Title: Cosmology from gravitational waves

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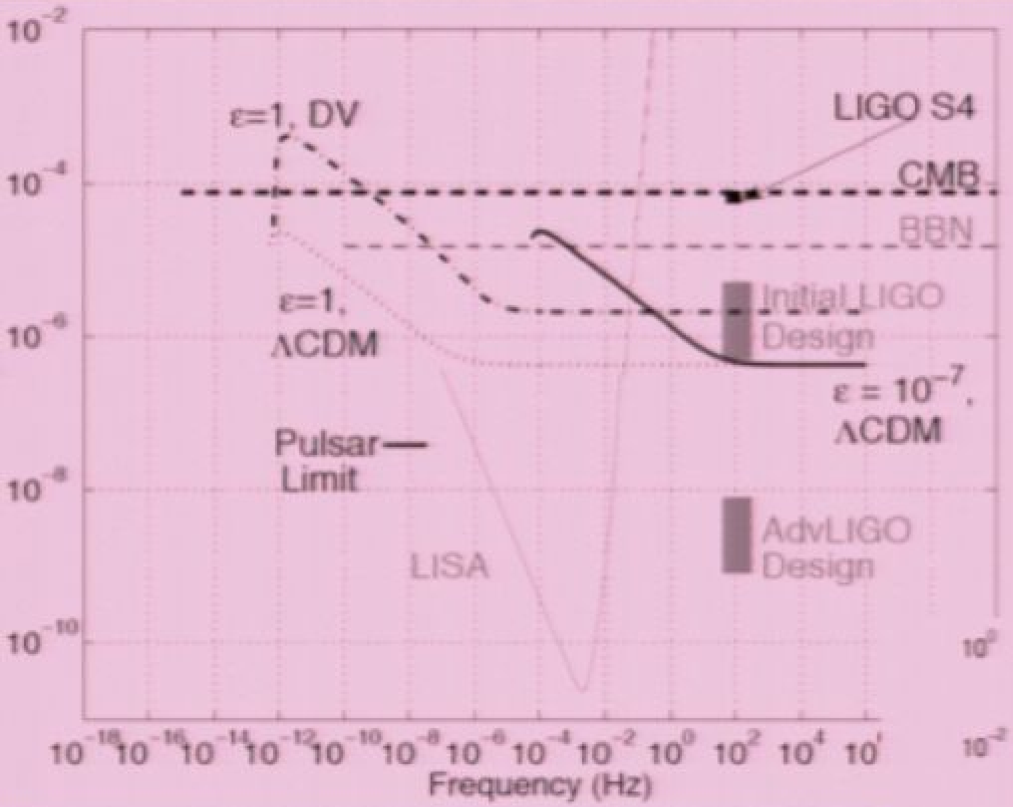
Abstract:

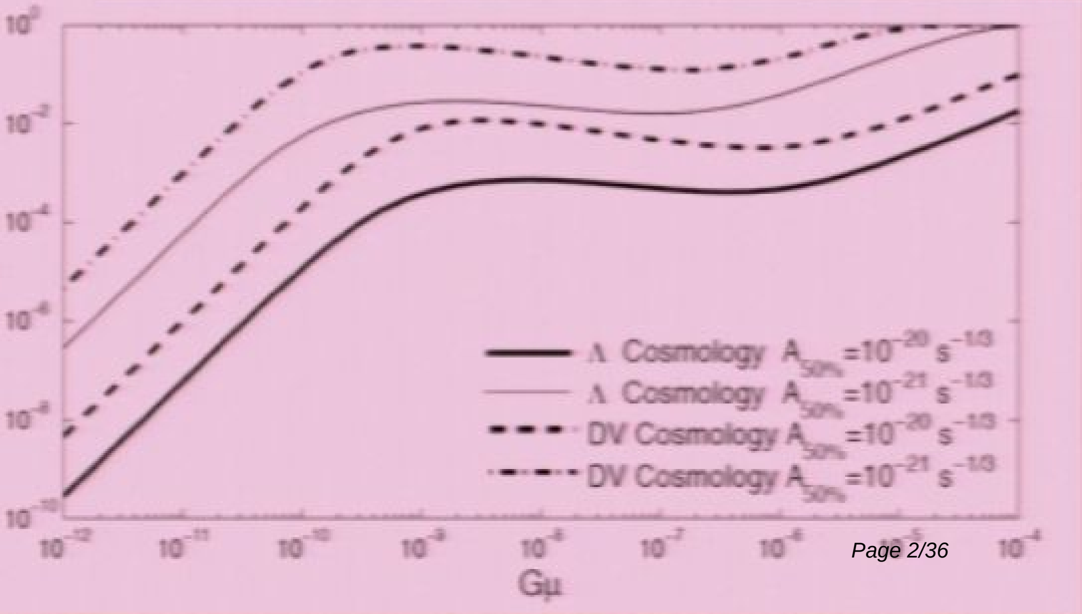
Cosmic strings



stochastic background

Siemens et al. 2006; 2007

bursts



Outline

- Cosmological background
- Gravitational waves
- Standard sirens
  - Supermassive binary black holes
  - Gamma-ray bursts
- Gravitational lensing

DH & Linder 2005, ApJ 631, 679
DH & Hughes 2005, ApJ, 629, 15
Cooray, DH, & Huterer 2006, ApJL 637, L77
Cooray, Huterer, & DH 2006, PRL 96, 1301
Dalal, DH, Hughes, & Jain 2006, PRD, 74, 063006
Berger et al. 2006, ApJ 664, 1000; Sarkar, Amblard, DH, & Cooray 2007

Cosmology

- What is the evolution history of the Universe?
- This is encapsulated in the

  luminosity distance – **redshift** relation
  - luminosity distance: related to time of emission through the speed of light; $t = d_{\mathrm{L}}/c$
  - redshift: gives the scale ratio of the Universe at time of emission; $a(z) = a_0/(1+z)$
- We know how to determine redshift:

  take a spectrum
- How does one measure distance?

  ● standard candles

Gravitational-wave Standard Sirens

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

GWs from binary systems

Strongest harmonic:

(wide separation)

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

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 $F(\text{angles})$

(redshifted) chirp mass:

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

Schutz 1986, Nature

Detecting Gravitational Waves

● This is HARD to do

- Gravitational waves are very, very, very weak

  Fractional strain due to strong gravitational waves:

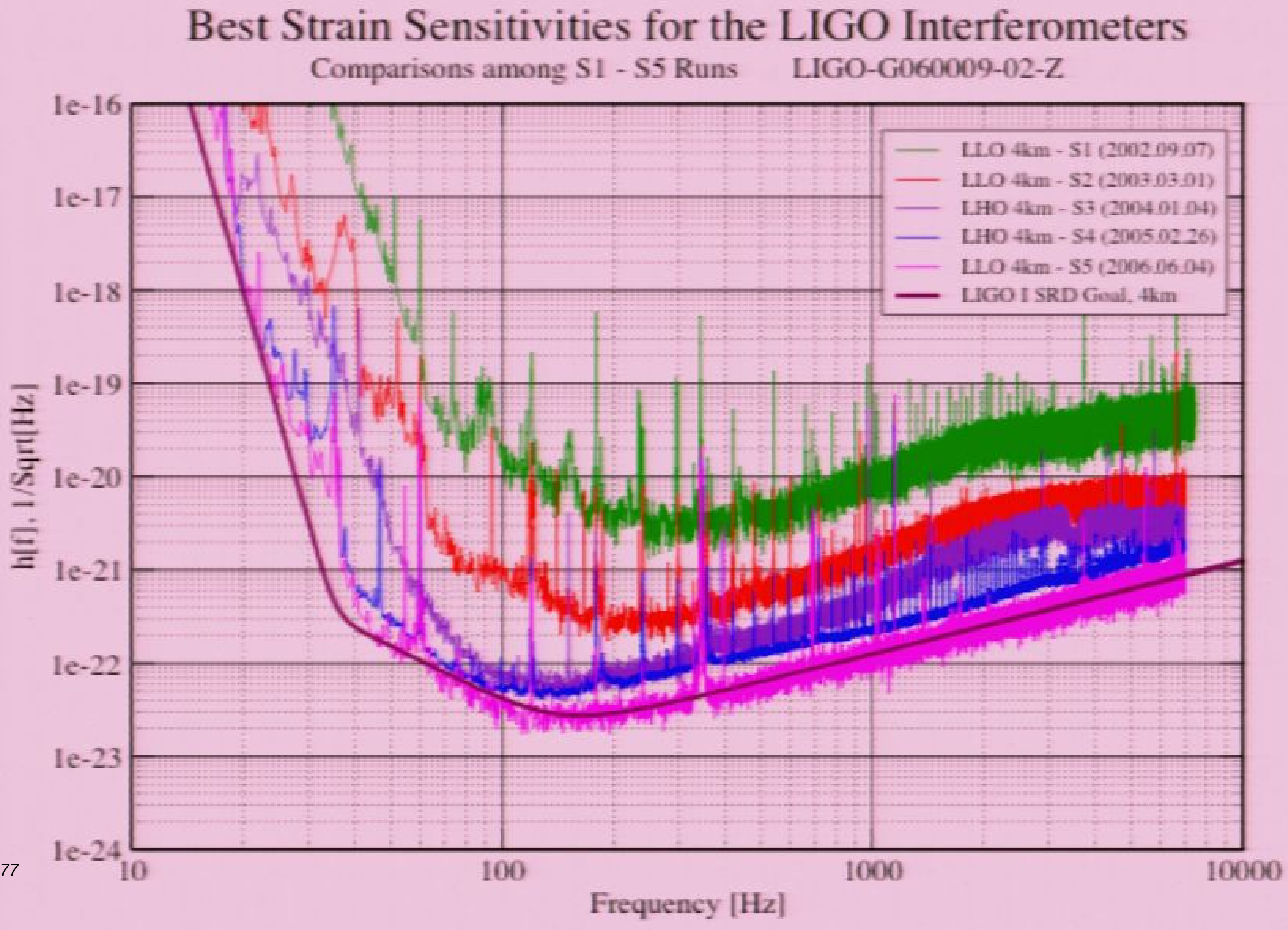
$$h \sim 10^{-22}$$

- Lots of sources of noise
  - thermal
  - seismic
  - shotnoise
  - quantum

LIGO

- Laser Interferometer Gravitational-Wave Observatory
- 2 observatories (Hanford, Washington & Livingston, Louisiana), each with 4km long interferometers
- operating at design sensitivity NOW

LIGO Sensitivity



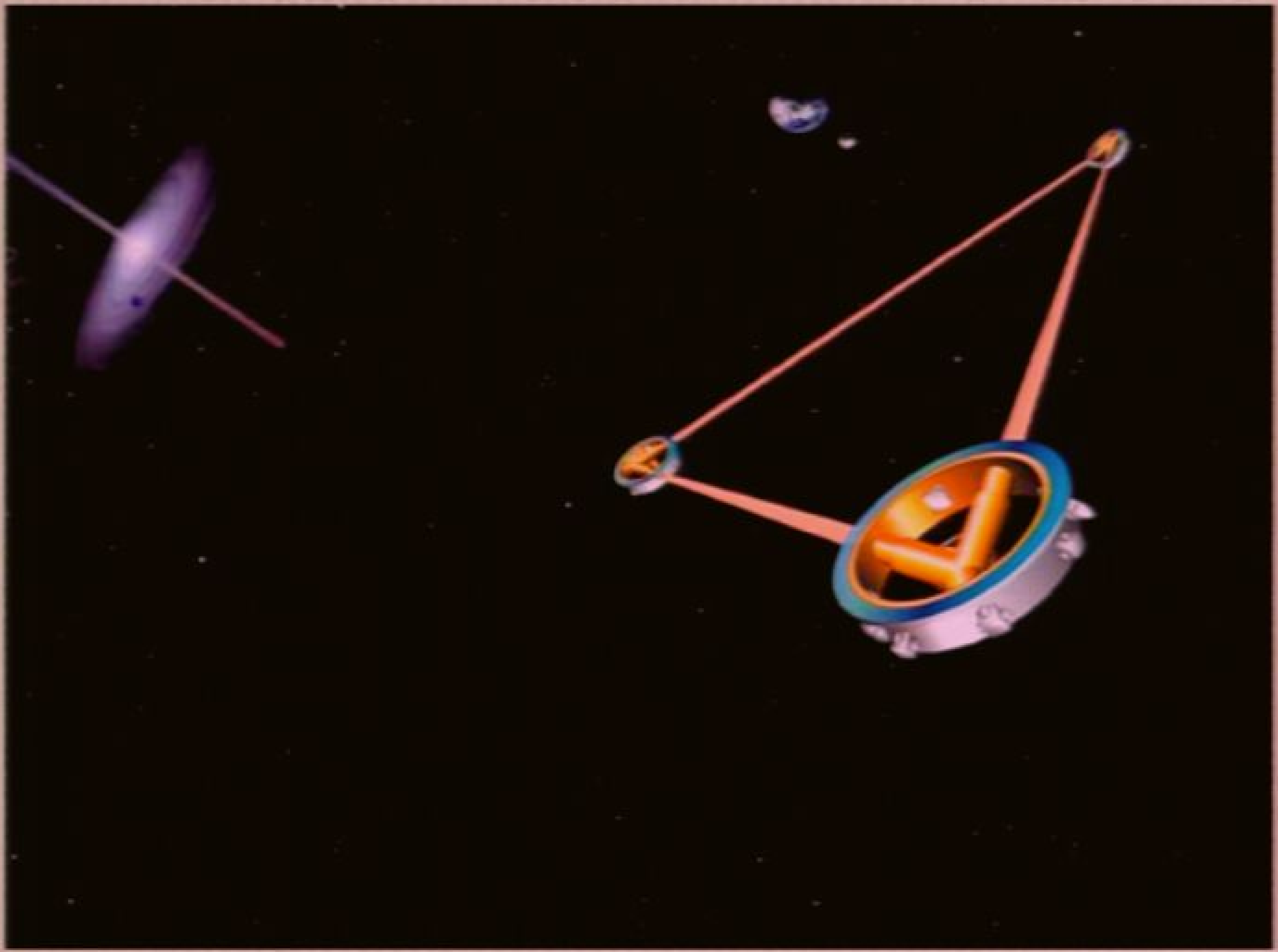
Best Strain Sensitivities for the LIGO Interferometers

