Closing gaps in the GW spectrum:

new physics with μHz GWs and how to detect them

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based on 2107.04063/2107.04601 (PRL/PRD22)

(w. Alex Jenkins)

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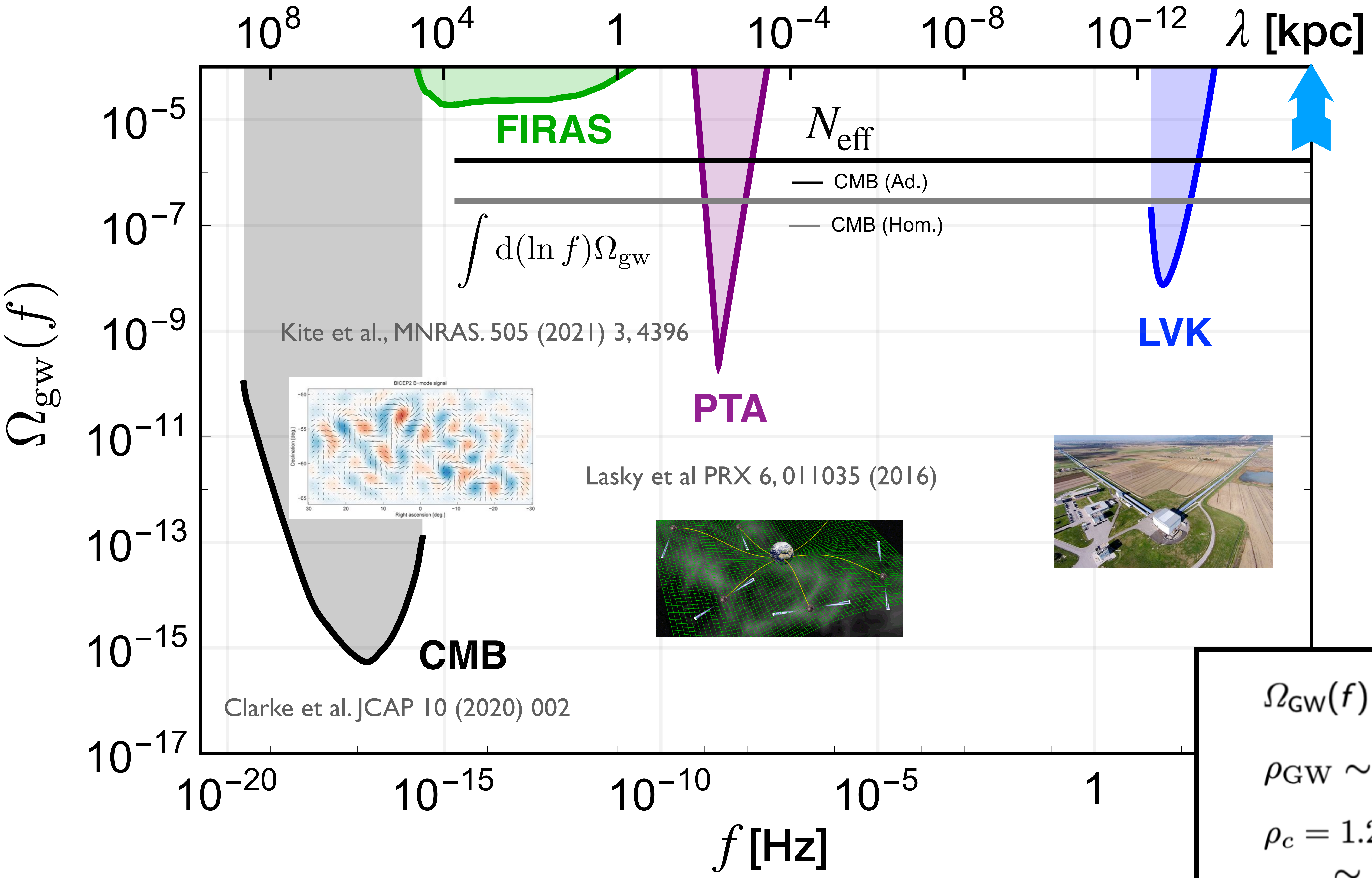
Ministerio de Ciencia e Innovación
Generalitat de Catalunya
Departament de Recerca i Universitats

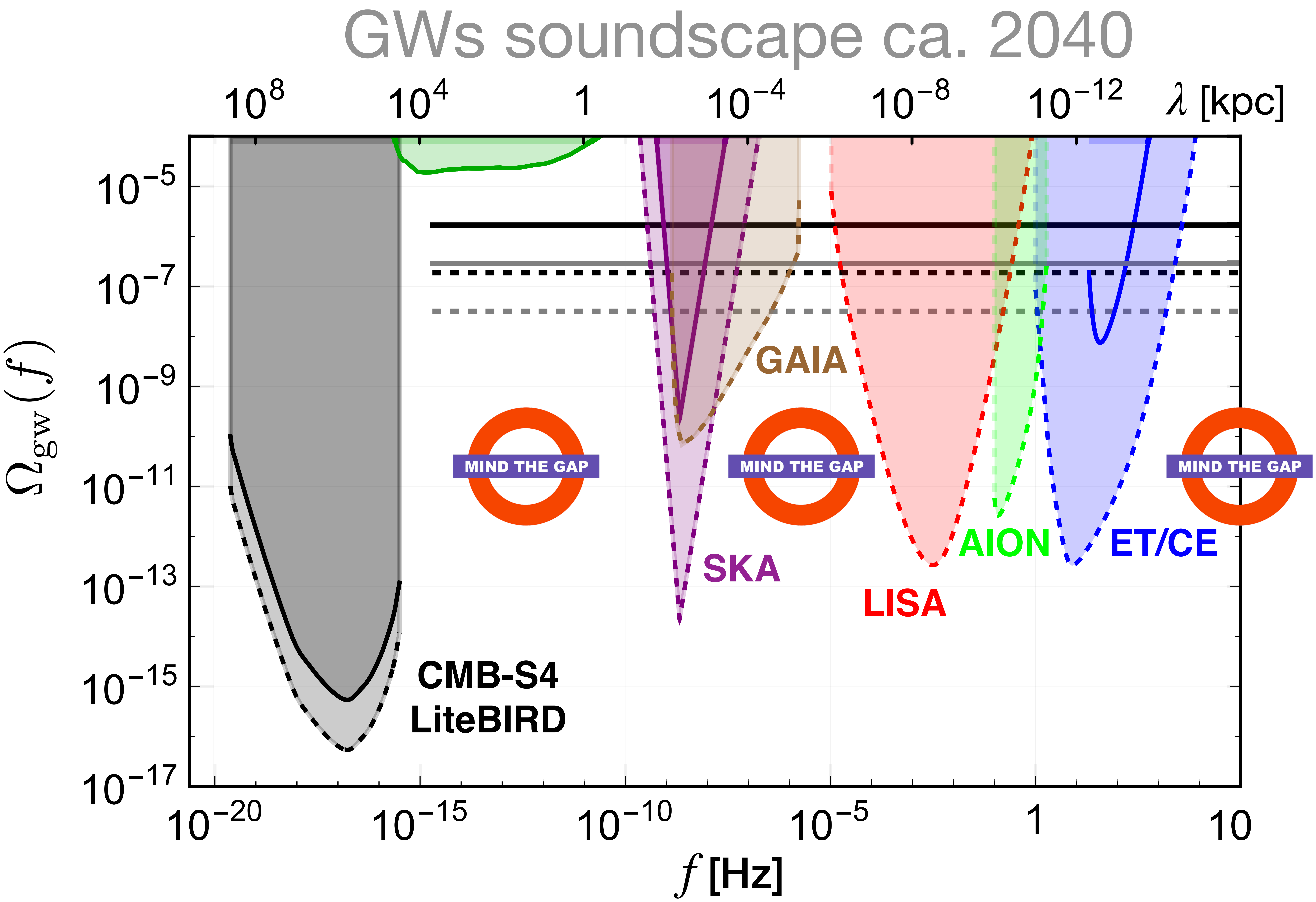
GWs soundscape today



$$\Omega_{\rm GW}(f) = \frac{1}{\rho_{\rm crit}} \frac{d\rho_{\rm GW}}{d(\ln f)}$$

$$\rho_{\rm GW} \sim M_P^2 \omega^2 h_{GW}^2$$

$$\rho_c = 1.2 \times 10^{11} M_\odot {\rm Mpc}^{-3}$$
$$\sim {\rm keV/cm}^3$$



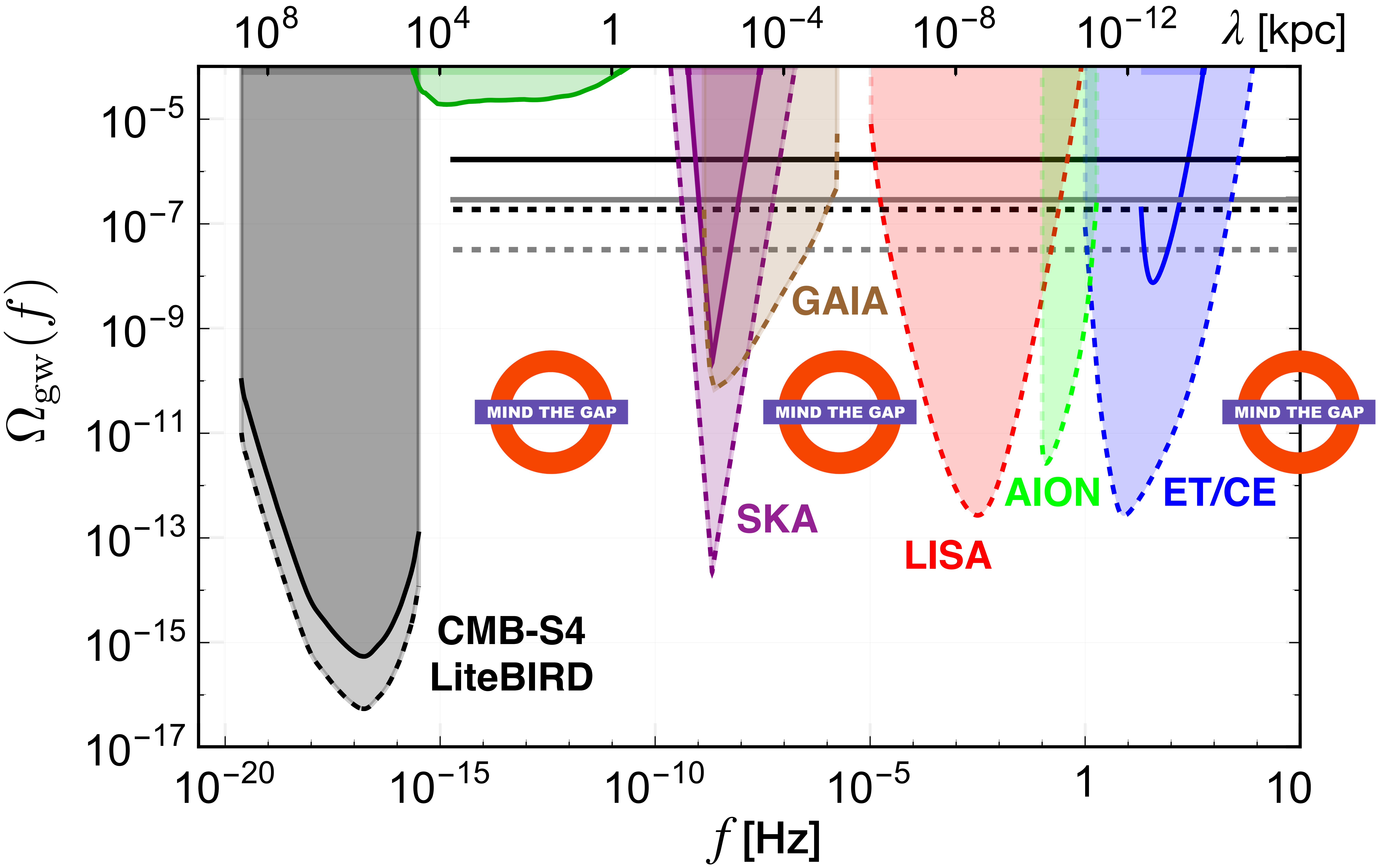
GWs soundscape ca. 2040
λ [kpc]
$\Omega_{gw}(f)$
f [Hz]
CMB-S4
LiteBIRD
SKA
GAIA
LISA
AION
ET/CE
MIND THE GAP
MIND THE GAP
MIND THE GAP

