Cosmology with standard sirens

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Cosmology in 1 slide

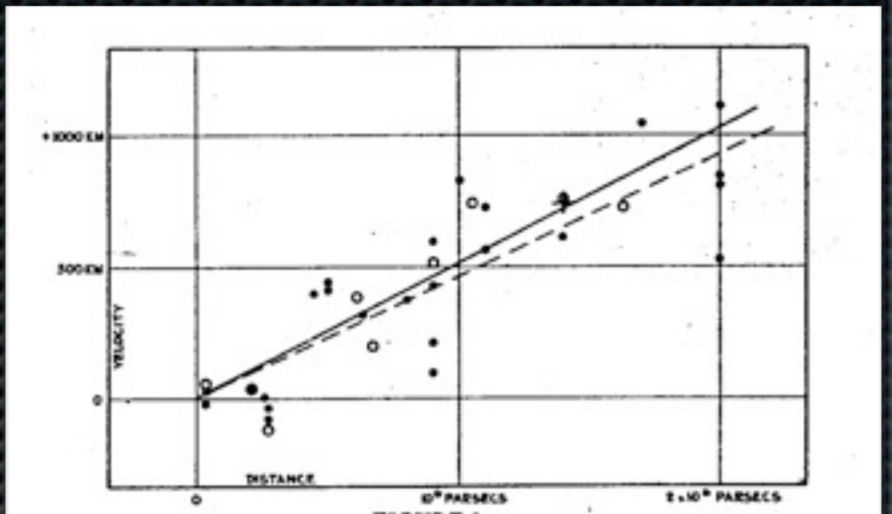
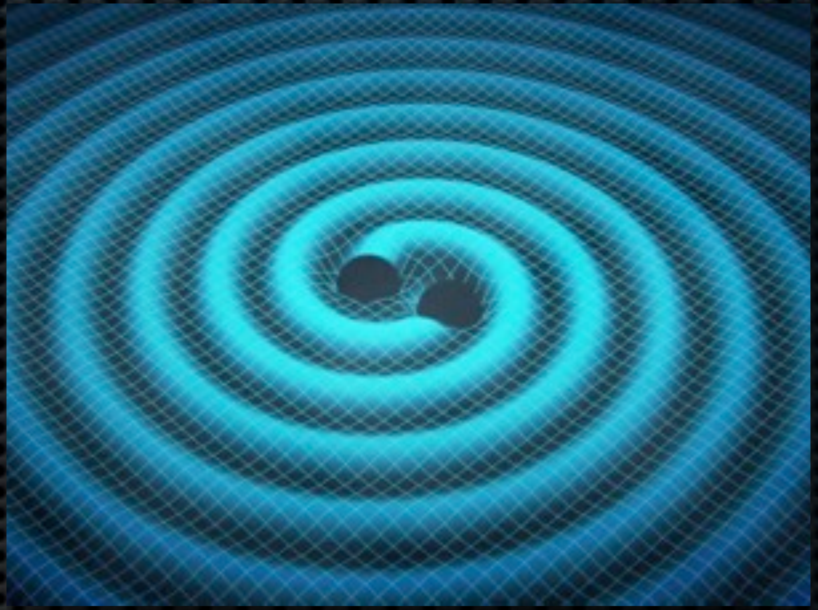


FIGURE 1

- Evolution history of the Universe?
    - distance-redshift relation
- redshift: size of Universe at time of emission
- distance: time of emission ($t = d/c$)
- measuring redshift is “easy”: take an EM spectrum
- measuring distance is hard: use standard candle, which is an object of known intrinsic luminosity. Or use a standard ruler, an object of known length.

GW standard sirens



- Black holes are "simple": they have no hair
- Binary black hole inspirals are well-modeled
- Binary black hole inspirals are understood from first principles

Schutz 1986, 2002
DH & Hughes 2005; Dalal, DH, Hughes, & Jain 2006
Arun, Iyer, Sathyaprakash, Sinha, & Van Den Broeck 2007
Cutler and DH 2009; Nissanke et al. 2010, 2013
Petiteau, Babak, & Sesana 2011

GWs from binary systems

- Strongest harmonic (widely separated):

$$h(t) = \frac{M_z^{5/3} f(t)^{2/3}}{D_L} F(\mathrm{angles}) \cos(\Phi(t))$$

- dimensionless strain $h(t)$
- luminosity distance D_L
- accumulated GW phase $\Phi(t)$
- GW frequency $f(t) = (1/2\pi) d\Phi/dt$
- position & orientation dependence $F(\mathrm{angles})$
- (redshifted) chirp mass:

$$M_z = (1+z)(m_1 m_2)^{3/5}/(m_1+m_2)^{1/5}$$

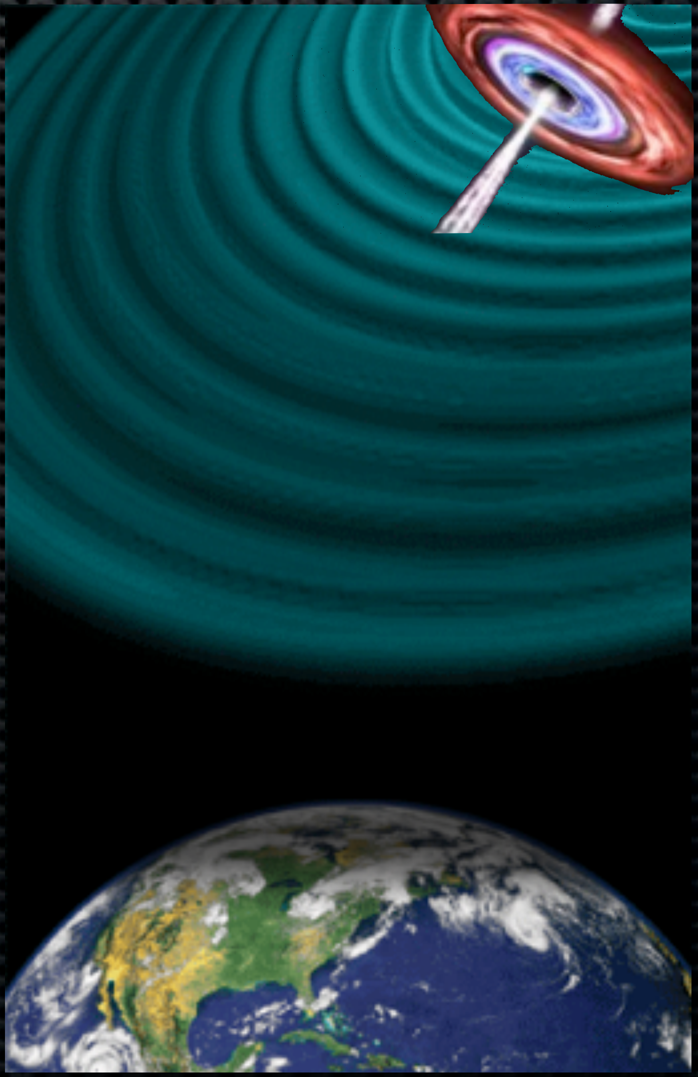
Distance, but not redshift

- Gravitational waves provide a direct measure of luminosity distance, but they give no independent information about redshift
- Gravitation is scale-free
  - GWs from a local binary with masses (m_1, m_2) are indistinguishable from masses $\left(\frac{m_1}{1+z}, \frac{m_2}{1+z}\right)$ at redshift z
- To measure cosmology, need independent measurement of redshift:

● electromagnetic counterpart

Potential standard sirens

- LIGO: stellar-mass binaries
- *eLISA*: supermassive binary black holes
- *BBO*: stellar-mass binaries



Calculations are for LISA, not eLISA!

- Qualitative message is the same
- Quantitative mesage may be different!

Supermassive binary black hole (SMBBH) standard sirens

- *eLISA* will see SMBBH mergers throughout the Universe
    - $10^{5.5}\,M_\odot$ BH binaries fall in sweetspot
    - Detect these out to $z \sim 10$
    - good mass coverage in range 10^4–$10^7\,M_\odot$
- *eLISA* can observe inspiral for ~months
    - use orbital modulation to infer sky position. measure this to ~1–10 deg
    - determine luminosity distance with accuracy (~1%–50%)
- Need “optical” counterpart for cosmology

Can we identify the host galaxy?

Error box contains ~10^1–10^3 galaxies

- use rough knowledge of cosmology to narrow the potential redshift range of host galaxies
- locate galaxies that are morphologically promising (e.g., merging galaxies, tidal tails, irregulars)
- calculate distances to all possible hosts, and demand concordance across multiple sources
- use statistical knowledge of source population
- use phase effects from changing Hubble

✱ Look for something that goes bang

“Optical” counterpart?

- Roughly 5% of system’s mass is being released in gravitational waves (~10^{58} ergs)
- Even if only one part in 10^{10} of the available energy is converted into photons, would easily detect optical source at high redshift
- Need phenomenal efficiency to remain invisible in electromagnetic band

“Optical” counterpart?

