Detecting gravitational waves with resonant effects in bound astrophysical systems

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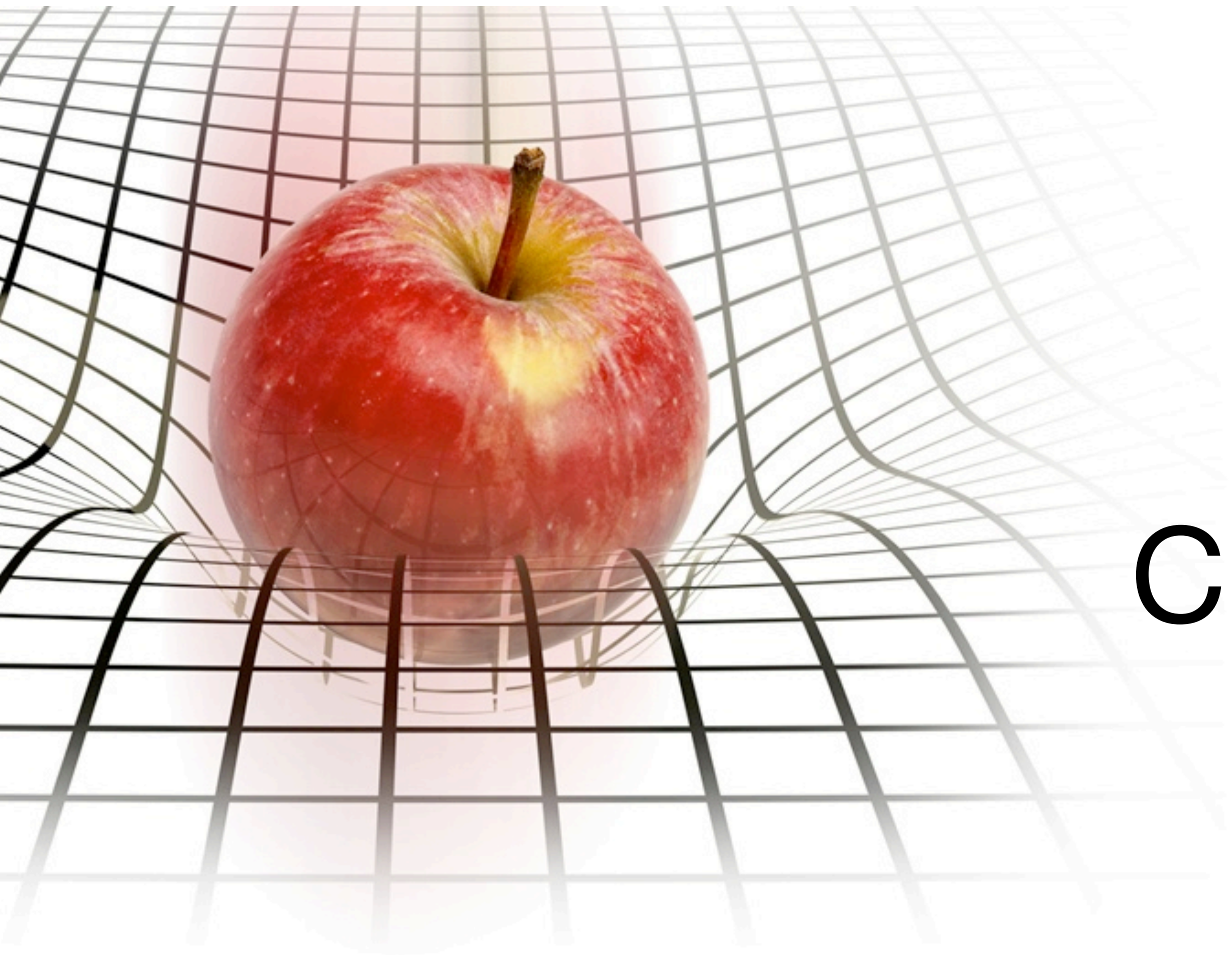
Fundación BBVA

GWs (essentials)



Perturbations of space-time

travelling as waves of frequency f

Characterised by 2 polarizations $h_{+,\times}$ (dimensionless)

$$h_{+,\times} \overset{c=1}{\approx} h_0 \cos\left(2\pi f (t-z) + \phi\right)$$

GWs carry energy. They have **energy density**

$$\rho_{\rm gw} = \frac{1}{16\pi G}\left\langle \dot{h}_+^2 + \dot{h}_\times^2 \right\rangle$$

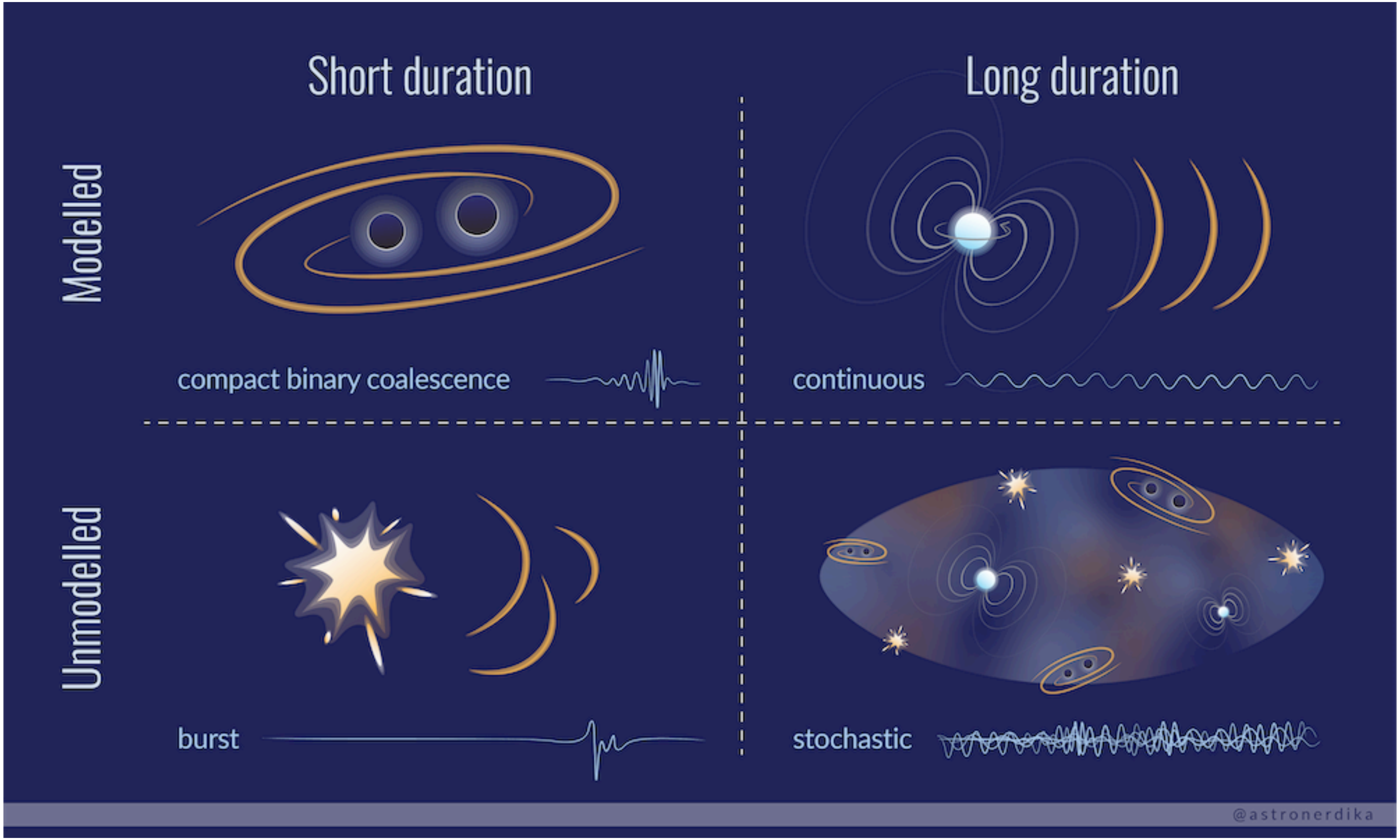
↓

$$\Omega_{\rm gw}(f) \equiv \frac{1}{\rho_c}\frac{{\rm d}\rho_{\rm gw}}{{\rm d}(\ln f)}$$

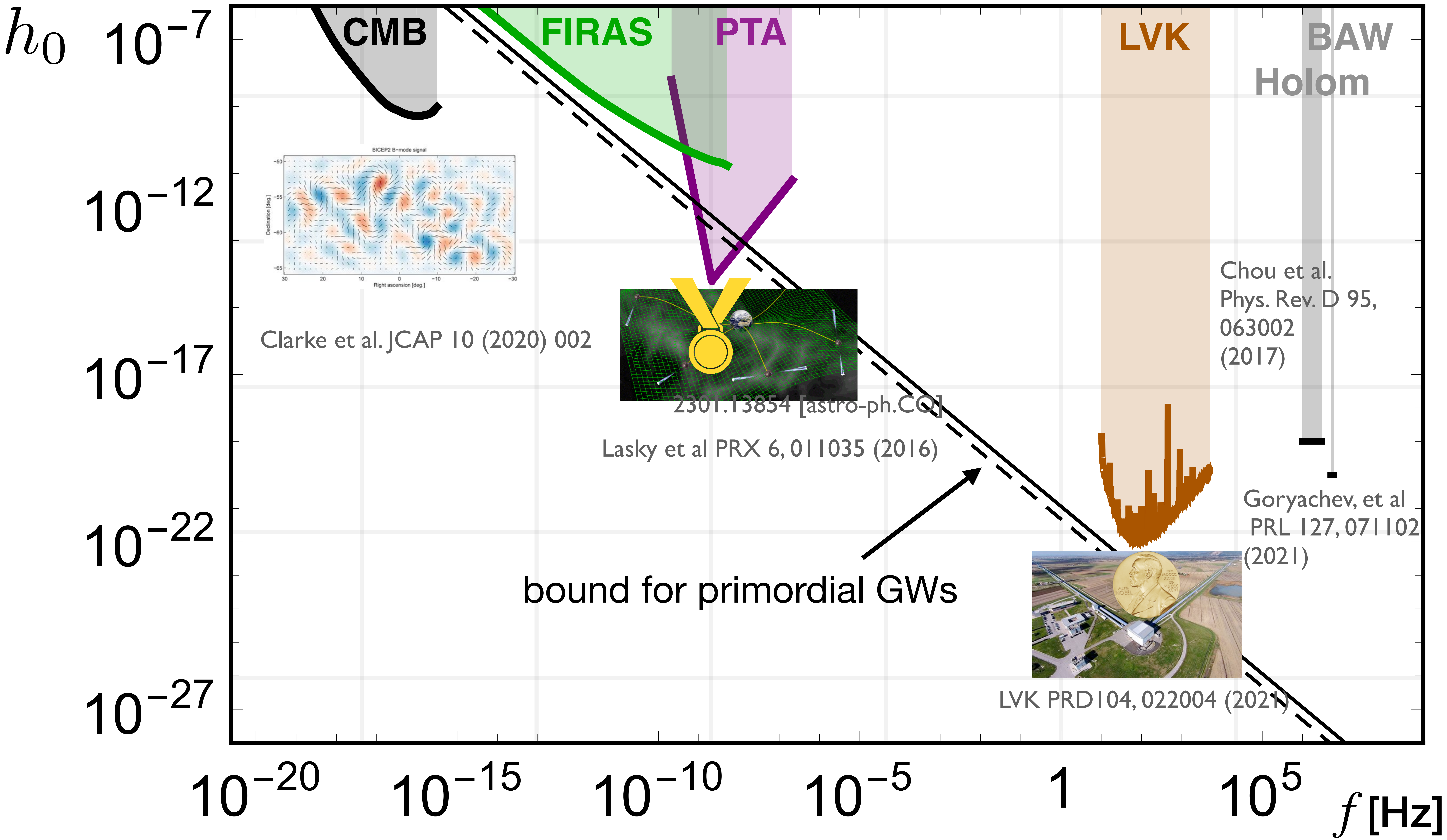
$h^2\Omega_{\rm gw}(f)$ $\quad h \approx 0.67$

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

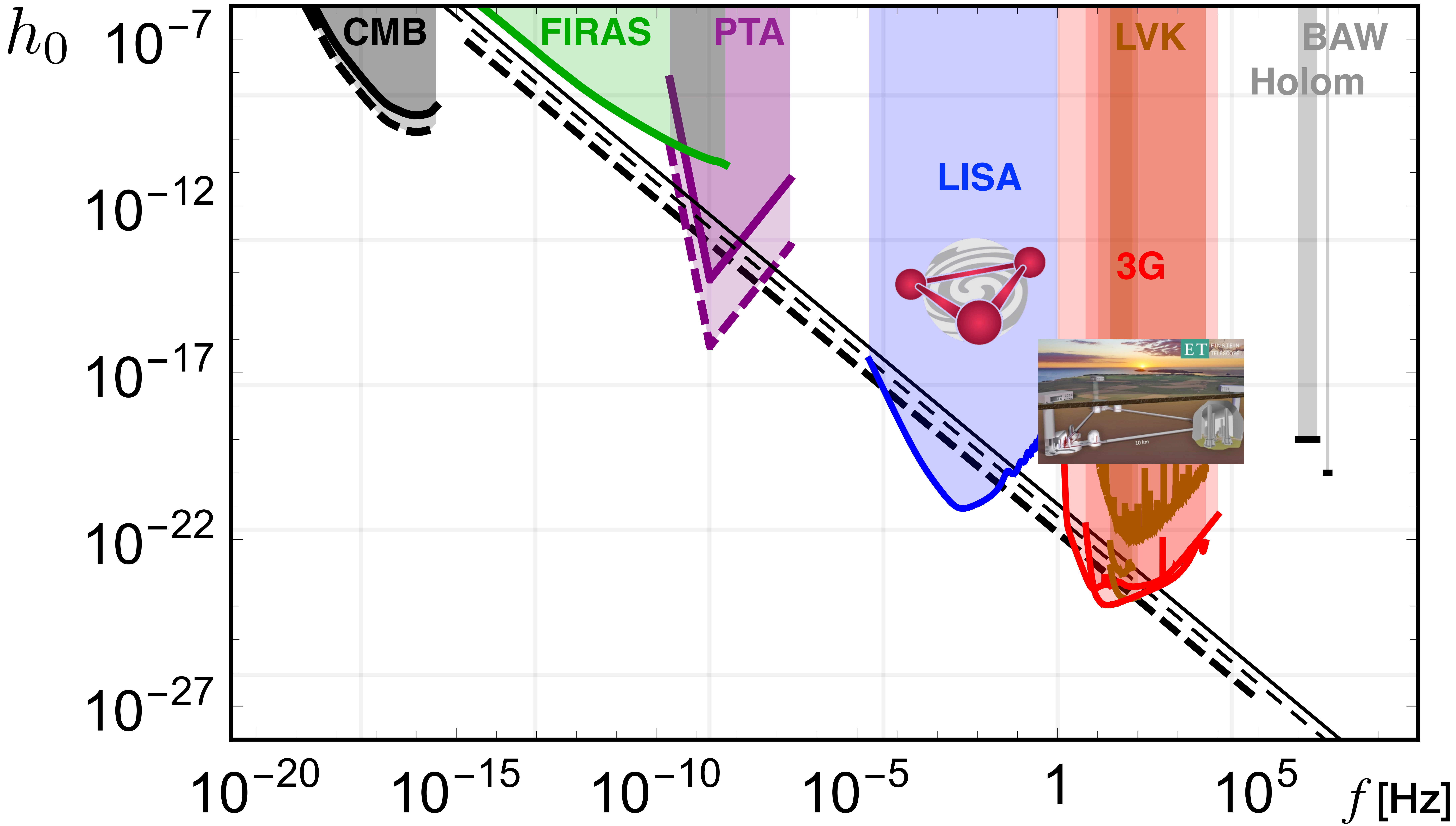
GWs (typologies)



