Gravitational waves as a probe for dark energy

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Abstracts

- Standard candle

  Type-Ia supernova data provide important evidence about cosmic acceleration (dark energy). However, there are various systematic erorrs. A large number of samples are required to constrain the property of dark energy.

- Standard siren

  Gravitational waves from a binary object are often called standard siren, which can be used to determine the distance to the source and can be an unique tool to measure cosmological expansion.

Supposing a future space-baced GW detector, we show that we can precisely measure the cosmological parameters, EOS of dark energy, and the Hubble parameter at each redshift, H(z), with the GW standard siren.

Introduction

Dark energy

Cosmic microwave background

→ Curvature is nearly flat

Distant supernovae

→ Expansion is accelerating

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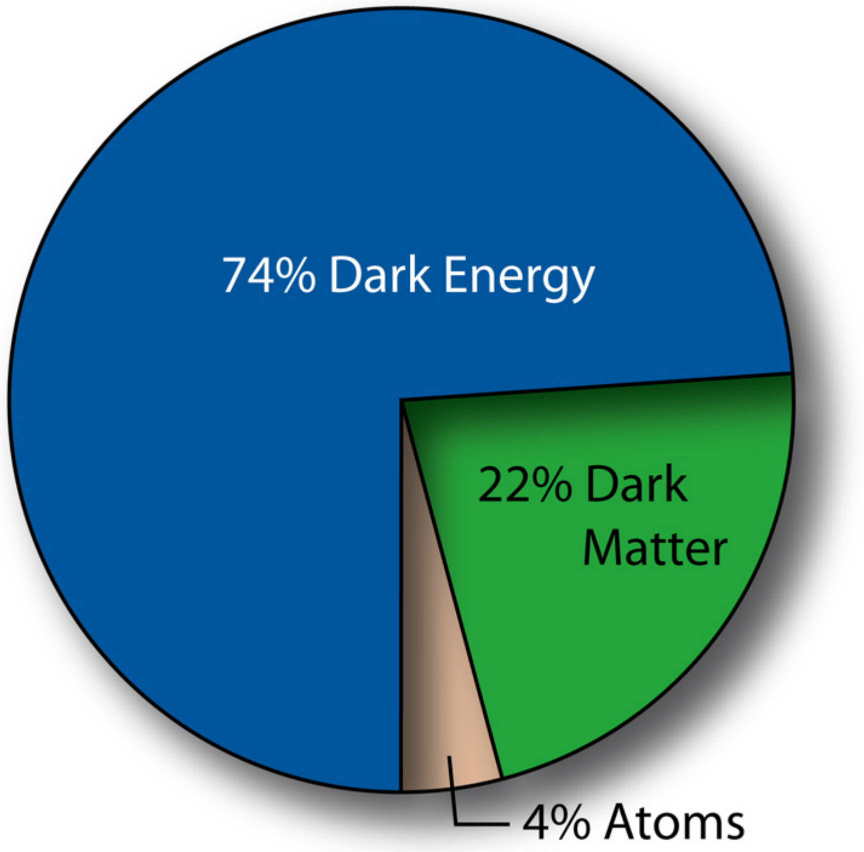
- smooth component with negative pressure (scalar field etc.)
- modification of gravity at large scale
- cosmological constant (vacuum energy)

