Prospects of GW standard siren cosmology

2025 Oct 29

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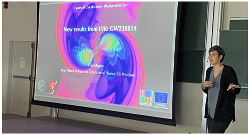
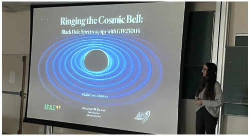
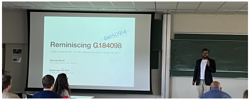
GHENT UNIVERSITY







15 Sep 2025 @ Ghent University

Plan of this talk

- Overview | results from current data

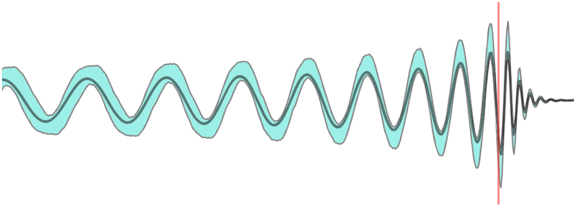
- Alternative tracers for dark standard sirens

- Future prospects and discussion items

Compact binaries observed in gravitational waves are standard distance indicators or “standard sirens”

Gravitational-wave standard sirens

Schutz (1986), Holz & Hughes (2005)



Phase evolution $\Rightarrow$ $\mathcal{M}^z \equiv \mathcal{M}(1+z)$ redshifted chirp **mass**

Amplitude $\sim \frac{\mathcal{M}^z}{d_L} \times$ fn.(angles) $\Rightarrow d_L$ luminosity **distance"** (inclination)

GW from compact binaries give direct access to distance!

self-calibrated independent of, in particular, the **distance ladder**

$(d_L, z) \rightarrow$ cosmological parameters

Distance-redshift relation: Late-time expansion / acceleration parameters

$$d_L = c(1+z)\int^z \frac{dz'}{H(z')}\,, \quad H(z') = H_0\sqrt{\Omega_m(1+z')^3 + \Omega_\Lambda}$$

$\uparrow$

Lemaître-Hubble law Hubble constant

Λ-CDM: dark matter, dark energy

Where does z come from?

$(d_L, z) \rightarrow$ cosmological parameters

Distance-redshift relation:

Late-time expansion / acceleration parameters

$$d_L = c(1+z)\int^z \frac{dz'}{H(z')}\,, \quad H(z') = H_0\sqrt{\Omega_m(1+z')^3 + \Omega_\Lambda}$$

$\uparrow$

Lemaître-Hubble law

Hubble constant

Where can z come from?

Spectral lines for GW?

For BBH, z degenerate with mass

NS physics / **population astrophysics** — spectral

EM counterparts | **galaxy catalogs** — bright | dark

Galaxy clustering / LSS of matter

Other??

LETTER

doi:10.1038/nature24471

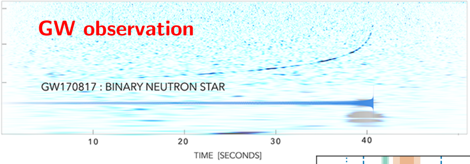
AG in LVC PWT

A gravitational-wave standard siren measurement of the Hubble constant

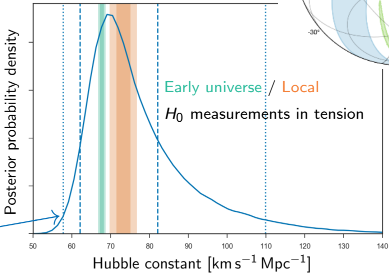
self-calibrated distance indicator

The LIGO Scientific Collaboration and The Virgo Collaboration*, The 1M2H Collaboration*, The Dark Energy Camera GW-EM Collaboration and the DES Collaboration*, The DLT40 Collaboration*, The Las Cumbres Observatory Collaboration*, The VINROUGE Collaboration* & The MASTER Collaboration*

GW observation

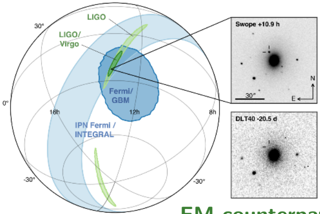


distance, d_L



Early universe / Local

H_0 measurements in tension



EM counterpart

redshift, z

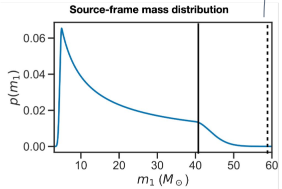
First GW standard siren measurement of H_0

