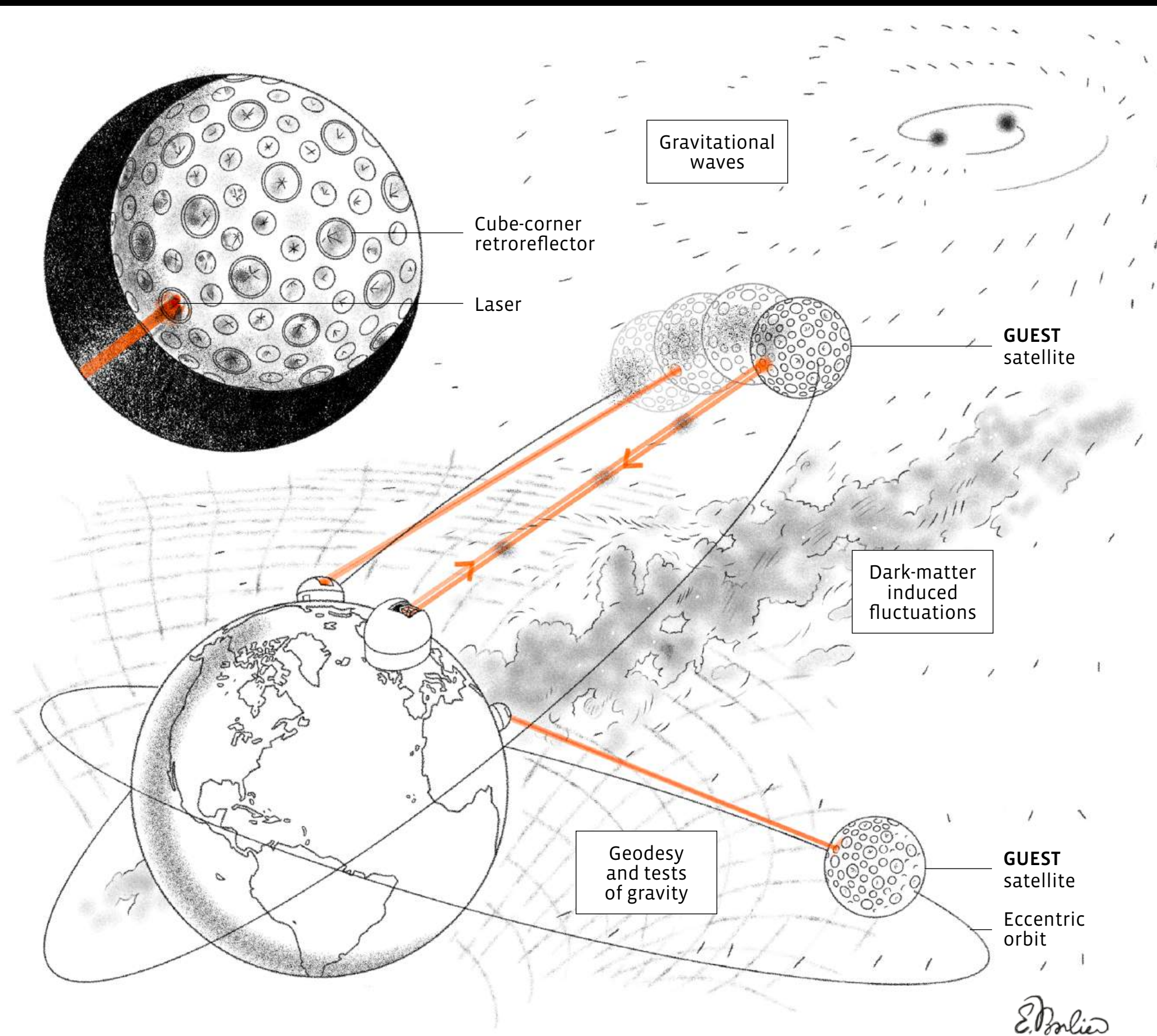




GUEST: Gravitational Universe Exploration with Satellite Tracking

<https://arxiv.org/abs/2607.18390>



Xiao Xue
A. Hees
J. Foster
A. Jenkins

+ proto
collaboration

Diego Blas



COSMIC OBSERVERS

IN DEVELOPMENT

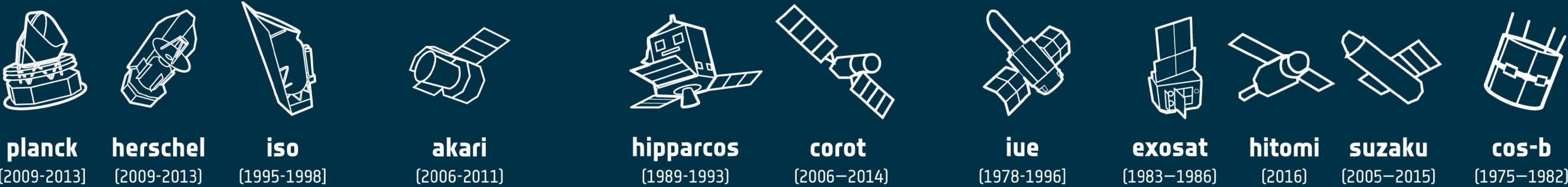


ACTIVE



microwaves sub-millimetre infrared optical ultraviolet x-rays gamma rays

LEGACY



COSMIC OBSERVERS

IN DEVELOPMENT



ariel
[2029]



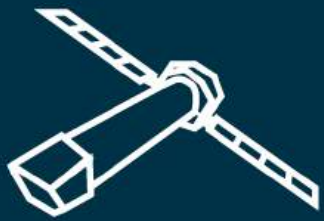
roman
[2026]



arrakihs
[2030]



plato
[2026]



new
athena
[~2037]

ACTIVE



webb
[2021-]



euclid
[2023-]



hubble
[1990-]



gaia
[2013-]



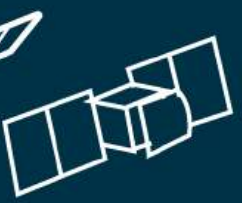
cheops
[2019-]



xrism
[2023-]



xmm-
newton
[1999-]



einstein
probe
[2024-]



integral
[2002-]

And for GWs?

microwaves

sub-millimetre

infrared

optical

ultraviolet

x-rays

gamma rays



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]



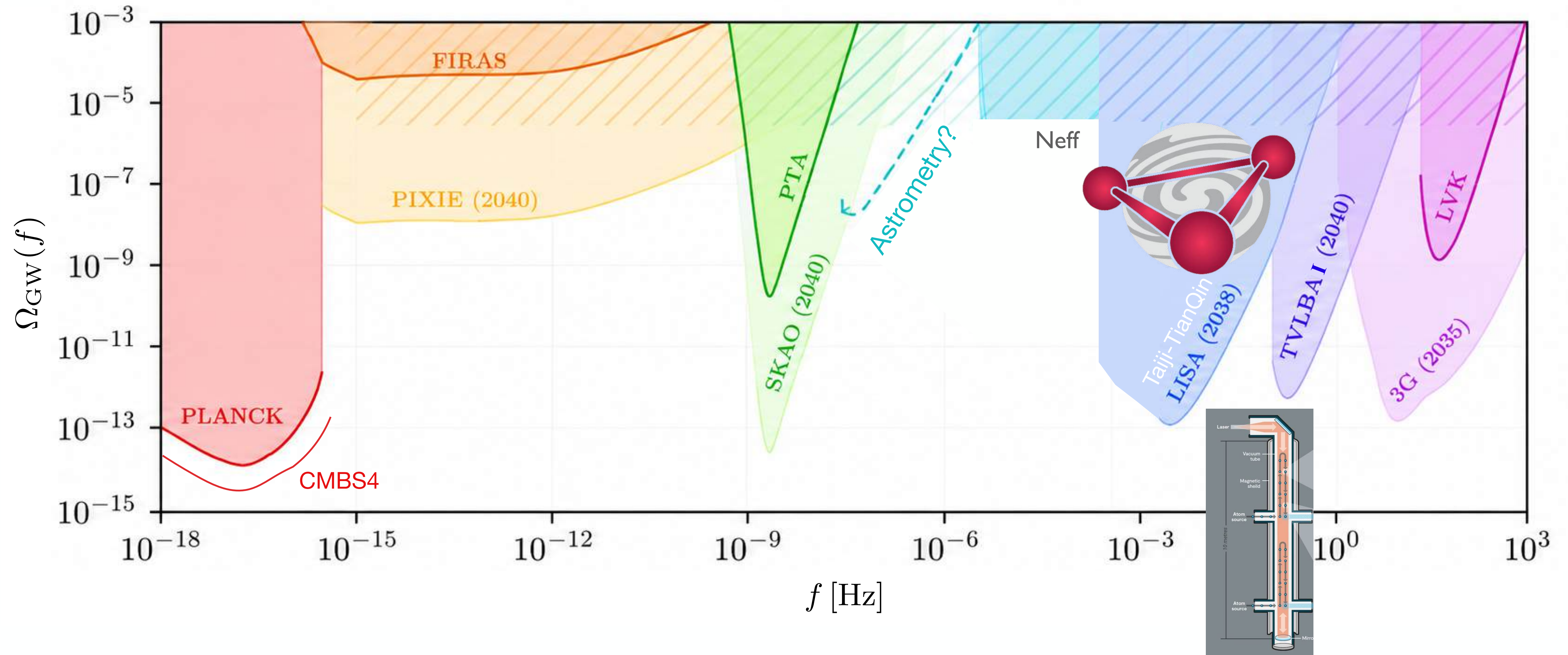
cos-b
[1975-1982]

LEGACY

Landscape of GW detectors: today to 2040

$$\Omega_{\text{gw}}(f) \equiv \frac{1}{\rho_c} \frac{d\rho_{\text{gw}}}{d \log f}$$

$$\rho_{\text{gw}} = \frac{c^2}{16\pi G} \langle \dot{h}_+^2 + \dot{h}_\times^2 \rangle = \frac{c^2}{32\pi G} \langle \dot{h}_{ij} \dot{h}^{ij} \rangle$$

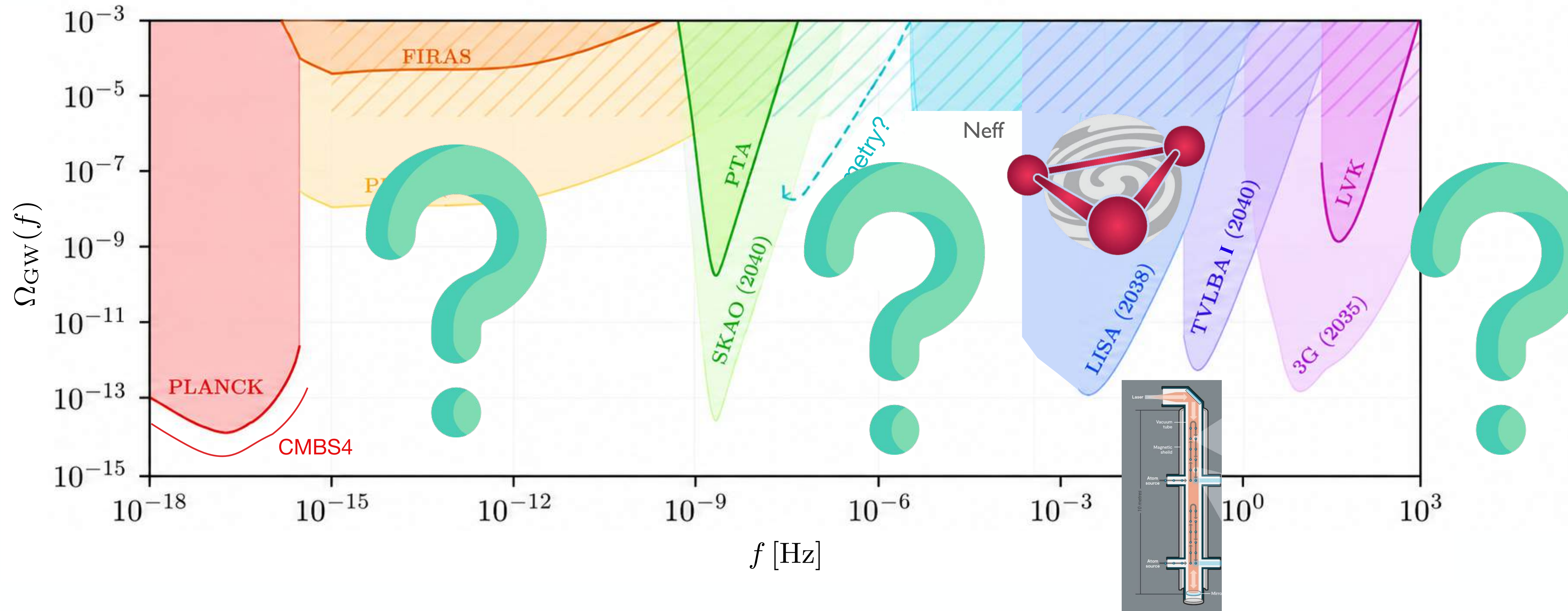


Very large baseline atomic interferometers

Landscape of GW detectors: today to 2045

$$\Omega_{\text{gw}}(f) \equiv \frac{1}{\rho_c} \frac{d\rho_{\text{gw}}}{d \log f}$$

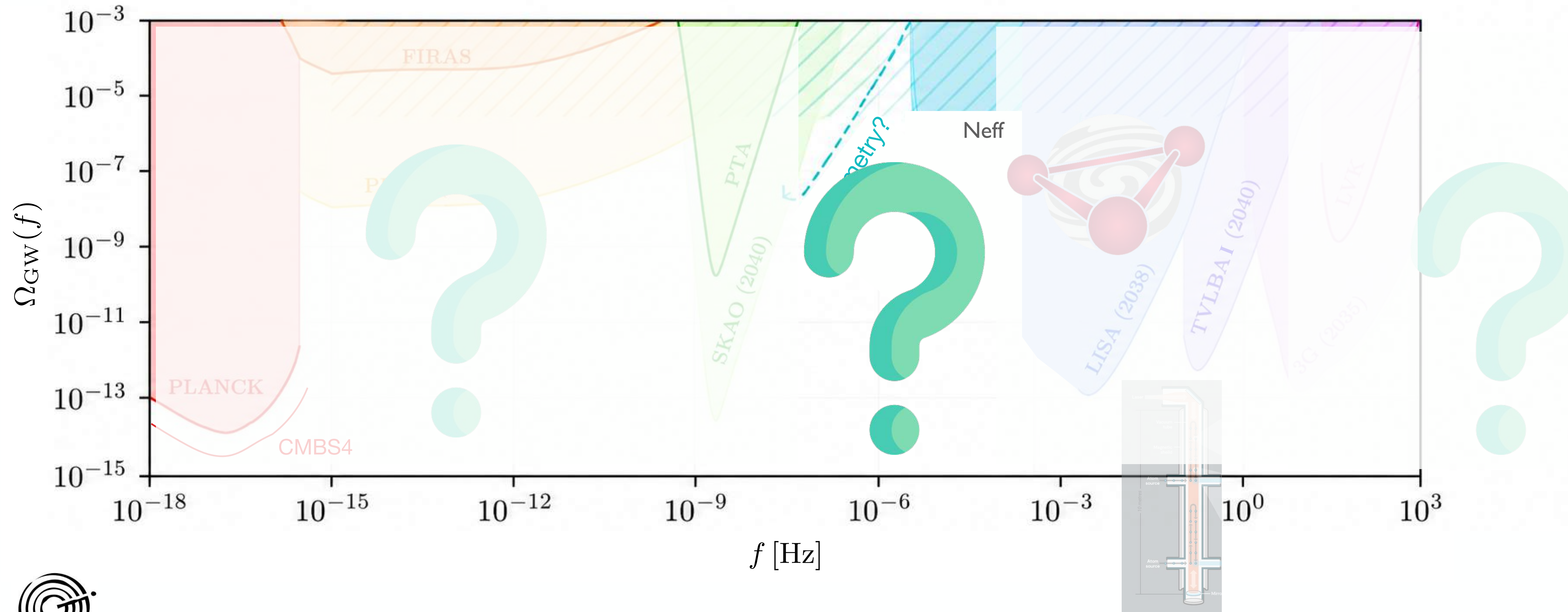
$$\rho_{\text{gw}} = \frac{c^2}{16\pi G} \langle \dot{h}_+^2 + \dot{h}_\times^2 \rangle = \frac{c^2}{32\pi G} \langle \dot{h}_{ij} \dot{h}^{ij} \rangle$$



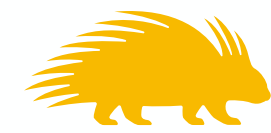
Very large baseline atomic interferometers

Landscape of GW detectors: today to 2045

MicroHz (μHz) is a band particularly rich in new signals



microHz to LISA band

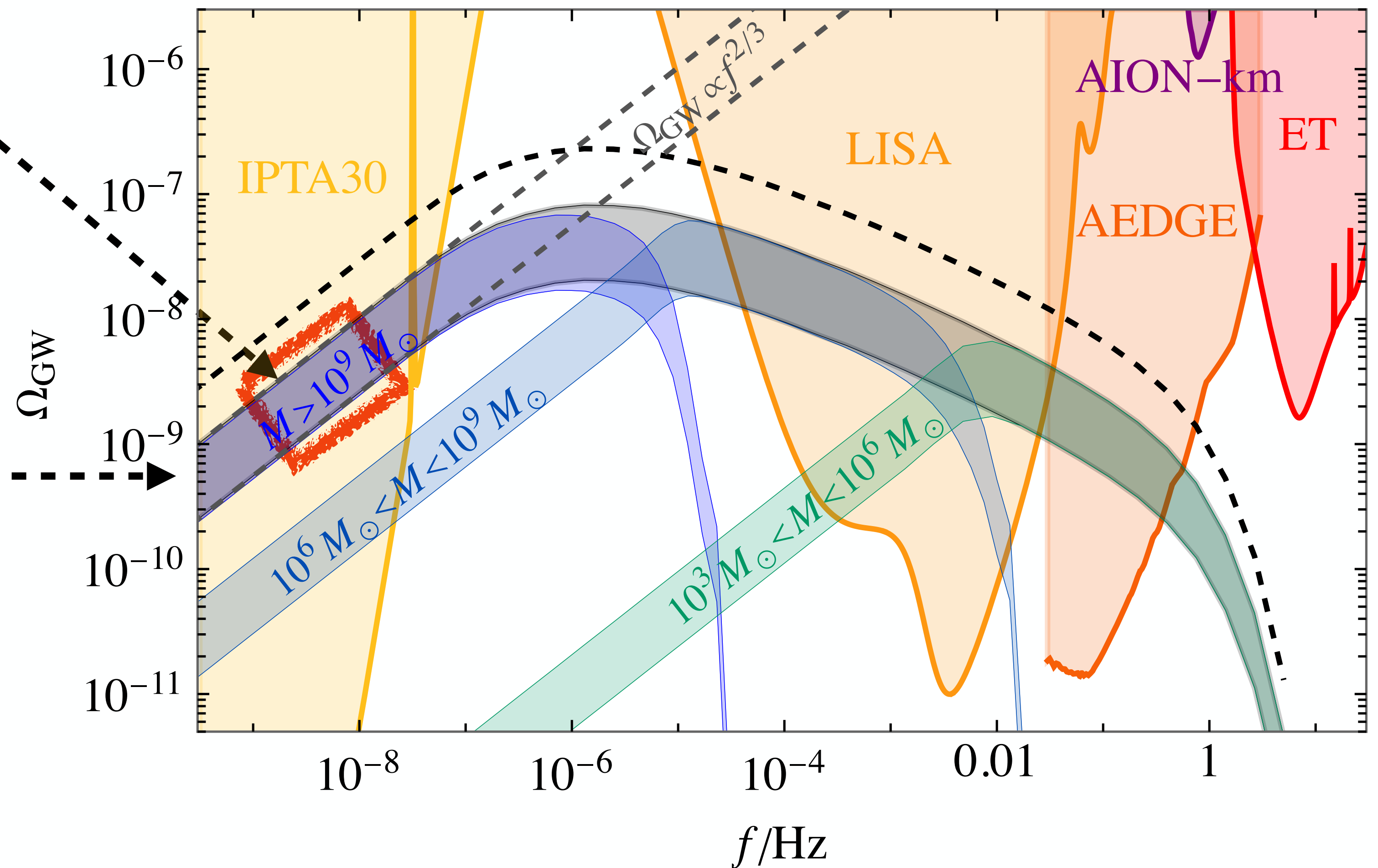


guaranteed signal by the corner?

2301.13854 Ellis et al

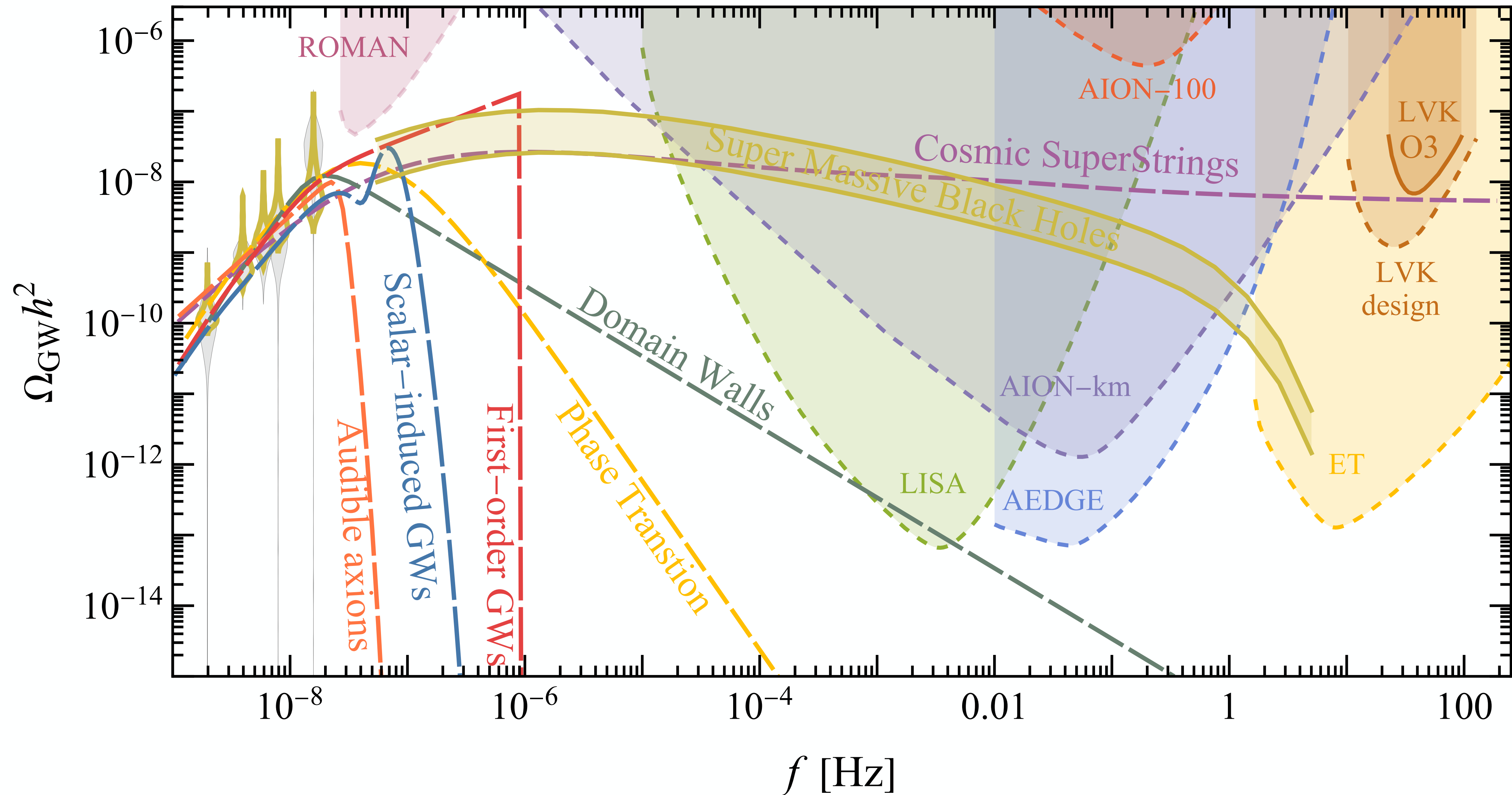
PTA Evidence 2023

Is it a signal of SMBHBs?



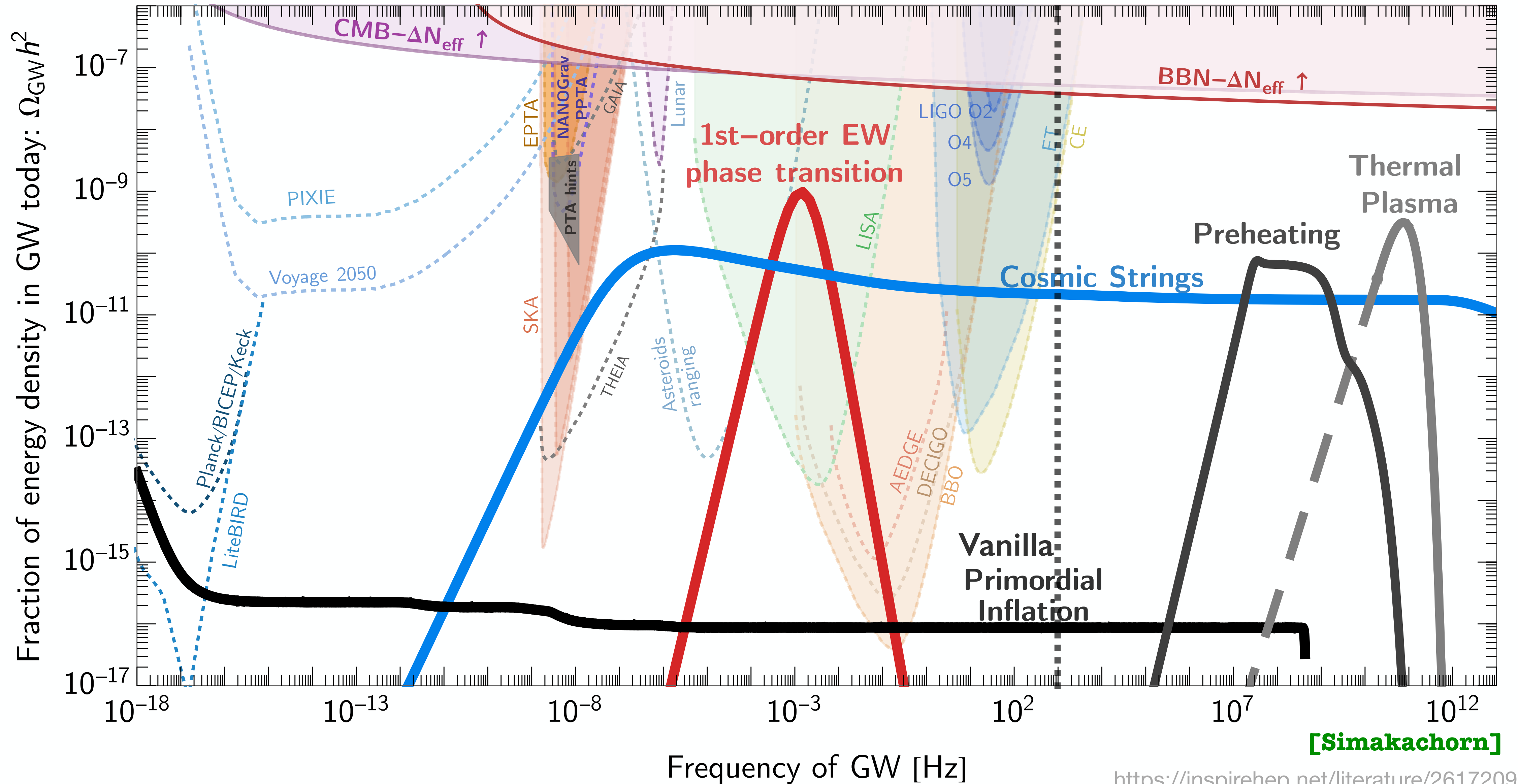
What's this PTA signal?

