# Probing Cosmology with Einstein Telescope


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Department of Physics “E. Fermi”
University of Pisa

INFN - Sezione di Pisa


# 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.

Virgo-PI workshop - May 22, 2024 G Losurdo 2

# Where we are - LVK

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

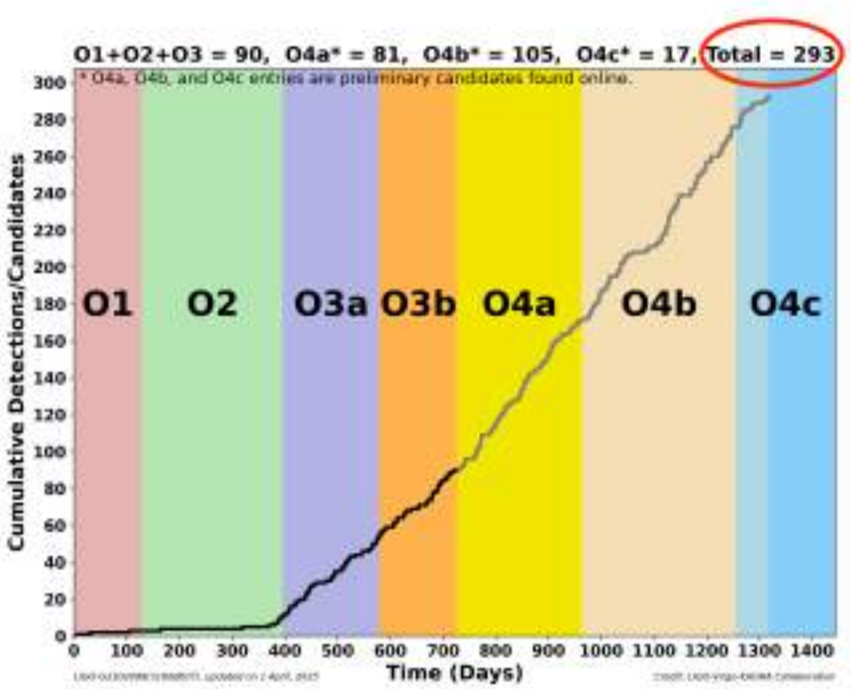
Total number of gravitational waves observed to date (with probability of astrophysical origin > 0.5): ~ **90**

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

GWTC-3 catalogue: arXiv:2111.03606

**The run O4a May 2023 - January 2024** (GW230529)

**The fourth run O4b+c has started in April** with Virgo online



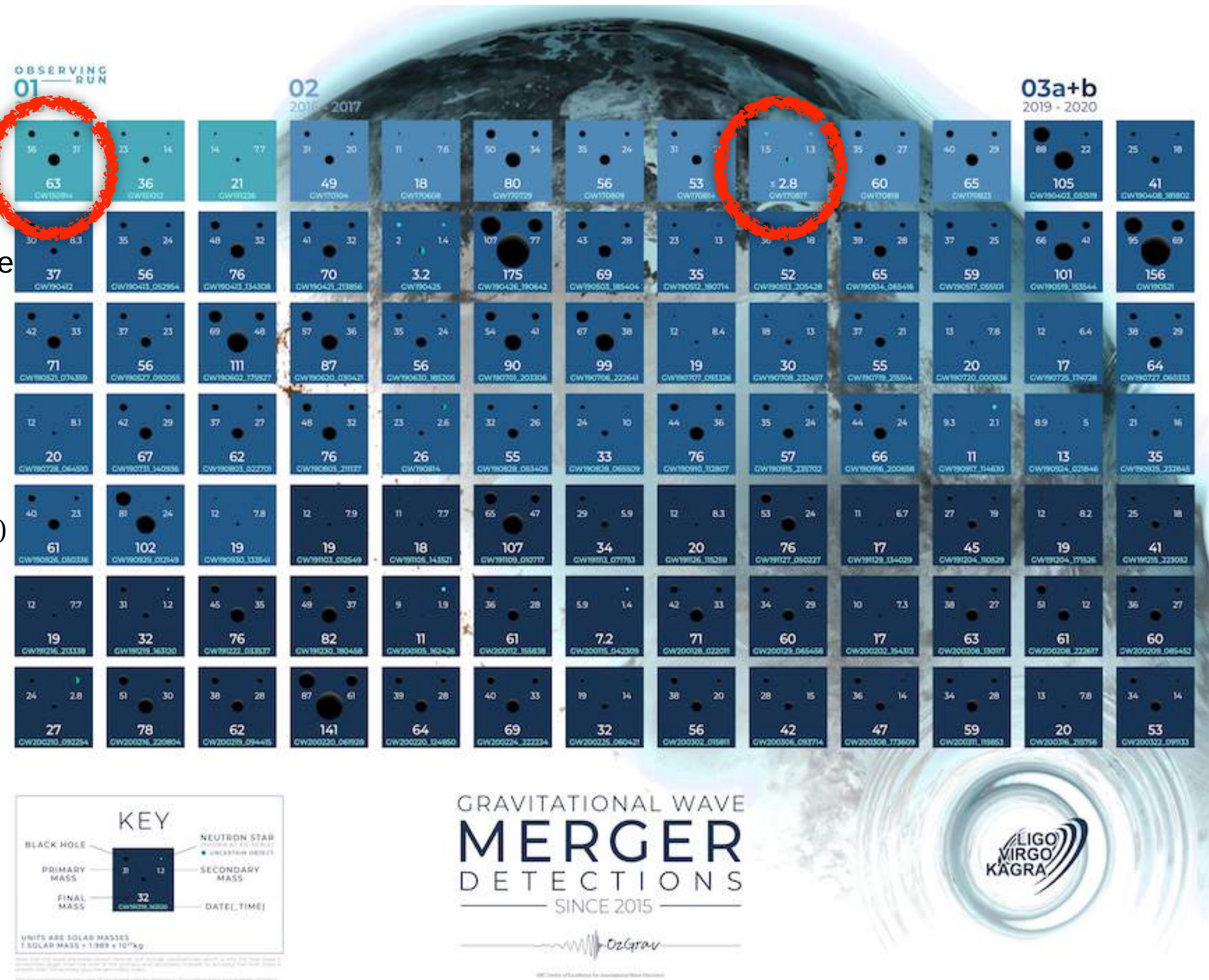
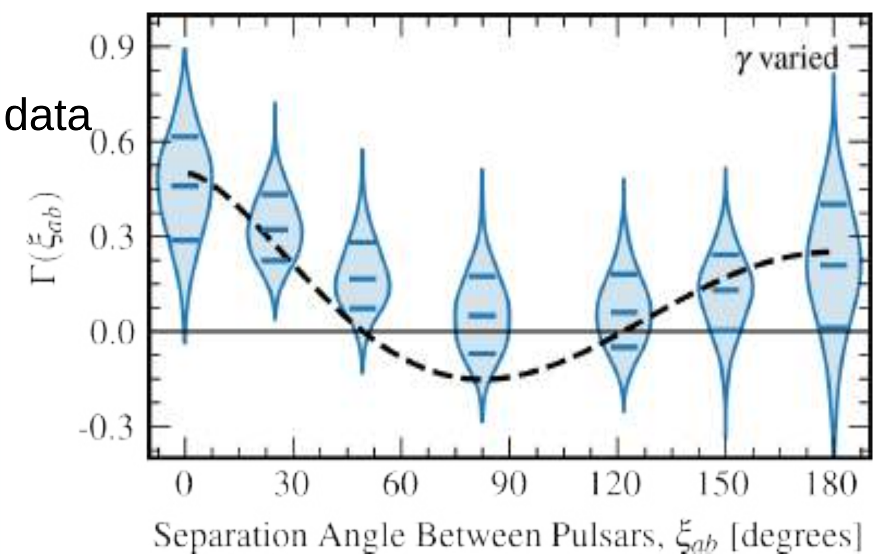




Image credit: LIGO / Virgo / KAGRA / C. Knox / H. Middleton

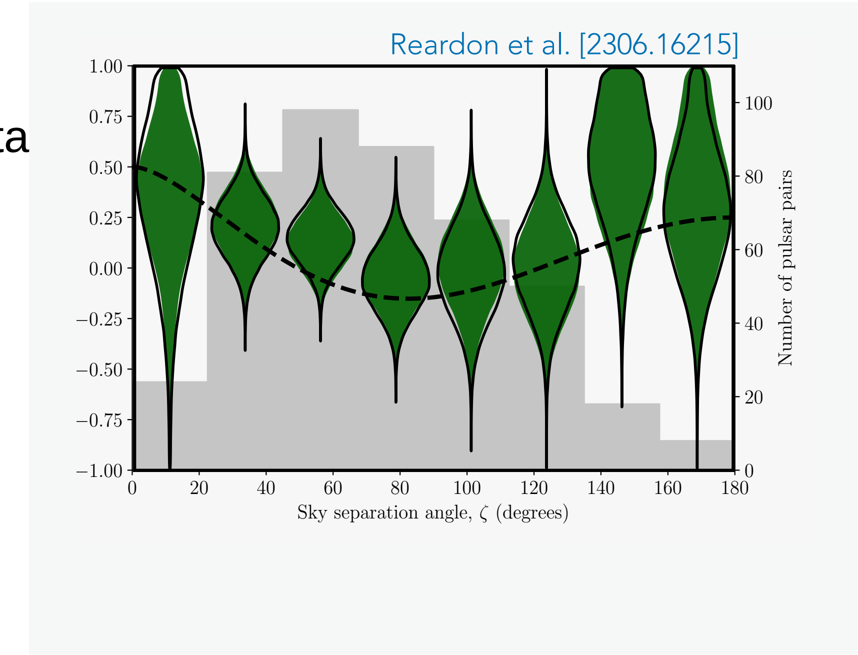
# Where we are - PTA

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

Agazie et al. [2306.16213]



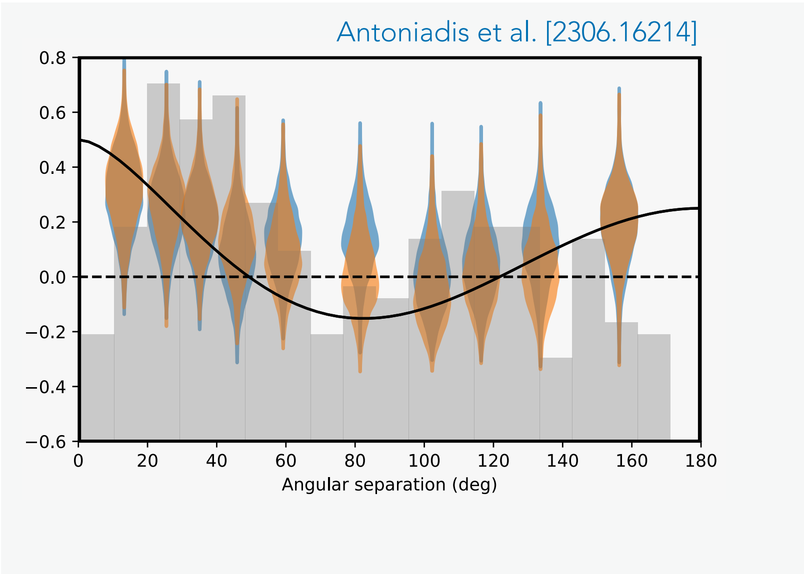

**PPTA:**
32 pulsars, 18 yrs of data
$\sim 2\sigma$ significance




## First Claim of Detection of a SGWB

**EPTA+InPTA:**
25 pulsars, 24 yrs of data

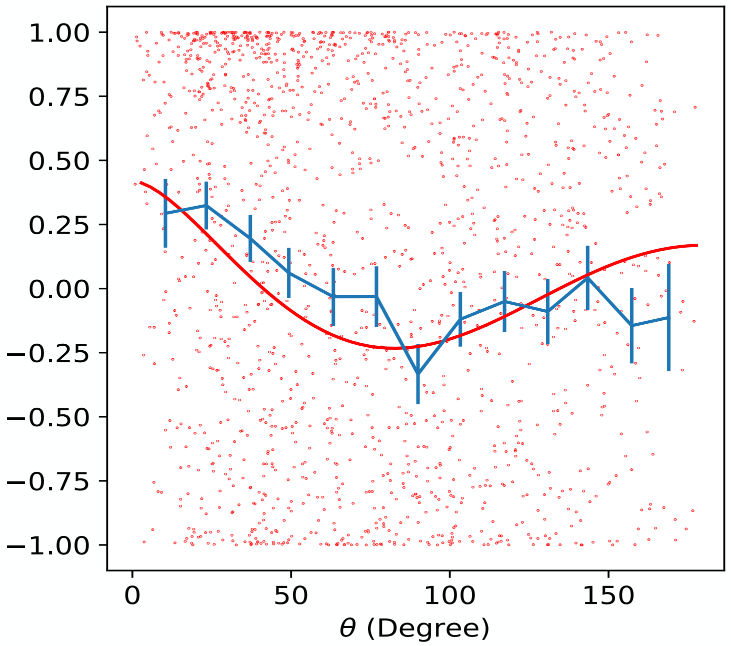
$\sim 3\sigma$ significance




**CPTA:**
57 pulsars, 3 yrs of data

$\sim 4.6\sigma$ significance

Xu et al. [2306.16216]

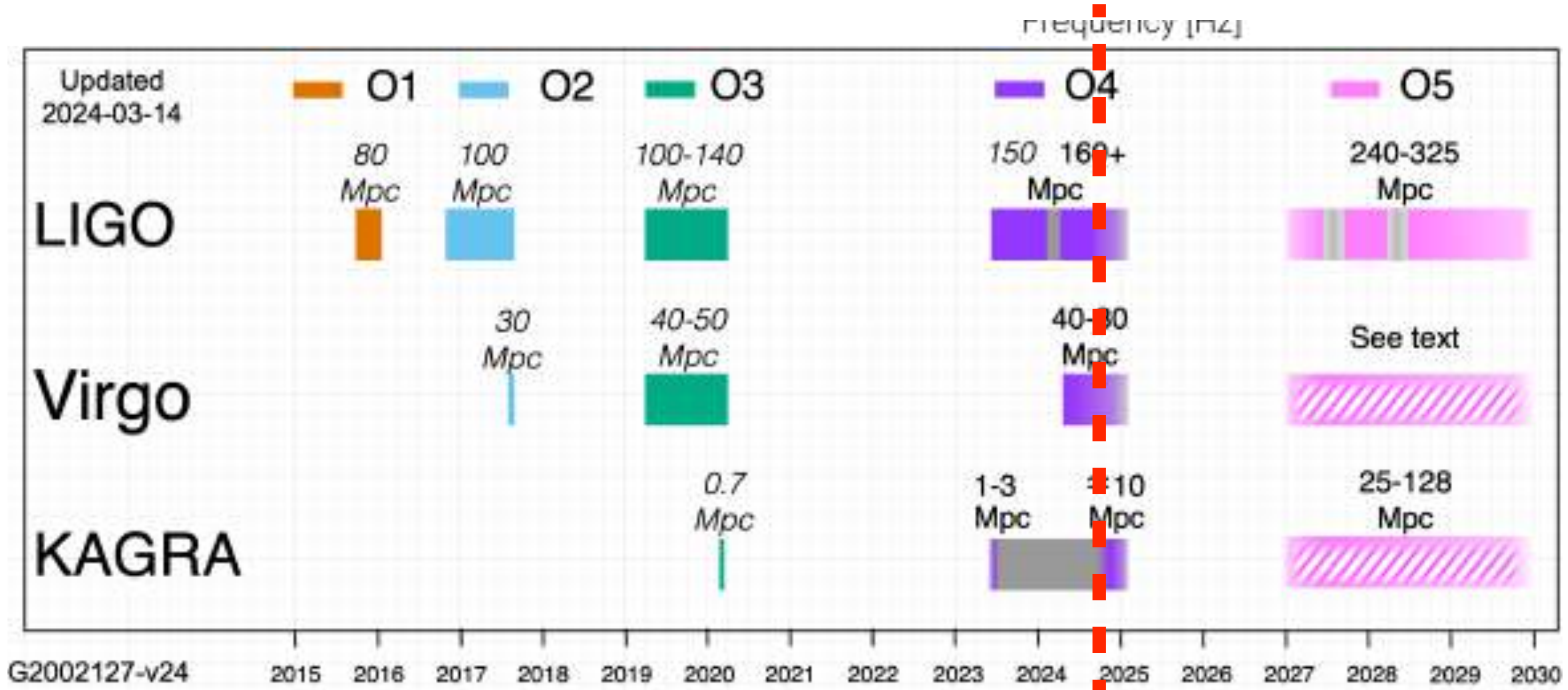



Bayesian reconstruction of normalized inter-pulsar correlations

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

# What are the plans for the LVK runs?

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




3G

**Multi-messenger facilities in the next years**

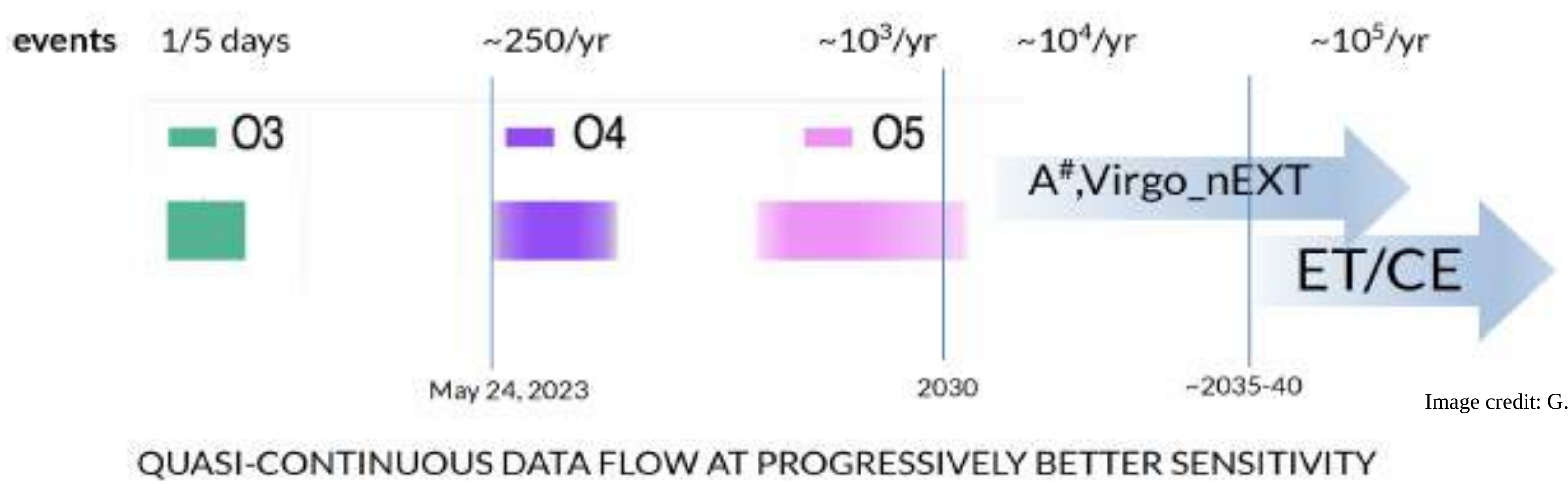




Image credit: G. Losurdo

# What are Gravitational Waves?

**Rock in a pond**

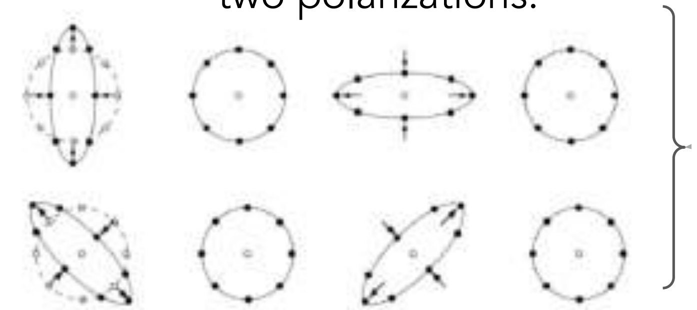
$$g_{\mu\nu} = \overbrace{\eta_{\mu\nu}}^{\text{flat}} + \overbrace{\boxed{h_{\mu\nu}}}^{\text{perturbation}}$$

**linearized theory**

$$\Box \bar{h}_{\mu\nu} = \frac{16\pi G}{c^4} T_{\mu\nu}$$

**wave equation** for the perturbative metric term

two polarizations:



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**Merging COs in our universe**

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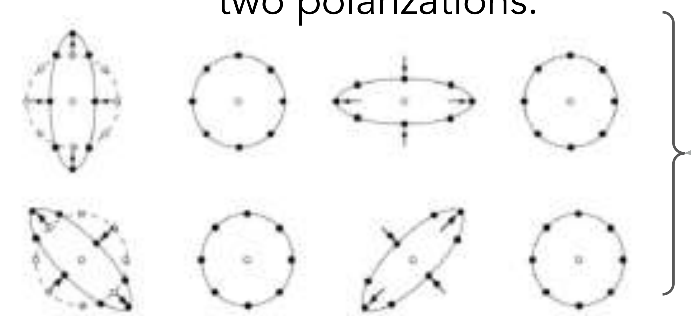

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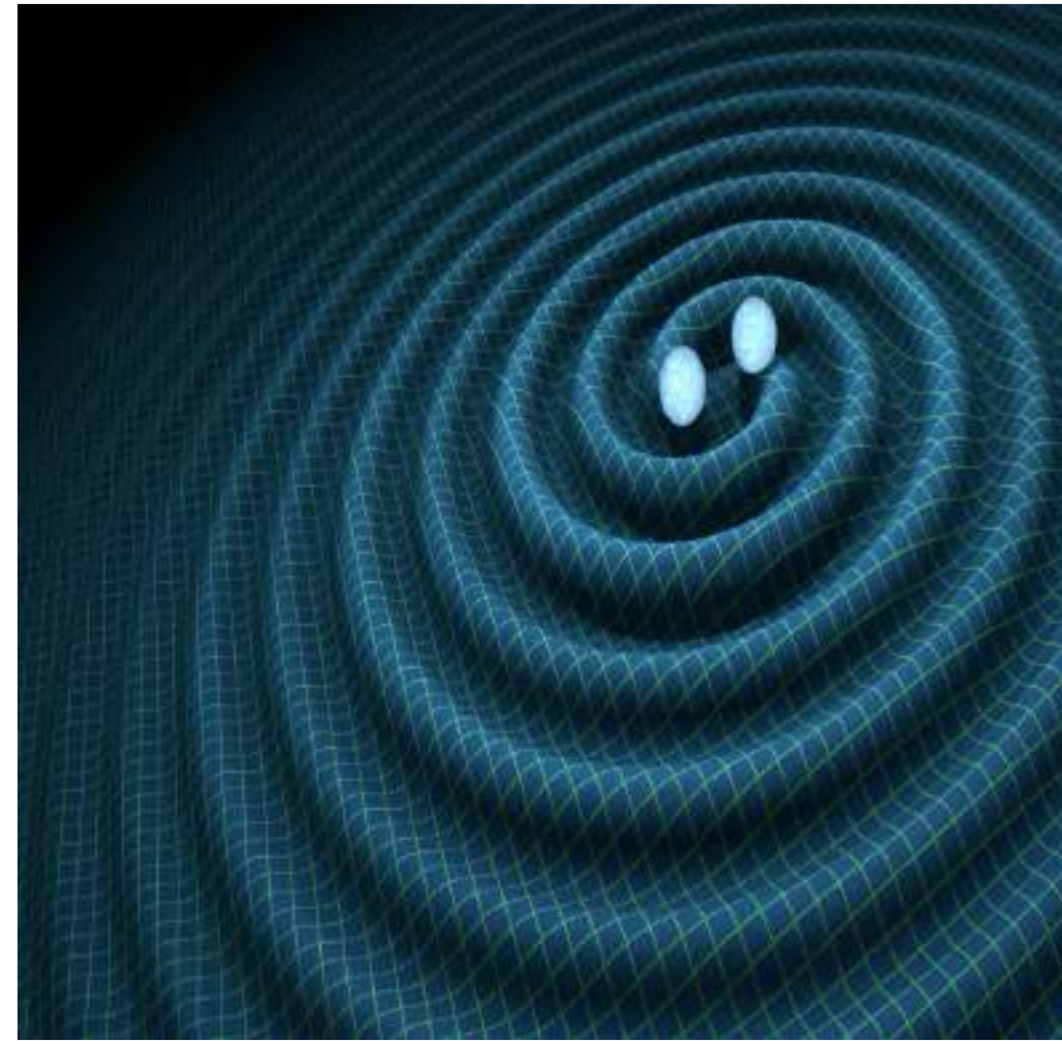

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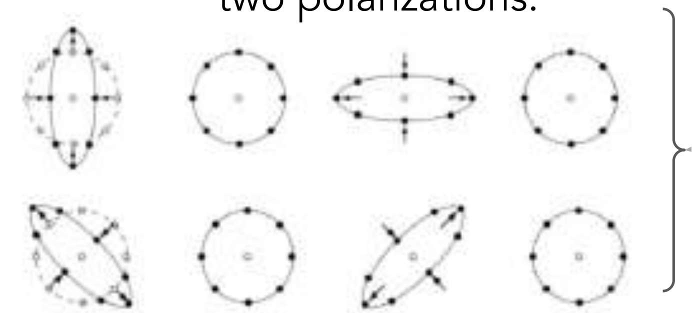

