Probing Cosmology with Gravitational Waves
- Current Status and Future Prospects with
LISA & ET

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11 September 2024 - Pollica

Latest Updates

In June 2021, the European Strategy Forum on Research Infrastructures (ESFRI) decided to include the Einstein Telescope (ET) in the update of its roadmap for 2021.

In June 2022 formal establishment of ET collaboration (today 1400 members)

In June 2023 Italian government present the Italian candidacy to host the Einstein Telescope,

On 25 January 2024 LISA has been adopted by ESA and construction will start in January 2025

On 25 March 2024 ASI presented the LISA mission to the scientific community

CERNCOURIER | Reporting on international high-energy physics

Physics ▾ Technology ▾ Community ▾ In focus Magazine

Link to article

ASTROPHYSICS AND COSMOLOGY | FEATURE

Gravitational waves: a golden era

23 August 2023

A Maleknejad, F Rompineve

Outlook

Precision detection of the gravitational-wave spectrum is essential to explore particle physics beyond the reach of particle colliders, as well as for understanding astrophysical phenomena in extreme regimes. Several projects are planned and proposed to detect GWs across more than 20 decades of frequency. Such a wealth of data will provide a great opportunity to explore the universe in new ways during the next decades and open a wide window on possible physics beyond the SM.

Where we are - LVK

The third observing run (B) from April 2019 to March 2020

Total number of gravitational waves observed to date (with probability of astrophysical origin > 0.5): ~ **90**

(mostly BBHs, 2 BNS and 2 NS-BH)

GWTC-3 catalogue: arXiv:2111.03606

The fourth run O4b has started with Virgo online

10 April

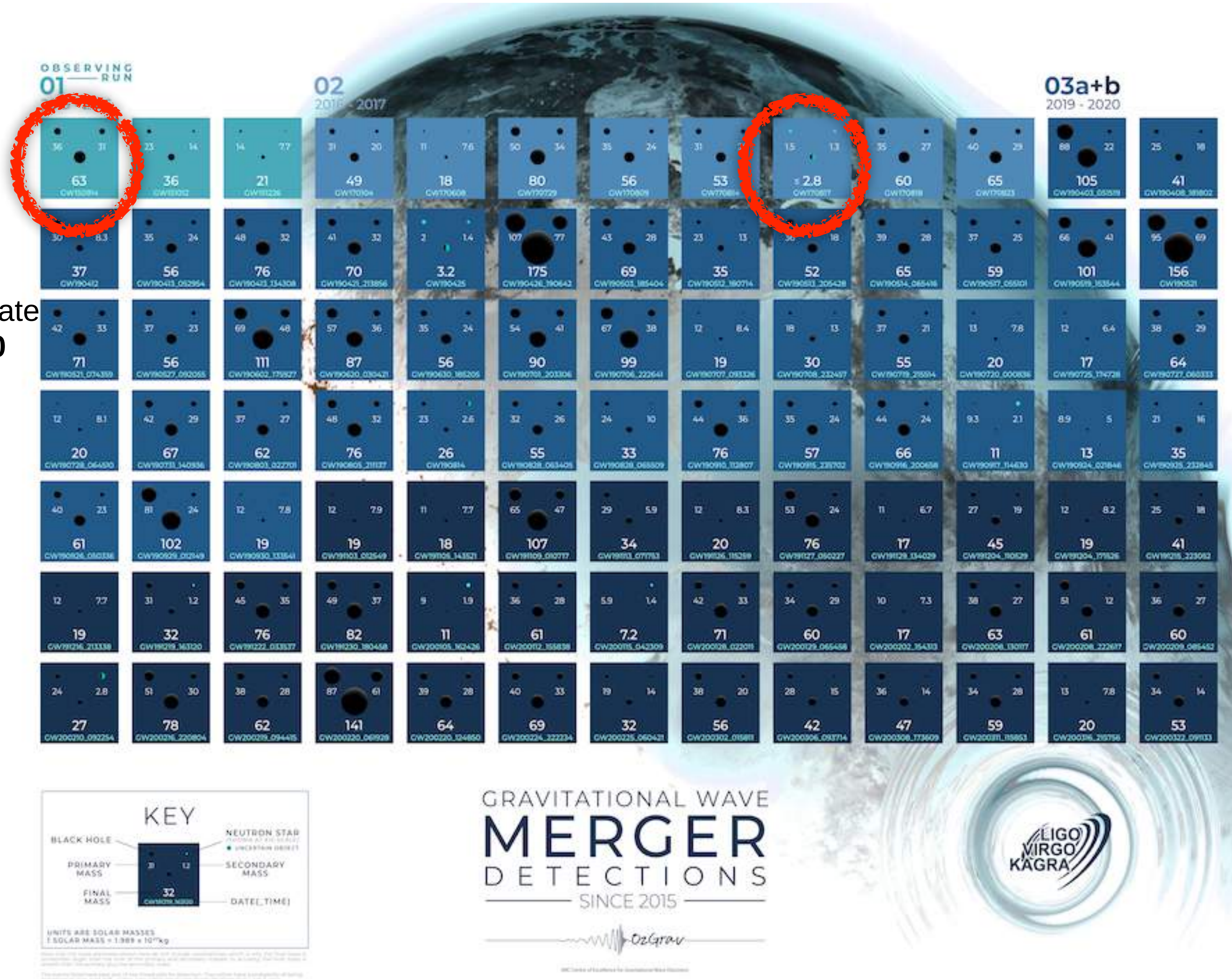
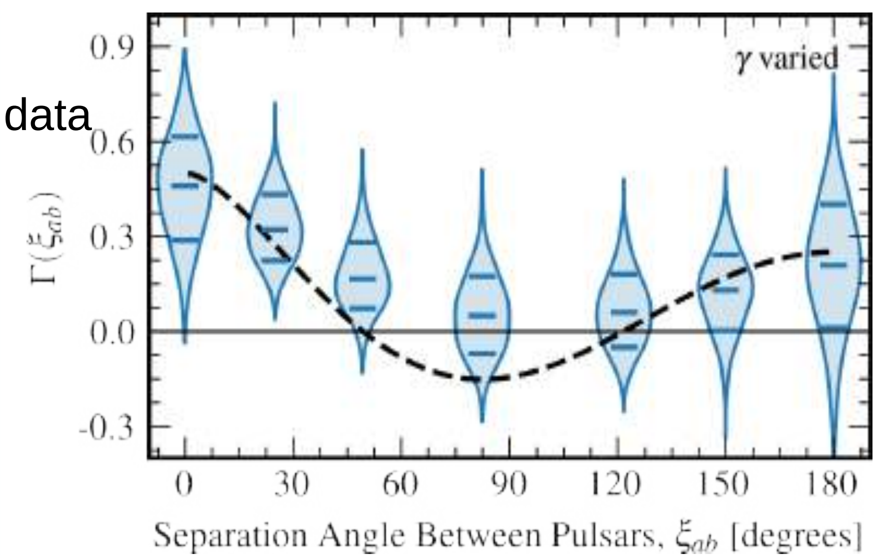


Image credit: LIGO / Virgo / KAGRA / C. Knox / H. Middleton

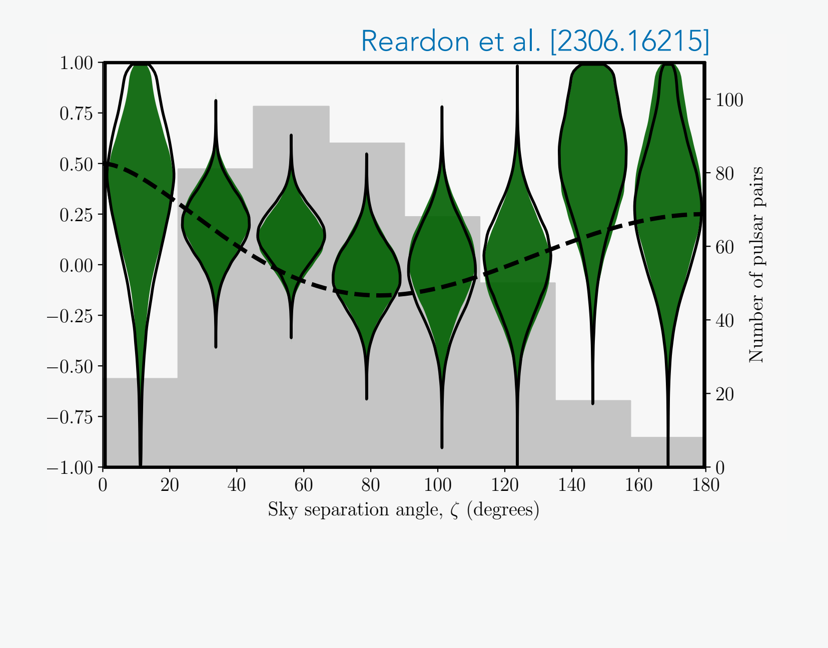
Where we are - PTA

Agazie et al. [2306.16213]

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



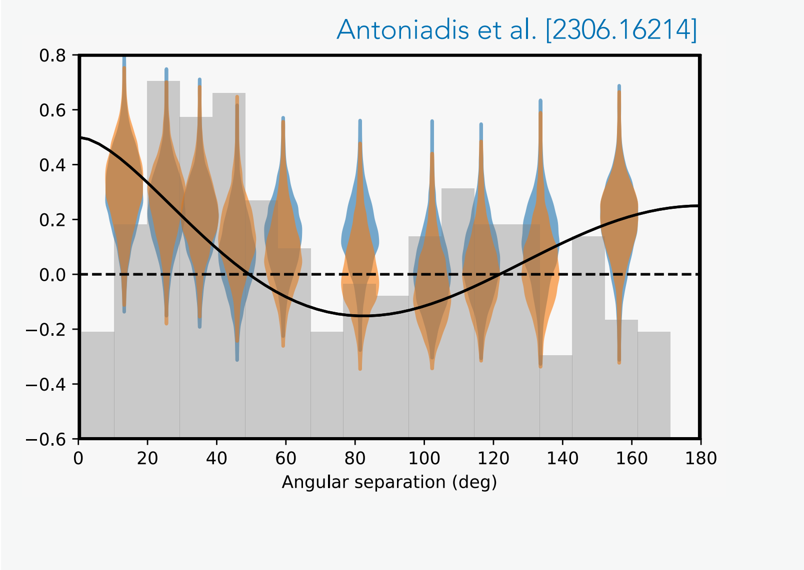
PPTA:
32 pulsars, 18 yrs of data
$\sim 2\sigma$ significance



First Detection of a SGWB

EPTA+InPTA:
25 pulsars, 24 yrs of data

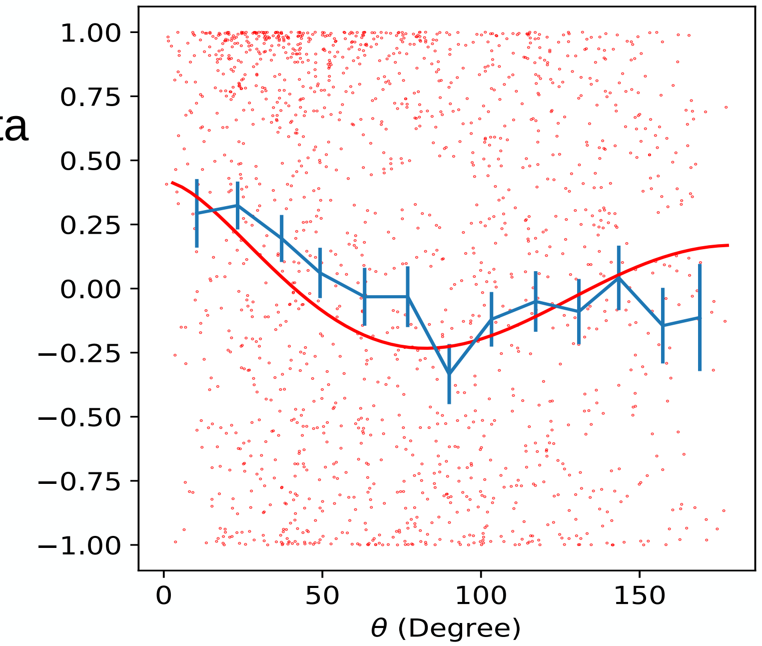
$\sim 3\sigma$ significance



CPTA:
57 pulsars, 3 yrs of data

$\sim 4.6\sigma$ significance

Xu et al. [2306.16216]



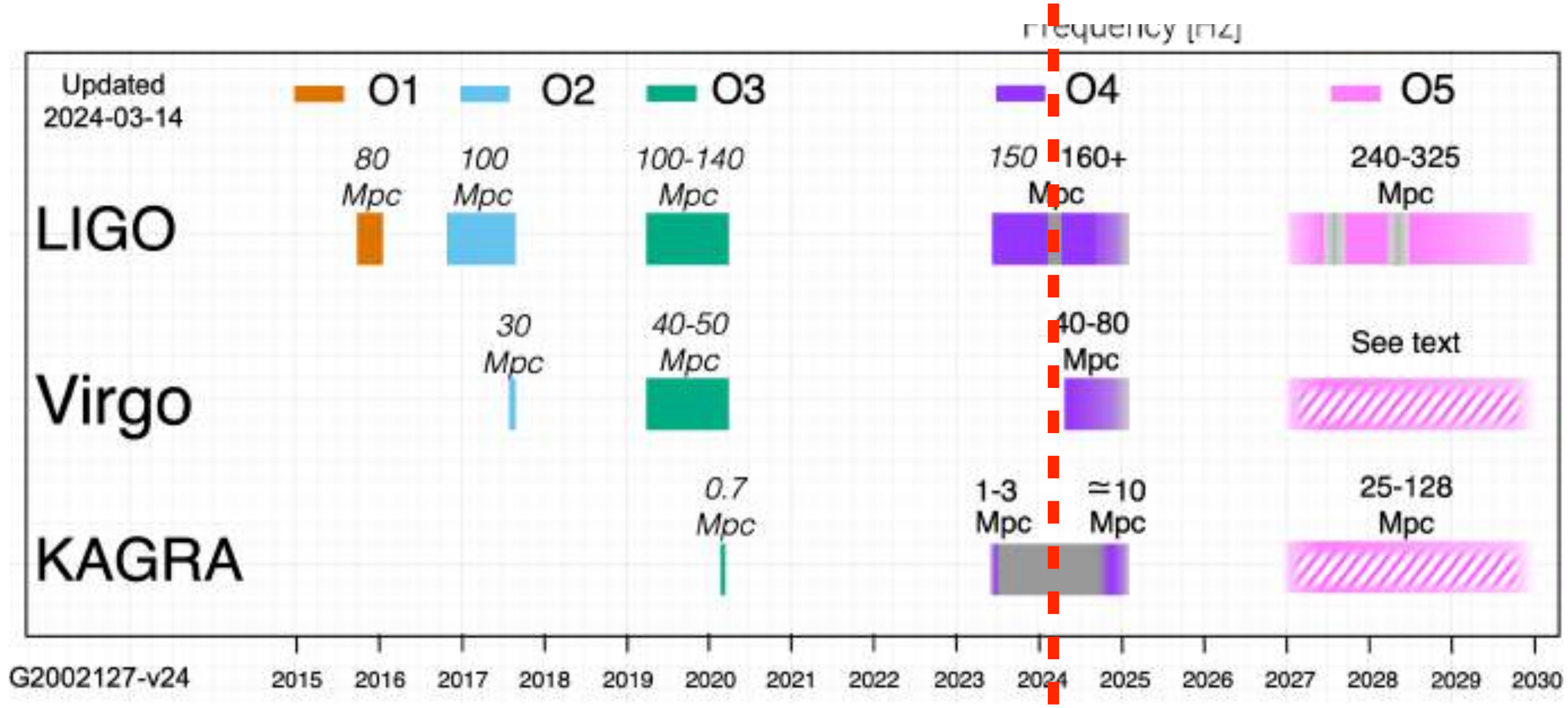
Bayesian reconstruction of normalized inter-pulsar correlations

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

See K. Schmitz, Stas and Matias talks

What are the plans for the LVK runs?

Advanced Virgo configuration(s) → AdV+ Phase I → AdV+ Phase II → Virgo_nEXT concept



We are here

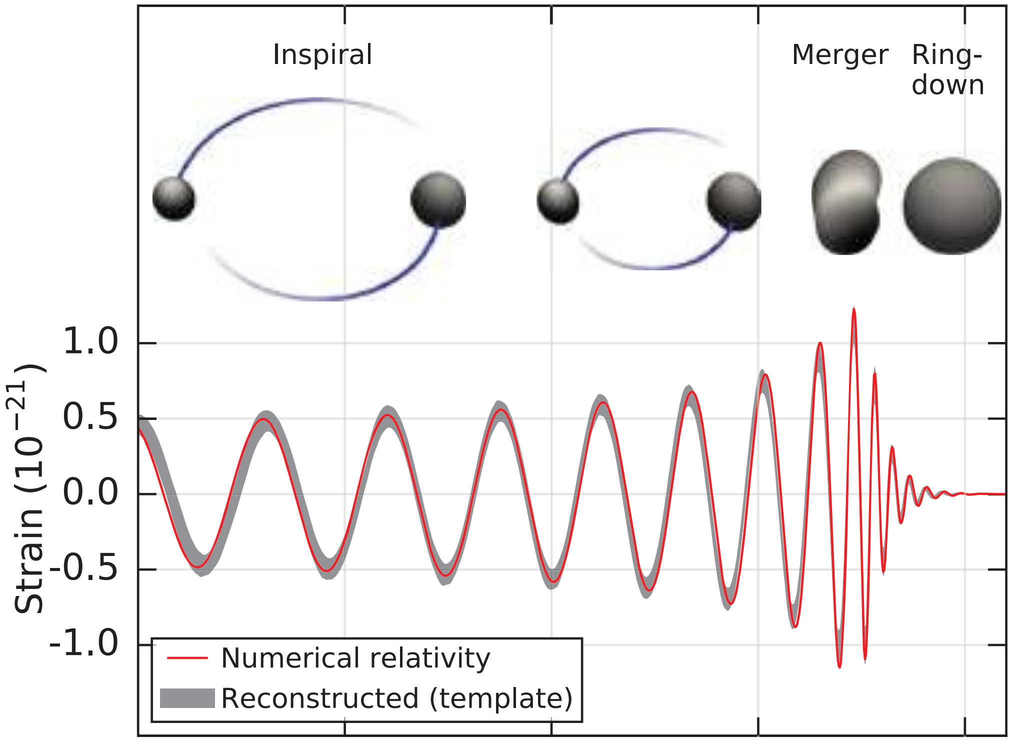
10/04/2024

3G

Sources of Gravitational Waves

Resolved Sources:

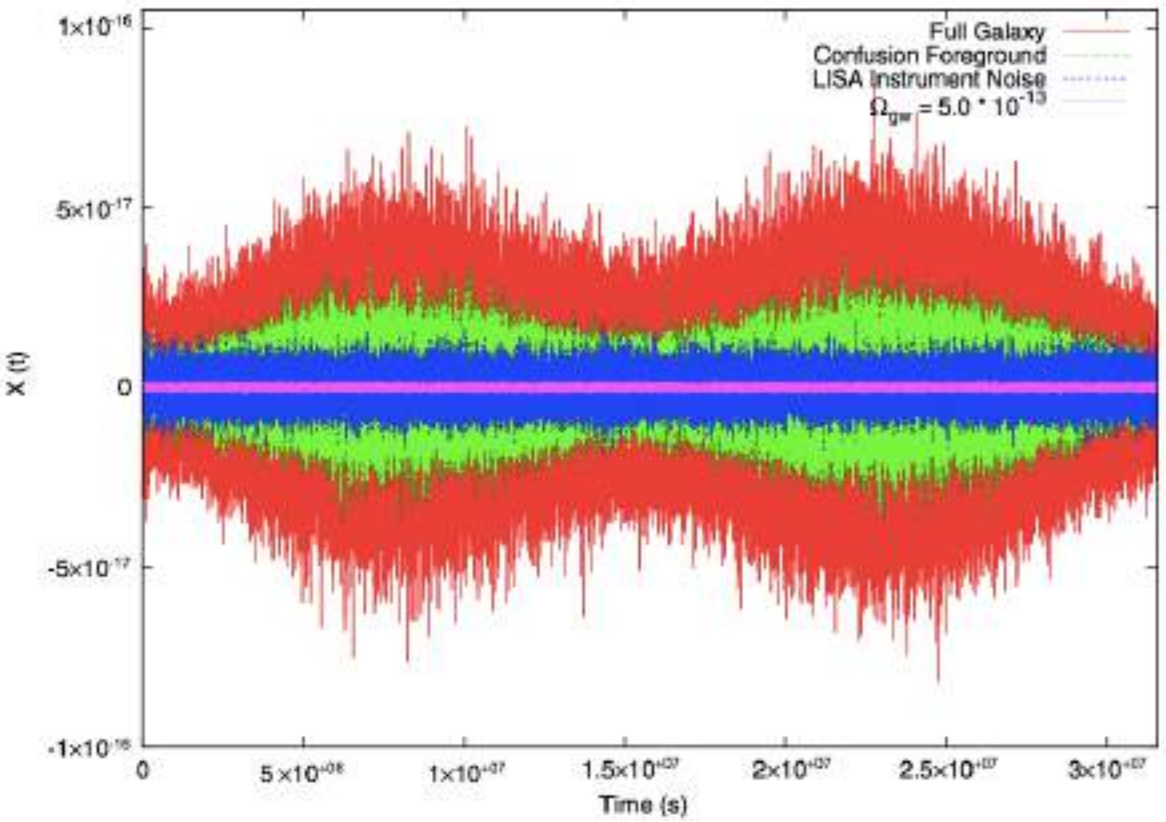
- Black Holes
- Neutron Stars
- White Dwarfs
- Supernovae
- …



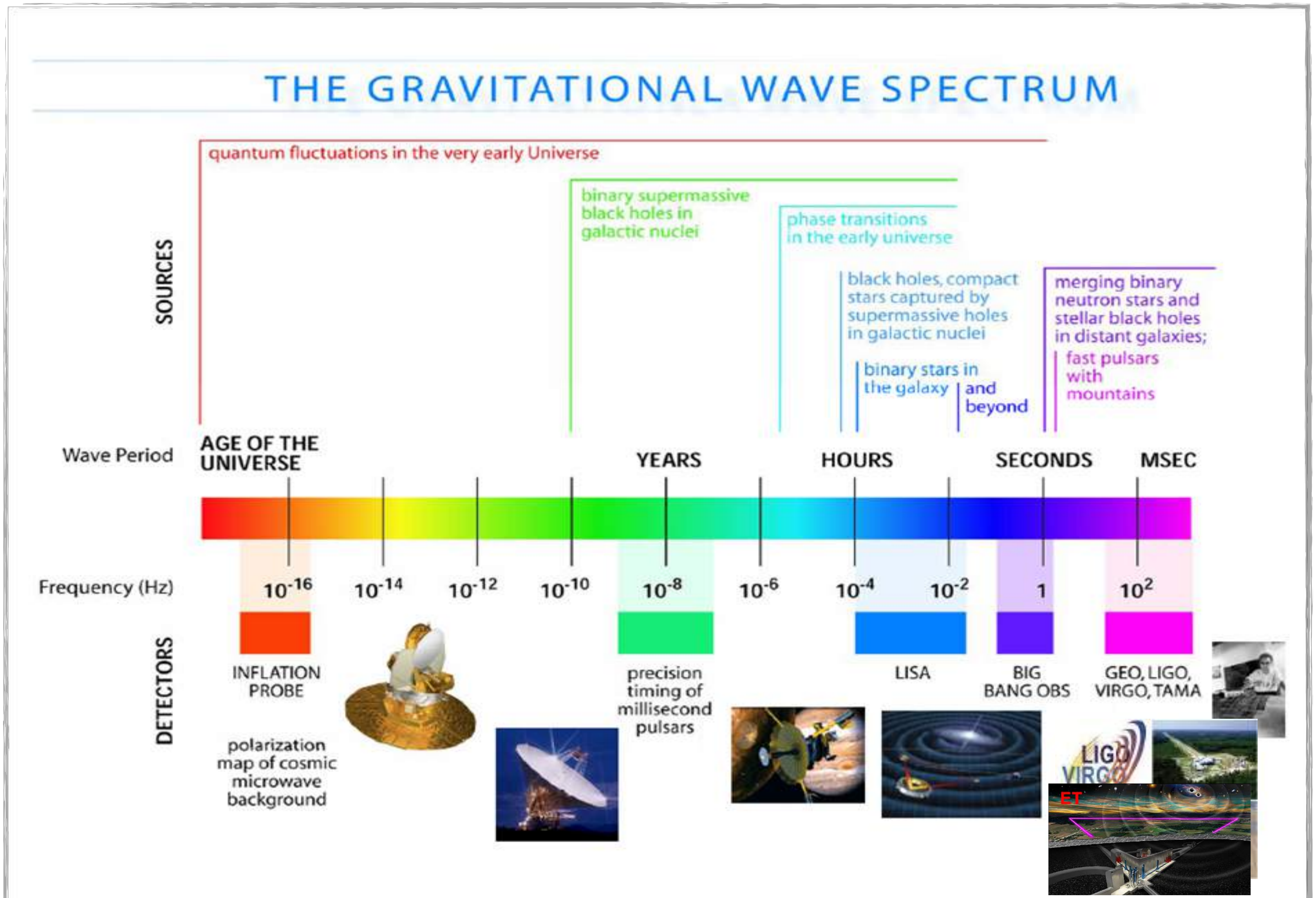
Unresolved Sources:

Stochastic Backgrounds

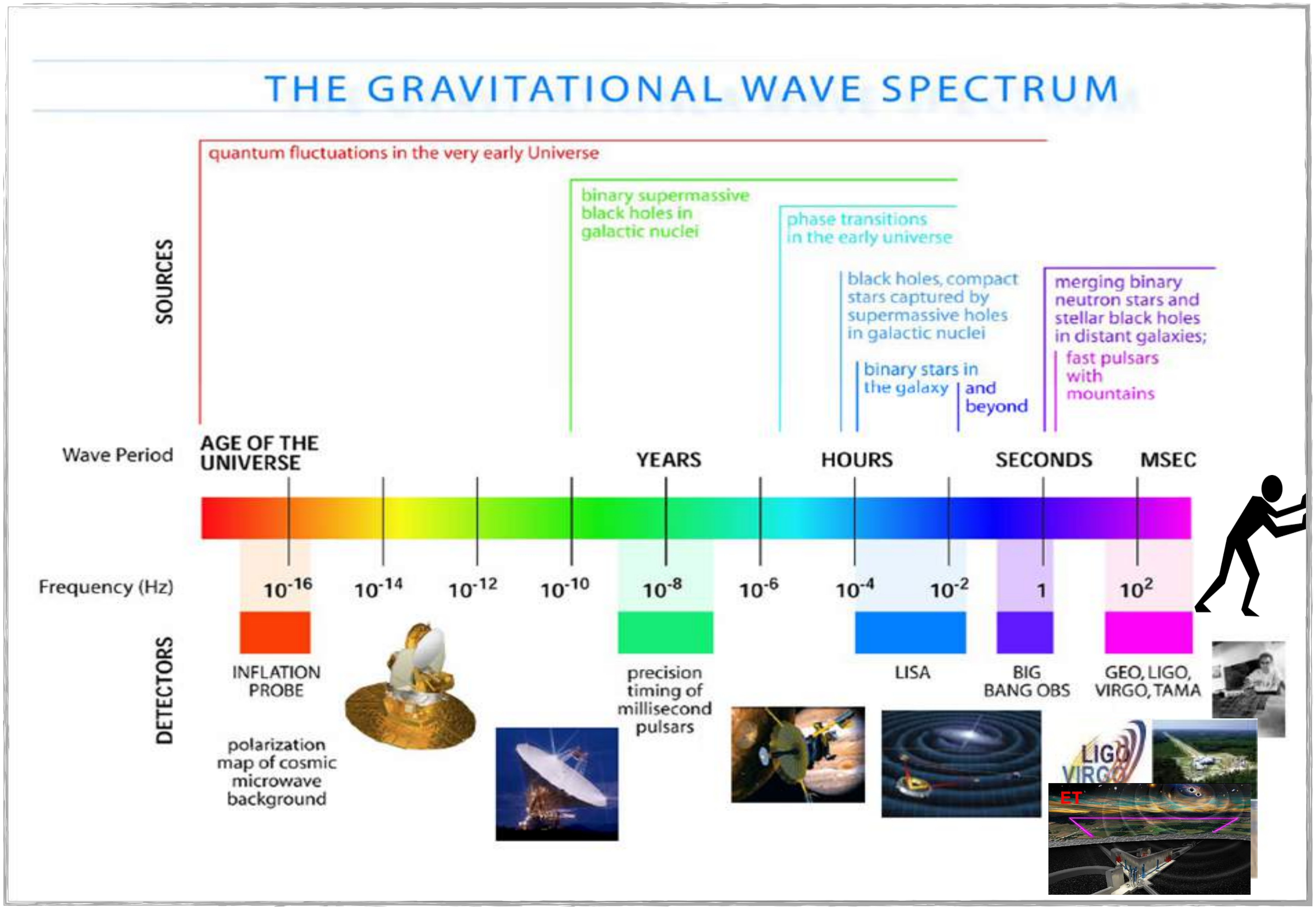
- **Astrophysical**
- **Cosmological**



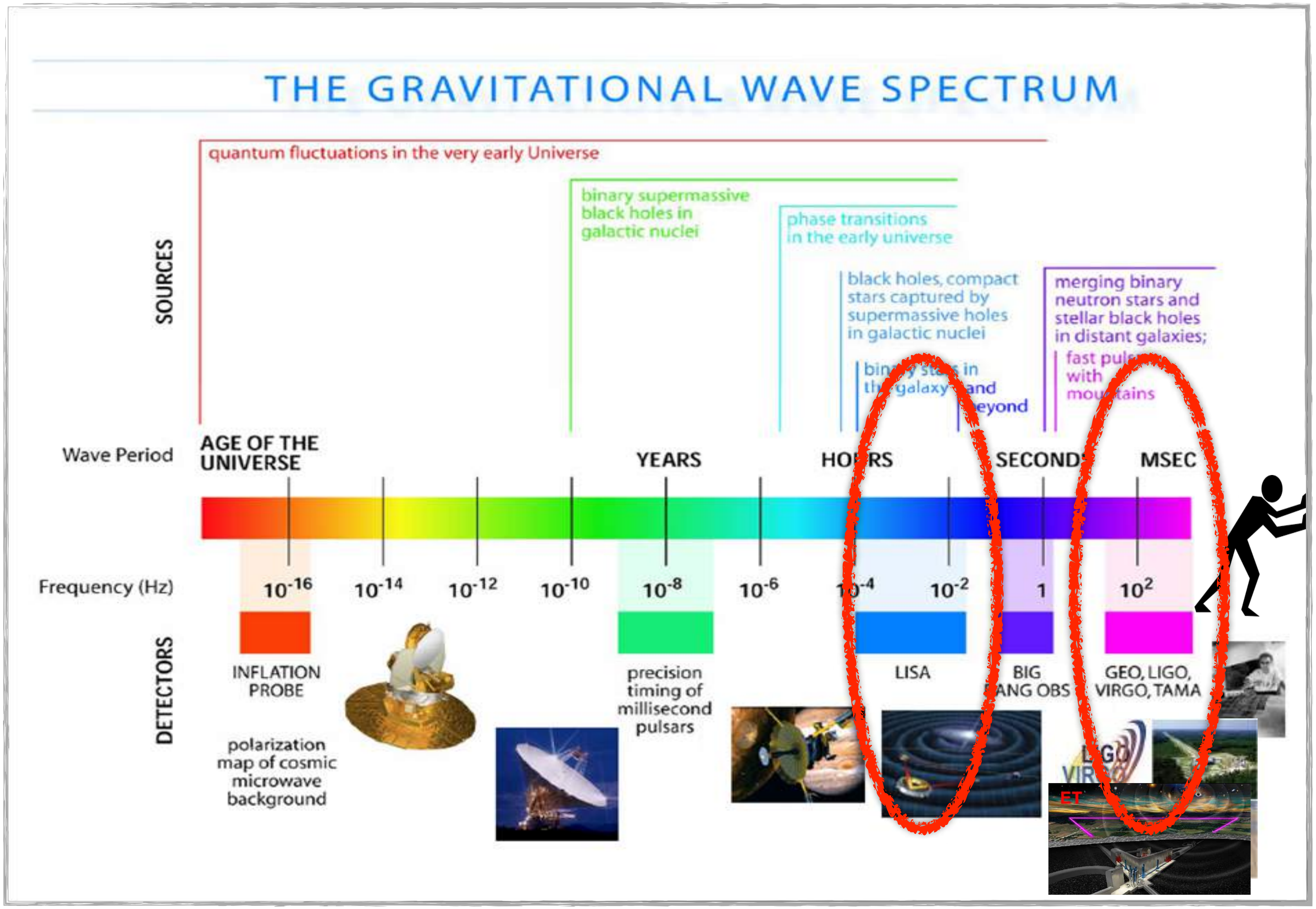
The Gravitational Wave Spectrum



The Gravitational Wave Spectrum

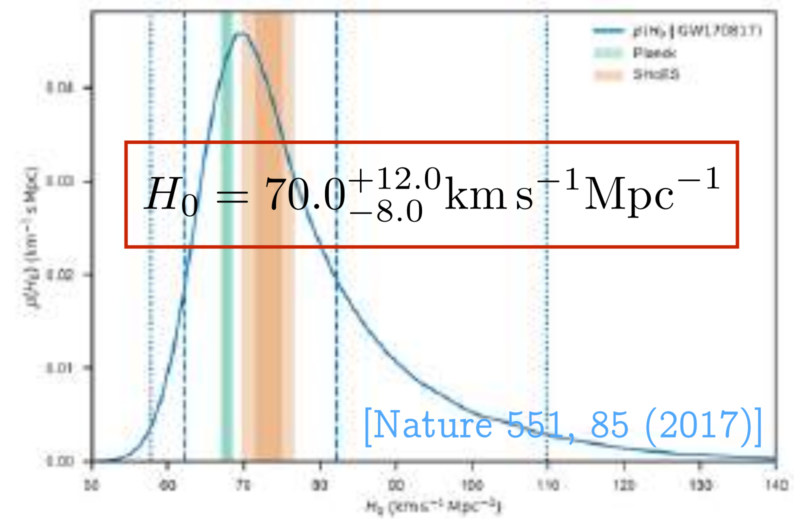


The Gravitational Wave Spectrum



What we have learned about Cosmology so far?

- We obtained the **first measurement of the Hubble constant using GWs**



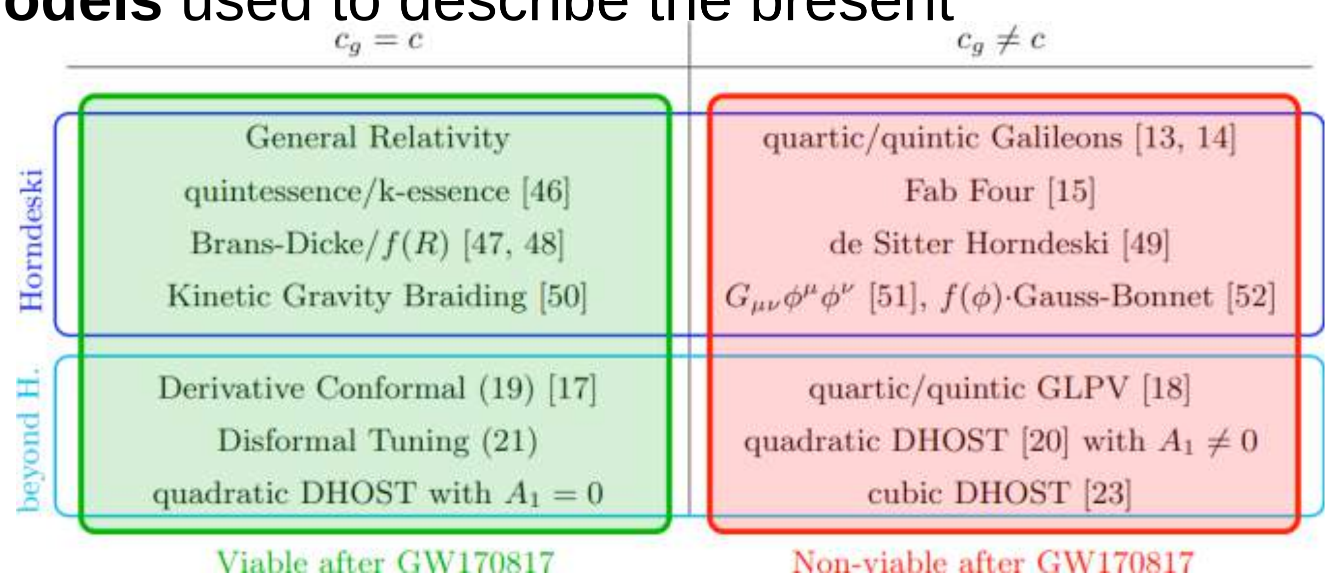
- **We have tested and bounded deviations from GR** (e.g., graviton mass, post-Newtonian coefficients, modified dispersion relations, etc.)

$$m_g \leq 1.27 \times 10^{-23}\,\mathrm{eV/c^2}$$

- **The speed of GWs is the same as the speed of light**

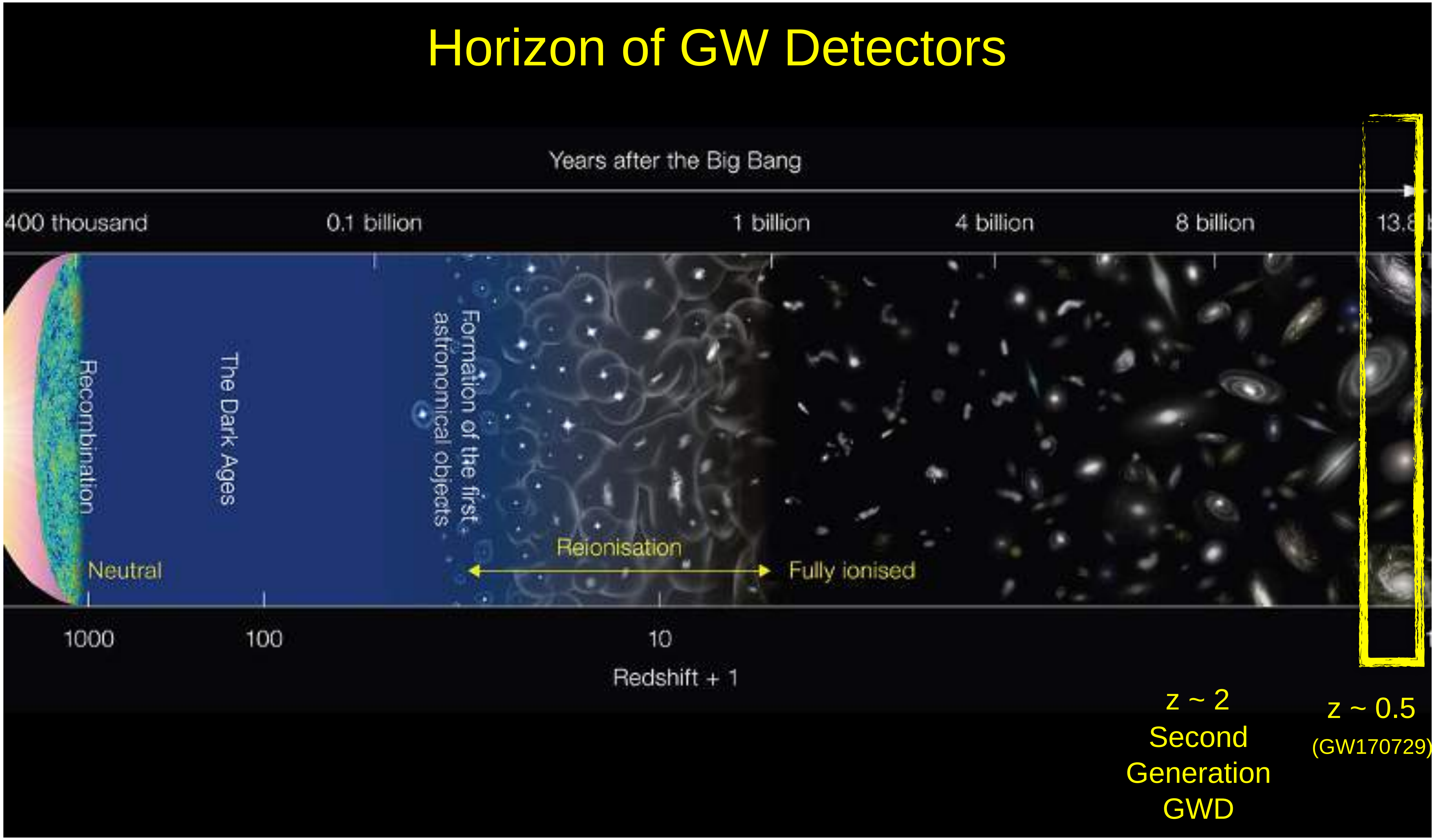
$$-3 \cdot 10^{-15} \leq c_g/c - 1 \leq 6 \cdot 10^{-16}$$

- We have **ruled out many Modified Gravity models** used to describe the present acceleration of our Universe



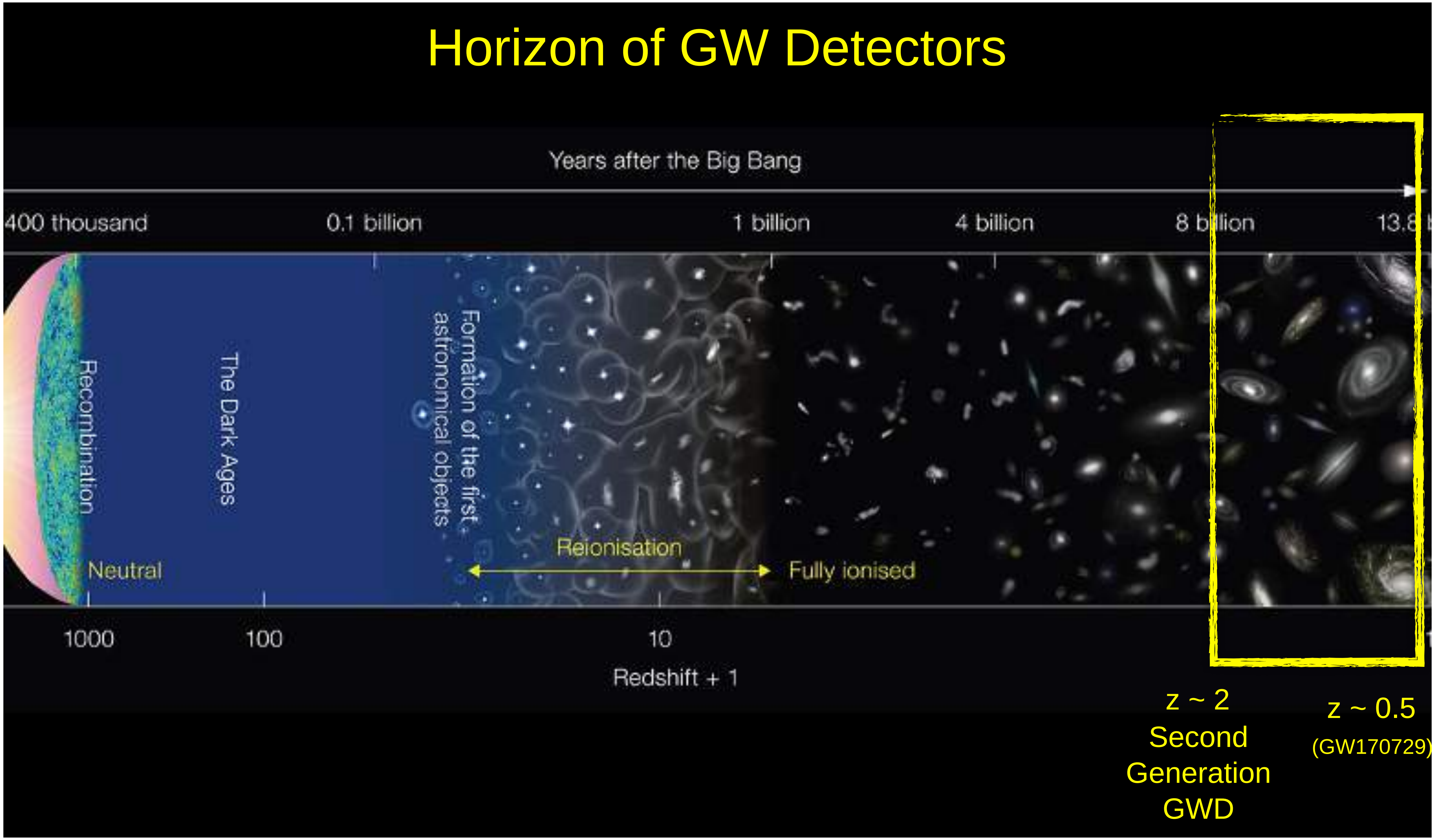
LVK arxiv:2112.06861

Where is the horizon?



