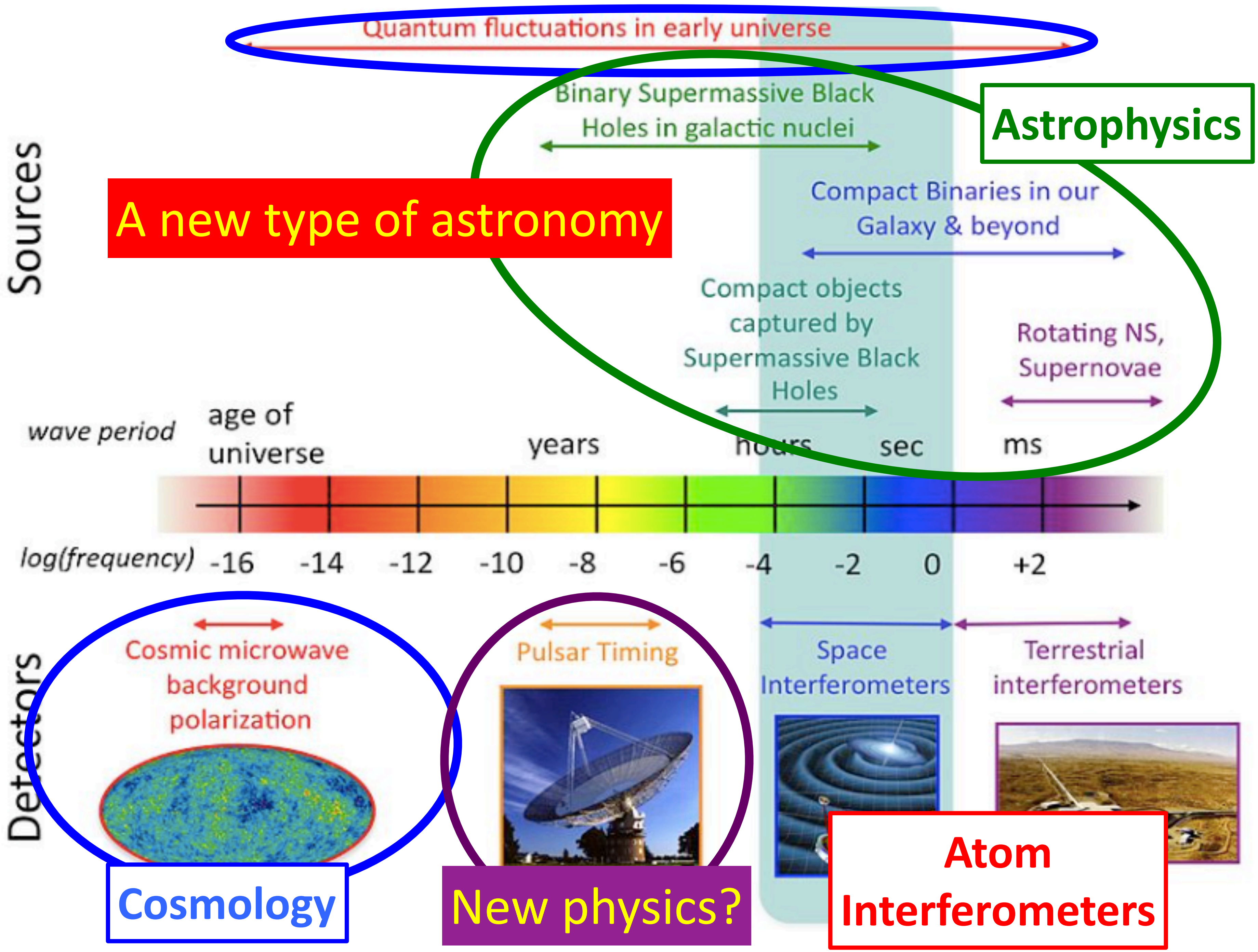
What is the source of the gravitational waves detected by NANOGrav and other PTA experiments?

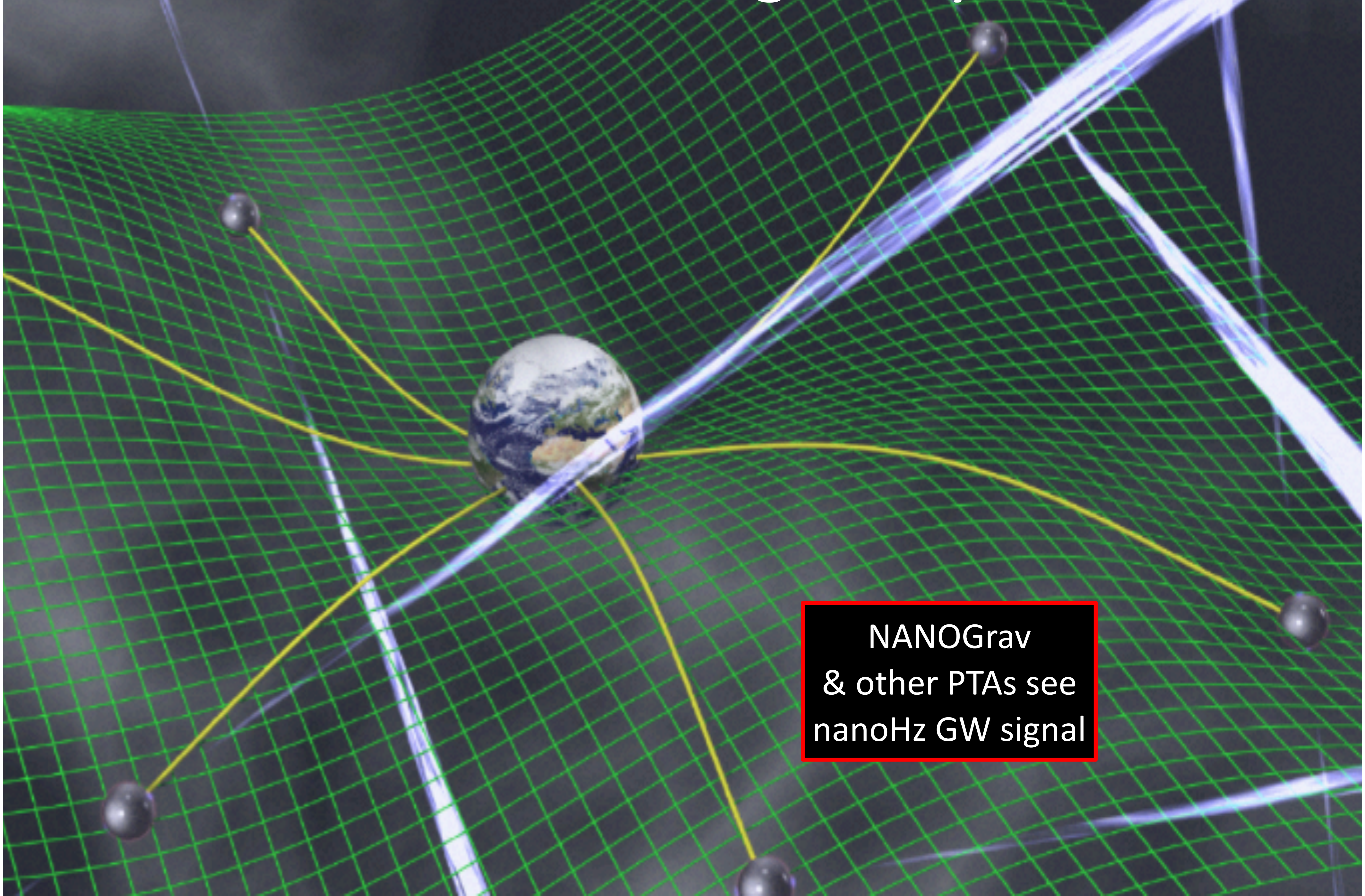
John Ellis

KING'S College LONDON

Gravitational Wave Spectrum

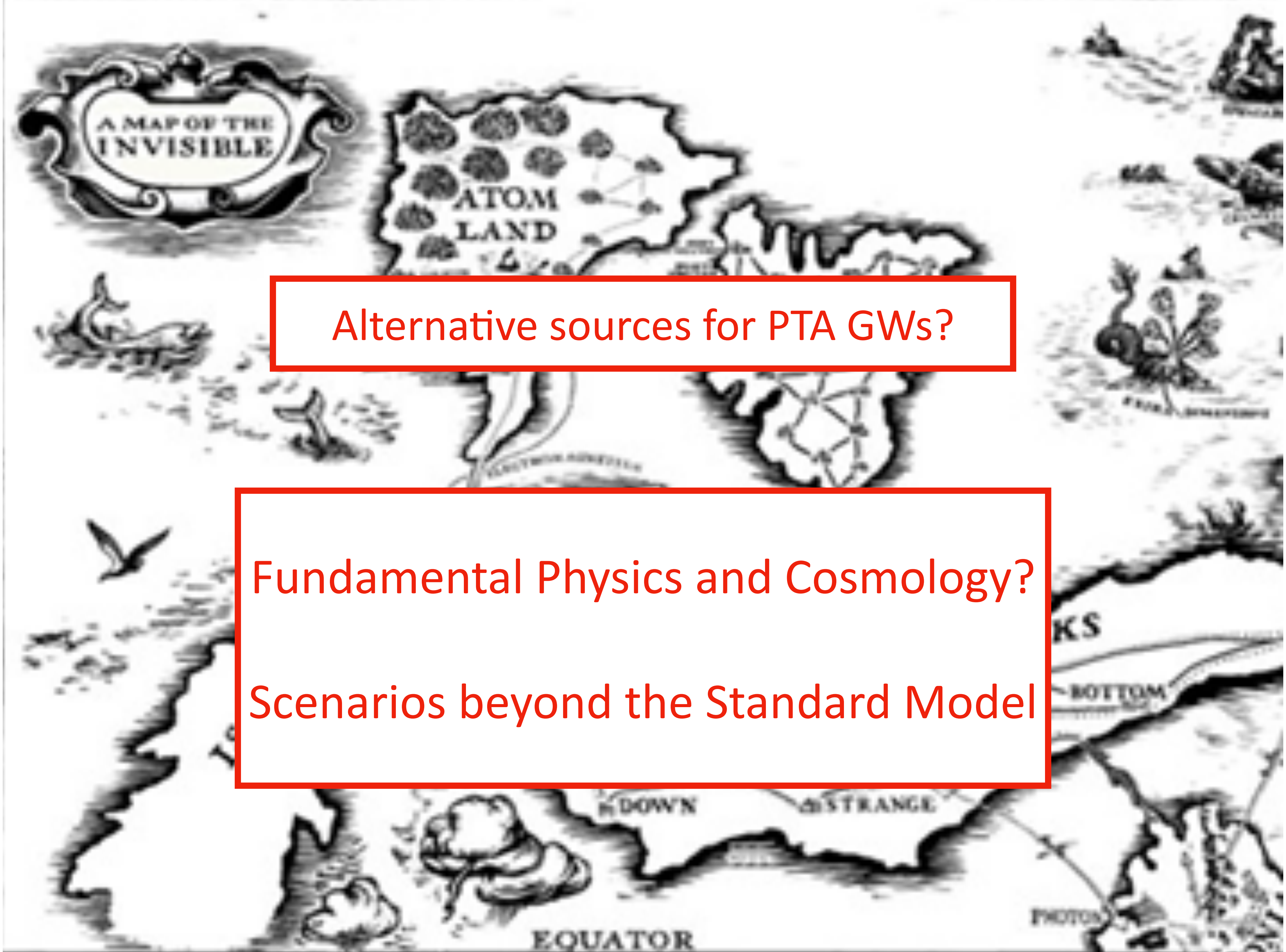


Pulsar Timing Arrays



The Biggest Bangs since the Big Bang?


STELIOS THOUKIDIDES

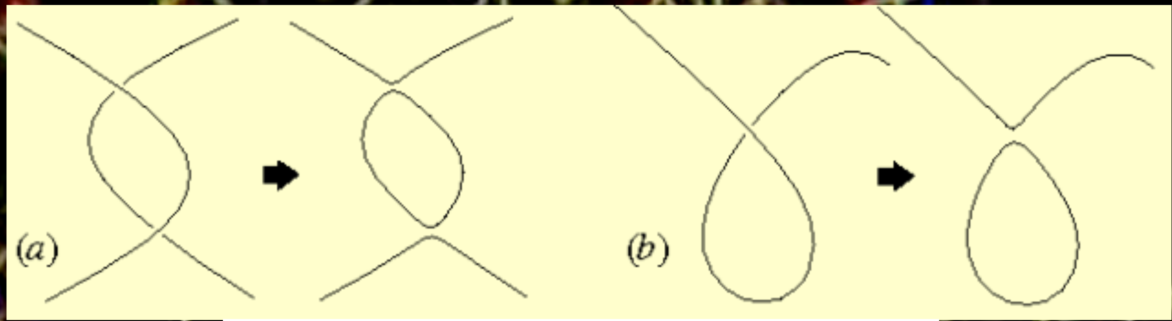


Alternative sources for PTA GWs?

Fundamental Physics and Cosmology?

Scenarios beyond the Standard Model

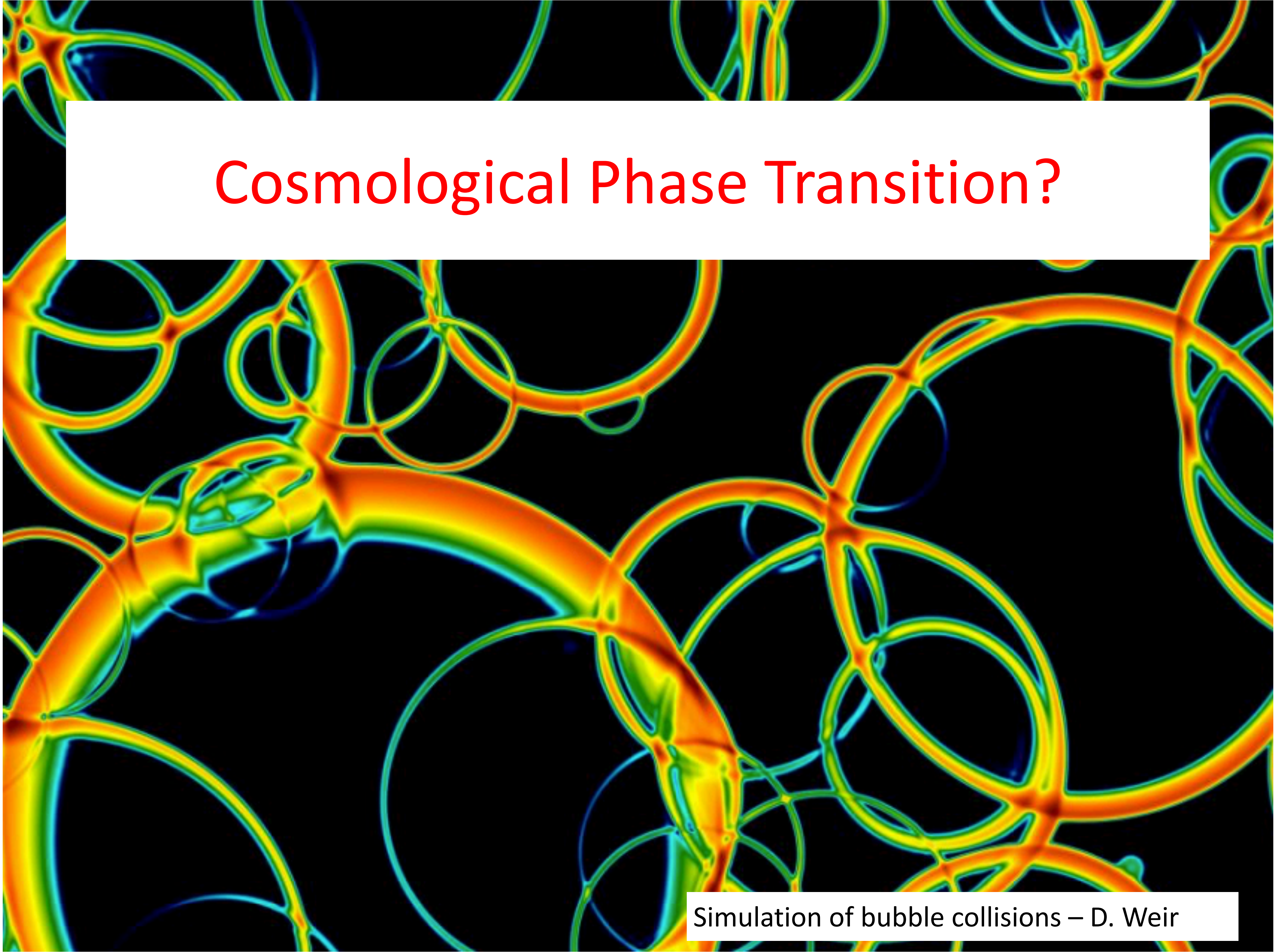
Cosmic Strings?



