P5 Town Hall Meeting
on the Future of High Energy Physics

Hosted by Brookhaven National Laboratory
April 12–14, 2023

Gravitational Waves

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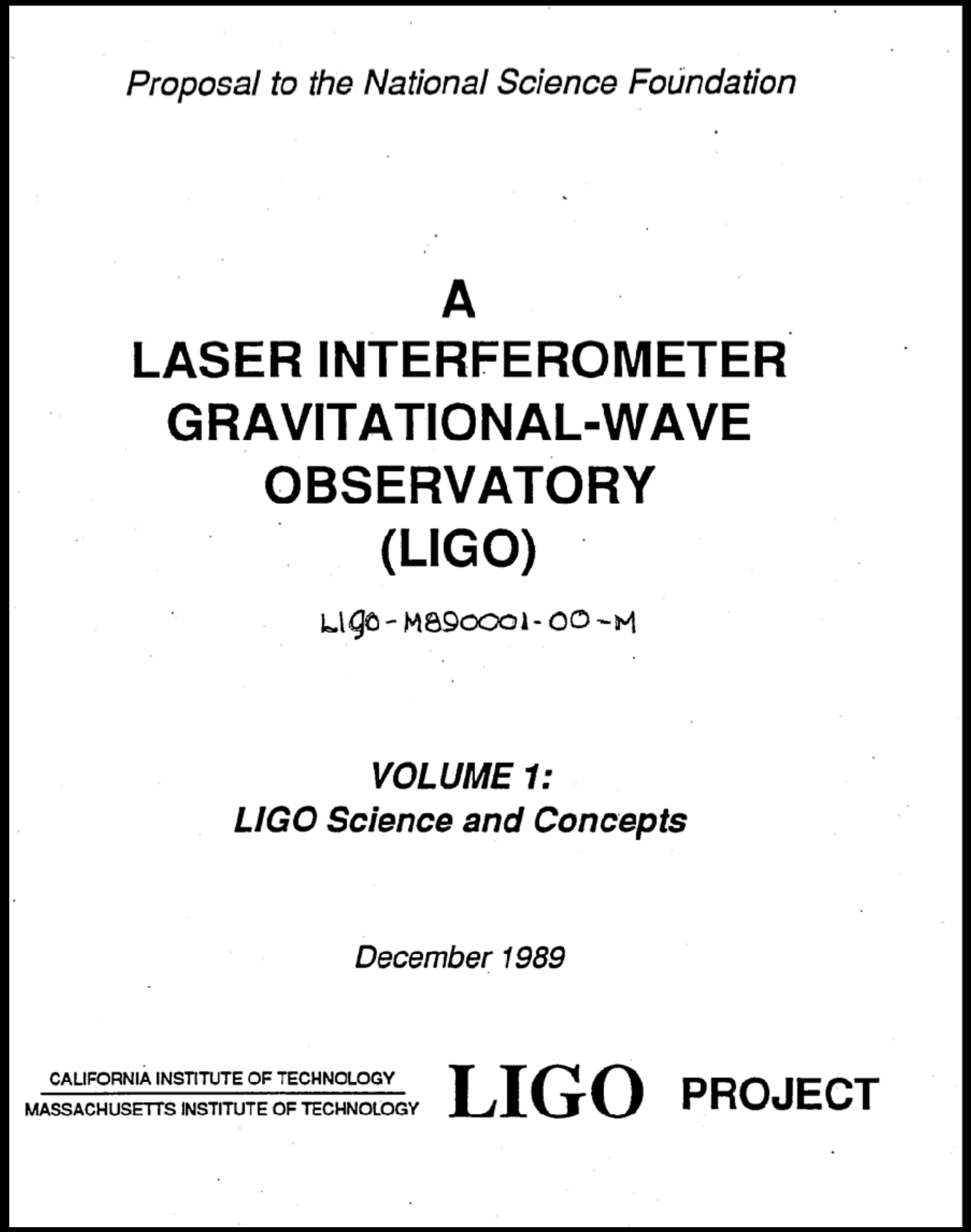
University of Washington

April 12, 2023

Artwork by Sandbox Studio, Chicago with Corinne Mucha

Gravitational Waves: New Eyes on our Universe


Proposal to the National Science Foundation

A
LASER INTERFEROMETER
GRAVITATIONAL-WAVE
OBSERVATORY
(LIGO)

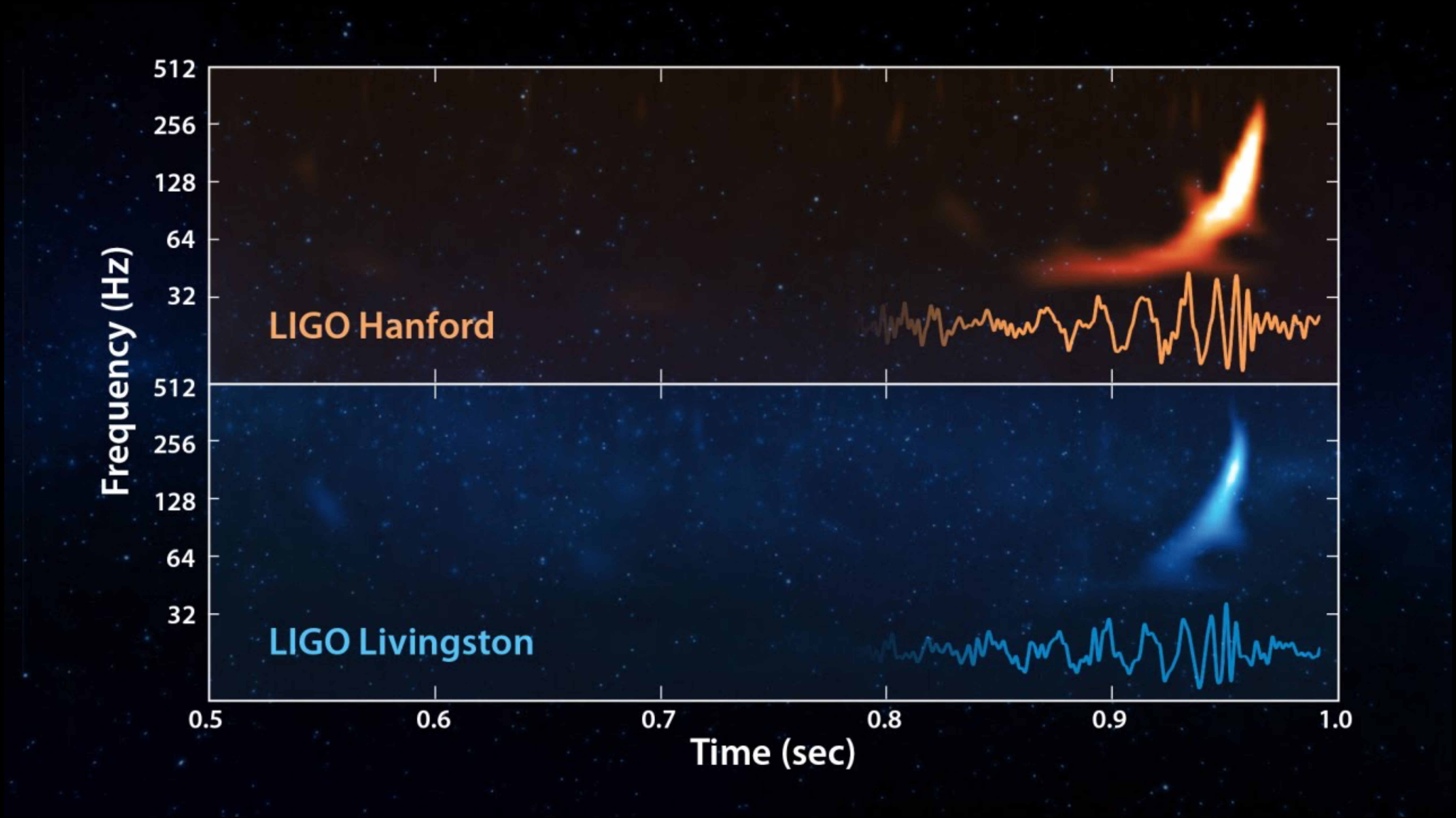
LIGO-M890001-00-M

VOLUME 1:
LIGO Science and Concepts

December 1989

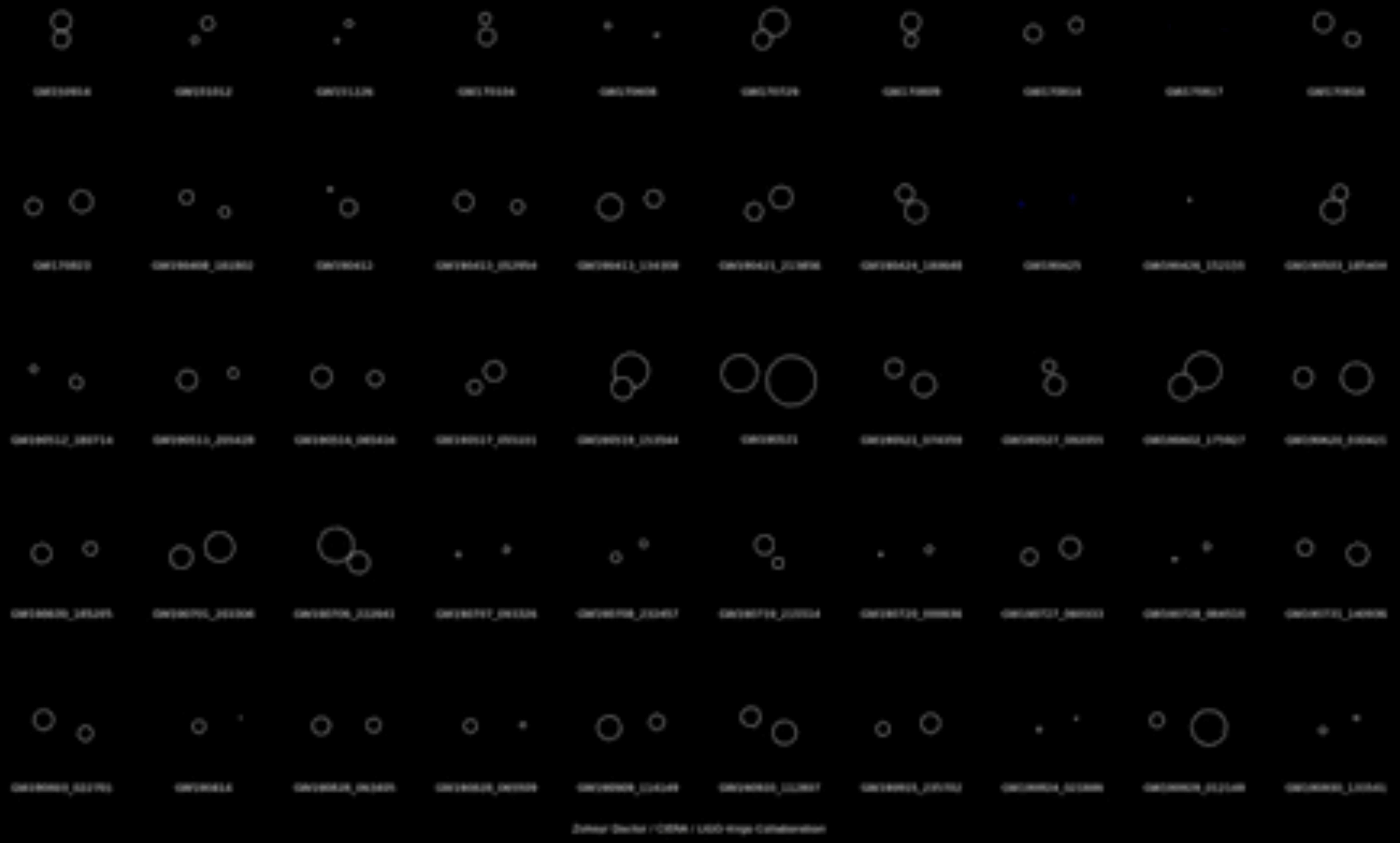
CALIFORNIA INSTITUTE OF TECHNOLOGY
MASSACHUSETTS INSTITUTE OF TECHNOLOGY
LIGO PROJECT

