Diego Blas Temiño (on behalf of A. Jenkins, M. Herrero, X. Xue, A. Bourguin, A. Hess, J. Foster)
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ICREA

IFAE

BIST Barcelona Institute of Science and Technology

Detecting gravitational waves with SLR

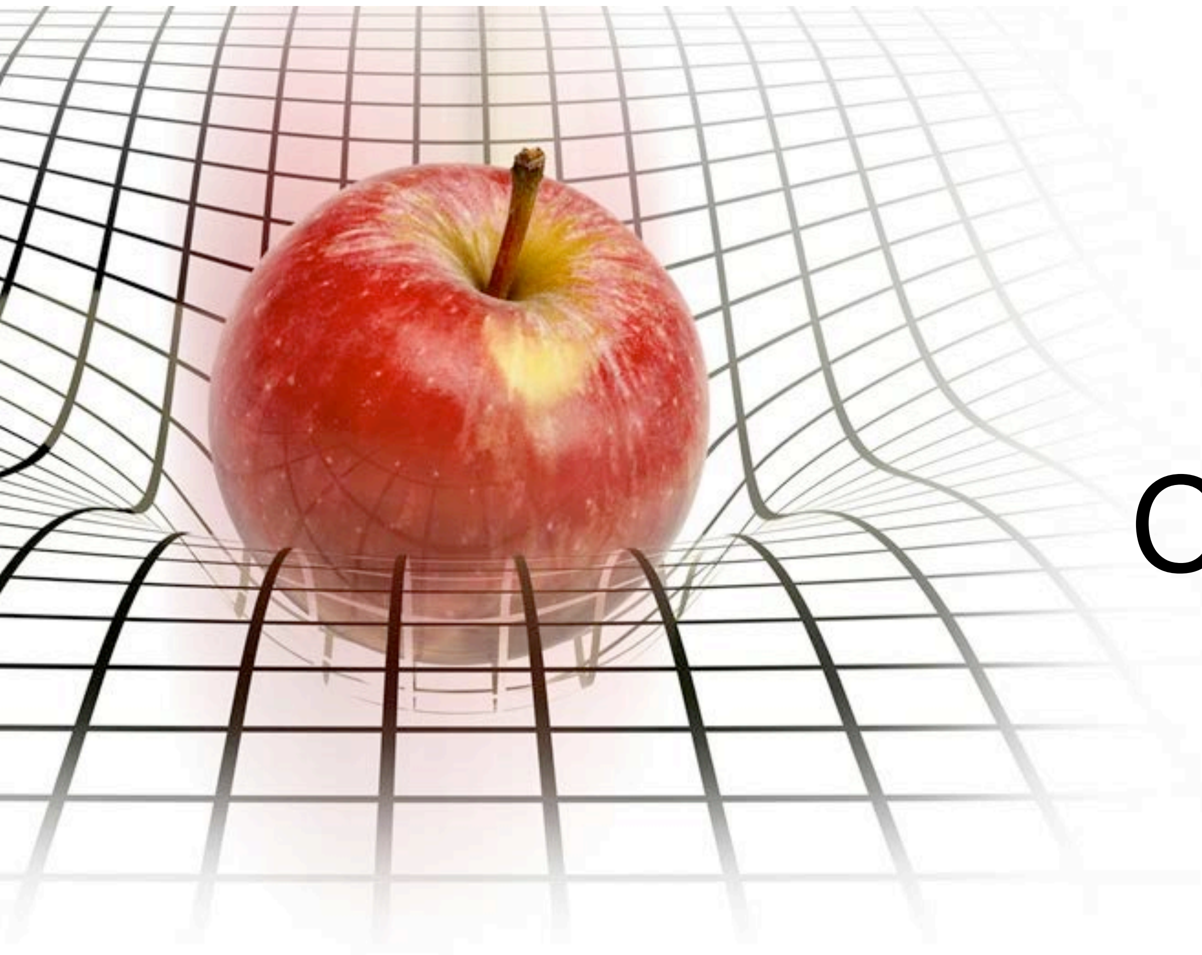
Published works

https://arxiv.org/abs/2107.04601 Blas&Jenkins Phys.Rev.Lett. 128 (2022) 10, 101103

https://arxiv.org/abs/2107.04063 Blas&Jenkins Phys.Rev.D 105 (2022) 6, 064021

+ *new papers to appear*

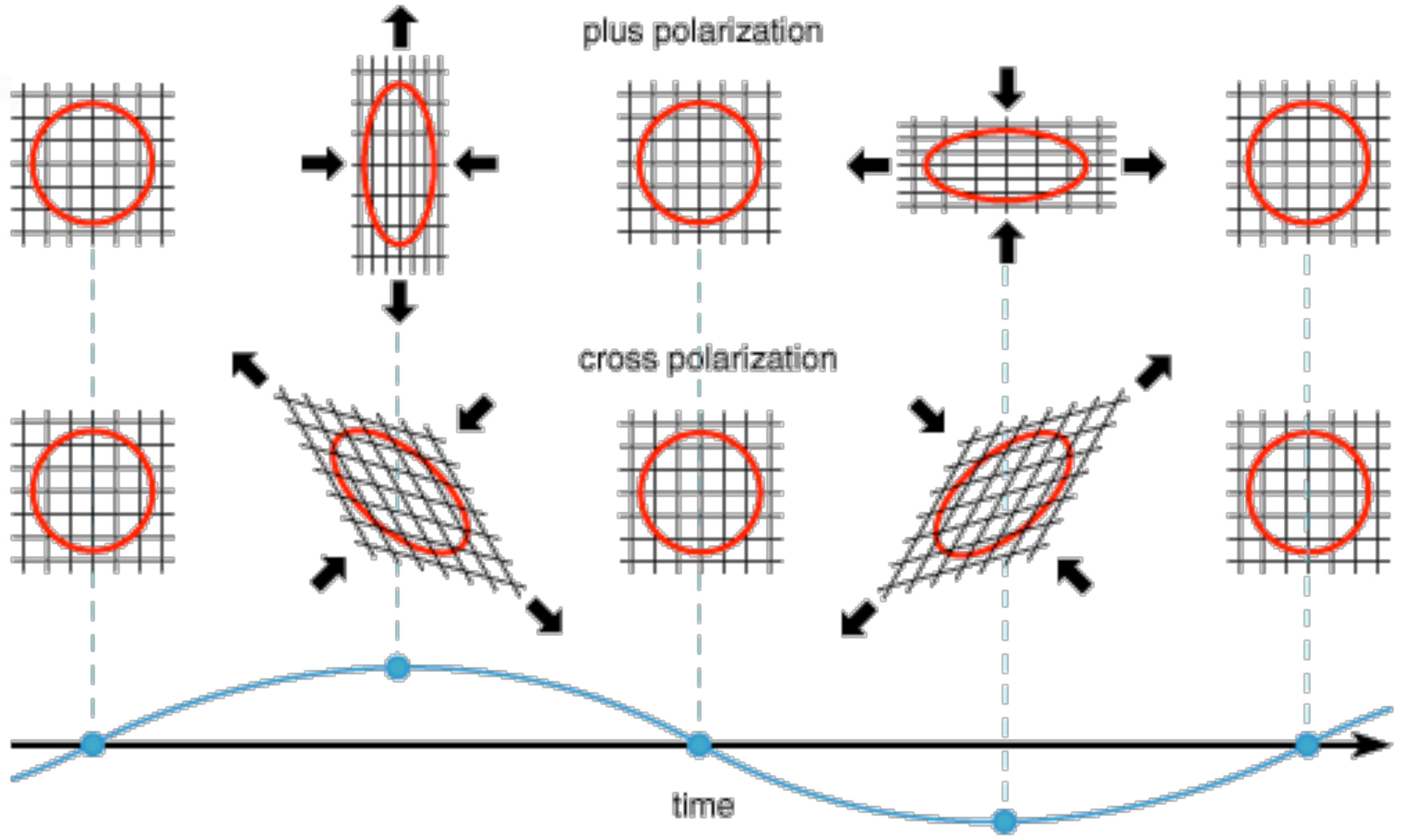
GWs (essentials)



Perturbations of space-time

travelling as waves of frequency f

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



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

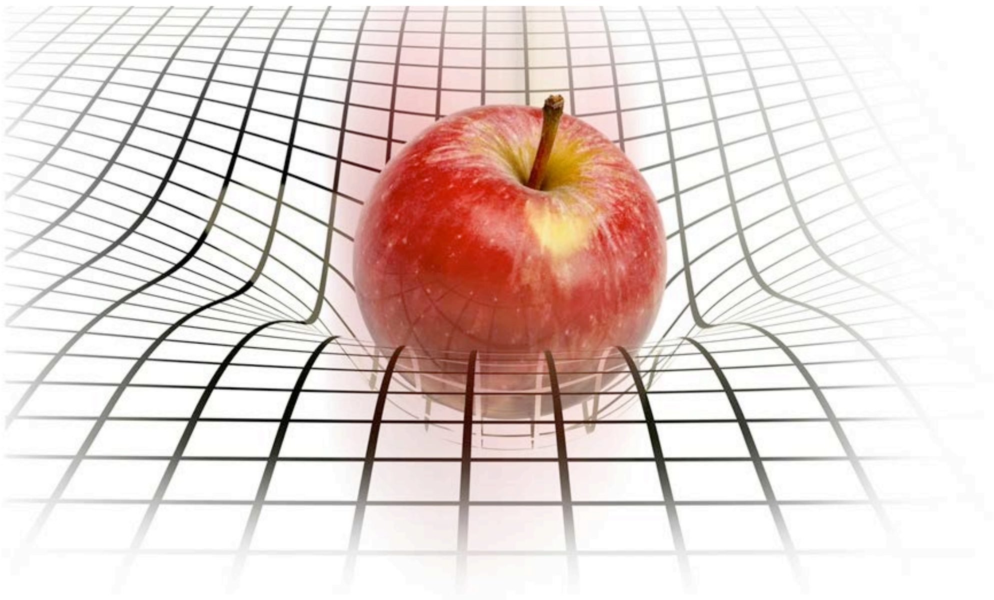
GWs carry energy. They have **energy density**

$$\rho_{\rm gw} = \frac{1}{16\pi G}\left\langle \dot{h}_+^2 + \dot{h}_\times^2 \right\rangle \quad \Rightarrow \quad \Omega_{\rm gw}(f) \equiv \frac{1}{\rho_c}\frac{{\rm d}\rho_{\rm gw}}{{\rm d}(\ln f)}$$

