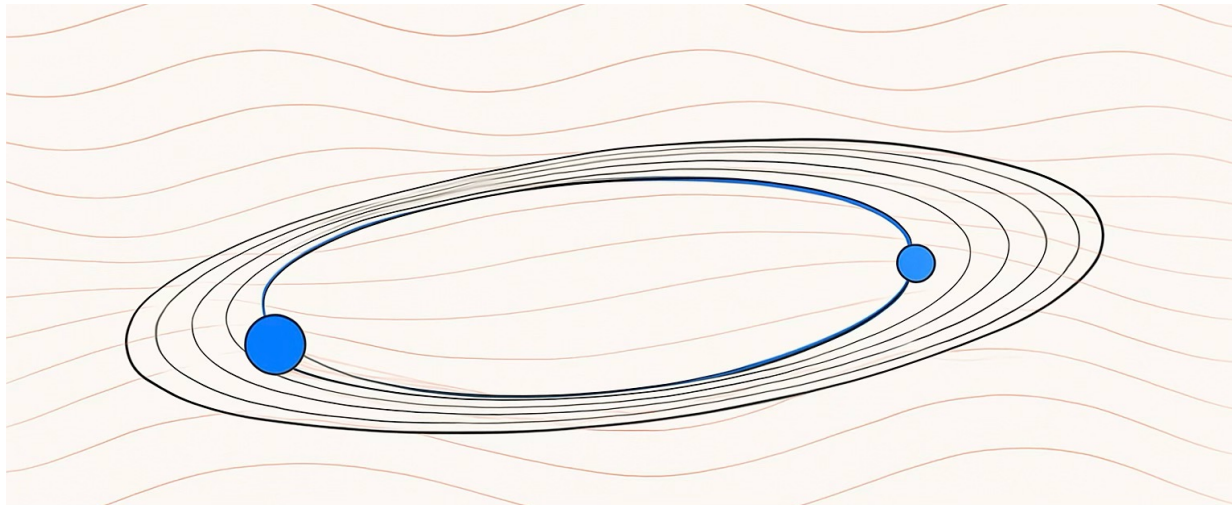


Searching for gravitational waves using the orbital dynamics of binary systems

A. Hees, LTE/OBSPM

in collaboration with D. Blas, A. Jenkins, J. Foster, A. Bourgoïn, X. Xue, ...

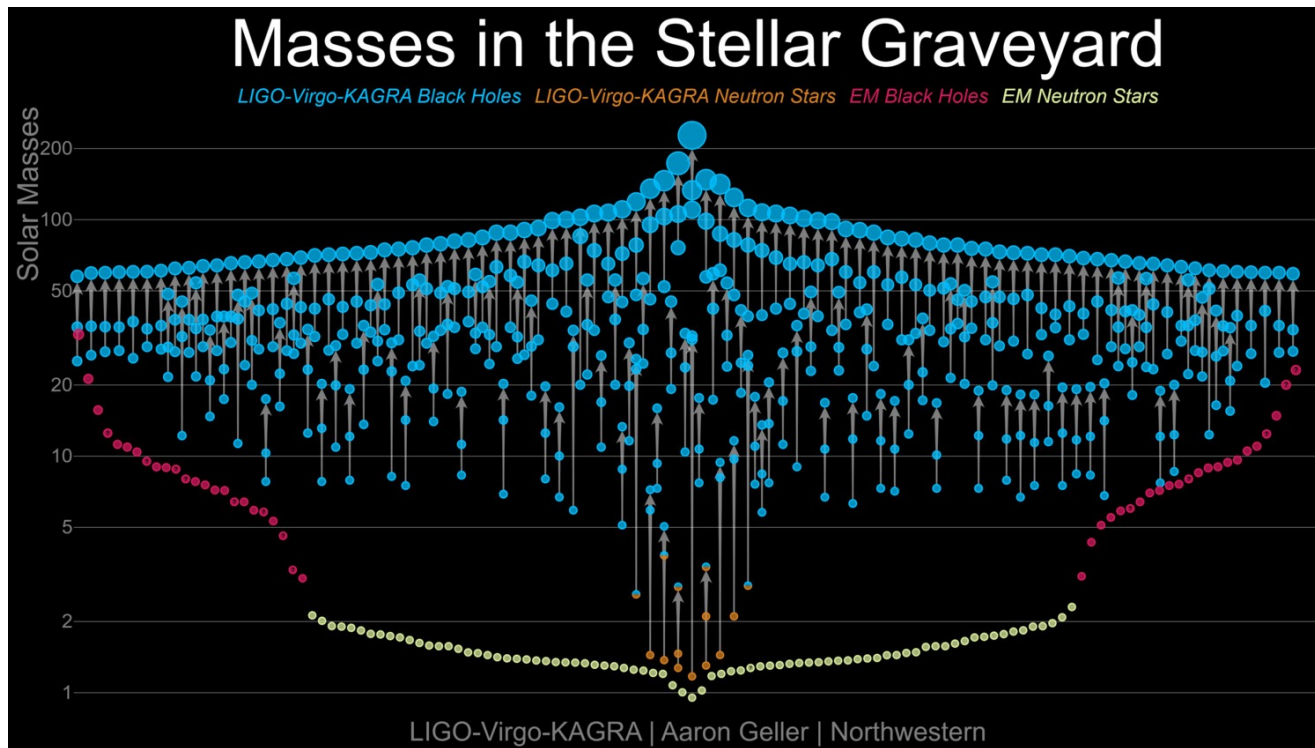
based on J. Foster et al, PRL 137, 091401 and PRD 114, 044068, 2026



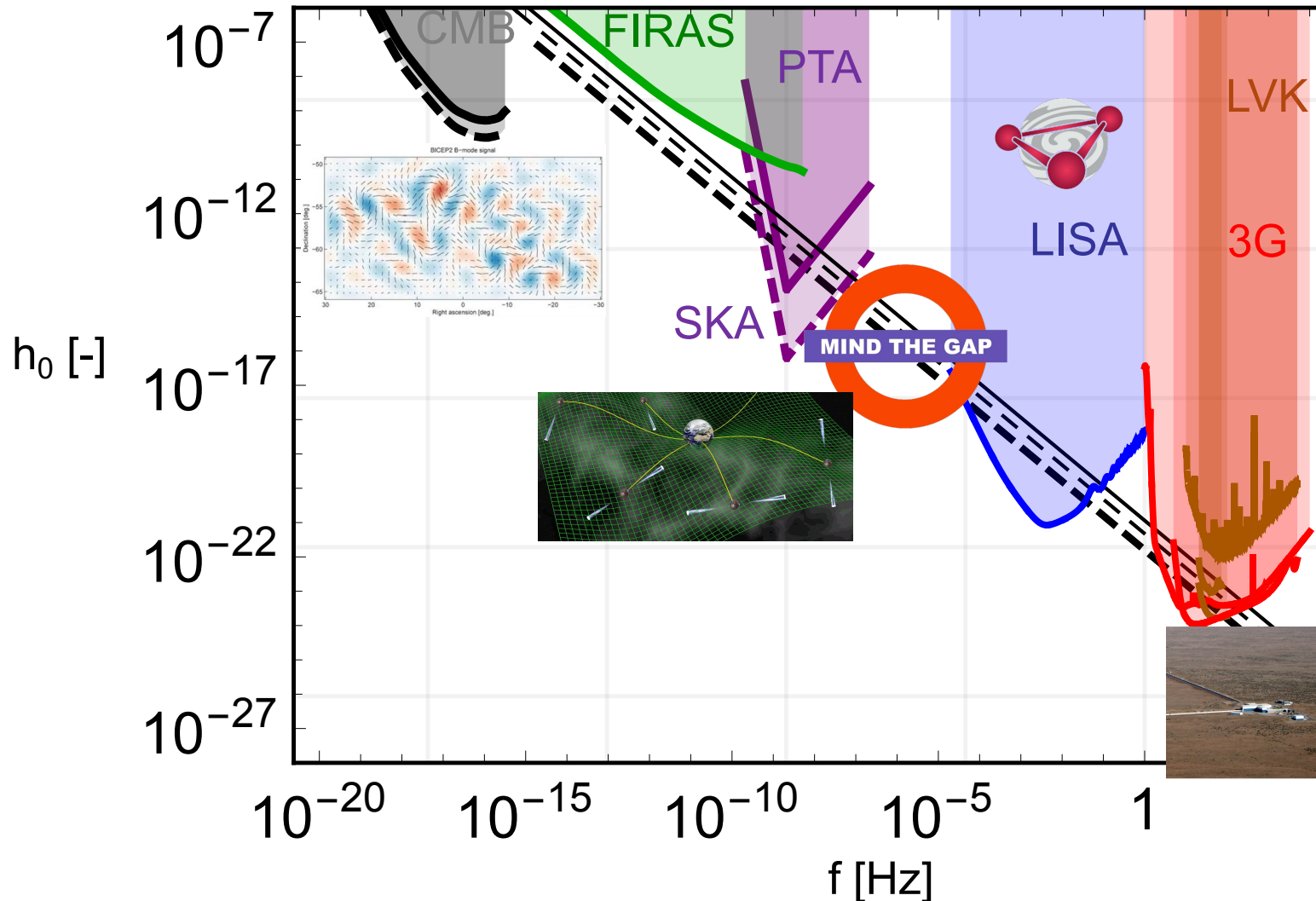
GDR Ondes Gravitationnelles – October 6th 2026

