Einstein Telescope OSB

Div 2: Cosmology

Archisman Ghosh, Angelo Ricciardone, Mairi Sakellariadou

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

XIII ET Symposium @ Cagliari: 08 May 2023

Cosmology with ET

- **Probe Early Universe Physics**

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

- **GW synergy with other cosmological probes**

Division wikipage:
https://wiki.et-gw.eu/OSB/Cosmology/WebHome

Overarching questions

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

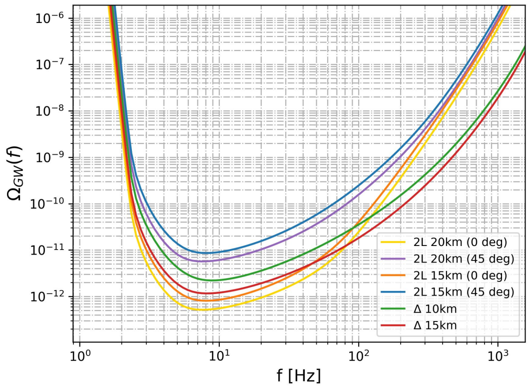
Stochastic (*persistent, incoherent*) GWB of cosmological origin: **probe of the early Universe at energy scales above the ones achievable at current particle colliders**

Evidence for new physics may emerge

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

ET, thanks to its better low-frequency sensitivity, could detect GWB between $\Omega_{GW} \sim 10^{-11.5}$ and $\Omega_{GW} \sim 10^{-12.5}$ at f ~ 10 Hz

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



Cosmology with ET

- **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]

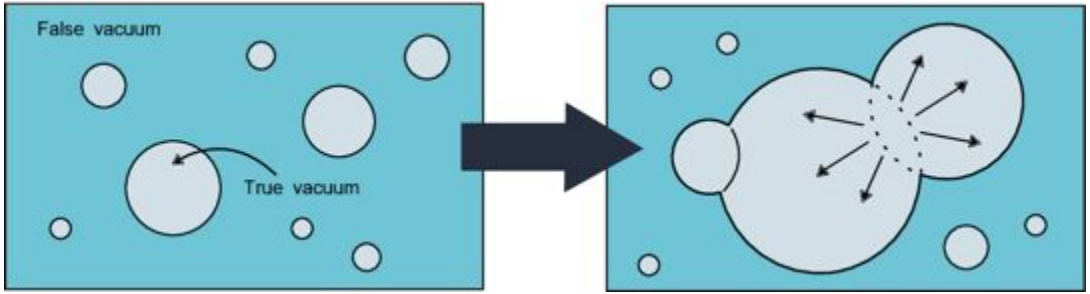
- **Minimise the possibility of false GWB detection**

  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)

- **Quantify the impact on the parameter estimation**

Cosmology with ET

- First-order cosmological phase transitions (FOPT)



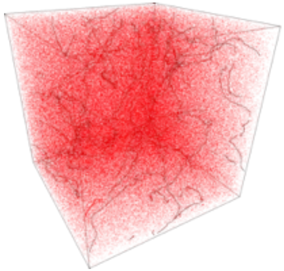
Generation mechanisms:
- bubble collisions
- sound waves
- magnetohydrodynamic turbulence

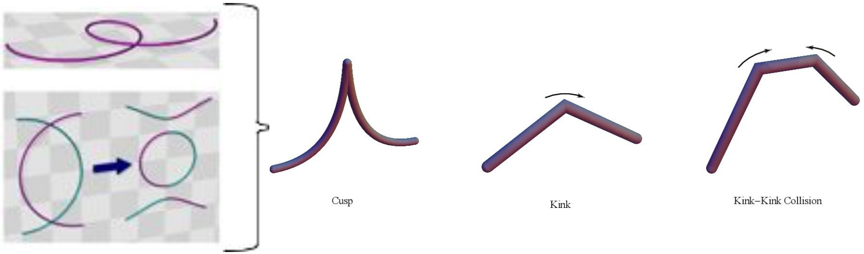
Stochastic GWB sourced by FOPT spans a wide frequency range with peak frequency determined by the FOPT temperature

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)

Cosmology with ET

- ## Early Universe processes

- ➢ Formation of PBHs from large scalar curvature perturbations leads to a stochastic GWB