GW emission from string loops

Simulation of cosmic string network – Cambridge cosmology group

Cosmological Phase Transition?



Simulation of bubble collisions – D. Weir

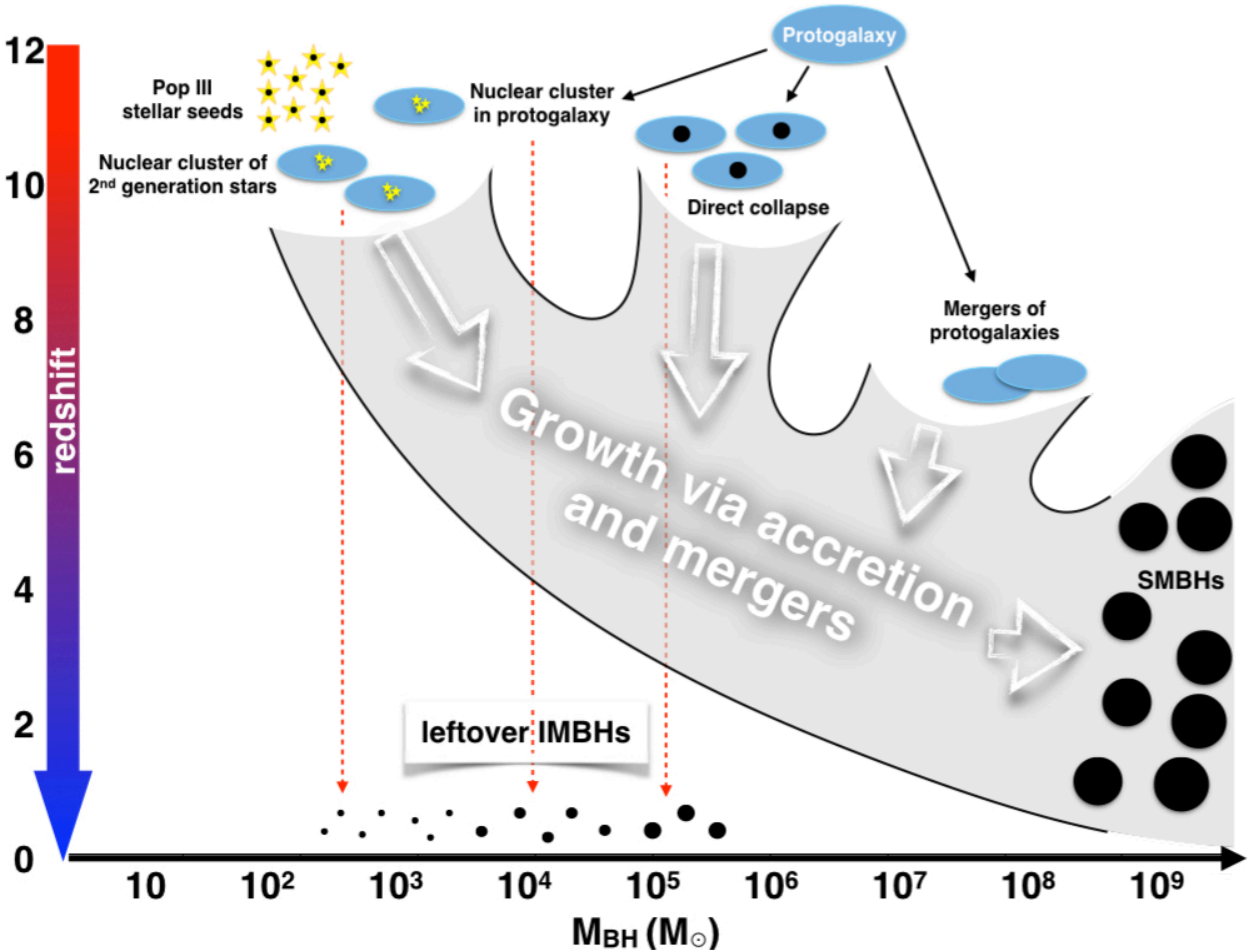
Outline

- Supermassive black hole binaries?
- Analysis of NANOGrav PTA data
- Better fit if binaries interact with environment
- BSM scenarios:
  - Strings, phase transition, domain walls, 1st/2nd-order inflationary scenarios, axion
- **All fit NANOGrav data better than BH binaries!**

JE & Lewicki: arXiv:2009.06555;
JE, Fairbairn, Hütsi, Raidal, Urrutia, Vaskonen & Veermäe: arXiv:2301.13854;
JE, Fairbairn, Hütsi, Raidal', Urrutia, Vaskonen & Veermäe: arXiv:2306.17021;
JE, Lewicki, Lin, & Vaskonen: arXiv:2306.17147;
JE, Fairbairn, Franciolini, Hütsi, Iovino, Lewicki, Urrutia, Vaskonen & Veermäe, arXiv:2308.08546

How to Make a Supermassive BH?

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



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,

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

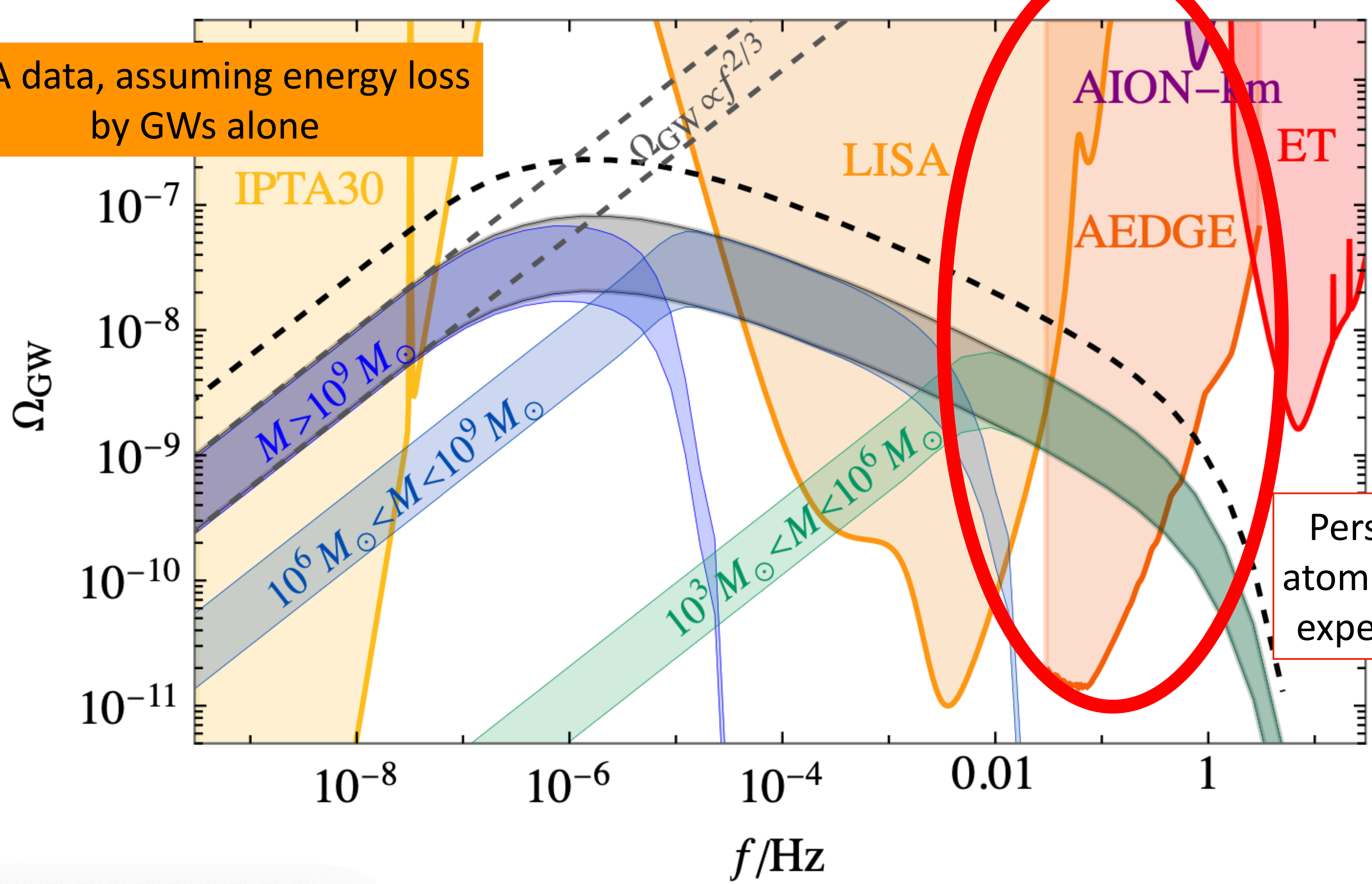
is merger probability, and

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

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

Stochastic GW Background from BH Mergers

IPTA data, assuming energy loss by GWs alone



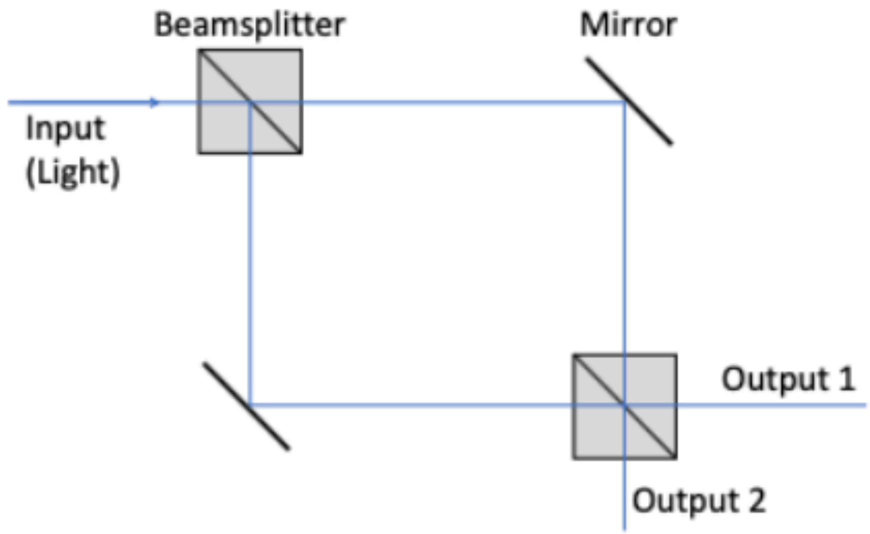
Personal interest: atom interferometer experiments: AION

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

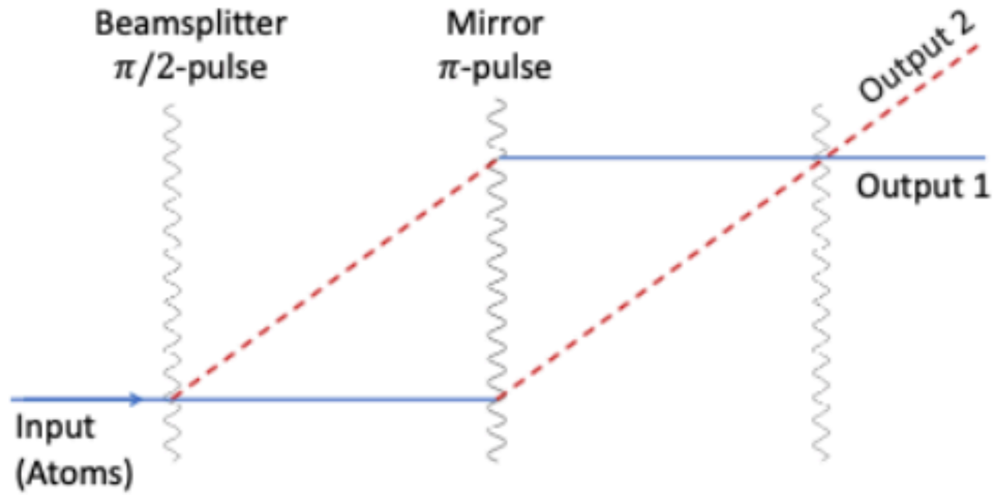
JE, Fairbairn, Hütsi, Raidal, Urrutia, Vaskonen & Veermäe: arXiv:2301.13854