Adv LIGO - Virgo - KAGRA:
BBHs only up to z ~ 2
BNSs in the very local Universe

Where is the horizon?



Adv LIGO - Virgo - KAGRA:
BBHs only up to z ~ 2
BNSs in the very local Universe

Open questions in Cosmology

Early Universe

Primordial GWs

Cosmic Structure

Dark Matter

Primordial BHs?

Axion particles

Late Universe

Dark Energy

Modified Gravity?

Cosmic Tensions

H_0 measurements?

Isotropy

Testing Cosmological Principle

RESOLVED SOURCES

SGWB

Open questions in Cosmology

Early Universe

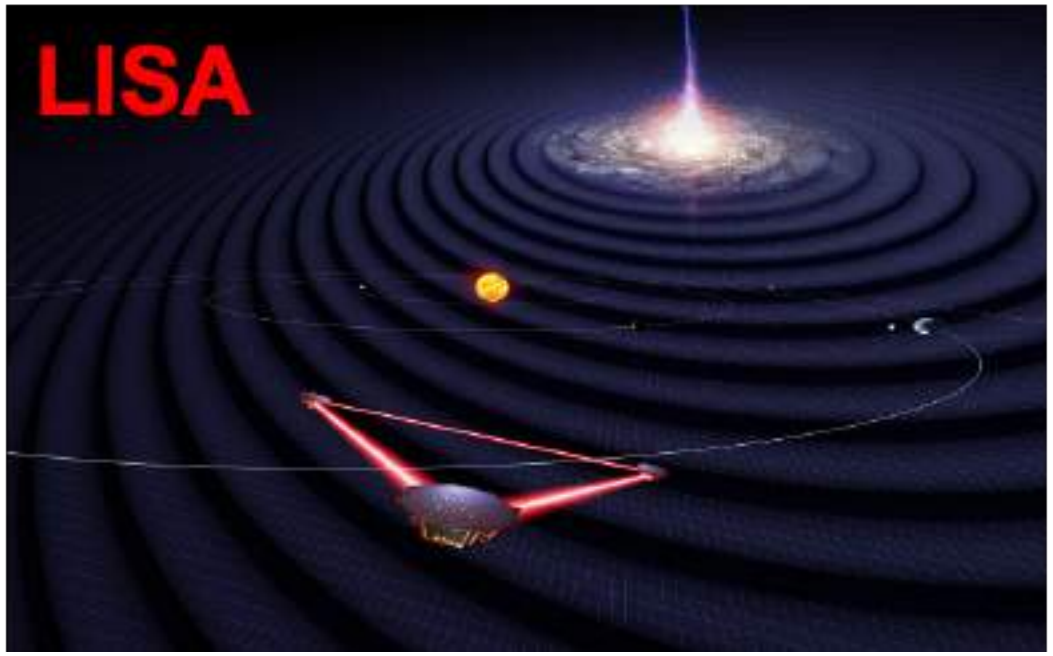
Primordial GWs

Cosmic Tensions

H_0 measurements?

RESOLVED SOURCES **SGWB**

Prospects for next Generation GW Interferometers

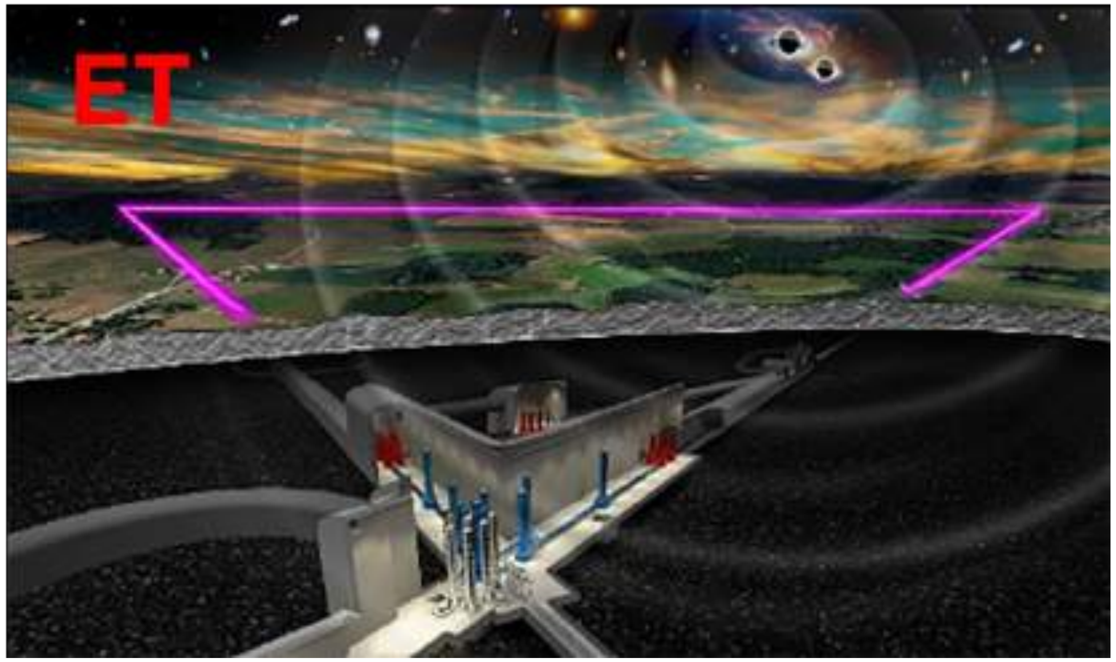


Geometry: **Constellation of 3 spacecraft in an equilateral configuration** (a giant interferometer)

Mission duration: **4 y science mission**
10 y nominal mission

Arm Length: **2.5 million km**

Expected Launch: 2034



Geometry: **Ground-based Triangular detector (HF+LF)**

Arm Length: **10 km**

Expected to be operative in: 2034

ET collaboration officially launched

+ CE, DECIGO, BBO, Taiji, TianQin, etc

Without forgetting AdV -> Virgo-nEXT

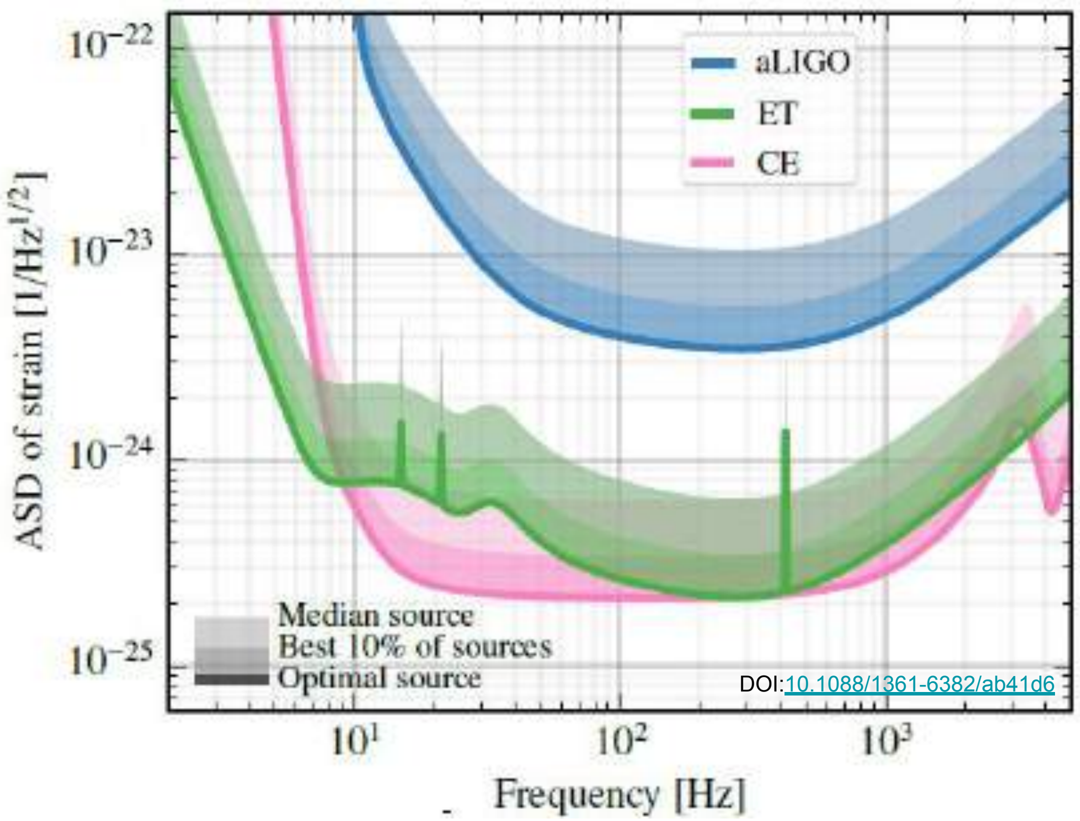
New PTA data

Einstein Telescope

But current LVK detectors have limitations: need to jump to next generation detectors:

- **Einstein Telescope (ET)**:
  - EU proposal for 3G observatory
  - Design study (baseline) triangle with arms of 10km
- **Cosmic Explorer (CE)**:
  - US proposal for 3G observatory
  - L-shaped 40km interferometer

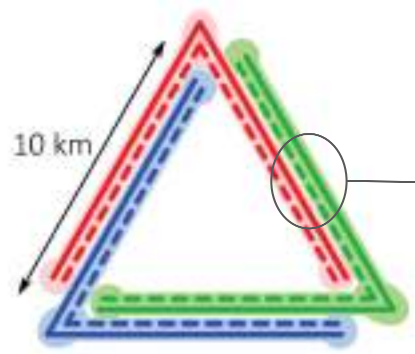
ET and CE will provide an improvement in sensitivity by one order of magnitude and a significant enlargement of the bandwidth



DOI:10.1088/1361-6382/ab41d6

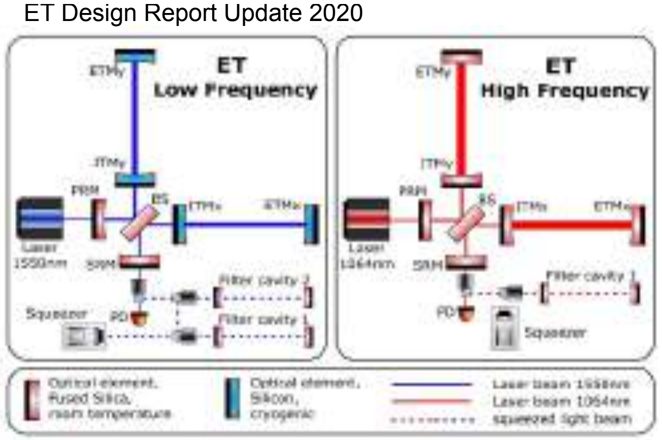
The current design of ET:

- **single site** located **200-300 meters underground** in order to significantly reduce seismic noise;
- **triangular shape**, consisting of three nested detectors
  - providing redundancy
  - resolving the GW polarizations and a null stream
- **'xylophone'** configuration: each detector consists of two interferometers
  - ○ one tuned toward **high frequencies (HF)**, and using high laser power
  - ○ one tuned toward **low-frequency (LF)**, working at cryogenic temperatures and low laser power



ET Design Report Update 2020

ET Design Report Update 2020



Einstein Telescope - possible designs

In the last years, proposals for **different designs** were made as they may bring **scientific advantages** with respect to the baseline design.

PAPER • OPEN ACCESS

Science with the Einstein Telescope: a comparison of different designs

Marica Branchesi[1,2], Michele Maggiore[3,4], David Alonso[5], Charles Badger[6], Biswajit Banerjee[1,2], Freija Beirnaert[7], Enis Belgacem[3,4], Swetha Bhagwat[8,9], Guillaume Boileau[10,11], Ssohrab Borhanian[12]

+ Show full author list

Published 28 July 2023 • © 2023 The Author(s)

Journal of Cosmology and Astroparticle Physics, Volume 2023, July 2023

Citation Marica Branchesi *et al* JCAP07(2023)068

DOI 10.1088/1475-7516/2023/07/068

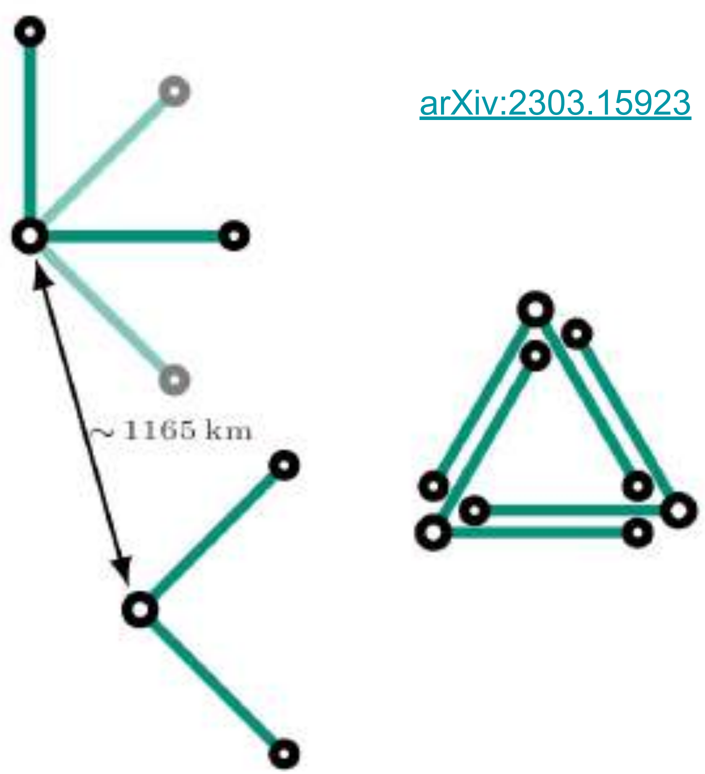
- 197 pages
- 75 authors

Different geometries are studied:

- **1 Triangular detector** vs **2 L-shaped detector**
- **different arm length** (10, 15, 20 km)
- Cryo LF may be challenging to achieve: **HF+LF** vs **HF only**

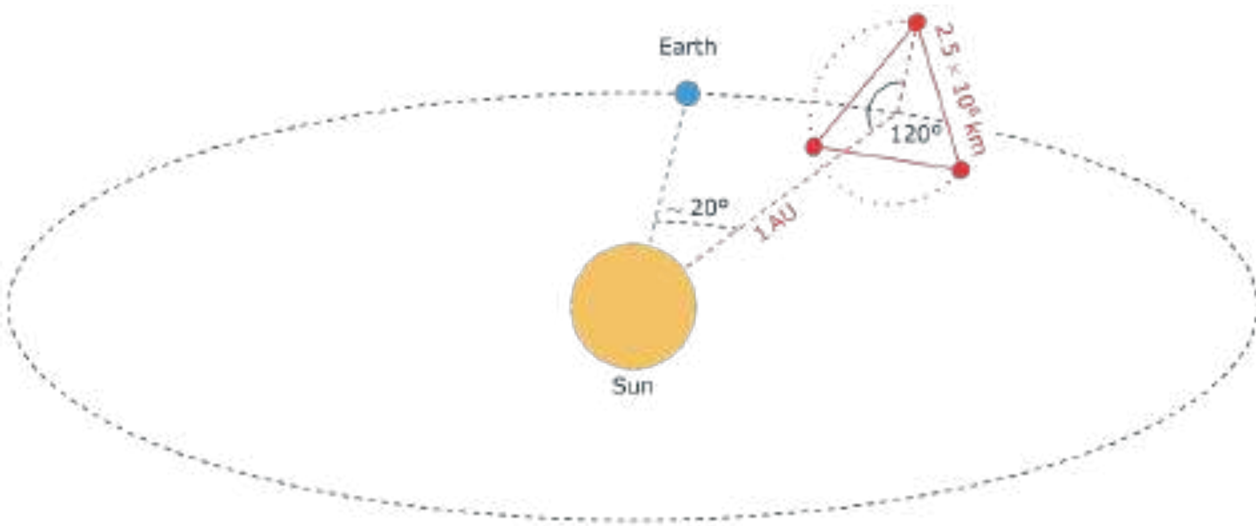
For **2L-shape** two different orientations are proposed:

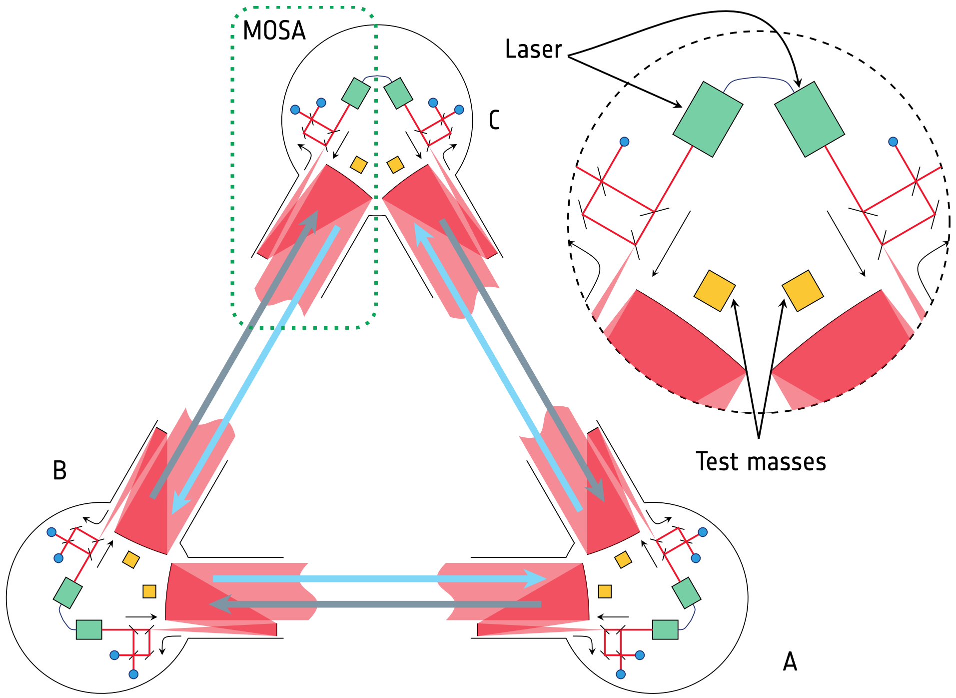
- parallel
- 45° angle



arXiv:2303.15923

LISA





Mission	
Duration	4.5 years science orbit • >82 % duty cycle • ~6.25 years including transfer and commissioning
Constellation	Three drag-free satellites forming an equilateral triangle • 2.5×10^6 km separation • trailing/leading Earth by ~20° • inclined by 60° with respect to the ecliptic
Orbits	Heliocentric orbits • semimajor axis ~1 AU • eccentricity $e \approx 0.0096$ • inclination $i \approx 0.96°$

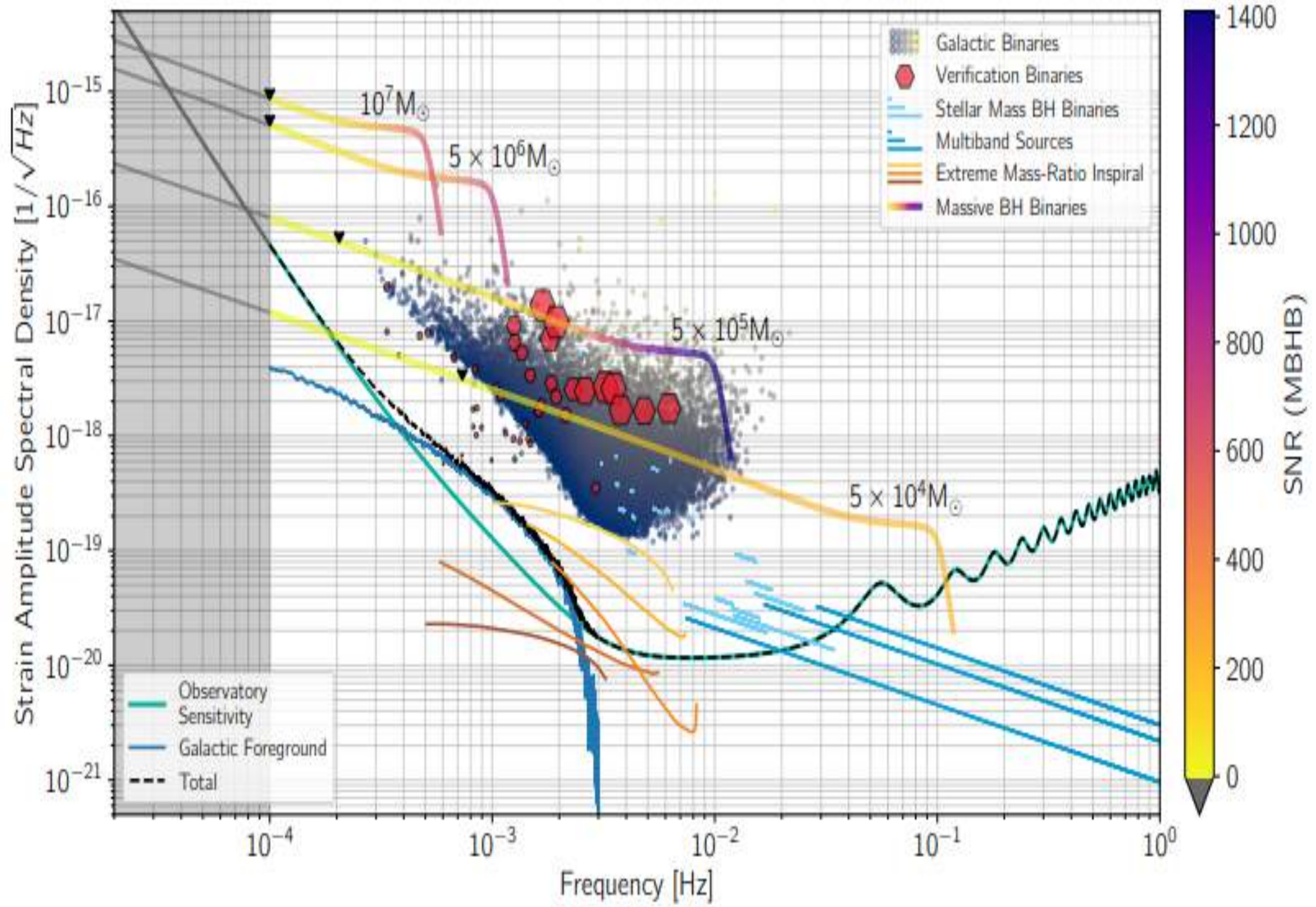
Payload	
Lasers	2 per spacecraft • 2 W output power • wavelength 1064 nm • frequency stability $300\,\mathrm{Hz}/\sqrt{\mathrm{Hz}}$
Optical Bench	2 per spacecraft • double-sided use • high thermal stability (Zerodur)
Interferometry	heterodyne interferometry • $15\,\mathrm{pm}/\sqrt{\mathrm{Hz}}$ precision • Inter-spacecraft ranging to ~1 m
Telescope	2 per spacecraft • 30 cm off-axis telescope • high thermal stability
Gravitational Reference System	2 per spacecraft • acceleration noise $<3\,\mathrm{fm}/(\mathrm{s}^2\sqrt{\mathrm{Hz}})$ • 46 mm cubic AuPt test mass • Faraday cage housing • electrostatic actuation in 5 degree of freedom

LISA RED BOOK- ESA

LISA - Science Objectives

Science Objectives

- Study the formation and evolution of **compact binary stars** and the structure of the Milky Way Galaxy
- Trace the origins, growth and merger histories of **massive Black Holes** across cosmic epochs
- Probe the properties and immediate environments of Black Holes in the local Universe using **extreme mass-ratio inspirals** and **intermediate mass-ratio inspirals**
- Understand the astrophysics of **stellar-mass Black Holes**
- Explore the **fundamental nature of gravity** and Black Holes
- Probe the rate of **expansion of the Universe** with standard sirens
- Understand **stochastic gravitational wave backgrounds** and their implications for the early Universe and TeV-scale particle physics
- Search for gravitational wave bursts and **unforeseen sources**

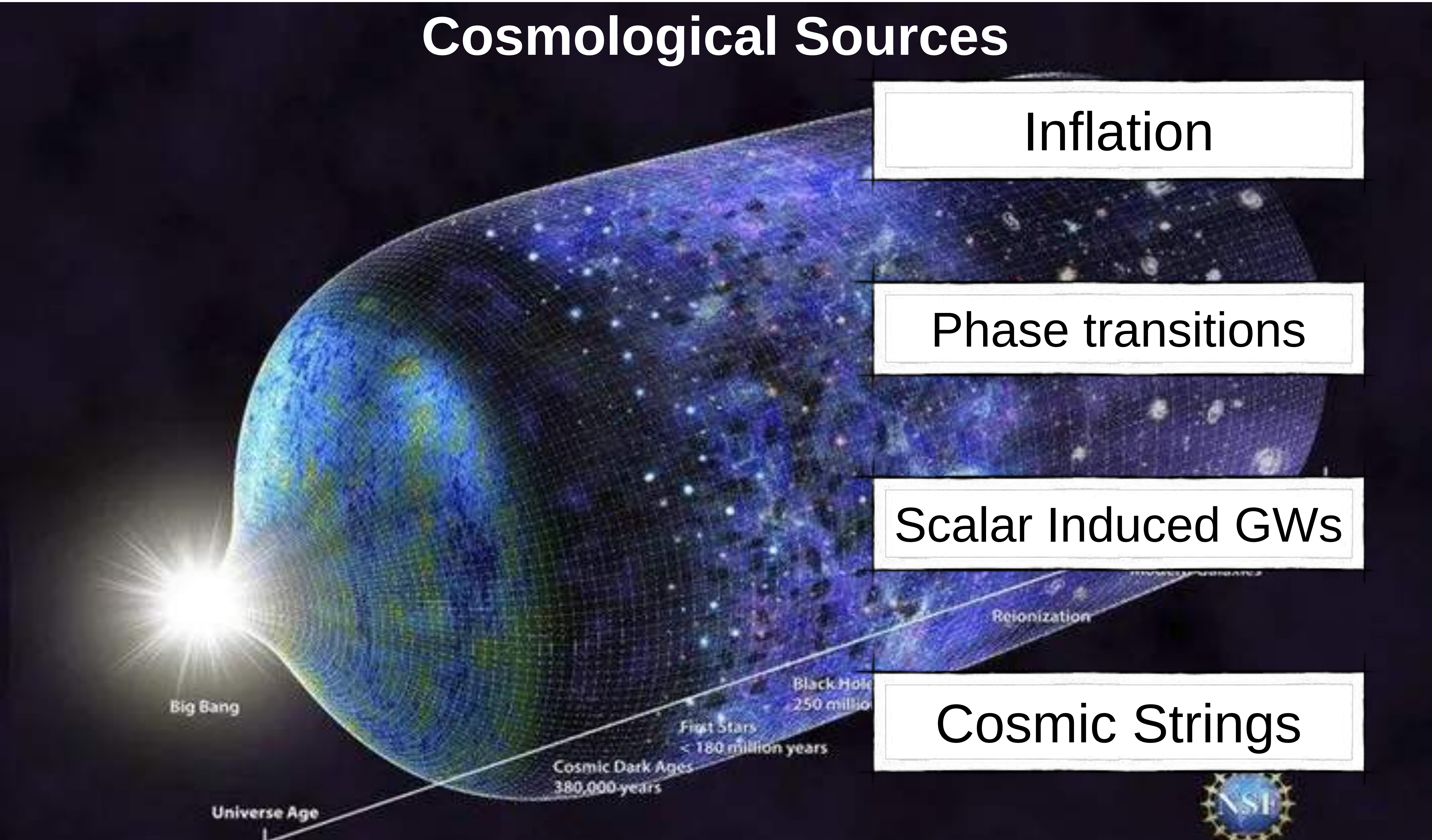


LISA RED BOOK- ESA

Probing the Early Universe

Cosmological Sources

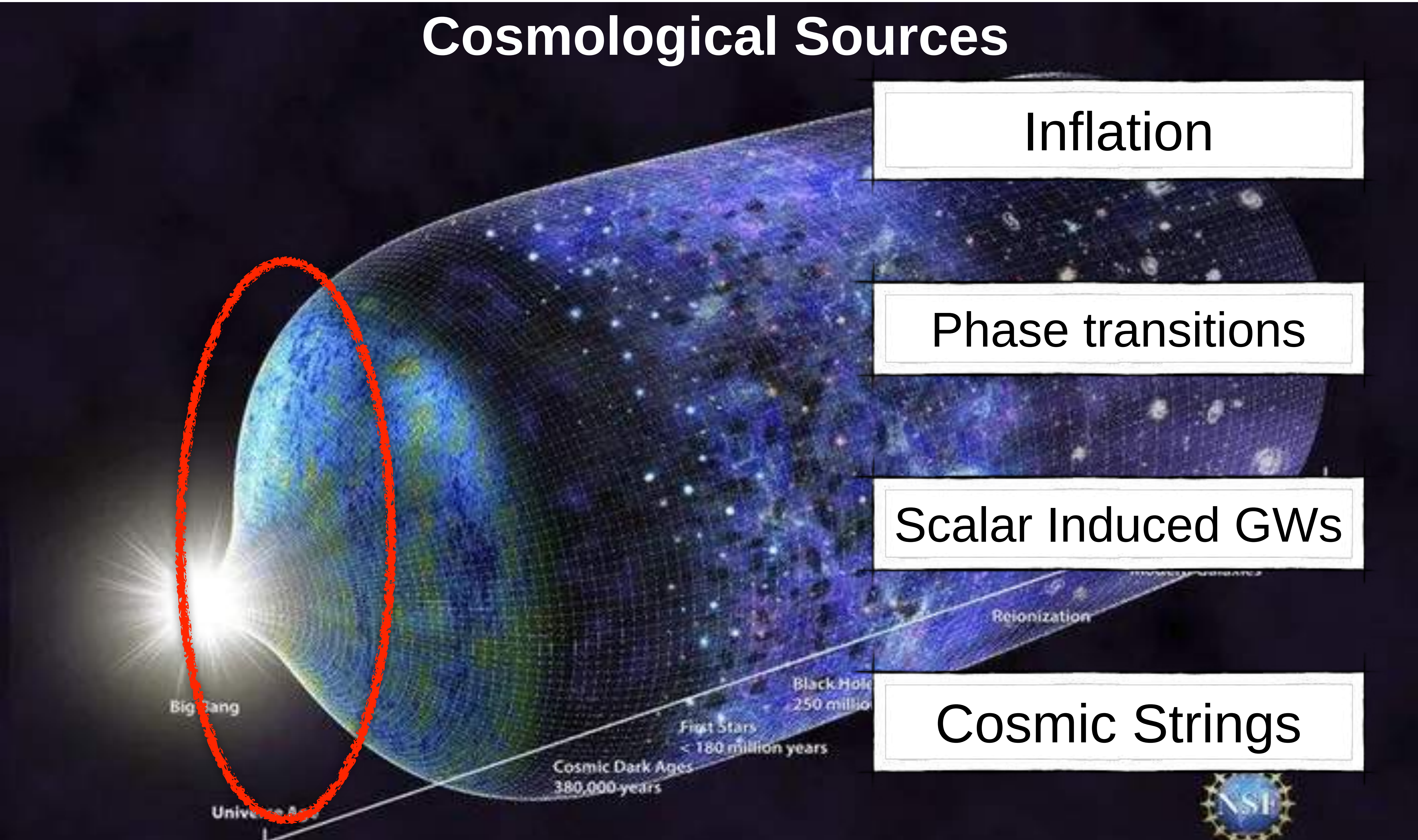
- Inflation
- Phase transitions
- Scalar Induced GWs
- Cosmic Strings



Stochastic (i.e., *persistent, incoherent*) GWB of cosmological origin: **probe of the early Universe at energy scales above the ones achievable at current particle colliders**

Probing the Early Universe

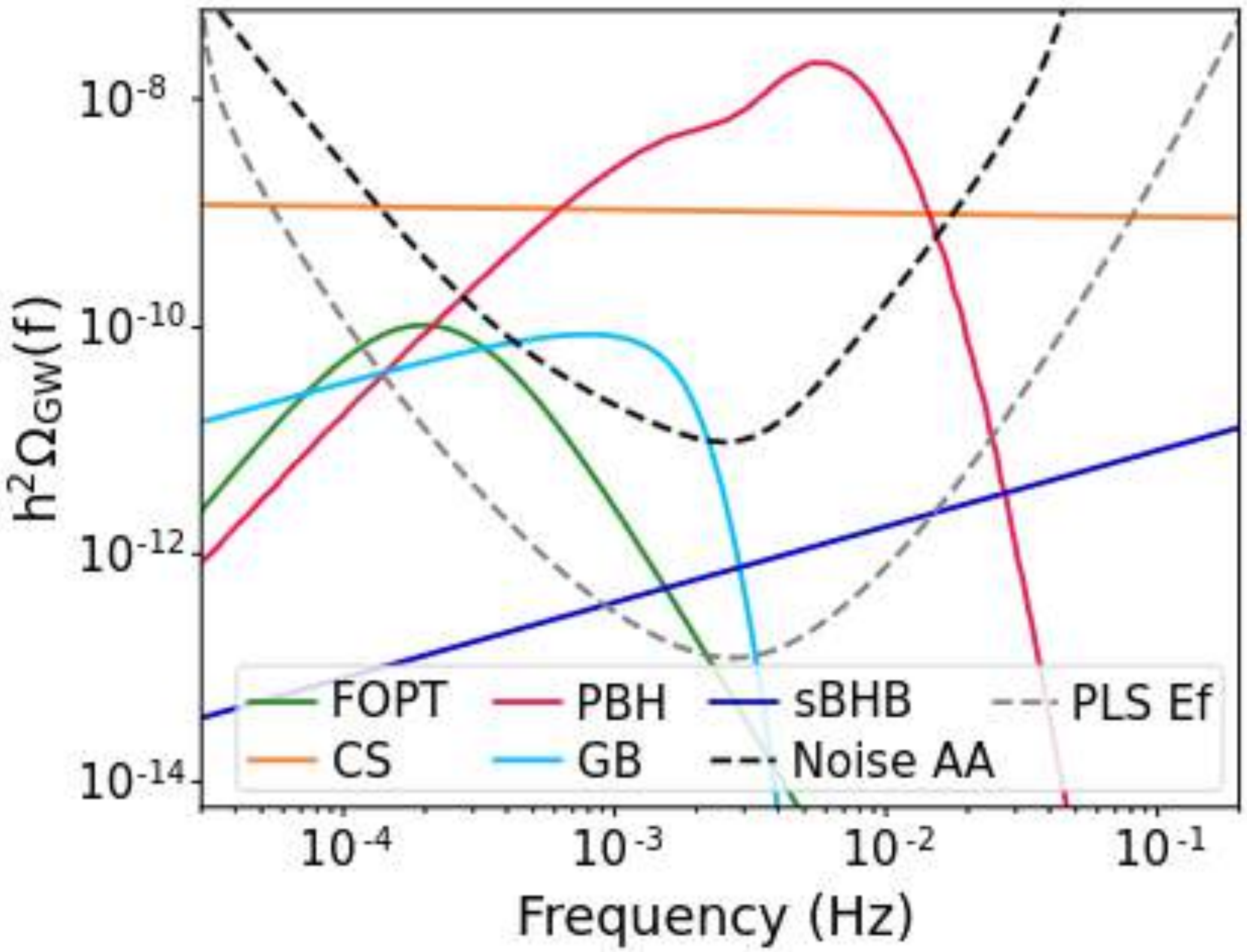
Cosmological Sources



- Inflation
- Phase transitions
- Scalar Induced GWs
- Cosmic Strings

Stochastic (i.e., *persistent, incoherent*) GWB of cosmological origin: **probe of the early Universe at energy scales above the ones achievable at current particle colliders**

GWB sources in the LISA band

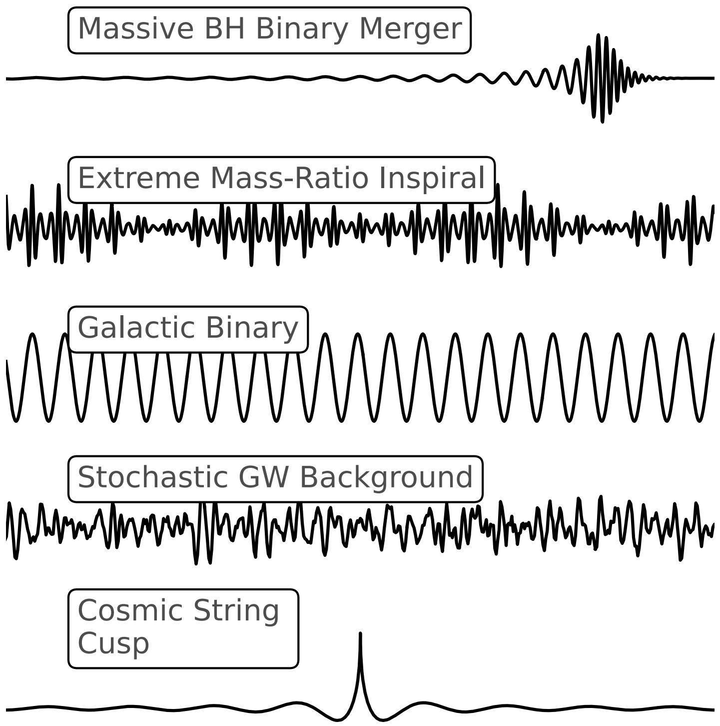


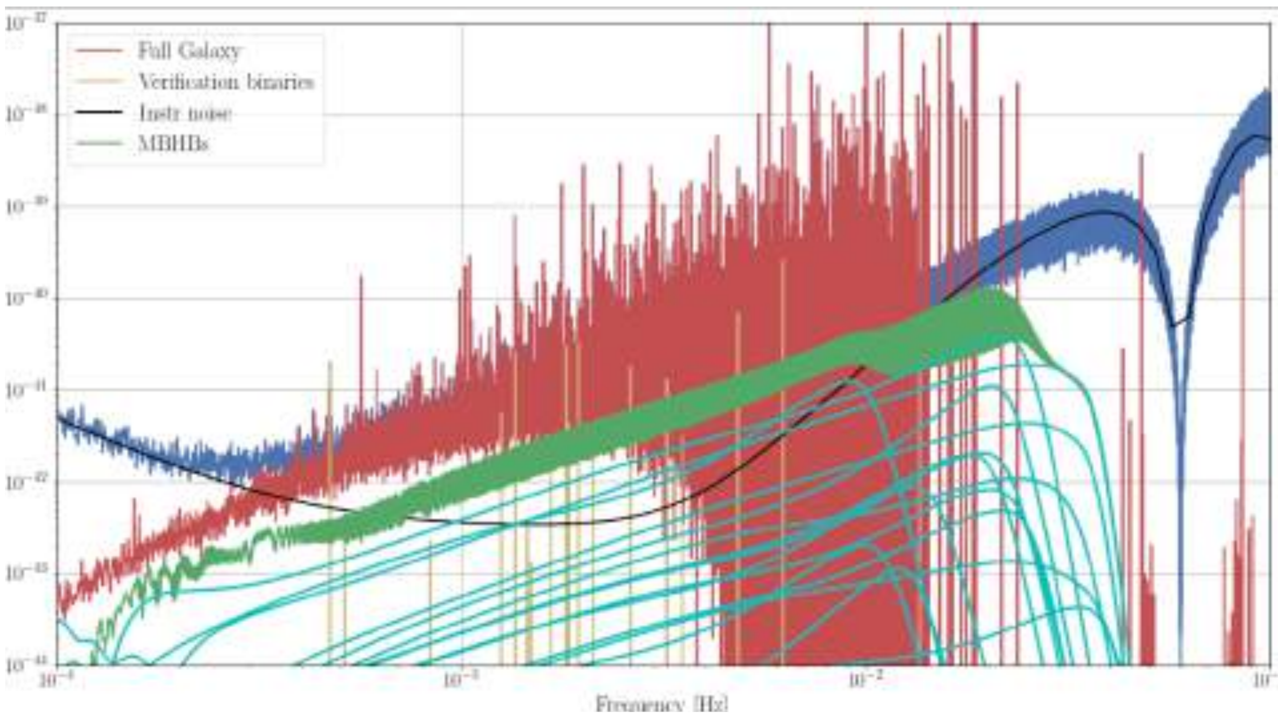
* Figure from M. Colpi et al., ArXiv:2402.07571

At least two AGWB components (sBHBs and CGBs) are guaranteed signals for LISA!

