White Paper 3: Fundamental physics and beyond the Standard Model

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JOHNS HOPKINS
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White Paper 3: Fundamental physics and beyond the Standard Model

Topics: **Tests of general relativity**
Nature of black holes and exotic compact objects (gravastars, boson stars, fuzzballs, etc.)
Dark matter: ultra-light bosons, dark photons, axions (overlap with WP6*)

This White Paper will combine 5 Letters of Interest (LOIs):

Emanuele Berti <berti@jhu.edu>
Fundamental Physics with Gravitational Wave Detectors [CF#044]
Suvodip Mukherjee <smukherjee1@perimeterinstitute.ca>
Multi-messenger Probes of Cosmology and Fundamental Physics using Gravitational Waves [CF#143]
Xavier Siemens <xavier.siemens@oregonstate.edu>
Fundamental Physics with Pulsar Timing Arrays [CF#149]
Craig Hogan craighogan@uchicago.edu
Physical Effects of Nonlocally Coherent Quantum Gravity [CF#032]
Emil Mottola <emil@lanl.gov>
Searching for Scalar Gravitational Waves in Neutron Star Binary Mergers [CF#166]

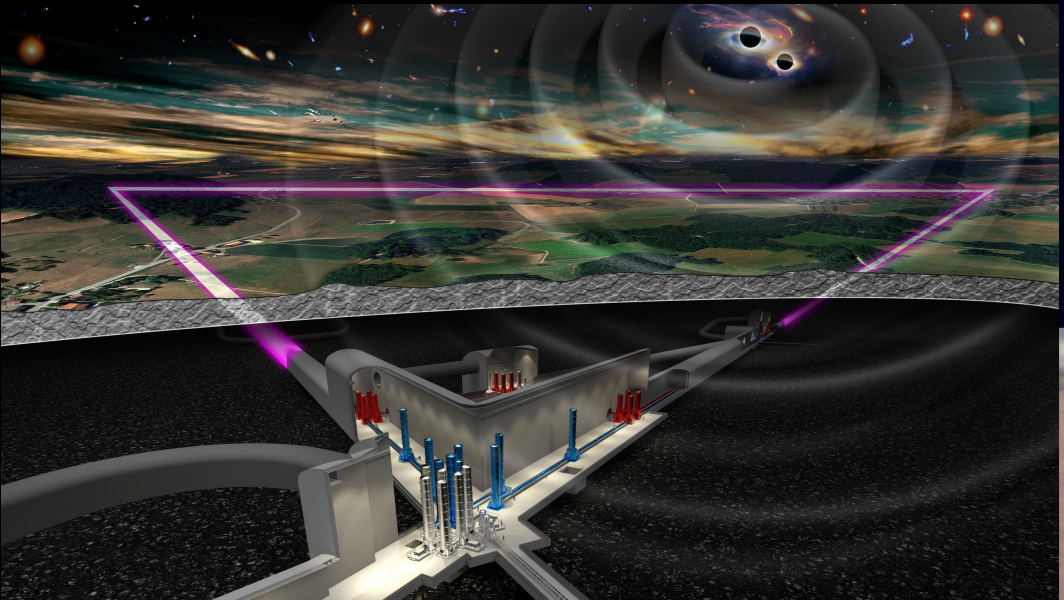
*** WP6: Early Universe Phase Transitions: Correlating SGWB with EM Observations**
Michael Ramsey-Musolf <mjrm@sjtu.edu.cn>, Yue Zhao <zhaoyue@physics.utah.edu>, Vuk Mandic <vuk@umn.edu>, Robert Caldwell <robert.r.caldwell@dartmouth.edu>, Haipeng An <anhp@mail.tsinghua.edu.cn>

