Overview of gravitational-wave cosmology

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Nikhef, Amsterdam

The Future of Gravitational-Wave Astronomy
International Centre for Theoretical Sciences
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Plan of this talk

Standard sirens

H_0 from current / upcoming detections

Prospects with 3G / LISA

Other ideas

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 $\sim \frac{\mathcal{M}^z}{d_L} \times \text{fn.(angles)} \Rightarrow d_L$ "luminosity distance" (degenerate with inclination)

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

Redshift-distance relation:

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

GW redshift (largely) degenerate with total mass

Where does the redshift come from?

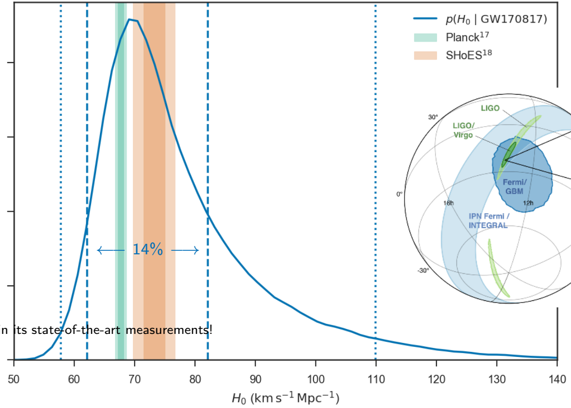
EM for most of this talk . . .

LETTER

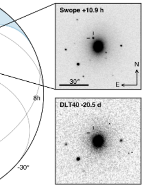
doi:10.1038/nature24471

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

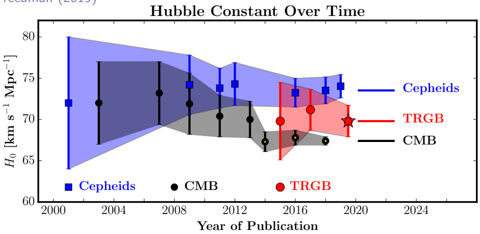
Discrepancy in its state-of-the-art measurements!

Multimessenger astronomy with GW and EM

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

Two contrasting methods applied on nearby and very distant cosmological scales

Freedman (2019)

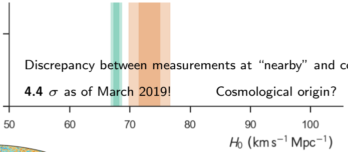


Planck $\approx$ 0.7%

SHoES $\approx$ 2%

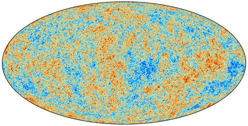
Standard candles

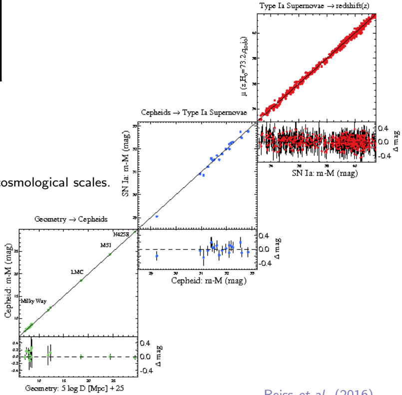
Cosmic distance ladder



Discrepancy between measurements at "nearby" and cosmological scales.

4.4 σ as of March 2019! Cosmological origin?





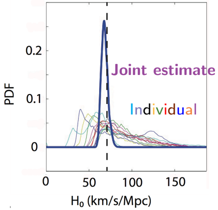
Planck collaboration (2015) + Λ-CDM

Reiss *et al.* (2016)

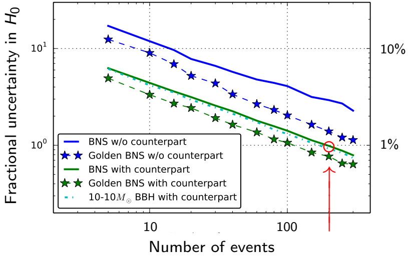
Better with more detections

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

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)

Better with more detections

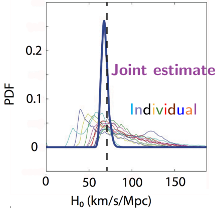
Careful of systematic effects!

