Searching for the Biggest Bangs since the Big Bang

KING'S College LONDON

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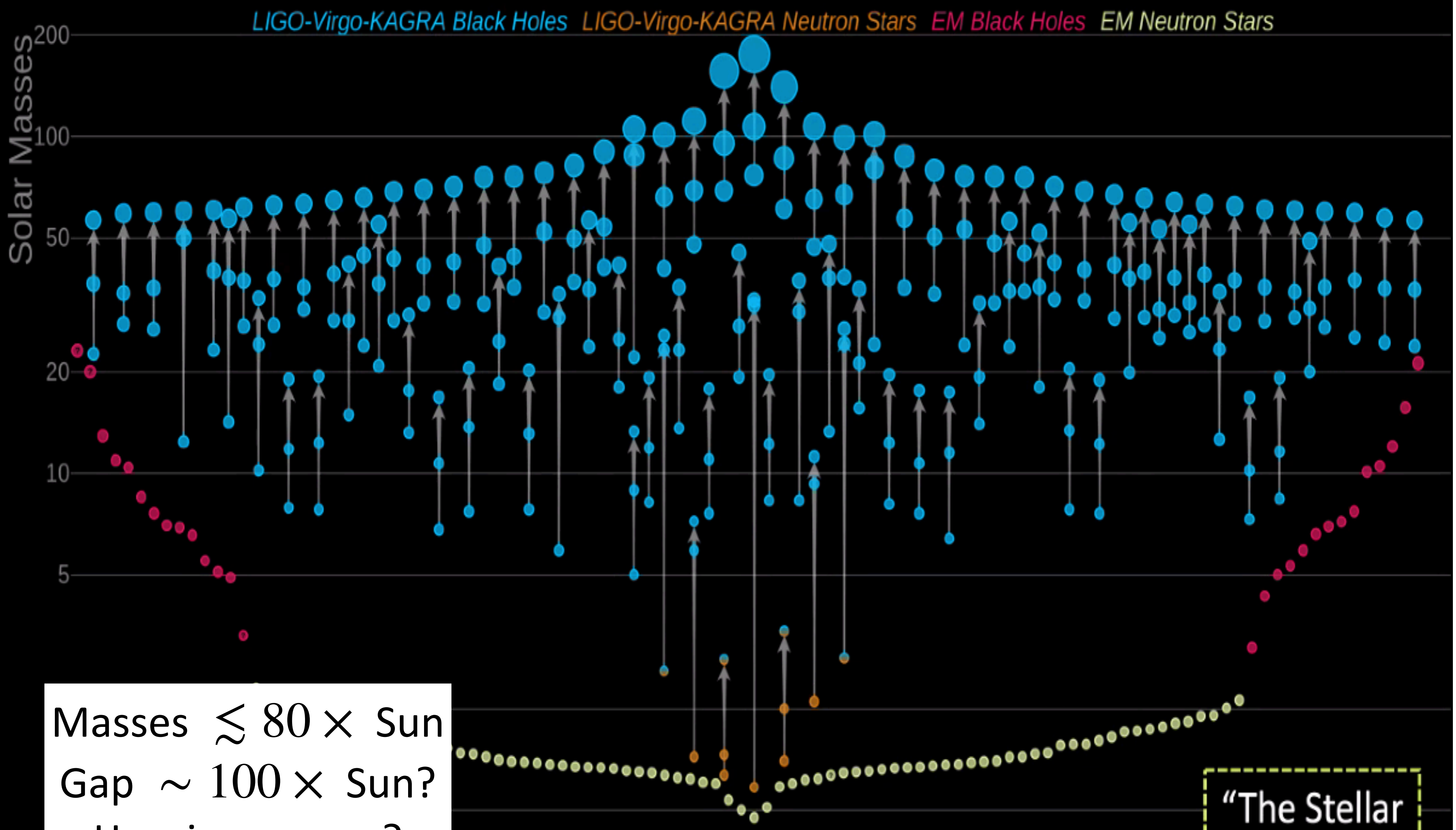
IHEP, Beijing,
July 20, 2024

Outline

- Discovery of black hole binaries
- Supermassive black holes: how to assemble them?
    - Via intermediate mass black holes?
- Atom interferometry AION
- Discovery of nanoHz GW background by Pulsar Timing Arrays (PTAs)
- Supermassive black hole binaries?
    - Prospects for observing mergers of intermediate mass black holes?
- **BSM scenarios that fit NANOGrav data**

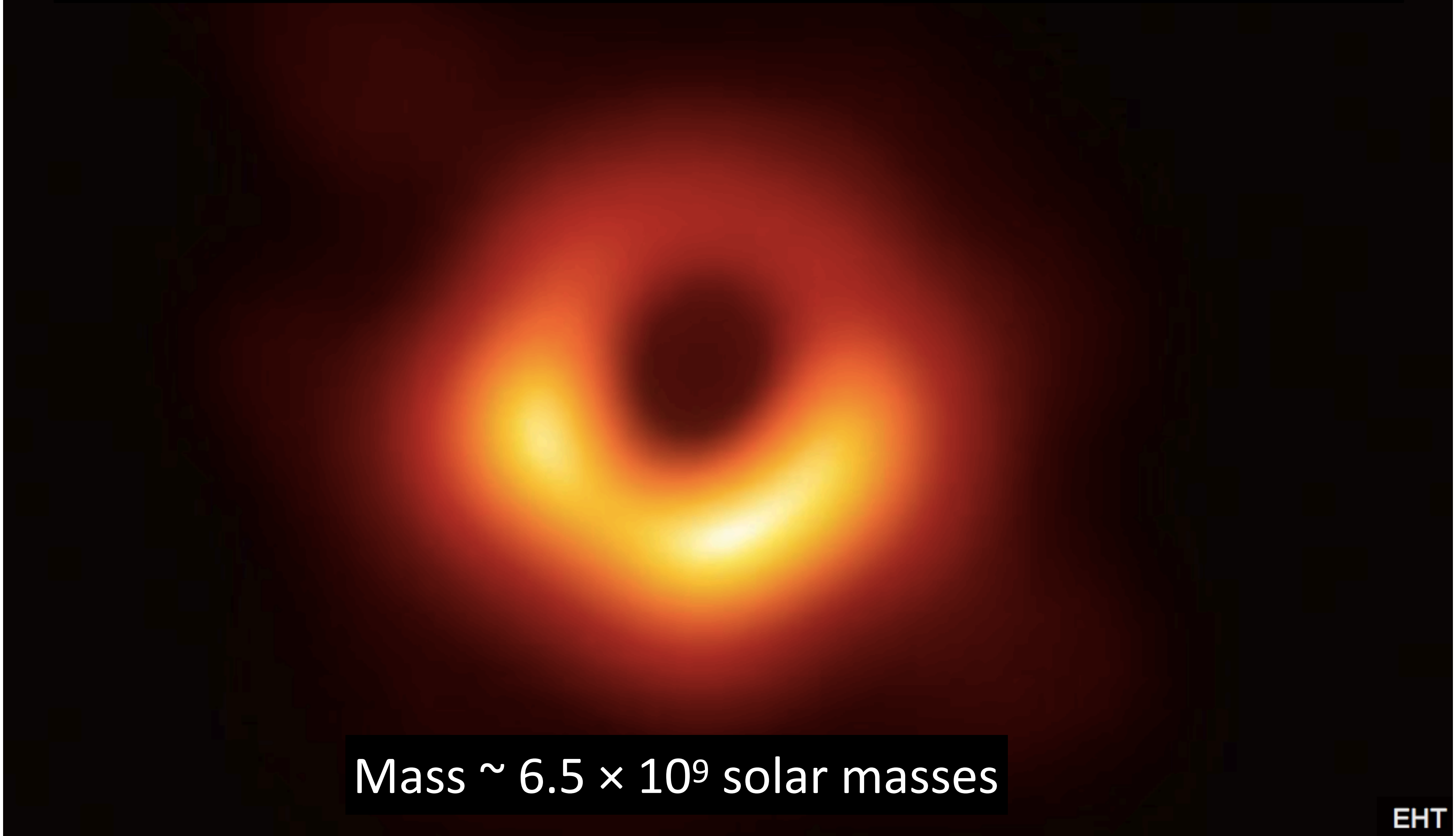
LIGO-Virgo-KAGRA Black Holes & Neutron Stars



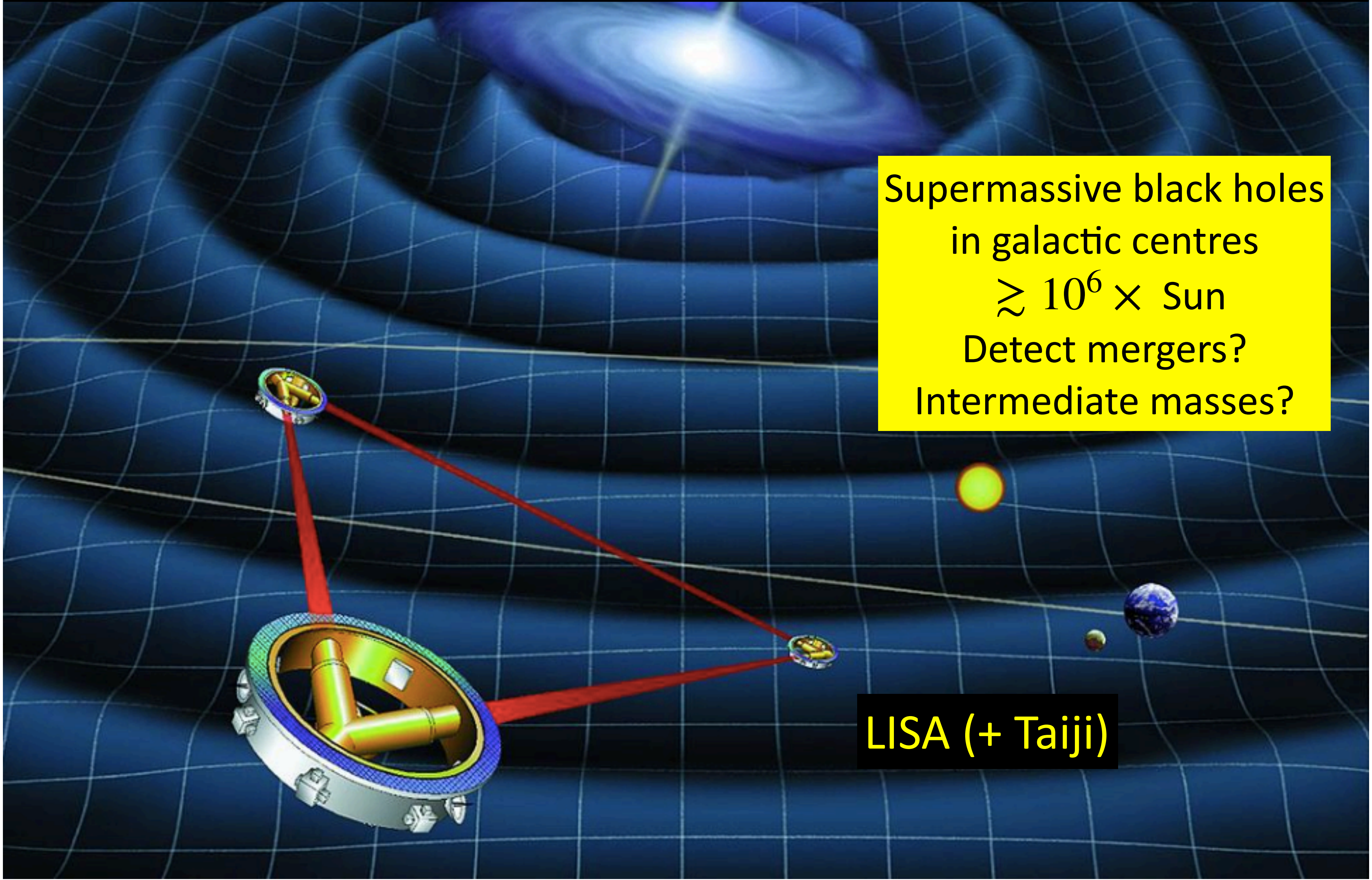
Masses $\lesssim 80 \times$ Sun
Gap $\sim 100 \times$ Sun?
Heavier masses?

