Cosmology with GW detections

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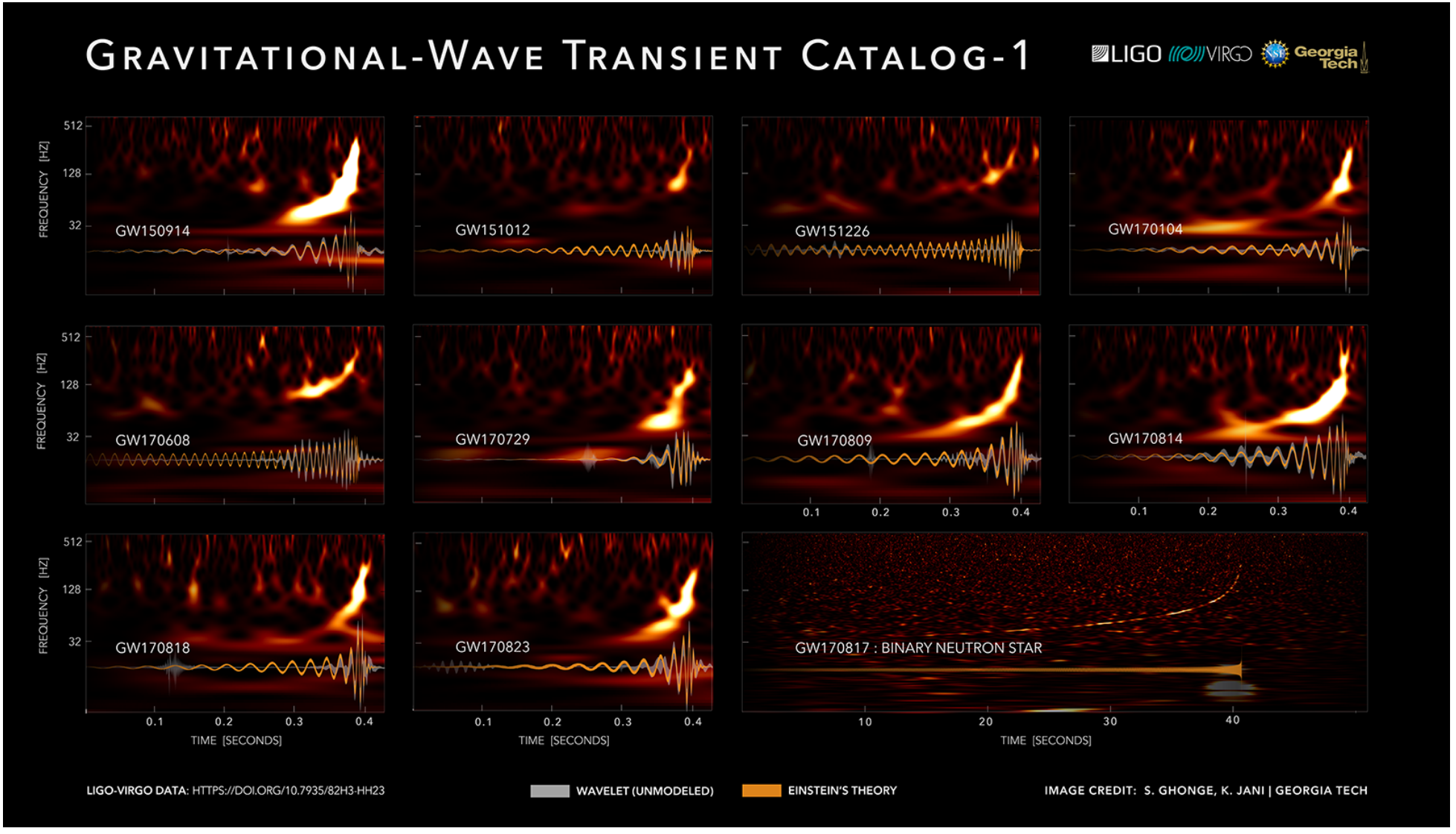
Astrophysics with GW detections
Uniwersytet Warszawski
06 września 2019



This talk will be in the context of compact binary coalescences!

Plan of the talk

- Compact binaries as standard sirens
- H_0 measurement from current / upcoming observations

  Standard siren H_0 from GW170817

  Galaxy catalogue method — simulations, projections

  H_0 with O1 & O2 BBHs

  Systematic effects
- Concluding remarks

  Towards the immediate future

  Outlook

Compact binaries as standard sirens

Schutz (1986), Holz & Hughes (2005)

GW from compact binaries give us a direct access to luminosity distance.

Independent measurement of phase evolution and amplitude

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" (degenerate with inclination)

Independent of other measurements, in particular, the distance ladder.

Redshift-distance relation:

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

GW redshift (largely) degenerate with total mass

Where does the redshift come from?

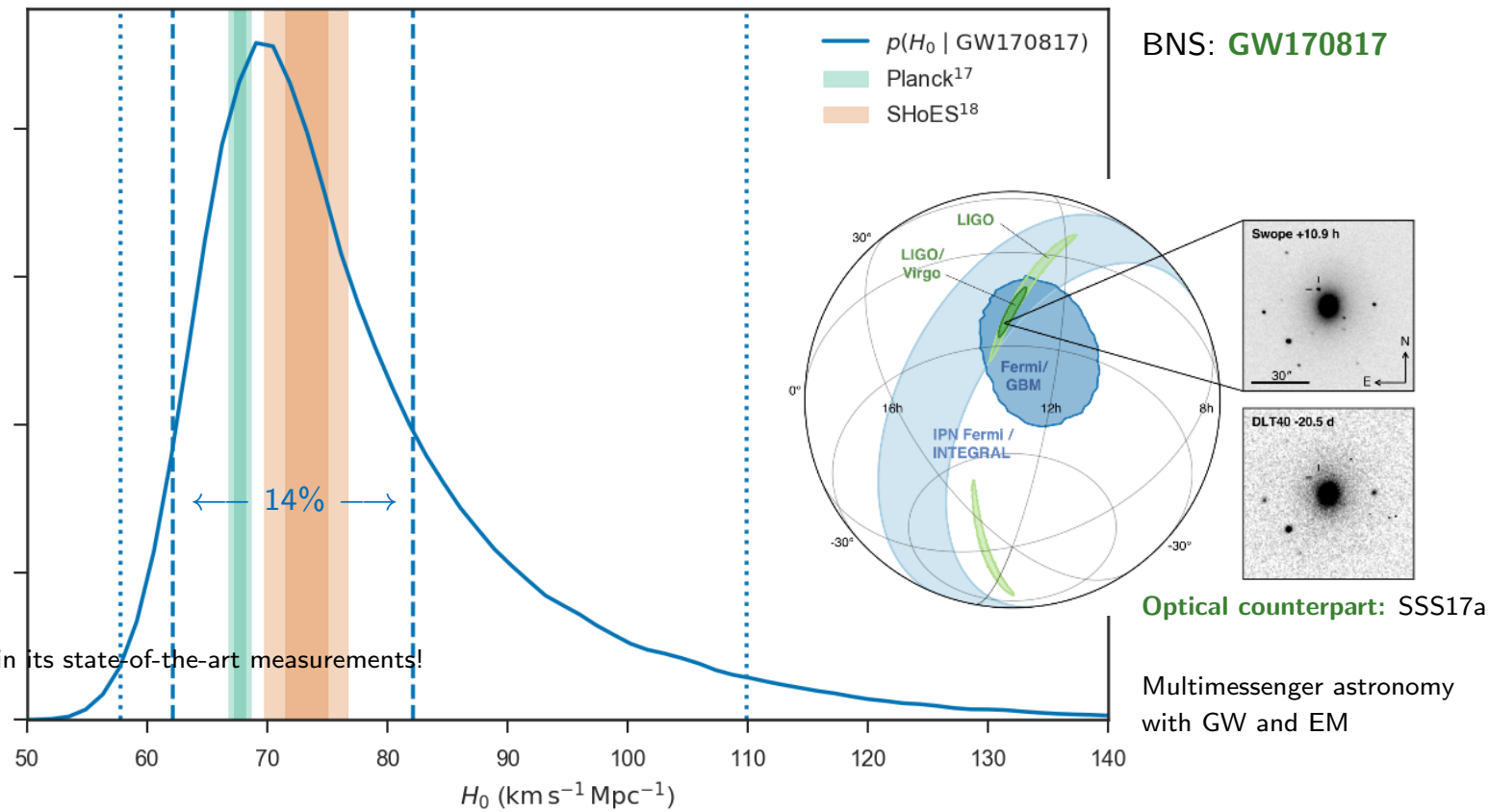
EM for this talk

LETTER

doi:10.1038/nature24471

A gravitational-wave standard siren measurement of the Hubble constant

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*



BNS: **GW170817**

Optical counterpart: SSS17a

Discrepancy in its state-of-the-art measurements!