# Gravitational Waves:
# waves of space–time curvature
# that accelerate free–falling particles

S. Vitale U.Trento/TIFPA

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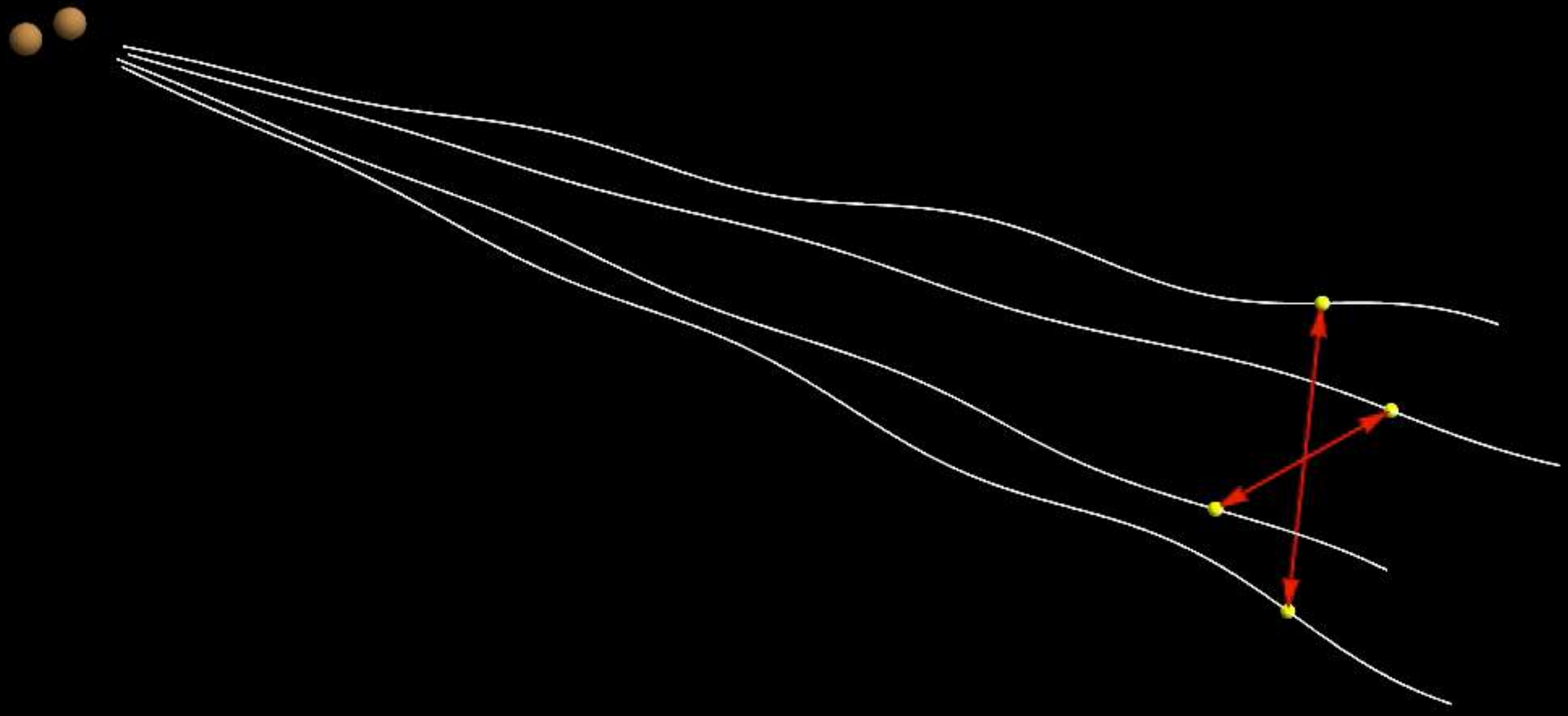
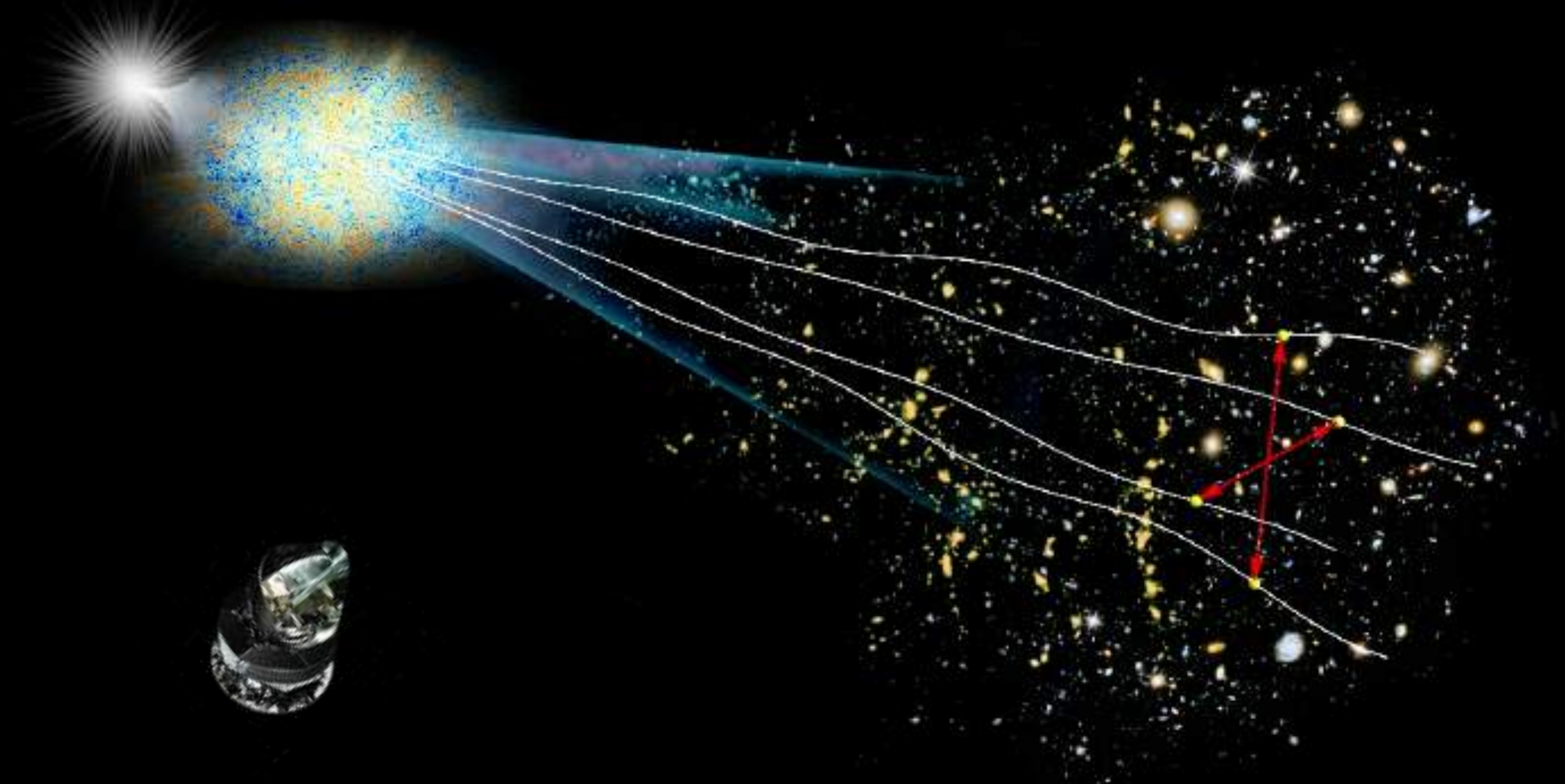


S. Vitale U.Trento/TIFPA

# “Indirect” vs Direct GW detection



**Polarization of CMB photons through Thomson scattering of electron and photon**

**Only Tensor perturbations can source B-mode**

Poor and contaminated signal:

- foregrounds
- gravitational lensing (E->B at small scales)

**Distortion of space as GW passes detector arms**

- ground-based
- space-based
- pulsar timing arrays

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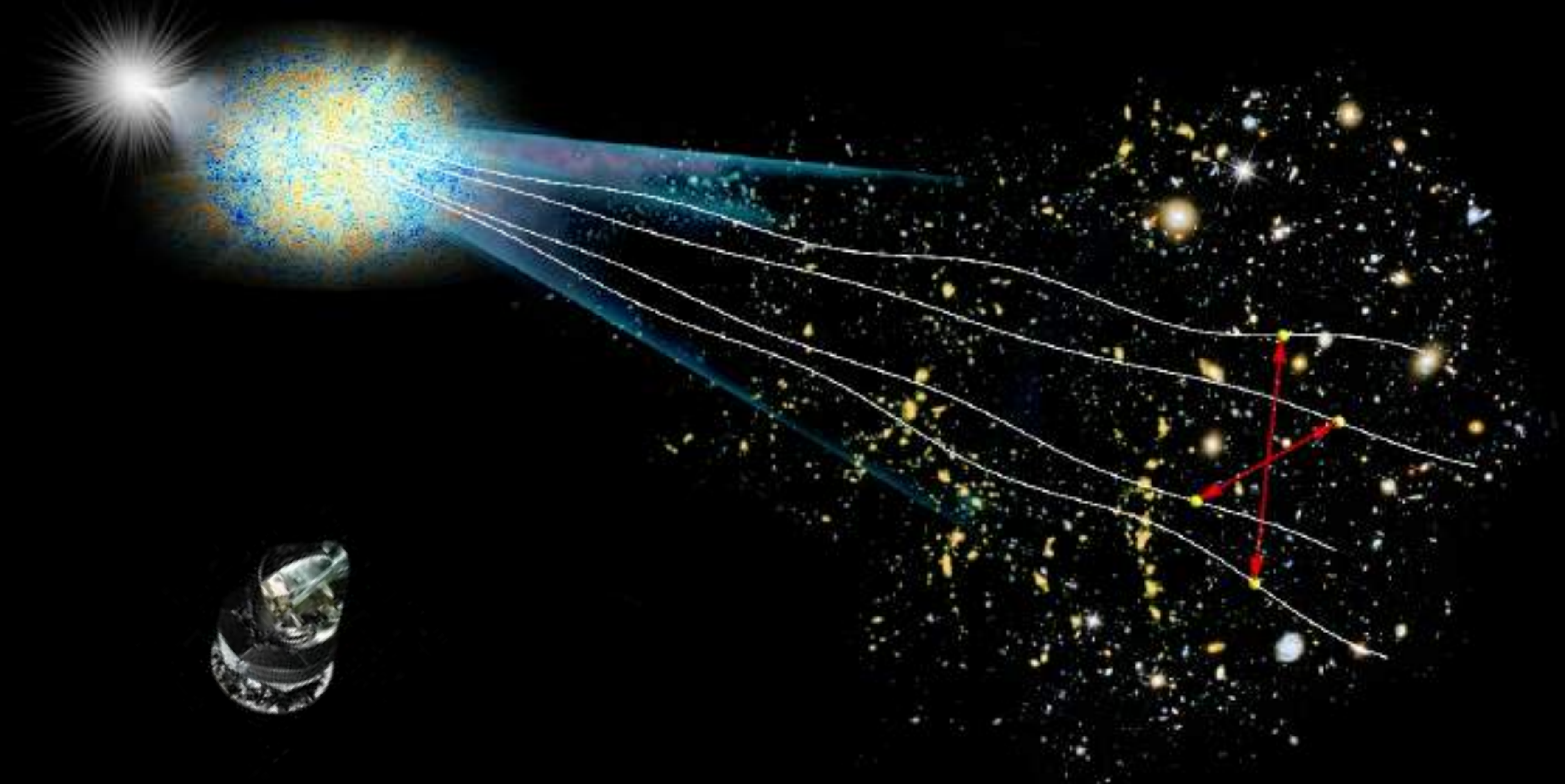

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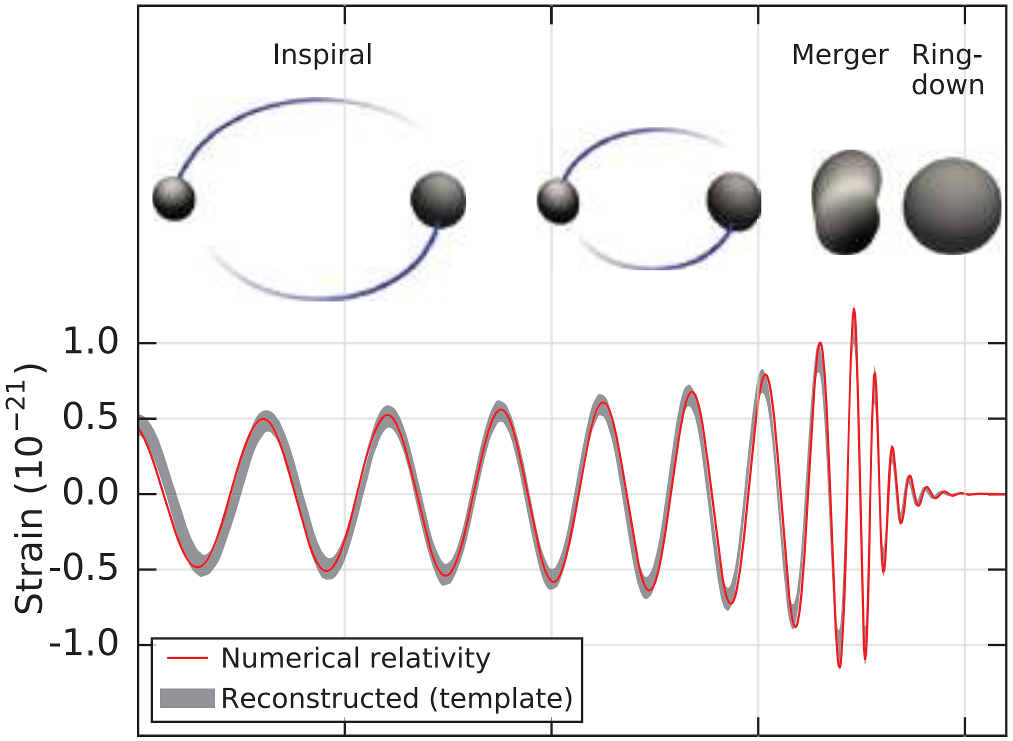
# Sources of Gravitational Waves

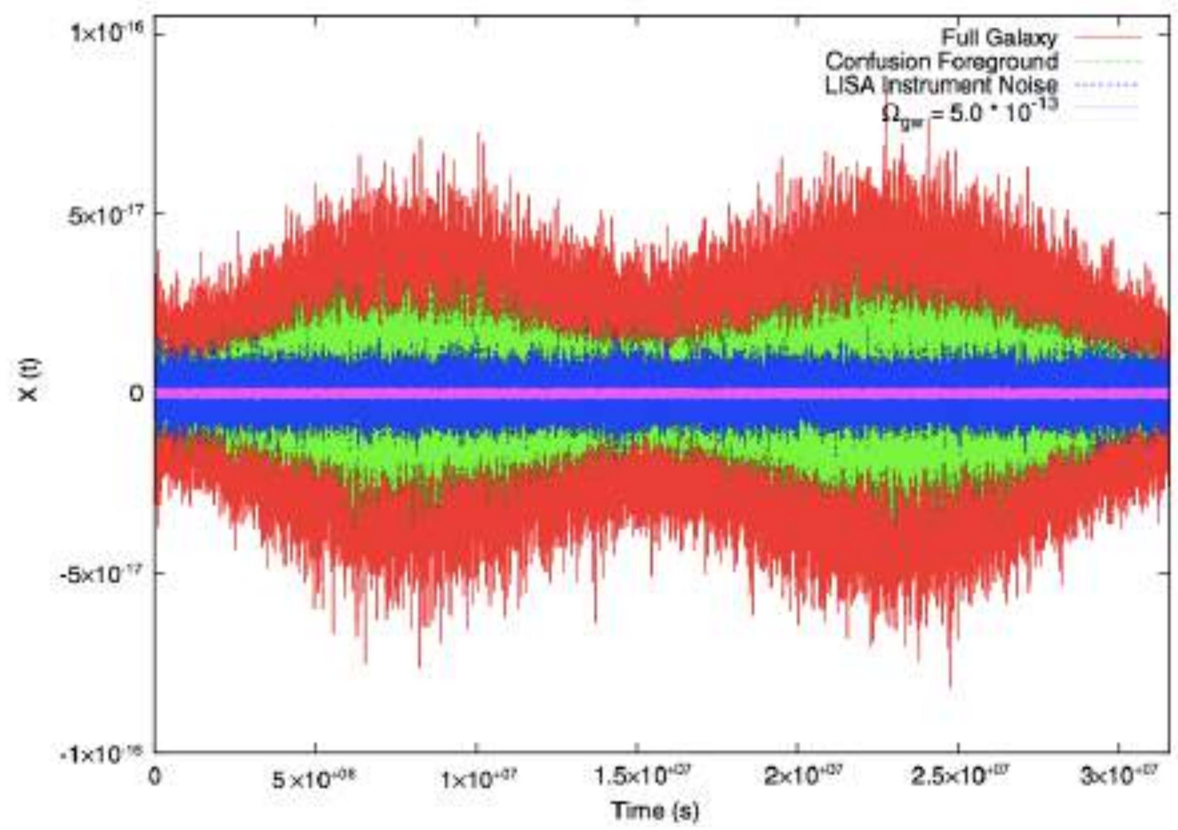
**Resolved Sources:**

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

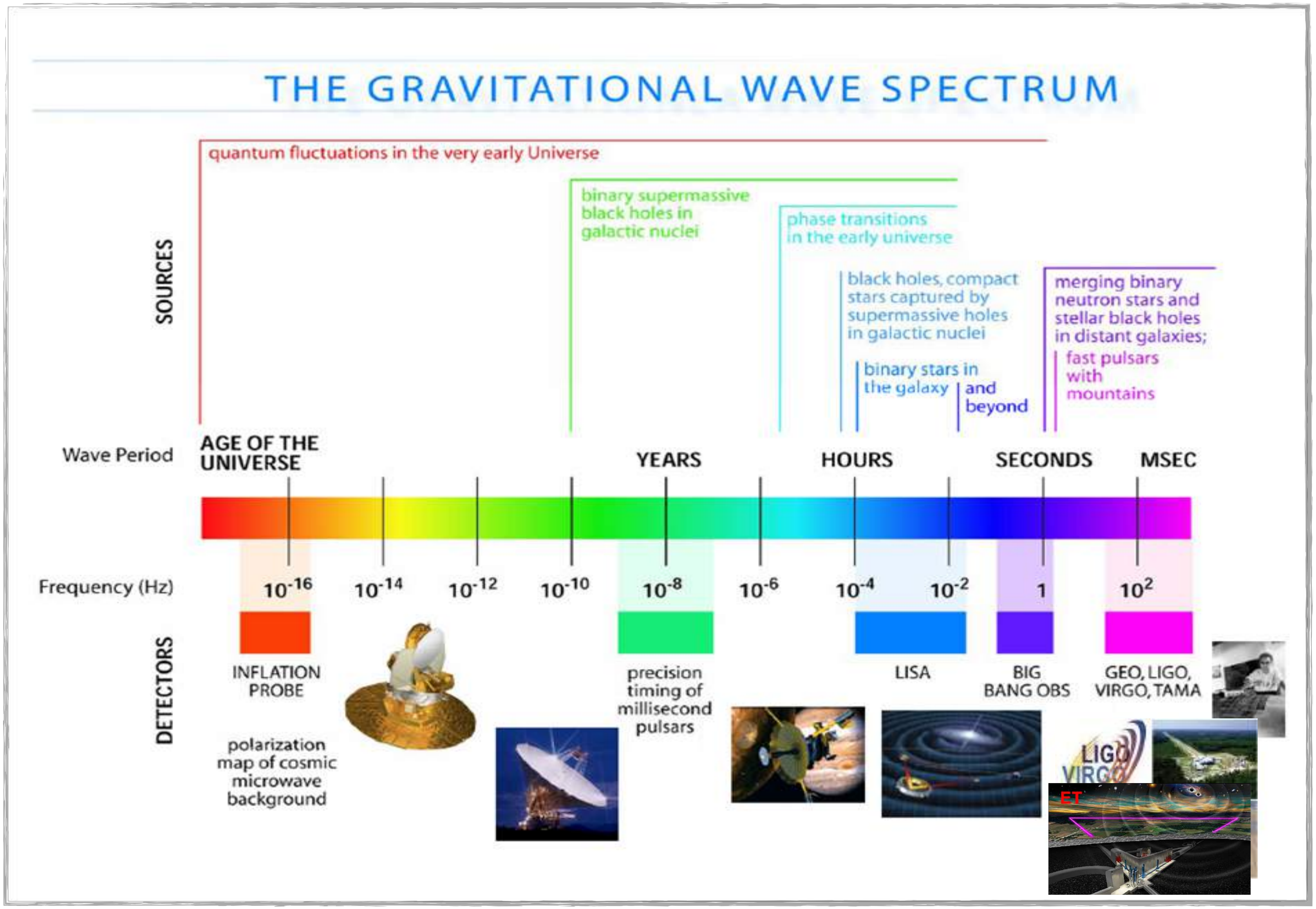



**Unresolved Sources:** Stochastic Backgrounds

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



# The Gravitational Wave Spectrum



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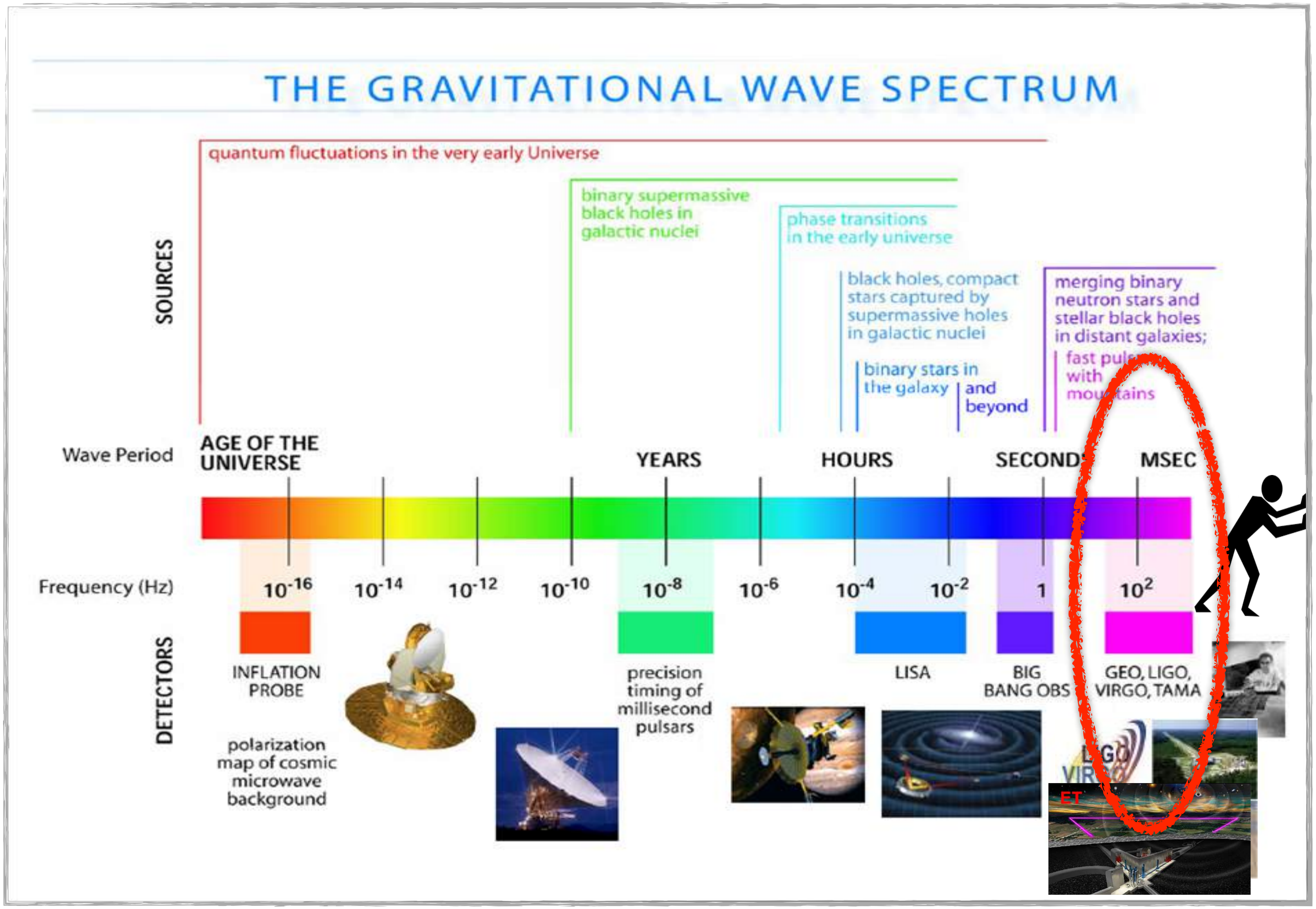
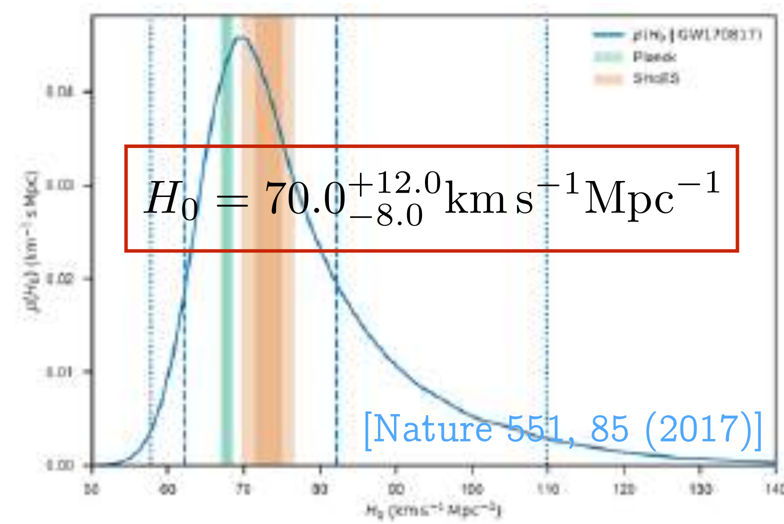


# What we have learned about Cosmology so far?

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



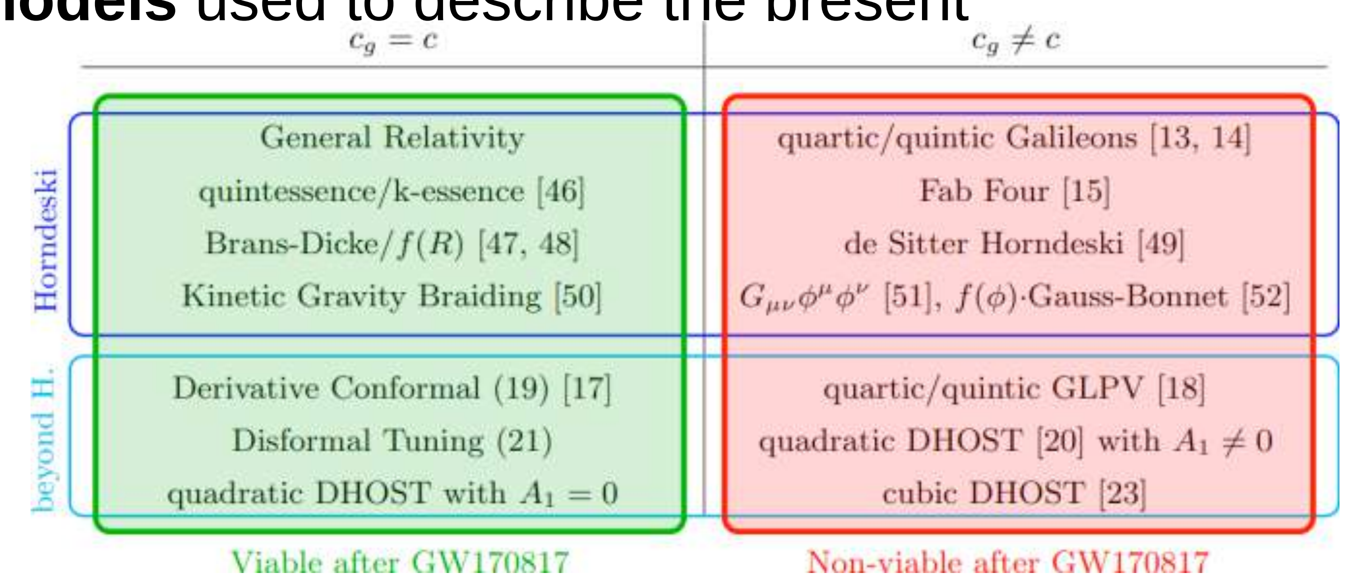

- **We have tested and bounded deviations from GR** (e.g., graviton mass, post-Newtonian coefficients, modified dispersion relations, etc.)

