Searching for anisotropic stochastic GW backgrounds with constellations of space-based interferometers

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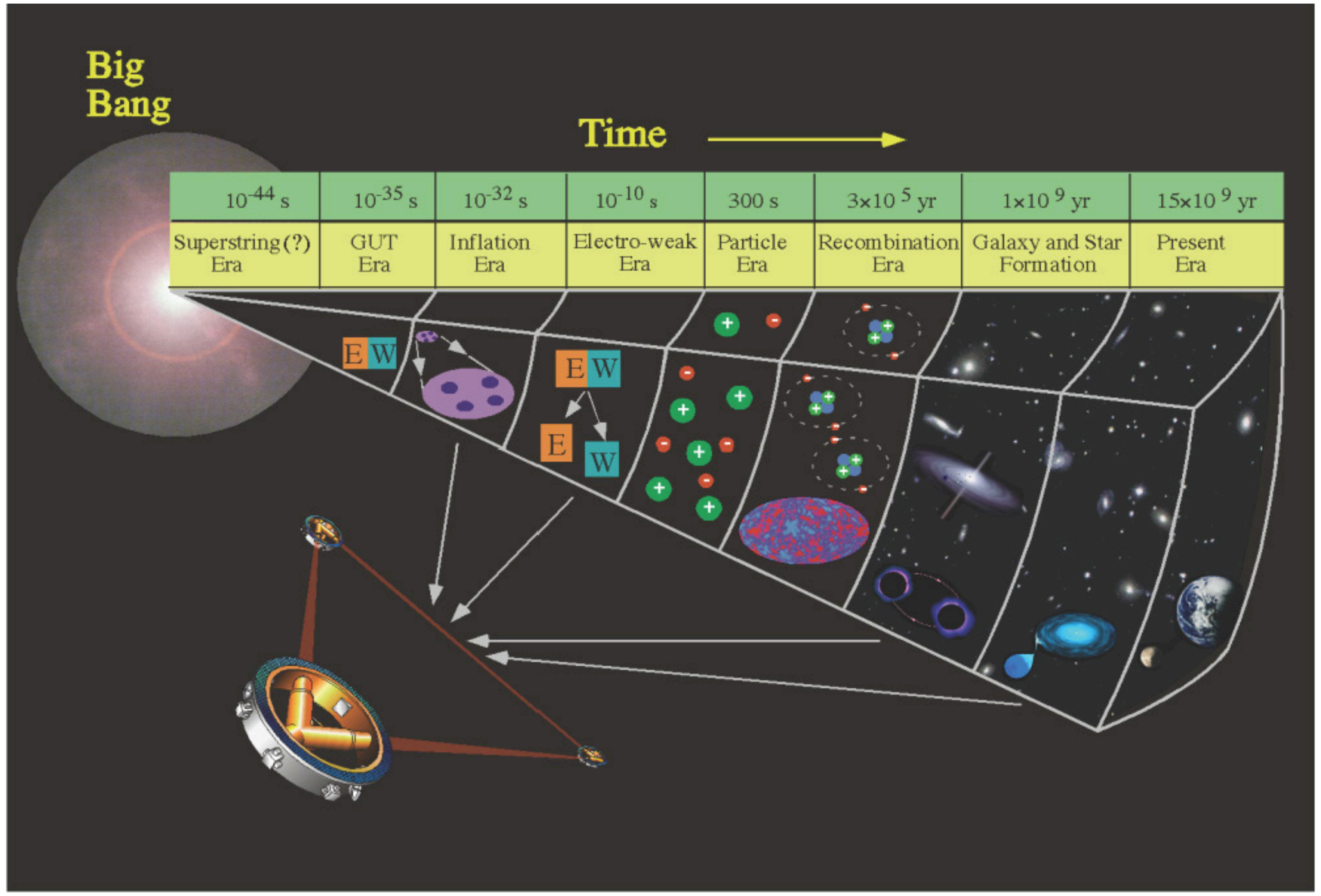
Stochastic gravitational-wave backgrounds



Credit: LISA Consortium, ESA

The stochastic gravitational-wave background (SGWB) results from the **superposition of numerous unresolved GW signals produced since the Big Bang.**

Two contributions:

- Cosmological SGWB

  Inflation, reheating, pre-Big Bang scenarios, cosmic strings, phase transitions…

- Astrophysical SGWB

  Compact binaries, supernovae, rotating NS, core collapse, supermassive BHs …

General properties of the SGWB

- Incoherent sum of numerous unresolved GW signals
- Comes from all directions in the sky
- Isotropic at first approximation…
- … with tiny anisotropies
- Can be described through the **energy density parameter**

$$\Omega_{\rm gw}(f,\hat{n}) = \frac{1}{\rho_c}\frac{d^3\rho_{\rm gw}(f,\hat{n})}{d\ln f\, d^2\Omega} =$$

$$= \frac{\bar{\Omega}_{\rm gw}(f)}{4\pi} + \delta\Omega_{\rm gw}(f,\hat{n})$$

Isotropic component — Anisotropic component

Critical energy density of the Universe $\rho_c \sim 10^{-29}\,\mathrm{g\,cm^{-3}}$

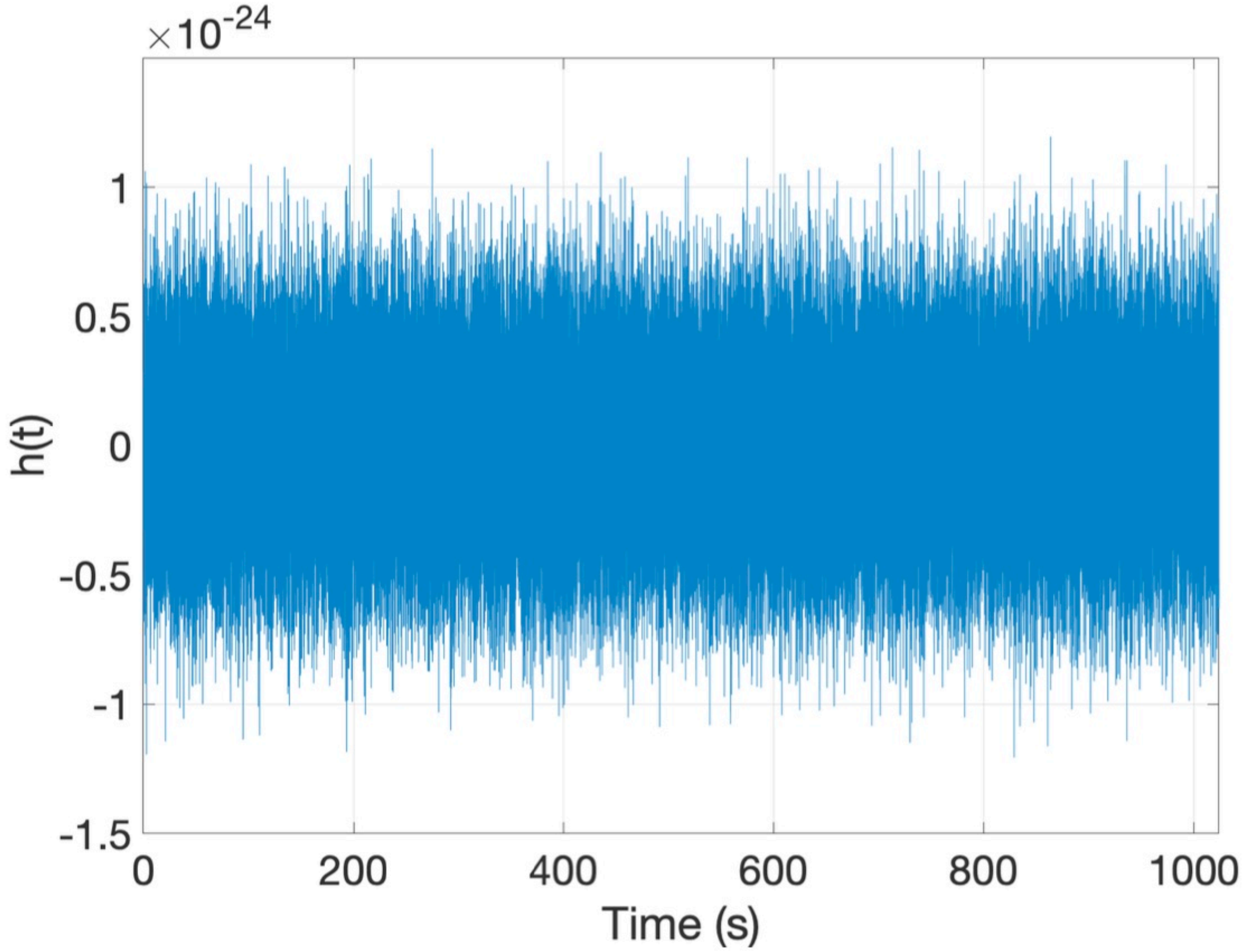
Detecting the SGWB

It appears like noise in the detector:

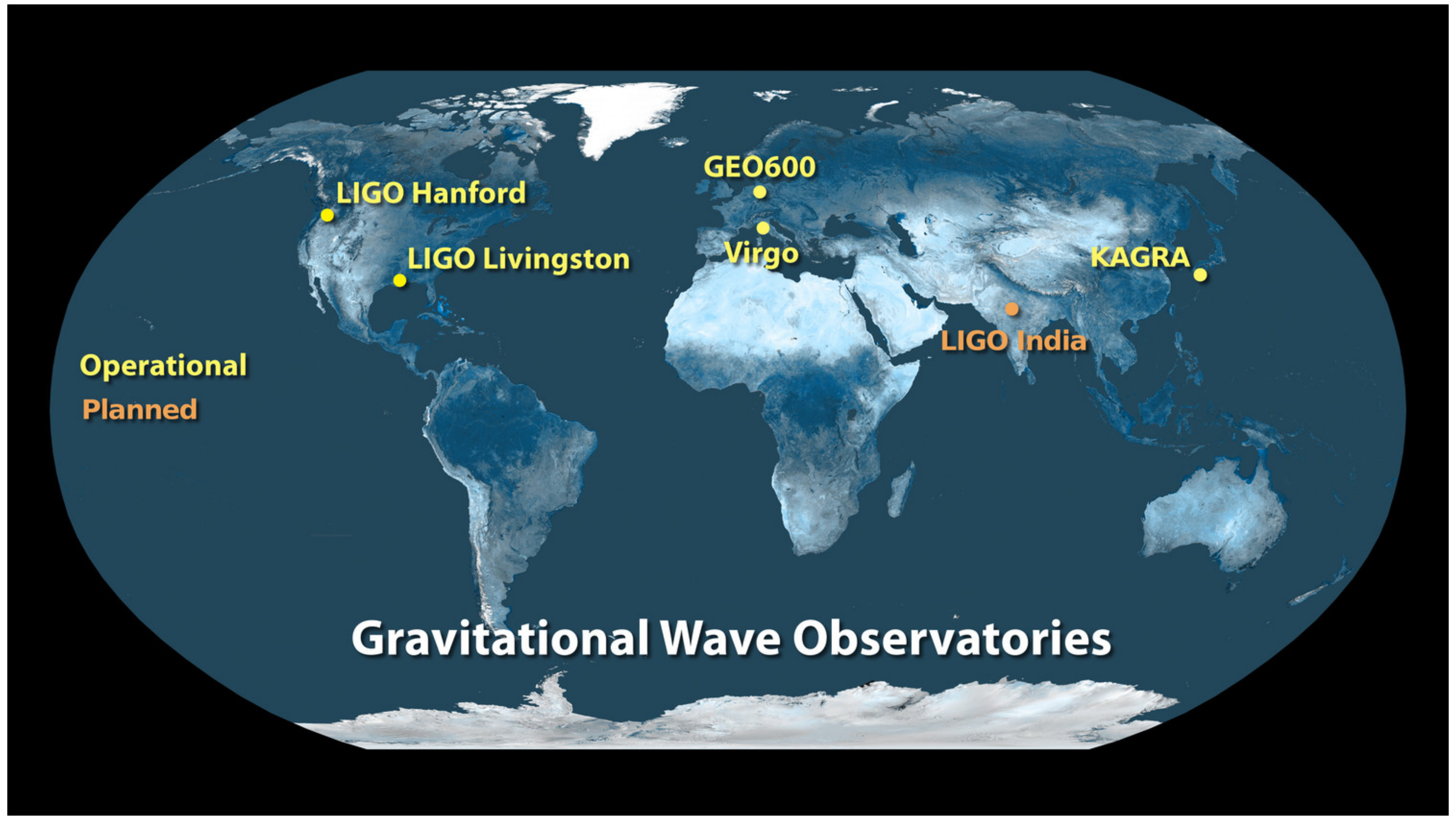
$$s(t) = n(t) + h(t) \quad \text{with } n(t) \gg h(t)$$

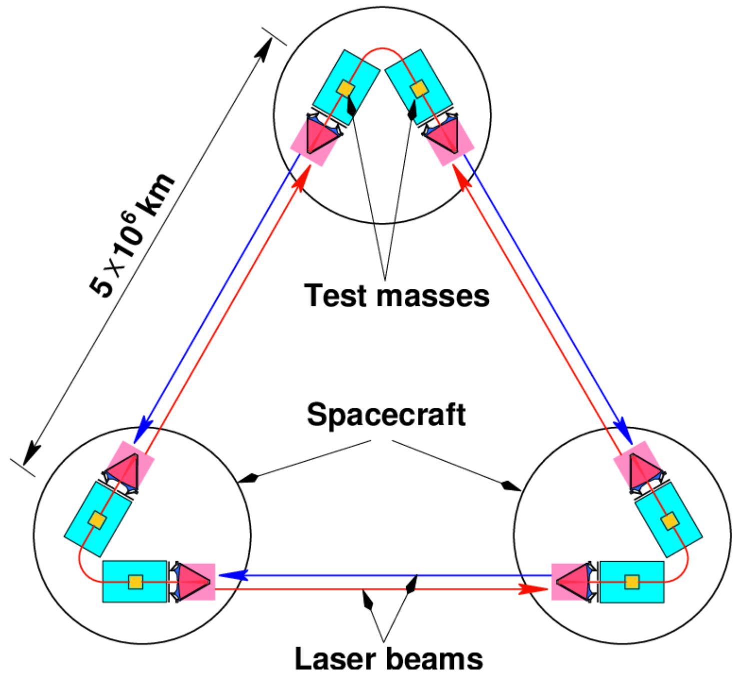
Cross-correlate the outputs of two (or more) detectors:

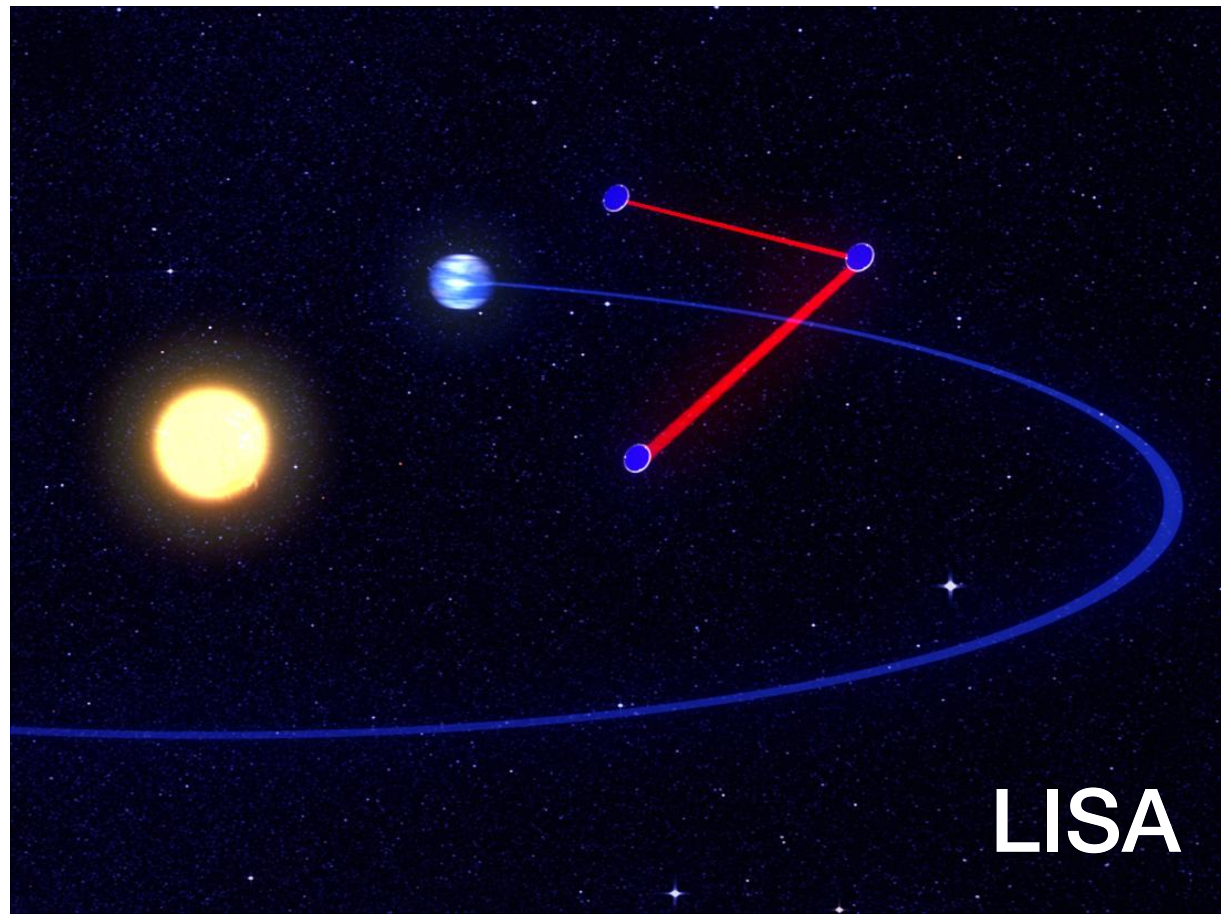
$$\langle s_1(t)\, s_2(t) \rangle \approx \langle h_1(t)\, h_2(t) \rangle$$



