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Cosmology with gravitational wave observations

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GWADW Elba 2013

Talk outline

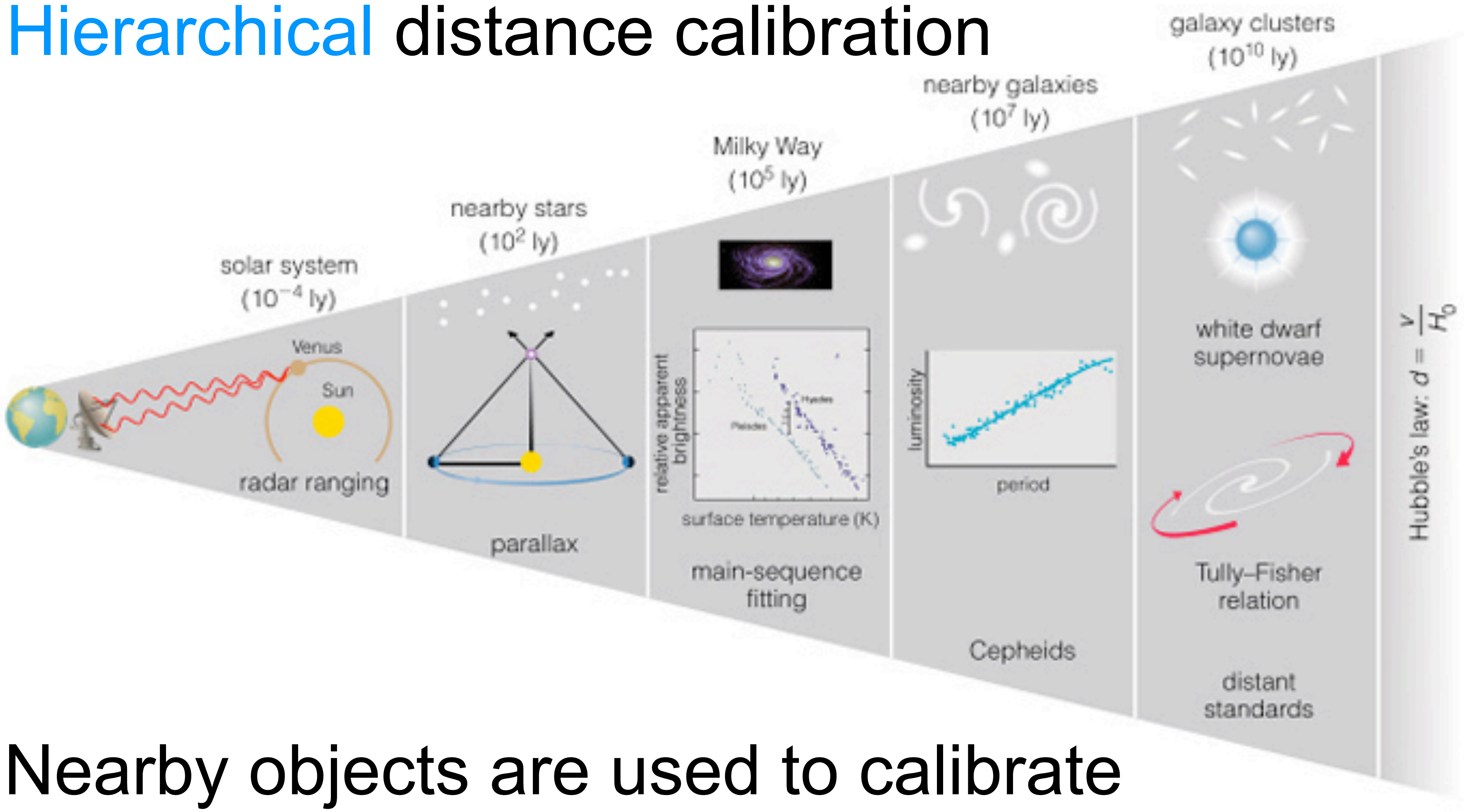
- Motivation
- The cosmic distance ladder and distance measures in cosmology
- The main ideas in GW cosmology
  - focussing on Advanced and 3rd generation detectors
  - making use of GW "standard sirens"
- Summary

Motivation

- GW detection will be pretty good, *but*
- The detection and characterisation of a population of GW sources will allow
  - the study of the large-scale structure of the Universe.
  - us to infer the formation history of the massive black hole population.
  - precision mapping of the expansion history of the Universe.
  - the use of cosmic distance markers (standard sirens).
  - provide a “powerful” probe of the dark energy content of the universe.

Distance ladder

- Hierarchical distance calibration



- Nearby objects are used to calibrate more distant measurements
- GW measurements would be independent of this ladder

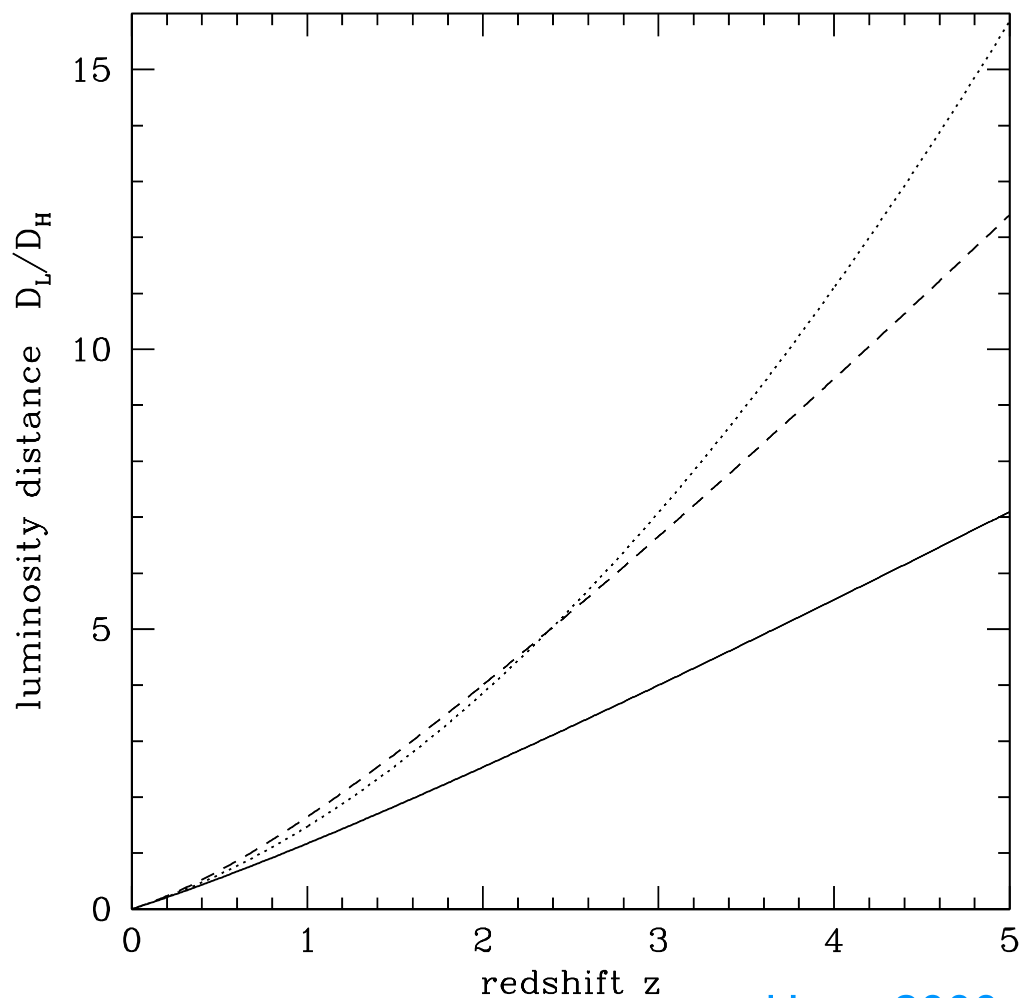
Distance measures

- The redshift $1 + z = \sqrt{\frac{1 + v/c}{1 - v/c}}$
- Luminosity distance

"The distance to an object of luminosity L with measured flux S"

$$D_{\rm L} \equiv \sqrt{\frac{L}{4\pi\, S}}$$

- D_L and z are related in a complicated way.