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

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

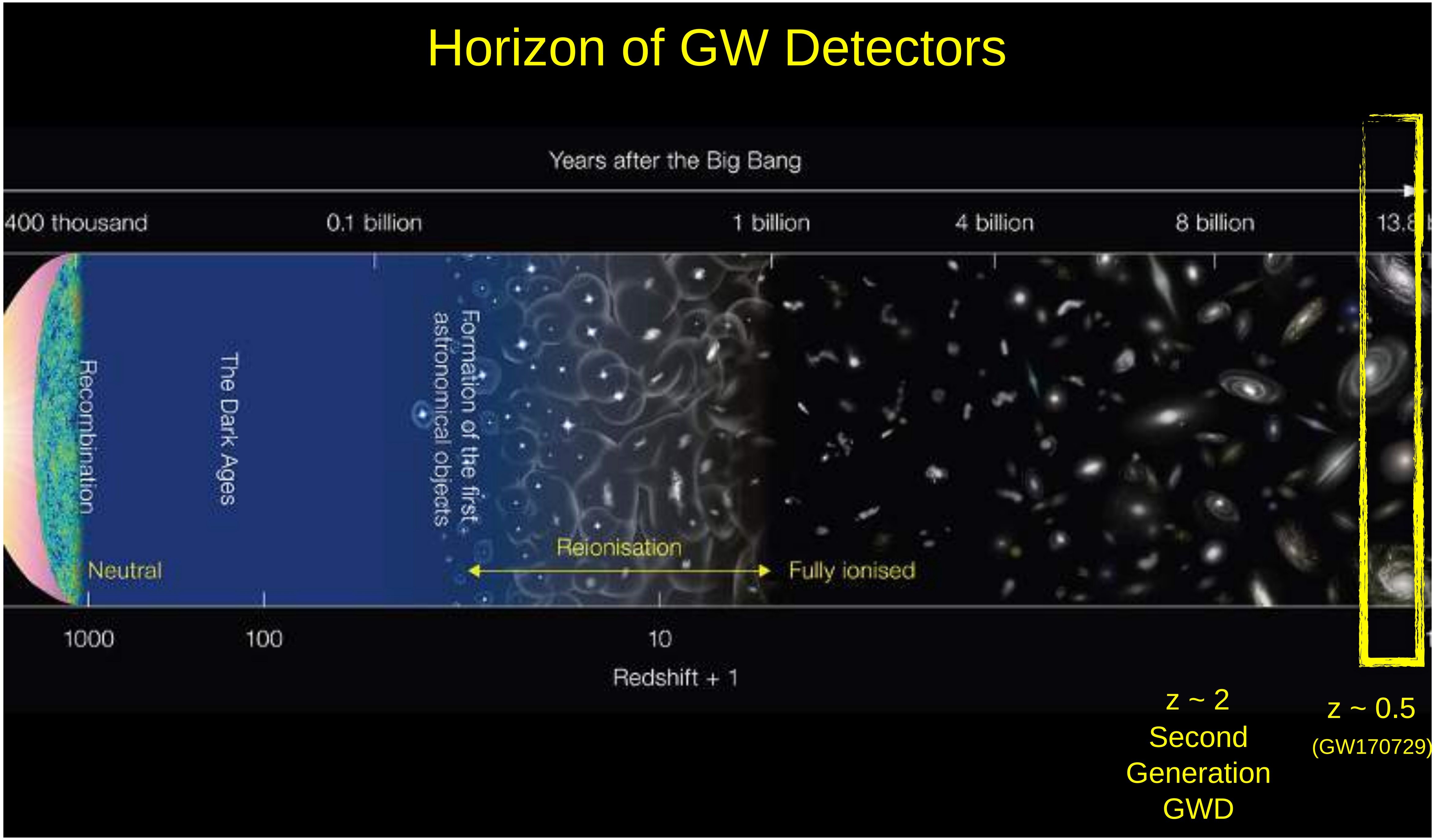
$$-3 \cdot 10^{-15} \leq c_g/c - 1 \leq 6 \cdot 10^{-16}$$

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



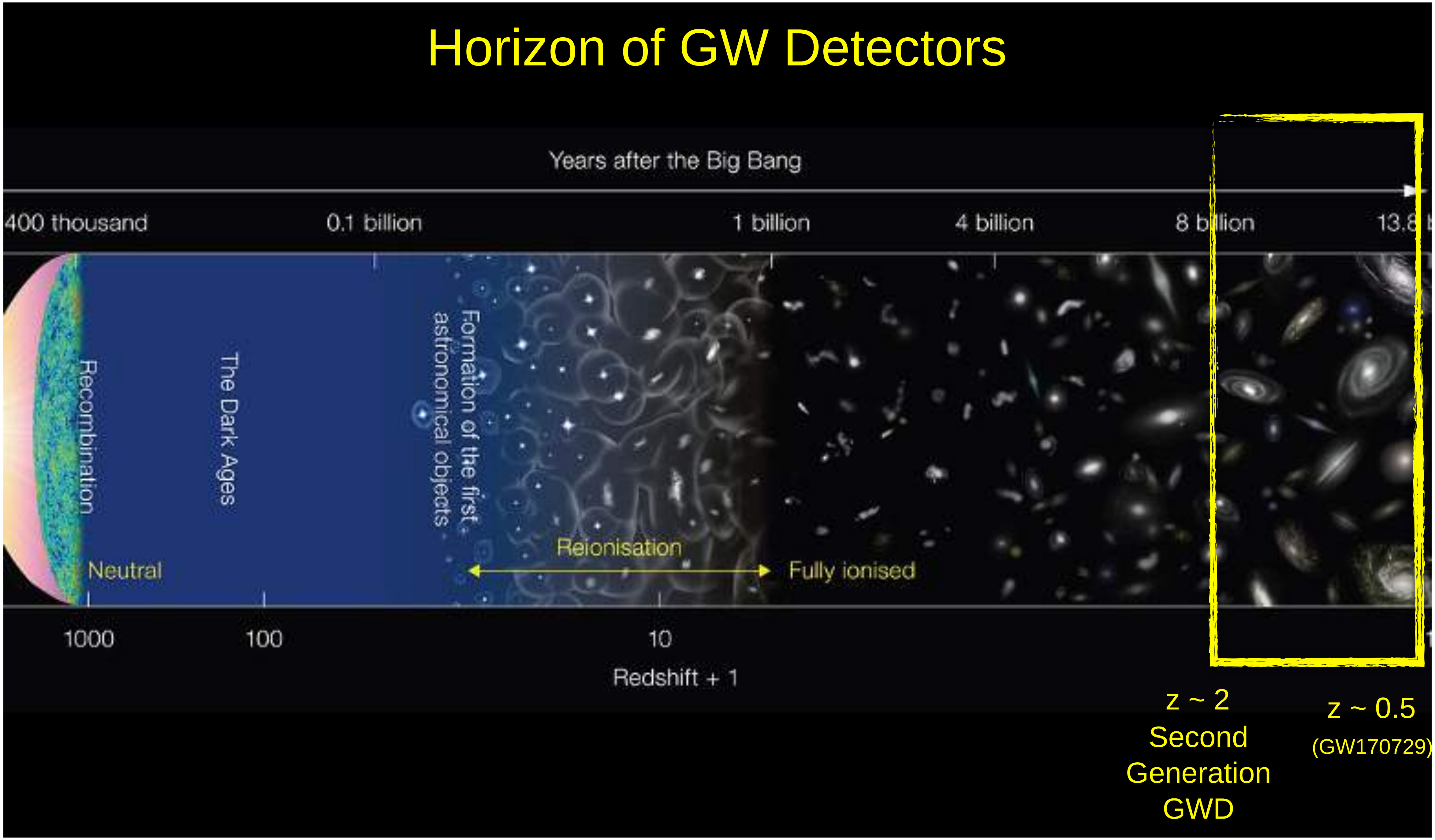

LVK arxiv:2112.06861

# Where is the horizon?




Adv LIGO - Virgo - KAGRA:
- BBHs only up to $z \sim 2$
- 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

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Dark Energy

Modified Gravity?

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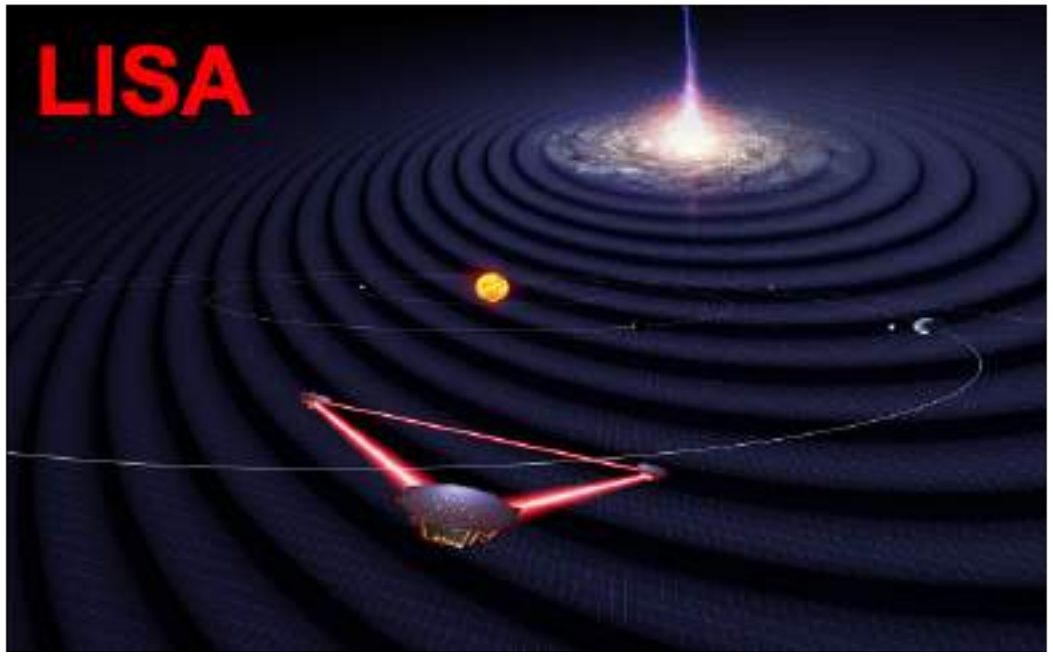
$H_0$ measurements?

**RESOLVED SOURCES**

**SGWB**

# Prospects for next Generation GW Interferometers

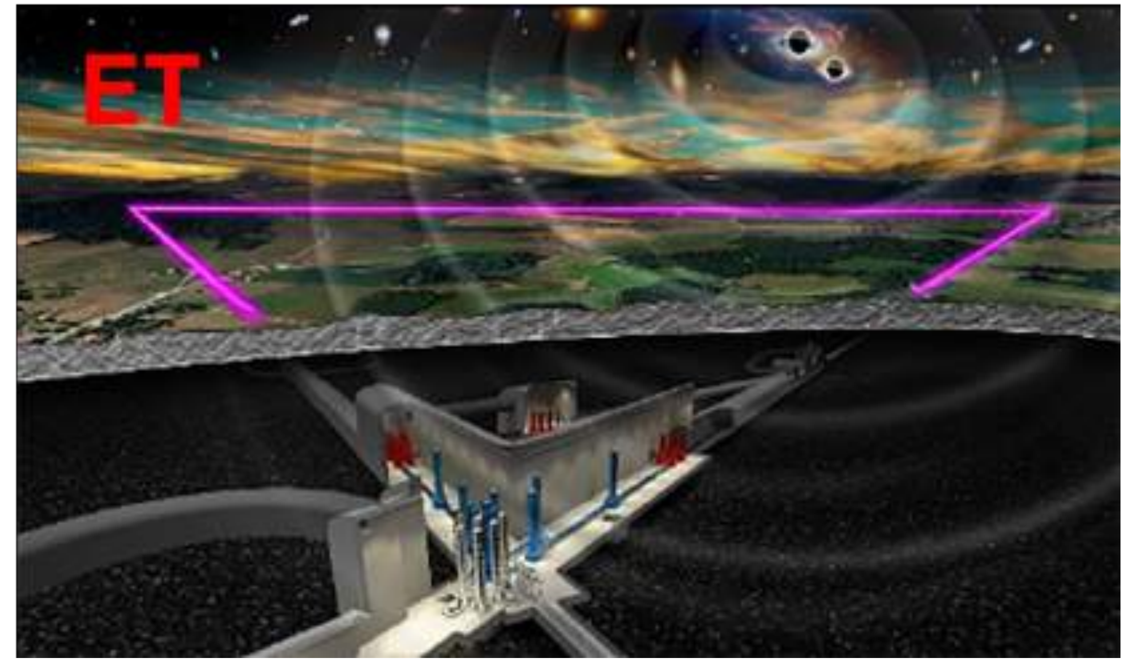



Geometry: **Constellation of 3 spacecraft in an equilateral configuration** (a giant interferometer)

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

AdV -> Virgo-nEXT

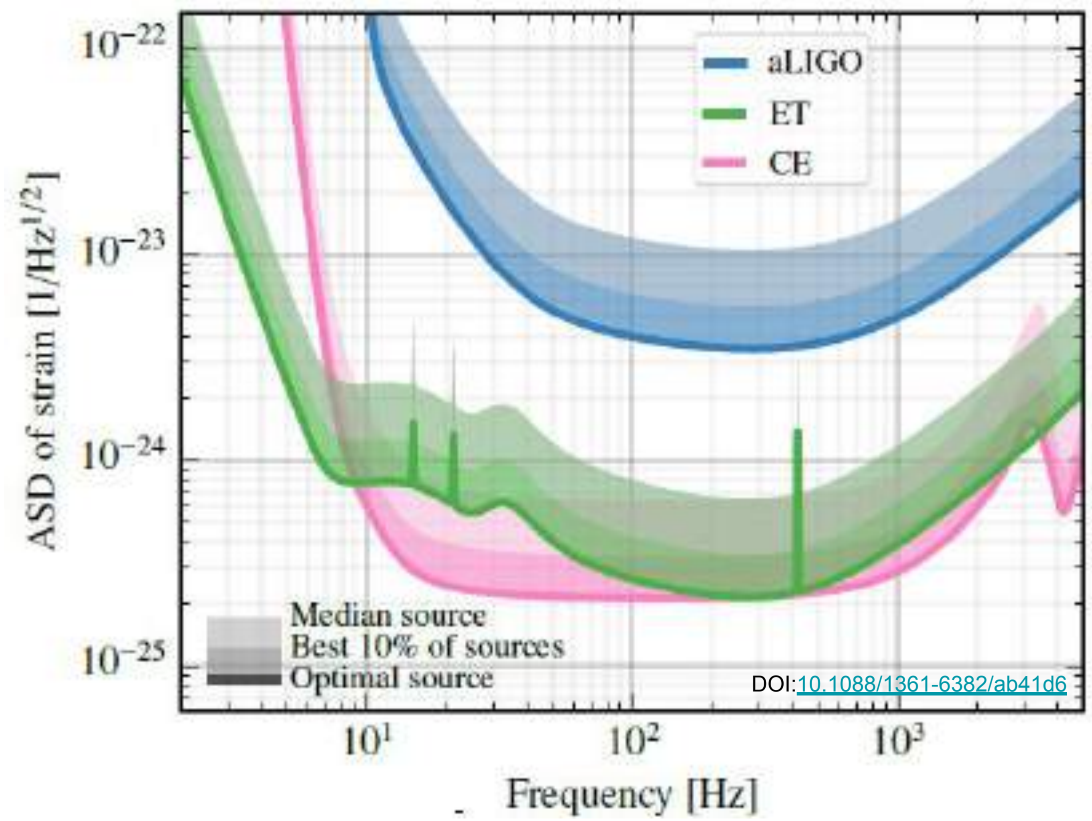
New PTA data

# Einstein Telescope

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

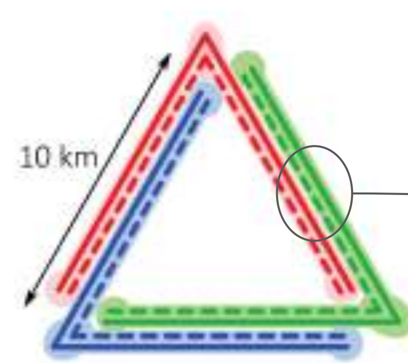
- **Einstein Telescope (ET)**:
  - EU proposal for 3G observatory
  - Design study (baseline) triangle with arms of 10km
- **Cosmic Explorer (CE)**:
  - US proposal for 3G observatory
  - L-shaped 40km interferometer

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




## 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

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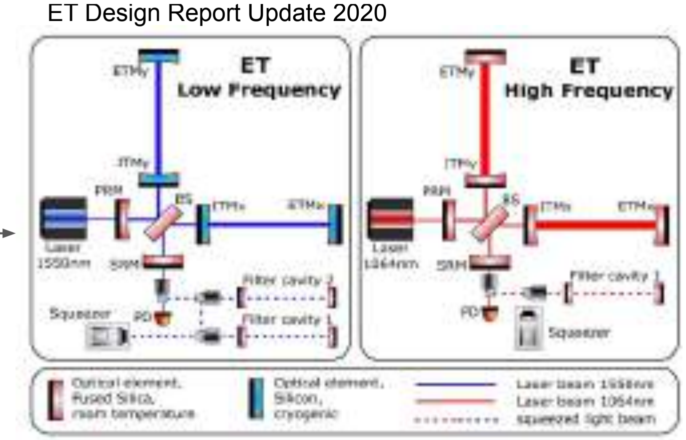


# Einstein Telescope - possible designs

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

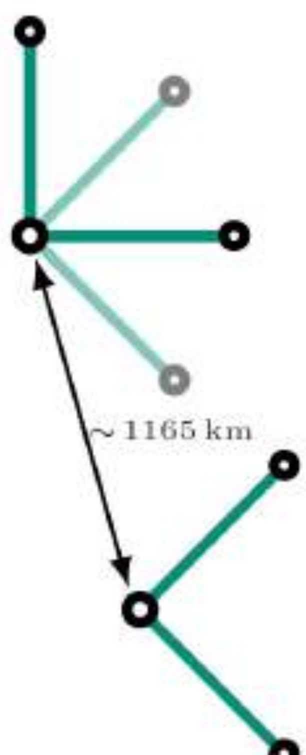
- 197 pages
- 75 authors

Different geometries are studied:

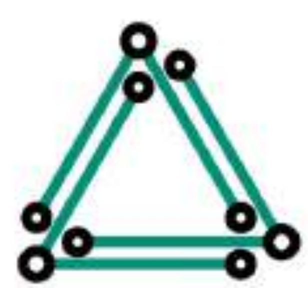
- **1 Triangular detector** vs **2 L-shaped detector**
- **different arm length** (10, 15, 20 km)
- Cryo LF may be challenging to achieve: **HF+LF** vs **HF only**

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

- parallel
- 45° angle




arXiv:2303.15923

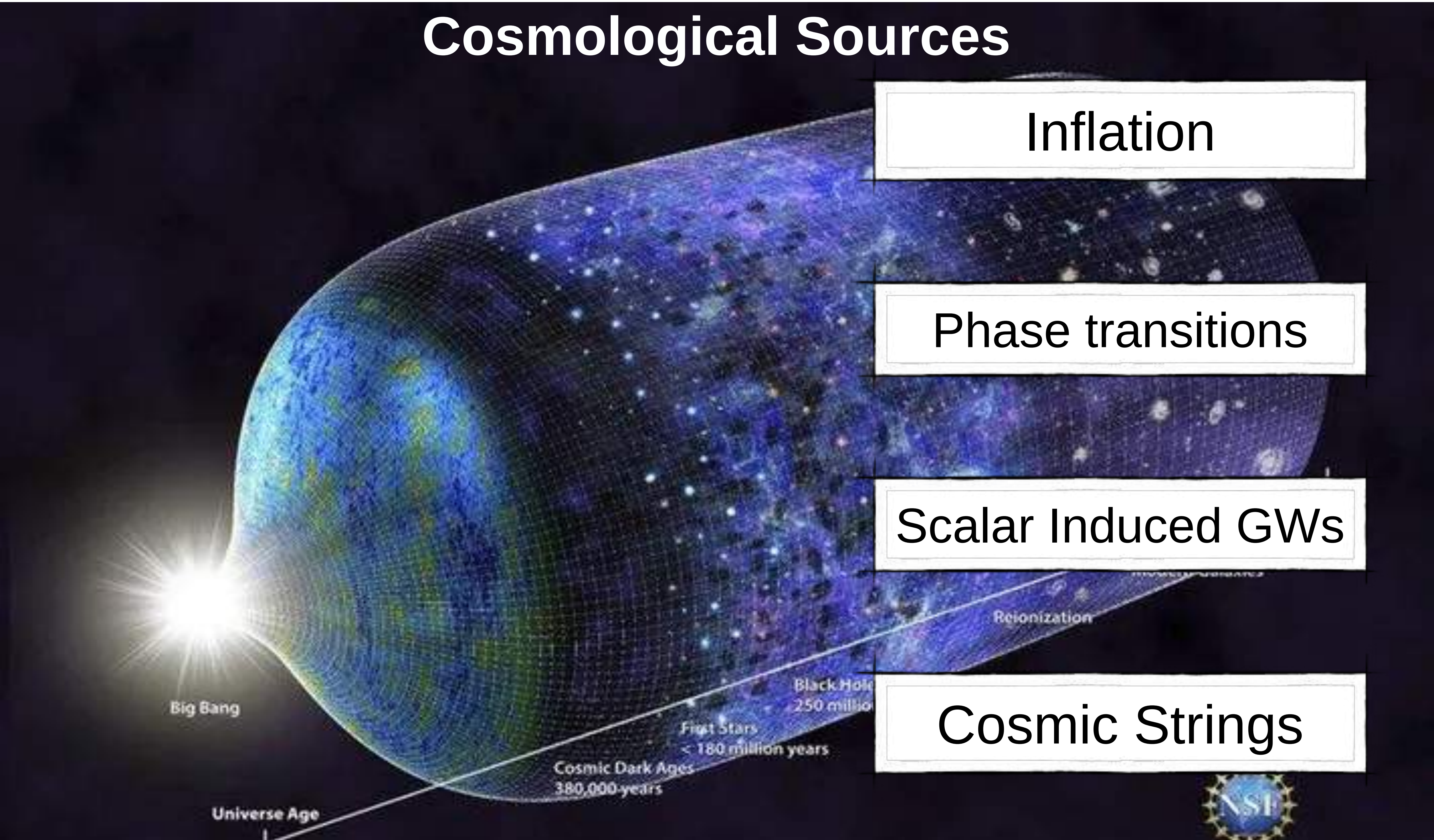



- More on the ET Blue Book (ArXiv: 2503.12263)

# Early Universe Cosmology with Gravitational Waves

# Probing the Early Universe

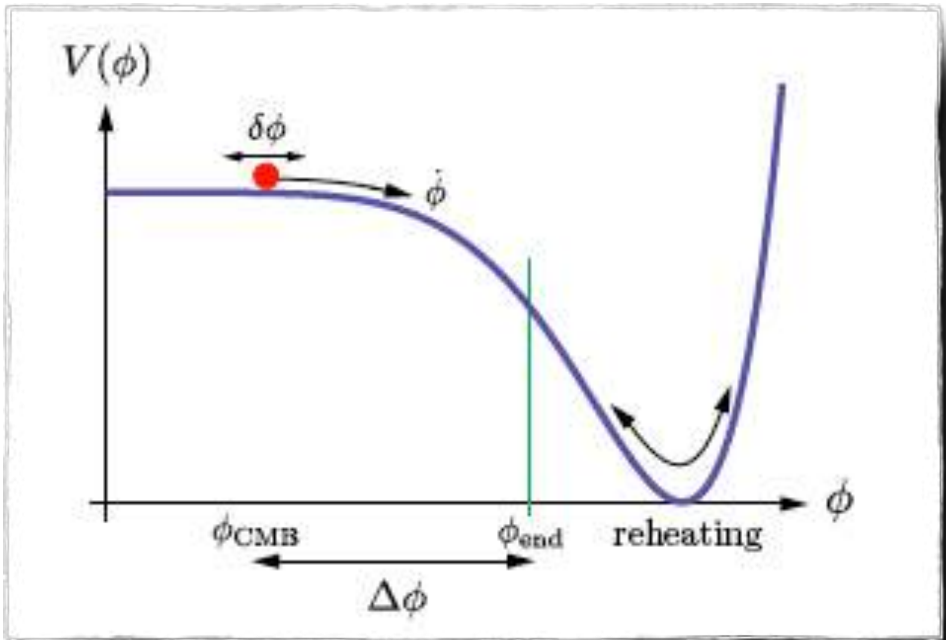
## Cosmological Sources




- 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**

# Inflation and Primordial GWs




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

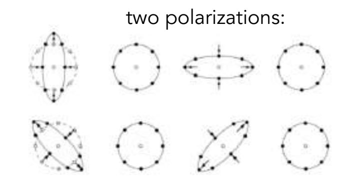
Solve Standard Big-Bang shortcomings

Generation of **TENSOR** and scalar perturbations

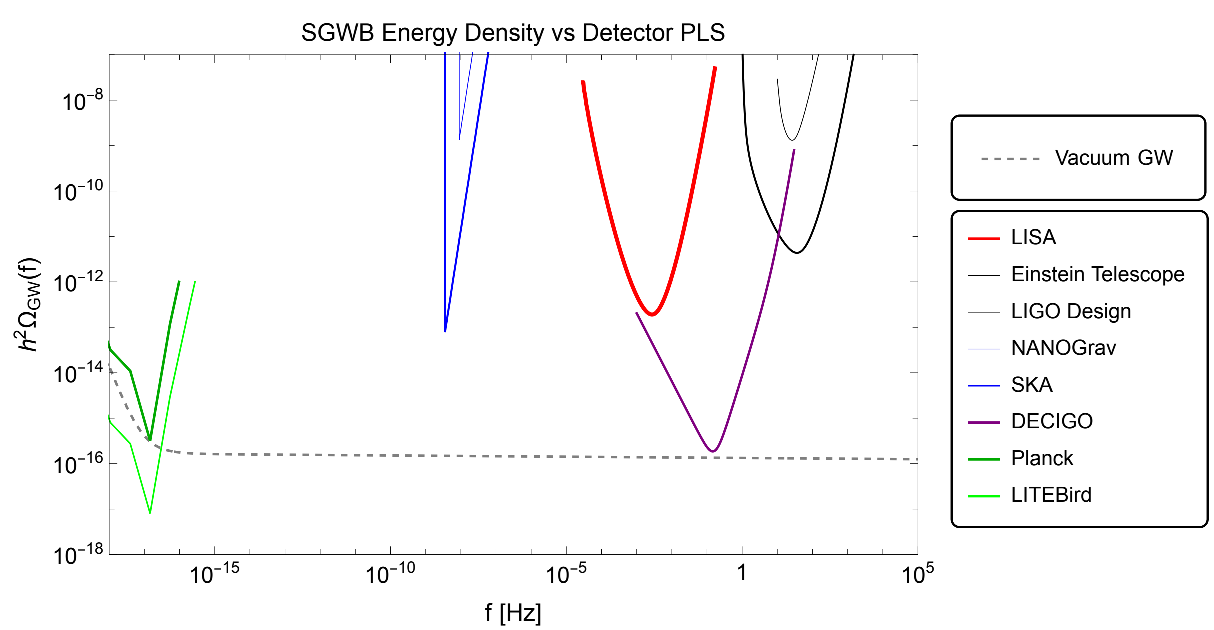
Stretches the microphysics scales to super-horizon sizes

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

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




| | $k$ [Mpc$^{-1}$] | $N_{\rm estim.}$ |
|---|---|---|
| CMB / LSS | $10^{-4} - 10^{-1}$ | $56 - 63$ |
| $y-$ & $\mu-$distortions | $10^{-1} - 10^{4}$ | $45 - 56$ |
| $P_\zeta \rightarrow$ PBH $\rightarrow$ GW @ PTA | $10^{4} - 10^{5}$ | $41 - 44$ |
| $P_\zeta \rightarrow$ PBH $\rightarrow$ GW @ **LISA** | $10^{5} - 10^{7}$ | $38 - 41$ |
| $P_\zeta \rightarrow$ PBH $\rightarrow$ GW @ **ET** | $10^{7} - 10^{8}$ | $35 - 37$ |
| $P_{\delta g} \rightarrow$ GW @ PTA | $10^{6} - 10^{8}$ | $36 - 40$ |
| $P_{\delta g} \rightarrow$ GW @ **ET** | $10^{11} - 10^{14}$ | $22 - 28$ |
| $P_{\delta g} \rightarrow$ GW @ AdvLIGO | $10^{16} - 10^{17}$ | $15 - 17$ |




**LISA/ET → Possibility to test regions for which we have poor information**

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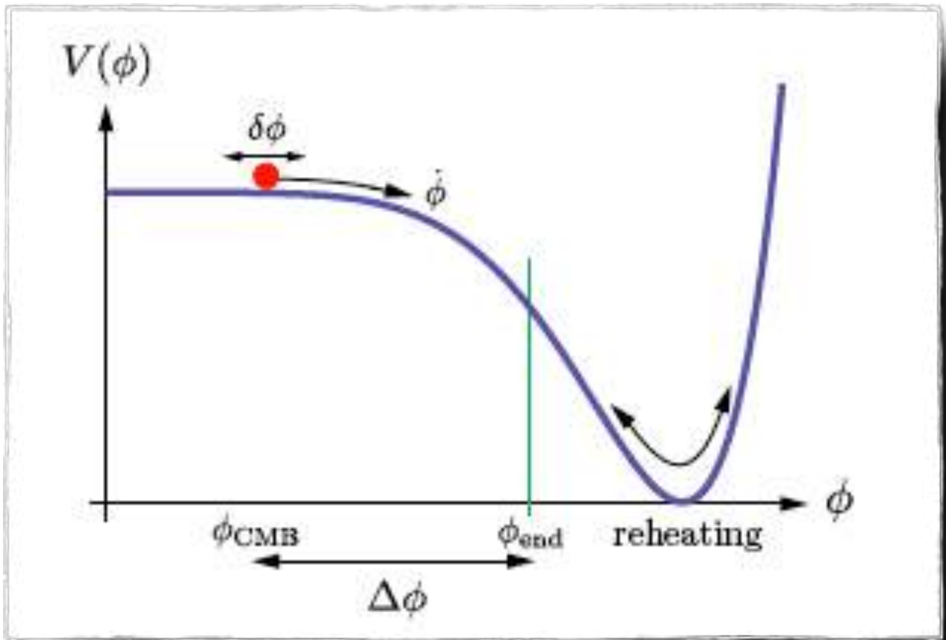


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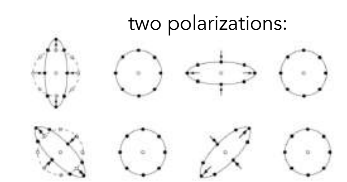


