Einstein Telescope OSB

Cosmology Division

Archisman Ghosh, Angelo Ricciardone, Mairi Sakellariadou

[archisman.ghosh@ugent.be, angelo.ricciardone@pd.infn.it, mairi.sakellariadou@kcl.ac.uk]

ET kick-off meeting - 21-22 September 2021

Cosmology with ET

Goals:

- **Probe Early Universe Physics**

  Mairi Sakellariadou

- **Cosmography, Dark Matter and Dark Energy**

  Archisman Ghosh

- **GW synergy with other cosmological probes**

  Angelo Ricciardone

Cosmology with ET

Several mechanisms in the early Universe lead to the production of a **background of GWs** (GWB), which travel to us unharmed as a consequence of their weak coupling to matter

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

⇨

Evidence for new physics may emerge

- Particles beyond the Standard Model
- High-temperature cosmological phase transitions
- Topological defects
- Inflation and reheating
- Extra spatial dimensions

ET, thanks to its better low-frequency sensitivity, could detect GWB $\Omega_{\rm GW} \sim 10^{-12}$ at f ~ 10 Hz

LIGO/Virgo O3: $\Omega_{\rm GW} \leq 5.8 \times 10^{-9}$ at f ~ 25 Hz

Mairi Sakellariadou

Cosmology with ET

Gravitational wave background (GWB):

- **Minimise the possibility of false GWB detection**

  Isotropic searches use cross-correlation techniques between multiple detectors assuming absence of correlated noise, however globally coherent magnetic fields are a limiting noise source for Earth-based GW detectors (LIGO/Virgo and ET)

⇨ **Set upper limits on the coupling function of magnetic fields to the interferometer arms**

- **Distinguish astrophysical from cosmological contributions to GWB**

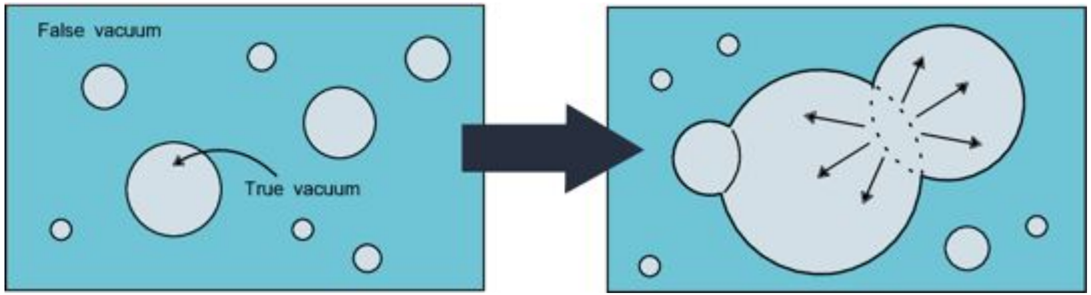
  ET sensitive to most individual compact binary mergers, can reduce the astrophysical signal via subtraction of individual sources, and reveal a cosmological background

[synergy with Population Studies]

Mairi Sakellariadou

Cosmology with ET

- First-order cosmological phase transitions (FOPT)



Generation mechanisms:

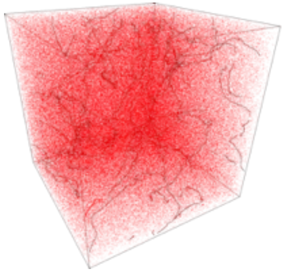
- bubble collisions
- sound waves
- magnetohydrodynamic turbulence

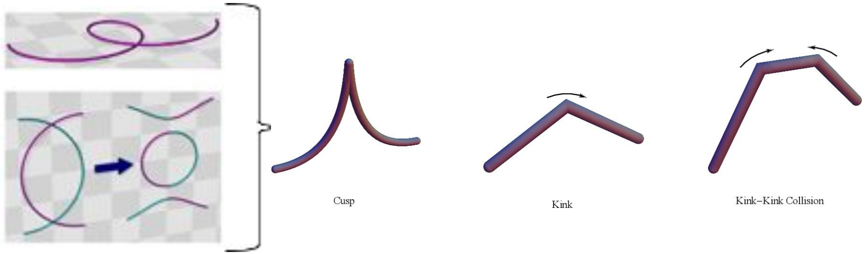
Stochastic GWB sourced by FOPT spans a wide frequency range with peak frequency determined by the FOPT temperature

