Stochastic Gravitational Wave Backgrounds

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2nd EuCAPT Symposium - Zoom

Where we are

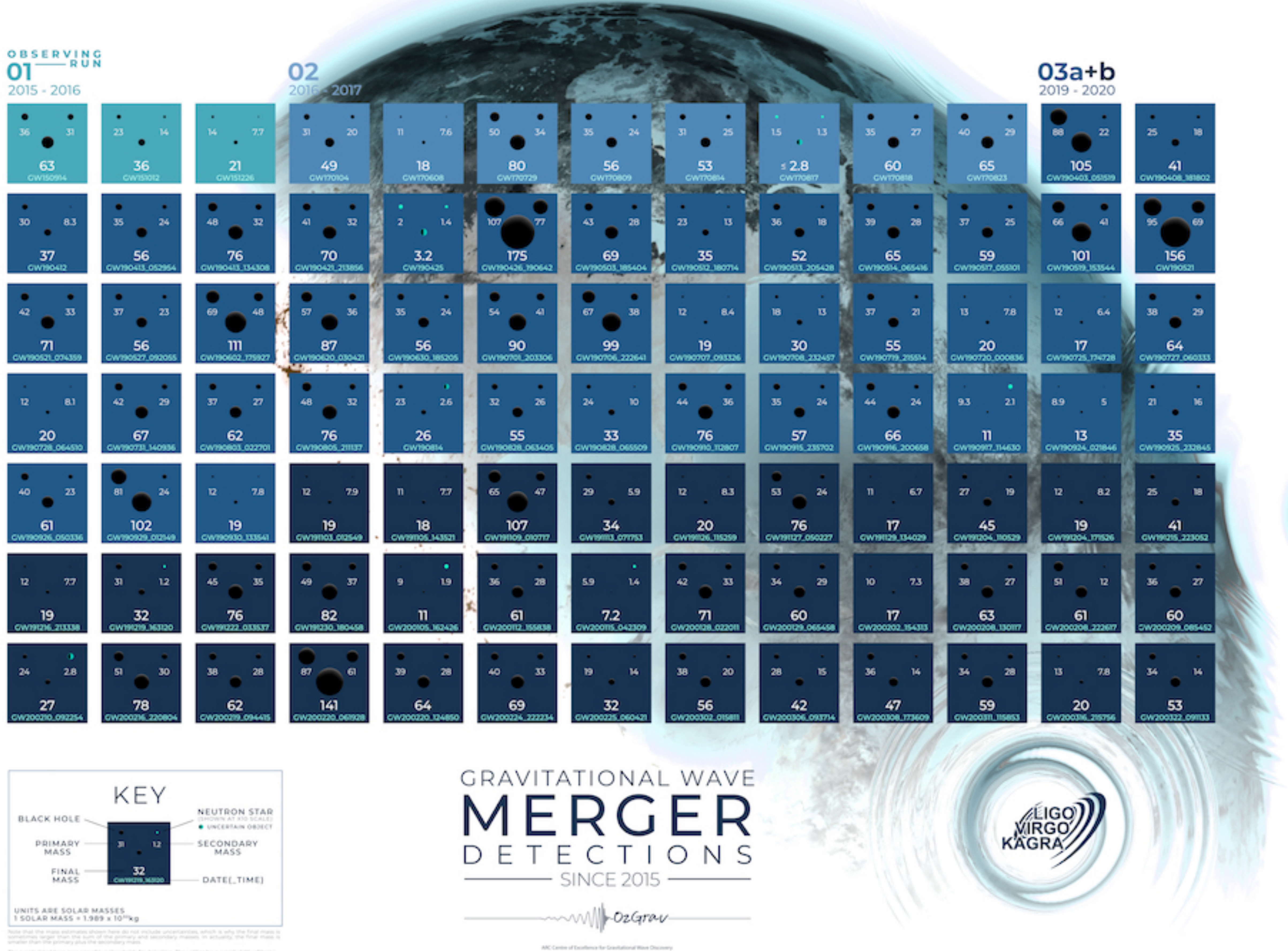


Image credit: LIGO / Virgo / KAGRA / C. Knox / H. Middleton

Where we are

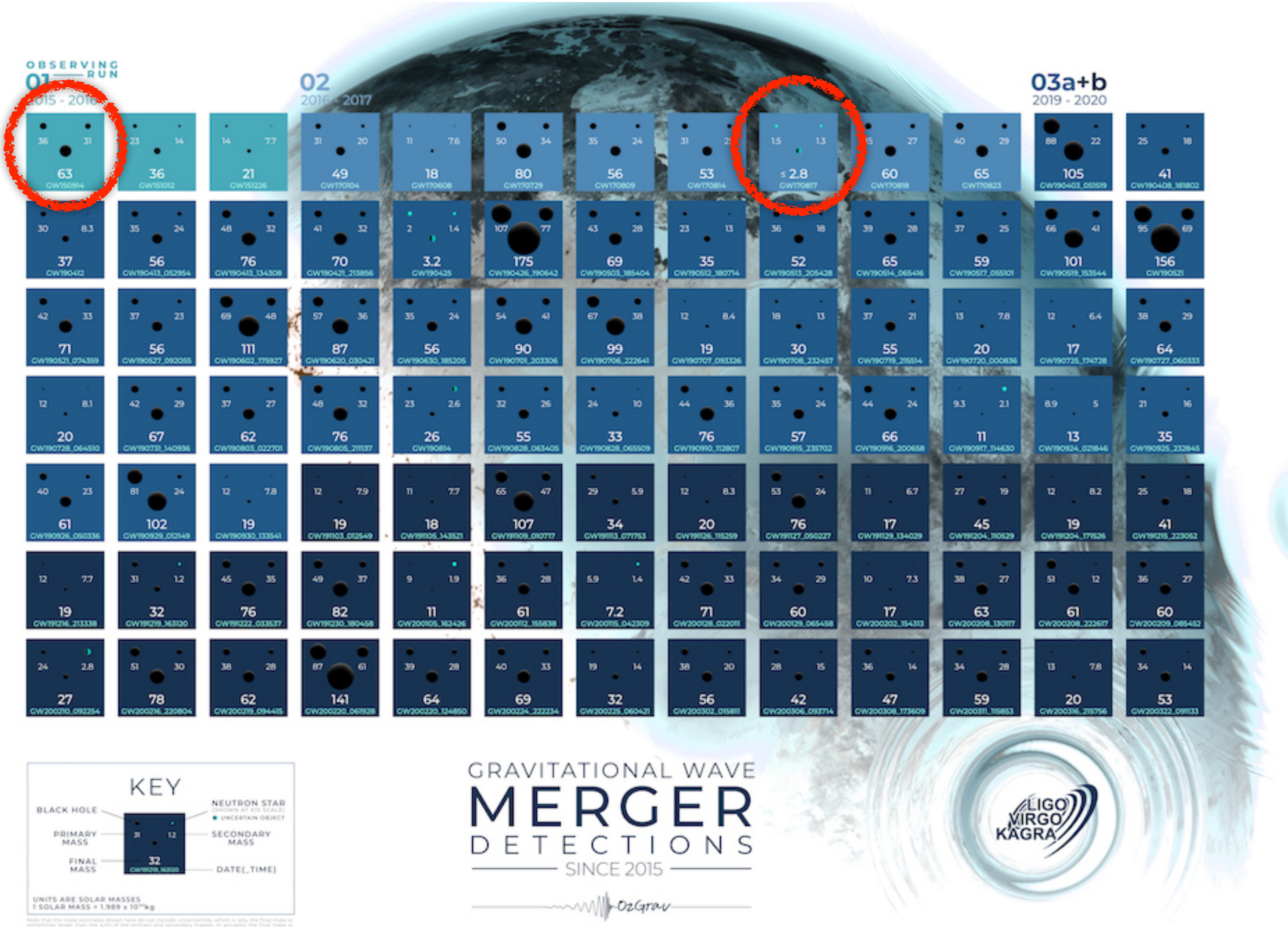
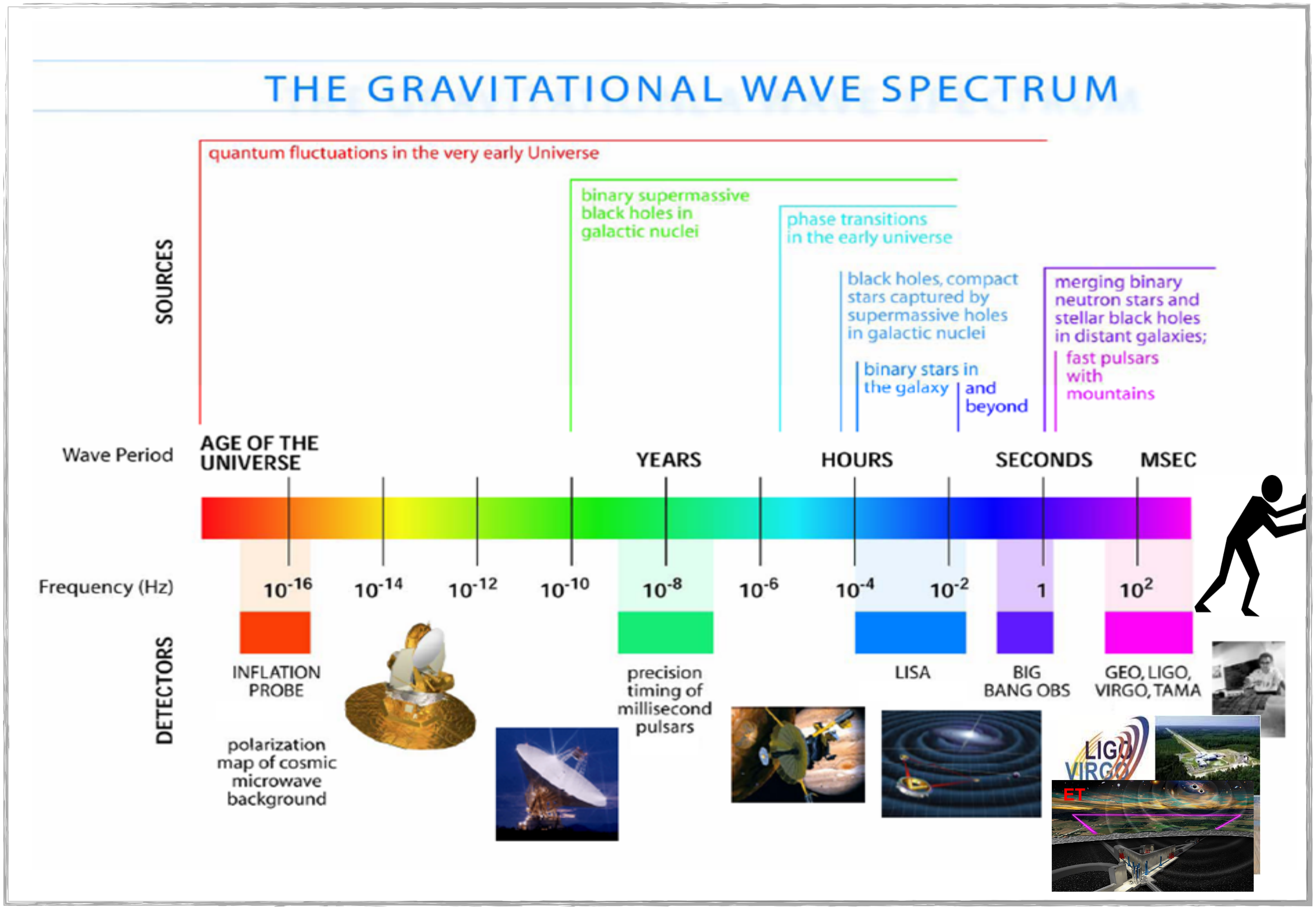


Image credit: LIGO / Virgo / KAGRA / C. Knox / H. Middleton

The Gravitational Wave Spectrum



What is a Stochastic Gravitational Wave Background (SGWB)

A SGWB is, by definition, made up of an incoherent superposition of signals from sources that are unresolved in both the time and angular domain

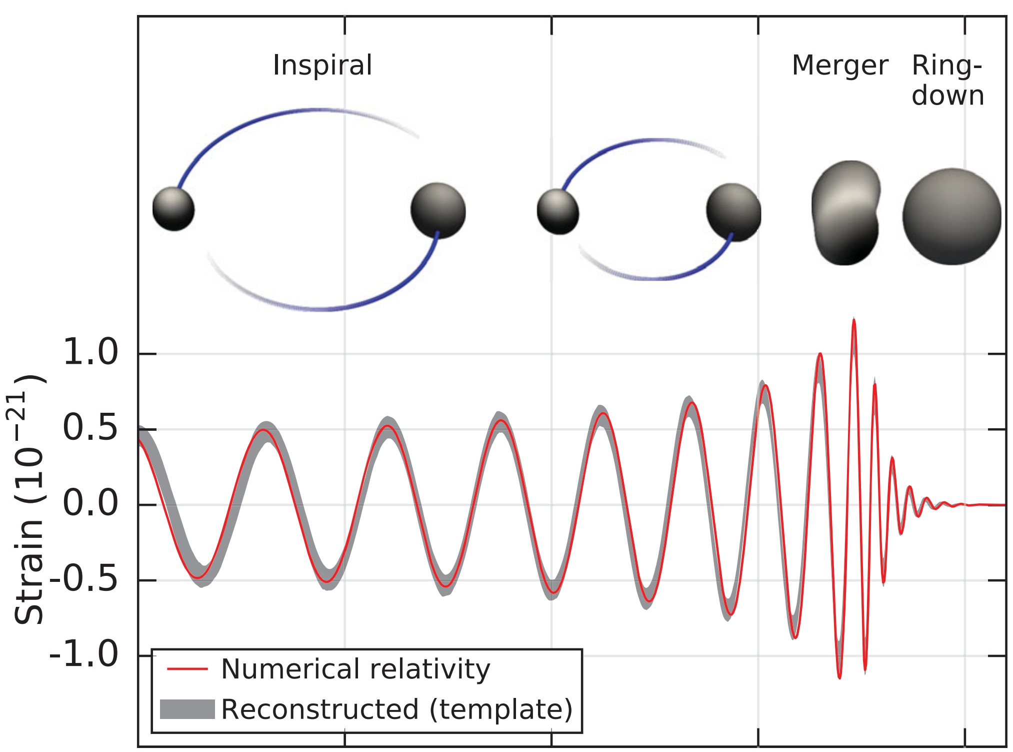
Resolved Sources:

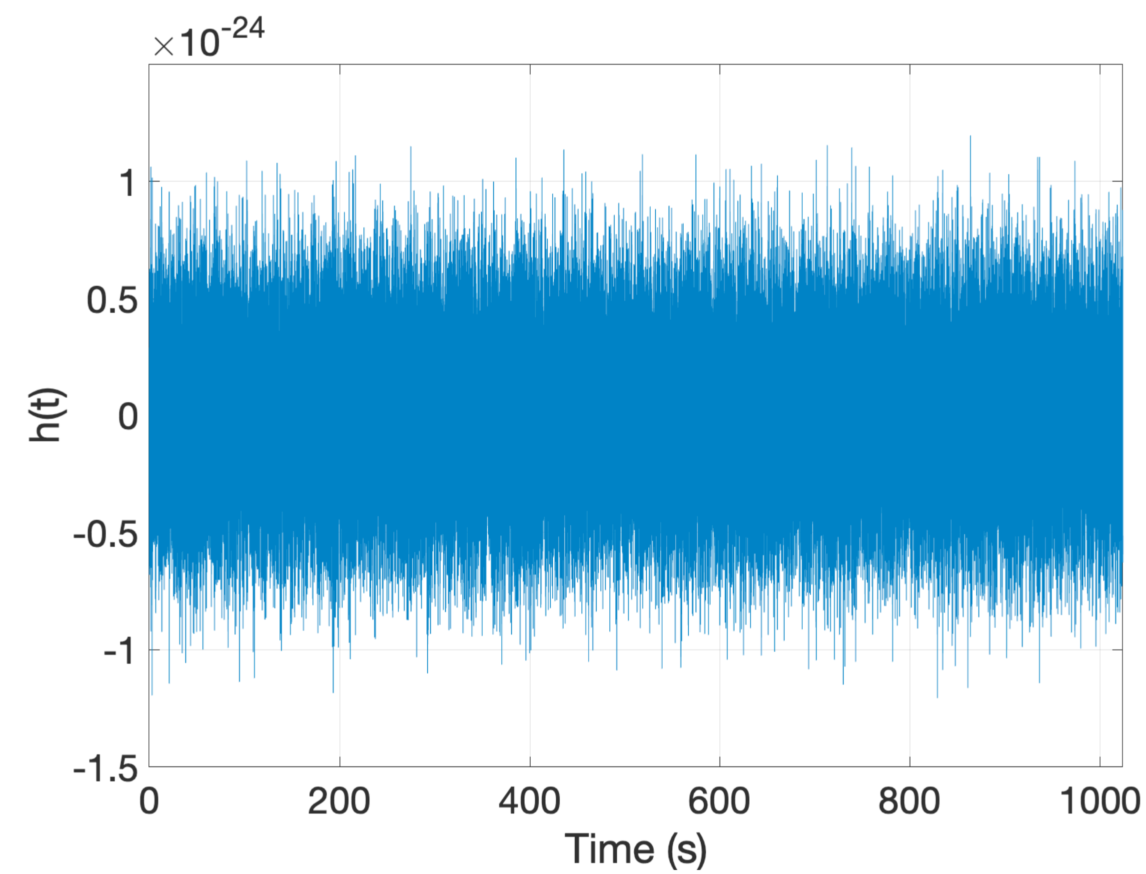
- Black Holes
- Neutron Stars
- White Dwarfs
- Supernovae
- …

Unresolved Sources:

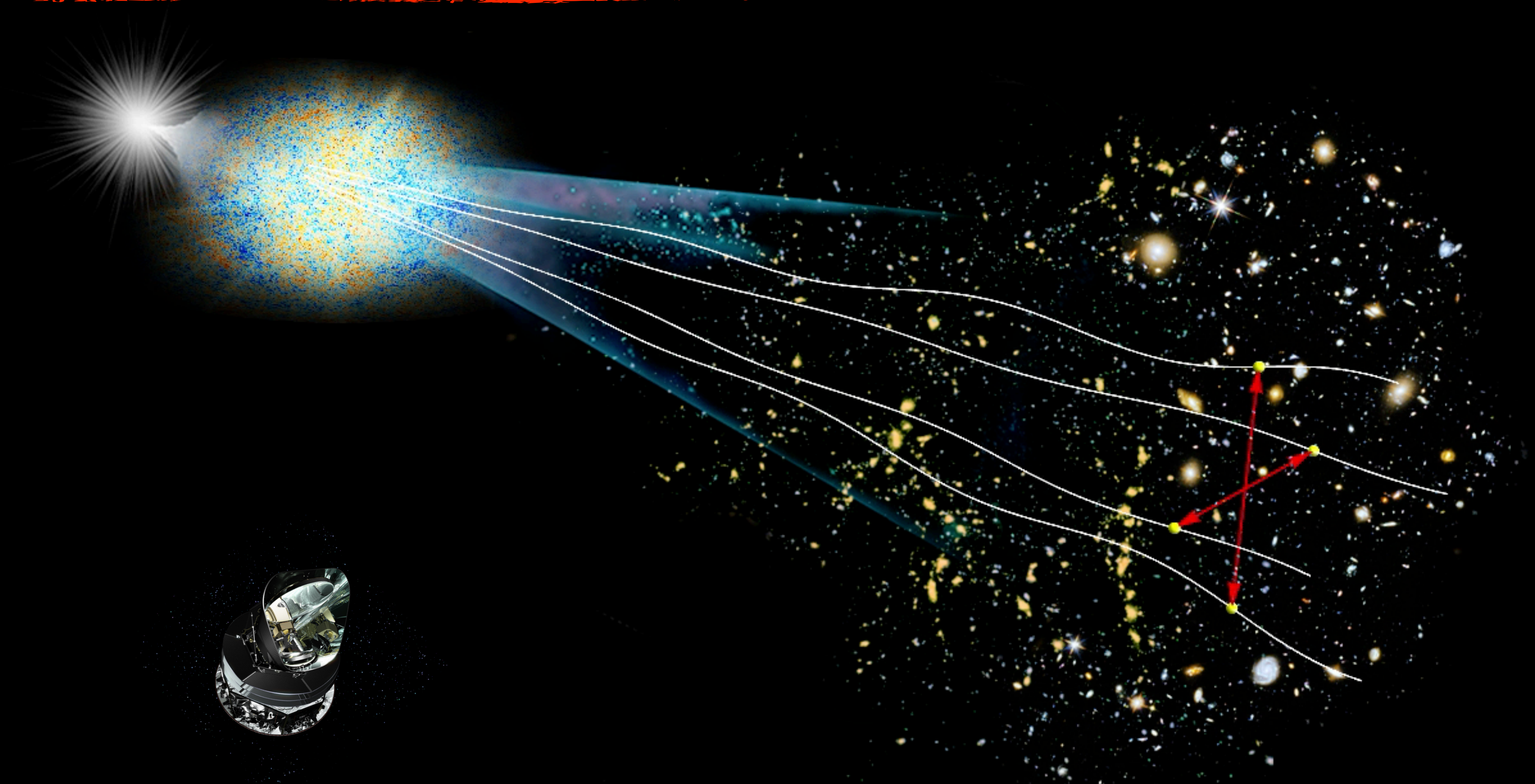
Stochastic Backgrounds

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





"Indirect" vs Direct GW detection



Polarization of CMB photons through Thomson scattering of electron and photon

Only Tensor perturbations can source B-mode

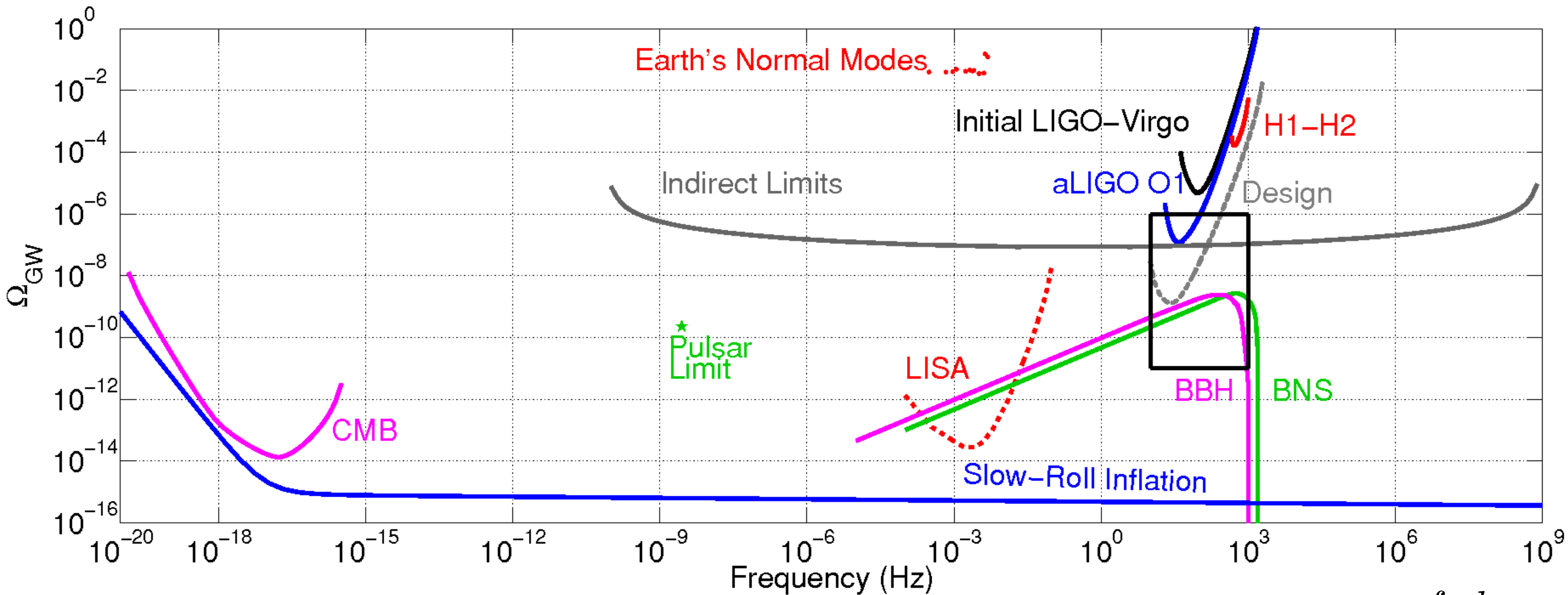
Poor and contaminated signal:

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

Distortion of space as GW passes detector arms

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

LVC bounds on the AGWB



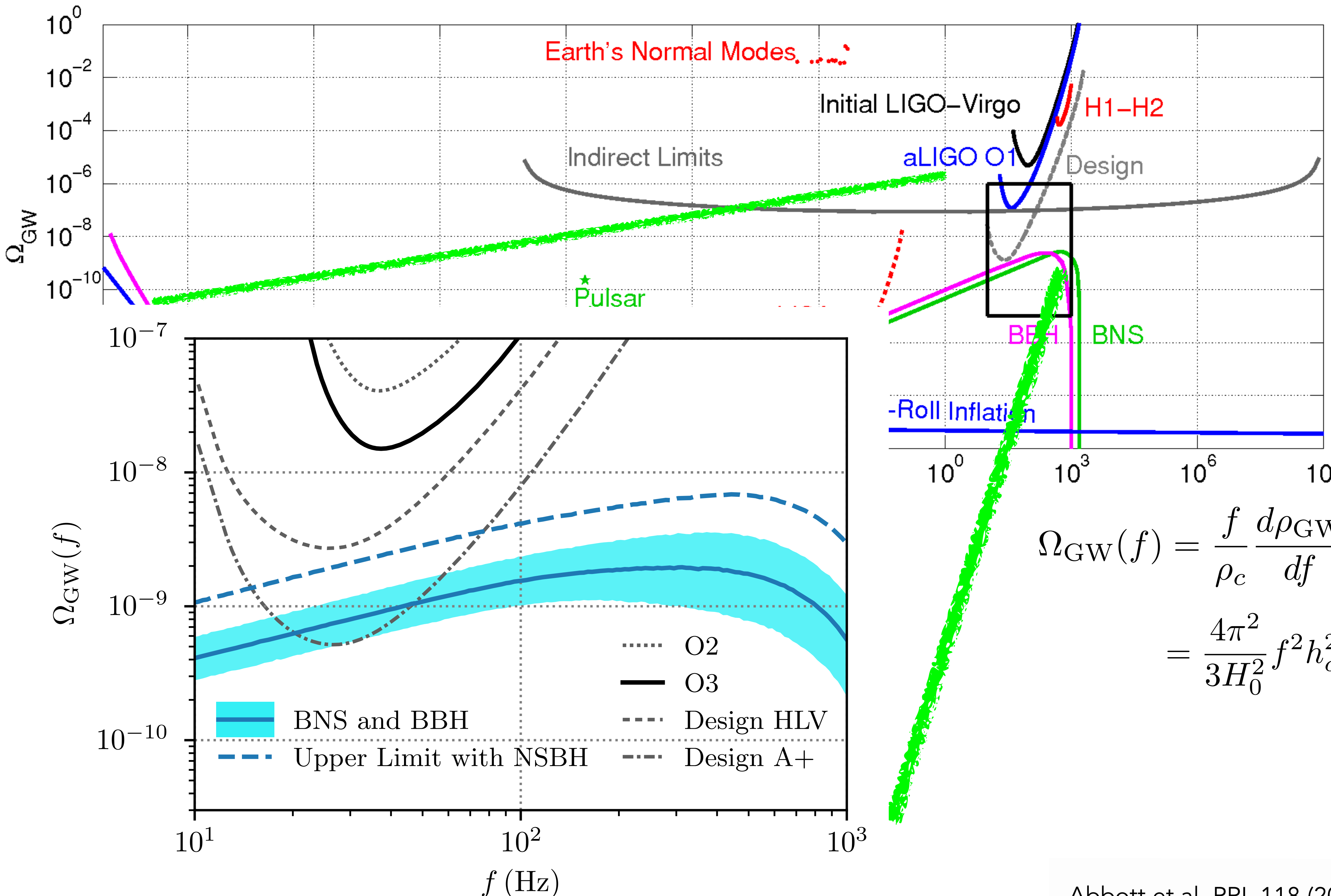
$$\Omega_{\mathrm{GW}}(f) = \frac{f}{\rho_c}\frac{d\rho_{\mathrm{GW}}}{df}$$

$$= \frac{4\pi^2}{3H_0^2} f^2 h_c^2(f)$$

Abbott et al, PRL 118 (2017) 121101

Abbott et al., PRD' 2021

LVC bounds on the AGWB



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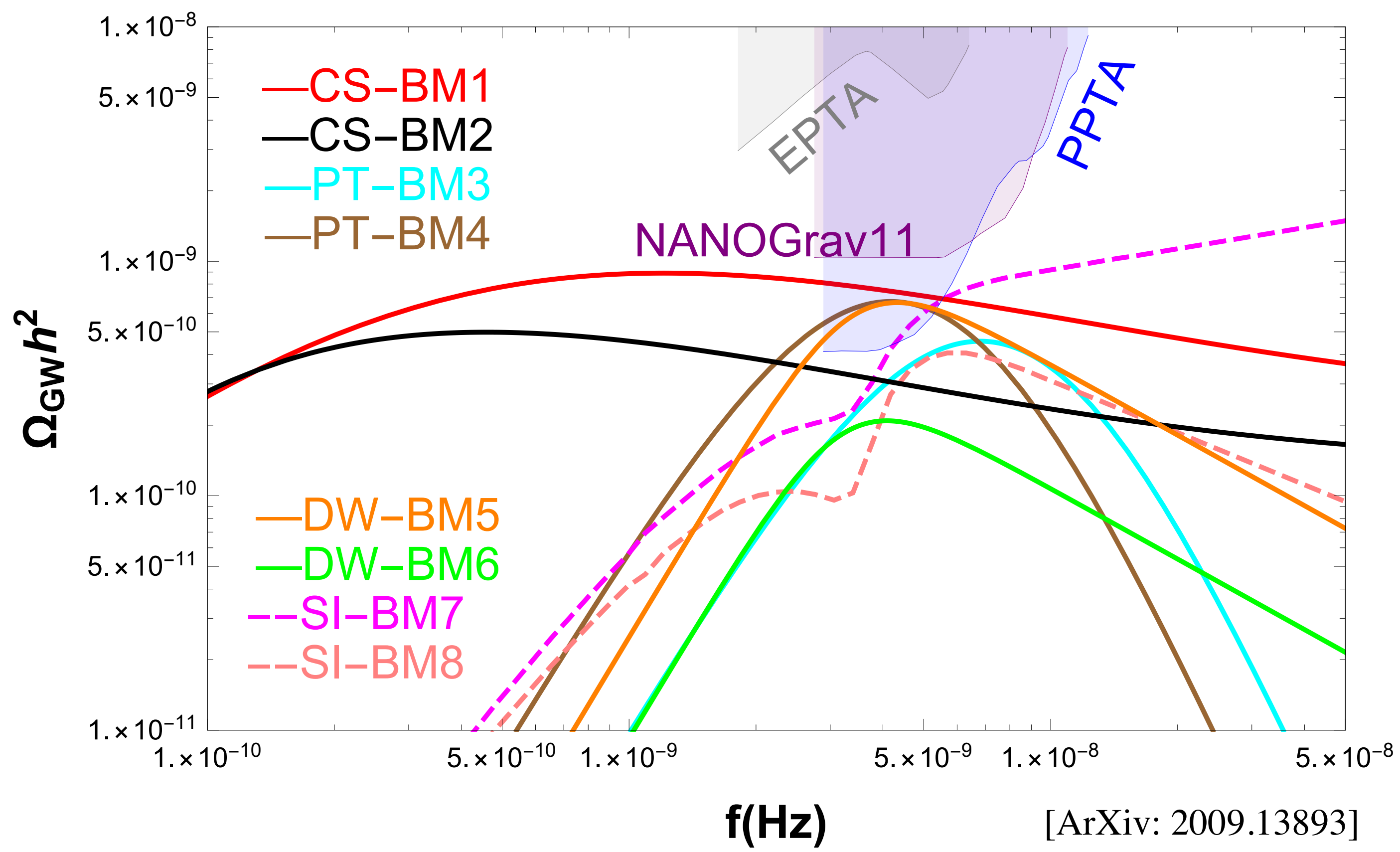
Abbott et al, PRL 118 (2017) 121101

Abbott et al., PRD' 2021

NANOGrav SGWB detection?

From S. Chen's talk

The NANOGrav collaboration found strong evidence in the 12.5 yr data set of a stochastic process that has a common amplitude and spectral slope across the 45 millisecond pulsars!



[ArXiv: 2009.13893]

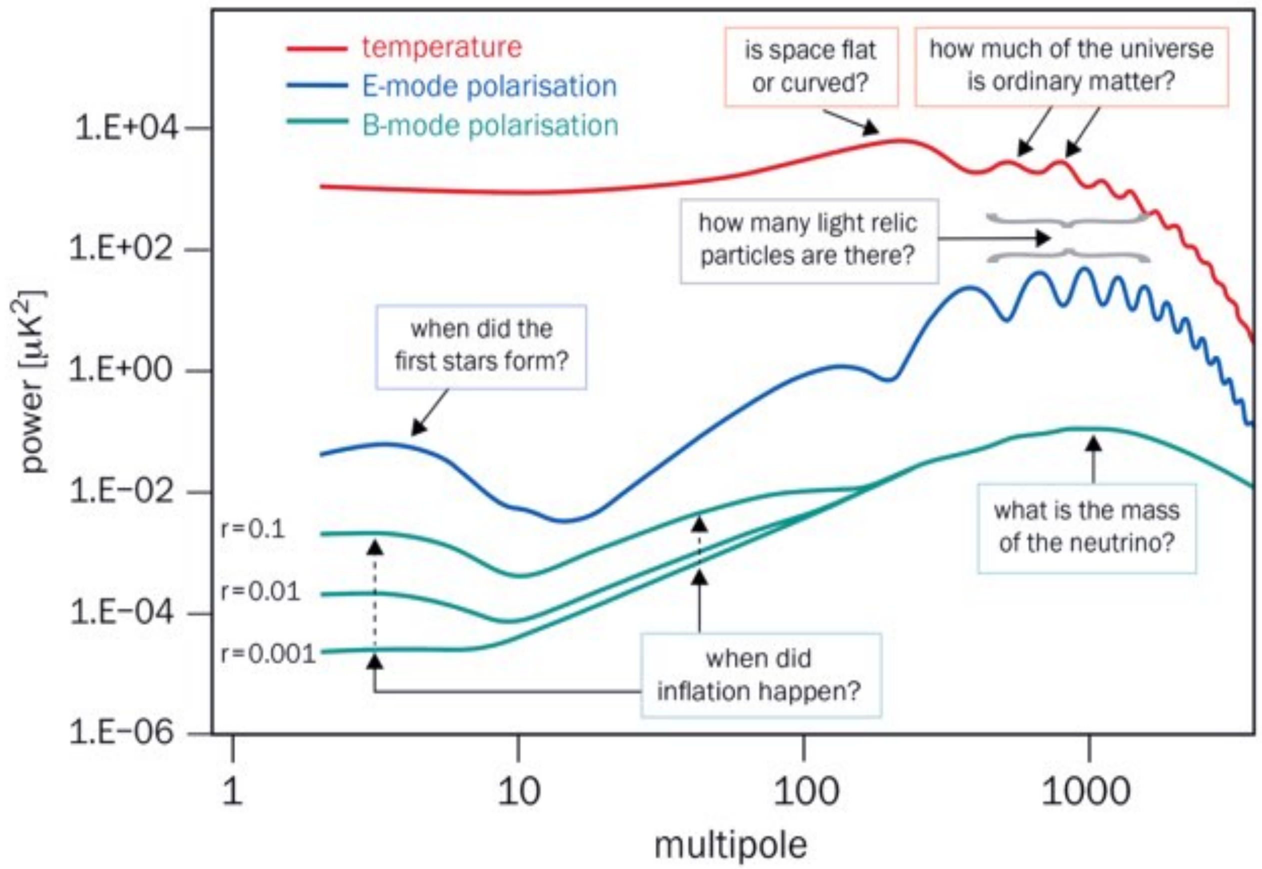
Consistent with signal from Super Massive Black Hole binaries

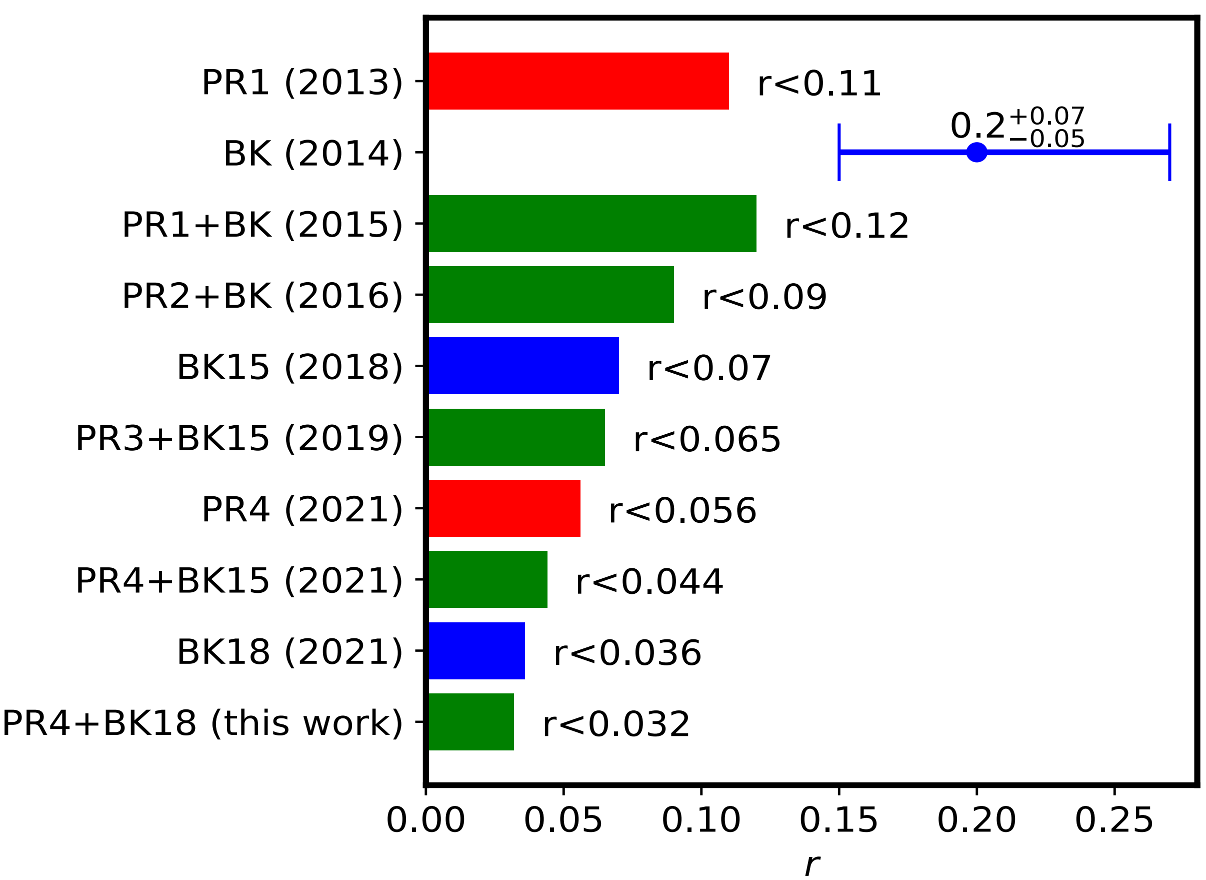
Consistent with cosmological signals (Primordial Black Holes, Cosmic Strings, Phase Transition…)

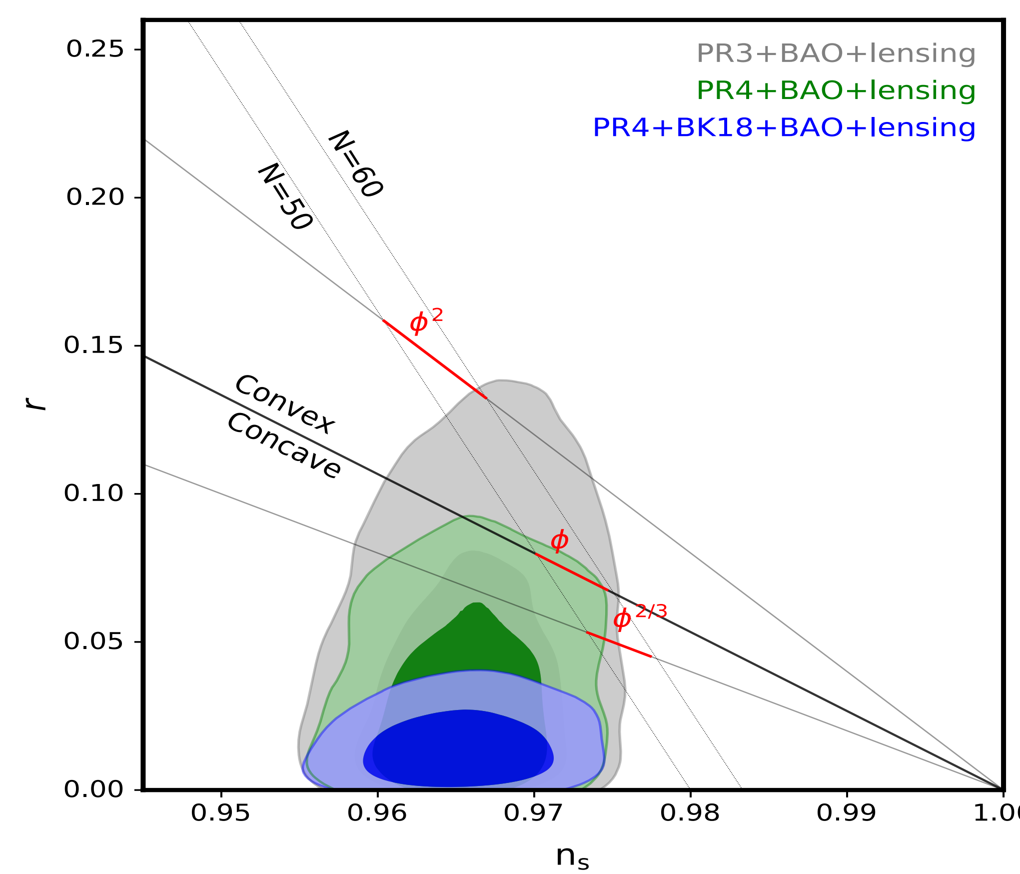
e.g. De Luca V., et al., 2021; Vaskonen & Veermäe, 2021; Ellis & Lewicki, 2021; Blasi et al.,2021; Addazi et al.,2020; Nakai et al., 2021; Benetti M. et al., 2021; Ratzinger & Schwaller 2021; Buchmuller et al., 2021;

Looking forward for the quadrupolar spatial correlations (Hellings-Downs) predicted by General Relativity and necessary to claim a SGWB detection.

GW from Cosmic Microwave Background





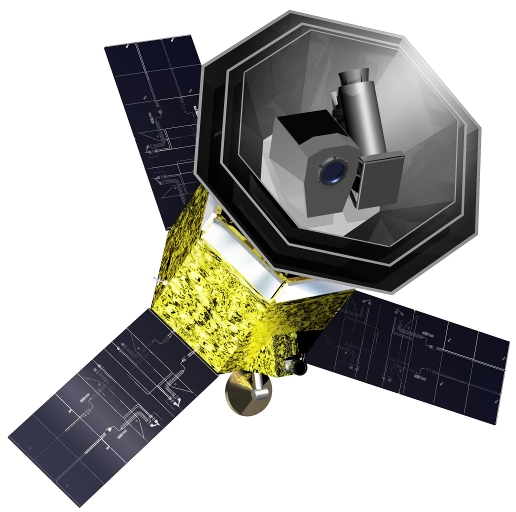


[Tristram et al., 2021]

What come next?