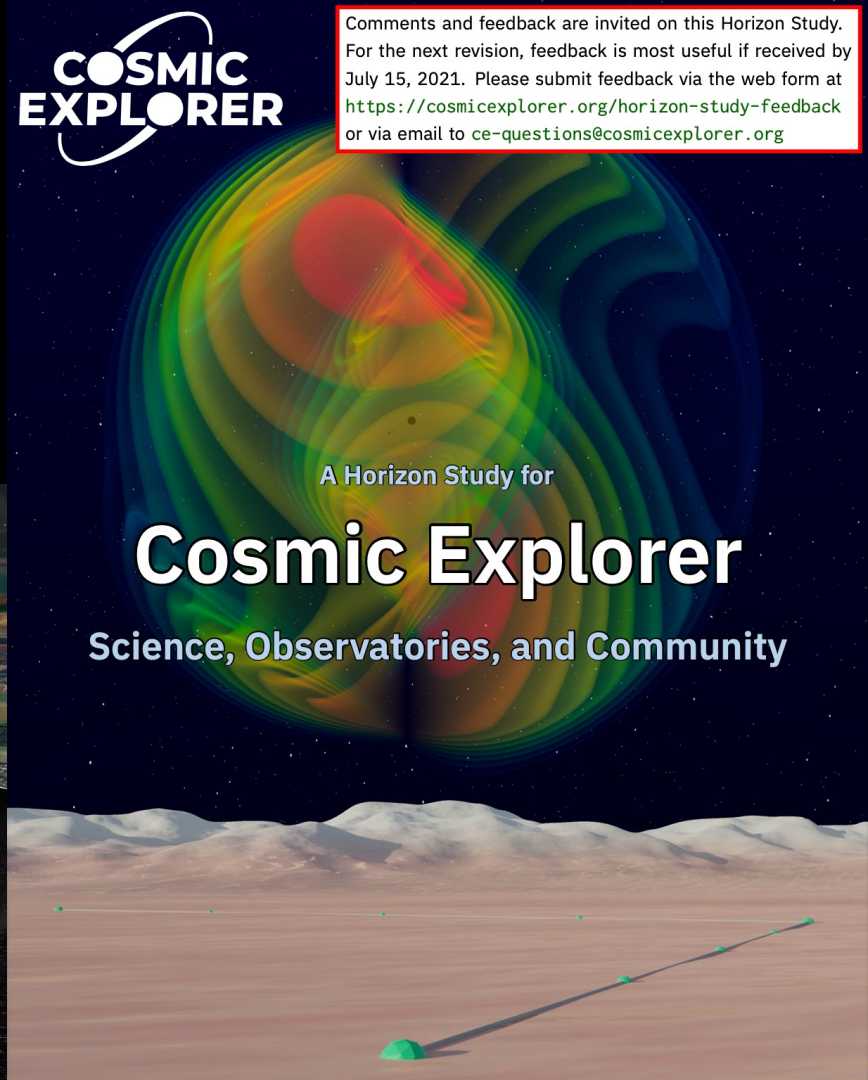
LIGO/Virgo/KAGRA + IPTA + MMA

Cosmic Explorer: Horizon Study

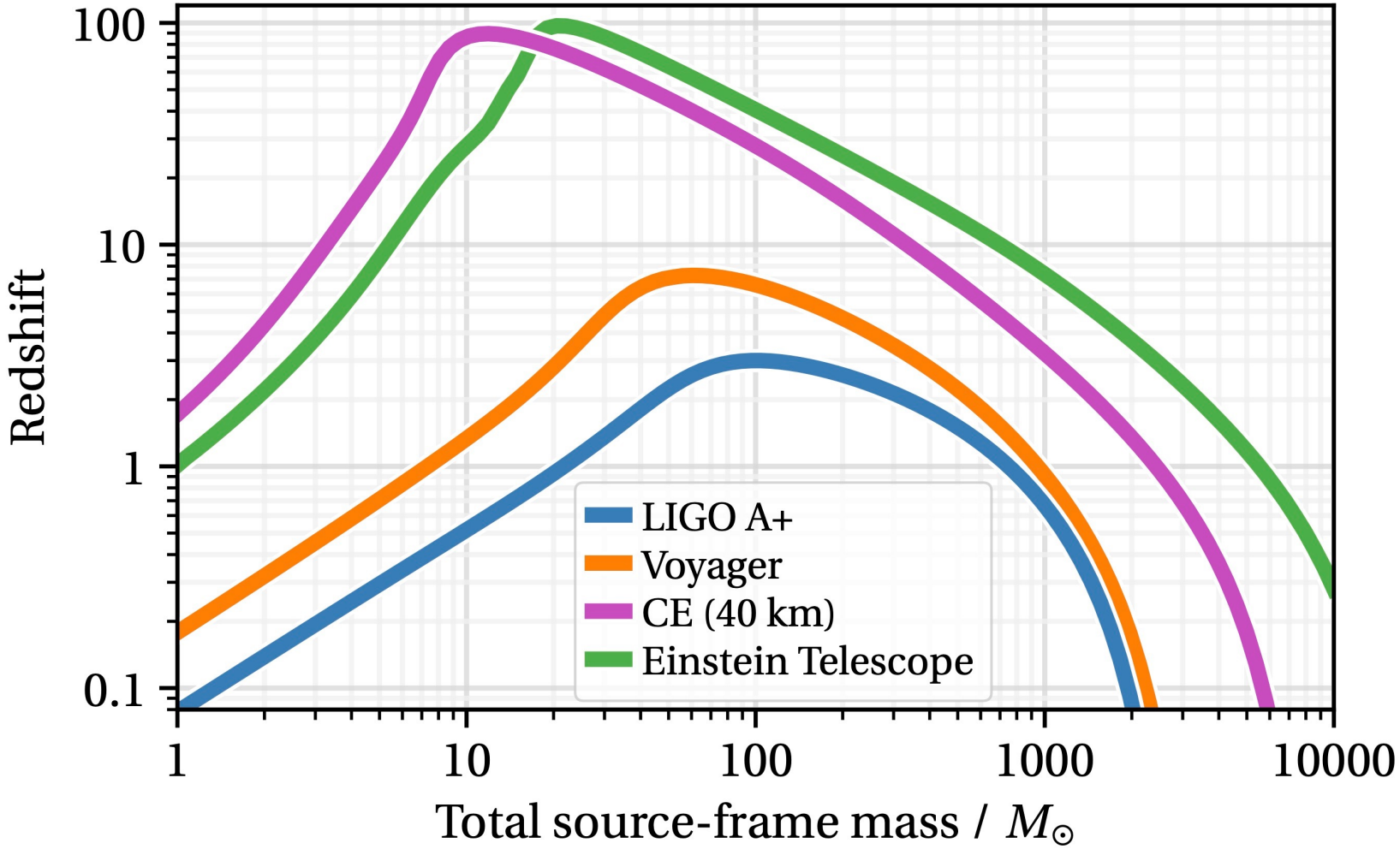