Principle of Atom Interferometry

Mach-Zehnder Laser Interferometer

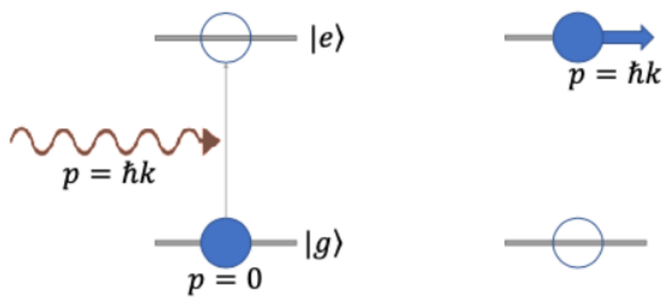


Atom Interferometer



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

Interference between atoms following different paths

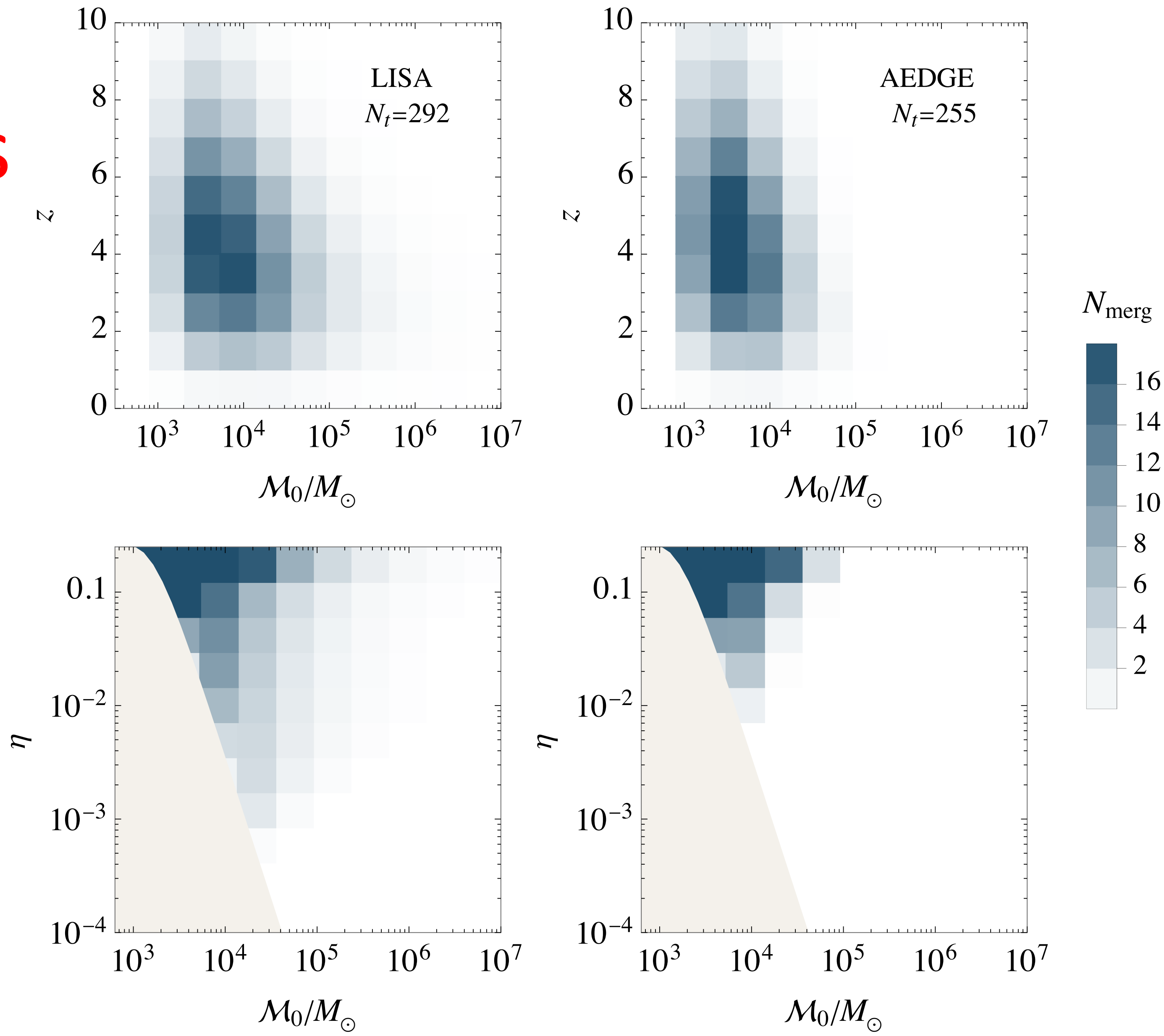


Detecting IMBH Mergers

LISA and AEDGE would observe similar numbers of IMBH mergers

AEDGE mergers would have been observed by LISA during infall

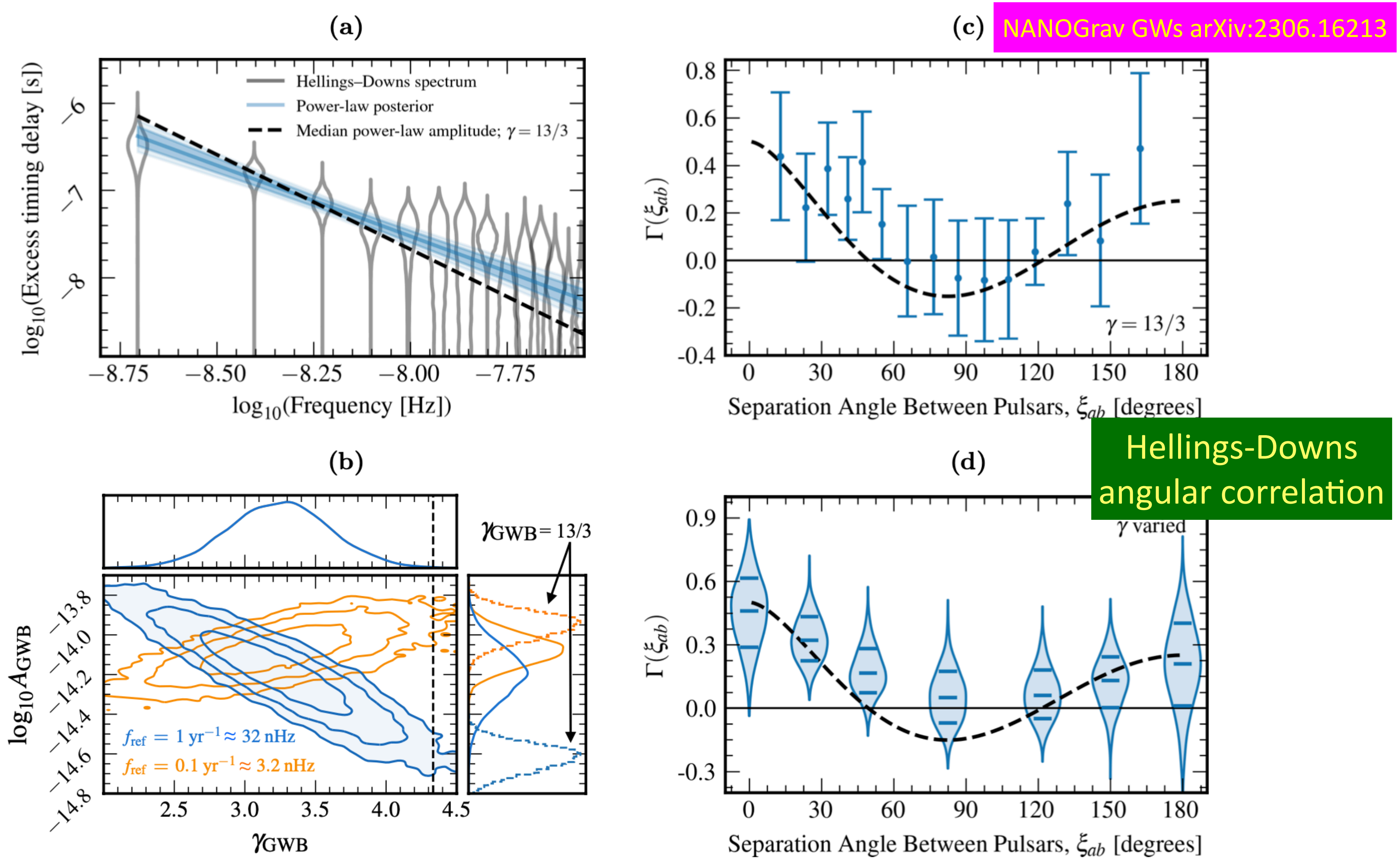
Opportunities to test GR, multi-messenger astronomy



$\mathcal{M}_0$ = chirp mass, η = mass ratio

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

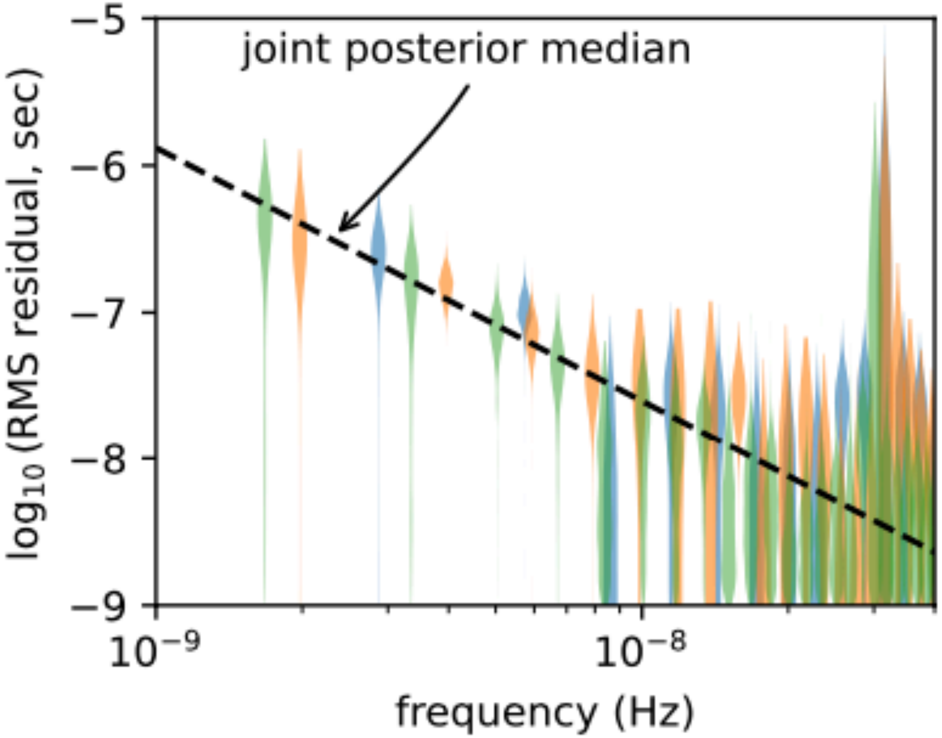
NANOGrav 15-Year Data



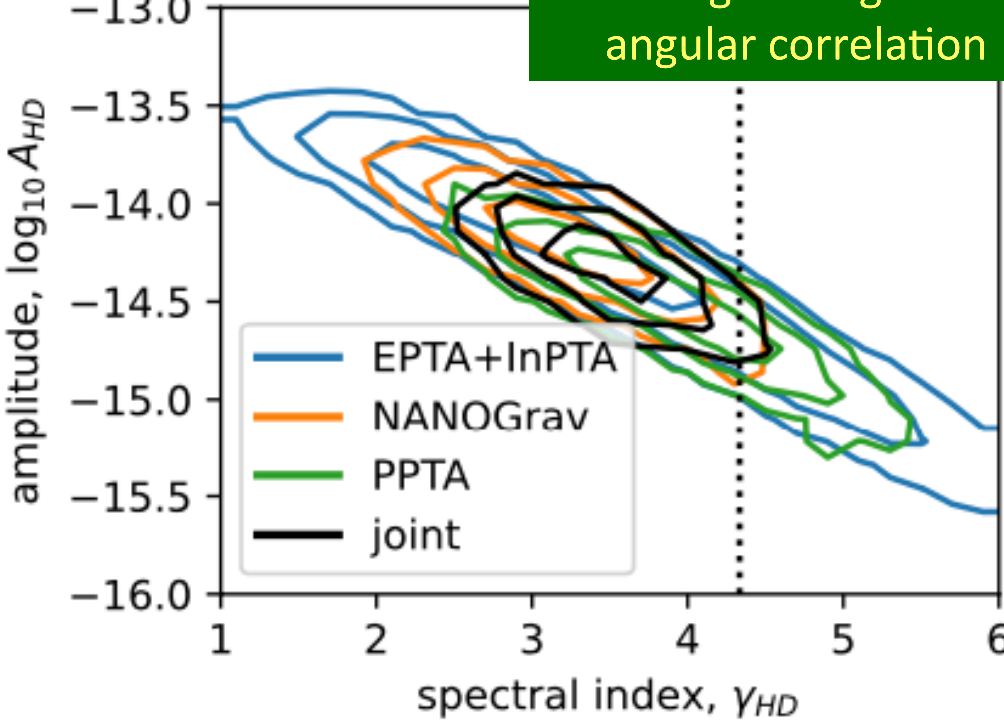
Expect spectral index $\gamma = 13/3$ for SMBH binaries: not a good fit

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

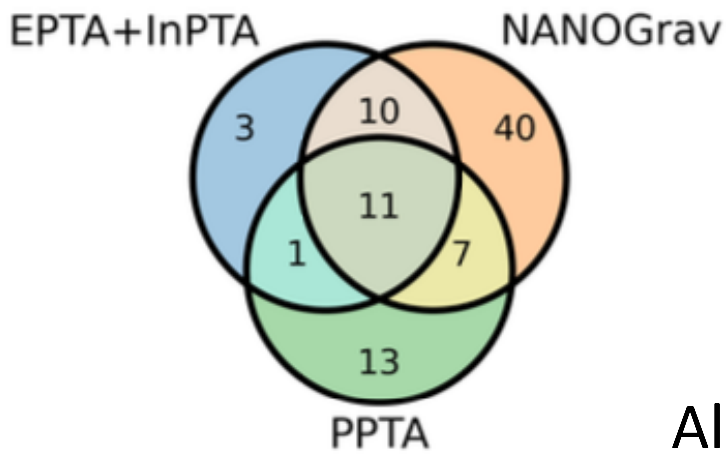
IPTA Data Compilation



Assuming Hellings-Downs angular correlation



Venn diagram of PTA data sets

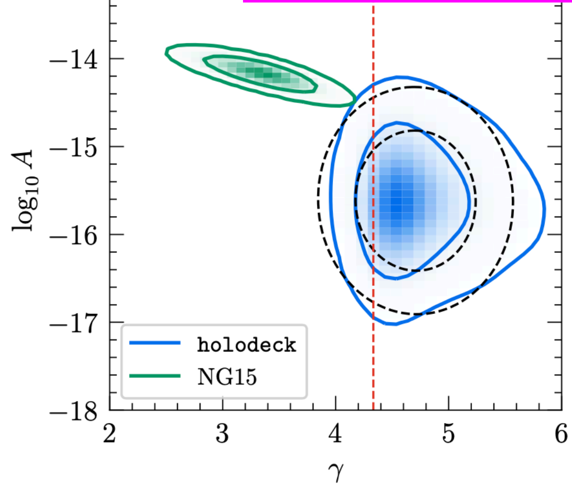


IPTA Collaboration, arXiv:2309.00693

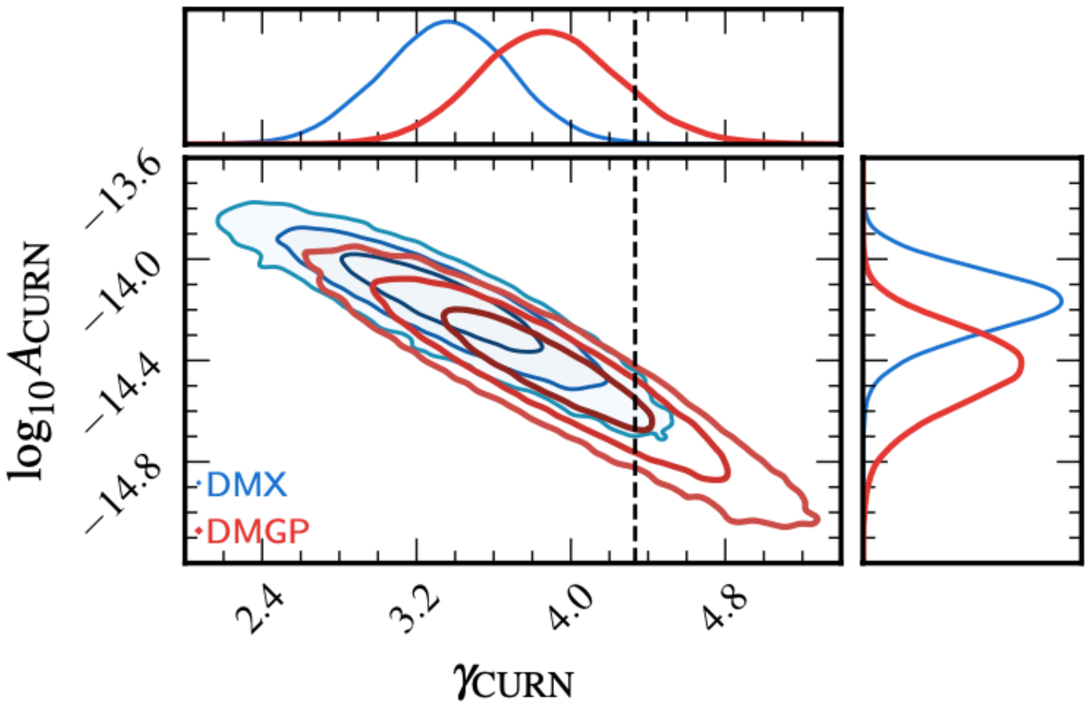
Also Chinese PTA

NANOGrav 15-Year Data

NANOGrav BSM arXiv:2306.16219

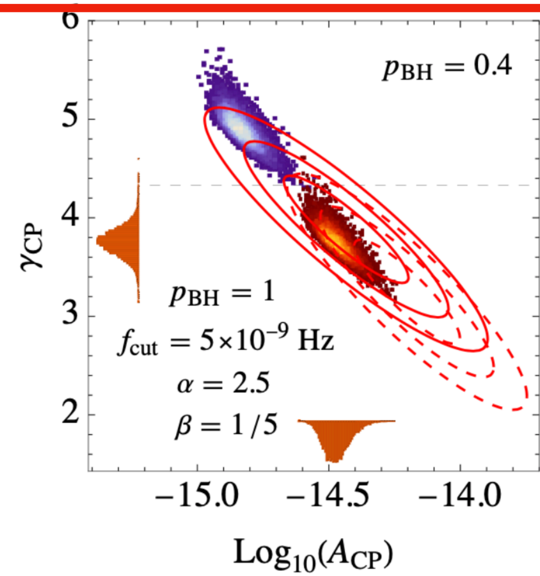


NANOGrav GWs arXiv:2306.16213



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

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: $\dot{E} = -\dot{E}_{\mathrm{GW}} - \dot{E}_{\mathrm{env}}$
- Characteristic time scales: $t_{\mathrm{GW}} \equiv E/\dot{E}_{\mathrm{GW}} = 4\tau\,,\; t_{\mathrm{env}} \equiv E/\dot{E}_{\mathrm{env}}$
- Where $\tau = \frac{5}{256}(\pi f_r)^{-8/3}\mathcal{M}^{-5/3}$
- Energy radiated in GWs reduced because of accelerated evolution:

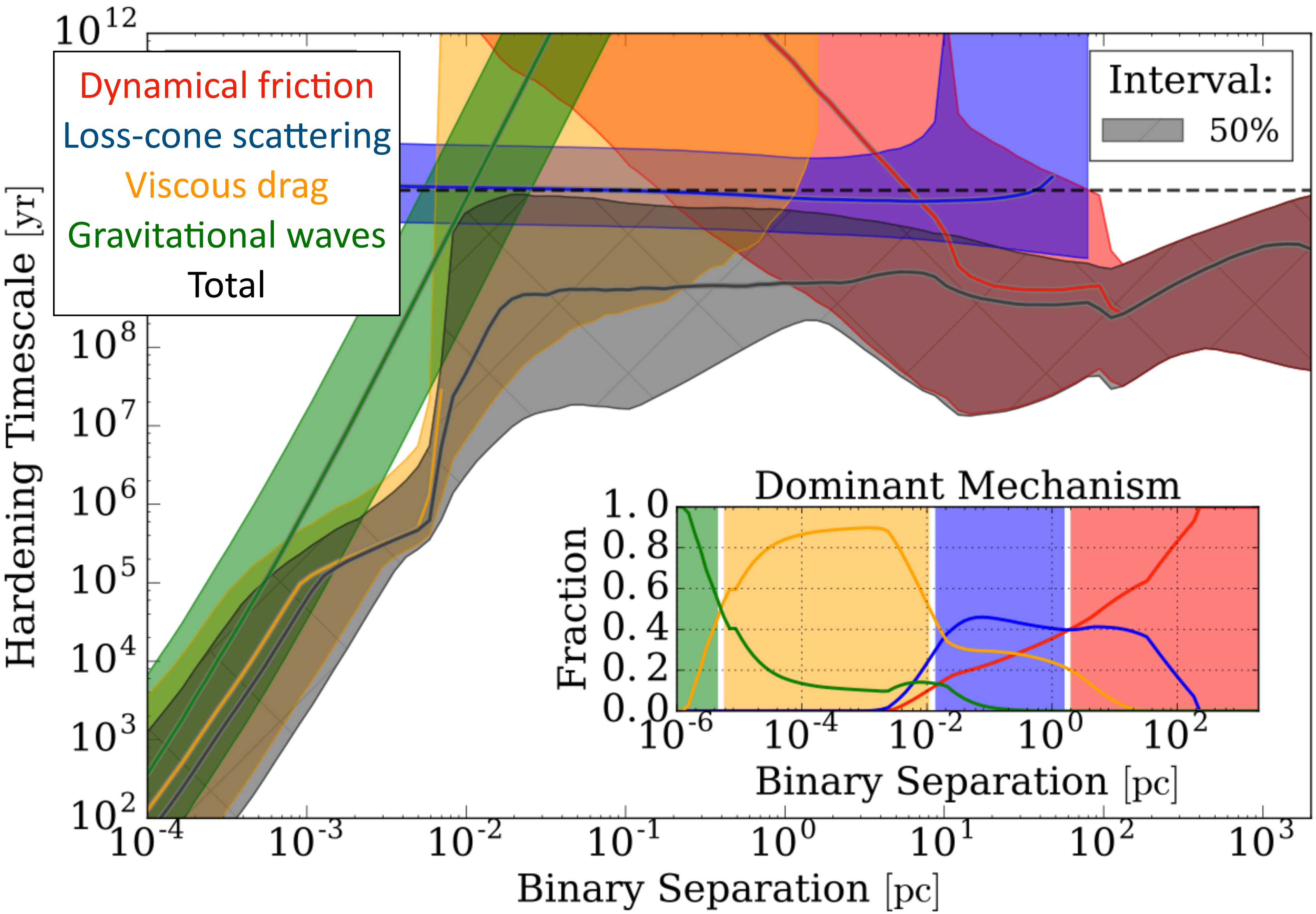
$$\frac{\mathrm{dE_{GW}}}{\mathrm{d\,ln\,f_r}} = \frac{1}{3}\frac{(\pi f_r)^{\frac{2}{3}}\mathcal{M}^{\frac{5}{3}}}{1 + t_{\mathrm{GW}}/t_{\mathrm{env}}}$$

- Phenomenological parametrization:

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

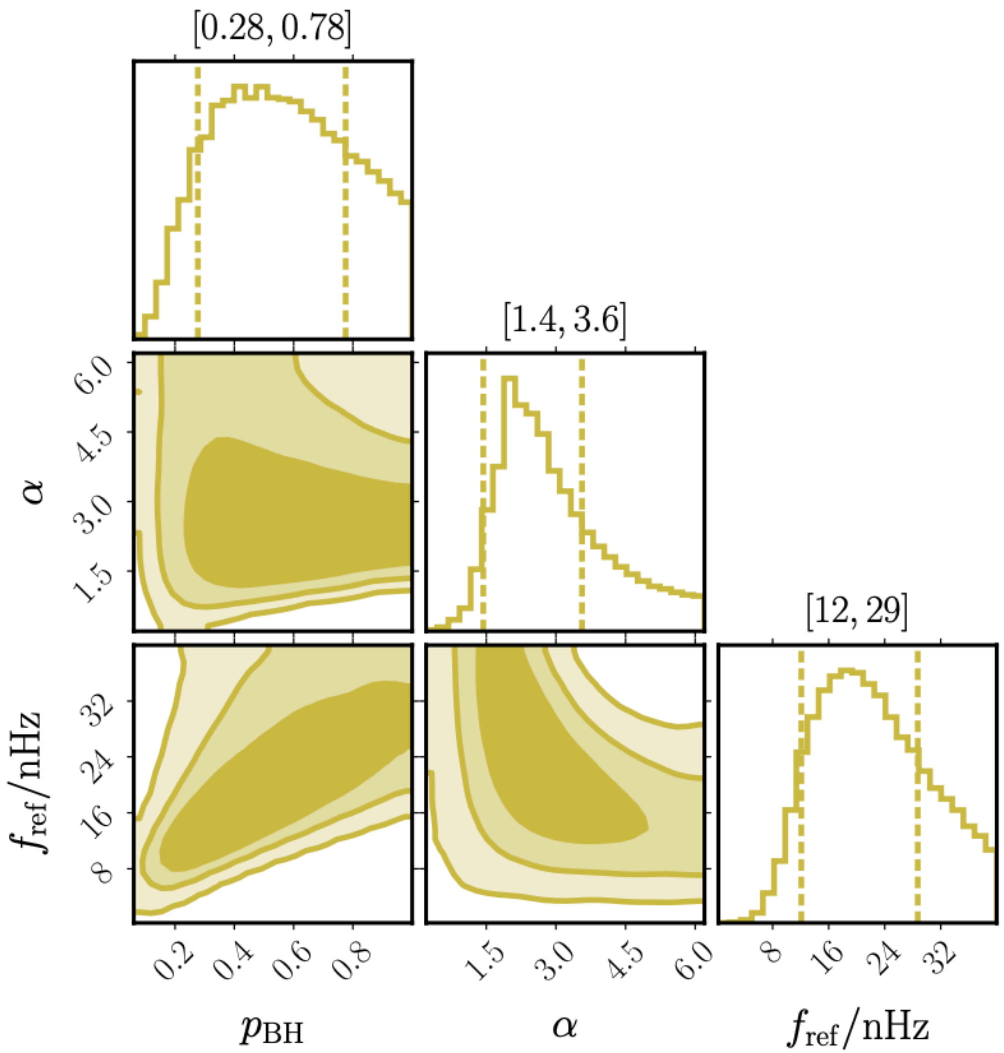
JE, Fairbairn, Hütsi, Raidal’, Urrutia, Vaskonen & Veermäe: arXiv:2306.17021

Mechanisms for Energy Loss



Kelley, Blecha & Hernquist, arXiv:1606.01900

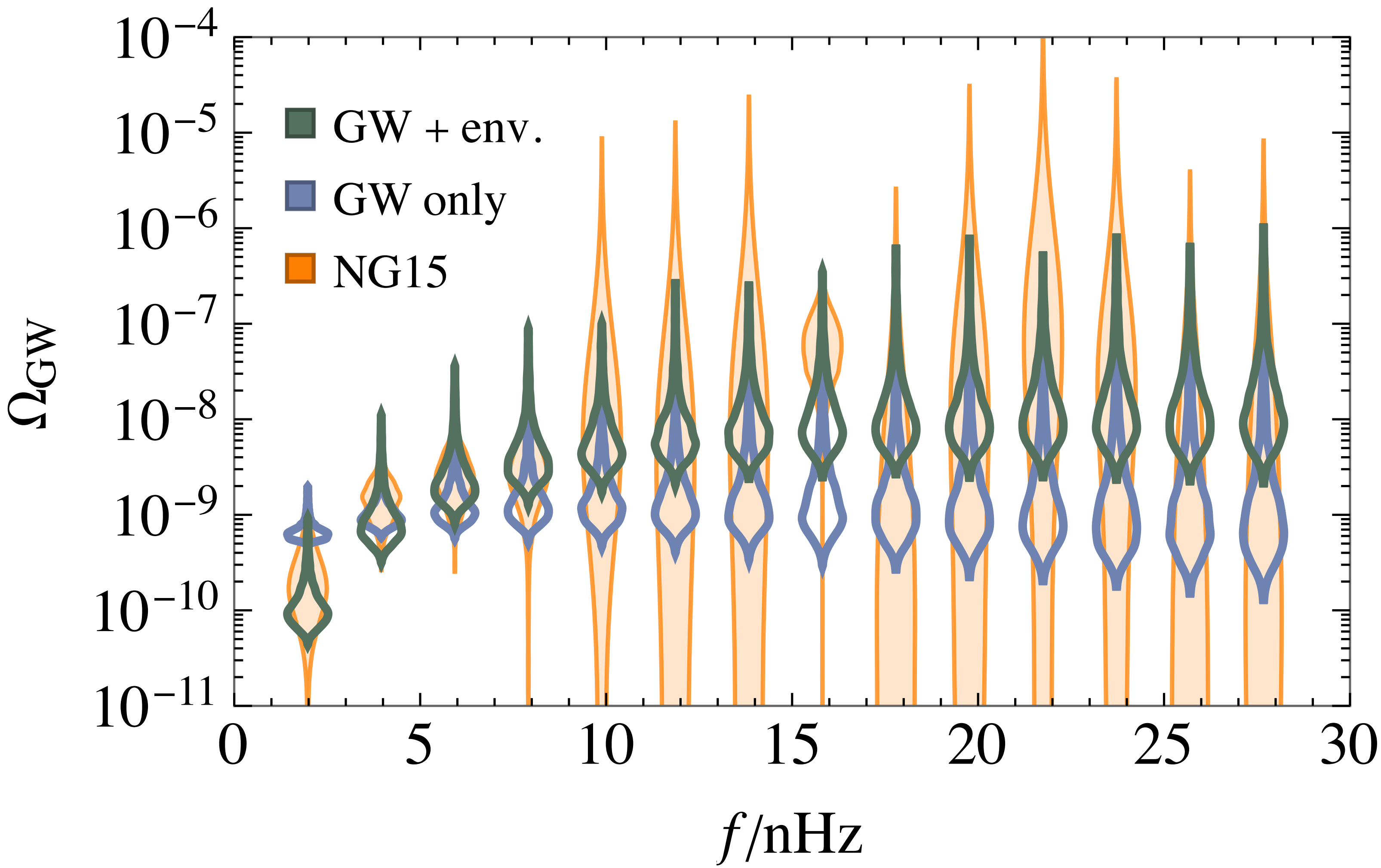
SMBH Fits to NANOGrav



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

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

Astrophysical Interpretations AION



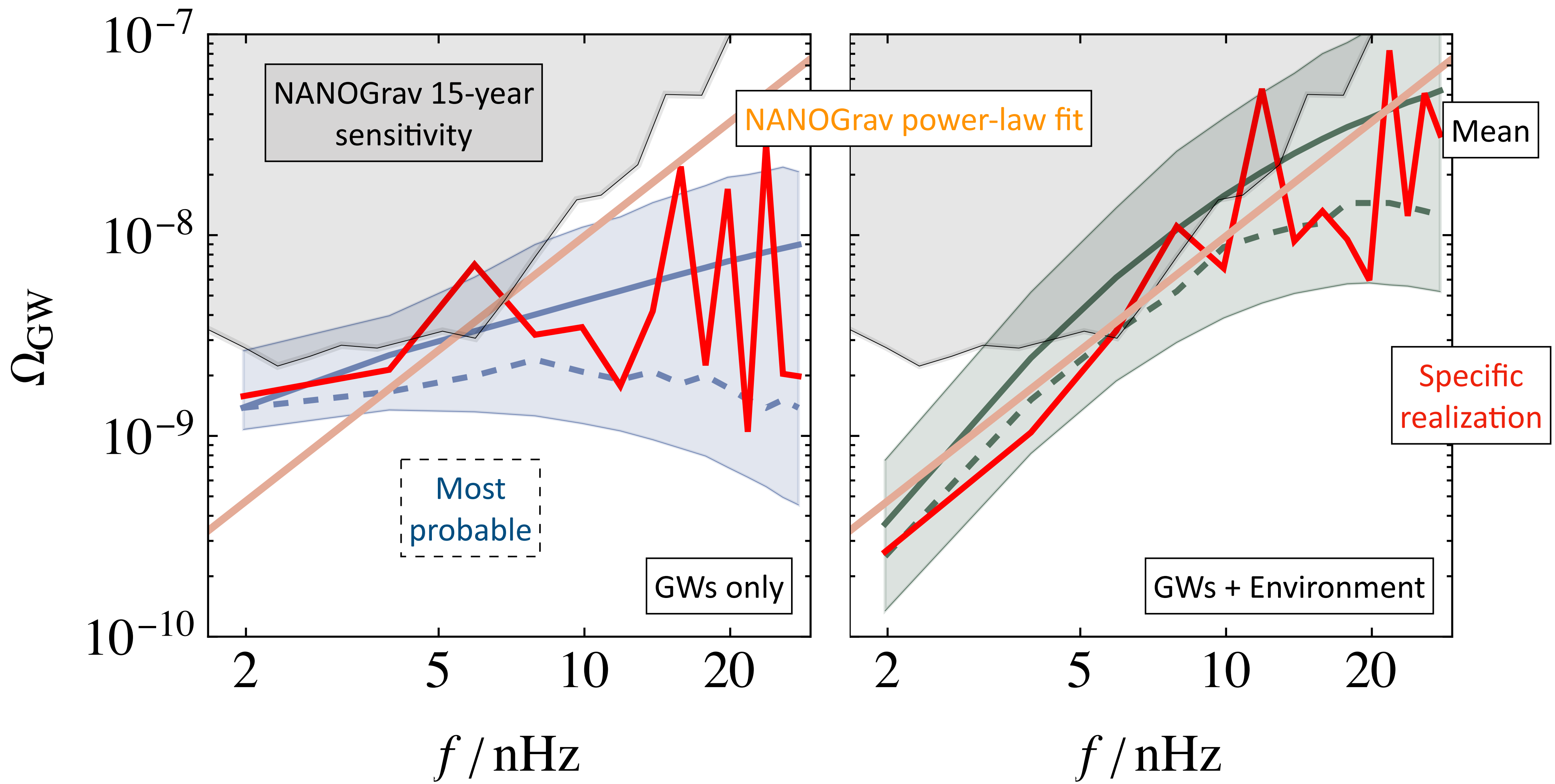
Fits use overlaps of data and model violins in each bin

