Adding color to the gravitational wave spectrum

Diego Blas

Funded by the European Union

ICREA

IFAE
Institut de Física d'Altes Energies
EXCELENCIA SEVERO OCHOA
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AGENCIA ESTATAL DE INVESTIGACIÓN

erc
European Research Council

UNDARK

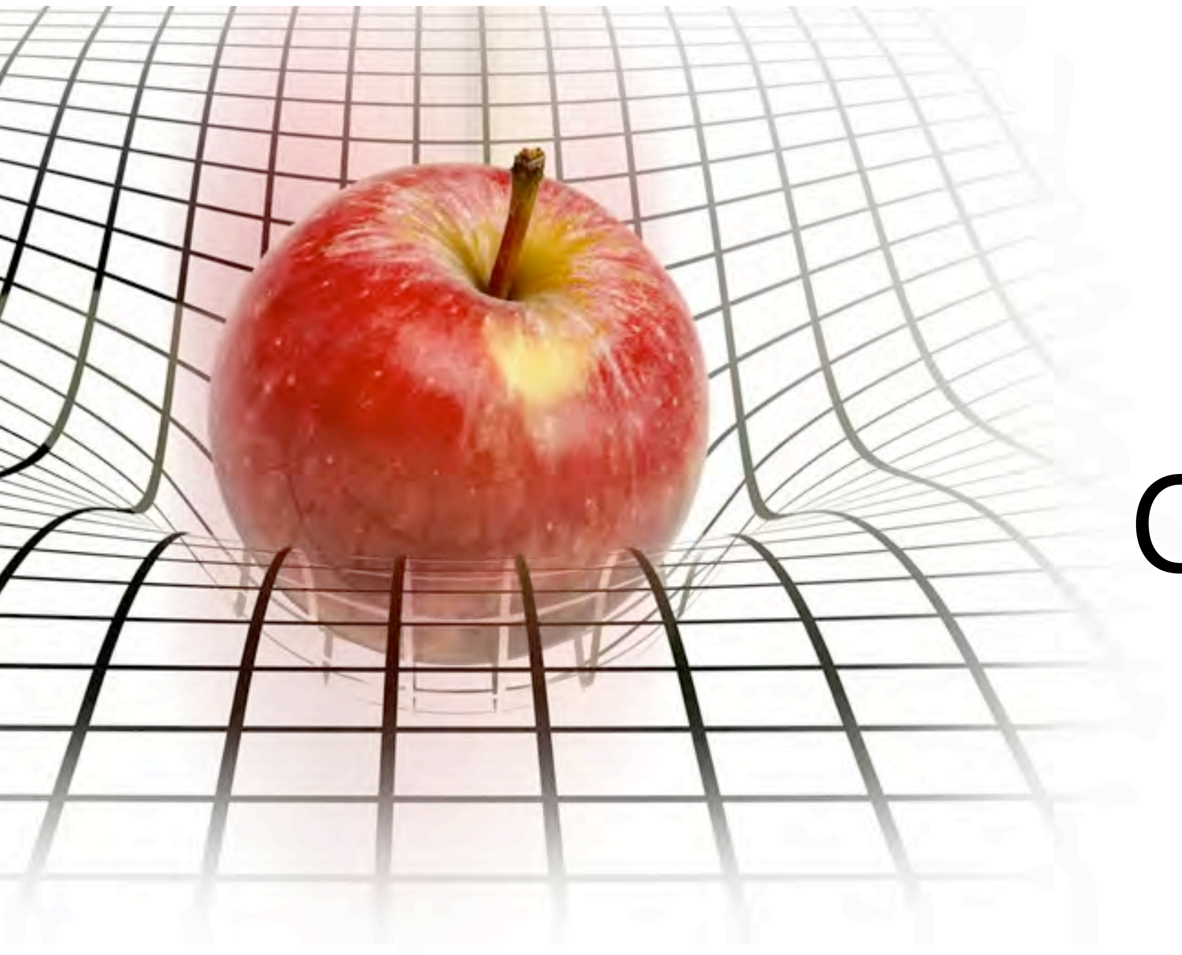
Milky Way in visible band


Milky Way in X rays
Spektr-RG–eROSITA all-sky map Nature volume 588, pages 227–231 (2020).


COSMIC OBSERVERS
IN DEVELOPMENT
ariel
(2029)
roman
(2026)
arrakihs
(2030)
plato
(2026)
new athena
(~2037)
ACTIVE
webb
(2021–)
euclid
(2023–)
hubble
(1990–)
gaia
(2013–)
cheops
(2019–)
xrism
(2023–)
xmm-newton
(1999–)
einstein probe
(2024–)
integral
(2002–)
microwaves
sub-millimetre
infrared
optical
ultraviolet
x-rays
gamma rays
LEGACY
planck
(2009-2013)
herschel
(2009-2013)
iso
(1995-1998)
akari
(2006-2011)
hipparcos
(1989-1993)
corot
(2006–2014)
iue
(1978-1996)
exosat
(1983–1986)
hitomi
(2016)
suzaku
(2005–2015)
cos-b
(1975–1982)

COSMIC OBSERVERS

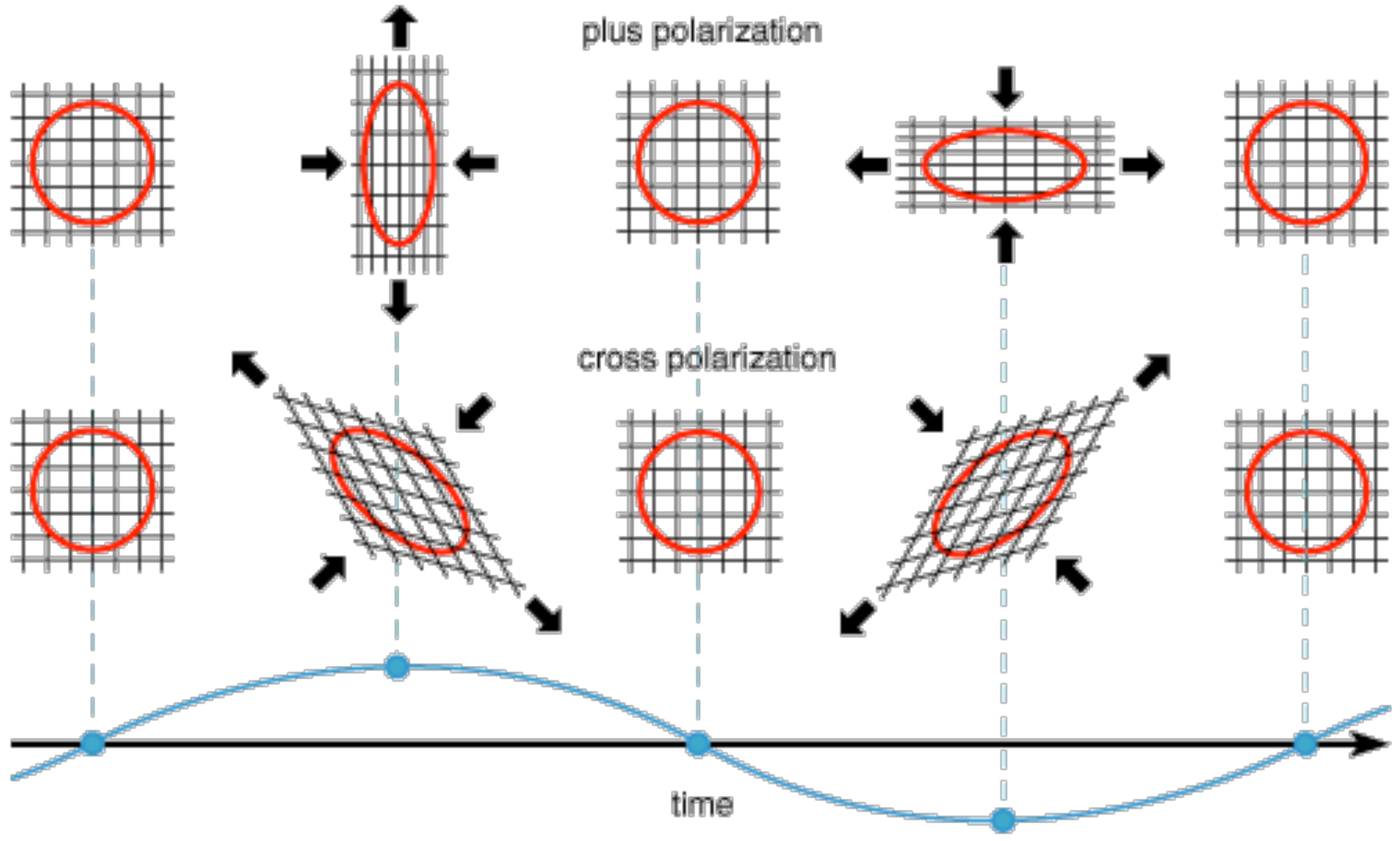
GWs (essentials)



Perturbations of space-time

travelling as waves of frequency f

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



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

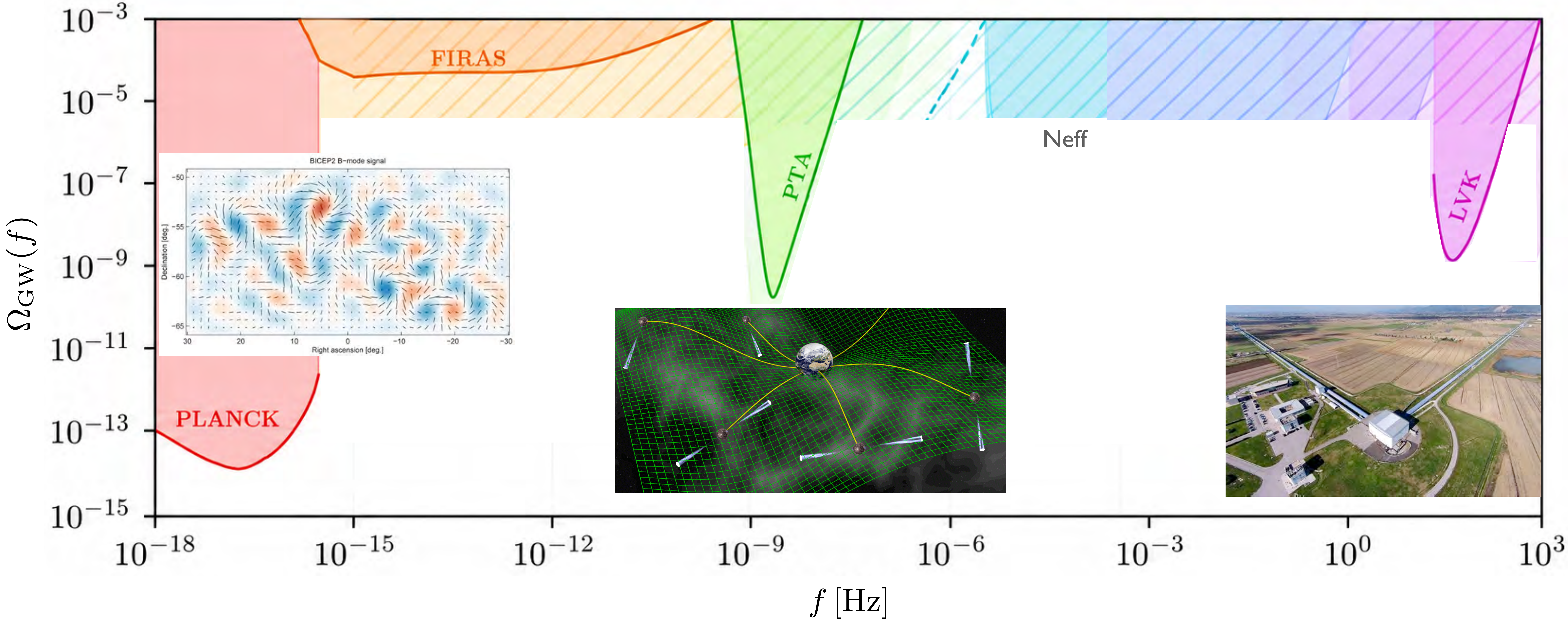
$$h_0 \approx \delta L/L \approx \delta E/E....$$

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

GWs couple to **ANYTHING** in your lab!

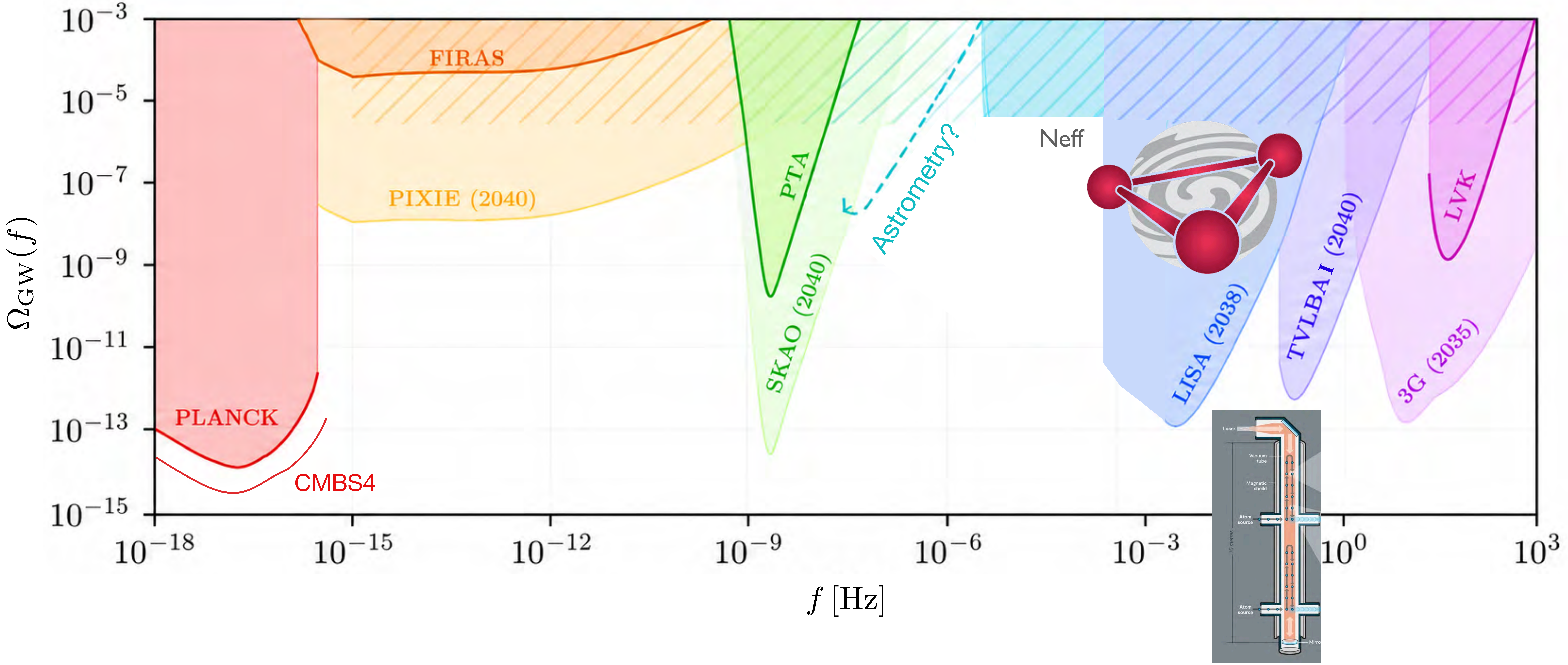
Landscape of GW detectors: today

$$\rho_{\rm gw} = \frac{c^2}{16\pi G}\left\langle \dot{h}_+^2 + \dot{h}_\times^2 \right\rangle = \frac{c^2}{32\pi G}\langle \dot{h}_{ij}\dot{h}^{ij}\rangle \qquad \Omega_{\rm gw}(f) \equiv \frac{1}{\rho_c}\frac{d\rho_{\rm gw}}{d\log f}$$



Landscape of GW detectors: today to 2045

$$\Omega_{\rm gw}(f) \equiv \frac{1}{\rho_c}\frac{d\rho_{\rm gw}}{d\log f} \qquad \rho_{\rm gw} = \frac{c^2}{16\pi G}\left\langle \dot h_+^2 + \dot h_\times^2 \right\rangle = \frac{c^2}{32\pi G}\langle \dot h_{ij}\dot h^{ij}\rangle$$



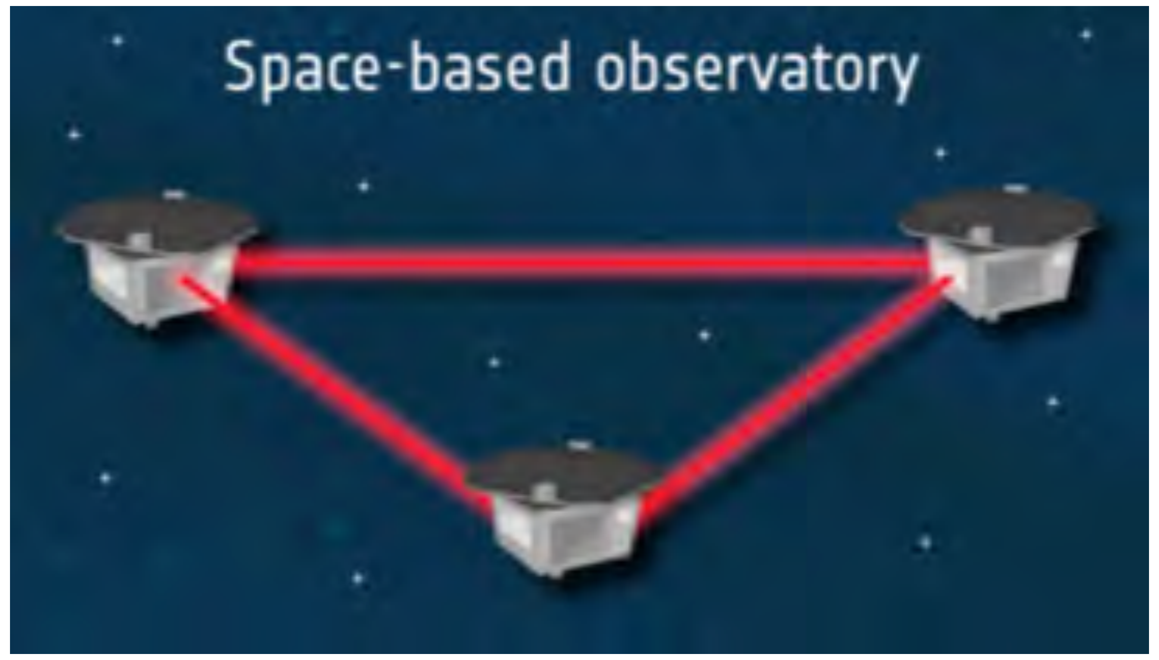
Very large baseline atomic interferometers

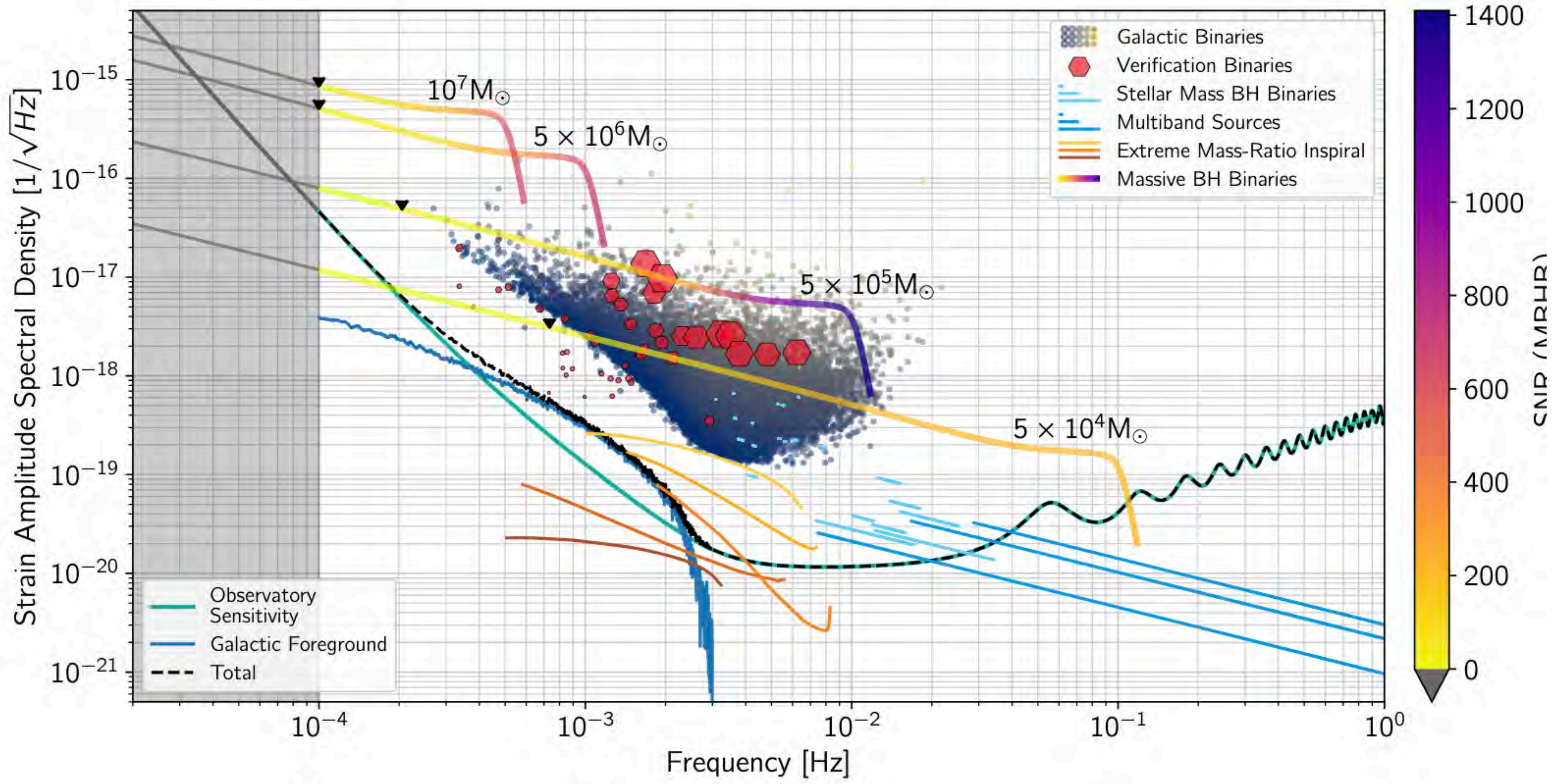
Searches for fundamental physics in LISA/3G

SM:

Astrophysical models of black holes (of several masses)
Astrophysical models of stars (white dwarfs, neutron stars…)
Supernovae explosions
…

