Stochastic gravitational-wave backgrounds with LGWA

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LGWA Meeting 2026 - Liegi, September 30th - 2026

Can the Moon separate a stochastic GW signal from its own seismic noise?

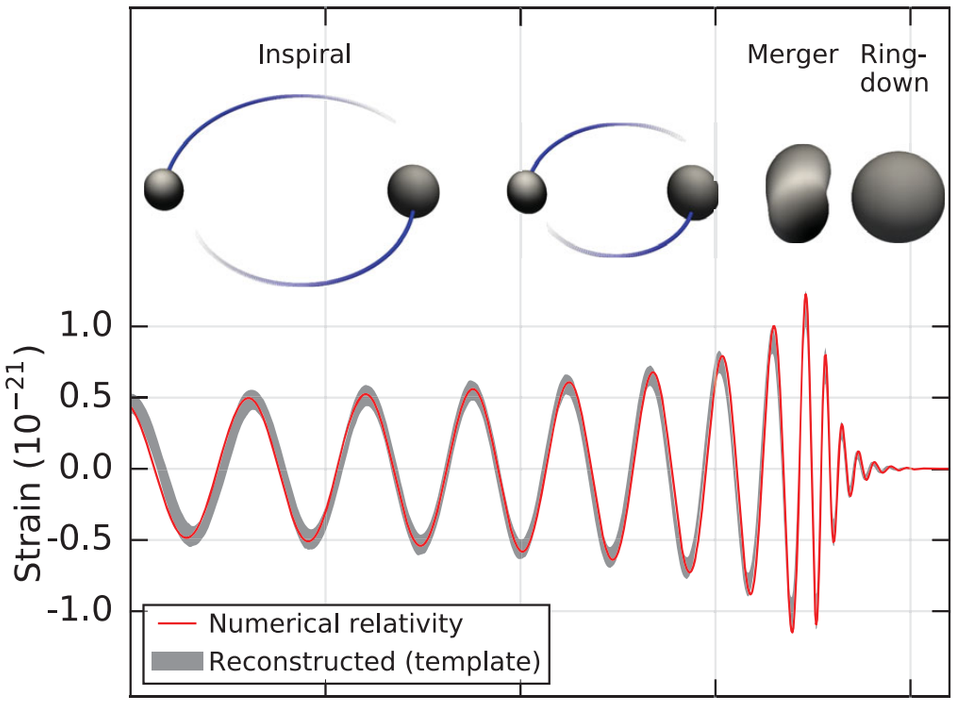
The answer depends on geometry as much as on sensor sensitivity

1. **The Moon as a resonant GW antenna**
2. **Cross-correlation and the antipodal baseline**
3. **Science reach, foregrounds and caveats**

Sources of Gravitational Waves

Resolved Sources:

- Black Holes
- Neutron Stars
- White Dwarfs
- Supernovae
-…

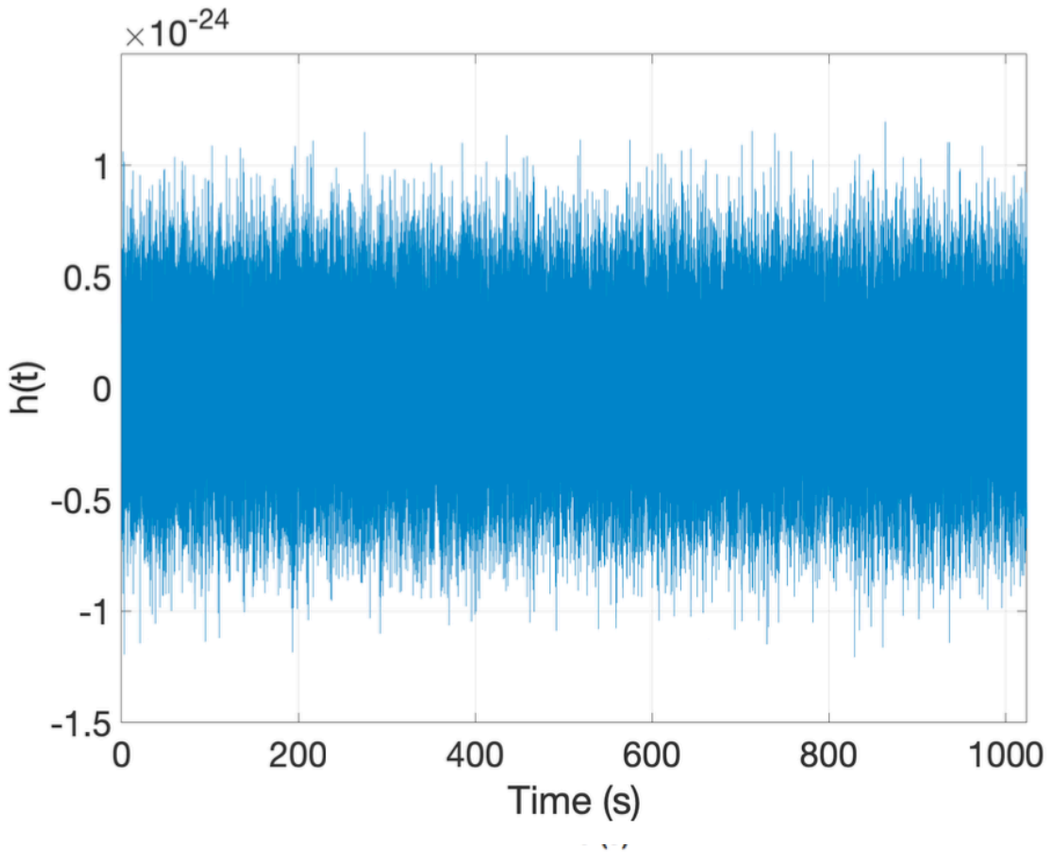


$$h(t) = h_+ F_+ + h_\times F_\times$$

Unresolved Sources:

Stochastic Backgrounds

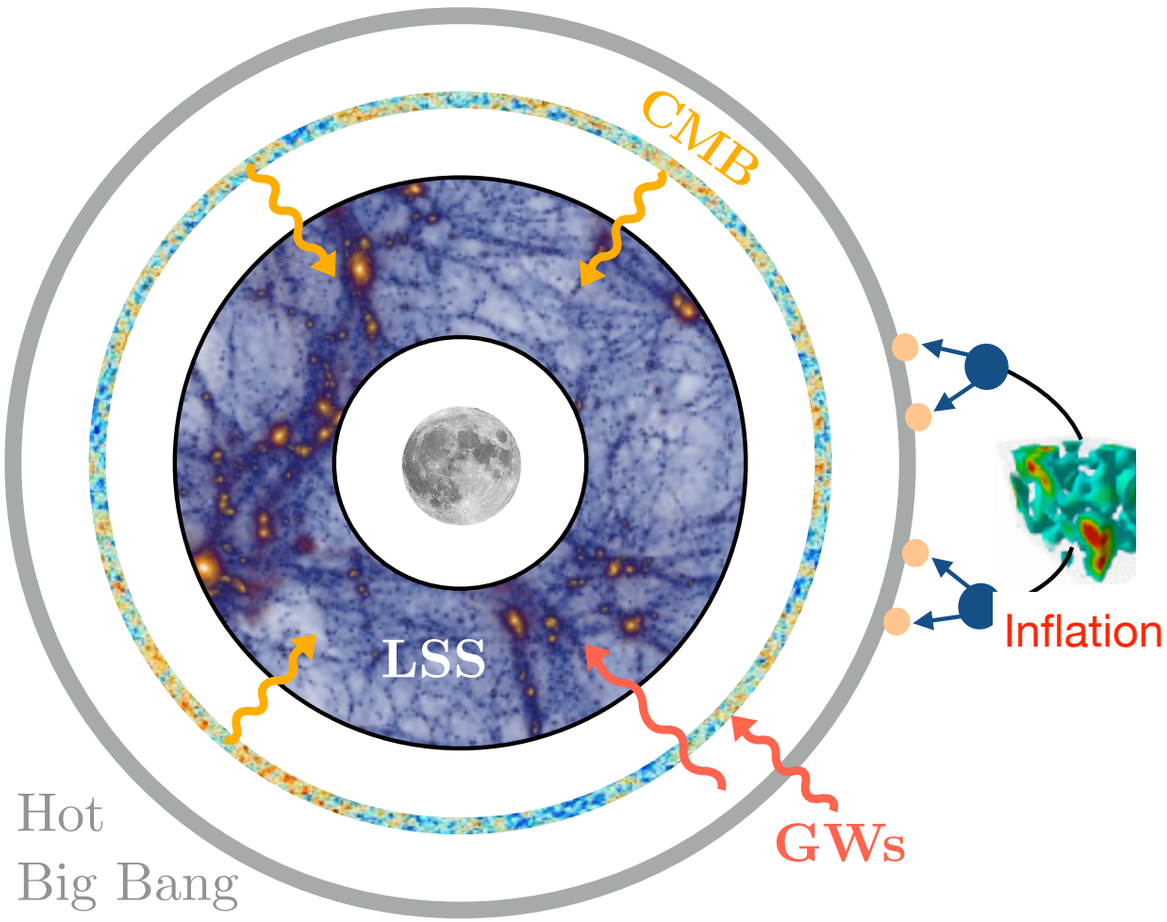
- **Astrophysical**
- **Cosmological**



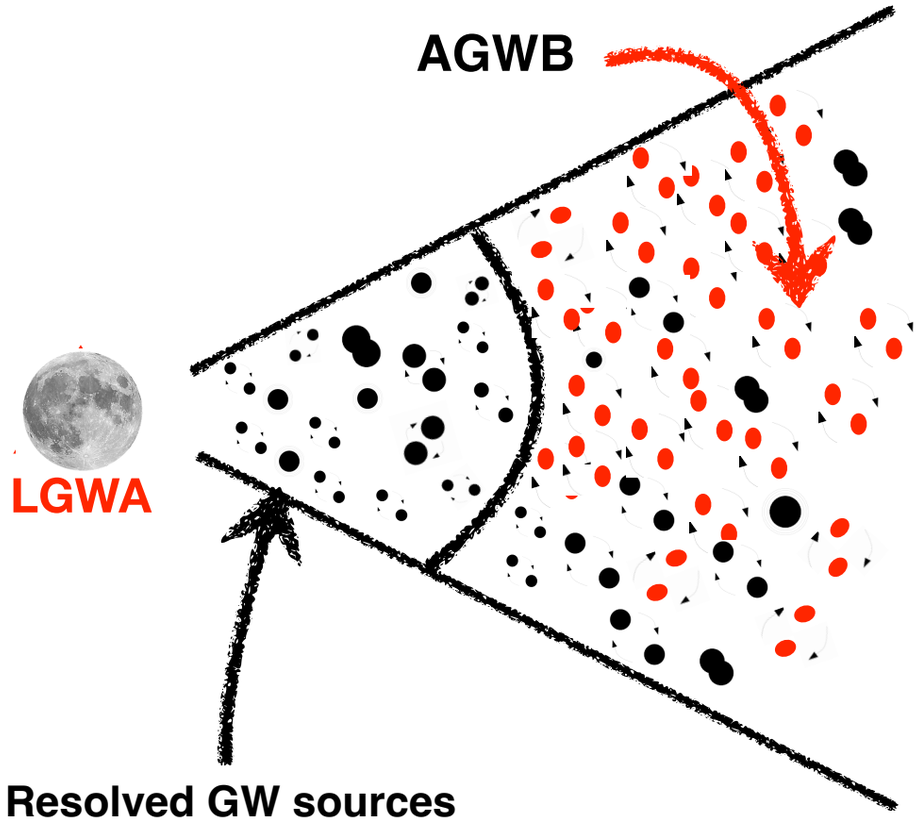
$$\Omega_{\mathrm{GW}}(f) = \frac{1}{\rho_c}\frac{d\rho_{\mathrm{GW}}}{d\ln f}$$

Cosmological VS Astrophysical

COSMOLOGICAL (i.e., quantum)



ASTROPHYSICAL



Stochastic GW Background characterization

Each detector sees

$$\tilde{s}_i(f) = \tilde{h}_i(f) + \tilde{n}_i(f)$$

For current detectors the random noise is larger than the strain in each channel.

noise ≫ strain

$$\tilde{h}(f) = \int d\Omega^2_{\hat{k}} \sum_{\lambda=+,\times} h_\lambda(f,\hat{k})\, F^\lambda(f,\vec{k})\, e^{-i2\pi f\left(\frac{\hat{k}\cdot\vec{x}}{c}\right)}$$

(background is a sky average)

For resolved sources $\langle \tilde{h}_i \rangle \neq 0$

For SGWB $\langle \tilde{h}_i \rangle = 0$

For noise $\langle \tilde{n} \rangle = 0$

→ **A GWB looks random in one detector, just like noise.** → **statistical information encoded in two-point functions.**

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$$\left\langle \tilde{h}_i(f)\tilde{h}_j^*(f')\right\rangle = \frac{1}{2}\delta(f-f')\frac{3H_0^2}{10\pi^2 f^3}\,\Omega_{\rm GW}(f)\gamma_{ij}(f)\,,$$

$\gamma_{ij}(f)$ Overlap reduction function

(i.e., detector geometry: separation + relative orientation + sky average)