MW in visible band

MW in X rays

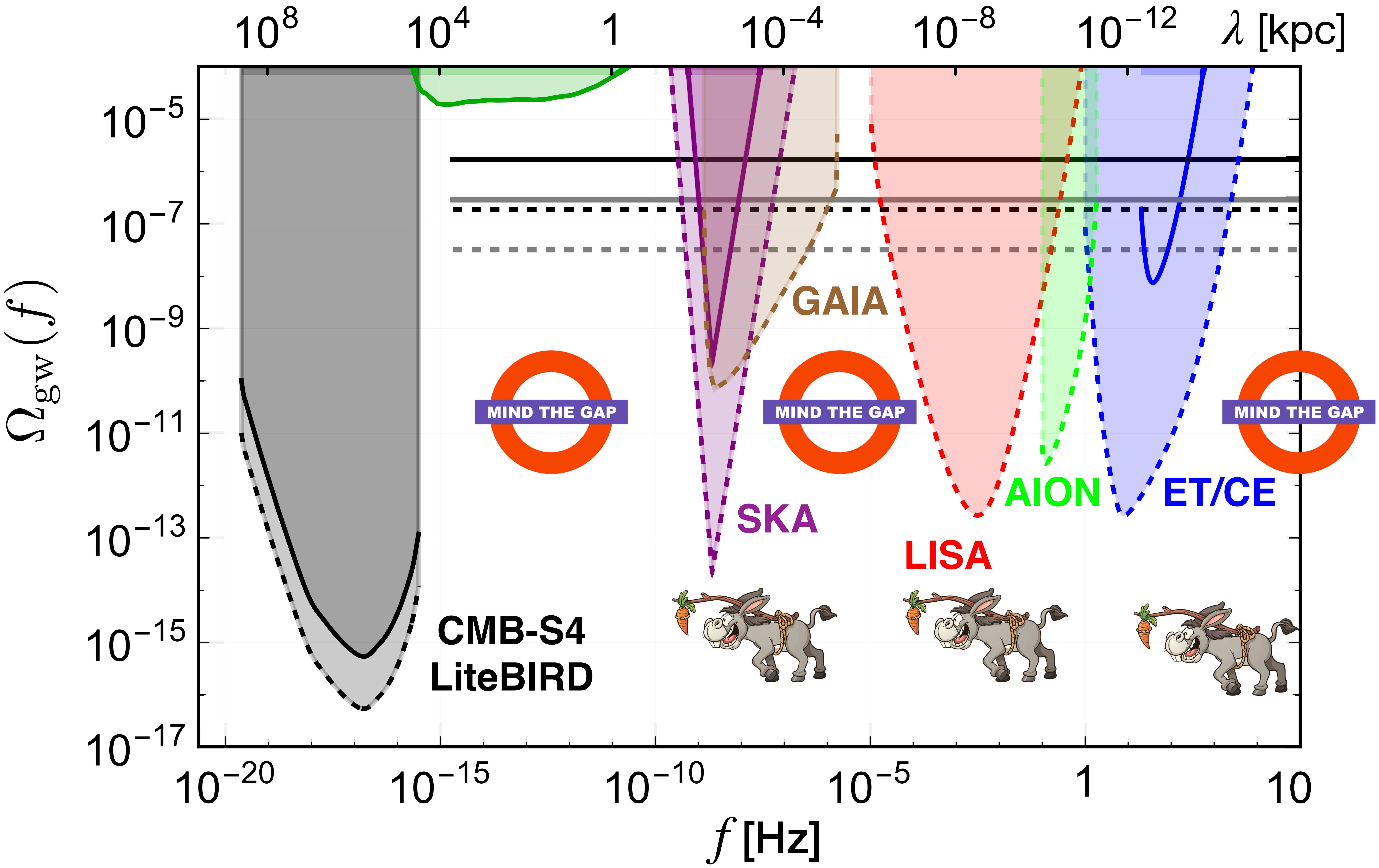
Spektr-RG–eROSITA all-sky map Nature volume 588, pages 227–231 (2020).

GWs soundscape ca. 2040

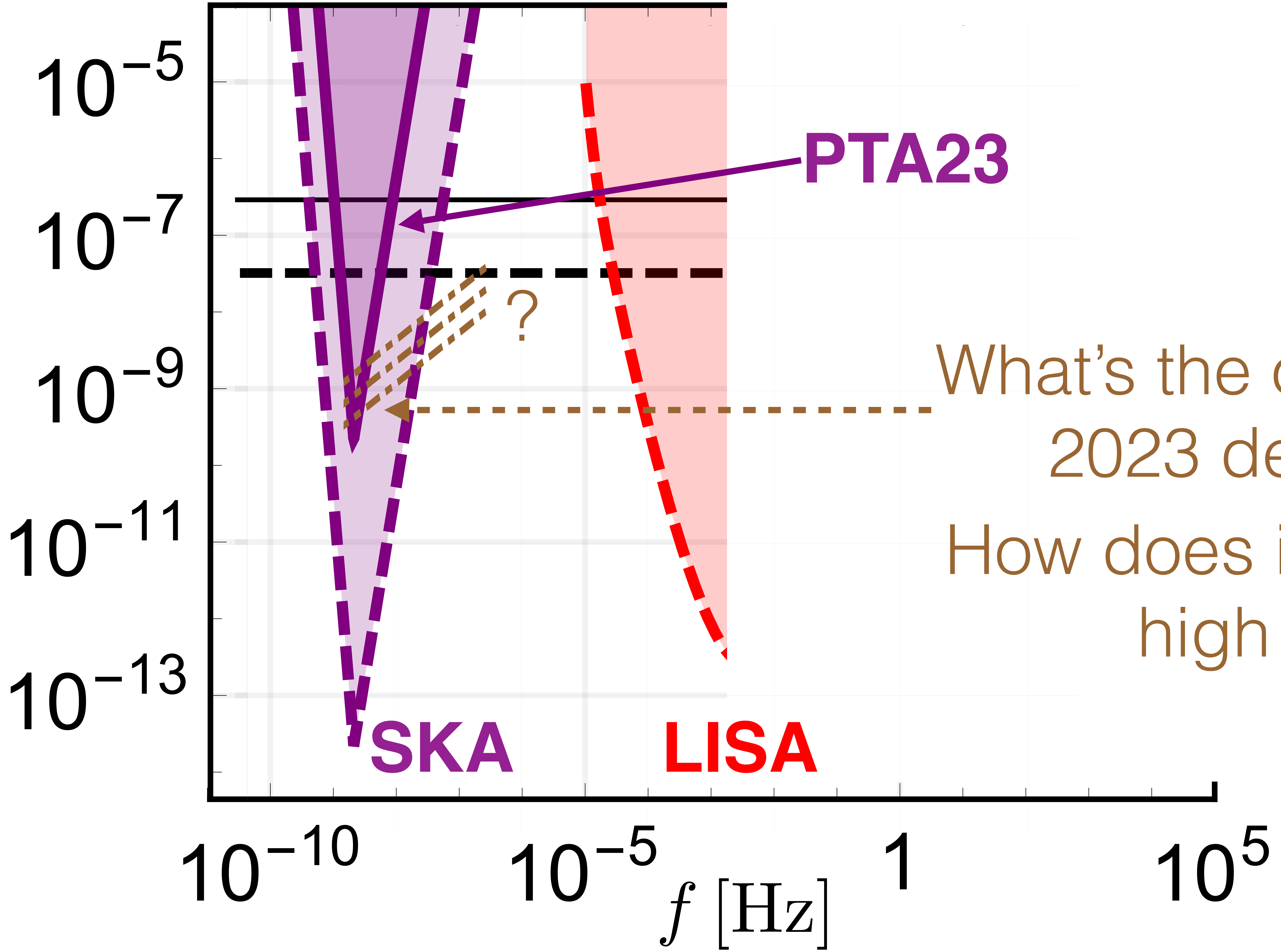


Possible **backgrounds** at μHz: a rich band

GWs soundscape ca. 2040



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

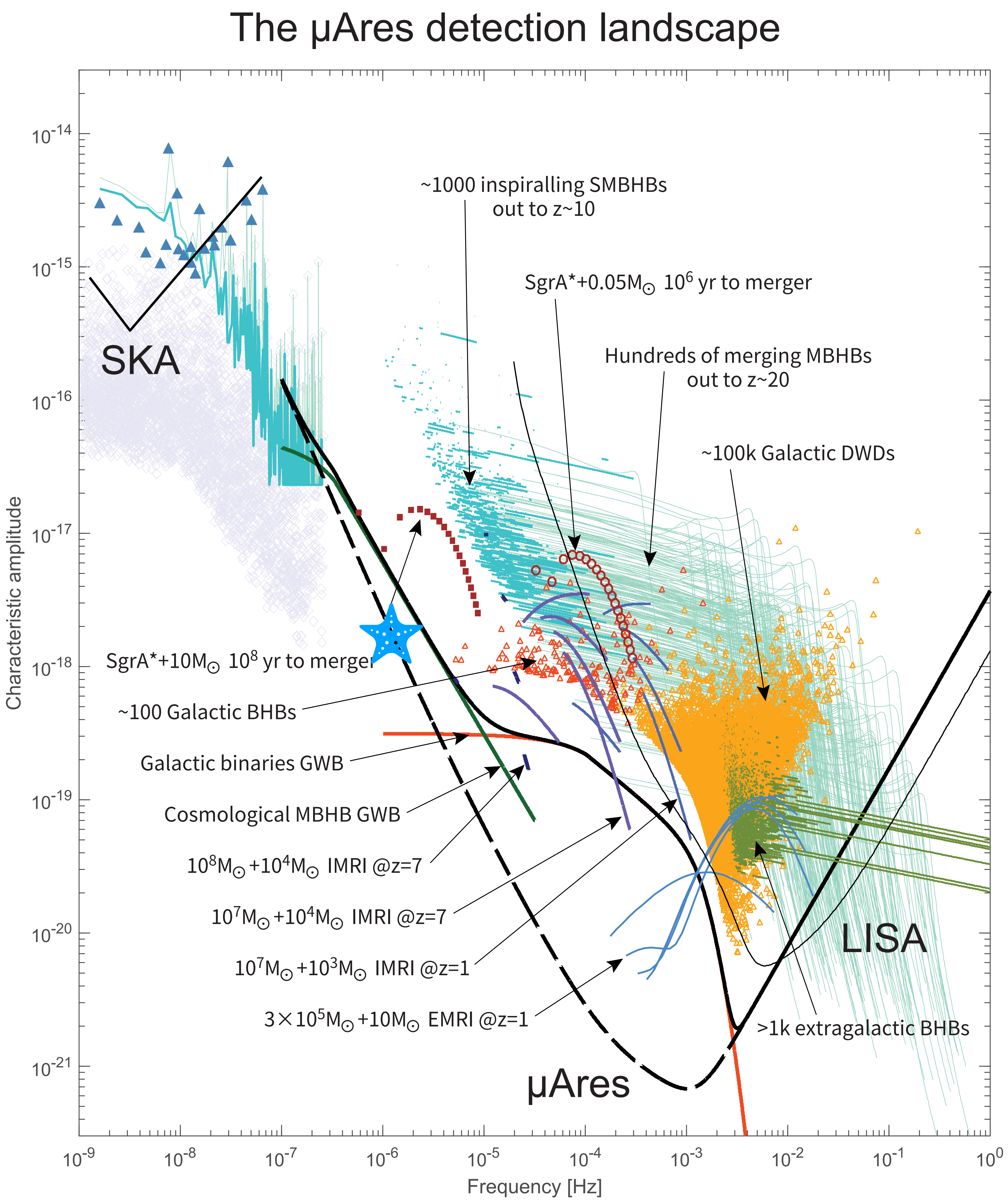


What's the origin of the 2023 detection?

How does it change at high freq?

Review of sources

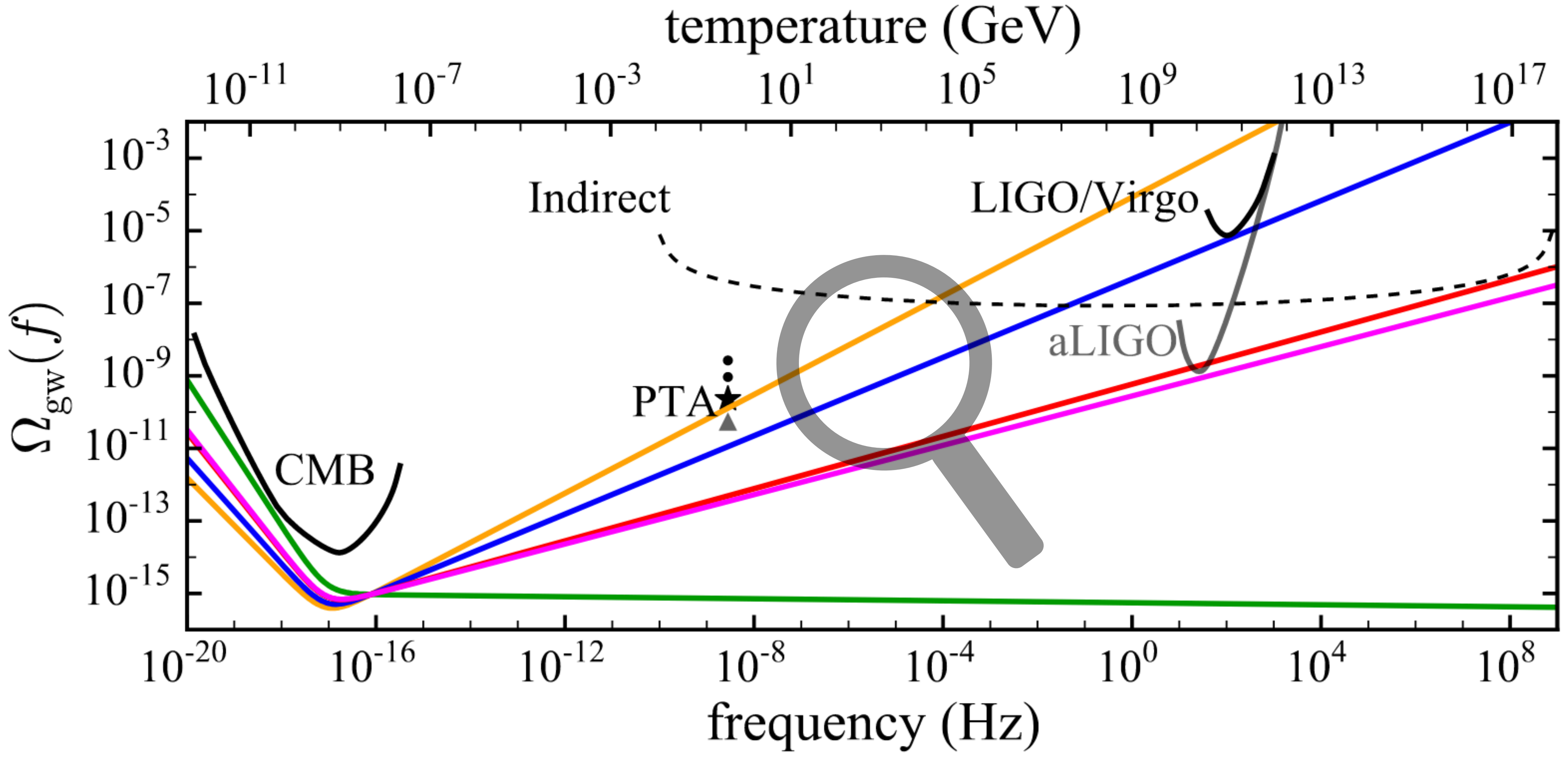
arXiv:1908.11391v1 [astro-ph.IM] 29 Aug 2019



