# Multiband gravitational-wave cosmology

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# Plan of the talk

- cosmology with CBCs
  - what we want to measure and why:

    $H_0$, DE eq. of state , modified GW propagation

    standard sirens/dark sirens
  - multiband CBC with LGWA

- cosmological stochastic backgrounds

# GWs as probes of cosmology

GWs from coalescing binaries provide an absolute measurement of the luminosity distance to the source

$$d_L(z) = \frac{1+z}{H_0} \int_0^z \frac{d\tilde{z}}{\sqrt{\Omega_M (1+\tilde{z})^3 + \rho_{\rm DE}(\tilde{z})/\rho_0}}$$

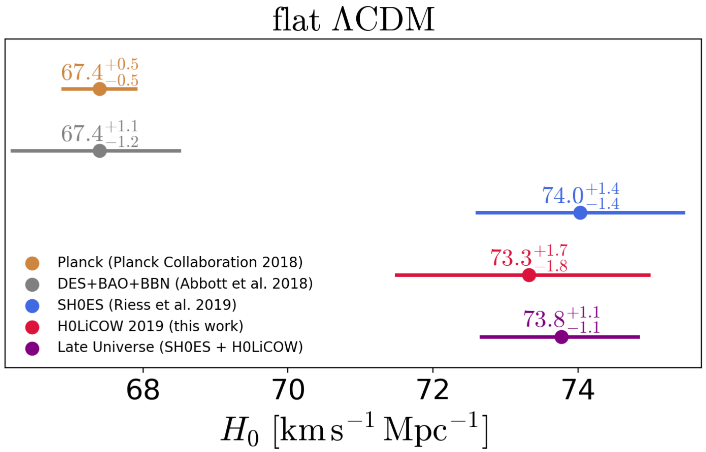
$$\Omega_M = \frac{\rho_M(t_0)}{\rho_0}, \quad \rho_0 = \frac{3H_0^2}{8\pi G}$$

- need an independent determination of z
  - electromagnetic counterpart (bright sirens)
  - statistical methods (dark sirens)

- low z: Hubble law, $d_L \simeq H_0^{-1} z$
- moderate z: access $\Omega_M, \rho_{\rm DE}(z)$

# low-z important for the tension in $H_0$:

Observational tensions, in particular early- vs late-Universe probes of $H_0$




LIGO/Virgo measurement of $H_0$ from GW170817:

$$H_0 = 70.0^{+12.0}_{-8.0} \qquad (z \simeq 0.01)$$

O(50-100) standard sirens at advanced LIGO/Virgo needed to arbitrate the discrepancy

At higher z, accessible only to 3G detectors or LISA, we access the redshift evolution of the dark energy density

$$p_{\rm DE}(z) = w_{\rm DE}(z)\rho_{\rm DE}(z) \quad \Longrightarrow \quad \frac{\rho_{\rm DE}(z)}{\rho_0} = \Omega_{\rm DE} \exp\left\{3\int_0^z \frac{d\tilde{z}}{1+\tilde{z}}\,[1+w_{\rm DE}(\tilde{z})]\right\}$$

Several studies of forecasts for $w_{DE}$ at ET

Result: not a significant improvement on $w_{DE}$ compared with what we already know from CMB+BAO+SNe

A potentially more interesting observable: modified GW propagation

Belgacem, Dirian, Foffa, MM 1712.08108 , 1805.08731

Belgacem, Dirian, Finke, Foffa, MM 1907.02047, 2001.07619

Belgacem et al, LISA CosWG, 1907.01487

# Modified GW propagation

in GR : $$\tilde{h}''_A + 2\mathcal{H}\tilde{h}'_A + k^2\tilde{h}_A = 0$$

In all theories that modify GR on cosmological scales:

$$\tilde{h}''_A + 2\mathcal{H}[1-\delta(\eta)]\tilde{h}'_A + k^2\tilde{h}_A = 0$$

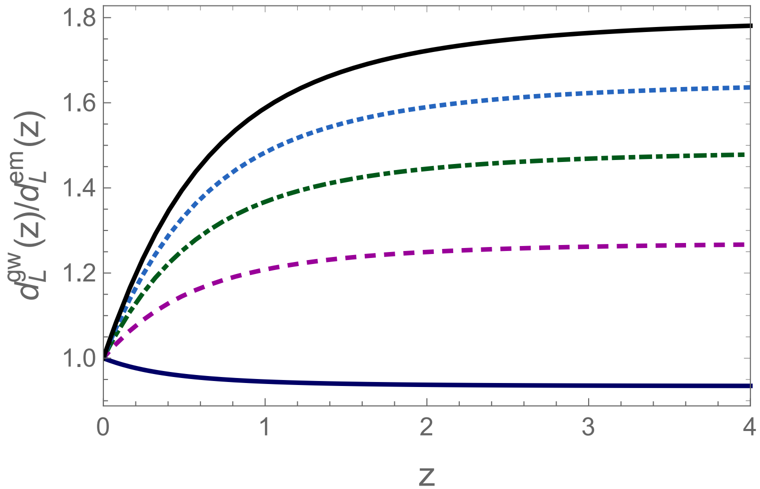
This affects the propagation of GWs across cosmological distances

The net effect is that the quantity extracted from GW observations is a `GW luminosity distance'

$$d_L^{\rm gw}(z) = d_L^{\rm em}(z)\exp\left\{-\int_0^z \frac{dz'}{1+z'}\,\delta(z')\right\}$$

- at the background level and for scalar perturbations, deviations from GR are bounded at the level (5-10)%

- one would expect similar deviations in the tensor sector. Instead, in a viable model (non-local gravity) the deviations at the redshifts explored by ET can reach 80% !




