Early Universe **Cosmology** with **LISA**

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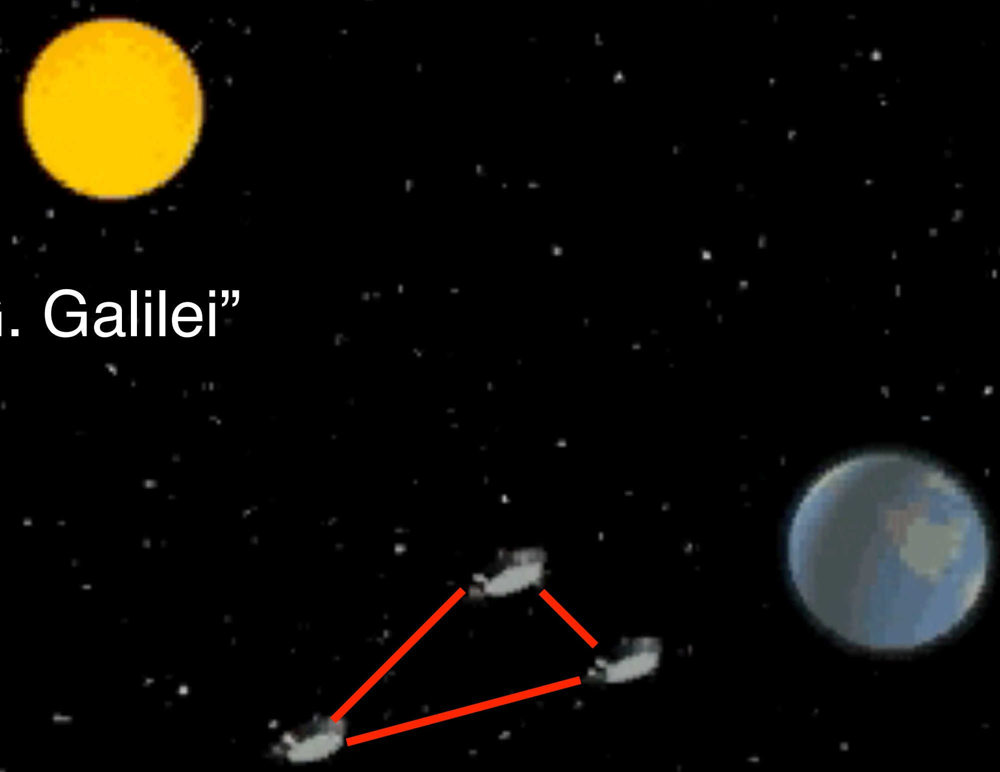

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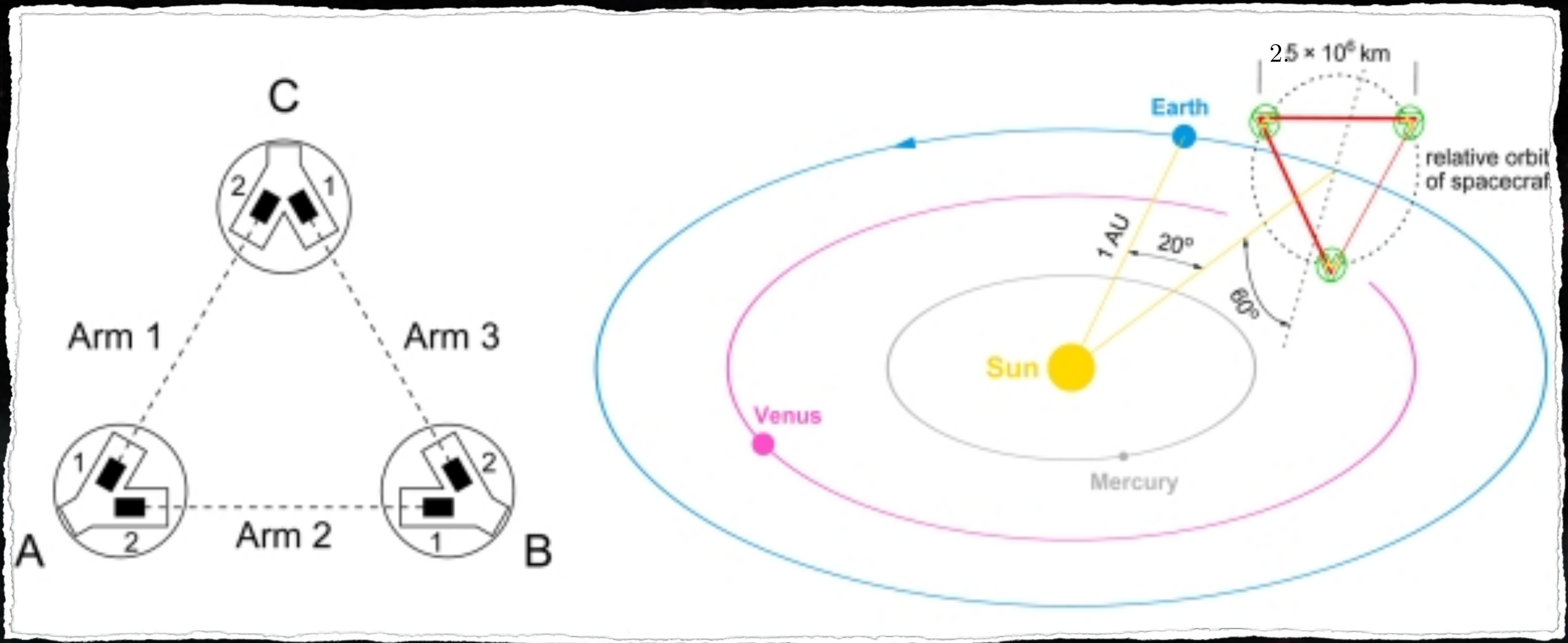
LISA detector proposal L3

Constellation of 3 spacecraft in an equilateral configuration
(a giant interferometer)
with 2.5 million-km arms



Fixed the **Noise Level to N2 (better than expected)**

L3 Proposal -> Mission duration: 4 **years science mission**
10 years nominal mission

-> Length of the arms: **2,5 million of Km**

-> **Laser: 1064 nm**

-> **Mirror size: 30 cm**

Expected launch in 2034

LISA now in PHASE B1 (phase of development)

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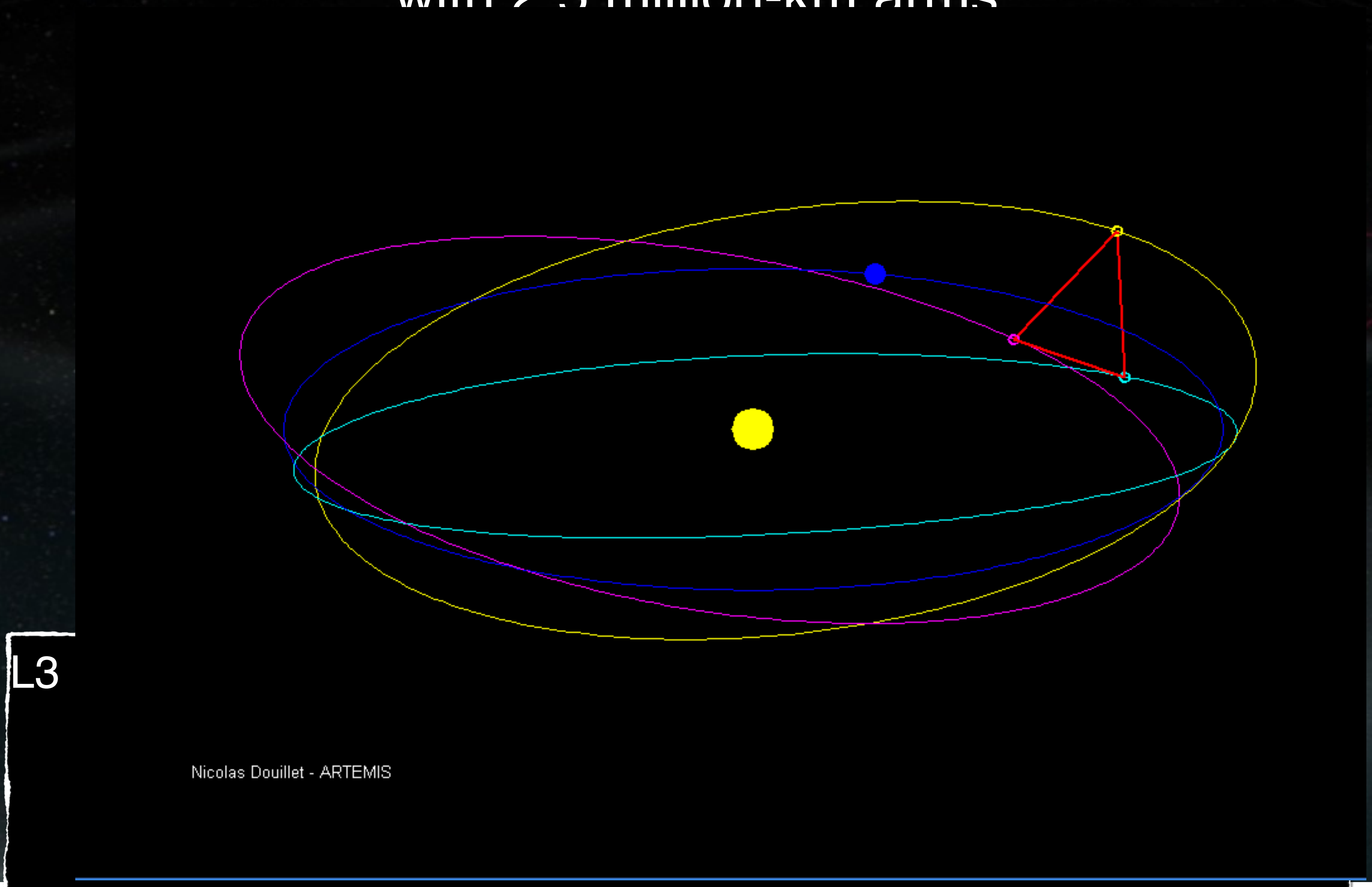

-> Mirror size: 30 cm

Expected launch in 2034

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GW sources and LISA scientific goals

[LISA L3 proposal 2017]

LISA Main Scientific Targets

- MBHBs — Klein A., et al. '15
- EMRIs — Gair J. R., et al. 17
- MBHBs as Standard Sirens — Tamanini N., et al '15 — See A. Mangiagli talk
- Compact WDs — [Karnesis N., et al., 2021]

LISA Cosmological Scientific Targets

- First order phase transition around Tev — Caprini C., et al '15, '19
- Cosmic Strings — Figueroa D., et al '19
- Inflationary GWs — Figueroa D., Ricciardone A., et al '16
- Primordial Black Holes — In preparation

Potentially interesting scenarios

Inflationary GWs generated by the amplification of the vacuum fluctuations
have an amplitude **OUT of LIGO, ET/CE and LISA range**

- Presence of extra degrees of freedom during inflation

Axion Inflation

Spectator Field

[M. Shiraishi, A. R., S. Saga, '13]
[J. Cook, L. Sorbo, '11]
[N. Barnaby, E. Pajer, M. Peloso '11]
[N. Barnaby et al. '12]
[R. Namba et al. '15]

- New patterns of symmetry during inflation

Massive graviton during inflation

[S. Endlich, A. Nicolis, J. Wang '12]
[N. Bartolo, D. Cannone, A. R., G. Tasinato '15]
[D. Cannone, G. Tasinato, D. Wands '14]

- Merging of Primordial BHs after inflation

[S. Clesse, J. G-Bellido, 15]
[S. Bird et al, 16]
[M. Sasaki et al, 16]

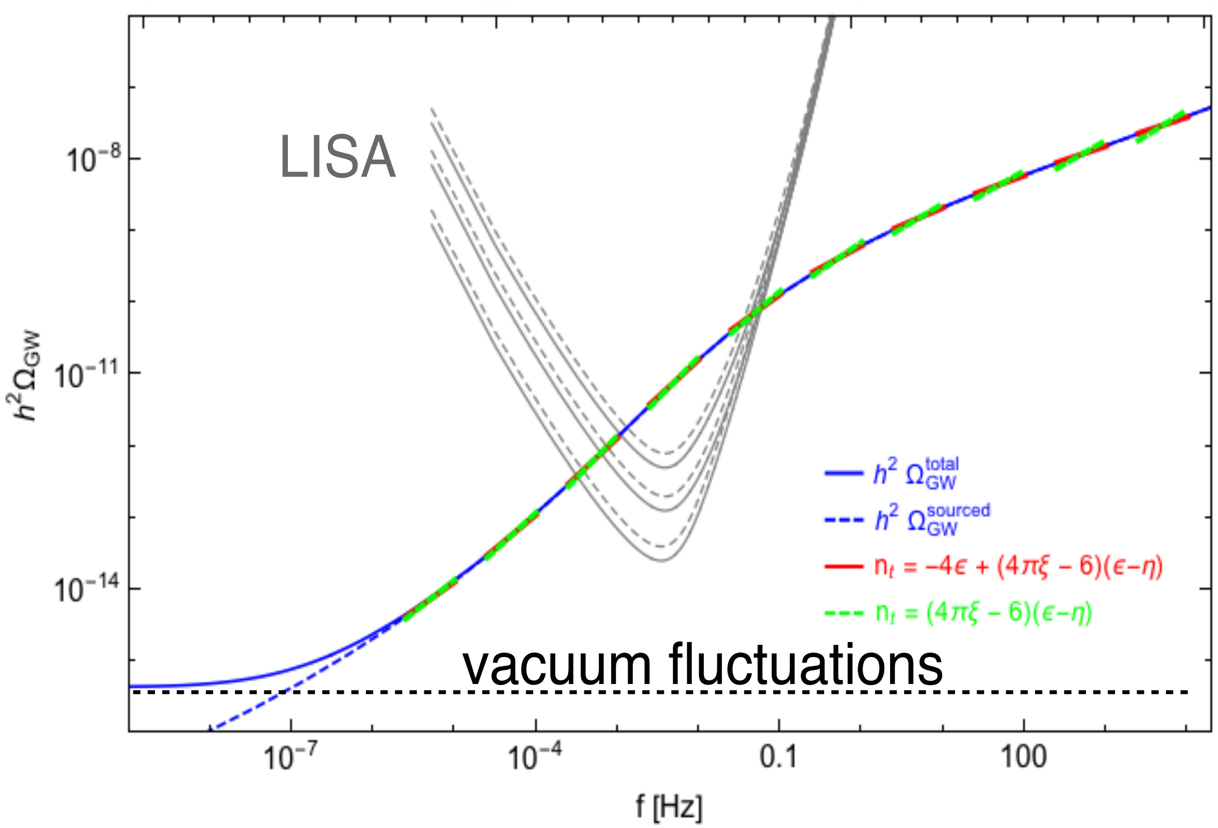
- . . .