After 11 years of GW measurements

- more than 400 events detected
- impressive consequences in astrophysics, cosmology, fundamental physics, ...



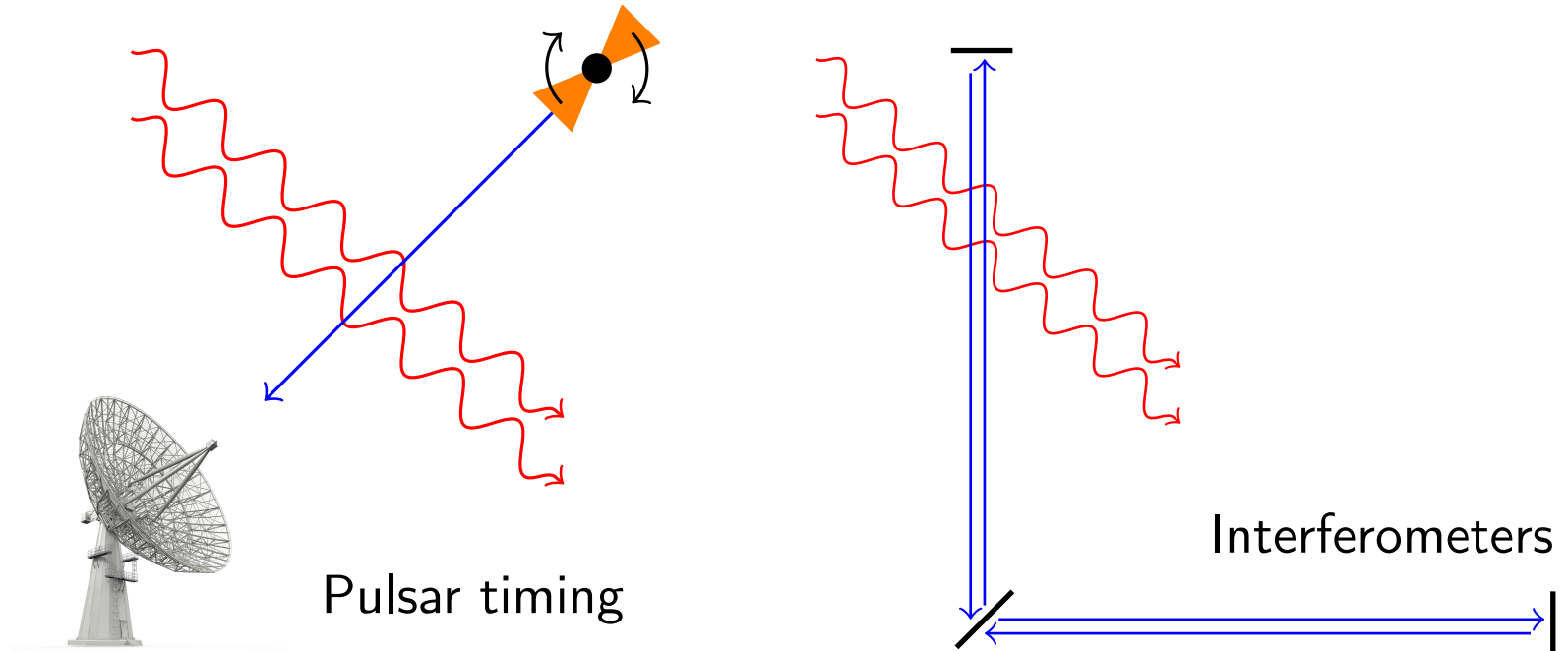
The GW landscape in 2040: with a notorious gap in the μHz regime



How to detect such GW?

Current detection techniques for GW rely mainly on light propagation

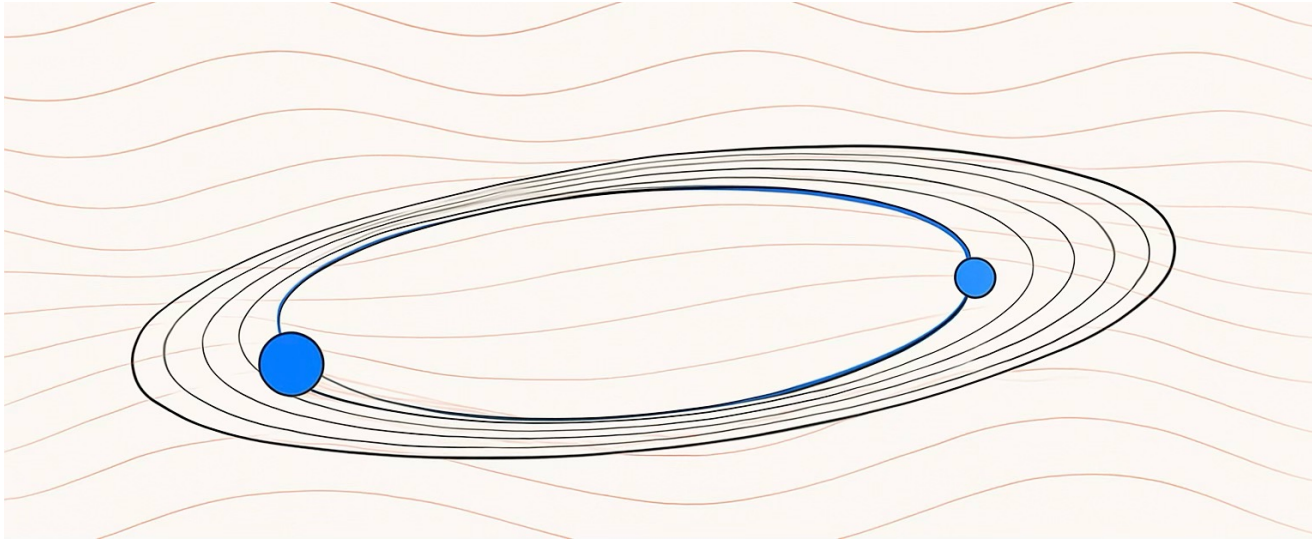
- GW impacts the time of propagation or frequency shift of light ray



- “usual” difficulties to develop such detectors in the μHz regime:
 - Size of the instrument ($\sim$ a.u. e.g. μ Ares proposal or asteroid laser ranging)
 - Stable observations over long period ($\sim$ year)
 - Usually not that great low frequency behavior of optics, clocks, ...

