After nHz, μHz?

Binaries to explore the μHz band of GWs

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w/ A. Jenkins (UCL)

based on 2107.04063 (PRL)/2107.04601 (PRD)

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Departament de Recerca i Universitats

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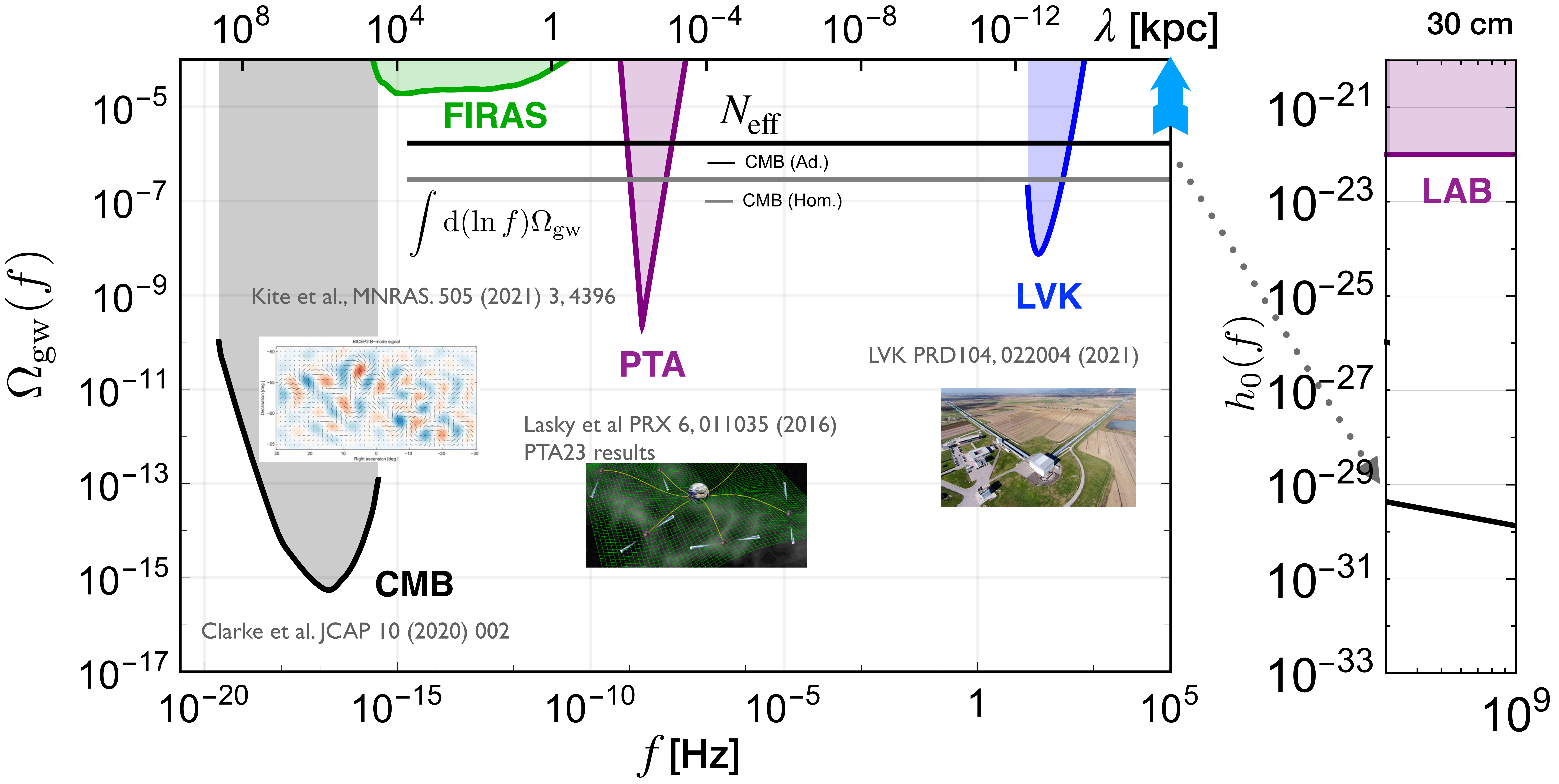
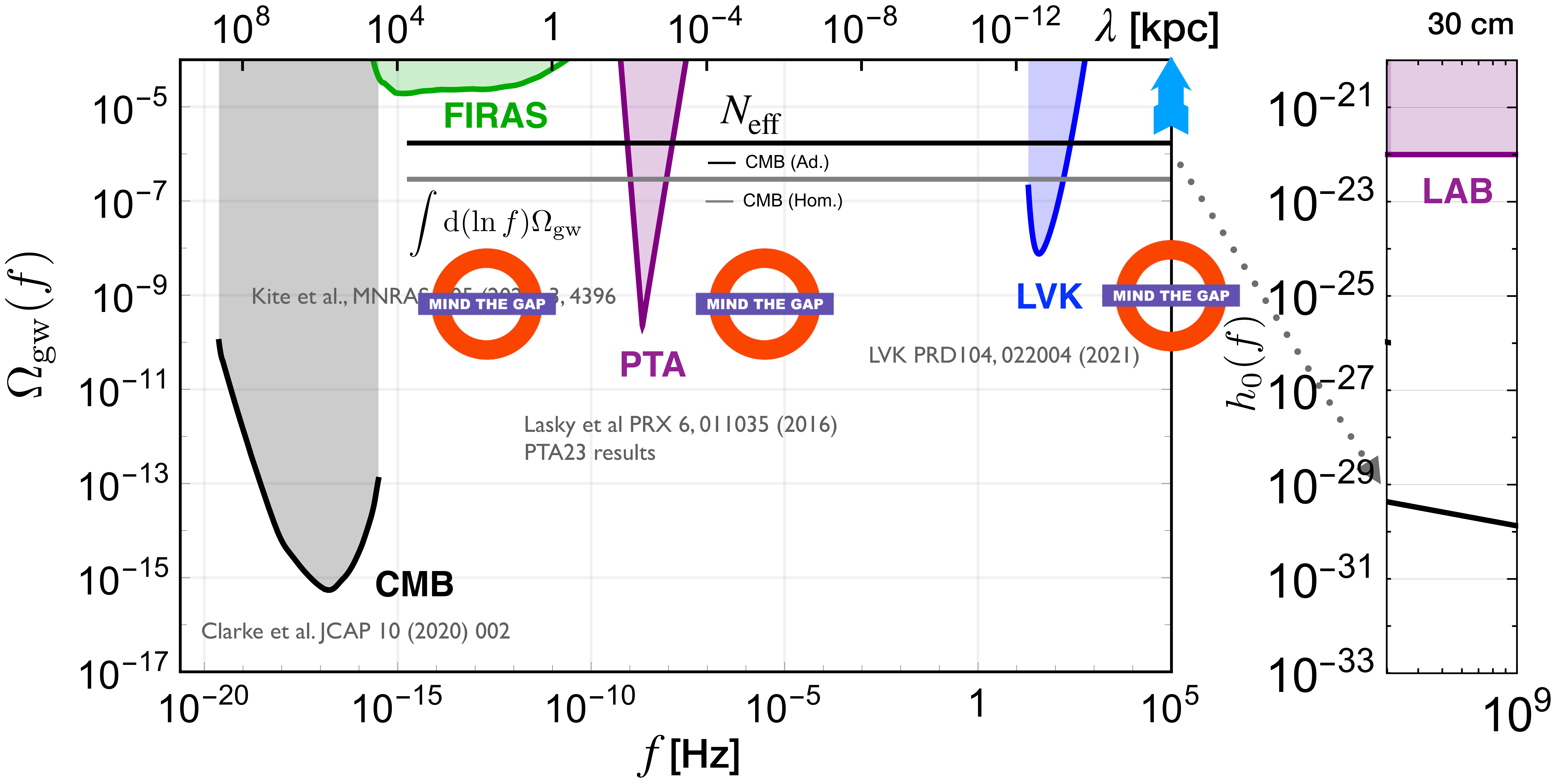
MINISTERIO DE UNIVERSIDADES
MINISTERIO DE CIENCIA E INNOVACIÓN
AGENCIA ESTATAL DE INVESTIGACIÓN

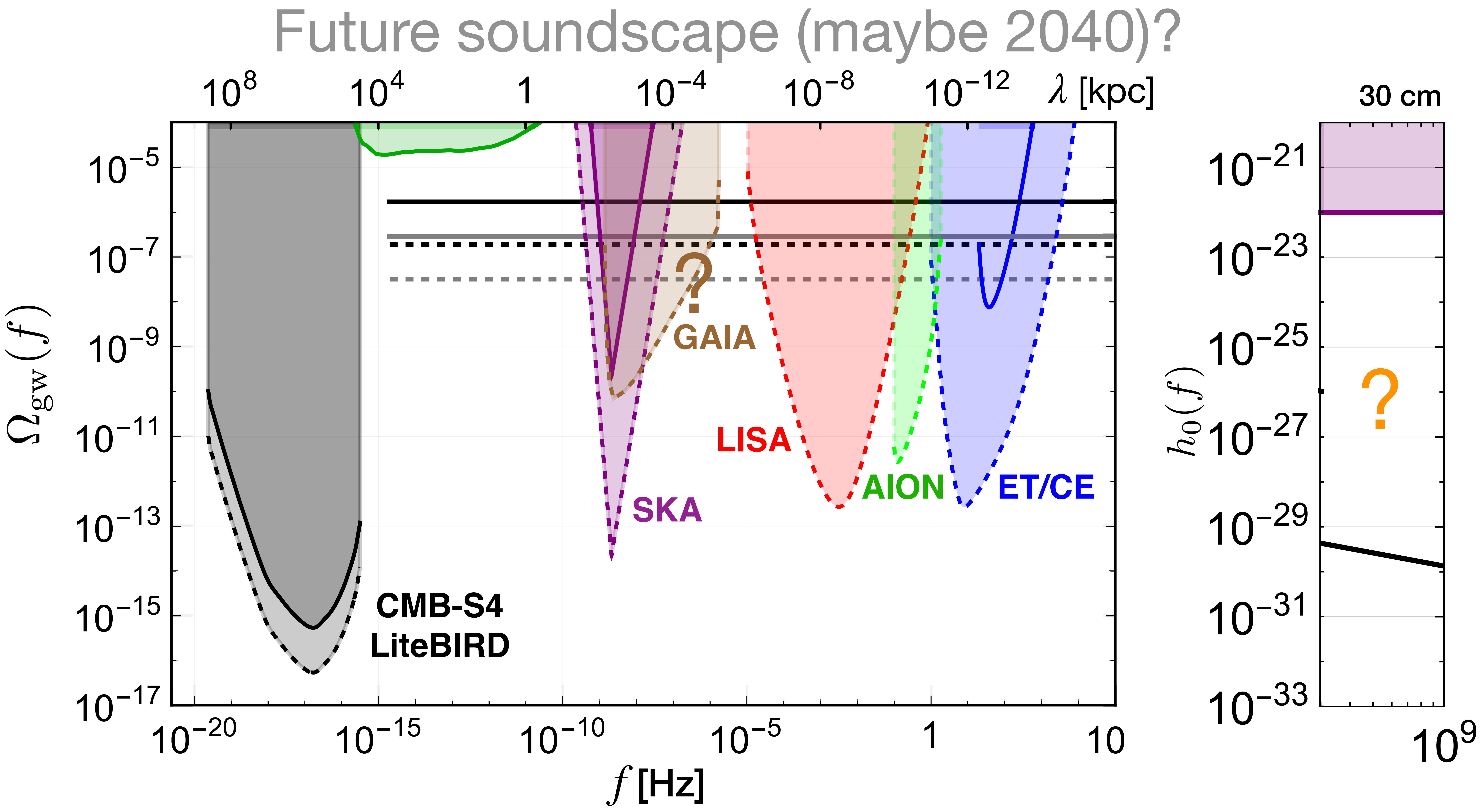
UAB
Universitat Autònoma de Barcelona
IFAE
BIST Barcelona Institute of Science and Technology

Soundscape today



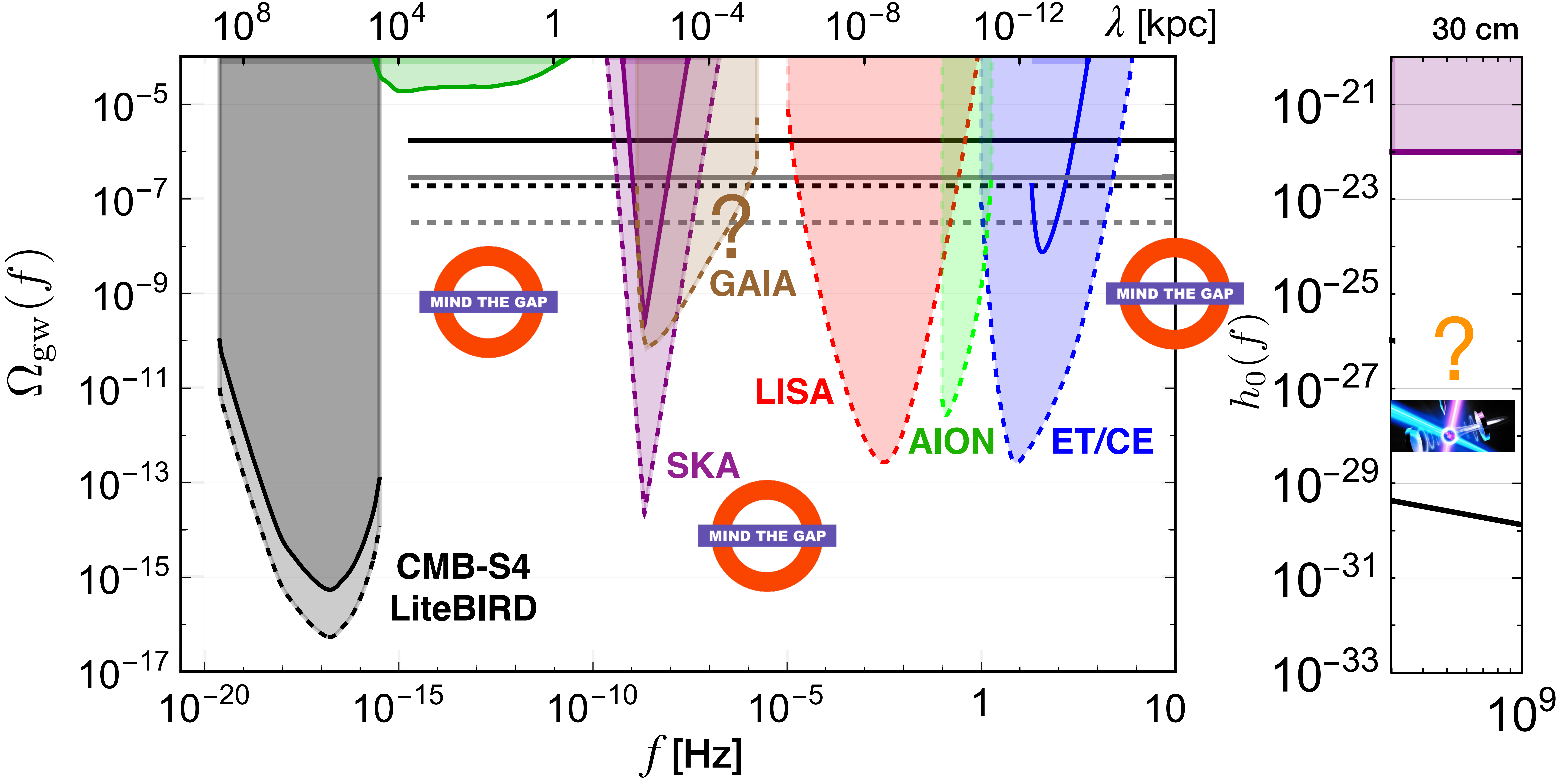
Soundscape today





Future soundscape (maybe 2040)?
λ [kpc]
10^8
10^4
1
10^{-4}
10^{-8}
10^{-12}
30 cm
$\Omega_{gw}(f)$
10^{-5}
10^{-7}
10^{-9}
10^{-11}
10^{-13}
10^{-15}
10^{-17}
?
GAIA
LISA
AION
ET/CE
SKA
CMB-S4
LiteBIRD
10^{-20}
10^{-15}
10^{-10}
10^{-5}
1
10
f [Hz]
$h_0(f)$
10^{-21}
10^{-23}
10^{-25}
10^{-27}
10^{-29}
10^{-31}
10^{-33}
?
10^9

Future soundscape (maybe 2040)?



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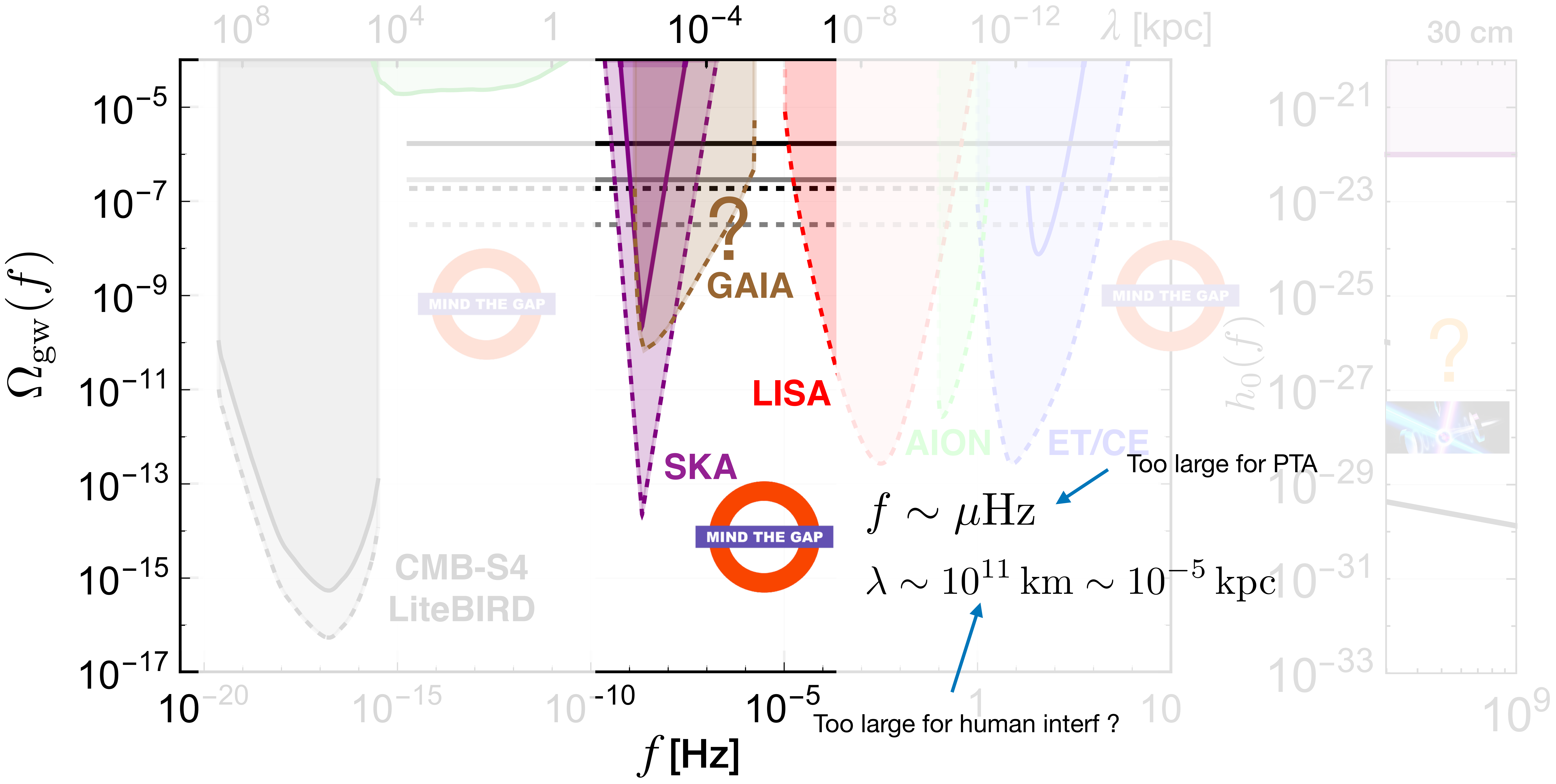
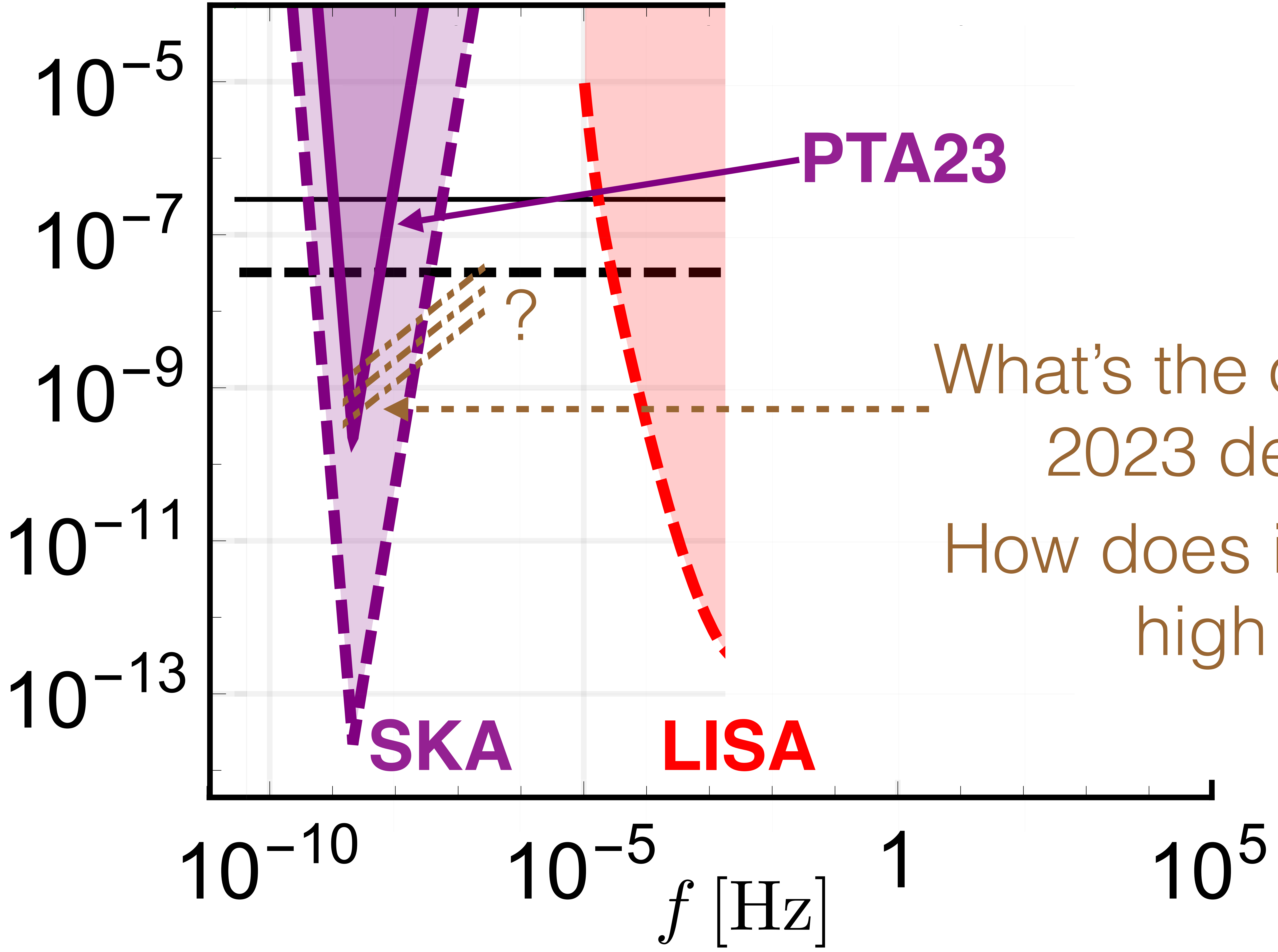


