Gravitational Waves:
Searching for BSM Physics in the Biggest Bangs since the Big Bang

KING'S College LONDON

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PPC, Hyderabad,
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Gravitational Waves

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

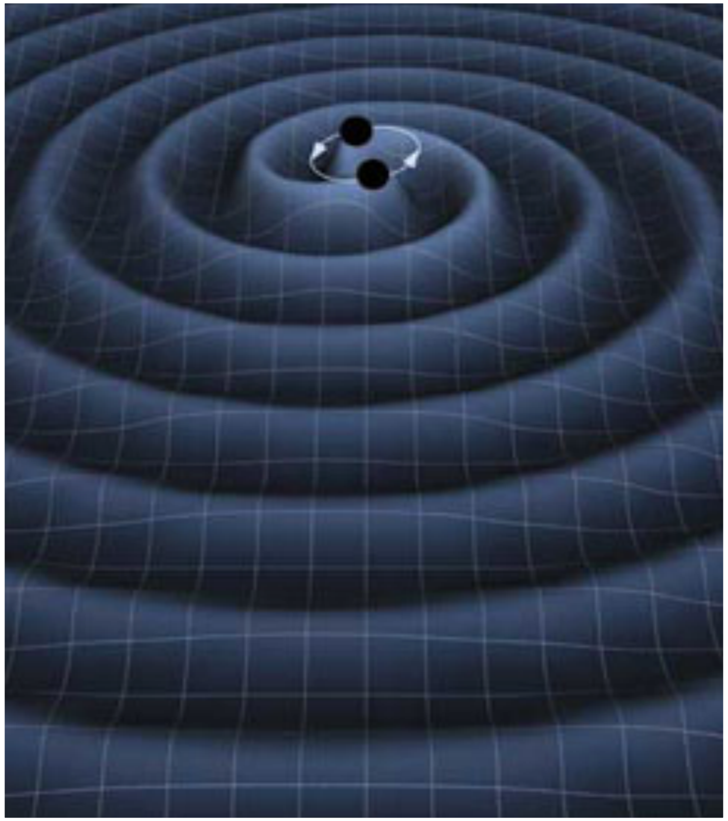
Näherungsweise Integration der Feldgleichungen der Gravitation.

Von A. Einstein.

Bei der Behandlung der meisten speziellen (nicht prinzipiellen) Prob… 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

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

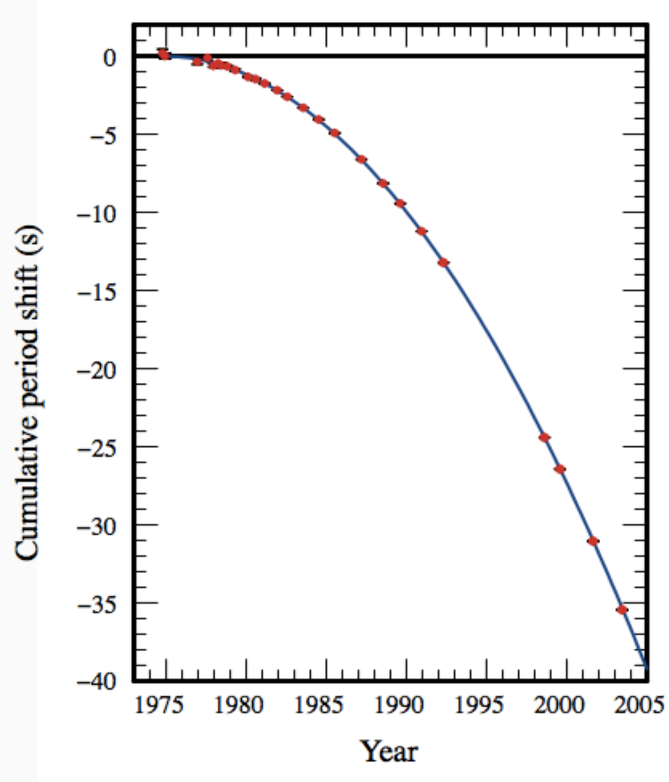
Albert Einstein, *Näherungsweise Integration der Feldgleichungen der Gravitation*, 22.6.Berlin 1916



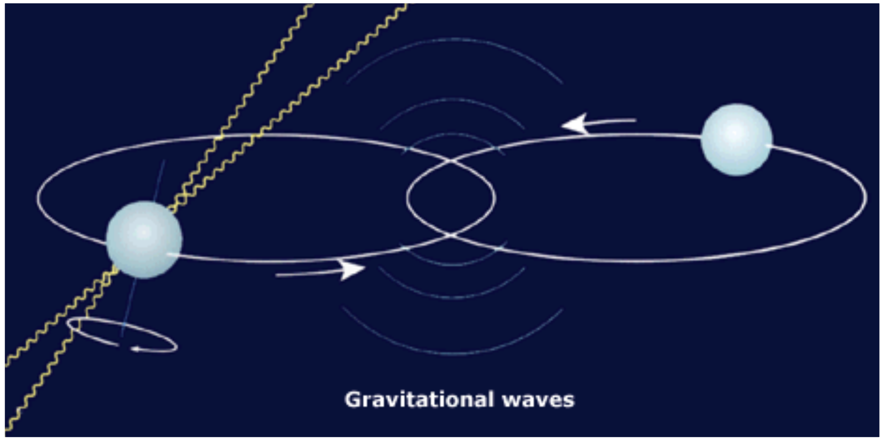
- Tried to retract prediction in 1936!

Indirect Detection

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



for years

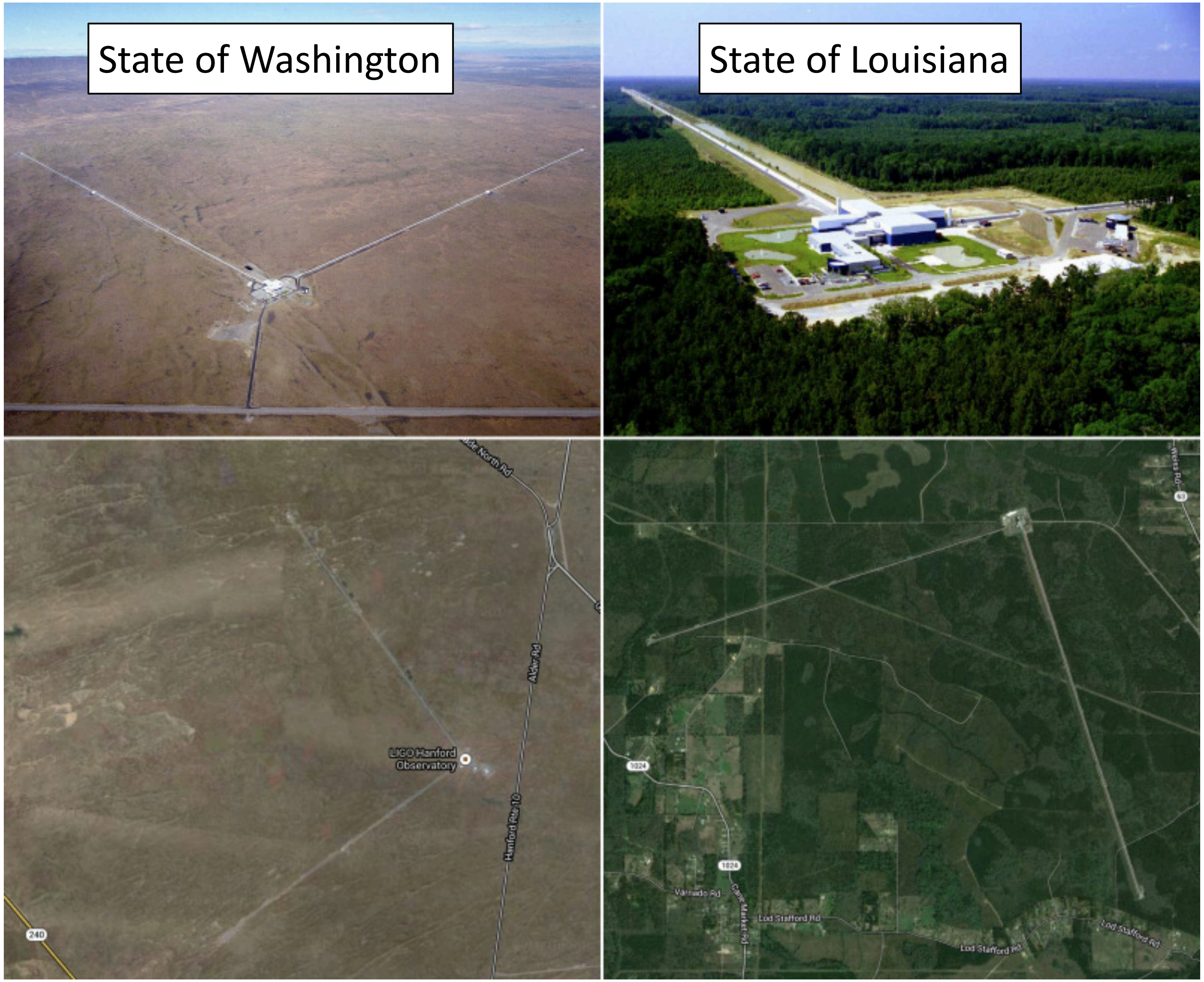


Perfect agreement with Einstein

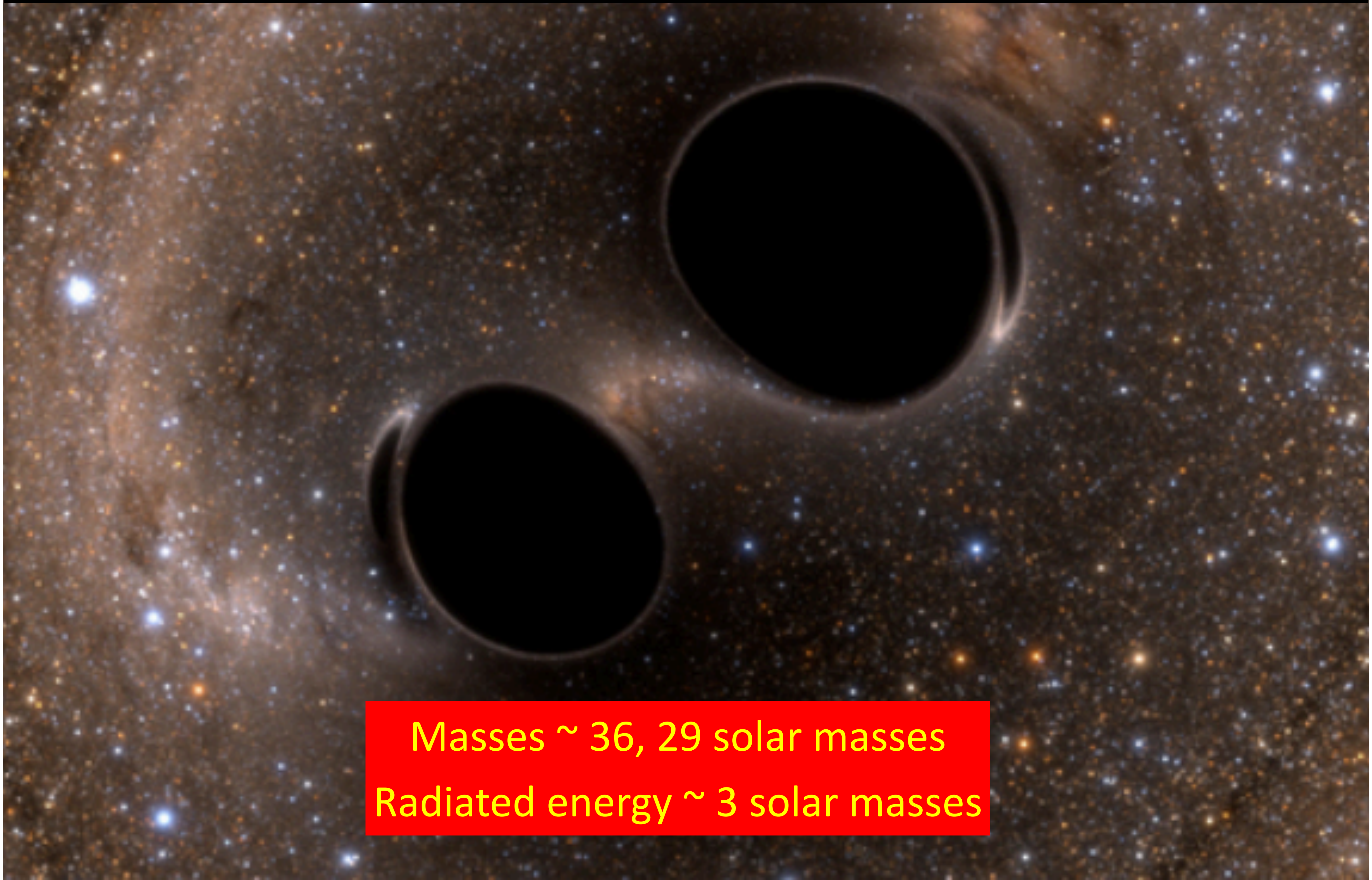
Nobel Prize 1993

Direct Discovery of Gravitational Waves

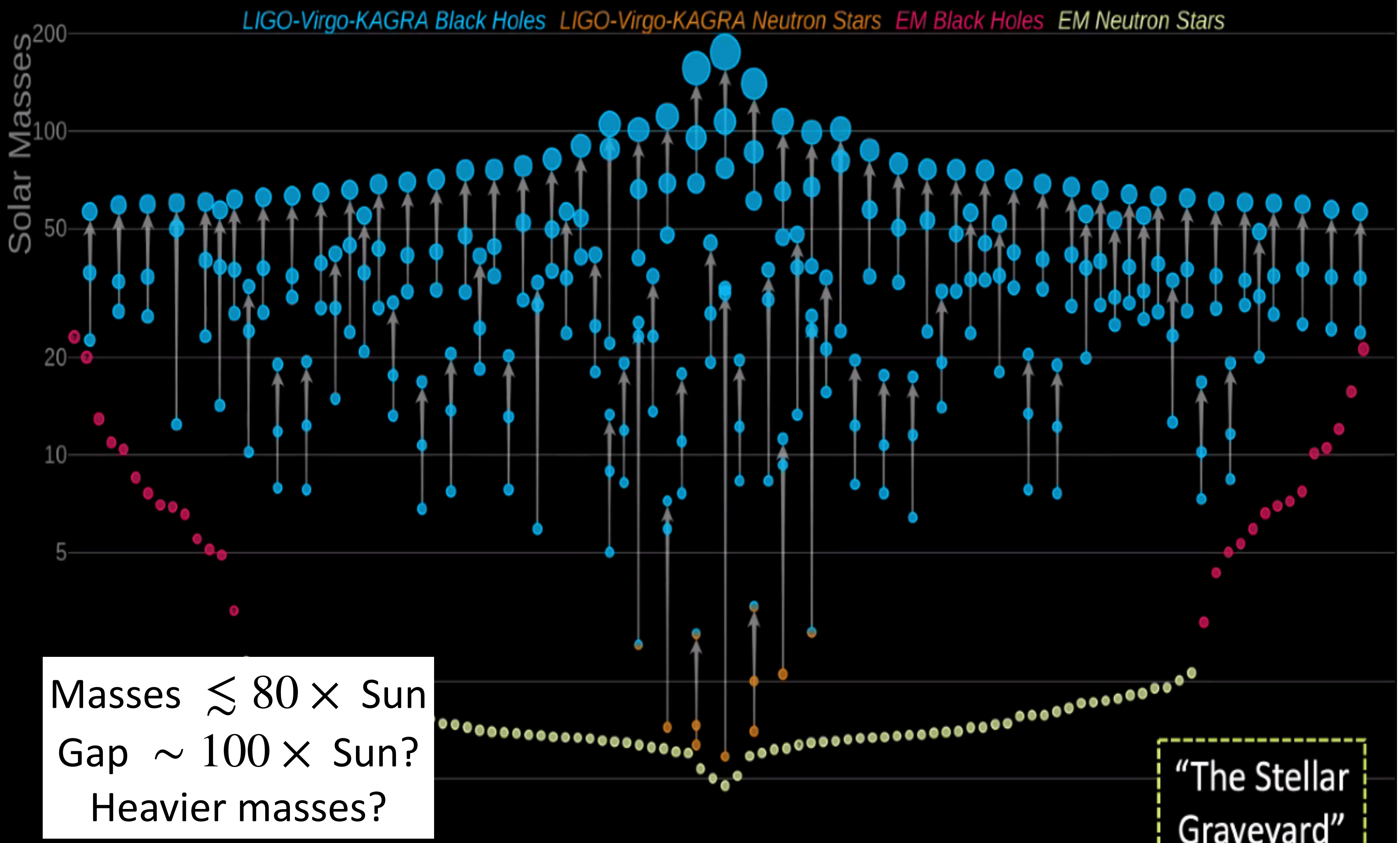
- Measured by the LIGO experiment in 2 locations