Belgacem, Dirian, Finke, Foffa, MM , 2020

$\Longrightarrow$ the next generation of GW detectors could be the best experiments for studying dark energy

# bright vs dark sirens

- bright sirens
  - possibly only BNS
  - large uncertainty in the rate
  - number of EM counterparts will depend also on EM facilities

key information required from GWs:

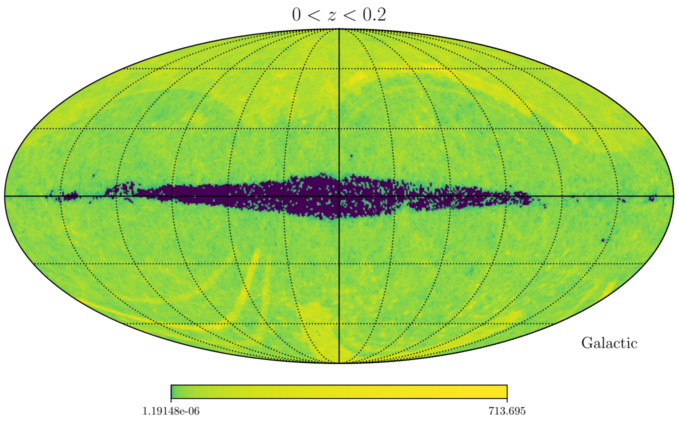
- accurate measurement of $d_L$
- angular localization (say, at least sufficient to pass information to large FOV telescopes)
- ideally, pre-merger alert with good angular localization

dHz detectors are very well suited. Signals in band for long time

# dark sirens

- correlation with galaxy catalogs

GW catalogs in $d_L$ space, galaxy catalogs in z space, cosmology chosen to maximize overlap




challenges:

- completeness of galaxy catalogs, currently (GLADE) has very low completeness at $z>0.2$

however, DESI and Euclid could produce catalogs complete up to $z\sim1$

- GWs must provide accurate volume localization ($d_L$+ angular localization) such that there will be a small number of galaxies in the localization volume

- correlation with mass distribution

GWs measure $m_{det}=m\,(1+z)$ . If we know $m$ statistically, we get statistical info on $z$

BNSs have a narrow mass distribution, but useful also for BBHs

challenges:

- measure accurately m and $d_L$ and, for BBH, have a good model of the mass distribution

- tidal effects in the phase break the (m,z) degeneracy

challenges:

- precision limited by partial degeneracies between tidal effect and mass ratio, that can be obtained from the inspiral at low-f

# Multiband with LGWA

- relatively new topic. First results in our White Paper

for CBCs, most results below taken from:

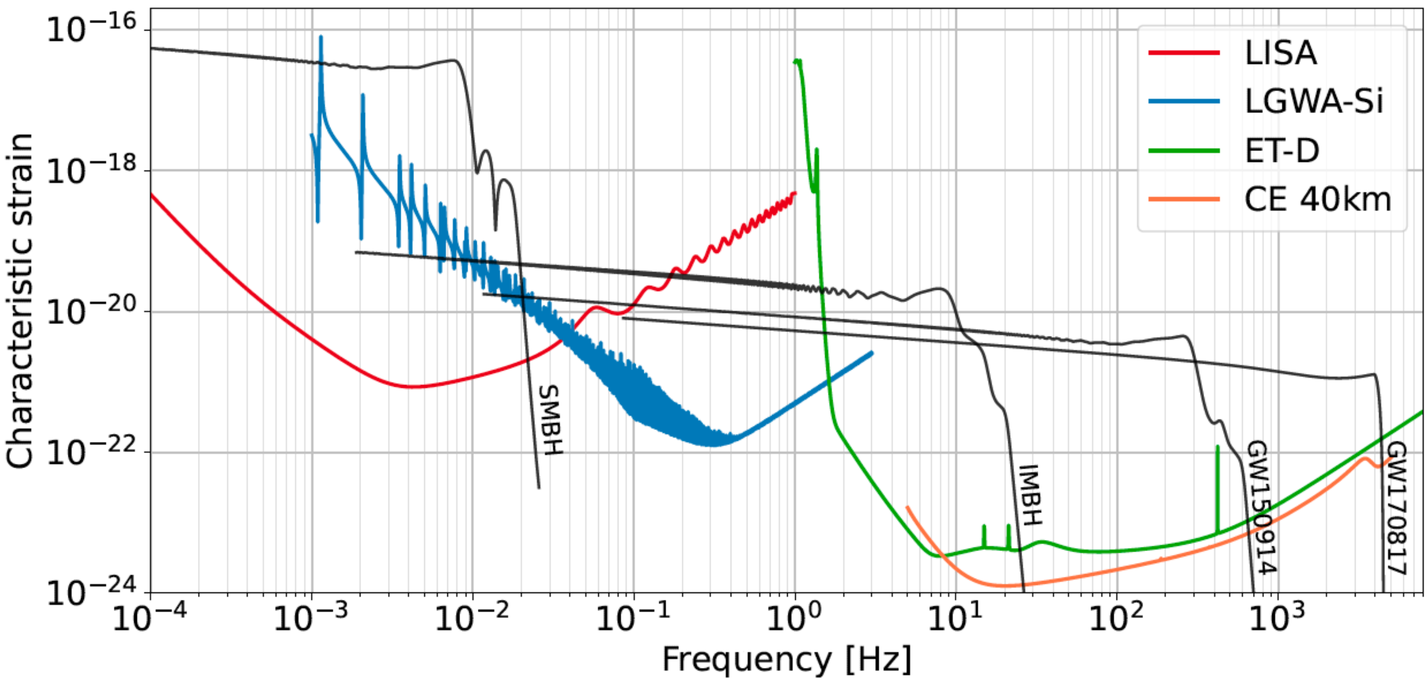
**2.2.1 Detection horizons**

*Main contributors:* Jacopo Tissino, Jan Harms, Martina Toscani, Manuel Arca Sedda, Alberto Sesana

**2.2.4 Multiband GW observations**

*Main contributors:* Michele Mancarella, Francesco Iacovelli, Pau Amaro Seoane, Niccolò Muttoni, Alberto Sesana

- some useful inspiration from work on B-DECIGO
  (but their target sensitivity is one order of magnitude better)