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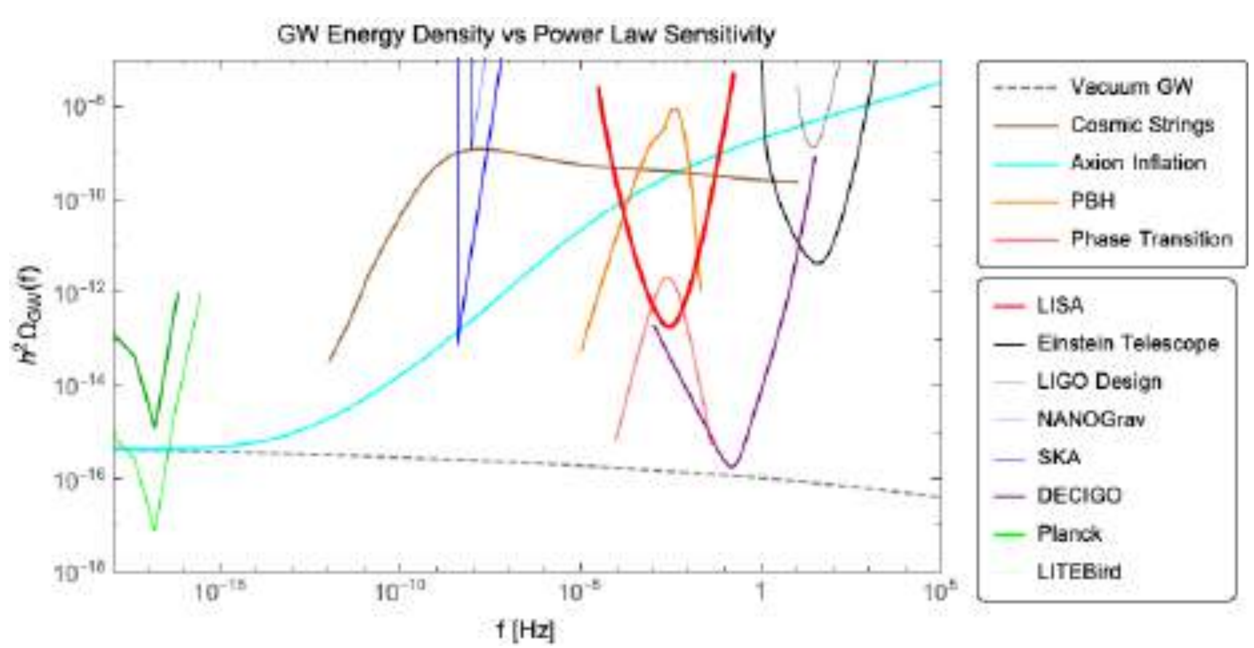


f [Hz]

**LISA/ET → Possibility to test regions for which we have poor information**

# Inflationary models producing such a signal

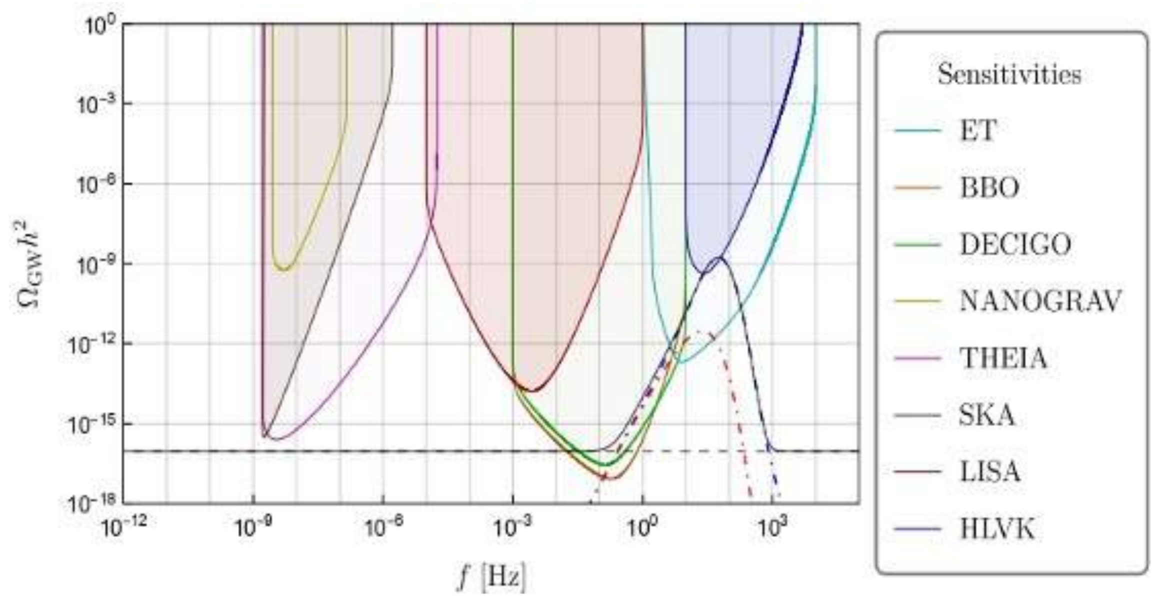
## Axion inflation:

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

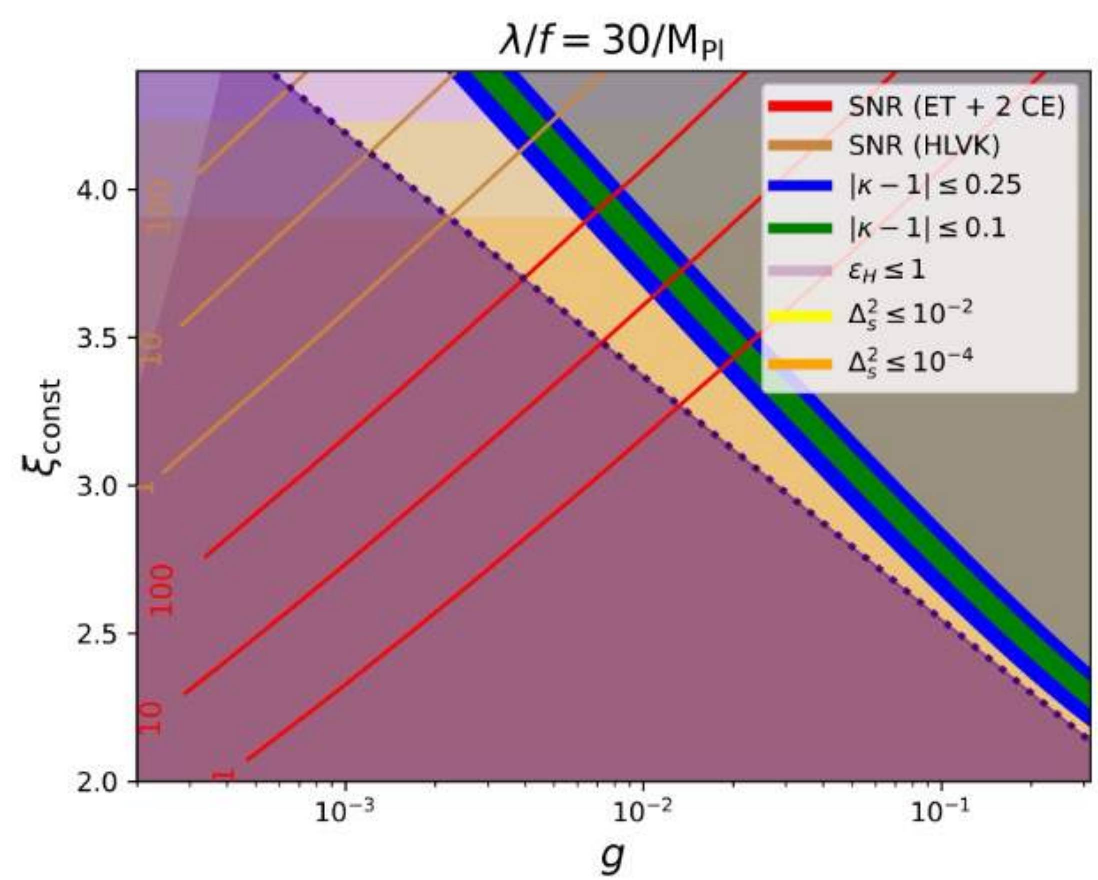
$$\mathcal{L} = -\frac{1}{2}\partial_\mu\phi\partial^\mu\phi - \frac{1}{4}F^I_{\mu\nu}F_I^{\mu\nu} - V(\phi) - \frac{\lambda^I}{4f}\phi F^I_{\mu\nu}\tilde{F}_I^{\mu\nu}$$

[Barnaby & Peloso 1011.1500]
[Sorbo 1101.1525]

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




$$\Omega_{\rm GW} \simeq \begin{cases} \frac{1}{12}\Omega_{R,0}\left(\frac{H^2}{\pi^2 M_{\rm Pl}^2}\right)\left(1 + 4.3\times 10^{-7}\frac{H^2}{M_{\rm Pl}^2\xi^6}e^{4\pi\xi}\right), & \texttt{for } U(1) \\ \frac{1}{12}\Omega_{R,0}\left(\frac{H^2}{\pi^2 M_{\rm Pl}^2}\right)_{\xi=\xi_{cr}}\left[1 + \frac{1}{2}\xi_{cr}^6\left(\frac{2^{7/4}H}{g\sqrt{\xi}}e^{(2-\sqrt{2})\pi\xi}\right)^2_{\xi=\xi_{\rm ref}}\right], & \texttt{for } SU(2) \end{cases}$$

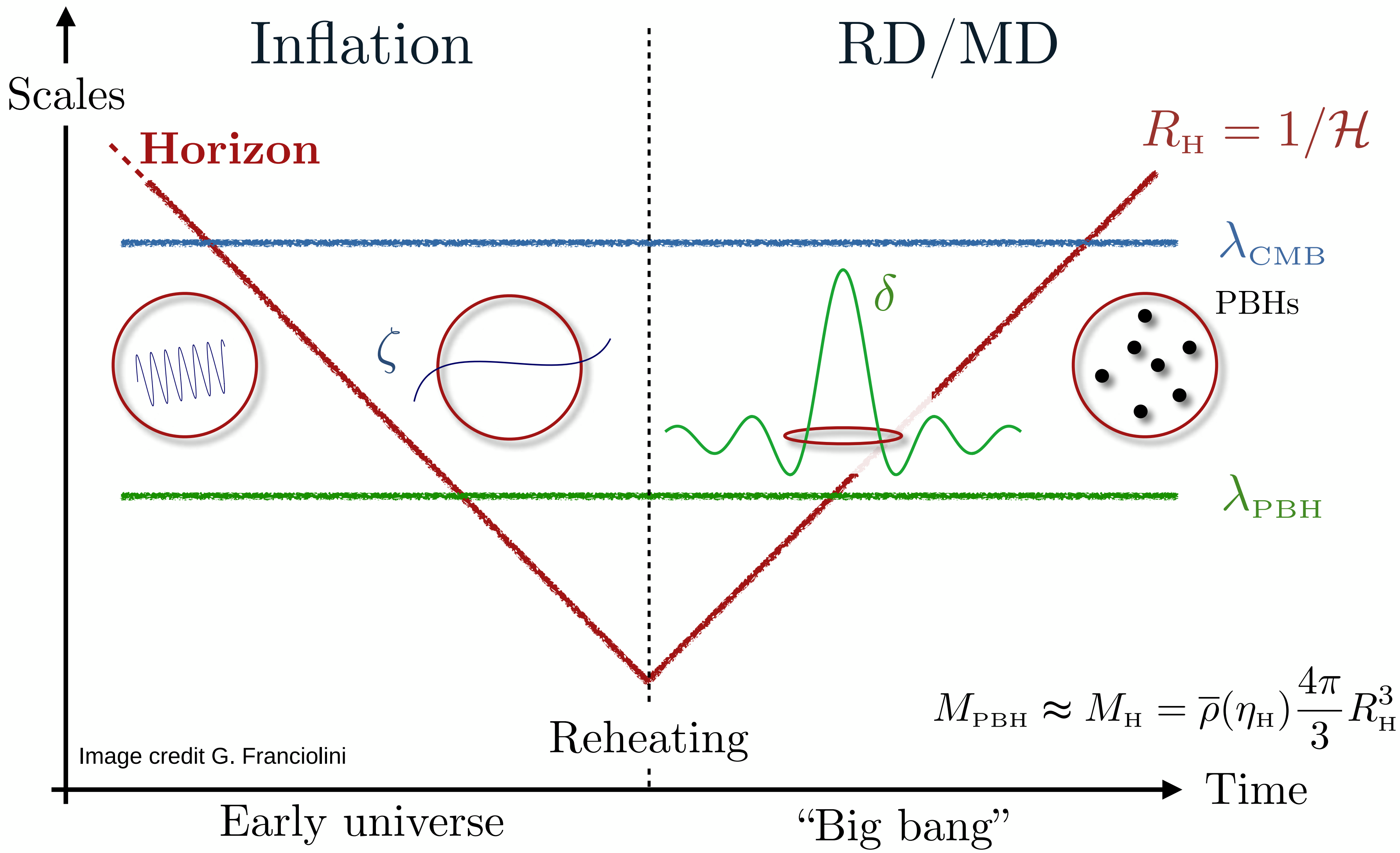



**Presence of other fields (e.g. axions) in the Early Universe**

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

# 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

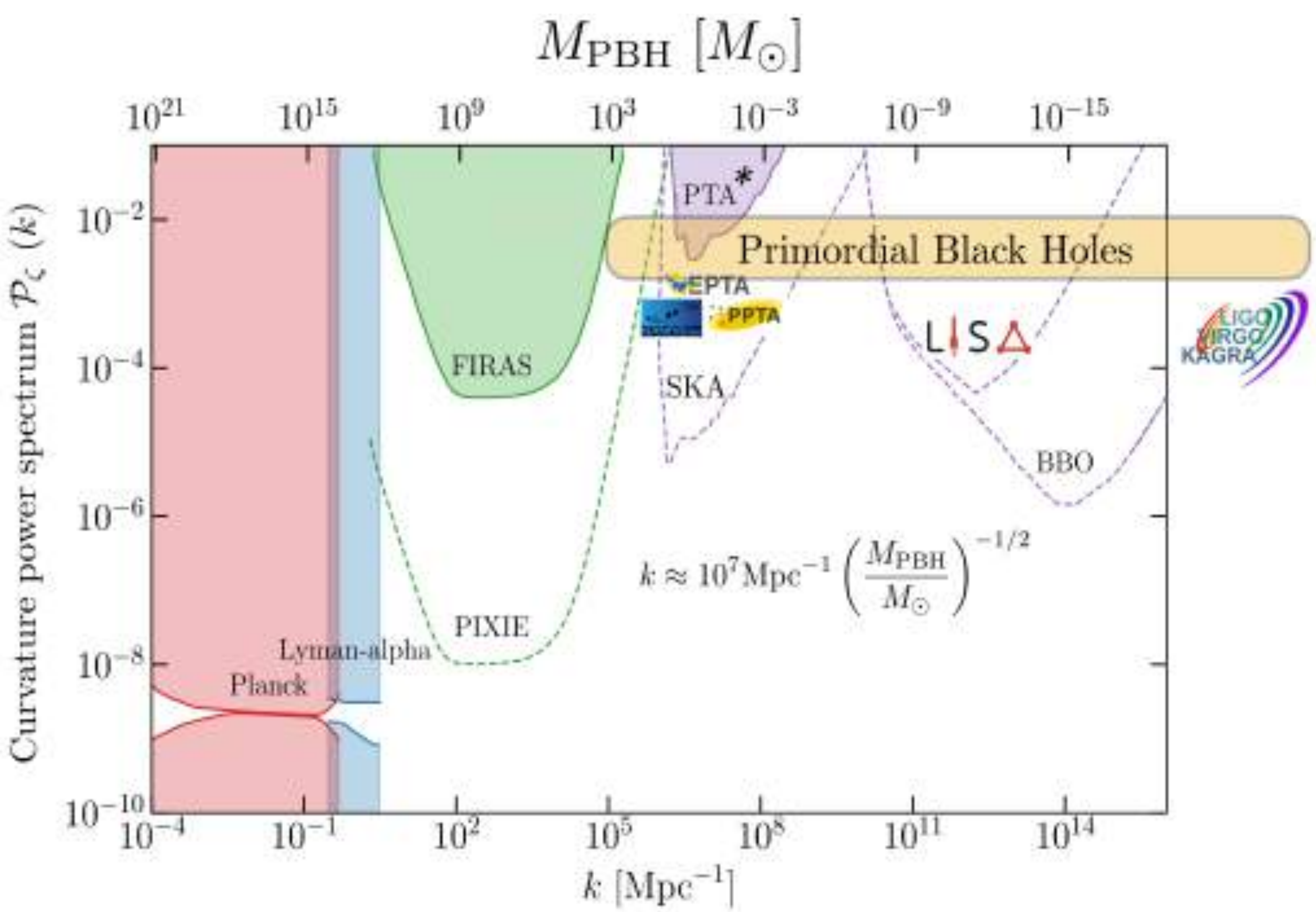



$$h''_{ij} + 2\mathcal{H}h'_{ij} - \nabla^2 h_{ij} = \mathcal{O}(\partial_i\zeta\partial_j\zeta)$$

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

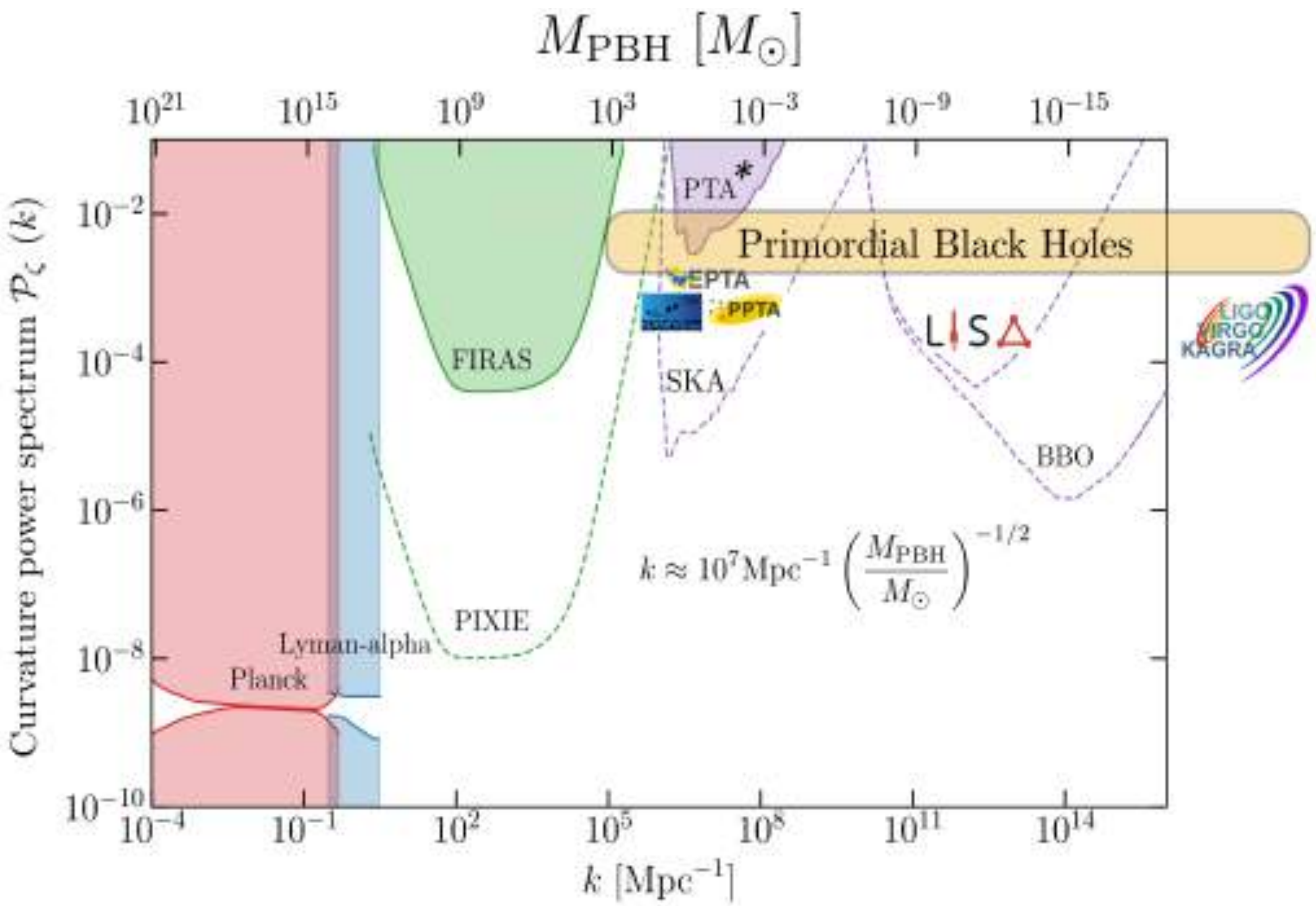
# GWs - Primordial Black Holes and Dark Matter

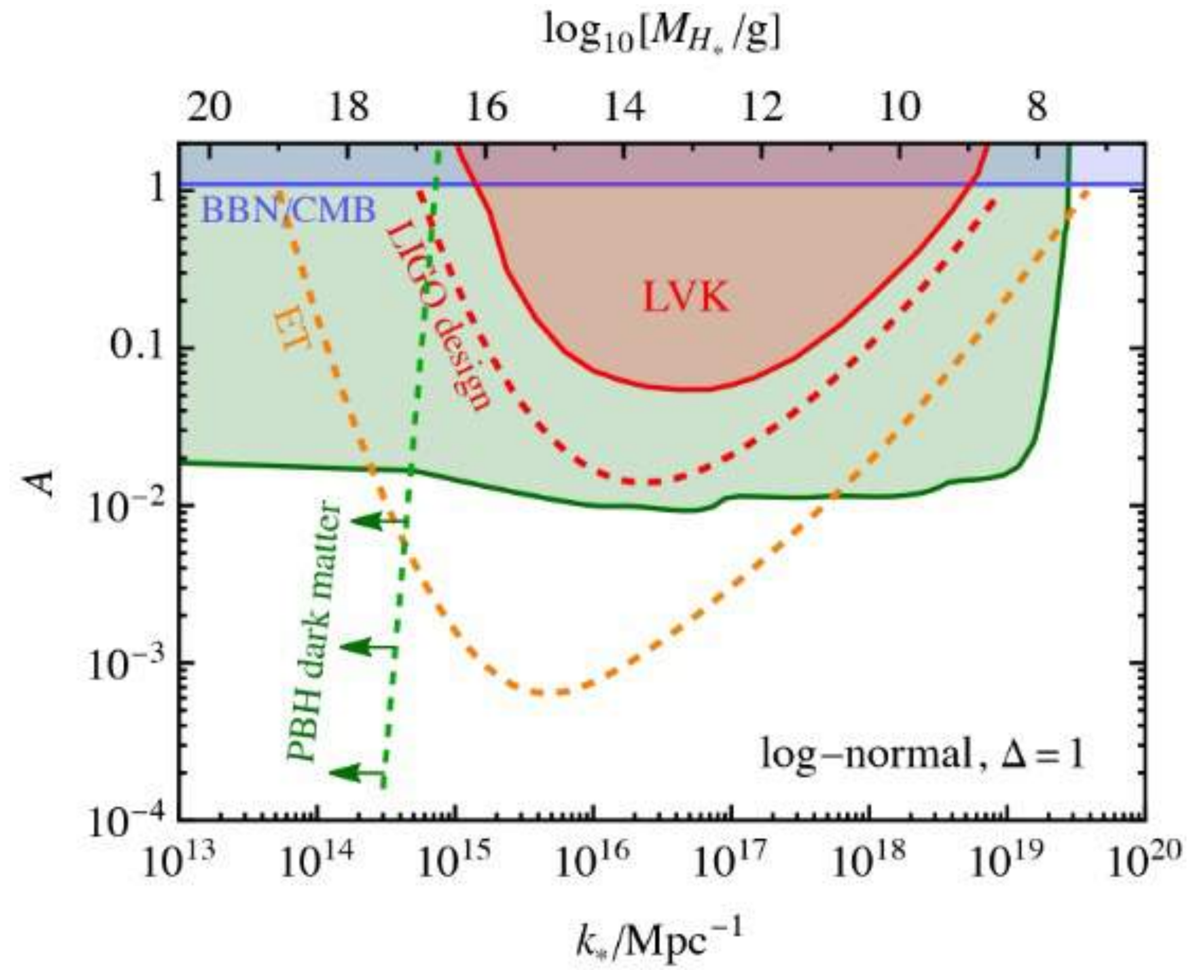
$$\Omega_{GW} \simeq \Omega_{rad} A_\zeta^2$$



# GWs - Primordial Black Holes and Dark Matter

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



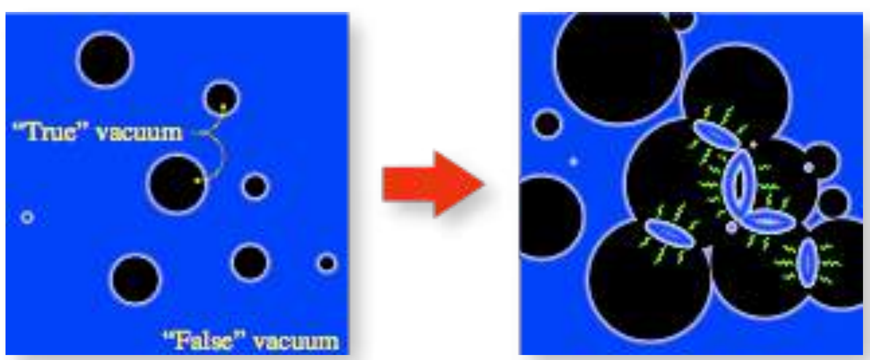




$$f_{\rm GW} = 4.1\,\mathrm{Hz}\left(\frac{\kappa}{2.51}\right)\left(\frac{g_*}{106.75}\right)^{-1/12}\left(\frac{M_H}{10^{-17}M_\odot}\right)^{-1/2}$$

# Phase Transition in the Early Universe

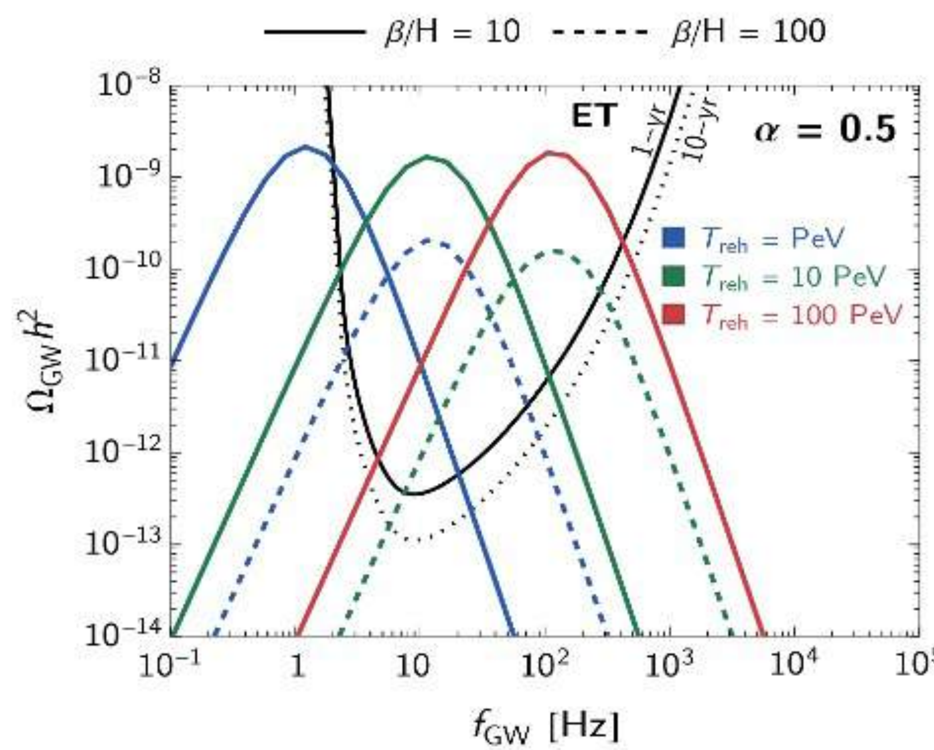
As the temperature in the very early universe decreases, there can be several **PTs: QCD, EW.**...Beyond Standard Model?

