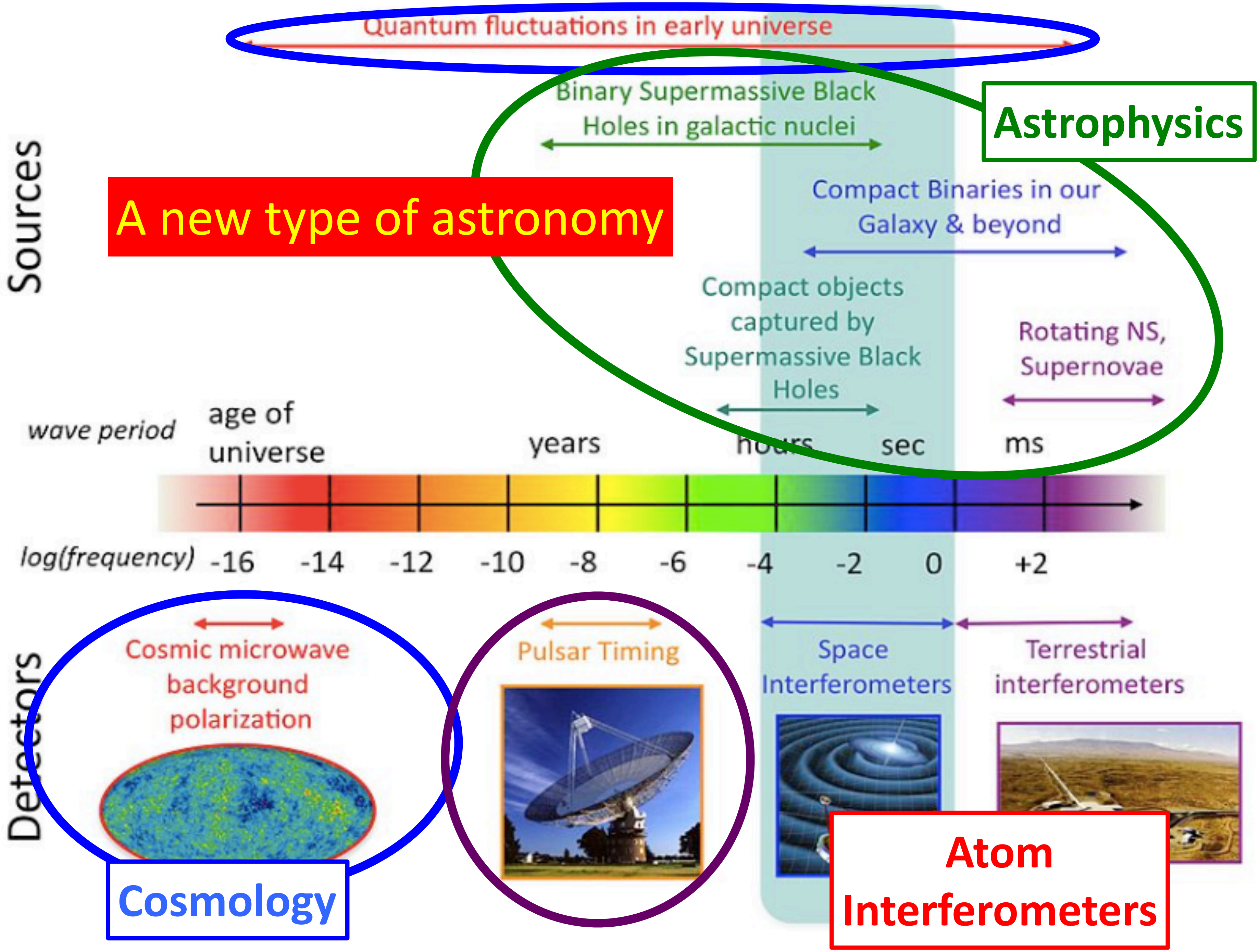
Atom Interferometry to Search for Gravitational Waves and Dark Matter

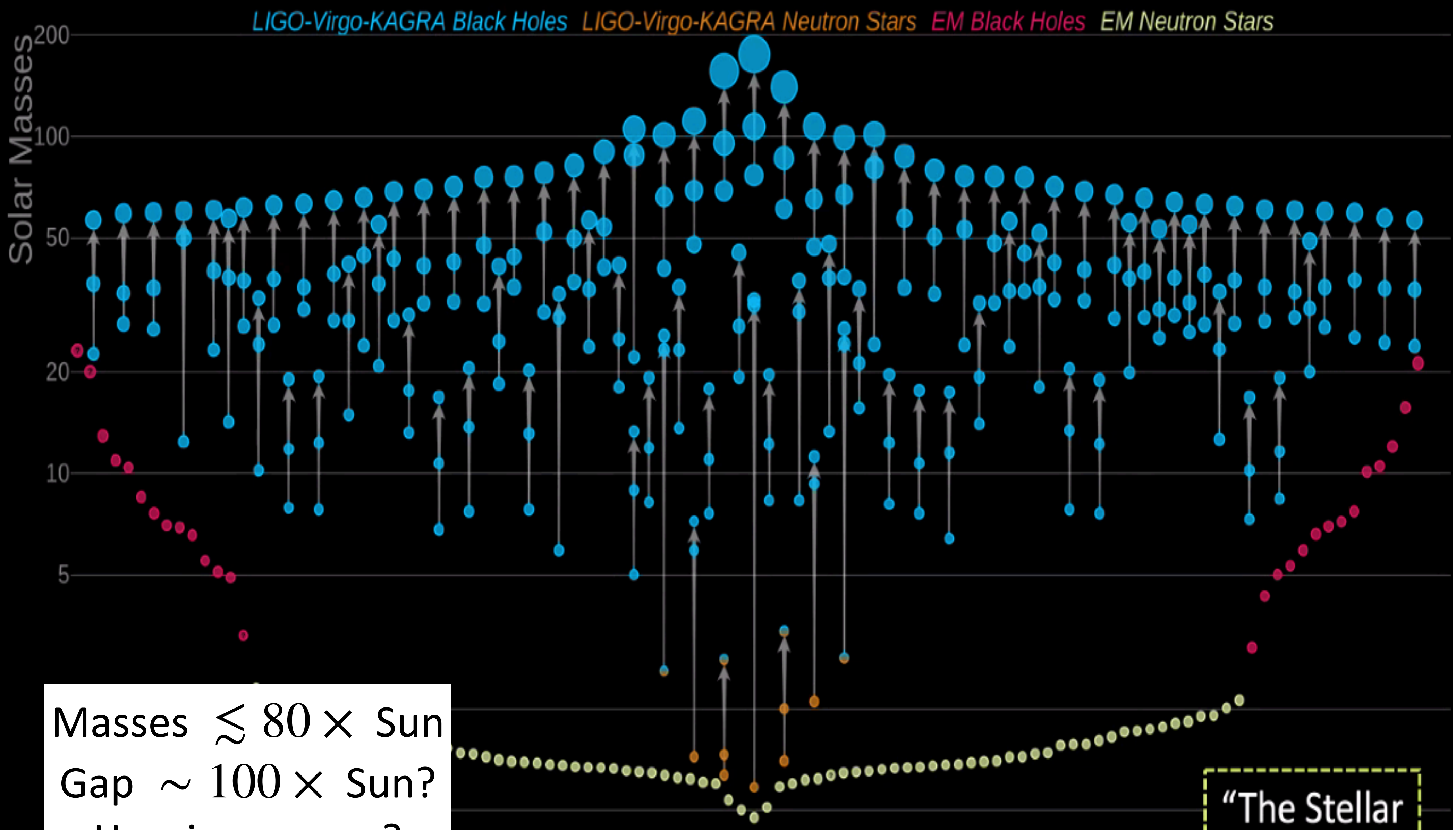
KING'S College LONDON

John Ellis

Gravitational Wave Spectrum

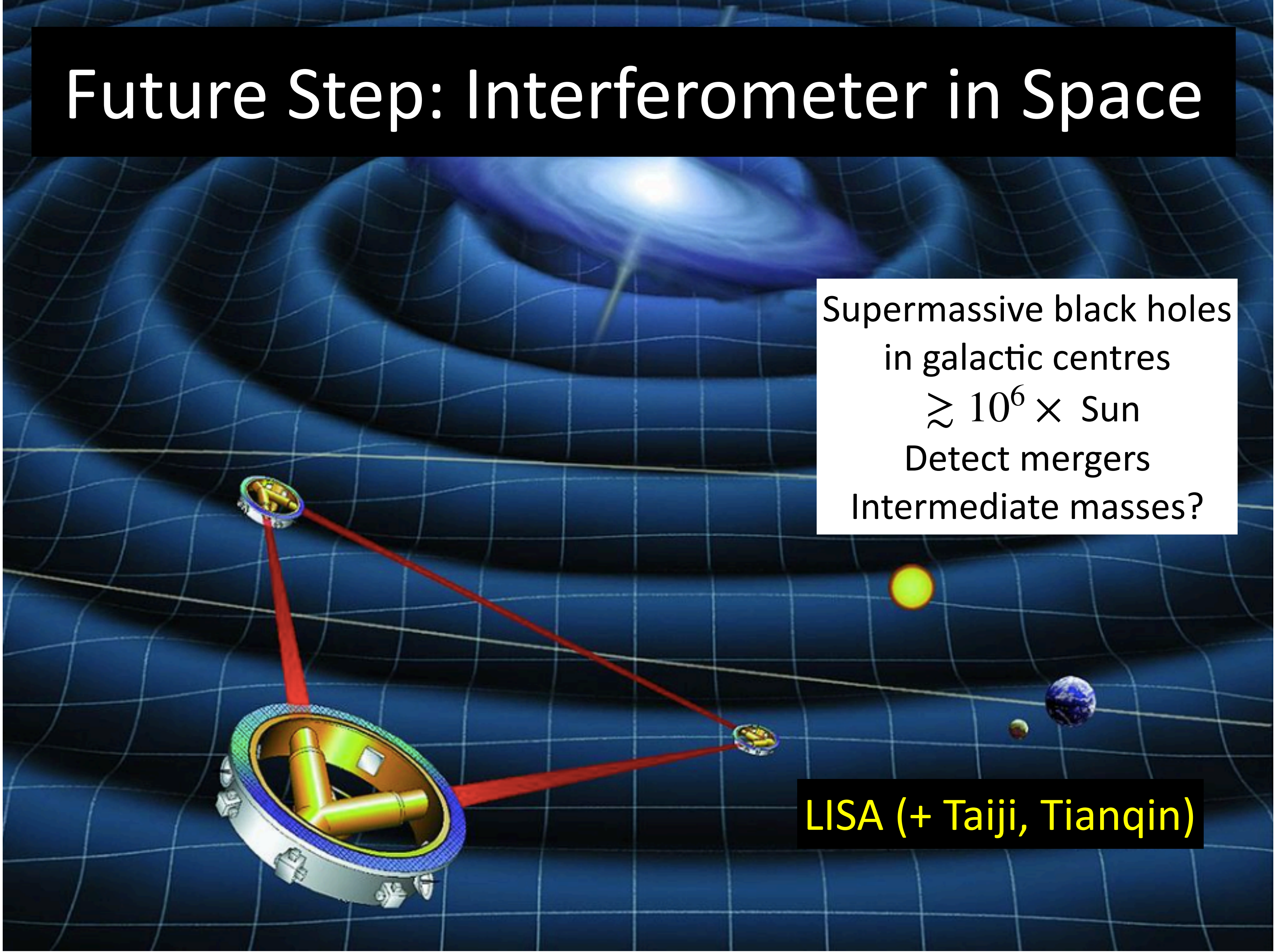


LIGO-Virgo-KAGRA Black Holes & Neutron Stars



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

Future Step: Interferometer in Space

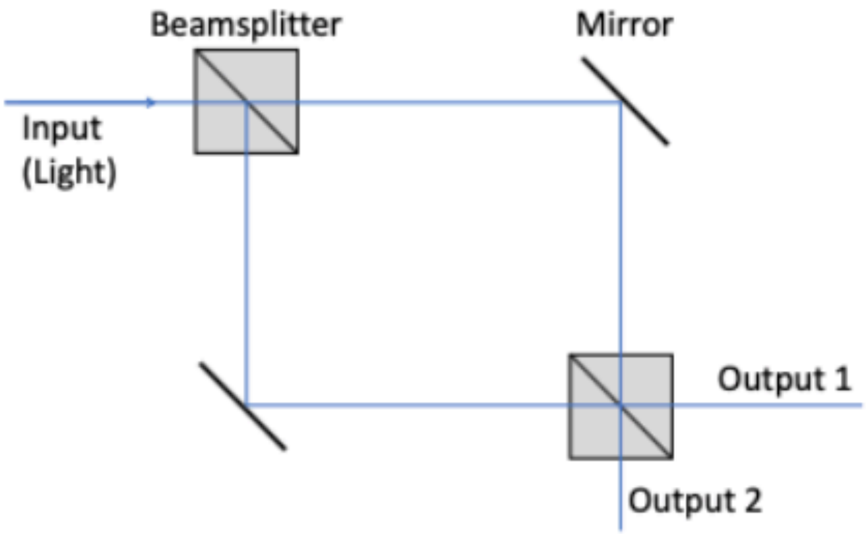


Supermassive black holes
in galactic centres
$\gtrsim 10^6 \times$ Sun
Detect mergers
Intermediate masses?