Caporali & Ricciardone 2025



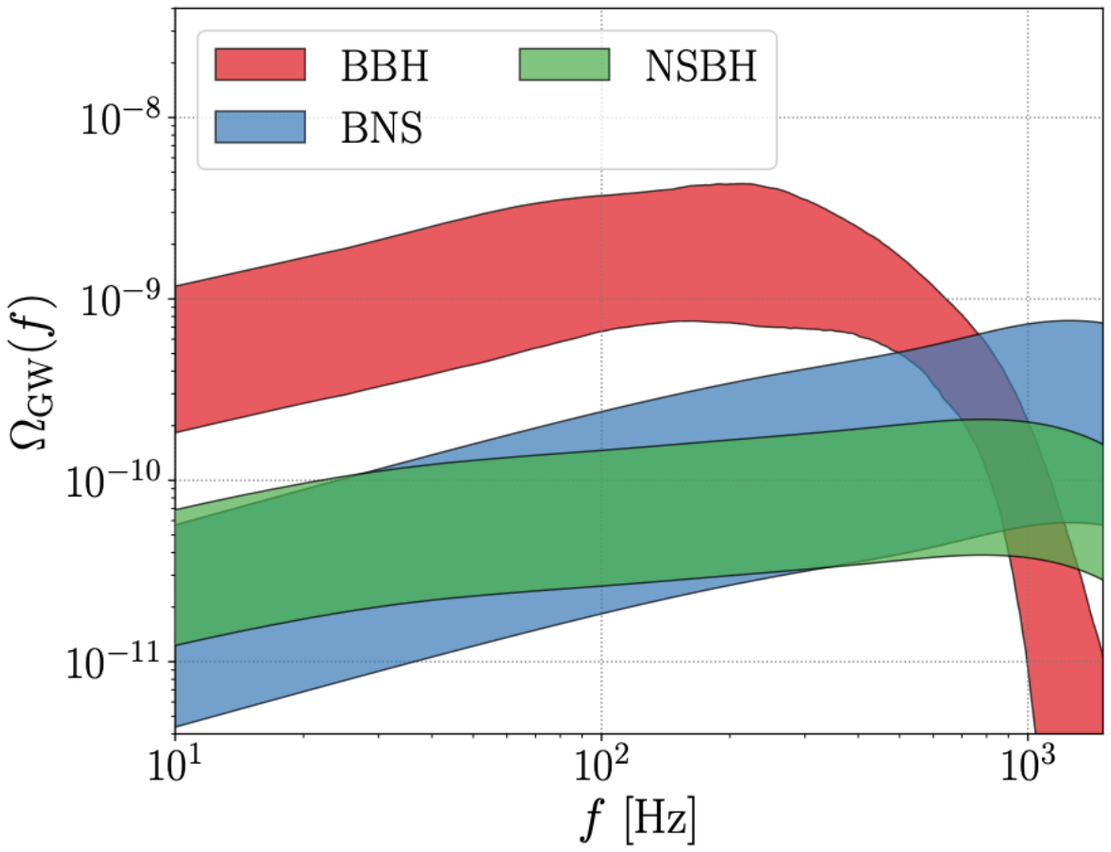
$\Omega_{\rm GW}(f)$ GWB energy density

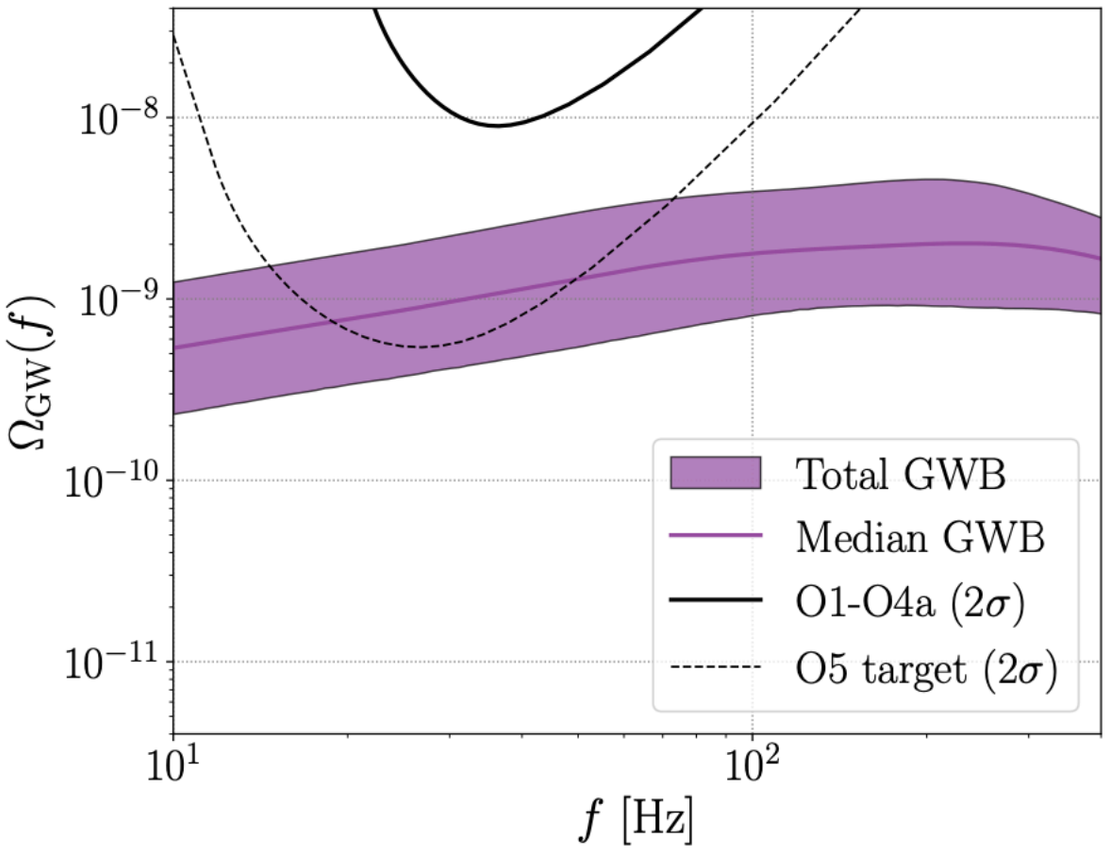
(i.e., model dependent: cosmo or astro origin)

Takeaway: A SGWB is not detected by seeing a waveform! It is detected by measuring a common, geometry-weighted two-point correlation.

Where we are - LVK

Compare combined CBC energy density spectra, and (2σ) power-law integrated curves





$$\Omega_{\rm GW}(f;\theta_k) = \frac{f}{\rho_c H_0}\int_0^{z_{\rm max}} dz \frac{R_m(z;\theta_k)\langle \frac{dE_{\rm GW}}{df_s}(f_s;\theta_k)\rangle}{(1+z)E(\Omega_{\rm m,0},\Omega_{\Lambda,0},z)},$$

$$\frac{dE_{\rm GW}}{df} = \frac{(G\pi)^{2/3}}{3}\frac{m_1 m_2}{(m_1+m_2)^{1/3}} f^{-1/3}$$

$$R_{\rm BBH}(z) = C(\alpha_z,\beta_z,z_{\rm p})\frac{R_0(1+z)^{\alpha_z}}{1+\left(\frac{1+z}{1+z_{\rm p}}\right)^{\alpha_z+\beta_z}}$$

$$\Omega_{\rm BBH+BNS+BHNS}(25{\rm Hz}) = 0.9^{+1.1}_{-0.5}\times 10^{-9}.$$

$$\Omega_{\rm BBH}(25\,{\rm Hz}) = 0.8^{+1.1}_{-0.5}\times 10^{-9}$$

LVK Collaboration, ArXiv:2508.20721

Where we are - Pulsar Timing Array

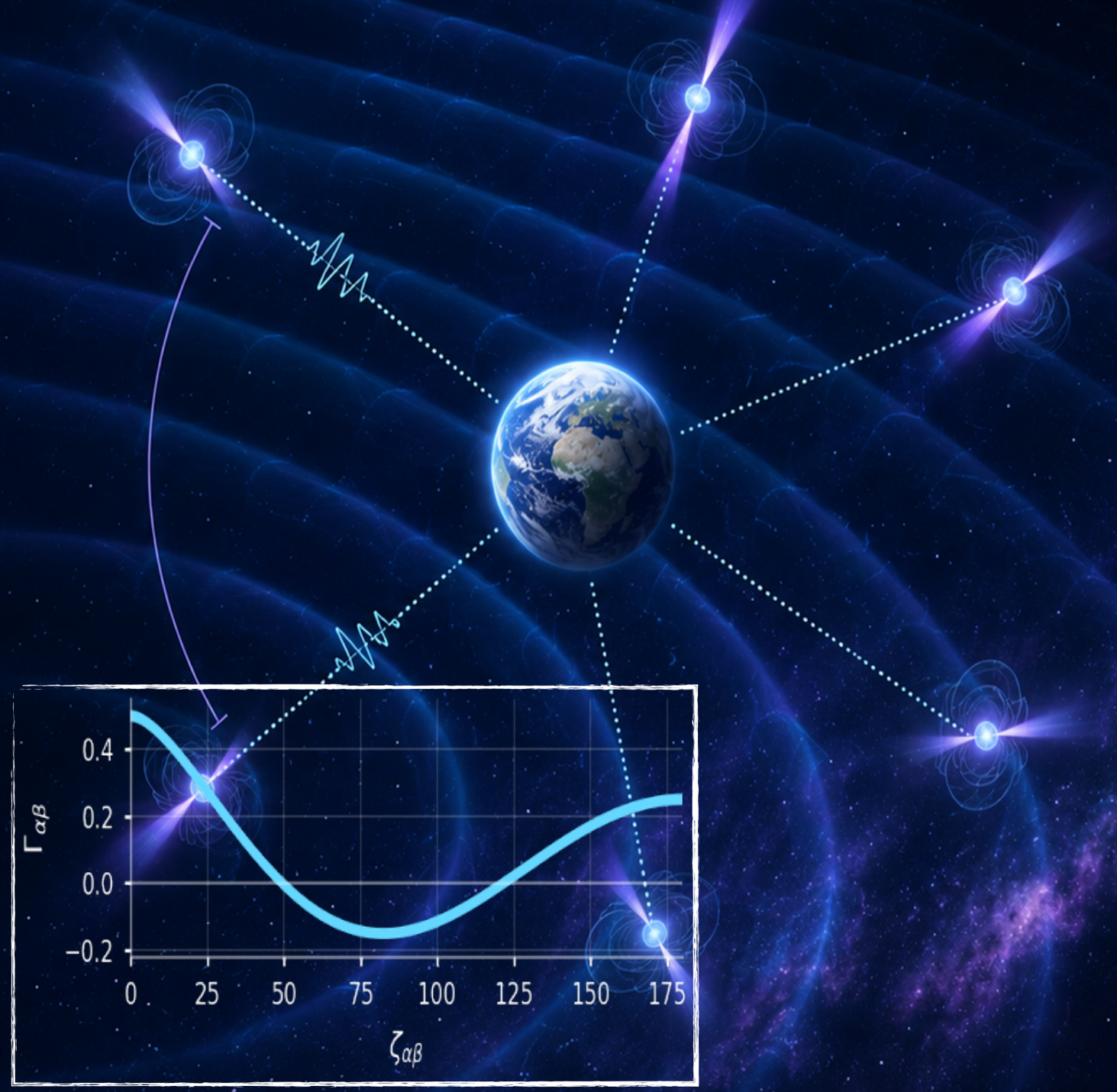
Millisecond pulsars are **Galactic clocks**

A nanohertz SGWB shifts pulse arrival times: δt

OBSERVABLE

timing residual

$\delta t = t_TOA - t_model$



Smoking gun

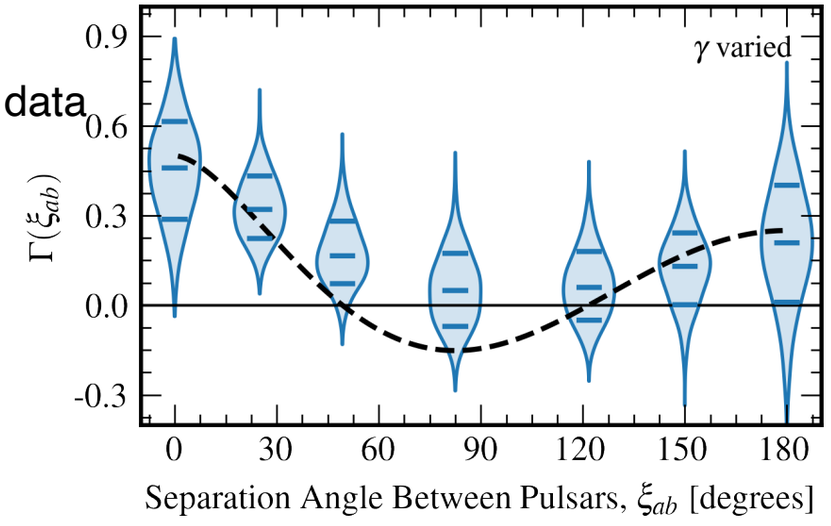
$$\langle \delta t_a \, \delta t_\beta \rangle \propto \Gamma_{a\beta}(\zeta_{a\beta})$$

correlated residuals follow the Hellings–Downs angular curve

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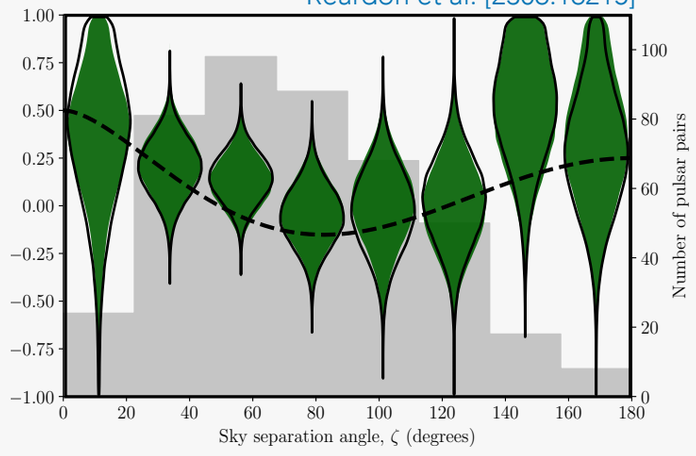
NANOGRav:
68 pulsars, 16 yrs of data
$\sim 3-4\sigma$significance