Multimessenger astronomy with GW and EM

LETTER

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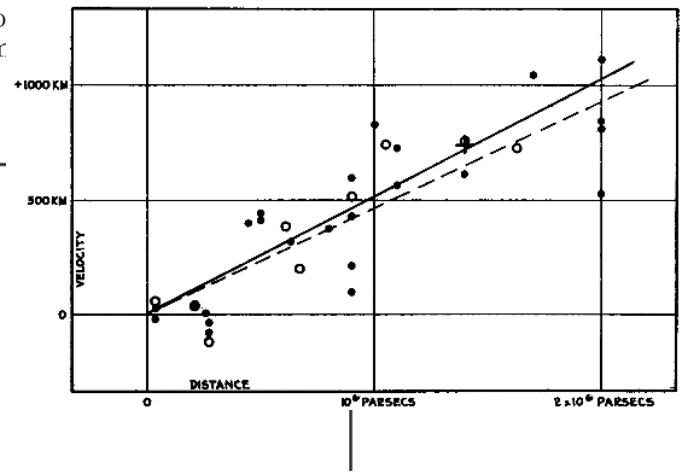
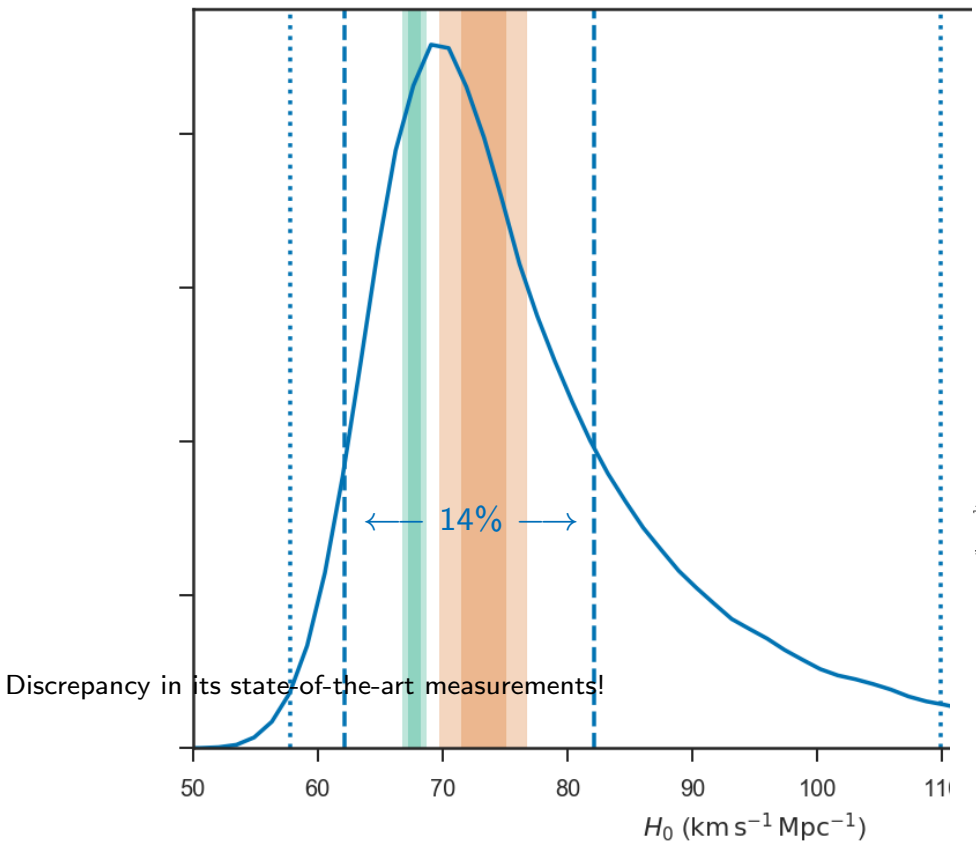
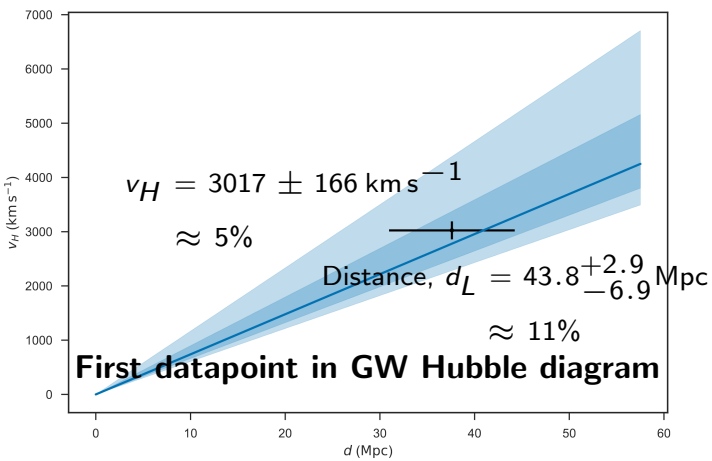
Edwin Hubble, *Proc. Nat. Acad. Sciences.* (1929)





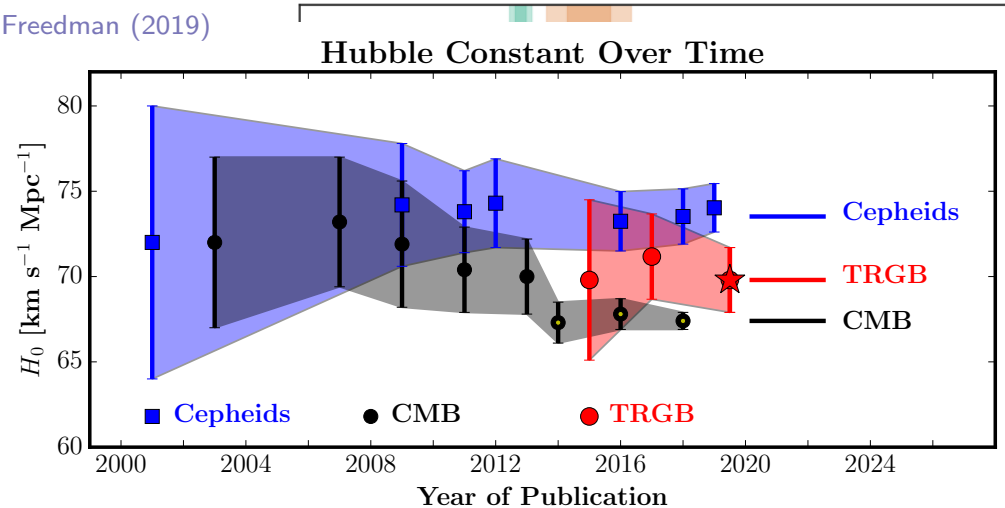
Discrepancy in its state-of-the-art measurements!



Discrepancy in state-of-the-art measurements of H_0!

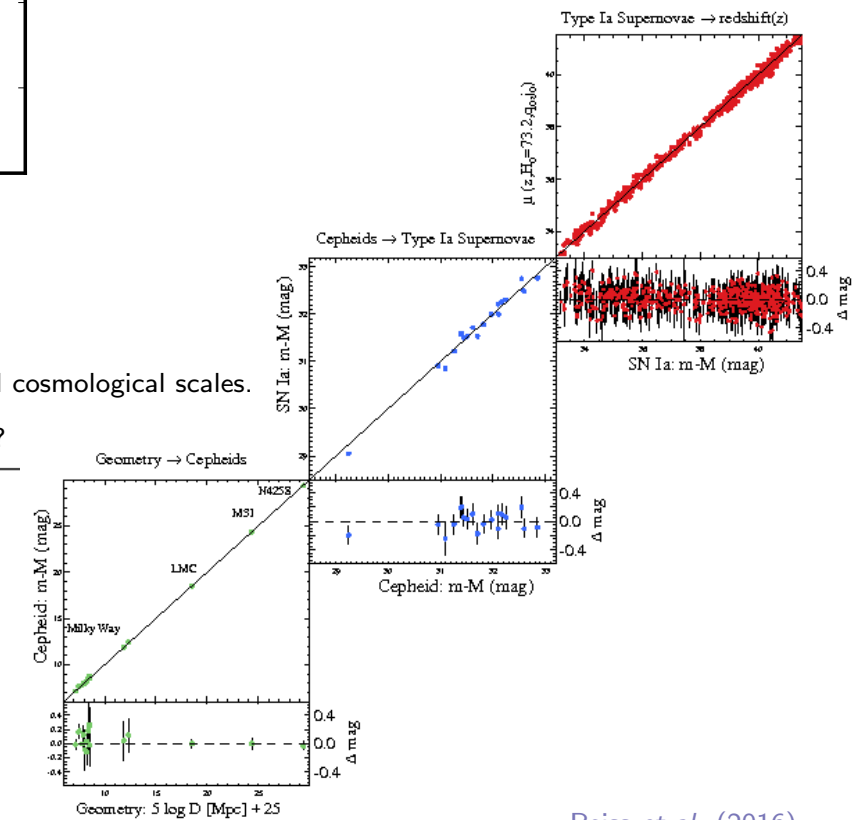
Two contrasting methods applied on nearby and very distant cosmological scales

Freedman (2019)



Standard candles

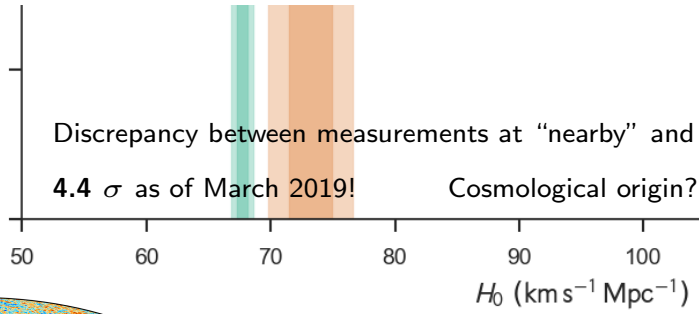
Cosmic distance ladder

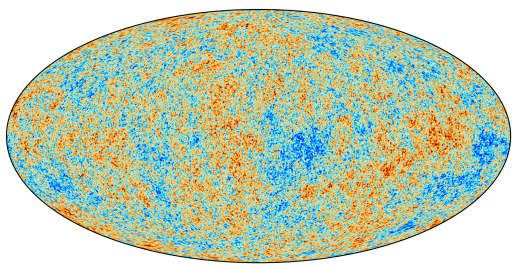


Discrepancy between measurements at "nearby" and cosmological scales.

4.4 σ as of March 2019!

Cosmological origin?





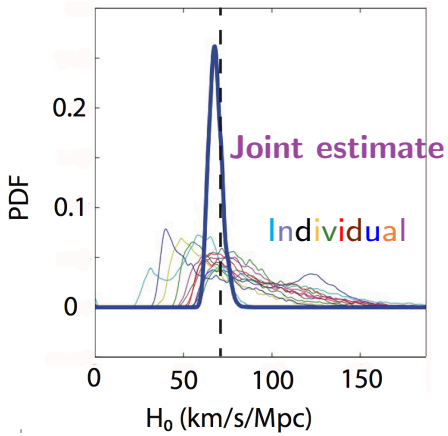
Planck collaboration (2015) + **Λ-CDM**

Reiss *et al.* (2016)

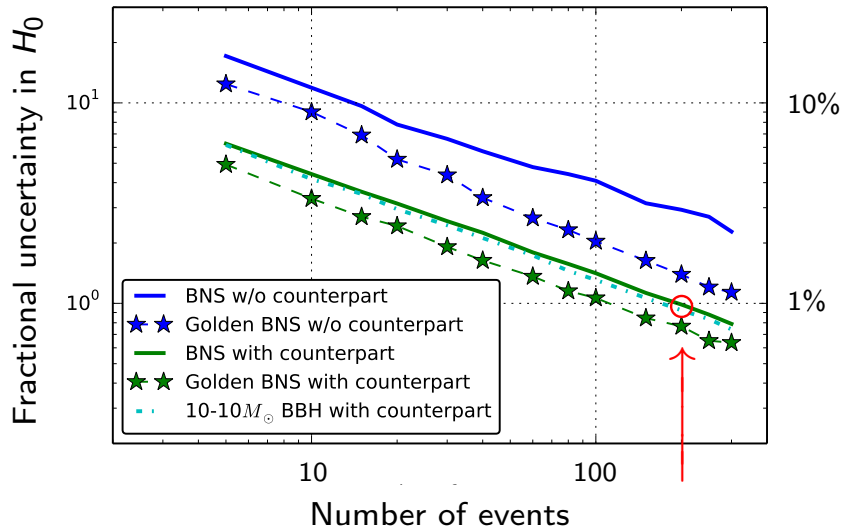
Better with more detections

Combine information from multiple similar detections.

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



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



Chen *et al.* (2018)

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

Better with more detections

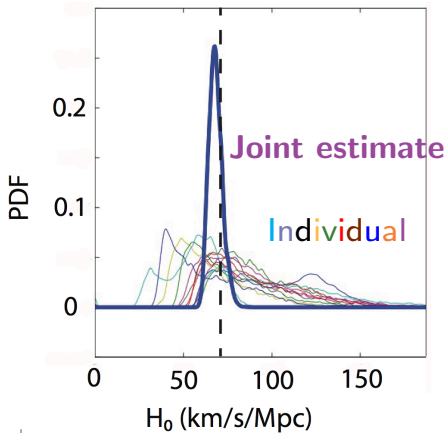
Careful of systematic effects!