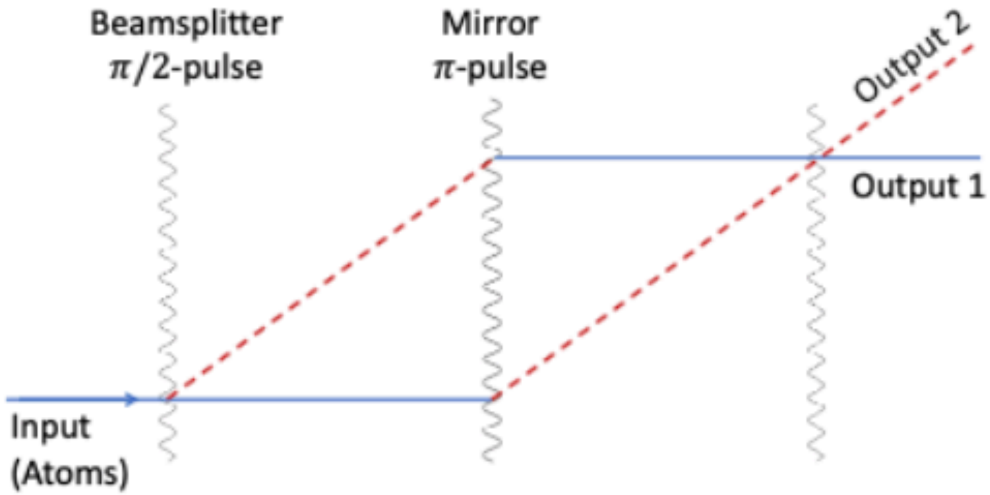
LISA (+ Taiji, Tianqin)

Principle of Atom Interferometry

Mach-Zehnder Laser Interferometer

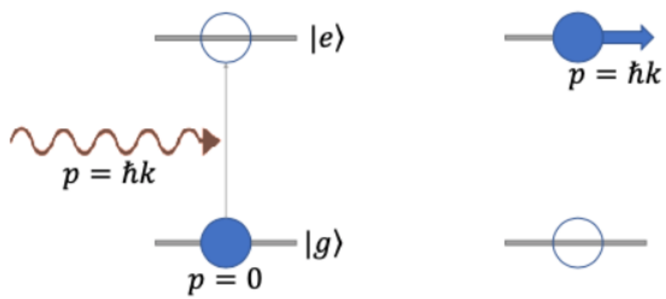


Atom Interferometer



Laser excitation gives momentum kick to excited atom, which follows separated space-time path

Interference between atoms following different paths



AION Collaboration

L. Badurina[1], S. Balashov[2], E. Bentine[3], D. Blas[1], J. Boehm[2], K. Bongs[4], A Beniwal[1], D. Bortoletto[3], T. Bowcock[5], W. Bowden[6,*], C. Brew[2], O. Buchmueller[6], J. Coleman[5], J. Carlton[1], G. Elertas[5], J. Ellis[1,6,&], C. Foot[3], V. Gibson[7], M. Haehnelt[7], T. Harte[7], R. Hobson[6,*], M. Holynski[4], A. Khazov[2], M. Langlois[4], S. Lellouch[4], Y.H. Lien[4], R. Maiolino[7], P. Majewski[2], S. Malik[6], J. March-Russell[3], C. McCabe[1], D. Newbold[2], R. Preece[3], B. Sauer[6], U. Schneider[7], I. Shipsey[3], Y. Singh[4], M. Tarbutt[6], M. A. Uchida[7], T. V-Salazar[2], M. van der Grinten[2], J. Vossebeld[4], D. Weatherill[3], I. Wilmut[7], J. Zielinska[6]

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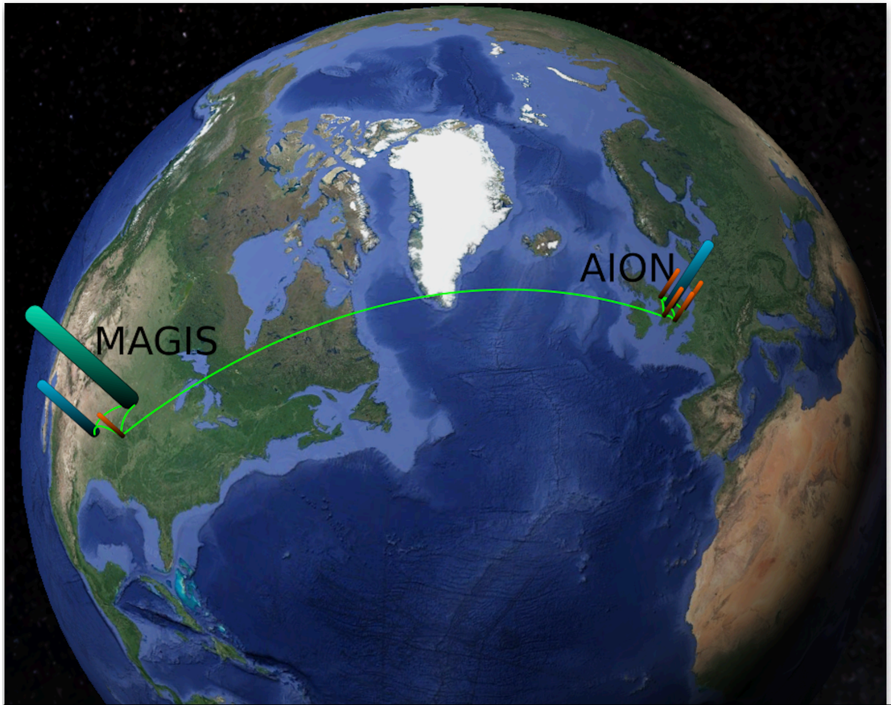
AION



Network with MAGIS project in US

MAGIS Collaboration (Abe et al): arXiv:2104.02835

Also MIGA (France), ZAIGA (China)

AION – Staged Programme

AION

- AION-10: Stage 1 [year 1 to 3]
  - 1 & 10 m Interferometers & site investigation for 100m baseline

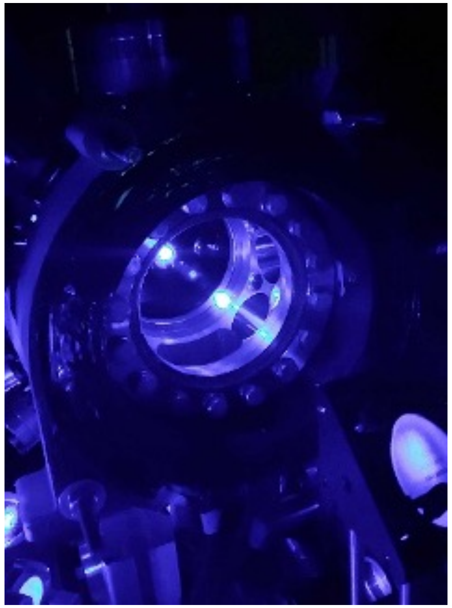
Initial funding from UK STFC

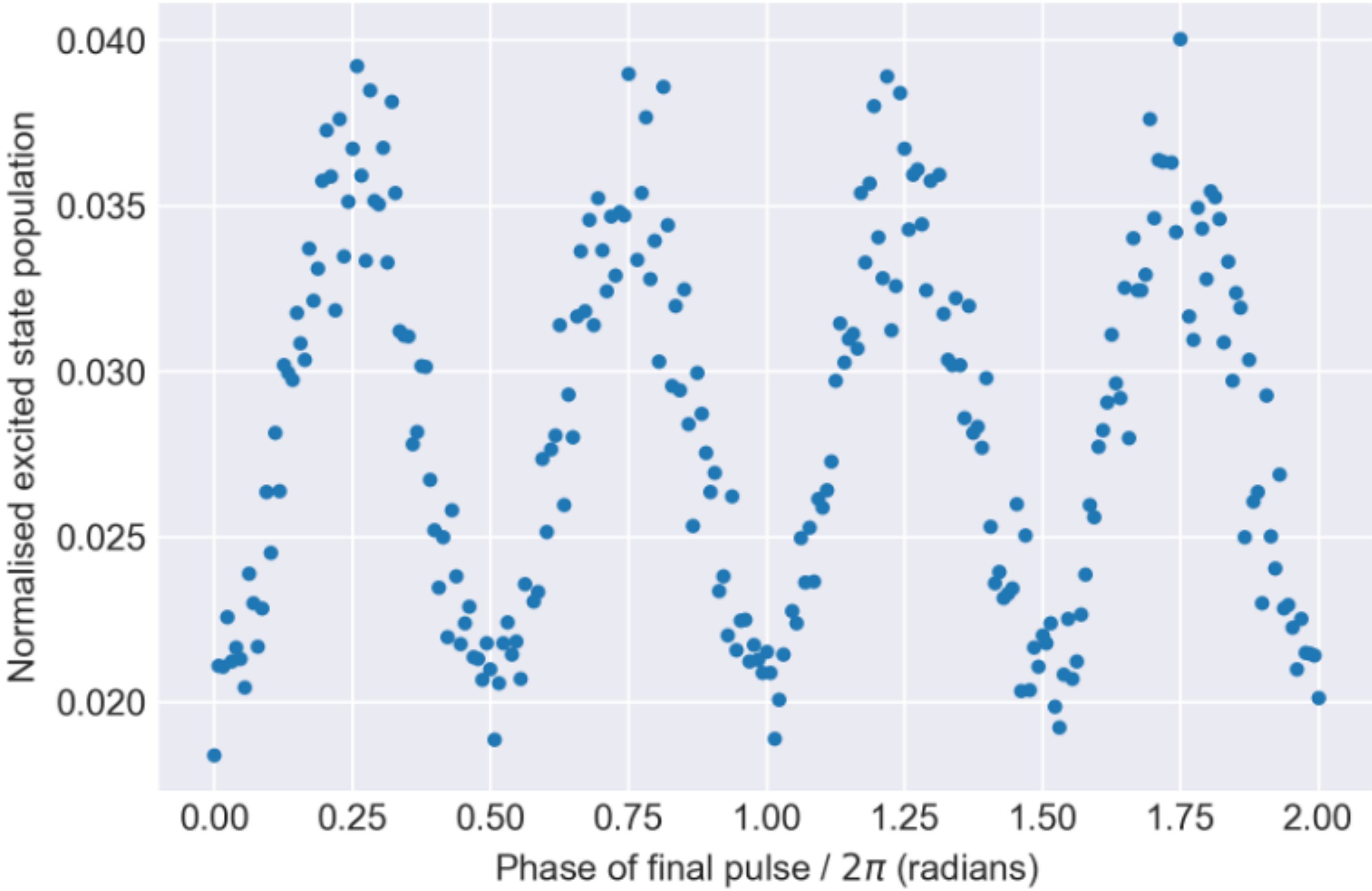
- AION-100: Stage 2 [year 3 to 6]
  - 100m Construction & commissioning
- AION-KM: Stage 3 [> year 6]
  - Operating AION-100 and planning for 1 km & beyond
- AION-SPACE (AEDGE): Stage 4 [after AION-km]
  - Space-based version

AION Collaboration (Badurina, …, JE et al): arXiv:1911.11755

Rabi Oscillations & Interference Fringes

Atomic analogue of Mach-Zehnder optical interferometer





Using 689 nm transition in Sr

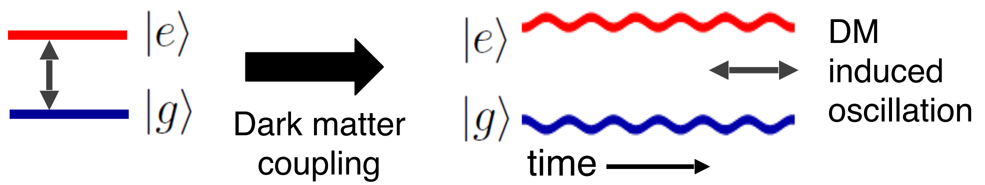
AION Collaboration

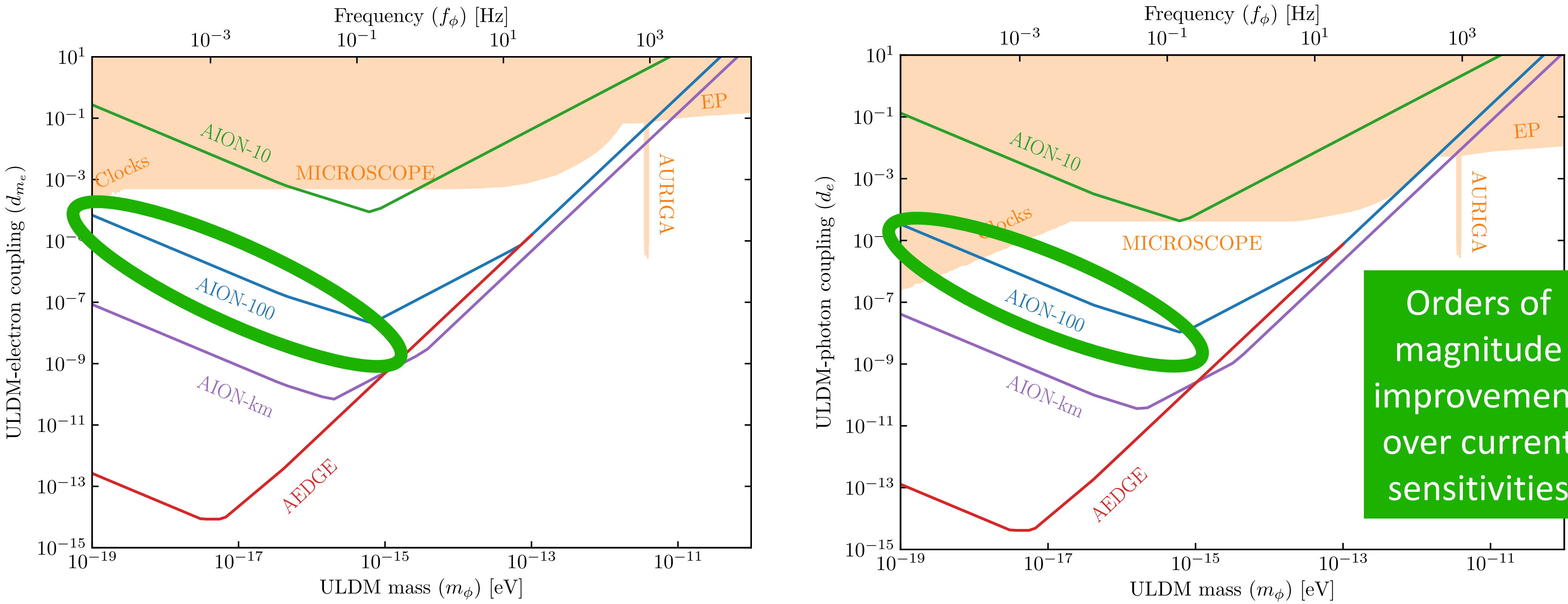
Searches for Light Dark Matter

AION

Linear couplings to gauge fields and matter fermions

$$\mathcal{L}_{\text{int}\phi} = \kappa\phi\left[+\frac{d_e}{4e^2}F_{\mu\nu}F^{\mu\nu} - \frac{d_g\beta_3}{2g_3}F^A_{\mu\nu}F^{A\mu\nu} - \sum_{i=e,u,d}(d_{m_i}+\gamma_{m_i}d_g)m_i\bar{\psi}_i\psi_i\right]$$