The Cosmological GWB would be an invaluable source of information for HEP

How to approach the data analysis





- Large number of overlapping sources
- Residuals from sources subtraction
- Confusion from unresolved sources
- One doesn't cross-correlate like LVK
- Prediction of the instrumental noise?
- Artefacts: gaps in the data, glitches...

LISA Ground Segment - Italia

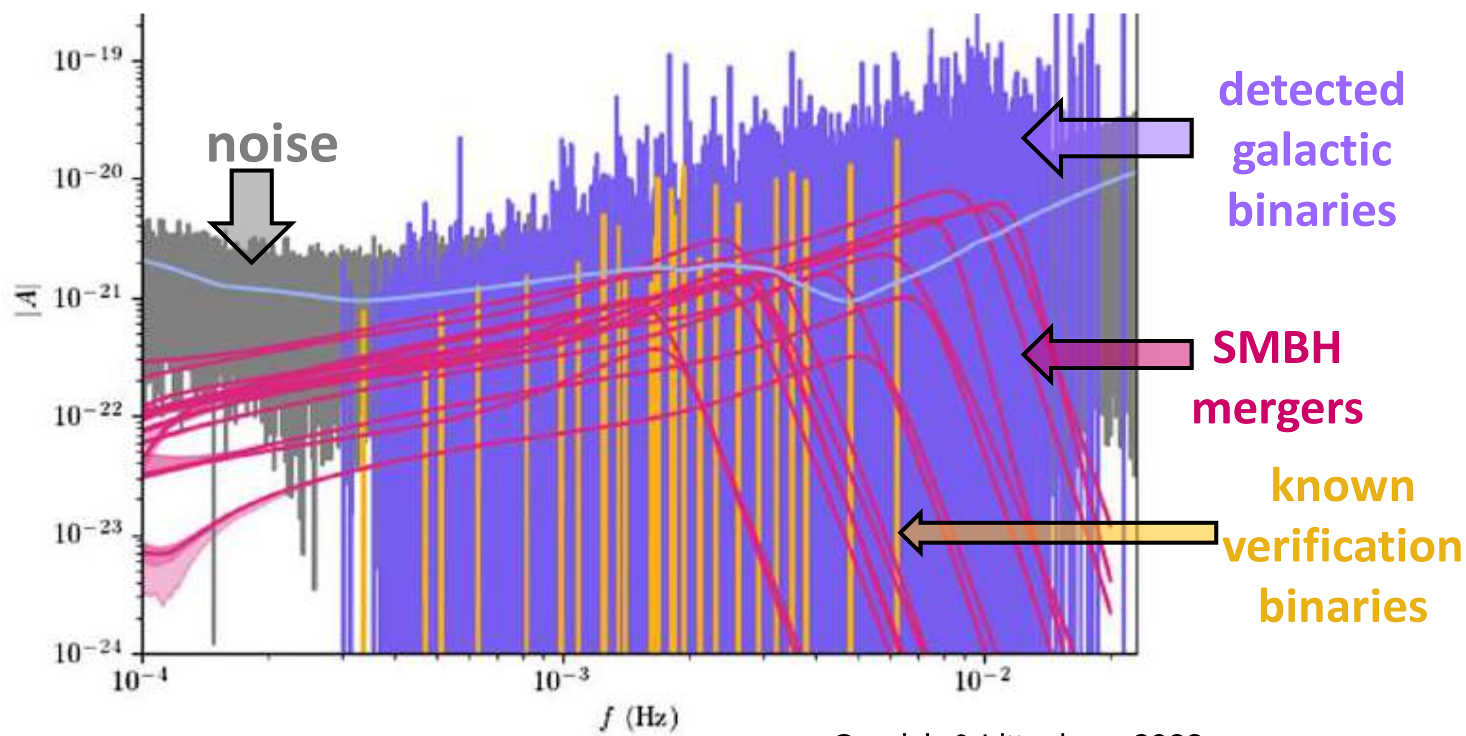
Develop a GLOBAL FIT pipeline for LISA

(Similar approach for ET)

Cornish, Littenberg, 23

Marsat+,24

Katz, Karnesis et al, '23



Cornish & Littenberg 2023

Template Search Algorithm - SGWBinner

SURVEY (INFLATIONARY) MODELS

↓

GROUP THEM ACCORDING TO THE SPECTRAL SHAPE OF Ω_{GW}

↓

BUILD A TEMPLATE BANK

↓

FORECAST CONSTRAINTS ON TEMPLATES → **SGWBinner Code**

↓

DRAW CONCLUSIONS ABOUT EARLY UNIVERSE PHYSICS

LISA CosGW project Arxiv: 2407.04356 (inflation)

Template-based reconstruction with SGWBinner

Based on two LISA COSWG projects:

1906.09244: C. Caprini, D. Figueroa, R. Flauger, M.Pieroni., G. Nardini, M. Peloso, A. R., G. Tasinato

2009.11845: R. Flauger, N. Karnesis, G. Nardini, M. Pieroni, A. Ricciardone, J. Torrado

We look for best approximation of the signal with a multi-PL

$$h^2\Omega_{\rm GW}\left(f,\,\vec{\theta}\right) = \sum_i 10^{\alpha_i}\left(\frac{f}{\sqrt{f_{{\rm min},i}\, f_{{\rm max},i}}}\right)^{p_i} \Theta\left(f - f_{{\rm min},i}\right)\Theta\left(f_{{\rm max},i} - f\right)$$

N bins $\rightarrow 4N$ $(f_{{\rm min},i}, f_{{\rm max},i}, \alpha_i, p_i)$ $+2N$ (noise) parameters.

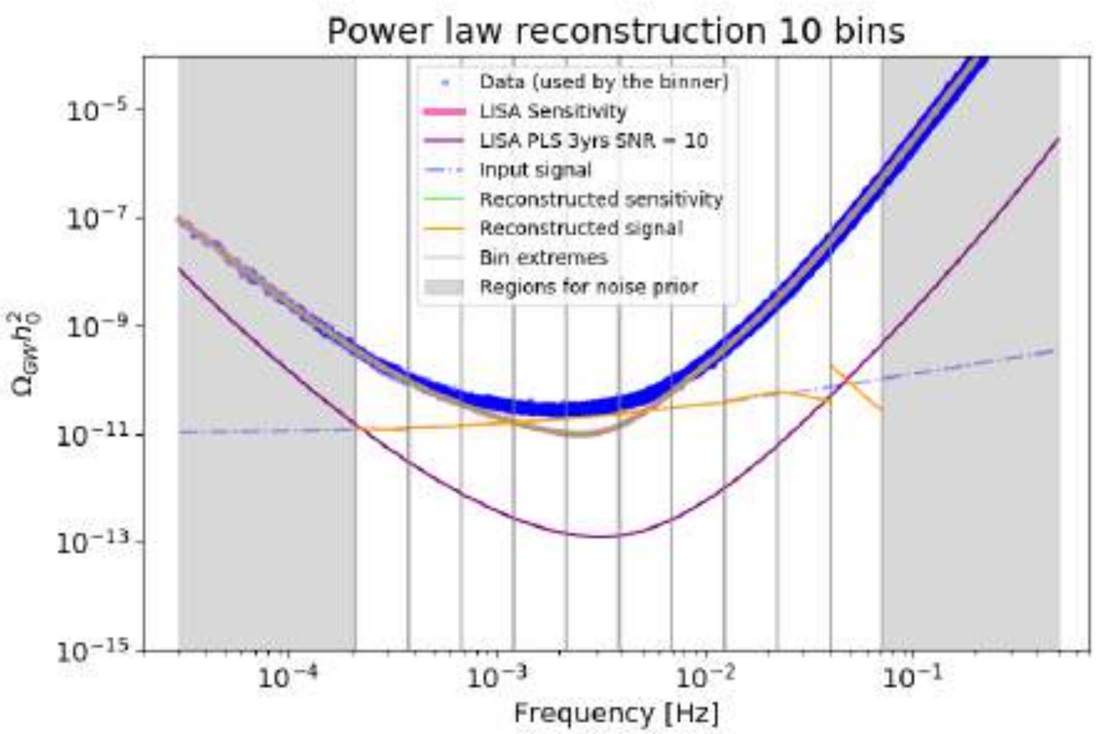
The basic procedure is composed of four steps

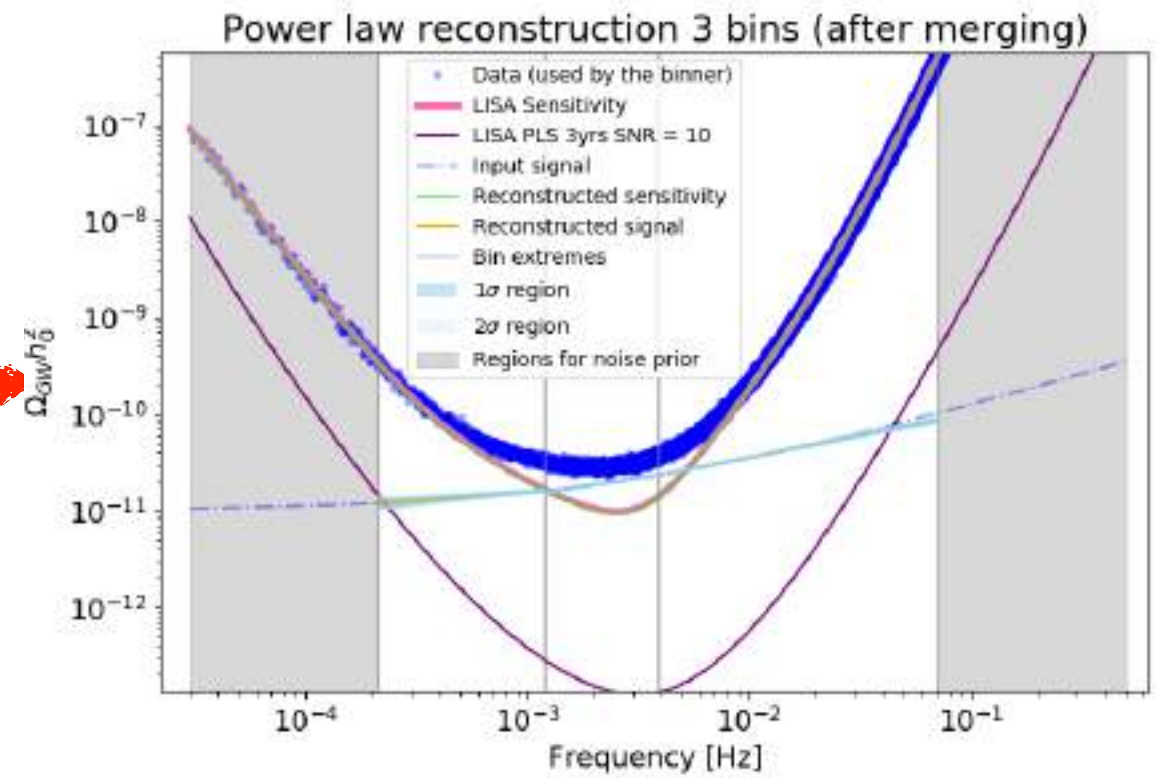
- Build a robust prior for the noise model (to force bin-by-bin measurements)
- Split the frequency range in a set of bins and reconstruct the signal
- Merge as many bins as possible (to avoid overfitting)
- Define a procedure to compute the error on the reconstruction
- Final MCMC run with common noise parameters

SGWBinner code algorithm

Simple application

$$h^2\Omega_{\rm GW}(f) = h^2\Omega_{\rm GW,const}(f) + h^2\Omega_{\rm GW,BHB+NSB}(f) = 10^{-11} + 5.4\times10^{-12}\left(\frac{f}{0.001}\right)^{2/3}$$





After the merging procedure only 3 bins with small error bands are left.

Template-based reconstruction with SGWBinner

LISA will provide three time-domain data streams d_i(t) that we divide in segment of duration τ and then we Fourier transform

$$\tilde{d}_i(f) = \int_{-\tau/2}^{\tau/2} d_i(t)\, \mathrm{e}^{-2\pi i f t}\, \mathrm{d}t$$

I = LISA channel (X, Y, Z or A, E, T)

$$\tilde{d}_i(f) = \sum_\nu \tilde{n}_i^\nu(f_{i,j}) + \sum_\sigma \tilde{s}_i^\sigma(f)$$

Resolved sources $\langle \tilde{d}_i(f) \rangle \neq 0$

SGWB

$$\langle \tilde{d}_i(f) \rangle = 0\,, \qquad \langle \tilde{d}_i(f) \tilde{d}_j^*(f') \rangle = \frac{\delta(f-f')}{2} \left[\sum_\nu P_{N,ij}^\nu(f) + \sum_\sigma P_{S,ij}^\sigma(f) \right]$$

noise and signal power spectra

Time Delay Interferometry

Time-Delay Interferometry (TDI) is employed to suppress laser frequency noise

TDI is a post-processing technique that, combining measurements performed at different times, produces synthesized data streams representing laser-noise-free virtual interferometers.

$\eta_{ij}(t)$ phase measurement performed in spacecraft i at time t of a signal emitted from spacecraft j at time $t - L_{ij}$

L_{ij} Distance between spacecraft

D_{ij} delay operator defined as $D_{ij}x(t) \equiv x(t - L_{ij})$

In practice, TDI consists in defining variables as a linear combination of single-link measurements and delay operators.

The most common choice for LISA data analysis is to use three Michelson-like variables X, Y, Z

$$\mathrm{X} = (1 - D_{13}D_{31})(\eta_{12} + D_{12}\eta_{21}) + (D_{12}D_{21} - 1)(\eta_{13} + D_{13}\eta_{31})$$

Time Delay Interferometry

Then you can build (quasi-)orthogonal channels

$$A = \frac{Z - X}{\sqrt{2}}, \qquad E = \frac{X - 2Y + Z}{\sqrt{6}}, \qquad T = \frac{X + Y + Z}{\sqrt{3}}$$

the T channel strongly suppresses GW signals compared to instrumental noise,

Assuming TDI suppresses laser noise, the main residual noise sources for LISA (also known as secondary noises) are:

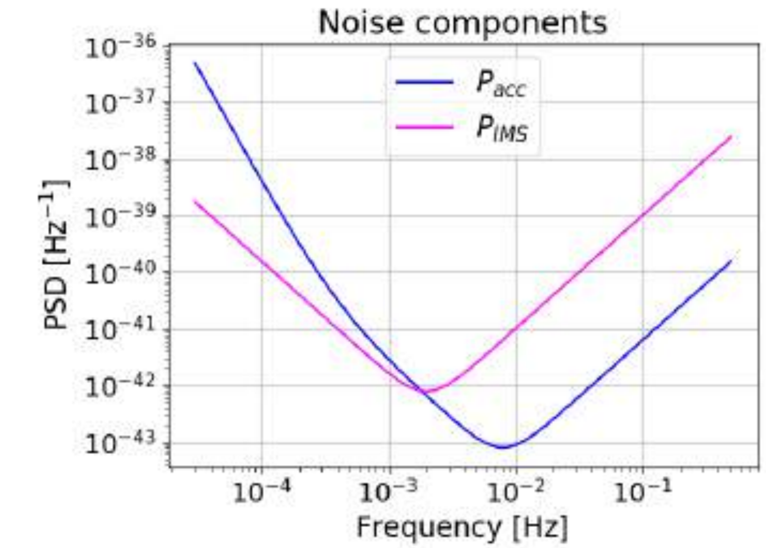
- **Test Mass (TM) noise,** representing deviations from free- fall in the TM trajectories,
- **Optical Metrology System (OMS) noise**, representing uncertainties in the determination of the TM positions.

$$P_{N,ij}(f) \equiv \sum_{\nu} P^{\nu}_{N,ij}(f) = \left[T^{\rm TM}_{ij,lk}(f) S^{\rm TM}_{lk}(f) + T^{\rm OMS}_{ij,lk}(f) S^{\rm OMS}_{lk}(f)\right]$$

With

$$S^{\rm TM}_{lk}(f) = A^2_{lk}\left(1 + \left(\frac{0.4\rm mHz}{f}\right)^2\right)\left(1 + \left(\frac{f}{8\rm mHz}\right)^4\right)\left(\frac{1}{2\pi f c}\right)^2 \left(\frac{\rm fm^2}{\rm s^3}\right)$$

$$S^{\rm OMS}_{lk}(f) = P^2_{lk}\left(1 + \left(\frac{2\times 10^{-3}\rm Hz}{f}\right)^4\right) \times \left(\frac{2\pi f}{c}\right)^2 \times \left(\frac{\rm pm^2}{\rm Hz}\right)$$



Signal Power Spectral Density

$$P_{S,ij}(f) \equiv \sum_{\sigma} P^{\sigma}_{S,ij}(f) = \mathcal{R}_{ij}(f)\left[S_{\rm Gal}(f) + S_{\rm Ext}(f) + S_{\rm Cosmo}(f)\right]$$

Spectral density for galactic binaries

$$h^2\Omega_{\rm GW}(f) \equiv \frac{4\pi^2 f^3}{3H_0^2} S_h(f)$$

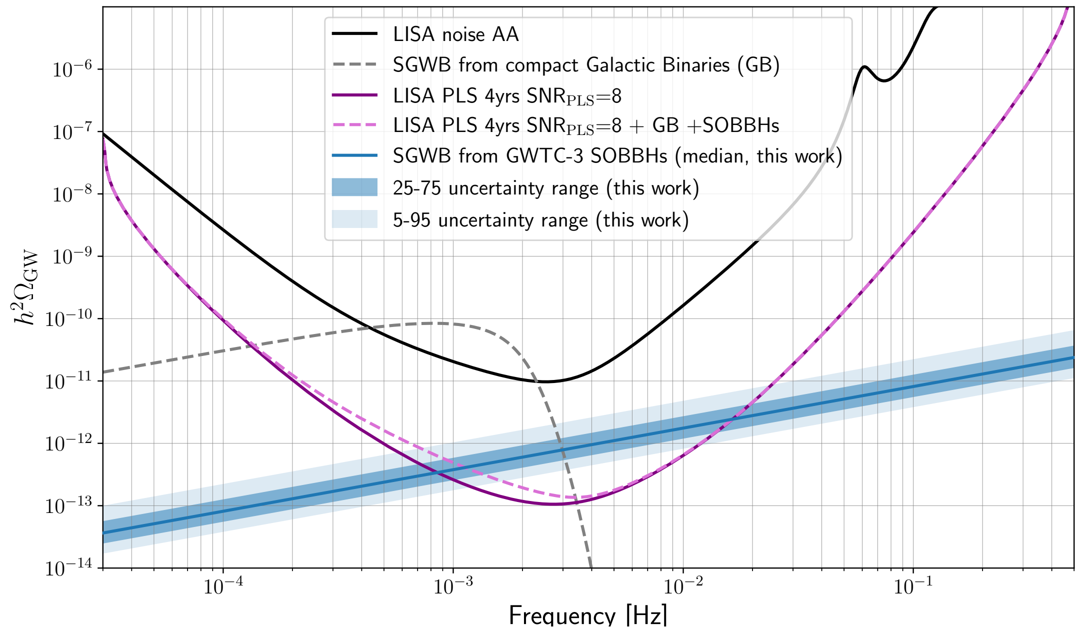
$$\log_{10}(f_1) = a_1 \log_{10}(T_{obs}) + b_1$$

$$\log_{10}(f_{\rm knee}) = a_k \log_{10}(T_{obs}) + b_k$$

$$S_{\rm Gal}(f) = A_{\rm Gal}\left(\frac{f}{1\,{\rm Hz}}\right)^{-\frac{7}{3}} \times e^{-(f/f_1)^{\alpha}} \times \frac{1}{2}\left[1 + \tanh\frac{f_{\rm knee} - f}{f_2}\right]$$

Spectral density for Stellar Origin Black Holes

$$h^2\Omega_{\rm Ext} = 10^{\log_{10}(h^2\Omega_{\rm Ext})}\left(\frac{f}{0.001{\rm Hz}}\right)^{2/3}$$



S. Babak et al., ’23

Data Generation and Likelihood

We generate N_d Gaussian realisations for the signal and all noise components, with zero mean and variances defined by their respective power spectral densities.

We perform a Fourier transform in each of the segments to get the frequency domain data

$$\bar{D}^{\rm k}_{ij} \equiv \sum_{s=1}^{N_d} \tilde{d}^s_i(f_{\rm k})\tilde{d}^s_j(f_{\rm k})/N_d$$

We coarse grain and average over segments

Full Likelihood

$$\ln \mathcal{L}(\vec{\theta}) = \frac{1}{3}\ln \mathcal{L}_{\rm G}(\vec{\theta}|D^k_{ij}) + \frac{2}{3}\ln \mathcal{L}_{\rm LN}(\vec{\theta}|D^k_{ij})$$

$$\ln \mathcal{L}_{\rm G}(\vec{\theta}|D^k_{ij}) = -\frac{N_d}{2}\sum_k\sum_{i,j} w^k_{ij}\left[1 - D^k_{ij}/D^{\rm Th}_{ij}(f^k_{ij},\vec{\theta})\right]^2$$

$$\ln \mathcal{L}_{\rm LN}(\vec{\theta}|D^k_{ij}) = -\frac{N_d}{2}\sum_k\sum_{i,j} w^k_{ij}\ln^2\left[D^{\rm Th}_{ij}(f^k_{ij},\vec{\theta})/D^k_{ij}\right]$$

to take into account the mild non-Gaussianity introduced by the data generation, and to avoid biased results

[S. Hamimeche and A. Lewis 0801.0554]

$D^{\rm Th}_{ij}(f_k,\vec{\theta})$ theoretical model for the data (containing both signal and noise)

Forecast parameters

Parameters

$$\vec{\theta} = \{\vec{\theta}_s, \vec{\theta}_n\}$$

$$\vec{\theta}_n = \{A, P\}\,, \qquad \vec{\theta}_s = \{\vec{\theta}_{\rm fg}, \vec{\theta}_{\rm cosmo}\}$$

Astrophysical parameters

Cosmological parameters

$$\vec{\theta}_{\rm fg} = \{h^2\Omega_{\rm Gal}, h^2\Omega_{\rm Ext}\}$$

$$\vec{\theta}_{\rm cosmo} \qquad \text{(template dependent)}$$

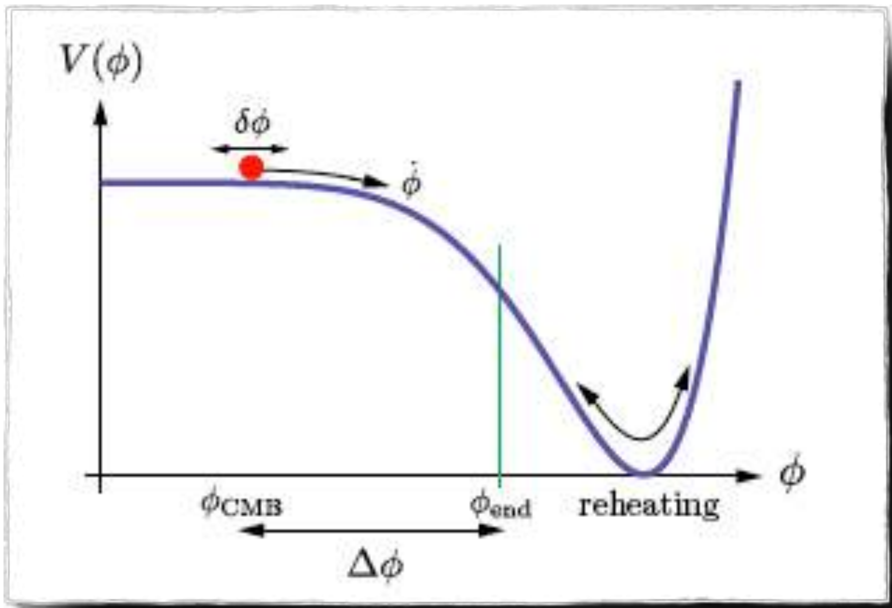
Fisher Matrix

$$F_{\alpha\beta} \equiv T_{\rm obs} \sum_{i\in\{\rm AET\}} \int_{f_{\rm min}}^{f_{\rm max}} \frac{\partial \ln C_{ii}}{\partial\theta^\alpha} \frac{\partial \ln C_{ii}}{\partial\theta^\beta}\, {\rm d}f$$

$$C_{ij}(f_k, \theta_0) = \tilde{d}_i^k \tilde{d}_j^{k*}$$

$$\text{SNR} \equiv \sqrt{T_{\rm obs} \sum_{i\in\{\rm AET\}} \int_{f_{\rm min}}^{f_{\rm max}} \left(\frac{S_{i,\rm GW}}{S_{i,\rm N}}\right)^2 {\rm d}f}\,.$$

Inflation and Primordial GWs



- Period of accelerated (exponential) expansion driven by a scalar field (inflaton) that rolls down on its flat potential

Solve Standard Big-Bang shortcomings

Generation of TENSOR and scalar perturbations

Stretches the microphysics scales to super-horizon sizes

GW are represented by tensor perturbation h_{ij} of the FLRW metric

$$ds^2 = -dt^2 + a^2(t)(\delta_{ij} + h_{ij})dx^i dx^j$$

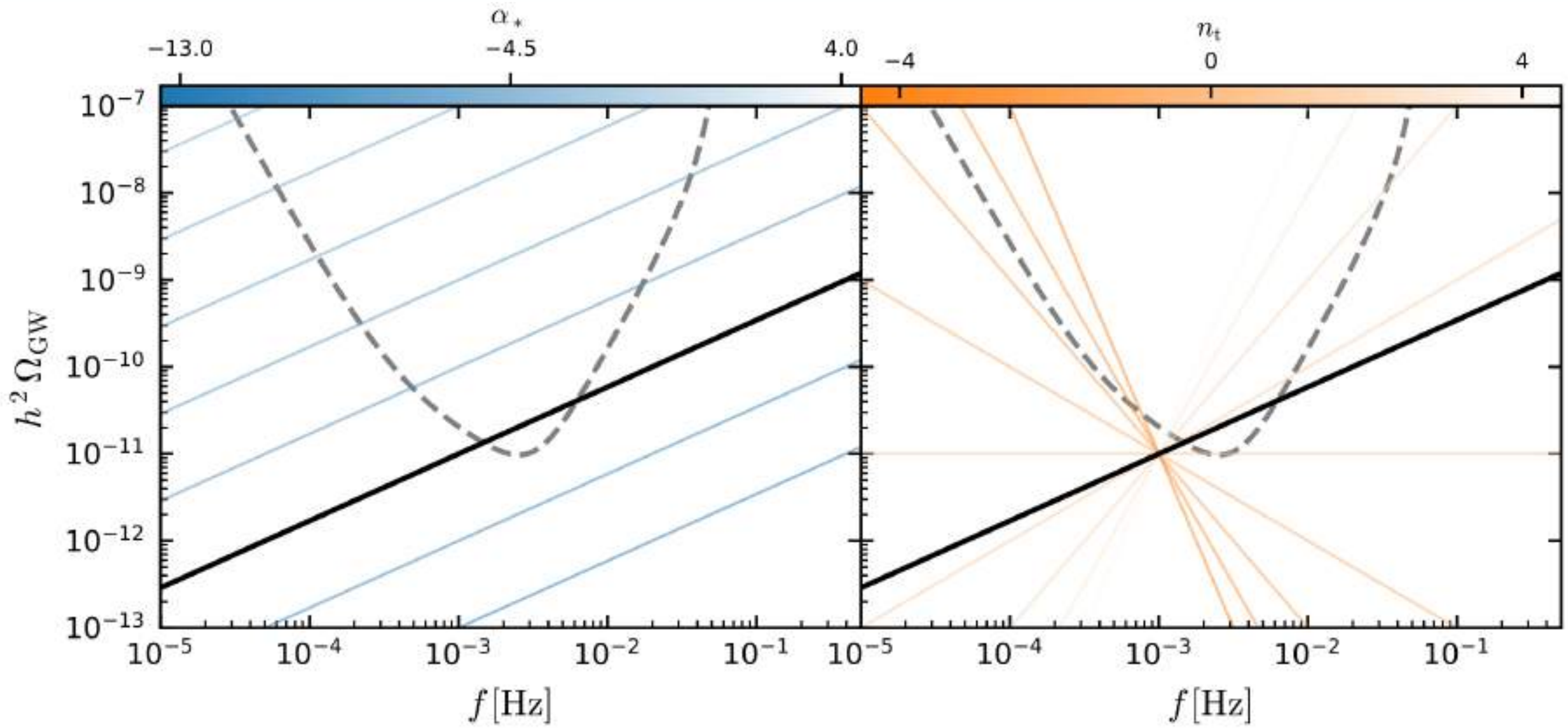
Transverse and Traceless $\partial_i h^i_{\ j} = h_{ii} = 0$ → 2 D.O.F

(2 polarizations)

Power Law Template

$$h^2\Omega_{\rm GW}^{\rm PL}(f,\vec{p}) = 10^{\alpha_*}\left(\frac{f}{f_*}\right)^{n_t}$$

$$\vec{p} = \{\alpha_*, f_*, n_t\}$$



Inflationary models producing such a signal

Axion inflation:

$$\mathcal{L} \supset -\frac{\varphi}{4f} F_{\mu\nu} \tilde{F}^{\mu\nu}$$

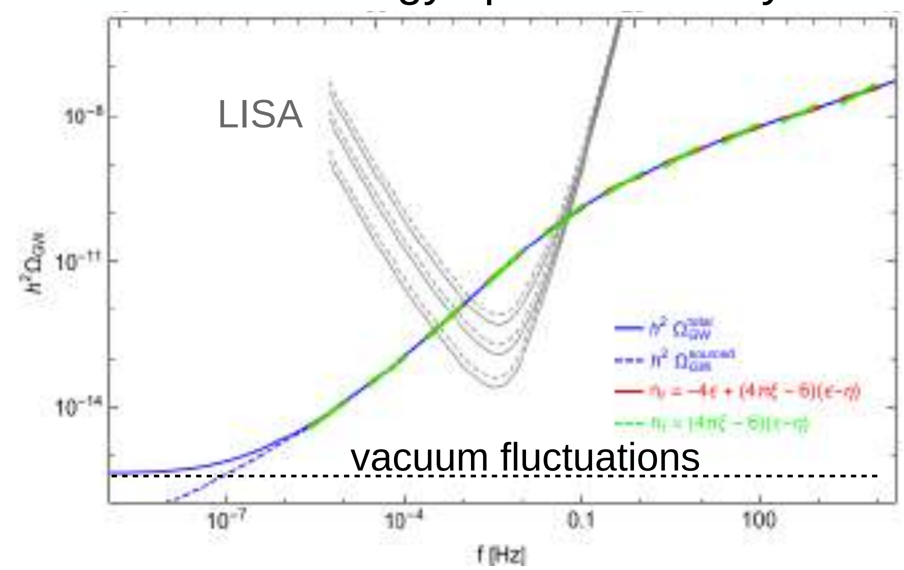
$$\xi \equiv \frac{\dot{\varphi}}{2fH}$$

[Barnaby & Peloso 1011.1500]
[Sorbo 1101.1525]

The **rolling axion strongly amplifies the gauge field, which in turn produces a strong SGWB.**

See M. Peloso's talk

GW energy spectrum today



$$h^2\Omega_* \simeq 1.5 \times 10^{-13} \frac{H_*^4}{M^4} \frac{e^{4\pi\xi_*}}{\xi^6}$$

$$n_t \simeq -4\epsilon_* + (4\pi\xi_* - 6)(\epsilon_* - \eta_*)$$

Broken space diffeomorphisms:

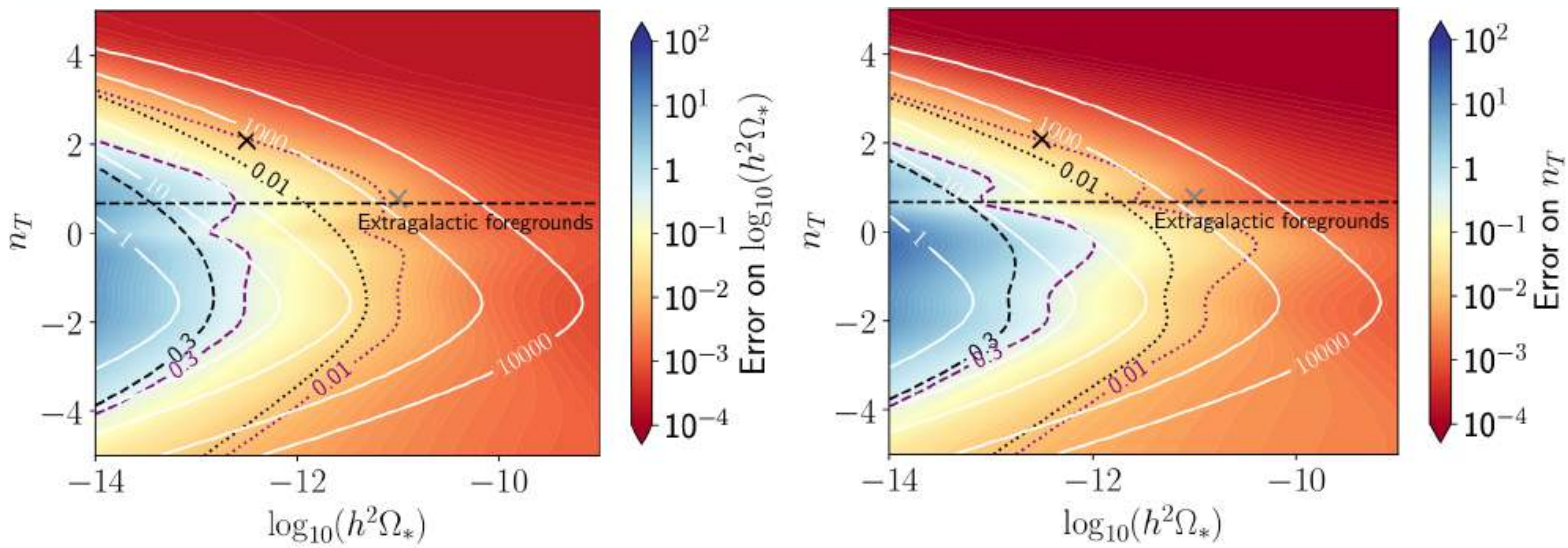
[Ricciardone & Tasinato 1611.04516, 1711.02635]
[Fujita et al 1808.02381]

$h^2\Omega_* =$ Model dependent

The breaking of space diffeomorphisms can give rise to a **massive graviton during the inflationary epoch** which tilts the SGWB spectrum towards the **blue**

$$n_t \simeq \frac{2}{3} \frac{m_h^2}{H_*^2} > 0$$

(Fisher) Forecast for Power Law GWB



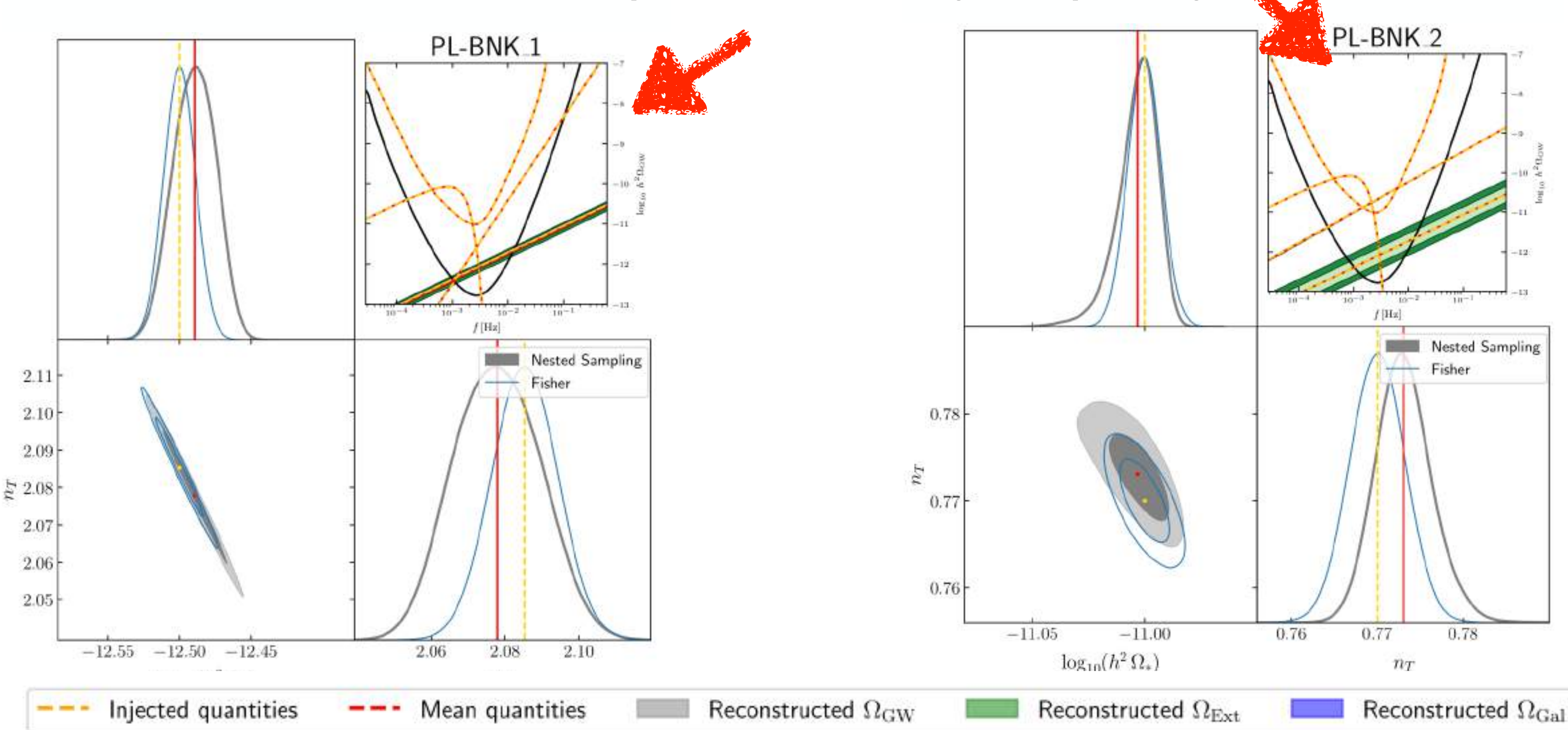
- For a flat signal (i.e., nT = 0), an accuracy σ ≃ O(0.01) on the logarithm of the amplitude requires $h^2\Omega_* \simeq 10^{-12}$ without foregrounds

- In presence of foregrounds only slightly larger errors.

- Peculiar behavior along the line at nT = 2/3, where the primordial SGWB is degenerate with the foreground due to the extragalactic compact binaries.

(Nested Sampling) Forecast

Predictive posterior distribution of noise, foregrounds and primordial signal.