GW selection effects

threshold SNR $\rightarrow$ interferometer horizon

only nearby signals detected

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



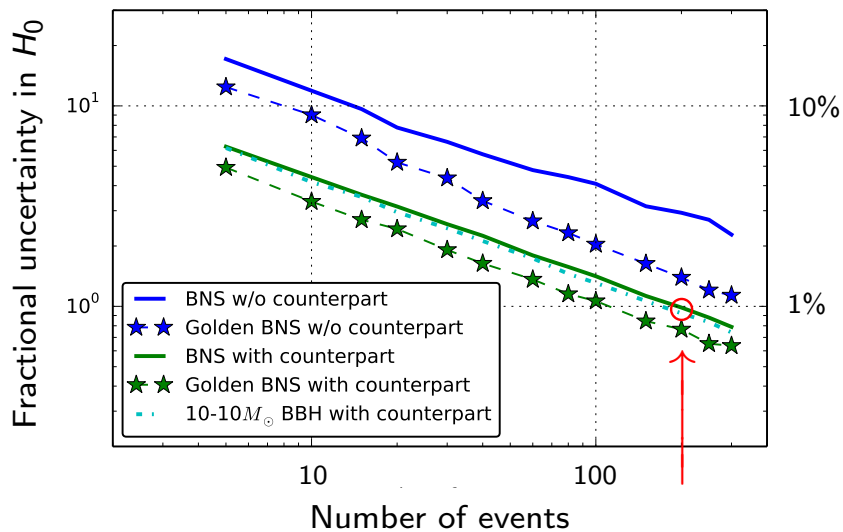
Detection efficiency (selection function):

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

Integrate over all **detectable data sets**

Abbott *et al.* Nature **551** #7678, 85-88 (2017)

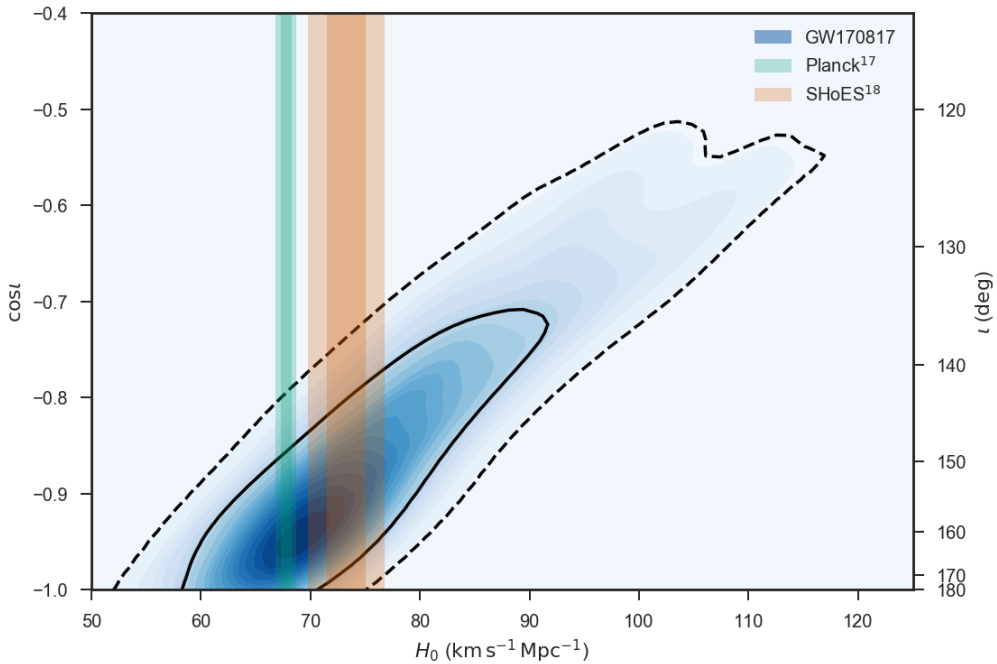
Mandel, Farr, Gair (2018); Chen *et al.* (2018); Mortlock *et al.* (2018)



Chen *et al.* (2018)

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

Degeneracy with inclination



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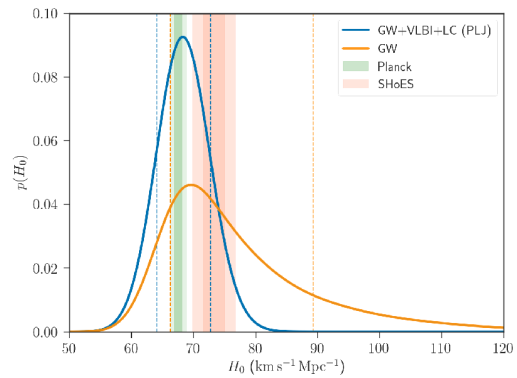
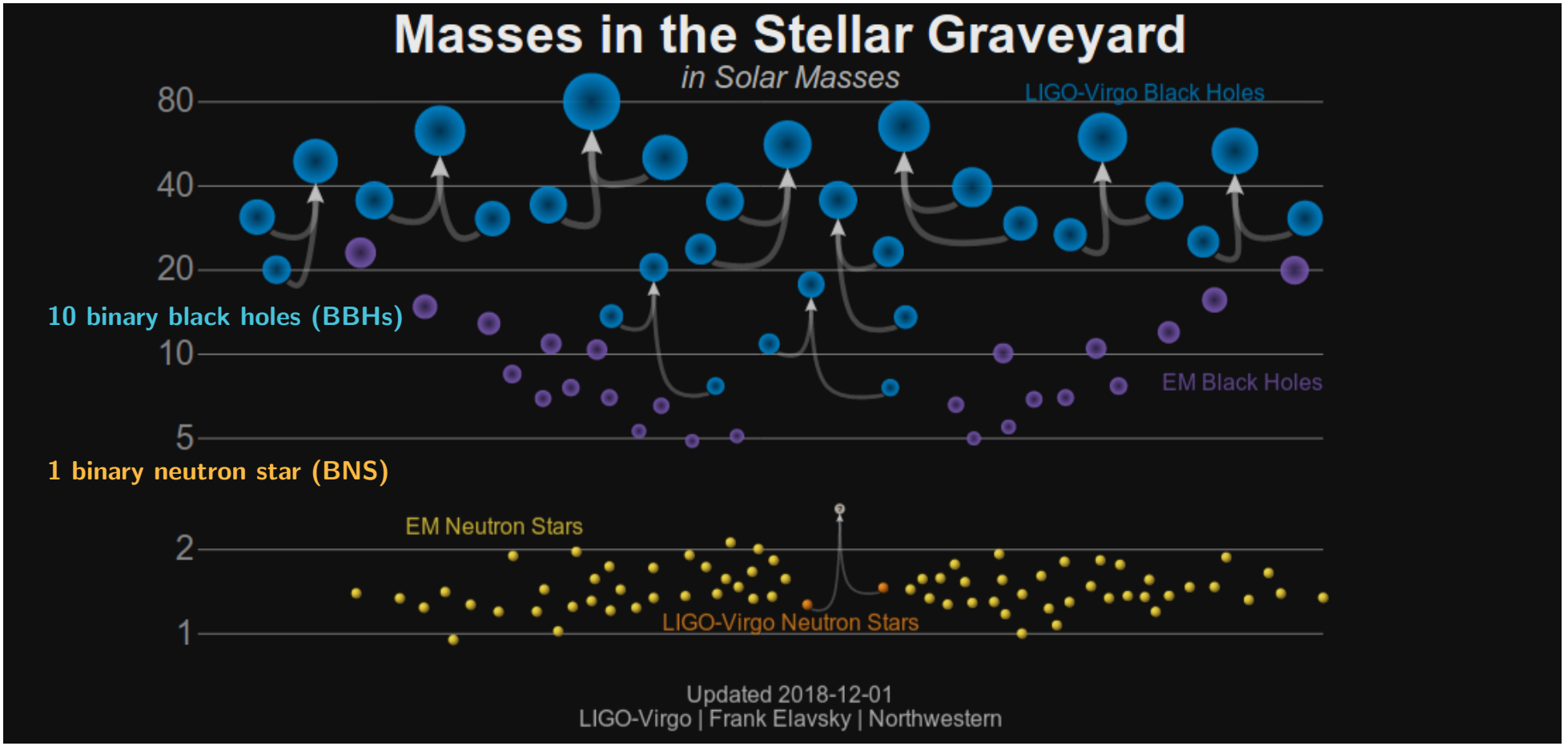
Distance-inclination degeneracy: GW amplitude from by a distant binary viewed face-on (or face-off) is similar to that of a closer binary viewed edge-on.

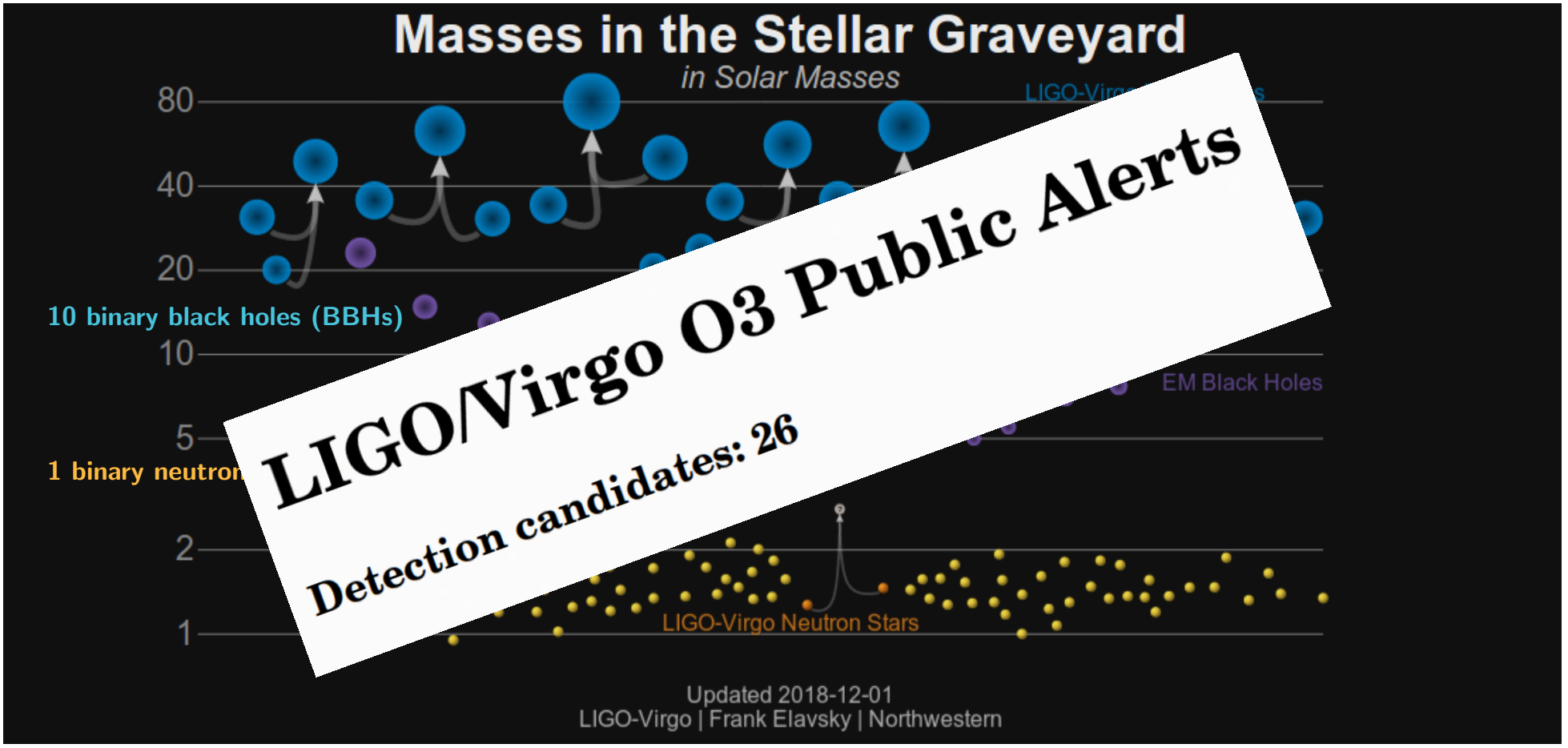
Hotokezaka *et al.* (2018): jet $\longrightarrow$ **inclination** $\longrightarrow$ H_0



Broken with GW alone? Multiple detectors. Higher modes.