  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**

➢ Several 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,
finite number of astro sources)
Search for PV with ET to test/constrain theoretical models

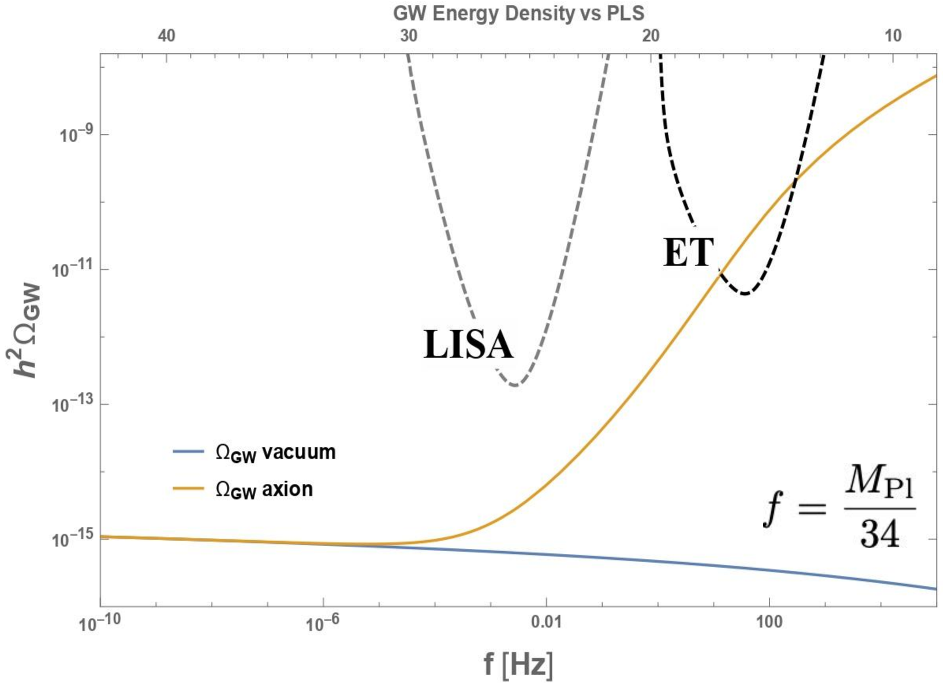
➢ Search for ultra-light dark matter particles, like axions and dark photons.
If the axion is coupled to a dark photon it could have also generated a stochastic GWB through exponential particle production
[*synergy with fundamental physics*]

➢ Search for anisotropies in the SGWB angular distribution

Cosmology with ET

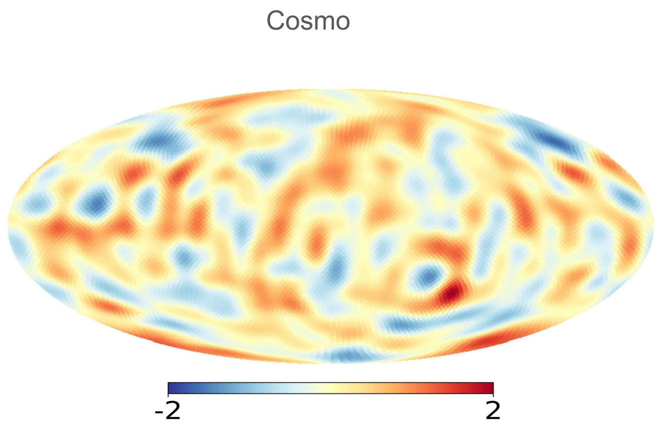
- Probing inflationary physics

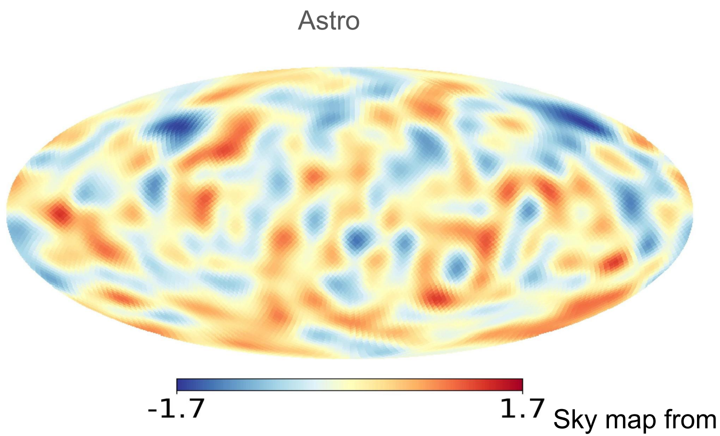
  - **Axion inflation model**
  - Second order GWs (i.e. PBH)
  - Blue tensor spectra
  - ...