- Can select morphologically promising targets
- Can use wide-field, deep instruments
    - Optical, X-ray, Radio, . . .
- Can fully cover *LISA* error box
- Can predict time of merger
- Is there an optical counterpart?
    - galaxy mergers are cataclysmic events
    - some modeling suggests counterparts:

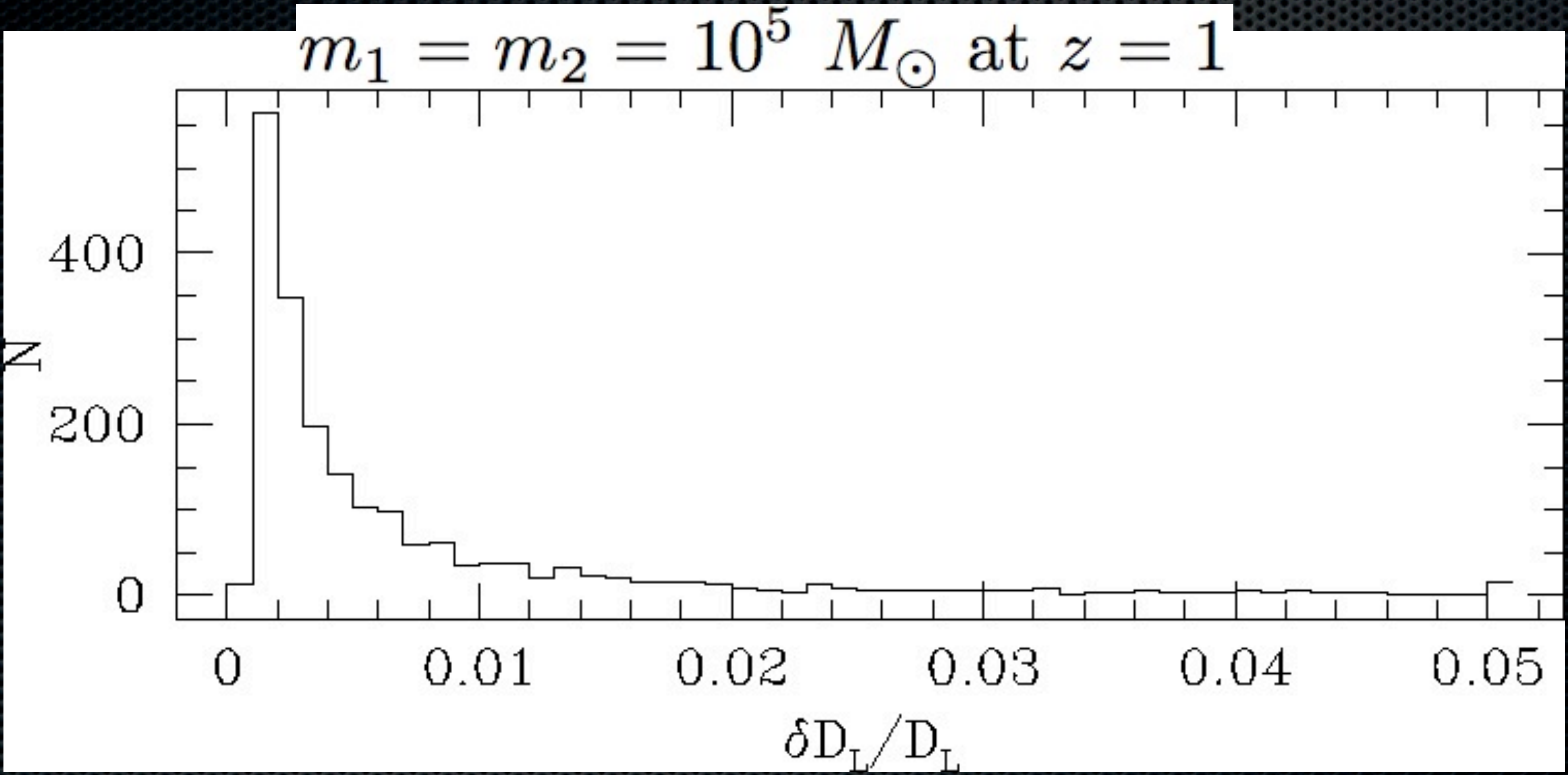
      Gas driven onto larger BH: super-Eddington accretion, outflows/jets. Delayed afterglows: inspiral hollows out circumbinary gas, which subsequently infalls after merger; GW “monopole” from energy loss; Shear in accretion disk; BH recoil causes shocks; AGN variability

Begelman, Blandford & Rees 1980; Goldreich & Tremaine 1980; Armitage & Natarajan 2002
Milosavljevic & Phinney 2004; Kocsis, Frei, Haiman, & Menou 2006; Dotti et al. 2006
Bode & Phinney 2007; Kocsis, Haiman & Loeb 2012; Farris et al. 2012; Roedig et al. 2012

What good is a counterpart?

