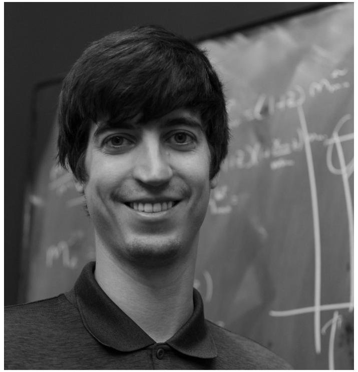
Cosmology (PAX 2022)

Jose Ezquiaga, Suvodip Mukherjee, Antonella Palmese
SOC: Will M. Farr, Eleonora di Valentino

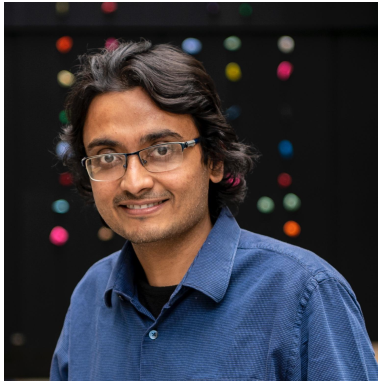
https://tinyurl.com/23v87p4c

Your Panel

Will Farr
Stony Brook / CCA



Jose M. Ezquiaga
UChicago



Suvodip Mukherjee
TIFR

Antonella Palmese
Berkeley

Eleonora di Valentino
U. Sheffield

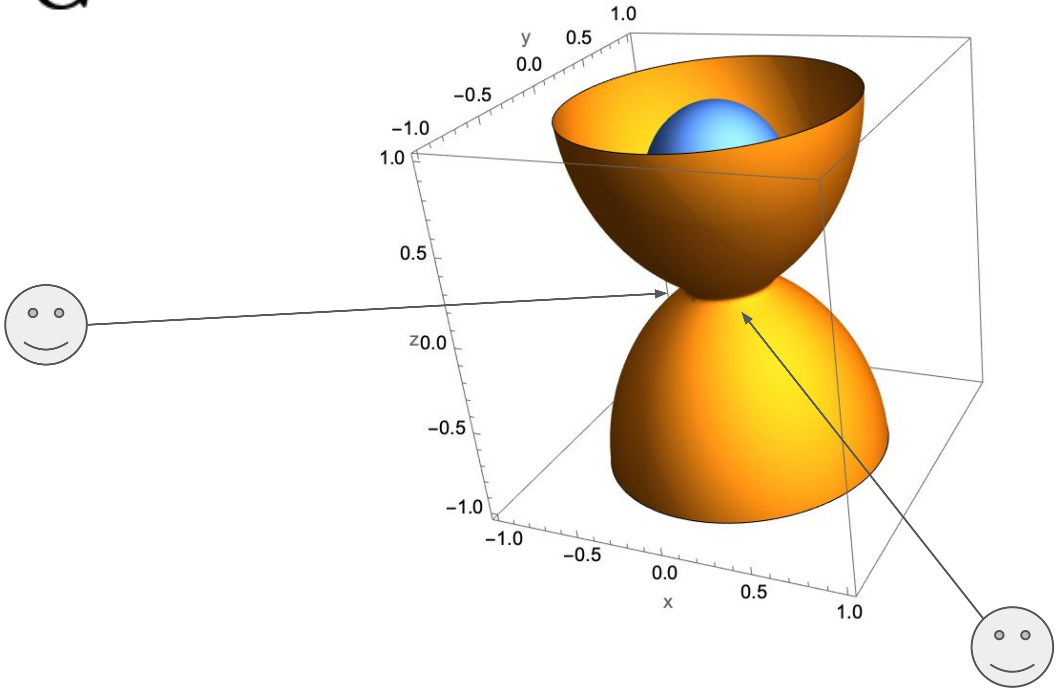
Intro: dL, inclination, hard to measure z (Will)

GW Distances are Easy

$$\frac{c^5}{G} \simeq 3 \times 10^{59}\,\mathrm{erg\,s^{-1}} \simeq 10^6\,\mathrm{SNe}$$

GW Distances are Sort of Easy

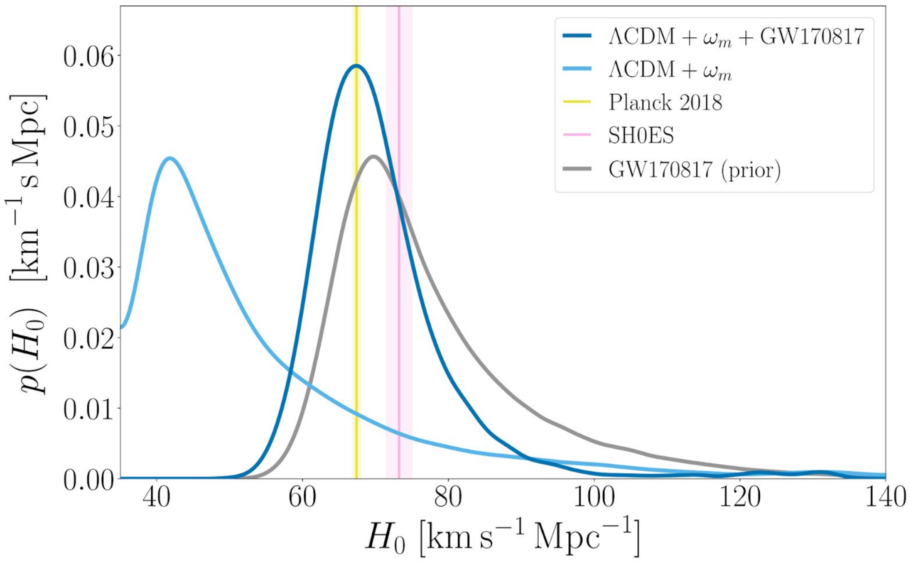
$$\frac{c^5}{G} \simeq 3 \times 10^{59}\,\mathrm{erg\,s^{-1}} \simeq 10^6\,\mathrm{SNe}$$

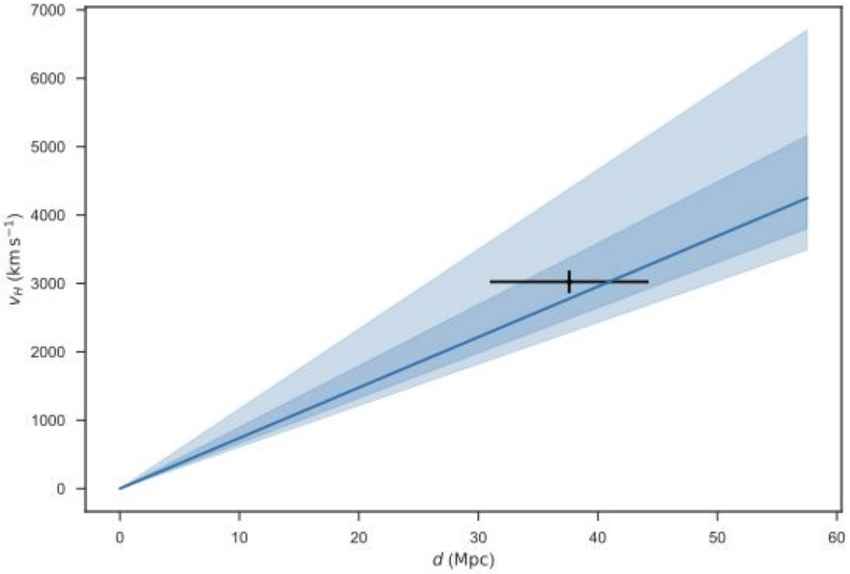


GW Redshifts Are Hard

$$m_{\mathrm{obs}} = m\,(1 + z)$$

GW + EM Counterpart Measurements





Abbott, et al. (2017)
Chen, et al. (2020)

Redshifts Without EM Observations (Mass Function Cosmology)

$$m_{\text{obs}} = m\,(1+z)$$

Redshifts Without EM Observations (Mass Function Cosmology)