Agazie et al. [2306.16213]



PPTA:
32 pulsars, 18 yrs of data
$\sim 2\sigma$ significance

Reardon et al. [2306.16215]

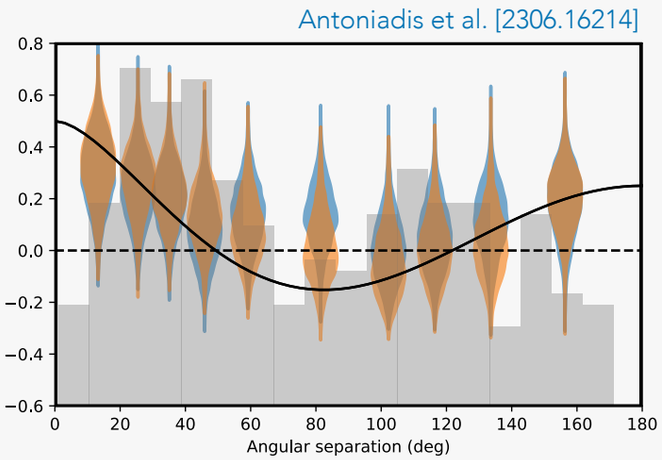


First Claim of Detection of a SGWB

EPTA+InPTA:
25 pulsars, 24 yrs of data

$\sim 3\sigma$ significance

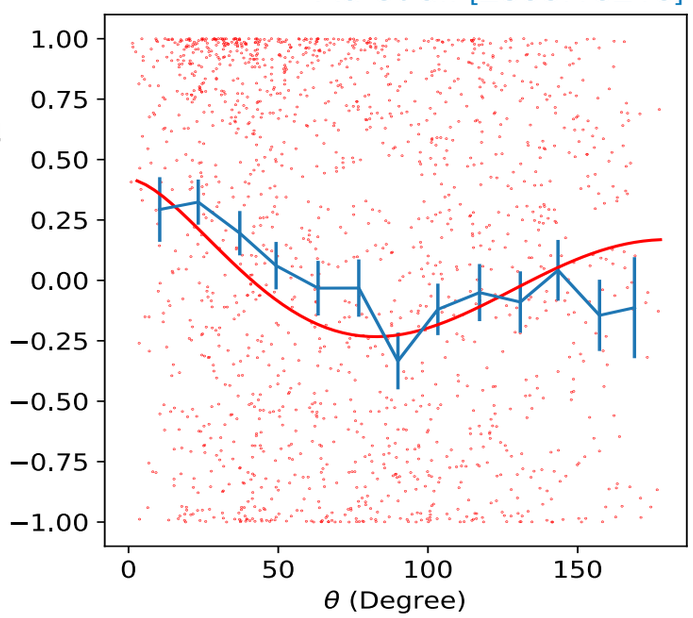
Antoniadis et al. [2306.16214]



CPTA:
57 pulsars, 3 yrs of data

$\sim 4.6\sigma$ significance

Xu et al. [2306.16216]



Bayesian reconstruction of normalized inter-pulsar correlations

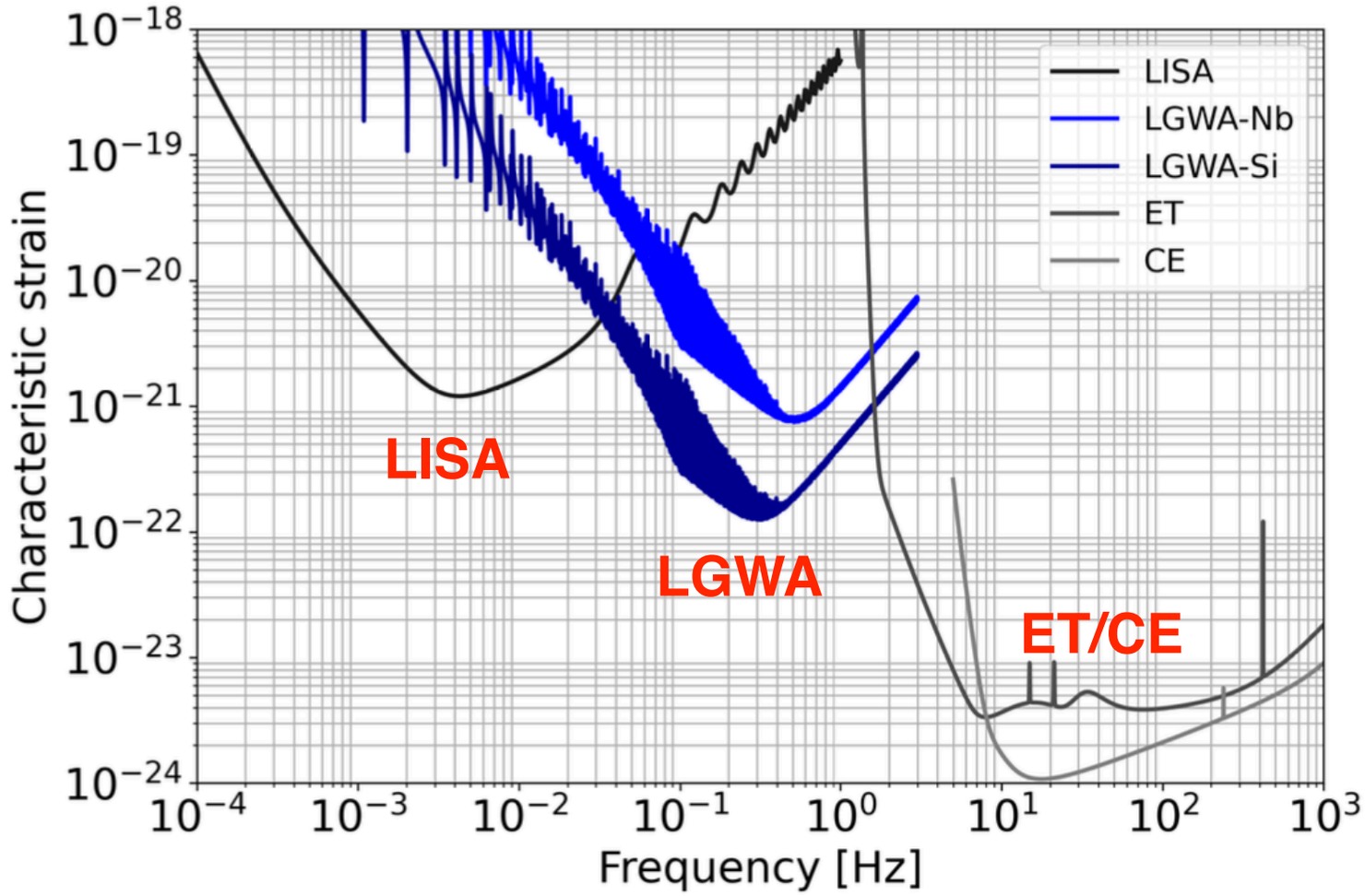
Violins plot = marginal posterior densities (plus median and 68% credible values)

LGWA occupies the millihertz-to-hertz gap

From 1 mHz to 1 Hz

Below: LISA reaches its best sensitivity at a few millihertz

Above: ET and CE dominate from a few hertz upward



LGWA extends coverage through the decihertz band

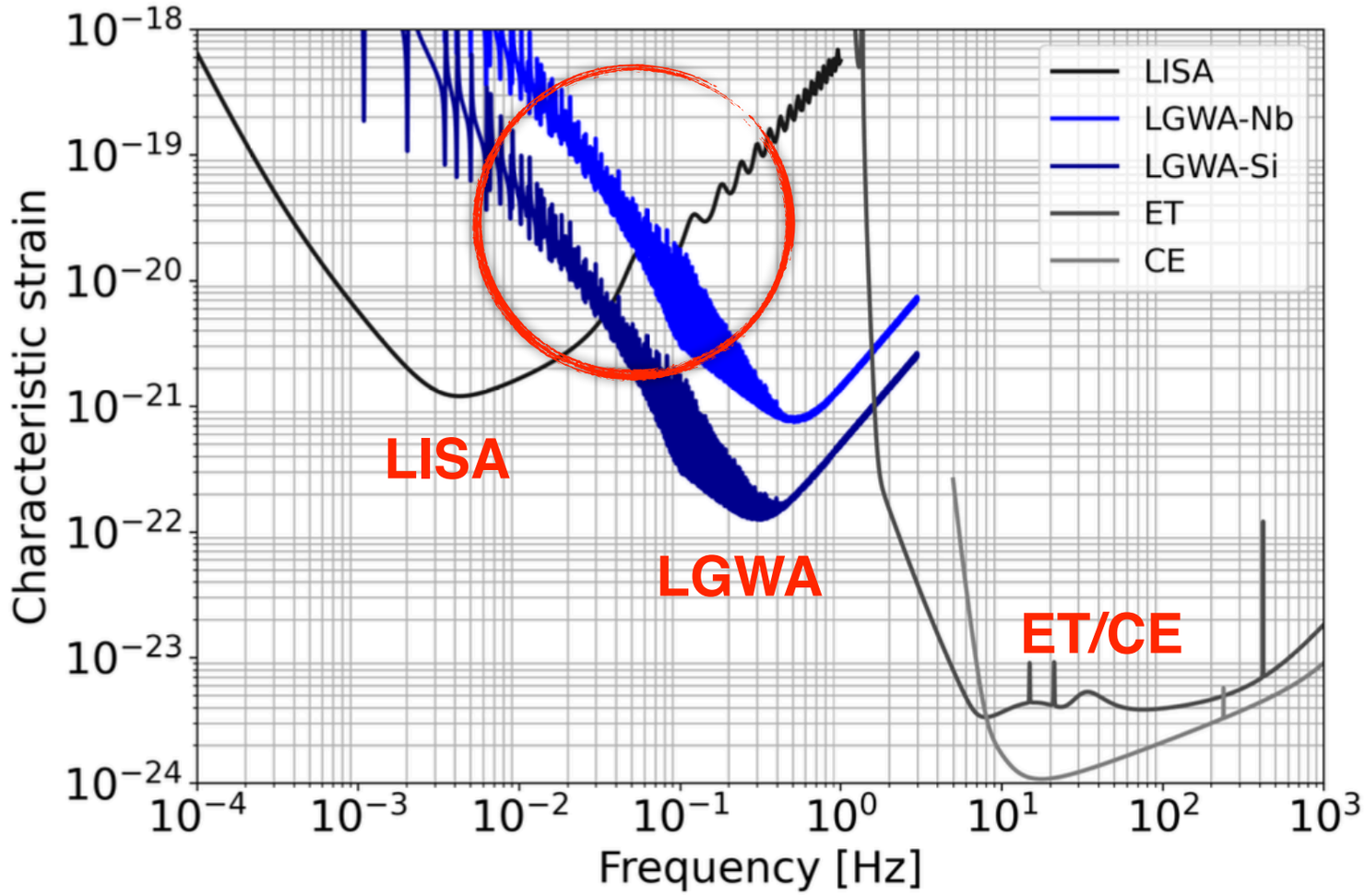
Ajith et al., The Lunar Gravitational-wave Antenna: Mission Studies and Science Case, arXiv:2404.09181v2