A transition temperature of 10^6–10^7 GeV corresponds to the sensitive range of ET (*e.g., for phase transitions between metastable SUSY-breaking vacua*)

Cosmology with ET

• Cosmic strings (CS)





Oscillating CS loops generate a stochastic GWB that is strongly non-Gaussian and includes occasional sharp bursts due to cusps and kinks

Once the cosmic string loop distribution and number of kinks/cusps is fixed from numerical simulations, the only free parameter is the string tension $G\mu$

Energy scale	Linear density
GUT : 10^{16} GeV	$G\mu \approx 10^{-6}$
3×10^{10} GeV	$G\mu \approx 10^{-17}$
10^{8} GeV	$G\mu \approx 10^{-22}$
EW : 100 GeV	$G\mu \approx 10^{-34}$

O3 LIGO/Virgo: CS with tension above 10^{-15} are excluded (strongest limit that the one from BBN, CMB, PTA)

ET will be able to constrain CS tensions $G\mu \lesssim 10^{-17}$ ($10^{7.5}$ TeV)

Mairi Sakellariadou

Cosmology with ET

- **Early Universe processes**

➢ Formation of PBHs from large curvature perturbations during inflation leads to a strong stochastic GWB generated at 2nd order in perturbation theory from scalar perturbations
Use ET to constrain the parameters of the curvature power spectrum and probe the standard formation mechanism of very light PBHs

➢ Inflationary models, e.g., axion inflation that include couplings to gauge fields resulting to a stochastic GWB with a strong a detectable blue tilt within ET sensitivity

➢ Test alternatives to inflationary cosmology models (e.g., pre-big-bang, ekpyrotic/cyclic)

➢ Combine large-wavelength constraints on tensor-to-scalar ratio (from CMB) with small-wavelength bounds on the GWB energy density (e.g., with ET) to test the existence of an exotic ``stiff '' ($w>1/3$) energy component after inflation but before BBN

Cosmology with ET

- Early Universe processes

➢ Early universe mechanisms can create parity violation (PV) : a production of asymmetric amounts of right- and left-handed circularly polarised isotropic GWs

(*e.g., Chern-Simons gravitational term, axion inflation, turbulence in primordial plasma*)

Search for PV with ET to test/constrain theoretical models

➢ Search for ultra-light dark matter particles, like axions and dark photons.
If the axion is coupled to a dark photon it could have also generated a stochastic GWB through exponential particle production

[*synergy with fundamental physics*]

➢ Stochastic GWB from PBHs
Use ET to search for a primordial binary black holes GW background

[*synergy with population studies*]

Cosmography with GWs

Standard sirens: GWs from compact binaries are self-calibrated distance indicators! [*Schutz (1986)*]

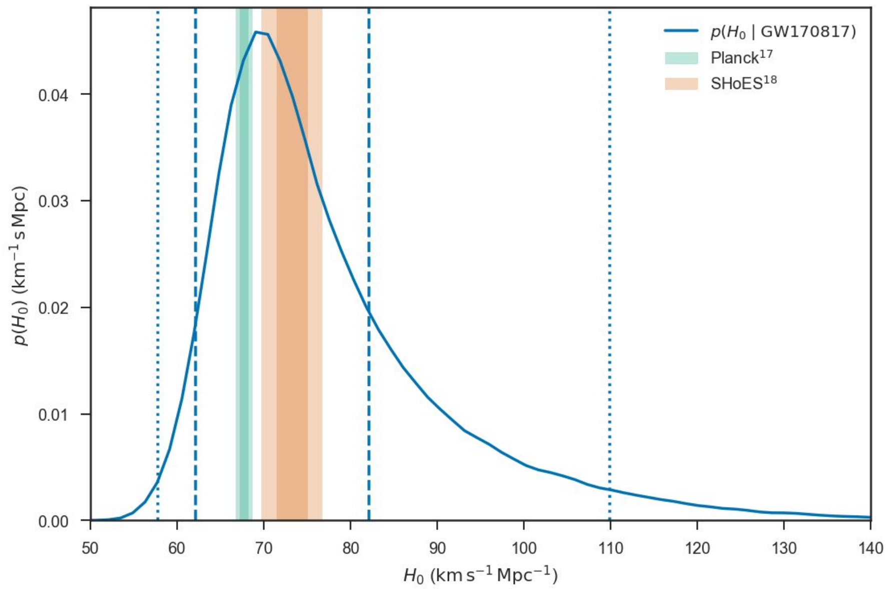
⇨ parameters of cosmology via z-d_L relation.