Possible **backgrounds** & ideas at μHz: a rich band

Possible **backgrounds** & ideas at μHz: a rich band



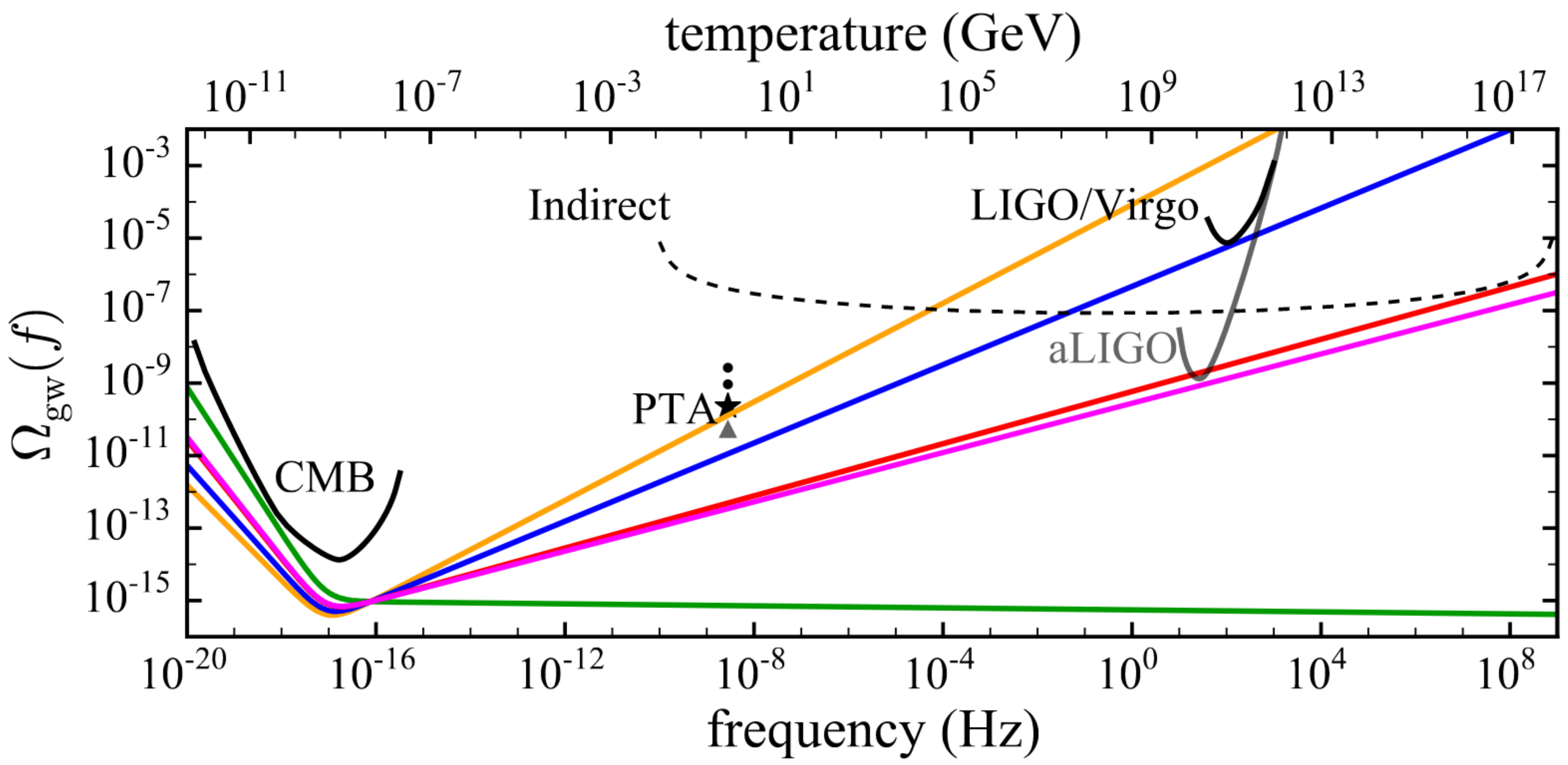
What's the origin of the 2023 detection?

How does it change at high freq?

Backgrounds from fundamental physics

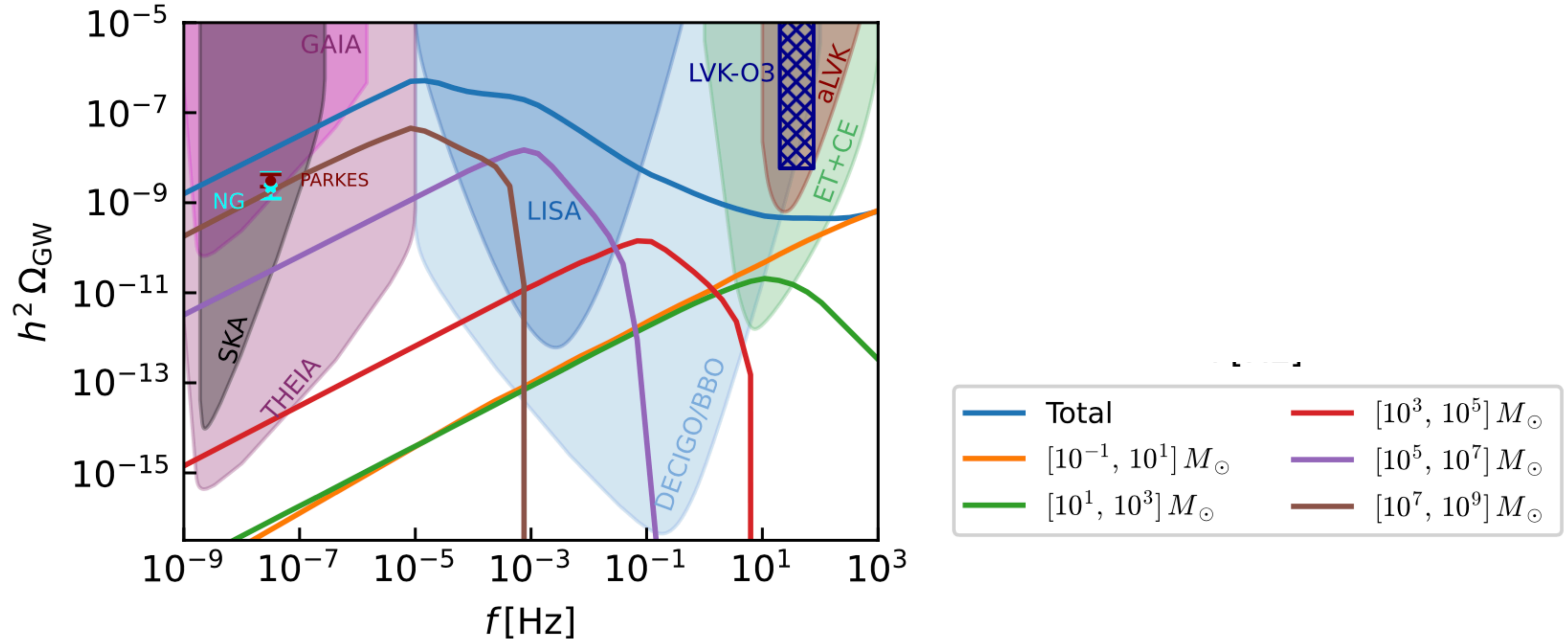
Inflation

Lasky et al PRX 6, 011035 (2016)



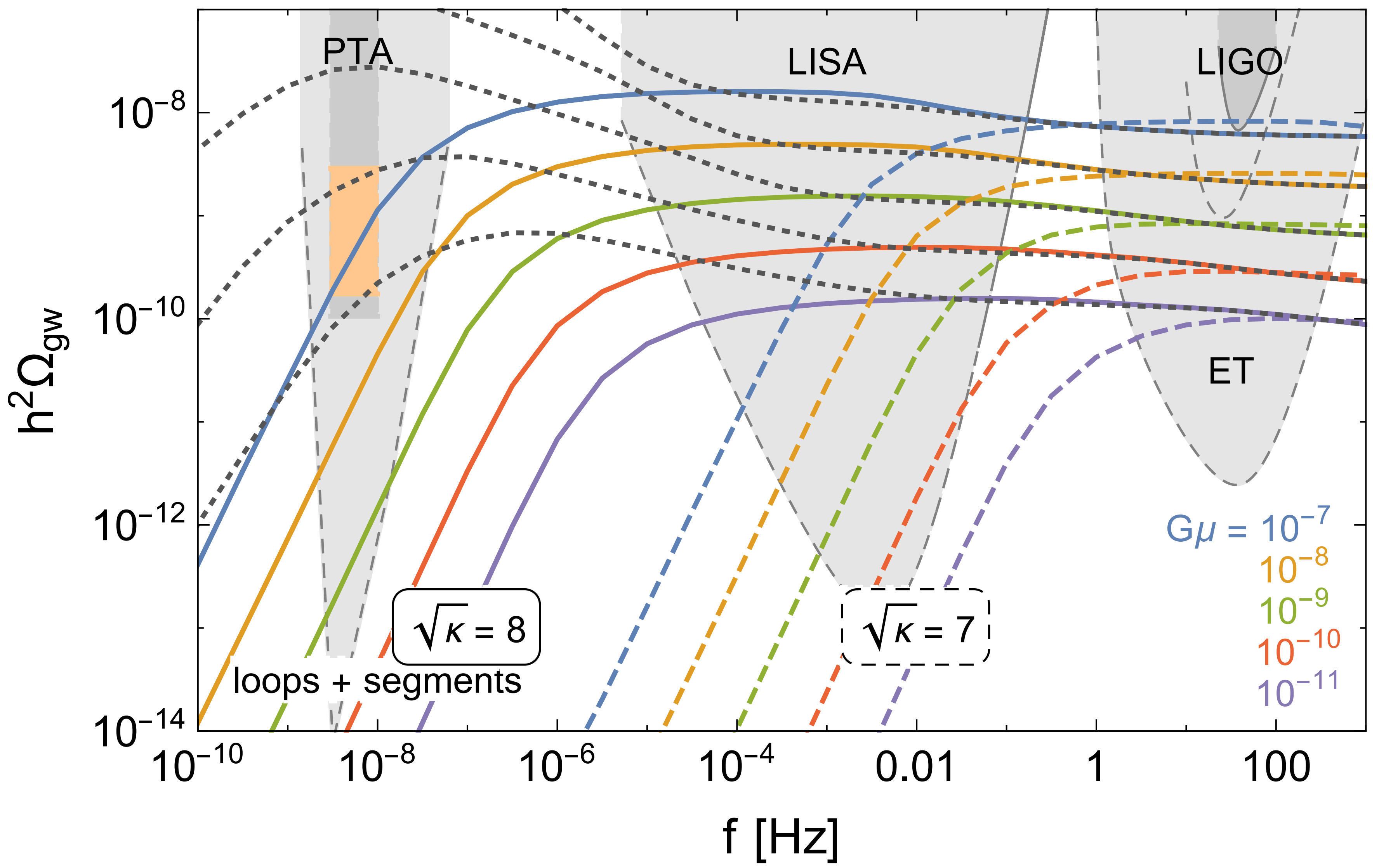
PBH

Braglia et al. JCAP 12 (2021) 12



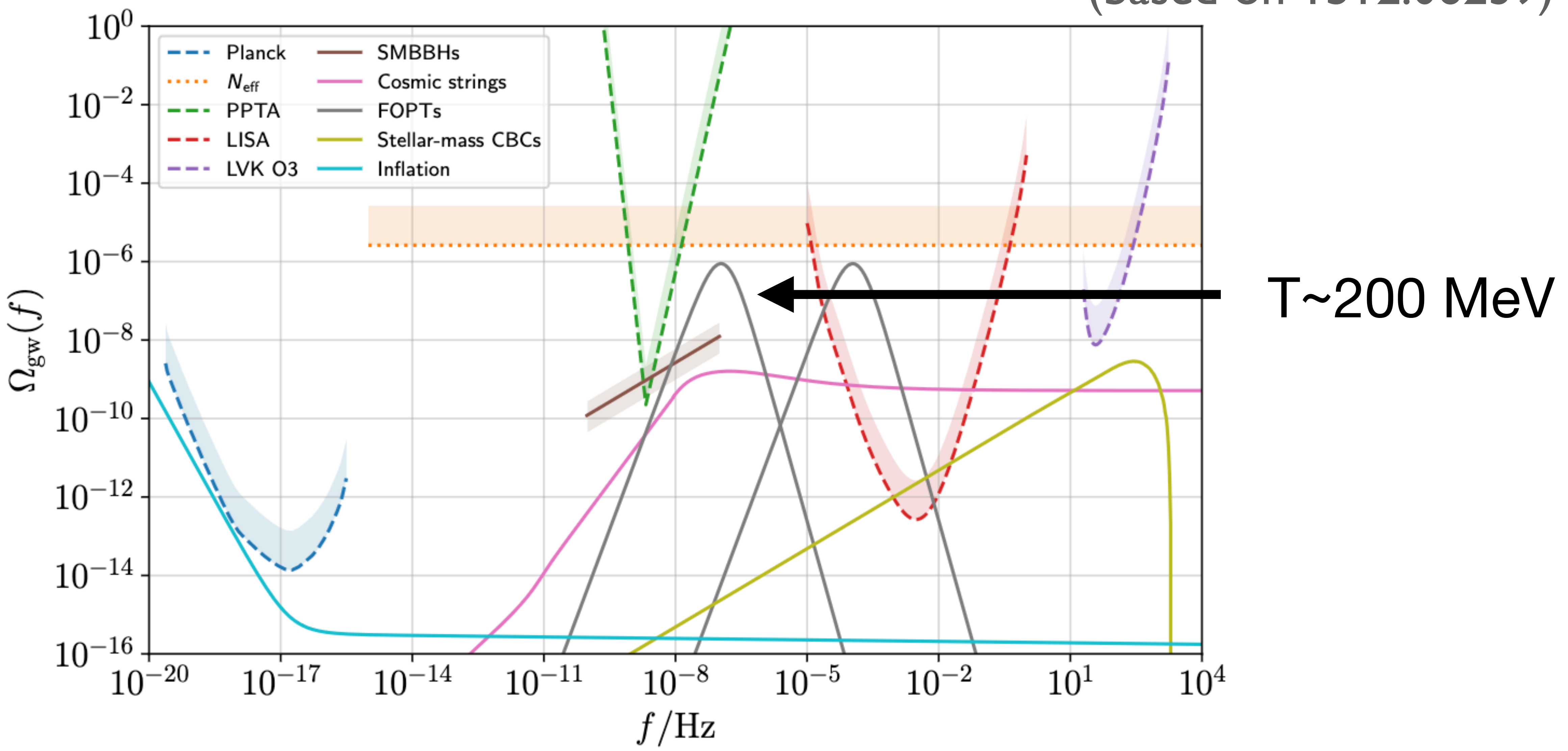
Cosmic Strings

Buchmuller et al. 2107.04578



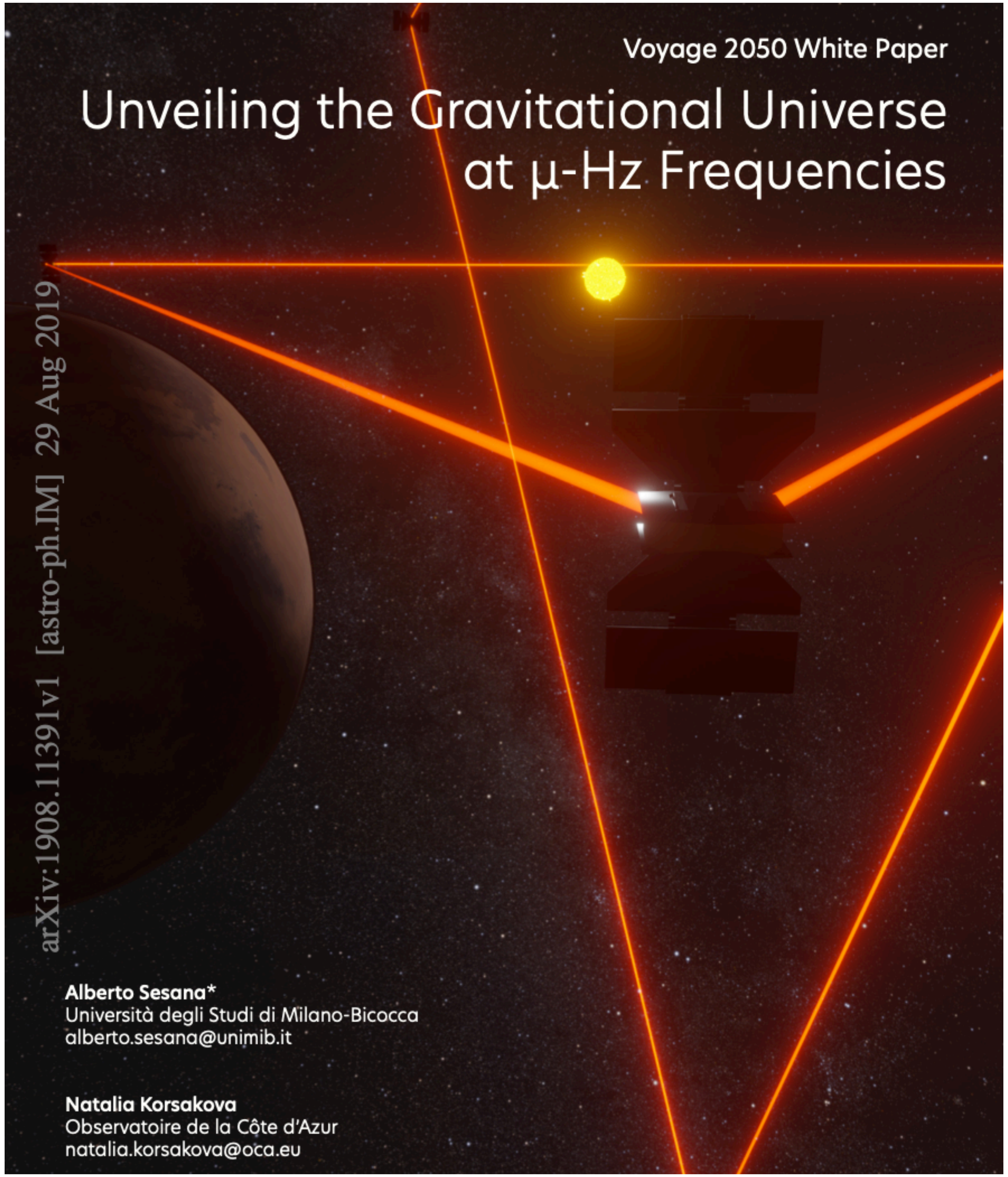
FOPT

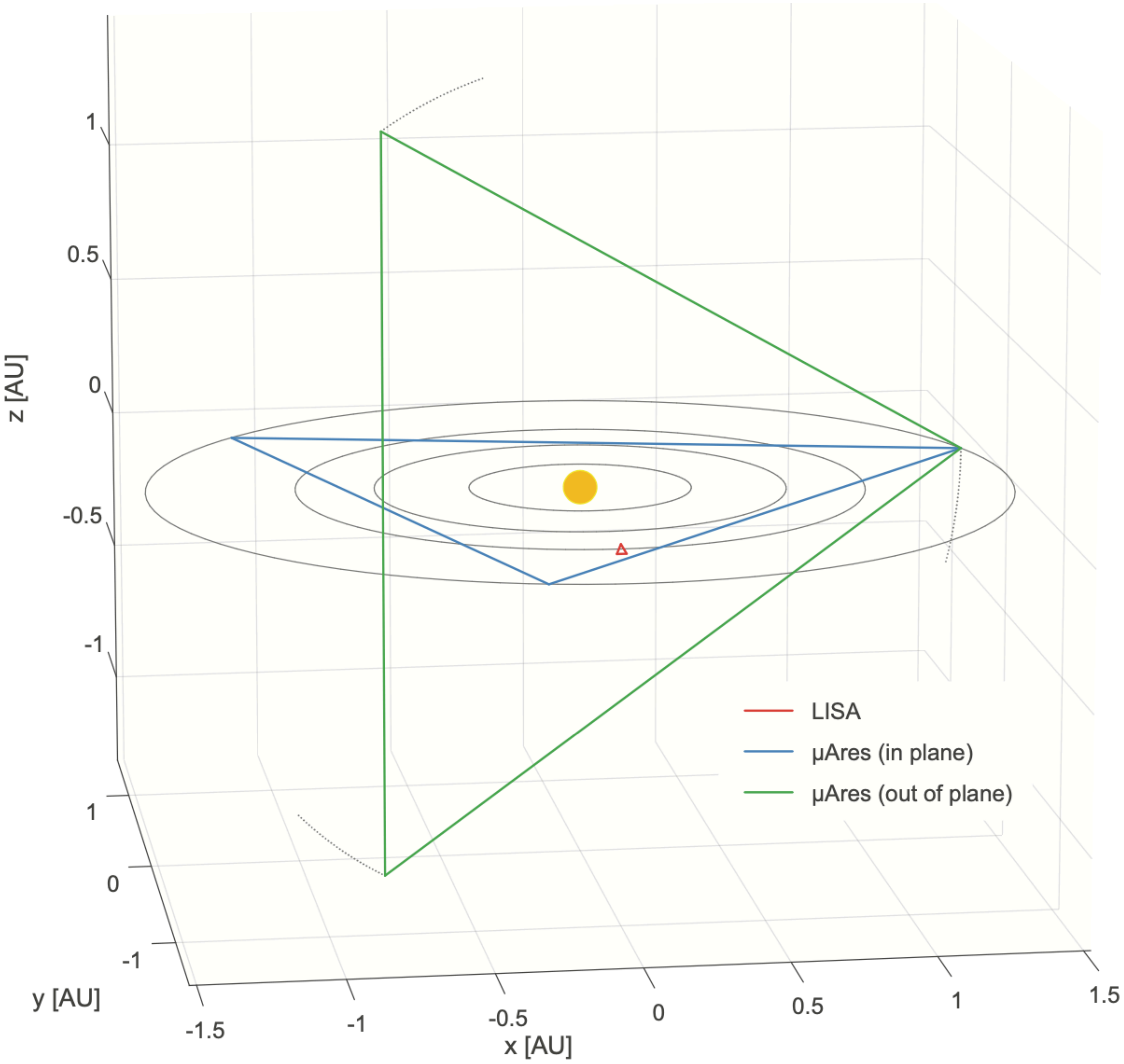
Renzini et al 2202.00178
(based on 1512.06239)