Einstein Telescope: 2021 ESFRI roadmap

LISA: 2034

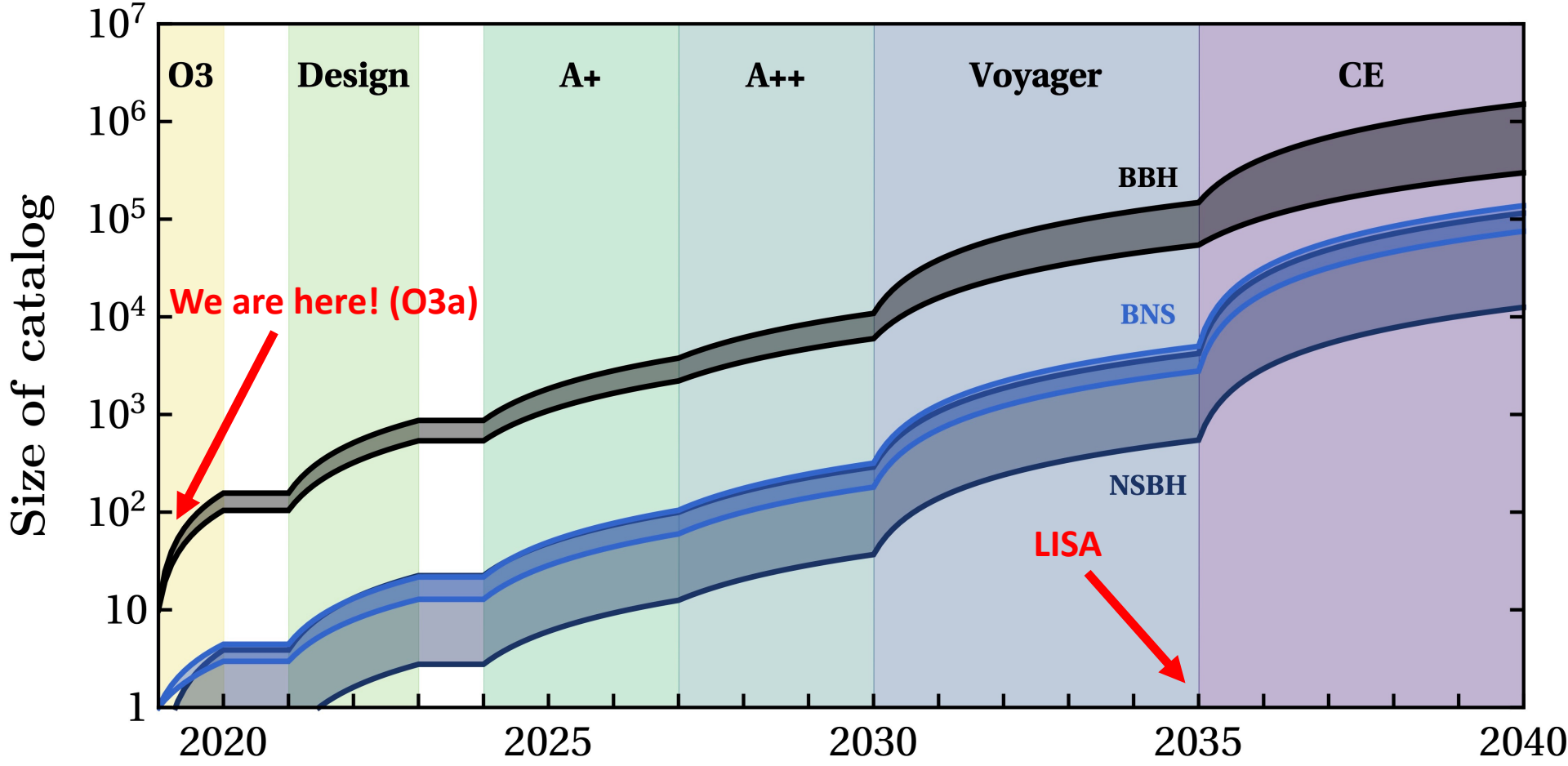




CE and ET horizons

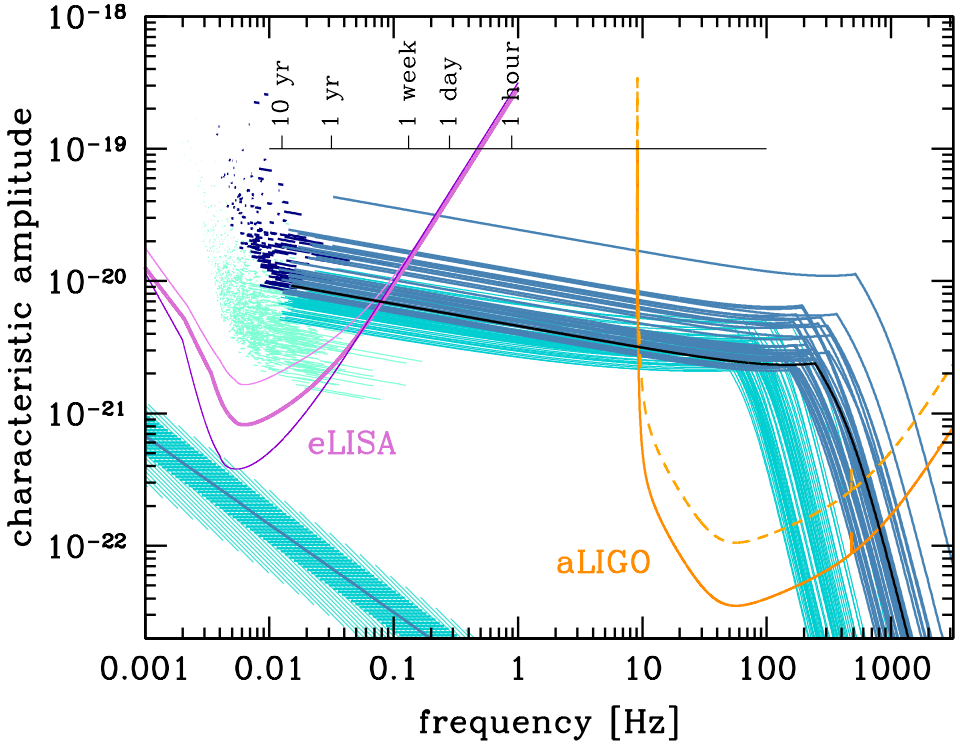