Mapping the GWB with ET

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





Sky map from LIGO O1

Combine ET with CMB experiments to forecast cosmological parameters (see GW_CLASS code)

Cosmography with GWs

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

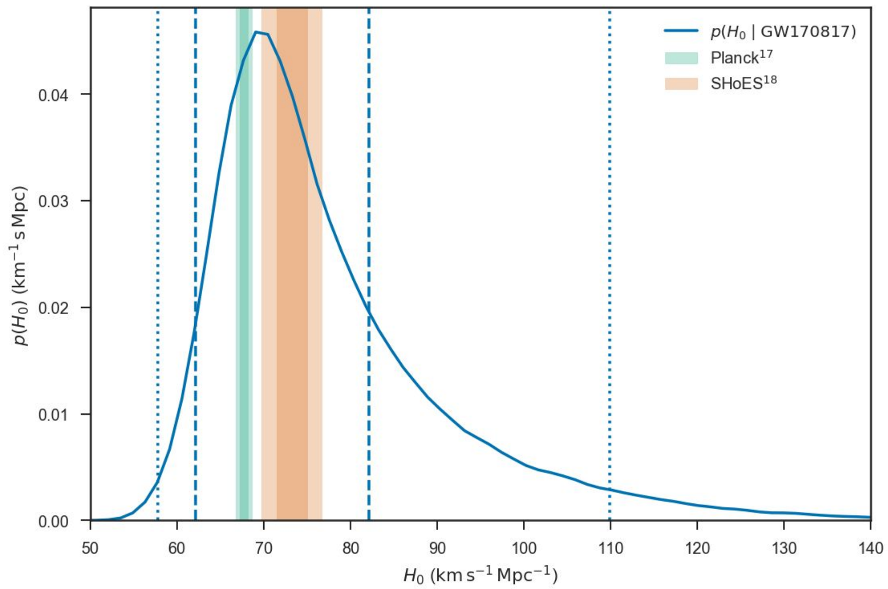
⇨ parameters of cosmology via z-d_L relation.

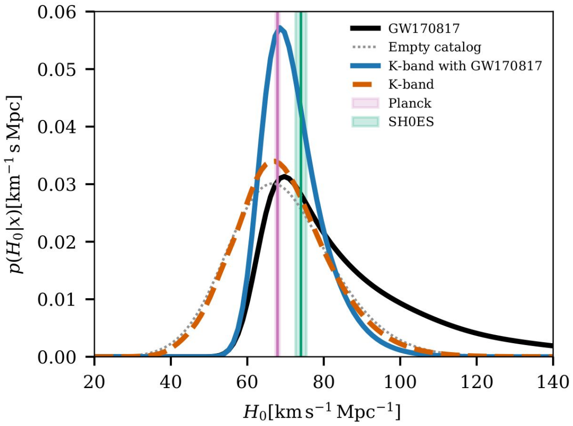
Where can the redshift come from? LIGO/Virgo relevant for ET

- 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

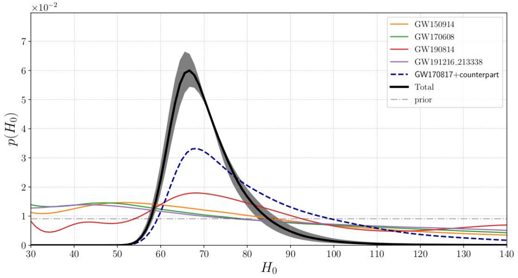
Current LIGO/Virgo results





LVK results from Abbott+ 2111.03604 [astro-ph.CO]

See also Finke+ *JCAP* 08 (2021); Mancarella+ Moriond 2022



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?