A binary system acts as a GW antenna: it can emit GW but also detect them

see e.g. Turner, APJ 233, 685, 1979 or Mashoon, AJ 223, 285, 1978



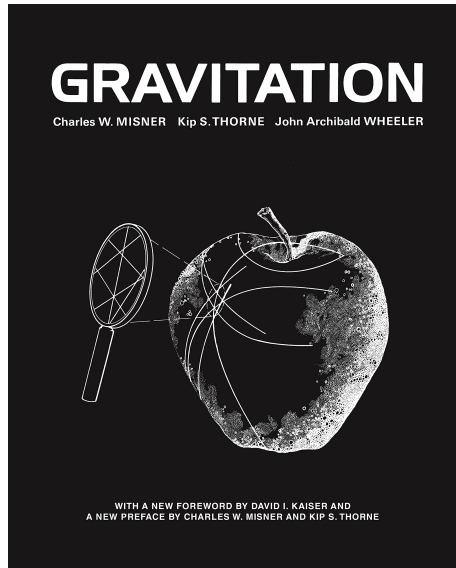
Newton
acceleration

$$\ddot{r}_i + \frac{GM}{r^3} r_i = \frac{1}{2} \ddot{h}_{ij} r^j \leftarrow \text{GW perturbation}$$

- if the **GW is resonant with the orbital period**: produces a secular evolution of all orbital elements (in particular a quadratic evolution of the true anomaly, a linear drift of the semi-major axis and eccentricity). This can be detected.

see e.g. Blas and Jenkins PRD and PRL, 2021
Foster et al, PRD and PRL, 2026

Such an idea is already mentioned in everyone's favorite bedbook

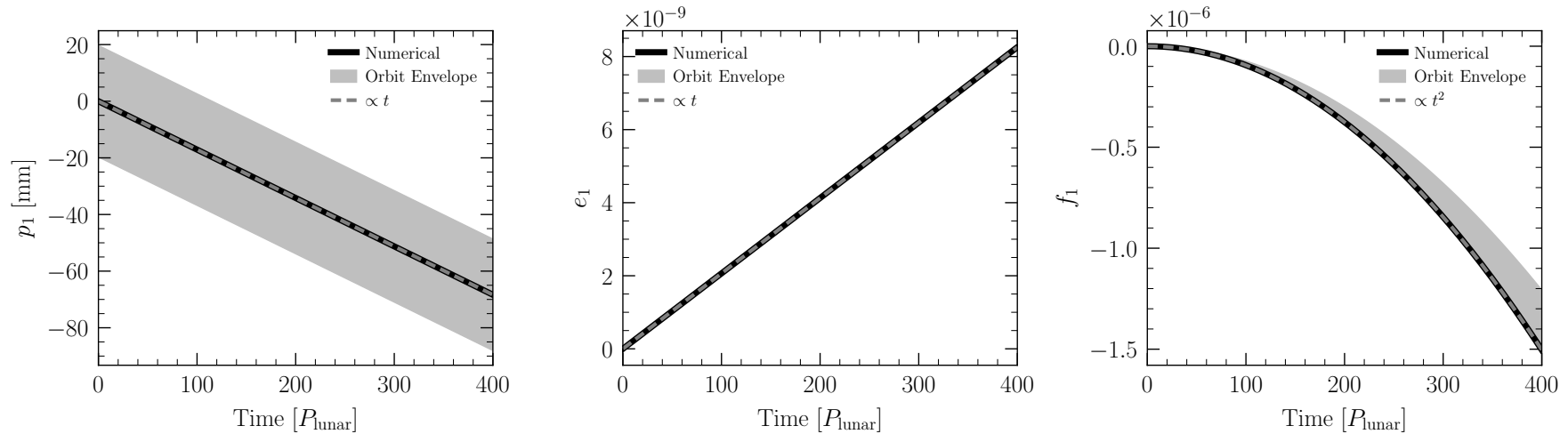


1. The Relative Motions of Two Freely Falling Bodies

As a gravitational wave passes two freely falling bodies, their proper separation oscillates (Figure 37.3). This produces corresponding oscillations in the redshift and round-trip travel times for electromagnetic signals propagating back and forth between the two bodies. Either effect, oscillating redshift or oscillating travel time, could be used in principle to detect the passage of the waves. Examples of such detectors are the Earth-Moon separation, as monitored by laser ranging [Fig. 37.2(a)]; Earth-spacecraft separations as monitored by radio ranging; and the separation between two test masses in an Earth-orbiting laboratory, as monitored by redshift measurements or by laser interferometry. Several features of such detectors are explored in exercises 37.6 and 37.7. As shown in exercise 37.7, such detectors have so low a sensitivity that they are of little experimental interest.

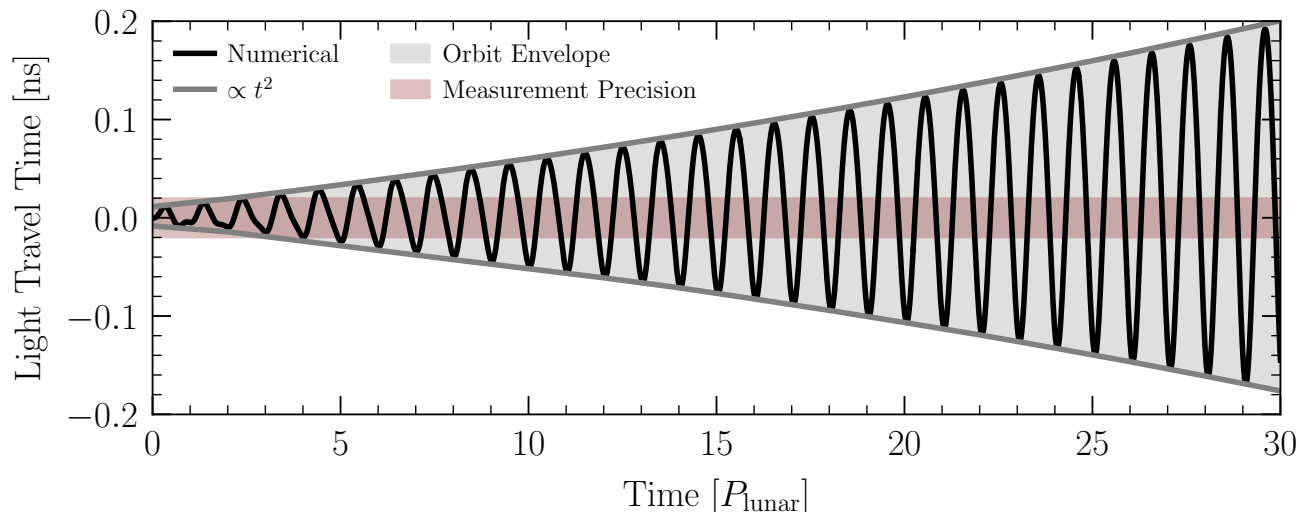
- such a pessimistic statement does not account for resonant effects
- first exploration of resonant effect in Hui et al, PRD, 2013 (binary pulsar)
- careful analysis of the resonant effect using secular approximation by D. Blas and A. Jenkins with prediction for SGWB for LLR, SLR, BPS in PRL, PRD 2021
- beyond secular approximation and more realistic simulation closer to data analysis in J. Foster et al, PRL, PRD 2026
- 2025/2026: development of a research program to analyze existing data (LLR, SLR, pulsars)
- 2025: dedicated space mission proposal “GUEST” (PI: D. Blas) as an answer to the ESA F-3 call (currently under evaluation)