Proposal 1989



First detection 2015

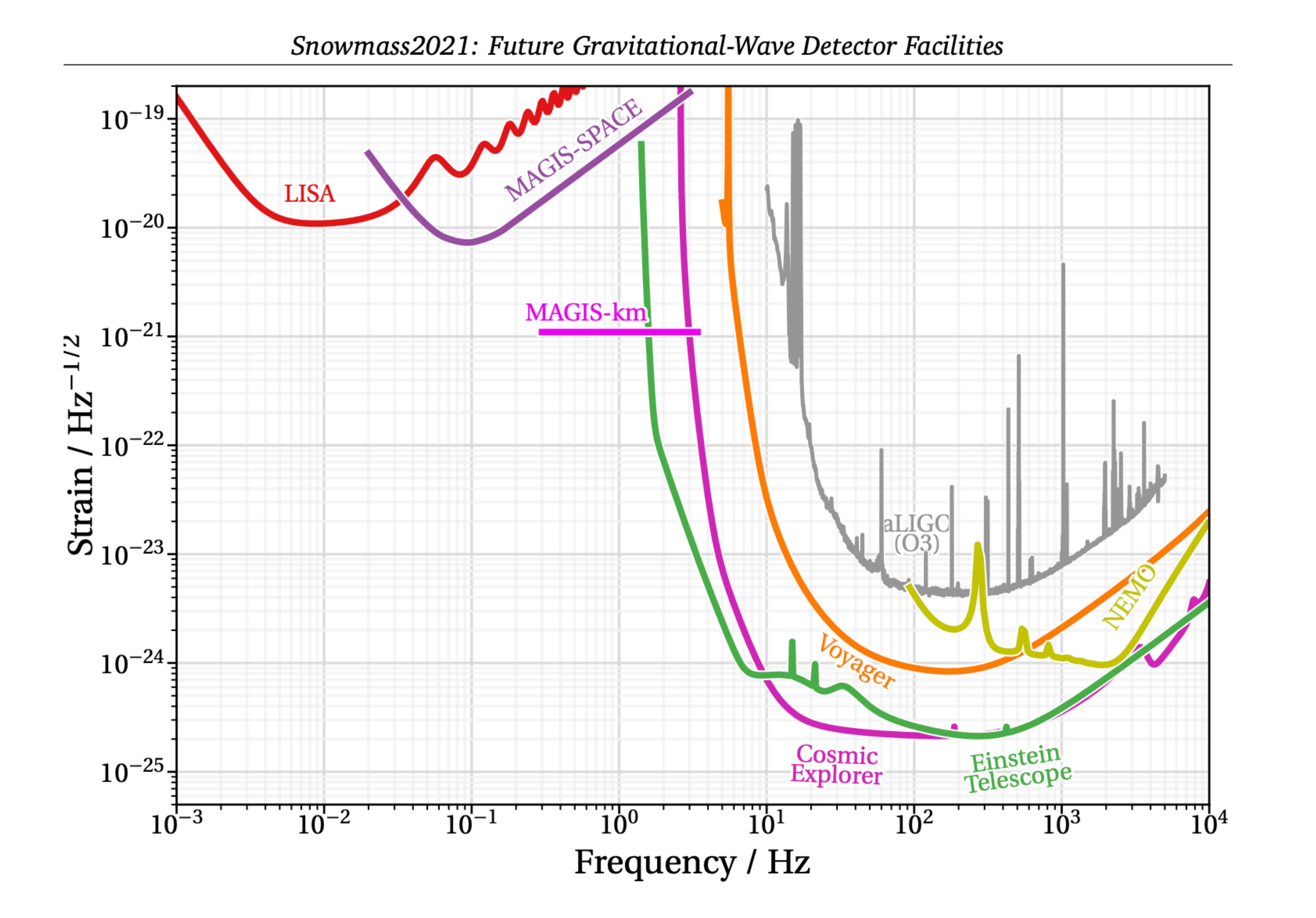
Gravitational Waves: New Eyes on our Universe



April-October 2019 dataset O3a

LIGO and Virgo detectors have been observing a wide range of black hole-black hole, neutron star-neutron star, and black hole-neutron star mergers at a rate of ~1/week, up to redshifts of z~1

Gravitational Waves: New Eyes on our Universe



Planned and Proposed Gravitational Wave Facilities

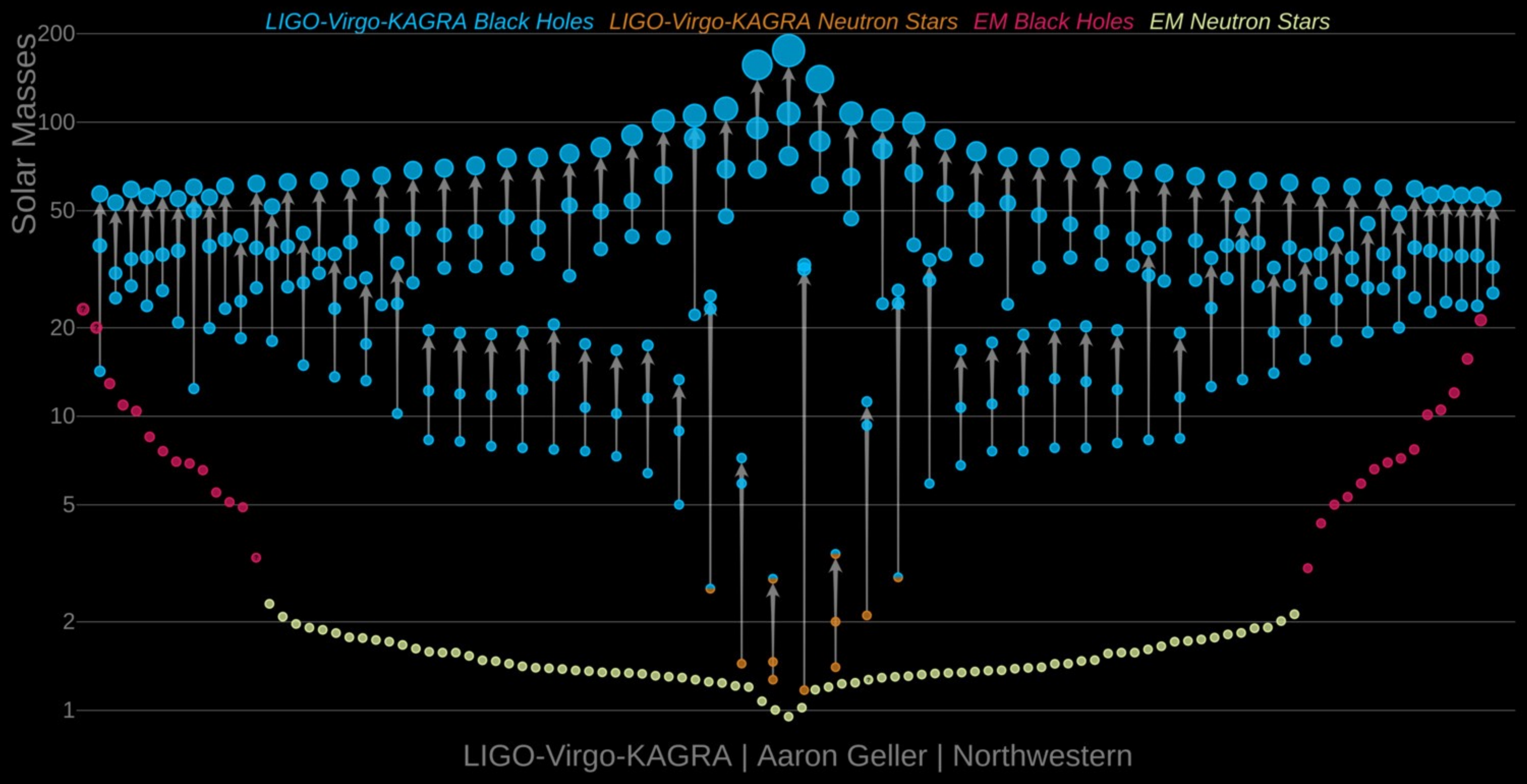
Next generation facilities have a chance to see >10x farther than current detectors and expand the reach in frequency

High Energy Physics Opportunities in Gravitational Waves

- ✓ Physics of compact objects and dense matter
- ✓ Hidden particle sectors and dark matter
- ✓ Structure and history of our universe
- ✓ New theoretical insights and techniques
- ✓ Unexpected surprises!

Physics of Compact Objects and Dense Matter

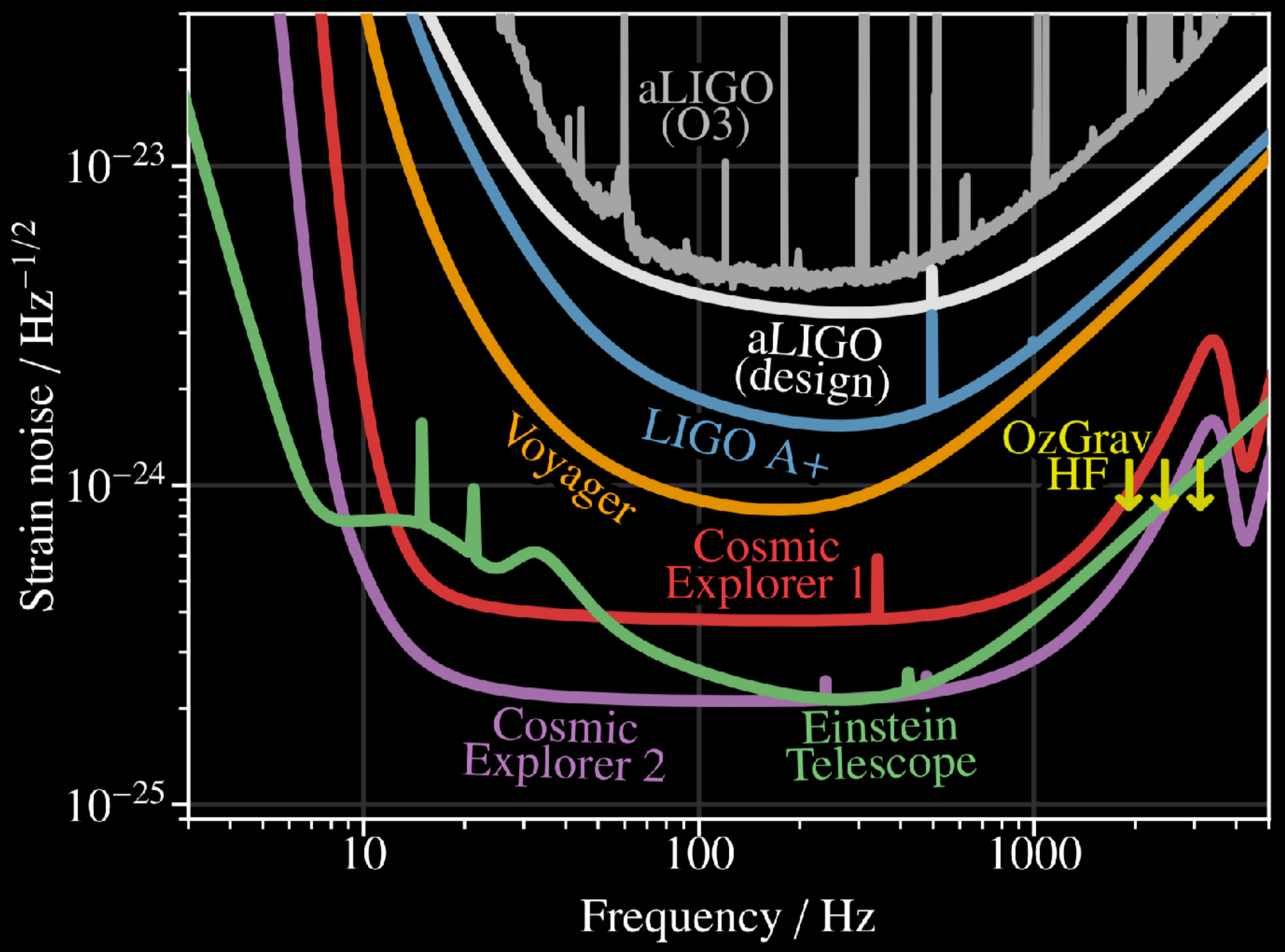
Black holes and Neutron Stars: Already Some Surprises



