Fundamental Physics Breakout Group Summary
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1 Gravity

1.1 Low-Frequency Gravitational Wave Detection with Pulsar Timing Arrays

Regular observations of an array of fast-spinning millisecond pulsars can be used to detect time-of-arrival perturbations due to low-frequency gravitational waves. This project requires the observation of 50–100 millisecond pulsars with large radio telescopes at frequencies of 0.5–5 GHz. Closely spaced (within days) observations are necessary to precisely measure dispersion delays due to the ionized interstellar medium. Given the expected strains of the stochastic background and individual gravitational wave sources detectable with pulsar timing arrays and the sensitivities of the current efforts, a detection of low-frequency gravitational waves using pulsar timing is likely within the next decade. In addition to regular timing observations, radio interferometer and X-ray observations which search for signatures of super-massive black hole binaries are critical to improve models for the stochastic background and to identify individual sources for which to search in pulsar timing array data.

1.2 Observing Black Hole Event Horizons with Millimeter VLBI

The direct imaging of the near-horizon region of supermassive black holes presents a number of novel opportunities to explore strong field gravity through its impact on the dynamics and gravitational lensing of nearby emission regions. At least two clear targets exist (Sagittarius A* and M87) that are accessible from ground-based mm-VLBI experiments (source sizes of ≈ 50 microarcseconds). An order of magnitude more objects would be accessible from a space-based mm-VLBI capability (source sizes > 1 microarcseconds). These observations are uniquely possible at millimeter and sub-millimeter wavelengths due to: sufficient resolution on Earth-sized baselines, optical depth of the intervening accretion flow and/or outflow, interstellar scattering (Galactic center), applicability of standard radio VLBI techniques. Early experiments have already proven feasibility and provided clear evidence for an event horizon in astrophysical black holes. However, fully exploiting the ultra-high resolution mm/sub-mm window requires a multiwavelength monitoring effort, from mm through X-rays, to repeatedly catch variable structures that can be used to reconstruct the near-horizon spacetime. In the Galactic center these are expected in conjunction with the observed infrared and X-ray flares, which occur roughly daily.

1.3 Tests of Gravity using Pulsar Binary Systems

Regular timing observations of recycled pulsars in binary systems with either white dwarf or neutron star companions provide a number of tests of gravity. Observations of double neutron star binaries provided the most robust evidence for the existence of gravitational waves prior to their direct detection, with orbital decay rates exactly matching those predicted by general relativity. This and a number of other relativistic parameters, such as the Shapiro delay due to light travel time delays through the gravitational well of a companion, can be measured in both double neutron star and neutron star-white dwarf binaries. Neutron star-white dwarf binaries with a large mass asymmetry are the most precise tests of the strong equivalence principle, which states that the gravitational and inertial masses of self-gravitating bodies are identical. All-sky surveys to discover more binary systems appropriate for these tests, followed by regular high-precision timing, are critical. Two specific aims are to discover another double pulsar system, in which the detectability of both neutron stars greatly improves the constraints, and a pulsar-black hole binary, which would allow measurements of the black hole mass and spin. In addition, VLBI observations that provide parallax measurements are important for removing any degeneracies due to distance uncertainties (this is currently the limiting factor in the most precise measurements).

1.4 Tests of Gravity using Galactic Center Pulsars

A pulsar orbiting the supermassive black hole at the Galactic center presents a special case of pulsar binary. In addition to the tests mentioned above such an object would presumably provide a key comparison with ongoing infrared observations of stellar dynamics in the Galactic center (S-star orbits) and mm-VLBI imaging. Moreover, such objects are expected in tight orbits as the result of mass segregation and their longevity in the crowded stellar and remnant cusps surrounding supermassive black holes. While the Galactic center has been the subject of a number of focused pulsar searches already, their lack of success has typically been attributed to the large scattering delays delays anticipated at sub-GHz frequencies. The recent discovery of a magnetar in the Galactic center, first in gamma rays and now in radio, has proven this interpretation is necessarily more complicated. Nevertheless, the obvious scientific value of a pulsar in the Galactic center region strongly motivates continued efforts at high frequencies, where propagation effects are less significant. The steep spectra of most pulsars require correspondingly high sensitivities, and therefore large phased apertures.