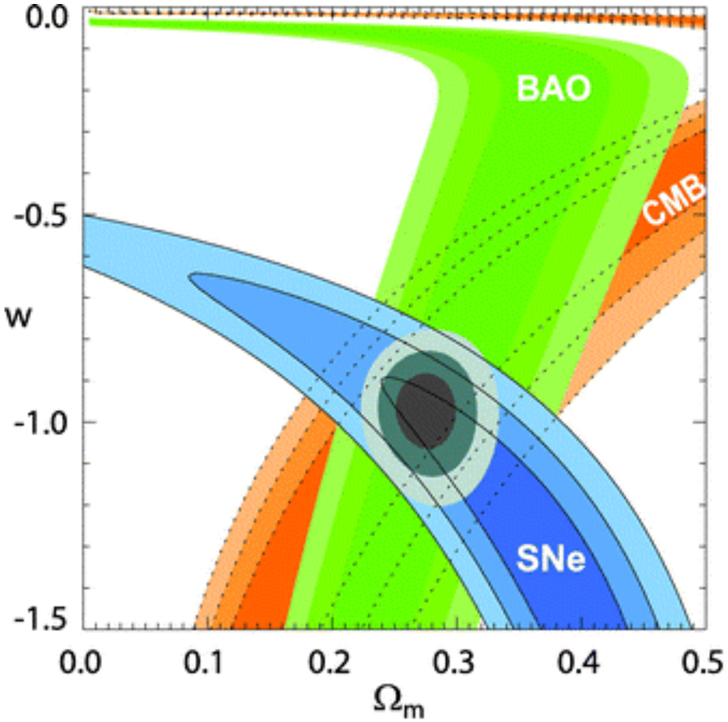


Constraints on dark energy

[Kowalski+ 2008]

$p = w\rho$ (w: const.)

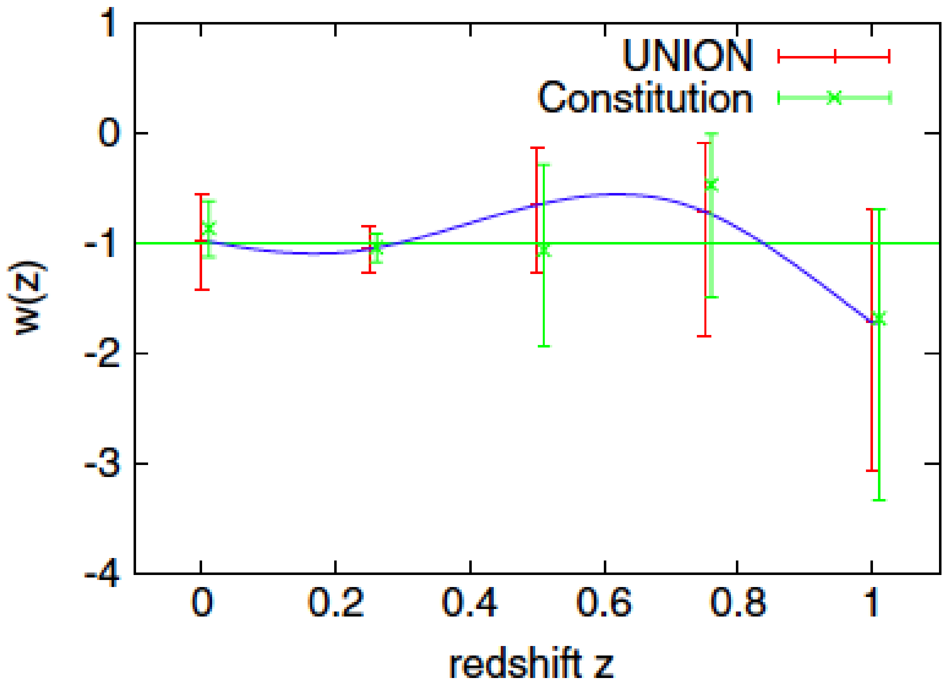
Assume flat universe.



[Serra+ 2009]

w(z) in each bin is uncorrelated.

WMAP+BAO+SNe



Determination of time variation of w is very importtant but difficult. Less than 10% accuracy is needed to discriminate various theoretical models.

Gravitational waves

- Ripple of spacetime propagating with speed of light, predicted in general relativity.

- Produced by violent change of gravitational field e.g. stellar explosion and merger

- amplitude is expected to be very small.

