

Beyond LISA

A Space-Based Gravitational-Wave Program for the micro-Hz to deci-Hz Frontier

Daniele Vetrugno
on behalf of the GW space 2050 group

Max Planck Institute for Gravitational Physics
(Albert Einstein Institute, AEI)
daniele.vetrugno@aei.mpg.de

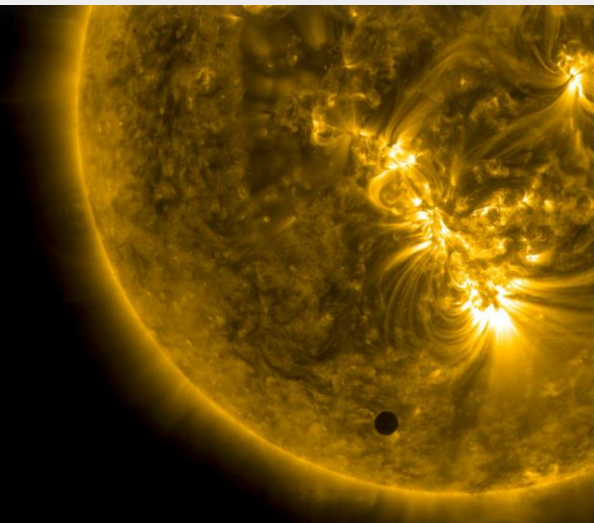
Voyage 2050

SCHEDULE FOR THIS CALL AND IMPORTANT DATES

Activity	Date
Senior Committee appointed	<u>December 2018</u>
Call for Membership of Topical Teams issued	4 March 2019
Call for White Papers issued	4 March 2019
	6 May 2019, 12:00 (noon) CEST
	July 2019
	5 August 2019, 12:00 (noon) CEST
	29 - 31 October 2019
	February 2020
	<u>Late 2020</u>

Voyage 2050

Final recommendations from
the Voyage 2050 Senior Committee

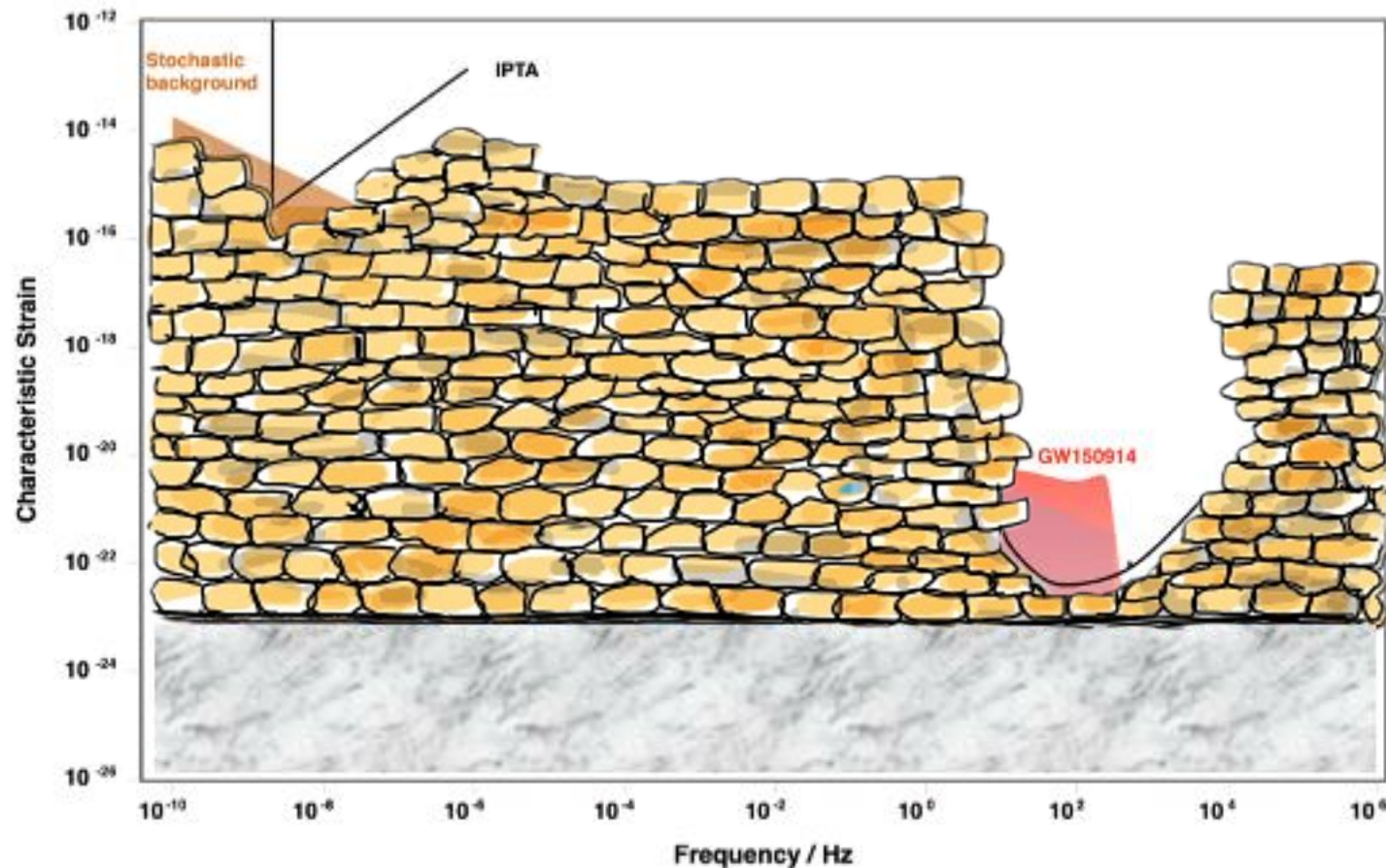


- **New Physical Probes of the Early Universe.** How did the Universe begin? How did the first cosmic structures and black holes form and evolve? These are outstanding questions in fundamental physics and astrophysics, and we now have new astronomical messengers that can address them. Our recommendation is for a Large mission deploying gravitational wave detectors or precision microwave spectrometers to explore the early Universe at large redshifts. This theme follows the breakthrough science from *Planck* and the expected scientific return from *LISA*.