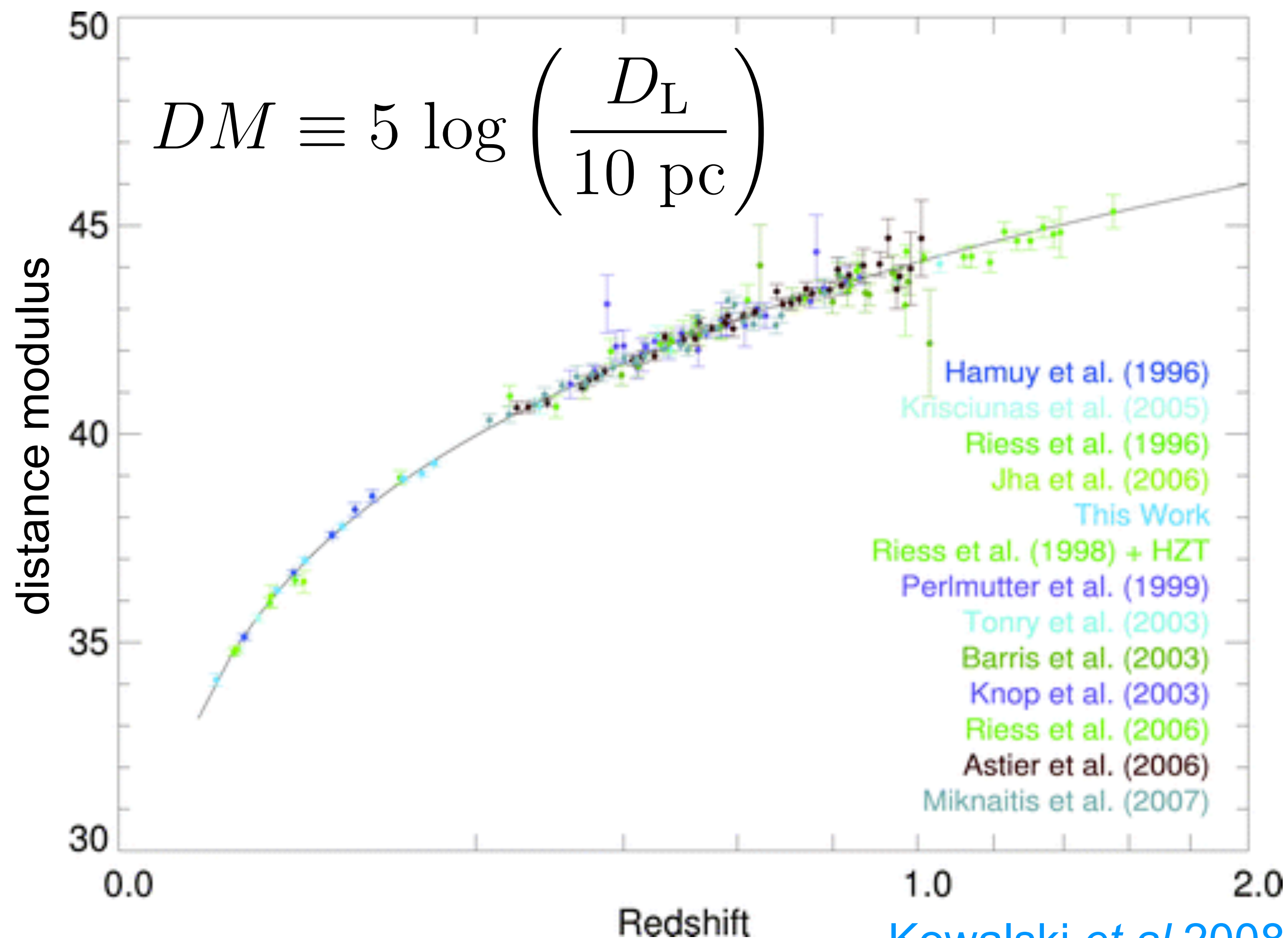


Hogg 2000

- Governed by the parameters $\vec{\Omega} = (H_0, \Omega_m, \Omega_k, w(t))$

DL-z relation

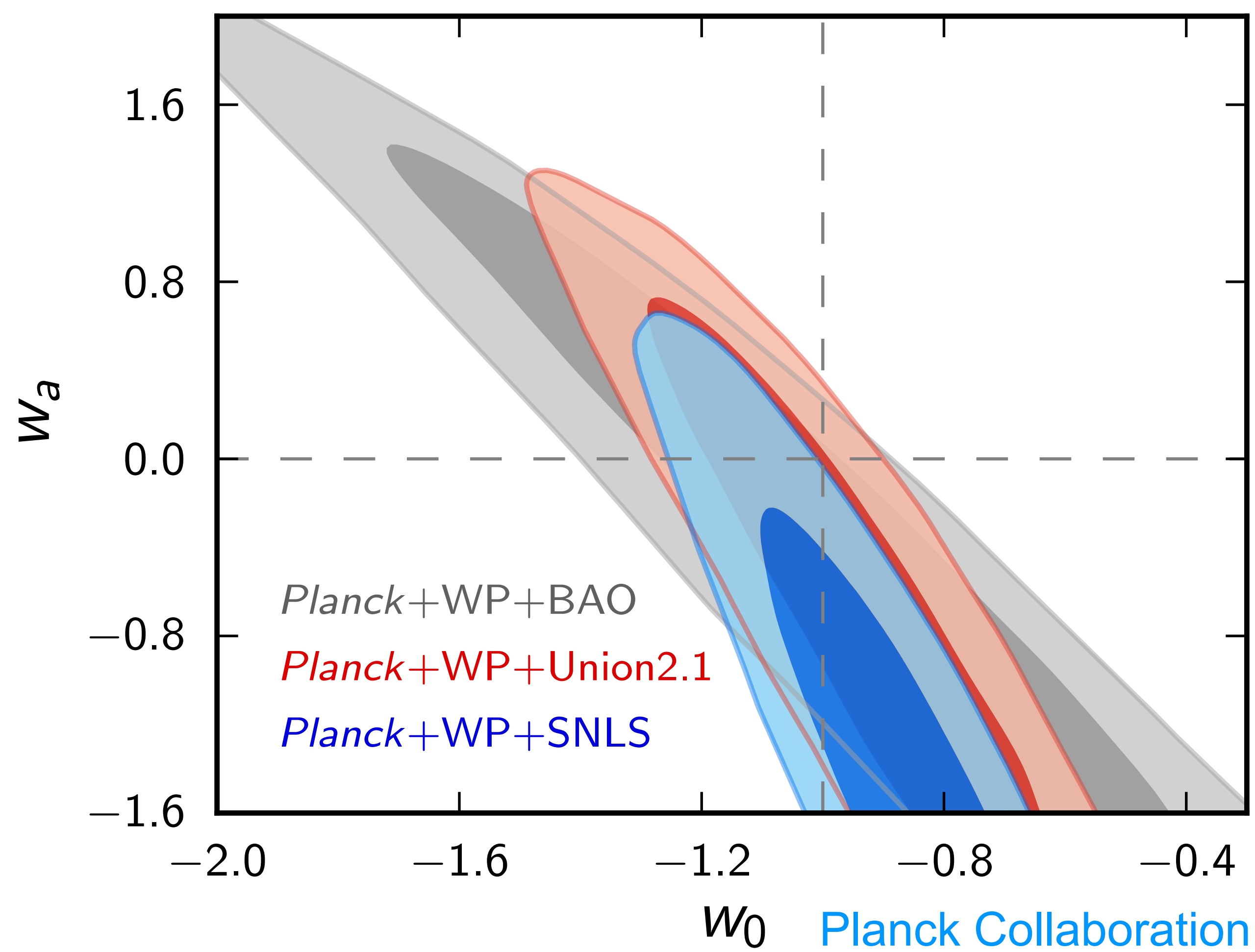
- One of our best observational probes of the cosmological parameters is the D_L-z relation, which maps the expansion history of the universe.