GW selection effects

threshold SNR $\rightarrow$ interferometer horizon

only nearby signals detected

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



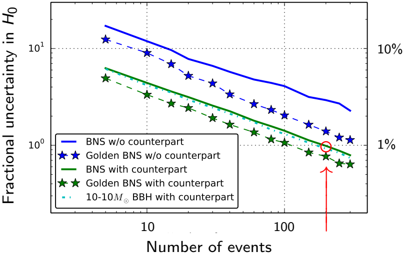
Detection efficiency (selection function):

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

Integrate over all **detectable data sets**

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

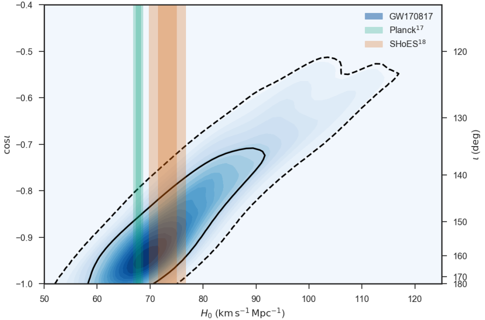
Mandel, Farr, Gair (2018); Chen *et al.* (2018); Mortlock *et al.* (2018)



Chen *et al.* (2018)

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

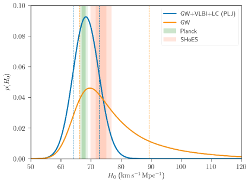
Degeneracy with inclination



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

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 → **inclination** → H_0



H_0 with galaxy catalogues: Schutz method

Idea in Schutz (1986).

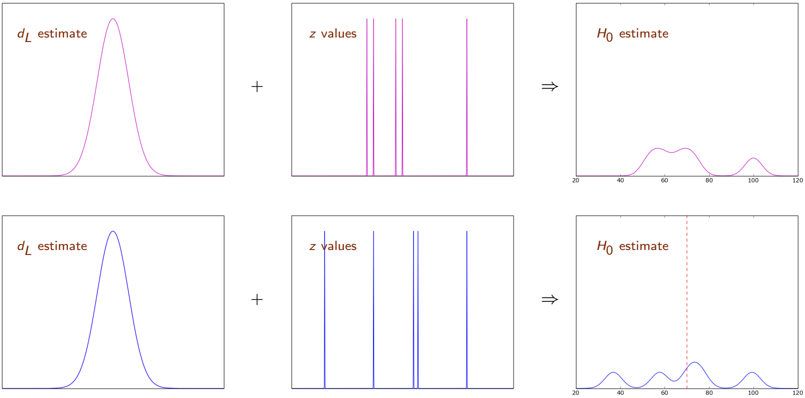
MacLeod and Hogan (2008) in context of LISA.

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)

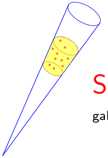
Independent events

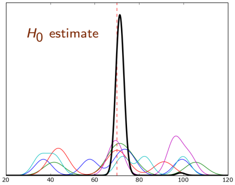


Combine information from all observed events ⇓

Different possible galaxies for single event

Multimodal H_0 estimate for each event





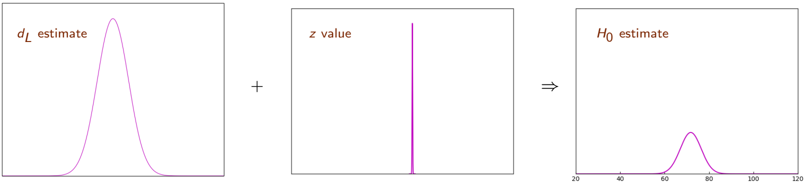
Unimodal joint H_0 result

Schutz method

galaxy catalogues in absence of transient EM counterparts

applicable also for **binary black holes**

Schutz (1986)



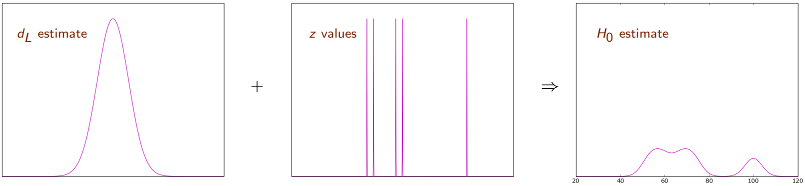
Counterpart / identified host galaxy

Schutz method

galaxy catalogues in absence of transient EM counterparts

applicable also for **binary black holes**

Schutz (1986)



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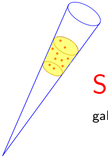
Multimodal H_0 estimate



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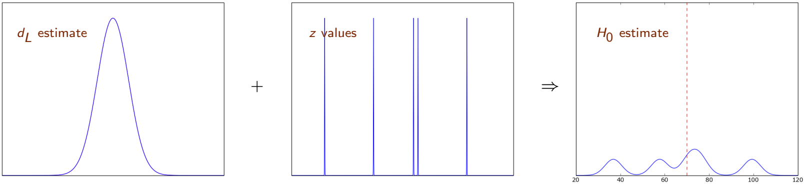

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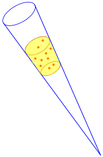