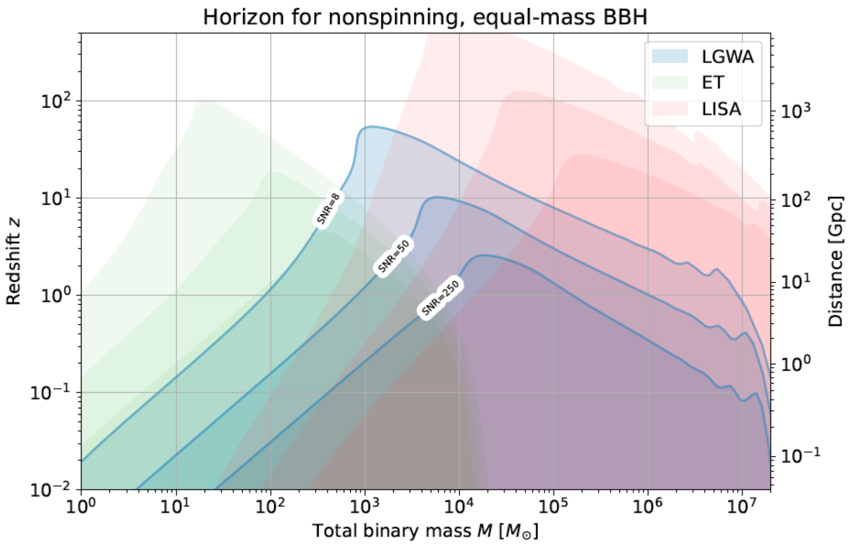



LGWA White paper 2404.09181

example: GW150914 (36+29 $M_\odot$) emits at

- 0.016 Hz (LISA band) 5yrs before merger
- 0.26 Hz (peak sensitivity of LGWA) 1 day before merger

# • stellar-mass BBHs




at $M_{tot} = 100\ M_\odot$ the LGWA horizon is $z \simeq 1$

$\Longrightarrow$ we expect 6'600 sources/yr

out of 80 LIGO-Virgo BBH detections in GWTC1-GWTC3,
28 would have been seen in LGWA

(more would be seen in coincidence with ET, since GWTC signals are a subset of those in the LIGO/Virgo and LGWA horizons)

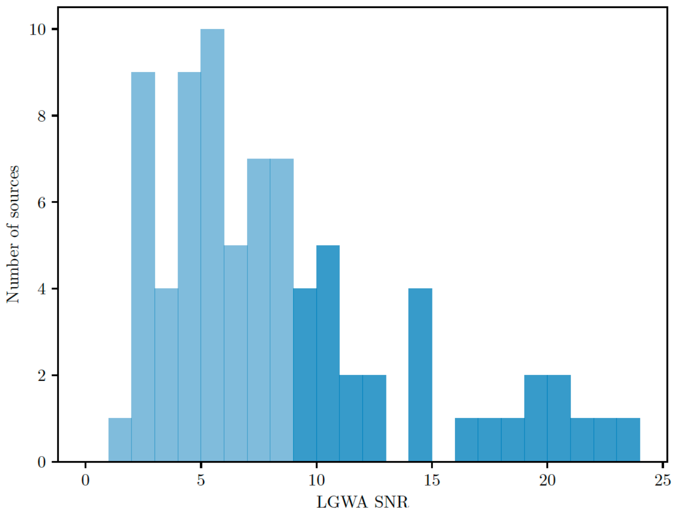



**Figure 6.** Signal to noise ratios of GWTC-3 signals simulated in LGWA. Even when assuming the

# Joint LGWA-ET stellar-mass BBH detections

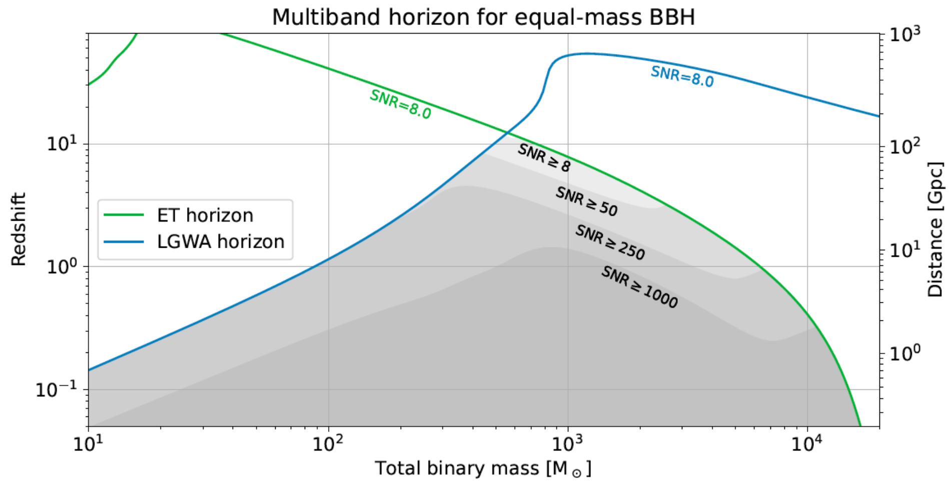



**Figure 13**. Multiband horizon for a network of Einstein Telescope and LGWA (with the Silicon sensitivity curve). As discussed in section 2.2.1, this is showing the maximum distance and redshift for which an optimally-oriented source can be detected with a given signal to noise ratio (SNR). In

LGWA-ET multiband horizon

simulating 10 yrs of joint observations between LGWA and ET-Δ

(using gwfish)

- ~ 960 BBHs observed both by ET and LGWA with SNR > 8 (of which 1 observed also by LISA)