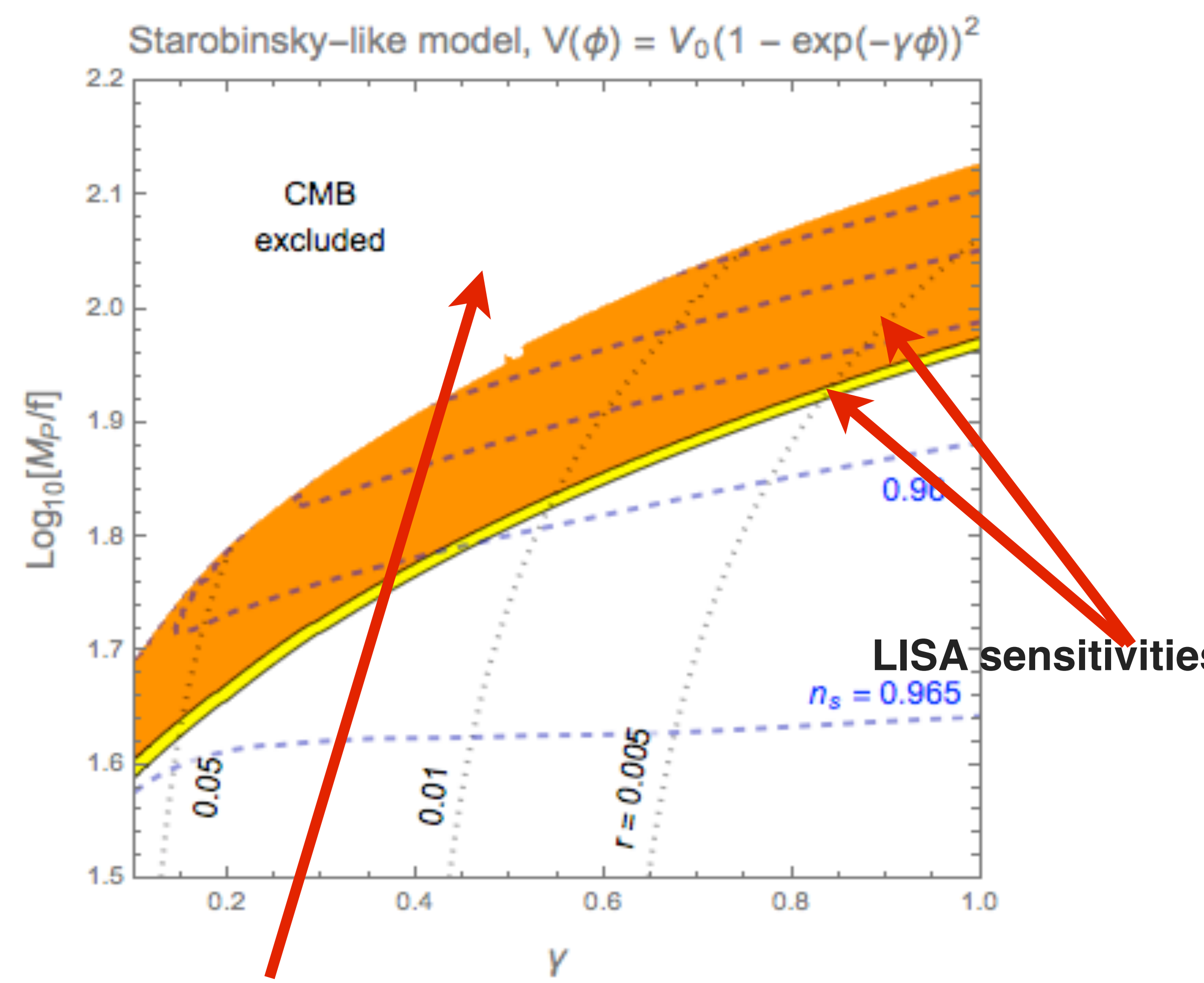
[Figueroa D., Ricciardone A., et al '16 - CosWG paper]

Inflationary sources: Axion-inflation

$$\mathcal{L} \supset -\frac{\varphi}{4f} F_{\mu\nu}\tilde{F}^{\mu\nu} \qquad \xi \equiv \frac{\dot{\varphi}}{2fH}$$

GW energy spectrum today





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

non-Gaussianity, mu-distorsion (+LIGO)

Peculiar features

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

complementarity between CMB and direct GW observations

[Bartolo N., et al. '16 - LISA CosWG paper]

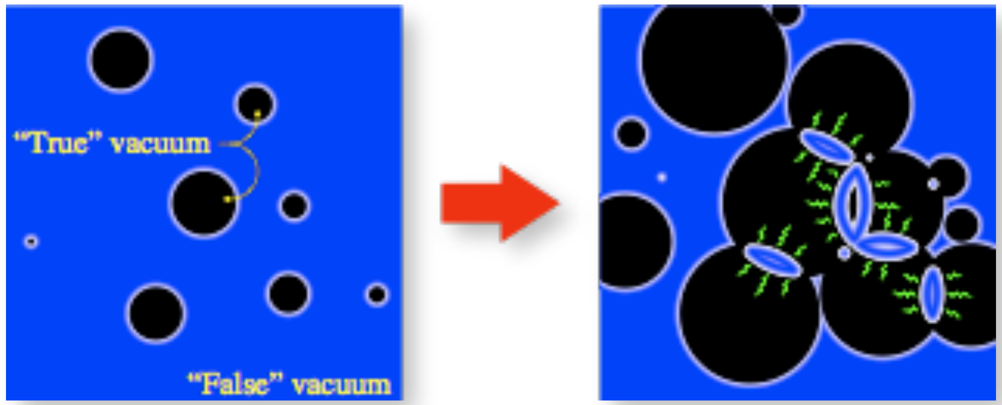
[Cook & Sorbo, '11] [Namba et al., '15]

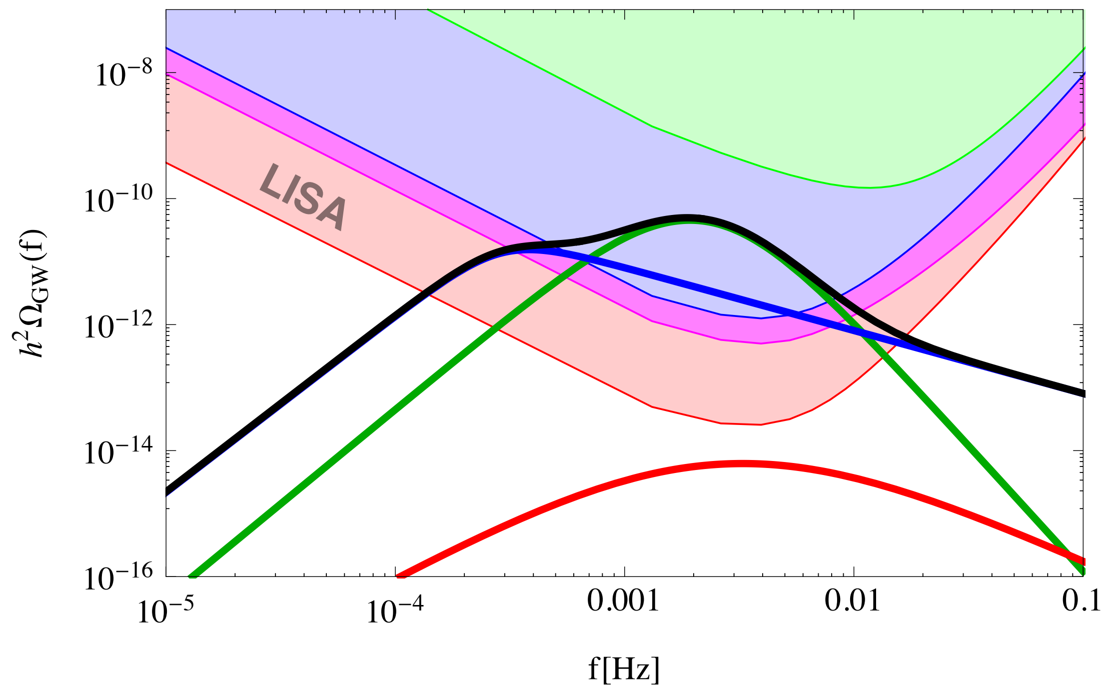
[Domcke, Pieroni, Binetruy, '16]

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





Processes

- Bubble collisions
- MHD Turbulence
- Sound Waves

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

- peaked spectrum with

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

First-order PT

Since LISA is sensitive to energy scales 10 GeV-100 TeV:

- LISA can probe EWPT in BSM models...
  - direct extensions of MSSM
  - direct coupling of Higgs sector with scalars
  - SM plus dimension six operator

- ...and beyond the EWPT
  - DM sector: provides DM candidate and confining PT
  - Warped extra dimensions: PT from the dilaton/radion stabilisation in RS-like models

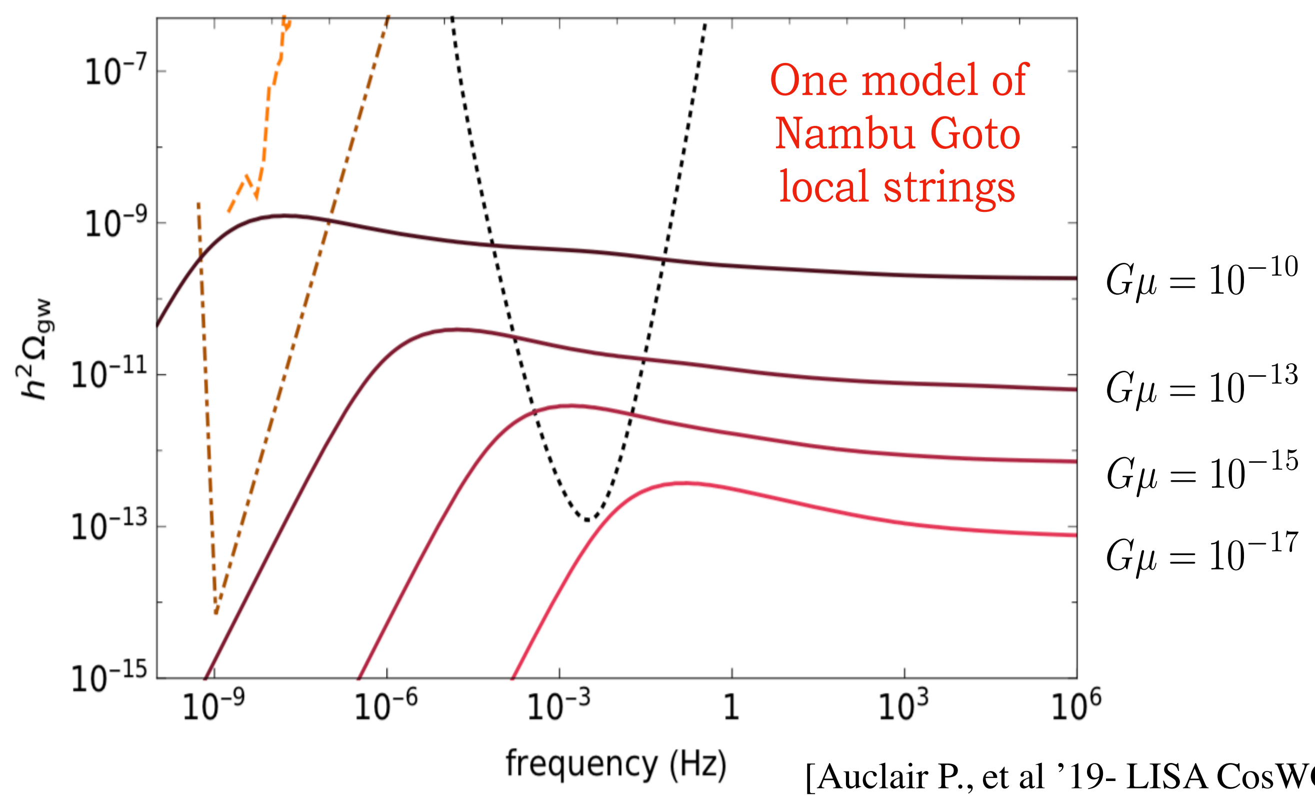
LISA as a new probe of BSM physics complementary to colliders