Following two observing runs of Advanced LIGO-Virgo . . .




Masses in the Stellar Graveyard
in Solar Masses
80
40
20
10
5
2
1
10 binary black holes (BBHs)
1 binary neutron
EM Black Holes
LIGO-Virgo Neutron Stars
LIGO/Virgo O3 Public Alerts
Detection candidates: 26
Updated 2018-12-01
LIGO-Virgo | Frank Elavsky | Northwestern

H_0 with galaxy catalogues: Schutz method

Idea in Schutz (1986).

MacLeod and Hogan (2008) in context of LISA.

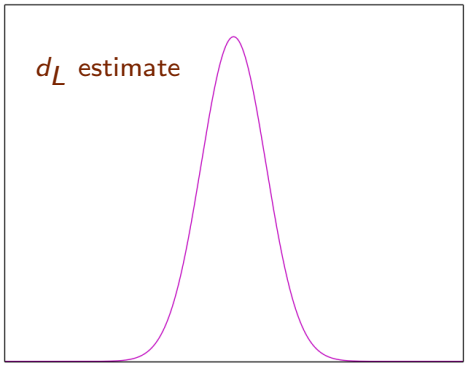
Del Pozzo (2012) Bayesian method in context of Adv-LIGO.

aLIGO-Virgo; 30 CBCs to $z = 0.1$ + SDSS $\Rightarrow$ H_0 to $\sim$ 5%

Nair *et al.* (2018)

Chen *et al.* (2018); Fishbach *et al.* (2018); Gray *et al.* (2019) (with **AG**)

Independent events



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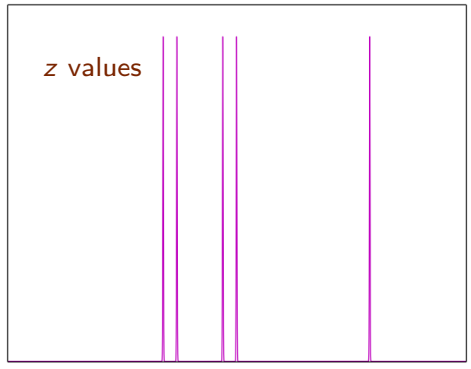

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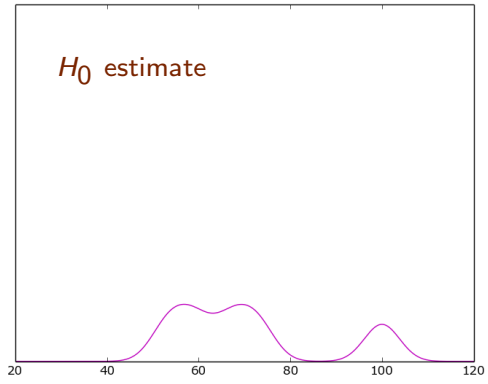

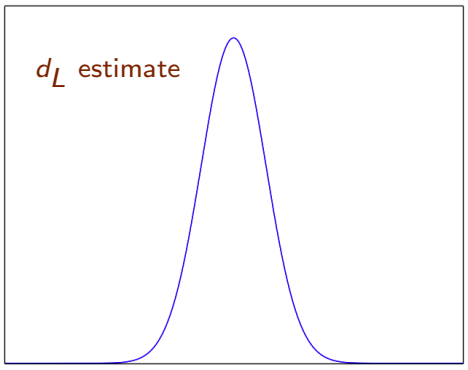

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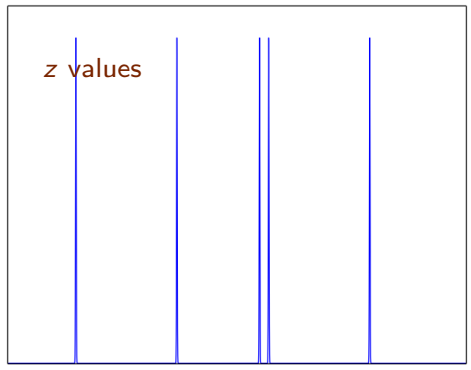

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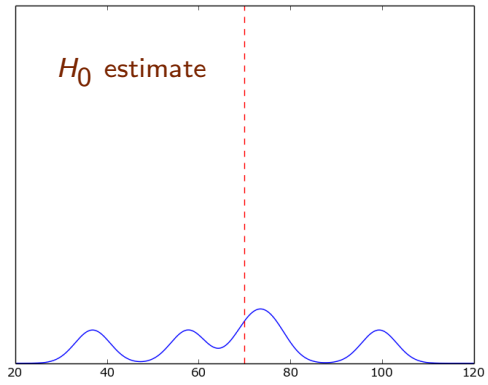
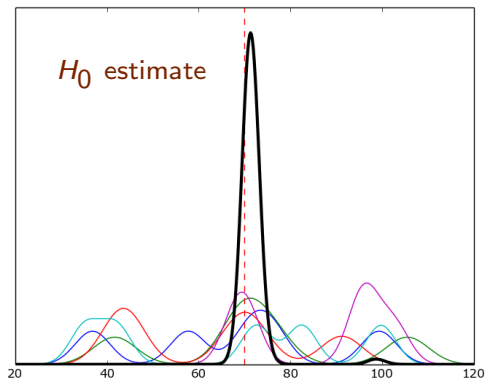


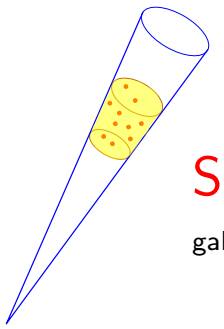
Combine information from all observed events ⇒

Different possible galaxies for single event

Multimodal H_0 estimate for each event



Unimodal joint H_0 result

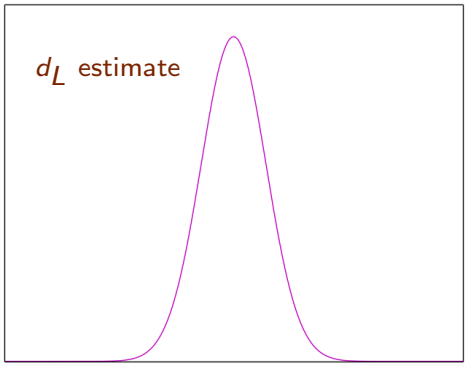


Schutz method

galaxy catalogues in absence of transient EM counterparts

applicable also for **binary black holes**

Schutz (1986)



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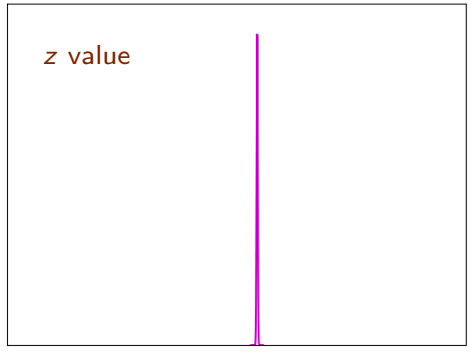
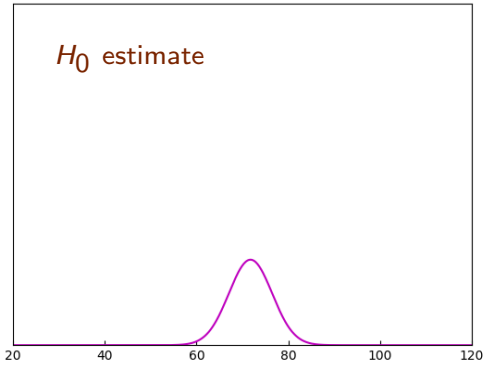


Counterpart / identified host galaxy

$\Rightarrow$



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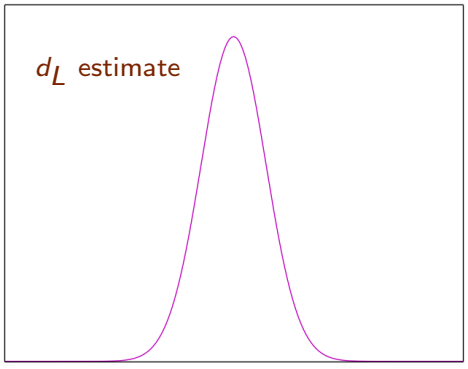

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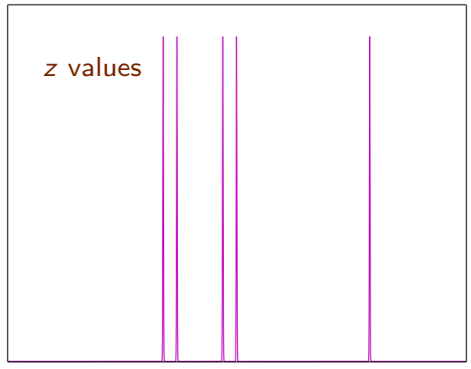
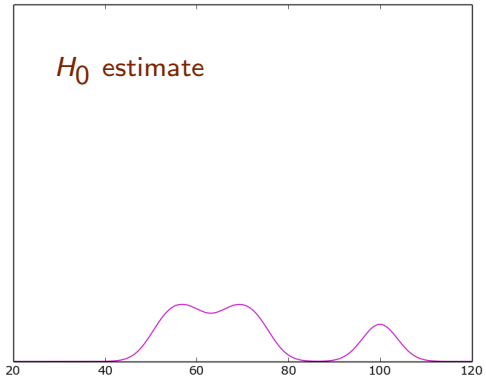
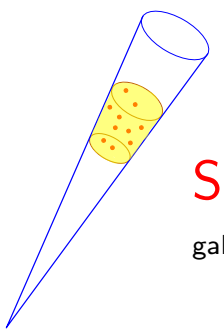