Comparisons among S1 - S5 Runs LIGO-G060009-02-Z

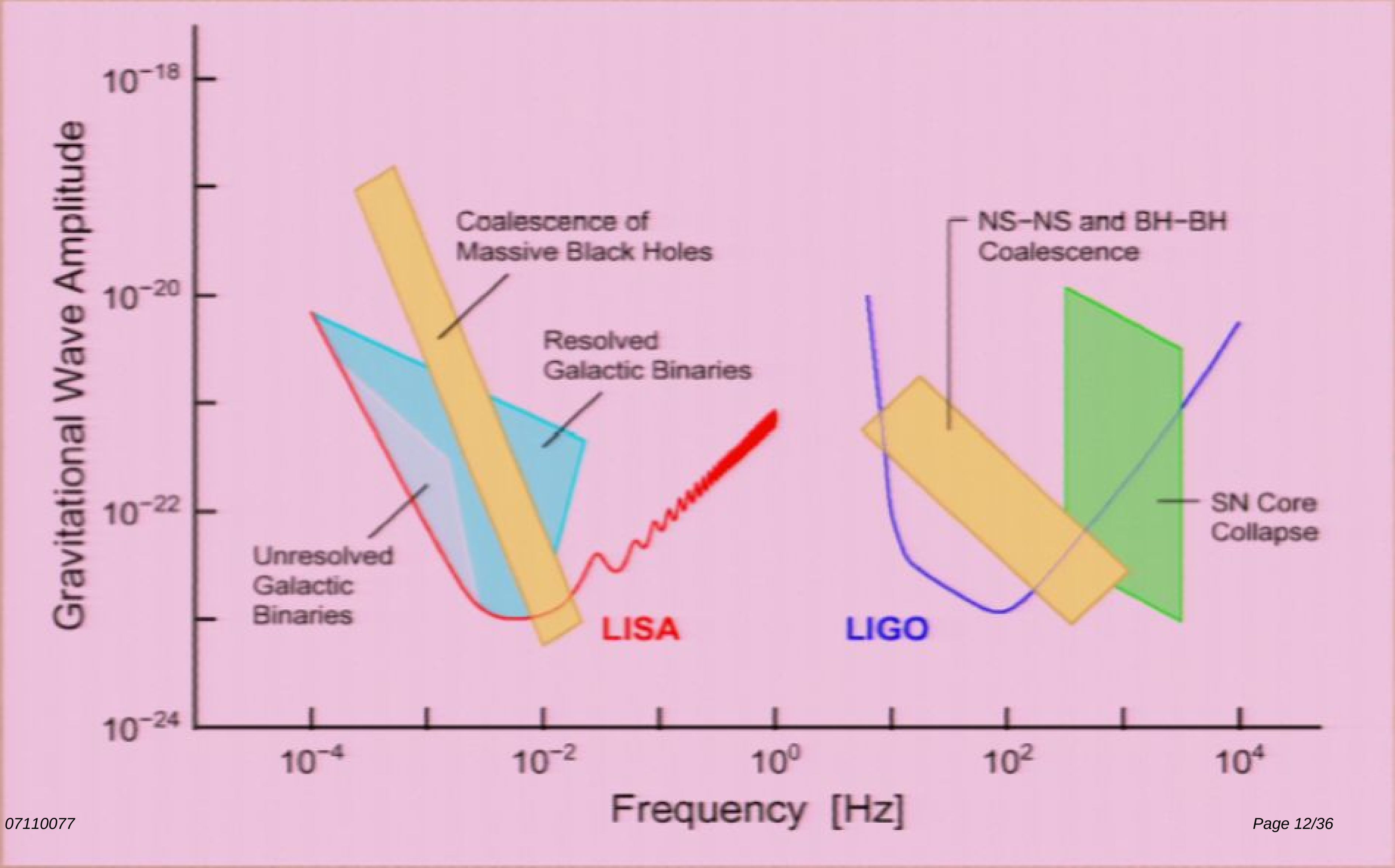
Worldwide GW Network

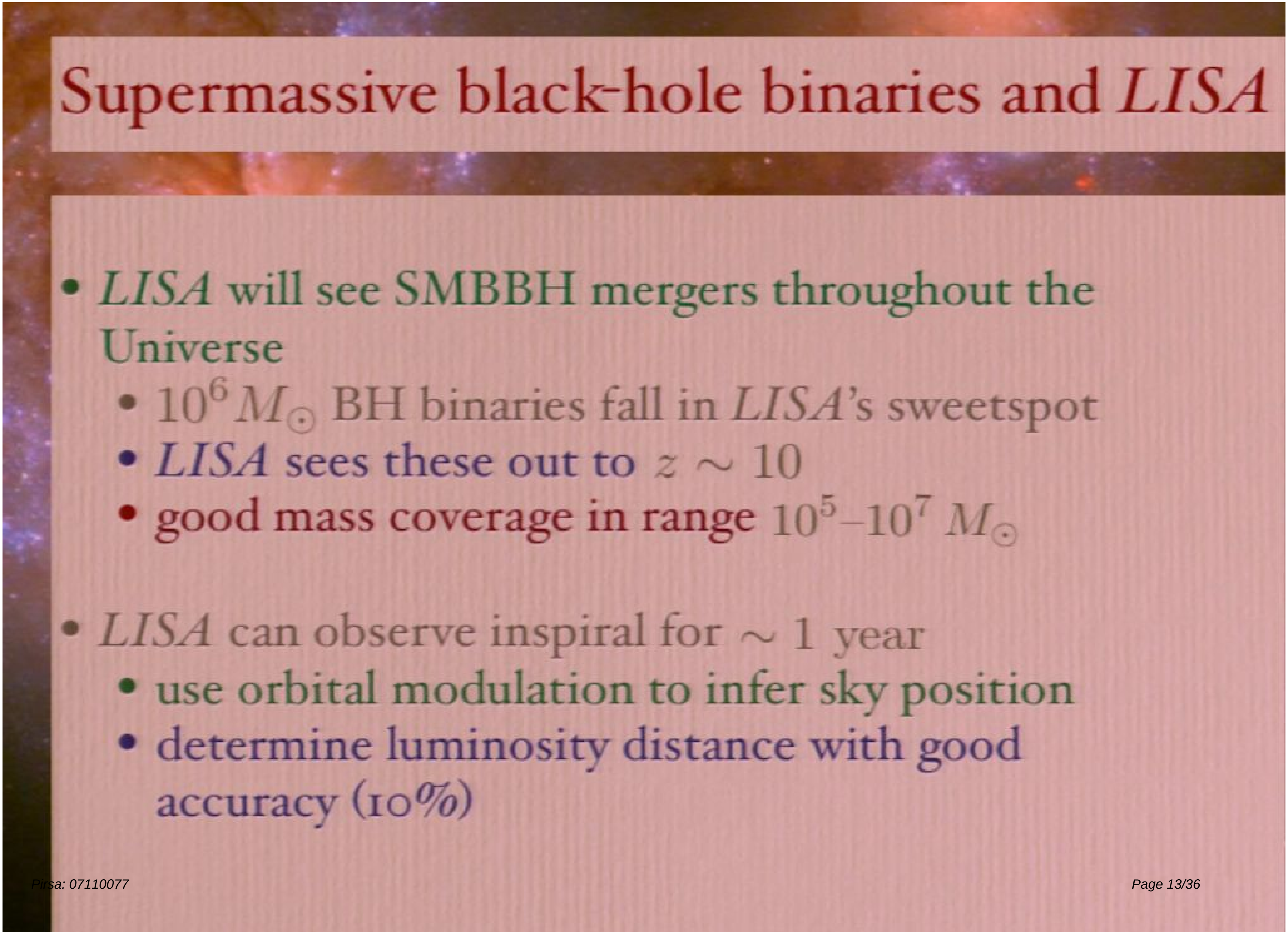
Also Space!: *LISA*

Laser Interferometer Space Antenna



GW science reach





Supermassive black-hole binaries and *LISA*

- *LISA* will see SMBBH mergers throughout the Universe
  - $10^6 M_\odot$ 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 good accuracy (10%)

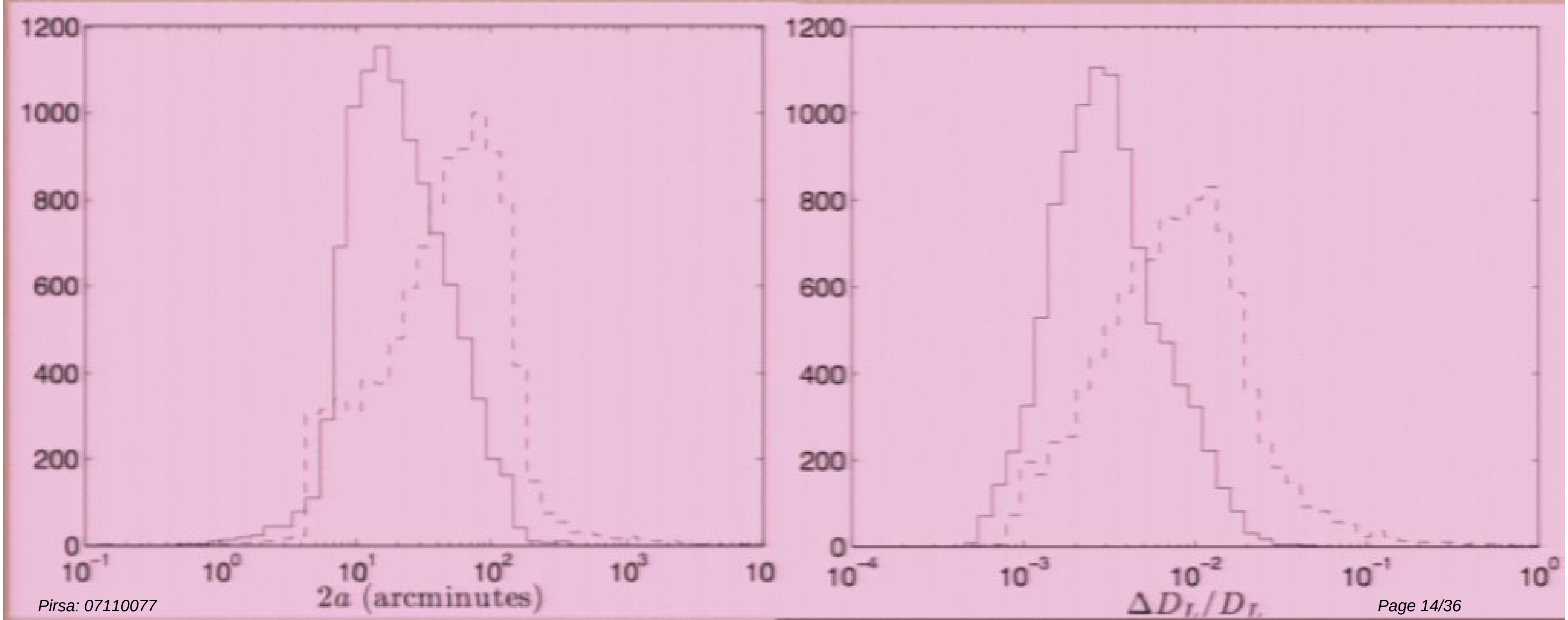
Luminosity-distance determination from *LISA*

Sky position

$< 1\,\mathrm{deg}$

Luminosity distance

$< 1\%$



$3\times10^5 M_\odot$ into $10^6 M_\odot$ black holes at $z = 1$ (DH & Hughes 2005; Lang & Hughes 2006)