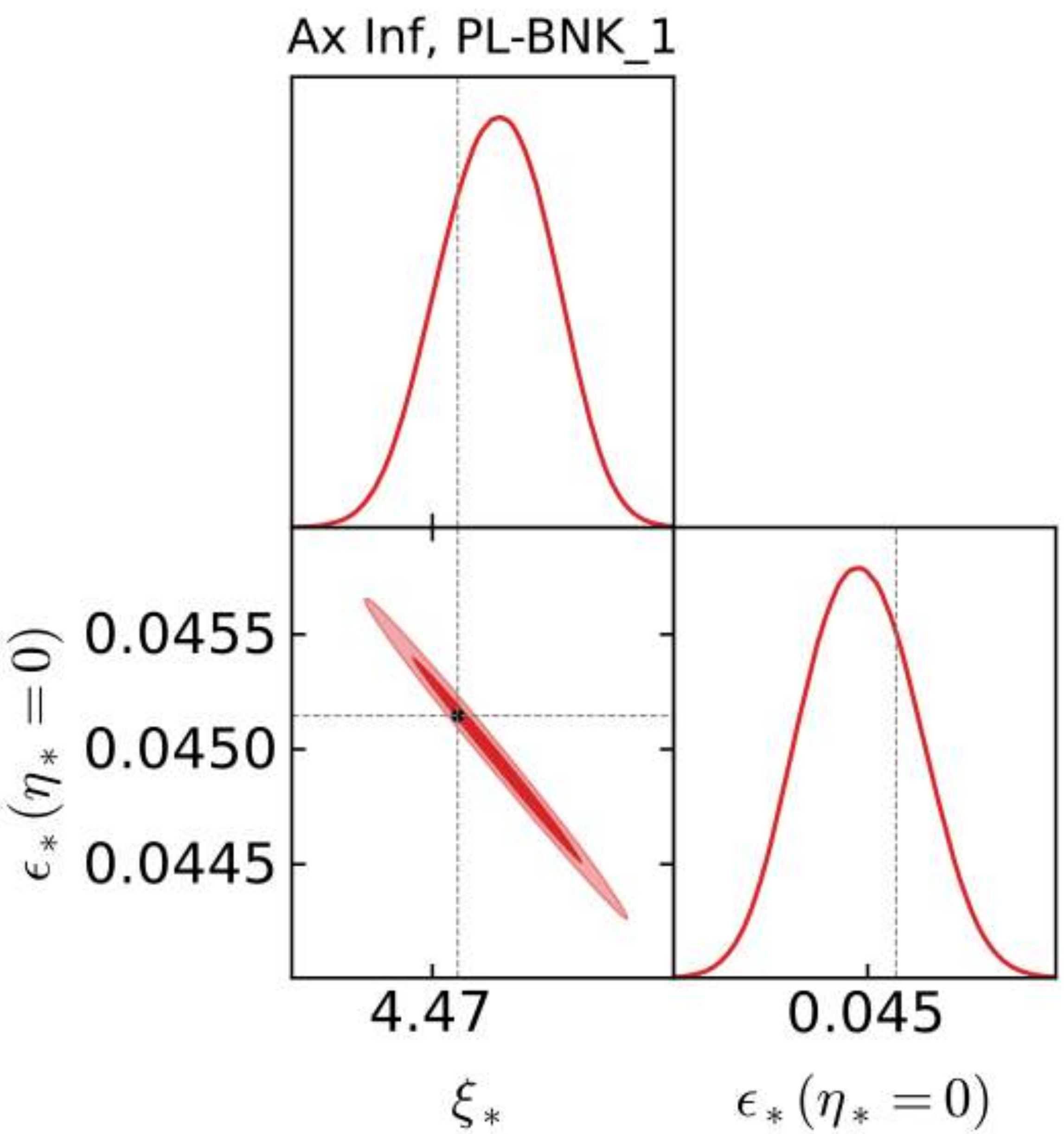
the injected values of both benchmarks are reconstructed well within the 68 % CL contours

For the galactic foreground, the reconstruction is very accurate, with the reconstructed amplitude within the 68 % CL error band (recall that we vary only the amplitude in our analysis, keeping the spectral shape of foregrounds fixed) while the error bands on the extragalactic foreground are larger, but still within the 68 % CL error band

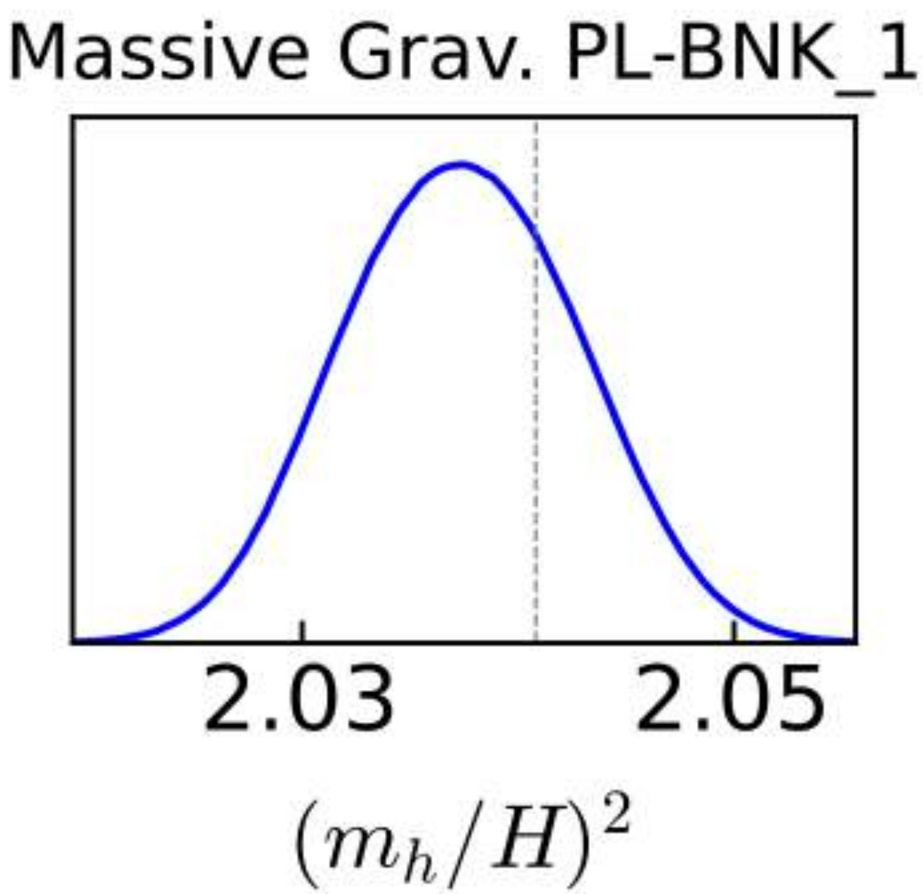
Benchmark 1: $\{\log_{10}(h^2\,\Omega_*), n_T\} = \{-12.5,\ 2.085\}$

The parameter reconstruction allows to set tight constraints on axion inflation and massive-gravity inflation.

Axion inflation:

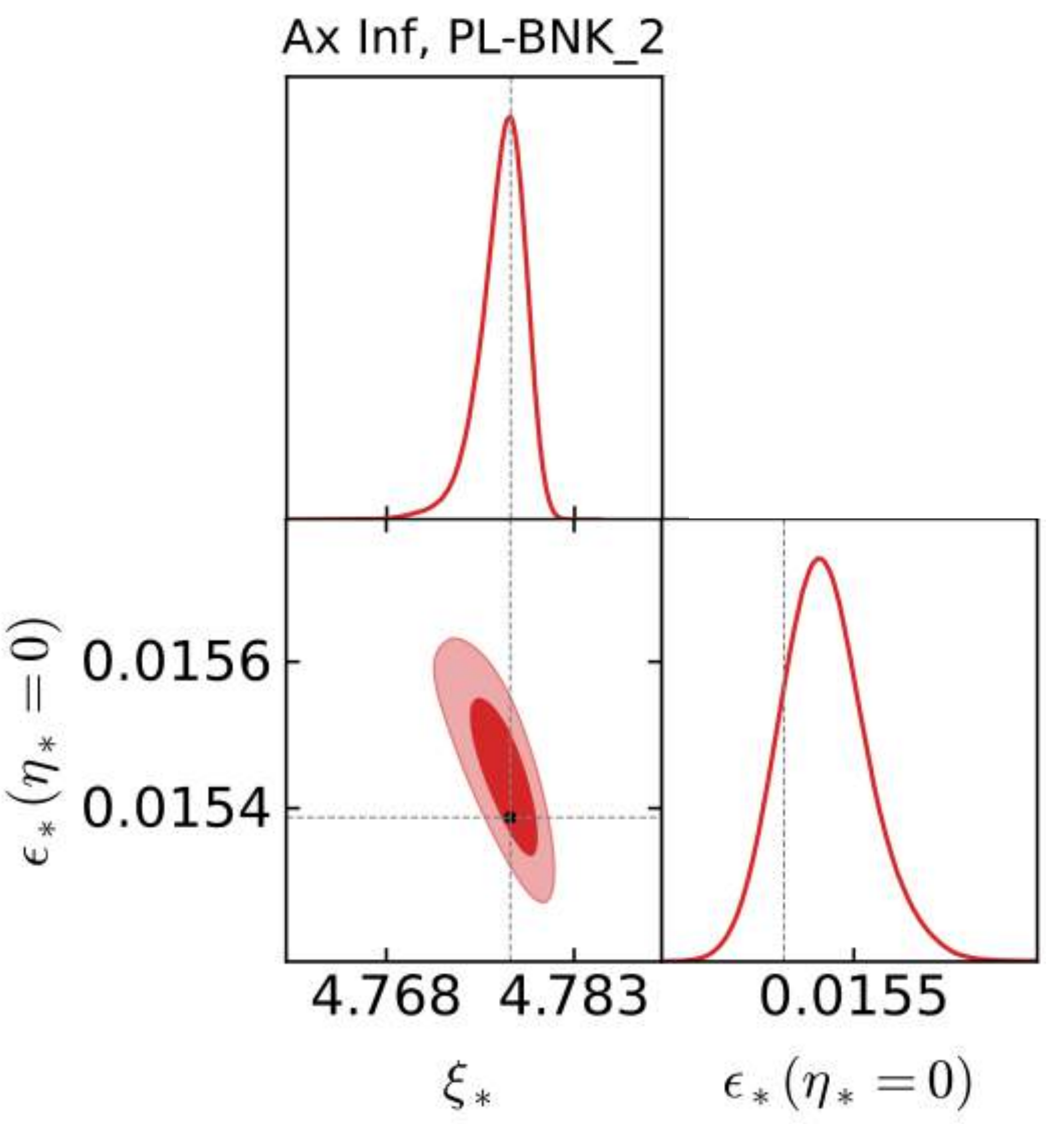


Broken space diffeomorphisms:

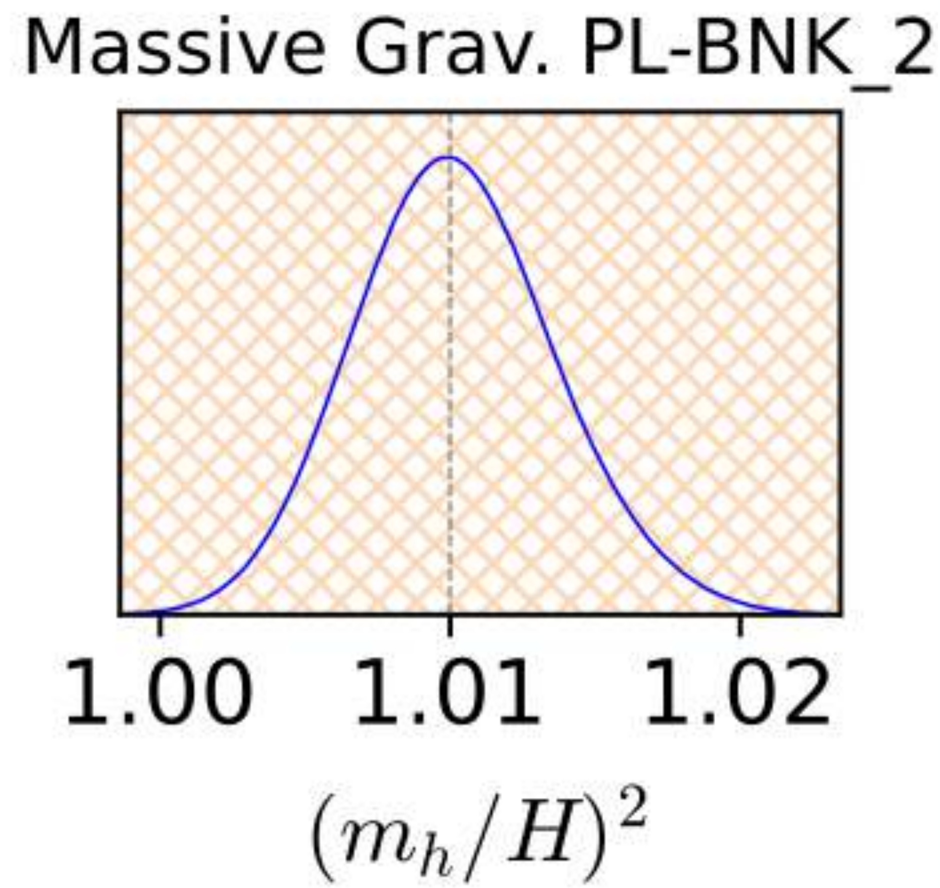


Benchmark 2: $\{\log_{10}(h^2\,\Omega_*), n_T\} = \{-11,\, 0.77\}$

Axion inflation:

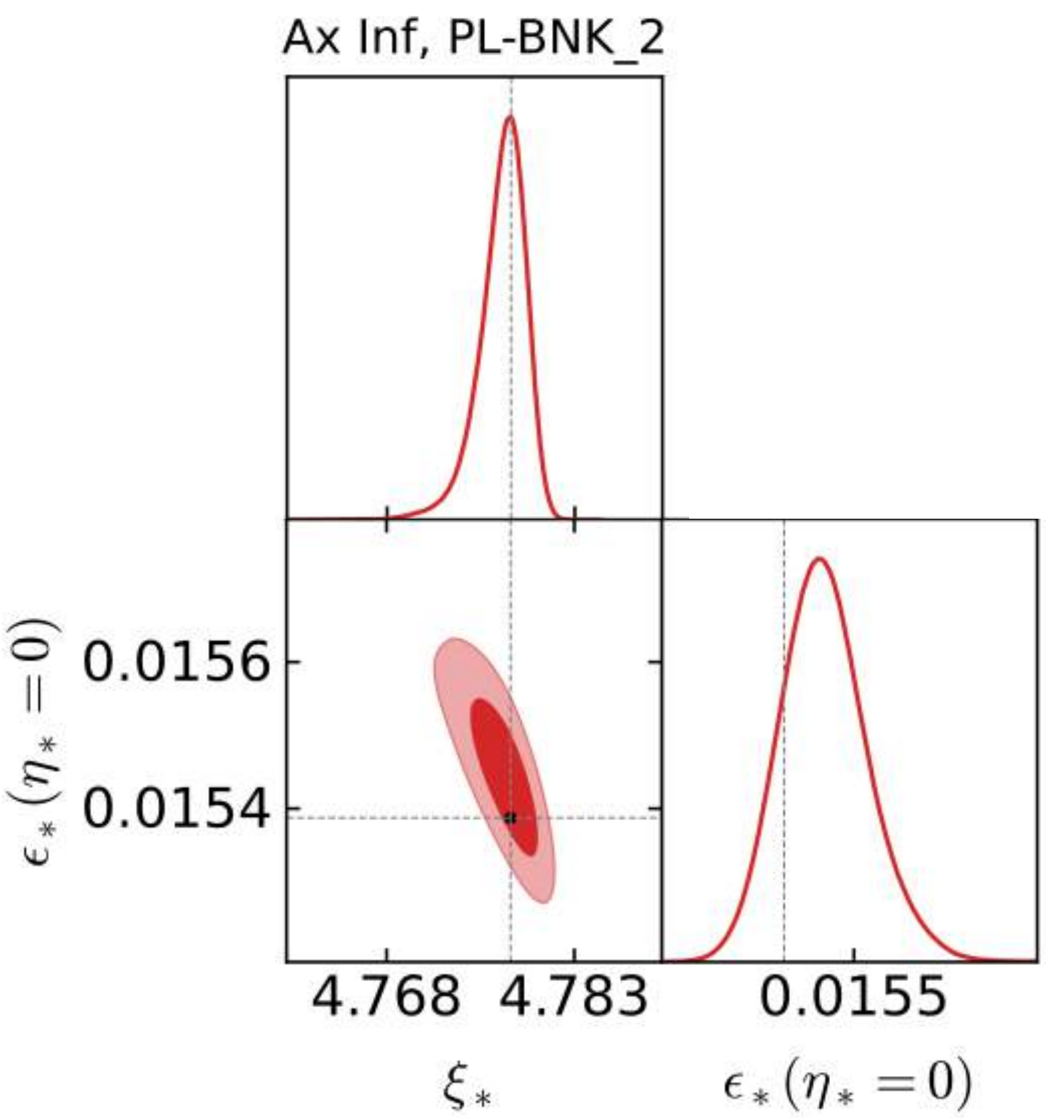


Broken space diffeomorphisms:

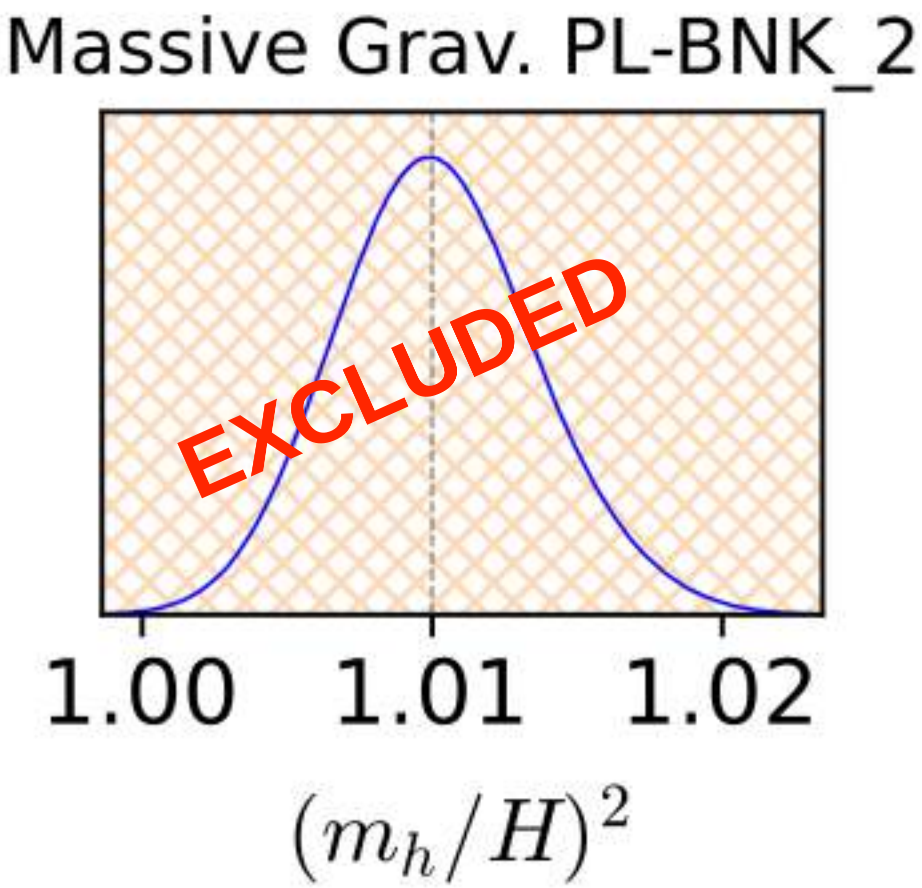


Benchmark 2: $\{\log_{10}(h^2\,\Omega_*), n_T\} = \{-11,\, 0.77\}$

Axion inflation:



Broken space diffeomorphisms:



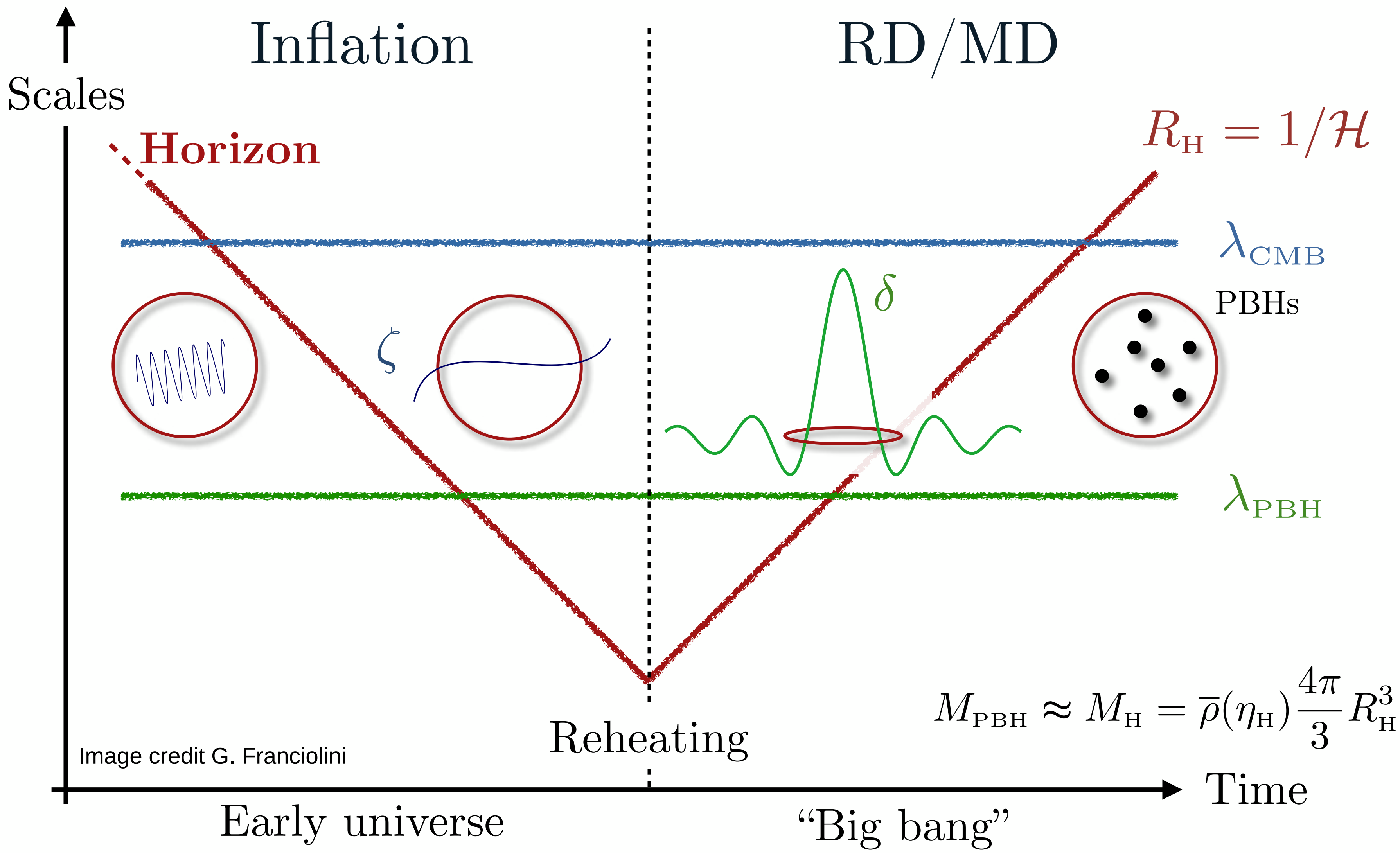
Presence of other fields (e.g. axions) in the Early Universe

Testing fundamental physics (e.g. axion decay constant) - related to high energy physics

Testing peculiar features of the SGWB - parity violation

GWs - Primordial Black Holes and Dark Matter

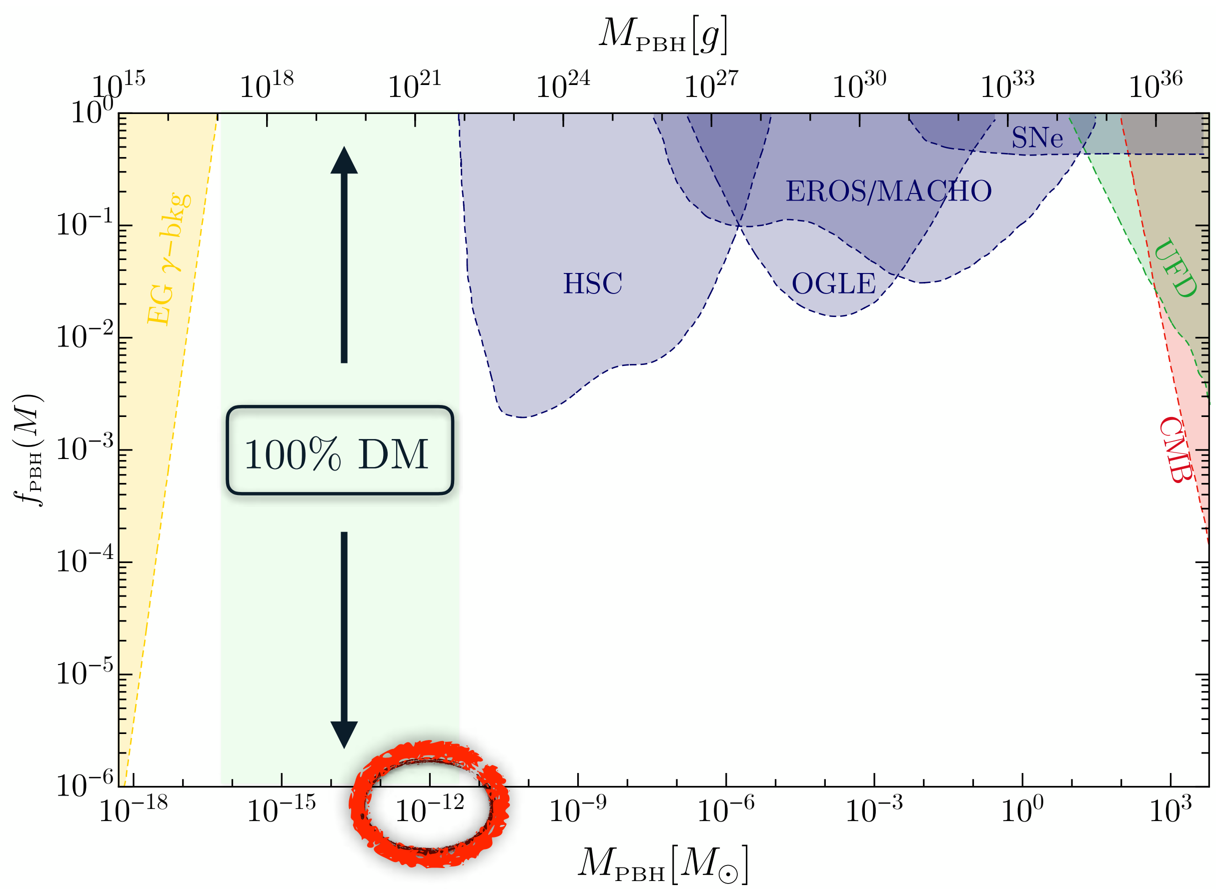
Large scalar perturbations source gravitational waves at 2nd order in perturbation theory when they re-enter the horizon during radiation era



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

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

GWs - Primordial Black Holes and Dark Matter



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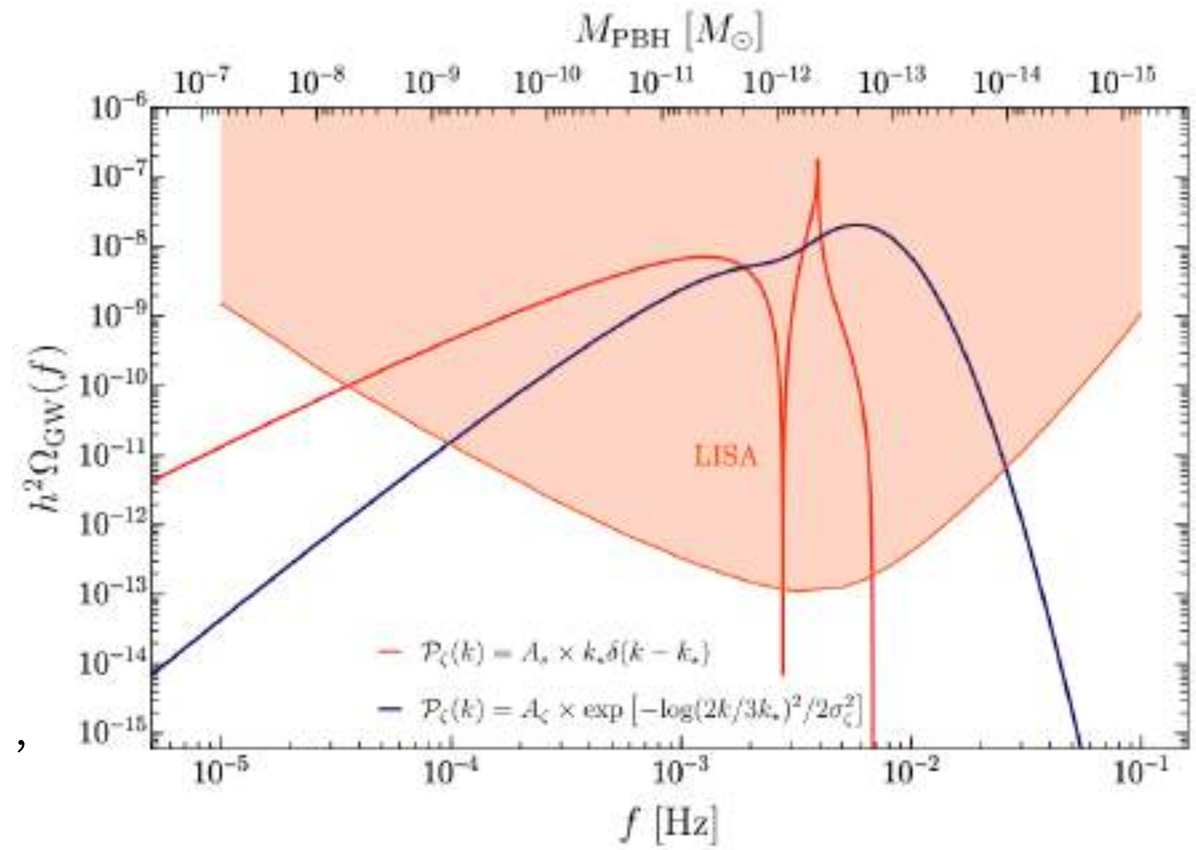


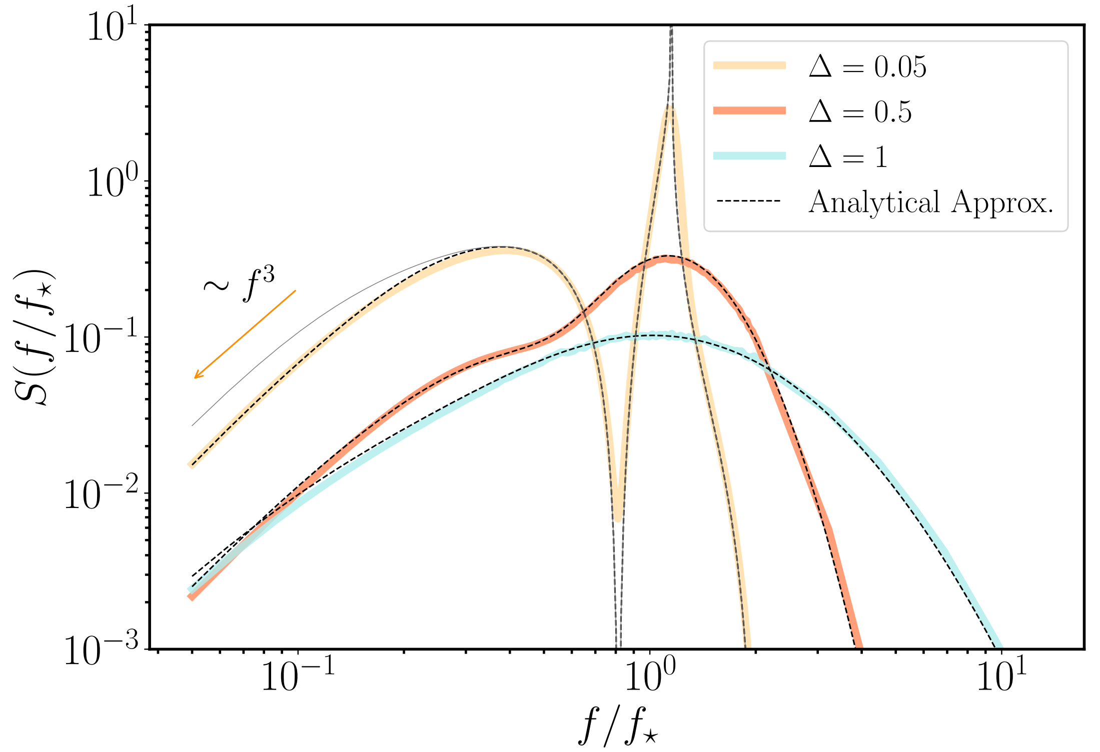
$$f \simeq 3 \cdot 10^{-9}\,\mathrm{Hz} \left(\frac{\gamma}{0.2}\right)^{1/2} \left(\frac{M}{M_\odot}\right)^{-1/2}$$

$$M \simeq 10^{-12} M_\odot \quad \longleftrightarrow \quad f \simeq 10^{-3}\mathrm{Hz}$$

[Espinosa, et al., 2018]
[Bartolo, N., et al., PRL 2019]
[De Luca, V., et al., PRL 2021]

Scalar Power Spectrum seed

$$P_\zeta(k) = \frac{A_\zeta}{\sqrt{2\pi}\Delta}\exp\left[-\frac{\log^2(k/k_\star)}{2\Delta^2}\right] \longrightarrow \Omega_{\rm gw}h^2 = 10^{-9}\left(\frac{A_\zeta}{0.01}\right)^2\left(\frac{\Omega_r h^2}{10^{-5}}\right) S(f/f_*,\Delta)$$

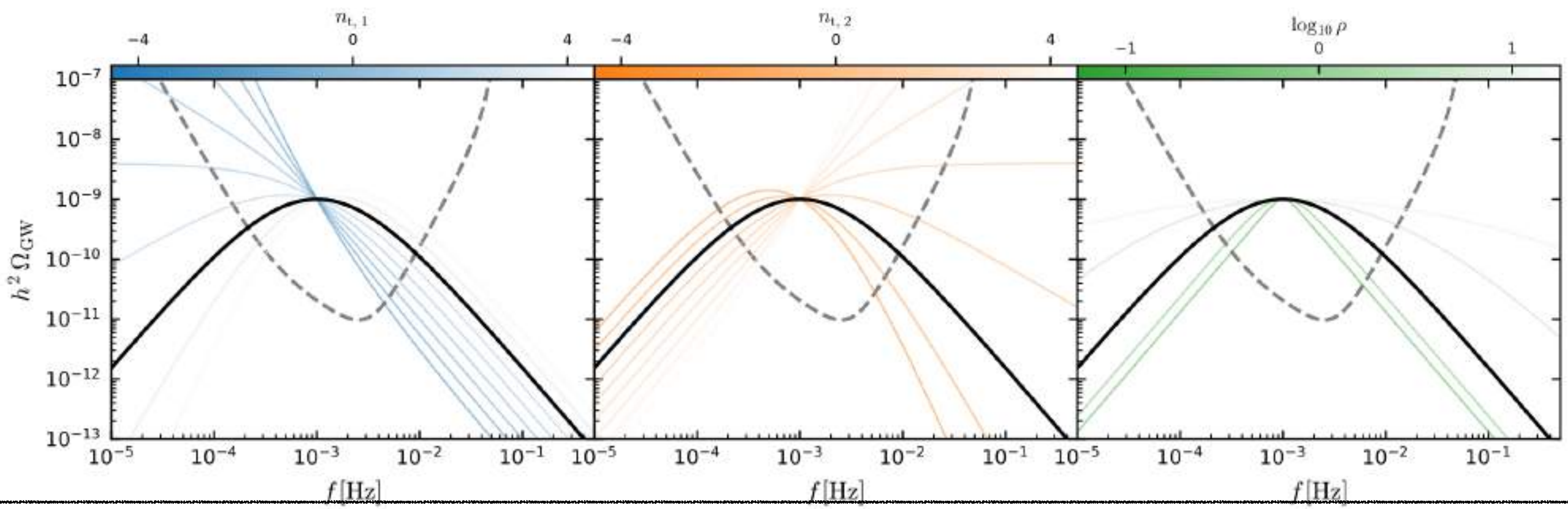


Pi & Sasaki 2005.12306

TEMPLATE

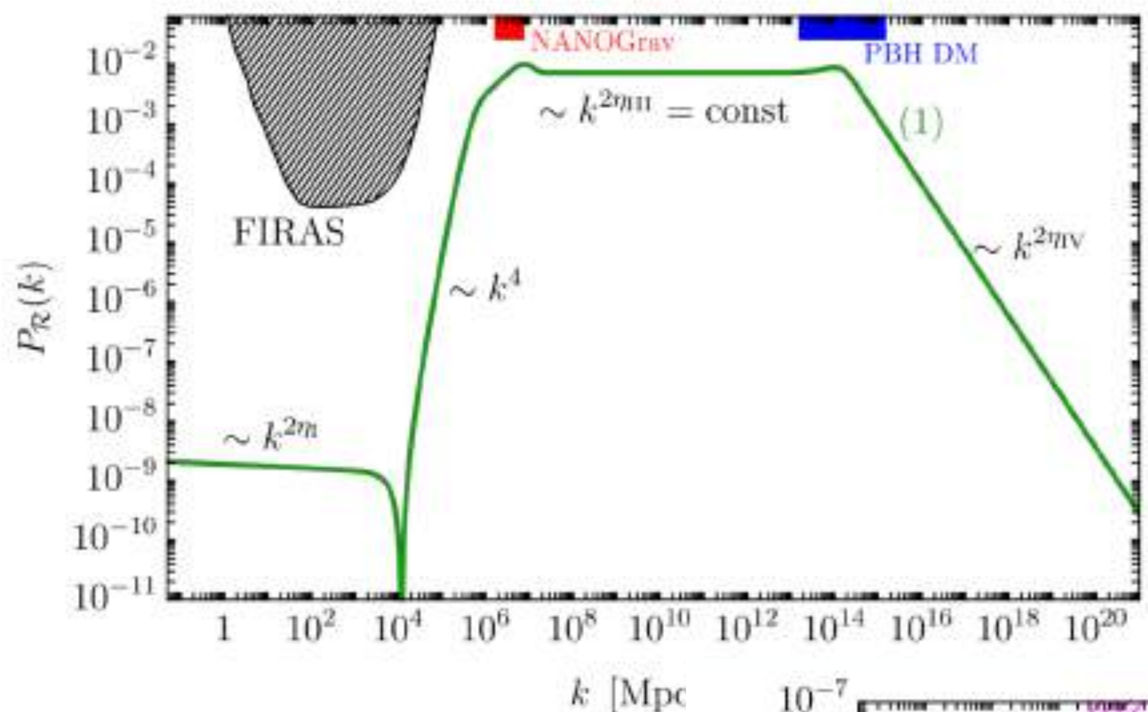
$$h^2\Omega_{\rm GW}^{\rm BPL}(f,\vec{p}) = 10^{\alpha_*}\frac{\left(\frac{f}{f_*}\right)^{n_{t,1}}}{\left\{\frac{1}{2}\left[1+\left(\frac{f}{f_*}\right)^{1/\delta}\right]\right\}^{(n_{t,1}-n_{t,2})\delta}}$$

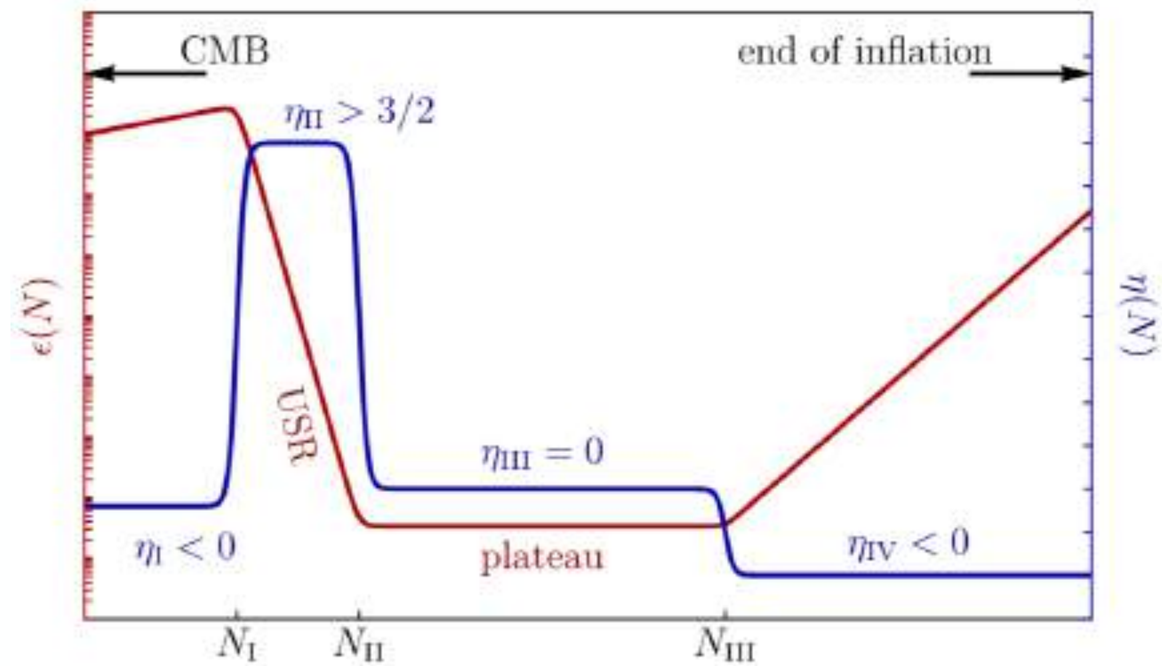
$$\vec{p} = \{\alpha_*, f_*, n_{t,1}, n_{t,2}, \delta\}$$

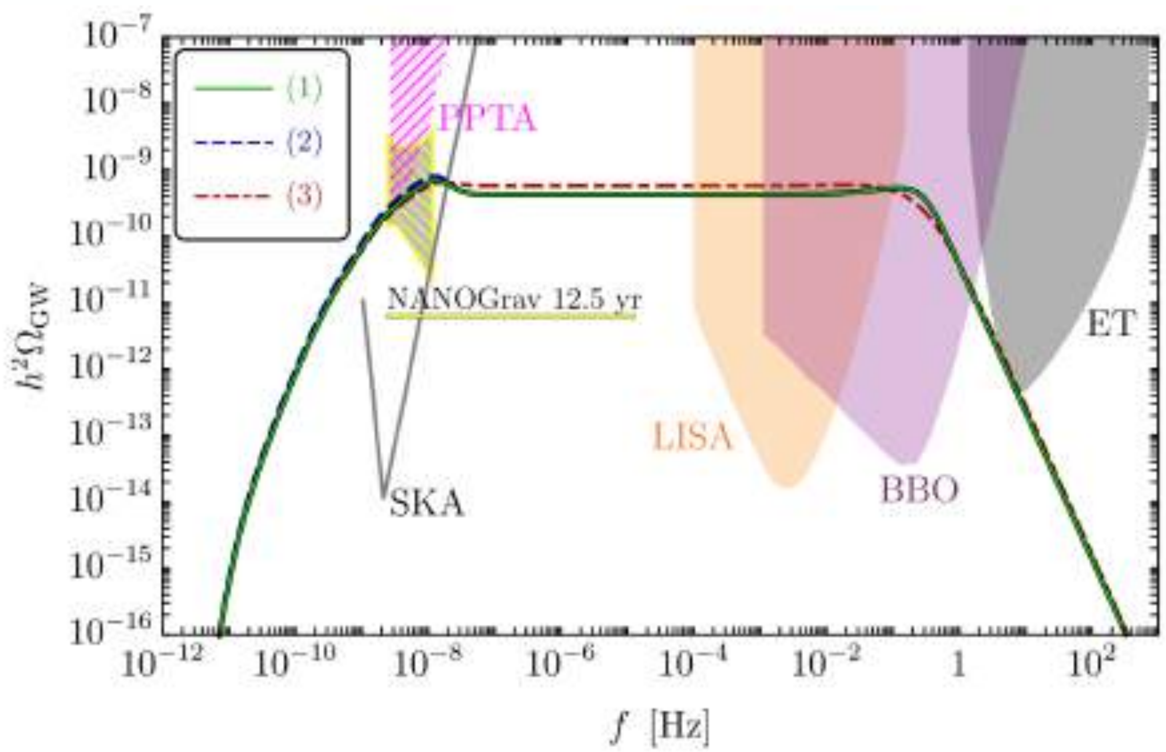


Inflationary models producing such a signal

Second slow-roll stage: An ultra-slow-roll phase amplifies primordial scalar perturbations and is followed by a second slow-roll regime generating a plateau.