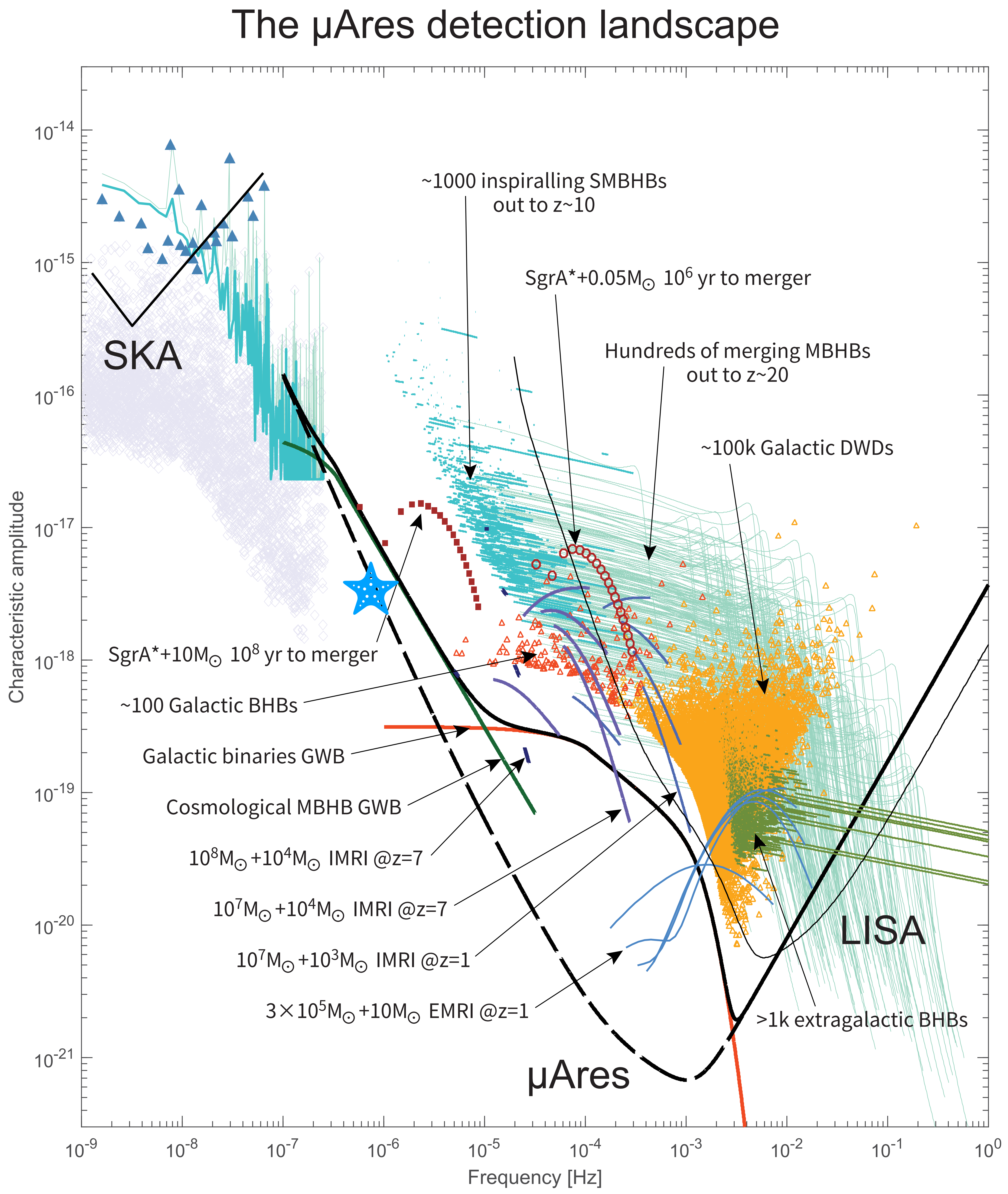


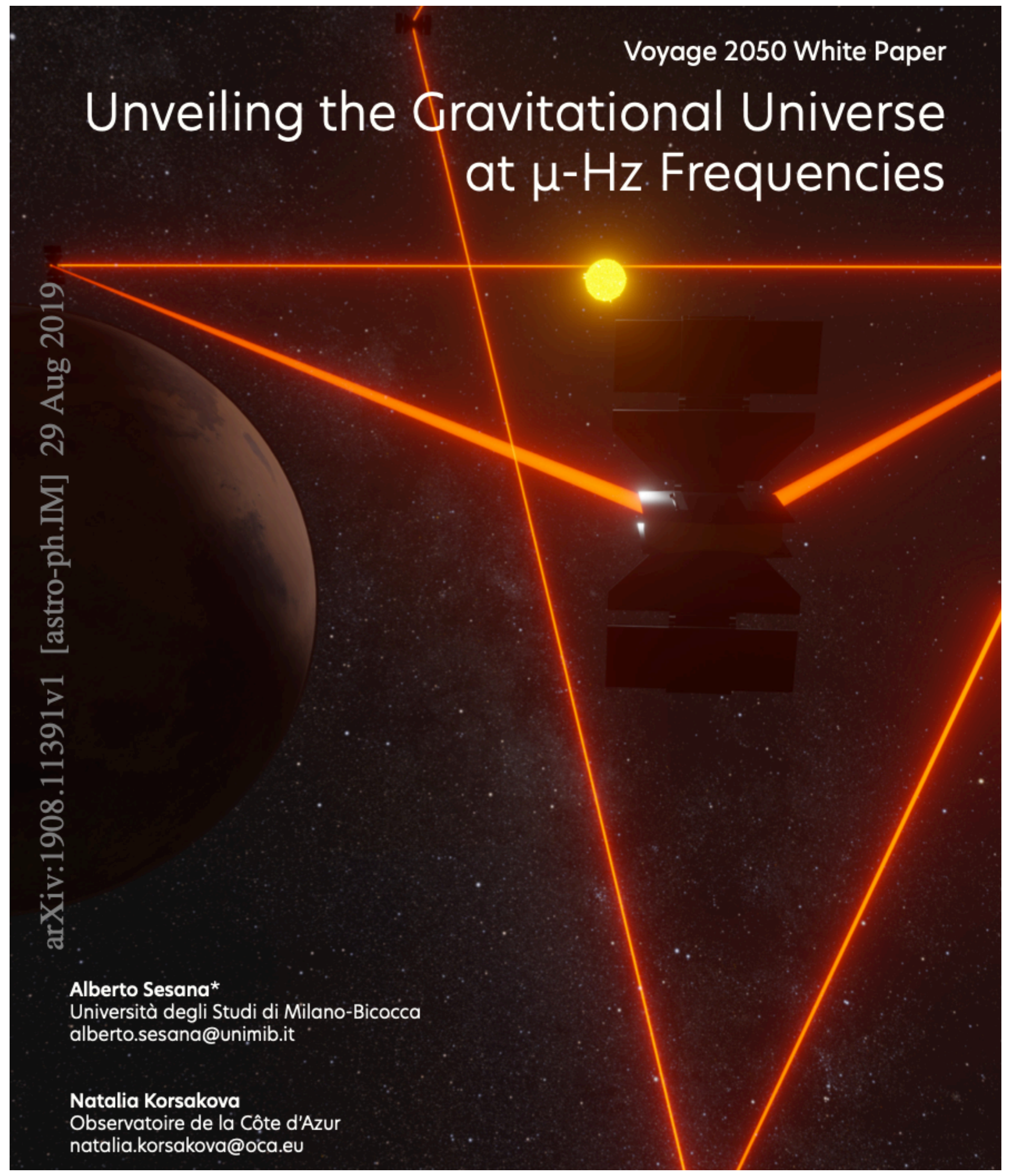
Possible backgrounds & **ideas** at μHz: a rich band

i) μAres: LISA-like concept




z [AU]
y [AU]
x [AU]
LISA
μAres (in plane)
μAres (out of plane)


The μAres detection landscape
Characteristic amplitude
Frequency [Hz]
SKA
LISA
μAres
~1000 inspiralling SMBHBs out to z~10
SgrA*+0.05M$_\odot$ 10^6 yr to merger
Hundreds of merging MBHBs out to z~20
~100k Galactic DWDs
SgrA*+10M$_\odot$ 10^8 yr to merger
~100 Galactic BHBs
Galactic binaries GWB
Cosmological MBHB GWB
10^{8}M$_\odot$+10^{4}M$_\odot$ IMRI @z=7
10^{7}M$_\odot$+10^{4}M$_\odot$ IMRI @z=7
10^{7}M$_\odot$+10^{3}M$_\odot$ IMRI @z=1
3×10^{5}M$_\odot$+10M$_\odot$ EMRI @z=1
>1k extragalactic BHBs



Summary of multimessenger and multiband science goals:

- identify the characteristic signatures of inspiralling MBHBs, providing the key to search for them in millions of AGN spectra and lightcurves;
- investigate the interplay between gravity, matter, and light in the dynamical spacetime of inspiralling/merging MBHBs;
- establish the connection between MBHBs and their hosts;
- provide a unique sample of standard sirens out to $z \gtrsim 5$;
- fully characterize the MBHB population at low frequency, in connection with PTAs.

Summary of Milky Way science goals:

- understand common envelope physics via detection of mixed (CO + MS star) binaries and the distribution of DWD at $f < 10^{-4}$ Hz;
- physics of contact and over-contact binaries via joint GW + EM detection;
- characterization of BHB, NSB and BH-NS population in the Galaxy, synergies with PTAs and SKA;
- unveil the dynamics of stars and COs around SgrA*.

Summary of cosmology and cosmography science goals:

- investigate a vast region of the allowed parameter space of QCD phase transitions;
- explore beyond standard physics by searching for an EW phase transition;
- explore first order phase transitions in the hidden sector;
- probe the geometry of the Universe, constraining deviations from ΛCDM out to $z \approx 10$ by means of $\mathcal{O}(10^3)$ MBHB standard sirens.

Summary of General relativity and beyond science goals:

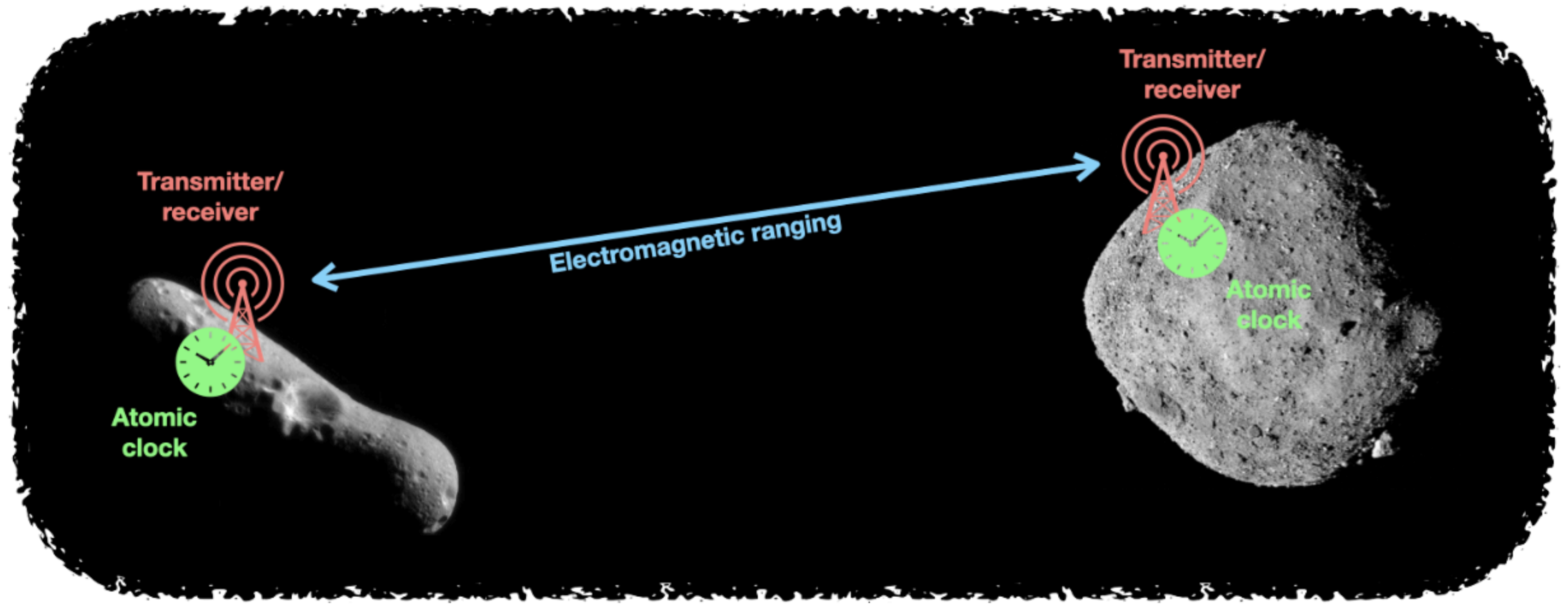
- probe DM substructures and the Universe expansion via strong GW lensing;
- detect non-linear GW memory with high SNR from merging MBHBs;
- improve sensitivity to graviton mass and other deviations from GR by more than two orders of magnitude with respect to LISA.

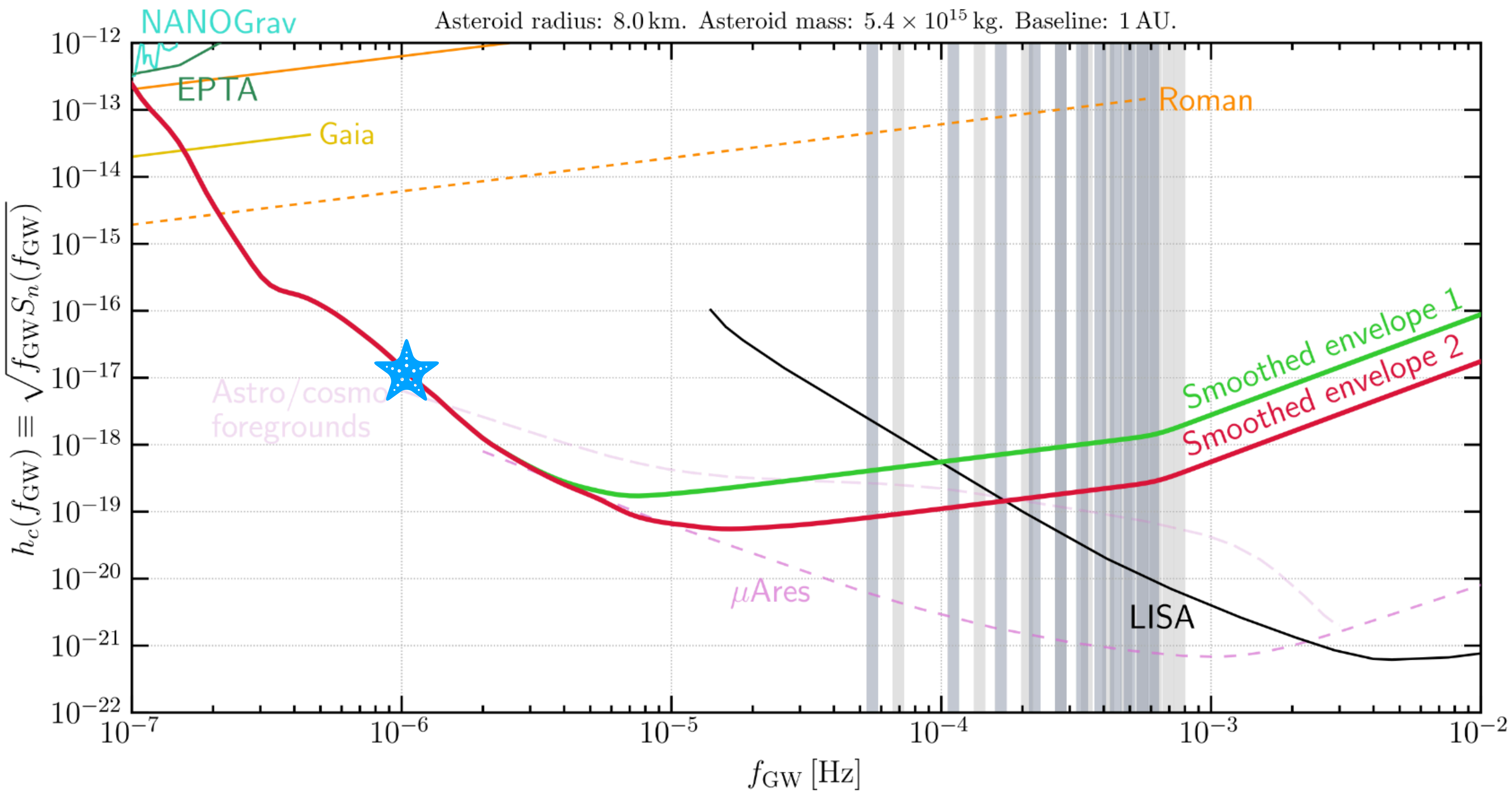
Summary of MBH science goals:

- probe the emergence of the high-redshift quasars;
- establish the relative importance of accretion vs mergers in growing MBHs;
- disentangle seed formation models at the high-mass end of the seed spectrum;
- probe the population of inspiralling MBHs in low-redshift dwarf galaxies;
- pin down the physics of MBHB dynamics, including stellar hardening, gaseous drag, triplets, and multiplets MBH interactions;
- probe the formation and dynamics of IMBHs in galactic nuclei.

Ranging of asteroids?

Fedderke et al 2112.11431





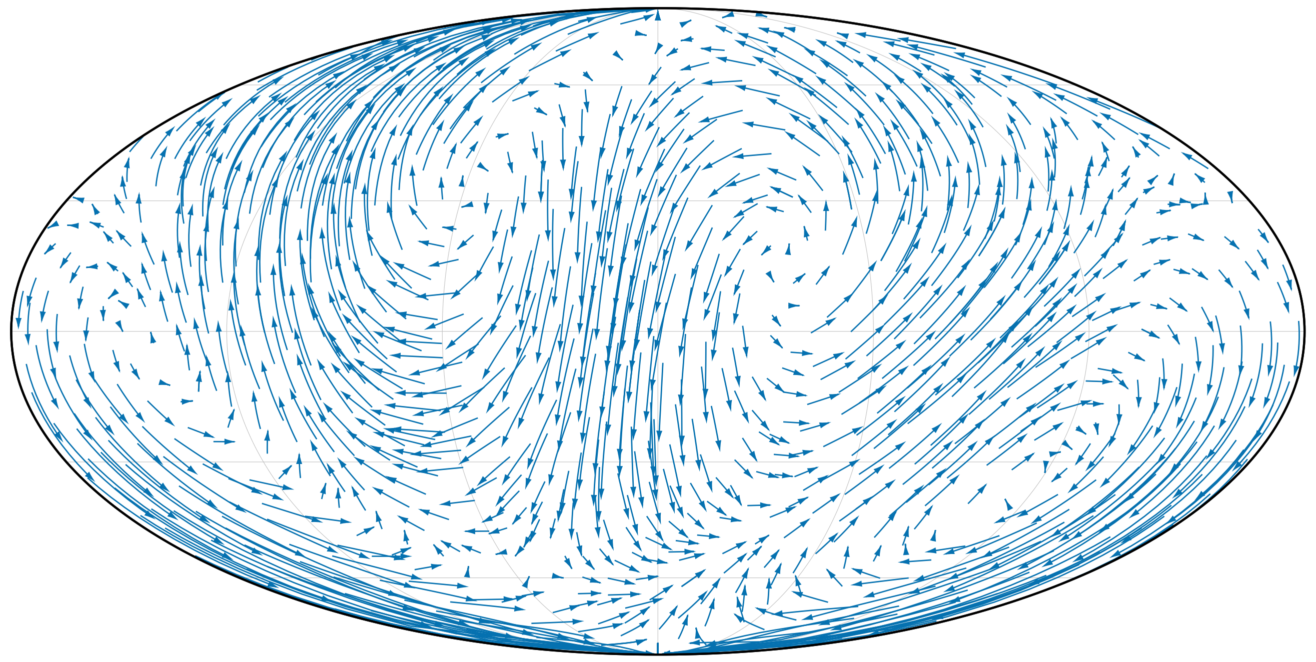
Future astrometry?