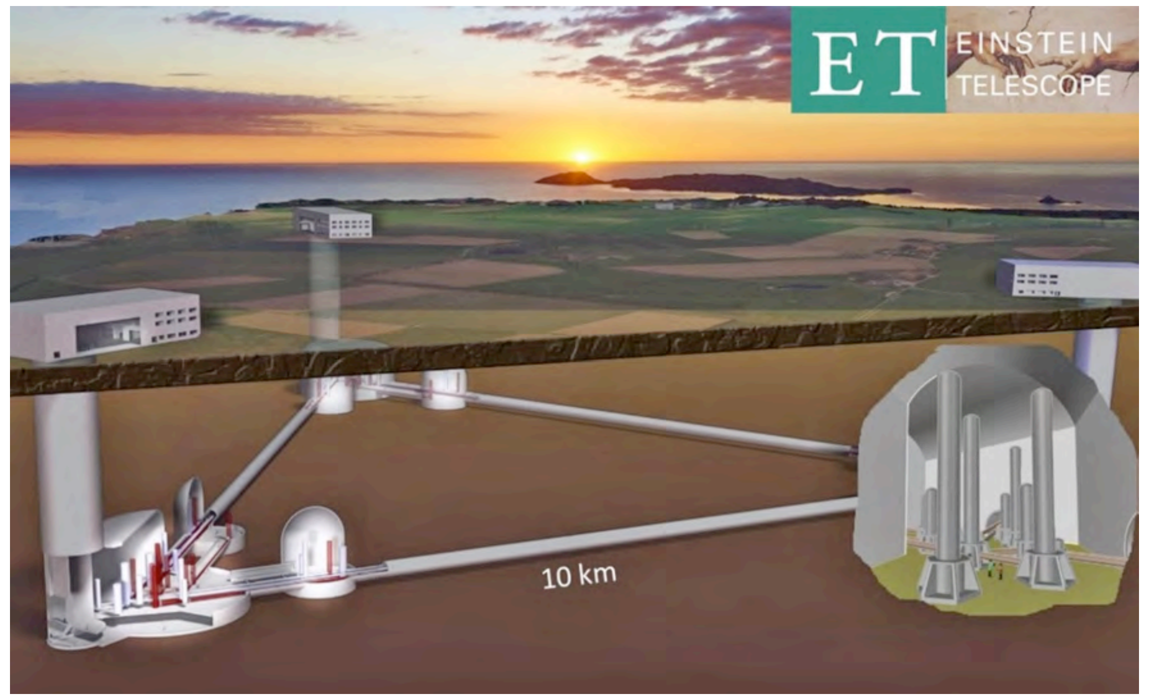
LISA

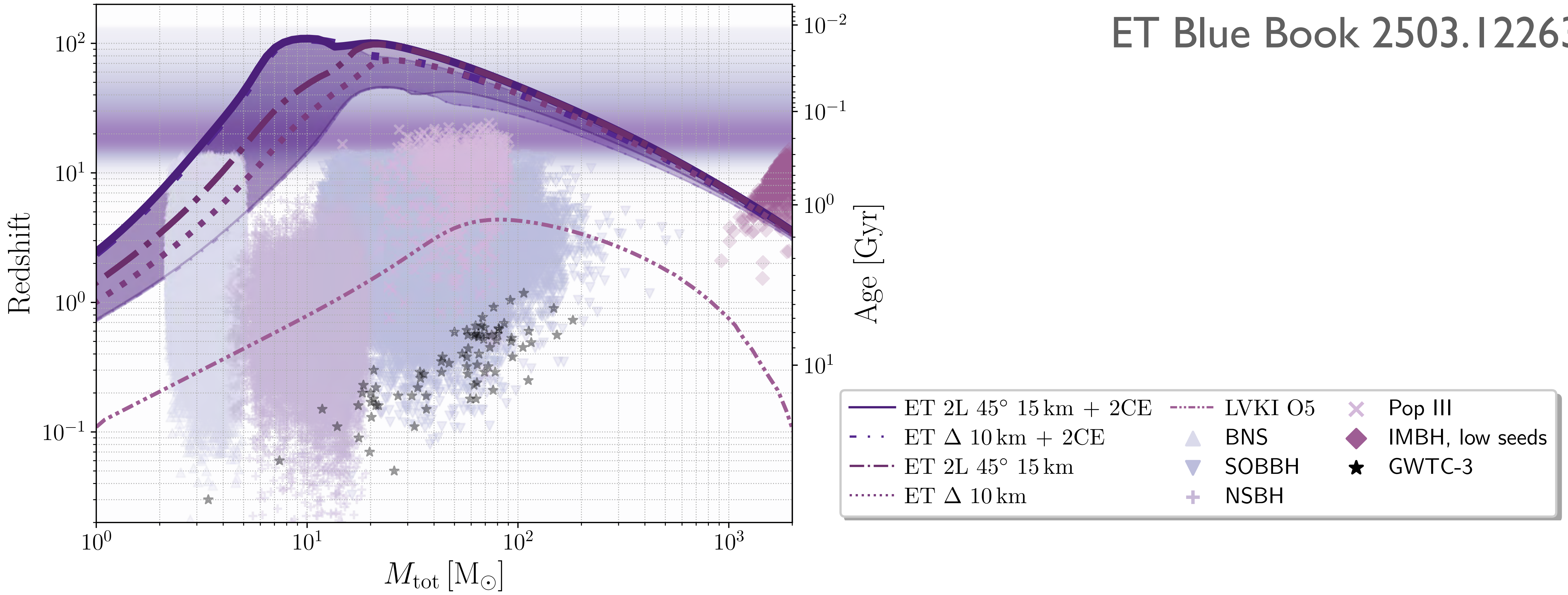




LISA Red Book 2402.07571

3G





ET Blue Book 2503.12263

Searches for fundamental physics in LISA/3G

SM: Astrophysical models of black holes (of several masses)
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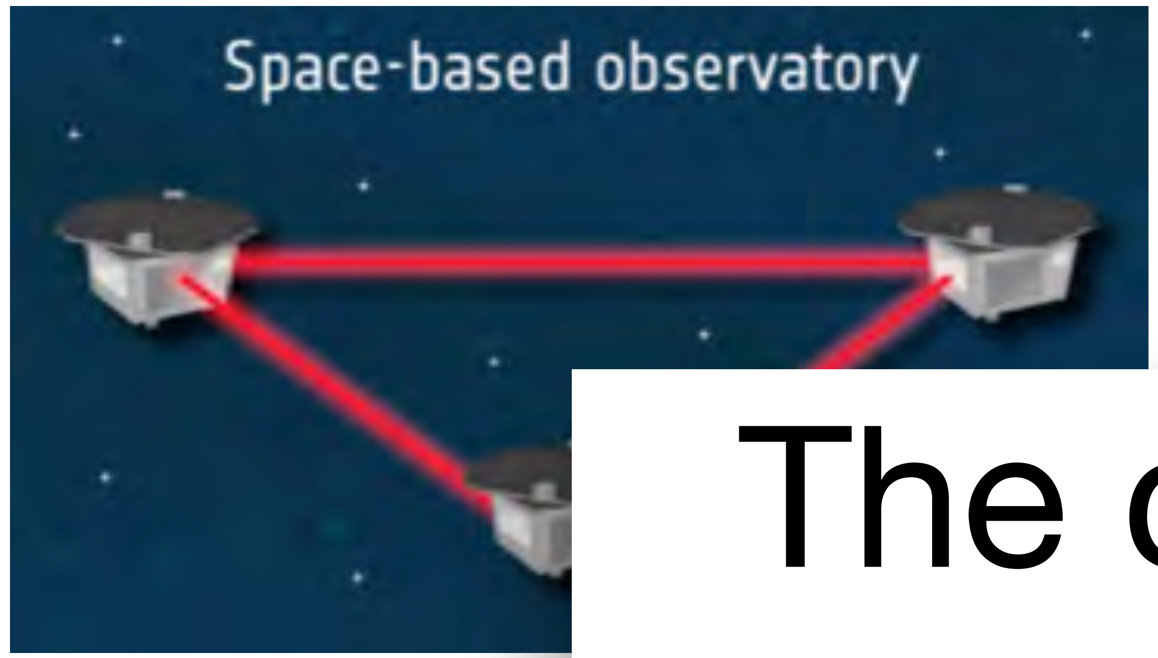
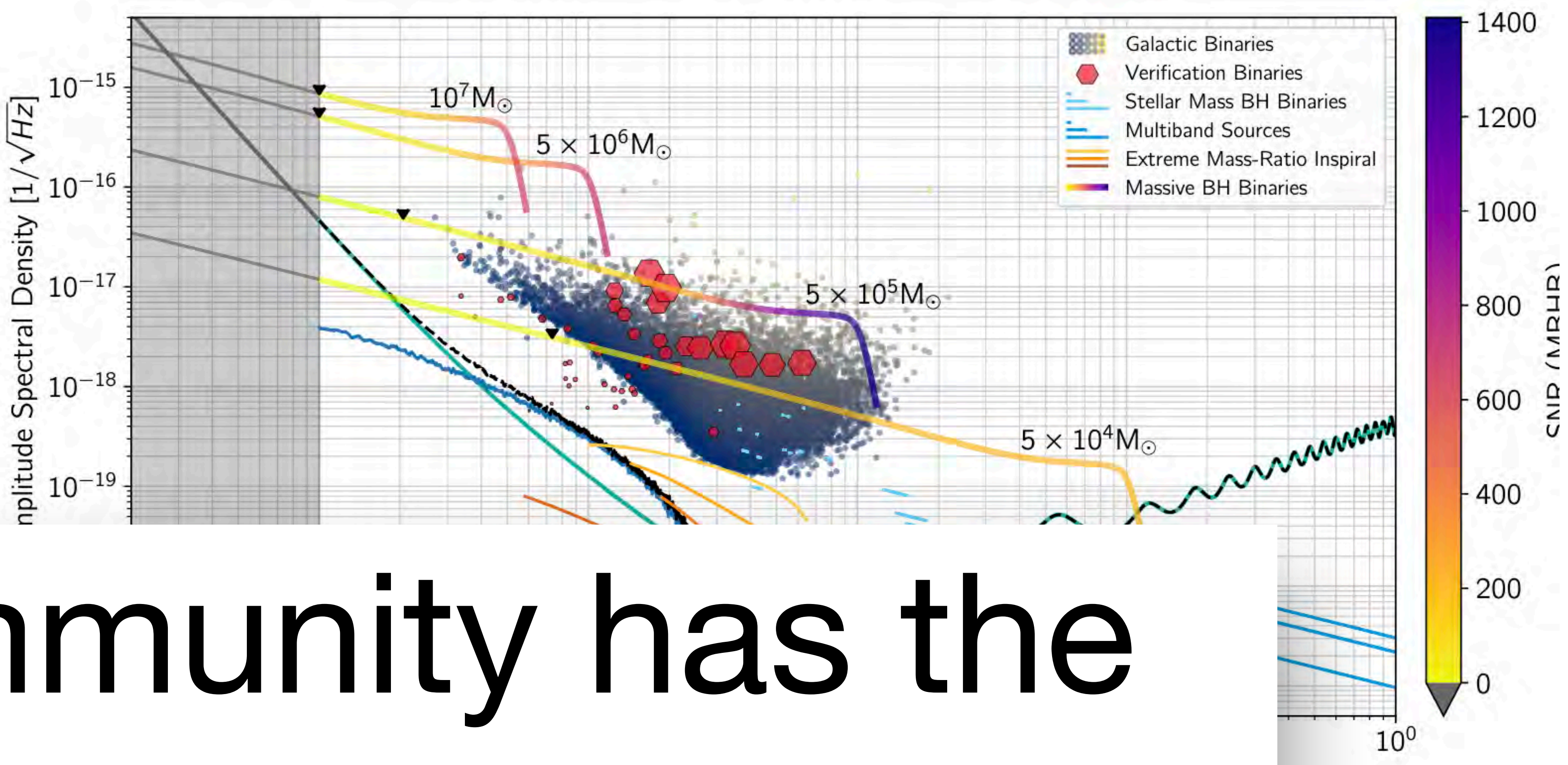


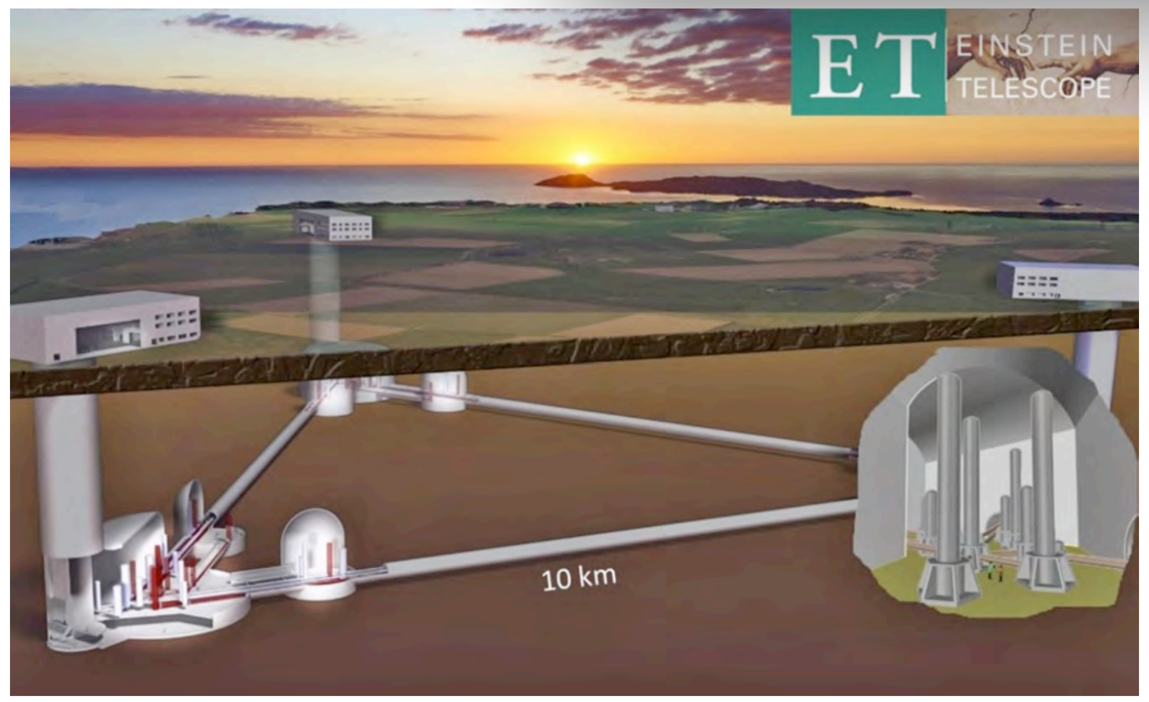


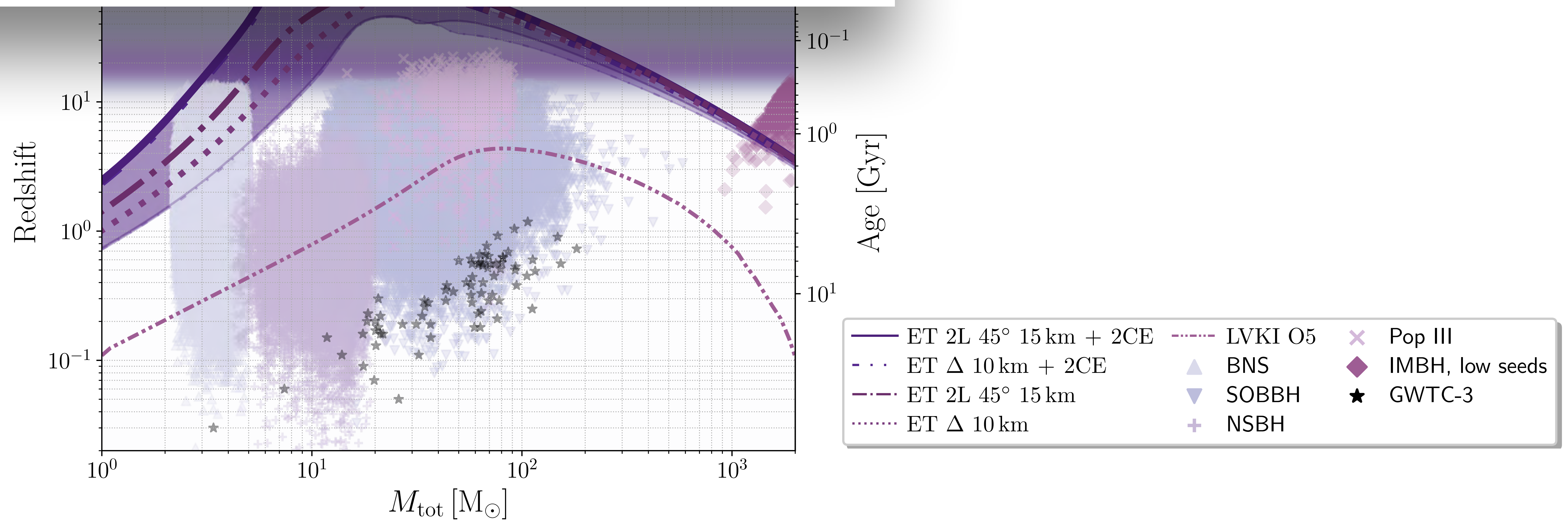
LISA Red Book 2402.07571

The community has the next 15 years clear for **SM**

ET Blue Book 2503.12263

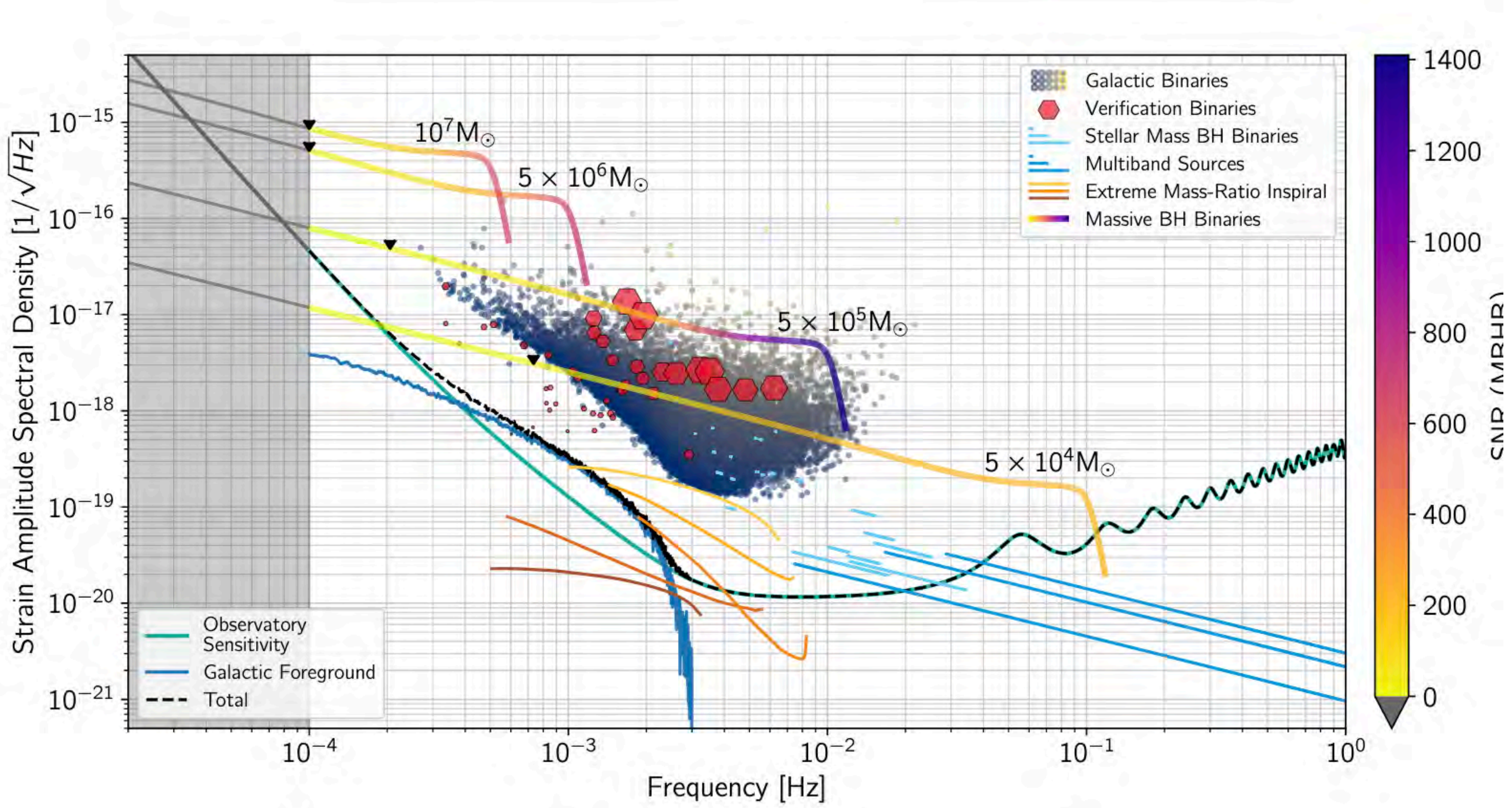
3G

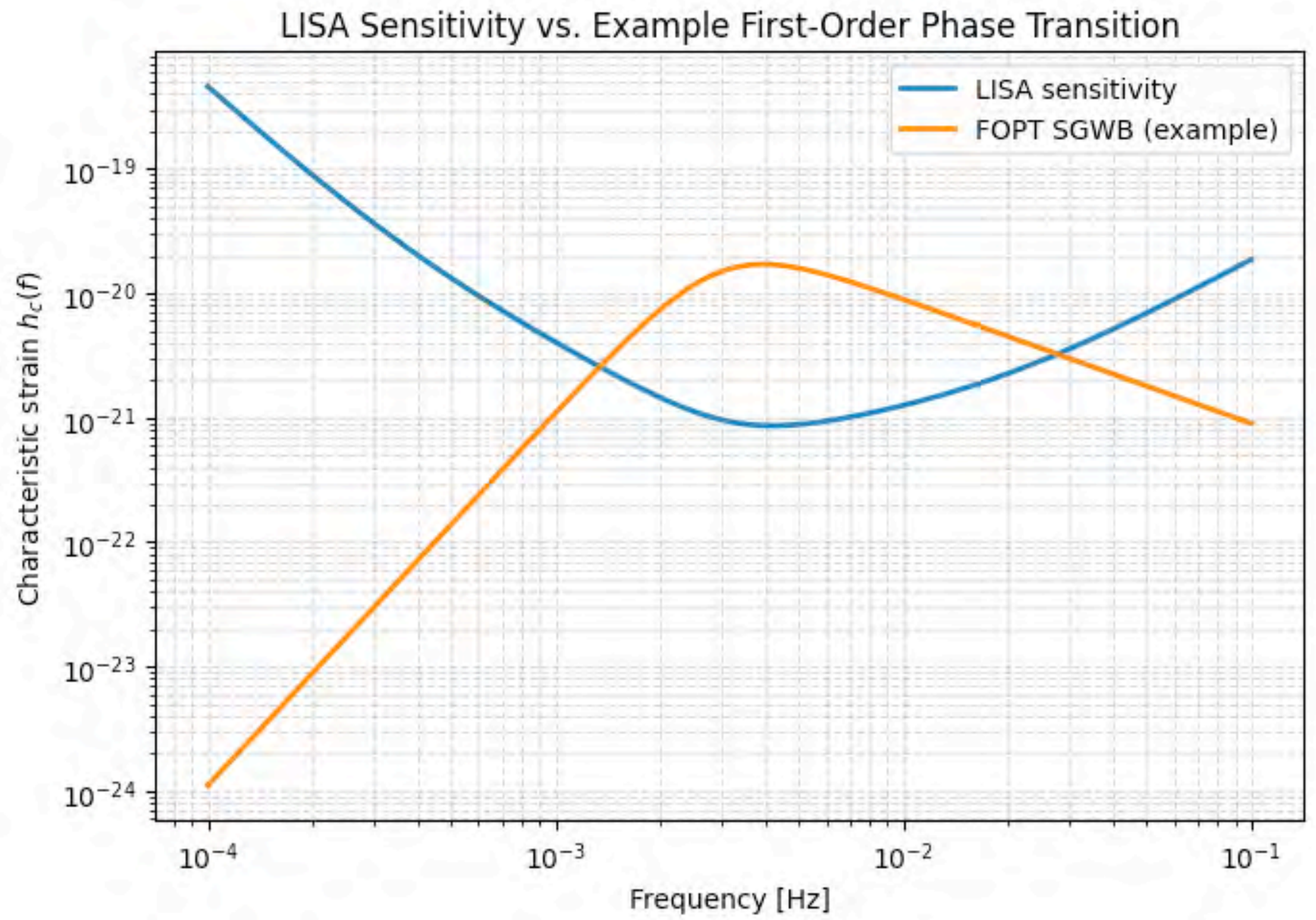




Searches for fundamental physics in LISA/3G

If one looks for **new physics** all the bands from may be too loud





BSM: Early Universe: inflation, new particles at high *E*

Signals from dark matter

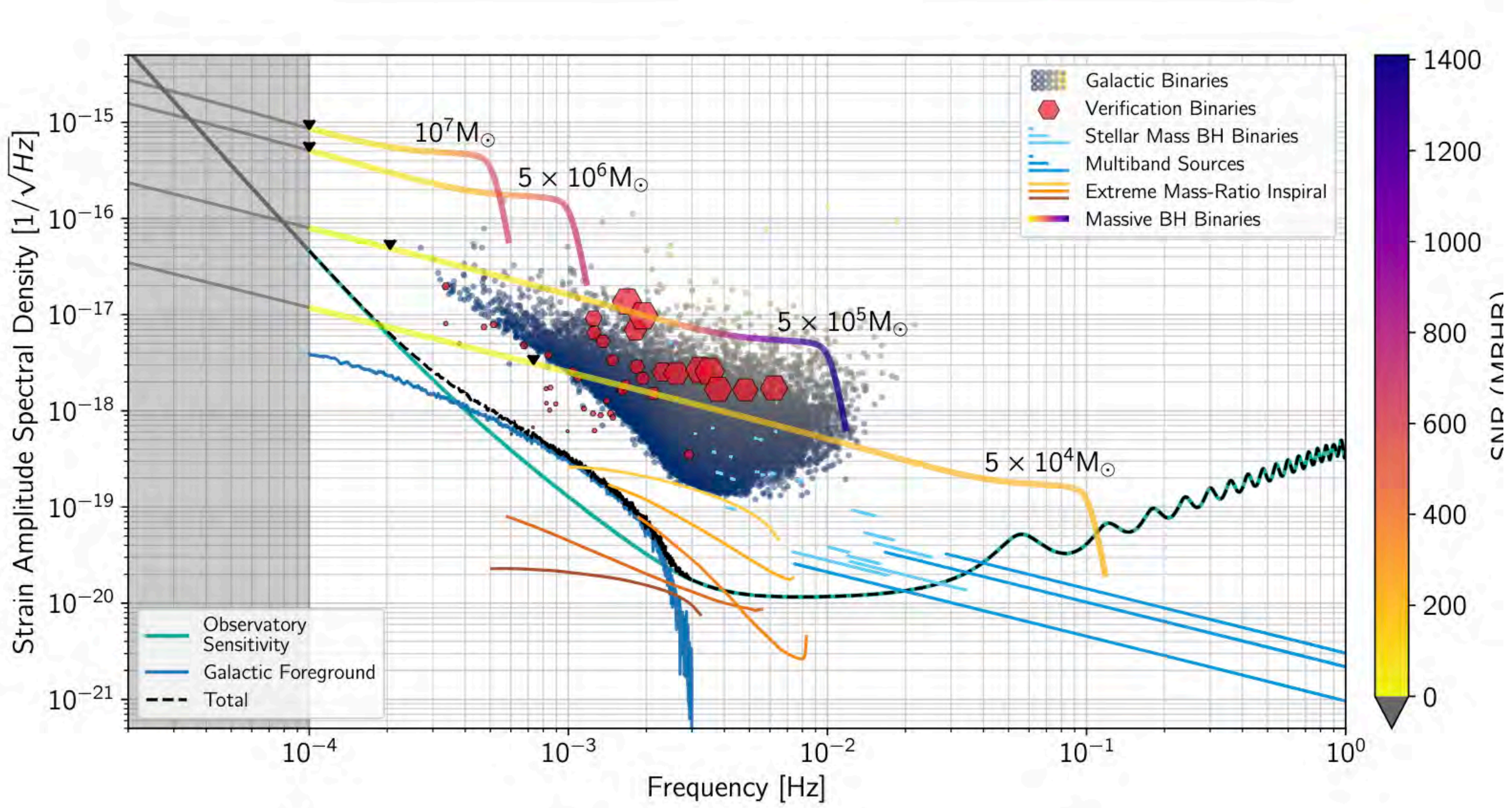
Signals from new particles

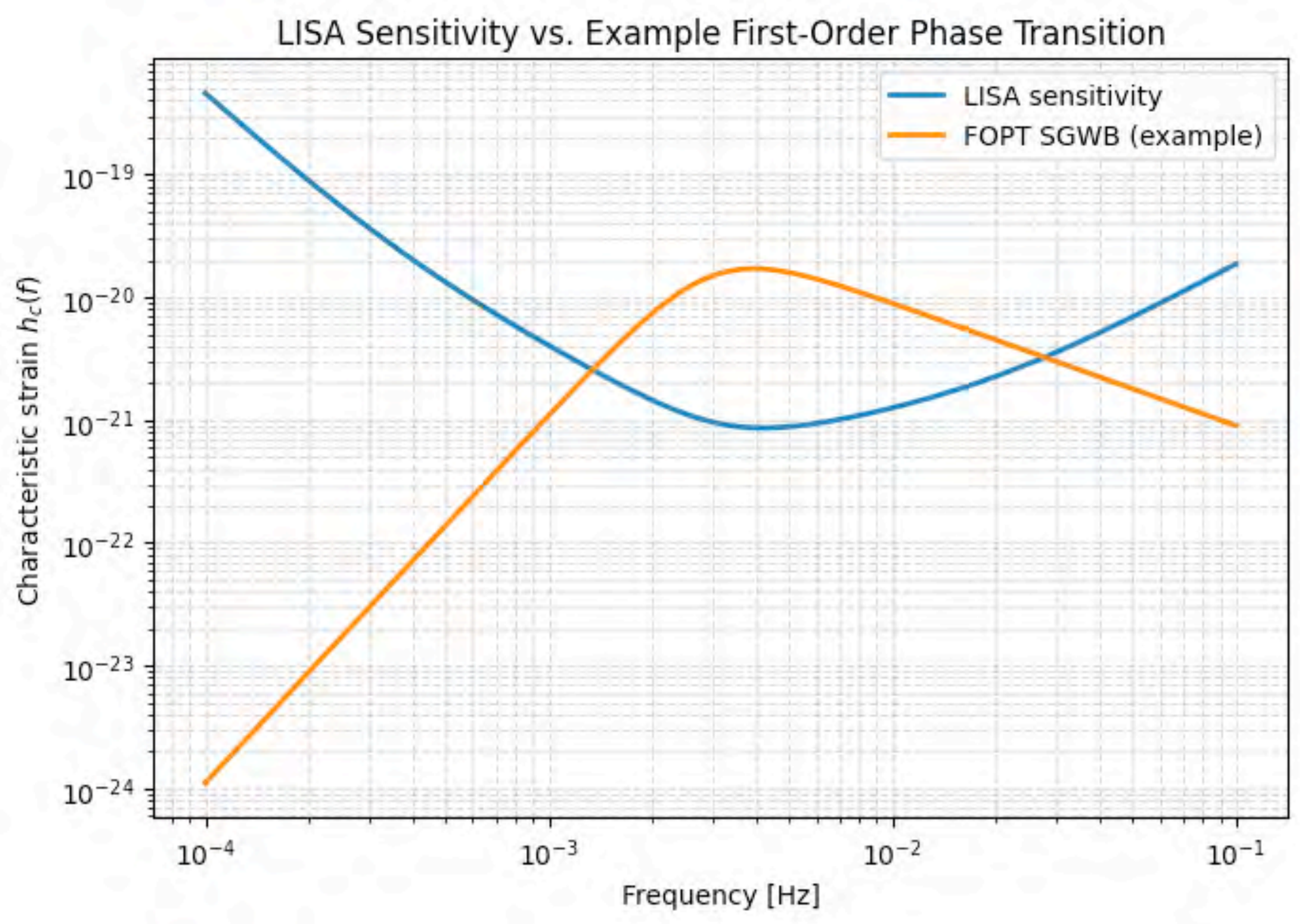
Fundamental properties of gravity

...