Gravitational wave astronomy in the 2030s: Big Data

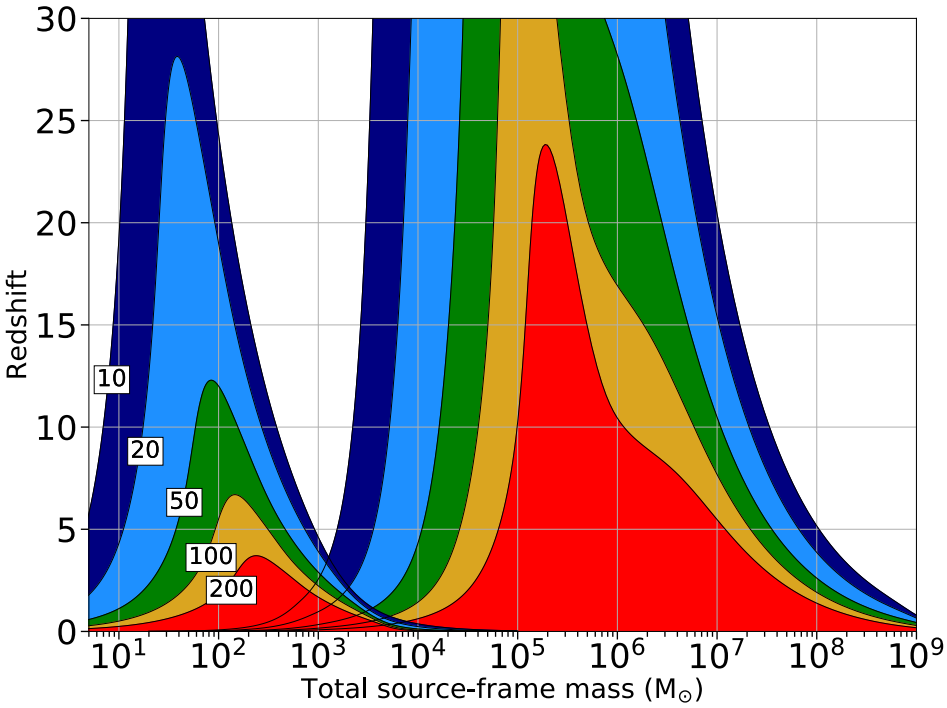


[Baibhav+, 1906.04197]