GWs soundscape today



GWs searches ca. 2036



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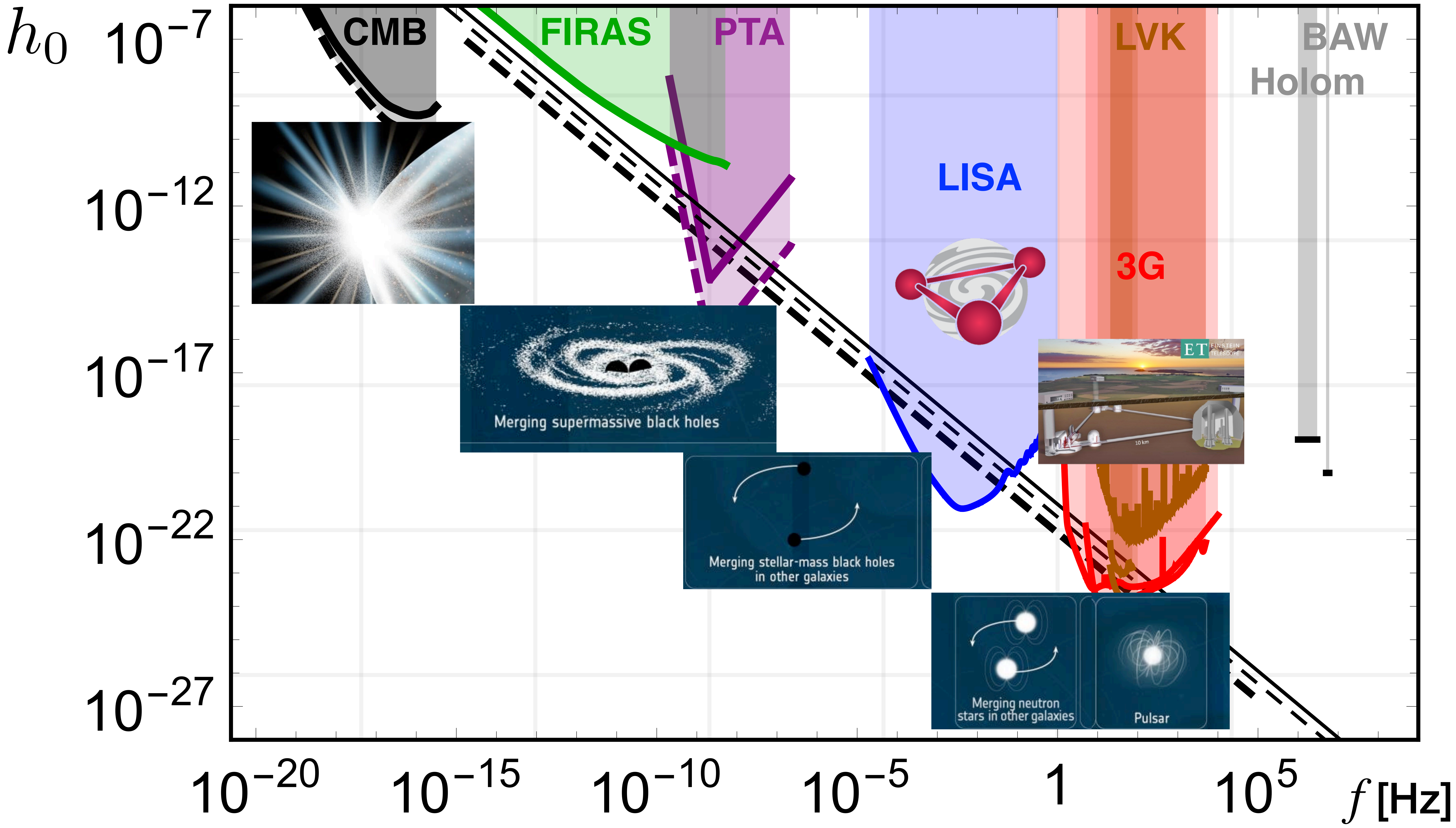
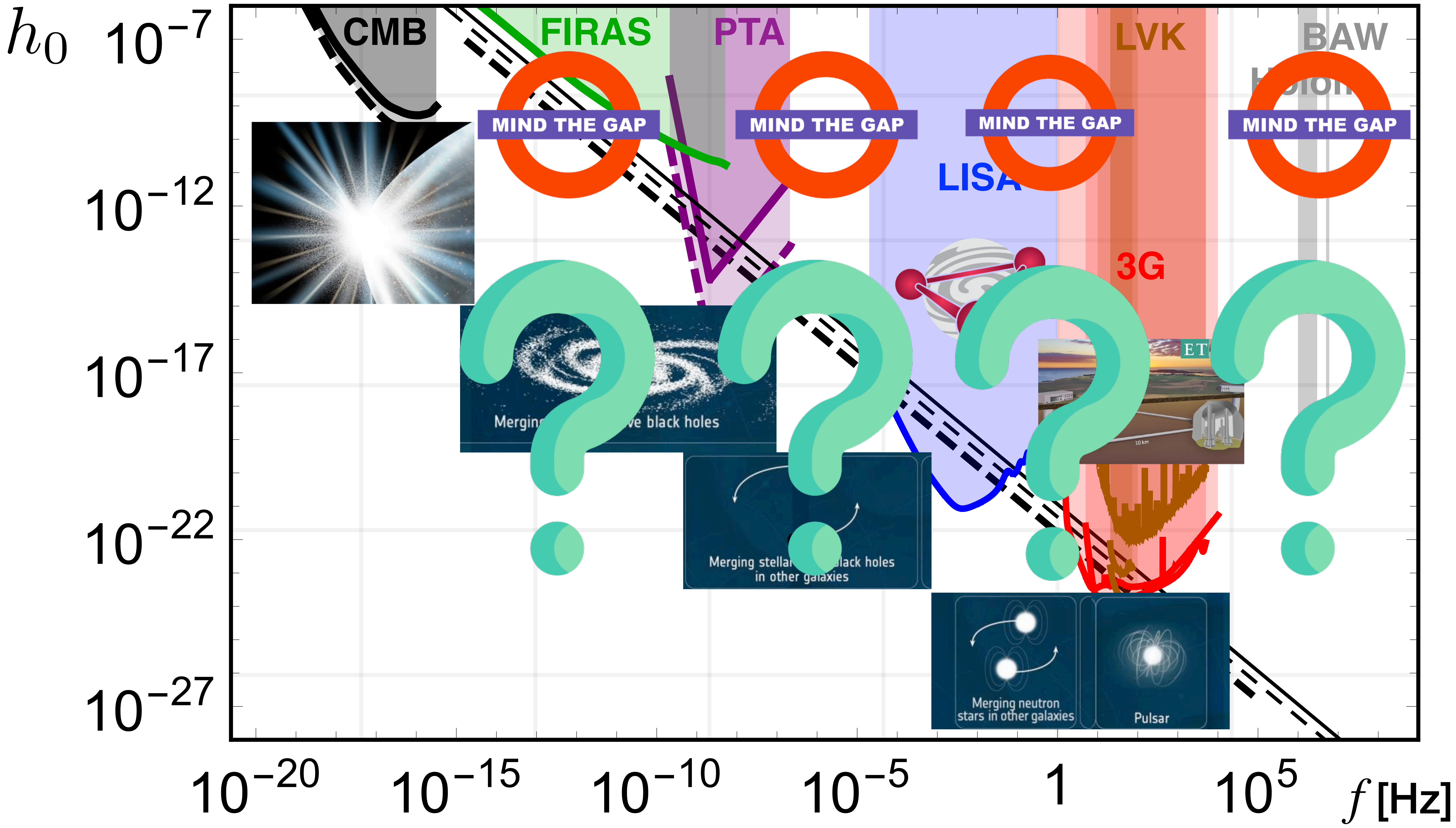


GWs searches ca. 2036: gaps



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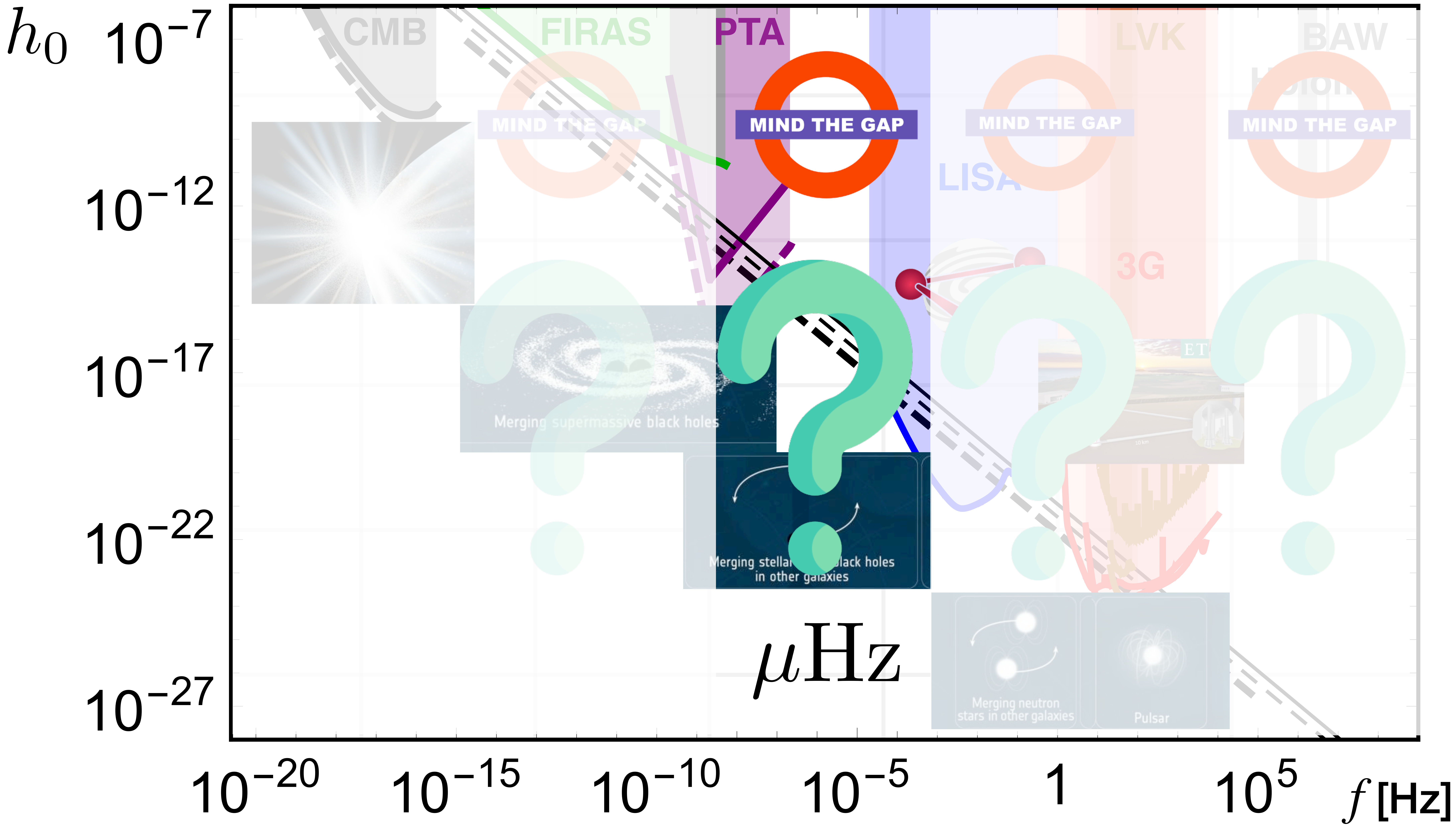
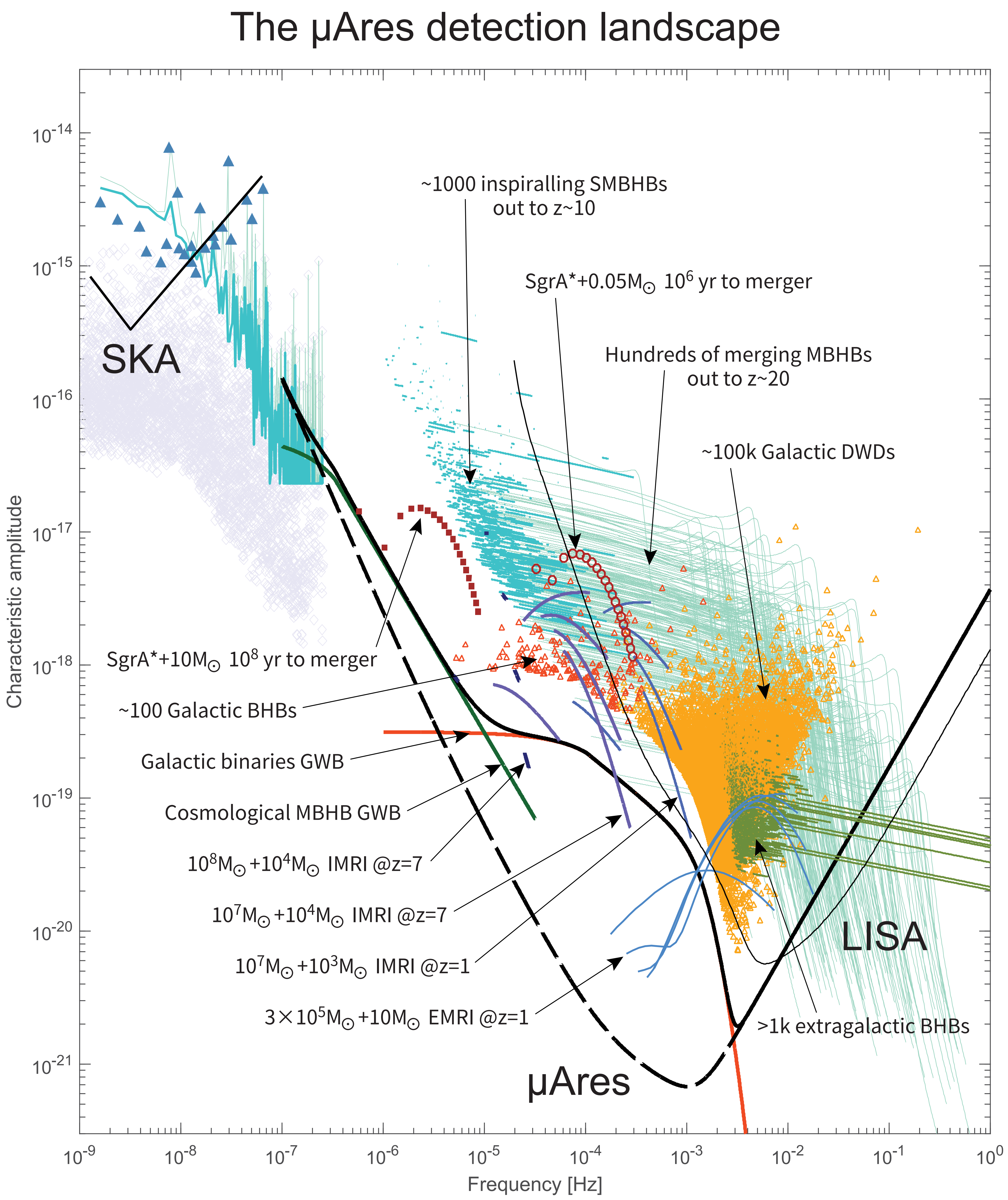


Astrophysical backgrounds

1908.11391 [astro-ph.IM]
Sesana et al.

