Gravitational-Wave Standard Sirens

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Standard Candles

- Type Ia supernovae are good standard candles
  - intrinsic luminosity can be calibrated to ~15%
  - phenomenology, not physics, underlies calibration
  - worry about evolution, systematics, etc.

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Can we do better?

Holz & Hughes 2005, ApJ, 629, 15

Gravitational-wave Standard Sirens

- Black holes have no hair
- Binary black hole inspirals are potentially excellent standard candles
- Well modeled, “simple” systems

Gravitational-wave Standard Sirens

Strongest harmonic:
(wide separation)

$$h(t) = \frac{{M_z}^{5/3} f(t)^{2/3}}{D_L} F(\text{angles}) \cos\left[\Phi(t)\right]$$

$h(t)$ dimensionless strain

see talk by Emanuele Berti

D_L luminosity distance

$\Phi(t)$ accumulated GW phase

$f(t) = (1/2\pi)\, d\Phi/dt$ GW frequency

$F(\text{angles})$ position & orientation dependence

(redshifted) chirp mass:

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

Schutz 1986, Nature 323, 310; Schutz 2001, gr-qc/0111095; Chernoff & Finn 1993, ApJ 411, L5; Finn 1996, PRD 53, 2878; Wang & Turner 1997, PRD 56, 724

Supermassive black-hole binaries and *LISA*

- *LISA* will see SMBBH mergers throughout the Universe
  - $10^5\ M_\odot$ BH binaries fall in *LISA*'s sweetspot
  - *LISA* sees these out to $z \sim 10$
  - good mass coverage in range 10^5–$10^7\ M_\odot$

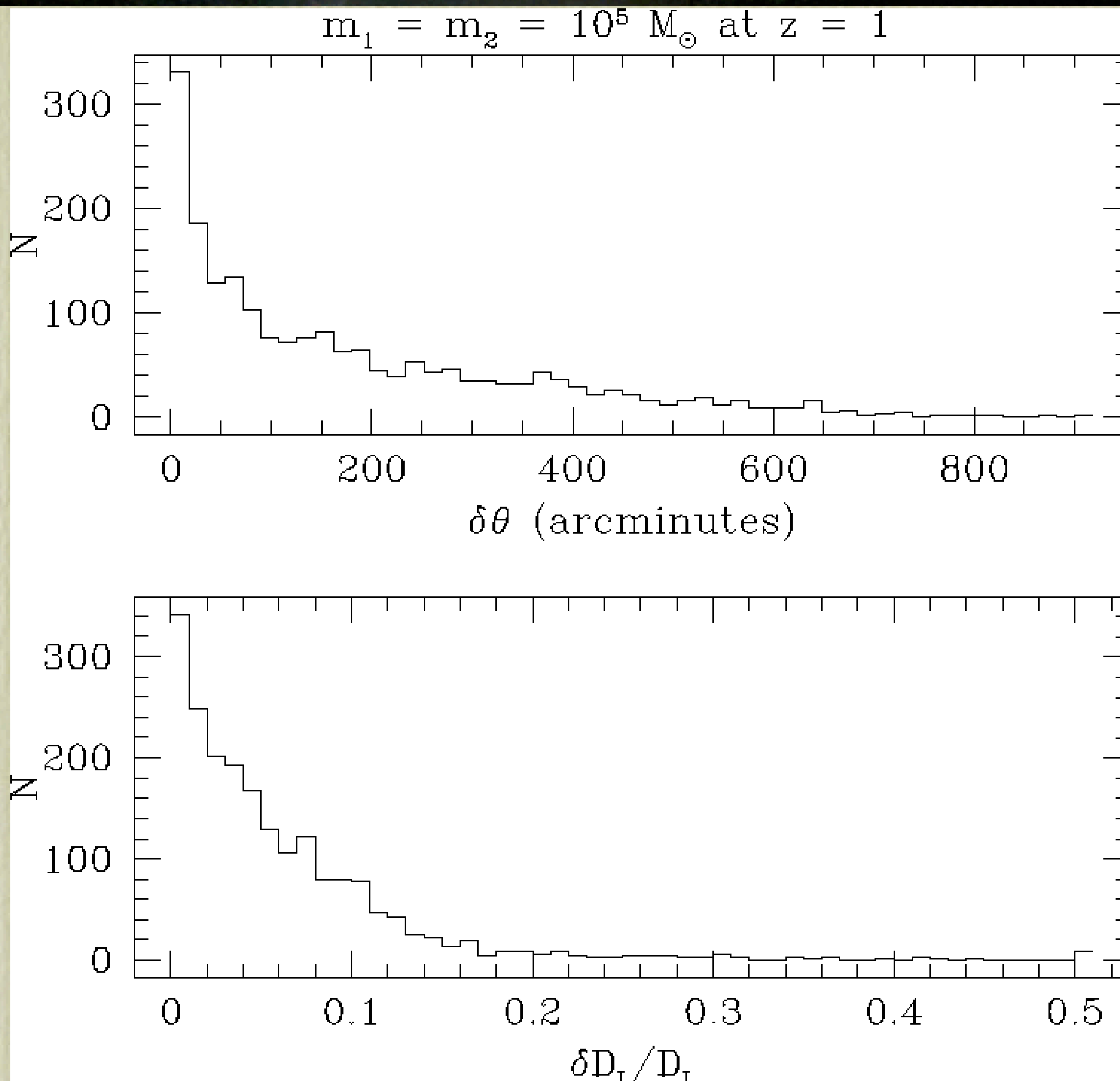
- *LISA* can observe inspiral for ~ 1 year
  - use orbital modulation to infer sky position
  - determine luminosity distance with reasonable accuracy (10%)

