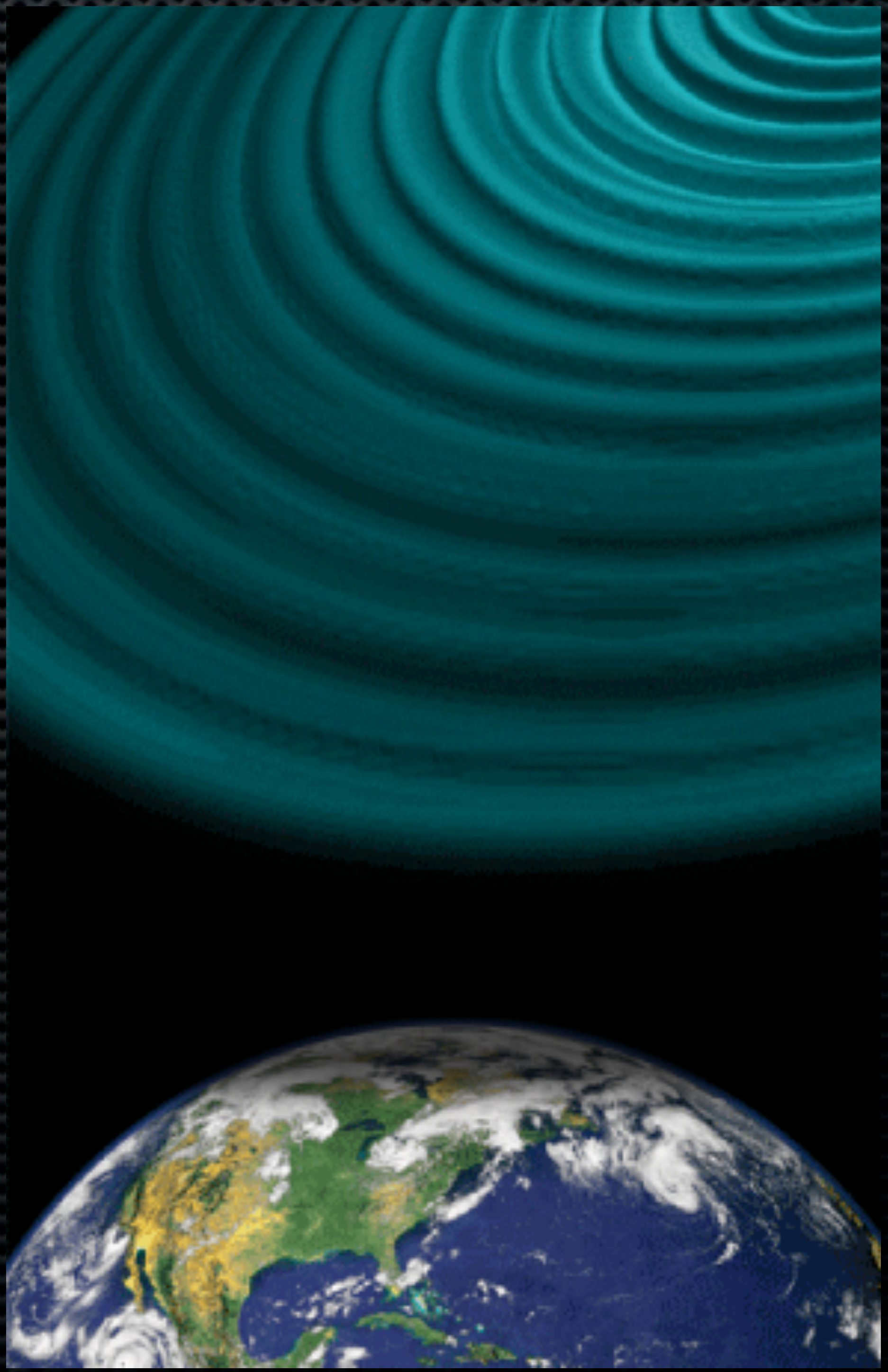
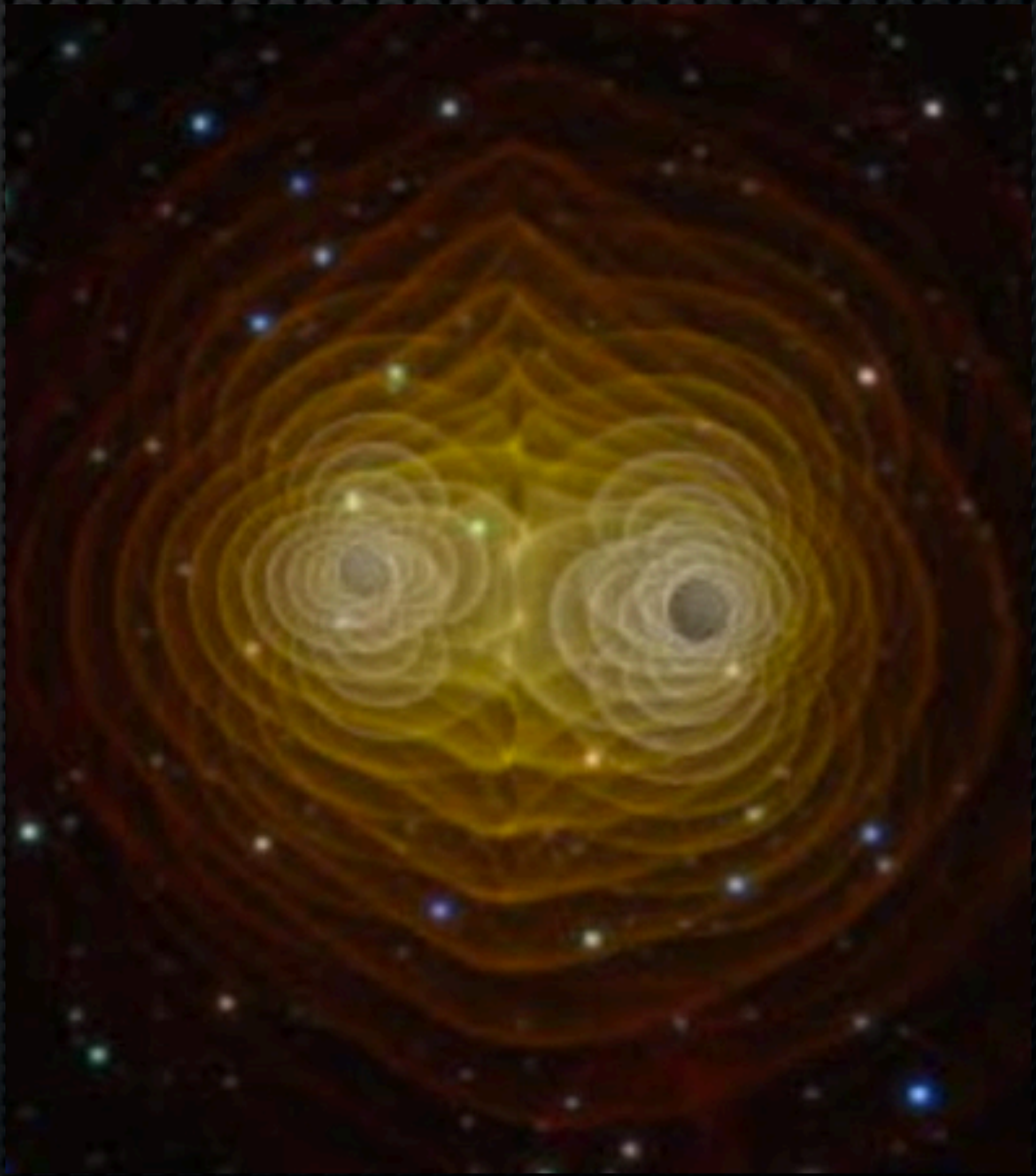
Gravitational wave cosmology
Lecture 3