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

GWs + Environment? AION



Bigger chance to see specific binaries if evolution also driven by environment

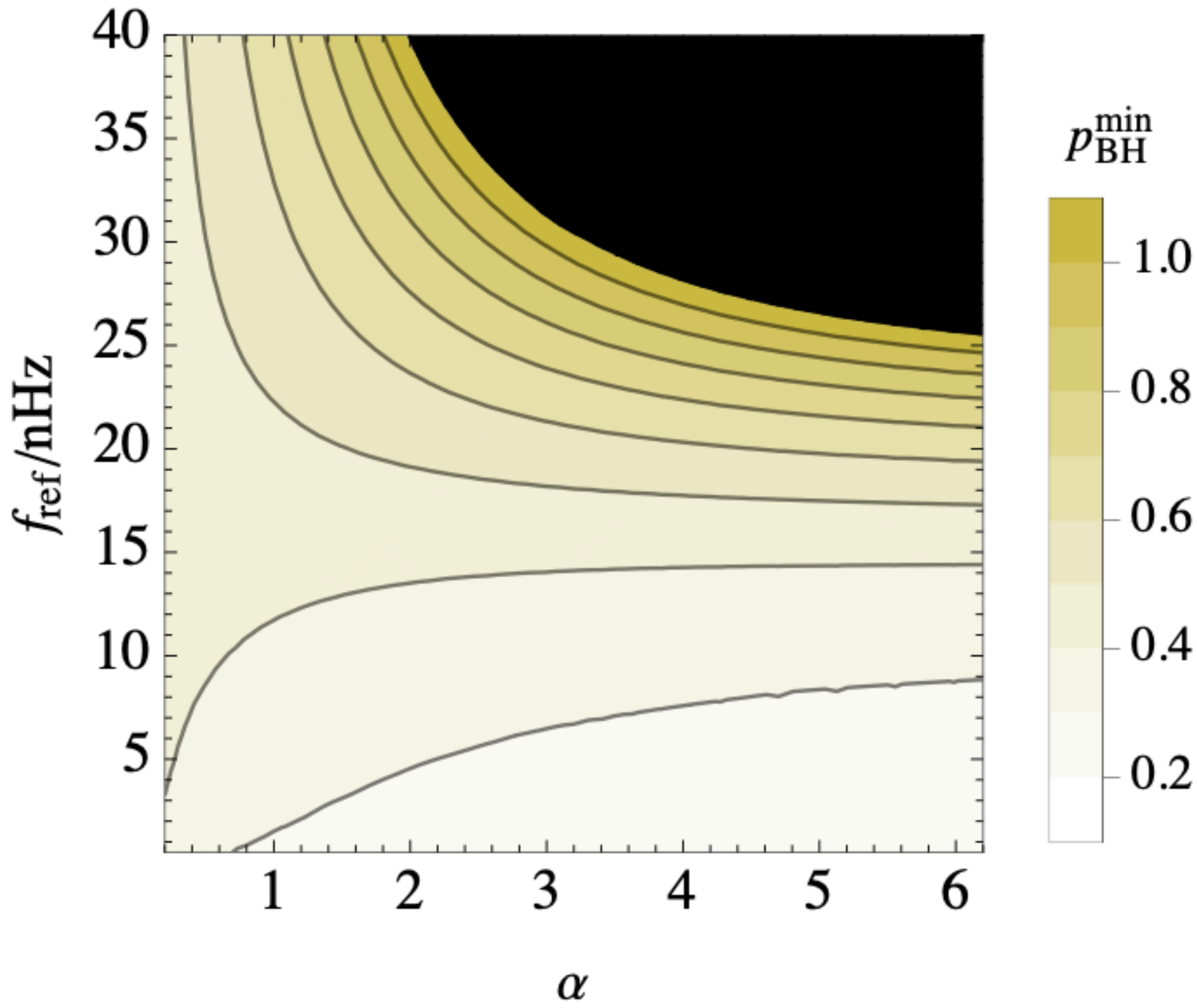
(0.8 events vs 0.4 if GW only, most likely ~ 5 nHz)

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

NANOGrav & EPTA @ 4 nHz?

AION

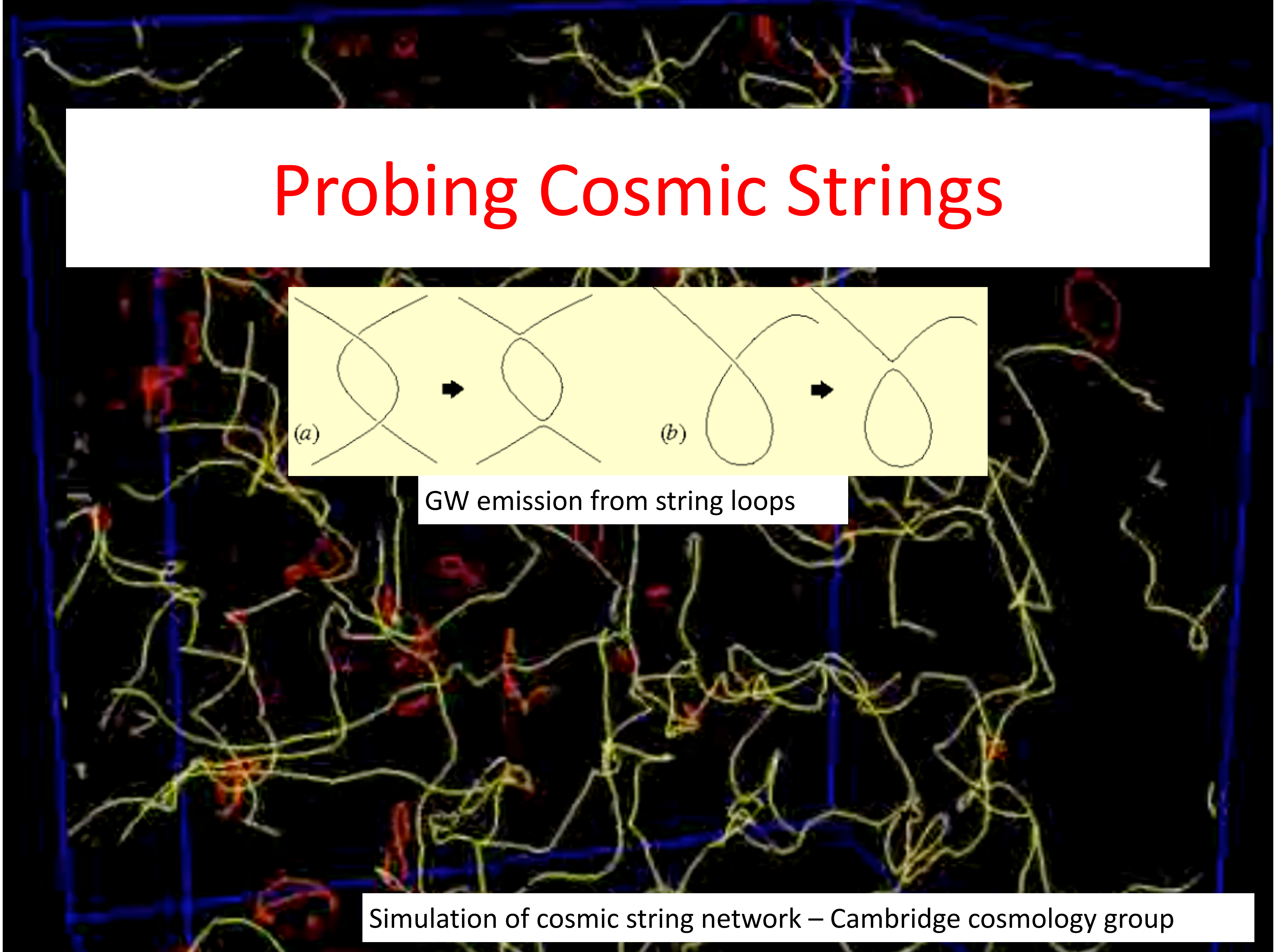
NANOgrav and EPTA both report hint of up-fluctuation at ~ 4 nHz



Region of parameter space of SMBH + environment: probability $> 5\,\%$

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

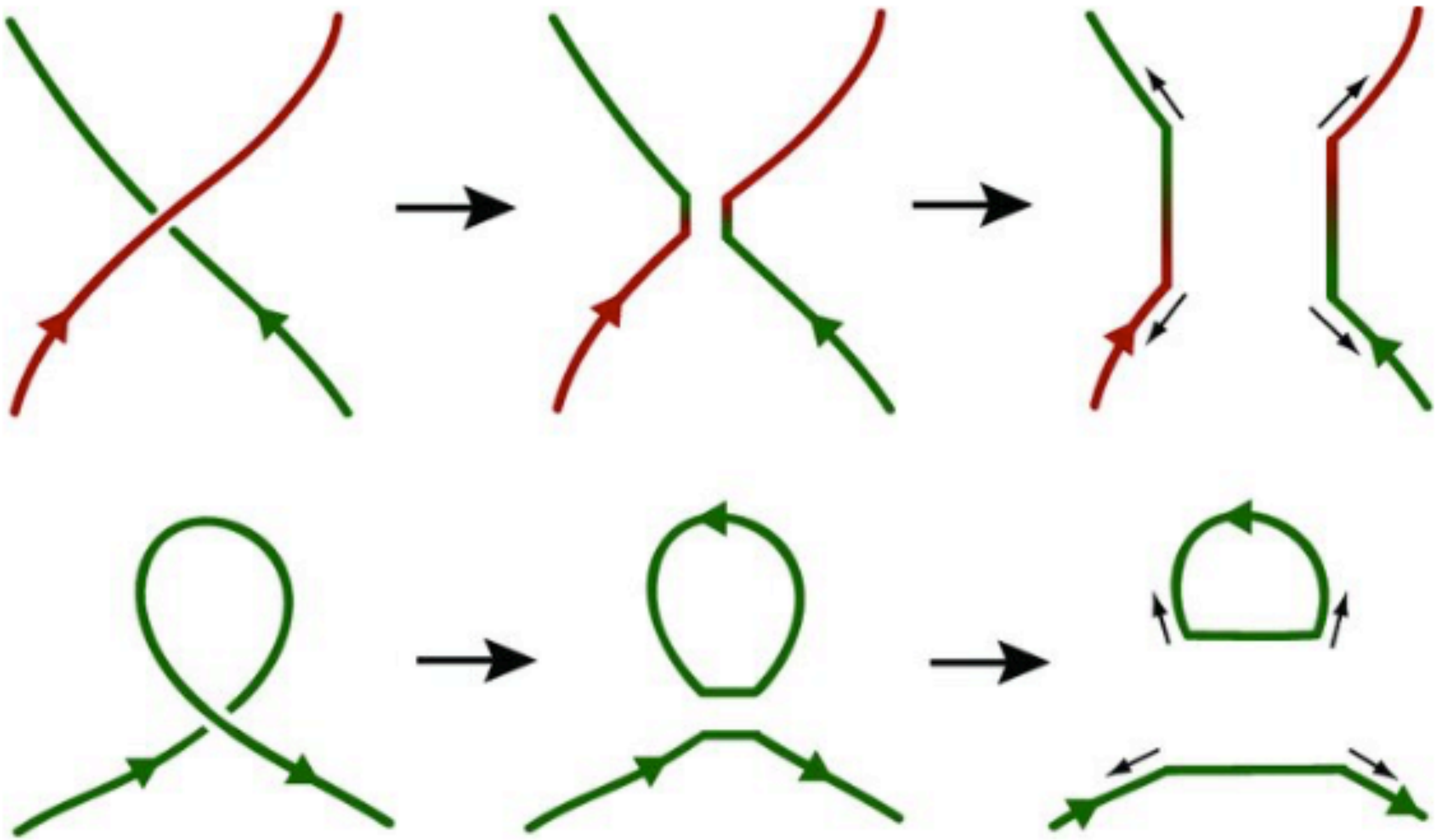
Probing Cosmic Strings



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 $p < 1$

JE & Lewicki: arXiv:2009.06555

Calculation of GWs from Cosmic Strings

- Use Velocity-dependent One-Scale (VOS) Model
- Network of strings produces loops, lengths:

$$\ell = \alpha_\ell t_i - \Gamma G\mu (t - t_i)$$

- Loops emit at normal mode frequencies:

$$f = \frac{a(\tilde{t})}{a(t_0)} \frac{2k}{\alpha_\ell t_i - \Gamma G\mu(\tilde{t} - t_i)}$$

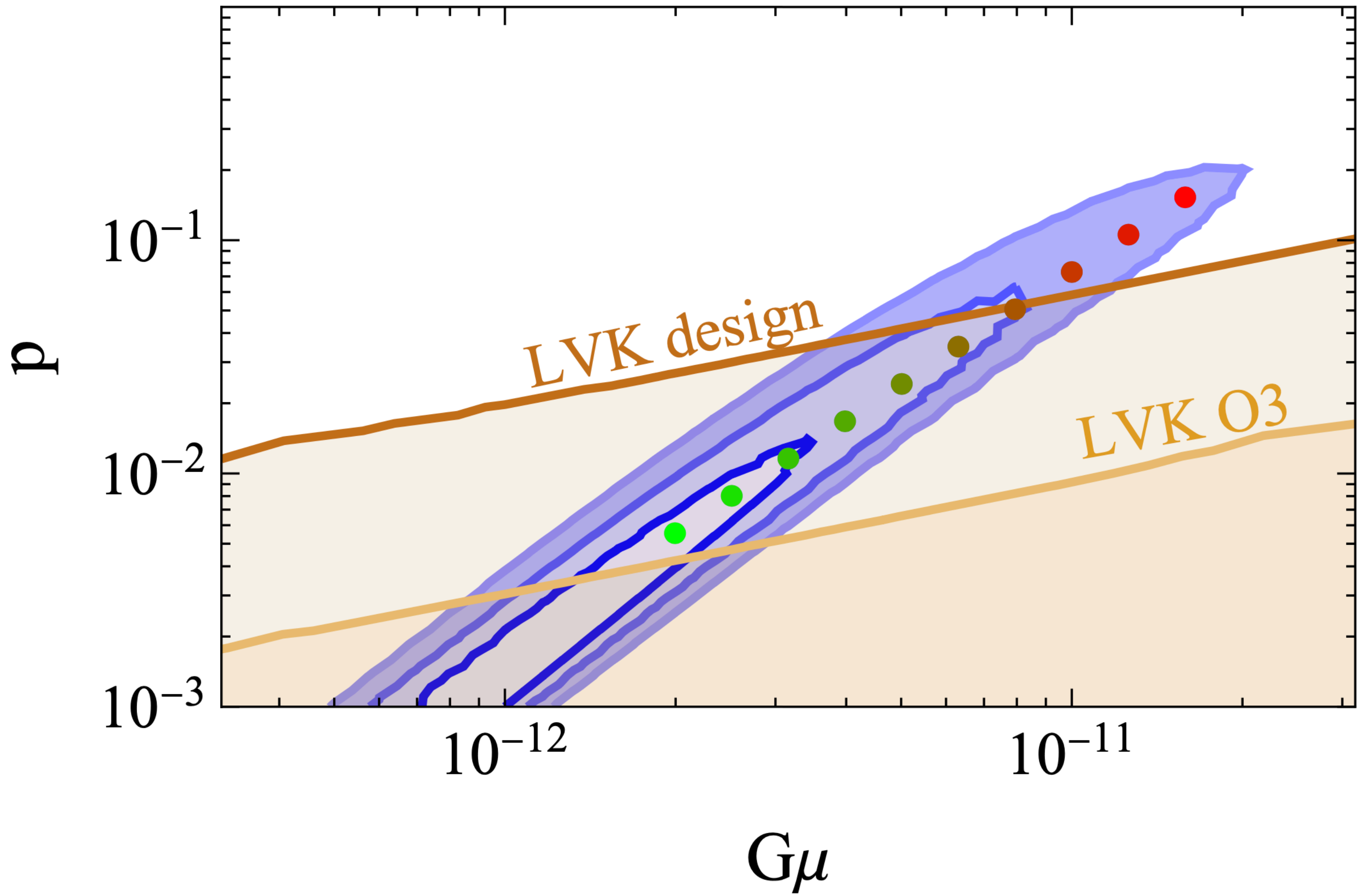
- Density of GWs: $\Omega_{GW}^{CS}(f) = \sum_{k=1}^{\infty} k\Gamma^{(k)} \Omega_{GW}^{(k)}(f), \Gamma^{(k)} = \Gamma k^{-\frac{4}{3}} / (\sum_{m=1}^{\infty} m^{-\frac{4}{3}})$

