Recent advances in gravitational-wave cosmology

S. Mastrogiovanni

Astroparticule et Cosmologie Laboratoire, University of Paris

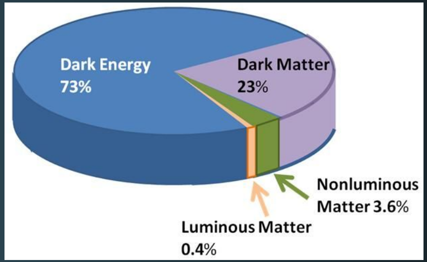
Amaldi Research Center Seminar, Sapienza University of Rome, 30/09/2021

The standard cosmological model

According to General Relativity, and confirmed by many observations, the Universe is expanding with a rate described by

$$\frac{H(z)}{H_0} = \sqrt{\Omega_{m,0}(1+z)^3 + \Omega_\Lambda + \Omega_r(1+z)^4 + \Omega_k(1+z)^2}$$

Hubble constant — Dark matter — Dark energy — Radiation — Curvature



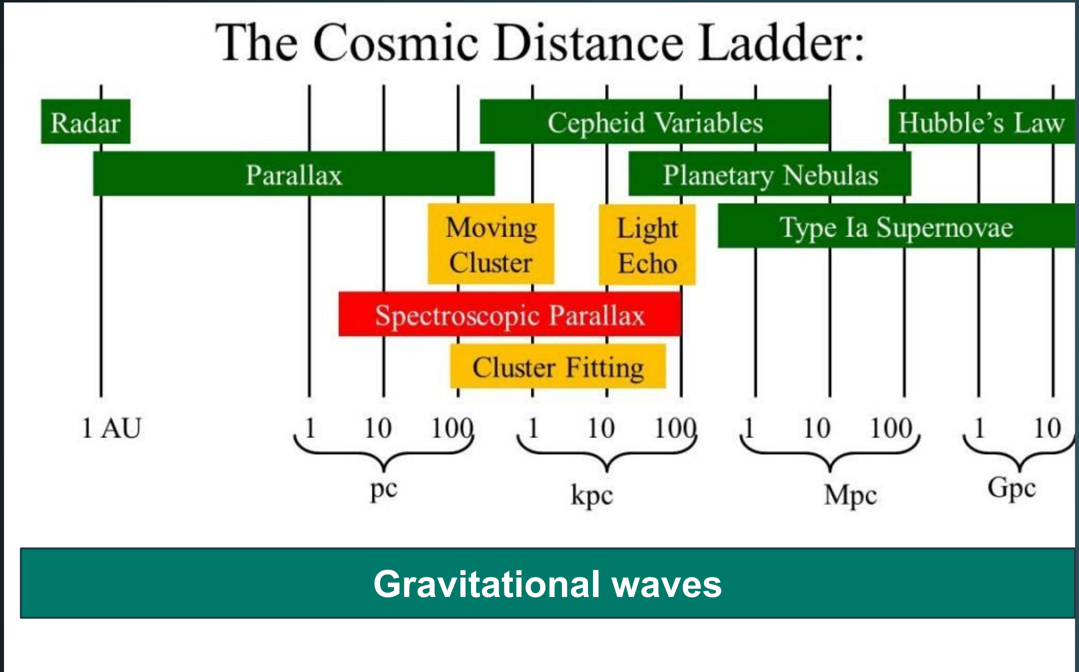
W. Freedman, Nature Astronomy, 1, 0169 (2017)

Despite its success in the standard cosmological model suffers:

Redshift = Age of the Universe

- **Theoretical problems:** What is the nature of Dark Energy?
- **Observational problems:** Why the measure of the Hubble constant does not agree at the level of the CMB and today? (There is a 4.6 sigma discrepancy)

Why cosmology with GWs?



Standard candles:

- Known absolute luminosity.
- We measure the flux and we calculate the luminosity distance of the source.
- Often comes with a redshift measure.

Standard sirens:

- Directly measure the luminosity distance of the source.
- Do not provide a redshift measure.

What events we have so far?

- **During O1 (~4 months):**
  - 3 confident BBHs
- **During O2 (~8 months):**
  - 7 confident BBHs
  - 1 confident BNS+EM counterpart
- **During O3a (~6 months)**:
  - 1 consistent with BNS masses (GW190425)
  - 2 BH+lighter object (GW190814, GW190426_152155)
  - 36 consistent with BBHs
  - 1 Massive event merging in an IMBH (+tentative EM counterpart)

How do we measure the redshift?

