Gravitational Wave Measurement of Dark Energy

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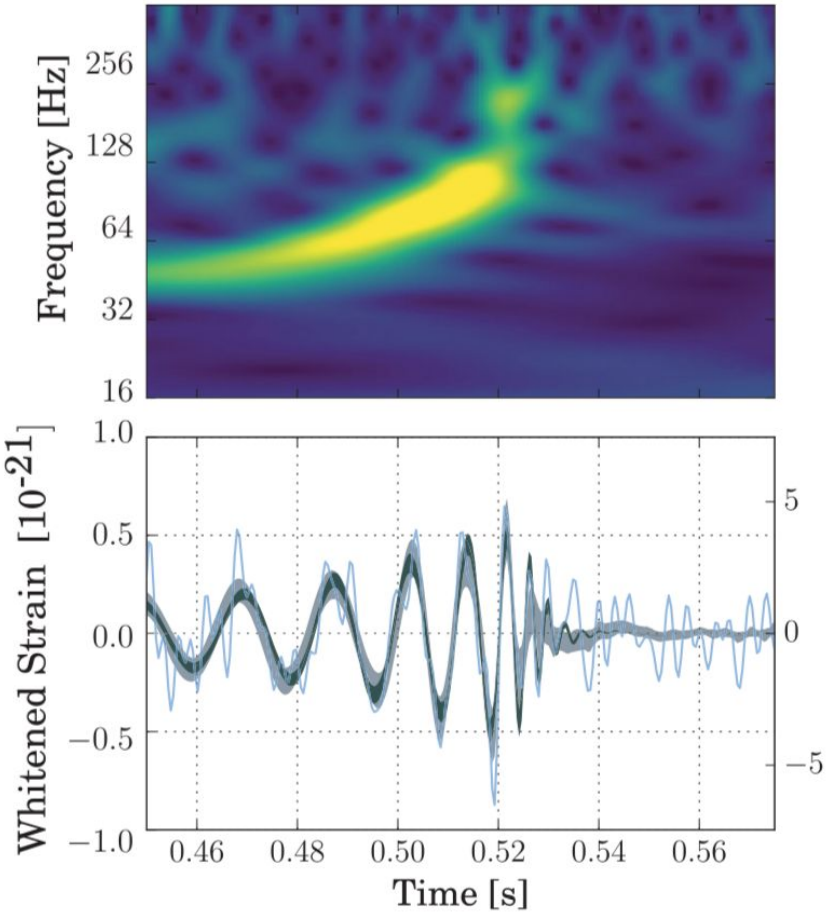
GWs as Standard Sirens

- GWs from binary mergers act as “standard sirens”
- The “volume” of this siren is determined by the characteristic size of the system, the chirp mass:

$$\mathcal{M} = \left(\mu^3 M^2\right)^{1/5}$$

$$\mathcal{M} = \frac{c^3}{G}\left(\frac{5}{96}\,\omega^{-11/3}\,\dot{\omega}\right)^{3/5}$$

GW170814



Abbott+17

Measuring the Luminosity Distance

- The chirp mass can be used to estimate the strain at a distance *r* from the merger:

$$h \simeq \frac{G^{5/3}}{c^4}\mathcal{M}^{5/3}\omega^{2/3}r^{-1}$$

- We can use these equations to get the luminosity distance in terms of gravitational wave observables:

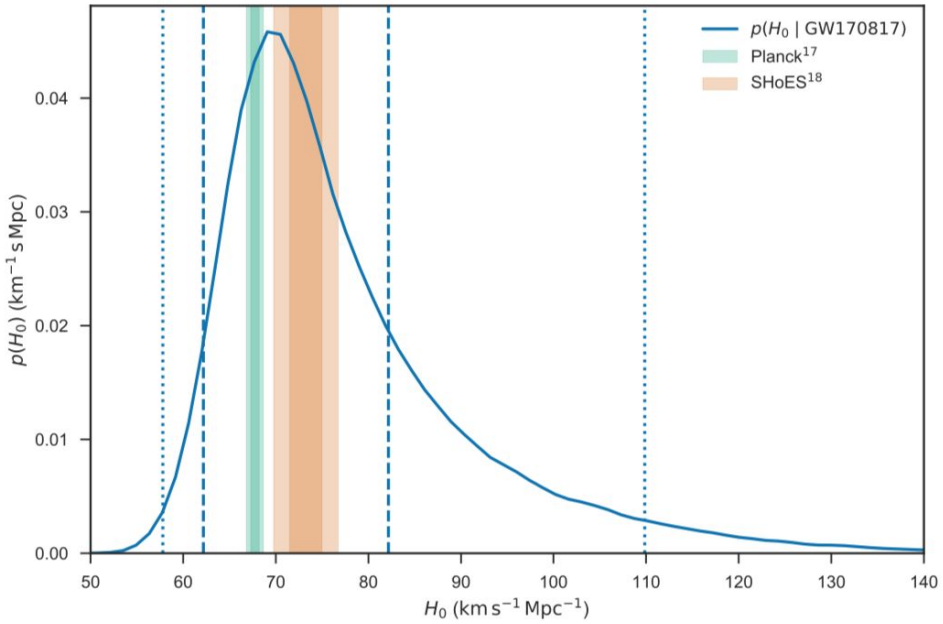
$$r = \frac{5c}{96\pi^2}\,\frac{\dot{f}}{h\ f^3}$$