Backgrounds from fundamental physics

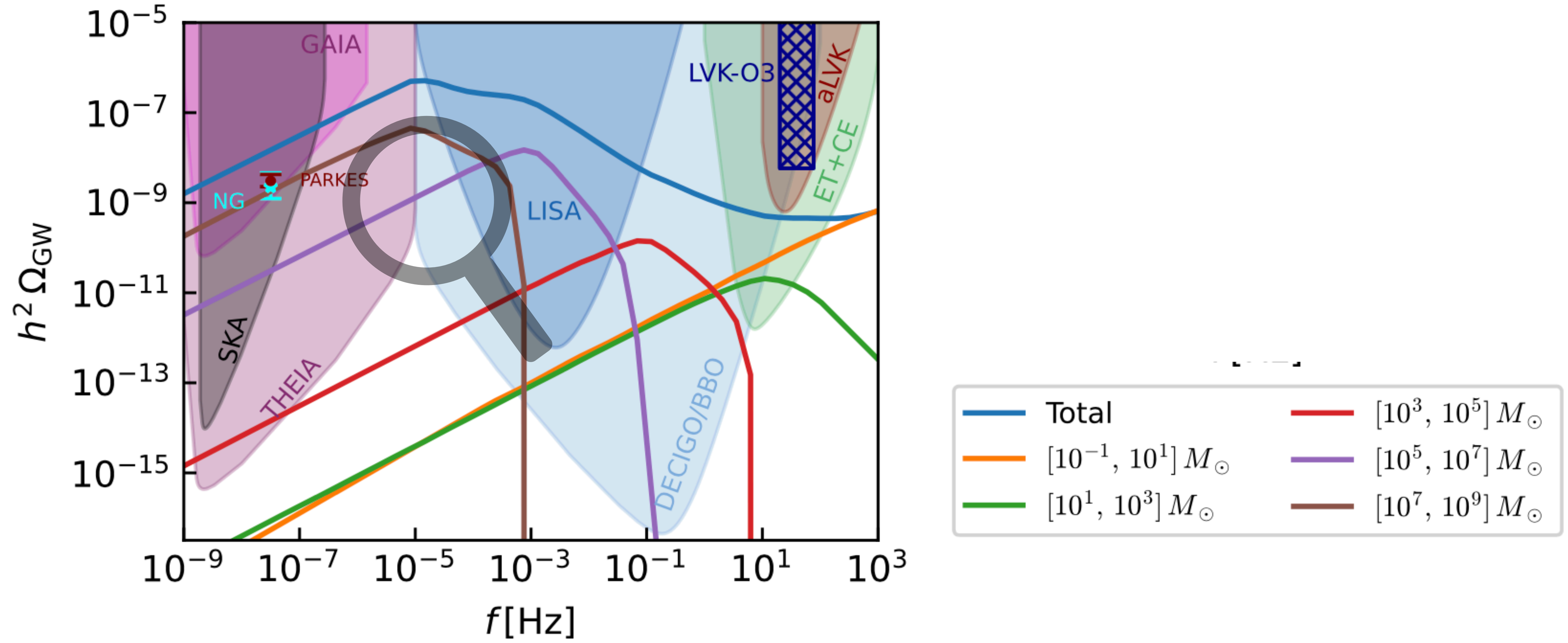
Inflation

Lasky et al PRX 6, 011035 (2016)



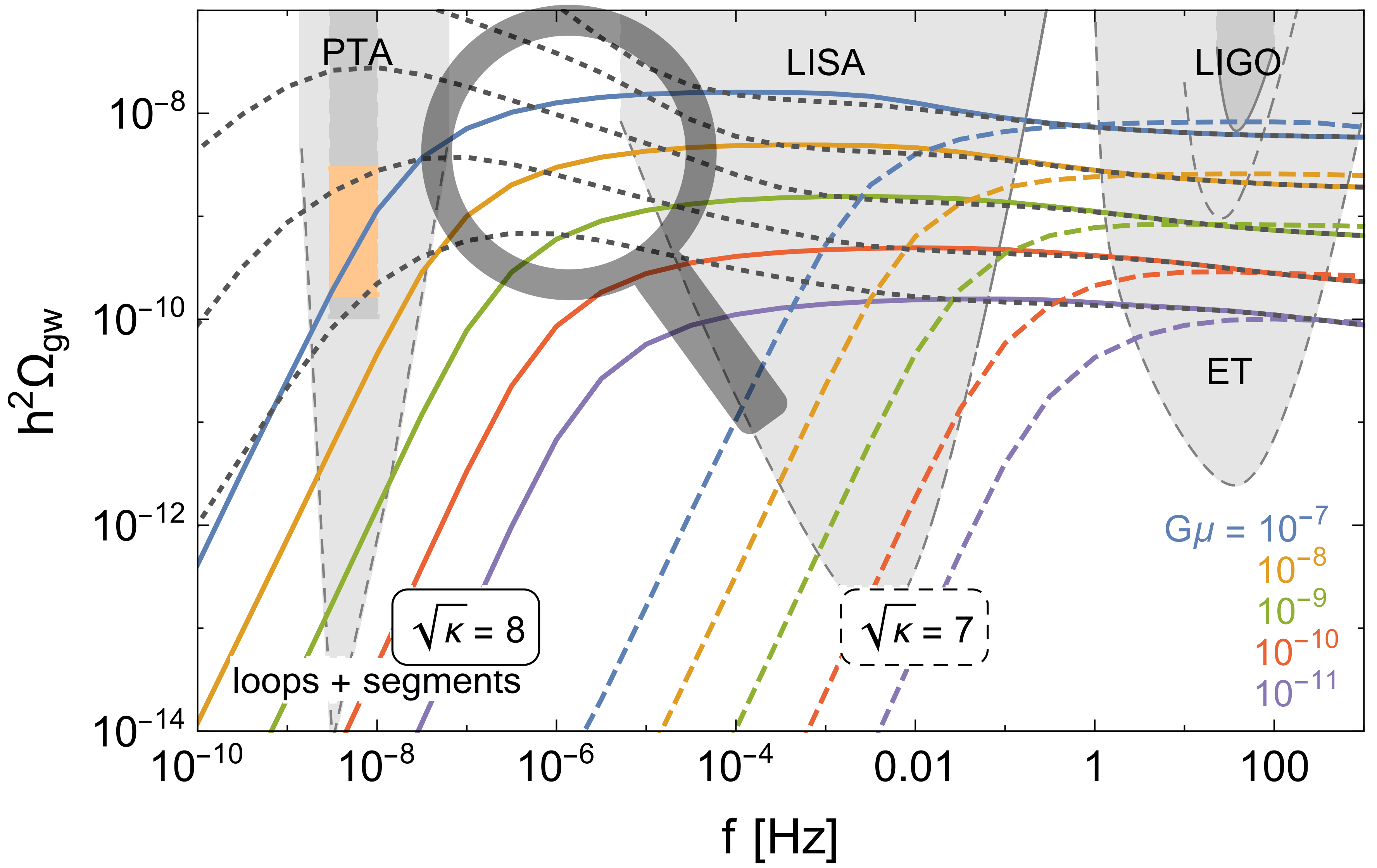
PBH

Braglia et al. JCAP 12 (2021) 12



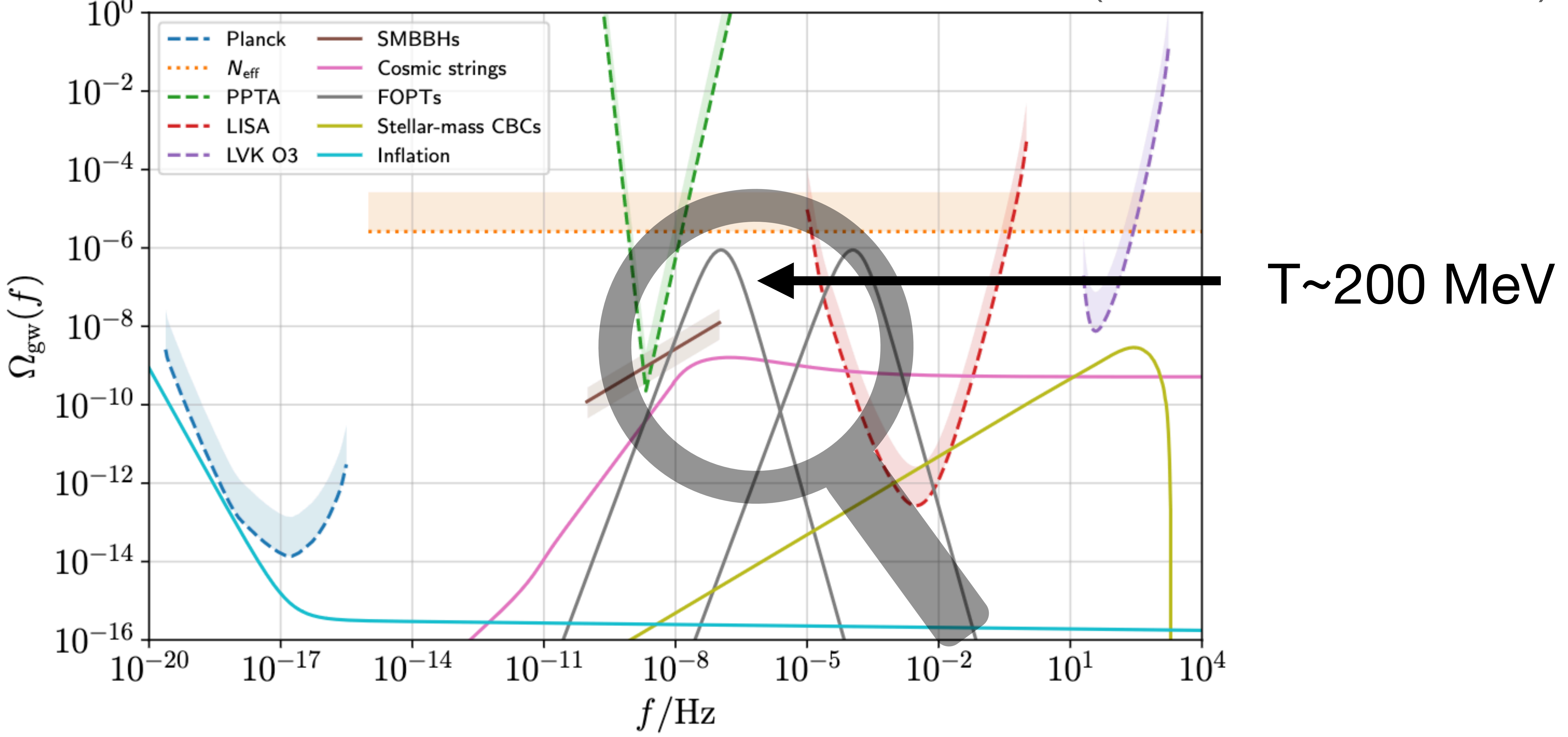
Cosmic Strings

Buchmuller et al. 2107.04578



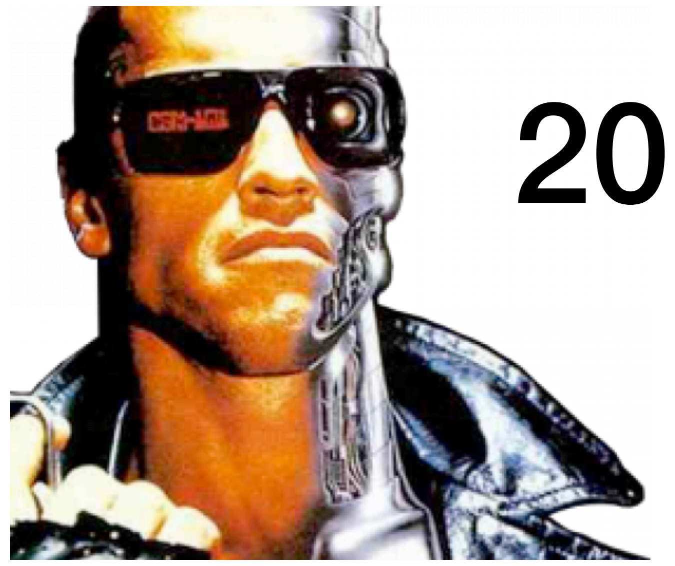
FOPT

Renzini et al 2202.00178
(based on 1512.06239)



