Joint cosmological and gravitational-wave population inference using dark sirens and galaxy catalogues

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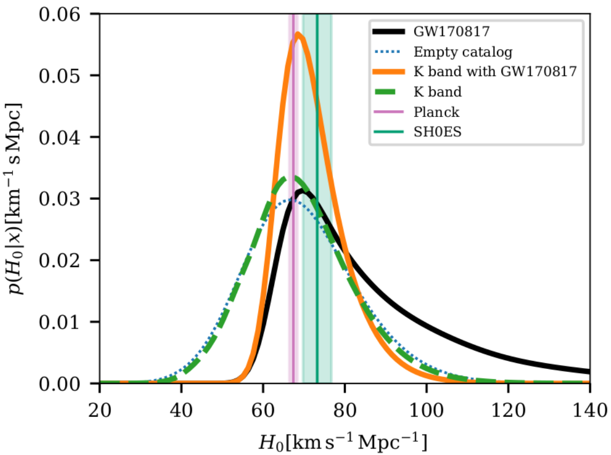
O3 result LVK Cosmology group



Constraints on the cosmic expansion history from the third LIGO–Virgo–KAGRA Gravitational-Wave Transient Catalog (using `gwcosmo`) 2021

Why did we need to rewrite the method?

The previous version of `gwcosmo` was slow

- We expect more events during Run O4
- The resulting H_0 posterior depends on
  - BH mass distribution
  - CBC merger rate (with z)

  $\longrightarrow$ informative priors impact the result and introduce a bias

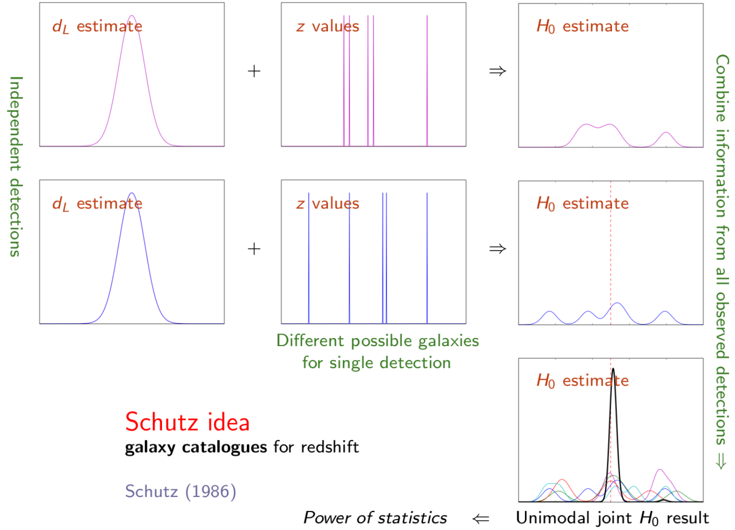
Before, `gwcosmo` was too computationally expensive to vary these inputs.
$\longrightarrow$ any hyperparameters were fixed
The new version (1000x faster) allows joint estimation of cosmological and compact binary population parameters

Content

Theory of the 'Dark Siren' method

$$H_0 d_L \approx cz$$

- d_L: GW data
- z: EM data
  - Bright siren
    EM counterpart
  - Dark siren
    Marginalize over galaxies
    LOS Redshift Prior



Schutz idea

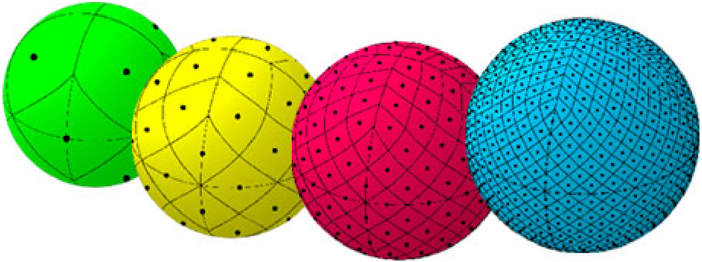
galaxy catalogues for redshift

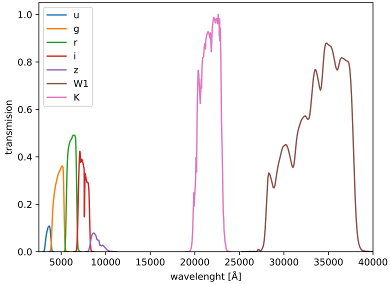
Schutz (1986)

LOS redshift prior

Contains the redshift information from galaxies in a galaxy catalogue

Divide the sky into Healpy pixels
Healpix: python package
For each pixel compute a probability array along redshift
For different observation bands (B, K, bJ, W1)