A different set of questions

- 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!

$$d_L^{\mathrm{GW}}(z) = \left[(1+z)\int_0^z \frac{\mathrm{d}z'}{H(z'; H_0, \Omega_\mathrm{m}, w_0, \ldots)}\right] \times \left[\Xi_0 + \frac{1-\Xi_0}{(1+z)^n}\right]$$

$$h_A'' + [2 + \alpha_M(\eta)]\mathcal{H}h_A' + c^2k^2h_A = 0$$

- Lambda-CDM model: dark matter and dark energy
- Modified GW propagation: beyond general relativity

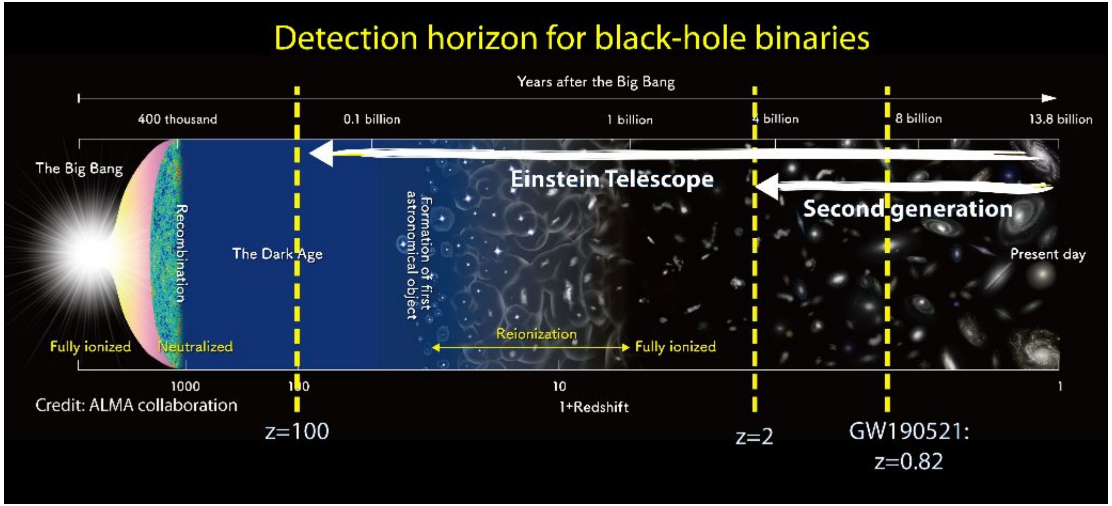
- What can this tell us about the nature of dark matter?

[synergy with Fundamental Physics]

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

Explore questions that can be answered by ET/3G alone ..