Methods based on complementary observations

- ✓ Direct EM counterparts: e.g. a GRB, Kilonova or AGN flare
- ✓ Statistical association with galaxy surveys
- ❑ GW clustering properties
- ❑ Quadruply lensed GW events

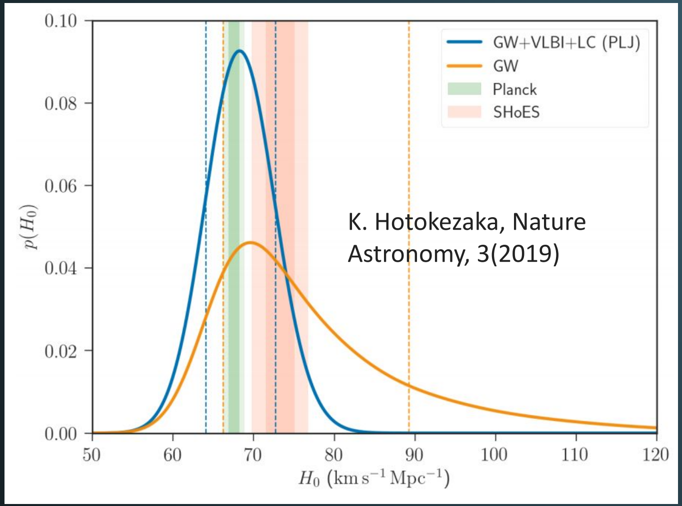
Methods based on Astrophysical Models

- ❑ Knowledge of the star formation rate
- ❑ Source-frame mass knowledge
- ❑ Equation of state and Tidal deformability

Direct EM counterparts

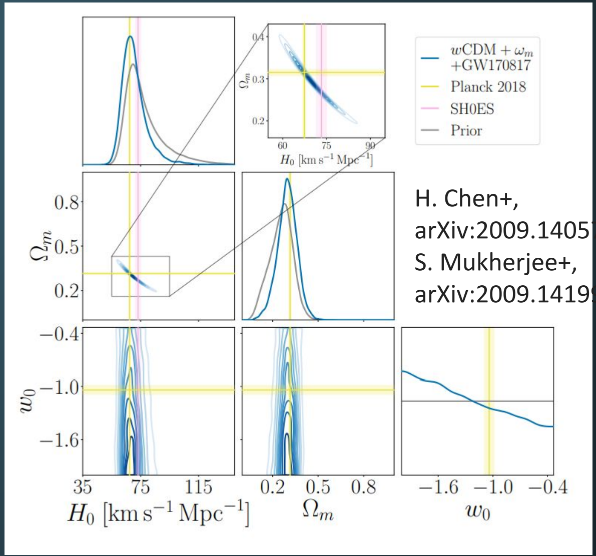
The BNS GW170817

- EM information (GRB+KN) provided the identification of the host galaxy.
- Extra information from the jet centroid motion can improve H0 estimate.
- Extremely rare event.



The BBH GW190521

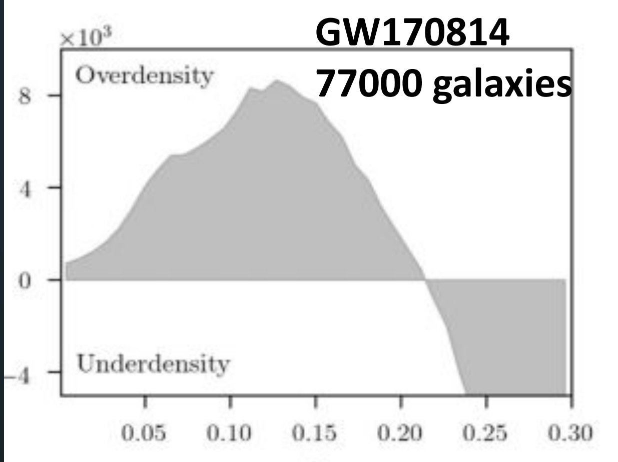
- An AGN flare observed by ZTF provided the redshift identification.
- Association between GW190521 and AGN flare still not confident.