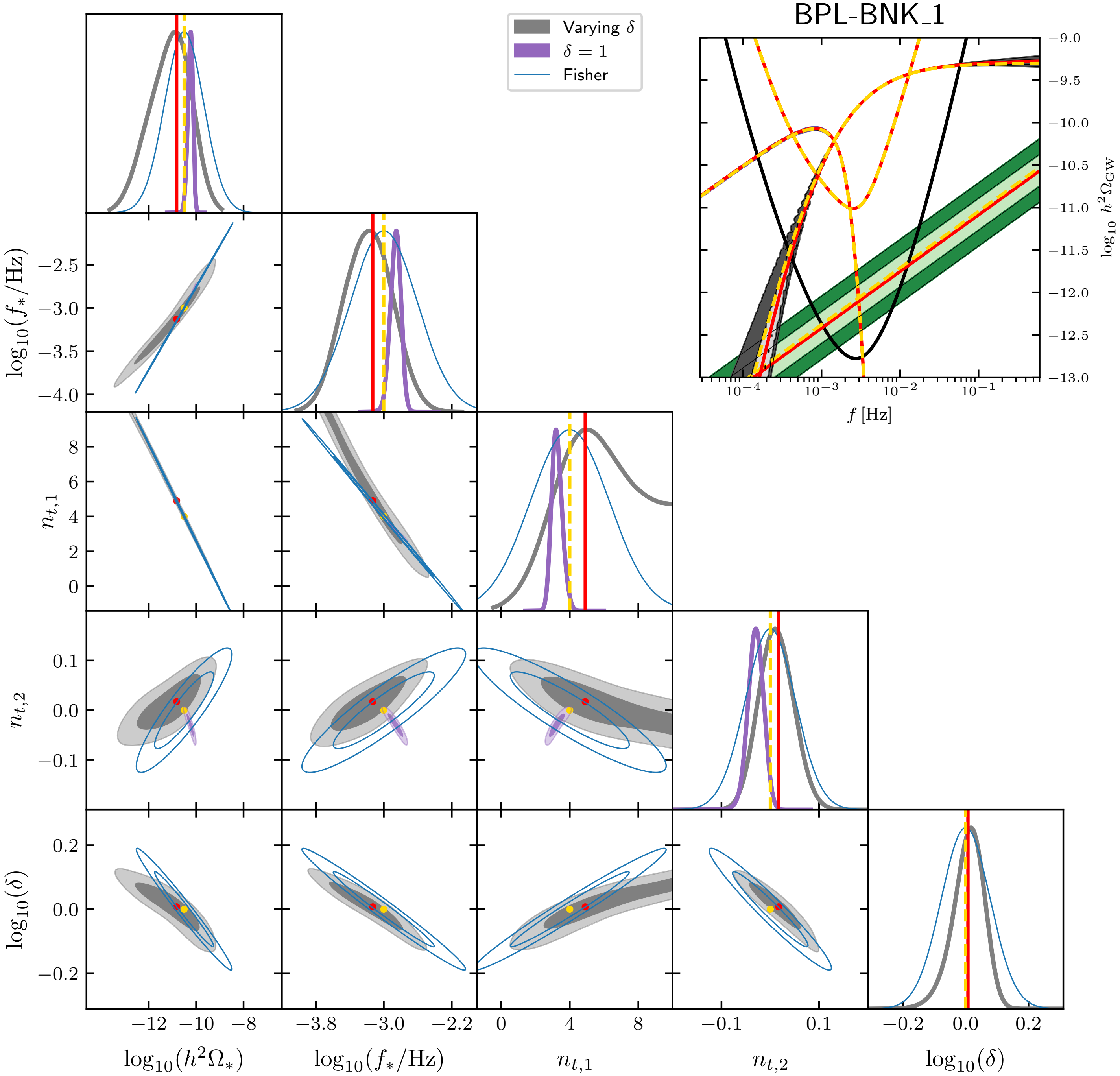




[Franciolini & Urbano 2207.10056]

See M. Redi's talk

Forecast



Amplitude ratio H^2/ϵ during the second SR stage, abundance of Primordial Black Holes f_PBH

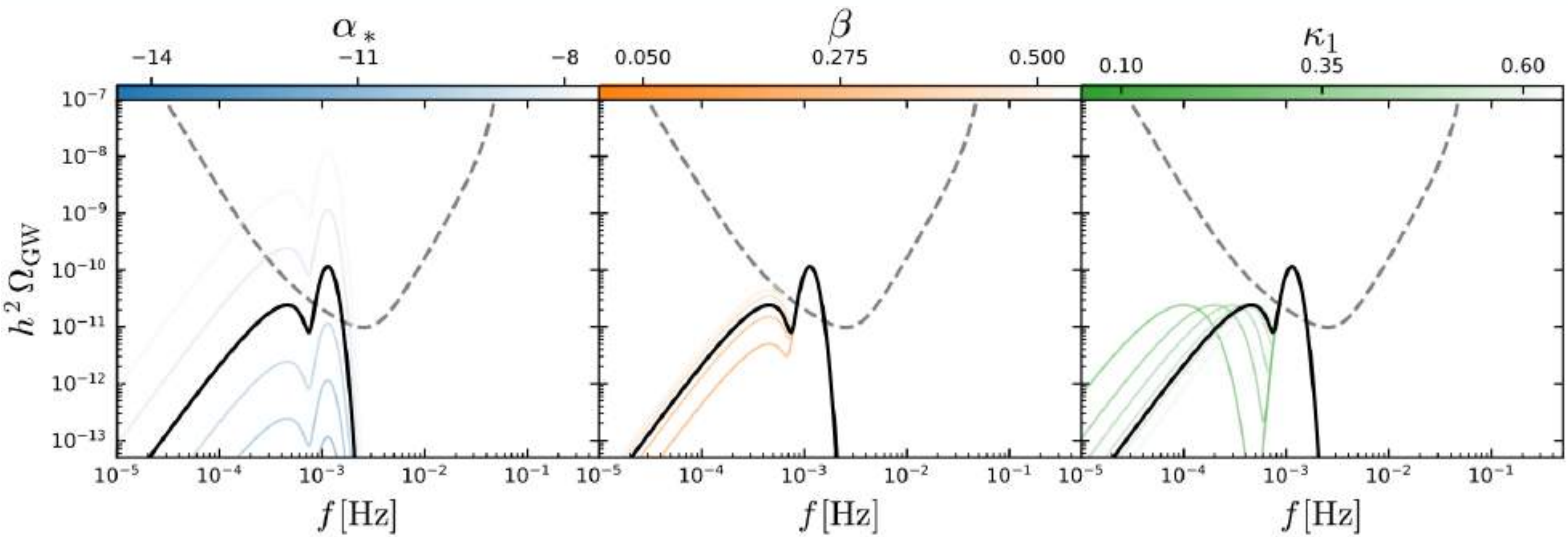
Frequency of the turn: time of the onset of the second SR stage, mass of Primordial Black Holes $M/M_{\odot}$

IR spectral index: related to the scalar IR spectral index.

UV spectral index. predicted to be flat in this model

Smoothing parameter: related to the sharpness of the USR-SR transition.

Double Peak signal



$$h^2\Omega_{\rm GW}^{\rm DP}(f,\vec{p}) = 10^{\alpha_*}\left[\beta\,\left(\frac{f}{\kappa_1 f_*}\right)^{n_p}\left[\frac{c_1 - f/f_*}{c_1-\kappa_1}\right]^{\frac{n_p}{\kappa_1}(c_1-\kappa_1)}\Theta\left(c_1-\frac{f}{f_*}\right)\right.$$

$$\left.+\exp\left[-\frac{1}{2\rho^2}\log_{10}^2\left(\frac{f}{\kappa_2 f_*}\right)\right]\left\{1+\mathrm{erf}\left[-\gamma\log_{10}\left(\frac{f}{\kappa_2 f_*}\right)\right]\right\}\right]$$

$$\vec{p} = \{\alpha_*, f_*, \beta, \kappa_1, \kappa_2, \rho, \gamma\}$$

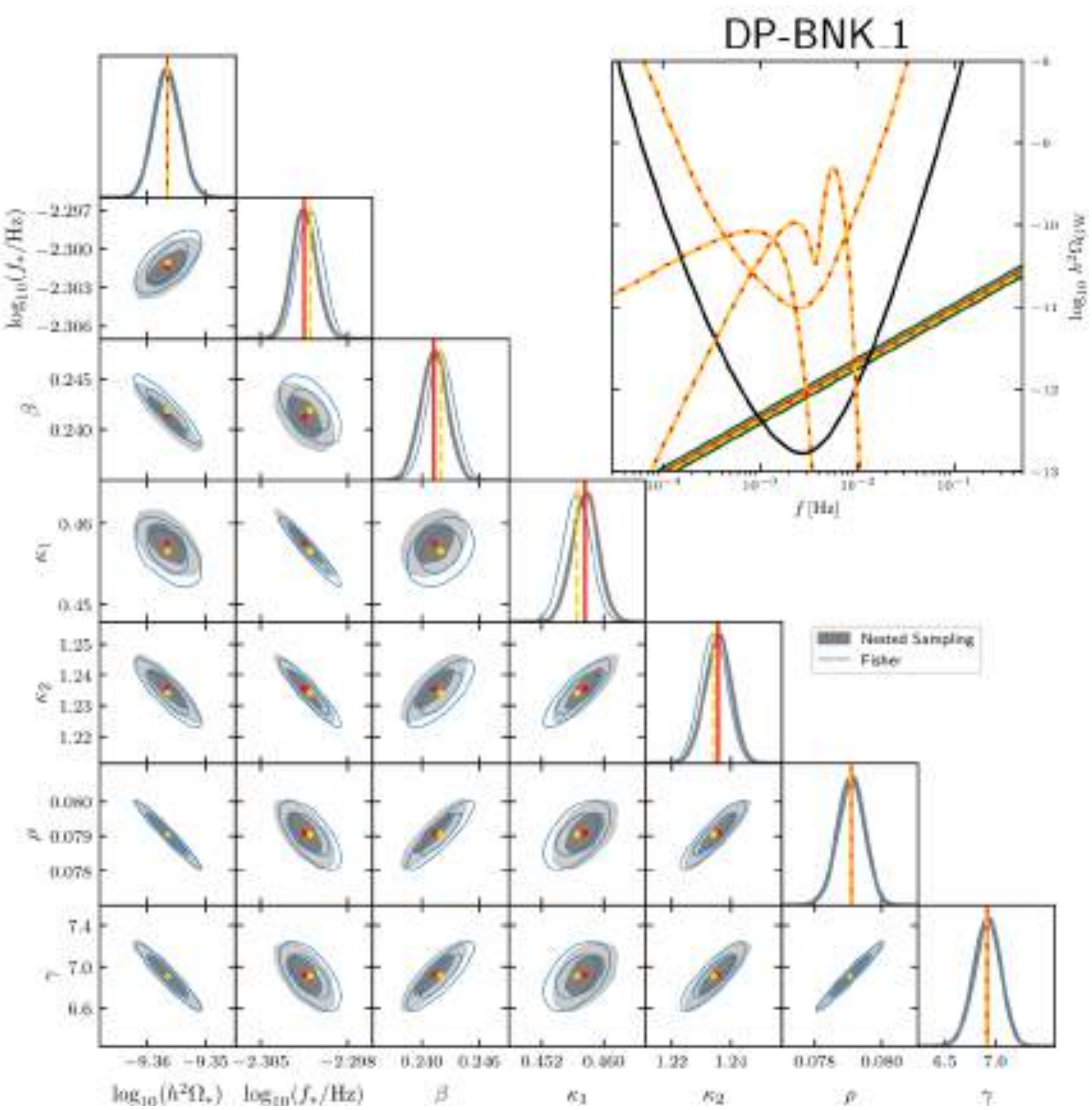
Inflationary models producing such a signal

Broken power law $\mathscr{P}_\zeta(k)$:

$$\mathcal{P}_\zeta^{\rm bpl}(k) = \frac{\mathcal{A}_s(p_1+p_2)}{\left[p_2\left(\frac{k}{k_*}\right)^{-p_1} + p_1\left(\frac{k}{k_*}\right)^{p_2}\right]}$$

Lognormal $\mathscr{P}_\zeta(k)$:

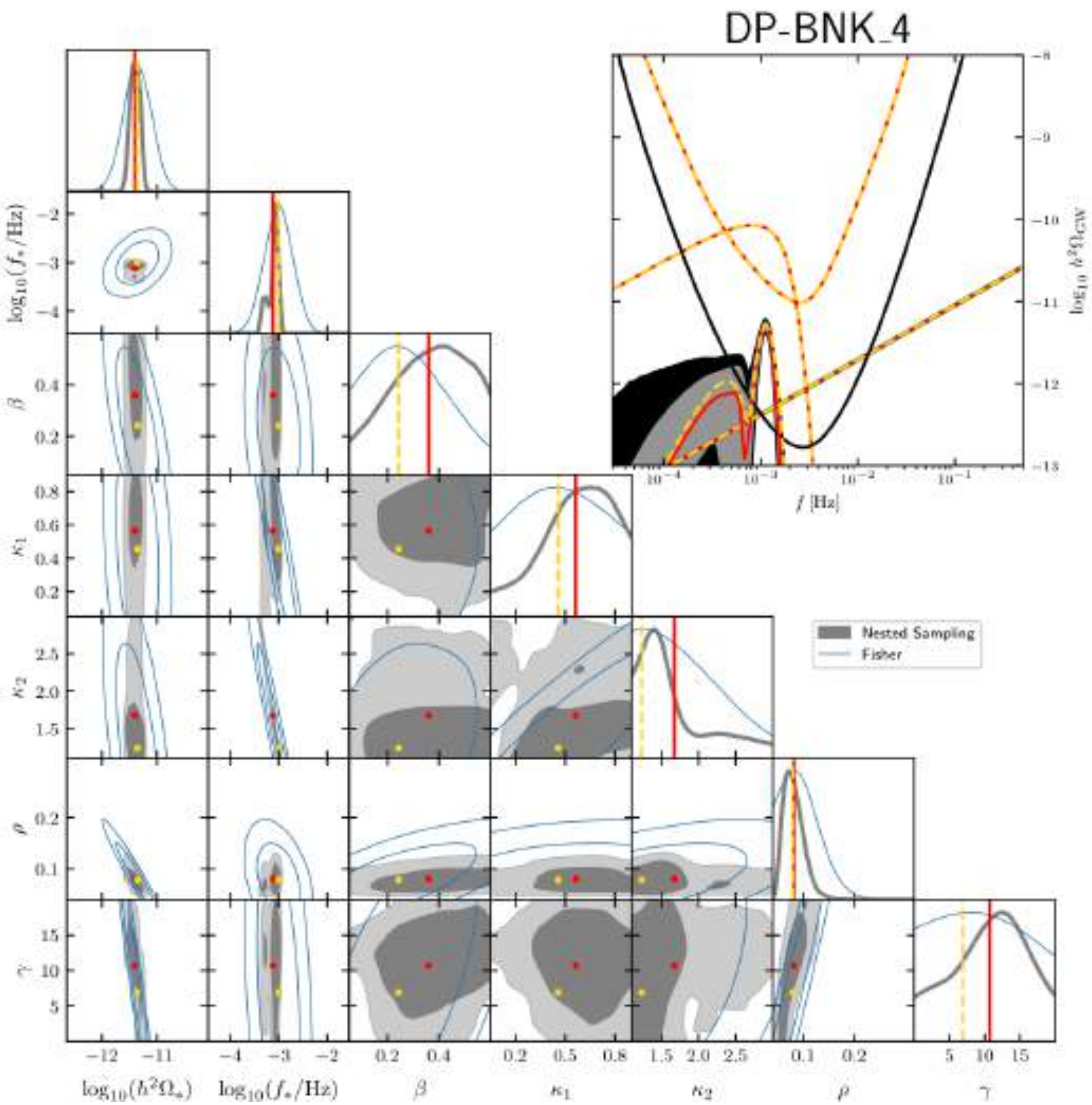
$$\mathcal{P}_\zeta^{\rm ln}(k) = \mathcal{A}_s \exp\left[-\frac{1}{2\Delta^2}\ln^2\left(\frac{k}{k_*}\right)\right]$$



Very loud signal:
tight constraints on all parameters.

[Ozsoy & Tasinato 2301.03600]

Double Peak (faint) signal



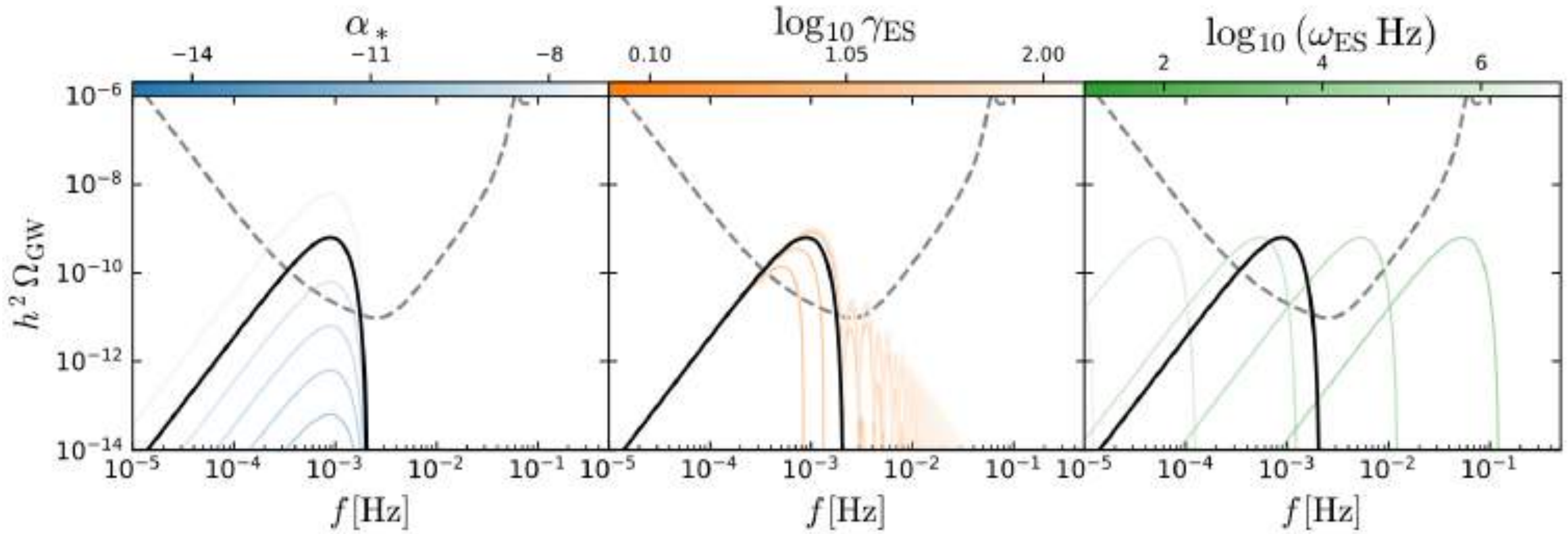
Faint signal: only certain features of the signal are constrained.

Other Templates

Excited States

$$h^2\Omega_{\rm GW}^{\rm ES}(f,\vec{p}) = \frac{10^{\alpha_*}}{0.052}\frac{1}{x^3}\left[1-\frac{x^2}{4\gamma_{\rm ES}^2}\right]^2\left[\sin(x)-2\frac{1-\cos(x)}{x}\right]^2\Theta(x_{\rm cut}-x)$$

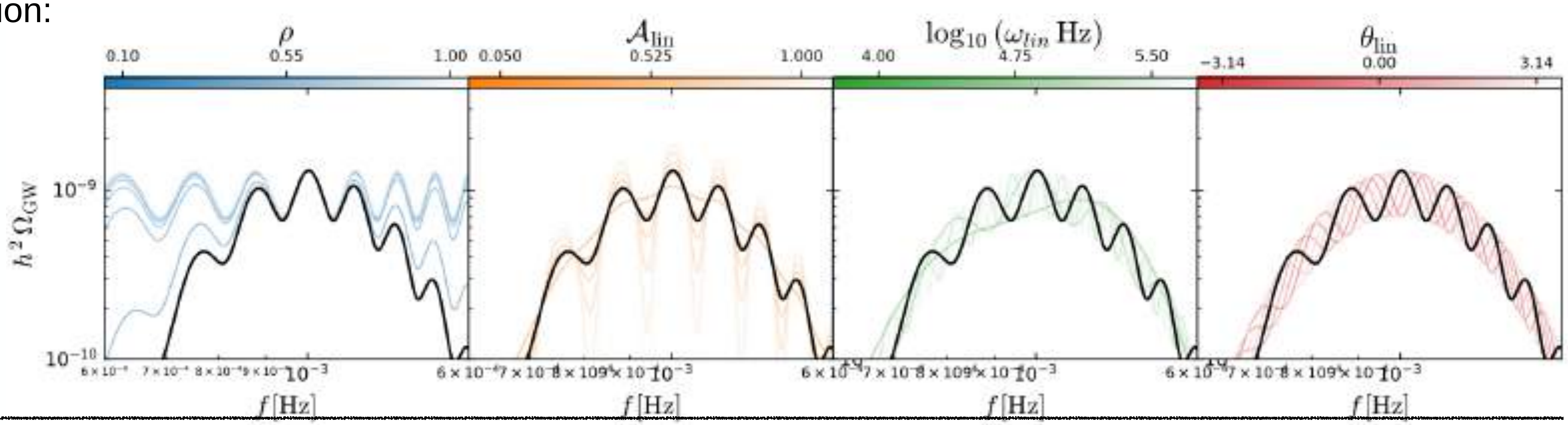
Model:
Scalar- induced GWs during inflation



Linear Oscillation

$$h^2\Omega_{\rm GW}^{\rm LO}(f,\vec{p}) = \left[1+\mathcal{A}_{\rm lin}\cos\left(\omega_{\rm lin}f+\theta_{\rm lin}\right)\right]h^2\Omega_{\rm GW}^{\rm env}(f,\vec{p}_{\rm env})$$

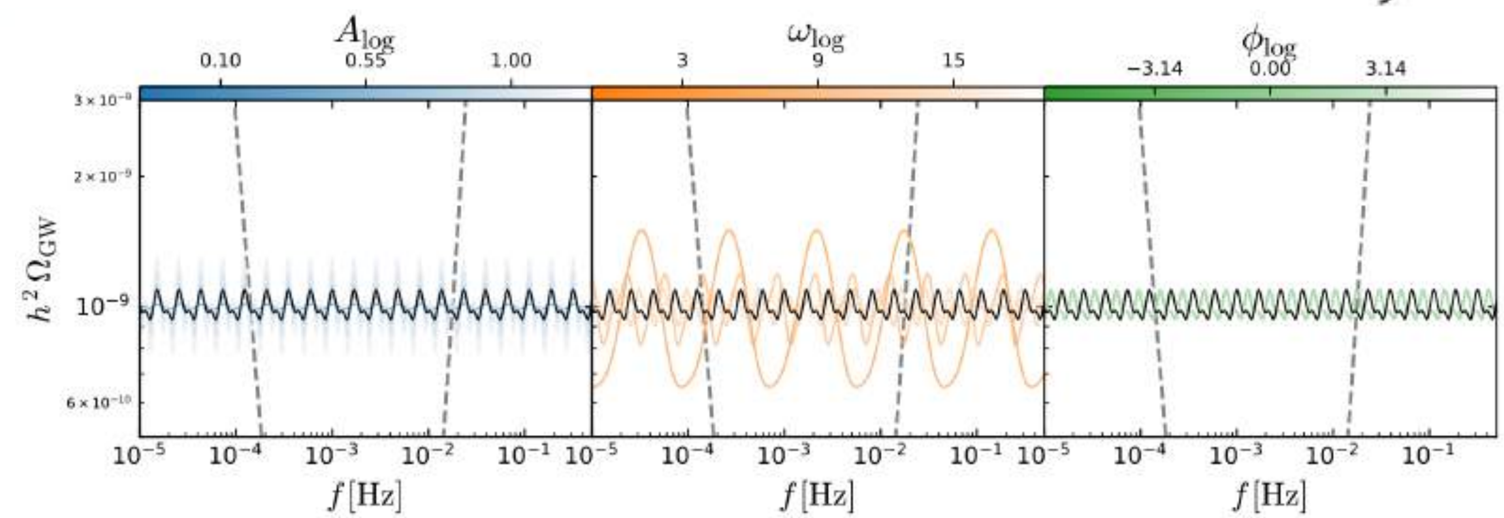
Model:
Sharp features during inflation:

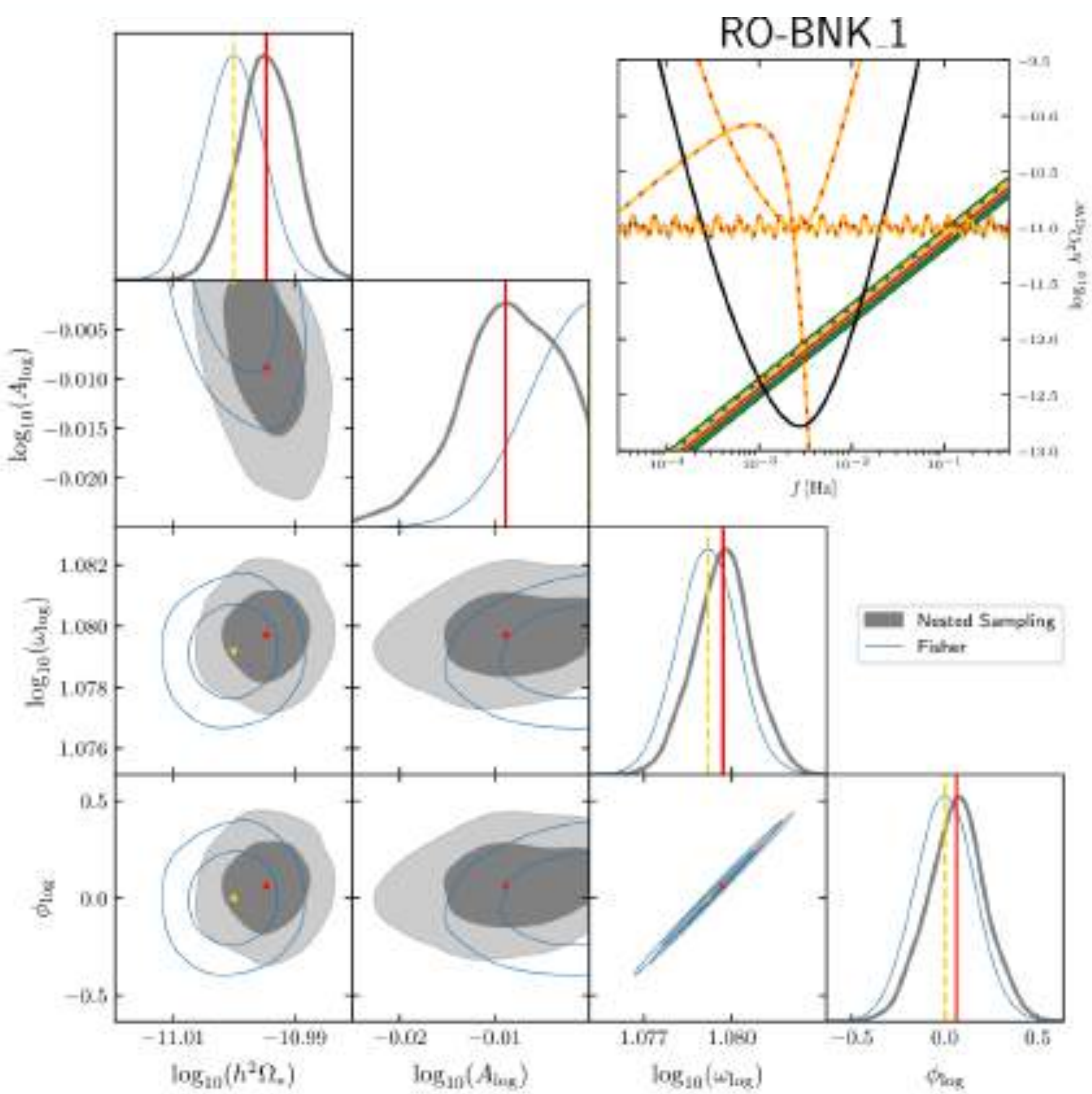


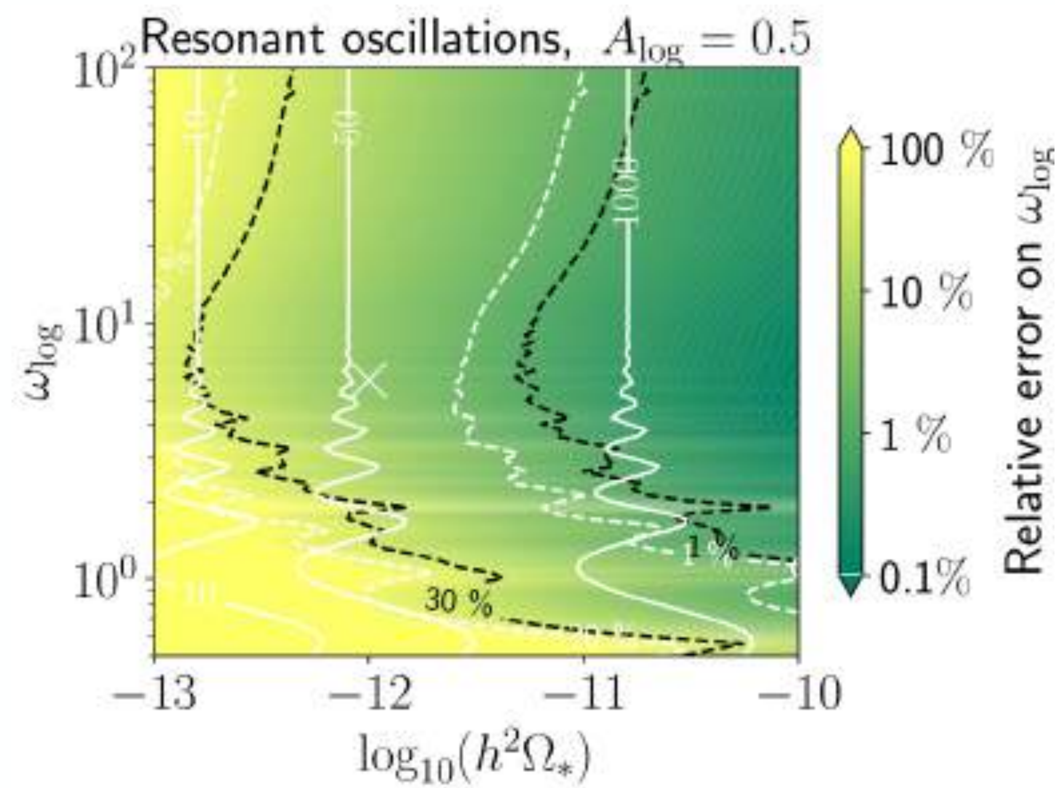
Resonant Oscillations

$$h^2\Omega_{\rm GW}^{\rm RO}(f,\vec{p}) = \Big\{1 + \mathcal{A}_1(A_{\log},\omega_{\log})\cos\left[\omega_{\log}\ln(f/{\rm Hz}) + \theta_{\log,1}\right] + \mathcal{A}_2(A_{\log},\omega_{\log})\cos\left[2\omega_{\log}\ln(f/{\rm Hz}) + \theta_{\log,2}\right]\Big\} h^2\Omega_{\rm GW}^{\rm env}(f,\vec{p}_{\rm env})$$

Model:
Resonant features during inflation



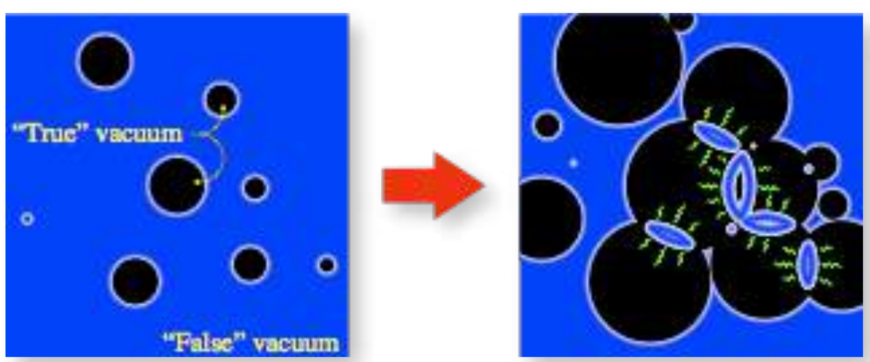




Phase Transition in the Early Universe

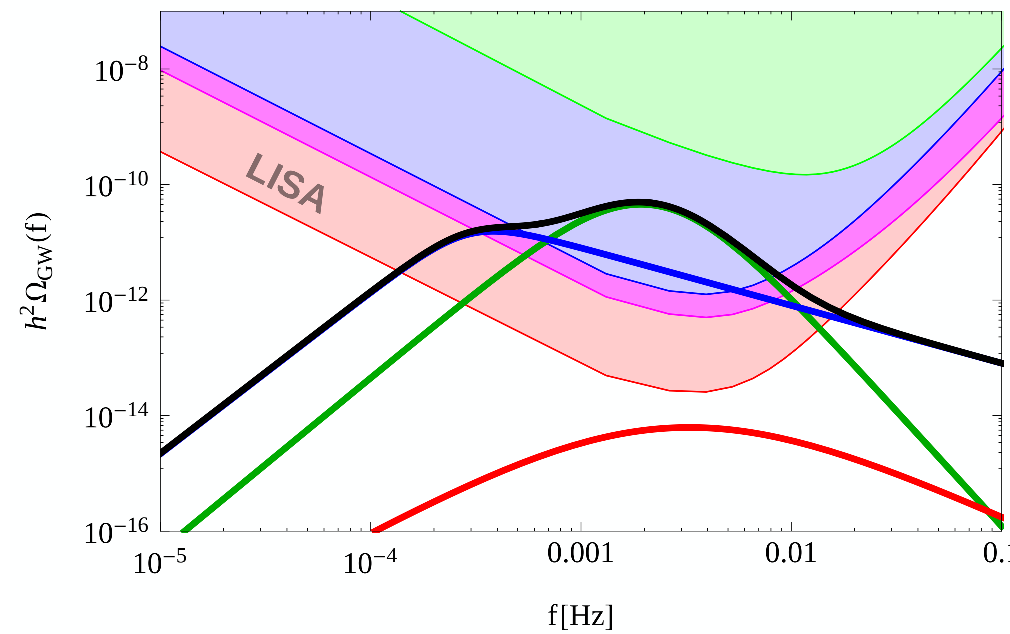
As the temperature in the very early universe decreases, there can be several **PTs: QCD, EW.**...Beyond Standard Model?

