Parameter estimation and cosmology with gravitational waves

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TATA INSTITUTE OF FUNDAMENTAL RESEARCH

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Abhirup Ghosh, Siddharth Mohite

Detection of gravitational waves round the corner!

– first data from Adv-LIGO upcoming from the O1 runs . . .

– first detections expected soon after.

GW observations $\Rightarrow$ physics / astrophysics.

Estimation of parameters is a crucial step in getting any physics output from gravitational-wave observations.

[Background: LIGO Hanford Observatory]

Science with GW observations

Gravitational-wave observations

Waveform modelling $\upharpoonleft\downharpoonright$ Test of GR

Rates, horizon $\upharpoonleft\downharpoonright$ Cosmological parameters

Stellar evolution, Population / rates $\upharpoonleft\downharpoonright$ Triggered searches, masses, spin, e.o.s.

Physics

Cosmology

Astronomy

Parameter estimation as a crucial step

- Astrophysics:

  "Where in the sky?"

  "What masses / angular momenta?"

- Cosmology:

  "What redshifts and distances?"

- Fundamental physics:

  "E.o.s. of NS?", "Parameters of non-GR theories?"

  "Consistency between observed parameters?"

This talk

- Basics

  Detectors, sensitivity, sources

- Parameter estimation

  Parameter estimation as a challenge

  Procedure, algorithms employed, some results

- Cosmology

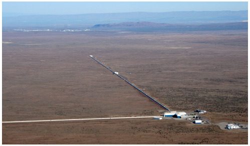
  Cosmology motivation

  Prospects of cosmology with GW

- Future directions

Basics

Detectors



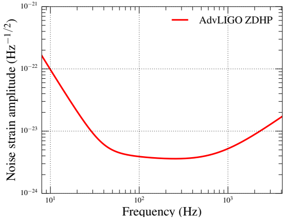
Detector network and baselines (*ms*)

[Source: http://www.gw-indigo.org, Pic: B. S. Sathyaprakash]

LIGO detectors in Hanford, Livingston (U.S.A) and Virgo in Cascina (Italy).

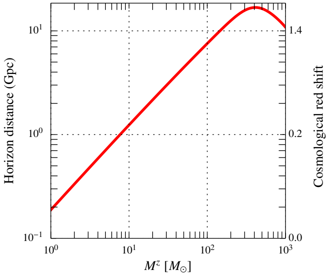
KAGRA (Japan) and LIGO India . . .

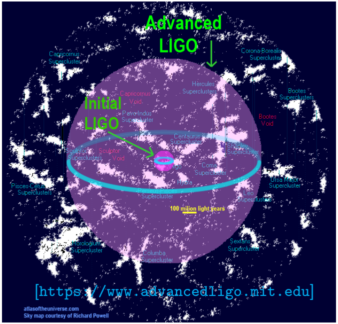
Sensitivity



♣ Ad-LIGO has 10 times more sensitivity than initial LIGO; one can survey 1000 times the volume of the sky.

Amplitude detectors!





Sources

Compact binary coalescences (CBCs):

Mergers of binary systems of NS / BH
$\Rightarrow$ well-modelled "chirp" waveform.

NS-NS:

Expected rates $\sim$ 40 (0.4 – 400) yr^{-1},

Horizon distance $\sim 0.4 Gpc$.

NS-BH:

Expected rates $\sim$ 20 (0.2 – 300) yr^{-1},

Horizon distance $\sim 1 Gpc$.

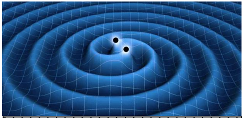
NS-NS:

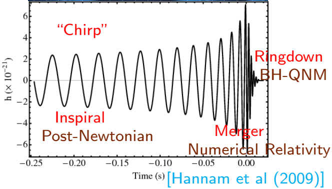
Expected rates $\sim$ 40 (0.4 – 1000) yr^{-1},

Horizon distance: $\sim 8 Gpc$.