Searches for fundamental physics in LISA/3G

If one looks for **new physics** all the bands from may be too loud





BSM: Early Universe: inflation, new particles at high *E*

Signals from dark matter

Signals from new particles

How do we access **BSM?**

...

tough global fits
(as in hadron colliders)

move to other bands

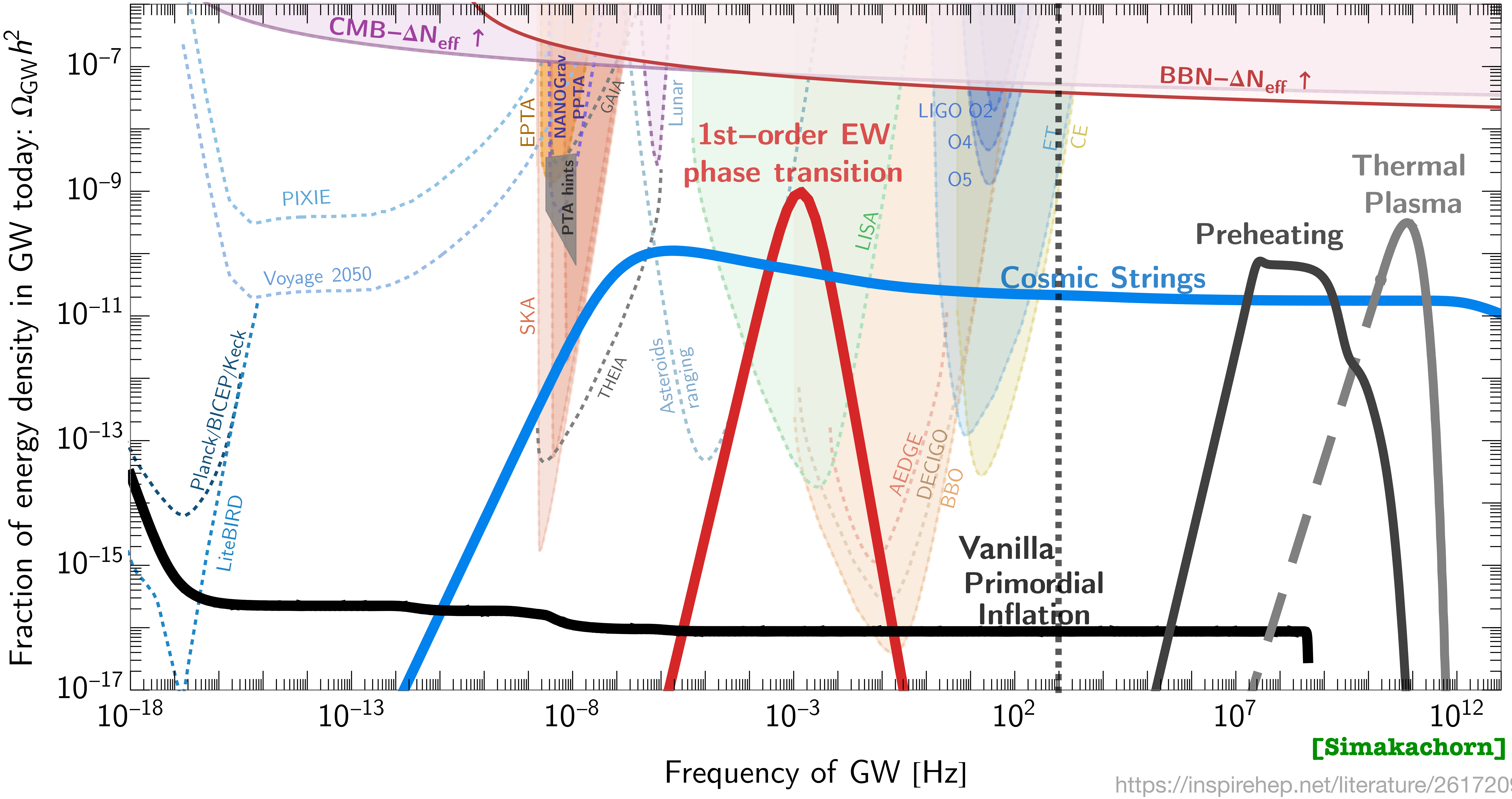
Landscape of GW detectors: today to 2045

$$\Omega_{\rm gw}(f) \equiv \frac{1}{\rho_c}\frac{d\rho_{\rm gw}}{d\log f} \qquad \rho_{\rm gw} = \frac{c^2}{16\pi G}\left\langle \dot{h}_+^2 + \dot{h}_\times^2 \right\rangle = \frac{c^2}{32\pi G}\langle \dot{h}_{ij}\dot{h}^{ij}\rangle$$

Very large baseline atomic interferometers

Gravitational waves for fundamental physics

Gravitational waves are a messenger of every violent process in the Universe



[Simakachorn]

https://inspirehep.net/literature/2617209

Gravitational waves for fundamental physics

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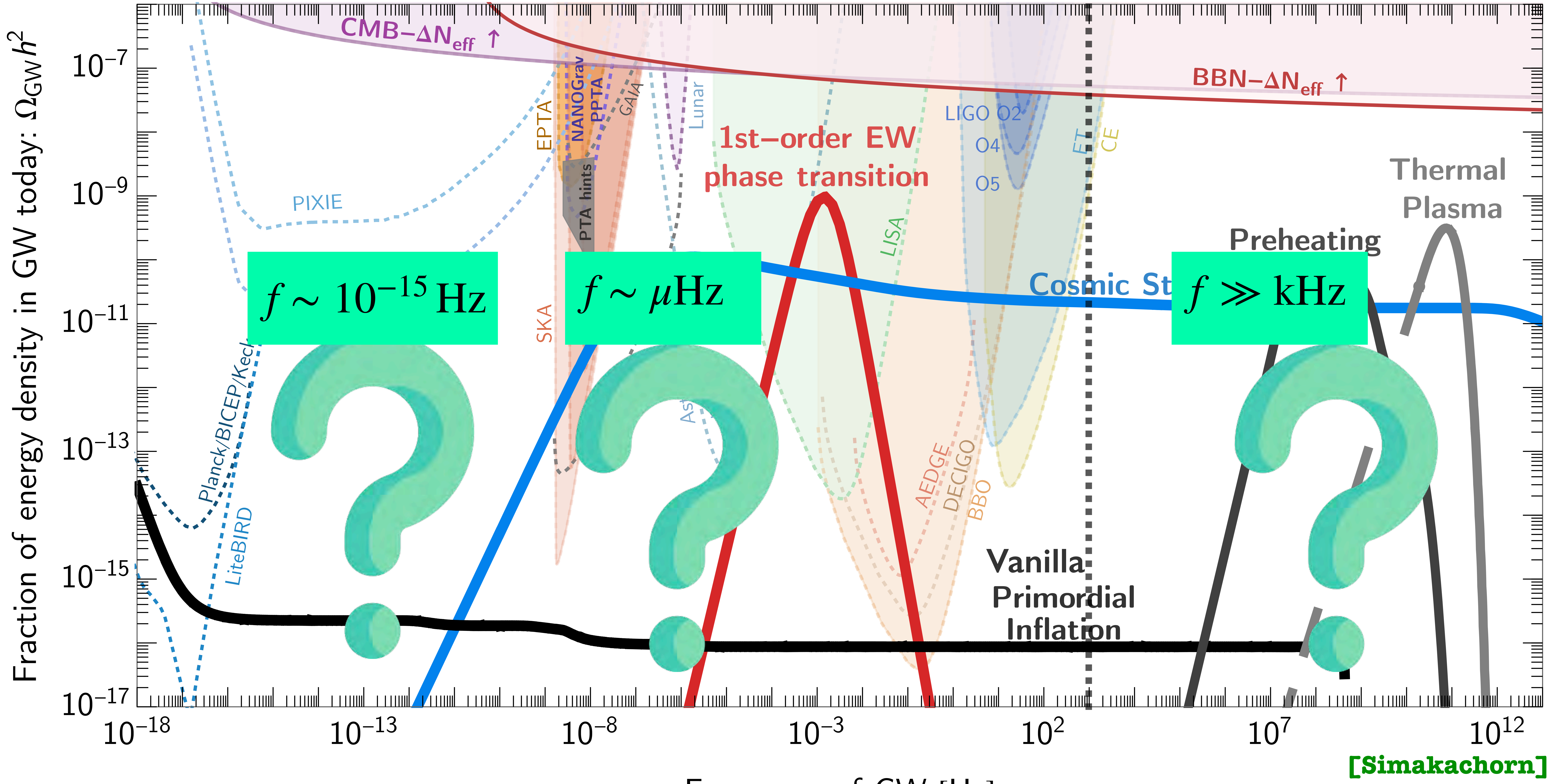
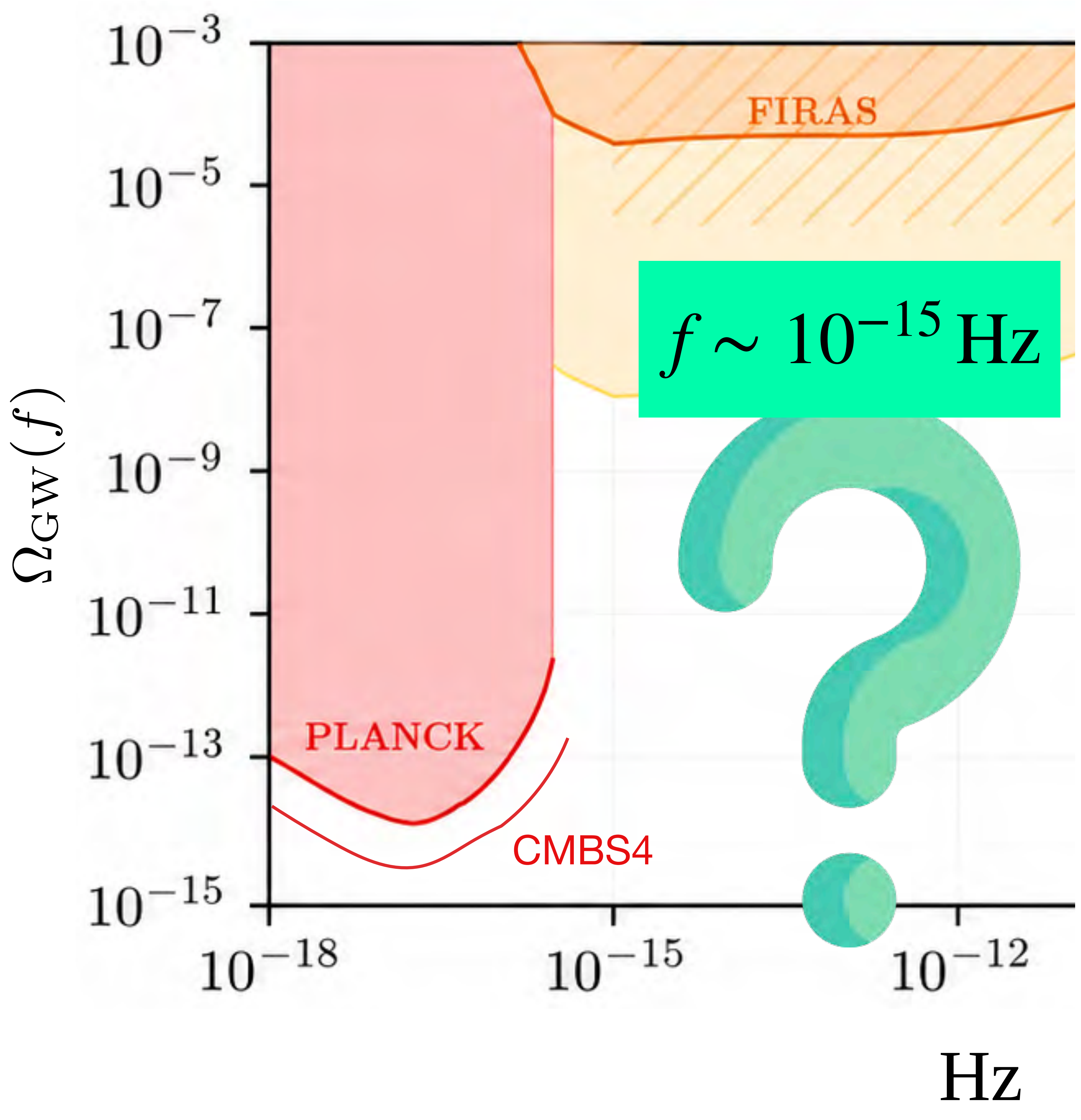


https://inspirehep.net/literature/2617209

femtoHz to picoHz



This is the **less** explored:

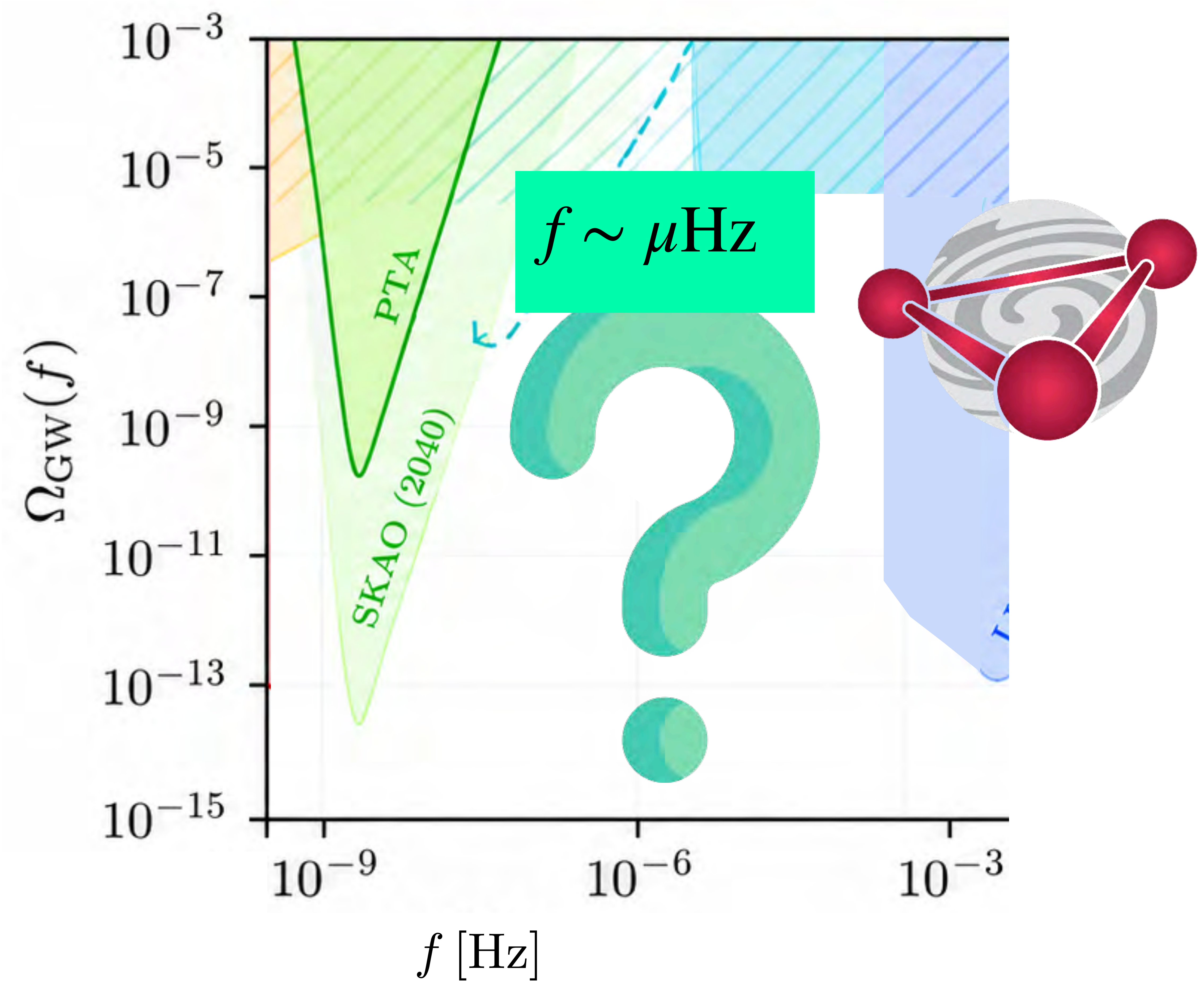
- No strong astrophysical sources
- Not easy to get BSM here compatible with other bounds
- Hard to observe

(Mpc wavelength or 1/kyr to 1/Myr in frequency)

microHz to 0.1 mHz

This is the **Higgs-like** band:

- guaranteed Physics by the corner
- reasonable ideas for searches
- possible new Physics



microHz to 0.1 mHz

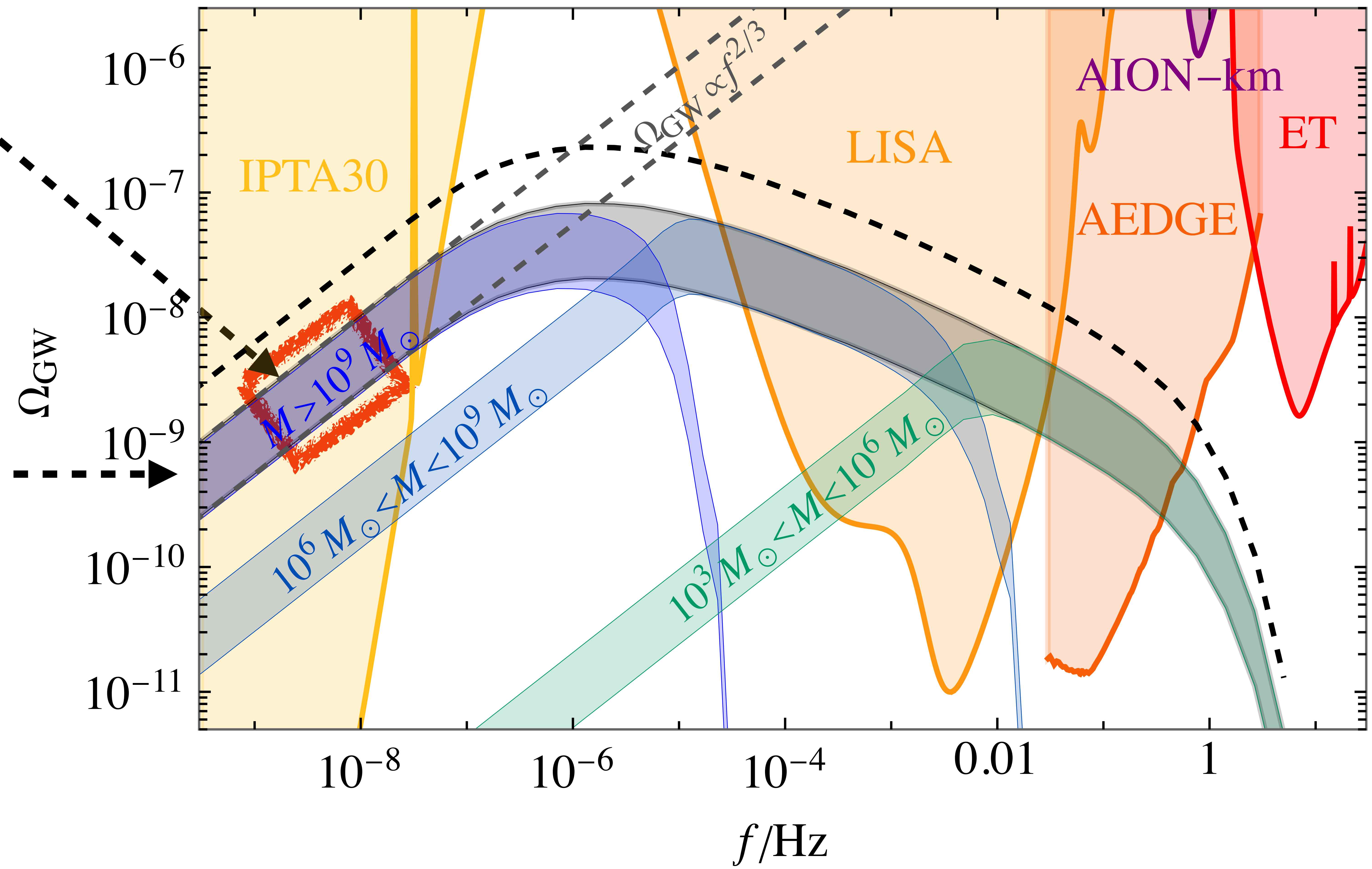
This is the **Higgs-like** band:

- guaranteed Physics by the corner
- reasonable ideas for searches

2301.13854 [astro-ph.CO] Ellis et al

PTA Evidence 2023

Is it a signal of SMBHBs?

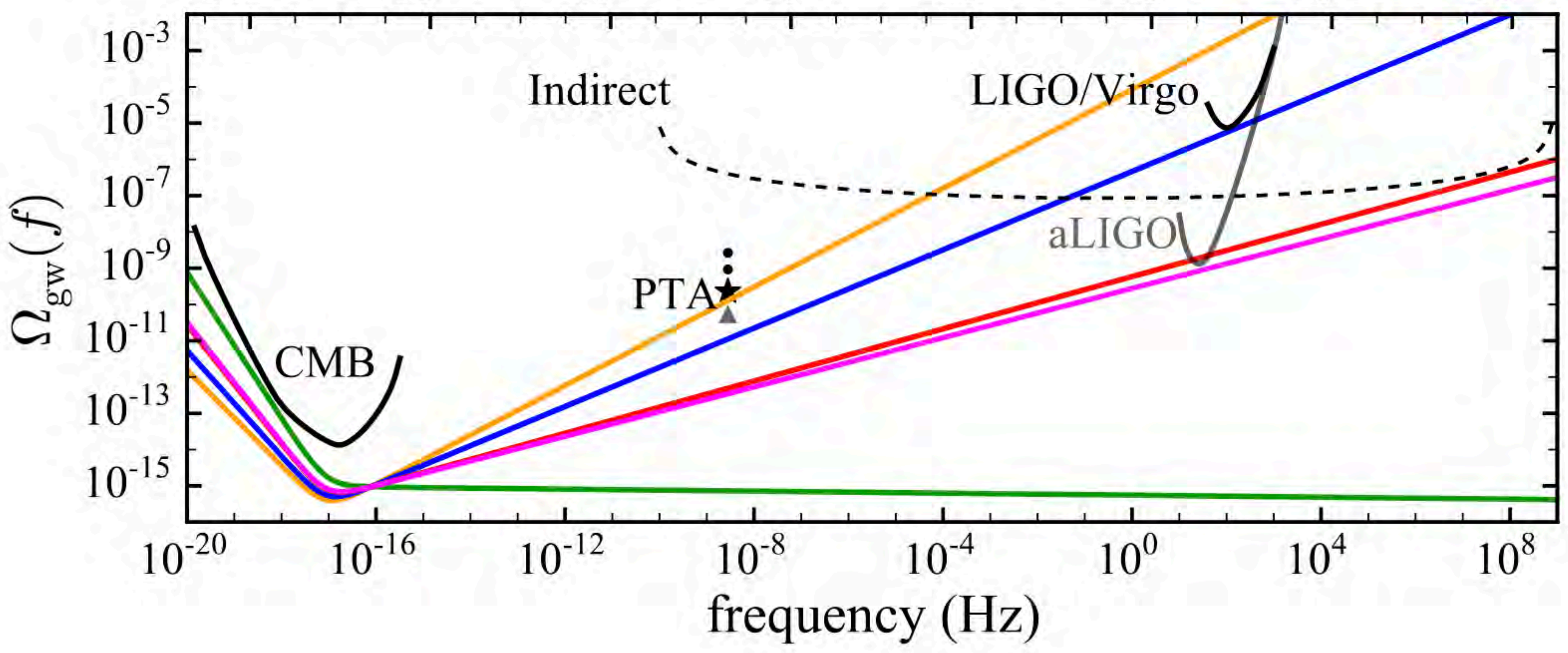


microHz to LISA band

Plentiful new Physics possible

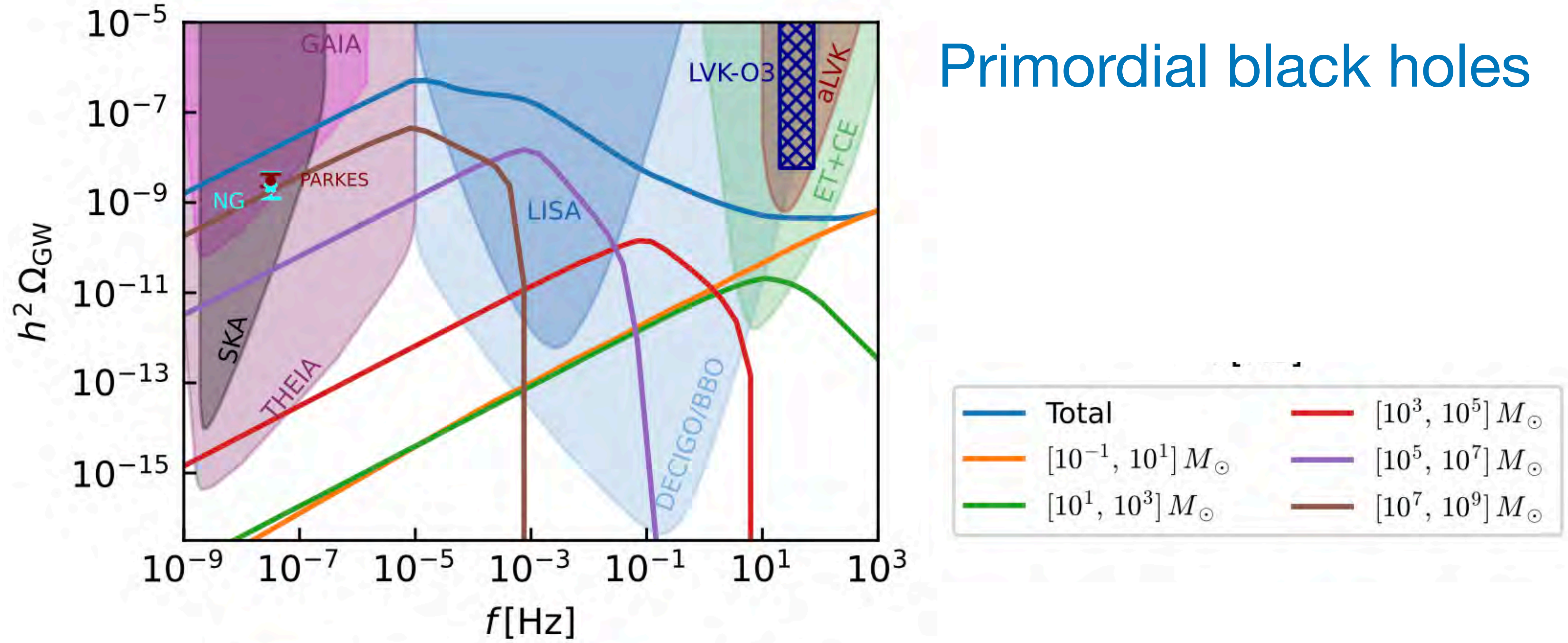
Inflation

Lasky et al PRX 6, 011035 (2016)