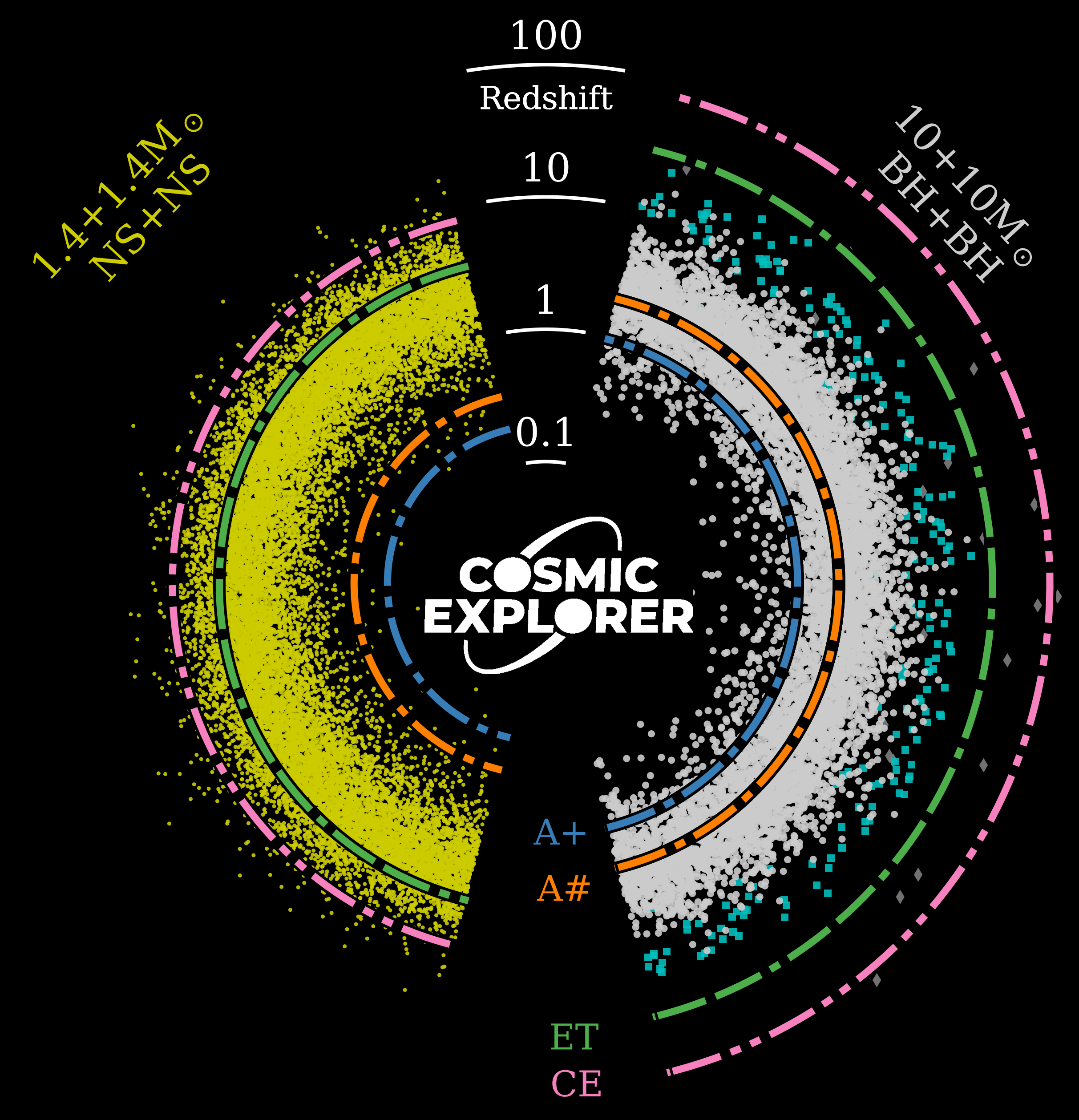
- Many black hole mergers
- New black hole populations: heavier, more slowly rotating than E&M observations
- Objects with masses in \`mass gaps'

Black holes and Neutron Stars Throughout History

- Next generation of detectors will see all Standard Model compact object mergers throughout the history of the universe

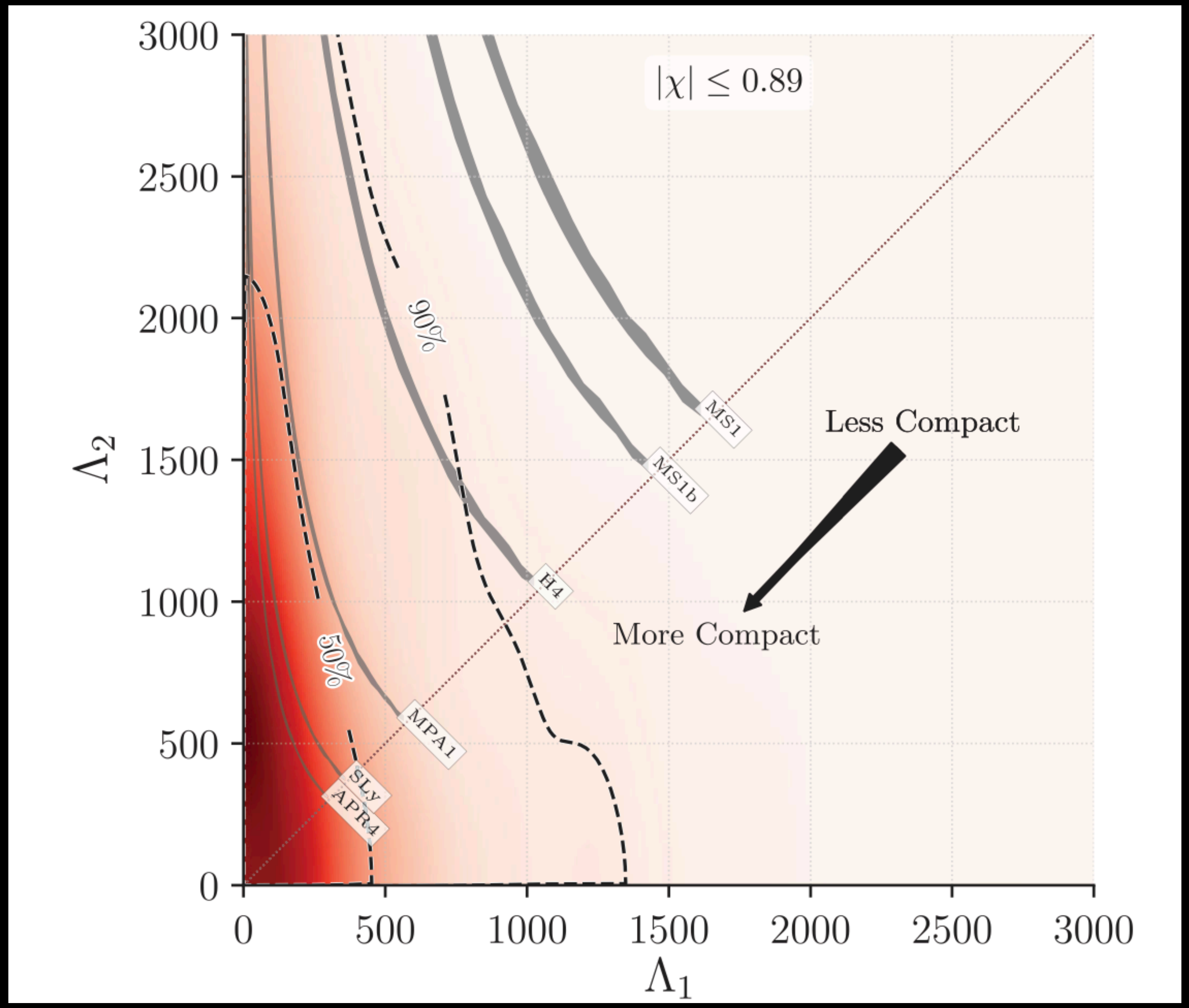


- Binary neutron stars out to $z \approx 6$
- Binary black holes out to $z \approx 30$
- Supernovae out to 20 Mpc



S. Vitale & E. Hall, data from Ng et al

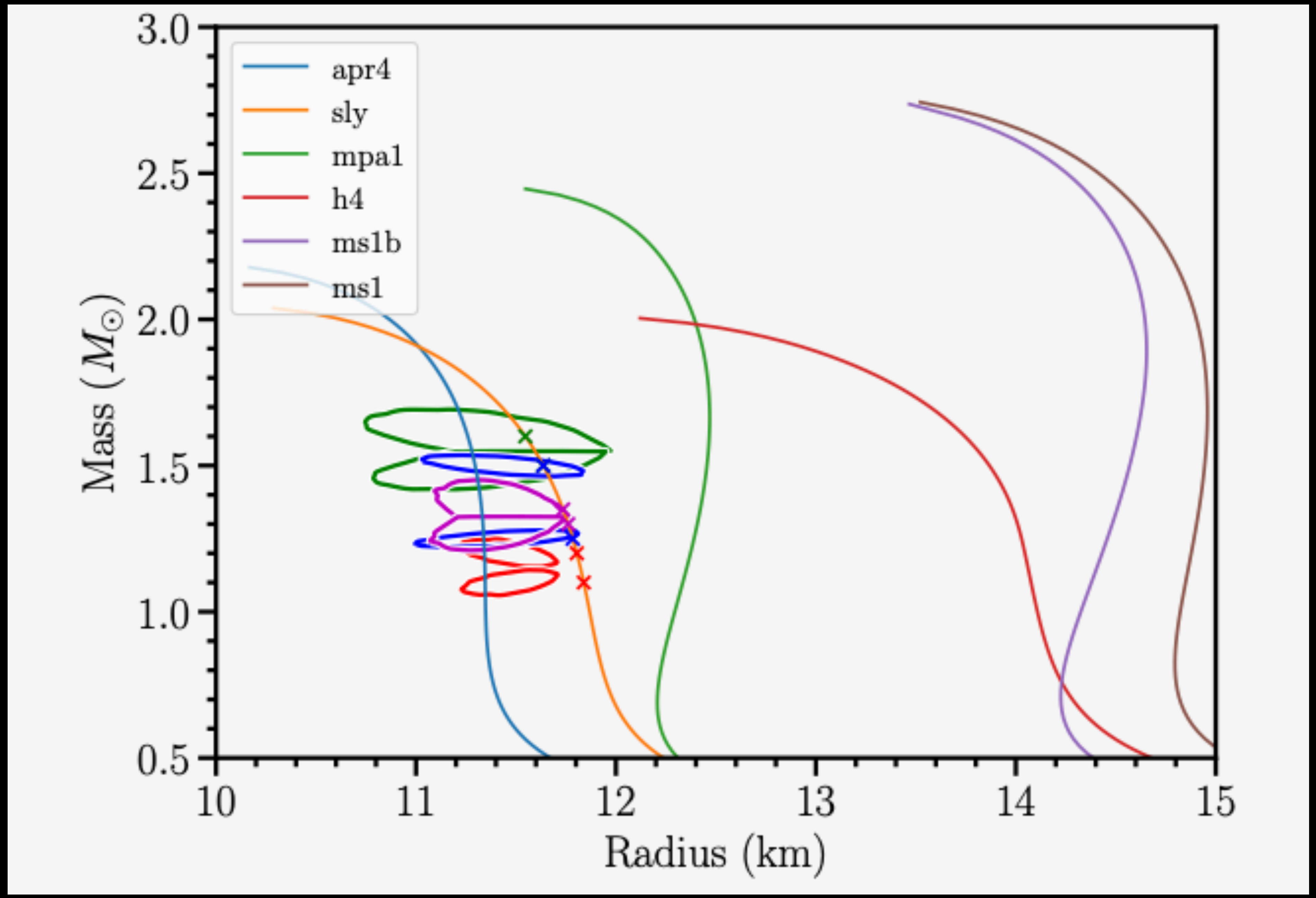
Measurement of Neutron Star Equation of State



LIGO/Virgo collaboration, Phys. Rev. Lett. 119 161101 (2017)

Upper bound on deformability constrains size and equation of state of neutron star

Next generation observatories can transform our understanding and shape theoretical models of dense matter