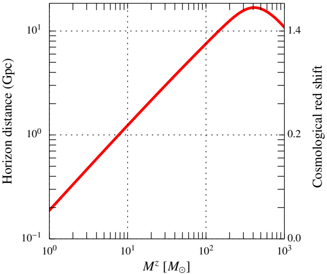
[Abadie et al (2010)]

Bala's talk!





[Hannam et al (2009)]



Parameter estimation

What parameters to estimate?

$\{m_1, m_2, \vec{s}_1, \vec{s}_2\}$: Intrinsic parameters.

$\{\alpha, \delta, z, d_L, \iota, \psi, \phi_c, t_c\}$: Extrinsic parameters.

The masses are completely degenerate with the redshift and it is only possible to measure the redshifted mass, $m^z \equiv m(1+z)$.

phase $\Rightarrow$ redshifted chirp mass, $\mathcal{M}^z \equiv \frac{(m_1^z m_2^z)^{3/5}}{(m_1^z + m_2^z)^{1/5}}$, very accurately

$\Rightarrow$ mass ratio, $q \equiv \frac{m_2}{m_1}$, to a reasonable degree

amplitude $\Rightarrow$ the combination, $\frac{\mathcal{M}^z \cos^2 \iota}{d_L}$, very accurately

$\Rightarrow$ d_L to a reasonable degree

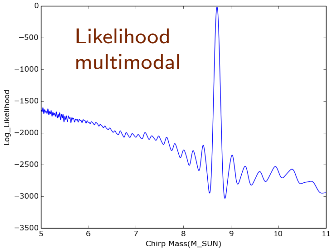
The challenge!

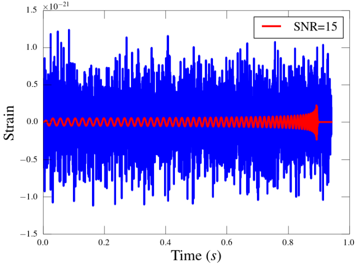
$$\{\mathcal{M}, q, \vec{s}_1, \vec{s}_2, \alpha, \delta, d_L, \iota, \psi, \phi_c, t_c\}$$

9 parameters for non-spinning binaries.

15 parameters including spin.

Additional parameters (tidal, etc. terms) for NS.





[Plot by: Siddharth Mohite]

Bayesian Inference

Bayesian parameter estimation: stochastic technique to sample the posterior probability on the parameters given the data and a prior.

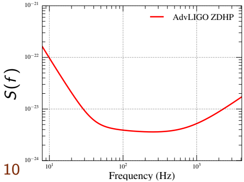
$$Posterior(\vec{\Omega}|\mathrm{data}, I) = \frac{Prior(\vec{\Omega}|I)\,\mathcal{L}(\mathrm{data}|\vec{\Omega}, I)}{Evidence(\mathrm{data}, I)}$$

$$\vec{\Omega} = \{\mathcal{M}, q, \vec{s}_1, \vec{s}_2, \alpha, \delta, d_L, \iota, \psi, \phi_c, t_c\}$$

$$\mathcal{L}(\mathrm{data}|\vec{\Omega}, I) = P(\mathrm{data}|\mathrm{signal}(\vec{\Omega}), I)$$

$\mathrm{data} = \mathrm{signal}(\vec{\Omega}) + \mathrm{noise}, n$

$$= \exp\left(-\frac{1}{2}\left\langle \mathrm{data} - \mathrm{signal}(\vec{\Omega}) | \mathrm{data} - \mathrm{signal}(\vec{\Omega})\right\rangle\right)$$



$$\langle n|n\rangle \equiv \int df \frac{||n(f)||^2}{S^2(f)}$$

Gaussian noise

Algorithms and software

Documented in: Veitch et al (2014)

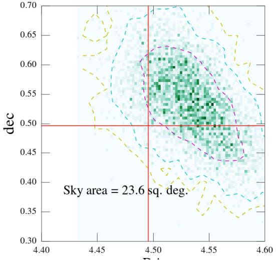
The parameter estimation algorithms are implemented LIGO Algorithms Library (LAL) as `LALInference`.

