Gravitational Waves:
What can Atom Interferometers Contribute?

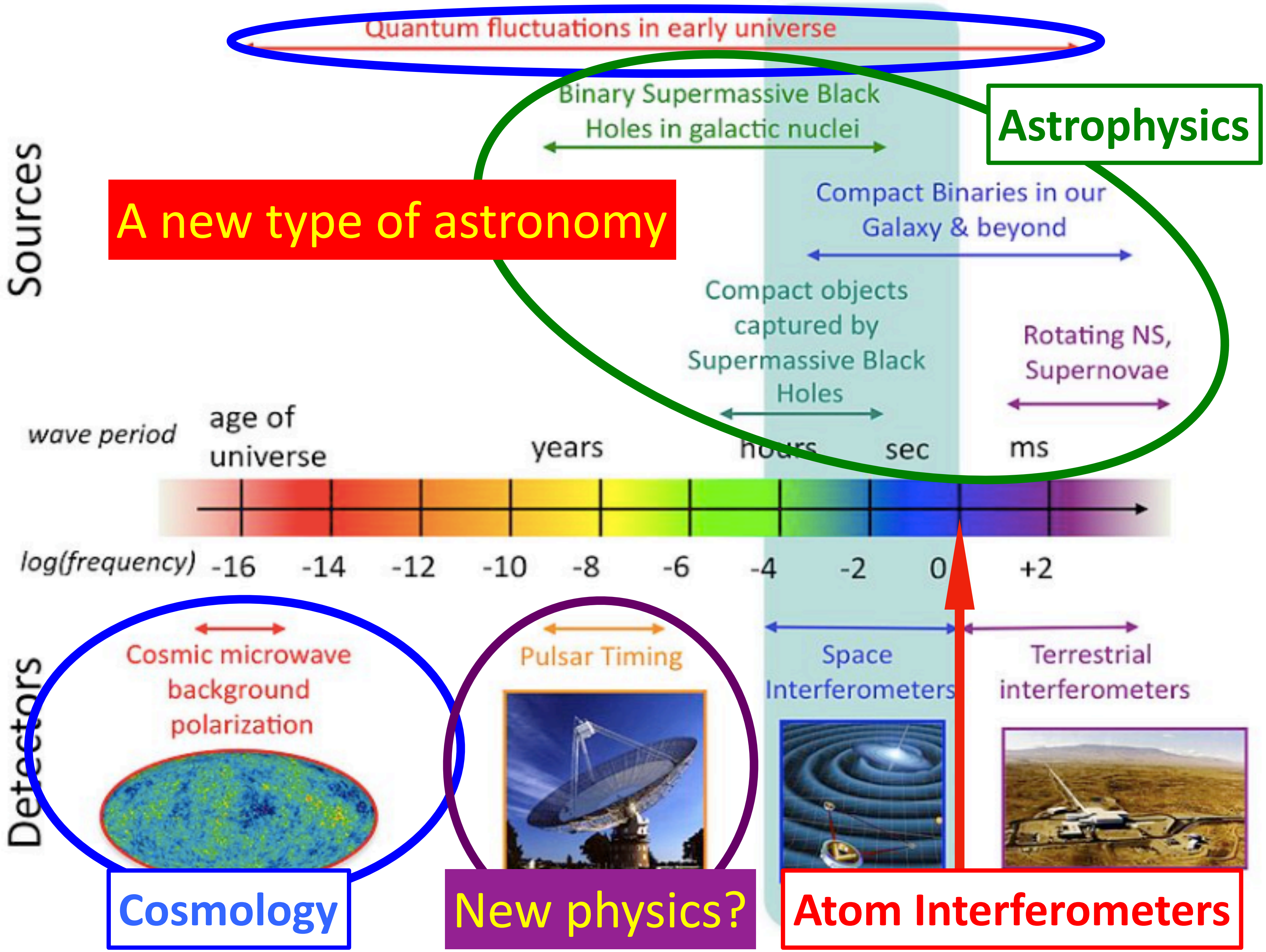
*"If one could ever prove the existence of gravitational waves,
the processes responsible for their generation
would probably be much more curious and interesting
than even the waves themselves."*
(Gustav Mie)

John Ellis

KING'S College LONDON

JE, arXiv:2402.10755

Gravitational Wave Spectrum



Outline

- Discovery of black hole binaries
- Supermassive black holes: how to assemble them?
  - Atom interferometry
- Discovery of nanoHz GW background by Pulsar Timing Arrays (PTAs)
  - Supermassive black hole binaries?
  - Cosmology and BSM physics
- **BSM scenarios fit NANOGrav data better than BH binaries!**
  - Distinguish models using atom interferometers

Gravitational Waves

- General relativity proposed by Einstein 1915
- He predicted gravitational waves in 1916

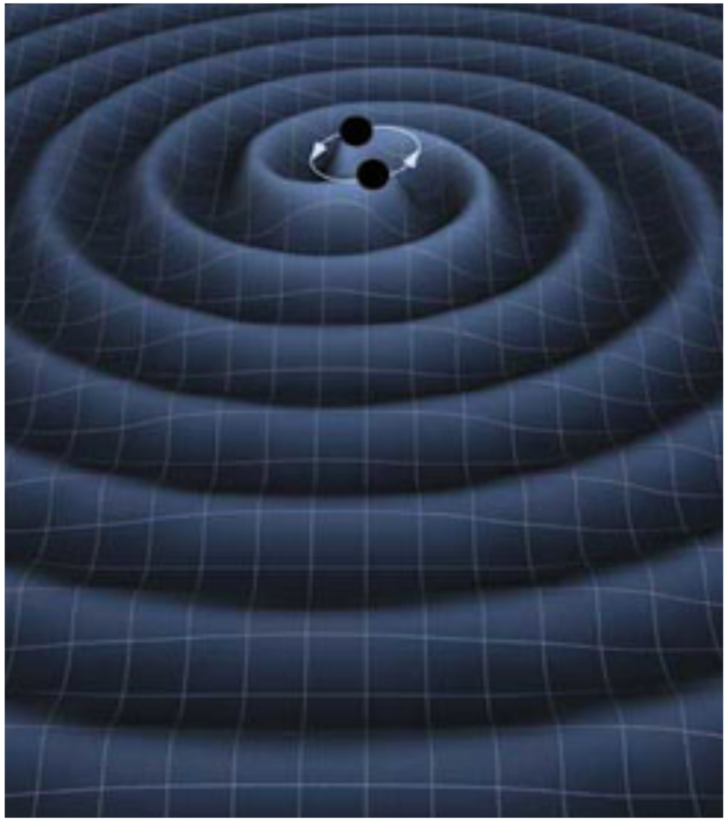
Näherungsweise Integration der Feldgleichungen der Gravitation.

Von A. Einstein.

Bei der Behandlung der meisten speziellen (nicht prinzipiellen) Probl
auf dem Gebiete der Gravitationstheorie kann man sich damit begnü
die $g_{\mu\nu}$ in erster Näherung zu berechnen. Dabei bedient man sich
Vorteil der imaginären Zeitvariable x_4 = it aus denselben Gründen
in der speziellen Relativitätstheorie. Unter »erster Näherung« ist d
verstanden, daß die durch die Gleichung

$$g_{\mu\nu} = -\delta_{\mu\nu} + \gamma_{\mu\nu}$$

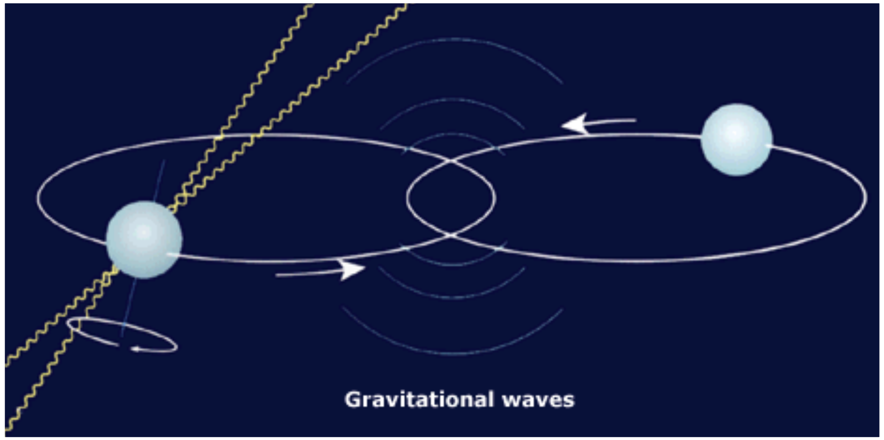
Albert Einstein, *Näherungsweise Integration der Feldgleichungen der Gravitation*, 22.6.Berlin 1916

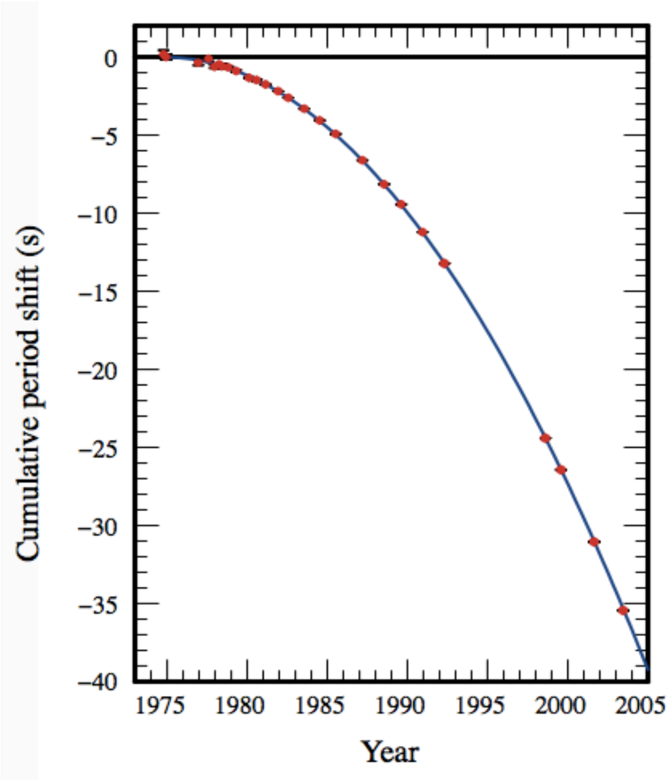


- Tried to retract prediction in 1936!

Indirect Detection

- Binary pulsar discovered 1974 (Hulse & Taylor)
- Emits gravitational waves
- Change in orbit measured