If I know this

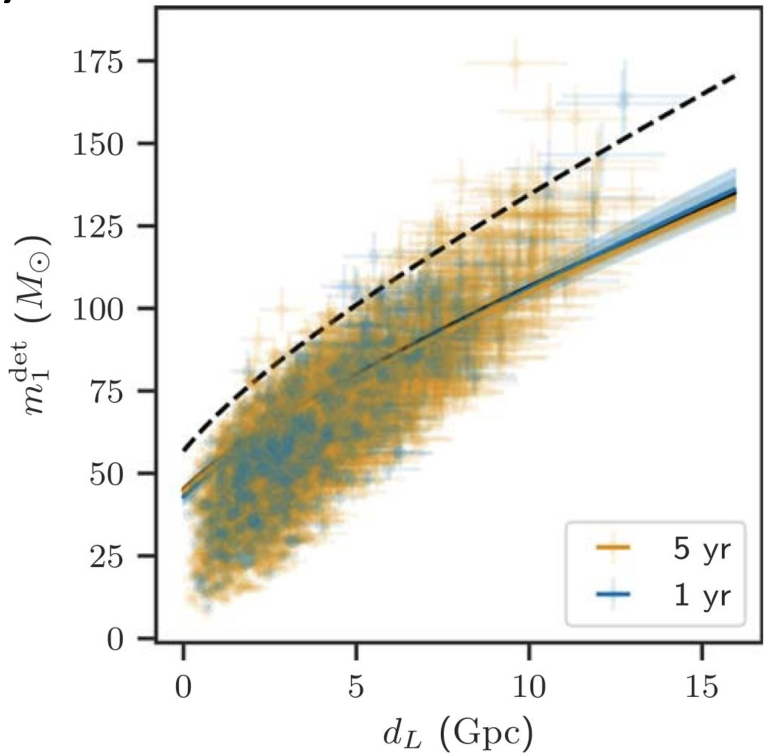
$$m_{\mathrm{obs}} = m\,(1 + z)$$

Redshifts Without EM Observations (Mass Function Cosmology)

If I know this

$$m_{\mathrm{obs}} = m\,(1 + z)$$

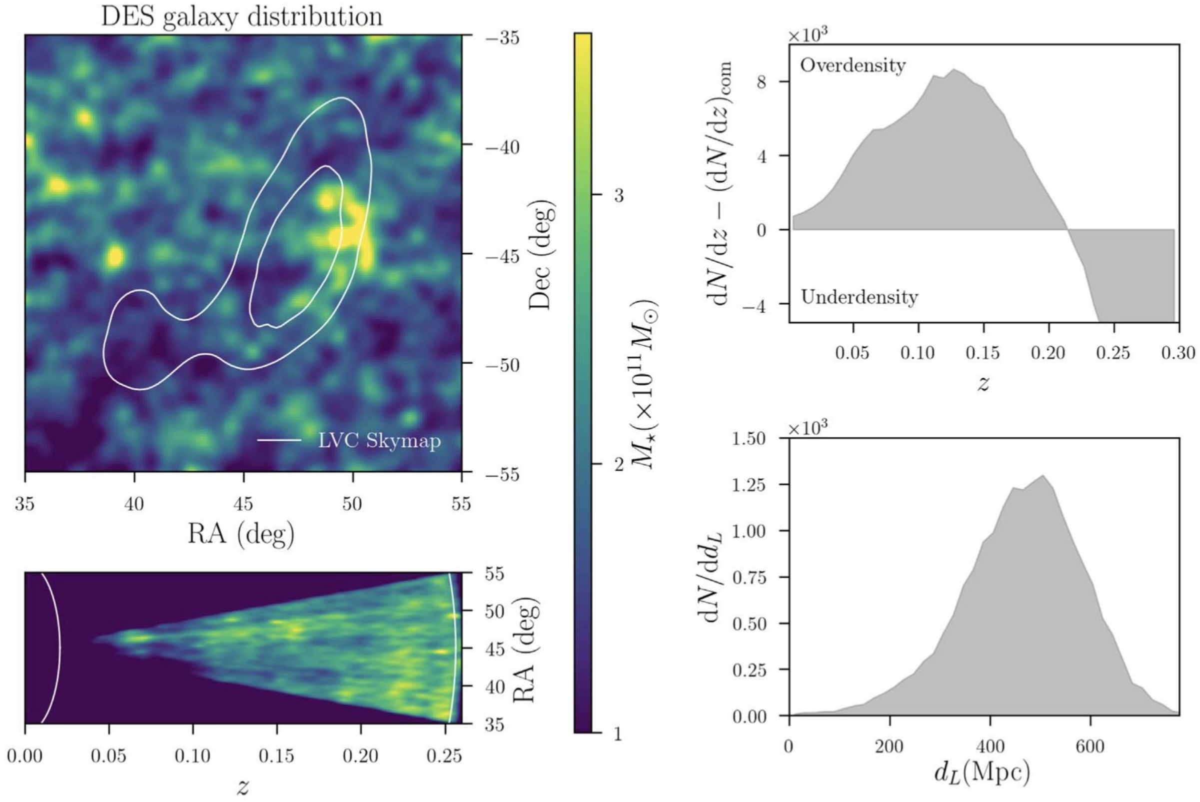
Then I can measure this.



Chernoff & Finn (1993)
Taylor & Gair (2012)
Ezquiaga & Holz (2022)

Farr, et al. (2019)