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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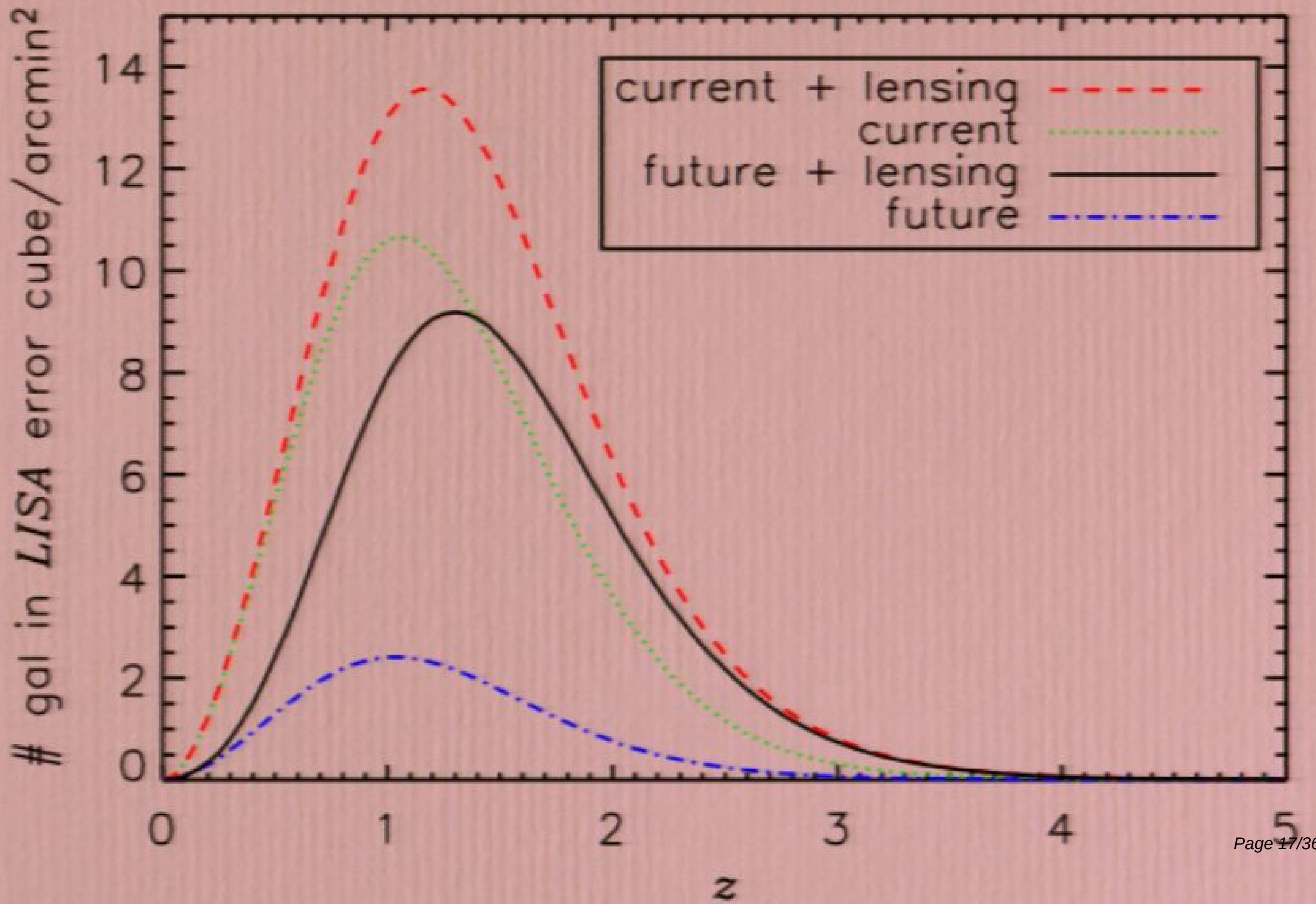
  - Electromagnetic counterpart

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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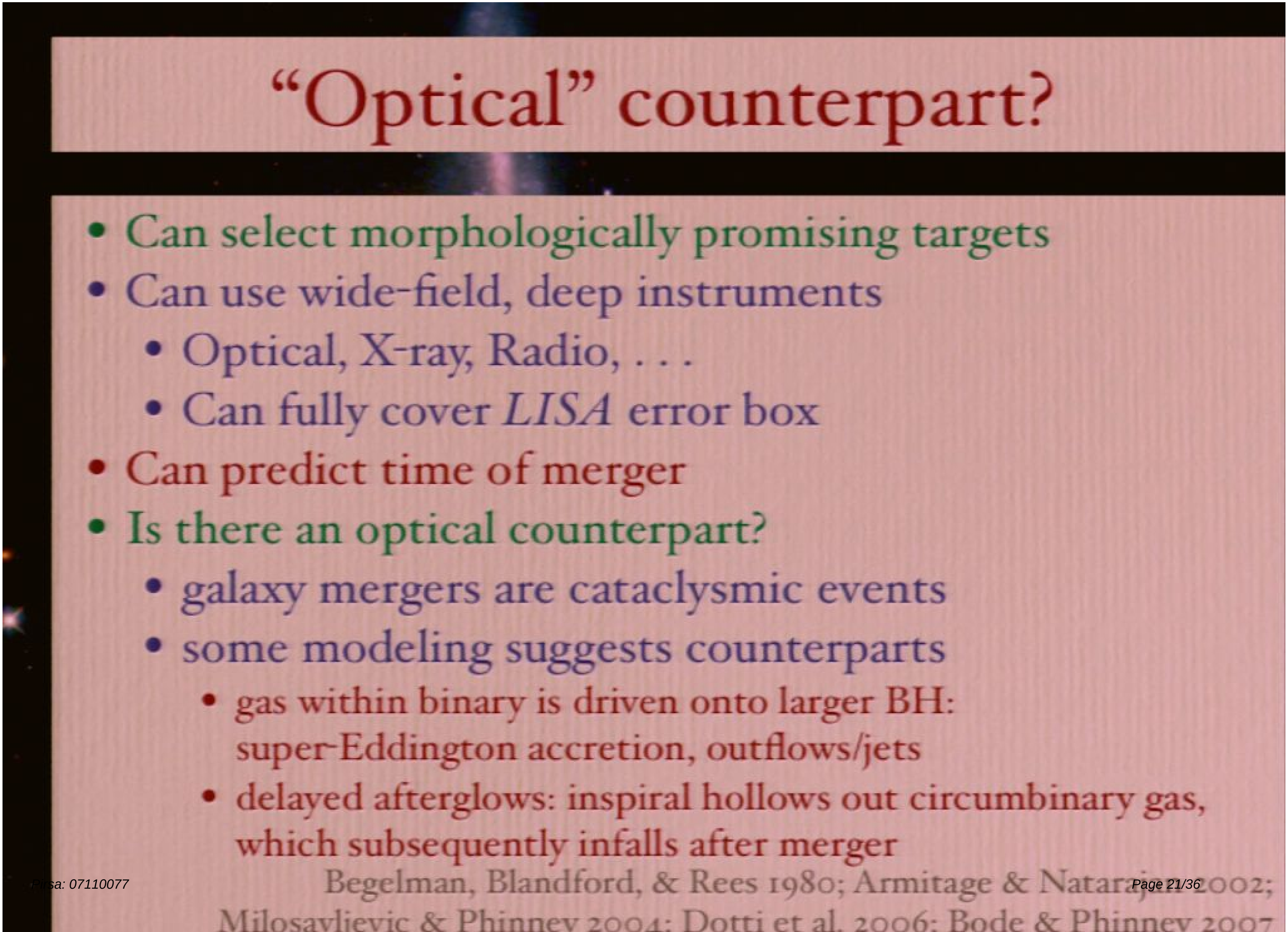
● Look for something that goes BANG

“Optical” counterpart?

- Roughly 10% 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?