At resonance, all orbital elements of the binary system are impacted by the GW



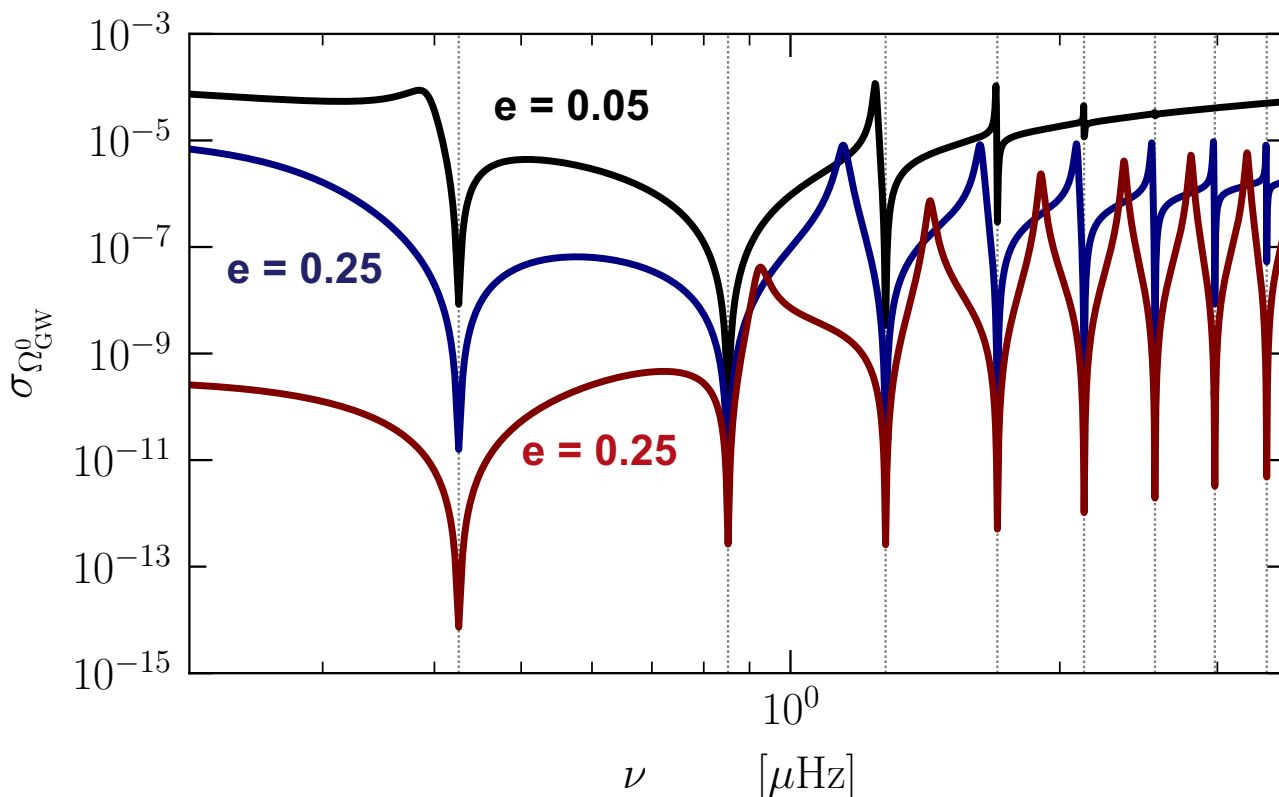
- a **quadratic** drift of the true anomaly
- a **linear** drift for all other orbital elements (including semi-major axis)

Which can be transformed into an observable 2-ways LTT

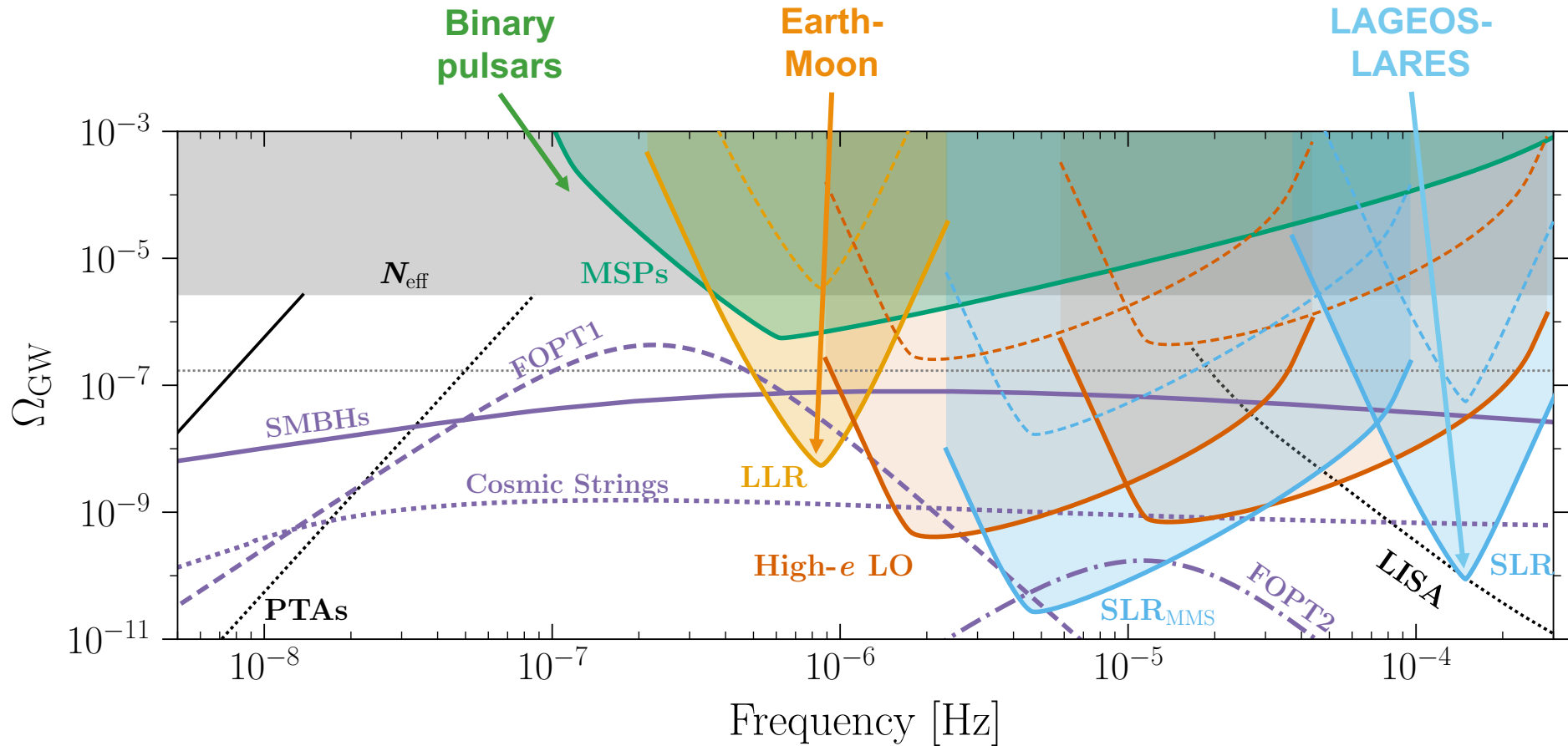


Importance of orbital period and eccentricity

- orbital period / semi-major axis: the binary system is sensitive to GW frequency $\sim n f_{\text{orb}}$
- Orbital eccentricity:
 - increases the signal amplitude
 - increases the number of resonances (i.e. sensitive to more frequencies)



Sensitivity analysis



- optimistic sensitivity analysis but this has pushed us to start developing real data analysis but
- none of these systems have been optimized for this (small eccentricity)