“The Stellar Graveyard”

Supermassive Black Holes in Active Galactic Nuclei: Image of M87

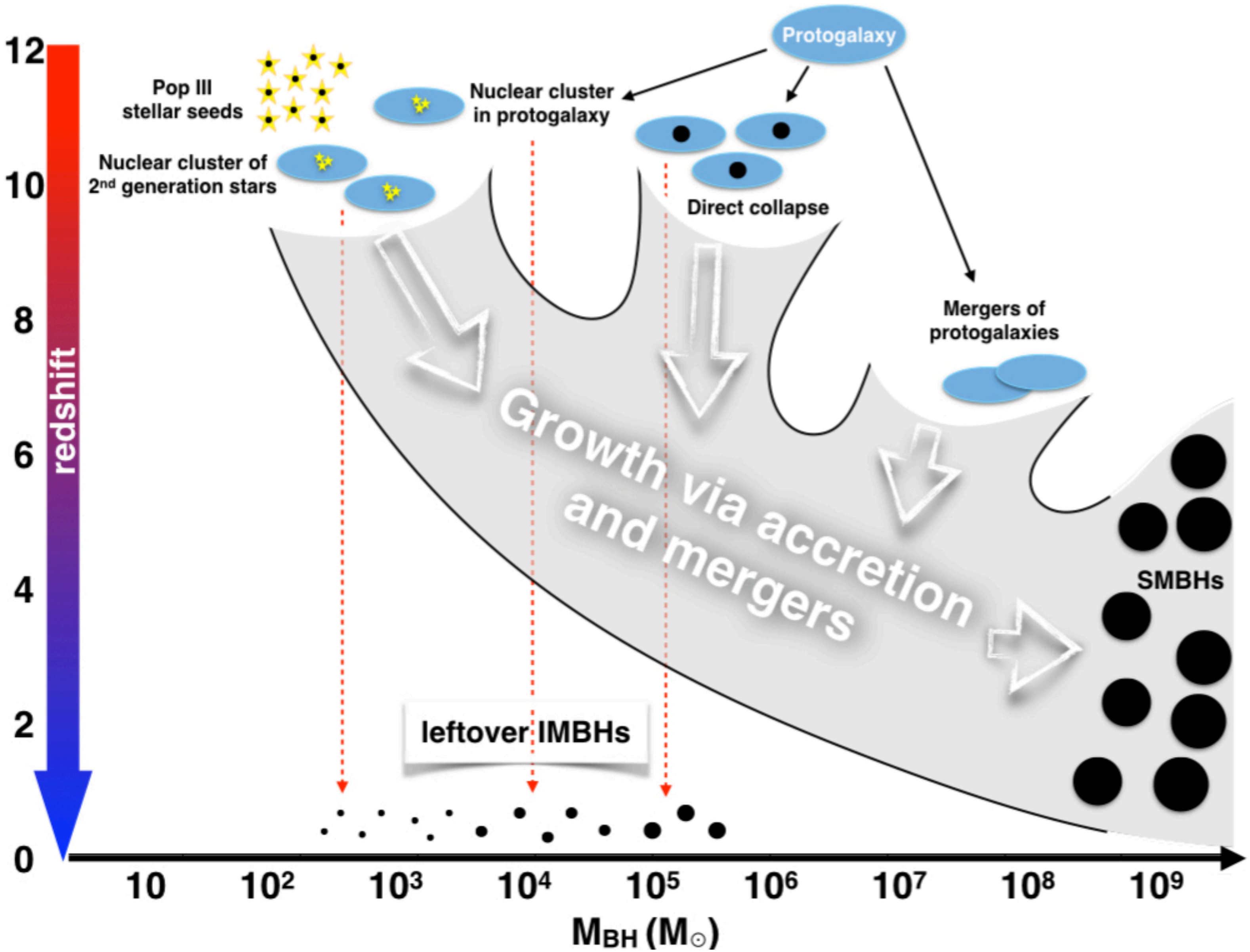


Future Step: Interferometer in Space

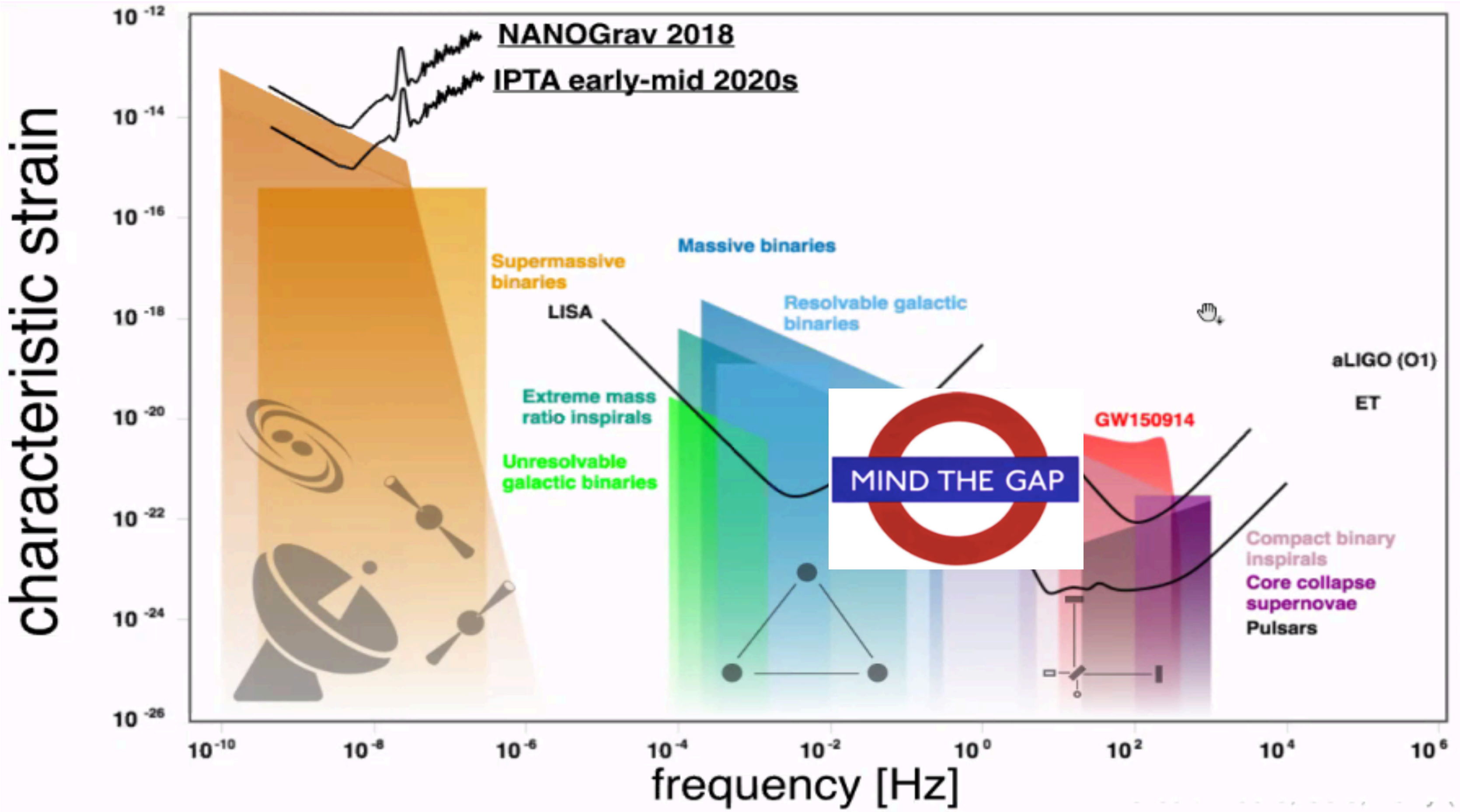


How to Make a Supermassive BH?