  $h \sim 10^{-21}$ @ ~100Hz (fractional change of distance)

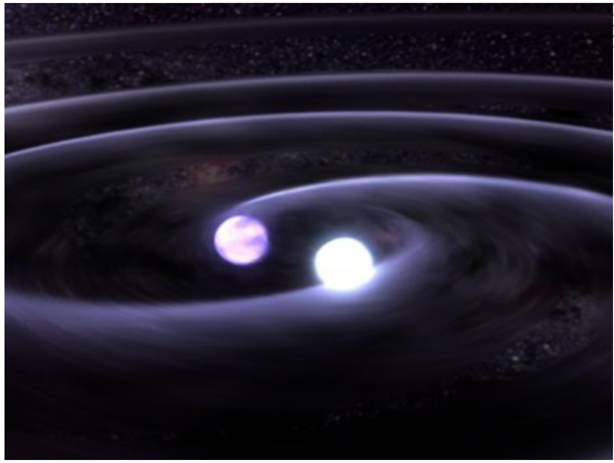
  e.g. for the distance between the earth and the sun,
  size of displacement is $\sim 10^{-10} m$ ≈ radius of hydrogen atom

- Indirect evidence of GWs (Decay of orbital period of binary pulsar, PSR B1913+16)

- Not directly detected yet in GW detectors

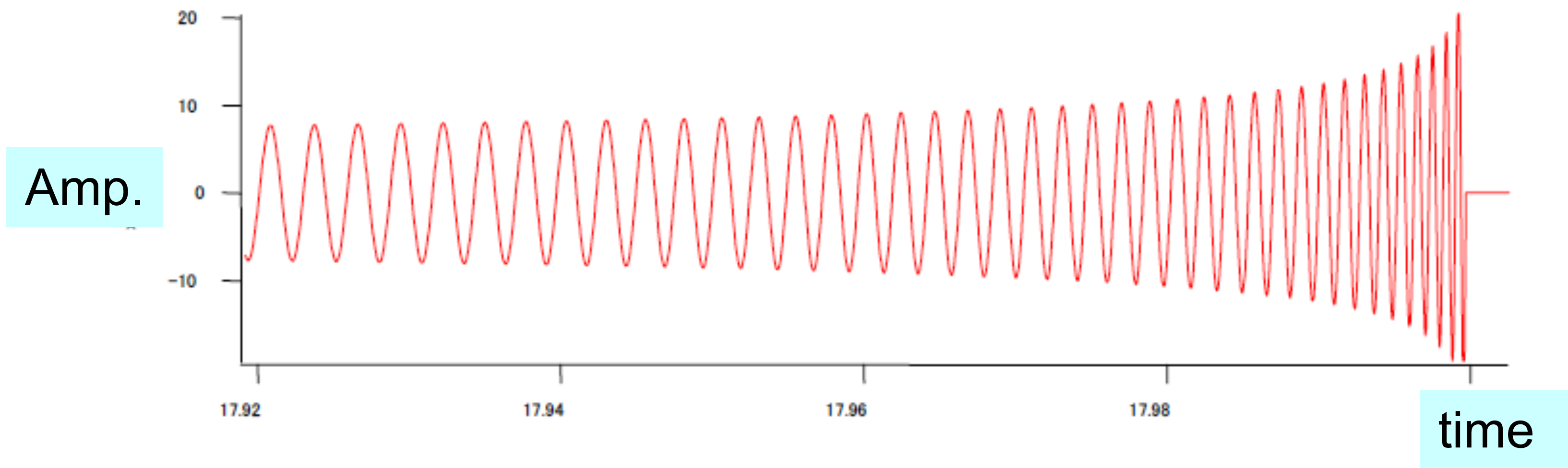
GW from inspiraling binary

Post-Newtonian theory is well developed. Given mass, spin parameters etc, the waveform can be calculated analytically.



- frequency and amplitude increase with time.

Chirp signal



- (probably) most important target source in observation.

GW standard siren

Standard siren

[Schutz 1986]

Gravitational waves from a compact binary

chirp mass

$$M_c = \frac{(m_1 m_2)^{3/5}}{(m_1 + m_2)^{1/5}}$$

$$\dot{f}(t) \propto [(1+z)M_c]^{5/3} f^{11/3},$$

GW waveform

$$h_{+\times}(t) \propto \frac{[(1+z)M_c]^{5/3} f^{2/3}}{D_L},$$

From observational data,

$$h_{+\times}, f, \dot{f},$$

$\Downarrow$

redshifted chirp mass

$$M_z \equiv (1+z)M_c$$

$\Downarrow$

luminosity distance

$$D_L;$$

However, z and Mc is degenerated.