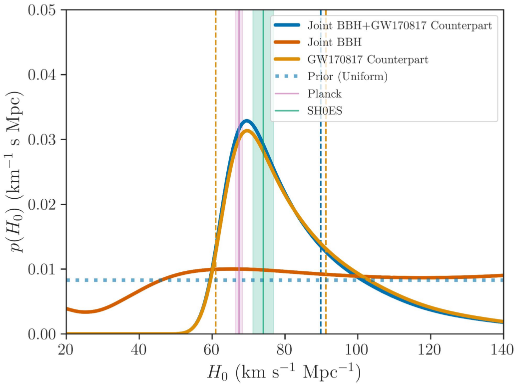
Where can the redshift come from? LIGO/Virgo relevant for ET

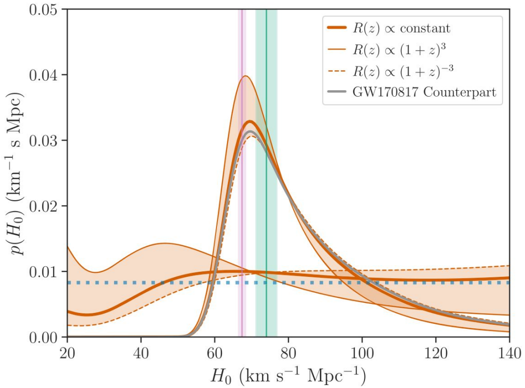
- Internal physics of neutron stars
- Electromagnetic counterparts | statistically from galaxy catalogues
- Mass scale set by astrophysical mechanisms
- Large scale structure of matter in the Universe

} coupled

Current LIGO/Virgo results







Dependence of results on unknown astrophysical distributions.

[Synergies with Population Studies and Multimessenger Observations]

What is this going to look like in the ET era?

From LIGO/Virgo towards ET

- Current “tensions” in cosmology may be resolved by the ET era. However GW standard sirens will remain (possibly the only) direct probe of luminosity distance.

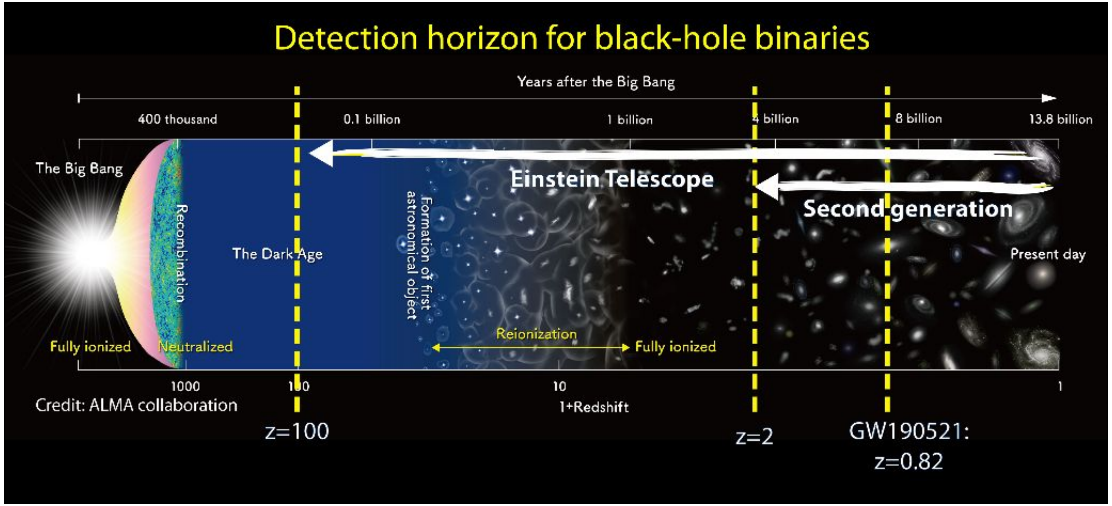
- How does the ET help us?
  - distances, localizations, event rates!