Tania Regimbau
Symmetry 2022, 14(2), 270

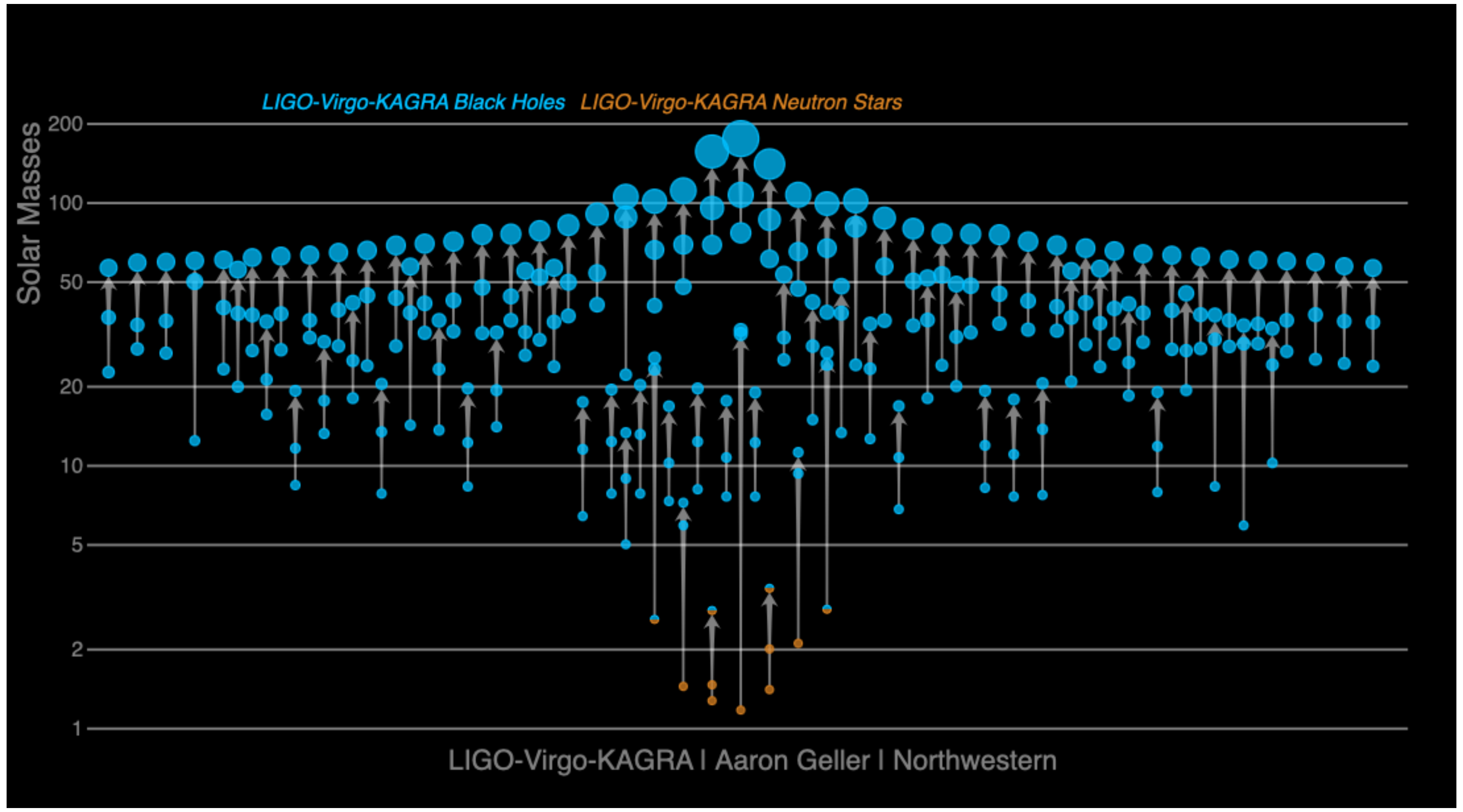






SGWB from merging stellar compact binaries

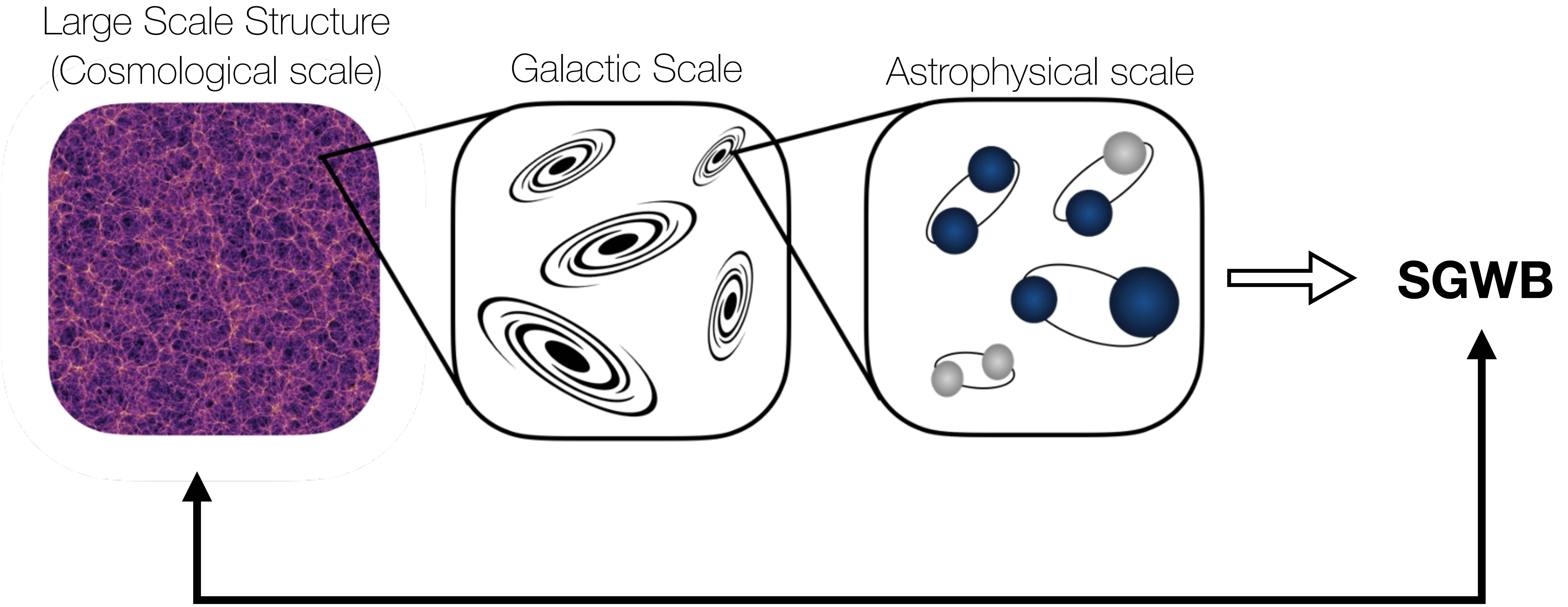
Incoherent superposition of all the unresolved GW signals produced by merging stellar compact binaries



Why is it worth studying?

1) Dominant contribution in the 10 Hz-1 kHz band
2) It is produced by all compact binaries since the beginning of stellar activity
3) Many processes involved, at different times and spatial scales
4) Its detailed modeling is needed in order to isolate other SGWB components

The SGWB as a tracer of the Large Scale Structure



The anisotropies of the SGWB reflect those of the underlying dark matter distribution!

Isotropic component

$$\Omega_{\rm gw} = \boxed{\frac{\bar{\Omega}_{\rm gw}(f)}{4\pi}} + \delta\Omega_{\rm gw}(f,\hat{e})$$

$$\bar{\Omega}_{\rm gw} = \frac{8\pi G f_o}{3H_0^3c^2}\int dz \int d\mathcal{M}_c \, \frac{R_{\rm merge}(\mathcal{M}_c, z)}{(1+z)\,h(z)} \, \frac{dE}{df}(f_e(z)\,|\,\mathcal{M}_c) \int_0^{\bar{\rho}} d\rho \, P_\rho(\rho\,|\,\mathcal{M}_c, z)$$

See e.g. *Regimbau Res. Astron. Astrophys.* ***11*** *(2011) 369*

Intrinsic merging rate

per unit comoving volume and per unit chirp mass

From *Boco+19*, *Boco+20*

Energy spectrum

of the signal emitted by a merging binary with a given chirp mass at a given redshift