Different possible galaxies for single event

$\Rightarrow$



Multimodal H_0 estimate



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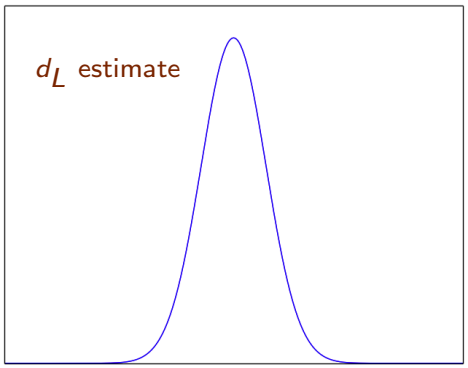

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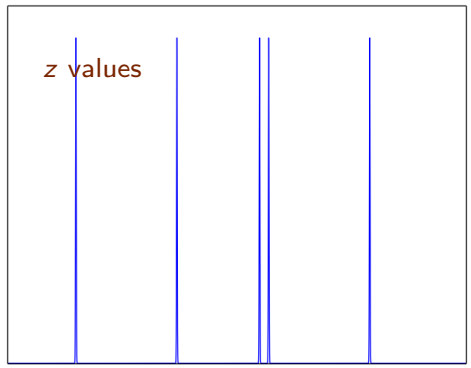

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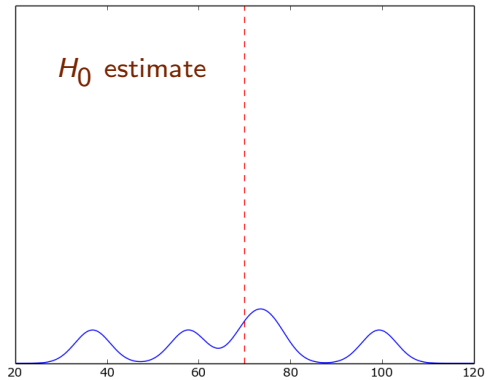

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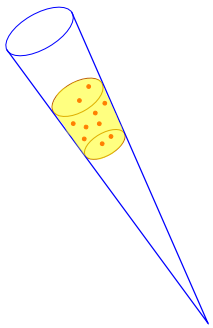

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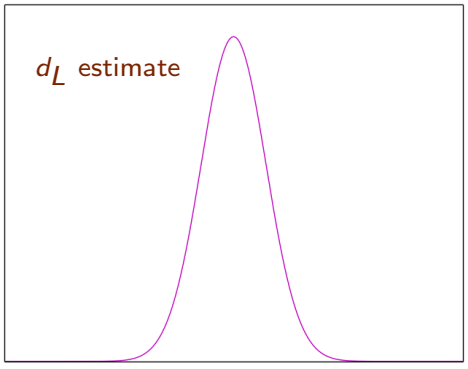
Independent events



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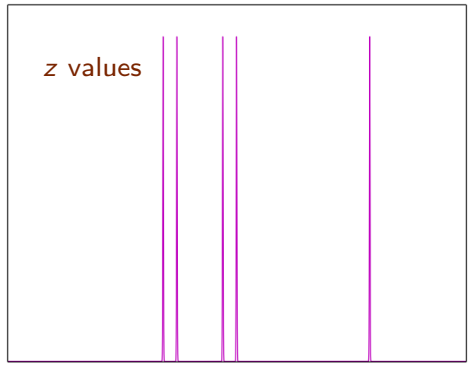

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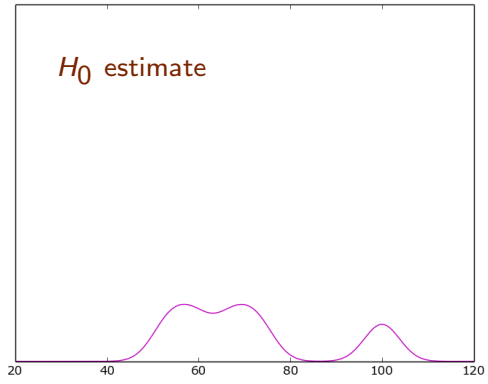

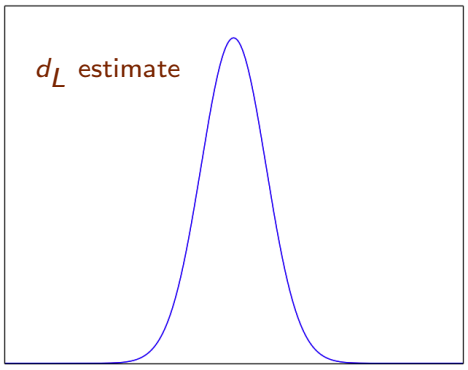

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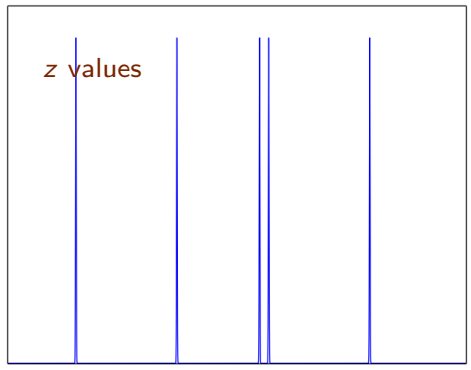

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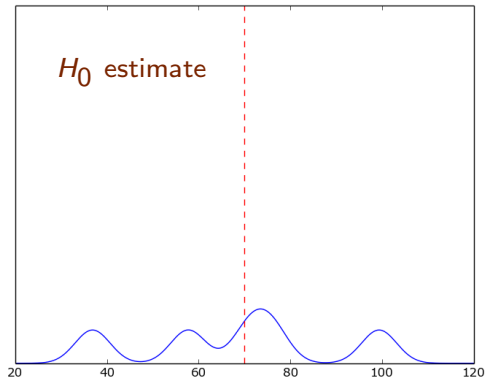

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Different possible galaxies for single event

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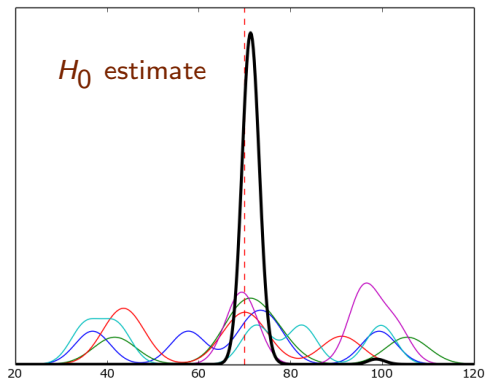
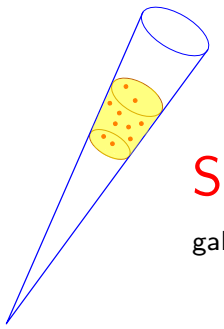


Unimodal joint H_0 result



Schutz method

galaxy catalogues in absence of transient EM counterparts

applicable also for **binary black holes**

Schutz (1986)

H_0 with galaxy catalogues: the complete story

GW selection effects

threshold SNR $\rightarrow$ interferometer 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

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

Detection efficiency (selection function):

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

Integrate over all **detectable data sets**

Abbott *et al.* Nature **551** #7678, 85-88 (2017)

Mandel, Farr, Gair (2018); Chen *et al.* (2018); Mortlock *et al.* (2018)

Integrated method of taking into account both effects.

Messenger & Veitch (2013); Gray *et al.* (2019) (with **AG**)

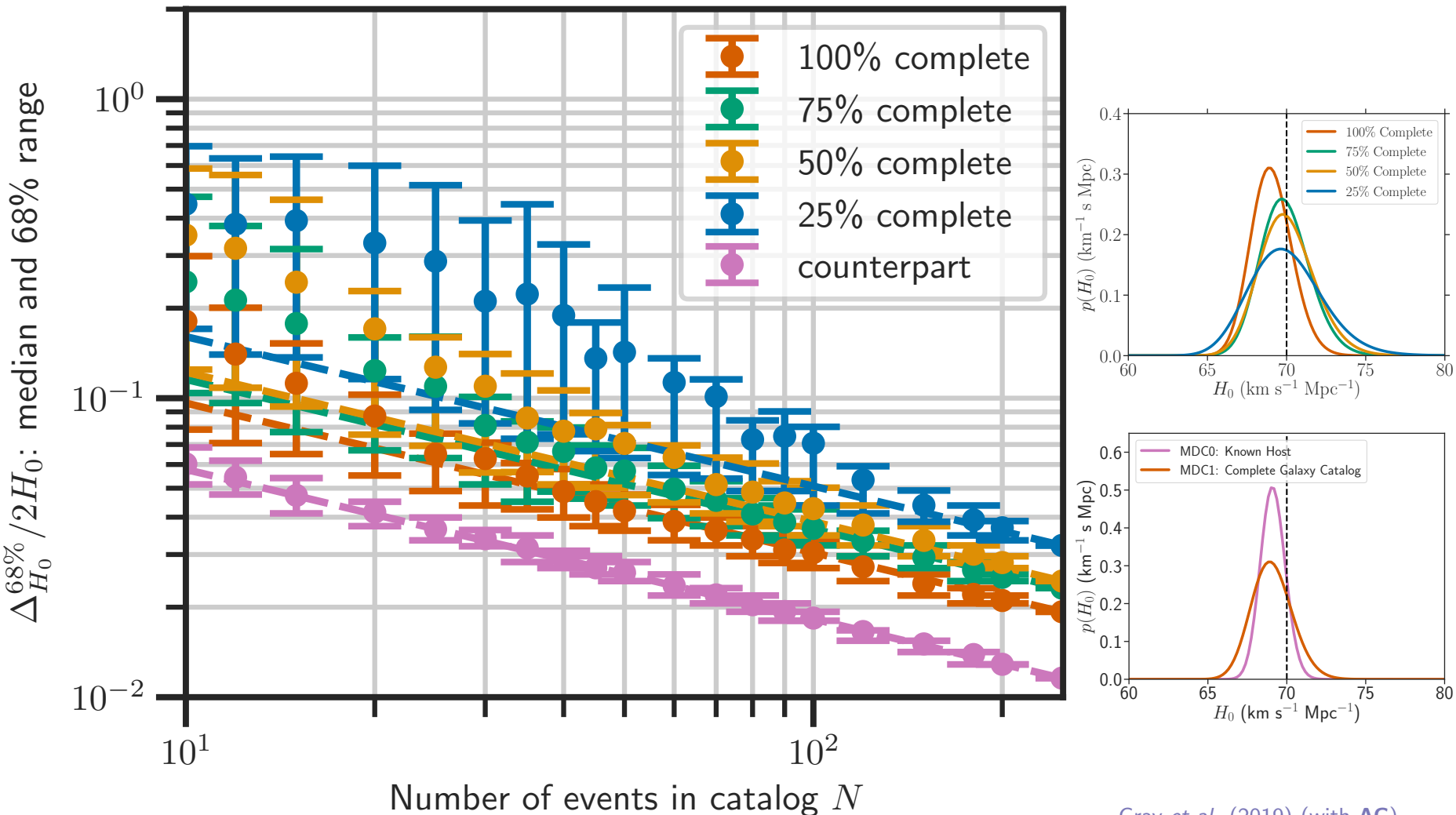
H_0 with galaxy catalogues: simulations

Gray *et al.* (2019) (with **AG**)