see talks by Tuck Stebbins, Pete Bender, Marta Volonteri, Martin Haehnelt, David Merritt, Savvas Koushiappas

Luminosity-distance determination from *LISA*

Sky position

Luminosity distance



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
    - GW signal from a local binary with masses (m_1, m_2) is indistinguishable from a binary with masses $(m_1/(1+z), m_2/(1+z))$ at redshift z
- If one assumes cosmology, then can infer redshift
- To measure cosmology, need an independent determination of redshift

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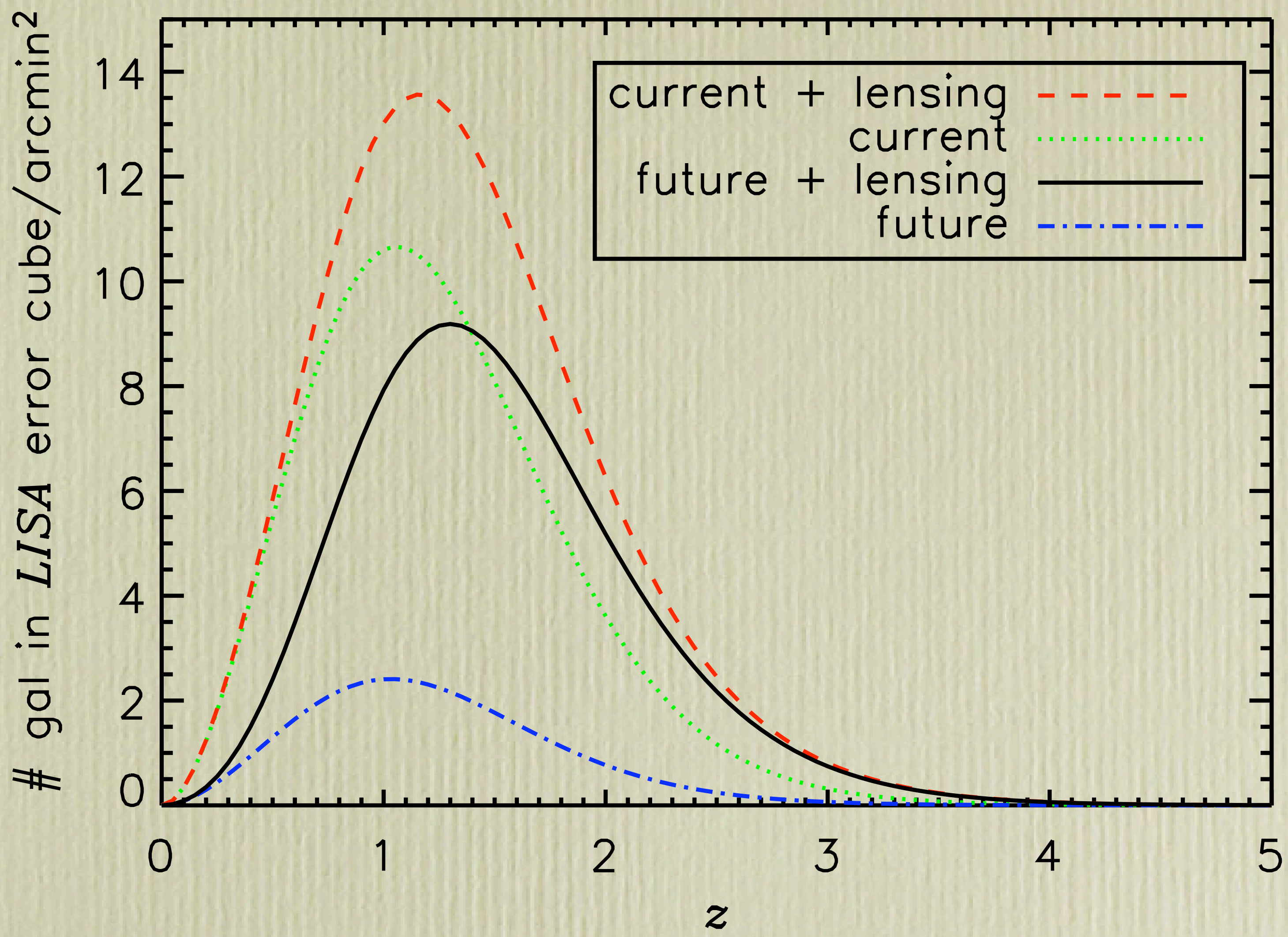
Electromagnetic counterpart!