Complementarity: multi-band



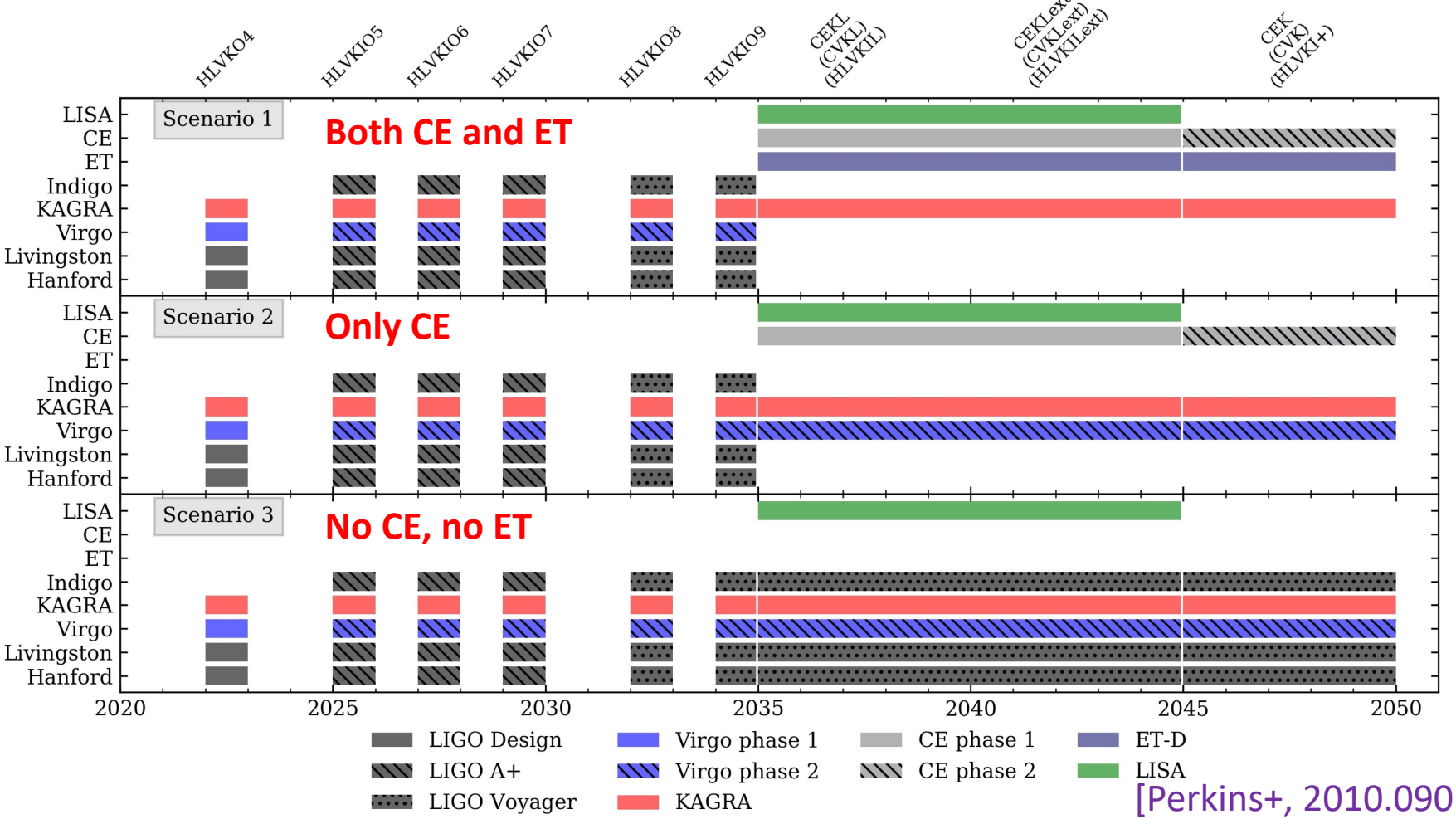
2030s: 3G (e.g., ET) vs. LISA



[Sesana,1602.06951; Nishizawa+, 1606.09295]

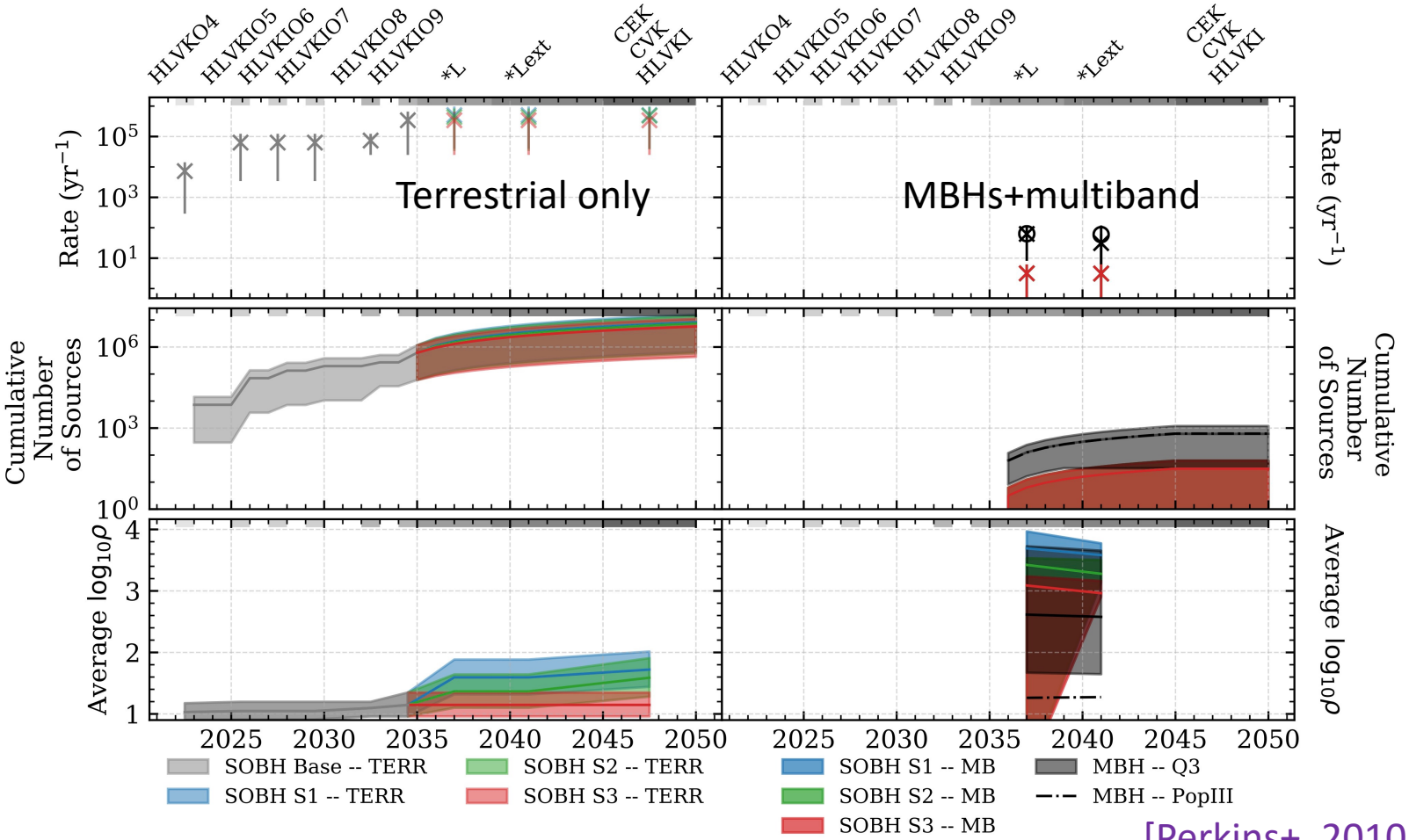
[Figure by Evan Hall]

How will tests of GR improve? Depends on detector timeline



[Perkins+, 2010.09010]

How will tests of GR improve? Number of sources and SNR evolution over time



[Perkins+, 2010.09010]

What sources/detectors are best? Depends…

$$\tilde{h}\left(\vec{\lambda}_{\mathrm{PhenomPv2}}, \beta\right) = \tilde{h}_{\mathrm{GR}} e^{i\beta(\mathcal{M}\pi f)^{b/3}}$$