From *Ajith+07*

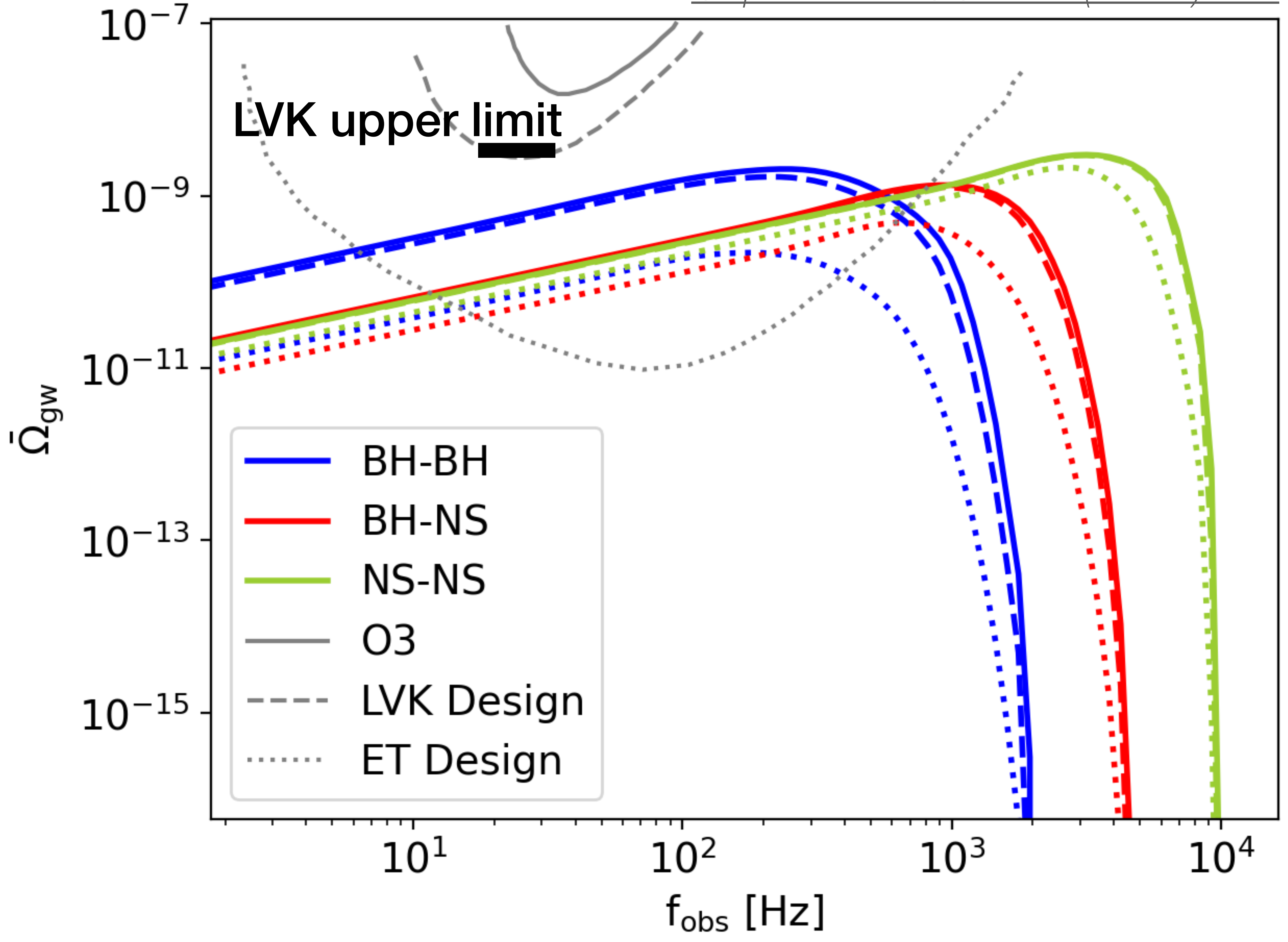
Distribution of sky-averaged signal-to-noise ratio (S/N)

for a given detector at given chirp mass and redshift

From e.g. *Taylor & Gair 2012*

Results: frequency spectrum of the isotropic SGWB

Capurri et al JCAP11(2021)032



DETECTORS:

- LIGO/Virgo/KAGRA
- Einstein Telescope

SIGNALS:

- Solid lines = **total SGWB**
- Dashed/dotted lines = **residual SGWB**

Anisotropies of the SGWB

Angular power spectrum
of the anisotropies

$$C_\ell = \frac{2}{\pi} \int \frac{dk}{k} P(k) \left[\frac{\delta\Omega_\ell(k)}{\bar{\Omega}_{\text{gw}}/4\pi} \right]^2$$

P(k) primordial matter power spectrum

Relativistic angular fluctuation of the SGWB energy density

Other works modelling the SGWB anisotropies:

Jenkins et al Phys. Rev. D 98, 063501 (2018)
Cusin et al Phys. Rev. Lett. 120, 231101 (2018)
Bertacca ed al Phys. Rev. D 101, 103513 (2020)

The relativistic fluctuation $\delta\Omega_\ell(k)$:

1) Contains all density, velocity, lensing and gravity effects
2) Depends on 3 main ingredients:

a) Redshift distribution
b) Bias
c) Magnification bias

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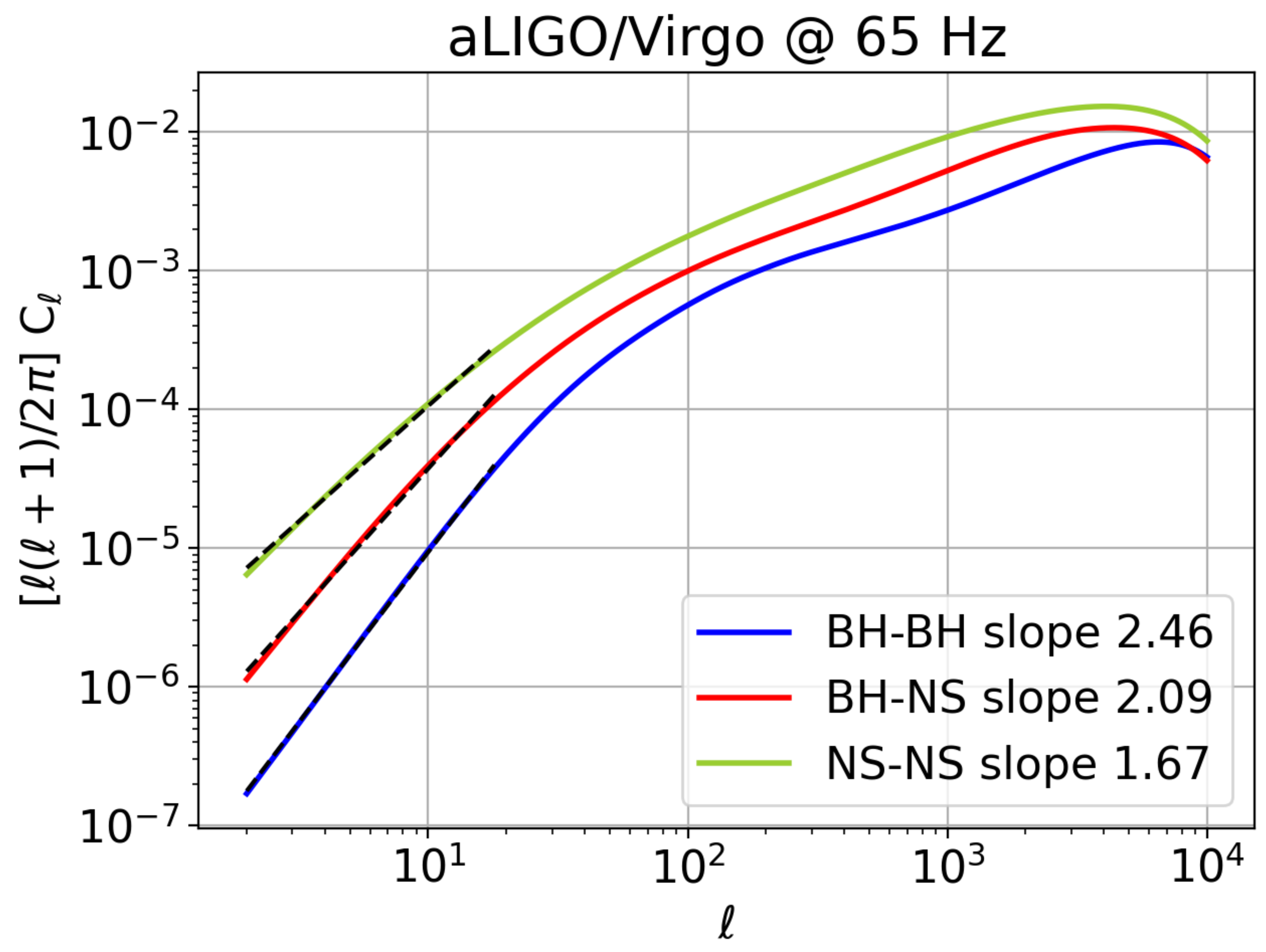
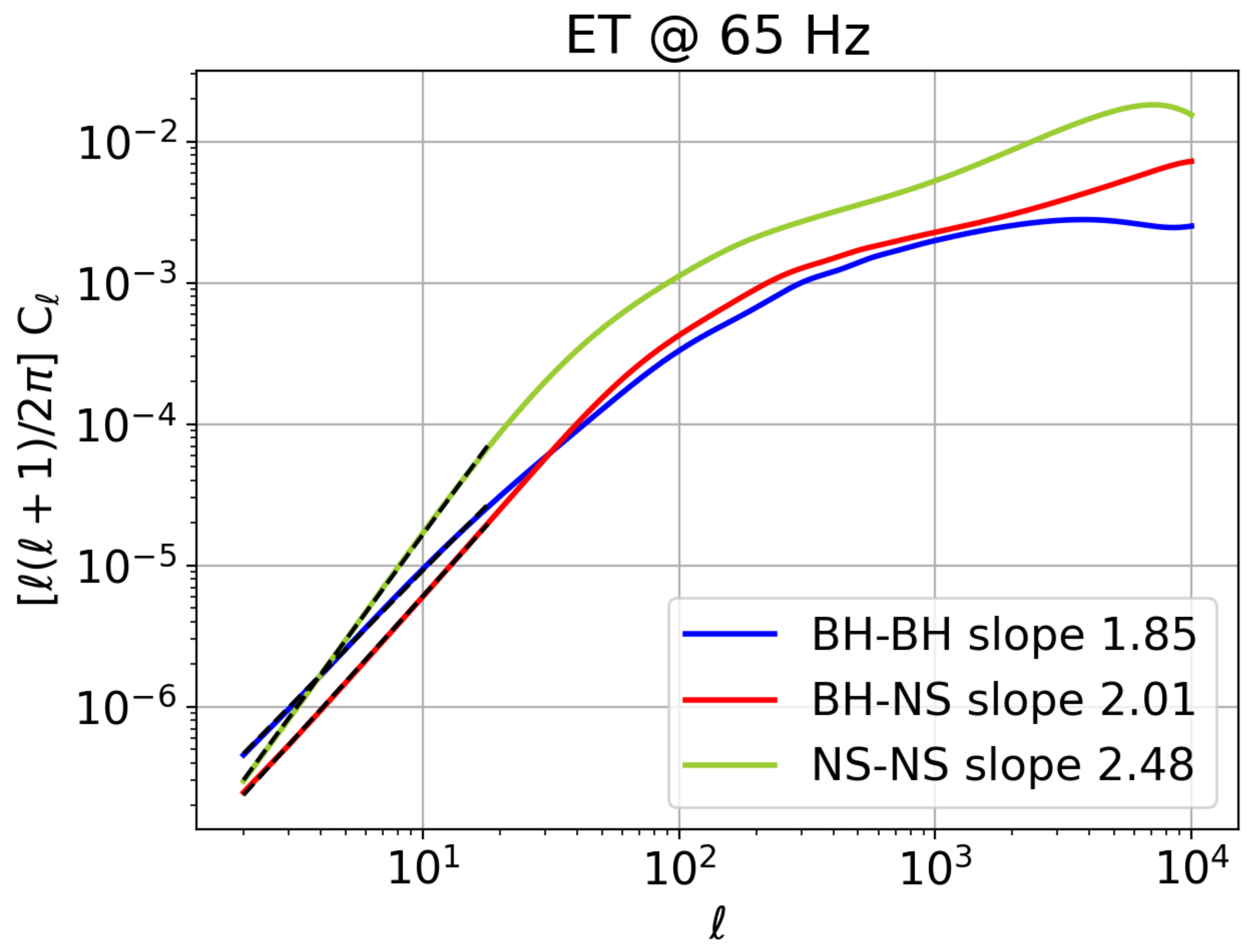
CLASS
The Cosmic Linear Anisotropy Solving System
Lesgourgues, 2011