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

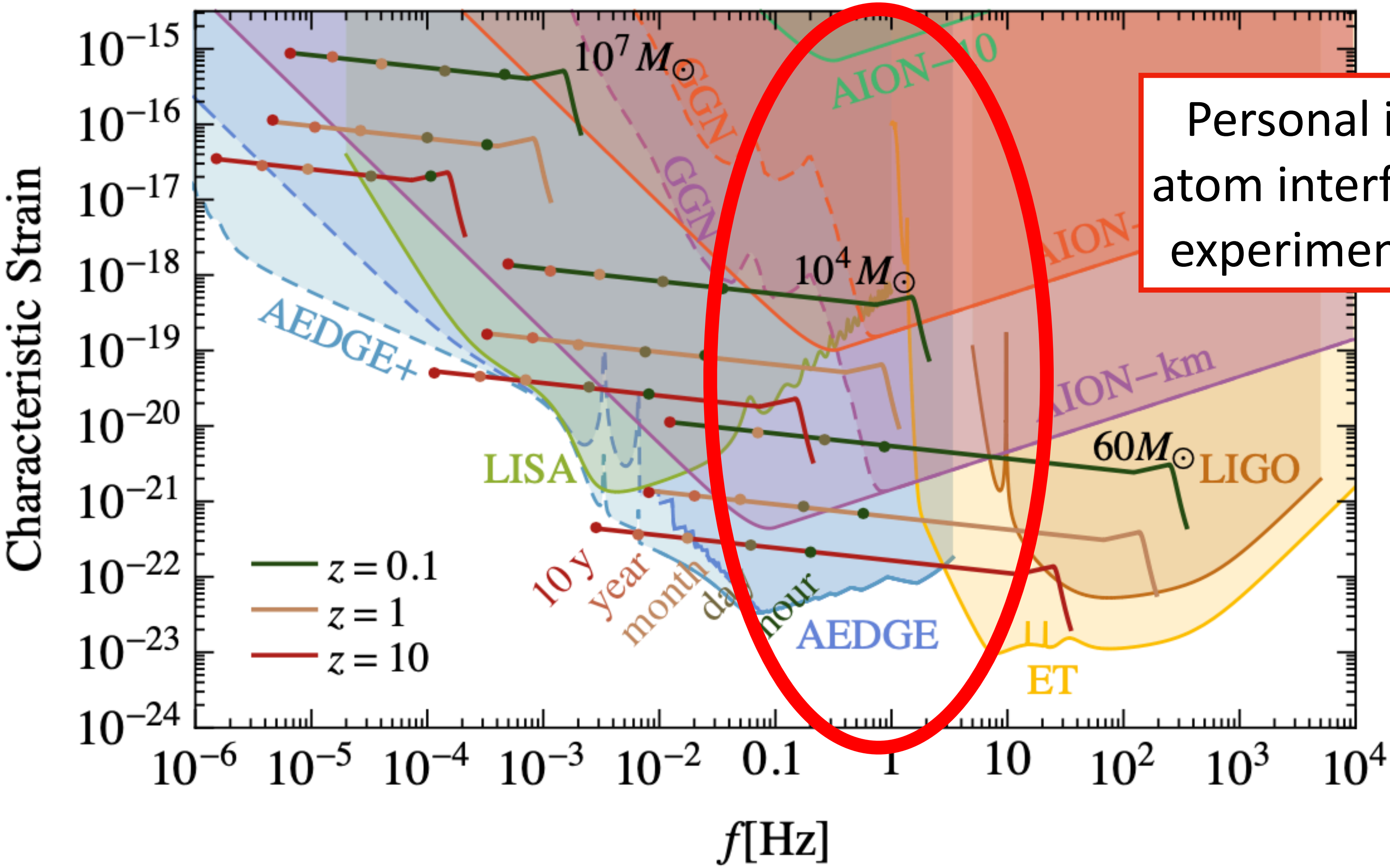


Gravitational Wave Spectrum



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

Gravitational Waves from IMBH Mergers



Personal interest: atom interferometer experiments: AION

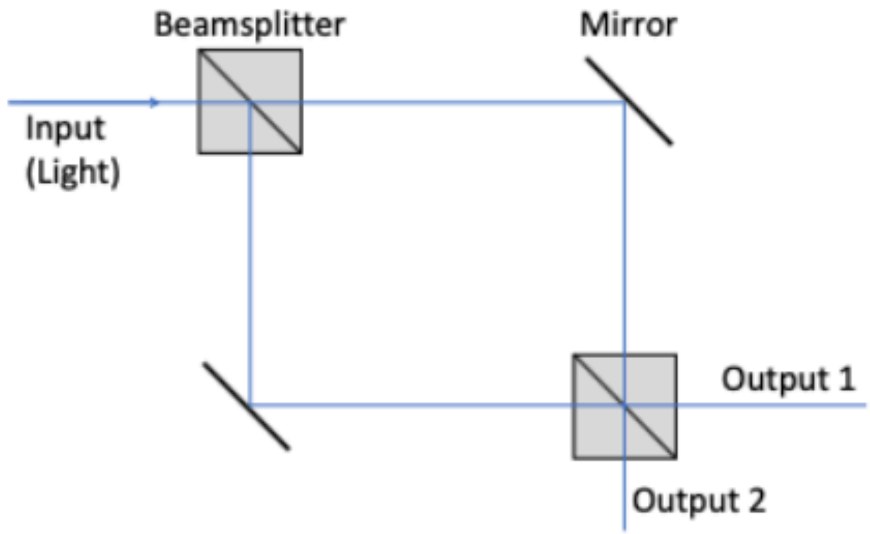
Probe formation of SMBHs

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

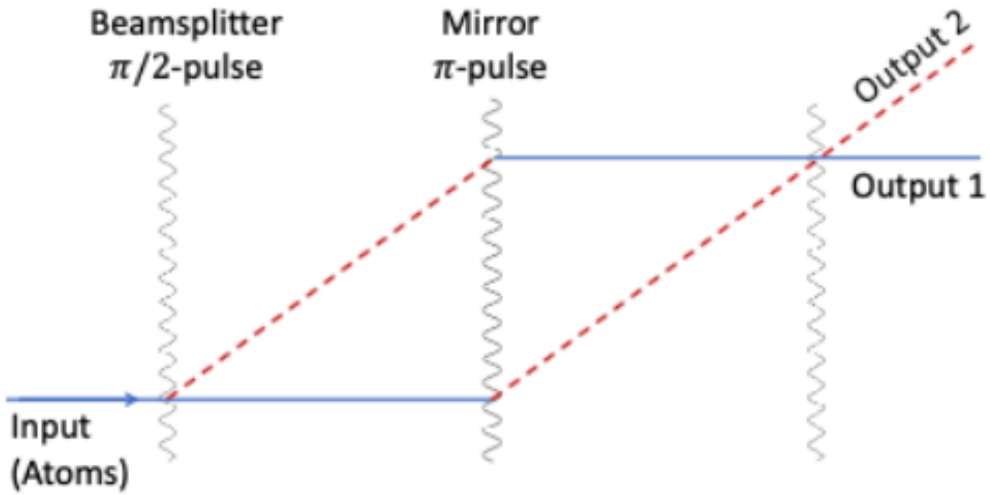
Badurina, Buchmueller, JE, Lewicki, McCabe & Vaskonen: arXiv:2108.02468

Principle of Atom Interferometry

Mach-Zehnder Laser Interferometer

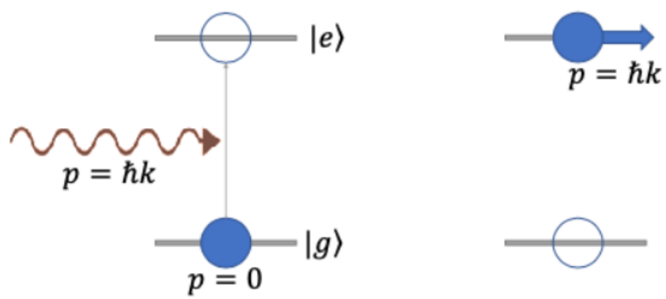


Atom Interferometer



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

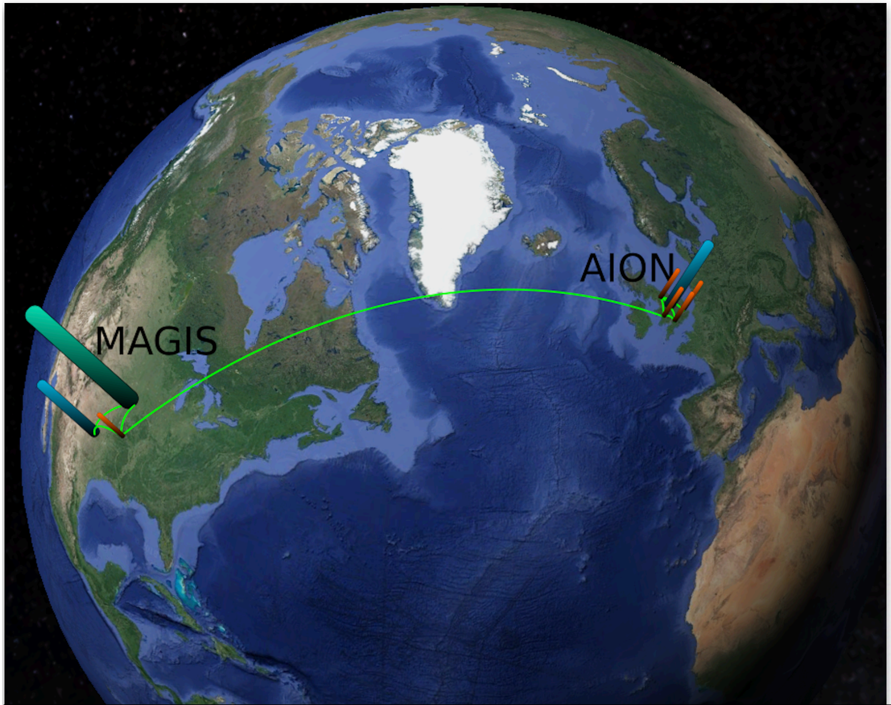
Interference between atoms following different paths



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], ...owcock[5], W. Bowden[6,*], C. Brew[2], O. Buchmueller[6], J. Coleman[5], J. Carlton[1], G. Elertas[5], J. Ellis[1,&], 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]

[1]Kings College London, [2]STFC Rutherford Appleton Laboratory, [3]University of Oxford, [4]University of Birmingham, [5]University of Liverpool, [6]Imperial College London, [7]University of Cambridge



Network with MAGIS project in US

MAGIS Collaboration (Abe et al): arXiv:2104.02835

Also MIGA (France), ZAIGA (China)

AION – Proposed Programme

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

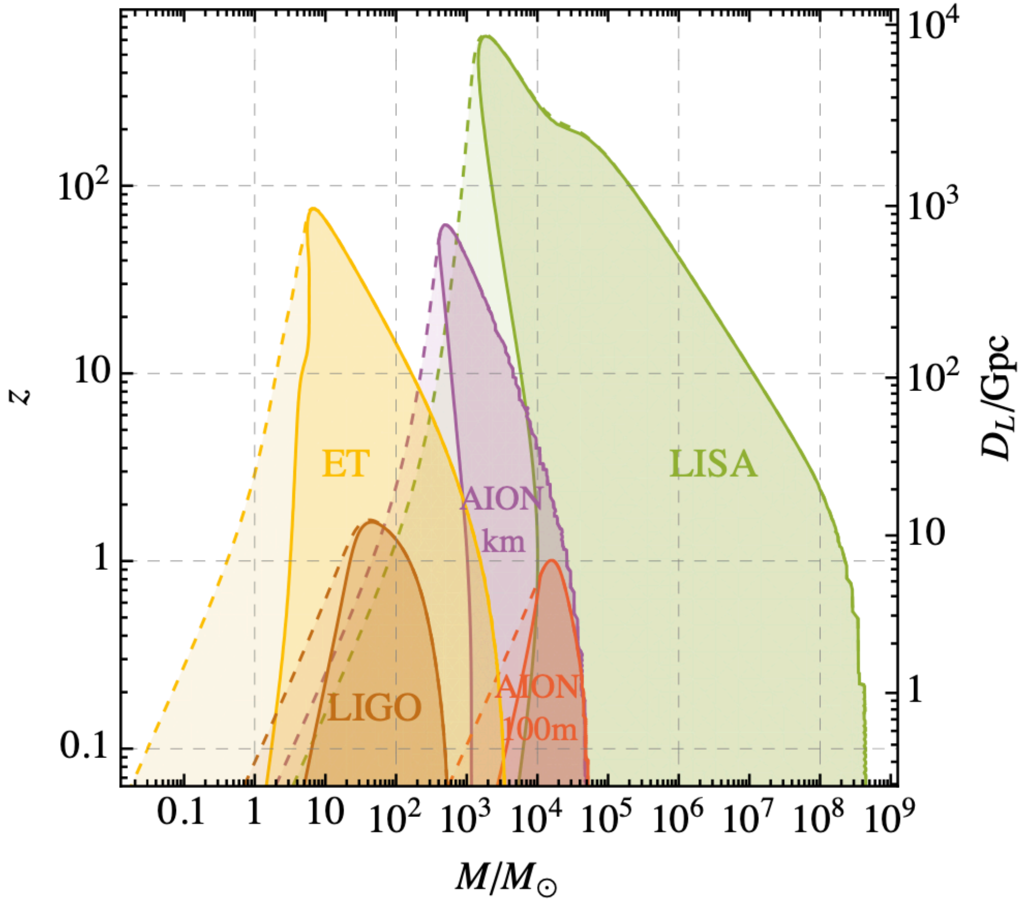
Oxford

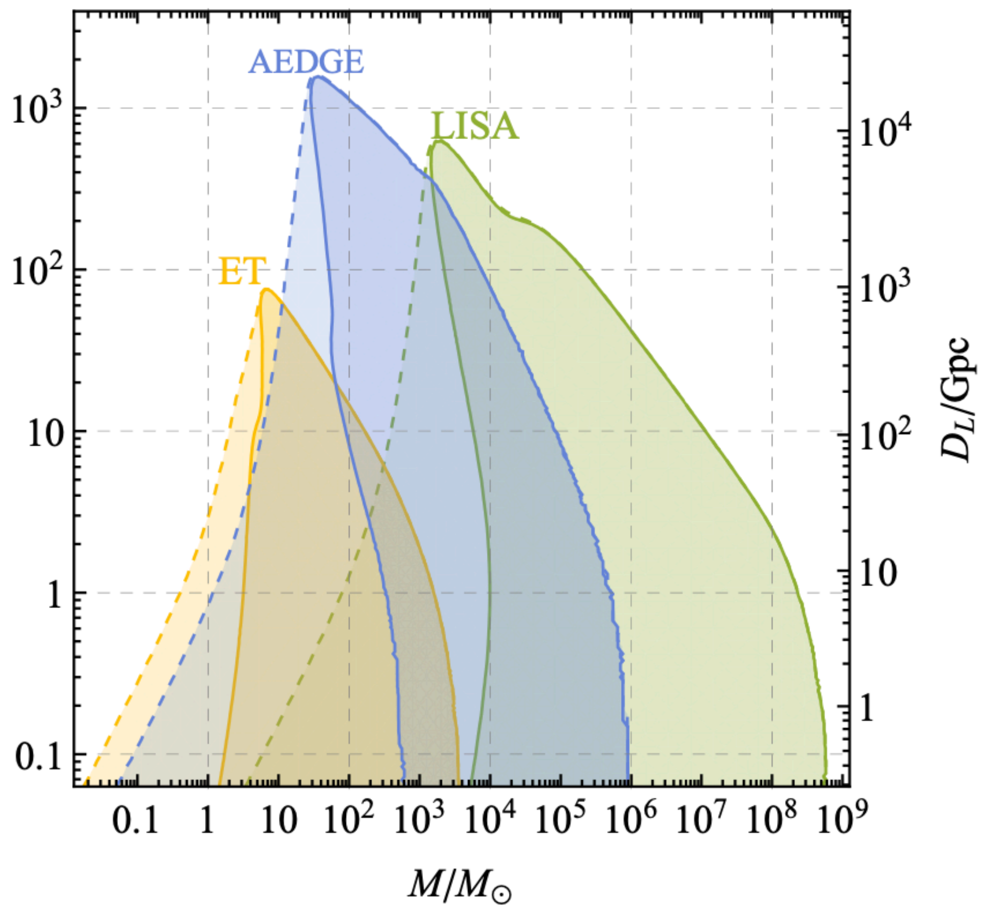
Initial funding from UK STFC

Boulby? CERN?