1.5 Issues/Requirements/Goals

- all-sky searches at frequencies of 300 MHz (out of the Galactic plane) to 5 GHz (in the Galactic plane), with integration times of minutes to hours, for recycled pulsar binary systems
- searches at frequencies of 5 – 20 GHz, with integration times of hours, for pulsars close to the Galactic Center
- regular (weekly–monthly) timing observations of 50–100 recycled pulsars at 500 MHz – 5 GHz frequencies, with wide-band frequency coverage, for each pulsar
- VLBI observations of pulsars for precise parallax measurements at frequencies of $\sim$1 GHz
- Multi-wavelength high-frequency ($\geq$ 230 GHz) mm- and sub-mm-VLBI capabilities
- High bandwidth (64 GHz)receivers and recorders at mm- and sub-mm-VLBI sites
- High-cadence mm- and sub-mm-VLBI observations over extended campaigns, i.e. daily observations over many months.
- Additional mm- and sub-mm-VLBI sites, permitting imaging on timescales below 30 min.

2 Dark Matter

2.1 Direct Detection of Dark Matter Particles

Dark matter annihilation signals remain a promising avenue for the direct detection of WIMPs. While the substantial uncertainty in the properties of putative WIMPs lead to a commensurate uncertainty in the expected annihilation signal, should WIMP cross sections be dominated by S-wave interactions the synchrotron signal from leptonic products may already have been observed. Promising sites for dark matter annihilation searches included dwarf galaxies, due to their high concentrations, and the Galactic center, due to its proximity. Key to capitalizing on these opportunities is improvement in the understanding of potential astrophysical systematics (e.g., pulsars in the Galactic center). Thus, these efforts will directly benefit from high-energy astrophysics studies described elsewhere.

2.2 Radio Observations as a Constraint for Observations at Other Wavelengths

Both the local and cosmological impacts of dark matter annihilation are writ large across the electromagnetic spectrum. This includes direct inverse-Compton gamma-ray and X-ray signals, perturbation during the epoch of reionization, and additional heating of the intergalactic medium. In all cases radio provides an important constraint for the physical interpretation of observations at other wavelengths. That is, progress will depend on multi-band studies that can carefully control potential astrophysical systematics and generate a comprehensive picture of the impact of dark matter annihilation over cosmological timescales and assess potential astrophysical alternatives. Apart from participation in the general Cosmological program, a specific contribution would be the measurement of the Compton-y and -μ distortions of the CMB by a hot intergalactic medium.

2.3 Probing Substructure in Gravitational Lenses via Radio Observations

A key prediction of ΛCDM is structure across a vast array of scales. The largest dark matter halos are visible via the galaxy groups and clusters that form within them. Smaller halos become more difficult to see. Dwarf galaxy-sized halos are susceptible to violent stellar feedback which can severely reduce or eliminate altogether their baryonic component. Hence, the existence and distribution of small-scale dark matter concentrations remain poorly constrained. Nevertheless, these are sensitive to the assumed dark matter physics (e.g., to WIMP interactions) and therefore of substantial scientific interest. Where large-scale halos are revealed through gross features in gravitational lenses, small-scale halos are visible in fluctuations in the substructure of individual lensed background objects. Current and anticipated observational capabilities should permit probing halo masses as small as $10^8 M_\odot$ and $10^4 M_\odot$, respectively. Disentangling the achromatic lens substructure from the source substructure requires high-resolution, multi-wavelength images.

2.4 Issues/Requirements/Goals

- Measuring dark matter annihilation induced Compton-y and -μ distortions CMB monopole measurements with a fractional precision of 10^{-8}.
- Exploiting high-frequency images of lenses requires imaging resolution better than 0.005$''$ over fields of view larger than 3$''$ above 100 GHz and flux limits of 2 μJy/beam.
- Finding and exploiting many additional strong lenses requires resolution better than 0.005$''$ over fields larger than 3$''$ above 1 GHz and flux limits of 1 nJy/beam.
- Broad coordination with other bands.

3 Particle Physics

3.1 Probing Neutrino Emission through Radio Observations of Supernovae

Radio observations of supernovae provide constraints on the asymmetry of the explosion. This in turn provides constraints on the neutrino emission mechanism, and in particular its spherical symmetry.