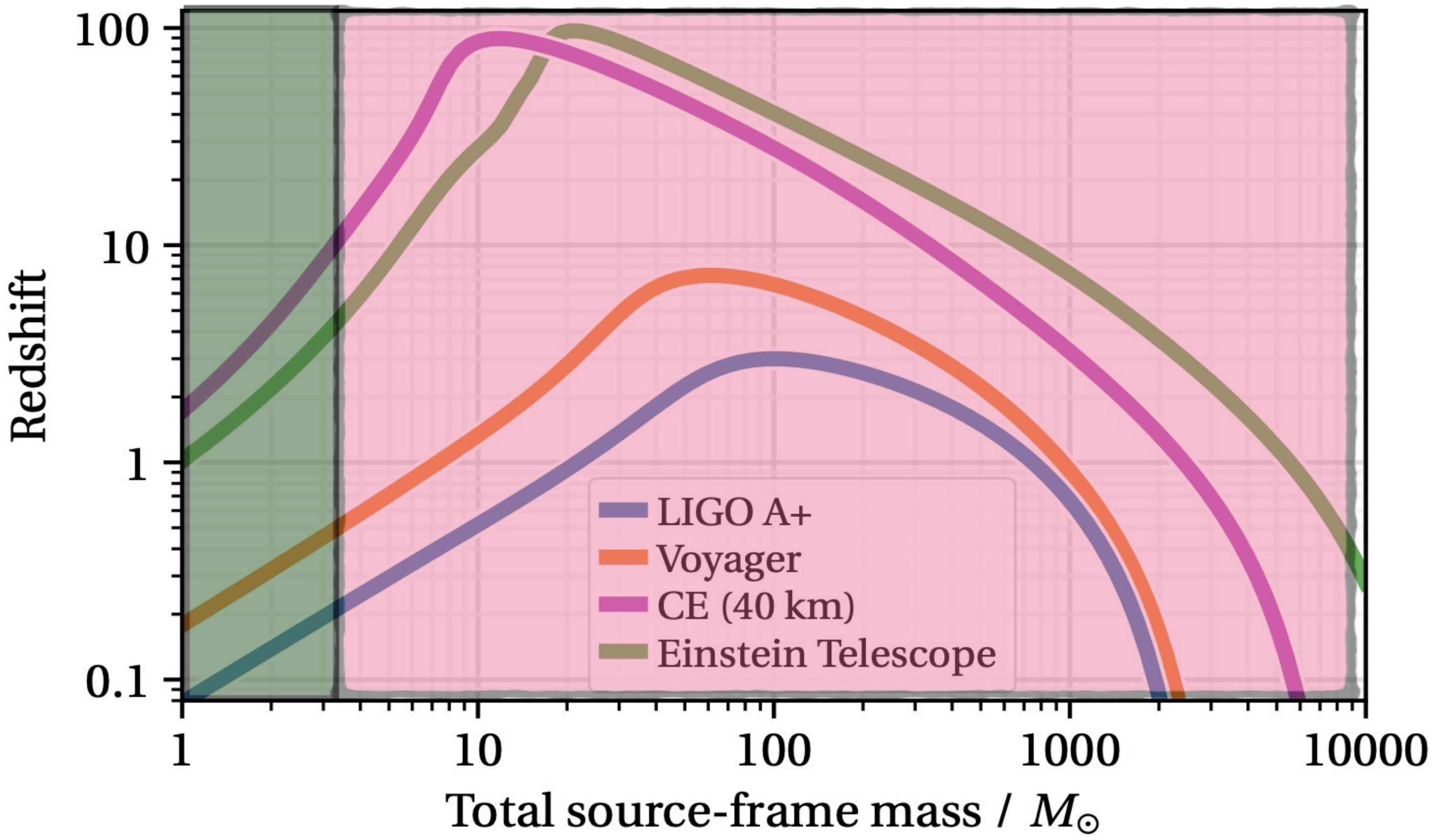
Redshifts By Association



Soares-Santos, et al. (2019)

Methods

3G GW detectors: Going up to high redshift



How do we get redshift to the source?

- Counterpart
- Statistical host identification
- Cross-correlation
- Mass-scale
- Astrophysical distribution
- Tidal deformation

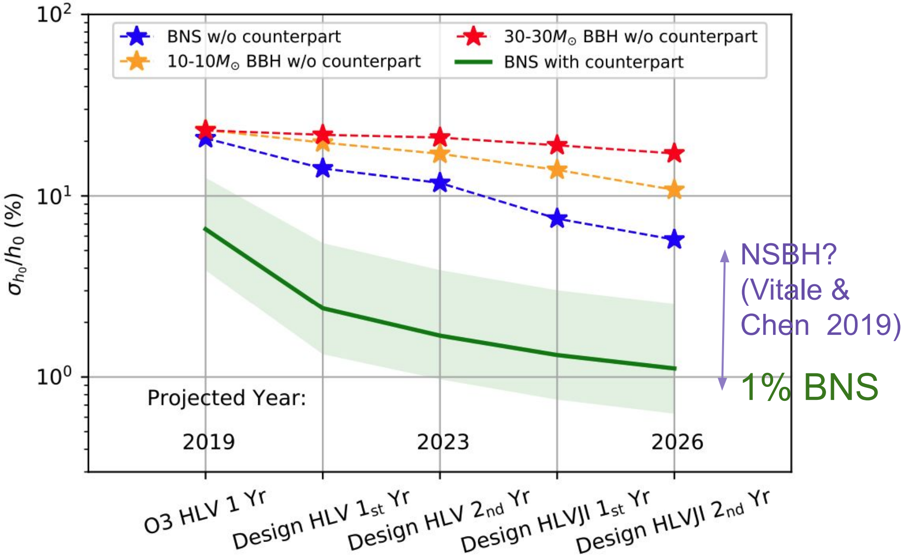
Counterpart cosmology

BNSs/fraction of NSBH expected to have EM counterparts at several wavelengths (GRB, KN - optical/IR, afterglow - X-ray/optical/radio..)

➔ Which counterpart will be the most promising for 3G cosmology?
  - GRBs and afterglows only detectable close to on axis (~<O(1%)). Helpful to constrain inc angle, but unlikely to be useful for 3G
  - KNe are ~isotropic, but faint and fading fast

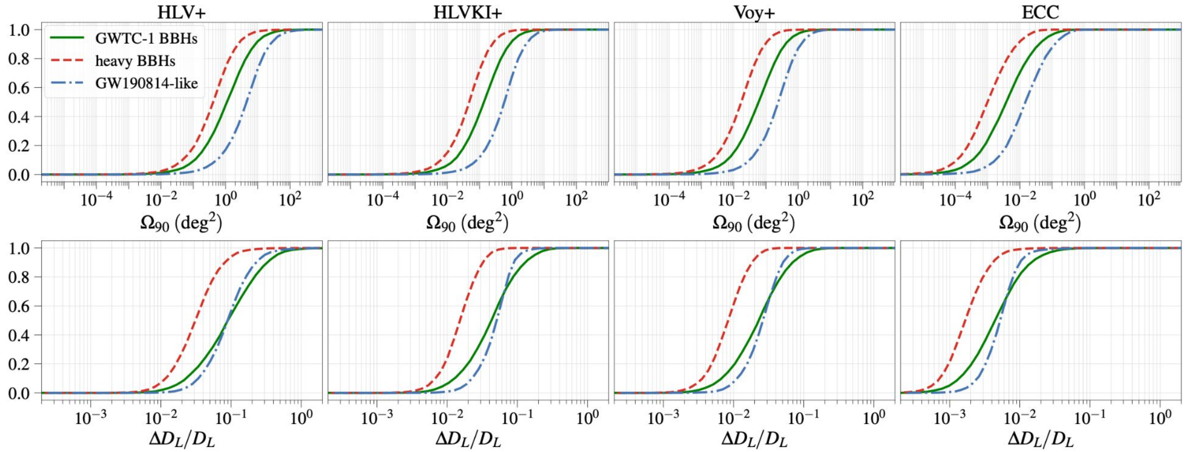
BBH in AGN disks may also be promising (Bartos+17, McKernan+19)

Chen, Fishbach, Holz 2018



Statistical host cosmology with nearly single galaxy

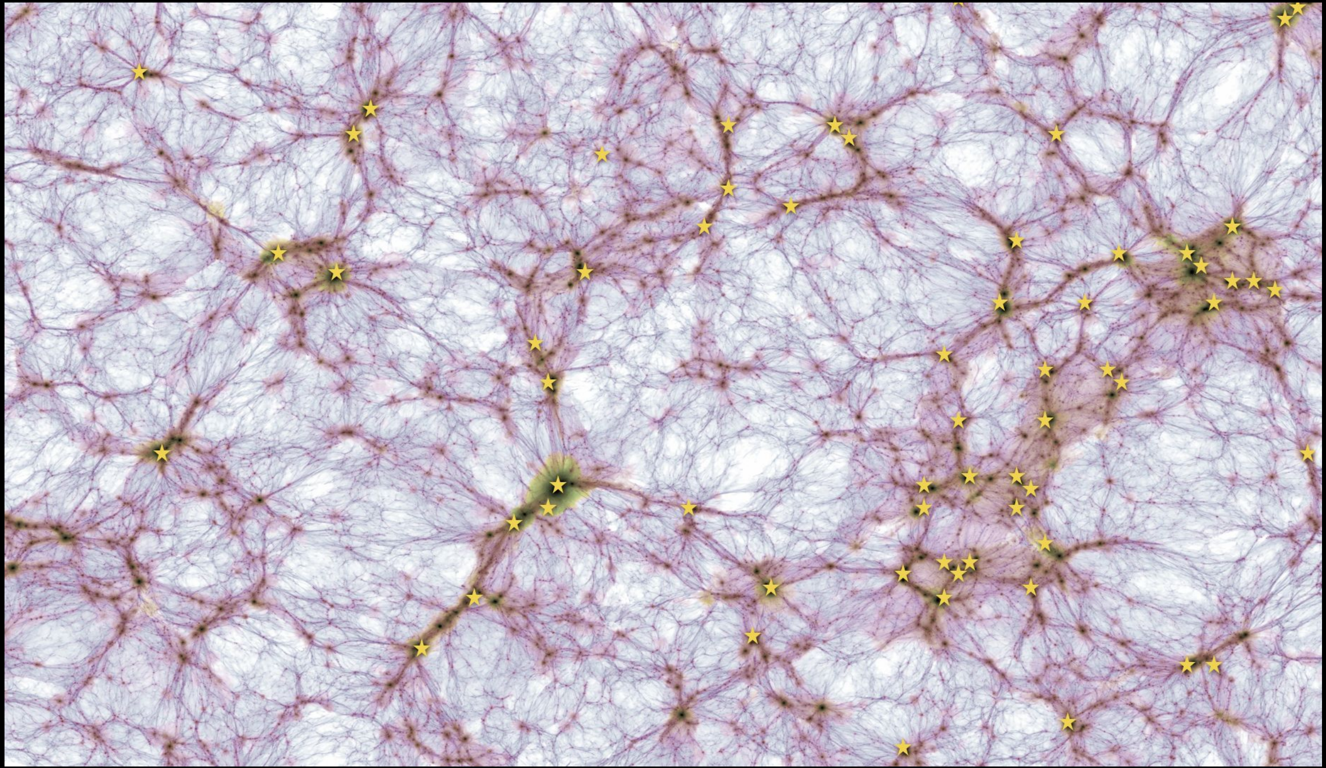
Statistical host identification can limit up to one galaxy in 3G