- Determination of redshift
    - puts a point on the luminosity distance-redshift curve
- Precise location of GW source
    - drastic improvement in GW modeling, and hence distance determination

Distance determination



Luminosity distance to much better than 1%

- Fantastic cosmological distance measurement

Gravity giveth, and gravity taketh away

Gravitational lensing

- Data in cosmology comes almost exclusively from the observation of distant photons
- In interpreting this data, a uniform, isotropic Friedmann-Robertson-Walker universe is generally assumed. Key assumption: homogeneous matter
- The Universe is mostly vacuum, with occasional areas of high density
- Photons do not experience FRW
- Gravitational lensing due to matter inhomogeneities causes a change in brightness of observed images

  strong lensing: multiple images

  weak lensing: percent-level effects

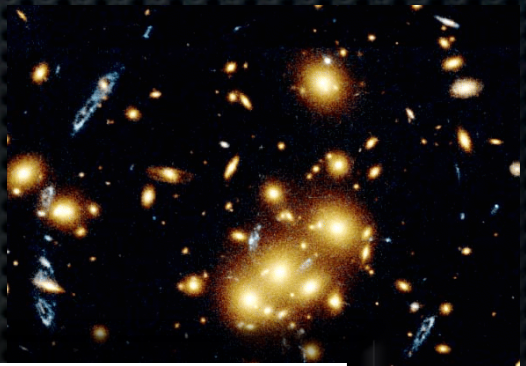
Lensing is hard to fix

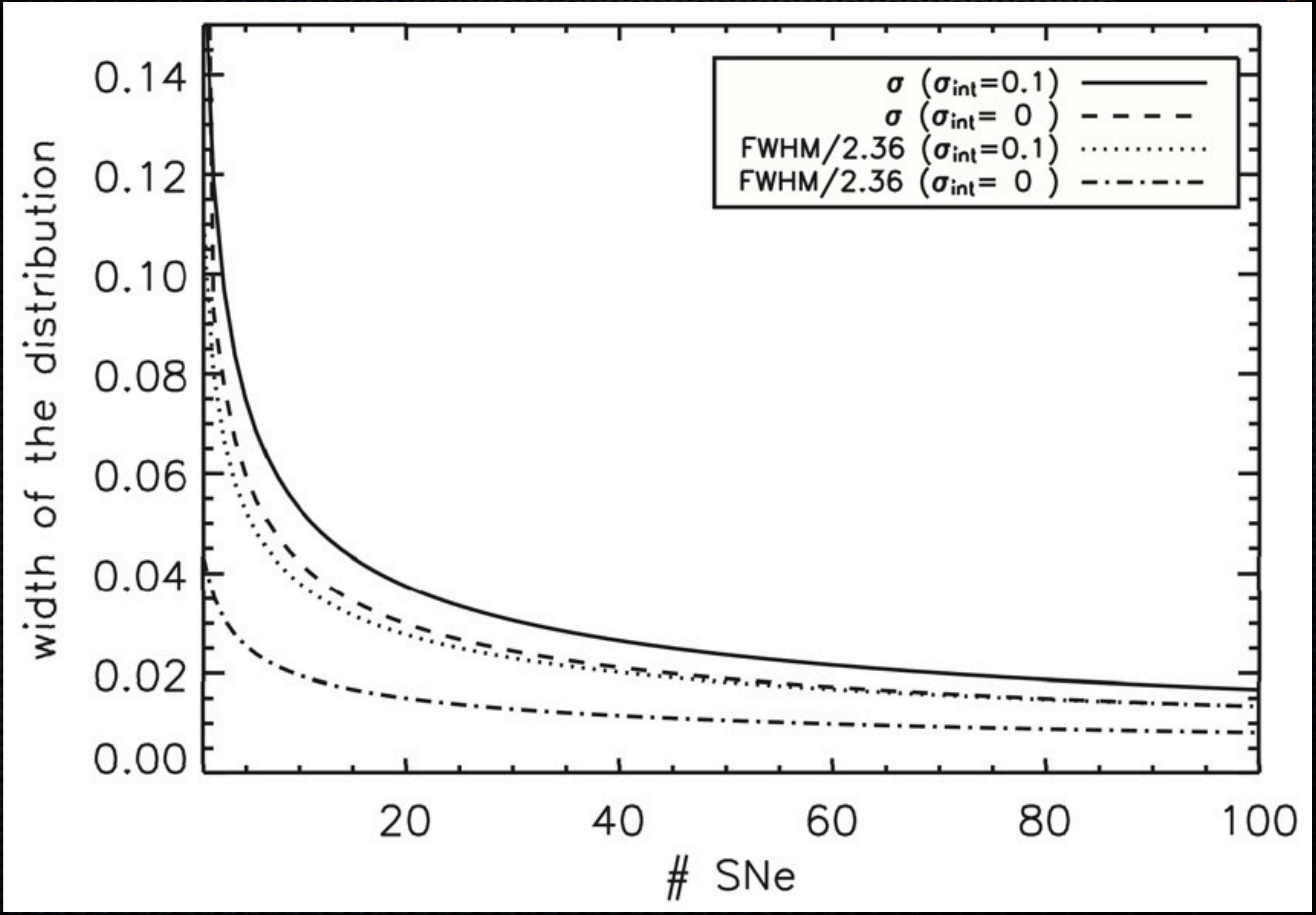
- At high redshift, the “noise” due to lensing is comparable to the intrinsic noise of type Ia supernovae, and dwarfs standard siren precision
- The lensing noise is non-Gaussian, and can therefore lead to bias in parameter estimation
- Can we correct for gravitational lensing on a case-by-case basis?
  - direct lens reconstruction: identify luminous objects along the line-of-sight, estimate the mass, and calculate the lensing effects
  - complementary weak-lensing map: use deep images of surrounding field to observe lensing shear, invert to a mass map, and calculate lensing