SGWB anisotropies angular power spectrum

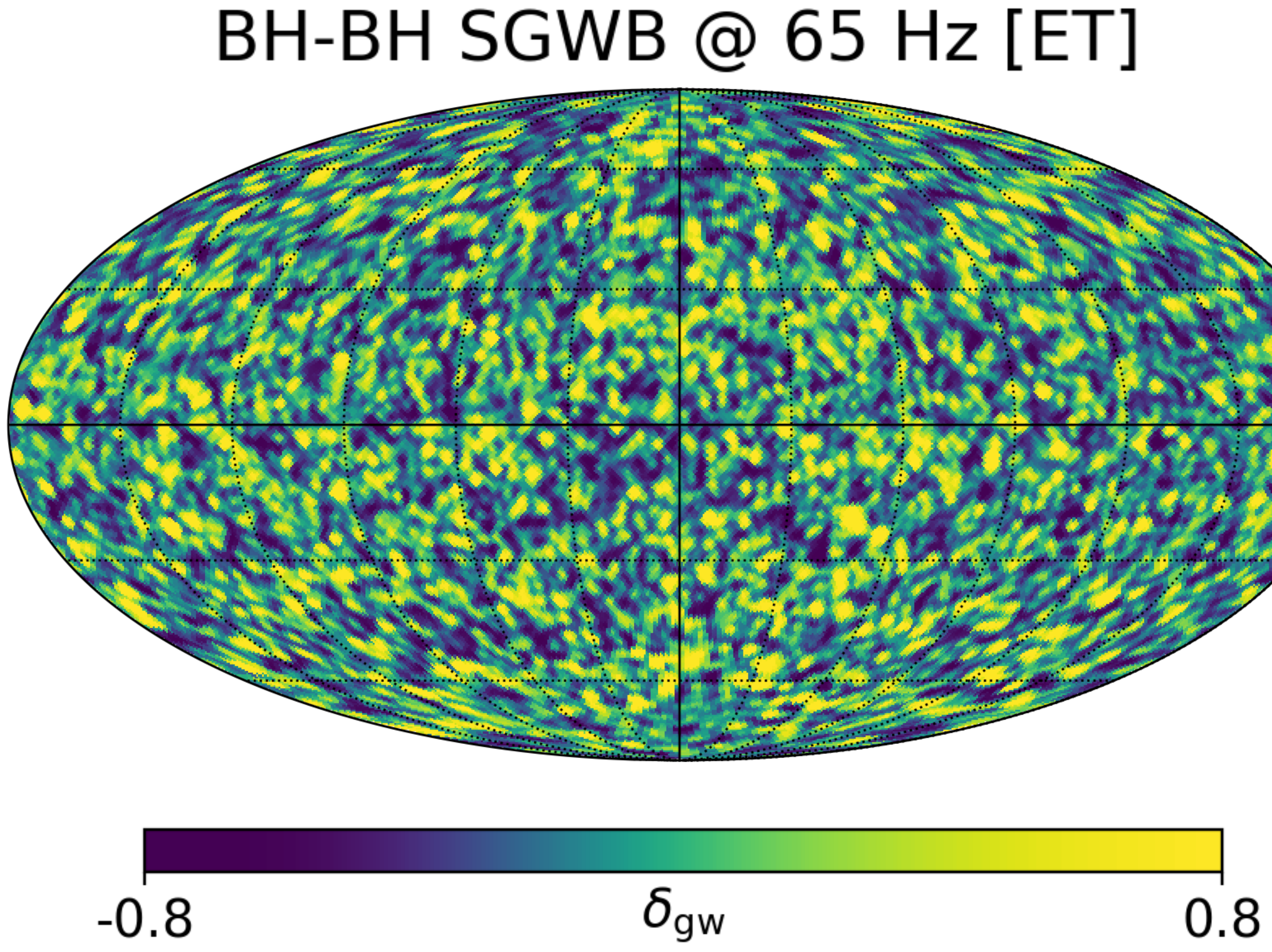
Residual SGWB: only unresolved events, detector dependent