Fusion of two massive black holes

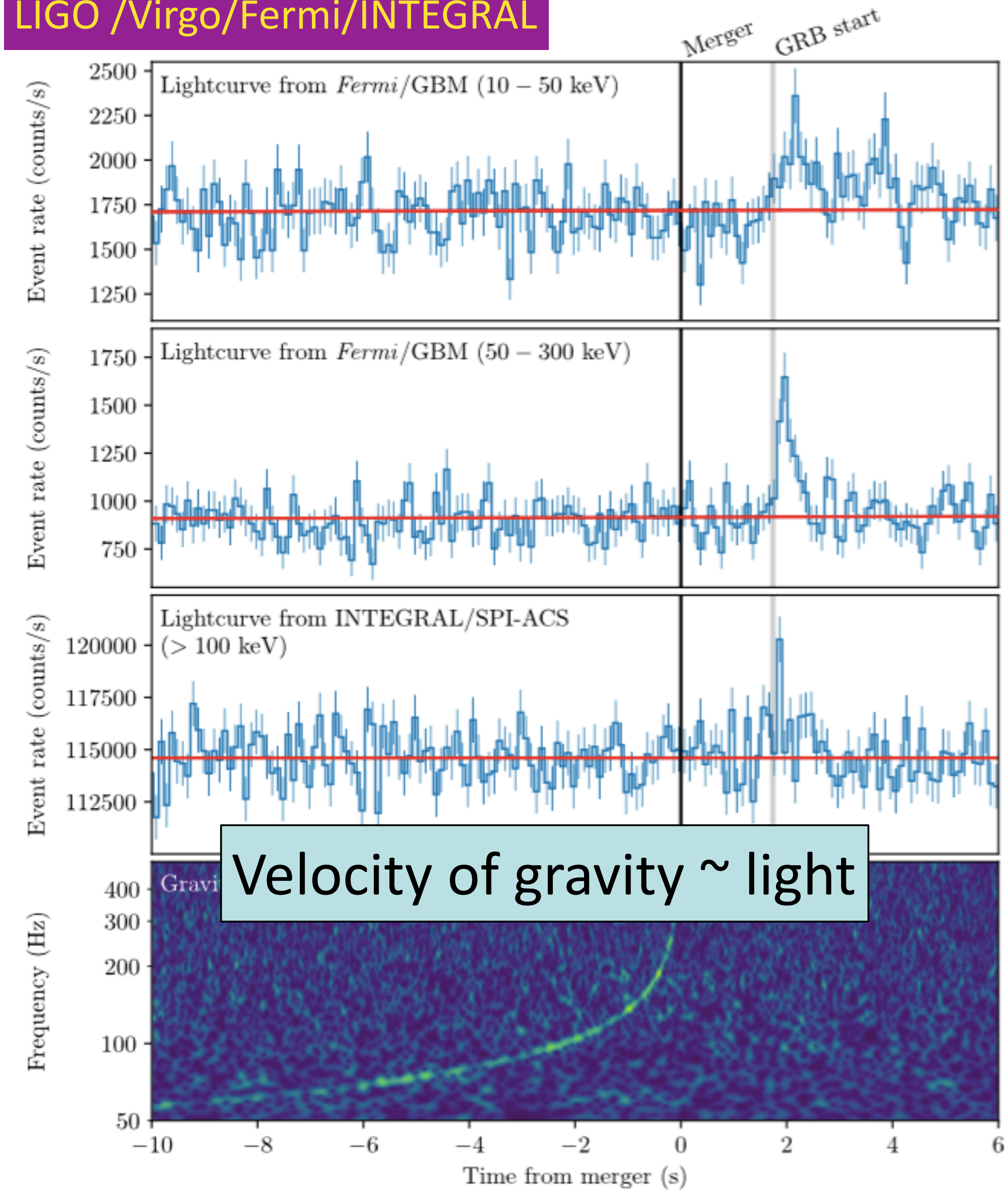


LIGO-Virgo-KAGRA Black Holes & Neutron Stars



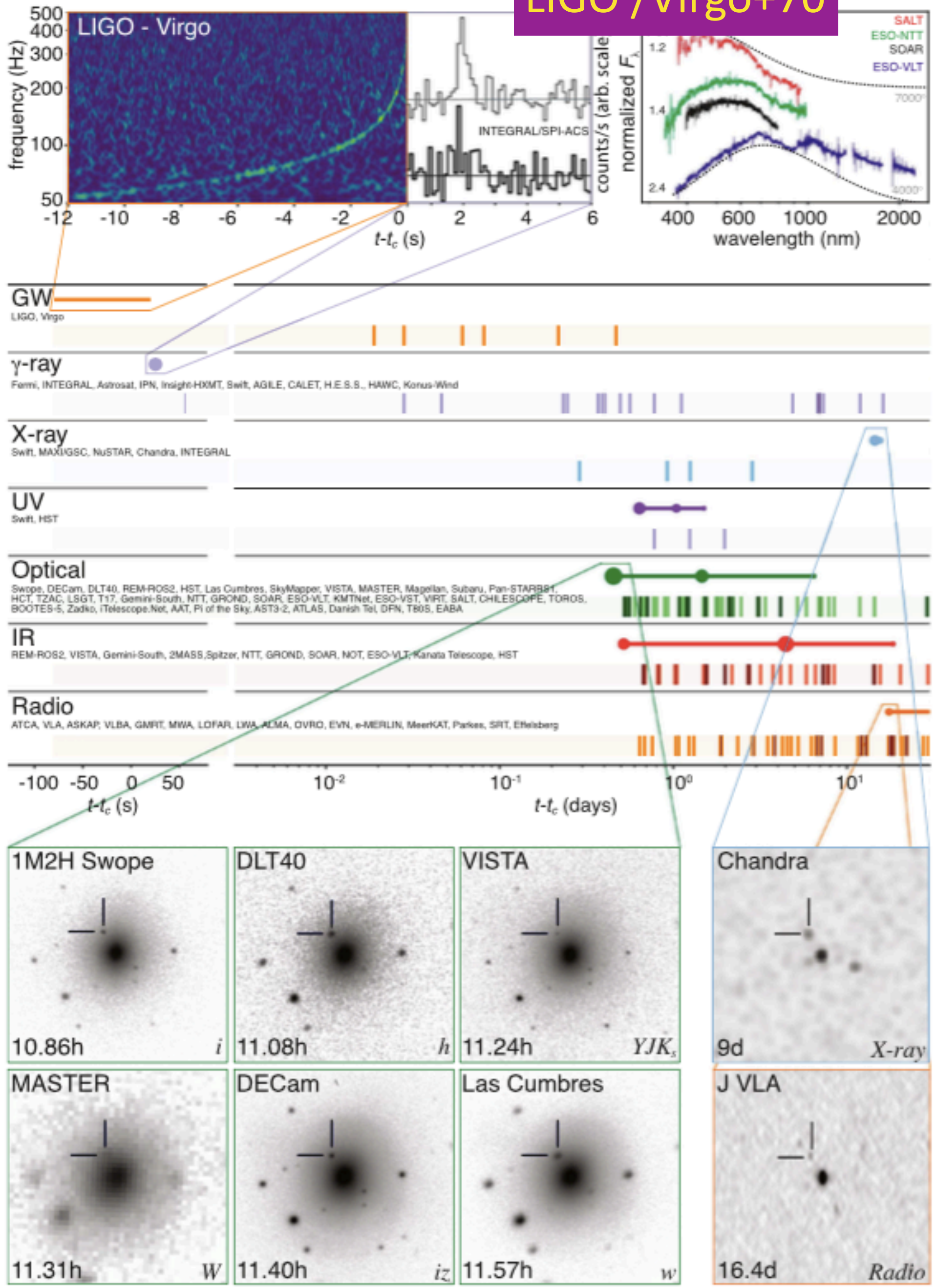
Observations of Neutron Star Merger (Kilonova)

LIGO /Virgo/Fermi/INTEGRAL

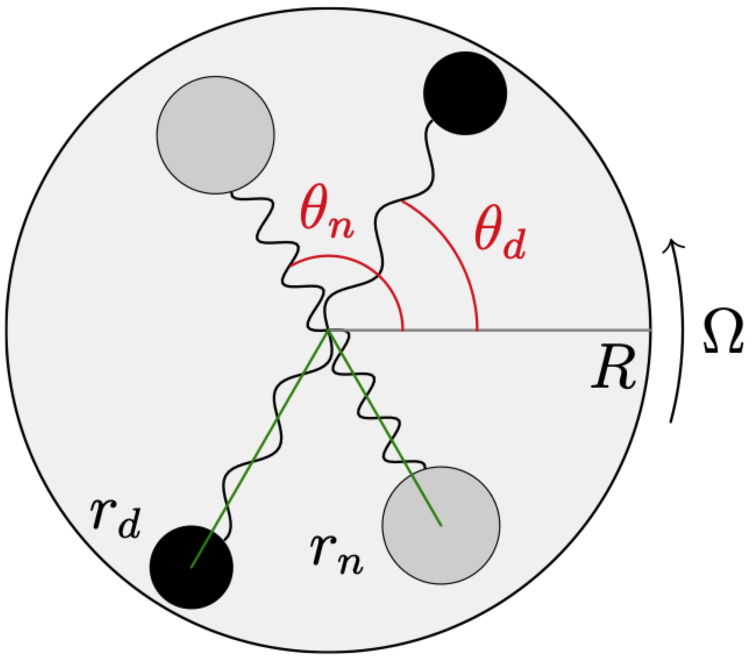


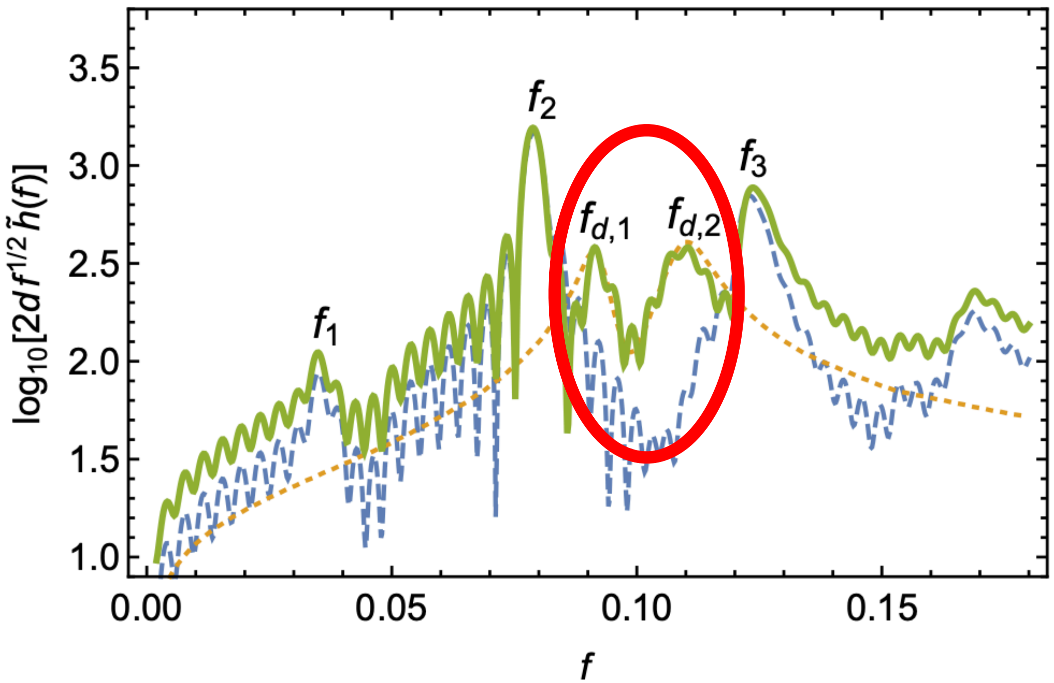
Velocity of gravity ~ light

LIGO /Virgo+70



Dark Matter Effects in Neutron-Star Mergers?

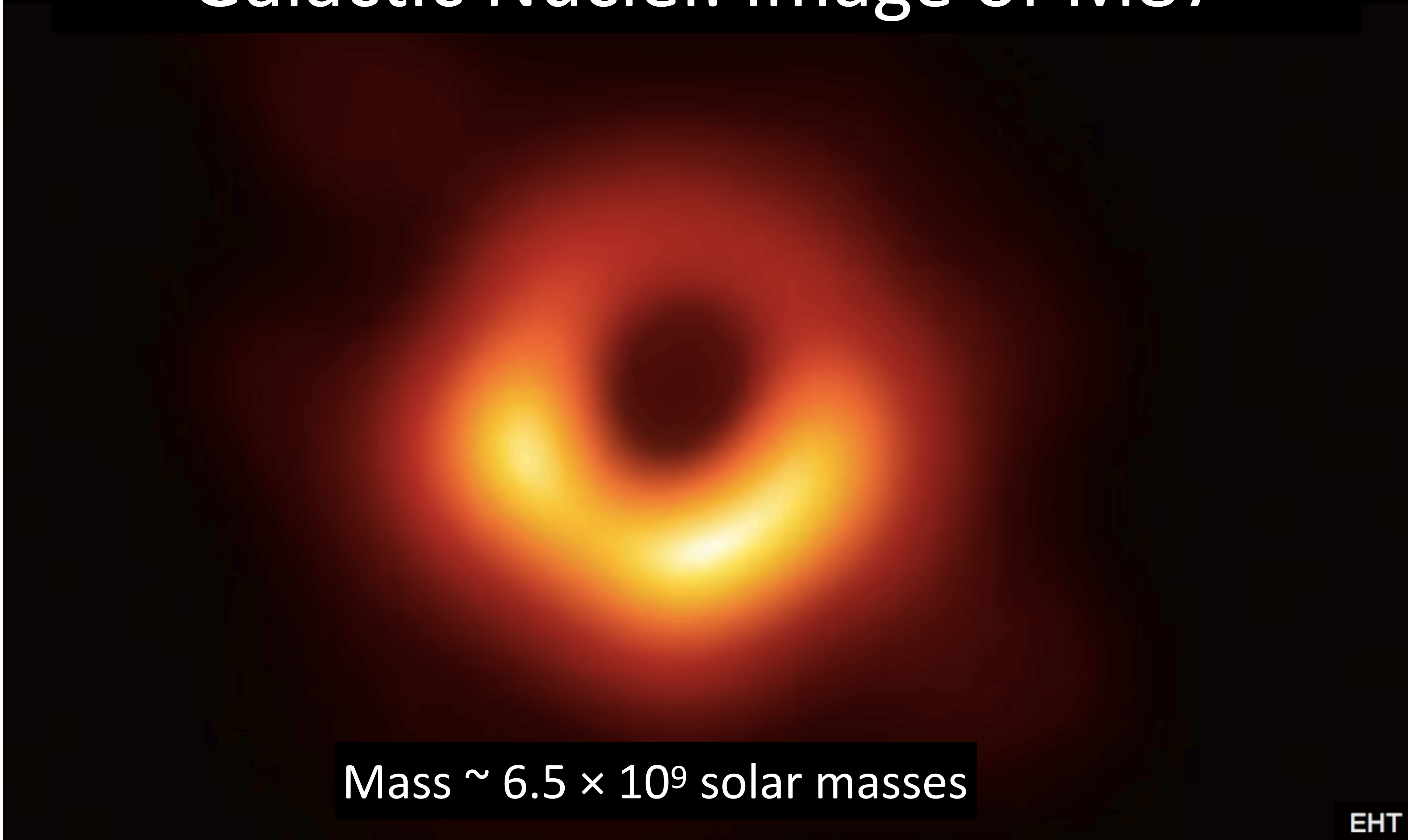




Large DM fraction could give additional feature in GW spectrum & have measurable effect on equation of state