- SNR in LGWA between 8 and 20, in ET between $10^2$ and $\sim 10^3$

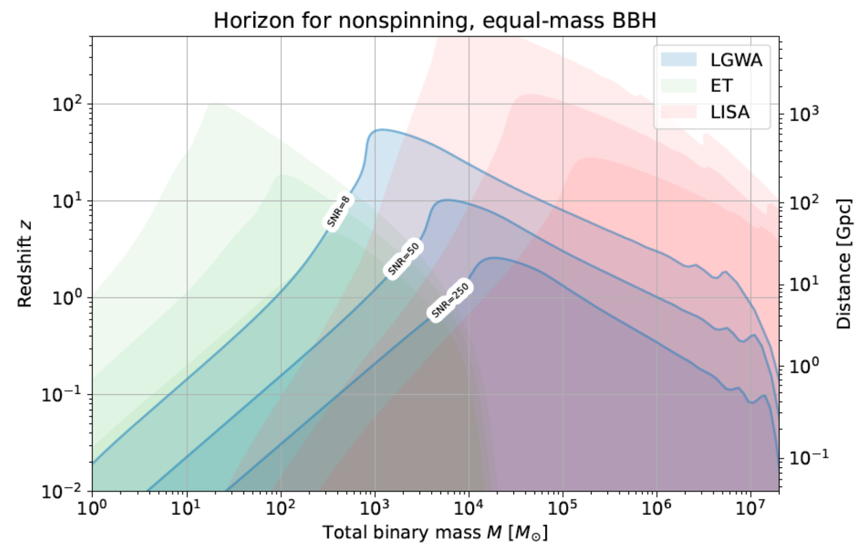
# • BNS

at $M_{tot}$ = 3-4 $M_\odot$ the LGWA horizon is $z \simeq 0.1$

large uncertainty in the rate,

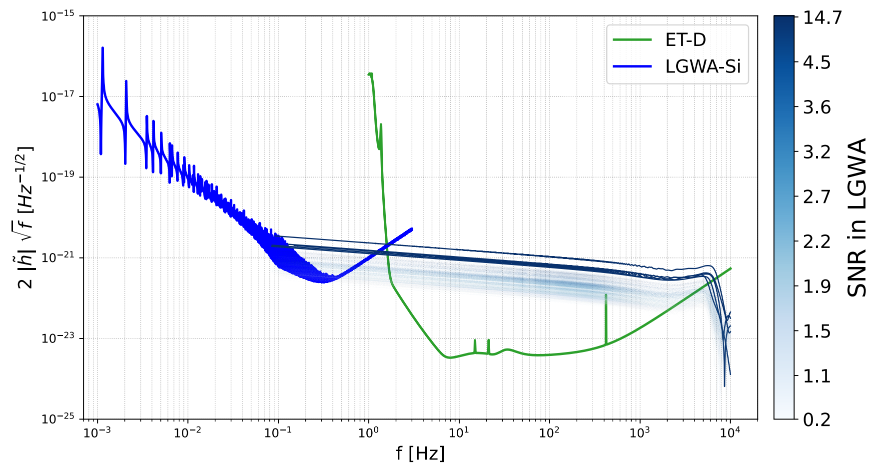
$$R_0 = 105^{+190}_{-83}\,\mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$$

using the central value, in the LGWA horizon there are ~ 360 BNS in 10 yr but LGWA will only detect 5 of them. ET will detect all of them, so 5 joint ET-LGWA detections in 10 yr




using the upper and lower limits on $R_0$
in 10 yr between 1 and 24 joint ET-LGWA detections

no multiband with LISA for BNS
(LISA not very sensitive at these masses, and BNS would inspiral in the LISA band > 45 yr before merger)

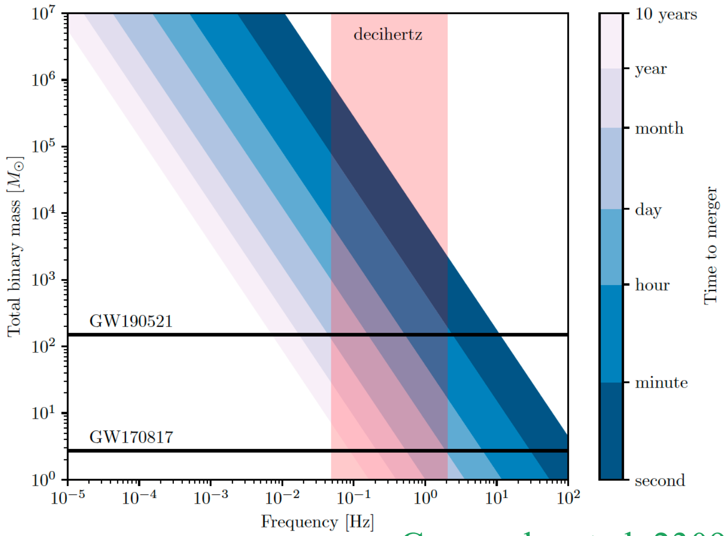



BNS in LGWA and ET
(plot courtesy of M.Mancarella)

# How can these joint detections be useful for cosmology?

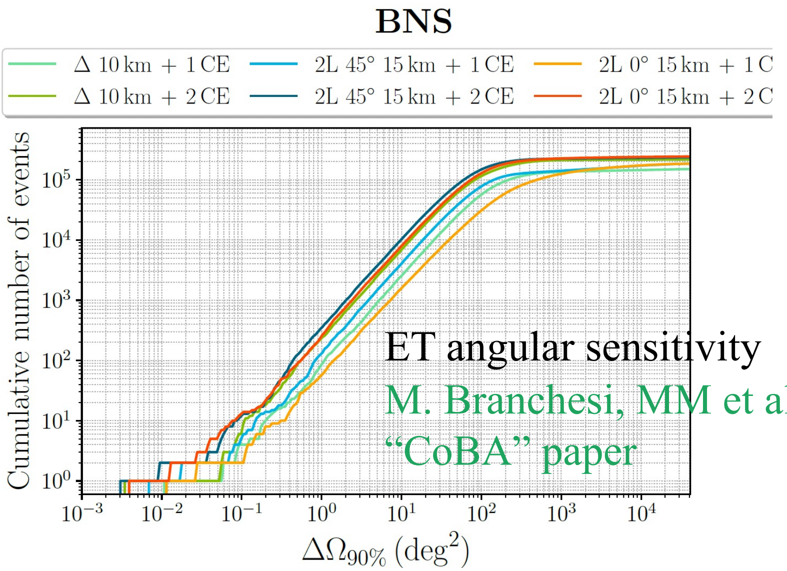
- BNS pre-merger alerts:

for a BNS such as GW170817,
$\Delta\Omega \sim 10^{-3}$ deg$^2$
thanks to the very long time spent in the LGWA band.




Cozzumbo et al, 2309.15160

FIG. 11. Time to merger for a compact binary as a function of total mass (in the detector frame) and frequency




ET angular sensitivity
M. Branchesi, MM et al
"CoBA" paper

angular sensitivity even better than ET+2CE !

however, we have seen that, in 10 yr, only between 1 and 24 BNS will be detected by LGWA

- joint detection with ground based detectors improves parameter estimation

example from studies of B-DECIGO:

- detector motion breaks degeneracies among angles

  (important also for accurate determination of $d_L$)

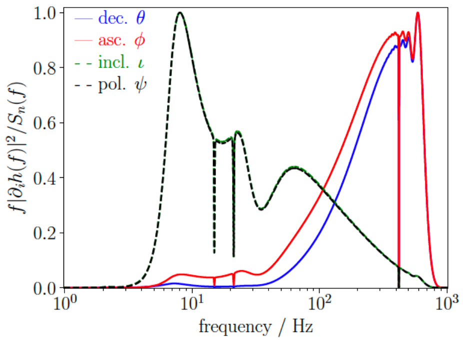



FIG. 15. Frequency dependence of the information content of the diagonal element of the Fisher matrix in ET. The spikes are due to ET's sensitivity curve, see fig. 1.

