational potential, and thus they reveal the true structure and movements of the galaxies those stars inhabit. *Hubble* has pushed this astrometric proper-motion technique to its limits, searching nearby stellar clusters for signs of black holes and tracking the orbits of galaxies in the Local Group. *JWST*'s comparable precision will allow this work to continue, yielding longer time baselines for fields previously studied with *Hubble*. While the forthcoming *Gaia* and *WFIRST* space missions will measure proper motions over huge fields, revealing internal Milky Way dynamics with billions of stars, even these major advances are not enough to reveal the true nature of dark matter or to resolve the detailed motions of distant galaxies. In contrast, LUVOIR has the spatial resolution at visible wavelengths to achieve an entirely new level of precision in measuring the effects of dark on normal matter. The key to these gains is its aperture: at 12 meters, with 10 mas spatial resolution, millipixel astrometry, and rapid high-S/N photometry, *HDST for example*, will be able to measure the motions of stars on the sky to unprecedented low limits. At the limits achievable in the Milky Way, virtually every star can be seen to move. Measurements of this precision can directly constrain the nature of dark matter. In the ultra-faint dwarf satellites of the Milky Way (and the hundreds of additional dwarfs that LSST is likely to reveal), baryons contribute essentially nothing to the mass of the galaxy, making their stars ideal tracer particles of the dark matter potential.

Precision Measurements of the Growth of Structure. The bulk of the stellar mass assembled in galaxies between $z \sim 3$ and $z \sim 1$, by which time the Hubble sequence was essentially in place. To precisely test the gravitational instability paradigm we must follow the growth of mass and stellar populations over this key cosmic period. The total (dynamical) masses and metallicities of galaxies can be measured by means of gas kinematics from absorption spectroscopy of background galaxies, if sufficient

spectroscopic sensitivity is available, essentially using galaxies in the same way as quasars have been used to study the IGM. Galaxies are vastly more abundant than quasars, especially at high redshifts, by ~ 100 -fold down to a common flux level. This allows one to perform spatially resolved kinematics of individual foreground galaxies. An 8-m to 16-m UVOIR space telescope can uniquely probe the $1 < z < 3.5$ range where the absorption lines are superposed on nearly featureless parts of the emitter's rest-UV spectrum.

Dark Matter Halo Maps with Strong Lensing. LUVOIR will improve in dark matter halo maps of clusters and galaxies using high-resolution images of strong lensing systems. Near-infrared imaging with the *Hubble Space Telescope* has already traced the earliest detected seeds of modern galaxies to within a few hundred million years of the Big Bang. This process started with the Deep Field in 1995 and continued through each new generation of *Hubble* instruments, allowing *Hubble* to push back the redshift frontier and identify the brightest star-forming galaxies at redshift $z \sim 10$, when the Universe was only 400 million years old. The on-going *Hubble* "Frontier Fields" are carrying this search to potentially higher redshifts and lower galaxy luminosities, by using gravitational lensing to magnify the more distant universe in select regions where the lensing effect is particularly strong. LUVOIR'S higher resolution and greater sensitivity match the typical increase in resolution and depth offered by gravitational lensing, and thus LUVOIR could effectively carry out the same search as the Frontier Fields, but anywhere in the Universe it chooses to point.