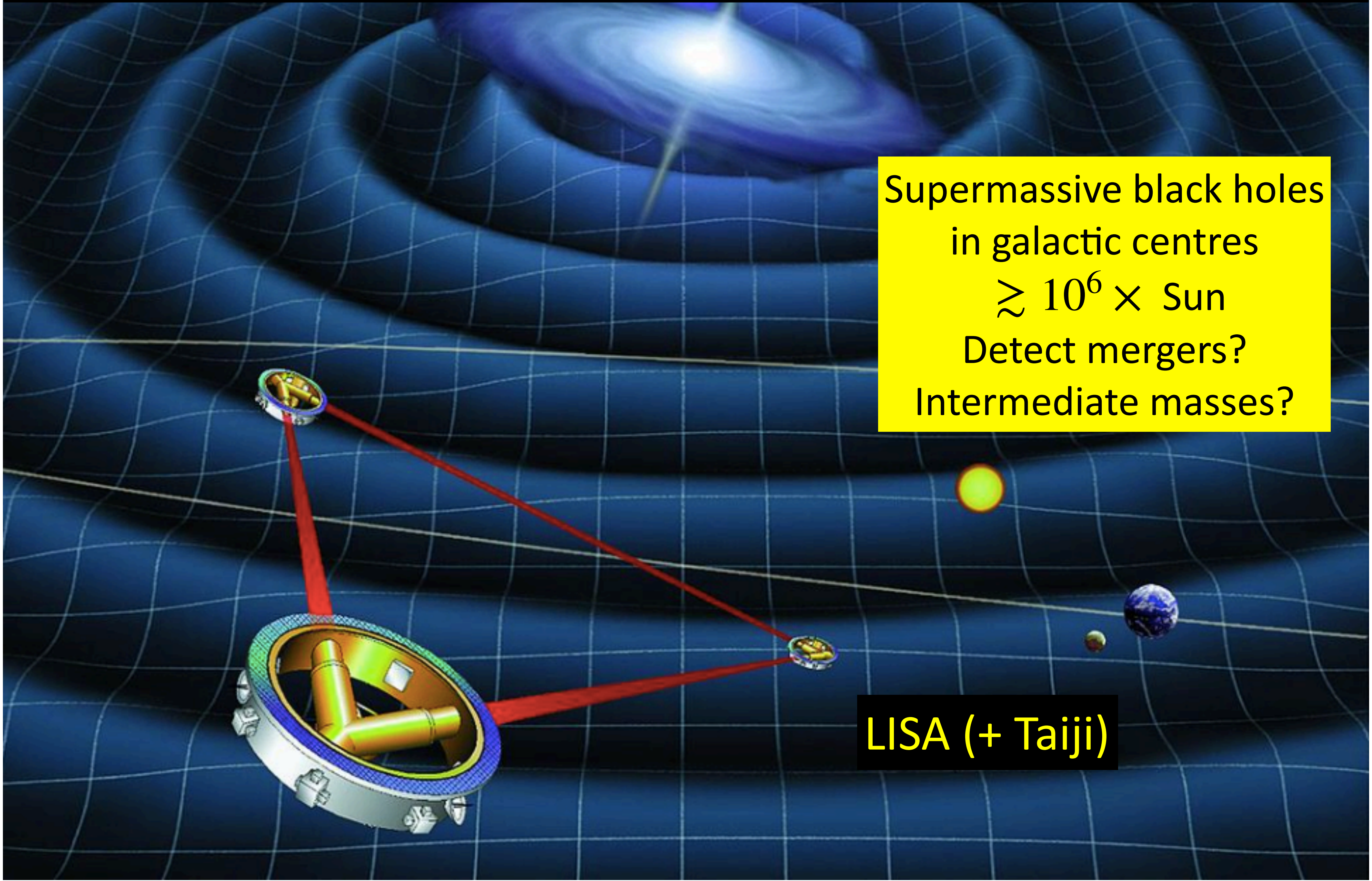
JE, Hektor, Hütsi, Kannike, Marzola, Raidal & Vaskonen: arXiv:1710.05540, arXiv:1804.01418

Supermassive Black Holes in Active Galactic Nuclei: Image of M87

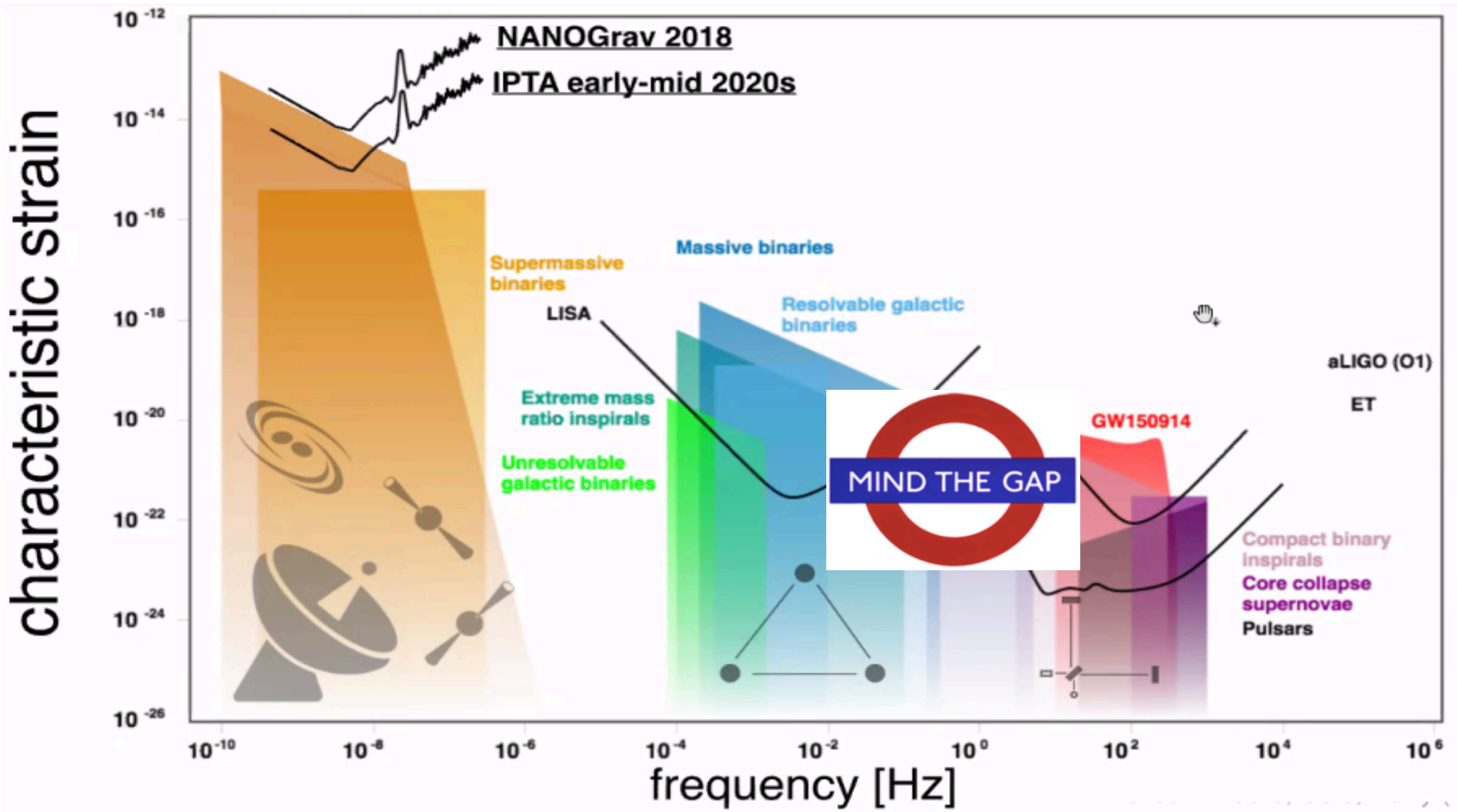


Mass ~ 6.5 × 10^9 solar masses

Future Step: Interferometer in Space



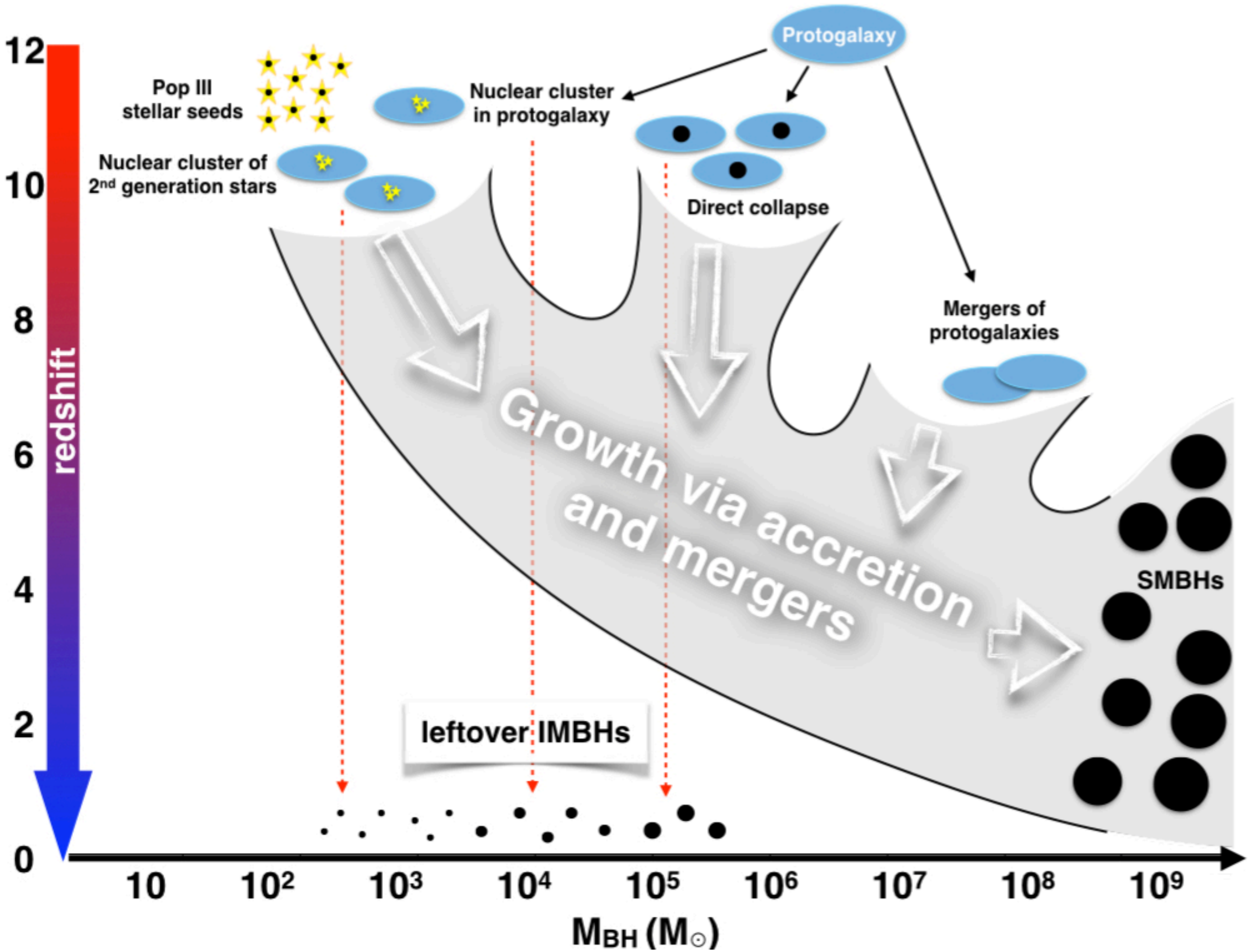
Gravitational Wave Spectrum



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

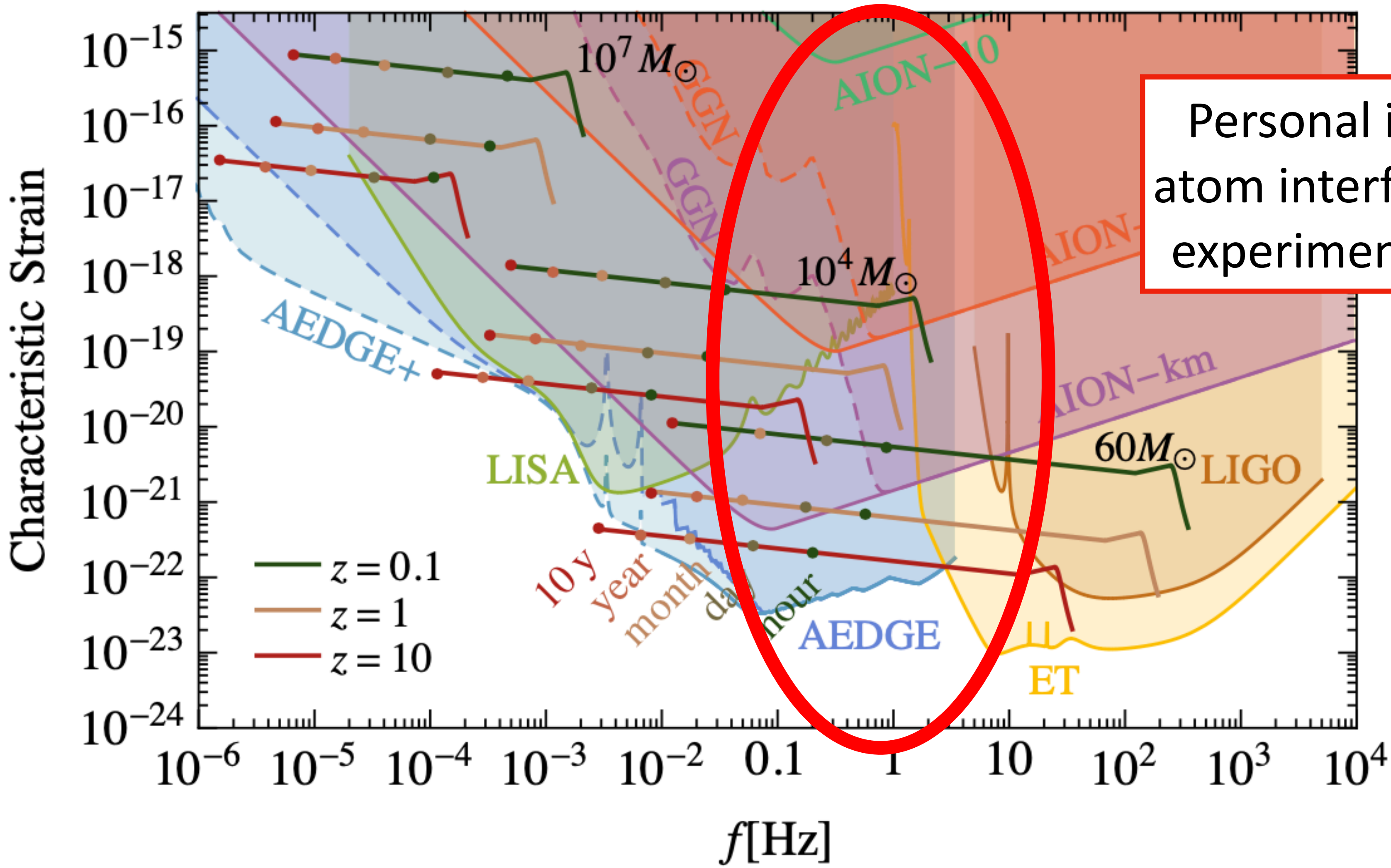
How to Make a Supermassive BH?