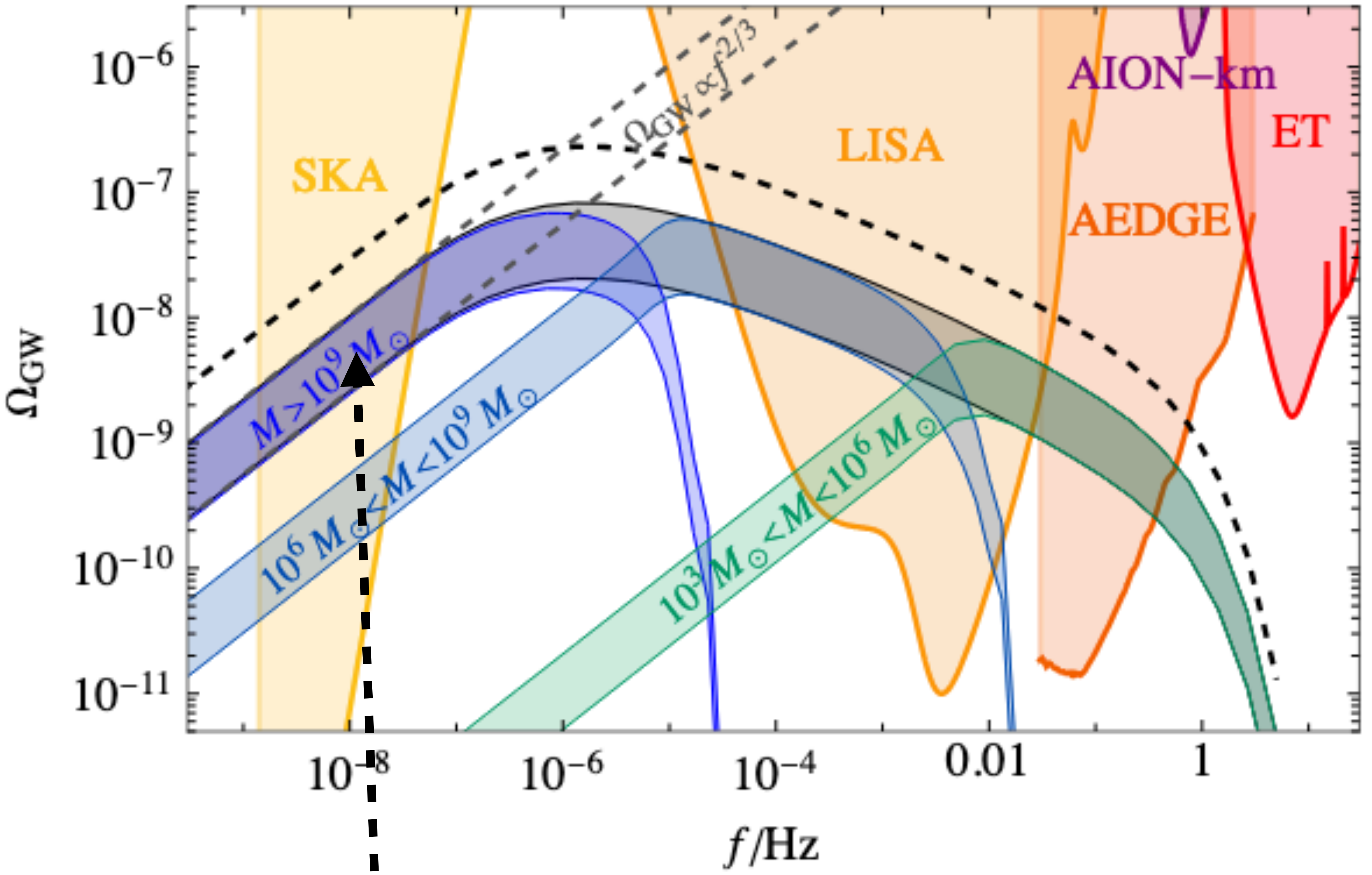
2301.13854 [astro-ph.CO]
Ellis et al

h



$$\rho_{\mathrm{gw}} = \frac{1}{16\pi G}\left\langle \dot{h}_+^2 + \dot{h}_\times^2 \right\rangle$$

$$\Omega_{\mathrm{gw}}(f) \equiv \frac{1}{\rho_c}\frac{\mathrm{d}\rho_{\mathrm{gw}}}{\mathrm{d}(\ln f)}$$

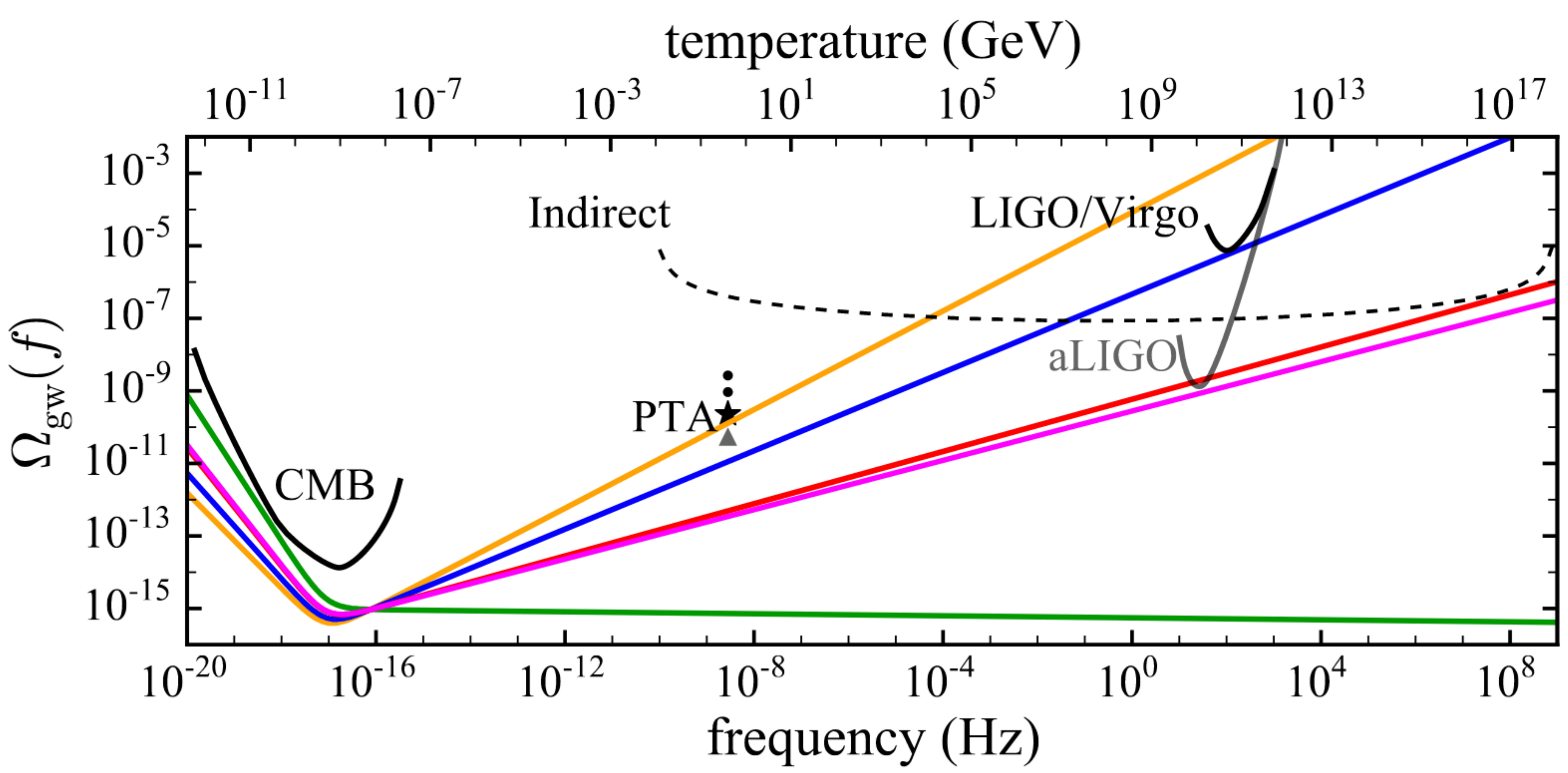


Evidence form PTA 2023

Backgrounds from fundamental physics

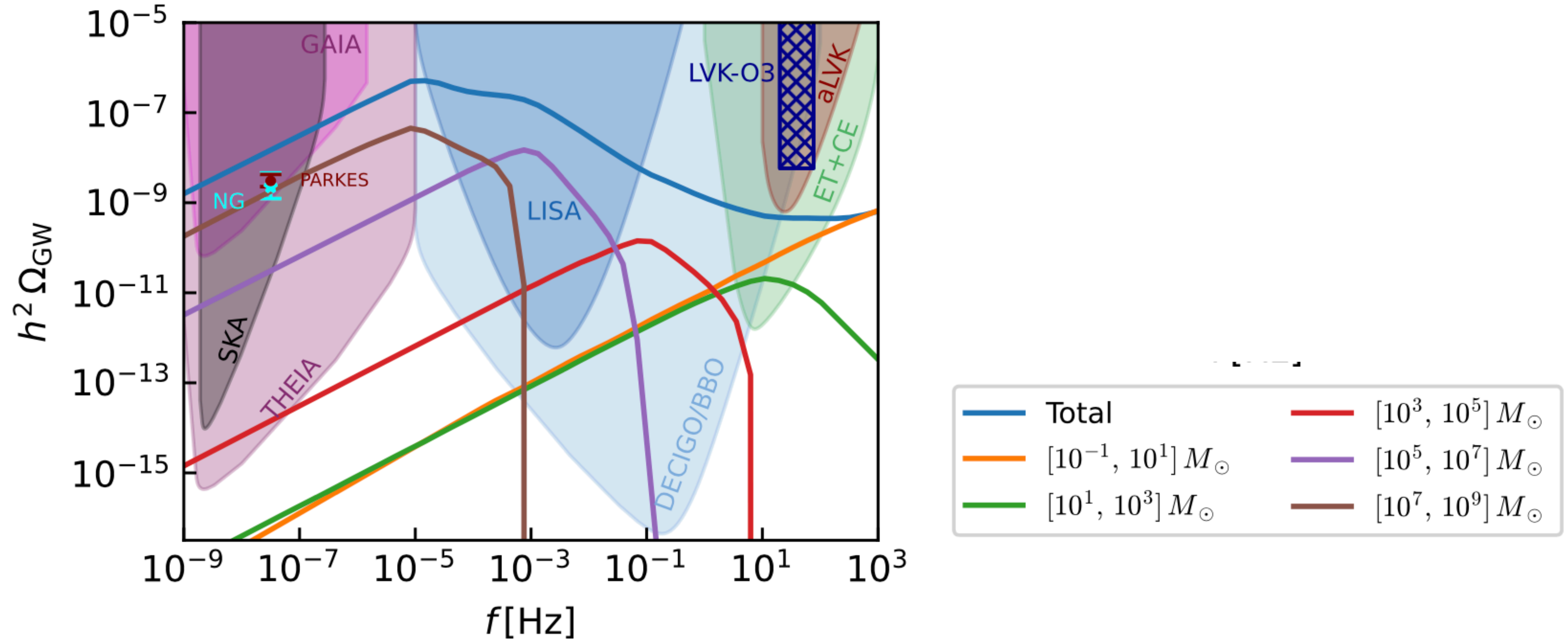
Inflation

Lasky et al PRX 6, 011035 (2016)