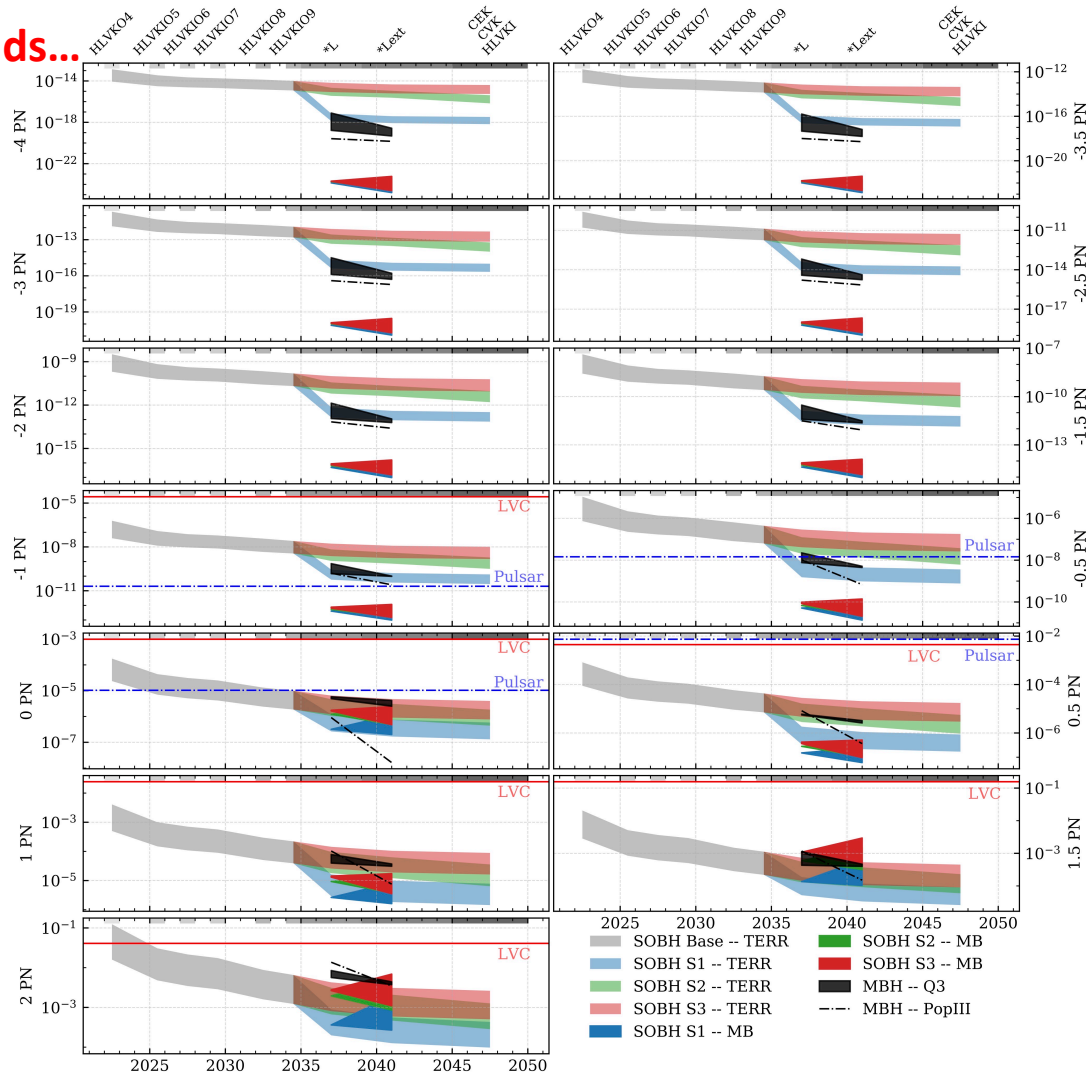
A term $(\pi\mathcal{M}f)^{b/3}$ in the phasing is of $(b+5)/2$ PN order

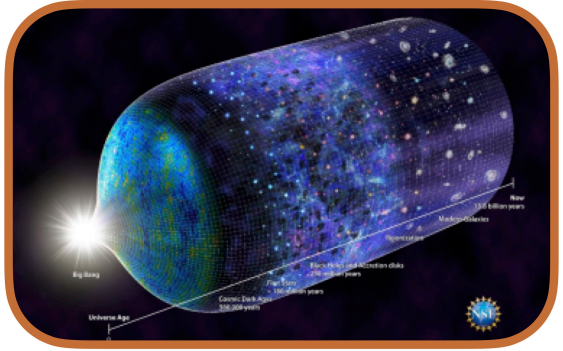
Multiband (MB) sources best at negative PN orders

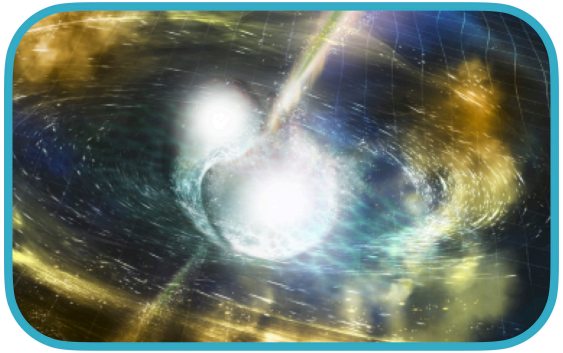
MBH better than SOBH at negative PN orders