$$\Omega_{GW}^{(k)}(f) = \frac{16\pi}{3H_0^2} \frac{(0.1)\,(G\mu)^2}{\alpha_\ell(\alpha_\ell + \Gamma G\mu)} \frac{1}{f} \times \int_{t_F}^{t_0} d\tilde{t}\, \frac{C_{eff}(t_i)}{t_i^4} \left(\frac{a(\tilde{t})}{a(t_0)}\right)^5 \left(\frac{a(t_i)}{a(\tilde{t})}\right)^3 \Theta(t_i - t_F)$$

where factor $0.1, \Gamma \simeq 50$ from simulations,

$C_{eff} = 5.4\ (0.39)$ during radiation (matter) domination

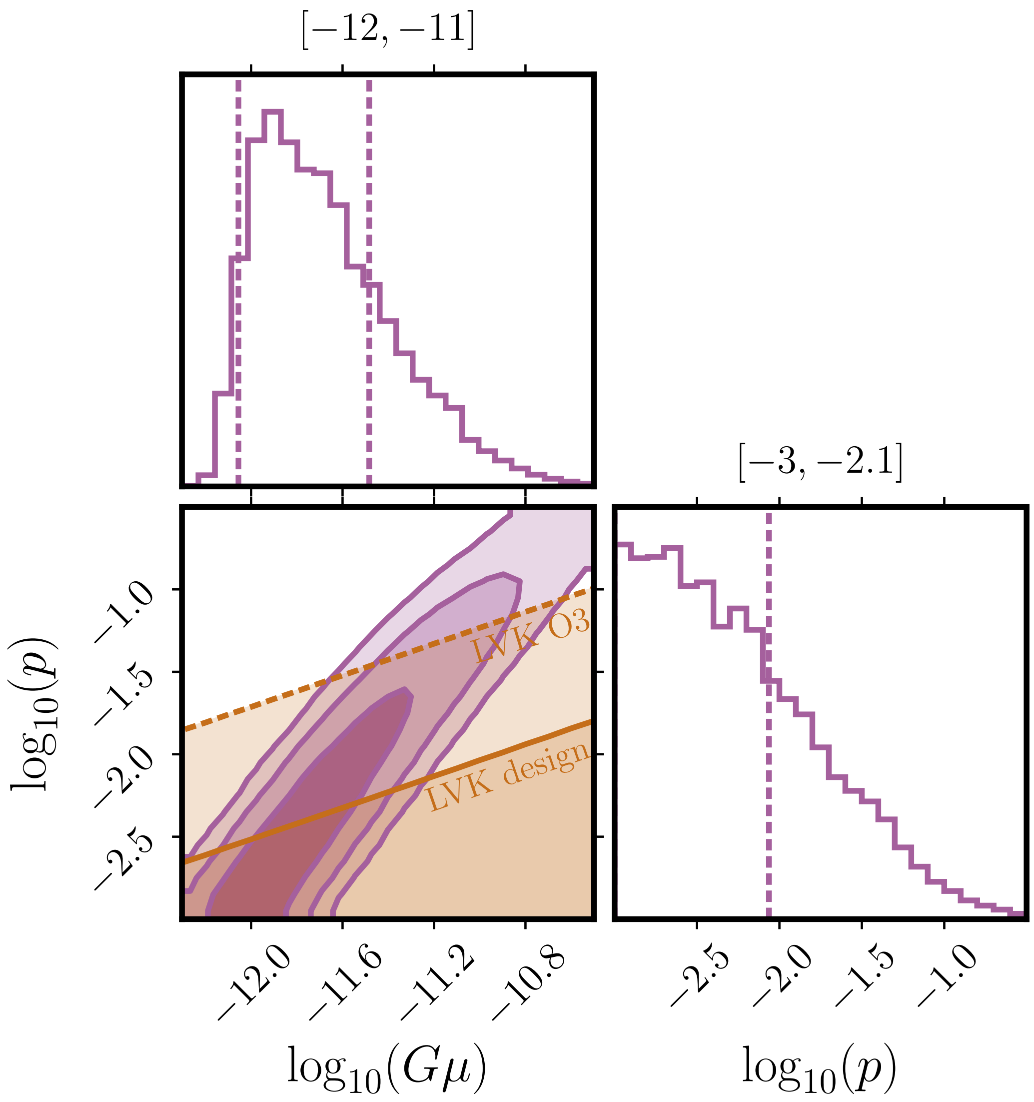
Superstrings vs LVK



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

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

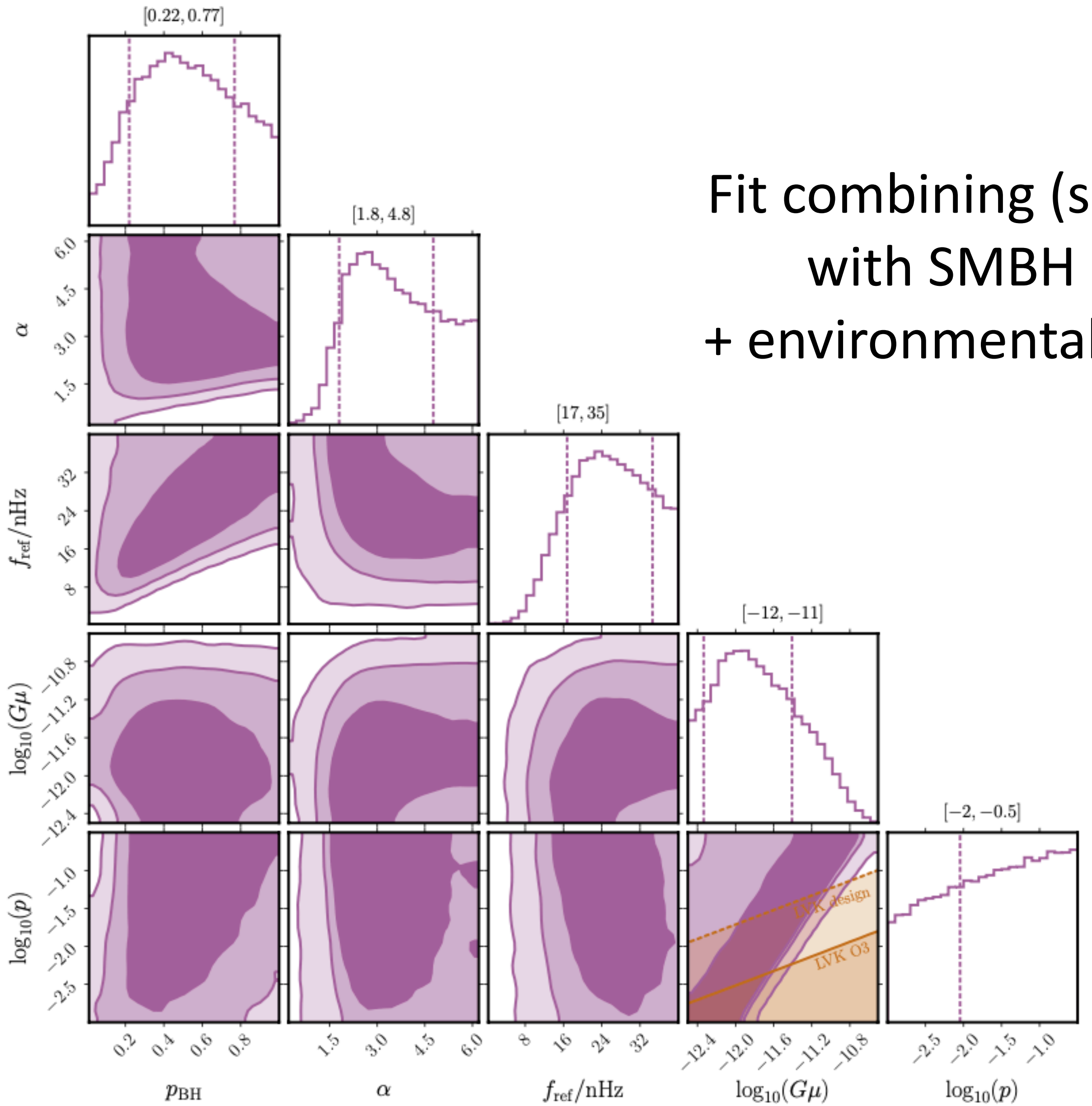
Superstring Fit to NANOGrav



(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

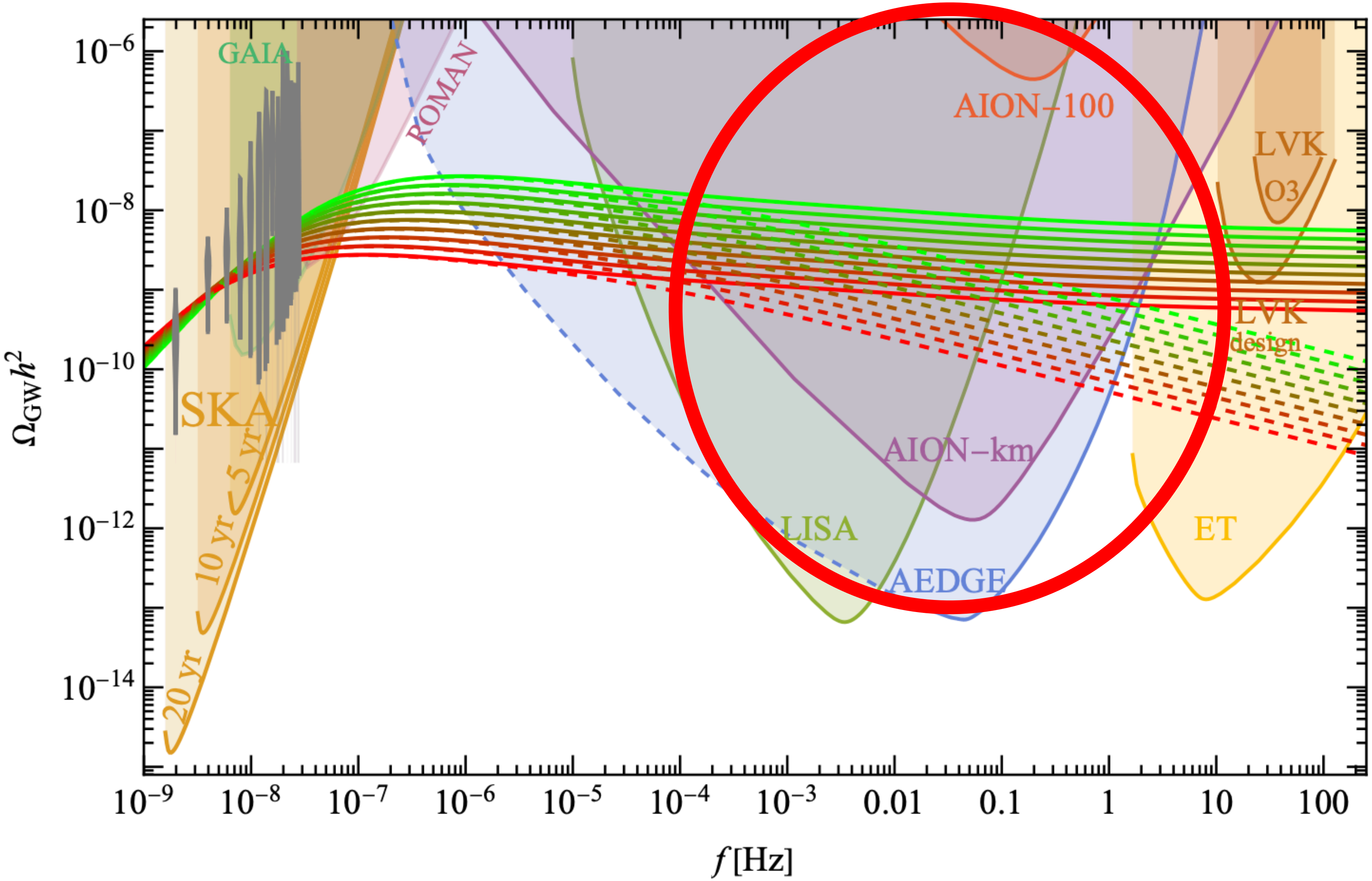
Superstring + SMBH Fit



Fit combining (super)strings
with SMBH binaries
+ environmental energy loss

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

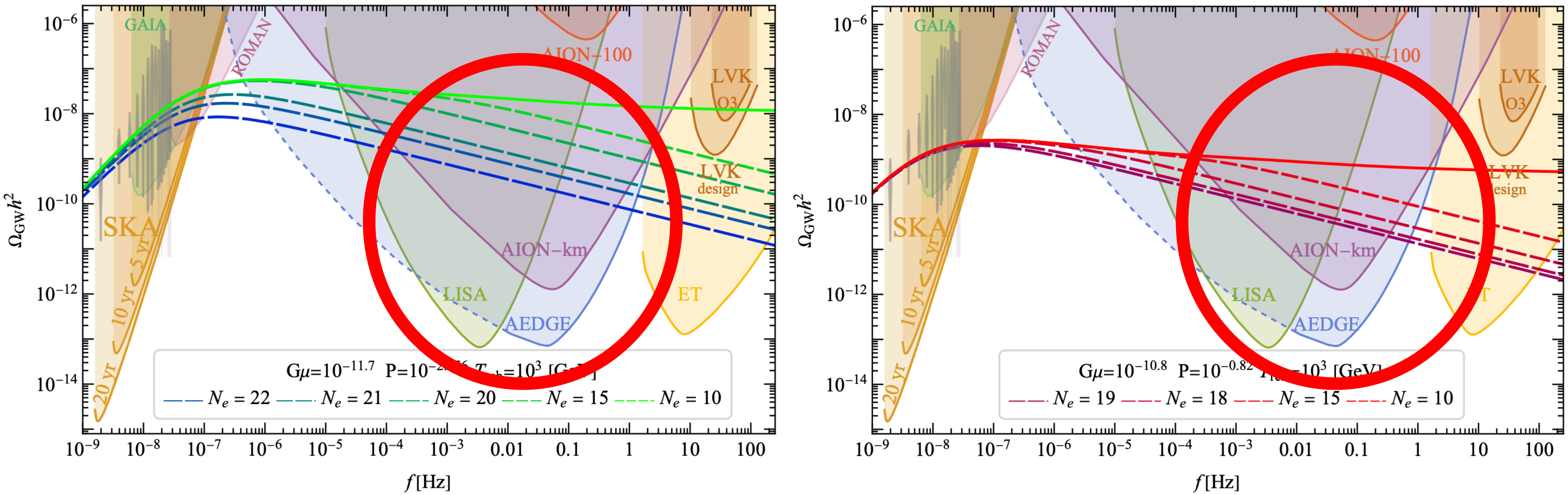
Effect of Matter Domination



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

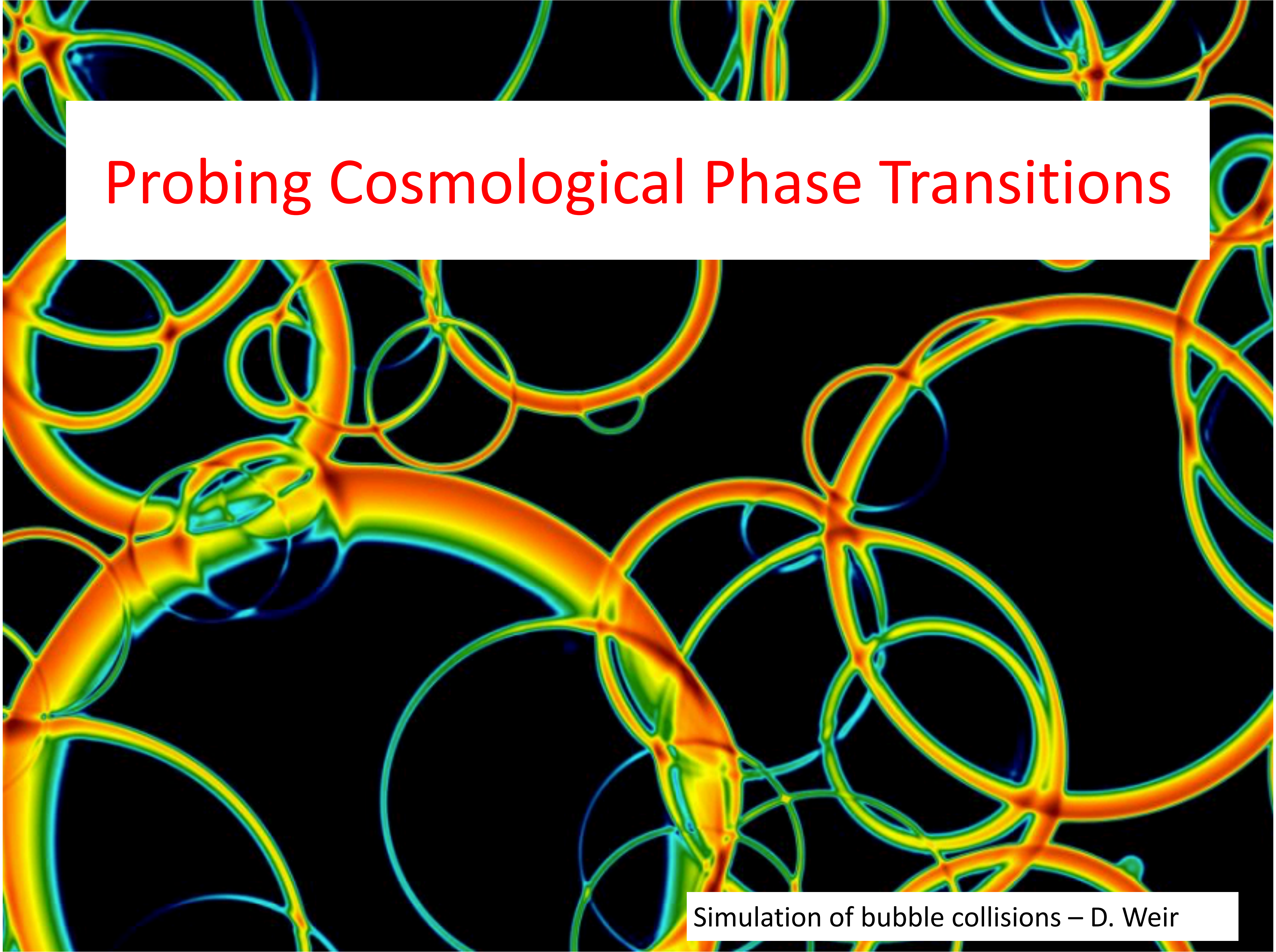
Effects of Thermal Inflation



Could also push superstrings beyond LVK,
but still detectable by LISA, AION/AEDGE, ET

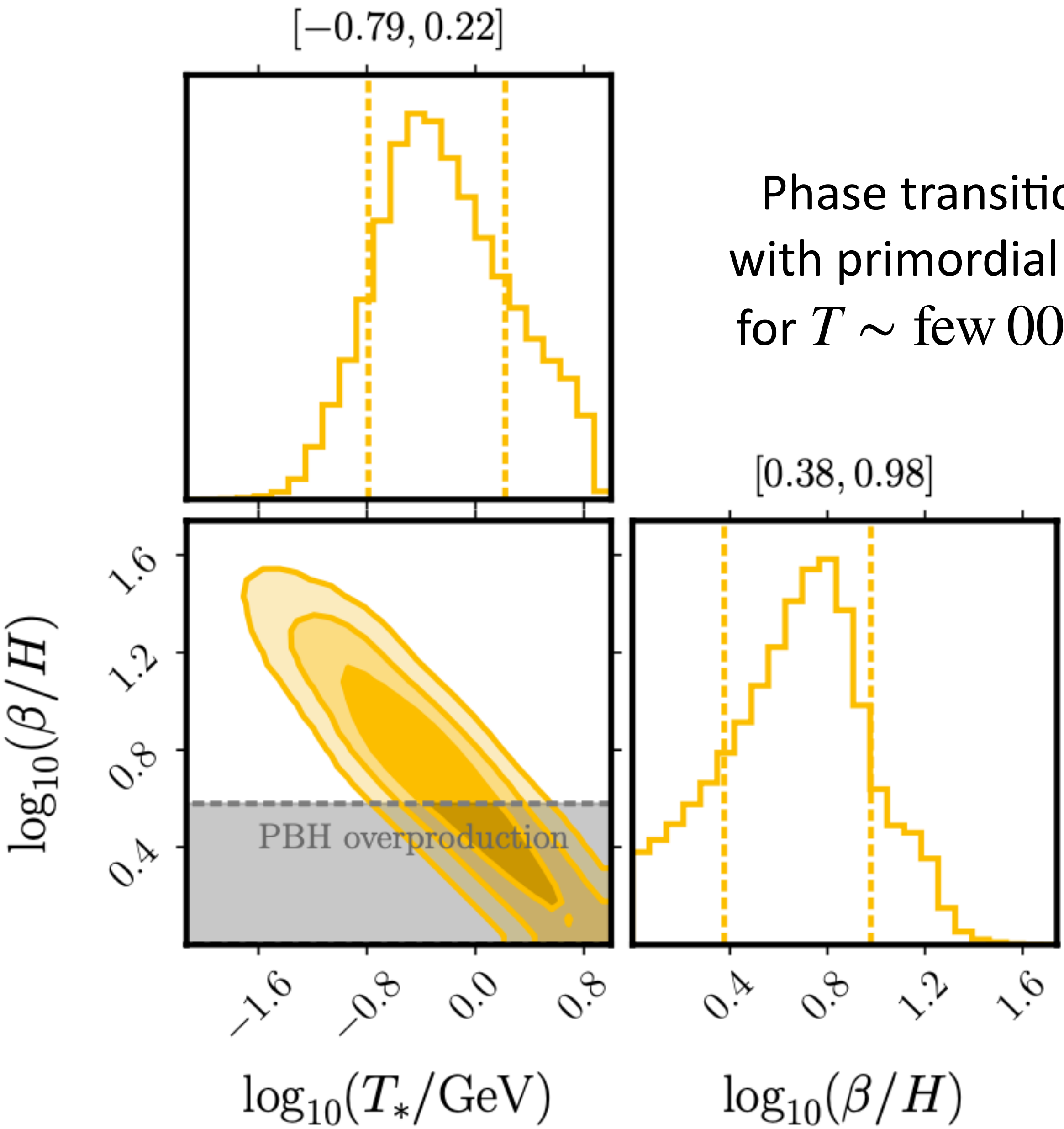
JE, Lewicki, Lin, & Vaskonen: arXiv:2306.17147