Kowalski *et al* 2008

Current knowledge

- The recently published Planck CMB results (combined with others) give the best constraints to date.
- Consistent with the standard ΛCDM model.
- These (EM) results are likely to improve before GWs are competitive.

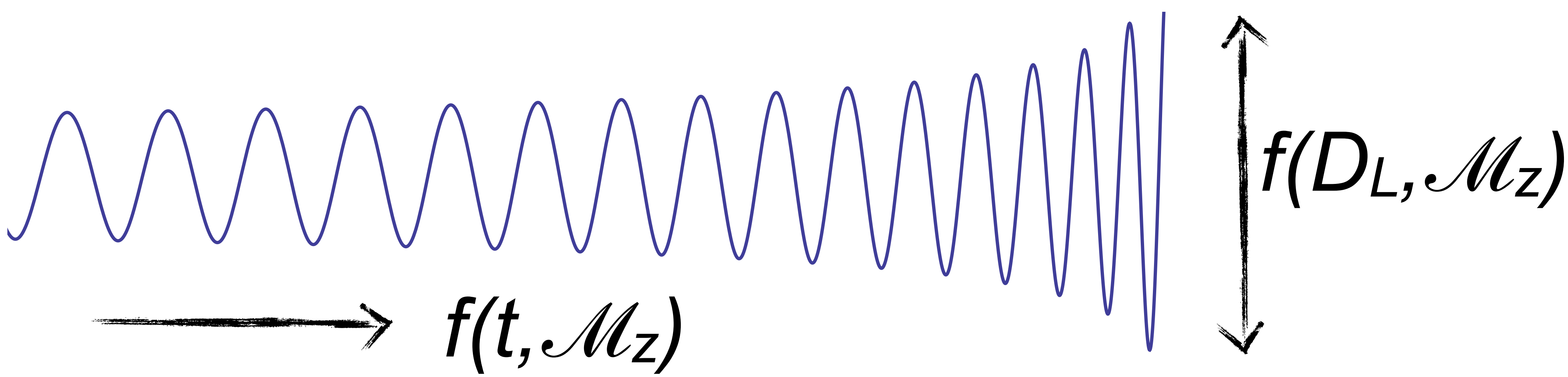


Planck Collaboration 2013

GW standard sirens

- Schutz in 86' proposed using compact-binary-coalescences as *"standard sirens"*. [Schutz 1986 Nature]

- Phase measurement gives redshifted chirp-mass $\mathcal{M}_z = (1+z)\mathcal{M}$.

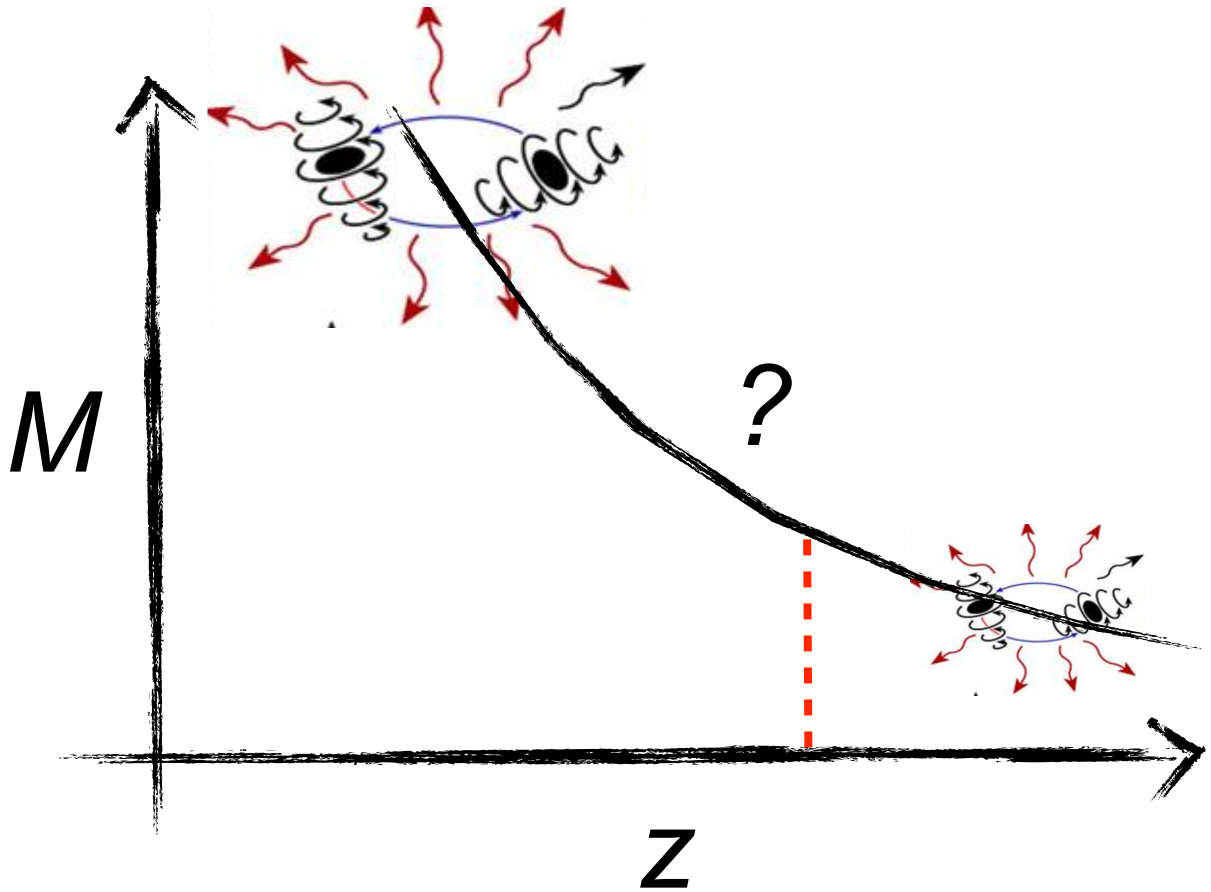


- Amplitude gives ratio of redshifted chirpmass$^{5/3}$ with luminosity distance D_L.

- "Self-Calibrating" sources but no redshift.