A few key features from the "mock data challenge":

- Performed at BNS distances
- With galaxy catalogs about 35 times sparse / 3 times dense
- $\mathcal{O}(10 - 100)$ galaxies per event
- Redshift uncertainties, clustering ignored

H_0 with galaxy catalogues: results on simulations



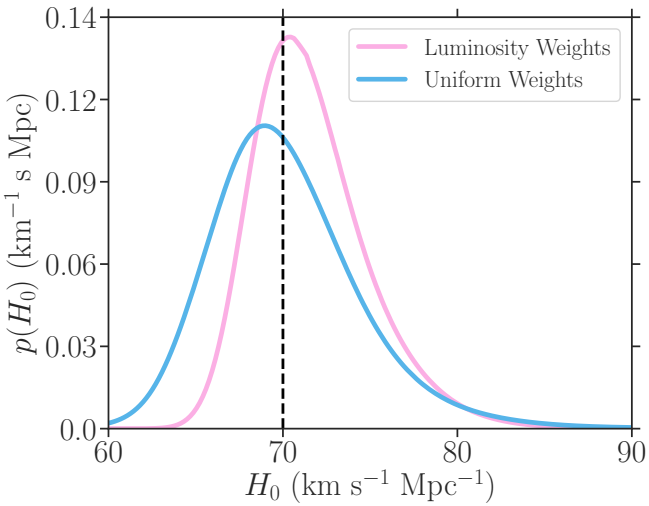
Gray *et al.* (2019) (with **AG**)

H_0 with galaxy catalogues: results on simulations

Luminosity weighting of galaxies: improves by ~ 1.3

Gray *et al.* (2019) (with **AG**)

Brighter (visible) galaxies are more likely hosts



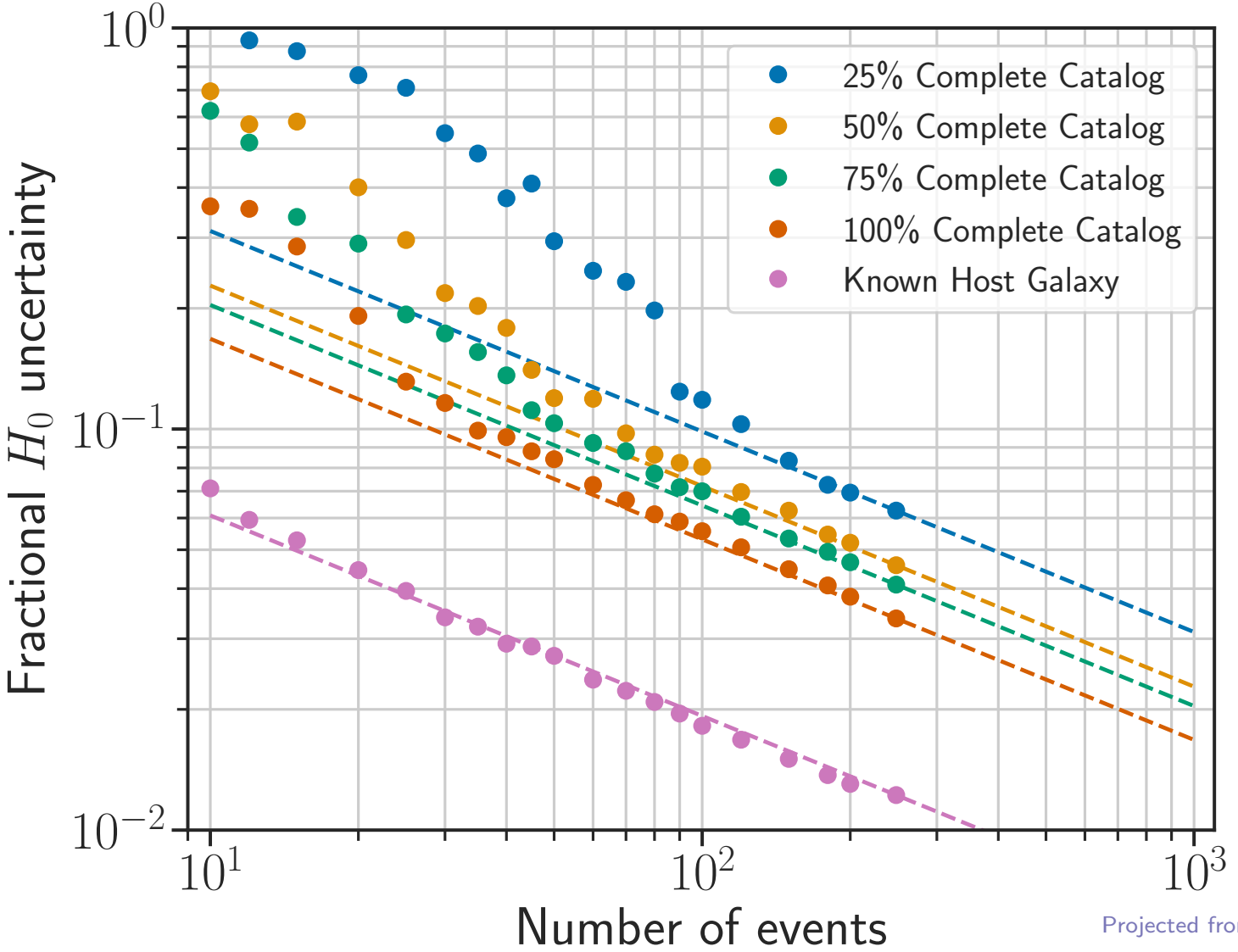
B-band: star formation rate

K-band: total mass

Clustering of galaxies: improves by ~ 2.5

Chen *et al.* (2018)

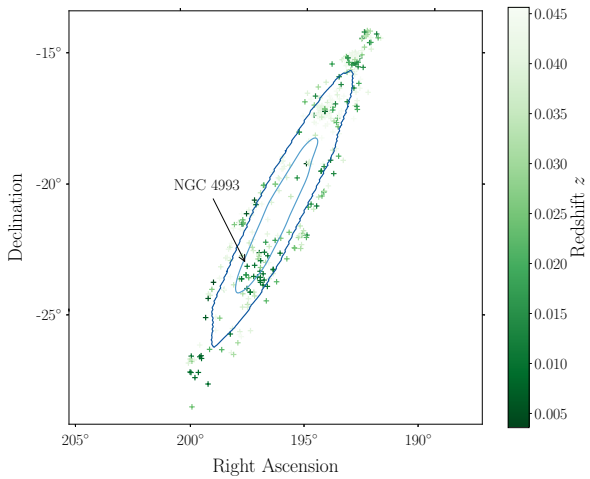
H_0 with galaxy catalogues: projections from results on simulations



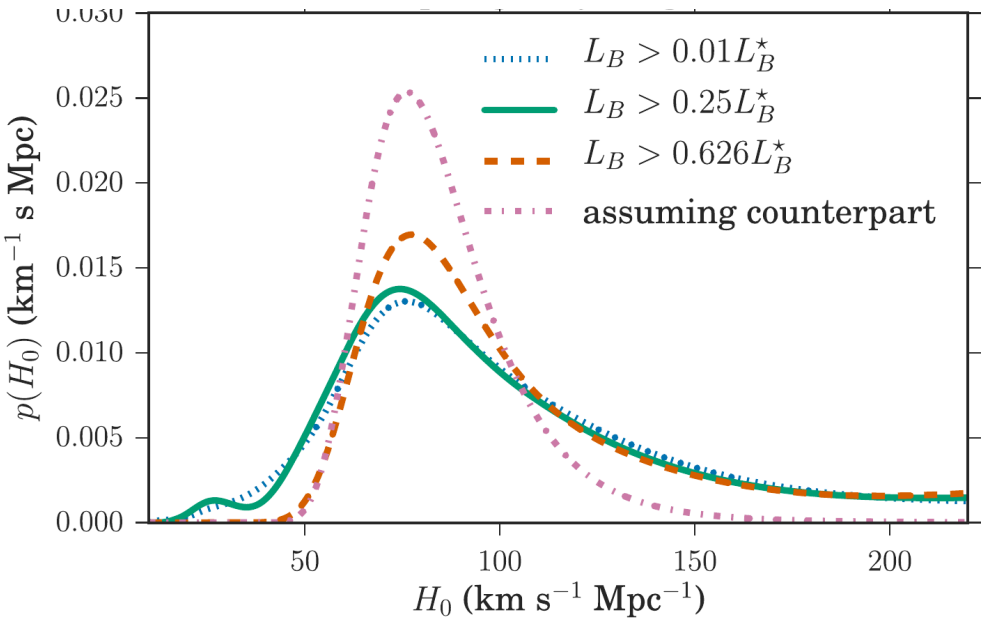
Projected from Gray *et al.* (2019) (with **AG**)

H_0 from GW170817 with GLADE catalogue

- GW170817 assuming no counterpart:



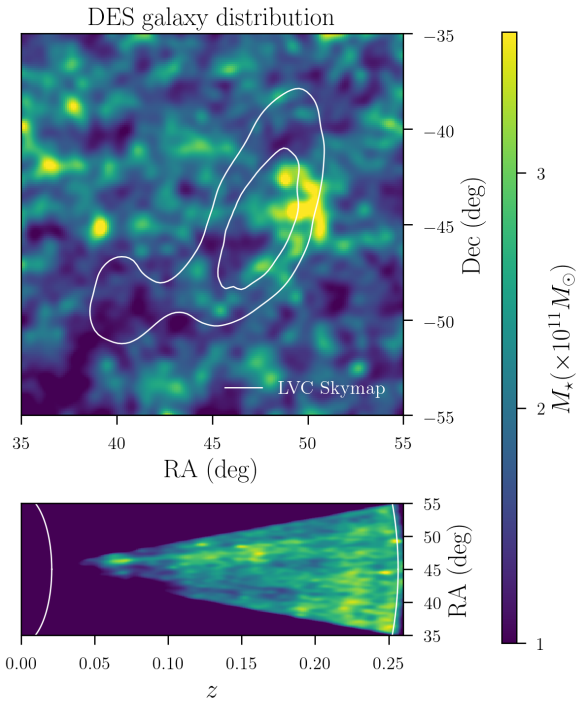
Fishbach *et al.* (2018)



- Correcting for catalogue incompleteness
- Luminosity weighting

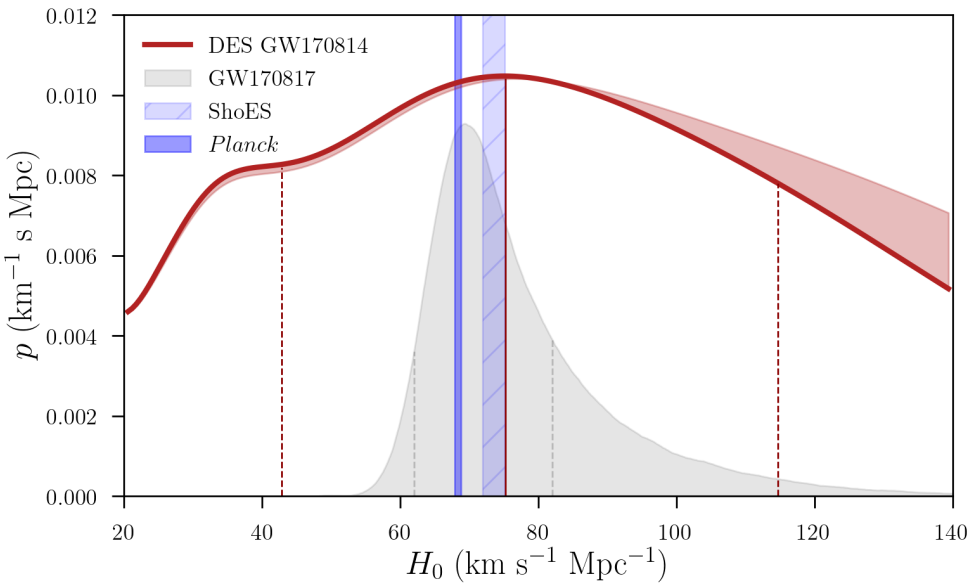
H_0 from GW170814 with DES catalogue

- **DES Y3 "gold" catalogue:** thoroughly surveyed GW170814 sky region.