Future B-mode Experiments

LiteBIRD



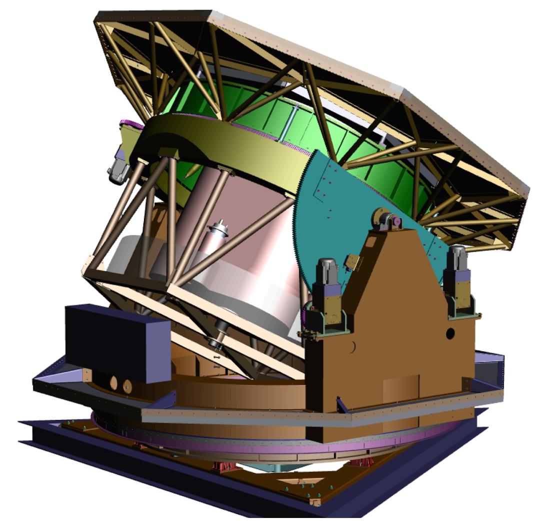
Satellite mission

~ 2028

Full sky (60%)

$\ell \sim 2 - 1000$

CMB-S4



Ground-based

~ 2028

Sky fraction 3%

$\ell \sim 30 - 4000$

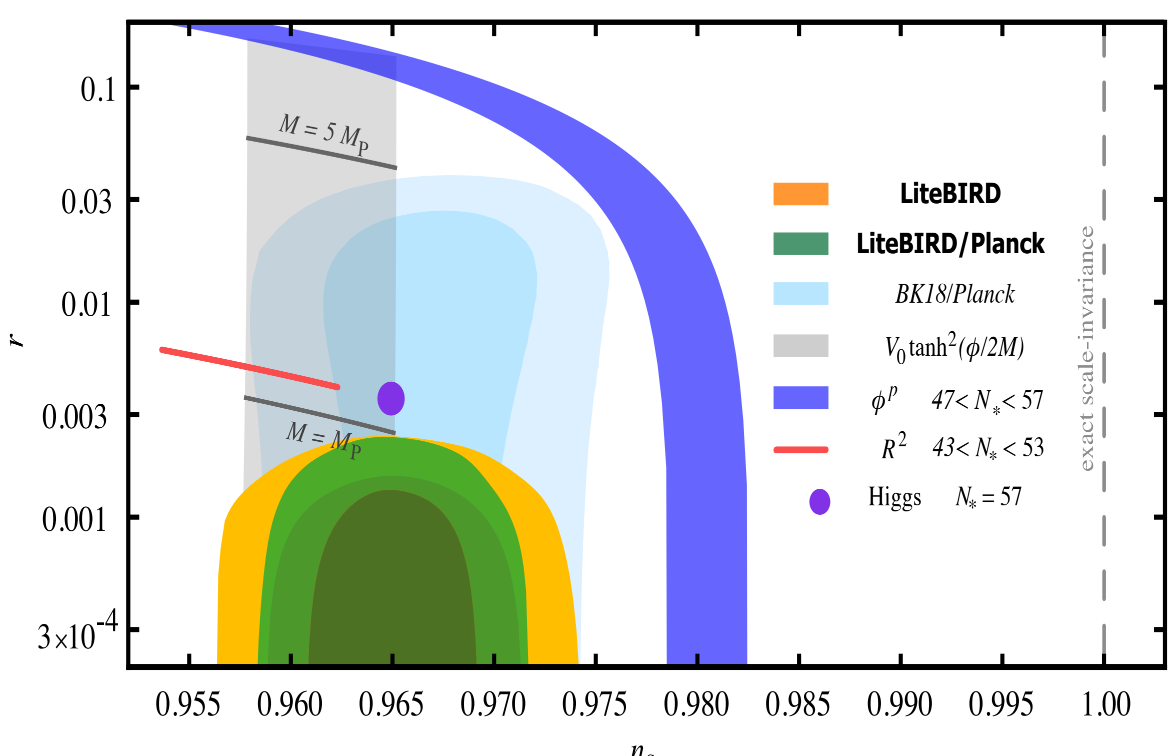
Simons Observatory

Ground-based

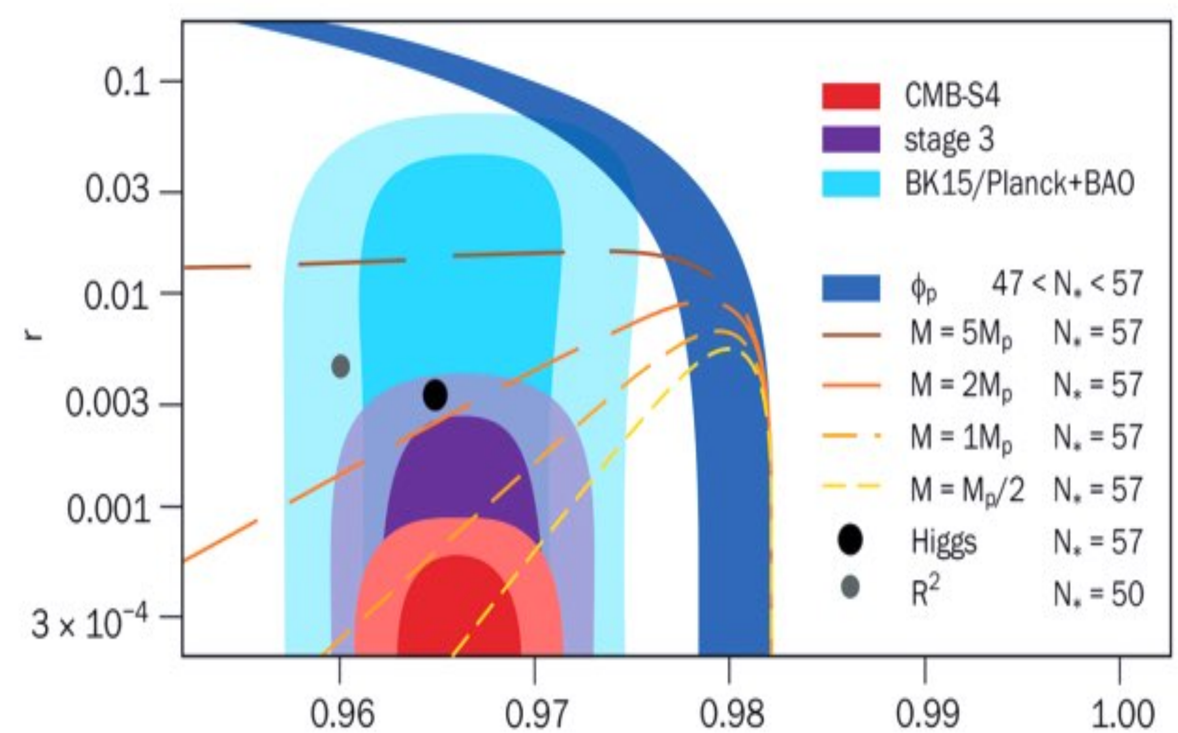
~ 2022

Sky fraction 10%

$\ell \sim 30 - 4000$

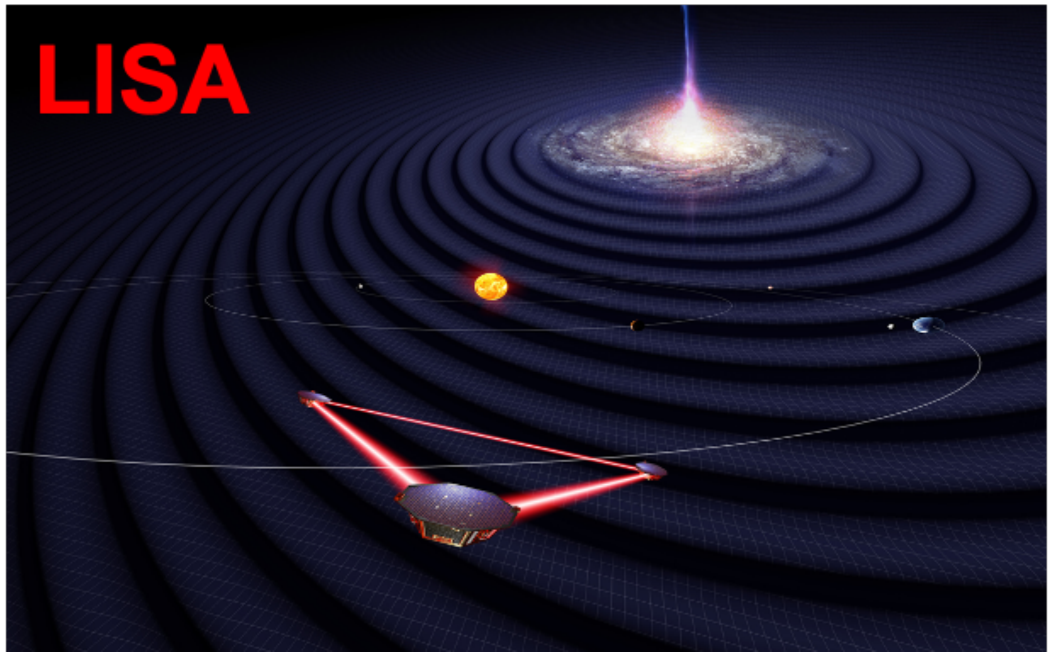


[LiteBIRD collaboration, 2022]



n_s [CMB-S4 Science case, 2019]

Next Generation GW Interferometers

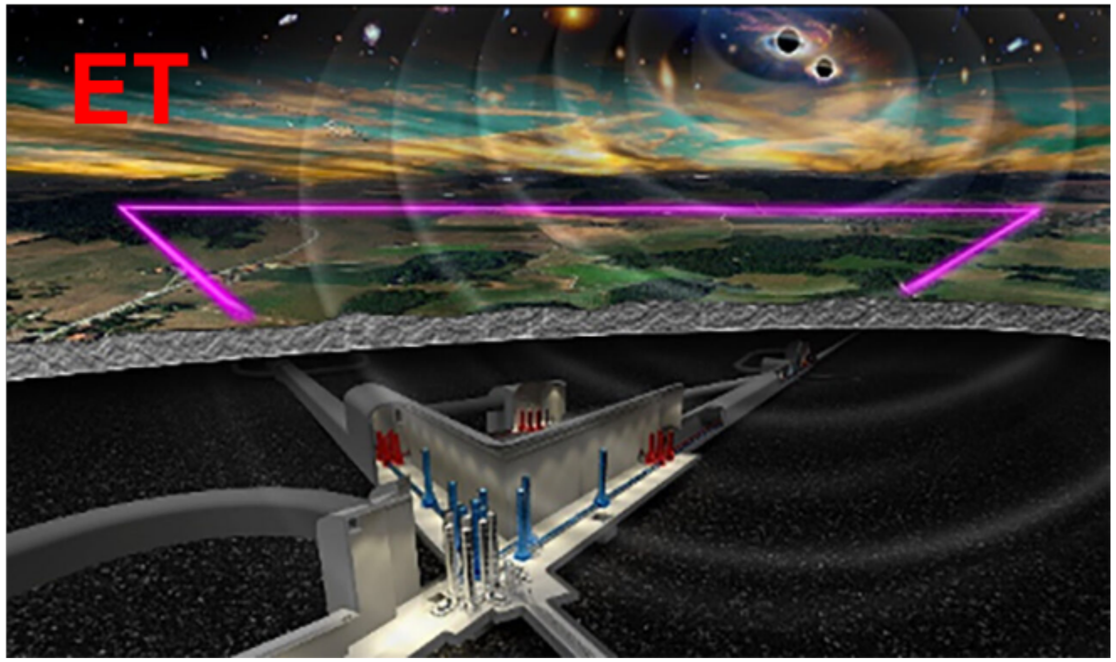


Geometry: **Constellation of 3 spacecraft in an equilateral configuration** (a giant interferometer)

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

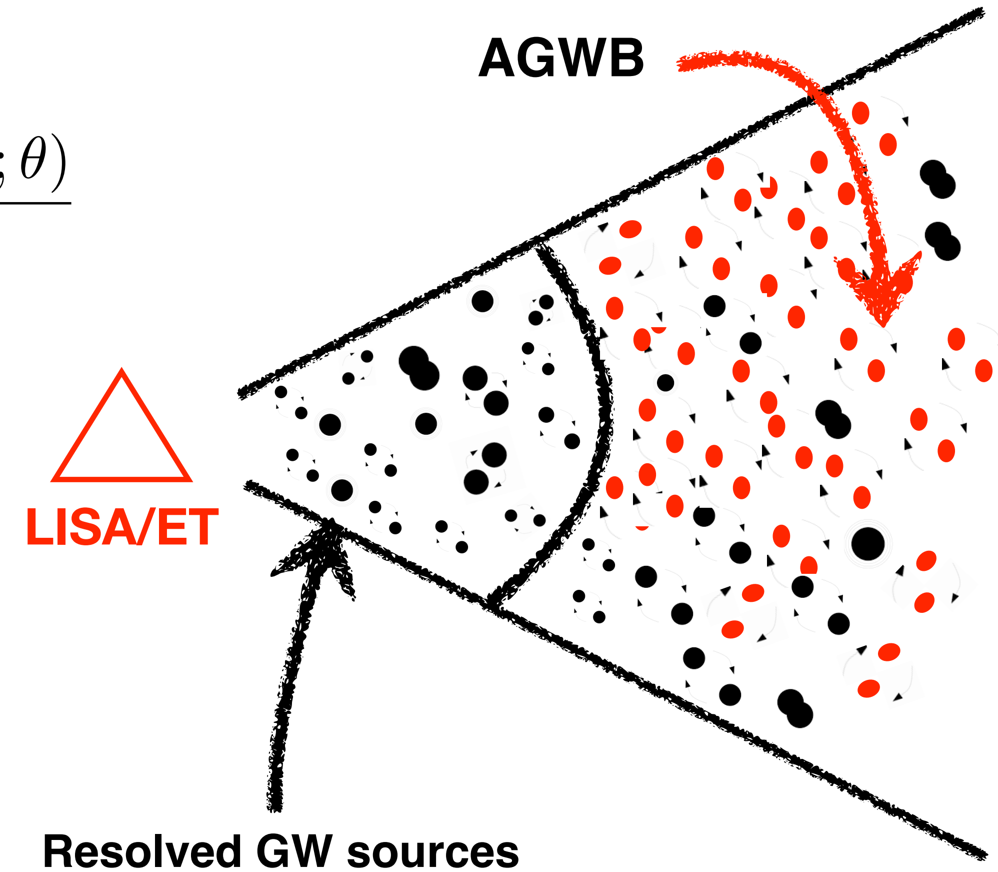
LISA now in PHASE B1 (phase of development)

ET included in the ESFRI roadmap for 2021

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

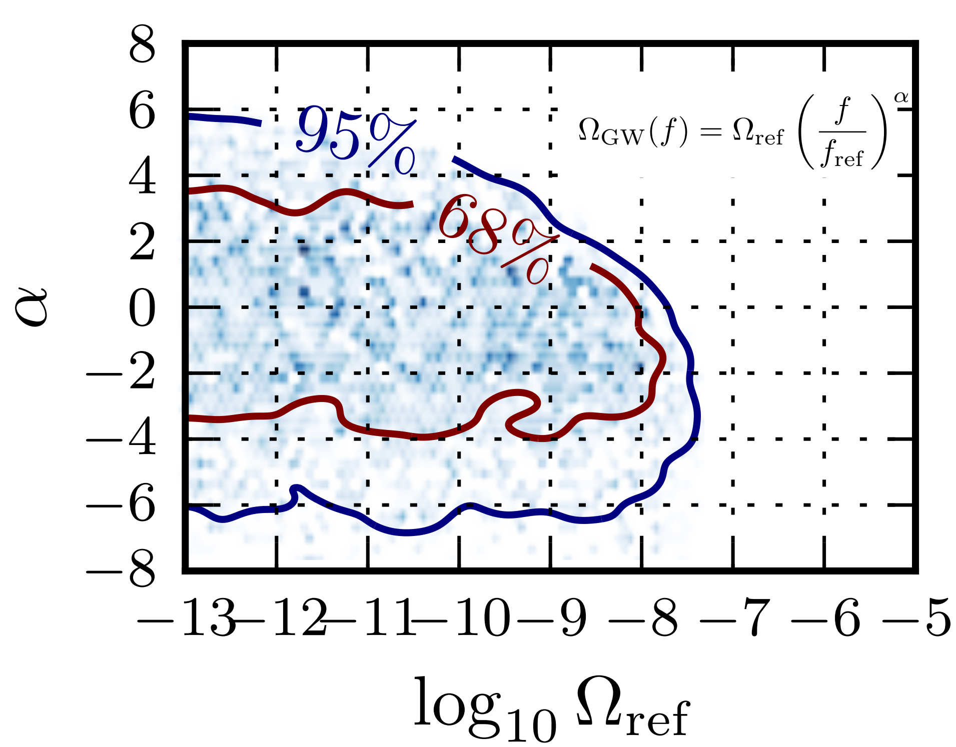
Astrophysical GW Background

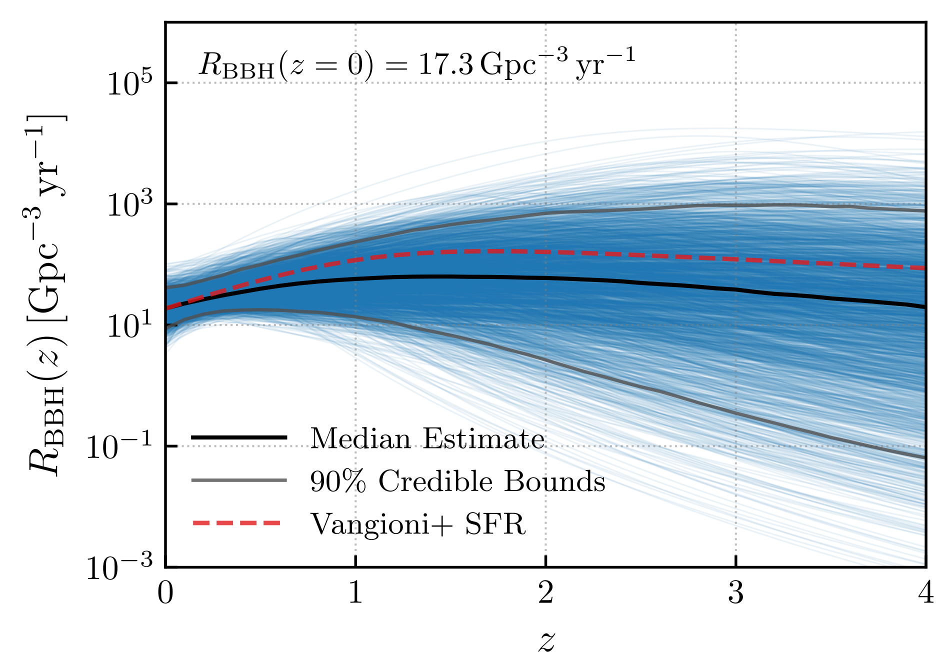
$$\Omega(f) = \frac{f}{\rho_c} \int d\theta\, p(\theta) \int_0^{z_{max}(\theta)} dz \frac{R(z;\theta)}{(1+z)H(z)} \frac{dE_{GW}(f_s;\theta)}{df_s}$$



Carry information about:

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



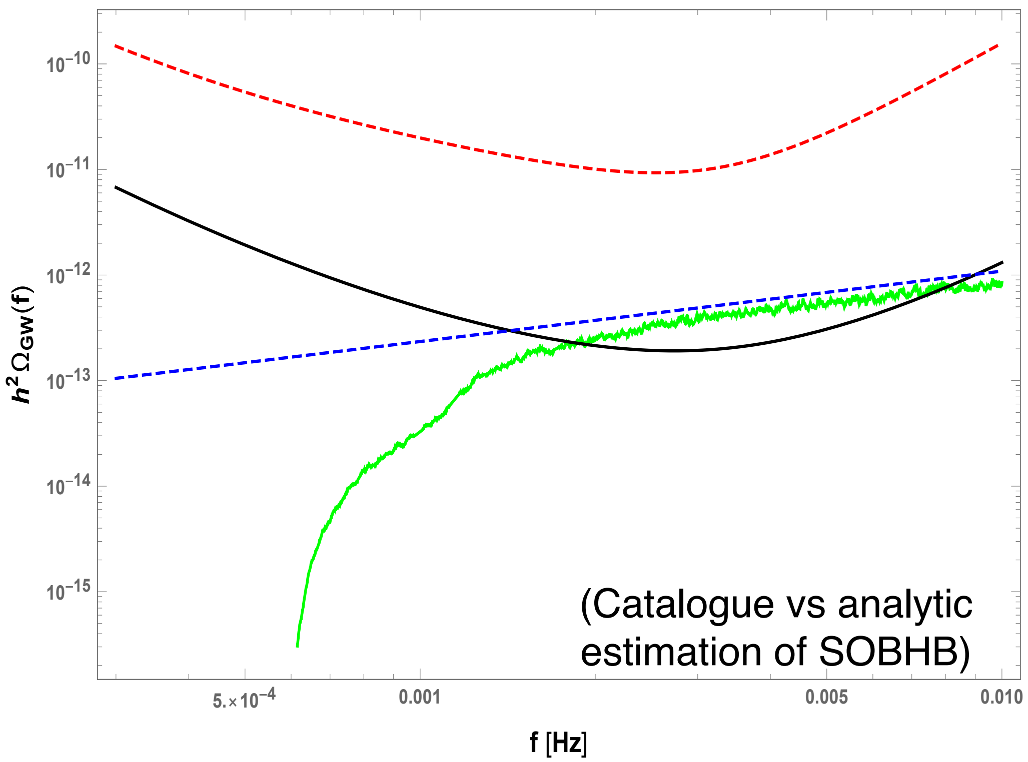


[LVK Collaboration 2021]