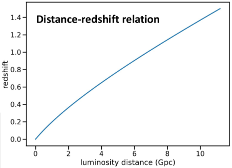
H_0 from source population

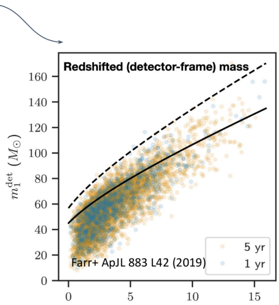
Key idea: masses / mass distributions are redshifted!

Source population method

"spectral sirens"



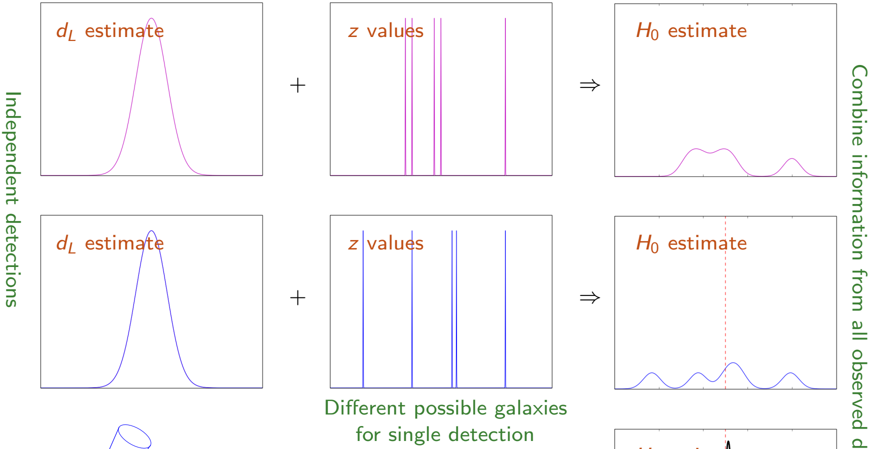


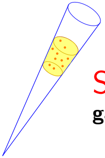


Chernoff & Finn 1993; Taylor & Gair 2012; Farr, Fishbach, Holz 2019

Mastrogiovanni+ 2021 (with **AG**): `icarogw` (LVK pipeline)

Mukherjee arXiv:2021; Ezquiaga & Holz 2202

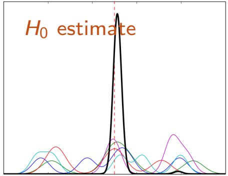




Schutz idea

galaxy catalogues for redshift

Schutz (1986)



Power of statistics ⇐ Unimodal joint H_0 result

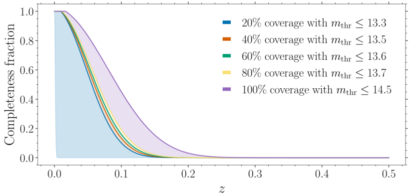
One approach or both?

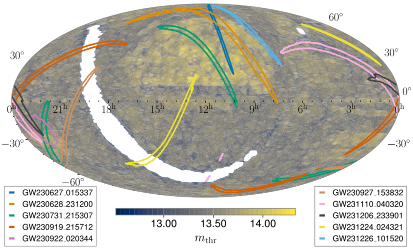
- Binary mass distribution and merger rate (evolution) enter as a selection effect in the dark standard siren likelihood.

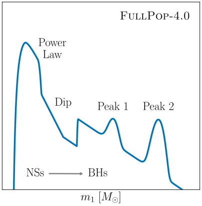
- As of O4a both LVK pipelines `gwcosmo` and `icarogw` marginalize over population parameters to obtain cosmology.