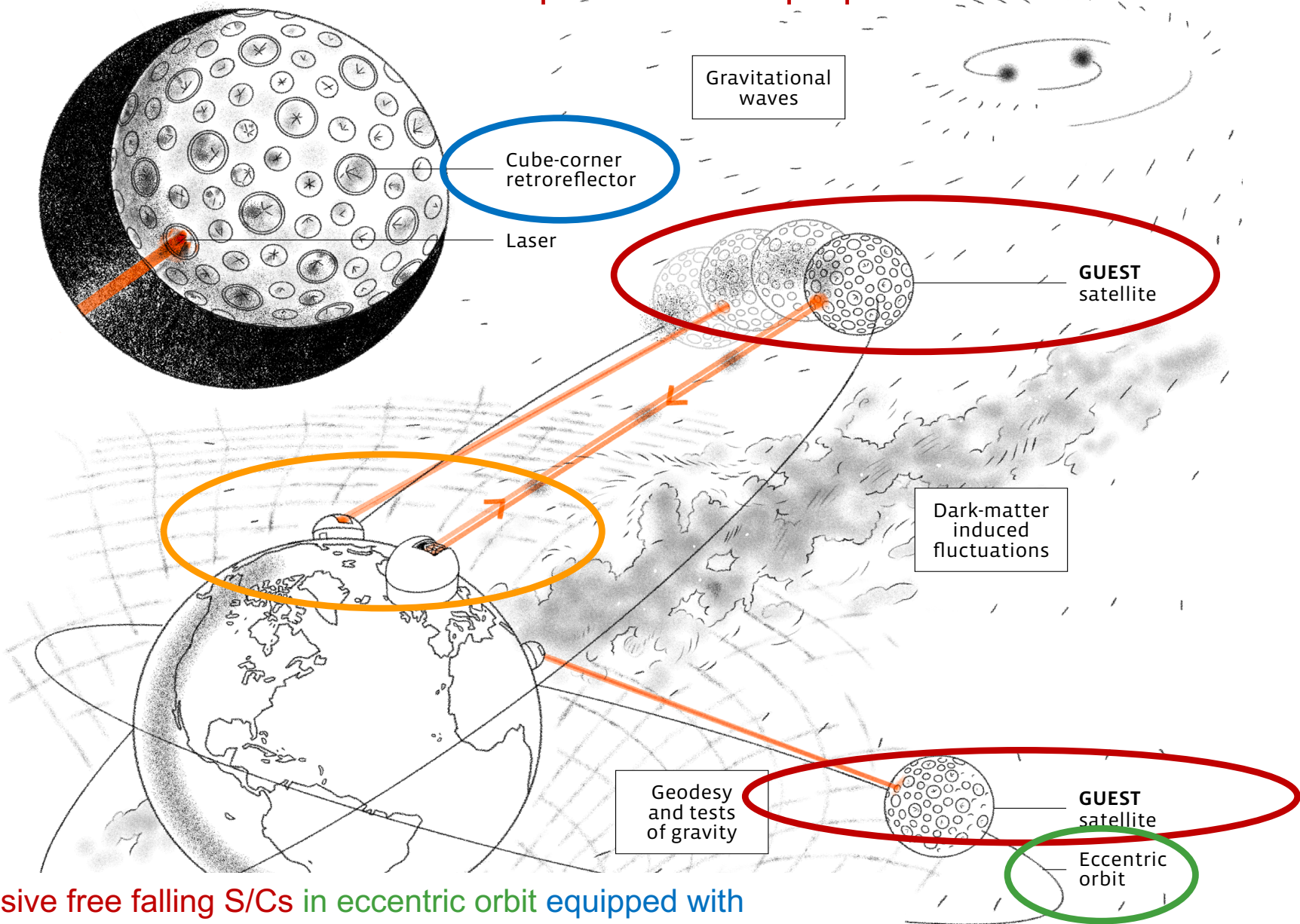
Real data analysis is on-going but is way more complex: LLR, LAGEOS/LARES, Binary Pulsars

- non-Keplerian motion: detector response function is way more complex (and not analytical anymore)
- GW should be fitted simultaneously with a lot of other parameters (initial conditions, tidal interaction, gravity field, drag force, solar radiation pressure, ...): presence of correlations
- fits using arcs
- estimation of systematics is quite challenging (mis-modeling)

Solid results obtained using existing data would be the best way to demonstrate that this method works

Gravitational Universe Exploration with Satellite Tracking (GUEST)

a space mission proposal for the F3 ESA call



2 passive free falling S/Cs in eccentric orbit equipped with retroreflectors tracked using Satellite Laser Ranging (SLR)

Gravitational Universe Exploration with Satellite Tracking – GUEST

*Exploring the Dark Universe using eccentric geocentric S/C tracking
An answer to the ESA F3 call*

Lead proposer: *Diego Blas* – Institut de Física d'Altes Energies (IFAE), Barcelona, Spain

French contributors:

- Clément Courde, Julien Chabé: OCA/GeoAzur
- Alice Perego: LAGRANGE/OCA
- Nicola Tamanini: L2IT
- Pascal Rosenblatt: LPG Nantes
- Aurélien Hees, Adrien Bourgoïn: LTE/OBSPM

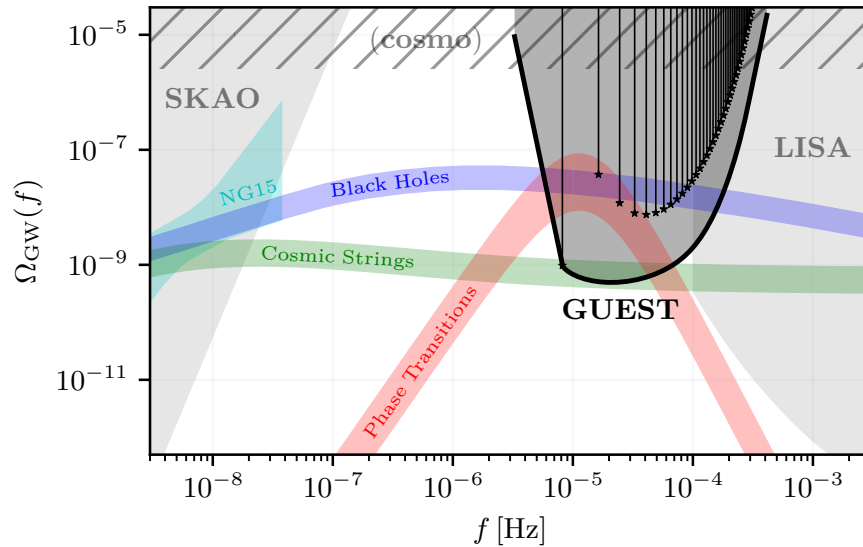
Collaboration very open to new scientists – feel free to reach us if you are interested

GUEST: a conceptually simple mission with 3 scientific objectives

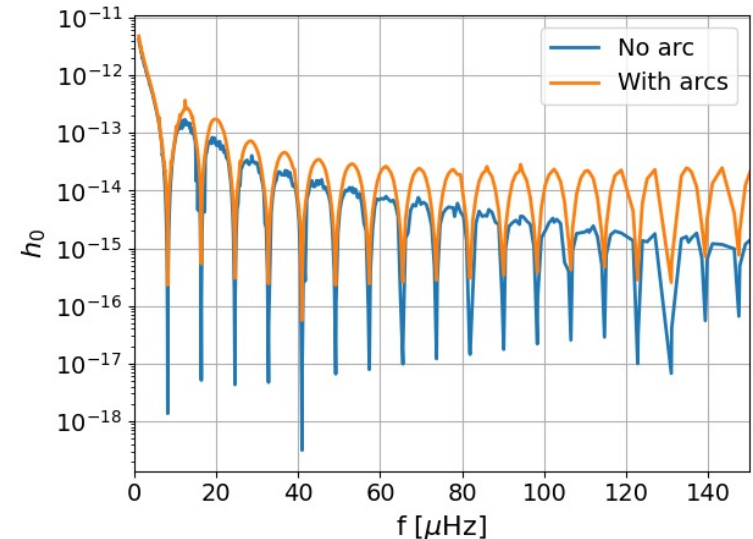
1. Detect GW in the μHz regime

- Improvement wrt phase 1: full simulations using realistic orbits and POD (Earth gravity field fitted, SRP, ...)