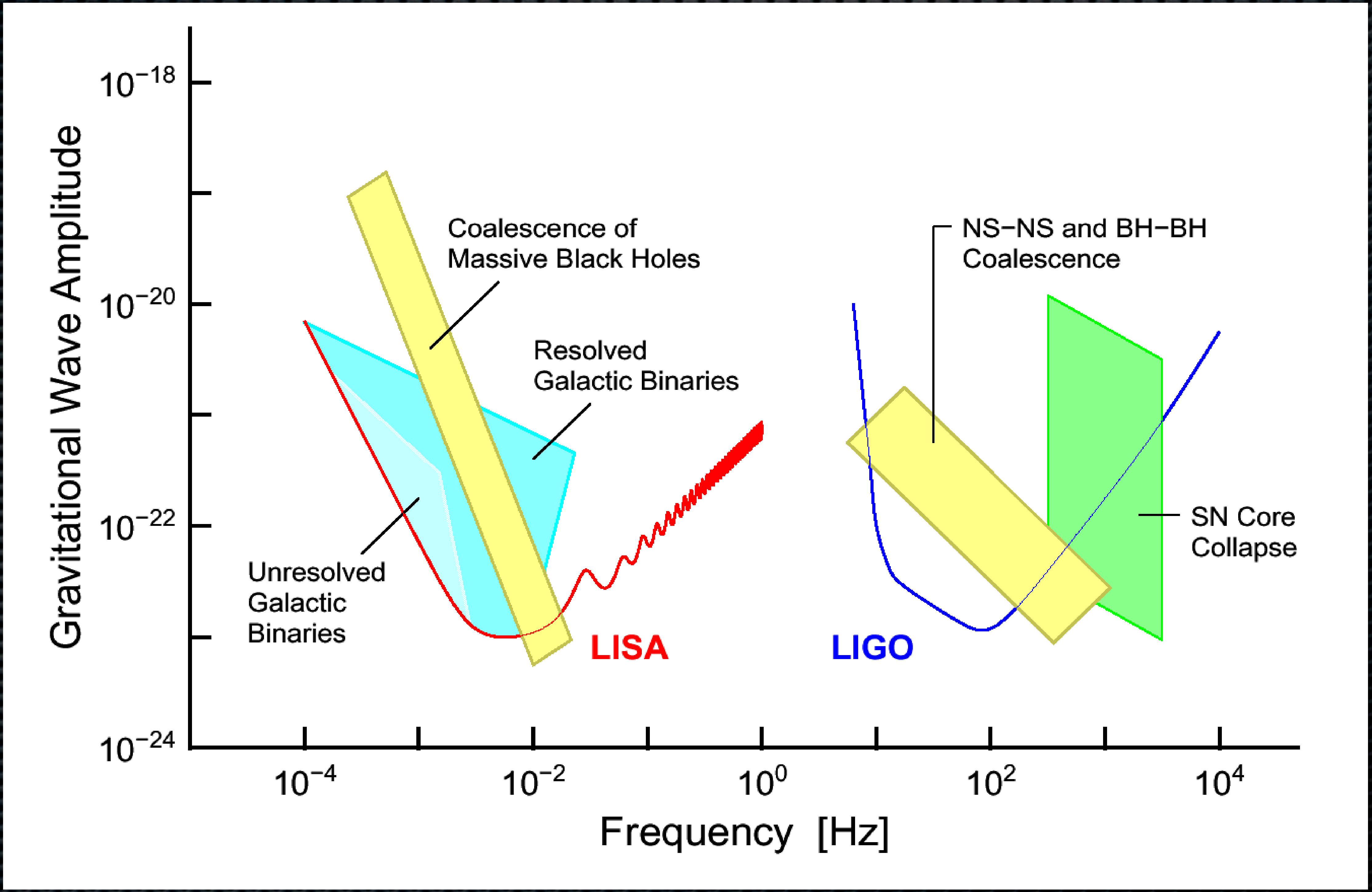
Daniel Holz
The University of Chicago

Outline

- Lecture 1: introduction to gravitational waves
- Lecture 2: detecting gravitational waves
- Lecture 3: what we might learn from gravitational waves