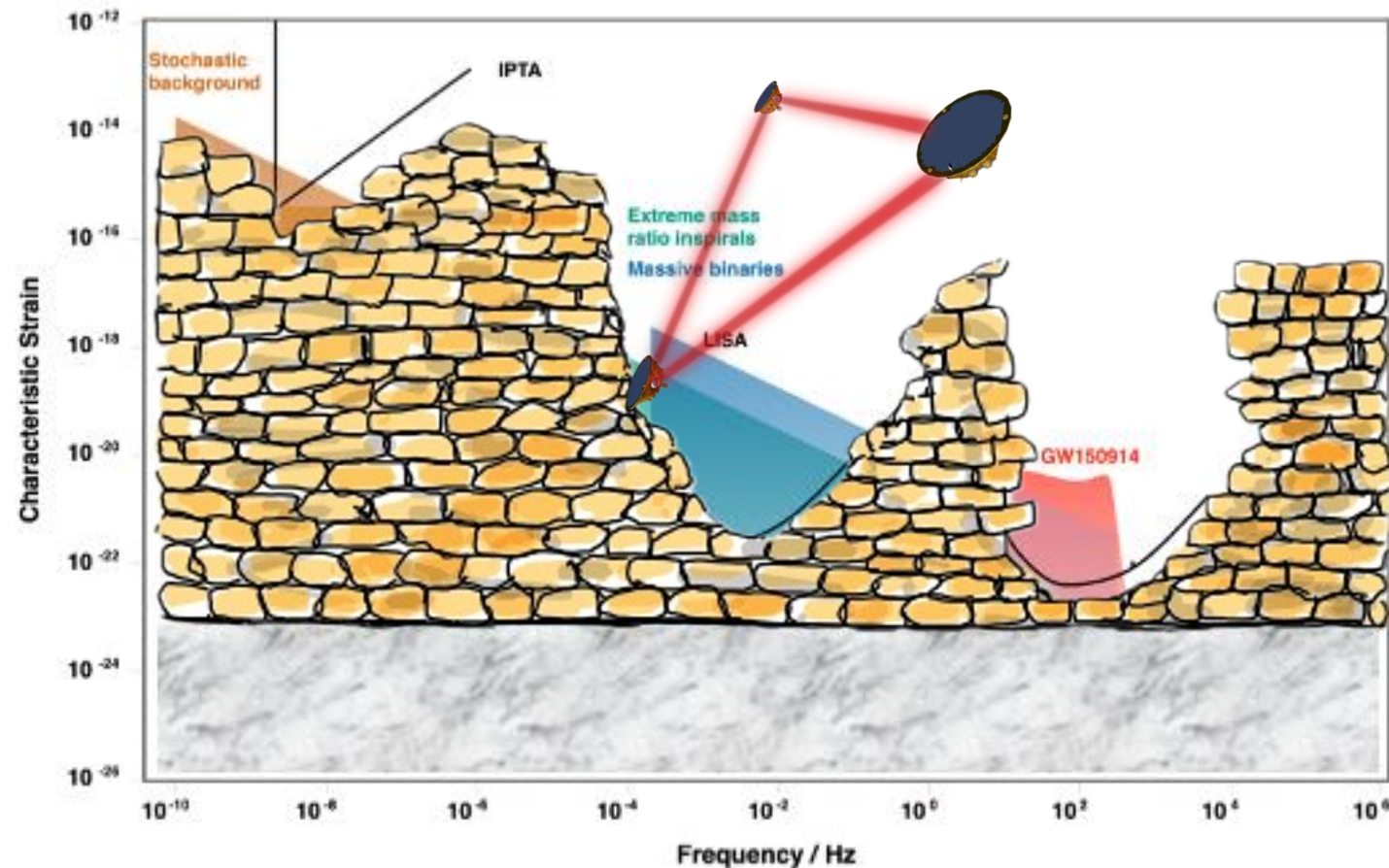
GW space 2050

- Established in 2023, sponsored by the Gravitational Wave International Committee (GWIC), ~60 active members worldwide, organized into a Science Group and an Instrument Design Group.
- Developing the science cases and assessing the technological feasibility of three candidate mission concepts.
- Enabling groundwork now in place:
 - LISA data-analysis tools extended to the micro-Hz and deci-Hz
 - Bayesian and Fisher projections;
 - high-redshift population catalogs (COSMIC, B-POP, Population III models at $z \geq 10$)
 - realistic noise curves beyond earlier strawperson concepts
- White Paper expected in late 2026.