- `LALInferenceMCMC`: Parallel tempering
- `LALInferenceNest`: Nested sampling
- `LALInferenceBambi`: Multinest

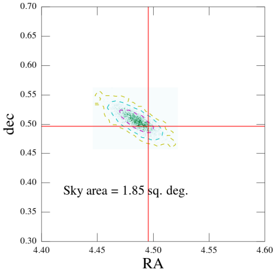
- `pyPE`: Ensemble samplers, etc. [Siddharth Mohite, AG, Walter Del Pozzo]

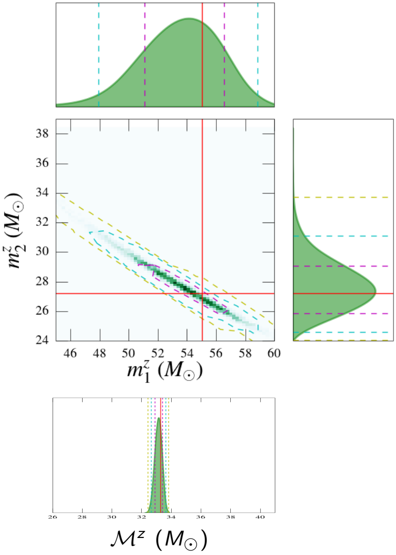
Estimated parameters . . .

3 detectors: HLV



5 detectors: HLVIJ





Parameter estimation of high-mass BBH

AG, Walter Del Pozzo, P. Ajith

- Uniform distribution of $m_{1,2} \in [20, 50] M_\odot$.
- $z \lesssim 0.5$.
- SNR ≥ 8.

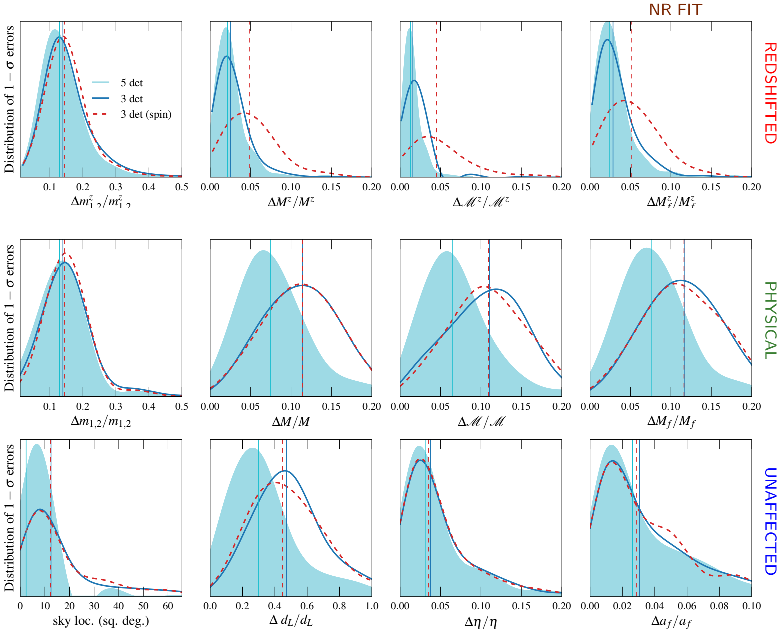
`LALInference` $\Rightarrow$ Usual (redshifted) quantities, $\{\mathcal{M}^z, q, m^z_{1,2}, d_L\}$