Standard siren

The redshift can NOT determined only by GW observation.

Assuming the redshift determined by EM observation
of the host galaxy,

M_c can be determined.
z - dL relation can be obtained.

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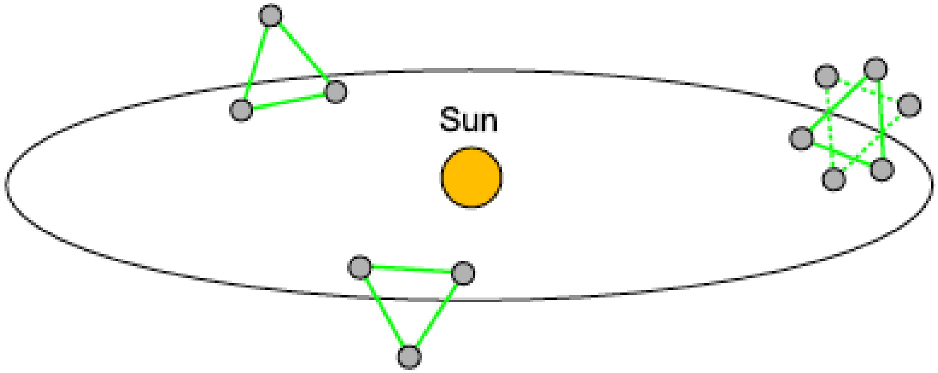
Measurement of cosmological expansion with GWs

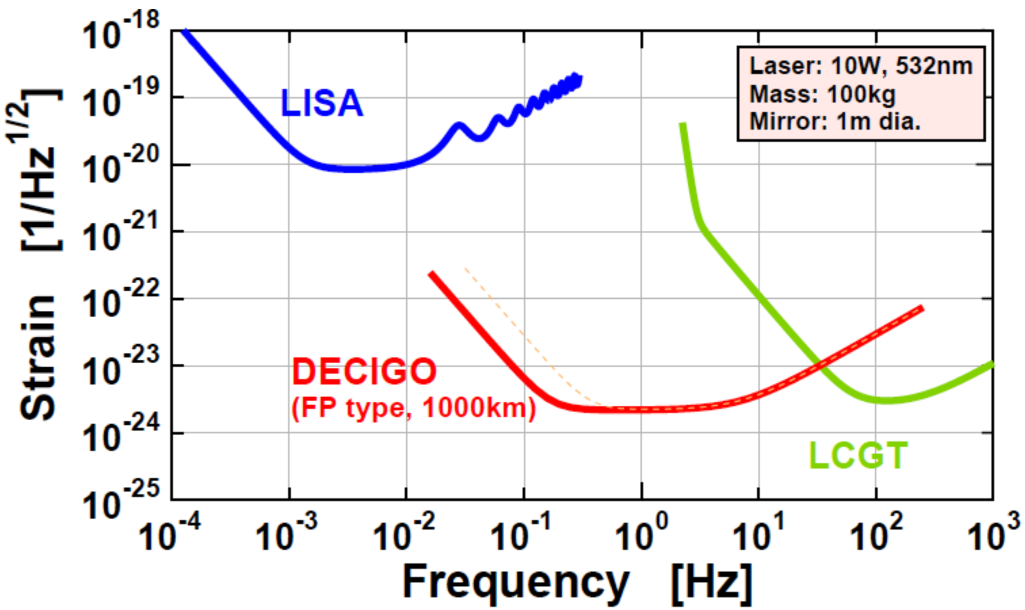
No need of distance ladder.
Consistency test of SNe observation.

GWs are powerful tool to probe for dark energy !!