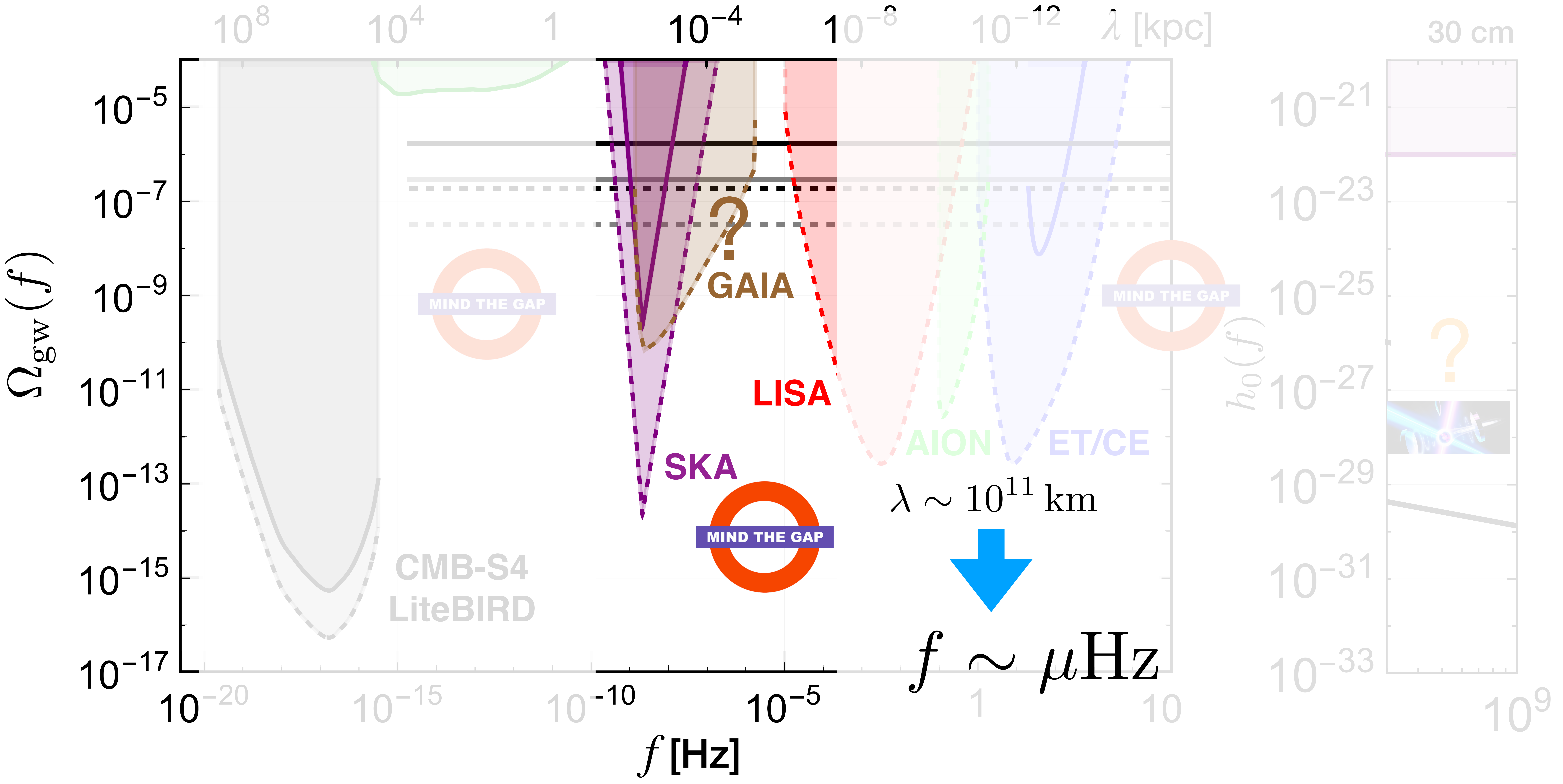
Can we detect them?

Can we detect them?

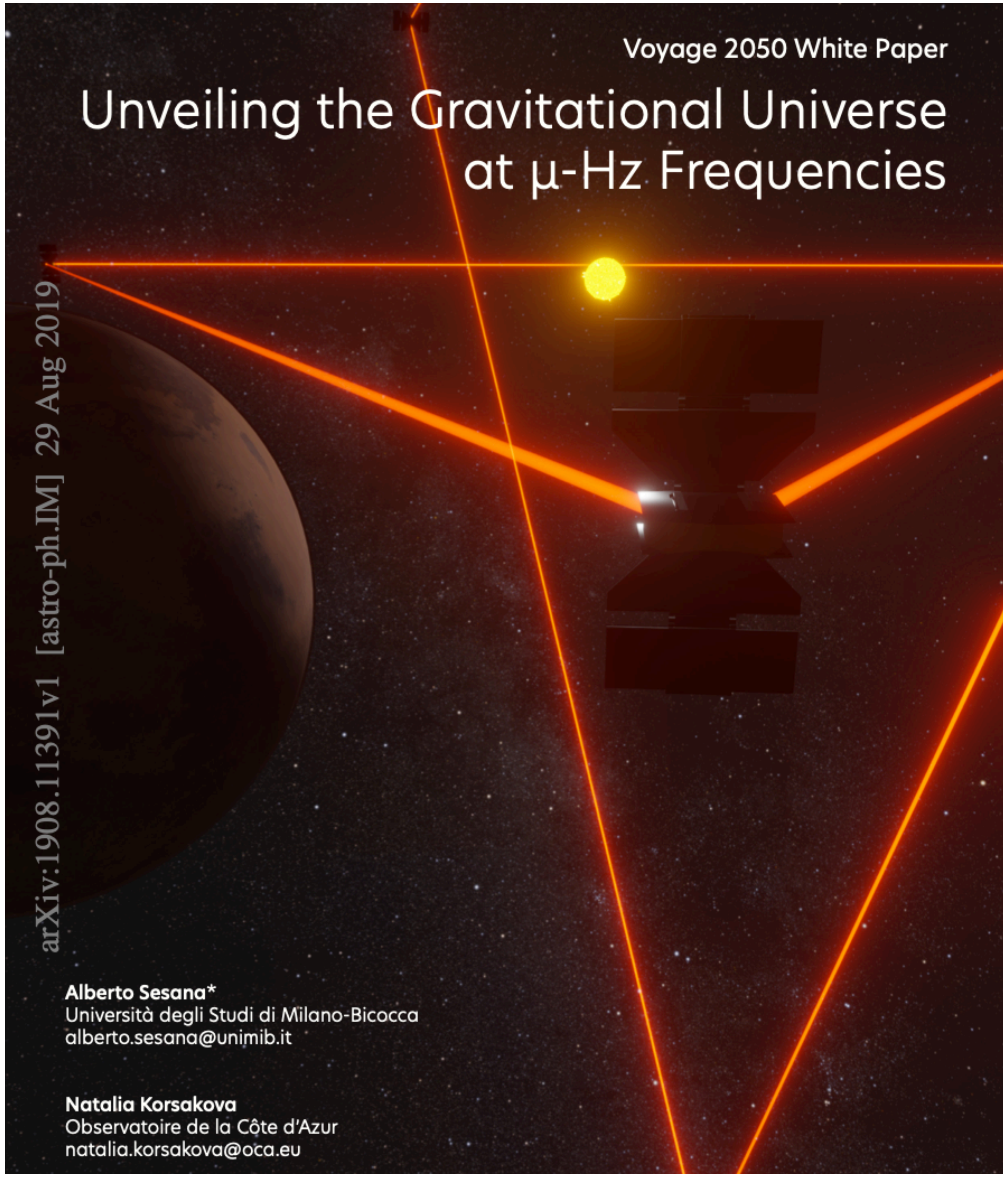


2029

Future soundscape (maybe 2040)?



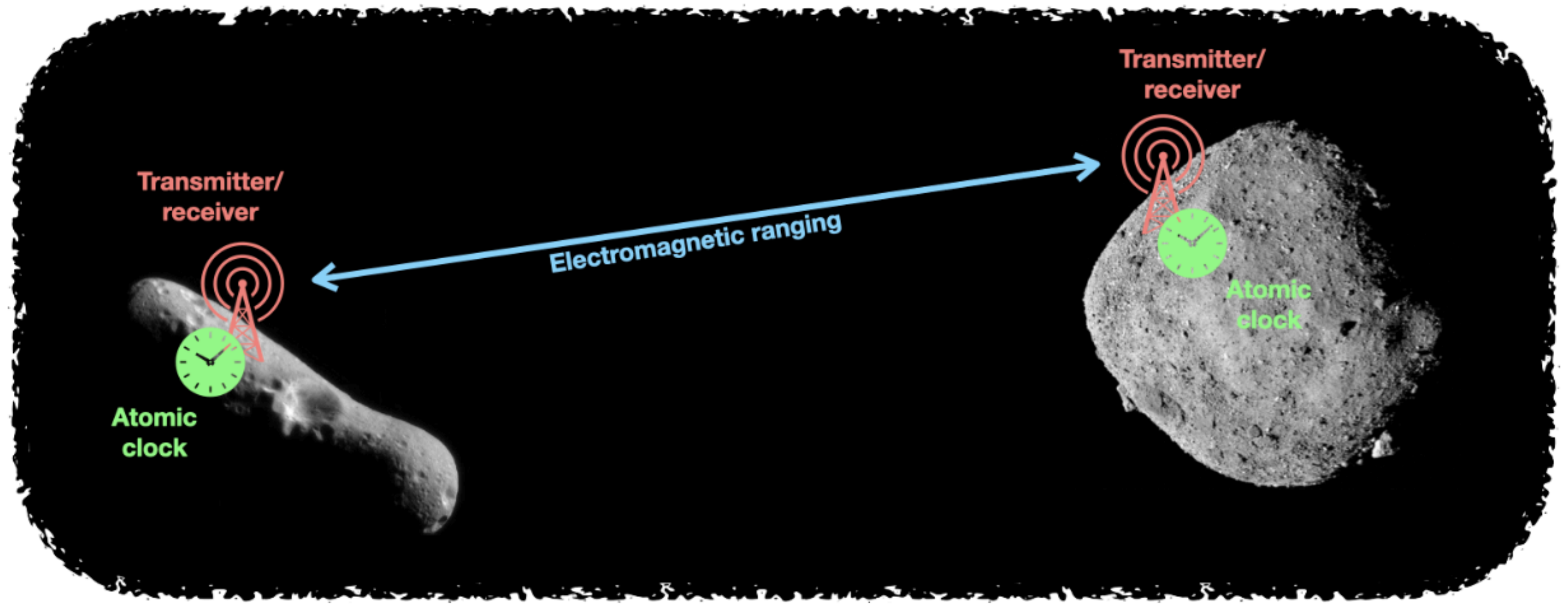
i) μAres: LISA-like concept

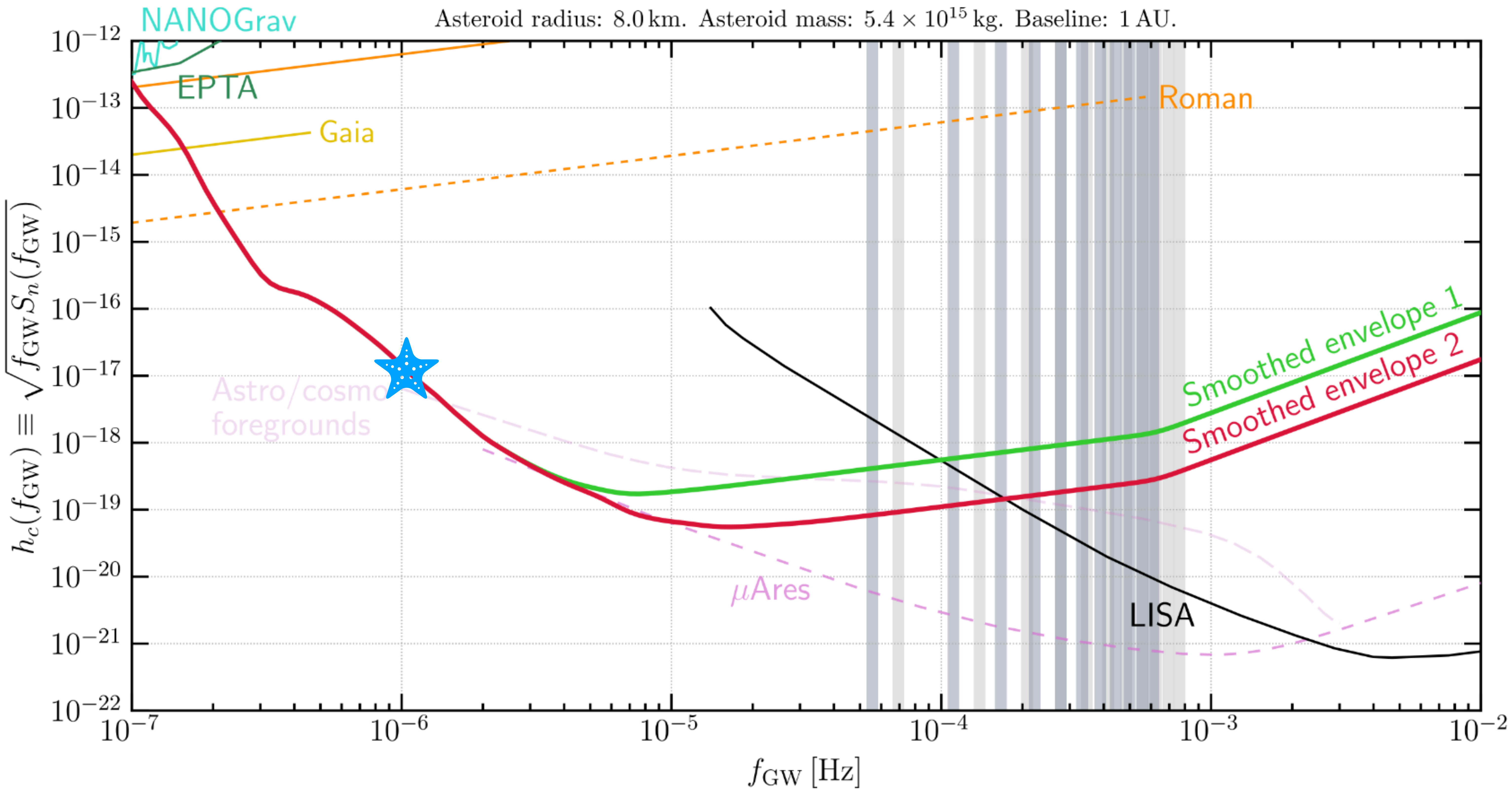



z [AU]
y [AU]
x [AU]
LISA
μAres (in plane)
μAres (out of plane)
The μAres detection landscape
Characteristic amplitude
Frequency [Hz]
SKA
LISA
μAres
~1000 inspiralling SMBHBs out to z~10
SgrA*+0.05M⊙ 10^6 yr to merger
Hundreds of merging MBHBs out to z~20
~100k Galactic DWDs
SgrA*+10M⊙ 10^8 yr to merger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

ii) Ranging of asteroids?