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



Gravitational Waves from IMBH Mergers

AION



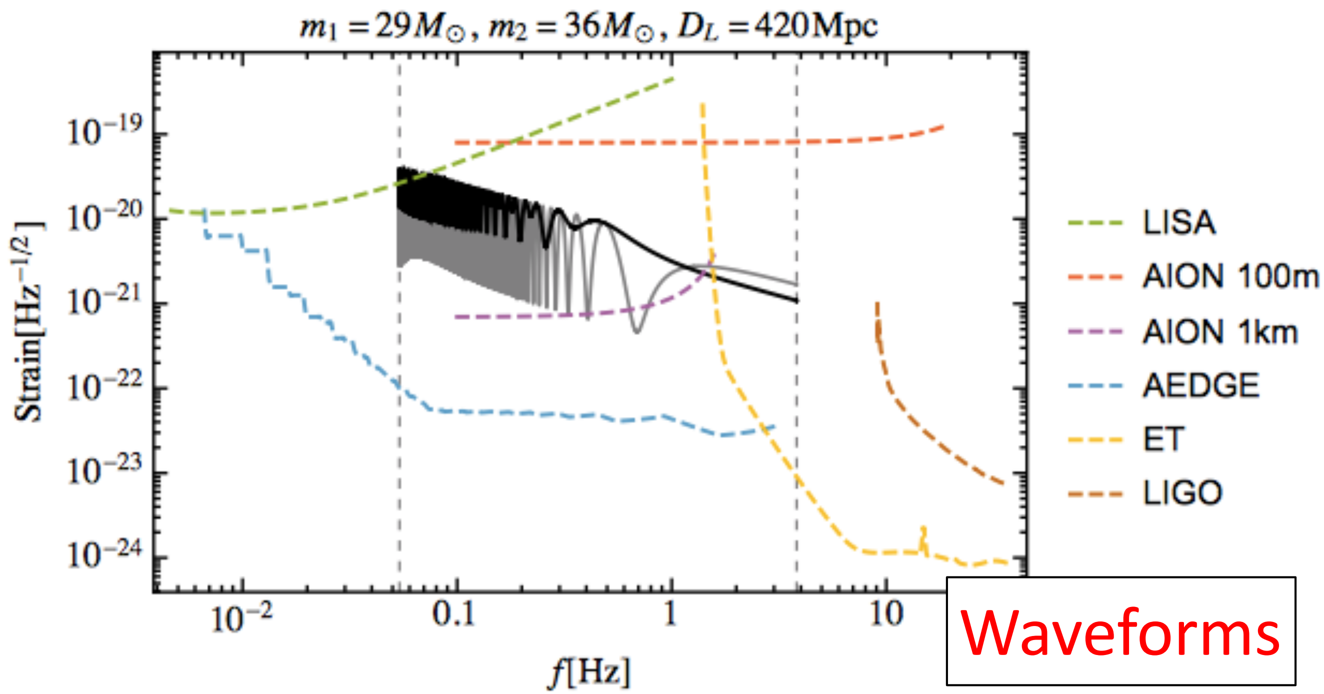
Personal interest: atom interferometer experiments: AION

Probe formation of SMBHs

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

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

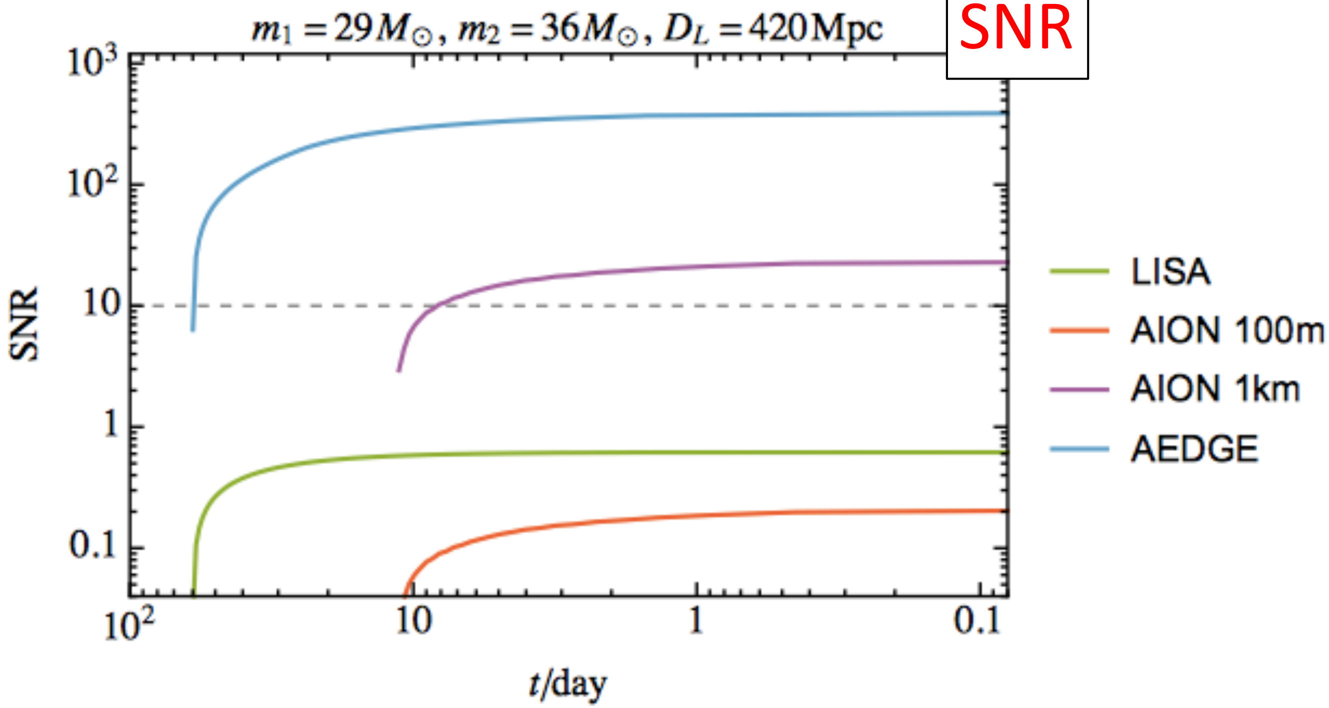
Constraints on Graviton Mass



Waveforms

LIGO/Virgo: arXiv:2010.14529

- Current LIGO/Virgo limit: 1.76 × 10^{-23} eV
- Future sensitivity with LIGO/Virgo-like event?
  Longer observations
- With merger of heavier BHs?
  Lower frequencies

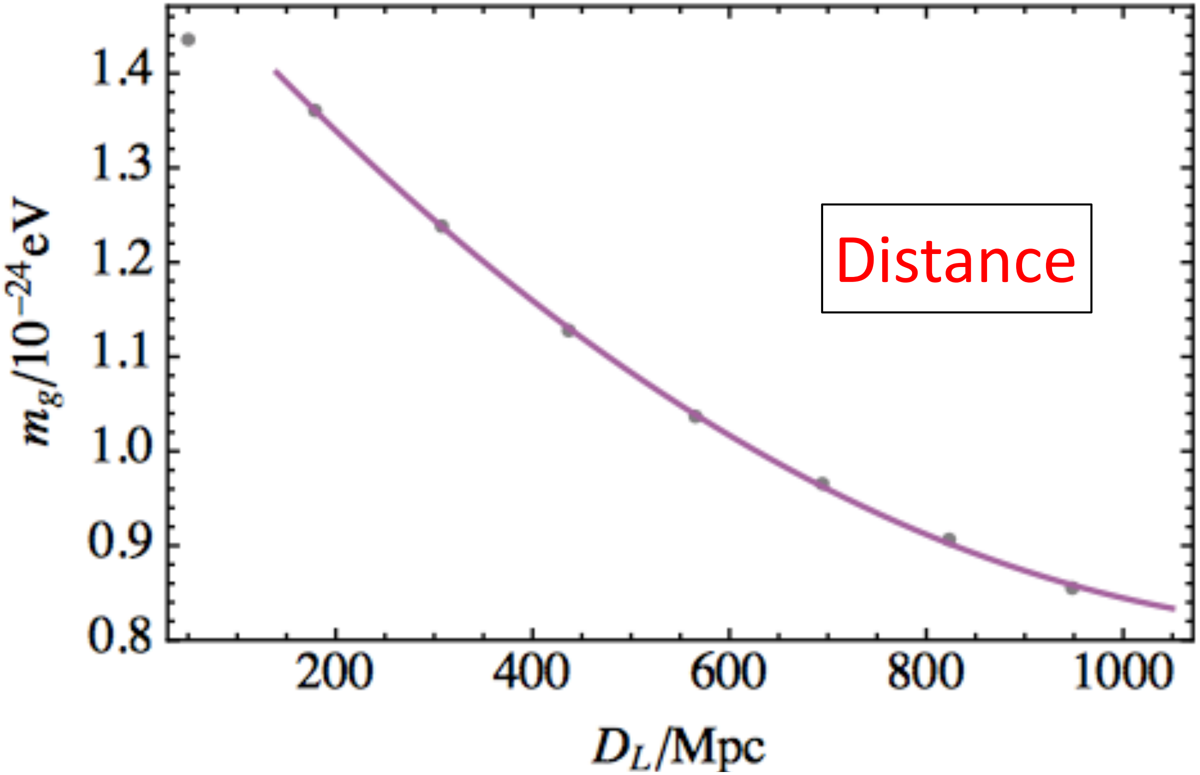


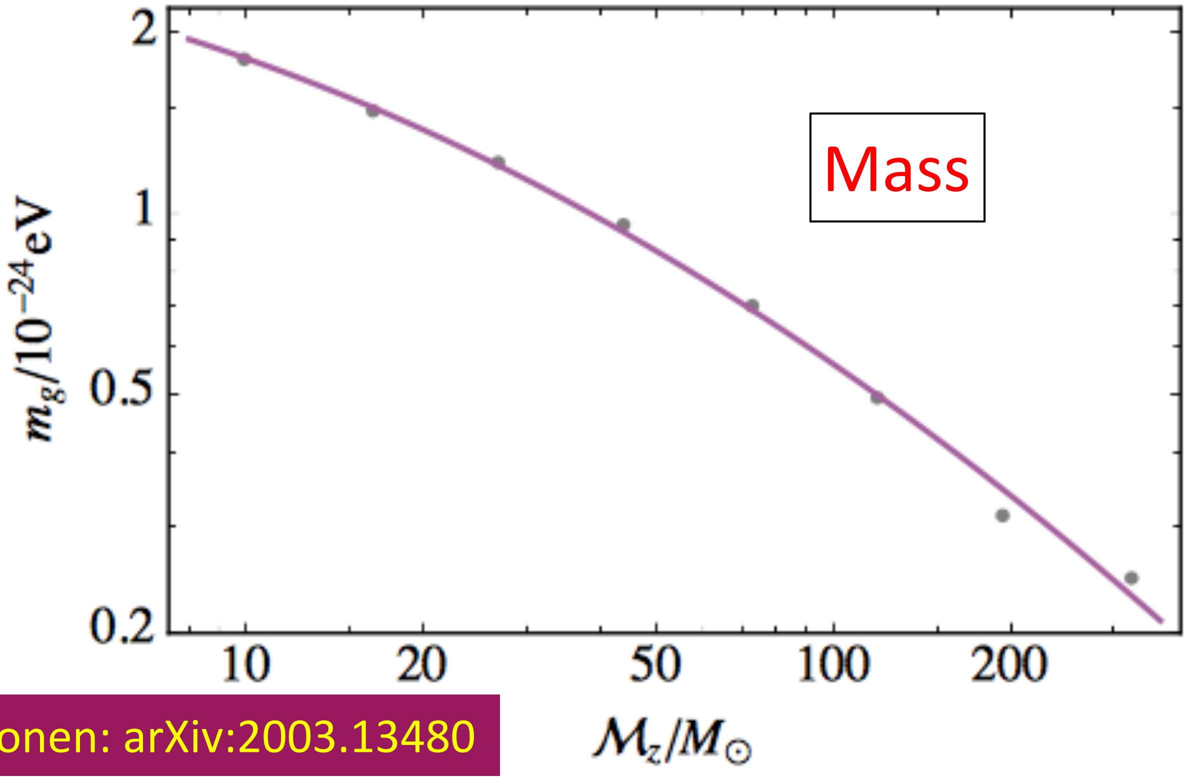
SNR

JE & Vaskonen: arXiv:2003.13480

Constraints on Graviton Mass

- AION 1-km:
- 10^{-24} eV with LIGO/Virgo-like event
- 2×10^{-25} eV with heavier BHs
- AEDGE:
- Order of magnitude more sensitive