Compute: Physical (non-redshifted) quantities, $\{\mathcal{M}, m_{1,2}\}$

NR fit formulae to compute mass and spin of final BH:

$$M_f = M \left[1 + \left(\sqrt{8/9} - 1\right) \eta - 0.4333\, \eta^2 - 0.4392\, \eta^3\right] ,$$
$$\frac{a_f}{M_f} = \sqrt{12}\, \eta - 3.87\, \eta^2 + 4.028\, \eta^3 .$$

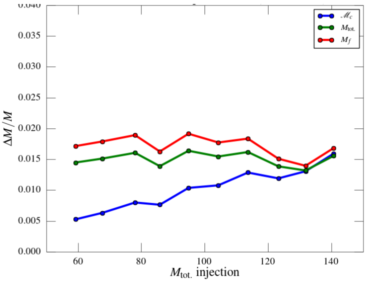
[Pan et al (2011)]



AG, Walter Del Pozzo, P. Ajith (*in preparation*)

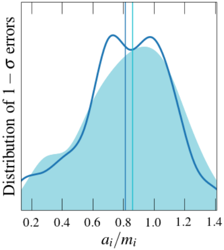
Parameter	3 detector	5 detector
Component masses $m_{1,2}$	13.9%	12.9%
Total mass M	11.4%	7.5%
Chirp mass $\mathcal{M}$	11.0%	6.5%
Final mass M_f	11.7%	7.6%
Mass ratio q	31.6%	29.2%
Symmetric mass ratio η	3.7%	3.1%
Final spin $a_f\,/\,M_f$	3.1%	2.6%
Luminosity distance d_L	47.1%	30.0%
Sky location Ω (sq. deg.)	12.50	2.39

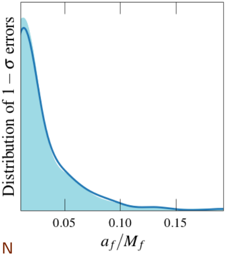
MASSES



COMPONENT

FINAL





SPIN

Cosmology

Measuring cosmological parameters

Which cosmological parameters?

H_0 : Hubble parameter
Ω_m : Matter fraction
Ω_K : Curvature fraction
Ω_Λ : Dark energy fraction

$\Omega_r + \Omega_m + \Omega_k + \Omega_\Lambda = 1$

$$\frac{\dot{a}}{a} \equiv H_0 \, ; \qquad \frac{\ddot{a}}{a} = H_0^2 \left\{ -\overset{\approx 0}{\cancel{\Omega_r}} - \frac{1}{2}\Omega_m + \Omega_\Lambda \right\}$$

Expansion and acceleration of the universe.

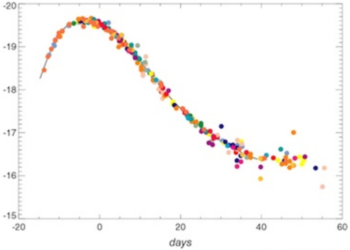
Measurable is redshift $\Rightarrow$ Redshift-distance relation:

$$d_L = c(1+z)\int^z \frac{dz'}{H(z')} \, , \; H(z) = H_0\sqrt{\Omega_m(1+z)^3 + \Omega_K(1+z)^2 + \Omega_\Lambda}$$

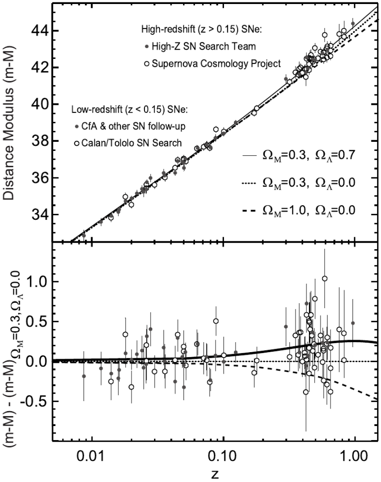
Standard candles

♣ Sources of known luminosity – like Supernovae of Type Ia.

Sriram's talk.