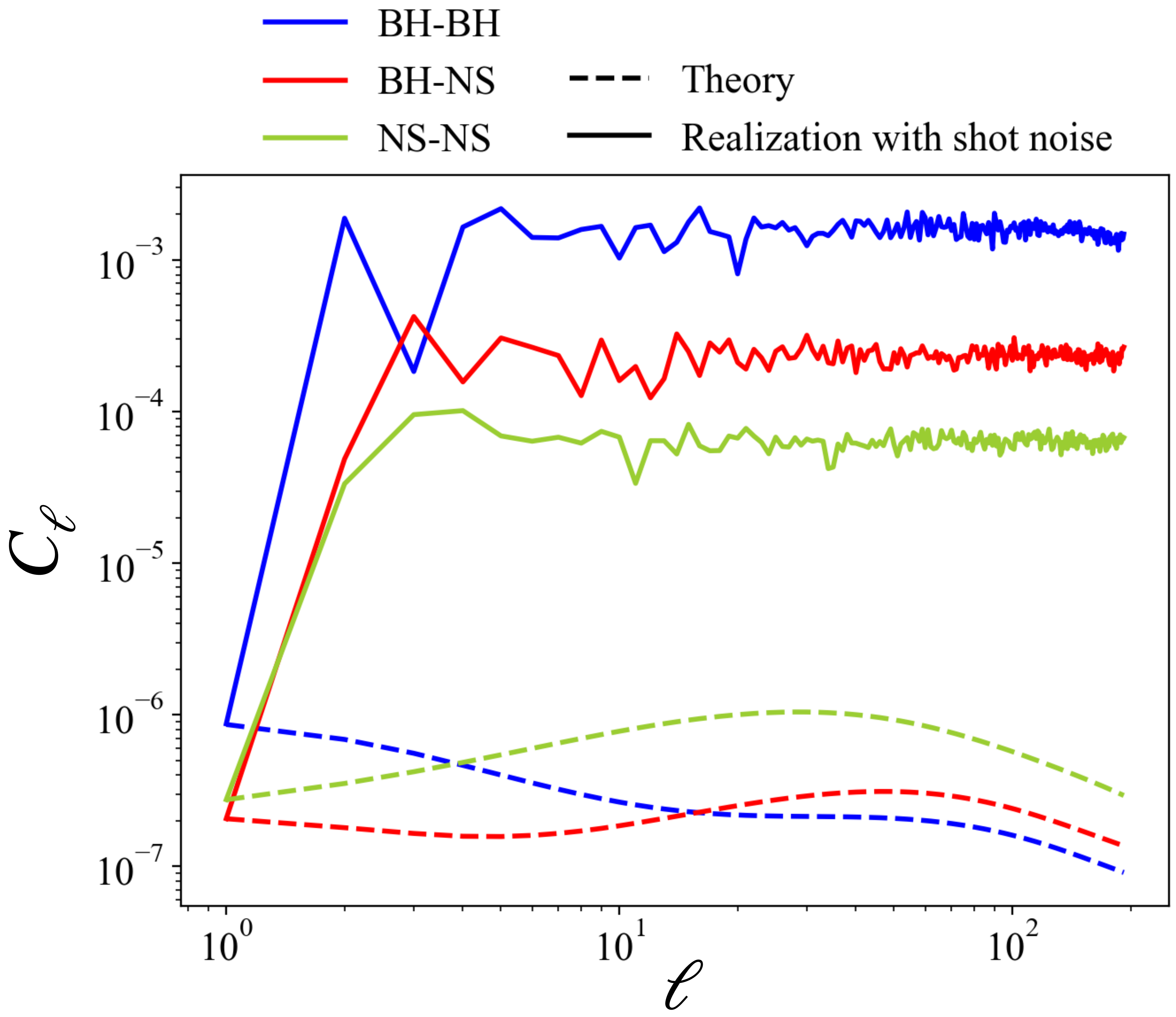


Are these signals detectable?

The shot noise issue



$$\delta_{gw} = \frac{\Omega_{gw} - \langle \Omega_{gw} \rangle}{\langle \Omega_{gw} \rangle}$$



! Shot noise caused by the discreteness of the sources in space and time.

The detector noise issue

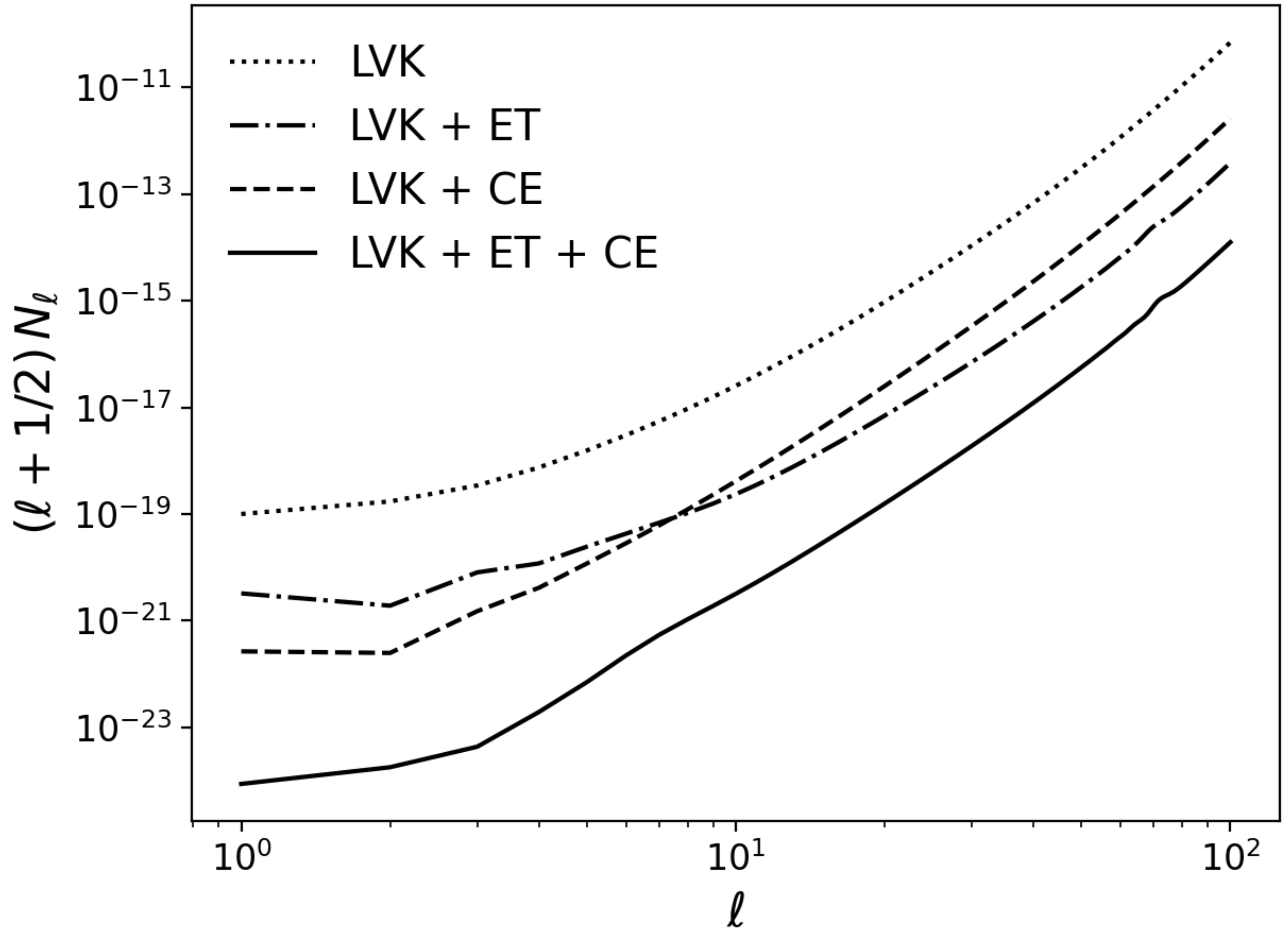
Public software **schNell**

Alonso et al. Phys. Rev. D 2020, 101, 124048

schNell computes the **angular power spectrum of the instrumental noise** in interferometer networks mapping SGWB by considering:

- network configuration
- noise properties
- scan strategy

Detector	Latitude (deg)	Longitude (deg)	Orientation (deg)
LIGO Hanford	46.6	-119.4	171.8
LIGO Livingston	30.7	-90.8	243.0
Virgo	43.6	10.5	116.5
KAGRA	36.3	137.2	225.0
ET*	40.1	9.0	90.0
CE*	40.8	-113.8	90.0



Cross-correlation with other cosmic fields

Shot noise + instrumental noise

How to reduce their effect?

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1) Increase integration time