Grimm & Harms 2004.01434

- accurate determination of mass ratio from the inspiral allows determination of spin- and tidal-induced deformations

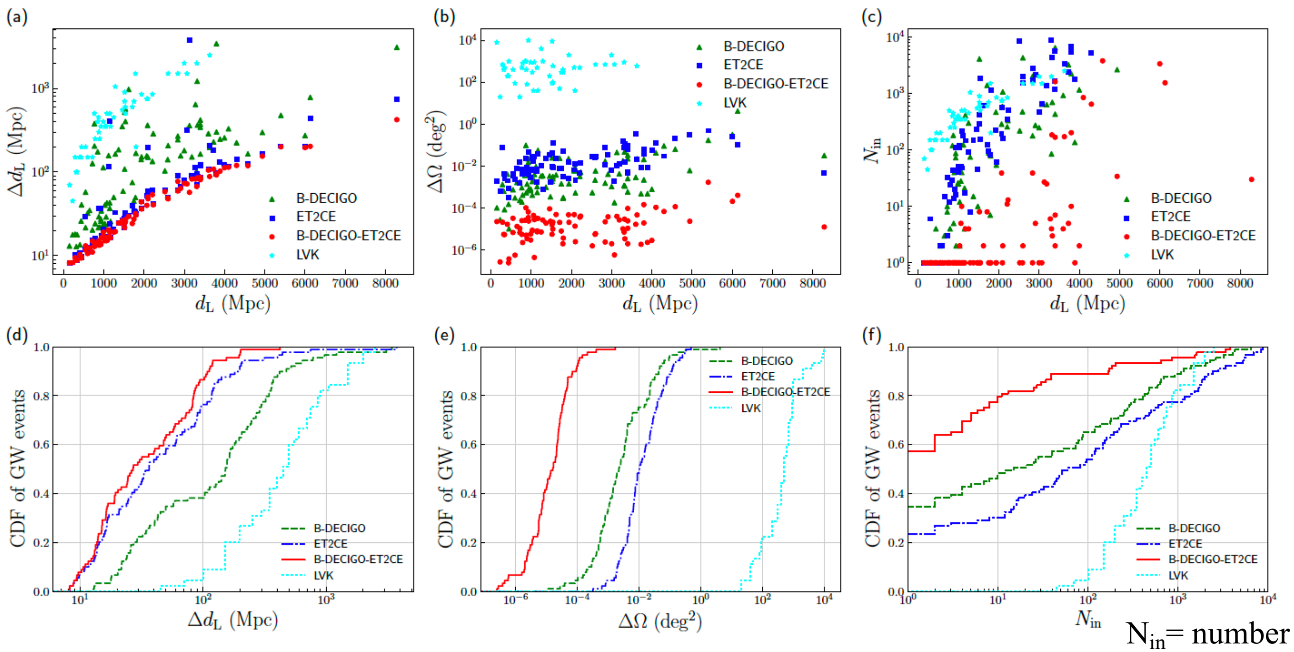
Isoyama et al 1802.06977

and these can be used to break to (m,z) degeneracy

# Multiband dark sirens cosmology

Example from multiband DECIGO –ET2CE

Dong et al. 2404.18188




$N_{in}$= number of galaxies in localization volume

Multiband observations with a dHz detector dramatically shrink the error on sky localization, thanks to the long time spent in bandwidth

(instead, at low z, improvement on $d_L$ is limited by lensing and peculiar velocities)

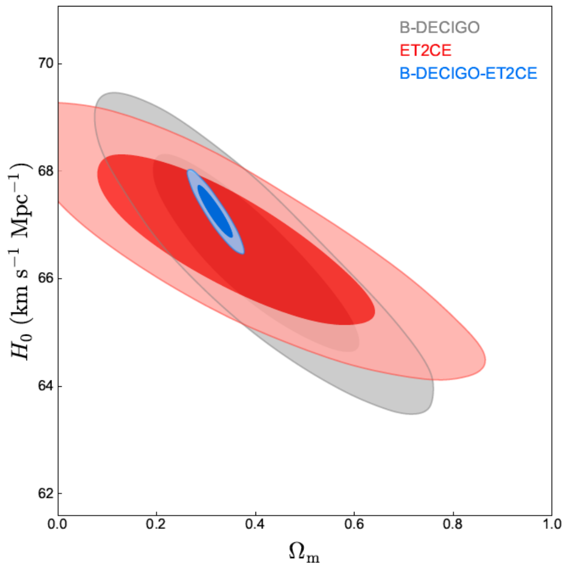
- Dong et al. consider the 88 events in GWTC-3 and assume (optimistically) a galaxy catalog complete to z=1

TABLE I: The number of GW events used in cosmological inference $N_{\rm GW}$ and the number of GW events with $N_{\rm in} = 1$, alongside the absolute errors ($1\sigma$) and the relative errors of the cosmological parameters in the $\Lambda$CDM model. Here the unit of $H_0$ is km s$^{-1}$ Mpc$^{-1}$.

| Result type | ET | 2CE | B-DECIGO | ET2CE | B-DECIGO-ET | B-DECIGO-2CE | B-DECIGO-ET2CE |
|---|---|---|---|---|---|---|---|
| $N_{\rm GW}$ | 37 | 51 | 68 | 75 | 87 | 87 | 88 |
| $N_{\rm in}=1$ | 2 | 2 | 10 | 7 | 40 | 45 | 50 |
| $\sigma(\Omega_{\rm m})$ | – | – | 0.135 | 0.180 | 0.027 | 0.026 | 0.023 |
| $\sigma(H_0)$ | 1.70 | 1.70 | 1.20 | 1.05 | 0.37 | 0.35 | 0.32 |
| $\varepsilon(\Omega_{\rm m})$ | – | – | 33.75% | 48.60% | 8.46% | 8.25% | 7.23% |
| $\varepsilon(H_0)$ | 2.60% | 2.60% | 1.80% | 1.56% | 0.55% | 0.52% | 0.48% |