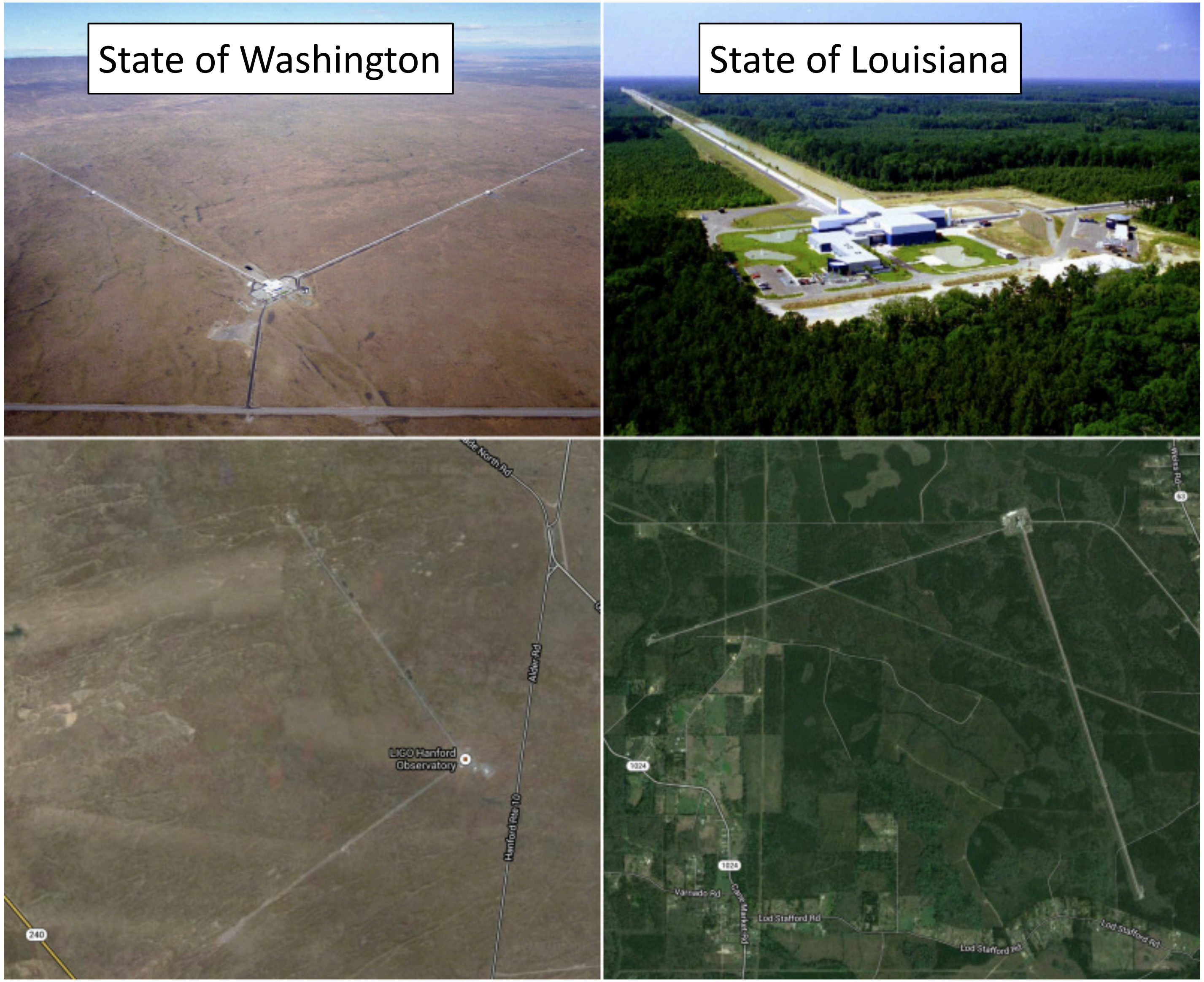
for decades

Perfect agreement with Einstein

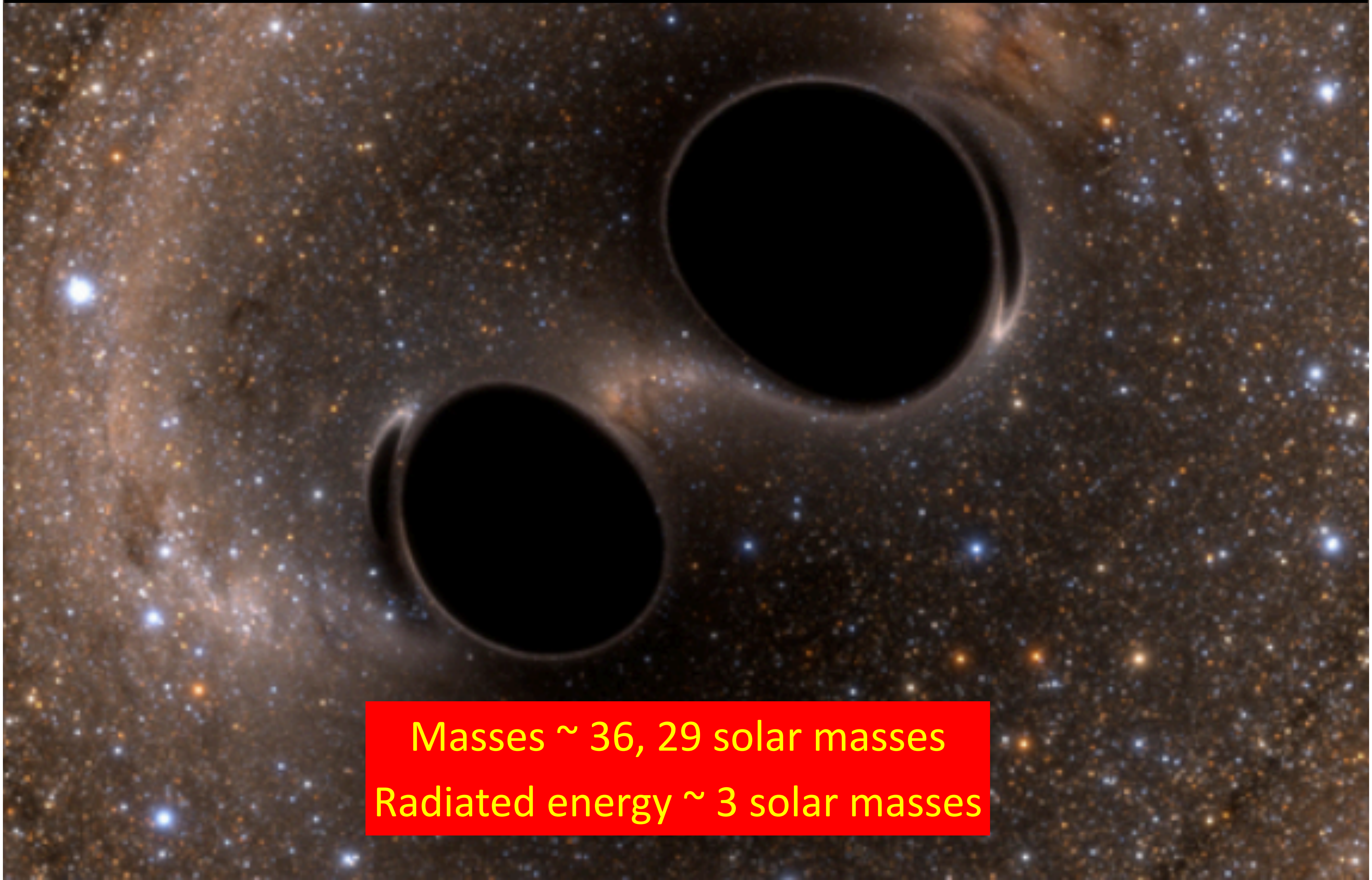
Nobel Prize 1993

Direct Discovery of Gravitational Waves

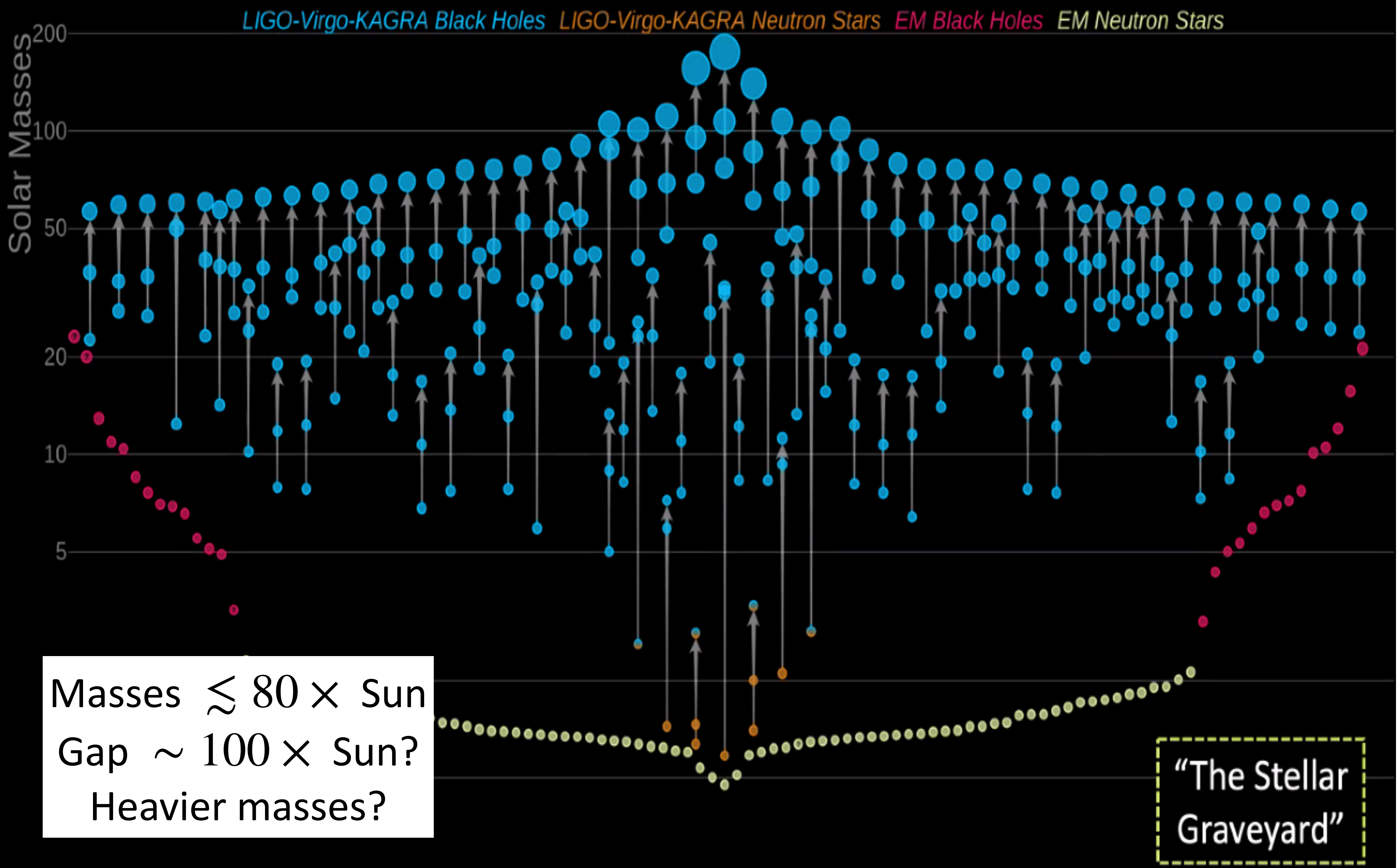
- Measured by the LIGO experiment in 2 locations



Fusion of two massive black holes

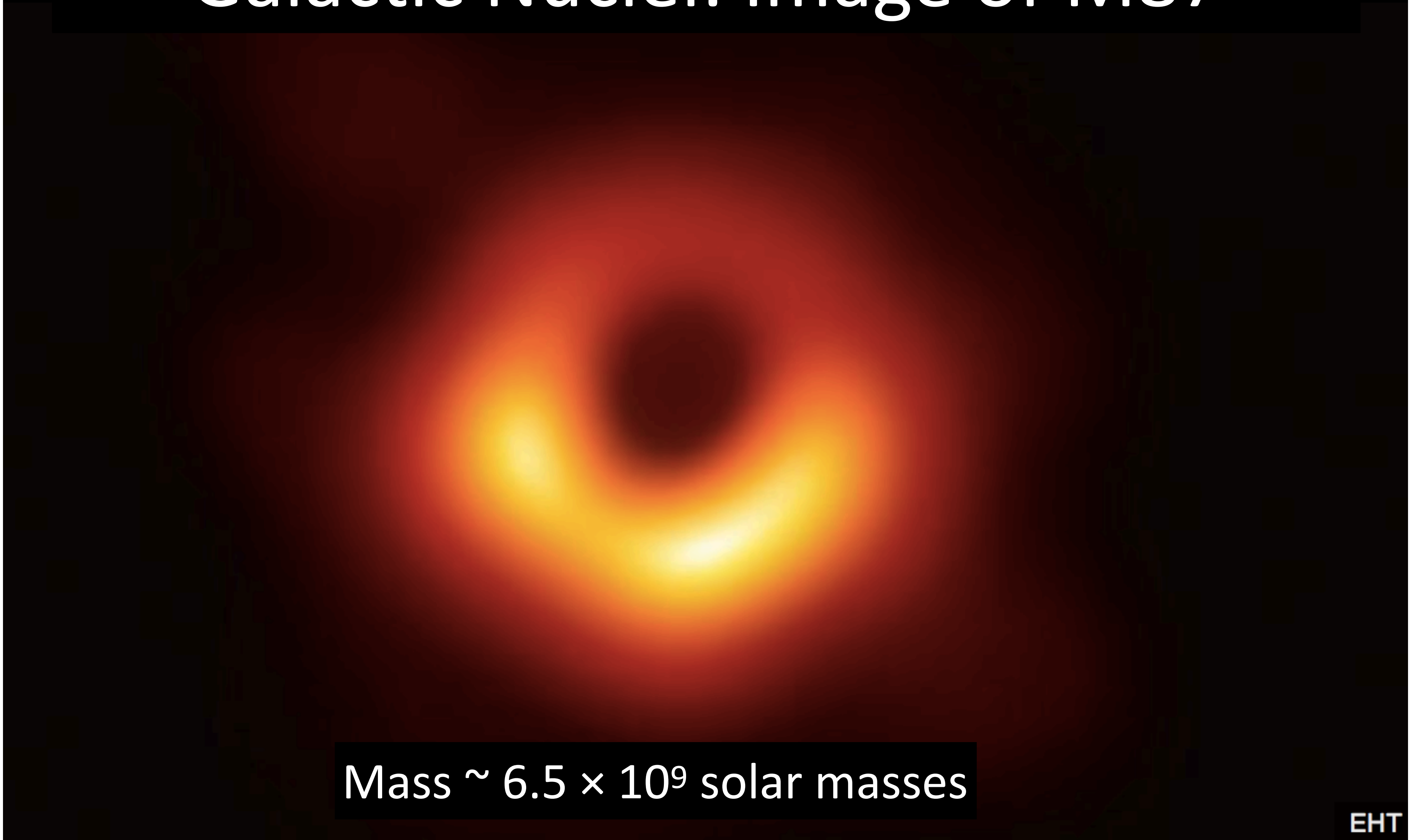


LIGO-Virgo-KAGRA Black Holes & Neutron Stars



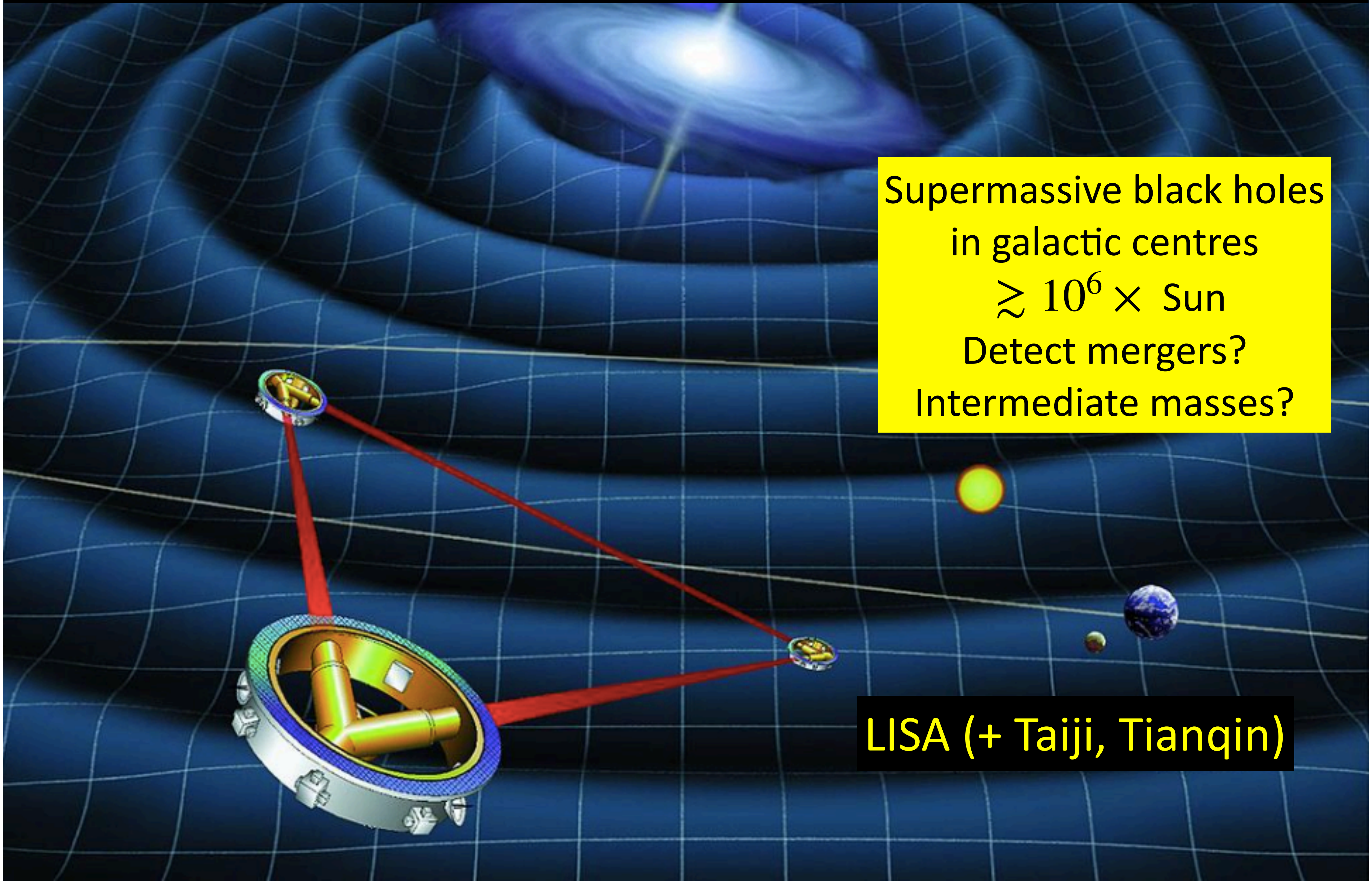
Masses $\lesssim 80 \times$ Sun
Gap $\sim 100 \times$ Sun?
Heavier masses?

Supermassive Black Holes in Active Galactic Nuclei: Image of M87



Mass ~ 6.5×10^9 solar masses

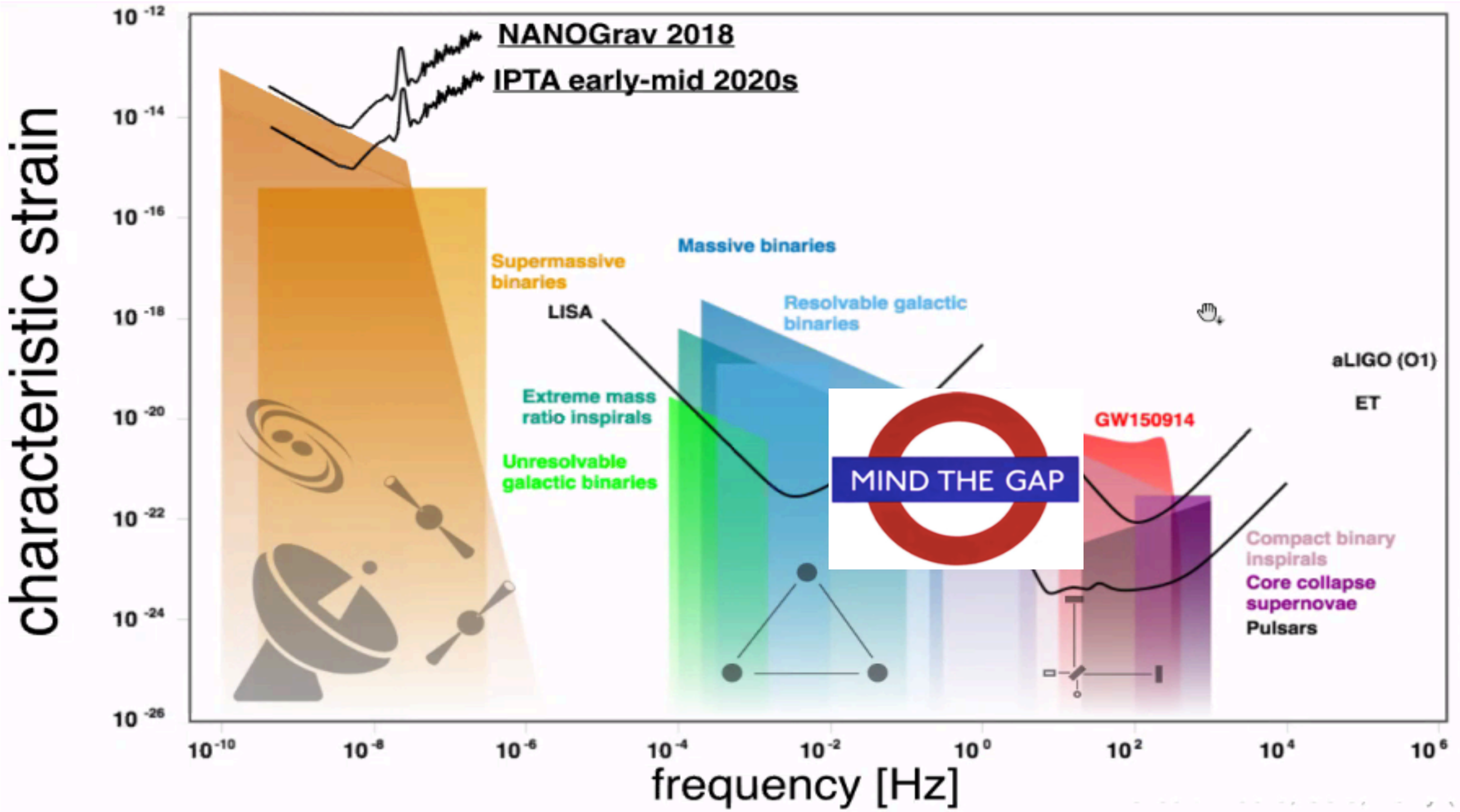
Future Step: Interferometer in Space



Supermassive black holes
in galactic centres
$\gtrsim 10^6 \times$ Sun
Detect mergers?
Intermediate masses?

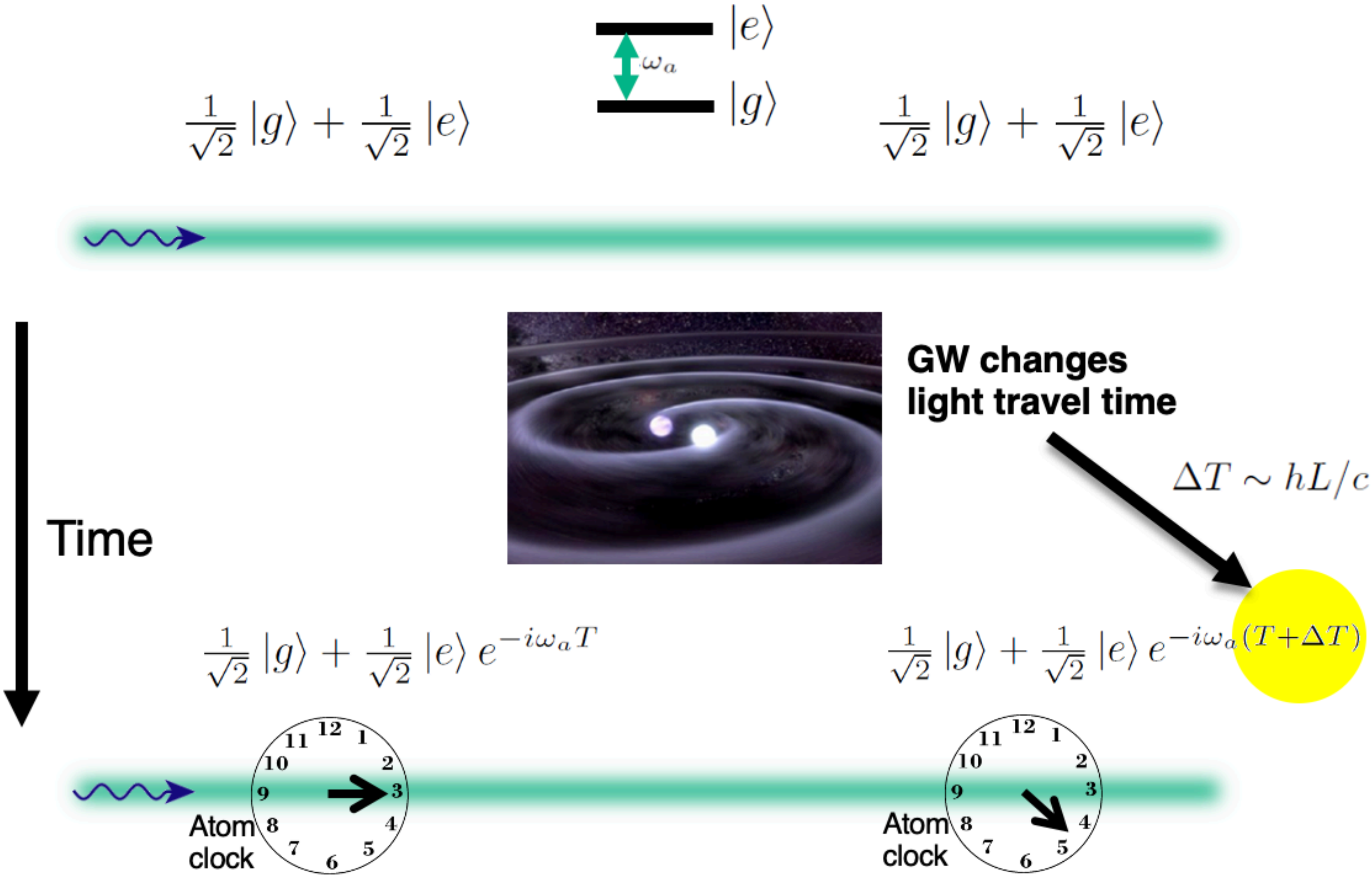
LISA (+ Taiji, Tianqin)