3.2 Radio Observations of Supernovae and Long Transients

Radio observations of supernovae can provide constraints on afterglow decay times, which can be used to infer properties of the ejecta, such as velocity, temperature, and composition. (What other long transients?)

3.3 Measuring Pulsar and Black Hole Velocities through Pulsar Timing and VLBI

Sensitive proper motion measurements of pulsars through VLBI, combined with parallax measurements, provide space velocities that provide important constraints on the physics of supernova explosions. In particular, they can be used to test models for asymmetric neutrino emission during supernovae explosions, which can impart a “kick velocity” to the neutron star. In addition, there is evidence for a correlation between the spin and velocity vectors of young pulsars. The existence of this correlation, which much be tested with a greater number of objects, has implications for the duration and number of impulsive kicks provided to the neutron star during the core collapse process. Searches for the youngest pulsars in the galaxy and follow-up VLBI observations are critical for these tests.

3.4 Issues/Requirements/Goals

- Galactic plane searches at frequencies of 1–5 GHz, with integration times of hours, for the youngest pulsars
- VLBI observations over timescales of years and at at frequencies of $\sim$1 GHz for precise parallax and proper motion measurements

4 Nuclear Physics

4.1 Mass and Moment of Inertia Measurements through Radio Pulsar Timing

The equation of state of high-density nuclear matter remains highly uncertain, with a range of viable models for the mass-radius relationship for neutron stars. Two important constraints on these models include the maximum mass of a neutron star and the radius of a neutron star of a certain mass. Both of these can be addressed through radio timing observations of binary millisecond pulsars. For most binary millisecond pulsars, the orbit can be fit with five Keplerian parameters, providing the total mass of the pulsar and its companion. For the most relativistic systems, however, up to five post-Keplerian parameters can be measured, allowing a determination of the masses of the pulsar and its companion, in addition to the orbital inclination. The highest well-measured masses, determined through Shapiro delay for two recycled pulsars, are roughly 2 $M_\odot$, already ruling out a number of equations of state. Accurate measurements of more neutron star masses will constrain equations of state even further, but radius measurements are also necessary. The moment of inertia of a neutron could be measured if second-order corrections to the post-Keplerian parameters are measurable. This may soon be possible for the relativistic double pulsar system, consisting of two neutron stars in a 2.45-hr orbit.

4.2 Radio Observations of Gravitational Wave Counterparts

Neutron star-neutron star and neutron star-black hole mergers present a primary source class for ongoing and anticipated gravitational wave searches. With the recent direct detection of gravitational waves from a black hole-black hole binary, it appears all but certain that these will detected as well in the coming years. Tidal interactions during merging in neutron star binaries, and therefore imprinted in the gravitational wave signal, provide a probe of the high-density nuclear equation of state. These are made robust using the phenomenologically universal relations between the moment of inertia, tidal susceptibility, and mass quadrupole, the so-called I-Love-Q relations. Additionally, the tidal disruption radius of the binary dramatically affects the merger ejecta velocities and neutron fractions, which in turn impact the r-process nucleosynthesis. Therefore, radio/millimeter/sub-millimeter observations of the prompt emission and subsequent kilonova can potentially independently constrain the high-density nuclear equation of state. Such additional observables appear to be necessary in systems with unequal mass ratios to fully characterize the event.

The merger of magnetized neutron star binaries can power pulsar-like emission, driven by dynamical magnetospheres powered by orbital instead of stellar motions. These can be many orders of magnitude brighter than Galactic pulsars, and therefore even with current facilities can be detected at cosmological distances, making them a natural electromagnetic counter-part to gravitational wave events, enabling unique multi-messenger cosmological studies and/or tests of the equivalence principle in the dynamical regime. By virtue of the similarity of their physics and observational requirements to pulsars, these are well-matched to radio bands.