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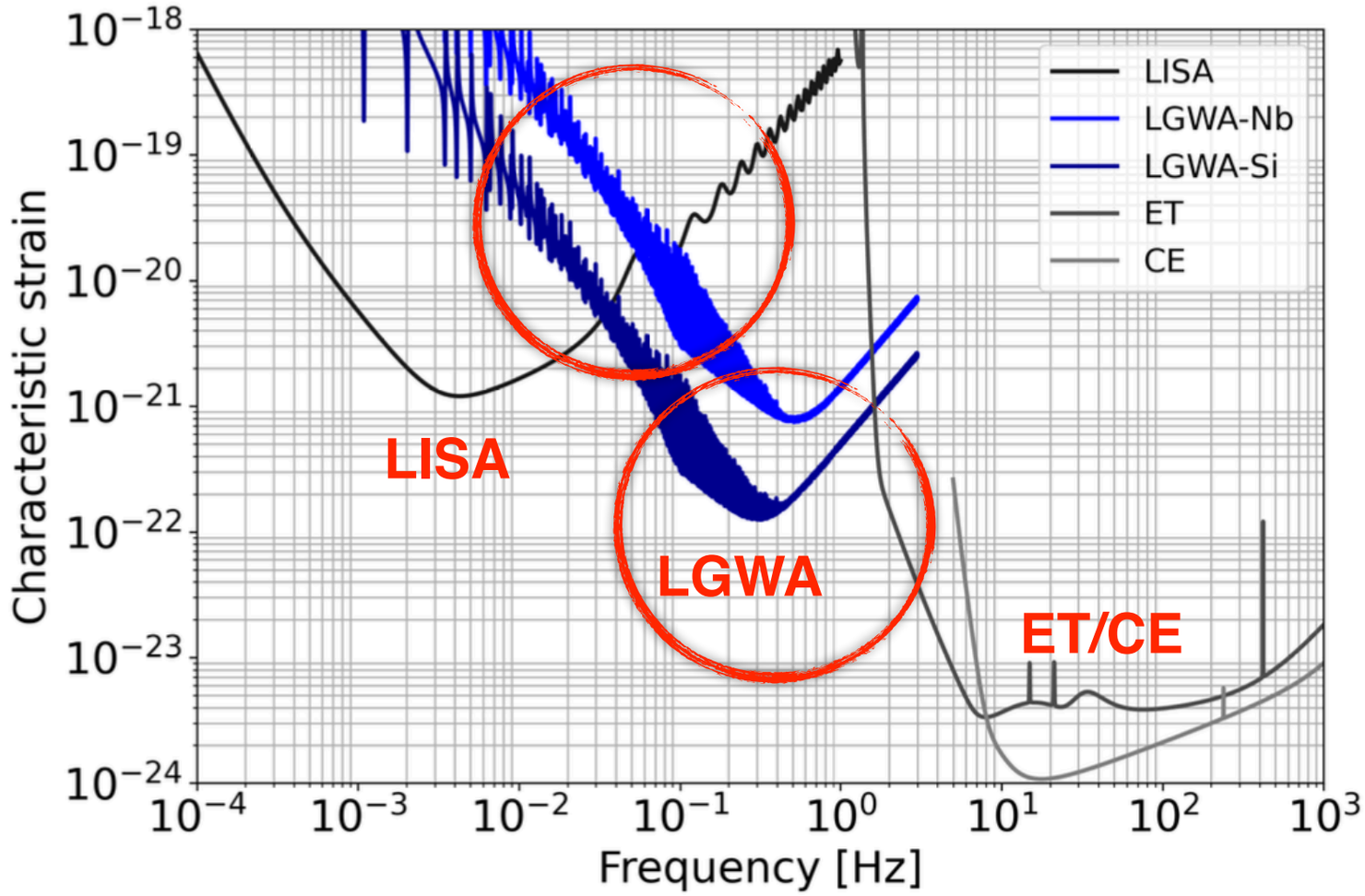
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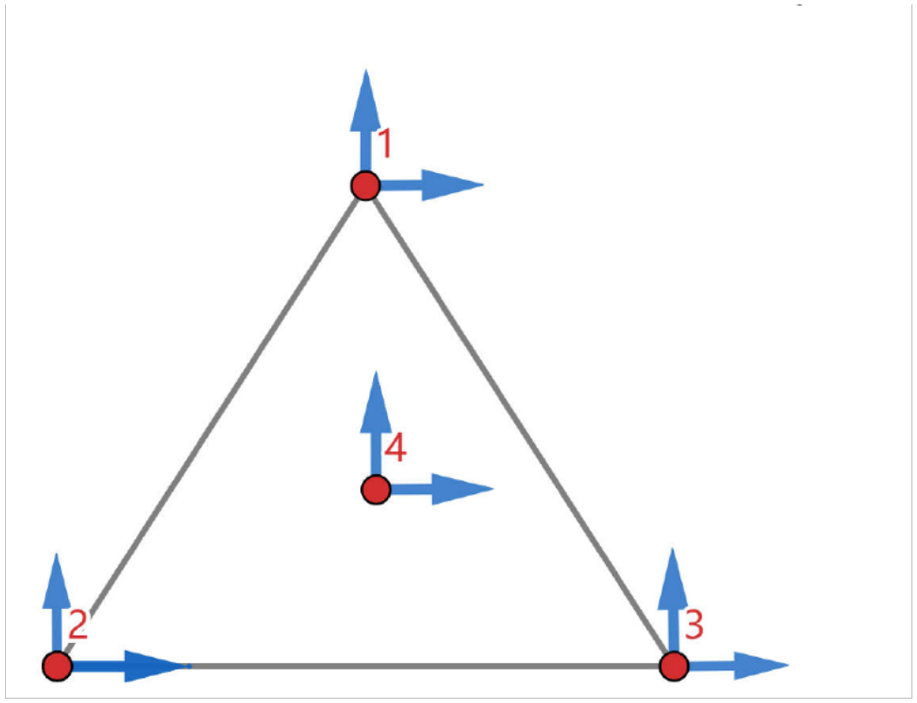
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The baseline array offers multiple local cross-correlations



4 stations × 2 horizontal channels

Three stations define a kilometre-scale triangle; one sits near the centre

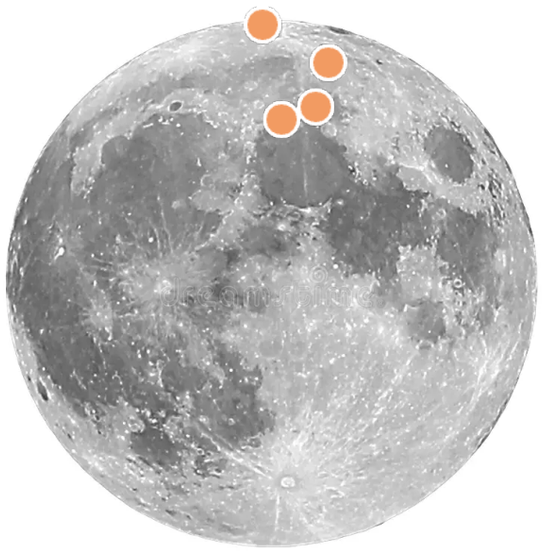
Pairwise correlations improve rejection of independent readout noise

Nearby stations can share moonquake, impact and scattering noise

A local array is necessary for seismic subtraction, but it does not guarantee a clean SGWB baseline

Two baselines answer different questions

Local array



Purpose

Estimate and subtract the local seismic field

Antipodal pair



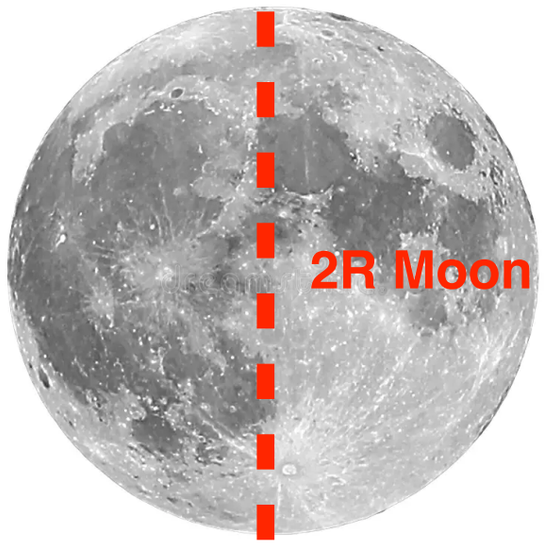
Purpose

Suppress common environmental noise while retaining coherent GW power

SGWB science needs both scales

Harms et al., LGWA, arXiv:2010.13726v1

Antipodal lunar stations remain coherently sensitive



$$\gamma(f) = 15\frac{j_2(\Phi)}{\Phi^2} \qquad \Phi = \frac{4\pi f R_{\mathrm{Moon}}}{c}$$

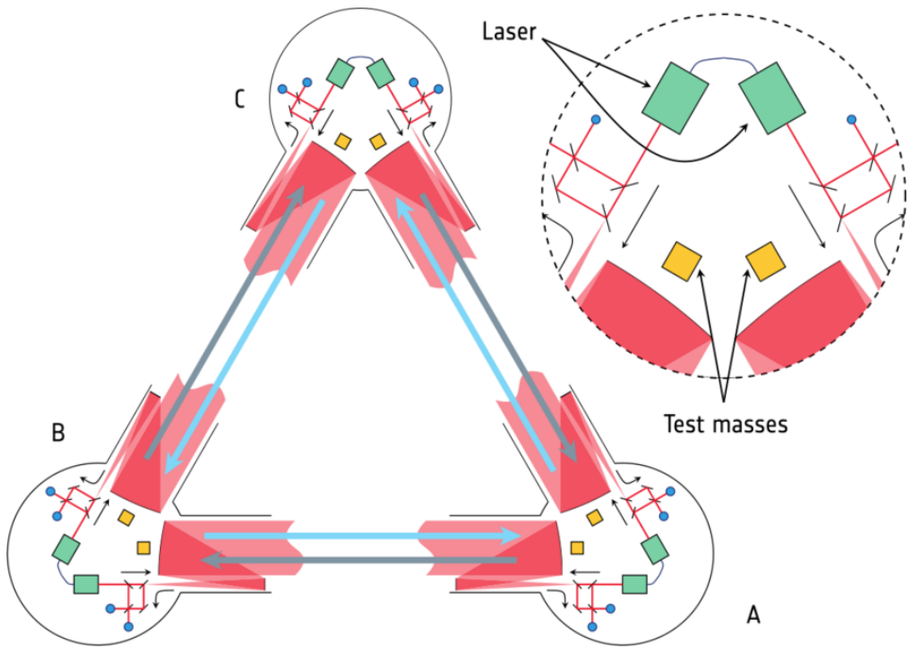
Through the LGWA band $\gamma(f) \simeq 1$

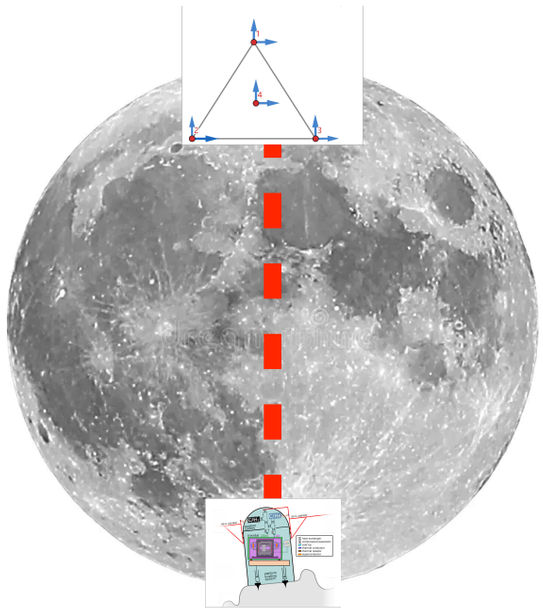
The Moon is small compared with the GW wavelength from 1 mHz to a few hertz

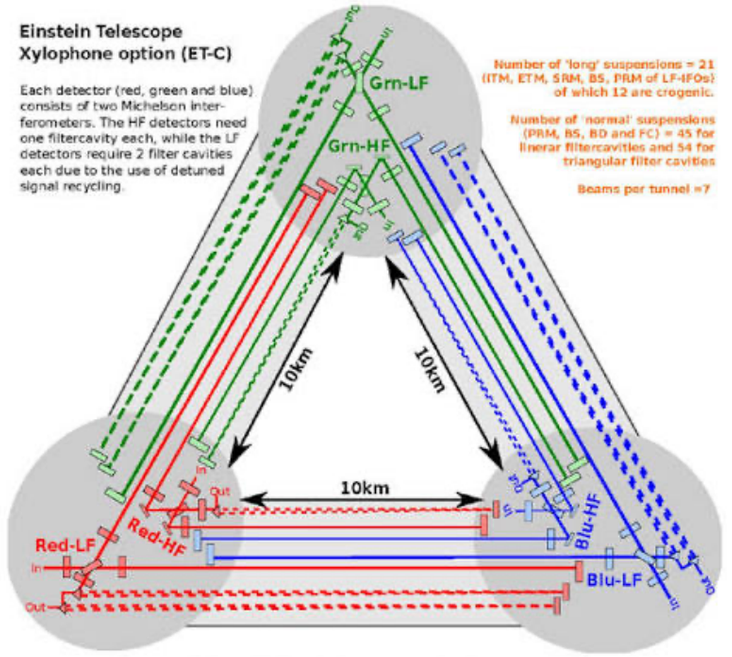
How far apart must LGWA stations be for correlated lunar noise not to bias an SGWB measurement?

Harms et al., LGWA, arXiv:2010.13726v1

Shared design principles: LISA, LGWA and triangular ET







LISA

multiple TDI combinations

LGWA

Antipodal Correlation

ET T

Multiple Channel correlation

Shared features

Triangular, multi-channel geometry: → Multiple orientations provide complementary GW responses

Redundancy and noise rejection → Channel combinations help identify instrumental and environmental noise.

Stochastic-background science → Multiple outputs can improve reconstruction and enable cross-correlation searches.

Shared “limitations”: Correlated Noise?

K. Janssens et al. 2022, 2024
J. Harms 2608.22401
I. Caporali et al. 2501.09057

How the Sensitivity to the SGWB scales?