Lensing averages away

- Gravitational lensing moves photons around, but does not create or destroy them (i.e. lensing conserves surface brightness)
- For sufficient numbers of sources, can average away the effects of lensing
- How many standard sirens sources do we need to measure cosmology instead of lensing?

Lensing averages away





How many SMBBH sources will eLISA hear?

- We don’t know
- Lots of approaches: mostly based on putting BHs into (galaxies put into) dark matter halos from cosmological N-body simulations
- Lots of uncertainties: BH formation (pop III or direct collapse?), BH seed masses, galaxy evolution and mergers, BH accretion, BH binary formation and inspiral processes, etc. etc.

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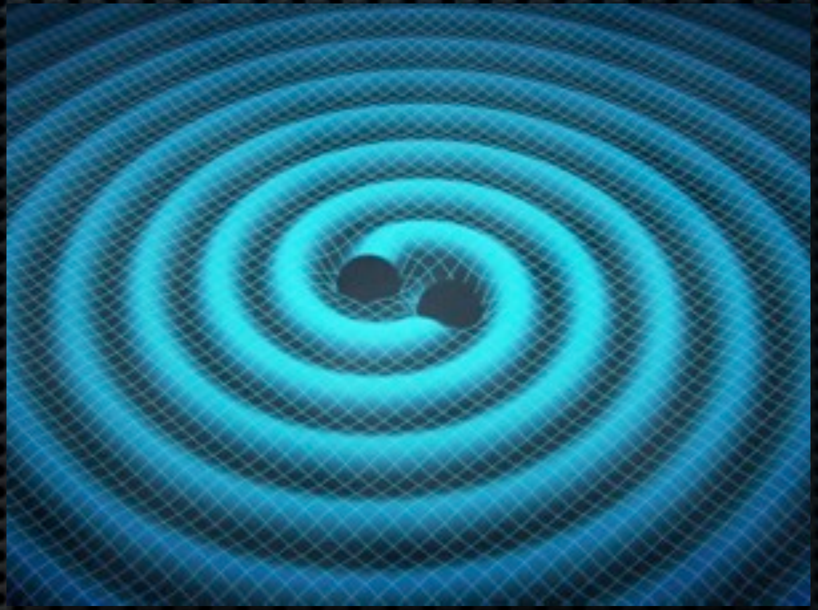
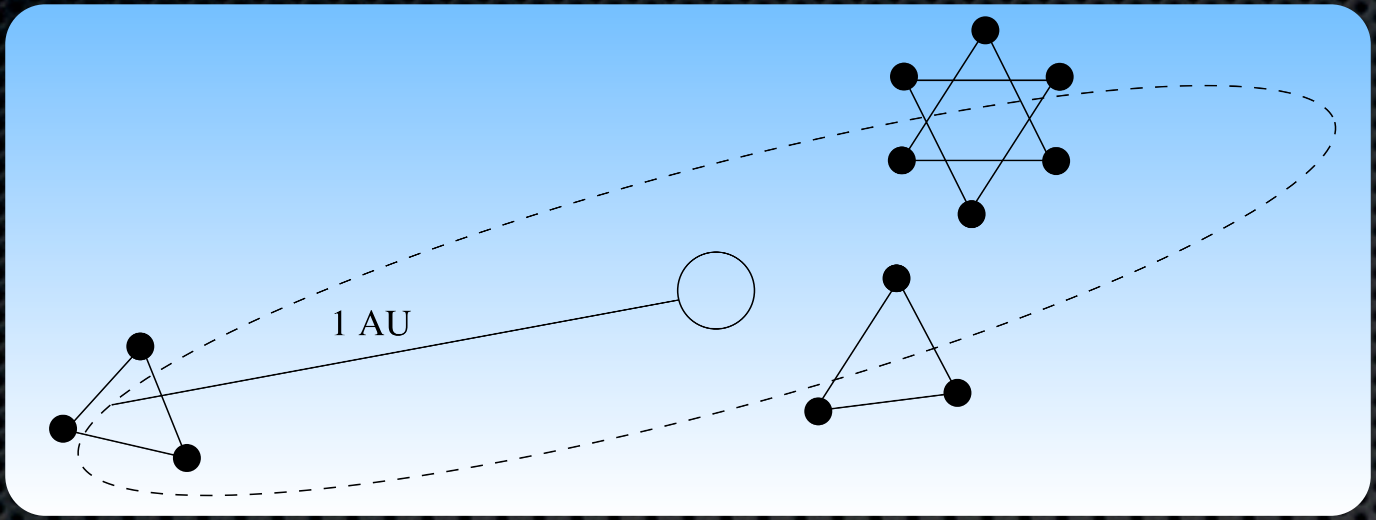