Uniquely by the ET

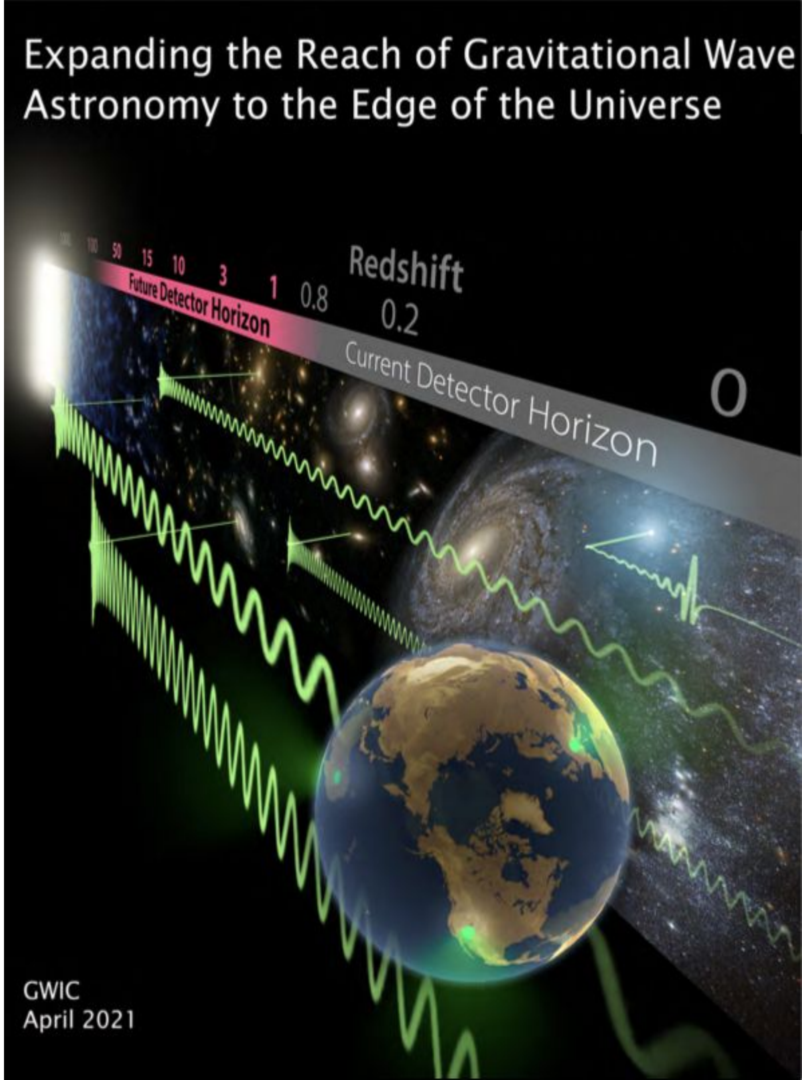


- How does the universe look in GWs?
  - What do GWs reveal about the underlying LSS?
  - **Probe GW bias**: possible only with the ET

Cross-Correlation GW

- 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**

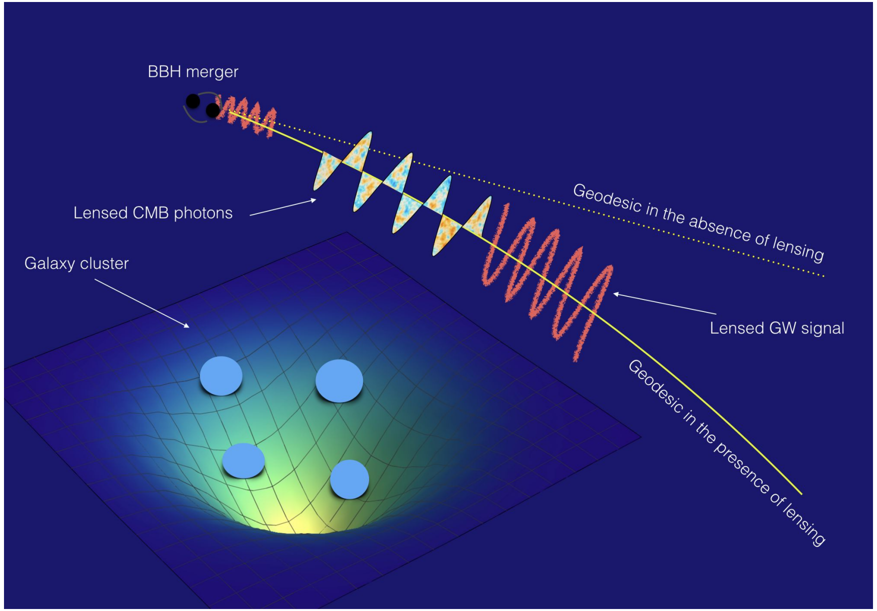
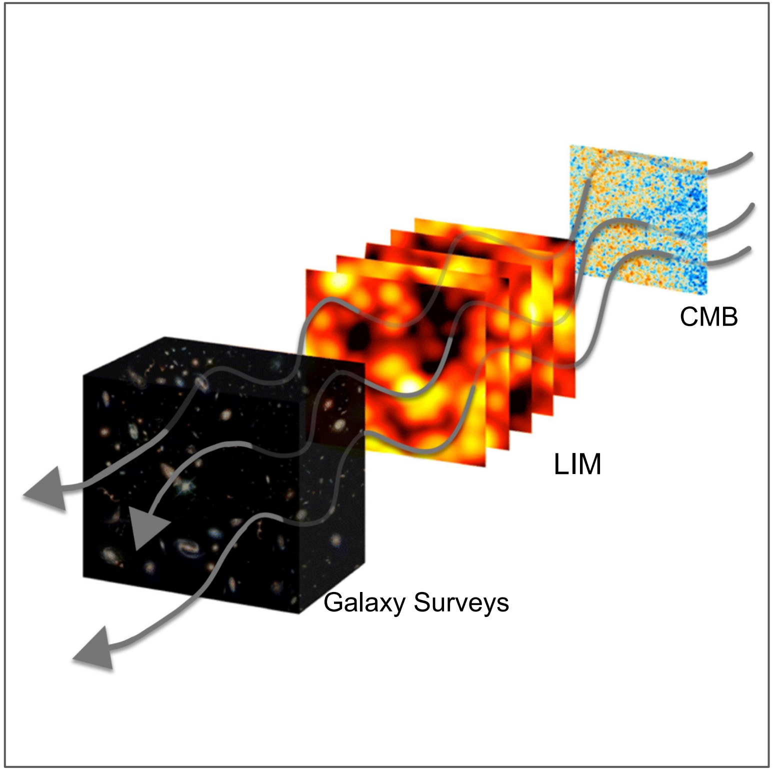