SGWB reach follows from cross-power accumulation

$$SNR^2 = 2T\int_{10^{-3}\mathrm{Hz}}^{1\mathrm{Hz}} df\,\frac{|\gamma_{12}(f)|^2 S_h^2(f)}{P_1(f)P_2(f)} \quad \Rightarrow \quad \Omega_{min}^{\mathrm{GW}} \propto \frac{1}{\sqrt{T}}\left[\int df\,\frac{|\gamma_{12}(f)|^2 S_h^2(f)}{f^6 P_1(f)P_2(f)}\right]^{-1/2}$$

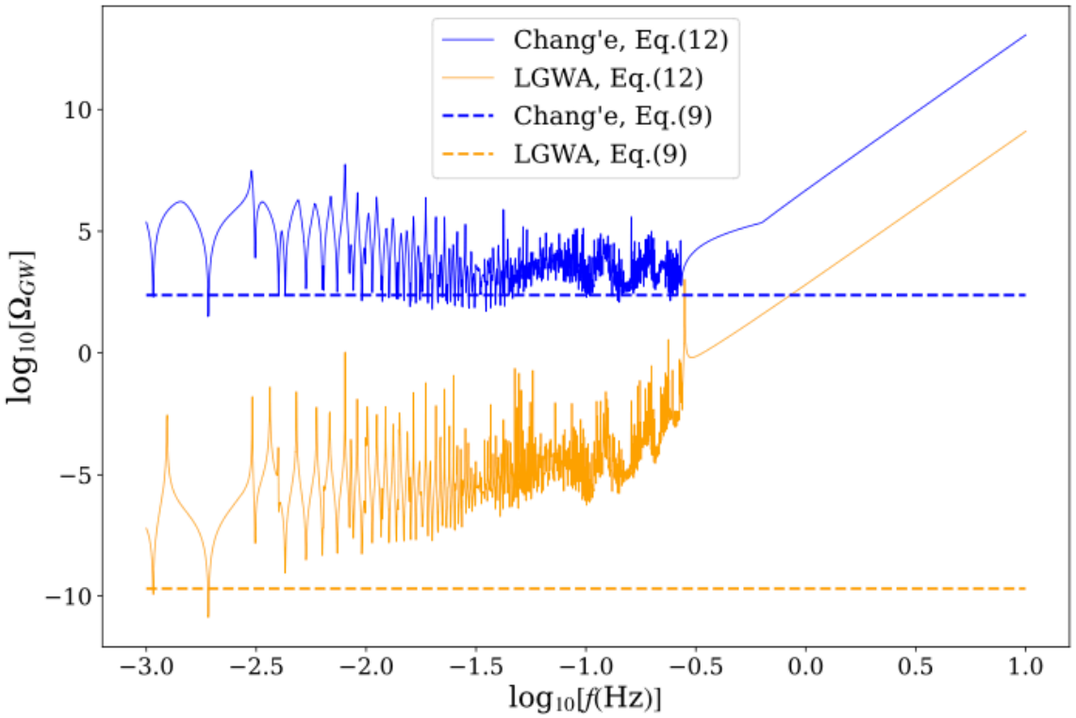
For a flat signal and fixed noise

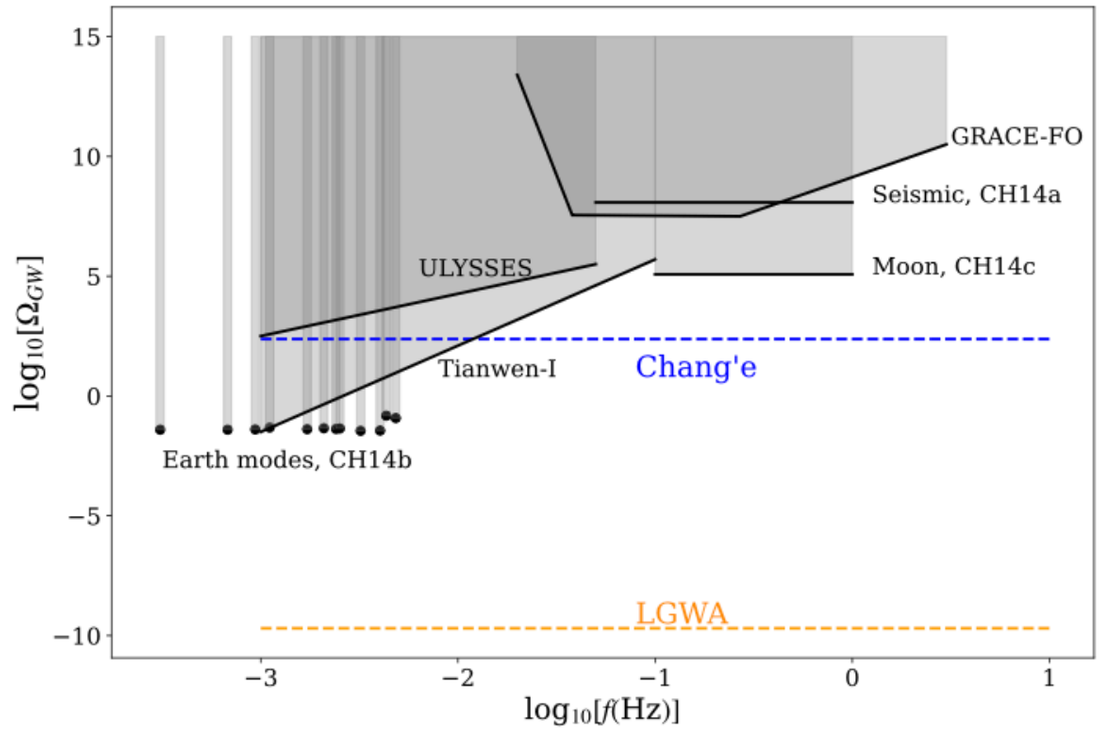
$$\Omega_{\mathrm{min}} \propto \frac{1}{\sqrt{T}} \qquad \Omega_{\mathrm{min}} \propto \sqrt{P_1 P_2} \qquad \Omega_{\mathrm{min}} \propto \frac{1}{|\gamma_{12}|}$$

Long observing time helps only after correlated environmental noise is controlled

Harms et al., LGWA, arXiv:2010.13726v1

How much sensitive?





One-year (optimistic) forecast reaches $\Omega_{\mathrm{GW}} \simeq 2 \times 10^{-10}$

Assumptions:

- Flat Signal T = 1 yr SNR = 3 Cryomagnetic LGWA
- No noise correlation among seismometers
- No complex structure at the surface of the moon
- No interaction between GW and elastic body

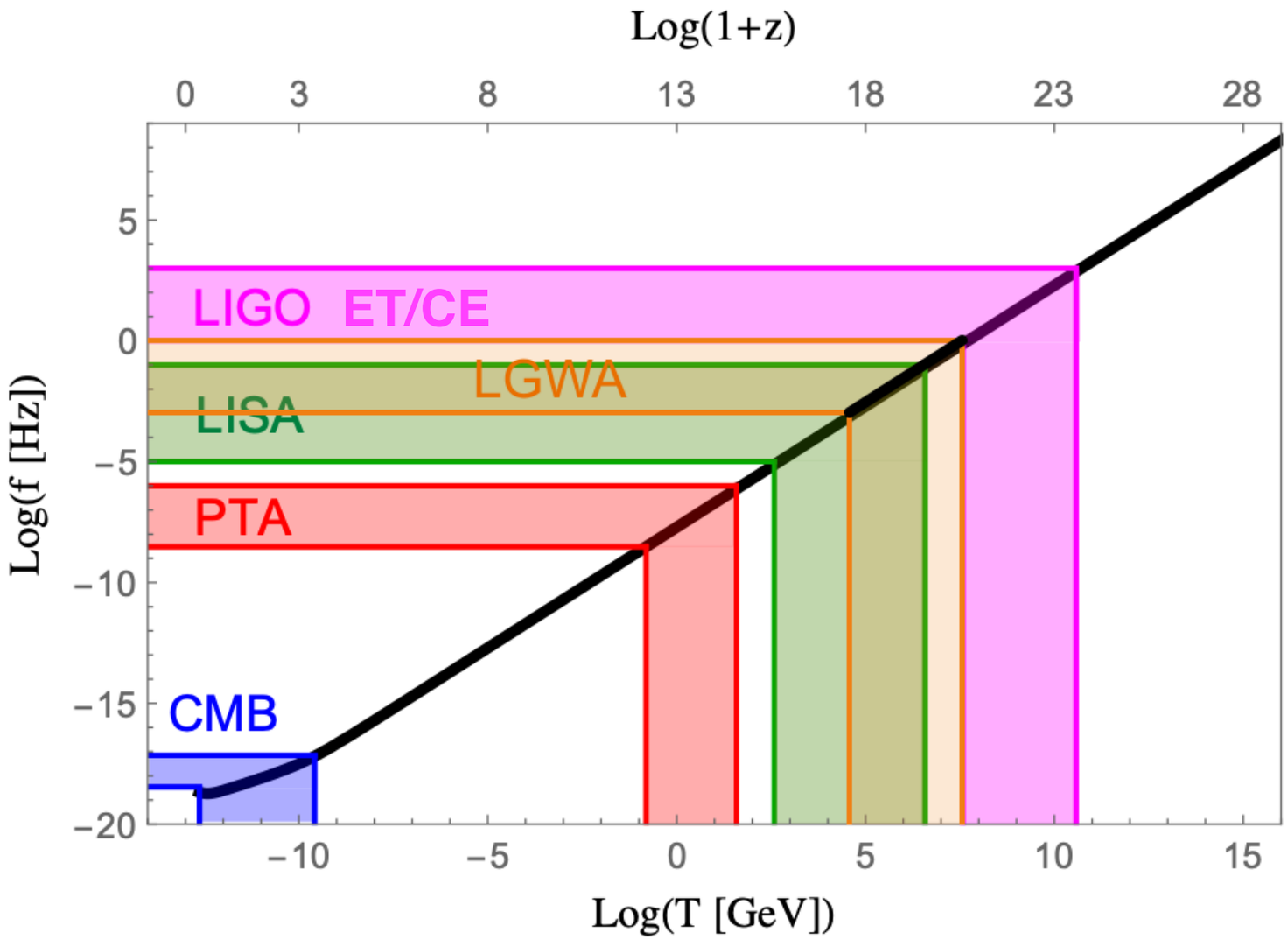
Long observing time helps only after correlated environmental noise is controlled

Yan et al., arXiv:2405.12640v2

Which sources in the LGWA frequency band?

COSMOLOGICAL BACKGROUNDS

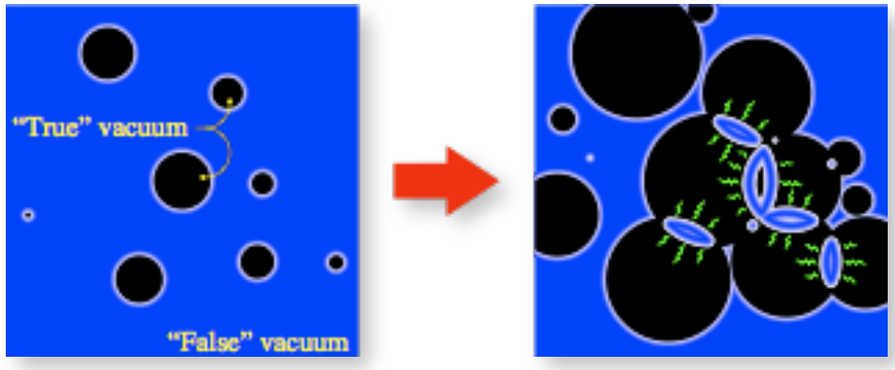
Frequency maps the thermal history of the early Universe



$$f_0 = H_* \frac{a_*}{a_0} \simeq 1.65 \times 10^{-7}\,\mathrm{Hz}\,\frac{T_*}{\mathrm{GeV}}\left(\frac{g_*}{100}\right)^{1/6}$$

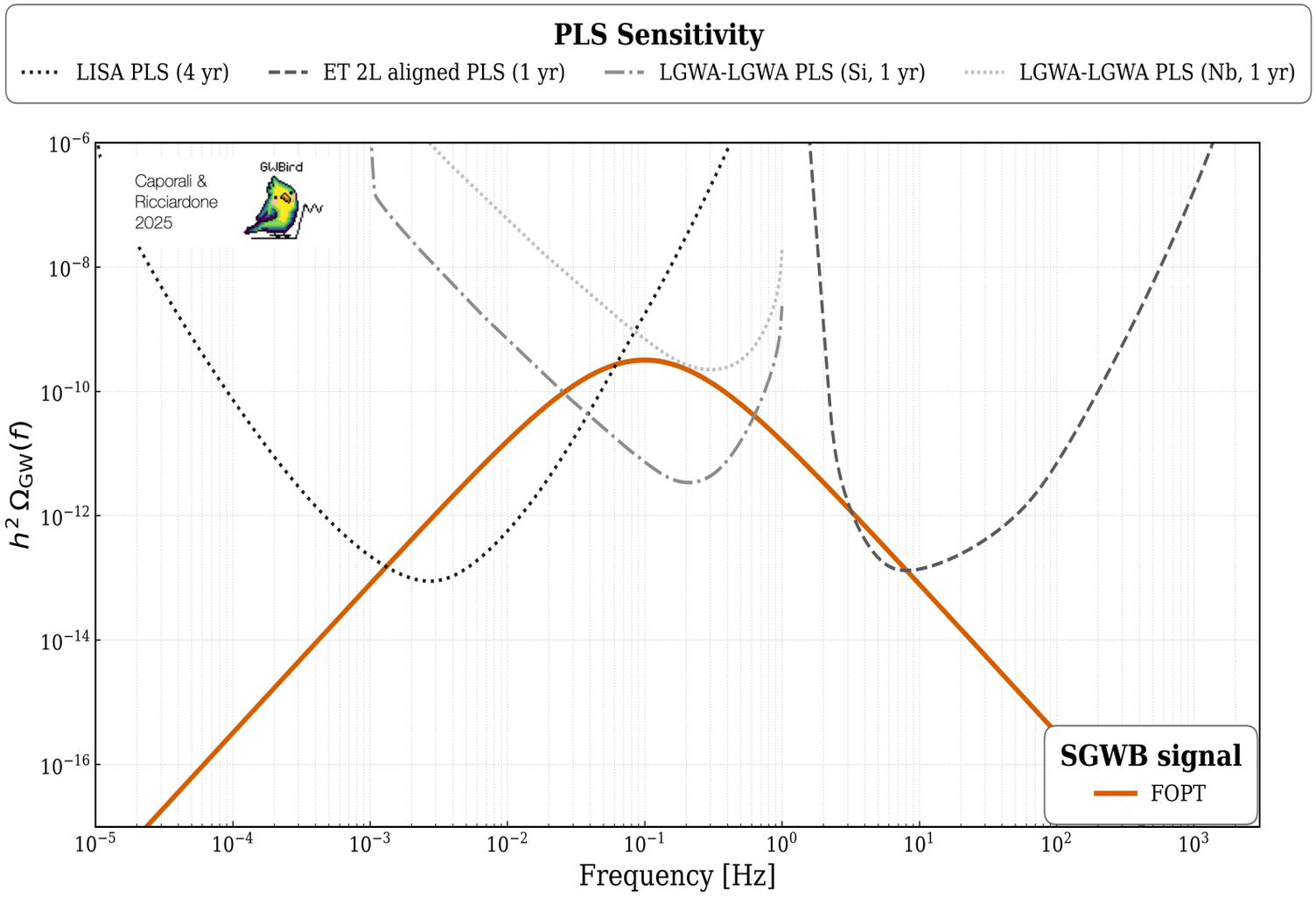
First Order Phase Transition in LGWA

As the temperature in the very early universe decreases, there can be several **PTs: QCD, EW**....Beyond Standard Model?