If the PT is first order, the SGWB signal could be detectable by LISA



Processes

- Bubble collisions
- MHD Turbulence
- Sound Waves



- peaked spectrum with

$$f_{\rm peak} \sim 10^{-3}\ {\rm Hz}\ \frac{T}{100\ {\rm GeV}}$$

[Caprini C., et al ’16, ’19- LISA CosWG paper]

LISA Red Book

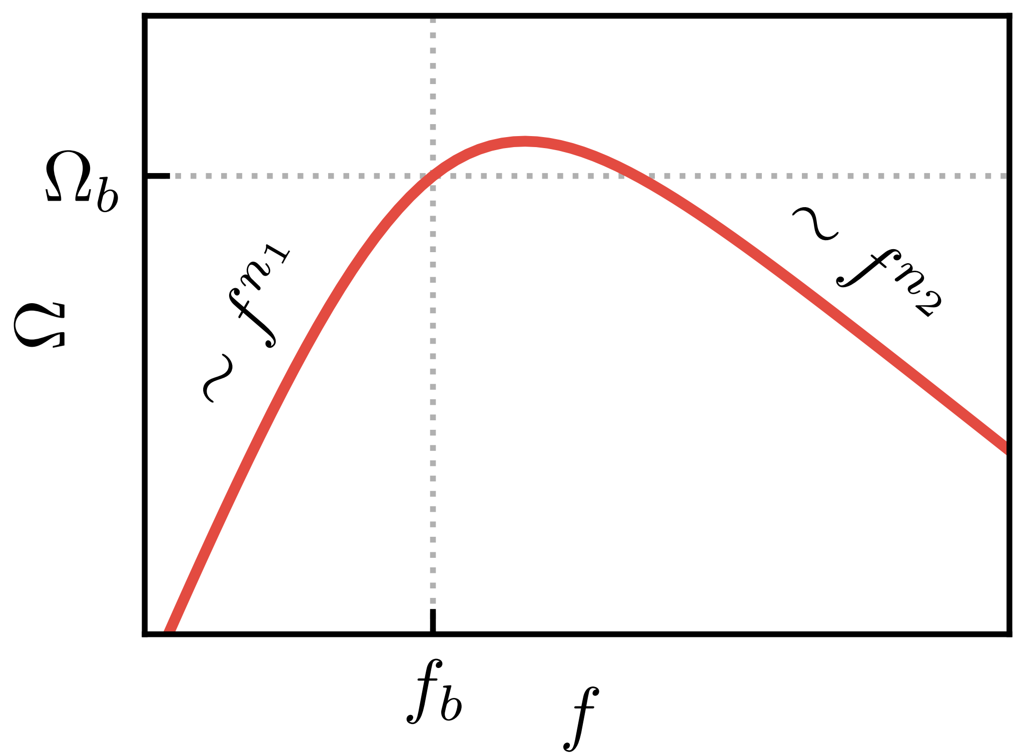
Template for Phase Transition

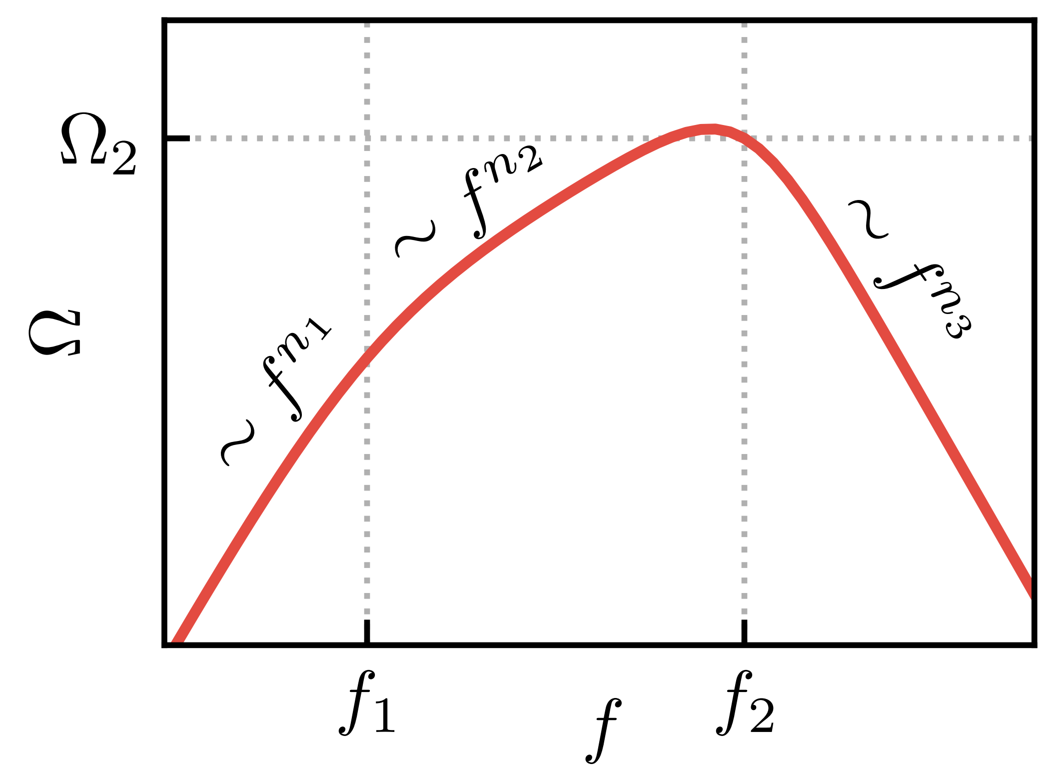
broken power-law

$$\Omega_b \mathcal{N} \left(\frac{f}{f_b}\right)^{n_1} \left[1+\left(\frac{f}{f_b}\right)^{a_1}\right]^{\frac{n_2-n_1}{a_1}}$$

double broken power-law

$$\Omega_2 \mathcal{N}\left(\frac{f}{f_1}\right)^{n_1}\left[1+\left(\frac{f}{f_1}\right)^{a_1}\right]^{\frac{n_2-n_1}{a_1}}\left[1+\left(\frac{f}{f_2}\right)^{a_2}\right]^{\frac{n_3-n_2}{a_2}}$$





bubble collisions: $(n_1, n_2, a_1) = (2.4, -2.4, 4)$

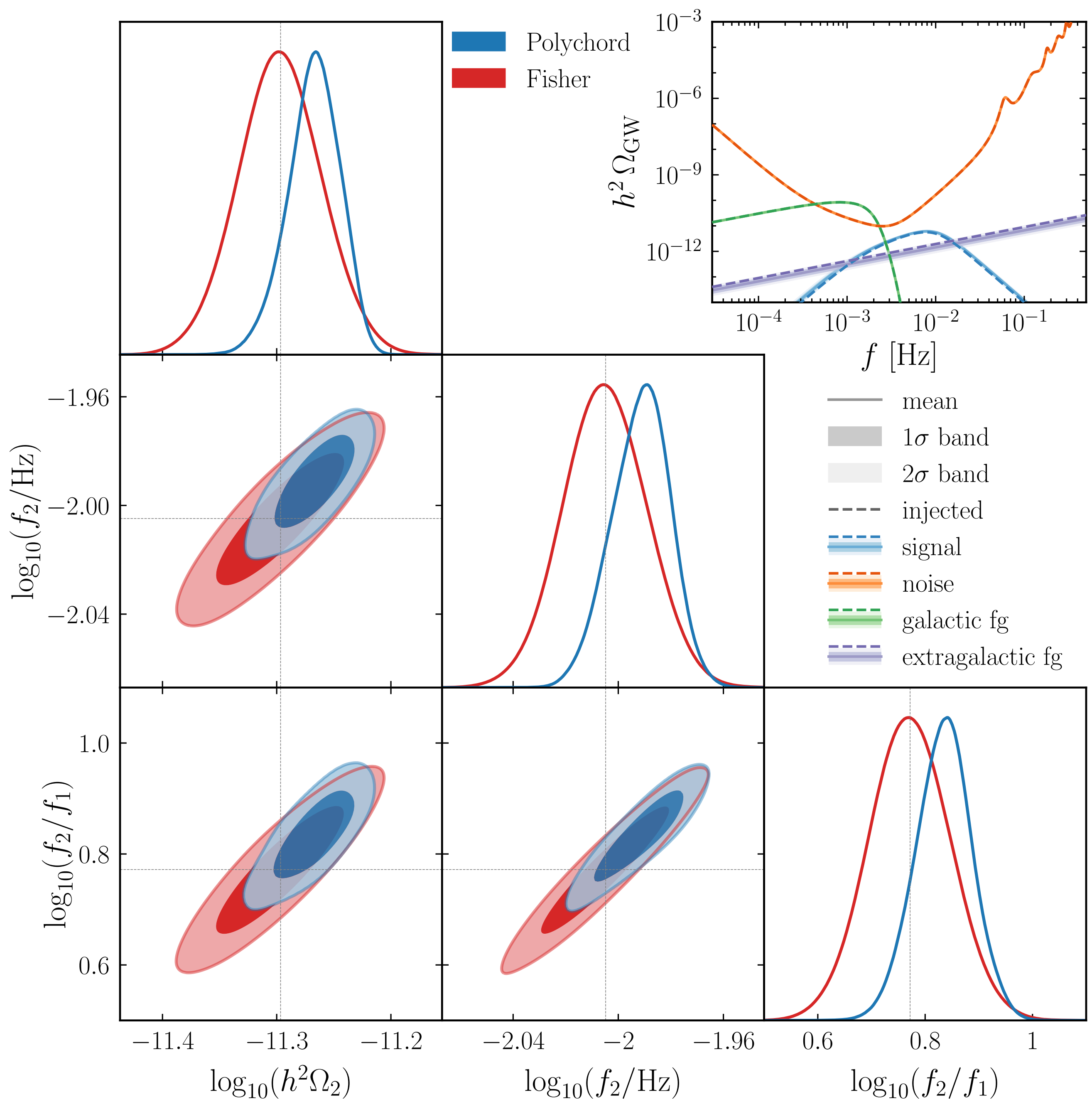
Sound waves: $(n_1, n_2, n_2, a_1, a_2) = (3, 1, -3, 2, 4)$

MHD turbulence: $(n_1, n_2, n_2, a_1, a_2) = (3, 1, -\frac{8}{3}, 4, 2.15)$

[Lewicki & Vaskonen, 2023]

LISA CosGW project Arxiv: 2407.04356 (phase transition)

Forecast: Nested Sampling vs Fisher



$$h^2\Omega_2 = 5\times10^{-12},\ f_2 = 10\,\mathrm{mHz},\ \frac{f_2}{f_1}\approx 6$$

estimation of parameter reconstruction based on Polychord vs Fisher

Reconstructing thermodynamics parameters

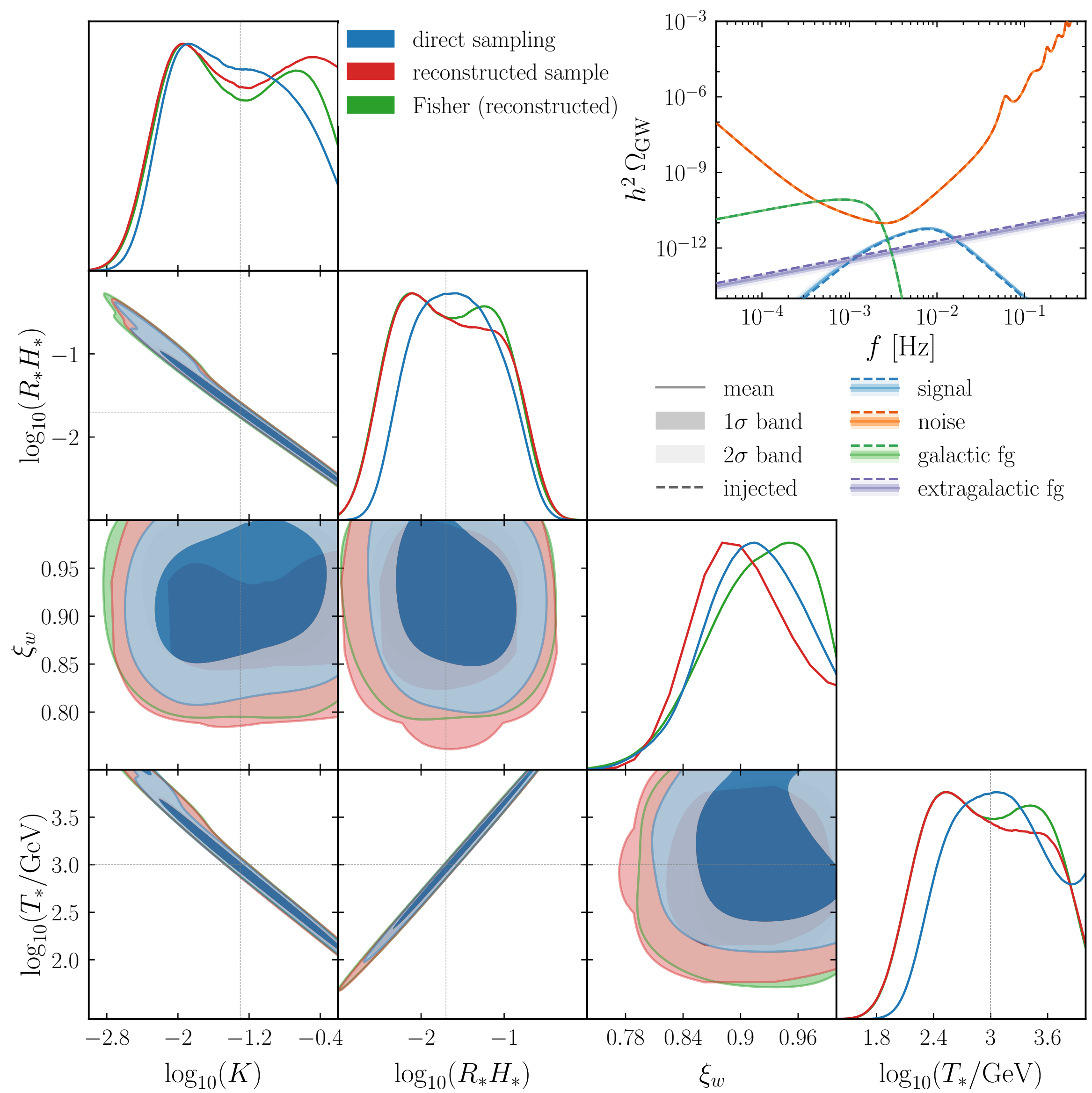
3 geom. params.: $\Omega_2, \ f_2, \ f_1$
4 therm. params.: $K, \ H_* R_*, \ \xi_w, \ T_*$
$\Longrightarrow$ degenerate

consider fixed T_*:

$$\Omega_2 \propto \frac{\xi_{\text{shell}}}{\xi_w} \begin{cases} K^2 \, H_* R_* & \text{if } H_*\tau > 1 \\ K^{3/2} (H_* R_*)^2 & \text{if } H_*\tau < 1 \end{cases}$$

$$f_2 \propto T_*/(H_* R_*)$$

$$\frac{f_2}{f_1} \propto \xi_w / \xi_{\text{shell}}$$



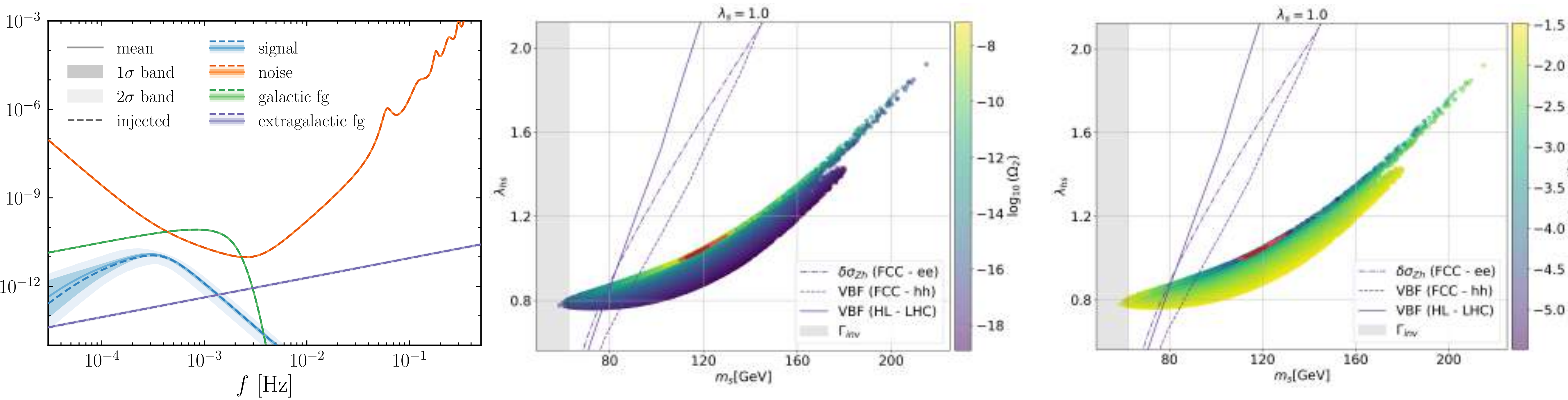
$K = 0.05, \ R_* H_* = 0.02, \ \xi_w = 1, \ T_* = 1\,\text{TeV}$

What we can learn from Phase Transition?

- LISA could act as a **probe of Beyond Standard Model physics, complementary to colliders**

Simplest extensions of the SM $$V_{\text{tree}}(\Phi, s) = -\mu_h^2 \Phi^\dagger \Phi + \lambda (\Phi^\dagger \Phi)^2 + \mu_s^2 \frac{s^2}{2} + \frac{\lambda_s}{4} s^4 + \frac{\lambda_{hs}}{2} s^2 \Phi^\dagger \Phi,$$

Extra scalar singlet under the SM gauge group endowed with a Z_2 symmetry

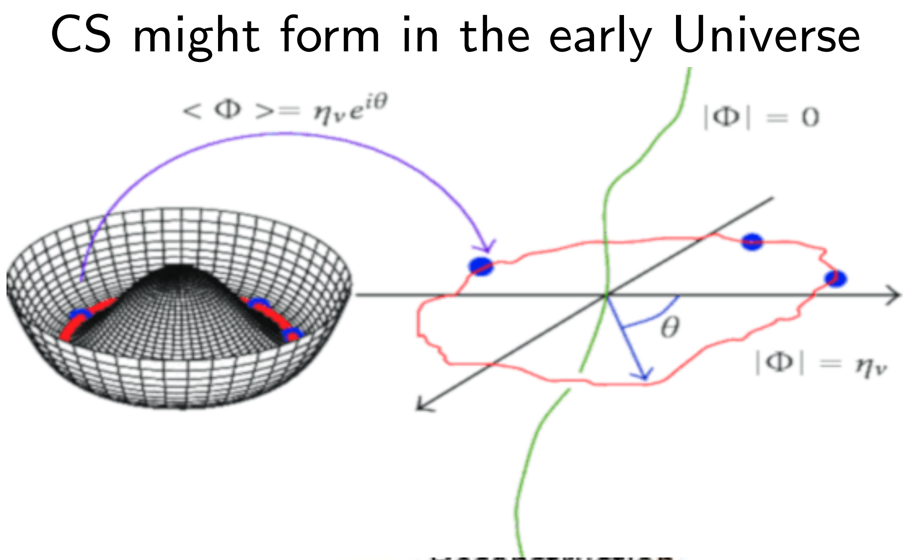


- LISA could act as a **probe of Beyond Standard Model physics, complementary to colliders**
- In some BSM scenarios possible **joint detection at LISA and LHC/FCC**

λ_{hs} Singlet coupling

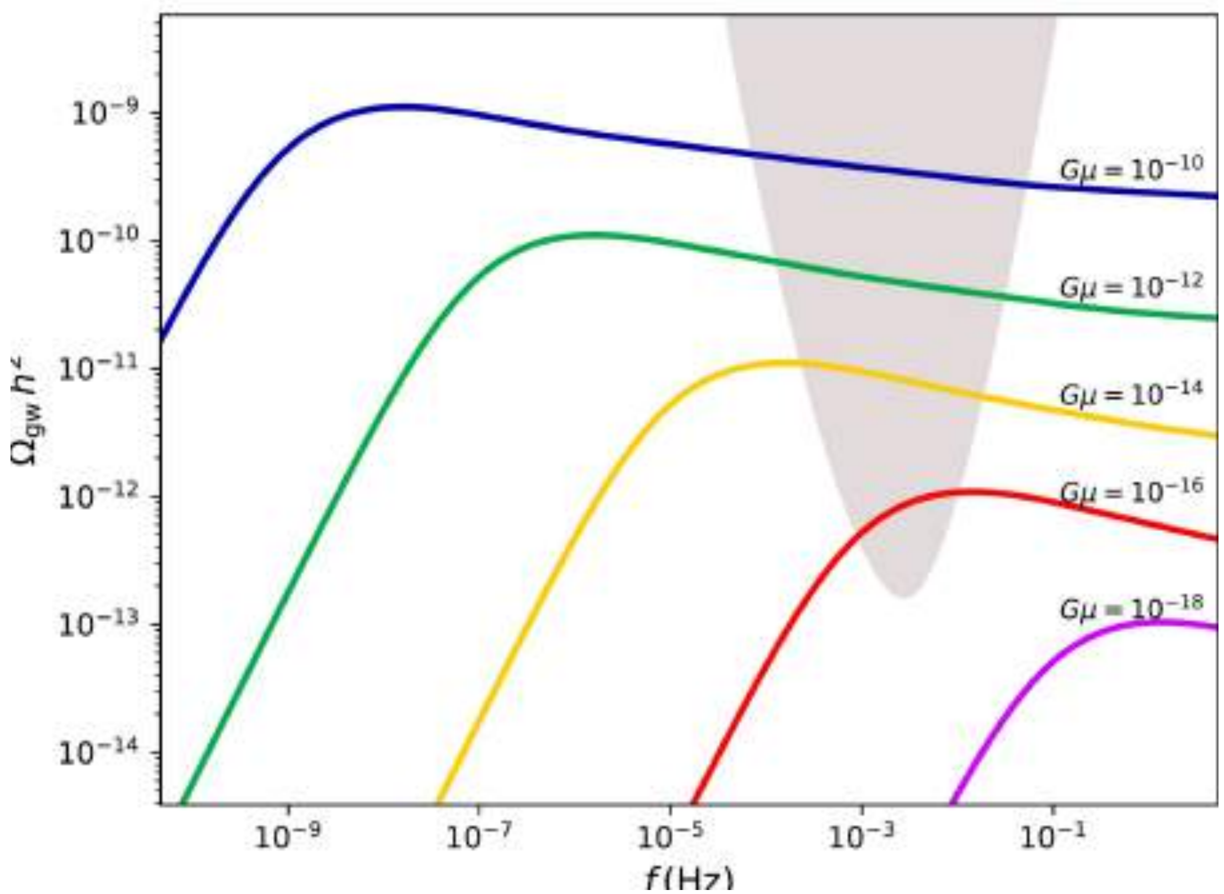
m_s Singlet mass

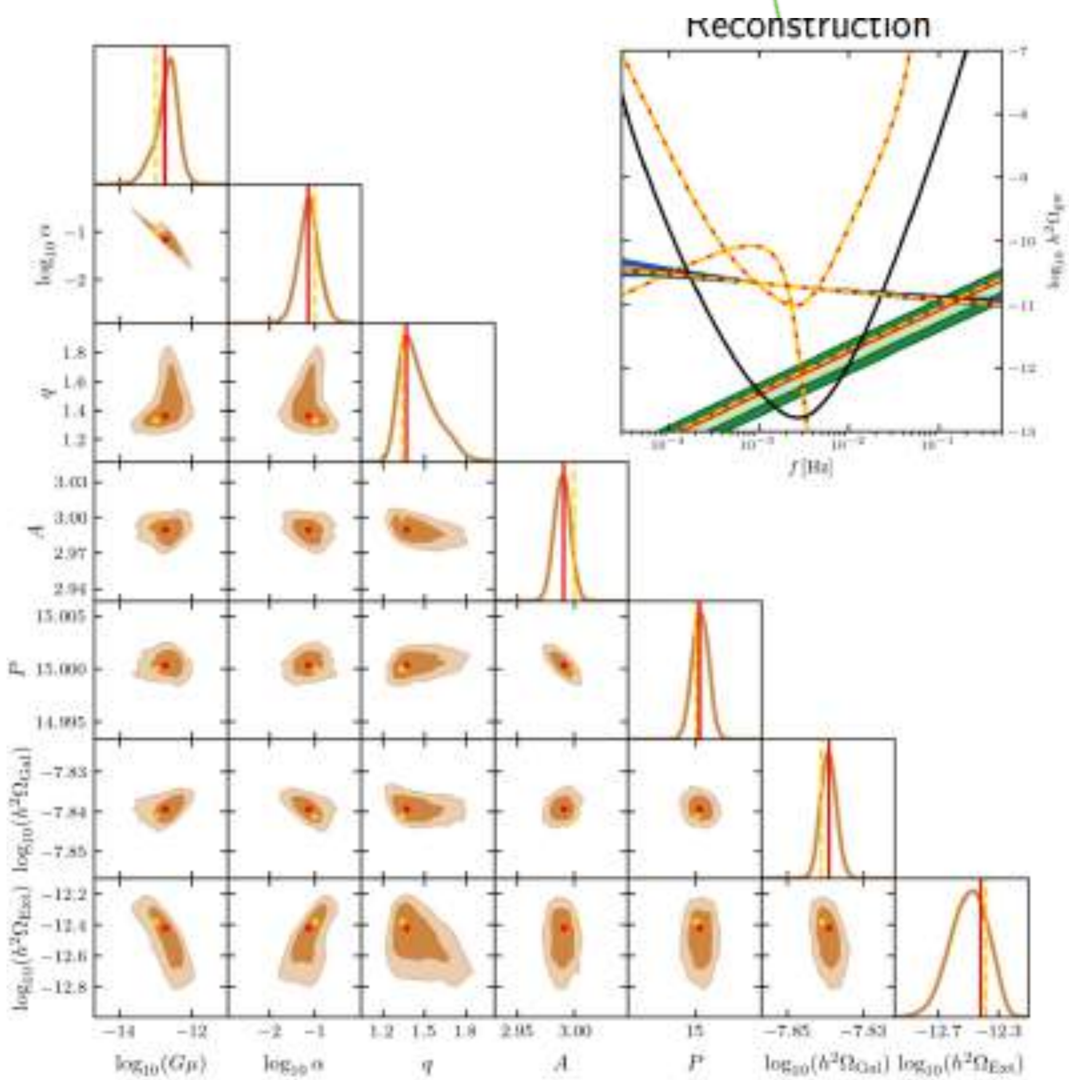
Cosmic Strings in the Early Universe



Cosmic Strings (or other kind of topological defects) are non-trivial field configurations left-over after the phase transition has completed

A network of cosmic strings emits GWB





String parameters: q - spectral index

α - loops size

Gμ - tension

LISA CosGW project Arxiv: 2407.04356 (cosmic strings)

Non-Gaussianity with LISA through SIGW

$$h''_{ij} + 2\mathcal{H}h'_{ij} - \nabla^2 h_{ij} = -4\hat{\mathcal{T}}_{ij}^{lm}\mathcal{S}_{lm}$$

[Matarrese et al; ‘93,’94]
[Ananda et al; ‘06]
[Baumann et al; ’07]
[Domenech ’21 review] ...

Source term

$$\mathcal{S}_{ij}(\mathbf{x},\eta) \equiv 4\Phi\partial_i\partial_j\Phi + \frac{2(1+3w)}{3(1+w)}\partial_i\Phi\partial_j\Phi - \frac{4}{3(1+w)\mathcal{H}^2}\left[\partial_i\Phi'\partial_j\Phi' + \mathcal{H}\partial_i\Phi\partial_j\Phi' + \mathcal{H}\partial_i\Phi'\partial_j\Phi\right]$$

We can include the presence of **primordial non-Gaussianity**

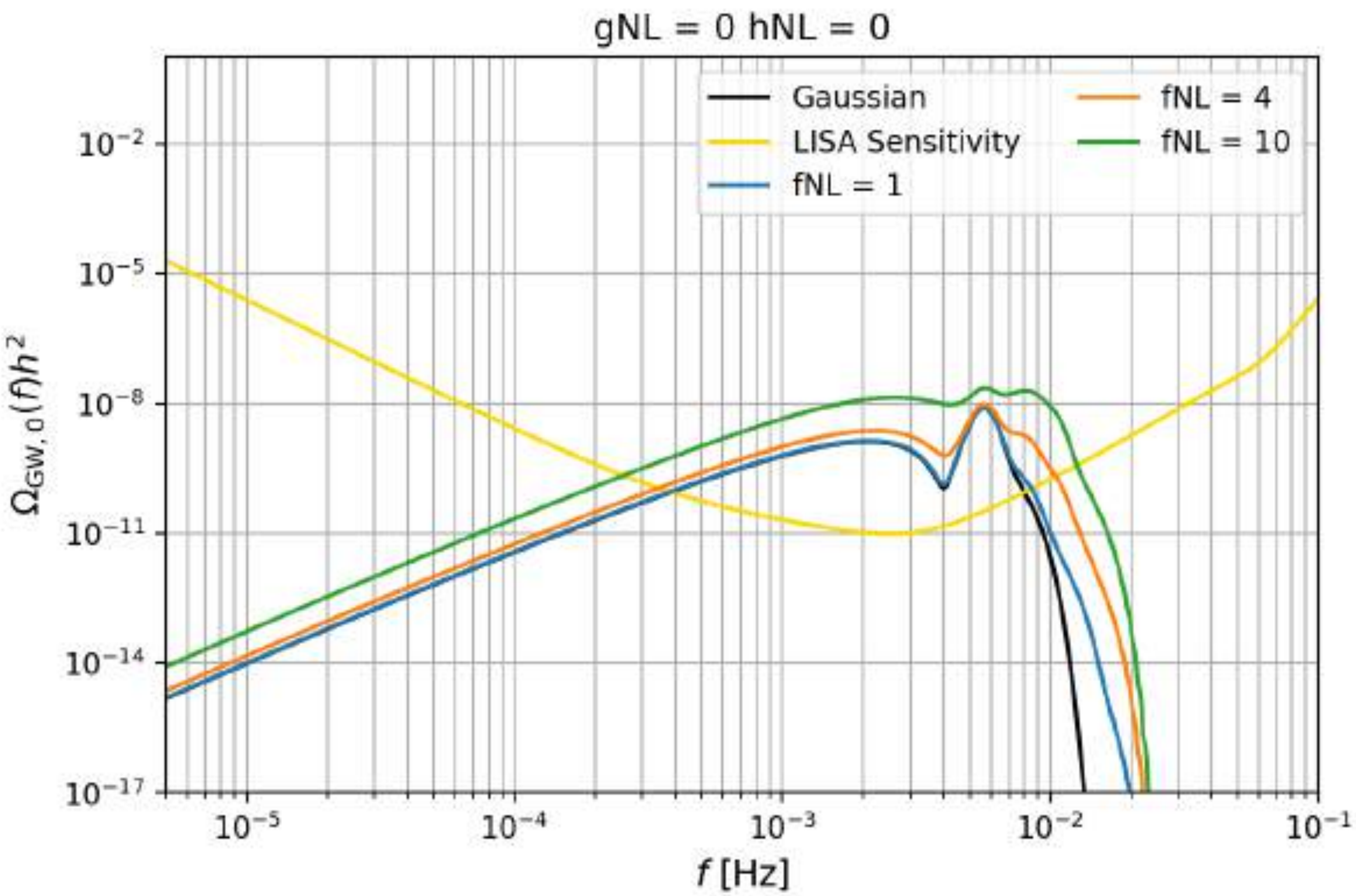
$$\mathcal{R}(\mathbf{x}) = \mathcal{R}_g(\mathbf{x}) + f_{\rm NL}\left(\mathcal{R}_g^2(\mathbf{x}) - \langle\mathcal{R}_g^2\rangle\right)$$

$$\Phi(\mathbf{k},\eta) = \frac{3+3w}{5+3w}\phi(k\eta)\mathcal{R}(\mathbf{k})$$

We focus on local non-Gaussianity

$$\Omega_{\rm GW}(k,\eta) = \Omega_{\rm GW}^{G}(k,\eta) + f_{\rm NL}^2\Omega_{\rm GW}^{(2)}(k,\eta) + f_{\rm NL}^4\Omega_{\rm GW}^{(4)}(k,\eta)$$

Non-Gaussianity with LISA through SIGW



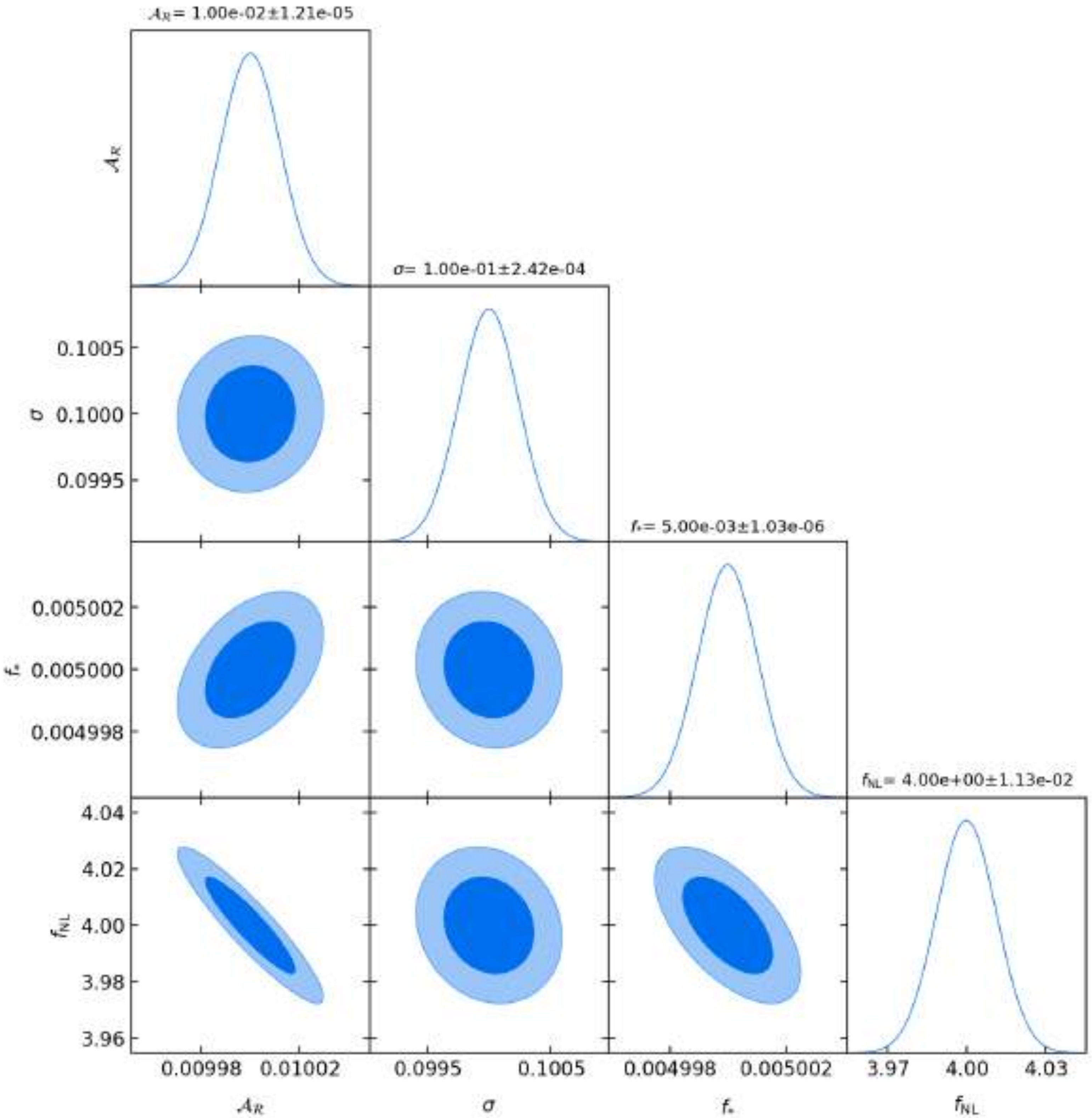
- Radiation domination
- LogNormal scalar power spectrum

$$\Delta_g^2(k) = \frac{\mathcal{A}_{\mathcal{R}}}{\sqrt{2\pi\sigma^2}} \exp\left(-\frac{\ln^2(k/k_*)}{2\sigma^2}\right)$$

Non-Gaussianity has an impact on the amplitude and on the shape

G. Perna, C. Testini, A. R., S. Matarrese [Arxiv 2403.06962]

Probing non-Gaussianity with LISA through SIGW



- Radiation domination
- LogNormal scalar power spectrum

$$\Delta_g^2(k) = \frac{\mathcal{A}_\mathcal{R}}{\sqrt{2\pi\sigma^2}} \exp\left(-\frac{\ln^2(k/k_*)}{2\sigma^2}\right)$$

Fiducial values

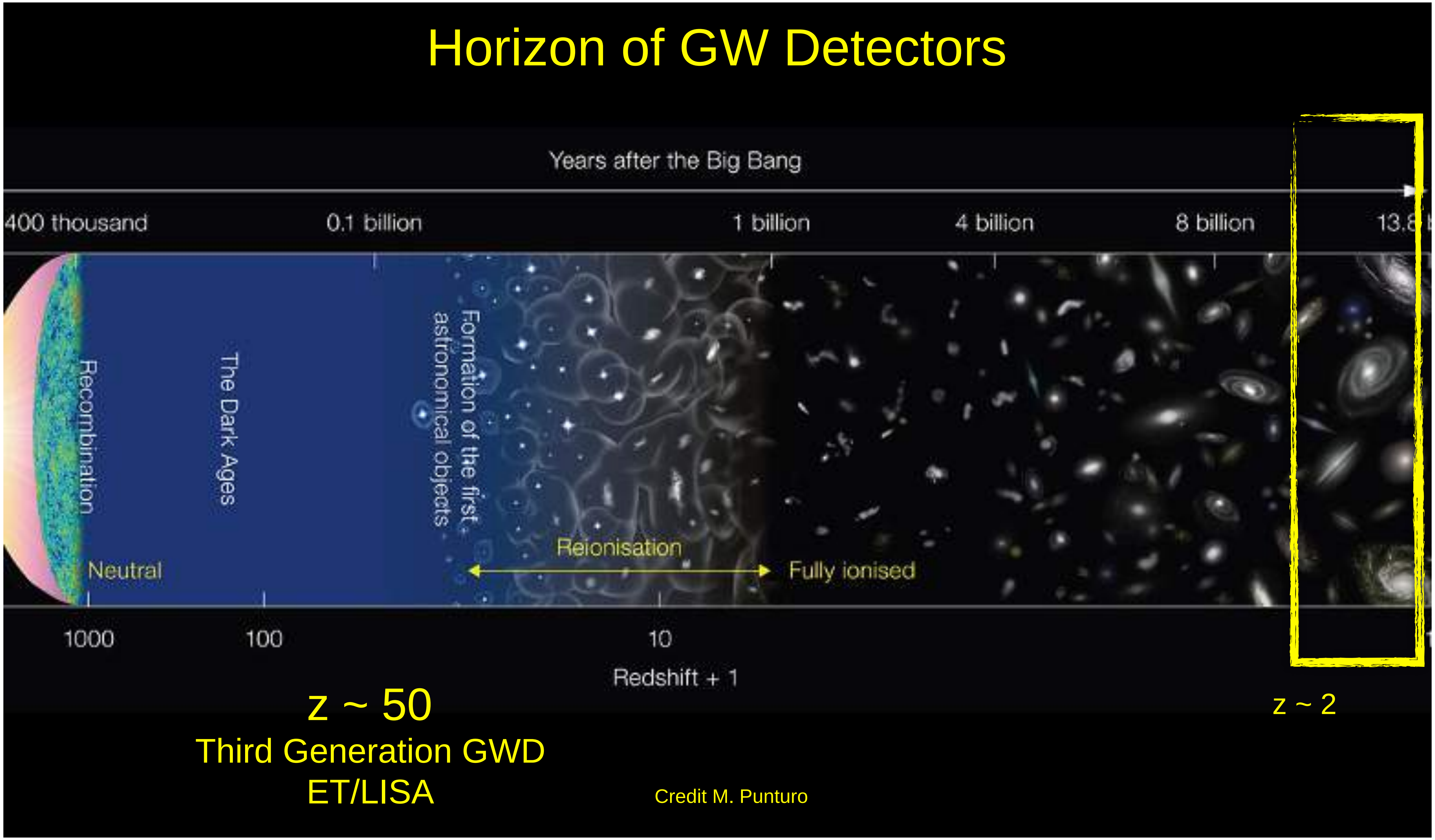
$$A_\mathcal{R} = 10^{-2}$$

$$\sigma = 0.1$$

$$f_* = 0.005\ Hz$$

G. Perna, C. Testini, A. R., S. Matarrese [Arxiv 2403.06962]

Where is the horizon for 3G detectors?

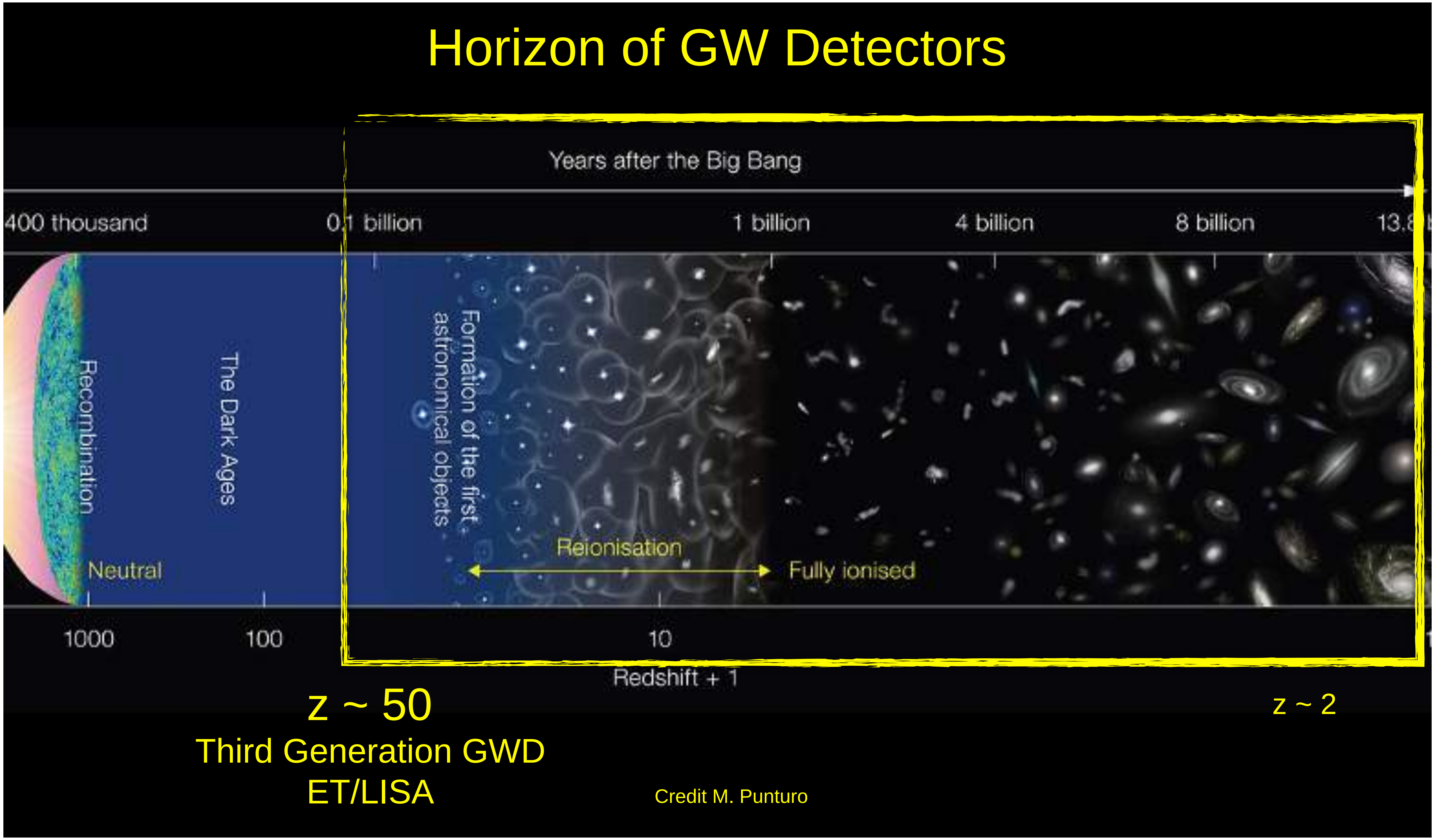


Einstein Telescope:

BBHs up to cosmic Dark Ages (z > 30)

BNSs up to cosmic Noon (z~2)

Where is the horizon for 3G detectors?