DECIGO



Deci-hertz Interferometer
Gravitational wave
Observatory

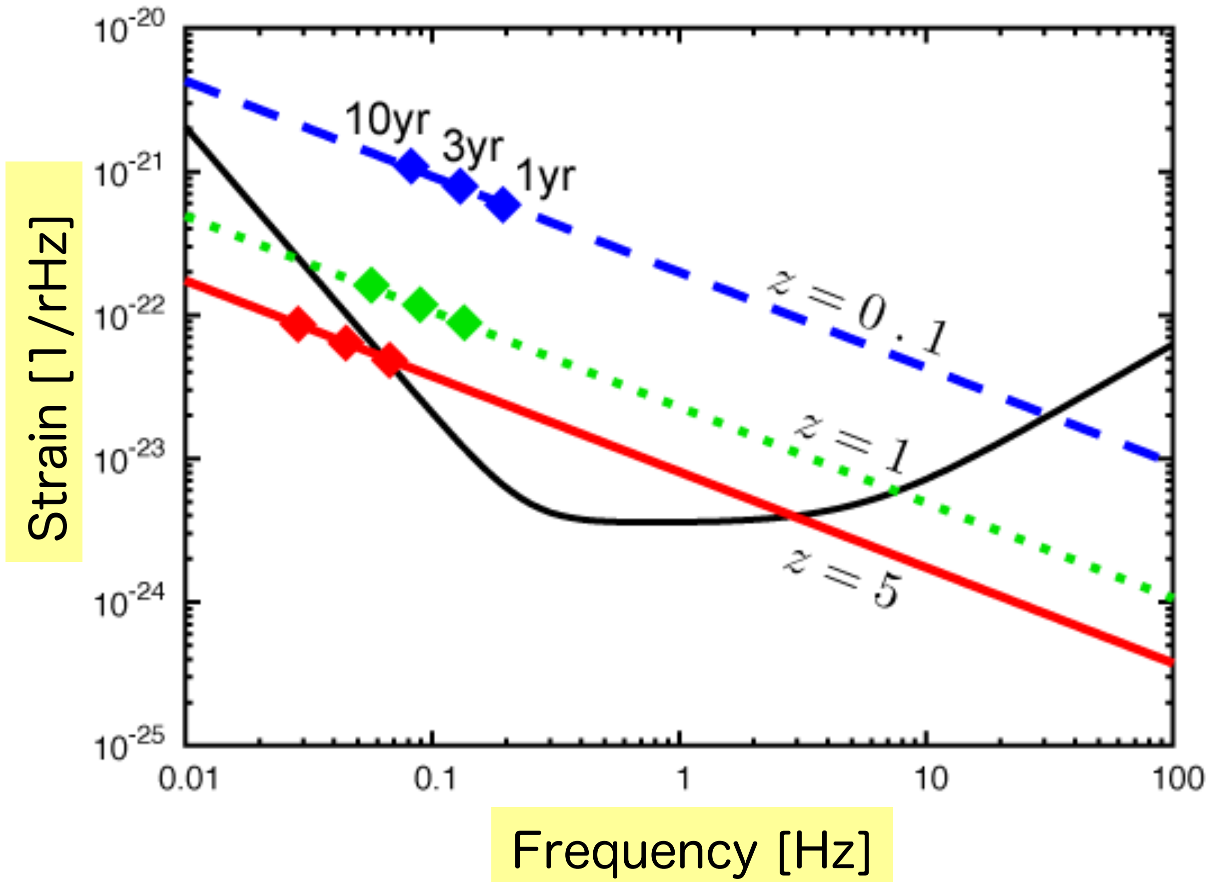


- Launch 2027-
- 4 clusters
- independent
  8 interferometers
- arm length： 1000 km
- targeted sources
  inflationary GWB,
  IMBH binaries,
  NS binaries

NS binaries seen by DECIGO

z=0.1 → S/N~700
z=1 → ~80
z=10 → ~20

$\sim 10^6$ NS binaries
up to z~5 are observable
with high SNR.