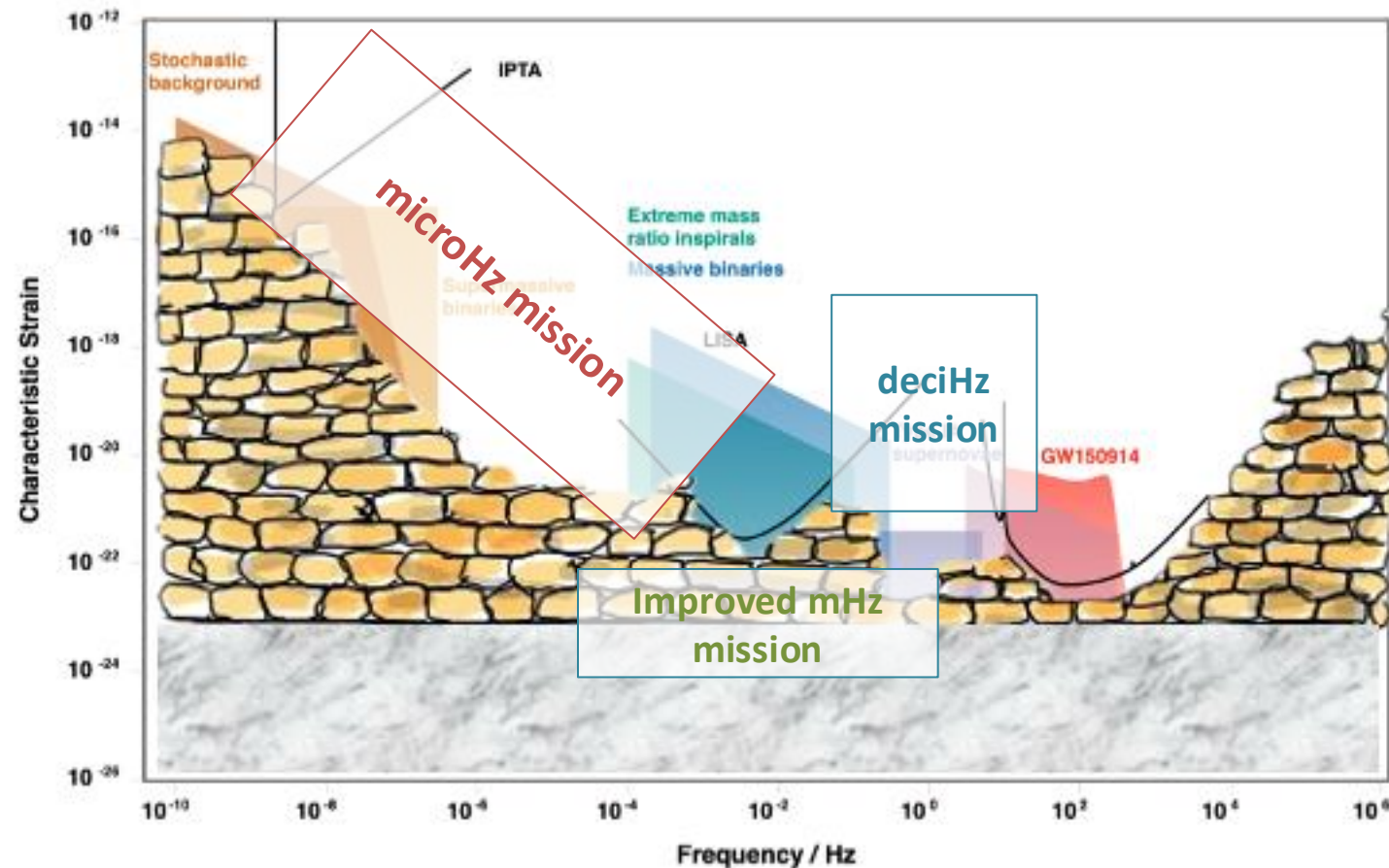
Goal: *we want to break this walls!*



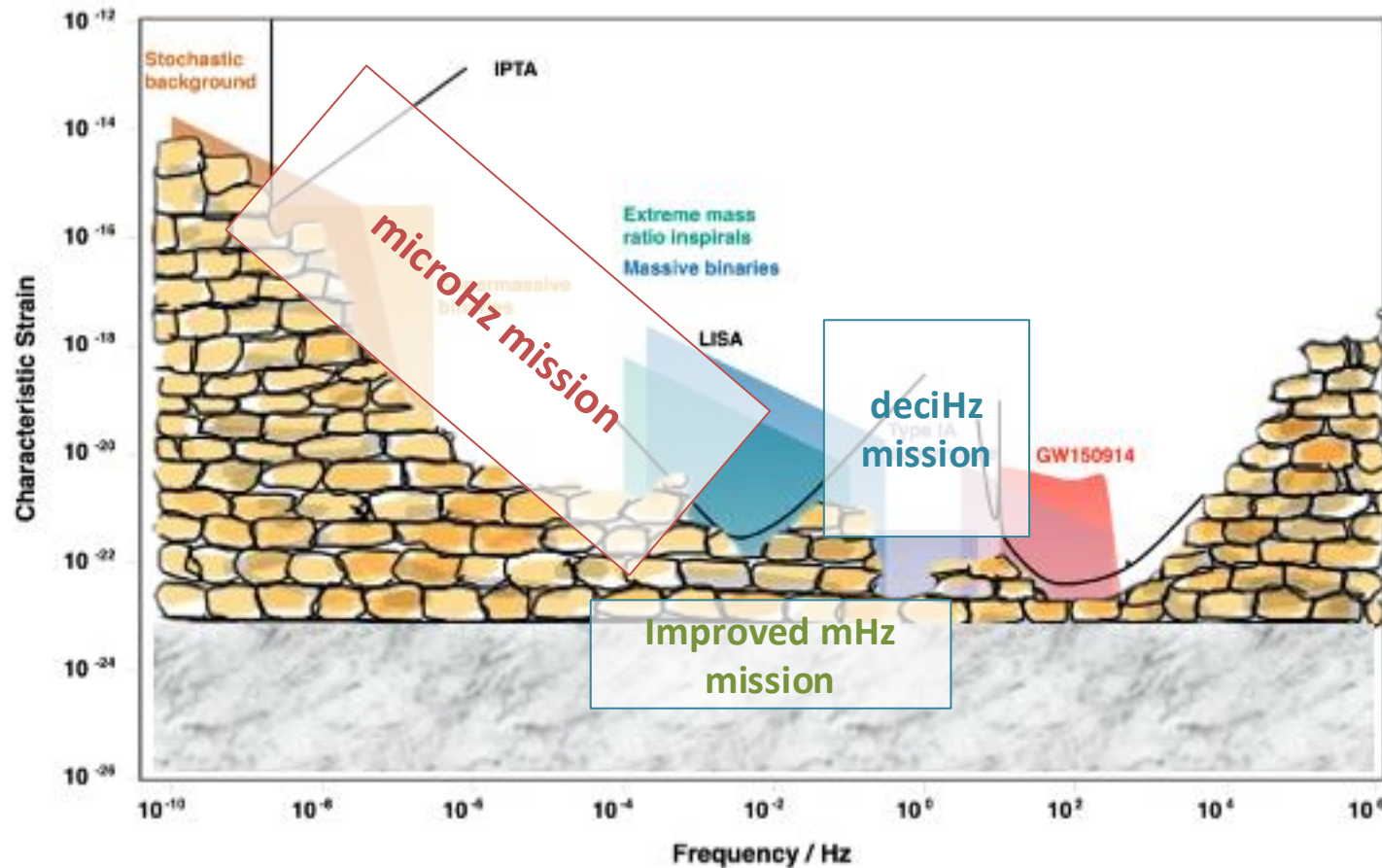
... and we have already a few ideas in the mHz



... but we want to look behind the entire wall!

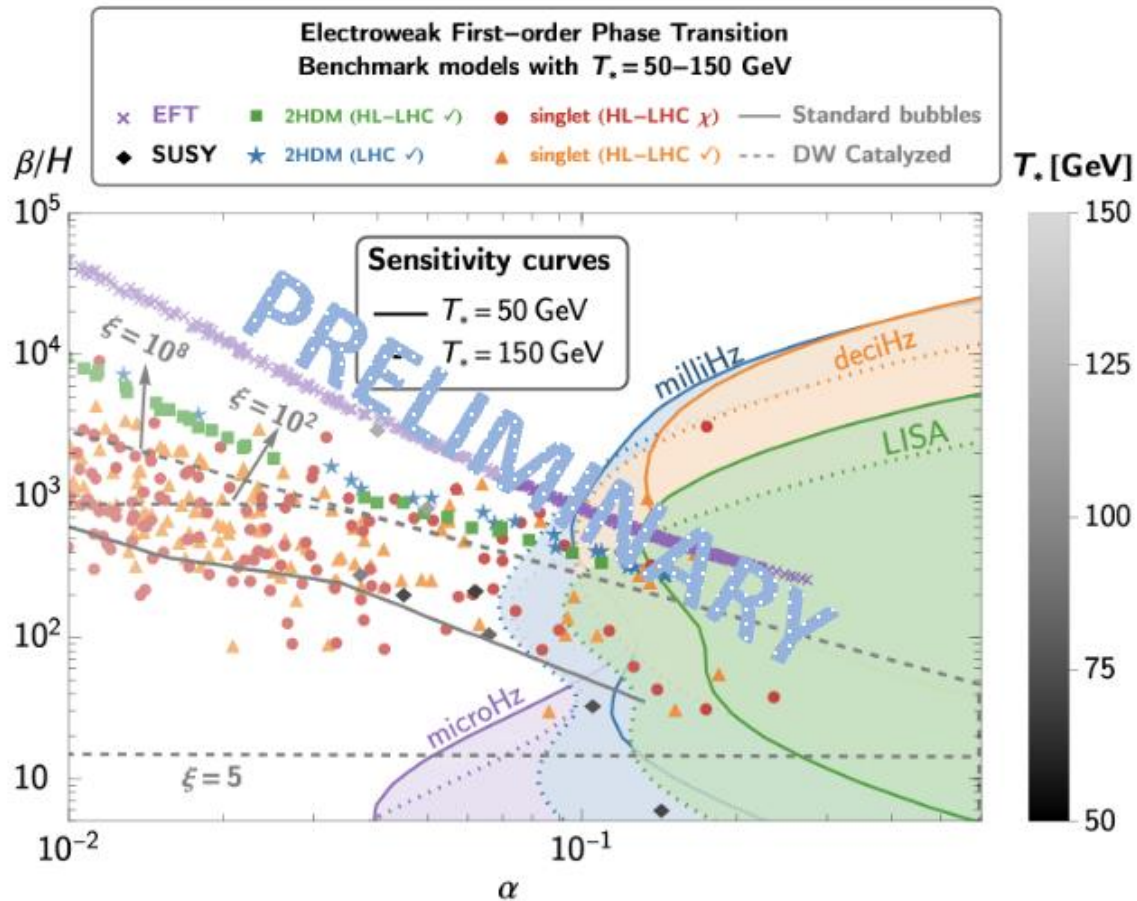


Why breaking the wall?