Probing Cosmological Phase Transitions



Simulation of bubble collisions – D. Weir

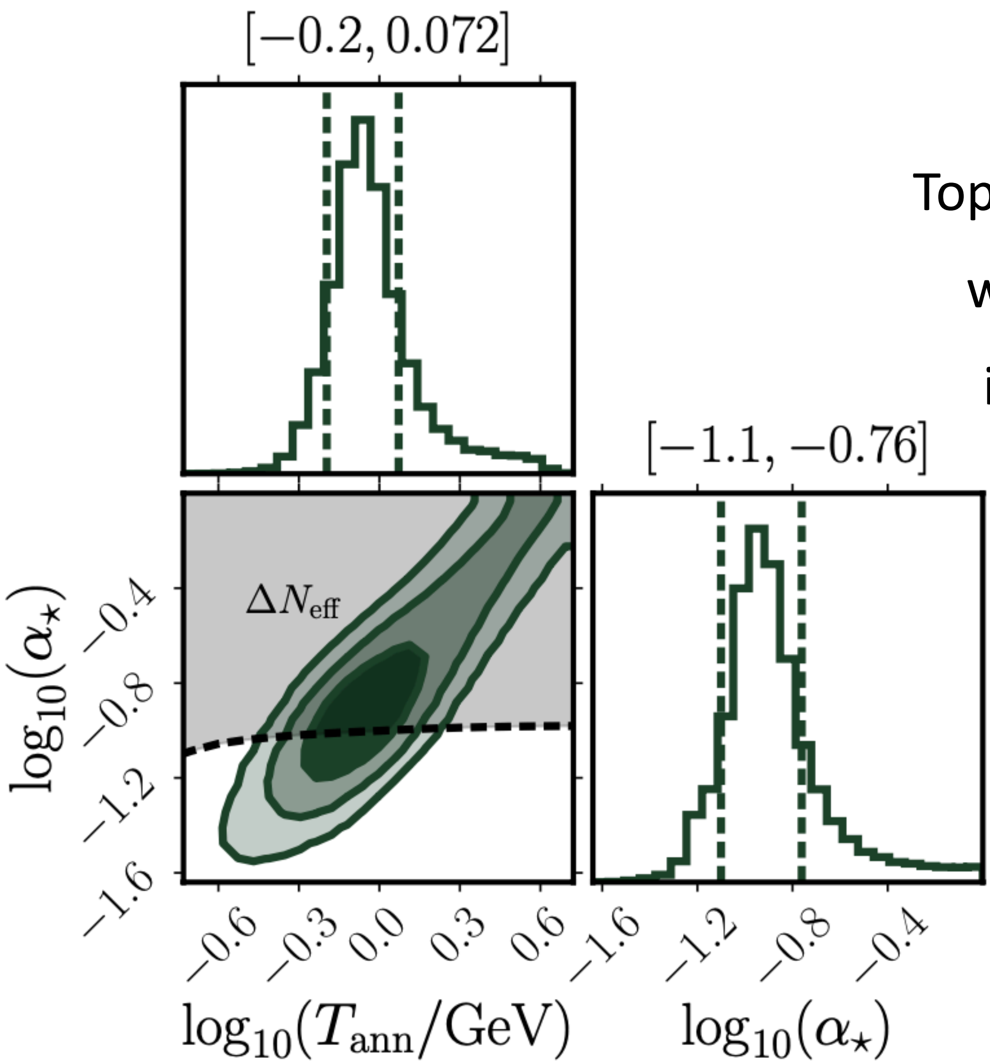
Phase Transition Fit to NANOGrav AION



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

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

Domain Wall Fit to NANOGrav

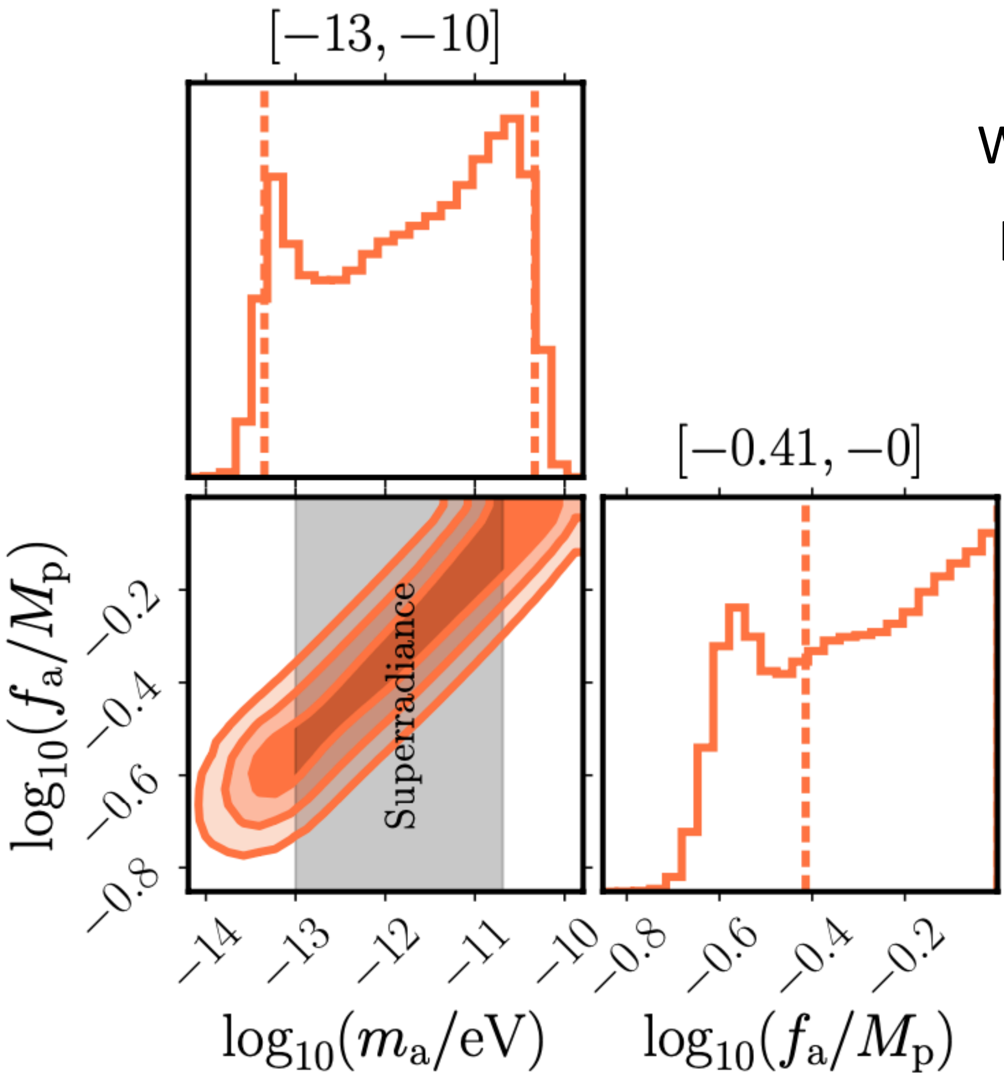


Topological defects produced when discrete symmetry is broken after inflation

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

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

Axion Fit to NANOGrav



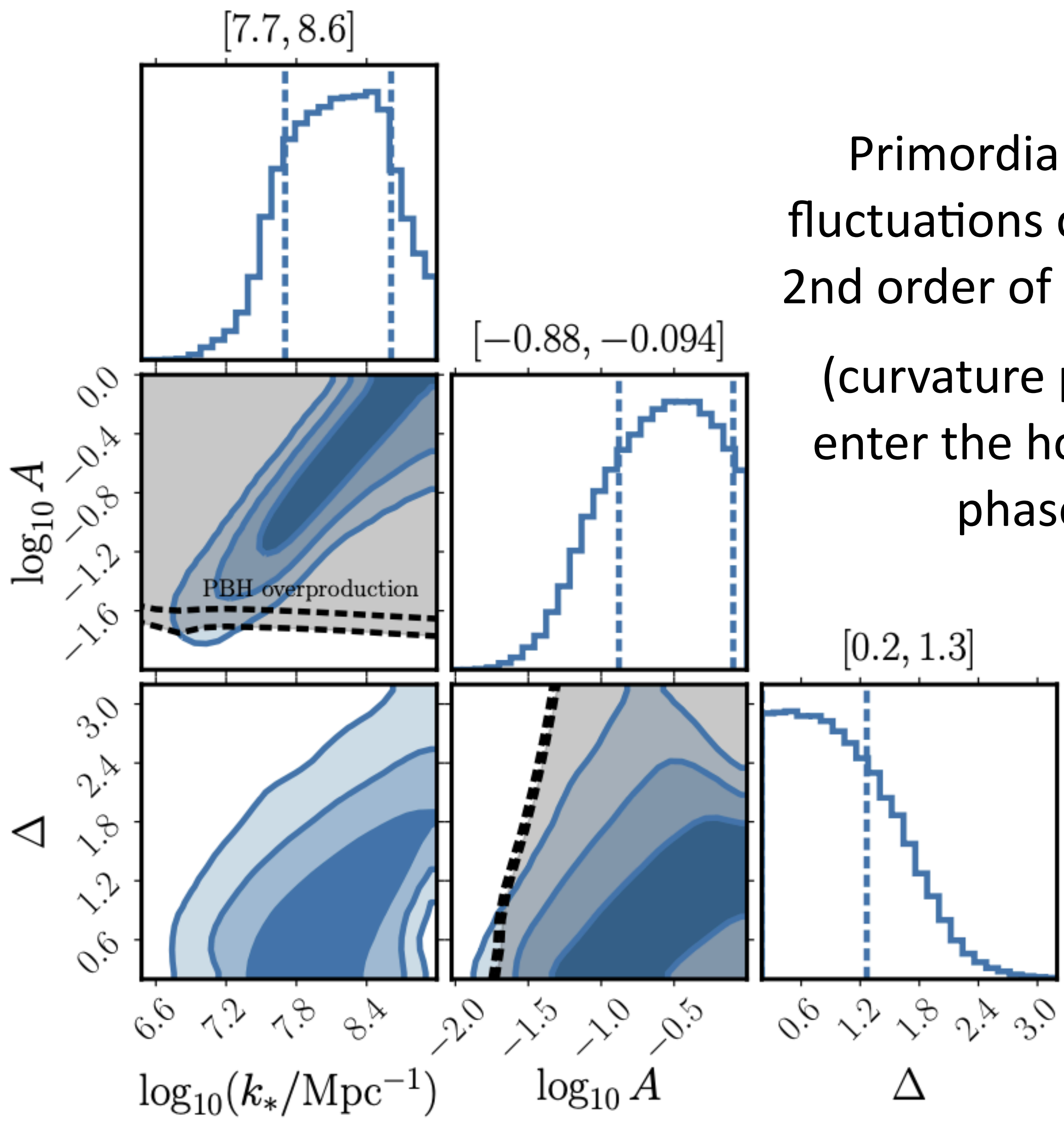
When an axion-like particle has weak coupling to SM, GWs can be produced via tachyonic instability light dark photon helicity state

Axion model compatible with cosmology for

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

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

Scalar-Induced GWs Fit to NANOGrav

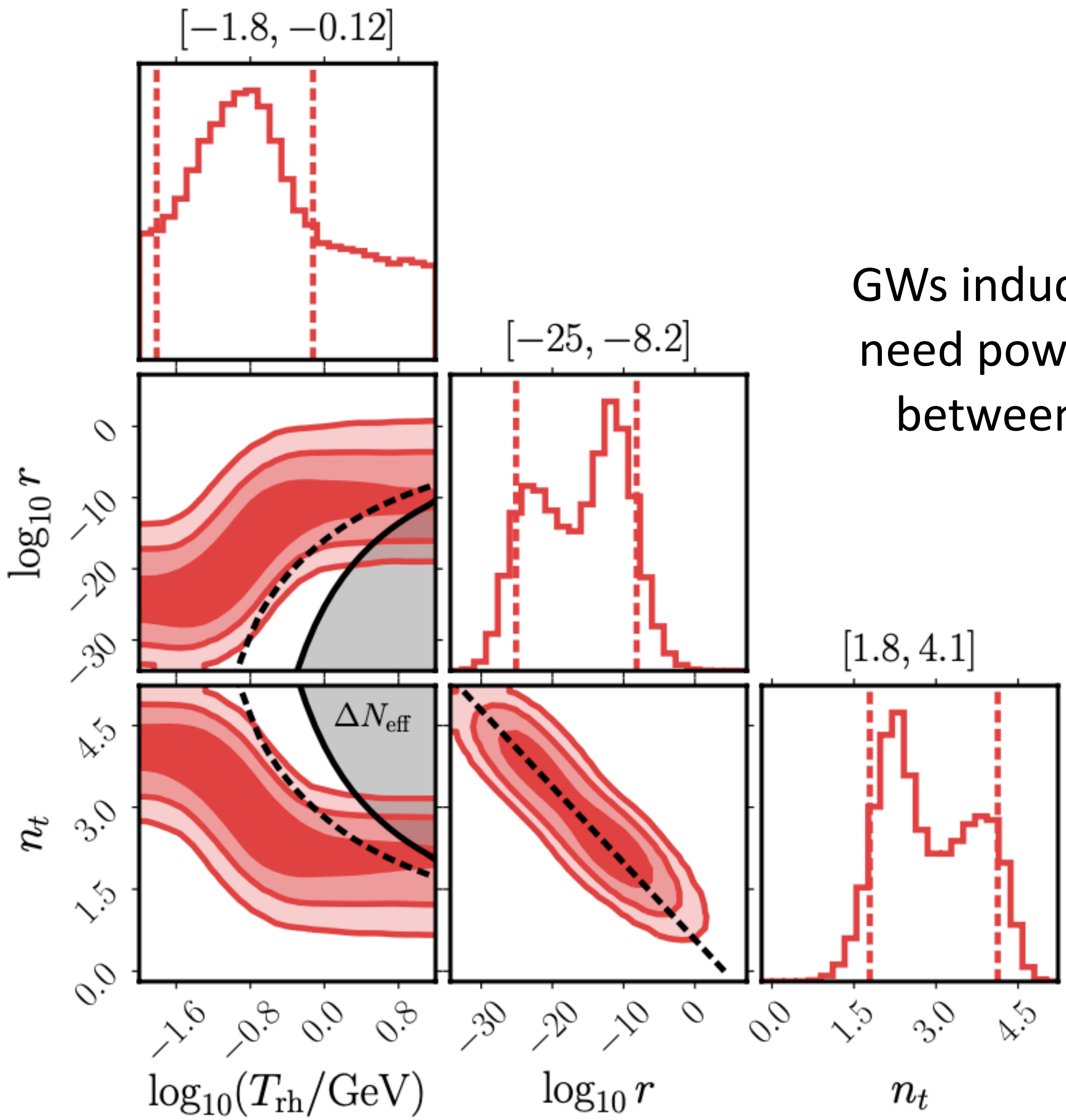