2308.08546 Ellis et al



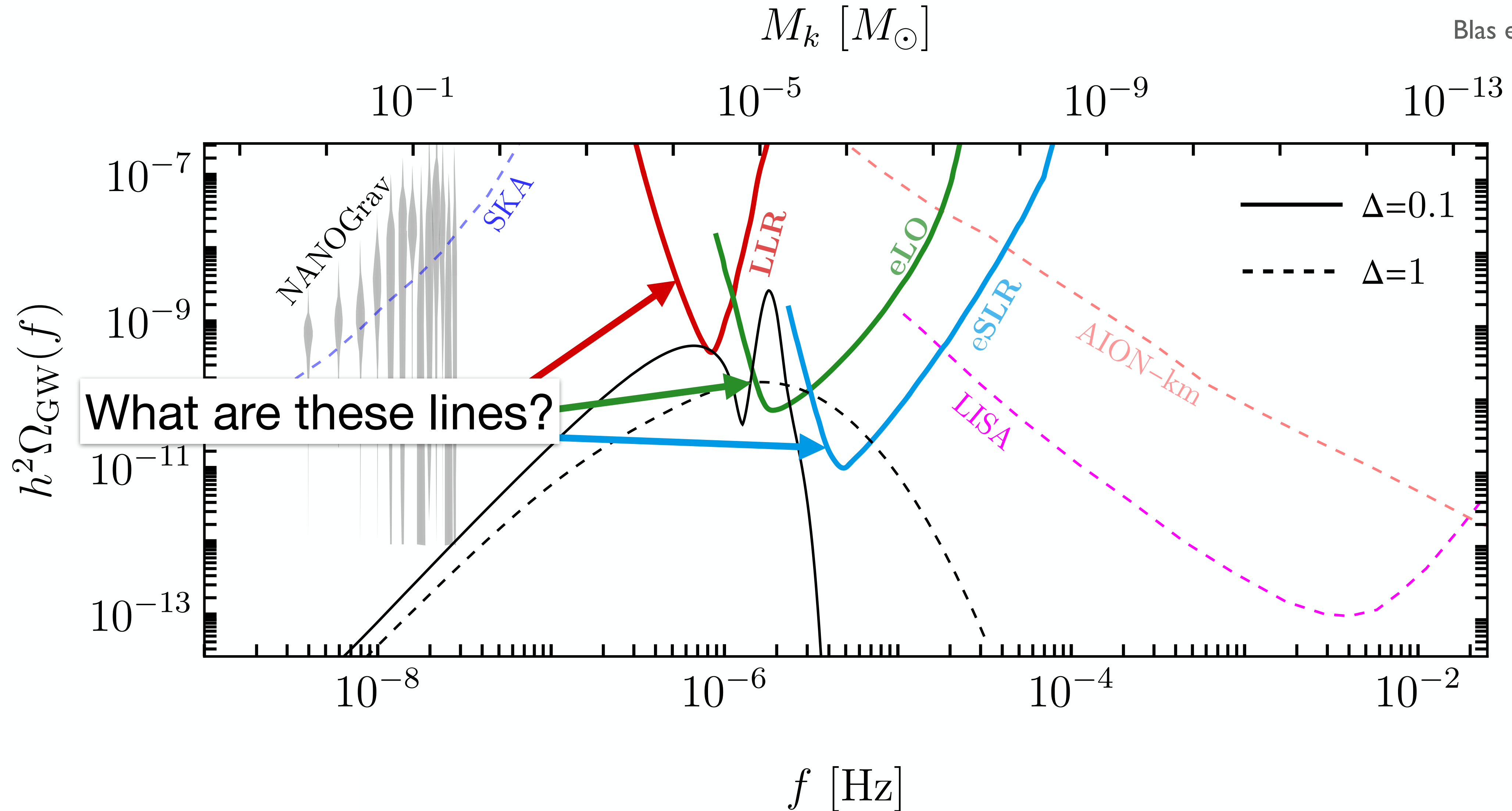
microHz to LISA band

Full of new physics



Another PBH signal: scalar-Induced GWs

Blas et al 2602.12252



in black the SIGW spectra for two benchmark scenarios, with $A = 10^{-2}$,
 $k_\star = 10^9 \text{ Mpc}^{-1}$, $\Delta = 0.1$ (solid) and $\Delta = 1$ (dashed).

Our proposal for μ Hz band: binary resonance!

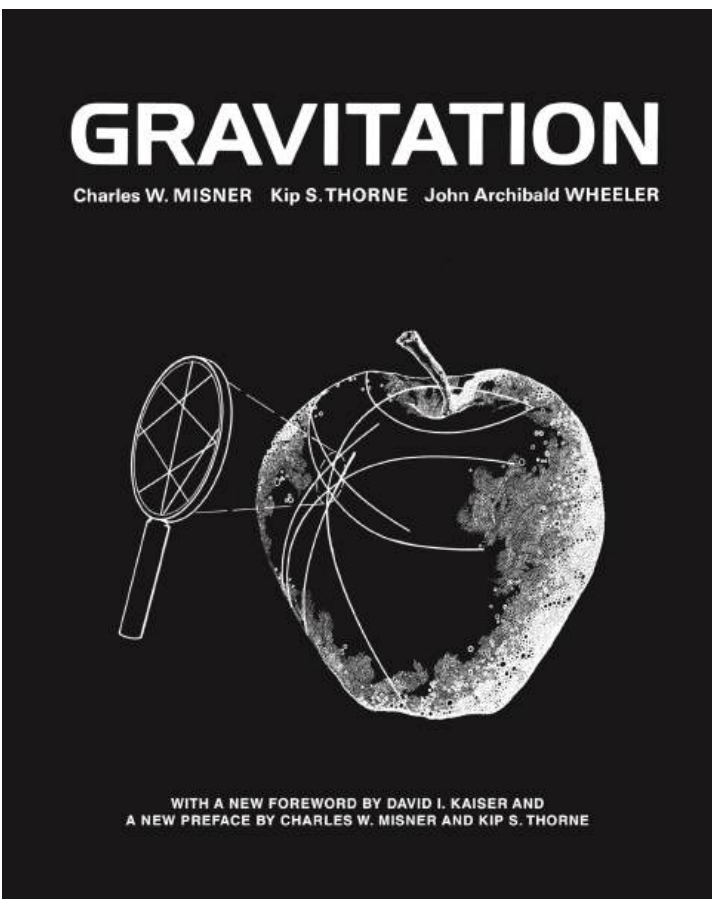
DB, **A. Jenkins**, 2107.04061, 2107.04063

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

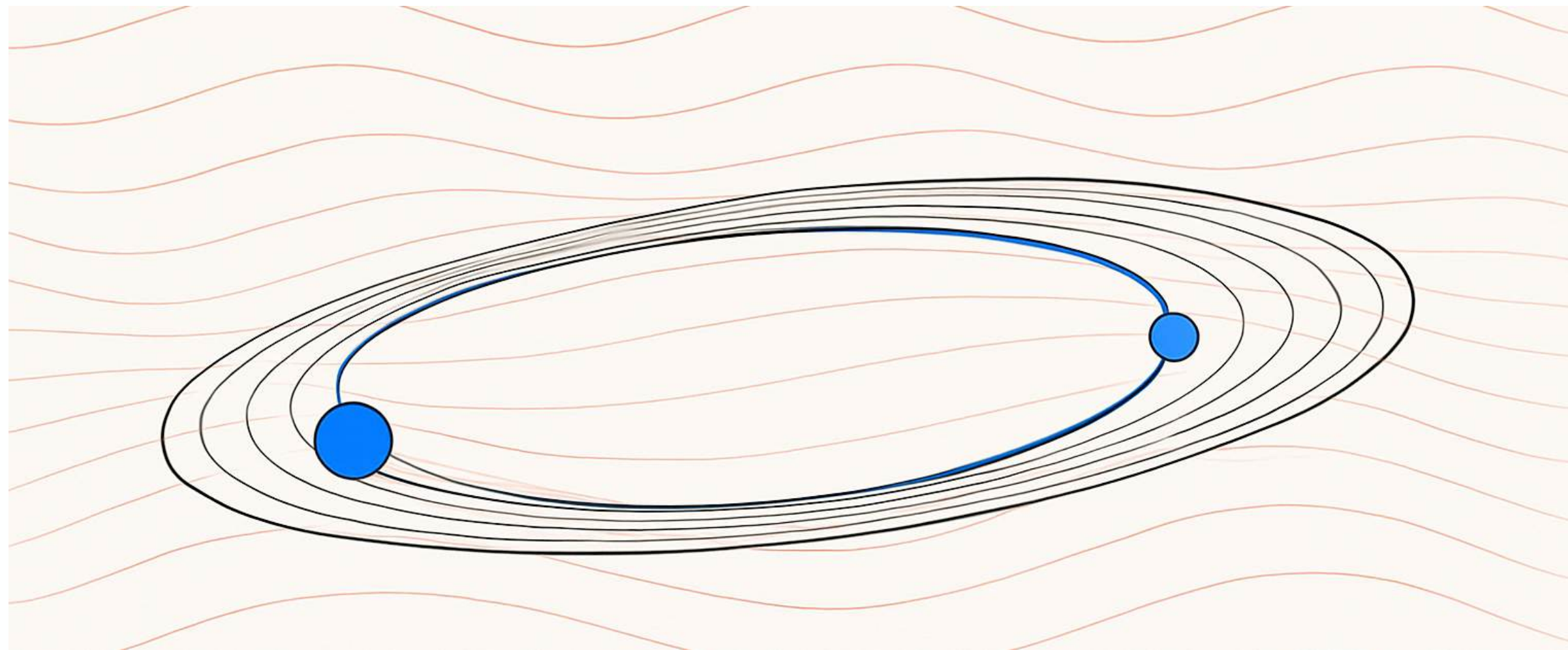
Foster, DB et al., arXiv:2504.16988 [gr-qc]

X. Xue, DB, et al. to appear

Our proposal for μHz band: binary resonance!



gravitational waves affect gravitationally bound systems



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. ??

$$\lambda \gg a$$

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

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

← Perturbing Gravitational Wave

Newtonian Potential

$$h \sim \cos(2\pi f t)$$

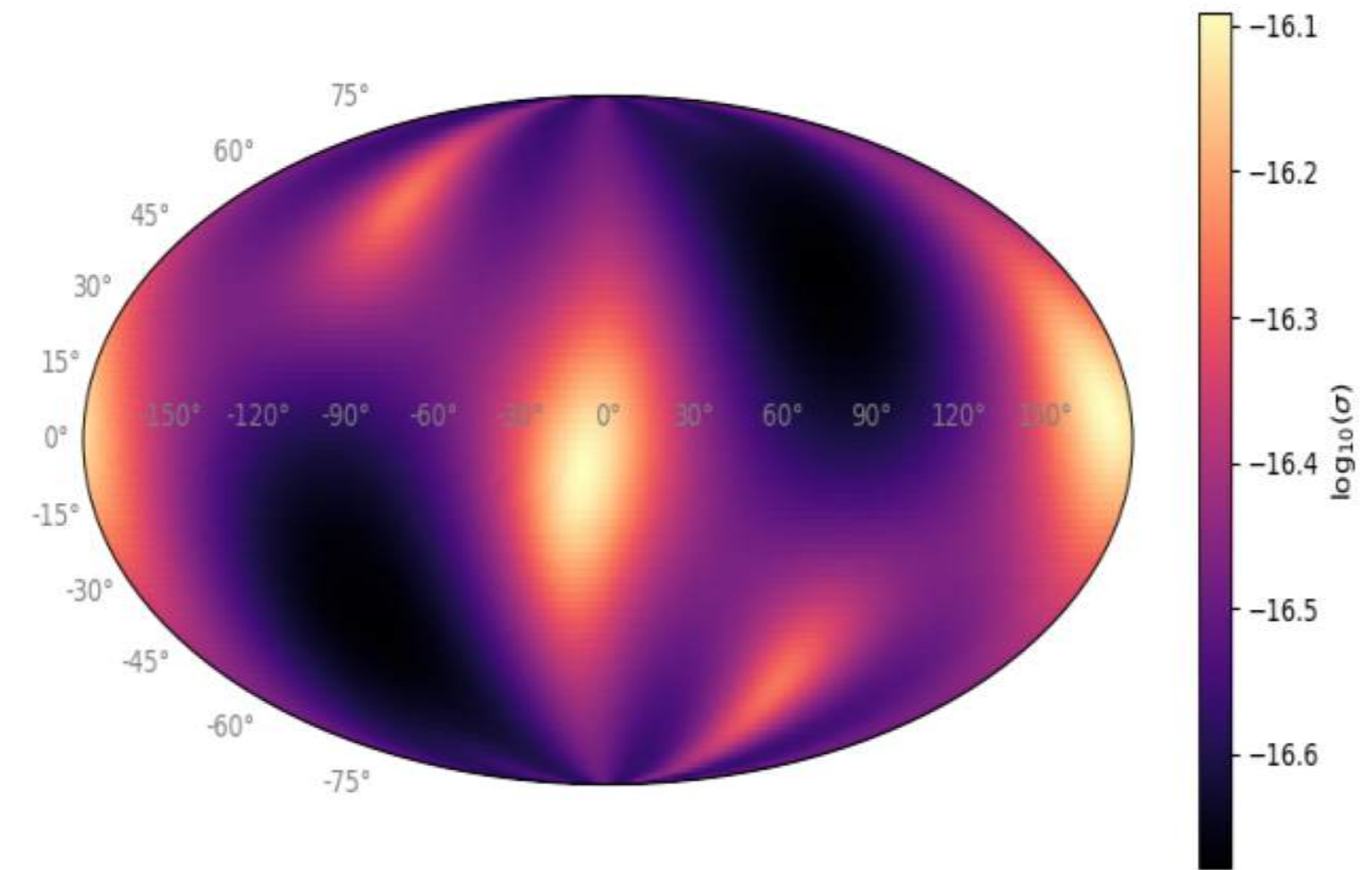
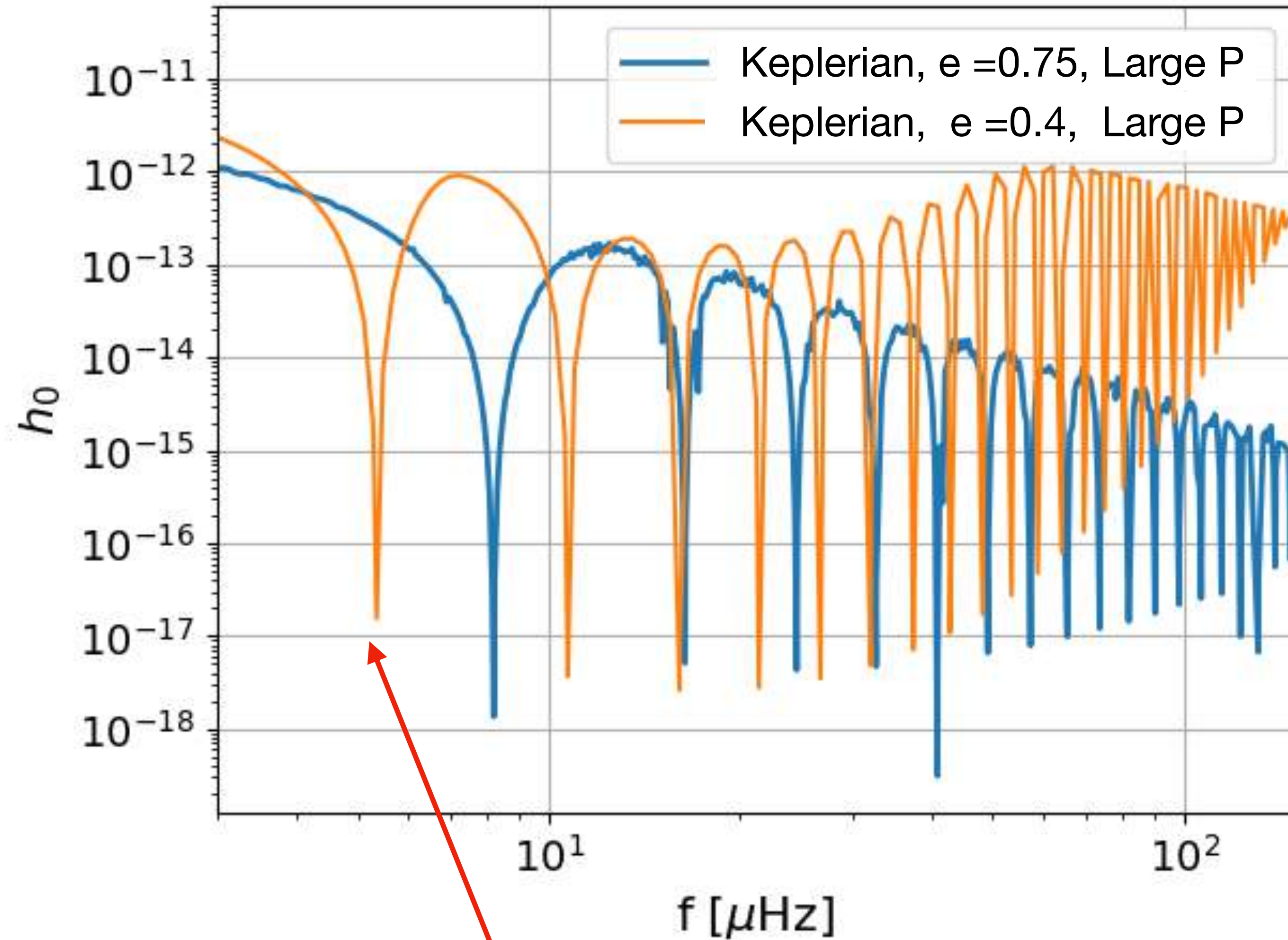
$$r \sim e \cos(2\pi t/P)$$

possible resonances at $f=n/P$

μHz
~ few days

Response of the system

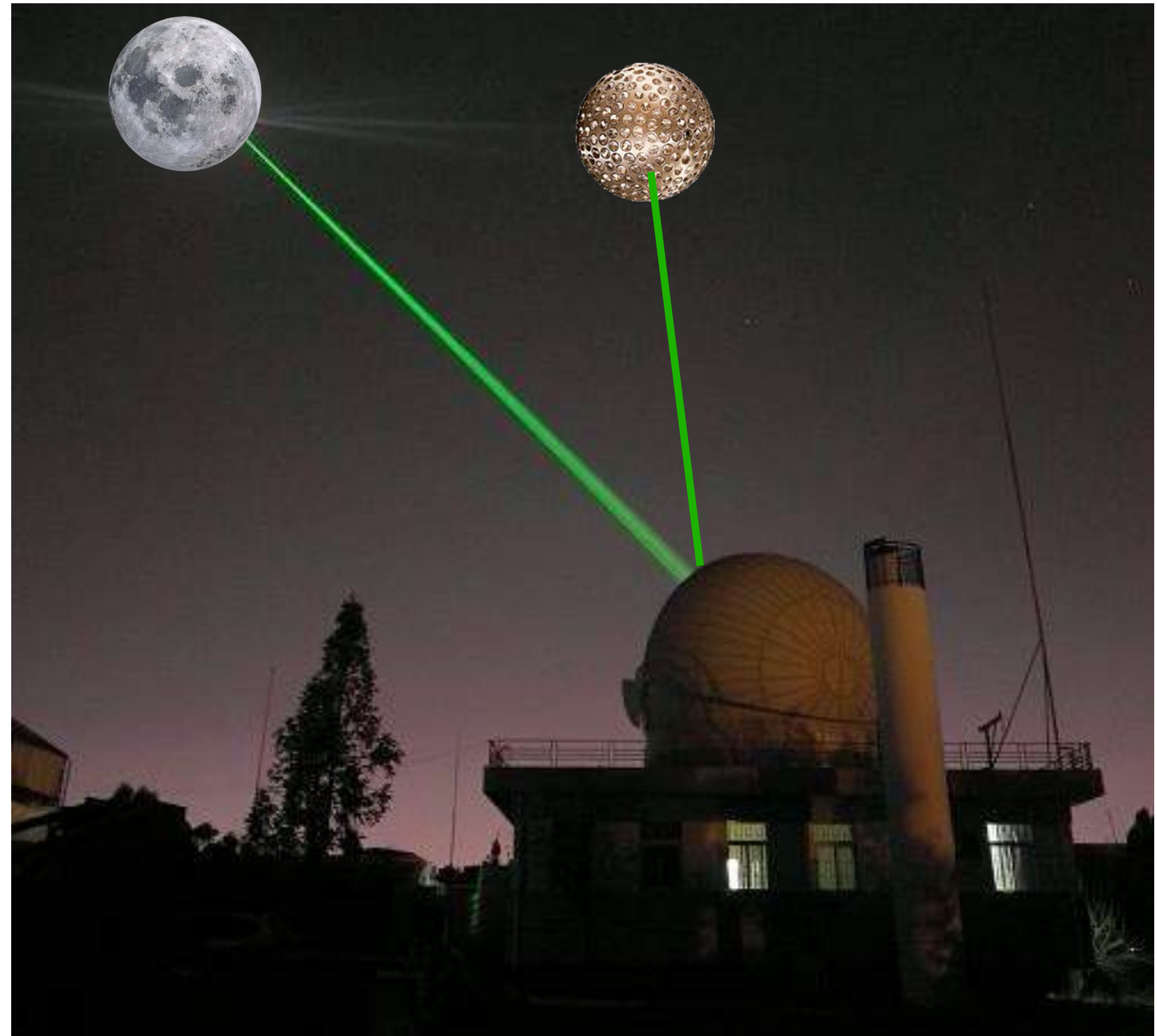
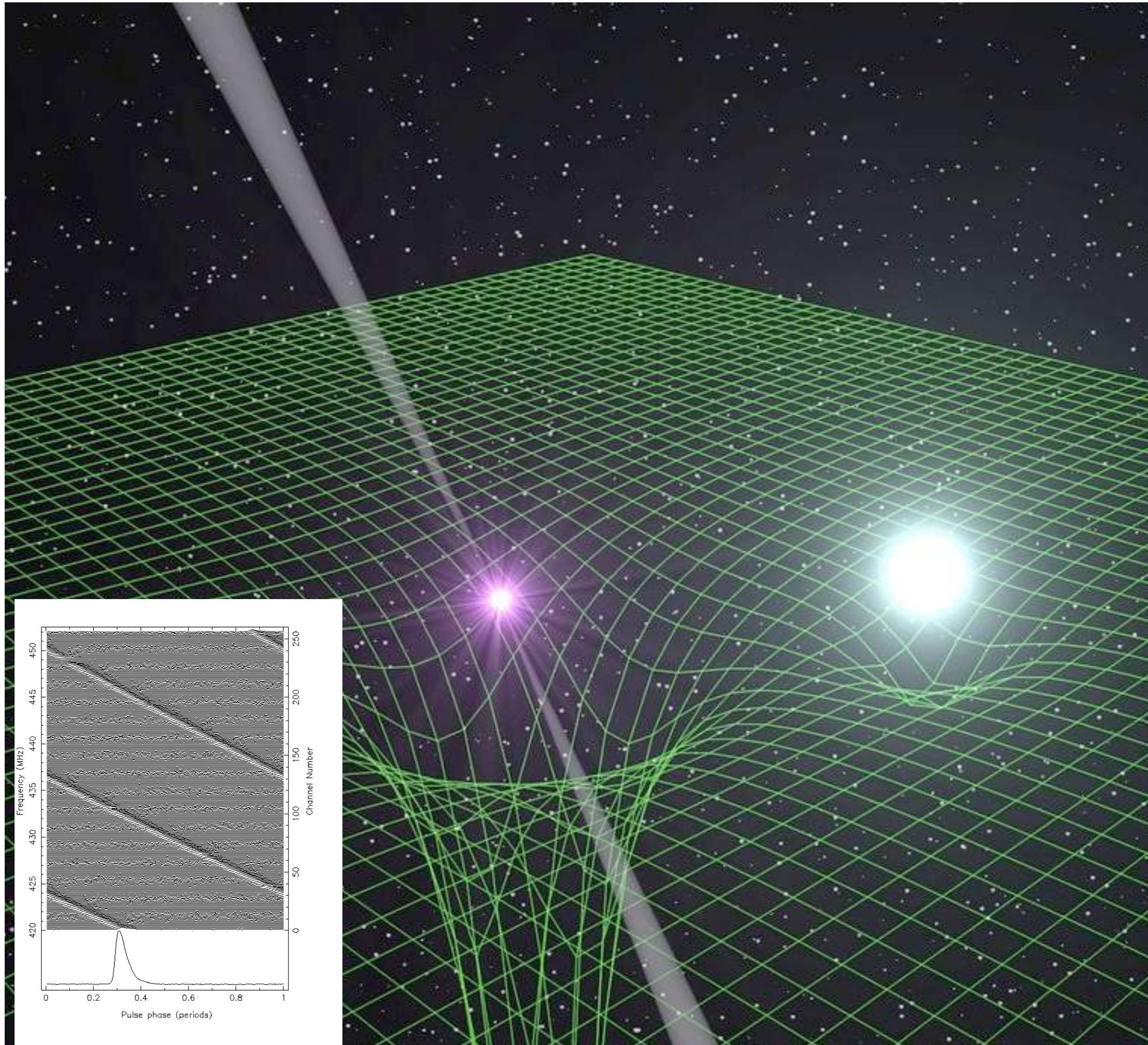
Foster, DB et al., arXiv: 2504.15334 [astro-ph.CO]
Foster, DB et al., arXiv:2504.16988 [gr-qc]
Xue, DB, et al. to appear