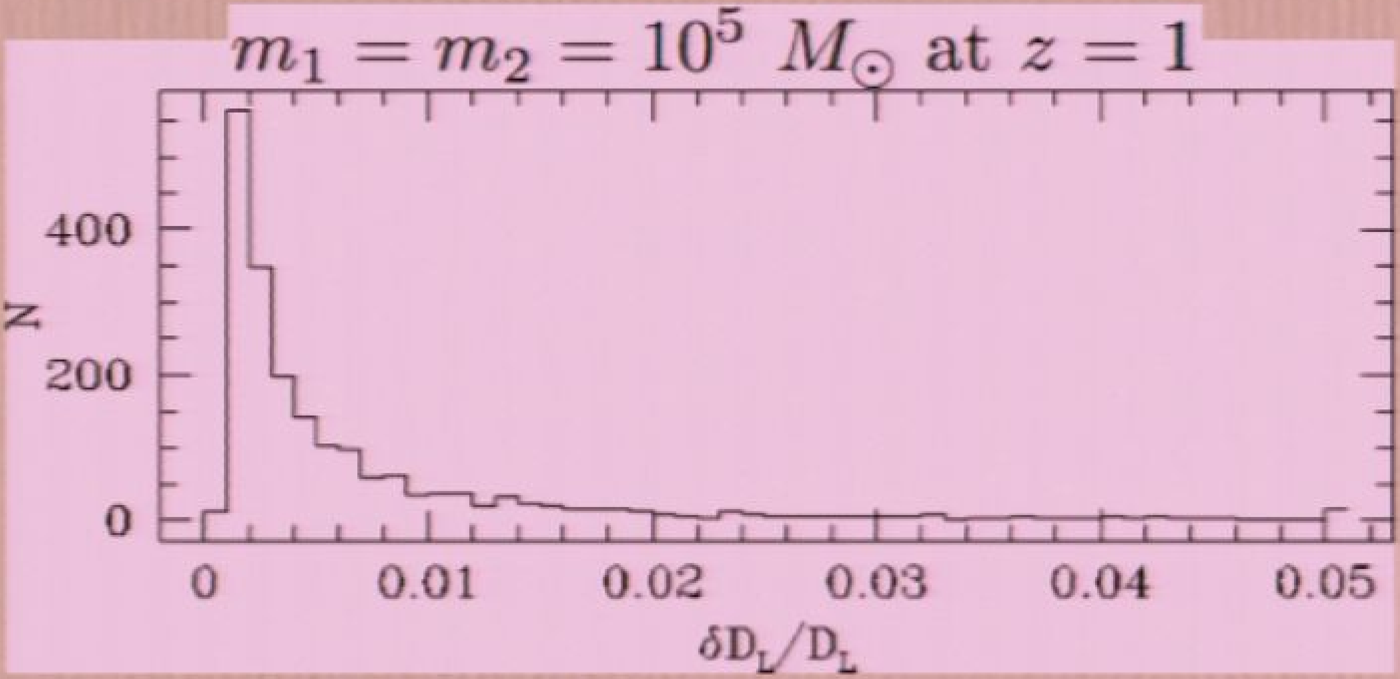
- Can select morphologically promising targets
- Can use wide-field, deep instruments
  - Optical, X-ray, Radio, . . .
  - Can fully cover *LISA* error box
- Can predict time of merger
- Is there an optical counterpart?
  - galaxy mergers are cataclysmic events
  - some modeling suggests counterparts
    - gas within binary is driven onto larger BH: super-Eddington accretion, outflows/jets
    - delayed afterglows: inspiral hollows out circumbinary gas, which subsequently infalls after merger

Begelman, Blandford, & Rees 1980; Armitage & Natarajan 2002; Milosavljevic & Phinney 2004; Dotti et al. 2006; Bode & Phinney 2007

What good is a counterpart?

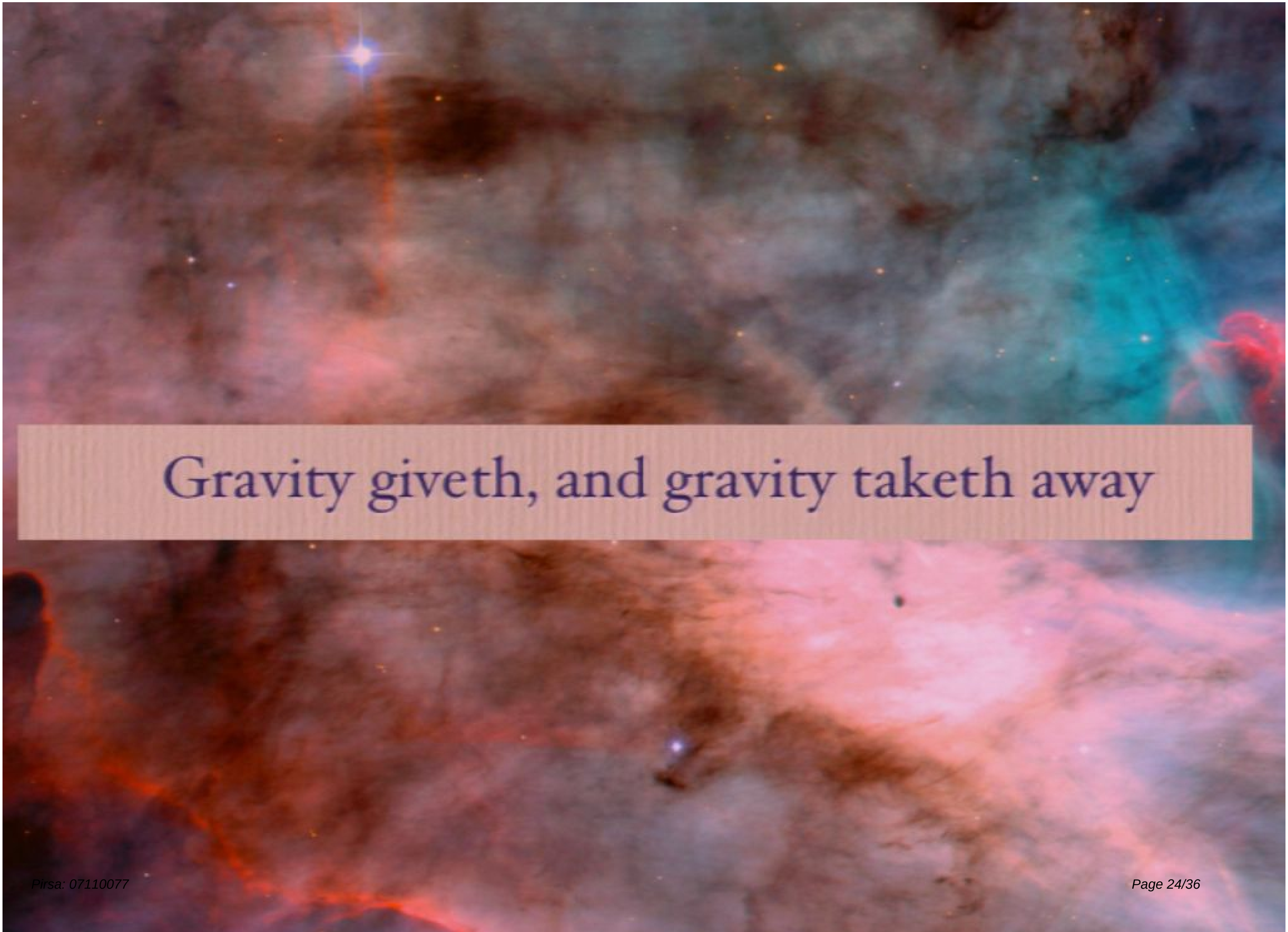
- Determination of redshift
  - puts a point on the luminosity-distance redshift curve
- Precise location of GW source
  - drastic improvement in GW modeling, and hence distance determination