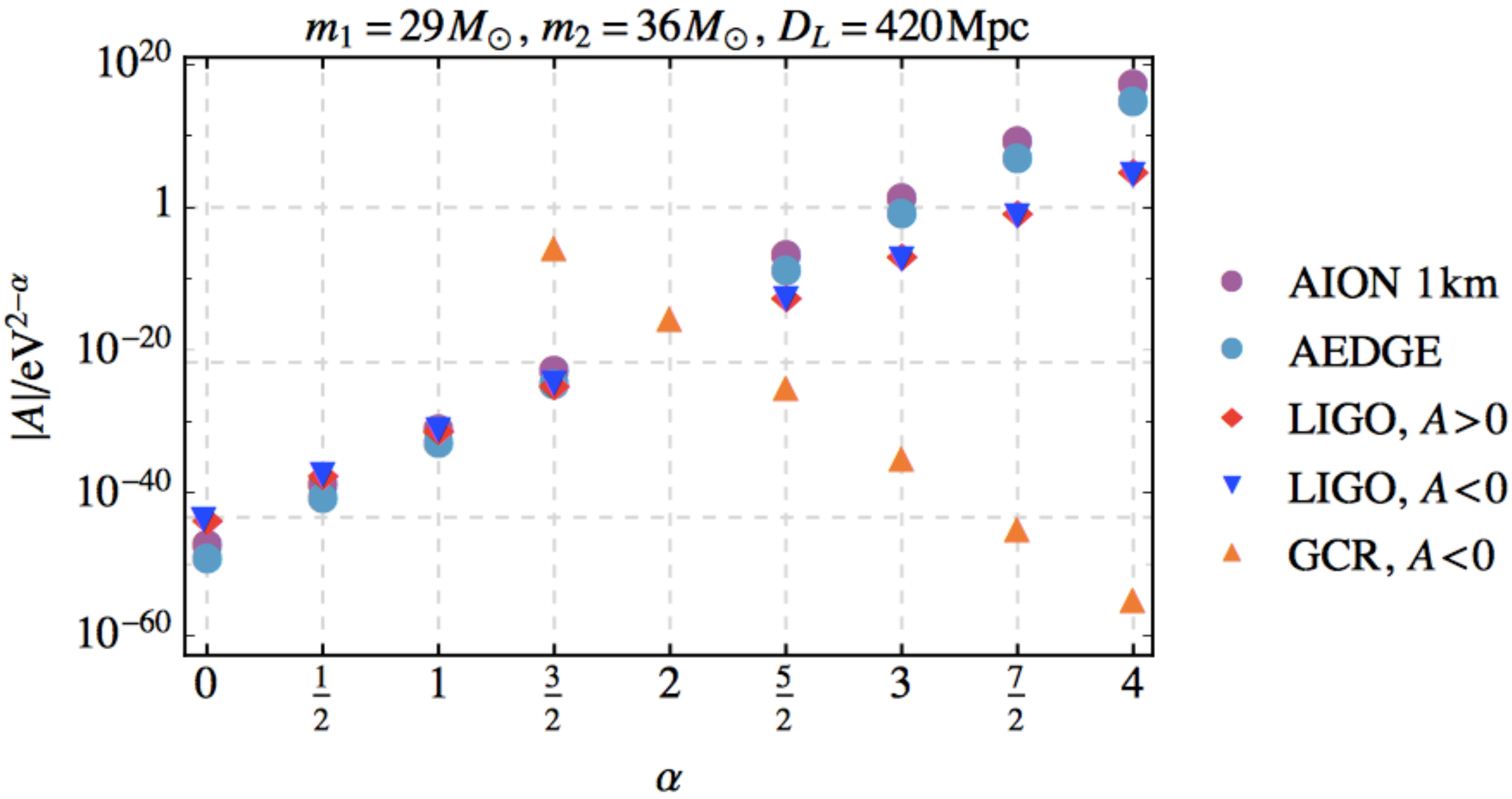




JE & Vaskonen: arXiv:2003.13480

Lorentz Violation

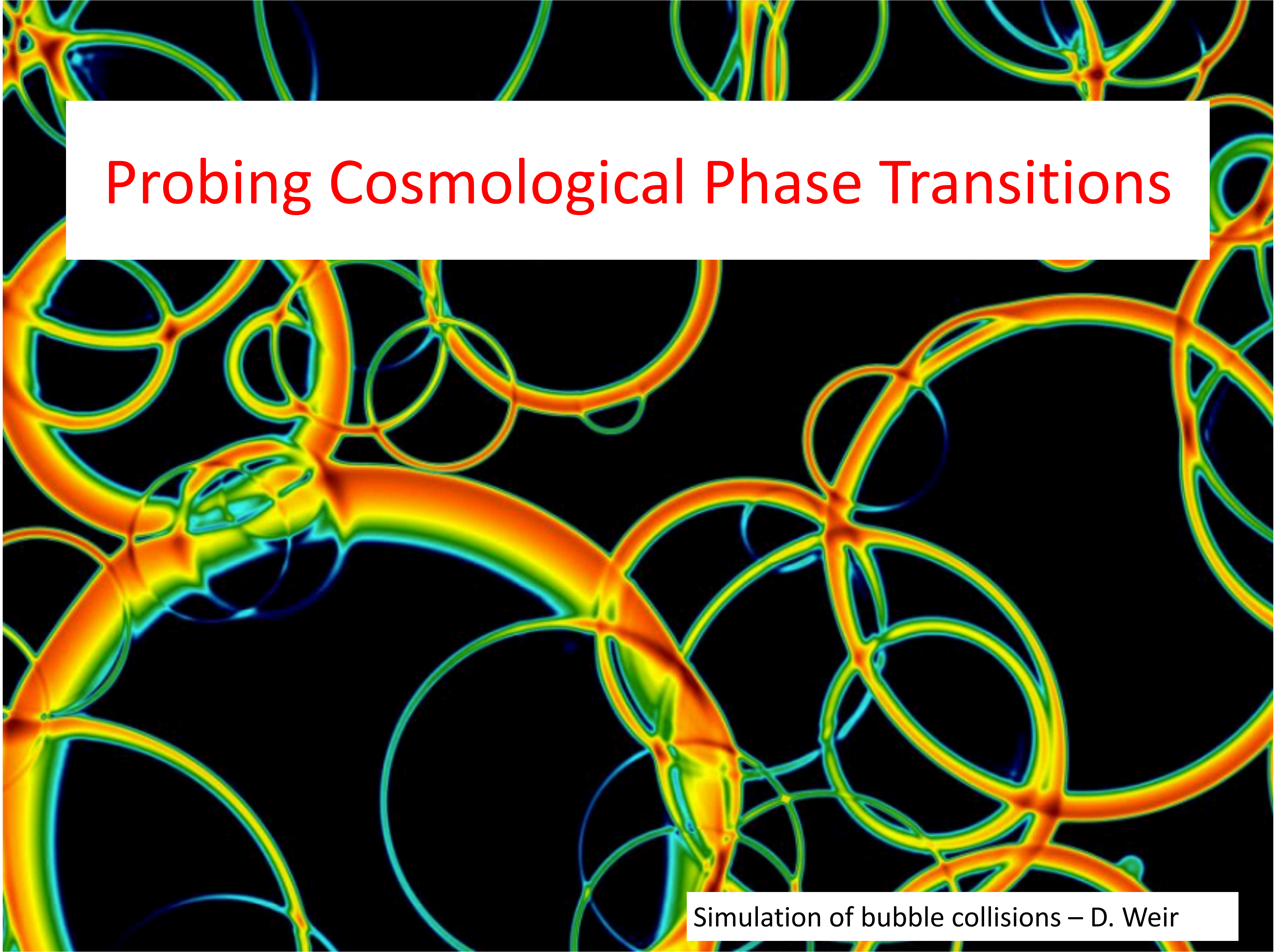
- Modified dispersion relation: $E^2 = p^2 + Ap^\alpha$



- AION 1-km: sensitivity 10 × LIGO/Virgo for α = ½
- AEDGE: sensitivity 1000 × LIGO/Virgo for α = ½

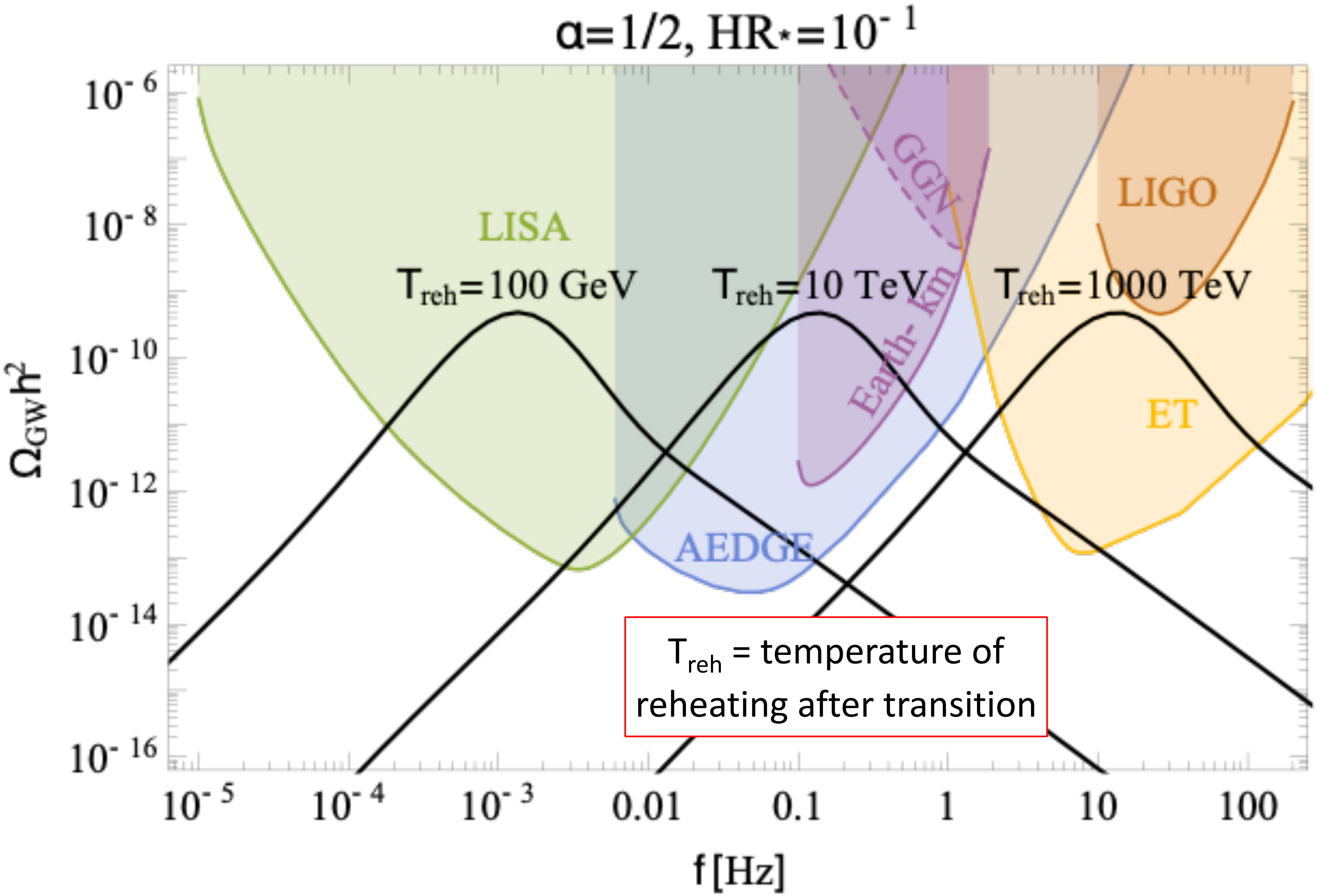
JE & Vaskonen: arXiv:2003.13480

Probing Cosmological Phase Transitions



Simulation of bubble collisions – D. Weir

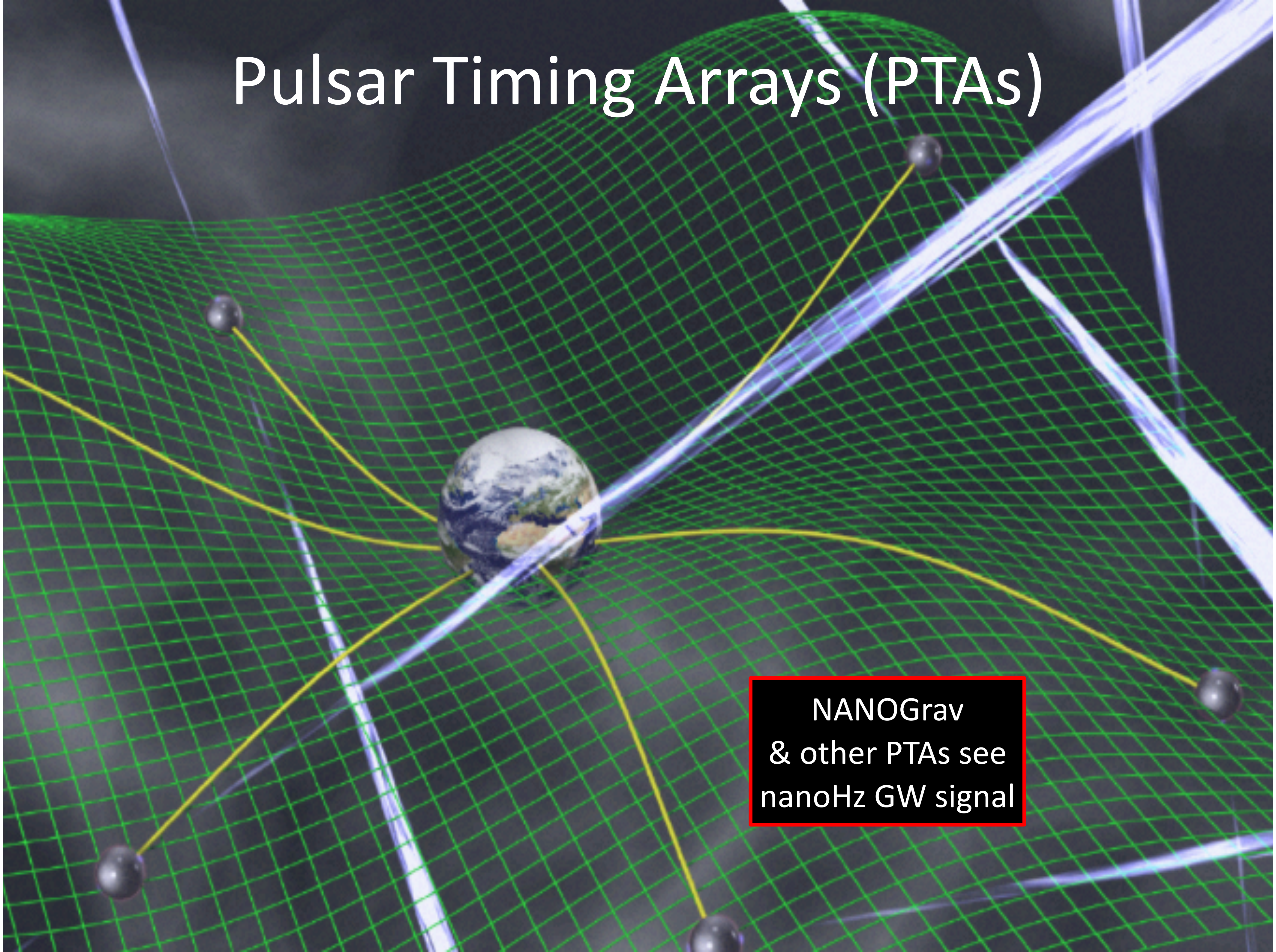
Gravitational Waves from $U(1)_{B-L}$ Phase Transition



T_{reh} = temperature of reheating after transition

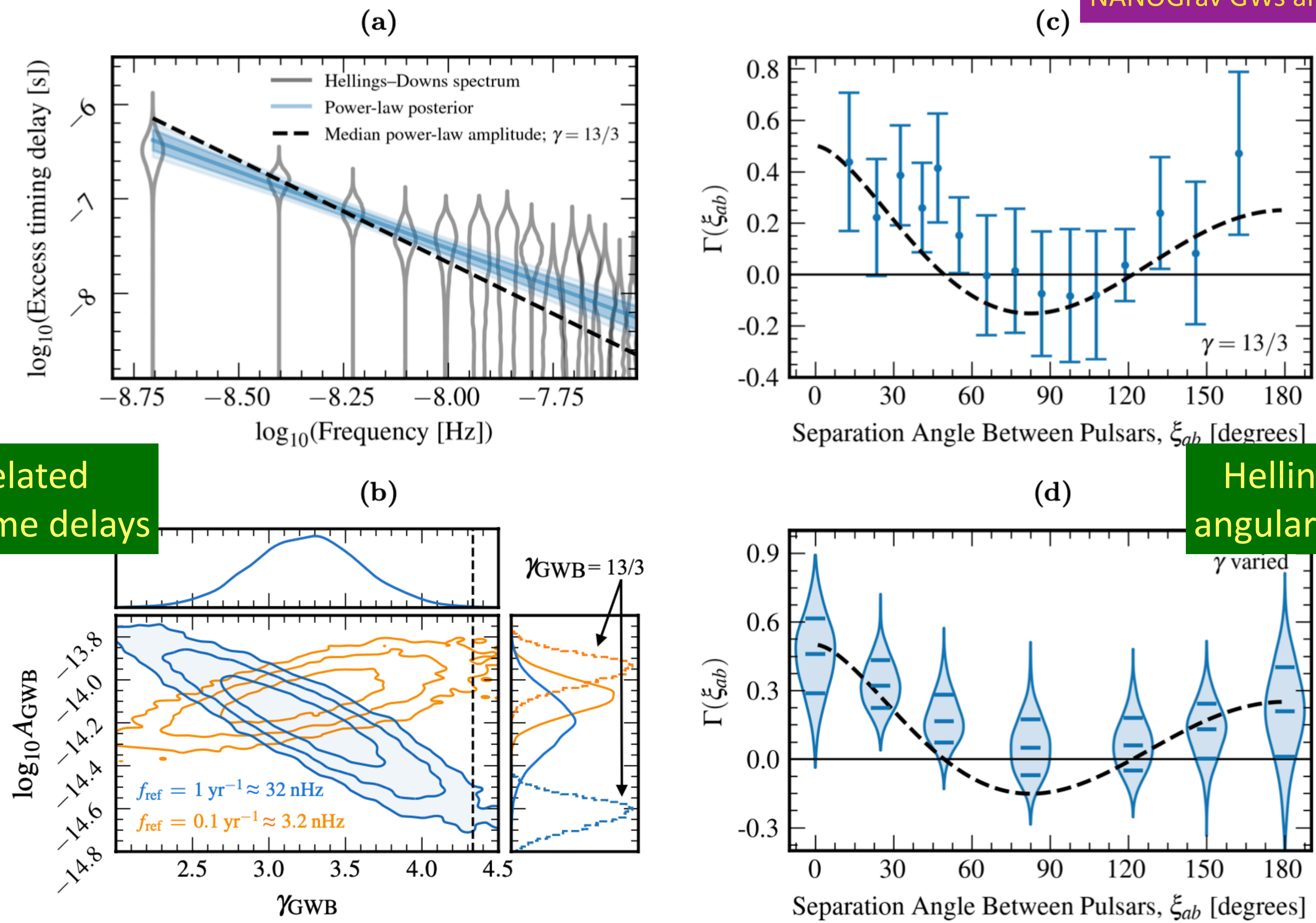
AEDGE: Bertoldi, …, JE et al: arXiv:1908.00802