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

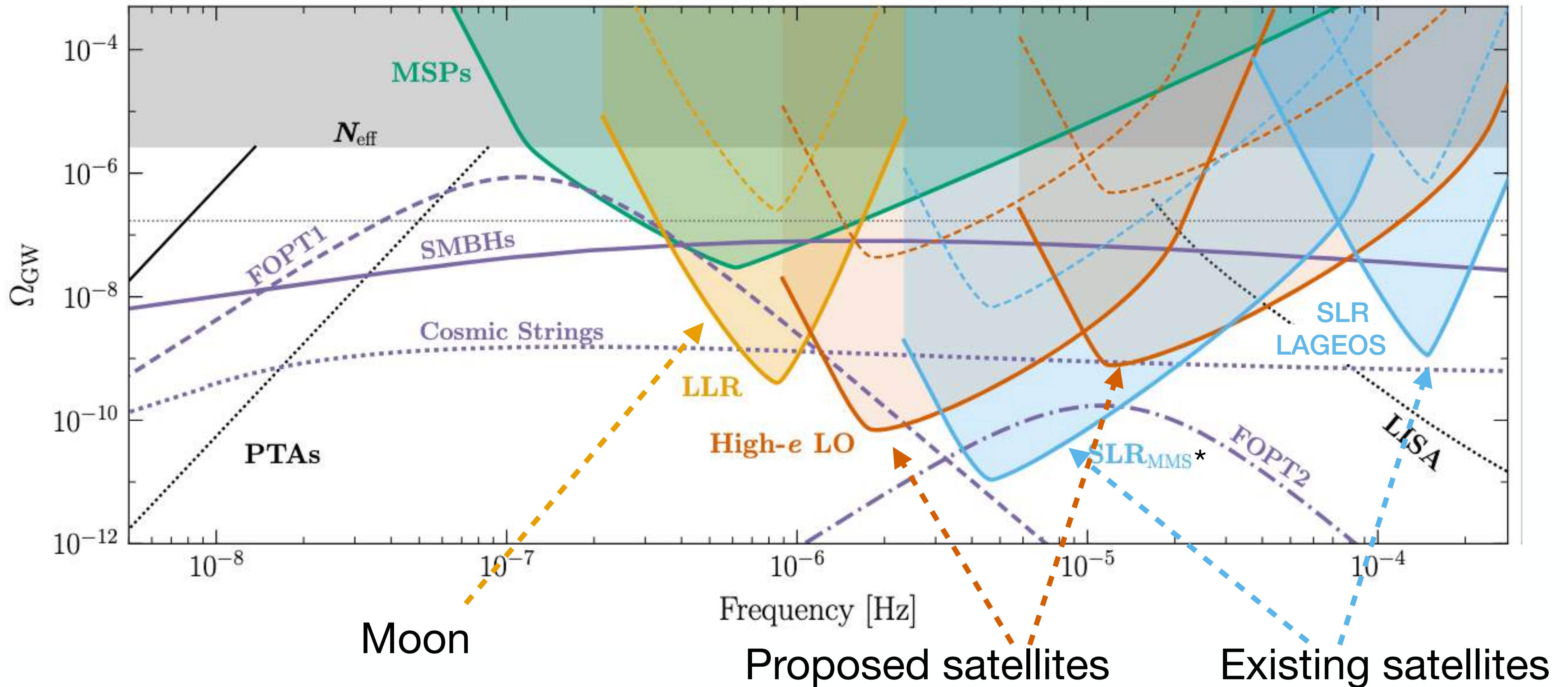
Two probes: precise timing of binaries

timing of binary pulsars lunar and satellite laser ranging



Our estimates from 2025 for 2035

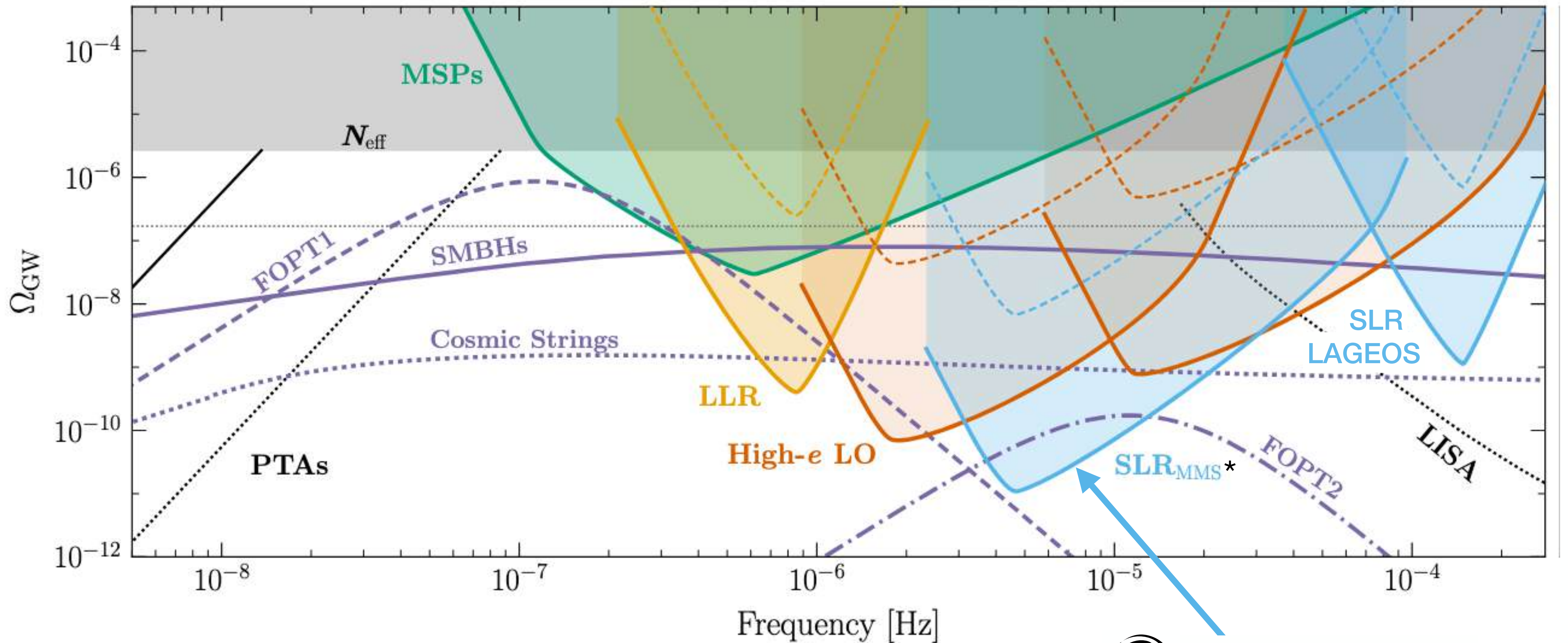
Foster, DB et al., arXiv: 2504.15334 [astro-ph.CO]
Foster, DB et al., arXiv:2504.16988 [gr-qc]



* MMS: 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 al., arXiv:2504.16988 [gr-qc]



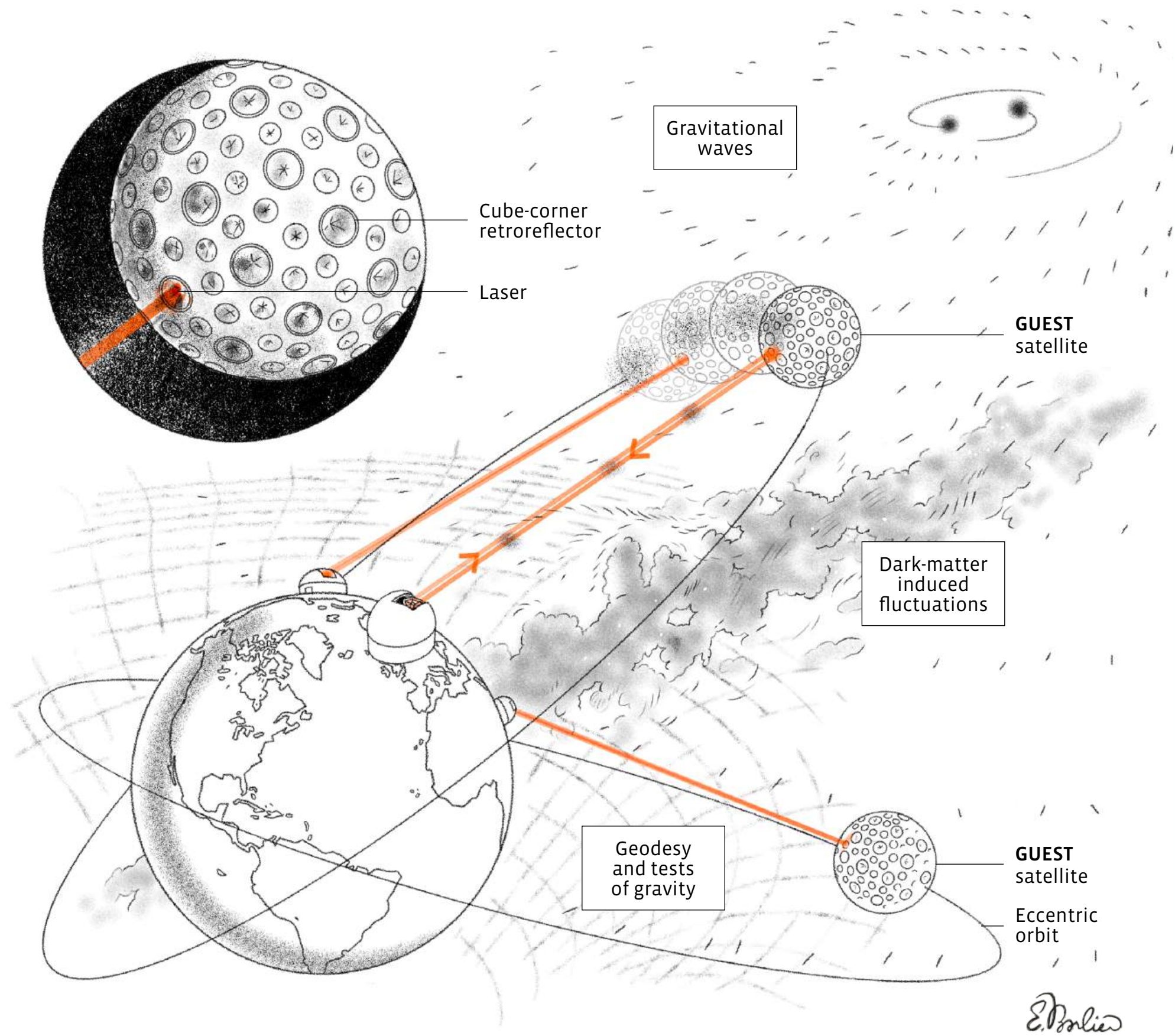
GUEST

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



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

<https://arxiv.org/abs/2607.18390>



Core members

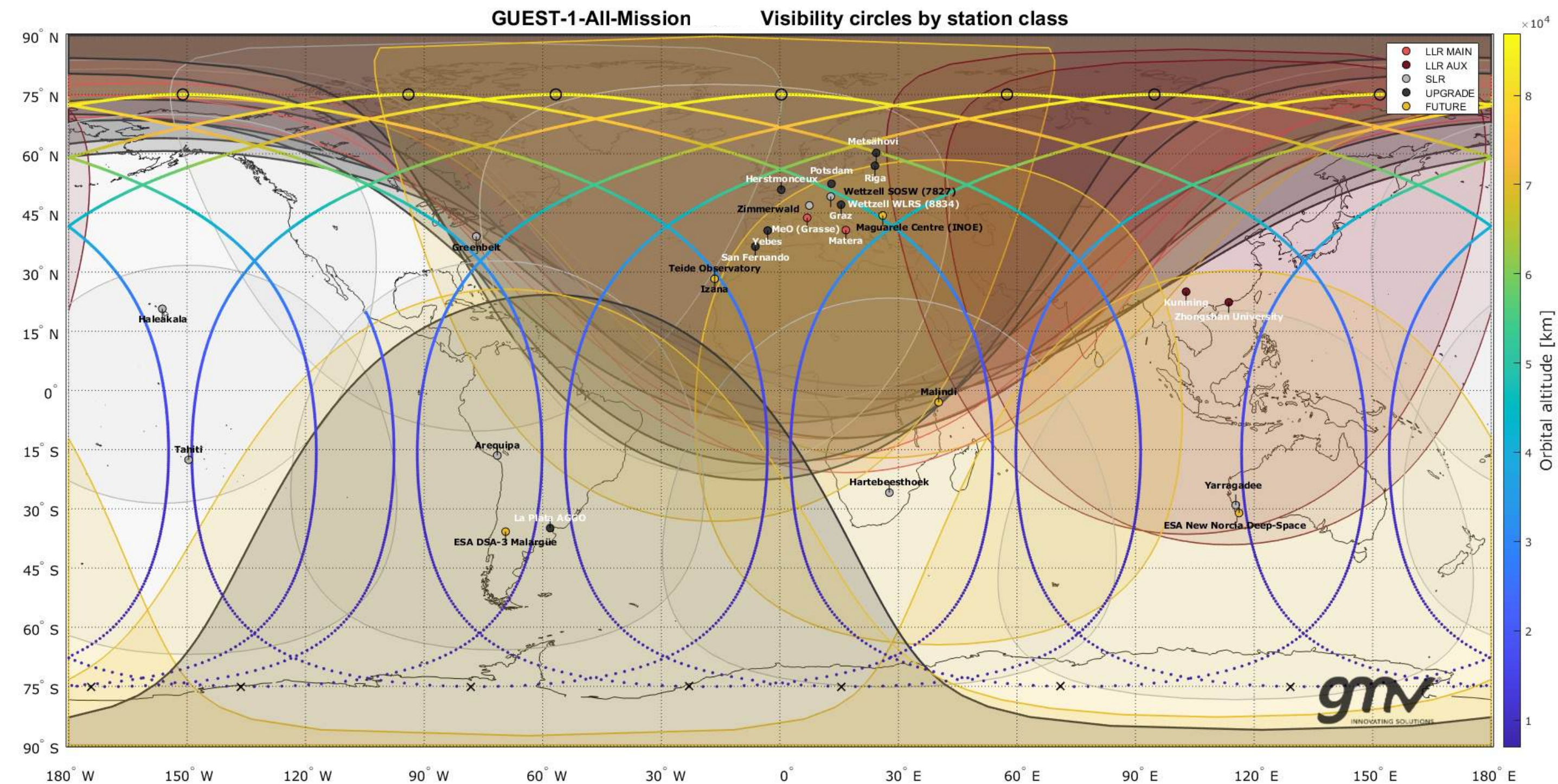
Country	Name	Email	Institution
Spain	Diego Blas (Lead)	dblas@ifae.es	IFAE/ICREA
Spain	José C. Rodriguez	jcrodriguez@transportes.gob.es	IGN
Spain	Jorge M. Camalich	jcamalich@iac.es	IAC
Belgium	Bruno Bertrand	bruno.bertrand@observatory.be	ROB
Belgium	Sebastien Le Maistre	sebastien.lemaistre@oma.be	ROB/UCLouvain
France	Julien Chabé	Julien.CHABE@geoazur.unice.fr	OCA/GeoAzur
France	Clément Courde	courde@geoazur.unice.fr	CNRS/Geoazur
France	Aurelien Hees	aurelien.hees@obspm.fr	LTE-Paris Obs.
France	Nicola Tamanini	nicola.tamanini@l2it.in2p3.fr	L2IT-CNRS
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Germany	Albert Roura	albert.roura.dlr@gmail.com	DLR
Italy	Giada Bargiacchi	Giada.Bargiacchi@lnf.infn.it	LNF-INFN
Italy	Nicolò Burzillà	nicolo.burzilla@lnf.infn.it	LNF-INFN
Italy	Marco Cinelli	marco.cinelli@inaf.it	IAPS-INAF
Italy	Simone Dell'Agnello	simone.dellagnello@lnf.infn.it	LNF-INFN
Italy	David Lucchesi	david.lucchesi@inaf.it	IAPS-INAF
Italy	Dario Vetrano	d.vetrano@lnf.infn.it	LNF-INFN
Romania	Laurentiu Caramete	lcaramete@spacescience.ro	I. Space Science
UK	Alexander C. Jenkins	acj46@cam.ac.uk	U. Cambridge
USA	Joshua W. Foster	jwfooster@fnal.gov	U. Wisconsin



GUEST Orbits

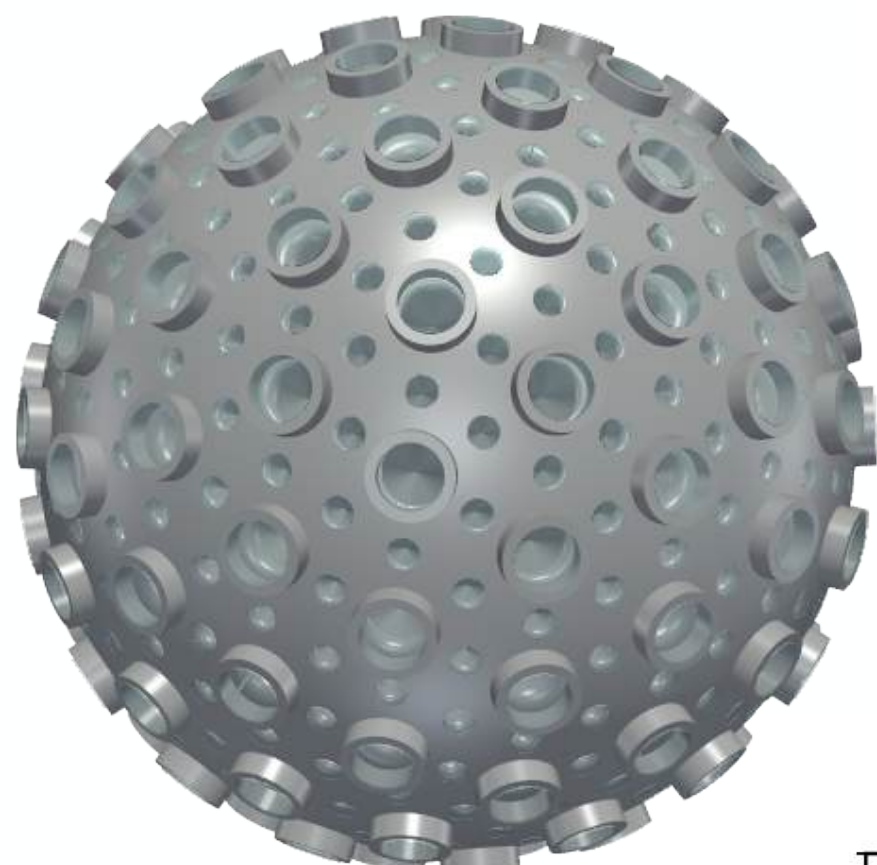
Orbits at t_0	Perigee altitude	Apogee altitude	AOP	RAAN	e_0	ι	Period
Orb1 / Orb2	6926 km	86700 km	270^0	$0^0/220^0$	0.75	$75^0/50^0$	33.8 h

- Optimized for:
 - Science: large period and eccentricity
 - End of life: these orbits reenter after the mission life-time (10yr +20yr extended phase)
 - Visibility from the ground stations: not too high, geometric visibility optimized

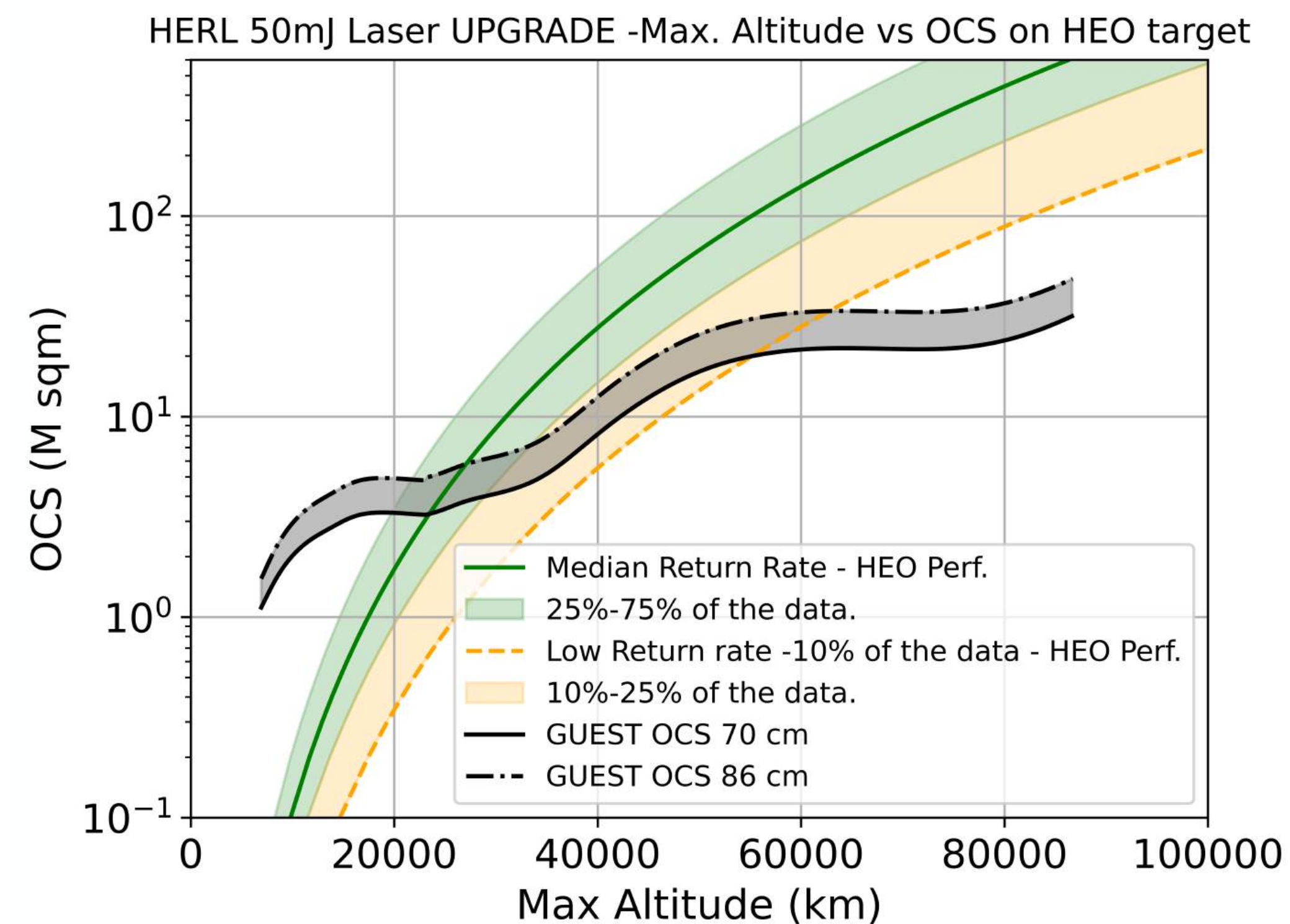
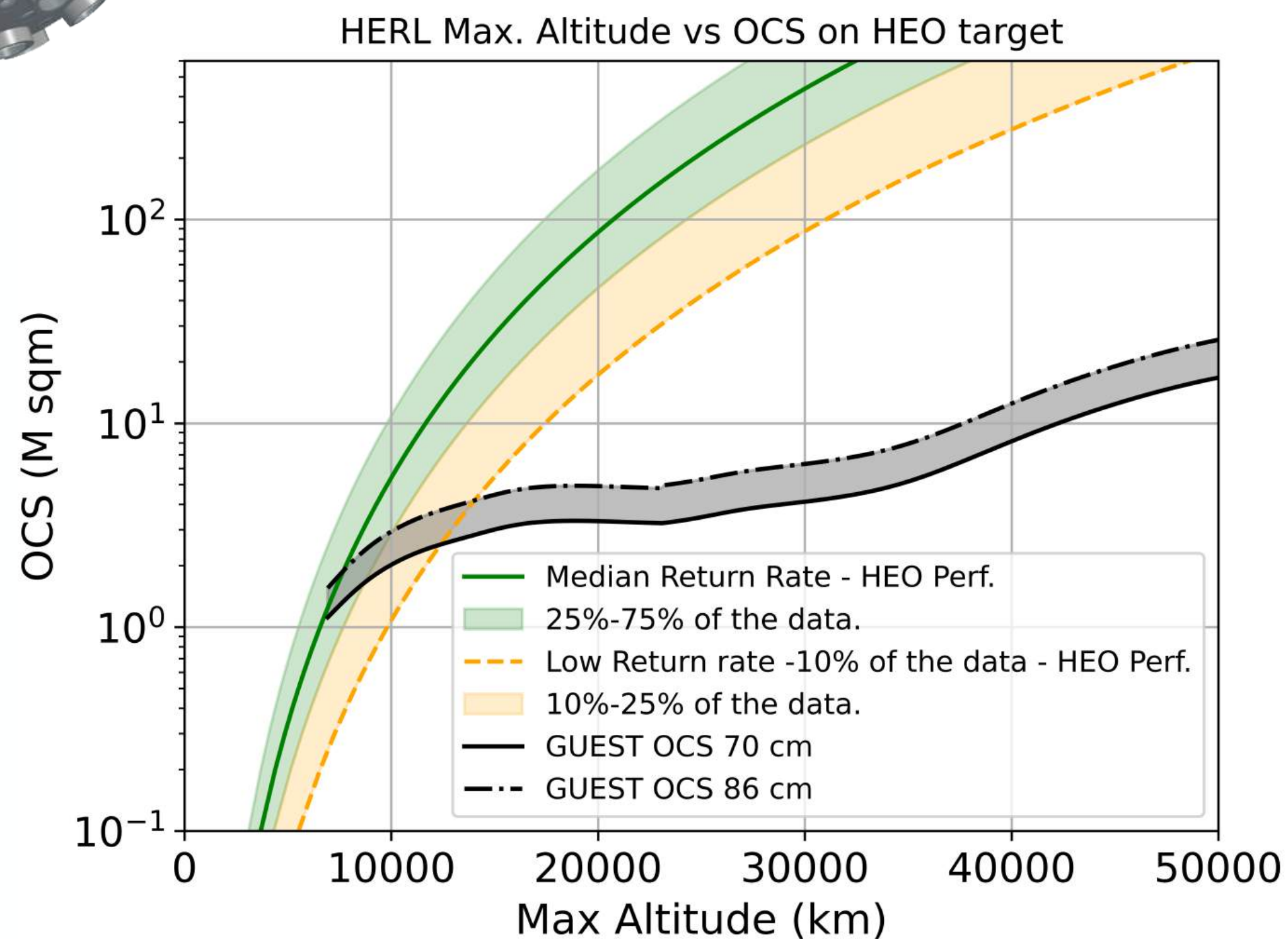