2) Cross-correlate with other probes

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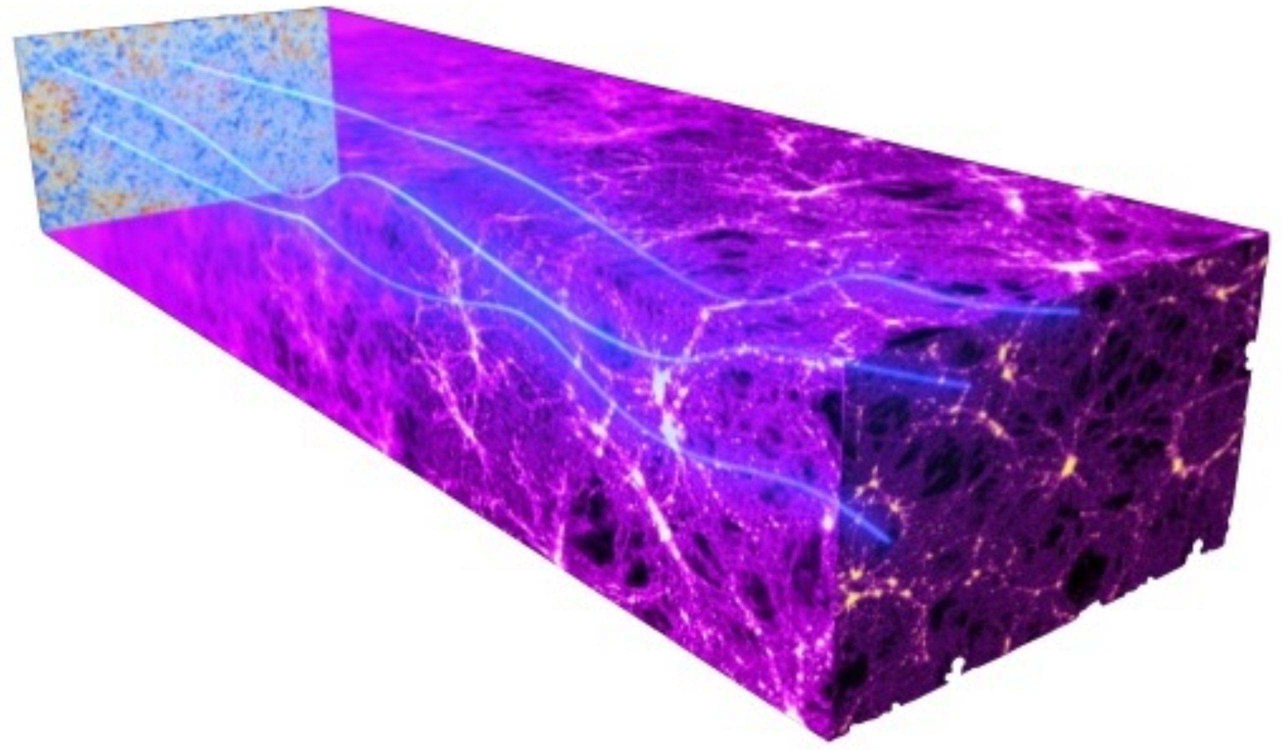
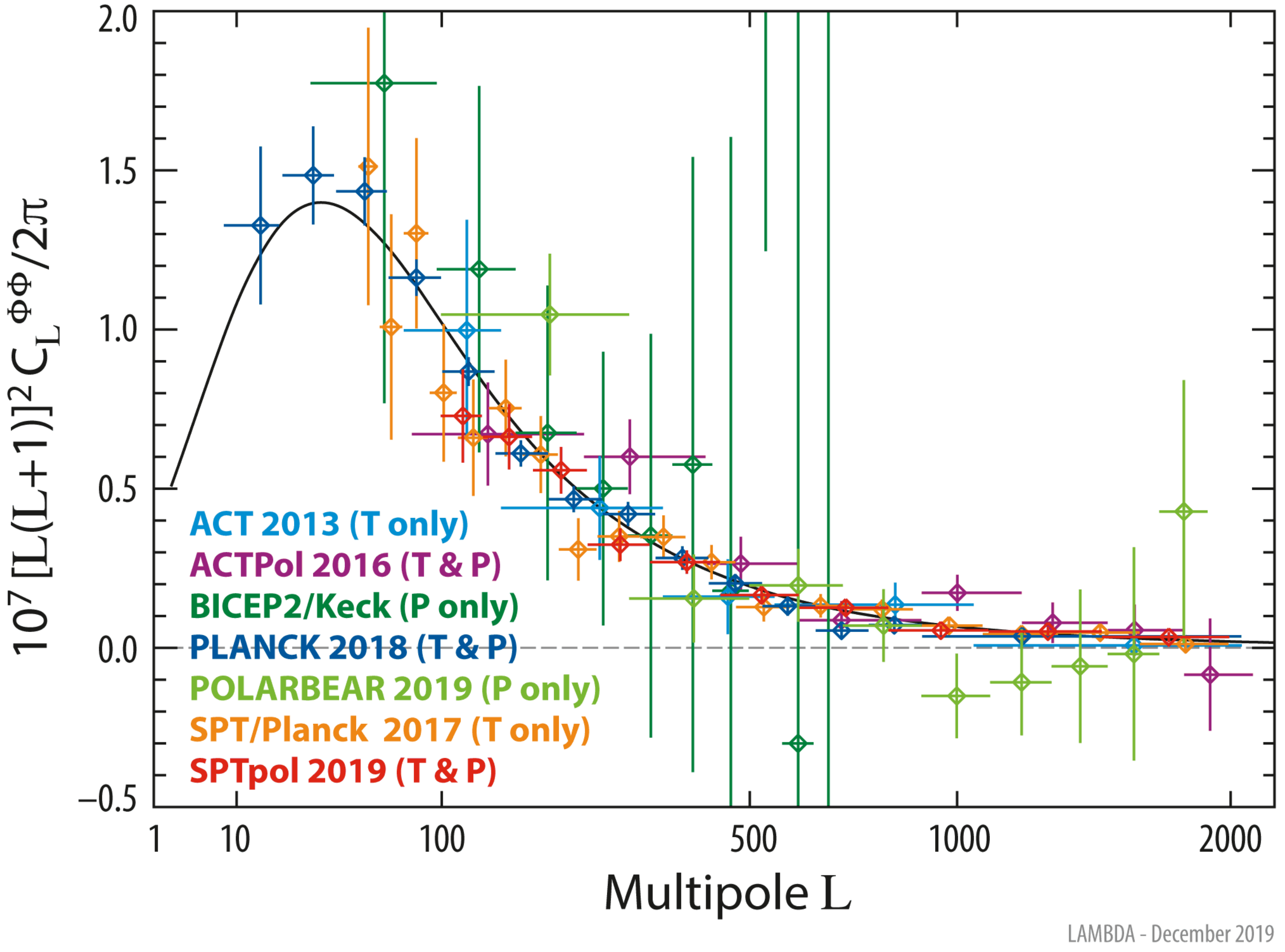
- galaxy clustering (e.g. *Canas-Herrera+20*)
- galaxy weak lensing (e.g. *Cusin+19*)
- CMB anisotropies (e.g. *Ricciardone+21*)
- **CMB lensing** (*Capurri+22*)



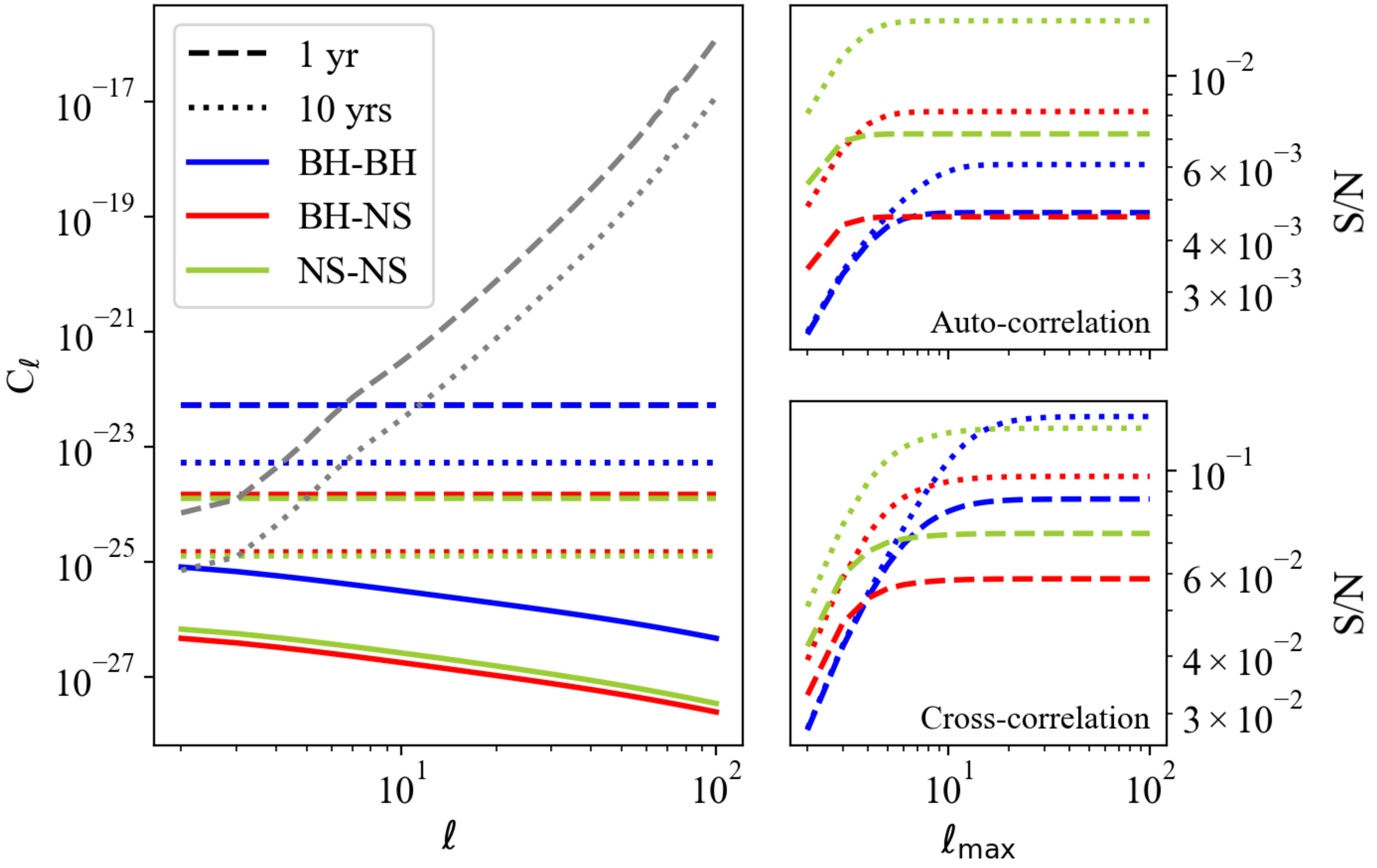
CMB lensing potential power spectrum



Detection prospects with ground-based instruments

Signal vs noises comparison

Signal-to-noise ratio



Capurri at al, Universe ***2022****, 8(3), 160*

Detector network:

- LIGO
- Virgo
- KAGRA
- Einstein Telescope
- Cosmic Explorer

Cross-correlation enhances the S/N…
…but not enough!