4.3 Issues/Requirements/Goals

- all-sky searches at frequencies of 300 MHz (out of the Galactic plane) to 5 GHz (in the Galactic plane), with integration times of minutes to hours, for recycled pulsar binary systems
- regular (weekly–monthly) timing observations of 10–20 recycled binary pulsars with the highest timing precisions at 500 MHz – 5 GHz frequencies, with coverage at at least two frequencies for each pulsar
- VLBI observations of recycled binary pulsars for precise parallax measurements at frequencies of $\sim$1 GHz
- searches of nearby galaxies for radio signatures of mergers at frequencies of 1 to 5 GHz, with integration times of hours
- prompt wide-field follow-up of identified LIGO merger events to search for signatures of mergers at frequencies of 1 to 5 GHz, with integration times of minutes

5 Opportunities for New Physics

The high time and frequency resolution afforded by new correlators and data processing capabilities provide opportunities for novel modes of observations which probe new source classes and provide unique fundamental physics applications.

5.1 Searches for Fast Radio Transients

Over the past decade, a number of new source classes which exhibit variability on a variety of timescales have been identified. The most notable of these are the Fast Radio Bursts (FRBs), or short-duration flashes of radio emission with dispersion measured indicating an extragalactic origin. The physical mechanism for these bursts is not clear, but the energetics imply that a compact, high-energy source is necessary. Very recently, an FRB was potentially identified with a host galaxy, allowing a distance measurement and allowing the FRB to be used as a probe of the intergalactic electron density. More such detections and measurements will allow constraints on the intergalactic medium, as well as on the underlying physical mechanism of these bursts. In addition, as the transient sky is explored at increasingly high time resolution, new source classes are likely to be discovered.

5.2 Issues/Requirements/Goals

- all-sky searches at frequencies $\sim$ 1 GHz for transient radio emission
- interferometric searches with millisecond time resolution which are capable of localizing transients in real-time, facilitating immediate following at other wavelengths and identification with a galaxy

6 Radio Observations in the Gravitational-Wave Era

The recent detection of gravitational waves from a black hole binary has signaled the birth of gravitational wave astronomy. In addition to probing the gravitational and astrophysical properties of mergers, gravitational wave observations open a new window on the evolution of mass and compact objects within the universe. However, most gravitational wave sources are a highly specialized class of astronomical objects, and therefore the relationship to the known classes of astronomical objects is far from clear. Therefore, over the coming two decades finding novel ways to relate the electromagnetic and gravitational wave sky will be a fertile ground for discovery.

6.1 An Unbiased Search for Stellar Mass Black Holes

All current methods for finding and studying black hole binaries are extremely biased. Both X-ray binaries and gravitational wave sources must arise from complicated, unlikely, and uncertain formation histories that produce very compact systems. Therefore, even in the era of gravitational wave astronomy the relationship between these and the larger stellar mass black hole population will remain unclear despite the anticipated flood of data. An unbiased census of Galactic stellar mass black holes, including the fraction of wide binaries, would directly inform these formation histories, filling the gap between massive star populations and compact object binaries. Finding isolated Galactic stellar mass black holes necessarily requires indirect methods due to their extremely low expected luminosities. Radio microlensing surveys supplemented with high-resolution imaging provides a natural way in which to identify and characterize these objects. Modest improvements in sensitivity will enable the construction of an unbiased Galactic black hole sample over the course of a decade.

6.2 Millimeter VLBI Studies of AGN

Current gravitational-wave events are not repeatable, probe stellar-mass black holes, and often will not have electromagnetic counterparts. However, radio/mm/sub-mm observations can make long-term studies of the similar object classes, e.g., black holes, for which the electromagnetic and gravitational properties are believed to be intimately related. As a result, the electromagnetic manifestations of the gravitational properties of black holes are a crucial step in connecting the electromagnetic and gravitational wave samples.

An extensive theoretical understanding has been developed, the compact nature of black holes has precluded empirical verification of the many key elements. This includes the relationship of accretion efficiency and relativistic outflows to the black hole parameters mass and spin. Ongoing mm-VLBI observations of nearby supermassive black holes, resolving the near-horizon structure of accretion flows and relativistic jets on sub-Schwarzschild radius scales, shows considerable promise as a means to directly connect their electromagnetic and gravitational properties. Existing mm-VLBI targets, including the Galactic center, are well matched to future space-based gravitational wave missions, providing a clearly complimentary capability.

6.3 Issues/Requirements/Goals

- A 10 μJy week-cadence all-sky microlensing survey.
- Triggered VLBI follow-up with sub-mas resolution and a 10-μJy flux limit of between 10-300 sources per year.
- High-cadence, high-frequency ($\geq$ 230 GHz), multi-wavelength VLBI capabilities.