Borhanian+ 2020

Inferring redshift from dark compact objects using cross-correlation

Black holes will trace the underlying galaxies/dark matter distribution



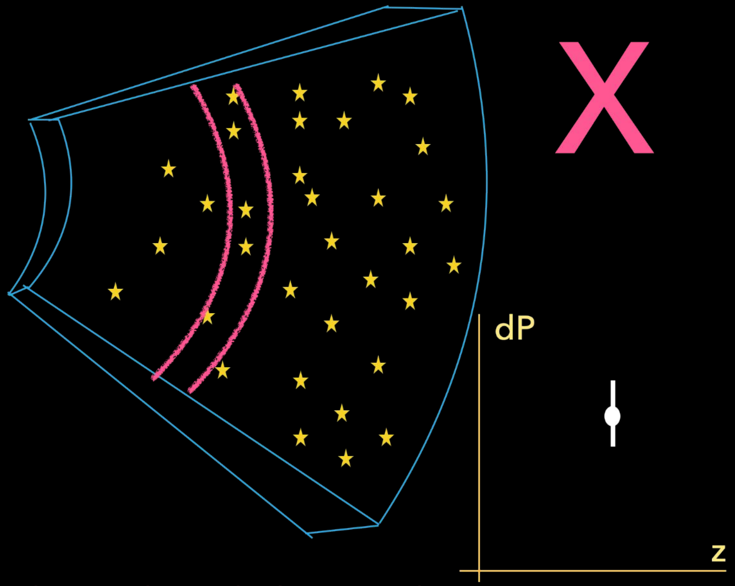
Oguri 2016,
Mukherjee+ 2018, 2019, 2020,2021
Calore+ 2020
Scelfo 2020
Bera+ 2020
Diaz+2021

Inferring redshift from dark compact objects using cross-correlation

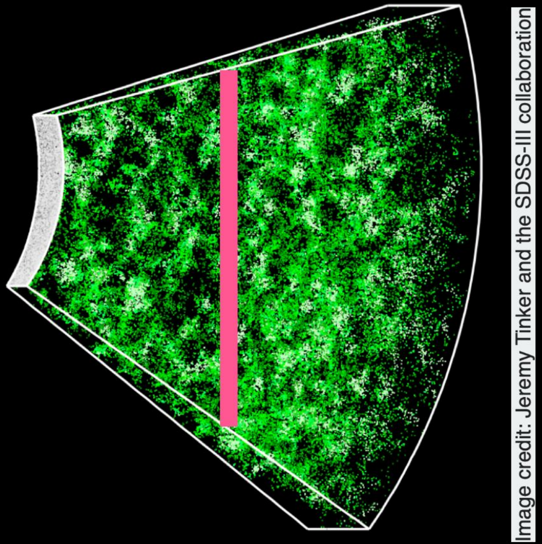
Black holes will trace the underlying galaxies/dark matter distribution

$$dP = n_{GW} n_g (1 + \xi(r)) dV_{GW} dV_g$$

Mukherjee+ 2020



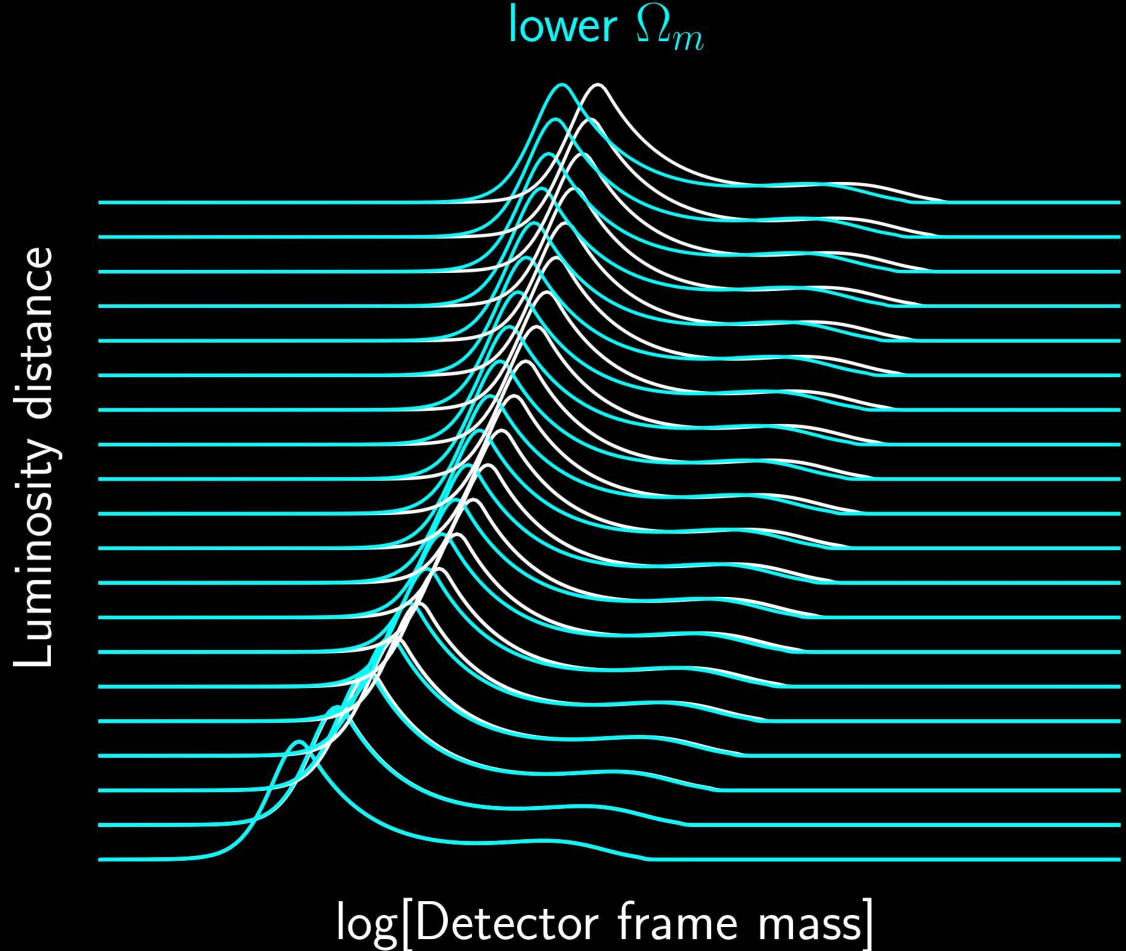
Dark sirens observed in luminosity distance space



Galaxy samples observed in redshift space

Oguri 2016,
Mukherjee+ 2018, 2019, 2020,2021
Calore+ 2020
Scelfo 2020
Bera+ 2020
Diaz+2021

SPECTRAL SIRENS



[Chernoff&Finn'93]

[Taylor+'11]

[Farr+'19]

[Mastrogiovanni+'21]

[LVC Cosmo GWTC-3 '2

[You+'20]

[Ezquiaga&Holz'20]