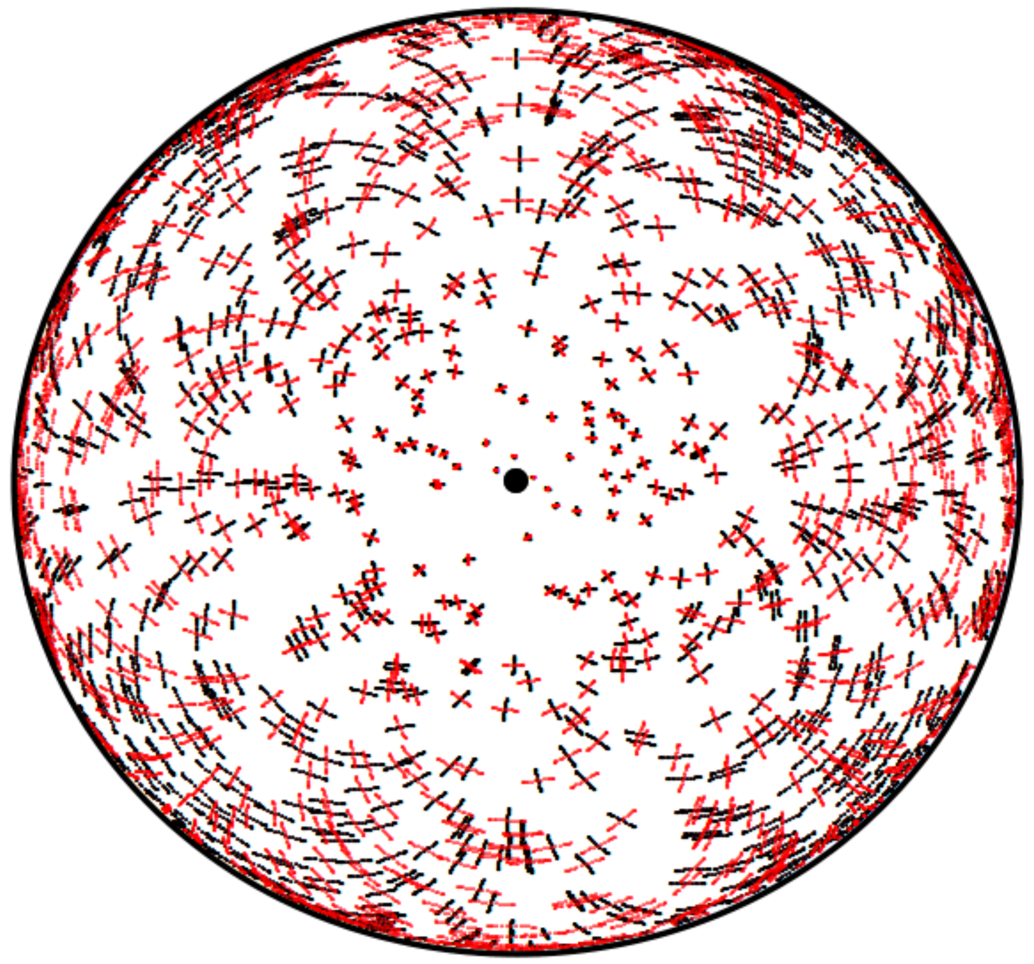
e.g. Moore et al 1707.06239
Mihaylov et al. 1804.00660

Klioner 1710.11474

Garcia-Bellido et al. 2104.04778

Monitoring many stars (GAIA or better)





Fedderke et al 2204.07677

Stellar interferometry

We evaluate the potential for gravitational-wave (GW) detection in the frequency band from 10 nHz to 1 μHz using extremely high-precision astrometry of a small number of stars

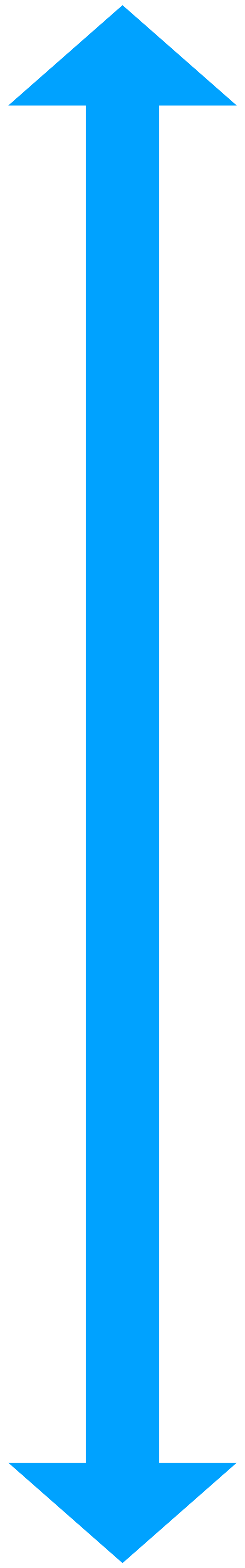
at characteristic strains around $h_c \sim 10^{-17} \times (\mu\text{Hz}/f_{\text{GW}})$. The astrometric angular precision required to see these sources is $\Delta\theta \sim h_c$ after integrating for a time $T \sim 1/f_{\text{GW}}$. We show that jitter in the photometric center of WD of this type due to starspots is bounded to be small enough to permit this high-precision, small-N approach. We discuss possible noise arising from stellar reflex motion induced by orbiting objects and show how it can be mitigated. The only plausible technology able to achieve the requisite astrometric precision is a space-based stellar interferometer. Such a future mission with few-meter-scale collecting dishes and baselines of $\mathcal{O}(100\,\text{km})$ is sufficient to achieve the target precision. This collector size is broadly in line with the collectors proposed for

Atomic interferometry in space: AEDGE

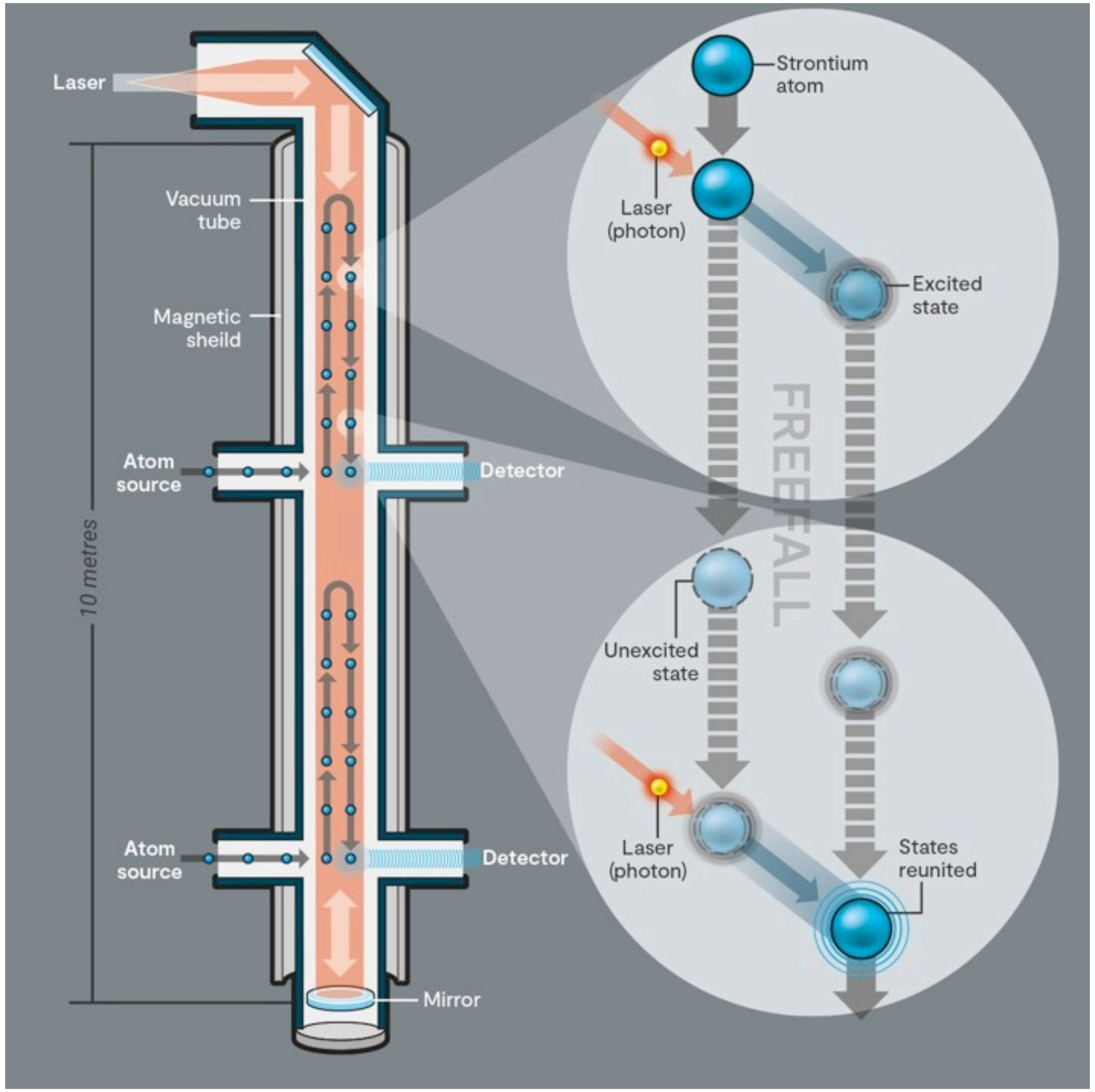
Abou El-Neaj et al 1908.00802

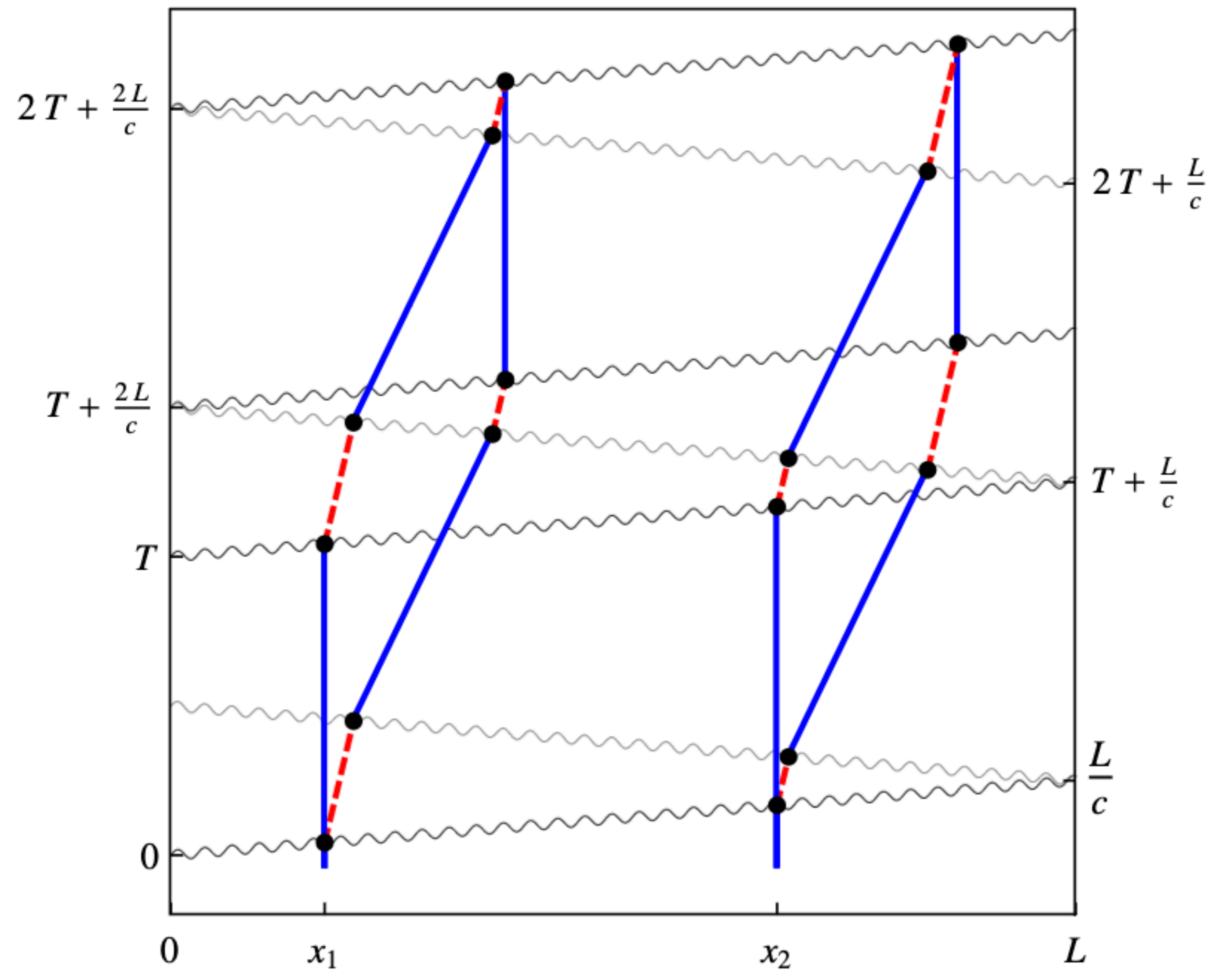
Graham et al 1206.0818 (MAGIS)

Badurina et al 2108.02468 (AION)