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




**Processes**

- Bubble collisions
- MHD Turbulence
- Sound Waves




$$\Omega_{\rm GW}(f) \propto \frac{(a+b)^c f_{\rm peak}^b f^a}{\left(b f_{\rm peak}^{\frac{a+b}{c}} + a f^{\frac{a+b}{c}}\right)^c}$$

$$f_{\rm peak} \approx \mathcal{O}(1) \times 10^{-5} \frac{1}{H_{\rm reh} R_{\rm coll}} \frac{T_{\rm reh}}{100\,{\rm GeV}}\ {\rm Hz}$$

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

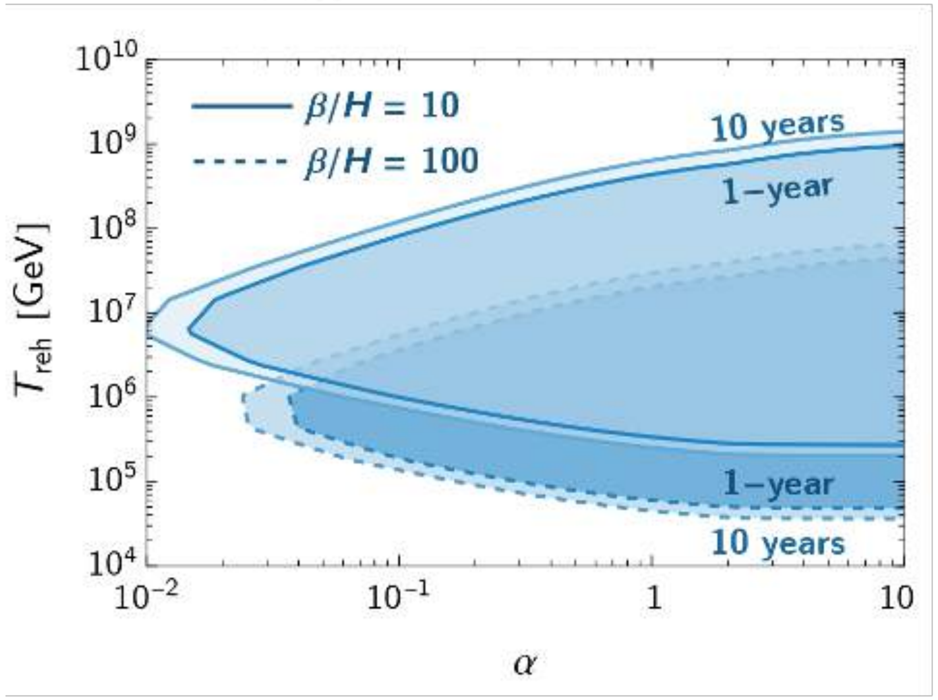
# What we can learn from Phase Transition?

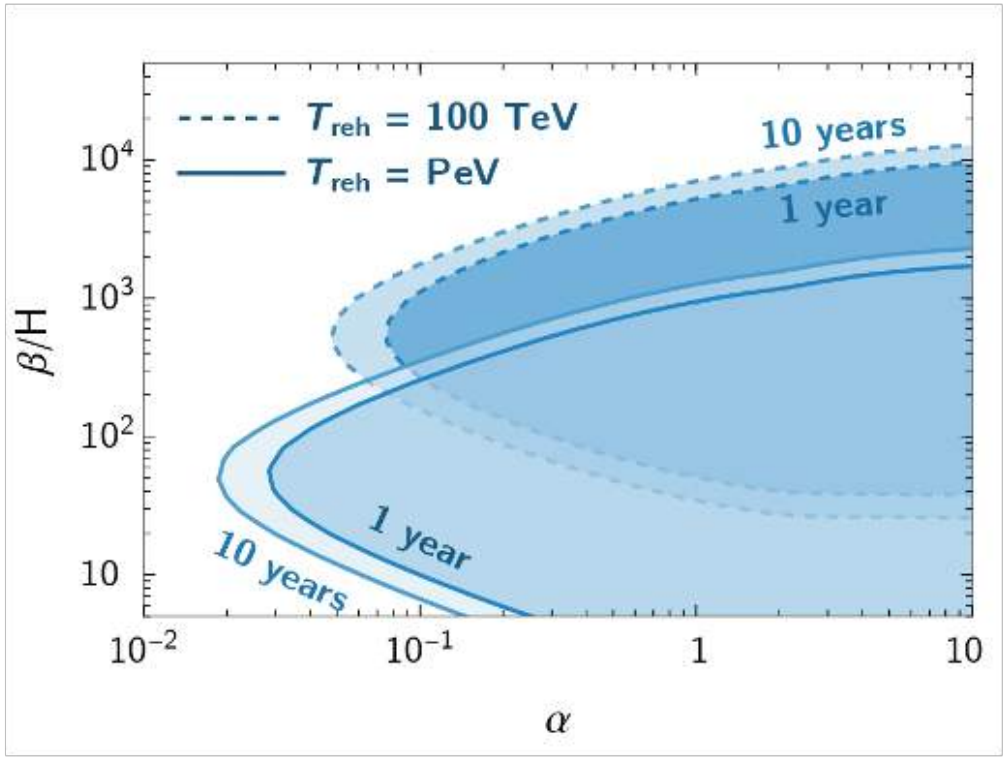
- ET could act as a **probe of Beyond Standard Model physics, complementary to colliders**

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

$$\boxed{\text{BSM parameters}(\textbf{couplings},\textbf{masses}\ldots) \Rightarrow (\alpha, \beta, T_{\rm reh}, v_w)}$$

$$\boxed{(\alpha, \beta, T_{\rm reh}, v_w) \Rightarrow (f_{\rm peak}, \Omega_{\rm peak}, \text{GW spectrum}).}$$




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

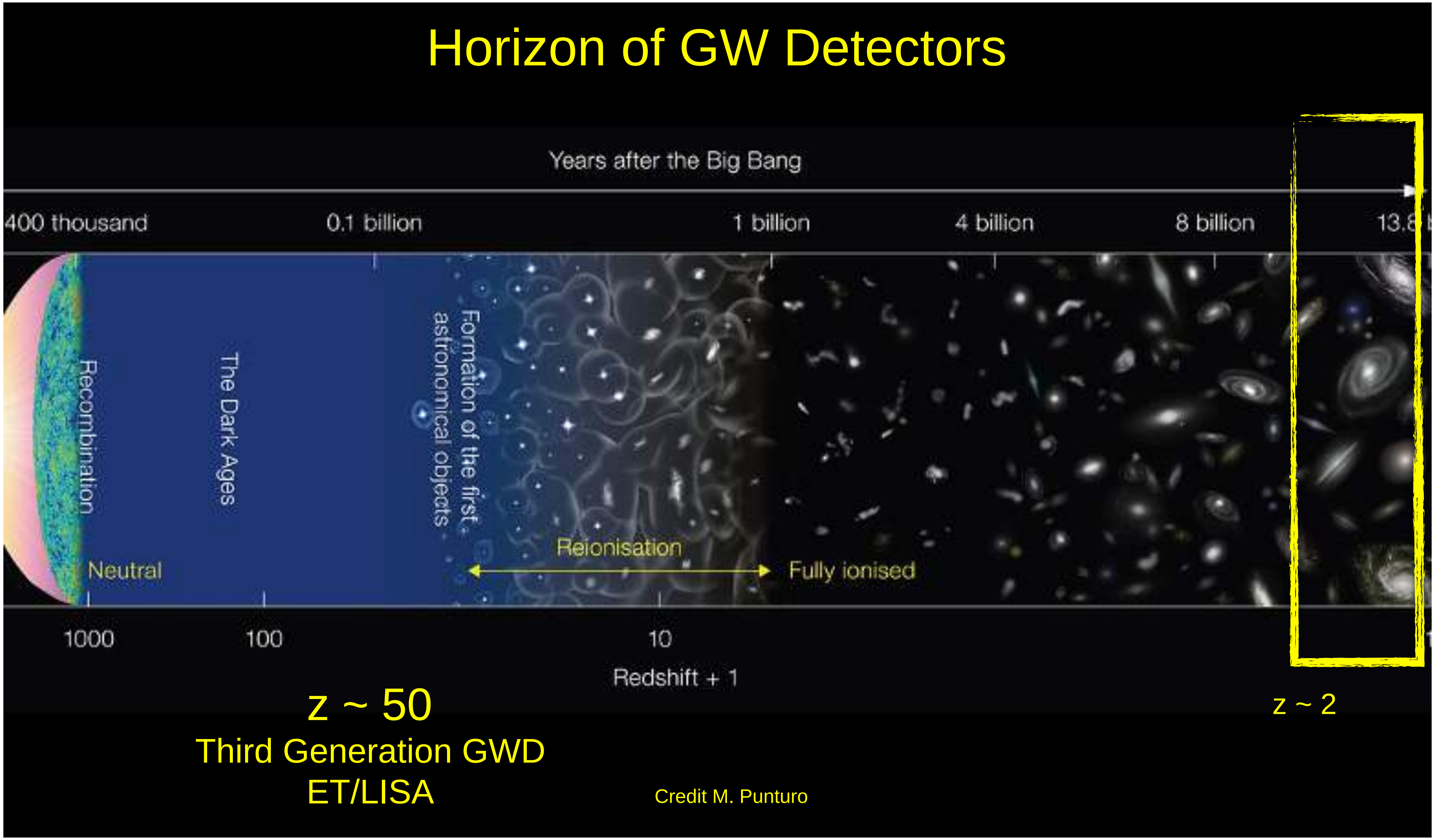
$\lambda_{hs}$ Singlet coupling

$m_s$ Singlet mass

ET Blue book 2503.12263 (PT)

# Late Universe Cosmology with Gravitational Waves

# Where is the horizon for 3G detectors?

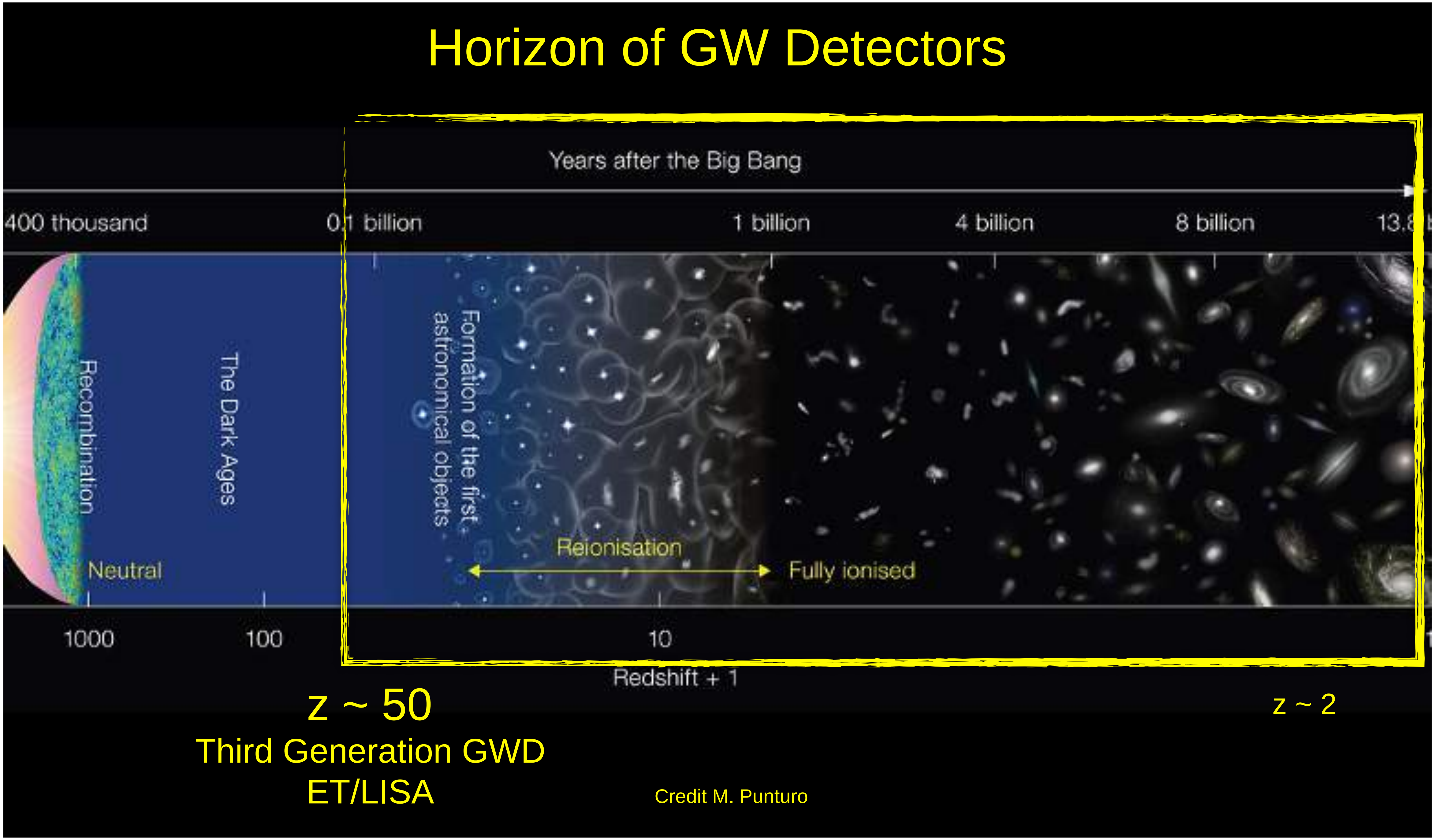



**Einstein Telescope:**

**BBHs up to cosmic Dark Ages (z > 30)**

**BNSs up to cosmic Noon (z~2)**

# Where is the horizon for 3G detectors?



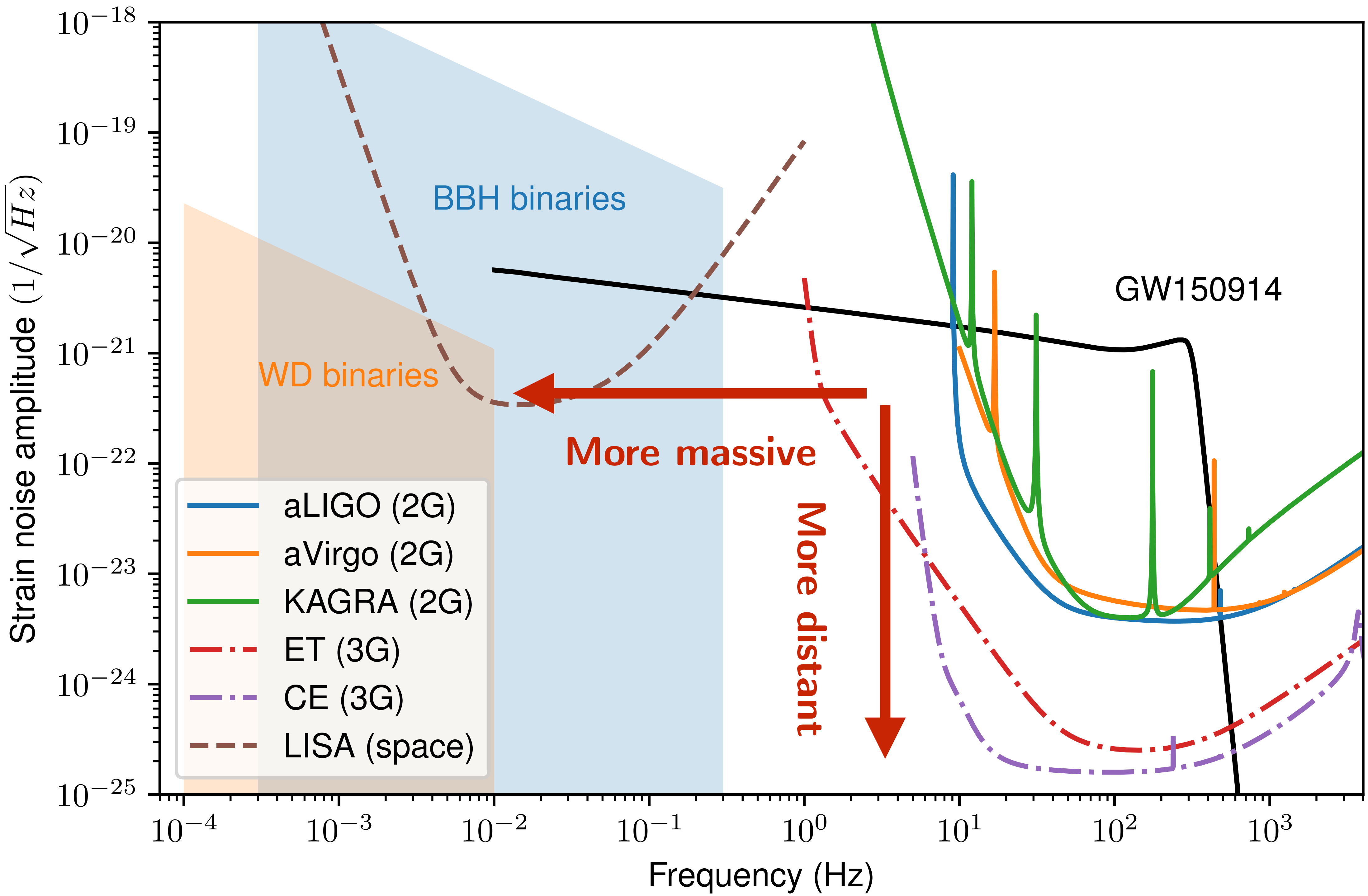

**Einstein Telescope:**

**BBHs up to cosmic Dark Ages (z > 30)**

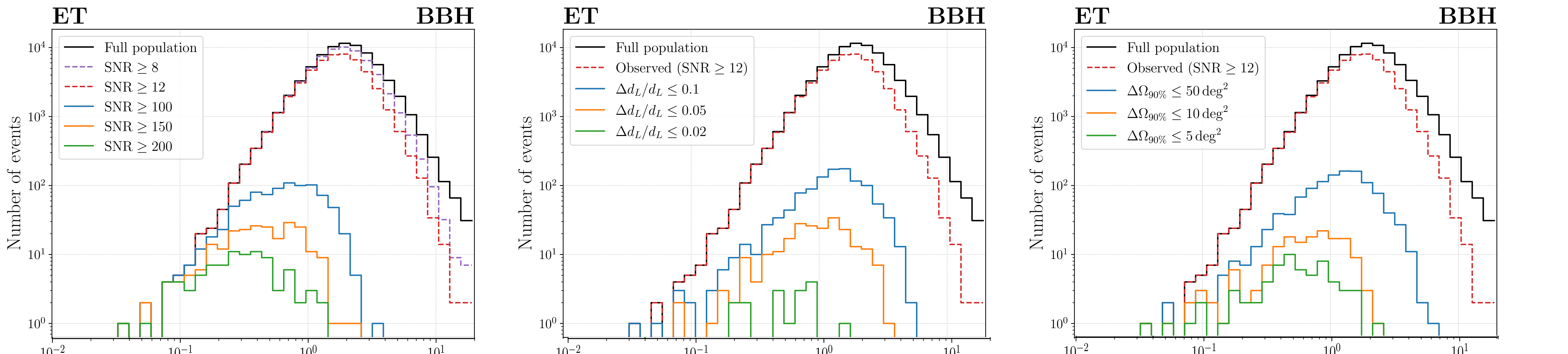
**BNSs up to cosmic Noon (z~2)**

# From 2G to 3G detectors: ET and LISA

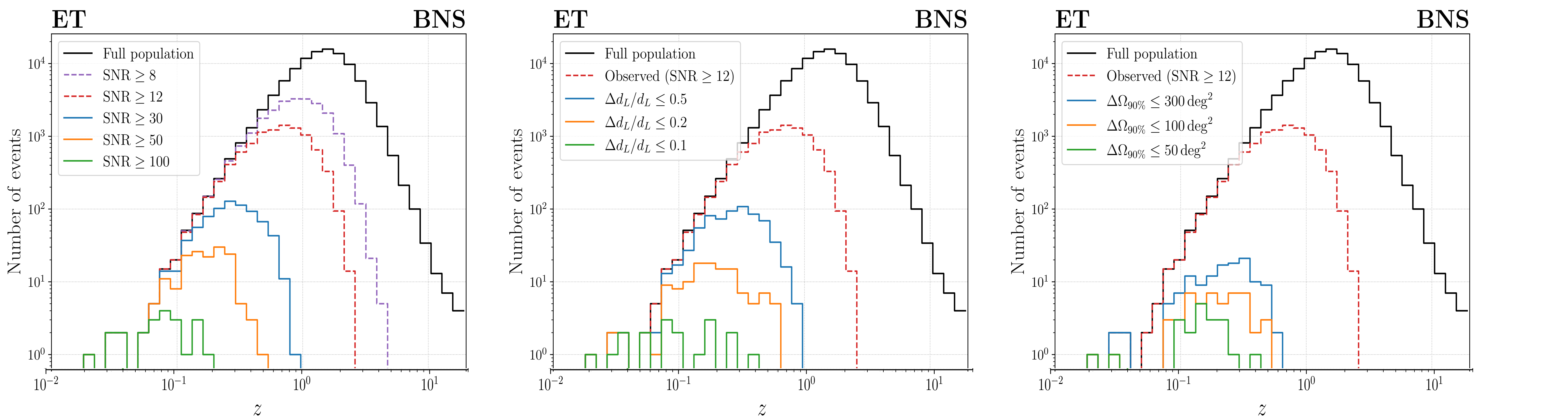
$$h_{\rm gw} \sim 1/d_L \qquad f_{\rm gw} \sim 1{\rm kHz}\left(\frac{10M_\odot}{M}\right)$$



# 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

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

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).

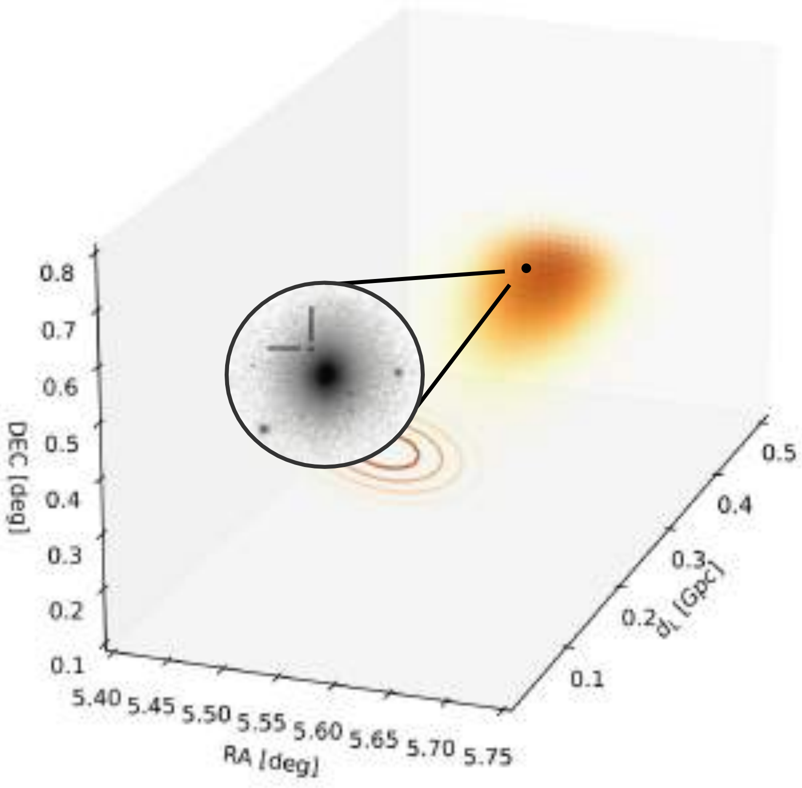
=> independent measure of $H_0$

**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**

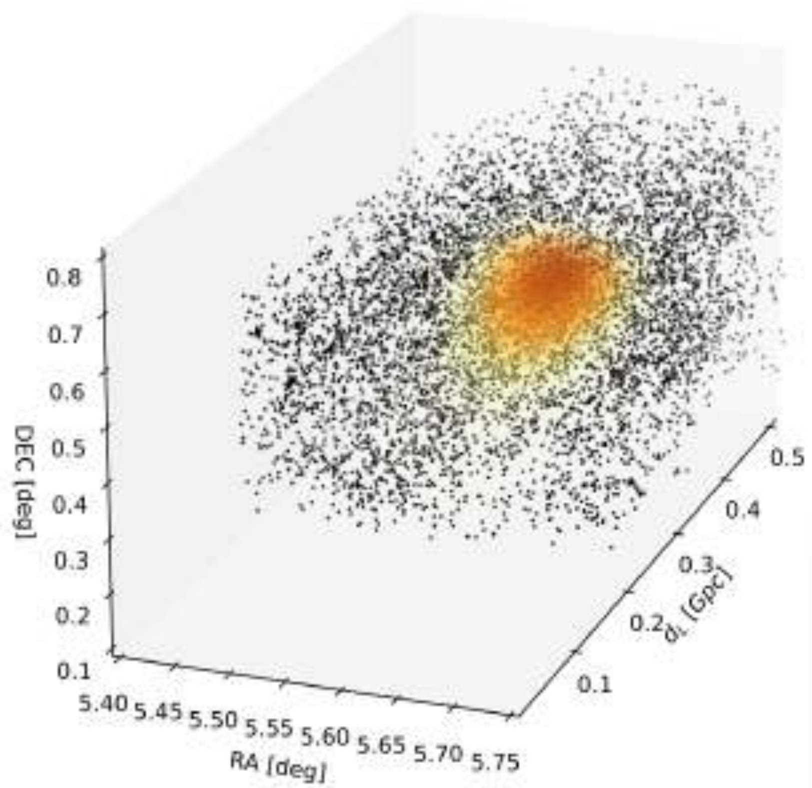
An **EM counterpart** is observed and used to obtain the host galaxy redshift.




(Holz & Hughes 2005)

**Dark Sirens**

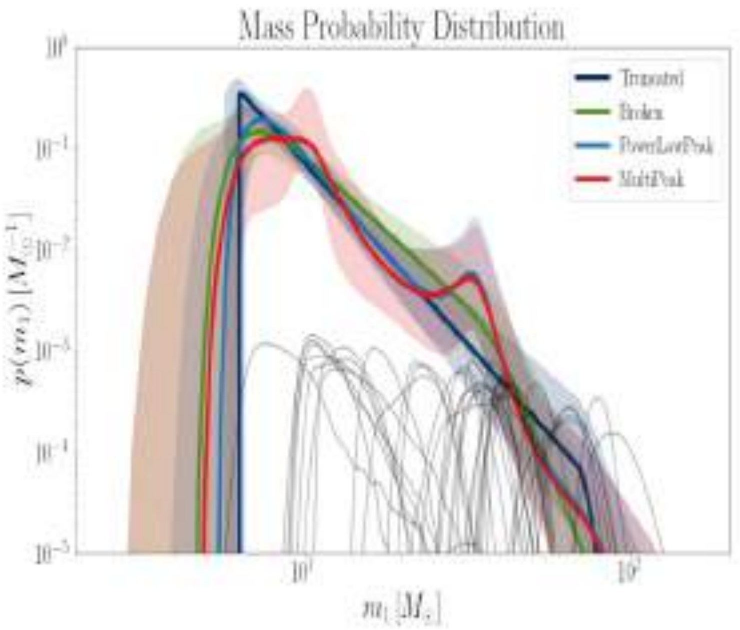
No EM counterpart observed. **Galaxy surveys** are used to provide redshift estimates for potential host galaxies.