Processes

- Bubble collisions
- MHD Turbulence
- **Sound Waves**



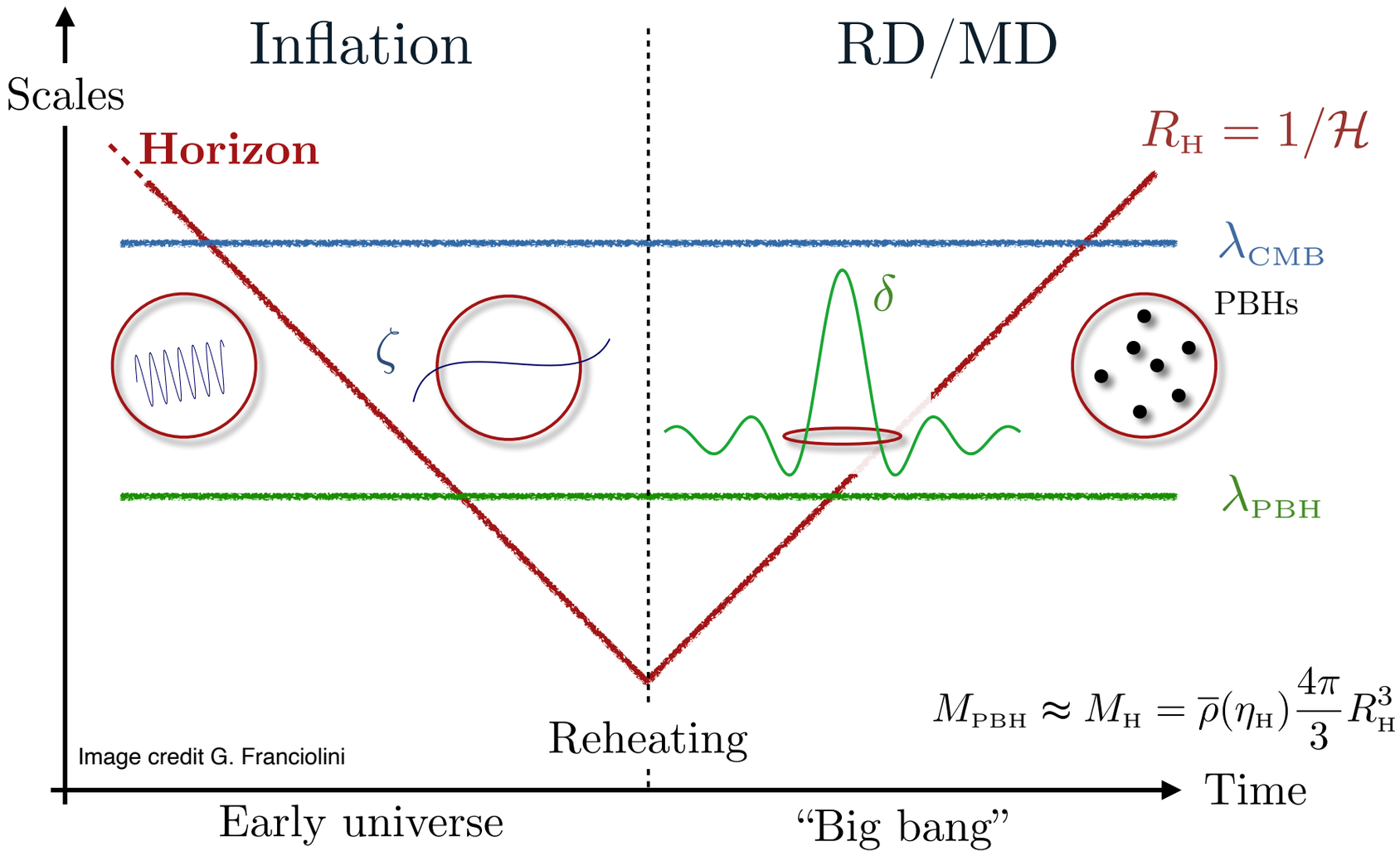
$$f_0 = H_* \frac{a_*}{a_0} \simeq 1.65 \times 10^{-7}\,\mathrm{Hz}\,\frac{T_*}{\mathrm{GeV}}\left(\frac{g_*}{100}\right)^{1/6}$$

$$T_* \sim \mathcal{O}(10^6)\,\mathrm{GeV}$$

Energy scales well above LHC

Scalar Induced GWs & Primordial Black Holes in LGWA

Large scalar perturbations source gravitational waves at 2nd order in perturbation theory when they re-enter the horizon during radiation era



$$M_{\rm PBH} \approx M_{\rm H} = \overline{\rho}(\eta_{\rm H})\frac{4\pi}{3}R_{\rm H}^3$$

$$h_{ij}'' + 2\mathcal{H}h_{ij}' - \nabla^2 h_{ij} = \mathcal{O}(\partial_i\zeta\partial_j\zeta)$$

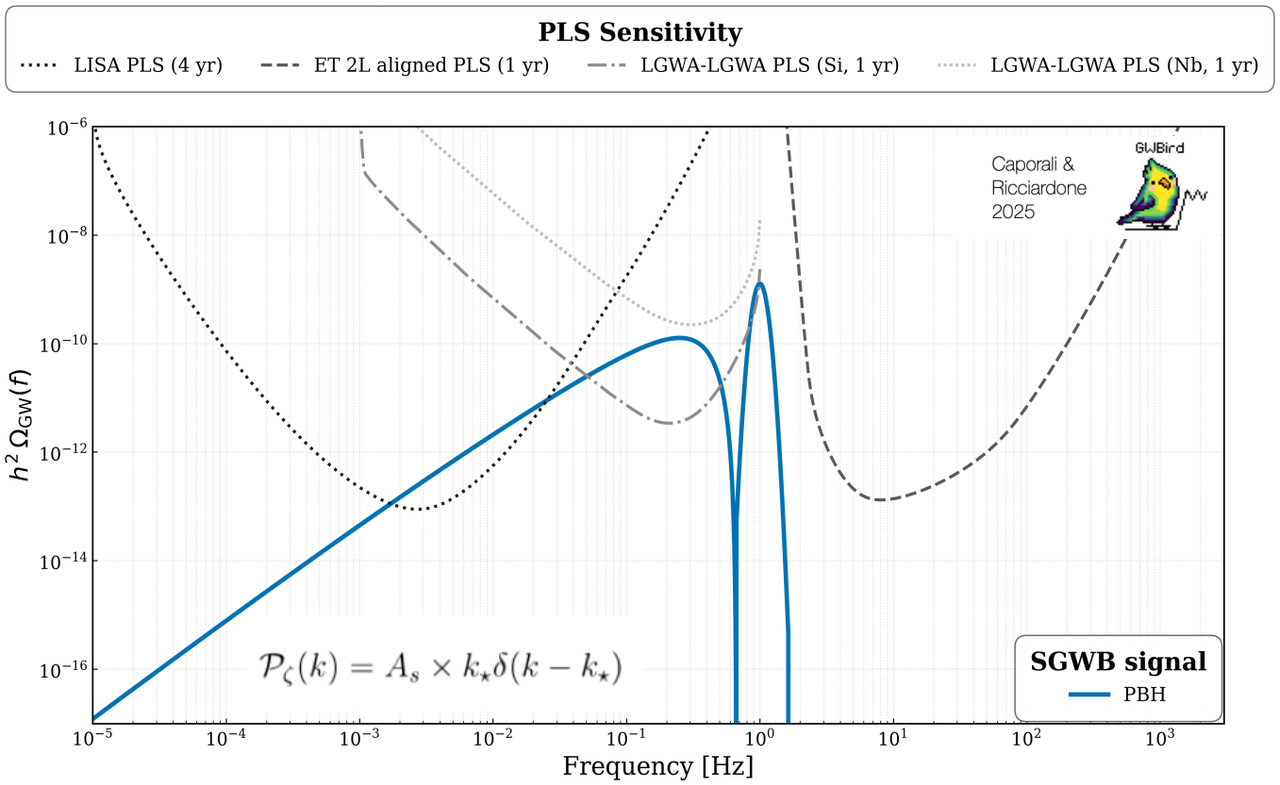
[Tomita, K., 1967]
[Matarrese, S., et al., 1993]
[Domenech, G., review '21]

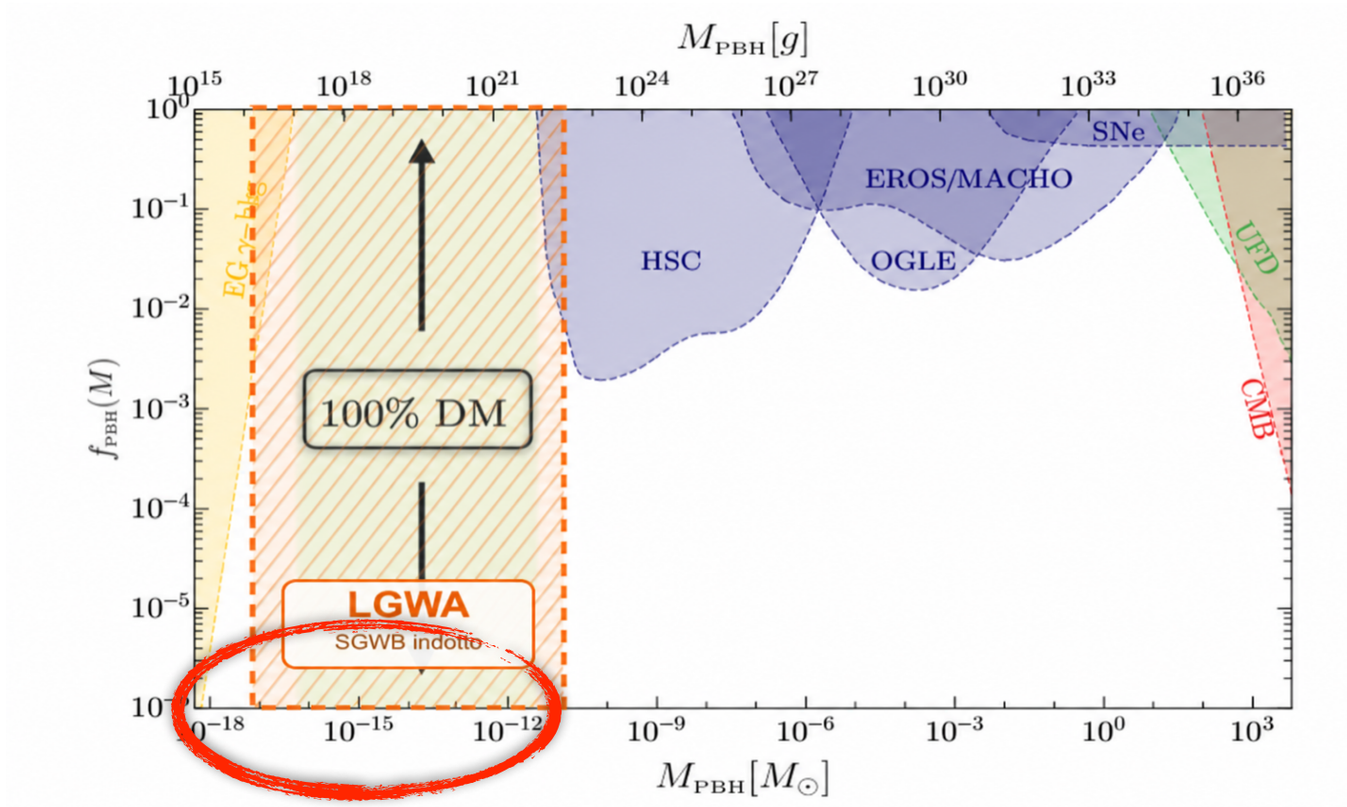
Scalar Induced GWs & Primordial Black Holes in LGWA

$$\Omega_{\rm GW} \simeq \Omega_{\rm rad} A_\zeta^2$$

$$f \simeq 3 \cdot 10^{-9}\,{\rm Hz} \left(\frac{\gamma}{0.2}\right)^{1/2} \left(\frac{M}{M_\odot}\right)^{-1/2}$$