SGWB from Topological Defects

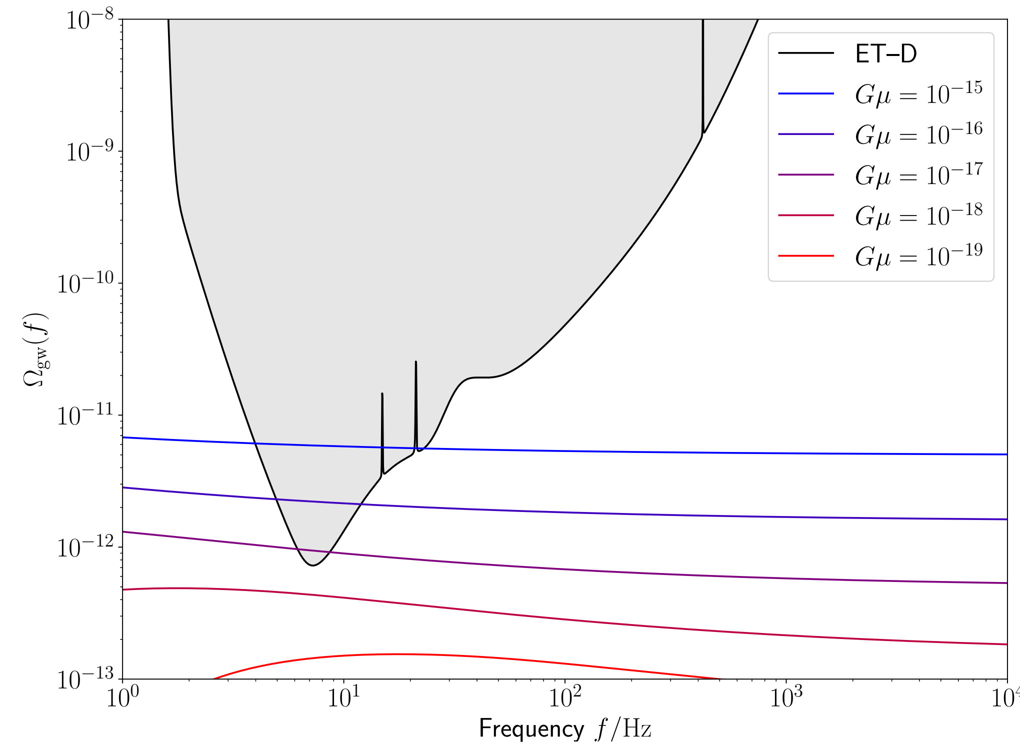
Cosmic Strings (or other kind of topological defects) are non-trivial field configurations left-over after the phase transition has completed

A network of cosmic strings emits GWs

(results are model dependent)



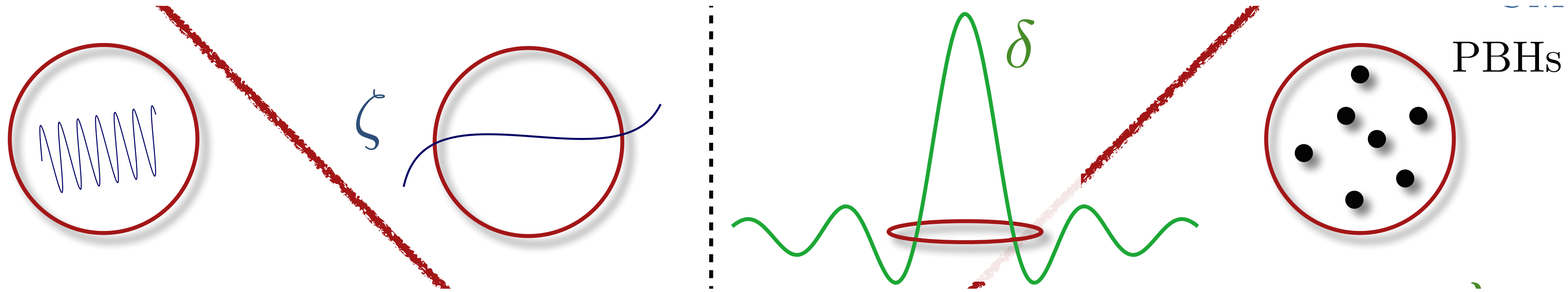
[Auclair P., et al '19- LISA CosWG]



[ET Science Case, 2020]

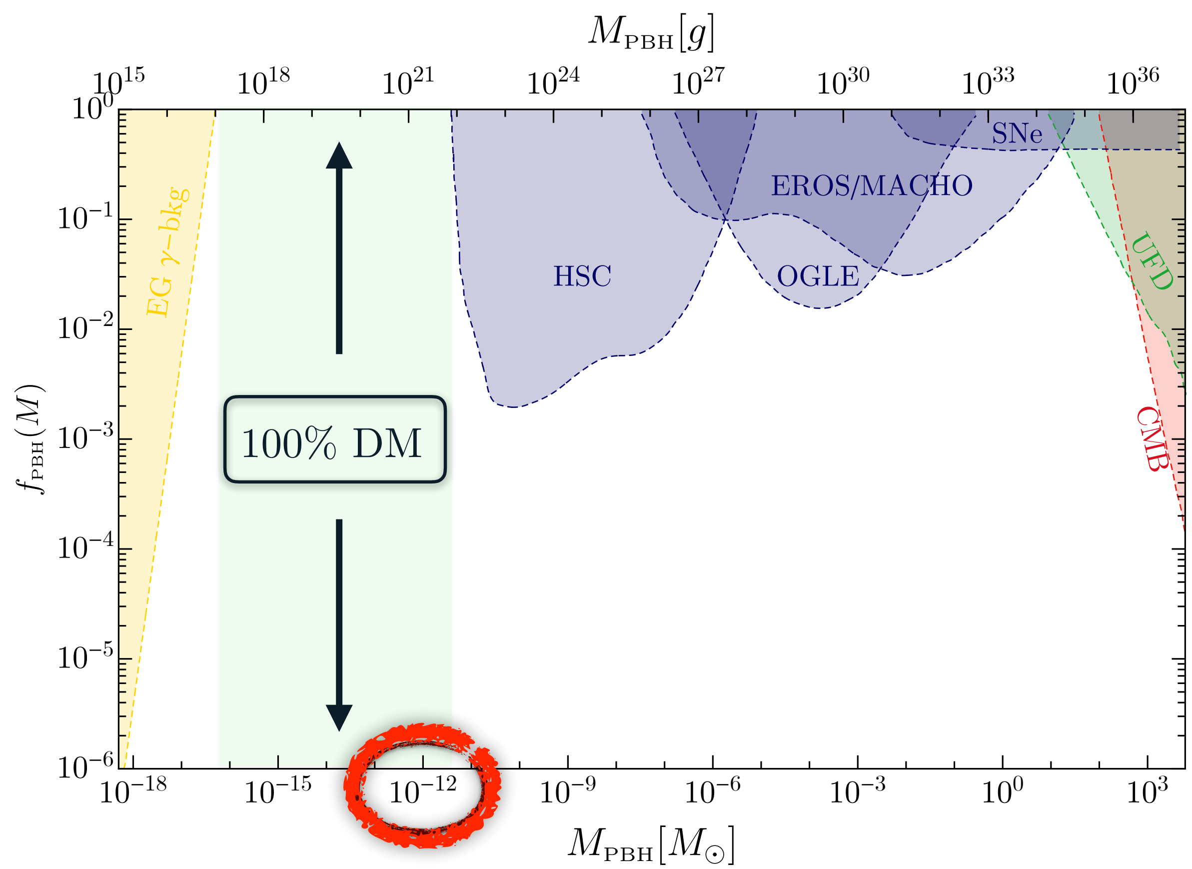
Future CMB B-mode	LIGO/Virgo bound	LISA or ET	
$G\mu \sim 10^{-9}$	$G\mu \sim 10^{-14}$	$G\mu \gtrsim 10^{-17}$	$G\mu \sim 10^{-6}\left(\frac{\eta}{10^{16}\ \mathrm{GeV}}\right)^2$

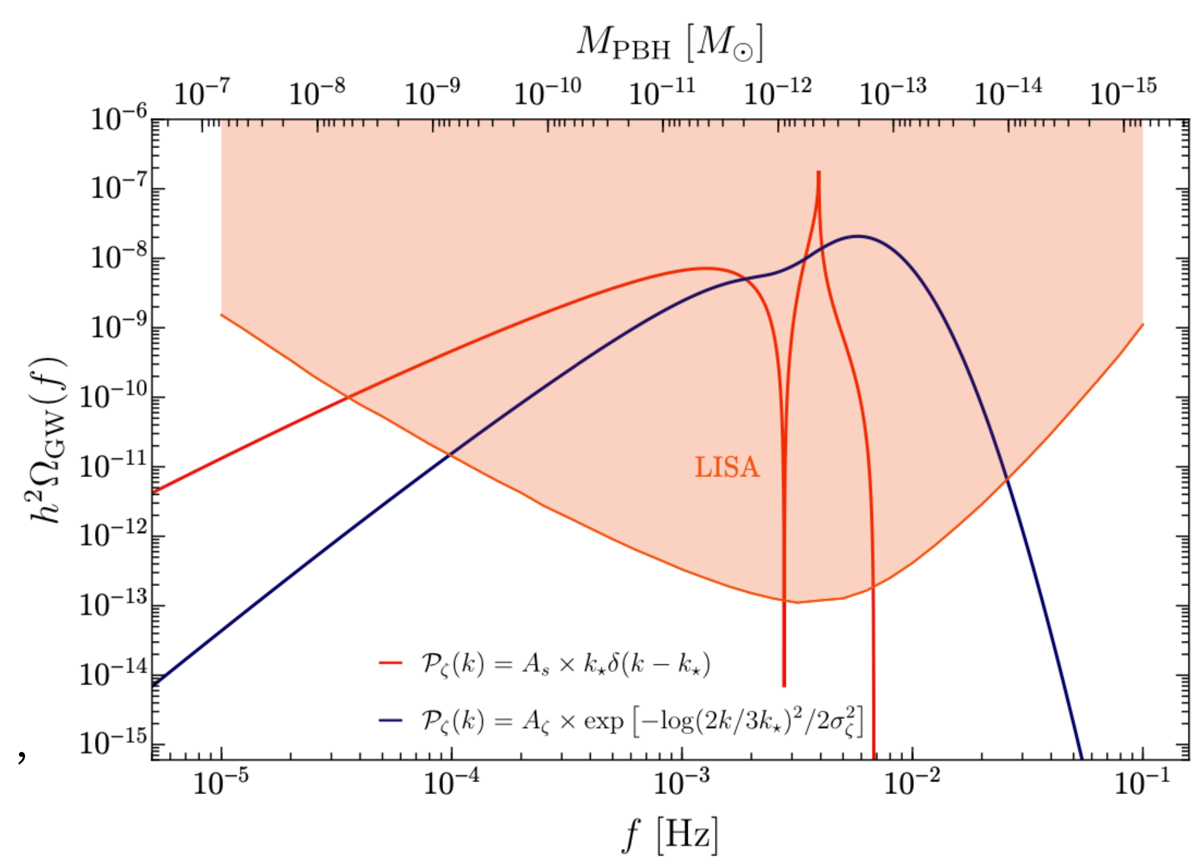
GW from Primordial Black Holes



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

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





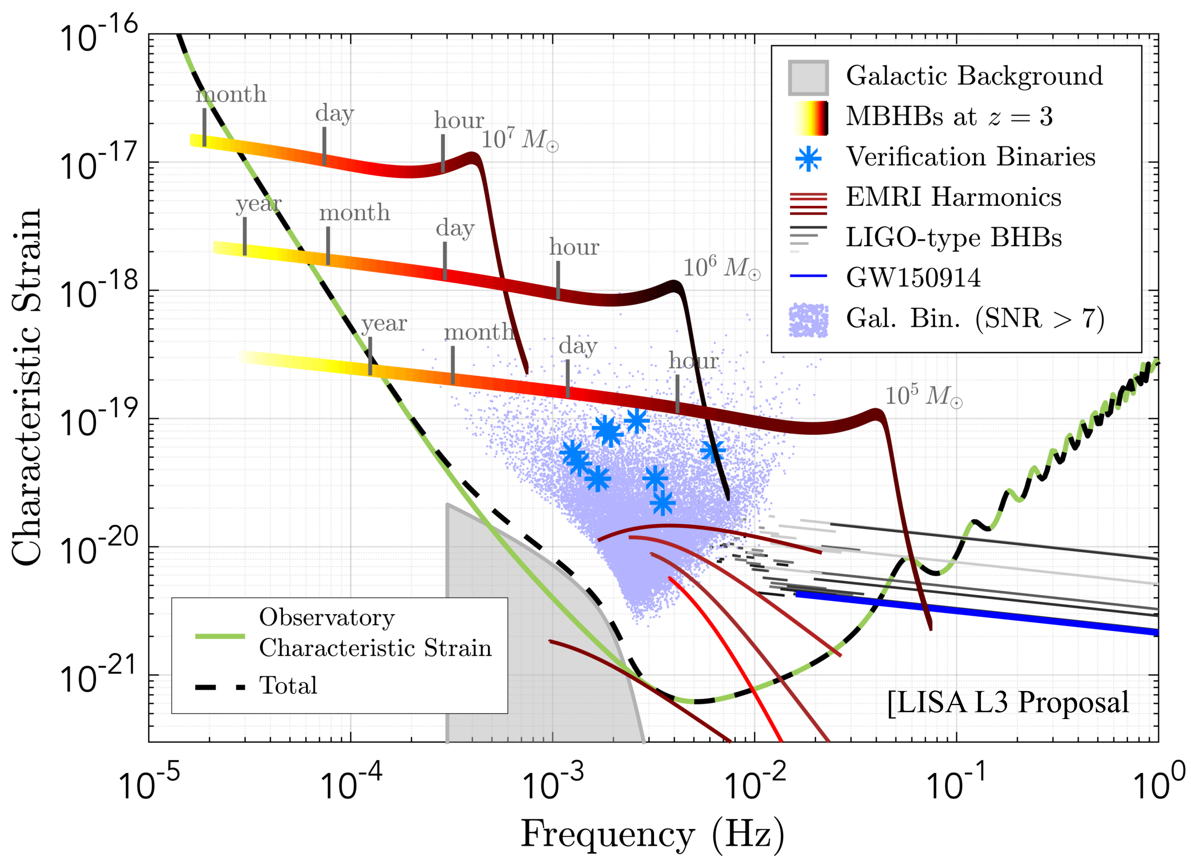
[Espinosa, et al., 2018]
[Bartolo, N., et al., PRL 2019]
[De Luca, V., et al., PRL 2021]