Gravitational Wave Spectrum



- Gap between ground-based laser interferometers & LISA
  - Formation of supermassive black holes (SMBHs)
  - Supernovae? Phase transitions? …
- **Atom interferometry?**

Effect of Gravitational Wave on Atom Interferometer



AION Collaboration

L. Badurina, S. Balashov[2], E. Bentine[3], D. Blas[1], J. Boehm[2], K. Bongs, A Beniwal[1]
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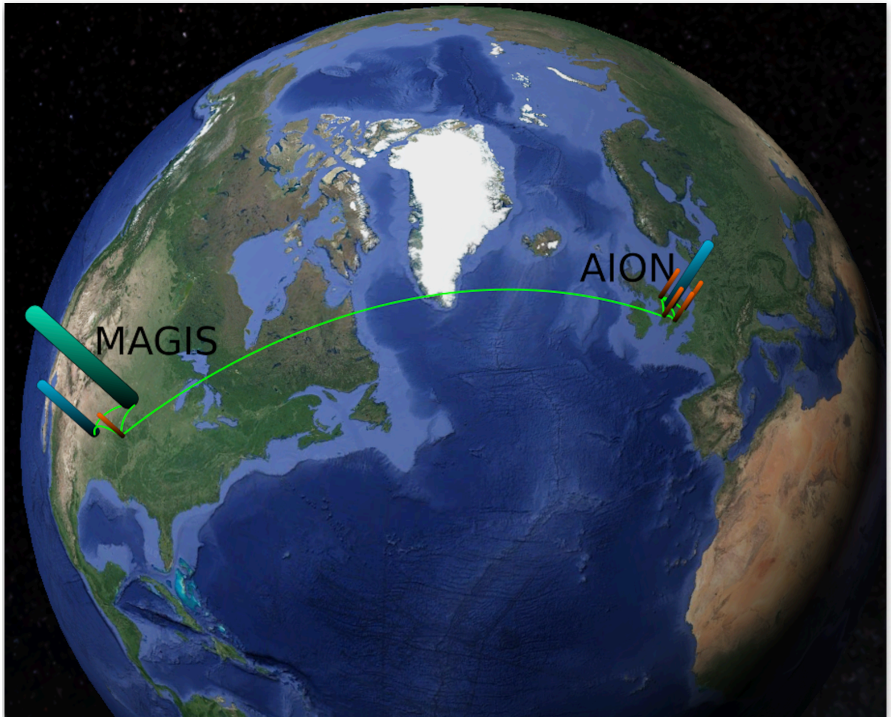
AION



Network with MAGIS project in US

MAGIS Collaboration (Abe et al): arXiv:2104.02835

AION

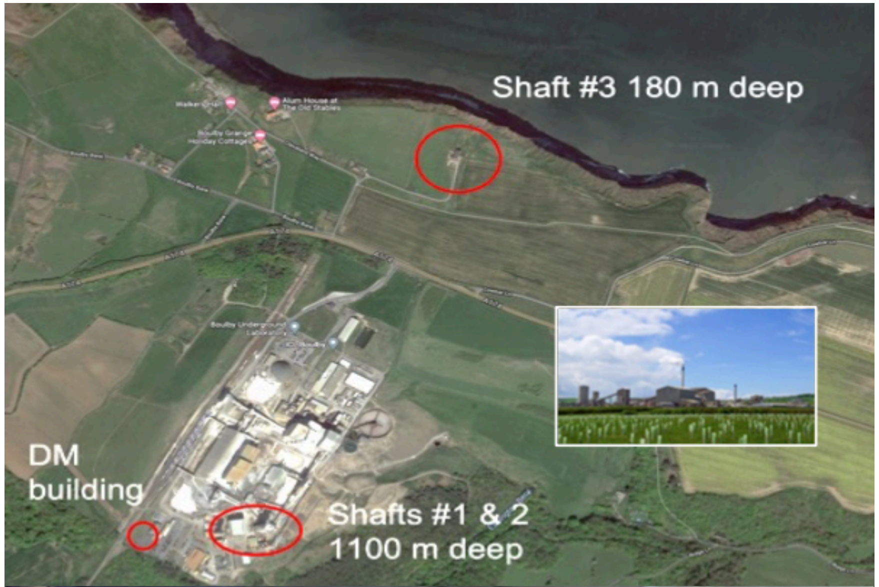
180m and 1km shafts @ Boulby

Shaft 3: 180m:

Space use in shaft?
Proximity to sea shore?
Water extraction tube?
Magnetic environment?

Shaft 1: 1.1km

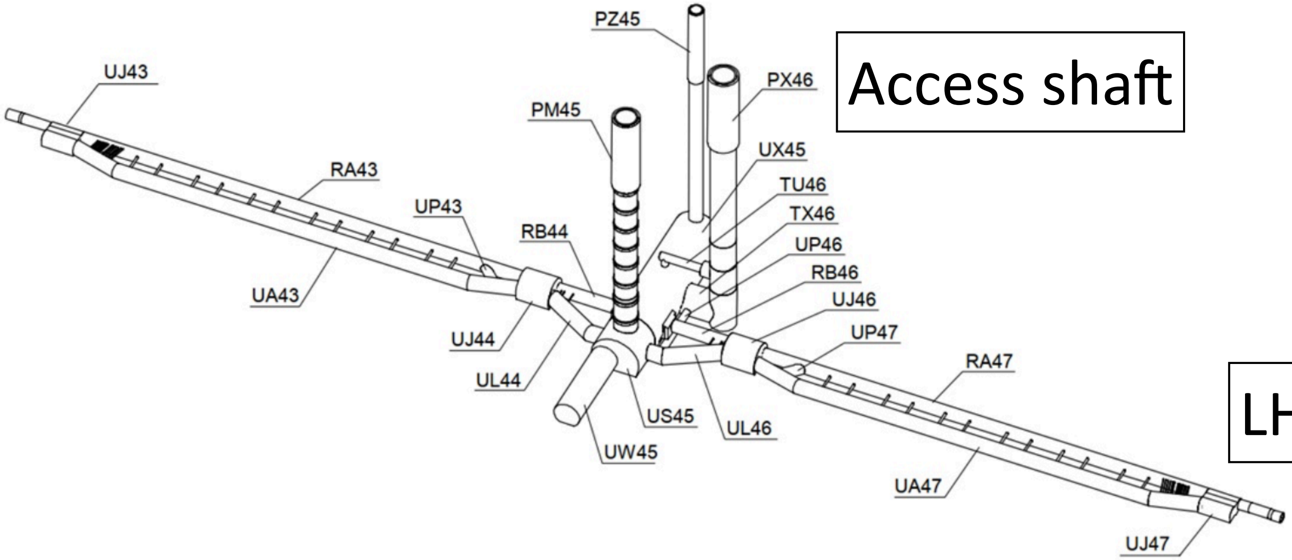
Operational access shaft
Space use in shaft?
Effects of physical activities?
Air flow?



140m Access Shaft @ CERN

AION

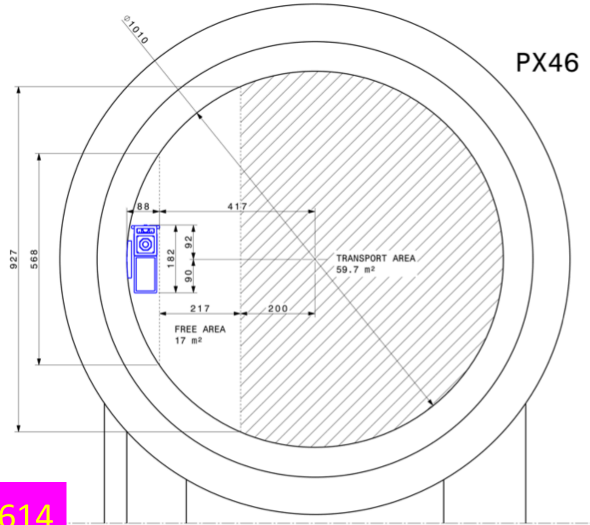
LHC

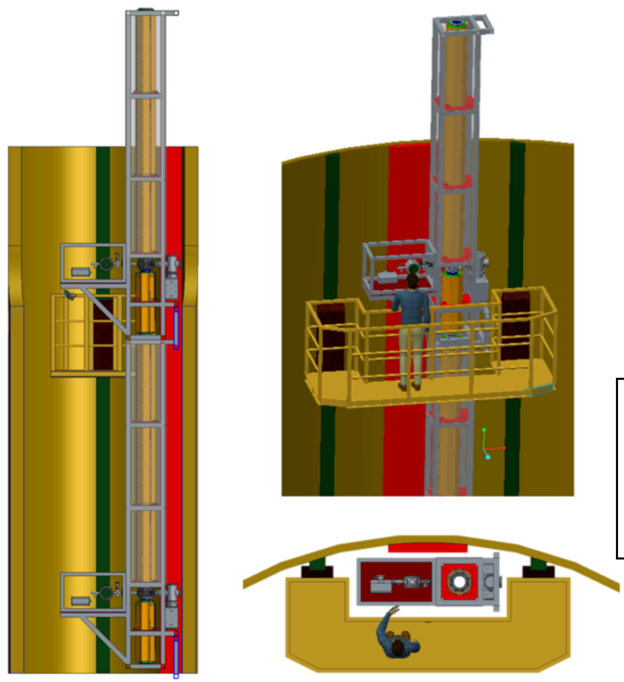


Access shaft

LHC

Cross-section of access shaft



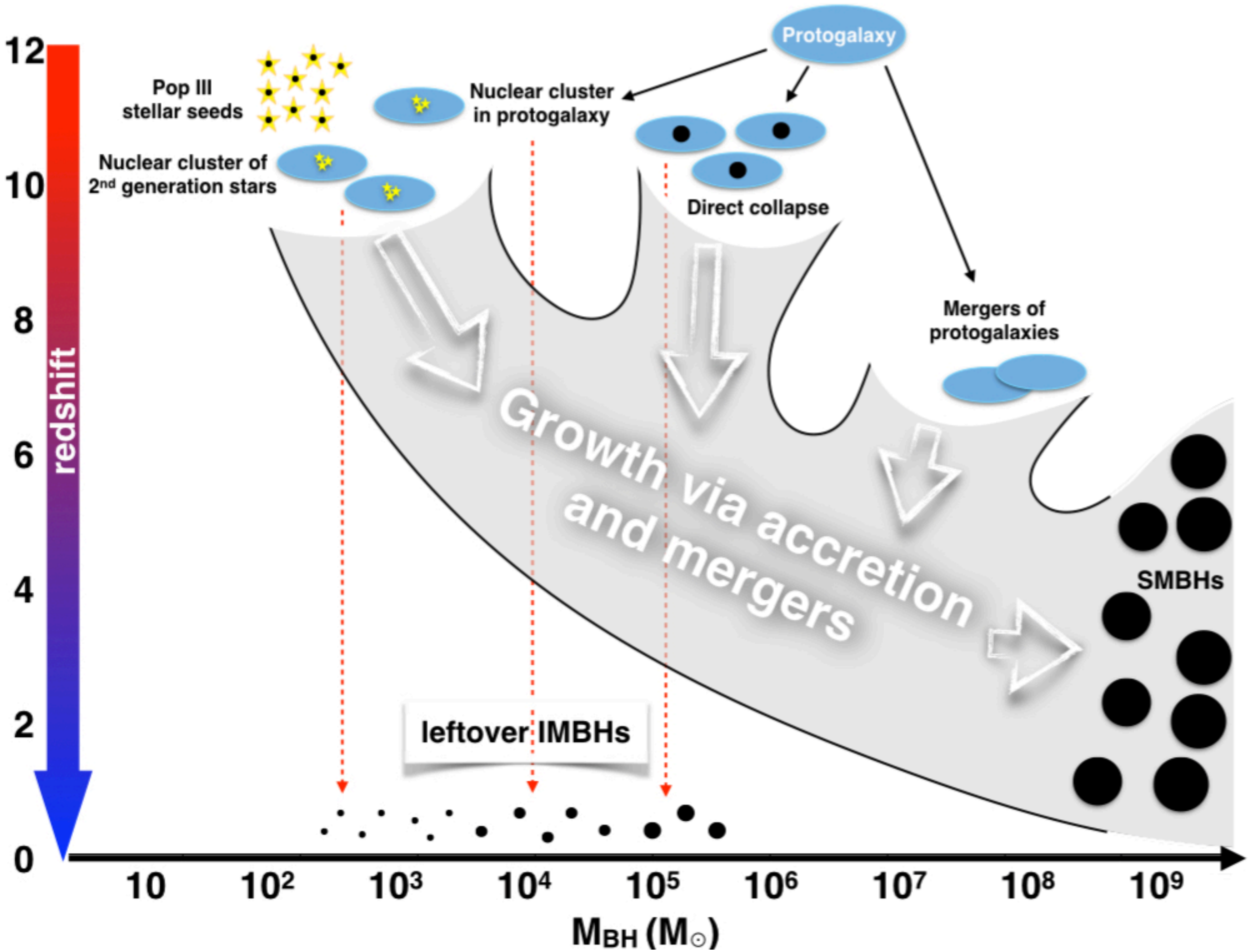


Layout of experiment

Arduini et al: arXiv:2304.00614

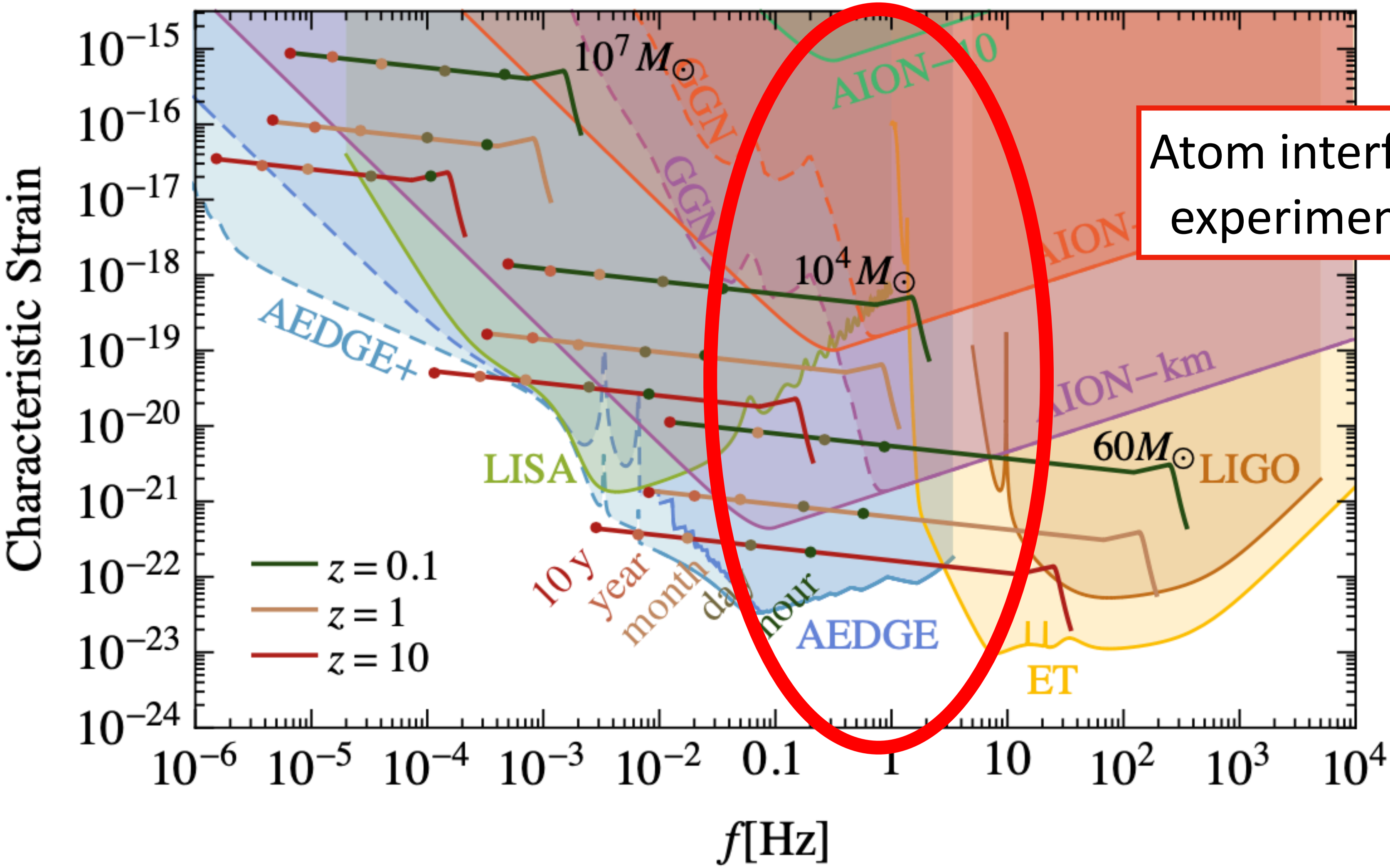
How to Make a Supermassive BH?

SMBHs from mergers of intermediate-mass BHs (IMBHs)?