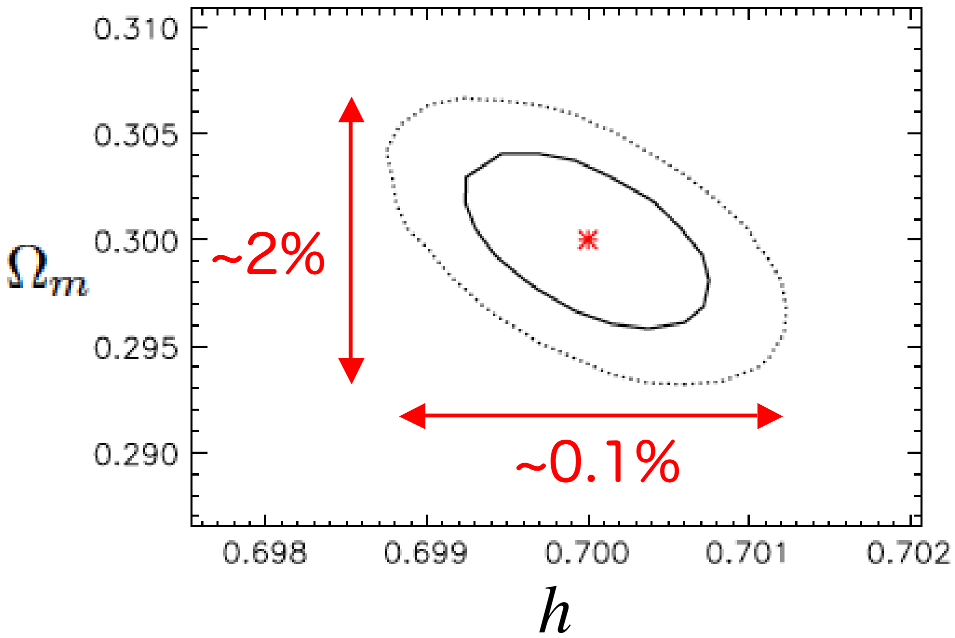


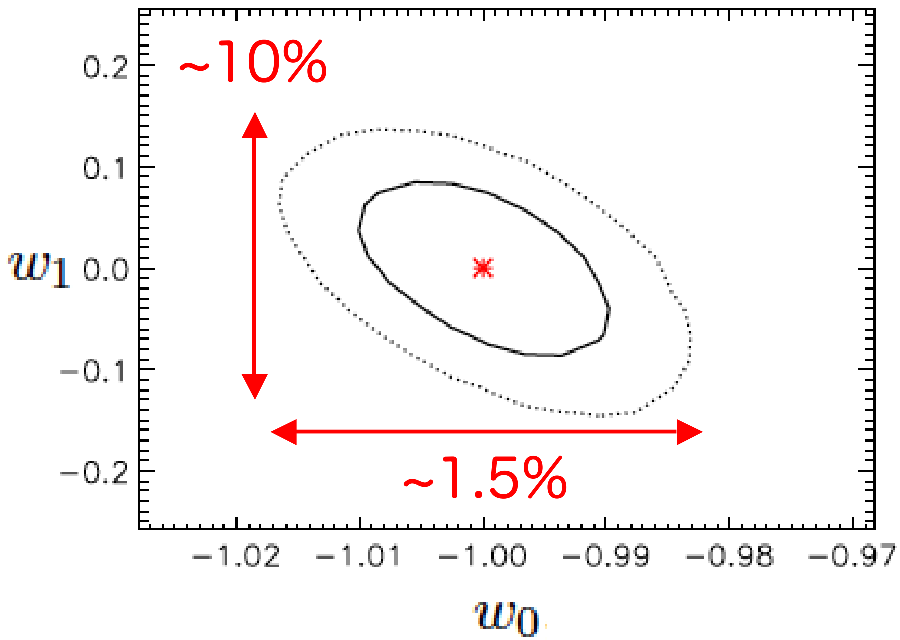
Measurement accuracy of cosmo. parameters

Using all NS binaies observed.
Determine cosmo. Parameters.

$$w(z) = w_0 + w_1 \frac{z}{1+z}$$

Flat universe, Obs. time 3yr





These accuracies are very good,
compared with EM observation !!