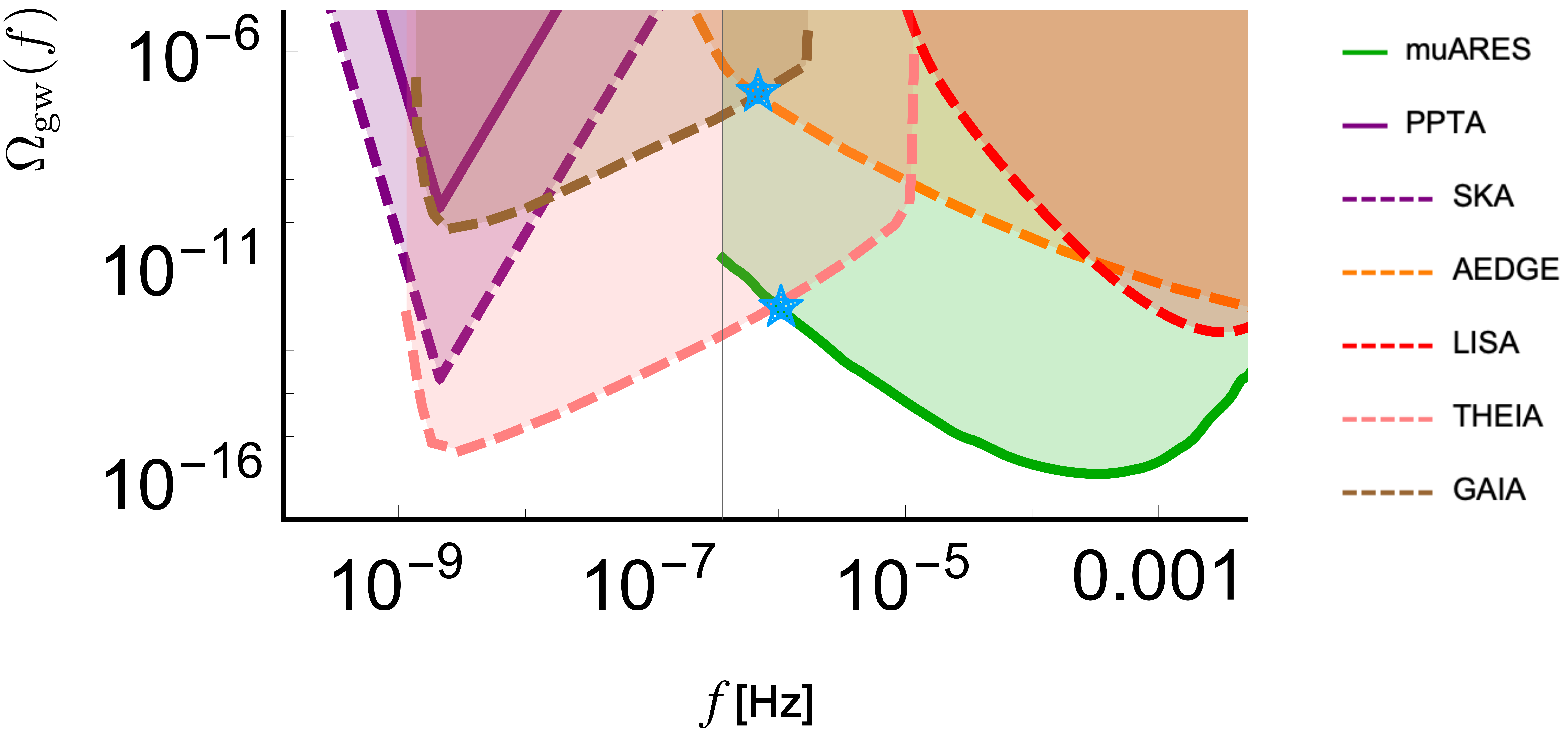
40000 km





$$\Delta\phi \sim \omega L h$$

The most optimistic future…



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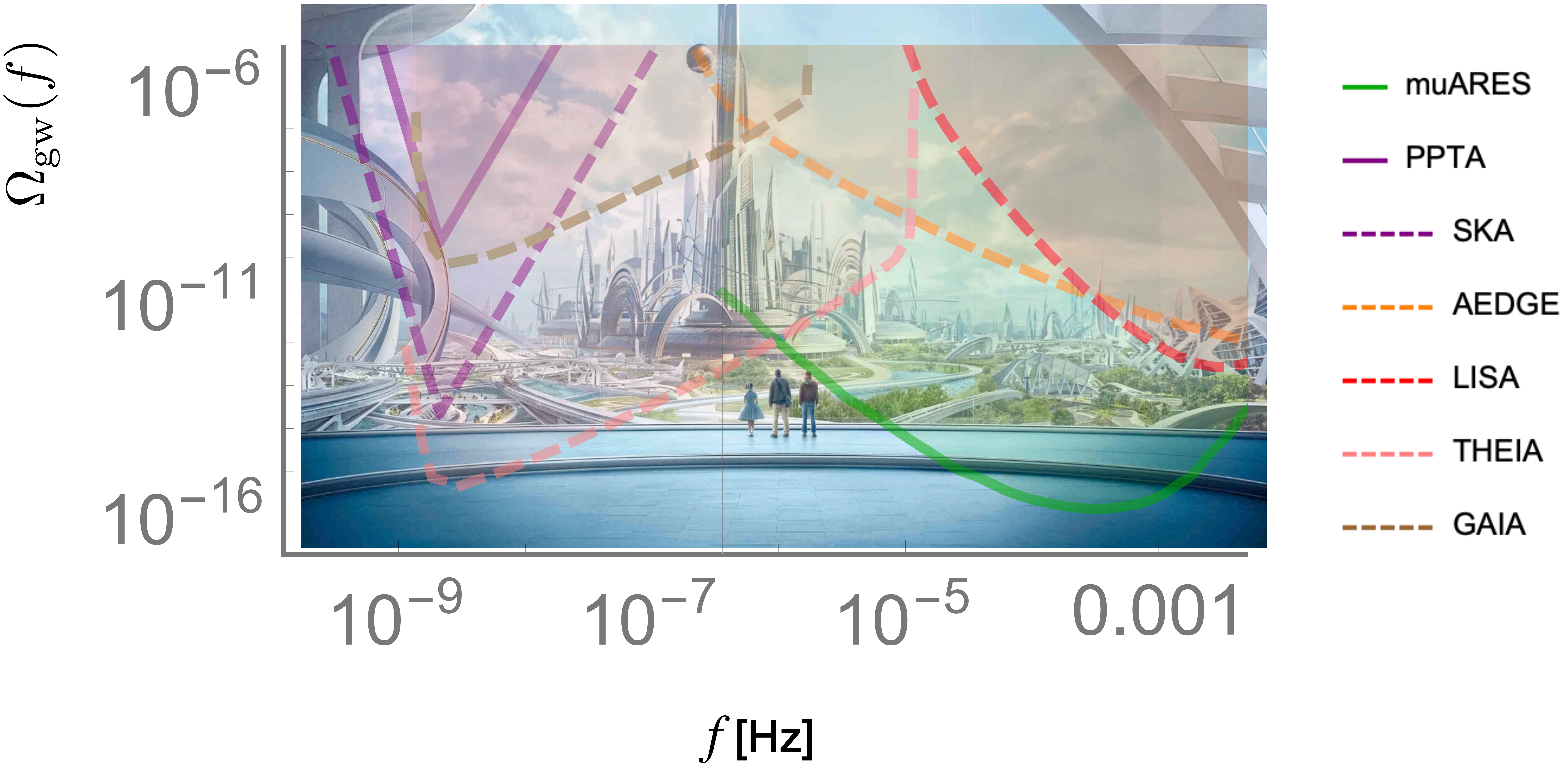
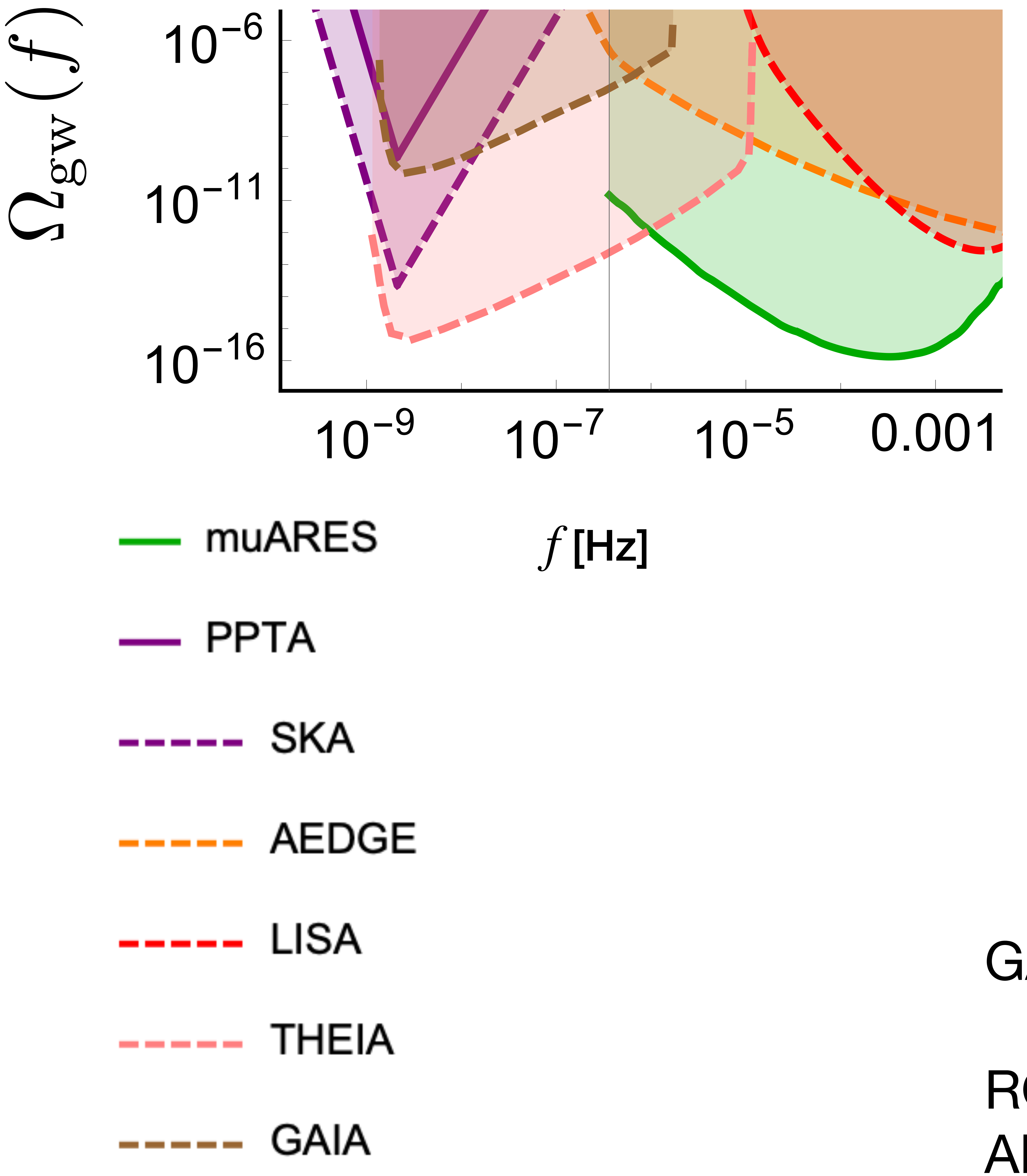
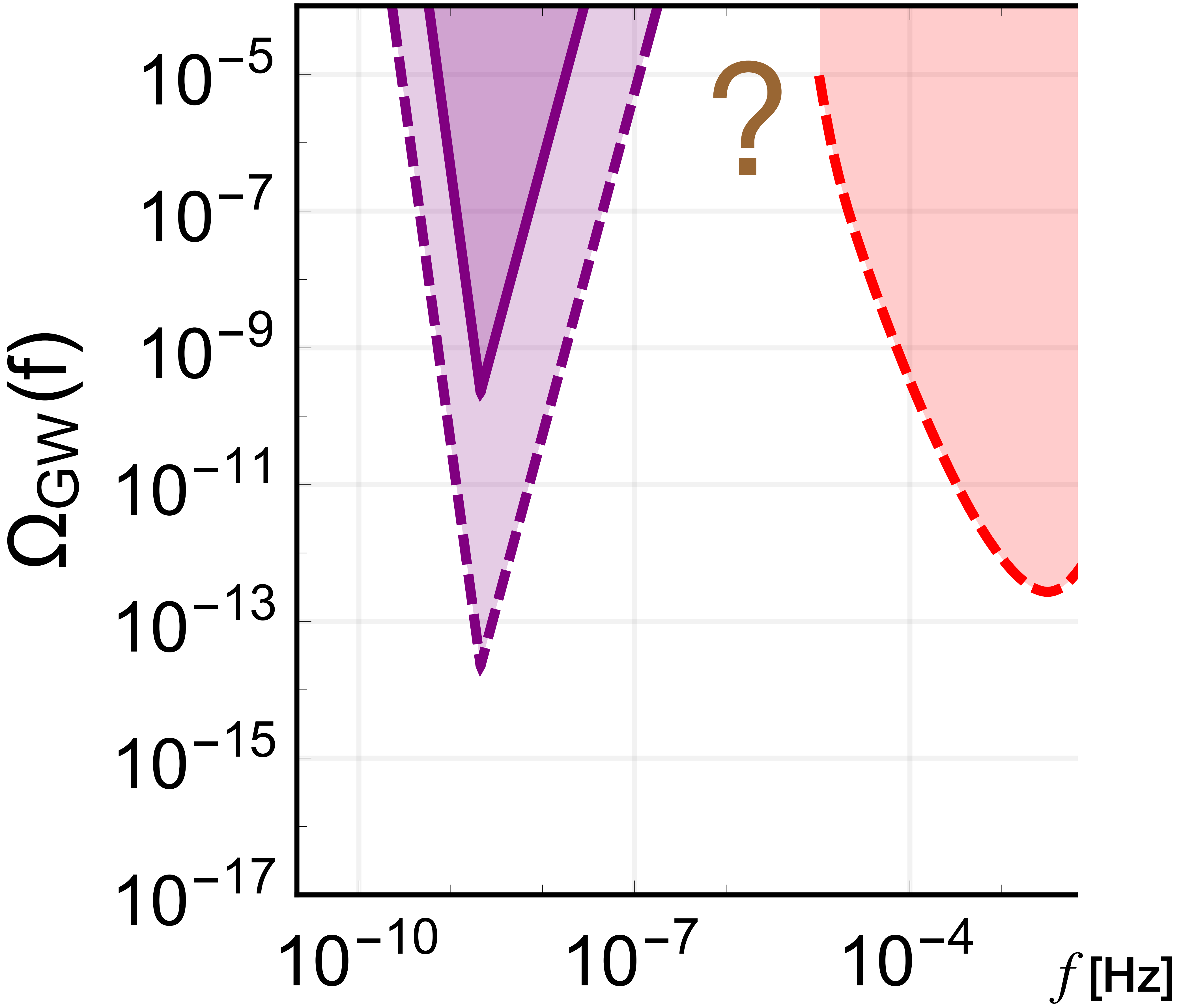


The most optimistic future… vs 2038





GAIA DR3 Jaraba et al 2304.06350

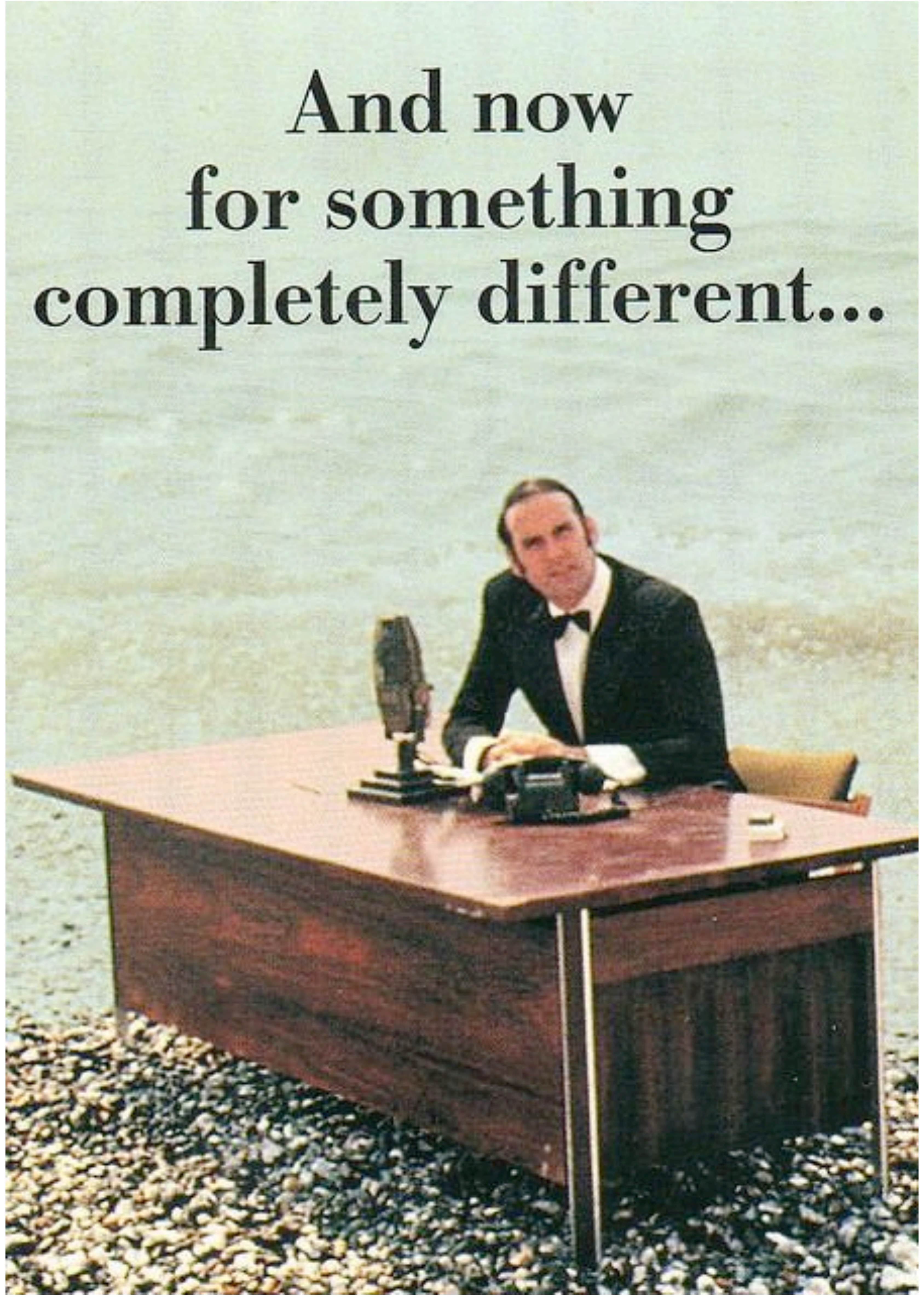
$$h_{70}^2 \Omega_{\rm GW} \lesssim 0.087 \text{ for } 4.2 \times 10^{-18} \text{ Hz} \lesssim f \lesssim 1.1 \times 10^{-8} \text{ Hz}$$

ROMAN? Wang et al 2205.07962

AION 10m/MAGIS 100m in 2025? (small interferometers)

Is this all we can do in this band?

Is this all we can do in this band? No!



$$f \sim \mu\text{Hz}$$

few days

Absorption of GWs by binaries

$f \sim \mu\text{Hz}$

few days

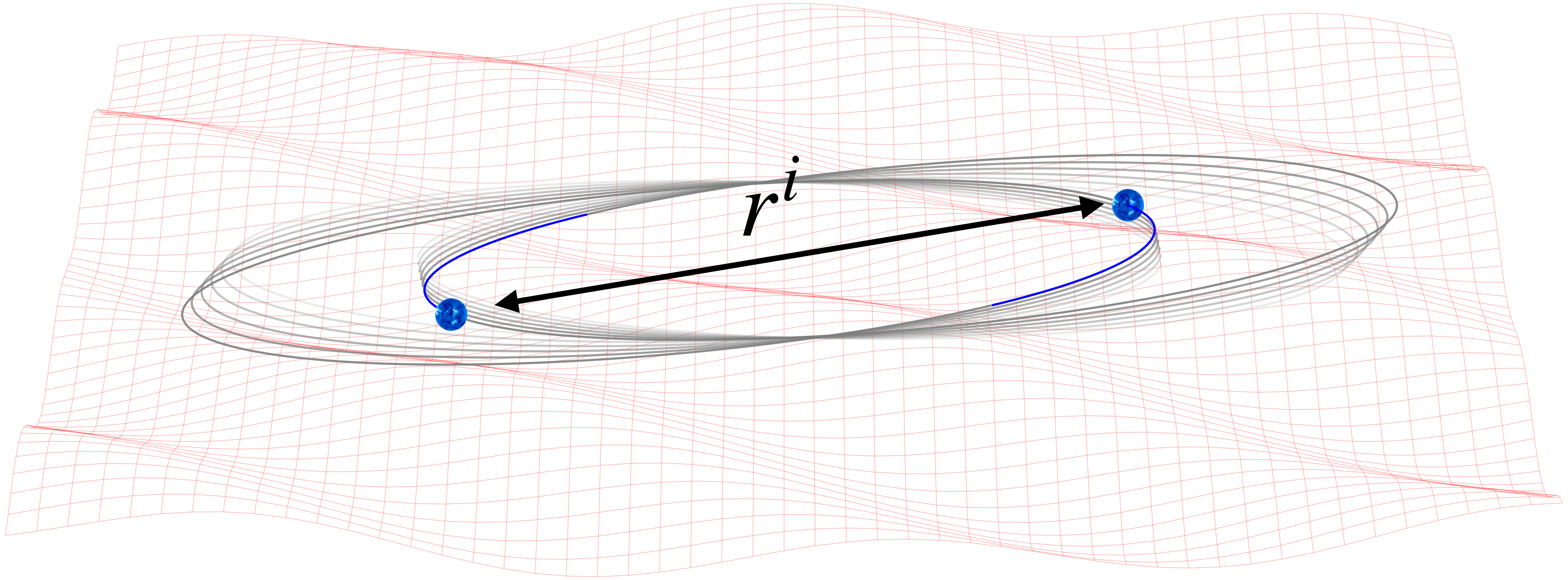
Intuitive idea (from '60s)

Influence of a GW on a binary system (e.g. non-relativistic)

$$\ddot{r}^i + \frac{GM}{r^3} r^i = \delta^{ik} \frac{1}{2} \ddot{h}_{kj} r^j$$

Newtonian potential

GW

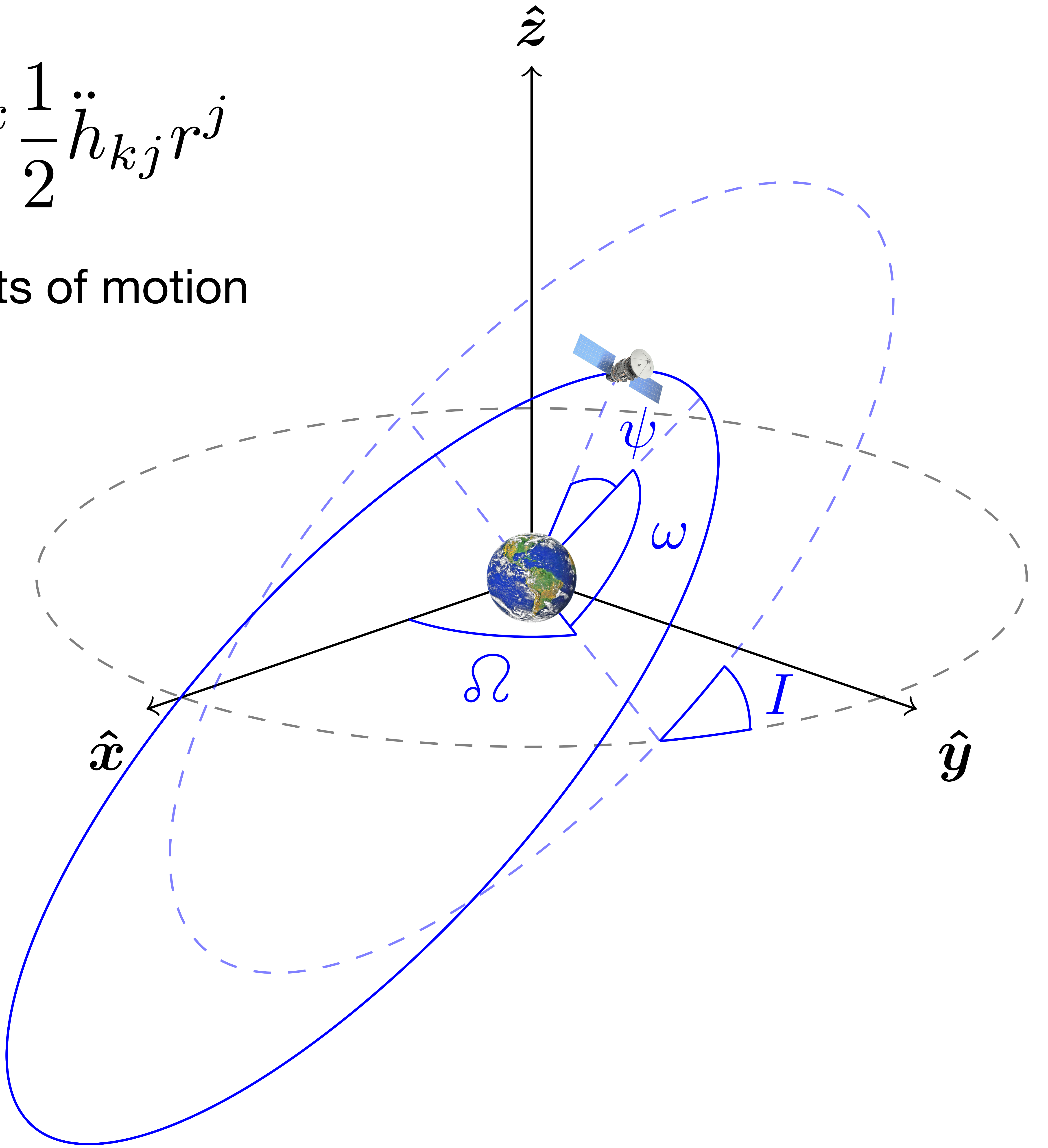


Absorption of GWs by binaries

$$\ddot{r}^i + \frac{GM}{r^3} r^i = \delta^{ik} \frac{1}{2} \ddot{h}_{kj} r^j$$

Better characterised for its 6 Newtonian constants of motion

- **period** P**, eccentricity** e:
  size and *shape* of orbit
- **inlination** I**, ascending node** Ω:
  orientation in space
- **pericentre** ω**,**
  mean anomaly at epoch ε:
  radial and angular *phases*



Absorption of GWs by binaries

$$\ddot{\boldsymbol{r}} + \frac{GM}{r^2}\hat{\boldsymbol{r}} = \delta\ddot{\boldsymbol{r}}.$$

- for generic perturbation:

$$\delta\ddot{\boldsymbol{r}} = r(\mathcal{F}_r\hat{\boldsymbol{r}} + \mathcal{F}_\theta\hat{\boldsymbol{\theta}} + \mathcal{F}_\ell\hat{\boldsymbol{\ell}}),$$