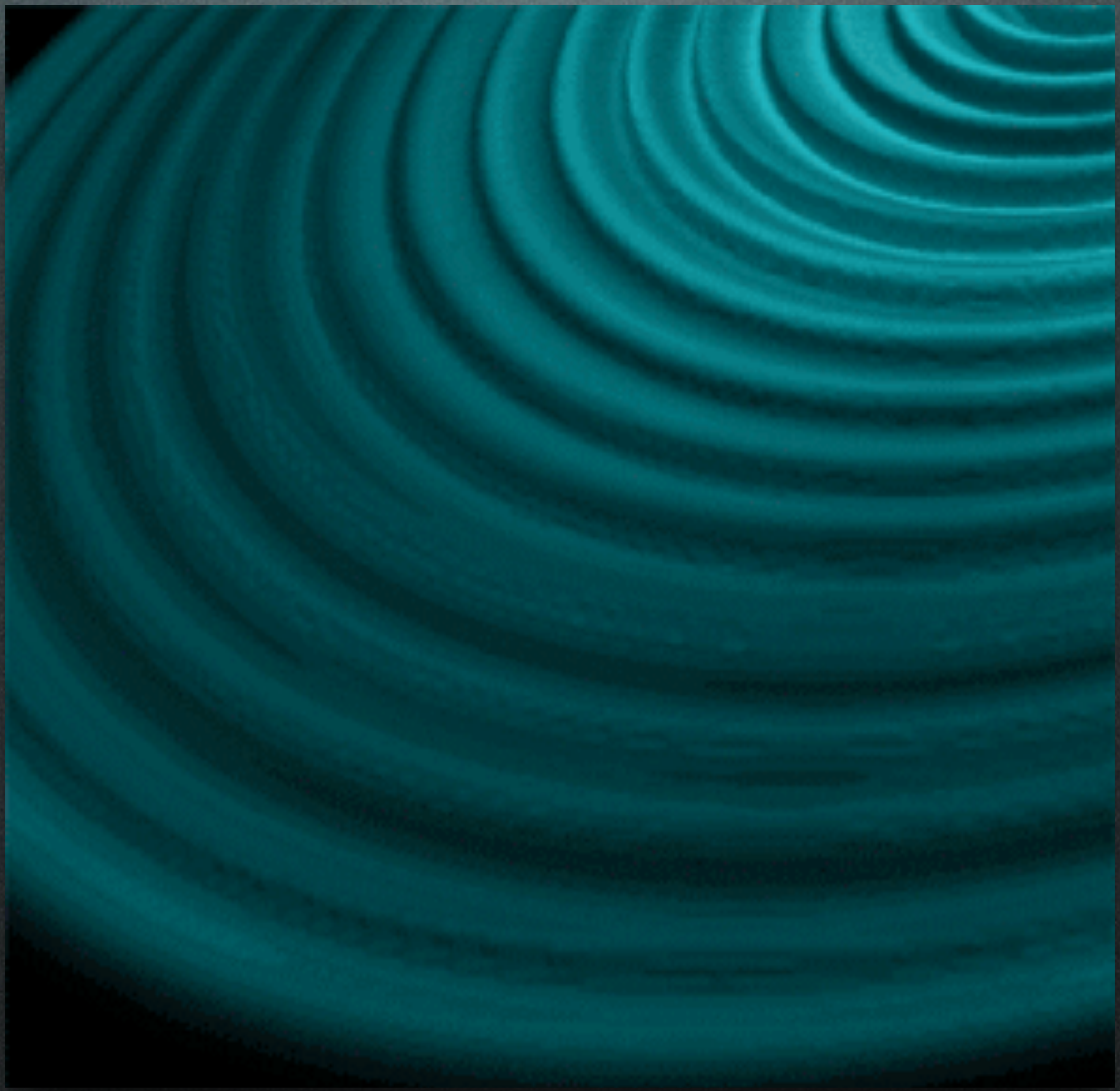
GW science reach



Listening to the Universe

GWs are like sound, not light:

- detectors are omnidirectional
- detectors don't image
- GWs from bulk, not surface, processes
- phase coherent
- weak
- difficult to scatter/absorb
- frequencies of stellar
mass events occur in human auditory band



What will we hear?

Lots of sources I won't discuss

- Quasi-normal ringdown modes of black holes
- Extreme mass ratio inspiral
- Intermediate mass ratio inspirals
- Testing GR
- Good review:
  Sathyaprakash & Schutz 2009
  Living Reviews in Relativity
  http://www.livingreviews.org/lrr-2009-2

GWs from inflation

- Quantum fluctuations (tensor in addition to scalar) in the early universe are amplified by inflation. Subsequent phase transitions also might generate GWs
- Once emitted, GWs travel (almost) unimpeded
- If detected, give pristine measurement of the very, very early universe: 10^{-24} seconds, not 400,000 years, after the Big Bang
- Directly measure the expansion rate during inflation

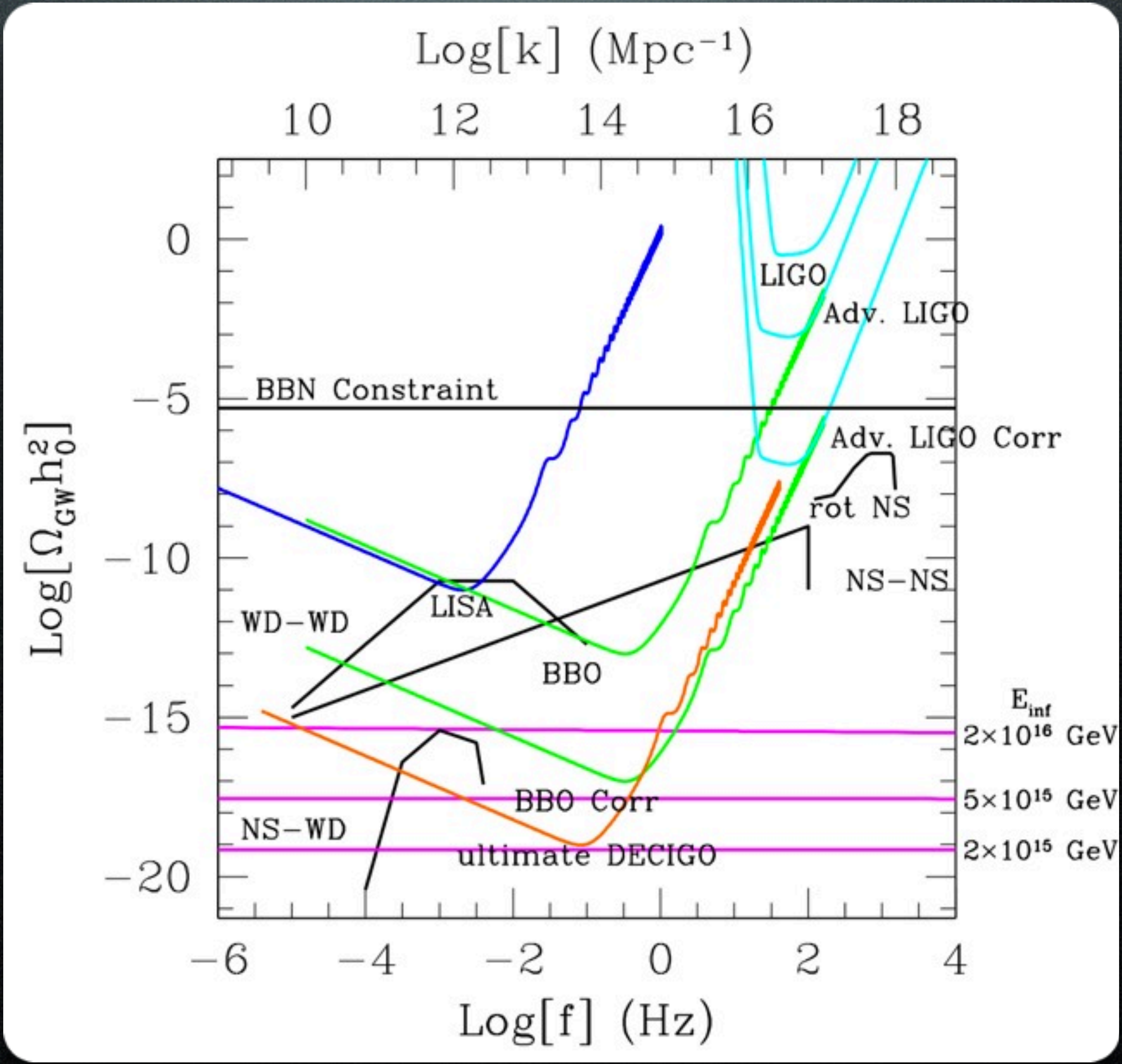
GWs from inflation

- Show up as Gaussian noise
- Noise is correlated for detectors separated by less than relevant wavelength
- Use correlations to detect background (assuming instrumental noise is uncorrelated)
- Energy density/strain noise in GWs in a frequency bin:

$$\Omega_{\mathrm{GW}} = \frac{1}{\rho_c} \frac{d\rho_{\mathrm{GW}}}{d \ln f} \qquad S_{\mathrm{GW}}(f) = \frac{3H_0^2}{10\pi^2} f^{-3} \Omega_{\mathrm{GW}}(f)$$

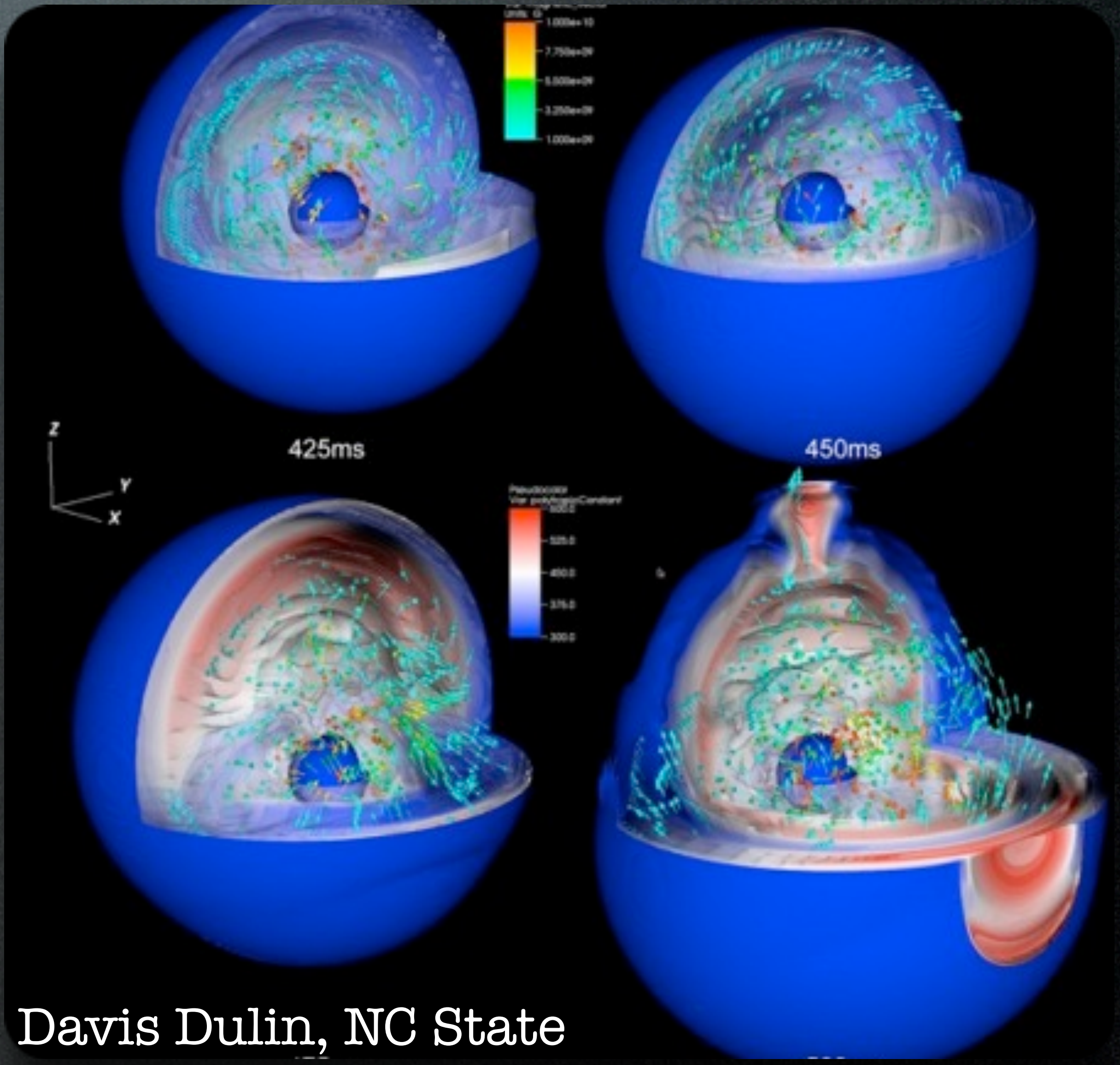
$$S_{\mathrm{GW}}(f)^{1/2} = 5.6 \times 10^{-22}\, \Omega_{\mathrm{GW}}^{1/2} \left(\frac{f}{100\,\mathrm{Hz}} \right)^{-3/2} h_{100}\, \mathrm{Hz}^{-1/2}$$