Gravitational Waves from IMBH Mergers

AION



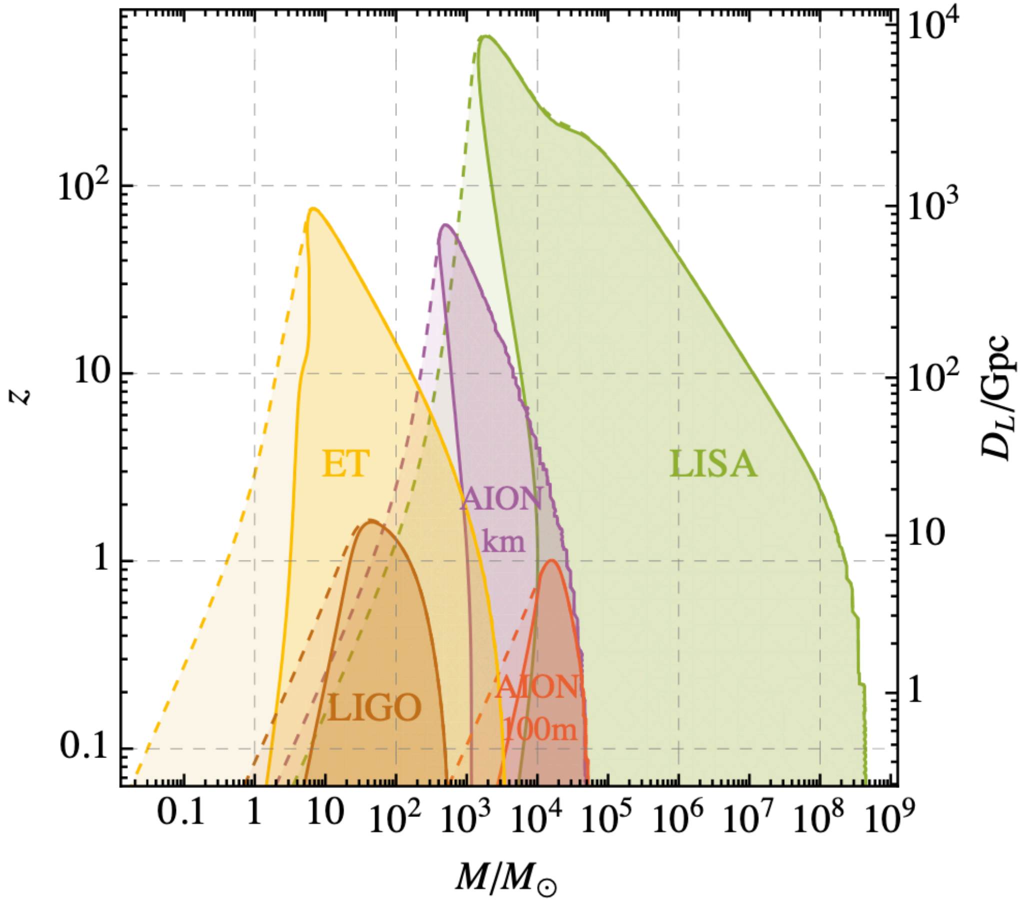
Atom interferometer experiments: AION

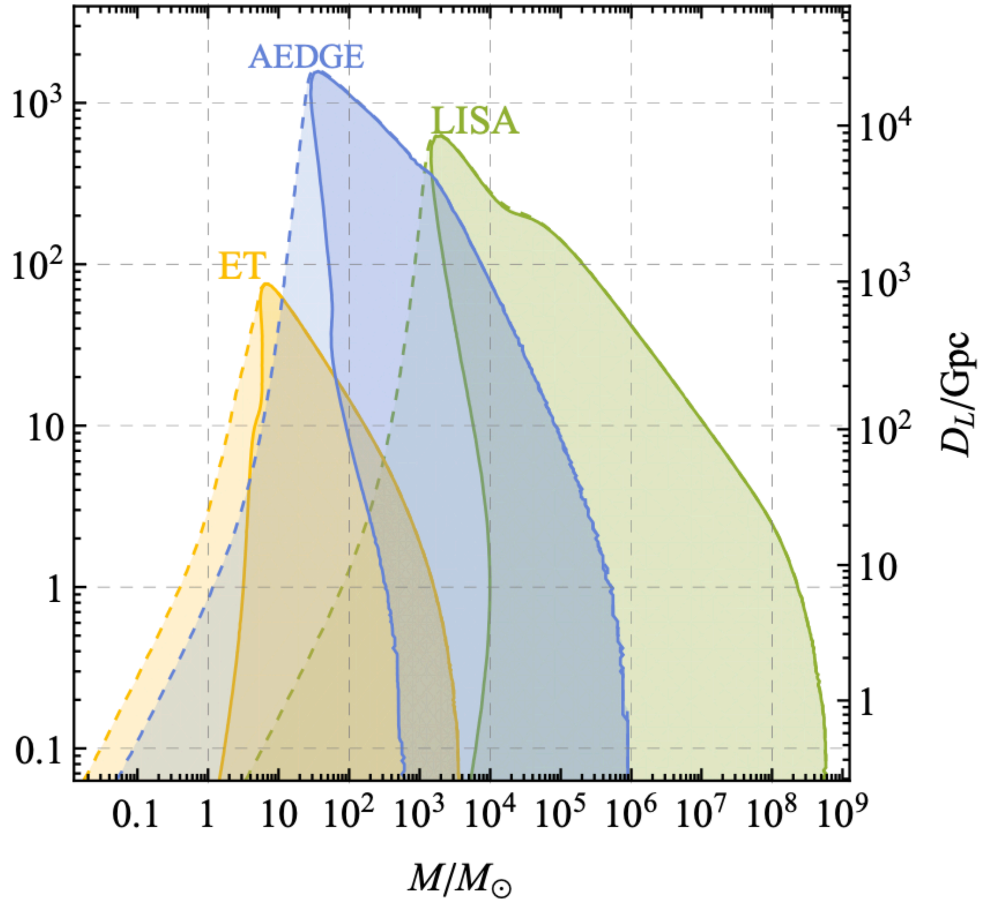
Probe formation of SMBHs

Synergies with other GW experiments (LIGO, LISA), test GR

Badurina, Buchmueller, JE, Lewicki, McCabe & Vaskonen: arXiv:2108.02468

SNR = 8 Sensitivities to GWs from Mergers



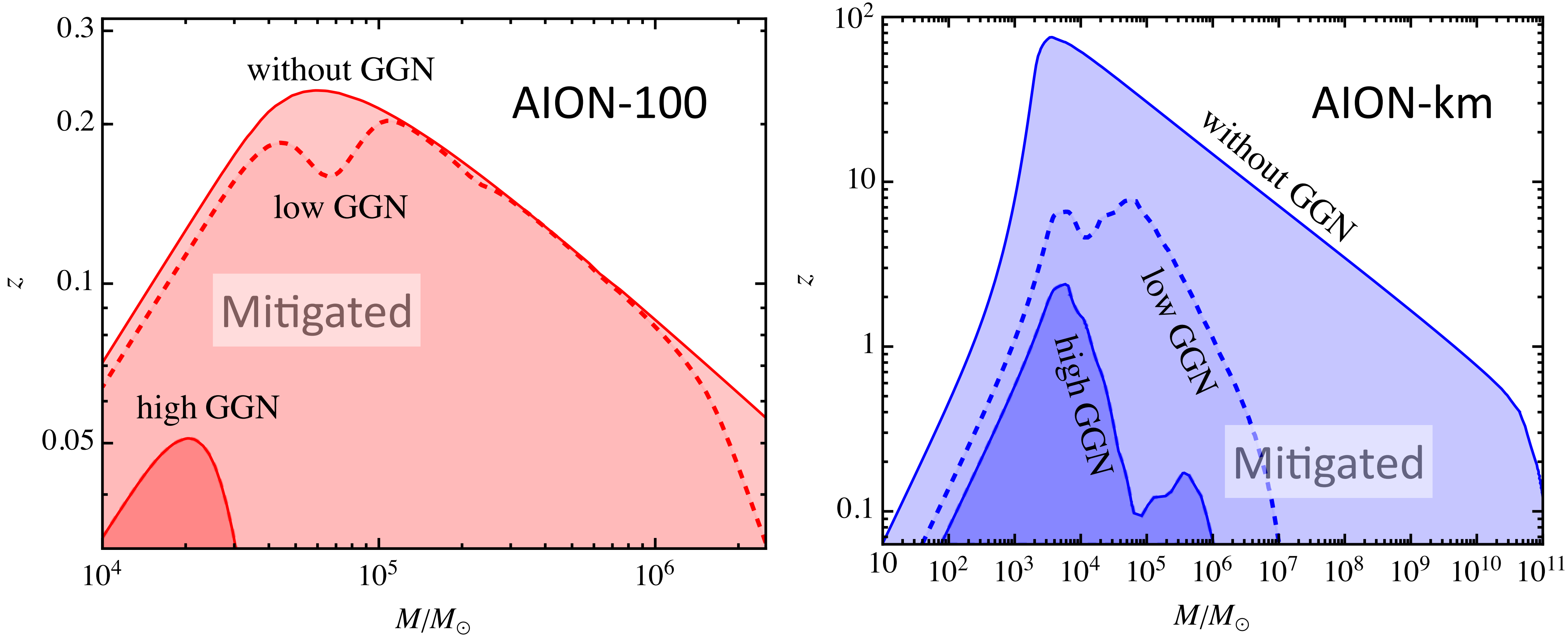


In the lighter regions between the dashed and solid lines the corresponding detector observes only the inspiral phase.

AION, arXiv:1911.11755

AEDGE, arXiv:1908.00802

Searching for IMBH Mergers

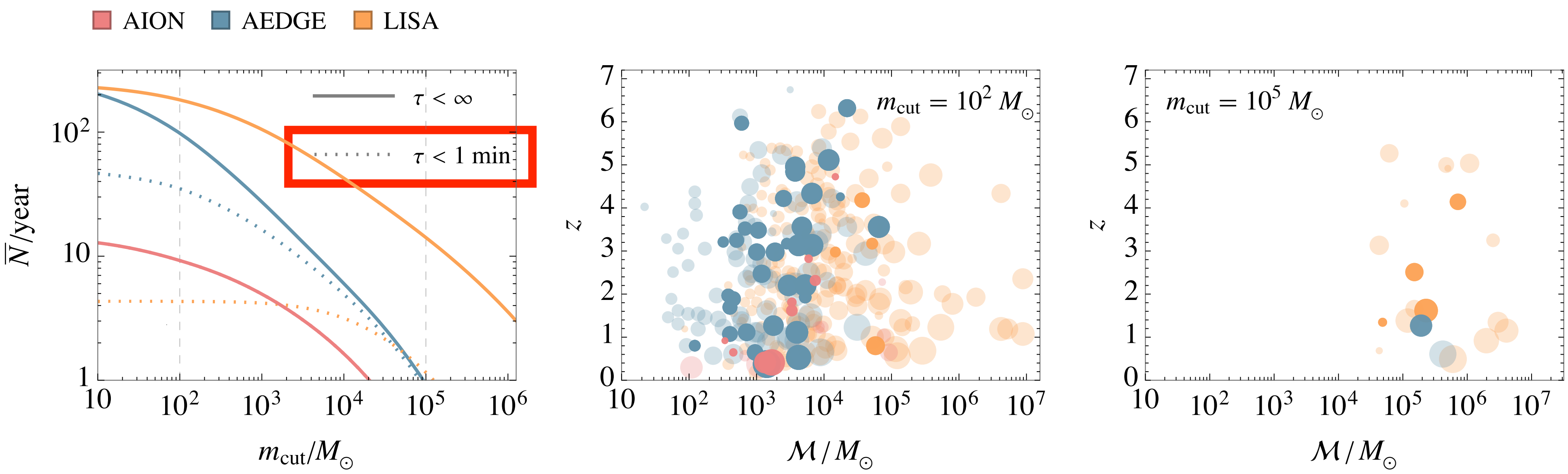


Gravity Gradient Noise (GGN) can be mitigated using multiple interferometers;