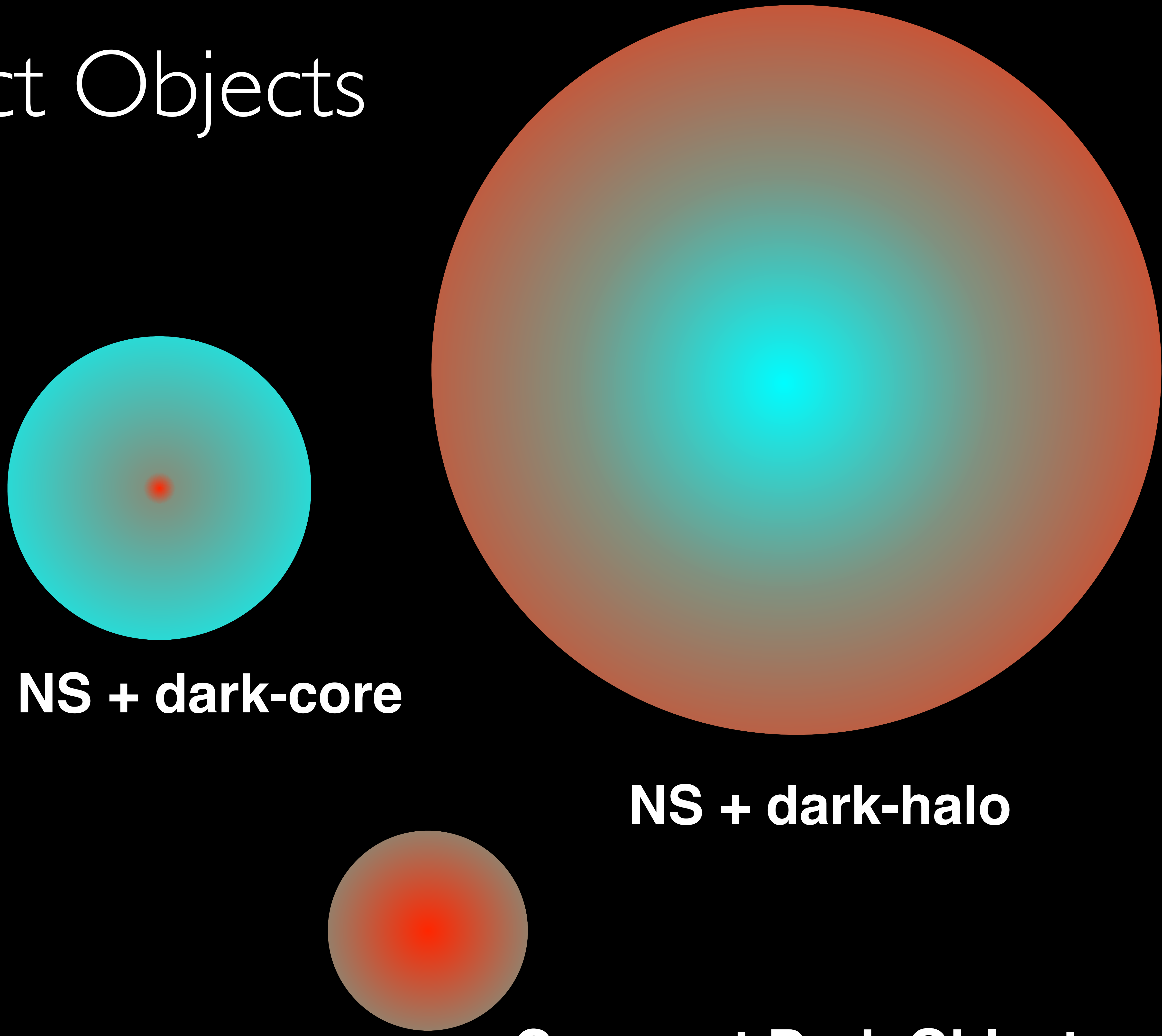
The Next Generation Global Gravitational Wave Observatory: The Science Book arXiv:2111.06990

Anomalous Compact Objects

Gravitational wave observations of binary compact objects whose masses and tidal deformabilities differ from those expected from neutron stars and stellar black holes would provide conclusive evidence for new physics

Mass < 0.1 M_{solar}
Tidal Deformability > 600

Nelson, Reddy, Zhou (2018)   Horowitz & Reddy (2018)



[Sanjay Reddy]

The Physics of Compact Objects

- GW observations in concert with theory are already uncovering physics of neutron stars and black holes, the most extreme objects in our universe
- With next generation detectors can zero in on the physics of dense matter and the formation history of compact objects in the early universe
- Precise measurements could uncover surprises such as primordial black holes and non standard compact objects as (a subcomponent of) dark matter

Extreme Environments are a Unique Source of Feebly Interacting Dark Matter and New Particles

Dark matter production in supernovae and Neutron Star Mergers

- Binary neutron star mergers are a promising environment to probe weakly interacting light particles, reaching temperatures in the 30–100 MeV range and densities above 10^14 g/cm^3

- Supernovae can produce (thermally) $10^{-2}\,M_{solar}$ of $<$ 100 MeV dark matter.

Phys. Rev. D 100 (2019) 083005 Phys. Rev. Lett. **128**, 211101 JCAP **07** (2020)023

$$n + n \rightarrow n + n + a$$

$$n + n \rightarrow n + n + \chi + \bar{\chi}$$

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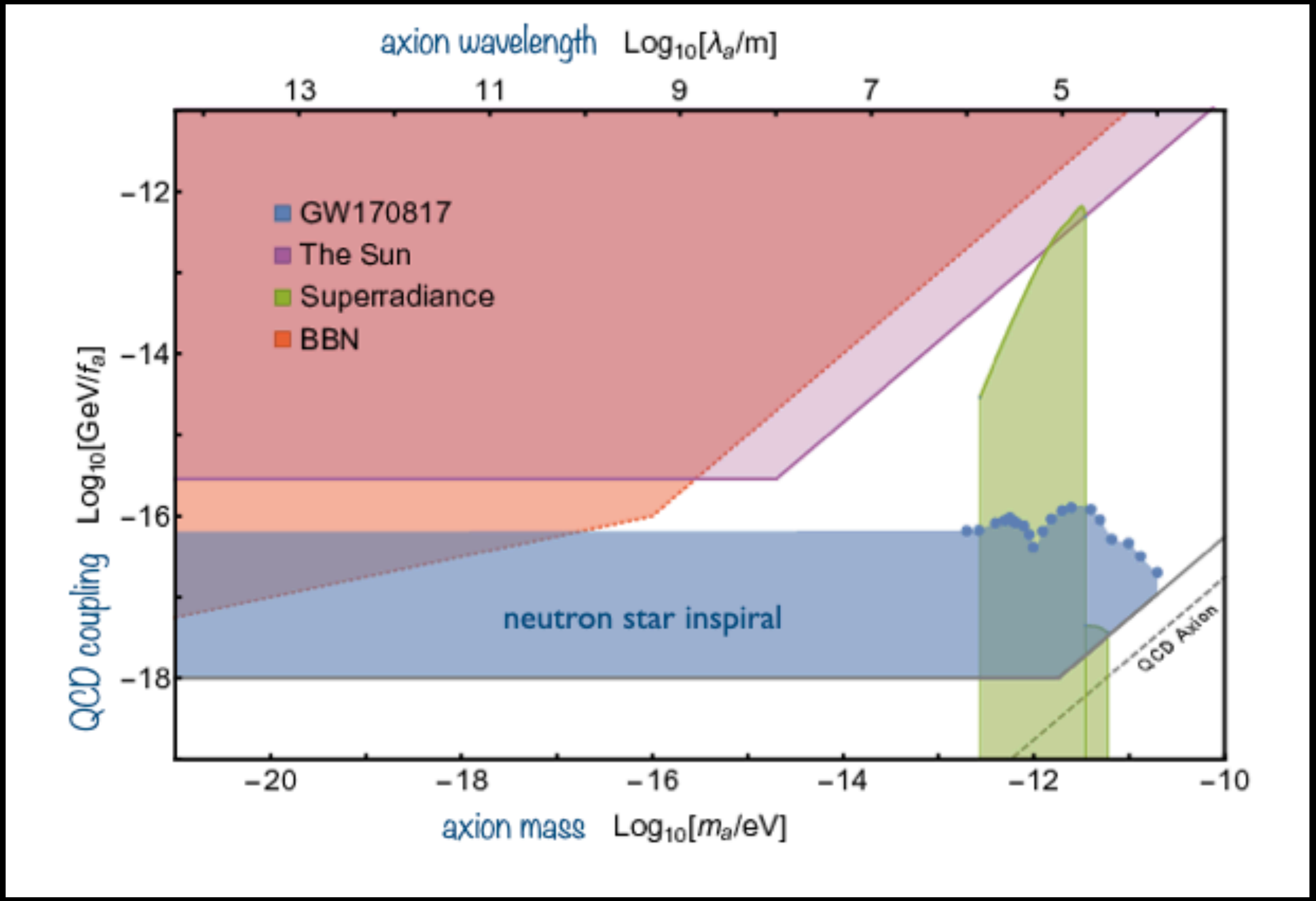
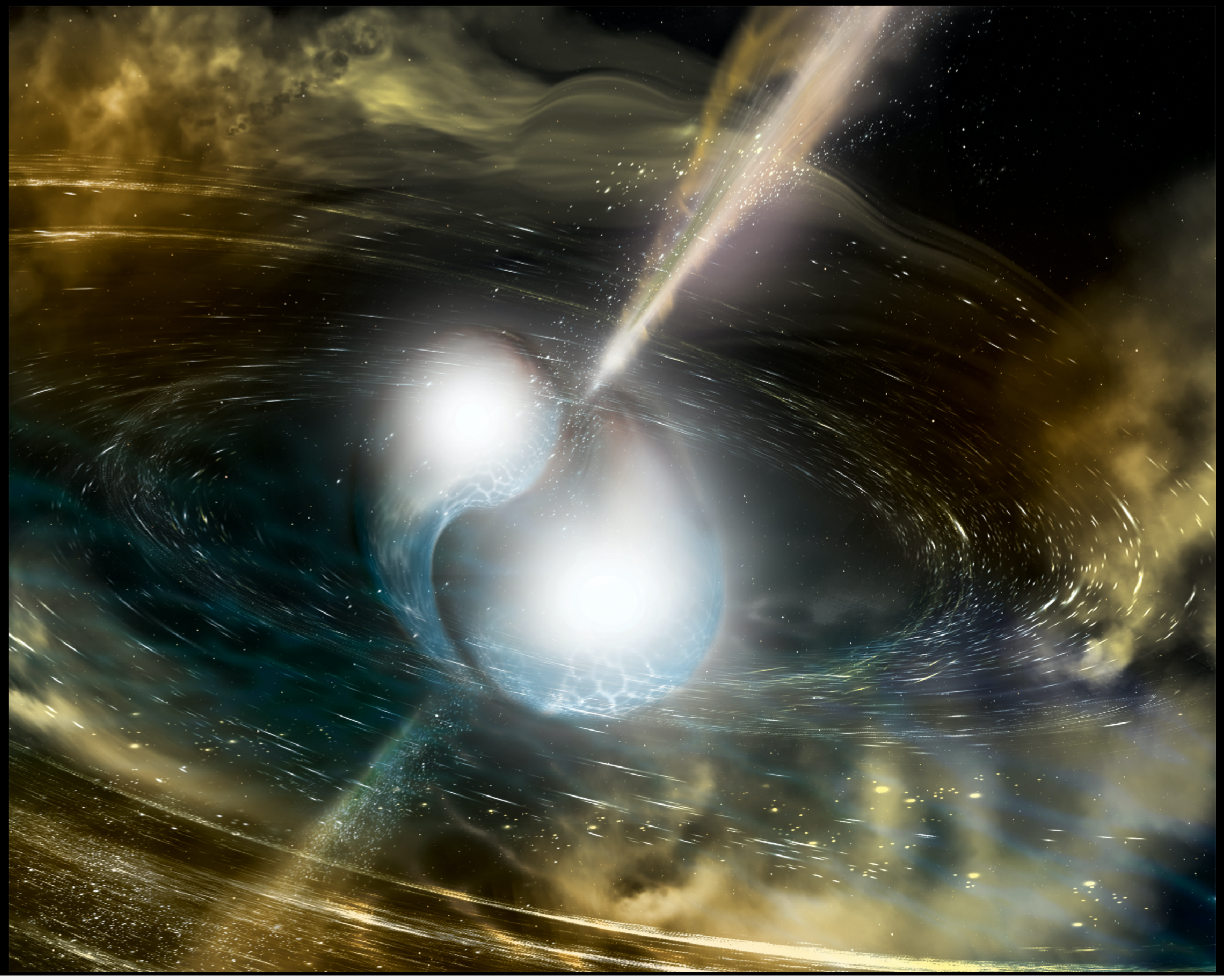
[Sanjay Reddy]