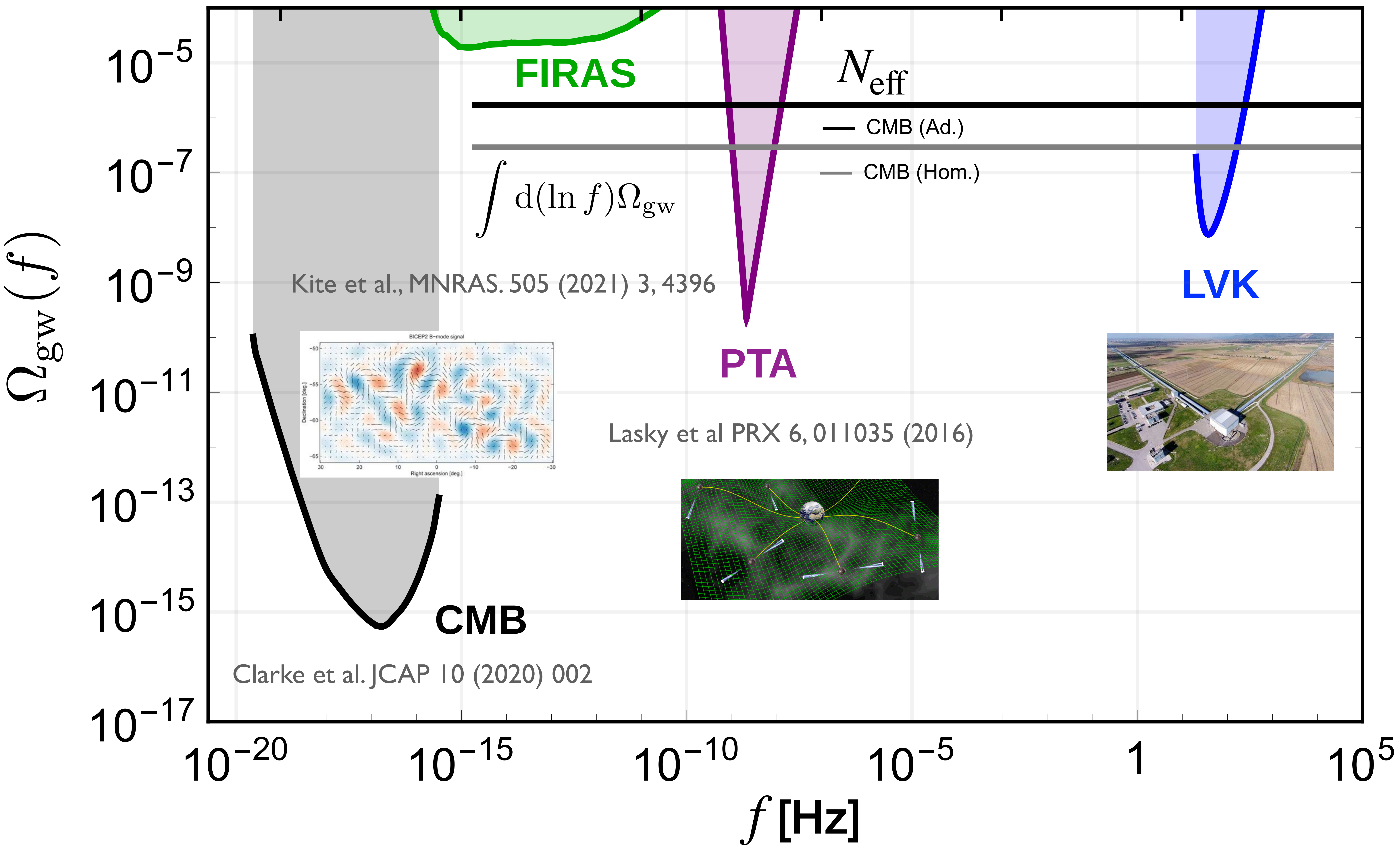
$$\rho_c = 1.2 \times 10^{11} M_\odot {\rm Mpc}^{-3} \sim {\rm keV/cm}^3$$