further mitigation possible with external seismometer network, to be studied

Vaskonen, AION Collaboration

Rates in Models with 10^2, 10^5 Solar Mass Seeds

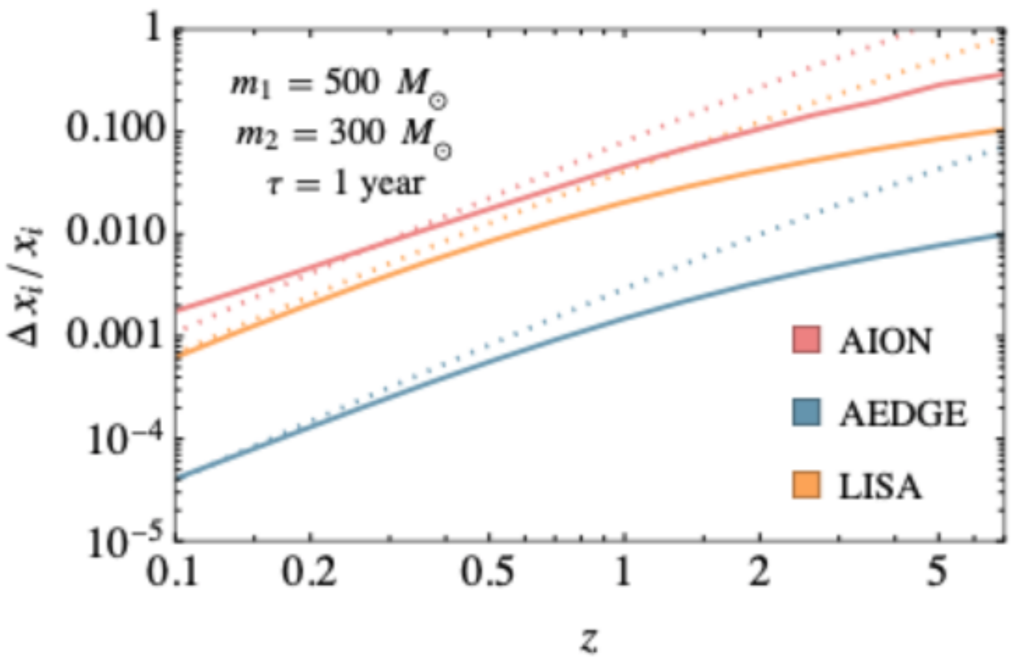


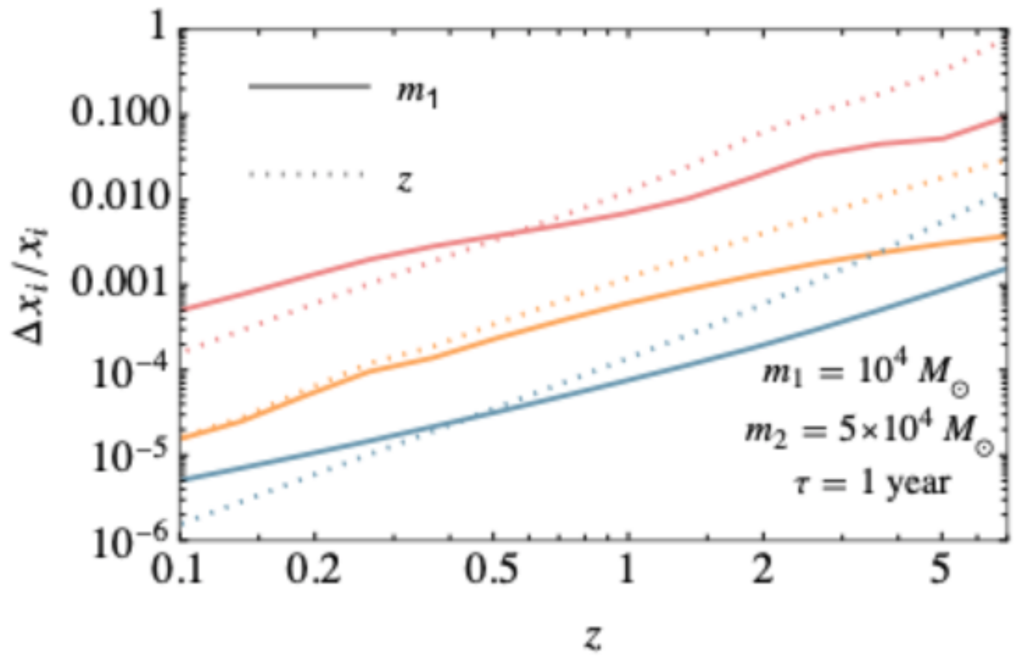
LISA loses events before mergers

Smaller dots = better signal-to noise ratio

JE, Fairbairn, Urrutia & Vaskonen, arXiv:2312.02983

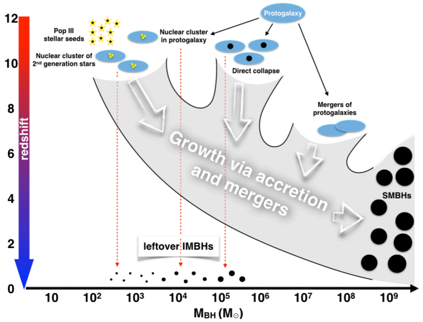
Precision of Merger Parameters



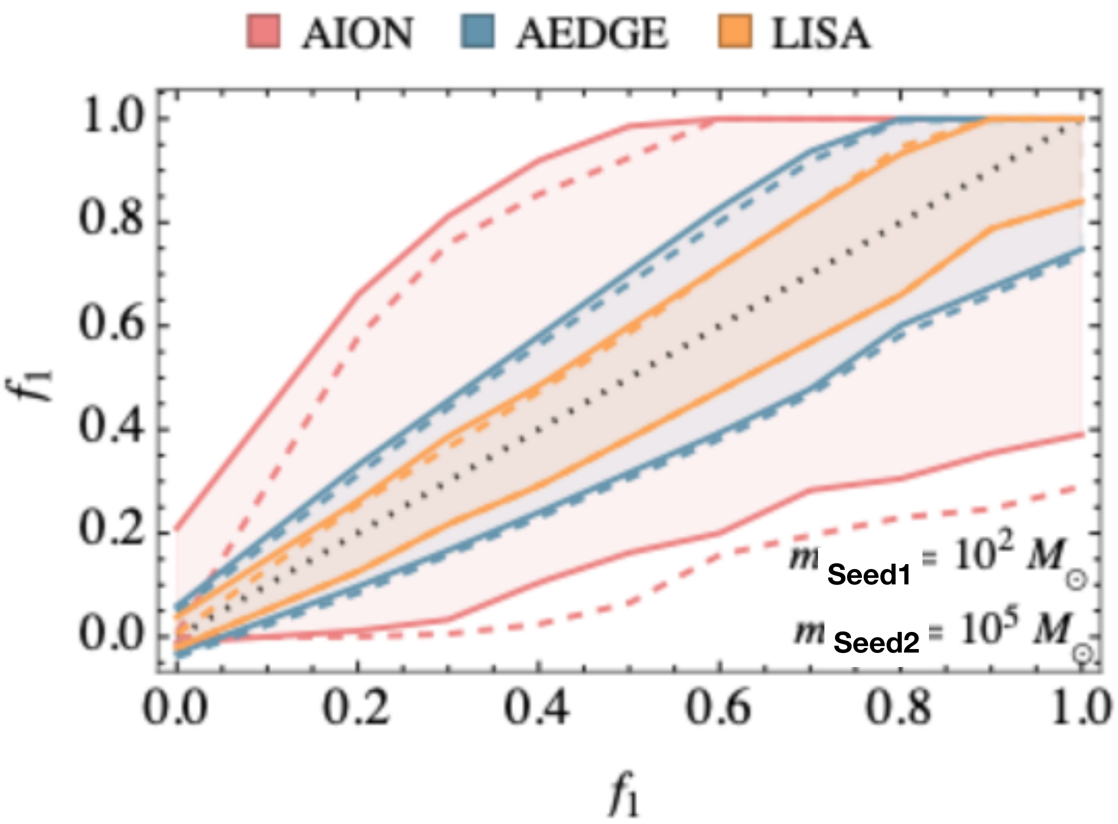


AION-km less precise than LISA, AEDGE more precise

JE, Fairbairn, Urrutia & Vaskonen, arXiv:2312.02983



Distinguishing Seed Sizes



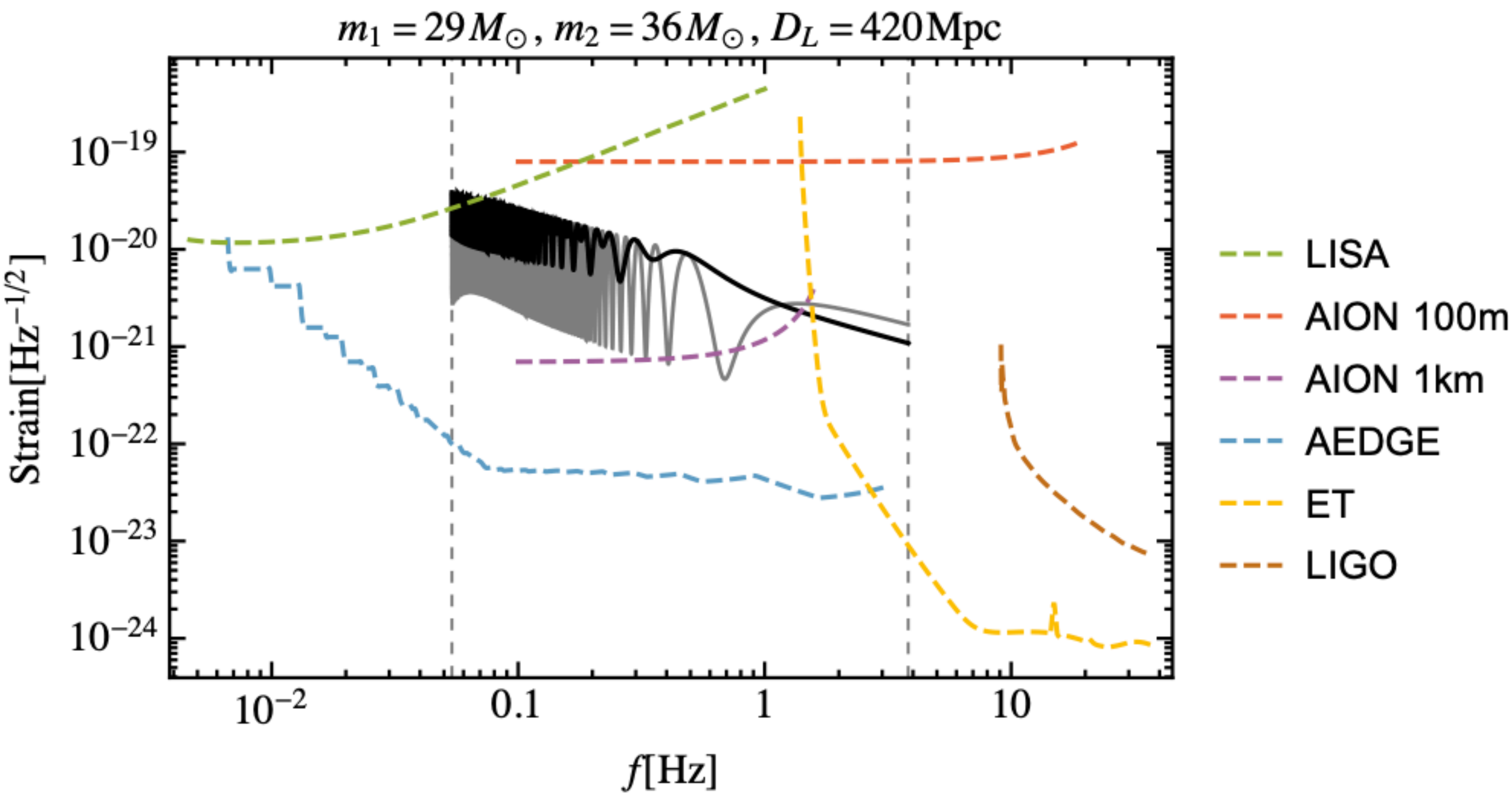
f_1 = fraction of light seeds,

horizontal axis = input, vertical axis = measurement

AION-km less precise than LISA, AEDGE more precise

JE, Fairbairn, Urrutia & Vaskonen, arXiv:2312.02983

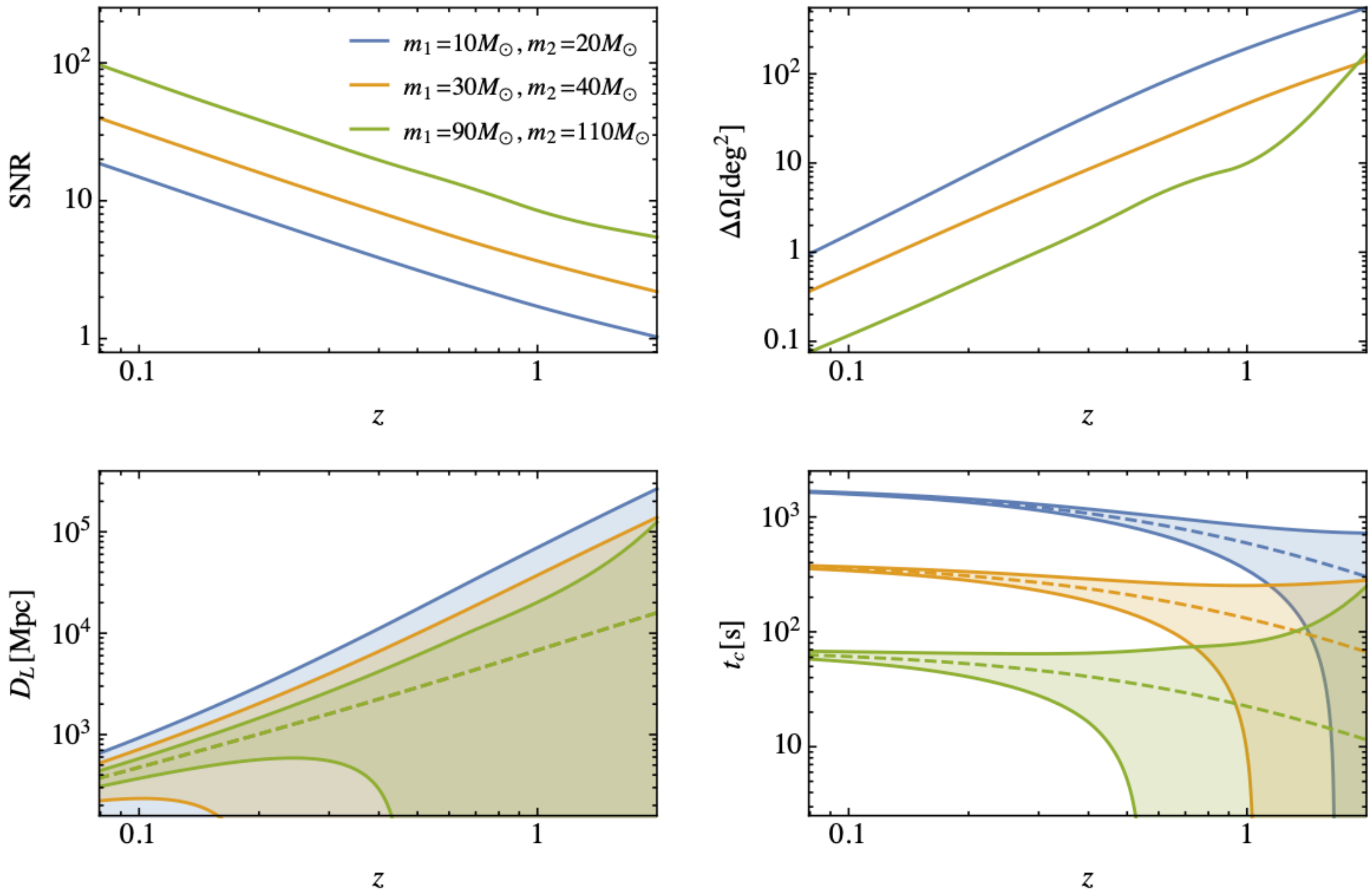
Synergies with Higher-Frequency Experiments



Inspiral waveforms for **ground**-/space-based detectors

JE & Vaskonen: arXiv:2003.13480

Synergies with Higher-Frequency Experiments



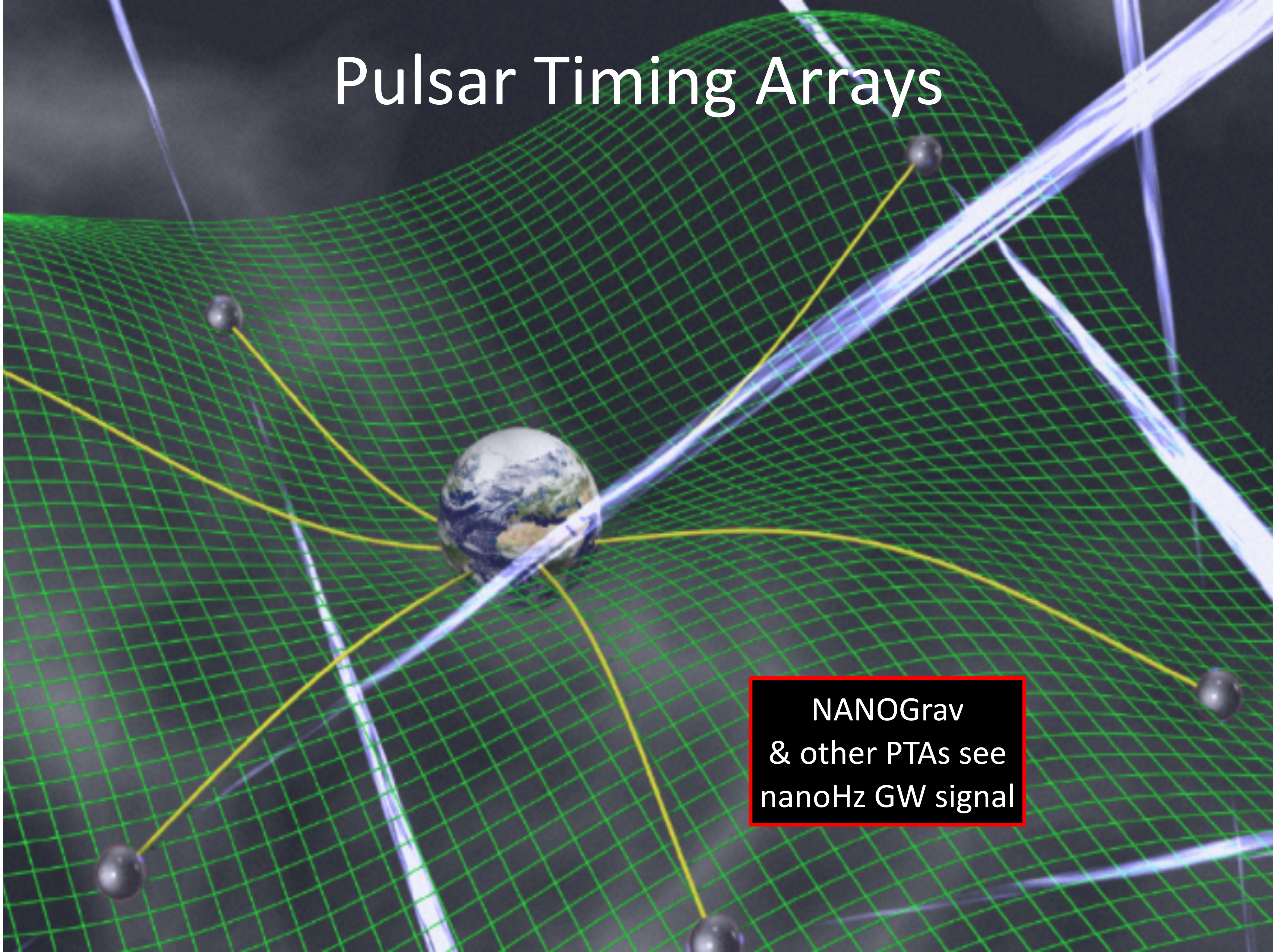
Predictions for future LVK/ET/CE measurements:

Direction, distance, time of merger

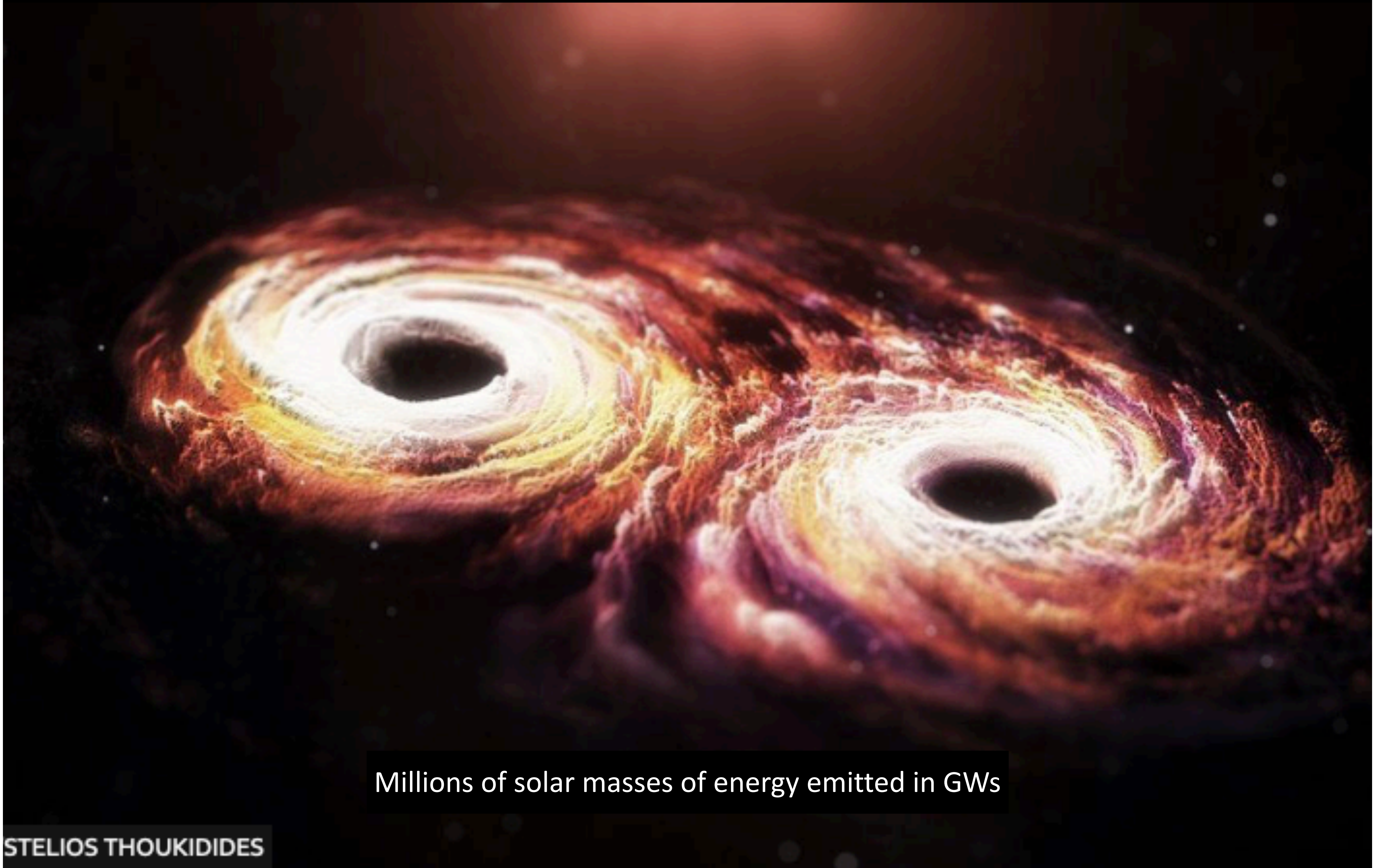
JE & Vaskonen: arXiv:2003.13480

Early warnings for multi-messenger observations

Pulsar Timing Arrays



The Biggest Bangs since the Big Bang?