Cosmology with dark standard sirens: Galaxy catalogs

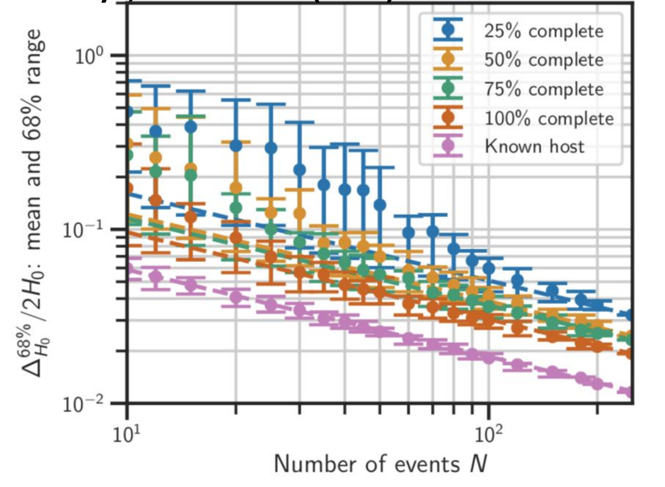
- We can study the underdensity or overdensity of galaxies in the localization volume of the GW source and assign a probability to each galaxy to host the event.

- Inference can be done even if the galaxy catalog is not *complete* (correcting for the incompleteness).



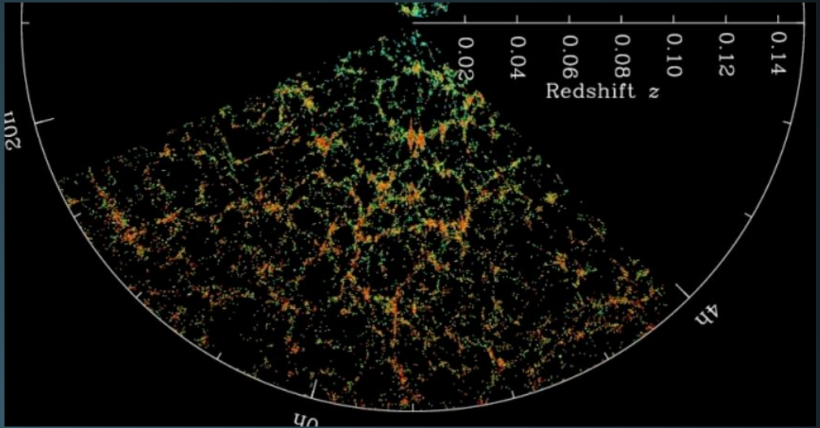
Soares-Santos+, ApJL,, Volume 876, 1, L7 (2019)

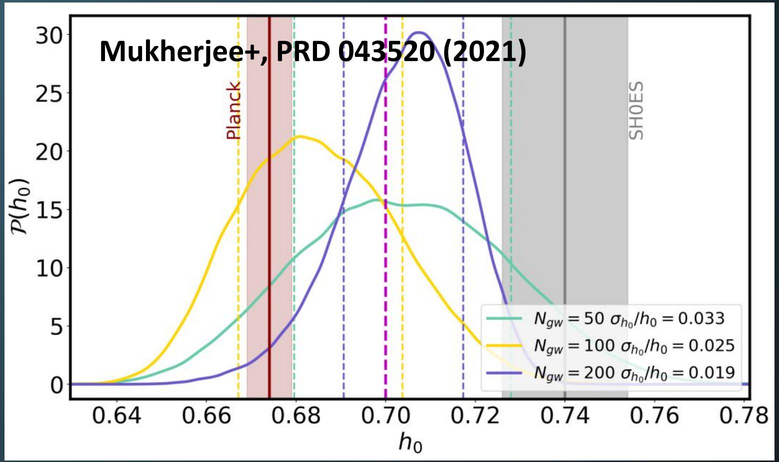
R. Gray+, PRD 122001 (2020)