(Schutz 1986, Del Pozzo 2012)

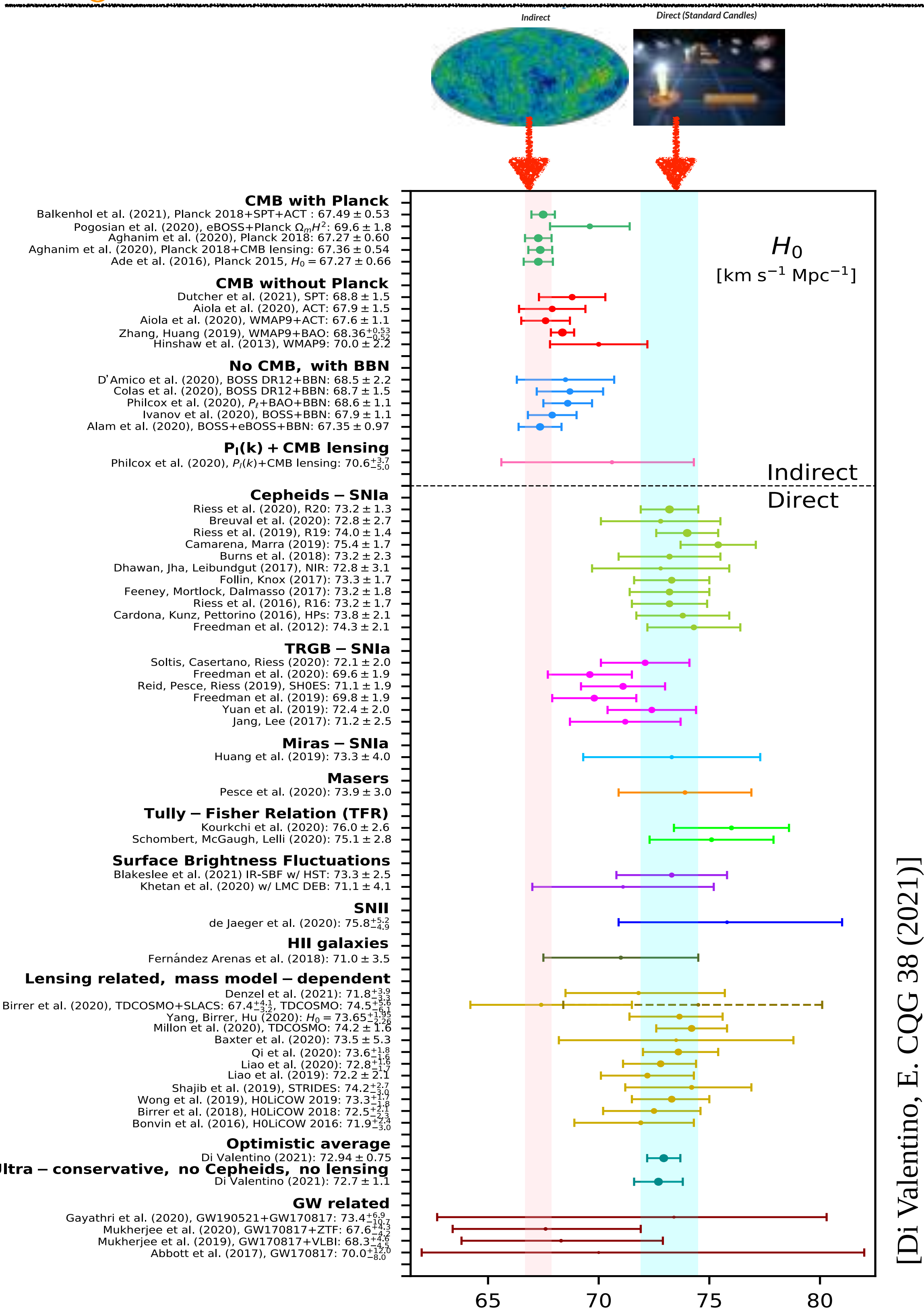
**Spectral sirens**

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

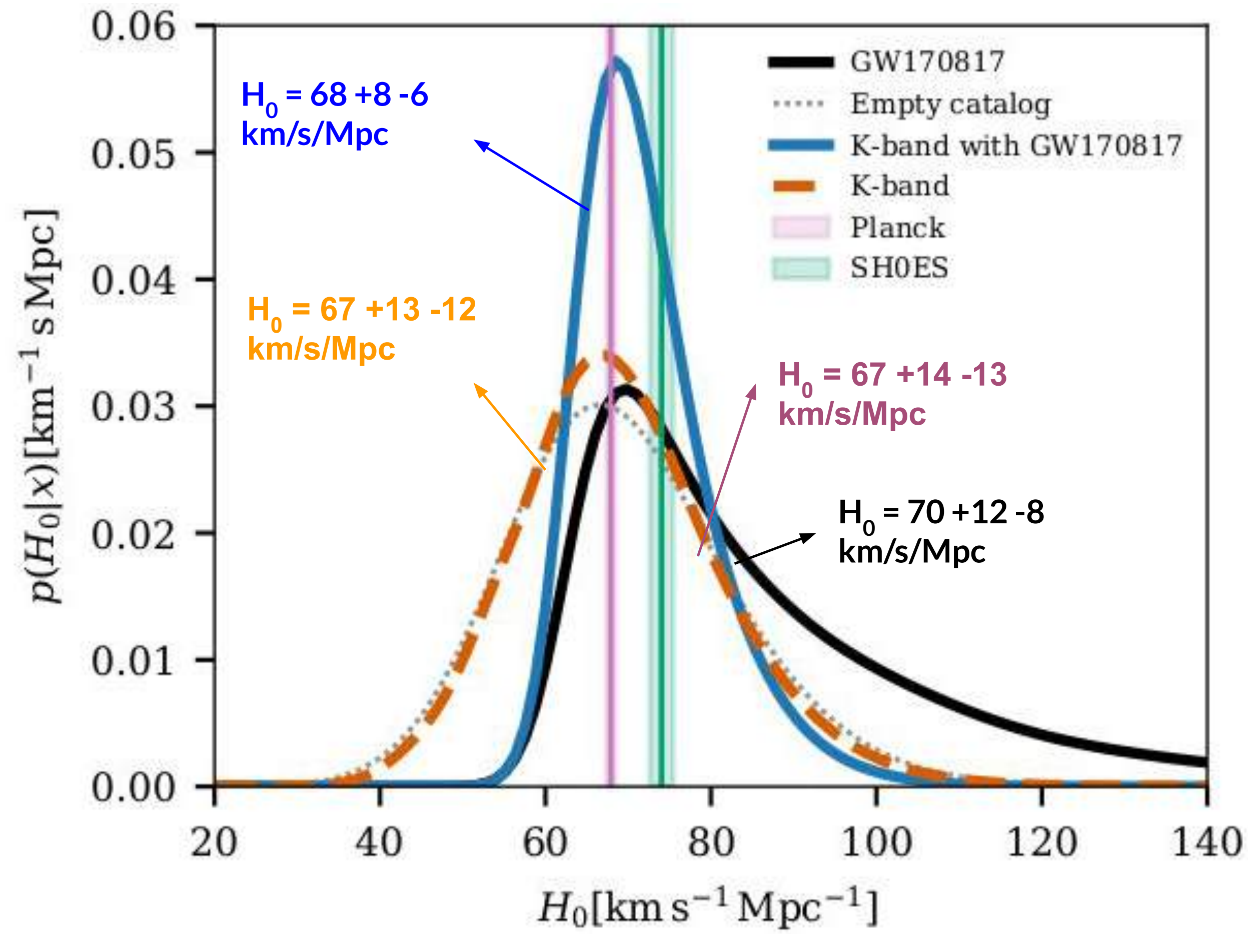



(Chernoff & Finn 1993)

# $H_0$ - where we are: after GWTC-3 with Dark Sirens




[**GWCT3** - LVK+, ApJ 949 76 (2023)]

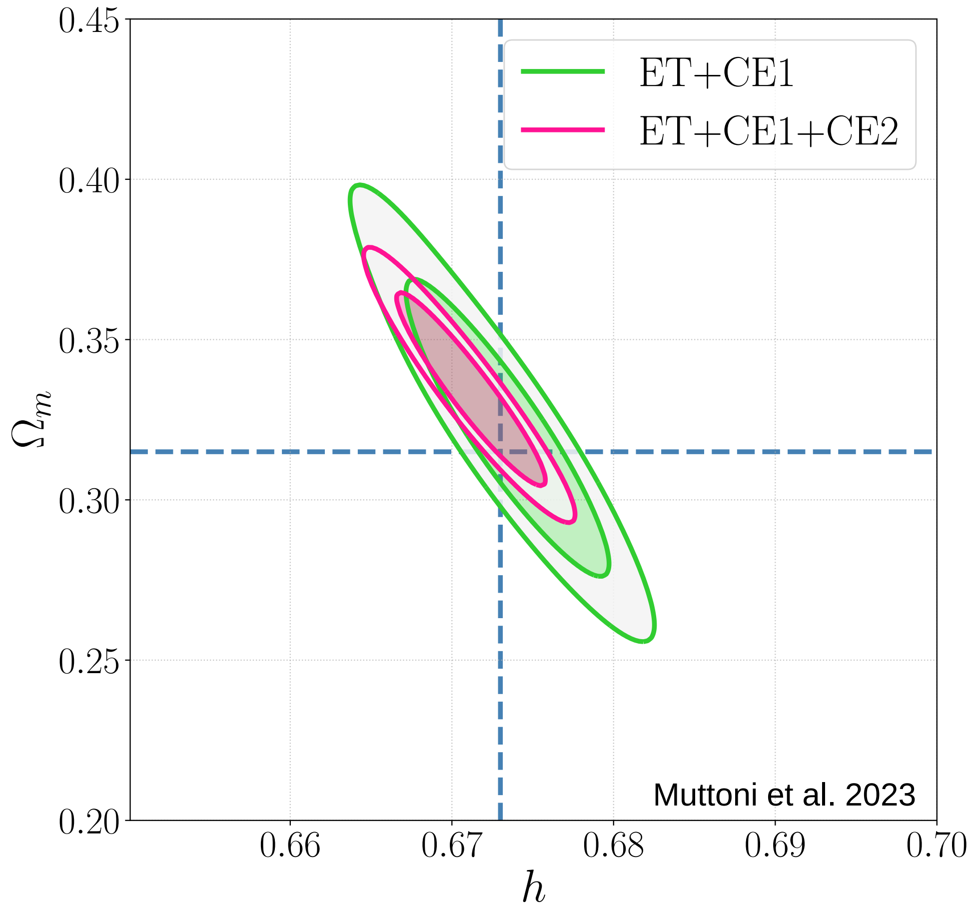



K-band for the luminosities of galaxies and the preferred mass model (Power Law+Gaussian peak)

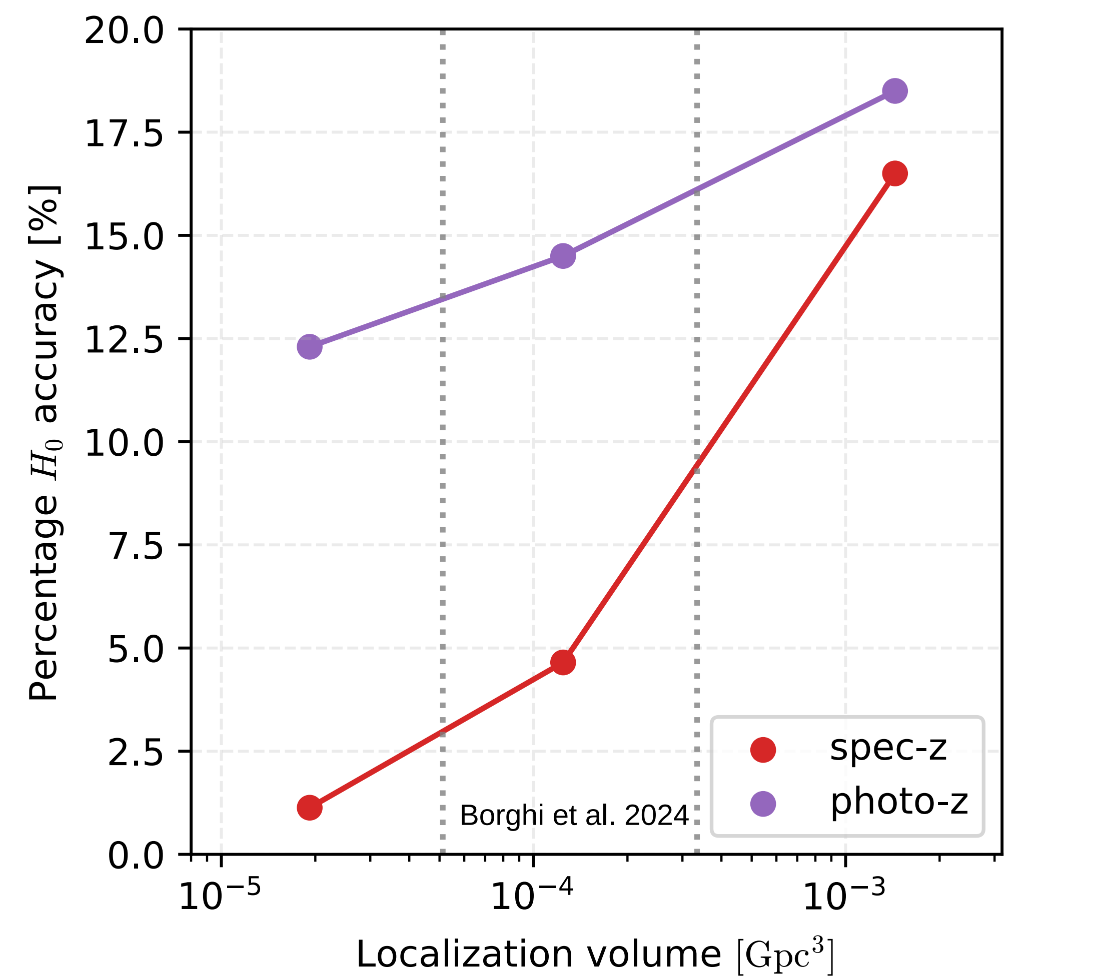
**~ 5 \sigma tension between low and high redshift measurements of the Hubble parameter**

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

**Posterior joint distribution on $H_0$ and $\Omega_{m,0}$**




**H_0 accuracy dependence VS redshift error of the galaxy catalogue**




**Fiducial scenario**

- 1 year of observation
- Full duty cycle
- Loudest GW event localization
- Complete galaxy catalogue (generated using L-Galaxies running SAM on the Millennium simulation)
- Halo mass resolution (2 × 10^10 M⊙)
- Box size (685 Mpc)

[D. Izquierdo-Villalba et al 2019]

| Network | $N$ | | $\Delta h/h$ (%) | | | | $\Delta\Omega_m/\Omega_m$ (%) | | |
|---|---|---|---|---|---|---|---|---|---|
| | $z<1$ | $z<3$ | $z<1$ | $z<1$ fixed $\Omega_m$ | $z<1$ 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

# Using GWs to Constrain Dark Energy

If the Dark Energy equation of states evolves in time $p_{\rm DE}(z) = w_{\rm DE}(z)\rho_{\rm DE}(z)$

$$\frac{\rho_{\rm DE}(z)}{\rho_0} = \Omega_{\rm DE} \exp\left\{3\int_0^z \frac{d\tilde{z}}{1+\tilde{z}}\left[1+w_{\rm DE}(\tilde{z})\right]\right\}$$

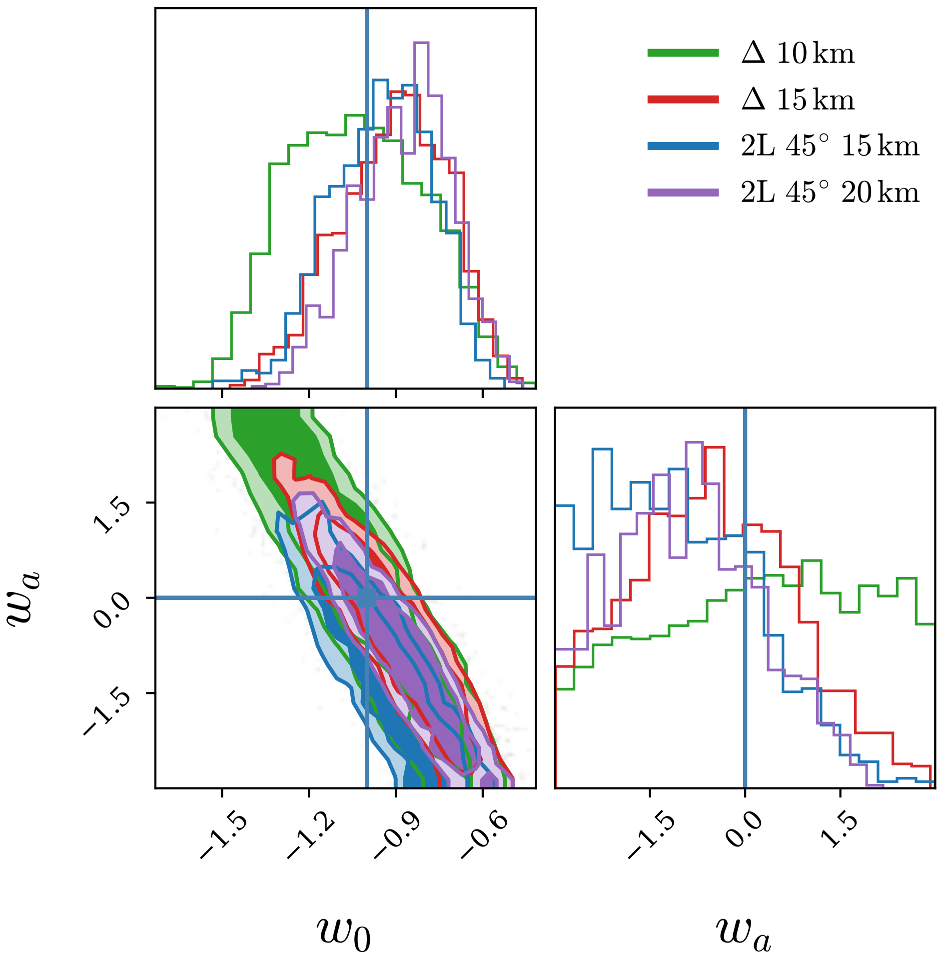
$$d_L(z) = \frac{c}{H_0}(1+z)\int_0^z \frac{d\tilde{z}}{\sqrt{\Omega_{\rm M}(1+\tilde{z})^3+\Omega_{\rm R}(1+\tilde{z})^4+\Omega_\Lambda}} \Rightarrow d_L(z) = \frac{c}{H_0}(1+z)\int_0^z \frac{d\tilde{z}}{\sqrt{\Omega_{\rm M}(1+\tilde{z})^3+\Omega_{\rm R}(1+\tilde{z})^4+\rho_{\rm DE}(\tilde{z})/\rho_0}}$$

$$w_{\rm DE}(z) = w_0 + \frac{z}{1+z}w_a$$

Linder parameterization

| Configuration | $\Delta w_0$ | $\Delta w_a$ |
|---|---|---|
| $\Delta$-10km | 0.49 | 3.81 |
| $\Delta$-15km | 0.40 | 2.65 |
| 2L-15km-45° | 0.35 | 2.55 |
| 2L-20km-45° | 0.34 | 2.40 |

Einstein Telescope with $10^3$ bright sirens

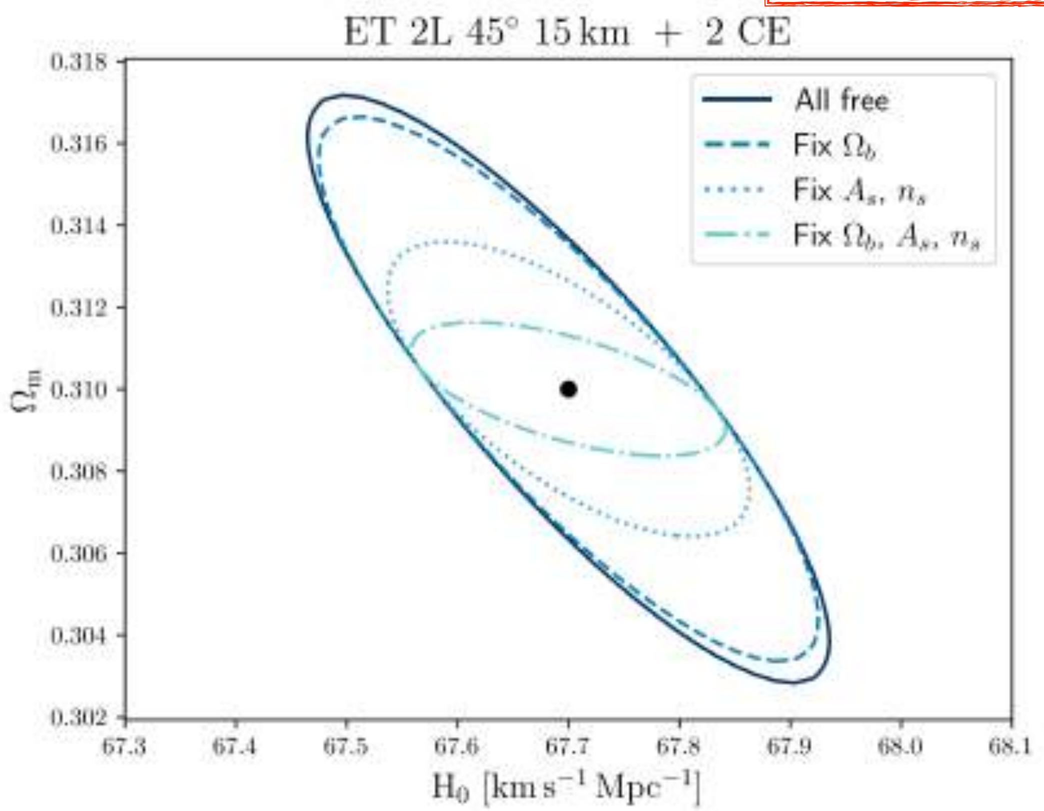



**joint GW+EM events obtained with ET+THESEUS, 5 yrs observation**

ET CoBA document

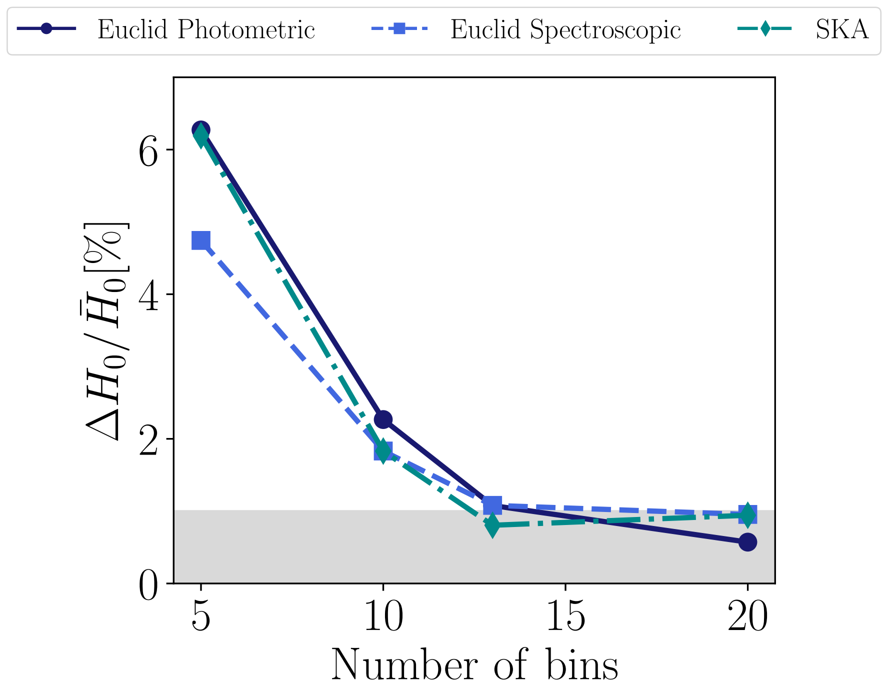
# Cross-correlation between GW and LSS (ETxEuclid)

$$C_\ell^{XY}(x_i, x_j) = \frac{2}{\pi}\int \mathrm{d}k\, k^2\, P(k)\Delta_\ell^{X,x_i}(k)\Delta_\ell^{Y,x_j}(k)$$




| Parameter | All nuisance parameters free | Fix $\Omega_b$ | Fix $A_s, n_s$ | Fix $\Omega_b$, $A_s, n_s$ |
|---|---|---|---|---|
| ET 2L 45° 15 km + 2CE | | | | |
| $H_0$ | 0.8 | 0.75 | 0.55 | 0.47 |
| $\Omega_m$ | 5.3 | 4.9 | 2.6 | 1.2 |
| ET $\Delta$ 10 km + 2CE | | | | |
| $H_0$ | 0.8 | 0.79 | 0.6 | 0.53 |
| $\Omega_m$ | 5.3 | 4.9 | 2.6 | 1.2 |

**~ % level precision with one year of observation**




**(sky coverage of 15,000 square degrees and ~1.6 × 10^9 observed galaxies)**

**Photometric sample of the Euclid satellite**

Pedrotti et al ArXiv 2504.10482

Ongoing forecasts for ETxEuclid **SkyFast pipeline - in preparation**

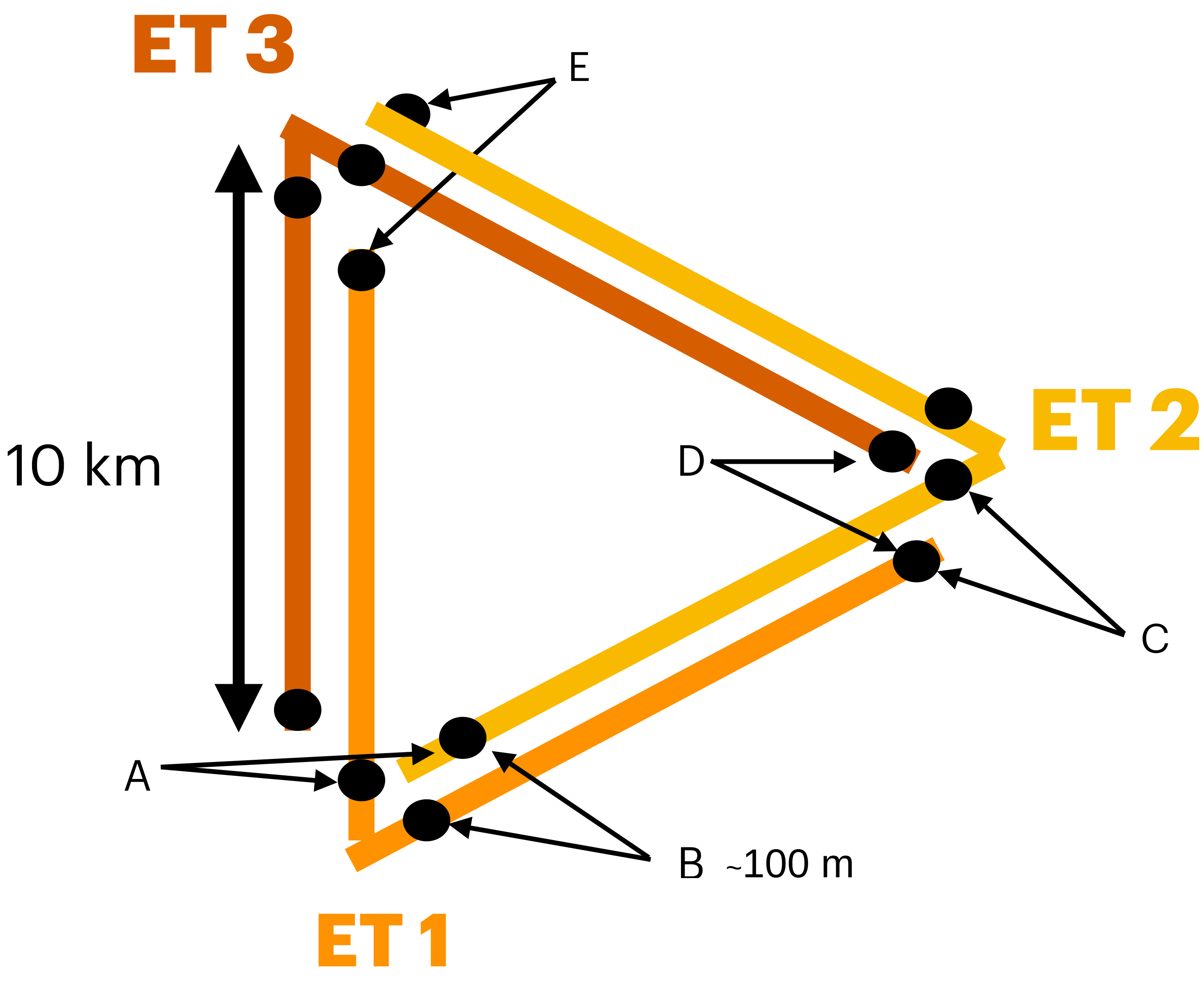
# Impact of ET Correlated Noise on SGWB searches

Based on ArXiv: 2501.09057

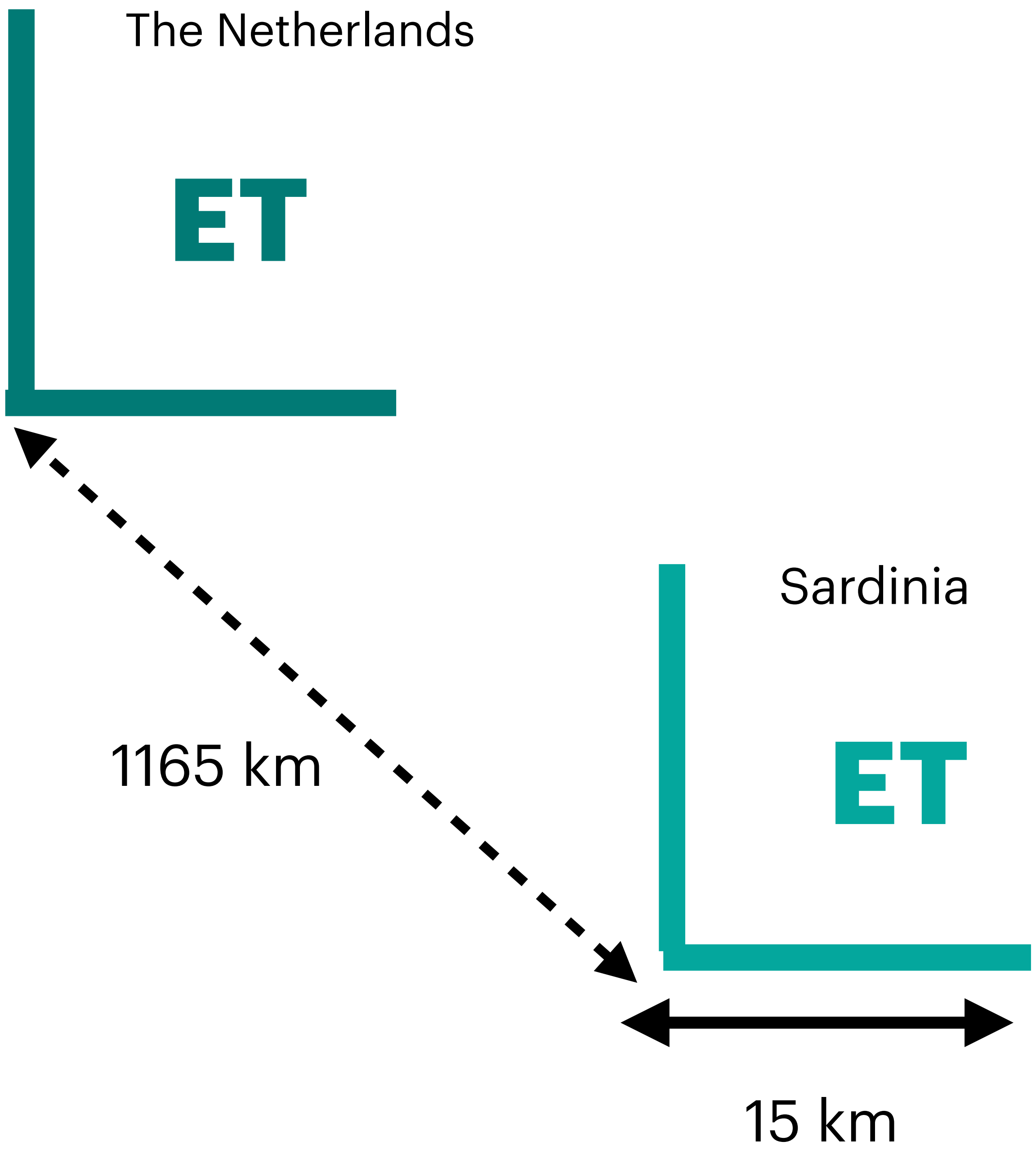
(I. Caporali, G. Capurri, W. Del Pozzo, AR, L. Valbusa Dall’Armi)