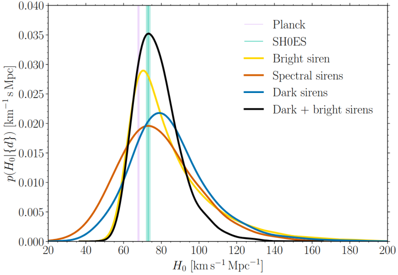
LVK O4a H_0 results

GLADE+ galaxy catalog: Dálya+ (2021) [K band]



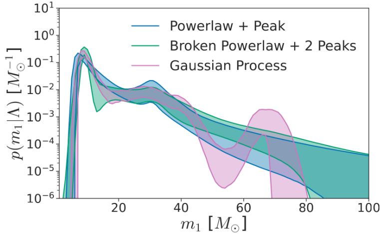


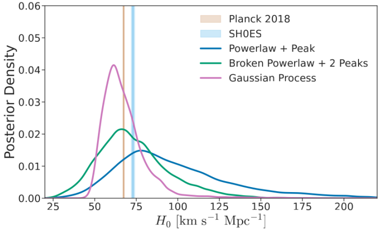


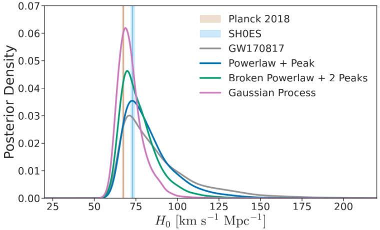


LVK: arXiv:2509.04348

Magaña-Hernandez+ arXiv:2509.03607

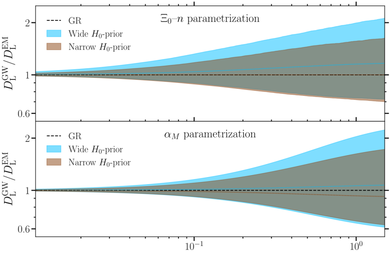






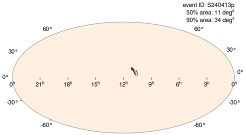
LVK O4a and further prospects

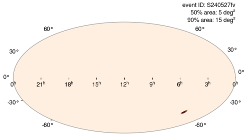
Other cosmological parameters / modified gravity:

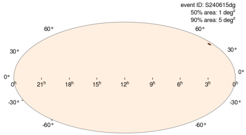


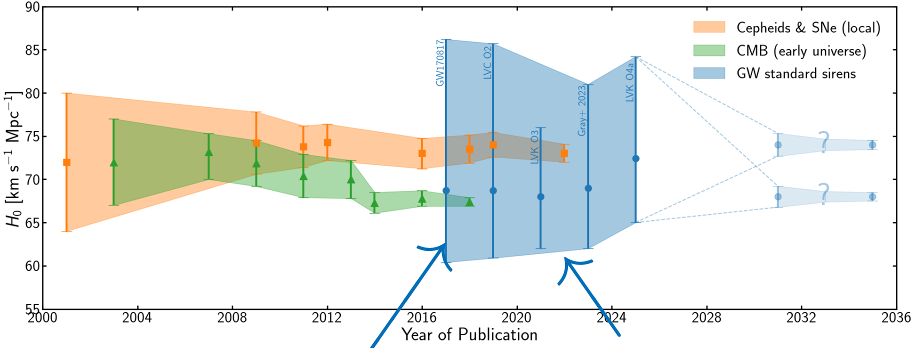
LVK: arXiv:2509.04348

Better localized events in O4b/c:









dark siren contribution

GW170817 + EM counterpart

Challenges

- Number of sources with counterparts

  rapid follow-up, early warning?

- Incompleteness of galaxy catalogues

  upcoming surveys: Vera Rubin Observatory, DESI, SPHEREx

  alternative tracers: rest of **this talk**

- Systematic effects

  Modelling of peculiar velocities

  Uncertainties coming from galaxy catalogues

  GW waveform modelling, GW detector calibration

Possible sources of systematics

- Peculiar velocities (nearby detections) — Goode+ (to appear soon)

- Uncertainties in galaxy catalogues

    Photometric measurements of redshifts — Palmese+ 2020, Turski+ 2023

    Estimates of luminosities for weighting

- Unknown astrophysics

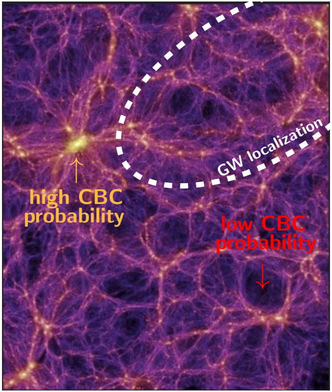
    Luminosity weighting model — Perna+ 2025, Hanselman+ 2025

    Galaxy type: colour, metallicity . . . — work ongoing

- Waveform systematic effects — Kunert+ 2024
- Detector calibration uncertainties — Huang+ 2025

Alternative tracers?

