

Bright and dark sirens

GW cosmology with or without EM counterparts

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2020 January 23

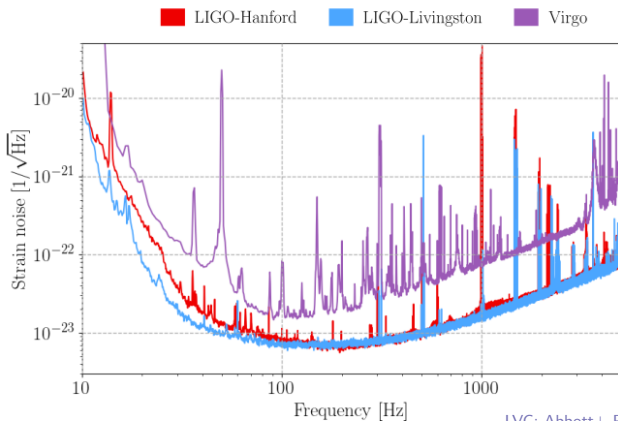


Credit: Aurore Simonnet, EPO Sonoma State University

2015 Sep 14

DIRECT OBSERVATION OF GRAVITATIONAL WAVES
FROM A BINARY BLACK HOLE MERGER

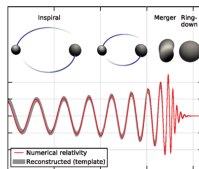
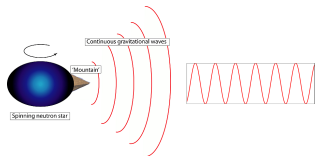
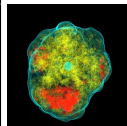
a new window to the observable universe



LVC: Abbott+ PRX 9, 031040 (2019)

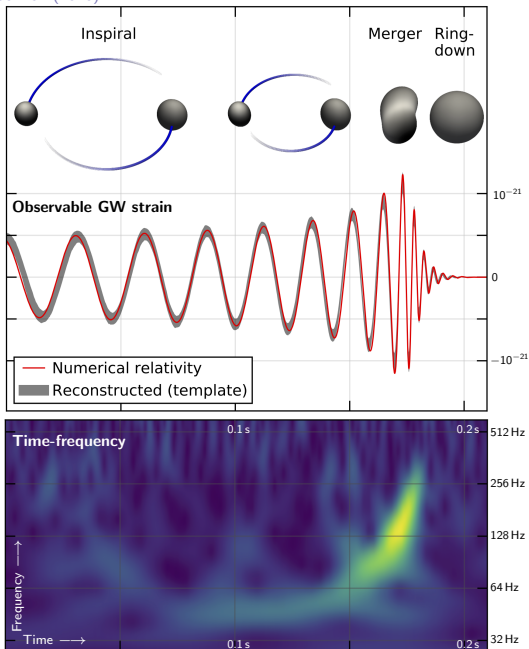
Gravitational-wave sources

	Persistent	Transient
Unmodelled	<p>Stochastic background</p> <p>Cosmological + BBH</p>	<p>Bursts</p> <p>Supernova explosions</p>
Modelled	<p>Continuous waves</p> <p>Spinning deformed NS</p>	<p>Compact binary coalescences</p> <p>NS-NS, NS-BH, BBH</p>



GW150914

2015 Sep 14



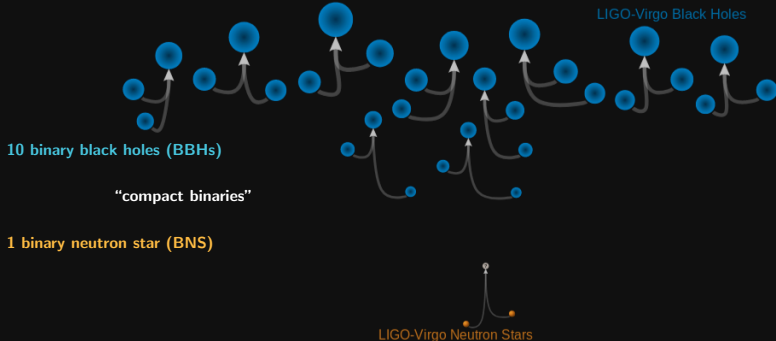
"chirp" signal

Gravitational-wave observations

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

O1: 2015 Sep – 2016 Jan

O2: 2016 Dec – 2017 Aug



Updated 2018-12-01
LIGO-Virgo | Frank Elavsky | Northwestern

Gravitational-wave observations

Ongoing third observing run of Advanced LIGO-Virgo ...

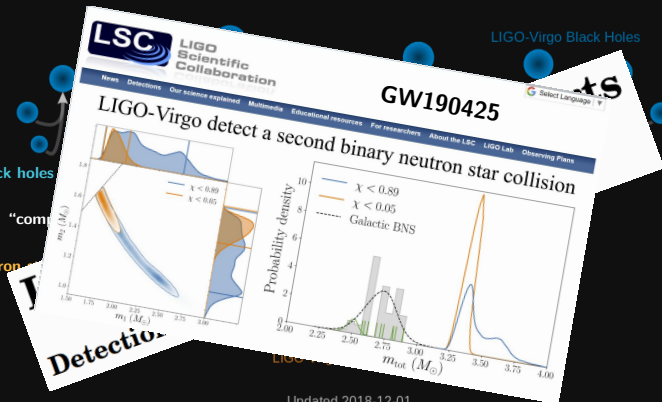
O3: 2019 Apr –
(improved sensitivity with each run)



Gravitational-wave observations

Ongoing third observing run of Advanced LIGO-Virgo ...