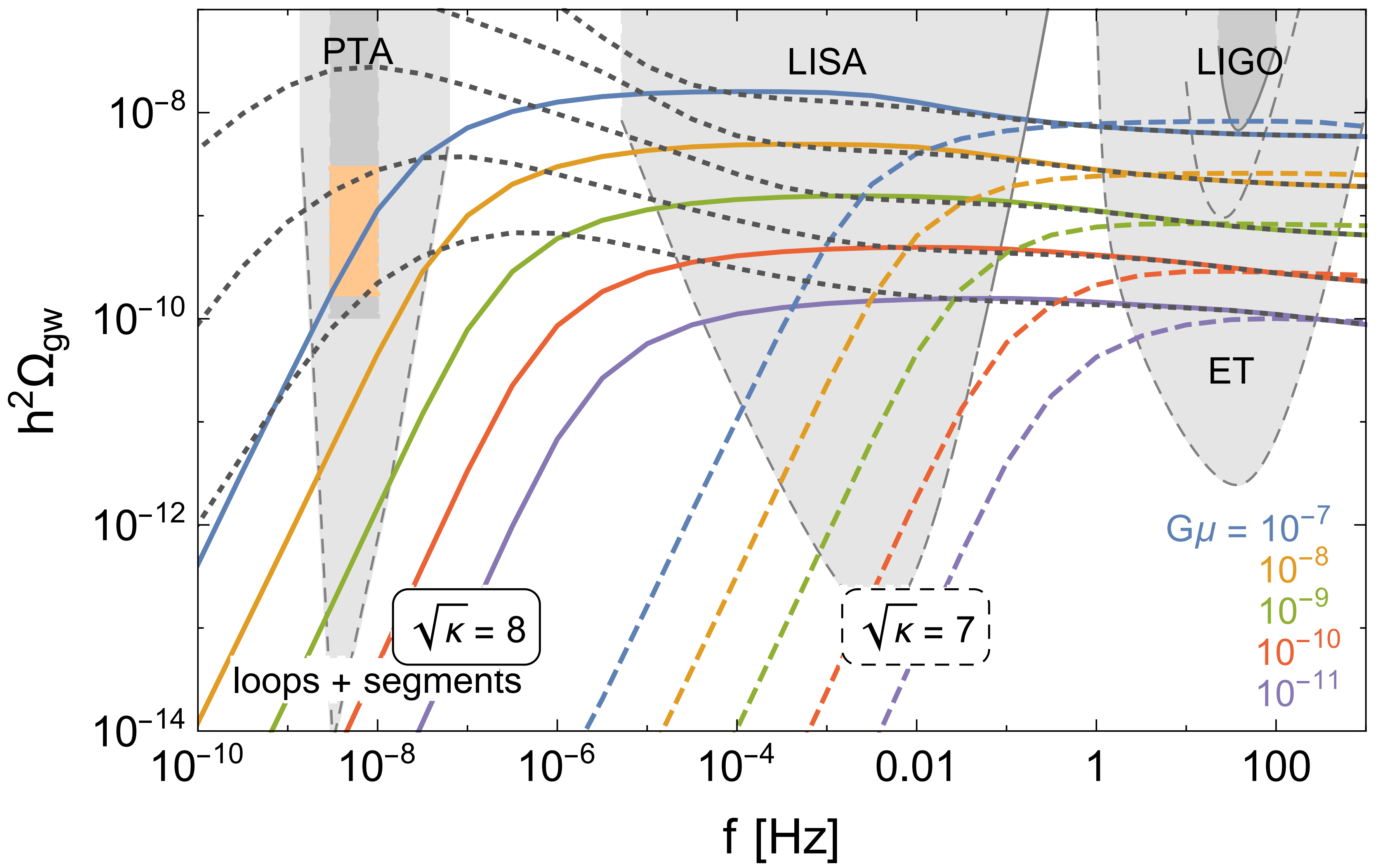
PBH

Braglia et al. JCAP 12 (2021) 12



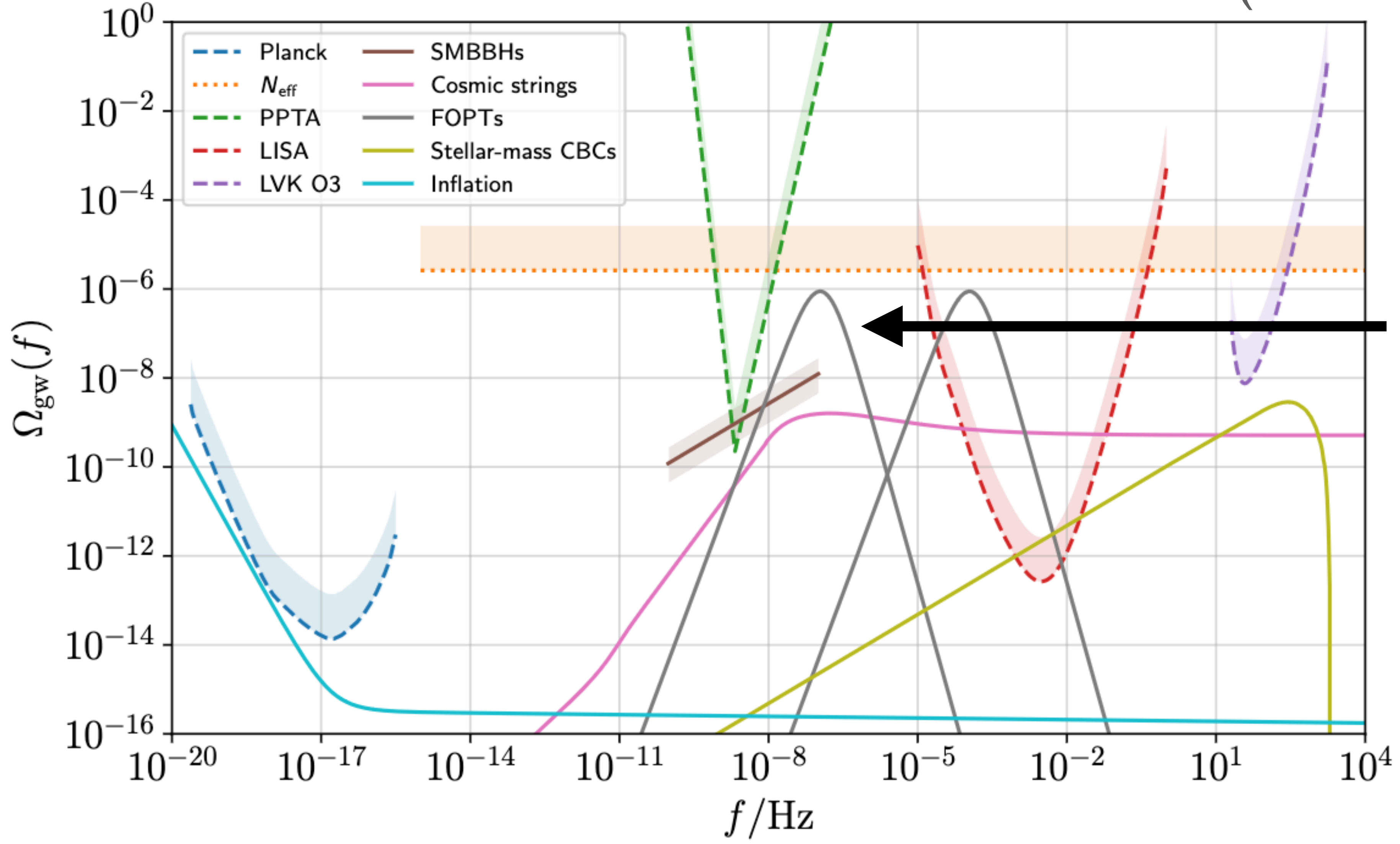
Cosmic Strings

Buchmuller et al. 2107.04578



FOPT

Renzini et al 2202.00178
(based on 1512.06239)



T~200 MeV

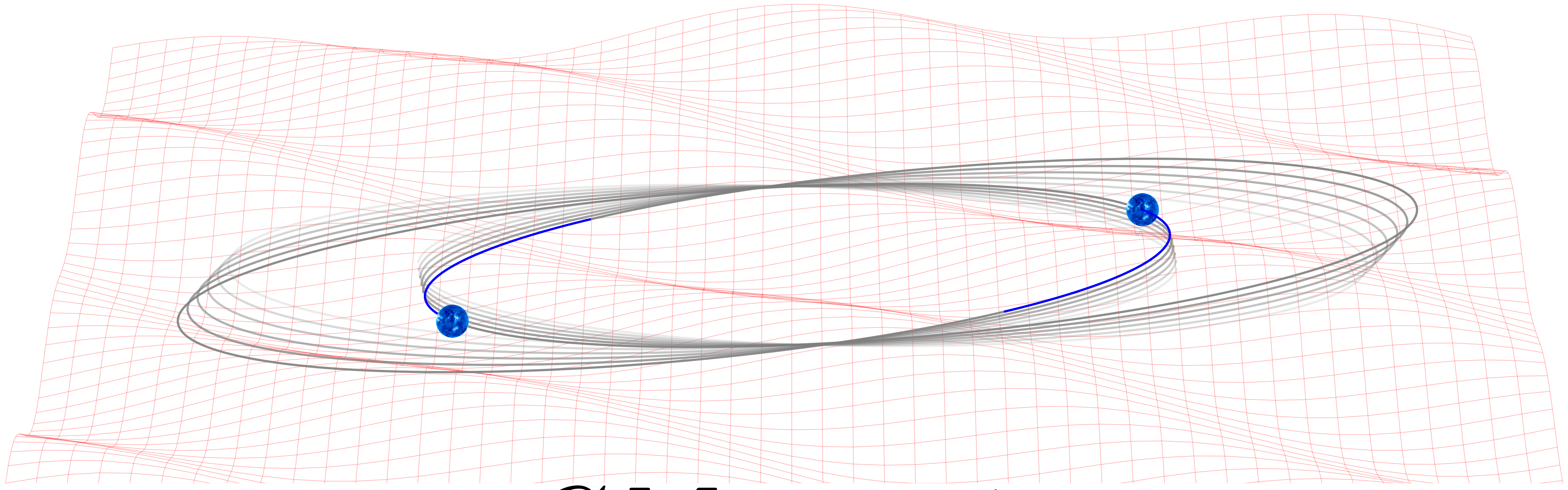
Absorption of GWs by binaries

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

few days

Intuitive idea (from '60s)

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



$$\ddot{r}_i + \frac{GM}{r^3} r_i = \frac{1}{2} h_{ij} r^j$$

Perturbing Gravitational Wave

Blas+Jenkins, 2107.04061, 2107.04063

Newtonian Potential

$h \sim \cos(2\pi f t)$
$r \sim e \cos(2\pi t / P)$
possible resonances at $f=n/P$

$\mu\mathrm{Hz}$

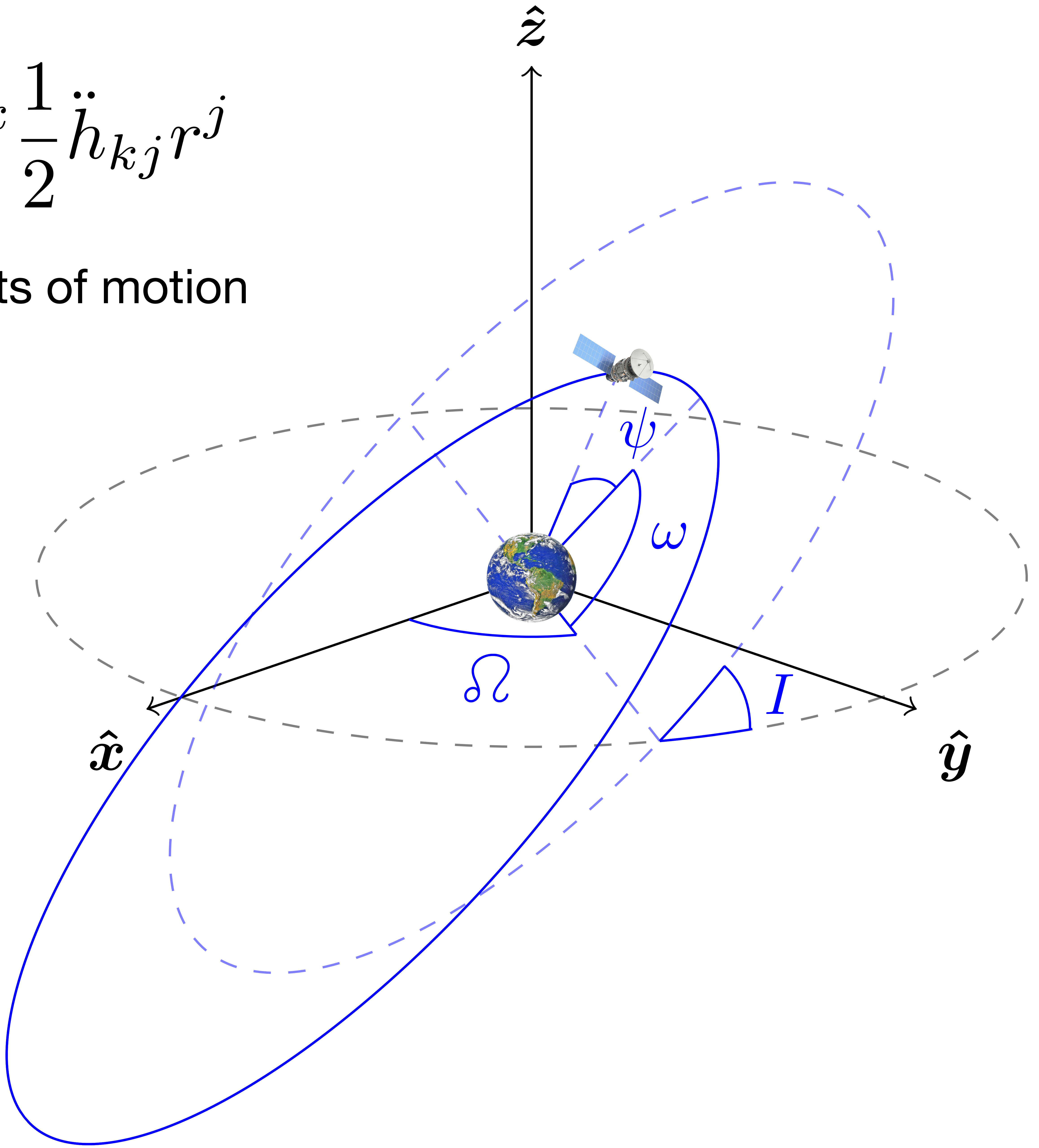
~ few days

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:

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

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

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

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

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

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

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

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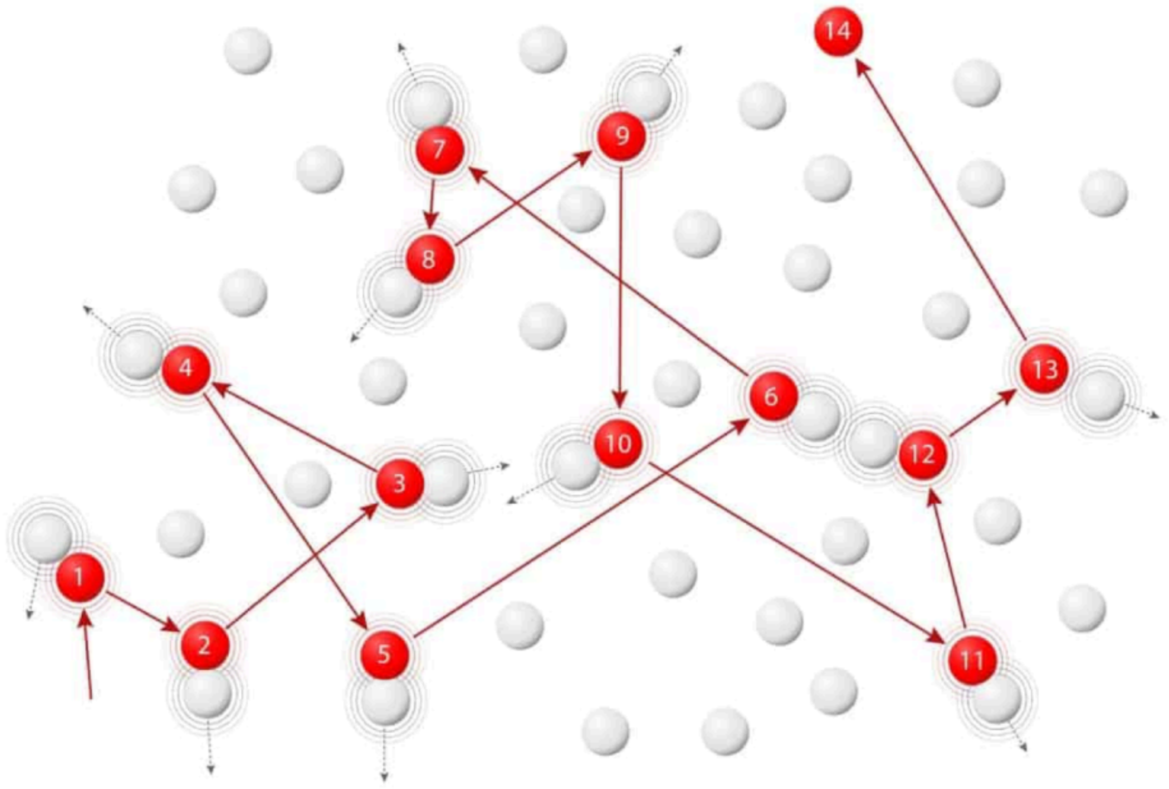