Primordial scalar curvature fluctuations can produce GWs at 2nd order of perturbation theory

(curvature perturbations that enter the horizon around QCD phase transition)

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

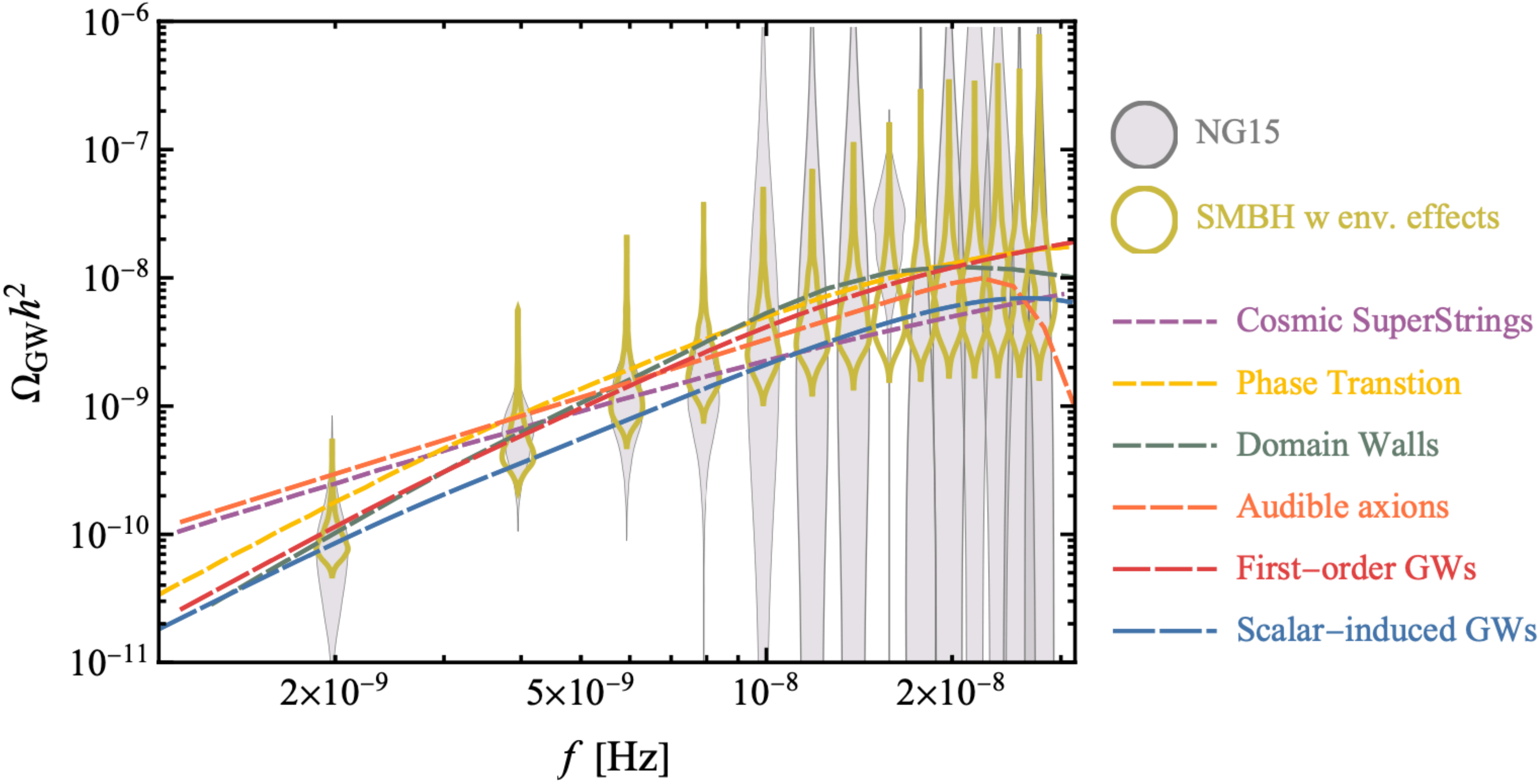
First-Order GWs Fit to NANOGrav



GWs induced at first order: need power-law spectrum between CMB and PTA scales

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

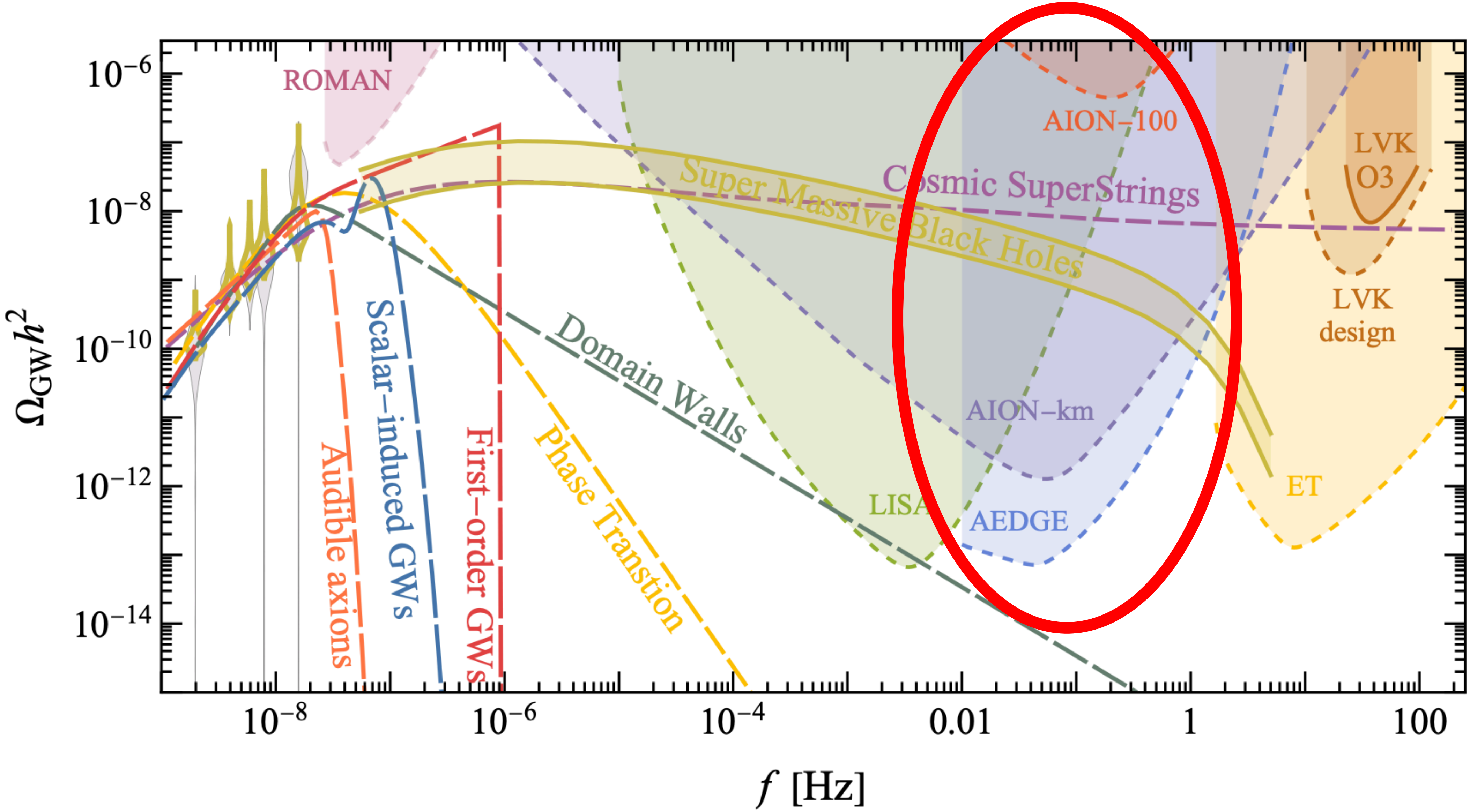
Fits to NANOGrav



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

Extension of Fits to Higher Frequencies

AION



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

FAPS ≡ fluctuations, anisotropies, polarization, sources, mid-f ≡ mid-frequency experiment, e.g., AION [308], AEDGE [310], LVK ≡ LIGO/Virgo/KAGRA [161–163], ET ≡ Einstein Telescope [312] (or Cosmic Explorer [313]), ~~signature~~ ≡ not detectable

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