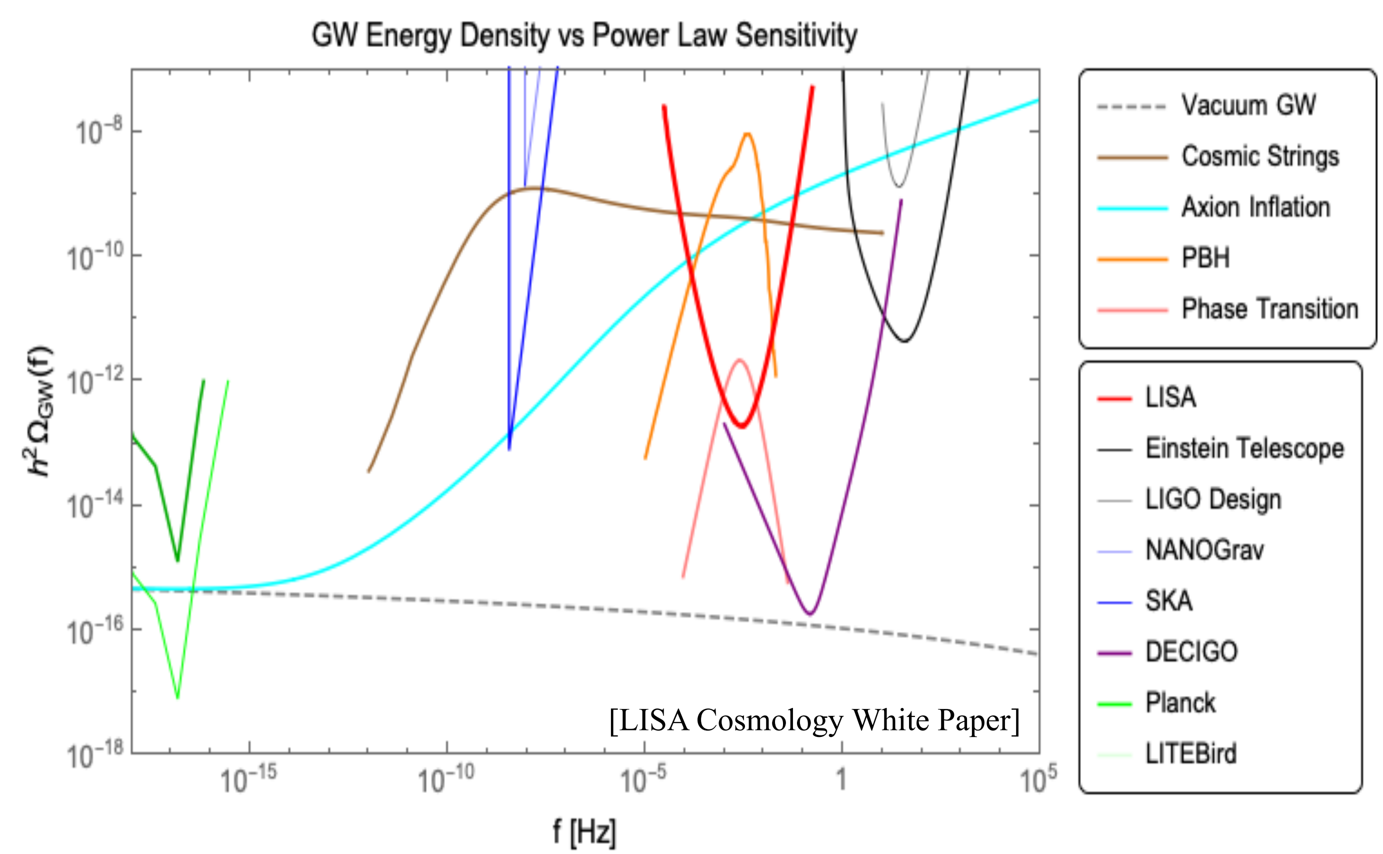
$$f \simeq 3\cdot 10^{-9}\,\mathrm{Hz}\left(\frac{\gamma}{0.2}\right)^{1/2}\left(\frac{M}{M_\odot}\right)^{-1/2}$$

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

Characterization of the SGWB

GWB from cosmological sources superimposed to the Astrophysical GWB

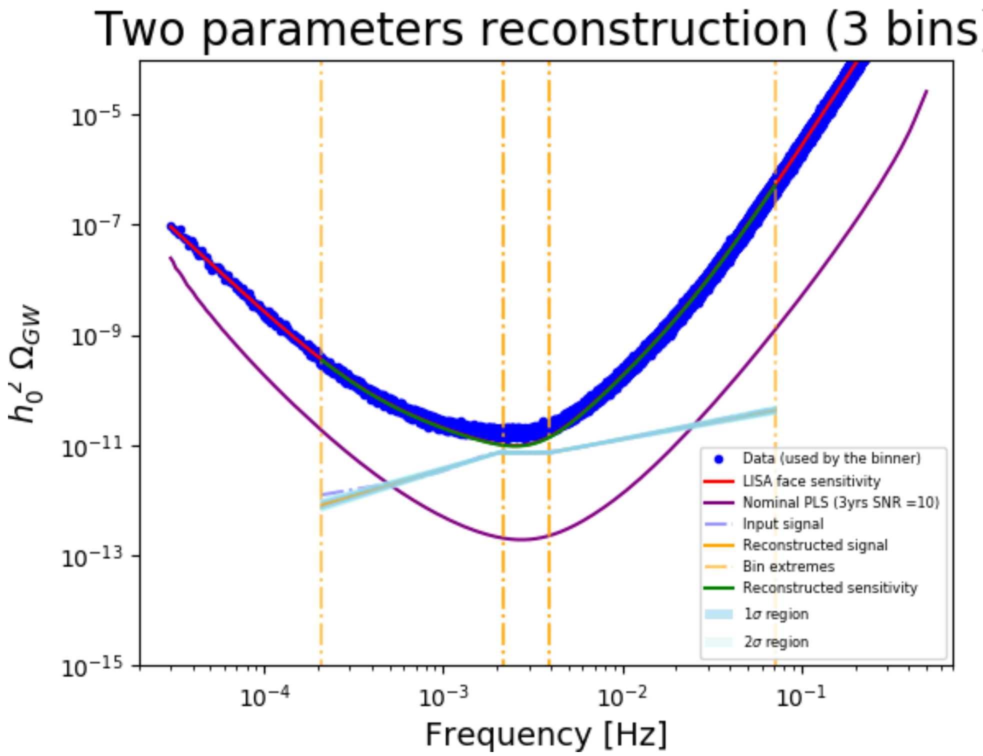




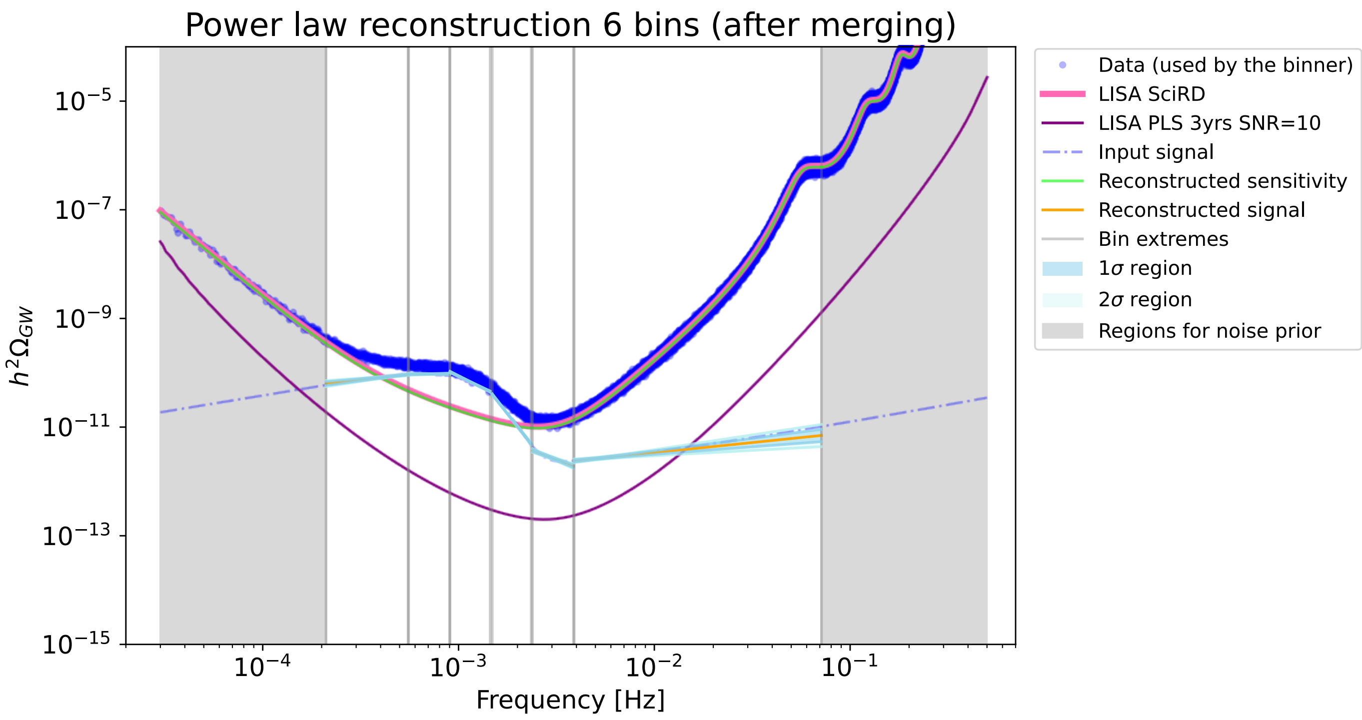
Peculiar features to distinguish them:

- **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:** $\Omega_{\rm GW}(f, \vec{x})$ [LISA anisotropies (LISA CosWG) '22]
- **Statistics:** $\langle \Omega_{\rm GW}^n \rangle$

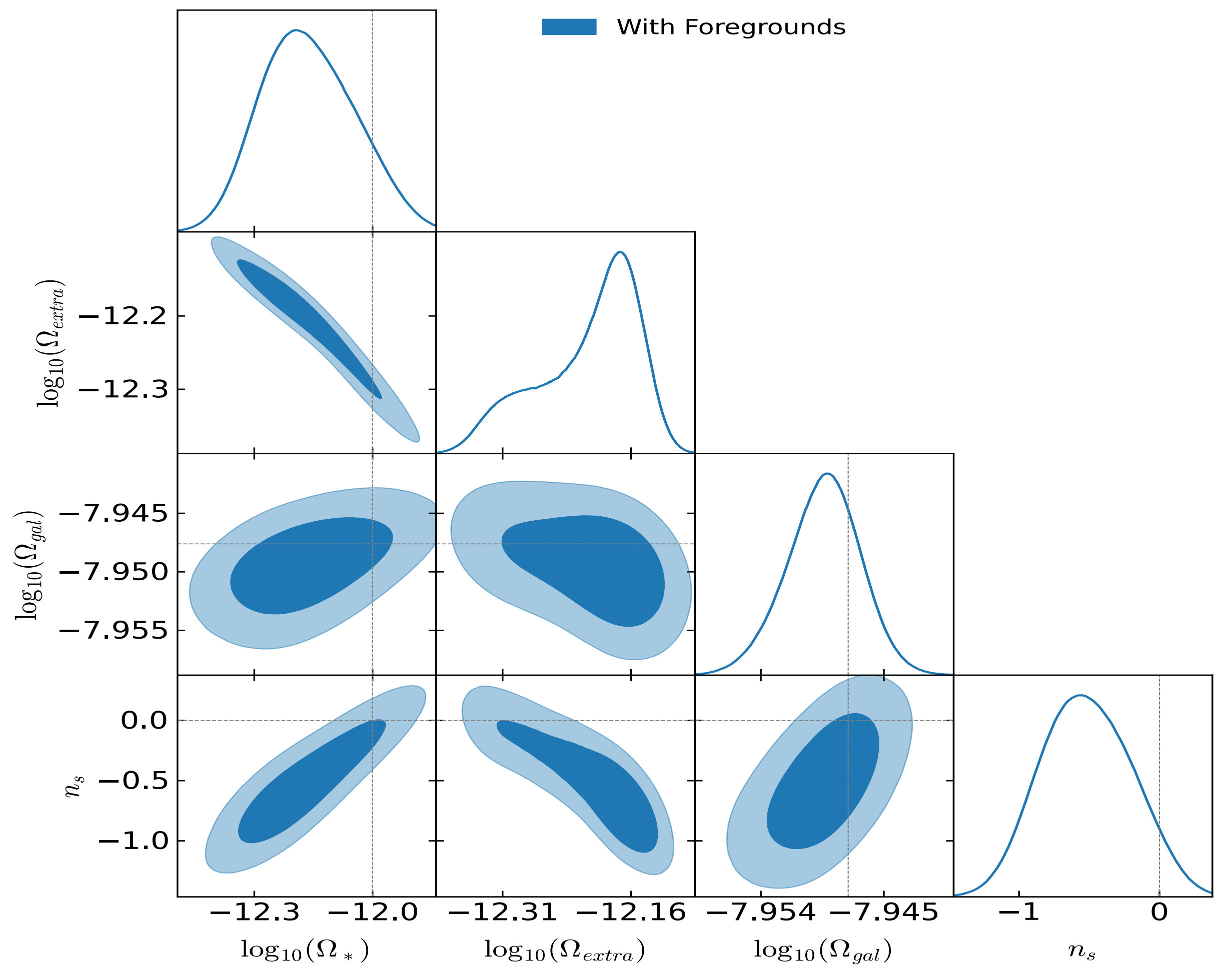
Spectral shape Reconstruction



(Axion inflation, Phase Transition beyond SM)