Fedderke et al 2112.11431





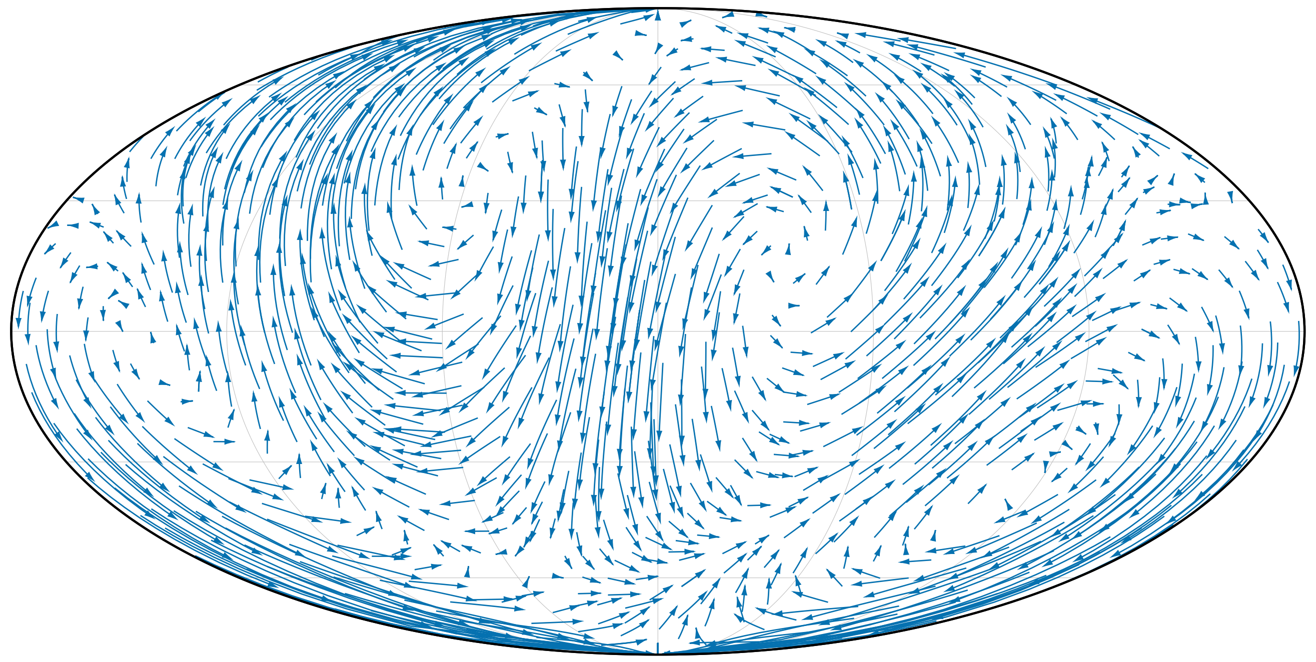
iii) Future astrometry?

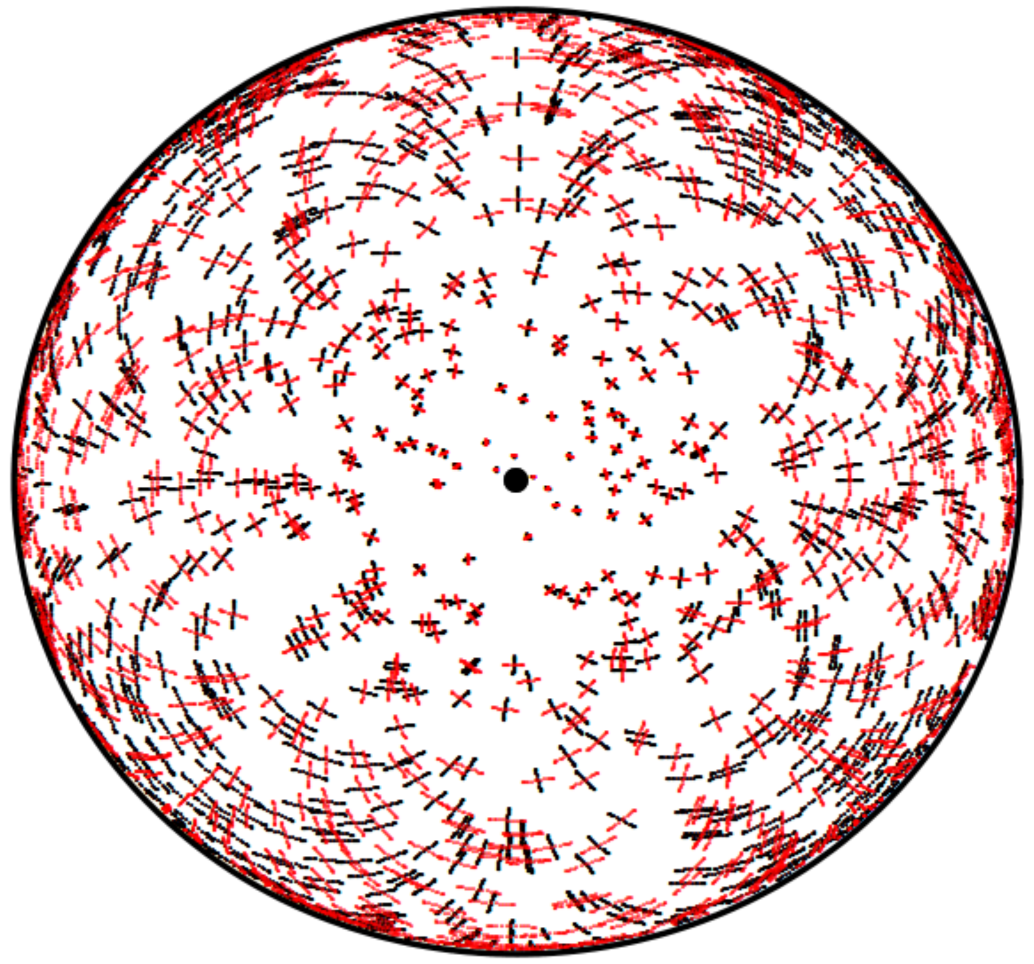
e.g. Moore et al 1707.06239
Mihaylov et al. 1804.00660

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

Çalışkan et al 2312.03069

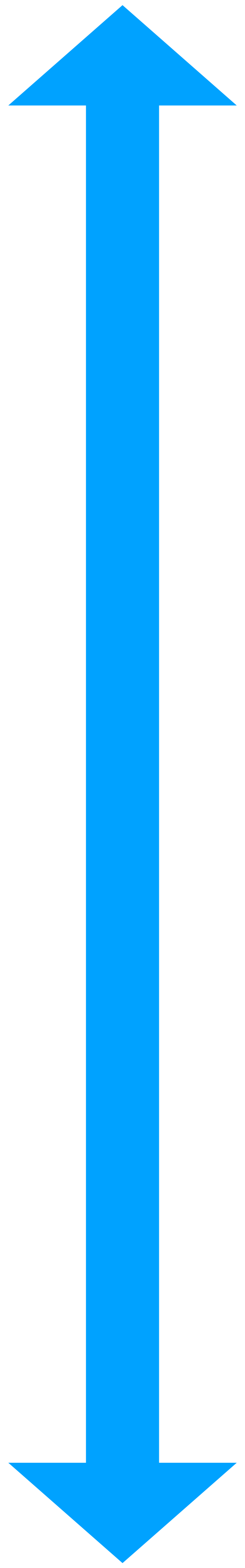
iv) Atomic interferometry in space: AEDGE

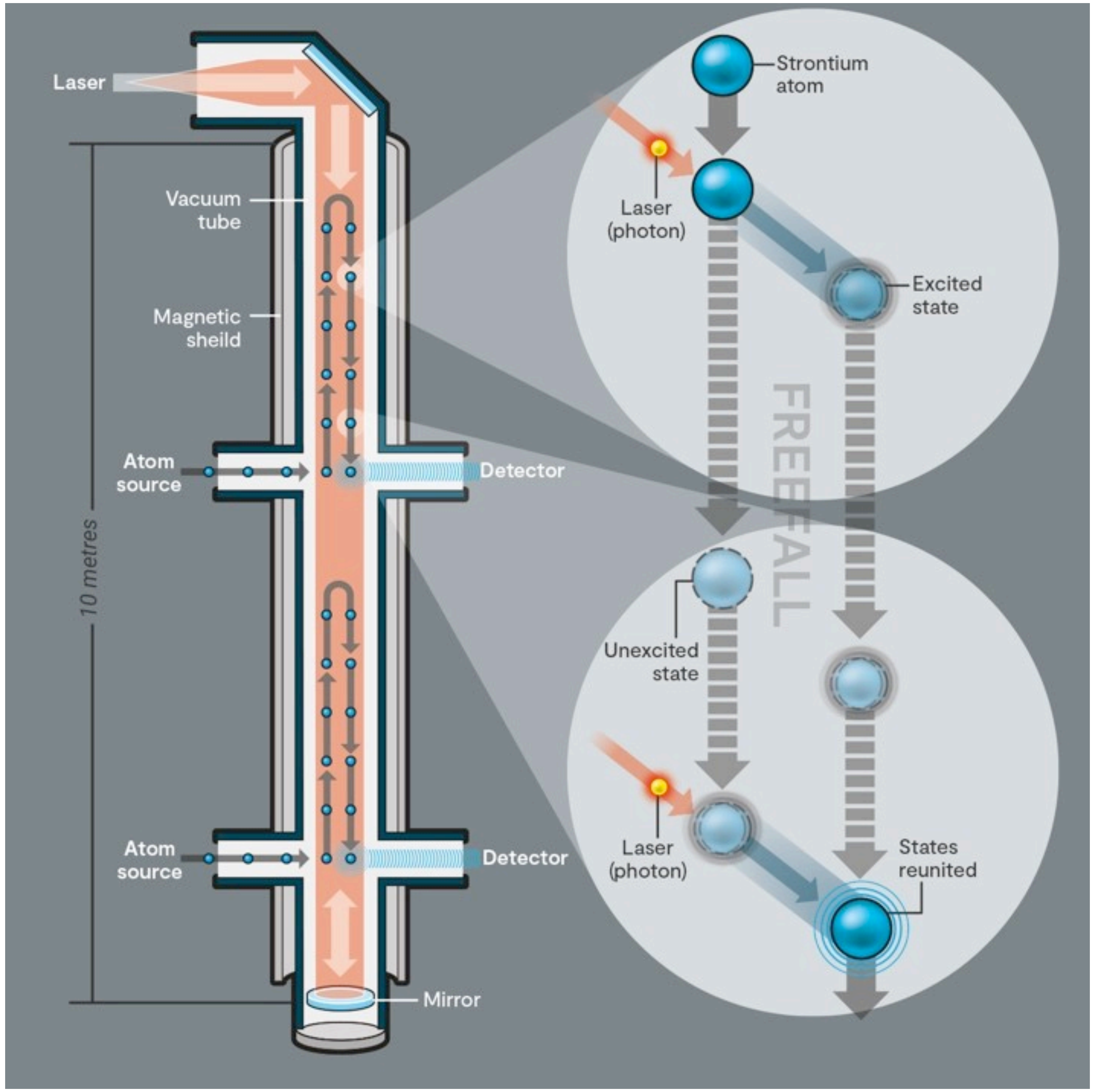
Abou El-Neaj et al 1908.00802

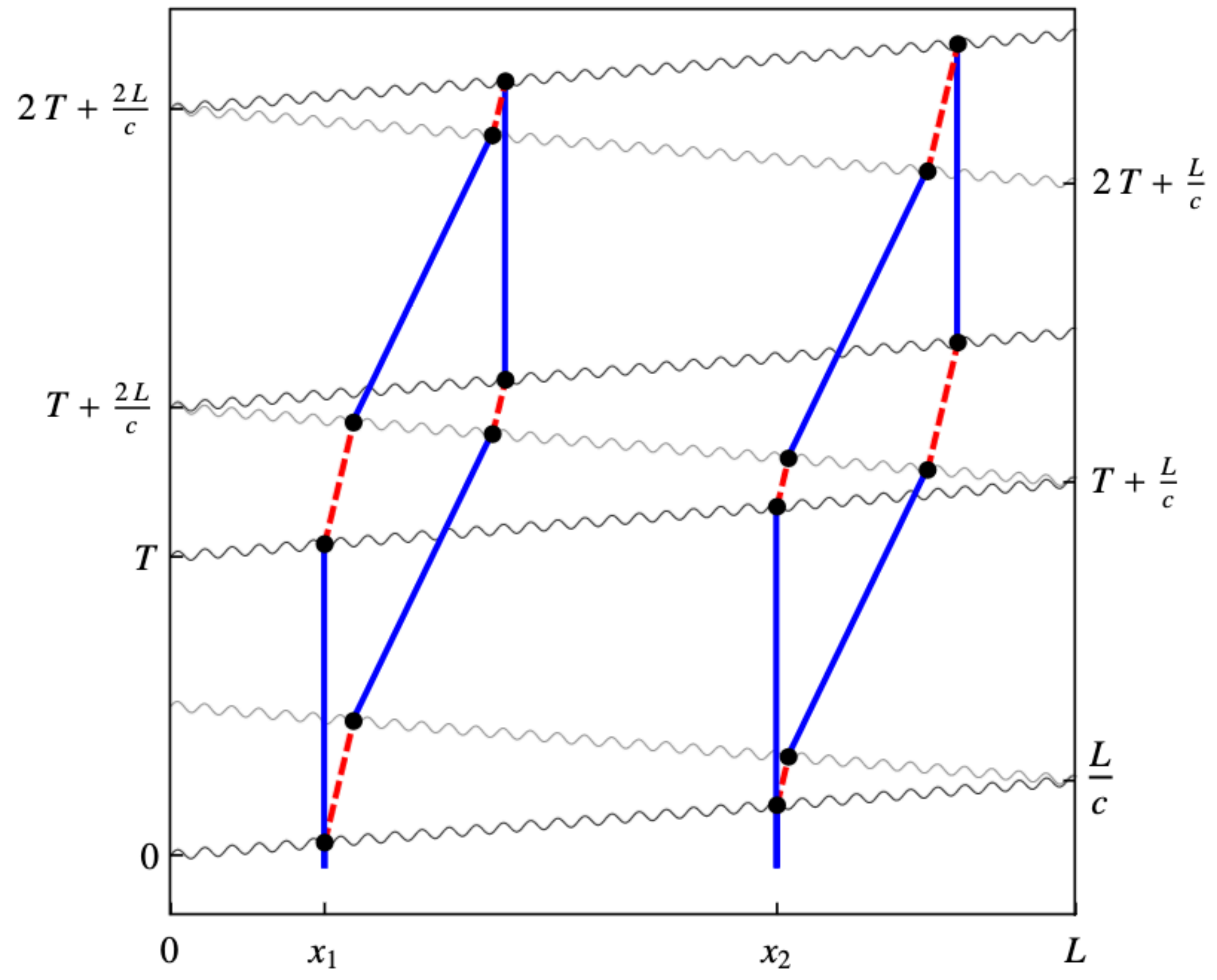
Badurina et al 2108.02468 (AION)