$h \approx 0.67$

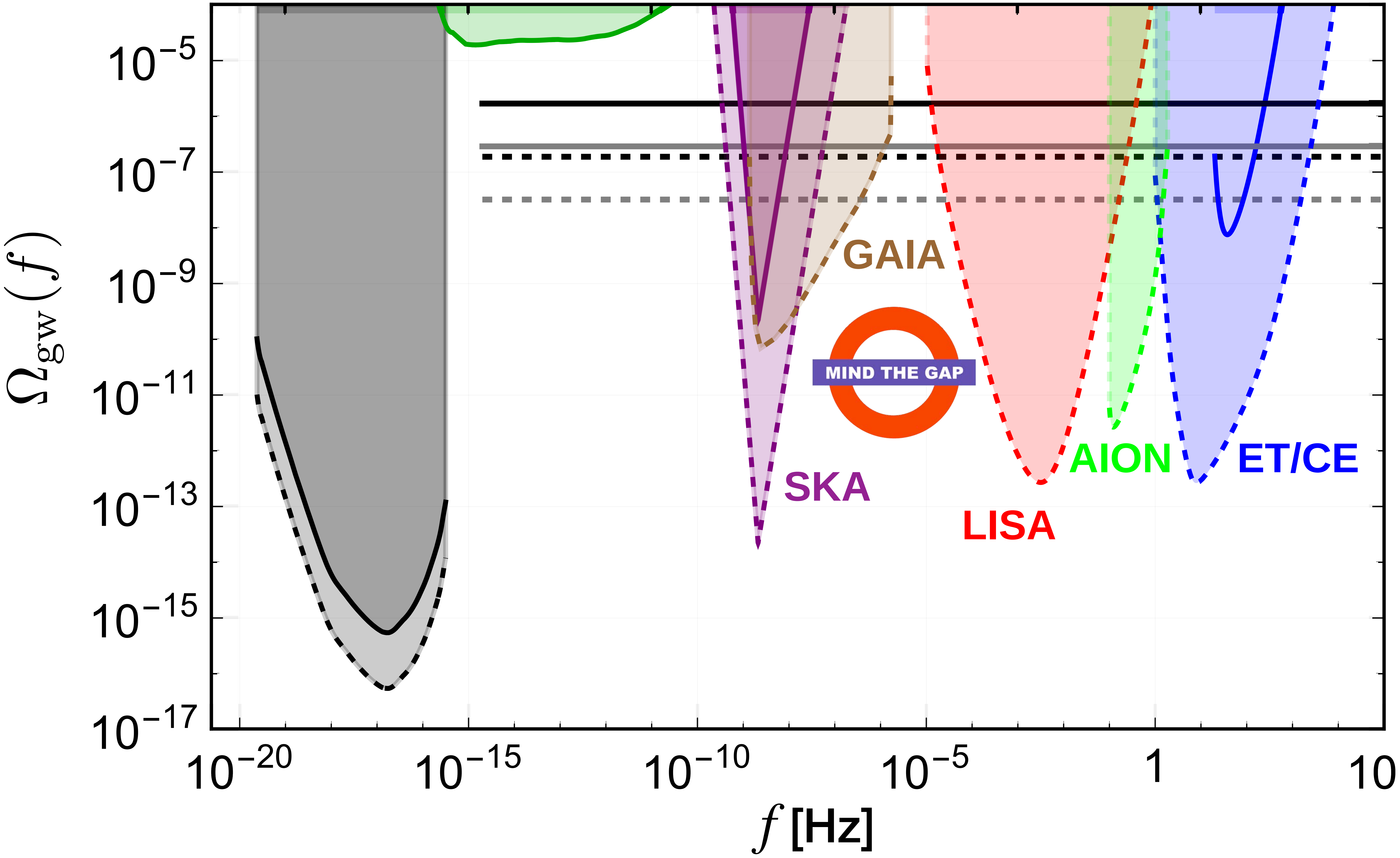
Taxonomy of GWs



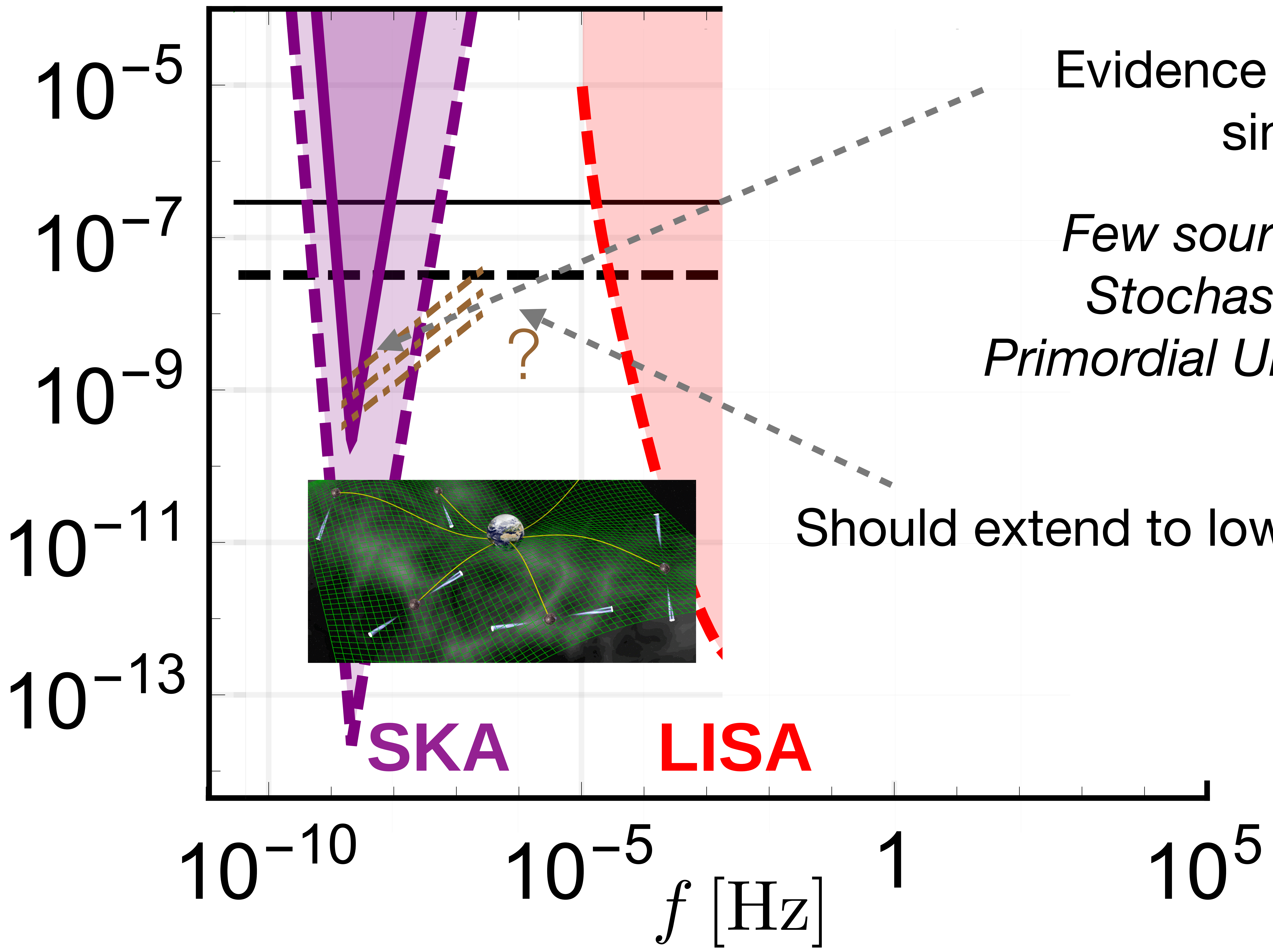
GWs landscape today



GWs landscape ca. 2040



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



Evidence of signal at nHz
since 2023

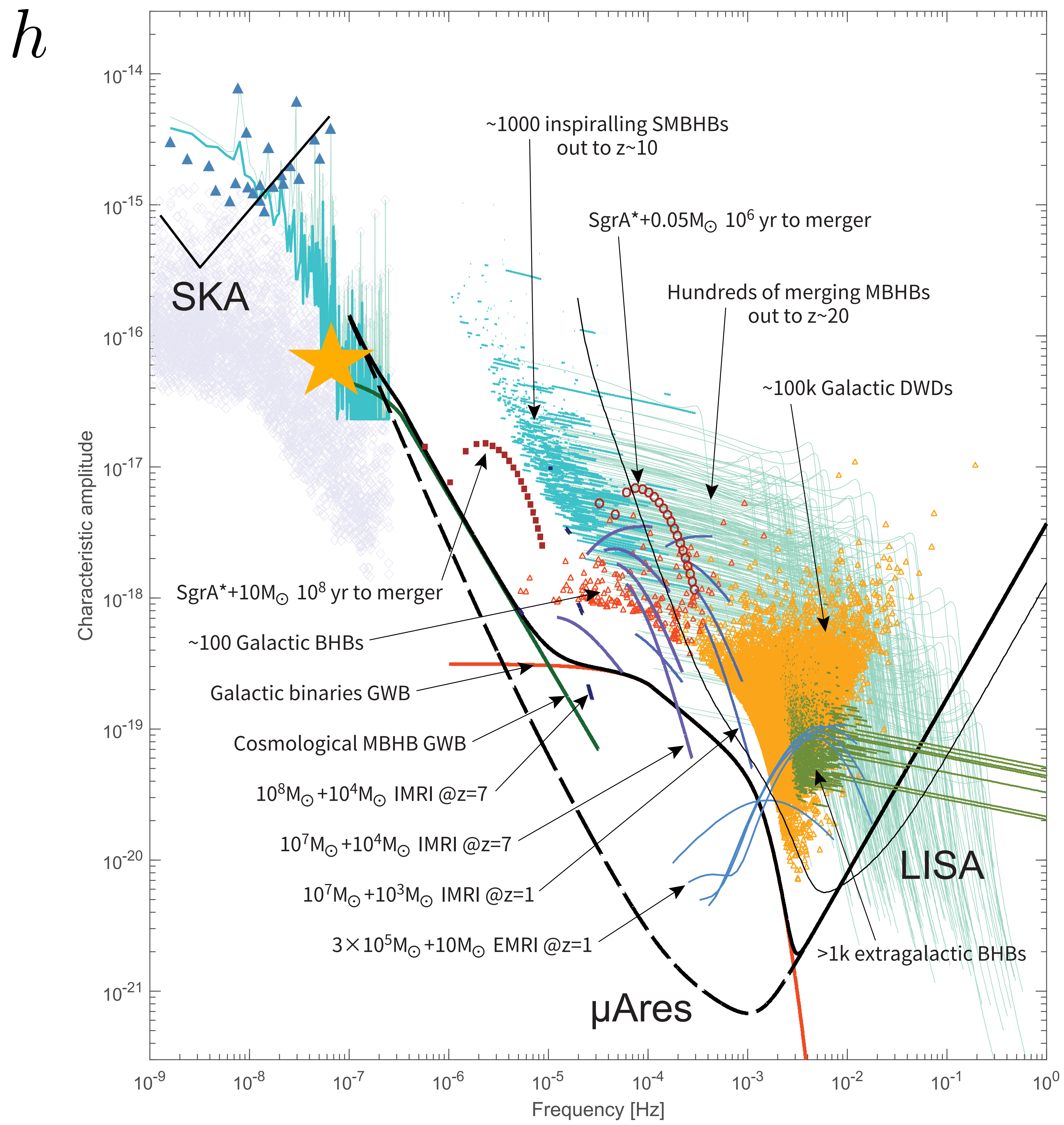
Few sources?
Stochastic?
Primordial Universe?

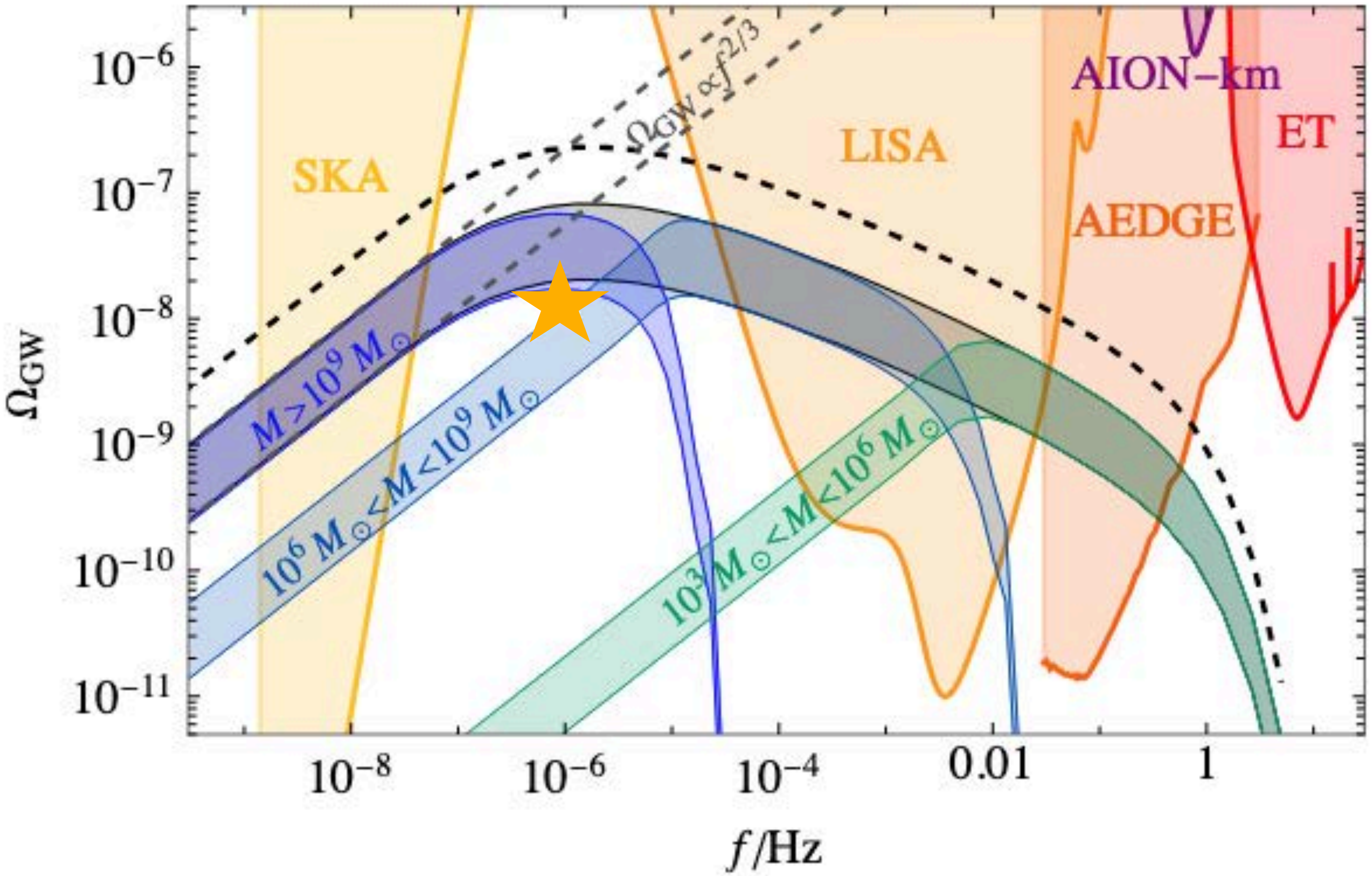
Should extend to low freqs!