[Kim *et al* (1997)]



[Perlmutter, Schmidt – Measuring Cosmology with Supernovae (2003)]

Necessity of new input

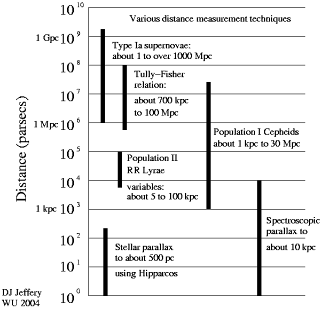
♣ Calibration relies on multiple steps in the cosmic distance ladder and a large amount of systematics can creep in.

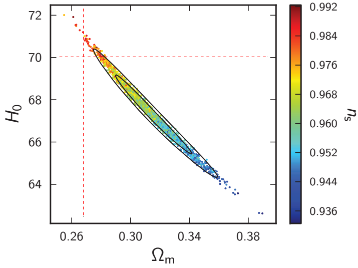
♣ There is a large variability in the light-curves of SNIa and their physics is not fully understood.

♣ Even the Hubble parameter is not measured to a great accuracy!

♣ Tension between supernova and Planck results! Sriram's talk.

♣ An independent measurement will be of prime significance.

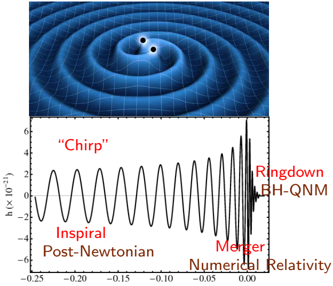




[PLANCK Collaboration (2013)]

Standard sirens

- ♣ Gravitational wave give direct access to the luminosity distance to the event without relying on any distance ladder.
- ♣ They can be used as “standard sirens” analogous to supernovae as standard candles.
- ♣ Unfortunately the redshift is totally degenerate with mass and cannot be independently estimated.



[Hannam et al (2009)]

Cosmology $\rightleftharpoons$ Redshift

Use cosmology: distance $\rightarrow$ redshift $\Rightarrow$ physical masses.

Use redshift information from coincident electromagnetic event:

redshift + distance $\Rightarrow$ cosmology.

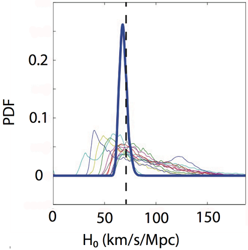
Opens up the possibility of an independent measurement of the cosmological parameters with an entirely different systematics.

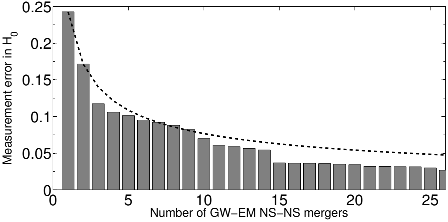
NS mergers $\Leftrightarrow$ Sh-GRBs

- A CBC involving a NS is believed to be associated with a Sh-GRB. Resmi's talk.
- Redshift of the coincident e.m. event.

[http://www.astro.caltech.edu/ avishay]

[Nissanke et al (2010), Nissanke et al (2013)]



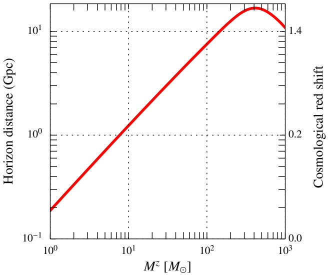


Drawbacks . . .

♣ Horizon distance for even NS-BH $\lesssim$ $1Gpc$ $\Rightarrow$ only limited cosmology can be probed.

♣ Probability of coincident observation is low (~ 1 event per year).

[Metzger & Berger (2009)] Varun's talk.



♣ Can one use BBH instead?

Cosmology with BBH

No electromagnetic counterpart. Only information can come from identification of potential host galaxies.

Q: Which part of the galaxy catalog should we look in?

A: The entire range of redshifts allowed by the prior on cosmology.