$N_{GW}$ = number of events localized in volumes with less than $10^4$ galaxies

$N_{in}$ = number of events localized in volumes with only 1 galaxy




Dong et al. 2404.18188

Actual accuracy for ET will be much better because there will many more detection. Here only the 88 from LVK are considered

It would be interesting to repeat this analysis for LGWA

# Multiband stochastic backgrounds

- cosmological GW backgrounds often cover many decades in frequency
- the peak frequency is related to the time at which the background was generated

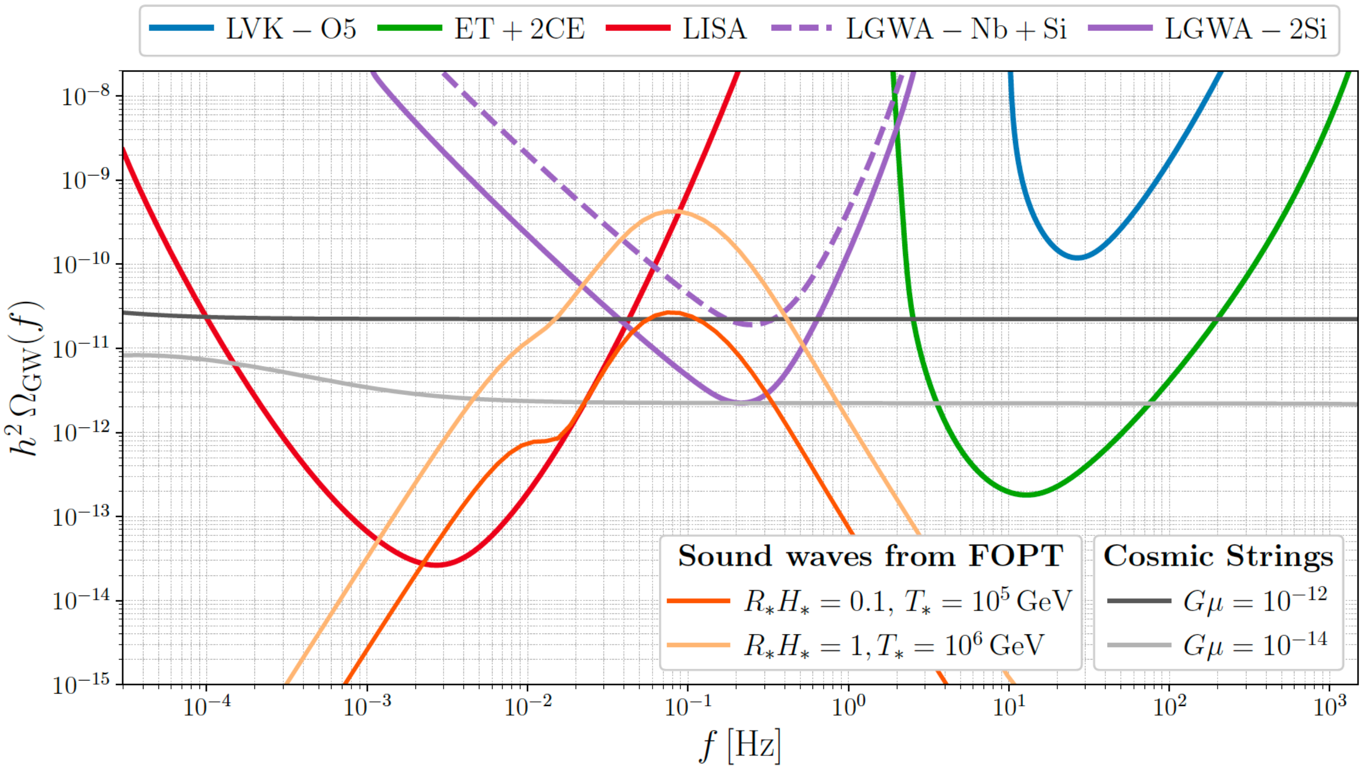
$\lambda\!\!\!^{-}_* = \epsilon_* H_*^{-1}$ at production $\Longrightarrow$ today $f_0 \simeq 2.7 \times 10^{-8} \frac{1}{\epsilon_*} \left( \frac{T_*}{1\,\text{GeV}} \right) \text{Hz}$

different GW bands explore different cosmological epochs

**Table 22.1** The production time $t_*$ and the production temperature $T_*$ for GWs observed today at frequency $f_0$, if at the time of production they had a reduced wavelength equal to the horizon scale.

| $f_0$ (Hz) | $t_*$ (s) | $T_*$ (GeV) |
|---|---|---|
| $10^{-4}$ | $1.6 \times 10^{-14}$ | $3.8 \times 10^{3}$ |
| 1 | $1.6 \times 10^{-22}$ | $3.8 \times 10^{7}$ |
| $10^{2}$ | $1.6 \times 10^{-26}$ | $3.8 \times 10^{9}$ |
| $10^{3}$ | $1.6 \times 10^{-28}$ | $3.8 \times 10^{10}$ |

MM, Gravitational Waves, Vol. II




LGWA White paper

**3.2.3 GW cosmology**

*Main contributors:* Francesco Iacovelli, Enis Belgacem, Marica Branchesi, Stefano Foffa, Arun Kenath, Michele Maggiore, Michele Mancarella, Suvodip Mukherjee, Niccolò Muttoni, Masroor C. Pookkillath, Alberto Roper Pol, Sourav Roy Chowdhury

Multiband observations can
- increase significance of detection
- give a much more powerful handle on the frequency spectrum
- greatly improve parameter estimation for given spectral shapes