Review of sources

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

The μAres detection landscape

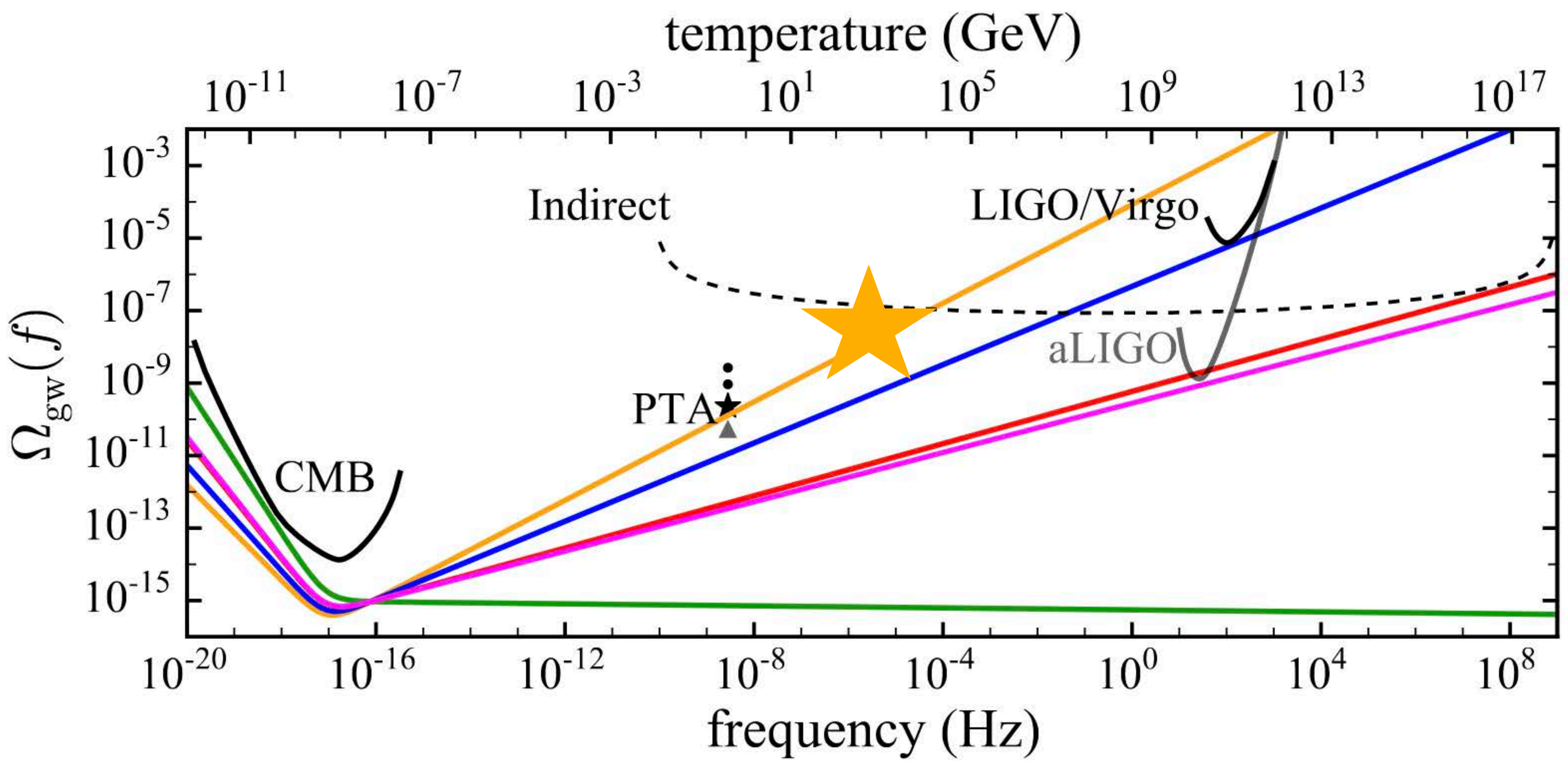




Backgrounds from fundamental physics

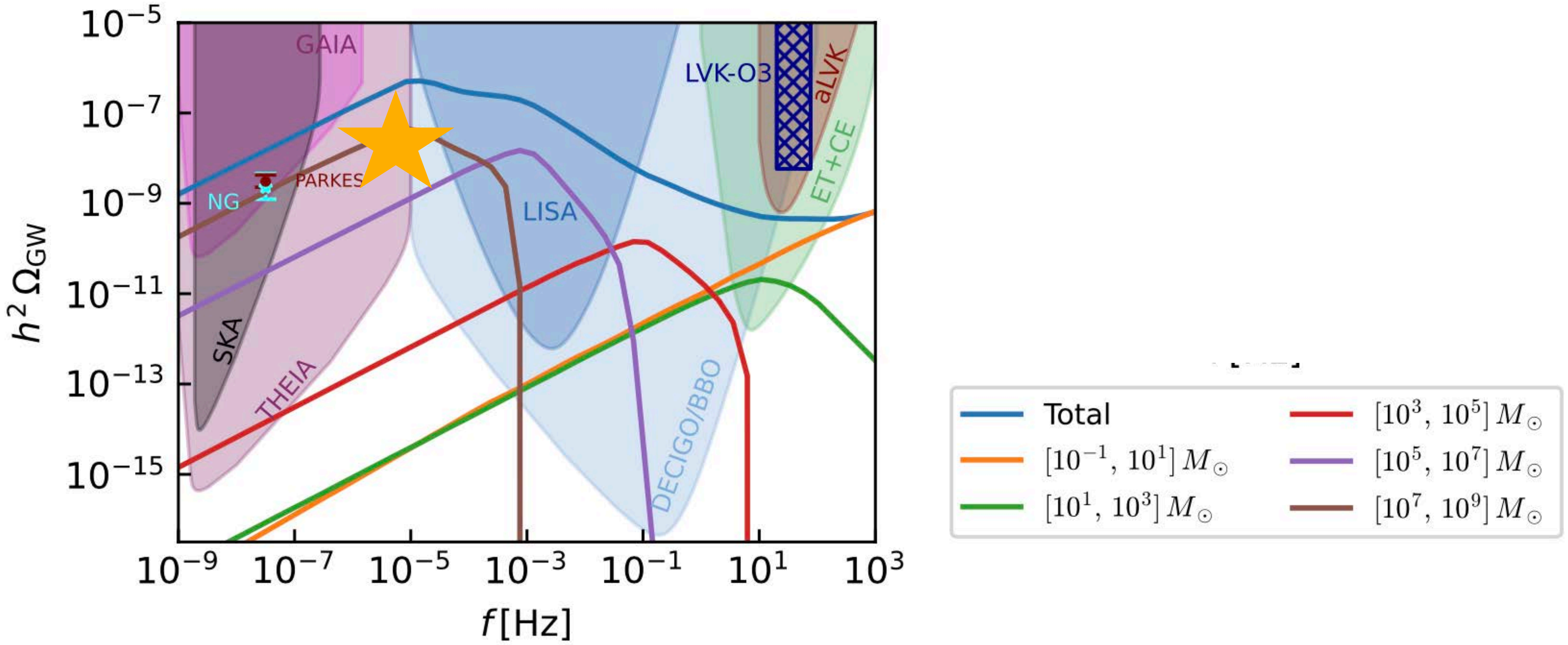
Inflation

Lasky et al PRX 6, 011035 (2016)



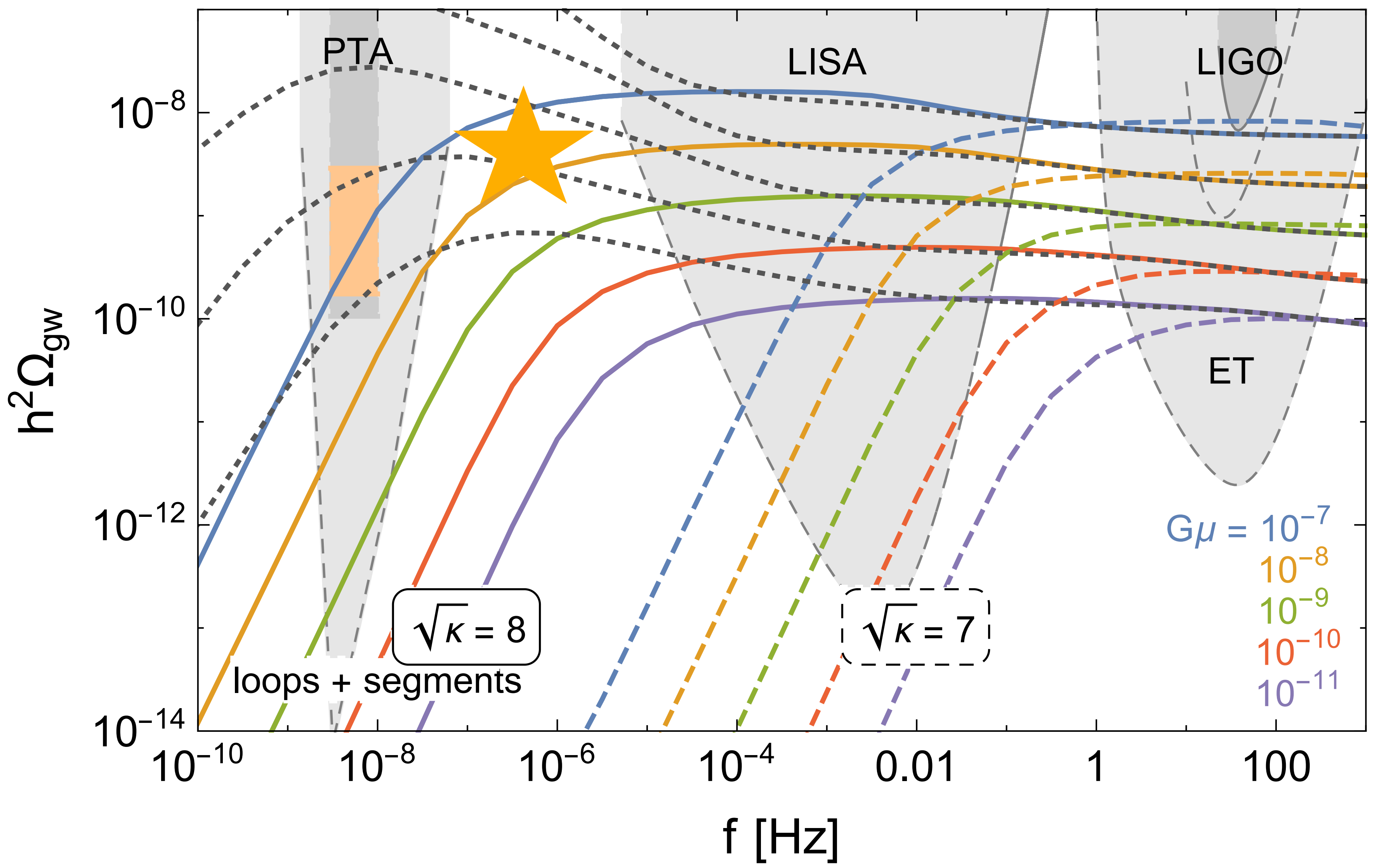
PBH

Braglia et al. JCAP 12 (2021) 12



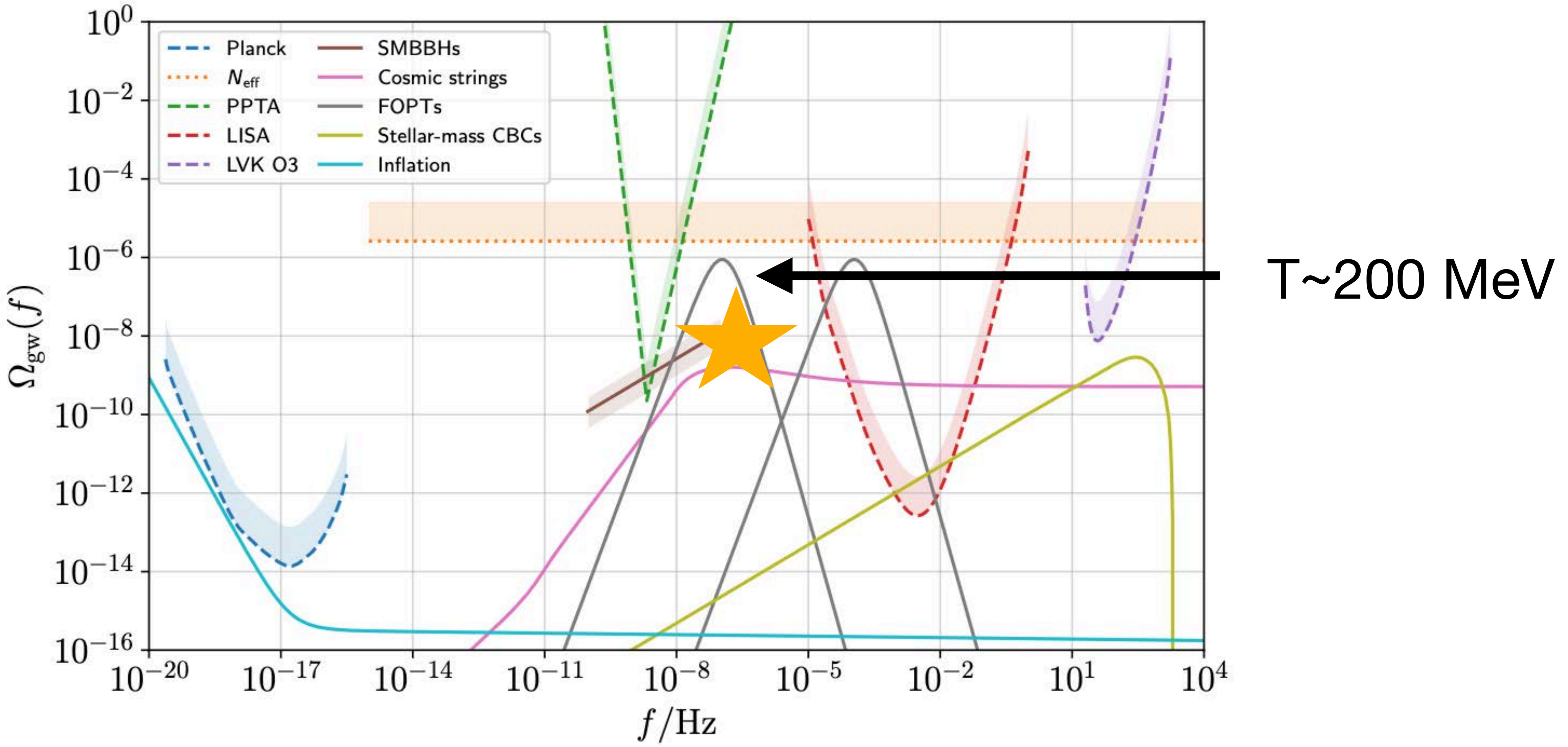
Cosmic Strings

Buchmuller et al. 2107.04578



FOPT

Renzini et al 2202.00178
(based on 1512.06239)