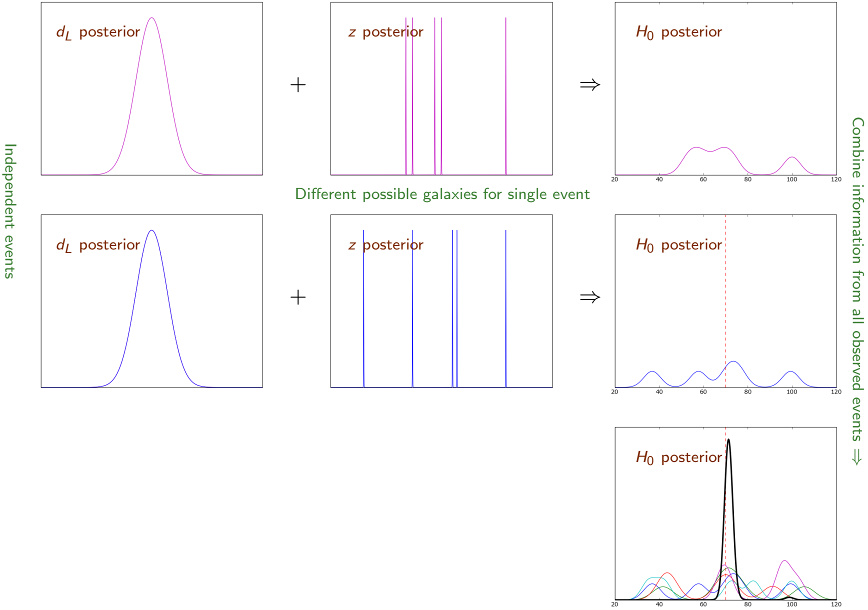
Cosmology with BBH

Walter Del Pozzo (2011)

Too many galaxies even within the allowed range . . .

Use all possible galaxies!

Stack information from independent observations.


d_L posterior
+
z posterior
⇒
H_0 posterior
20 40 60 80 100 120
Different possible galaxies for single event
d_L posterior
+
z posterior
⇒
H_0 posterior
20 40 60 80 100 120
H_0 posterior
20 40 60 80 100 120
Independent events
Combine information from all observed events ⇓

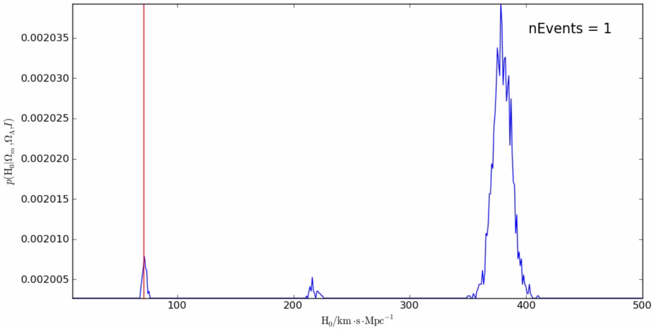
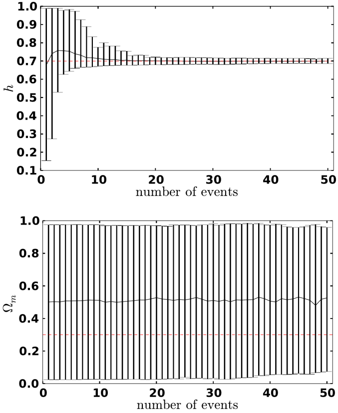


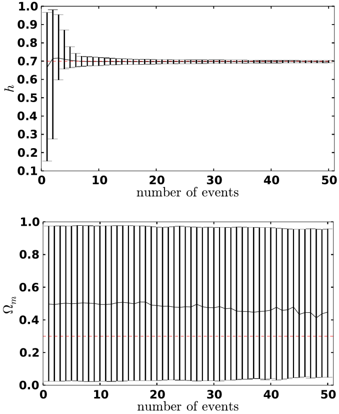
Figure : Evolution of H_0 with number of events.