# Conclusions

Many opportunities for LGWA multiband cosmology

- BNS as standard sirens

  great angular localization but small numbers

- stellar-mass BBHs as dark sirens

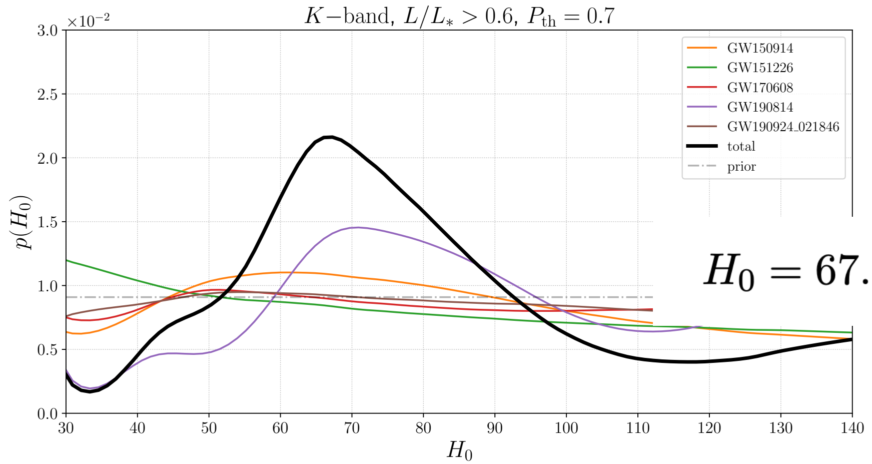
  Very promising, $O(10^2)$ joint LGWA-ET detections.
  Again LGWA could provide good angular localization and possibly reduce the localization volume to just a few galaxies, or a single one

- stochastic backgrounds across many decades in frequency

Thank you!

# after all this, the prize are posteriors that are not flat, even with a limited number of useful BBH events

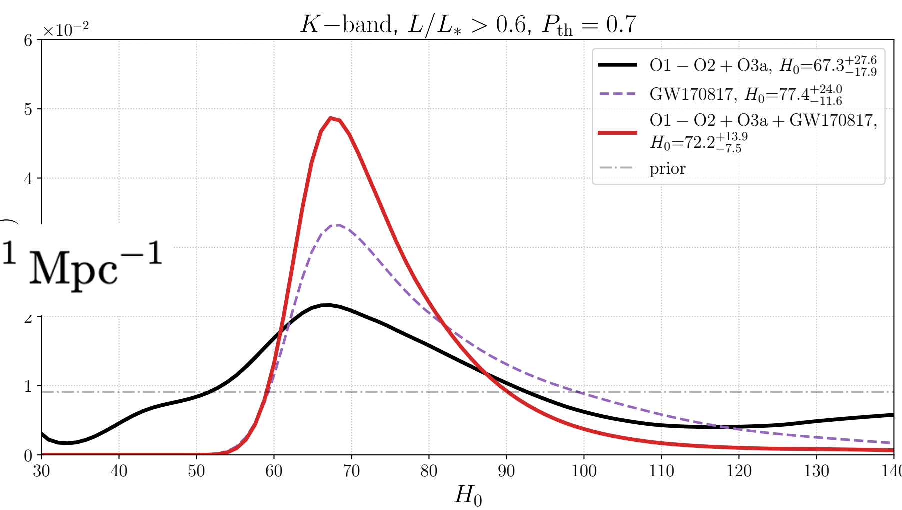
only well-localized events
that fall into sufficiently complete
region contribute