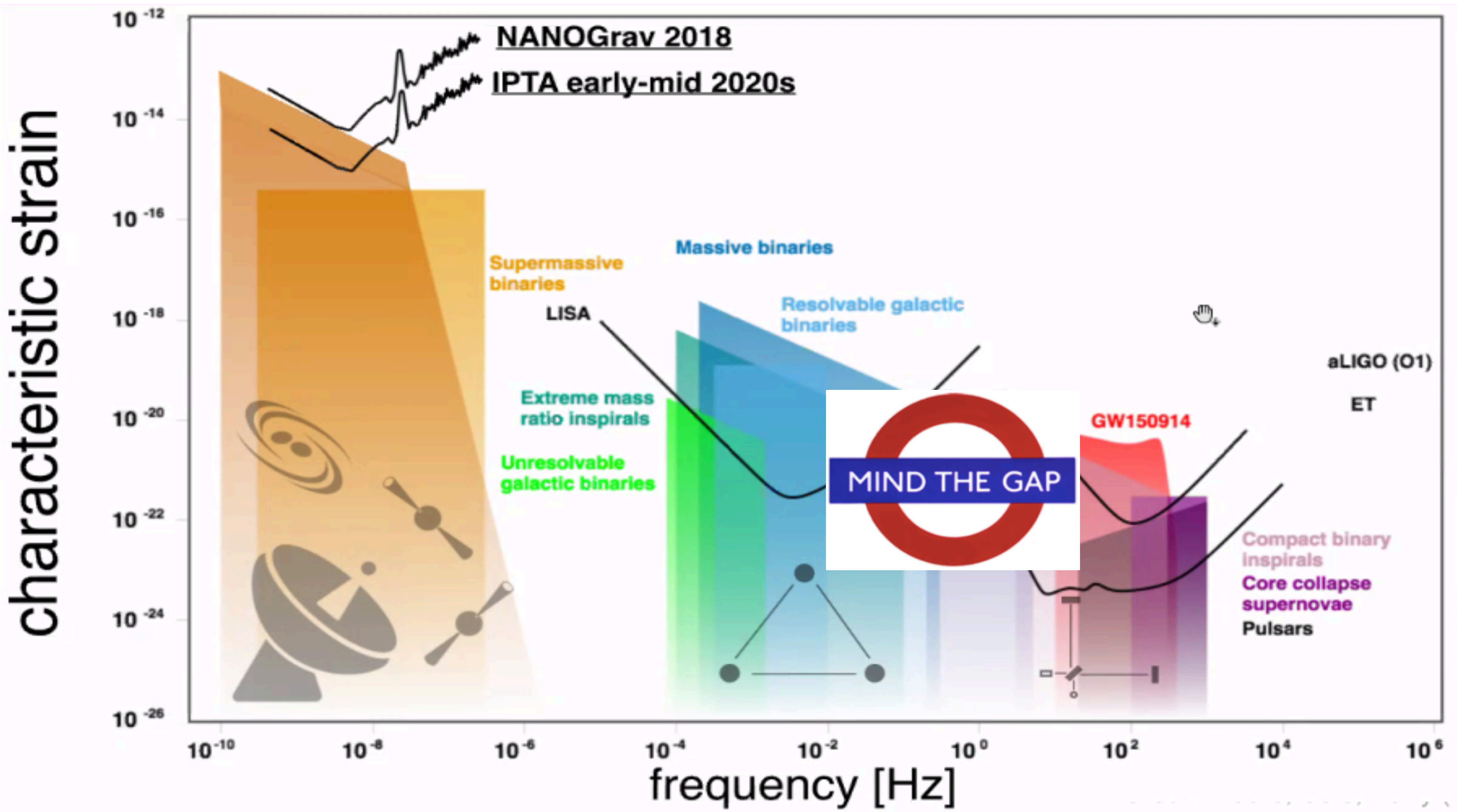




Orders of magnitude improvement over current sensitivities

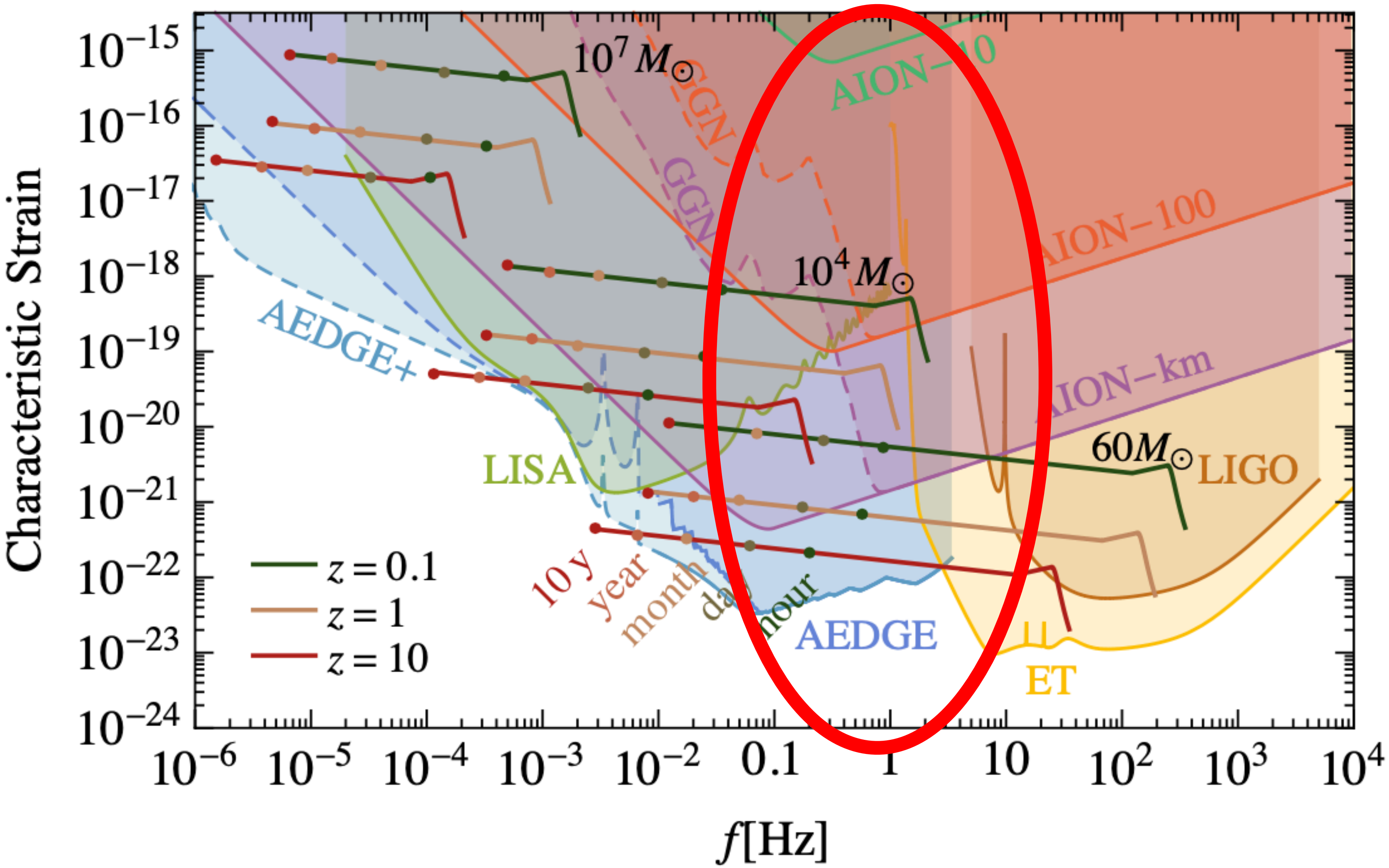
AION Collaboration (Badurina, …, JE et al): arXiv:1911.11755; Badurina, Buchmueller, JE, Lewicki, McCabe & Vaskonen: arXiv:2108.02468