Animation by: Walter Del Pozzo

Results of Del Pozzo (2011)



3 detectors



5 detectors

$z \lesssim 0.1$, SDSS catalogue $\Rightarrow$ Hubble parameter to $\sim 5\%$.

Merits . . .

♣ No immediate e.m. follow-up necessary. Varun's talk!

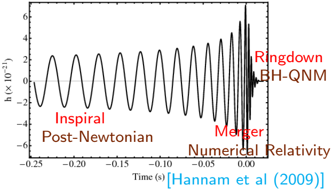
♣ Much greater horizon distance $\Rightarrow$ higher redshifts.

♣ Some recent pop. synth. models predict more BBH than NS-BH mergers.

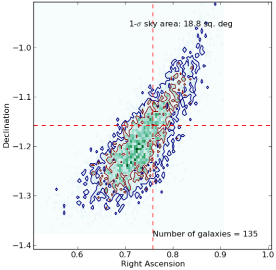
♣ Take advantage of these and see what more can be done . . .

IMR waveforms

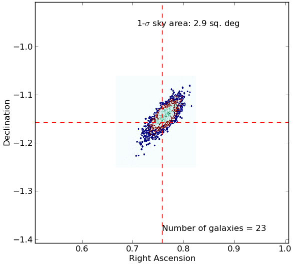
- Inspiral-merger-ringdown waveforms
  $\Rightarrow$ Improvement in sky localization.



[Hannam et al (2009)]



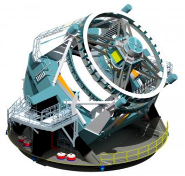
Inspiral only



Inspiral-Merger-Ringdown

Higher redshifts

- Higher redshifts, $z \lesssim 0.5$.
- Galaxy catalogues are incomplete.



Large Synoptic Survey Telescope
– extraordinarily wide and deep!
– reasonably complete to $z \sim 1$.
– start bringing in data by 2020.

Coincides with time-scale for reasonable obs. from LIGO.

- Until then, do optical follow-up on GW error box.
- Currently we simulate the optical follow-up.

Simulating the optical follow-up

Galaxy distribution – uniform in comoving volume.

$$n(z, \alpha, \delta) \propto \frac{dV}{dz d\alpha d\delta}$$

Luminosity distribution – Schecter function.

$$\Phi(M) = 0.4 * \log(10.0)\phi_* 10^{-0.4(\alpha+1)(M-M_*)} e^{-10^{-0.4(M-M_*)}}$$

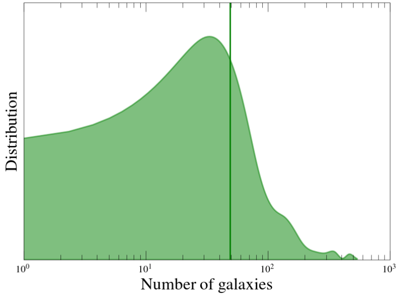
Selection function – step function.