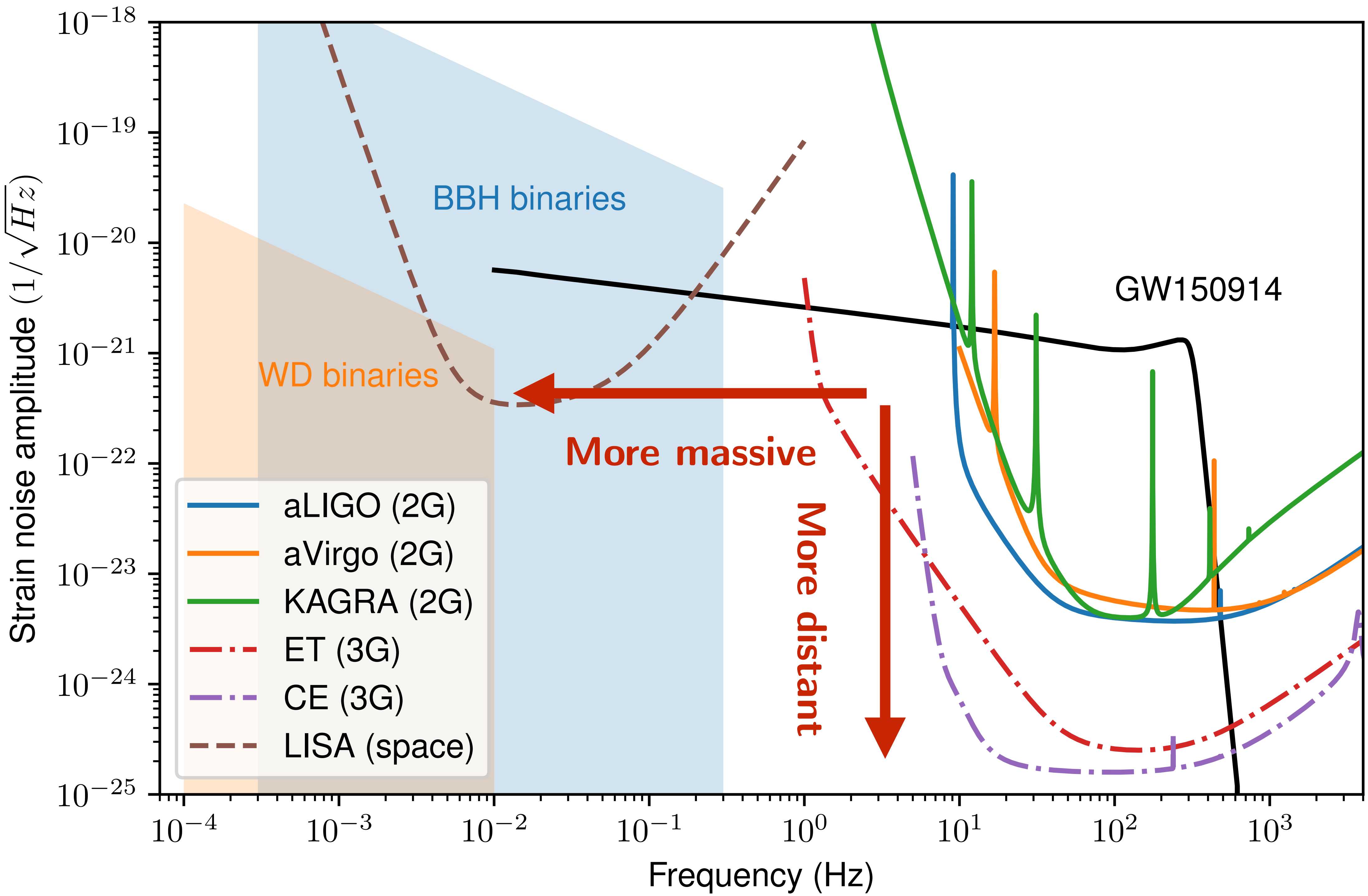
Einstein Telescope:

BBHs up to cosmic Dark Ages (z > 30)

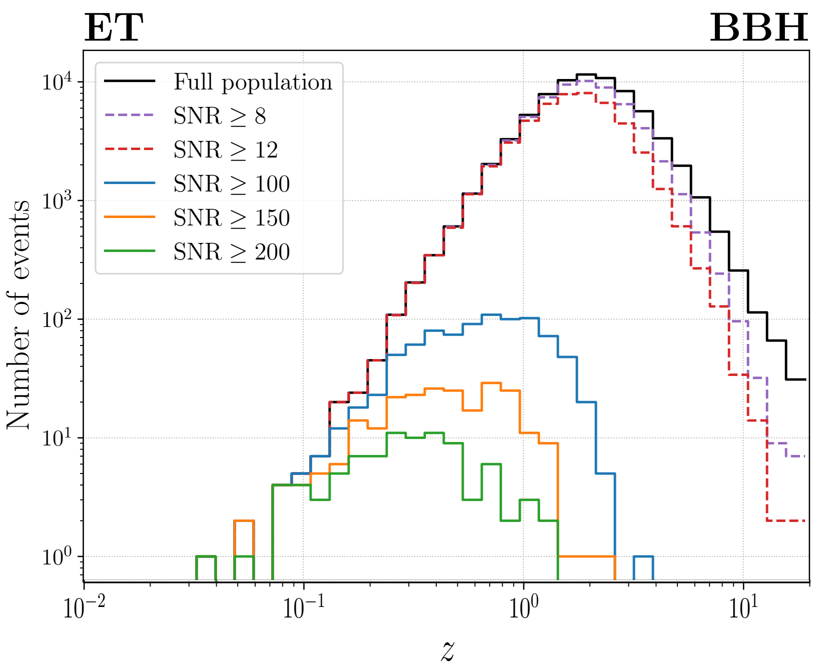
BNSs up to cosmic Noon (z~2)

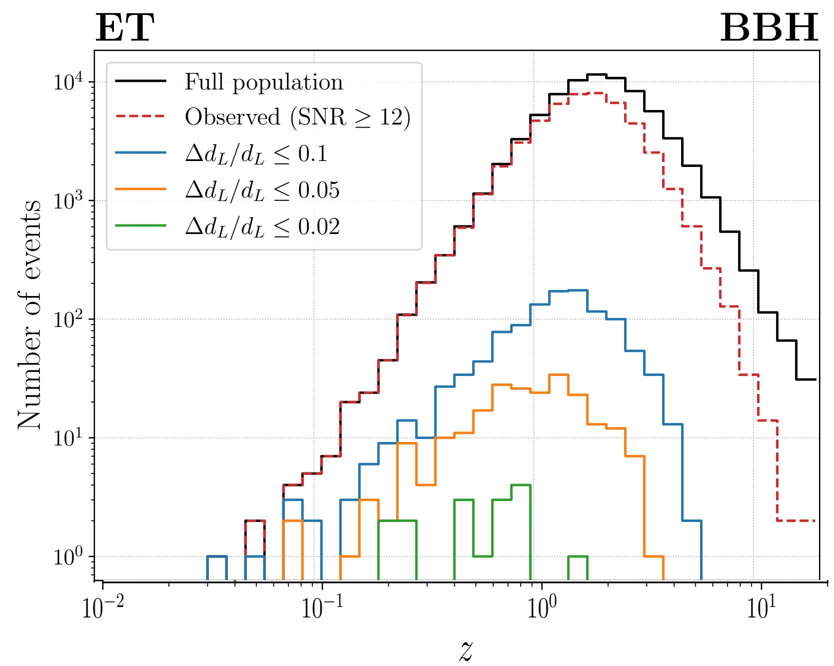
From 2G to 3G detectors: ET and LISA

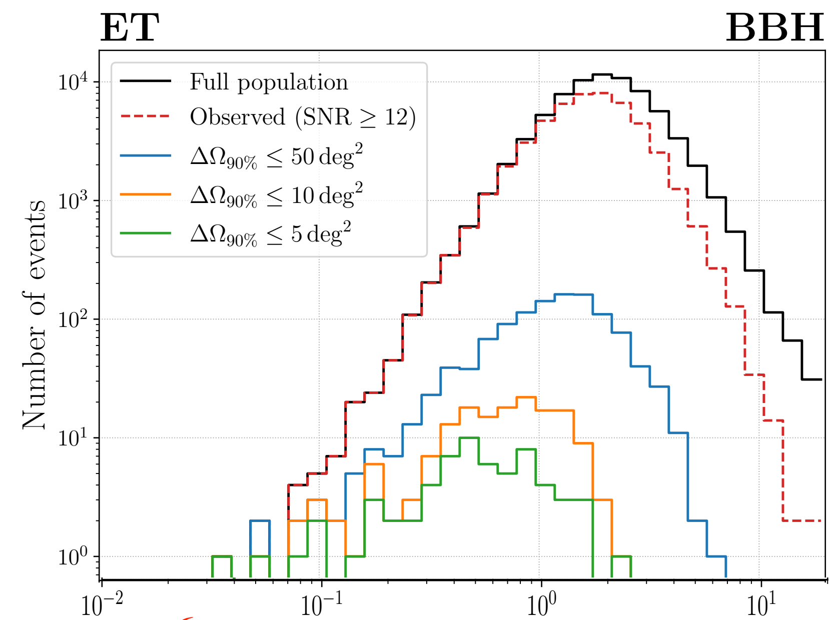
$$h_{\rm gw} \sim 1/d_L \qquad f_{\rm gw} \sim 1{\rm kHz}\left(\frac{10M_\odot}{M}\right)$$



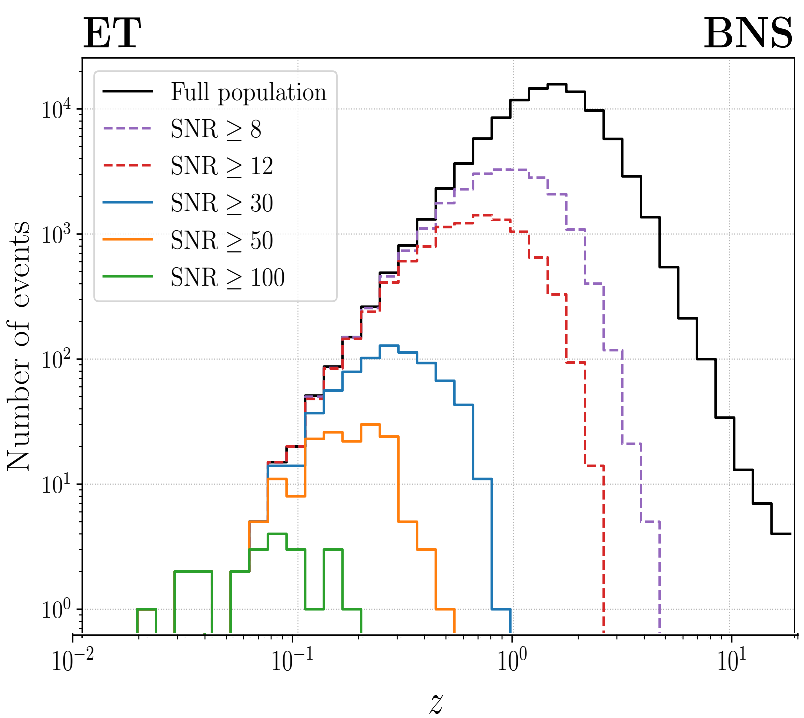
Probing the Late Universe with ET

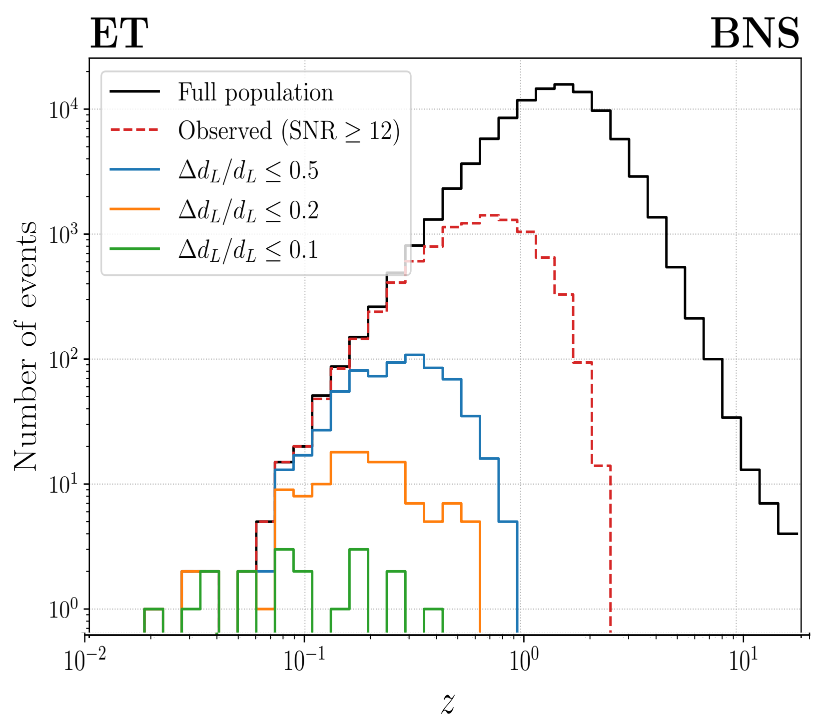


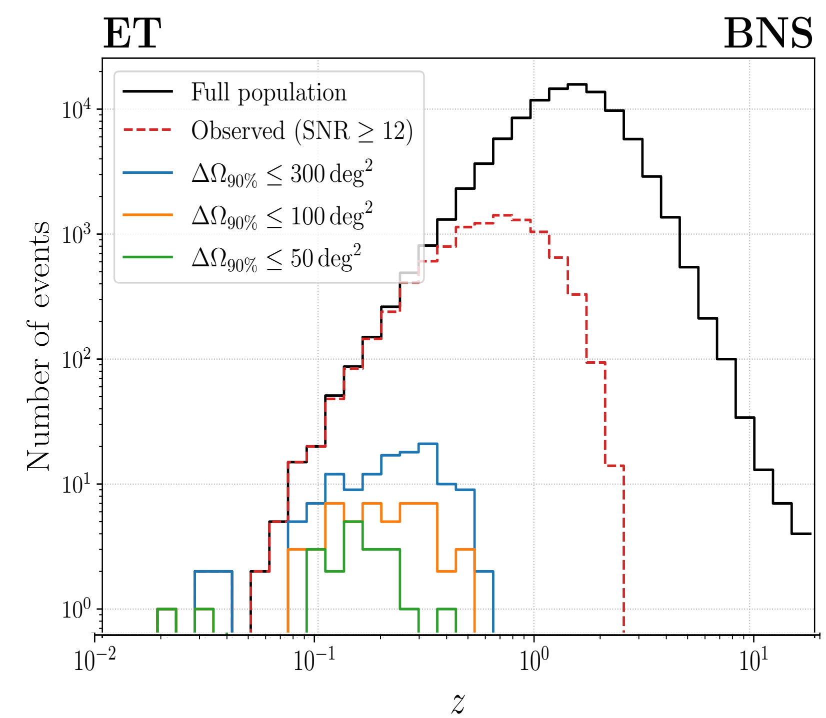




10^6 BBH mergers/yr up to z ~ 50







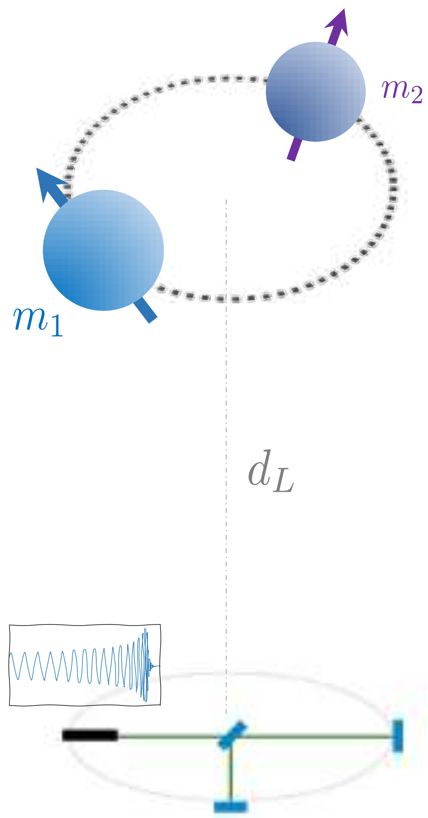
10^5 BNS mergers/yr up to z ~ 2

Many Golden Events

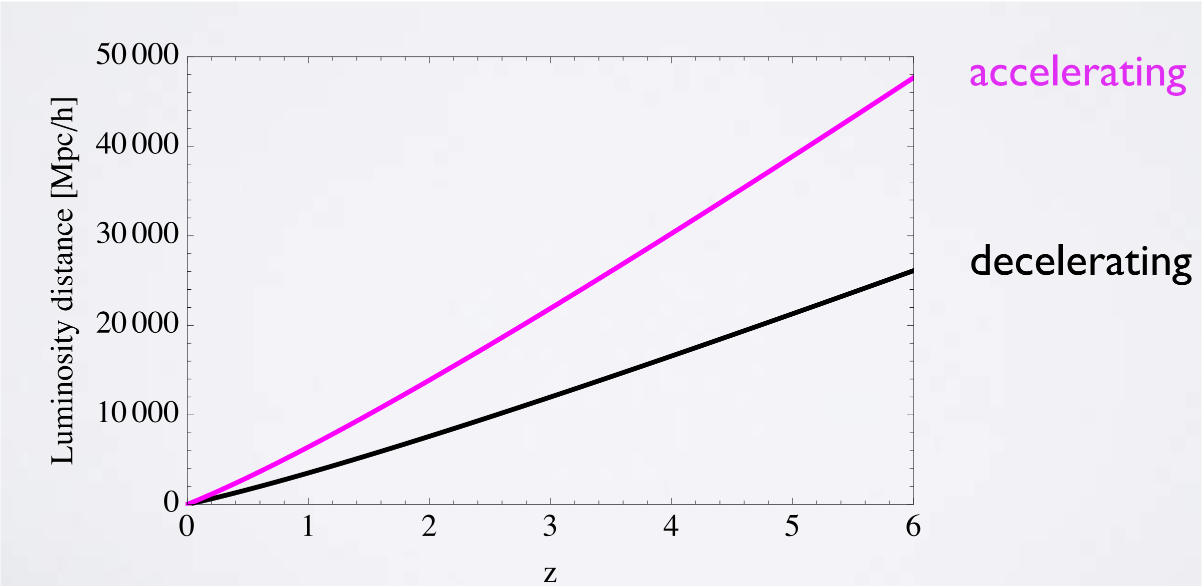
Using GWs as Standard Sirens

Gravitational waves from **individual sources at cosmological distances (e.g. binary black holes, binary neutron stars...) have the potential to give a <u>totally independent measurement of H0</u>**

[B.Schultz, Nature, 1986] standard sirens



- Detect GWs emitted by coalescing binaries
- From the waveform, measure directly the luminosity distance $d_L(z)$
- If, in addition, can determine the redshift z of the source, then have a point on curve $d_L(z)$



Direct probe of cosmology

$$D_{\rm L} = \frac{c(1+z)}{H_0} \int_0^z \frac{dz'}{\left[\Omega_{\rm M}(1+z')^3 + \Omega_\Lambda (1+z')^{3(1+w)}\right]^{1/2}}.$$

For $z \ll 1$, the relationship reduces simply to the Hubble law:

$$c\,z = H_0 \times d_L$$

redshift

Hubble constant

Luminosity distance

Using GWs as Standard Sirens

$$c\,z = H_0 \times d_L$$

redshift

Hubble constant

Luminosity distance

- three quantities: pick any two and infer the third.
- With standard sirens:

  d_L from GW measurements;

  z from, e.g. electromagnetic measurements (if have an optical counterpart, and know the host galaxy, can determine z).

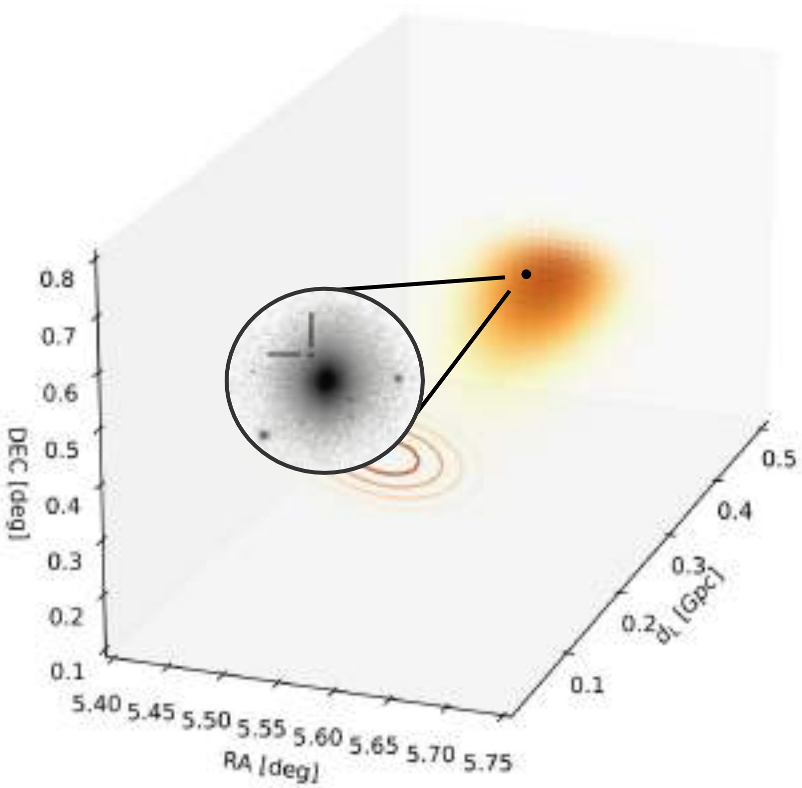
=> independent measure of H_0

Cosmology via the distance-redshift relation
... but no redshift measurement with GW data alone
(Degeneracy with masses)

Using GWs as Standard Sirens - Redshift Information

Bright Sirens

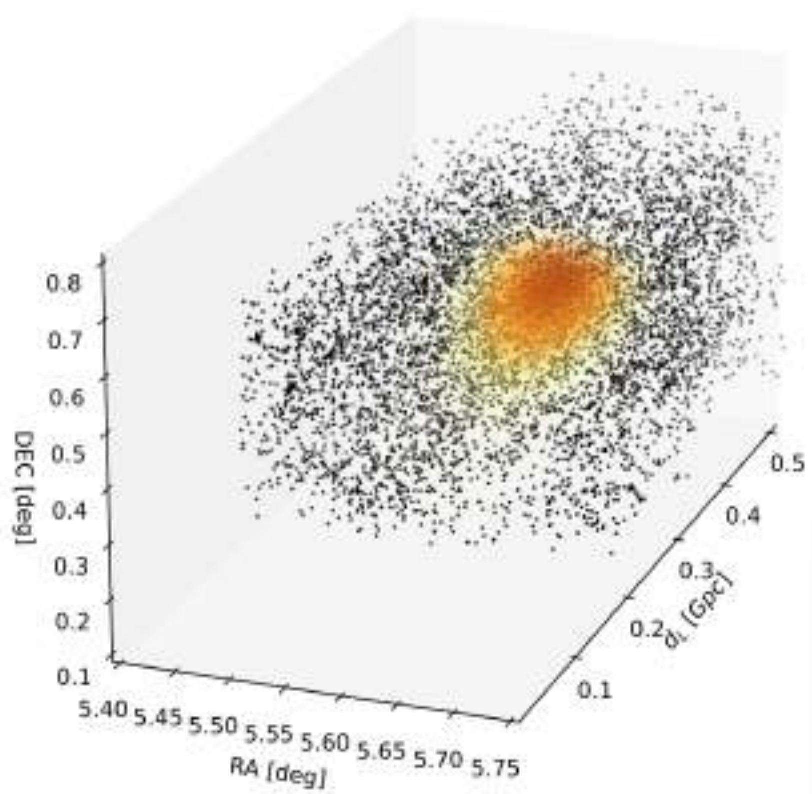
An **EM counterpart** is observed and used to obtain the host galaxy redshift.



(Holz & Hughes 2005)

Dark Sirens

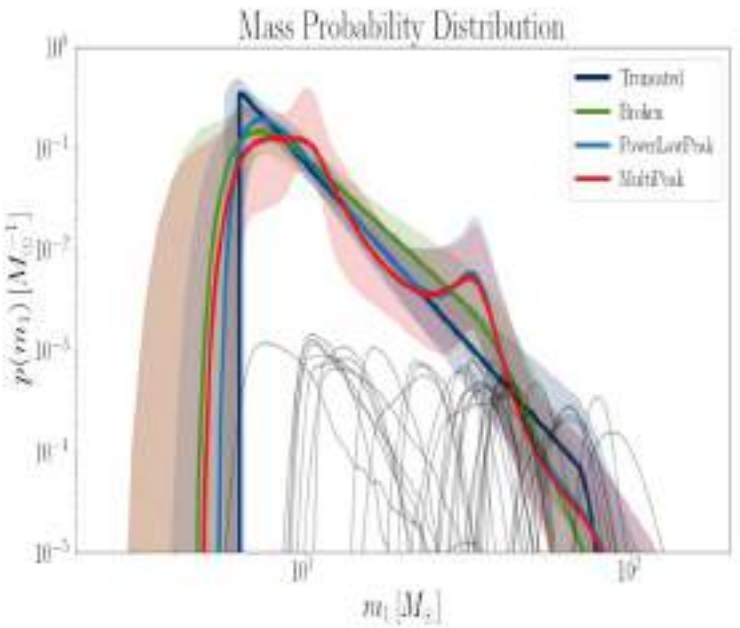
No EM counterpart observed. **Galaxy surveys** are used to provide redshift estimates for potential host galaxies.



(Schutz 1986, Del Pozzo 2012)

Spectral sirens

No EM counterpart or galaxy survey is used. Features in the **mass distribution** of the GW population break the mass-redshift degeneracy.

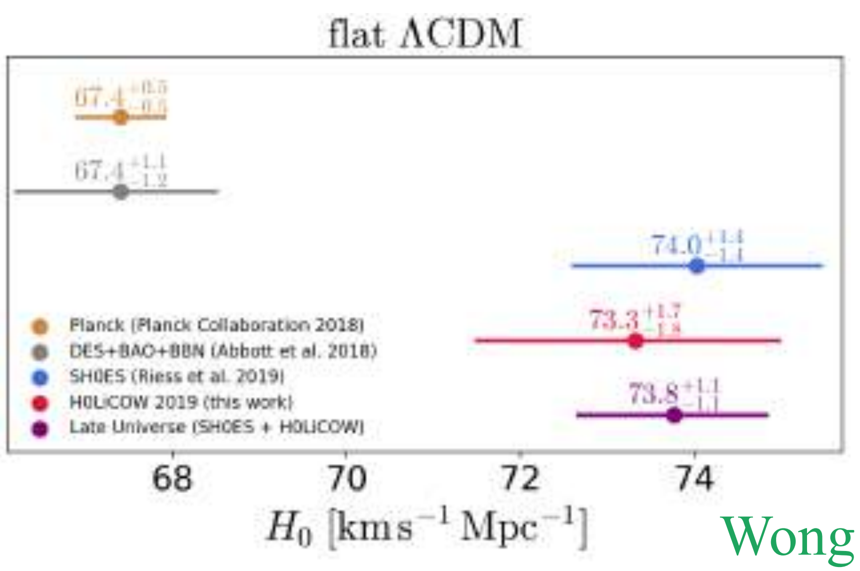


(Chernoff & Finn 1993)

H_0 - where we are

~ 4 \sigma tension between low and high redshift measurements of the Hubble parameter

$$H_0 = 67.36 \pm 0.54 \mathrm{km\,s^{-1}\,Mpc^{-1}} \text{ (Early Universe)}^1$$
$$H_0 = 73.30 \pm 1.04 \mathrm{km\,s^{-1}\,Mpc^{-1}} \text{ (Late Universe)}^2$$



Wong et al., H0LiCOW 2019

[a] Abbott et al., 2017 [arXiv:1710.05835]
[b] Abbott et al., 2021 [arXiv:2111.03604]

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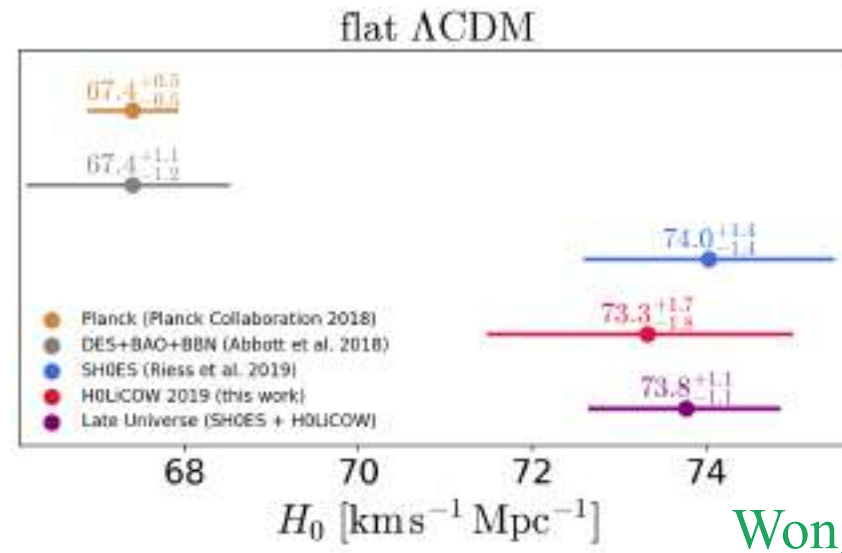
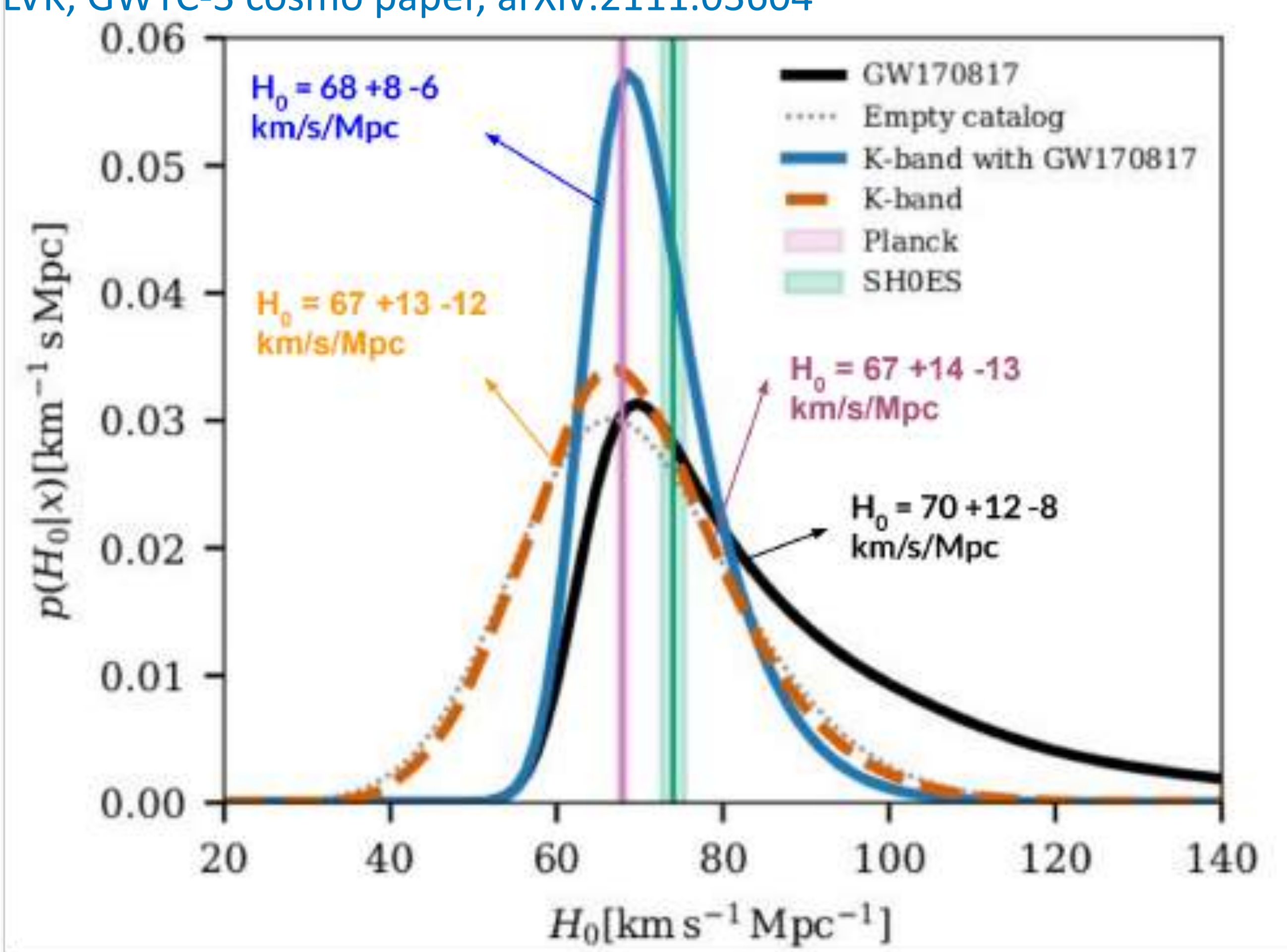


Wong et al., H0LiCOW 2019

LVK, GWTC-3 cosmo paper, arXiv:2111.03604

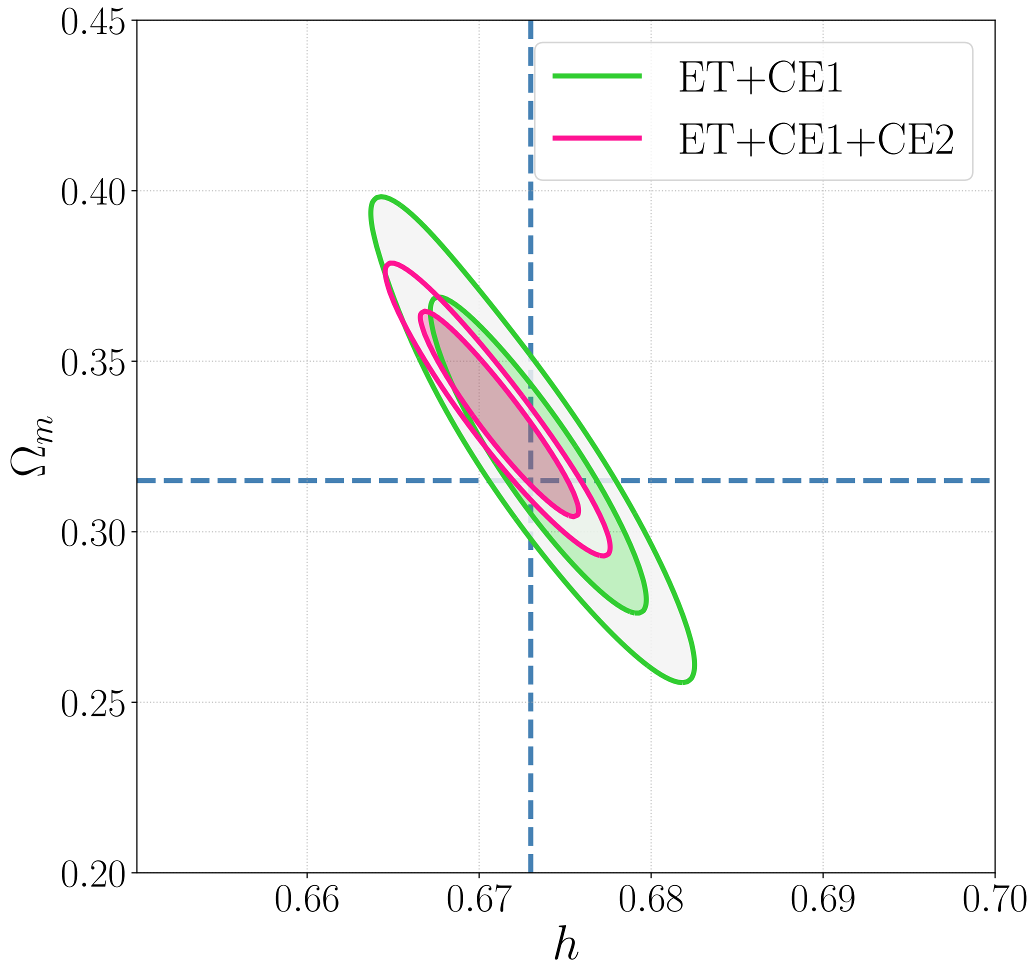


- $H_0 = 72.2^{+13.9}_{-7.5}$ km/s/Mpc
  [Finke et al., JCAP (2021) with GWTC-2 catalog]

- $H_0 = 72.8^{+11.0}_{-7.55}$ km/s/Mpc
  [Palmese et al., ApJ (2023) with GWTC-3 catalog]

[a] Abbott et al., 2017 [arXiv:1710.05835]
[b] Abbott et al., 2021 [arXiv:2111.03604]

H_0 - where we will be with ET? DARK SIRENS method

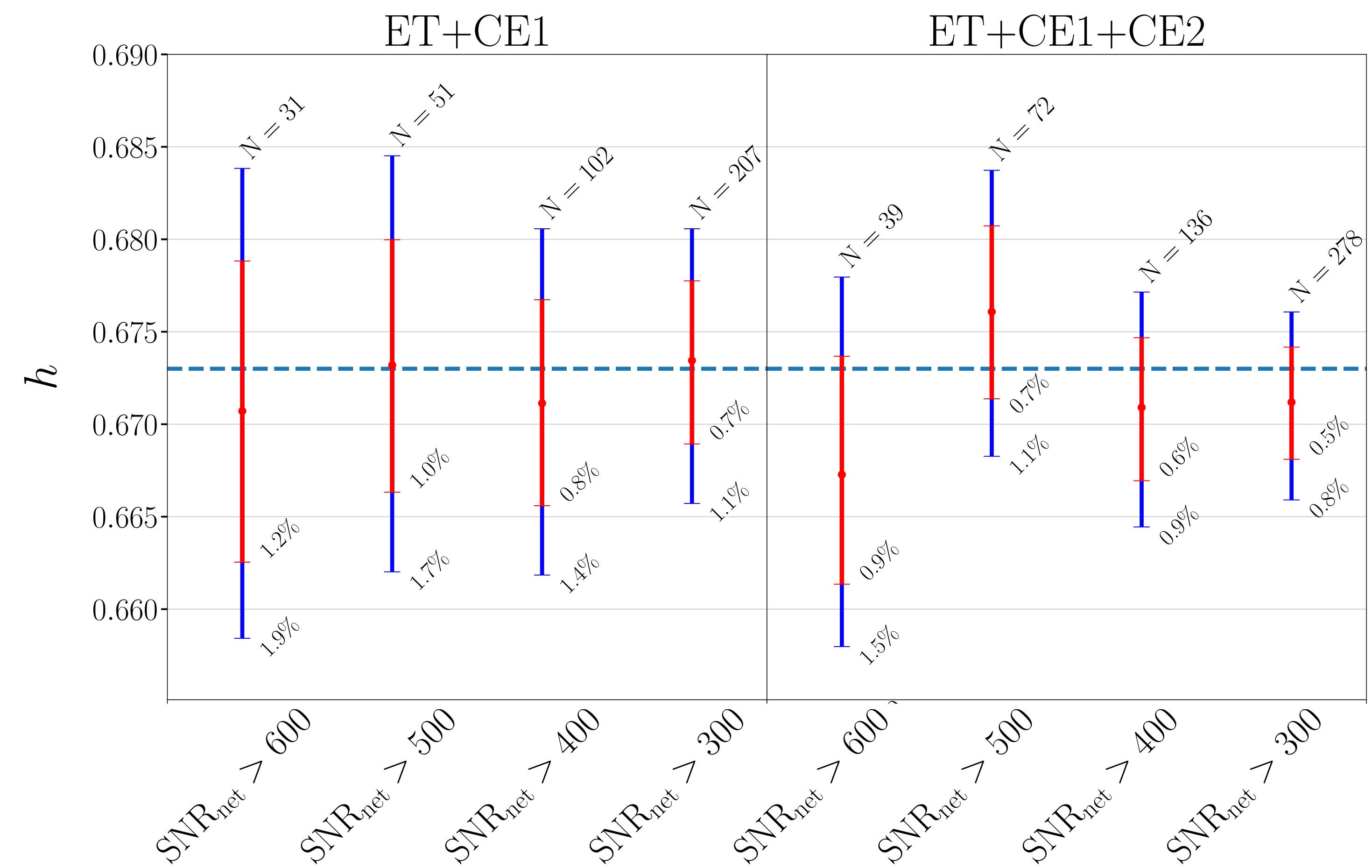


Fiducial scenario

1 year of observation

Complete galaxy catalogue

Full duty cycle



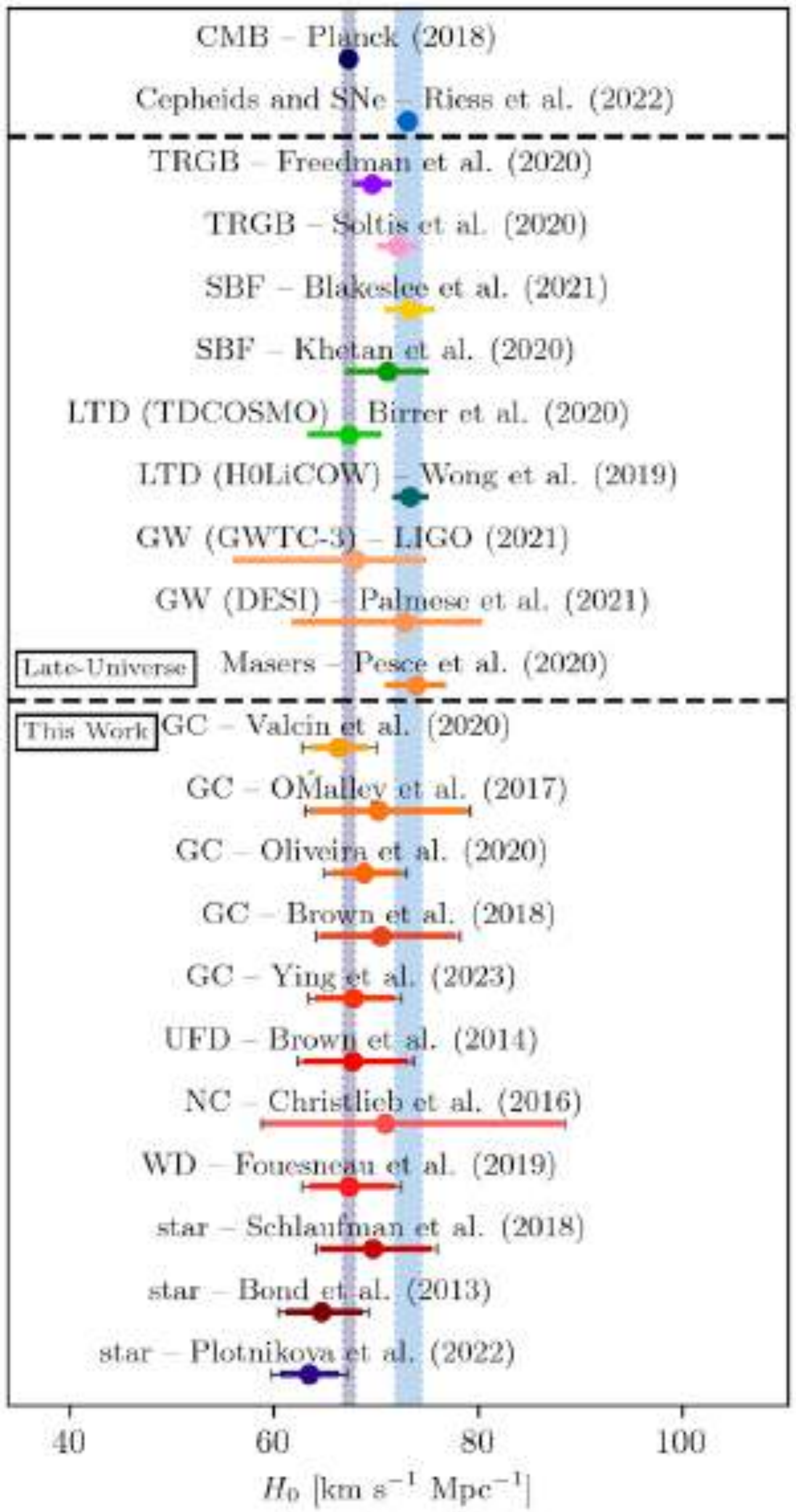
precision for the inference of h with dark sirens with a galaxy catalog complete up to z < 1