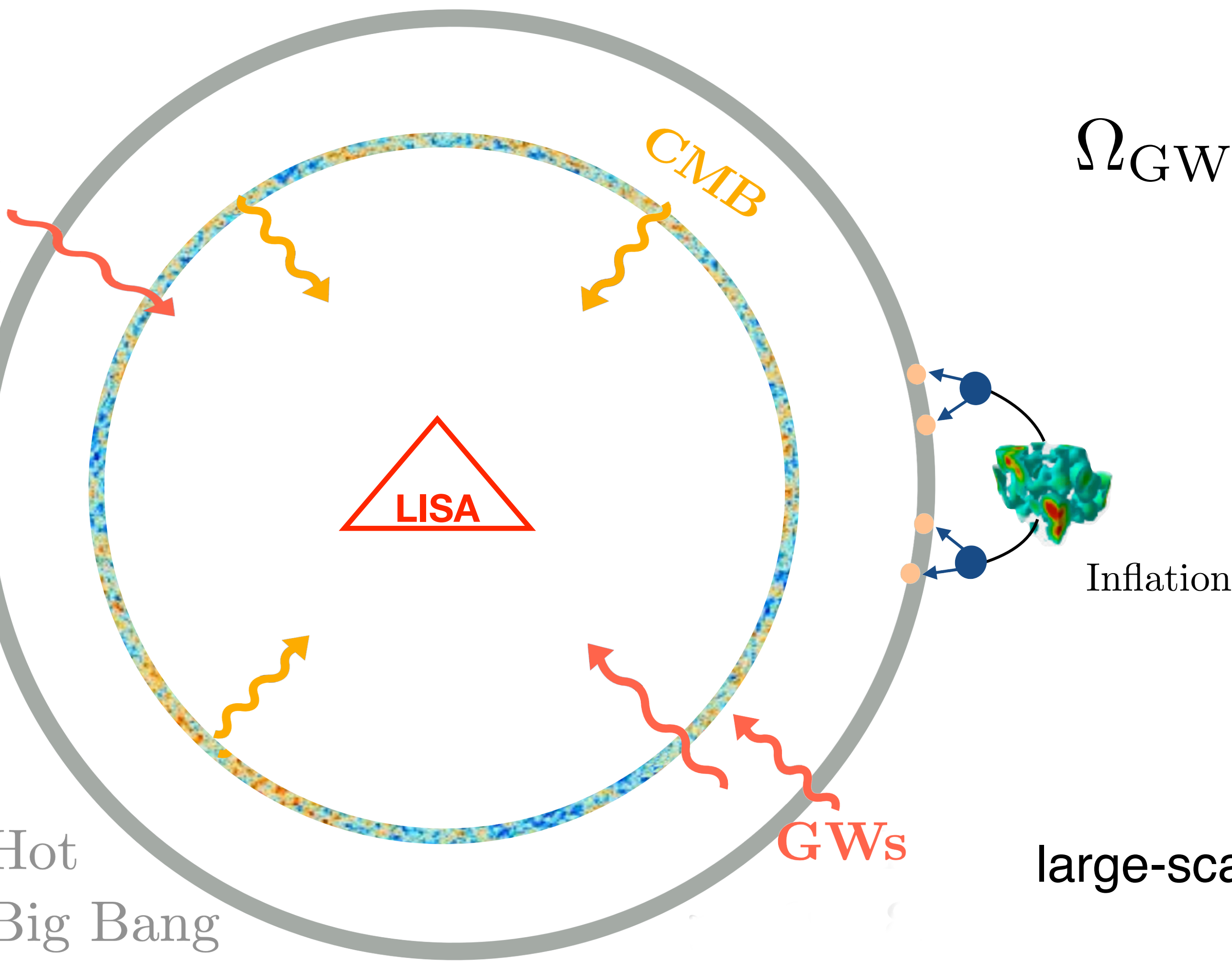
(Power law + astro (foregrounds) binaries)



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

See J. Fumagalli talk

AGWB Anisotropies



EuCAPT WP

Treatment as CMB

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

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]

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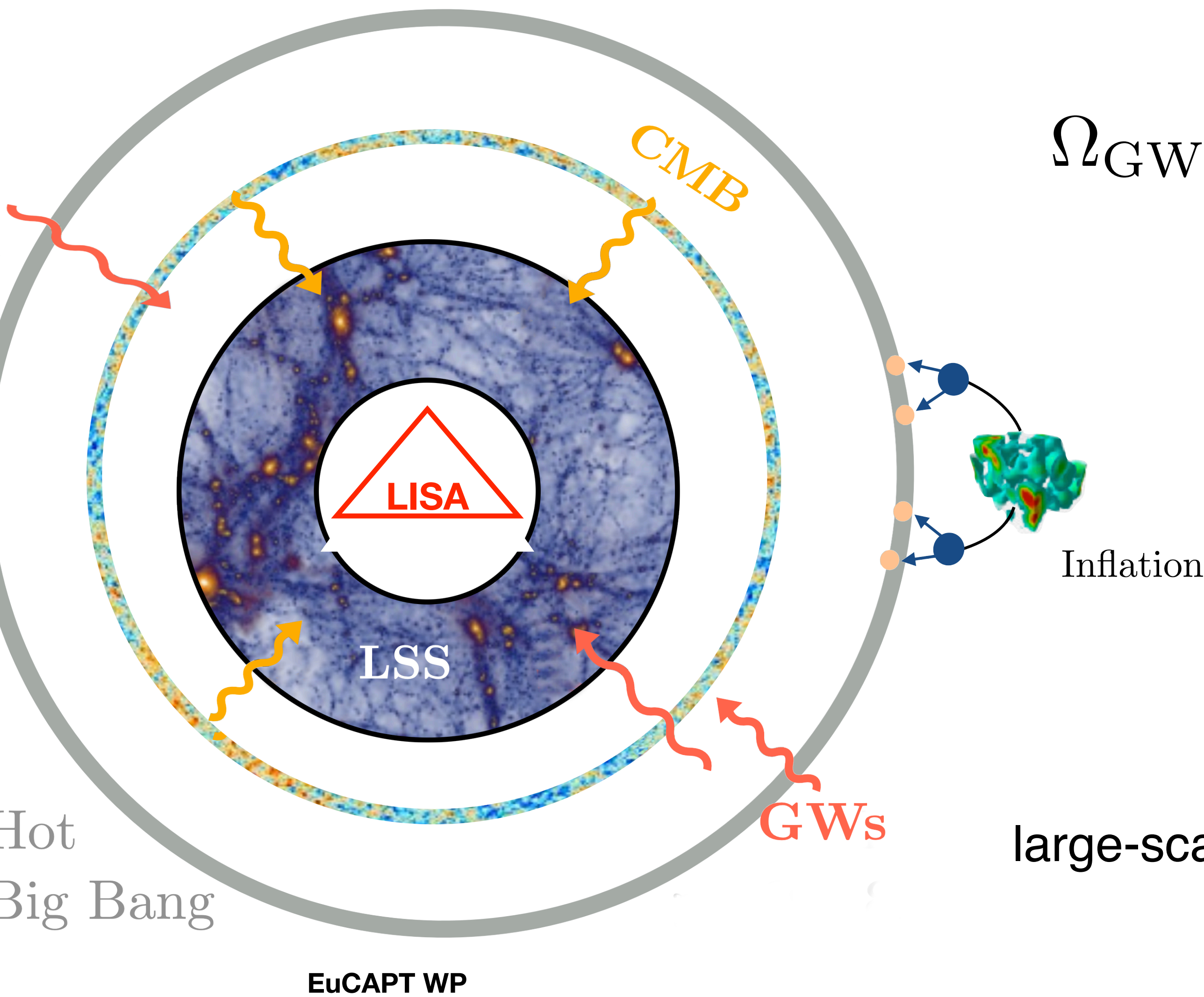

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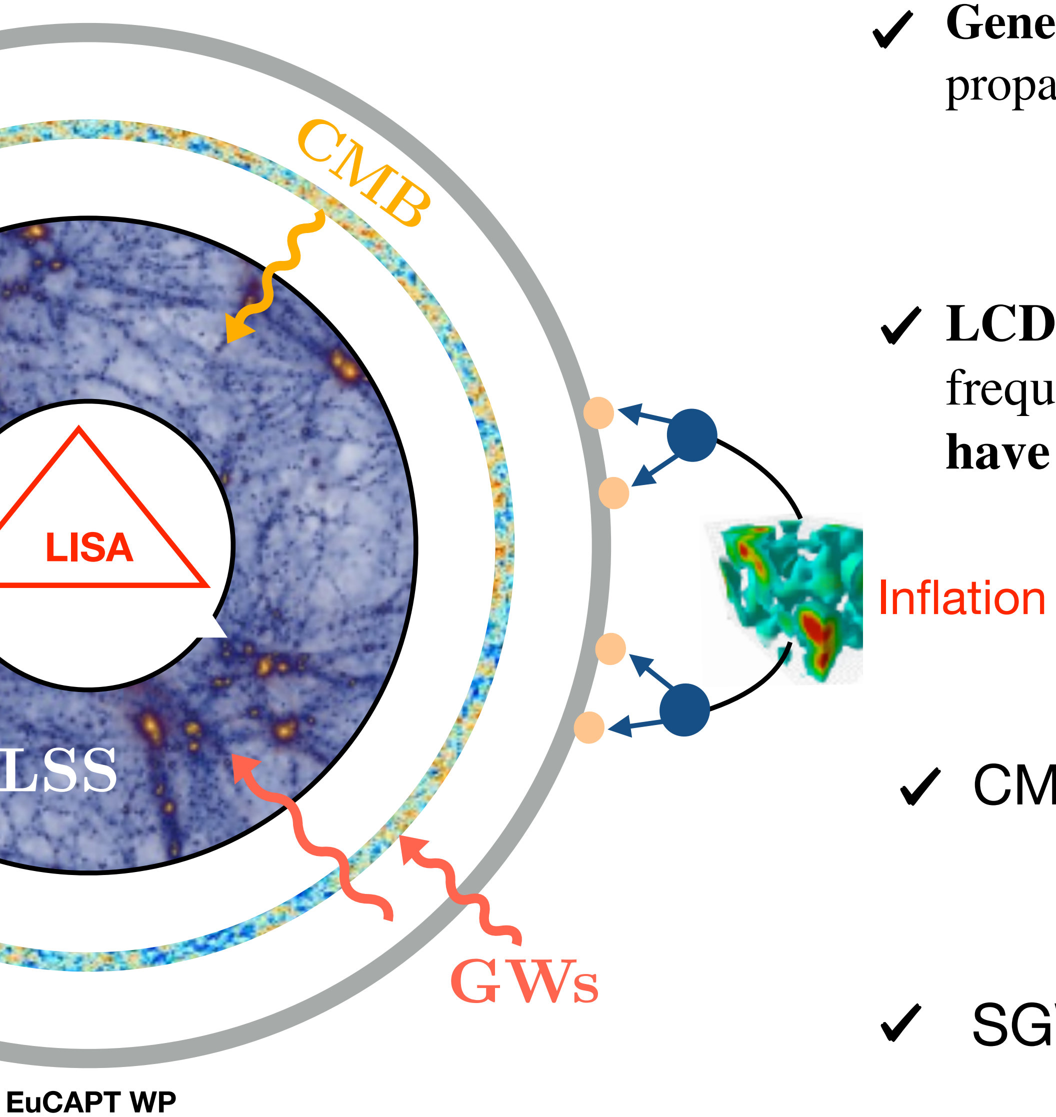
SGWB-CMB cross correlation