O3: 2019 Apr –
(improved sensitivity with each run)



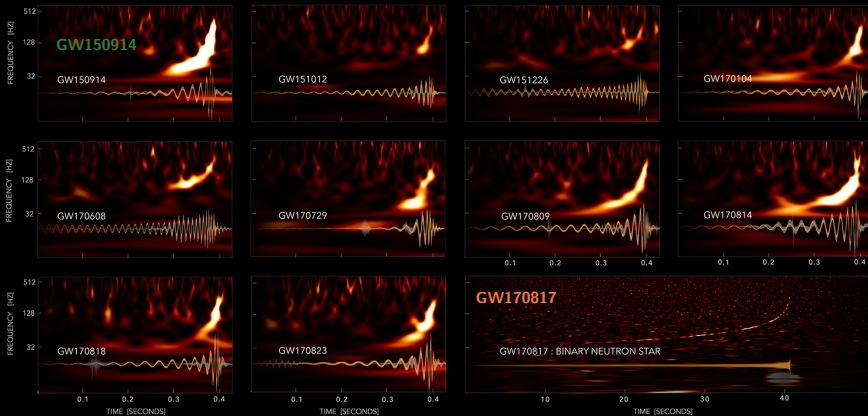
10 binary black holes

"com

1 binary neutron

Updated 2018-12-01
LIGO-Virgo | Frank Elavsky | Northwestern

GRAVITATIONAL-WAVE TRANSIENT CATALOG-1



LIGO-VIRGO DATA: [HTTPS://DOI.ORG/10.7935/B2H3.HH23](https://doi.org/10.7935/b2h3.hh23)

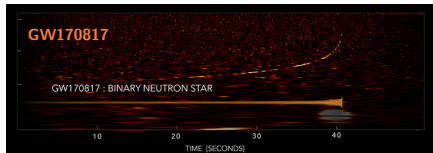
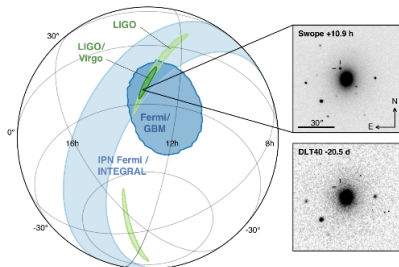
IMAGE CREDIT: S. GHONGE, K. JANI | GEORGIA TECH

GRAVITATIONAL-WAVE TRANSIENT CATALOG-1



LIGO-VIRGO DATA: [HTTPS://DOI.ORG/10.7935/B2H3-HH23](https://doi.org/10.7935/b2h3-hh23)

IMAGE CREDIT: S. GHONGE, K. JANI | GEORGIA TECH



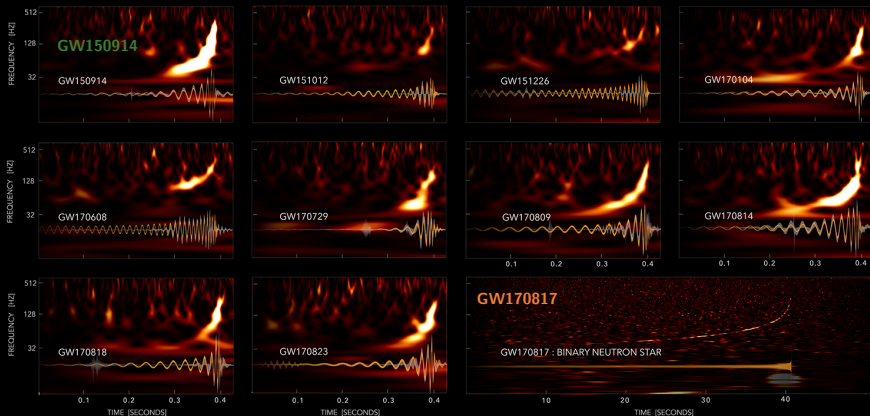
Gamma ray burst (1.7 s after GW chirp)

Optical counterpart, infrared, radio afterglow, ...

Multimessenger astronomy

with GW and EM

GRAVITATIONAL-WAVE TRANSIENT CATALOG-1



LIGO-VIRGO DATA: [HTTPS://DOI.ORG/10.7935/B2H3.HH23](https://doi.org/10.7935/B2H3.HH23)

WAVELET (UNMODELED)

EINSTEIN'S THEORY

IMAGE CREDIT: S. GHONGE, K. JANI | GEORGIA TECH

11 detections

exciting science

~ 40 publications

> 16,000 citations

My involvement: **probing strong-field gravity** **gravitational-wave cosmology**

Plan of the talk

- Introduction ✓
- GW standard sirens
- Hubble constant: the H_0 tension
- GW measurement of H_0

Standard siren H_0 from GW170817

Galaxy catalogue method

simulations, O1 & O2 BBHs

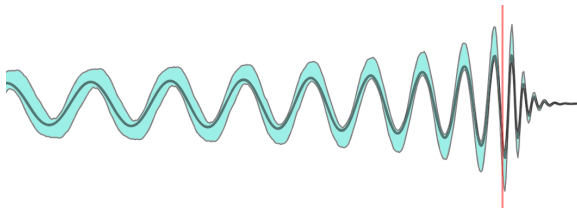
Required synergy

GW / EM / instrumentation

- Broader prospects

GW standard sirens

Schutz (1986), Holz & Hughes (2005)



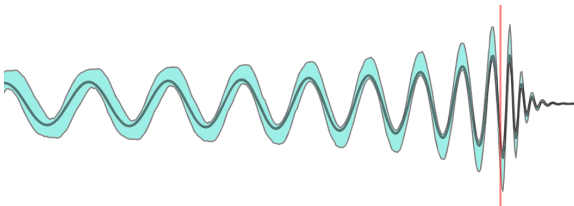
Phase evolution $\Rightarrow \mathcal{M}^z$ mass

Amplitude $\propto \frac{\mathcal{M}^z}{d_L} \Rightarrow d_L$ distance

GWs from compact binaries give us direct access to luminosity distance.

GW standard sirens

Schutz (1986), Holz & Hughes (2005)

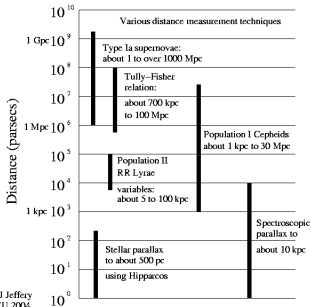


Phase evolution $\Rightarrow \mathcal{M}^z$ mass

Amplitude $\propto \frac{\mathcal{M}^z}{d_L} \Rightarrow d_L$ distance

GWs from compact binaries give us
direct access to luminosity distance.