GWs from inflation



Supernovae

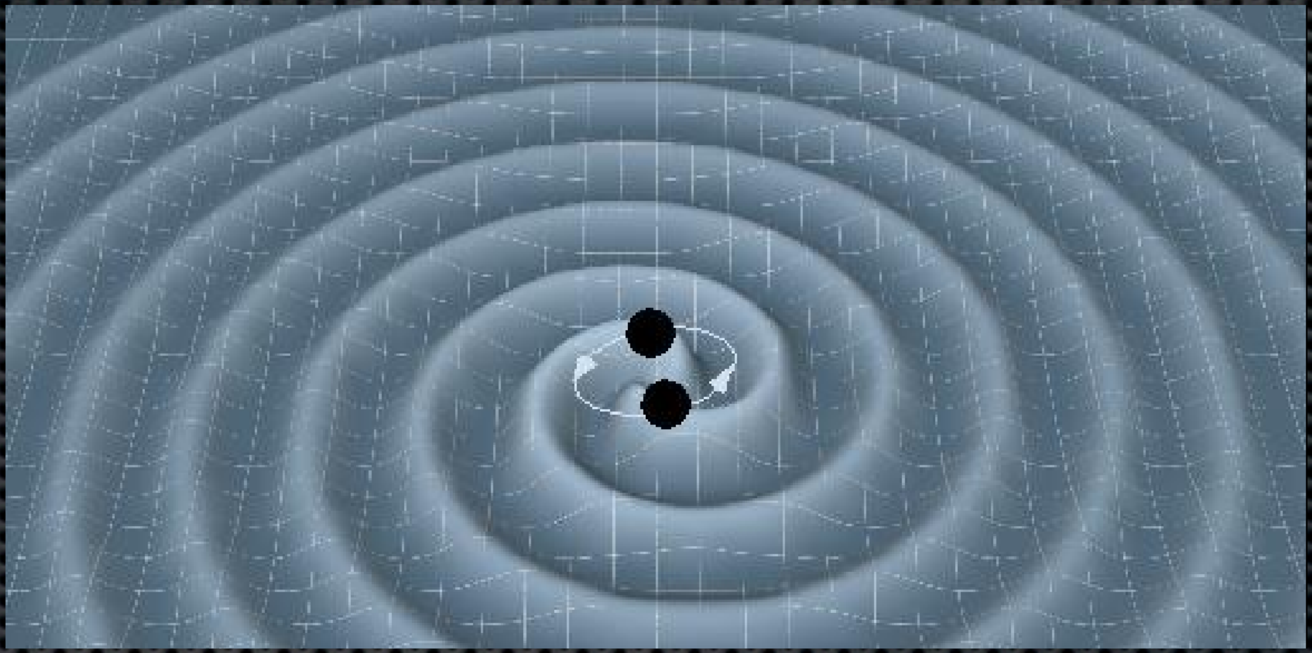
- Must be asymmetric!
- Large theoretical uncertainties
- Must be close (preferably in our galaxy)



Davis Dulin, NC State

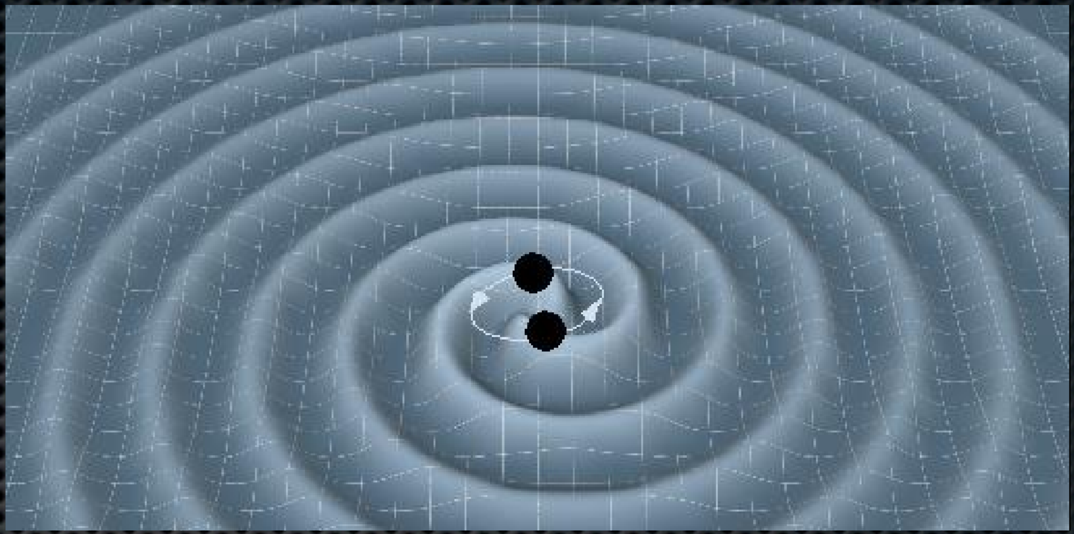
Compact binary coalescence

- Most promising source
- Neutron star and/or black hole binary coalescence



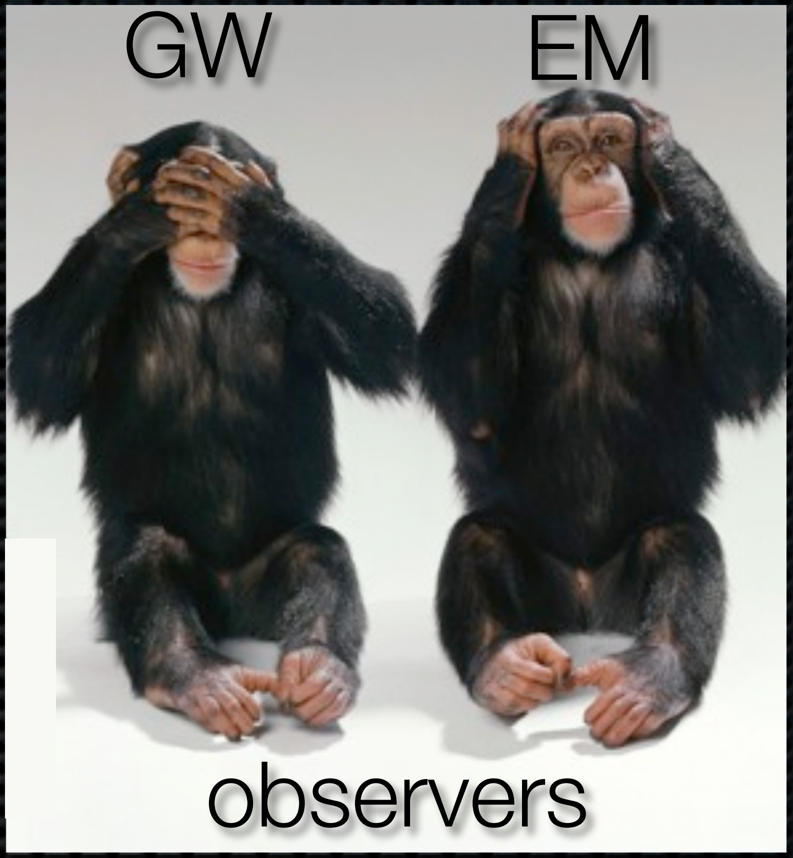
- Stellar mass systems merge in LIGO band
- Systems are strong gravitational wave emitters
- Advanced LIGO will see such systems to cosmological distances (>300 Mpc)

How many binaries will LIGO detect?