Absorption of GWs by binaries

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

few days

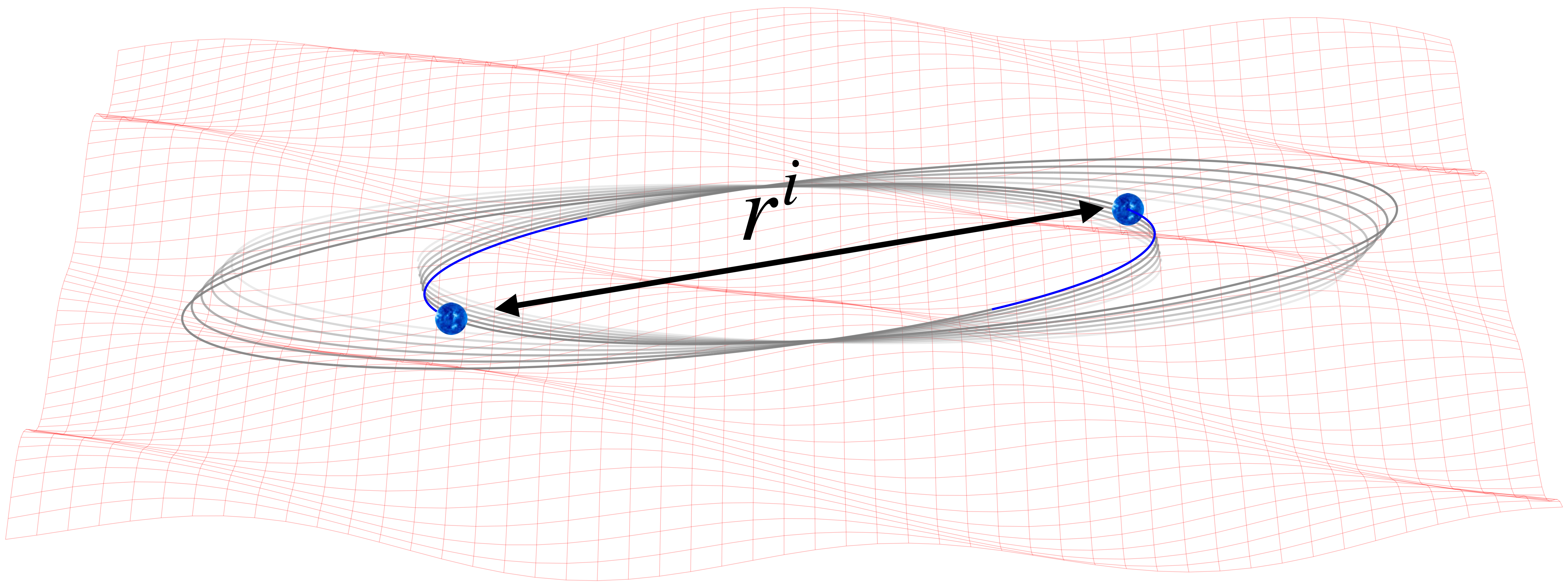
Intuitive idea (from '60s)

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

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

Newtonian potential

GW

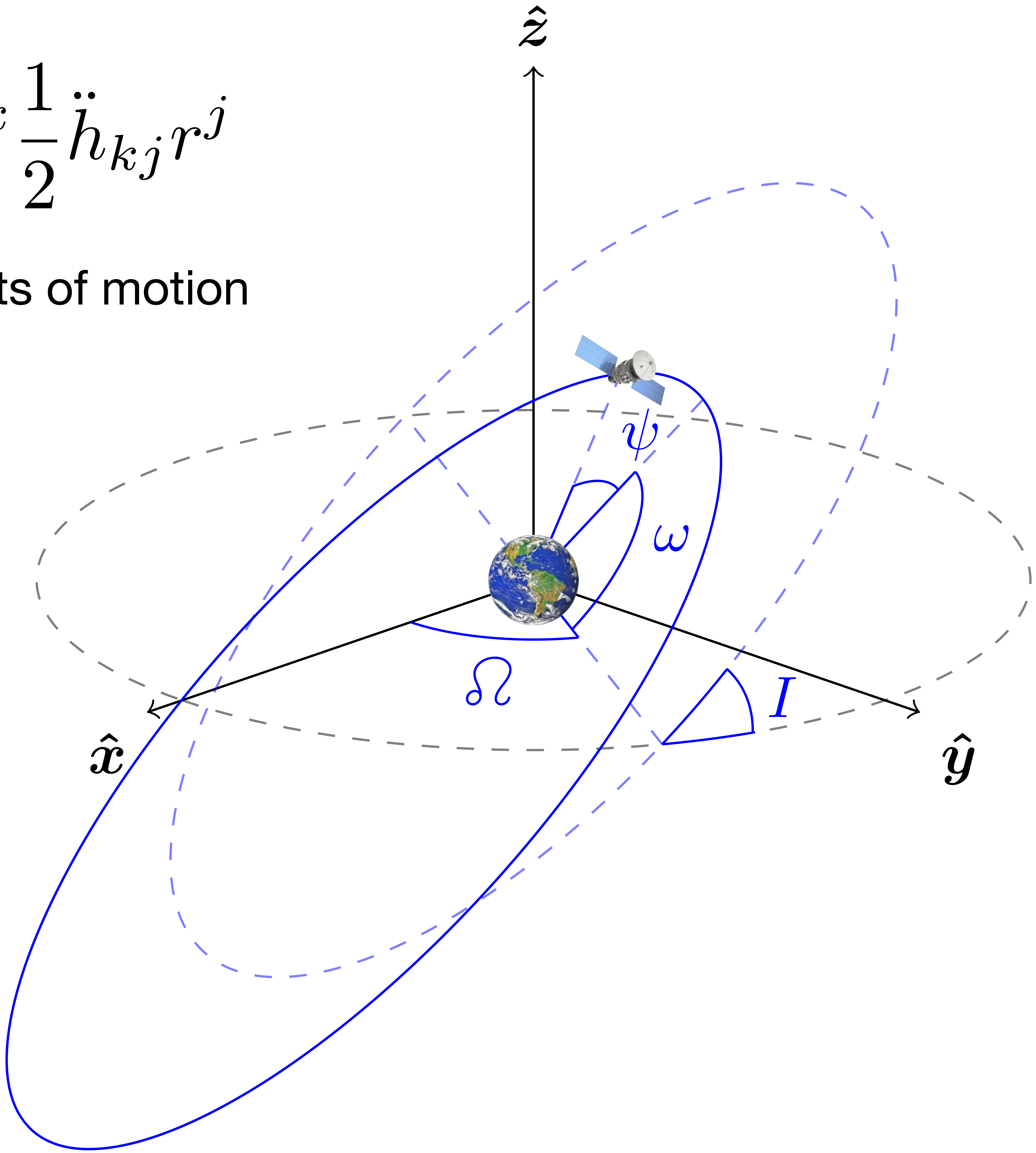


Absorption of GWs by binaries

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

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:

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

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

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

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

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

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

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

Notice resonance effects

$$\langle\sin(\omega t)\sin(\omega_{gw}t + \phi_0)\rangle \sim \frac{1}{2}\delta(\omega - \omega_{gw})$$

Absorption of GWs by binaries

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

- for generic perturbation:

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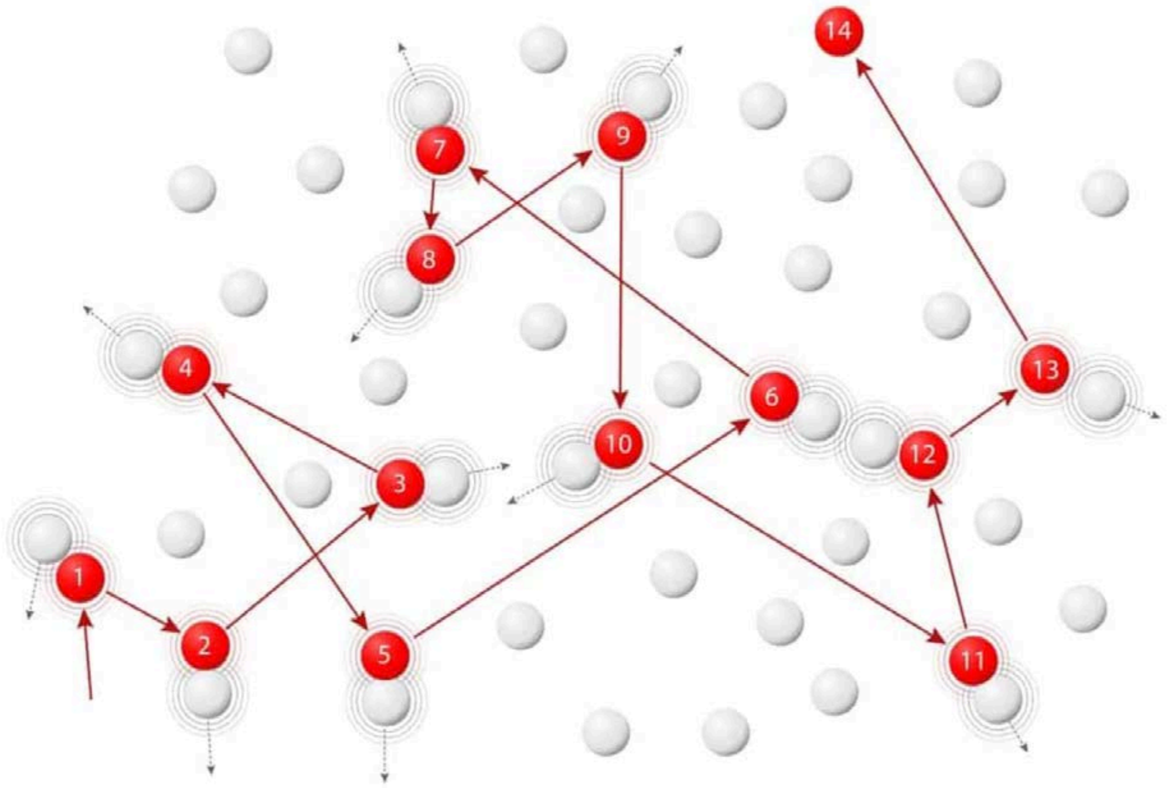

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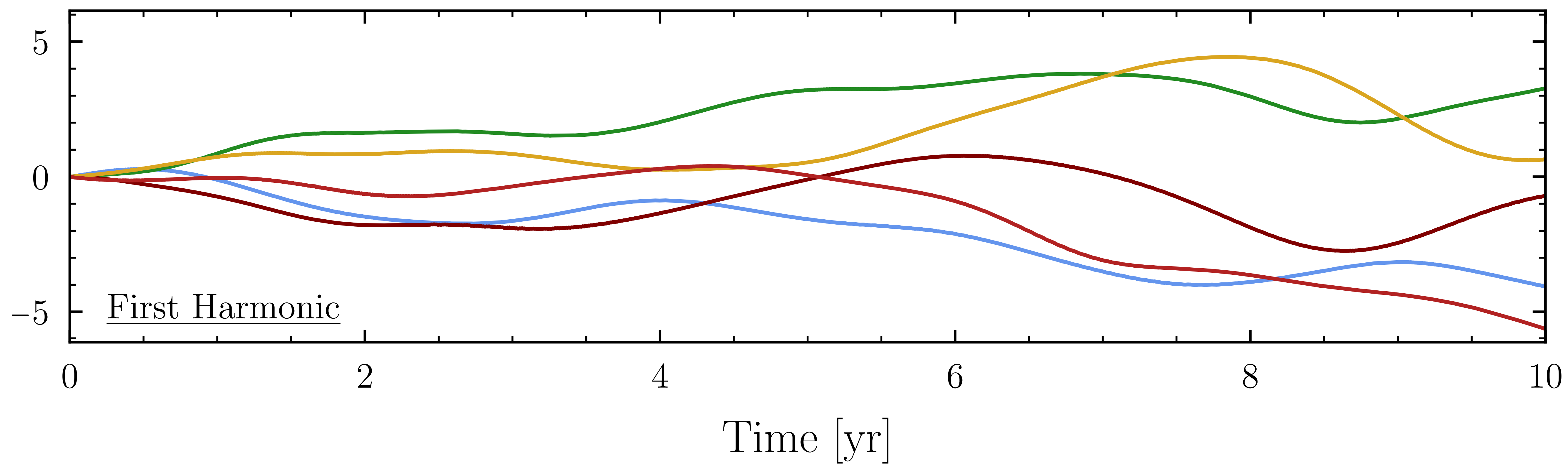
$$\dot{\varepsilon} = -\frac{P\gamma^4\mathcal{F}_r}{\pi(1+e\cos\psi)^2} - \gamma(\cos I\dot{\Omega} + \dot{\omega}),$$