It is a kind of “noise” for the cosmological background, even if with different properties

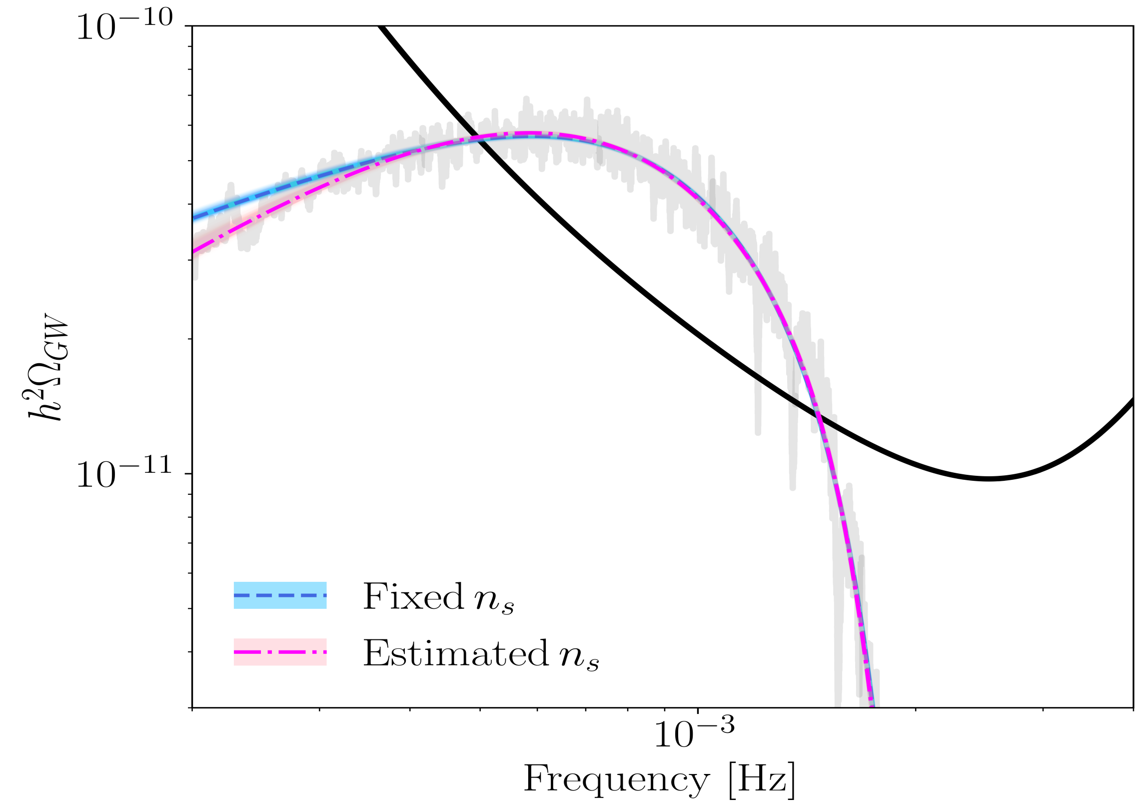
Astrophysical GW Background

LISA SOBHB



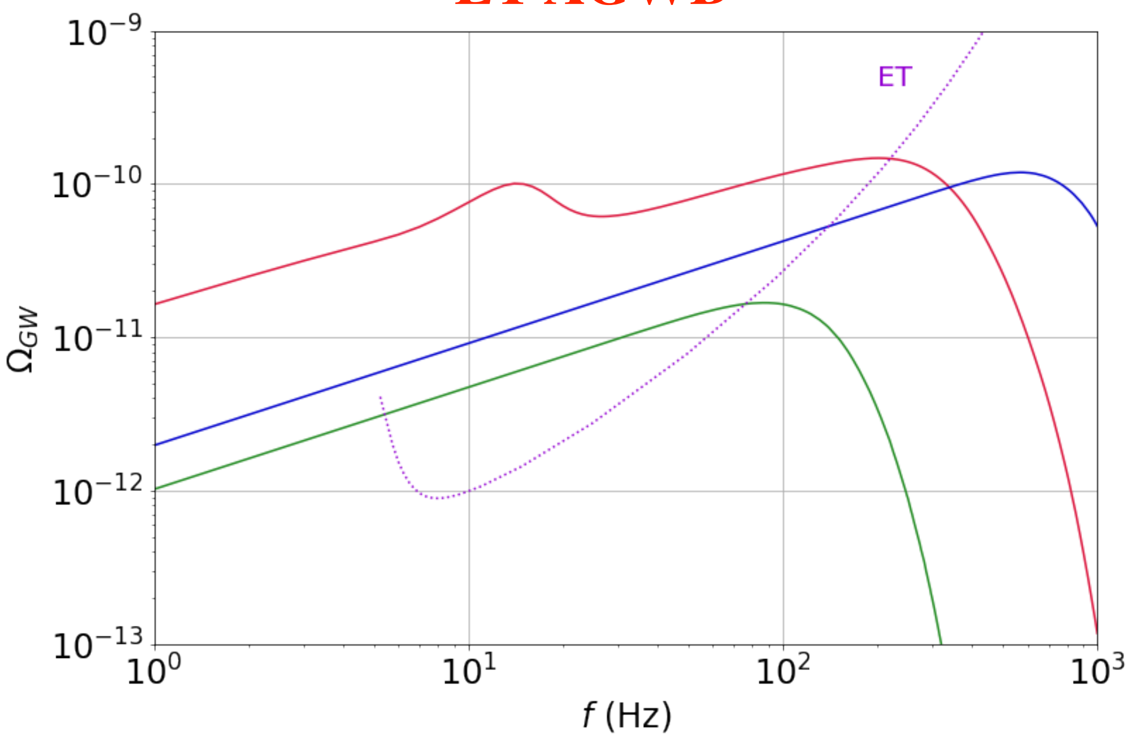
[Caprini C. et al., in preparation]

LISA GB

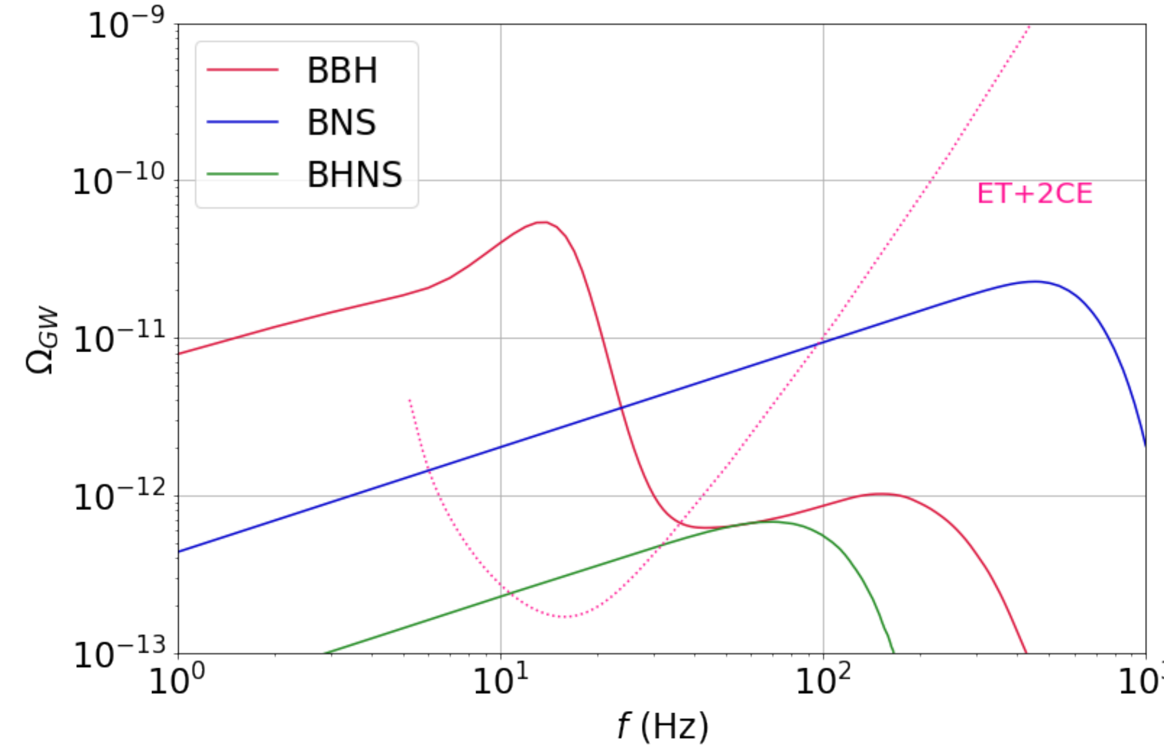


[Karnesis N., et al., 2021]

ET AGWB

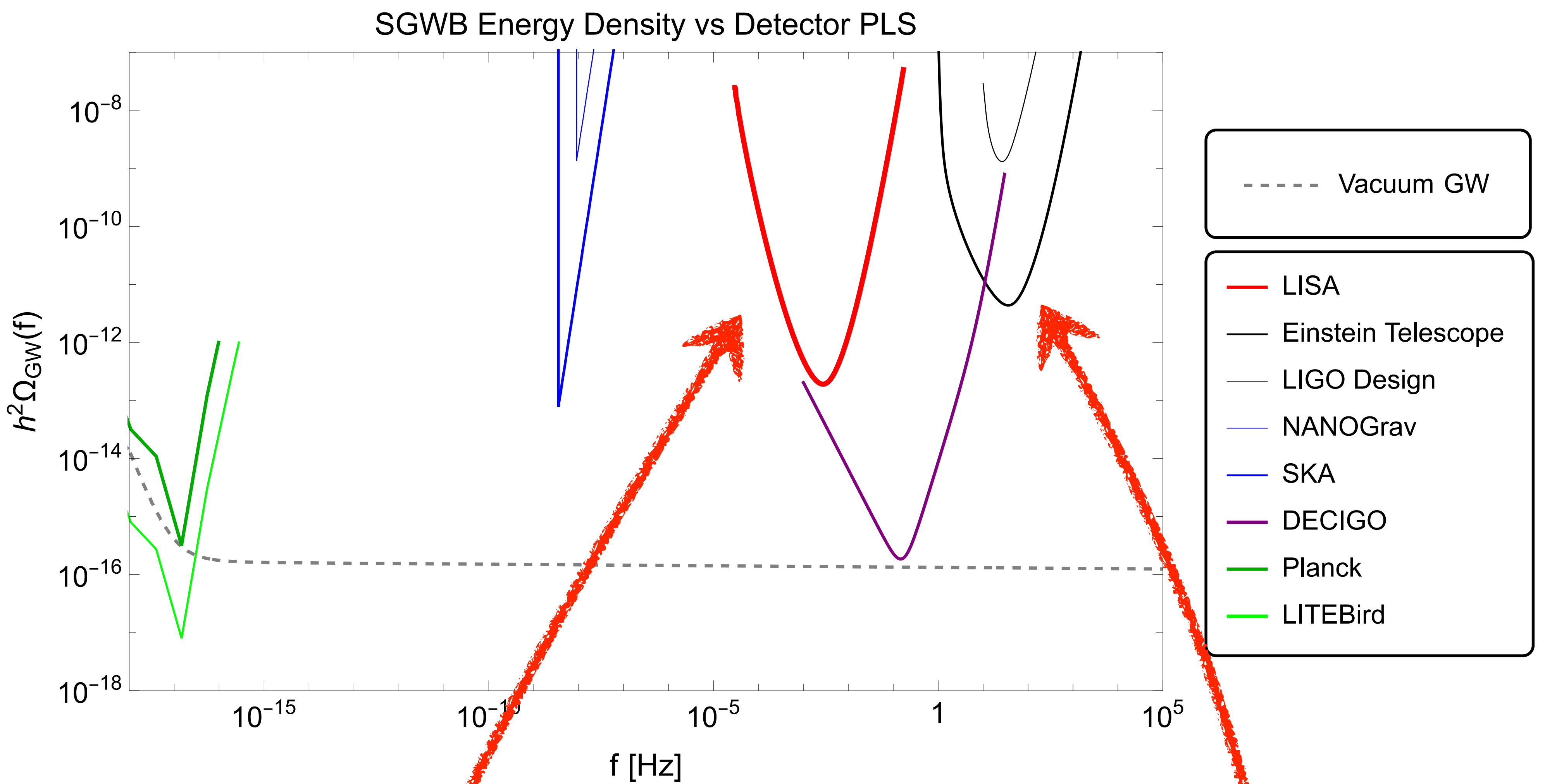


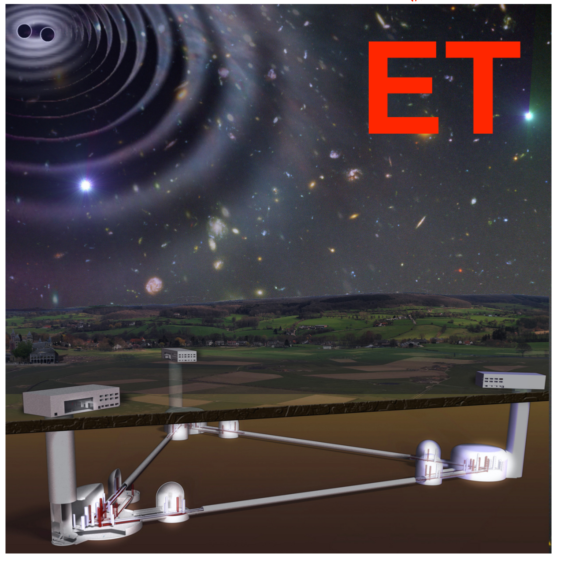
ET + 2CE



[Perigois C. et al., 2021]

Cosmological GW Background





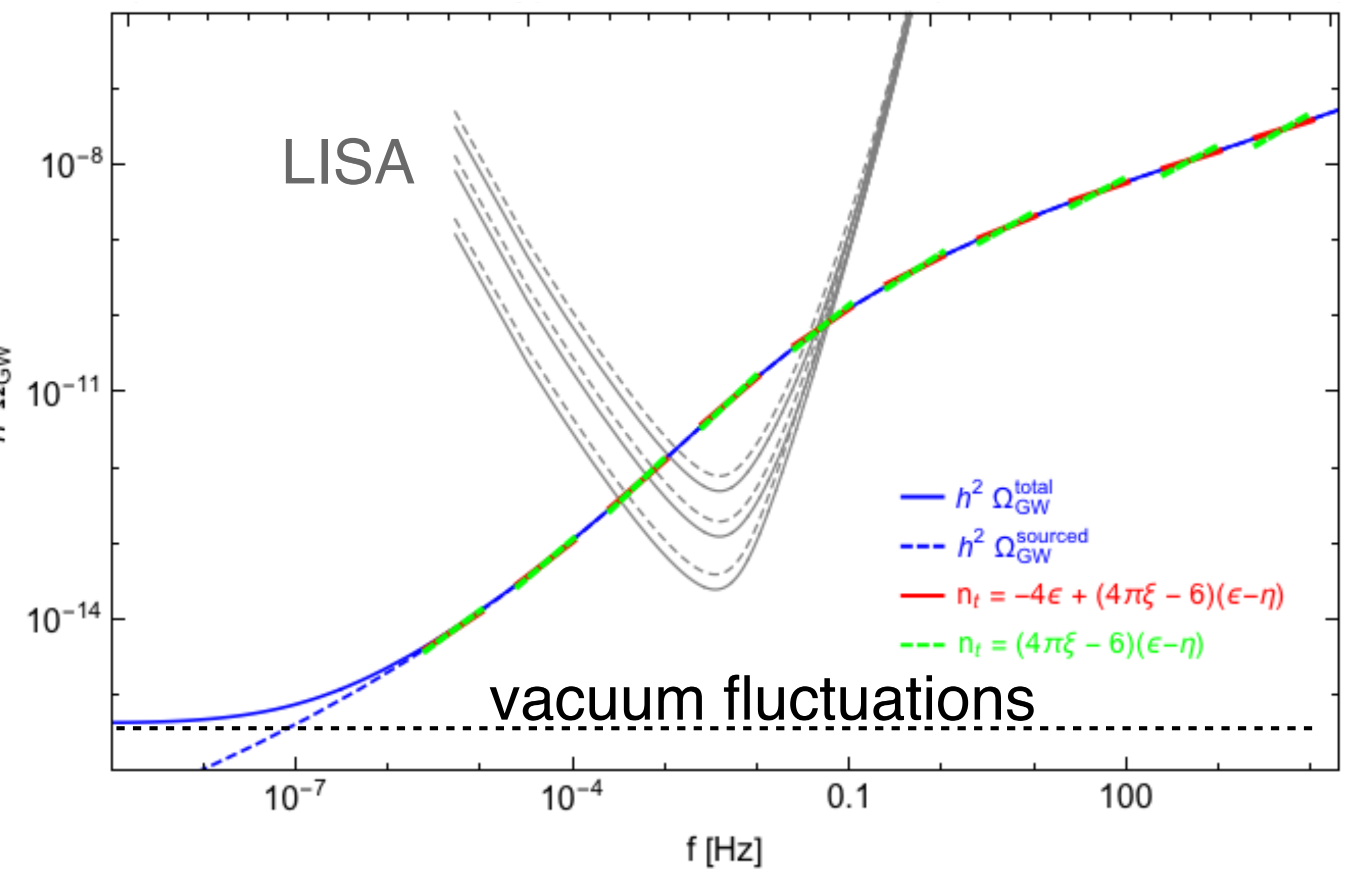
[LISA Cosmology White Paper]

Inflationary sources: Axion-inflation

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

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

GW energy spectrum today



$$\Omega_{GW}^{TOT}(f) = \Omega_{GW,vacuum}(f) + \Omega_{GW,sourced}(f)$$

Peculiar features

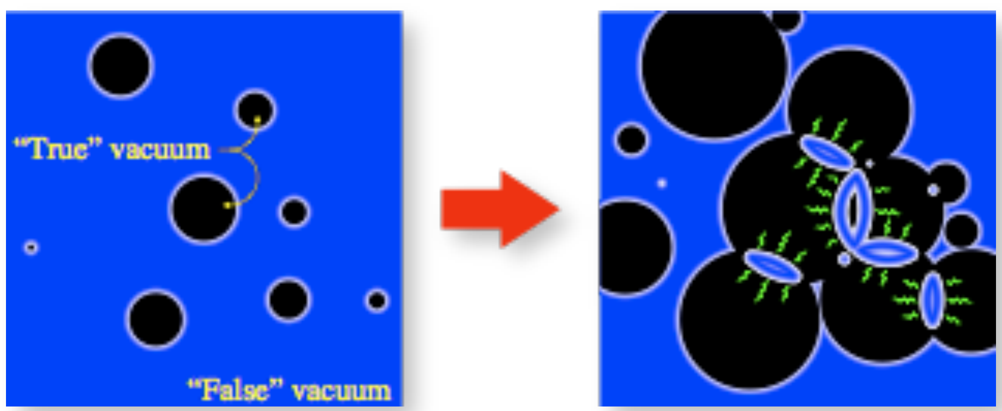
- Blue-Tilted SGWB Spectrum
- **Chiral** SGWB spectrum
- Non-Gaussian SGWB

[Bartolo N., et al. '16 - LISA CosWG paper]
[Cook & Sorbo, '11] [Namba et al., '15]
[Domcke, Pieroni, Binetruy, '16]

SGWB from Phase transition

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

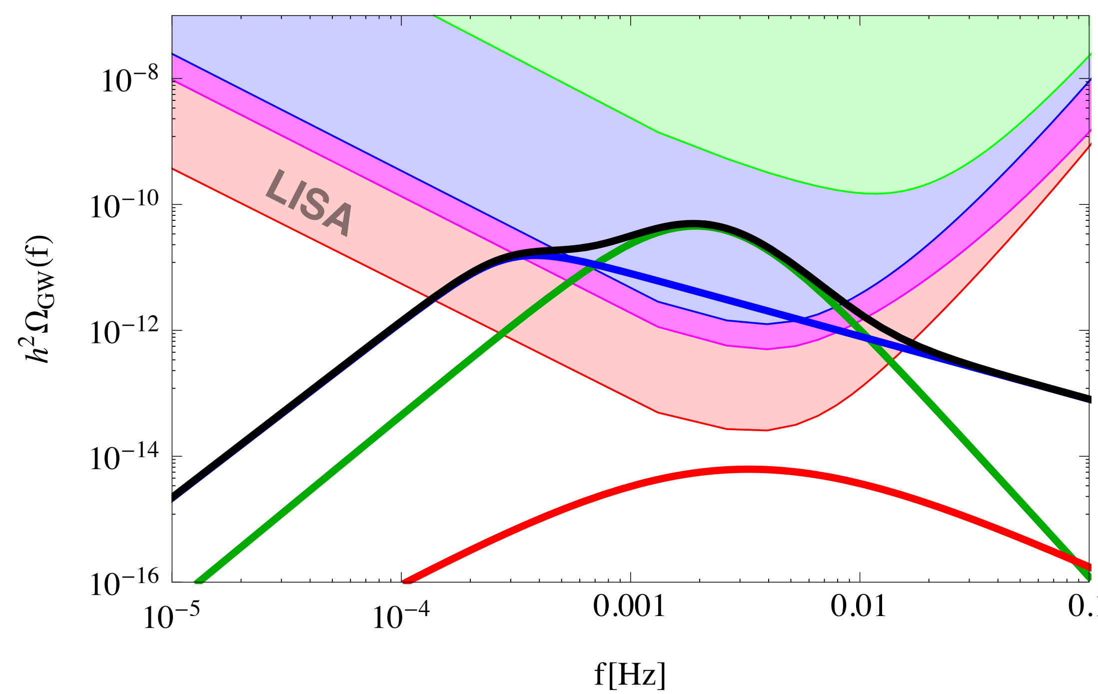
If the PT is first order, the SGWB signal could be detectable by LISA/ET