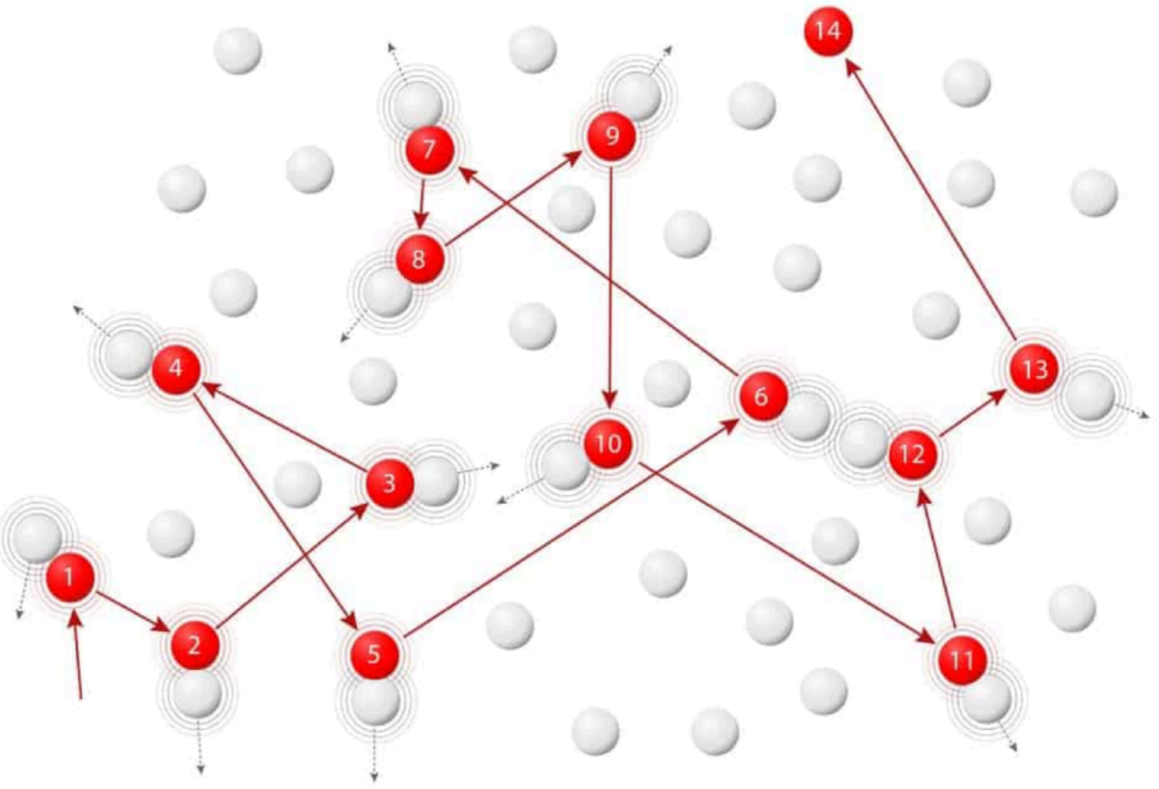
$$\begin{aligned}
\dot{P} &= \frac{3P^2\gamma}{2\pi}\left[\frac{e\sin\psi\mathcal{F}_r}{1+e\cos\psi} + \mathcal{F}_\theta\right],\\
\dot{e} &= \frac{\dot{P}\gamma^2}{3Pe} - \frac{P\gamma^5\mathcal{F}_\theta}{2\pi e(1+e\cos\psi)^2},\\
\dot{I} &= \frac{P\gamma^3\cos\theta\mathcal{F}_\ell}{2\pi(1+e\cos\psi)^2},\\
\dot{\Omega} &= \frac{\tan\theta}{\sin I}\dot{I},\\
\dot{\omega} &= \frac{P\gamma^3}{2\pi e}\left[\frac{(2+e\cos\psi)\sin\psi\mathcal{F}_\theta}{(1+e\cos\psi)^2} - \frac{\cos\psi\mathcal{F}_r}{1+e\cos\psi}\right] - \cos I\dot{\Omega},\\
\dot{\varepsilon} &= -\frac{P\gamma^4\mathcal{F}_r}{\pi(1+e\cos\psi)^2} - \gamma(\cos I\dot{\Omega} + \dot{\omega}),
\end{aligned}$$

Absorption of GWs by binaries

$$\ddot{\boldsymbol{r}} + \frac{GM}{r^2}\hat{\boldsymbol{r}} = \delta\ddot{\boldsymbol{r}}.$$

- for generic perturbation:

$$\delta\ddot{\boldsymbol{r}} = r(\mathcal{F}_r\hat{\boldsymbol{r}} + \mathcal{F}_\theta\hat{\boldsymbol{\theta}} + \mathcal{F}_\ell\hat{\boldsymbol{\ell}}),$$



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$$\dot{I} = \frac{P\gamma^3\cos\theta\mathcal{F}_\ell}{2\pi(1+e\cos\psi)^2},$$

$$\dot{\Omega} = \frac{\tan\theta}{\sin I}\dot{I},$$

$$\dot{\omega} = \frac{P\gamma^3}{2\pi e}\left[\frac{(2+e\cos\psi)\sin\psi\mathcal{F}_\theta}{(1+e\cos\psi)^2} - \frac{\cos\psi\mathcal{F}_r}{1+e\cos\psi}\right] - \cos I\dot{\Omega},$$

$$\dot{\varepsilon} = -\frac{P\gamma^4\mathcal{F}_r}{\pi(1+e\cos\psi)^2} - \gamma(\cos I\dot{\Omega} + \dot{\omega}),$$

For the SGWB… Fokker-Planck approach

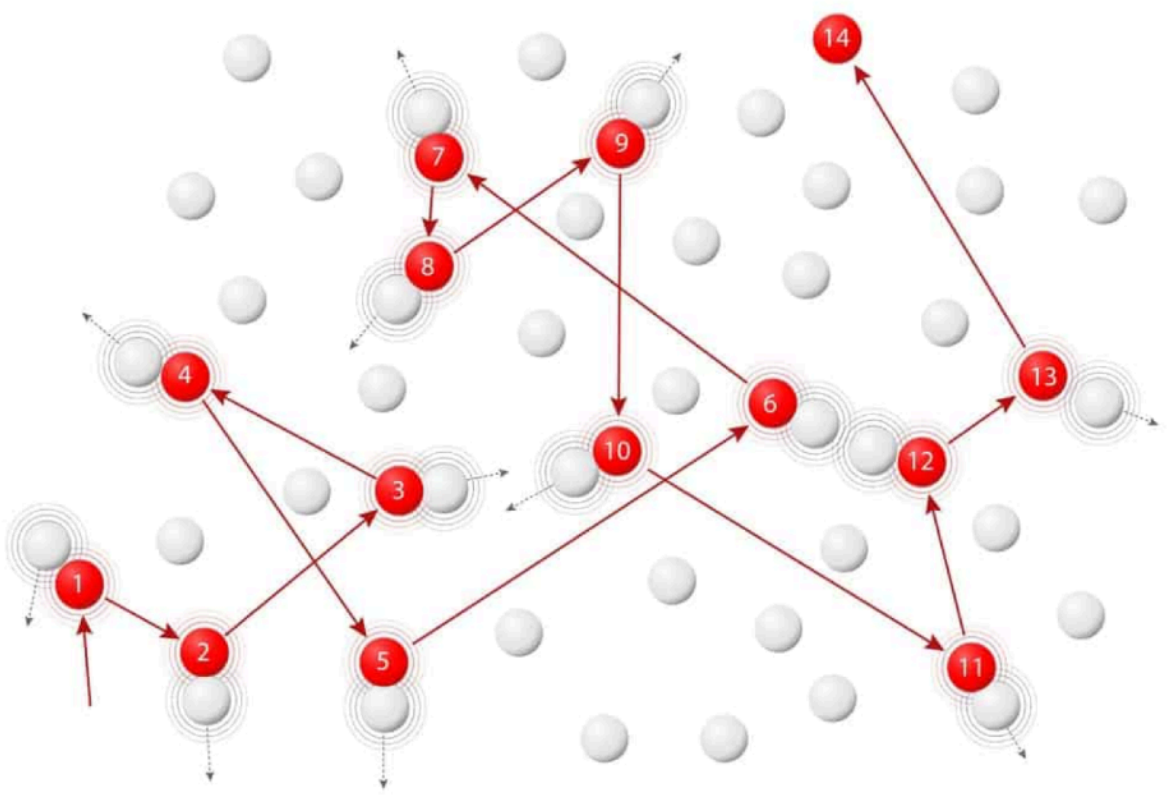
$$\ddot{r}^i + \frac{GM}{r^3} r^i = \delta^{ik} \frac{1}{2} \ddot{h}_{kj} r^j$$

deterministic

stochastic

$$\dot{X}_i(\boldsymbol{X}, t) = V_i(\boldsymbol{X}) + \Gamma_i(\boldsymbol{X}, t)$$

we move from dynamics of the variable to dynamics of the **distribution *W(X)***



$$\frac{\partial W}{\partial t} = -\partial_i \left(D_i^{(1)} W \right) + \partial_i \partial_j \left(D_{ij}^{(2)} W \right)$$

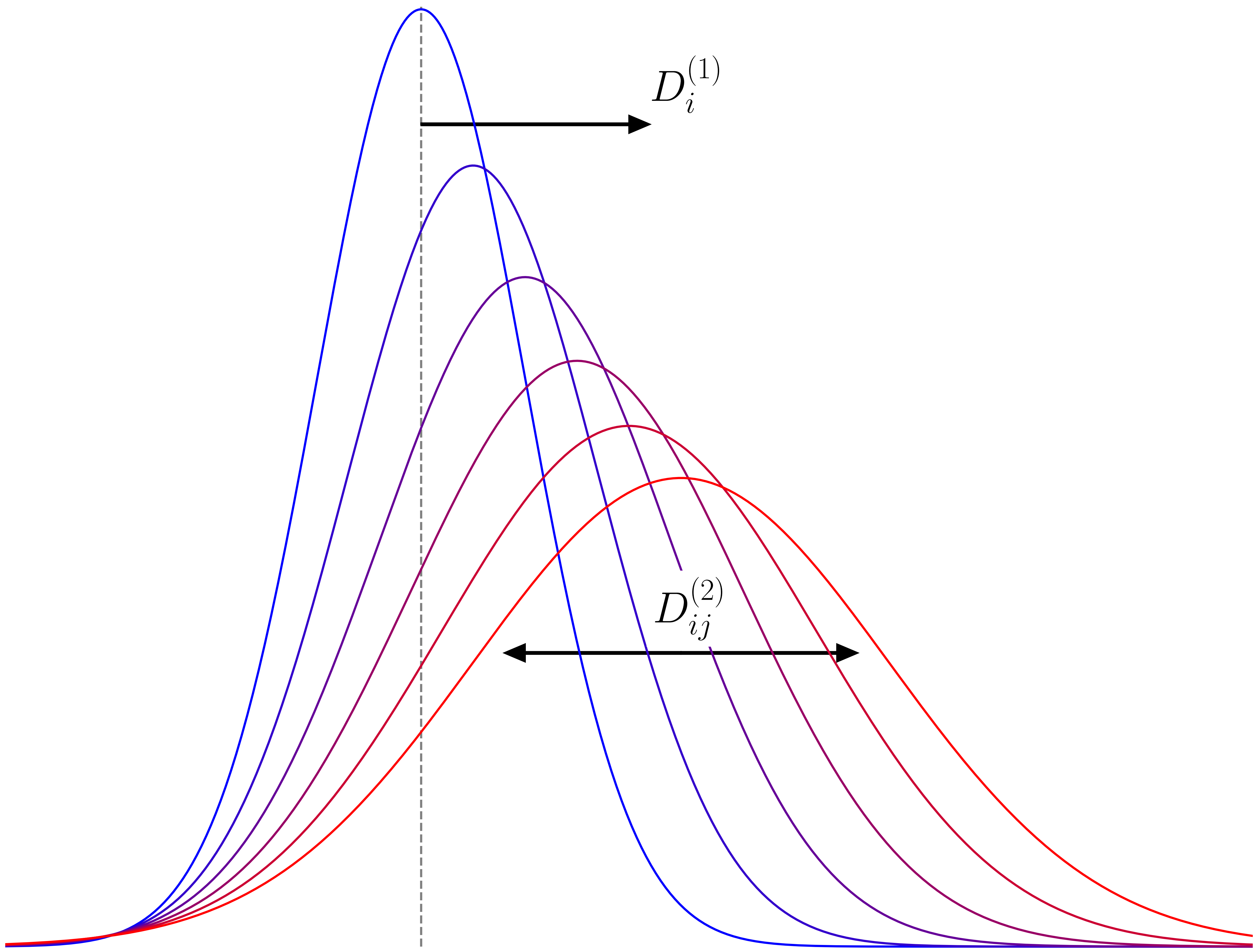
with $\partial_i \equiv \partial / \partial X_i$

$$D_i^{(1)} = V_i + \lim_{\tau \to 0} \frac{1}{\tau} \int_t^{t+\tau} \mathrm{d}t' \int_t^{t'} \mathrm{d}t'' \left\langle \Gamma_j \left(\boldsymbol{x}, t'' \right) \partial_j \Gamma_i \left(\boldsymbol{x}, t' \right) \right\rangle .$$

$$D_{ij}^{(2)} = \lim_{\tau \to 0} \frac{1}{2\tau} \int_t^{t+\tau} \mathrm{d}t' \int_t^{t+\tau} \mathrm{d}t'' \left\langle \Gamma_i \left(\boldsymbol{x}, t' \right) \Gamma_j \left(\boldsymbol{x}, t'' \right) \right\rangle .$$

Our approach to the problem

Blas&Jenkins Phys.Rev.Lett. 128 (2022) 10, 101103



- track distribution function $W(\boldsymbol{X}, t)$ of orbital elements $\boldsymbol{X} = (P, e, I, \Omega, \omega, \varepsilon)$
- evolves through *Fokker-Planck eqn.*

$$\frac{\partial W}{\partial t} = -\frac{\partial}{\partial X_i}\left(D_i^{(1)} W\right) + \frac{\partial}{\partial X_i}\frac{\partial}{\partial X_j}\left(D_{ij}^{(2)} W\right)$$

- *drift* and *diffusion* coefficients (averaged over orbits)

$$D_i^{(1)}(\boldsymbol{X}) = V_i(\boldsymbol{X}) + \sum_{n=1}^{\infty} \mathcal{A}_{n,i}(\boldsymbol{X})\Omega_{\text{gw}}(n/P)$$

$$D_{ij}^{(2)}(\boldsymbol{X}) = \sum_{n=1}^{\infty} \mathcal{B}_{n,ij}(\boldsymbol{X})\Omega_{\text{gw}}(n/P)$$

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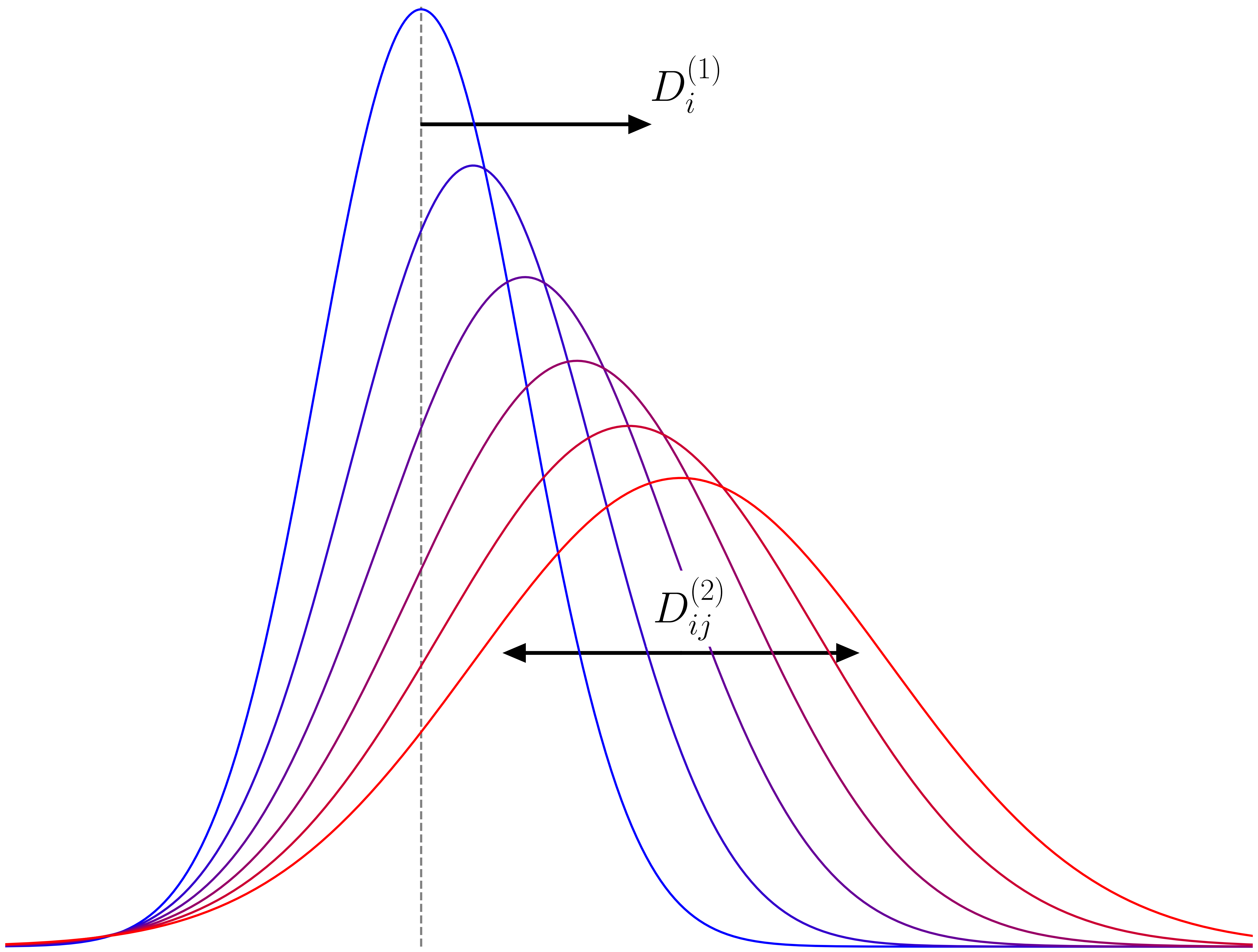

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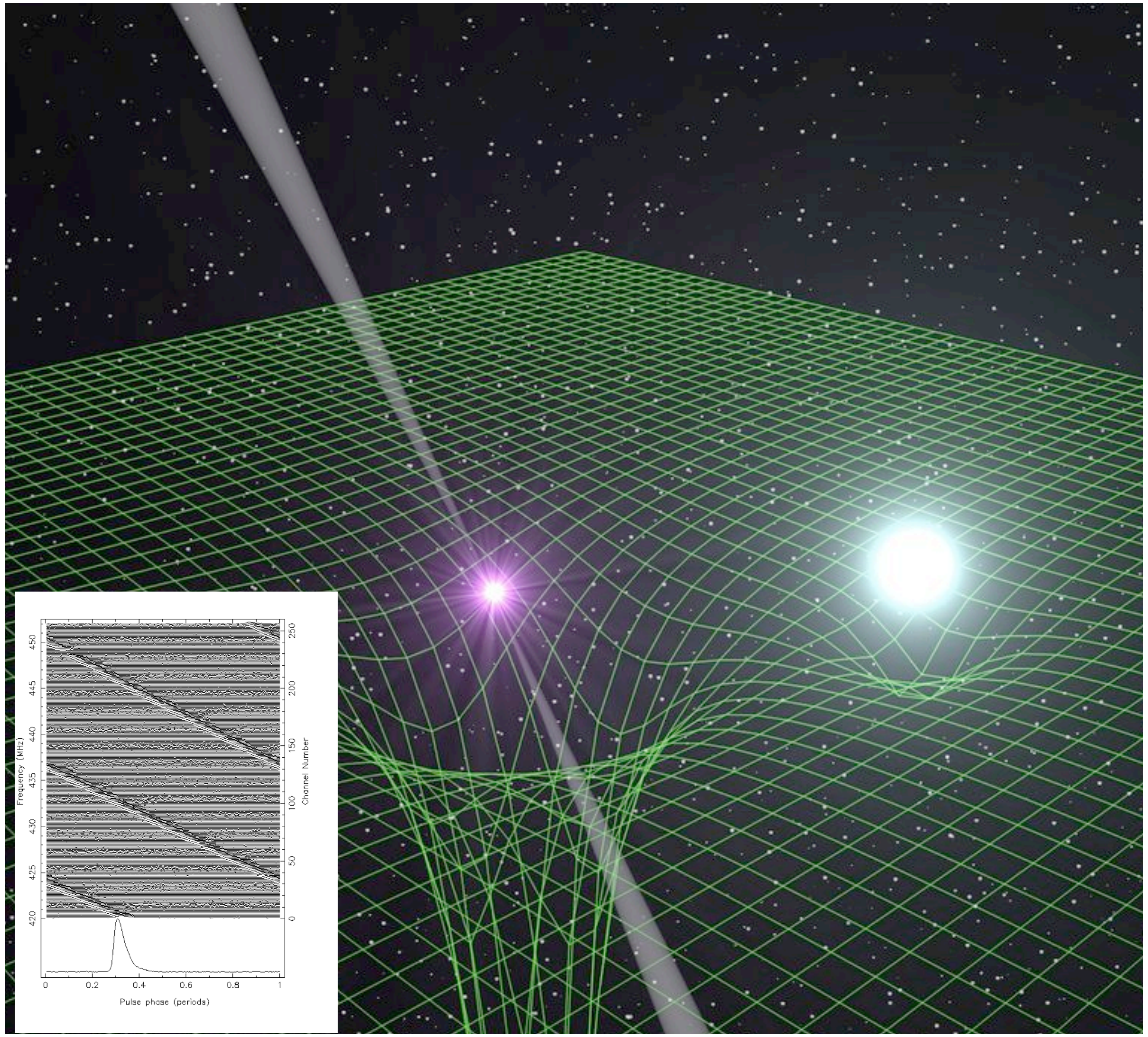
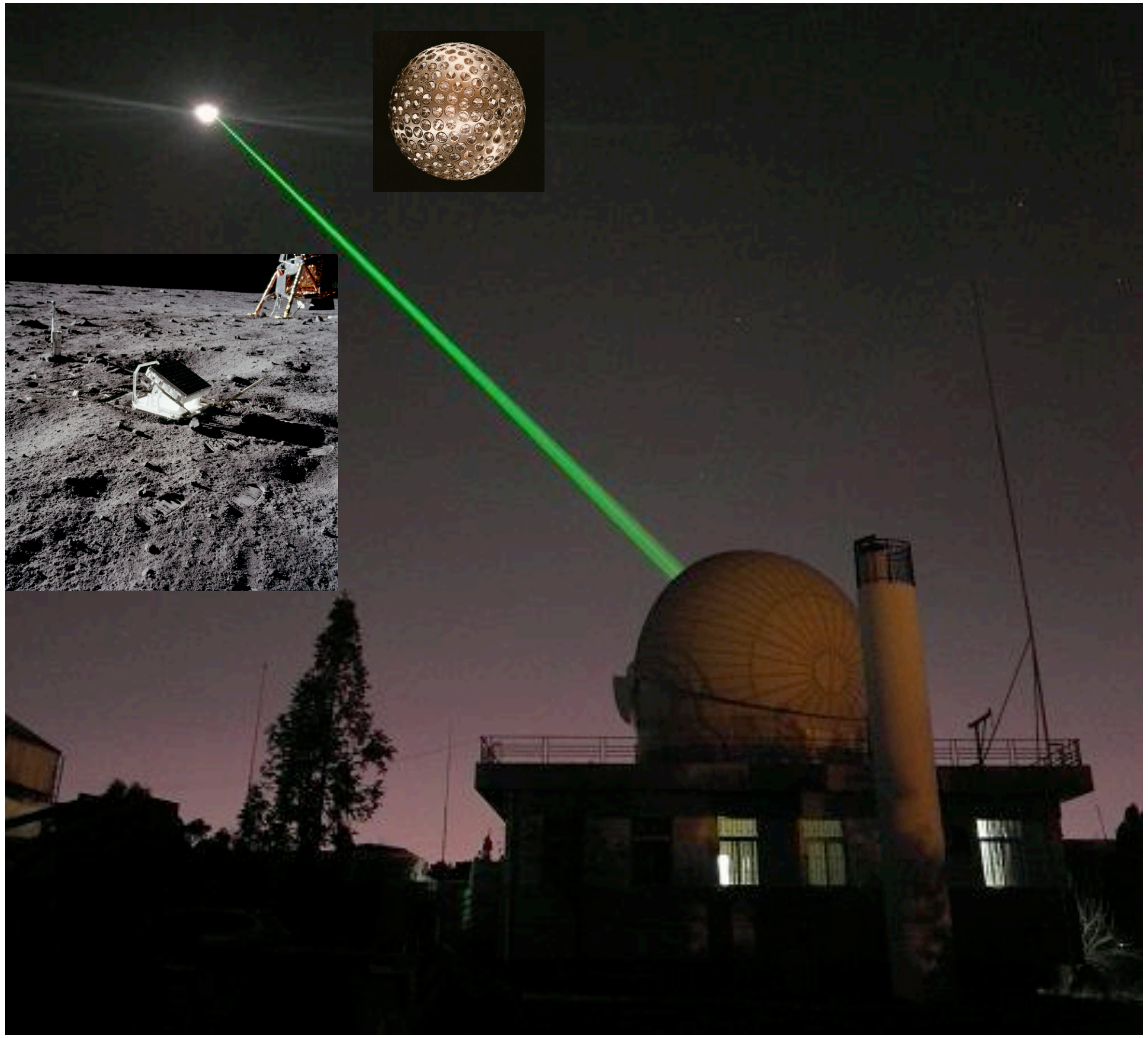
Two probes