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

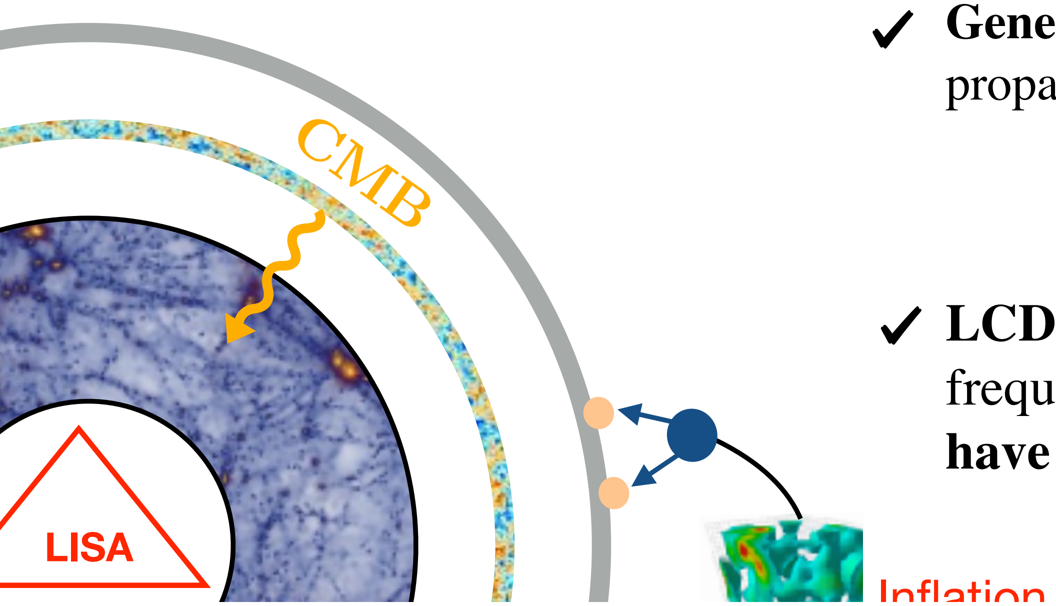
ISOTROPIC BACKGROUND

Small PERTURBATION (direction-dependent)

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

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

SGWB-CMB cross correlation



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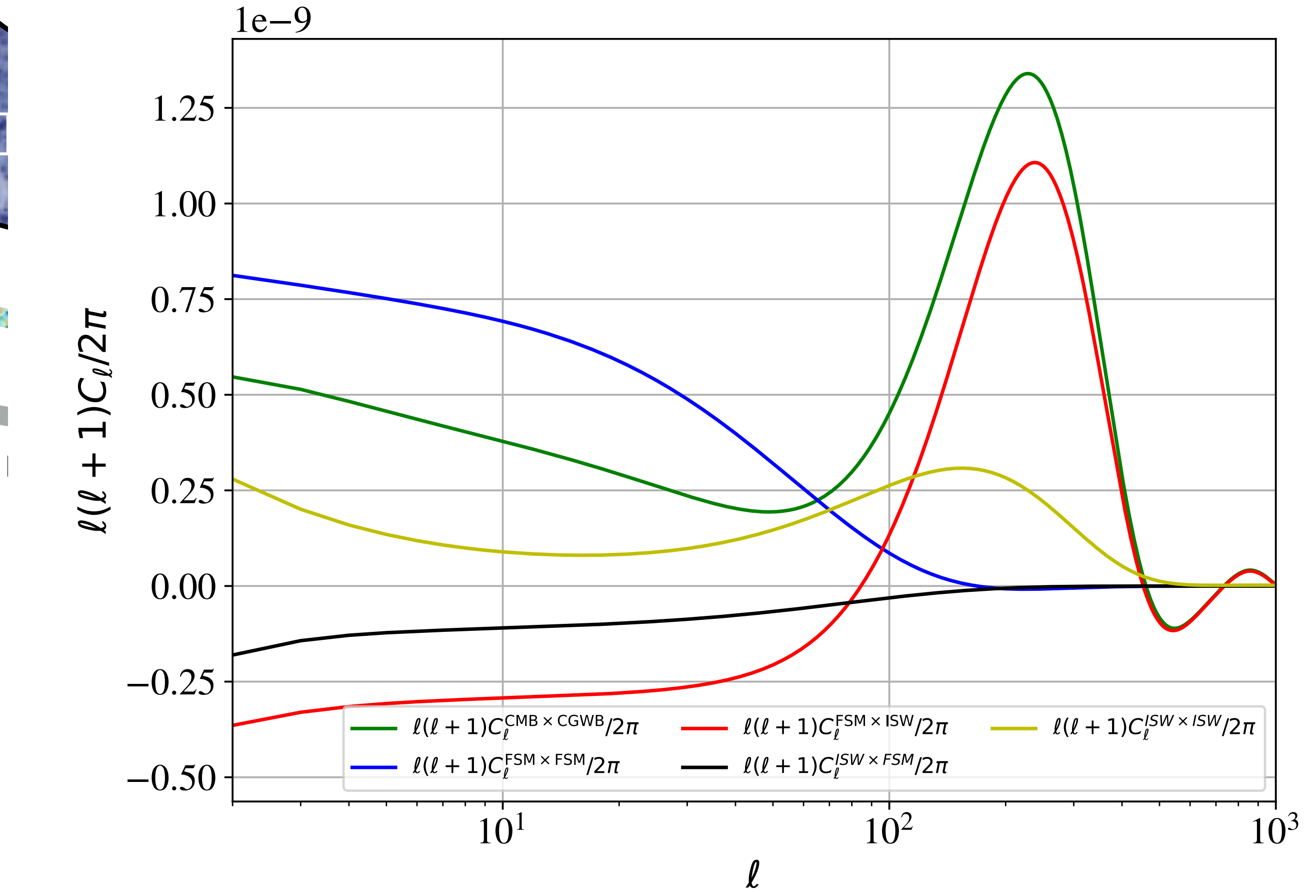

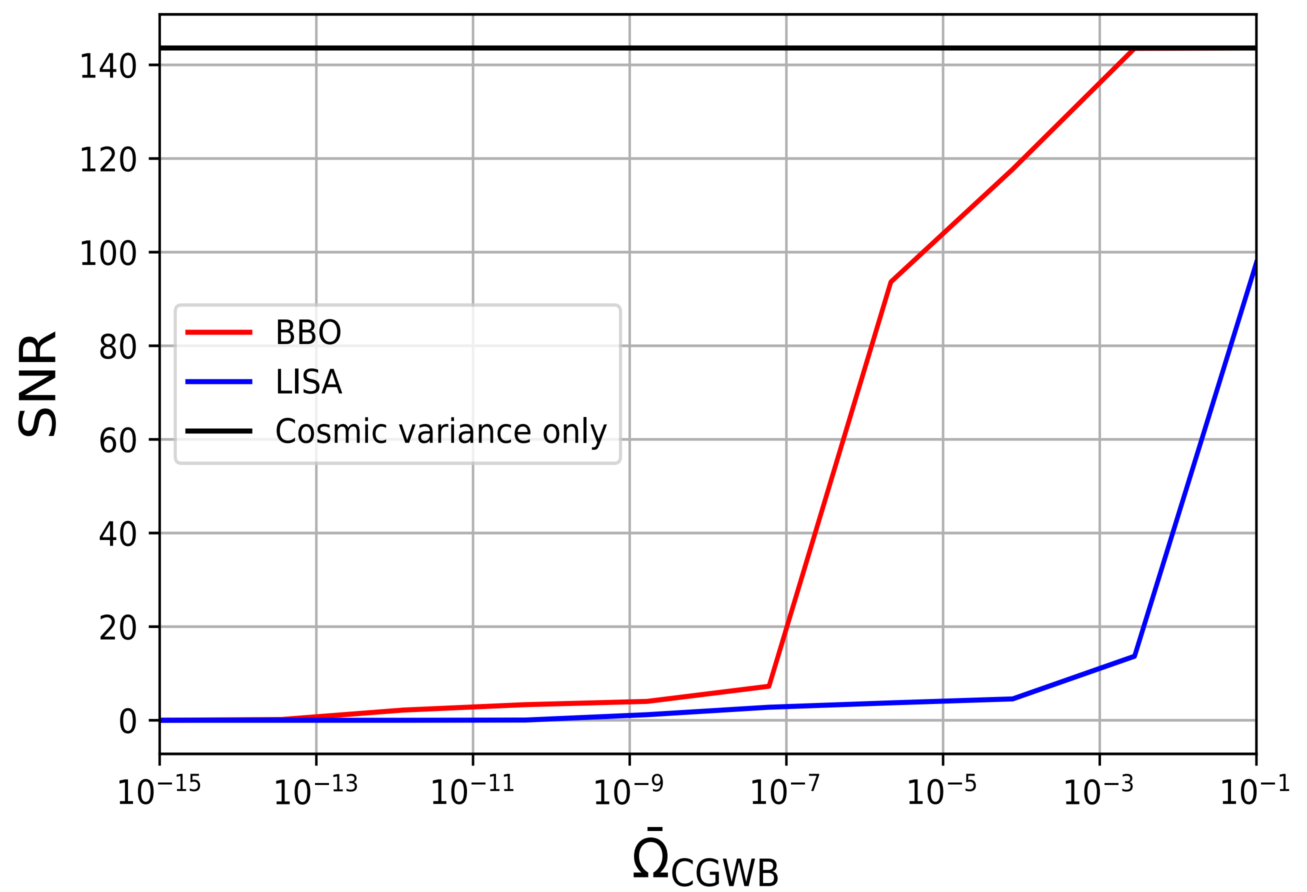

[**AR,** Valbusa, Bartolo, Bertacca, Liguori, Matarrese, PRL '21]

Conclusions

✓ The Cosmological SGWB is a powerful tool to shed light on the microphysics of the early universe, as well as the later evolutionary stage:

- Well motivated inflationary models
- First order phase transition
- Cosmic Strings
- …

✓ The detection or NOT of primordial GWs with LISA, constrains inflationary cosmological parameters complementary to CMB

✓ LISA will have the ability to probe several peculiar features of the SGWB:

- chirality
- anisotropies
- cross-correlation with other cosmological probes

Thank you!

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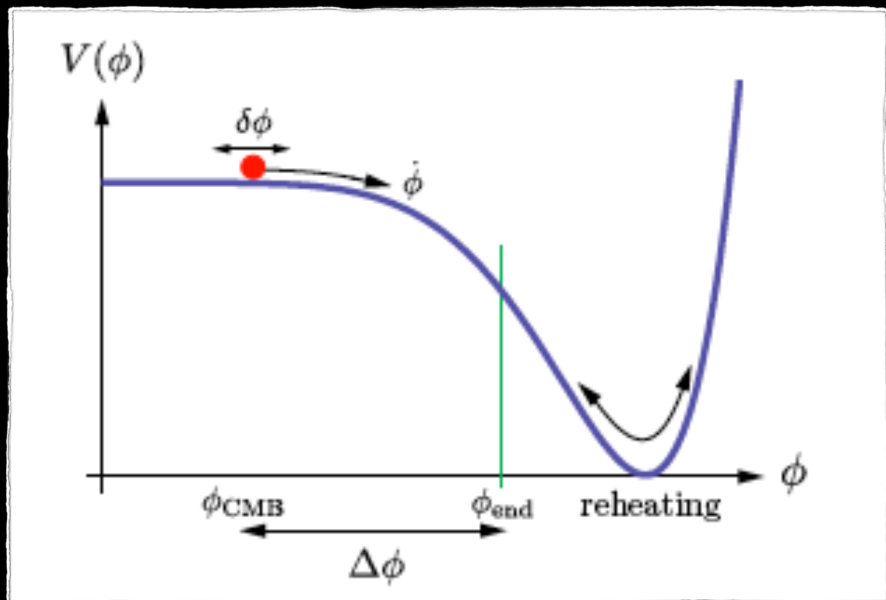
Inflation and Primordial GWs



- 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 perturbations

Stretches the microphysics scales to super-horizon sizes

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

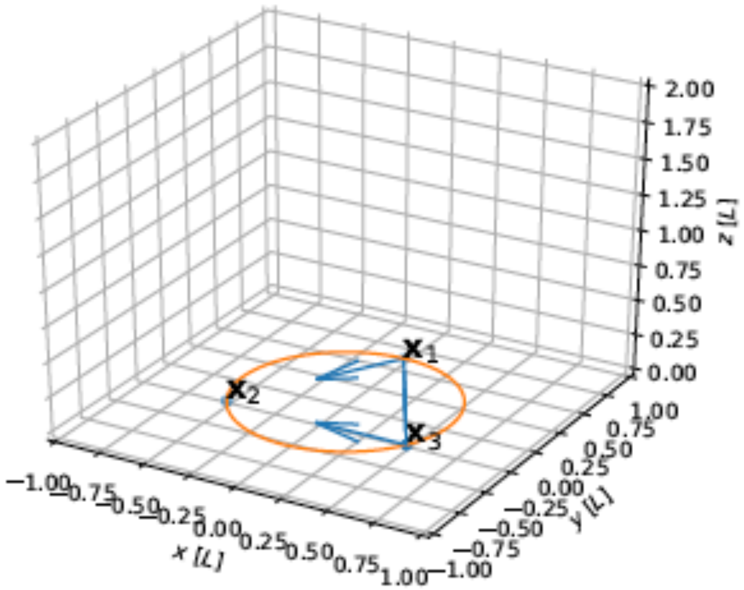
$$ds^2 = -dt^2 + a^2(t)(\delta_{ij} + h_{ij})dx^i dx^j$$

Transverse and traceless $\partial_i h_{ij} = h_{ii} = 0$ → 2 D.O.F

(2 polarizations)