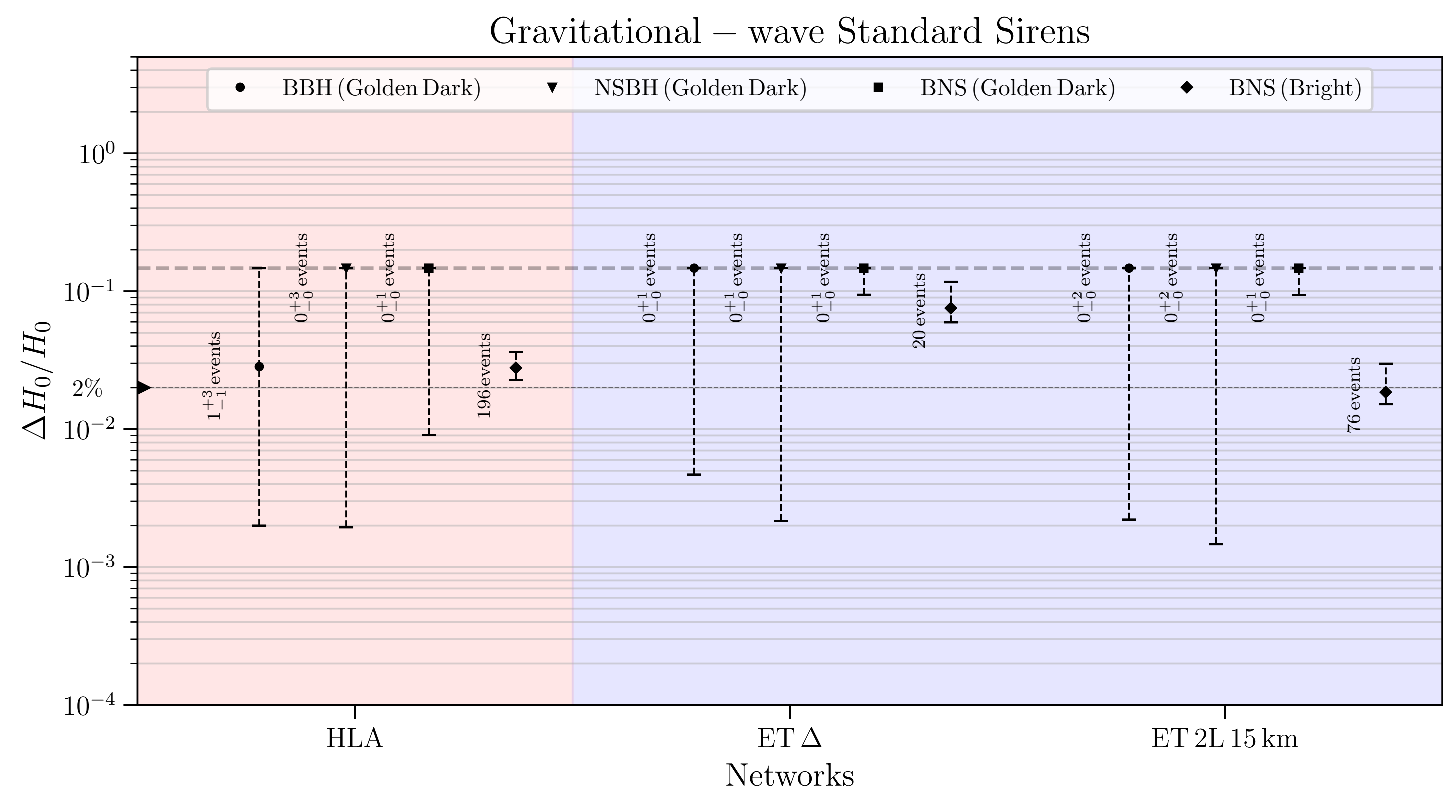
Network	N		$\Delta h/h$ (%)				$\Delta\Omega_m/\Omega_m$ (%)		
	$z<1$	$z<3$	$z<1$	$z<1$ fixed Ω_m	$z<1$ single-host	$z<3$	$z<1$	$z<1$ single-host	$z<3$
ET+CE1	207	248	0.6 (1.1)	0.2 (0.4)	3.3-7.1 (5.6-11.2)	0.7 (1.1)	8.8 (14.4)	-	8.8 (14.6)
ET+CE1+CE2	278	348	0.5 (0.8)	0.2 (0.3)	1.7-2.1 (2.7-3.3)	0.4 (0.7)	6.1 (10.0)	-	5.3 (8.7)

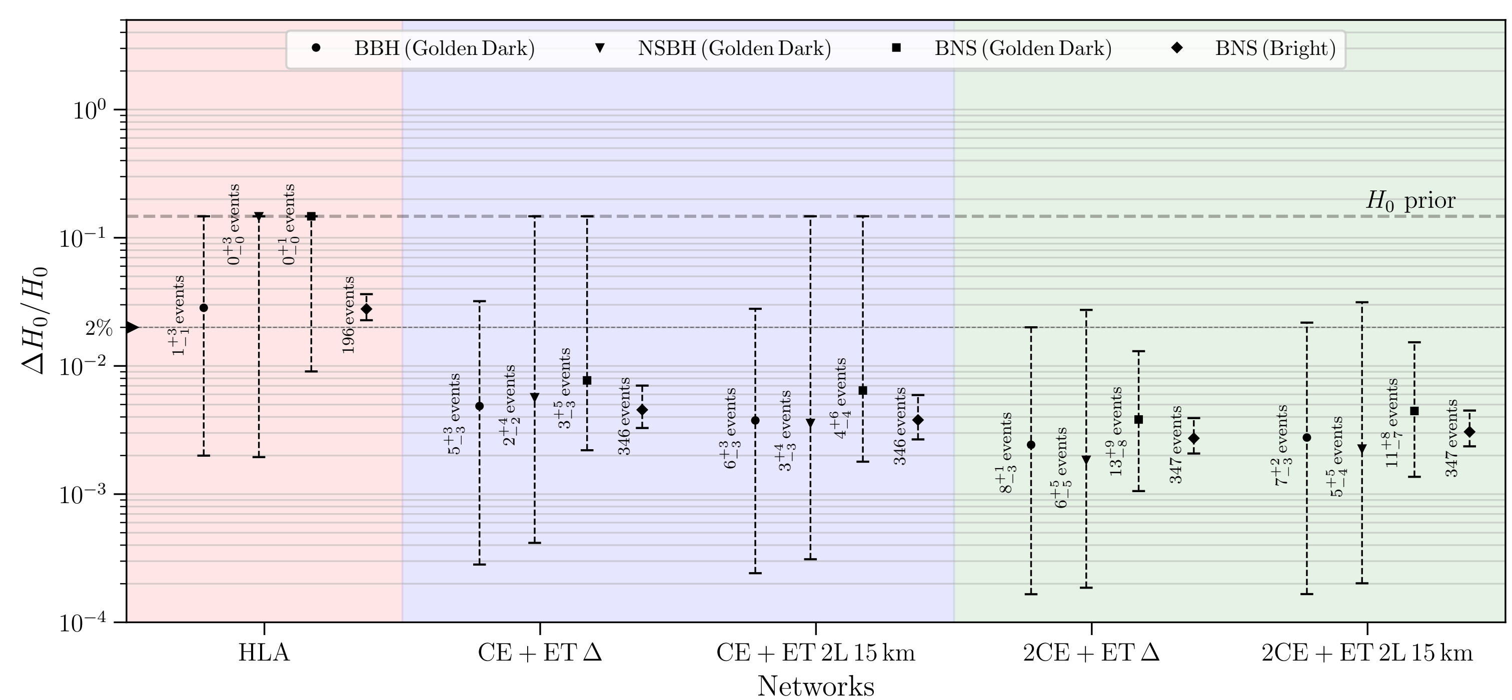
Expected cosmological constraints at the 68% (90%) CI for multiyear 3G observations estimated from the 1 year fiducial results

Nicolo Muttoni et al. 2023

H_0 - shedding light on the H_0 tension

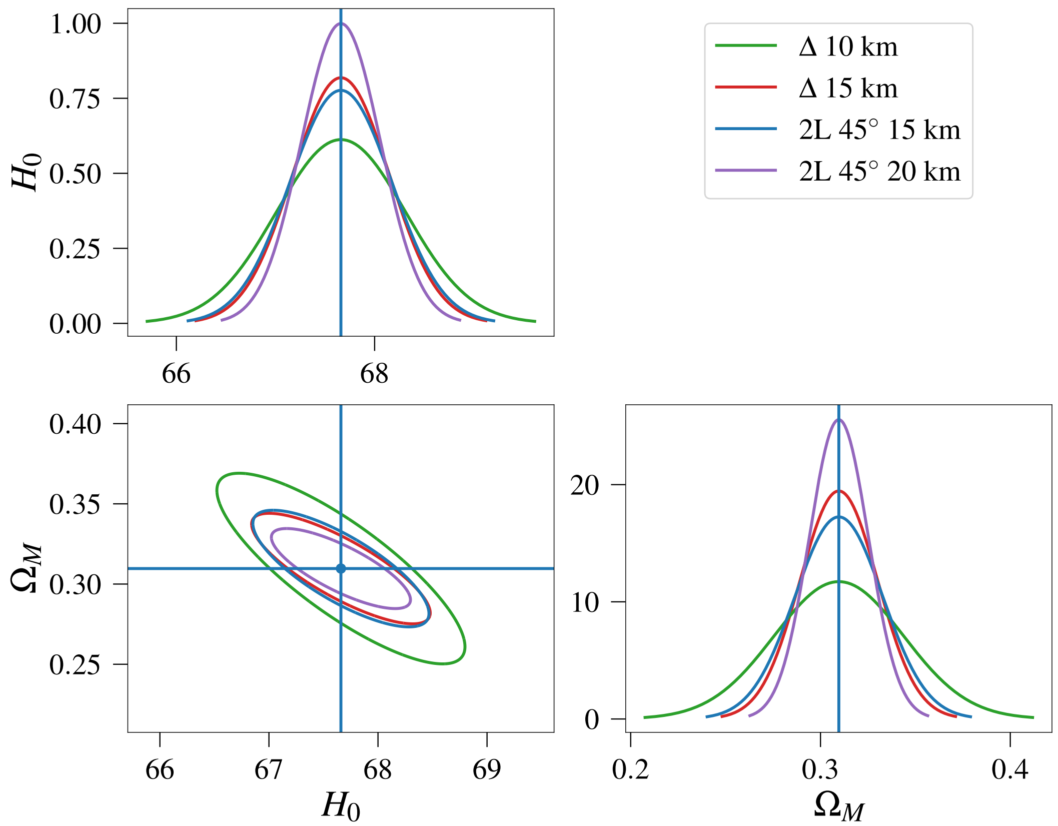


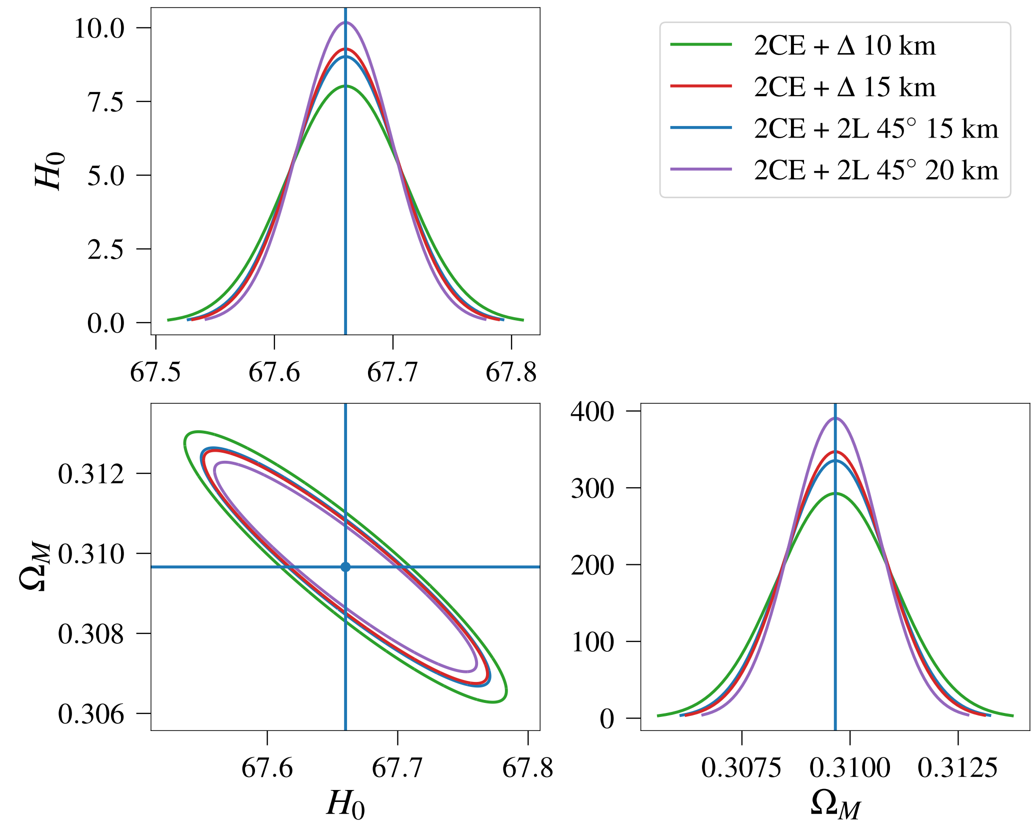




Work in progress

H_0 - where we will be with ET? EM counterpart (BNS)





Configuration	$\Delta H_0/H_0$	$\Delta\Omega_M/\Omega_M$
Δ-10km	9.63×10^{-3}	1.10×10^{-1}
Δ-15km	7.20×10^{-3}	6.62×10^{-2}
2L-15km-45°	7.59×10^{-3}	7.47×10^{-2}
2L-20km-45°	5.90×10^{-3}	5.04×10^{-2}

Configuration	$\Delta H_0/H_0$	$\Delta\Omega_M/\Omega_M$
Δ-10km +2CE	7.35×10^{-4}	4.40×10^{-3}
Δ-15km +2CE	6.35×10^{-4}	3.71×10^{-3}
2L-15km-45° +2CE	6.54×10^{-4}	3.84×10^{-3}
2L-20km-45° +2CE	5.79×10^{-4}	3.30×10^{-3}

Constraints on the parameters H0 and ΩM in ΛCDM model using one year GW observations from BNS alone for different ET geometries.

ET CoBA document

Conclusions

- All **GW interferometers** have been initially **conceived as GW astrophysics observatories**, they have **not been designed to do cosmology**

- **However**, they can provide new information on a variety of scales: from the Galaxy to Hubble scales, from the present time to the **very early universe** -> therefore they can be used as a **cosmological observatory** as well

- **We can have access to energy scales not accessible in any collider**

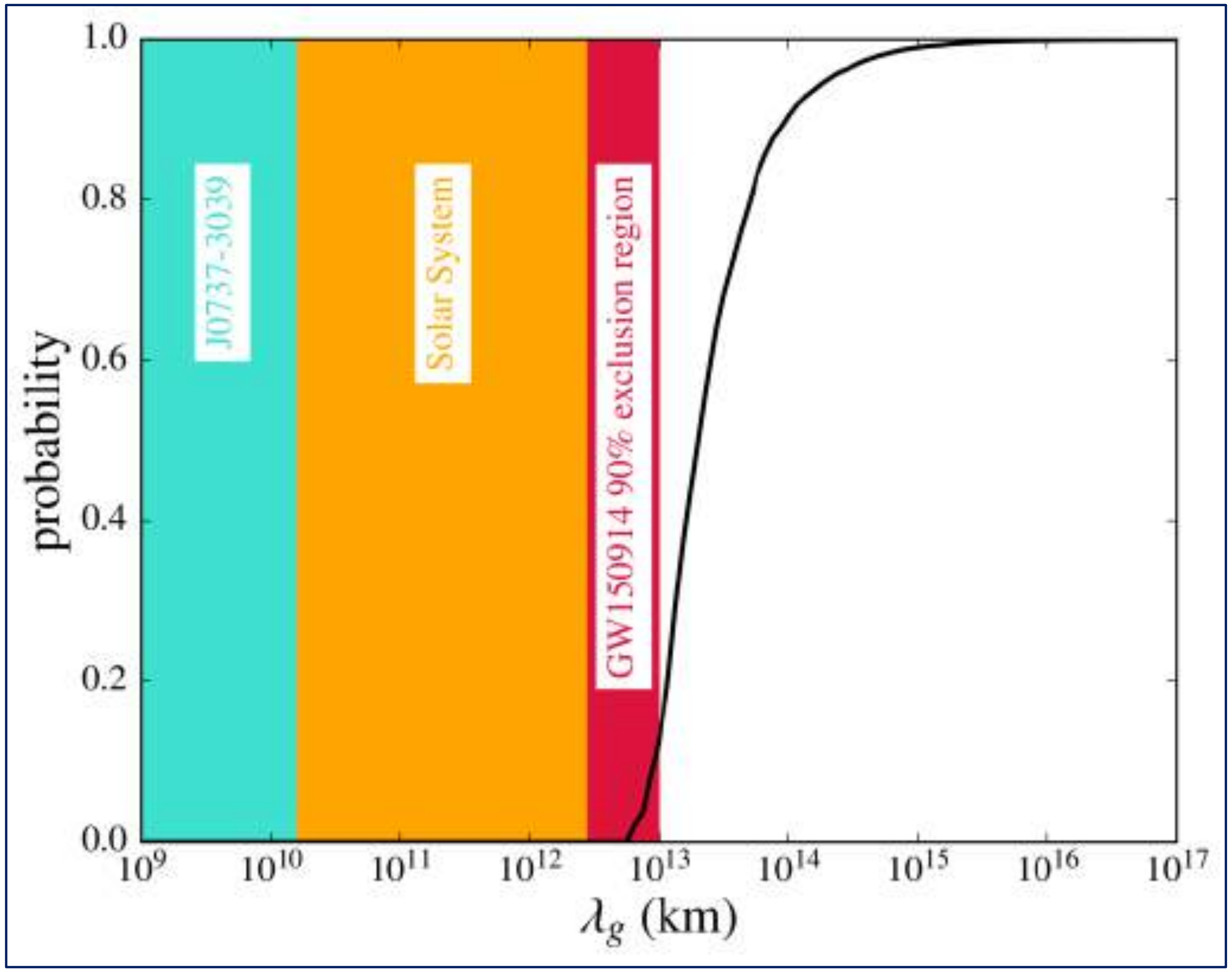
- We can test the ***late-time universe*** through the observation of the GW emission from compact binaries, and **measure cosmological parameters.**

- **A lot of expertise here in the GW community to push forward on these topics (astro+cosmo+fundamental physics+noise characterization)**

Thank you!

Limit on the mass of the graviton

Bounds on the Compton wavelength $\lambda_g = {}^{h}/_{m_g c}$ of the graviton compared to Solar System or double pulsar tests. Some cosmological tests are stronger (but make assumptions about dark matter)



$$\delta\Phi(f) = -\frac{\pi D c}{\lambda_g^2(1+z)} f^{-1}$$

Will, Phys. Rev. D **57**, 2061 (1998)

Massive-graviton theory dispersion relation $E^2 = p^2c^2 + m_g^2c^4$

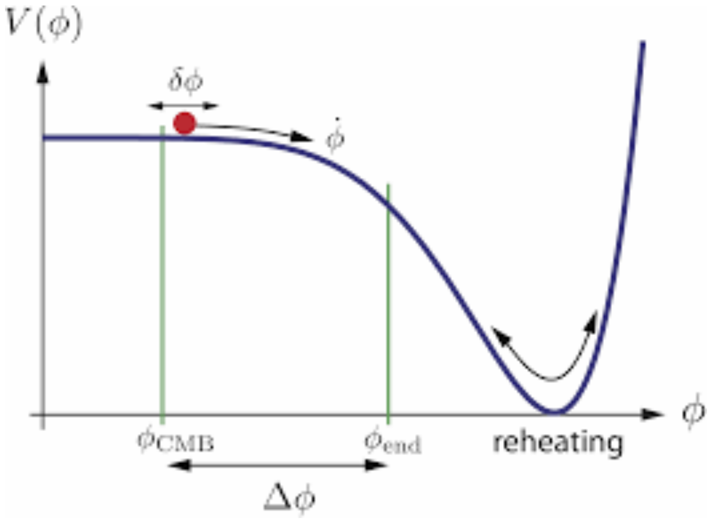
We have $\lambda_g = h/(m_g c)$

Thus frequency dependent speed $\frac{v_g^2}{c^2} \equiv \frac{c^2p^2}{E^2} \cong 1 - h^2c^2/(\lambda_g^2 E^2)$

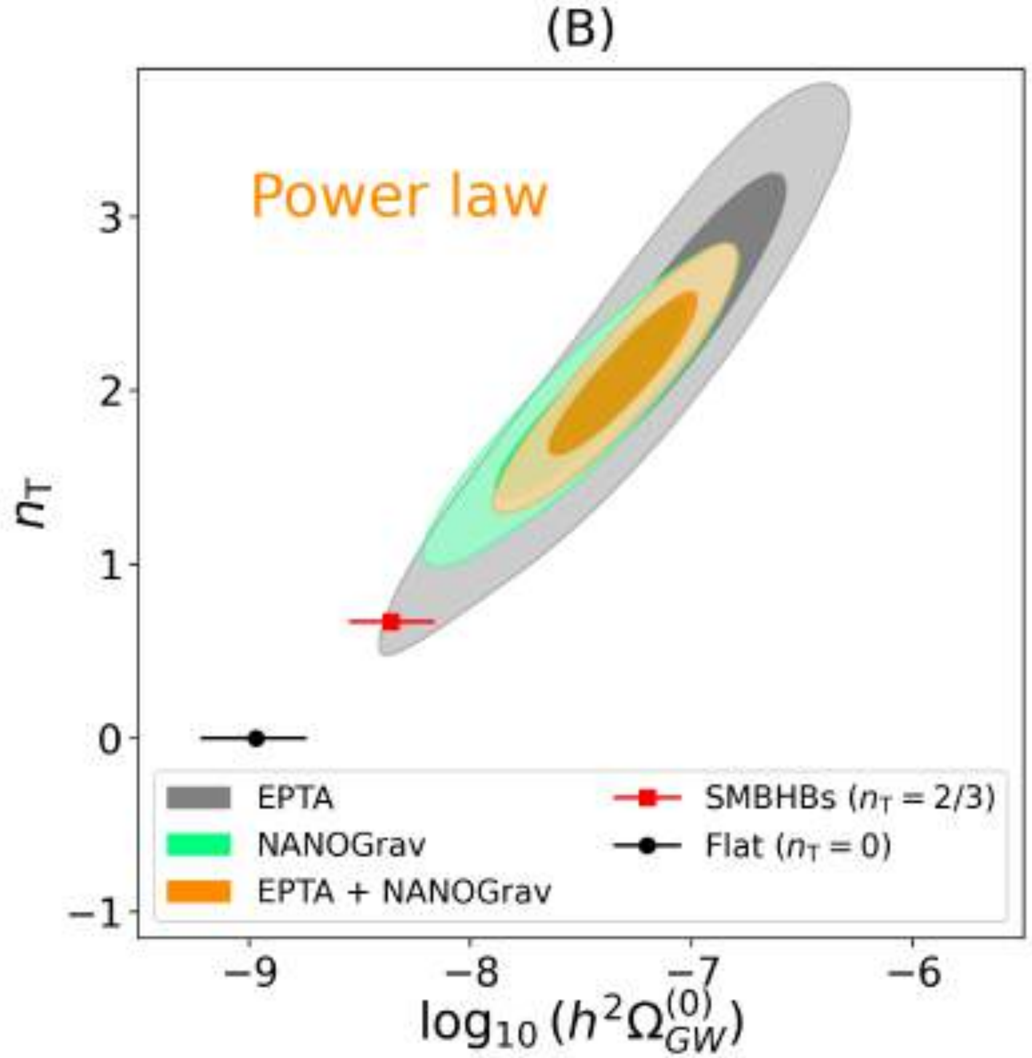
$\lambda_g > 10^{13}$ km
$m_g \leq 5 \times 10^{-23} \text{eV}/\text{c}^2$

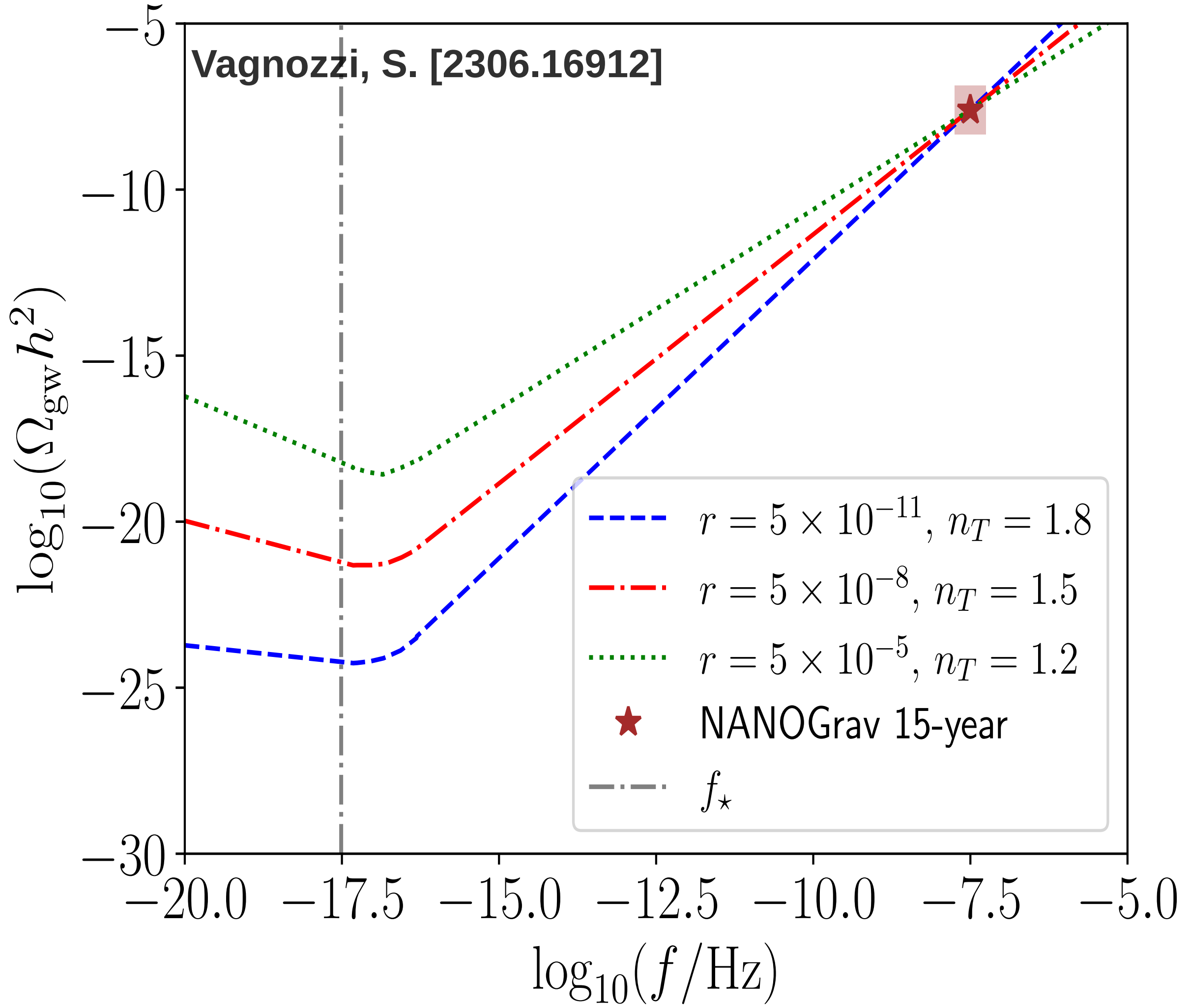
See "*Tests of general relativity with GW150914*" http://arxiv.org/abs/1602.03841

Inflation



$$\Omega_{\rm GW}^{(0)}(f) = \mathcal{A}_{\rm inf}^{(*)} \, (f/f_*)^{n_{\rm t}}$$





Figueroa, Pieroni, AR, Simakachorn, [2307.02399]

LISA noise model

Two analytical approximations for acceleration and interferometric noise:

$$P_{acc}(f,A) = A^2 \cdot 10^{-30} \cdot \left[1 + \left(\frac{4 \cdot 10^{-4}}{f}\right)^2\right] \left[1 + \left(\frac{f}{8 \cdot 10^{-3}}\right)^4\right] \left(\frac{1}{2\pi f}\right)^4 \left(\frac{2\pi f}{c}\right)^2 ,$$

$$P_{IMS}(f,P) = P^2 \cdot 10^{-24} \cdot \left[1 + \left(\frac{2 \cdot 10^{-3}}{f}\right)^4\right] \left(\frac{2\pi f}{c}\right)^2 .$$

The power spectral densities are ($L = 2.5 \times 10^9$m is the arm length):

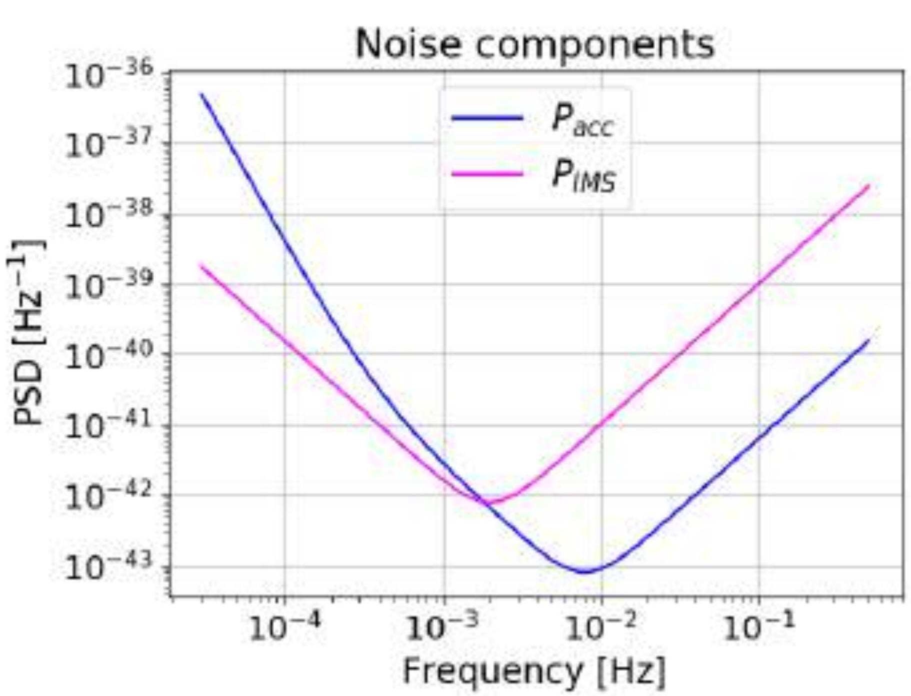
$$P_{PSD}^{XX}(f) = 16 \sin^2\left(\frac{2\pi f L}{c}\right) \left\{P_{IMS}(f,P) + \left[3 + \cos\left(\frac{4\pi f L}{c}\right)\right] P_{acc}(f,A)\right\} ,$$

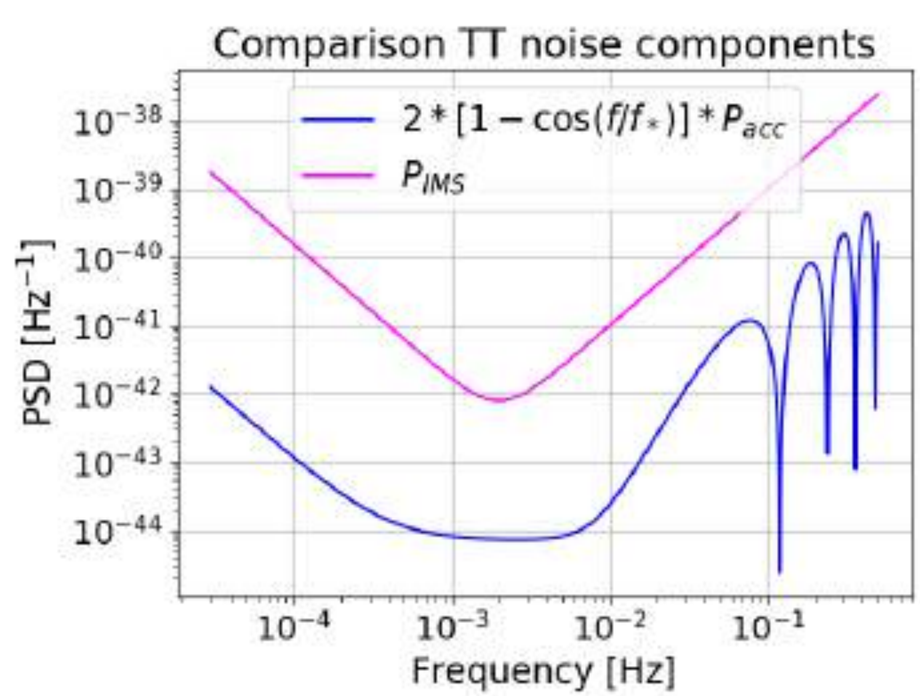
$$P_{PSD}^{XY}(f) = -8 \sin^2\left(\frac{2\pi f L}{c}\right) \cos\left(\frac{2\pi f L}{c}\right) \left\{P_{IMS}(f,P) + 4P_{acc}(f,A)\right\} ,$$

which for the TT combination gives:

$$P_{PSD}^{TT}(f,A,P) = 16 \sin^2\left(\frac{2\pi f L}{c}\right) \left\{2\left[1 - \cos\left(\frac{2\pi f L}{c}\right)\right]^2 P_{acc}(f,A) + \right.$$

$$\left. + \left[1 - \cos\left(\frac{2\pi f L}{c}\right)\right] P_{IMS}(f,P)\right\} .$$





LISA data generation

Assume signal and noise (Ω units) to be Gaussian distributed

The spectra ($\Omega_{\rm GW}$ and Ω_n) quantify the variance of fluctuations

$$\tilde{s}_c(f_i) = \left| \frac{G(0, \sqrt{\Omega_{\rm GW}(f_i)}) + i\, G(0, \sqrt{\Omega_{\rm GW}(f_i)})}{\sqrt{2}} \right|$$

$$\tilde{n}_c(f_i) = \left| \frac{G(0, \sqrt{\Omega_n(f_i)}) + i\, G(0, \sqrt{\Omega_n(f_i)})}{\sqrt{2}} \right|$$

For each data segment and frequency we generate a gaussian realization.

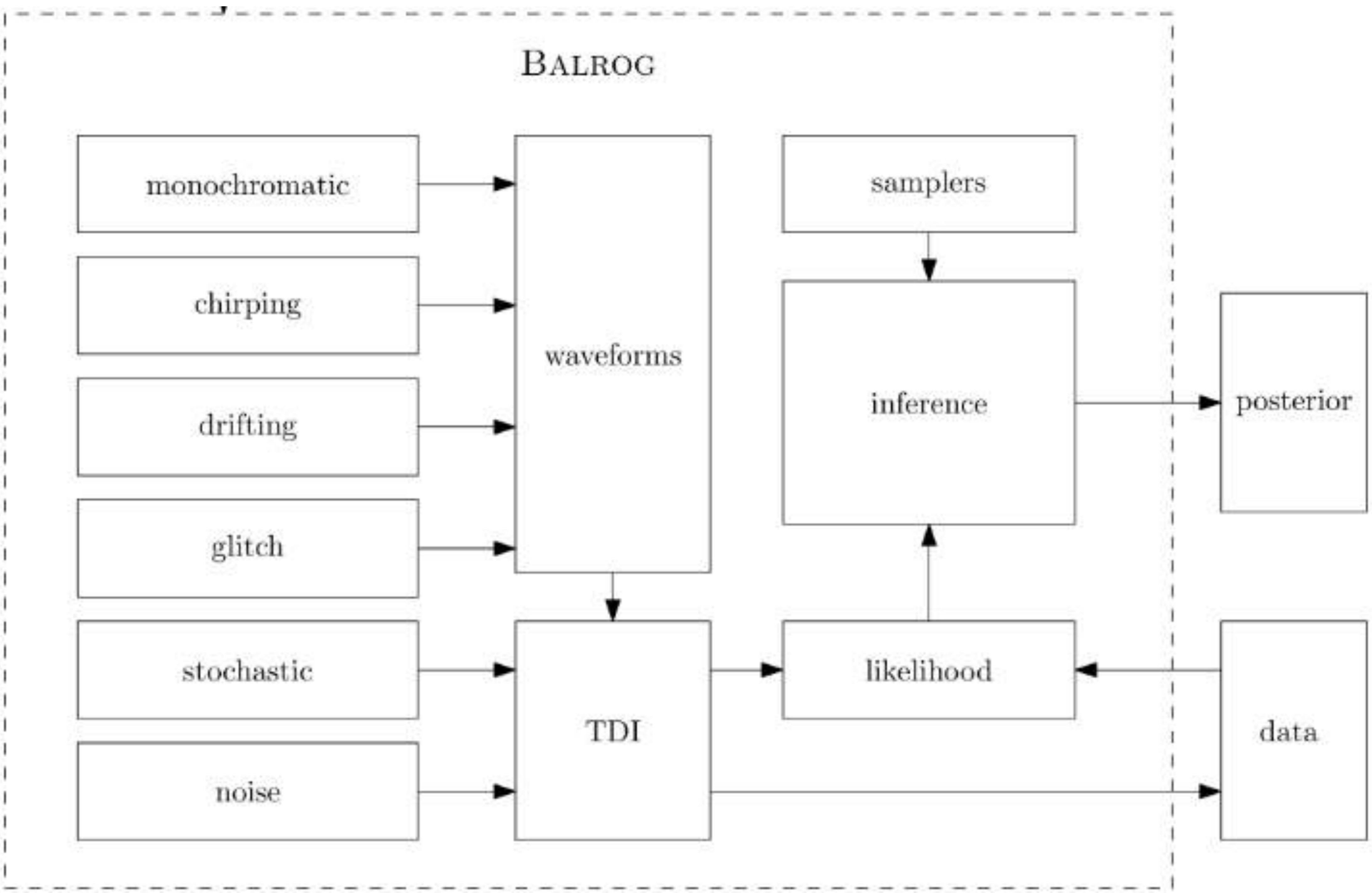
Given that:

- LISA will be operating for 4yrs (75% efficiency)
- We choose data segments of roughly 12 days

we conclude that:

- Roughly 95 independent measurements at each frequency.
- The resolution of the detector is roughly 10^{-6}Hz

Possible prototype



Buscicchio et al.