7 Fundamental Astrophysics

In addition to fundamental physical results, there are a number of directly-related foundational astrophysical questions addressed by radio/mm/sub-mm capabilities. Progress in these would have broad impacts throughout astronomy as many of the key processes (e.g., MHD turbulence, rotationally-powered jets, etc.) appear across a variety of scales. We presume that these will be treated in the context of star formation and galaxy formation in the appropriate group summaries, and thus focus on the impacts for compact objects here.

7.1 Growth of Black Holes

The processes by which supermassive black holes grow are critical to understanding their properties and influence. This, in turn, is predicated upon a great deal of uncertain physical processes, appearing on scales ranging from the size of galaxies to the Schwarzschild radius. These include the gas dynamics within galactic mergers, the formation and orbital dynamics of nuclear star clusters, and the feeding and plasma physics of accretion disks. Of these, the last has been typically the least well understood as a consequence of the small intrinsic length and time scales. It is also an area in which radio/mm/sub-mm observations can make unique contributions.

The structure of accretion flows are set by the plasma dynamics in strong spacetimes, often treated in the magnetohydrodynamic limit. Within this context the rate at which gas can move inward is dictated by the saturation of the MHD turbulence. How such accretion flows appear in the radio is further dependent on the highly uncertain processes underlying particle acceleration. Therefore, both of these are amenable to the horizon-resolving studies of accretion in the Galactic center and other nearby supermassive black holes enabled by mm- and sub-mm-VLBI.

7.2 Black Hole Outflows

Through winds and relativistic jets, supermassive black holes have a cosmological impact disproportionate to their comparatively small mass. The source of these outflows have been localized to very near the central black hole. However, the processes responsible for them remain uncertain, with a corresponding ambiguity regarding the relationship between the assembly of supermassive black holes and their parent galaxies, galaxy groups, and galaxy clusters. Again, the chief obstacles are the small length and time scales within the presumed jet launching region. Additionally, it is unclear if the putative accretion flows are necessary and/or important for setting the jet properties. Hence, despite decades of strong theoretical evidence for a connection between black hole properties and jet launching, little empirical evidence is present. Again this is a problem amenable to mm- and sub-mm-VLBI studies of AGN exhibiting strong jets.

Equally important is the content of relativistic jets, i.e., what are they made of and when/how does it appear within the jet. Similarly uncertain is the source of the nonthermal particles that produce the radio, optical, X-ray, and gamma-ray emission. In addition to high-resolution studies of the jet-launching region, high-resolution studies of pc-scale jets are required to determine jet structure and content in these region.

7.3 Pulsar Emission Mechanism

Rotating neutron stars are the source of power behind many energetic astrophysical processes, such as gamma-ray bursts, supernovae, and pulsar wind nebulae. Models for pulsar magnetospheres and emission mechanisms are therefore critical for understanding the energetics and timescales involved in these processes. However, accurately modeling pulsar emission is extremely difficult because of the incredibly high particle densities, energies, and magnetic fields involved. Over the past several years, three-dimensional numerical simulations have made great strides in developing models that can begin to describe important properties of pulsar emission. At the moment, our understanding seems to be limited by the models and not be a dearth of observational data, but that situation may change soon. Observations of pulsars at very high ($\sim$nanosecond) time resolutions can be used to constrain micro-structure in pulses and the size scales of emission regions, while polarization observations of single pulses can constrain pulsar emission geometries. Monitoring observations of pulsars which exhibit state changes can be used to understand the relationship between pulsar observables and magnetospheric particle densities. These studies have important implications for our understanding of other high-density, relativistic, highly magnetic environments.

7.4 Issues/Requirements/Goals

- High-sensitivity, high-frequency ($\geq$ 230 GHz), multi-wavelength VLBI capabilities.
- Monitoring studies coordinated with wavebands ranging from radio through gamma-rays.
- Sub-mas resolution, multi-band imaging above 15 GHz with sub-percent polarimetry.

- High time resolution, wide-band observations of bright pulsars at frequencies of 100 MHz to 20 GHz with accurate polarimetry.