Determining the Redshift

- Need to determine the host galaxy of the merger to get the redshift
- Straightforward if there is an electromagnetic counterpart (i.e., short GRBs)
  - Use EM observations to determine the host galaxy
- Not as easy without EM counterpart (binary BH mergers)
  - Can use galaxy surveys to estimate the redshift
- Measurements of *h* can be combined with CMB measurements to constrain *w*
- SMBH mergers can provide more direct measurements

Measurements from GW 170817

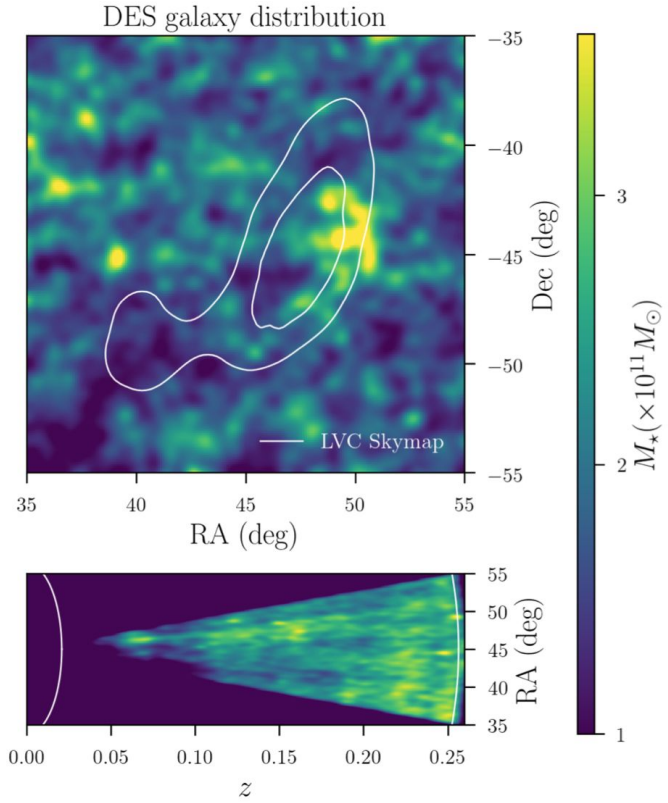
- $D_L = 43.8^{+2.9}_{-6.9}$ Mpc
- Localized to NGC 4993
- Radial velocity: 3017 ± 166 km/s
  - $Z \approx 0.01$
- $H_0 = 70\ ^{+12}_{-\ 8}$ km/s/Mpc