- Detect primordial stochastic GW backgrounds from the early Universe.
- Probe the expansion rate of the Universe at high redshift ($z > 8$).
- Probe the nature of dark matter.
- How and when did the first MBHs form and grow?
- Trace high- z IMBH formation and stellar-origin binaries

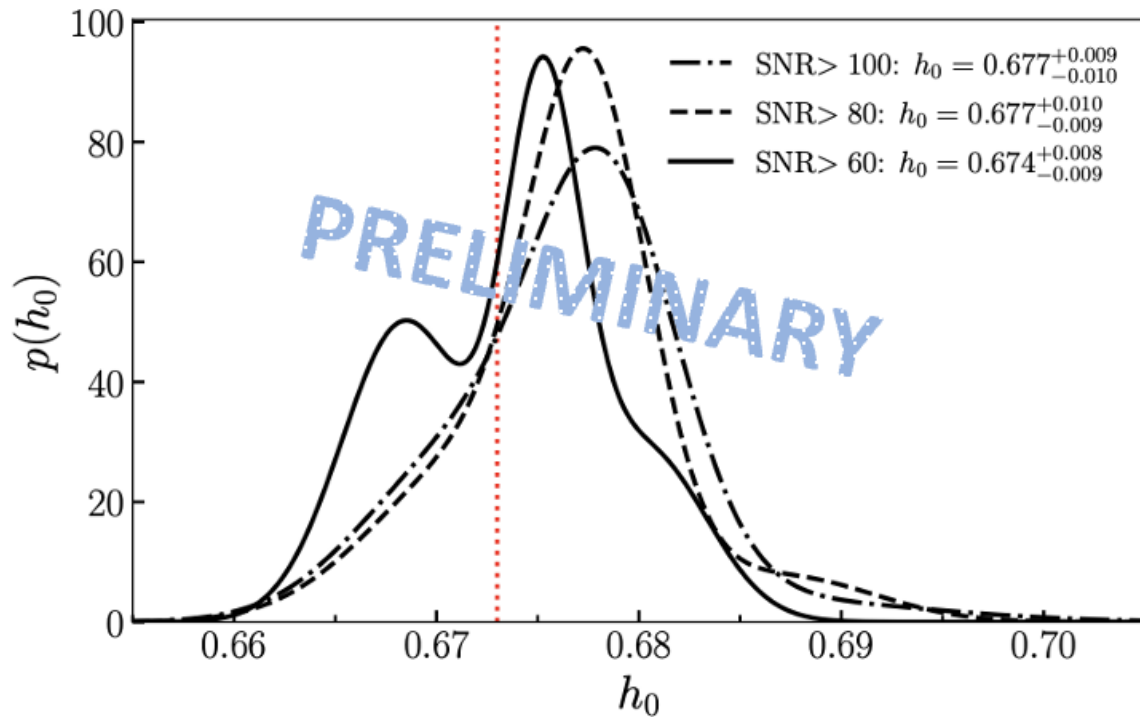
Why breaking the wall?



Credit: GW Space 2050 Working Group

- Detect primordial stochastic GW backgrounds from the early Universe.
 - maps the possible first-order electroweak phase transitions that may have occurred in the early Universe. Each point represents a theoretical prediction, while the coloured regions indicate which predictions could be tested by different gravitational-wave observatories.

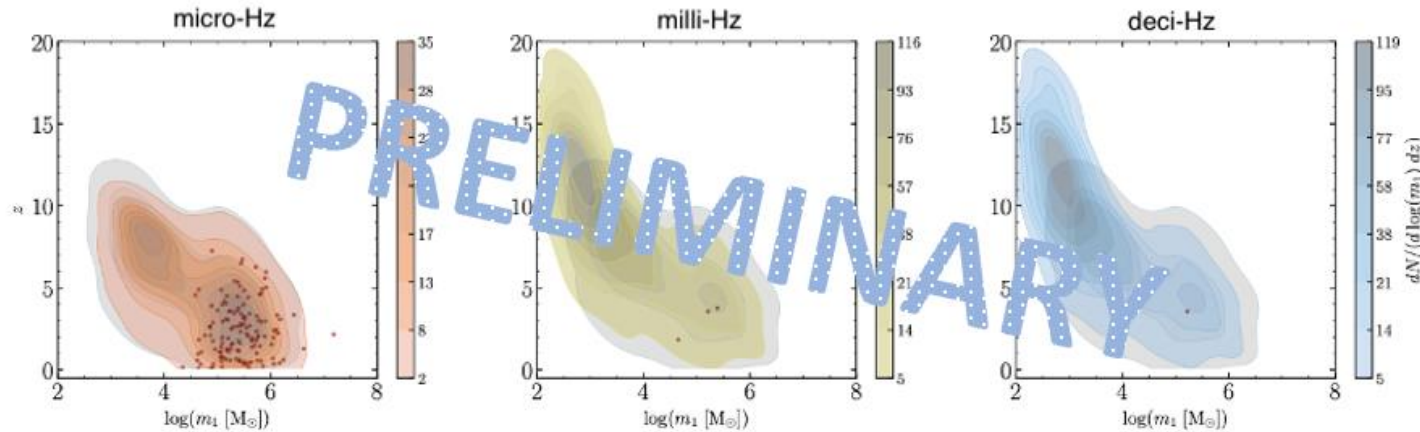
Why breaking the wall?



Credit: GW Space 2050 Working Group

- Probe the expansion rate of the Universe at high redshift ($z > 8$).
 - this is the measurement of the Hubble parameter using BBHs as dark sirens with deci-Hz, notice the tiny measurement error

Why breaking the wall?