- Systematic-free (at least, compared to most other probes)
- For sufficient statistics, gravitational lensing effects can be averaged away
- Probes all redshifts
- 30 eLISA sirens at $z<2$ measures DE to <5%
- 100 eLISA sirens equivalent to 3,000 SNe

Big Bang Observer

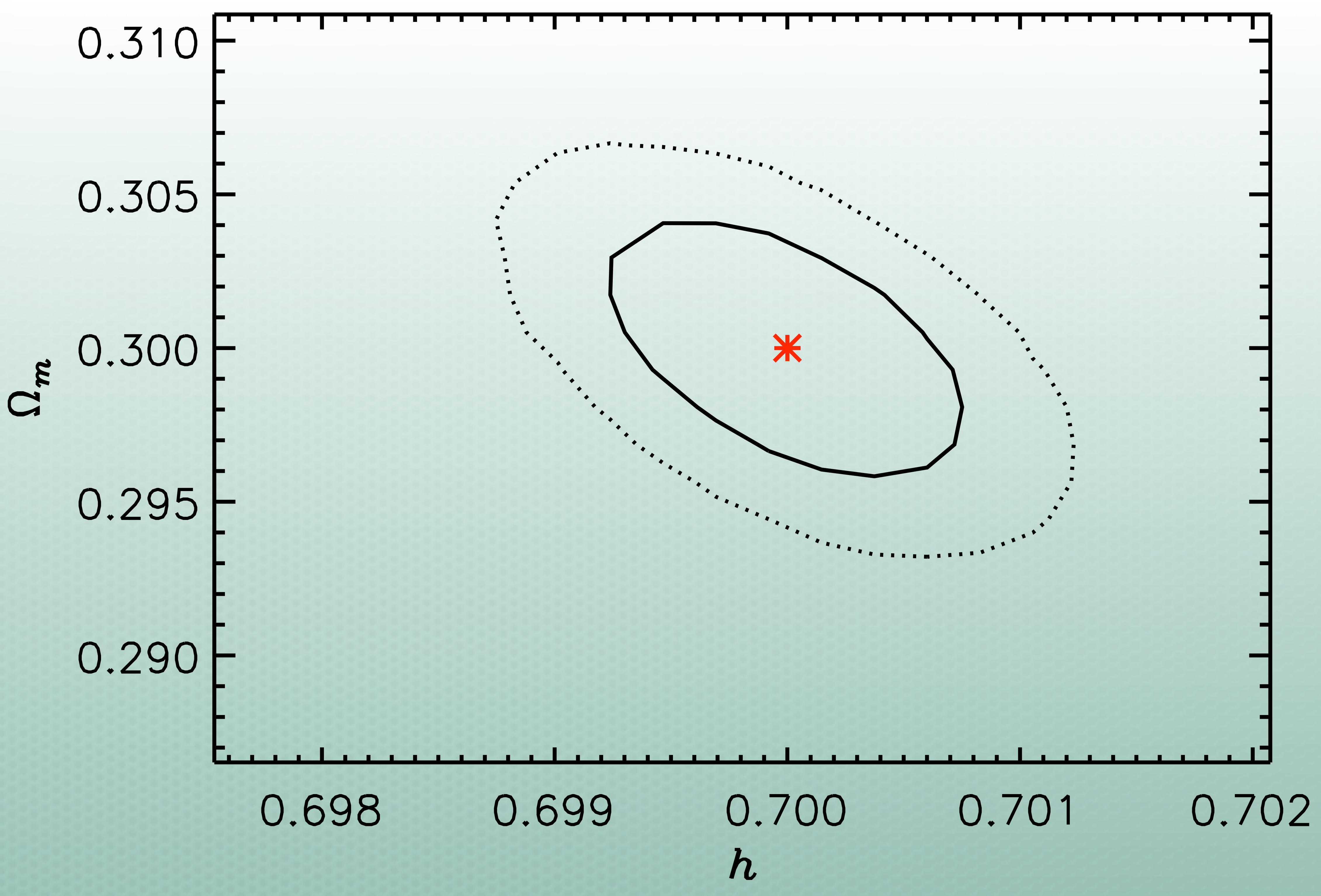


- BBO sees $\sim 10^5$ NS-NS binaries to $z \sim 5$
- BBO sky localization uniquely identifies host
  - Extraordinary measurement of luminosity distance-redshift relation
  - Extraordinary measurement of gravitational lensing (and hence structure formation)