Ultra-Faint Satellite Dynamic. Dwarf spheroidal galaxies (dSph) are extraordinary sites to explore the properties of non-baryonic dark matter (DM). Their mass is dominated by DM – they are observed to have mass-to-light ratios 10 to 100 times higher than the typical L^* galaxy. They are abundant nearby – to date 23 dSph galaxies have been found in the Local Group. Most striking, is the discovery that nearly all dSph satellites, covering more than four orders of magnitude in luminosity, inhabit dark matter halos with the same mass ($\sim 10^8 M_\odot$) within their central 300 pc. The ability of DM to cluster in phase space is limited by intrinsic properties such as mass and kinetic temperature. Cold DM particles have negligible velocity dispersion and very large central phase-space density, resulting in cuspy density profiles. Warm DM halos, in contrast, have smaller central phase-space densities, so that density profiles saturate to form constant central cores. The mean density profile of dSph galaxies is, thus, a fundamental constraint on the nature of dark matter. To measure the DM profiles, one needs to measure the proper motions and the radial velocities of stars in dSph. Both measurements are needed to break degeneracy between the inner slope of the profile and velocity anisotropies of stellar orbits. Fundamentally new constraints on DM can be reached by determining proper motions for ~ 100 stars per galaxy with accuracy < 10 km/s (< 40 mas/yr at a distance of 60 kpc) plus ~ 1000 radial velocities (*cf.* Bullock et al. 2009, Astro2010 White Paper). LUVOIR will have the required astrometric precision to perform these proper motion measurements owing to its very high wavefront stability and its wide-field imaging capability (Postman et al. 2010).

Multi-messenger astronomy. One of the most rapidly growing areas of astrophysics in the next decade will be multi-messenger time domain astronomy. By the mid-2020s, several powerful ground-based wide-field synoptic surveys will be in full operation, including the Large Synoptic Survey Telescope (LSST) at optical wavelengths, the Square Kilometer Array (SKA) at radio wavelengths, and the Advanced LIGO and Virgo detectors for gravitational waves. At the redshift limits shown for single visits by LSST (one night's observation), LUVOIR will reach localization precision sufficient to identify the stellar populations giving rise to the explosive phenomena, and with its spectroscopic capabilities, measure the metallicity local to the explosion (an important driver of stellar evolution and mass loss). The rest-frame UV capability of LUVOIR is particularly important for probing young (hot) SNe, and can be used as a sensitive diagnostic of their progenitor mass and radii, and explosion energies. The UV and optical diagnostics for the age and metallicity of the progenitor star and its host population are more effective than the near-IR diagnostics that would be used by ground-based telescopes, especially at young ages. The deep magnitude limits of LUVOIR are not achievable from the ground, and LUVOIR will be the only telescope capable of following the evolution of a faint optical/near-IR counterpart (postulated to be a kilonova) to a localized gravitational wave source for long periods after the event.

d. Habitable-Exoplanet Imaging Mission

While exoplanet surveys are generally not intended to further the exploration of new laws of physics in the cosmos, we find there are several scientific themes that have some connection with applications of PCOS science in questions of dynamics and gravitation. The HABEX development may find it fruitful to address astrophysical issues of interest to PCOS in the context of planet formation and evolution, such as:

- How do terrestrial planets form given the tendency of colliding rocky bodies to bounce or fragment, and for bodies growing in gaseous disks to spiral inward toward the host star?
- What is the role of phase transitions in planet formation? How do planets form within the snow line acquire water and other volatiles necessary for the origin of life?
- What is the role of gas dynamics in early stages of planet formation? How do the gas dynamics (laminar vs. turbulent flow) and chemistry of the protoplanetary disk affect the growth and composition of protoplanets that may become habitable?
- What is the role of external and internal ionization on early stages of planet formation? How do terrestrial atmospheres evolve over longer timescales as they interact with radiation and particles from the host star and bombardment from solids in the interplanetary environment?
- How do gravitational dynamics affect later stages of planet formation and planetary system evolution? How important are resonant orbits and major gravitational events (e.g. Nice and Grand Tack models of planetary orbit exchange) for forming habitable planets?