Graham et al 1206.0818 (MAGIS)

40000 km

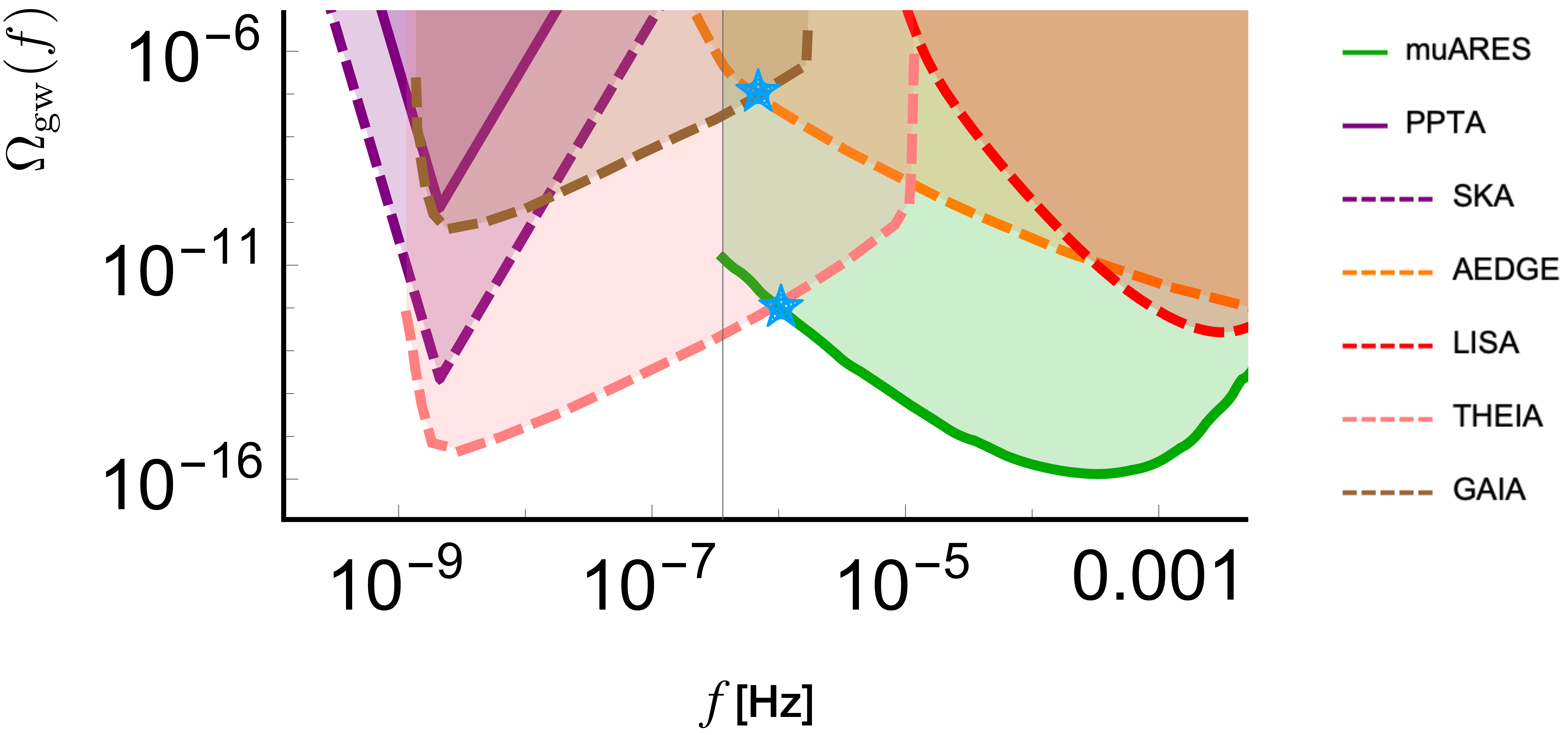




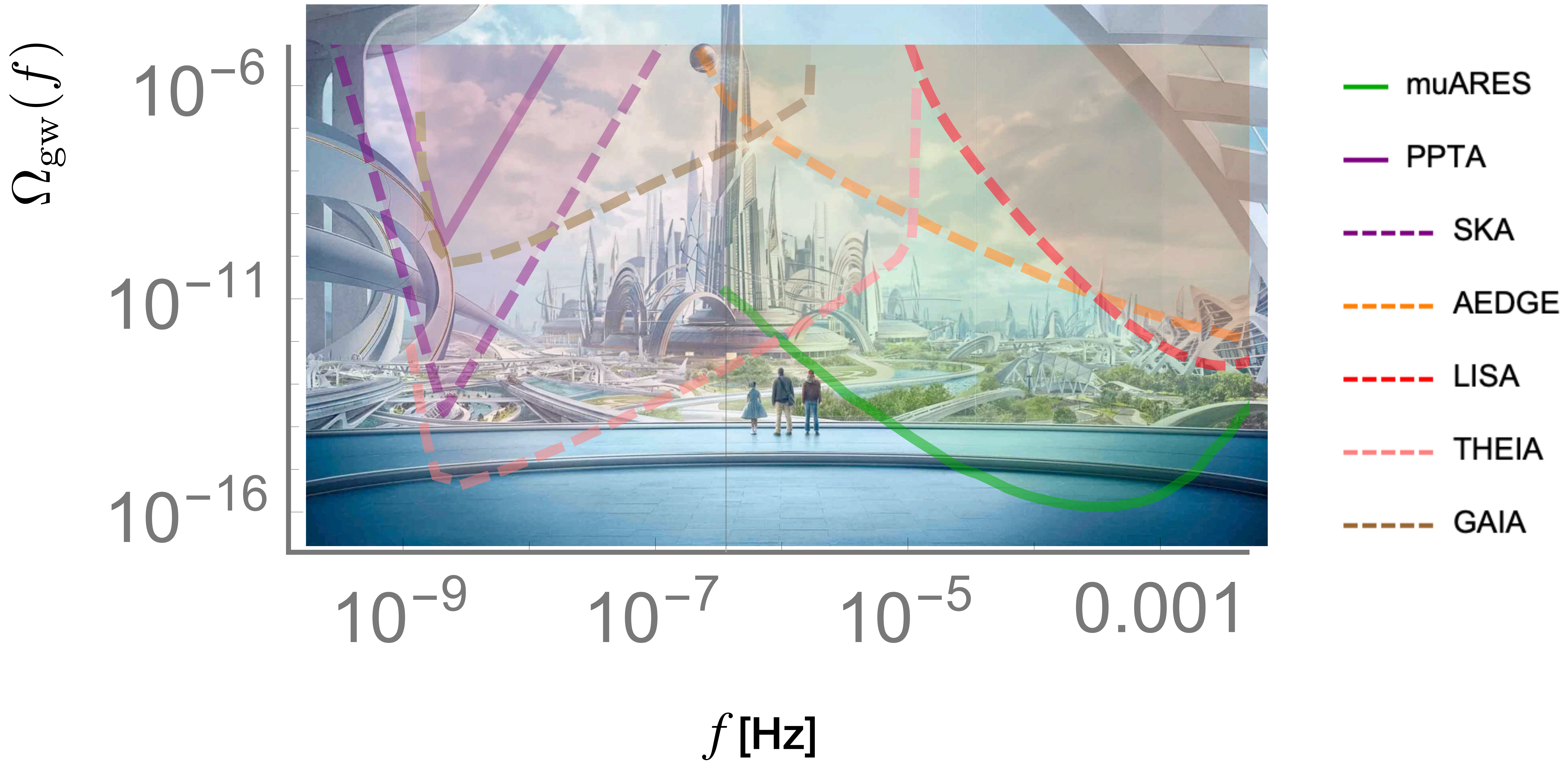


$$\Delta\phi \sim \omega L h$$

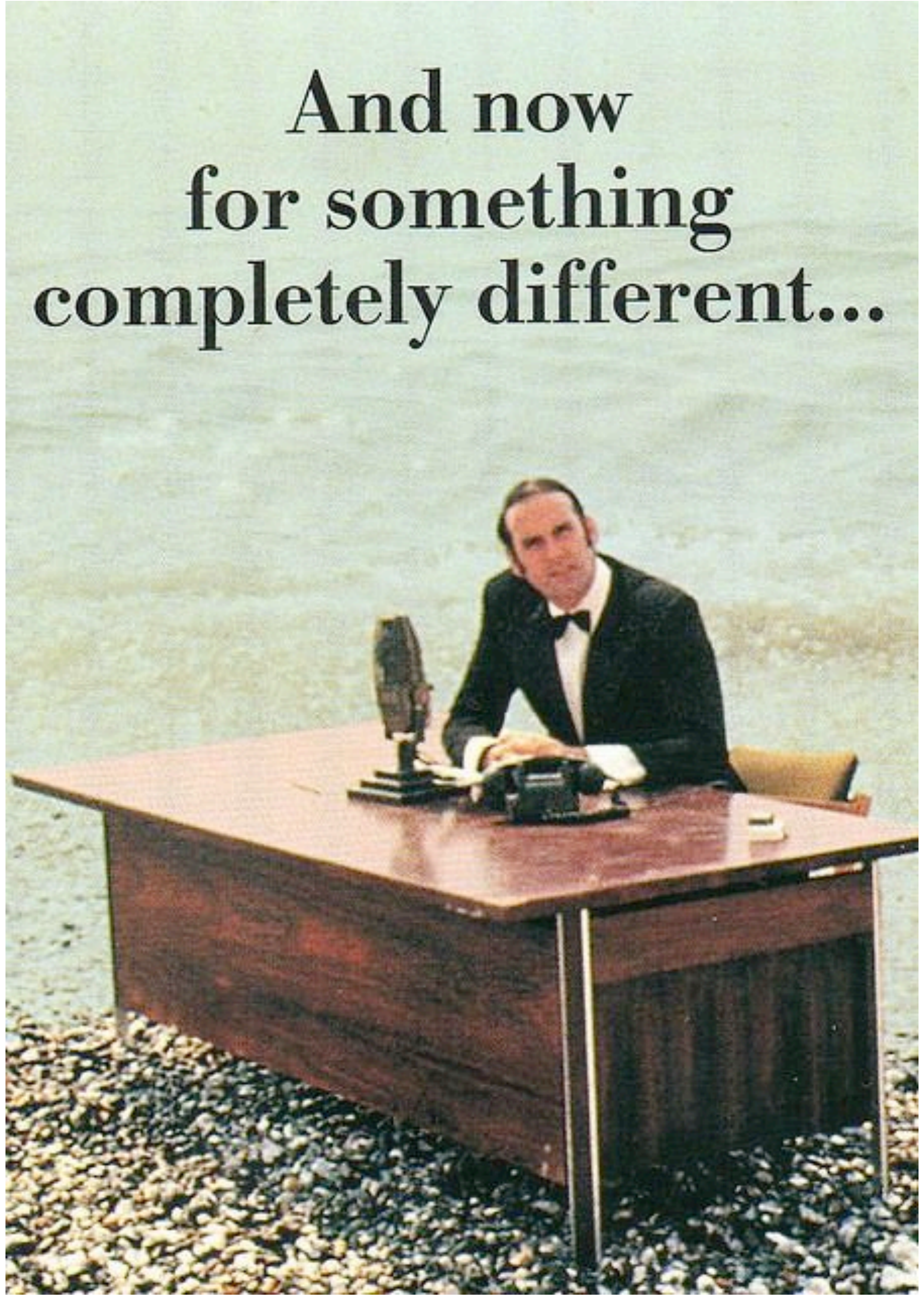
The most optimistic future…



The most optimistic future…



Is this all we can do in this band?