Gravitational Wave Spectrum



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

Gravitational Waves from IMBH Mergers



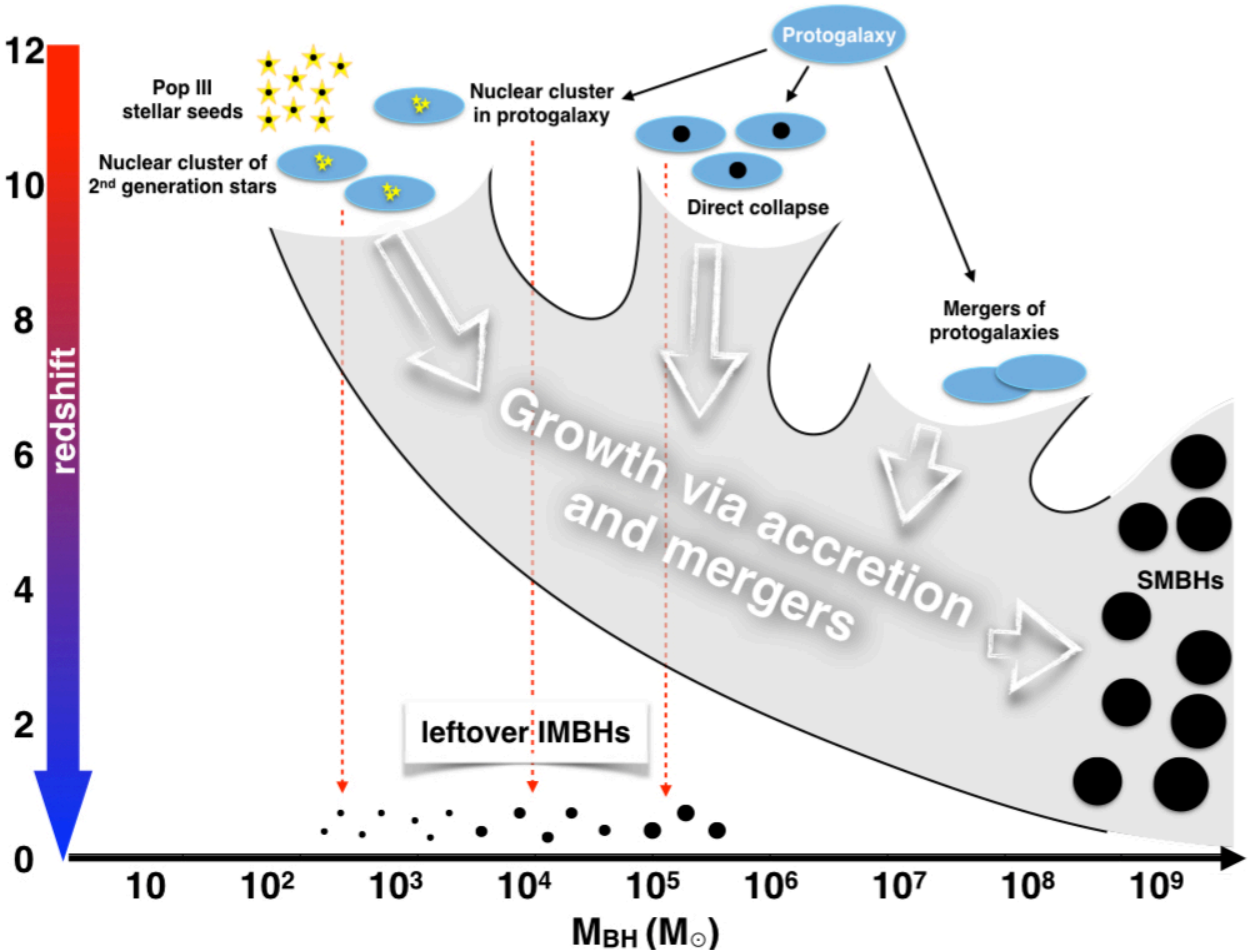
Probe formation of SMBHs

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

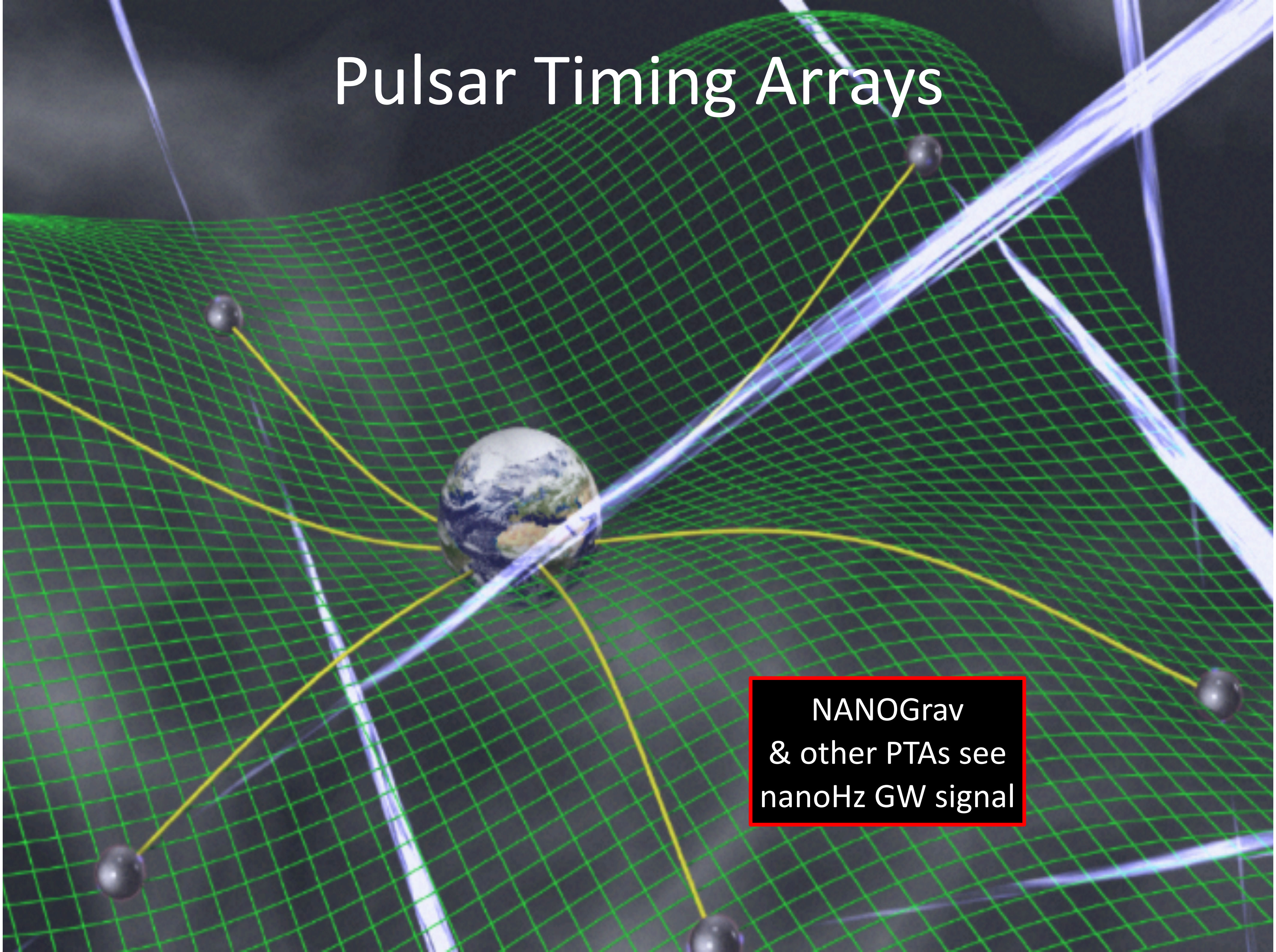
Badurina, Buchmueller, JE, Lewicki, McCabe & Vaskonen: arXiv:2108.02468

How to Make a Supermassive BH?

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



Pulsar Timing Arrays



The Biggest Bangs since the Big Bang

BH Merger Rate Estimate

BH merger rate $R_{\rm BH}$

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

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

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

is merger probability, and

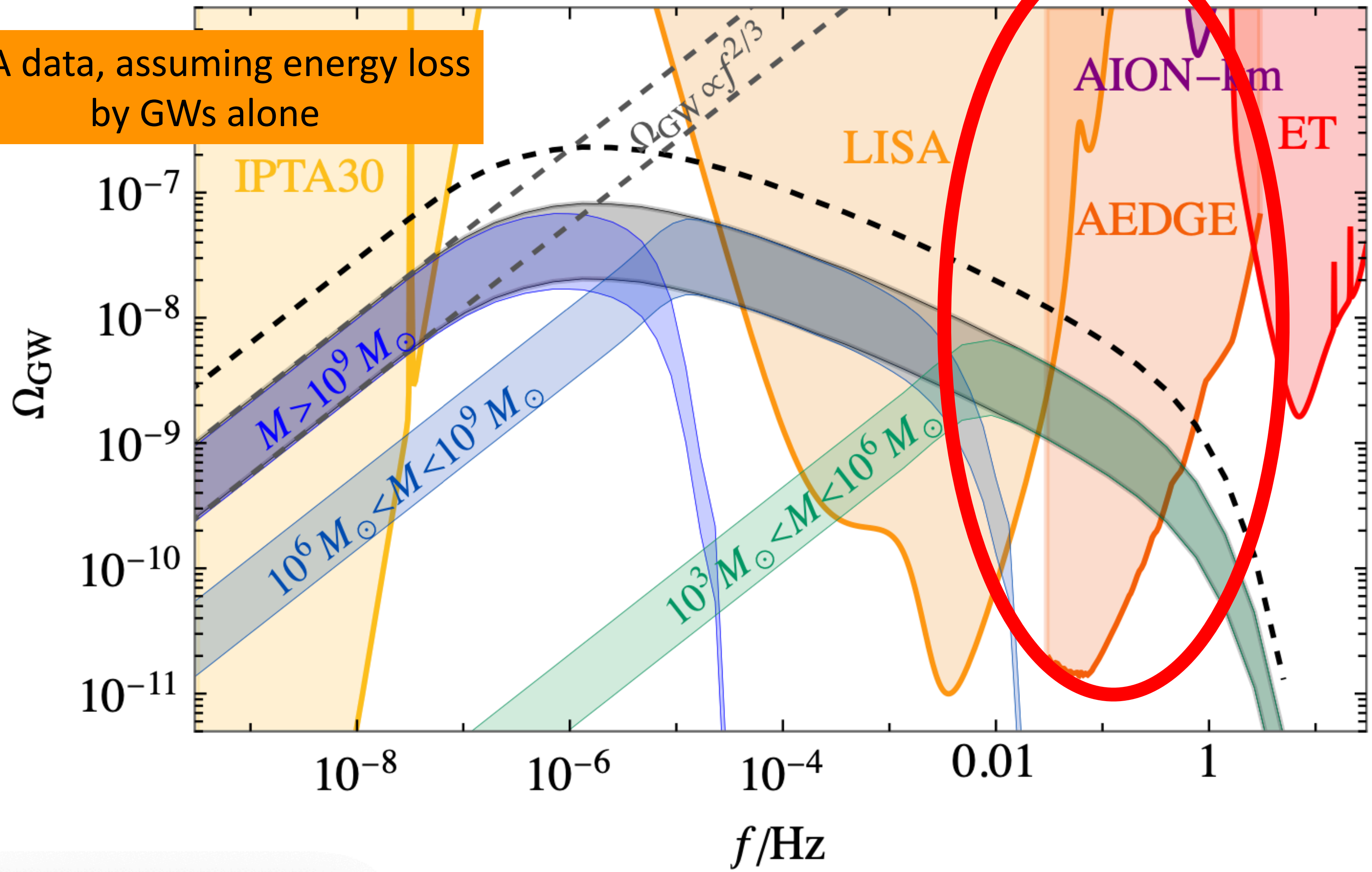
strength of IPTA signal can be fitted by constant

$$p_{\rm BH} = 0.17^{+0.18}_{-0.08}$$

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

Stochastic GW Background from BH Mergers

IPTA data, assuming energy loss by GWs alone

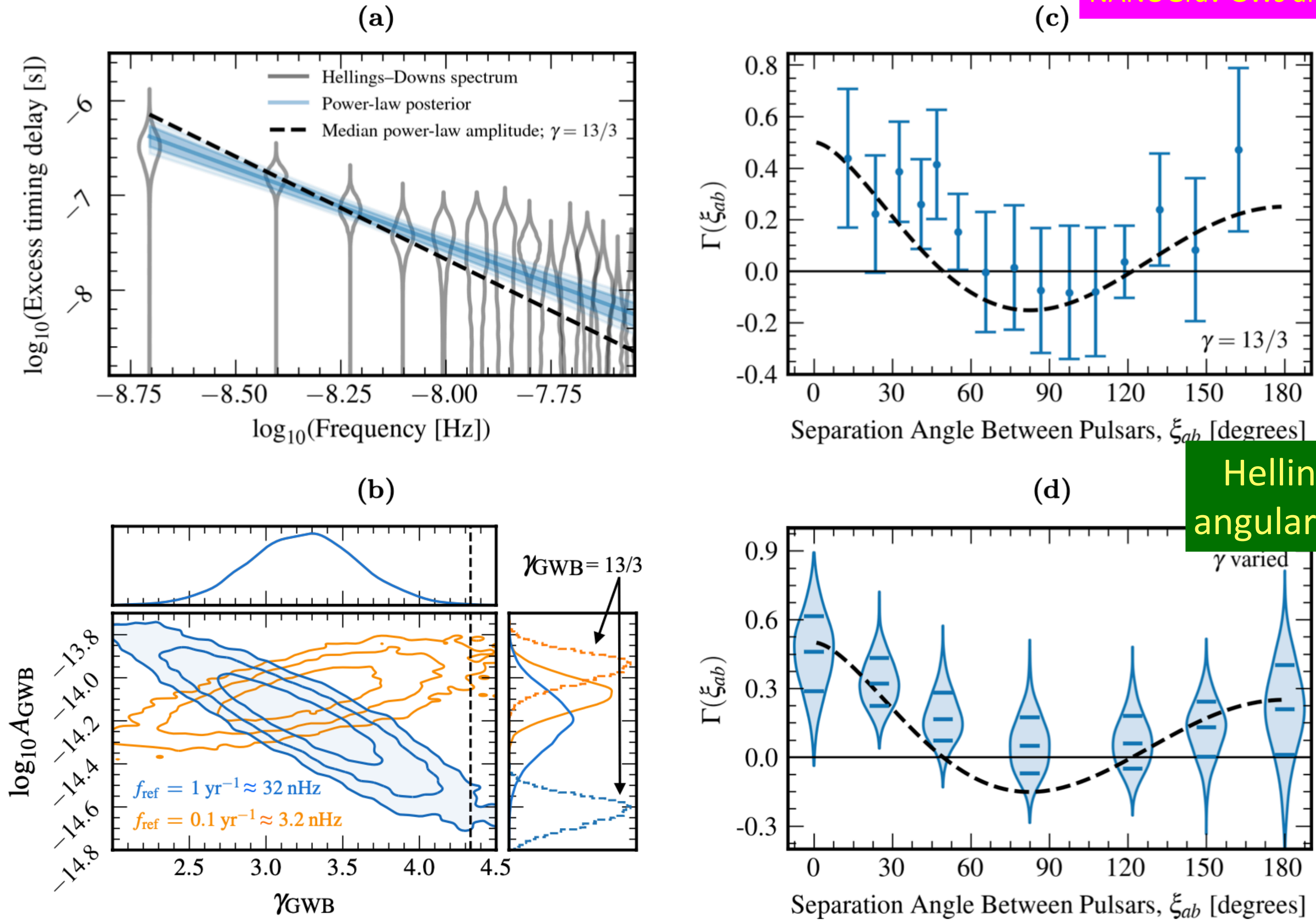


Black dashed line is maximum possible Ω_{GW}, i.e., $p_{BH} = 1$

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

NANOGrav 15-Year Data

NANOGrav GWs arXiv:2306.16213

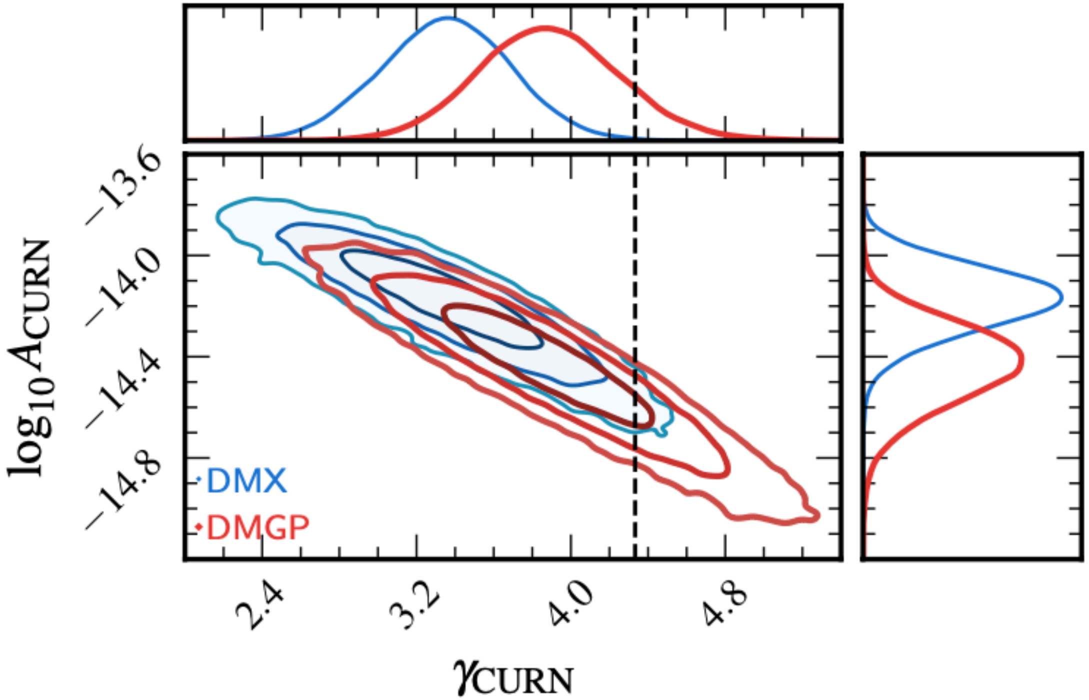


Hellings-Downs angular correlation

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

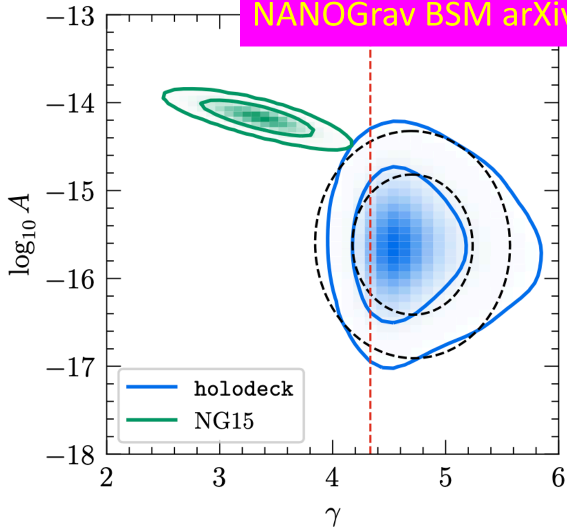
NANOGrav 15-Year Data

NANOGrav GWs arXiv:2306.16213

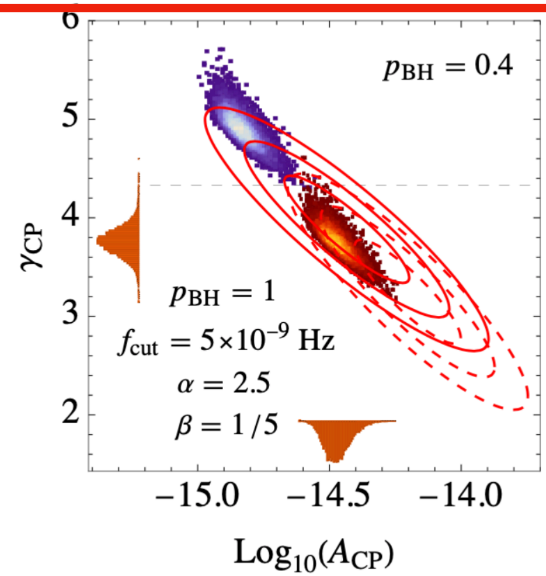


Range of γ depends on treatment of pulsar noise (spectrum not fitted well by single power law)