HI intensity mapping, **galaxy clusters** ...



GWs, galaxy clusters, ... trace underlying matter distribution (with different bias).

Given large GW localization uncertainties, not necessary to resolve individual galaxies.

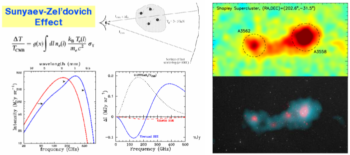
In this talk: galaxy cluster catalogues, brightest cluster gal / luminous red galaxies

↓

nodes, filaments

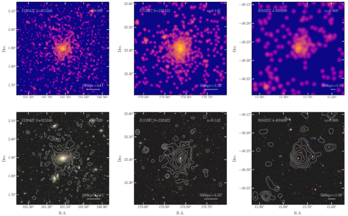
Graphic idea: Dounia Nanadoumgar Lacroze!

Galaxy cluster catalogues



Inverse Compton scattering of CMB photons

X-ray surveys



83% sky **Planck 15: PSZ2**

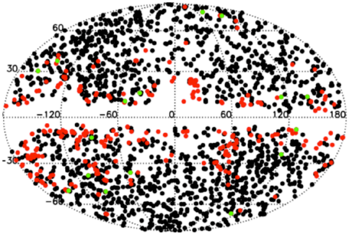
1094 clusters with z (from galaxies within cluster)

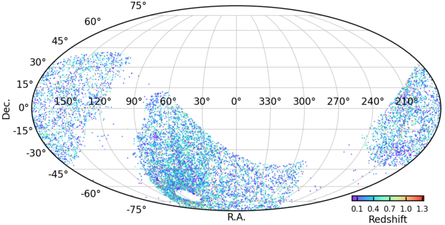
mass from SZ (direct)

eROSITA: eRASS 36% sky

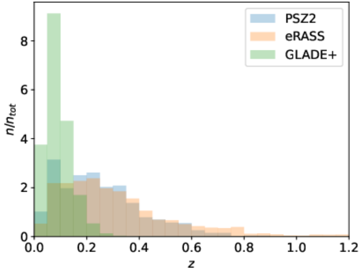
5259 high-purity clusters with z from "counterparts"

mass proxy from X-ray properties

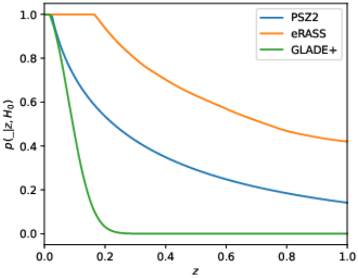




redshift ditributions in-catalogue:



in-catalogue fraction:



line-of-sight redshift prior (LOS-z)

`gwcosmo`: Gray+ JCAP **12** 023 (2023)

in-catalogue **out-of-catalogue**

redshifts ⟵ precise?

luminosities (for weighting)

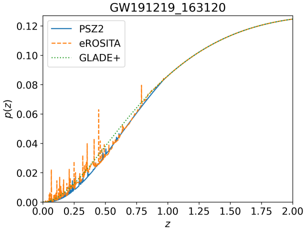
↓

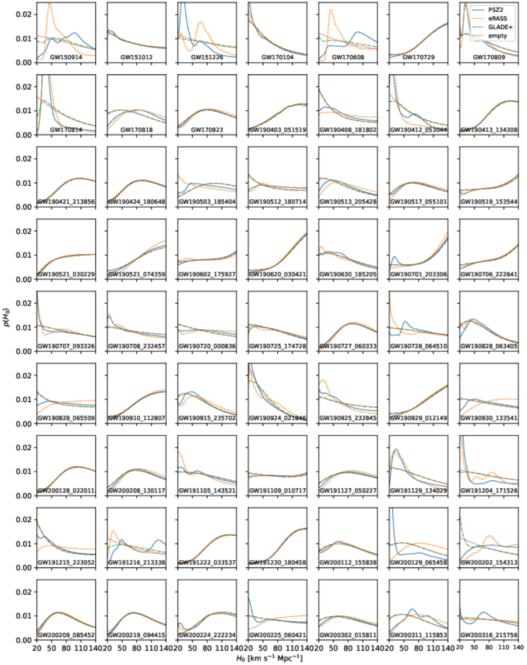
masses ⟵ direct?