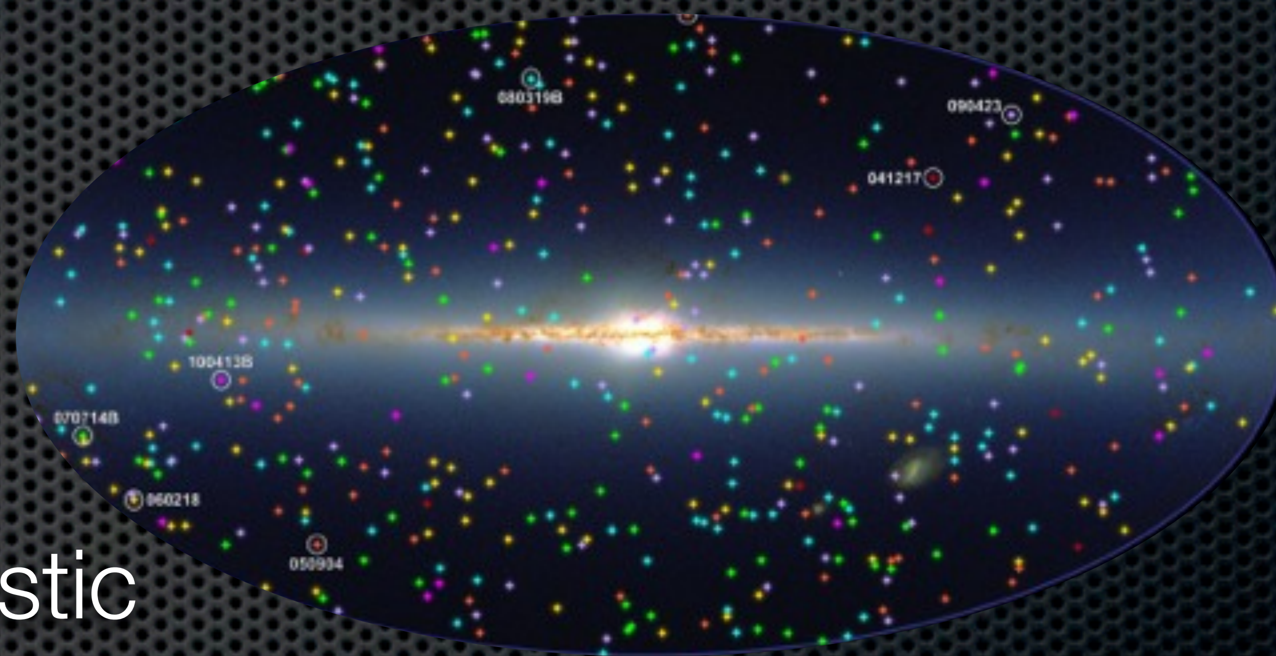
- Population synthesis
  - Stellar Initial Mass Function
  - Cosmological star formation rate
  - Binary synthesis/individual stellar evolution
  - Natal kicks, Common envelope evolution, ...
- Prediction: 40 events per year in advanced LIGO
- Uncertainty: ~2 orders of magnitude!

Multi-messenger astronomy



- Combine GW & EM
  (and neutrinos? cosmic rays?)
- GW: teaches us about the physics
  - measure masses, spins, geometry
- EM: teaches us about the astrophysics
  - measure energy, baryonic timescale, beaming, environment
- Need both GW+EM to fully understand relativistic sources
- GW+EM help identify sources (in either direction)

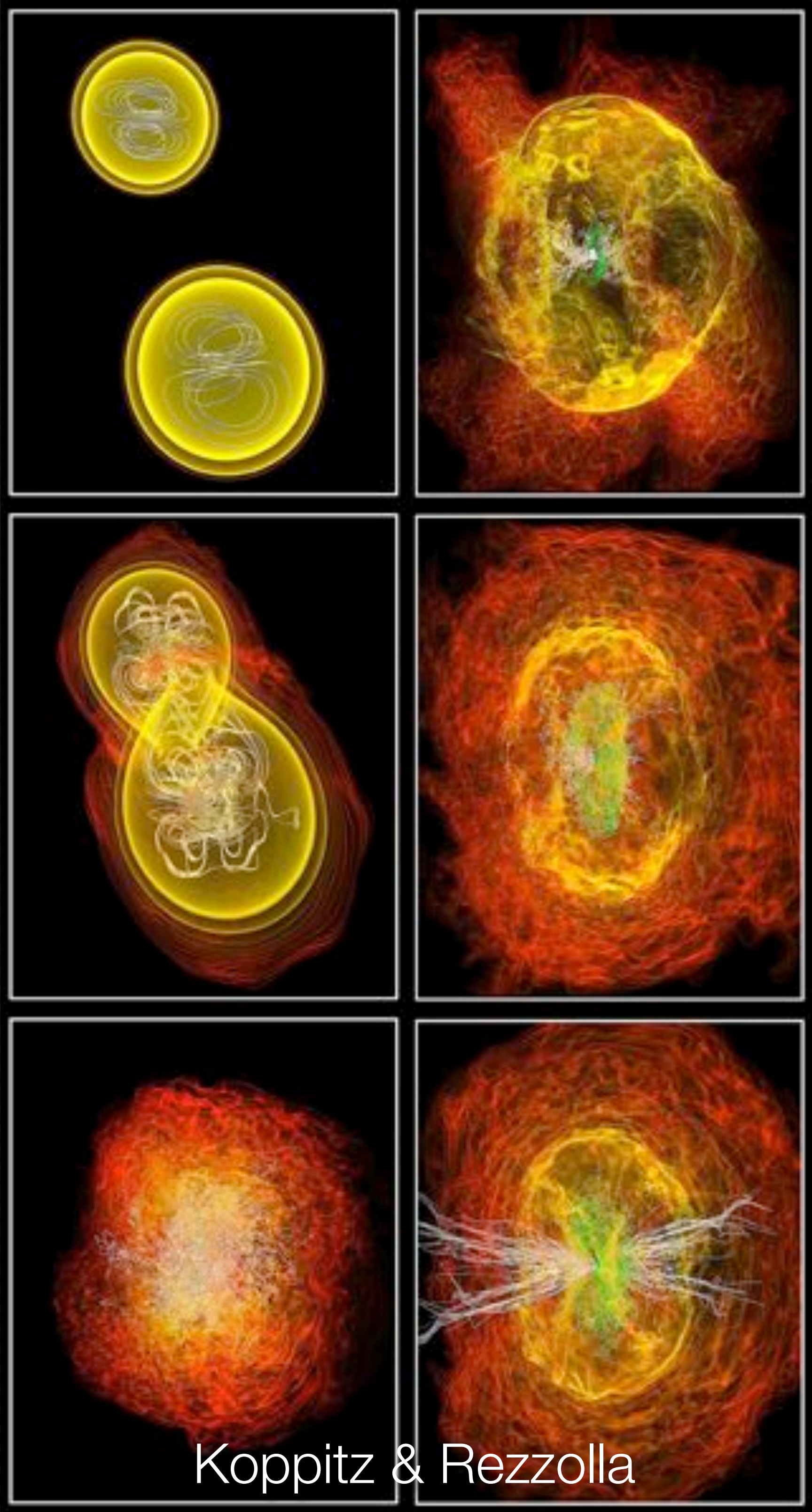
Most promising GW+EM source: Short/hard Gamma-ray burst