Schutz method

galaxy catalogues in absence of transient EM counterparts

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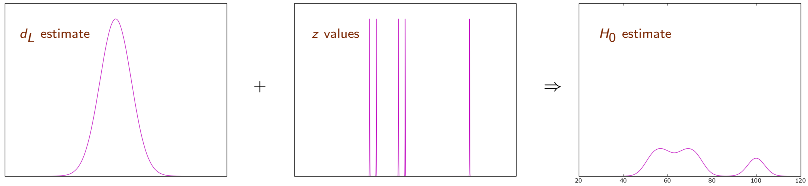
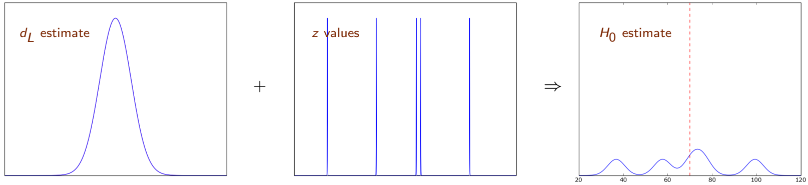
Schutz (1986)

Independent events





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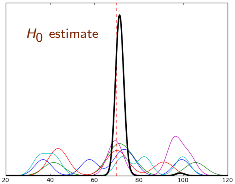
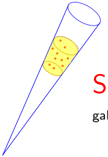
Multimodal H_0 estimate for each event

Combine information from all observed events ⇓



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

Detection efficiency (selection function):

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

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)

EM selection effects

depth of 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

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

Integrated method of taking into account both effects.

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

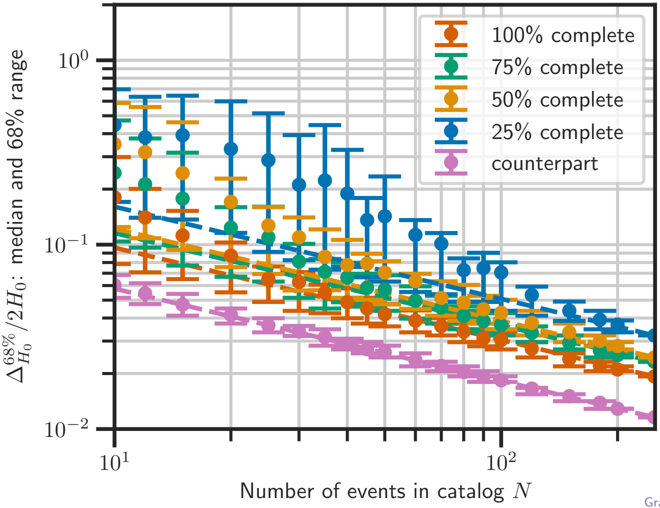
H_0 with galaxy catalogues: simulations

Gray *et al.* (2019)

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

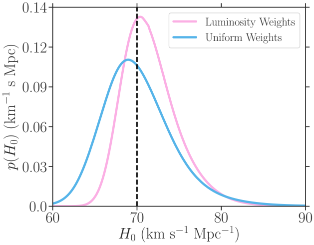


Gray *et al.* (2019)

H_0 with galaxy catalogues: results on simulations

Luminosity weighting of galaxies:

Gray *et al.* (2019)



B-band: star formation rate

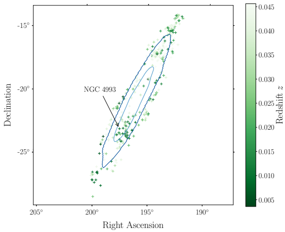
K-band: total mass

Clustering of galaxies: improves by ~ 2.5

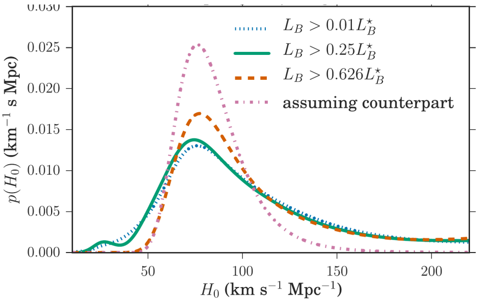
Chen *et al.* (2018)

H_0 from GW170817 with GLADE catalogue

- GW170817 assuming no counterpart:



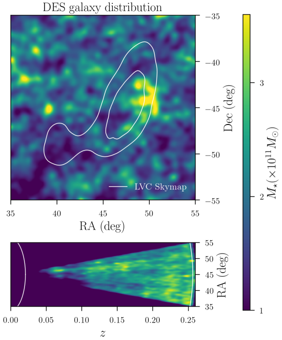
Fishbach *et al.* (2018)