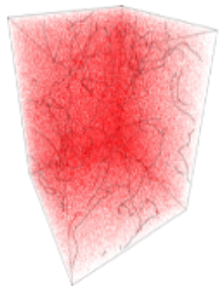
$$f \sim 10^{-1}{\rm Hz} \quad \Longleftrightarrow \quad M \simeq 10^{-14} - 10^{-17} M_\odot$$

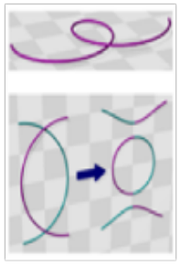




Cosmic Strings in LGWA

- Cosmic strings (CS)



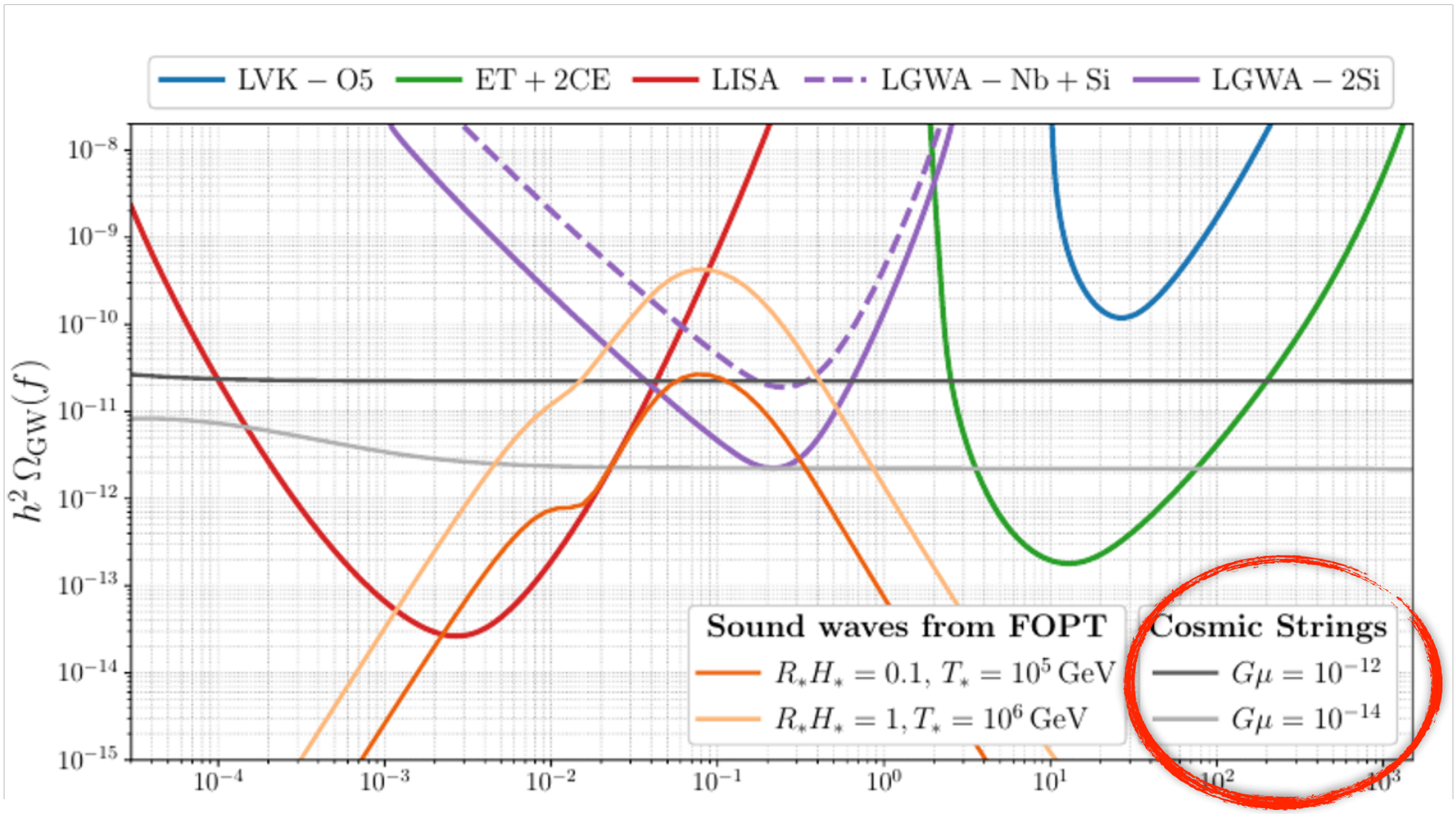




Oscillating CS loops generate a stochastic GWB that is strongly non-Gaussian and includes occasional sharp bursts due to cusps and kinks

String Tension

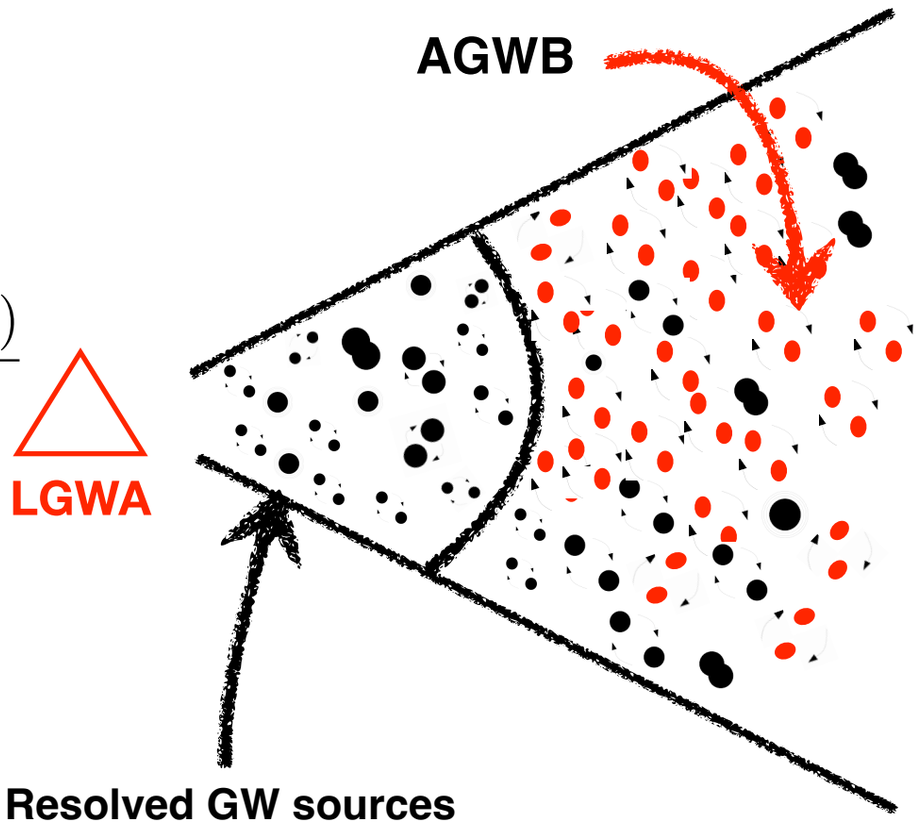
$$G\mu \sim 10^{-6} \left(\frac{\eta}{10^{16}\ \mathrm{GeV}} \right)^2$$



Ajith et al., The Lunar Gravitational-wave Antenna: Mission Studies and Science Case, arXiv:2404.09181v2

Astrophysical Backgrounds in LGWA

$$\Omega(f) = \frac{f}{\rho_c} \int d\theta\, p(\theta) \int_0^{z_{max}(\theta)} dz \frac{R(z;\theta)}{(1+z)H(z)} \frac{dE_{GW}(f_s;\theta)}{df_s}$$



Carry information about:

- star formation history
- statistical properties of source populations
- our cosmological model

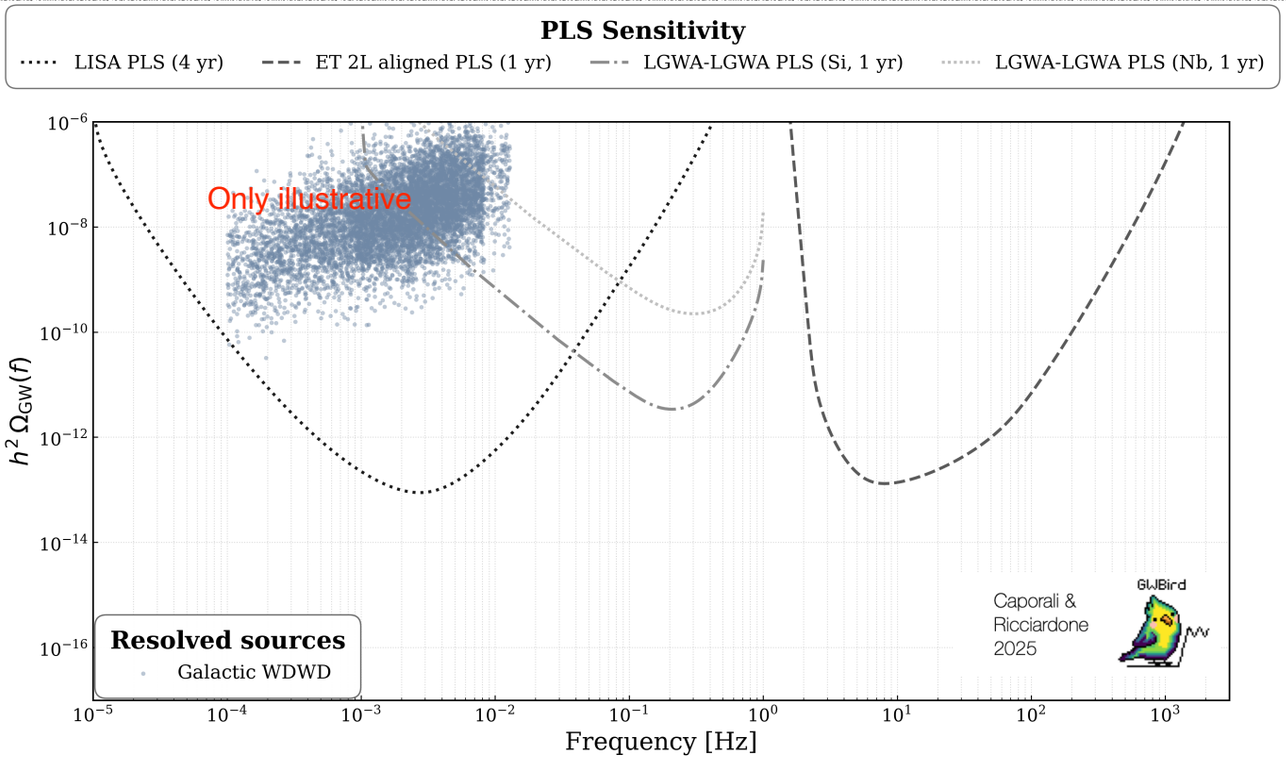
Galactic WD Binaries

- LISA will observe WD-WD of individual (resolved) GW signals and an unresolved Galactic foreground (LISA Astrophysics white paper 2023).

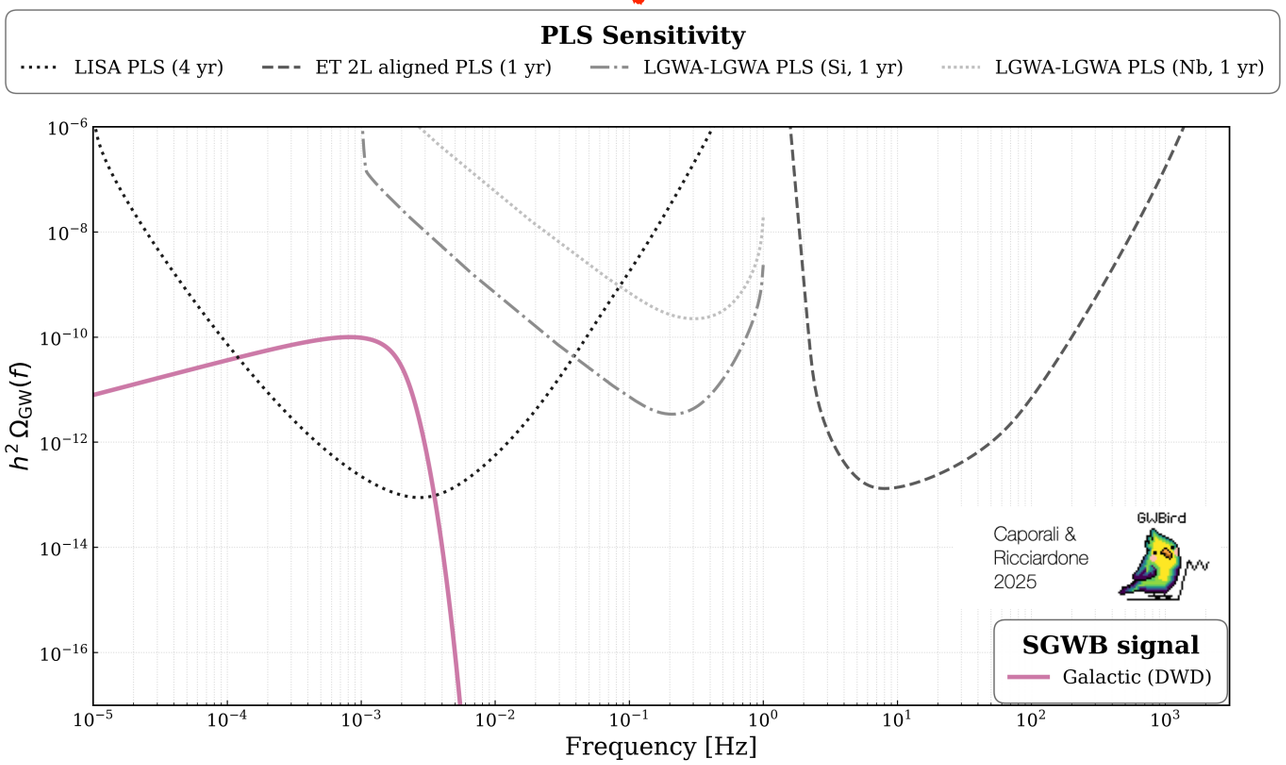
- Most are in the inspiral phase: **quasi-monochromatic**, permanent GW signal