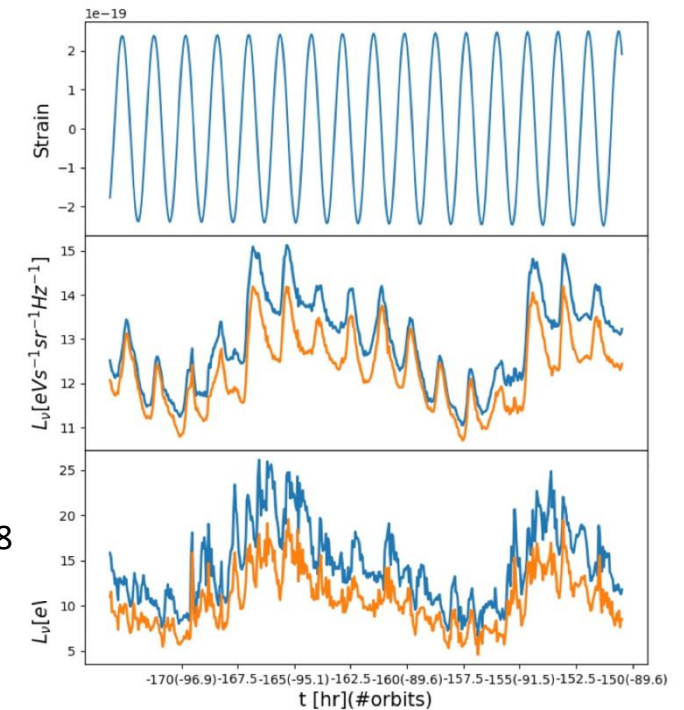
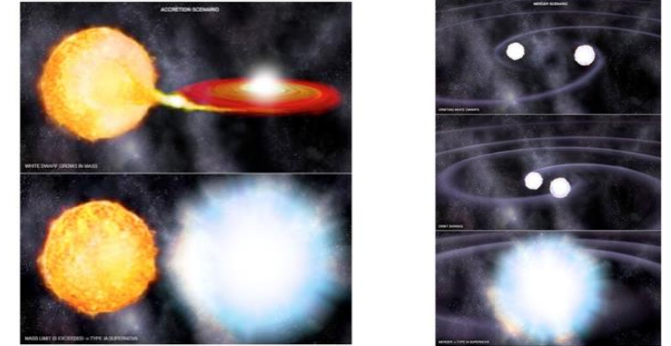
Credit: GW Space 2050 Working Group

- How and when did the first MBHs form and grow?
 - the red points are MBH that do not merge i.e., we only see the inspiral, when BHs may have still accretion disk around, so EM counterparts may be observed, as well

Permitting Unique Synergies with EM Observations

- A **deci-Hz detector** can localize BNS and NSBH to arcminute scales, enabling bright-standard-siren follow-up.
- **Rubin, Roman and SKA** can be positioned to observe a binary merger days—or even years—beforehand.
- WD binaries with EM counterparts test the origin of **Type Ia supernovae**: a GW detection would favor the double-WD channel. [*deci-Hz*]
- For 10^7 – 10^8 $M_\odot$ MBHs in AGNs, combine inspiral signals with UV/X-ray emission to track disk evolution and accretion. [*μ -Hz, m-Hz*]
- Observe IMRIs/EMRIs in AGNs—not only quiescent nuclei as with LISA—and combine them with X-ray observations. [*μ -Hz, m-Hz, deci-Hz*]

$$\Delta\theta \sim \frac{\lambda_{\text{GW}}}{D \text{ SNR}}$$



Science Table (1 / 2)

Science Objectives	Physical Parameters	Observables	Potential Challenges
Reveal the birth and growth of massive black holes; characterize MBH binaries and seed BHs across cosmic time.	Masses, redshifts/distances and spins; <10% intrinsic masses, ~10% distance/redshift at $z > 10$, spin <0.1. EM: accretion rate, luminosity and radiative efficiency.	Micro-/milli-Hz waveforms yield redshifted masses, luminosity distance and spin vectors. EM accretion signatures and orbital evolution add context.	Low-mass high- z BHs are extremely faint; $z \sim 20$ seed/growth space is beyond current facilities. Low SNR, inference and overlapping sources require beyond-LISA capability.
Trace high-z IMBH formation and stellar-origin binaries; complete a Galactic census of WDs, NSs and BHs.	Masses, distances, spins, eccentricities, redshifts and Doppler shifts; EM accretion, radiation and jet efficiencies.	Deci-Hz resolved sources and populations; EM accretion- and jet-powered signatures from IMBHs.	IMBH binaries require 0.01–1 Hz sensitivity—uncovered by any current or planned detector.
Detect the primordial stochastic GW background from the early Universe.	Phase-transition temperature, defect parameters, BSM mass scales, cosmic equation of state and inflationary features/energy scale.	All bands: $\Omega_{\text{GW}} h^2$ spectrum; multi-messenger data help reconstruct compact-binary populations and subtract foregrounds.	Requires on-board noise monitoring and separation of irreducible astrophysical foregrounds.

Science Table (2 / 2)

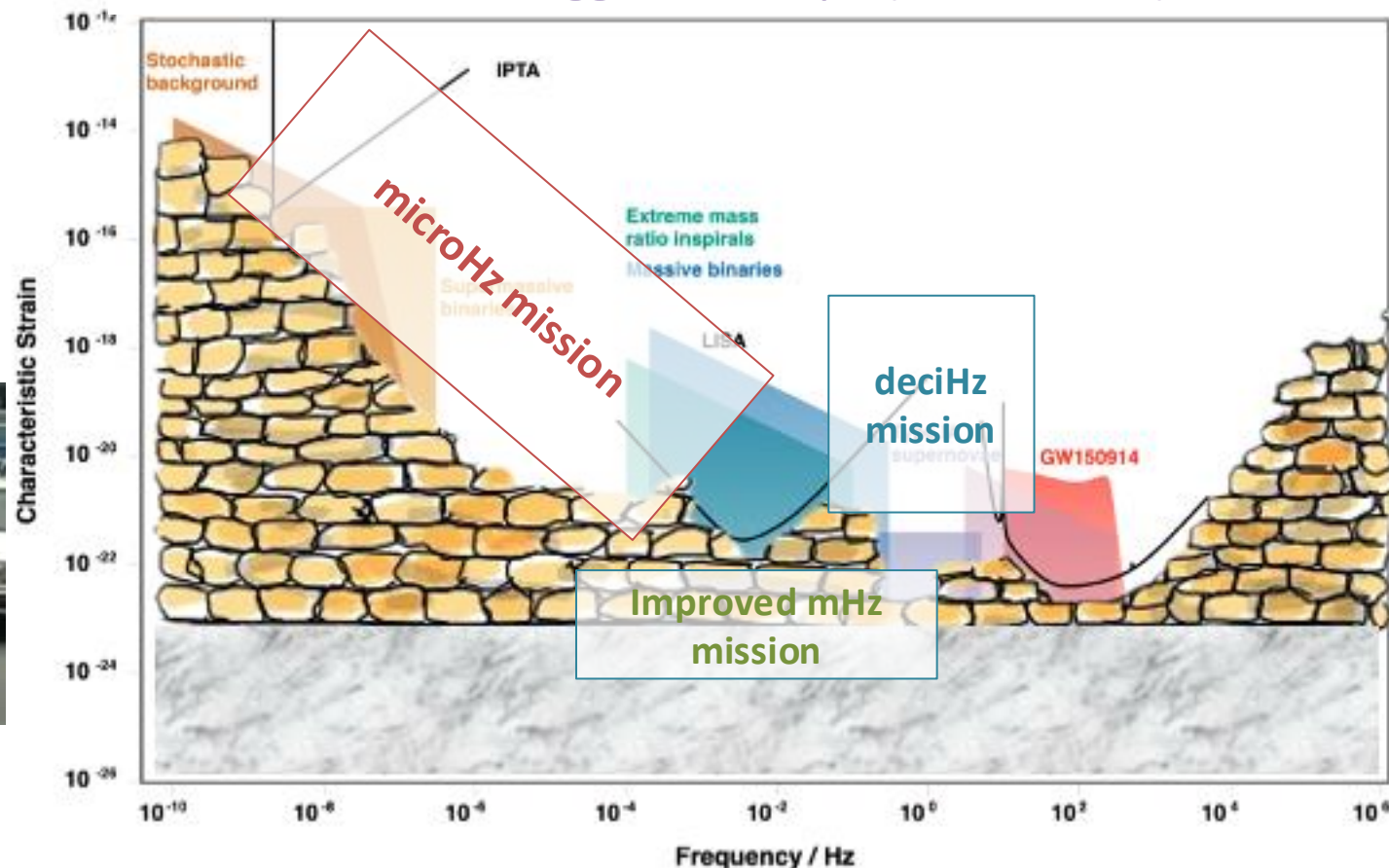
Science Objectives	Physical Parameters	Observables	Potential Challenges
Probe the expansion rate of the Universe at high redshift ($z > 8$).	The Hubble parameter $H(z)$ at $z > 8$.	All bands: GW luminosity distance plus EM redshift for MBH-merger counterparts.	Charts a poorly measured era, complementary to early- and late-time probes. LISA localization is inadequate for many systems at $z > 8$.
Probe the nature of dark matter.	Abundance, mass and morphology of compact dark-matter lenses.	All bands: wave-optics lensing effects in signals from distant GW sources.	Requires access to high-redshift halos beyond the reach of LIGO–Virgo–KAGRA sources.