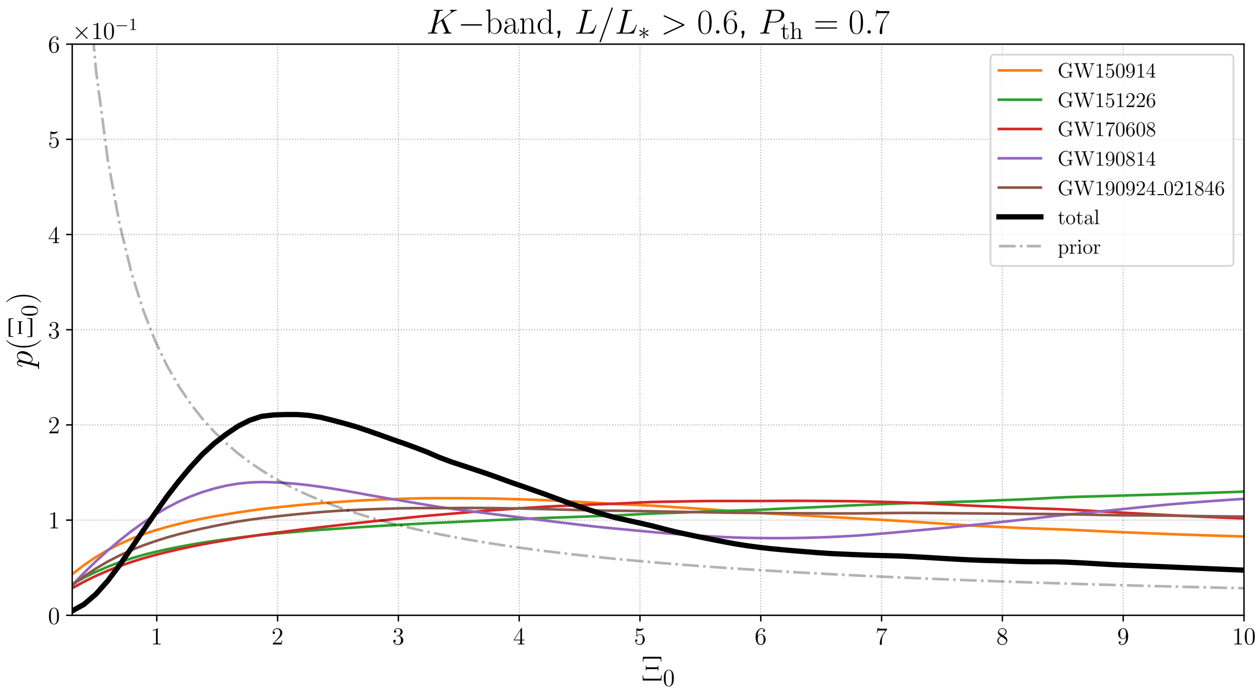

$$H_0 = 67.3^{+27.6}_{-17.9} \;\; \mathrm{km\,s^{-1}\,Mpc^{-1}}$$

combining dark sirens with
GW170817

$$H_0 = 72.2^{+13.9}_{-7.5} \;\; \mathrm{km\,s^{-1}\,Mpc^{-1}}$$



# first meaningful limits on $\Xi_0$




$$\Xi_0 = 2.1^{+3.2}_{-1.2}$$

# next step: joint population-cosmology inference

**Cosmology and modified gravitational wave propagation from binary black hole population models**

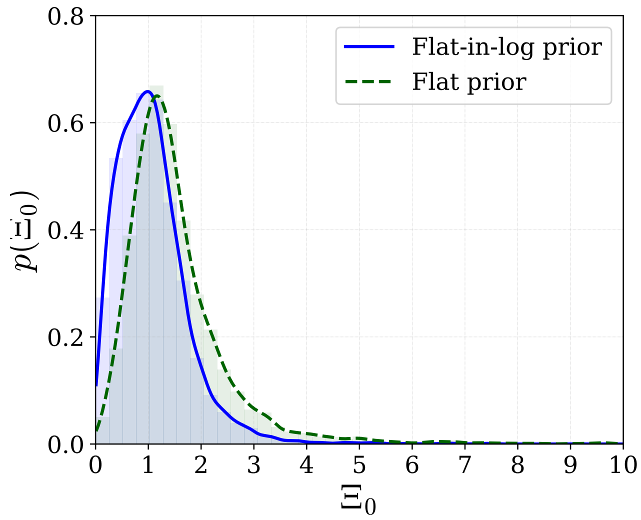
2112.05728, PRD 2022

Michele Mancarella,[1,*] Edwin Genoud-Prachex,[2,†] and Michele Maggiore[1,‡]

joint hierarchical Bayesian analysis of the BBH mass function, merger rate evolution and cosmological parameters

BBHs from GWTC-3

makes use of the mass scale in the BBH mass function due to the PISN process




$$\Xi_0 = 1.2^{+0.7}_{-0.7}$$ (68% c.l.)

Most stringent limit to date

with 5 yrs of LVK data, measure of $\Xi_0$ at 10-20%

Modified gravitational wave propagation and the binary neutron star mass function

Andreas Finke[a], Stefano Foffa[a], Francesco Iacovelli[a], Michele Maggiore[a,*], Michele Mancarella[a]

2108.04065, Phys. Dark. Univ. 2022

GW observations give $m_{det}=(1+z)\, m$ and $d_L$

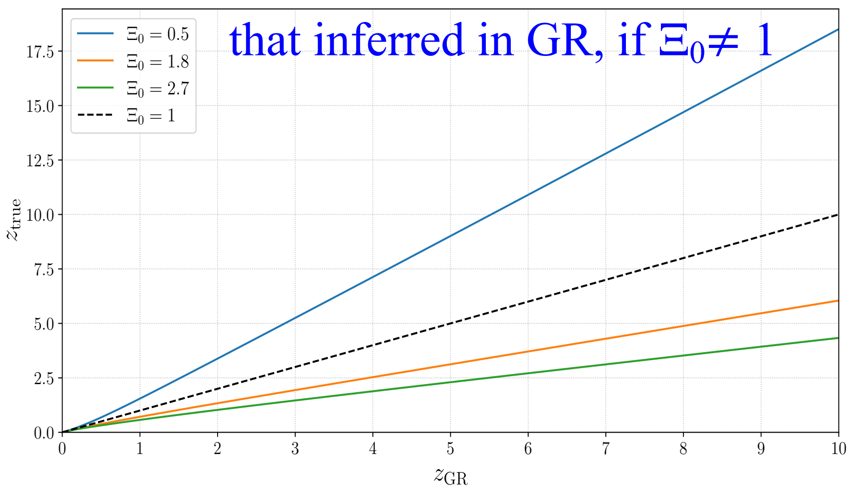
assuming ΛCDM, from $d_L$ we get z and therefore the true mass m

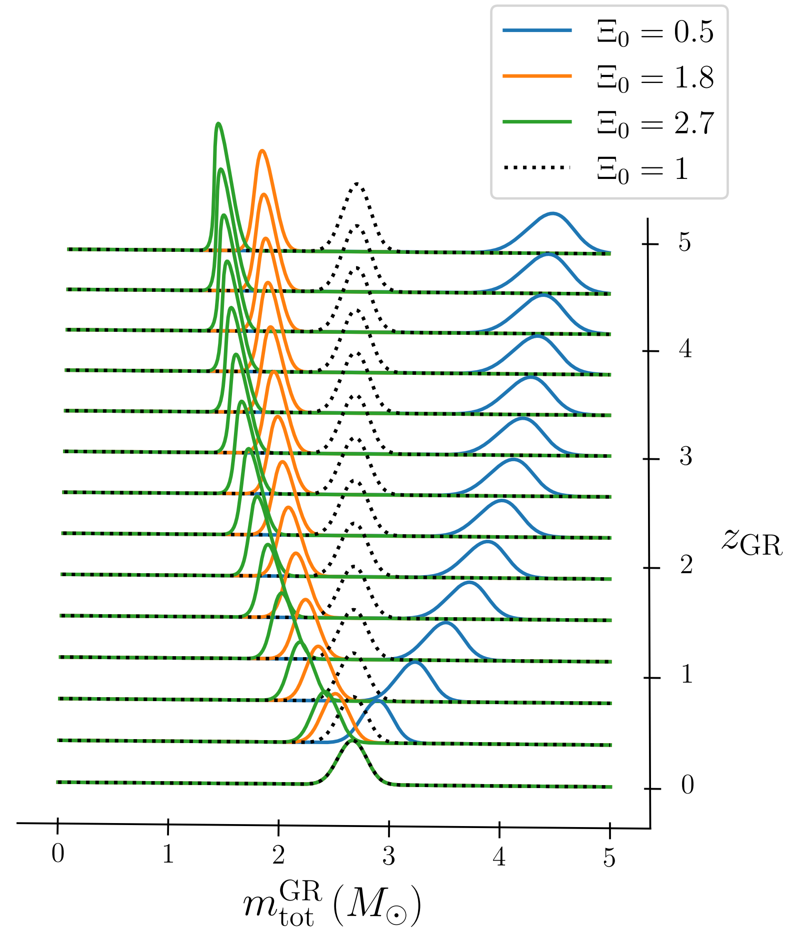
however, if Nature is described by modified GW propagation, GW observations give $d_L^{gw}$

interpreting the data within ΛCDM, we get the wrong z and the wrong mass

but the NS mass function is strongly constrained!

the true redshift as a function of that inferred in GR, if $\Xi_0 \neq 1$




assuming GR, at large z not a single NS with a `normal mass' !!

smoking gun of modified GW propagation

Work in progress UniGe-IFAE with Dounia Nanadoumgar, Giada Caneva, Mario Martinez