Processes

- Bubble collisions
- MHD Turbulence
- Sound Waves

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



- peaked spectrum with

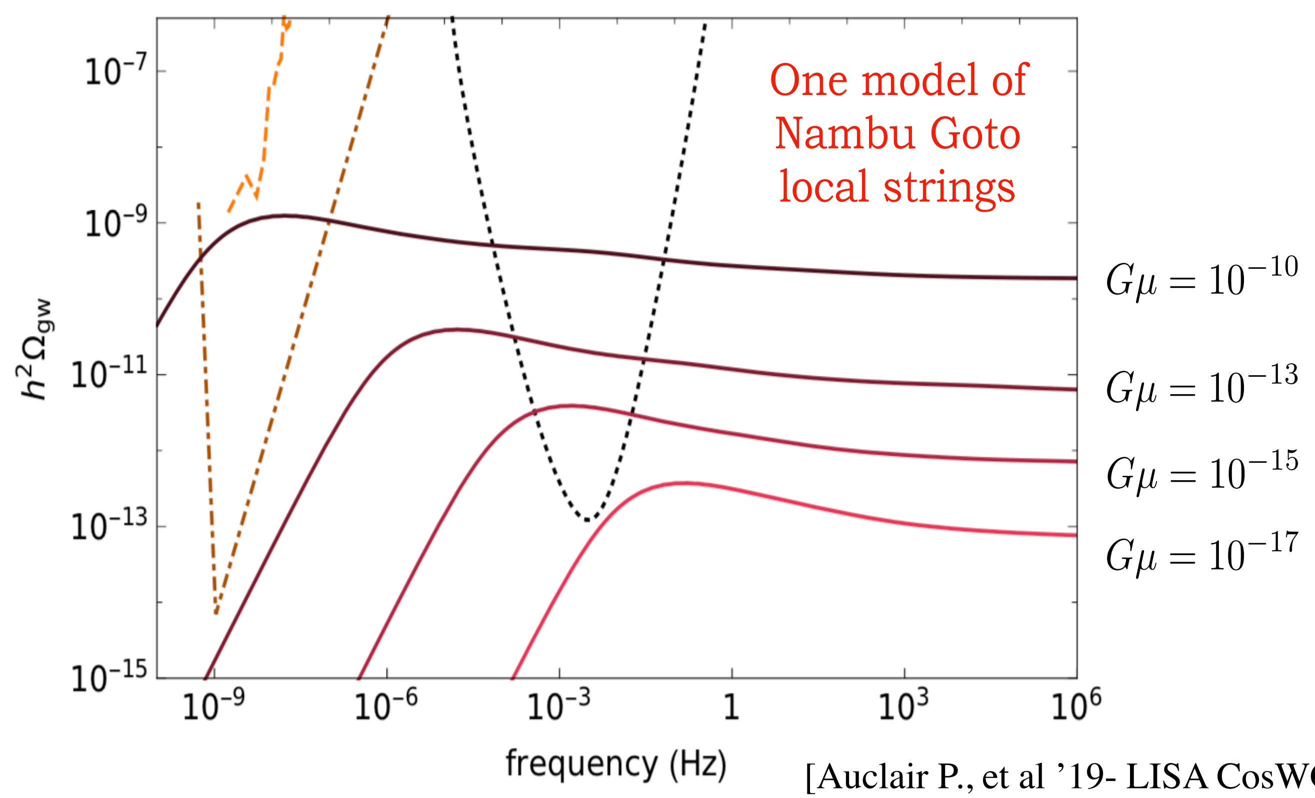
$$f_{\rm peak} \sim 10^{-3}\ {\rm Hz}\ \frac{T}{100\ {\rm GeV}}$$

SGWB from Topological Defects

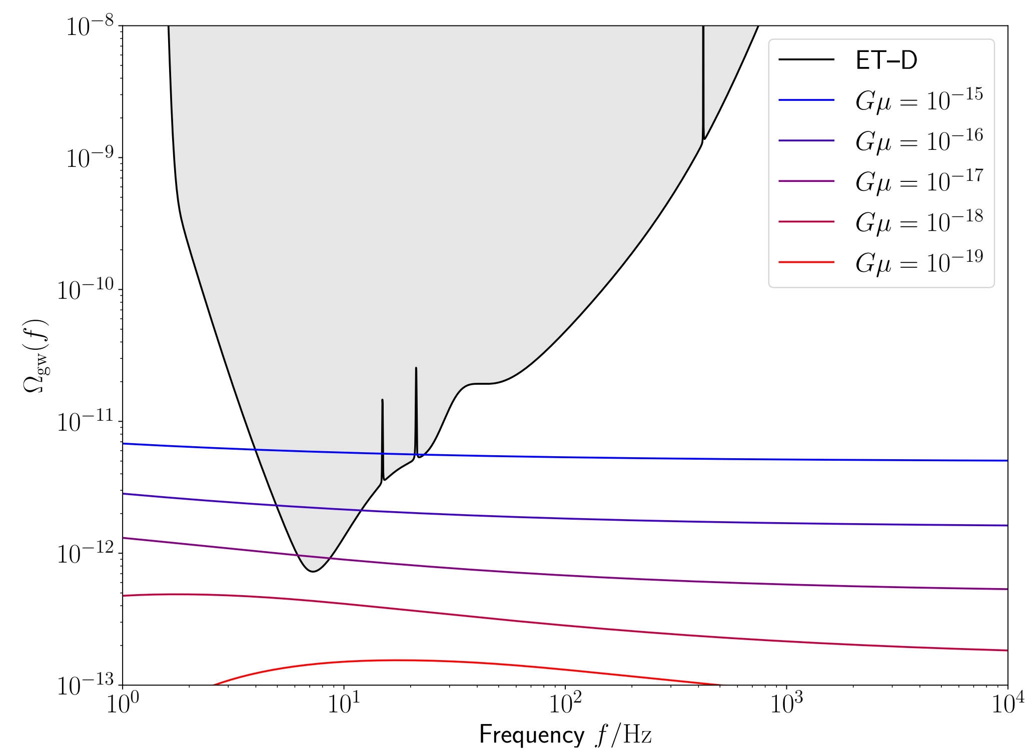
Cosmic Strings (or other kind of topological defects) are non-trivial field configurations left-over after the phase transition has completed

A network of cosmic strings emits GWs

(results are model dependent)



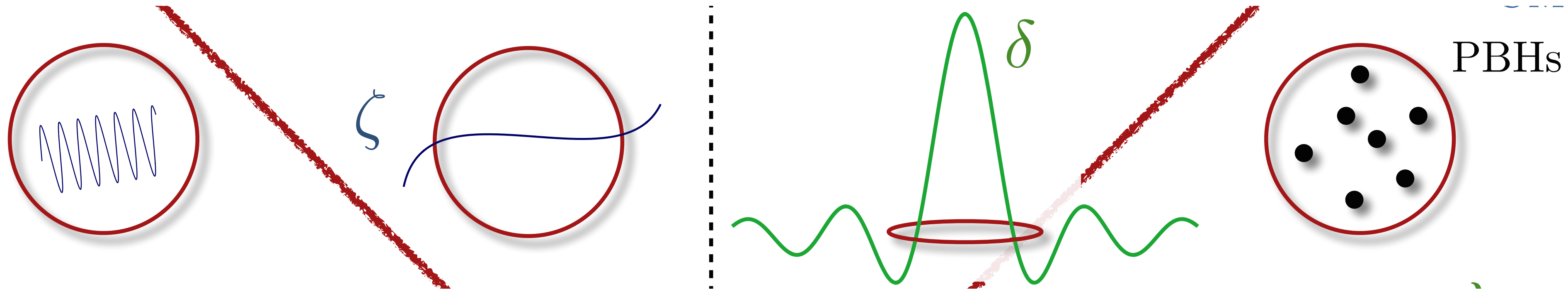
[Auclair P., et al '19- LISA CosWG]



[ET Science Case, 2020]

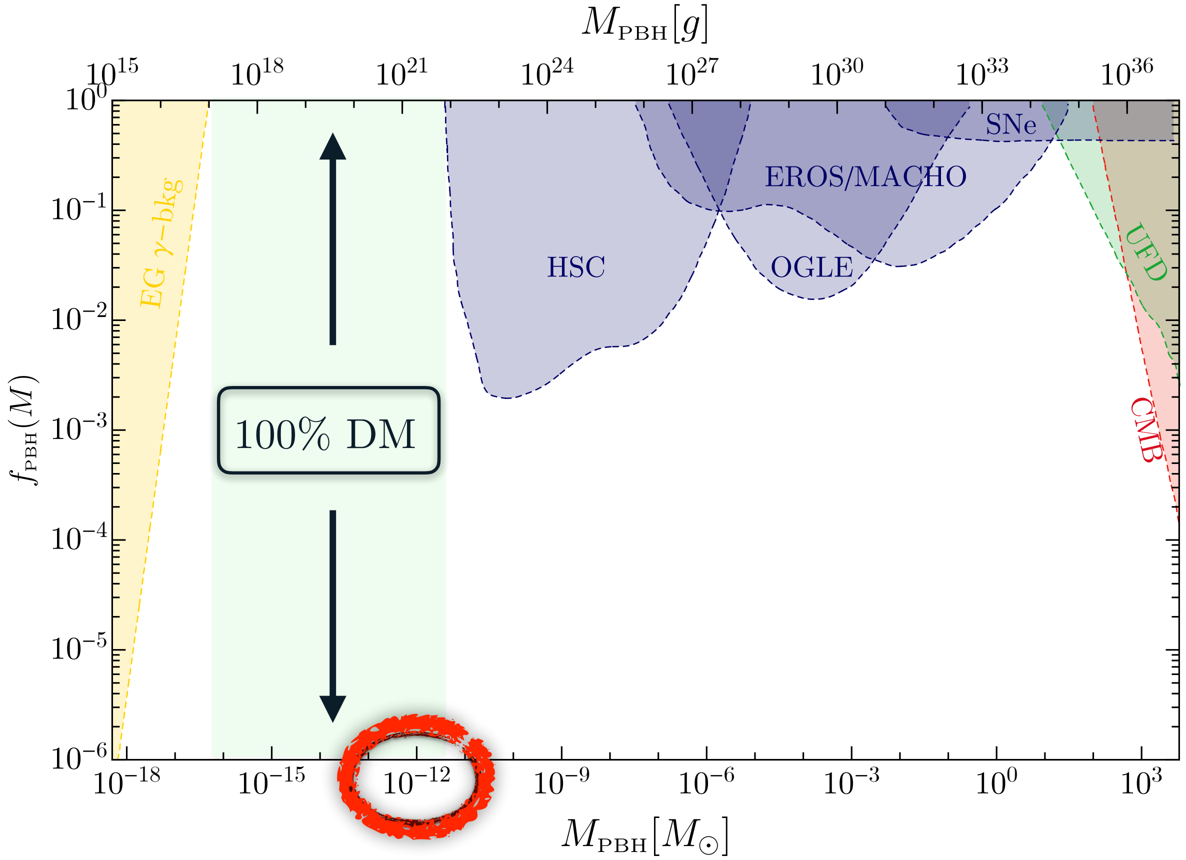
Future CMB B-mode	LIGO/Virgo bound	**LISA or ET**	
$G\mu \sim 10^{-9}$	$G\mu \sim 10^{-14}$	$G\mu \gtrsim 10^{-17}$	$G\mu \sim 10^{-6}\left(\frac{\eta}{10^{16}\ \mathrm{GeV}}\right)^2$

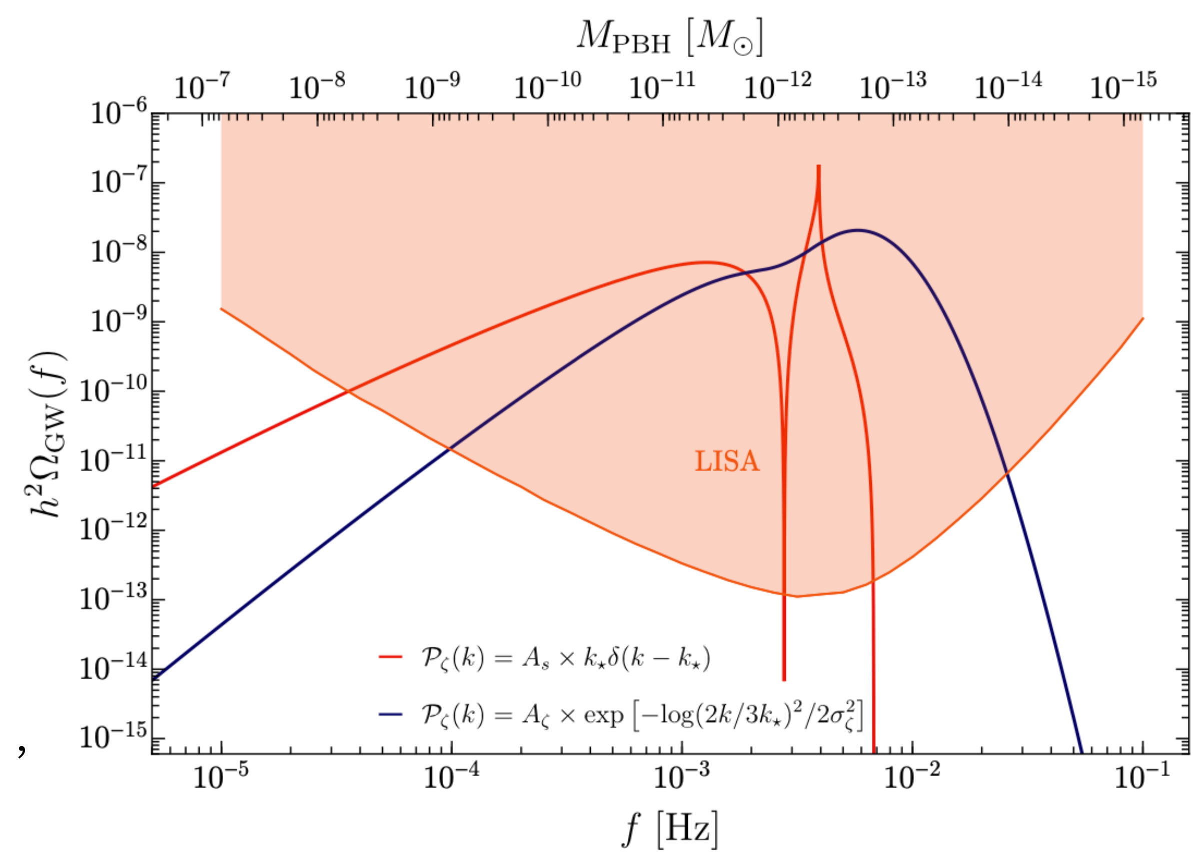
GW from Primordial Black Holes



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

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





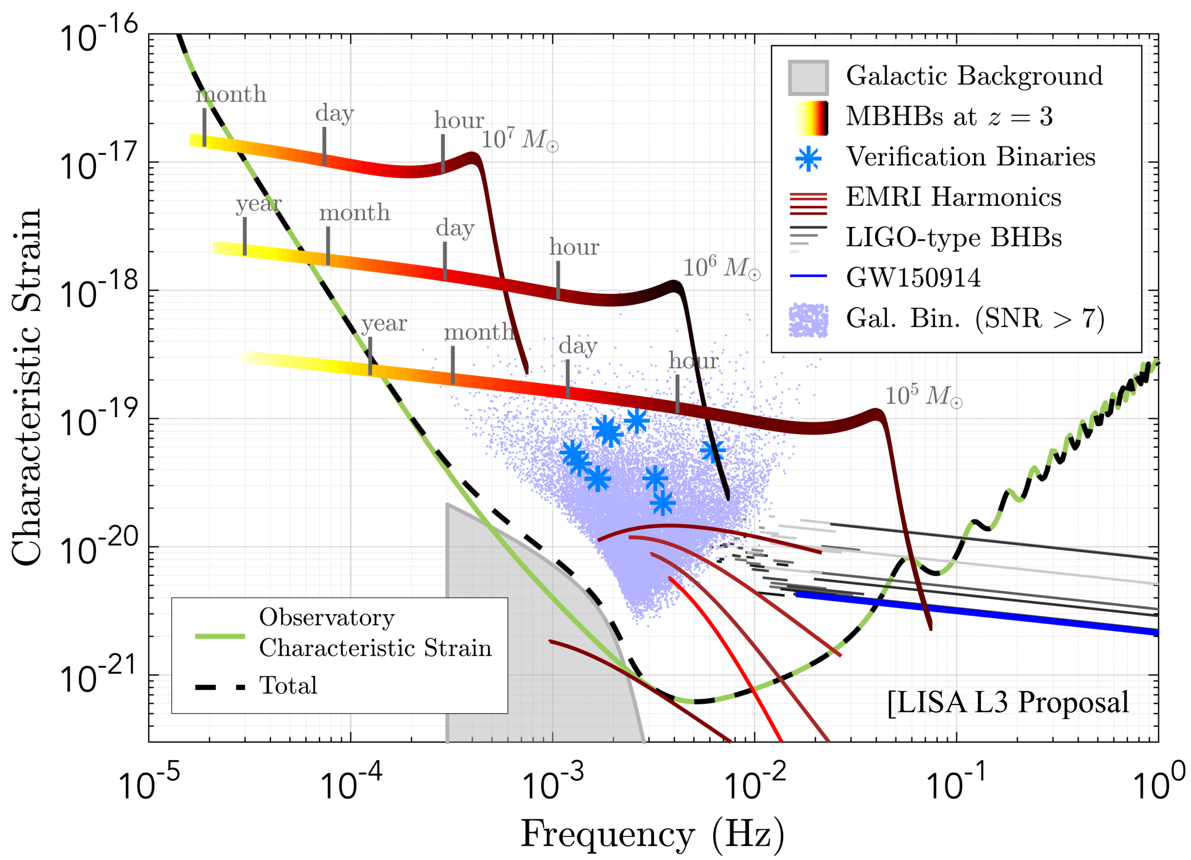
[Espinosa, et al., 2018]
[Bartolo, N., et al., PRL 2019]
[De Luca, V., et al., PRL 2021]

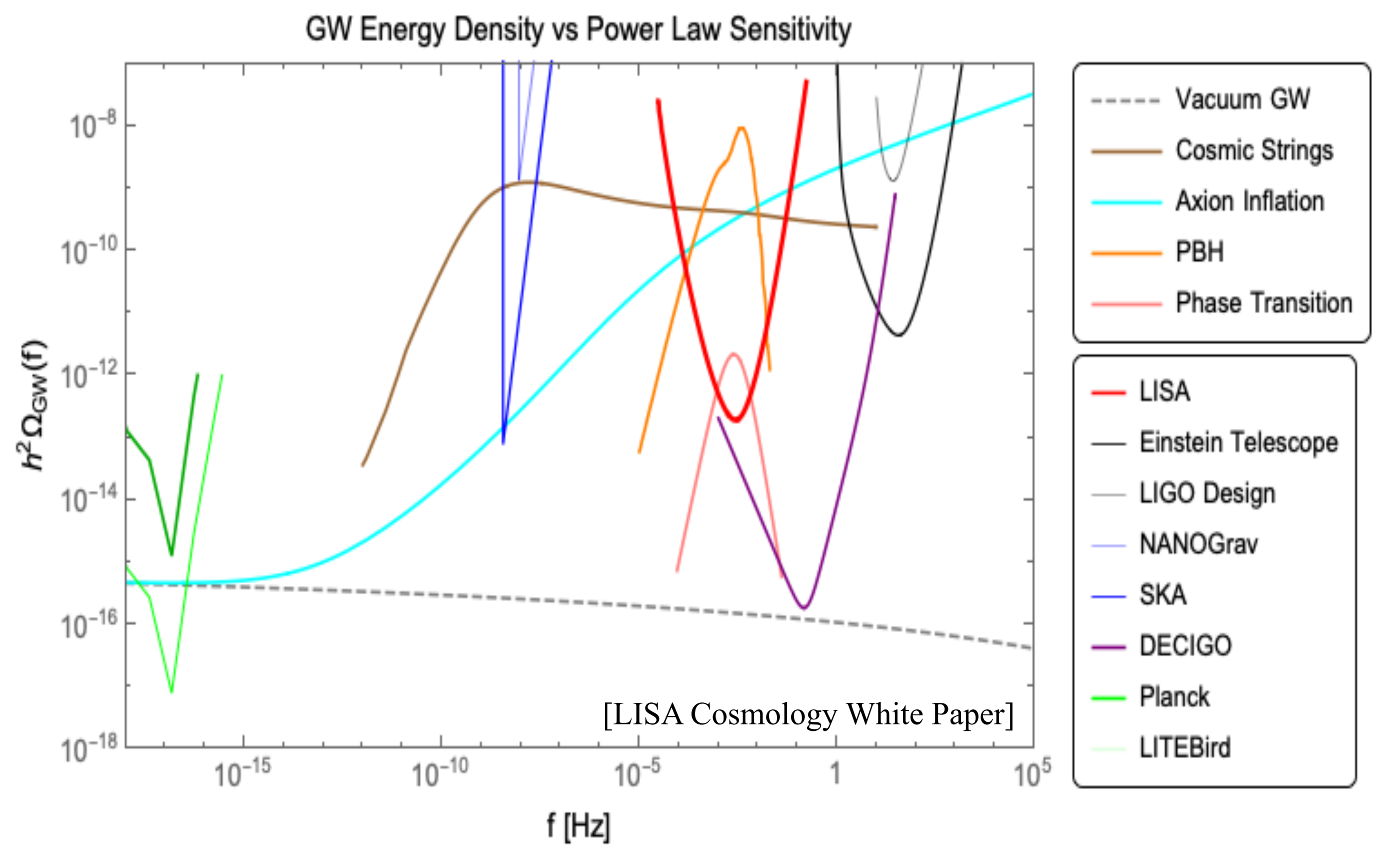
$$f \simeq 3 \cdot 10^{-9}\,\text{Hz} \left(\frac{\gamma}{0.2}\right)^{1/2} \left(\frac{M}{M_\odot}\right)^{-1/2}$$