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

SNR = 8 Sensitivities to GWs from Mergers



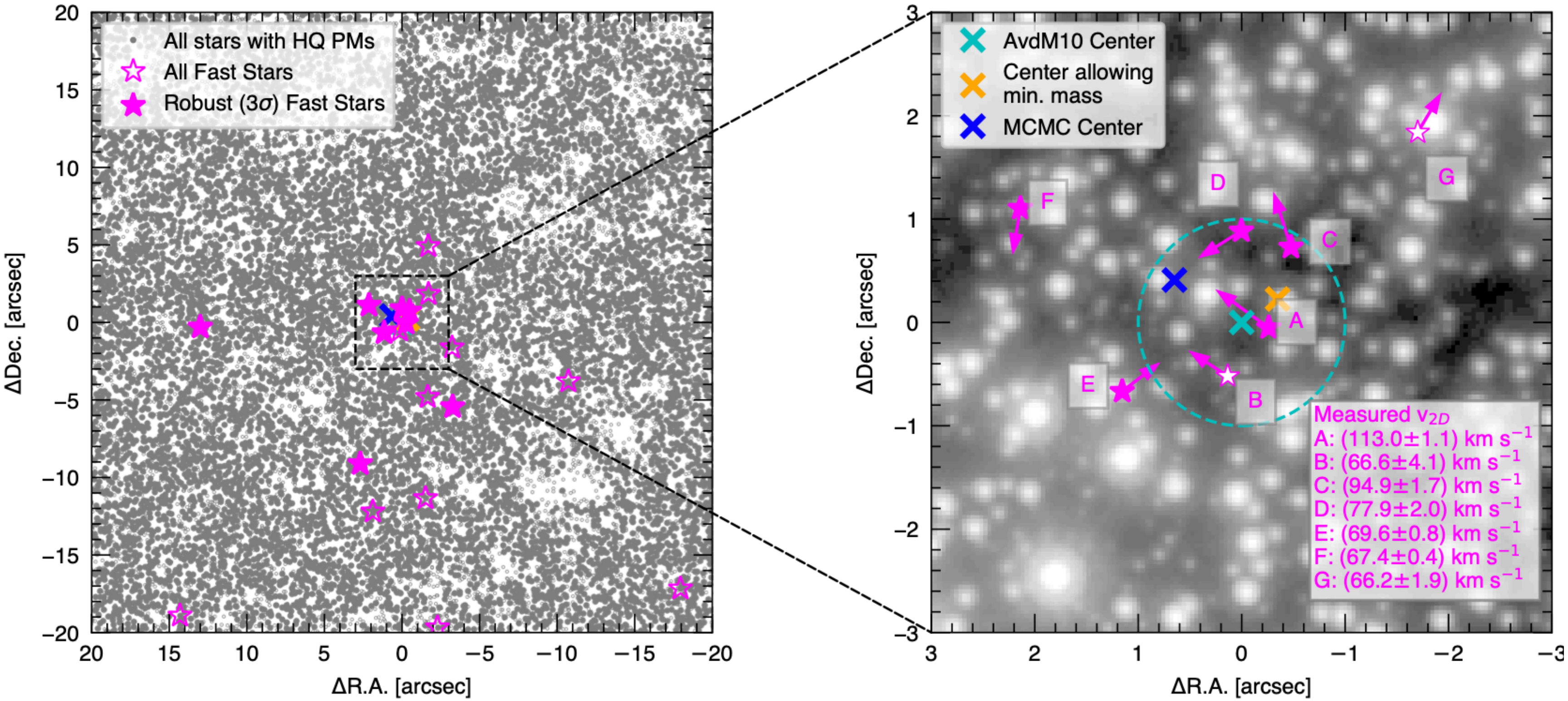


In the lighter regions between the dashed and solid lines the corresponding detector observes only the inspiral phase.

AION, arXiv:1911.11755

AEDGE, arXiv:1908.00802

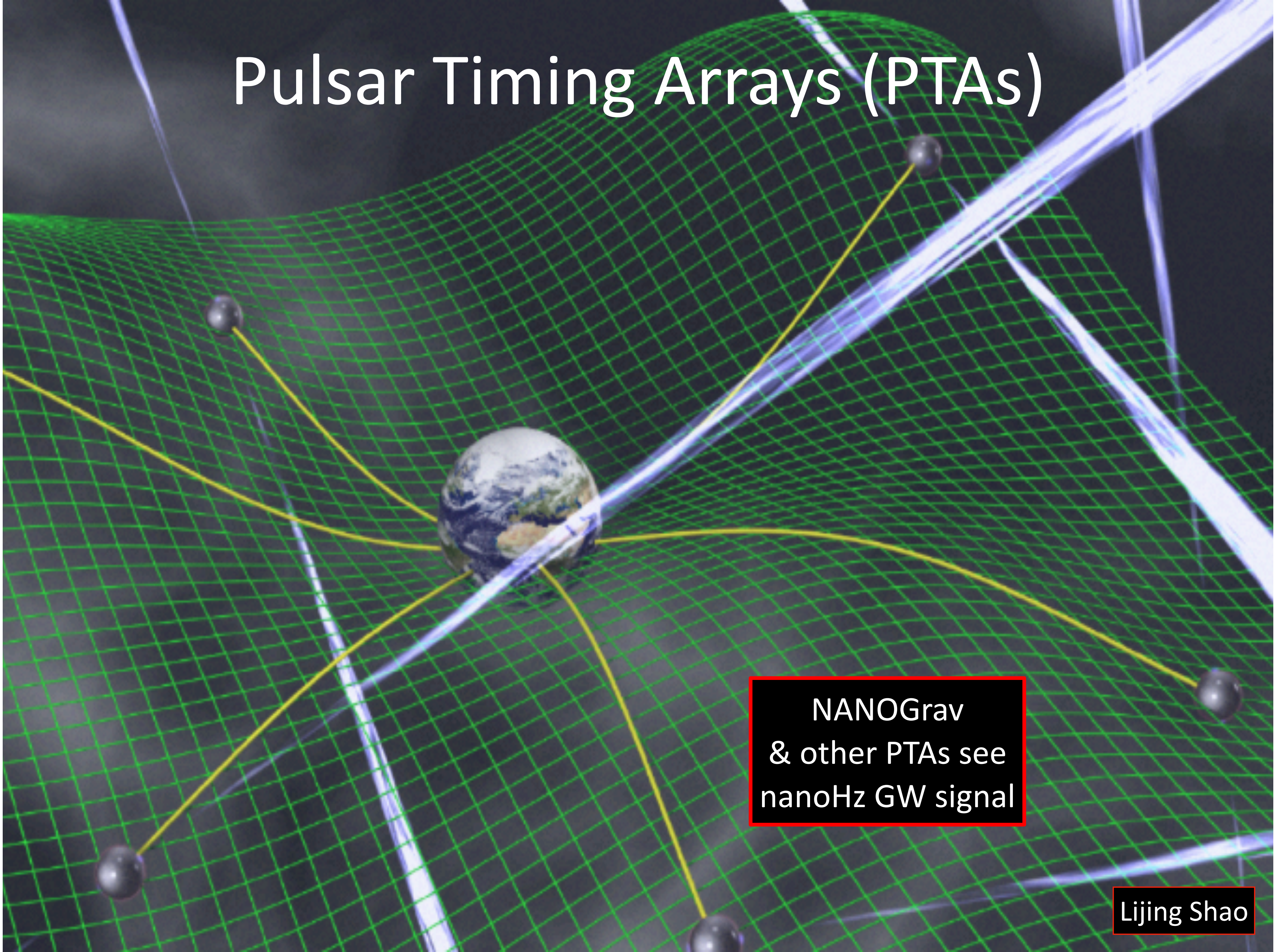
Discovery of a Nearby IMBH



- Discovered through rapid motions of adjacent stars
- In our galaxy, constellation ω Centauri
- Distance 5.43 kpc, mass 8200 solar masses

Häberle et al, Nature 631, 288 (July 10, 2024)

Pulsar Timing Arrays (PTAs)