  - Lambda-CDM model: dark matter and dark energy
  - Modified GW propagation: beyond general relativity
  - What can this tell us about the nature of dark matter?

[synergy with Fundamental Physics]

- GW lensing: strong lensing (time delay); weak lensing (d_L correction)

Uniquely by the ET

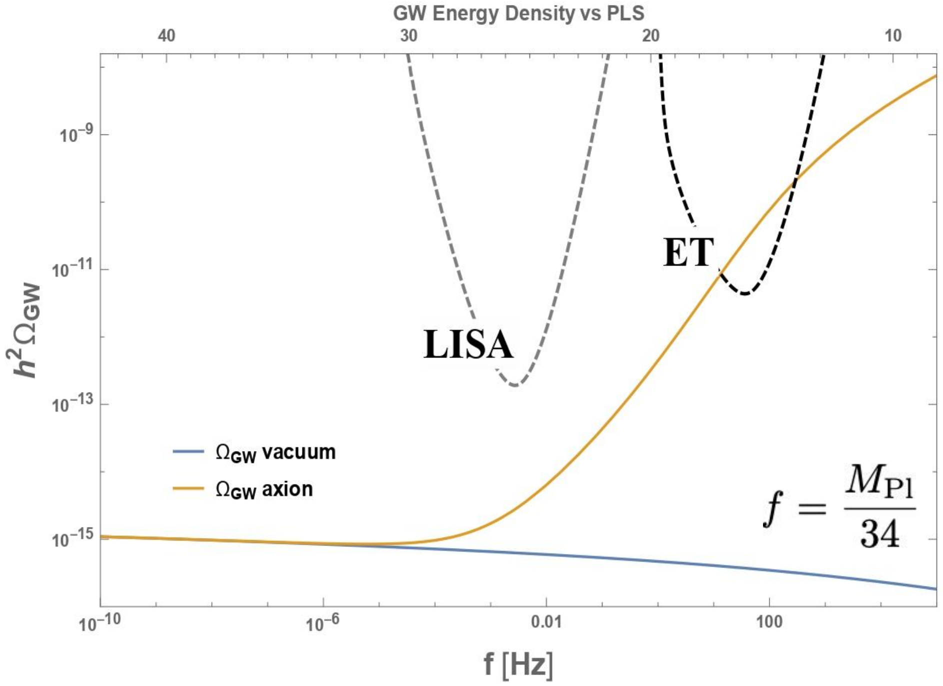


- How does the universe look in GWs?
  - What do GWs reveal about the underlying LSS?
  - Probe GW bias: possible only with the ET