Independent of the **cosmic distance ladder!**



$(d_L, z) \rightarrow$ cosmological parameters

Redshift-distance relation:

Late-time expansion / acceleration parameters

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



Hubble constant

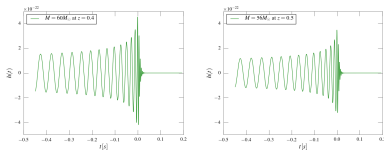
GWs from compact binaries give us direct access to luminosity distance.

Where can z come from?

Where can z come from?

- Spectral lines!

observed "frequency"; intrinsic "frequency" at source



- Spectral lines for compact binaries?

For BBH, features totally degenerate with total mass

For BNS, degeneracy only weakly broken

Need to fall back on EM for z !

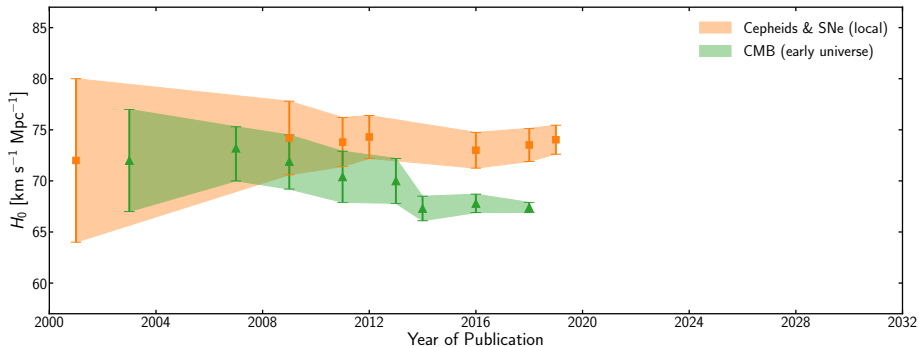
The H_0 tension

Two ways of measuring H_0 :

- **Local:** distance-redshift; relies on calibration via “distance ladder”
- **Early universe:** from CMB fluctuations; extrapolated via cosmological model

The H_0 tension

Two ways of measuring H_0 :

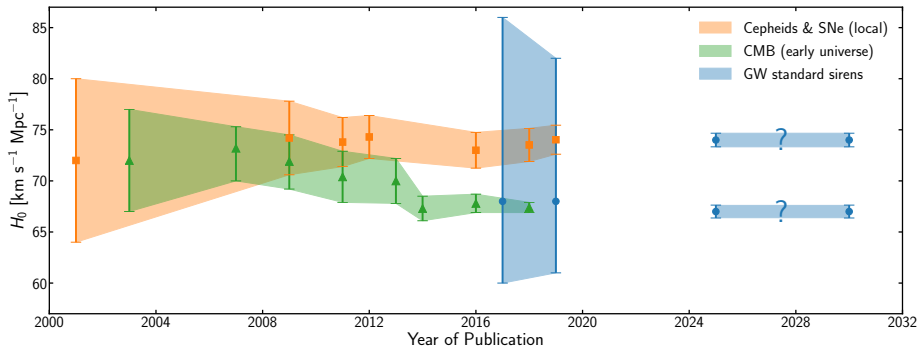


- **Local:** distance-redshift; relies on calibration via “distance ladder”
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A major cosmological problem?

The H_0 tension

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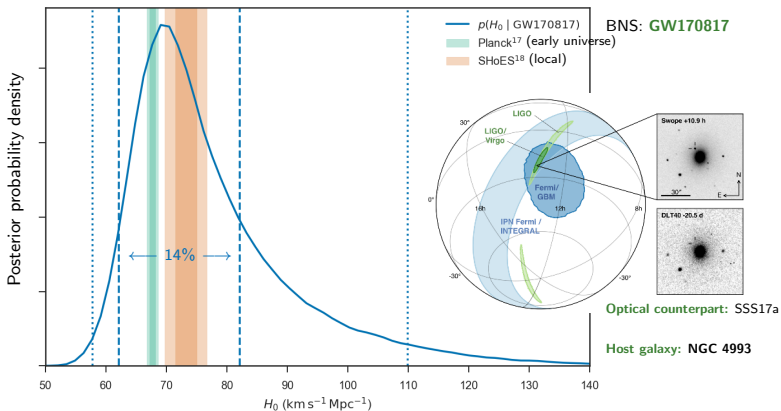


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A major cosmological problem?

A gravitational-wave standard siren measurement of the Hubble constant

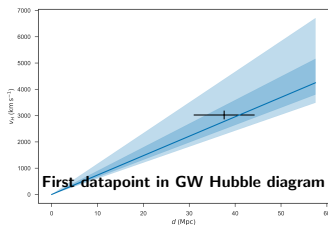
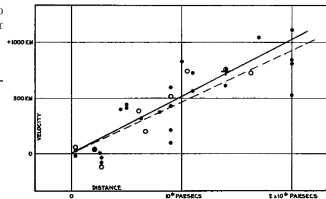
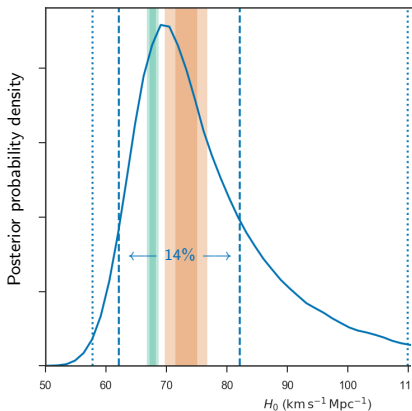
The LIGO Scientific Collaboration and The Virgo Collaboration*, The 1M2H Collaboration*, The Dark Energy Camera GW-EM Collaboration and the DES Collaboration*, The DLT40 Collaboration*, The Las Cumbres Observatory Collaboration*, The VINROUGE Collaboration* & The MASTER Collaboration*



A gravitational-wave standard siren measurement of the Hubble constant

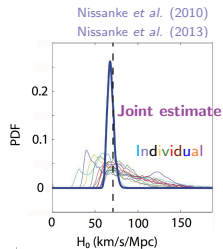
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Edwin Hubble, *Proc. Nat. Acad. Sciences.* (1929)

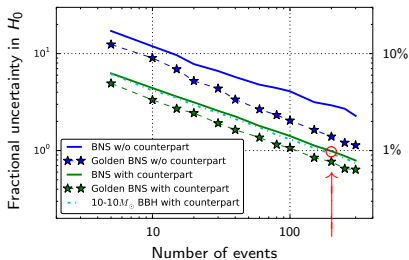


Better with more detections

Combine information from multiple similar detections.