- Resolved binaries: ~ 10^4 sources are expected with SNR 7-1000

- Stochastic foreground from sources with too low SNR, yearly modulated



Source subtraction and joint population inference

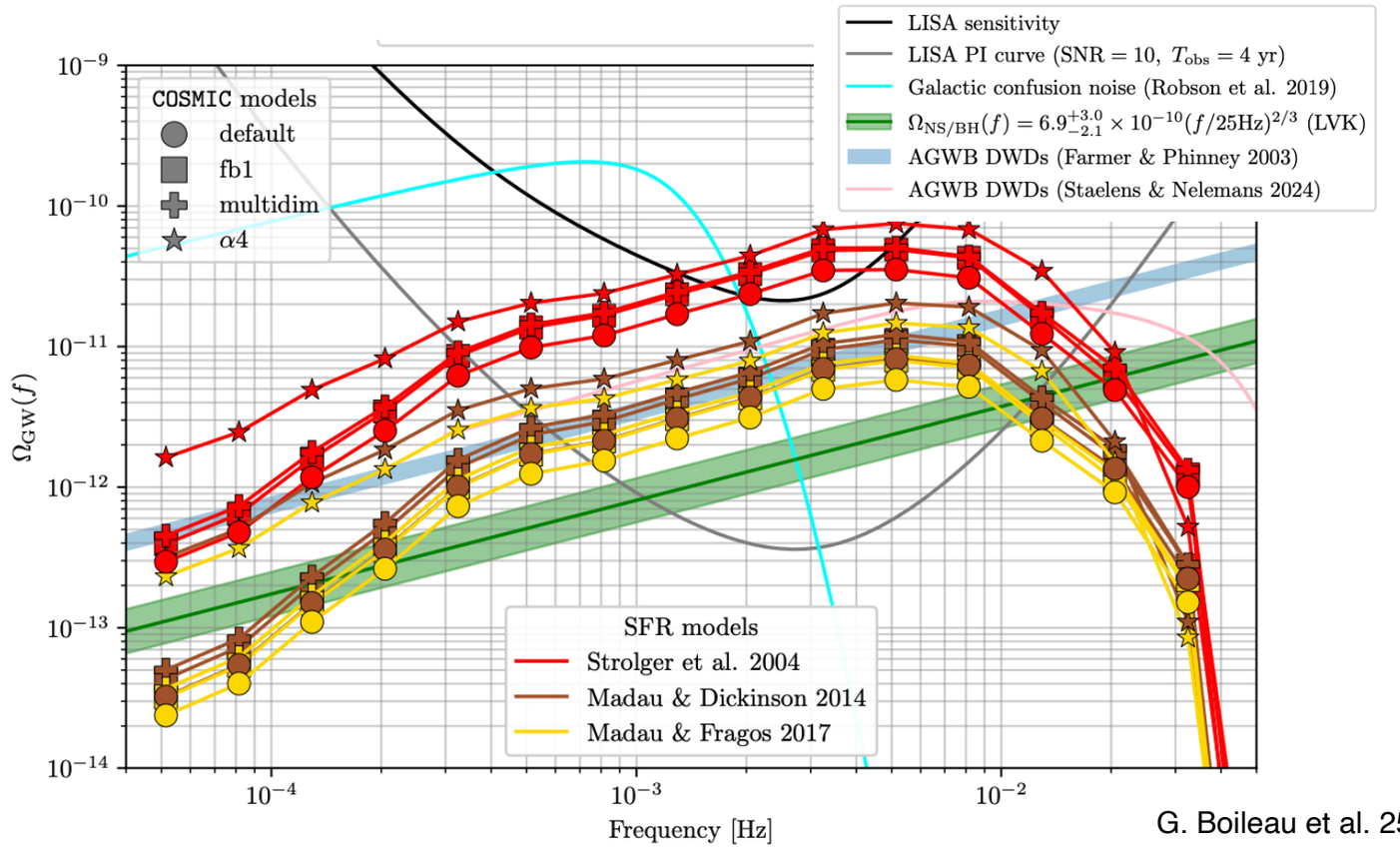


Extra-Galactic WD Binaries

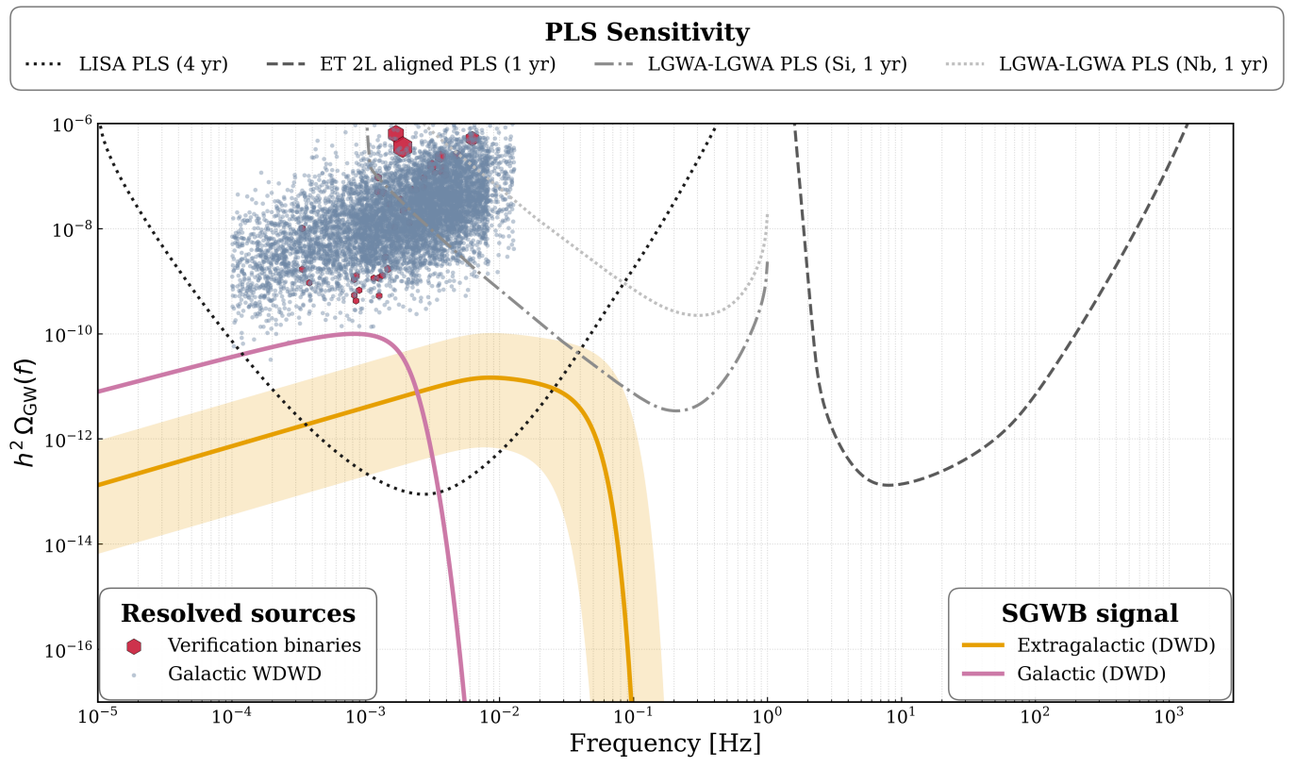
- Recently also the Extra-Galactic contribution from WD binaries has been considered (G. Nelemans+ 24)

- This comes with large astrophysical uncertainties

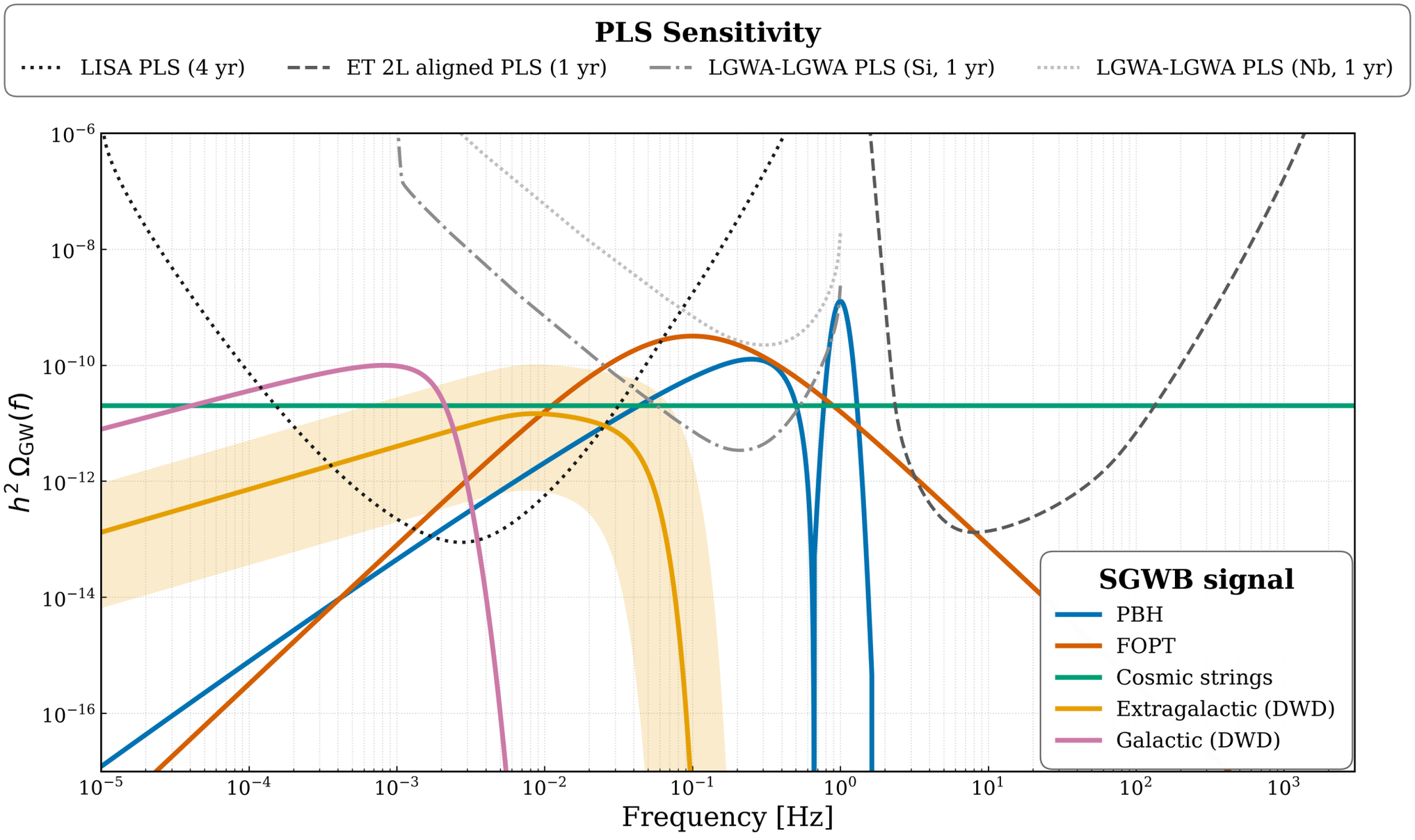
- Can LGWA help in this?



G. Boileau et al. 25



SGWBs in LGWA



What could limit the SGWB measurement?

01 **Correlated lunar seismic noise**

Moonquakes, meteoroid impacts and scattering can correlate nearby stations.

02 **Uncertain lunar transfer function**

Interior structure matters below 0.1 Hz; site geology matters above it.

03 **Astrophysical foreground**

Unresolved compact binaries may dominate the total stochastic power.

04 **Model-dependent inference**

Spectral priors and imperfect source subtraction can bias a cosmological component.

Take-home messages

01 **LGWA opens the 1 mHz–1 Hz band**

This band carries distinctive early-Universe spectra and compact-binary populations.

02 **Correlation geometry is the enabling technology**

A distant sensor could provide a low-environmental-correlation baseline with $\gamma \approx 1$.

03 **Treat the far-side or opposite-pole station as part of the SGWB concept, not merely an optional upgrade**

A local array controls seismic noise; an antipodal station provides the SGWB baseline.

04 **Jointly fit instrument noise, lunar response, compact binaries and SGWB components.**

The actual (optimistic) forecast assumes independent noise and a sufficiently accurate lunar response model.