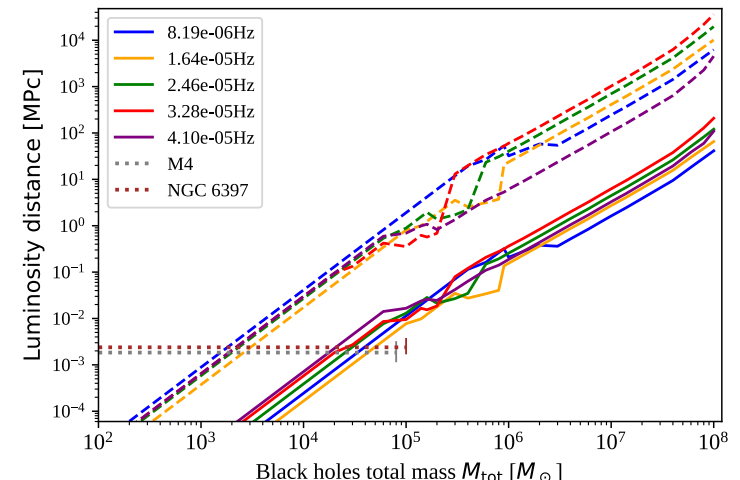
Stochastic GW background



Monochromatic GW



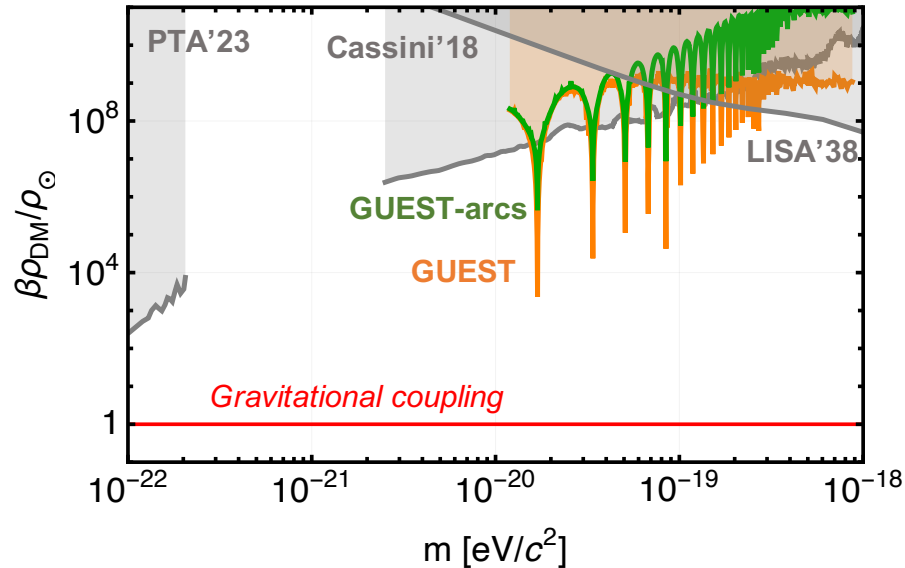
- GUEST competitive to detect GW from SMBH inspirals/mergers from our close universe
- GUEST competitive to detect a stochastic GW background



GUEST: a conceptually simple mission with 3 scientific objectives

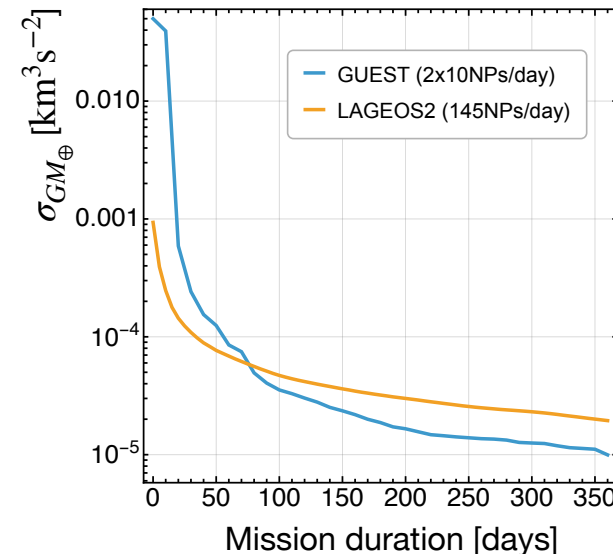
2. Search for ULDM and boson clouds

- ULDM



3. Geodesy

- Earth gravitational potential
- Calibration of stations
- Connection with GENESIS

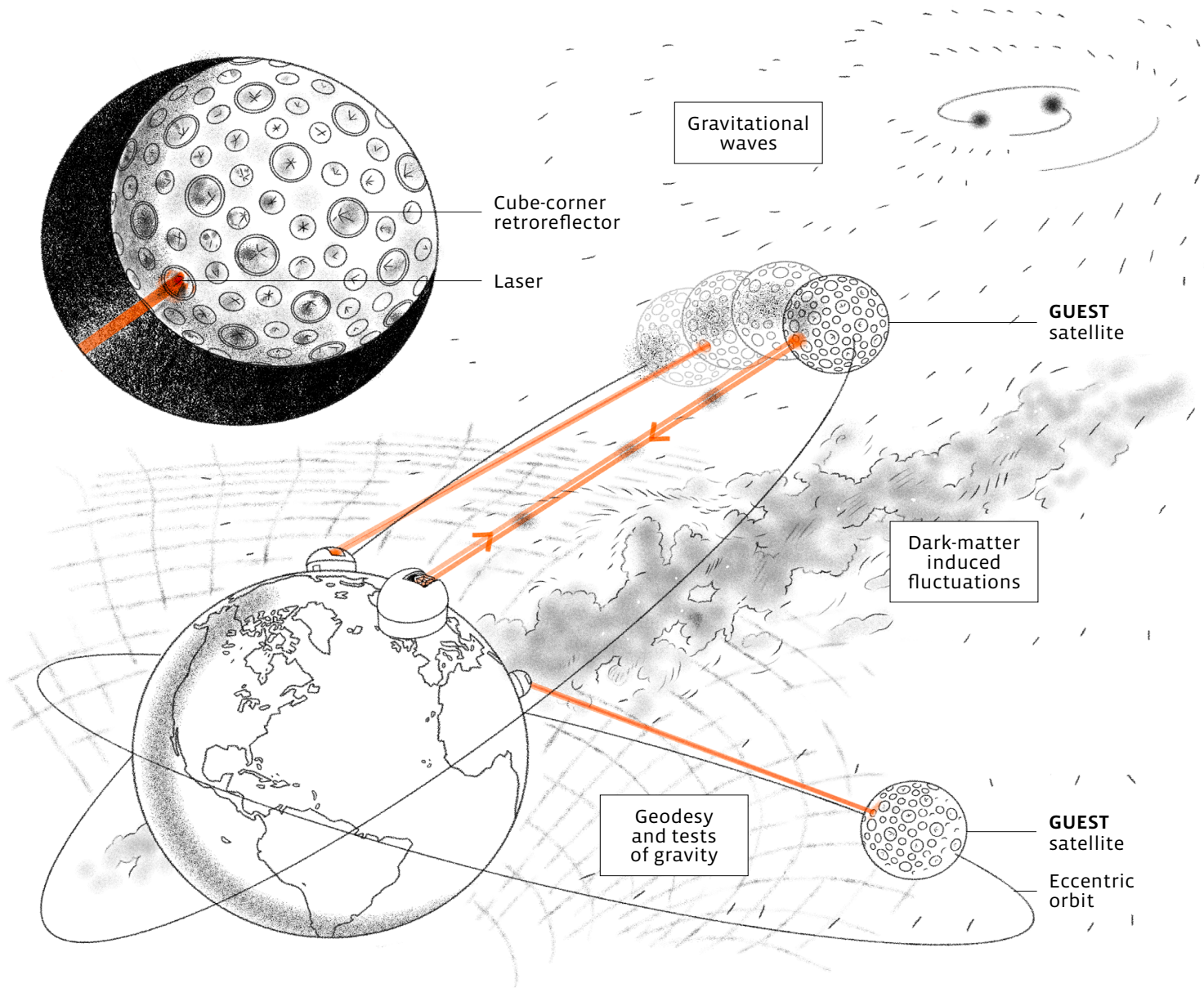


Binary systems: a promising avenue to explore the μHz GW frequency band?