Can we identify the host galaxy?



Can we identify the host galaxy?

- *LISA* error box, even in the best of cases, contains many handfuls of galaxies
    - use rough knowledge of cosmology to narrow the potential redshift range of host galaxies
    - locate galaxies that are morphologically promising
        - merging galaxies, tidal tails, irregulars
    - calculate distances to all possible hosts, and demand concordance across multiple sources
    - use statistical knowledge of source population

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Look for something that goes BANG

“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 within binary is driven onto larger BH: super-Eddington accretion, outflows/jets
    - delayed afterglows: inspiral hollows out circumbinary gas, which subsequently infalls after merger

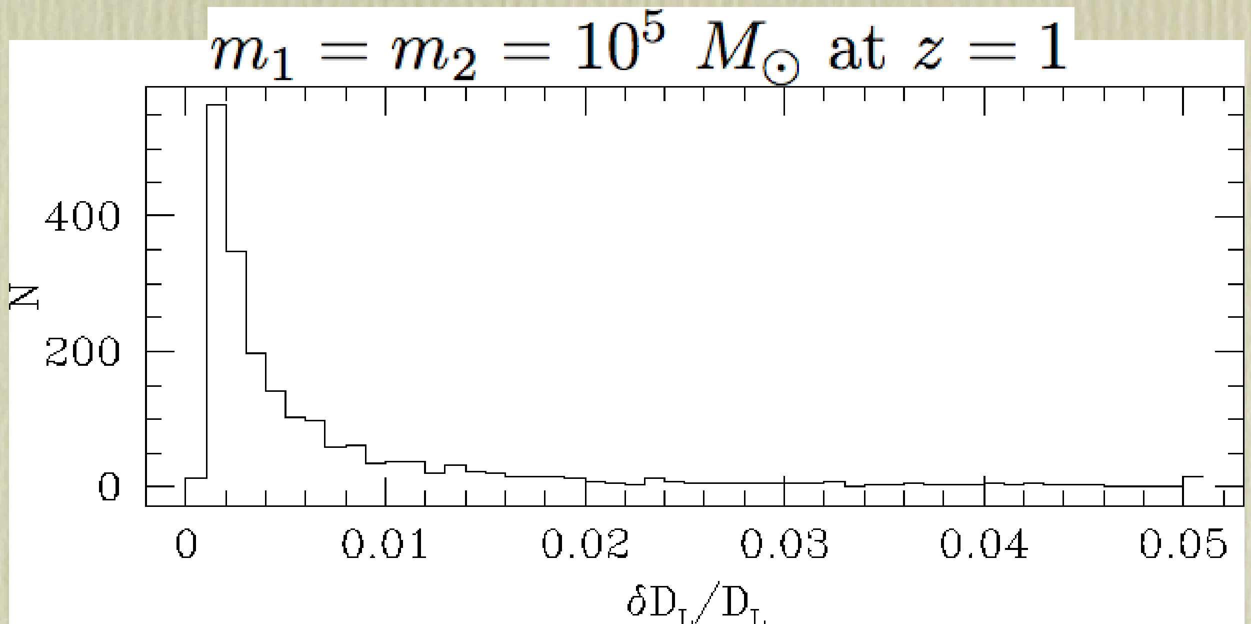
see talks by
Milos Milosavljevic,
Monica Colpi