Notice resonance effects

$$\langle\sin(\omega t)\sin(\omega_{gw}t + \phi_0)\rangle \sim \frac{1}{2}\delta(\omega - \omega_{gw})$$

Confirming with simulations

Semi-latus Rectum Perturbation [cm]



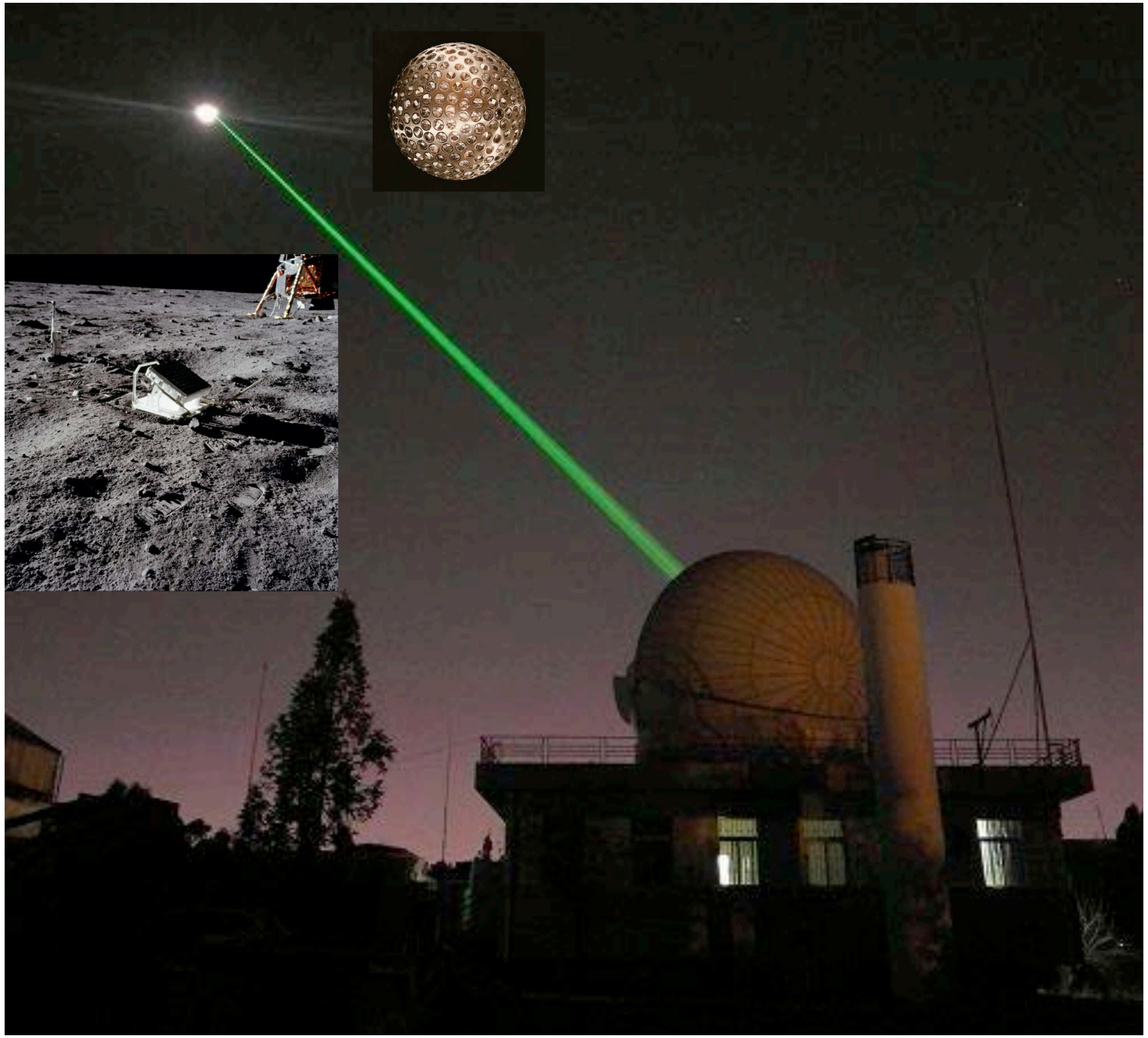
Credit: J. Foster

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

Summary results for SLR and LLR

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

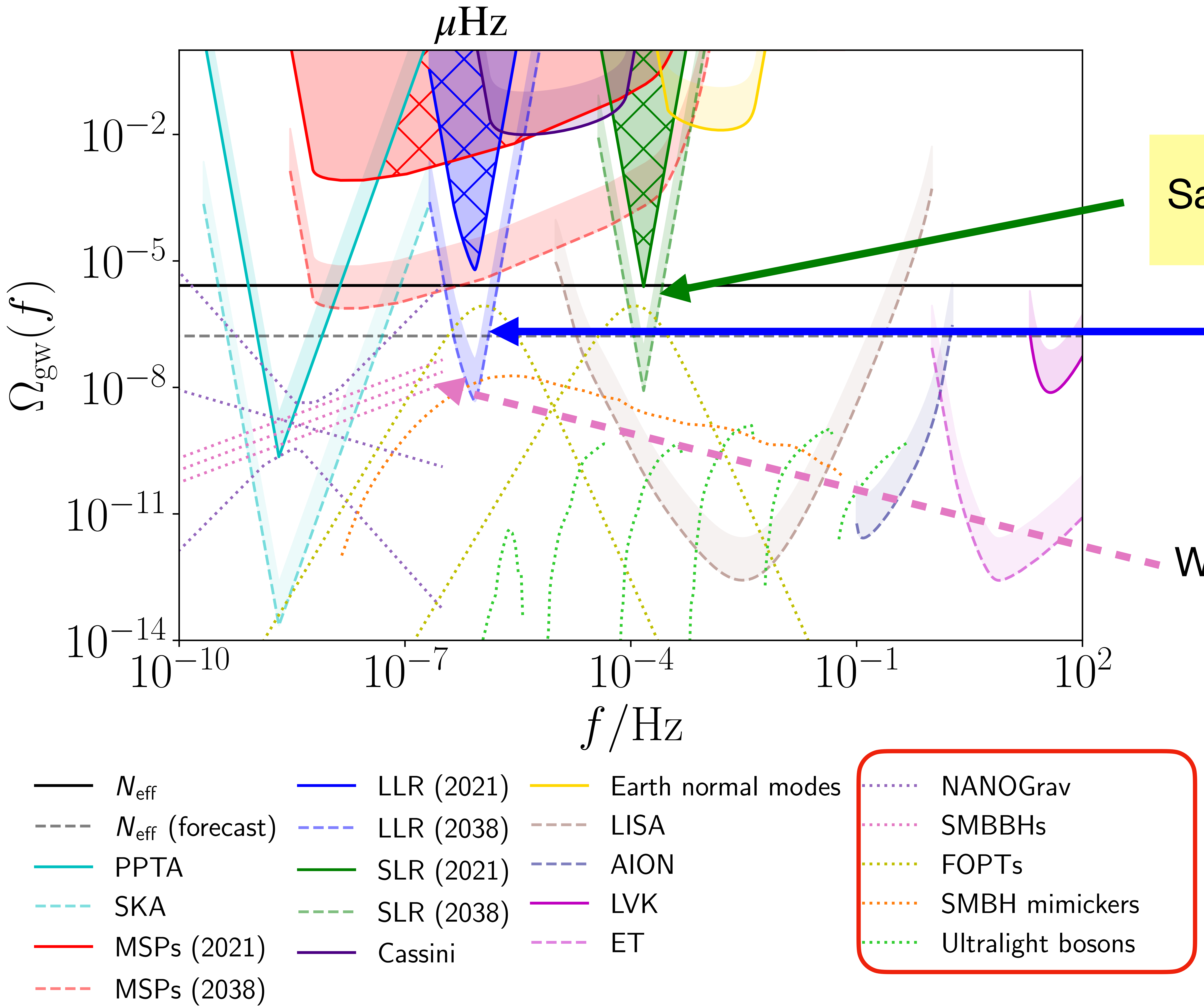
few days



Our estimates from 2021 for 2038

Our estimates from 2021 for 2038

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



Satellites Earth based LAGEOS (*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!!!

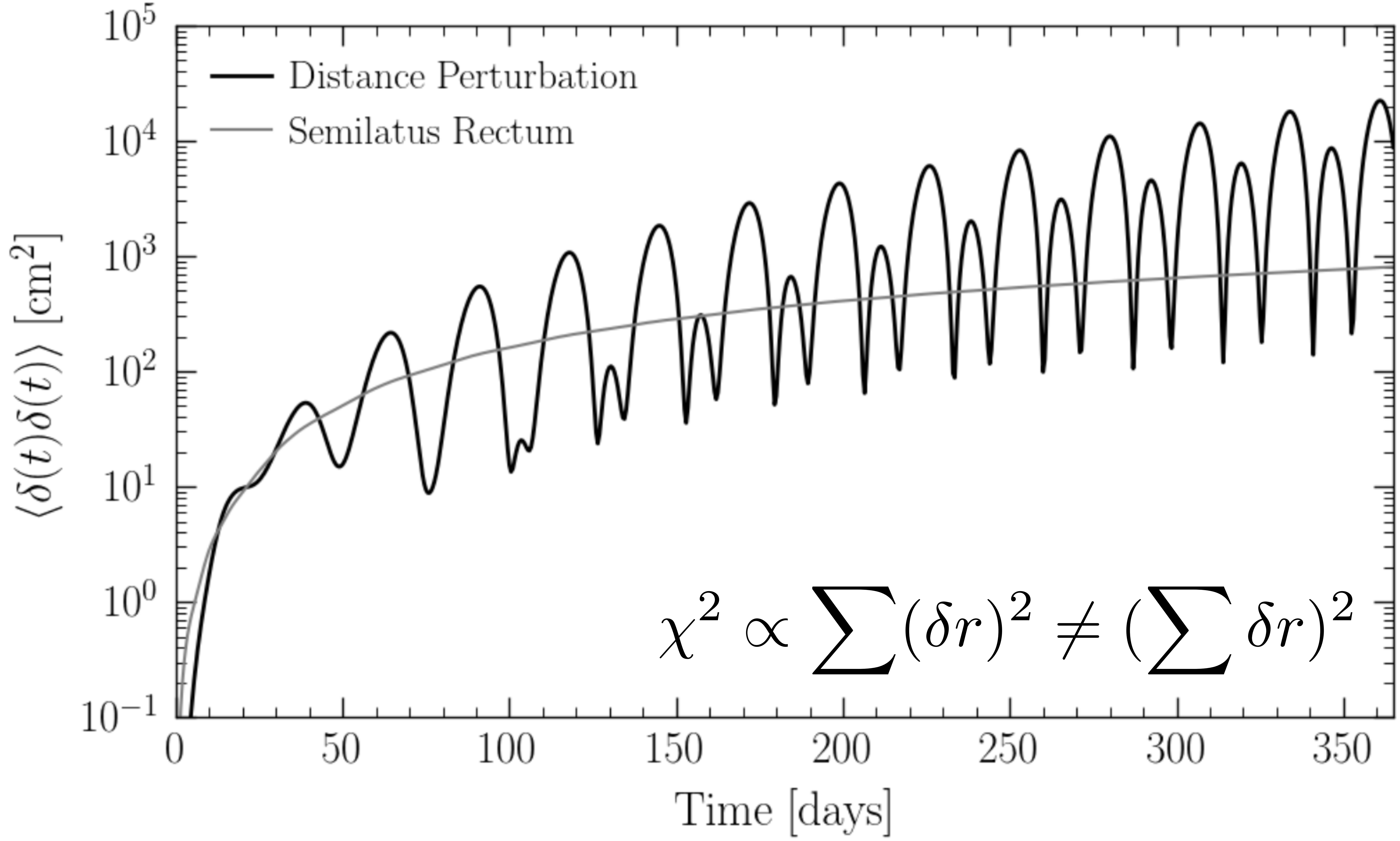
in 2050

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

Possible backgrounds

New results (to appear)