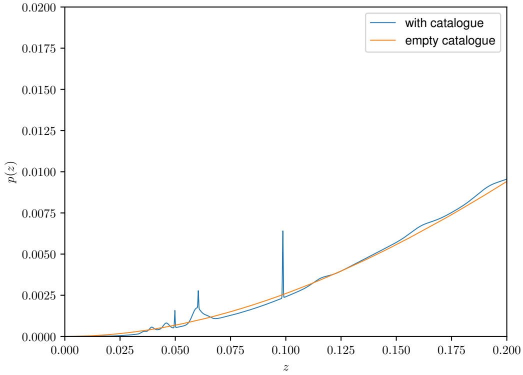


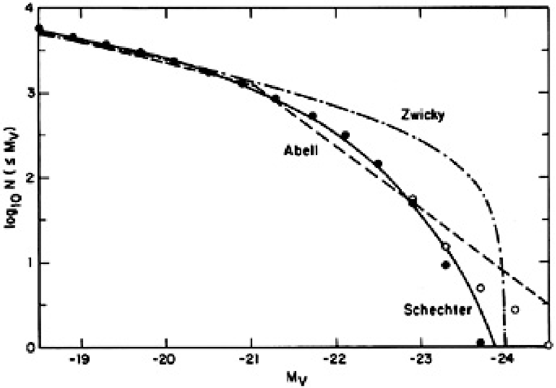
LOS redshift prior

One healpy pixel

In-catalogue contribution: Gaussian peaks corresponding to galaxies

Out-of-catalogue contribution: Galaxies uniformly distributed in comoving volume and luminosities following a Schechter function distribution



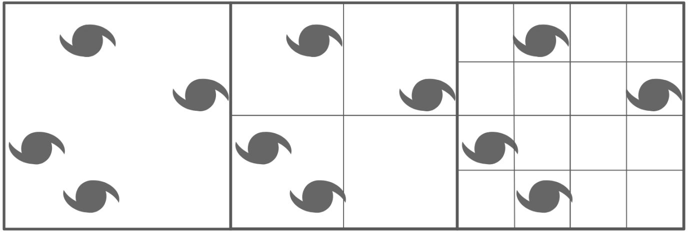


LOS redshift prior

- Pros
  - Precomputed object $\longrightarrow$ only calculate once and faster analysis
  - Independent of cosmological and population parameters
- Cons
  - Large file, grows with resolution, but not with number of galaxies
  - Within each pixel, angular position information about the galaxies is lost

LOS redshift prior

Implicit angular resolution dependence in galaxy weighting and magnitude thresholds



Ensure convergence for increasing angular resolution

Define 2 levels of resolution: n_{map} and n_{high}

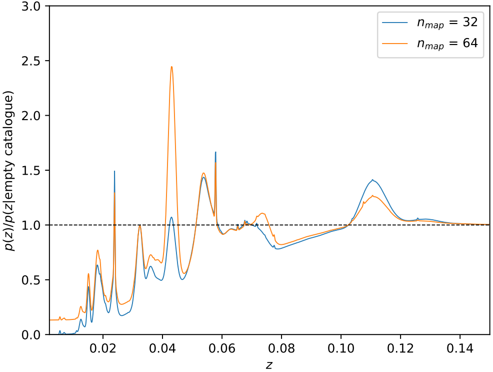
Calculate the effective number of galaxies at n_{map} and adjust to n_{high}

GW190814: LOS redshift prior

Most informative event

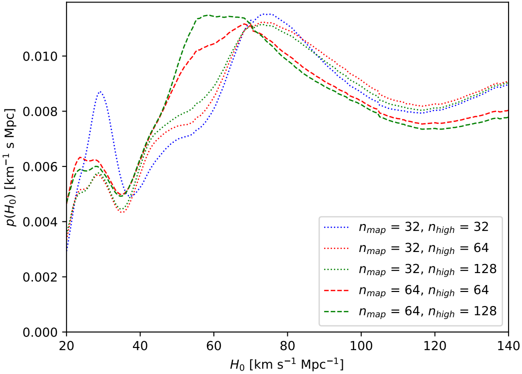
Weighted sum of LOS zpriors of multiple pixels

Illustrates over- and underdensities compared to the empty catalogue distribution



GW190814: H_0 posterior

Peak position depends on n_{map} and n_{high}
The results using $n_{\text{map}} = 32$ are more robust