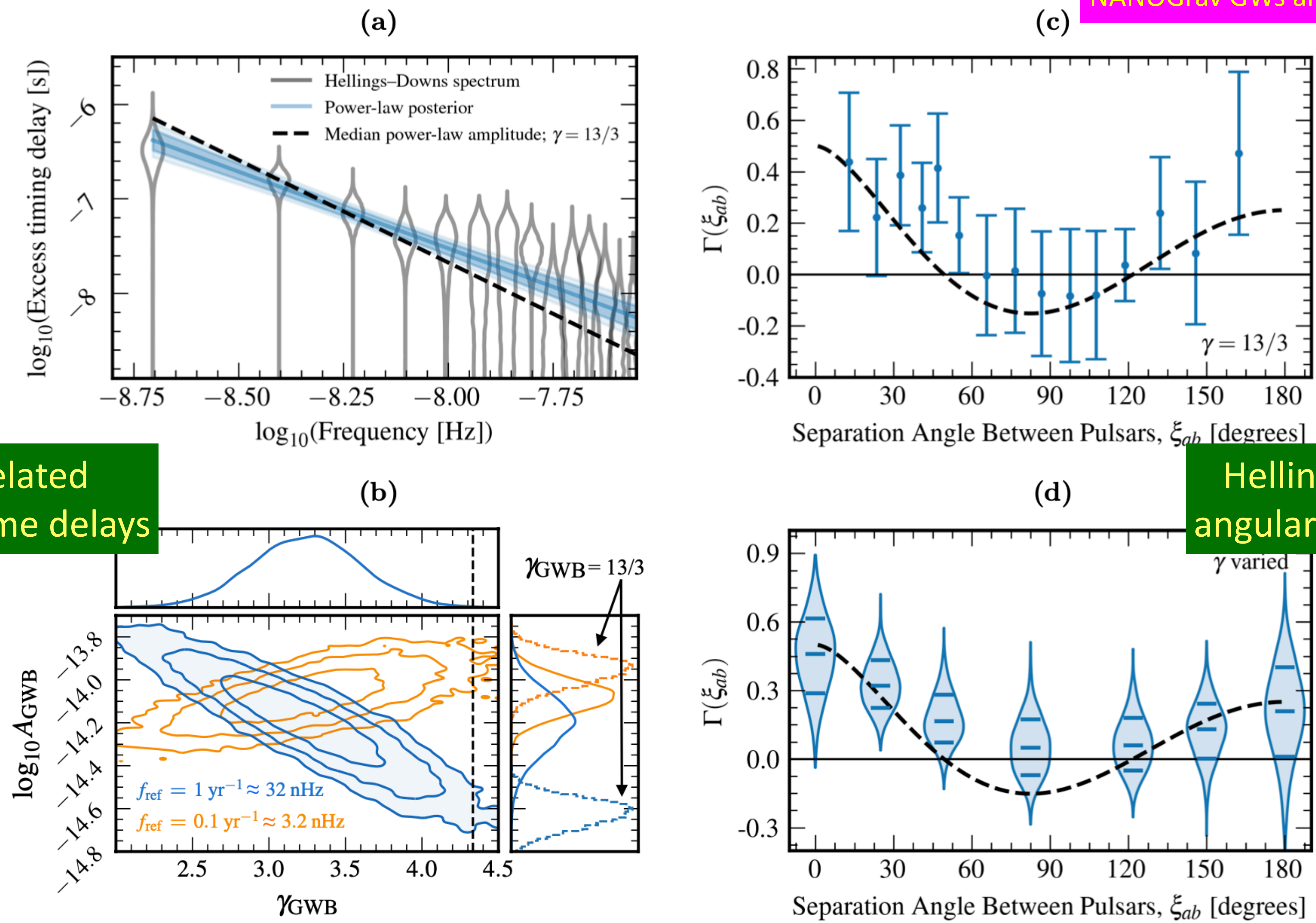


NANOGrav 15-Year Data

NANOGrav GWs arXiv:2306.16213

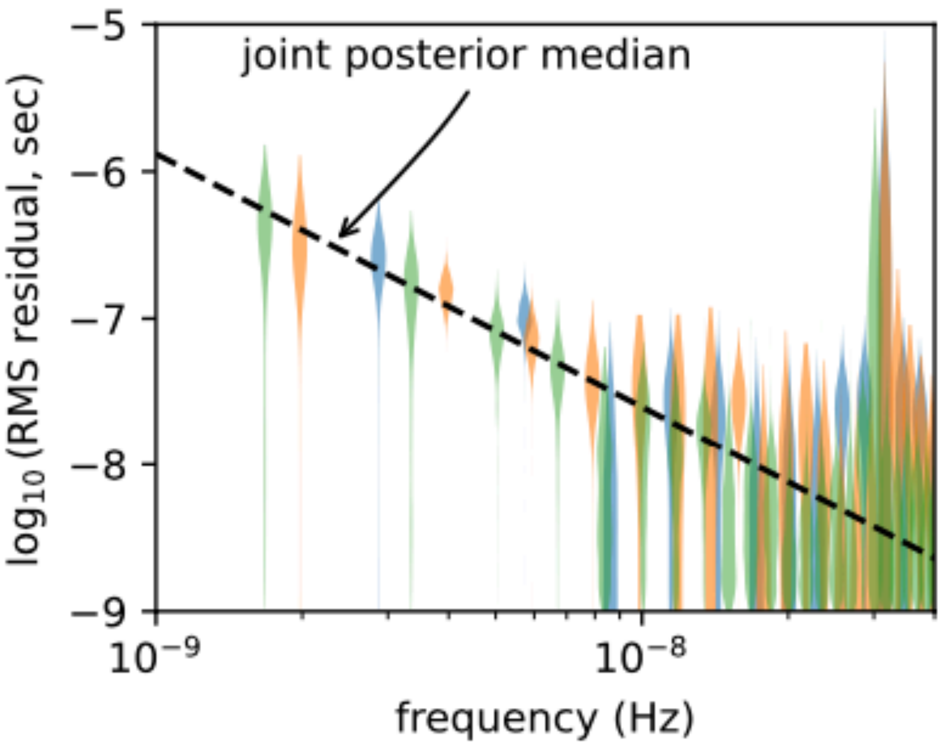
Correlated pulsar time delays

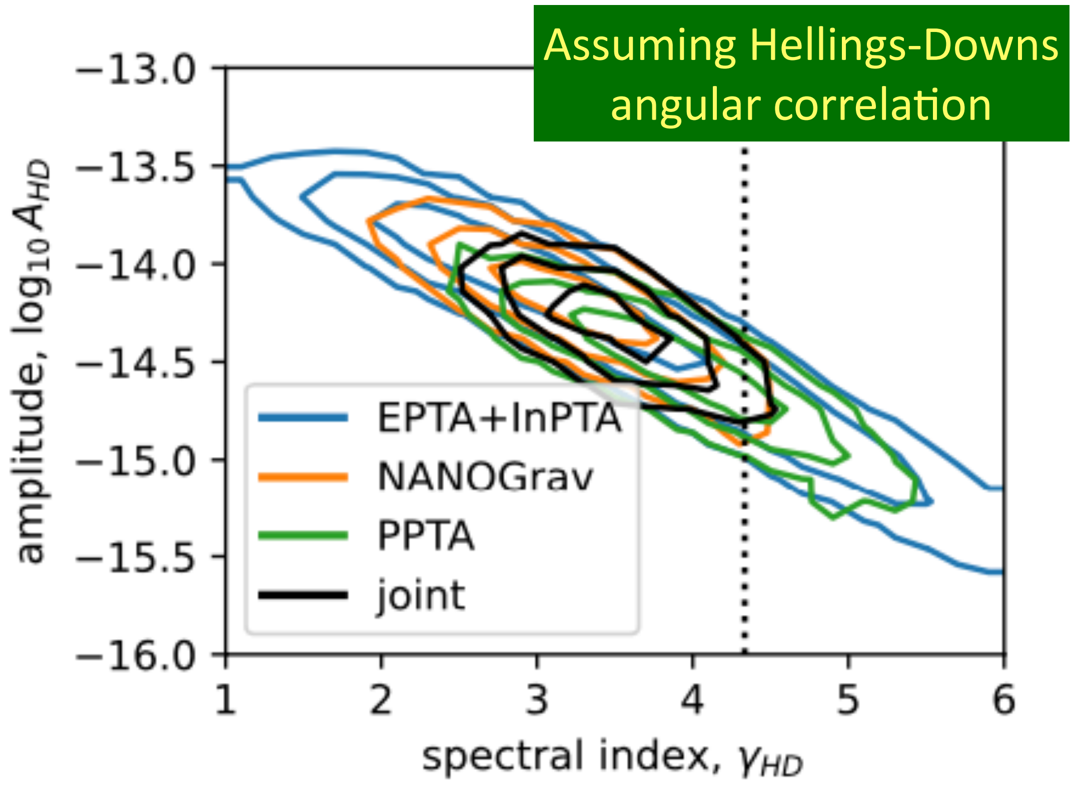
Hellings-Downs angular correlation



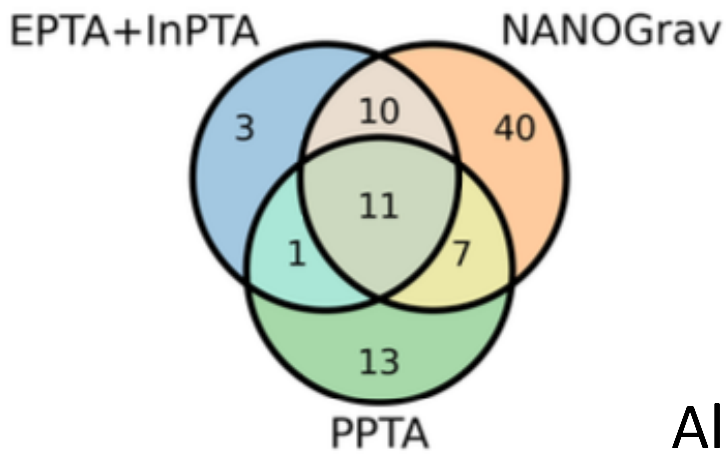
Evidence for GWs: Hellings-Downs angular correlation Bayes factor ~ 200

IPTA Data Compilation





Venn diagram of PTA data sets



Also Chinese PTA

IPTA Collaboration, arXiv:2309.00693

BH Merger Rate Estimate

BH merger rate R_{BH}

$$\frac{\mathrm{d}R_{\mathrm{BH}}}{\mathrm{d}m_1\mathrm{d}m_2} \approx p_{\mathrm{BH}} \frac{\mathrm{d}M_1}{\mathrm{d}m_1} \frac{\mathrm{d}M_2}{\mathrm{d}m_2} \frac{\mathrm{d}R_h}{\mathrm{d}M_1\mathrm{d}M_2}$$

where R_h is halo merger rate calculated using Extended Press-Schechter formalism,

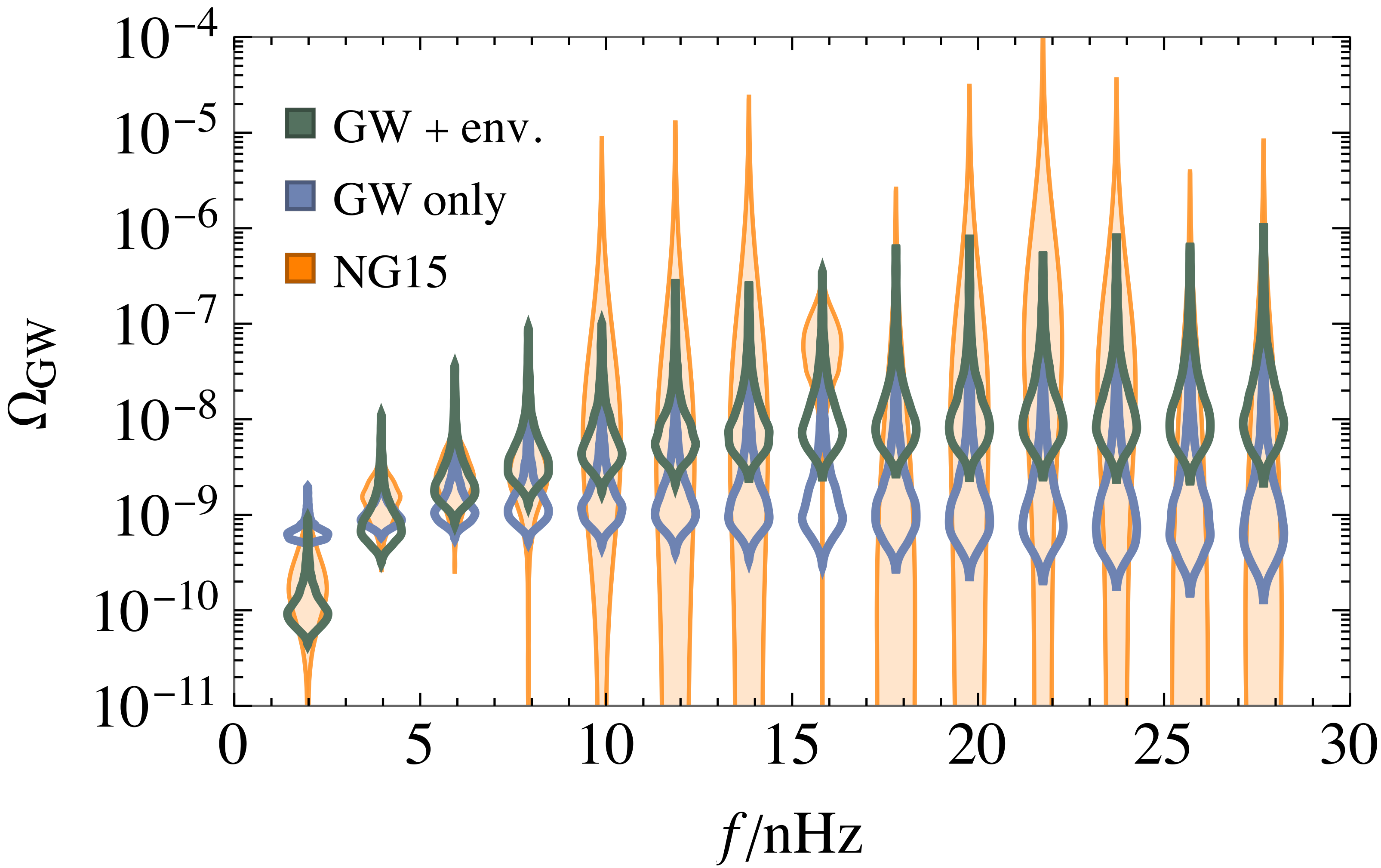
$$p_{\mathrm{BH}} \equiv p_{\mathrm{occ}}(m_1)p_{\mathrm{occ}}(m_2)p_{\mathrm{merg}}$$

is merger probability, and

strength of IPTA signal can be fitted by constant p_{BH}

JE, Fairbairn, Hütsi, Raidal, Urrutia, Vaskonen & Veermäe: arXiv:2301.13854

Astrophysical Interpretations AION



Fits use overlaps of data and model violins in each bin

NB: Fits go beyond simple power-law approximations

Better fit to spectrum if evolution driven by both environment & GWs

JE, Fairbairn, Hütsi, Raidal', Urrutia, Vaskonen & Veermäe: arXiv:2306.17021

Environmental energy loss AION

- Interactions with gas, stars, dark matter?
- Total energy loss rate: $\dot{E} = -\dot{E}_{\rm GW} - \dot{E}_{\rm env}$
- Characteristic time scales: $t_{\rm GW} \equiv E/\dot{E}_{\rm GW} = 4\tau\,,\ t_{\rm env} \equiv E/\dot{E}_{\rm env}$
- Where $\tau = \frac{5}{256}(\pi f_r)^{-8/3}\mathcal{M}^{-5/3}$
- Energy radiated in GWs reduced because of accelerated evolution:

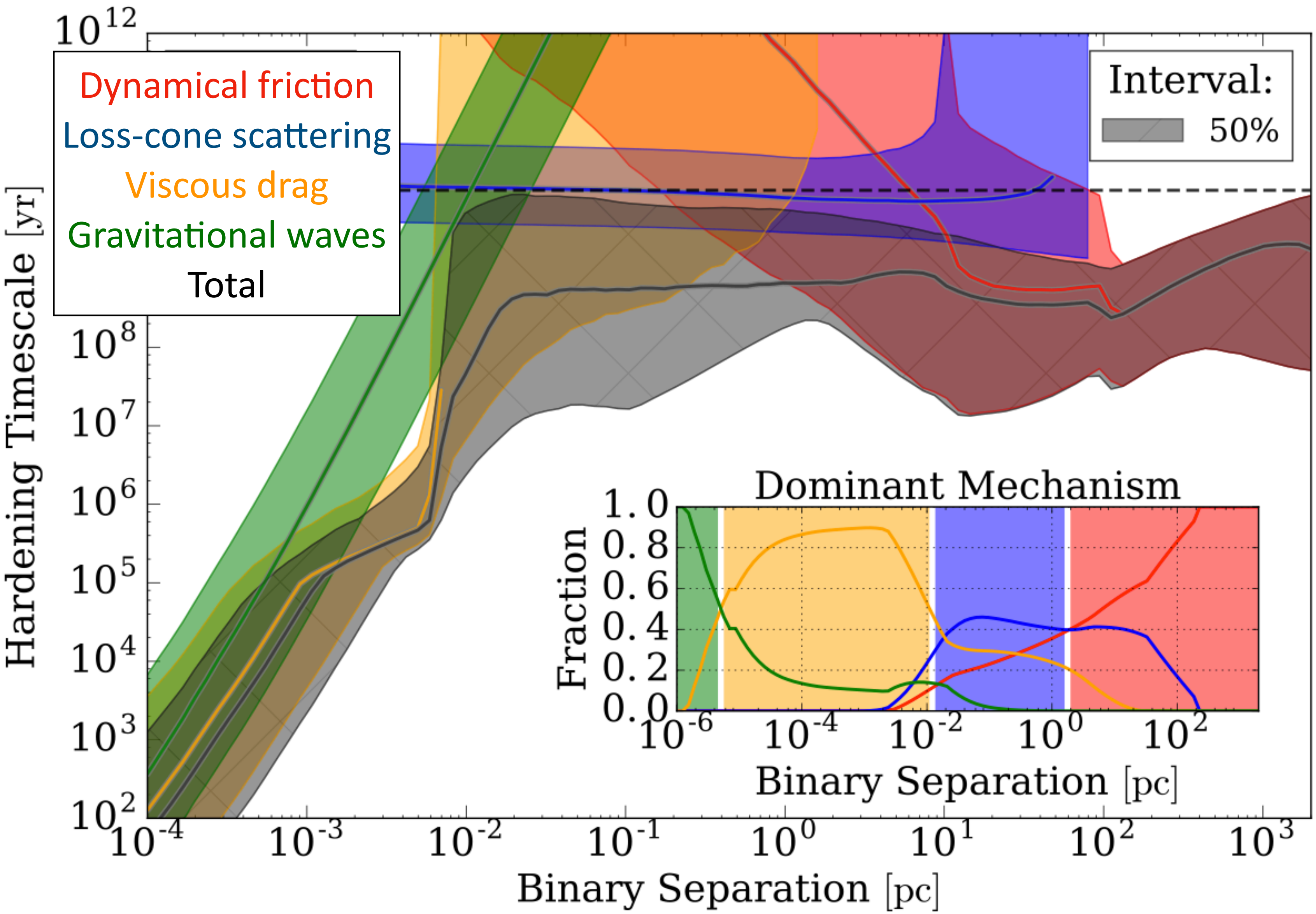
$$\frac{\mathrm{dE_{GW}}}{\mathrm{d\ln f_r}} = \frac{1}{3}\frac{(\pi f_r)^{\frac{2}{3}}\mathcal{M}^{\frac{5}{3}}}{1 + t_{\rm GW}/t_{\rm env}}$$

- Phenomenological parametrization:

$$\frac{t_{\rm env}}{t_{\rm GW}} = \left(\frac{f_r}{f_{\rm GW}}\right)^{\alpha}, \quad f_{\rm GW} = f_{\rm ref}\left(\frac{\mathcal{M}}{10^9 M_{\rm sun}}\right)^{-\beta}$$