$$S(m) = \theta(m - m_{th})$$

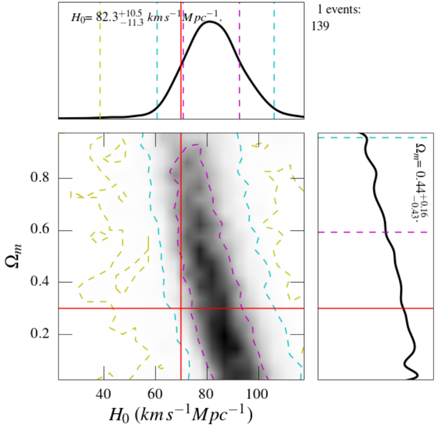
Cosmology from high-redshift BBH

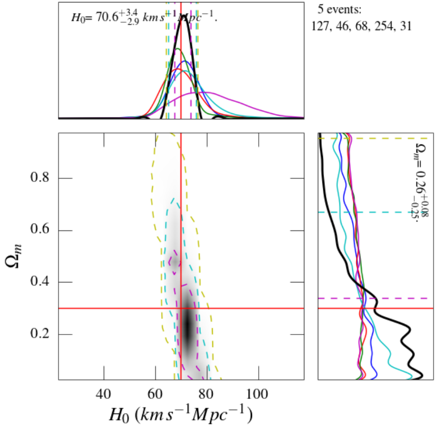
AG, Walter Del Pozzo, P. Ajith

- Uniform distribution of $m_{1,2} \in [20, 50] M_\odot$.
- $z \lesssim 0.5$.
- SNR ≥ 8.

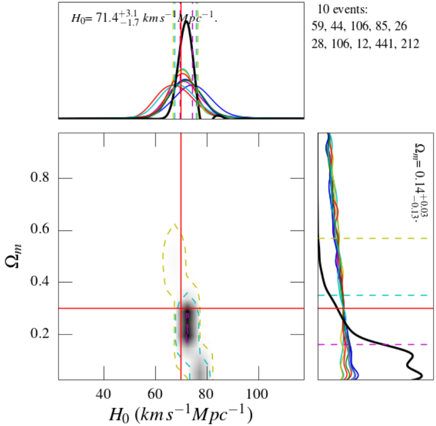


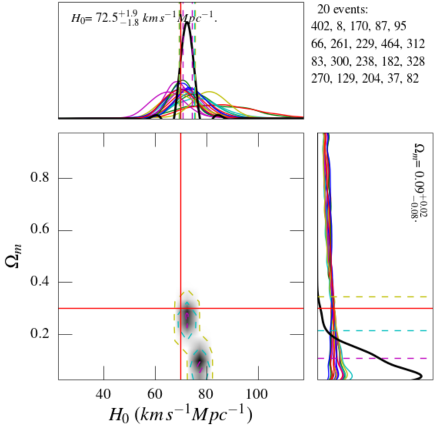
Cosmology results



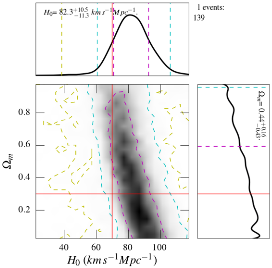


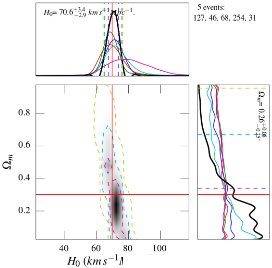
Cosmology results

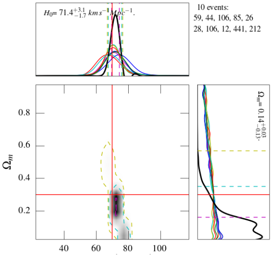


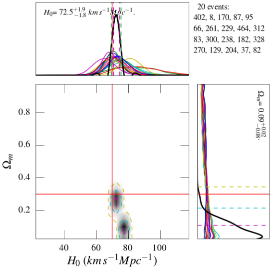


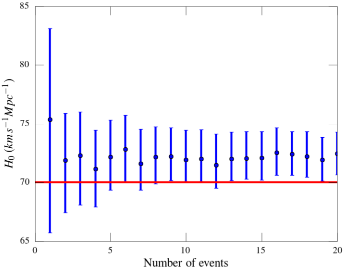
Summary of cosmology results











Further work and outlook

GW oriented:

- ♣ Systematics, sensitivity to calibration uncertainties.
- ♣ Inclusion of waveforms with higher harmonics.

Cosmology / astronomy oriented:

- ♣ Use e.m. results as a prior.
- ♣ Combine with GW results from a Sh-GRB.
- ♣ Weight galaxies with probabilities of hostings CBCs.
- ♣ Study dependence on completeness of catalogues.

THANK YOU!