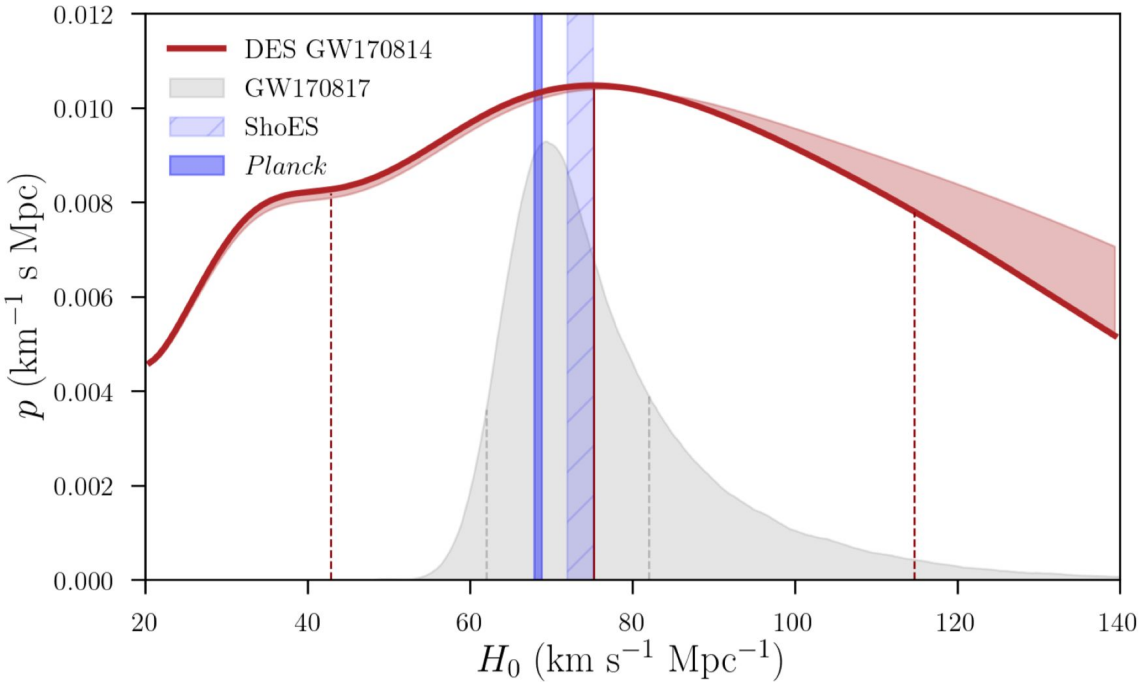


Measurements from GW 170814

D_L = 504.7 ± 91.9 Mpc

$H_0 = 75\ ^{+40}_{-32}$ km/s/Mpc



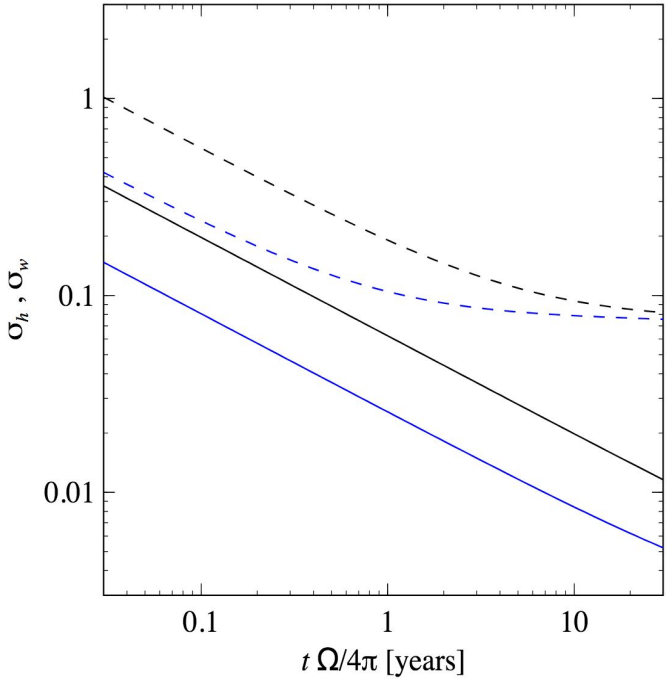


Positional Error

- GW measurement of DE relies on associated *z* measurement
- GWs are poorly constrained on the sky
  - NS mergers constrained to ~10^1 deg^2
- How do we find the EM counterpart?
- For LISA, inclusion of higher signal harmonics in SMBBH inspiral signals could identify host galaxy (Arun+08)

Effect of CMB in GRB Counterpart

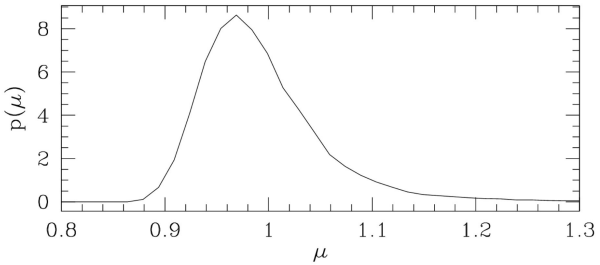
- 1% error in $\Omega_m h^2 \rightarrow$ 10% error in *w* due to cosmological model used (Planck-quality CMB constraints)
- Also, GRB progenitors can experience kicks, adding to peculiar $v \rightarrow z$ error