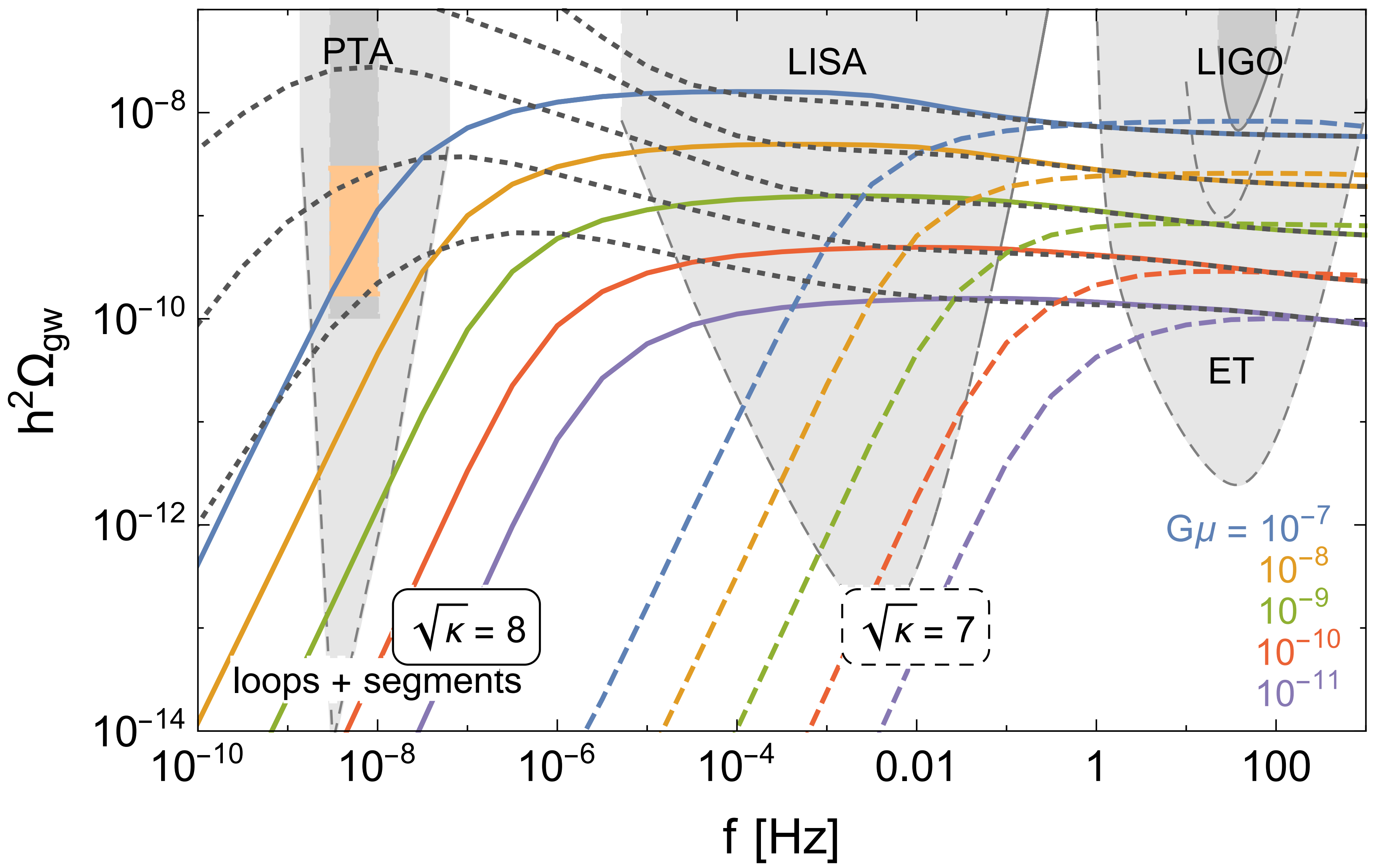
Braglia et al. JCAP 12 (2021) 12

Primordial black holes



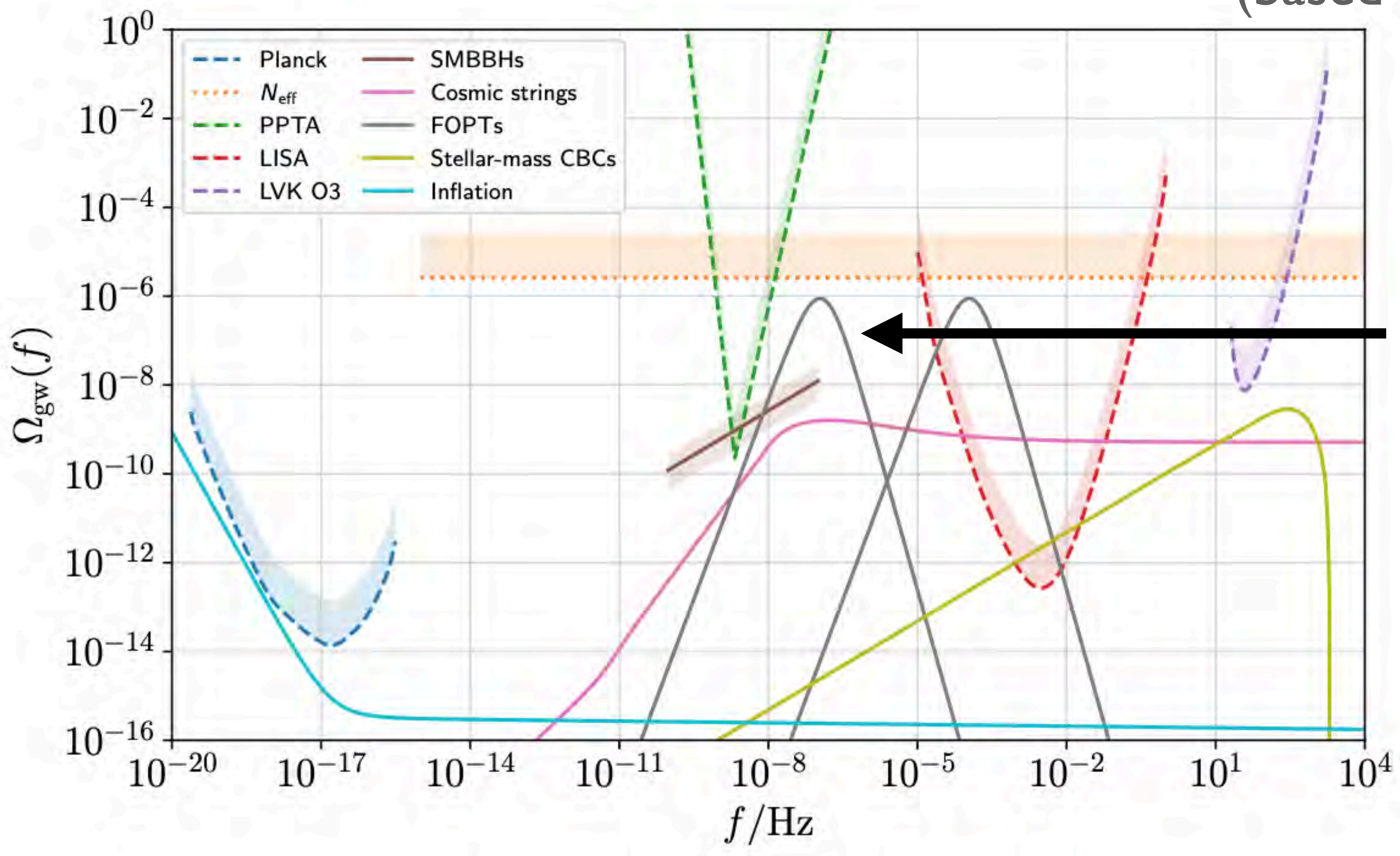
Cosmic Strings

Buchmuller et al. 2107.04578



FOPT

Renzini et al 2202.00178
(based on 1512.06239)

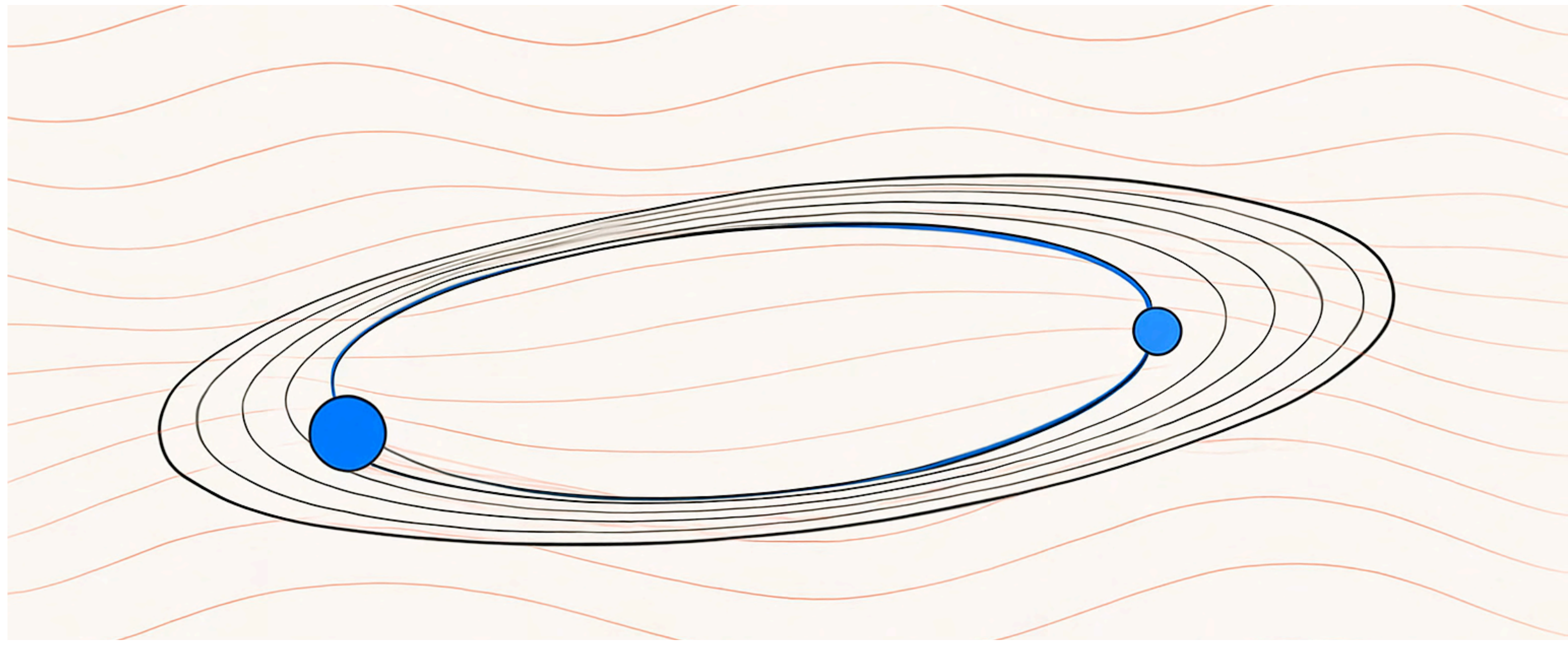


T~200 MeV

Our proposal for μHz band: binary resonance!

gravitational waves affect gravitationally bound systems

$$\ddot{r}^i = -\,\delta R^i{}_{0j0}\, r^j$$
$$\lambda \gg a$$



DB, **A. Jenkins**, 2107.04061, 2107.04063
J. Foster, DB et al., arXiv: 2504.15334 [astro-ph.CO]
Foster, DB et al., arXiv:2504.16988 [gr-qc]
X. Xue, DB, et al. to appear

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

Perturbing Gravitational Wave

Newtonian Potential

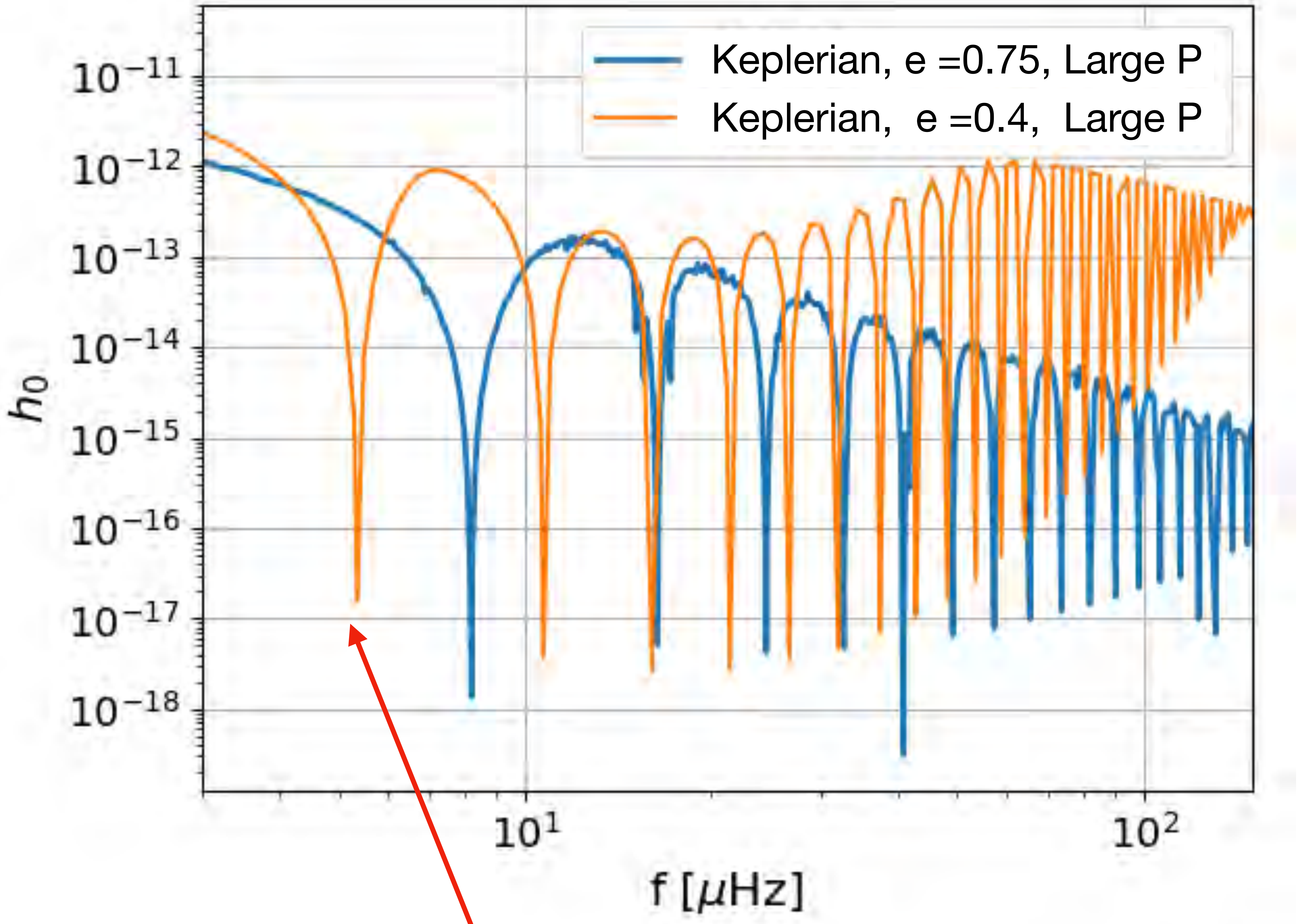
$h \sim \cos(2\pi f t)$
$r \sim e\cos(2\pi t/P)$
possible resonances at $f=n/P$

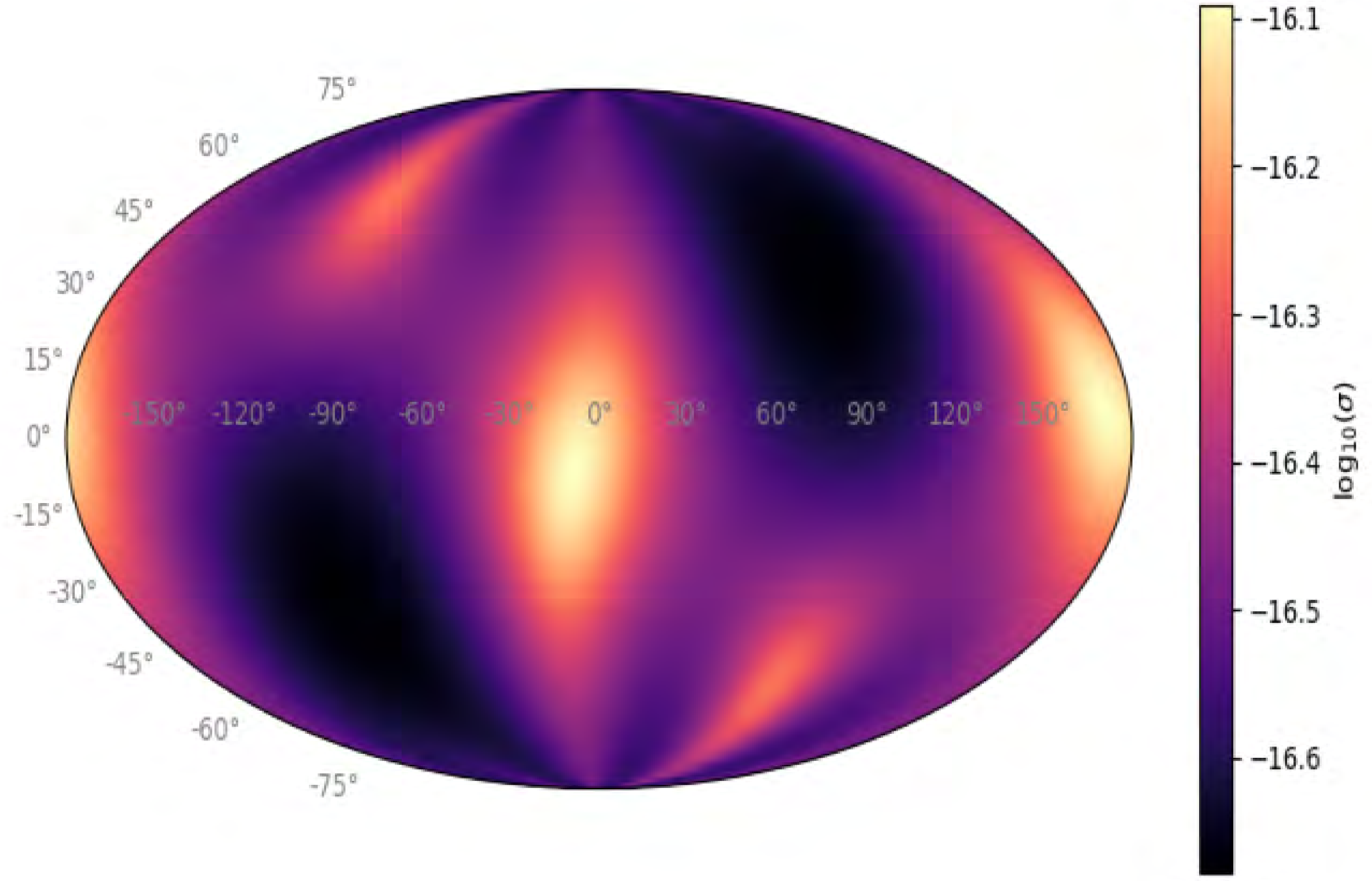
μHz

~ few days

Response of the system

Foster, DB et al., arXiv: 2504.15334 [astro-ph.CO]
Foster, DB et al., arXiv:2504.16988 [gr-qc]
Xue, DB, et al. to appear

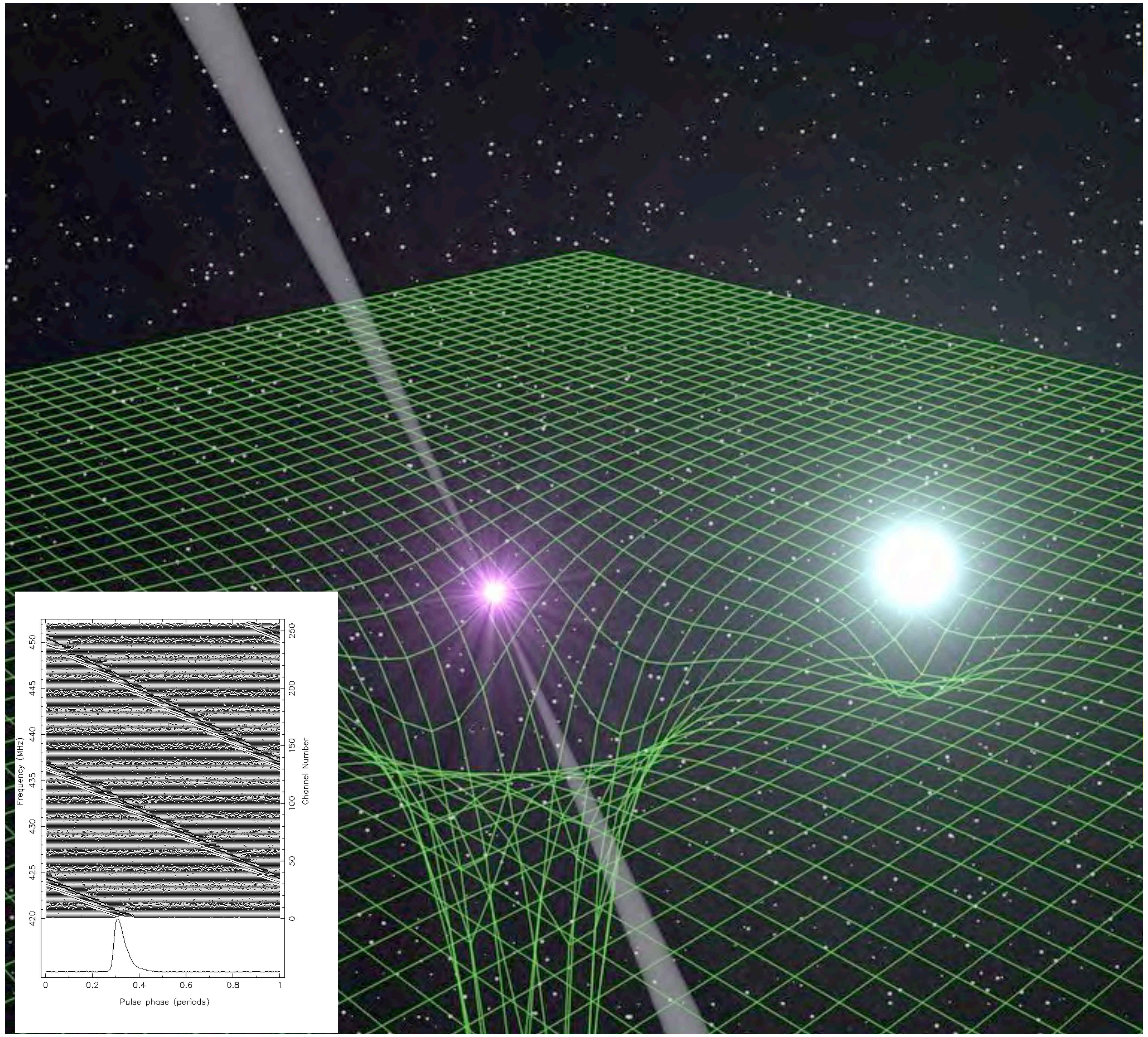




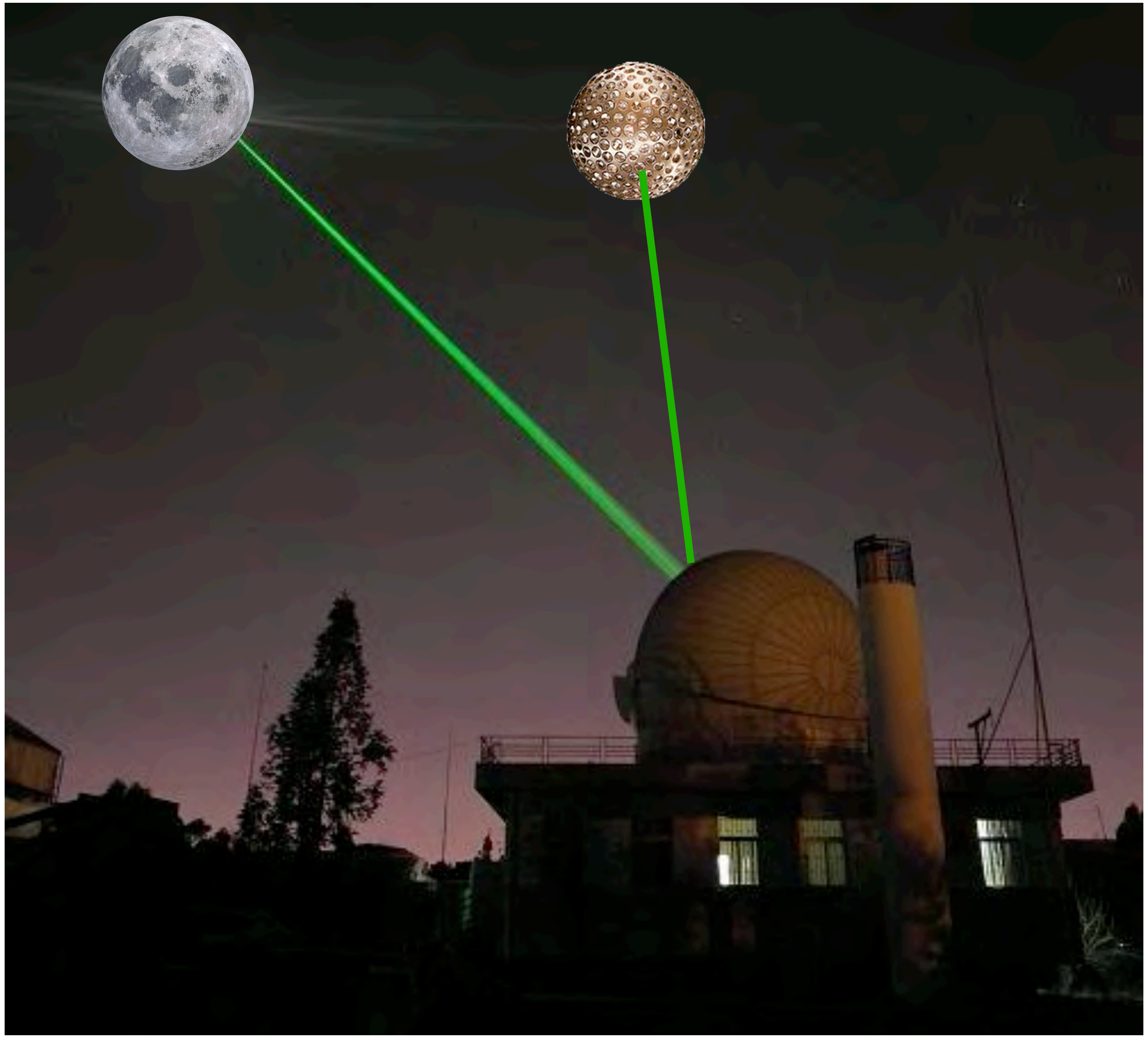
Resonant responses: for the μ**Hz** band, *P* from **days** to **months** (Moon)