- GRBs definitely exist
    - ~1/day in the Universe
- GRBs are very bright/relativistic
- GRBs can be detected “all sky” throughout the Universe
- GRBs have been observed “nearby”
- Some long, and some short (2 second divide)

Short GRBs are (almost certainly) binary systems

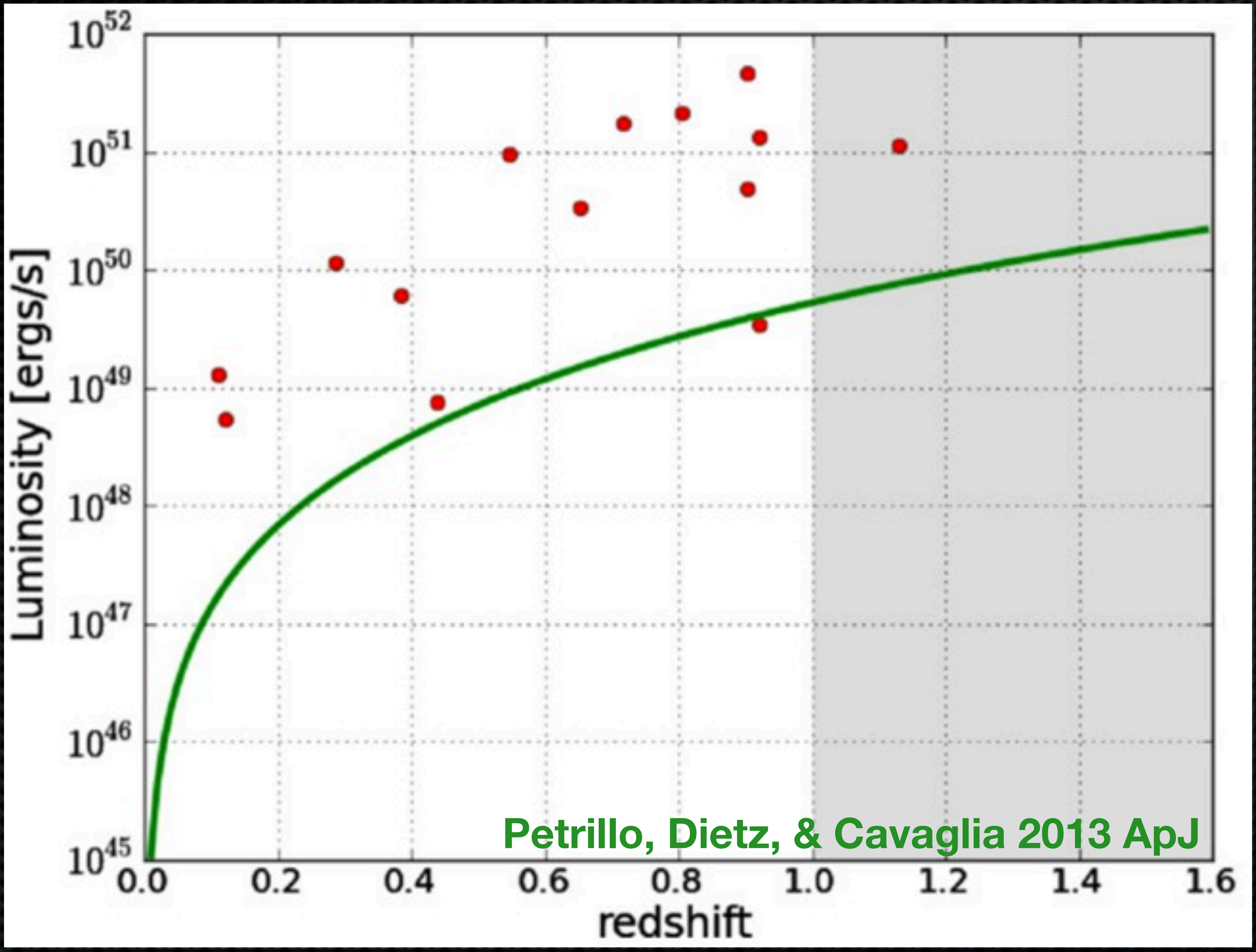
- Deep optical followup of GRBs does not show evidence for supernovae/stellar collapse
- GRBs are not associated with star formation
- GRBs are found far from the centers of their host galaxies
- Timescales are consistent
- Simulations produce GRBs



Listening to a gamma-ray burst

sound courtesy of Sam Finn (PSU)

GRB redshifts



- Short GRBs have happened at low redshift ($z < 0.2$)
- Within range of advanced LIGO!

Short GRBs are beamed

- Detailed observations of the afterglows of short GRBs (*Swift*, *XMM*, *Chandra*, optical, radio)
- Jet breaks are found, and imply beaming:
    - GRB 051221A: $\theta_j \approx 7^\circ$
    - GRB 111020A: $\theta_j \approx 3–8^\circ$
    - GRB 130603B: $\theta_j \approx 4–8^\circ$

Multi-messenger astronomy with GRBs

- Probe the inner engine of GRBs
  - binary progenitors? NS-NS vs NS-BH? masses?
  - beaming angles: measures total energy
- Properties of neutron star stuff
- Macronovae/r-process elements
- Event rates
  - predictions for LIGO
  - constraints on star formation and evolution
- Cosmological measurements