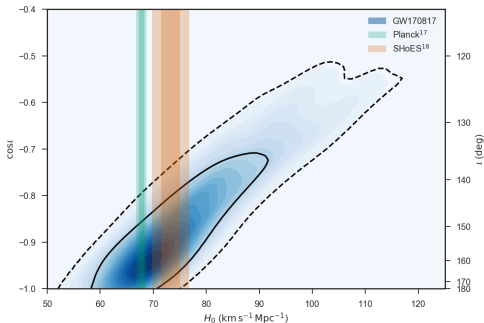
Precision: $\sigma_{H_0}/H_0 \sim 1/\sqrt{N}$



Chen *et al.* (2018)

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

Degeneracy with inclination

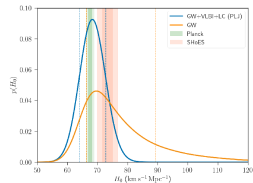


LVC: Abbott+ Nature 551 #7678, 85-88 (2017)

Broken with GW alone? Multiple detectors. Higher modes.

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 \rightarrow inclination $\rightarrow H_0$



What if a transient EM counterpart is not observed?

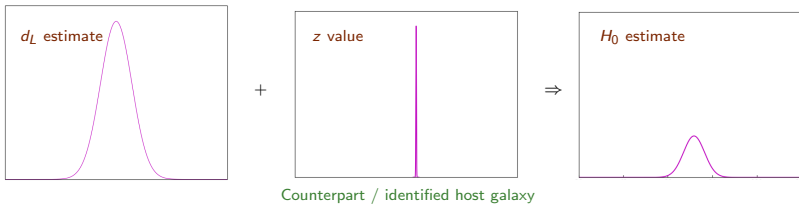
What if a transient EM counterpart is not observed?

Schutz idea

galaxy catalogues in absence of transient EM counterparts

applicable also for **binary black holes**

Schutz (1986)

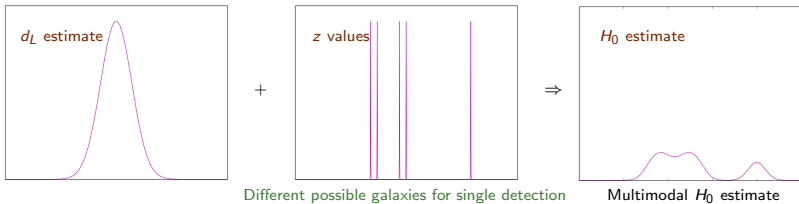


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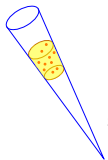
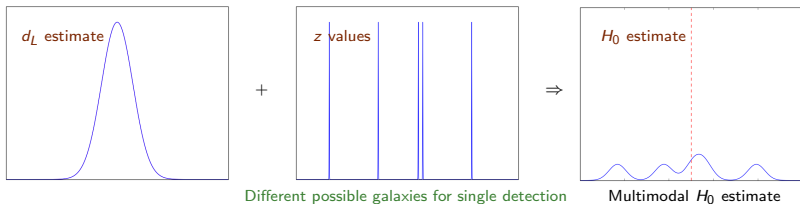
Schutz idea

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A **different** detection:



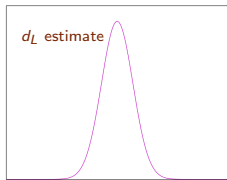
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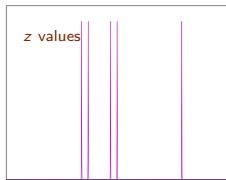
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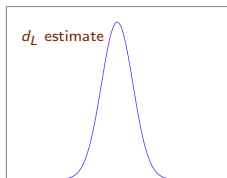
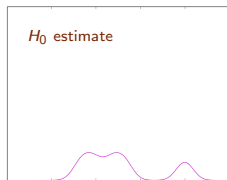
Independent detections



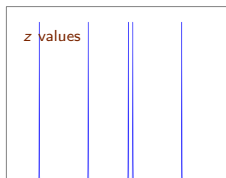
+



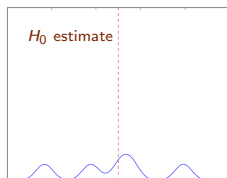
\Rightarrow



+



\Rightarrow



Different possible galaxies for single detection

Multimodal H_0 estimate for each detection

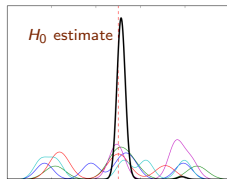


Schutz idea

galaxy catalogues in absence of transient EM counterparts

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Schutz (1986)



Unimodal joint H_0 result

Combine information from all observed detections \Rightarrow

Schutz “galaxy catalogue” method

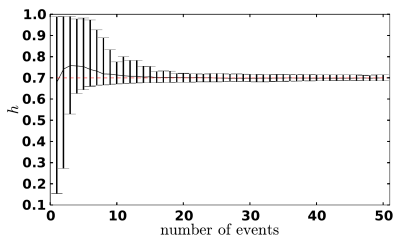
Idea in Schutz (1986)

MacLeod and Hogan (2008) in the context of LISA

Del Pozzo (2012) in the context of Adv-LIGO/Virgo

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

Power of statistics!



With great statistical power comes great systematic responsibility!