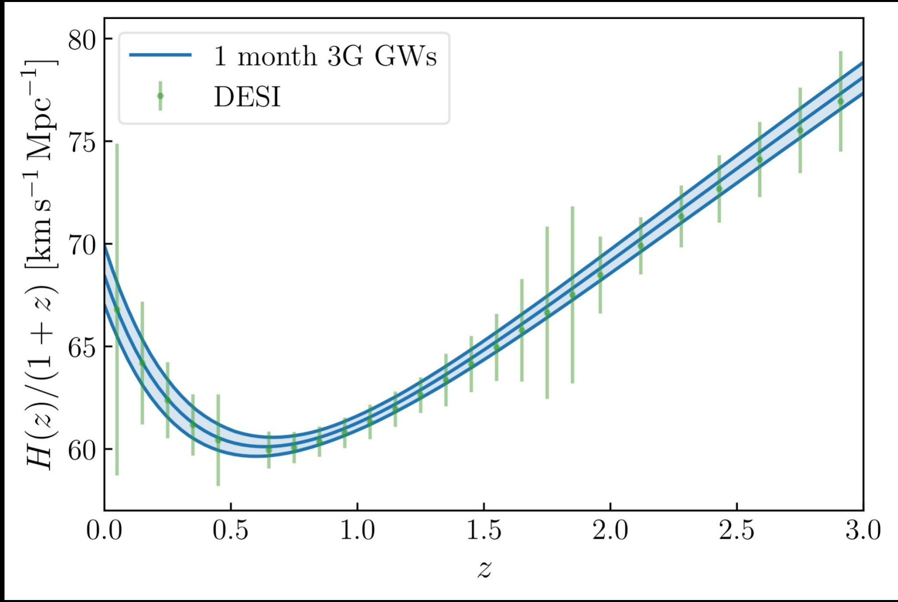
[Ezquiaga&Holz'22]

The promise:

Sub-percent cosmology at z > 2 with *only* GW data

The trouble:

Astrophysical uncertainties



[Ezquiaga & Holz '22]

Important notes!

- Next-generation detectors dominates by *low-mass* binaries (less affected by environmental effects ?!?)
- *Full* mass spectrum is key to break degeneracies between cosmology and astrophysics

Cosmology from Astrophysical population

Comparing the distribution of the black hole distribution with star formation rate

Depends on the astrophysical modeling of the SFR

Fig: Karathanasis+ 2022

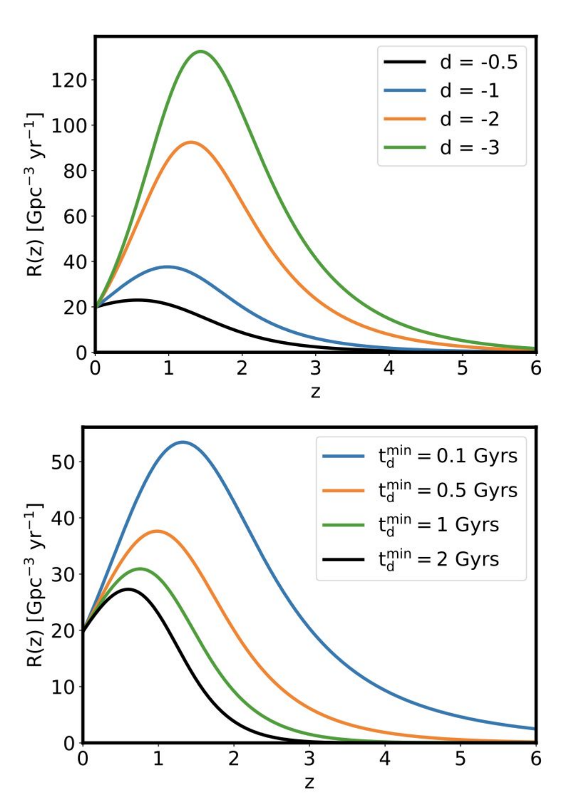
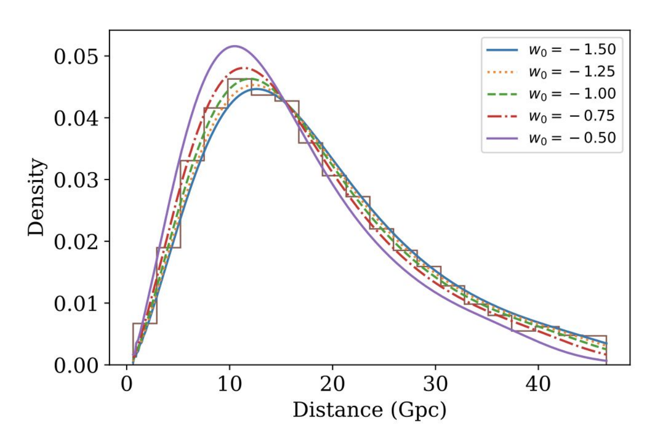