What is needed to break the deciHz and μ Hz walls?

A common issue is having enough light to keep shot noise under control and be able to do IFO

- more powerful laser (20-40 W)
- bigger telescope (about 0.5 m)

- Improve free fall quality (better force noise)
- Go BIG!



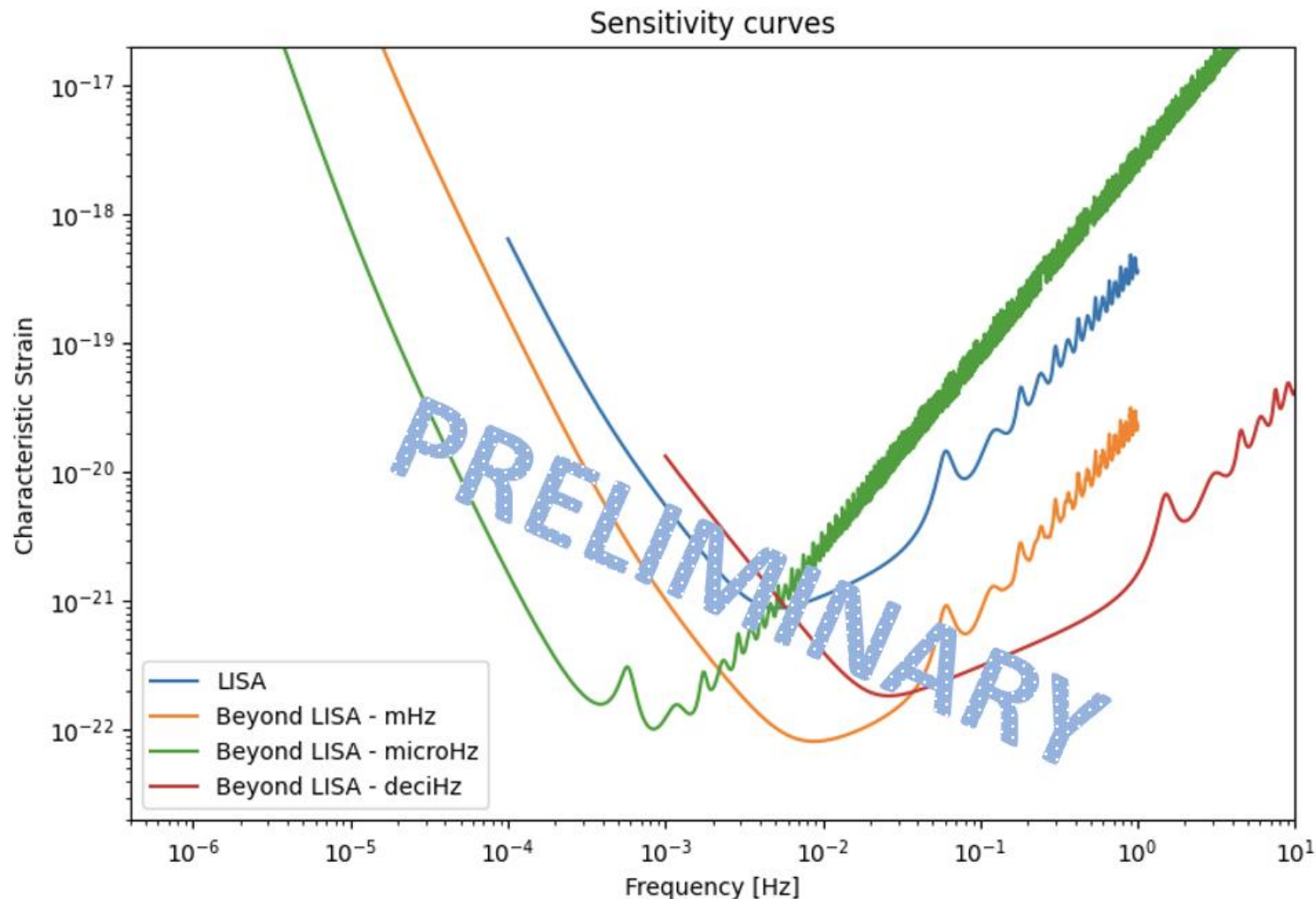
- Smaller constellation
- Push at limits the Optical Metrology System (OMS)

Beyond LISA

mission design and main noise assumptions

	LISA	beyond LISA mHz	beyond LISA deci-Hz	beyond LISA μ Hz
Arm length ($L/10^9$ m)	2.5	2.5	0.1	259
Orbits	Eliocentric Cartwheel	Eliocentric Cartwheel	Eliocentric Cartwheel	Sun-Earth L3, L4, L5
Optical Bench (OB) design	two moving OB per SC	single rigid OB	single rigid OB	single rigid OB
Pointing mechanism	MOSA	In-field pointing	In-field pointing	In-field pointing
Laser power (P/W)	2	20	20	20
Telescope diameter (D/m)	0.3	0.5	0.5	0.5
Laser wavelength (λ/nm)	1064	532	532	532
Phase noise (pm/ $\sqrt{Hz}$)	2.5	0.05	0.025	2.5
TM IFO noise (pm/ $\sqrt{Hz}$)	5	0.012	0.012	5
	(x, ϕ, η IFOs)	(all axes IFOs)	(all axes IFOs)	(all axes IFOs)
TDI noise (pm/ $\sqrt{Hz}$)	3	0.2	0.003	3
Acceleration noise (fm/ $s^2/\sqrt{Hz}$)	3	3×10^{-1} (over the full band)	3×10^{-1} (above 1 mHz)	3×10^{-1} (over the full band)