Two probes: precise timing of binaries

timing of binary pulsars



lunar and satellite laser ranging



Our estimates from 2025 for 2035

Foster, DB et al., arXiv: 2504.15334 [astro-ph.CO]
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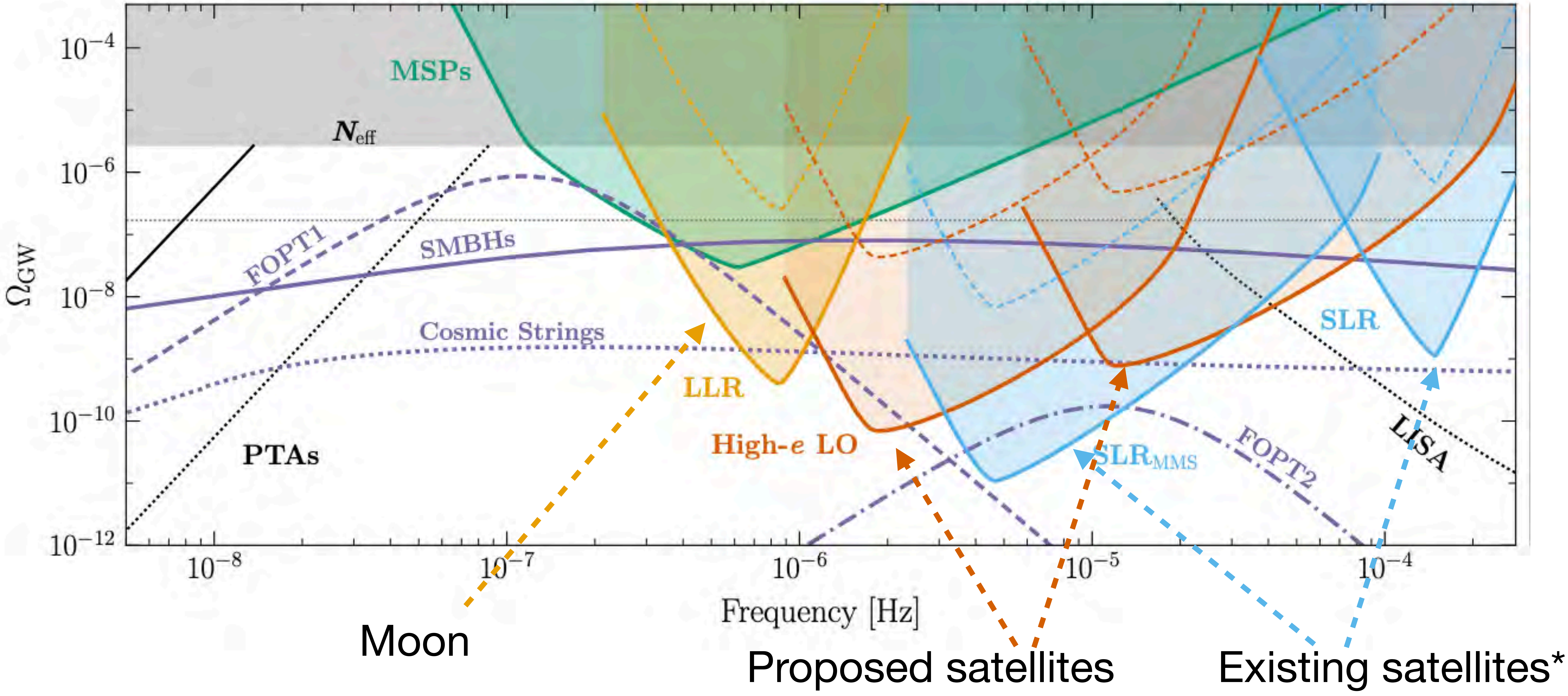
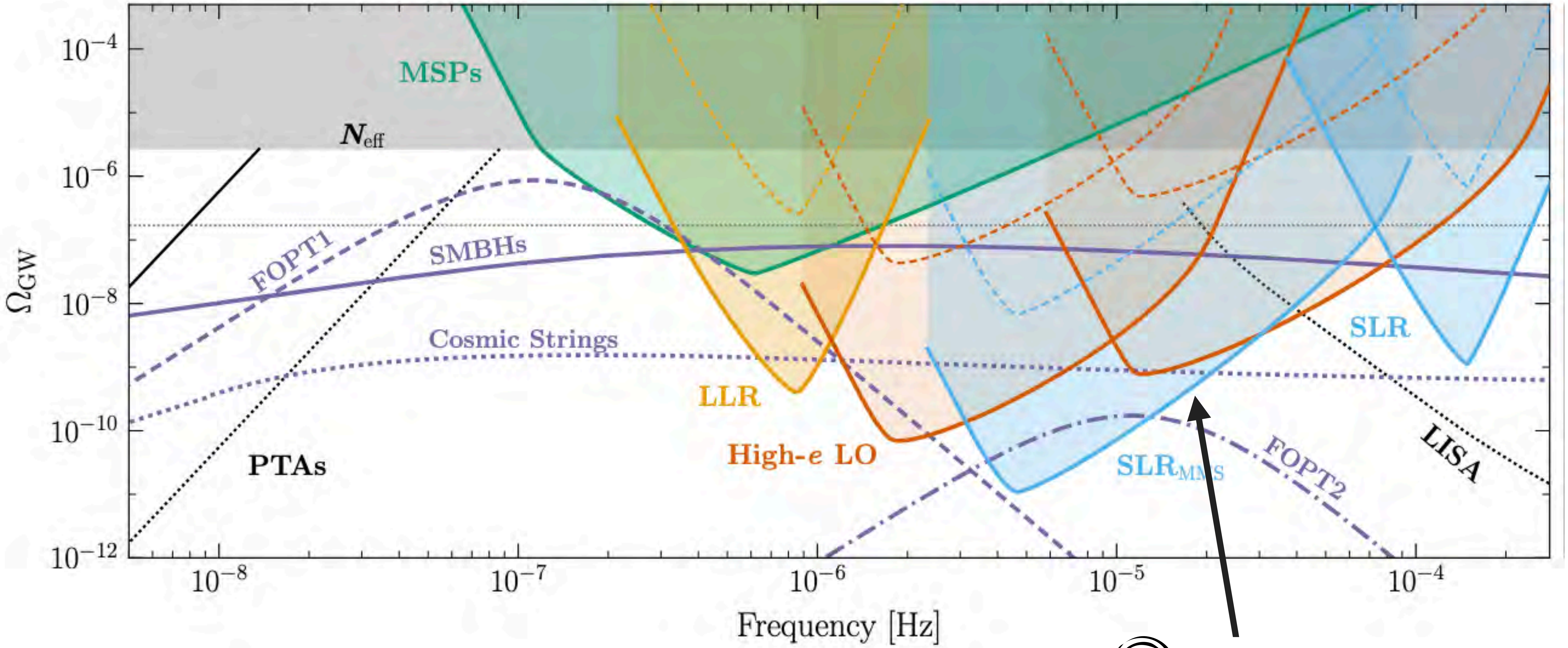


* if they were tracked at levels at which LAGEOS is tracked + idealized data analysis

Our estimates from 2025 for 2035

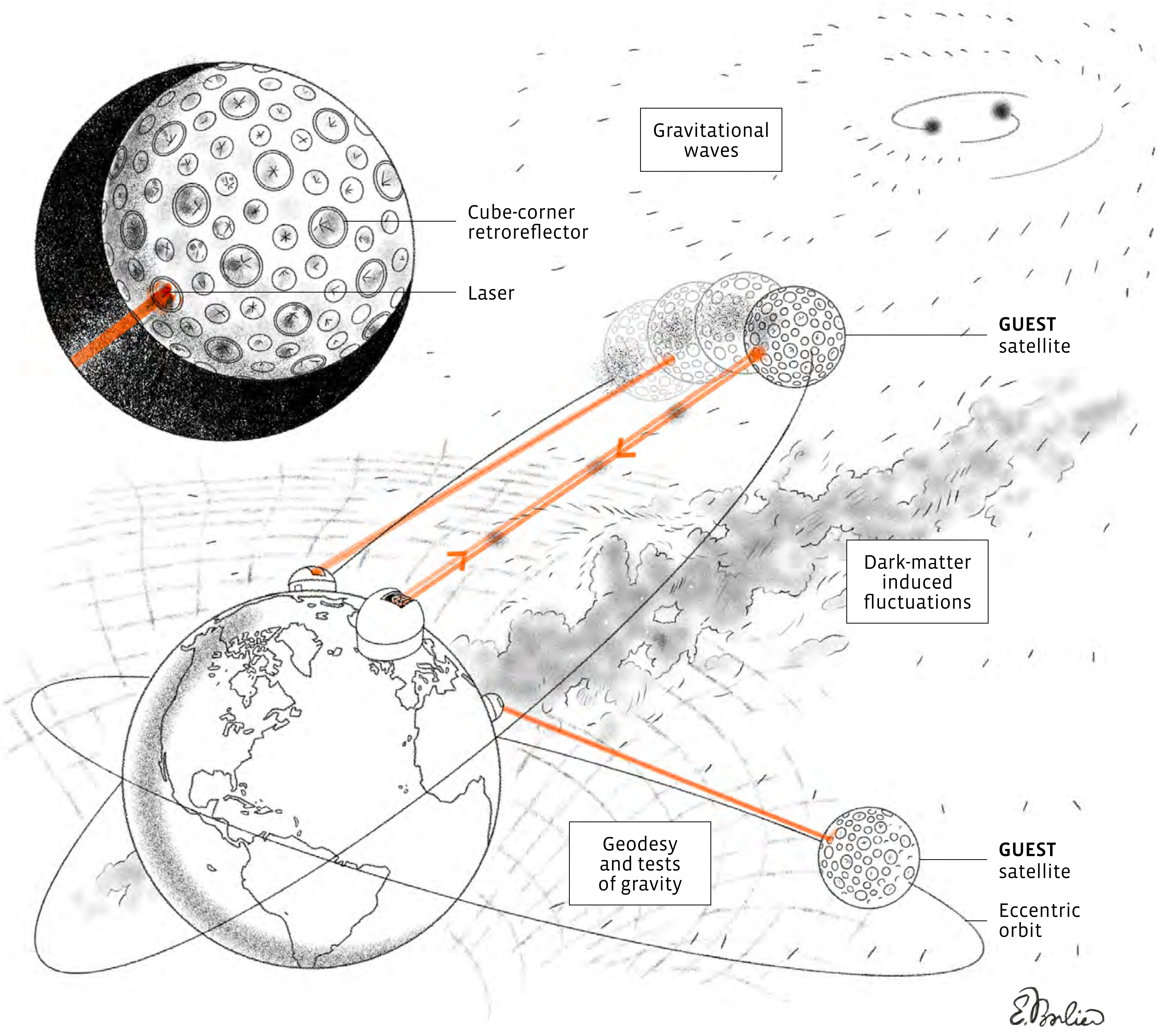
Foster, DB et al., arXiv: 2504.15334 [astro-ph.CO]
Foster, DB et a., arXiv:2504.16988 [gr-qc]



GUEST

* made be tracked as LAGEOS is tracked + from idealized to realistic data analysis

F3 ESA mission proposal (step-2 submitted April 26)



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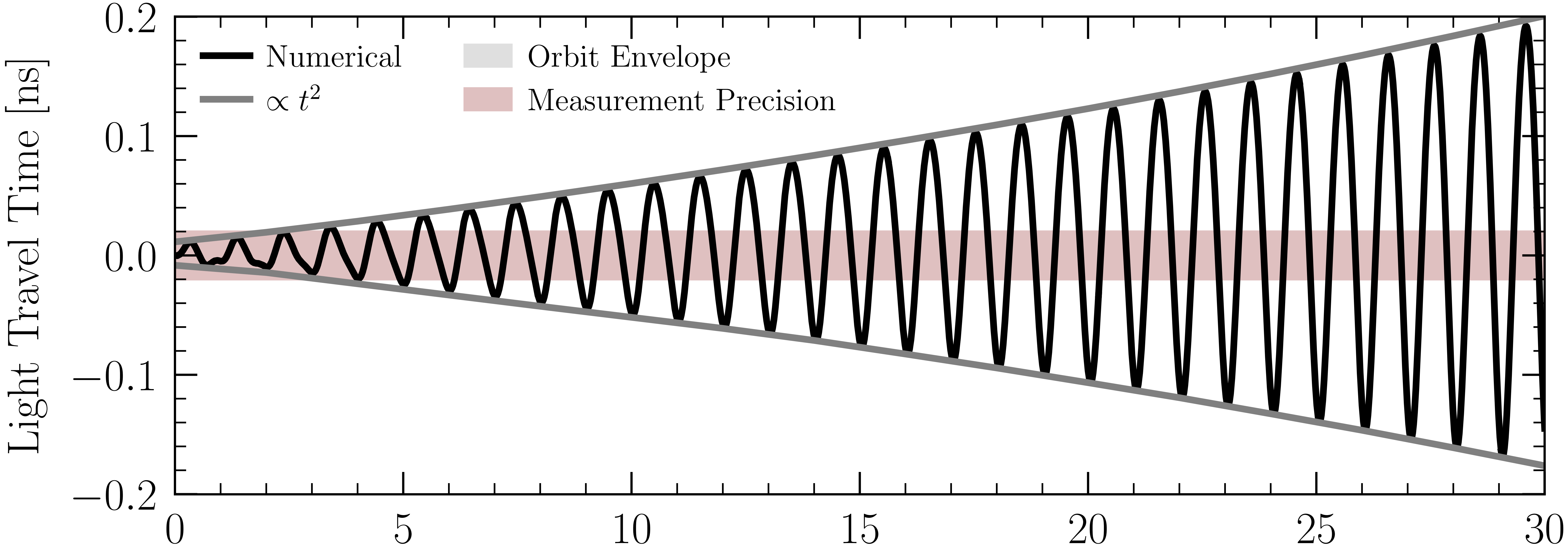
Sensitivity: way to go

$$\Delta_{\parallel}(\Upsilon) = \frac{2p}{c(1 + e\cos f)} + \Delta_{\parallel}^{n}$$

Data: set of points of time of travel of 2 ways laser



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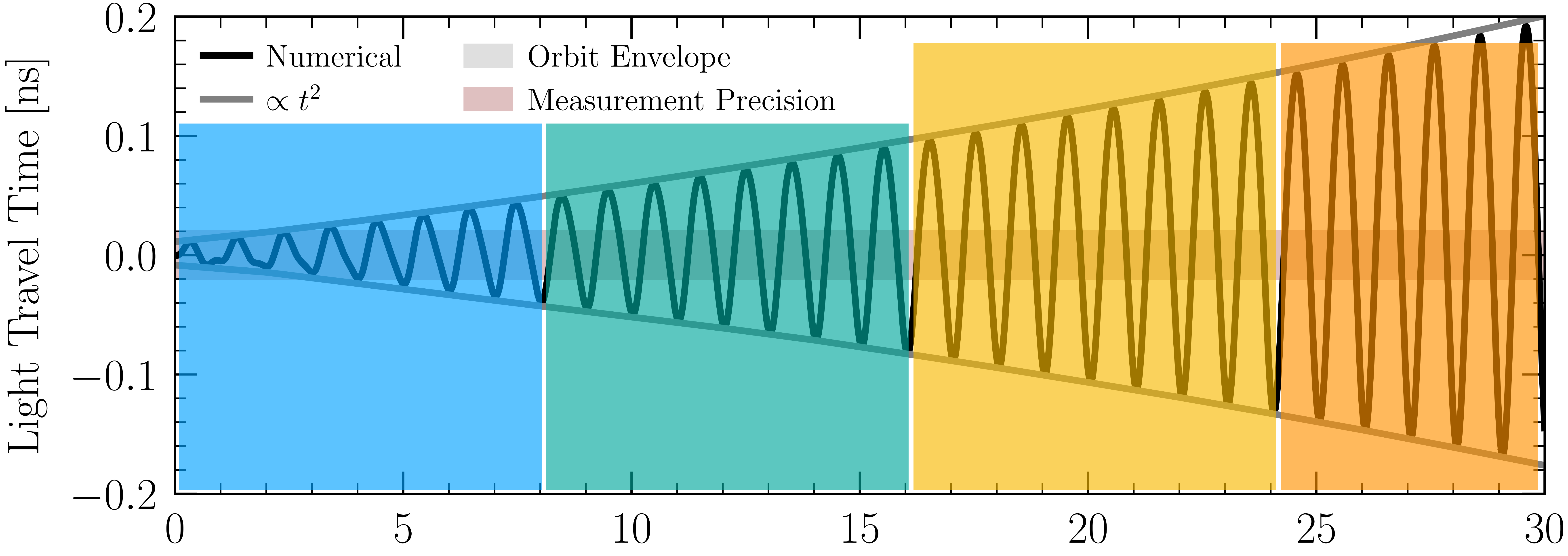


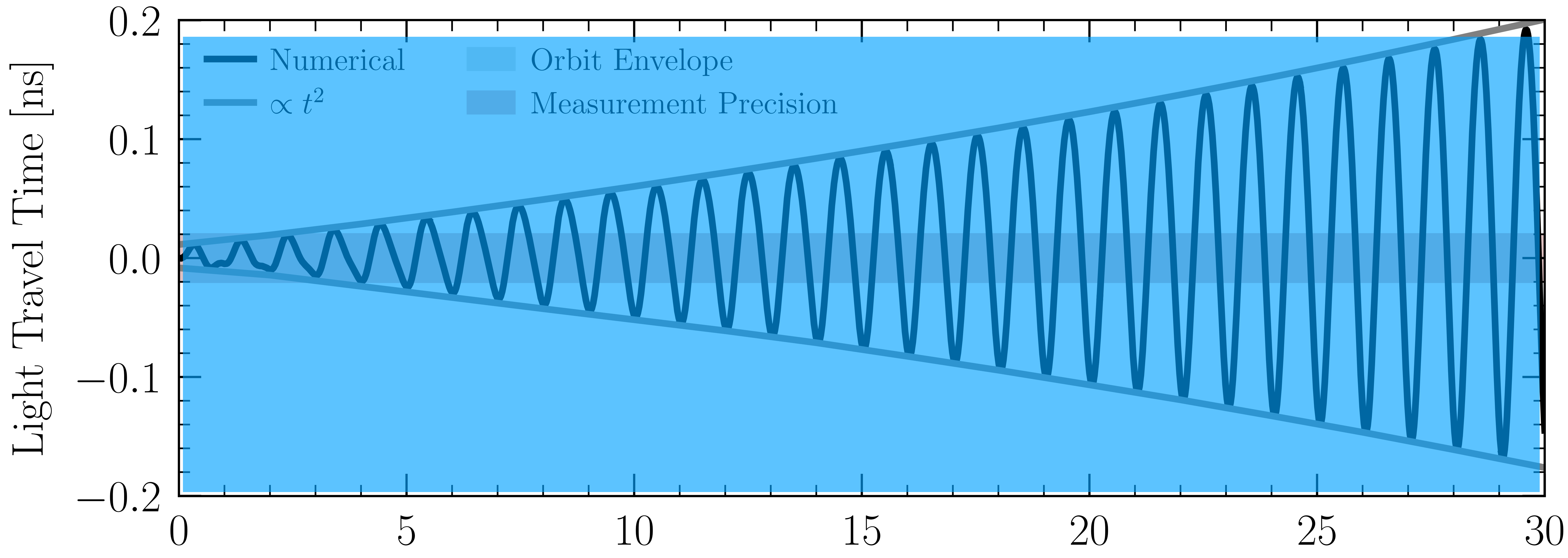
Standard Analysis: *Arcs method*. Fit a best orbit + signal every 7 days (~6 orbits).

Derived for geodesy

Sensitivity: way to go

$$\Delta_{\parallel}(\Upsilon) = \frac{2p}{c(1 + e\cos f)} + \Delta_{\parallel}^{n}$$

Data: set of points of time of travel of 2 ways laser



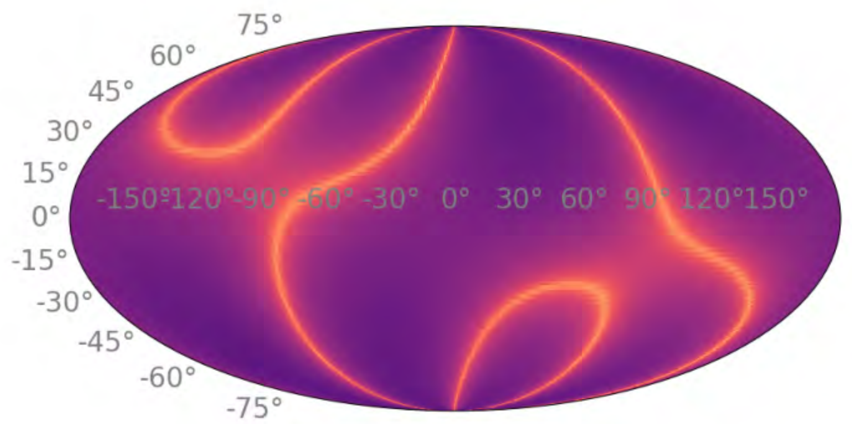
Standard Analysis: *Arcs method*. Fit a best orbit + signal every 7 days (~6 orbits).

Derived for geodesy

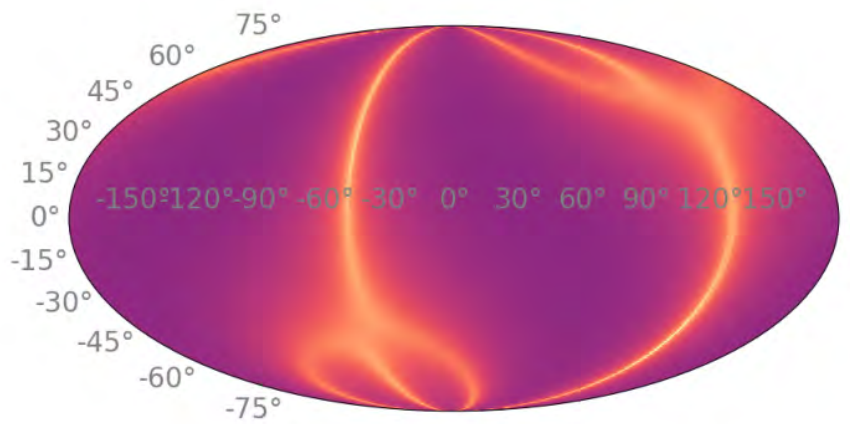
Global Analysis: Fit a more global orbit model + signal

GUEST 10 years sensitivity (one orbit)