GW selection effects

limited sensitivity of GW detector

only nearby signals detected

Detection efficiency (selection function)

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

Abbott+ Nature 551 #7678, 85-88 (2017); **Ankan Sur** masters thesis

Mandel, Farr, Gair 2018; Chen+ 2018; Mortlock+ 2018; Feeney+2019

H_0 with galaxy catalogues: the complete story

GW selection effects

limited sensitivity of GW detector
only nearby signals detected

EM selection effects

limited sensitivity of EM telescope
incomplete galaxy catalogues

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

in-catalogue

out-of-catalogue

Detection efficiency (selection function)

Integrated method of taking into account both effects
in `gwcosmo` codebase by LVC cosmology group led by **AG**

Gray+ arXiv:1908.06050 (with **AG**)

H_0 with galaxy catalogues: simulations

Gray et al. (2019) (with AG)

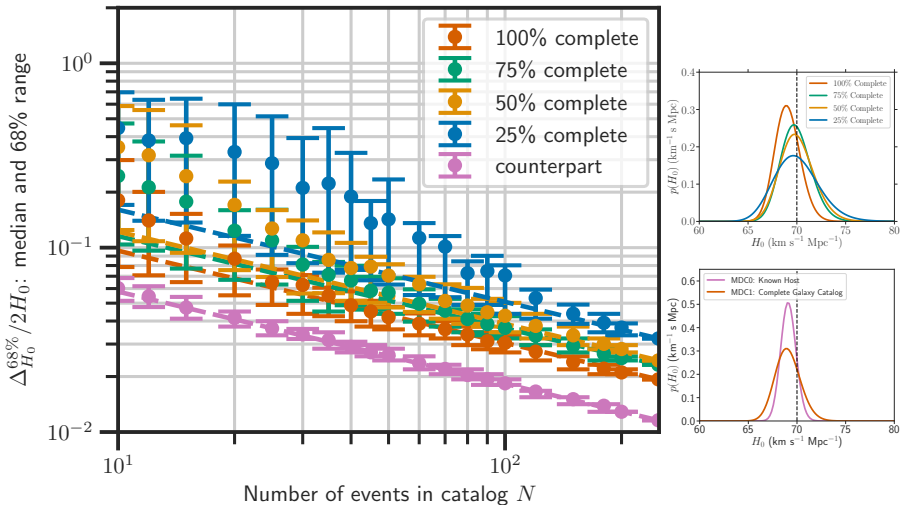
A few key features from the “mock data challenge”:

- 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+ arXiv:1908.06050

("mock data challenge" by the LVC cosmology group led by AG)



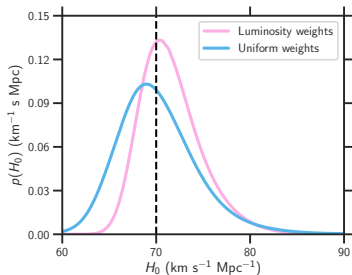
H_0 with galaxy catalogues: results on simulations

Gray+ arXiv:1908.06050

("mock data challenge" by the LVC cosmology group led by AG)

Luminosity weighting of galaxies: improves by ~ 1.3

Brighter (visible) galaxies are more likely hosts



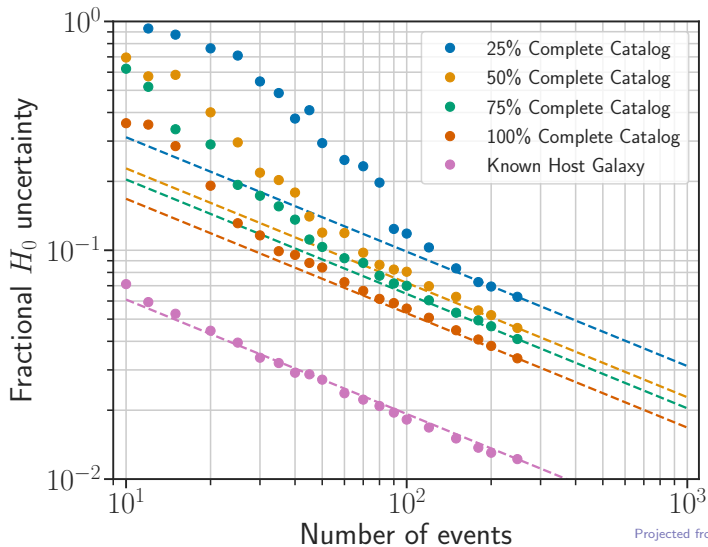
B-band: star formation rate

K-band: total mass

Clustering of galaxies: improves by ~ 2.5

Chen *et al.* (2018)

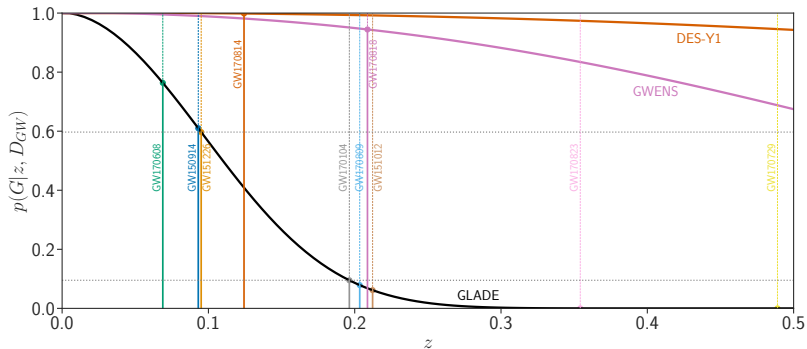
H_0 with galaxy catalogues: projections from results on simulations