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

few days

Absorption of GWs by binaries

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

few days

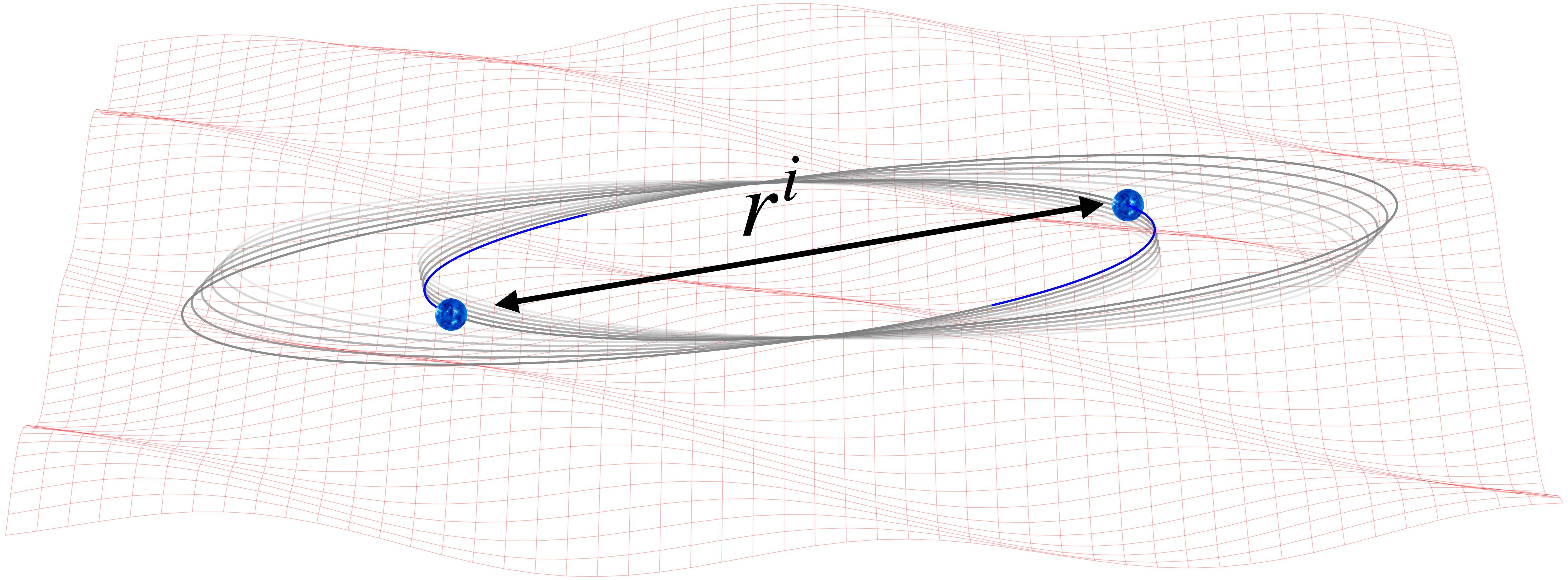
Intuitive idea (from '60s)

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

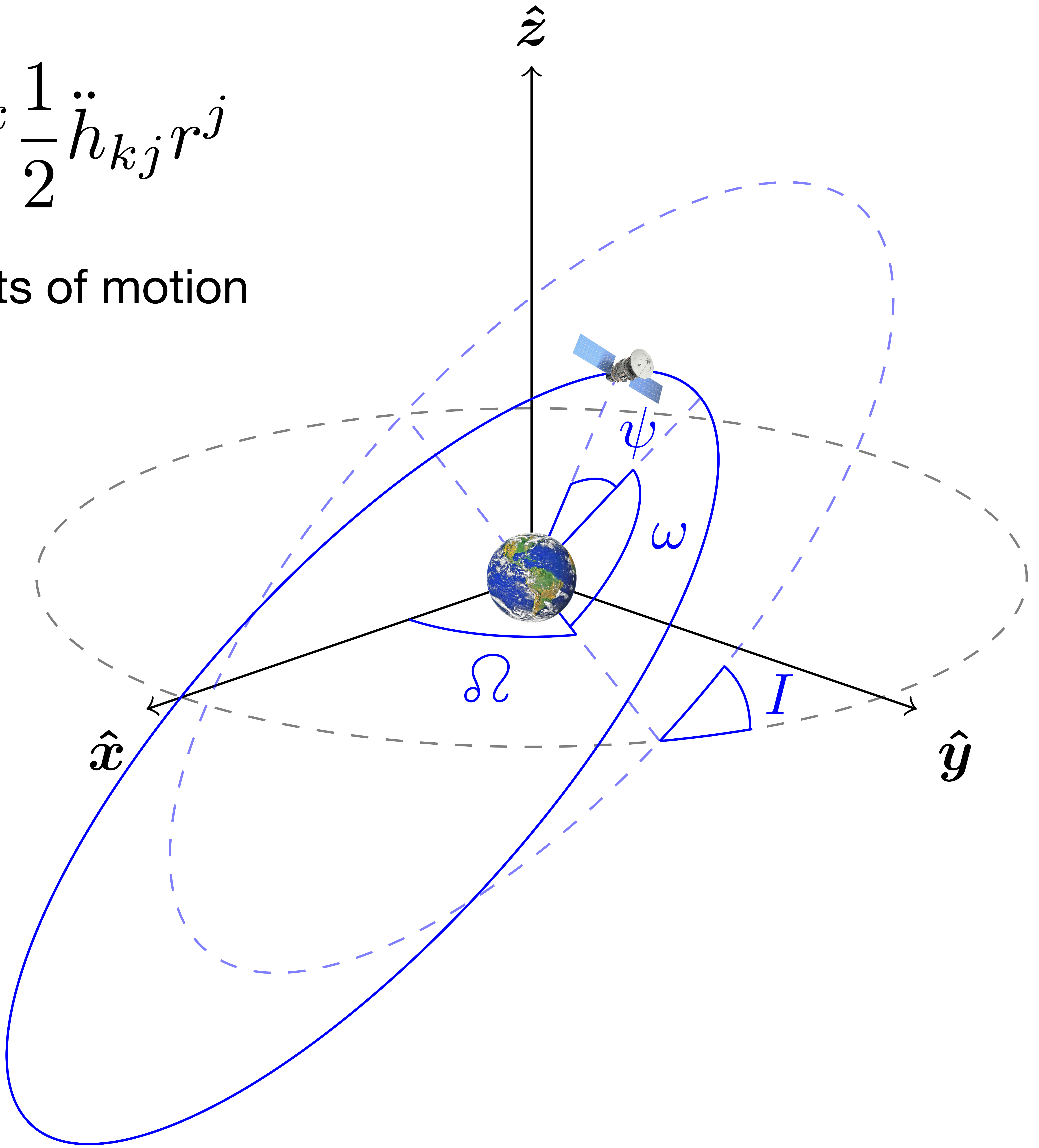


Absorption of GWs by binaries

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

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:

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

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

$$\dot{e} = \frac{\dot{P}\gamma^2}{3Pe} - \frac{P\gamma^5\mathcal{F}_\theta}{2\pi e(1+e\cos\psi)^2},$$

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

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

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

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

Absorption of GWs by binaries

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

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

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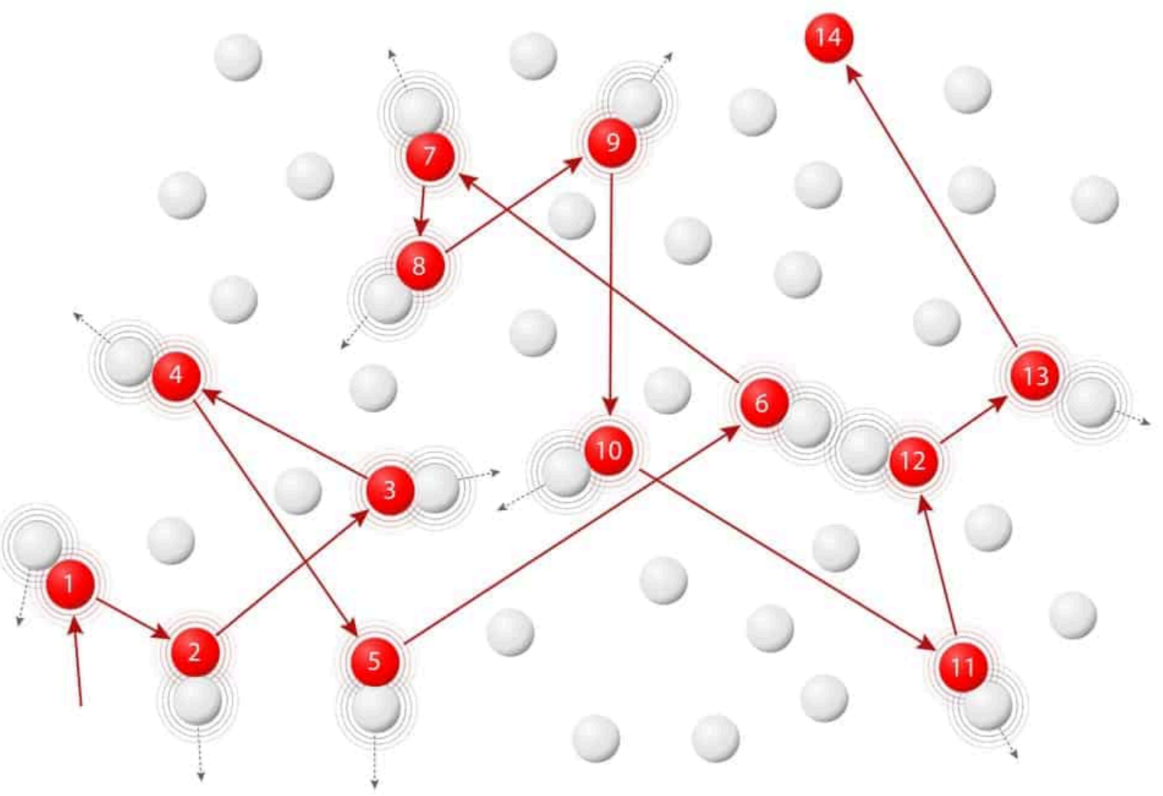
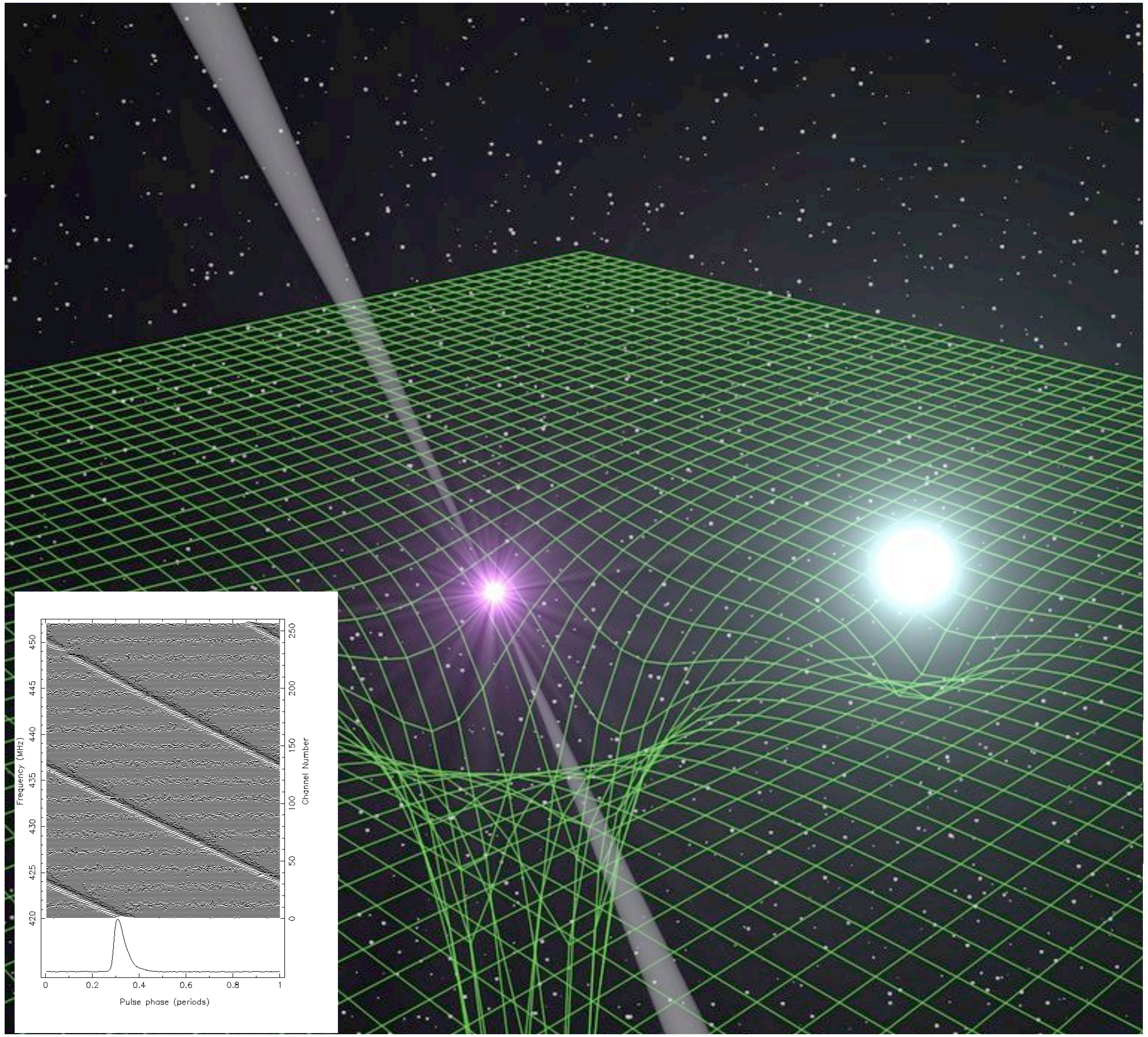
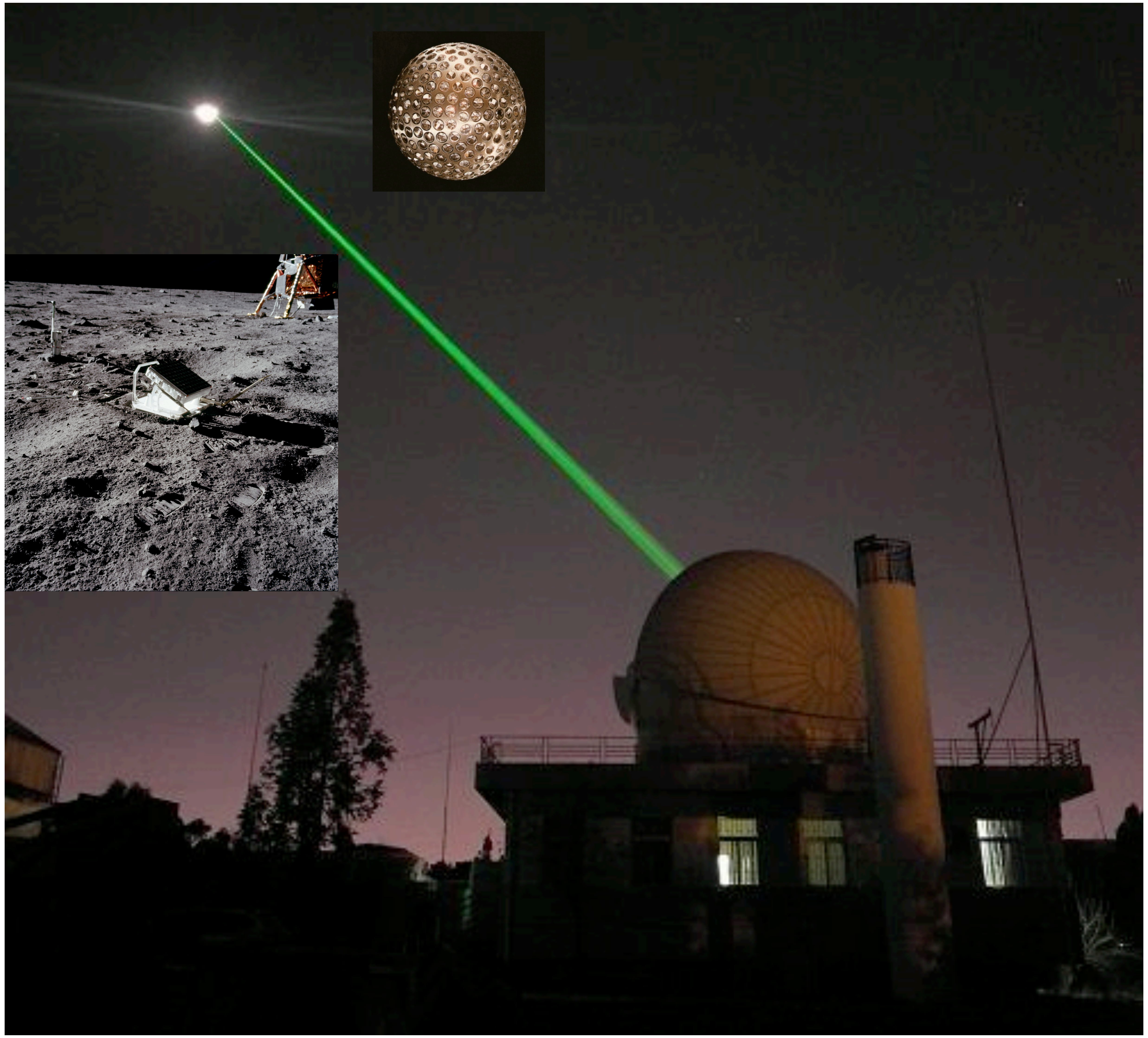