e. Table of Flagship Mission Parameters

X-Ray Surveyor	Far-Infrared Surveyor	UV/Optical/IR Surveyor	Habitable Exo-Planet Imaging Mission
<p>Primary Science Goals:</p> <ul style="list-style-type: none"> • Origin & growth of 1st supermassive black holes • Co-evolution of black holes, galaxies & cosmic structure • Physics of accretion, particle acceleration and cosmic plasmas <p>Measurement Requirements:</p> <ul style="list-style-type: none"> • Chandra-like (0.5") angular resolution • Detection sensitivity ~ $3 \times 10^{-19} \text{ erg cm}^{-2} \text{ s}^{-1}$ • Spectral resolving power: R>3000 @ 1 keV; R~1200 @ 6 keV <p>Architecture and Orbit:</p> <ul style="list-style-type: none"> • Eff. area ~3 m² • Sub-arcsecond angular resolution • High-resolution spectroscopy (R ~ few x 10³) over broad band via micro-calorimeter & grating spectrometer instruments • FOV ≥ 5' • Energy range ~0.1-10 keV • Orbit: L2 likely 	<p>Primary Science Goals:</p> <ul style="list-style-type: none"> • History of energy release in galaxies: formation of stars, and growth of black holes. • Rise of first heavy elements from primordial gas. • Formation of planetary systems and habitable planets. <p>Measurement Requirements:</p> <ul style="list-style-type: none"> • Spectral-line sensitivity better than 10^{-20} Wm^{-2} in the 25-500 μm band. (5σ, 1h) • Imaging spectroscopy at R~500 over tens of square degrees. • R~10,000 imaging spectroscopy of in thousands of z<1 galaxies and protoplanetary disks. • High-spectral-resolution capabilities desired for Galactic star-forming systems and the Galactic Center. <p>Architecture & Orbit:</p> <ul style="list-style-type: none"> • Complete spectroscopic coverage at R~500 from 25-500 μm. • Monolithic telescope cooled to <4 K, diameter ~5 m. • FOV = 1 deg at 500 μm • R~10,000 mode via etalon • Background limited detector arrays with few x 10⁵ pixels, likely at T<0.1 K. • Mission: 5 years+ in L2 halo orbit. • High-resolution (heterodyne) spectroscopy under study, possibly for warm phase. 	<p>Primary Science Goals:</p> <ul style="list-style-type: none"> • Direct imaging of Earthlike planets, search for bio-signatures • Broad range of cosmic origins science <p>Measurement Requirements:</p> <p><i>Cosmic Origins Science:</i></p> <ul style="list-style-type: none"> • HST-like wavelength sensitivity (FUV to Near IR) • Suite of imagers & spectrographs, properties to be determined <p><i>Exo-Earth Detection:</i></p> <ul style="list-style-type: none"> • ~10⁻¹⁰ contrast • Coronagraph (likely), perhaps with a starshade • Optical and near-IR camera for planet detection and characterization. • IFU, R>70 spectrum of 30 mag exoplanet • 1" radius FOV <p>Possible instrument for spectroscopic characterization of transiting planets.</p> <p>Architecture and Orbit:</p> <ul style="list-style-type: none"> • Aperture: ~8-16m likely • Likely segmented, obscured primary. • Orbit: L2 likely 	<p>Primary Science Goals:</p> <ul style="list-style-type: none"> • Direct imaging of Earthlike planets. • Cosmic origins science enabled by UV capabilities; considered baseline science. <p>Measurement Requirements:</p> <p><i>Exo-Earth Detection:</i></p> <ul style="list-style-type: none"> • ~10⁻¹⁰ contrast • Coronagraph and/or starshade • Optical and near-IR camera for planet detection and characterization • IFU, R>70 spectrum of 30 mag exoplanet • 1" radius FOV <p><i>Cosmic Origins Science:</i></p> <ul style="list-style-type: none"> • UV-capable telescope / instrument suite: properties and wavelength range to be determined. • Enable constraints on the high-energy radiation environment of planets. <p>Possible instrument for spectroscopic characterization of transiting planets.</p> <p>Architecture and Orbit:</p> <ul style="list-style-type: none"> • Aperture: <~8m likely • Monolithic or segmented primary • Optimized for exoplanet direct imaging, • Orbit: L2 or Earth-trailing likely.

Table 1: Notional Mission Parameters. These are the notional parameters of the four missions, developed through coordinated discussions with and between the three PAGs. We emphasize that these parameters are notional: they are not meant to provide definitive or restrictive specifications for range of possible range of architectures to be studied by the STDTs. We encourage the STDT to consider architectures and parameters outside of those indicated here, in order to explore the full range of science goals, and maximize the science achievable by these missions for a given cost, schedule, and technological readiness.