NANOGrav BSM arXiv:2306.16219



Prima facie disagreement with SMBH energy loss by GW alone



Consistent with 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:

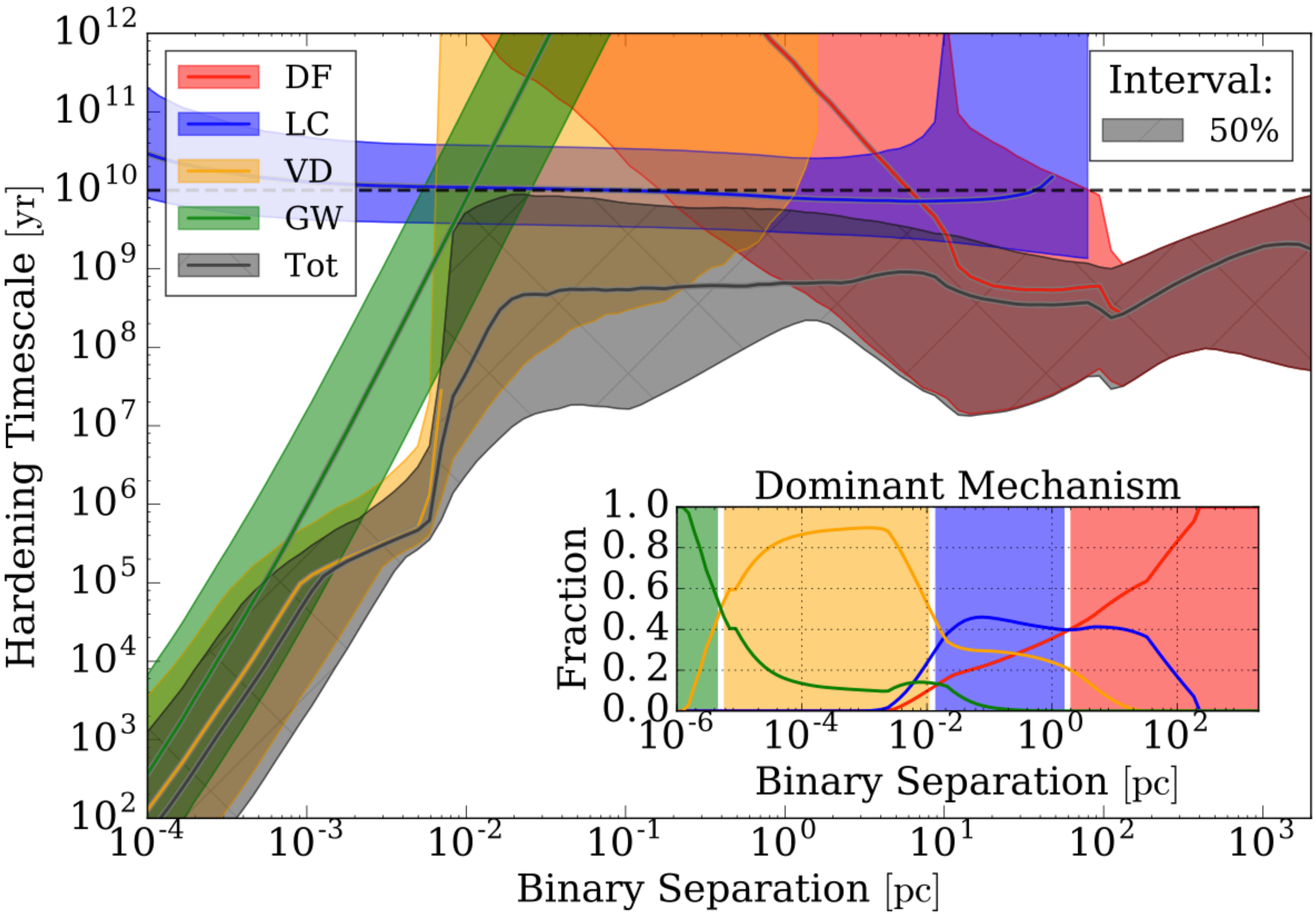
$$\frac{\mathrm{dE_{GW}}}{\mathrm{d\ln f_r}} = \frac{1}{3}\frac{(\pi f_r)^{\frac{2}{3}}\mathcal{M}^{\frac{5}{3}}}{1 + t_{\rm GW}/t_{\rm env}}$$

- Phenomenological parametrization:

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

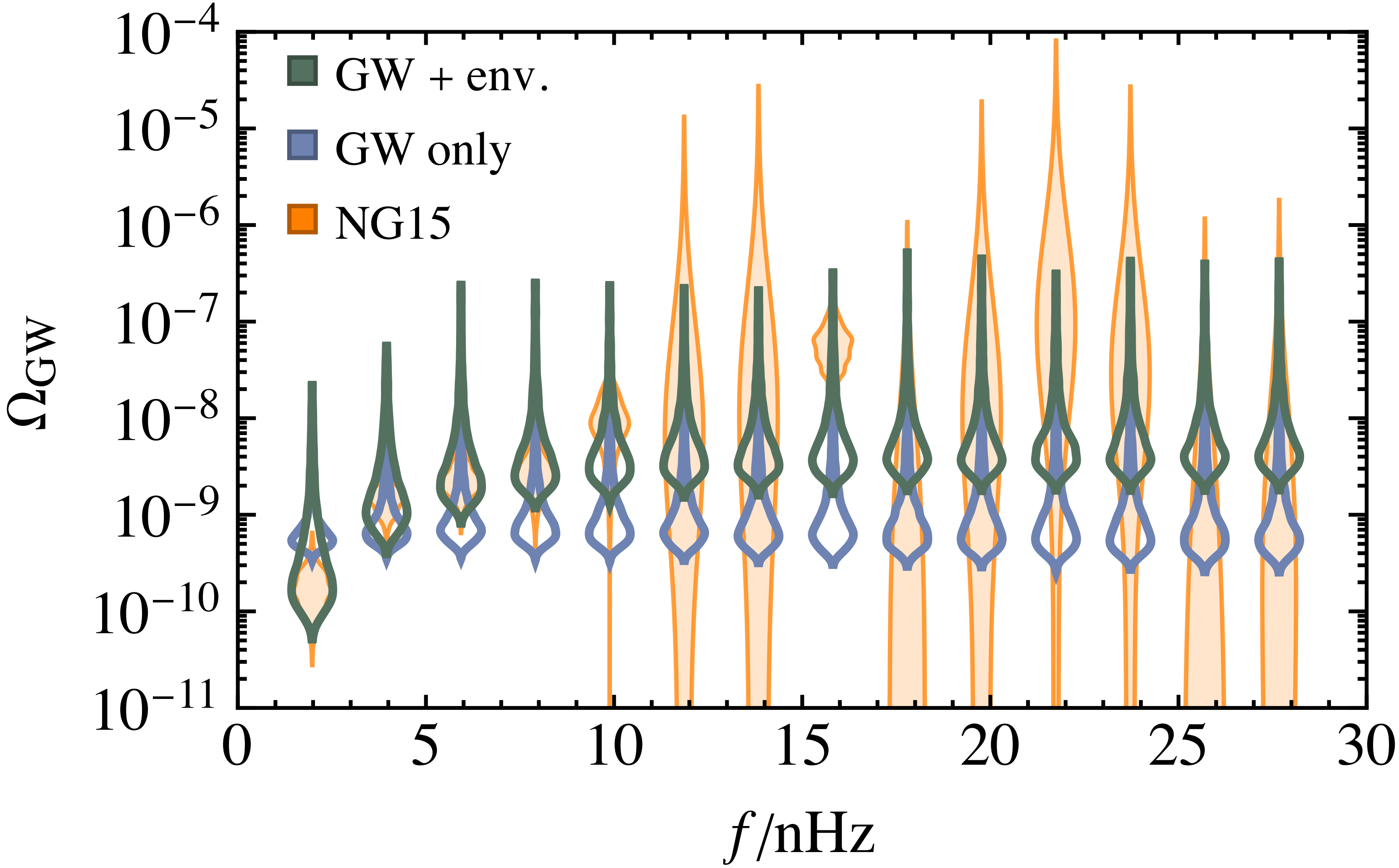
JE, Fairbairn, Hütsi, Raidal', Urrutia, Vaskonen & Veermäe: arXiv:2306.17021

Mechanisms for Energy Loss



Kelley, Blecha & Hernquist, arXiv:1606.01900

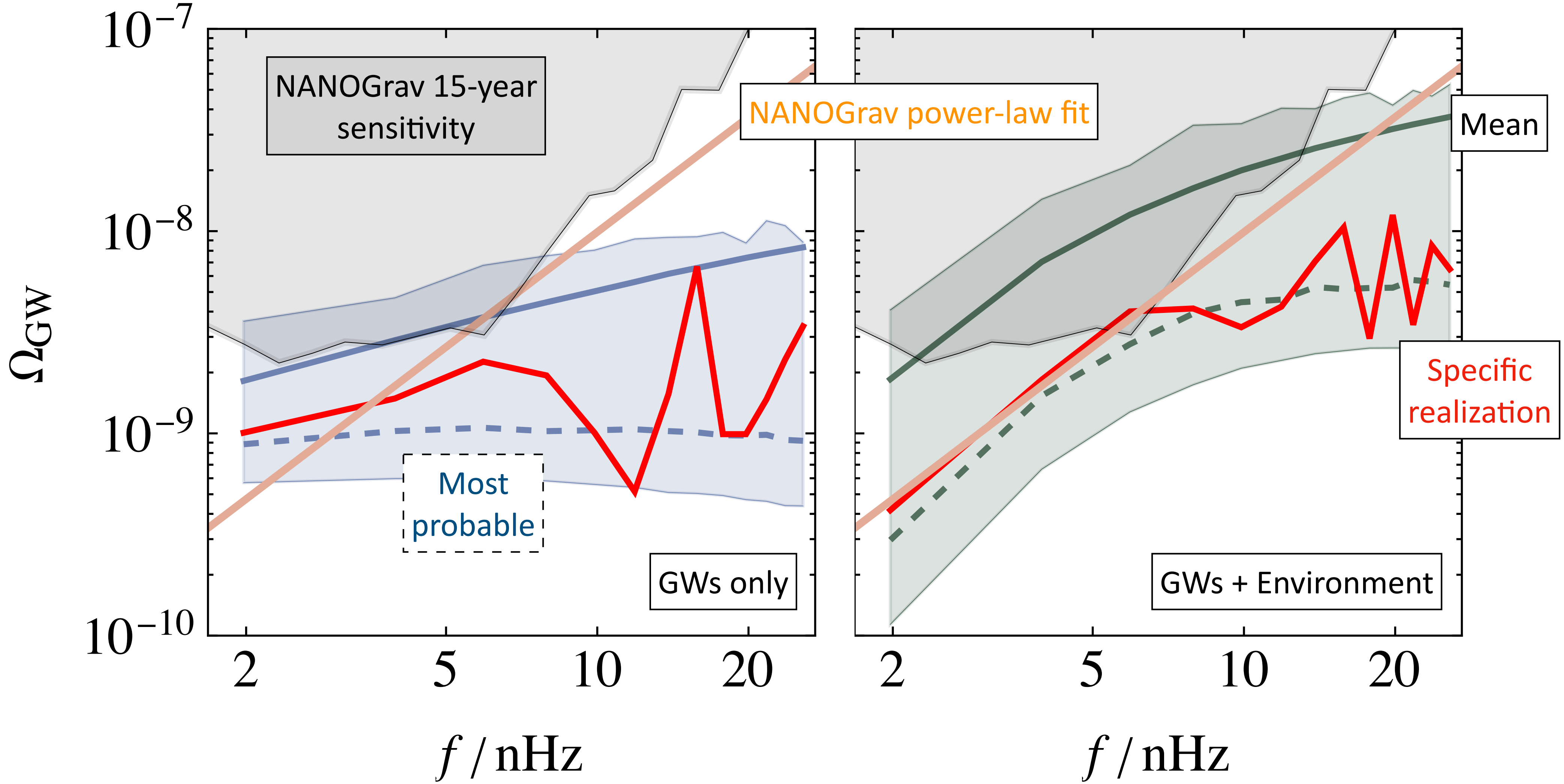
Astrophysical Interpretations AION



Fits use overlaps of data and model violins in each bin:
better fit to spectrum if evolution driven by both environment & GWs