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

Characterization of the SGWB

GWB from cosmological sources superimposed to the Astrophysical GWB

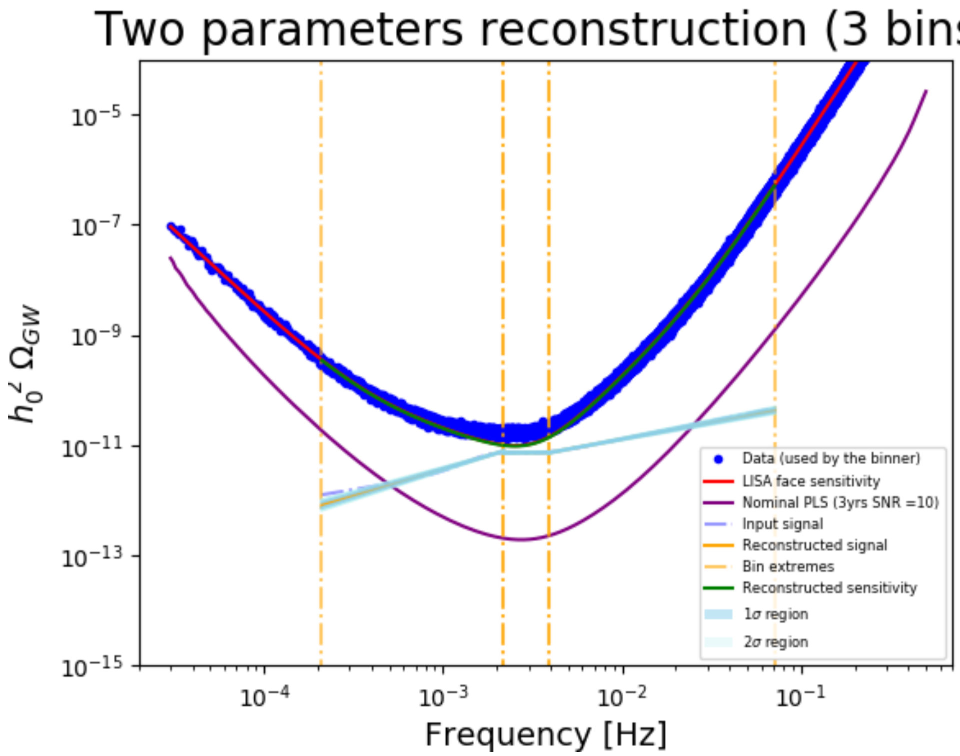




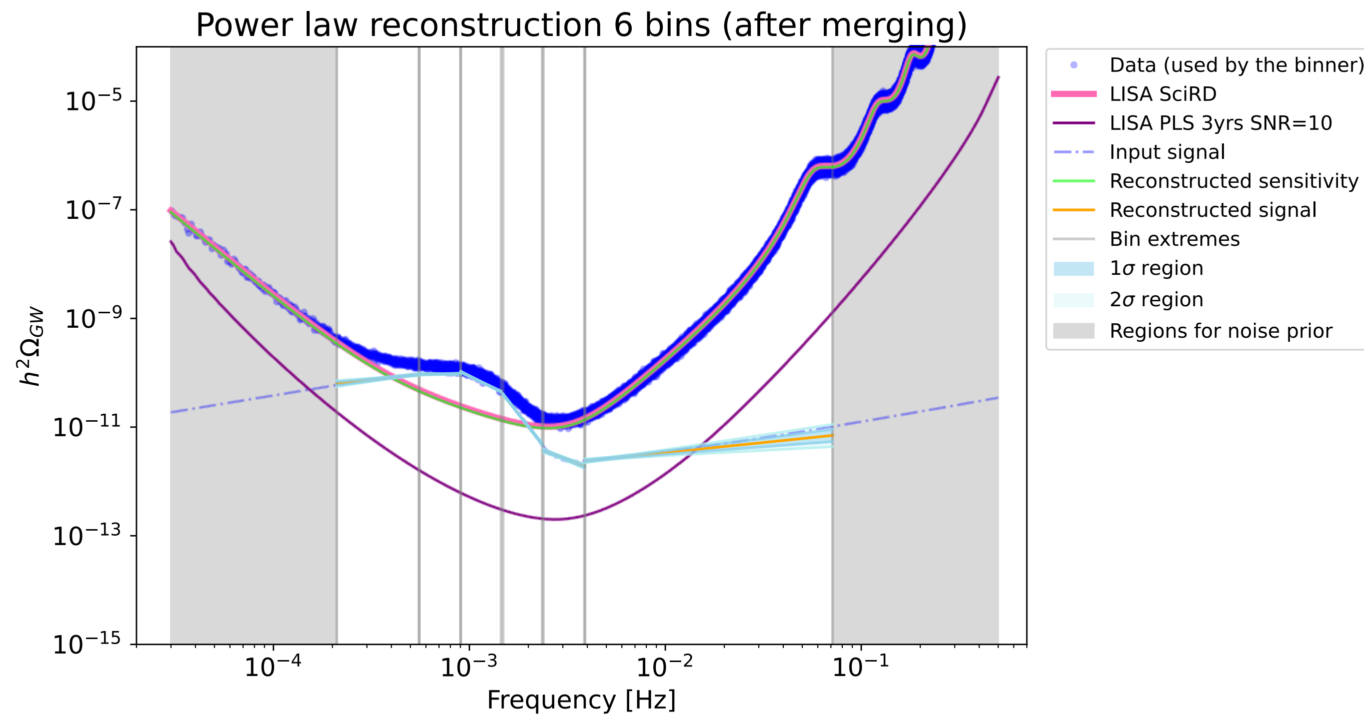
Peculiar features to distinguish them:

- **Spectral Dependence:** $\Omega_{\rm GW}(f)$ [SGWBinner code (LISA CosWG) '19, '20]
- **Net Polarization:** $\Omega_{\rm GW,\lambda}$ $\lambda = L, R$ [Domcke, V., et al.,'20]
- **Anisotropies/Directionality:** $\Omega_{\rm GW}(f, \vec{x})$
- **Statistics:** $\langle \Omega^n_{\rm GW} \rangle$

Spectral shape Reconstruction

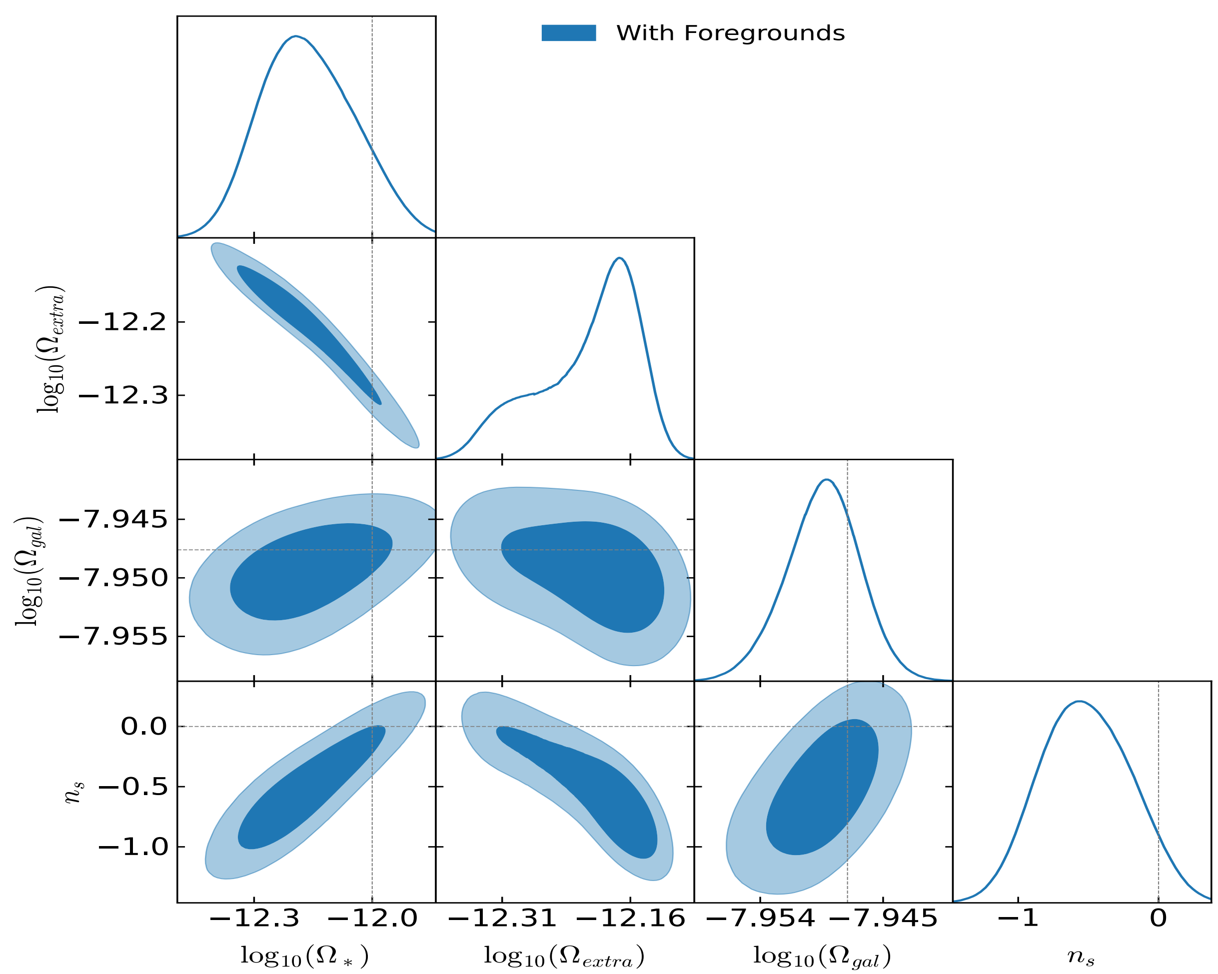


(Axion inflation, Phase Transition beyond SM)



(Power law + astro (foregrounds) binaries)

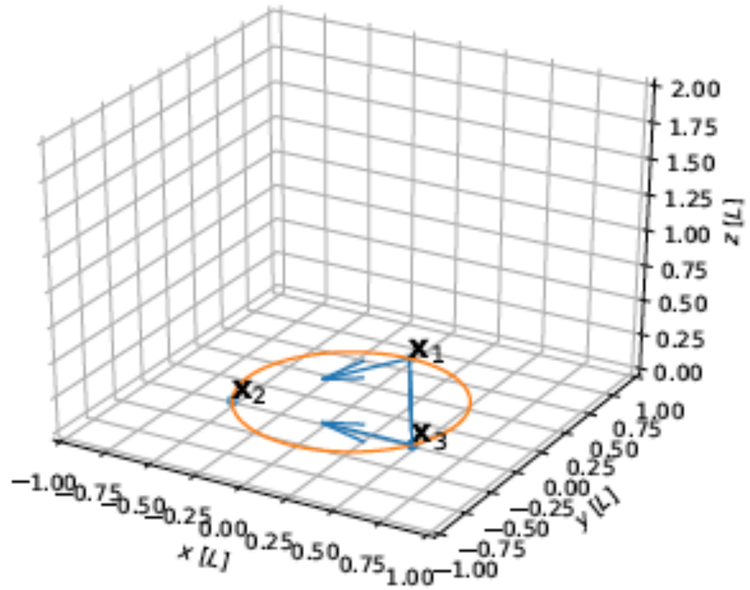
[SGWBinner code
(LISA CosWG) '19, '20]



See M. Braglia's talk

Chirality

For an ISOTROPIC SGWB

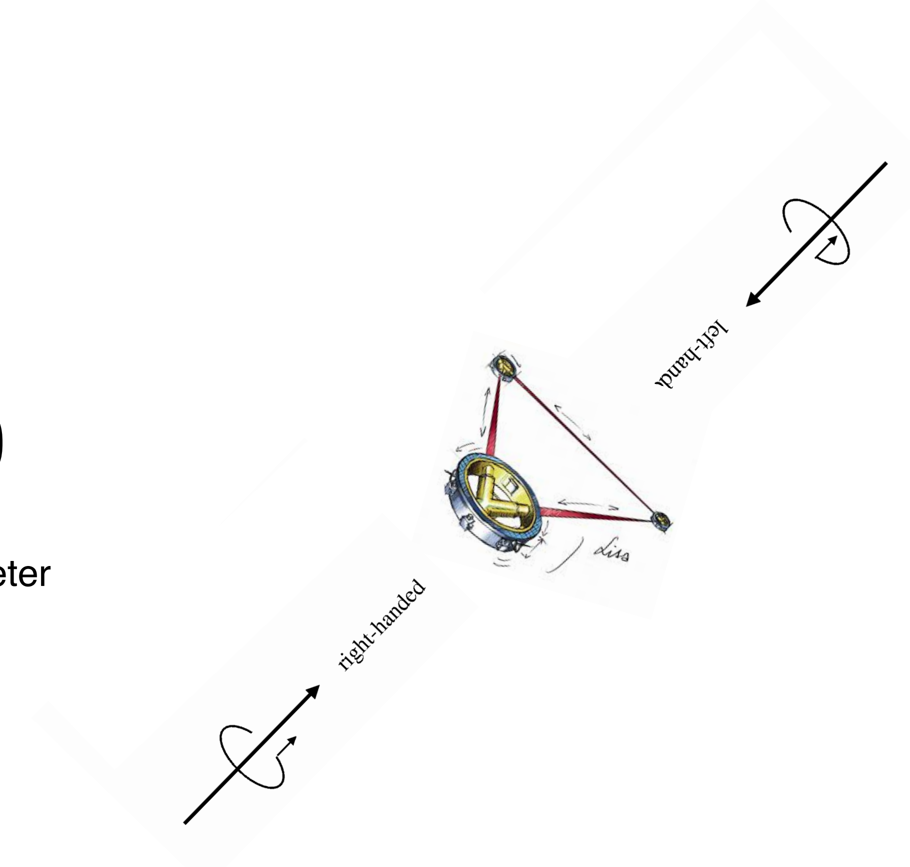


$$\mathcal{R}_{V}^{X_1 X_2}(f) = 0$$

V= circular polarization Stokes parameter

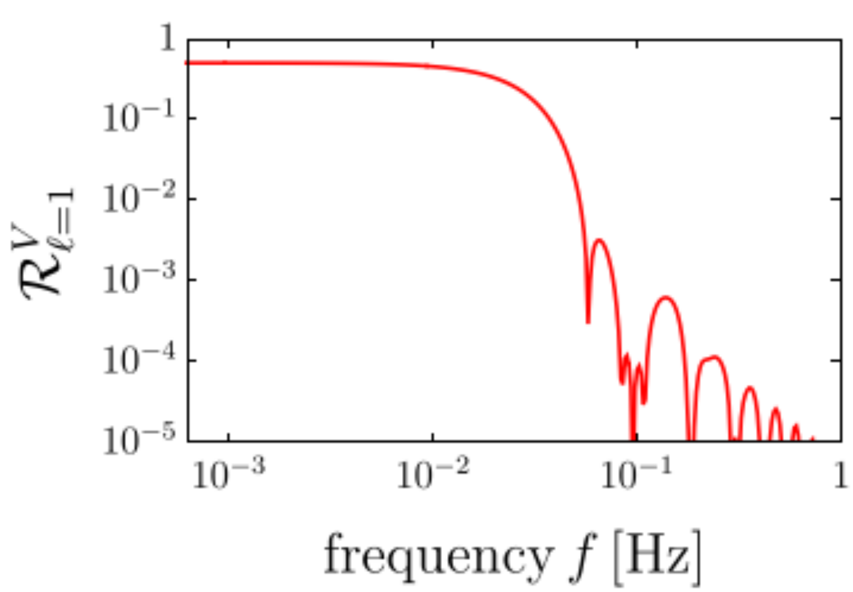
[Smith & Caldwell, ‘16]

[B. Thorne et al., ‘17]



Assuming a dipole modulation due to the motion of our Solar System with respect to the cosmic frame ->
BREAKING OF ISOTROPY

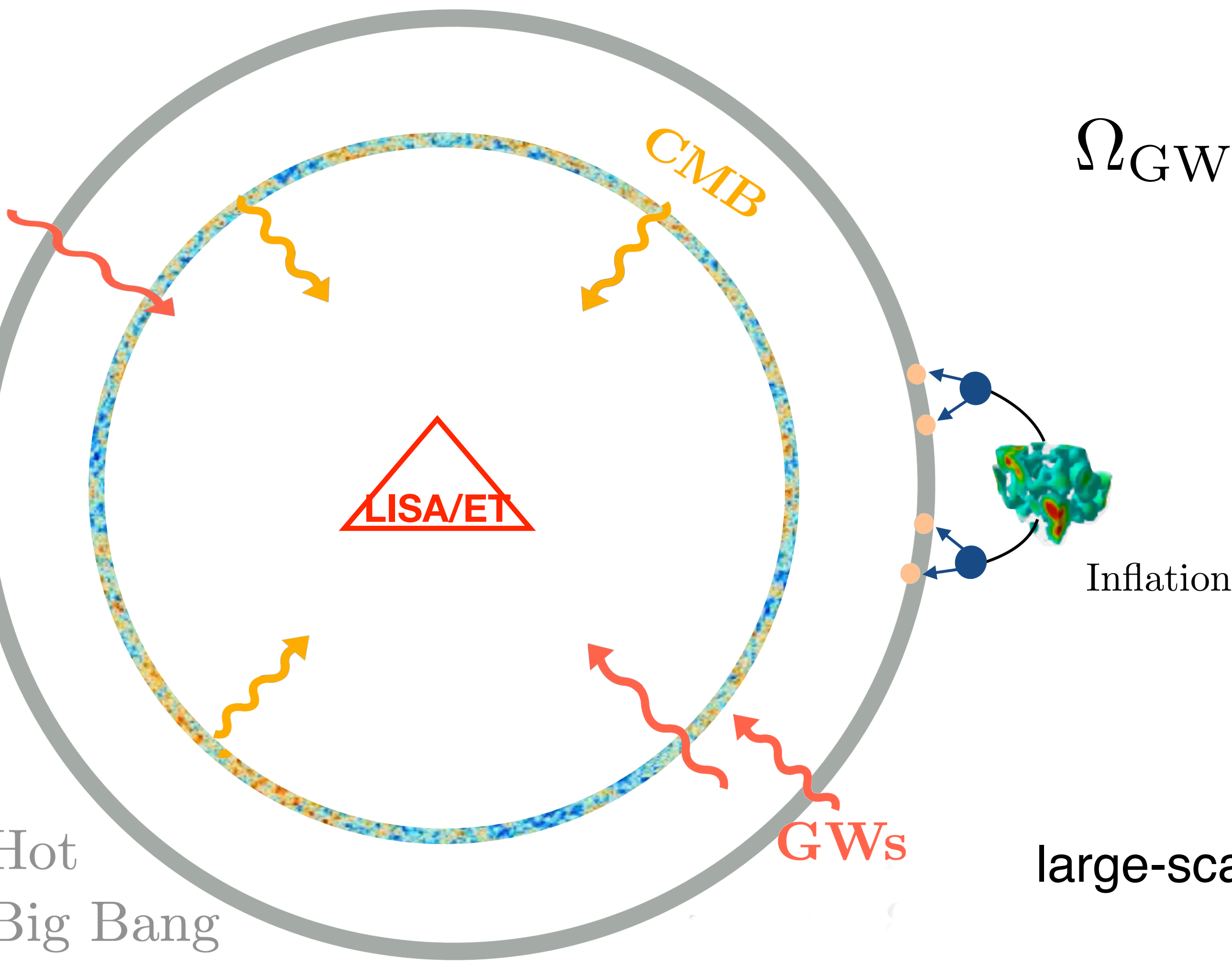
$$\Omega_{\rm GW}(\hat{n}) \propto (1 + \vec{\beta} \cdot \hat{n})\Omega^0_{\rm GW}$$



$$\mathrm{SNR}_{\rm LISA} \simeq \frac{v_d}{10^{-3}} \frac{\Omega_{\rm GW,R} - \Omega_{\rm GW,L}}{1.2 \cdot 10^{-11}} \sqrt{\frac{T}{3\,\text{years}}}$$

[Domcke, V., et al.,’20]

AGWB Anisotropies



EuCAPT WP

Treatment as CMB

$$\Omega_{\mathrm{GW}}(\eta_0, k, \hat{n}) \equiv \bar{\Omega}_{\mathrm{GW}}(\eta_0, k) + \delta\Omega_{\mathrm{GW}}(\eta_0, k, \hat{n})$$

ISOTROPIC BACKGROUND

Small PERTURBATION (direction-dependent)

GWs of high frequency propagating through large-scale (low frequency) cosmological perturbation due to LSS

(Geometric Optics Limit)