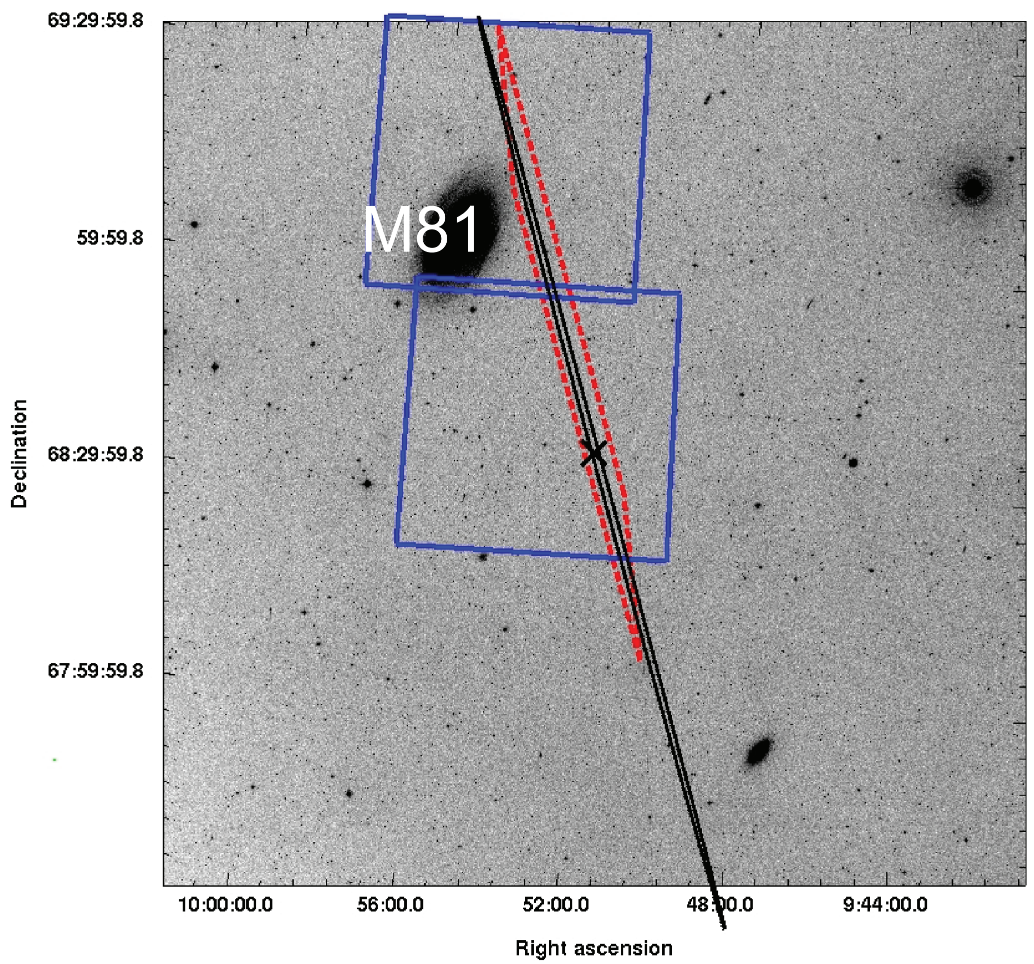
M,z degeneracy

- The problem is that we only get D_L and the redshifted mass $M_z=M(1+z)$
- We need EM measurements of redshift to break the degeneracy.
- Therefore we need host galaxy identification.

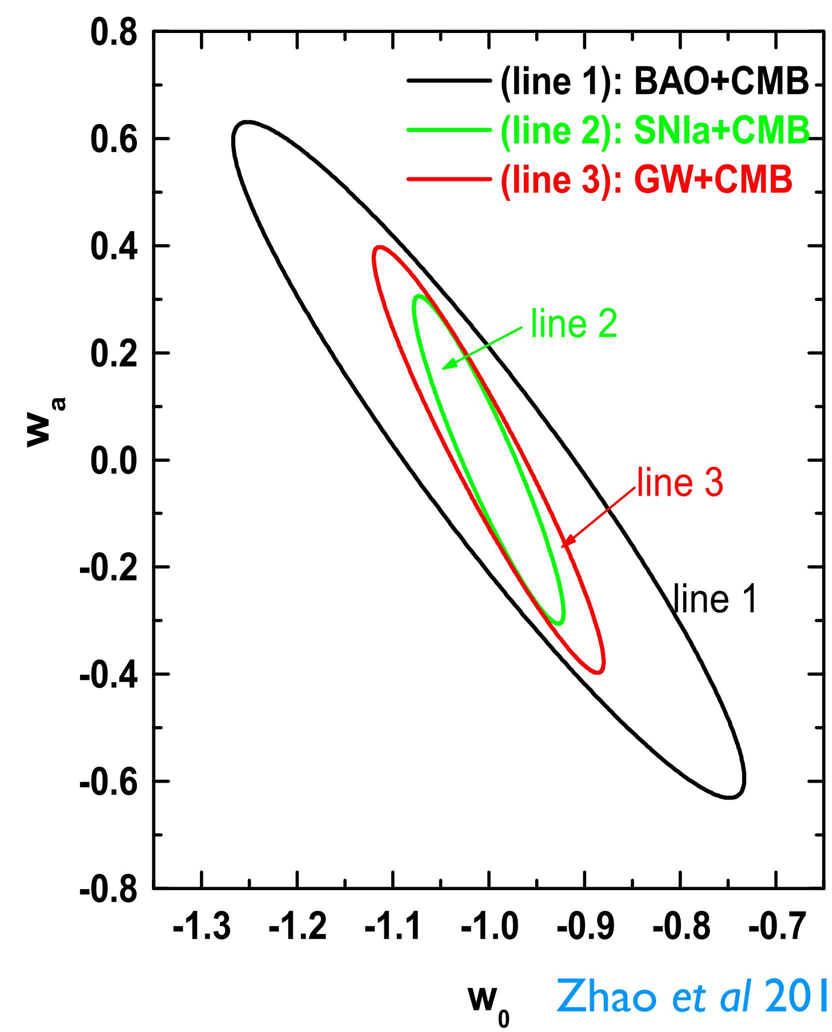


Gamma-ray bursts

- GRBs represent an EM counterpart with redshift obtained from the host galaxy. [Dalal *et al* 2006 PRD, Nissanke *et al* 2010 ApJ, Zhao *et al* 2011 PRD]



Hurley *et al* 2010



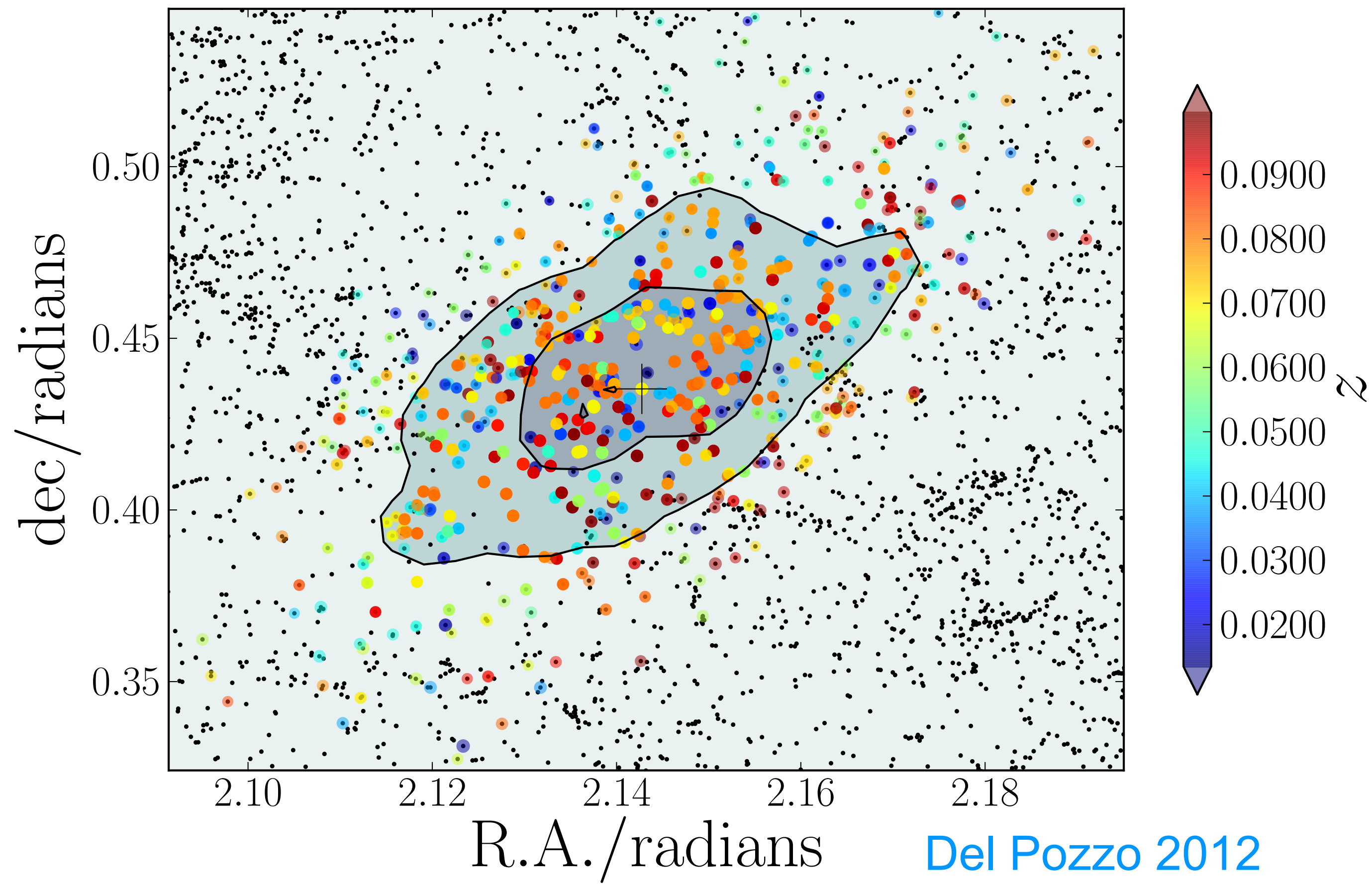
Zhao *et al* 2010

Galaxy catalogues

- Del Pozzo extended the idea to make use of galaxy catalogues to identify hosts. [Del Pozzo 2012 PRD]

- The redshift can then be obtained.