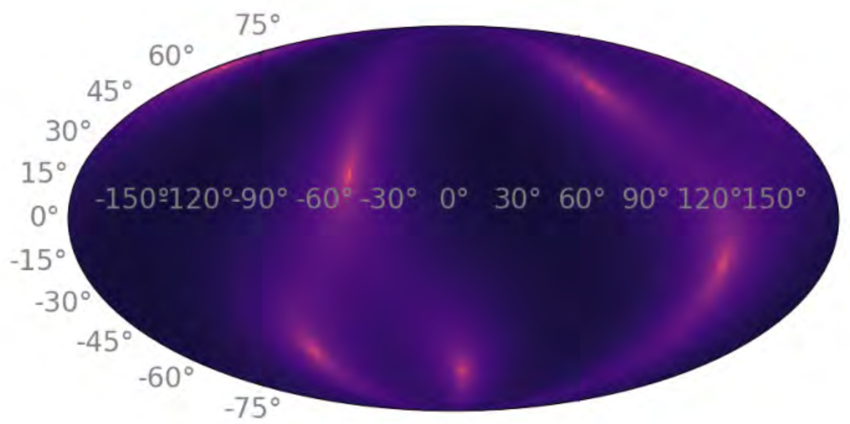
GUEST1

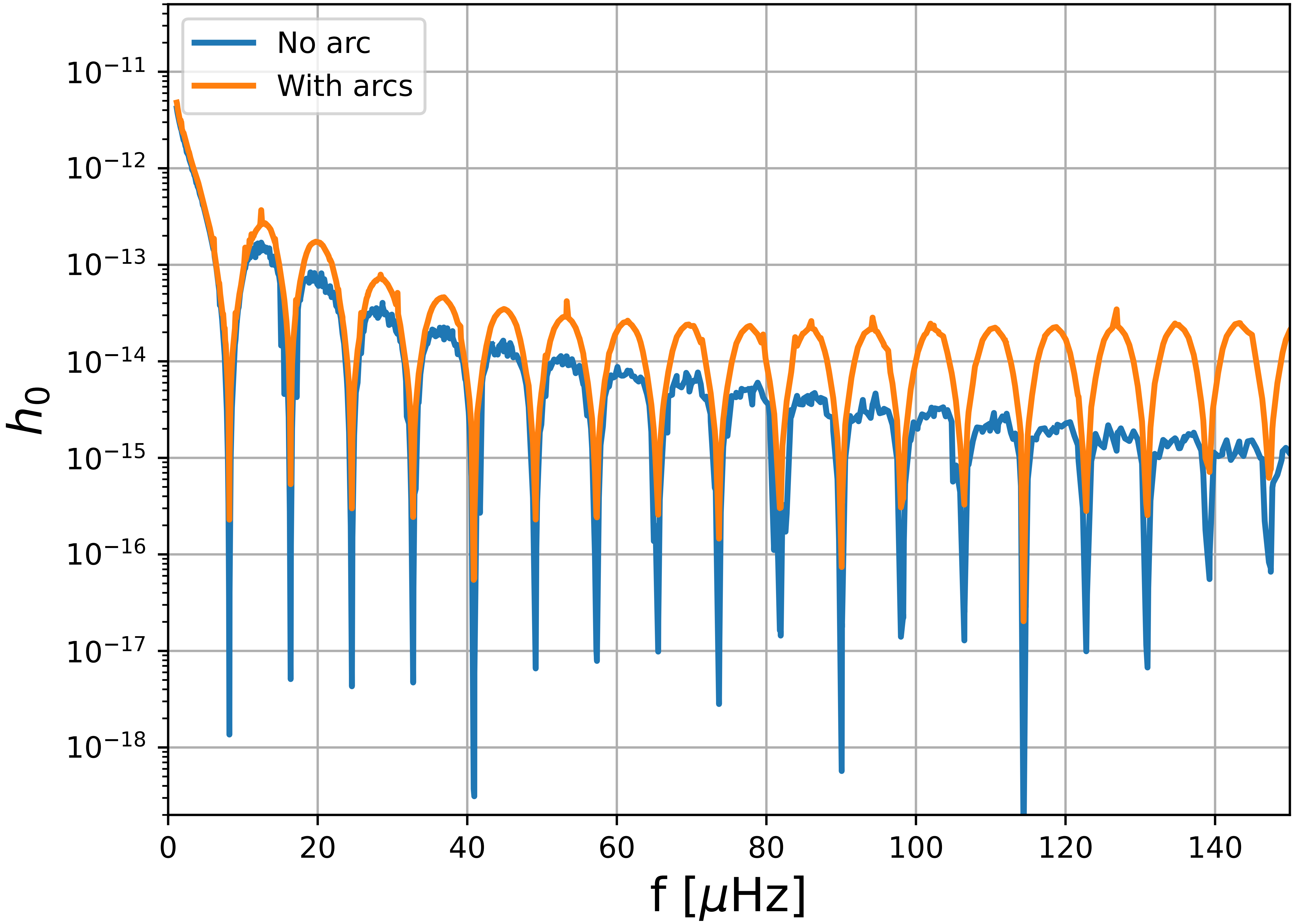


GUEST2



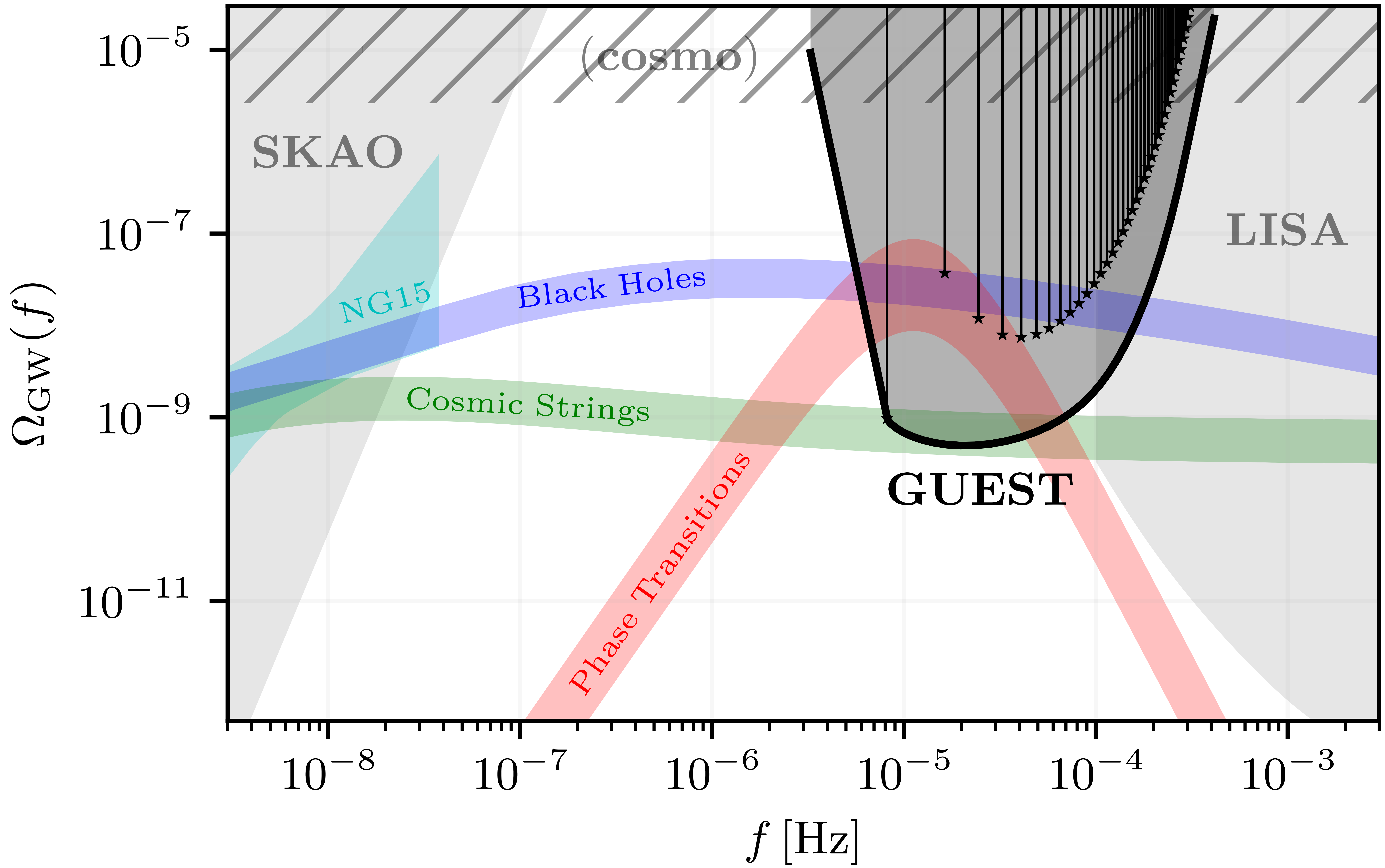
GUEST1+GUEST2





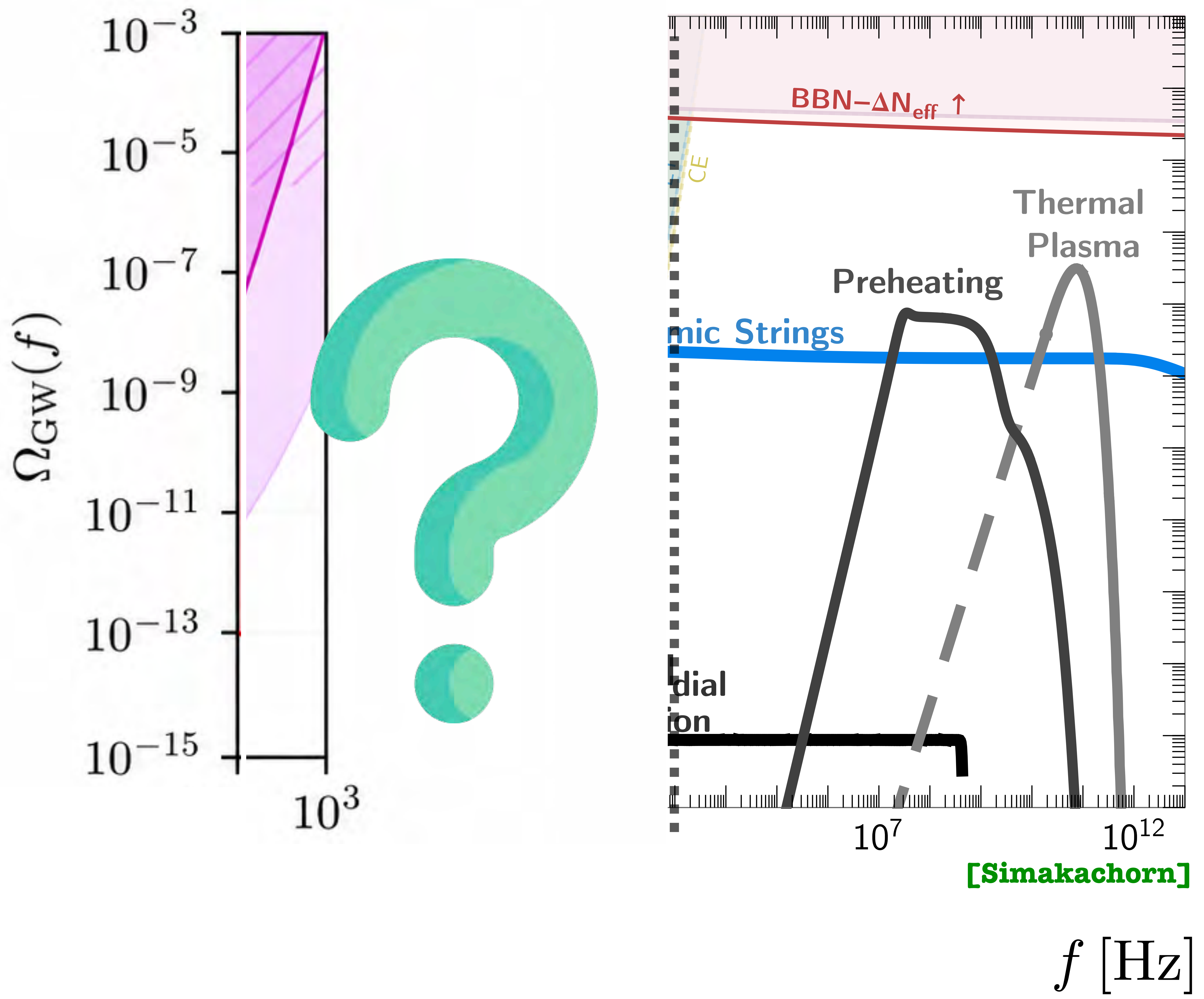
Data:
rms=1 cm per point,
10 points per orbit

GUEST 10 years sensitivity (one orbit)



High frequency GWs (>10 kHz)

- Exploratory: fundamental backgrounds & new technologies



High frequency GWs (>10 kHz)

How to **detect** them?

Sources?

High frequency GWs (>10 kHz)

How to **detect** them?

1) Frequencies and wavelengths closer to laboratory scales!

$$\mathrm{kHz} - \mathrm{GHz}$$
$$10^2\,\mathrm{km} - \mathrm{cm}$$

2) Gravity couples to everything in your lab with ‘known’ Hamiltonians

Great opportunity to leverage sensing revolution!

High frequency GWs (>10 kHz)

How to **detect** them? **Exploring all possibilities!**

Living Reviews in Relativity manuscript No.
(will be inserted by the editor)

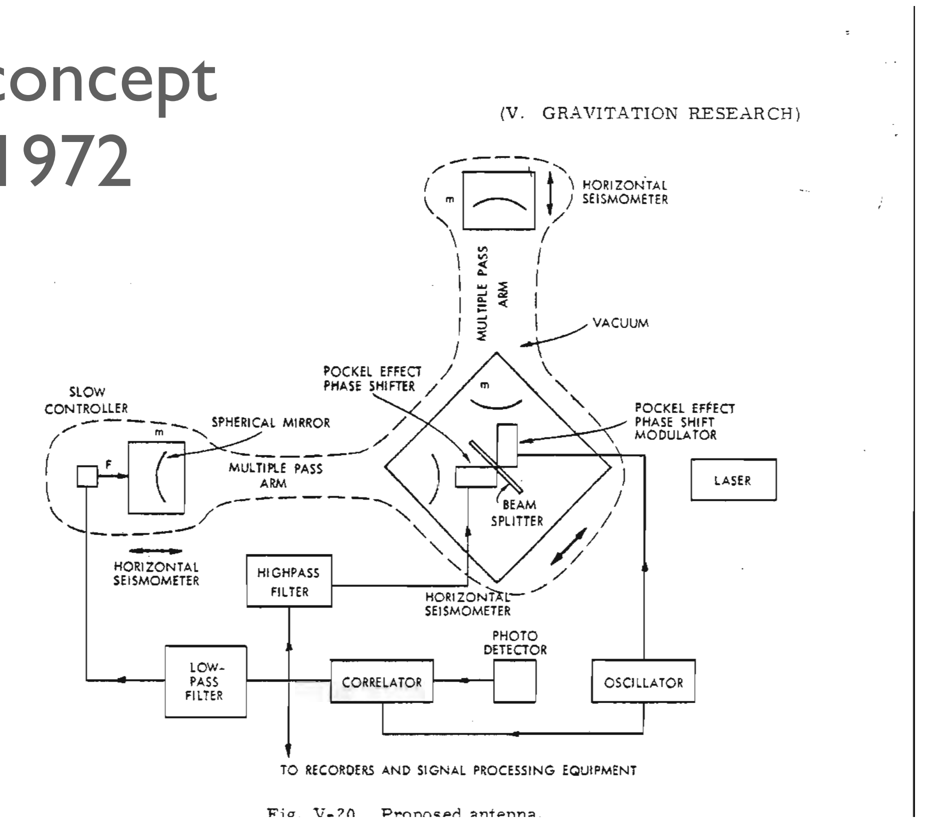
Challenges and Opportunities
of Gravitational Wave Searches above 10 kHz

2501.11723 [gr-qc] (v1 2011.12414 [gr-qc])

We are in the early days!

Rainer Weiss, ca. 1972

LIGO concept
Weiss 1972

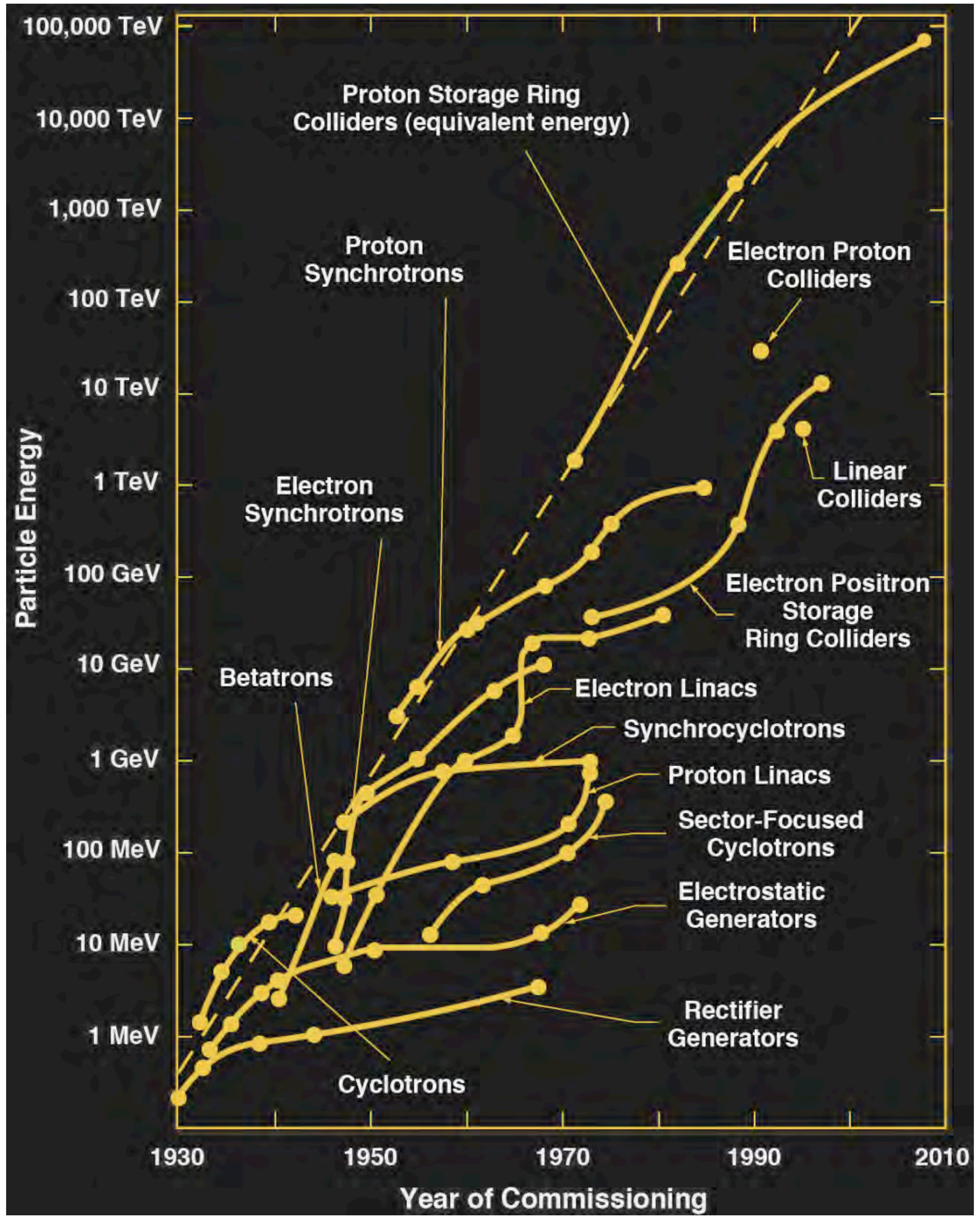


For continuous gravitational waves, the r
metric spectral density is then

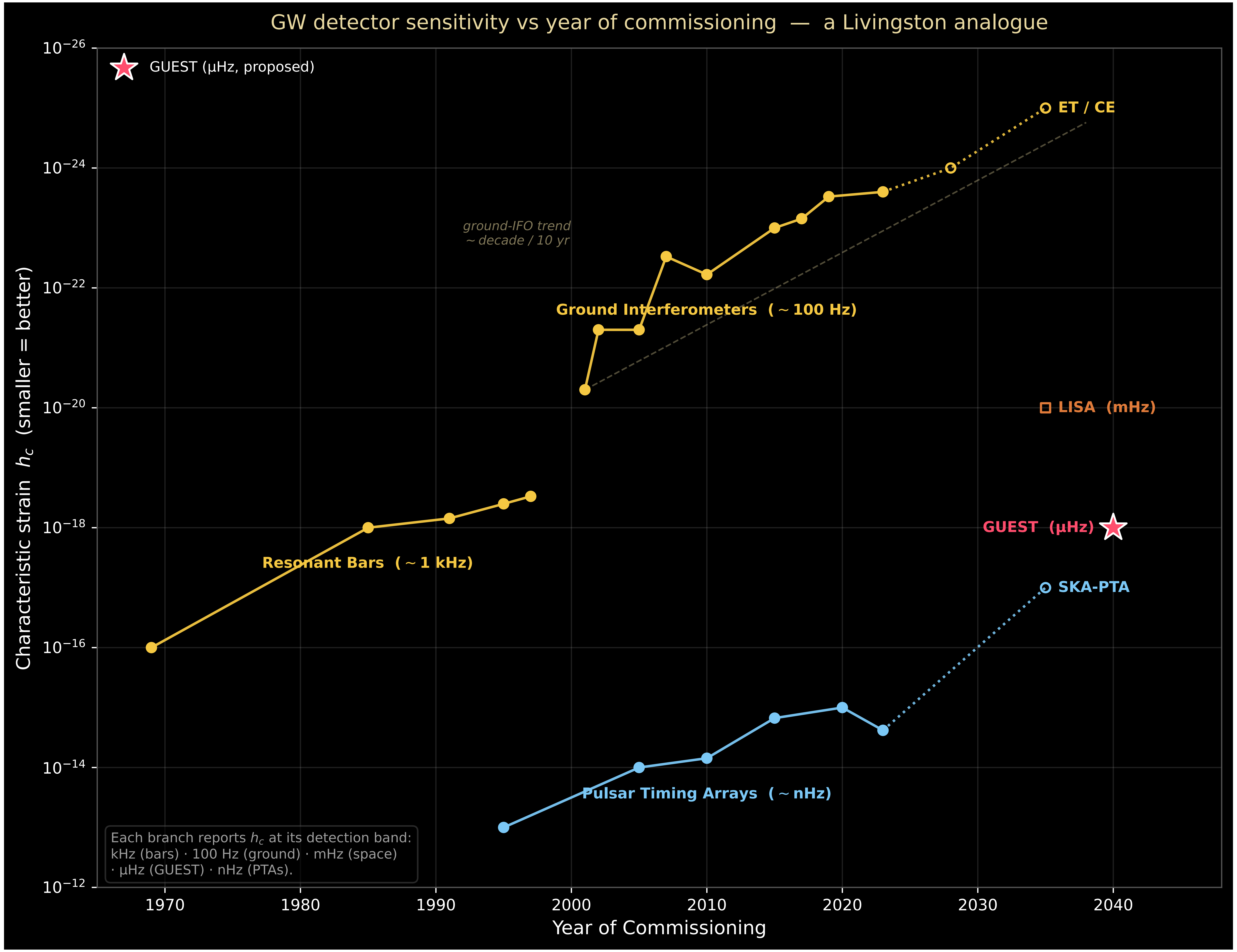
$$h^2(f) > \frac{4}{f^2} \frac{\Delta x_n^2(f)}{\Delta f} \approx \frac{4 \times 10^{-33}}{f^2(\mathrm{cm})} \qquad \mathrm{Hz}^{-1}.$$

E.O. Lawrence

Livingston plot



Livingston plot for GWs



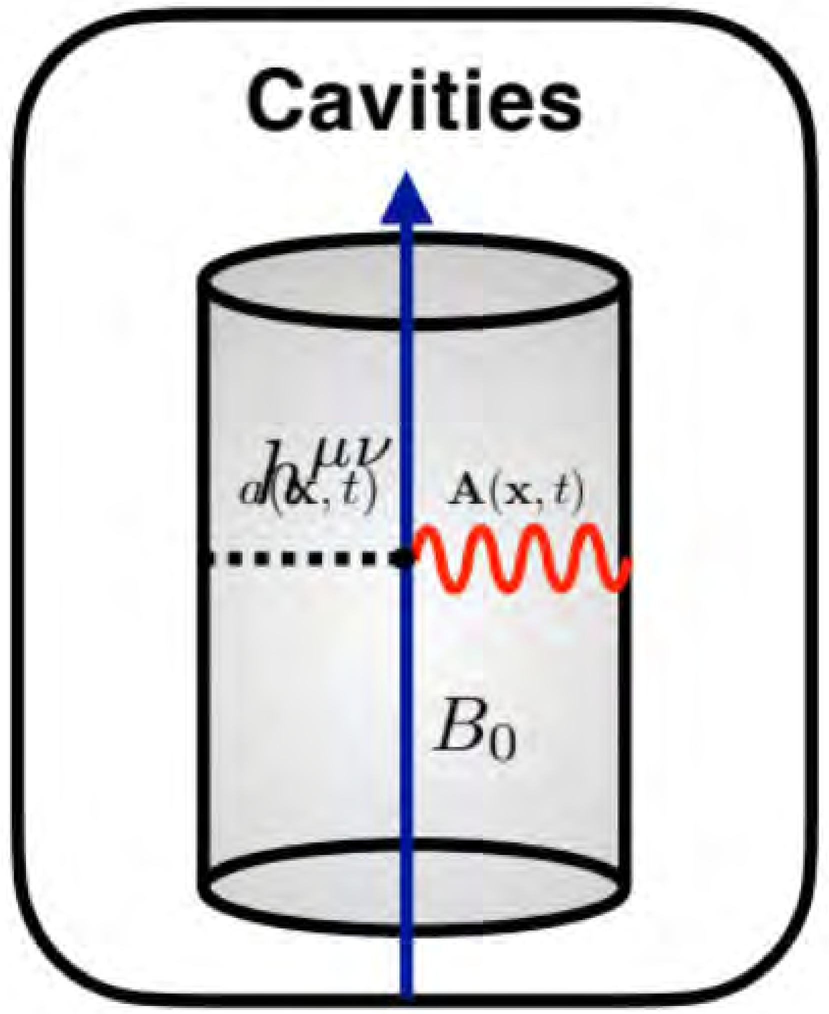
Interaction of GWs with your sensors

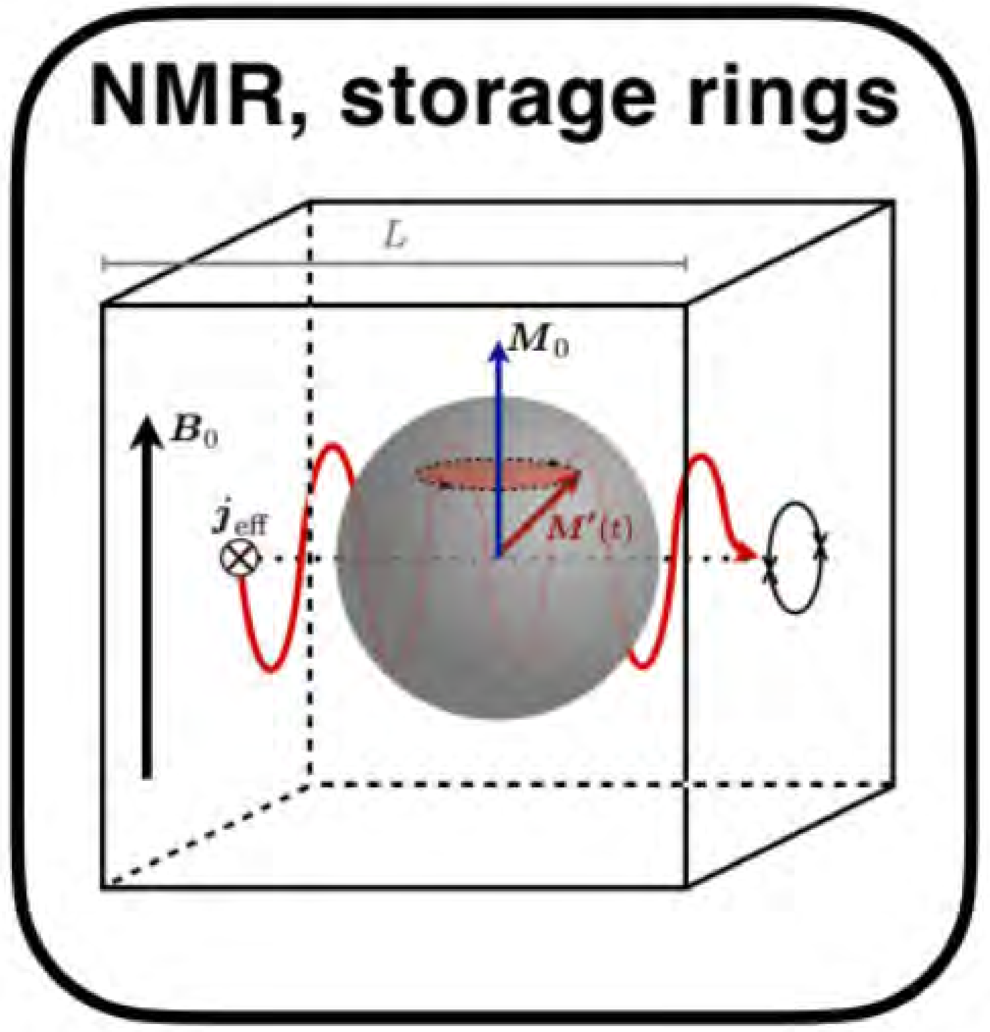
$h_{\mu\nu}T^{\mu\nu}$ *GWs couple to all energy/momentum and* $h_{+,\times} \approx h_0 \cos\left(2\pi f(t-z)+\phi\right)$

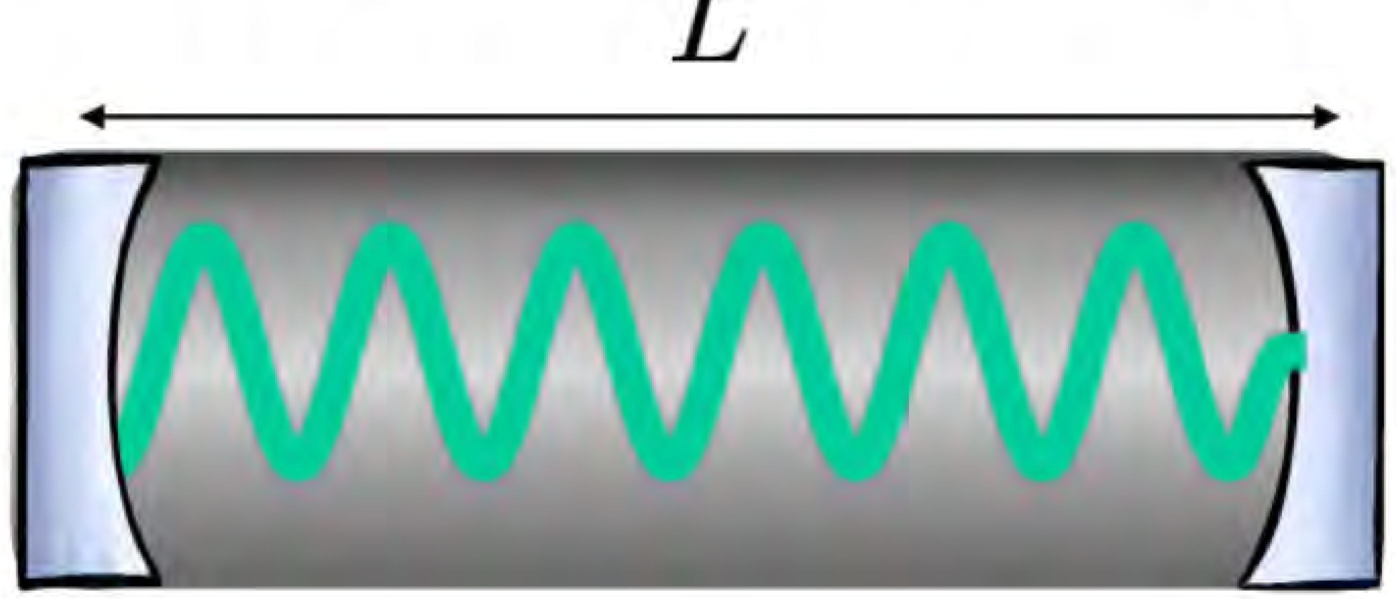
EM coupling **Spin coupling** **Energy/mechanical coupling**

$$\mathcal{H}^{lab}_{gw} \supset \boxed{A^{\nu}\partial_{\nu}\left(\frac{1}{2}hF^{\mu\nu} + h^{\nu}_{\alpha}F^{\alpha\mu} - h^{\mu}_{\alpha}F^{\alpha\nu}\right)}\boxed{+\,B_i h_{ij}\left(t_{\psi}\right)\Sigma^{j}}\boxed{+\,E_{\psi}\ddot{h}_{ij}\left(t_{\psi}\right)x^{i}_{\psi}x^{j}_{\psi}}$$

h+EM field = current! *NMR anomalous B* $\delta L \sim hL$ (shaking walls)