Chirality

For an ISOTROPIC SGWB

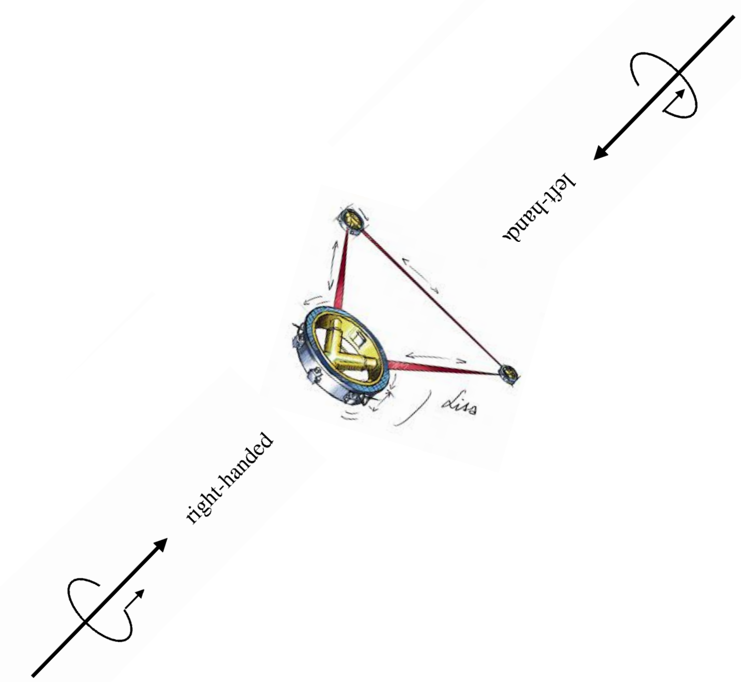


$$\mathcal{R}_V^{X_1 X_2}(f) = 0$$

V= circular polarization Stokes parameter

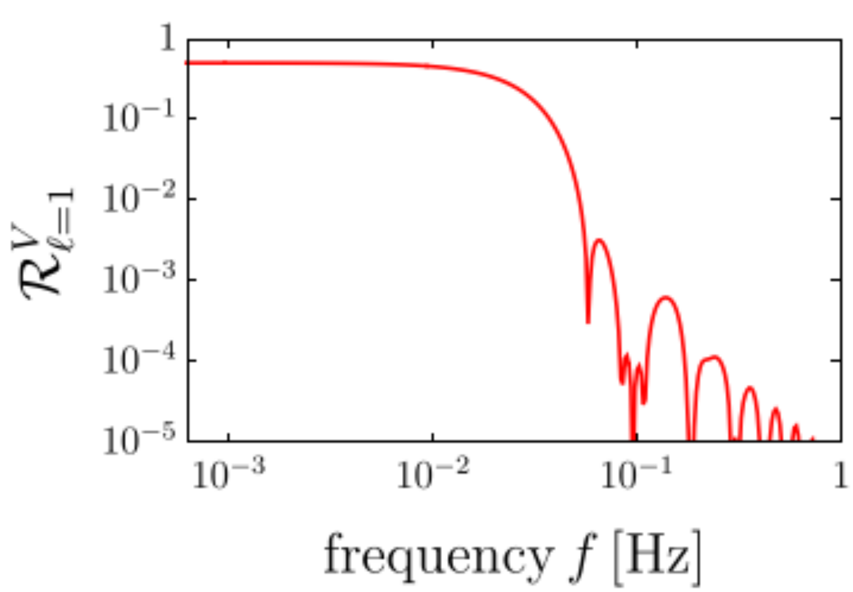
[Smith & Caldwell, ‘16]

[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

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

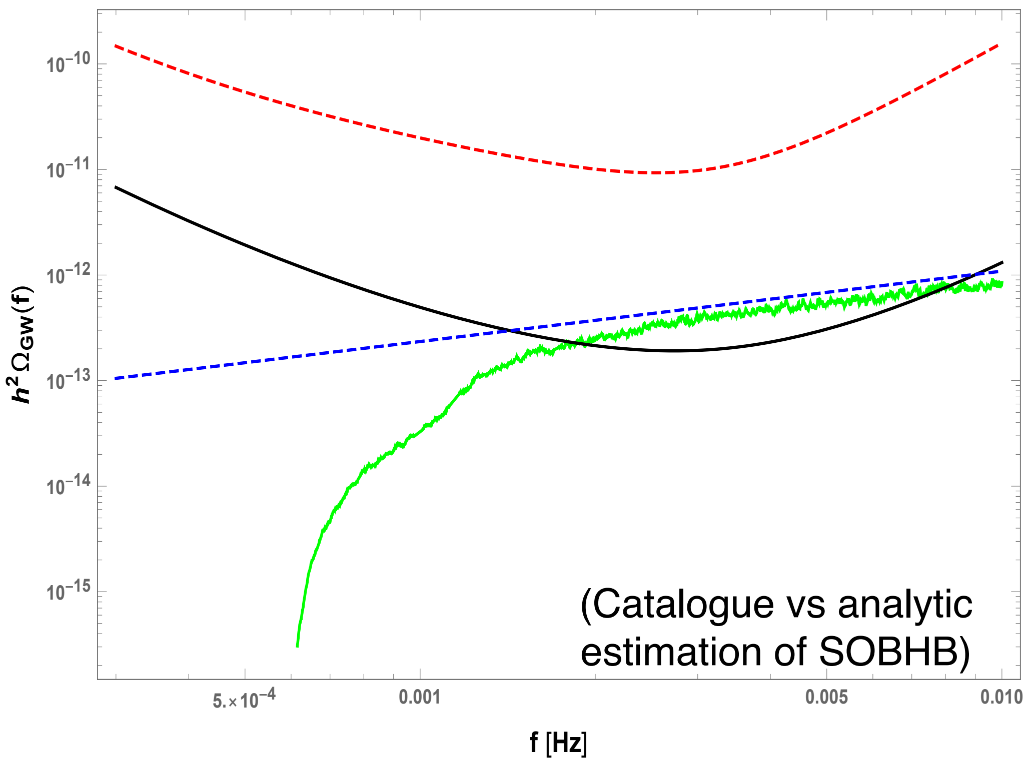


$$\text{SNR}_{\text{LISA}} \simeq \frac{v_d}{10^{-3}} \frac{\Omega_{\text{GW,R}} - \Omega_{\text{GW,L}}}{1.2\cdot 10^{-11}} \sqrt{\frac{T}{3\,\text{years}}}$$

[Domcke, V., et al.,’20]

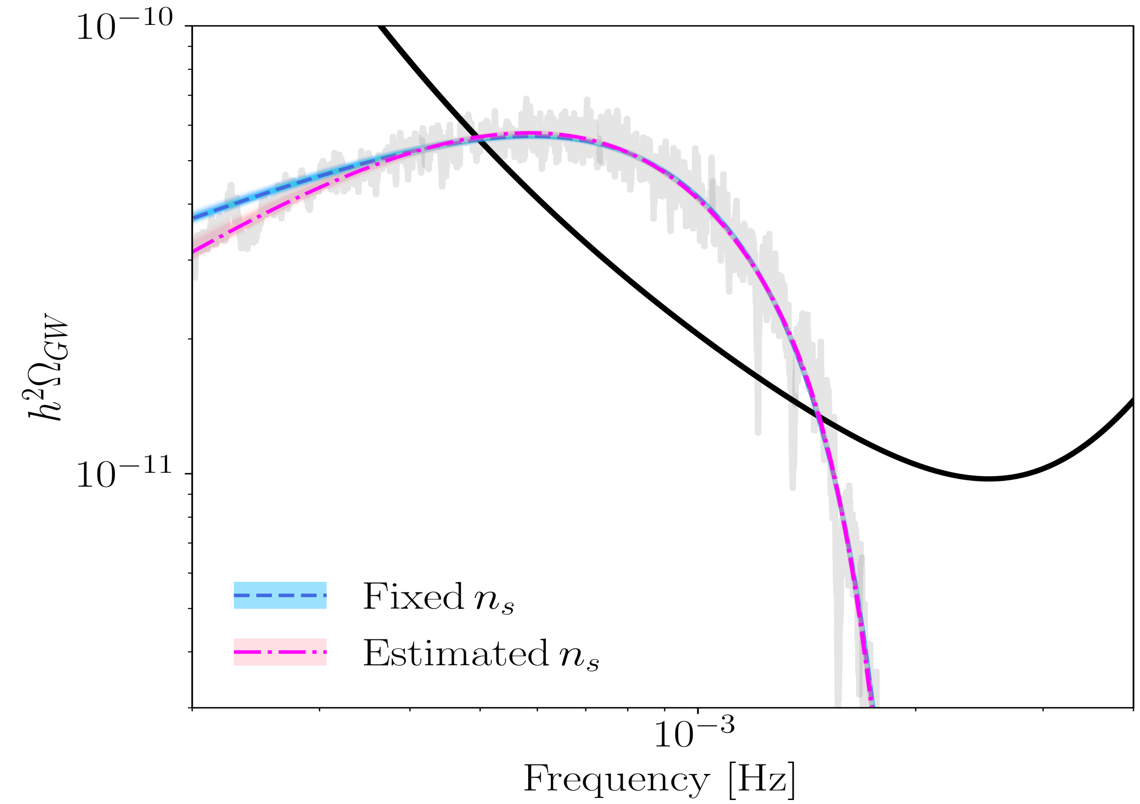
Astrophysical GW Background

LISA SOBHB



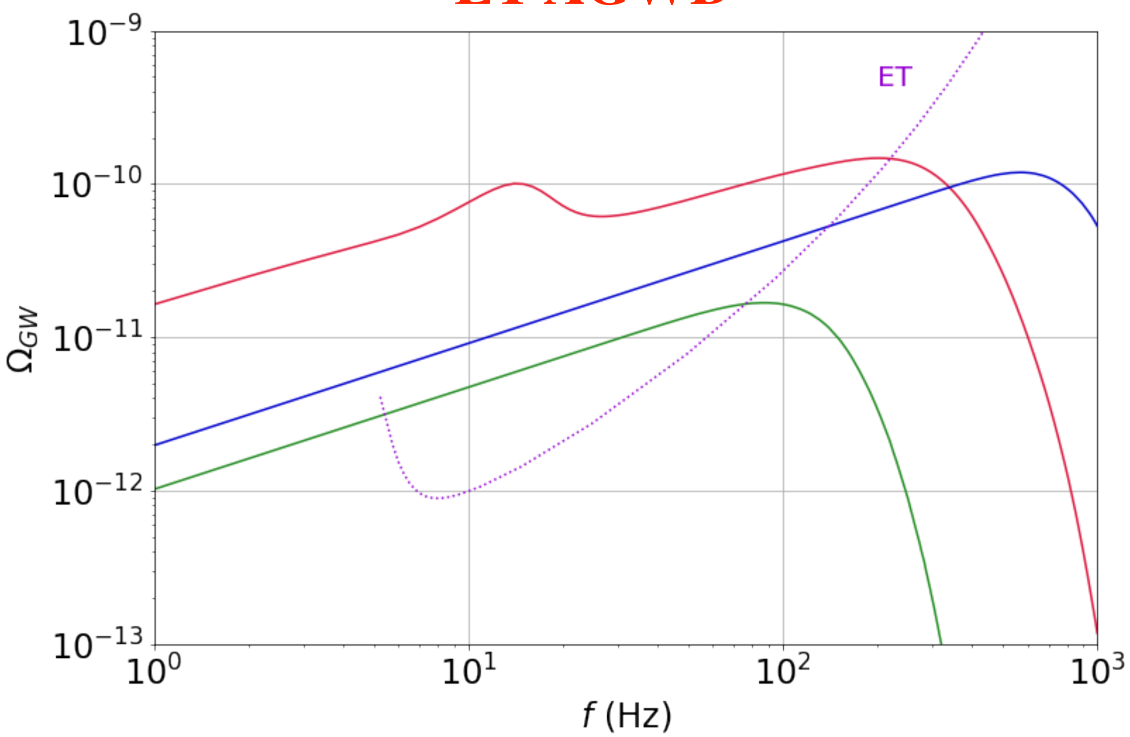
[Caprini C. et al., in preparation]

LISA GB

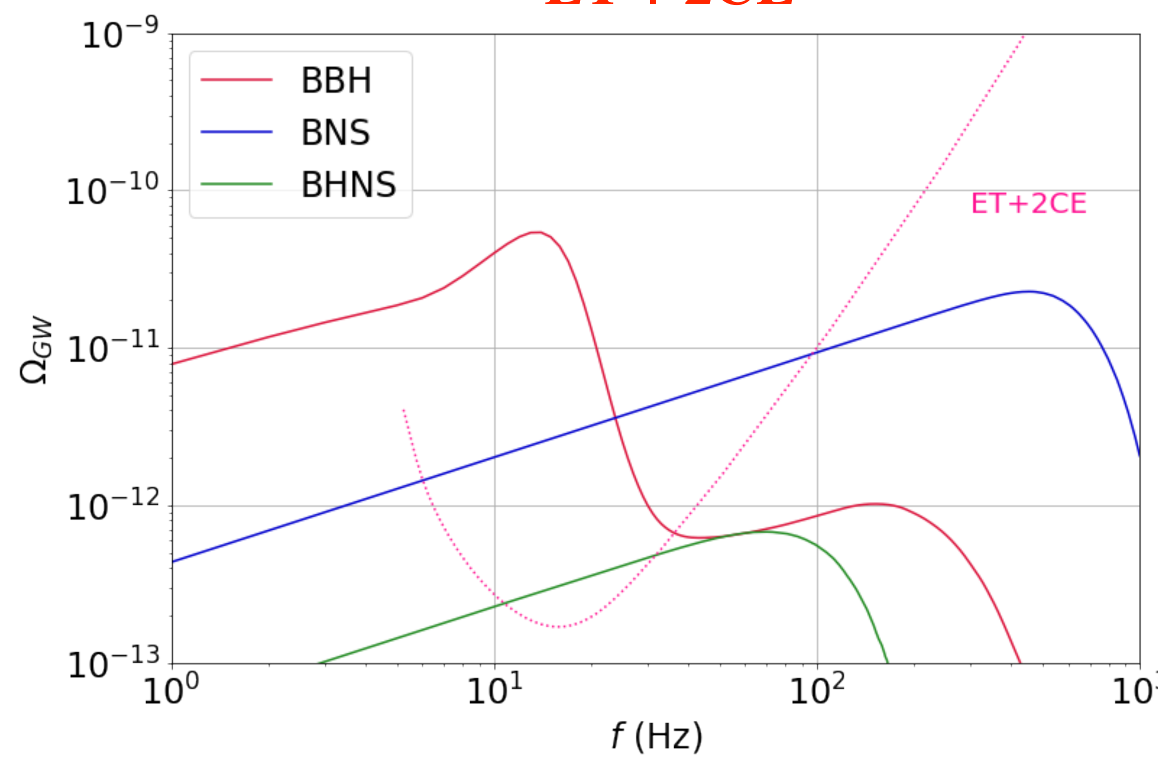


[Karnesis N., et al., 2021]