For the SGWB… Fokker-Planck approach

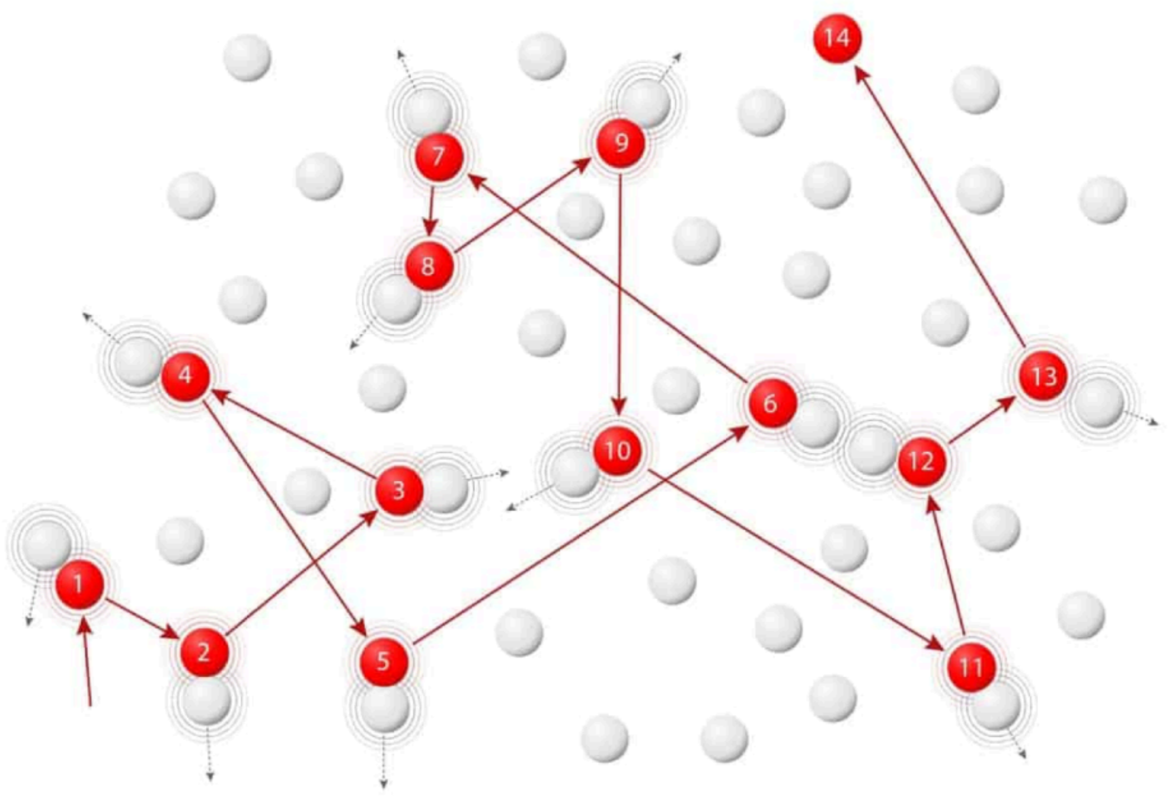
$$\ddot{r}^i + \frac{GM}{r^3} r^i = \delta^{ik} \frac{1}{2} \ddot{h}_{kj} r^j$$

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

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

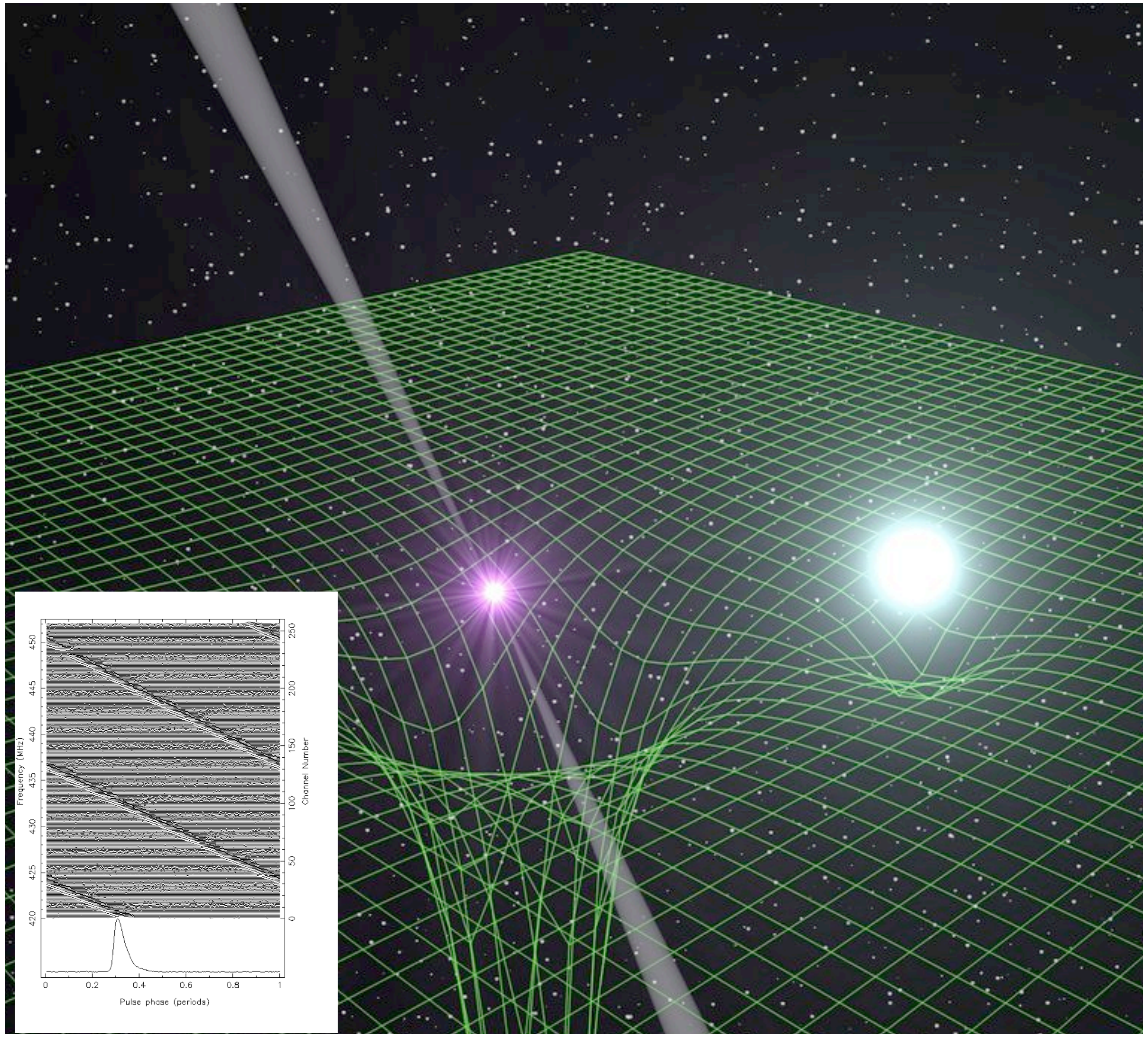
$$D_{ij}^{(2)} = \lim_{\tau \to 0} \frac{1}{2\tau} \int_t^{t+\tau} \mathrm{d}t' \int_t^{t+\tau} \mathrm{d}t'' \left\langle \Gamma_i \left(\boldsymbol{x}, t' \right) \Gamma_j \left(\boldsymbol{x}, t'' \right) \right\rangle .$$

Two probes

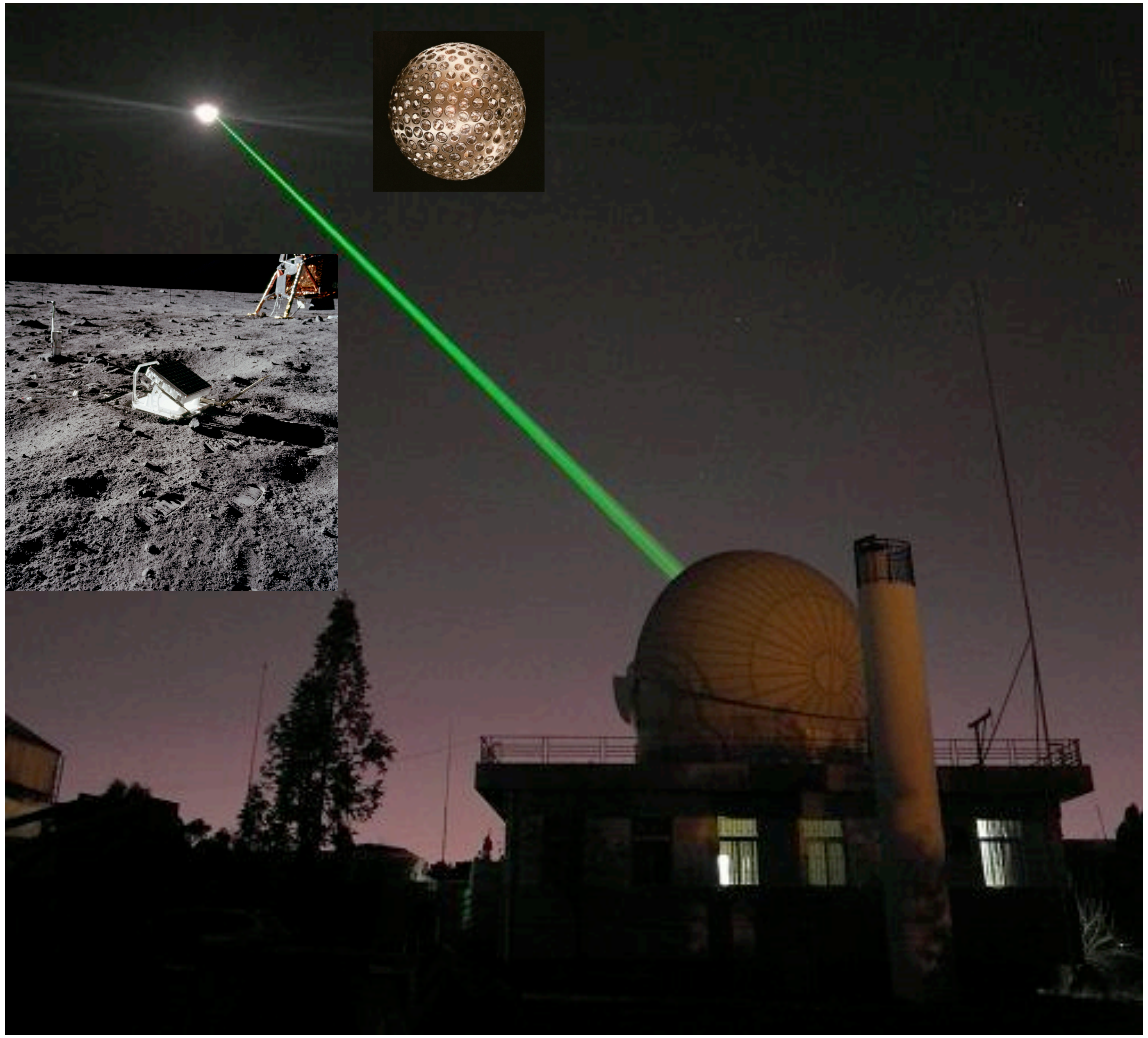
$f \sim \mu\text{Hz}$

few days

timing of binary pulsars

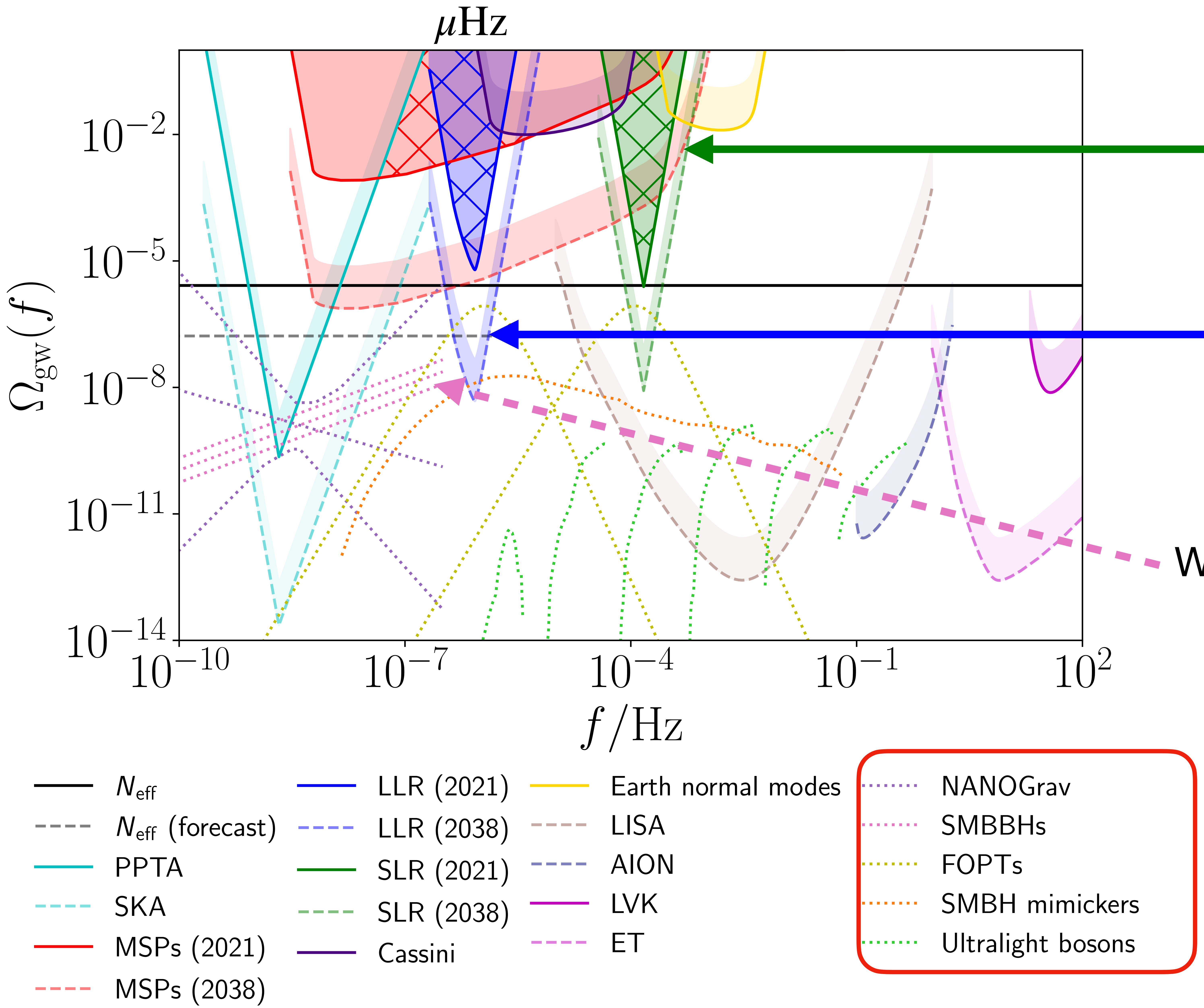


lunar and satellite laser ranging



Our estimates from 2021 for 2038

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



Satellites Earth based (*P*~hours)