timing of binary pulsars

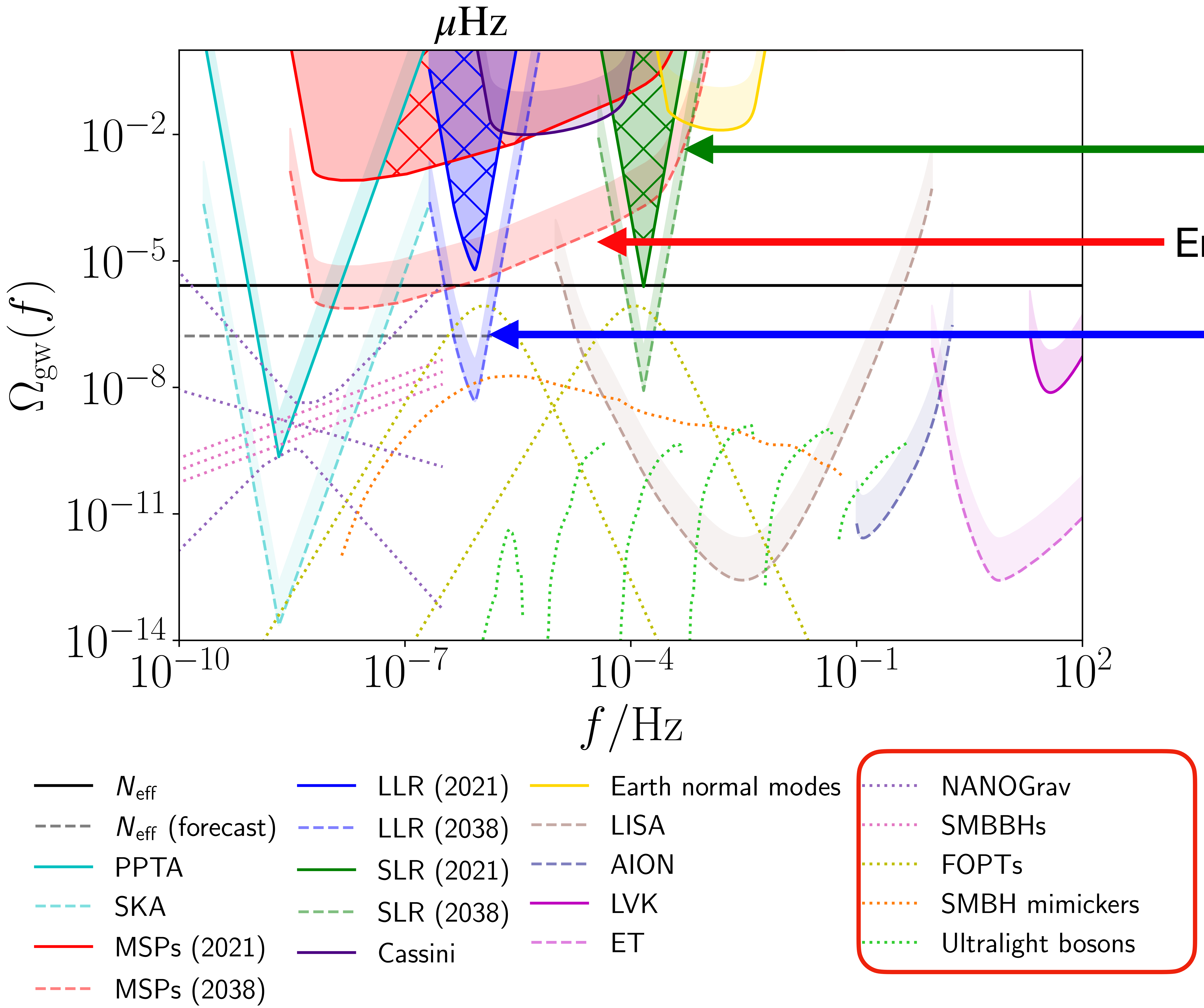


lunar and satellite laser ranging



Our estimates (solid: today; dashed 2038)

Blas&Jenkins Phys.Rev.Lett. 128 (2022) 10, 101103



Satellites (*P*~hours)

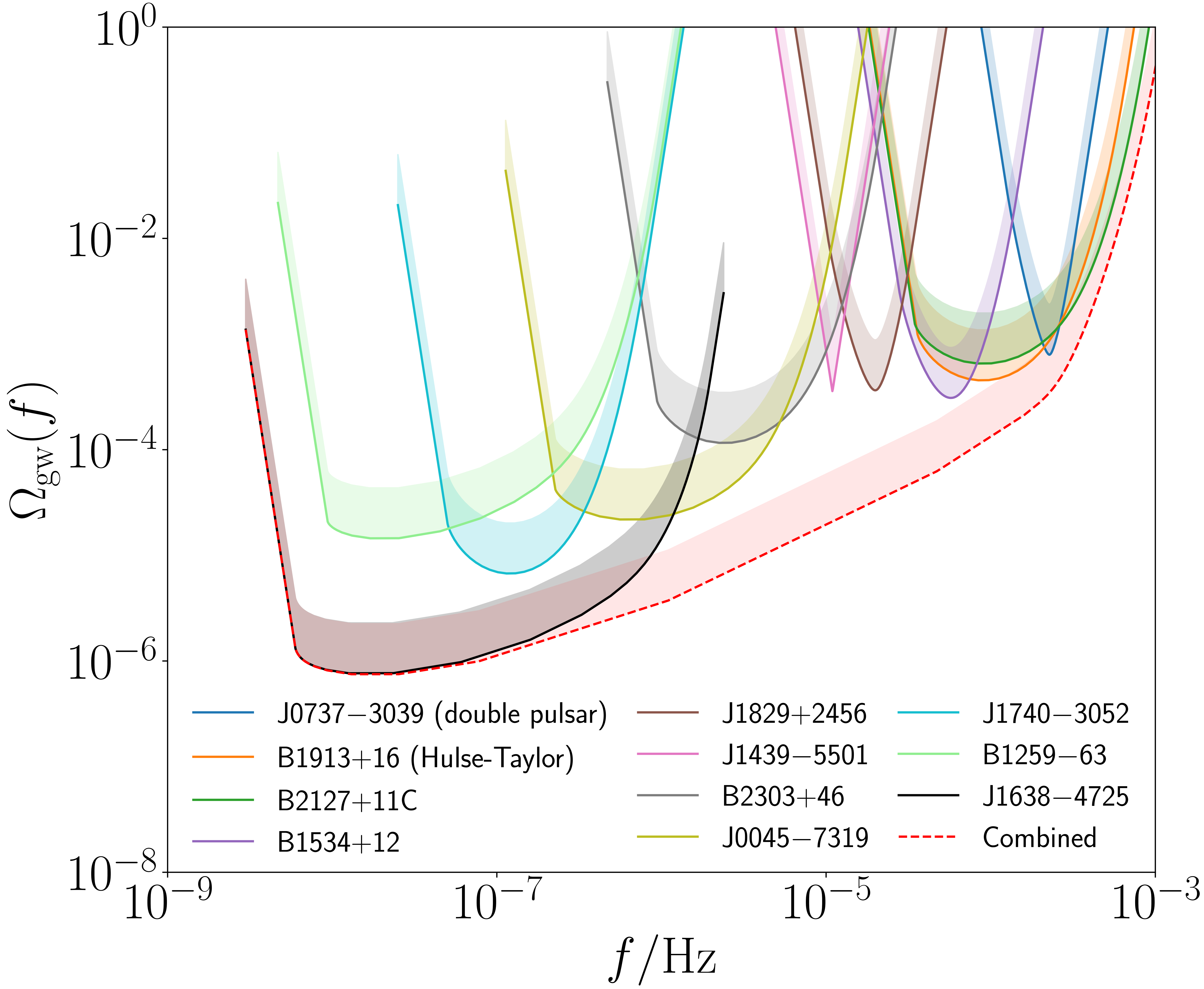
Envelope of pulsars (*P*~hours - 100 days)

Lunar laser ranging (*P*~month)

(2038 line requires replacing the mirrors …may/will happen before 2030!)

Possible backgrounds

Combining binary pulsar bounds



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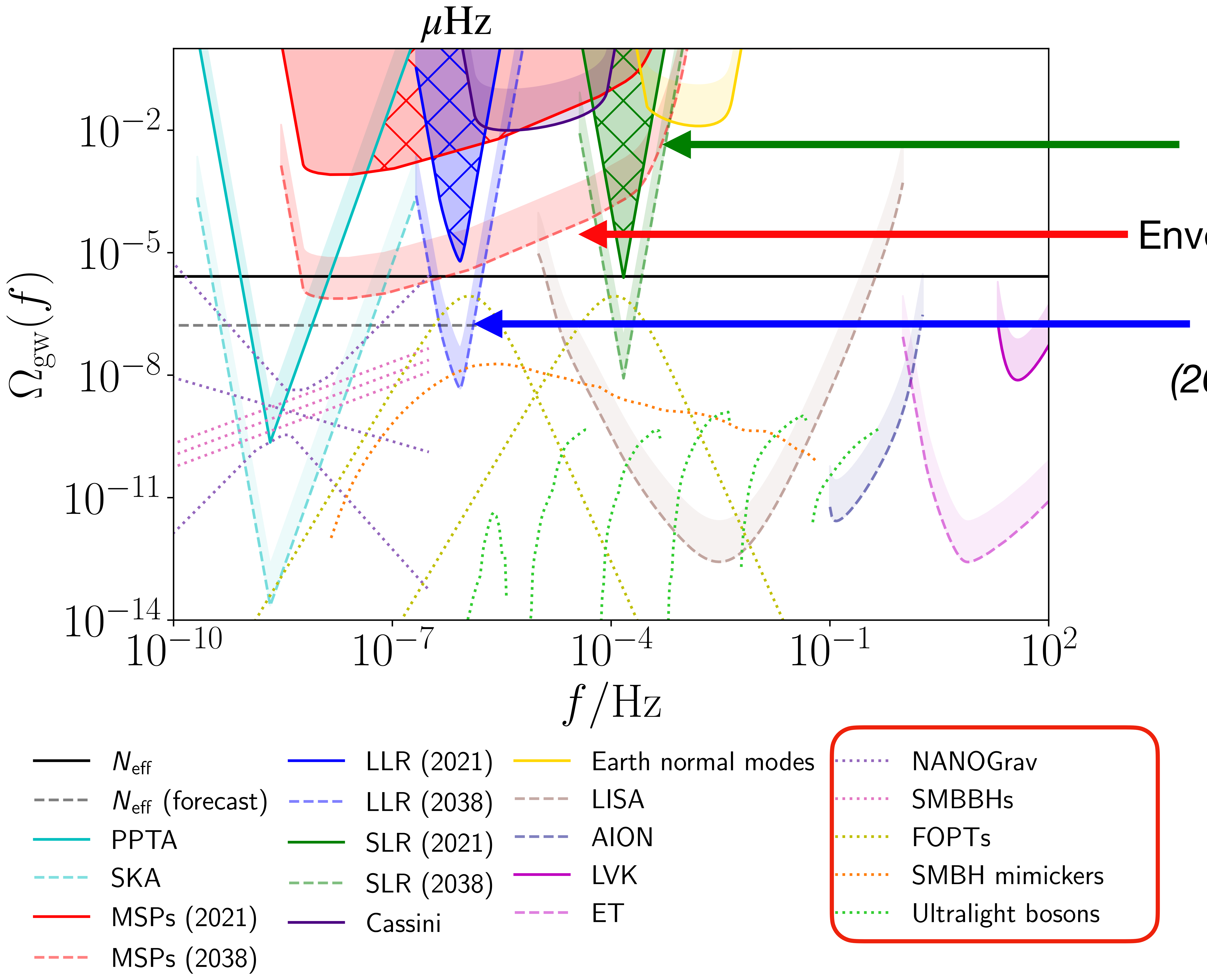

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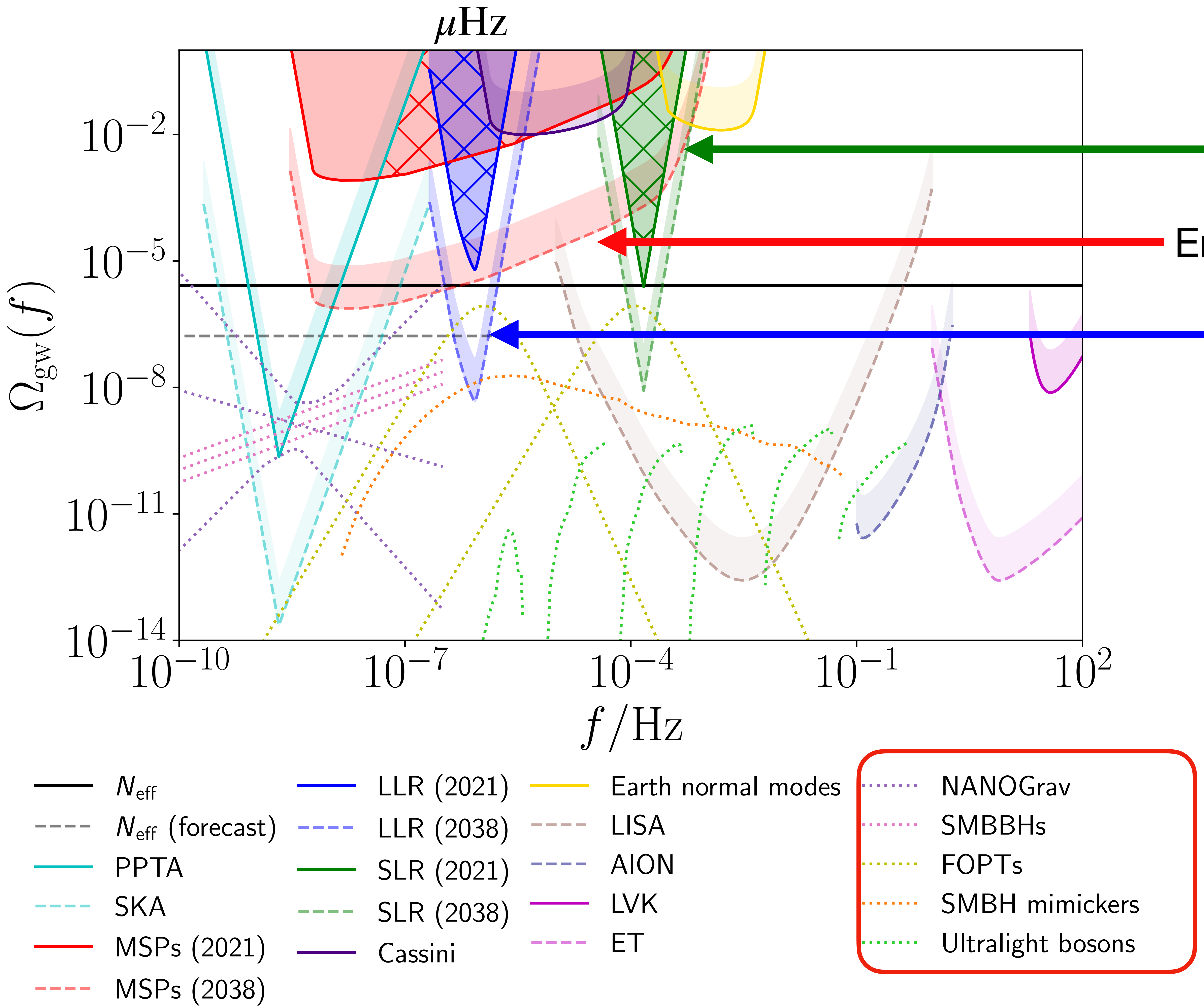
Blas&Jenkins Phys.Rev.Lett. 128 (2022) 10, 101103



Satellites (*P*~hours)

Envelope of pulsars (*P*~hours - 100 days)

Lunar laser ranging (*P*~month)

(2038 line requires replacing the mirrors …may/will happen before 2030!)

Murphy 1309.6294

in 2050

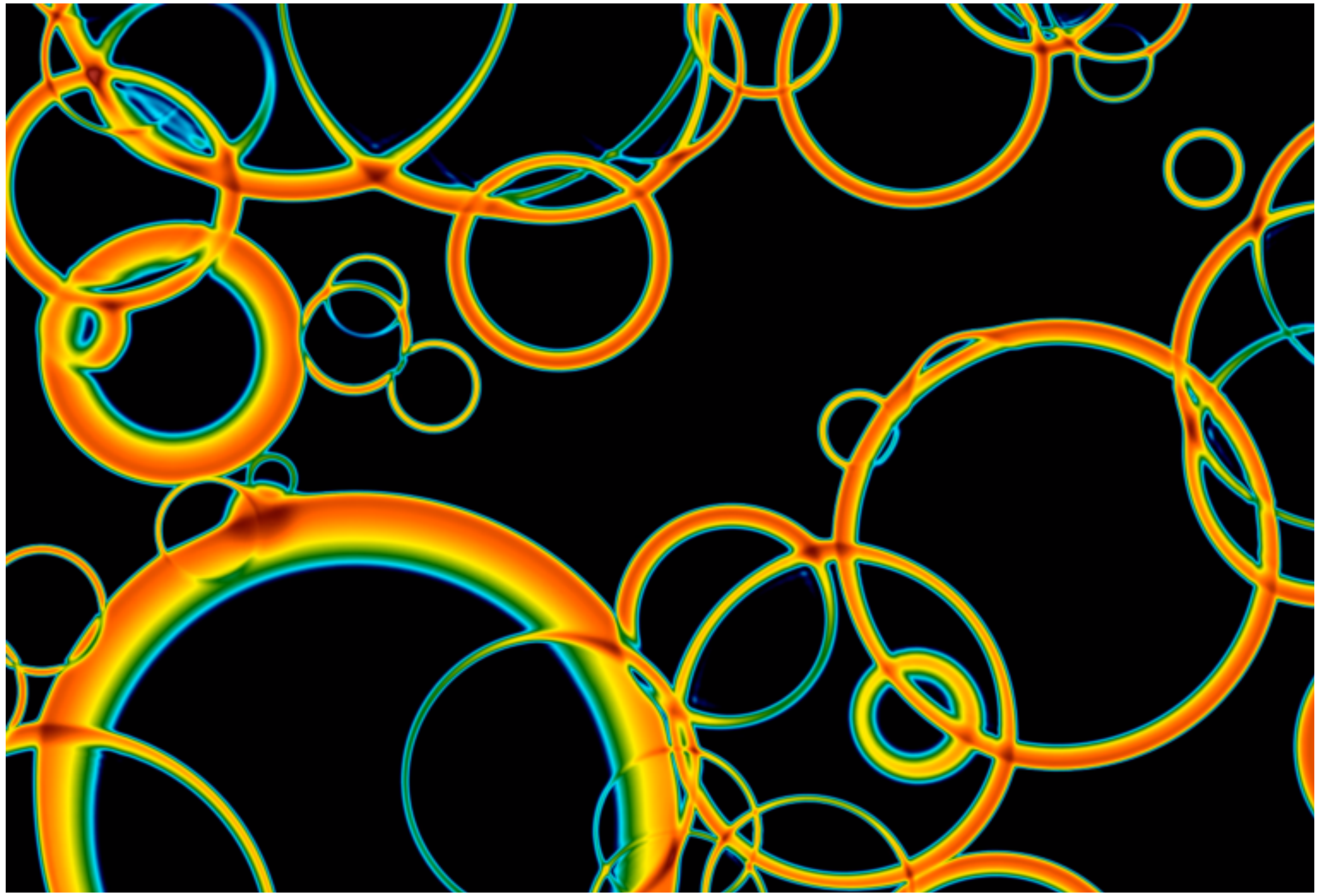
$$\Omega \lesssim 3\times10^{-9} \quad \text{at} \quad f\sim\mu\mathrm{Hz}$$