GW clustering properties

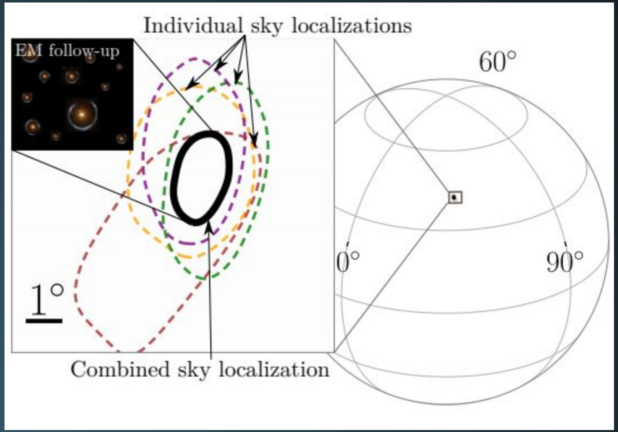
- GW sources are hoste in galaxy, therefore they should follow the clustering properties of galaxies.
- Galaxy clusters following the dark matter field.
- By knowing the distribution of the galaxy density field and GW density field it will be possible to measure the cosmological parameters.

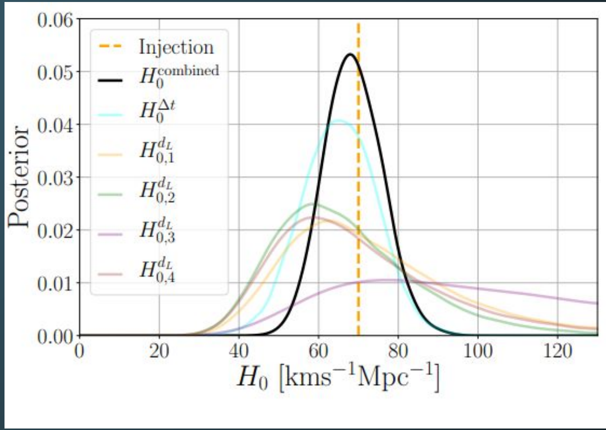




Strong lensing

- Quadruply lensed gravitational wave events (probable to happen around redshift 1) can be used to localize the GW event to a sub-arc sky region.
- EM follow-ups of lensed galaxy could pinpoint the host of the GW event.
- The Quadruply lensed GW event provides ``4`` standard sirens to measure cosmology.

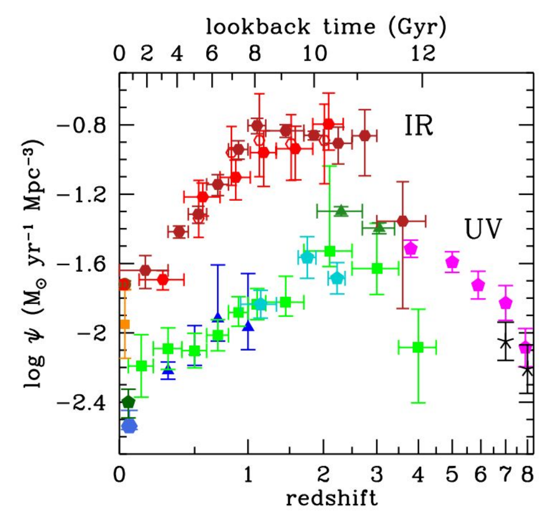




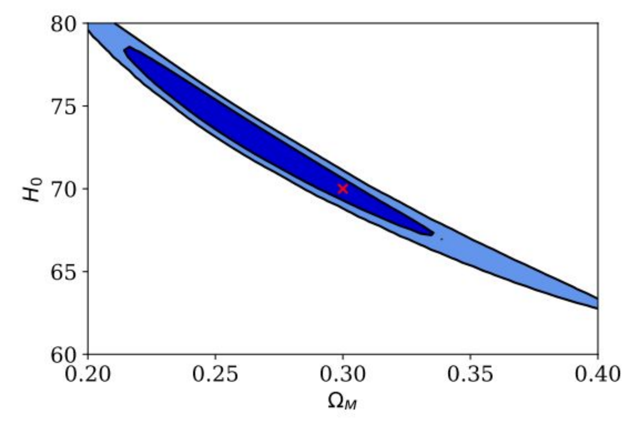
O. Hannuksela+, MNRAS 498 (2020)

Knowledge of the star formation rate

- The star formation rate peaks at redshift 2 (cosmic noon) and decrease at Early times.
- If the merger rate is correlated with the star formation rate, implicit redshift information might come from our prior knowledge on the most probable epoch for the merger of the binary.