- The GW μHz band is a promising band: IMBH, SMBH mergers, first order phase transition, topological defects, stochastic SMBH merger (probe PTA signal), possible unexpected sources?, ...
- The orbital evolution of binary system is impacted by GW – resonant effects increase such phenomenon and make it possibly detectable
- **Idealized theoretical studies** suggest this is a promising avenue to detect GW in the μHz band
- First data analysis using existing (non optimized) dataset on-going: important to **demonstrate the feasibility of such a method**
- A project of an optimized space mission (GUEST) at low cost is currently being explored

Young collaboration opened to newcomers, ideas, feedback

Thank you for your attention



The μHz GW frequency range contains exciting signals

1. Astrophysical signals: SMBH mergers

The μHz GW landscape: single sources

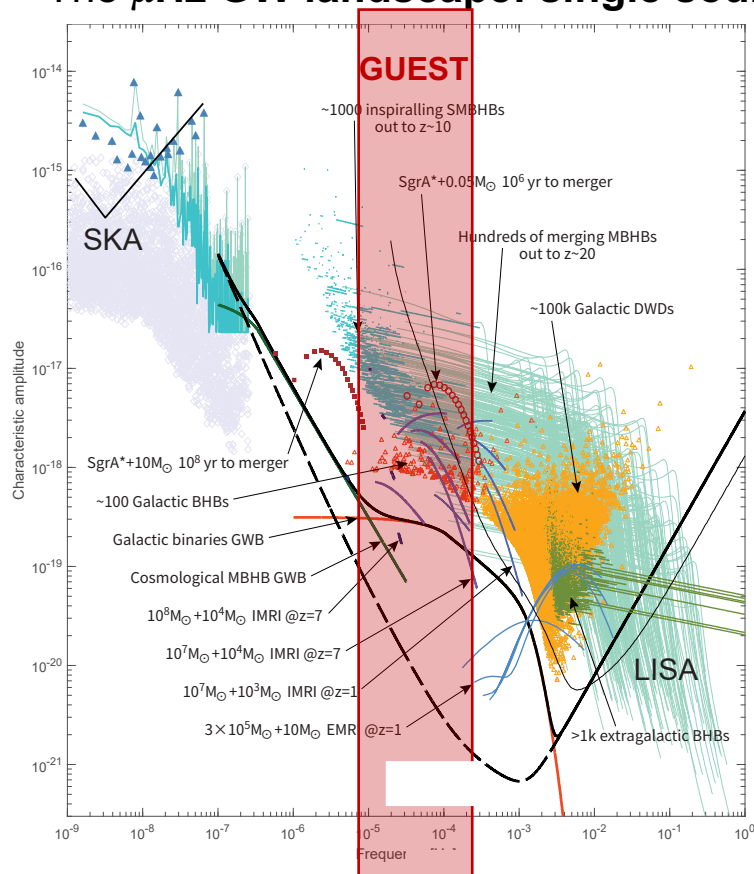


Figure from Voyage 2050 white paper, Sesana et al, arXiv:1908.11391

Will detect some MBHB $\sim$ weeks/yr
before they enter LISA band

The μHz GW landscape: SMBH stochastic distribution

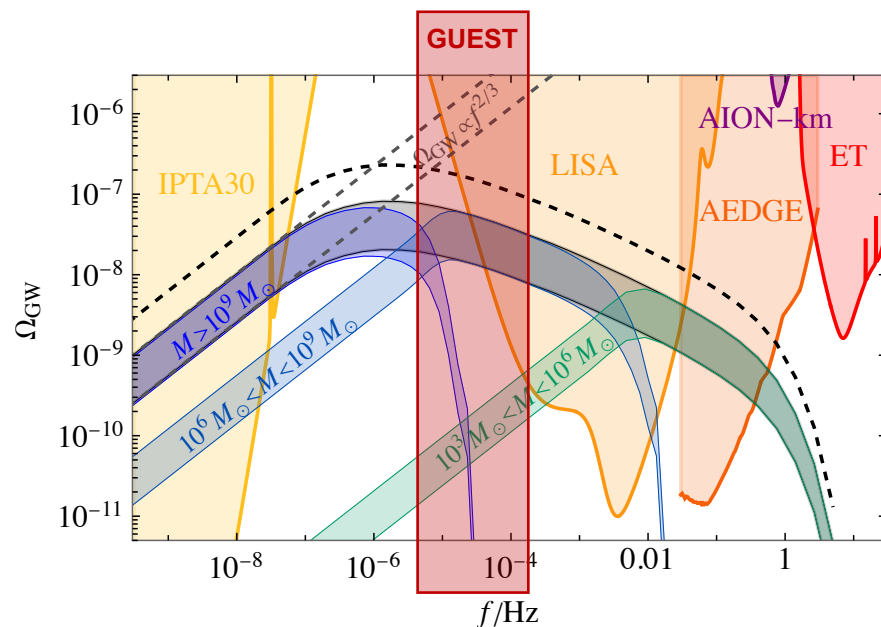


Figure from J. Ellis et al, A & A 676, A38, 2023

Will help understand evolution of galaxy, enable cosmography, multi-messenger (also with LISA), ...

The μHz GW frequency range contains exciting signals

1. Astrophysical signals: SMBH mergers
2. Fundamental physics: early Universe stochastic GW, e.g.

Cosmic strings and topological defects

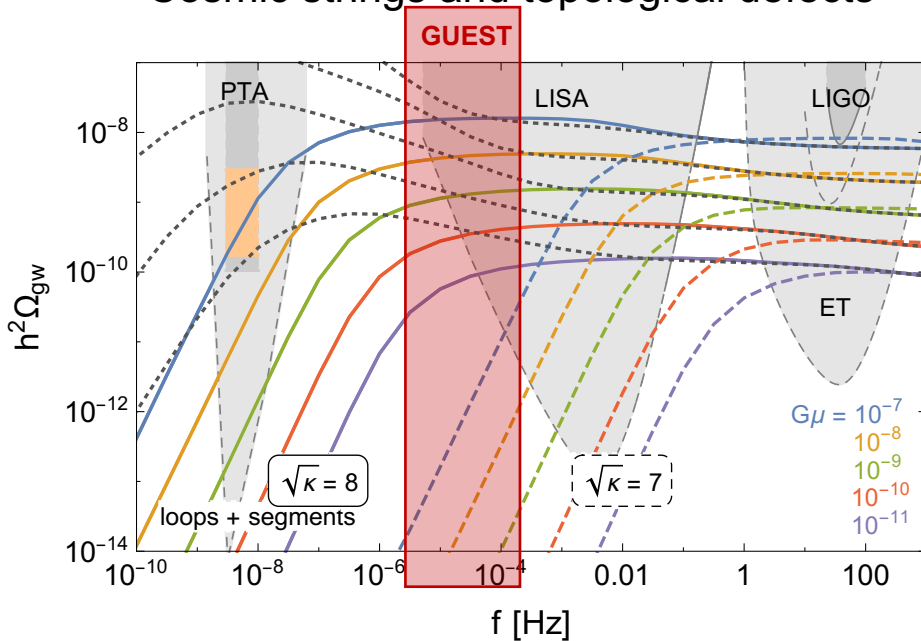
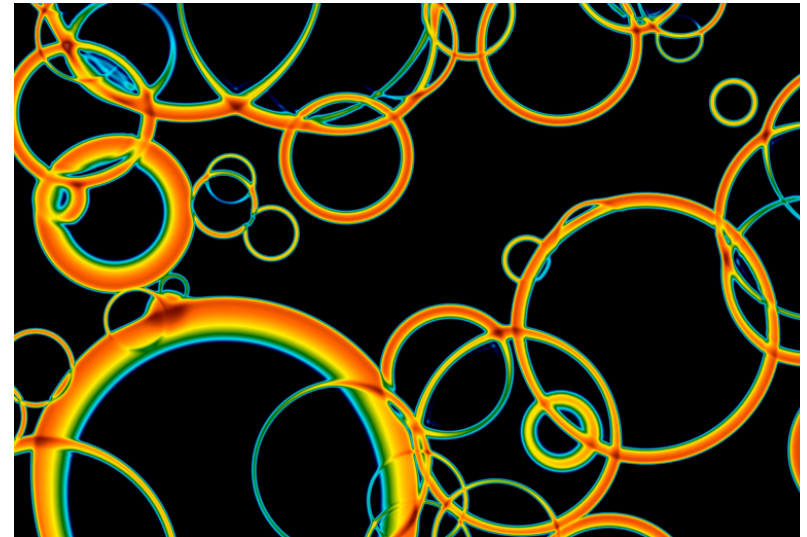


Figure from Buchmuller et al, JCAP 2021, 12, 06.