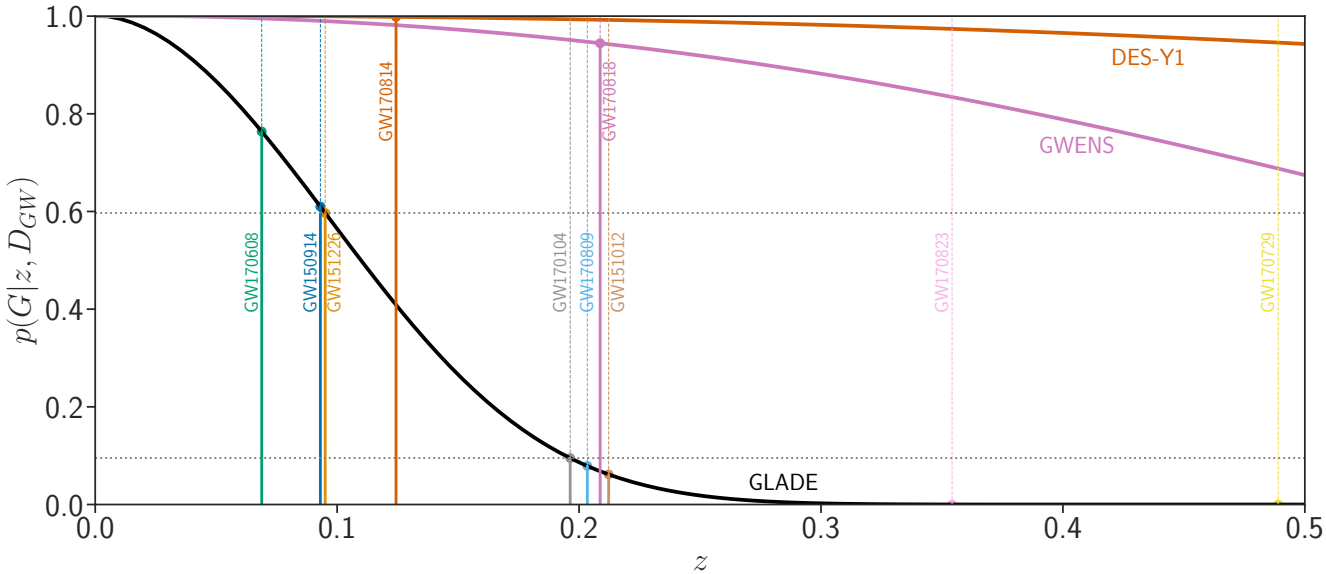


- First realistic application

Soares-Santos *et al.* (2019)



H_0 from O1 & O2 detections



Try to find public catalogues with support for O1 & O2 detections:

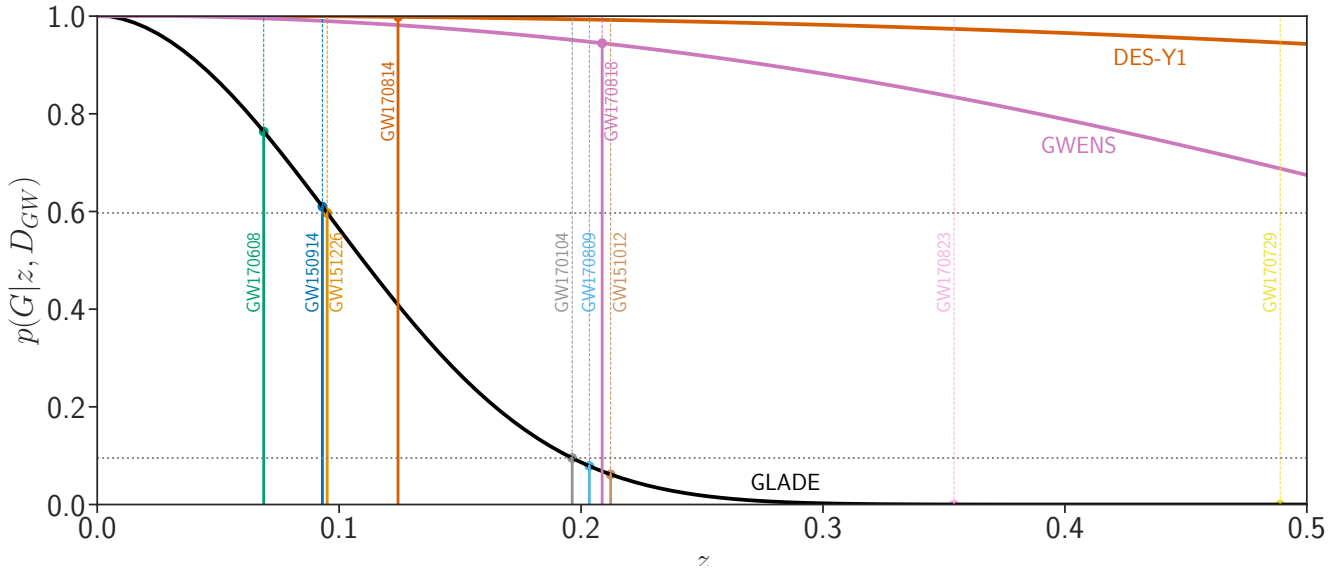
DES-Y1 for GW170814

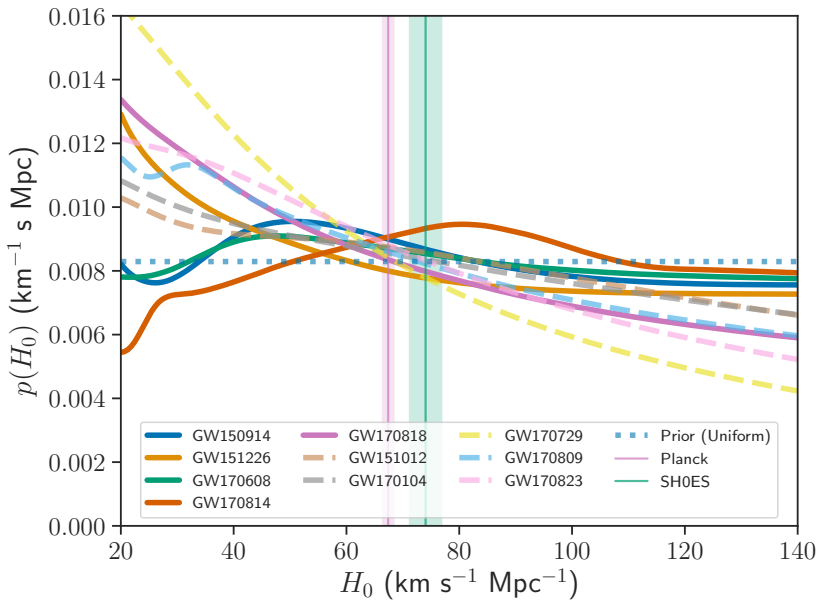
SDSS-based **GWENS** for GW170818

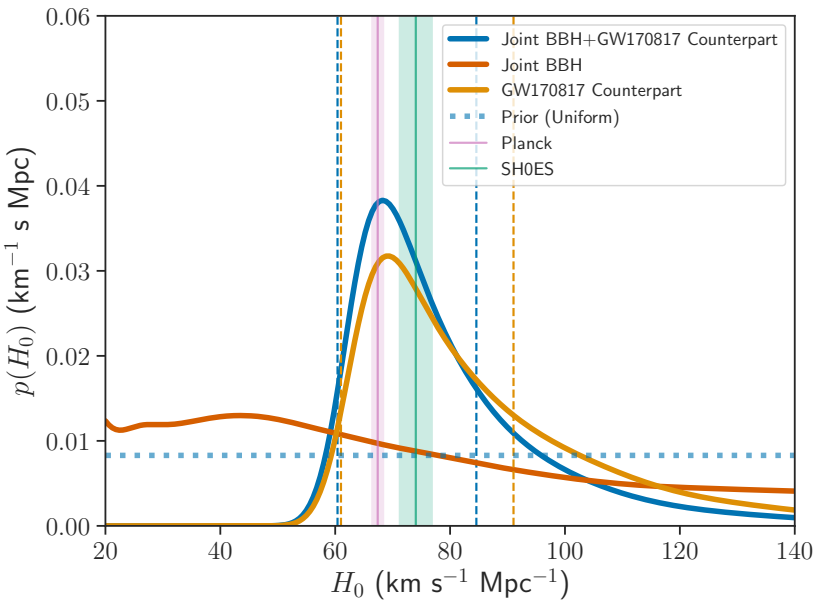
GLADE (compiled from GWGC, 2MPZ, 2MASS XSC, HyperLEDA, SDSS-DR12Q)