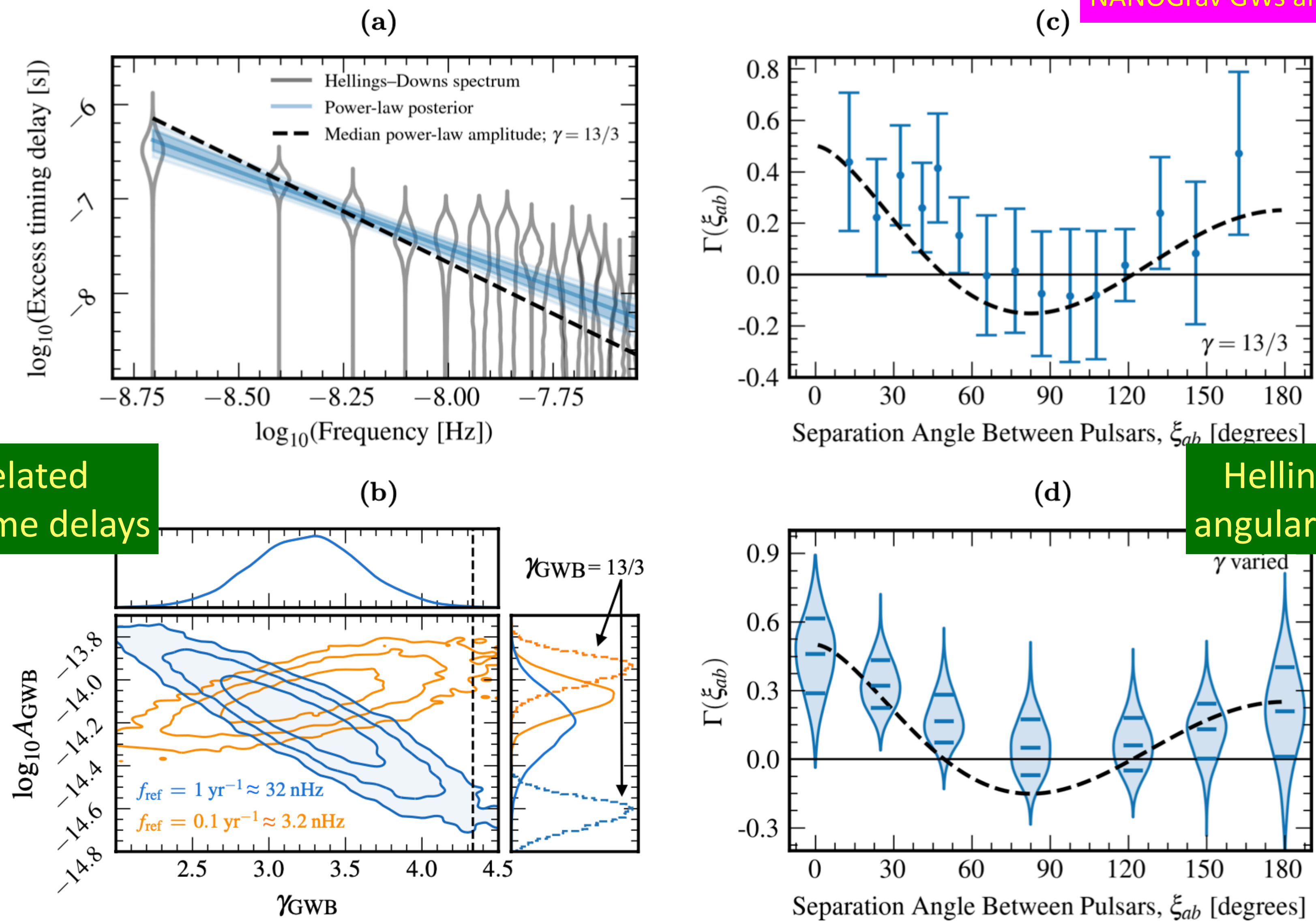


NANOGrav 15-Year Data

NANOGrav GWs arXiv:2306.16213

Correlated pulsar time delays

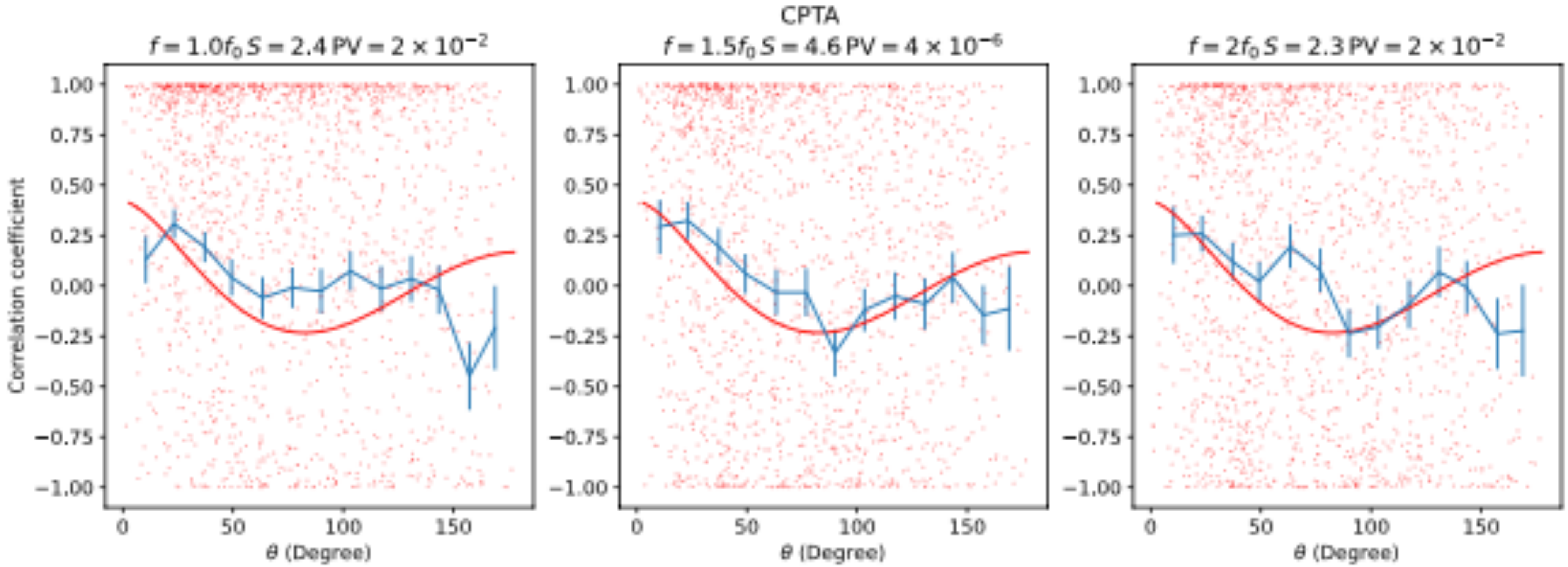
Hellings-Downs angular correlation



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

Chinese PTA Data

CPTA GWs arXiv:2306.16216



Evidence claimed for Hellings-Downs angular correlation

BH Merger Rate Estimate

BH merger rate $R_{\rm BH}$

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

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

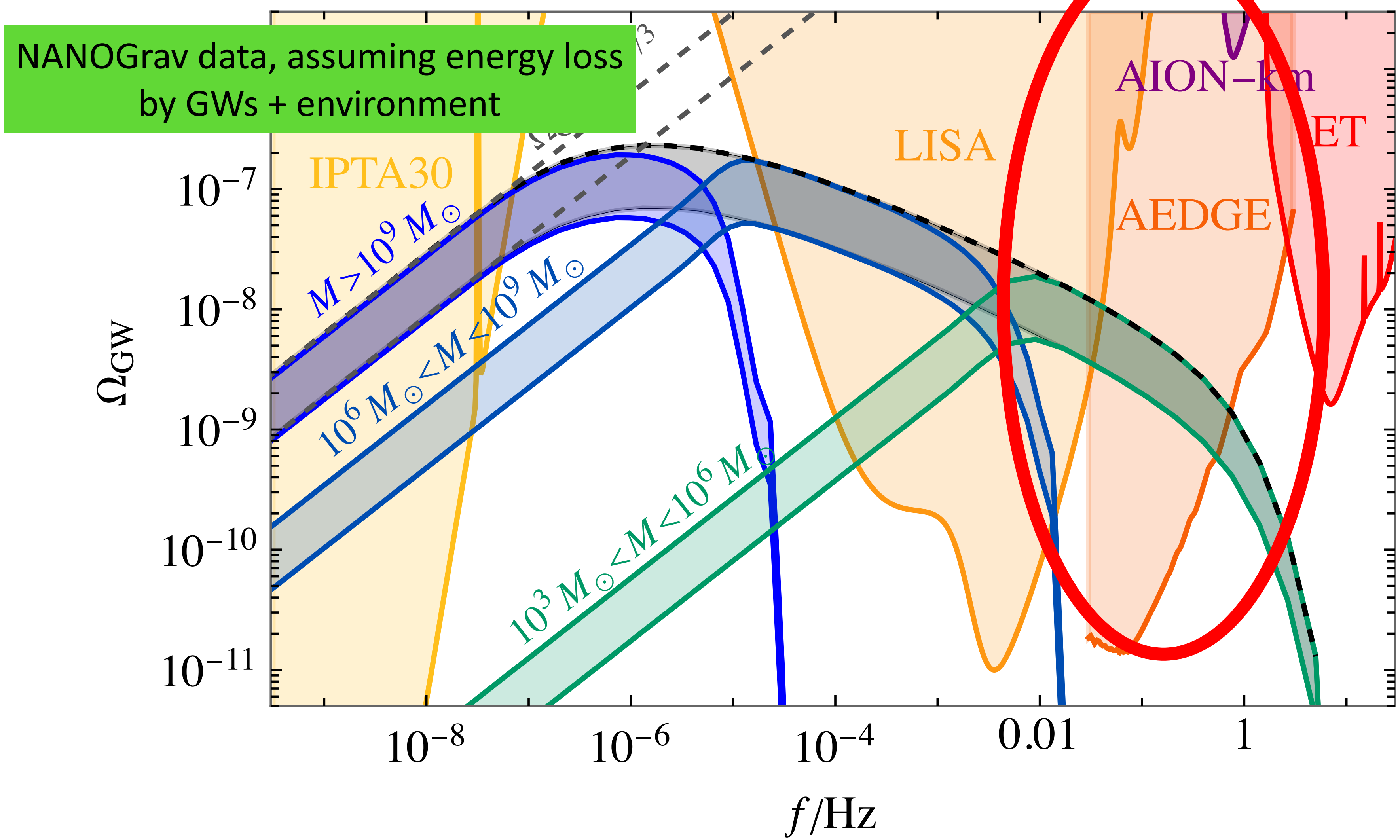
$$p_{\rm BH} \equiv p_{\rm occ}(m_1)p_{\rm occ}(m_2)p_{\rm merg}$$

is merger probability, and

strength of PTA signal can be fitted by constant $p_{\rm BH}$

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

Stochastic GW Background from BH Mergers



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

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:

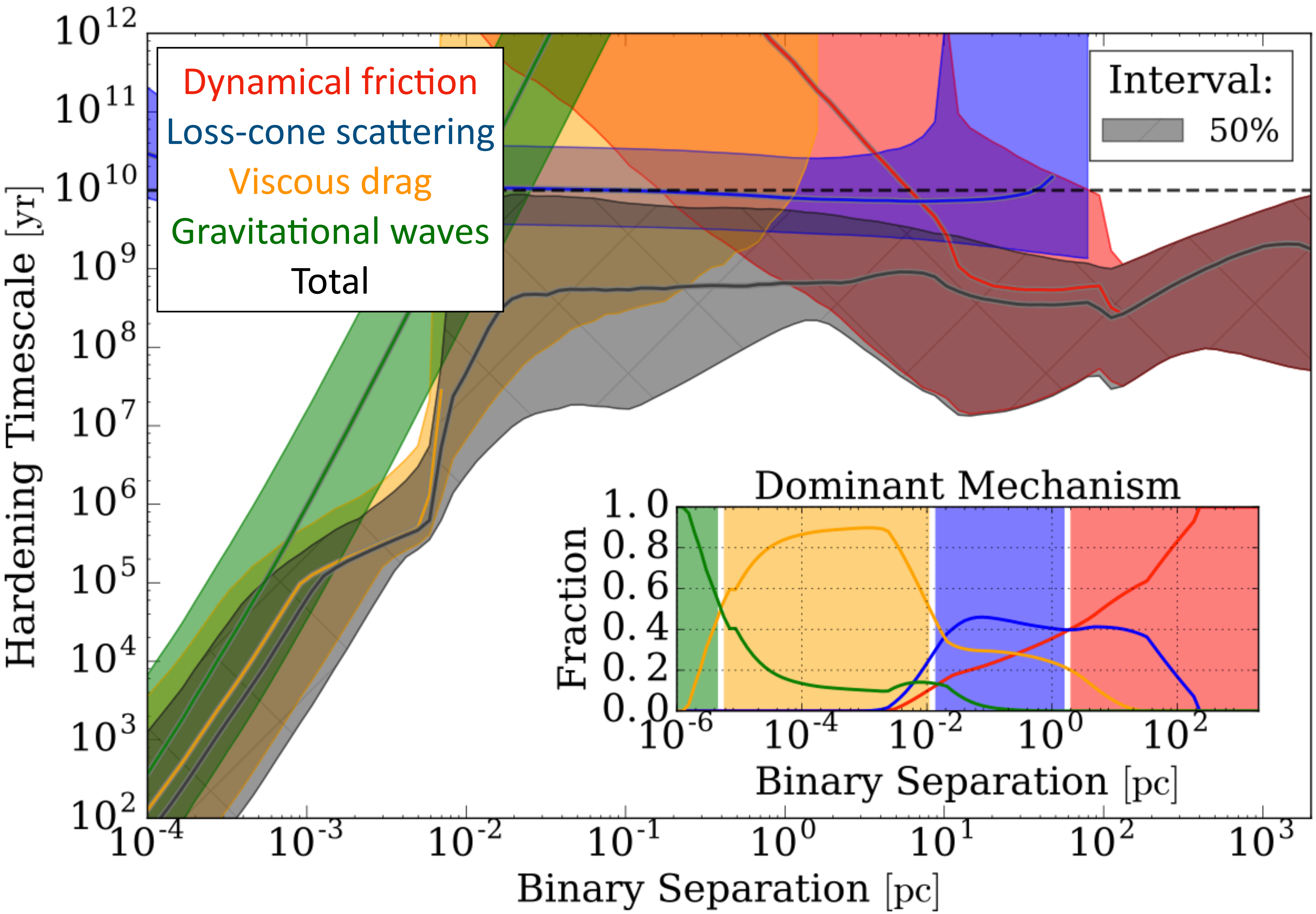
$$\frac{\mathrm{dE_{GW}}}{\mathrm{d\ln f_r}} = \frac{1}{3}\frac{(\pi f_r)^{\frac{2}{3}}\mathcal{M}^{\frac{5}{3}}}{1 + t_{\rm GW}/t_{\rm env}}$$