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

GWs + Environment? AION

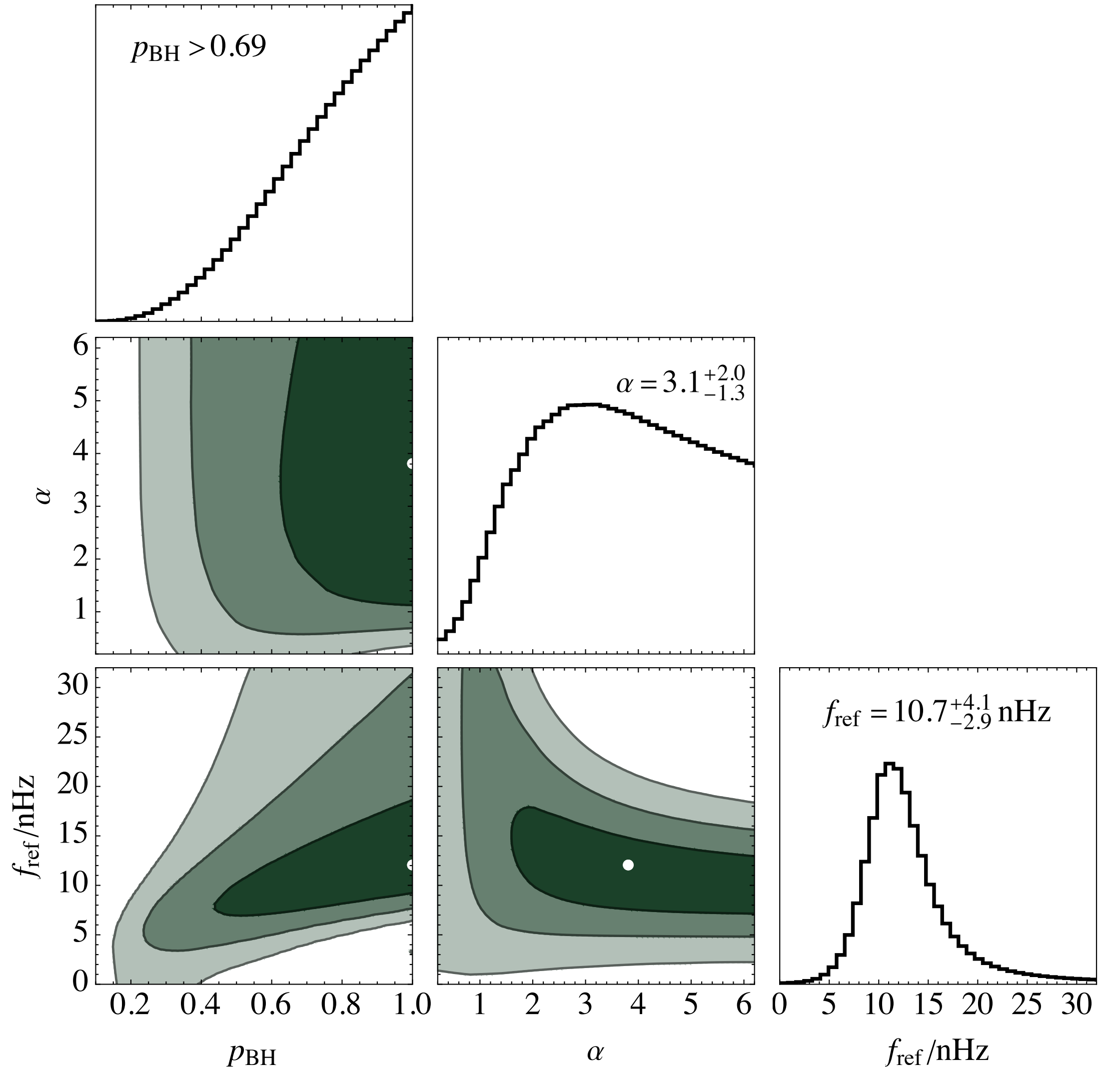


Bigger chance to see specific binaries if evolution also driven by environment (0.4 events vs 0.2 if GW only, most likely ~ 5 nHz)

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

SMBH Fits to NANOGrav

AION

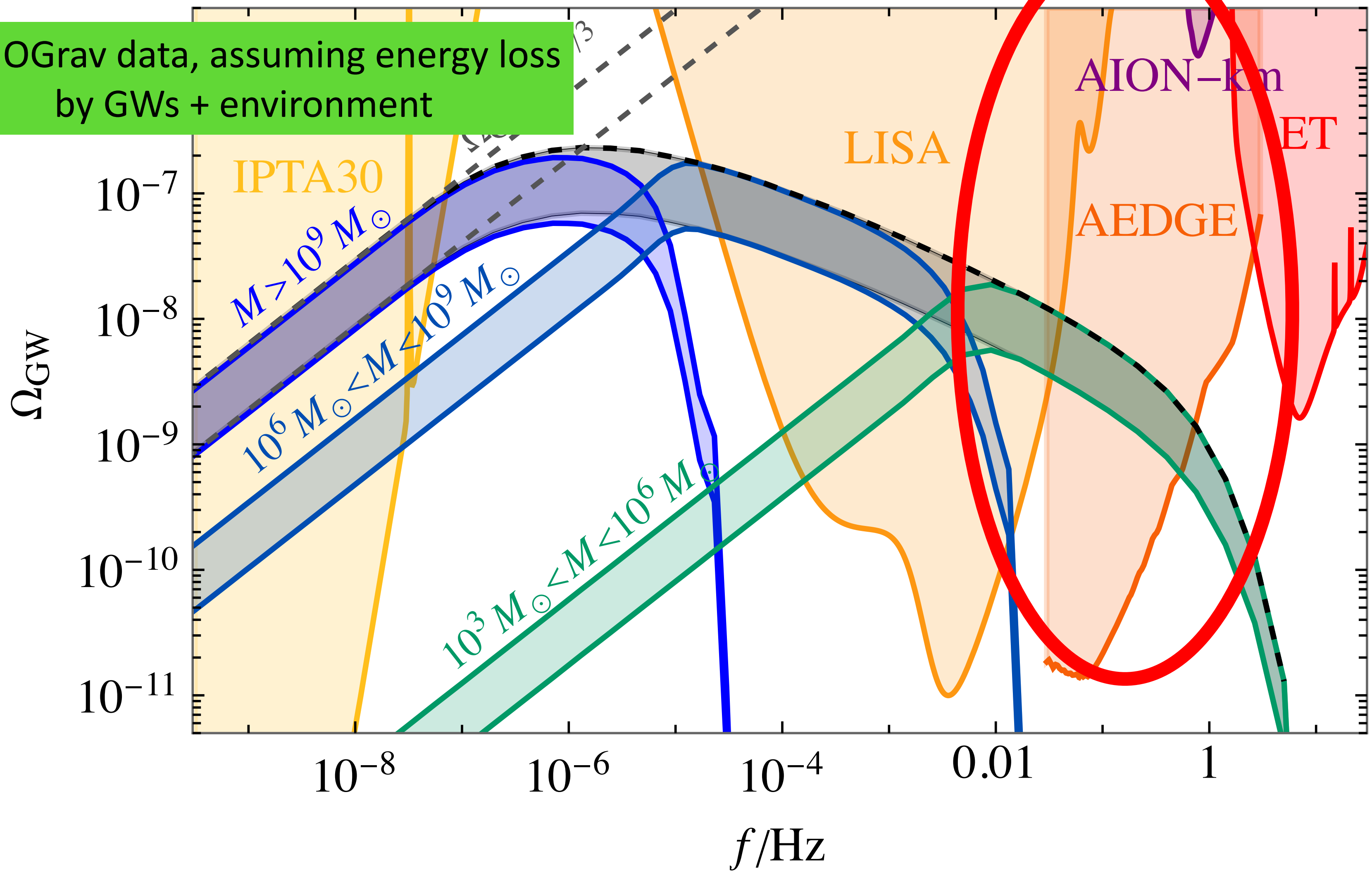


SMBH binary model fits NANOGrav data better if environmental energy-loss effects are included

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

Stochastic GW Background from BH Mergers

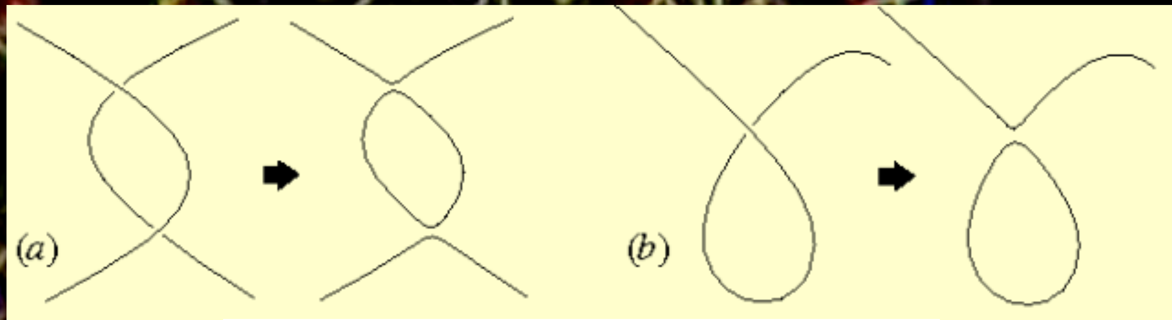
NANOGrav data, assuming energy loss by GWs + environment