H_0 from O1 & O2 detections

Abbott *et al.* arXiv:1908.06060







H_0 from O1 & O2 detections

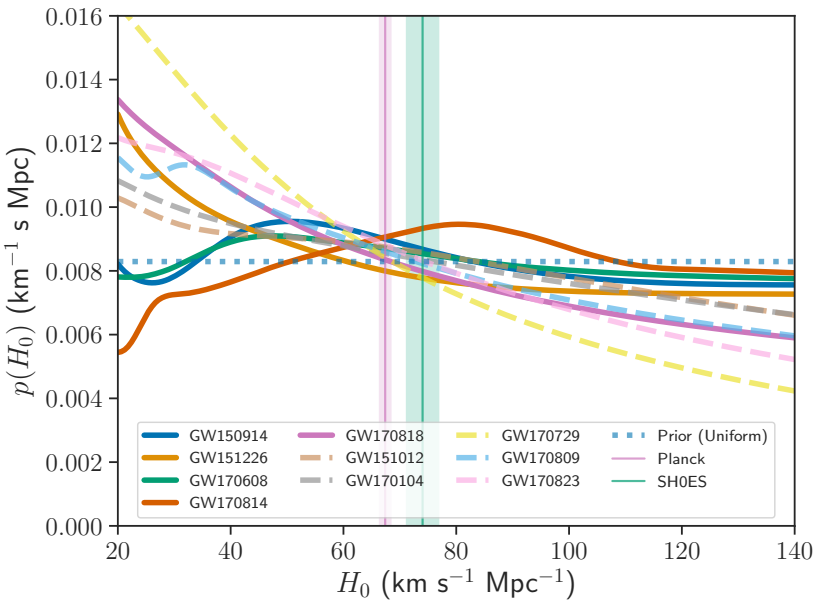
Abbott *et al.* arXiv:1908.06060

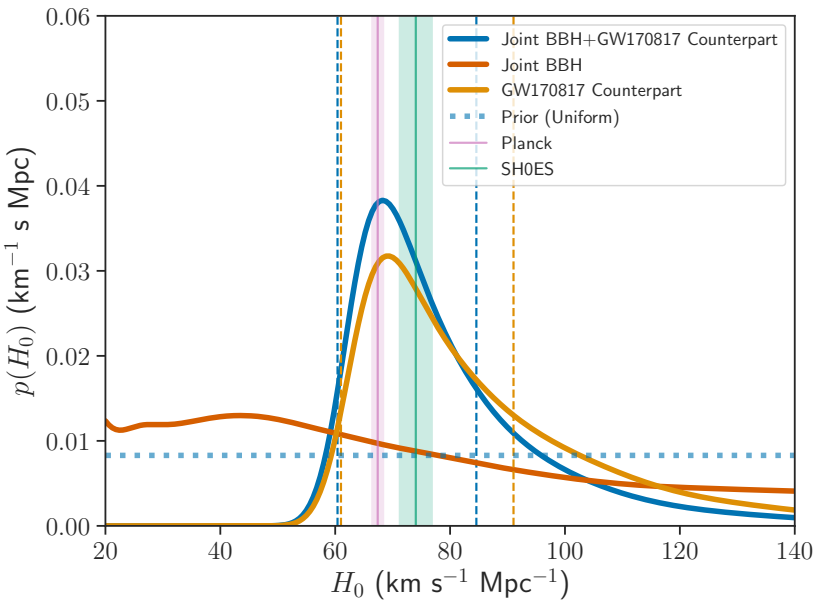
Detections with considerable catalogue support: features of galaxy catalogue

Detections with relatively empty catalogues: features of population assumptions

Detection efficiency in the denominator:

Depends on population parameters – mass distribution, rate evolution.





H_0 from O1 & O2 detections

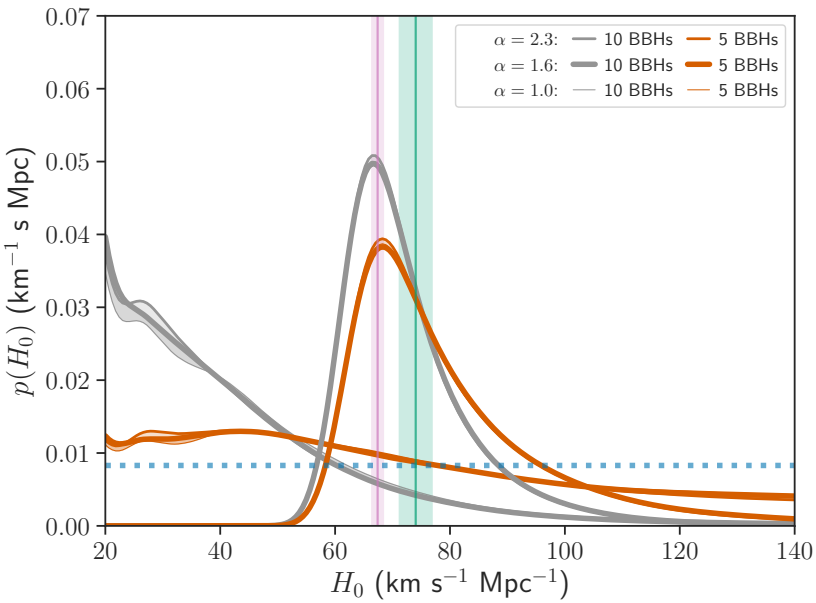
Detections with considerable catalogue support: features of galaxy catalogue

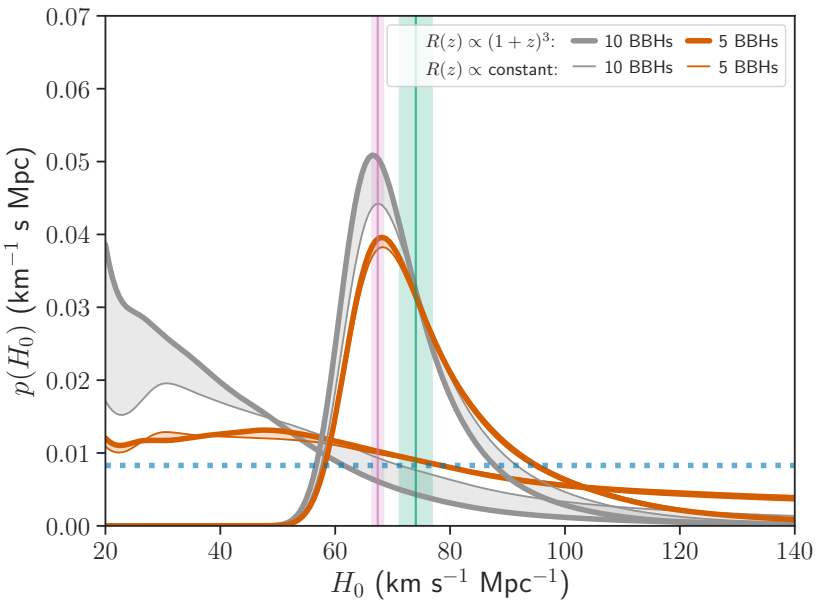
Detections with relatively empty catalogues: features of population assumptions

Detection efficiency in the denominator:

Depends on population parameters – mass distribution, rate evolution.

Perform robustness studies with varying assumptions:





Sources of systematic uncertainties

Crucial to understand and address accuracy towards a precise measurement

- Peculiar velocity flows (EM)
- Uncertainties in galaxy catalogues (EM)

  Photometric measurements of redshifts

  Luminosity estimates
- Selection effects (GW and EM)

  Population properties: mass distribution, rate evolution, ...
- Waveform systematic effects (GW)
- Detector calibration uncertainties (GW) ampl. $< 4\%$ systematic?

Towards the immediate future

- Fold in probabilities of regions hosting the sources

  Luminosity weighting: use luminosity as a proxy for mass and rate distribution

  Astrophysically-motivated weighting of host galaxies

- Galaxy clustering

  Sources correlated with visible matter distribution: clustering of galaxies

  Cluster catalogues $\Rightarrow$ probability density of mergers in redshift space

  Construct **merger density catalogues**

  Beyond H_0?

What I did not talk about . . .

- A wealth of LISA sources! MBHBs with counterparts!

  Tamanini *et al.* (2016)

- Correlations of GW/EM distributions Oguri (2016)

- Cosmology without EM – information from physics of NS: ET

  Mass-function Taylor *et al.* (2012); Taylor & Gair (2012)

  Tidal deformations Messenger & Read (2011); Del Pozzo *et al.* (2017)

Multiband: BBO/DECIGO

- Effect of cosmological constant over evolution of binary! Nishizawa (2012)

Outlook

- Short term: H_0 measurement jointly with EM observations.

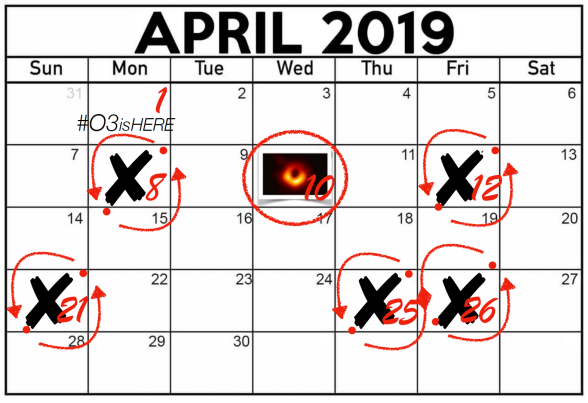
  Systematic effects in EM and GW!

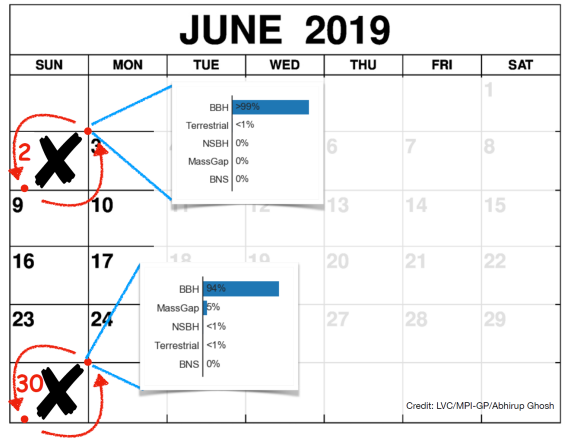
- Longer term: Other cosmological parameters 3G / LISA?

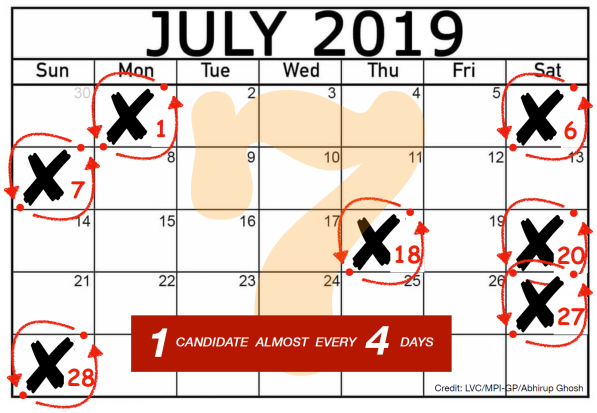
  Simultaneous study of modified cosmology and gravity

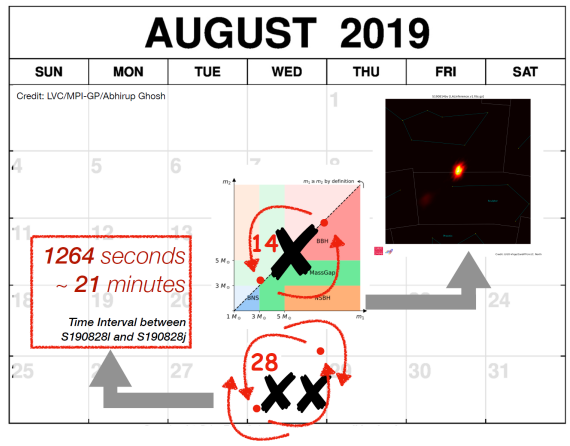
- GW sources as rungs of the distant ladder: nearby and distant.

  Standard candles, sirens, rulers, ...









The O3 fun has begun!