Payload and visibility



$\emptyset$	$\emptyset$ CCR1/CCR2	single OCS CCR1 (v_p)/ CCR2 (v_a)	# CCR1/CCR2	OCS range
86 cm	1 inch / 2 inches	$0.1 \text{ Mm}^2 / 16.5 \text{ Mm}^2$	561/189	$1.6\text{-}48.6 \text{ Mm}^2$
70 cm	1 inch / 2 inches	$0.1 \text{ Mm}^2 / 16.5 \text{ Mm}^2$	366/124	$1.0\text{-}31.8 \text{ Mm}^2$

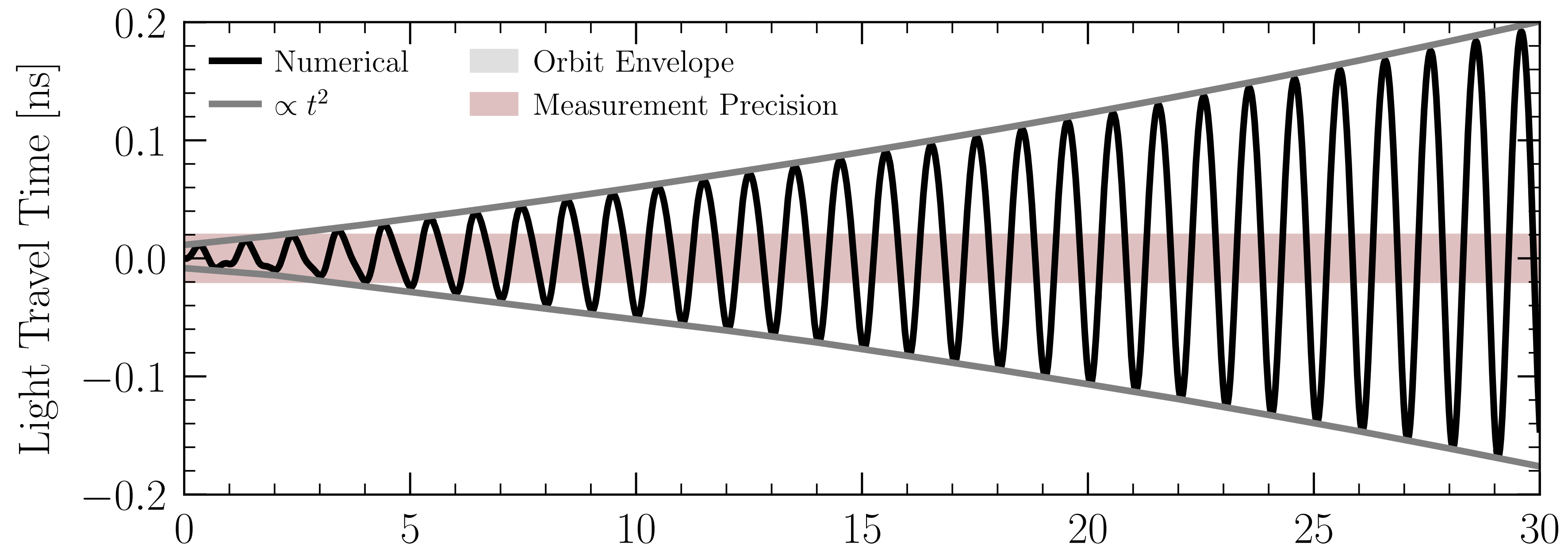




Sensitivity: way to go

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

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

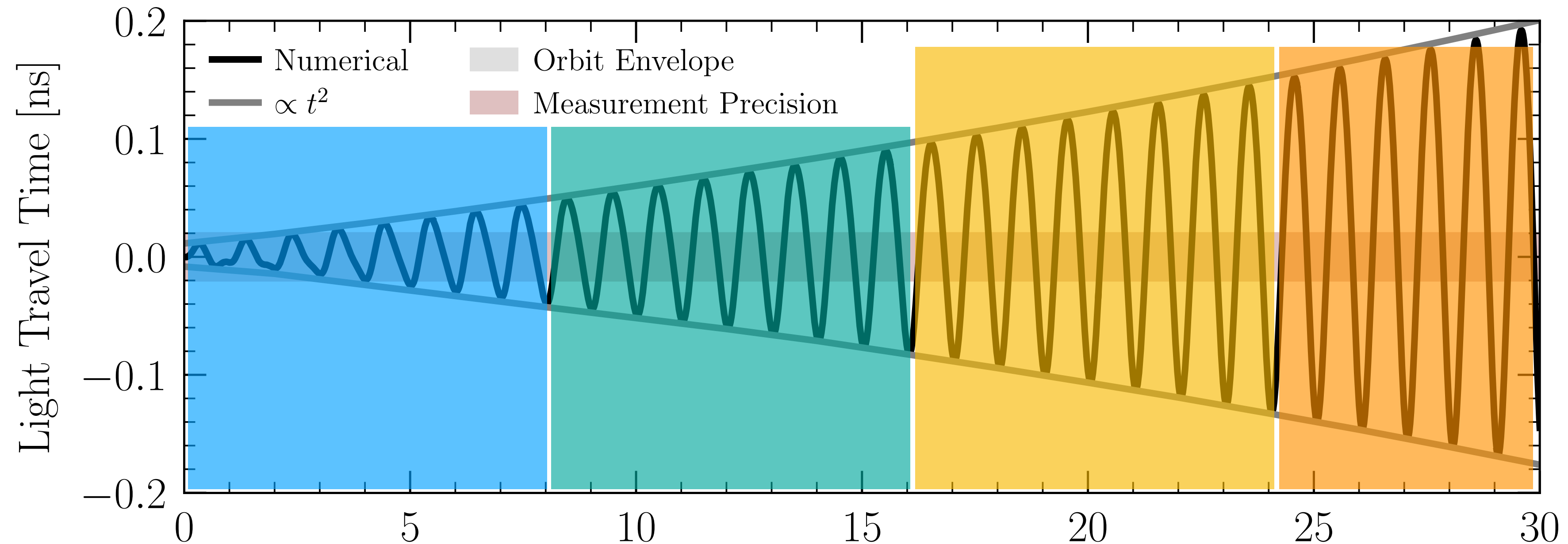




Sensitivity: way to go

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

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).

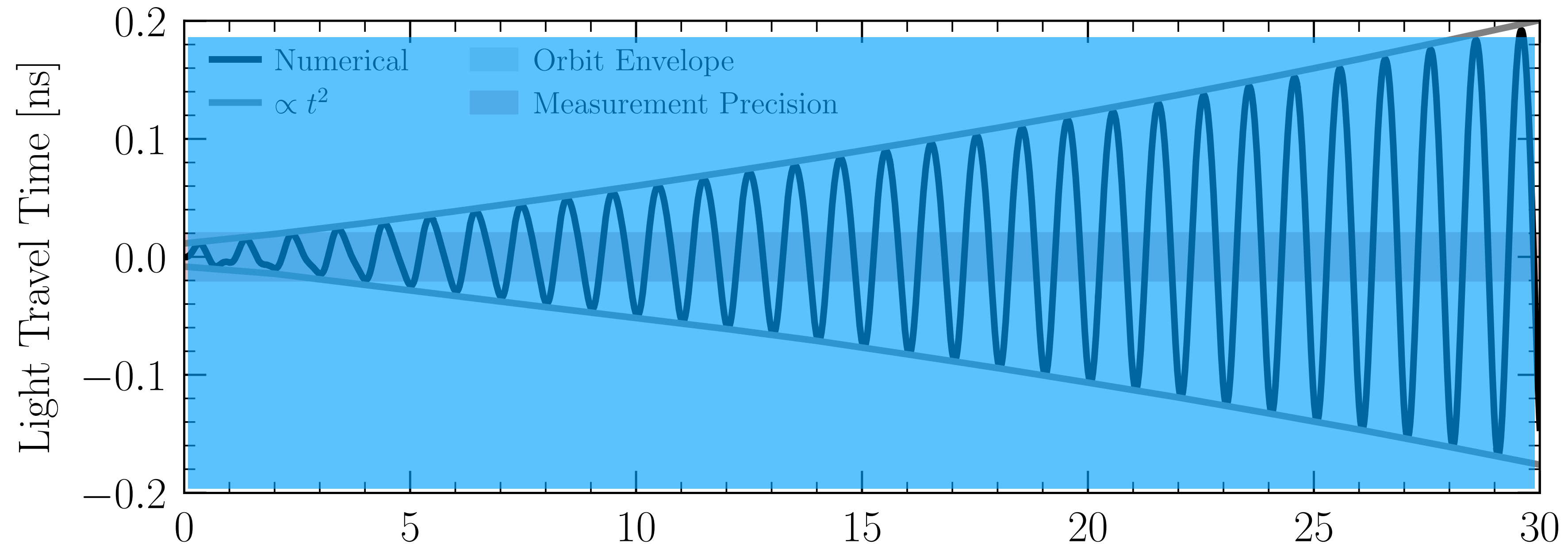
Derived for geodesy



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).

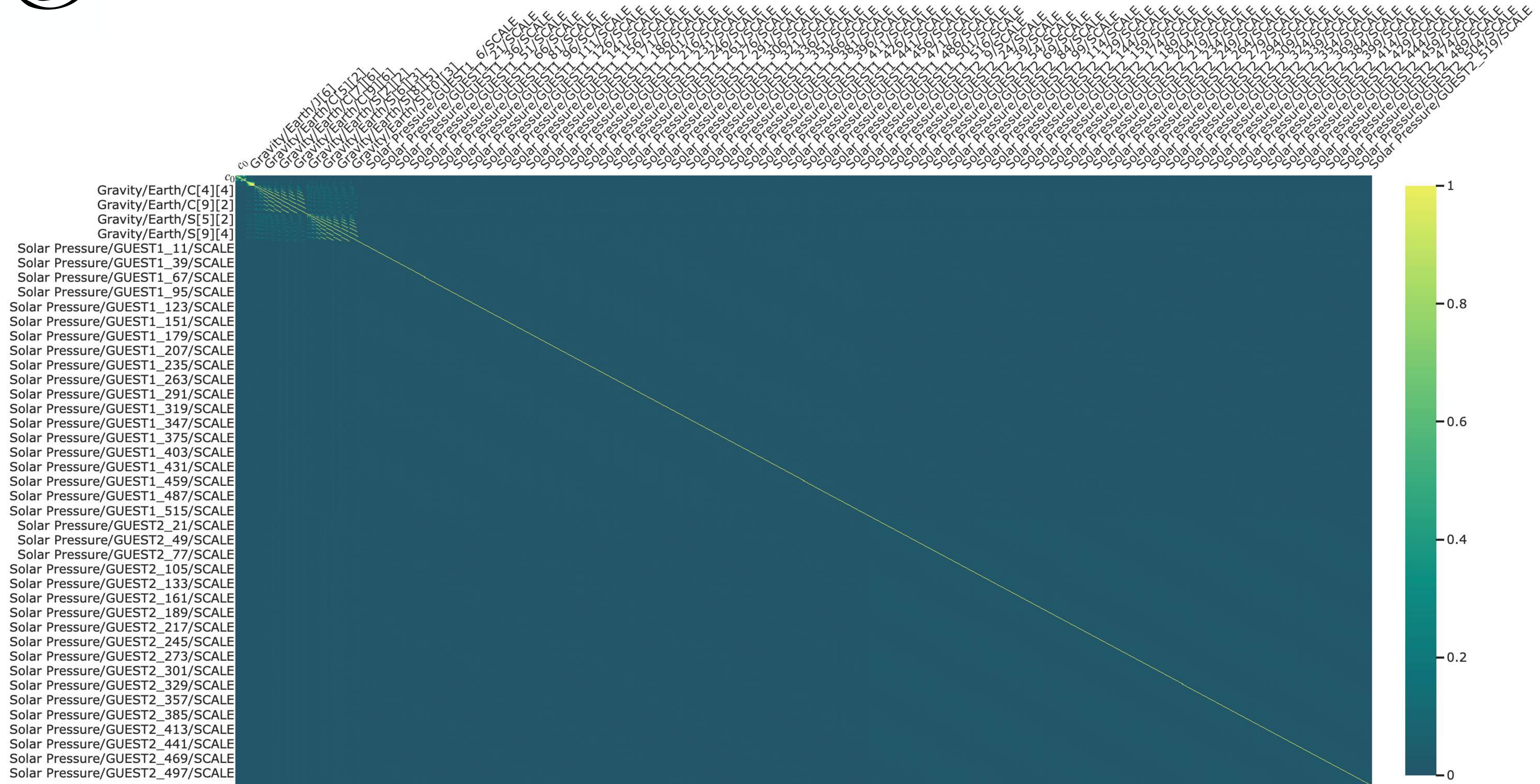
Derived for geodesy



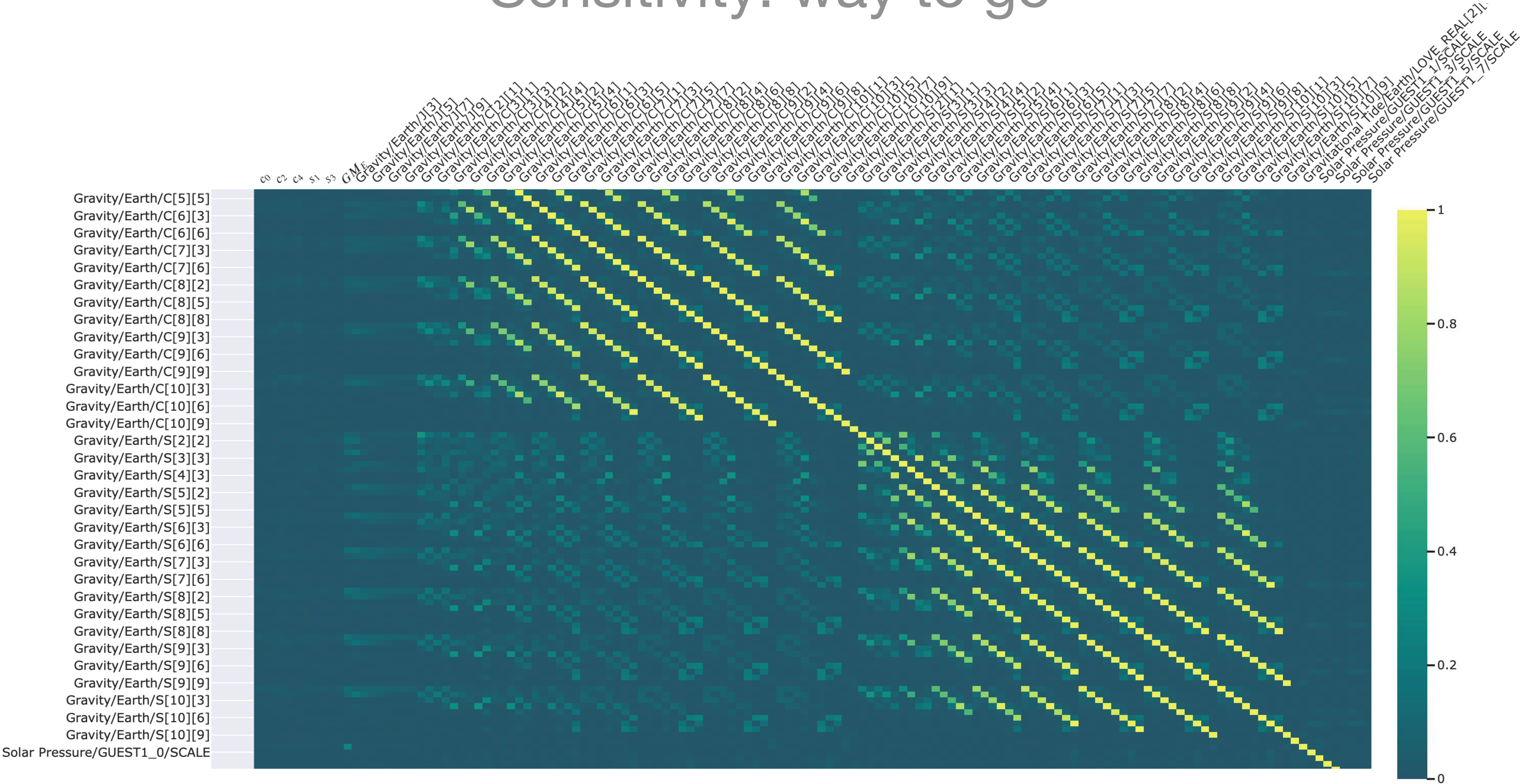
Global Analysis: Fit a more global orbit model + signal



Sensitivity: way to go



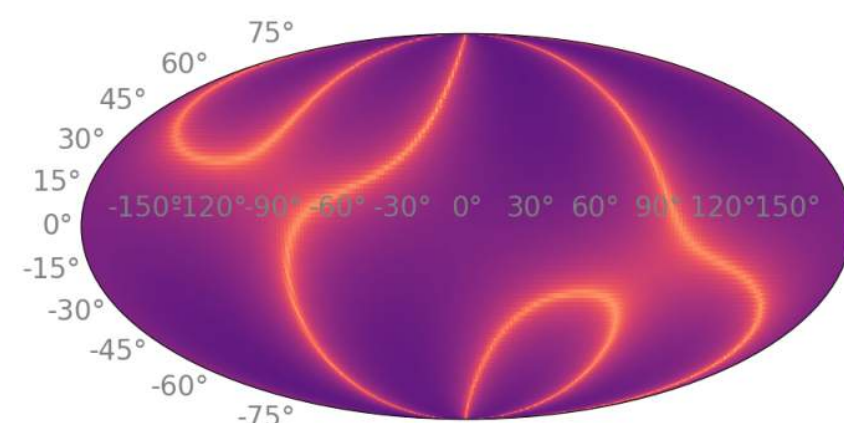
Sensitivity: way to go



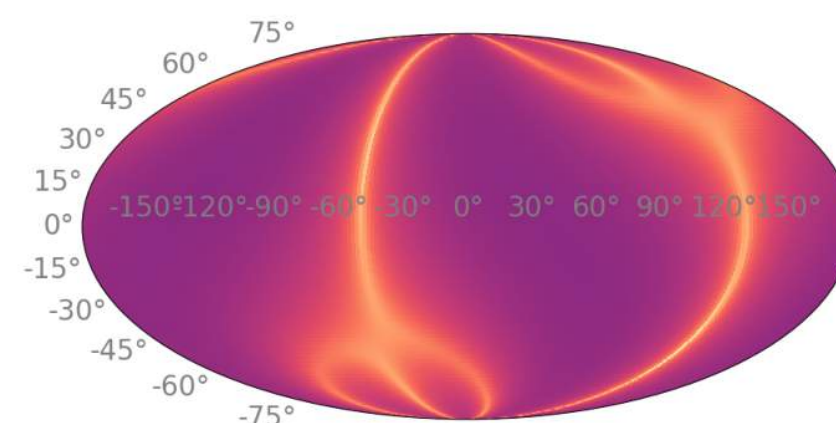


GUEST 10 years sensitivity (one orbit)

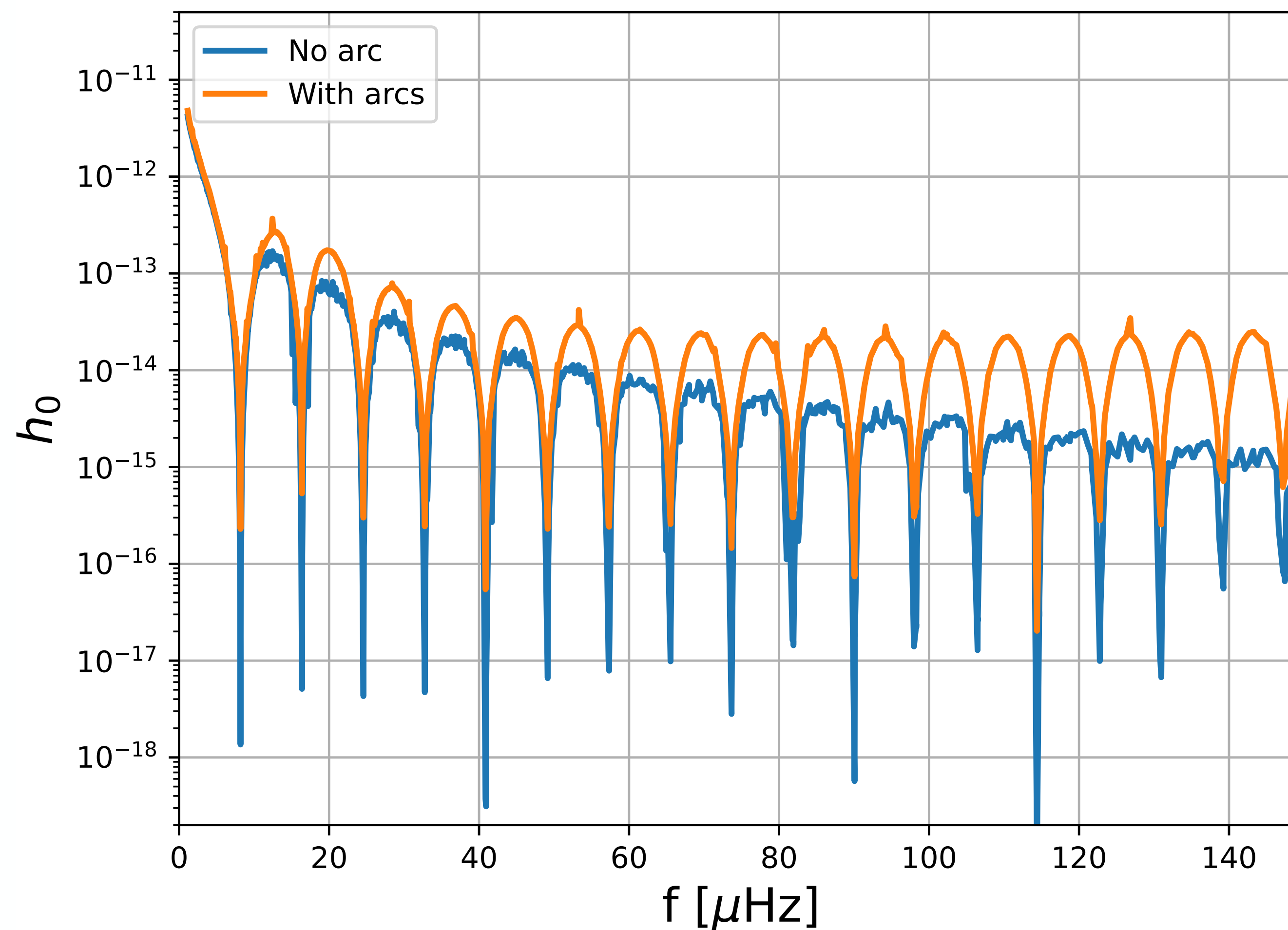
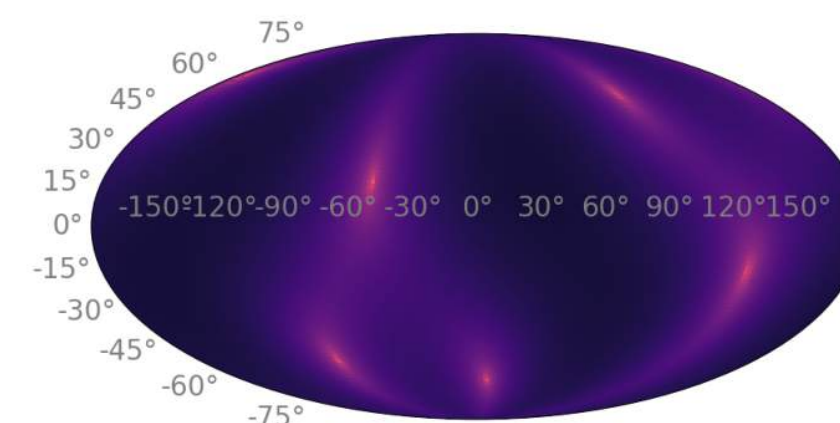
GUEST1



GUEST2



GUEST1+GUEST2



Data:

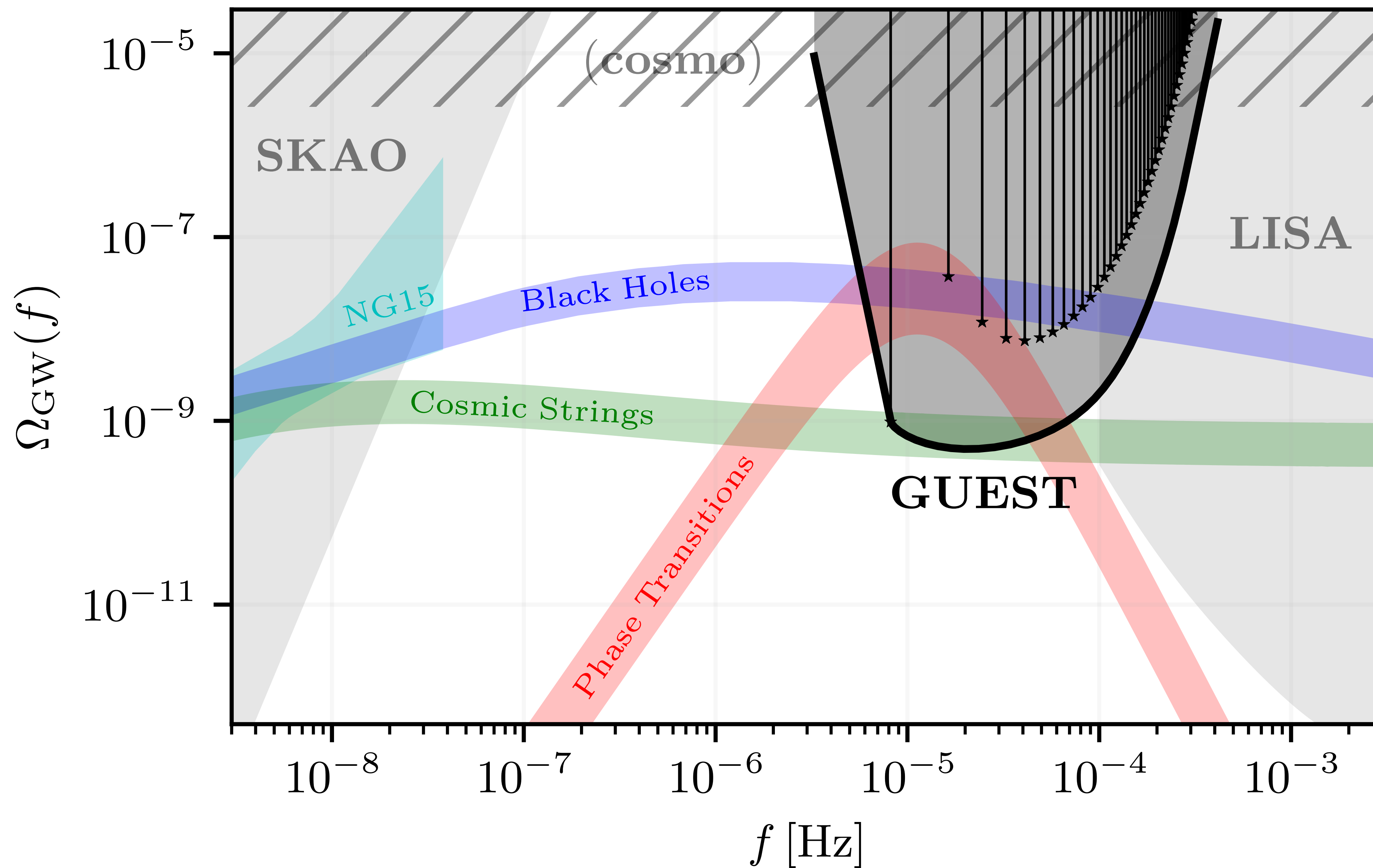
rms=1 cm per point,
10 points per orbit





GUEST 10 years sensitivity (one orbit)

<https://arxiv.org/abs/2607.18390>

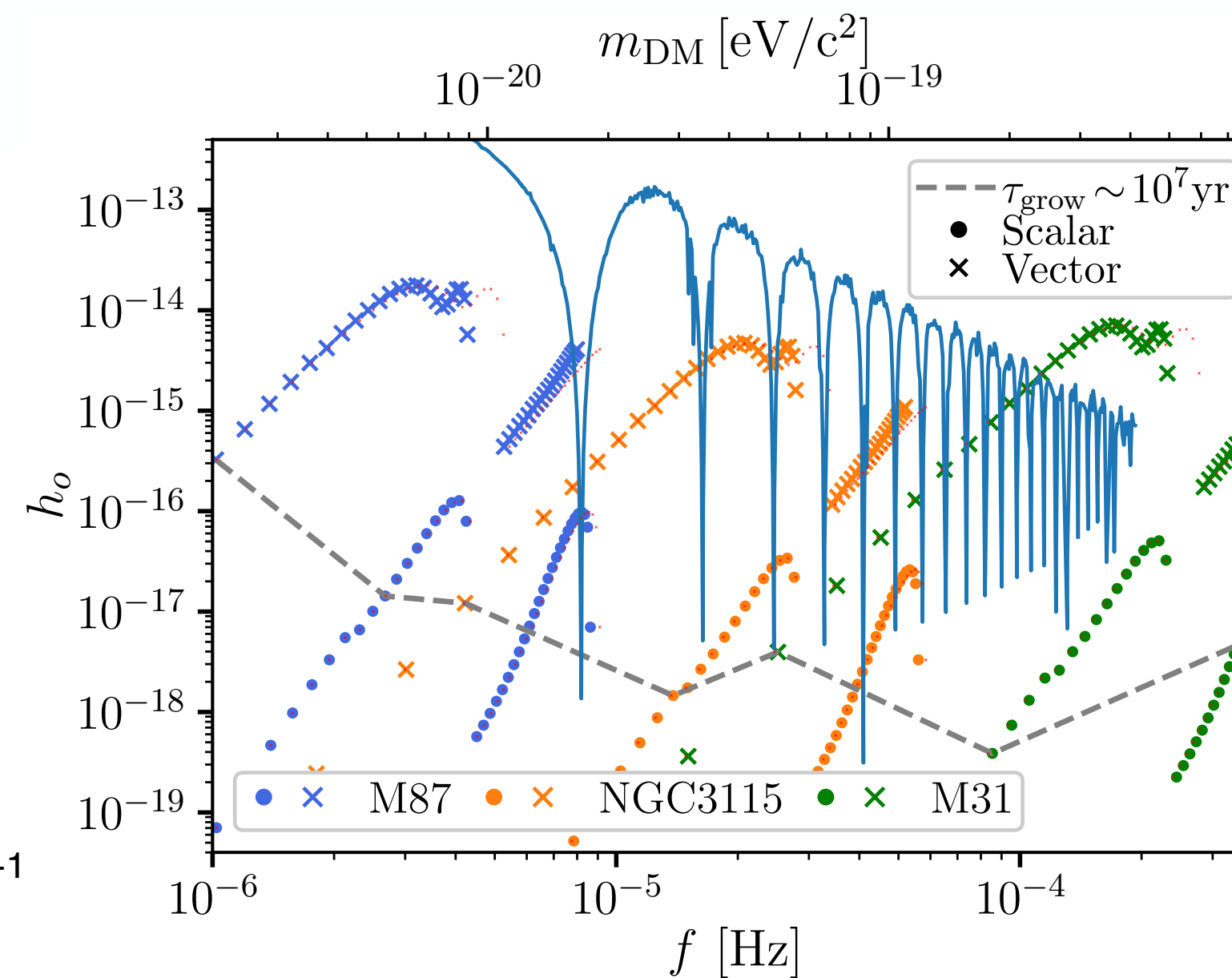
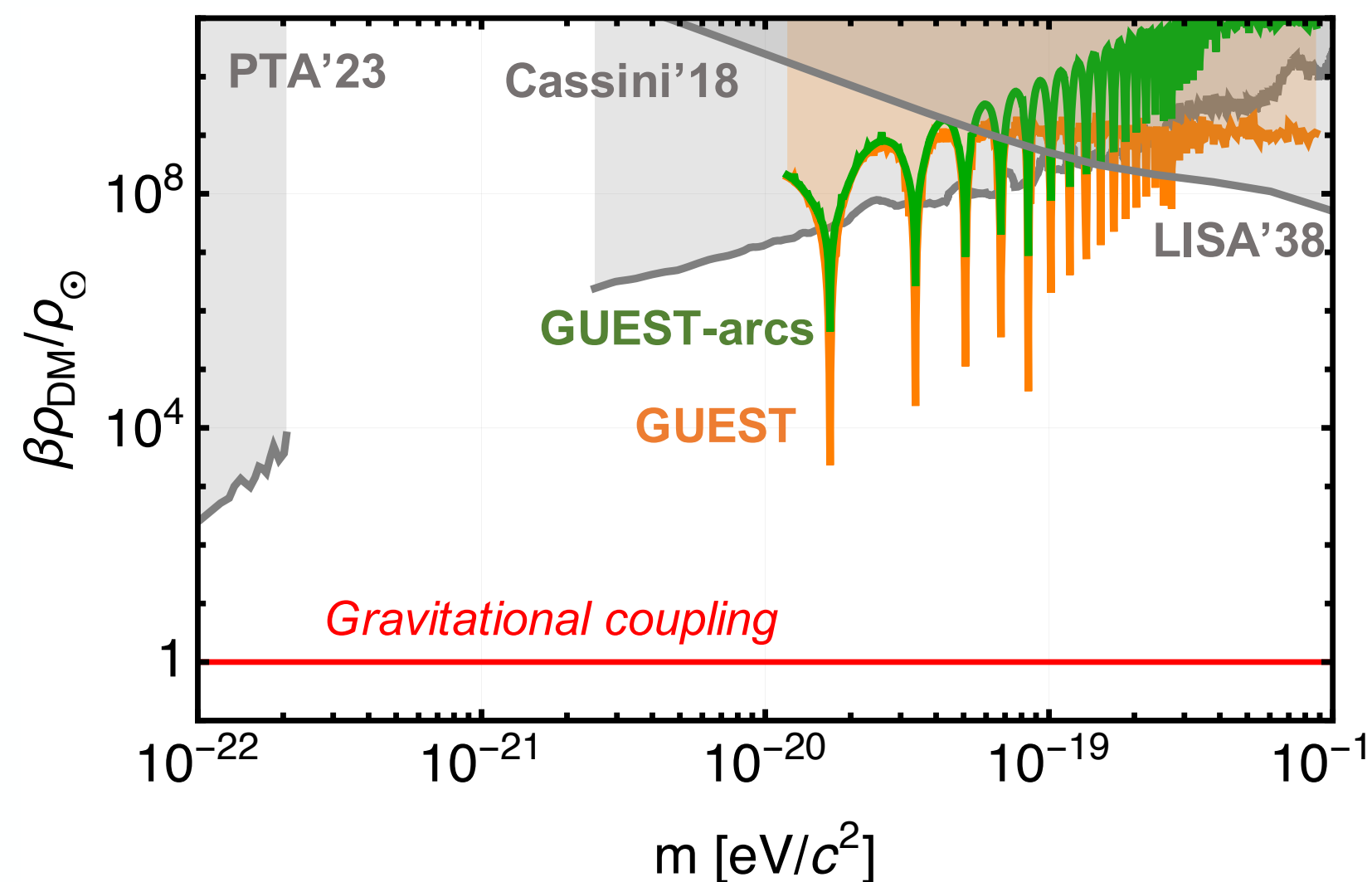




GUEST: more science

ULDM

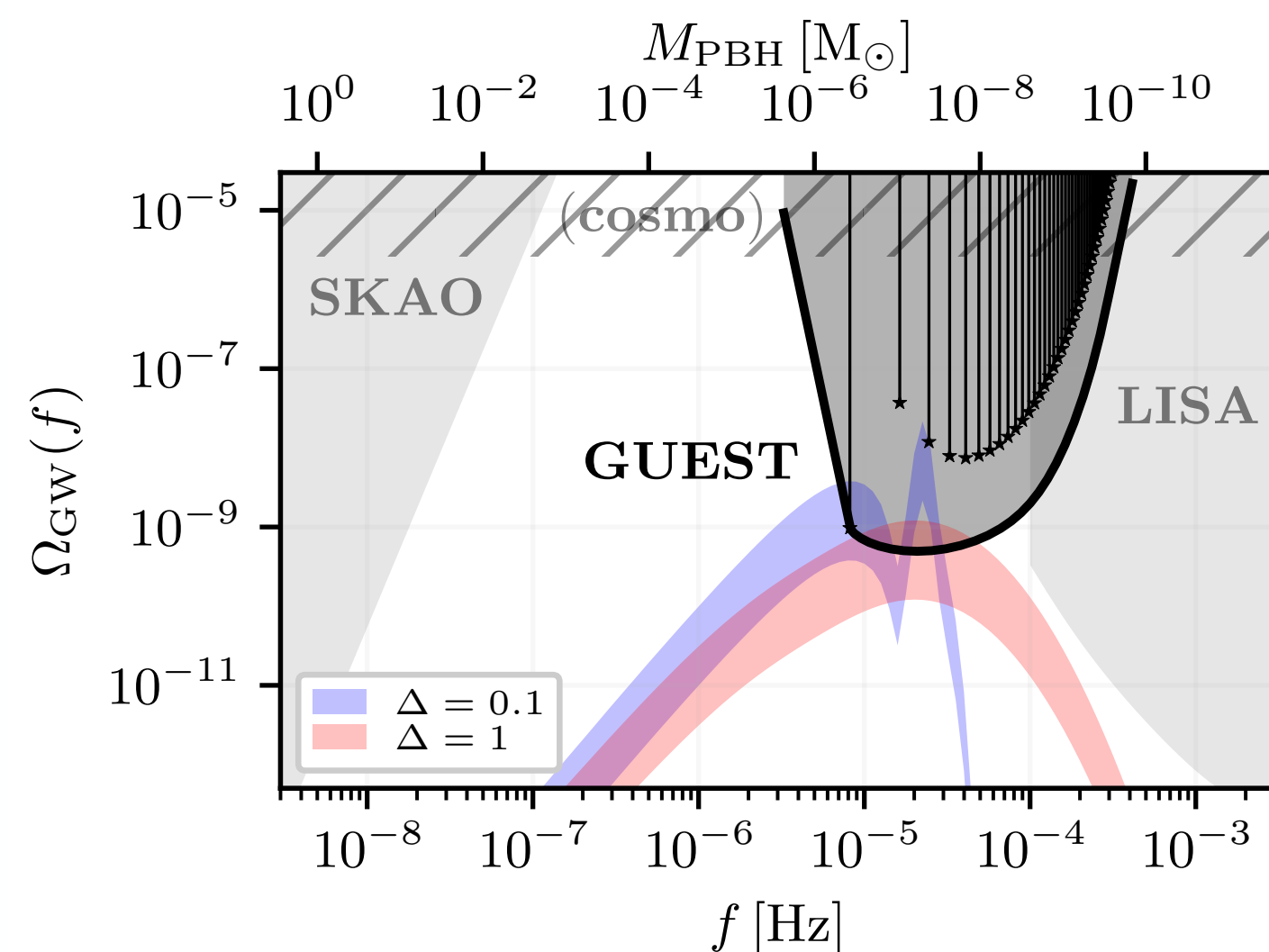
Direct coupling
to oscillating DM



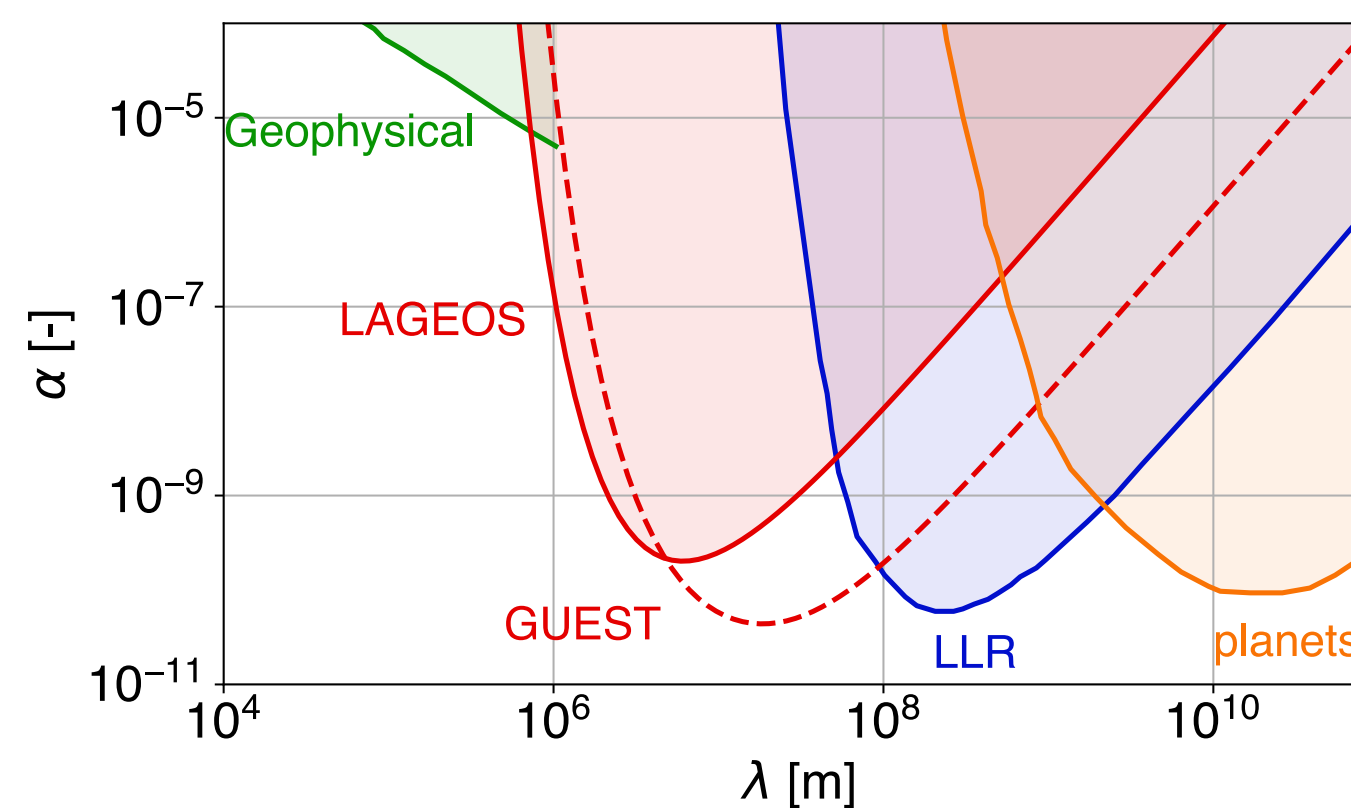
GWs from
SR clouds

PBHs

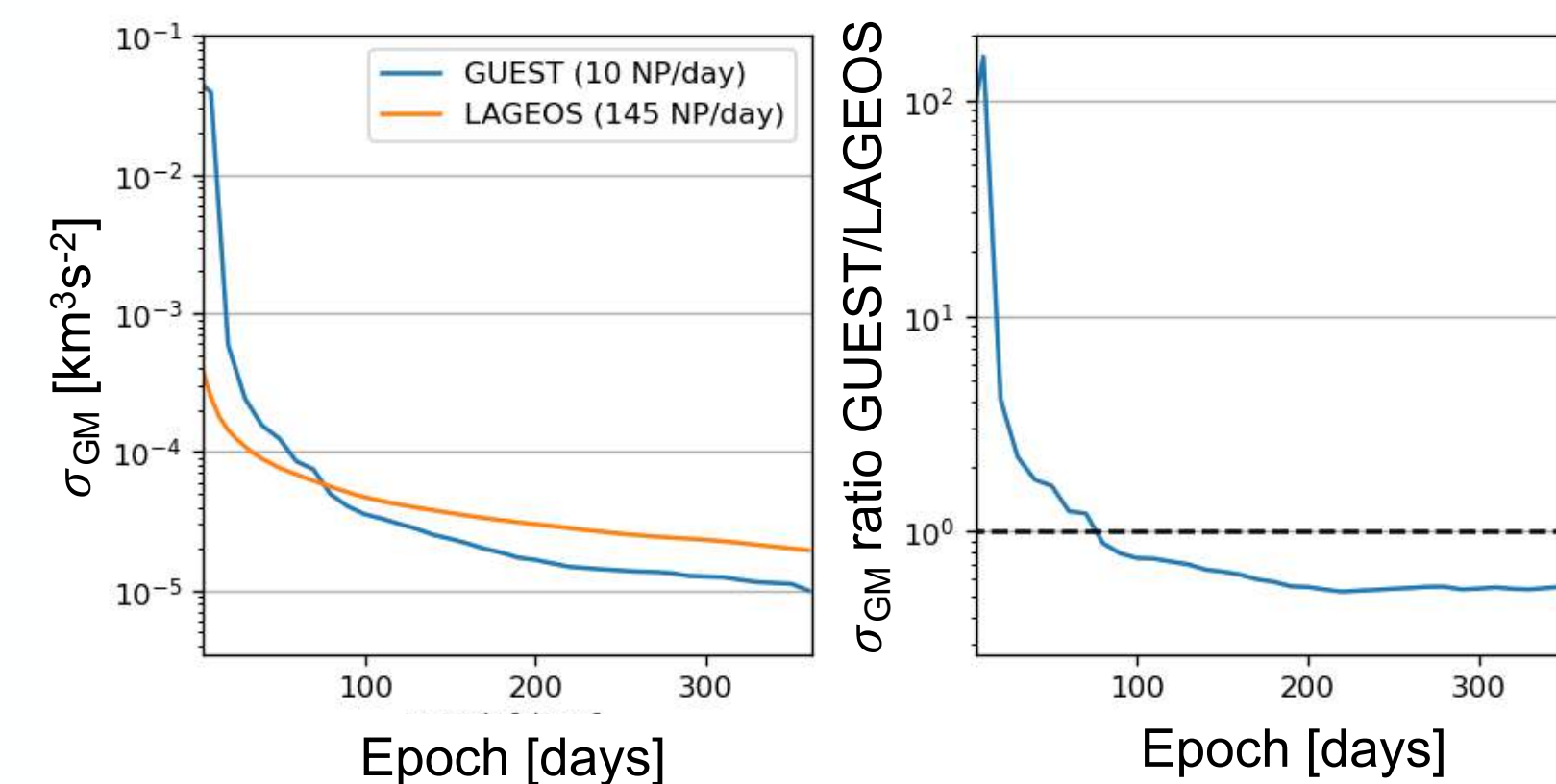
DB, Foster, Gouttenoire, Iovino,
Musco, Trifinopoulos, Vanvlasselaer 2602.12252



5th forces



Geodesy





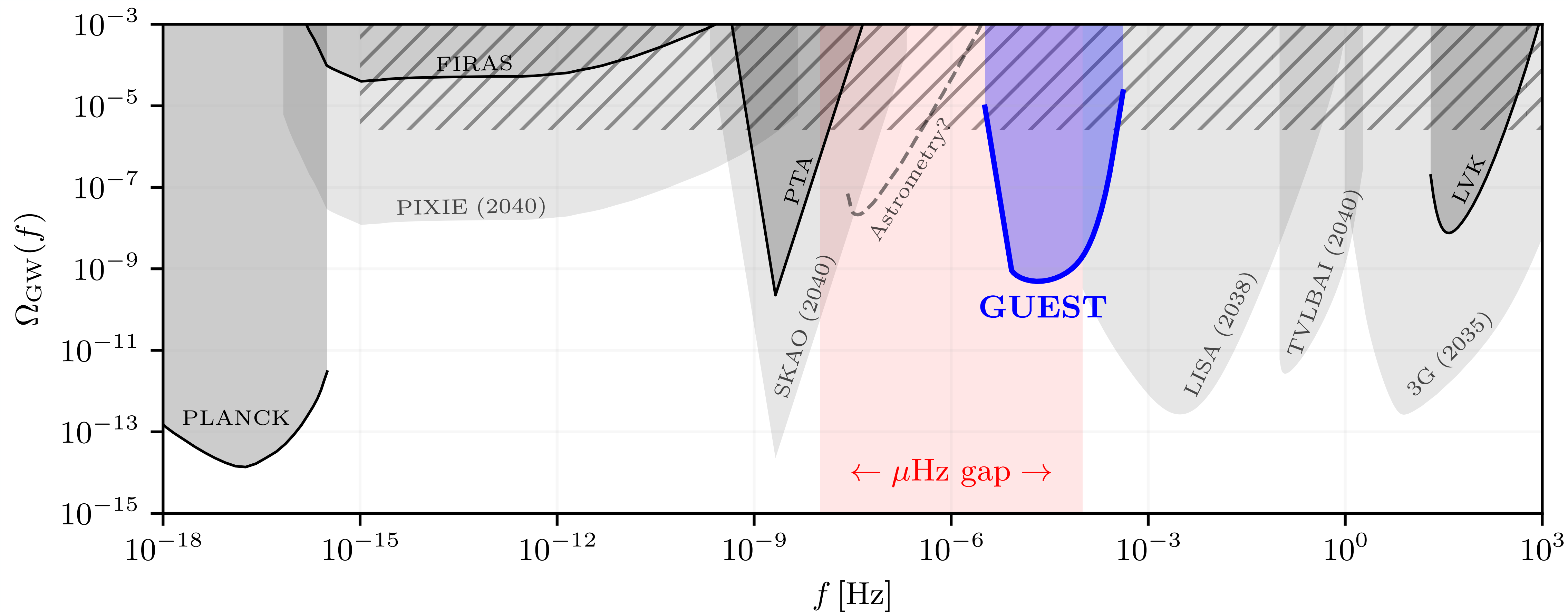
GUEST

 guaranteed Physics by the corner (PTA signal at μHz)