Two contributions: 1. At production

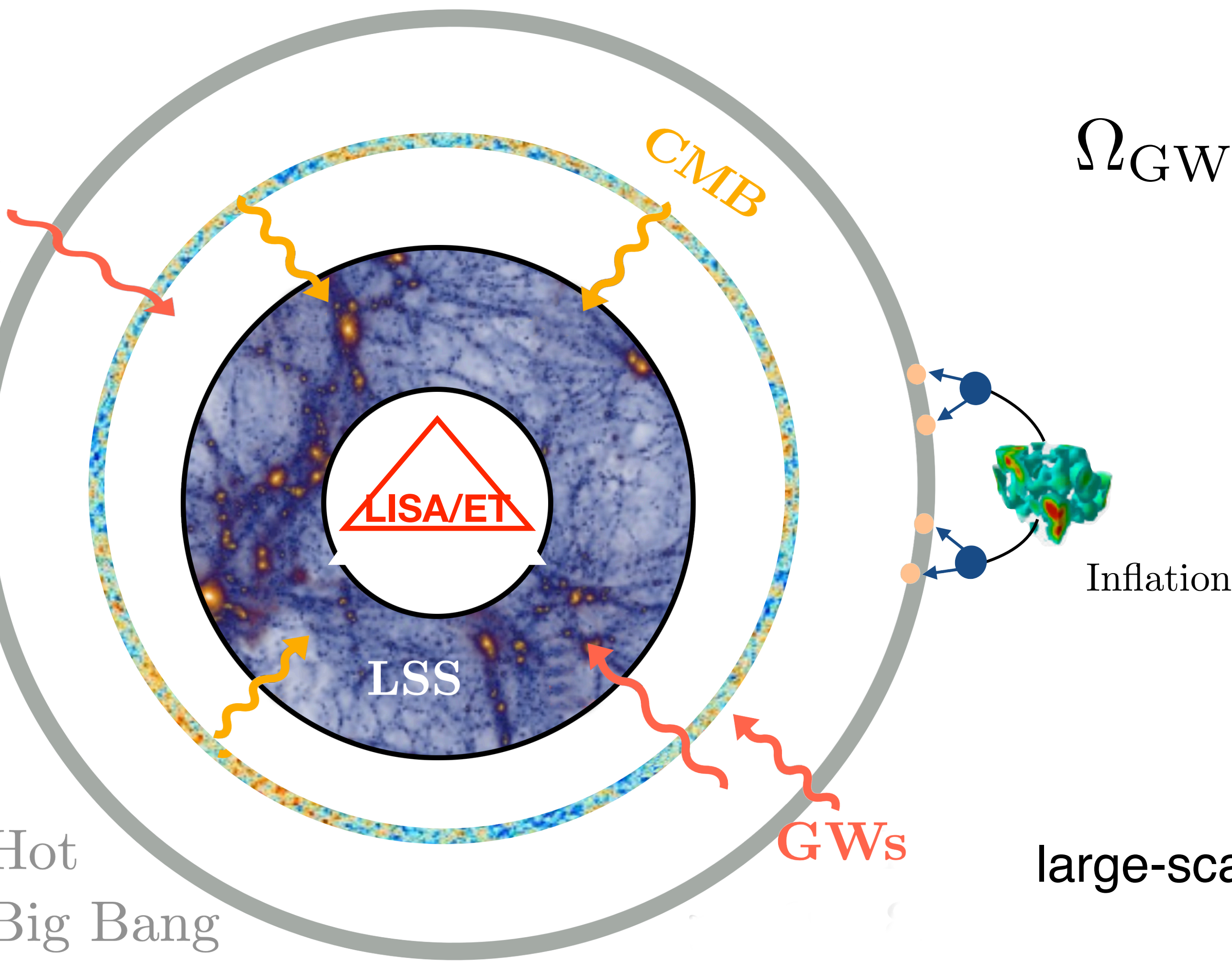
2. During the propagation through universe

[Alba, Maldacena, 2015]

[Contaldi, 2016]

[Bartolo, Bertacca, Matarrese, Peloso, AR, Riotto, Tasinato '19, '20]

AGWB Anisotropies



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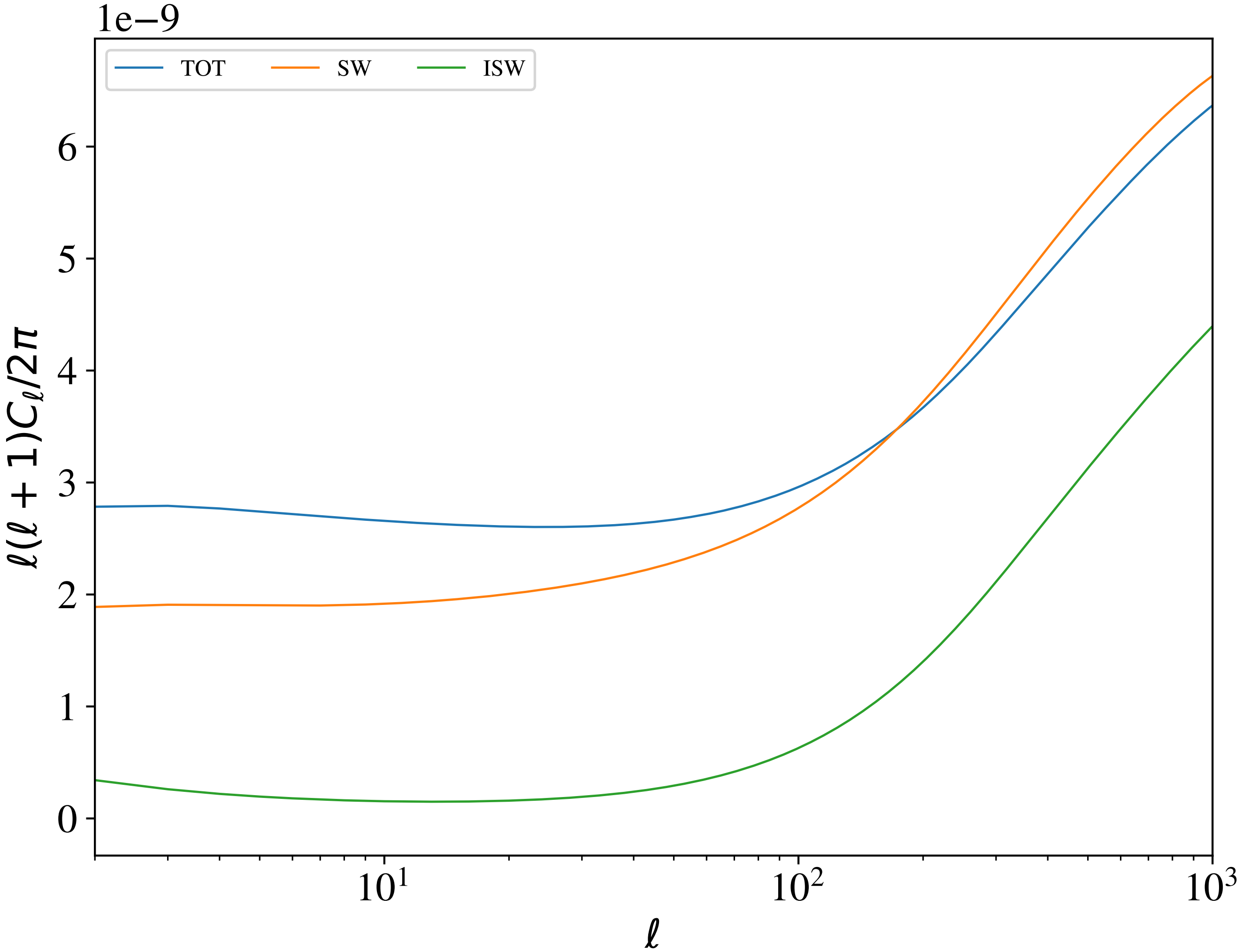
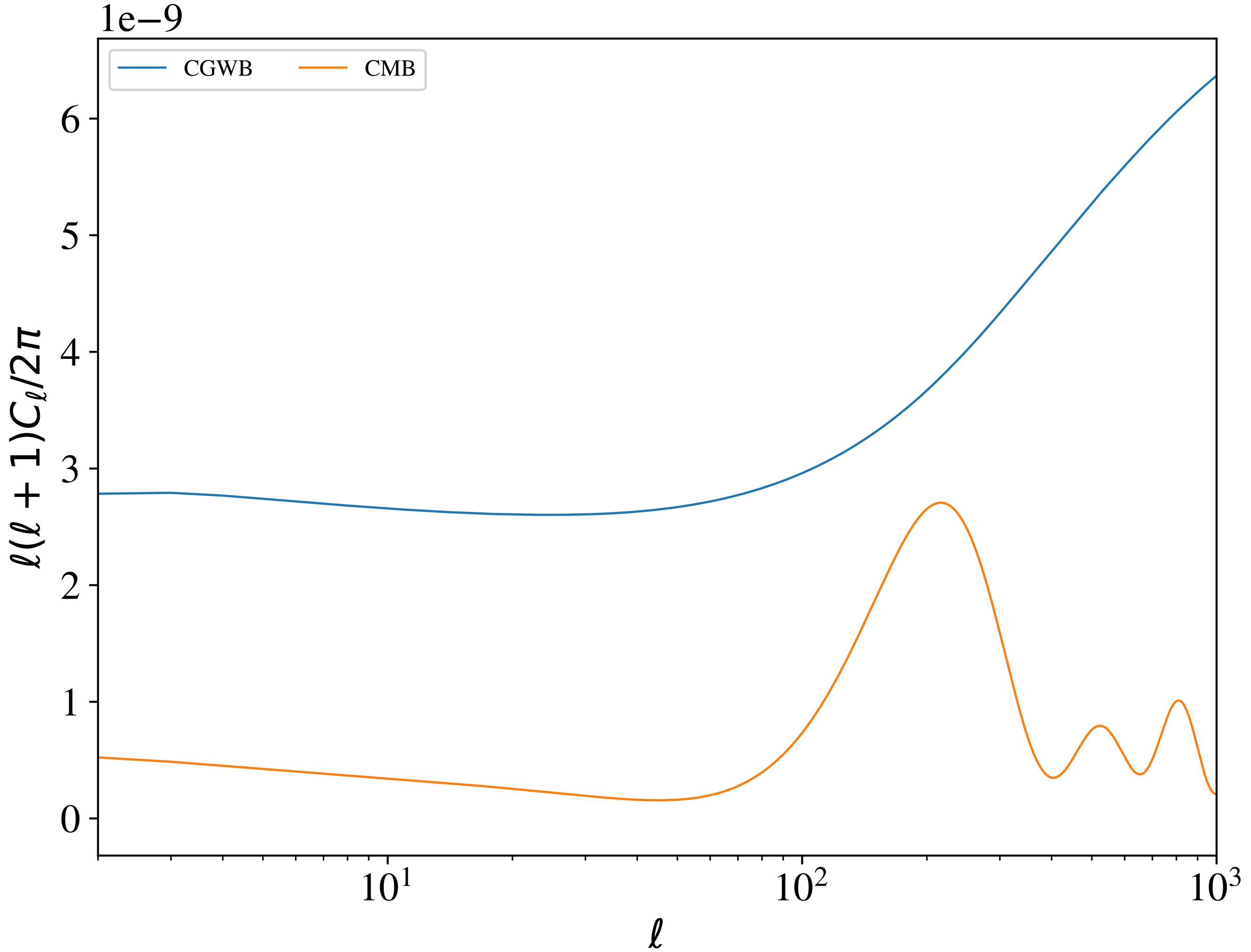
SGWB angular spectrum

$$\langle \delta^{\rm GW}_{\ell m} \delta^{\rm GW}_{\ell' m'} \rangle = C^{\rm GW}_\ell(\eta_0, q)\delta_{\ell\ell'}\delta_{mm'}$$



Cosmological GWB angular spectrum



CGWB vs CMB angular spectrum

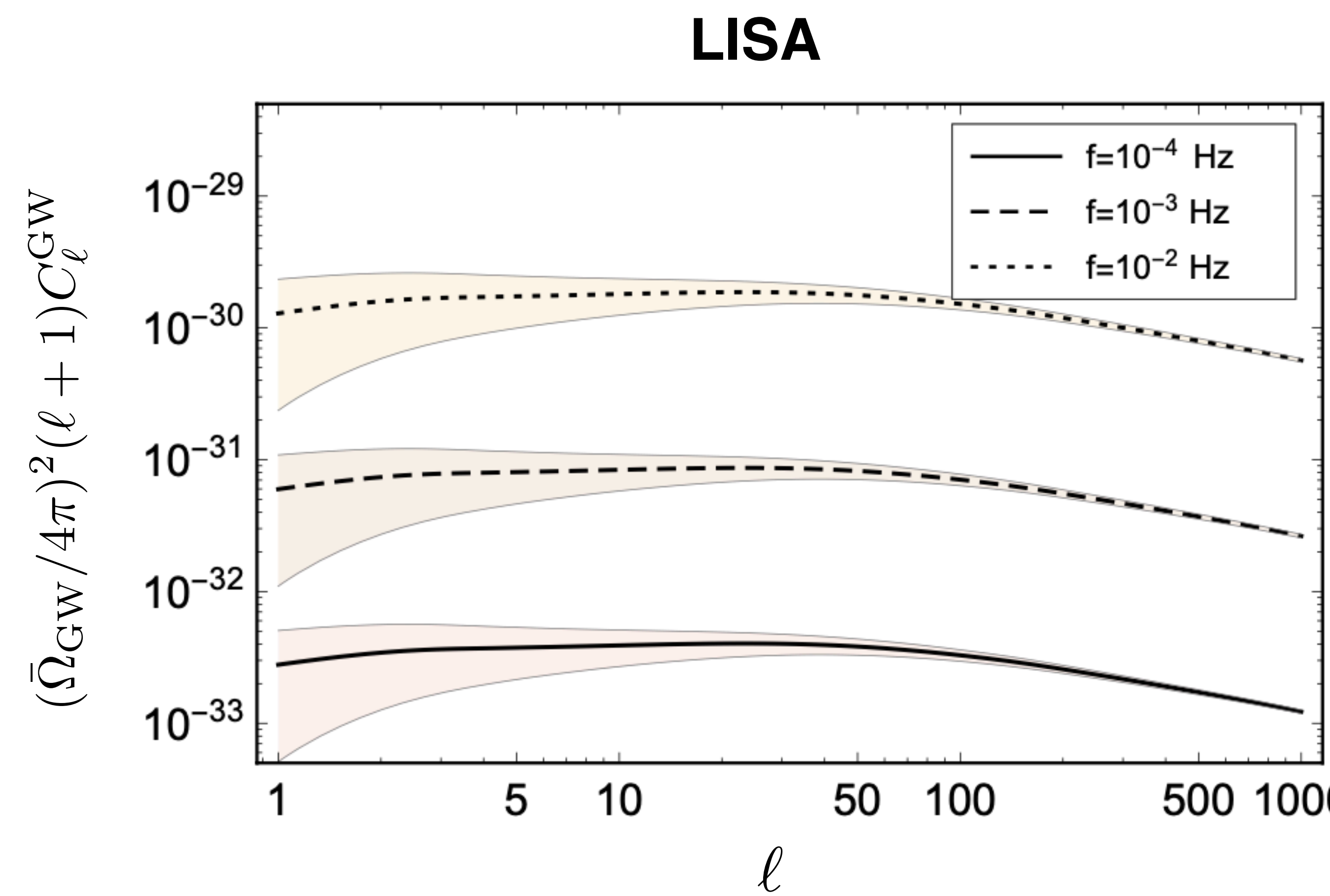
[**AR,** Valbusa, Bartolo, Bertacca, Liguori, Matarrese,'21]

AGWB Anisotropies

Stellar Origin Black Hole in LISA

[Cusin G., et al., '19]

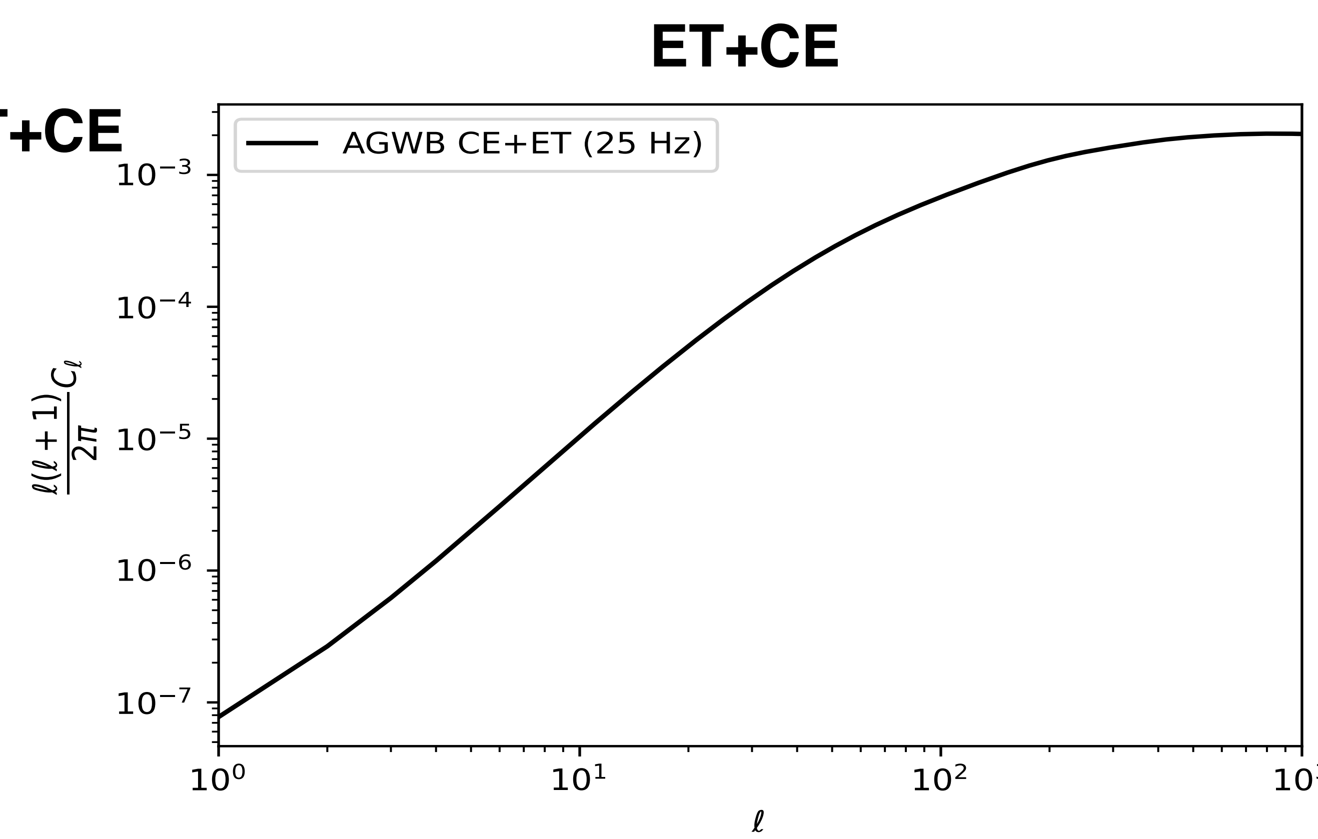
[LISA CosWG project '22, ArXiv: 2201.08782]



Stellar Origin Black Hole Anisotropies in ET+CE

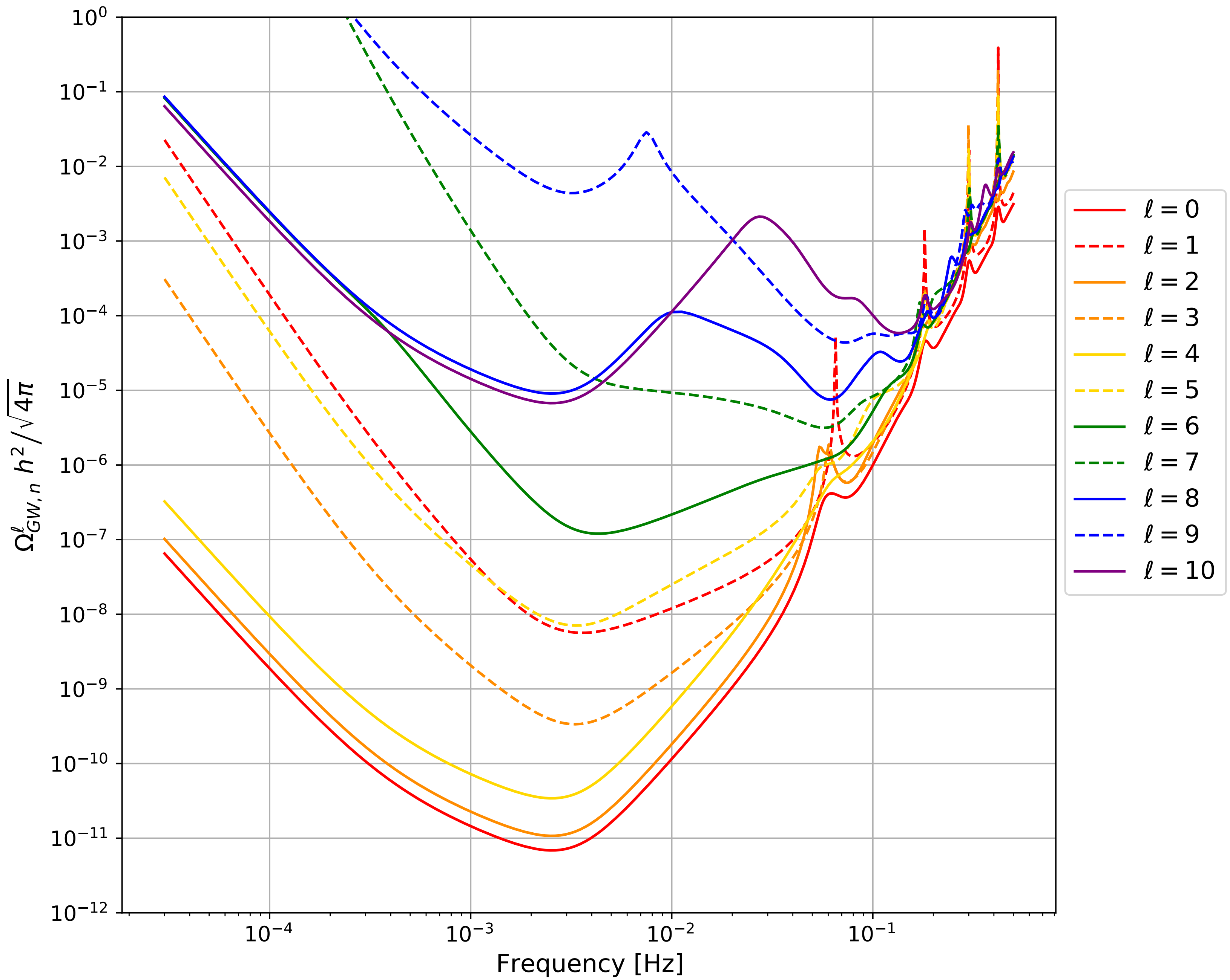
[CLASS_GWB, Bellomo, N. et el., 2110.15059]