An overview of the set of sensitivity curves



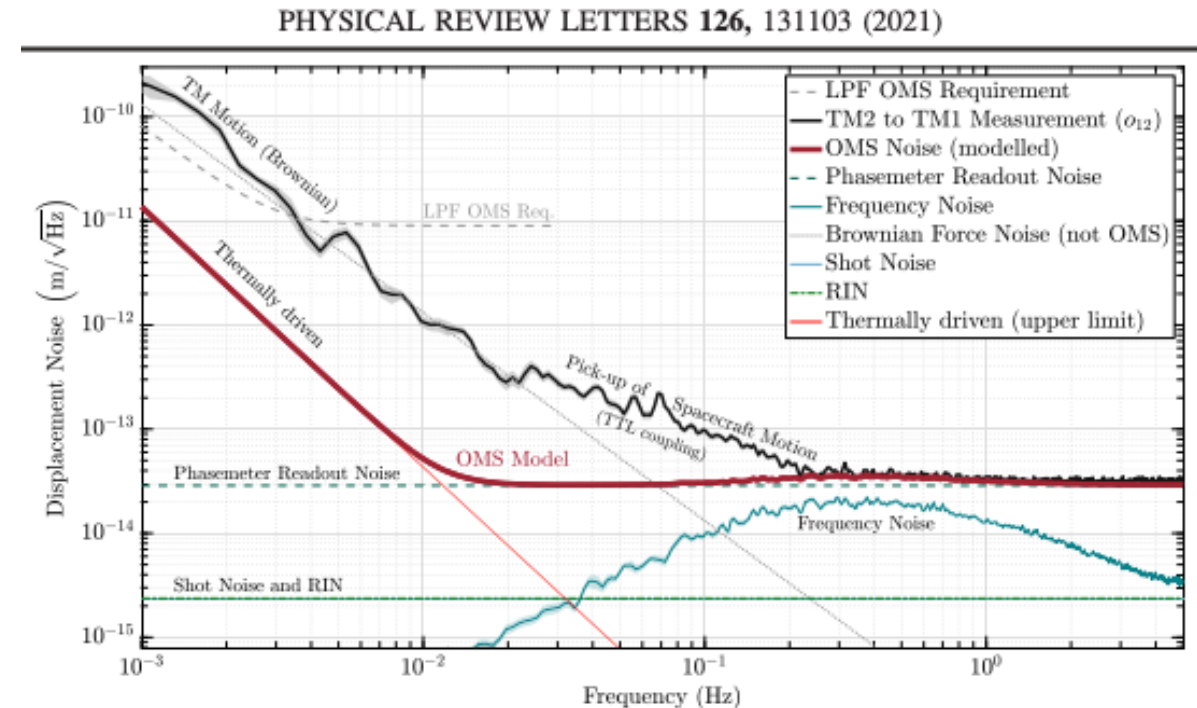
- LISA (2.5 Mkm)
- deciHz (0.1 Mkm)
 - OMS noise: LISA OMS noise breakdown with 20 W laser power, 0.5m telescope, 532 nm wavelength
 - Phasemeter noise assumed to about 20 fm/rtHz @0.1Hz
 - Acc noise: one order of magnitude better Brownian noise
- microHz (260 Mkm)
 - OMS noise: LISA OMS noise breakdown with 20 W laser power, 0.5m telescope, 532 nm wavelength
 - Not limited by phasemeter noise, here
 - Acc noise: LISA Acc noise breakdown (CBE) including TM-MOSA/SC coupling plus
 - 2x heavier TMs
 - 10x better Brownian noise (already including the mass increase improvement)
 - Active Temperature Control
 - No direct actuation noise from torque
- mHz (2.5 Mkm)
 - Same noise assumptions of deciHz and microHz mission

Long arm - noises that do not change “obviously” with input/receiving power...

- **Phasemeter noise:** more laser power (10-20 W) and stable orbits (~ 0.2 m/s) can help improving
 - But only in reducing the amount for amplification gain needed (lower electronic noise)
 - Experts agree that a reachable level of noise is 0.1 pm/rootHz
 - Being bold, ask for 0.05 pm/rootHz but that would require things that do not exist now

TM and REF IFO

- **TM IFO:** LPF proved 35 fm/rootHz, limited by phasemeter noise
 - LISA has a new more complex OB design wrt LPF
 - For beyond LISA
 - Cavity tracking readouts can help improving a bit on this
 - Digital interferometry can help reducing straylight in TM IFO
 - We would need **Full axes IFO for calibration**
- **REF IFO** noise could be neglected if single rigid OB (and in-field pointing)
 - But, in any case, we know how to reduce substantially the backlink non reciprocity (e.g., using more laser frequencies).



Acceleration noise

- One order of magnitude improvement of **Brownian noise** with respect to LPF performance seems feasible
 - It likely will require “monolithic GRS design”=> plastics out the vacuum chamber as much as possible
 - With this assumed level, below 40 mHz force noise starts to become the driving noise
- Also needed is a higher bandwidth for **SC controller** to avoid cross-stiffness at high frequencies, etc...

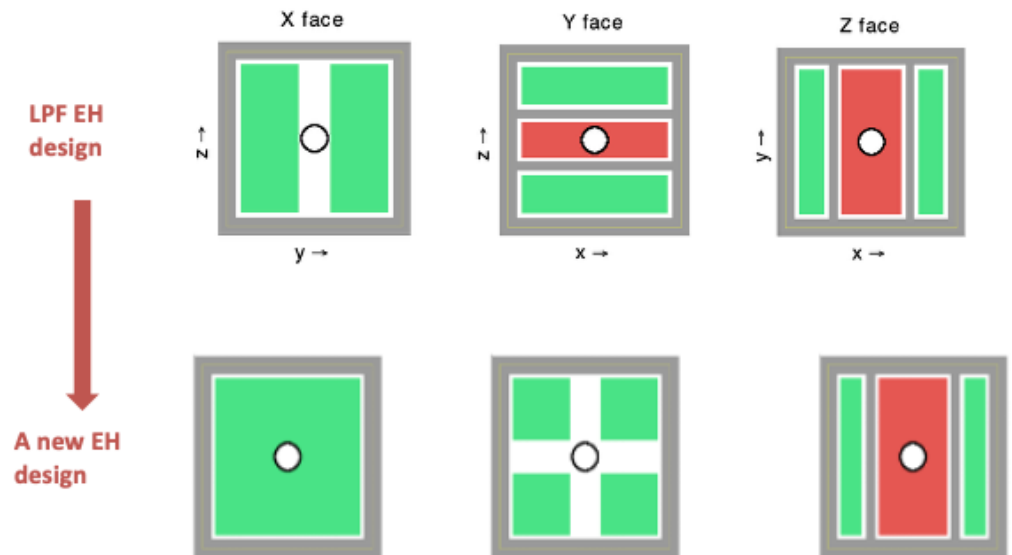
μ Hz design sensitivity improvements wrt LISAmass

The μ Hz LISA-like mission sensitivity depends mostly on force noise performances. In order to improve those, we will consider

- Heavier (4 kg) and larger (58 mm edge) TM mass
 - Factor 2 on any force noise
 - Together with larger gaps, “monolithic” GRS -> better Brownian noise
- Different actuation scheme to avoid direct actuation noise
- Thermal stability active control (TBC)
 - Needed stability of the order of 10 mK/rootHz@
 - Phasemeter low frequency noise
 - Frequency Distribution System
 - Straylight
 - ...