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

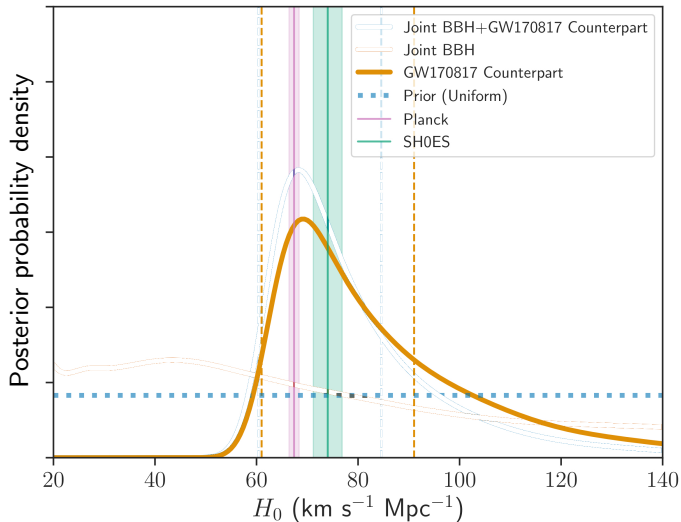
H_0 with galaxy catalogues: results on LIGO-Virgo detections

LVC: Abbott+ arXiv:1908.06060 (with AG as PWT lead)



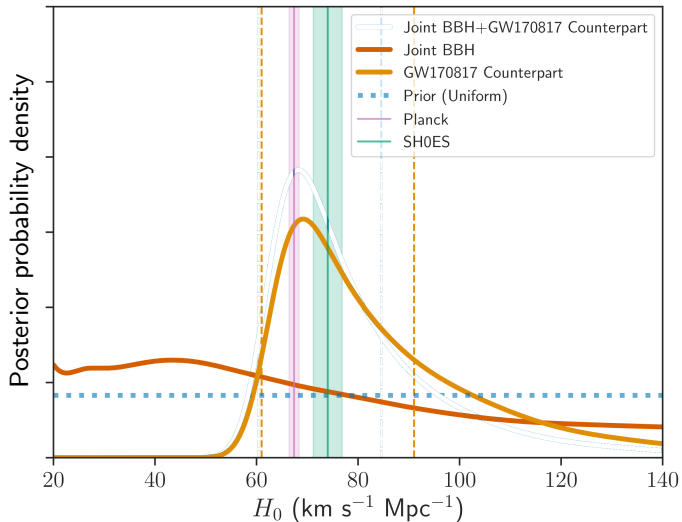
H_0 with galaxy catalogues: results on LIGO-Virgo detections

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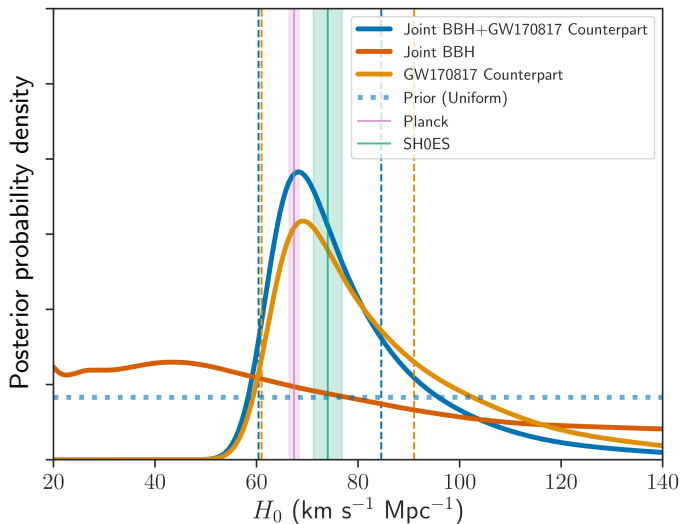
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H_0 with galaxy catalogues: results on LIGO-Virgo detections

LVC: Abbott+ arXiv:1908.06060 (with AG as PWT lead)



A compendium of possible sources of systematics

- Peculiar velocity flows for nearby detections

- Uncertainties in galaxy catalogues (EM)

Photometric measurements of redshifts

Estimates of luminosities for weighting

- Selection effects (GW and EM)

Catalogue completeness ✓

Population properties: mass distribution, rate evolution, ...

- Waveform systematic effects (GW)

- Detector calibration uncertainties (GW)

ampl. < 4%

systematic?

A compendium of possible sources of systematics

- Peculiar velocity flows for nearby detections

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systematic?

GW cosmology: moving forward

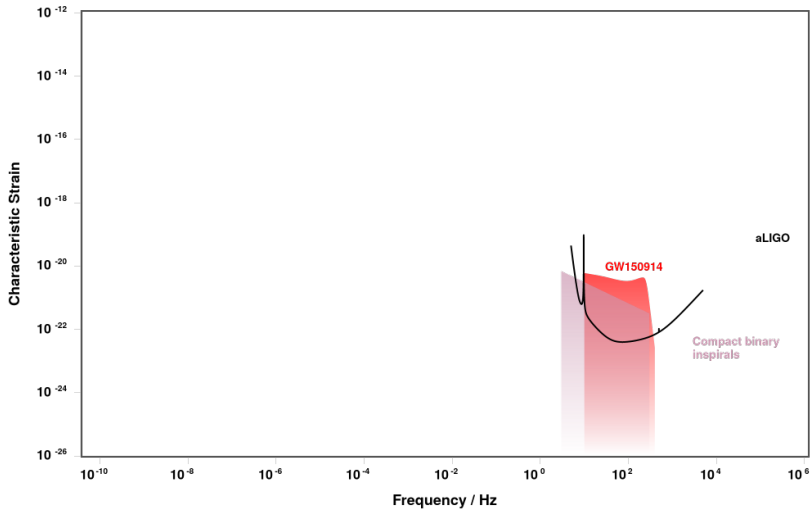
- Astrophysically-motivated weighting of host galaxies Chatterjee
- Galaxy clustering: move over from galaxy catalogues to cluster catalogues
Cluster cat + astrophysics \Rightarrow probability density of mergers in redshift space
merger density catalogues *Beyond H_0 ?*
- Cross-correlations of GW and EM Manrique Yus, Mukherjee, Silvestri, Nissanke, Dalal
3G: Cosmic Explorer, Einstein Telescope
- GW lensing? Hannuksela, Silvestri
Time delays, cross-correlations ...

GW cosmology: moving forward

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Time delays, cross-correlations . . .