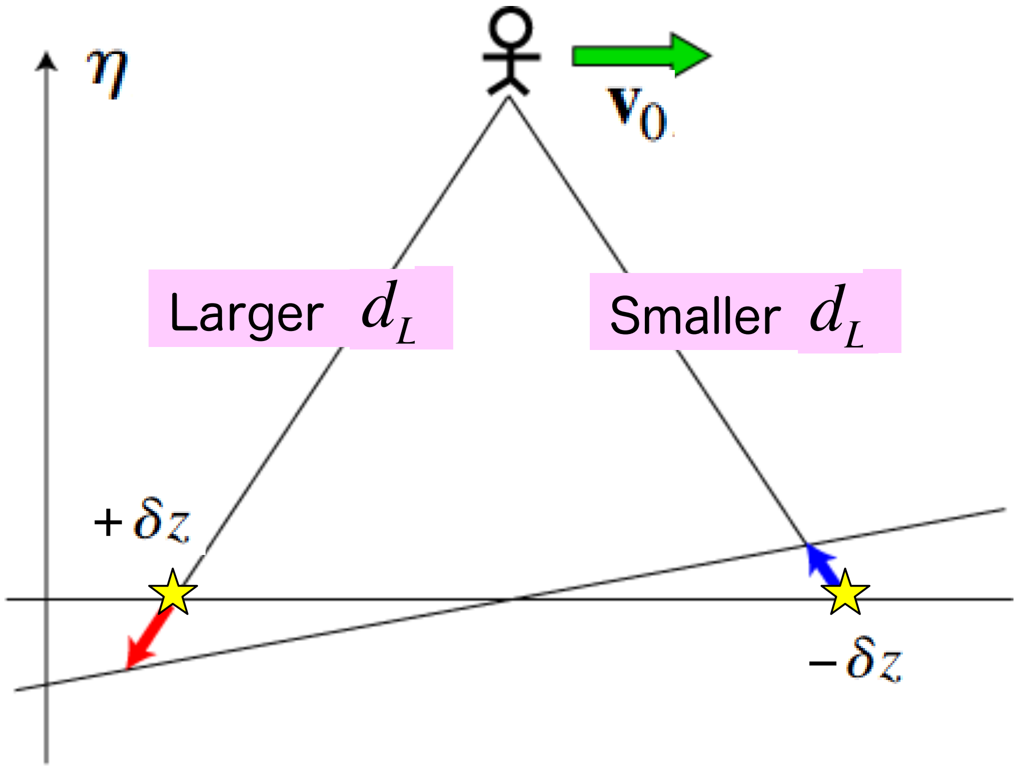
Measurement of $H(z)$

Dipole of luminosity distance

[Bonvin+ 2006]

Method was first proposed
in the context of a supernova.

Observer is at rest
relative to CMB frame.
→ We see only monopole.



Observer is moving
with respect to the CMB frame

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Luminosity of a binary
is Doppler-shifted.

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Dipole of the luminosity
Distance is induced.

Measurement of H(z)

monopole $$d_L^{(0)}(z) = \frac{1}{4\pi}\int d\Omega_{\mathbf{n}} d_L(z,\mathbf{n}) = (1+z)\int_0^z \frac{dz'}{H(z')},$$

dipole $$d_L^{(1)}(z) = \frac{3}{4\pi}\int d\Omega_{\mathbf{n}} (\mathbf{n}\cdot\mathbf{e}) d_L(z,\mathbf{n}). = \underline{\frac{|\mathbf{v}_0|(1+z)^2}{H(z)},}$$