 possible new Physics

 reasonable idea for μHz for ESA F Class / NASA SMEX

150 M€



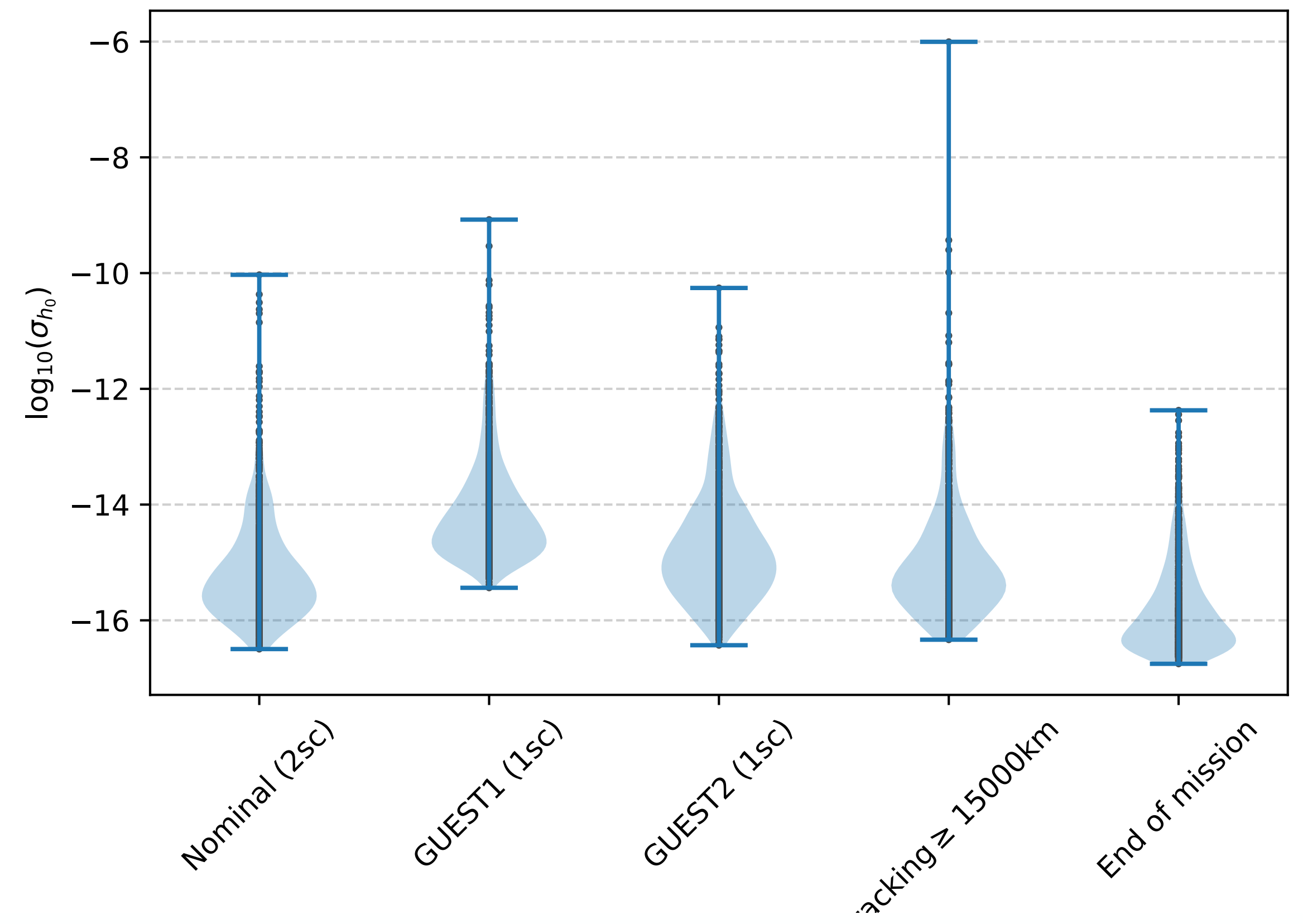
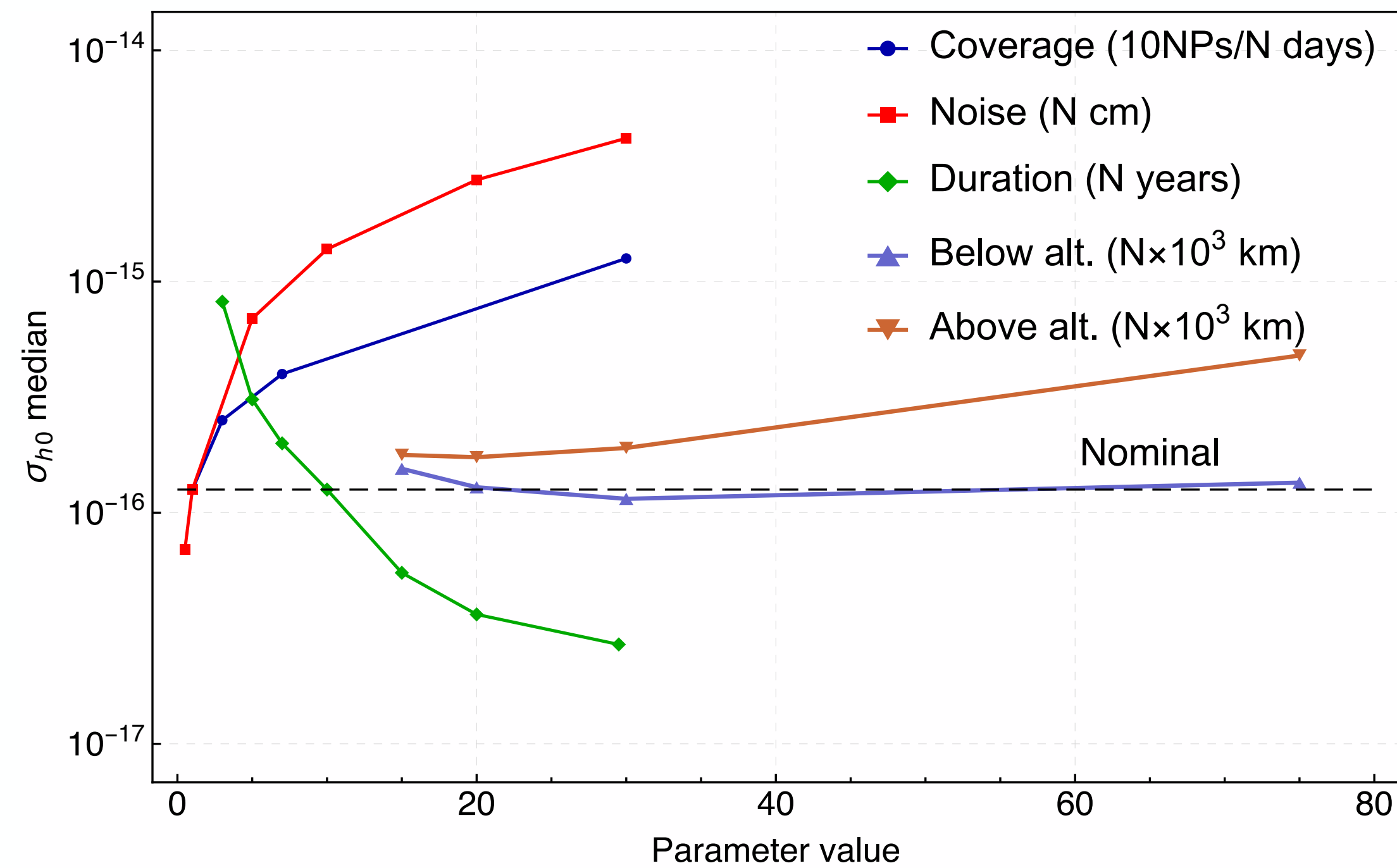


GUEST: next steps

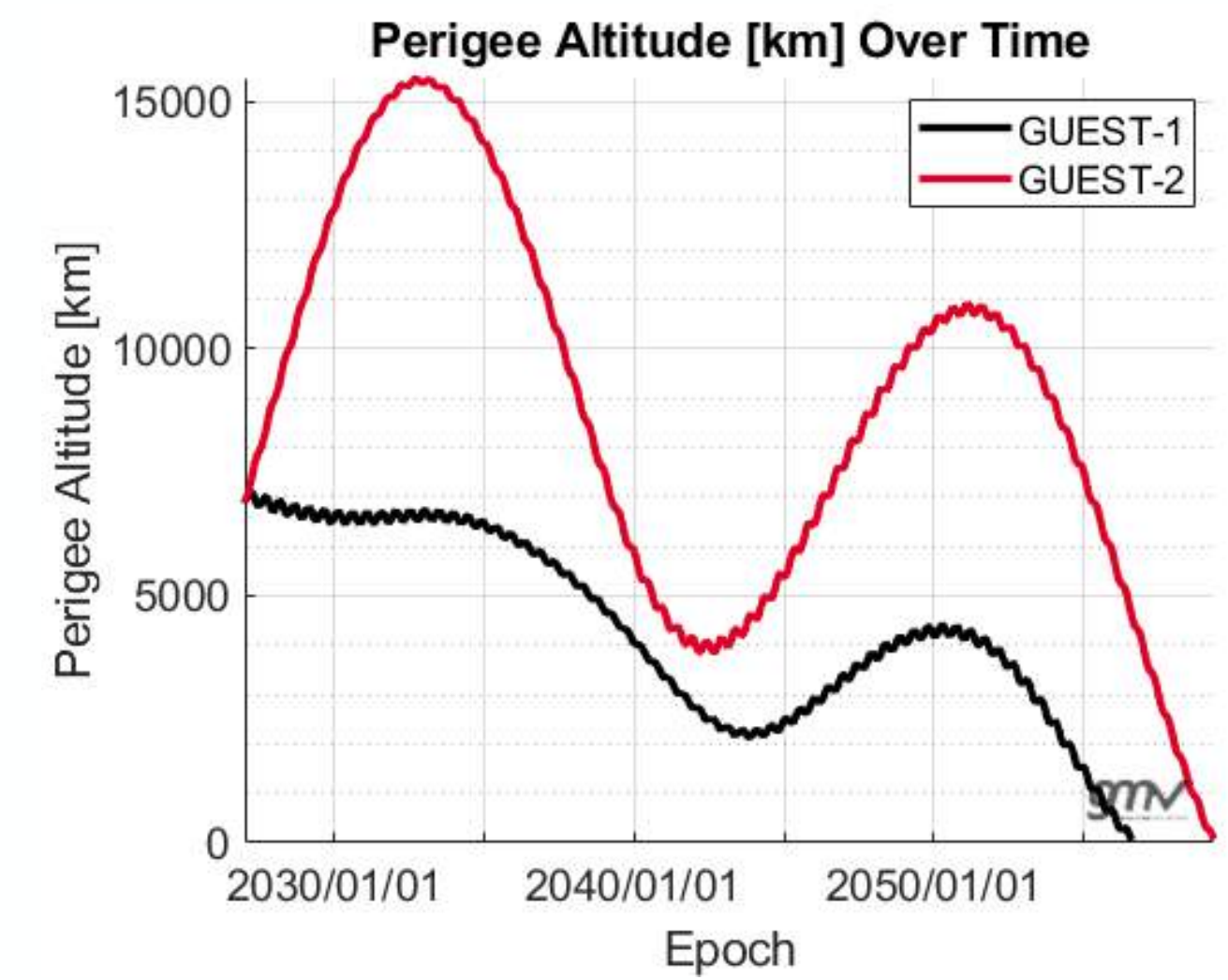
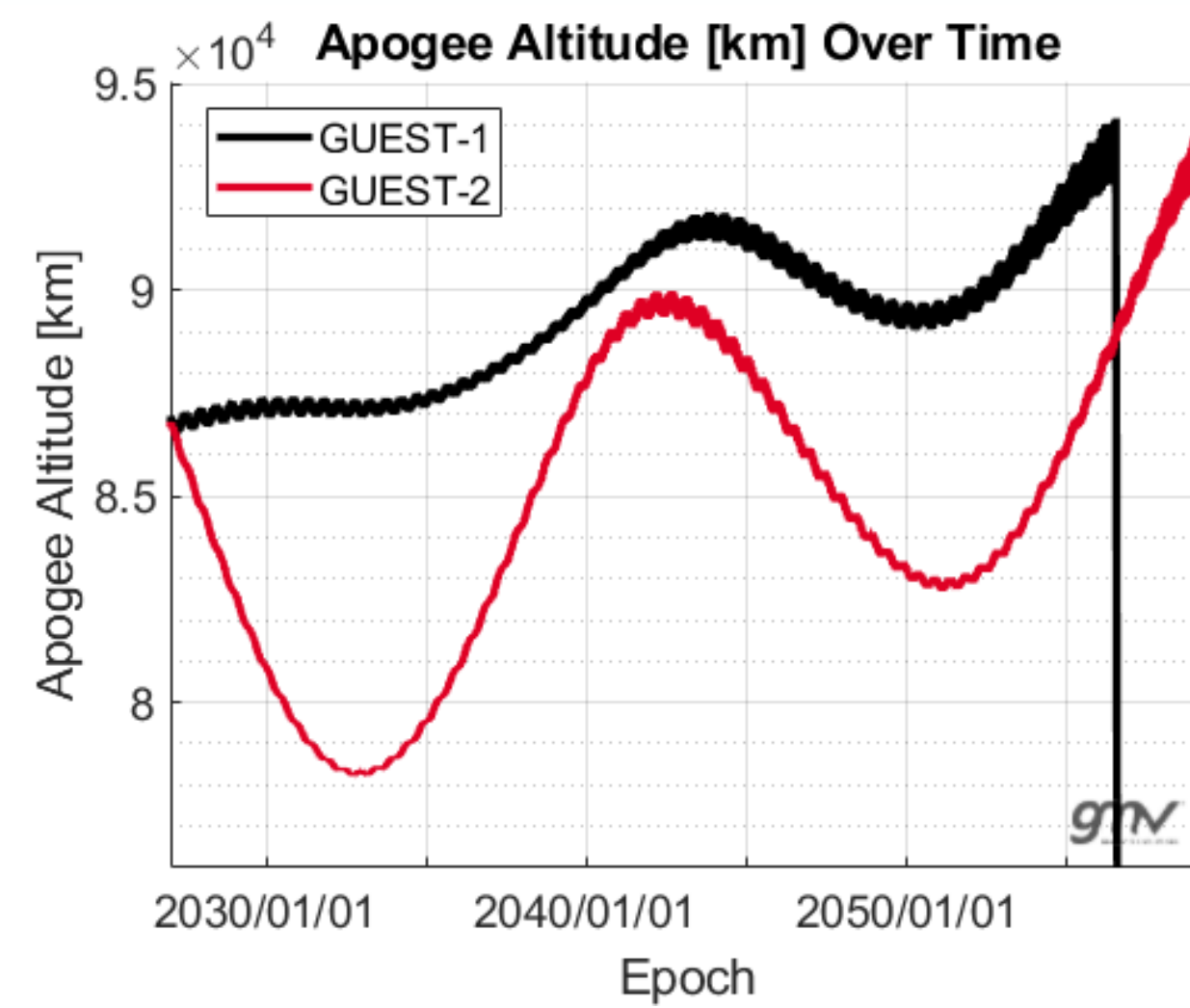
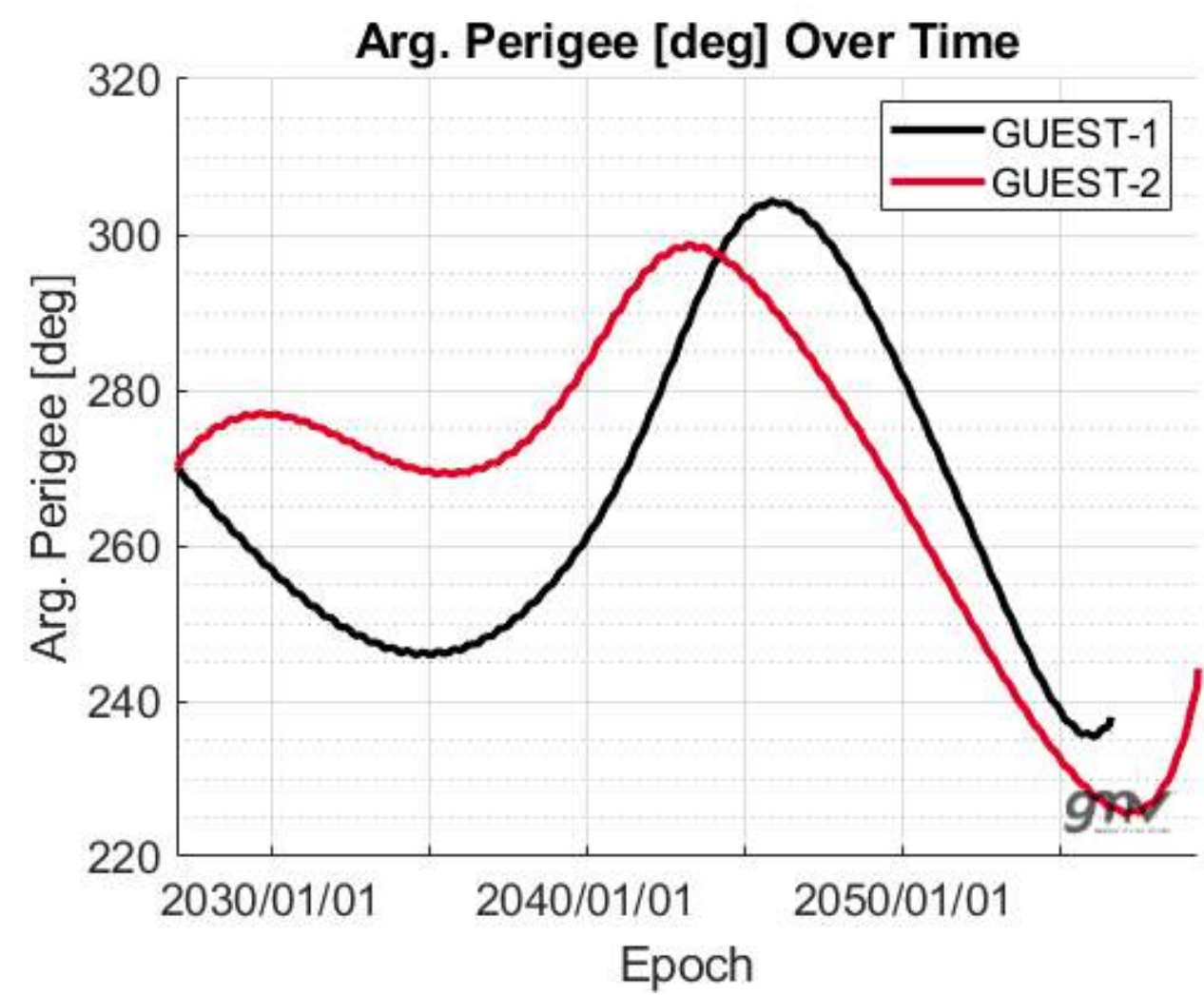
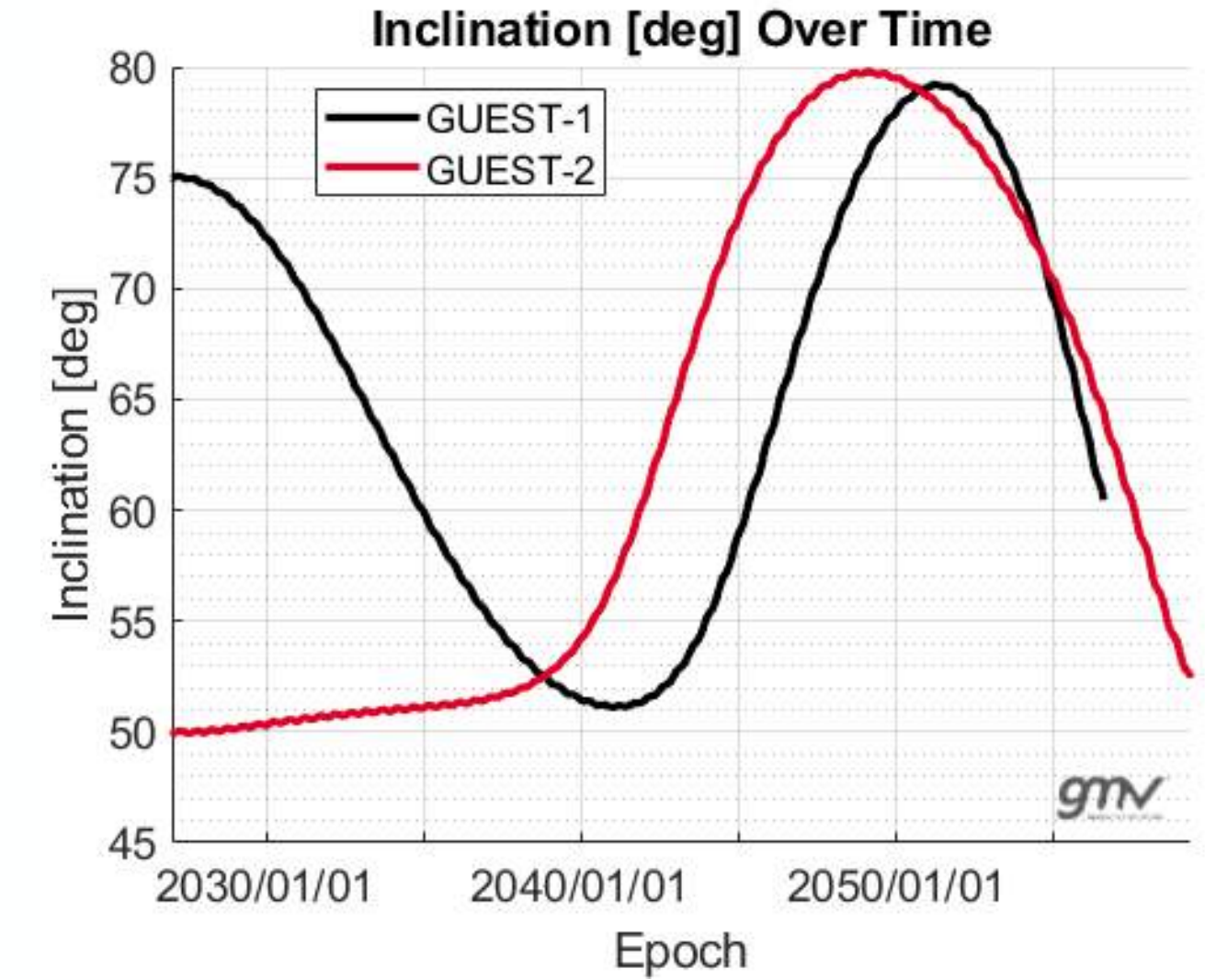
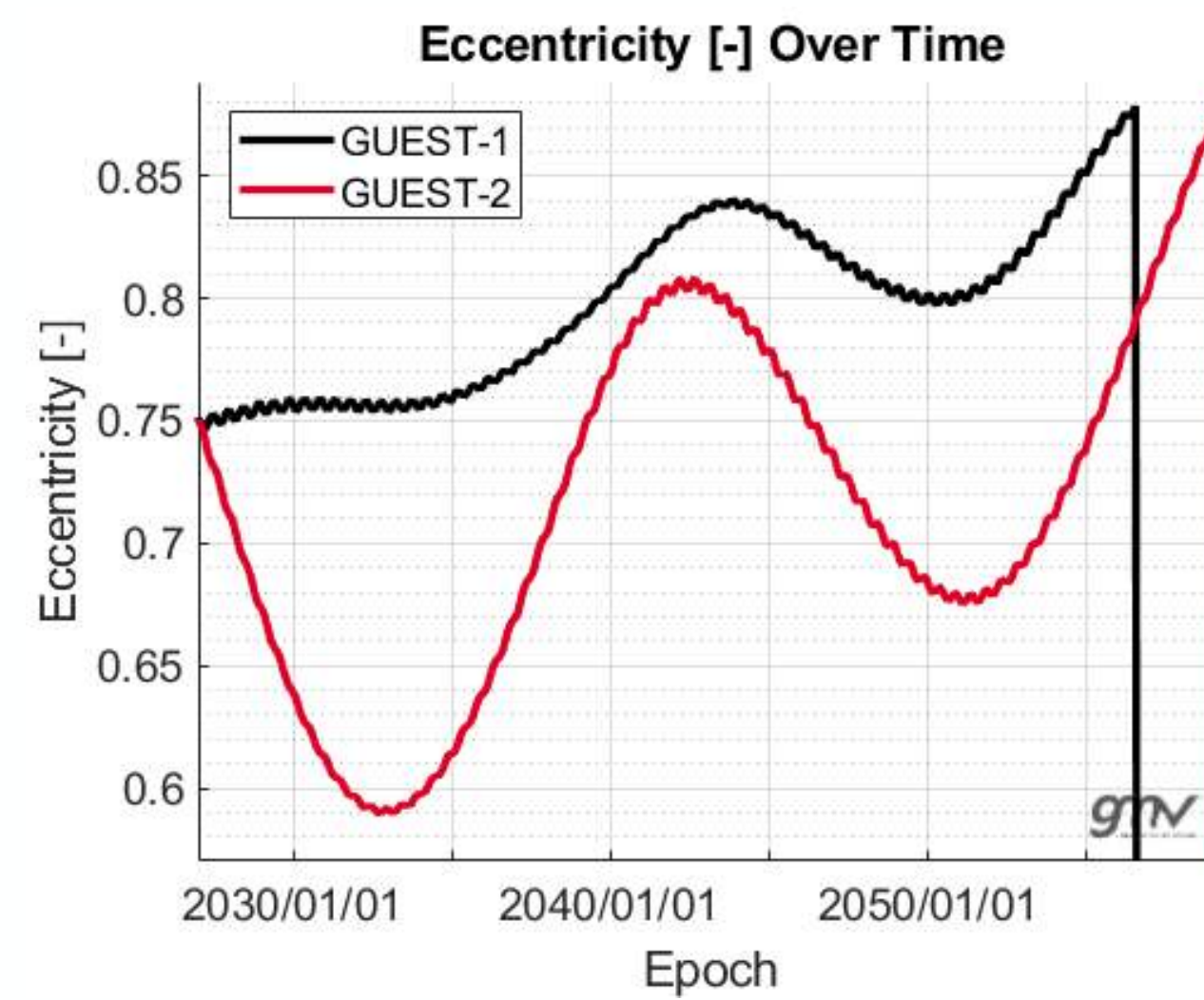
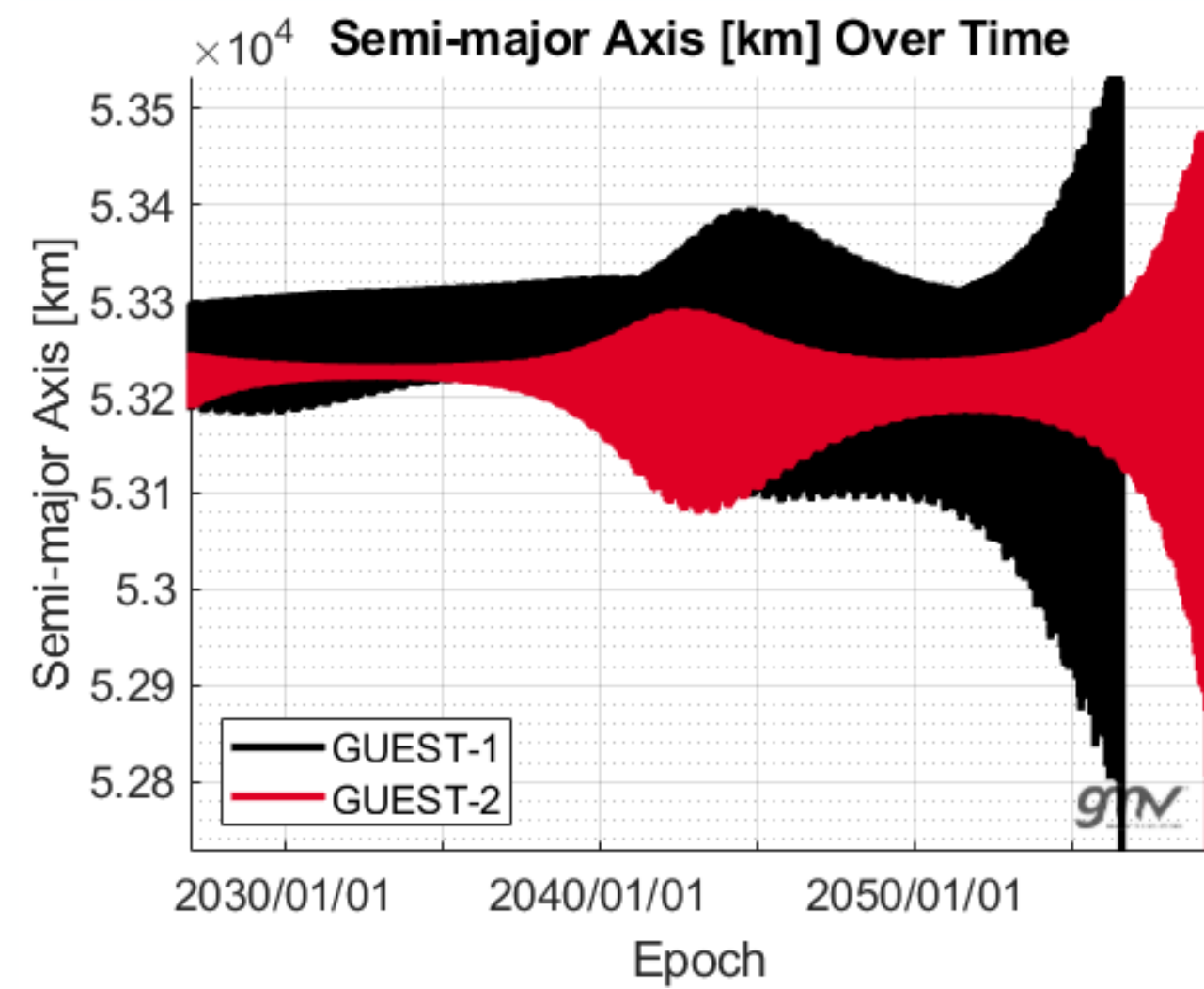
<https://arxiv.org/abs/2607.18390>

- Build a proto-collaboration: we are at LISA 20 years ago. But now we know a lot as a community. Be my GUEST!
- ✱ Study **arcs** vs (more) global fit
- ✱ Realistic merger with arcs / more global (waterfall plot changes dramatically)
- ✱ More physics cases (**EMRIs**) / multi band
- ✱ Decorrelation with 2 or more orbits
- ✱ Further ways to improve the orbit determination (**ML?**)
- ✱ Data analysis of LAGEOS data and Moon data (in progress)
- ✱ Data distribution and parameter determination
- ✱ Injection / null channels?