New Neutron Star Forces



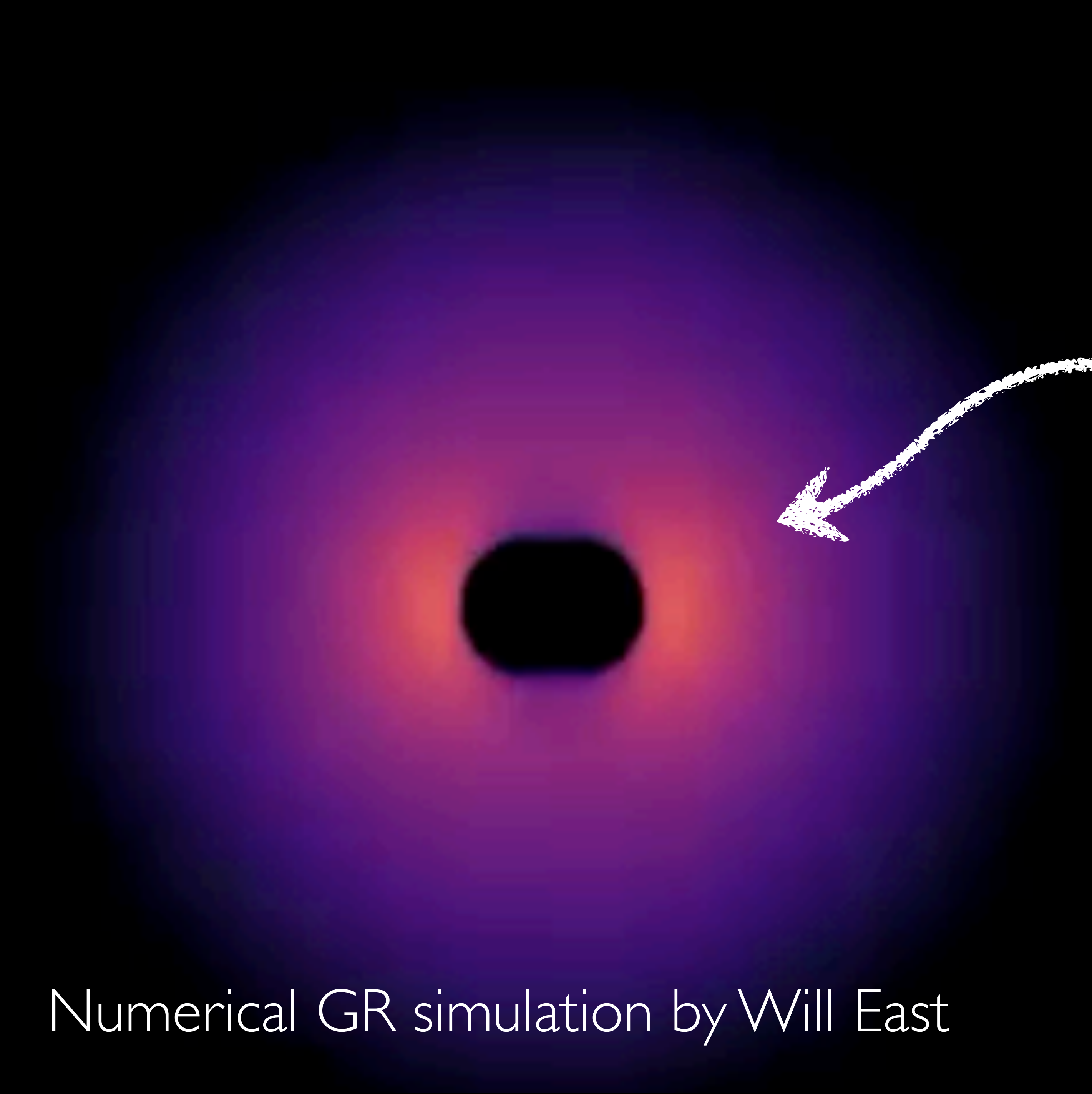
Phys.Rev.Lett. 127 (2021) 16, 161101



Credit: National Science Foundation/LIGO/Sonoma State University/A. Simonnet.

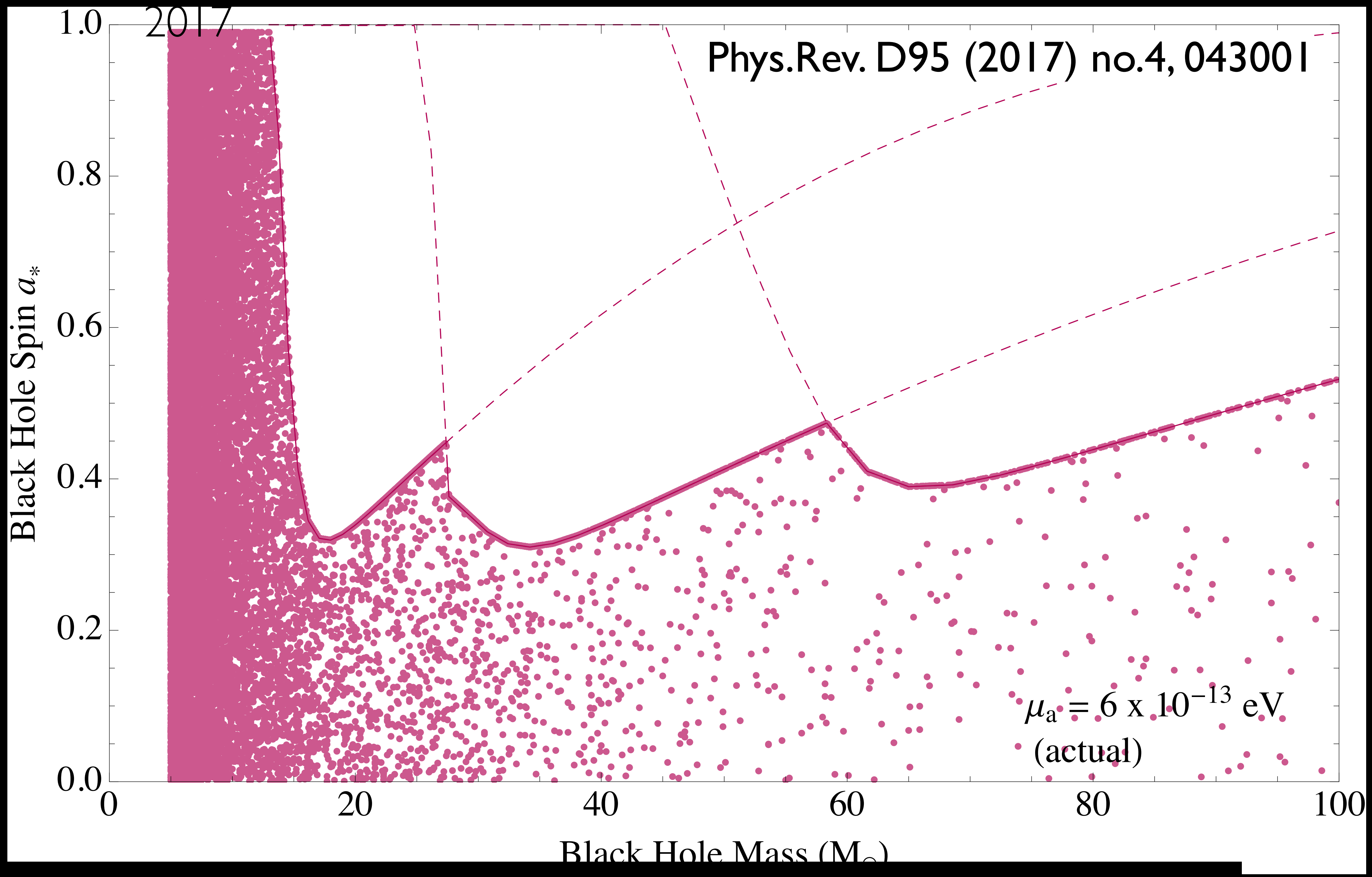
A lighter-than-expected axion can mediate forces between neutron stars that can be as strong as gravity and change their inspiral waveform

Black holes as laboratories for axions and ultralight particles



Numerical GR simulation by Will East

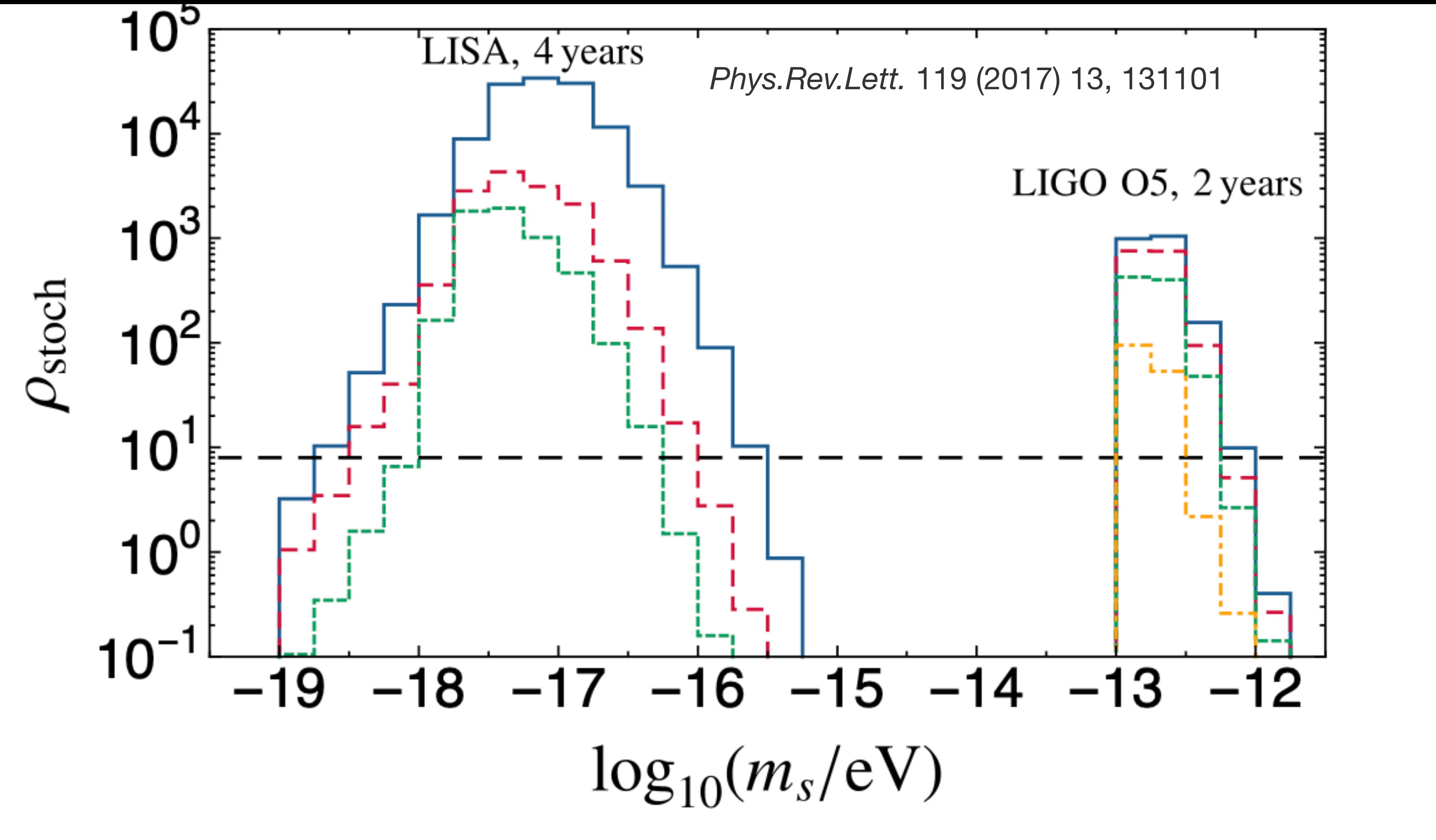
Density comparable to neutron star densities