Two probes

timing of binary pulsars

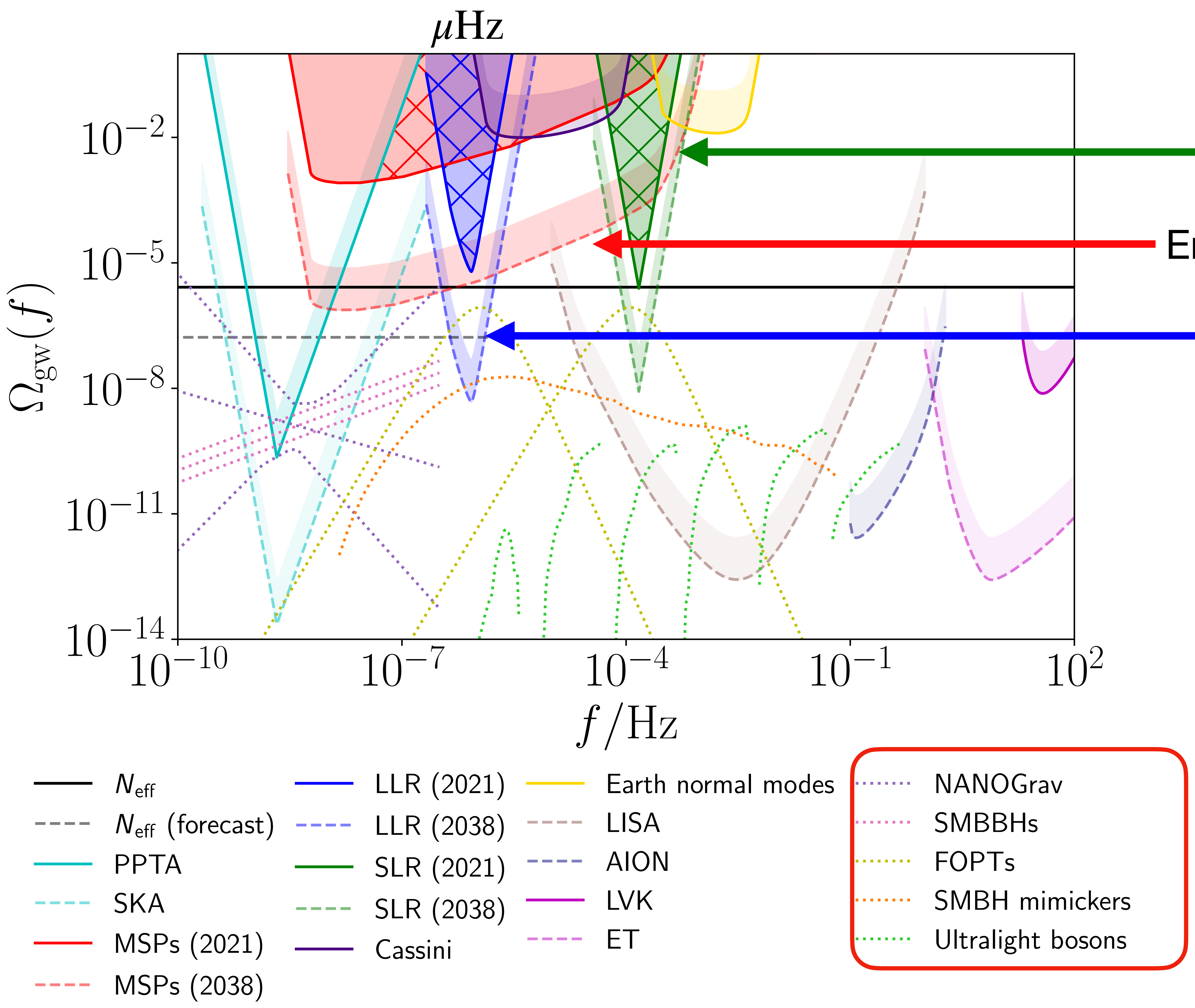


lunar and satellite laser ranging



Our estimates (solid: today; dashed 2038)

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



Satellites (P~hours)

(better ranging?)

Envelope of pulsars (P~hours - 100 days)

Lunar laser ranging (P~month)

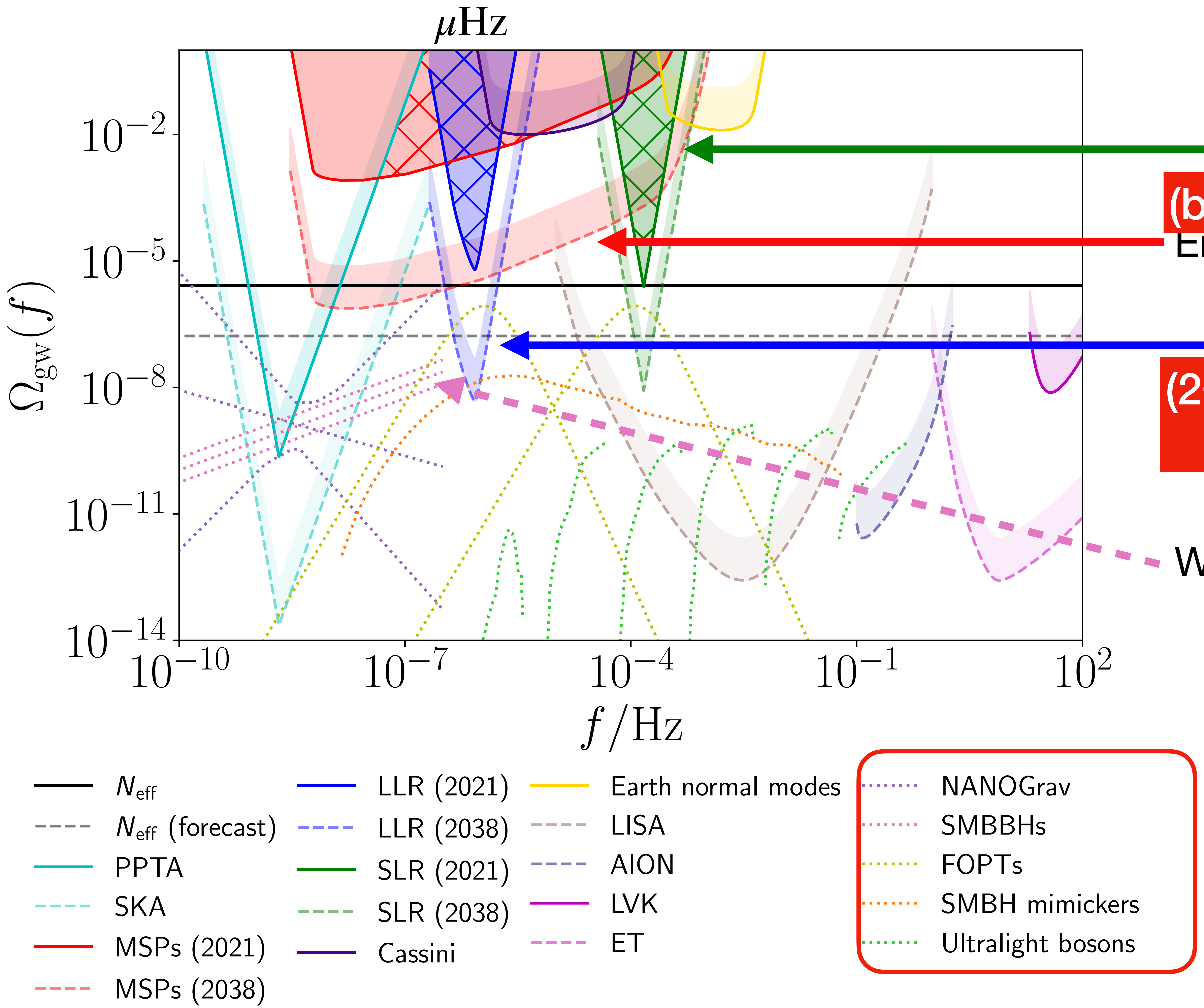
(2038 line requires replacing the mirrors …may/will happen before 2030!)

Murphy 1309.6294

Possible backgrounds

Our estimates (solid: today; dashed 2038)

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



Satellites (*P*~hours)

(better ranging? new satellites?)

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

Lunar laser ranging (*P*~month)

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

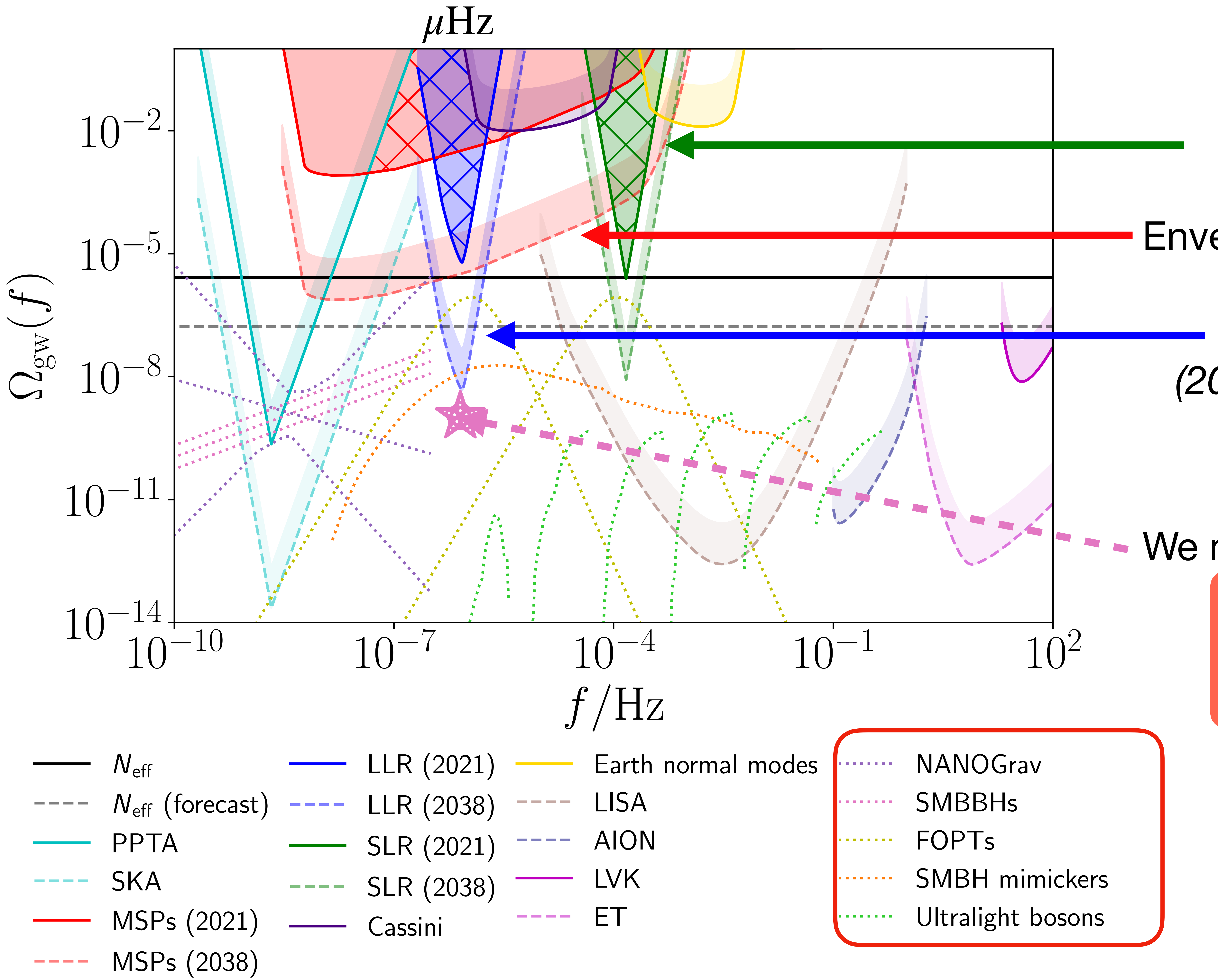
Murphy 1309.6294

We may see the signal of PTAs!!!

Possible backgrounds

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!)

Murphy 1309.6294

We may see the signal of PTAs!!!

in 2050

$$\Omega \lesssim 3\times 10^{-9} \quad \text{at} \quad f\sim \mu\text{Hz}$$

Possible backgrounds

μHz GWs

- 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)

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

- **Future plans:** new mirror in the Moon? New optimised satellites?