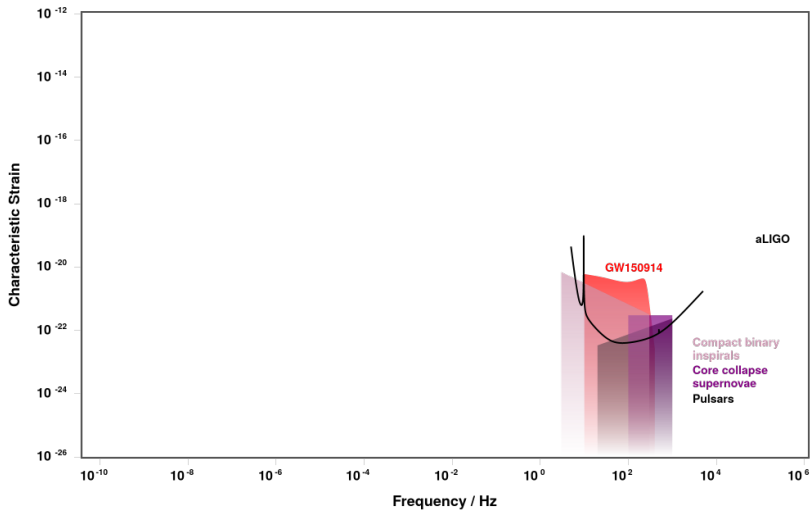
Future detectors

Moore, Cole, & Berry, <http://gwplotter.com/>



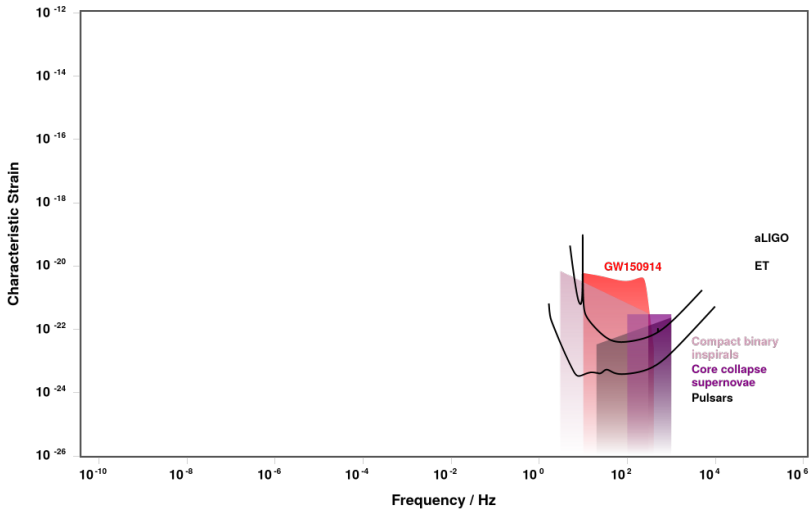
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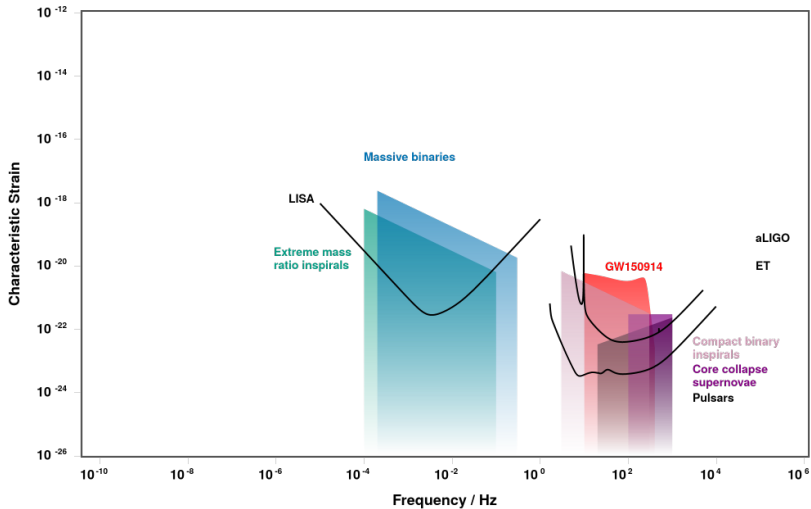
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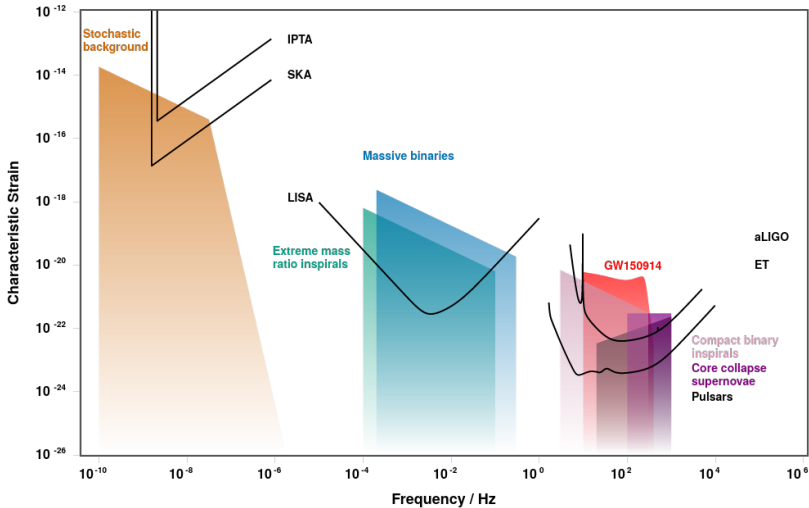
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Future detectors

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Other cosmological parameters?

$$\{\Omega_m, \Omega_\Lambda, w_0, w_a\}, \dots$$

Ground-based 3G / LISA

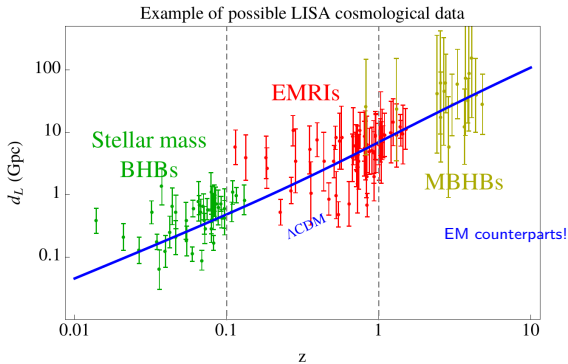
Sathyaprakash *et al.* (2010)

Simultaneous tests of modified gravity!