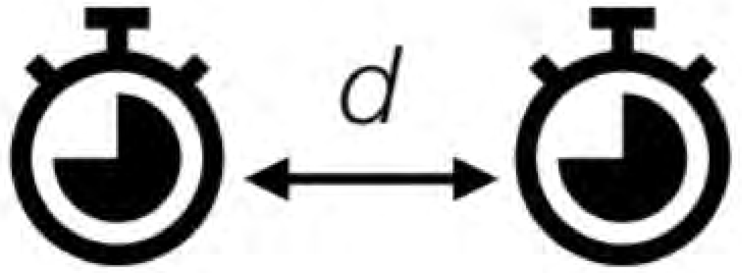




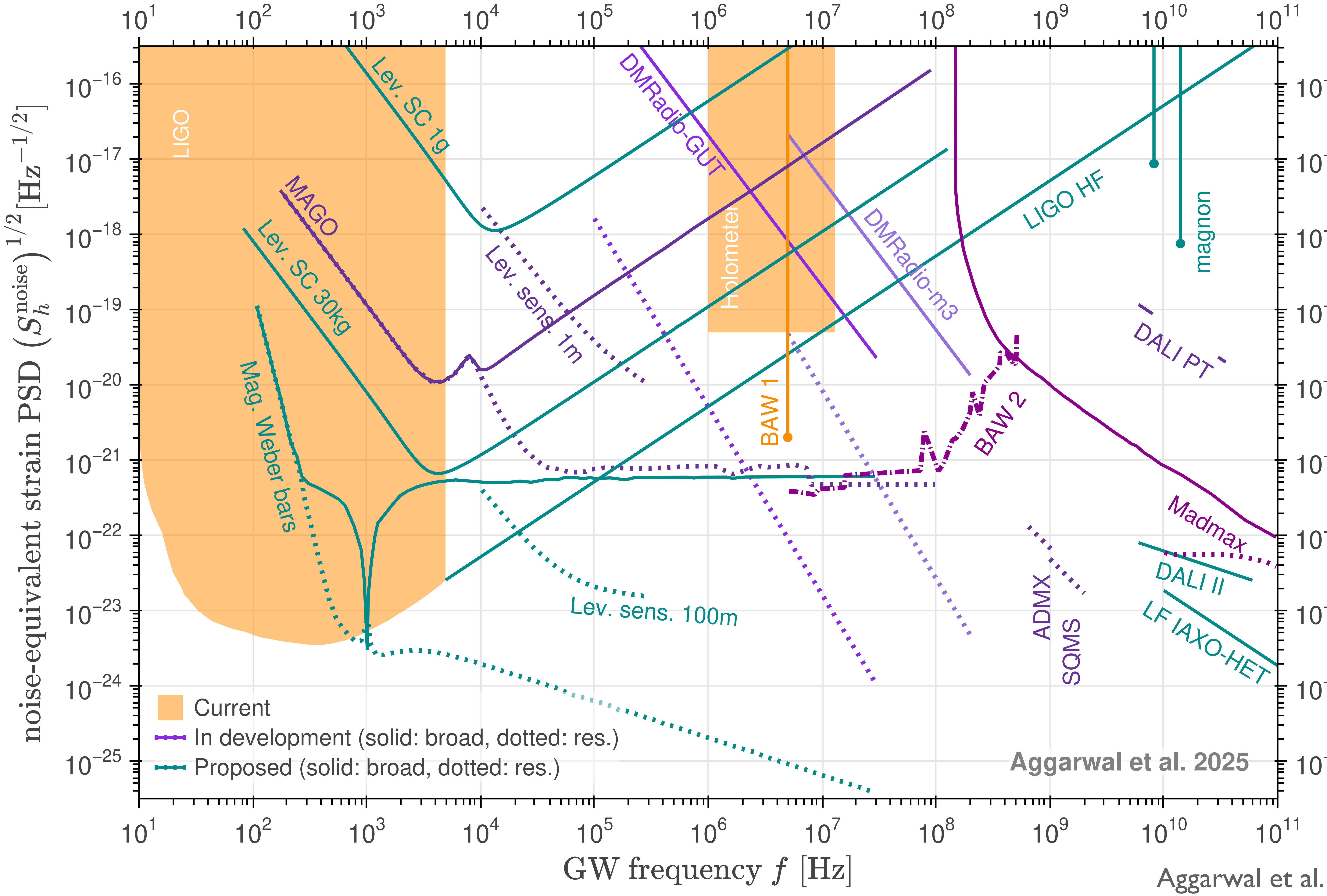


mode mixing when boundaries move

$\delta\omega \sim h\,\omega$



modify clocks at different locations



Aggarwal et al. 2501.11723 [gr-qc])

Ex1. GWs interact with light

Analogy with axion experiments, though different **current**

$$\partial_\nu F^{\mu\nu} = j^\mu_{\text{eff}} = (-\nabla \cdot \mathbf{P},\ \nabla \times \mathbf{M} + \partial_t \mathbf{P})$$

Key differences:

GWs can be

- monochromatic,
- **transient** with sweeping frequency
- stochastic

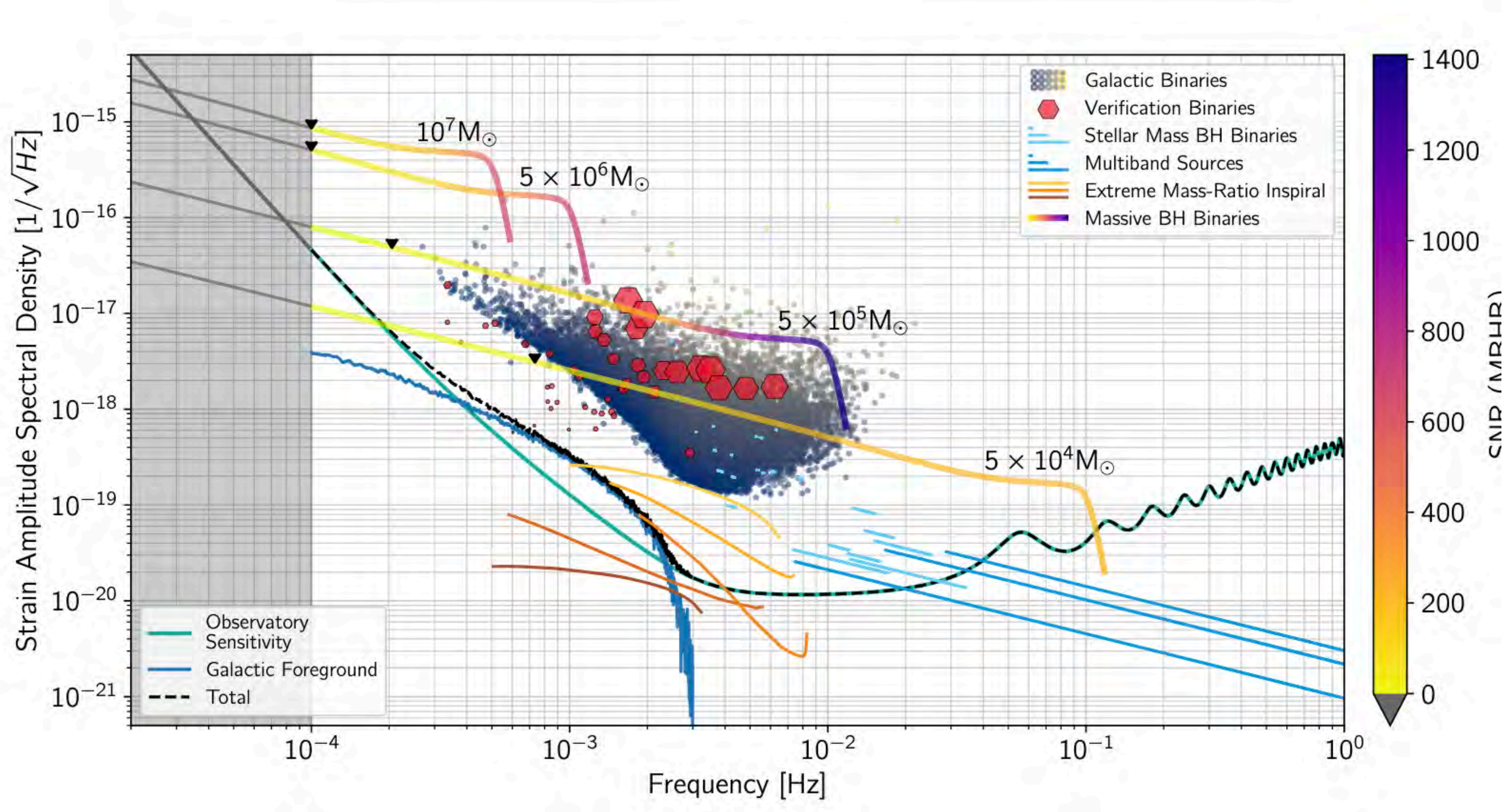
High frequency GWs (>10 kHz)

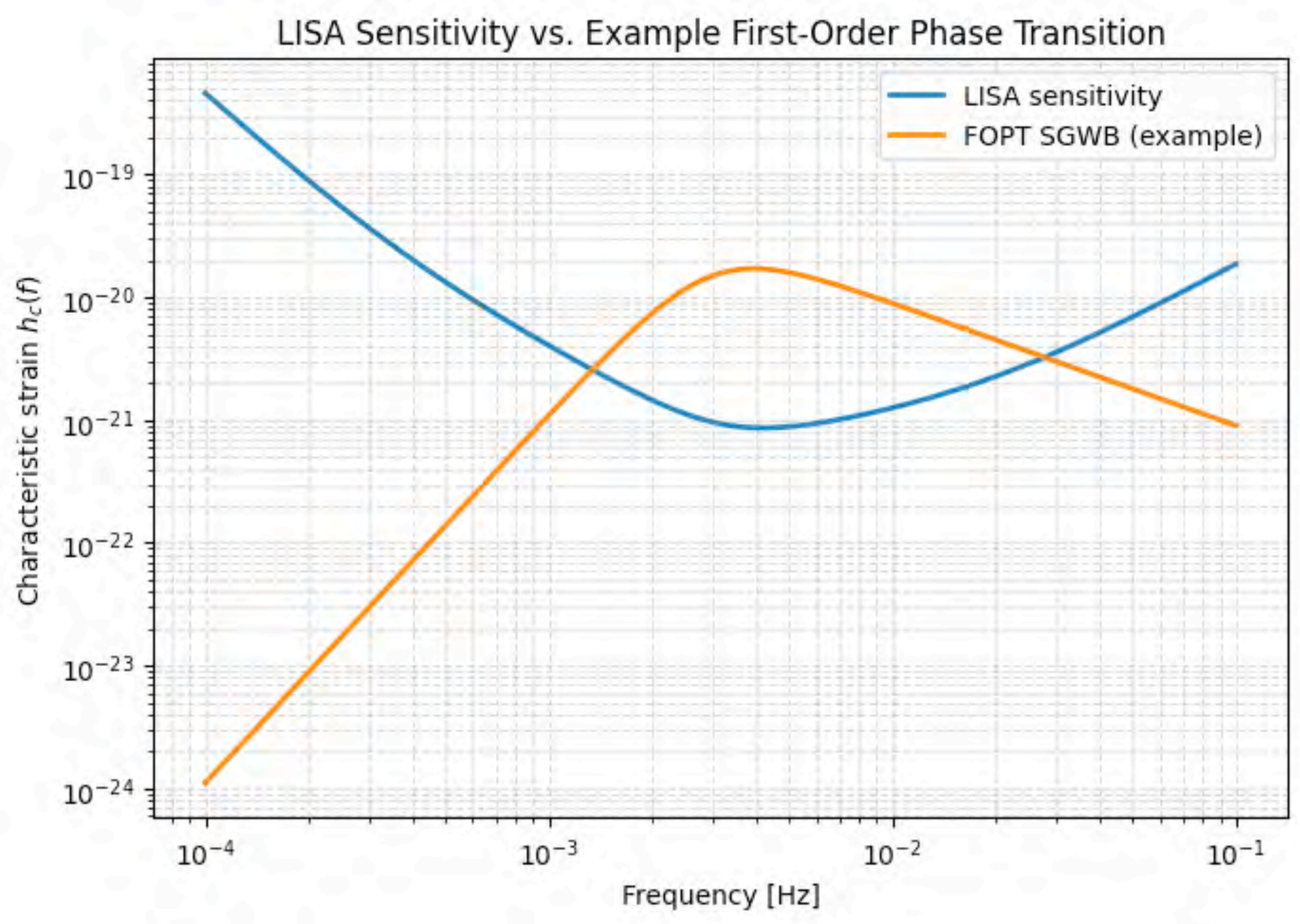
How to **detect** them?

Sources?

Searches for fundamental physics in LISA/3G

If one looks for **new physics** all the bands from may be too loud





BSM: Early Universe: inflation, new particles at high *E*

Signals from dark matter

Signals from new particles

...

How do we access BSM?

tough global fits
(as in hadron colliders)

move to other bands

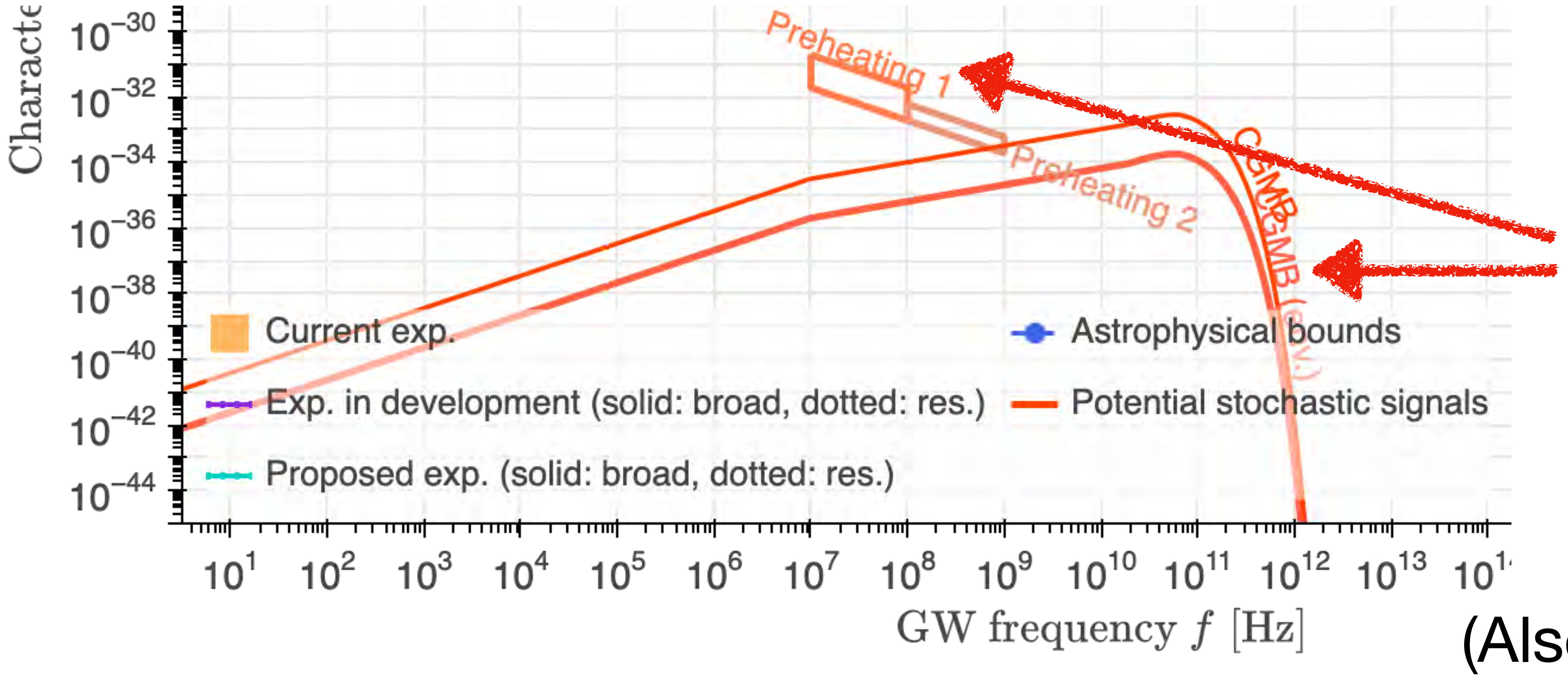
Sources of UHFGW: where to aim

BSM: Early Universe: inflation, new particles at high E ✓
Signals from dark matter ✓
Signals from new particles ✓
Fundamental properties of gravity ✓
…

More importantly there is a **‘Higgs like’** observable!

https://incandenza-01.zdv.uni-mainz.de/Omegaplot/

h_c

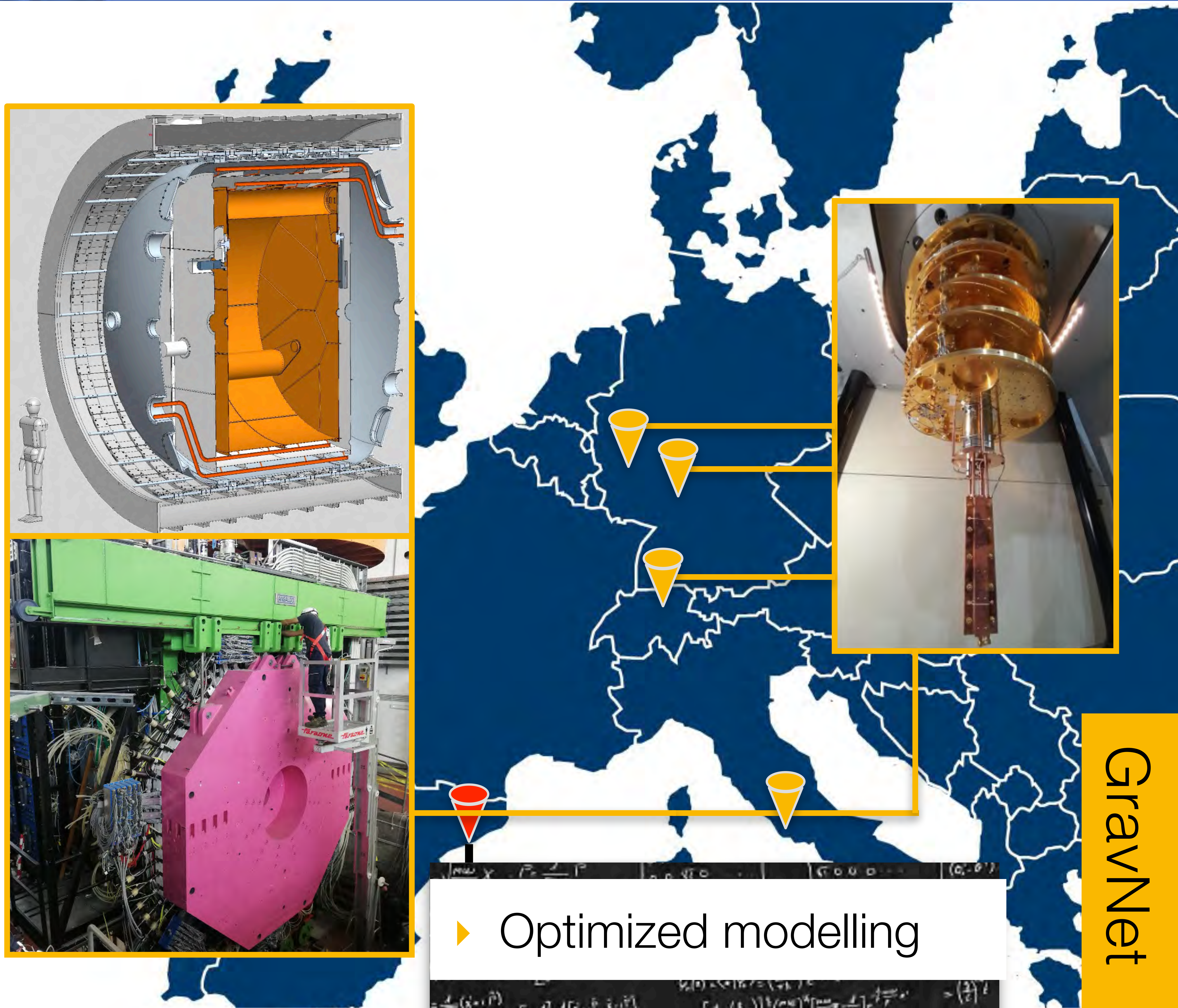


GWs from thermal fluctuations of early Universe

(Also non-stochastic sources possible)

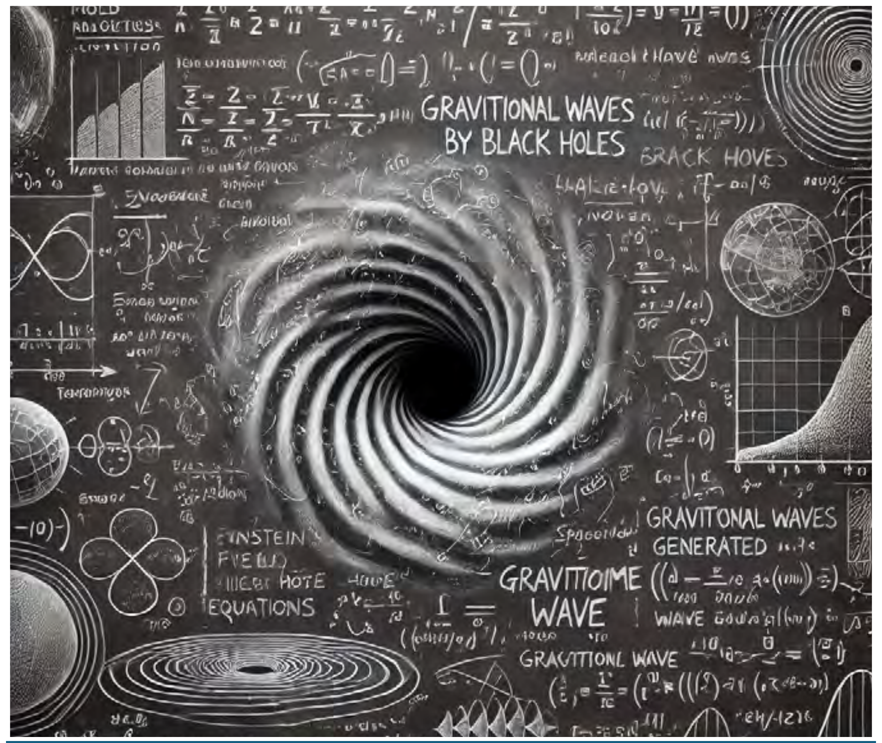
GravNet project (ERC funded)

- Further enhance sensitivity by combining HFGW detectors
  - Initial sites: Bonn, Mainz, Frascati, PSI
- GPS based data-acquisition scheme
  - Experience from GNOME Network
- Nine small resonant cavities (5-9 GHz)
  - operation of three cavities in one magnet
- One large resonant cavity (100 MHz)



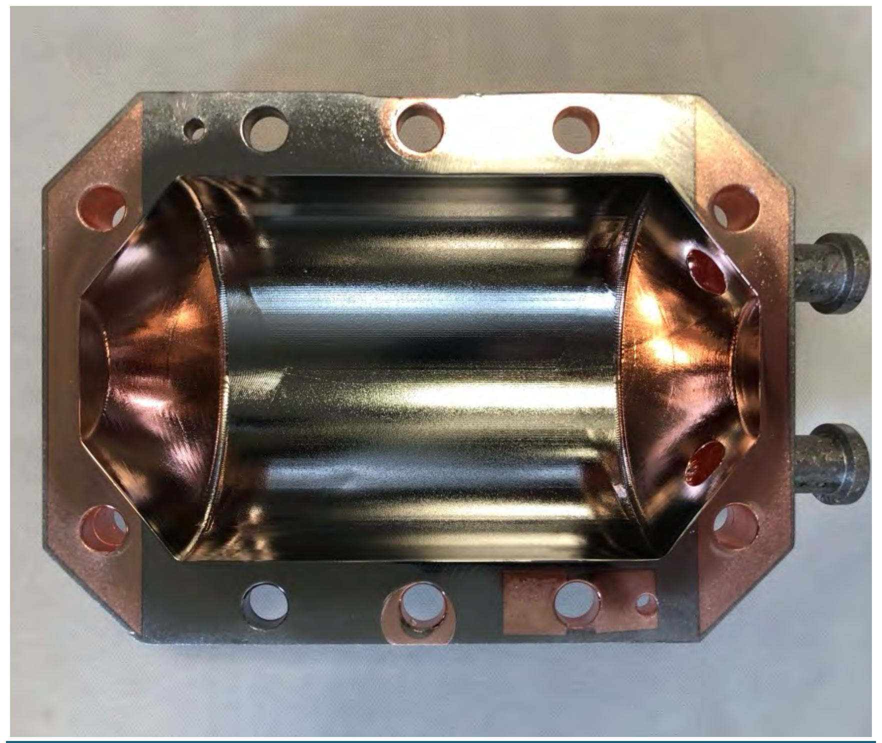
GravNet project (ERC funded)

European Research Council
Established by the European Commission



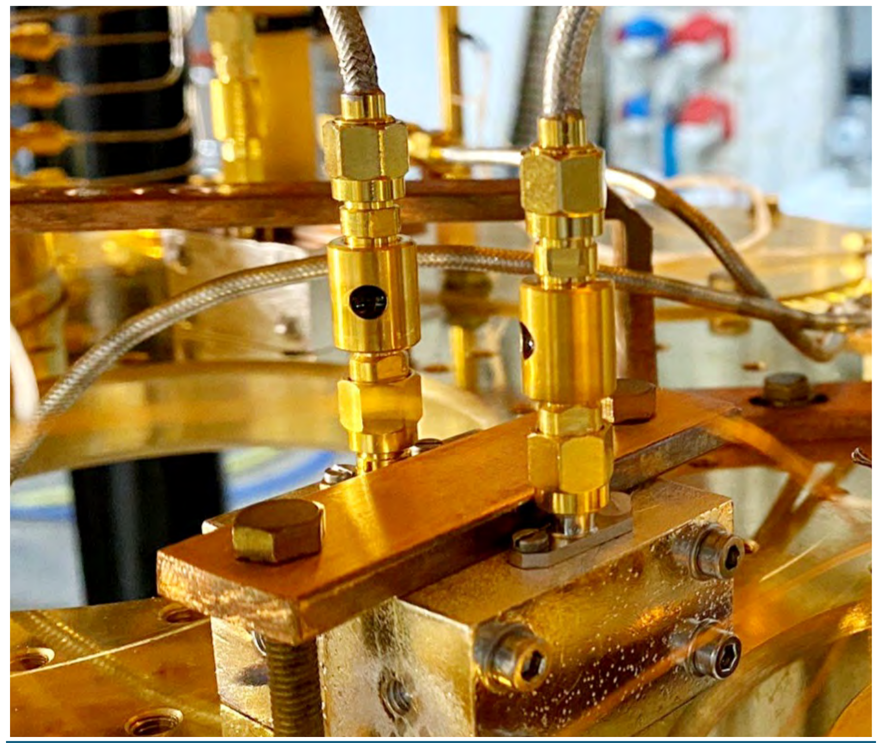
Source Modeling and Data Analysis

Diego Blas (IFAE)



Resonant Cavities

Matthias Schott (Bonn)



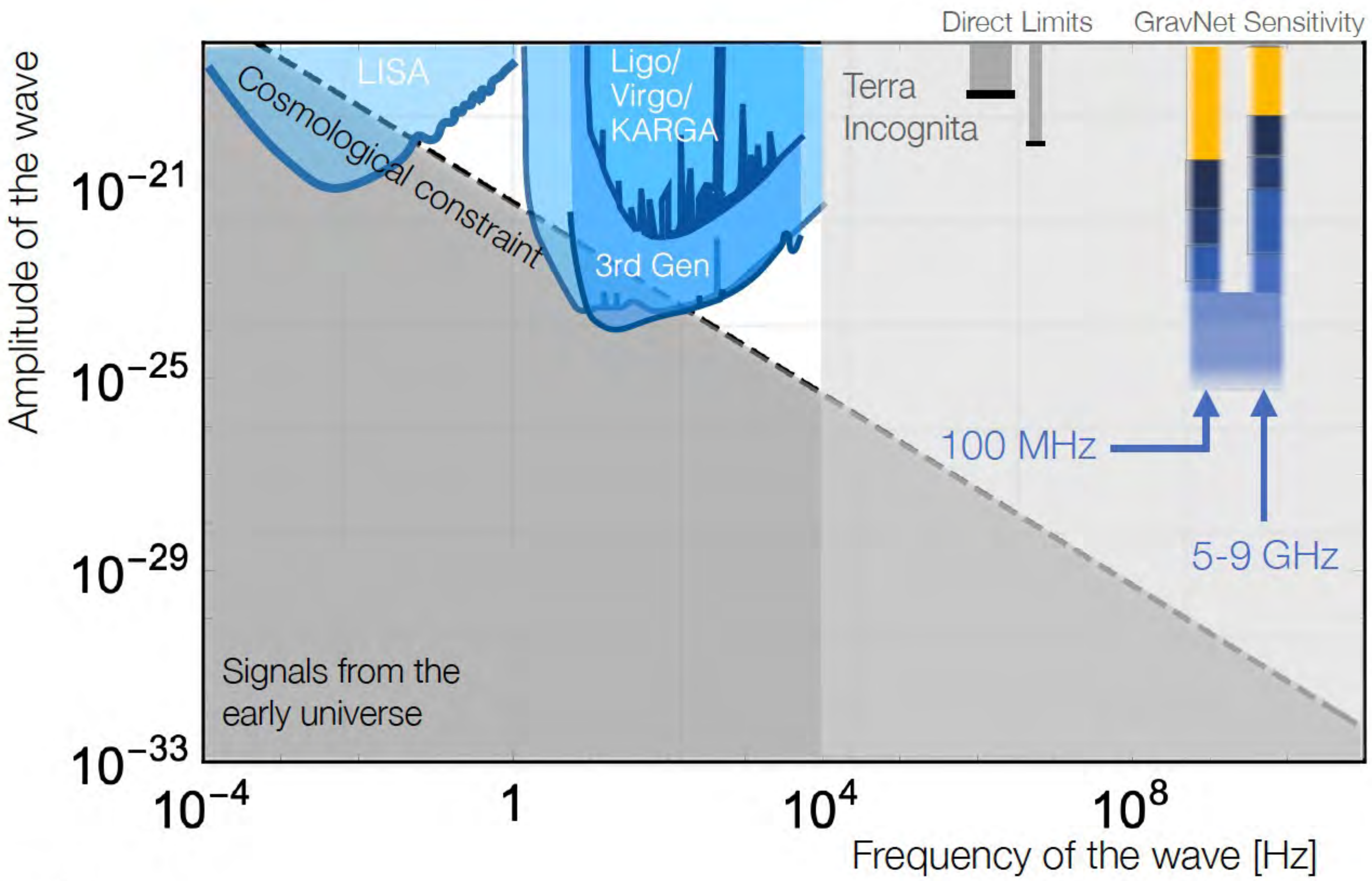
Quantum Sensing

Claudio Gatti (INFN)