JE, Fairbairn, Hütsi, Raidal', Urrutia, Vaskonen & Veermäe: arXiv:2306.17021

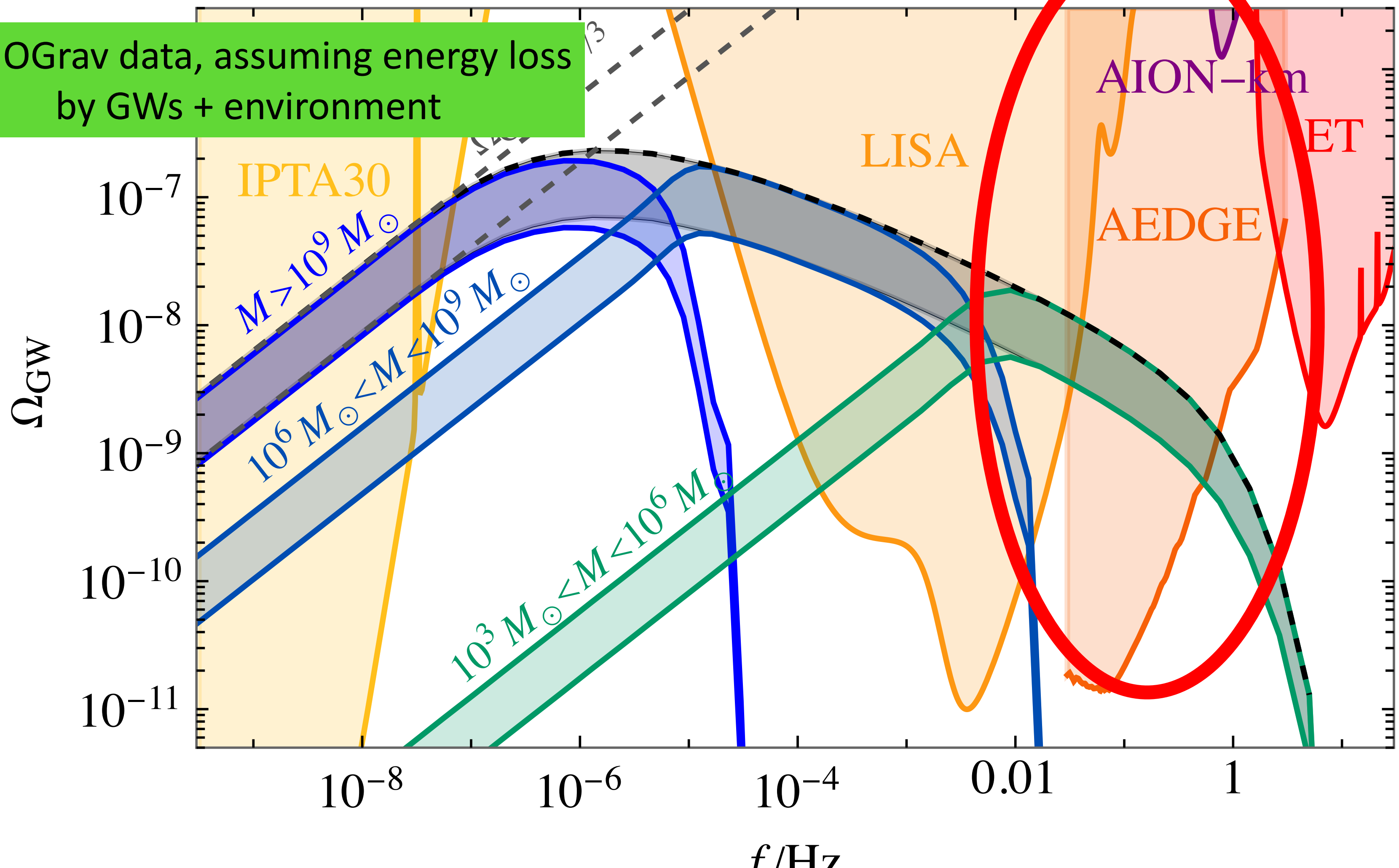
Mechanisms for Energy Loss



Kelley, Blecha & Hernquist, arXiv:1606.01900

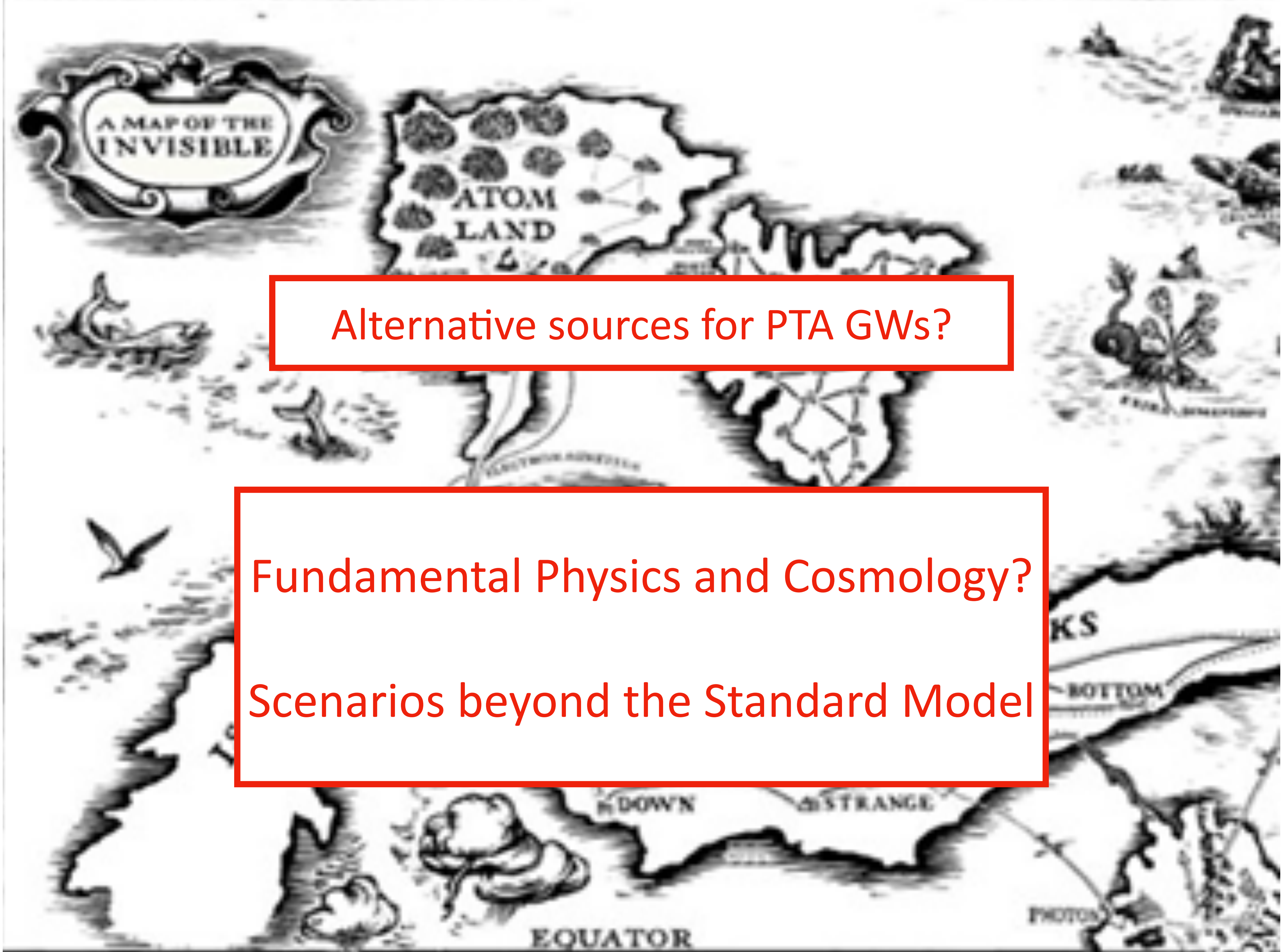
Stochastic GW Background from BH Mergers

NANOGrav data, assuming energy loss by GWs + environment



Black dashed line is maximum possible Ω_{GW}, i.e., $p_{BH} = 1$

JE, Fairbairn, Hütsi, Raidal', Urrutia, Vaskonen & Veermäe: arXiv:2306.17021

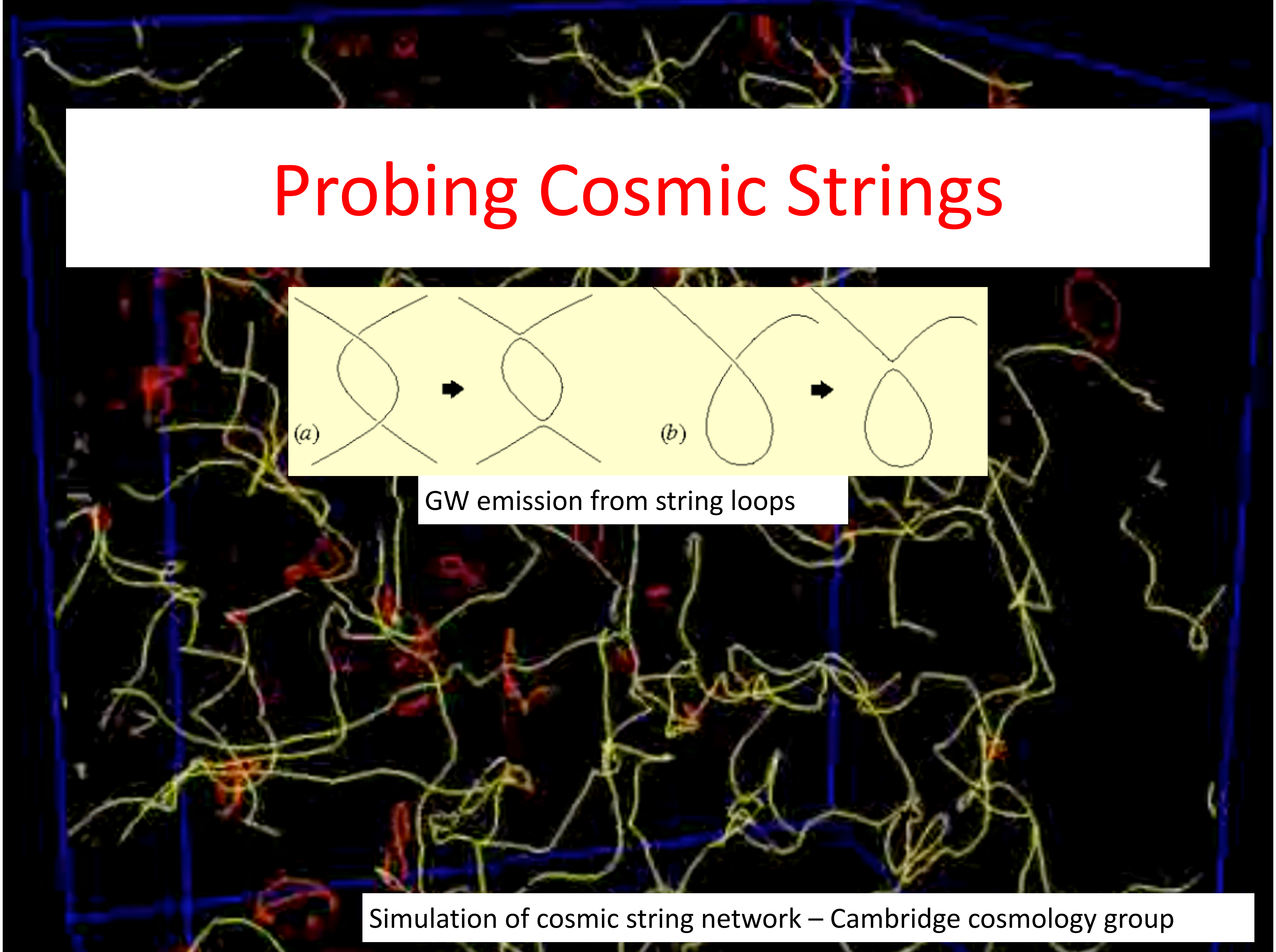


Alternative sources for PTA GWs?

Fundamental Physics and Cosmology?

Scenarios beyond the Standard Model

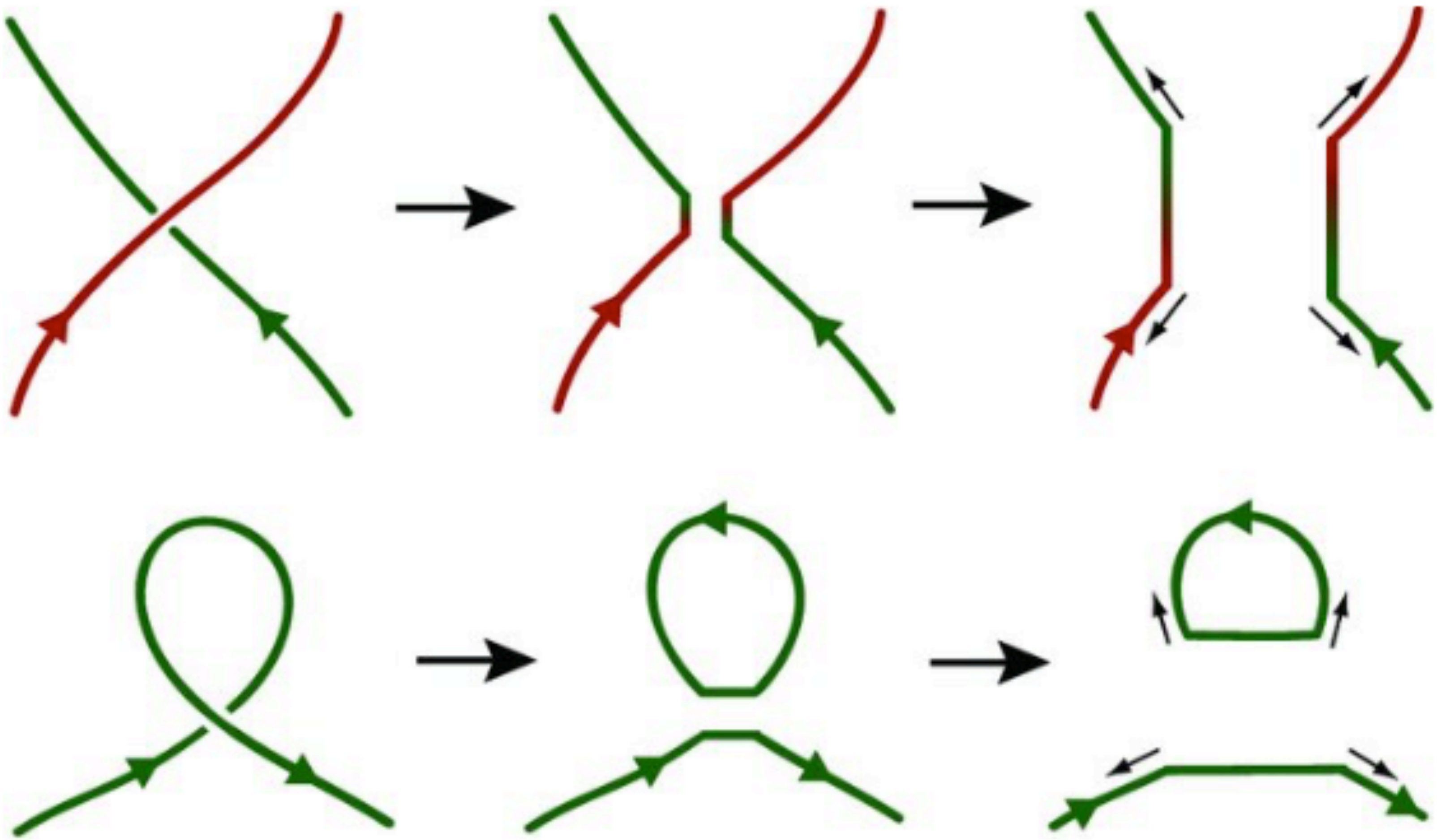
Probing Cosmic Strings



GW emission from string loops

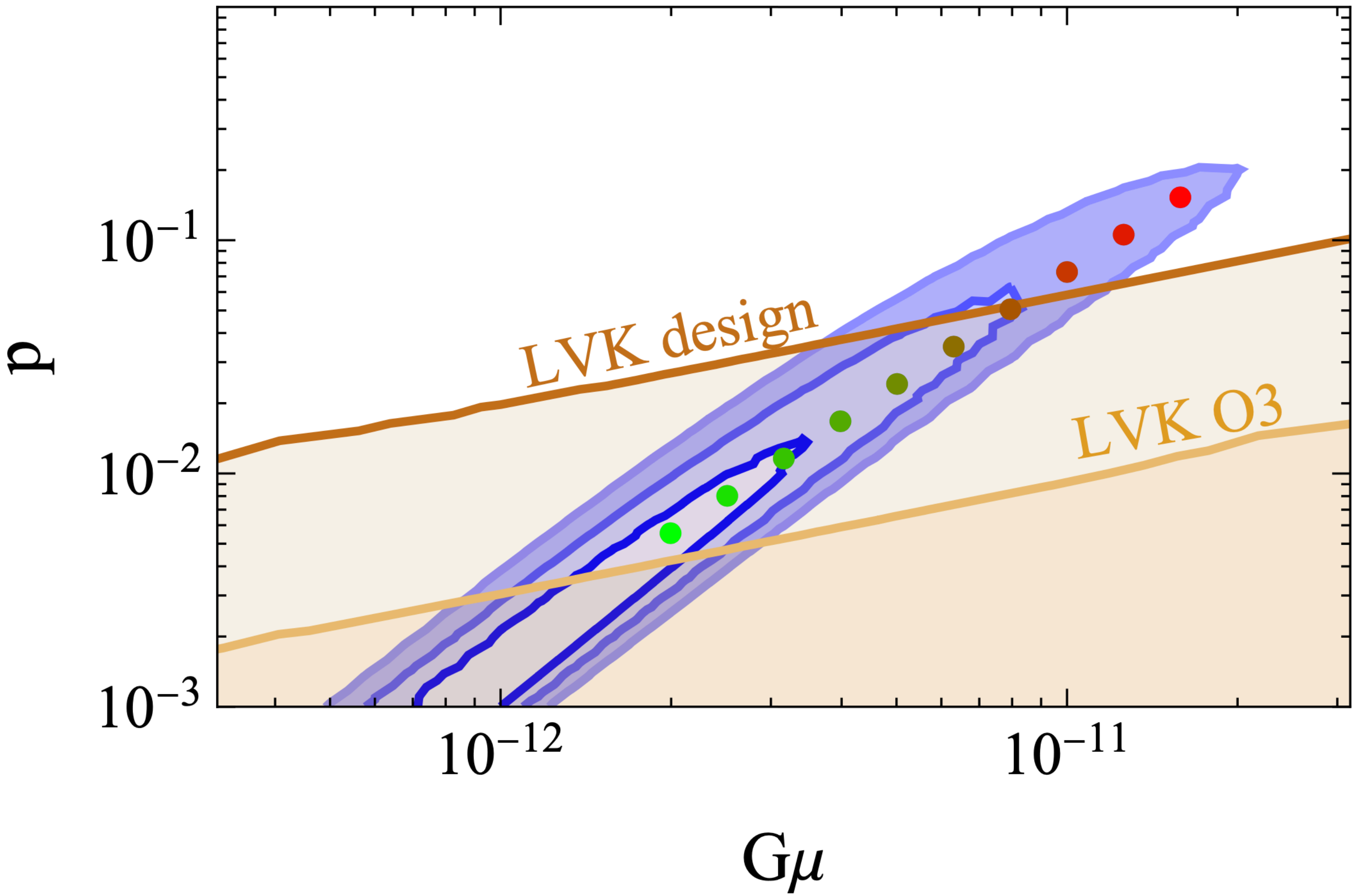
Simulation of cosmic string network – Cambridge cosmology group