Begelman, Blandford, & Rees 1980
Armitage & Natarajan 2002; Milosavljevic & Phinney 2004

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

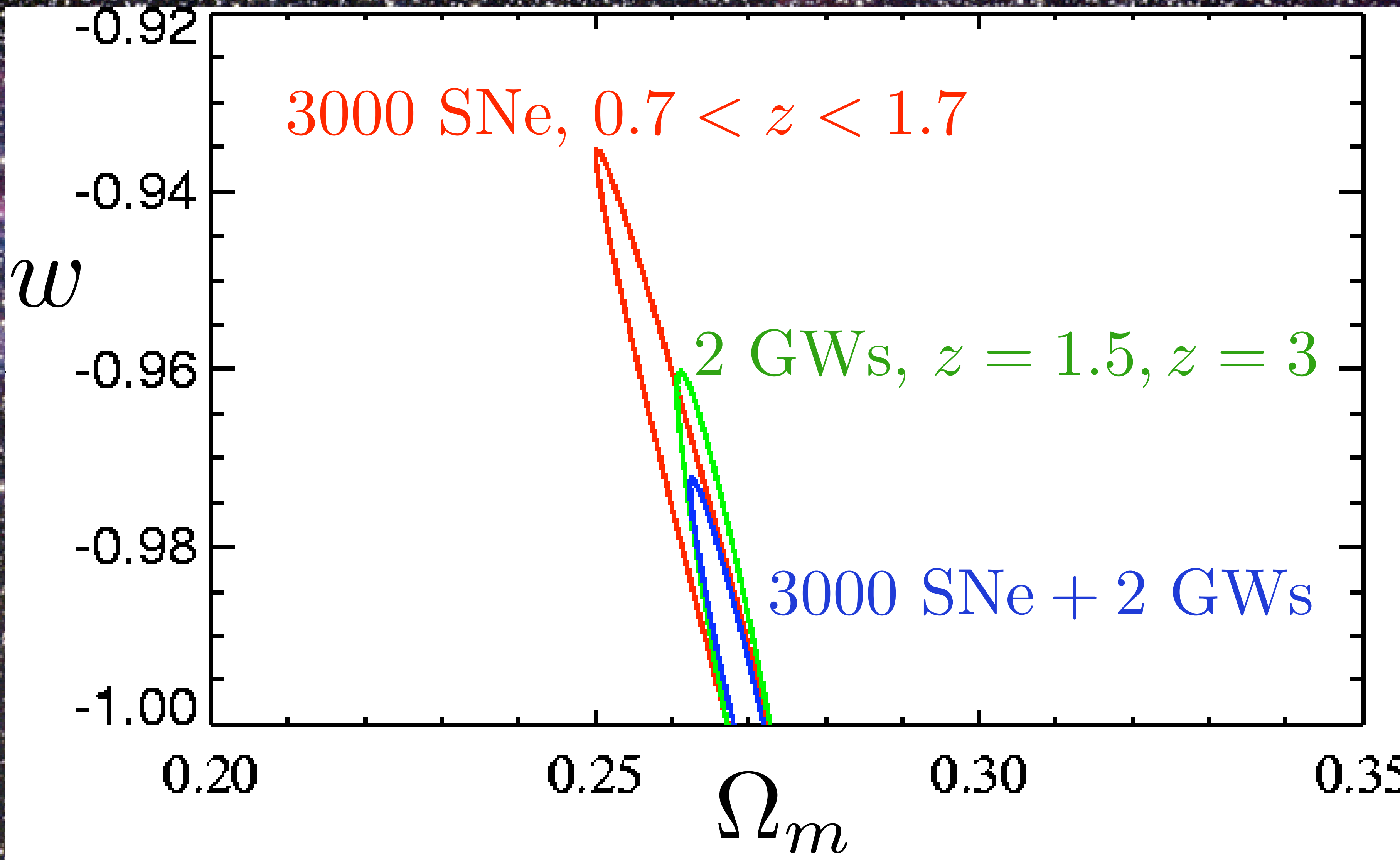
Distance determination with counterpart

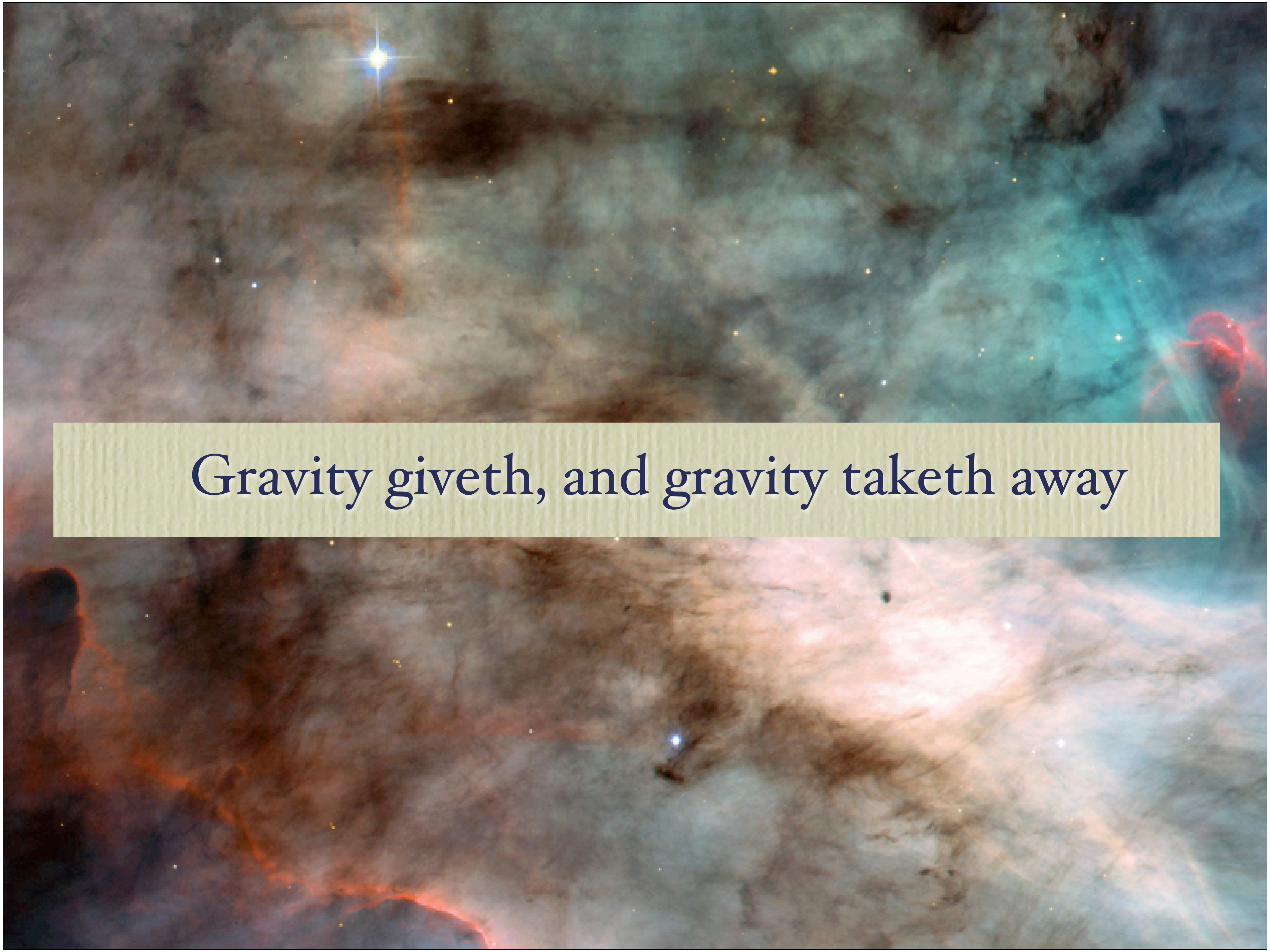