Cosmology with ET

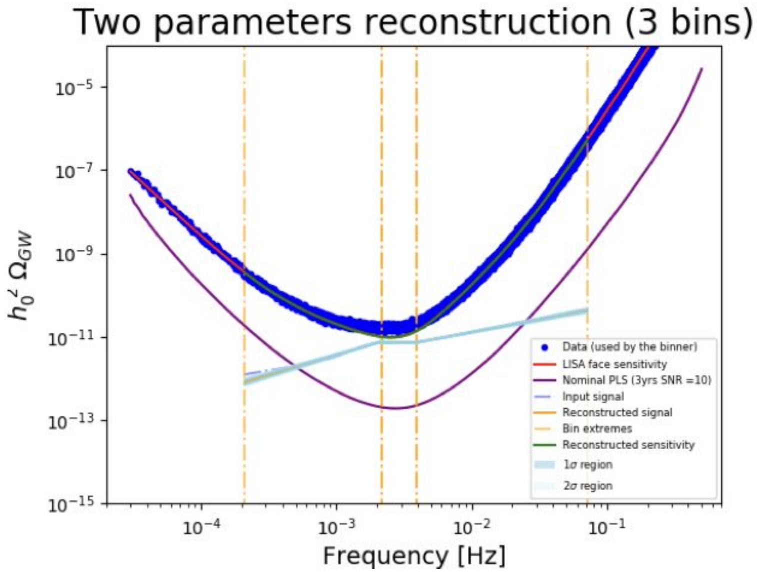
- Probing inflationary physics

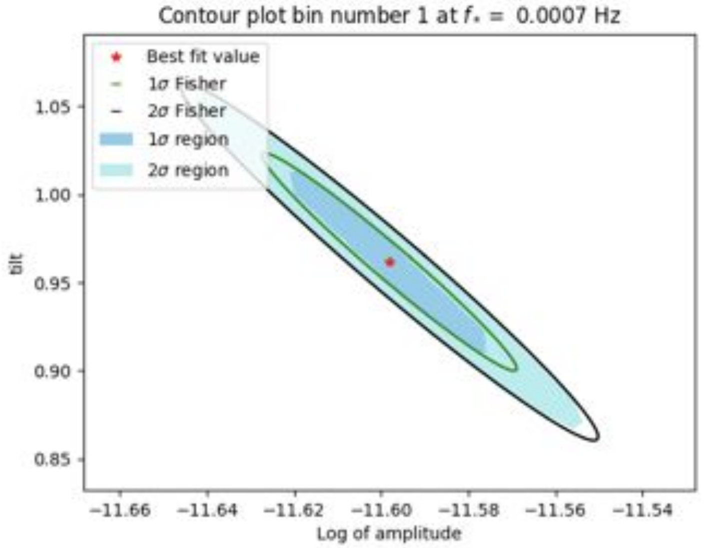
- Axion inflation model
- Second order GWs
- Primordial Black Holes
- Graviton Mass
- ...