Fig: Ye+ 2021



Also:
Ding+ 2019
Leandro+ 2021

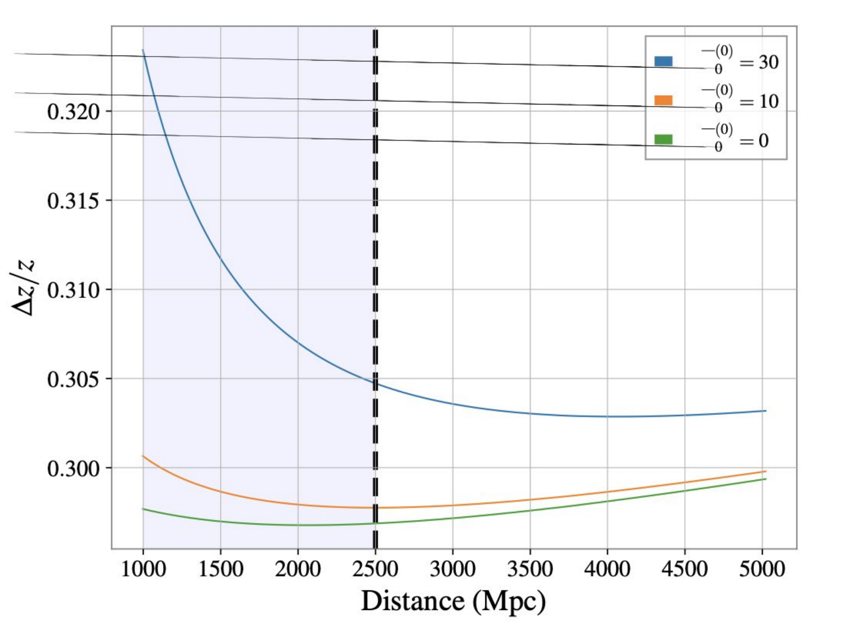
Cosmology from tidal deformation of BNS

Tidal deformation of neutron star can tell us about the redshift

Depends on the EoS of Neutron Star

Also:
Messenger+ 2011
Shirallilou+ 2022

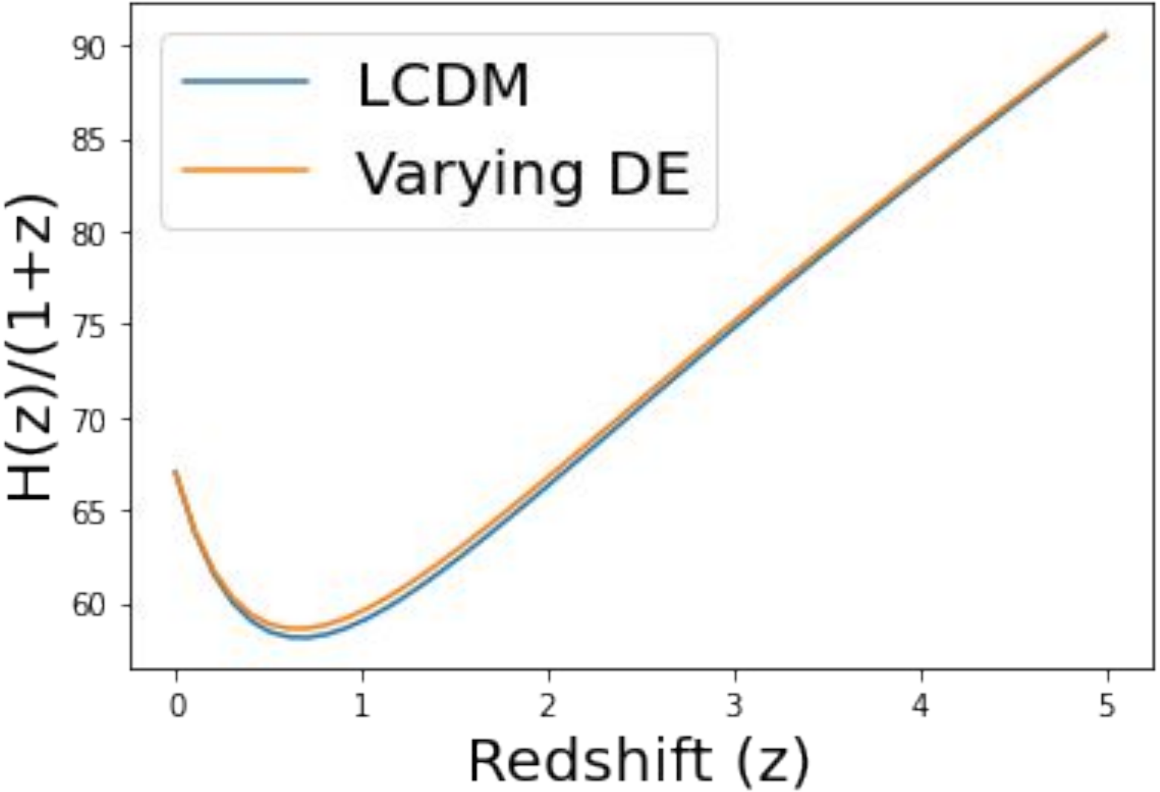
Fig: Chatterjee+ 2021



Low-Redshift Cosmology

Cosmology is **not** only about H_0

Mapping the Cosmic Expansion History



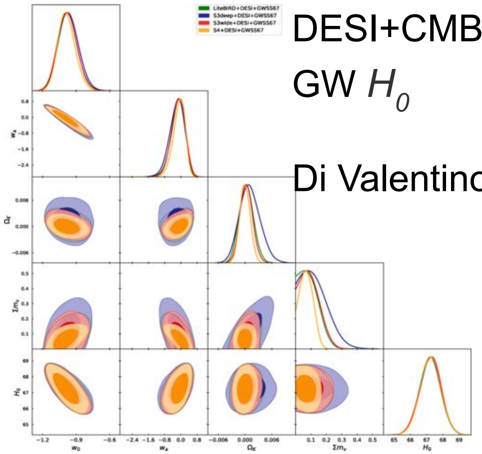
Very low-z cosmology with counterparts

Given how loud nearby BNS will be in 3G, can get precision H_0 measurements from few events. Let's assume it will be feasible to detect KNe out to z~0.3 in the 2030s.

Even if H_0 tension won't be interesting anymore in 2030s, percent-level H_0 measurements help break degeneracies from other probes for **beyond-LCDM** cosmologies (Di Valentino+19)

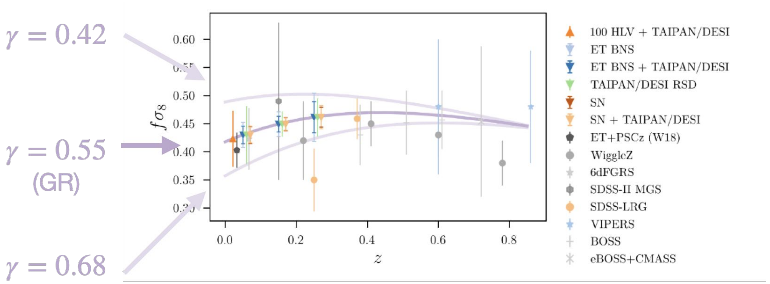
Sub-percent distance measurements in the very nearby universe will be unique to 3G observatories. They can be used to e.g. probe the **peculiar velocity field** and growth of structure (Palmese & Kim 21), **calibrate** SN distances (Gupta+19).

$\Lambda\mathrm{CDM} + \Omega_k + \Sigma m_\nu + w_0 + w_a$



DESI+CMB+1% GW H_0

Di Valentino+19



3% precision on $f\sigma_8$, ~0.02 uncertainty on growth index γ with 3G (Palmese & Kim 21)

Low-z cosmology with counterparts - dark energy

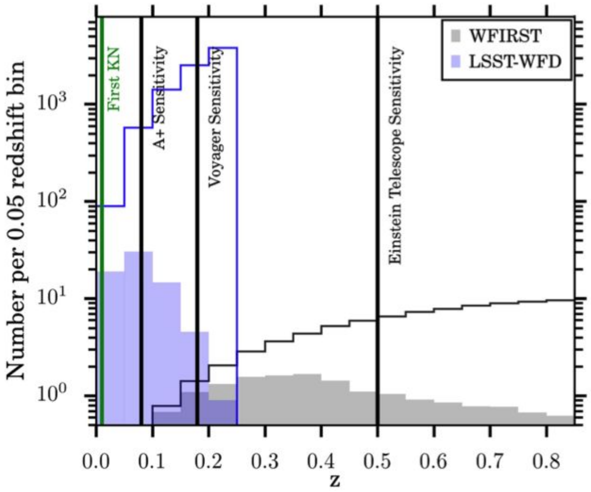
At least with sGRBs as BNS counterparts, combining w/ other probes seems the only way to get competitive constraints on DE EoS for 3G (e.g. Sathyaprakash+09, Zhao+11)

Modified gravity analyses would also benefit from counterpart identification (e.g. Belgacem+2018)

Feasibility of following up events out to z~1: Roman expected to detect GW170817-like KNe out to z~0.8. KN detectability to improve on statistics from GRB/afterglow counterparts, will probably depend upon good sky localizations, complete galaxy catalogs, and knowledge of host galaxy types/BNS formation channels to help with deep targeted searches.

At higher z, 3G will be interesting to probe Early Dark Energy (also as possible solution to H0 tension)

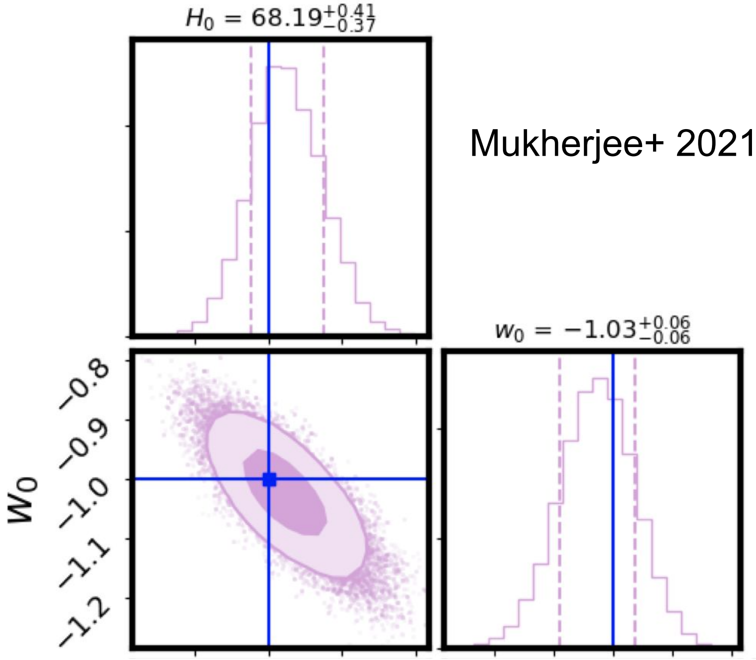
Other cosmic surveys will measure cosmological parameters with higher precision than 3G. There is still value in measuring them w/ 3G as modern cosmology relies on cross-probes to beat down statistical uncertainties and systematics. Plus, if deviations from LCDM are found in coming years, there is even more interest in new measurements!