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

There’s more information in the data

(work in progress: **Foster,** Blas, Bourguin, Foster, Hees, Herrero, Jenkins)

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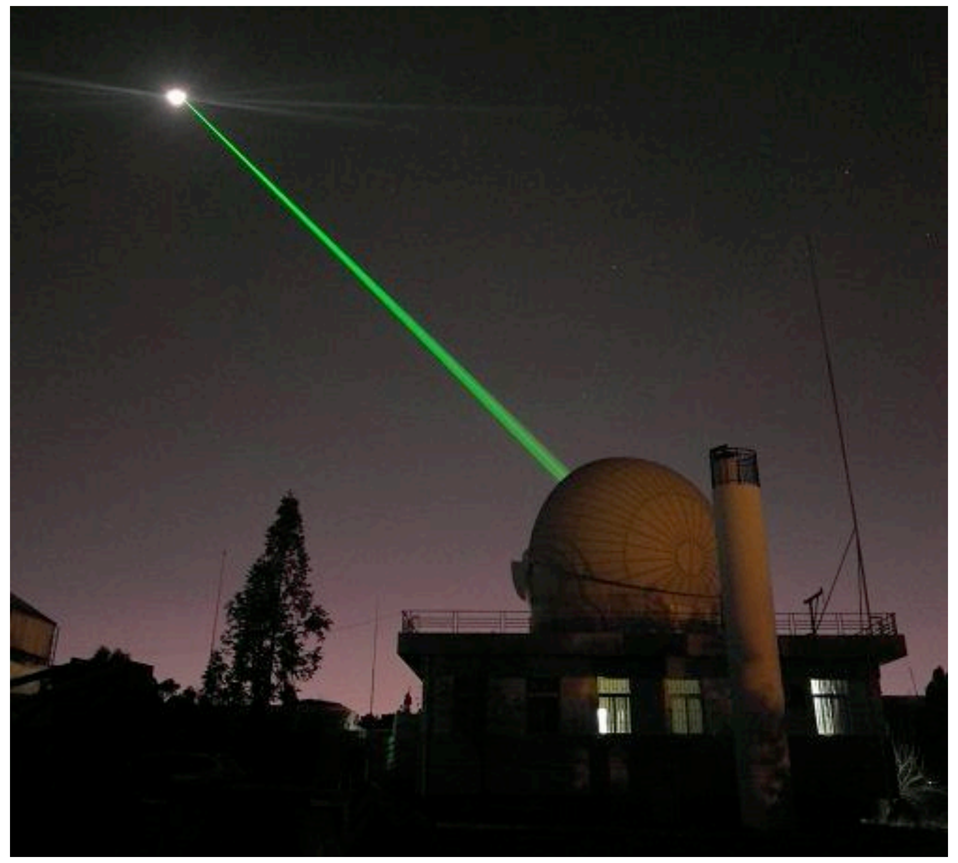
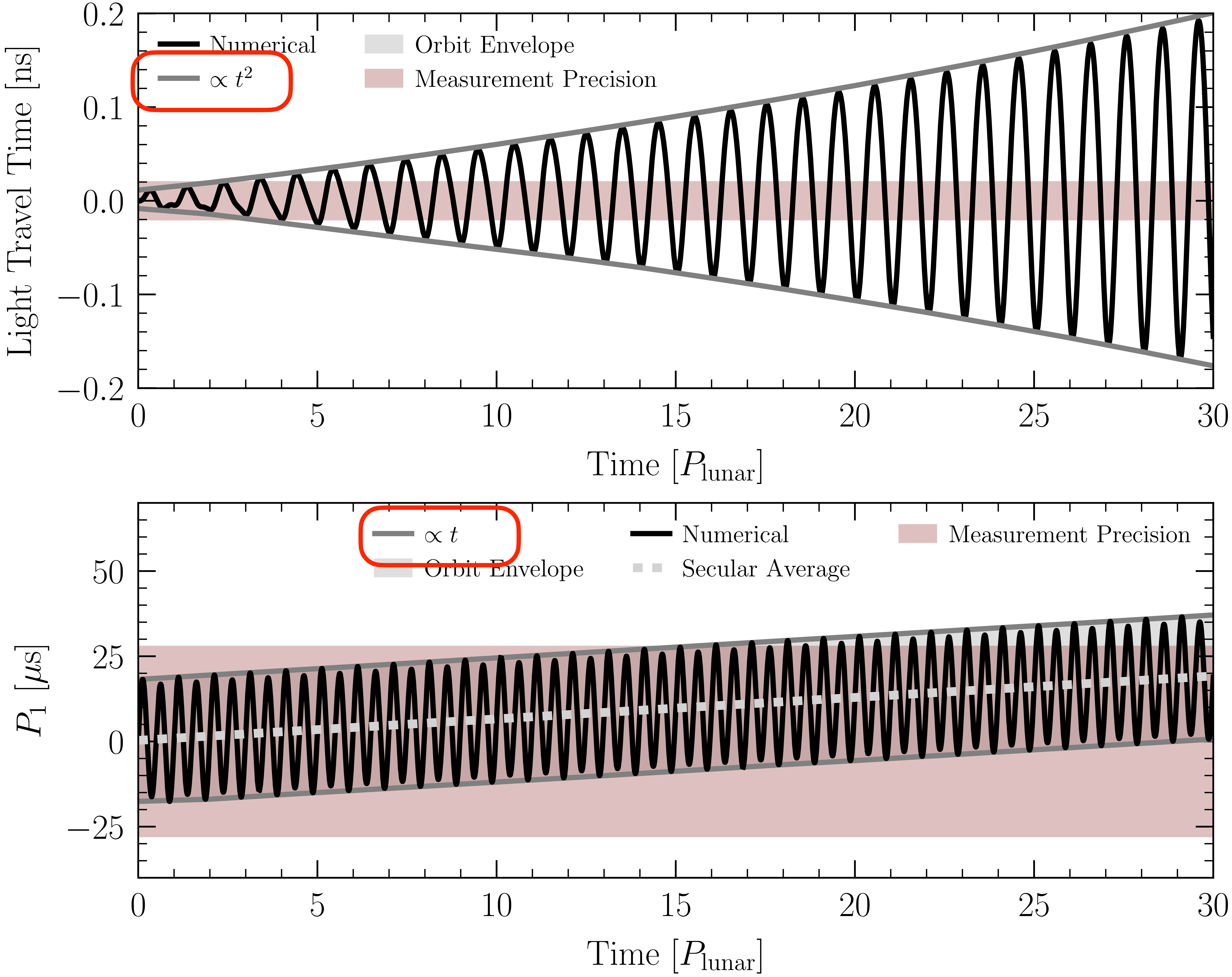
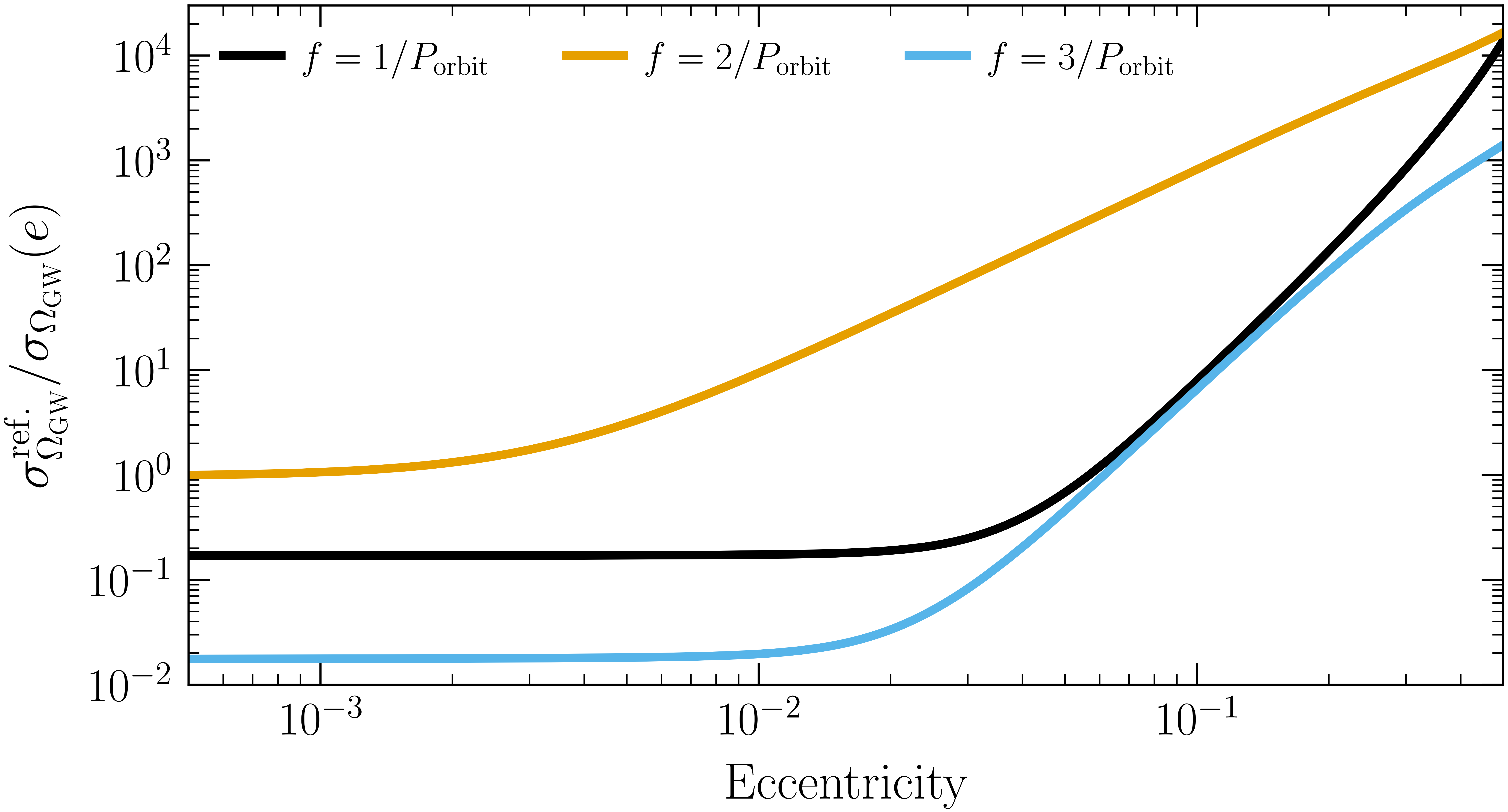




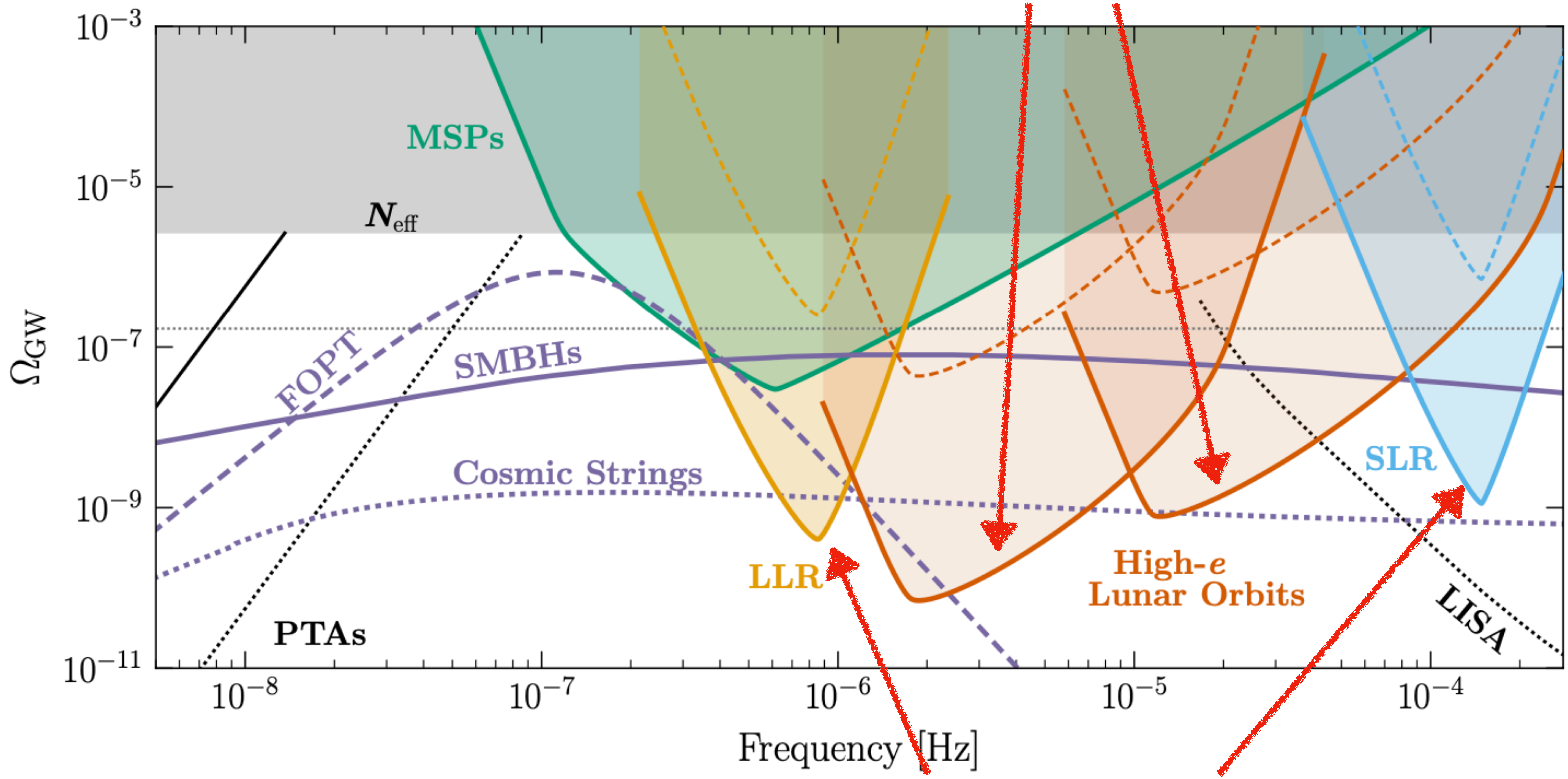
Sensitivity By ECCENtrICITY

(work in progress: **Foster,** Blas, Bourguin, Foster, Hees, Herrero, Jenkins)



We were too pessimistic!