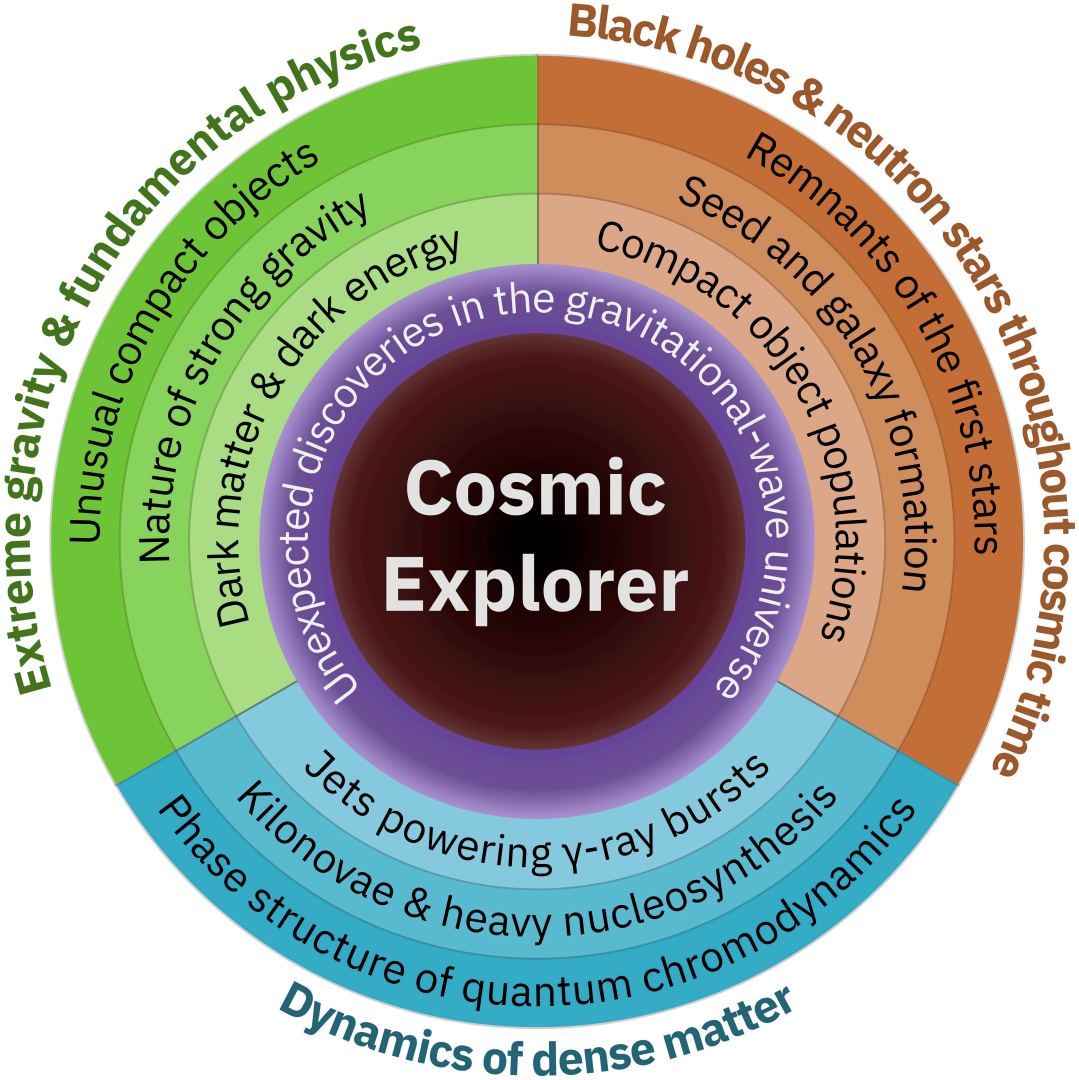
Terrestrial slightly better than LISA MBHs at positive PN orders