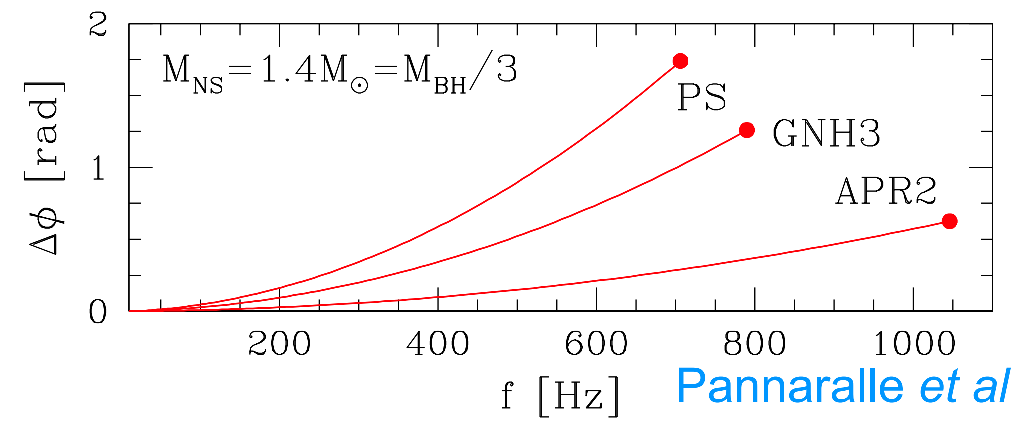
- Any confusion on between host galaxies is averaged out with many sources.



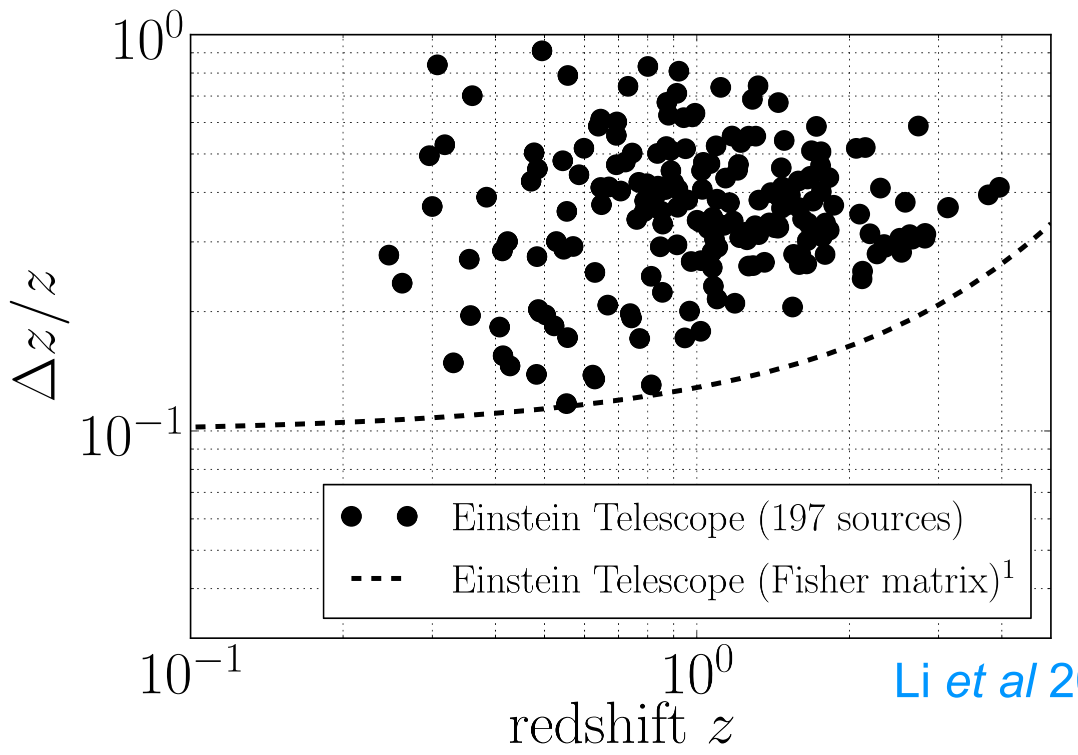
Del Pozzo 2012

NS tidal effects

- CM & Read discovered that tidal effects in NS binaries break the M,z degeneracy. [Messenger & Read 2012 PRL, Li *et al* 2013]
- The additional phase contribution is a function of the *intrinsic* mass!
- So you get the redshift *without an EM observation*.