Network Operation

Dmitry Budker (Mainz)

EM coupling



GravNet

- GravNet Baseline
- Modelling and Data Analysis
- Cavity Design & Construction
- Quantum Amplifiers and Sensors
- Network Operation
- Combination of different frequencies
- Adding further detectors to network

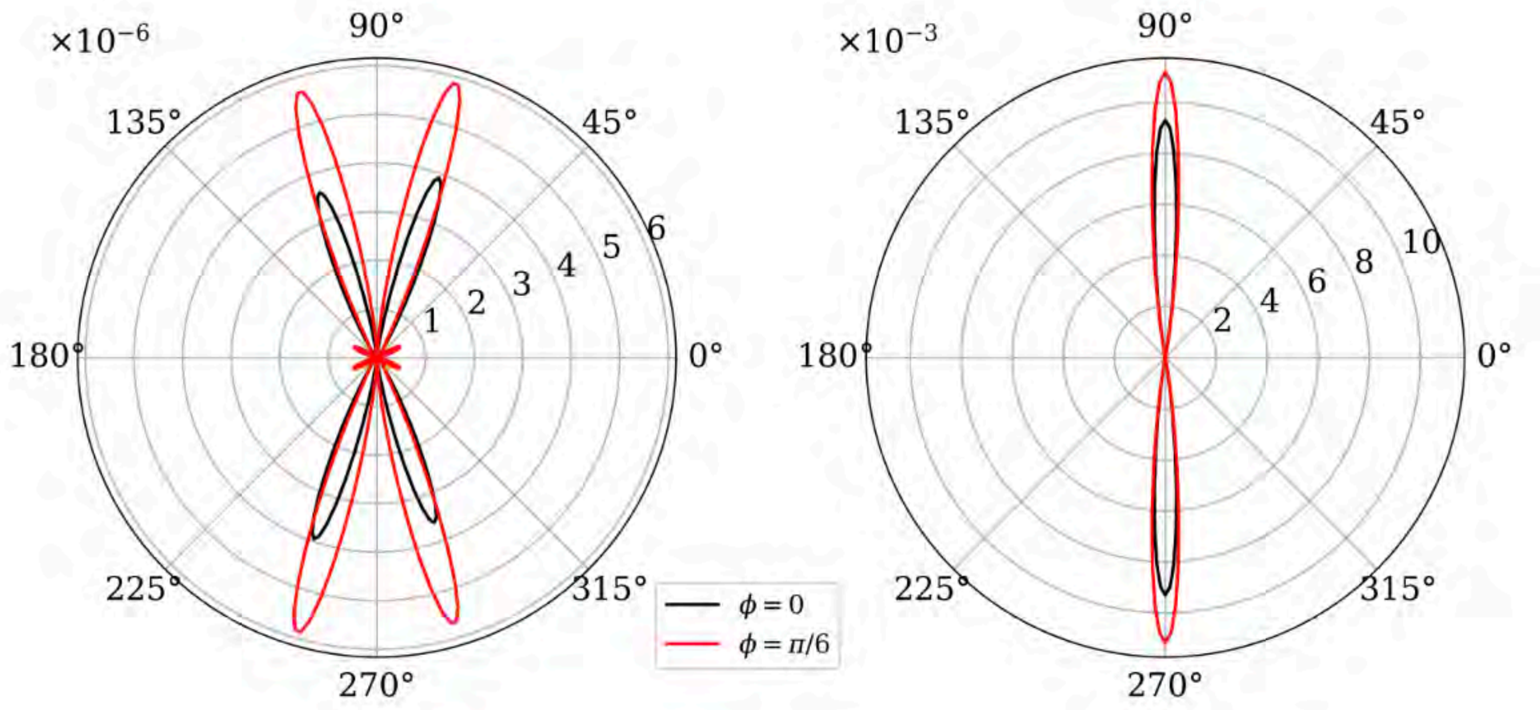
$$h_0 \approx 6.0 \times 10^{-23} \left(\frac{1\,\mathrm{T}}{B_0}\right) \left(\frac{0.14}{\eta}\right) \left(\frac{\mathrm{m}^3}{V}\right)^{5/6} \left(\frac{10^6}{Q_{\mathrm{eff}}}\right)^{1/2}$$
$$\times \left(\frac{T_{\mathrm{sys}}}{\mathrm{K}}\right)^{1/2} \left(\frac{\Delta f}{\mathrm{kHz}} \frac{1\,\mathrm{min}}{t_{\mathrm{eff}}^{\mathrm{int}}}\right)^{1/4} \left(\frac{\mathrm{GHz}}{\omega_n/2\pi}\right)^{3/2},$$

GravNet collaboration

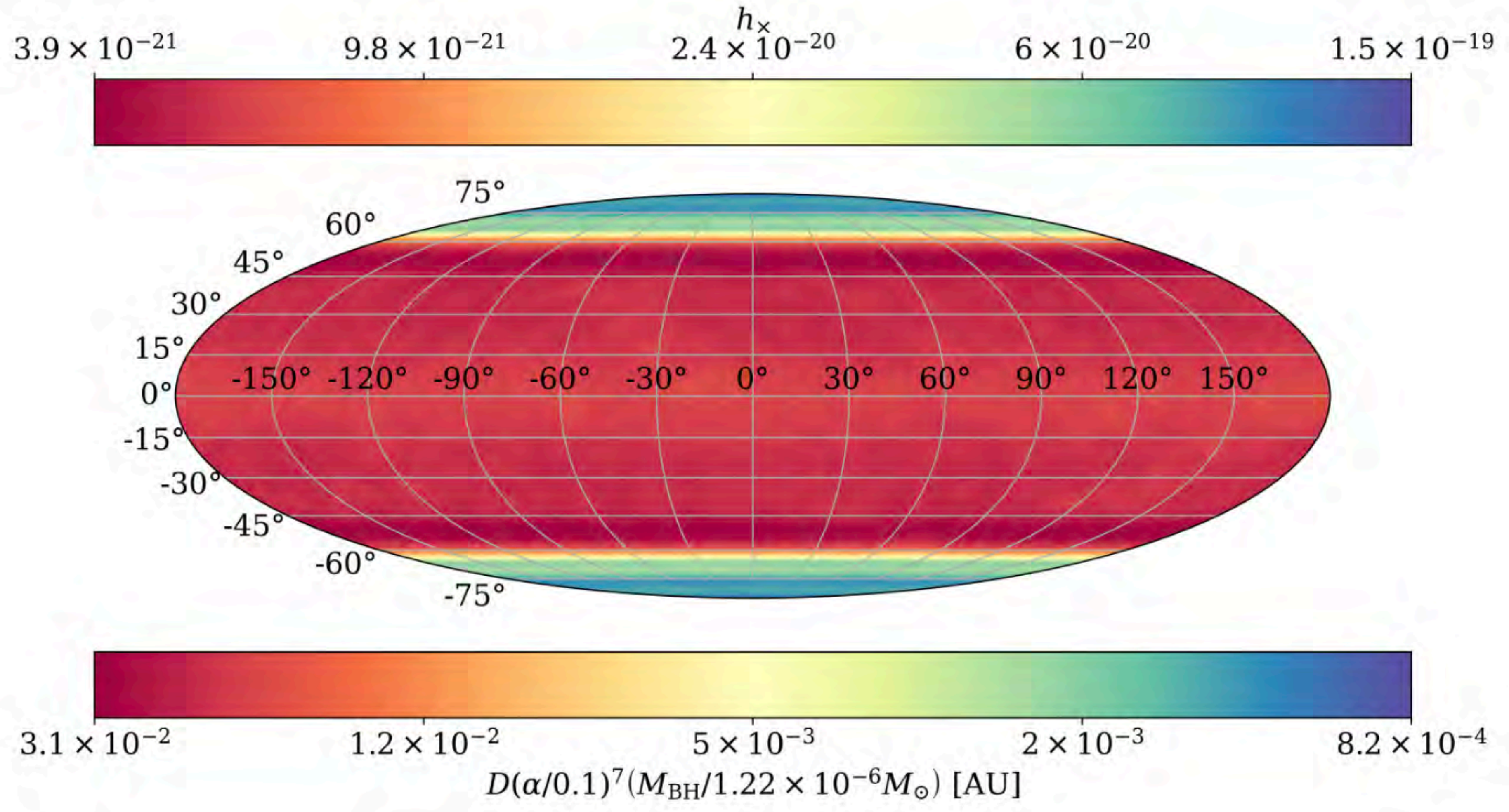
- First results:

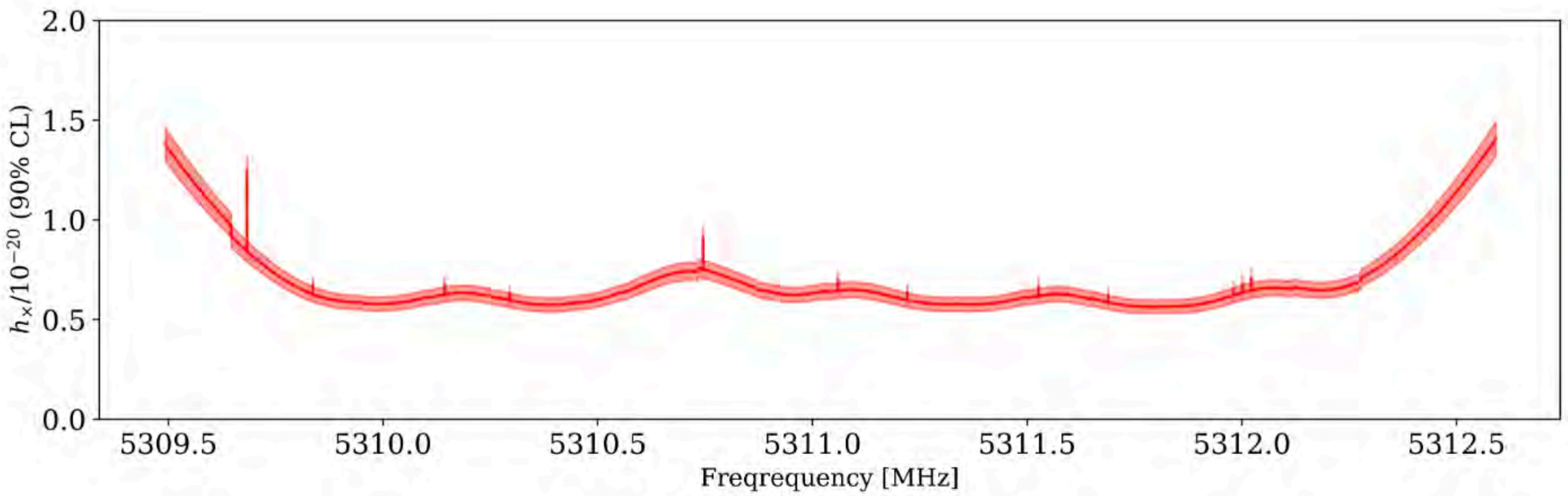
Search for high-frequency gravitational waves via re-analysis of cavity axion data

Younggeun Kim,[1,2,3,*] Jordan Gué,[4] Changhao Xu,[1,2,3] Diego Blas,[4,5] Dmitry Budker,[1,6,3,7] Sungjae Bae,[8,9] Claudio Gatti,[10] Junu Jeong,[11] Jihn E. Kim,[12] Kiwoong Lee,[9] Arjan F. van Loo,[13,14] Yasunobu Nakamura,[13,14] Seonjeong Oh,[8,9] Wolfram Ratzinger,[15] Taehyeon Seong,[8,9] Yannis K. Semertzidis,[9,16] Kristof Schmieden,[17] Mattias Schott,[17] Sergey Uchaikin,[8,9] and SungWoo Youn[8,9]



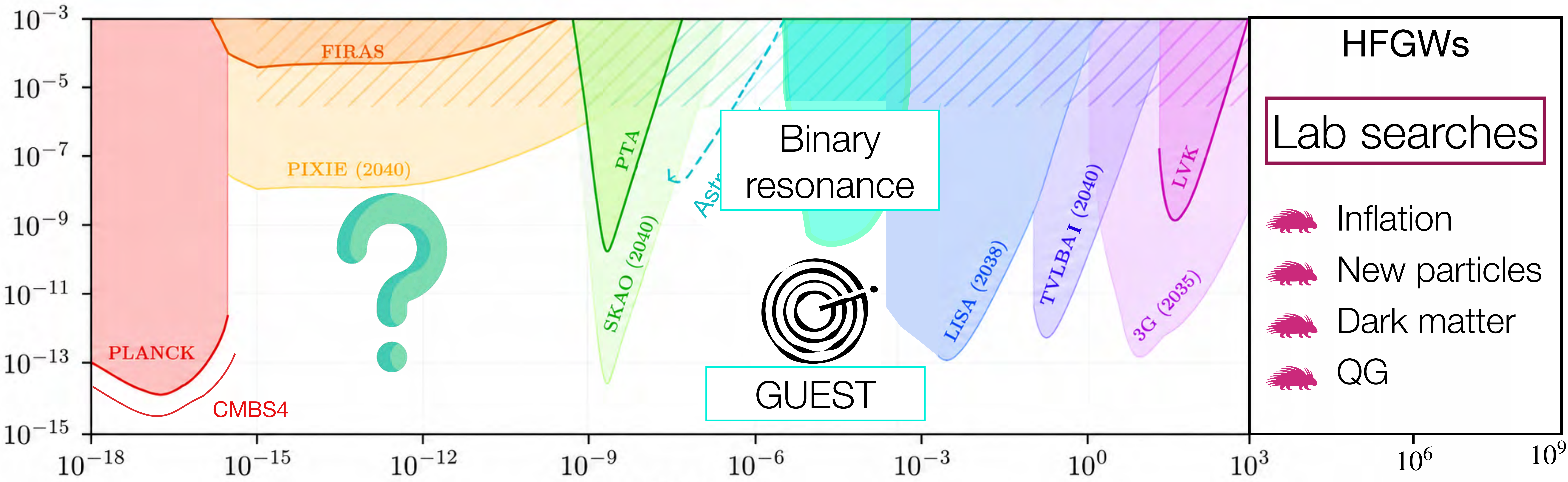
- CAPP-12T MC EXPERIMENTAL DATA USED FOR HFGWS





Adding color to the GWs spectrum: summary

Many exciting things to do in the next 15 years!



guaranteed Physics by the corner (PTA signal at muHz)

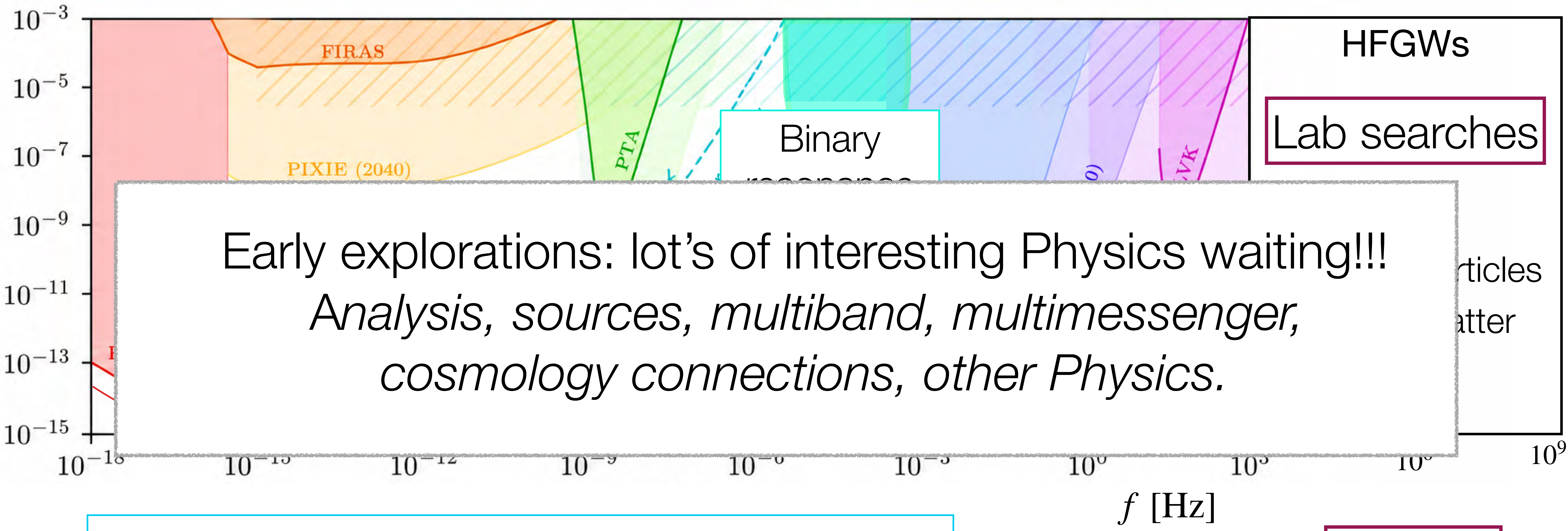
possible new Physics

reasonable ideas for searches

GravNet

Adding color to the GWs spectrum: summary

Many exciting things to do in the next 15 years!



Early explorations: lot's of interesting Physics waiting!!!

Analysis, sources, multiband, multimessenger, cosmology connections, other Physics.

guaranteed Physics by the corner (PTA signal at muHz)

possible new Physics

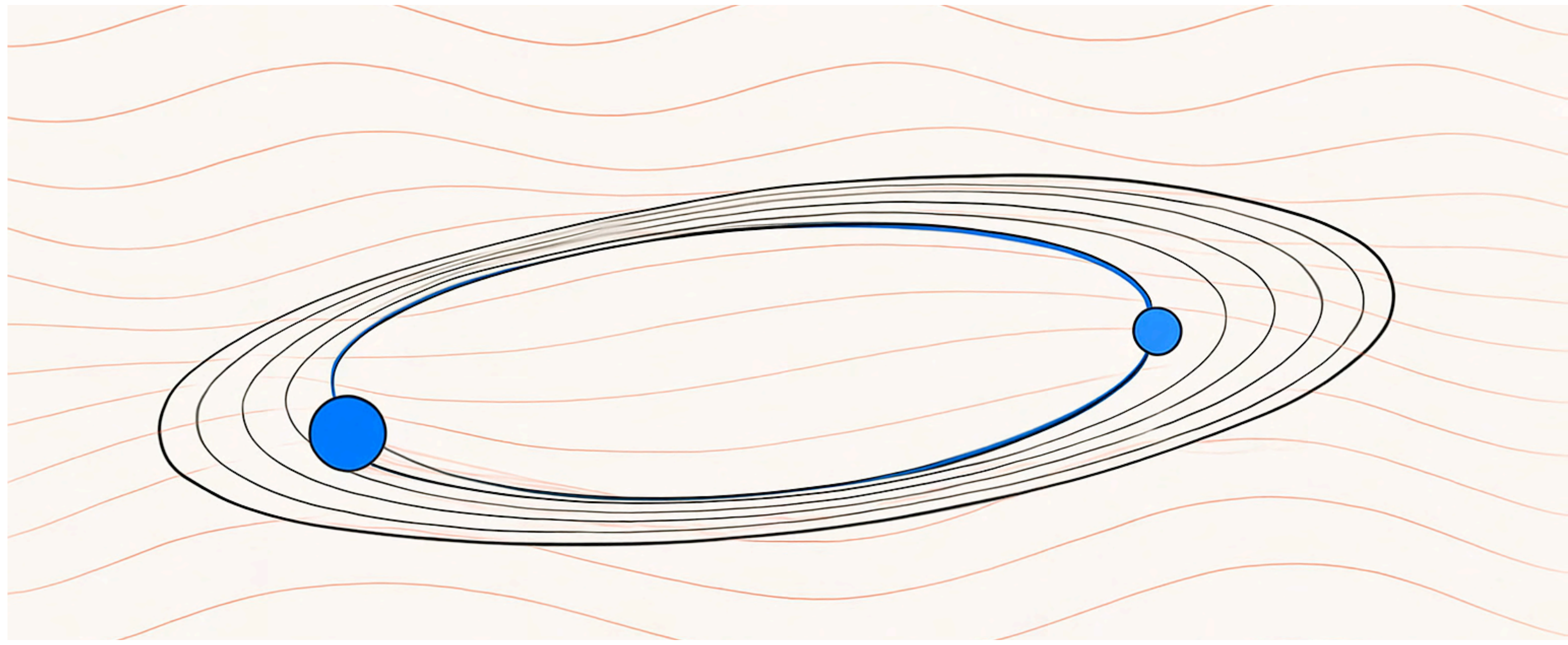
reasonable ideas for searches

GravNet

Our proposal: binary resonance!

gravitational waves affect gravitationally bound systems

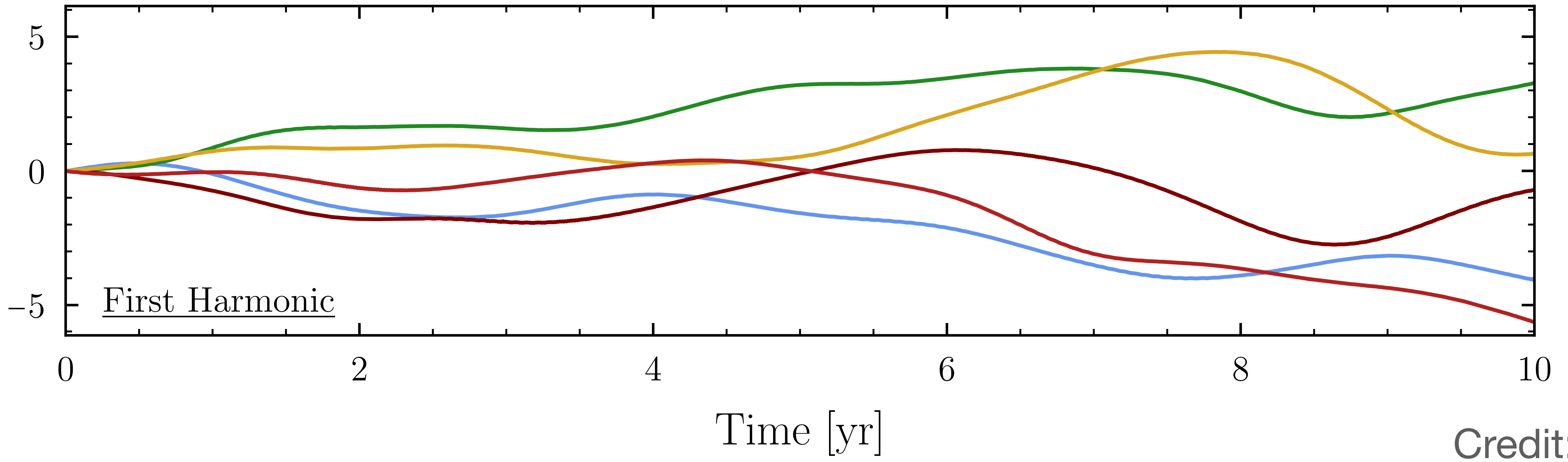
$$\delta \ddot{r}^i = -\,\delta R^i{}_{0j0} r^j$$



$$\lambda \gg a$$

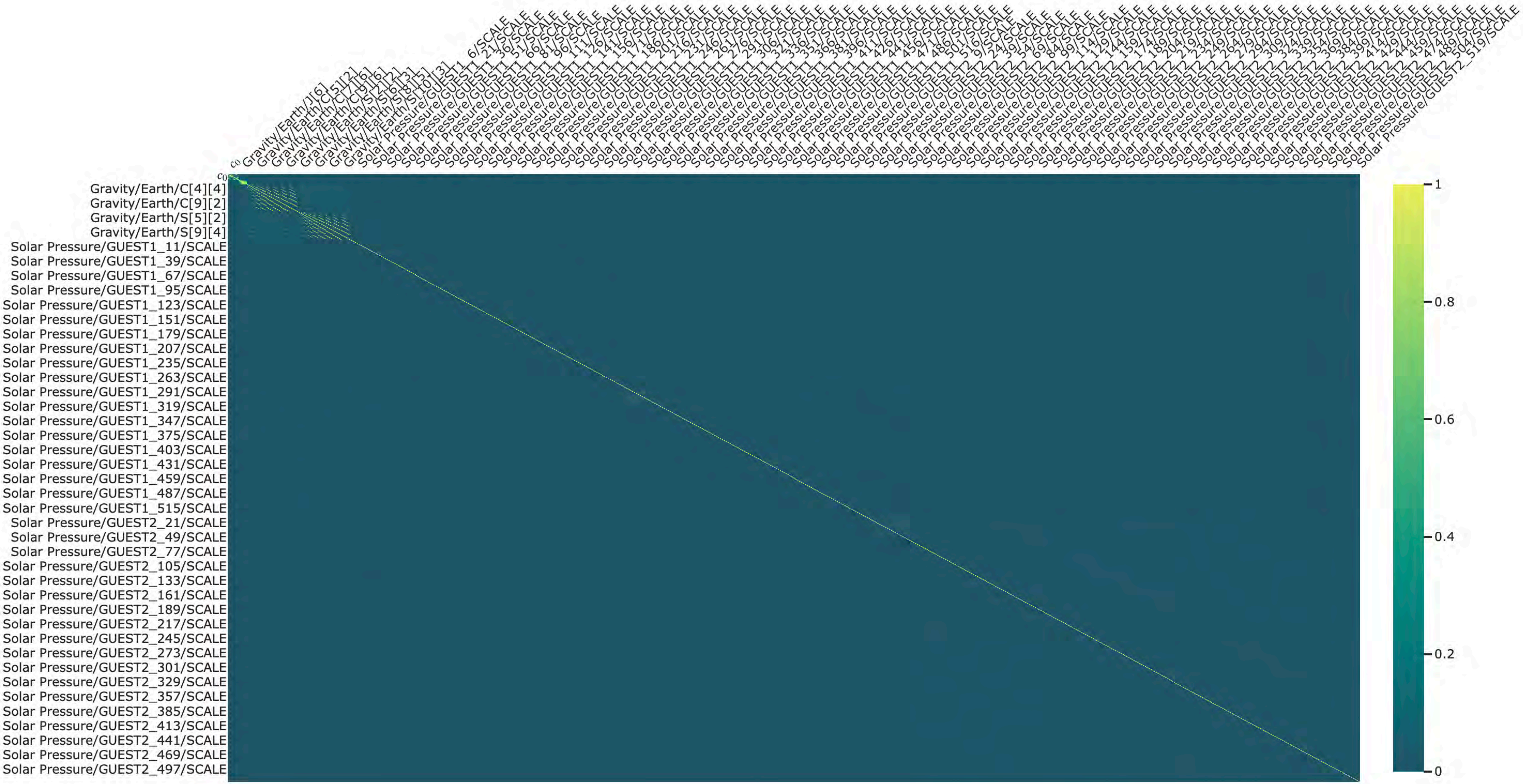
Semi-latus Rectum Perturbation (arbitrary units)

Evolution on stochastic backgrounds



Credit: J. Foster

Sensitivity: way to go



Sensitivity: way to go