Terrestrial improvements matter most at negative PN orders

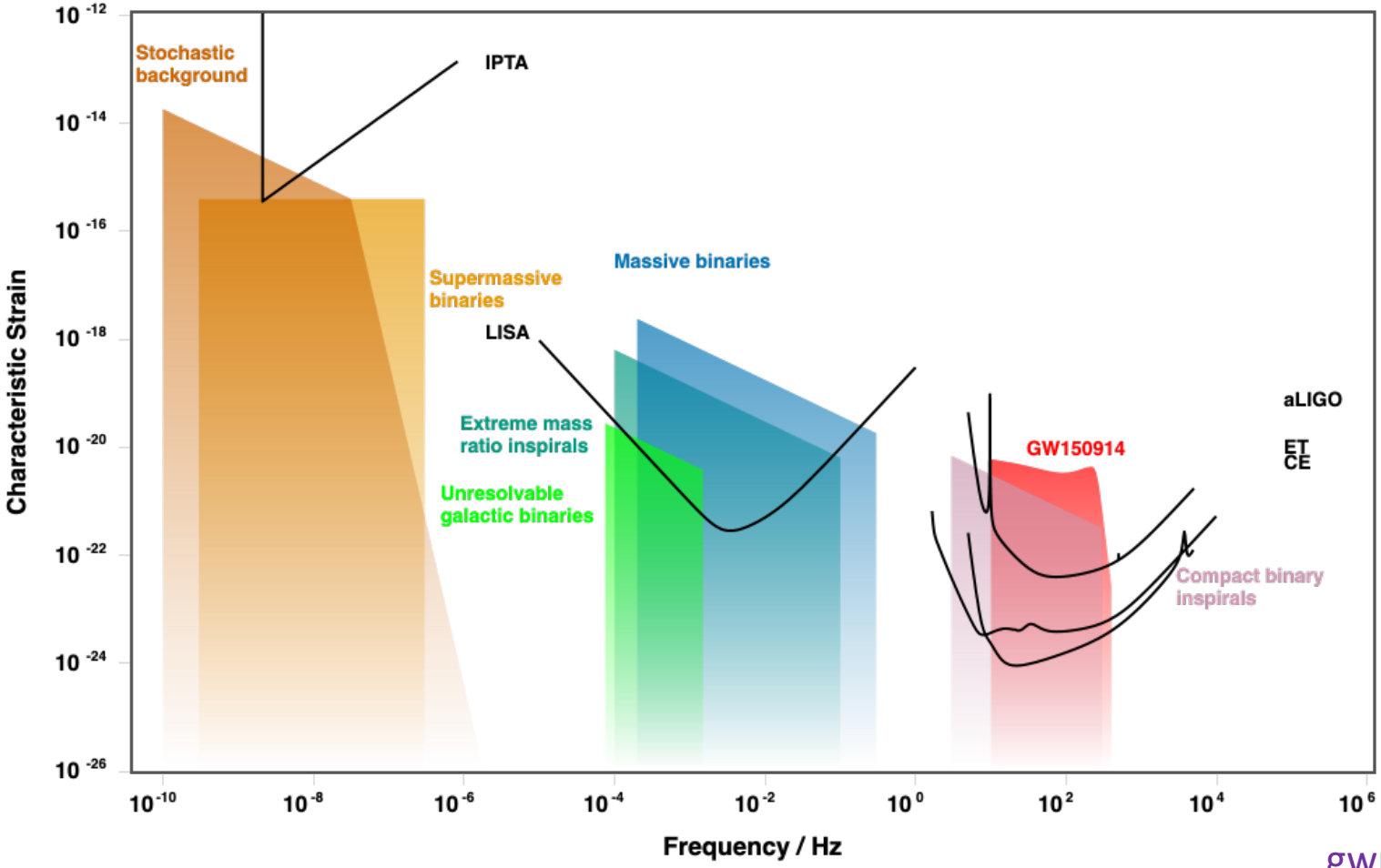







Cosmic Explorer
Unexpected discoveries in the gravitational-wave universe
Extreme gravity & fundamental physics
Unusual compact objects
Nature of strong gravity
Dark matter & dark energy
Black holes & neutron stars throughout cosmic time
Remnants of the first stars
Seed and galaxy formation
Compact object populations
Dynamics of dense matter
Jets powering γ-ray bursts
Kilonovae & heavy nucleosynthesis
Phase structure of quantum chromodynamics

PTAs + LISA + ground based detectors + multimessenger



gwplotter.com

Fundamental physics with gravitational wave detectors

LIGO/Virgo: black holes and neutron stars are nature-given fundamental physics laboratories

Upcoming experiments:

High-f: KAGRA, LIGO India, Cosmic Explorer, Einstein Telescope, NEMO (Neutron-star Merger Observatory)

Mid-band: MAGIS, AION, AEDGE, DECIGO

Low-f: LISA, Tianqin, PTAs

Black hole horizons, quantum gravity, information paradox

- Black hole spectroscopy
- Multipolar structure
- Quantum modifications at horizon scales?

Corrections to general relativity

- Additional fields, modifications of inspiral radiation
- Black hole uniqueness theorems violated: exotic compact objects?

Probing dark matter

- Primordial black holes?
- Minicharged dark matter
- Ultralight boson clouds, bosenovas, EM signatures?

Gravitational-wave propagation and graviton mass

- GW170817: constraints on Lorentz violation in the gravitational sector
- Dispersion: graviton mass, extra dimensions, parity violation

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Cosmology and fundamental physics with multimessenger observations

Hubble constant measurement

Hubble tension: discrepancy between Cepheids + Sne Ia and Planck observations of CMB

GW standard sirens with EM counterparts: identify host galaxy ($z<0.1$) or
LISA MBHs out to $z\sim10$

Dark energy and cosmological parameters

GWs at $z>0.1$ allow us to measure D_L and z, hence the dark energy EOS w(z)

Cross-correlate with galaxy distribution, peculiar velocities…

[Dark matter]

Dynamical friction in IMRIs

Ultralight boson clouds, bosenovas, EM signatures?

[Modified gravity]

GW170817: constraints on Lorentz violation in the gravitational sector

Dispersion: graviton mass, extra dimensions, parity violation

Time delays between photons and gravitons

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Fundamental physics with PTAs

Cosmic strings / superstrings

Phase transitions in the early Universe / string theory strings “stretched” due to expansion
Can produce SGWB or bursts; PTAs most sensitive to these sources until LISA launches (2034)

Primordial GWs from inflation

Broad-band; probably fainter than SMBH background, but depends on models
In some models spectrum rises with frequency, can be constrained

[Dark matter]

Periodic oscillations in gravitational potential from scalar fields with mass $\sim 10^{-23}$
CDM clumps near the Earth or a pulsar

[Modified gravity]

In general, up to six polarizations
Each line of sight to a pulsar gives an independent projection of the polarizations
Tens of pulsars: polarization constraints
Also enhanced response to longitudinal polarizations

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Summary

Obvious overlap in themes. Possible sections:

Black hole horizons, quantum gravity, information paradox
Modified gravity
Hubble constant measurement
Dark matter
Dark energy and cosmological parameters
Cosmic strings / superstrings
Primordial GWs from inflation

Will coordinate with corresponding authors and start assigning section captains

Timeline: **White Paper outline in November 2021**
First draft by March 2022
Final draft by July 2022