“High frequency” noise impact

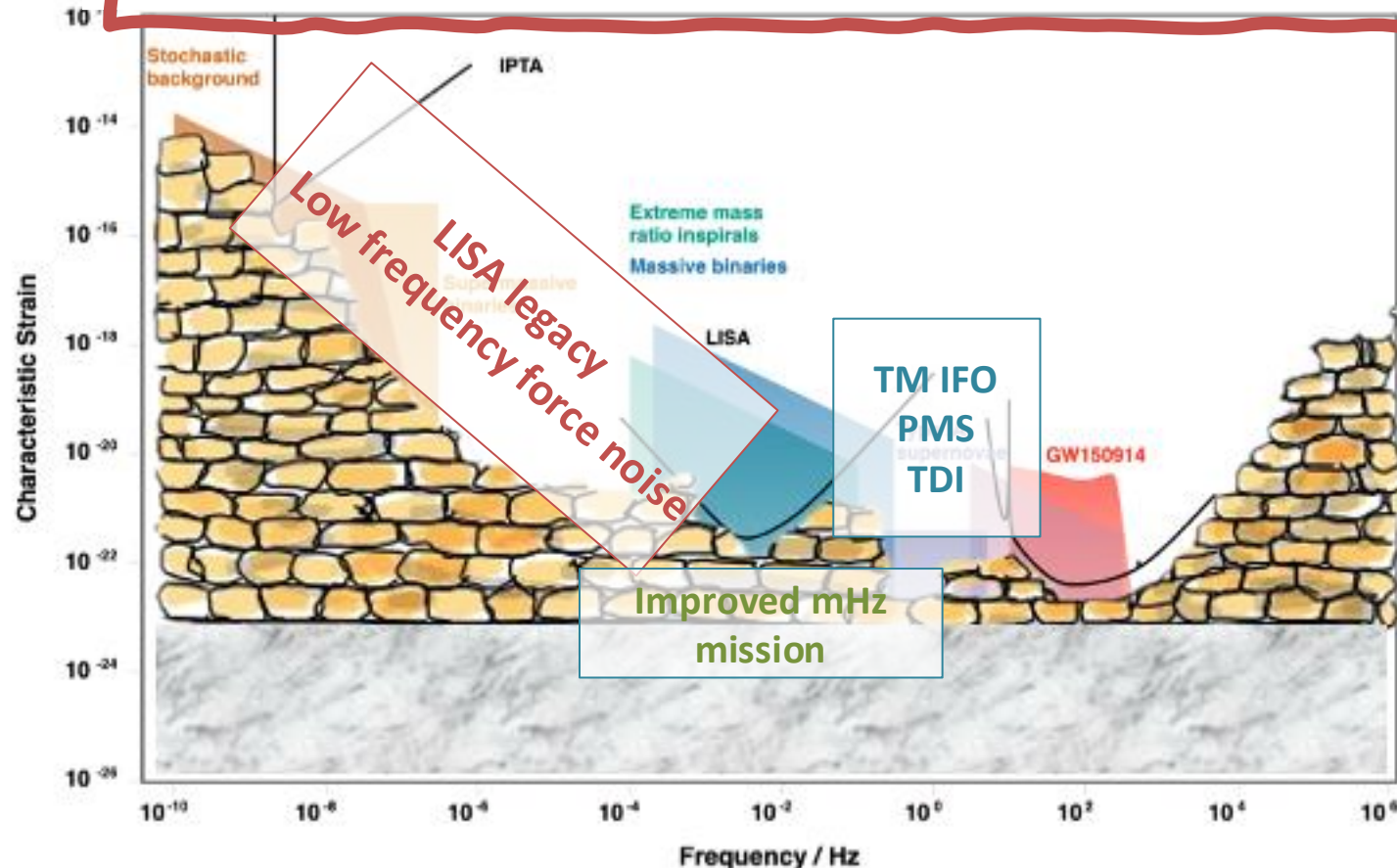
- OMS noise budget must be refined but no big iss
- Postprocessing residual noise under study



What is needed to break the deciHz and μ Hz walls?

Several R&D are common improvements
more powerful laser (20-40 W), bigger telescope (about 0.5 m),
all DoF interferometry, better performing GRS, 532 nm laser,
single OB and in-field pointing

- 259 Gm (L3, L4, L5)
- “QUIET” SC&ENVIR. (THERMAL STABILITY, ETC..)
- REDUCE/CONTROL VERY LOW FREQ NOISE + UNKNOWN
- LISA & LPF LEGACY
- ...



- 0.1 Gm cartwheel
- PMS @ fm/rootHz
- SINGLE OB
- ALL DOF TM IFO NOISE BETTER THAN LPF
- MONOLITHIC GRS
- ...

Strategic context

- 2014 NASA Astrophysics Roadmap (Enduring Quests, Daring Visions): space-based GW astronomy and black holes across cosmic time identified as a pivotal goal.
- Astro2020 Decadal Survey (Pathways to Discovery): endorsed “New Messengers and New Physics”, recognizing GWs as a transformational probe of the early Universe and of BH formation.
- ESA Voyage 2050 Senior Committee (2021): selected “New Physical Probes of the Early Universe” as a Large-mission theme, recommending a mission “deploying GW detectors ... to explore the early Universe at large redshifts”.
- Voyage 2050 noted that opening “a totally new spectral window for GW astronomy, either in the deci-Hz or micro-Hz” band would illuminate “the origin and growth of cosmic structures”.
- GW-Space 2050 provides quantitative input to NASA’s ASTRA program and ESA’s upcoming Expert Committee for the third Voyage 2050 Large-mission theme.

Why Ad ASTRA

- LISA is entering implementation and will deliver the first milli-Hz measurements — but no facility covers the micro-Hz or deci-Hz bands, and ground-based detectors will not reach below ~ 1 Hz.
- The enabling groundwork is now available within GW-Space 2050: LISA data-analysis tools extended to the micro-Hz and deci-Hz bands; Bayesian and Fisher projections; high-redshift population catalogs; “realistic” noise curves.
- Main cost-saving strategy: keep early development common across the three architectures; reuse the LISA measurement paradigm and ground-segment concepts; defer the final down-select until shared breadboards and mission trades are mature; preserve fallback paths (1064 nm operation, MOSA-like pointing) only where they reduce risk without compromising science.
- GW-Space 2050 is organized worldwide to provide quantitative scientific and technological input to NASA’s ASTRA program and ESA’s Expert Committee for the third Voyage 2050 Large-mission theme.

Per aspera, Ad ASTRA

- The science case is certainly huge and groundbreaking, supported by the community, and require missions that would cost likely > than 1B\$
- Multiple constellations could scale up the potential for breakthrough of such missions
- There is a lot of common R&D between the three different frequency bands. This is a strong point for a future gravitational wave Large mission!
 - Solidity/credibility of the design
 - but also, flexibility
- GW-space 2050 report expected end of this year