KN detections z distribution (Scolnic+2017)

Dark Energy using dark sirens

- GW sources and galaxies will be spatially clustered —> **'This can give us redshift information' using cross-correlation**
- Numerous black holes to at low redshift, N^{1/2} reduction in error
- No 'Fundamental limitation' to measure luminosity distance
- Dark energy EoS measurement at sub-percent accuracy from 3G

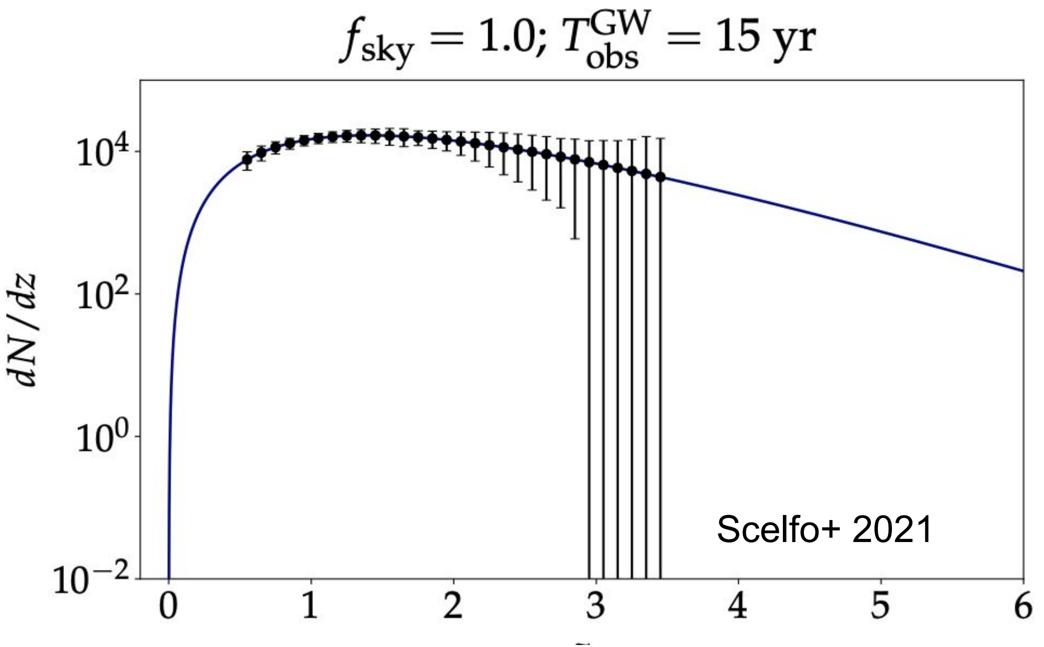


Mukherjee+ 2021

High-Redshift Cosmology

Measuring the high redshift Universe

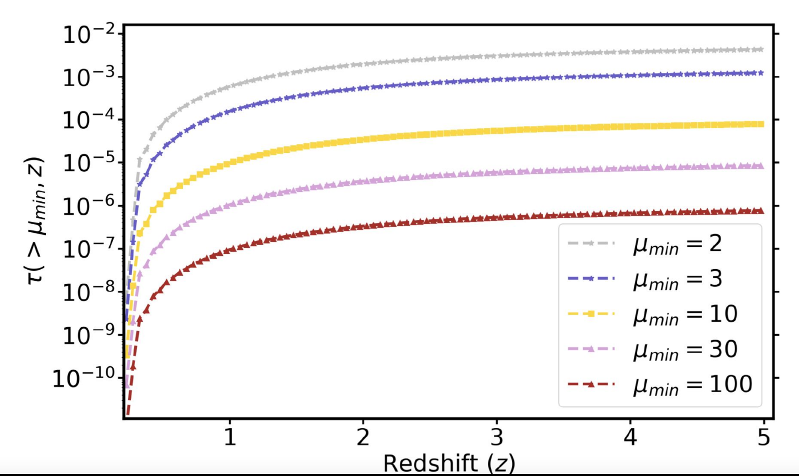
- Tomographic measurement of the cosmic expansion history using GWX gal, GWX 21 cm/ line intensity mapping, astrophysical distribution of BHs, mass distribution
- Progenitors of merging BHs
- Redshift evolution of the mass-spectrum of the BHs



Gravitational lensing of GWs

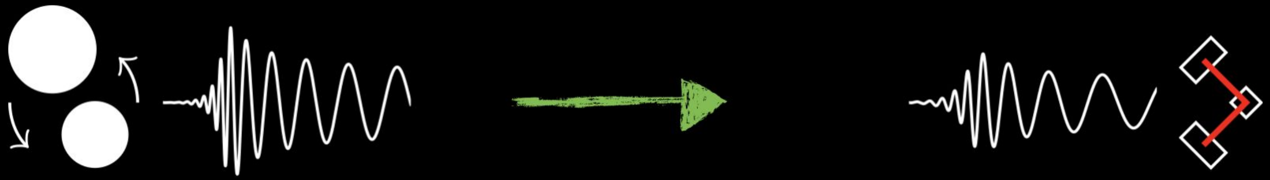
Lensing probability is more for source at high redshift

Fig: Mukherjee+ 2020



- Numerous lensed GW sources will be detected.
- We will measure the lensing effect weak to strong
- Will be a probe to dark matter properties
- Testing theories of gravity from GW propagation

Modified GW propagation



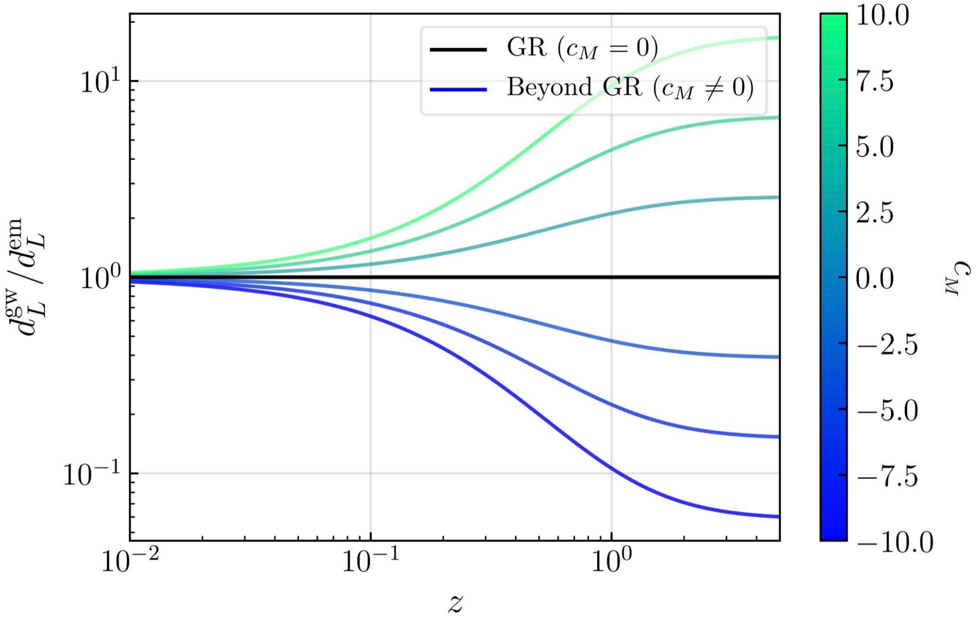
$$h''_A + (2+\nu)\mathcal{H}h'_A + (c_g^2 k^2 + \Delta\omega)h_A = \mathcal{O}_{AB}h_B$$