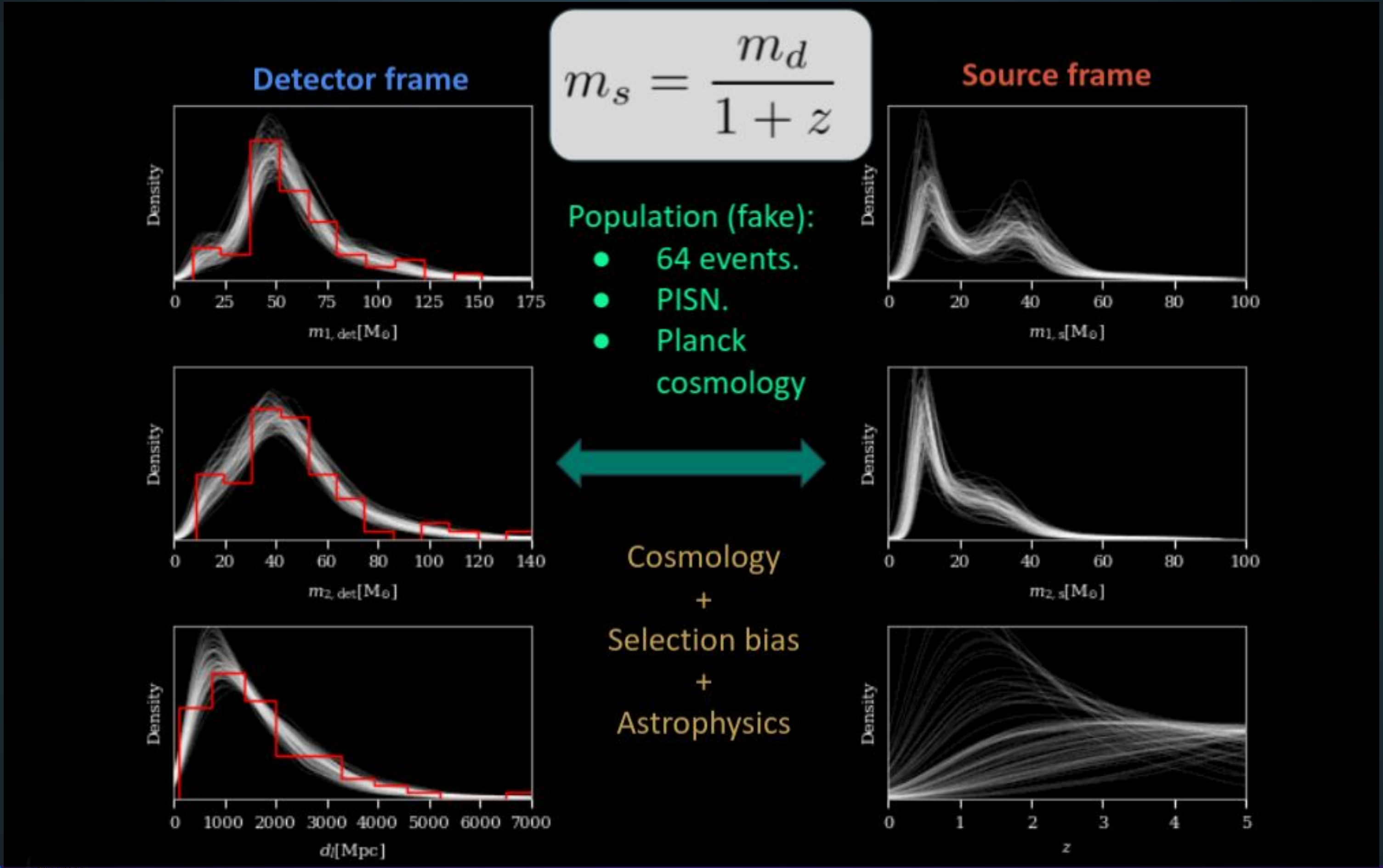


Madau+, Annual Rev. of A&A Aug 2014

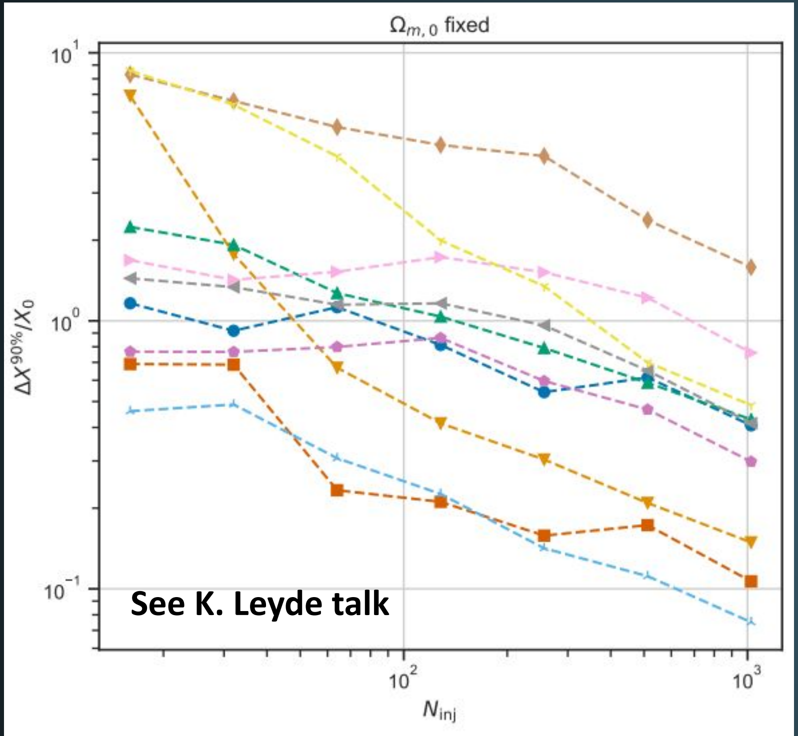


Ye, C. Physical Review D, Volume 104, Issue 4, article id.043507

Source-frame mass knowledge



Source-frame mass knowledge

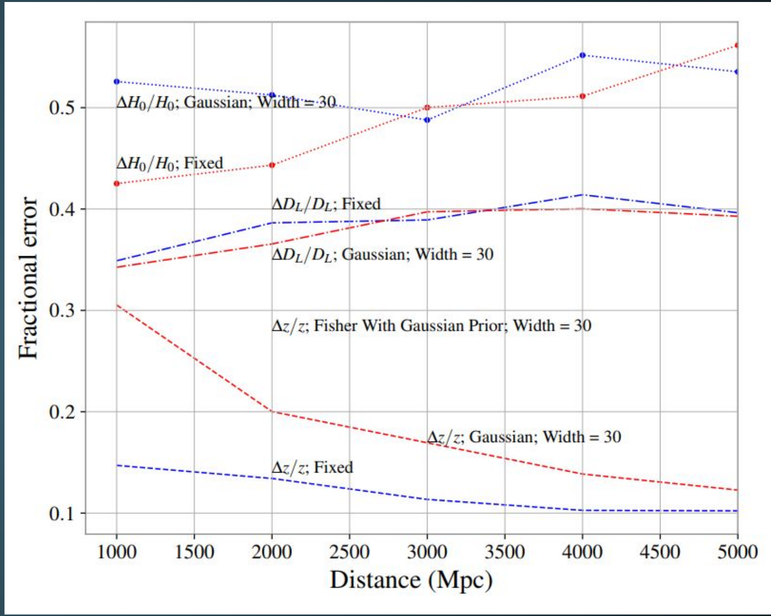


S. Mastrogiovanni+, PRD.104.062009 (2021)

- Knowledge on the source-frame mass distribution will allow us to measure cosmology.
- It will be possible to measure cosmology even if the source-frame mass distribution is unknown.
- Population assumptions introduce systematics on cosmology.
- This method will be promising with future observing runs, where we will have thousands of GWs sources without an observed EM counterpart.