Reconstruction of SGWB frequency shape

The ET frequency band will be extremely rich of sources, resolved and unresolved



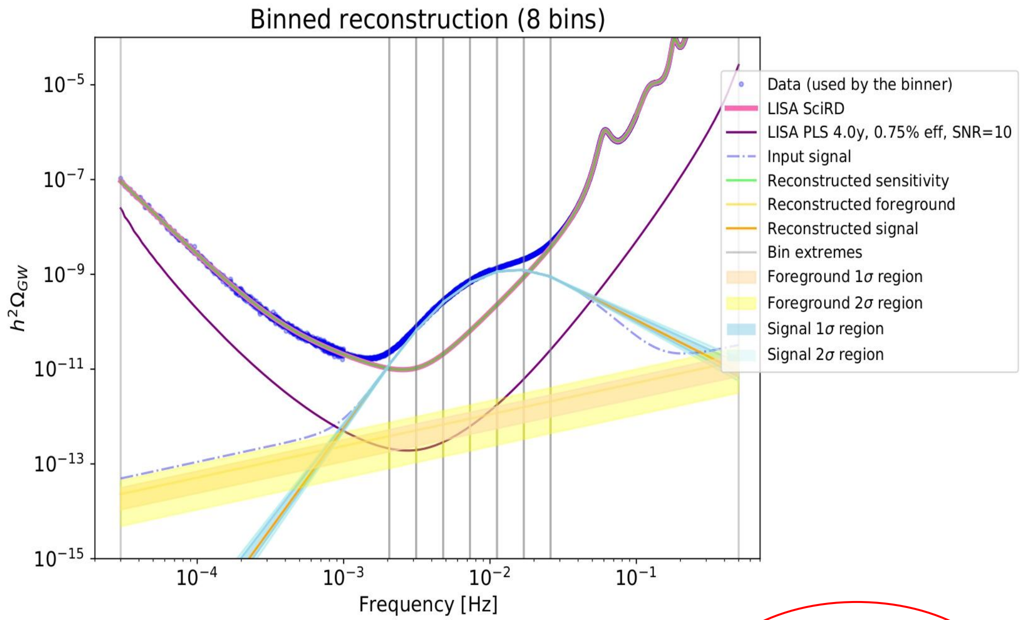


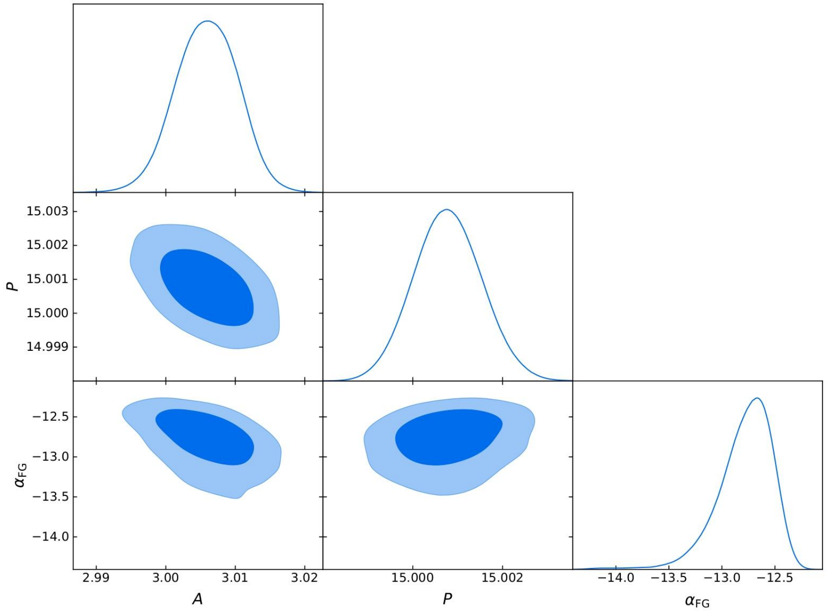
$$h_0^2\,\Omega_{GW}(f) = A_*\,\mathrm{Exp}\left\{-\frac{[\log_{10}(f/f_*)]^2}{\Delta^2}\right\}$$

(Axion inflation, Phase transition beyond SM)

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

Reconstruction and foreground subtraction





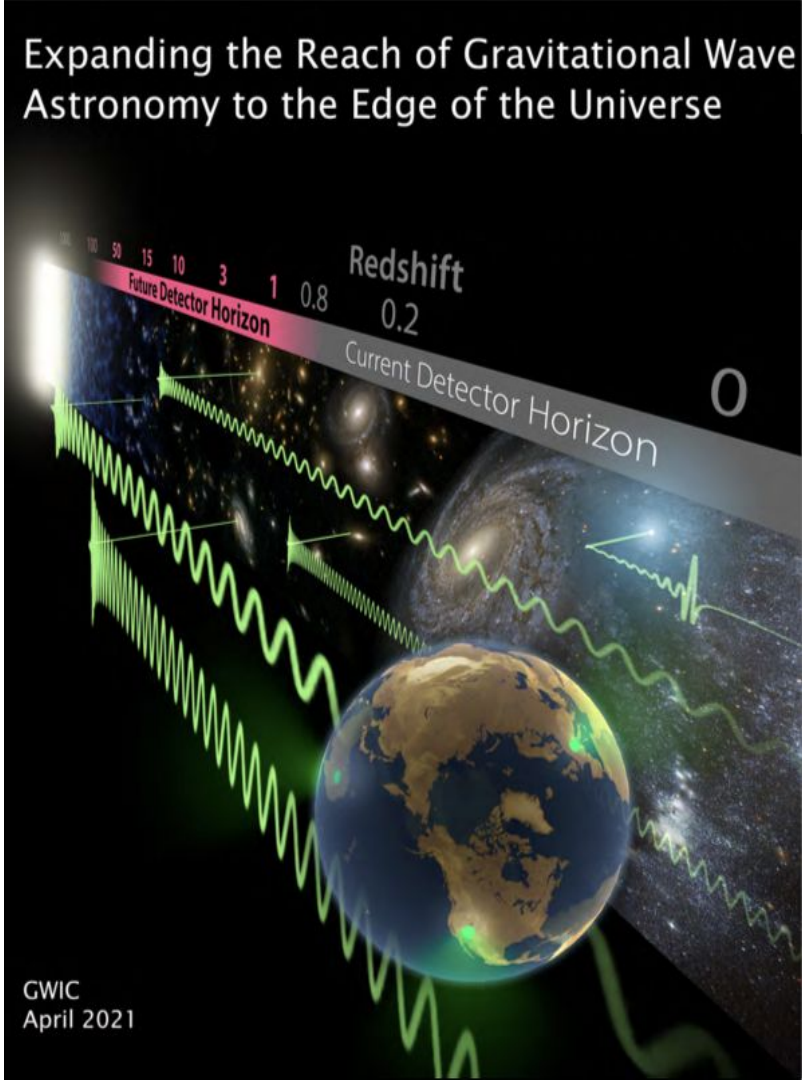
$$h^2\Omega_{\rm GW} = 10^{\alpha}\left(\frac{f}{f_*}\right)^{n_{t_1}}\left[1+\left(\frac{f}{f_*}\right)^{n_{t_2}-n_{t_1}}\right] + 10^{\alpha_{\rm FG}}\left(\frac{f}{f_*}\right)^{2/3}$$