New ideas for the Moon

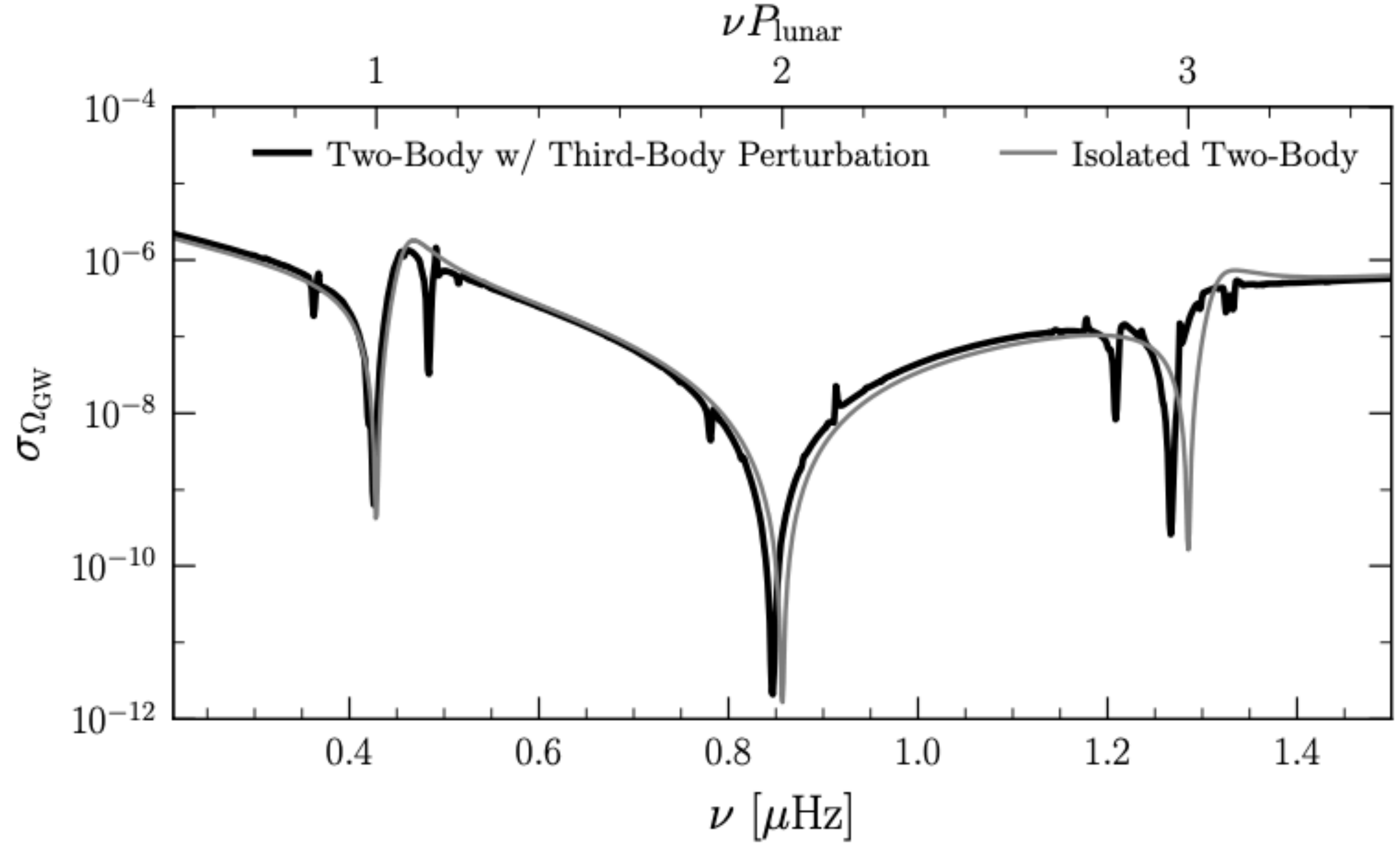


Current data, no degeneracies

- the orbital models are complex: degeneracies!

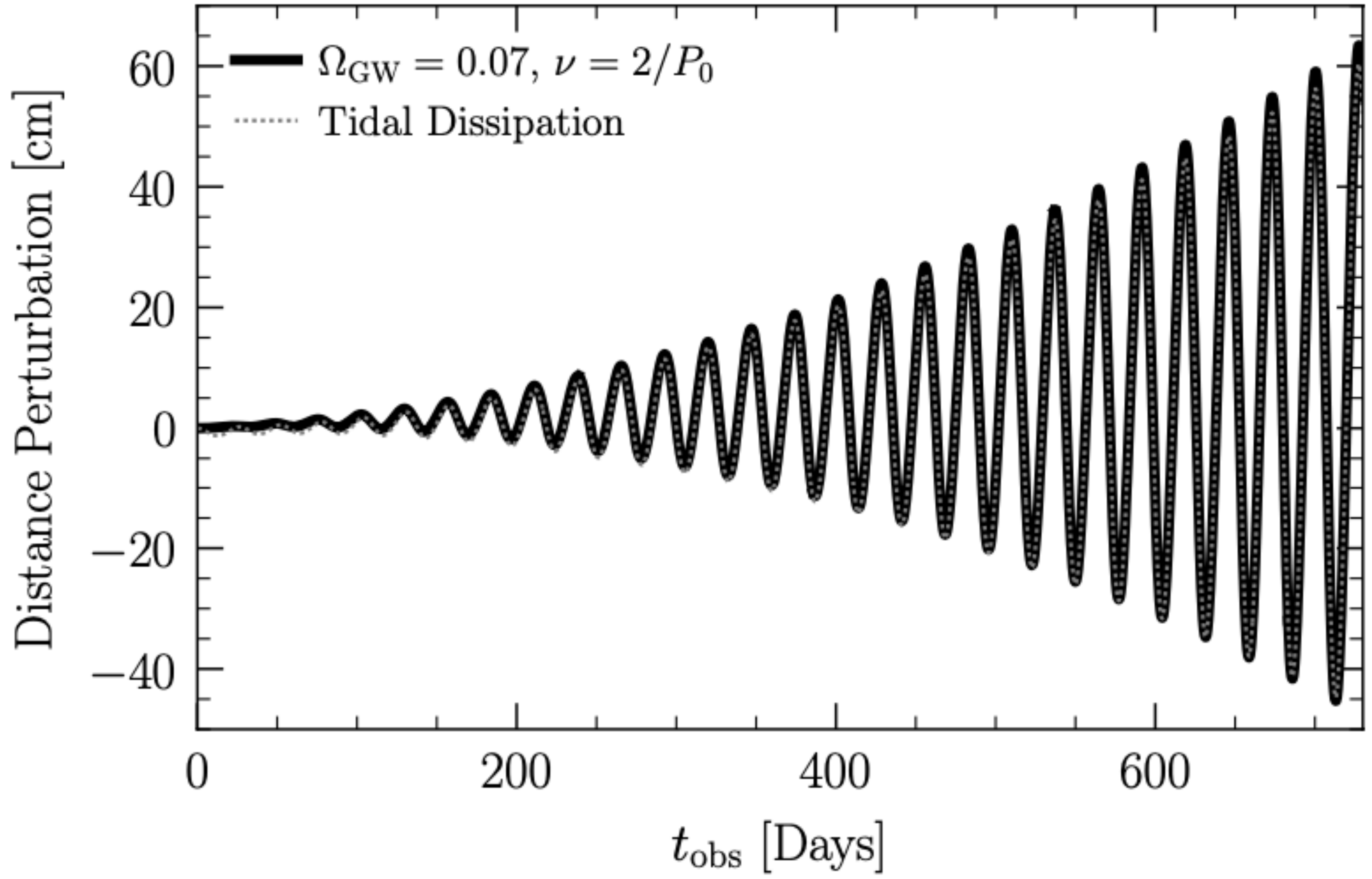
Caveats

Third body: OK, shifts the frequencies



✔

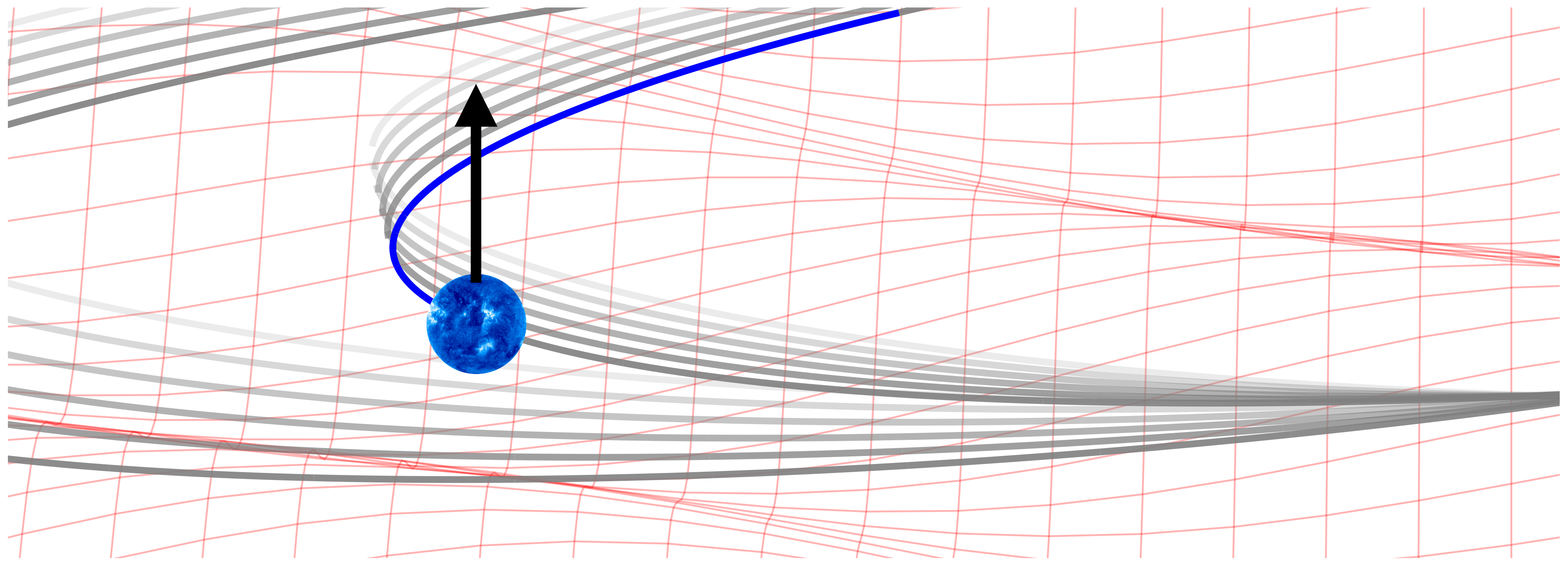
Other resonant effects (tidal dissipation)

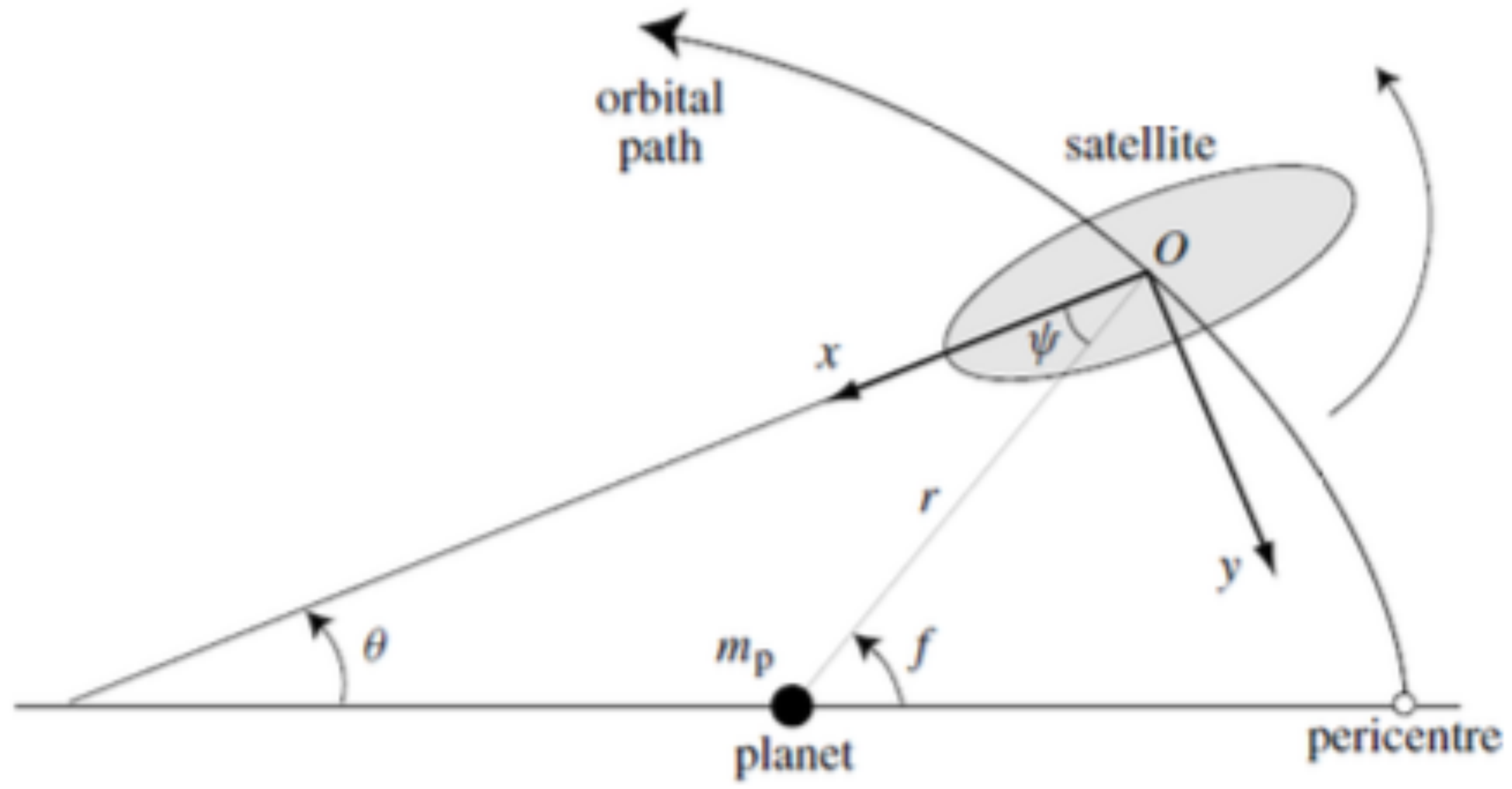


cherry picking the GW: full degeneracy

☠?