4. PhysPAG Science for the L3 Gravitational Wave and Inflation Probe Missions

a. L3 Gravitational Wave Mission Science

How and when did the first massive black holes form? The Gravitational Wave Surveyor (LISA/eLISA), will track the merger history of massive black holes (MBHs) from the first seeds out at $z \sim 20$. Black hole mergers with masses in the interval between $10^4 M_{\odot}$ and $10^7 M_{\odot}$ will be observed with significant signal-to-noise ratios, allowing the individual masses, spins and luminosity distances of the MBHs to be measured with unprecedented accuracy. The range of black hole masses and redshifts sampled is complementary to that of black-hole-powered phenomena that can be observed electromagnetically.

Evolution of galaxies and their supermassive black holes. LISA will provide the widest and deepest survey of the universe ever produced, measuring the vast majority of all merging MBH binaries. This will expose an unseen population of objects, revealing precise characteristics of the hearts of galaxies, tracing their merger history over cosmological time, and exposing the links between the black hole seed population and the bright tail of early EM observable galaxies. LISA's measurements of MBH binary masses, spins and eccentricities will provide information about their galactic environments. Gravitational wave observations alone will be able to distinguish between the different MBH formation and evolution scenarios.

Measure the spin distribution of supermassive black holes throughout the universe. The masses and spins of the merging black holes are faithfully encoded in the gravitational wave signals. The individual masses can be measured to a fraction of a percent, and the spins measured to a few percent, allowing precise characterization of the surveyed population.

Survey compact stellar-mass binary systems in our own galaxy and better understand the structure of the Milky Way. The ashes of stellar evolution are dark compact objects. LISA will survey compact binary systems in our galaxy, individually measuring the properties of over 10^4 binaries. These discoveries will shed light on the outcome of the common envelope phase, on the progenitors of type Ia supernovae and on binary evolution physics.

Explore the populations of stellar-mass compact objects in galactic nuclei. LISA will explore the large populations of stellar-mass black holes, neutron stars, and white dwarf stars, which are expected to be present in galactic centers. These compact objects occasionally scatter into the central MBH to form Extreme Mass-Ratio Inspiral binaries (EMRIs), that LISA can observe out to $z \sim 0.5$ to $z \sim 1$, depending on the detector design, providing precise information about galactic centers with MBHs between $10^4 M_{\odot}$ and $10^6 M_{\odot}$.

Multi-wavelength studies of GW populations and multi-messenger studies with EM observations. LISA will observe the growth of MBHs through the era of structure formation which are the likely progenitors for the local population of super massive BHs observable in the pulsar timing GW band; together, these observations will provide strong constraints on the merger population and evolutionary history of MBHs. At the other end of the GW spectrum, LIGO's binary mergers begin their history in LISA's band. LISA systems have the potential for direct counterpart observations with future EM instruments, including guaranteed counterparts such as compact galactic binaries, and possible signatures from MBH mergers.

Test strong GR in rich detail. LISA will provide the *most precise* tests of Einstein's theory of General Relativity in the *highly dynamical and non-linear* regime. The observation of MBH mergers will allow us to answer fundamental questions about gravity: does gravity propagate at the speed of light? does the graviton have a mass? does gravity violate Lorentz invariance? do gravitational waves have more than two polarization states? are the black hole "no-hair theorems" violated?. LISA observations will also allow us to *search for the unexpected*, letting the data determine whether there are anomalies, which in turn could point to a surprising deviation from Einstein's predictions. In addition, many of LISA's galactic binary systems will be precisely measurable through both GW and EM and observations, allowing end-to-end tests of GW emission, propagation and detection.

Map the spacetime of supermassive black holes with compact object captures. The spiral of small compact objects into MBHs will allow us to dynamically map the spacetime of the MBH to unprecedented precision. Such maps will reveal whether the unseen massive objects at the center of galaxies are the black holes of General Relativity.