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

Cross-Correlation GW-LSS

- Measuring new cosmological probes
  - **Cross-correlation** of ET **GW resolved sources** with **Large Scale Structure** (LSS) galaxy surveys
  - **Cross-correlation** of ET **GWB** with **Large Scale Structure** (LSS)
  - Synergy with Euclid galaxy maps

[synergy with Population Studies]



Cross-correlation GW-CMB

- Test the ΛCDM model and Theories of Gravity
  - **Cross-correlation** of **astrophysical GW with Cosmic Microwave Background (CMB)** to measure weak lensing of GW
  - **Cross-correlation** of **GWB** both **cosmological and astrophysical** with **CMB anisotropies**

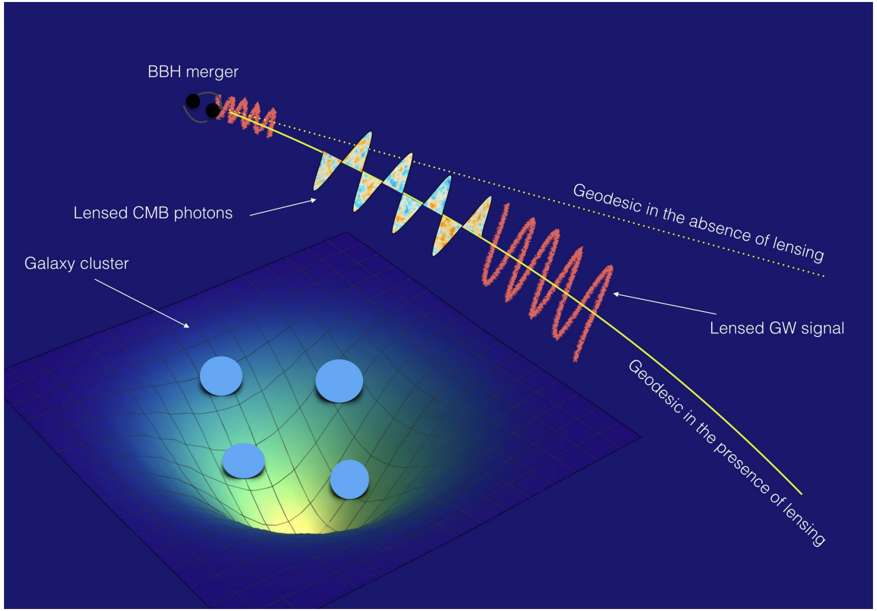
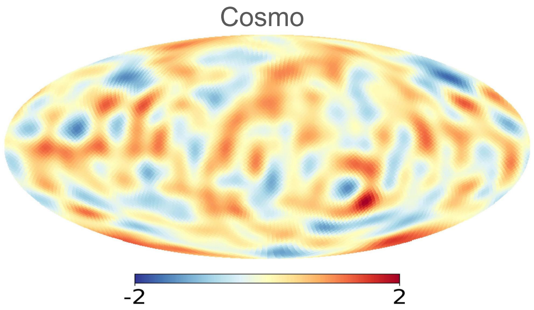
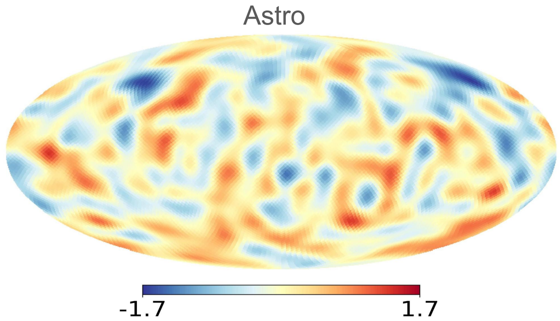