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

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

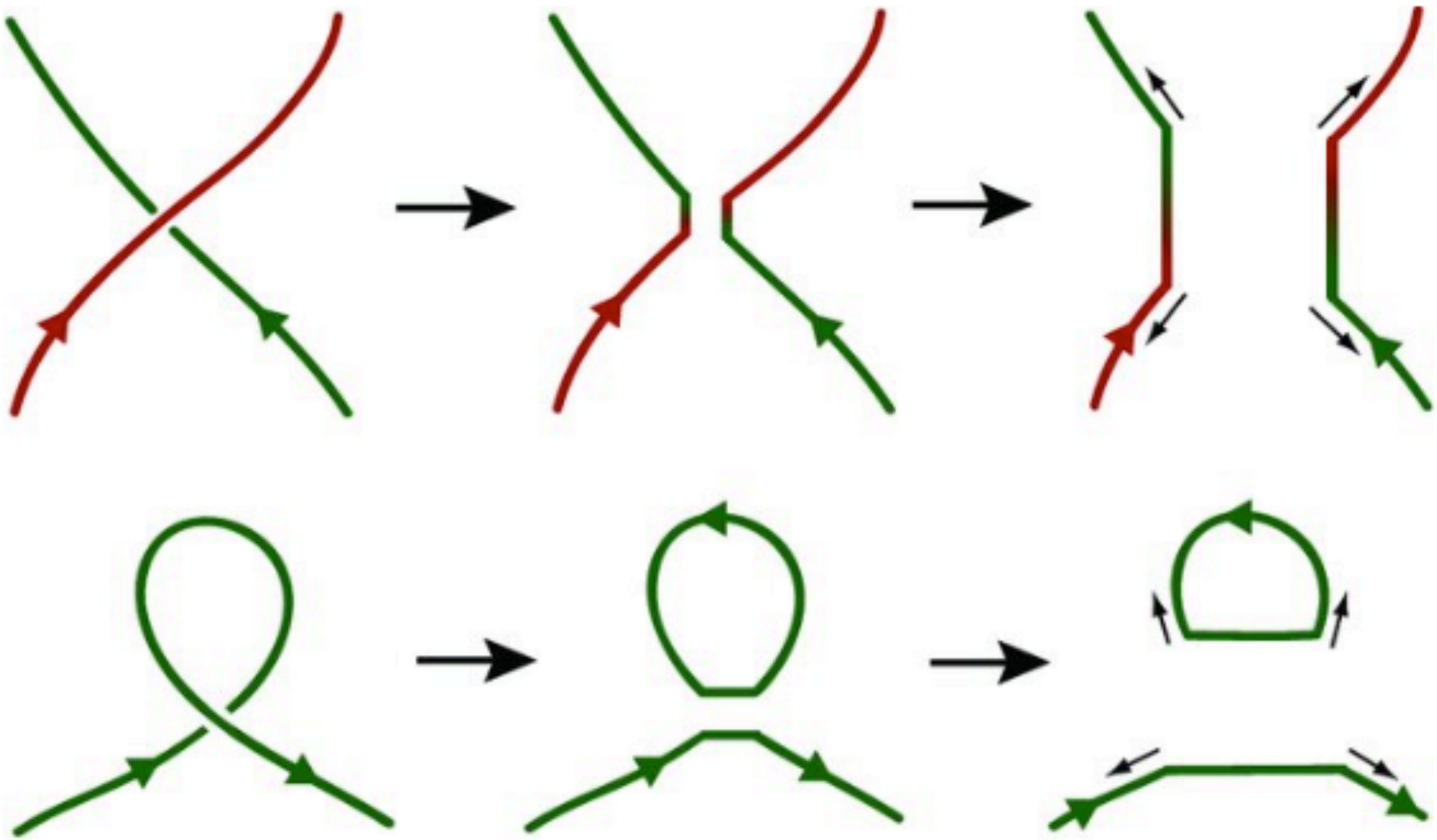
Probing Cosmic Strings



GW emission from string loops

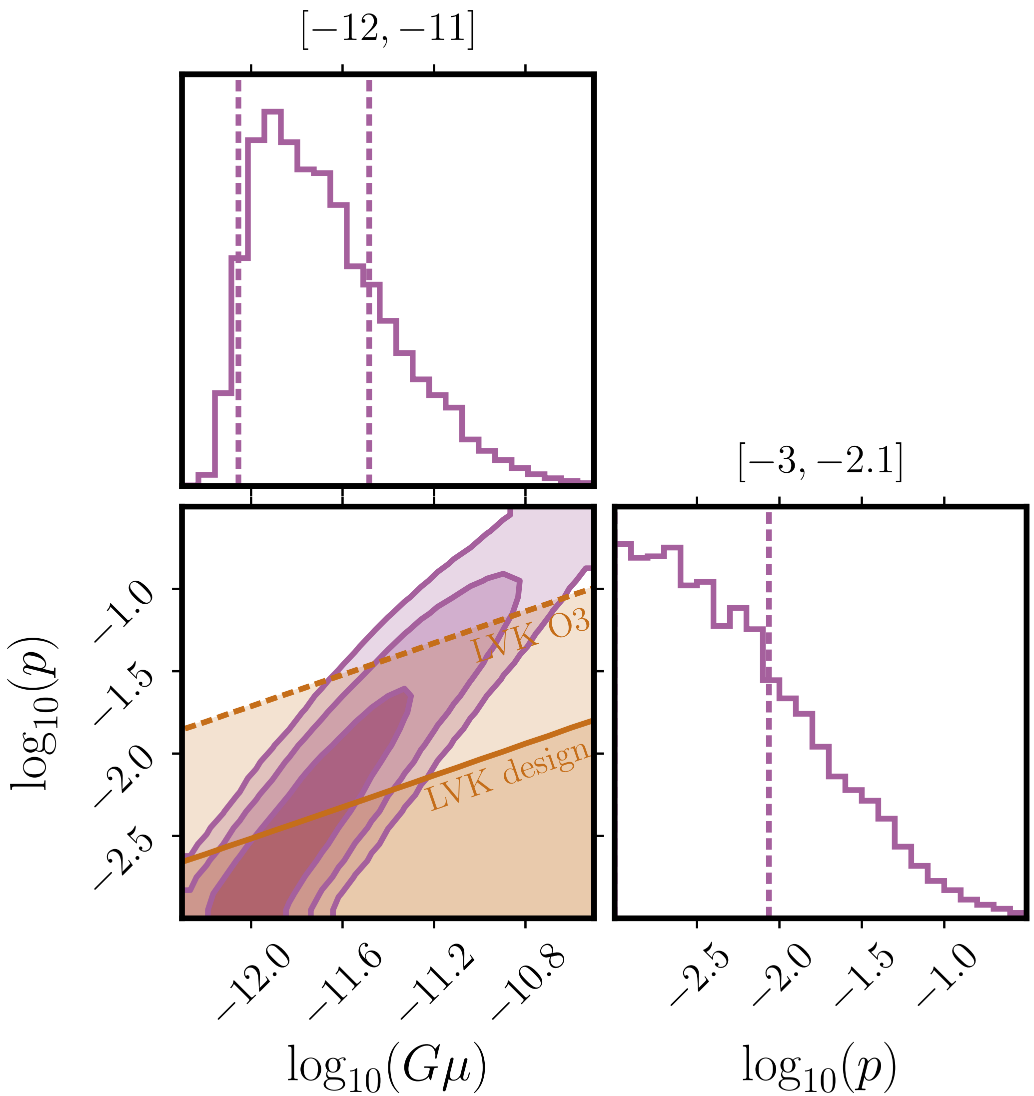
Simulation of cosmic string network – Cambridge cosmology group

String Intercommutation



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

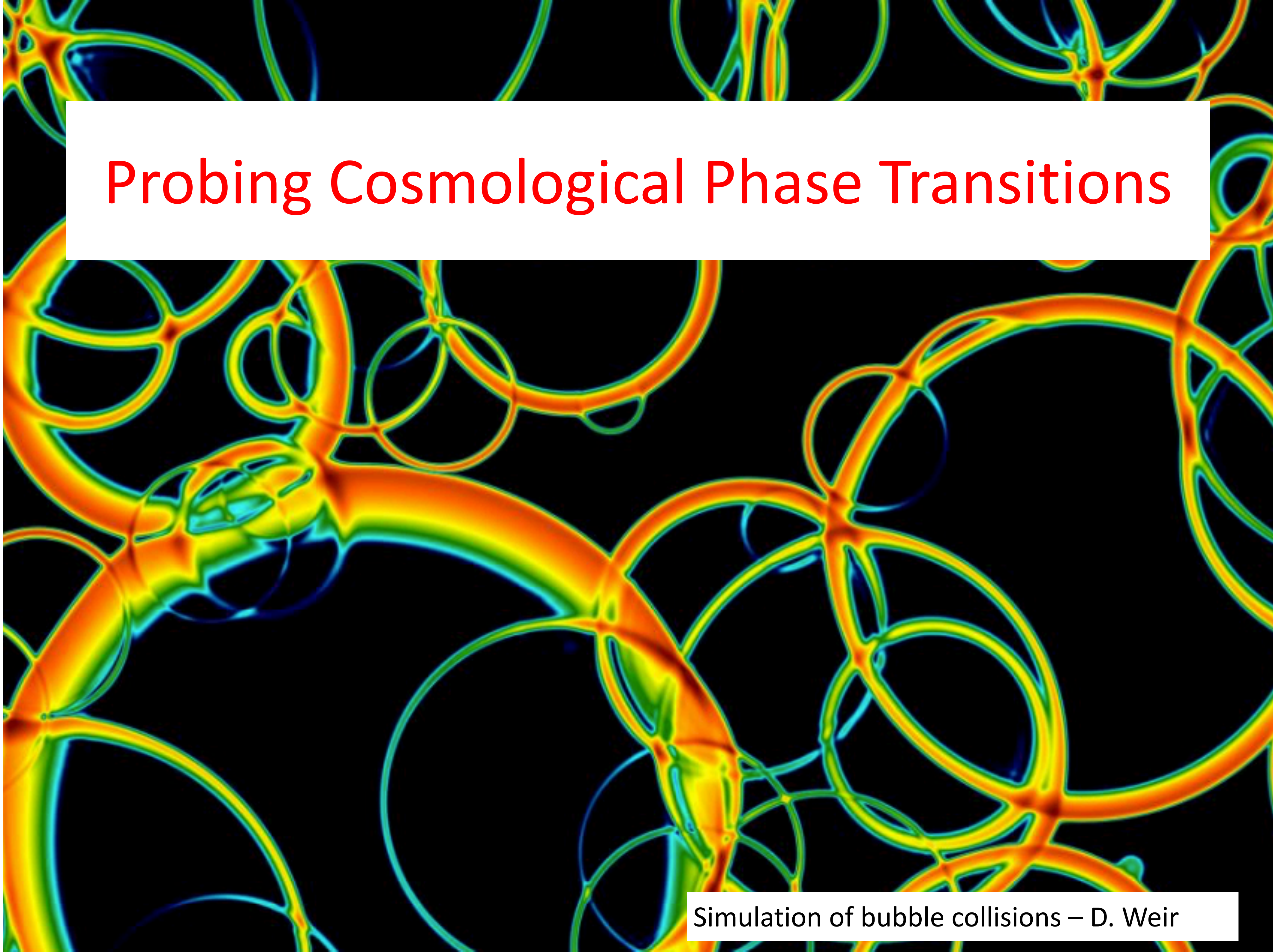
Superstring Fit to NANOGrav



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

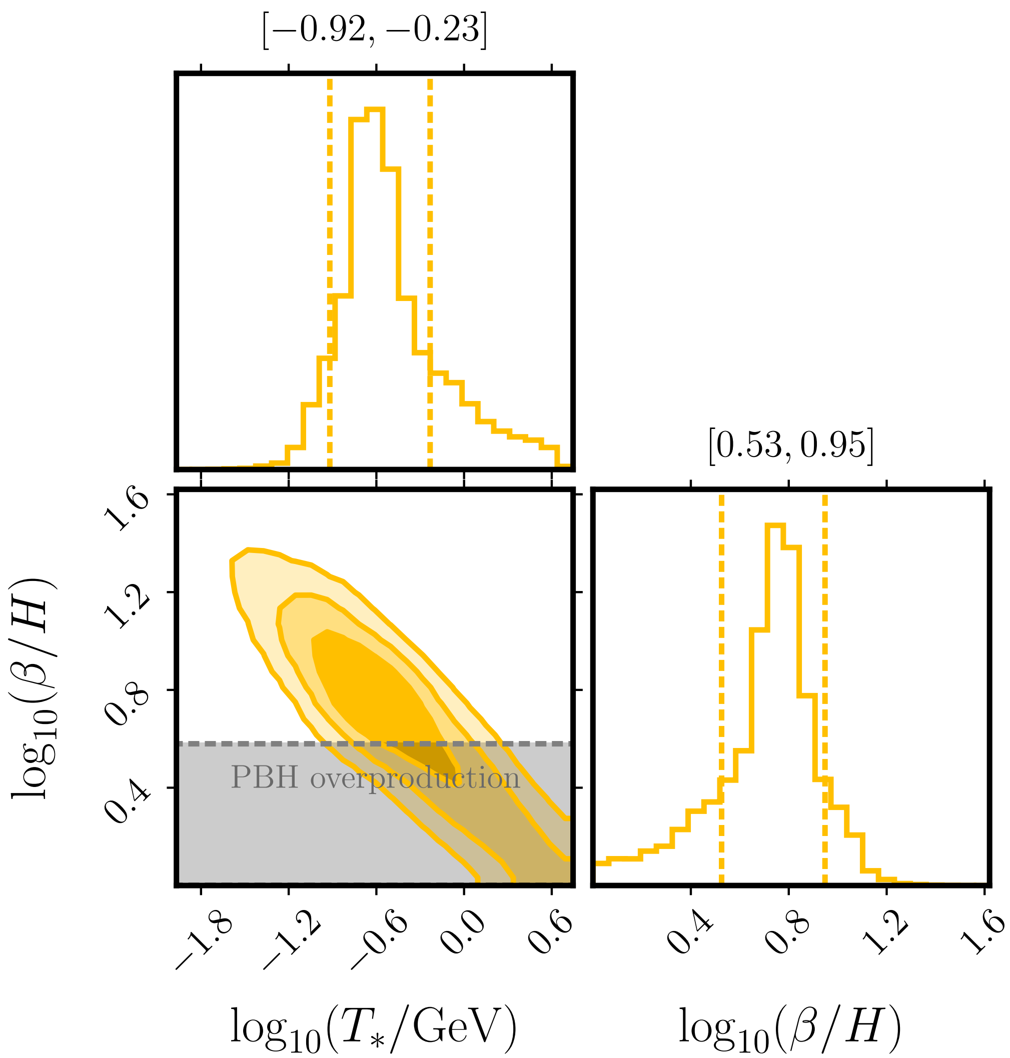
JE, Fairbairn, Franciolini, Hütsi,, Iovino, Lewicki, Urrutia, Vaskonen & Veermäe, arXiv:2308.08546