- Correcting for catalogue incompleteness
- Luminosity weighting

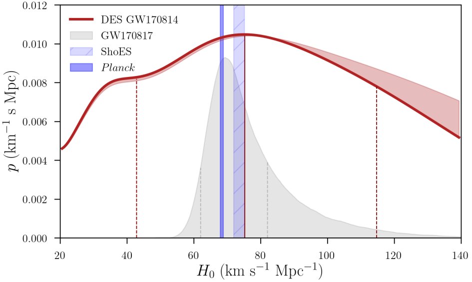
H_0 from GW170814 with DES catalogue

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



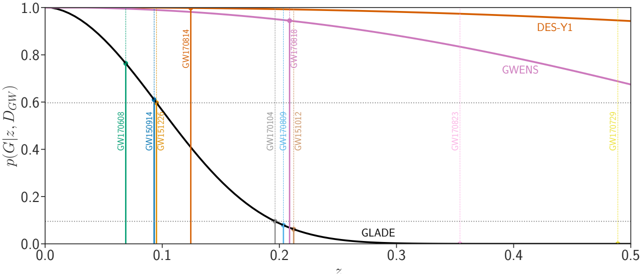
- First realistic application

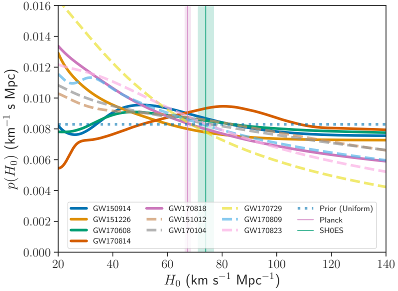
Soares-Santos *et al.* (2019)

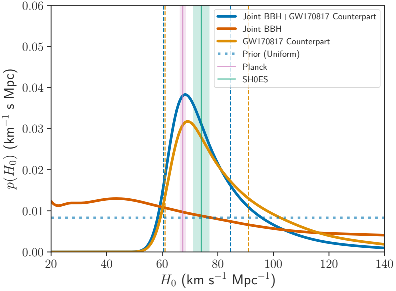


H_0 from O1 & O2 detections

Abbott *et al.* arXiv:1908.06060







Towards a precise and accurate GW measurement of H_0

Thorough understanding of systematic effects is crucial

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

  Photometric measurements of redshifts

  Estimates of luminosities for weighting
- Selection effects (GW and EM)

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

  Catalogue completeness
- Waveform systematic effects (GW)
- Detector calibration uncertainties (GW) ampl. $< 4\%$ systematic?

Other cosmological parameters?

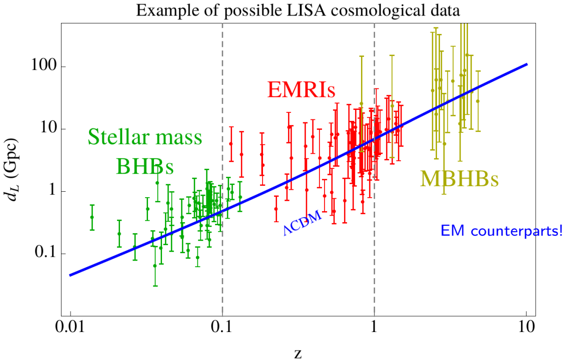
$\{\Omega_m, \Omega_\Lambda, w_0, w_a\}$, ...

Ground-based 3G / LISA — Sathyaprakash *et al.* (2010)

Simultaneous tests of modified gravity! — Belgacem *et al.* (2018)

LISA sources

Courtsey: 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
ΛCDM + 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		
ΛCDM	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	

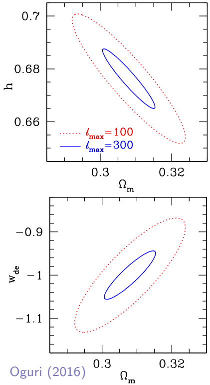
Correlations of GW/EM distributions

Angular / 3D correlation functions

GW distributions with cluster catalogues / LSS

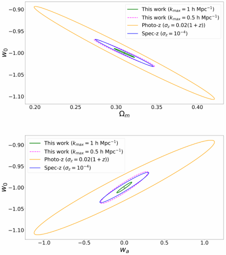
ET

BBO + Euclid / SKA

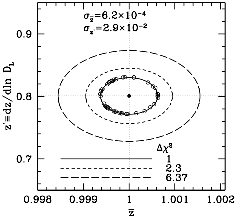


Oguri (2016)

DESI / Euclid



Mukherjee & Wandelt (2018)



Zhang (2018)

Vijaykumar+ (in progress)

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!

- More interaction between bi/multimessenger communities!

Cosmology from kilonova models?

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

Standard candles, sirens, rulers, . . .

Gupta *et al.* (2019): GW as SNe calibrators