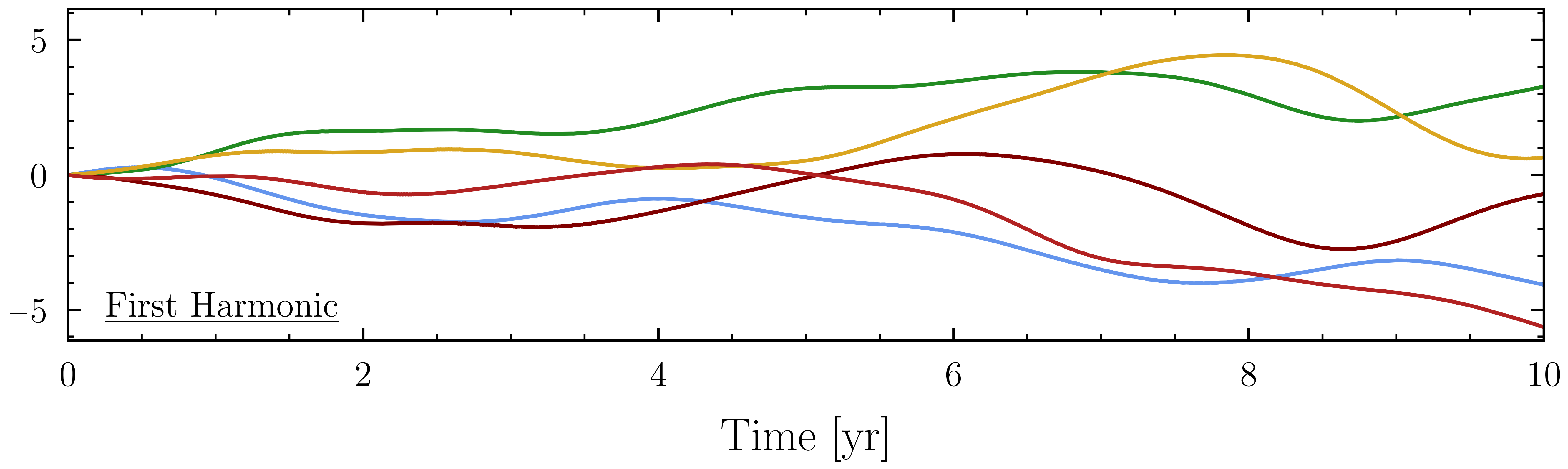
COMPARISON WITH PRIOR RESULTS (not using all the orbital info)



$$\chi^2 \propto \sum (\delta r)^2 \neq (\sum \delta r)^2$$

$$r = \frac{p}{1 + e\cos(f)}$$

New developments (using all the orbital info)

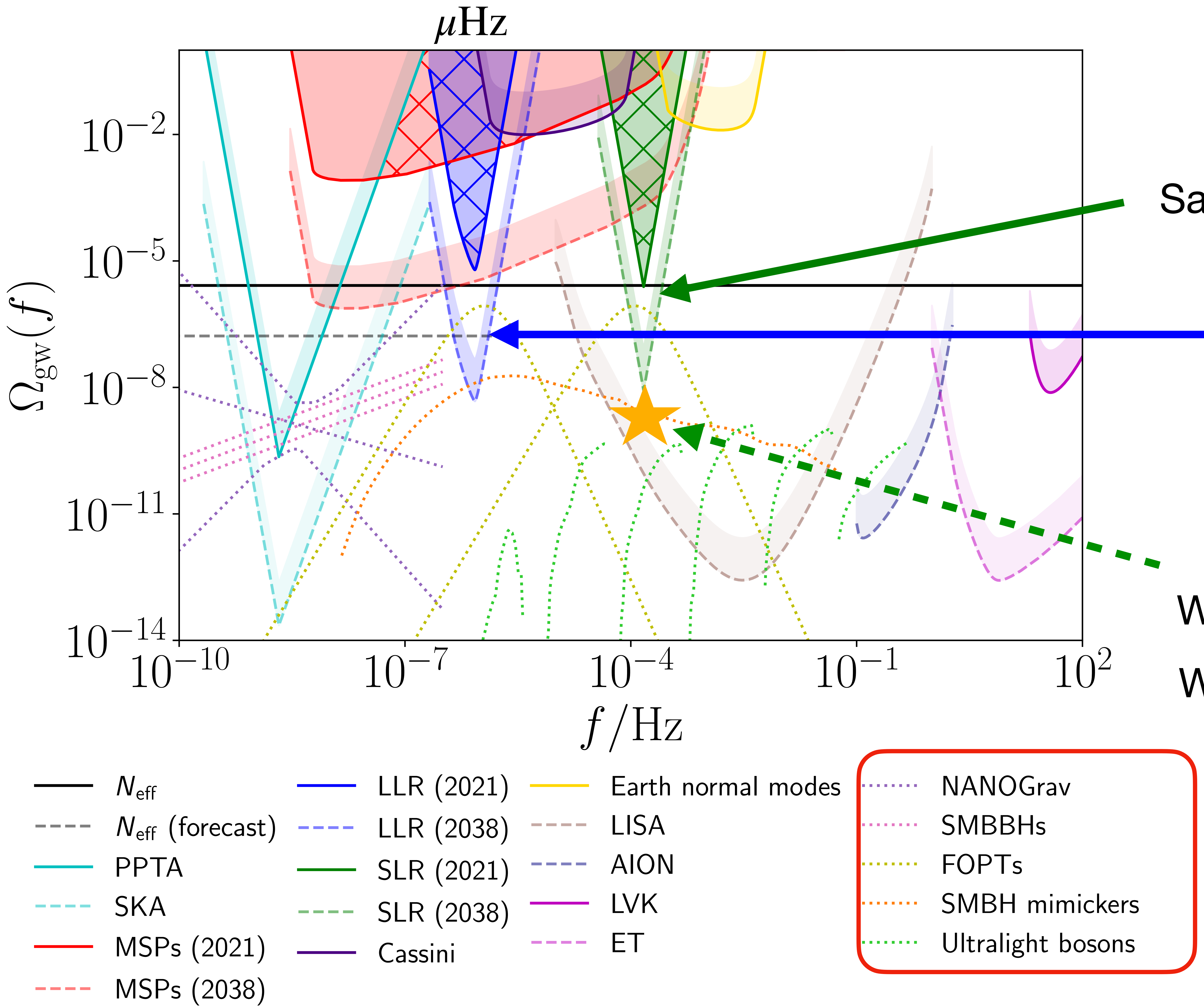


- **all the information of the orbit** (not only secular effects)
- **O(1000) better sensitivity**
- We need large **P**, **e** and **good orbital data**

Better SLR at the Moon??

Our estimates from 2021 for 2038

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



Satellites Earth based LAGEOS (*P*~hours)

Lunar laser ranging (*P*~month)

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

Murphy 1309.6294

We may achieve LISA-like sensitivity!!!