Achieving high angular resolution

The angular resolution if GW detectors scales as (Baker+20):

$$\Delta\theta \sim \frac{\lambda}{\rho D}$$

Rayleigh criterion scaled by S/N

λ: GW wavelength

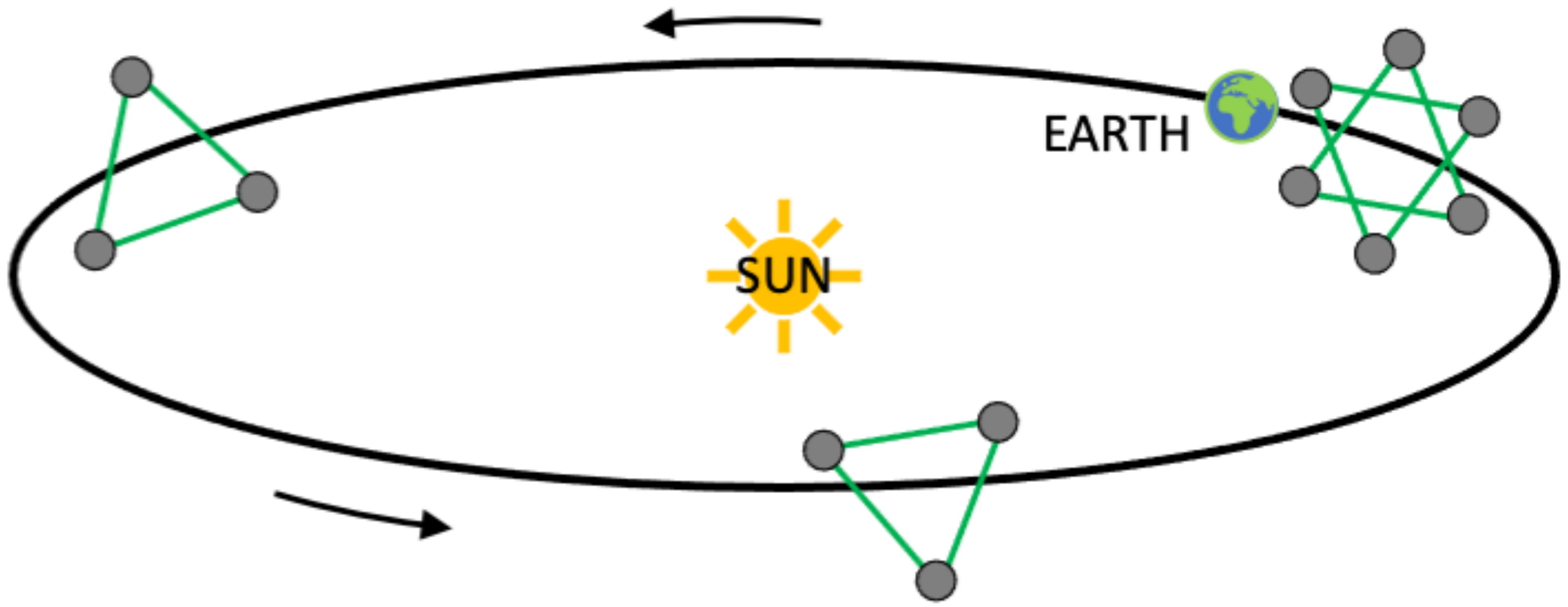
ρ: GW signal-to-noise ratio (S/R)

D: effective size of the baseline

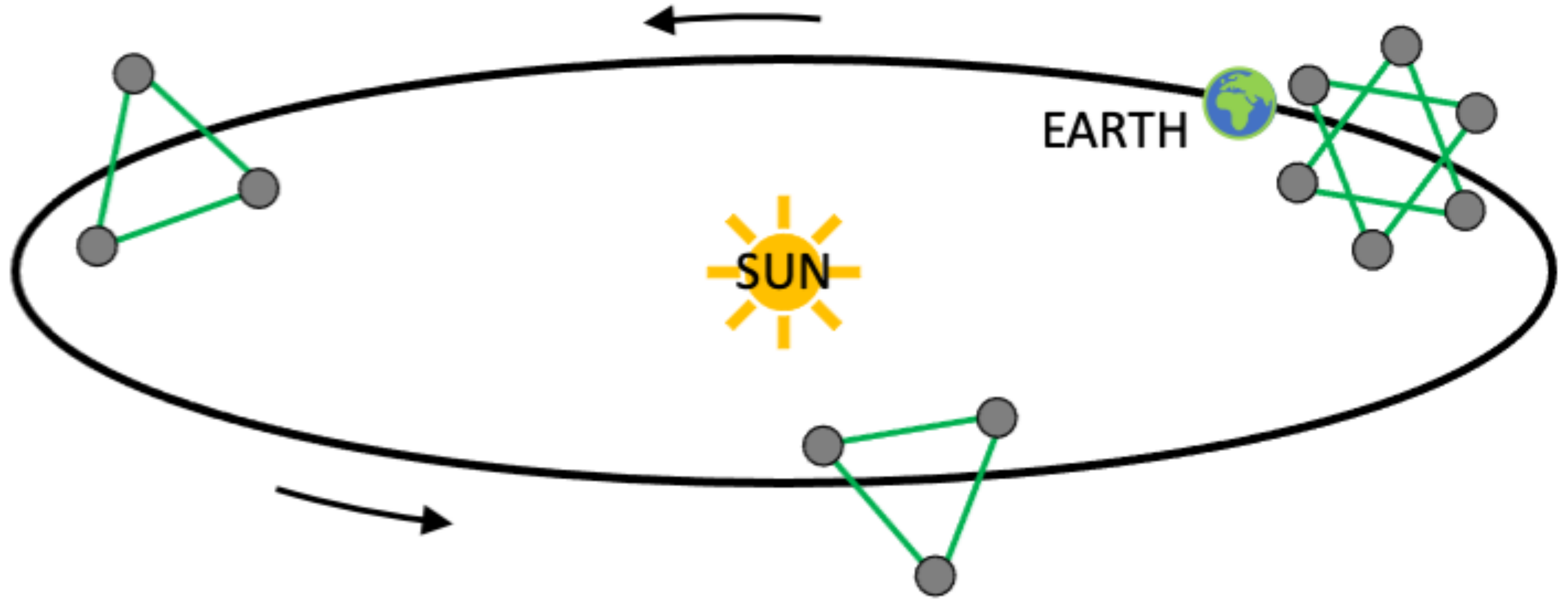
DECIGO

Deci-hertz Interferometer **G**ravitational-wave **O**bservatory

Sato+17
Kawamura+21

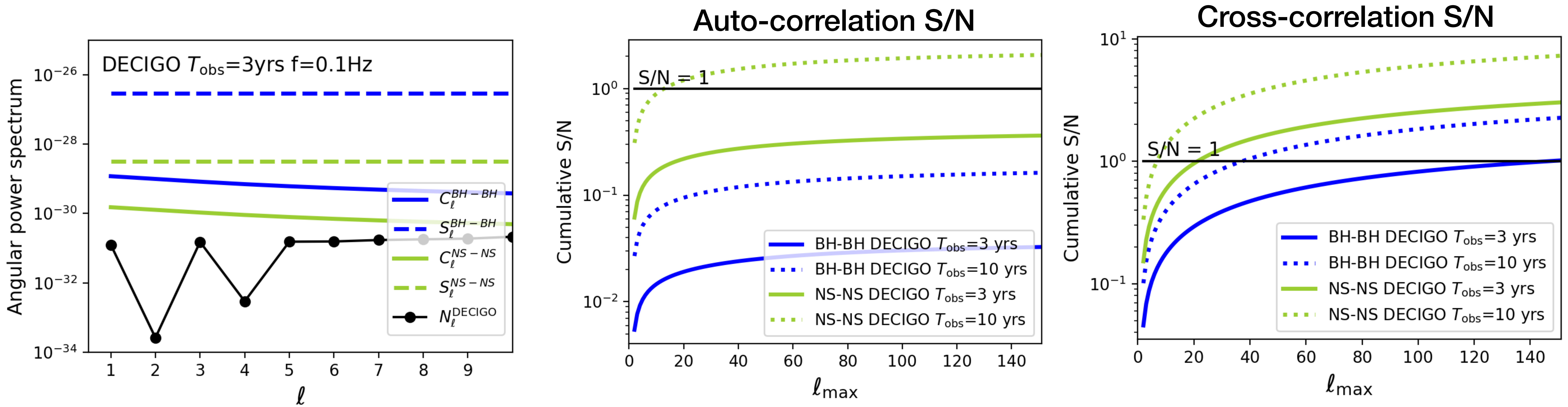


Prospects for a constellation of detectors



These configurations have an extraordinary **angular sensitivity**.

The main source of noise is the **shot noise**, whose impact can be reduced through **cross-correlations**



Capurri et al 2023 ApJ ***943*** *72*

Conclusions and outlook

- The astrophysical SGWB is a tracer of the LSS
- Main issues: shot noise and instrumental noise
- Cross-correlation with other cosmic fields enhances the S/N
- Constellations of space-based interferometers may detect the anisotropies of SGWB

Future perspective

- Refine detection prospects considering improved data analysis techniques
- Focus on the physics we can constrain with the first multipoles (and monopole too!)

Thank you so much for your attention!

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