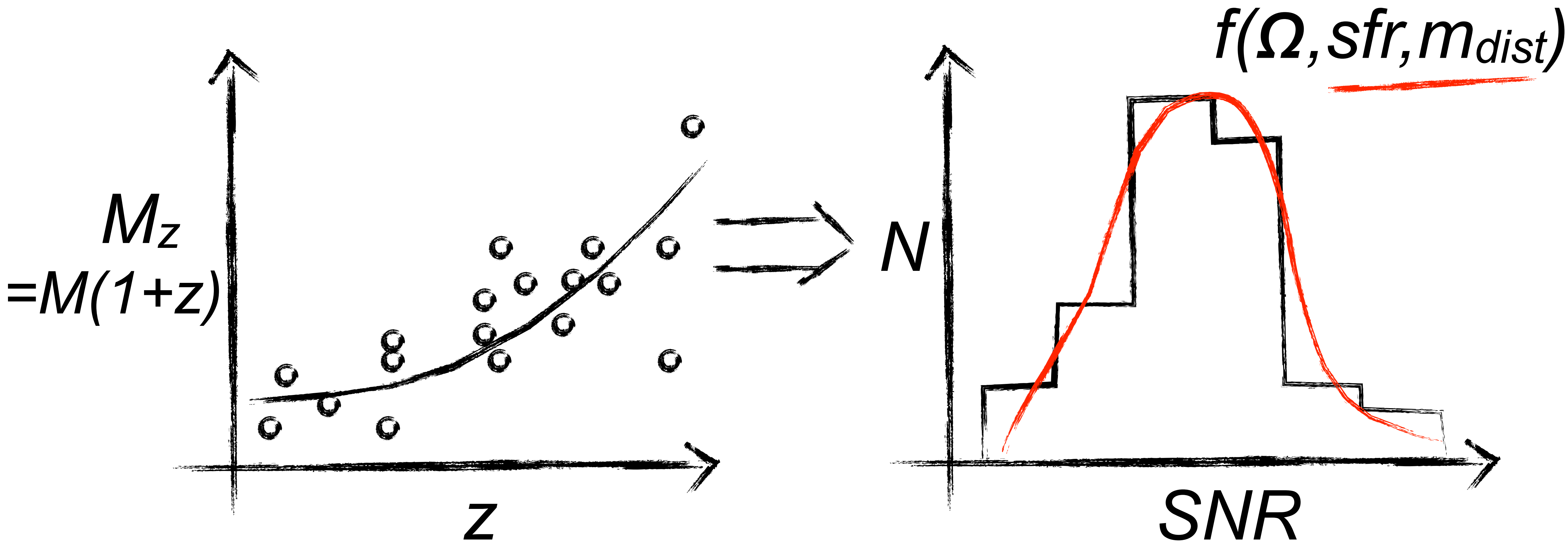
Pannaralle *et al* 2011



Li *et al* 2013

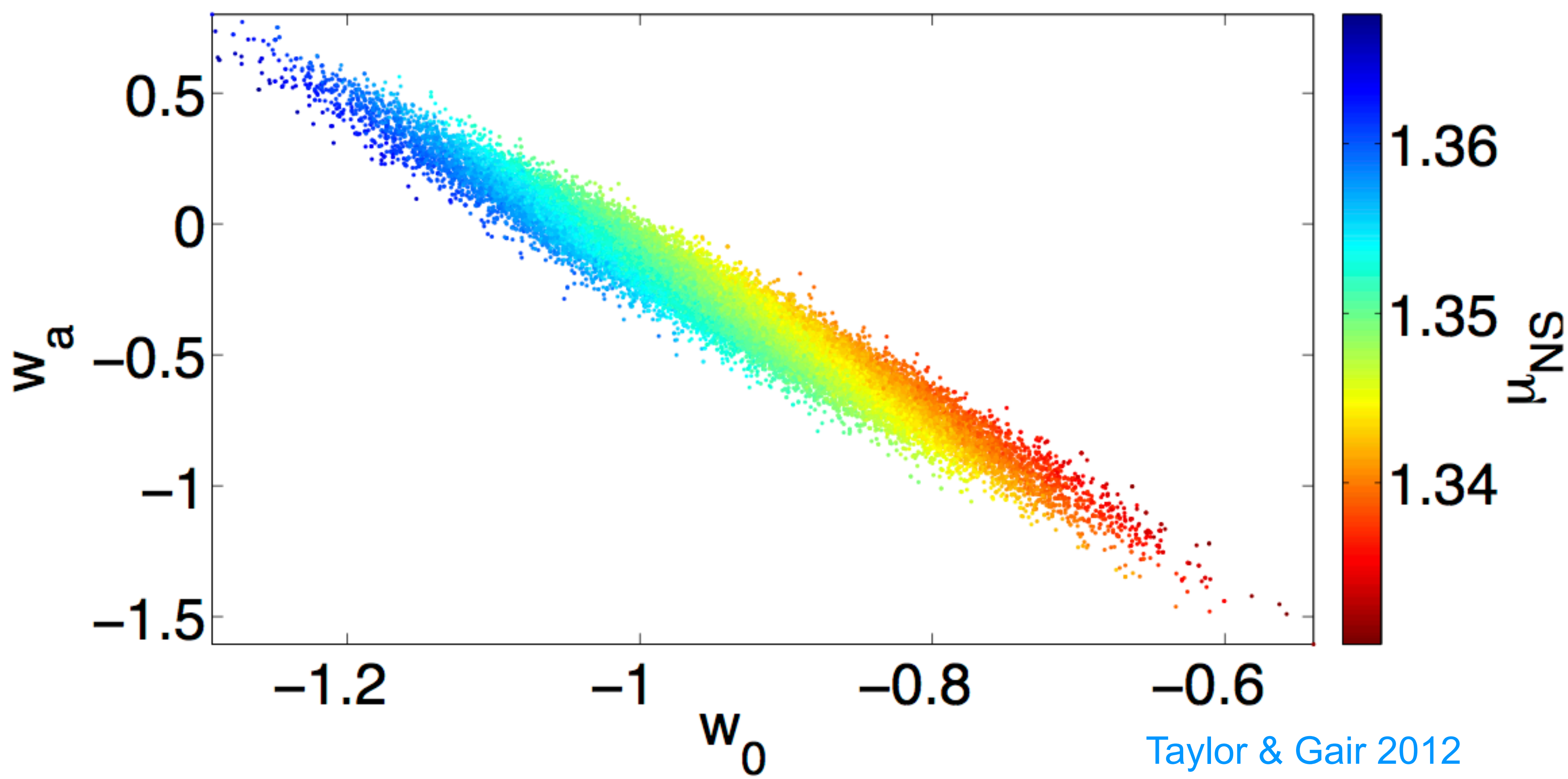
Statistical properties

- Idea first proposed by Marković 93’ and Finn & Chernoff 93’ to use the distribution of measured SNRs. [Markovic 1993 PRD, Finn & Chernoff 1993 ApJ, Finn 1996 PRD]



Statistical properties

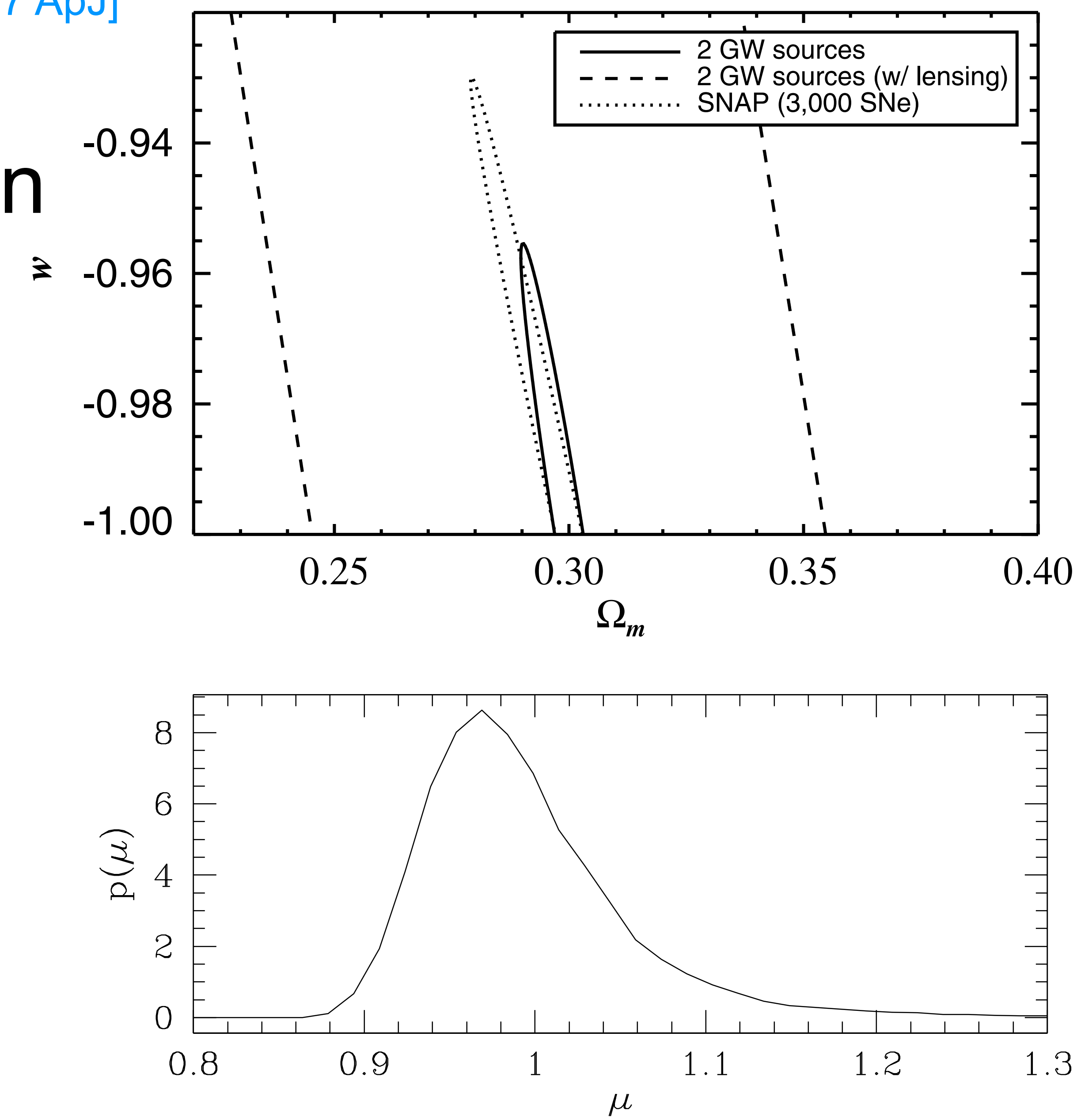
- The idea was expanded upon by Taylor et al 2011. [Taylor et al 2011 PRD, Taylor et al 2012 PRD]
- Where the mass distribution and star formation rate are included in the model.