Pulsar Timing Arrays (PTAs)



NANOGrav 15-Year Data

NANOGrav GWs arXiv:2306.16213

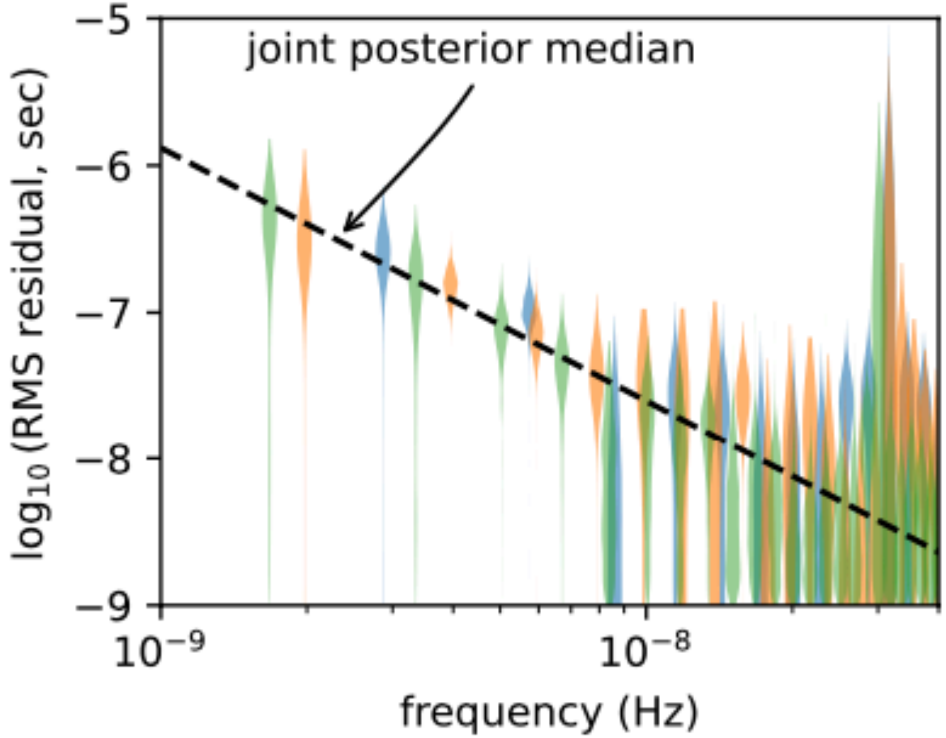


Correlated pulsar time delays

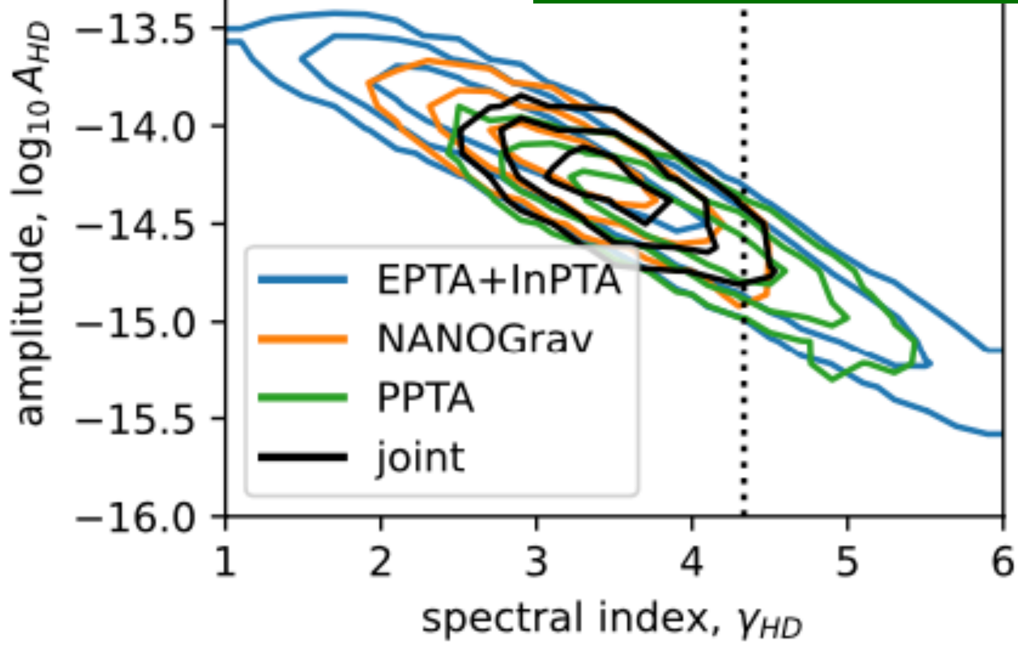
Hellings-Downs angular correlation

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

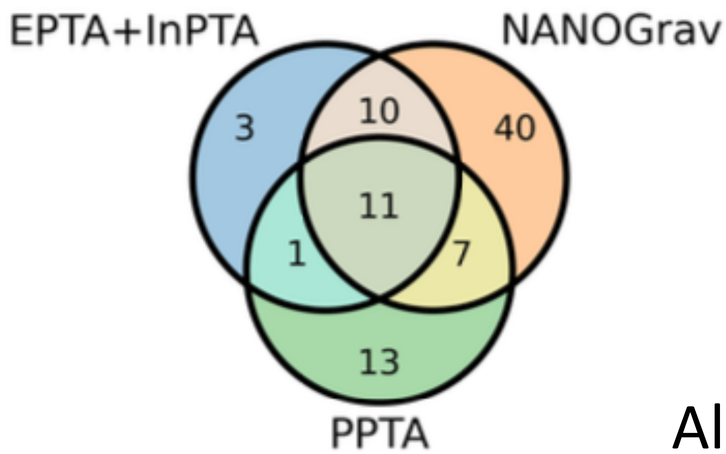
IPTA Data Compilation



Assuming Hellings-Downs angular correlation



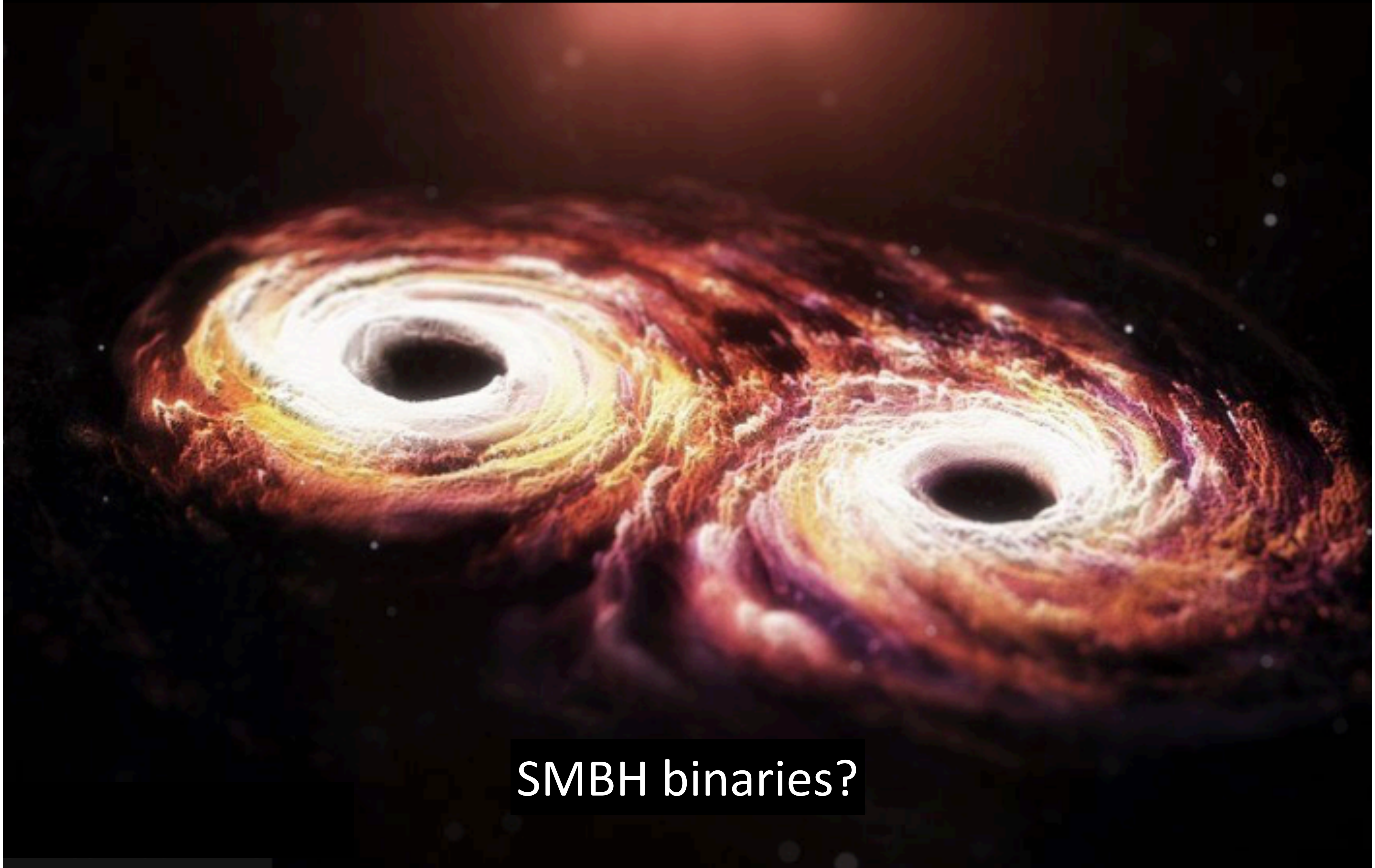
Venn diagram of PTA data sets



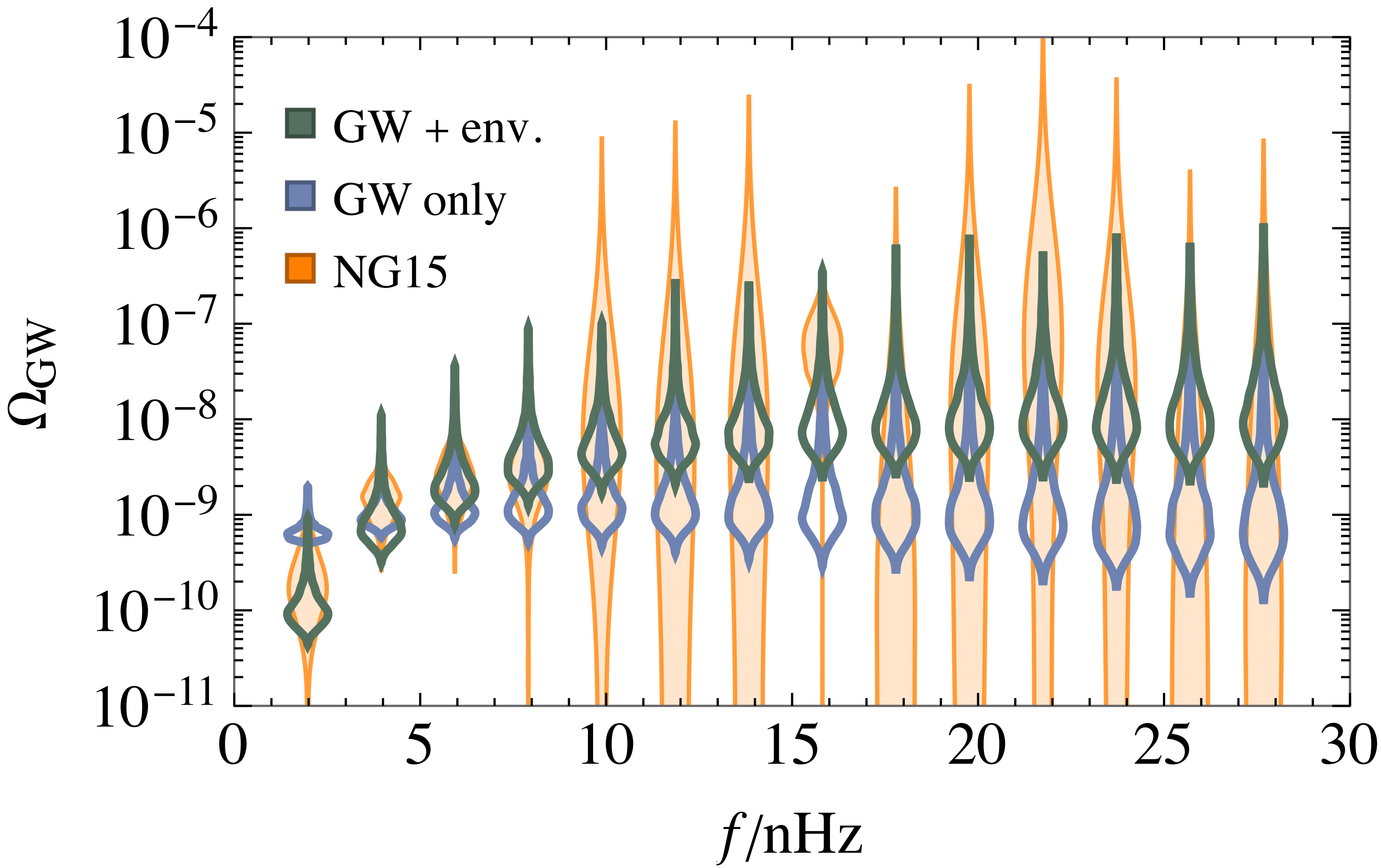
IPTA Collaboration, arXiv:2309.00693

Also Chinese PTA

The Biggest Bangs since the Big Bang?