# Einstein Telescope - possible designs

## Triangular Configuration




## 2L Configuration




[ET CoBa paper JCAP, vol. 07,2023]

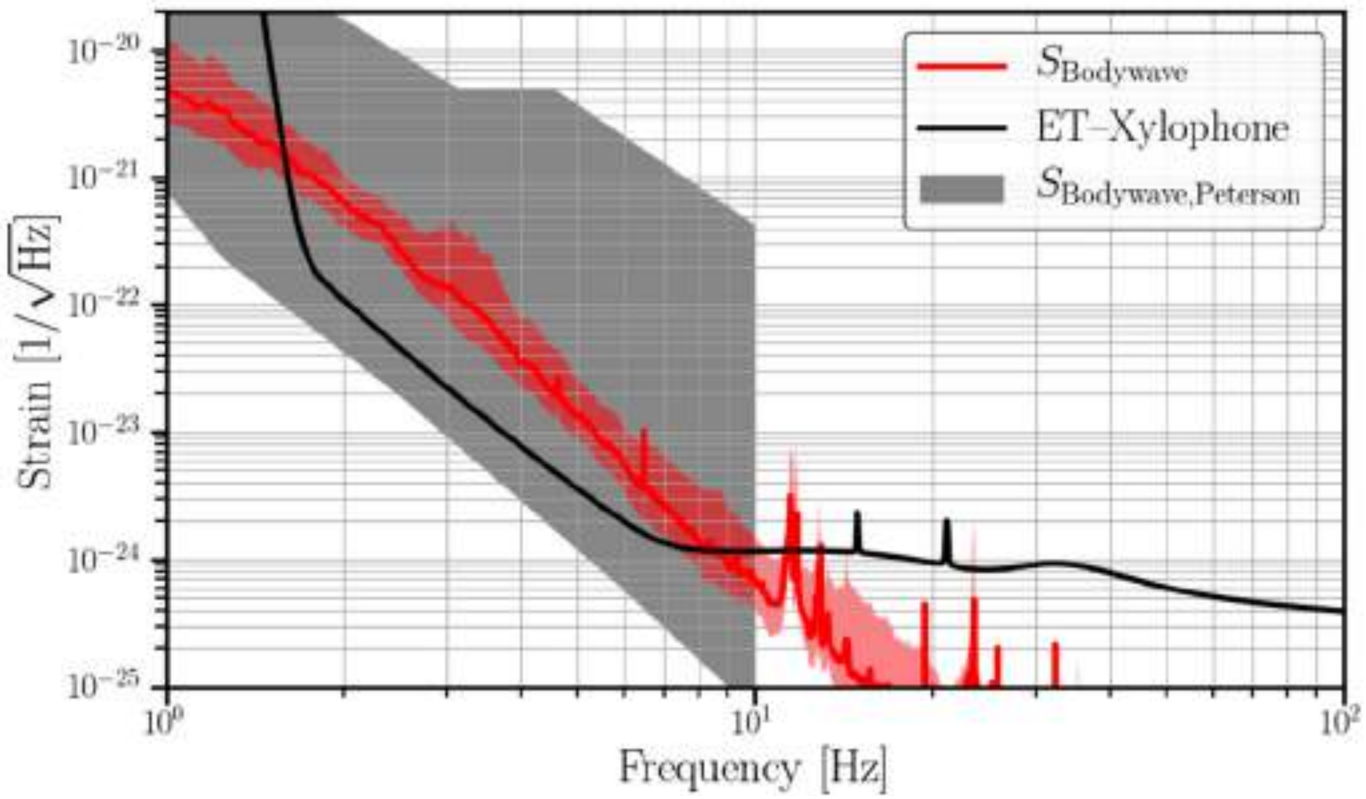
# Correlated Newtonian Noise

**Newtonian noise is a disturbance produced in GW detectors by local fluctuations in the Gravitational field**

Local fluctuations generated by **changes** in density of rocks → Originated by passing seismic waves

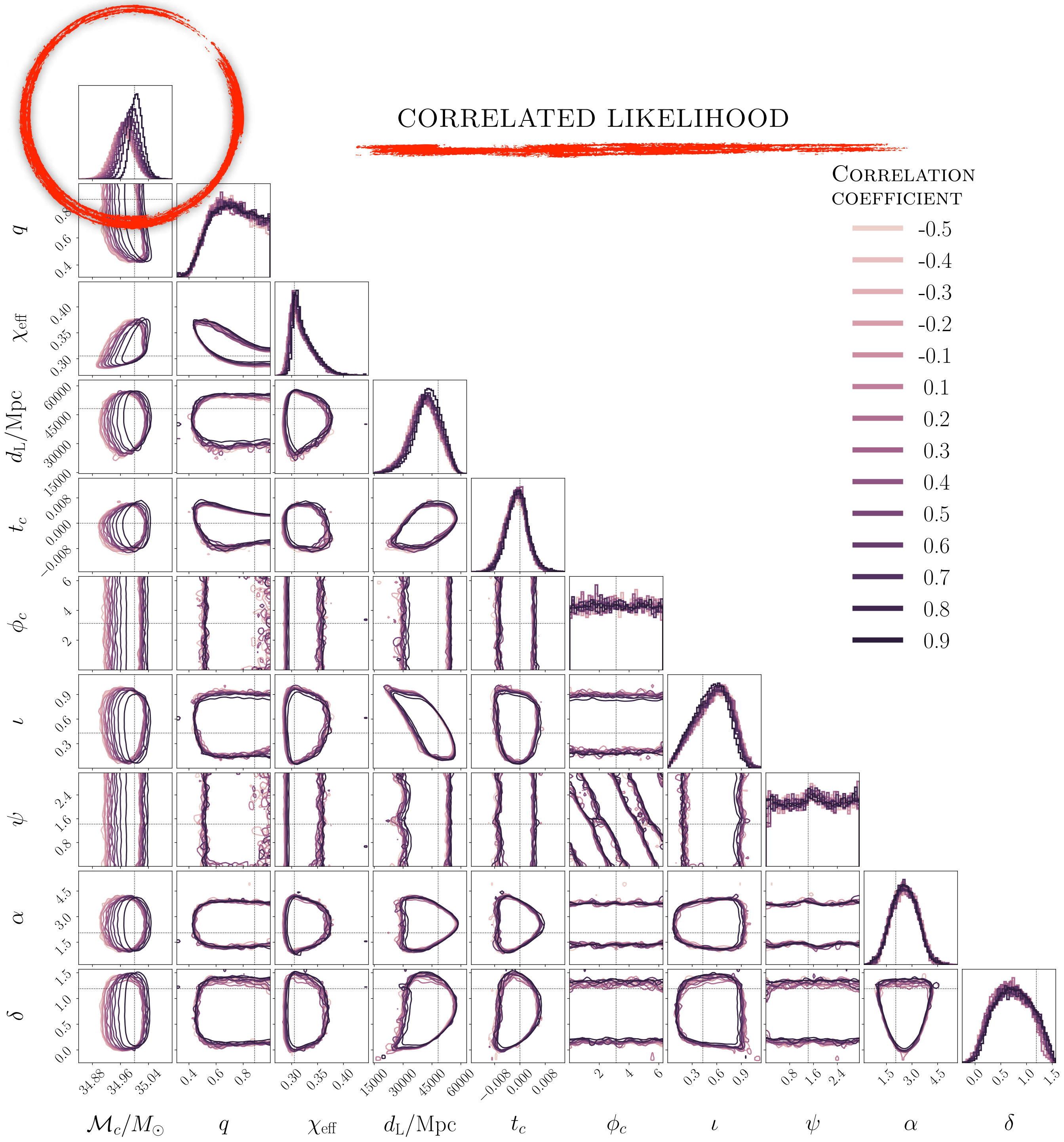
Body Waves → Underground colocated interferometers will only be affected by this effect

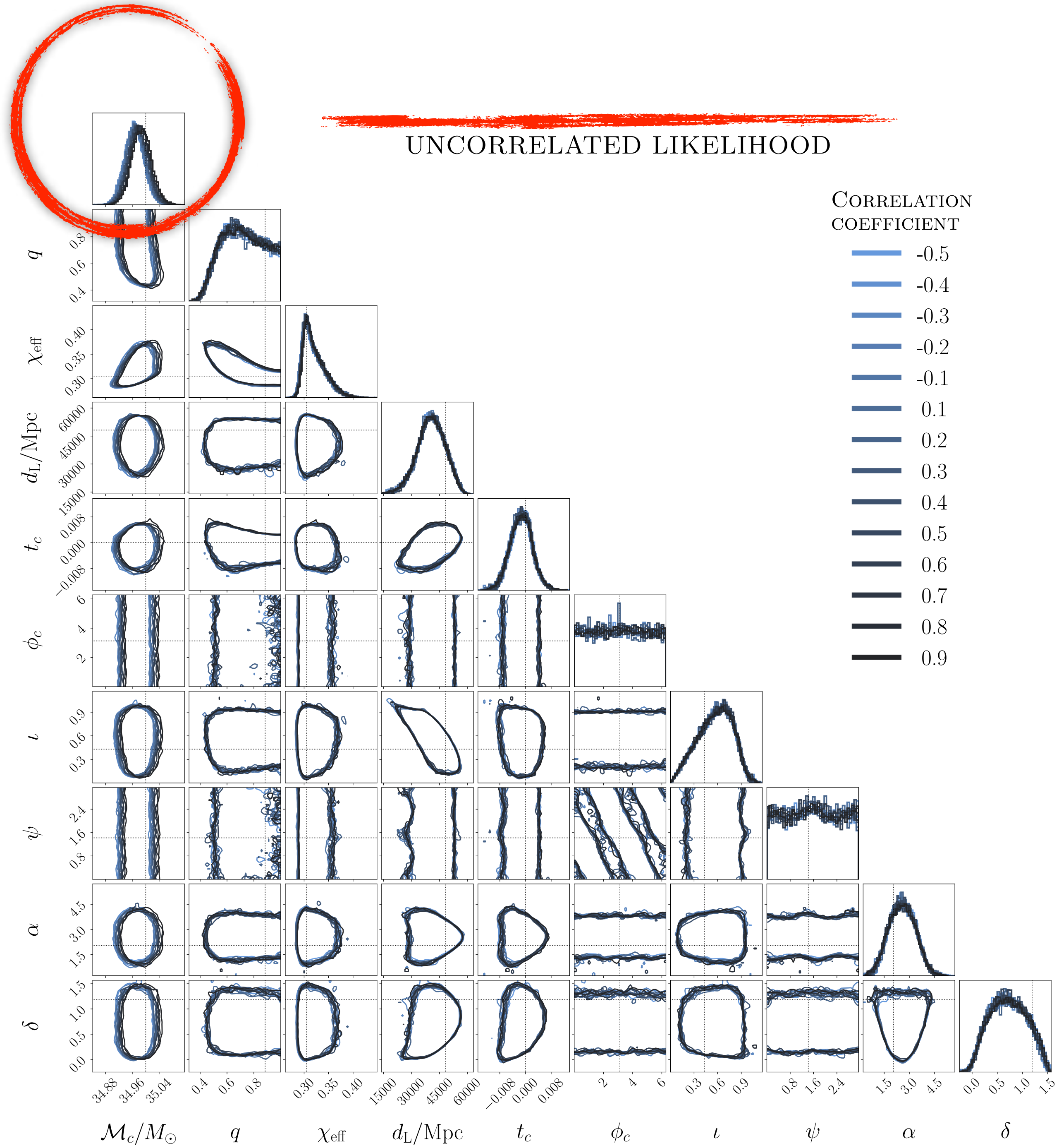
Surface Waves (Rayleigh Waves)




[Janssens et al. arXiv:2206.06809]

# Impact of Correlated Noise on PE Resolved Events




**Neglecting these correlations may significantly reduce the accuracy of the chirp mass reconstruction.**

[F.Cireddu et al. arXiv:2312.14614]

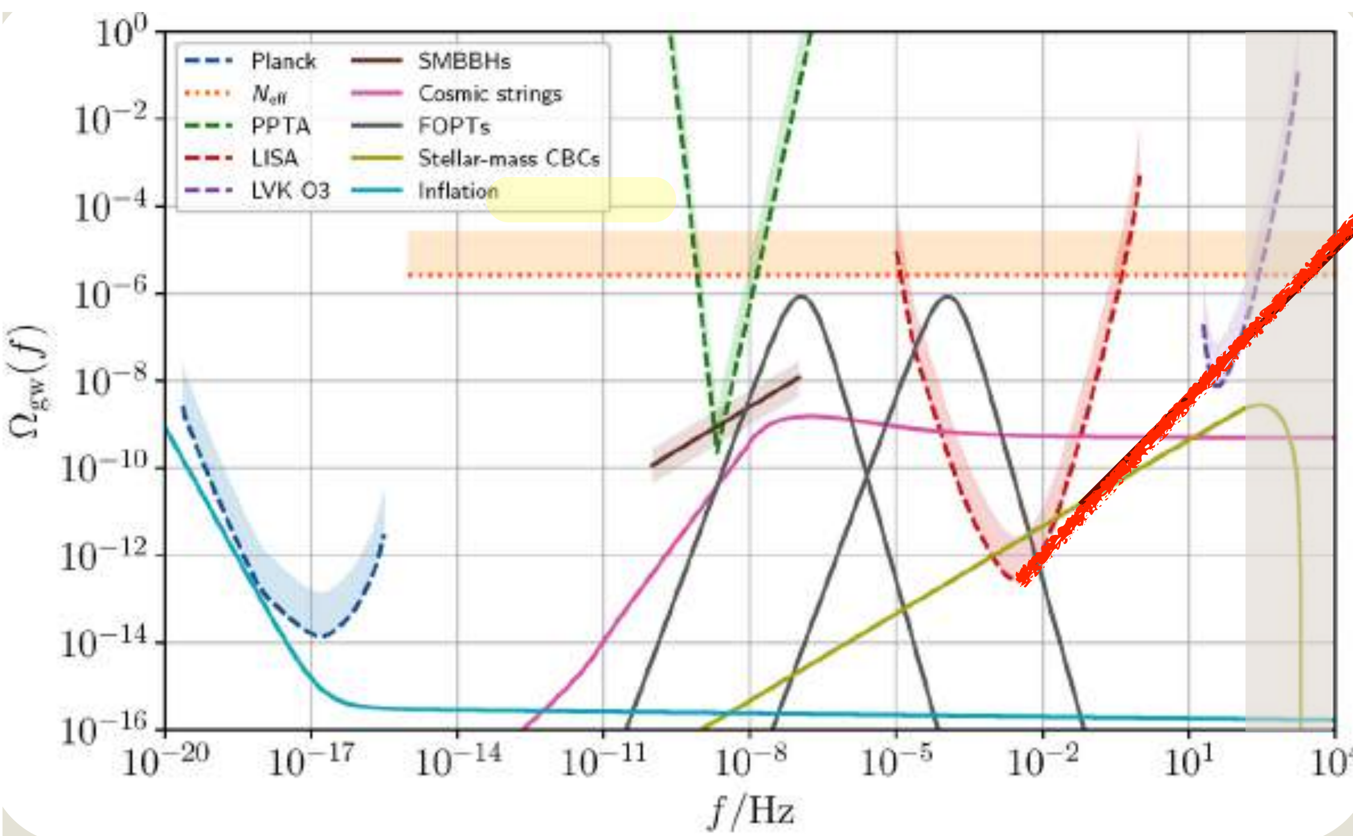
# Impact of Correlated Noise SGWB

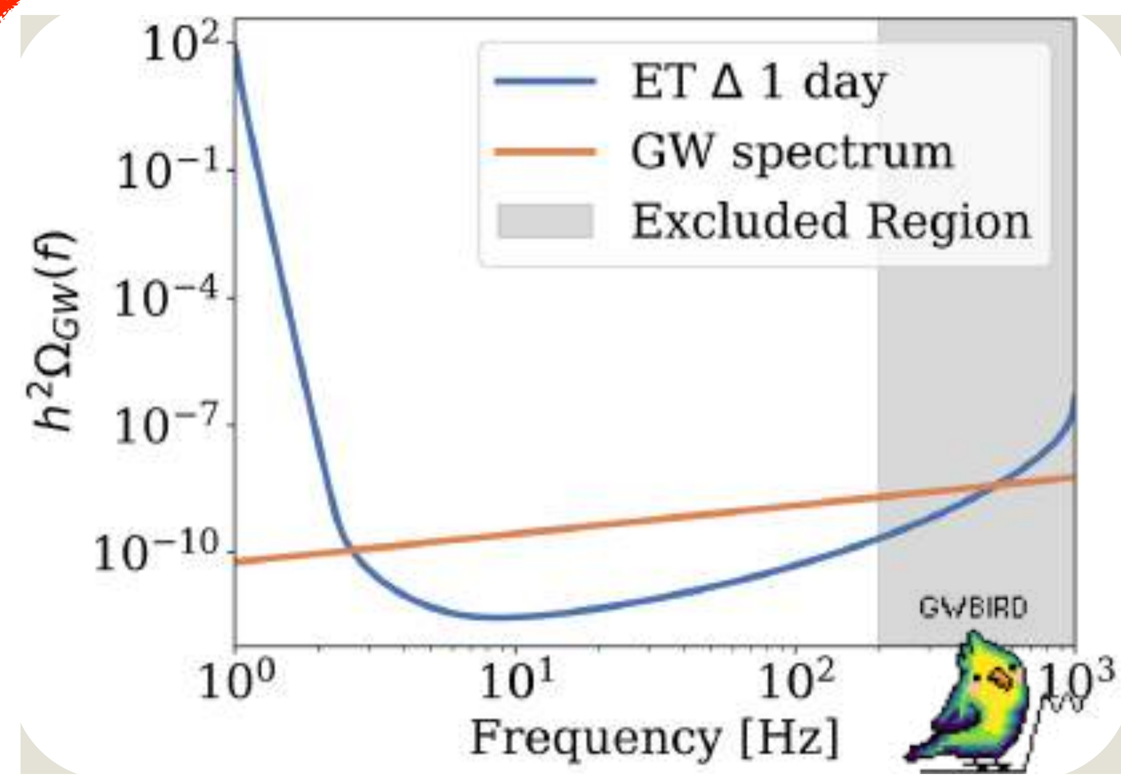
**Correlated noise is a threat** to all the possible **Astrophysical and Cosmological sources of SGWB**

$$\Omega_{\rm GW} = \frac{1}{\rho_c}\frac{d\rho_{\rm GW}}{d\log f}$$

$$\Omega_{\rm GW}(f) = A_{\rm GW}\left(\frac{f}{f_*}\right)^{n_{\rm GW}}$$

**Power Law Behavior**



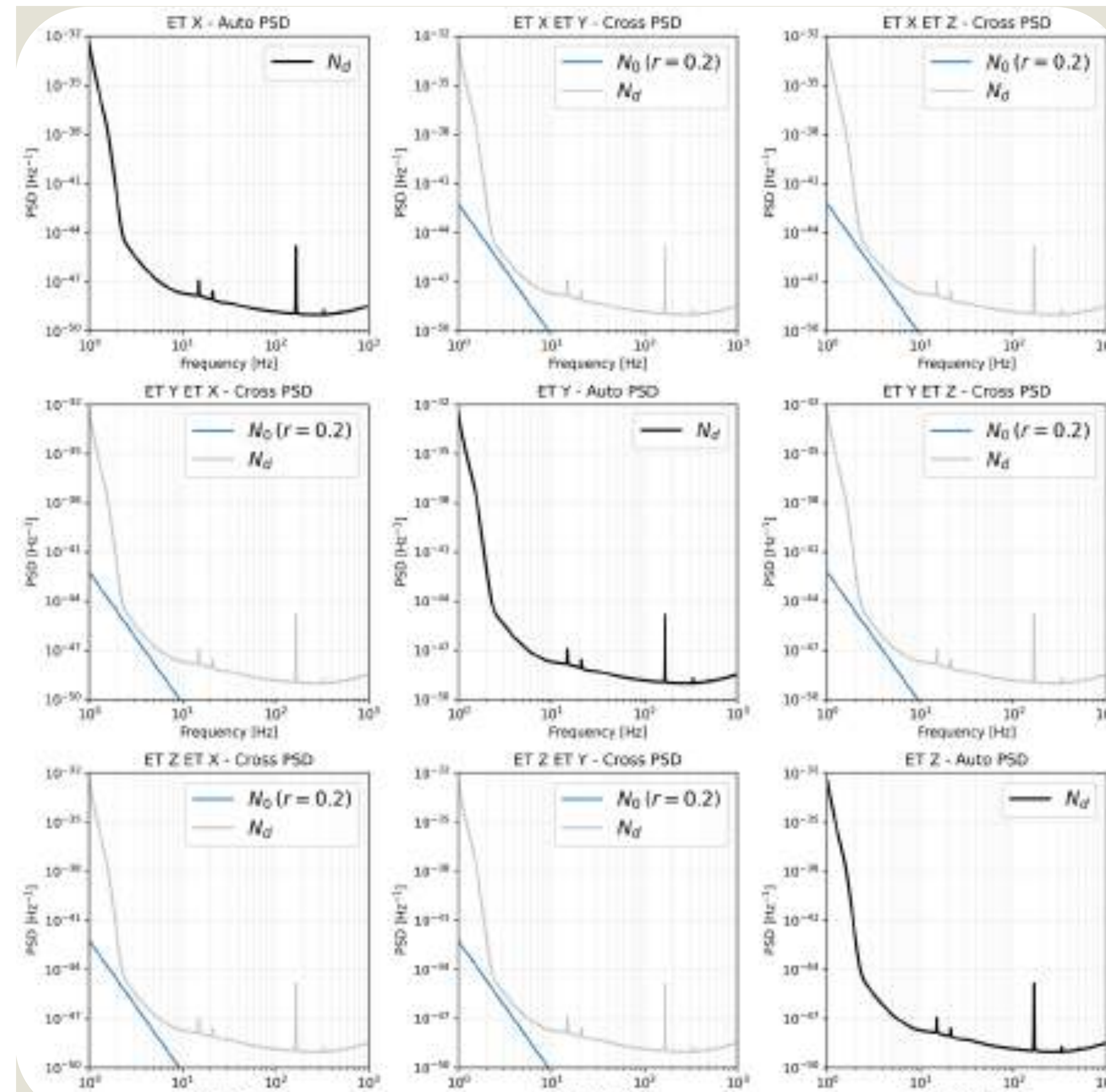

[I.Caporali, A. Ricciardone to appear]

# Noise Covariance Triangular configuration

$$\langle \tilde{n}_I(f)\tilde{n}_J^*(f')\rangle \equiv \frac{\delta(f-f')}{2} N_{IJ}(f)$$

$$N_{IJ}(f) \equiv \begin{pmatrix} N_d(f) & N_o(f) & N_o(f) \\ N_o(f) & N_d(f) & N_o(f) \\ N_o(f) & N_o(f) & N_d(f) \end{pmatrix}$$

$$-1/2 \leq N_o(f)/N_d(f) \leq 1$$




**Correlated noise template**

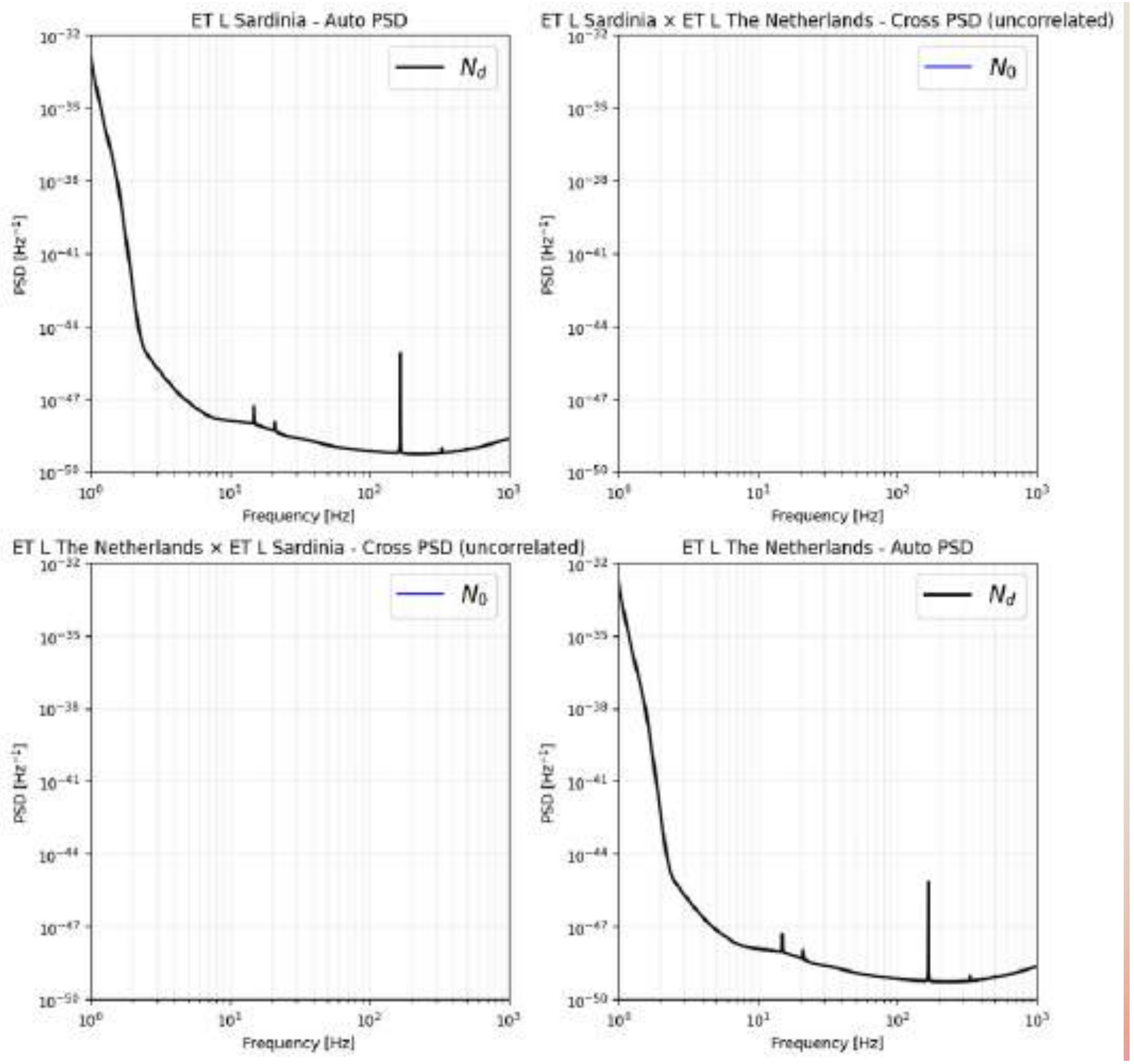
$$N_o(f) = N_d(2.75\,\mathrm{Hz})\, r \left(\frac{f}{2.75\,\mathrm{Hz}}\right)^{n_{\mathrm{noise}}}$$