Belgacem *et al.* (2018)

LISA sources

Courtesy: Nicola Tamanini



- **StMBHBs:** Del Pozzo *et al.* (2017); Kyutoku & Seto (2016)
- **EMRIs:** MacLeod & Hogan (2007)
- **MBHBs:** Tamanini *et al.* (2016); Petiteau *et al.* (2011)

LISA projections

Tamanini et al. (2016)

Model	N2A5M5L6						N2A2M5L4					
	$P(\%)$	$\Delta\Omega_M$	$\Delta\Omega_\Lambda$	Δh	Δw_0	Δw_a	$P(\%)$	$\Delta\Omega_M$	$\Delta\Omega_\Lambda$	Δh	Δw_0	Δw_a
5 param.	100	4.31	7.16	1.58	13.2	92.3	67.8	320	799	47.7	344	5530
	100	18.0	24.9	9.95	88.6	392	2.54	$\gg 10^4$	$\gg 10^4$	$\gg 10^4$	$\gg 10^4$	$\gg 10^4$
	100	2.80	5.15	0.681	4.66	55.7	68.6	138	306	13.3	127	2400
Λ CDM + curv.	100	0.0819	0.281	0.0521			91.5	0.471	2.66	0.429		
	100	0.220	0.541	0.136			12.7	$\gg 10^4$	$\gg 10^4$	$\gg 10^4$		
	100	0.0473	0.207	0.0316			90.7	0.174	1.26	0.145		
Λ CDM	100	0.0473	0.0473	0.0210			97.5	0.275	0.275	0.0910		
	100	0.0917	0.0917	0.0480			32.2	0.543	0.543	0.220		
	100	0.0371	0.0371	0.0146			99.2	0.126	0.126	0.0400		
DDE	100				0.253	1.32	97.5				1.03	6.36
	100				0.584	2.78	37.3				4.96	26.1
	100				0.176	1.00	95.8				0.427	2.87
Accel. & curv. test	100	0.0190	0.0735				99.2	0.211	0.396			
	100	0.0280	0.105				37.3	0.977	1.30			
	100	0.0213	0.0631				94.1	0.116	0.202			
Error on Ω_M	100	0.0173					100	0.0670				
	100	0.0238					53.4	0.0755				
	100	0.0172					100	0.0437				
Error on h	100			0.00712			100			0.0146		
	100			0.00996			53.4			0.0175		
	100			0.00531			100			0.00853		
Error on w_0	100				0.0590		100				0.121	
	100				0.0786		53.4				0.146	
	100				0.0467		100				0.0734	

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)

Broader prospects: upcoming years and the next decade

- Compact binaries:

 - **intrinsic** and **extrinsic** parameter space

 - GW polarizations, higher modes, distance-inclination degeneracy

 - Internal physics of NS (resonances, postmerger)

 - **Cosmology and testing general relativity need to go hand-in-hand!**

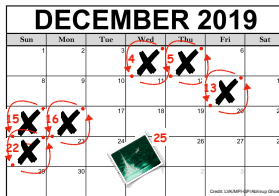
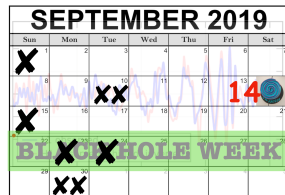
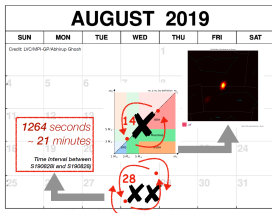
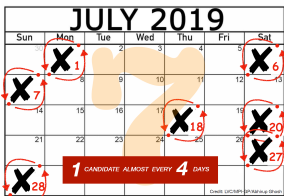
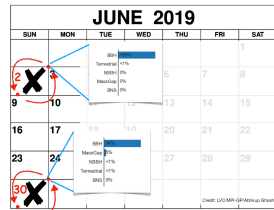
- Next big discovery?

 - Core-collapse supernovae / spinning neutron stars

 - Stochastic GW background

 - **Exotic cosmology might show signatures in (primordial) stochastic background**

- GWs may lead to the next breakthrough sooner than we expect!

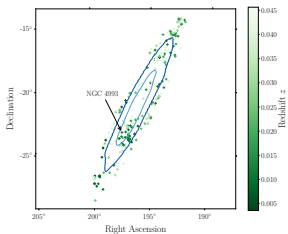


O3 has been very exciting so far!

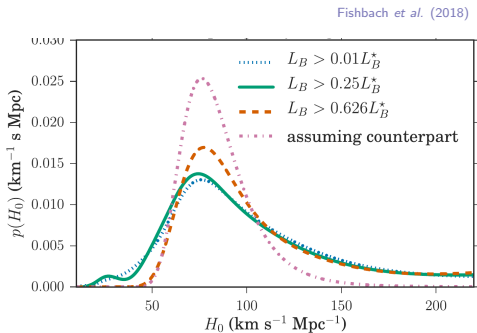
EXTRA SLIDES

H_0 from GW170817 with GLADE catalogue

- GW170817 assuming no counterpart:

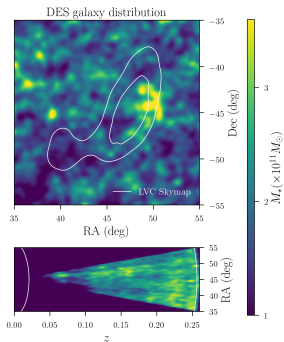


- Correcting for catalogue incompleteness
- Luminosity weighting



H_0 from GW170814 with DES catalogue

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



- **First realistic application**