- 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

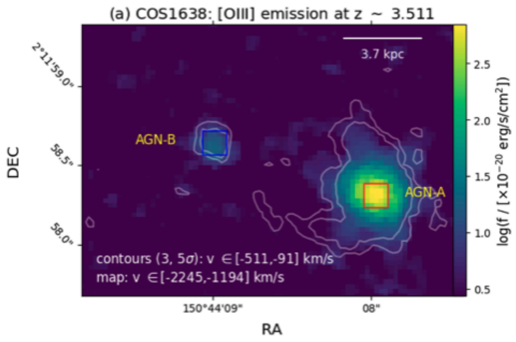


Kelley, Blecha & Hernquist, arXiv:1606.01900

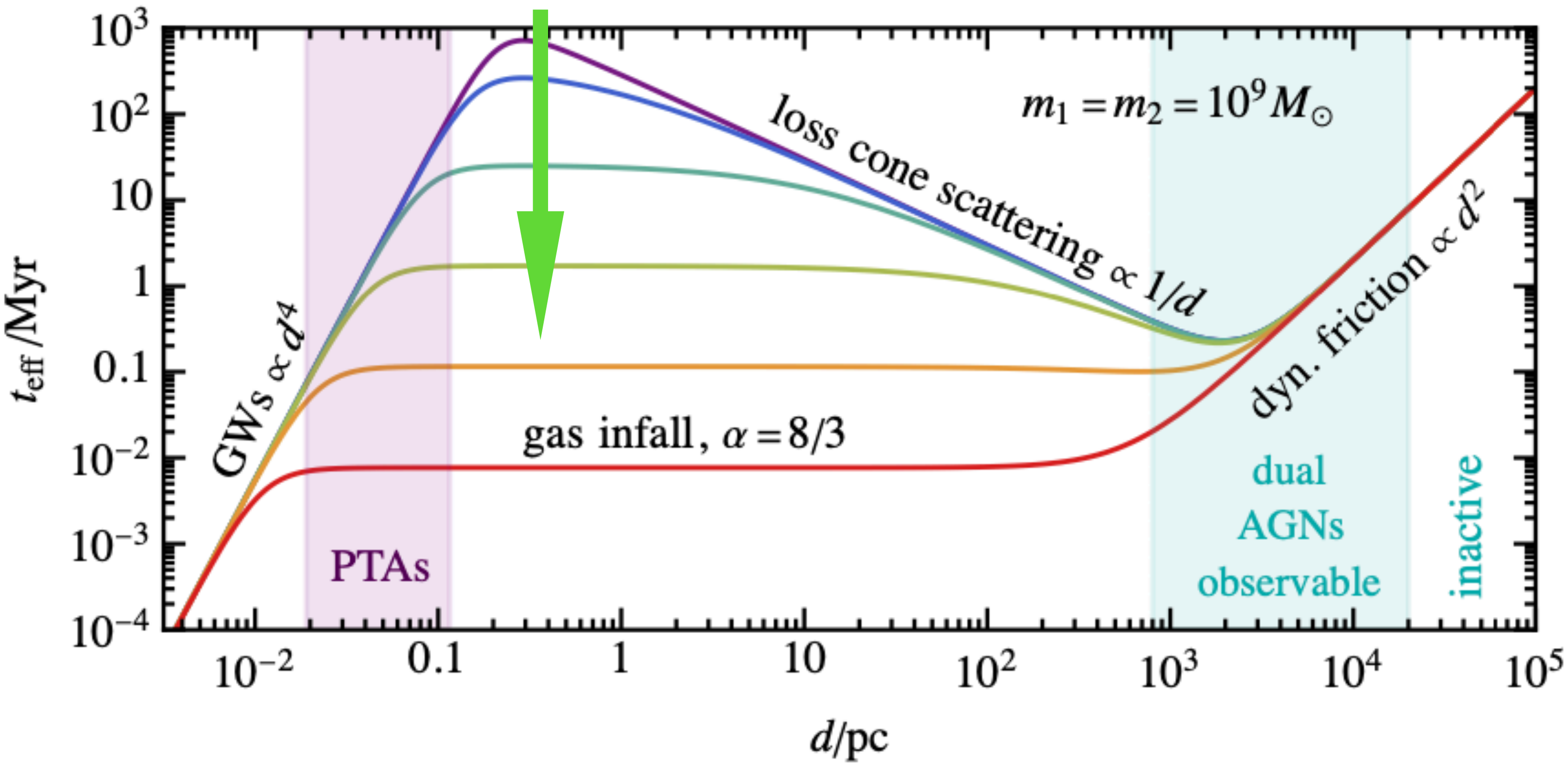
Modelling Environmental Effects

- "Surprisingly many" high-redshift dual AGNs

Perna et al, arXiv:2310.03067



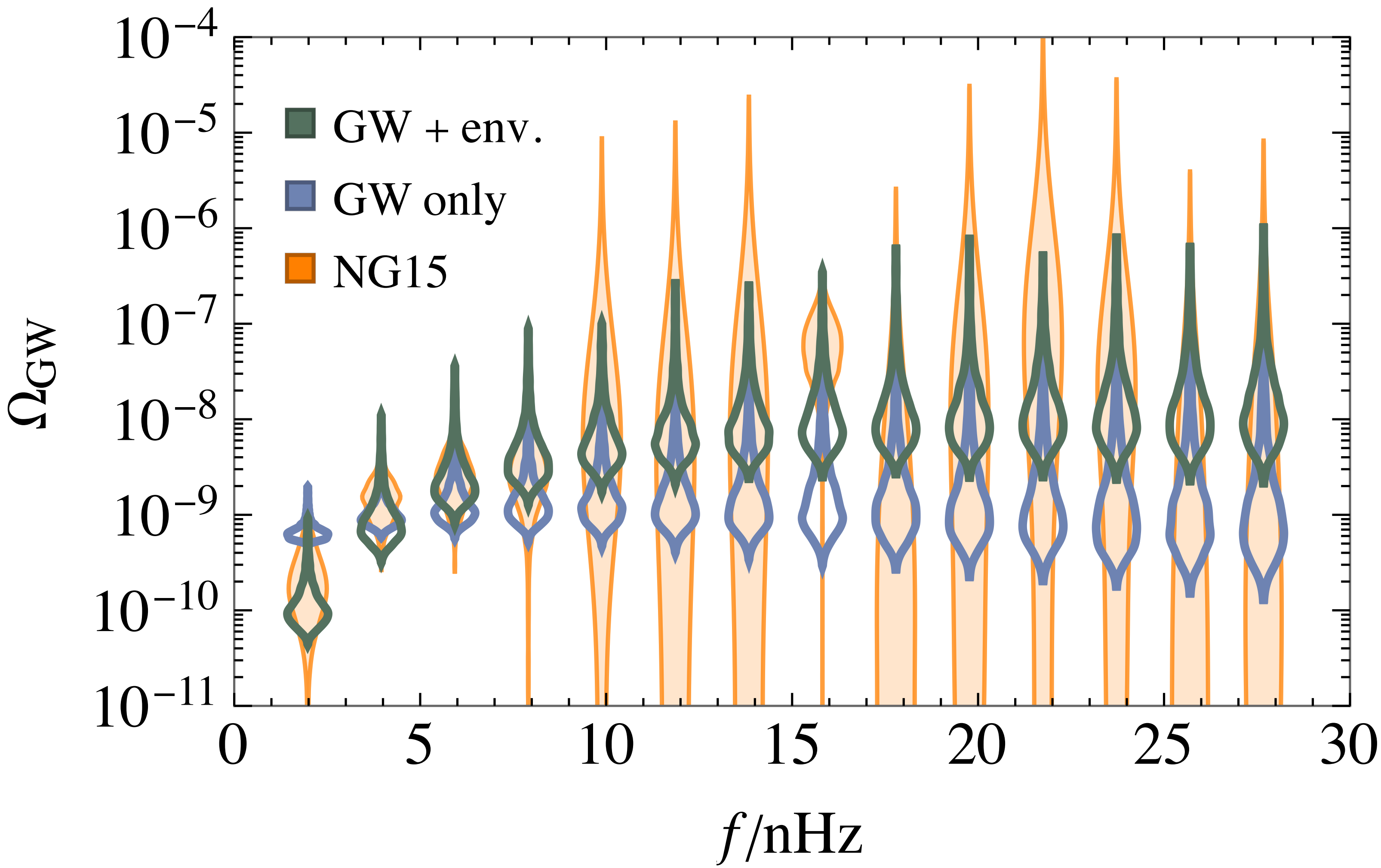
- Fit environmental energy loss effects to data on dual AGNs, "little red dots"



- Can be understood within global fit to JWST + NANOGrav

JE, Fairbairn, Hütsi, Urrutia, Vaskonen & Veermäe: arXiv:2403.19650

Astrophysical Interpretations AION



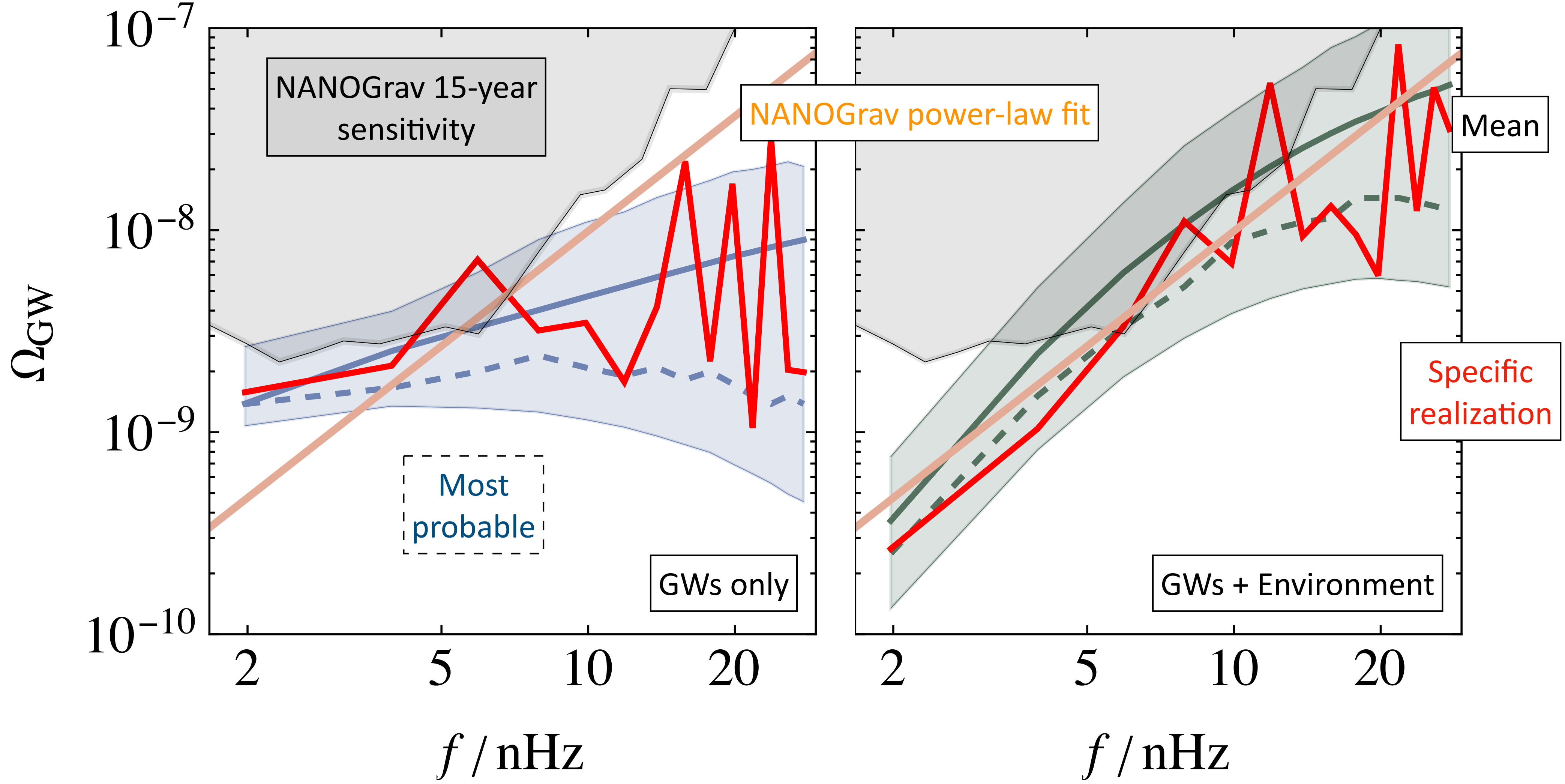
Fits use overlaps of data and model violins in each bin

NB: Fits go beyond simple power-law approximations

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

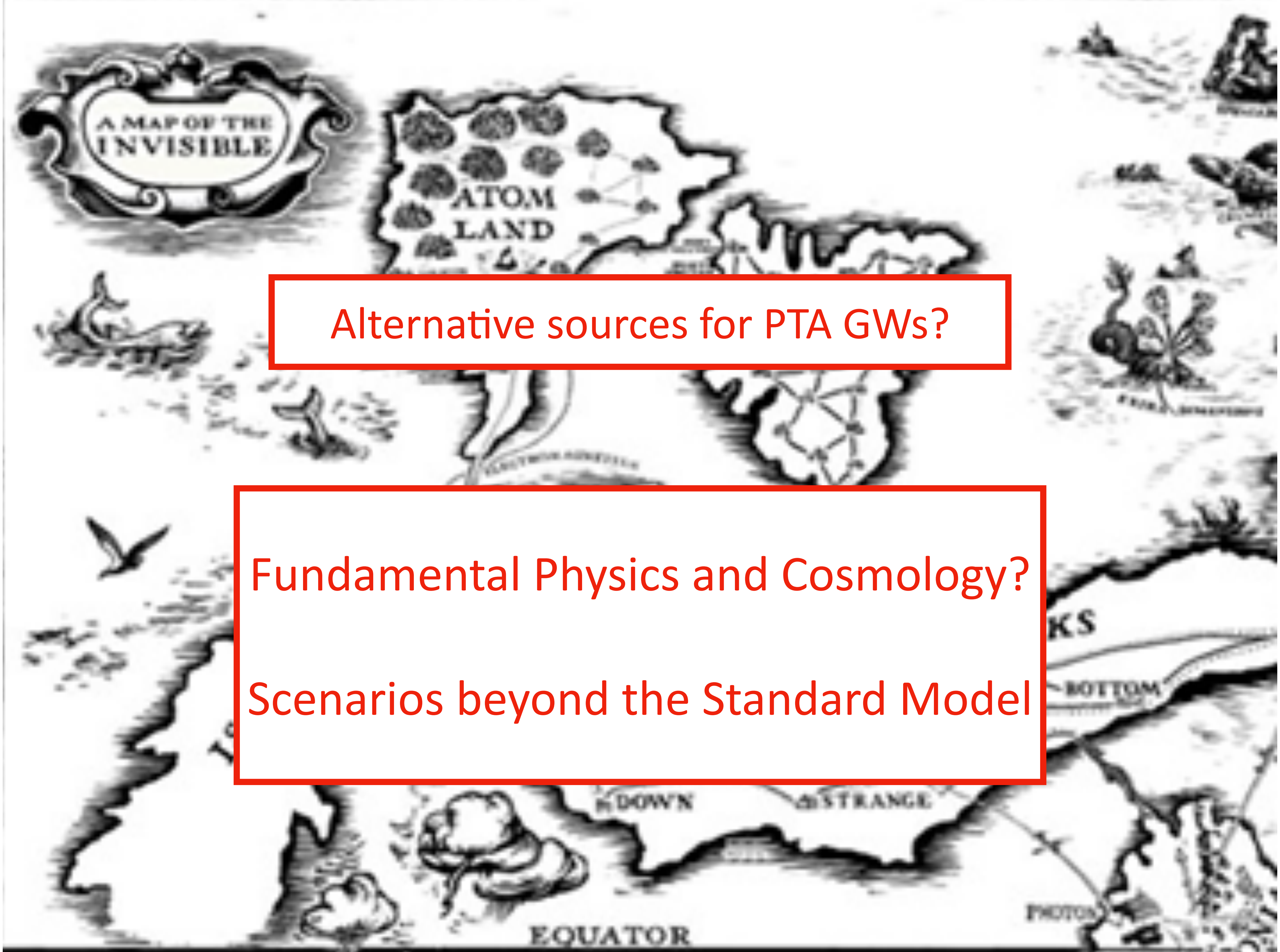
JE, Fairbairn, Hütsi, Raidal', Urrutia, Vaskonen & Veermäe: arXiv:2306.17021