Distance determination with counterpart



Luminosity distance to much better than 0.5%

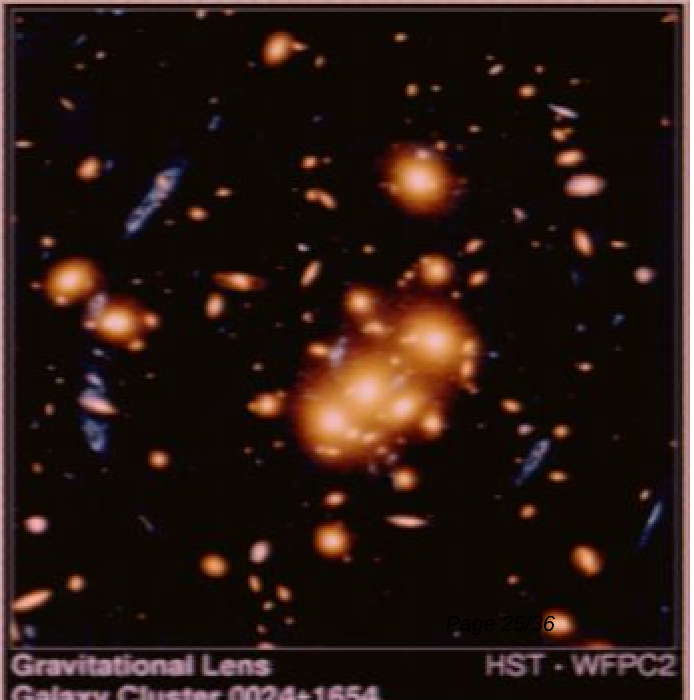
- Ultimate standard candle



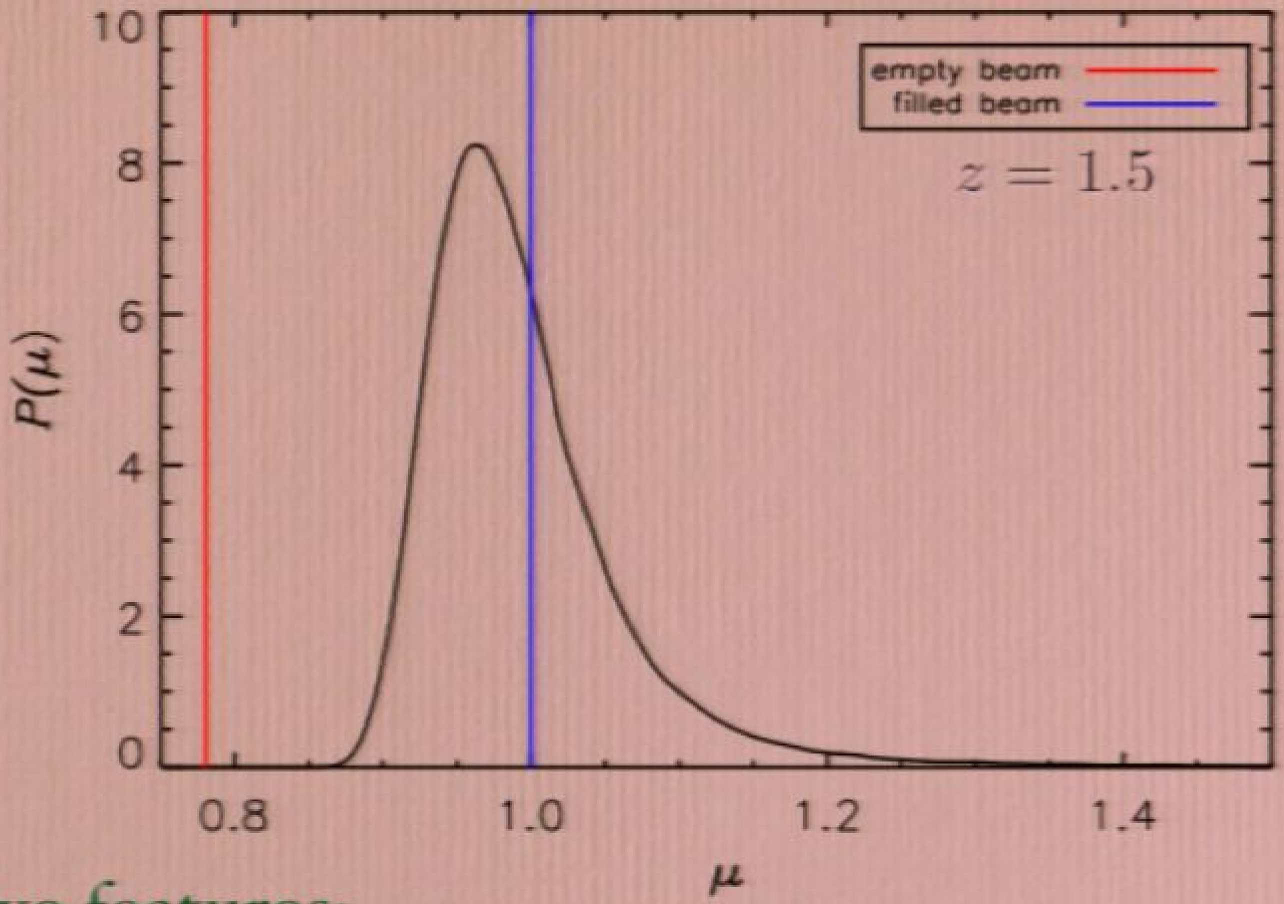
Gravity giveth, and gravity taketh away

Gravitational lensing

- Data in cosmology comes almost exclusively from the observation of distant photons
- In interpreting this data, a uniform, isotropic Friedman-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



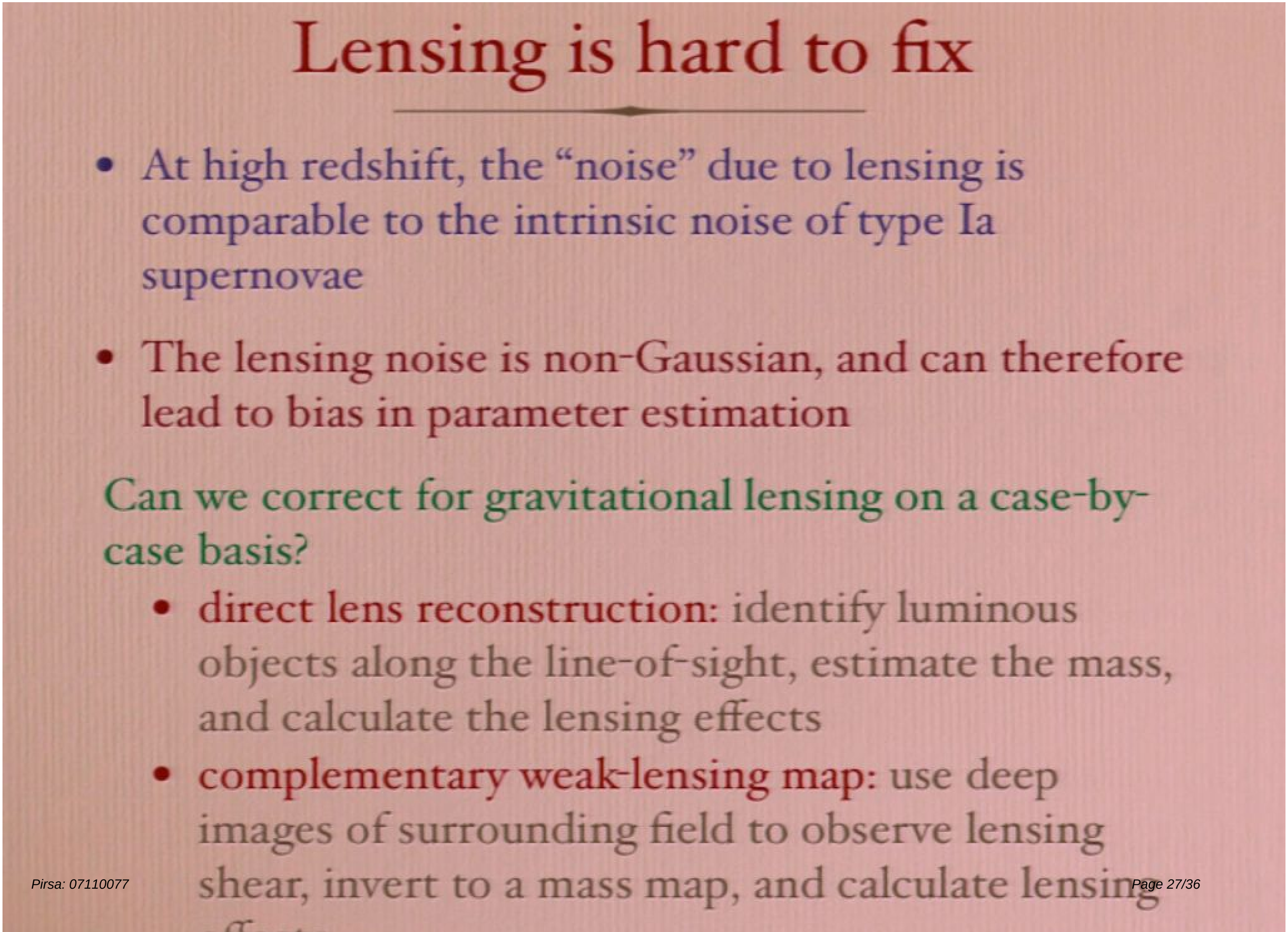
Magnification PDF



Qualitative features:

- **Conservation of flux:** $\langle \mu \rangle = \int d\mu \, \mu P(\mu) = 1$
- **Non-Gaussian:** mode is demagnified, long tail to high magnification