Revealing the gravitational universe. We can only speculate about what else LISA may observe. Cosmological, dynamical and gravitational lensing observations tell us that the majority of matter in the universe is dark and invisible, known only through large-scale gravitational interaction. LISA will peer into this void, potentially making discoveries that will revolutionize our understanding of the Universe.

b. Inflation Probe Science

The Cosmic Microwave Background (CMB) radiation consists of a bath of photons emitted nearly 14 billion years ago, when the universe was in its infancy. Observations of the small intensity variations in the CMB have led to precise measurements of the age, composition, and curvature of the universe, and provide strong evidence for the existence of dark matter and dark energy. We are now poised for another exciting era of discovery. The simplest models of inflation predict that a stochastic background of gravitational waves should exist that leave a faint signature on the CMB polarization. This signature can be detected and characterized with modern polarization-sensitive instruments.

A convincing detection of this distinctive “B-mode” signature provides a measure of the amplitude of gravitational waves emitted during a primordial inflationary epoch. Such a detection and spectral characterization would confirm the inflationary paradigm and identify the energy scale at which inflation took place, revealing fundamental physics at energy scales impossible to achieve in a terrestrial laboratory. A compelling characterization of the B-mode polarization signature, or an absence of detection at cosmologically meaningful levels would therefore represent, as described in the 2010 National Academy of Sciences Decadal Review of Astronomy and Astrophysics, “a watershed discovery” that would significantly advance our understanding of the physical conditions of the early universe. These efforts were identified by the decadal review as high priority science. In addition, there is much to be gained from a cosmic-variance limited measurement of the entire sky over a wide range of frequencies and angular scales. This will enable the scientific community to characterize astronomical foregrounds, to quantify the properties of our universe on its largest scales, including a definitive determination of the epoch of reionization and to explore in polarization the temperature anomalies that may ultimately lead to the discovery of new physics.

Rapid scientific and technical progress has been made since the beginning of the decade, and full-sky maps of CMB polarization to fundamental sensitivity limits are now technologically achievable. The tensor-to-scalar ratio, r , derived from these measurements, is a gauge of the presence of primordial gravitational waves, and a measure of the energy scale of inflation. Improved measurements of the scalar spectral index provide a compelling reason to believe that a non-negligible value of r is likely. A current upper limit of $r < 0.11$ derived from measurements of the temperature anisotropy alone is limited by cosmic variance, reflecting the reality that we only have one universe to observe. This means that polarization measurements are required to make further advances. Upper limits from polarization anisotropy measurements have reached a notable milestone for the field -- they are now comparable and will soon provide the dominant observational constraint on inflation. Combining all of the available CMB information, inflationary gravitational waves are currently constrained at $r < 0.09$.

The Inflation Probe mission will be critical in order to make full-sky, uniformly well-calibrated and interconnected maps, to minimize systematic errors, and to avoid atmospheric effects both in bands in which measurements are impossible from the ground, and also to maximize sensitivity and foreground rejection across the spectrum. The development of this mission stands in the context of plans for the next stage in ground-based observations for which the CMB community is optimizing mapping speed and sensitivity at frequencies accessible across available atmospheric windows to produce maps of the CMB. A satellite mission is unique in its ability to study large spatial scales with complete spectral coverage for removing polarized foregrounds. As has historically been the case, ground-based, sub-orbital, and orbital experiments are highly complementary. Overlap in angular and frequency coverage will be essential for consistency in calibration and systematic control between these complementary approaches, as will a robust exchange of technological developments, analysis techniques, and joint analysis of final data products. In addition, ground-

based and sub-orbital efforts provide tests of experimental techniques and technology development and readiness-raising experience for space missions.

5. PhysPAG Interest in Probe Missions

There is strong community support for “probe sized missions”, which cost between 500M\$ and 1B\$, and fill the gap between Explorer type SMEX and MIDEX missions and strategic flagship missions costing 1B\$ and more. At the meeting “High-Energy Space Missions in the 2020s” of the High Energy Astrophysics Division of the American Astronomical Society (June 29-July 1, 2015, Chicago, IL), a number of probe-sized mission concepts were discussed which offer compelling science lying at the heart of the science program described in the 2015 NASA Astrophysics Roadmap.