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

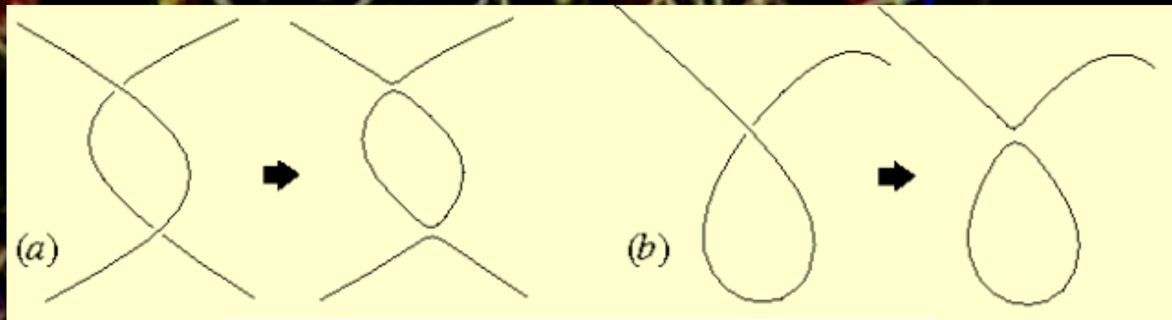


Alternative sources for PTA GWs?

Fundamental Physics and Cosmology?

Scenarios beyond the Standard Model

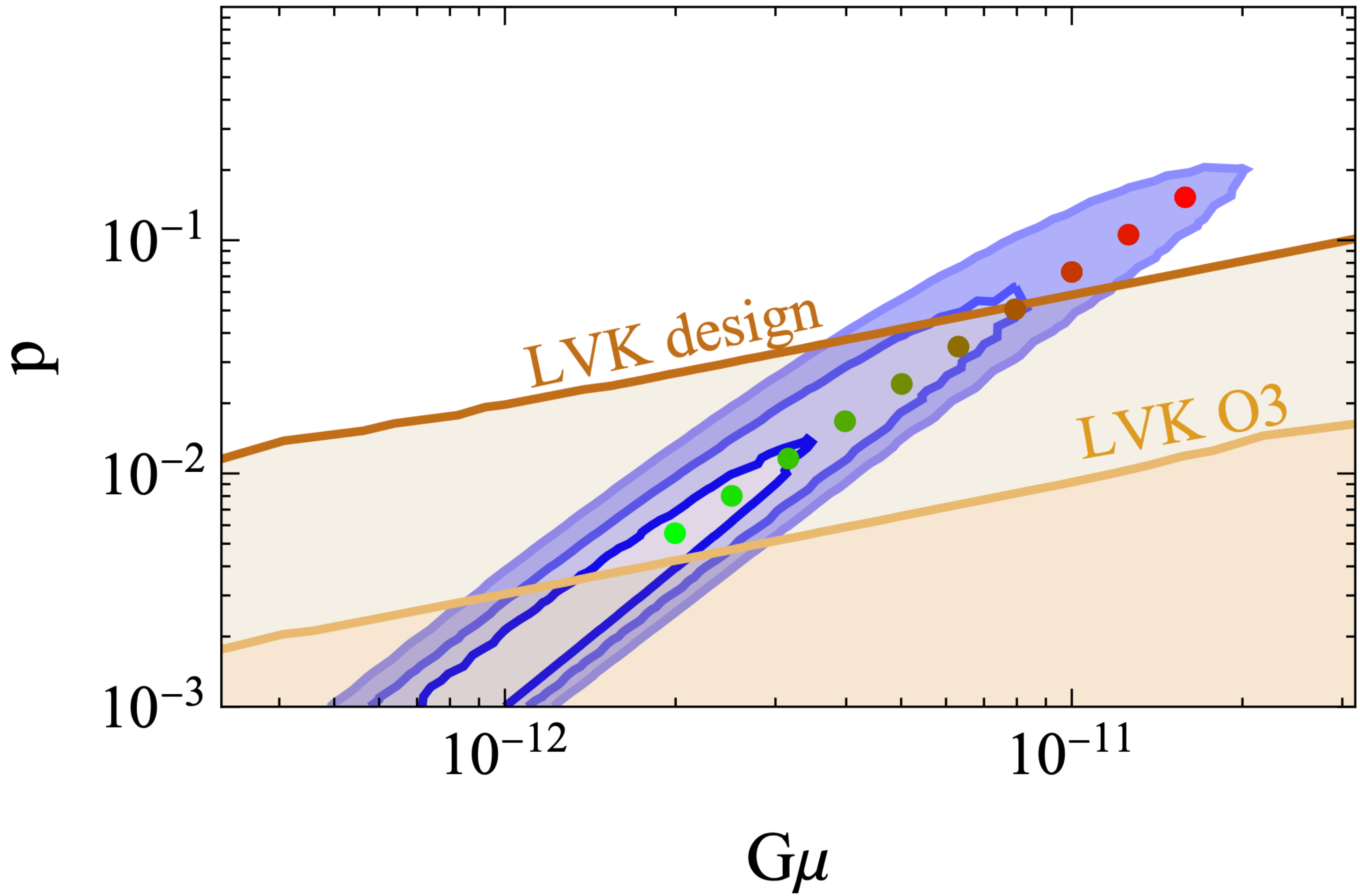
Probing Cosmic Strings



GW emission from string loops

Simulation of cosmic string network – Cambridge cosmology group

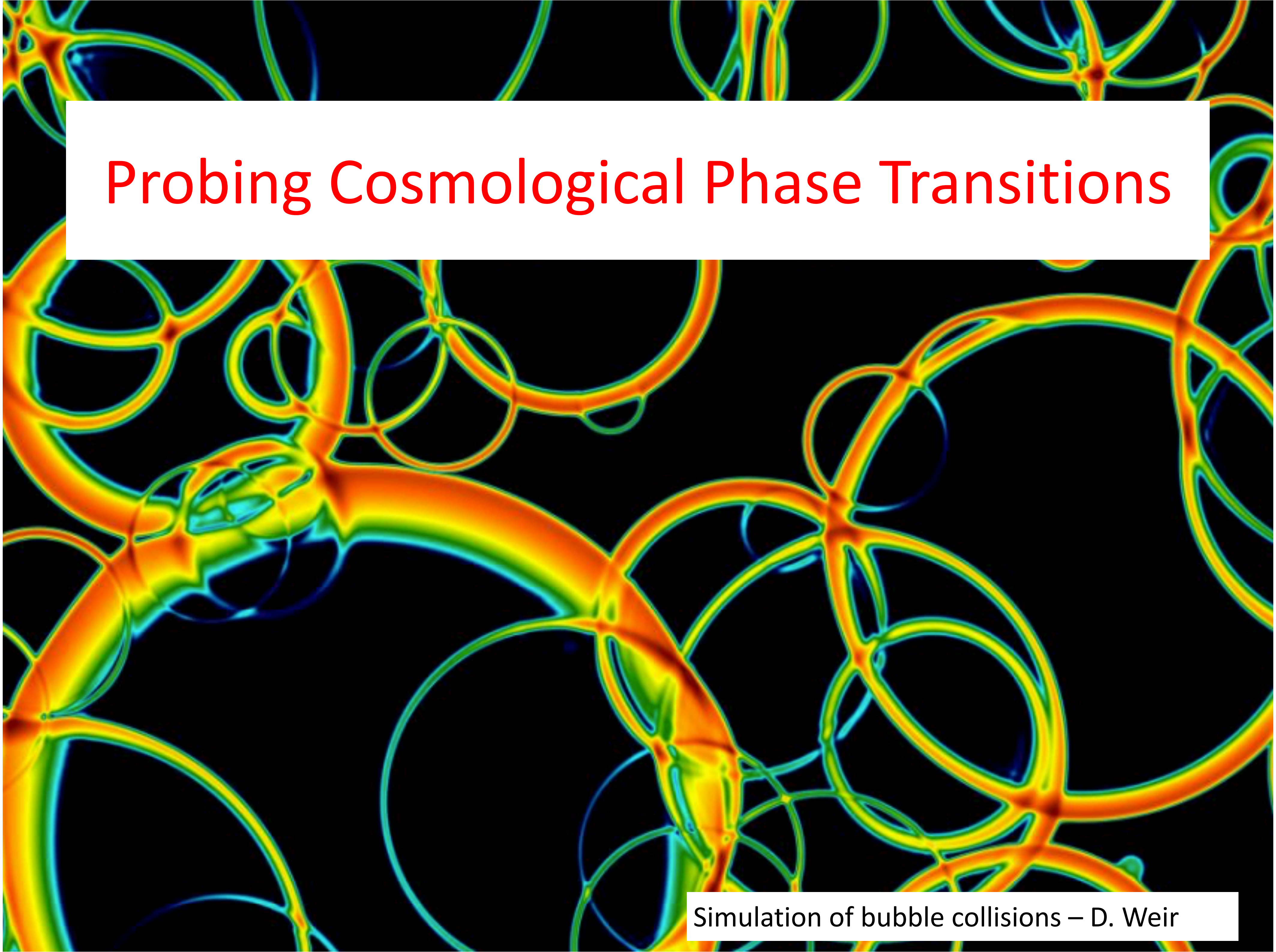
(Super)strings vs LVK



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

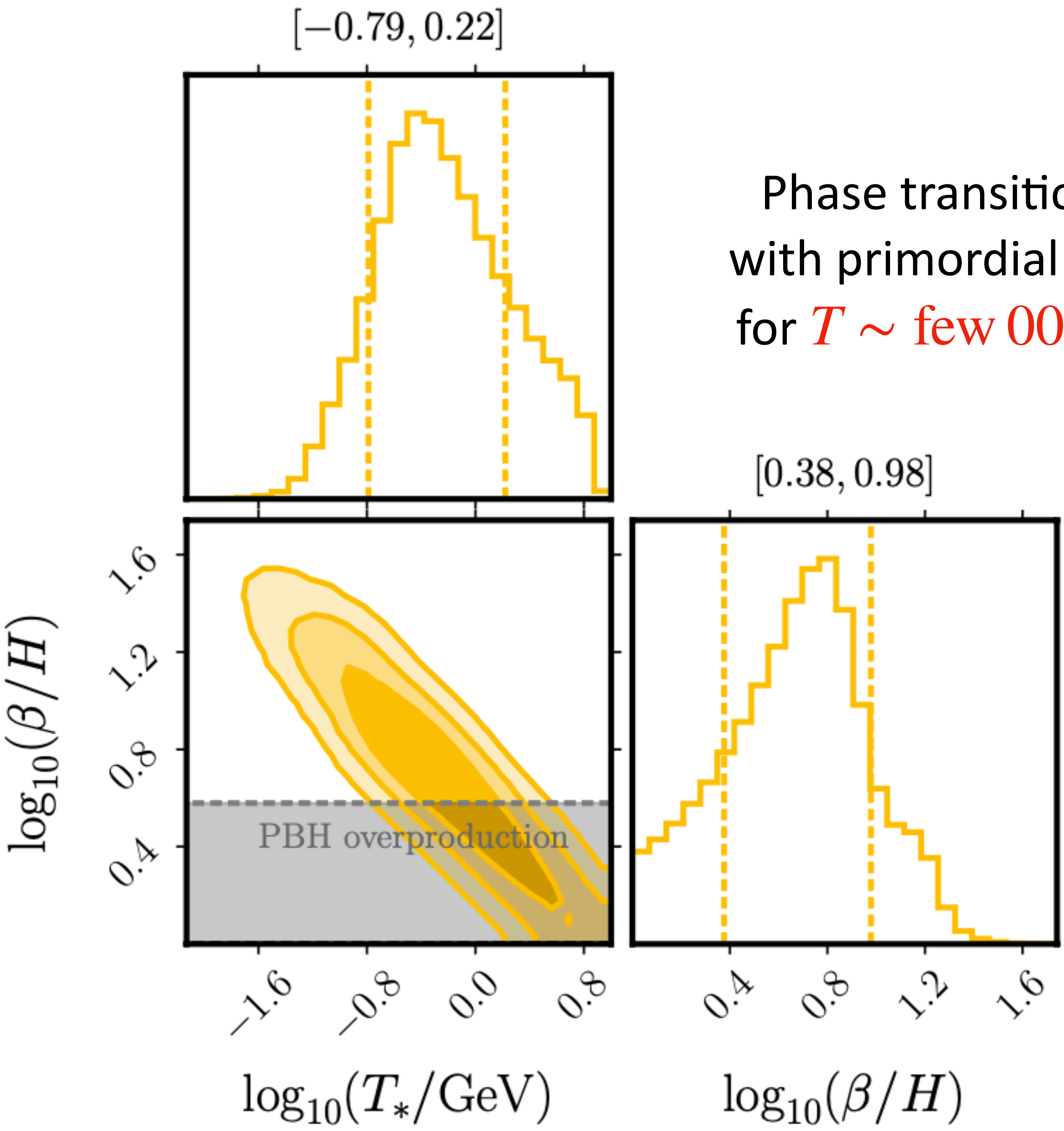
JE, Lewicki, Lin, & Vaskonen: arXiv:2306.17147