# Noise Covariance 2L config

$$\langle \tilde{n}_I(f)\tilde{n}^*_J(f')\rangle \equiv \frac{\delta(f-f')}{2} N_{IJ}(f)$$

$$N_{IJ}(f) \equiv \begin{pmatrix} N(f) & 0 \\ 0 & N(f) \end{pmatrix}$$

Neglecting correlated magnetic noise



# Likelihood for correlated and uncorrelated configurations

We introduce a time-averaged **estimator** of a **quadratic combination of the data**

$$\hat{C}_{IJ}(f) \equiv \sum_t \frac{2}{T_{\rm obs} S_0(f)} \Re[\tilde{s}_I(t,f)\tilde{s}_J^*(t,f)]$$

[Abbott et al. 1903.02886]
[Abbott et al. 2101.12130]

$t$ = time segments

$T_{\rm seg} = 4s$

$T_{\rm obs} = 1 \rm day$

$$S_0(f) = \frac{3H_0^2}{10\pi^2 f^3}$$

Averaging over many time segments allows us to treat the estimator of the SGWB as a **Gaussian random variable**, due to the central limit theorem

# Likelihood for correlated and uncorrelated configurations

Average of the estimator

$$\bar{C}_{IJ}(f) \equiv \left\langle \hat{C}_{IJ}(f) \right\rangle = \gamma_{IJ}(f)\Omega_{\rm GW}(f) + \frac{N_{IJ}(f)}{S_0(f)}$$

Covariance of estimator

$$\Sigma_{IJ}(f) \equiv \left\langle \left[\hat{C}_{IJ}(f) - \bar{C}_{IJ}(f)\right]^2 \right\rangle = \frac{\bar{C}_{II}\bar{C}_{JJ} + \bar{C}^2_{IJ}}{2N_{\rm seg}}$$

# (Gaussian) Likelihood

$$\mathcal{L} = \prod_{I,J} \frac{1}{\sqrt{2\pi\Sigma_{IJ}}} \exp\left[-\frac{1}{2}\frac{(\hat{C}_{IJ} - \bar{C}_{IJ})^2}{\Sigma_{IJ}}\right]$$

Triangular Configuration
(XYZ to the AET basis)
(I, J) = {(A,A), (E,E)}

2L Configuration

(I, J) = (ET1, ET2)

# SGWB Data Generation

**Noise and SGWB in different time segments are sampled from Nseg independent Gaussian distributions.**

**Data in different channels are correlated, implying they are generated from a multivariate Gaussian distribution.**

**Signal**

$$h_{\rm ampl}(f) = \sqrt{\frac{T_{obs}}{2}\frac{3H_0^2}{10\pi^2 f^3}\Omega_{\rm GW}(f)\gamma_{ij}(f)}$$

$$h(f) = h_{\rm ampl}\left(\mathcal{N}(0,1/\sqrt{2}) + i\mathcal{N}(0,1/\sqrt{2})\right)$$

**Noise**

$$n_{\rm ampl}(f) = \sqrt{\frac{T_{obs}}{2}N_{ij}(f)}$$

$$n(f) = n_{\rm ampl}\left(\mathcal{N}(0,1/\sqrt{2}) + i\mathcal{N}(0,1/\sqrt{2})\right)$$

**Data stream**

$$s(f) = h(f) + n(f)$$

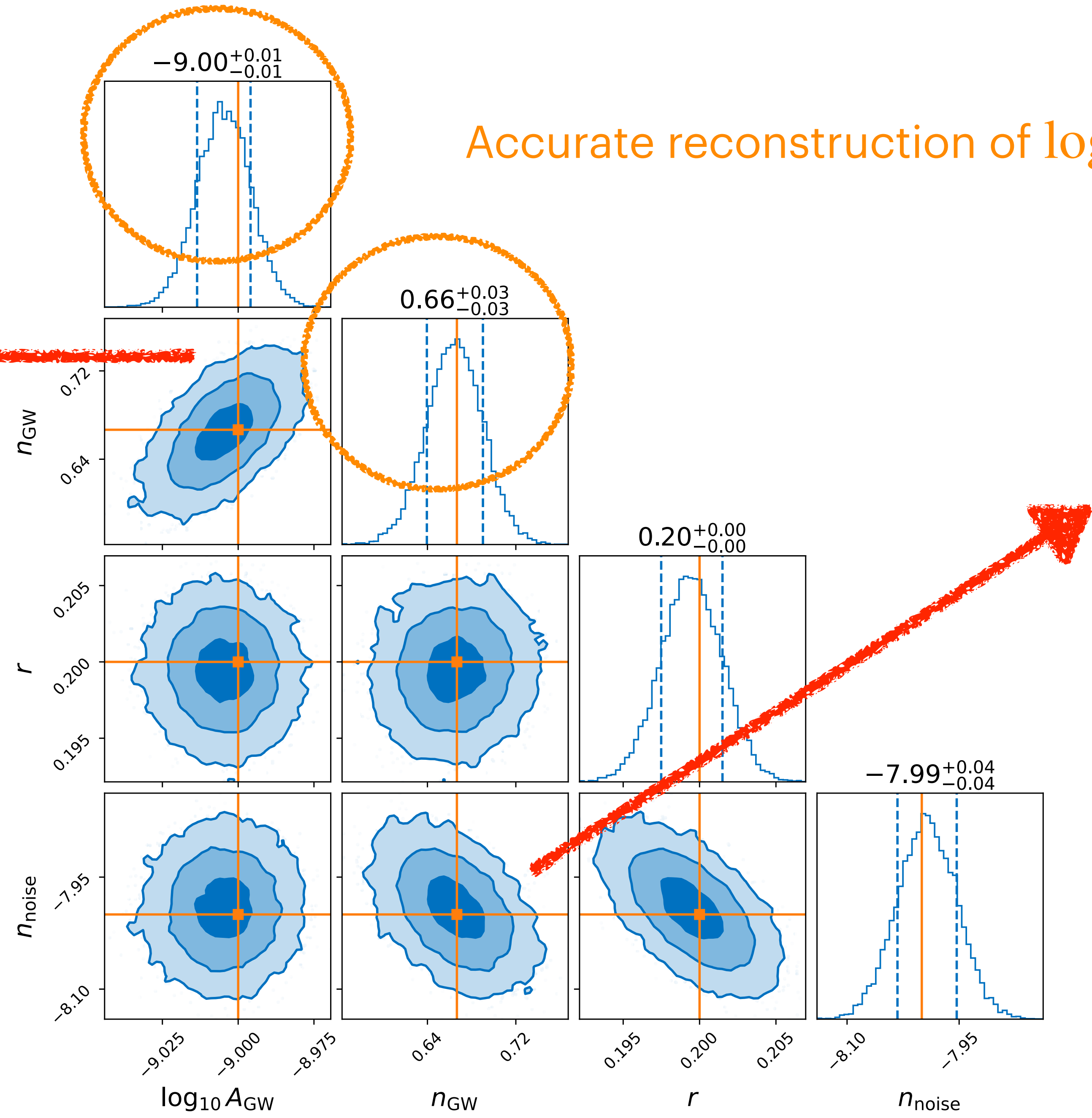
Assuming that resolved sources are perfectly subtracted and neglecting time-frequency induced correlation

# PE Outcomes

We implement our likelihood in **Bilby** and reconstruct the posterior using the **Dynesty** sampler

**Positive correlation**

Since the chosen pivot frequency for the SGWB, 25 Hz, is higher than the frequencies at which ET is most sensitive to the SGWB (~10 Hz), a larger retrieved value of $n_{\rm GW}$ requires a larger value of $\log_{10} A_{\rm GW}$ to fit the injected signal




Accurate reconstruction of $\log_{10} A_{\rm GW}$ and $n_{\rm GW}$

**Negative correlation**

Larger values of $n_{\rm GW}$ mean less power at low frequencies, which requires a smaller (i.e., more negative) $n_{\rm noise}$ to balance and fit the injected signal

Injected parameters:

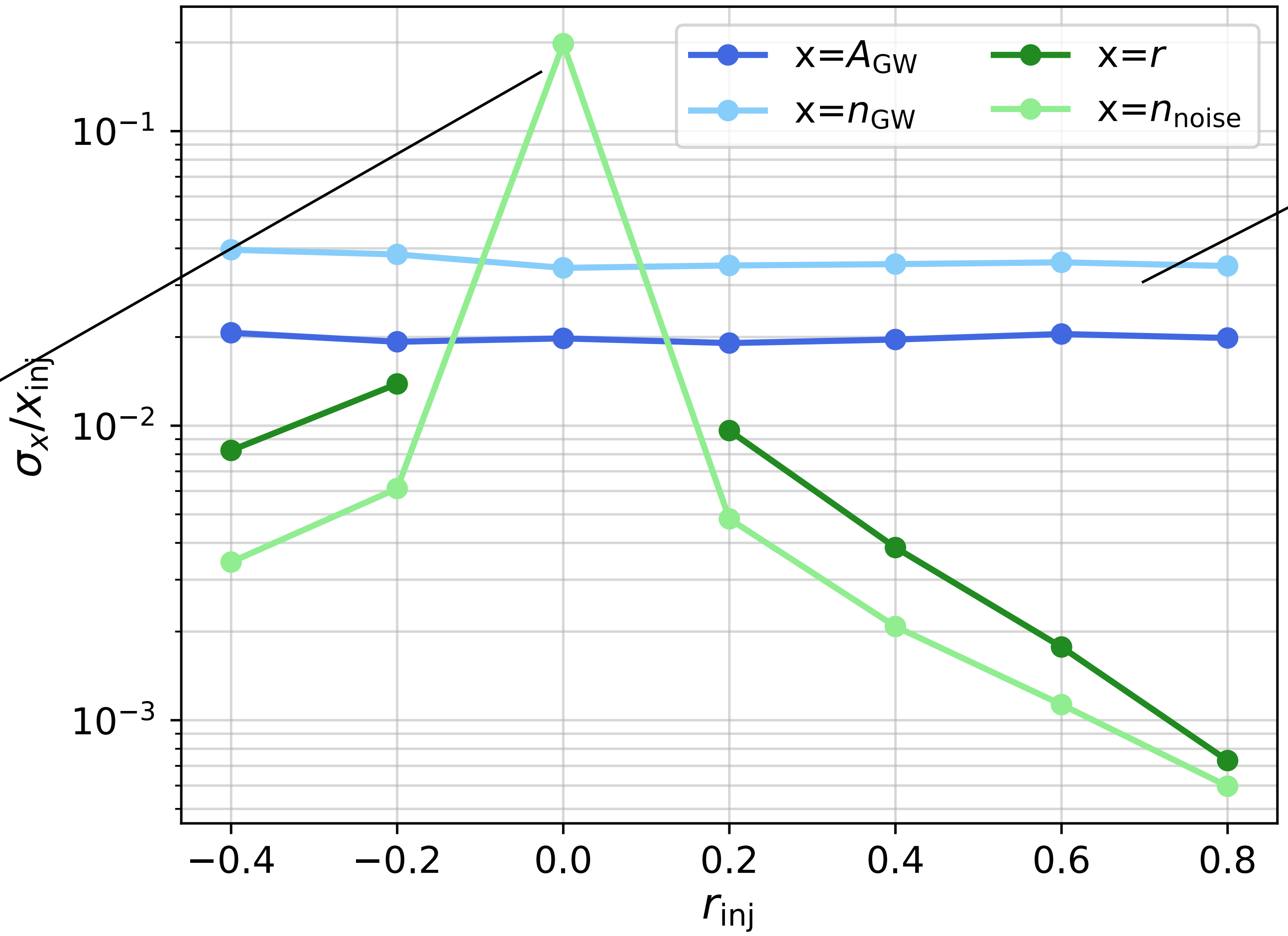
- $\log_{10} A_{\rm GW} = -9$
- $n_{\rm GW} = 2/3$
- $r = 0.2$
- $n_{\rm noise} = -8$

# PE Accuracy

## **Accurate reconstruction** of the SGWB

(Having a model for the noise)

noise parameters become less accurately reconstructed as $r_{\rm inj}$ approaches 0



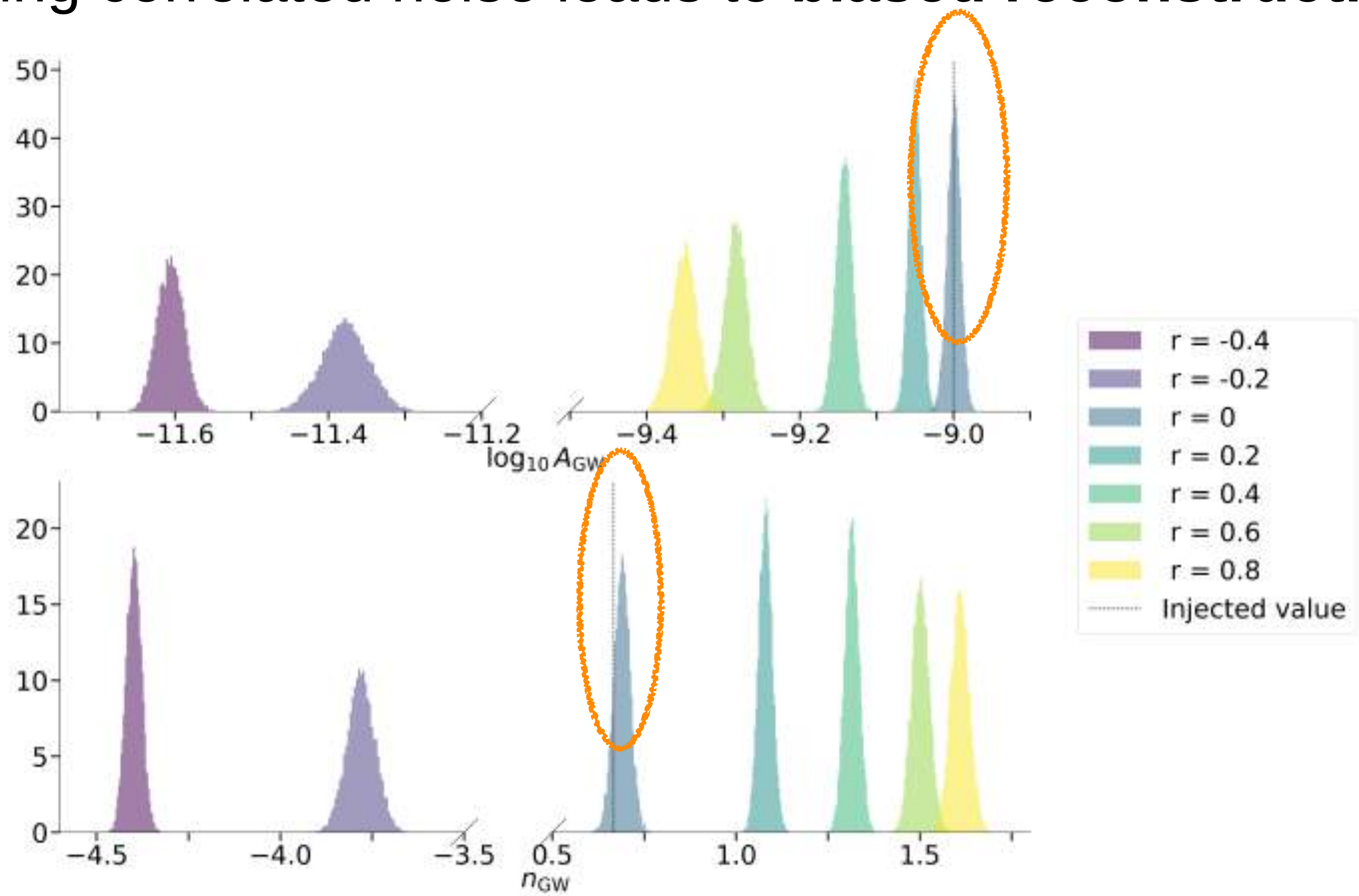

the errors on the SGWB parameters remain stable across this range

**Main message: correlated noise with smaller power is inherently harder to reconstruct.**

(To be tested also with noise agnostic searches)

# PE Biased Results

Neglecting correlated noise leads to **biased reconstruction**




The injected parameters are **correctly retrieved** only for $r_{inj} = 0$, since there is **no correlated noise** in this case and the likelihood that neglects it is accurate.

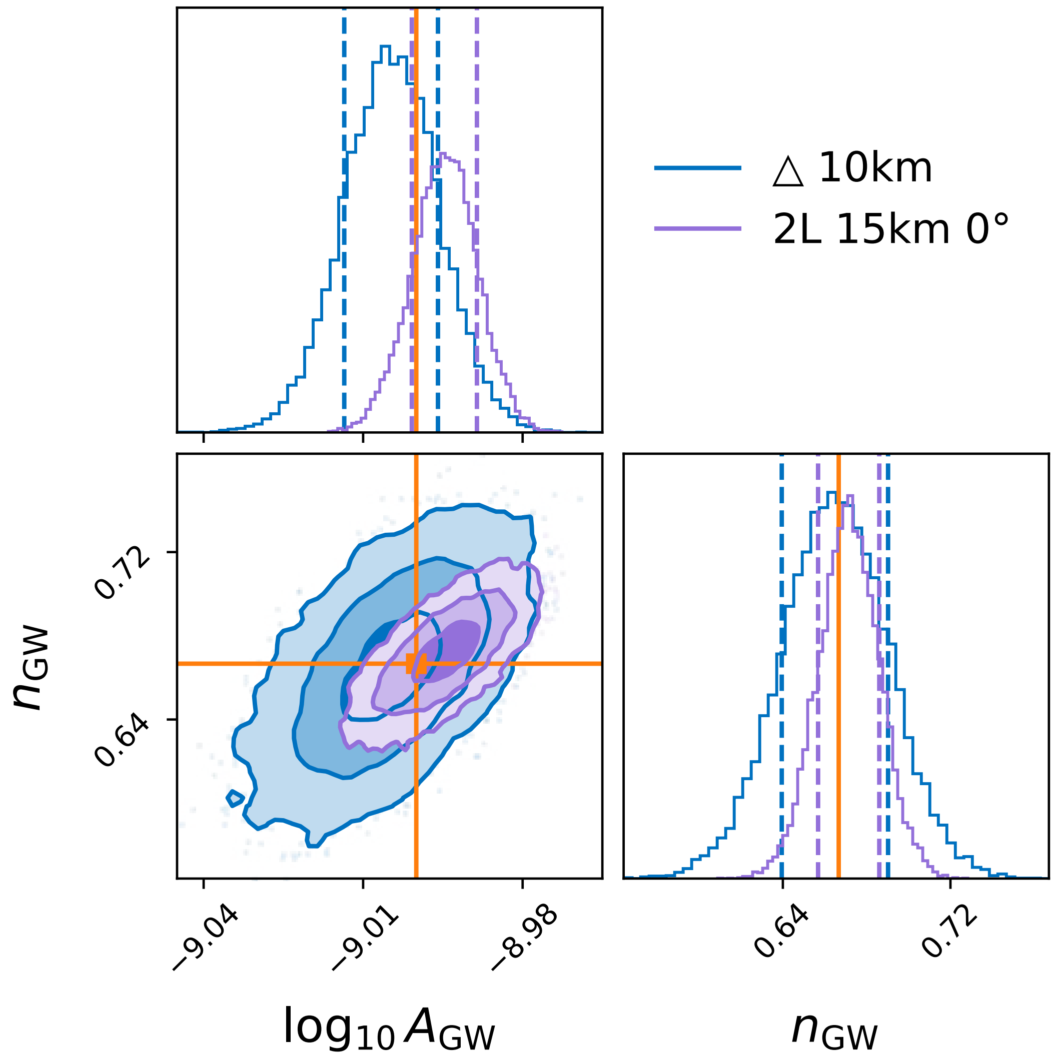


The presence of **correlated noise** completely disrupts the signal interpretation when using the incorrect likelihood that does not account for it

# Triangle vs 2L performance

Triangular configuration is **competitive** to the 2L

(If noise is properly modeled)

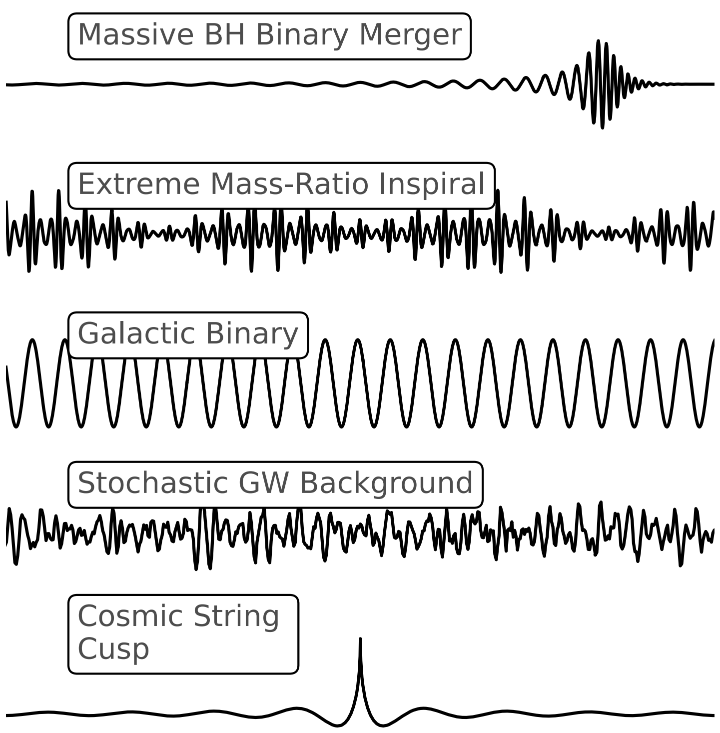


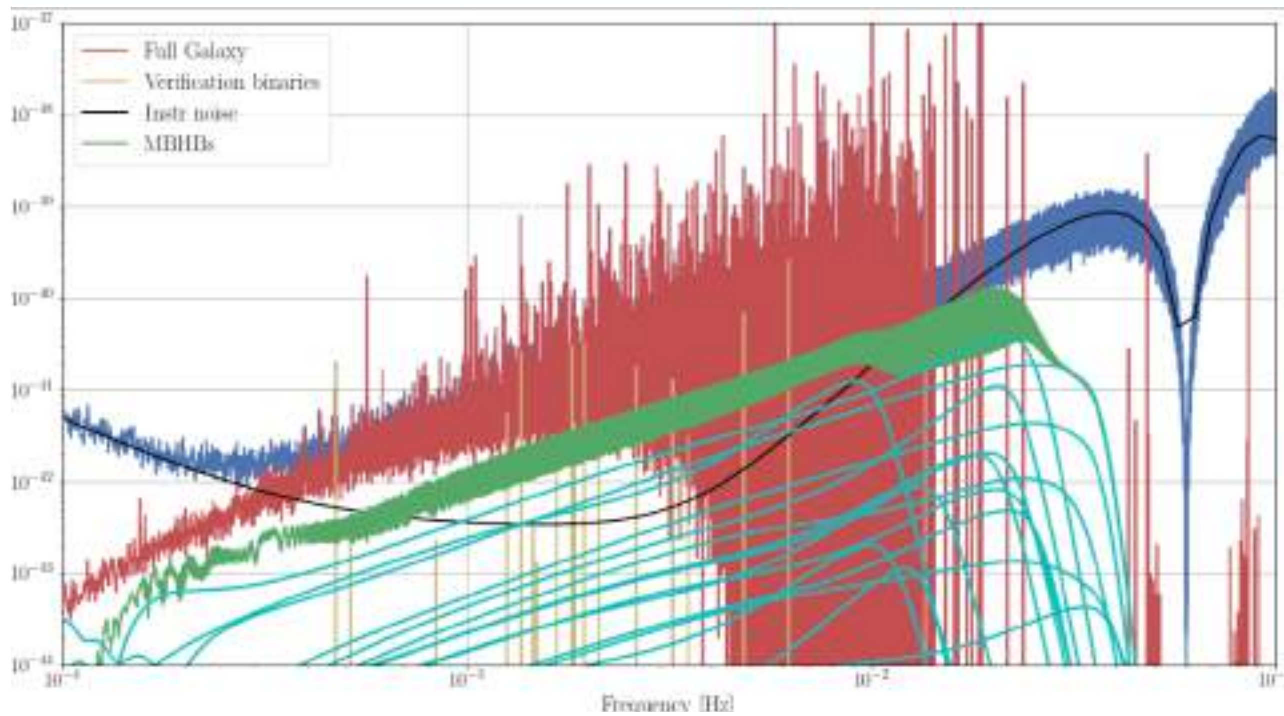

Why the 2L performs slightly better?



Mainly because the **15 km arms** of the 2L **provide better sensitivity** to the SGWB compared to the triangle with **10 km arms**.

# How to approach the data analysis - Global Fit




- 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**

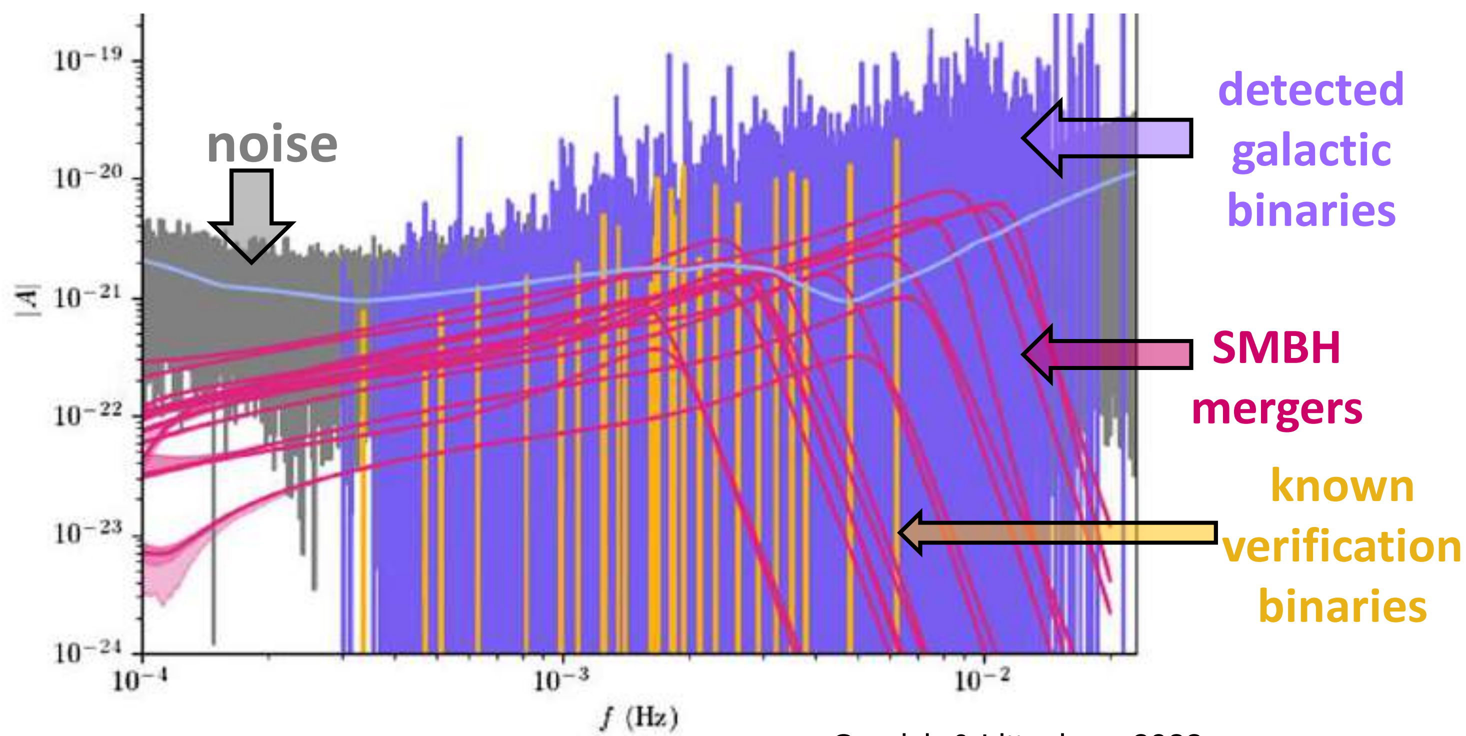
**Pisa node**

(Similar approach for ET)

Cornish, Littenberg, 23

Marsat+,24

Katz, Karnesis et al, '23




Cornish & Littenberg 2023

# 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 **constrain cosmological parameters.**
- **Importance of including all detector layout effect in SGWB parameter estimation**
- **A lot of cosmological expertise in this community to push forward on GW topics**

# Thank you!