ET AGWB

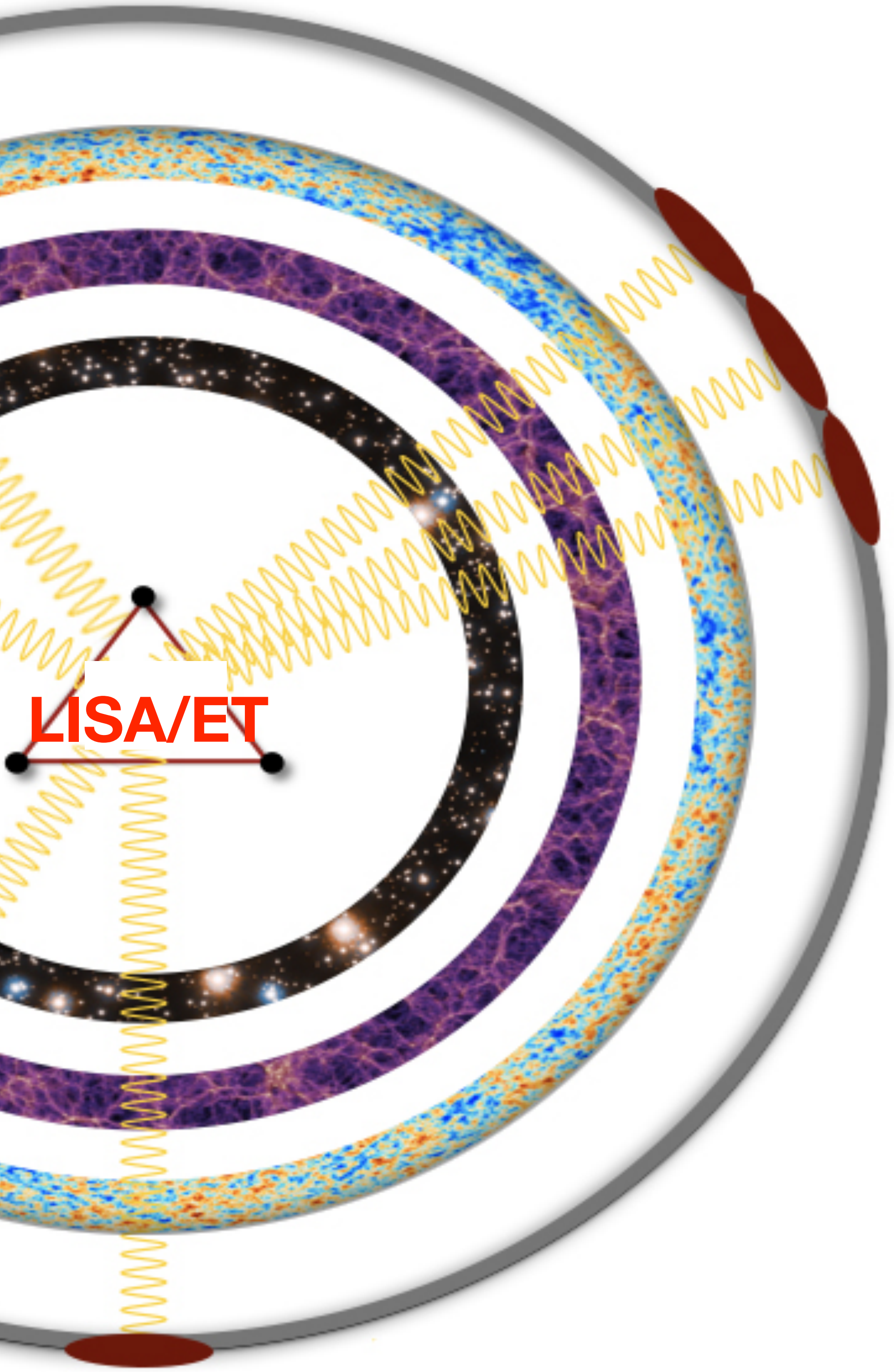


ET + 2CE



[Perigois C. et al., 2021]

SGWB Anisotropies



- ✓ **Using a Boltzmann approach (similar to CMB)**
- ✓ f **Graviton distribution function**
- ✓ $$\mathcal{L}[f] = \mathcal{C}[f(\lambda)] + \mathcal{I}[f(\lambda)]$$

Liouville operator **Collision operator** **Emissivity operator**

- ✓ Perturbed FLRW metric

$$ds^2 = a^2(\eta)\left[-e^{2\Phi}d\eta^2 + (e^{-2\Psi}\delta_{ij} + \chi_{ij})dx^i dx^j\right]$$

The SGWB also brings FREQUENCY information, in contrast with CMB (apart from Spectral Distorsions)

Anisotropies of the SGWB

✓ **At linearized level**

$$\frac{\partial f}{\partial \eta} + n^i \frac{\partial f}{\partial x^i} + \left[\frac{\partial \Psi}{\partial \eta} - n^i \frac{\partial \Phi}{\partial x^i} + \frac{1}{2} n_i n_j \frac{\partial \chi_{ij}}{\partial \eta} \right] q \frac{\partial f}{\partial q} = 0$$

Free streaming: keeps memory of initial condition

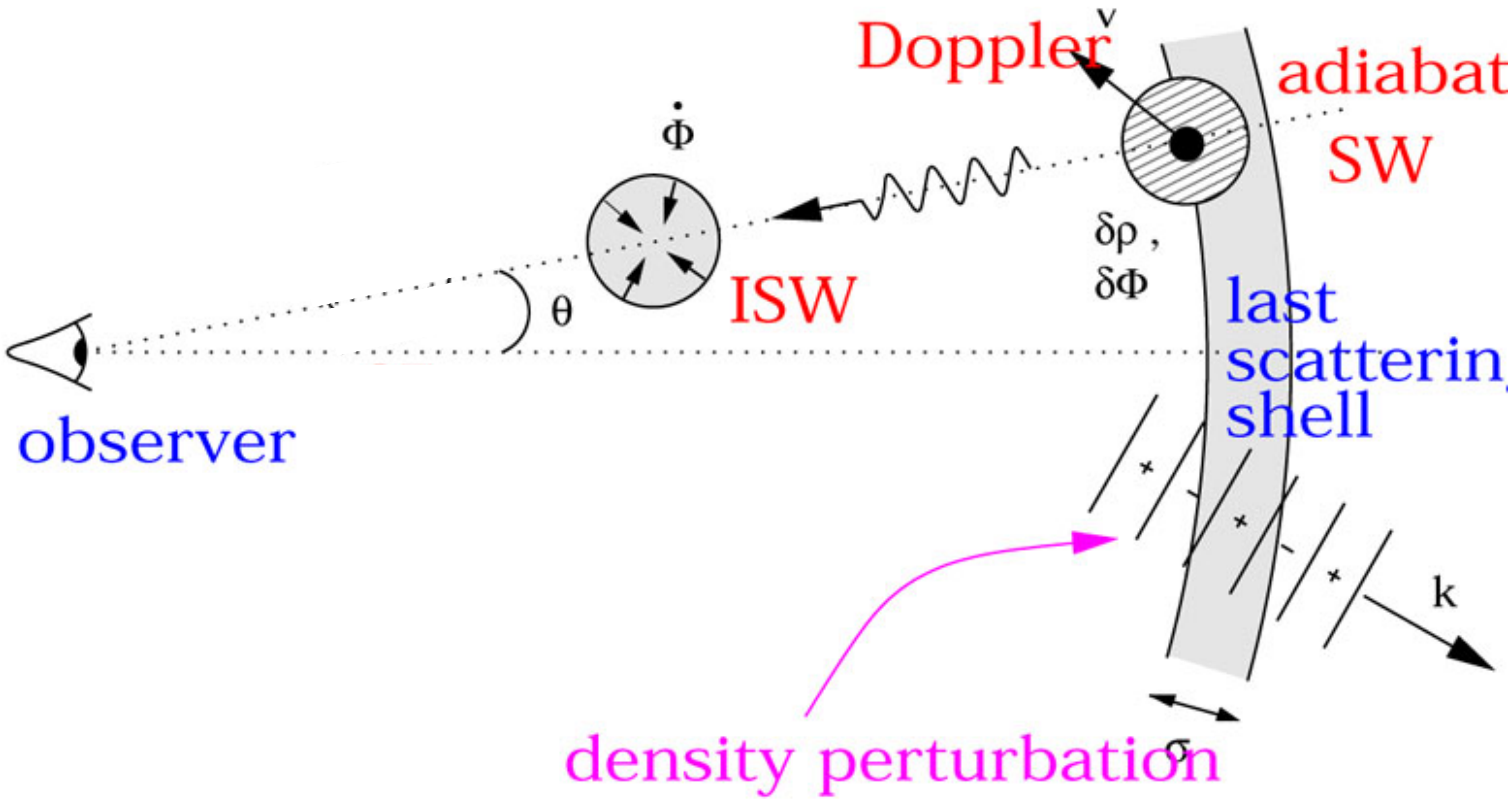
Gravitational effects that imprint anisotropies during propagation

✓ **Relation Graviton Distribution Function - Energy density**

$$\rho_{\rm GW} \left(\eta_0, \, \vec{x} \right) = \frac{1}{a_0^4} \int d^3 q \, q \, f \left(\eta_0, \, \vec{x}, \, q, \, \hat{n} \right) \equiv \rho_{\rm c,0} \int d \ln q \, \Omega_{\rm GW} \left(\eta_0, \vec{x}, \, q \right)$$

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

Sachs-Wolfe and Integrated SW



J. A. Peacock

SW: caused by the gravitational redshift due to the potential fluctuations at the decoupling epoch

ISW: caused by the time variation of gravitational potential integrated along the line of sight

Doppler: induced by the relative motion between the observer and the CMB/GW “last scattering surface”

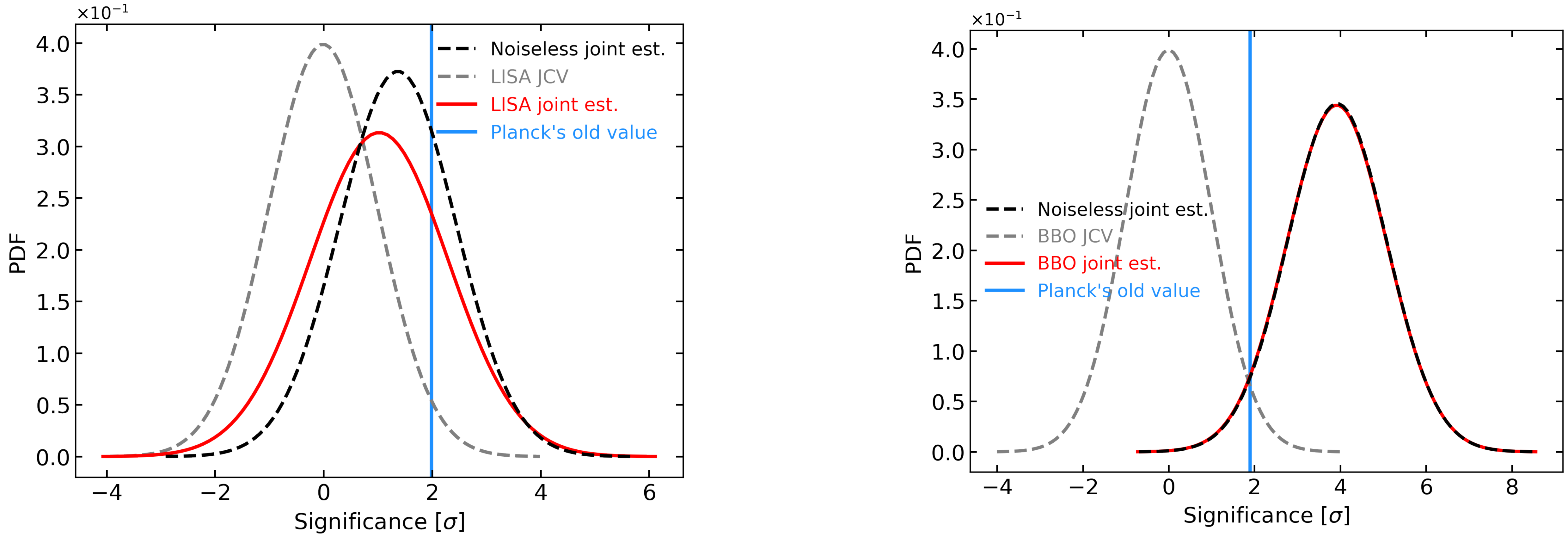
Test of the Statistical Isotropy of the Universe using GW

We focus on the **hemispherical power asymmetry** observed in CMB maps by WMAP and Planck

Study evolution of GW in presence of a modulating field:

$$\zeta(\vec{x}) = g(\vec{x})[1 + h(\vec{x})]$$

Using a minimal variance estimator (Hu & Dvorkin, 2008)



BBO have indeed the potential to shed light on the significance of the CMB power asymmetry

[Galloni, Bartolo, Matarrese, Migliaccio, AR, Vittorio, '22]