Possible backgrounds

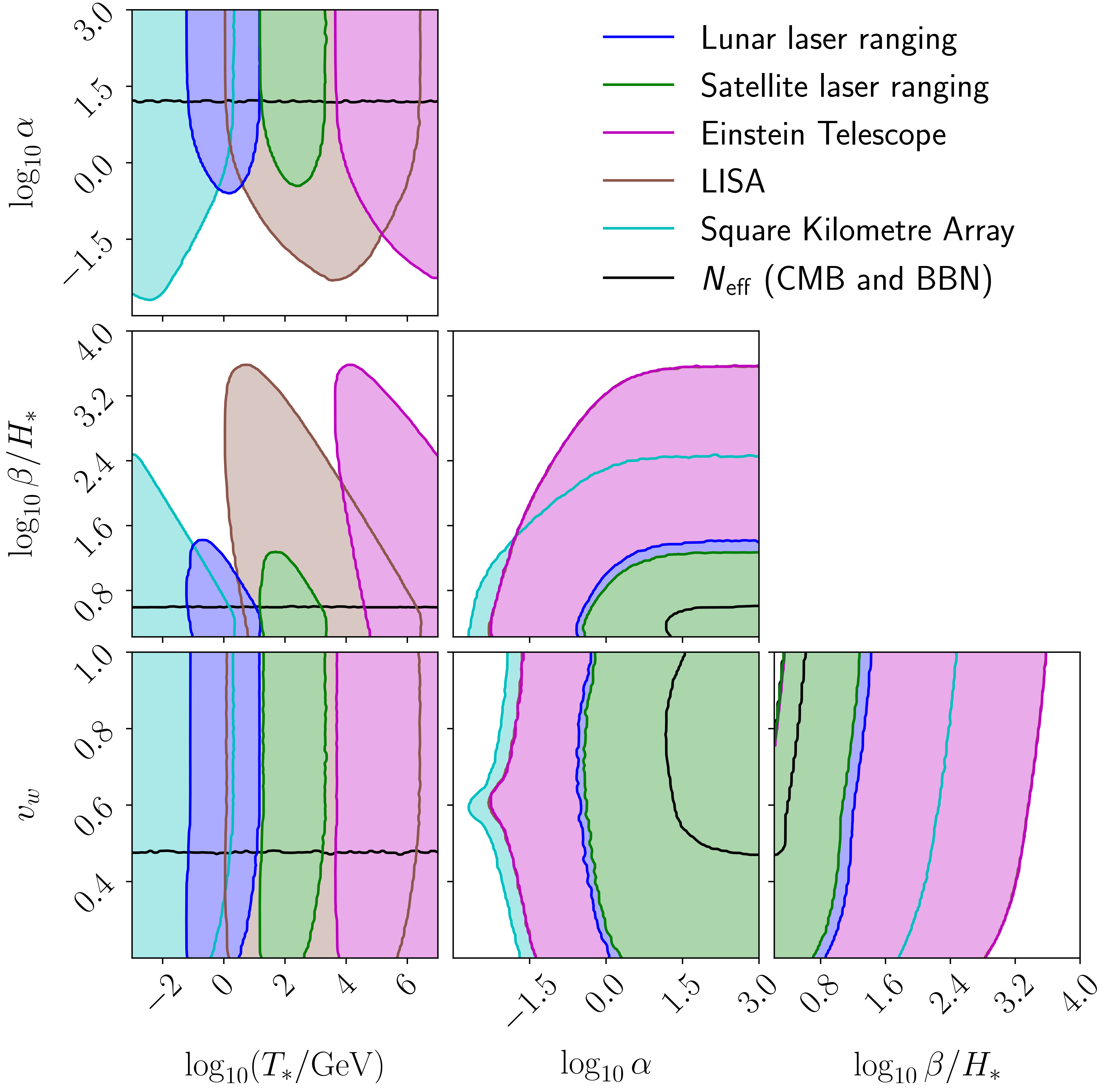
E.g. FOPT with peaks at μHz

- four parameters:
  - temperature T_*
  - strength α
  - rate β/H_*
  - bubble-wall velocity v_w
- peak frequency

$$f_* \approx 19\,\mu\text{Hz} \times \frac{T_*}{100\,\text{GeV}} \frac{\beta/H_*}{v_w}$$



Complementarity of probes for FOPT



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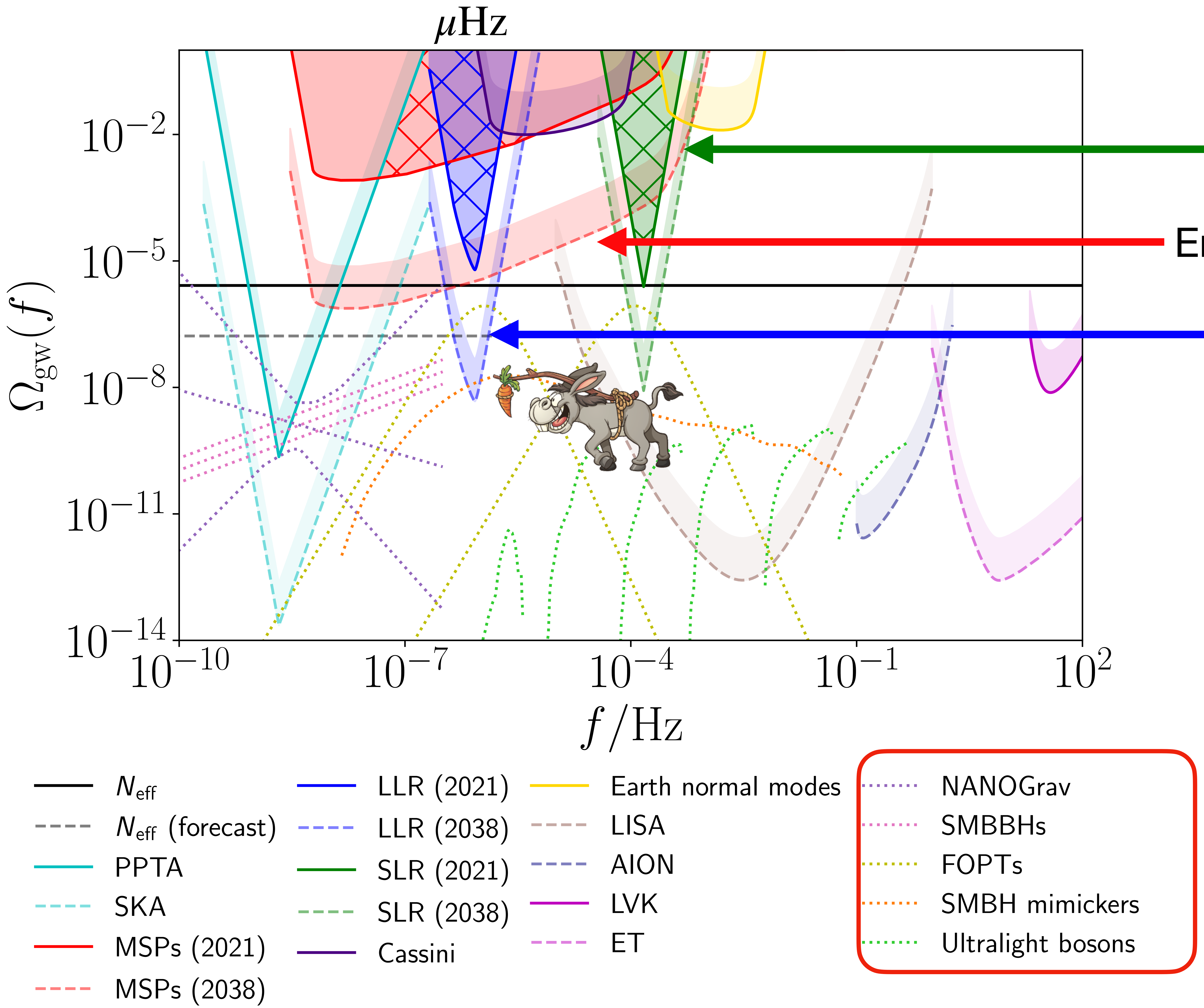

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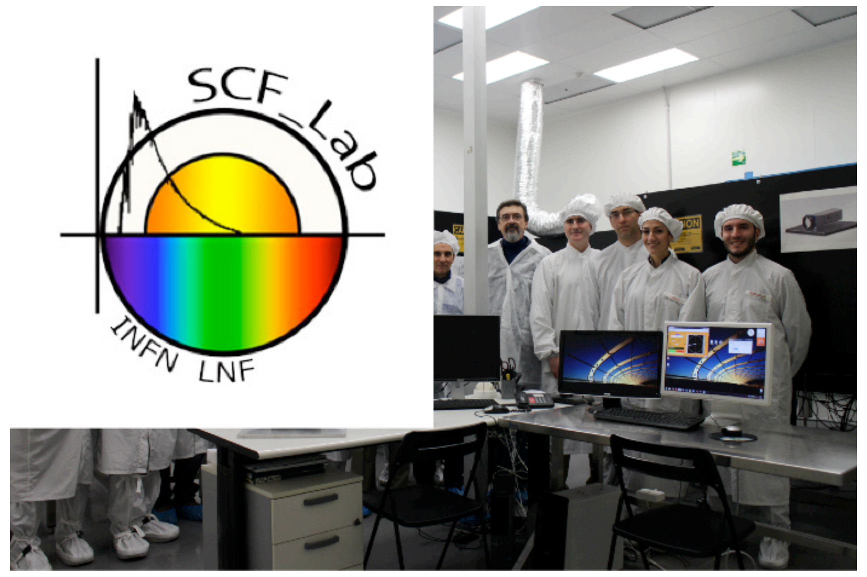


Help to perform the
real analysis welcome!

Miró, 1937.

After nHz, μHz?

- The μHz band is very rich for **astrophysical** and **cosmological** sources

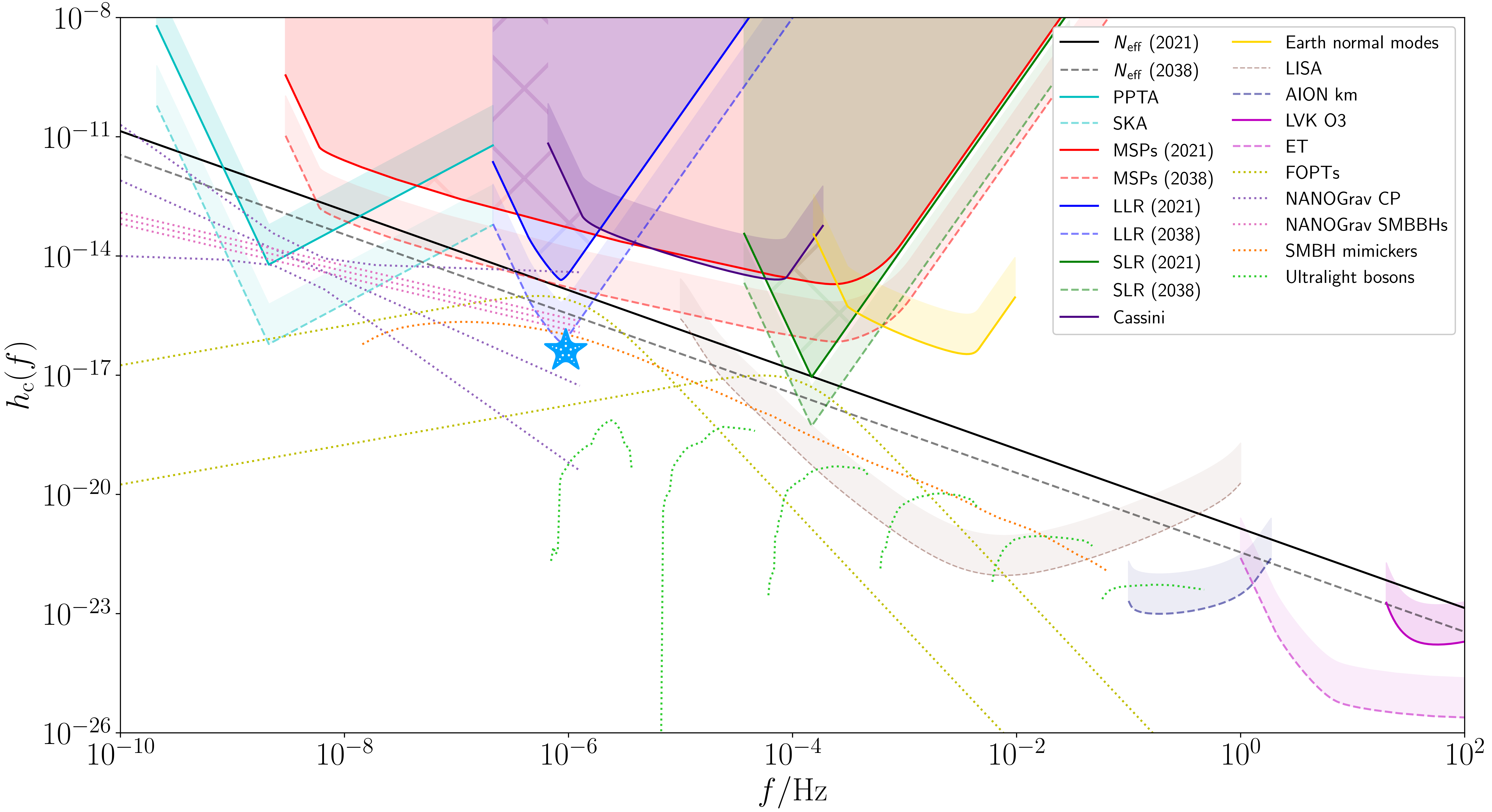
- There are **ideas** of how to access it, though **most** of them are **futuristic**

- The resonant **absorption of GWs by binaries** (LLR/SLR/pulsars) may give a handle at level (in 2038)

$$\Omega_{\rm gw} \geq 4.8 \times 10^{-9} \quad f = 0.85\,\mu\mathrm{Hz} \qquad\qquad \Omega_{\rm gw} \geq 8.3 \times 10^{-9} \quad f = 0.15\,\mathrm{mHz}$$

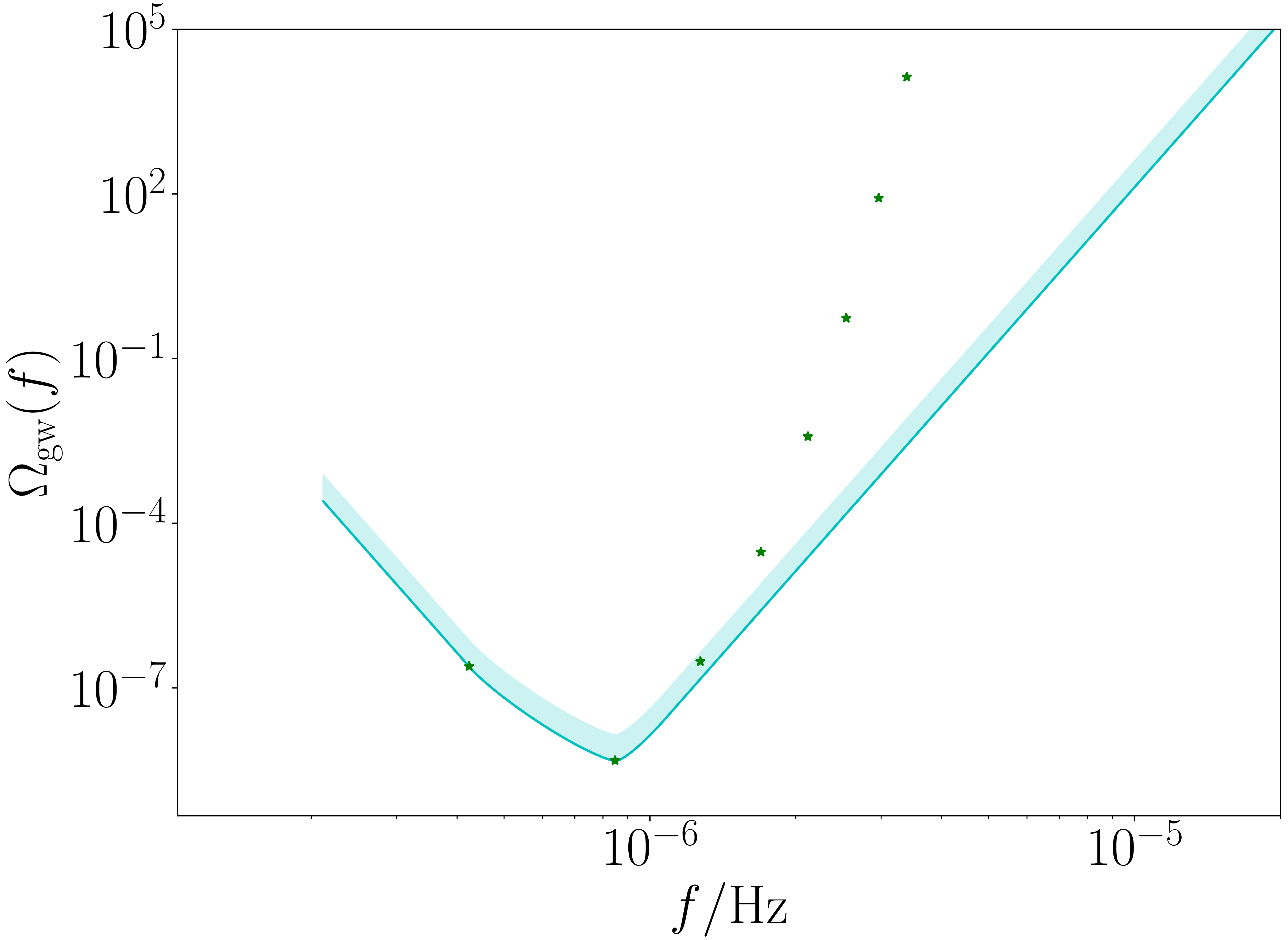
- **Future plans:** use LLR, SLR, pulsar ***data*** (w/ SYRTE, SCF_Lab, MPIfRA, Nanograv people…): we need/welcome new hands.
  Find ***other resonant effects*** (many possible, which frequencies?)

Characteristic strain

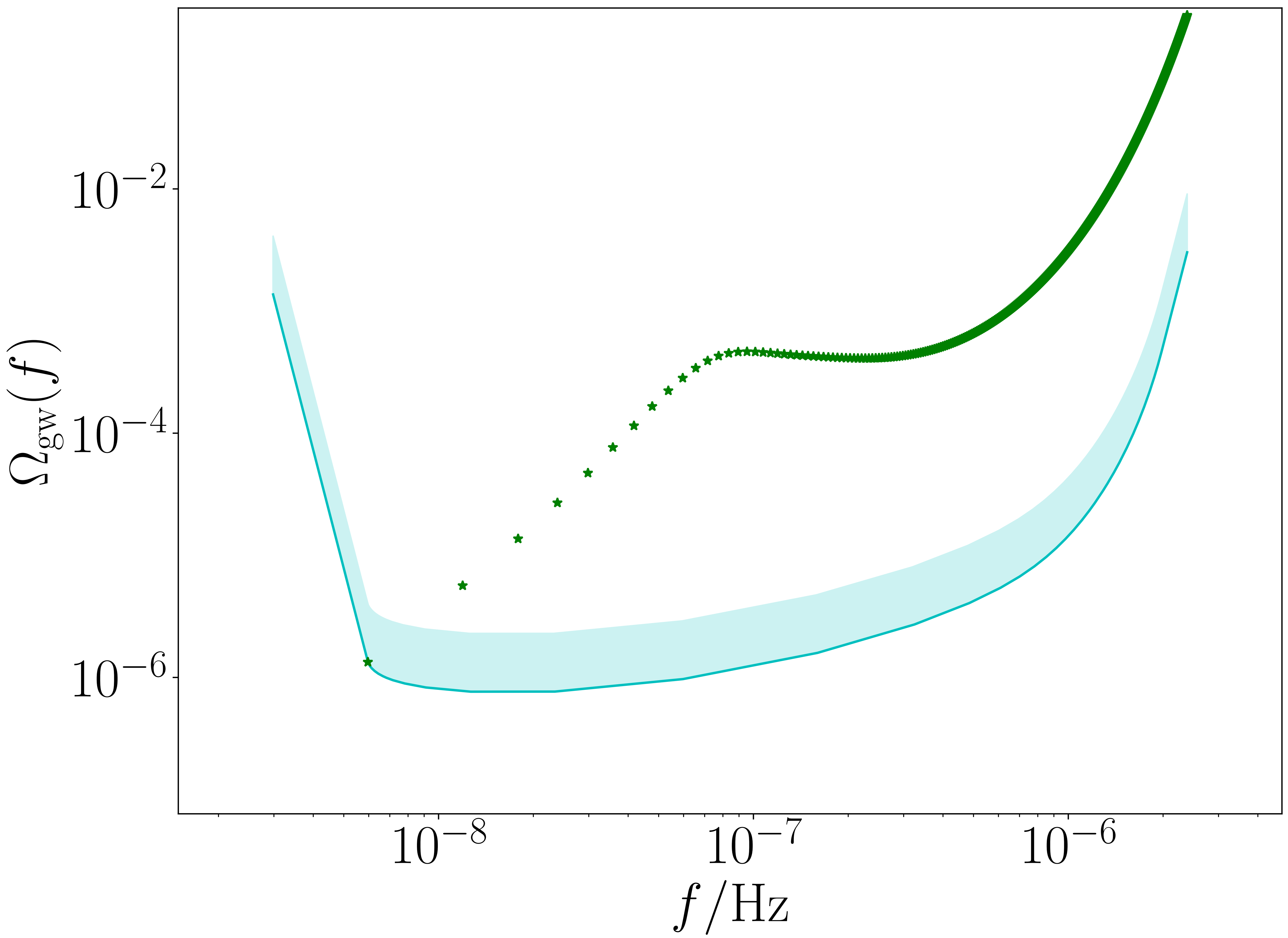


Power-law sensitivity vs. monochromatic sensitivity

lunar laser ranging, $e \approx 0.055$



pulsar timing (J1638-4725), $e \approx 0.955$



Solar system bounds