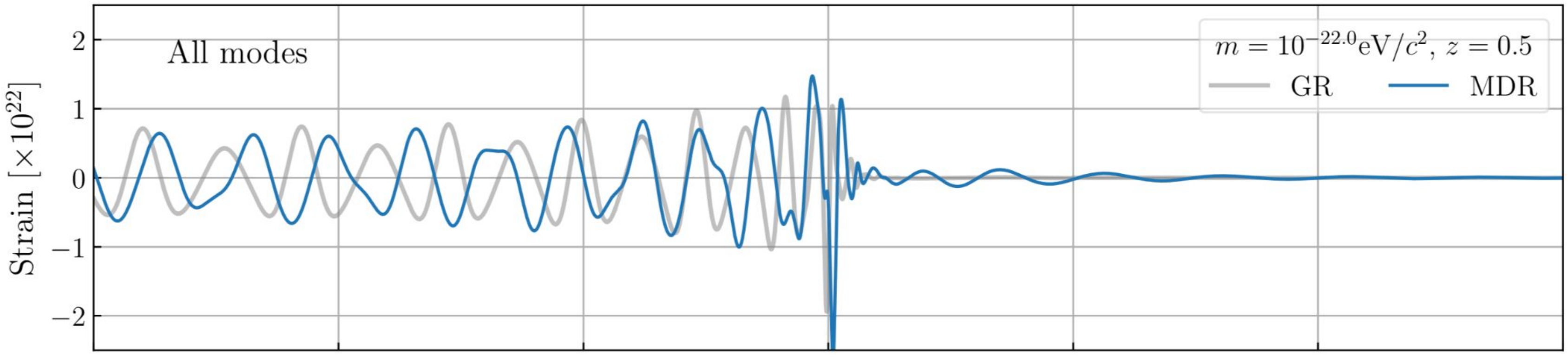
- Speed: changes arrival time
- Amplitude: modifies luminosity distance
- Phase: may produce waveform distortions
- Polarization: birefringence, additional tensor modes

Small deviations accumulate over cosmological propagation times!

3 points

1. Far, far away sources, very precise constraints
2. Inhomogeneous universe can excite additional polarizations!
3. Higher modes are key





Astrophysics from Cosmology

Black hole and galaxy/dark matter connection

GW bias Parameter

- Where and When Black holes are forming?
- How they follow the properties of the galaxies?
- Distinguishing between the ABHs and PBHs

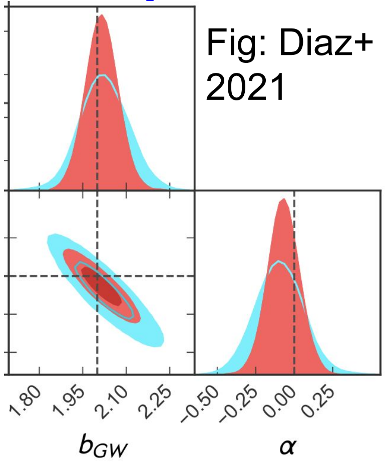
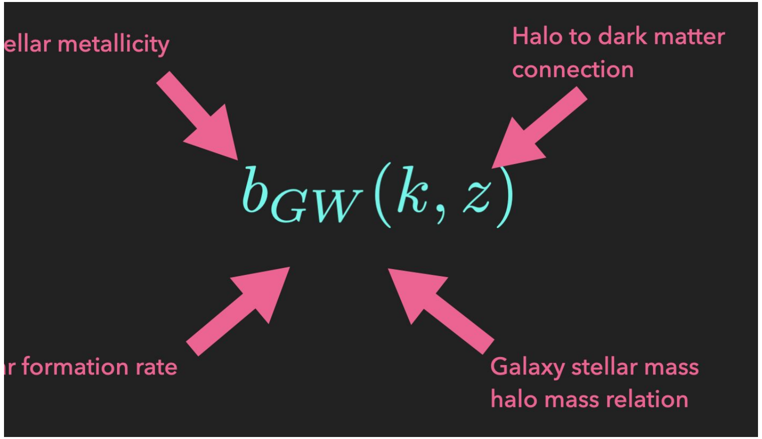


Fig: Diaz+ 2021



Black hole emission line correlation

- Redshift evolution of black hole properties and emission line will be related
- A tomographic estimation can tell us about the delay time distribution

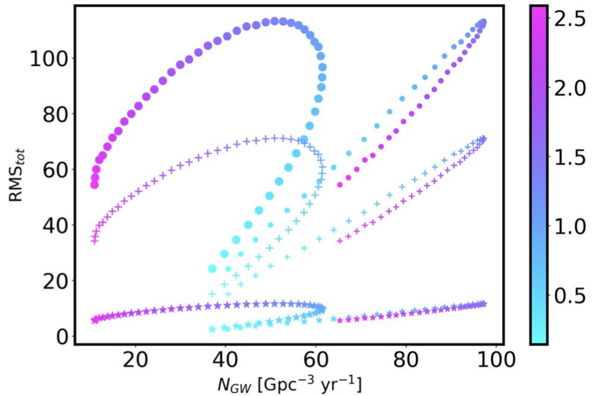


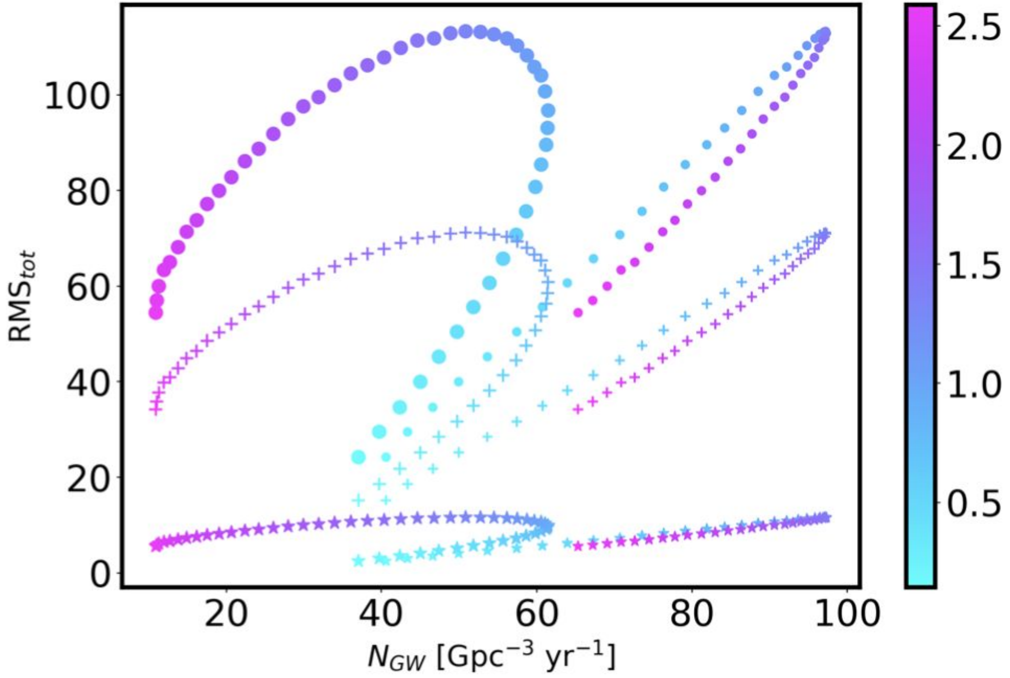
Fig: Mukherjee+ 2021

Black hole and emission lines connection

A probe to the delay time

- Redshift evolution of black hole properties and emission line will be related
- A tomographic estimation can tell us about the delay time distribution

Fig: Mukherjee+ 2021



Cosmology Bucket List From 3G

- Black hole and galaxy property connection
- GW bias parameter for ABHs and PBHs
- Modified Gravity
- GW lensing
- Dark Energy Eos
- Evolution of the mass spectrum
- Measurement of the cosmic expansion history up to high z

Open Questions and challenges

1. We will be able to detect the counterpart for how many bright sirens?
2. Peculiar velocity for low redshift sources
3. Completeness of the galaxy catalog
4. Availability of spectroscopic/photometric redshift surveys up to high redshift for cross-correlation
5. Redshift evolution of the black hole / NS mass distribution
6. BNS EoS uncertainties
7. Sky localization error of the GW sources
8. Identifying GW lensed events
9. Waveform uncertainties