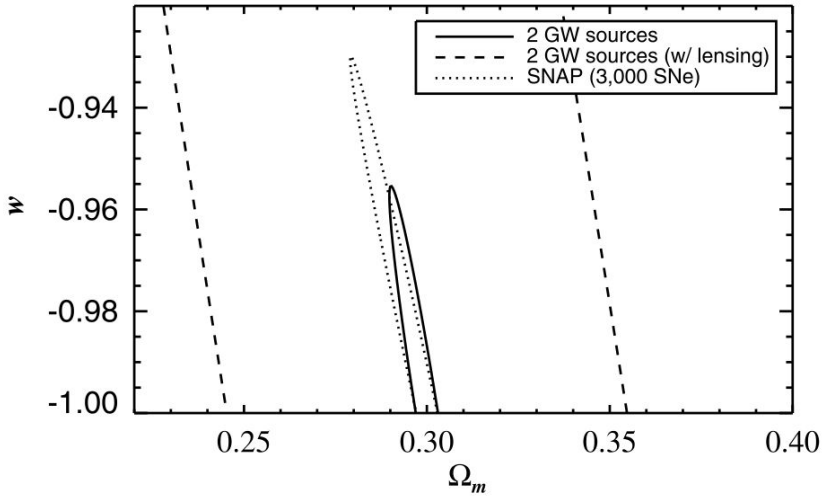
Error on *w* (dashed curves) vs. GRB exposure. **Black**: unbeamed GRB. **Blue**: beamed GRB.

Effect of Weak Lensing

- Grav. waves are lensed by mass just like EM waves
- At z > 1, we expect most GW sources to be lensed
- EM counterpart detection complements GW measurement
  - GW measurement is direct, no distance ladder involved
  - Without counterpart: $\delta D_L/D_L$ ~ 1 - 10%
  - With counterpart: $\delta D_L/D_L$ ~ 0.5 - 1%
- Lensing contains information of its own!

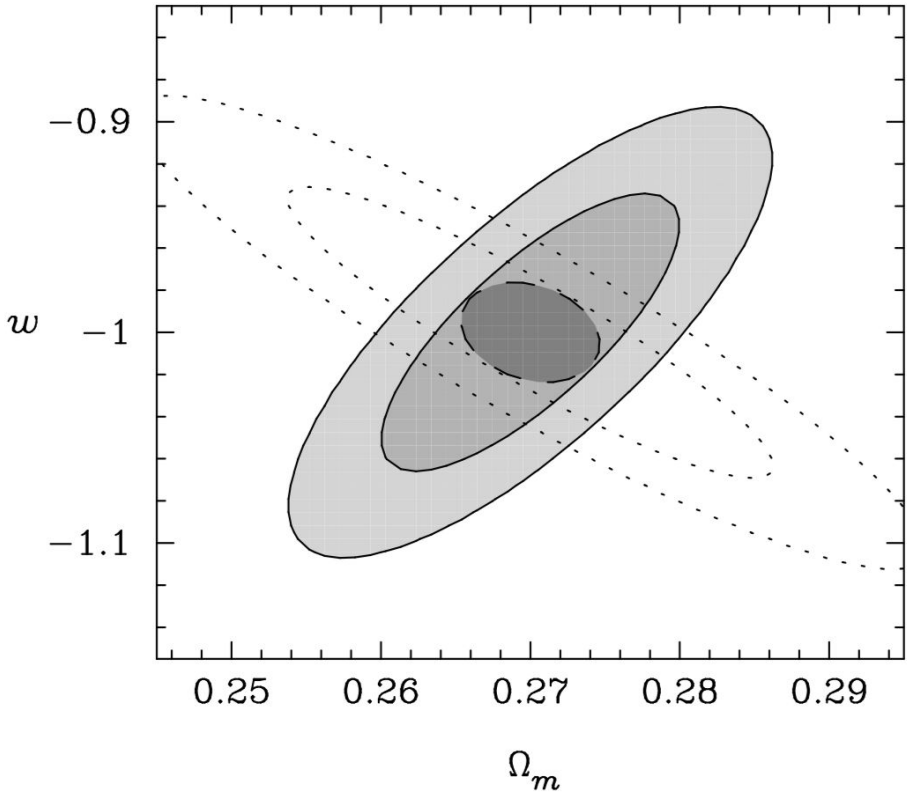


p.d.f. of magnification for z=1.5 sources (Wang+02)



Measurements with LISA

- Potential for excellent distance luminosity measurements, error ≲1%
- Could measure *h* to ≲1%, *w* to ≲10%
- If SMBBH mergers are frequent enough, lensing errors can be overcome to reach *w* errors ~4%
- Potential EM counterparts: quasar activity



Estimated error for LISA measurements of 100 SMBBH mergers. [Dalal+06] *Solid:* SMBBH *Dotted:* SNe *Dashed:* SMBBH+SNe+CMB

References

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Arun et al. (2008): https://arxiv.org/abs/0810.5727