Cosmo first order phase transition

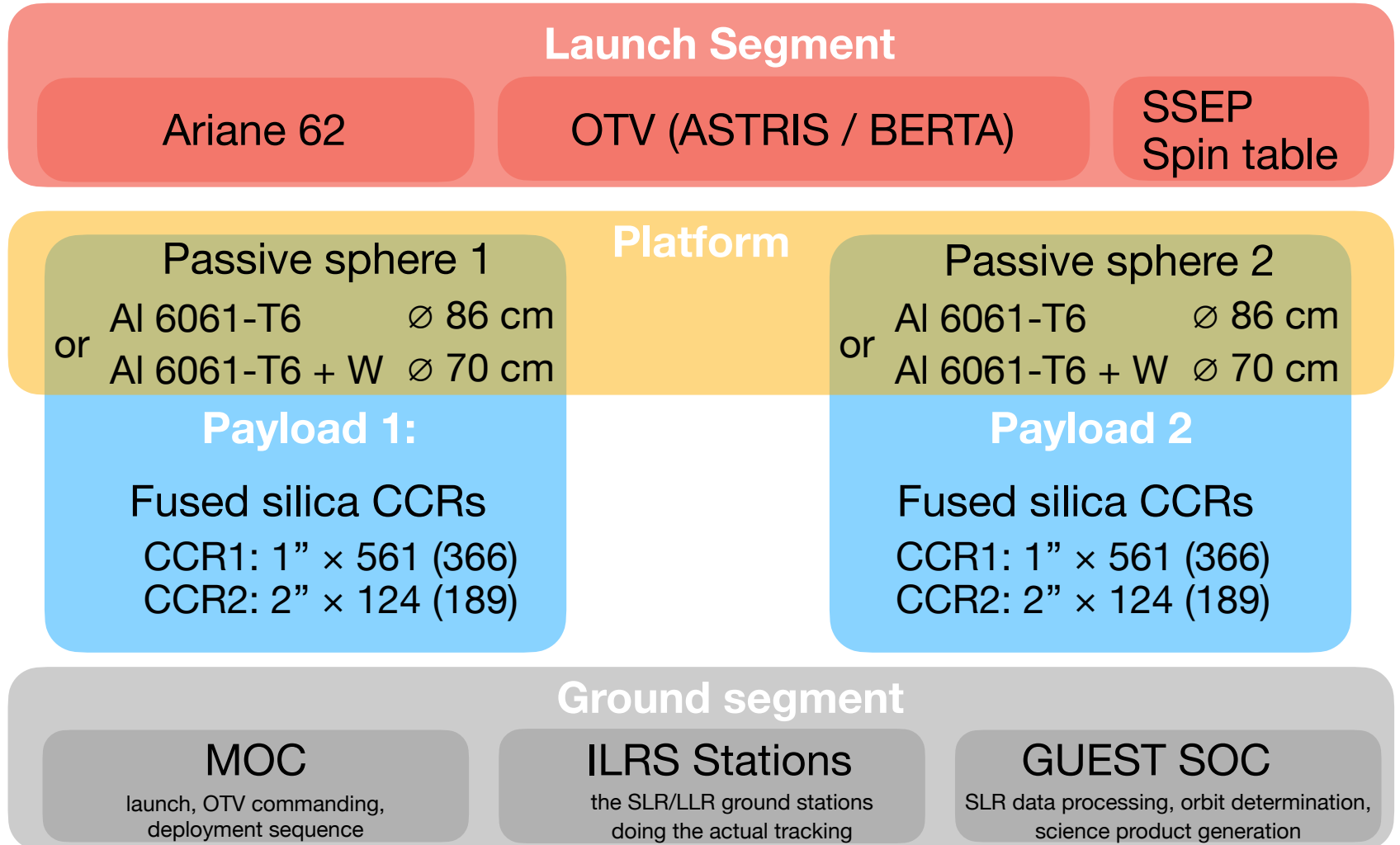


$$f_{\text{peak}} \approx 19 \mu\text{Hz} \times \left(\frac{T_*}{100 \text{ GeV}} \right) \left(\frac{\beta/H_*}{v_w} \right)$$

From Weir et al, Phil. Trans. R. Soc. A 2018 376 20170126

But also: primordial BH, inflation, ...

GUEST block diagram

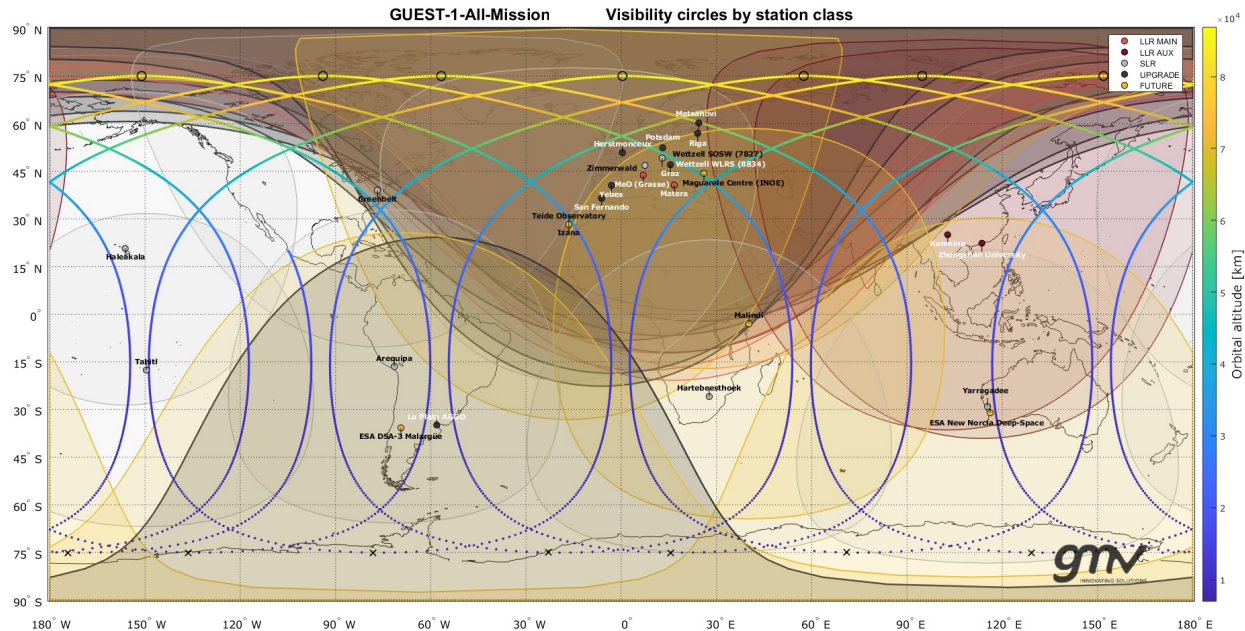


Orbits

- For this proposal: find 2 orbits that satisfy all requirements.

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 description: the spheres

Heritage from LAGEOS and LARES-2

- 2 identical **passive** spacecraft: two options still under studied
 - A: Monolithic Al 6061-T6 structure (LARES heritage), 86 cm – 840 kg
 - B: Two layers: Al 6061-T6 with a Tungsten core (LAGEOS heritage), 70 cm – 550 kg

Optimized in order to

- **Minimize surface-to-mass** ratio (minimize non gravitational forces)
- Total mass within launcher capabilities
- Thermal **noise budget**: thermal isothermality (high conductivity), thermal inertia (high specific heat)
- Electric conductivity: minimize eddy current and Lorentz braking
- Moment of inertia and gyroscopic stability (oblateness $\sim 12.4\%$ - ensure stable spin axis)
- Construction: heritage from LAGEOS and LARES
- Reentry: they **do not fragmentate in the atmosphere**



Spheres: Spanish contribution

Keplerian versus realistic response function