- all high-redshift sources are gravitationally lensed



Lensing is hard to fix

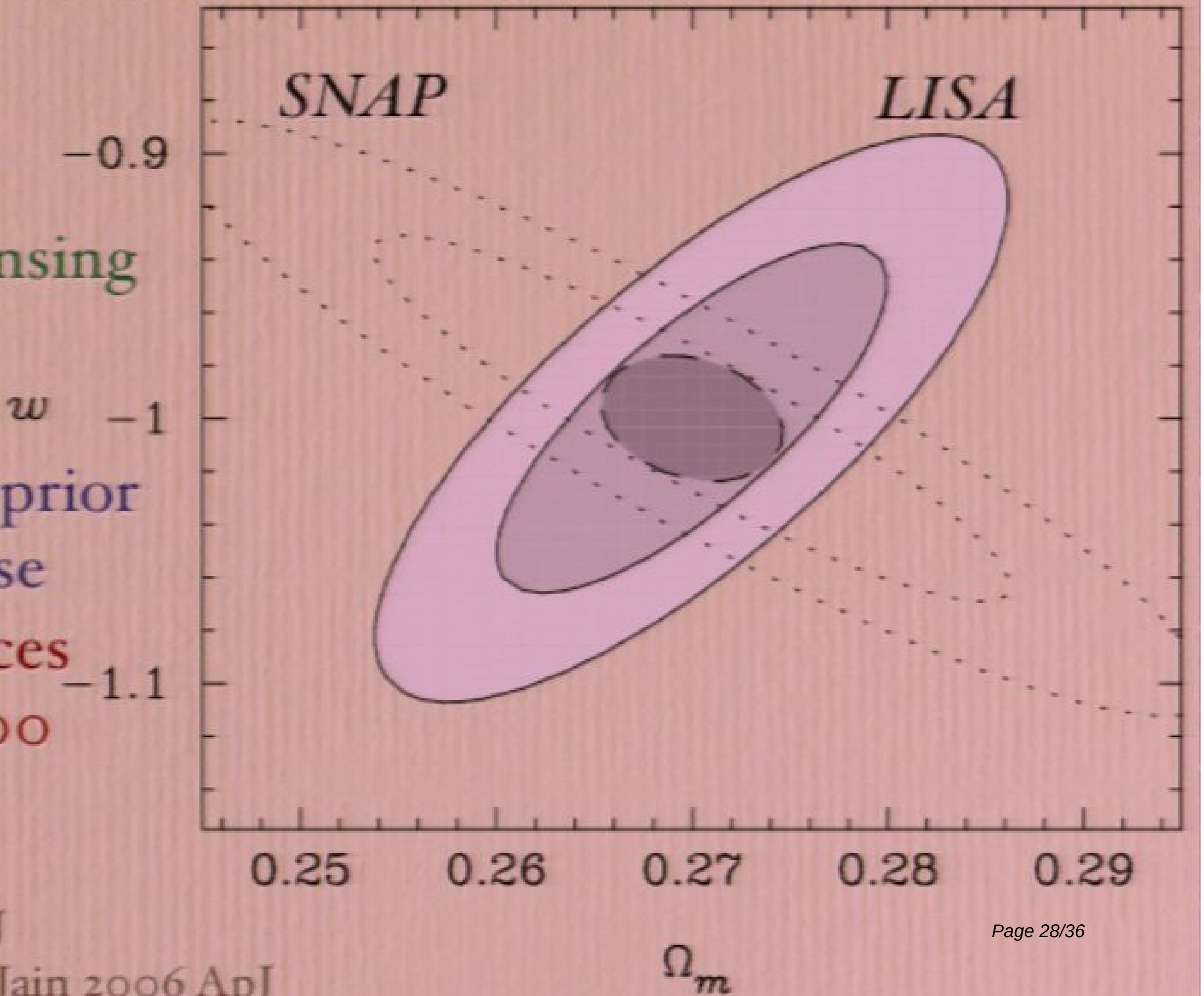
- At high redshift, the "noise" due to lensing is comparable to the intrinsic noise of type Ia supernovae
- The lensing noise is non-Gaussian, and can therefore lead to bias in parameter estimation

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

Safety in Numbers

- For sufficient statistics, gravitational lensing effects can be averaged away
- Assume *Planck* prior and flat Universe
- 100 *LISA* sources compare to 3000 SNe



DH & Linder 2005 ApJ

Dalal, DH, Hughes, & Jain 2006 ApJ

Caveats

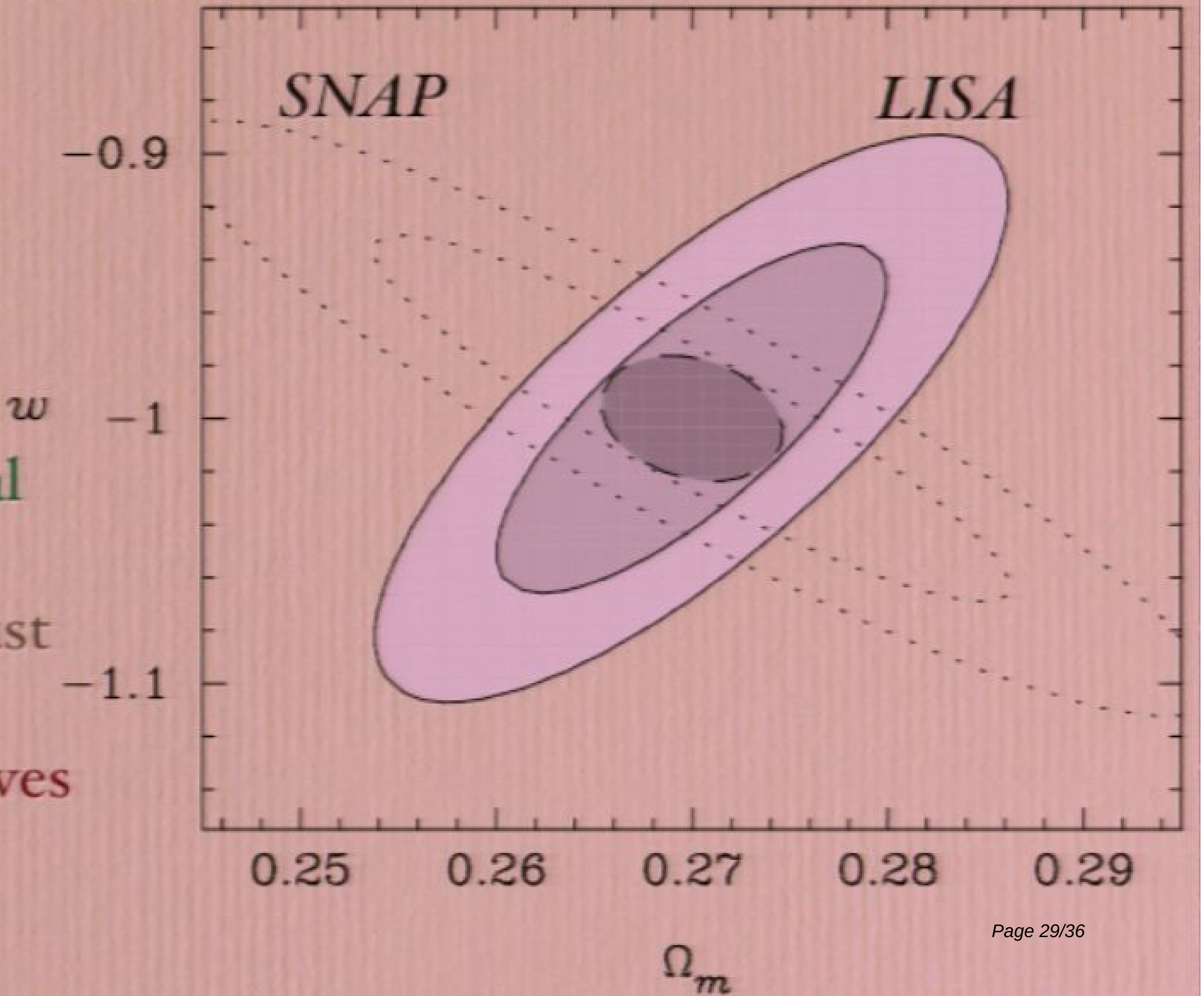
LISA has to be built, and work

SMBBHs must happen

Must have optical counterparts

Counterparts must be found

Gravitational waves must exist



Compact binaries and LIGO

- Compact binary systems (NS-NS, NS-BH, BH-BH) are strong gravitational wave emitters
- Advanced LIGO will see such systems to cosmological distances (>500 Mpc)
- Direct distance determination will be possible, with percent-level errors

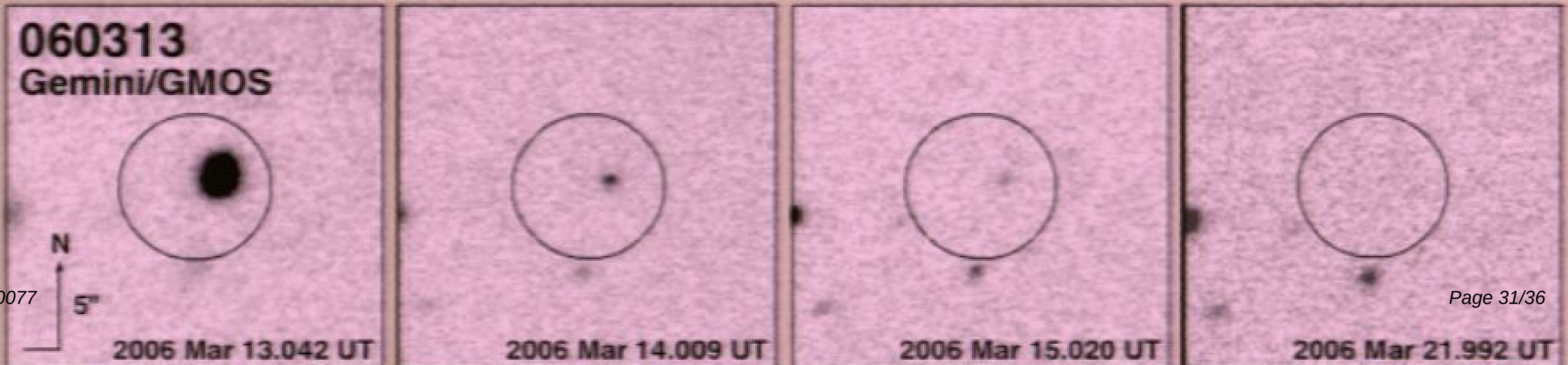
● Will there be an optical counterpart?