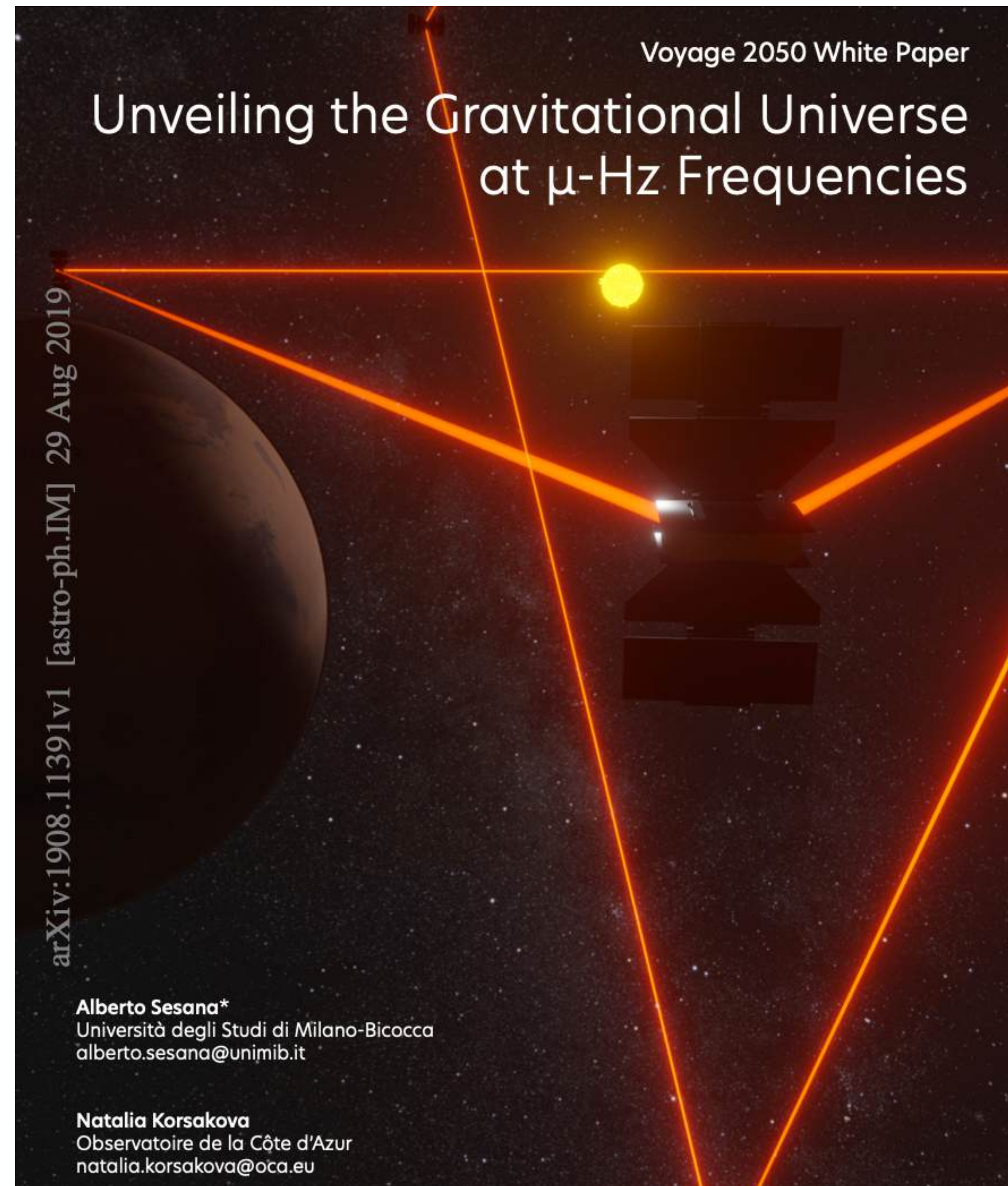
GUEST: more on orbits and data



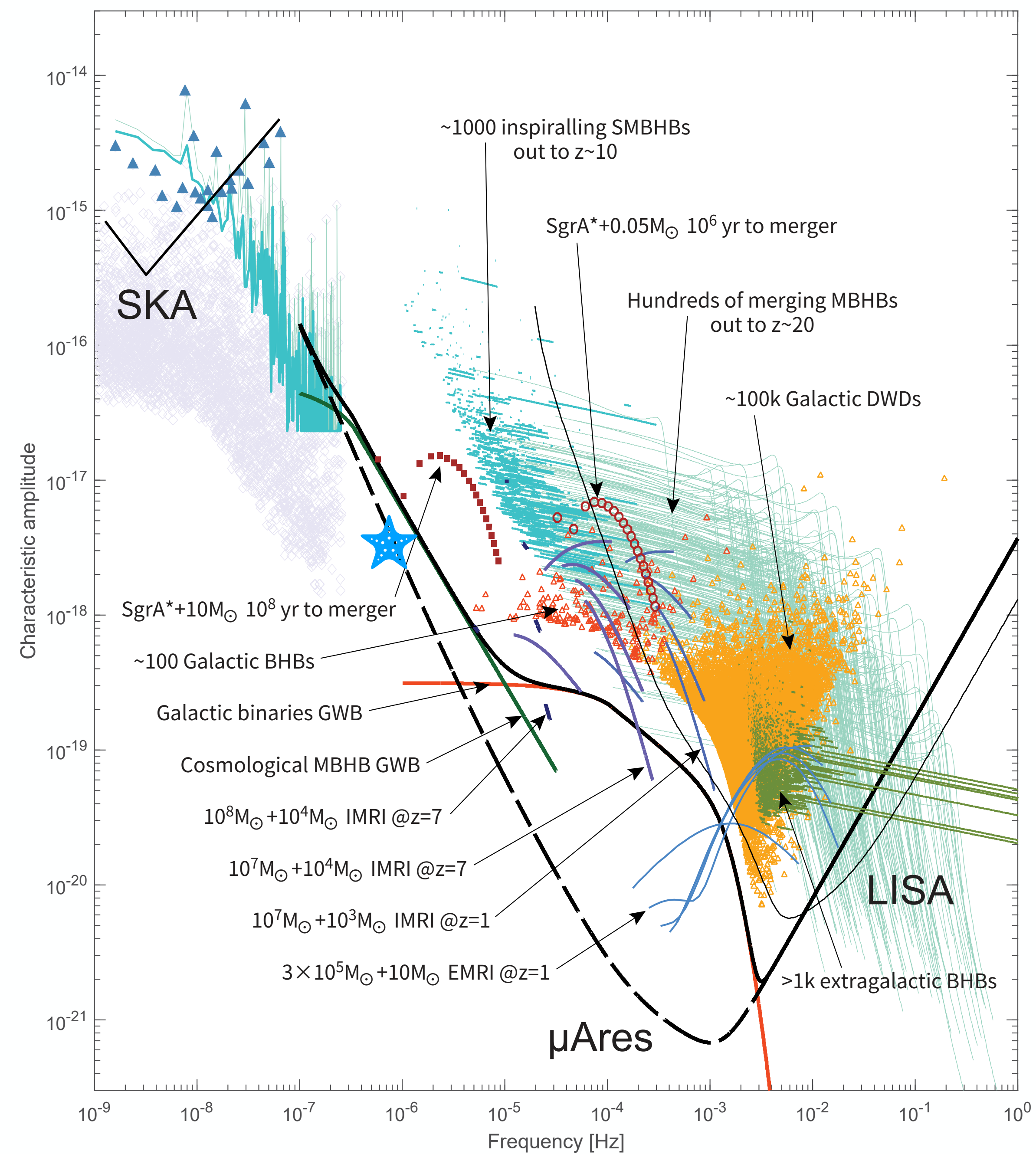
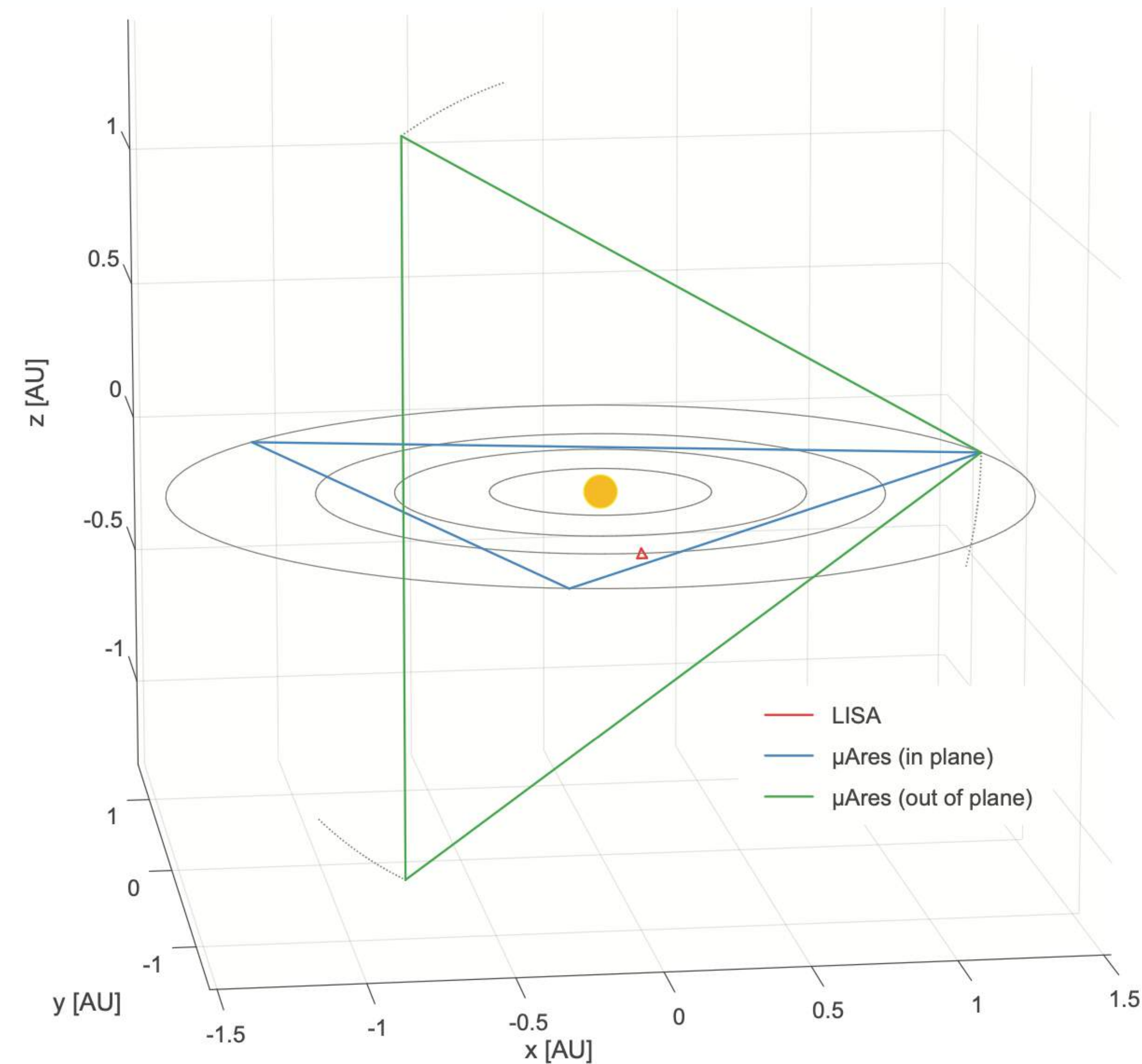
Orbit evolution

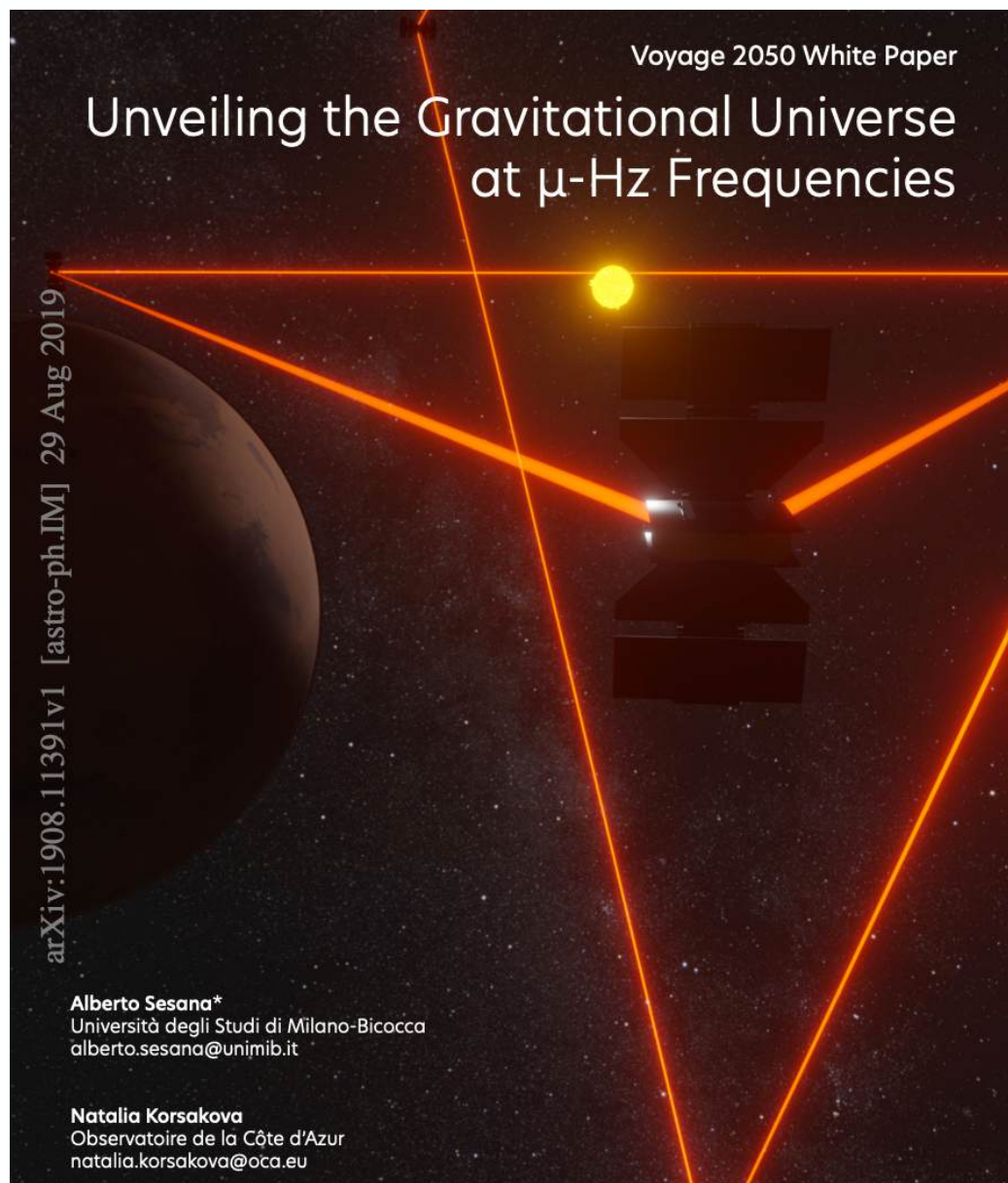


i) μ Ares: LISA-like concept



The μ Ares detection landscape





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 Λ CDM out to $z \approx 10$ by means of $\mathcal{O}(10^3)$ MBHB standard sirens.

Summary of General relativity and beyond science goals:

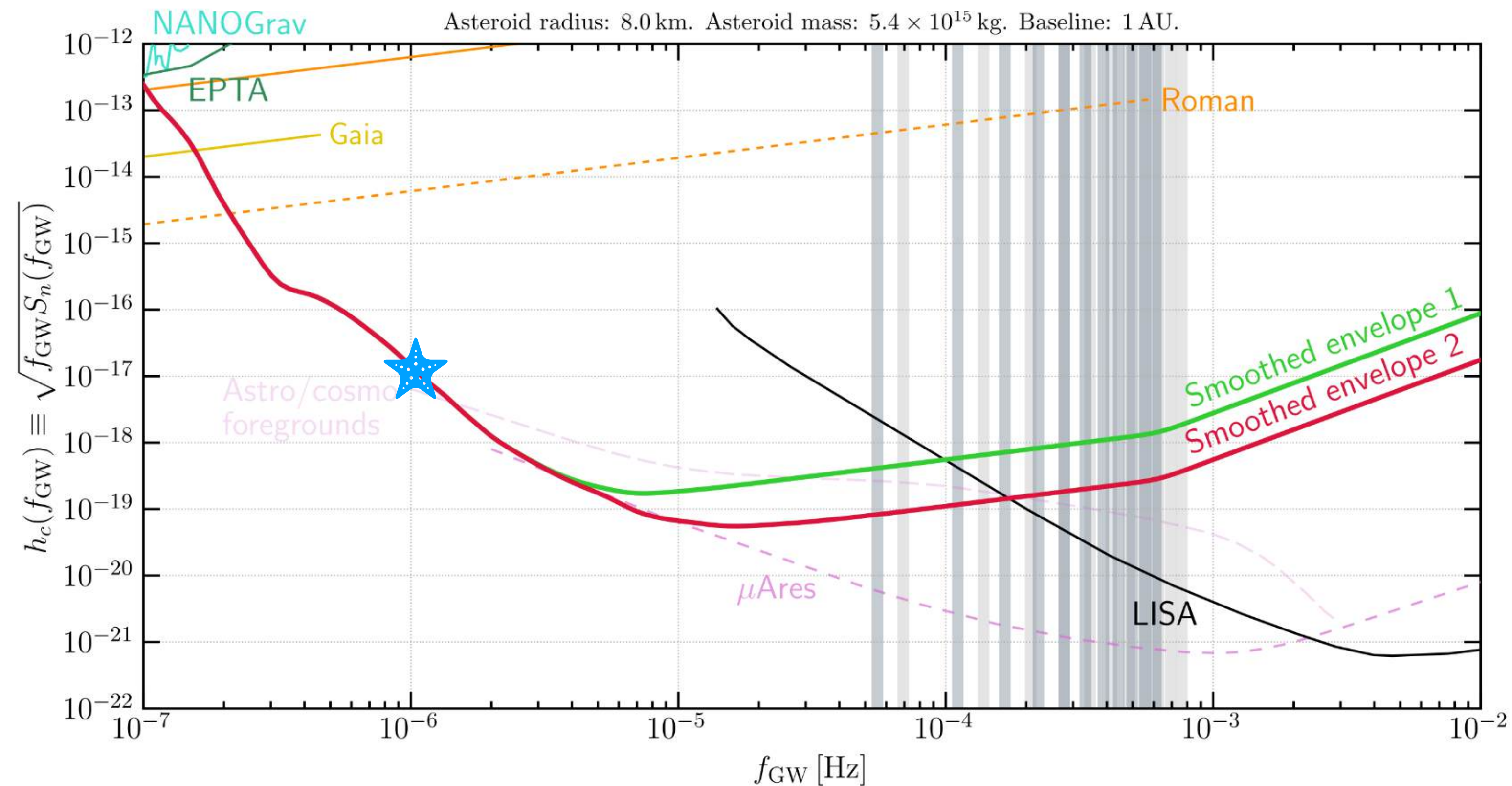
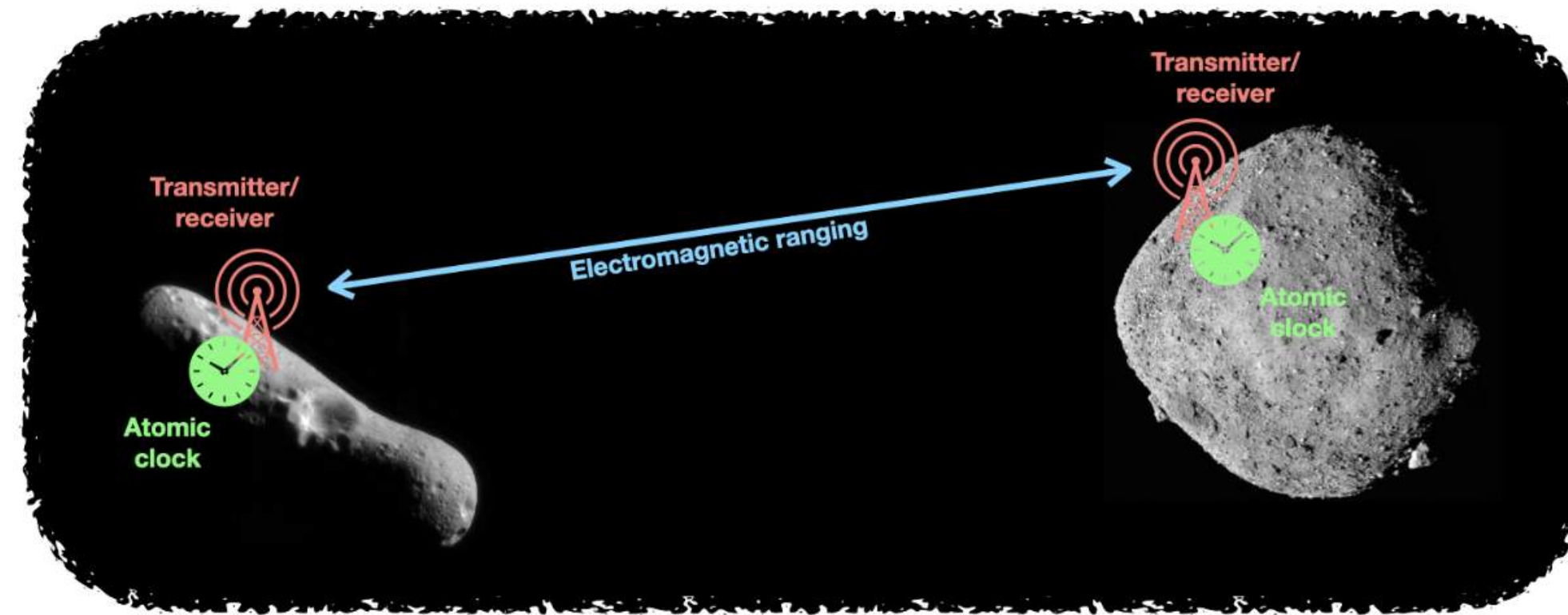
- probe DM substructures and the Universe expansion via strong GW lensing;
- detect non-linear GW memory with high SNR from merging MBHBs;
- improve sensitivity to graviton mass and other deviations from GR by more than two orders of magnitude with respect to LISA.