Astrophysical Interpretations AION

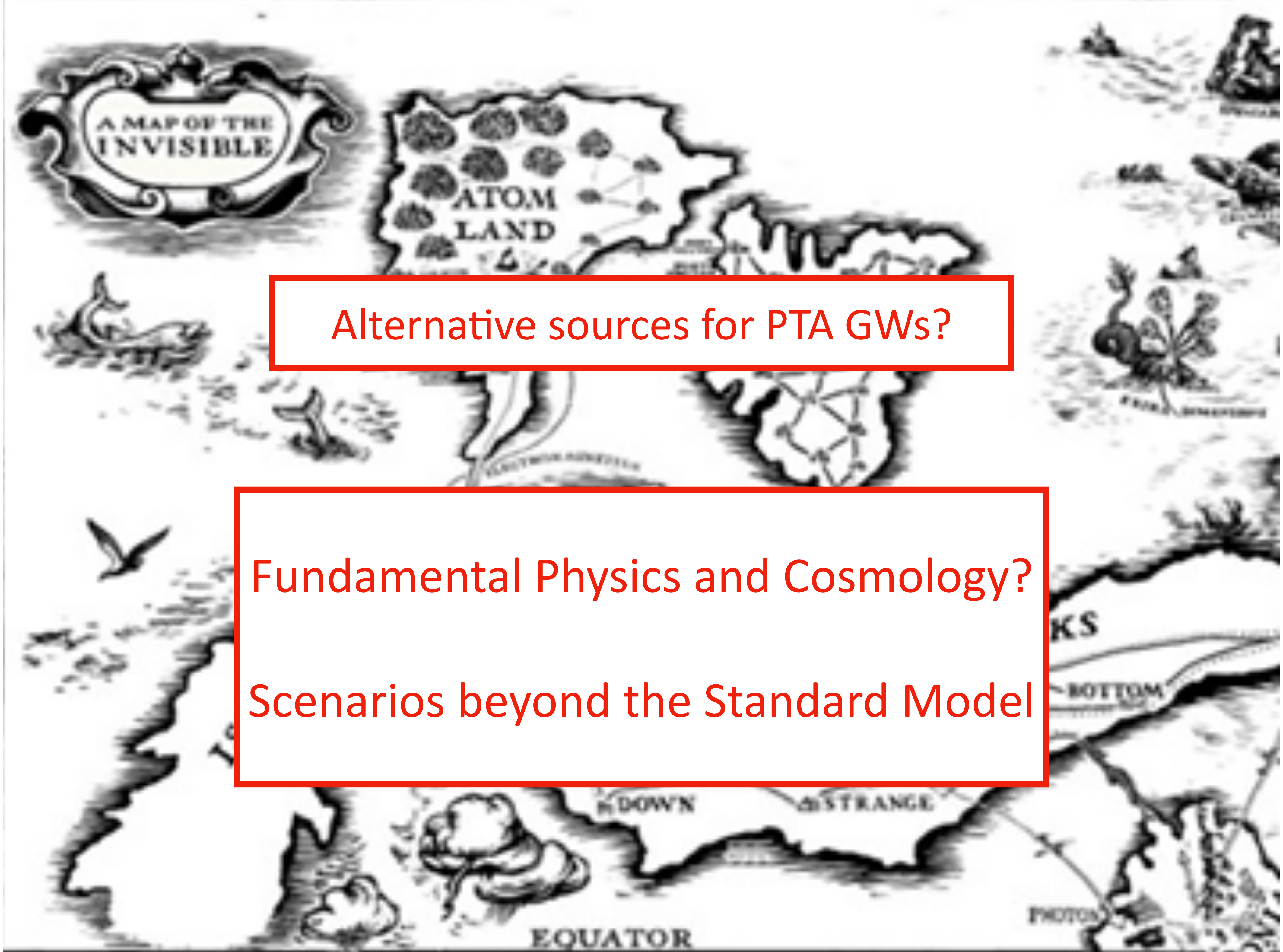


Fits use overlaps of data and model violins in each bin

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

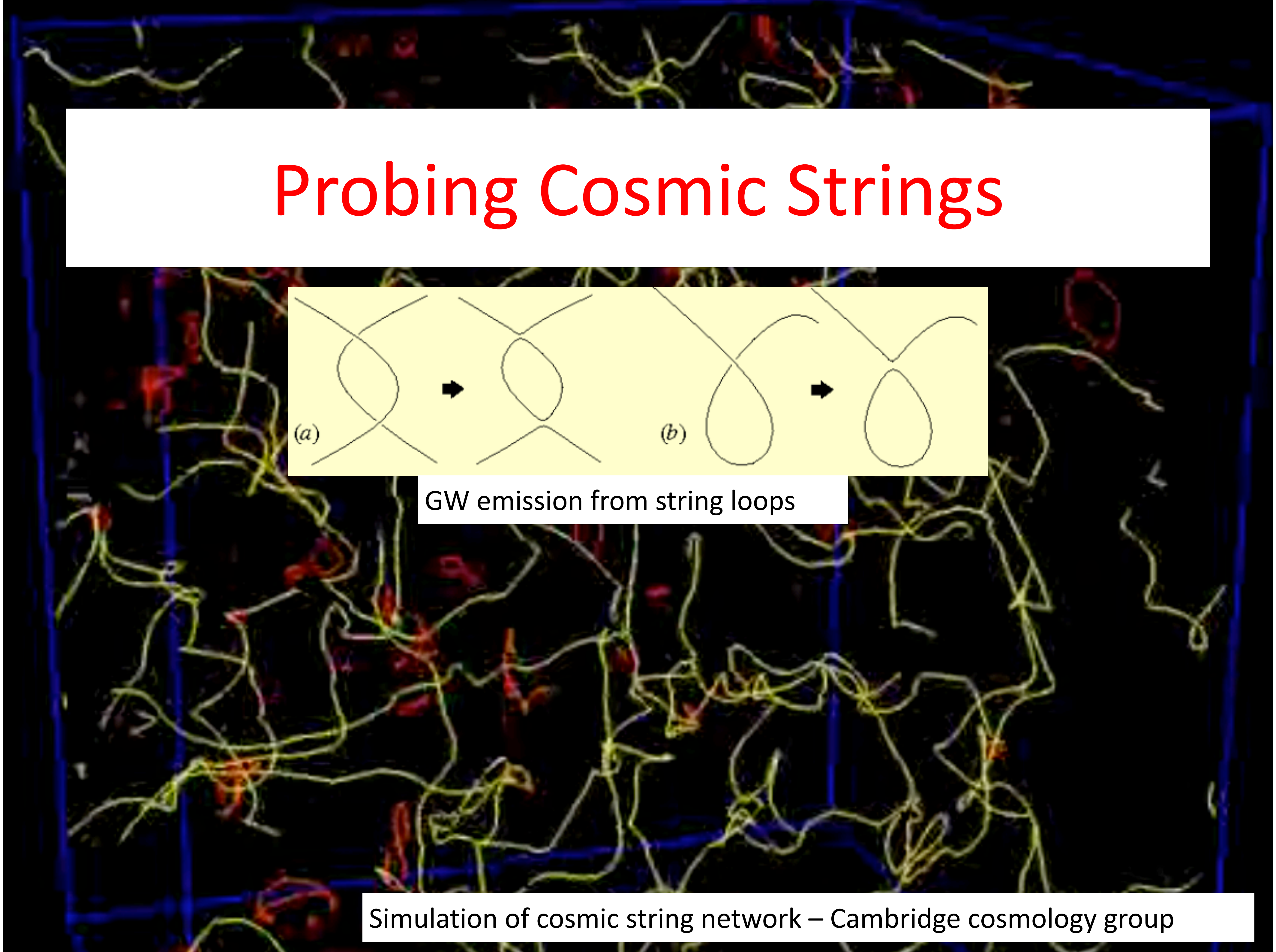


Alternative sources for PTA GWs?

Fundamental Physics and Cosmology?

Scenarios beyond the Standard Model

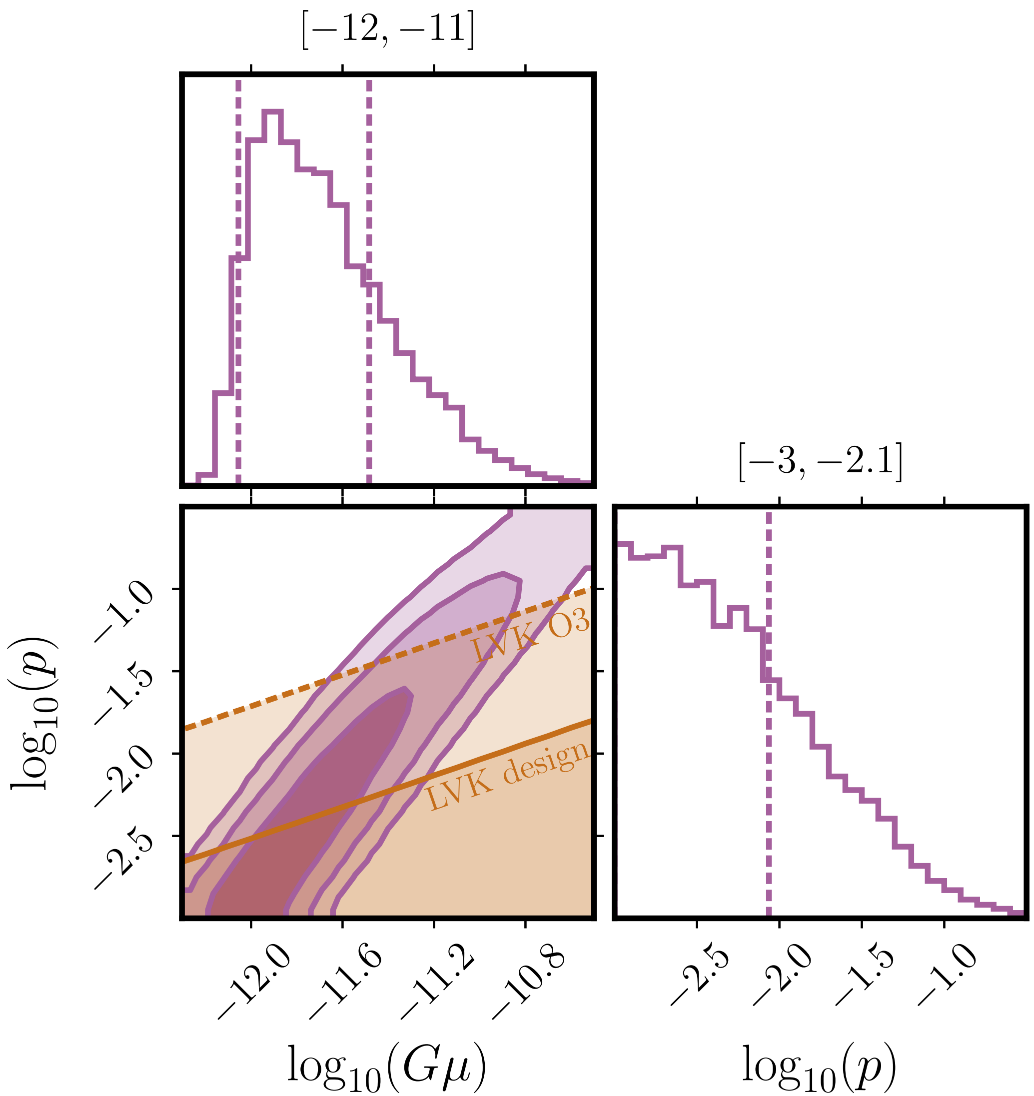
Probing Cosmic Strings



GW emission from string loops

Simulation of cosmic string network – Cambridge cosmology group

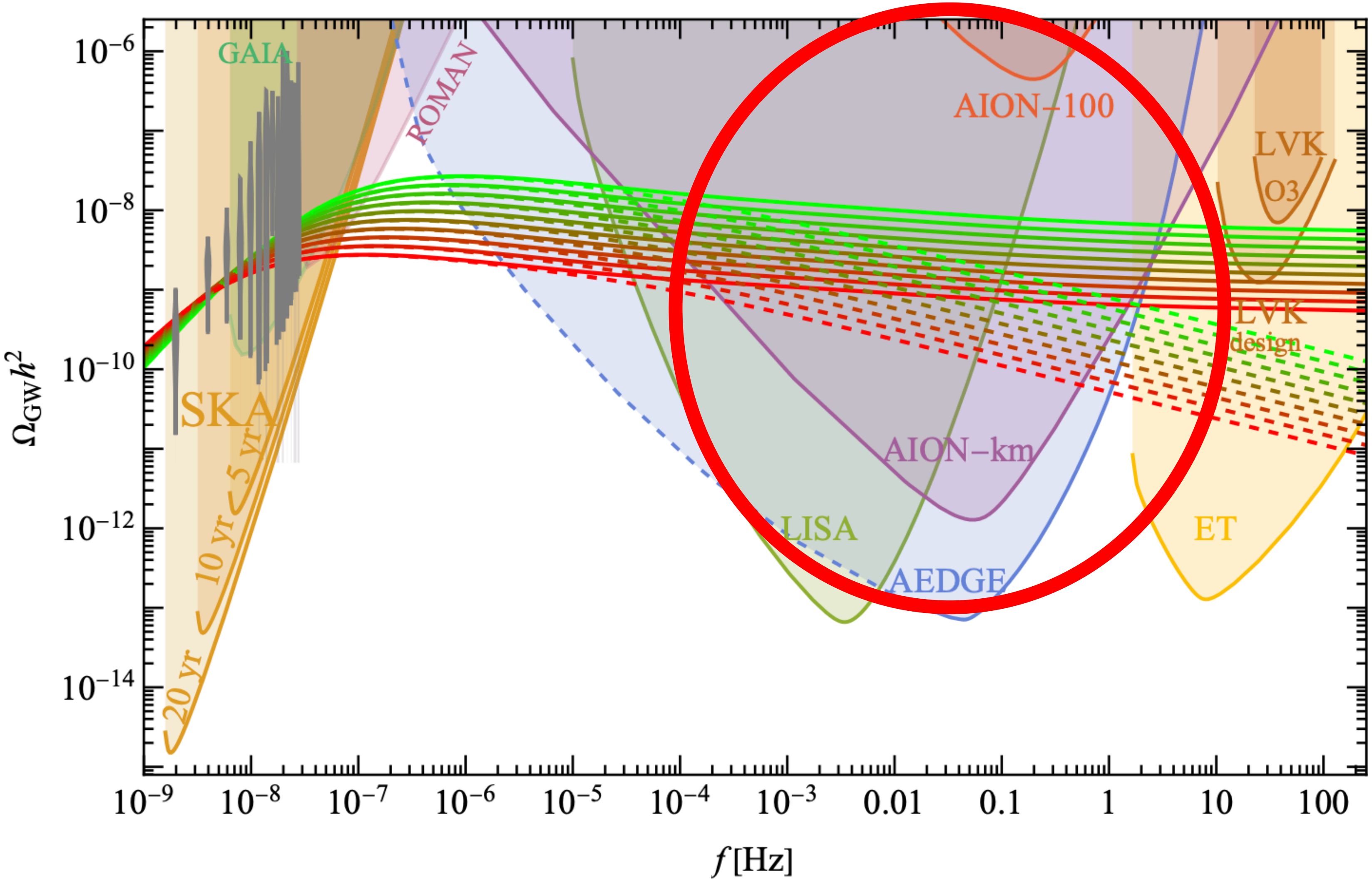
Superstring Fit to NANOGrav



(Super)string model compatible with LVK for string tension $G\mu \sim 10^{-12} - 10^{-11}$, intercommutation probability $p \sim 0.001 - 0.01$