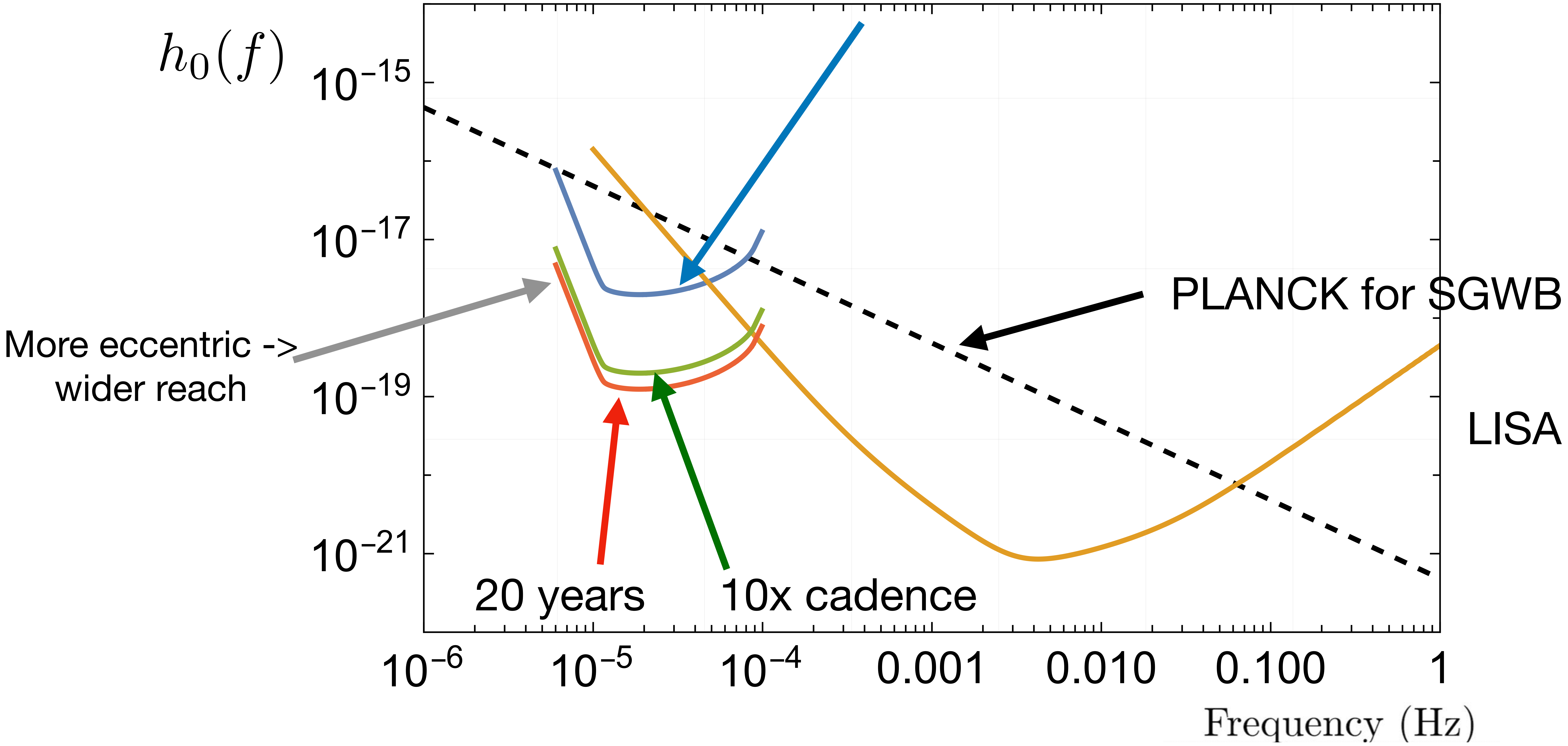
With more satellites, we cover the band

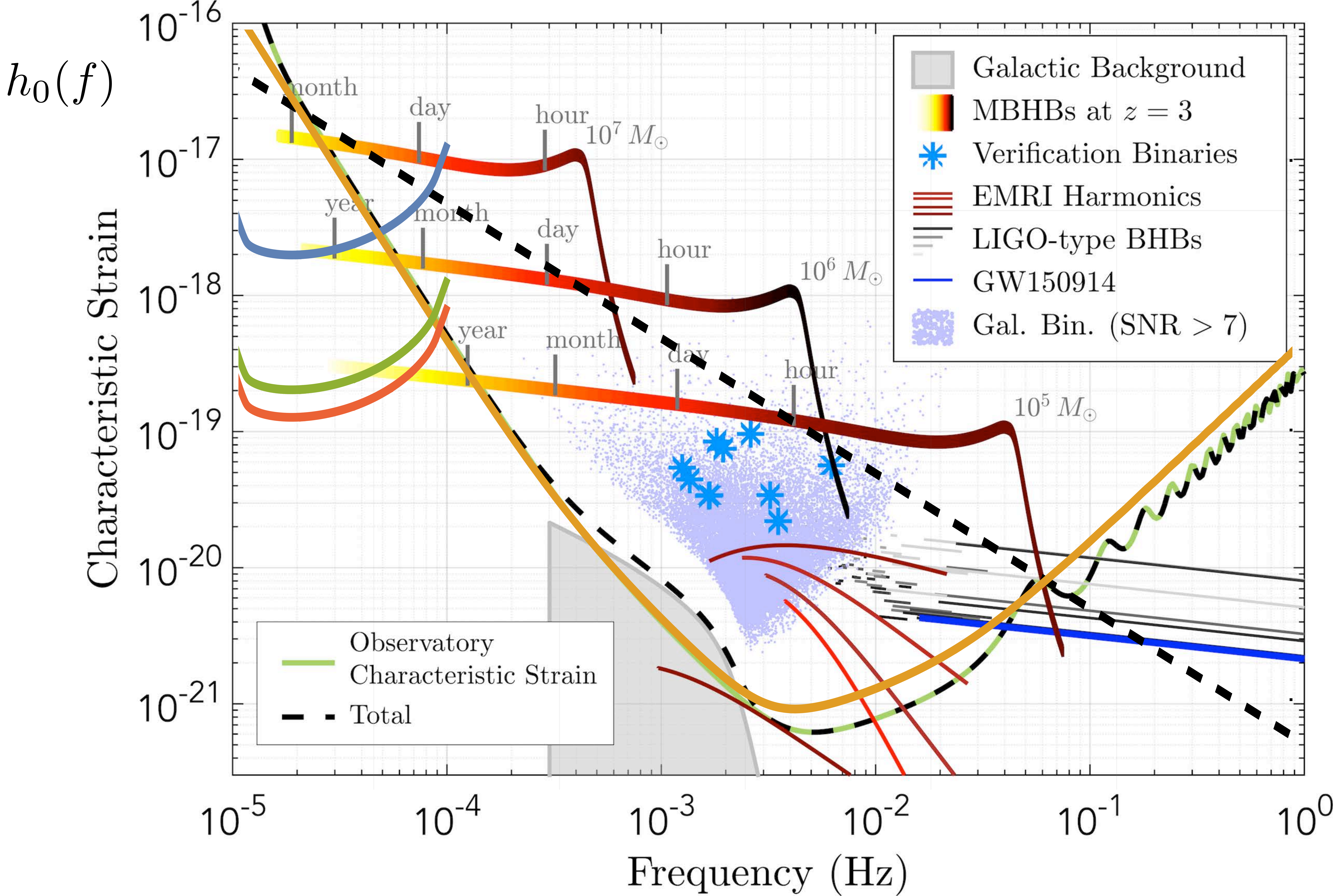
Possible backgrounds

Example for SLR in Moon orbits

Semi-Major Axis (km)	9750.73
Eccentricity	0.6383

10 years, 1000 points/ year, 1cm/point

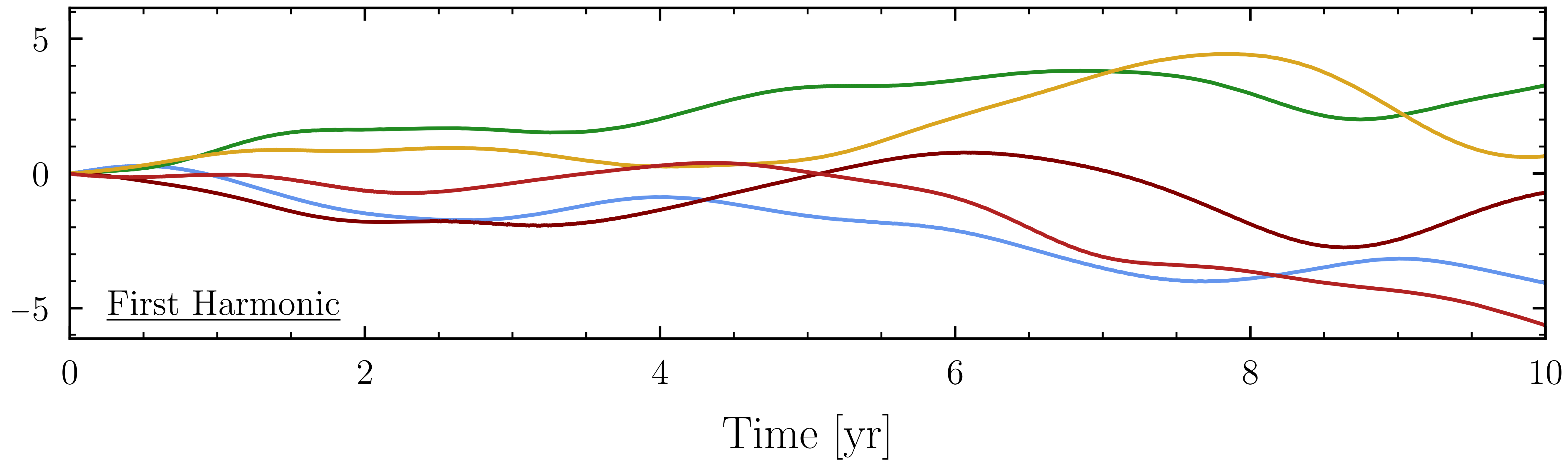




$h_0(f)$
Characteristic Strain
Frequency (Hz)
10^{-16}
10^{-17}
10^{-18}
10^{-19}
10^{-20}
10^{-21}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^{0}
Galactic Background
MBHBs at $z = 3$
Verification Binaries
EMRI Harmonics
LIGO-type BHBs
GW150914
Gal. Bin. (SNR > 7)
Observatory Characteristic Strain
Total
$10^7 M_\odot$
$10^6 M_\odot$
$10^5 M_\odot$
month
day
hour
year
month
day
hour
year
month
day
hour

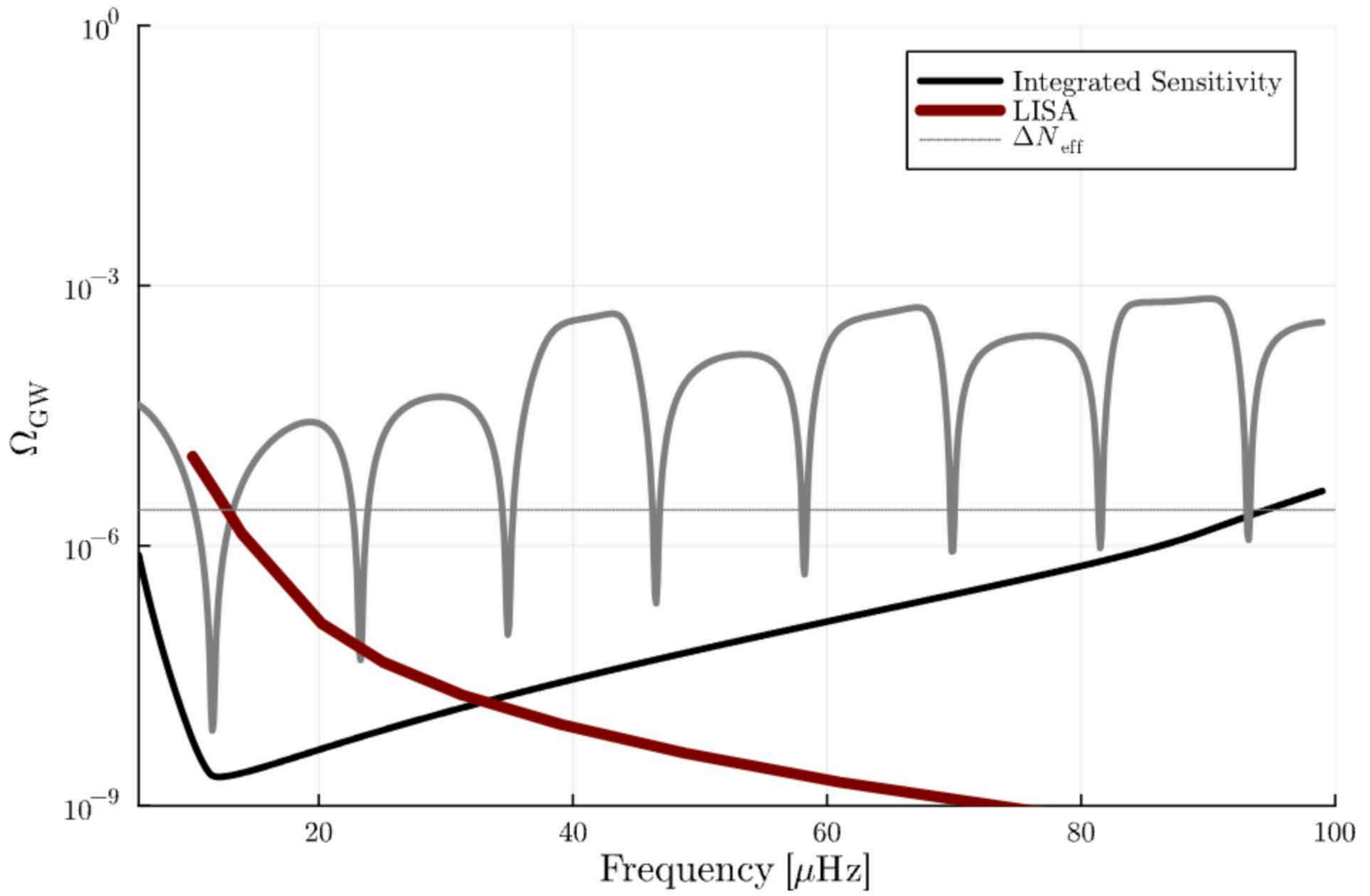

IGNORE
ME

Are we seeing GWs??



- **Benefit of several orbits**
- **More data from several orbits**

Out of resonance?



Detecting gravitational waves with SLR

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

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

We are looking forward to collaboration with SLR/GNSS colleagues!