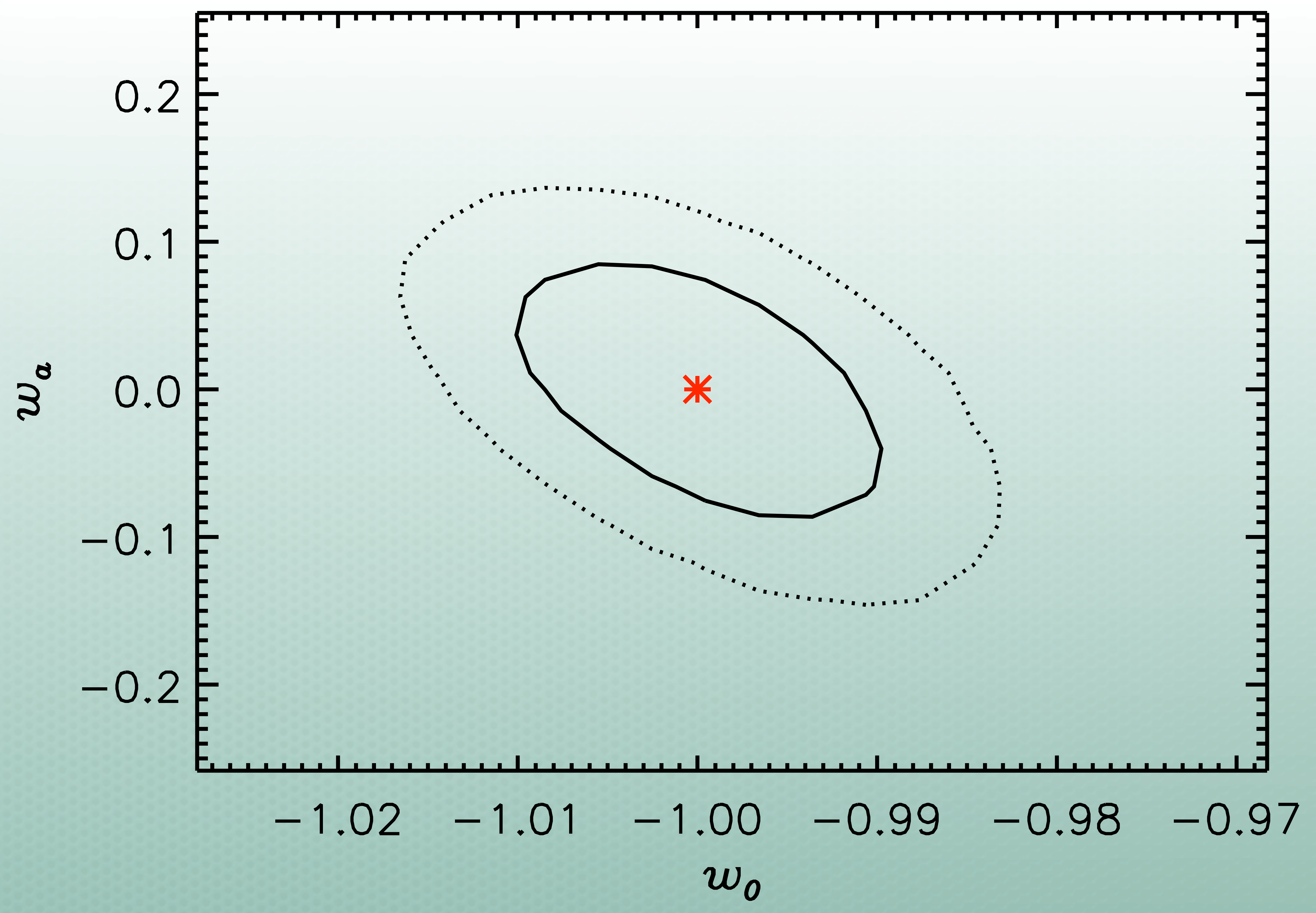
● Ultra-precise cosmology

Cutler & DH 2009

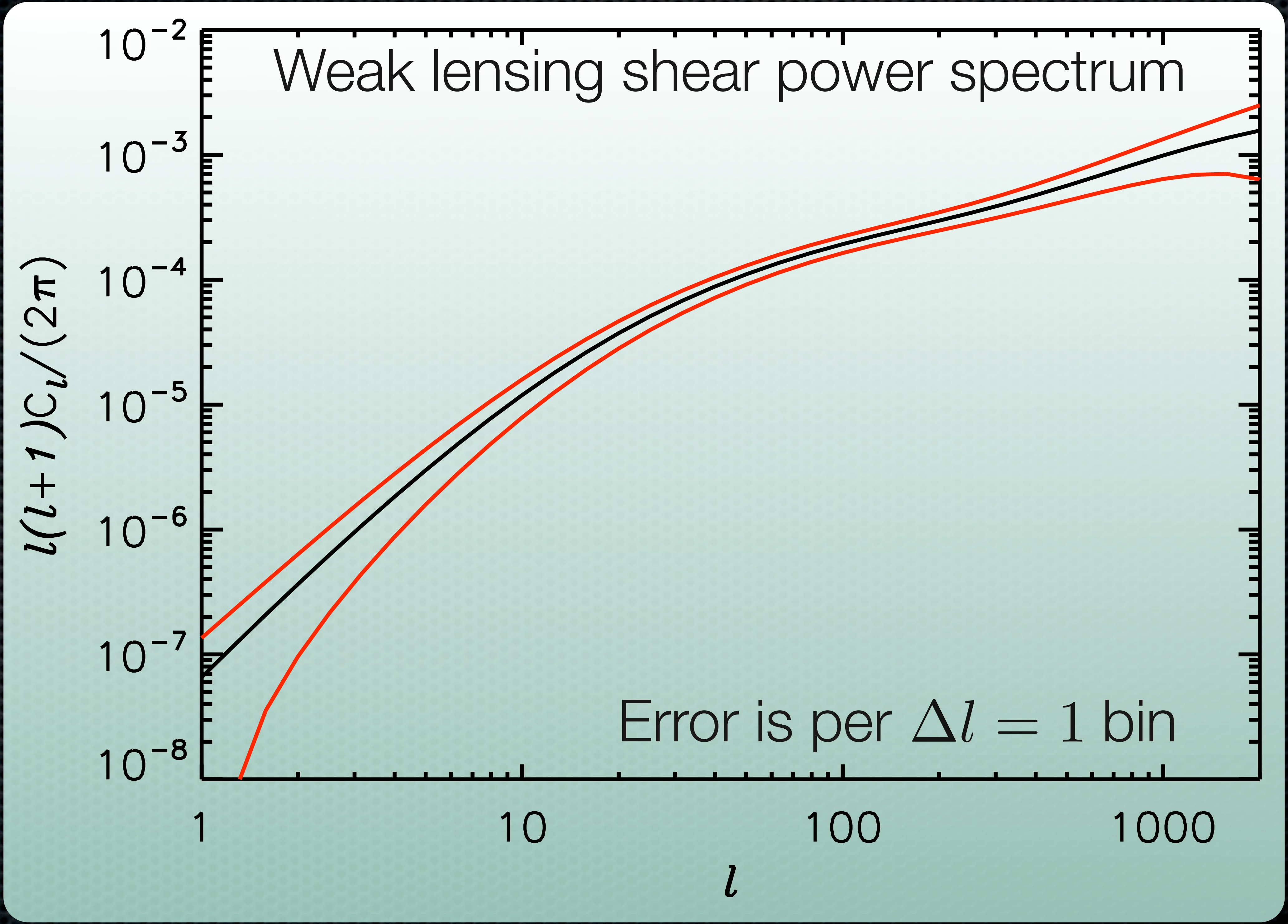
Hubble constant to 0.1%



Evolving dark energy to ~5%



Growth of structure to unprecedented precision



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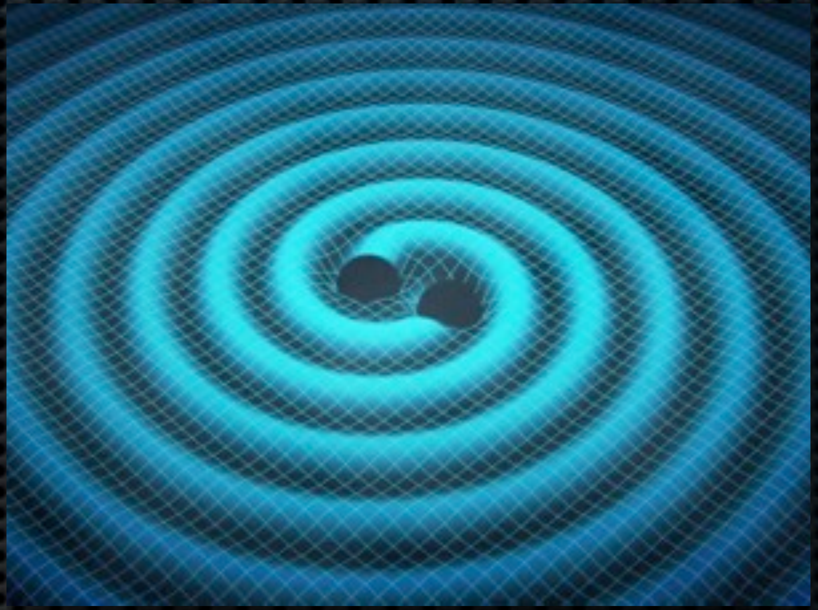

- Supermassive black hole binaries can be used as GW standard sirens
  - Need an EM counterpart to get a redshift
  - Need sufficient statistics to overcome lensing
- Standard sirens offer a uniquely clean and powerful method to measure the luminosity distnace relation and the growth of structure