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

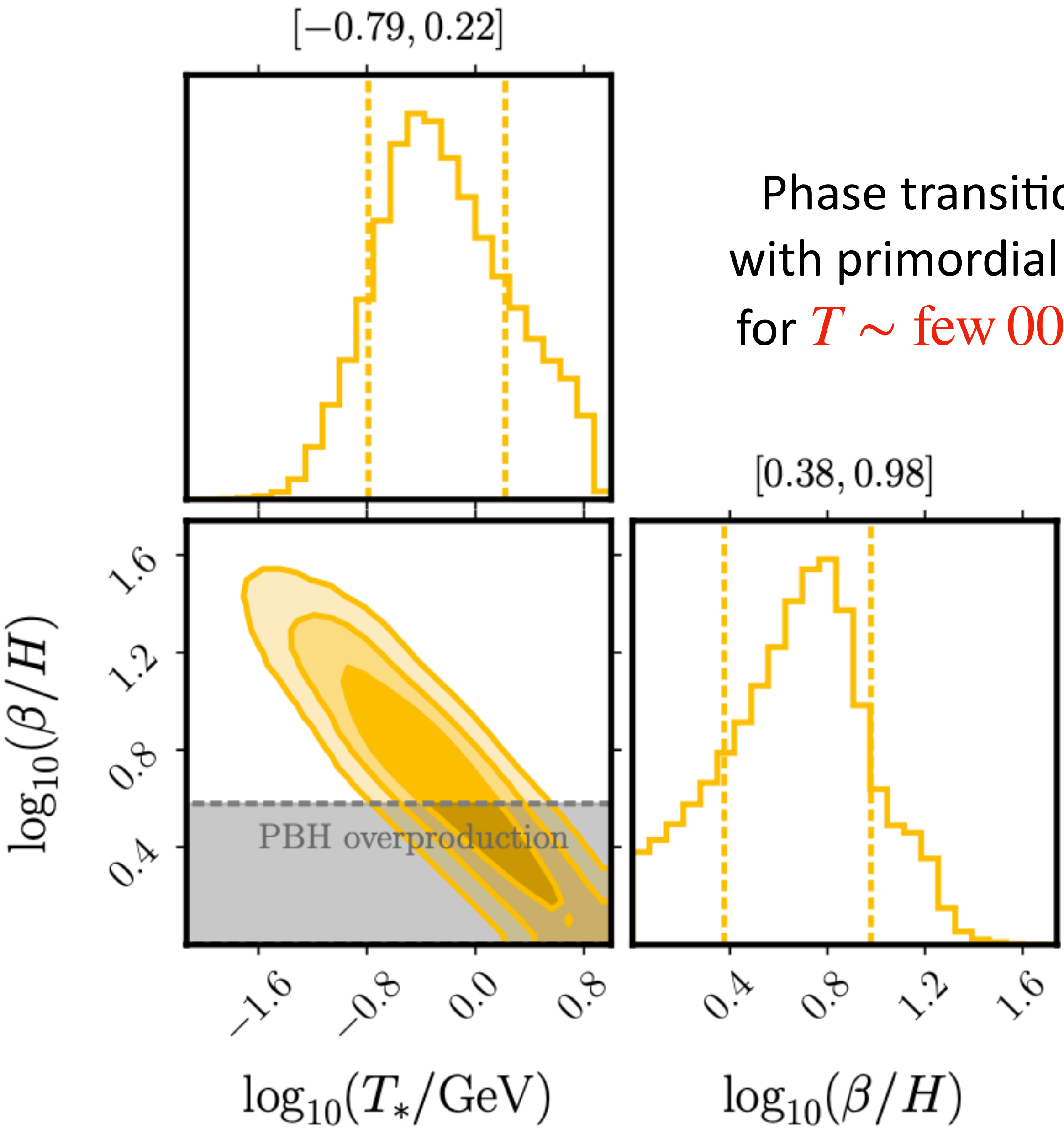
Effect of Matter Domination



Late period of matter domination could push superstrings beyond LVK, but still detectable by LISA, AION/AEDGE, ET

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

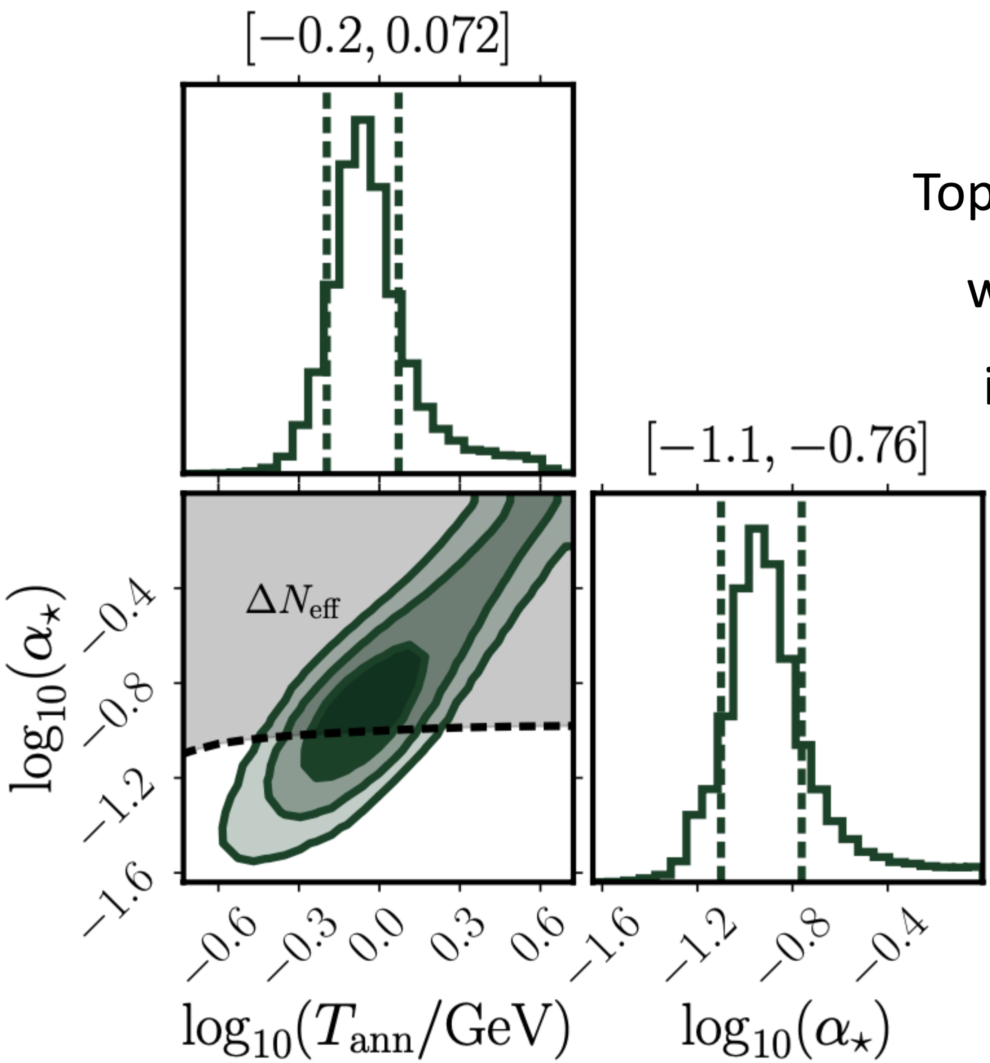
Phase Transition Fit to NANOGrav



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

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

Domain Wall Fit to NANOGrav AION

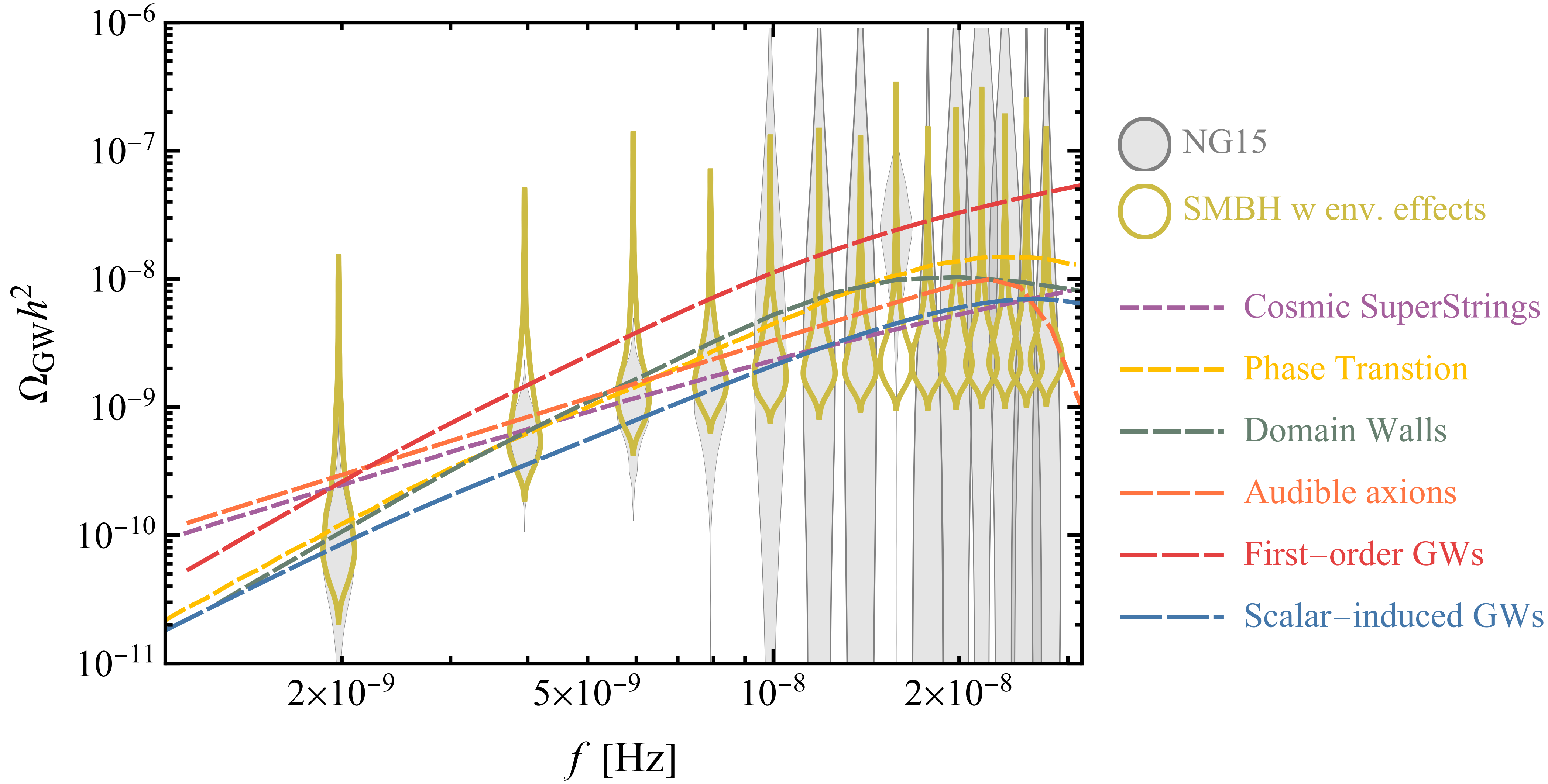


Topological defects produced when discrete symmetry is broken after inflation

Domain wall model compatible with cosmology for annihilation temperature $T_{\rm ann} \sim {\rm GeV}$ (hidden sector)

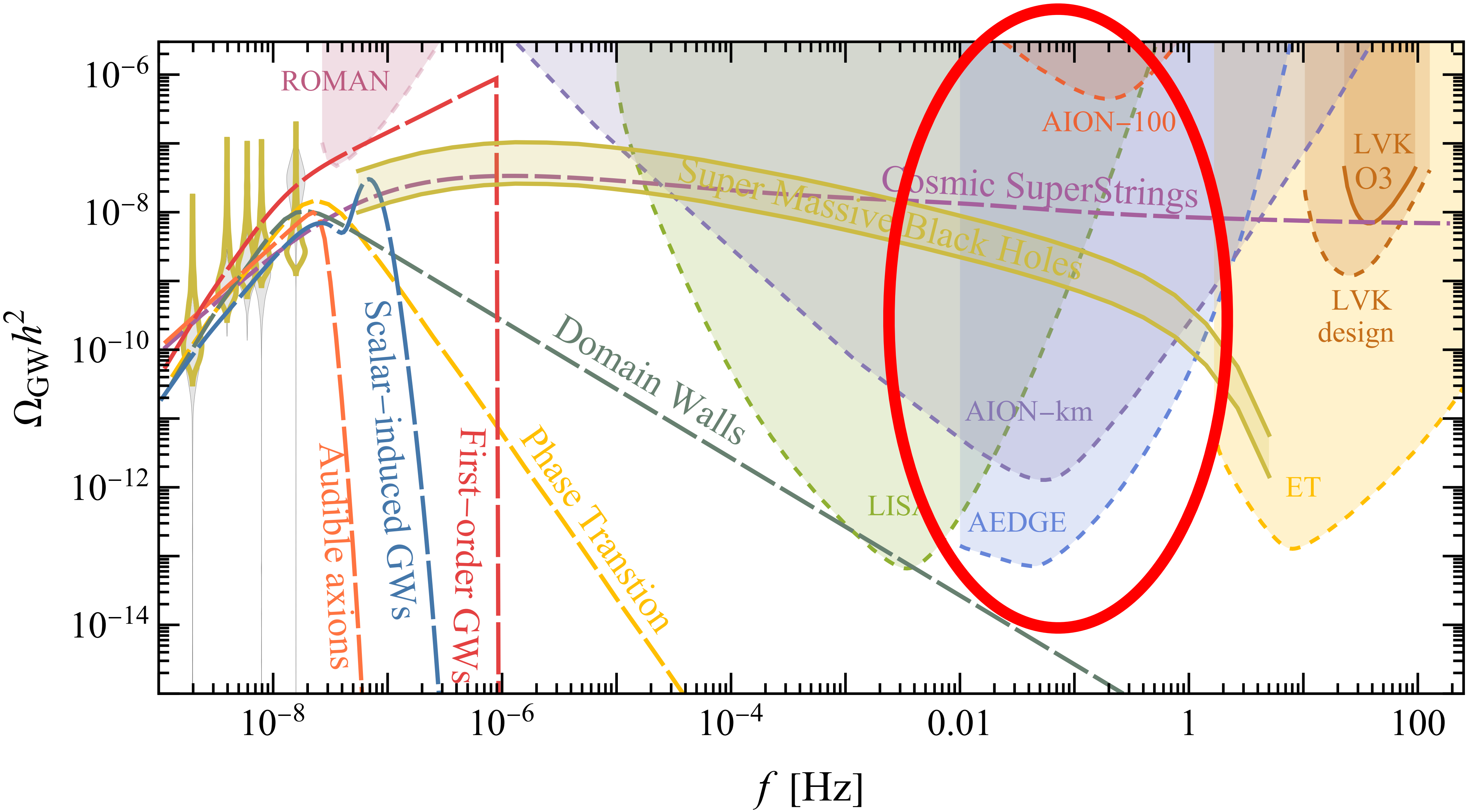
JE, Fairbairn, Franciolini, Hütsi, Iovino, Lewicki, Raidal, Urrutia, Vaskonen & Veermäe, arXiv:2308.08546

Fits to NANOGrav



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

Extension of Fits to Higher Frequencies



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

Results For NANOGrav Fits

AION

Scenario	Best-fit parameters	ΔBIC	Signatures
GW-driven SMBH binaries	$p_{\rm BH} = 0.07$	6.0	FAPS, LISA, mid-f, ——, ——
GW + environment-driven SMBH binaries	$p_{\rm BH} = 0.84$ $\alpha = 2.0$ $f_{\rm ref} = 34$ nHz	Baseline (BIC = 53.9)	FAPS, LISA, mid-f, ——, ——
Cosmic (super)strings (CS)	$G\mu = 2 \times 10^{-12}$ $p = 6.3 \times 10^{-3}$	-1.2 (4.6)	——, LISA, mid-f, LVK, ET
Phase transition (PT)	$T_* = 0.34$ GeV $\beta/H = 6.0$	-4.9 (2.9)	——, ——, ——, ——, ——
Domain walls (DWs)	$T_{\rm ann} = 0.85$ GeV $\alpha_* = 0.11$	-5.7 (2.2)	——, LISA?, ——, ——, ——
Scalar-induced GWs (SIGWs)	$k_* = 10^{7.7}$/Mpc $A = 0.06$ $\Delta = 0.21$	-2.1 (5.8)	——, ——, ——, ——, ——
First-order GWs (FOGWs)	$\log_{10} r = -14$ $n_{\rm t} = 2.6$ $\log_{10}(T_{\rm rh}/\text{GeV}) = -0.67$	-2.0 (6.0)	——, ——, ——, ——, ——
"Audible" axions	$m_a = 3.1 \times 10^{-11}$ eV $f_a = 0.87\, M_{\rm P}$	-4.2 (3.7)	——, ——, ——, ——, ——

FAPS ≡ fluctuations, anisotropies, polarization, sources, mid-f ≡ mid-frequency experiment, e.g., AION [1], AEDGE [2], LVK ≡ LIGO/Virgo/KAGRA [3–5], ET ≡ Einstein Telescope [6] (or Cosmic Explorer [7]), ———— ≡ not detectable

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

Outline

- Discovery of gravitational waves from mergers of black holes and neutron star mergers (kilonovae)
  - Dark matter signal in gravitational waves from kilonovae?
- Supermassive black holes exist: how to assemble them?
  - Atom interferometry! Can also probe graviton mass, test Lorentz invariance

AION

- Discovery of nanoHz GW background by Pulsar Timing Arrays (PTAs)
- Supermassive black hole binaries?
- **BSM scenarios fit NANOGrav data better than BH binaries!**

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