Results and comparison

Compare results from the previous and new method

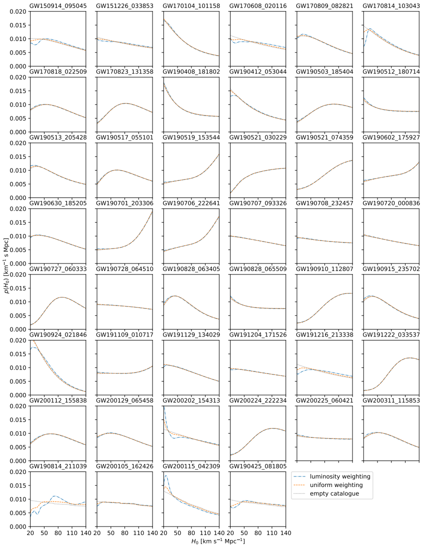
GW events from GWTC-3 catalogue with SNR > 11

- 42 BBHs
- 2 NSBH (GW200105 and GW200115)
- 2 BNS (GW170817 and GW190425)
- 1 asymmetric mass binary (GW190814), treated as NSBH

GLADE+ galaxy catalogue K-band

Same fixed population assumptions

Results and comparison



3 cases:

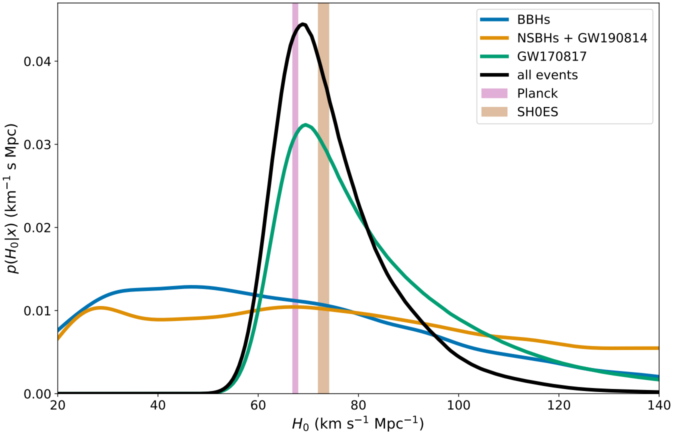
- luminosity weighting
- uniform weighting
- empty catalogue

Observations:

- Adding galaxies makes events more informative
- Luminosity weighting makes events more informative
- All cases behave the same at high z

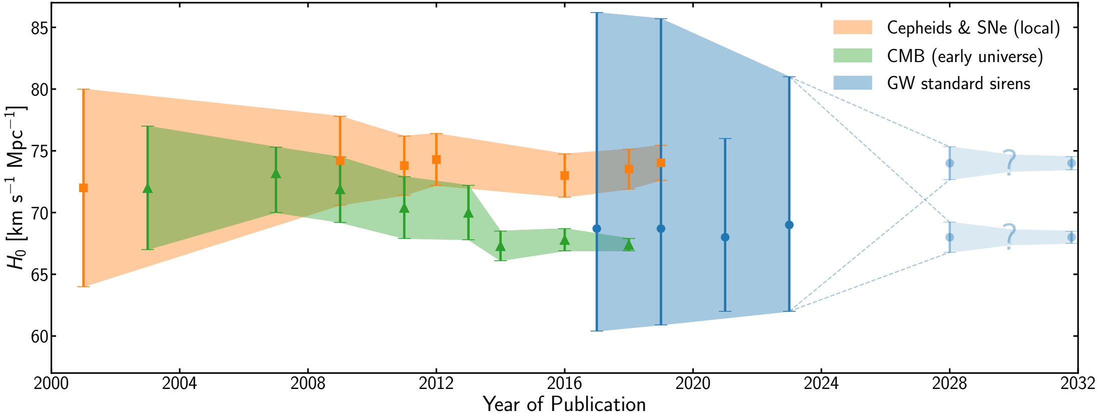
Results and comparison

The galaxy catalogue analysis of GWTC-3 with fixed population assumptions



Results and comparison

H_0 measurements over time



Future plans

Extend `gwcosmo` with galaxy cluster catalogue information

Galaxy catalogues are limited, and very incomplete at higher redshifts
Galaxy cluster catalogues (from X-ray surveys) are expected to be more complete up to higher redshifts, thus they can complement the data from galaxy catalogues

`gwcosmo` LOS zprior

- Now contains
  in-catalogue + out-of-catalogue
- Add cluster catalogue information
  in-catalogue + in-cluster-catalogue + out-of-catalogue