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 2012.11431



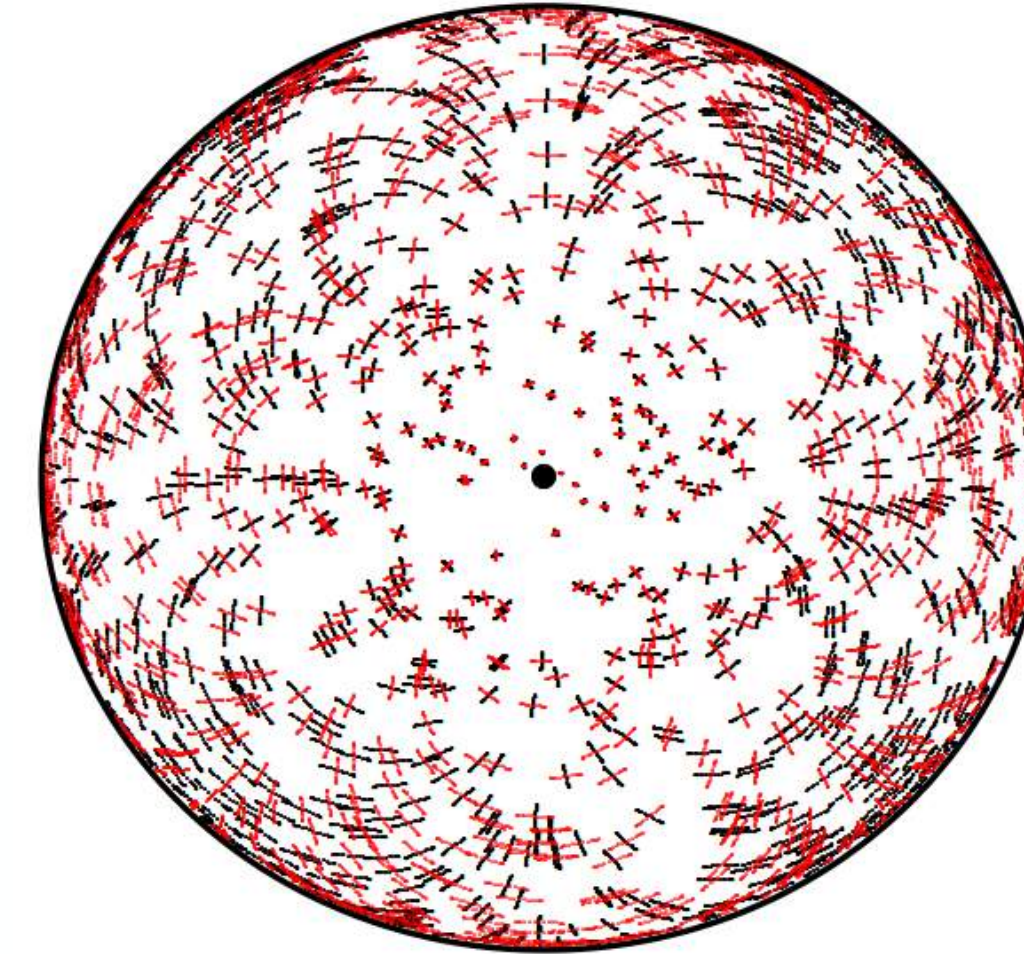
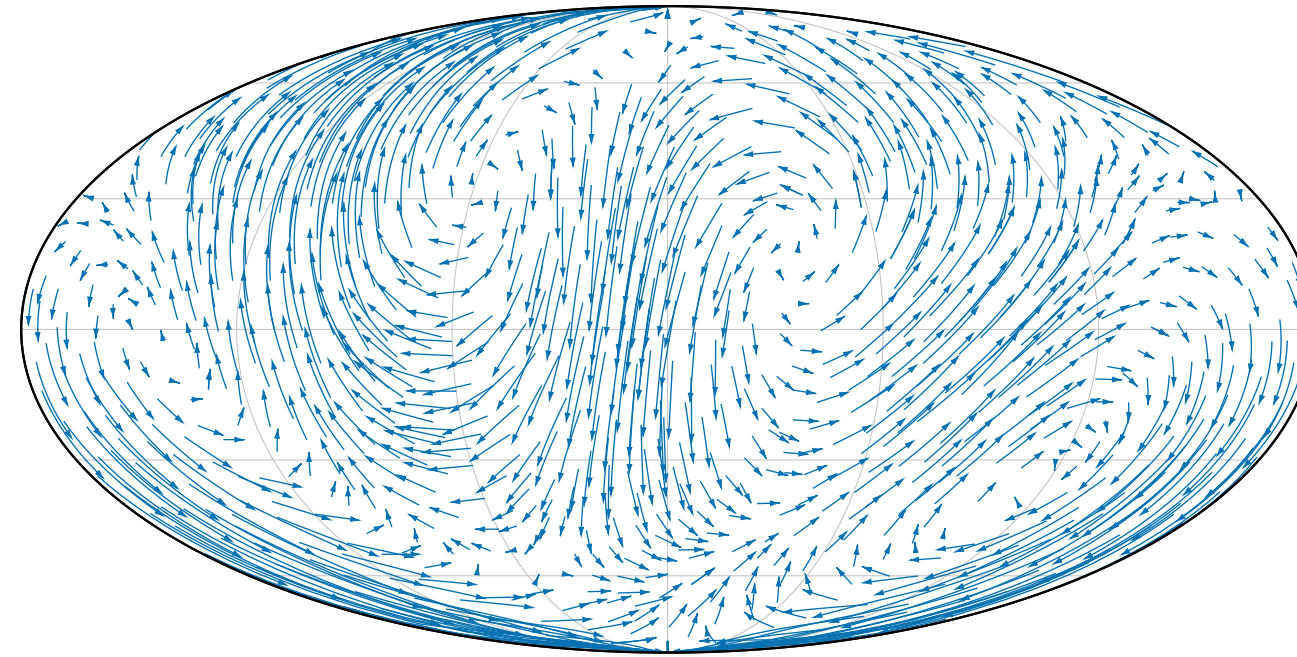
Future astrometry?

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 μ Hz 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

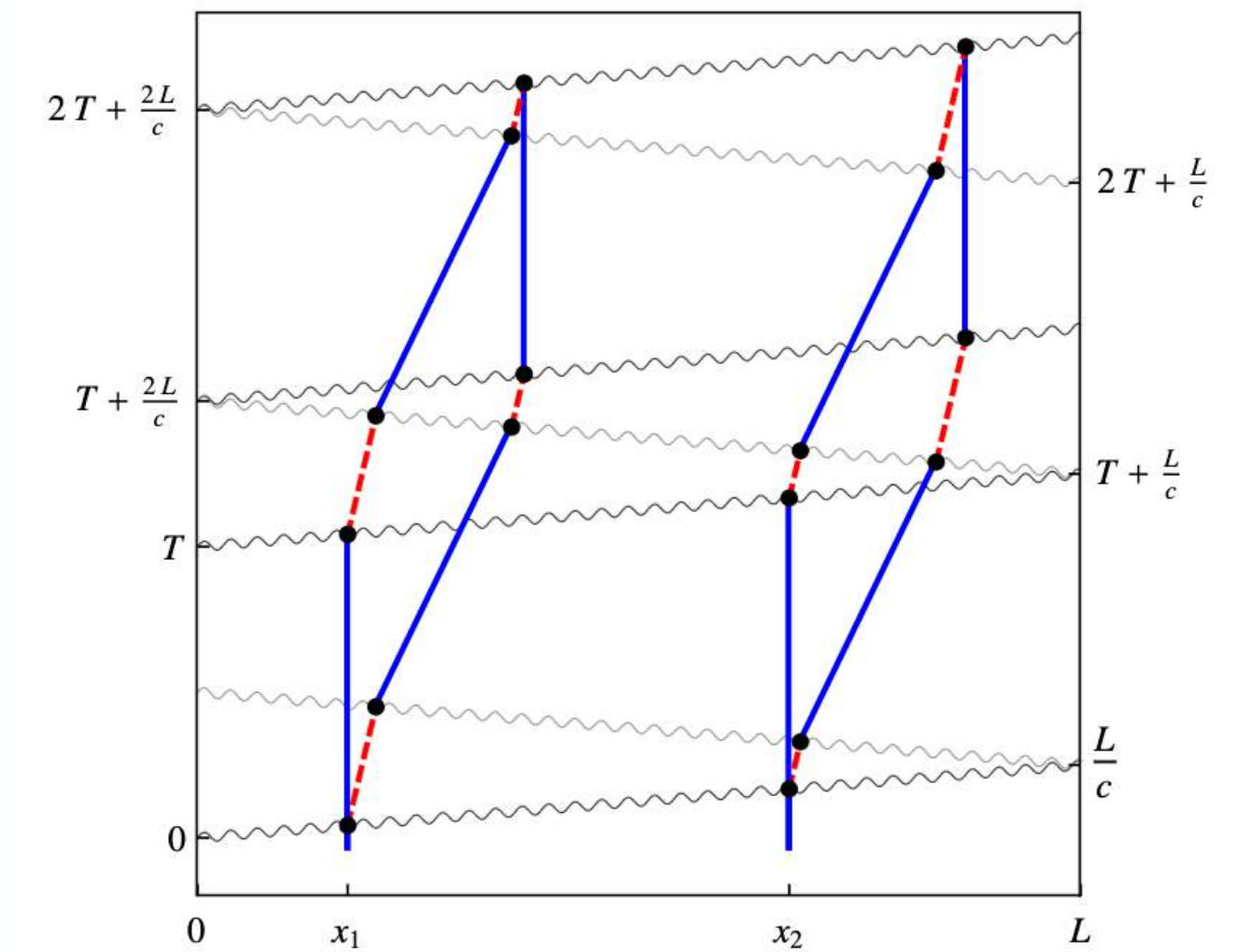
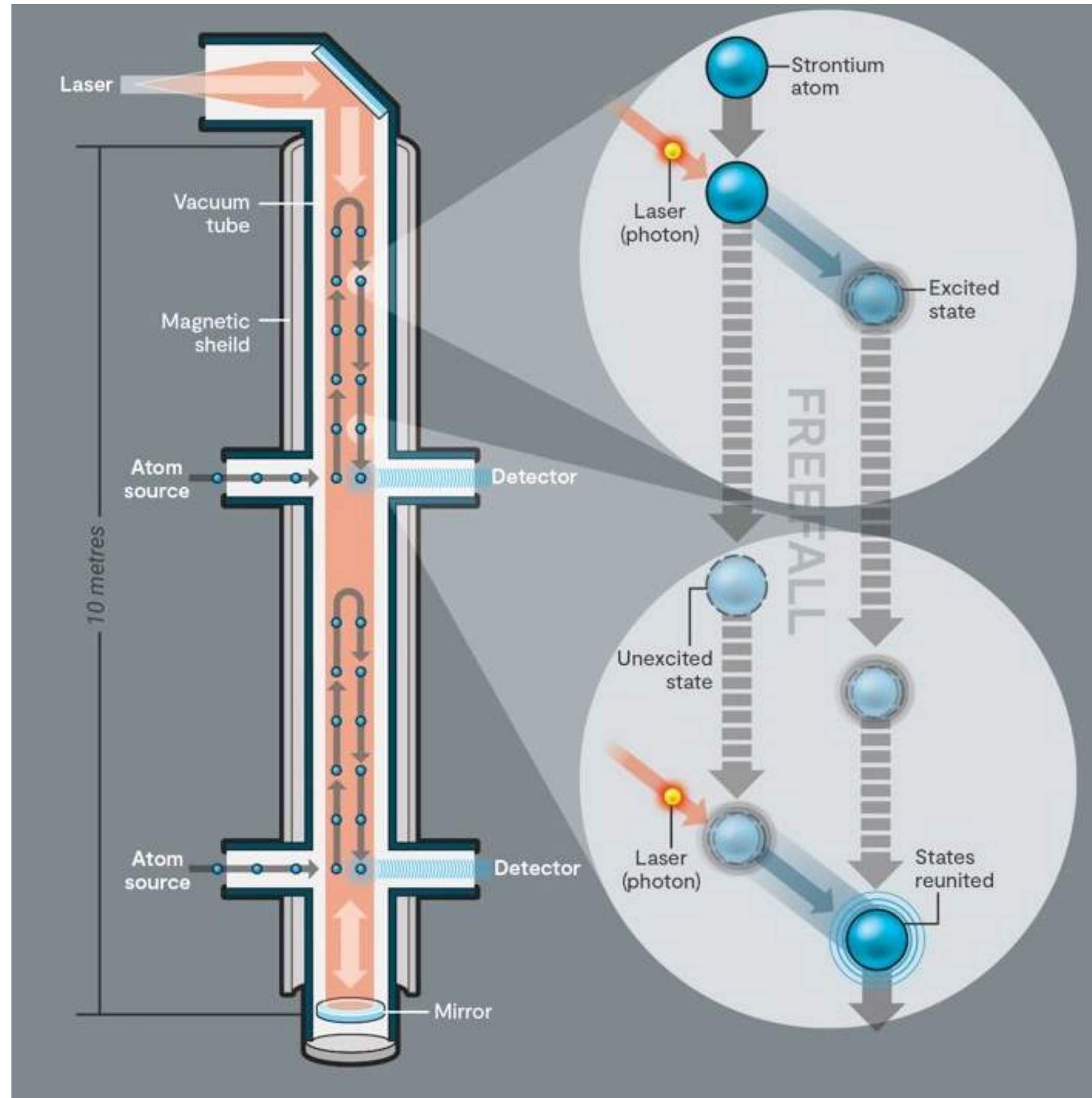
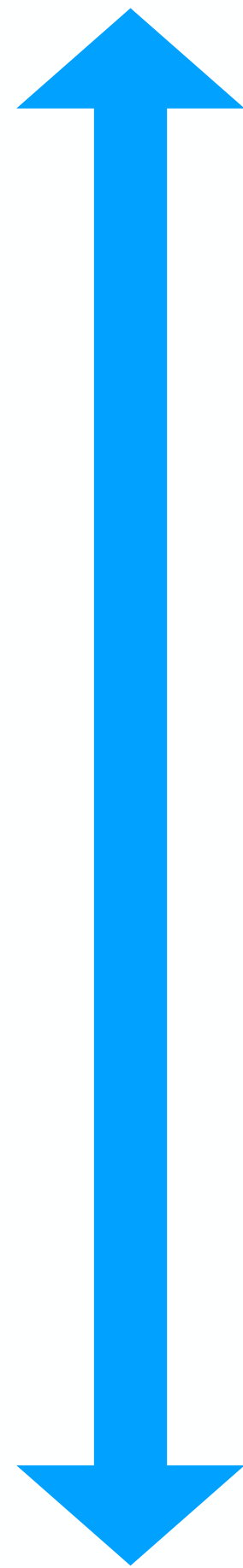
Atomic interferometry in space: AEDGE

Abou El-Neaj et al I 908.00802

Graham et al I 206.0818 (MAGIS)

Badurina et al 2108.02468 (AION)

40000 km

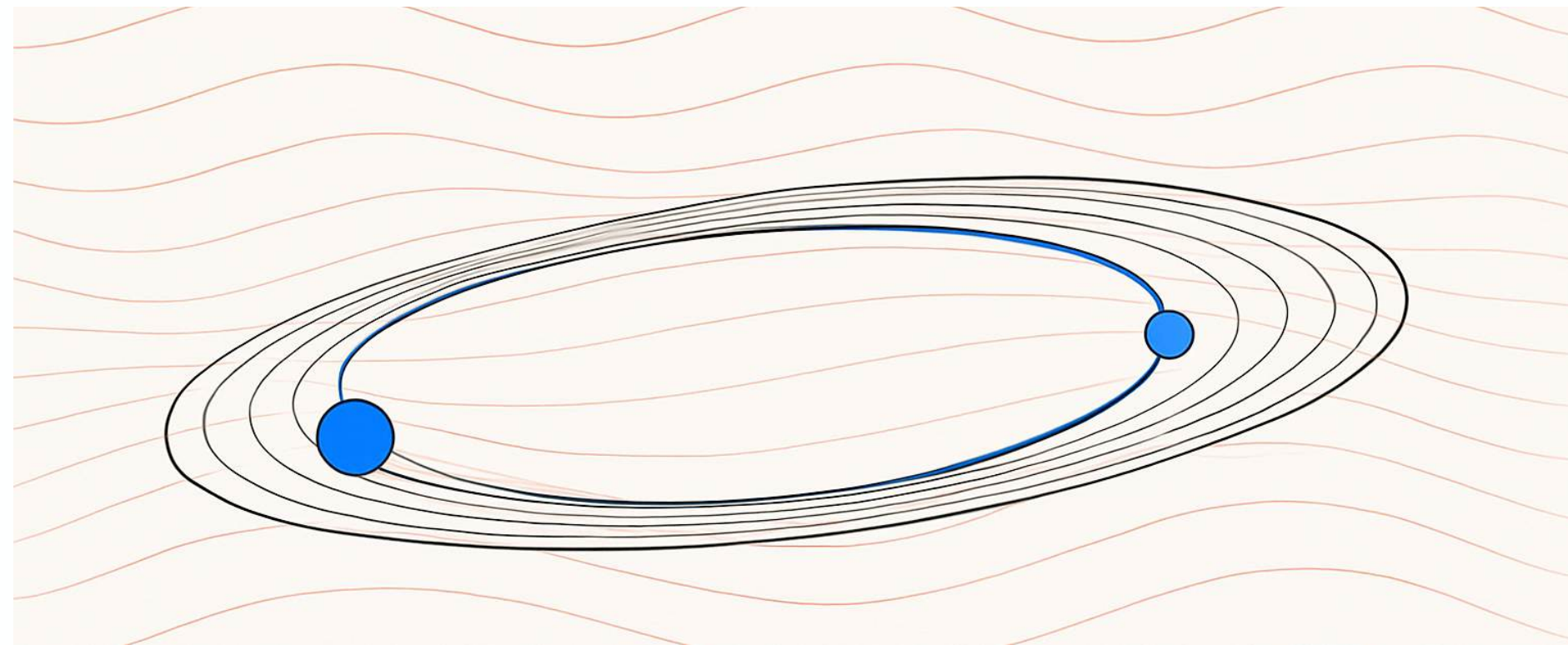


$$\Delta\phi \sim \omega Lh$$

Our proposal: binary resonance!

gravitational waves affect gravitationally bound systems

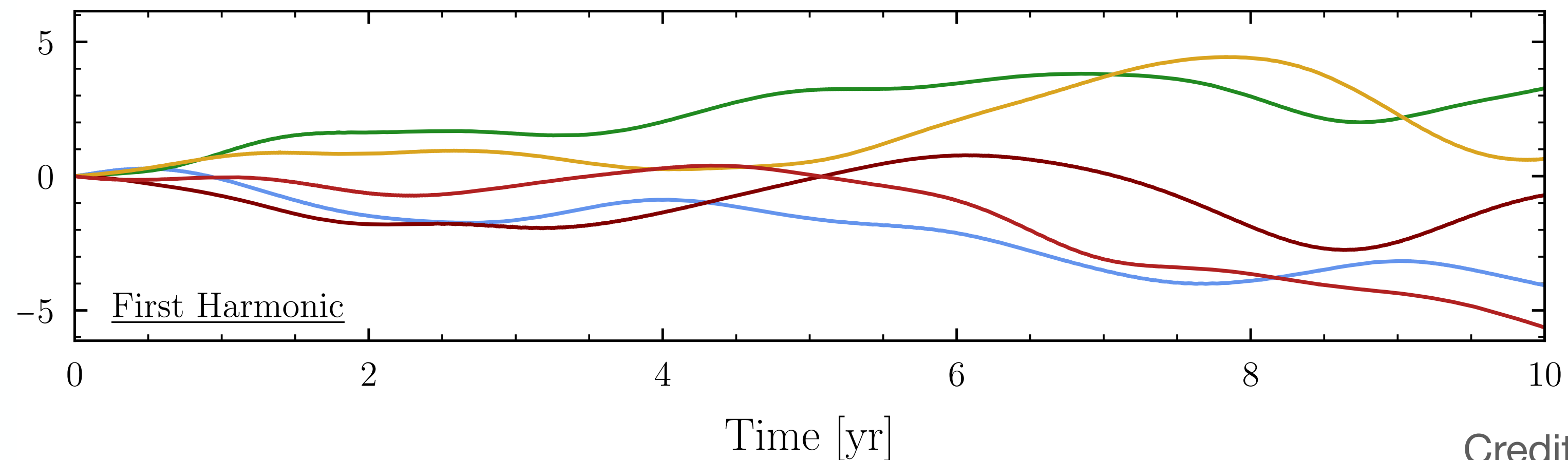
$$\delta \dot{r}^i = -\delta R^i_{0j0} r^j$$



$$\lambda \gg a$$

Semi-latus Rectum Perturbation (arbitrary units)

Evolution on stochastic backgrounds



Credit: J. Foster

Analytical results

$$\mathbf{a} = \mathcal{R}\hat{\mathbf{r}} + \mathcal{S}\hat{\boldsymbol{\theta}} + \mathcal{W}\hat{\mathbf{z}},$$

$$\dot{p} = 2\sqrt{\frac{p^3}{GM}} \frac{1}{1 + e \cos(f)} \mathcal{S},$$

$$\dot{e} = \sqrt{\frac{p}{GM}} \times \left[\sin(f) \mathcal{R} + \frac{2 \cos(f) + e[1 + \cos^2(f)]}{1 + e \cos(f)} \mathcal{S} \right],$$

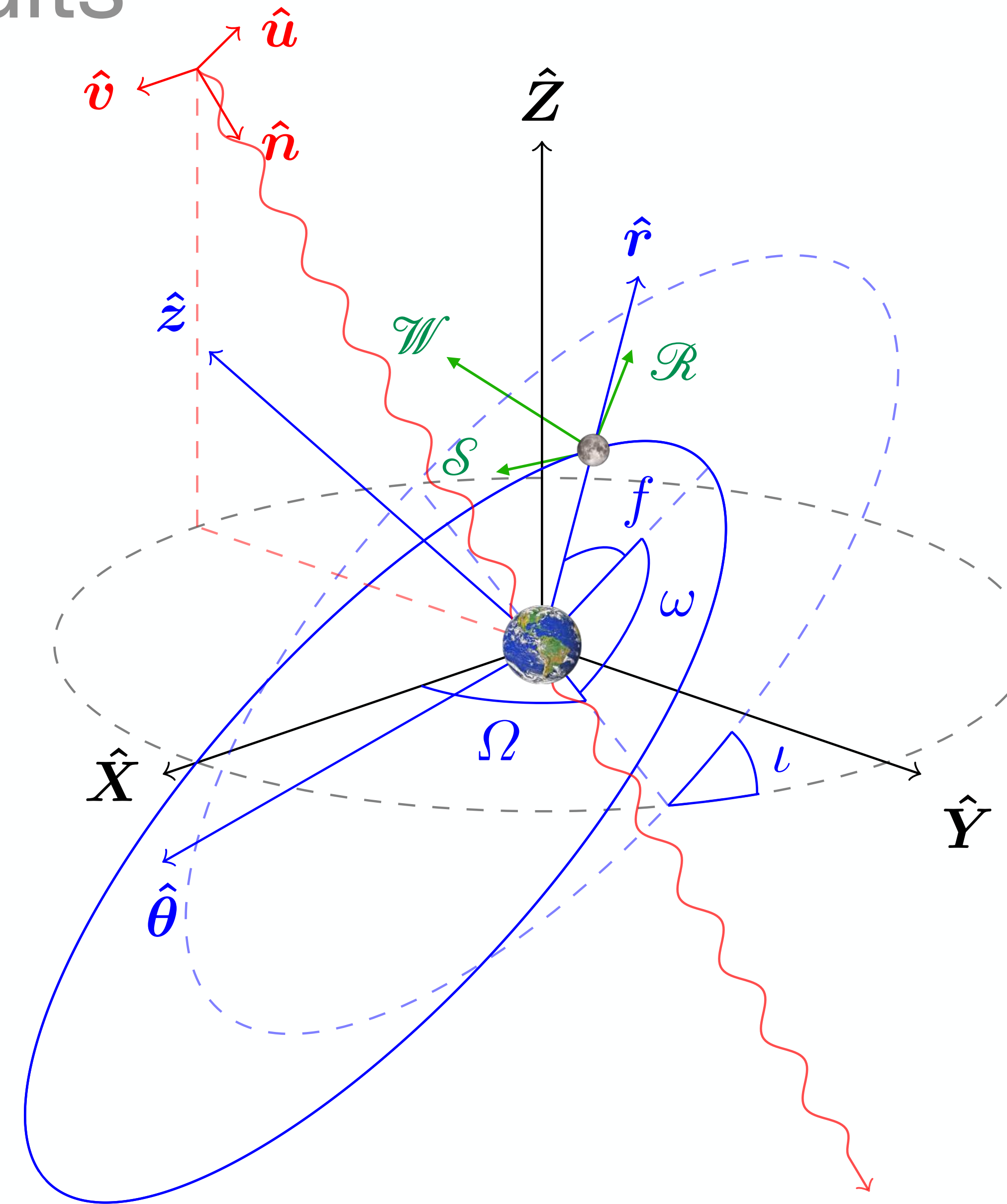
$$i = \sqrt{\frac{p}{GM}} \frac{\cos(\omega + f)}{1 + e \cos(f)} \mathcal{W},$$

$$\dot{\Omega} = \csc(\iota) \sqrt{\frac{p}{GM}} \frac{\sin(\omega + f)}{1 + e \cos(f)} \mathcal{W},$$

$$\dot{\omega} = \frac{1}{e} \sqrt{\frac{p}{GM}} \left[-\cos(f) \mathcal{R} + \frac{2 + e \cos(f)}{1 + e \cos(f)} \sin(f) \mathcal{S} - e \cot(\iota) \frac{\sin(\omega + f)}{1 + e \cos(f)} \mathcal{W} \right],$$

$$\dot{f} = \sqrt{\frac{GM}{p^3}} (1 + e \cos(f))^2 + \frac{1}{e} \sqrt{\frac{p}{GM}} \left[\cos(f) \mathcal{R} - \frac{2 + e \cos(f)}{1 + e \cos(f)} \sin(f) \mathcal{S} \right],$$

$$x^a \equiv (P, e, I, \Omega, \omega, f)$$



Analytical results

$$\mathbf{x}^a \equiv (P, e, I, \Omega, \omega, \epsilon)$$

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

$$\dot{\mathbf{x}}_1^a = \mathbf{F}_0^{ab}(t)\mathbf{x}_1^b + \mathbf{F}_{\text{GW}}^{aij}(\mathbf{x}_0(t), t)\ddot{h}_{ij}(t),$$

Periodic solvable system

Periodic external force

Ideal system for **Floquet** analysis

$$\dot{\tilde{\mathbf{x}}}_1^a = \mathbf{F}_0^{ab}(t)\tilde{\mathbf{x}}_1^b$$

Propagator: $\tilde{\mathbf{x}}_1(t)_a = \Phi_{ab}\tilde{\mathbf{x}}_1(0)_b$

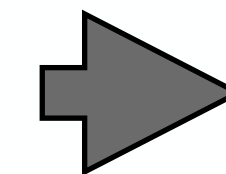
$$\dot{\Phi}_{ab} = F_0^{ac}(t)\Phi_{cb}, \quad \Phi(t=0) = I.$$

Final:

$$\mathbf{x}_1^a(t) = \Phi_{ab}(t) \int_0^t d\tau \Phi_{bc}^{-1}(\tau) \mathbf{F}_{\text{GW}}^{cij}(\tau) \ddot{h}_{ij}(\tau)$$

Periodic (orbital period)

Periodic (external time dependence)



Secular behavior expected
for $\omega \approx n/P$

Stochastic backgrounds

$$\mathbf{x}_1^a(t) = \mathbf{\Phi}_{ab}(t) \int_0^t d\tau \mathbf{\Phi}_{bc}^{-1}(\tau) \mathbf{F}_{\text{GW}}^{cij}(\tau) \dot{h}_{ij}(\tau)$$

$$\begin{aligned} \mathbf{\Sigma}_{\alpha\beta}(t, t') \equiv \langle x_1^\alpha(t) x_1^\beta(t') \rangle &= 3\pi H_0^2 C_{ij,lm} \mathbf{\Phi}_{\alpha\gamma}(t) \mathbf{\Phi}_{\beta\kappa}(t') \\ &\times \int_0^\infty d\nu \nu \Omega_{\text{GW}}(\nu) \int_0^t d\tau \int_0^{t'} d\tau' \mathbf{\Phi}_{\gamma\lambda}^{-1}(\tau) \mathbf{\Phi}_{\kappa\mu}^{-1}(\tau') F_{\text{GW}}^{\lambda ij}(\tau) F_{\text{GW}}^{\mu lm}(\tau') \cos[2\pi\nu(\tau - \tau')] \end{aligned}$$