Taylor & Gair 2012

Space based detectors

- D_L, z relation investigated for LISA by Holz & Hughes 2007. [Holz & Hughes 2007 ApJ]
- Statistical approach taken by Petiteau *et al* 2011. [Petiteau et al 2011 ApJ]
- Good localisation makes host identification tractable.
- Gravitational lensing is a *major* concern.

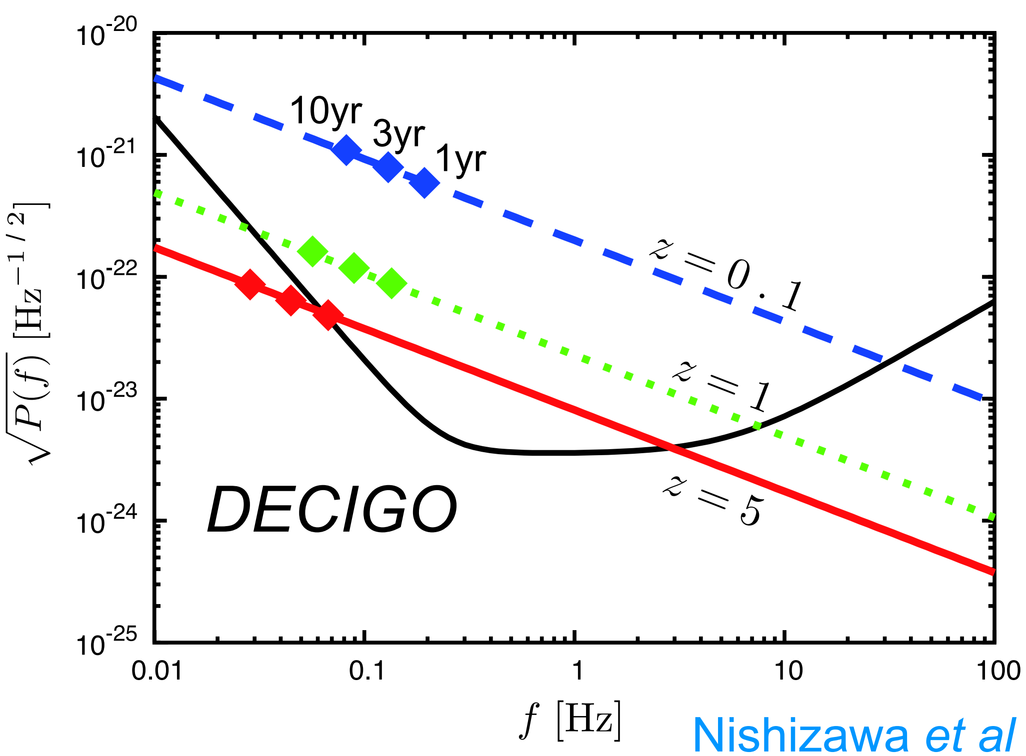


Holz & Hughes 2007

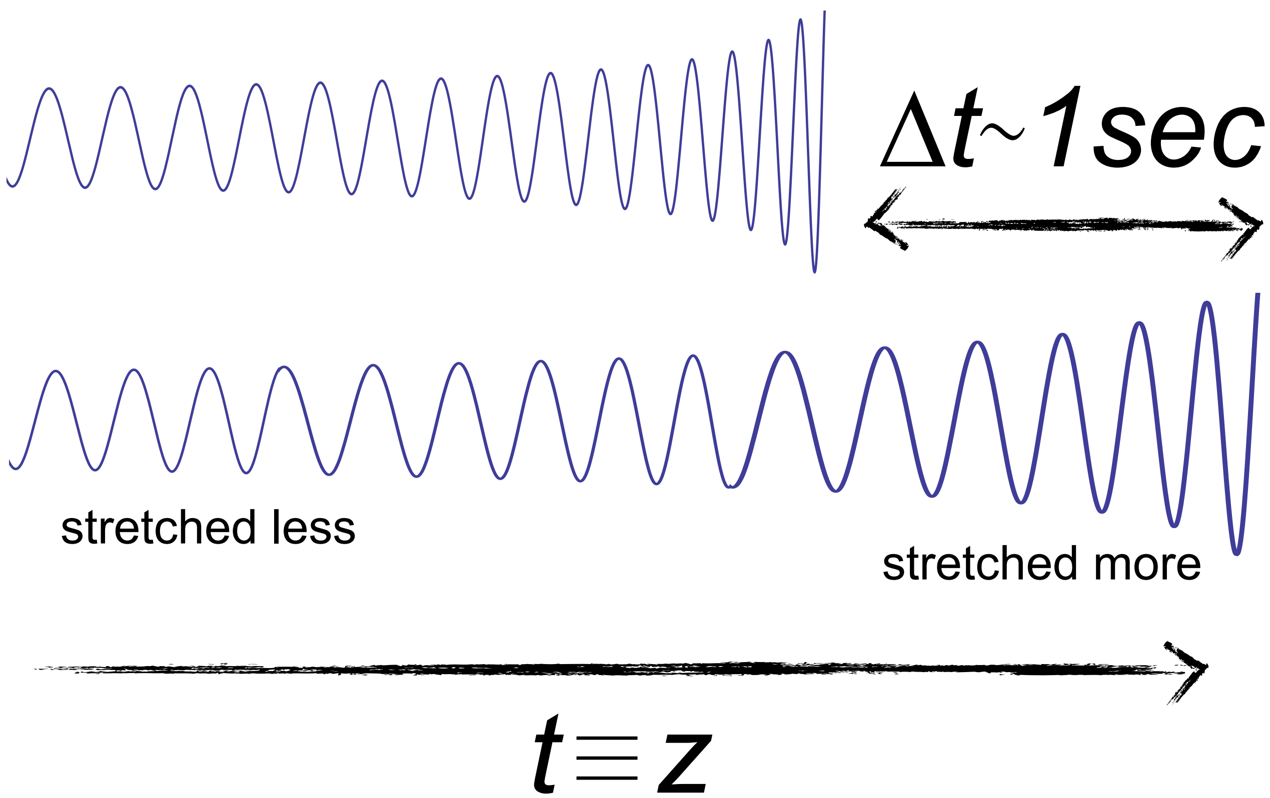
Space based detectors

- Directly measuring the expansion of the universe during a GW event. [Seto *et al* 2001 PRL, Nishizawa *et al* 2011 PRD]

- Again, breaks the M,z degeneracy.



Nishizawa *et al* 2011



Summary

- GW sources are *very* useful cosmological probes.
- They will provide measurements *independent* of the “cosmic distance ladder”.
- We have a number of different methods *with* and *without* EM counterparts.
- Calibration *may* end up being a limiting *systematic* factor.
- Lensing is a known limiting statistical factor.
- We need to compare our potential sensitivities to *future* EM experiments.