Image Credit: Mukherjee, Wandelt, Silk

Mapping the SGWB with ET

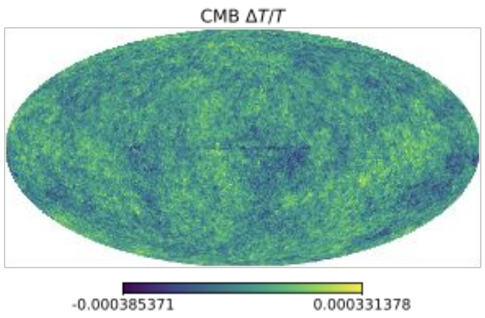
The ET improved resolution will allow to have a better mapping of the GW “sky”

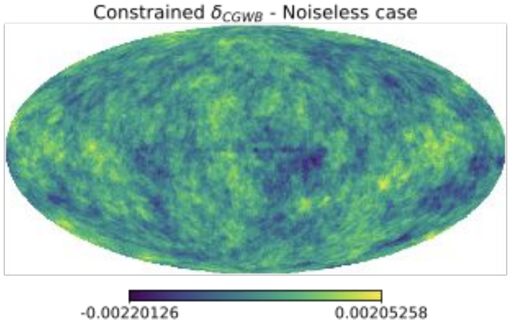


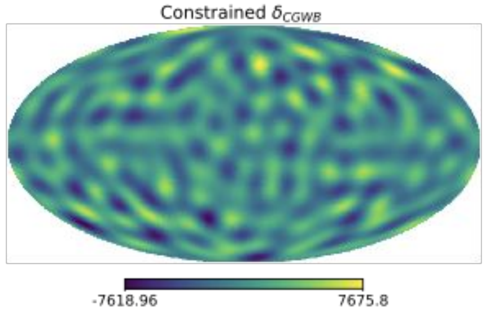


Sky map from LIGO O1

Extra information from the GWB x CMB cross correlation



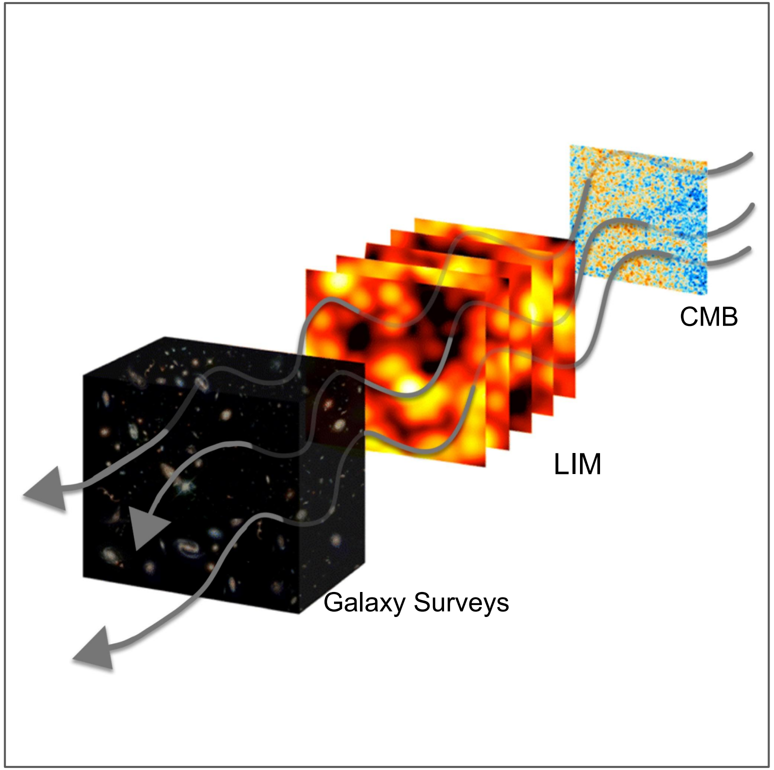




SGWB constrained maps obtained from high resolution CMB Planck maps

Cross-correlation GW-HI intensity mapping

- **Constraints on dynamical Dark Energy models**
- **Determination of the nature of the progenitors of merging binary black holes**
- Control foregrounds and systematics
- Multi-tracing cosmology



Conclusions

ET will allow to probe different cosmological aspects of our Universe

- Physics of the Early and Late Universe
- Dark Matter
- Dark Energy
- Test of Beyond SM particle physics
- Test of standard ΛCDM model and beyond

Next Plans

- Create a collaborative environment
- Identify unique science capabilities of ET
- Develop and encourage synergies with the relevant communities

Exciting GW era is in front of us

JOIN US