[Valbusa, L., AR, Bertacca, D., to appear]



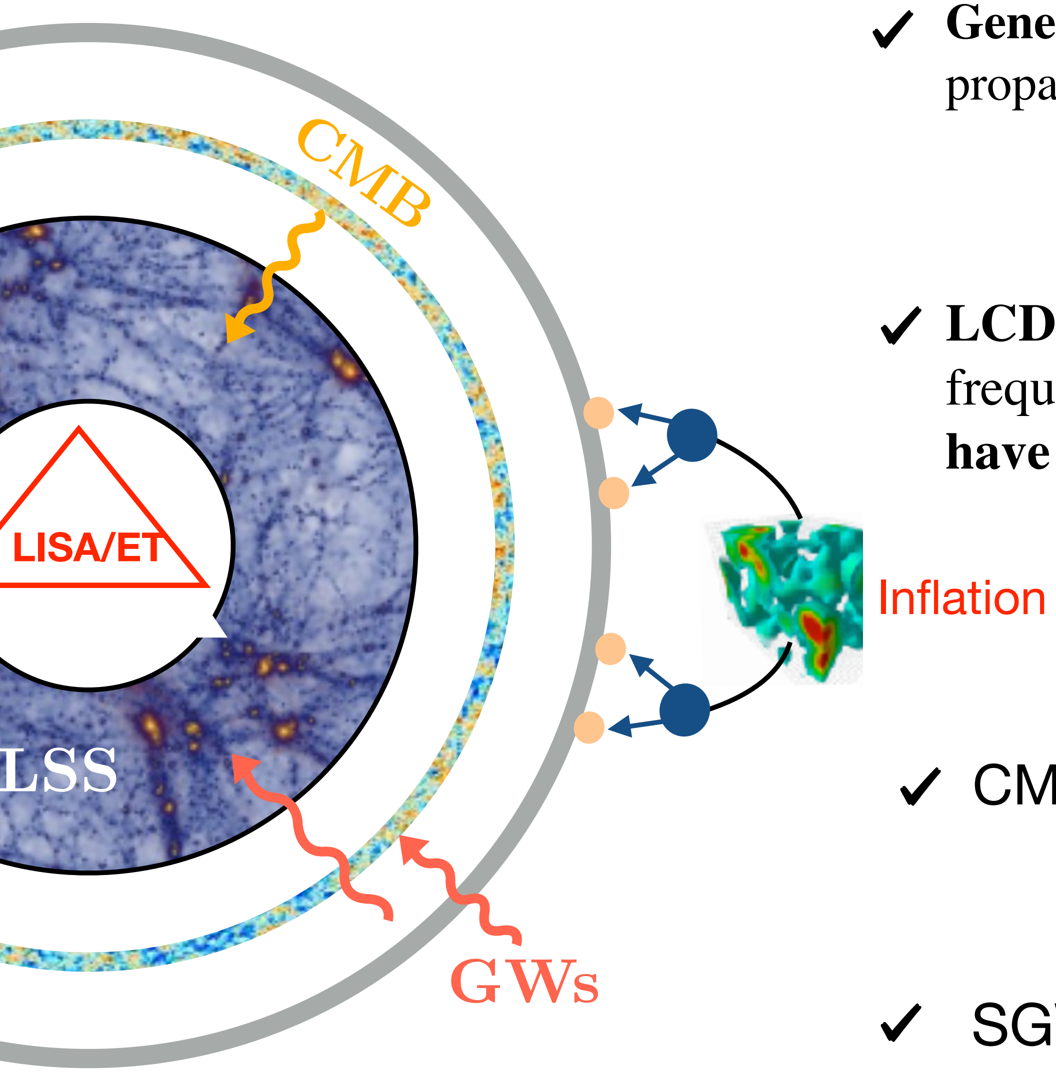
LISA Angular Sensitivity

$$\langle \mathrm{SNR} \rangle_\ell^2 = \int_0^\infty df \left[\frac{\sqrt{C_\ell^{\mathrm{GW}}}\, \Omega_{\mathrm{GW}}(f)\; h^2}{\Omega_{\mathrm{GW,n}}^\ell (f)\; h^2} \right]^2$$



[LISA CosWG project '22, ArXiv: 2201.08782]

SGWB-CMB cross correlation



EuCAPT WP

✓ **General Relativity** predicts a **non-zero correlation** since **photons** and **GW** propagate on **identical spacetime geodesics.**

✓ **LCDM model: GWs (and photons)** of high frequency **propagate through** (low frequency) **cosmological perturbations (i.e. Large-Scale Structure) which have a common origin from inflation**

✓ CMB: $T(\eta, k, \hat{n}) \equiv \bar{T}(\eta, k) + \delta T[\Phi(\eta, k), \Psi(\eta, k), \hat{n}]$

✓ SGWB: $\Omega_{GW}(\eta, k, \hat{n}) \equiv \bar{\Omega}_{GW}(\eta, k) + \delta\Omega_{GW}[\Phi(\eta, k), \Psi(\eta, k), \hat{n}]$

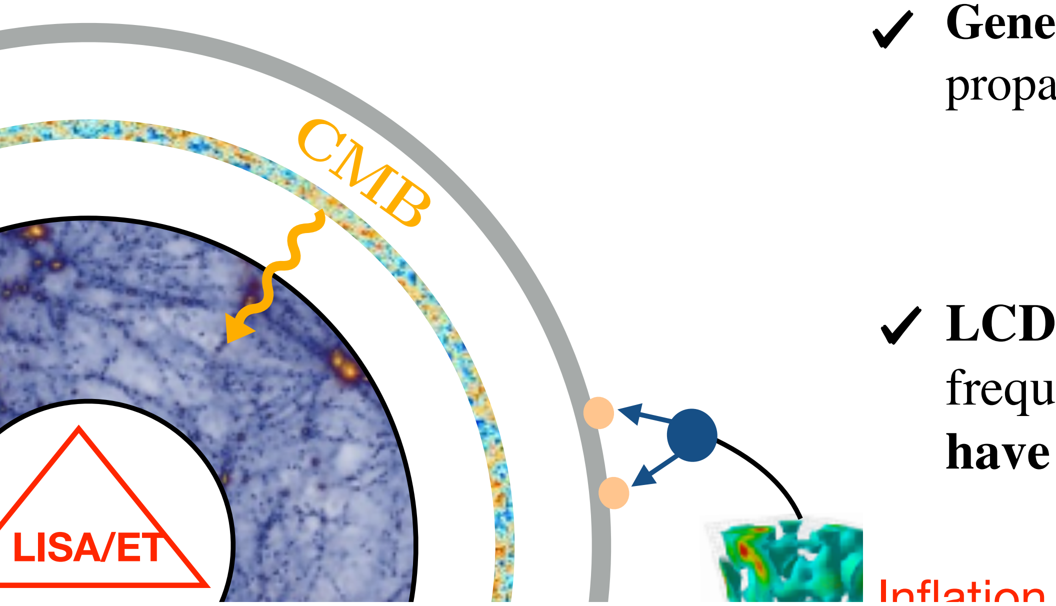
ISOTROPIC BACKGROUND

Small PERTURBATION (direction-dependent)

$$C_\ell^{LSS\times GW} \sim \langle \delta_{\rm GAL}\, \delta\Omega_{\rm GW} \rangle \qquad C_\ell^{CMB\times GW} \sim \langle \delta T \delta\Omega_{\rm GW} \rangle$$

[**AR,** Valbusa, Bartolo, Bertacca, Liguori, Matarrese, PRL '21]

SGWB-CMB cross correlation



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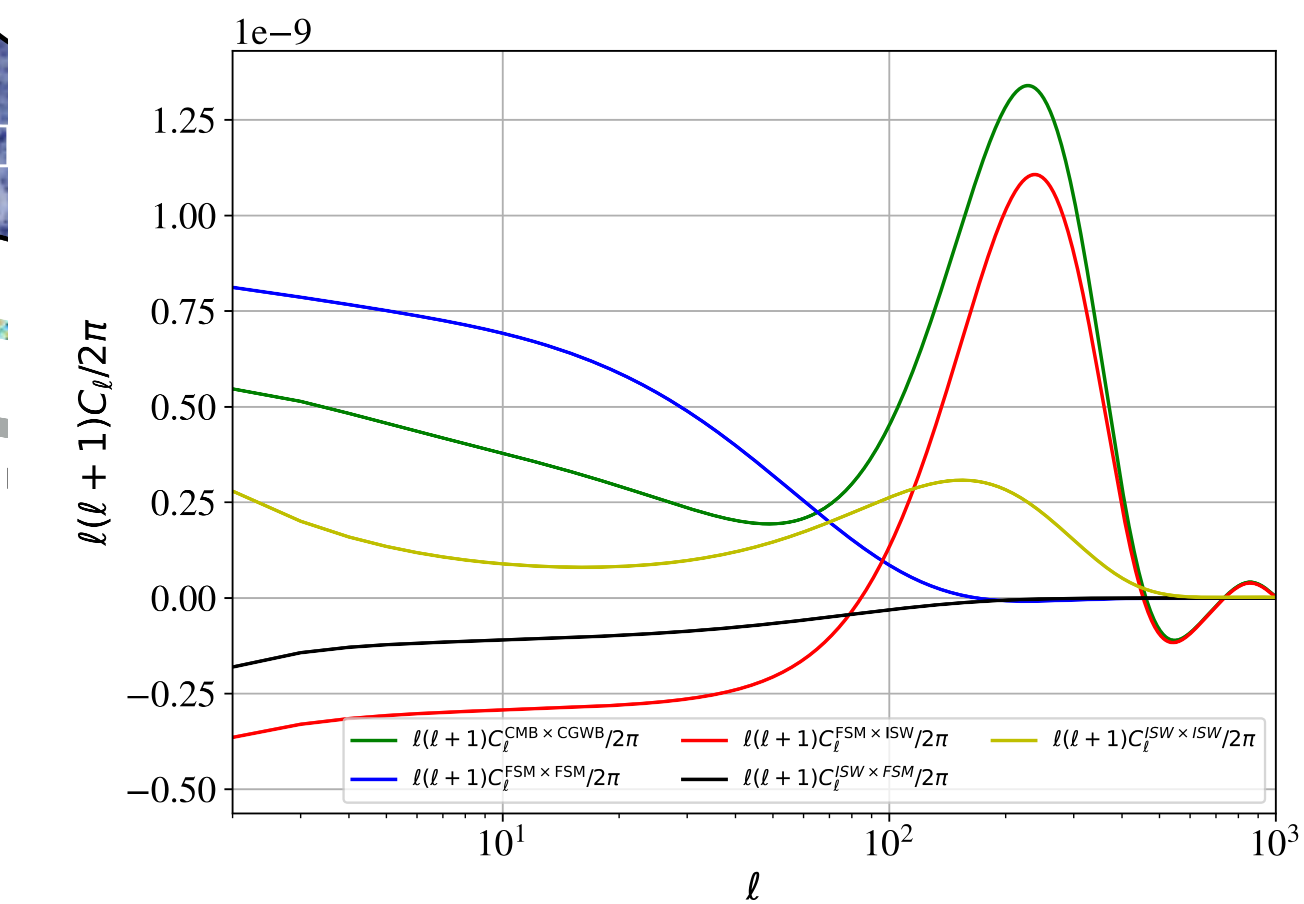
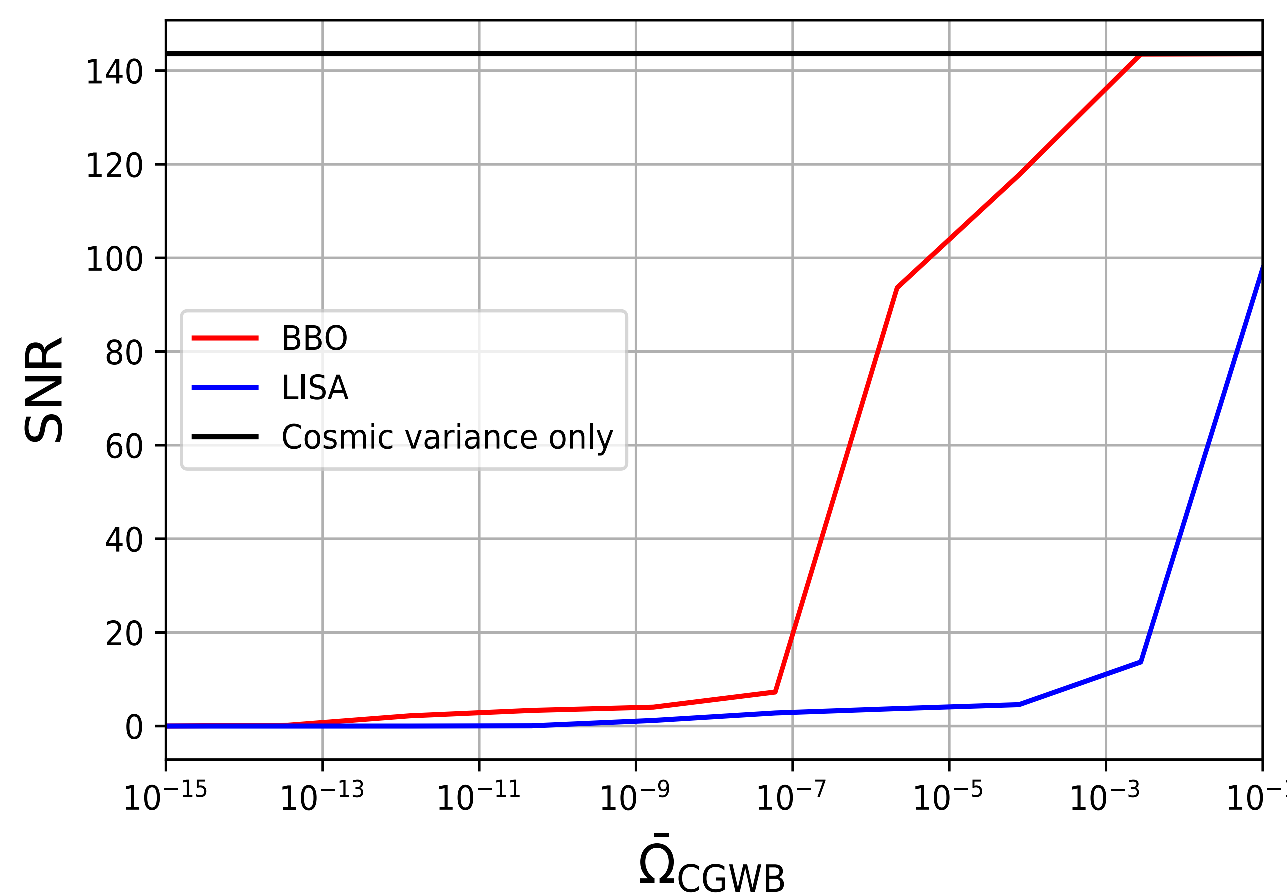




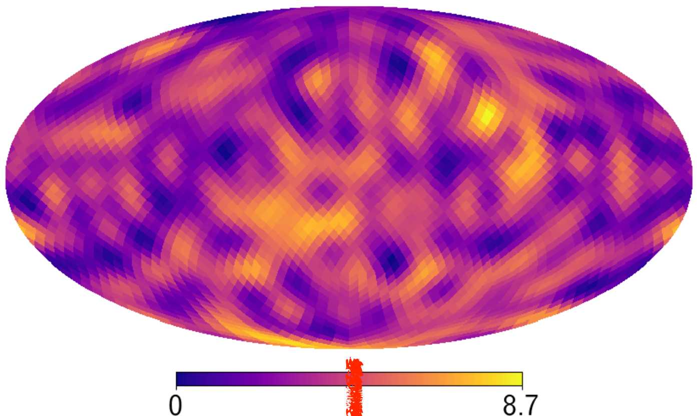
[**AR,** Valbusa, Bartolo, Bertacca, Liguori, Matarrese, PRL ’21]

Mapping the SGWB

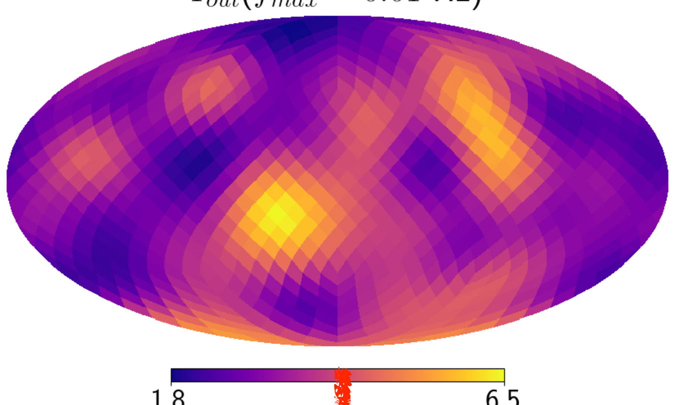
Maximum Likelihood Method

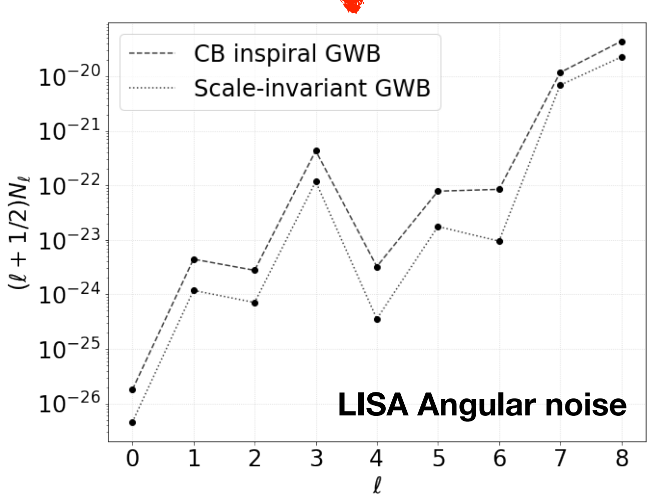
Simulated Input map

I_{in}



$I_{out}(f_{max} = 0.01$ Hz)





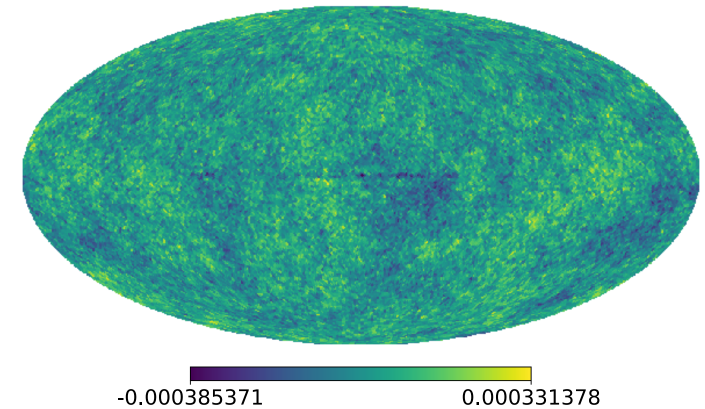
[Contaldi, C., et al., '20]

[LISA CosWG project '22, ArXiv: 2201.08782]

Constrained Realization Method

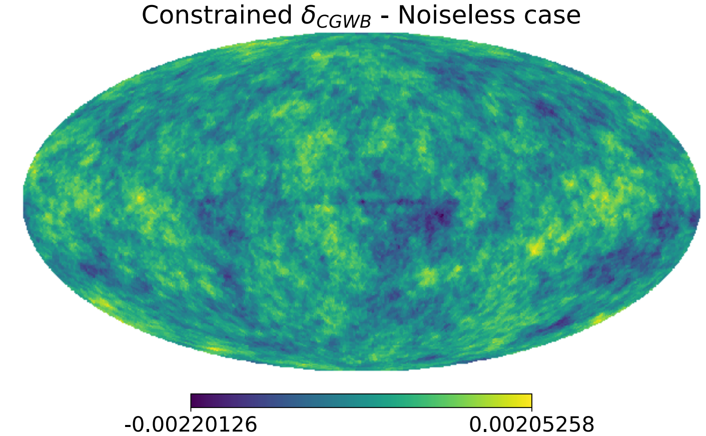
Planck SMICA map $\ell_{\max} \simeq 200$

CMB $\Delta T/T$

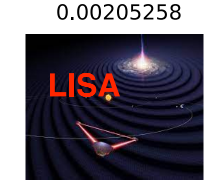


$a_{\ell m}$

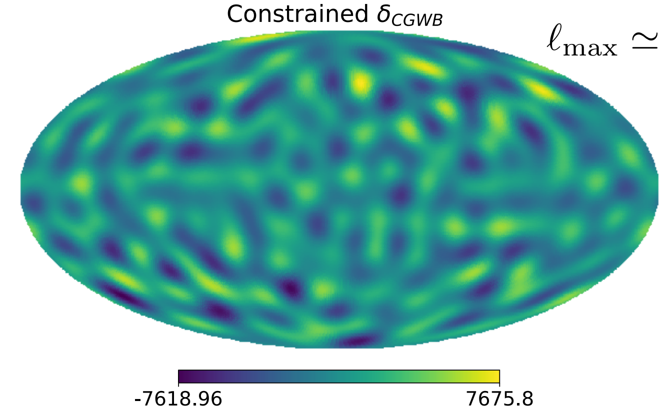
Constrained δ_{CGWB} - Noiseless case



$P(\delta^{\rm GW}_{\ell m}|a^{\rm CMB}_{\ell m})$



Constrained δ_{CGWB} $\ell_{\max} \simeq 20$



$\Sigma_{\ell m} + \mathcal{N}_\ell$

[AR, et al., PRL 21]

Conclusions

- ✓ The SGWBs are powerful probes to shed light on astrophysics, cosmology and fundamental physics
- ✓ Actual detectors are not so far from detecting the (isotropic) AGWB
- ✓ LISA and ET will allow to look into the window opened by LVK and probe different SGWB features
- ✓ The characterization of the SGWBs requires EuCAPT expertise

Thank you!

EuCAPT