Systems merge in LIGO band

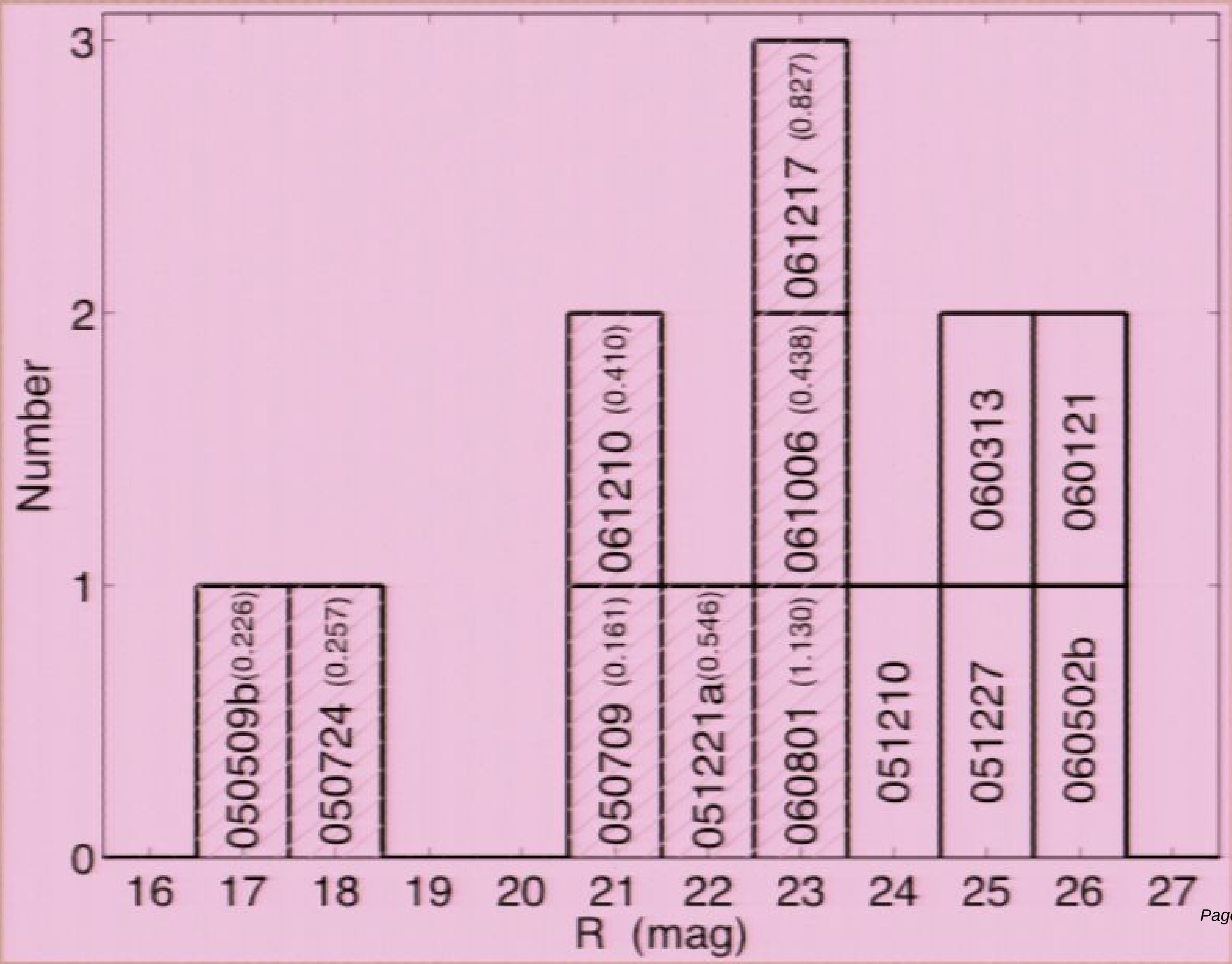
Gamma-ray Bursts

- Recently, HETE and SWIFT have seen afterglows for short-hard gamma-ray bursts
- These GRBs are thought to involve the merger of a NS-NS or NS-BH binary
- These GRBs occur relatively nearby (z<0.3)

● These would be observable
by Advanced LIGO



GRB redshift distribution



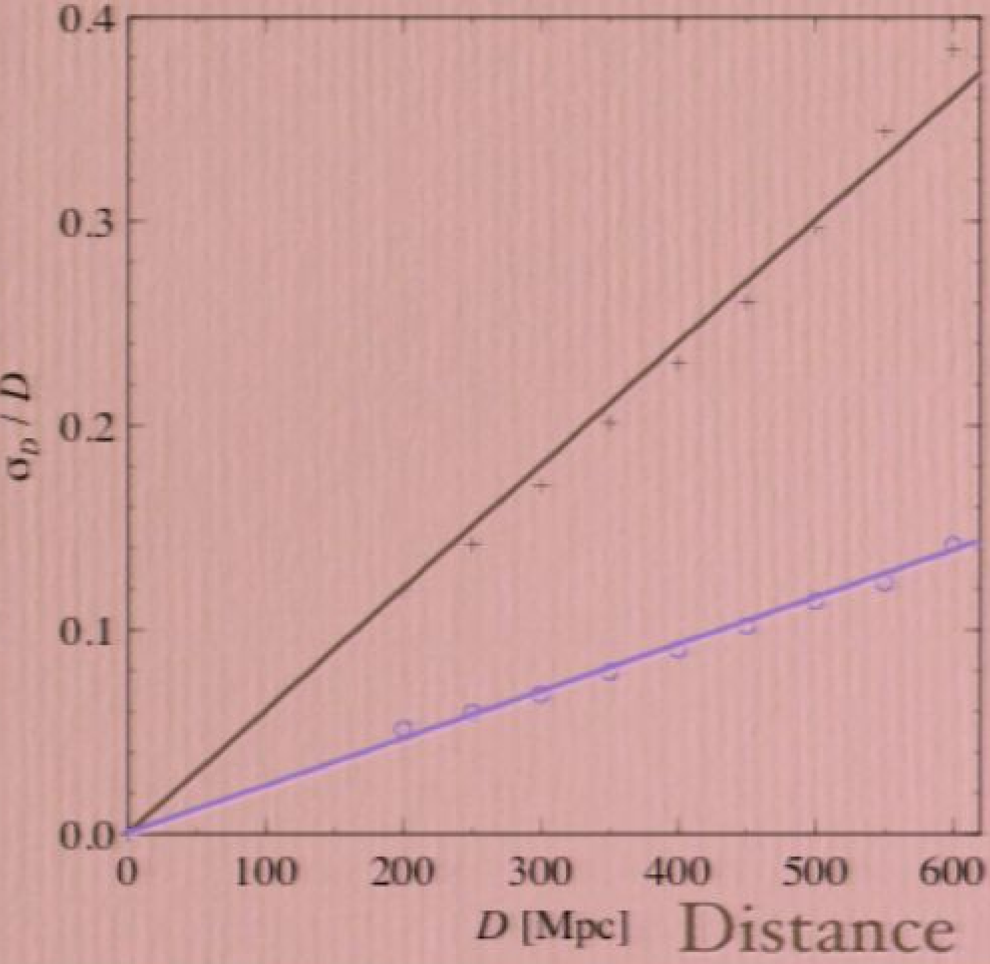
Gamma-ray bursts

- GRBs pinpoint the location of the source on the sky
- GRBs pinpoint the time of merger
- GRBs provide a redshift to the source
- In addition, if the GRBs are beamed:
  - The GW signal will be maximized
  - Observing GW polarization is less important

- Network of multiple GW observatories essential to determine the polarization of the waveform, and hence the inclination of the binary

GRB GW distance determination

- Assuming a network of 4 GW observatories
- Assuming the detectors have Advanced LIGO noise curves



Fractional error in distance

unbeamed

beamed (-20°)

Distance

GRBs and dark energy

- GRB sirens put points on the Hubble diagram
- GRBs are at lower redshift
  - No gravitational lensing
  - No dark energy?

- GRB standard sirens will measure the Hubble constant to the percent level
- A precise Hubble constant measurement, when combined with precision CMB observations, constrains the Dark Energy

Conclusions

- Gravitational-wave standard sirens offer an absolute measurement of luminosity distance on cosmological scales
- Supermassive binary black hole systems allow a measure of distance to very high (z>10) redshift
- If short GRBs are binary systems, they will offer an opportunity to measure the Hubble constant to the percent level

- Gravitational-wave standard sirens have a potentially important role to play in cosmology (let’s first detect some waves!)