Image Credit: Mukherjee, Wandelt, Silk

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



Recent activity and future plans

Telecons

- Division-wide telecons (~ 40 attendees)

Settling on a monthly rhythm: typically third Wed of every month

- Presentations on a range of topics (listed on next slide)
- *Encourage presentations by early career scientists!*

Div 2 Telecons

- Vuk Mandic (SGWB and the Snowmass process)
- Giulio Scelfo (Cross-correlation of GWs in cosmology)
- Michele Mancarella (Dark standard sirens with 3G detectors)
- Sumit Kumar (Probing Baryon Acoustic Oscillation peak with GWs)
- Alex Jenkins (Dark Matter microphysics from GW event rates)
- Simone Mastrogiovanni (Cosmic dipole with ET and CE)
- Lorenzo Valbusa Dall’Armi (Circular polarization of astrophysical SGWB)
- Michalis Agathos (SGWB from SNe in massive scalar-tensor gravity)
- Matteo Califano (ΛCDM and dark energy forecasts for ET)
- Konstantin Leyde & Grégoire Pierra (importance of population models for cosmology inference)
- Kamiel Janssens (correlated magnetic noise)
- Danny Laghi (Dark siren cosmology with BBH in 3G)

Div 2 Papers

We received ~ 30 papers focused on cosmology

Just on the last months…

- Rocco D'Agostino+ “The role of spatial curvature in the primordial gravitational wave power spectrum”
- Florian Schulze+ “GW_CLASS: Cosmological Gravitational Wave Background in the Cosmic Linear Anisotropy Solving System”
- Gabriele Franciolini+ “Stochastic gravitational-wave background at 3G detectors as a smoking gun for microscopic dark matter relics”
- Niccolò Muttoni+ “Dark siren cosmology with binary black holes in the era of third-generation gravitational wave detectors”

Full list on the WIKI of Div 2

Other Recent Activities

Involvement in the **CoBA studies** of various members and groups

- Power Law Sensitivities for SGWB
- Sensitivity to stochastic backgrounds of misaligned 2L configurations (see Appendix B)
- Cosmic Strings studies (see Sec. 6.5.1)
- Phase Transition studies (see Sec. 6.5.2)
- Source Separation (Astrophysical vs Cosmological GWB) (see Sec. 6.5.3)
- Expected GWB from Population III (see Sec. 5.3)
- Magnetic noise (see Sec. 5.4.2)

ET Blue Book

- Getting started

    - Thinking about the content of the Blue Book
    - Collecting expression of interest for the different sections (e.g., experts and recent presenters)

- Main content based on WPs listed above

BB Preliminary Contents

- WP 1: Early Universe
    - Topological defects: cosmic strings - domain walls (background & anisotropies)
    - Phase transitions
    - Inflation (overlap with Div 3)
    - Reconstruction and separation of GWBs
- WP 2: Cosmography
    - Modified gravity - Dark energy (overlap with Div 1)
    - Cosmography -- H0 measurement
    - BAO

- WP 3: GW cross-correlations
    - GWxLSS
    - Source Separation (astro vs cosmo)
    - GW clustering

- WP 4: Dark Matter & Dark Energy
    - Dark Photons
    - Dark Matter (i.e., Primordial Black Holes)
    - Axions and axion-like particles
    - Modified Gravity vs DE

- Impact of noise on the GWB determination
- Other observables (parity violation, anisotropies, polarizations)

More in presentations that follow ...

Division wikipage: https://wiki.et-gw.eu/OSB/Cosmology/WebHome

archisman.ghosh@ugent.be
angelo.ricciardone@unipi.it
mairi.sakellariadou@kcl.ac.uk