Schechter function

↓

simpler? ⟶ Press-Schechter distribution

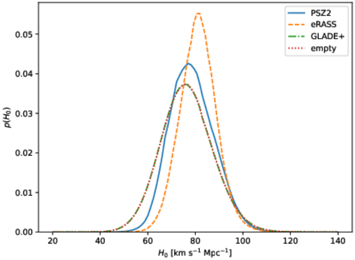




← Significant in-catalogue contribution!

10% | 38% improvements!

↓

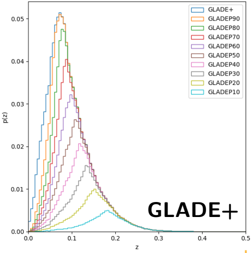


Beirnaert+ 2025

Luminous galaxies?

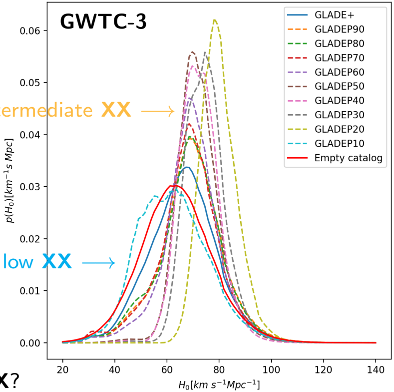
We select **XX** percentile of brightest galaxies.

highest *absolute* luminosity

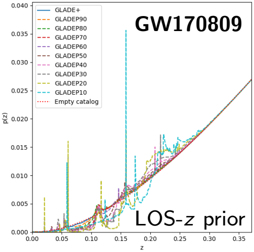


⟵ effective completeness increases!

sharper peaks for intermediate **XX** ⟶



uninformative for low **XX** ⟶



well-motivated **XX**?

Naveed+ 2025

Luminous galaxies?

VanWyngarden+ (to appear soon)

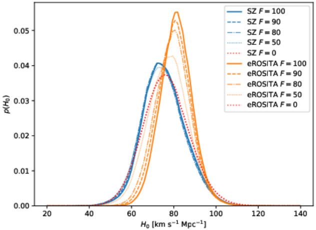
- Simulations on MICECAT.
- Importance of galaxy clustering.
- i-band serves as a better tracer than g-band.
- 1% of the brightest galaxies can lead to an unbiased H0 estimate!

The next steps . . .

Not all CBCs associated with galaxy clusters.

extra term to account for this ✓

from Beirnaert PhD thesis (in prep.)

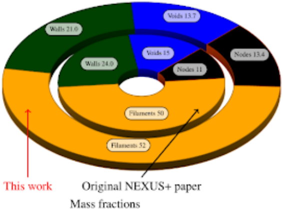


Combine multiple tracers!

galaxies, galaxy clusters ✓

luminous red galaxies: filaments

other tracers? HI, quasars?



Hellwing+ PRD **103** 6 (2021)

Fold in astrophysics! Test via large scale simulations.

FOR DISCUSSION

A different set of questions for 3G/XG

- Current "tensions" in cosmology may be resolved.

- Standard sirens: direct probe of $h(z)$ **fundamental physics**

  Other cosmological parameters? Beyond Λ-CDM?

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

Mancarella+ 2022; Leyde+2022; . . .

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

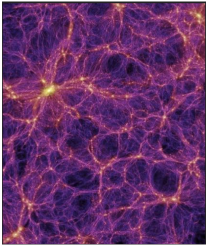
Modified GW propagation!

- Probe "GW bias"? **astrophysics ⟷ cosmology**

$$\delta_{\rm GW}(z,k) = b_{\rm GW}(z)\,\delta_m(z,k)$$

Libanore+ 2020; Calore+ 2020; Vijaykumar+ arXiv:2020; Cirragan-Diaz & Mukherjee 2021; . . .