Thanks

Schutz 1986 (Nature)

$$\langle h \rangle = 1 \times 10^{-23} m_T^{2/3} \mu f_{100}^{2/3} r_{100}^{-1} \quad (1)$$

$$\tau = f/\dot{f} = 7.8 m_T^{-2/3} \mu^{-1} f_{100}^{-8/3} \text{ s} \quad (2)$$

$$r_{100} = 7.8 f_{100}^{-2} (\langle h_{23} \rangle \tau)^{-1} \quad (3)$$

- Initially only focussed on H0 estimation at 3% accuracy
- First discussion of clustering of galaxies for identification
- The first to define a standard siren (but didn't use the term)
- Found 2 spelling typos in published version.
- Hinted at optical counterparts

- The redshift comes from EM identification of the host
- The main idea is that the distance is obtained from GW alone.

Chernoff & Finn 1993

- Characterise the rate of detections as function of SNR threshold, hubble constant and chirp mass.
- Estimating ~50 per year with Initial LIGO
- Predict H0 to 10% with 100 detections (and q to 20% with 3000).
- No reliance on additional EM measurements

- Assume chirp mass distribution is independent of z (age).
- They allow the coalescence rate to vary with z but assume it is known.
- Seems to show that rate variation with z is highly correlated with results.

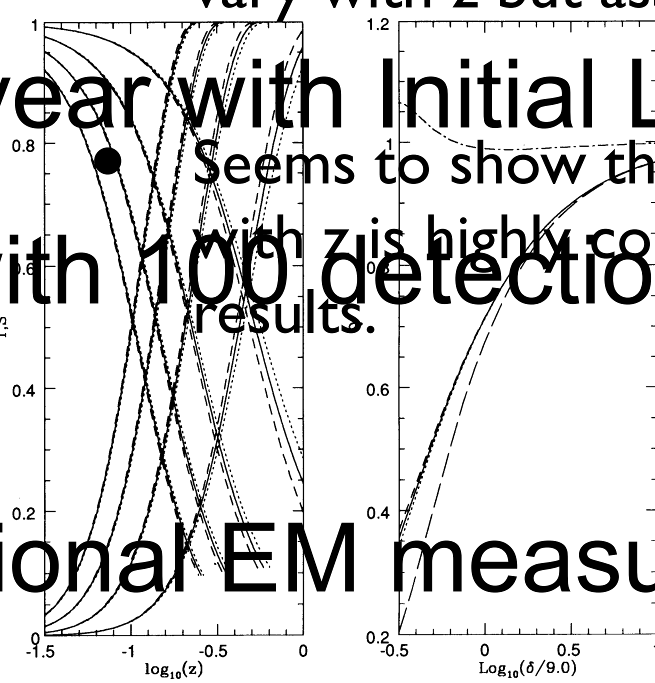


FIG. 1a FIG. 1b

FIG. 1.—(*a*) Observational volume accessible to the LD is characterized by the cumulative distribution of *detected* binaries $S(z, \rho_0) = \int_0^z dz' \dot{n}(z' | > \rho_0) / \dot{n}(> \rho_0)$ (*rising set of curves*) and by the sample's *completeness* $T(z, \rho_0) = \int_0^z dz' \dot{n}(z' | > \rho_0) / \int_0^z dz' \dot{n}(z' | > 0)$ (*falling curves*) for the case of no source evolution. The widely spaced families of curves represent $\delta = 4.5, 9.0, 13.5$, and 18.0 (eq. [5]) from right to left; these correspond to thresholds of $\rho_0 = 4, 8, 12$, and 16 for fiducial parameters. Each family consists of three closely spaced curves corresponding to different values of q_0 (*dashed line*—0.25; *solid line*—0.5; *dotted line*—0.75). The curves describing the sample's completeness terminate at the maximum z at which an inspiraling binary can be observed. (*b*) Ratio of the cosmological to the Euclidean rate of detections, Q, is given as a function of δ (eq. [5]). For the case of no source evolution, three different values of q_0 are

Finn 1996

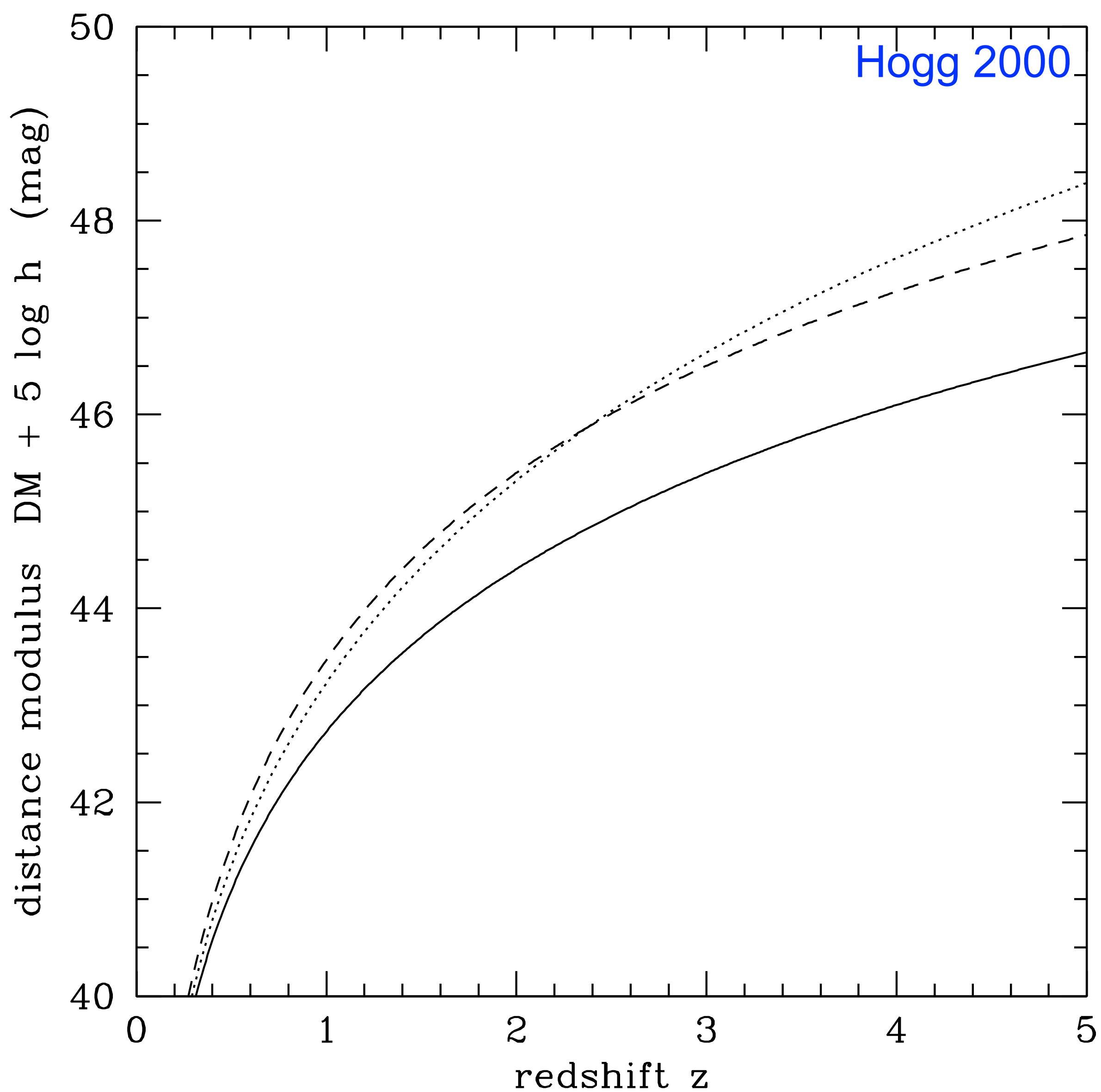
- Extension of the 93 work

Distance measures

- The distance modulus

"The magnitude difference between an object's observed bolometric flux and what it would be if it were at 10 pc."

$$DM \equiv 5 \log \left(\frac{D_L}{10 \text{ pc}} \right)$$



Distance measures

- Co-moving density

  "The volume measure in which number densities of non-evolving objects locked into Hubble flow are constant with redshift."