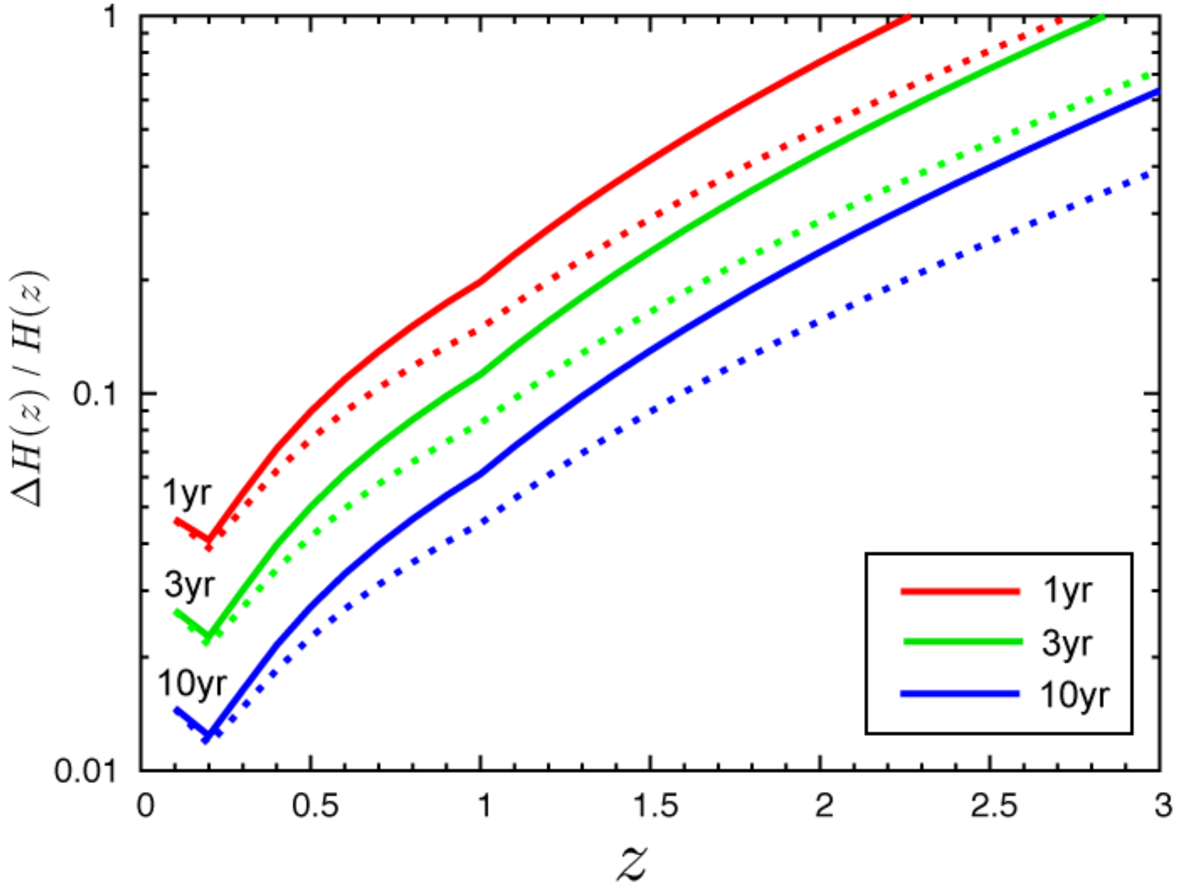
If v_0 is known from CMB measurement,
H(z) can be directly measured.

Estimate measurement accuracy of cosmological parameters with Fisher information matrix.

fiducial cosmological model
($w_0 = -1,\ w_a = 0,\ \Omega_m = 0.3,\ H_0 = 72\,\mathrm{km/sec/Mpc}$)

Measurement accuracy of H(z)

Solid curves: with lensing error,
Dotted curves: no lensing error (somehow subtracted)



Assuming 3yr observation,
H(z) can be constrained with 3-10% accuracy up to z=1.

Summary

GW standard siren is a powerful observational tool to probe for dark energy.

- **Measurement of dark energy parameters**

  Assuming the EOS of dark energy, we can determine constant w with ~1% accuracy and
  time varying w with ~10% accuracy.

- **Measurement of H(z)**

  From measurement of the dipole of luminosity distance, DECIGO can measure H(z) at 3-10% level below z=1 for 3yr observation.