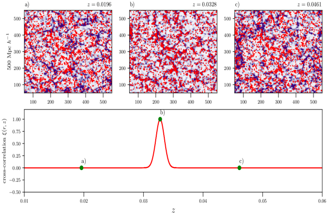
Dark standard sirens: more to exploit



Cross-correlations: beyond line-of-site contributions

Standard rulers

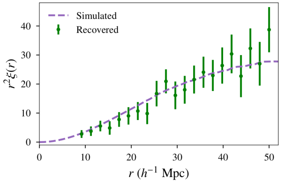
3G localizations of $\mathcal{O}(1\ \text{sq. deg.})$

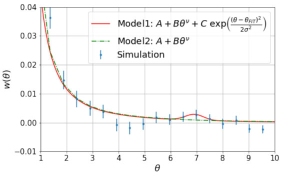


Oguri 2016; Scelfo+ 2018; Nair, Bose, & Saini 2019; Nakama 2020; Vijaykumar+ 2021; **Bera+ 2020**; **Mukherjee+ 2021**

Cosmography / cosmology with GWs alone?

- Love sirens?
- Probing the universe with GWs alone?





Correlation function: Vijaykumar+ 2020 | BAO peak: Kumar+ 2022

CONCLUDING SLIDE

Takeaway messages and thoughts

- GWs are an independent probe $\Rightarrow$ independent systematics!
- Direct measurement of $h(z)$! No local / early univ anchor needed.
- Uncertainties from GW are expected to shrink much faster.
- Will certainly give us complementary information.

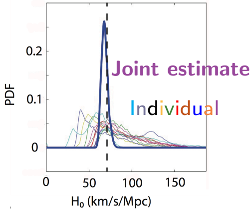
EXTRA SLIDES

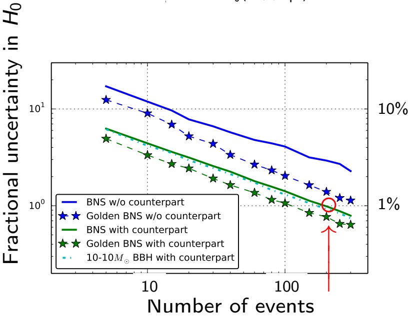
Better with more detections

Combine information from multiple similar detections.

Precision: $\sigma_{H_0}/H_0 \sim 1/\sqrt{N}$

Nissanke *et al.* (2010)
Nissanke *et al.* (2013)

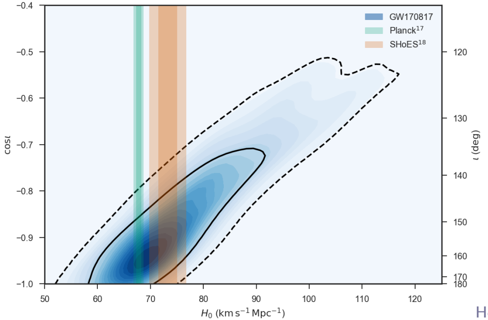




Chen *et al.* (2018)

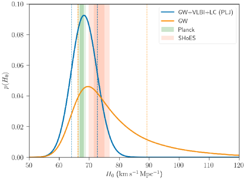
see also: Feeney *et al.* (2019)

Degeneracy with inclination



Őpaper

Hotokezaka+ 2018: jet ⟶ **inclination** ⟶ H_0

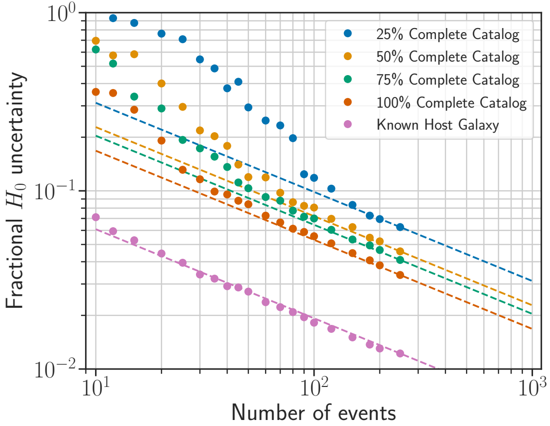


Broken with GW alone? **Higher harmonics!**

See, e.g., Calderón Bustillo+ 2021

H_0 with galaxy catalogues: projections

About 10 times more events without counterpart to get to same precision (at BNS distances)