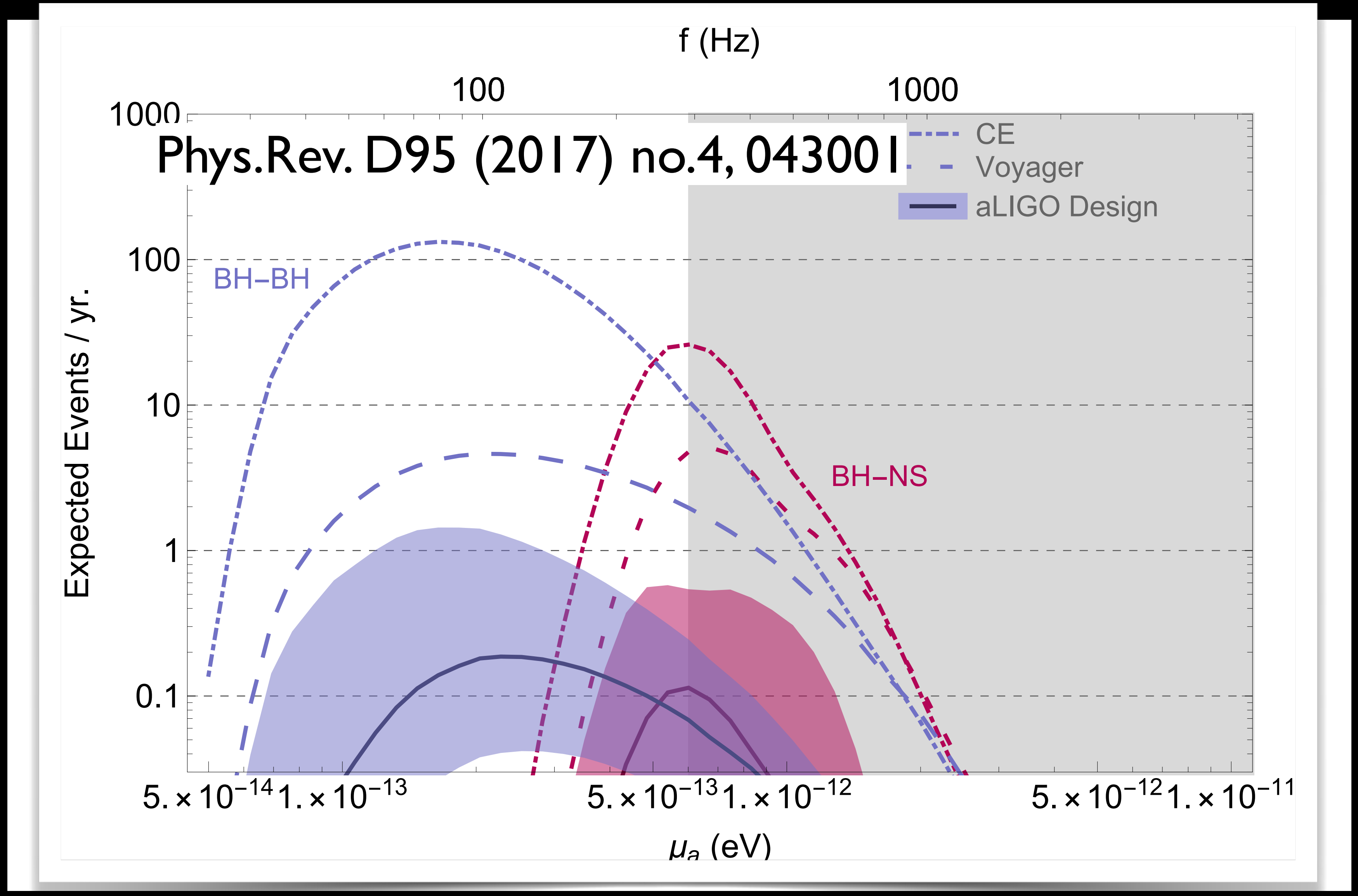


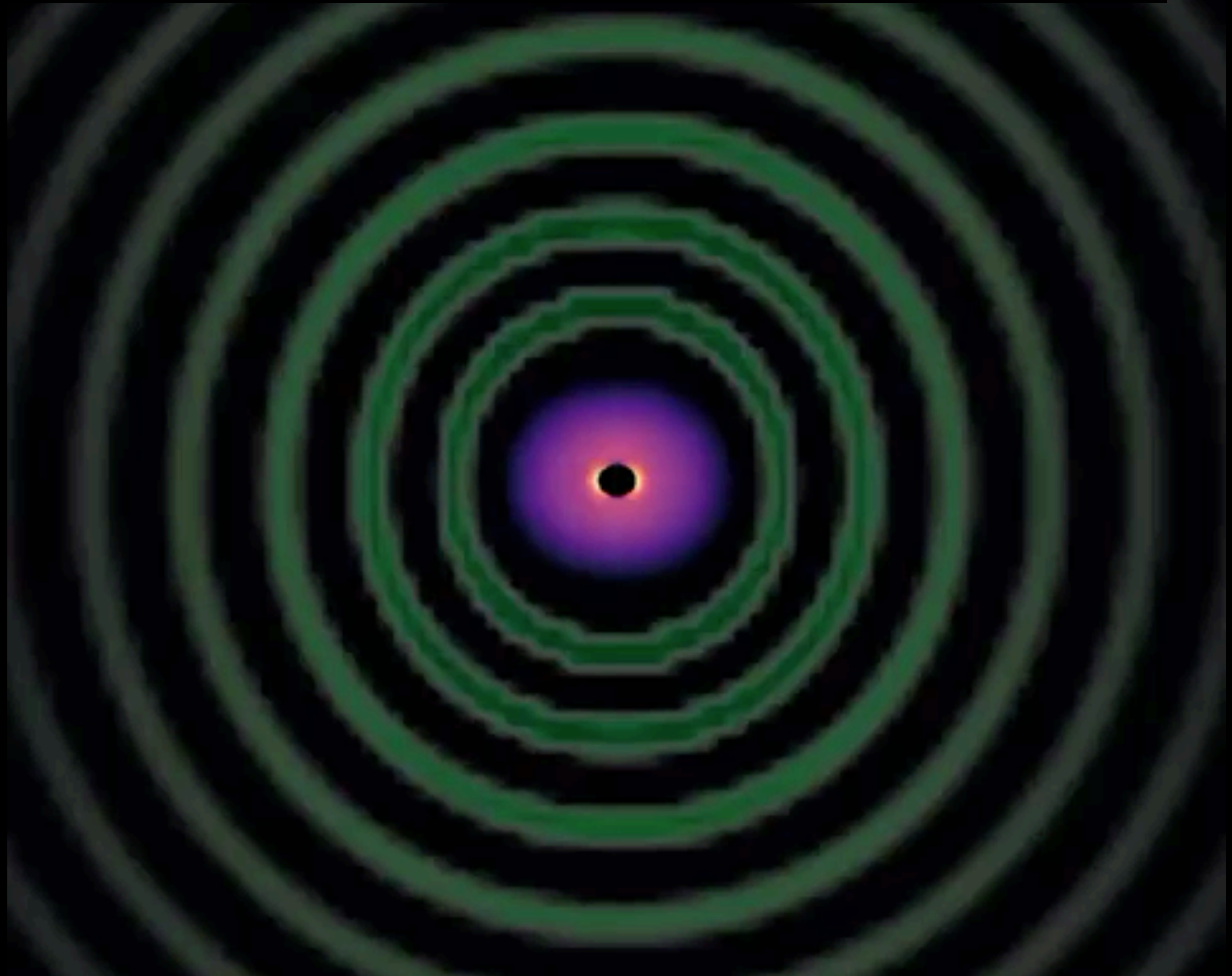
Bound state grows by spinning down rotating black holes through superradiance

LIGO Virgo measurements of black hole spin rule out weakly interacting axions around 10^-13 eV
Phys. Rev. Lett. **126**, 151102
Future observatories can probe wide range of masses

Black holes as laboratories for axions and ultralight particles







Numerical GR simulation by Will East (dark photon)

Black holes produce clouds of ultralight bosons through superradiance which in turn source gravitational wave radiation

Future facilities such as Cosmic Explorer and LISA can robustly discover or exclude new particles

Hidden particle sectors and dark matter

- Extreme environments are a unique source of feebly interacting dark matter and new particles: high energies and densities overcome weak interactions of particles that otherwise may be impossible to produce

- Sensitive to even (sub-) gravitational interactions: may be only way to detect `nightmare scenario' dark matter candidates

- Searches ongoing for theoretically motivated particles such as the QCD axion at current gravitational wave observatories

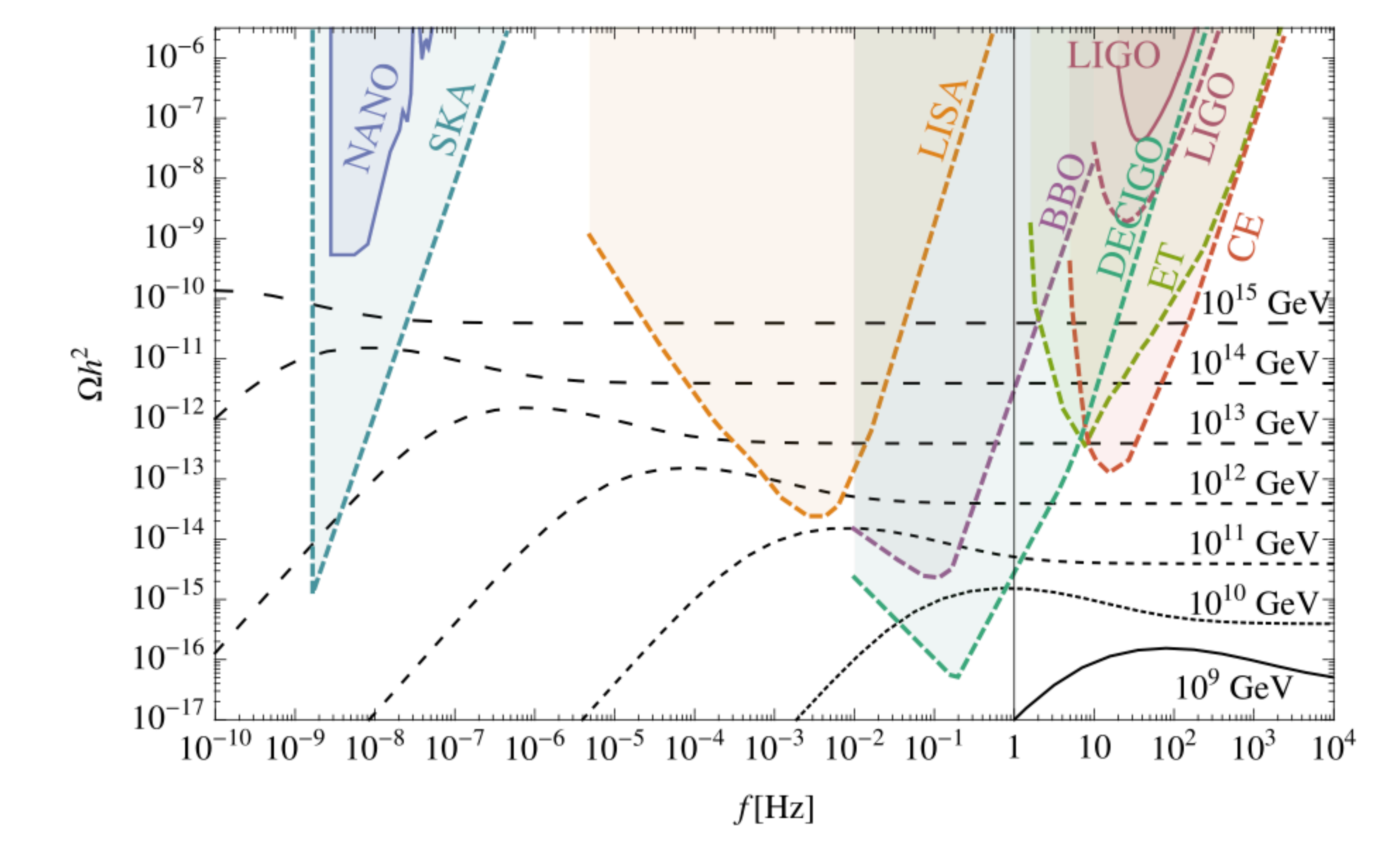
- Next generation detectors can extend the reach to particle parameter space; theory and modeling work in progress

Gravitational Waves Probe History of our Universe

Gravitational Waves Emitted During Phase Transitions

Gravitational waves cannot be screened (no negative mass charge) and are not efficiently absorbed (very weak interactions) so travel to us from the earliest times.