Probe concepts brought forth to the PhysPAG include:

- An **X-ray Grating Spectrometer Probe Mission** that would enable studies of the warm-hot intergalactic medium (WHIM), collimated and uncollimated outflows from accreting supermassive black holes, and bursting neutron stars. These capabilities are a particularly attractive compliment to ESA’s ATHENA mission.
- A **Large X-ray Timing Observatory Probe Mission** that would enable the measurement of the equation of state of neutron star matter, and studies of the structure of black hole and neutron star accretion flows.
- A **Transient X-ray Astrophysics Probe Mission** that incorporates a wide field-of-view X-ray telescope with a near infrared telescope to enable observations of high-redshift gamma-ray bursts, tidal disruption events, supernova shock breakouts, and electromagnetic counterparts of gravitational wave detections of merging binaries.
- A **High Energy X-ray Probe Mission** that would enable measurements of the spins of a large (O(100)) sample of stellar and supermassive black holes, deep supermassive black hole surveys which are not biased against obscured sources, and radio-nuclear studies of Type Ia supernovae. This mission can build upon the scientific discoveries of *NuSTAR*.
- An **Advanced Gamma-ray Telescope Probe Mission** operating in the keV to MeV energy range for the study of the 511 keV emission from the galactic center, a supernova census in nuclear gamma-rays, and polarimetric studies of the jets (collimated plasma outflows) from gamma-ray bursts and active galactic nuclei.
- An **Advanced Cosmic Ray Probe Mission** designed to discover the origin of ultrahigh energy cosmic rays by observing extremely energetic extensive air showers from space, accumulating significantly more events at the highest energies than ground-based observatories. The mission would incorporate a wide field of view with an ultrafast UV camera that records the extensive air shower fluorescence and

backscattered Cherenkov light. Extremely energetic neutrinos may also be observed as well as fast atmospheric phenomena and meteoroid emission.

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Appendix

The process for collecting community input and coordinating the PhysPAG report involved a series of open sessions at prominent conferences, as well as focused splinter meetings organized by the PhysPAG SIGs to reach out to particular scientific constituencies. In addition a series of planning telecons were held for the PhysPAG EC, and joint-PAG meetings were held to coordinate our report findings. A list of these sessions is collected in the following table.

Table 2. Meetings and Events Held in Response to Flagship Mission Charge

Date (2015)	Location	Meeting
4 January	Seattle, WA	PhysPAG and Joint PAG meetings at the <i>American Astronomical Society</i> conference
		Gamma-ray and X-ray SIG splinters at the AAS
		GW special session <i>The Centennial of General Relativity</i> at AAS
14-17 January	Minneapolis, MN	Inflation Probe SIG meeting at <i>Physics of the CMB and Its Polarization</i> conference
5-6 February	Greenbelt, MD	Gamma-ray SIG meeting at <i>Future of Space-Based Gamma-ray Observatories</i> workshop
19 March	Baltimore, MD	Joint PAG Executive Committee meeting
11-14 April	Baltimore, MD	PhysPAG session at <i>American Physical Society</i> conference
		Meetings of the Gravitational-wave, Cosmic-ray and Gamma-ray SIGs at APS
29 April	Telecon	PhysPAG EC meeting
22 May	Telecon	PhysPAG EC meeting
8 June	Telecon	PhysPAG EC meeting
26 June	Telecon	PhysPAG EC meeting
1 July	Chicago, IL	Panel discussion at AAS <i>High Energy Astrophysics Division</i> meeting
		X-ray and Gamma-ray SIG meetings at HEAD
3 July	Telecon	Joint PAG chair planning meeting
20 July	Telecon	PhysPAG EC meeting
7 August	Honolulu, HI	Joint PAG session at <i>International Astronomical Union</i> conference
28 August	Telecon	PhysPAG EC meeting
31 August	Pasadena, CA	Joint PAG presentation at special session of the <i>American Institute of Aeronautics and Astronautics</i>