Projected from Gray+ 2020 (with **AG**)

ongoing study led by S. Mukherjee

H_0 with galaxy catalogues: selection effects

GW selection effects

threshold SNR $\rightarrow$ ifo horizon

only nearby signals detected

EM selection effects

depth of telescope

incomplete galaxy catalogues

$$p(x_{\rm GW}|D_{\rm GW}, H_0) = \frac{p(x_{\rm GW}|G,H_0)}{p(D_{\rm GW}|G,H_0)} p(G|D_{\rm GW}, H_0) + \frac{p(x_{\rm GW}|\bar{G},H_0)}{p(D_{\rm GW}|\bar{G},H_0)} p(\bar{G}|D_{\rm GW}, H_0)$$

in-catalogue | out-of-catalogue

Detection efficiency (selection function):

$$\mathcal{N}_{\rm eff}(\boldsymbol{\Omega}) = \int_{\mathcal{E}_{\rm det}} d\mathcal{E} \int d\theta \, p(\mathcal{E}|\theta, \boldsymbol{\Omega}, \mathcal{H}, \mathcal{I}) \, p(\theta|\boldsymbol{\Omega}, \mathcal{H}, \mathcal{I})$$

Integrate over all **detectable data sets**

Correct for / take into account possible contribution of **galaxies missing from catalogue**

Schechter luminosity function

Integrated method of taking into account both effects.

Abbott+ Nature **551** #7678, 85-88 (2017)

Mandel, Farr, Gair 2018; Chen+ 2018; Mortlock+ 2018

Gray+ 2020; Gray+ 2022: `gwcosmo` (LVK pipeline)

GW selection effects

$$\mathcal{N}_{\text{eff}}(\boldsymbol{\Omega}) = \int_{\mathcal{E}_{\text{det}}} d\mathcal{E} \int d\theta \; p(\mathcal{E}|\theta, \boldsymbol{\Omega}, \mathcal{H}, \mathcal{I}) \, p(\theta|\boldsymbol{\Omega}, \mathcal{H}, \mathcal{I})$$

integrate over all **detectable data sets**

semi-analytical | MCMC

- $\mathcal{N}_{\text{eff}}$ depends on the source population parameters

  mass distribution, rate evolution

- H_0 depends on assumed (unknown) source population parameters
- Solution: infer population parameters and H_0 simultaneously
- Ties dark siren and spectral siren methods

Codebase improvement

Mastrogiovanni+ 2023; Mastrogiovanni+ arXiv:2305.17973

Rachel Gray @ U. Glasgow, . . . , Freija Beirnaert, Cezary Turski @ UGent arXiv:2308.02281

`icarogw`:

- Inclusion of galaxy catalogue information
- More flexible way of weighting with luminosities

`gwcosmo`:

- Inclusion of additional parameters: Ω_m, population parameters
- Marginalization over population parameters
- Injection infrastructure for computation of selection effects

  Monte Carlo integration for multi-dimensional integrals
- Line-of-sight redshift prior @ UGent

Line-of-sight redshift prior

Cross-correlating redshift space distributions with GW localizations

merger probability in redshift space

Don't need precise locations of galaxies; GW localizations are poor

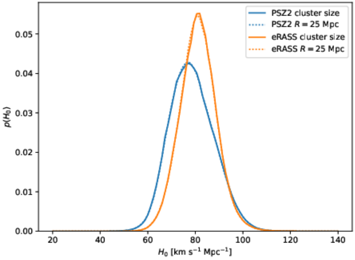
effects of **galaxy clustering** already taken into account

Can extend beyond galaxy catalogues to galaxy cluster catalogues

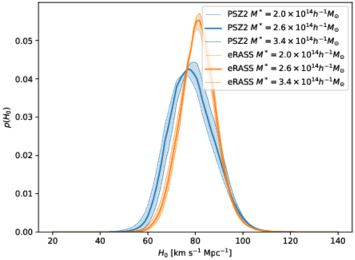
X-ray surveys; astrophysics?

Opposite approach as Ish Gupta

Limited systematic studies



⟵ varying cluster size (z uncert.)



⟵ varying Press-Schechter parameters