Gravitational waves from inflation in the CMB or from phase transitions in the early universe could be observed at LISA, PTA, or midband detectors like MAGIS

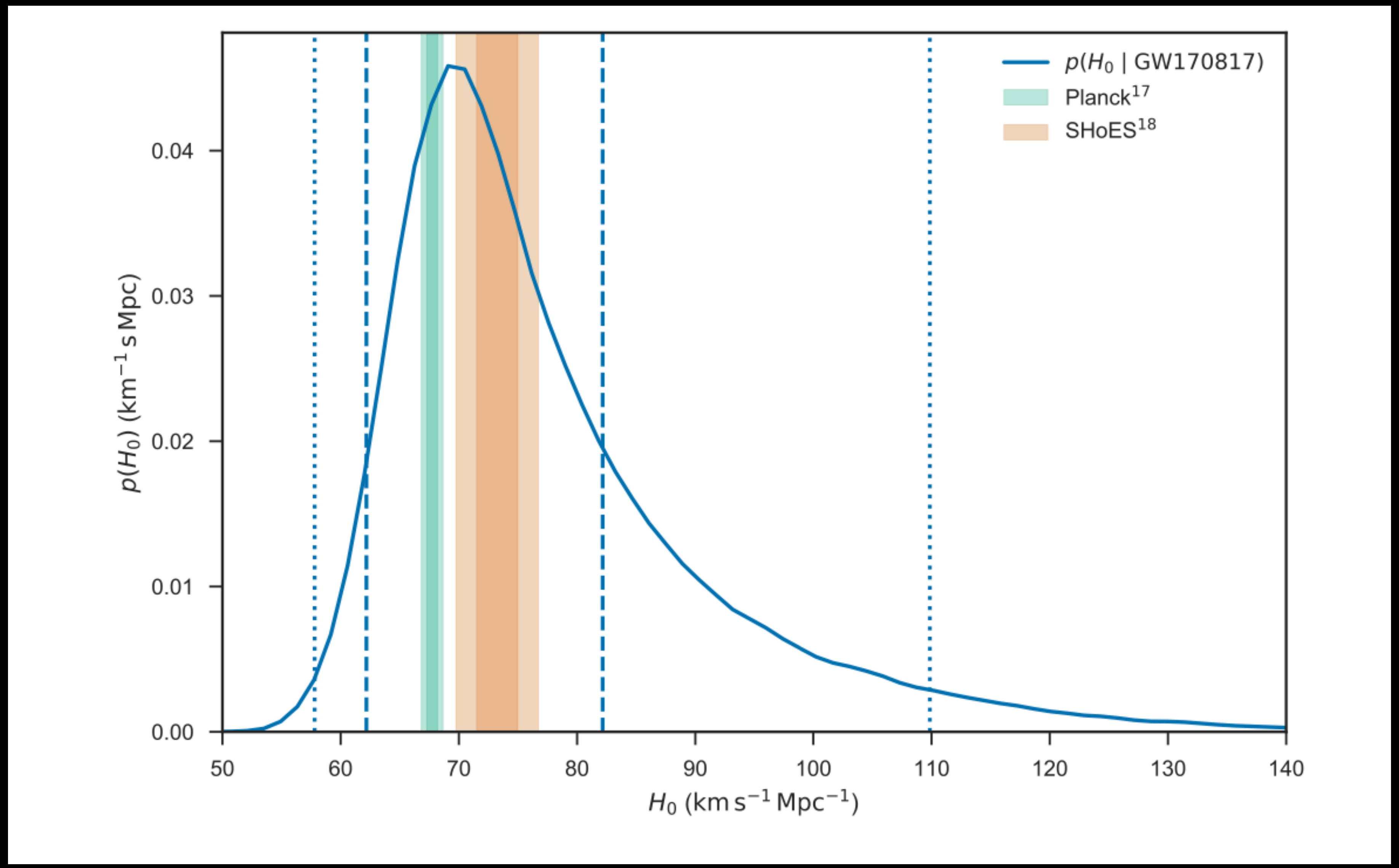


Phys.Rev.Lett. 124 (2020) 4, 041804

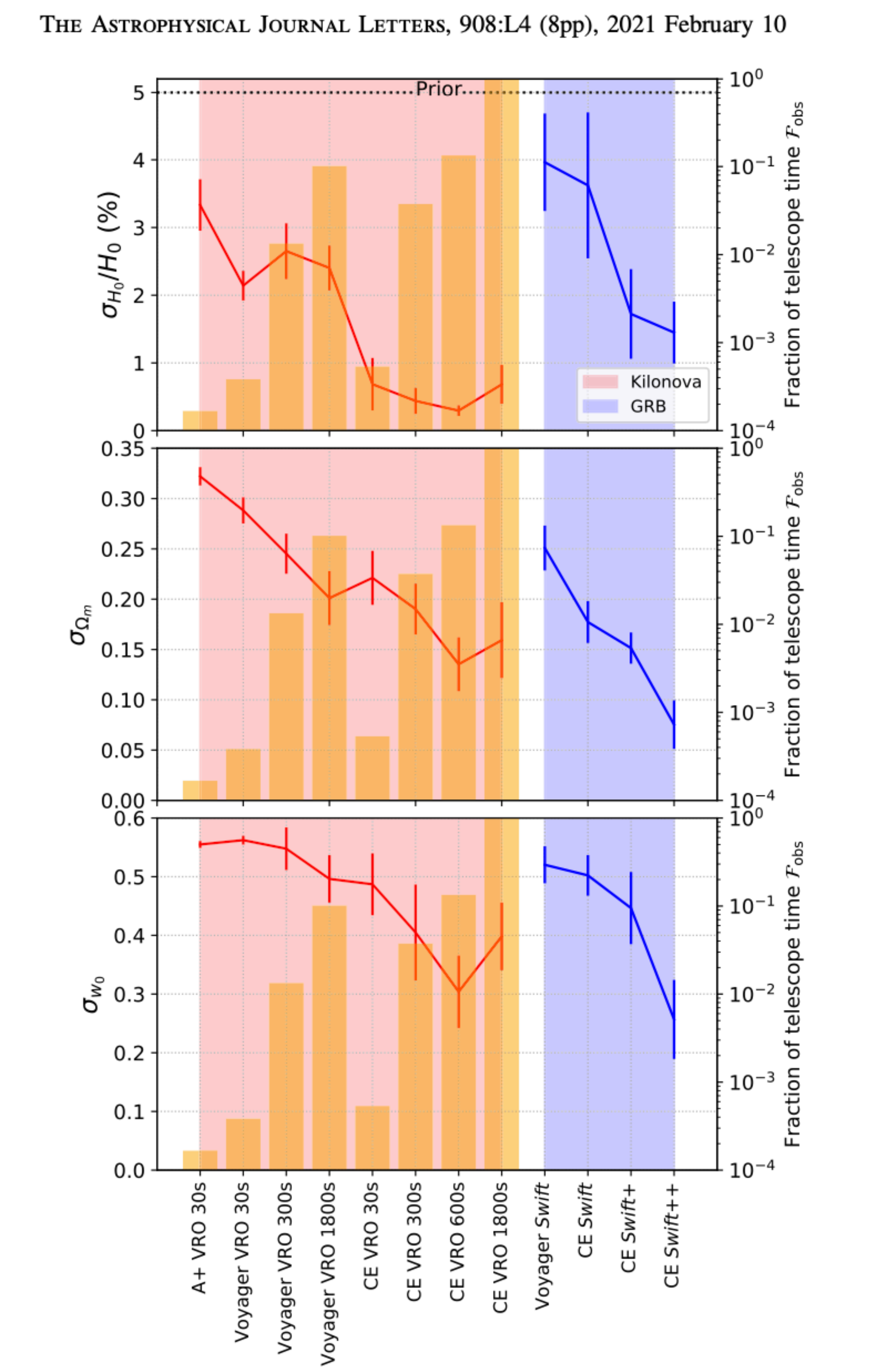
Figure 1: The predicted GW background from cosmic strings

Mergers Used as `Standard Sirens' for Cosmology

Nature 551 (2017) 7678, 85-88



H0 measurement with GW 170817



Next generation observatories would reach 1–2% precision; also contribute independent measurements of dark matter density and dark energy equation of state

Gravitational Waves Probe History of our Universe

- Gravitational Waves cannot be screened and so act as unique messengers of the structure and expansion of our Universe
- Lower frequency observatories could discover phase transitions in the early universe
- Multimessenger observations of neutron star mergers at next generation observatories can provide a new class of standard candles—`standard sirens'—for cosmological measurements

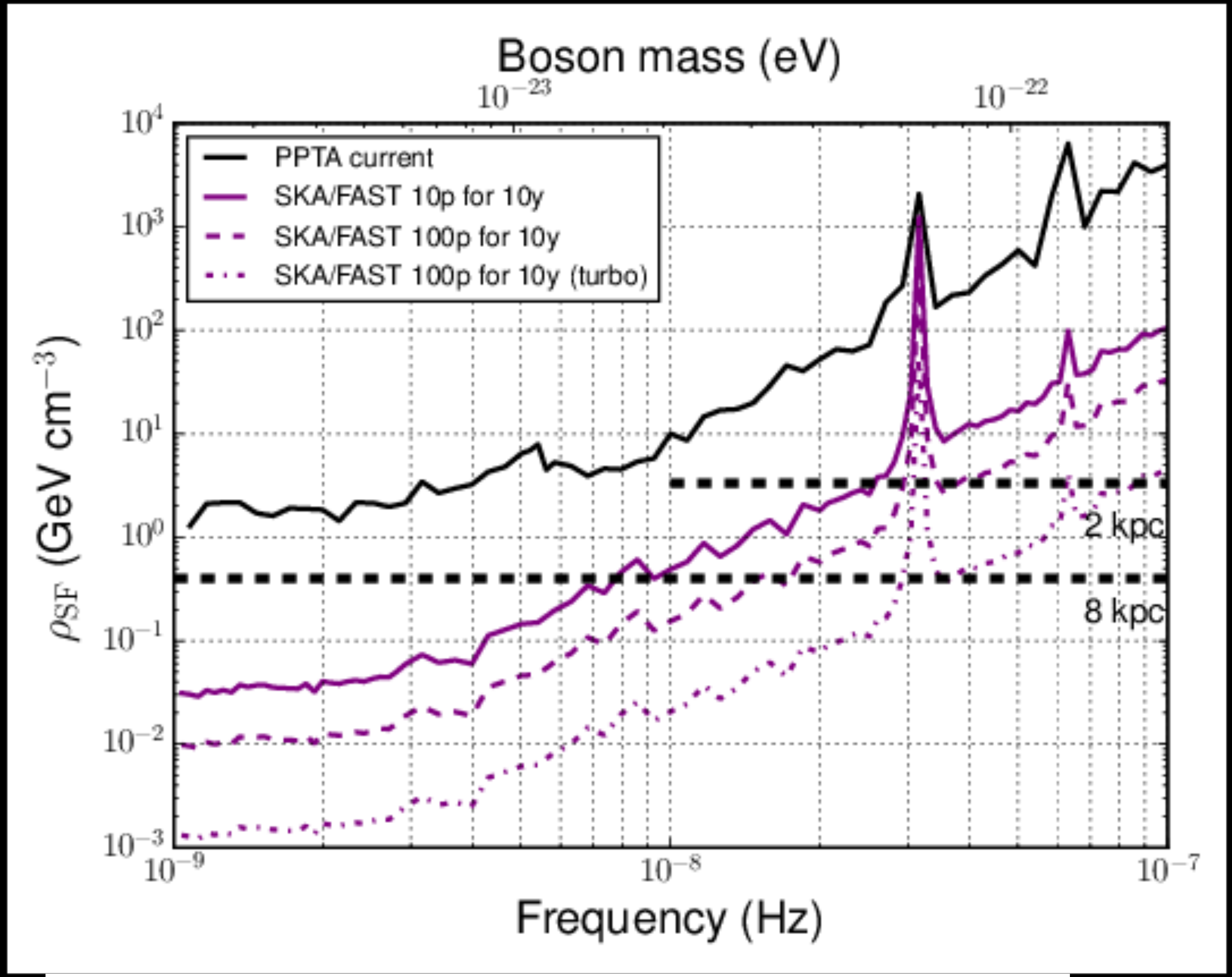
Gravitational Wave Detectors are Dark Matter Detectors

- Gravitational-wave detectors can in parallel search for ultralight dark matter that affects fundamental constants (such as the electron mass or the fine structure constant) or otherwise affects the `test masses'

- Searches for dark photon dark matter and scalar dark matter ongoing at current observatories setting competitive limits

- New data analysis ideas and theoretical modeling under development for existing and proposed facilities