Luminosity distance to much better than 1 percent

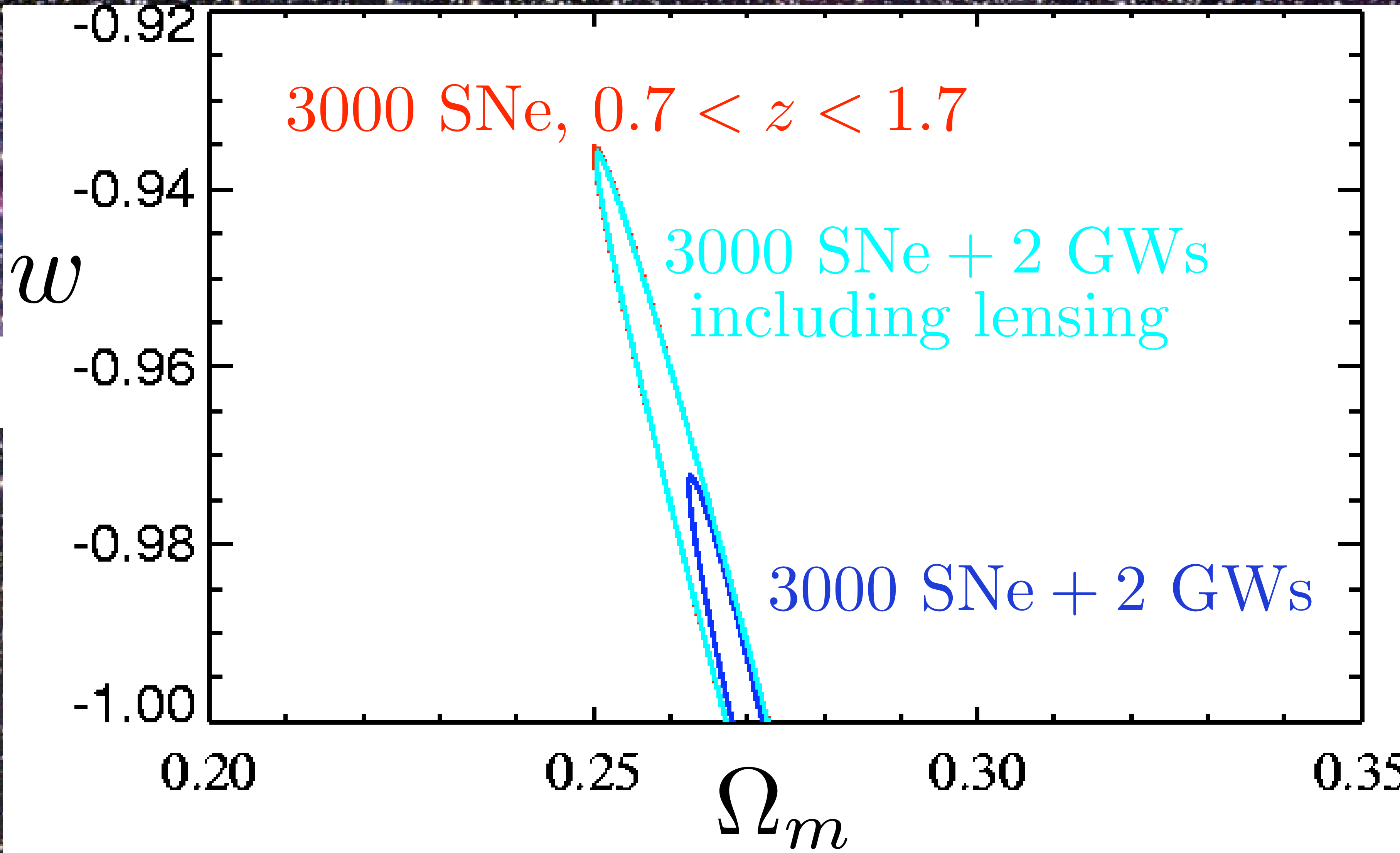
- Ultimate standard candle!!

Precision Cosmology




Gravity giveth, and gravity taketh away

Gravitational lensing



Conclusions

- Supermassive binary black holes offer perhaps the best high-redshift distance determination
    - need to identify electromagnetic counterpart
    - luminosity distance to better than a percent
- Gravitational lensing significantly degrades the distance measurement, and hence cosmological utility
- Gravitational-wave standard sirens will be an important, independent cosmological probe