Probing Cosmological Phase Transitions



Simulation of bubble collisions – D. Weir

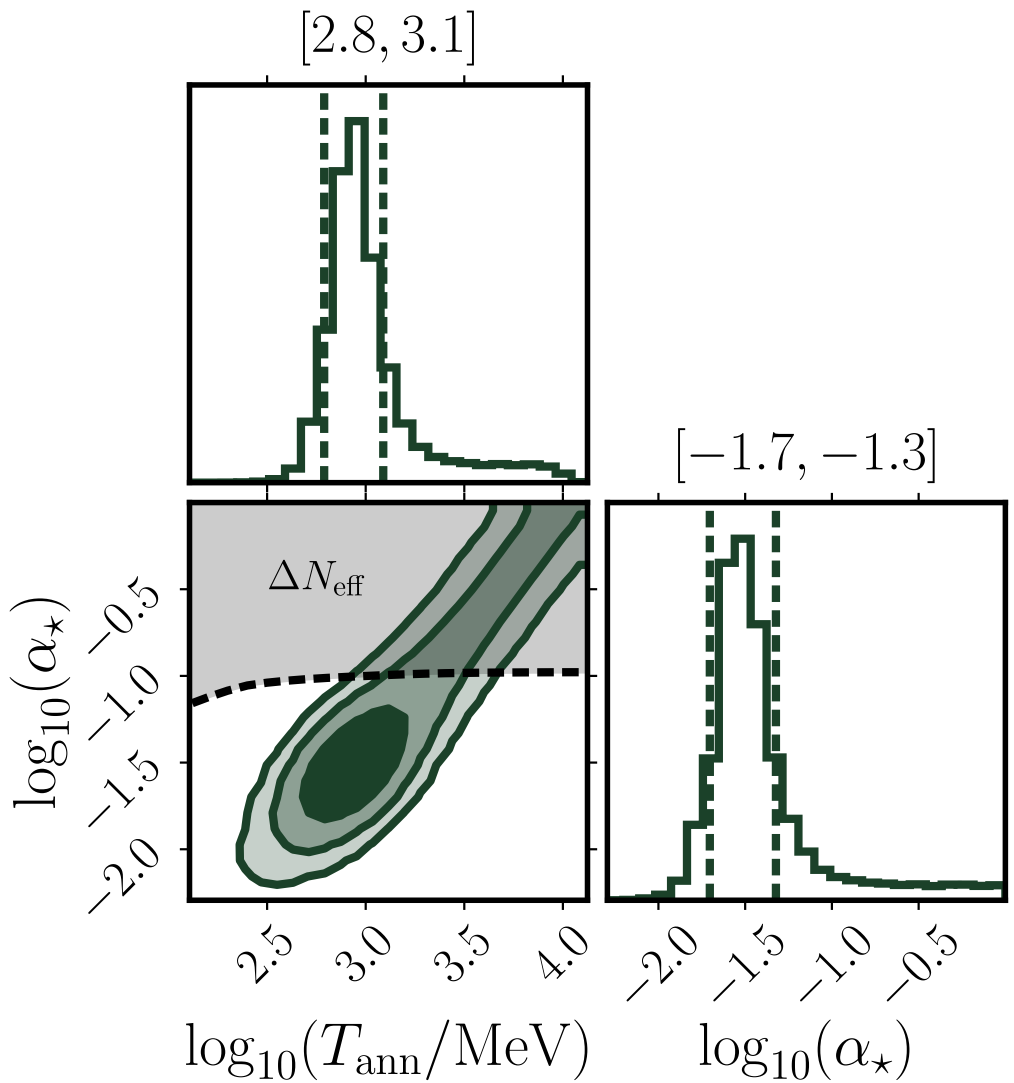
Phase Transition Fit to NANOGrav



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

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

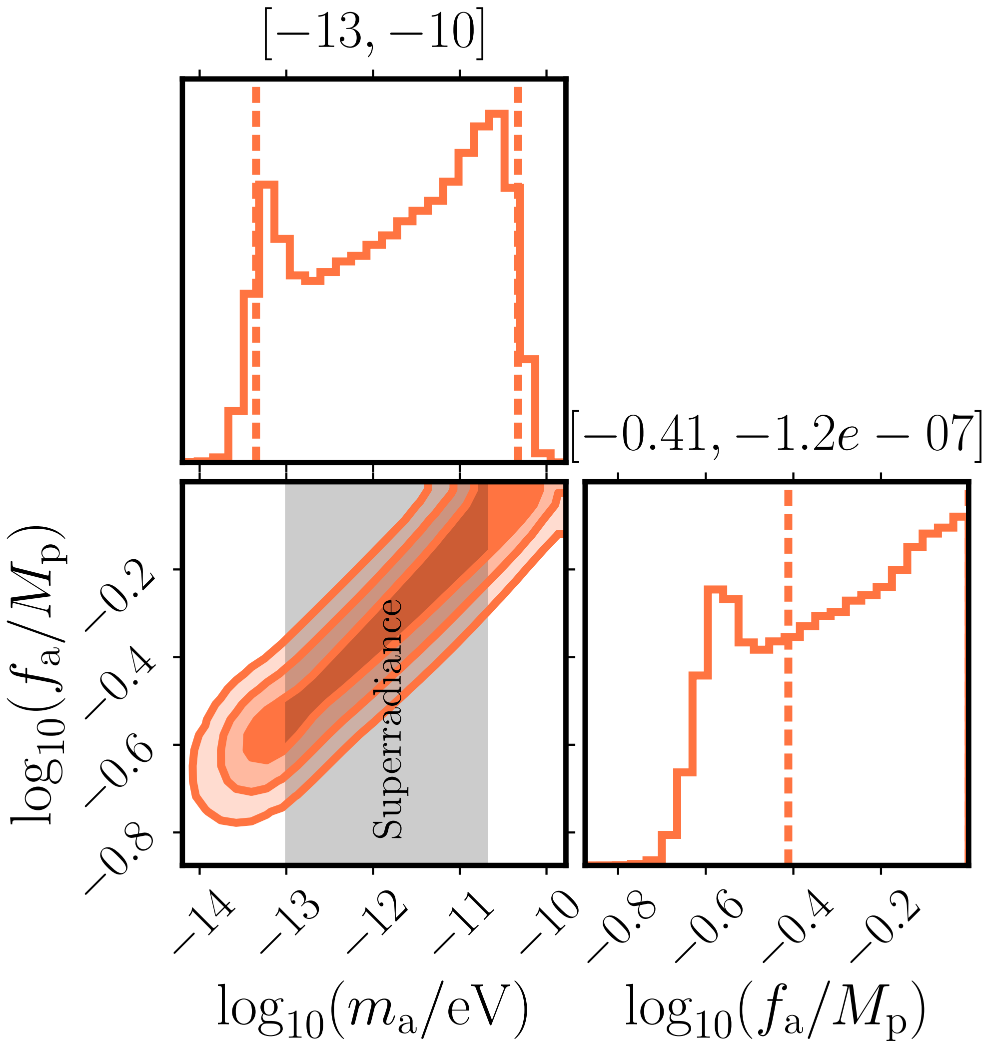
Domain Wall Fit to NANOGrav



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

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

Axion Fit to NANOGrav

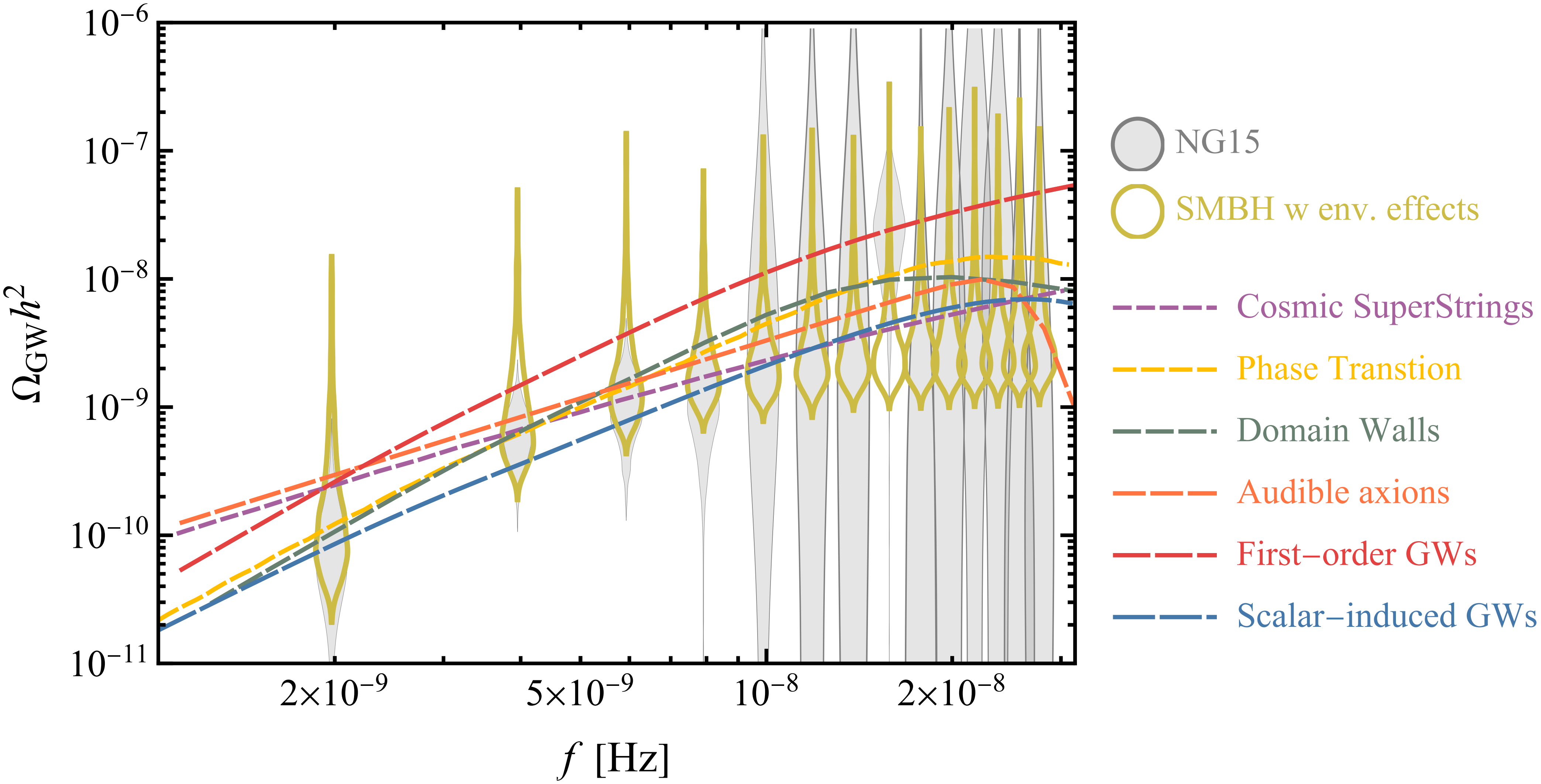


Axion model compatible with cosmology for

$m_a \sim 10^{-13}$ or $\sim 10^{-10}\,\mathrm{eV}$, $f_a \sim 10^{-6}$ or $\sim \mathcal{O}(1)\, M_P$

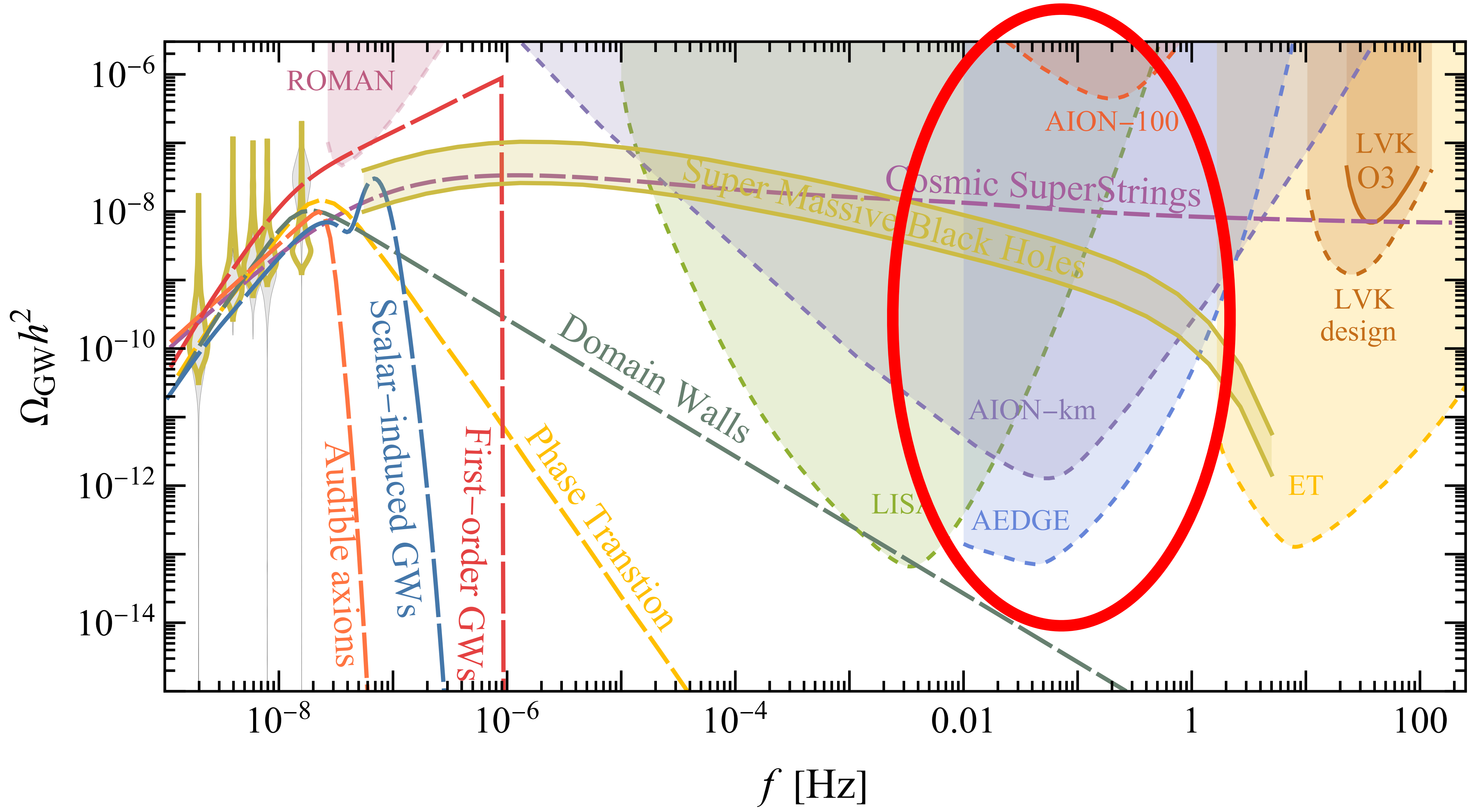
JE, Fairbairn, Franciolini, Hütsi,, Iovino, Lewicki, Urrutia, Vaskonen & Veermäe, arXiv:2308.08546

Fits to NANOGrav



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

Extension of Fits to Higher Frequencies



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

Results For NANOGrav Fits

Results from Multi-Model Analysis (MMA)

Scenario	Best-fit parameters	ΔBIC	Signatures
GW-driven SMBH binaries	$p_{\rm BH} = 0.25$	5.2	FAPS, LISA, mid-f, ~~LVK, ET~~
GW + environment-driven SMBH binaries	$p_{\rm BH} = 1$ $\alpha = 3.8$ $f_{\rm ref} = 12$ nHz	Baseline (BIC = 57.3)	FAPS, LISA, mid-f, ~~LVK, ET~~
Cosmic (super)strings (CS)	$G\mu = 2 \times 10^{-12}$ $p = 6.3 \times 10^{-3}$	-4.3 (2.5)	~~FAPS~~, LISA, mid-f, LVK, ET
Phase transition (PT)	$T_* = 0.24$ GeV $\beta/H = 6.0$	-8.9 (-1.0)	~~FAPS, LISA, mid-f, LVK, ET~~
Domain walls (DWs)	$T_{\rm ann} = 0.79$ GeV $\alpha_* = 0.026$	-8.8 (-1.5)	~~FAPS~~, LISA?, ~~mid-f, LVK, ET~~
Scalar-induced GWs (SIGWs)	$k_* = 10^{7.6}$/Mpc $A = 10^{-1.1}$ $\Delta = 0.28$	-5.4 (2.5)	~~FAPS, LISA, mid-f, LVK, ET~~
First-order GWs (FOGWs)	$\log_{10} r = -16.25$ $n_t = 2.87$ $\log_{10} T_{\rm rh} = -0.45$	-5.5 (2.6)	~~FAPS, LISA, mid-f, LVK, ET~~
"Audible" axions and Axion-Like Particles (ALPs)	$m_a = 3.1 \times 10^{-11}$ eV $f_a = 0.87\, M_{\rm P}$	-7.7 (0.7)	~~FAPS, LISA, mid-f, LVK, ET~~

FAPS ≡ fluctuations, anisotropies, polarization, sources, mid-f ≡ mid-frequency experiment, e.g., AION [281], AEDGE [283], LVK ≡ LIGO/Virgo/KAGRA [164–166], ET ≡ Einstein Telescope [285] (or Cosmic Explorer [286]), ~~signature~~ ≡ not detectable

TABLE I. *The parameters of the different models are defined in the text. For each model, we tabulate their best-fit values, and the Bayesian information criterion* $BIC \equiv -2\Delta\ell + k \ln 14$ *relative to that for the purely SMBH model with environmental effects that we take as the baseline. The quantity in the parentheses in the third column shows the* ΔBIC *for the best-fit combined SMBH+cosmological scenario. The last column summarizes the prospective signatures.*

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** AION
- **Time and more data will tell!**

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