Equation of state and Tidal deformability

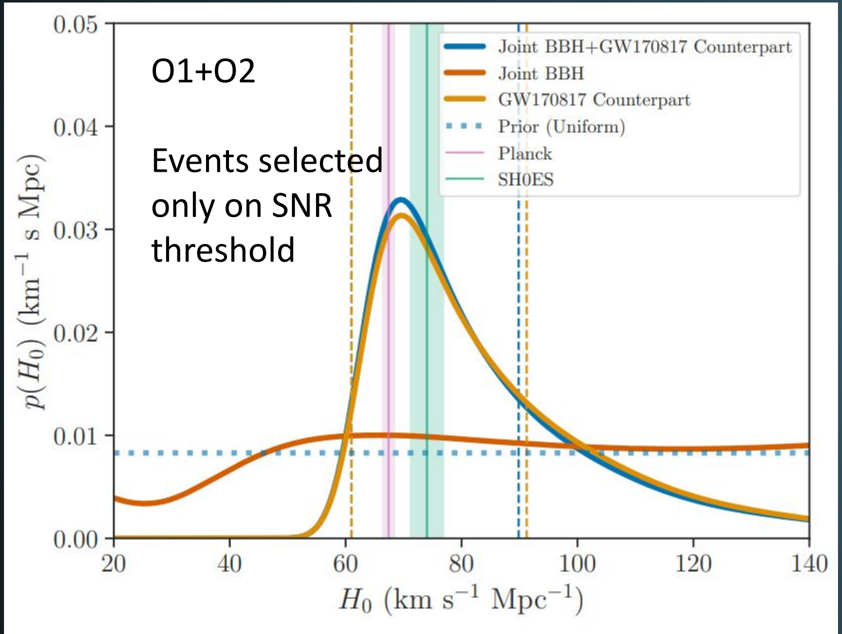
- NS can be tidally deformed during their inspiralling.
- A measure of their tidal deformability (i.e. knowledge about the Equation of State), can be used to infer the source-frame mass and therefore get a redshift estimation.
- The accuracy of this method will depend on our degree of knowledge about the Equation of State.



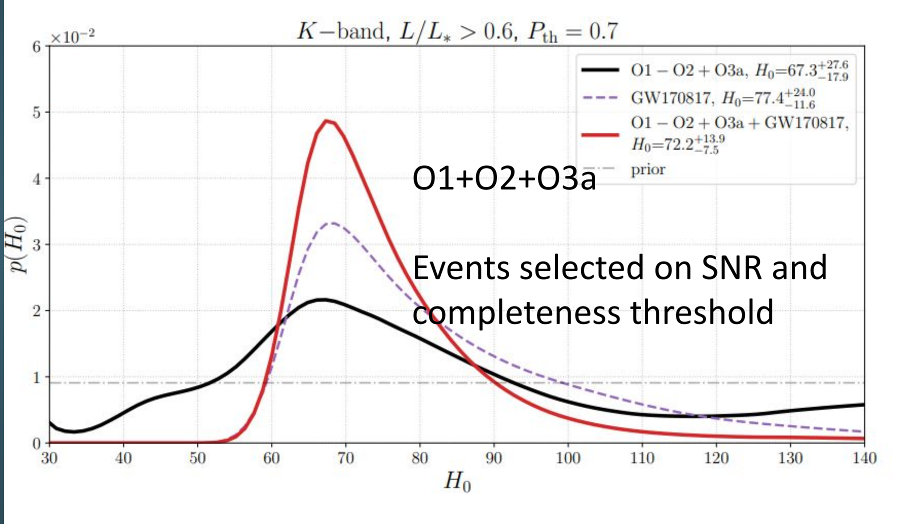
Chatterejee+, 2106.06589
Messenger+, PRL, 091101, 1107.5725.

Latest results

- The latests H0 measures uses the O1, O2 and O3a events.
- GW170817 is still the most informative event, followed by GW190814 and GW170814.



LVC+, APJ, 909:218 (18pp), 2021 March 10



Finke+, JCAP, Volume 2021, Issue 08, id.026, 97 pp.

Conclusions: outlook of methods and results

Method	Pros	Cons	Results
EM counterpart	Accurate redshift estimation, golden sirens	Infrequent and rare events, tentative associations	GW170817 and best measure of H0
Galaxy catalogs	Available even for BBHs, several EM bands to check consistency	Less and less incomplete, less constraining for poorly localized events	4%-15% improvement w.r.t GW170817
Clustering	No EM counterpart needed, more efficient for poorly localized events	Needs to know the dark matter density field. Incompleteness issue	
Quadruple lensing	Provides 4 bright golden sirens at the price of one.	Could be rare events and lensing follow-up could be difficult	
Source-frame mass	No needs of EM counterparts, can fit conjointly cosmology and astrophysics	Needs to be driven by some astrophysical expectation	
Rate evolution	As above	As above	
Tidal deformation	No need of EM counterpart, detectable from the waveform.	Needs to obtain a Universal EOS from few calibrators	