String Intercommutation



U(1) bosonic strings intercommute with probability $p = 1$
Other strings (super, QCD-like, …) may have $p < 1$

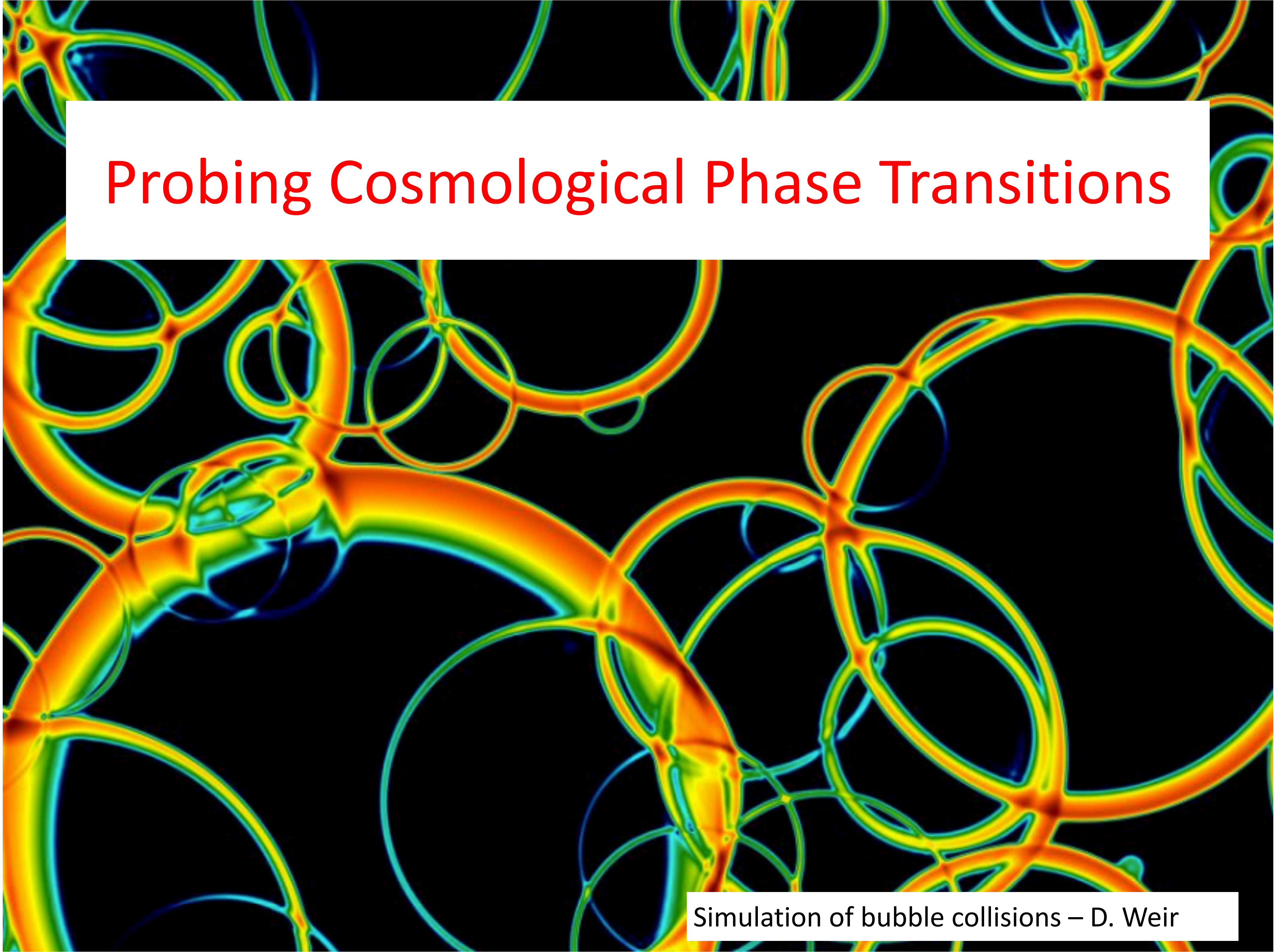
Superstrings vs LVK



(Super)string model compatible with LVK for $p \sim 0.001 - 0.1$

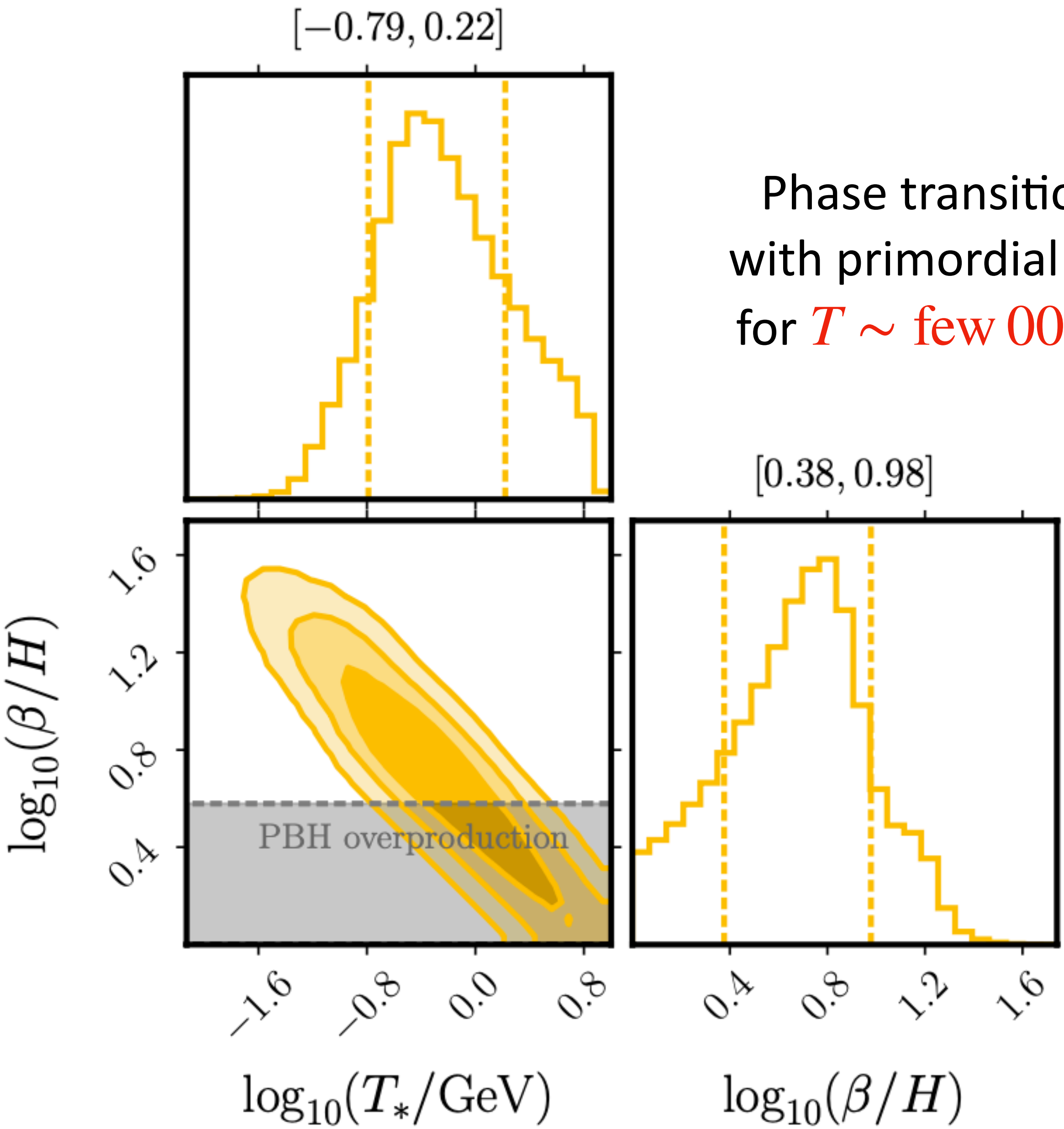
JE, Lewicki, Lin, & Vaskonen: arXiv:2306.17147

Probing Cosmological Phase Transitions



Simulation of bubble collisions – D. Weir

Phase Transition Fit to NANOGrav

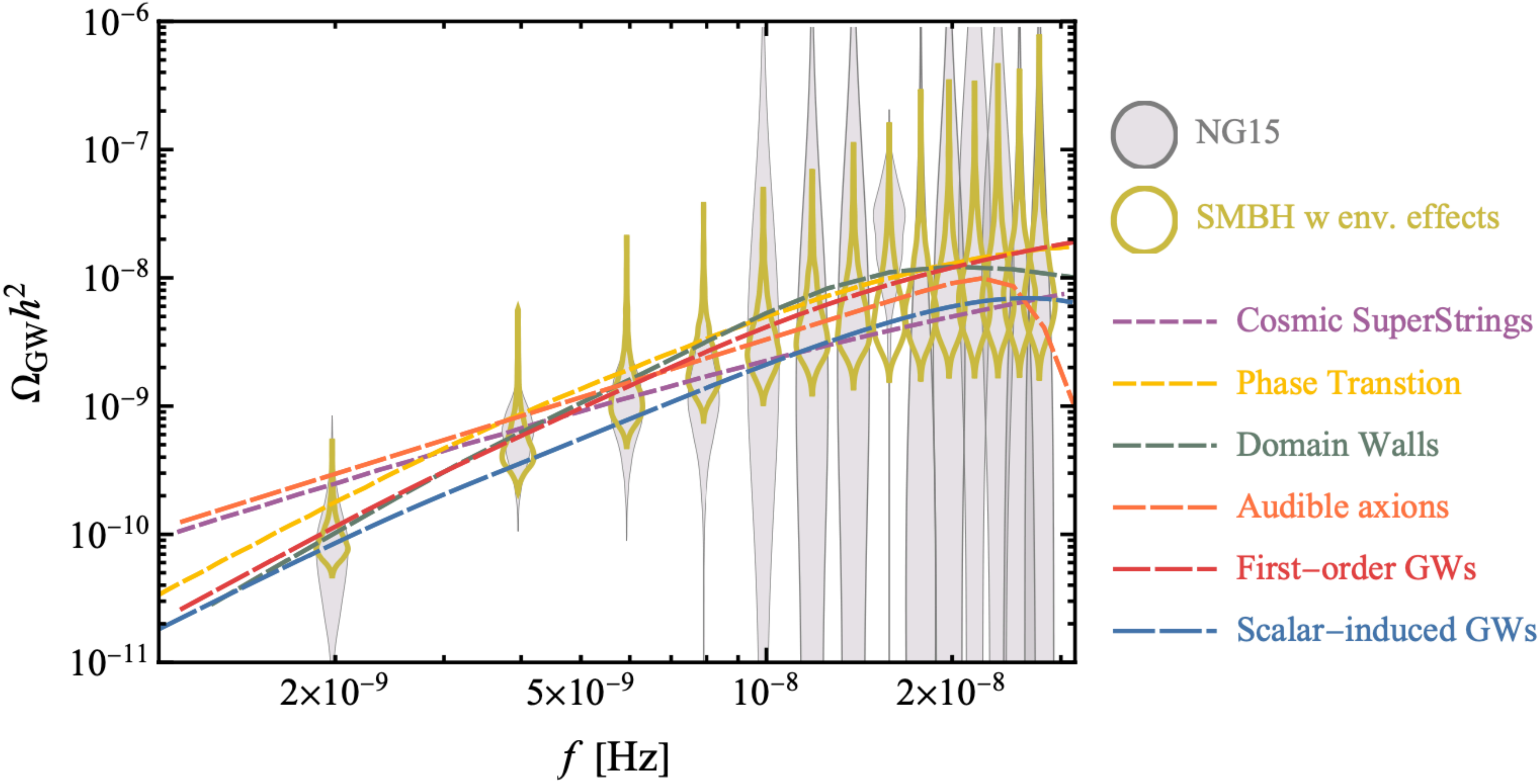


Phase transition model compatible with primordial black hole abundance for $T \sim$ few 00 MeV (hidden sector)

JE, Fairbairn, Franciolini, Hütsi, Iovino, Lewicki, Raidal, Urrutia, Vaskonen & Veermäe, arXiv:2308.08546

Fits to NANOGrav

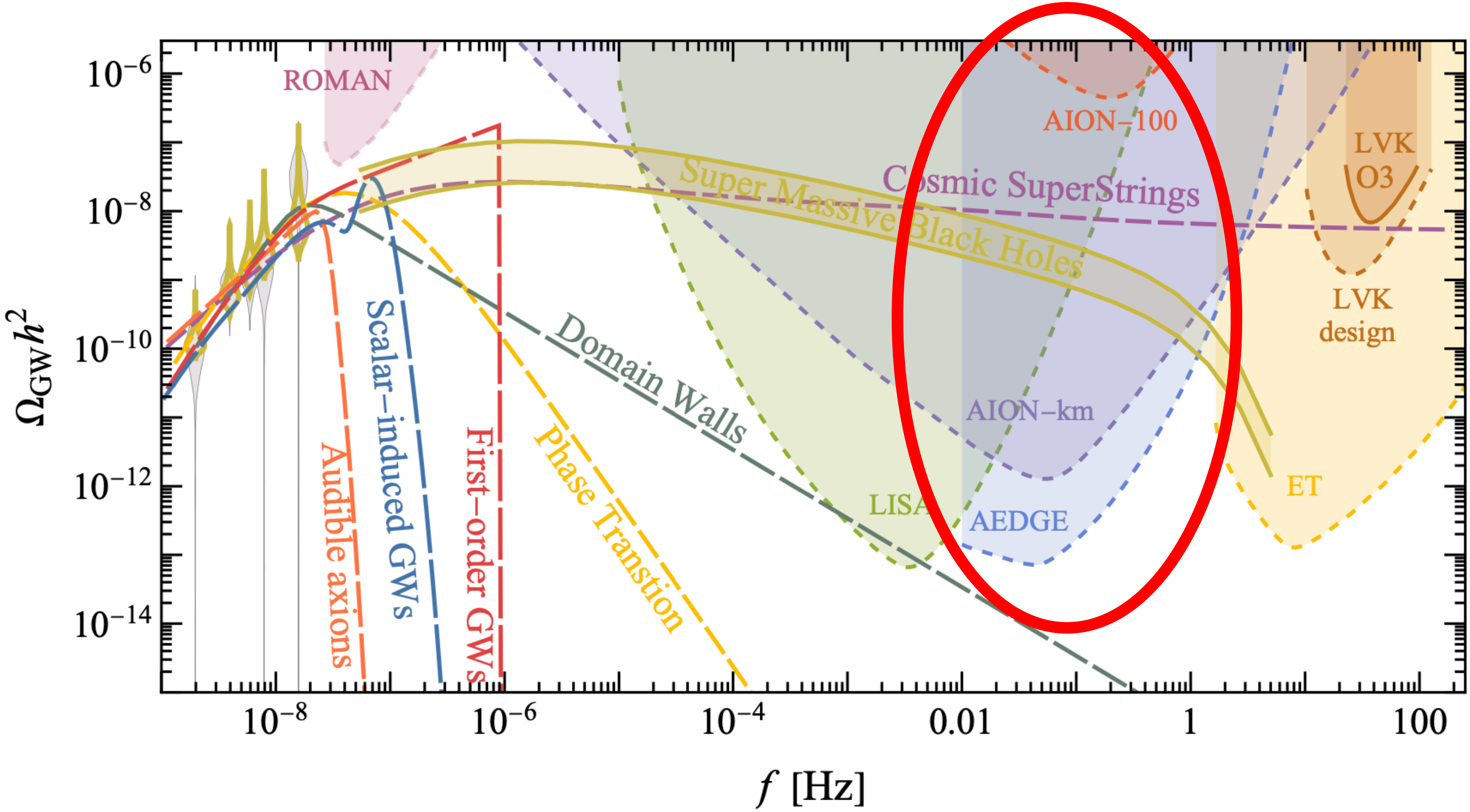
AION



JE, Fairbairn, Franciolini, Hütsi, Iovino, Lewicki, Urrutia, Vaskonen & Veermäe, arXiv:2308.08546

Extension of Fits to Higher Frequencies

AION



JE, Fairbairn, Franciolini, Hütsi, Iovino, Lewicki, Urrutia, Vaskonen & Veermäe, arXiv:2308.08546

Quo Vadis NANOGrav?

- **Astrophysics or fundamental physics?**
- Biggest bangs since the Big Bang, or physics beyond the SM?
  - SMBH binaries driven by GWs alone disfavoured
  - SMBH binaries driven by GWs and environmental effects fit better
- **Better fits with cosmological BSM models**
- Discrimination possible with future measurements: fluctuations, anisotropies, polarization, experiments at higher frequencies - including **atom interferometers**
- **Time and more data will tell!**

Summary

- Atom interferometry is a promising new technology
- AION Collaboration making progress with R&D
- Advanced plans for 10-m prototype detector @ Oxford, sites for 100-m and km including Boulby, CERN & Switzerland being investigated
- Exploring sensitivity including effects of (mitigated) GGN
- Atom interferometers have interesting stand-alone science, also potential synergies with laser interferometers
- PTA data evidence for a SGWB that is potentially observable by atom interferometers

AEDGE, arXiv:1908.00802,
AION, arXiv:1911.11755,
AION, arXiv:2305.20060,
JE, Schneider & Buchmueller, arXiv:2306.17726,
Terrestrial VLBAI, arXiv:2310.08183