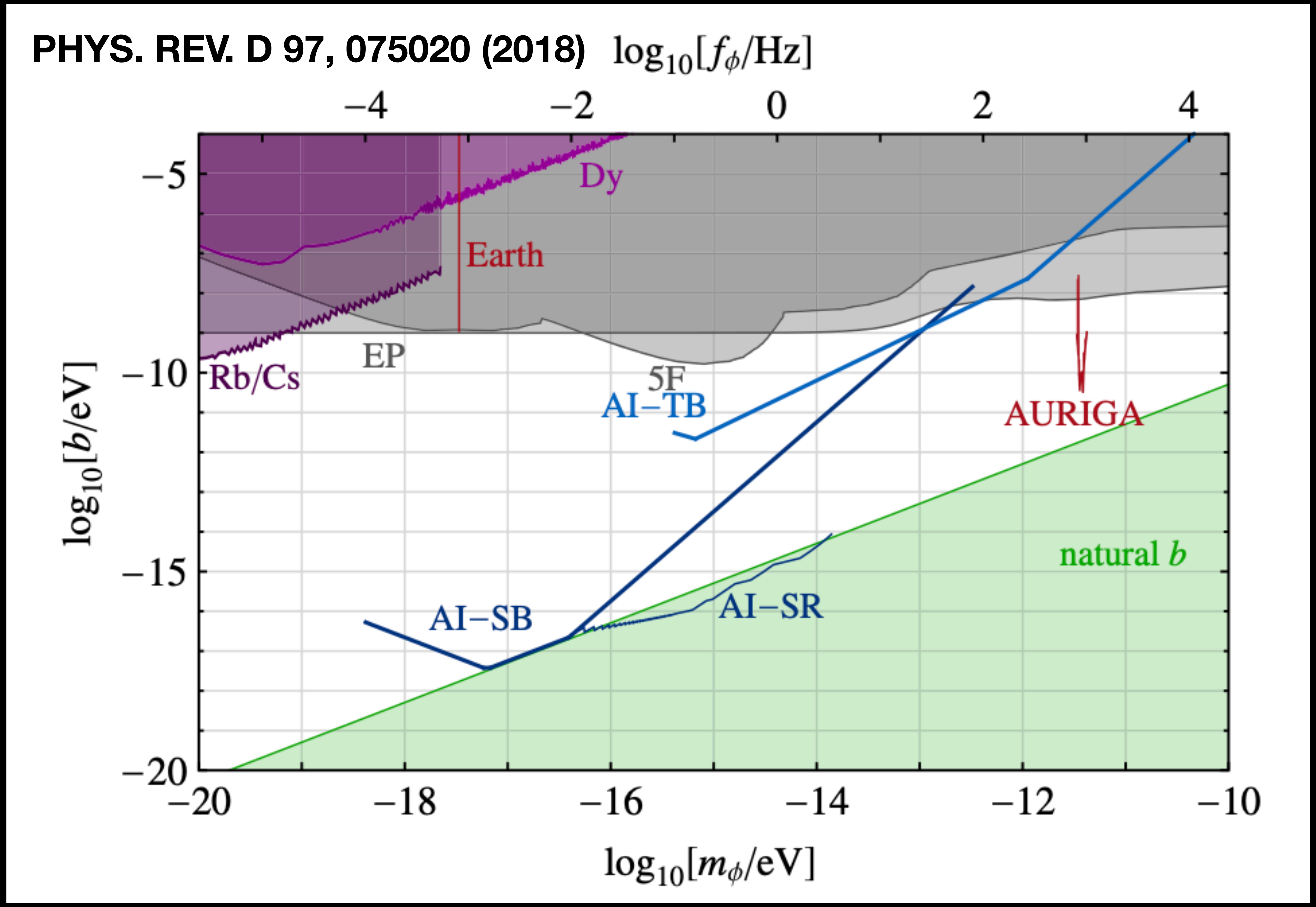
Gravitational Detector Searches for Ultralight Dark Matter



Yu-Mei Wu et al (PPTA Collaboration) *Phys.Rev.D* 106 (2022) 8, L081101

Nataliya K. Porayko *et al.* (PPTA Collaboration) *Phys.Rev.D* 98 (2018) 102002

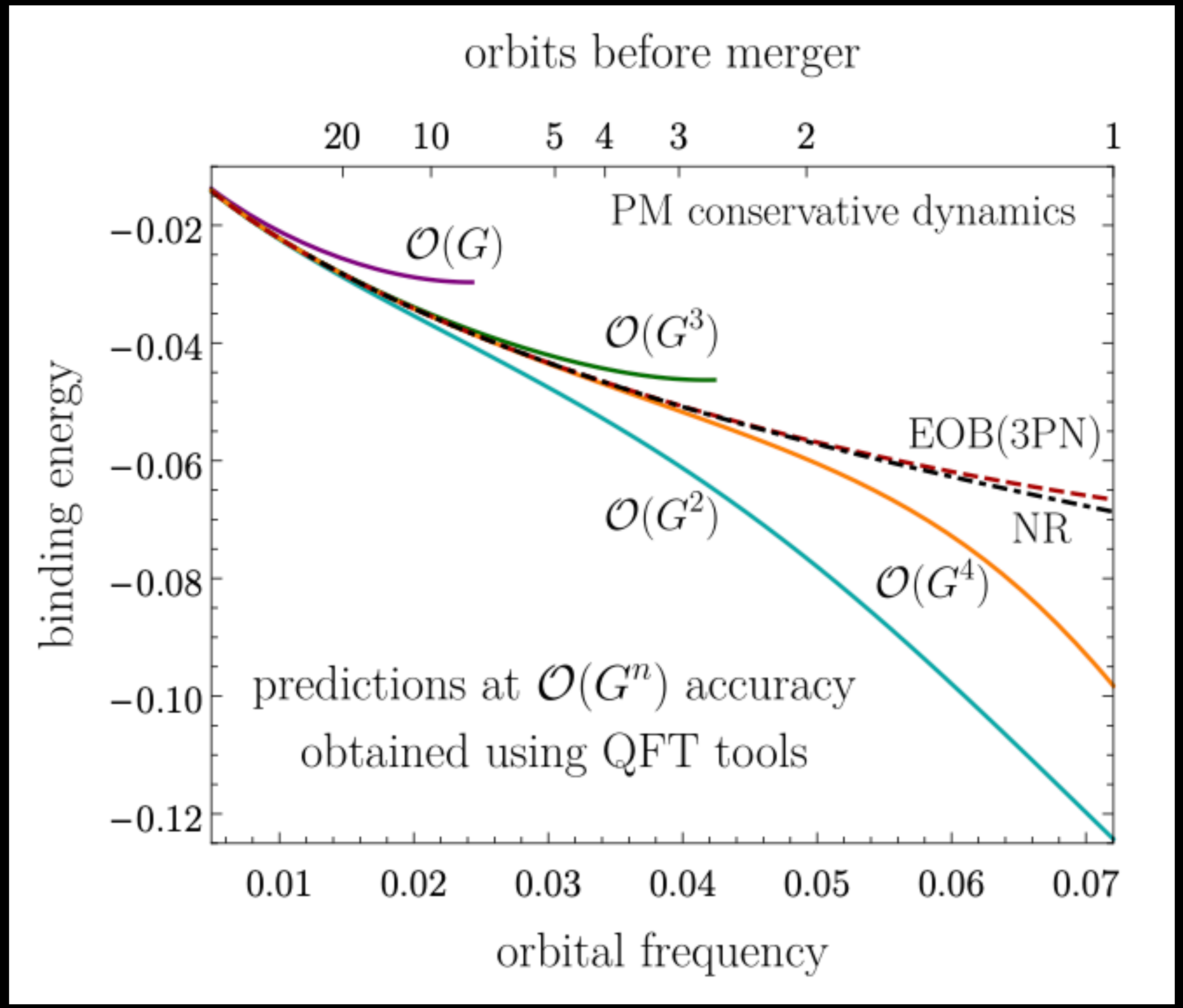
Constraints with PTA



Projections with MAGIS

Theory is Rapidly Developing Alongside New Observations

- Theory input and field theory techniques improving modeling and data analysis of waveforms
- Analytic work and numerical simulations essential to correctly predict and interpret gravitational wave signals
- New observables and connections to particle physics parameter space require theory development



Snowmass White Paper: Gravitational Waves and Scattering Amplitudes

Gravitational Waves: a New Opportunity for High Energy Physics

- Gravitational waves are a ***new tool to study the universe*** which did not exist during the last P5!

- Gravitational waves give us ***unique access*** to the ***most hidden of particle physics sectors*** and the ***furthest corners of the universe***

- ***Investment in new facilities*** will provide ***big leaps in sensitivity and frequency***, allowing deeper and broader searches

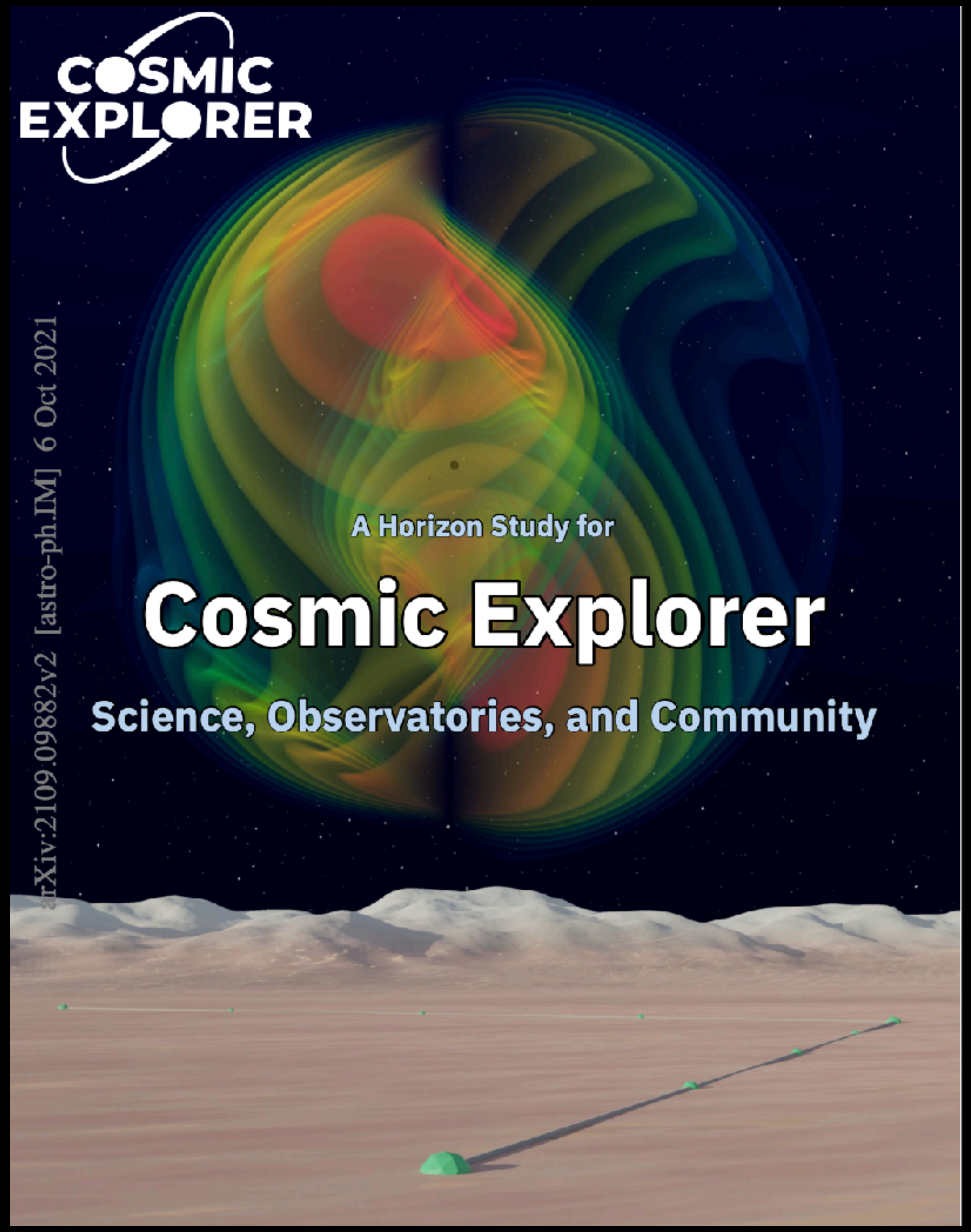
- Very new arena: support of ***theory development crucial*** to develop new ideas, design better searches, and learn as much as we can from the data

Gravitational Waves: a New Opportunity for High Energy Physics

Snowmass 2021

Gravitational wave probes of dark matter: challenges and opportunities

Gianfranco Bertone,[1,*] Djuna Croon,[2,†] Mustafa A. Amin,[3,‡] Kimberly K. Boddy,[4,§] Bradley J. Kavanagh,[1,¶] Katherine J. Mack,[5,‖] Priyamvada Natarajan,[6,**] Toby Opferkuch,[7,††] Katelin Schutz,[8,‡‡] Volodymyr Takhistov,[9,§§] Christoph Weniger,[1,¶¶] and Tien-Tien Yu[10,***]



The Next Generation Global Gravitational Wave Observatory

The Science Book

Submitted to the Proceedings of the US Community Study
on the Future of Particle Physics (Snowmass 2021)

Snowmass2021 Cosmic Frontier White Paper: Future Gravitational-Wave Detector Facilities

Stefan W. Ballmer,[1] Rana Adhikari,[2] Leonardo Badurina,[3] Duncan A. Brown,[1] Swapan Chattopadhyay,[4] Matthew Evans,[5] Peter Fritschel,[5] Evan Hall,[5] Jason M. Hogan,[6] Karan Jani,[7] Tim Kovachy,[6] Kevin Kuns,[5] Ariel Schwartzman,[8] Daniel Sigg,[9] Bram Slagmolen,[10] Salvatore Vitale,[11,5] and Christopher Wipf[2]