Libration





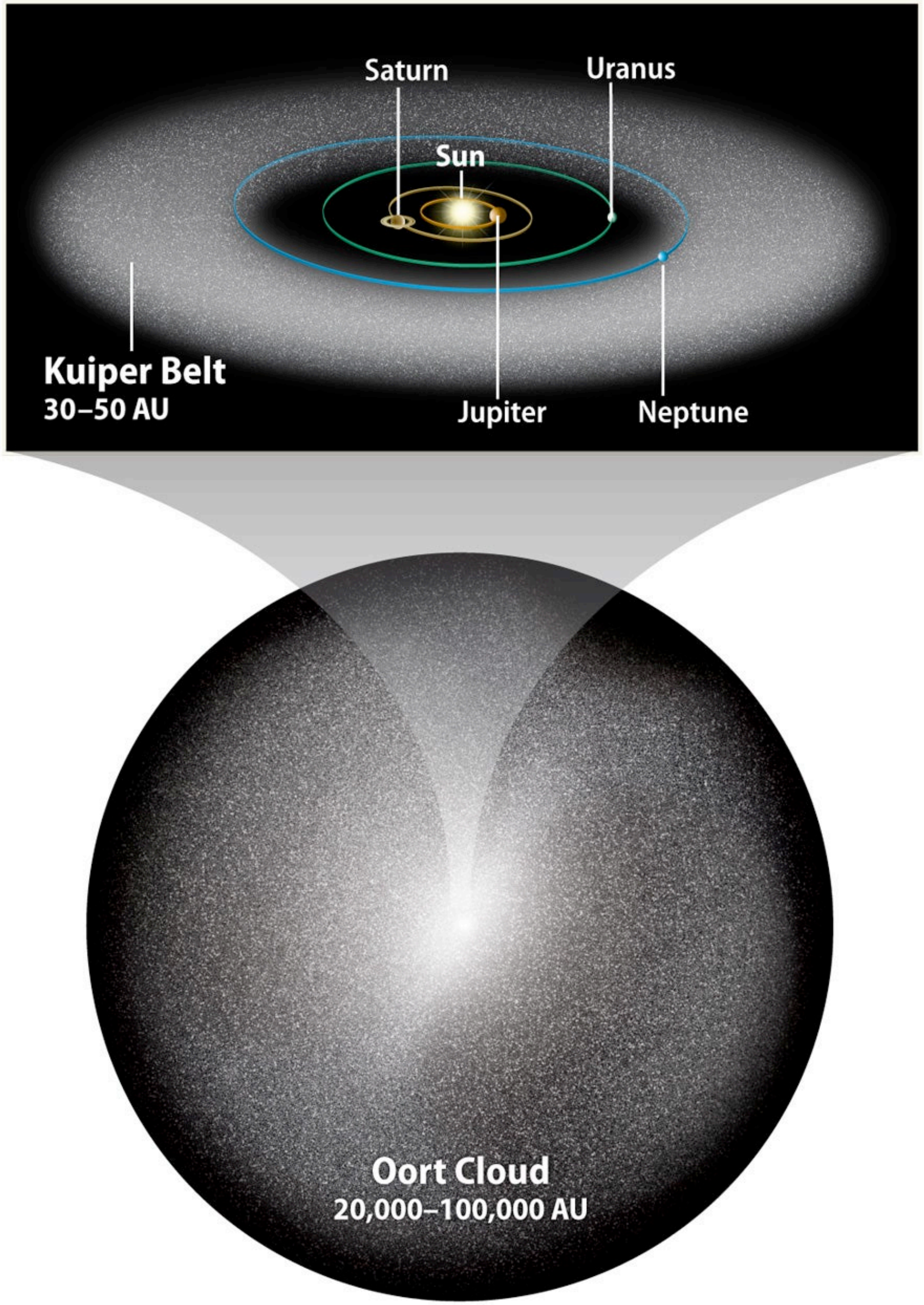
$$\ddot{r}^i + \frac{GM}{r^3} r^i = \delta^{ik} \frac{1}{2} \ddot{h}_{kj} r^j$$

$$\ddot{\tau} - \frac{3}{2} \frac{B-A}{C} \frac{G m_s}{r^3} \sin(2\psi) = \delta f$$

First study to appear with Lizalde and Giménez

we can generate enough **libration** to be detectable….

Other systems



Any gravitationally bound system can test this

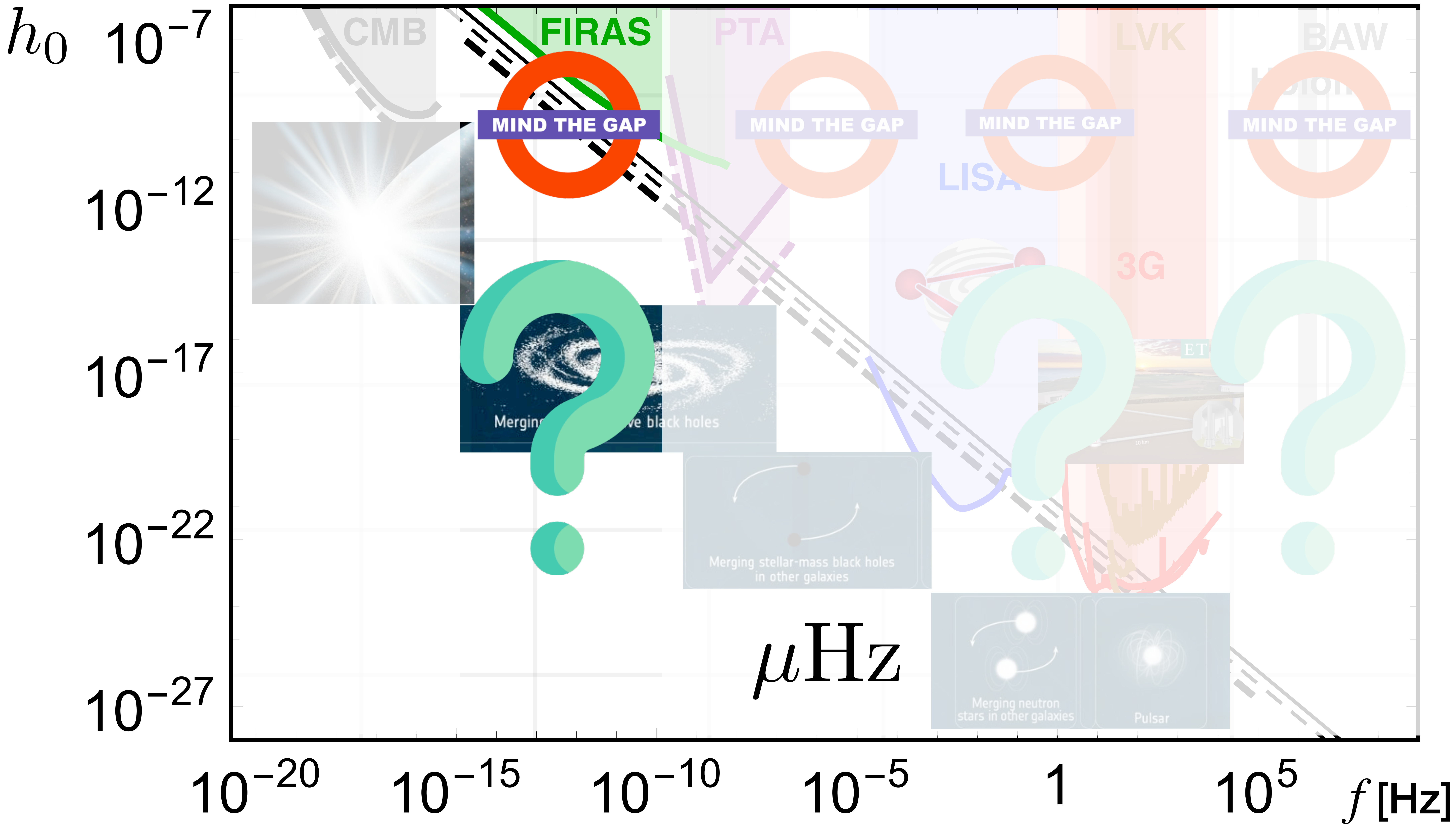
$$\ddot{r}^i + \frac{GM}{r^3} r^i = \delta^{ik} \frac{1}{2} \ddot{h}_{kj} r^j$$

the existence of a background heats up orbits

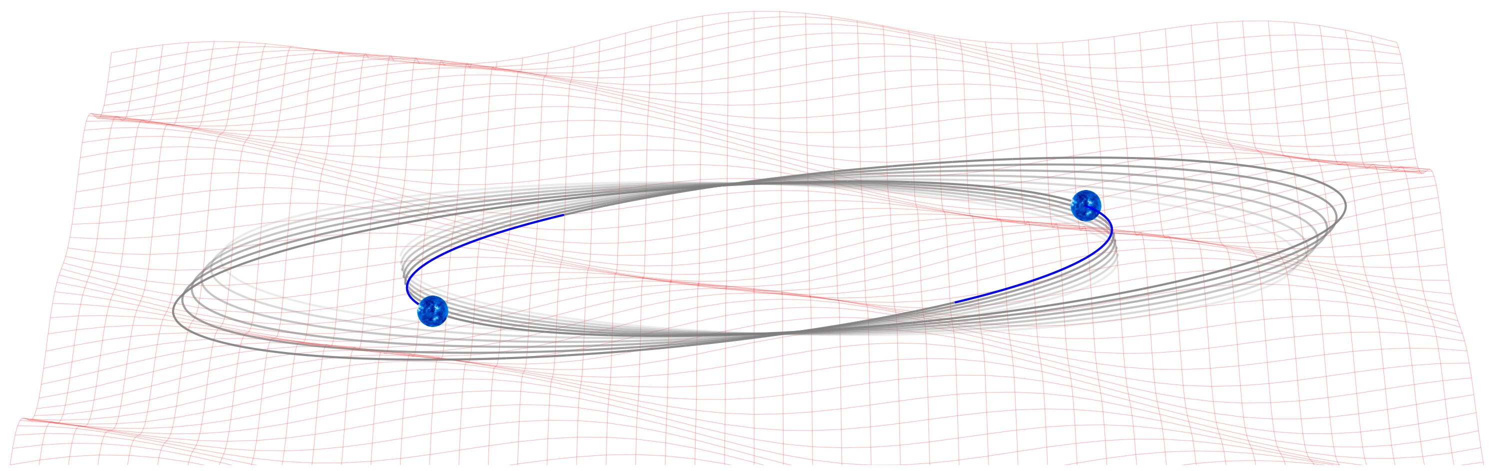
$$\frac{\delta P}{\delta t} \sim \frac{9P^2}{4} \sum_{n=1}^{\infty} n H_0^2 \Omega_n$$

in 5 billion years, this can have tremendous effects

GWs searches ca. 2036: gaps



Ultralight dark matter



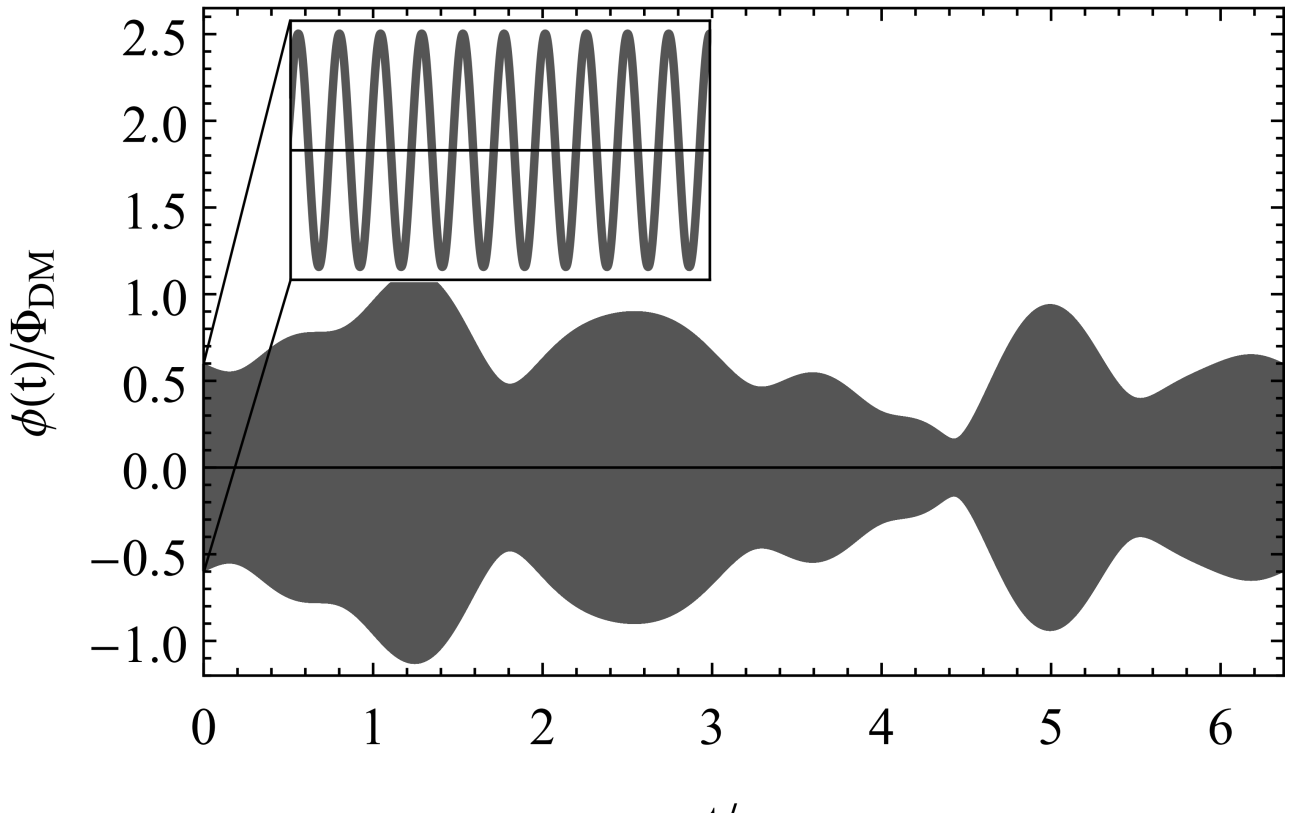
We are sensitive to oscillating gravitational potentials

If dark matter can be treated as a classical field (it happens for $m \ll 10^{-9} m_p$)

$$\mathcal{L} = \frac{1}{2}\left[(\partial_\mu \phi)^2 - m^2\phi^2\right] \rightarrow \phi_k \sim e^{i(\omega t - kx)}$$ in a virialized halo

$$\phi \propto \int_0^{v_{max}} \mathrm{d}^3 v\, e^{-v^2/\sigma_0^2} e^{i\omega_v t} e^{-im\vec{v}\cdot\vec{x}} e^{if_{\vec{v}}} + c.c. \rightarrow \phi \propto \phi_0 \cos(mt + f)$$

distribution: $\sigma_0 \sim 10^{-3}c$ in the MW $\quad \omega_v \approx m(1+v^2)$



$\rho = \frac{1}{2} m^2 \phi^2$ also oscillates $\rightarrow \delta\Phi_N$

Gravitational wave detection through their absorption by binaries

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

- The resonant **absorption of GWs by binaries** may give a handle

Blas&Jenkins Phys.Rev.Lett. 128 (2022) 10, 101103 (in 2038, from LLR)

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

🏆 guaranteed physics case!!!!

- **2025:** the use of time of arrival makes it even more sensitive!

- Future:
  - complete data analysis (work in progress: **Foster,** Blas, Bourguin, Foster, Hees, Herrero, Jenkins)
  - other systems (libration, Oort,…)
  - mini-F: dedicated mission with large P and e

esa

Help to perform the
real analysis welcome!

Miró, 1937.
“Help Spain” poster calling
for international help in
to support the democratic republic
in the Spanish Civil war.