Probing Cosmological Phase Transitions



Simulation of bubble collisions – D. Weir

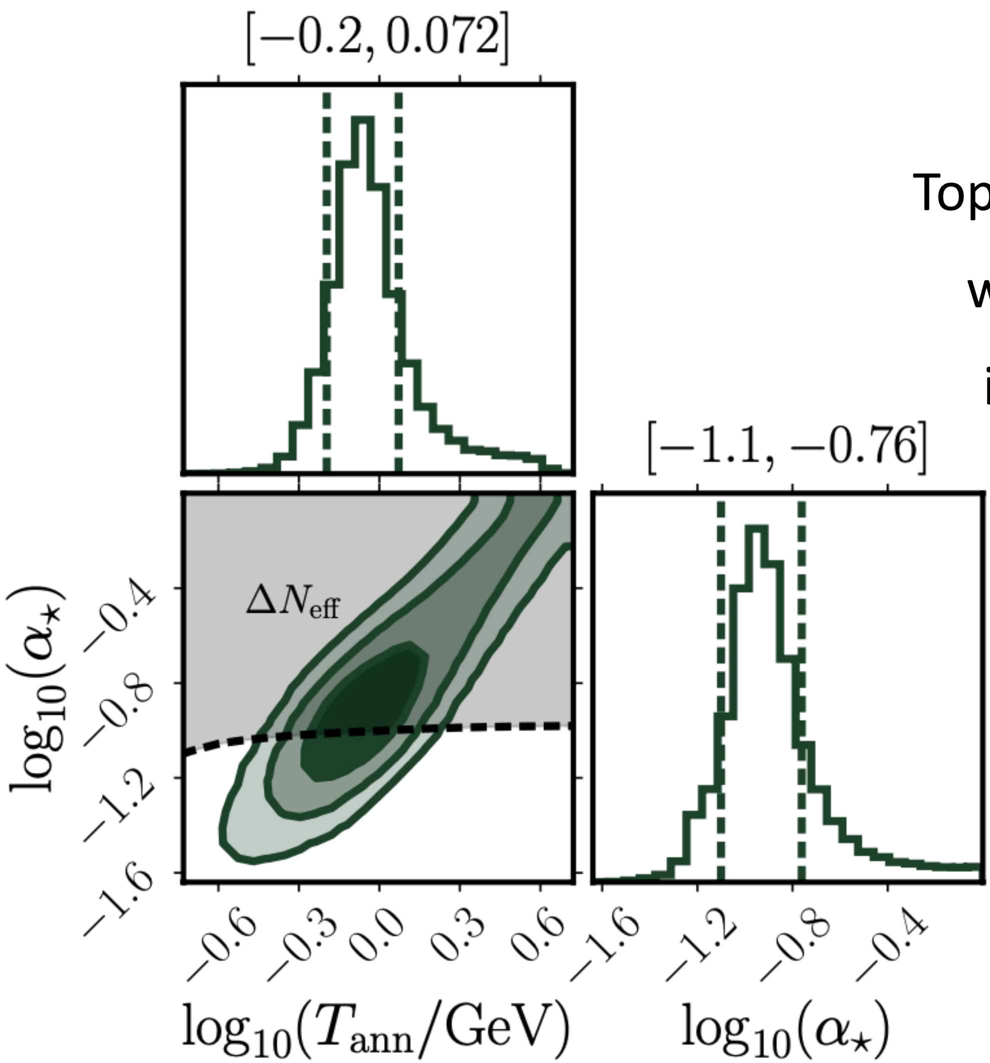
Phase Transition Fit to NANOGrav AION



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

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

Domain Wall Fit to NANOGrav AION



Topological defects produced

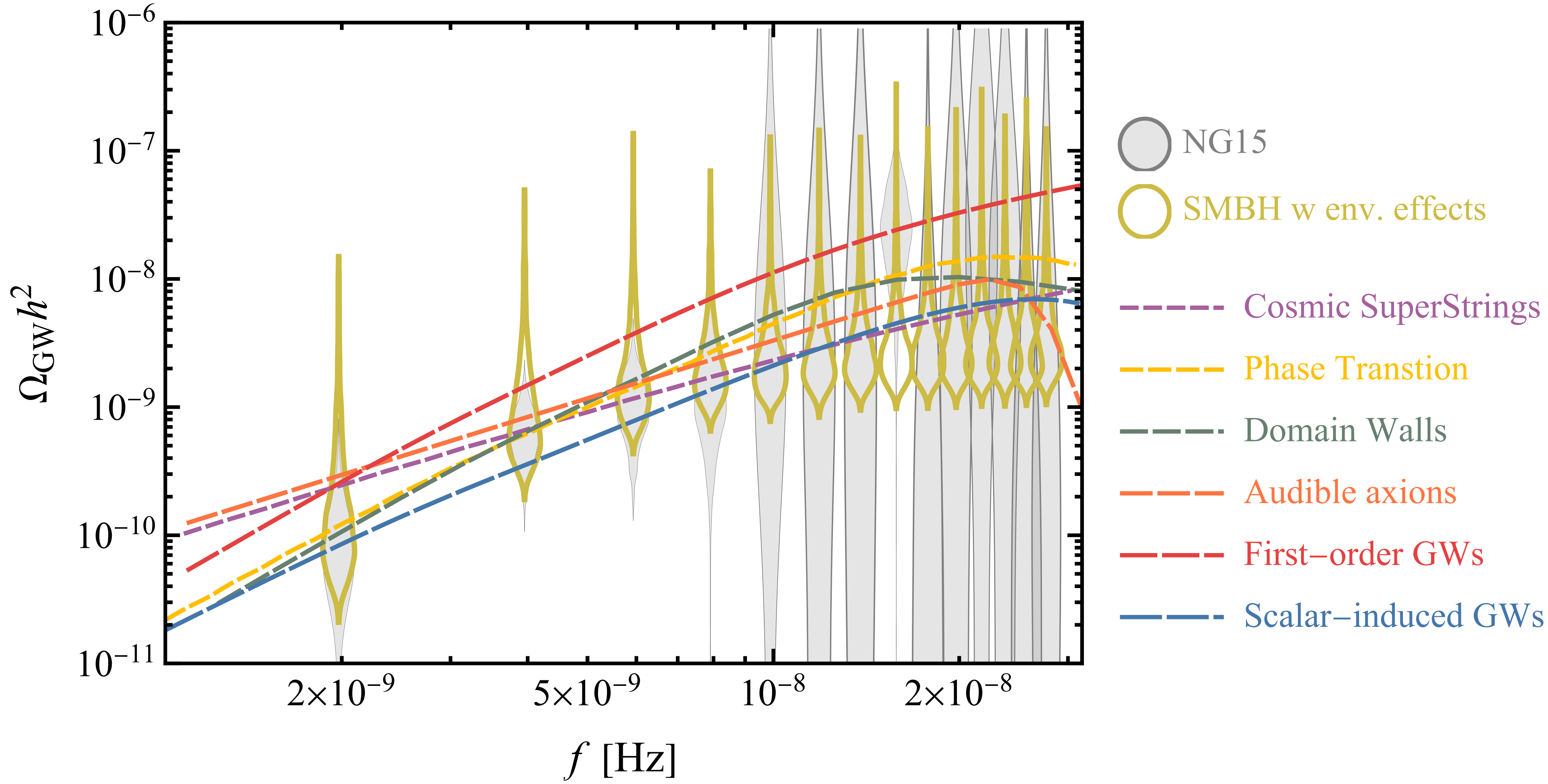
when discrete symmetry

is broken after inflation

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

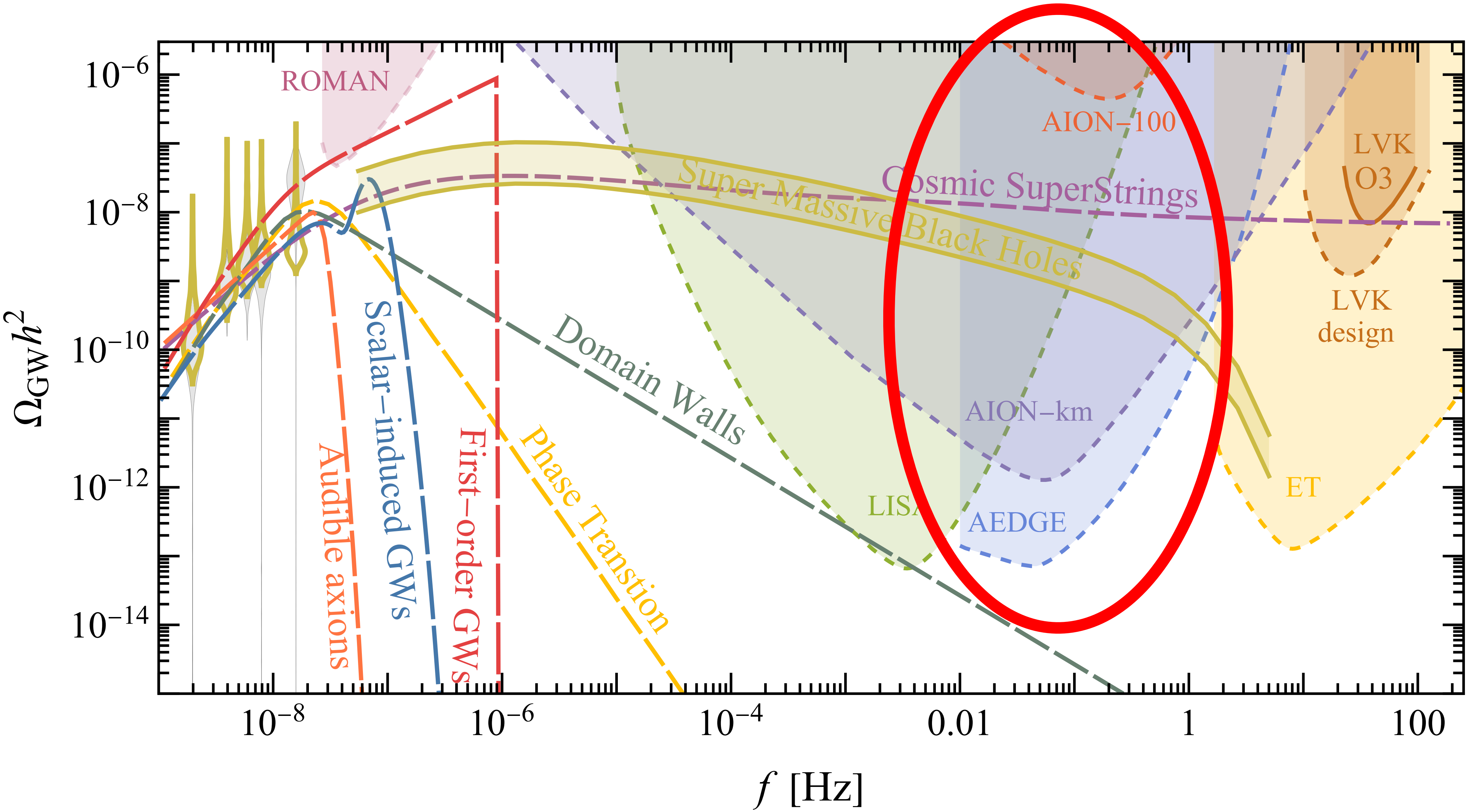
JE, Fairbairn, Franciolini, Hütsi, Iovino, Lewicki, Urrutia, Vaskonen & Veermäe, arXiv:2308.08546

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

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, Raidal, Urrutia, Vaskonen & Veermäe, arXiv:2308.08546