GWs and GRBs

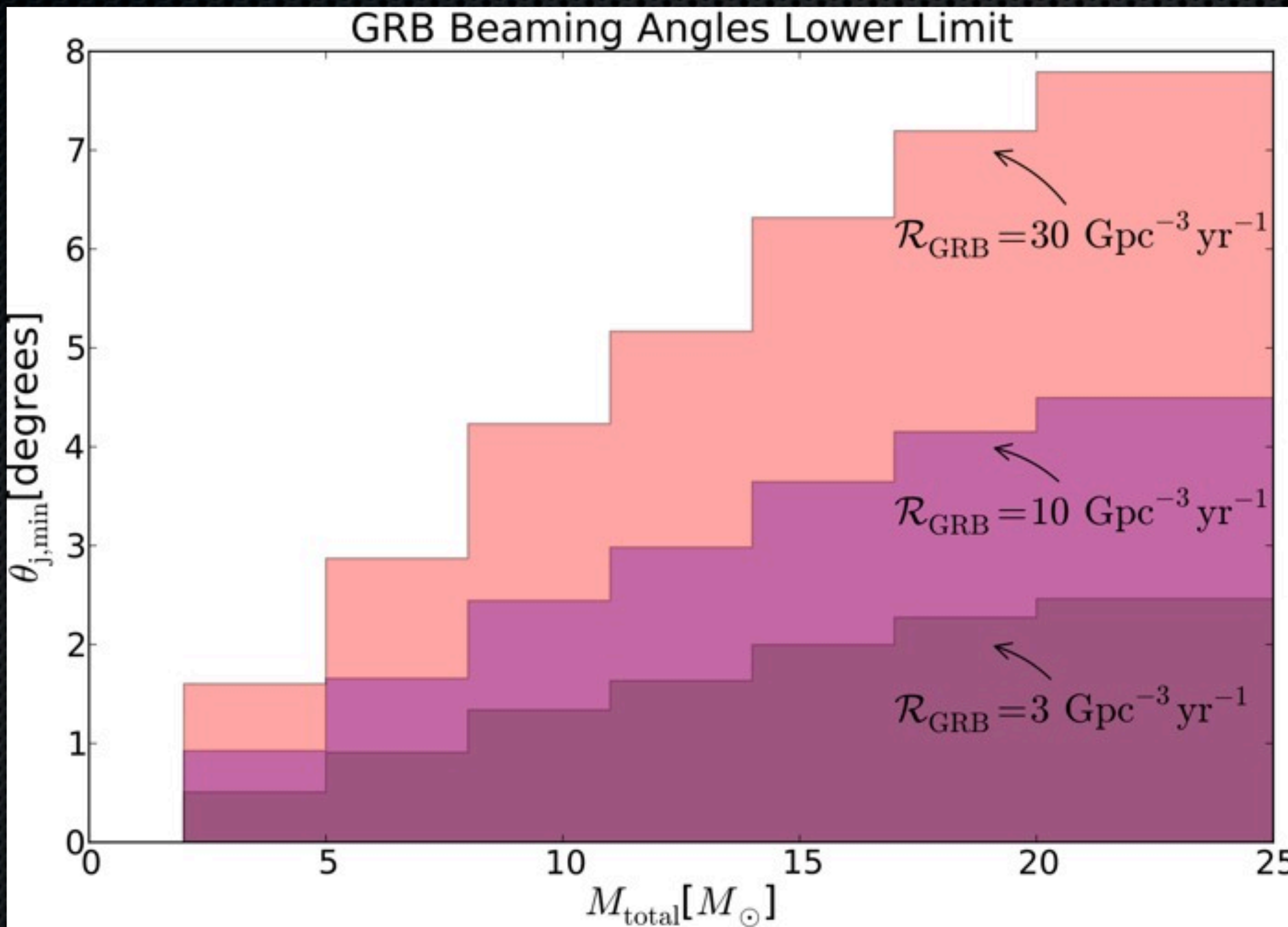
- If GRBs are binary systems, can observe them in EM (as GRBs) and in GW (as binary inspirals)
- Observables:
  - Rate of short GRBs (in gamma-rays):

    $$\mathcal{R}_{\mathrm{GRB}} \gtrsim 10\,\mathrm{yr}^{-1}\mathrm{Gpc}^{-3}$$

  - Beaming angle of short GRBs: θ
  - Rate of GRB progenitors (in GWs):

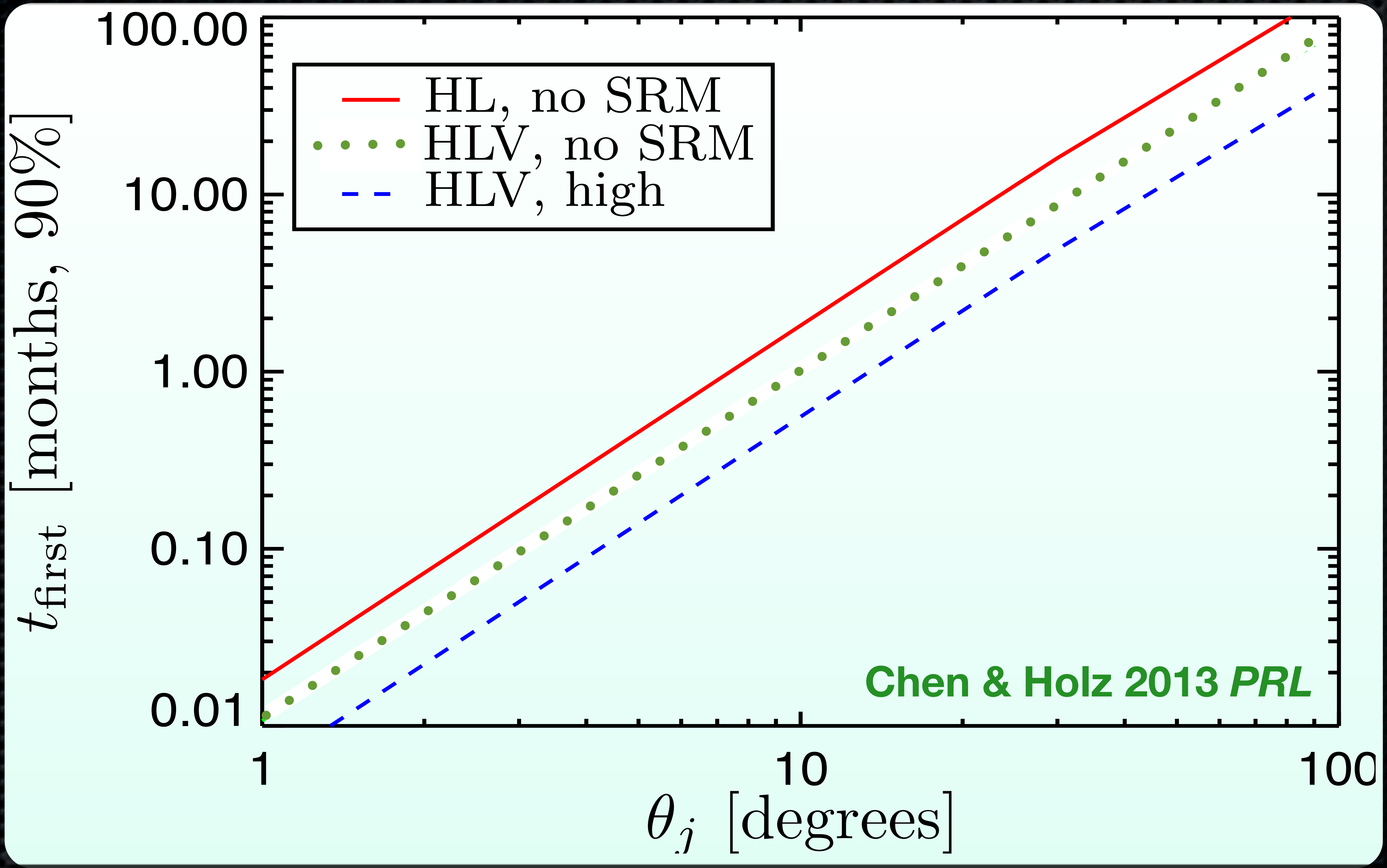
    $$\mathcal{R}_{\mathrm{GW}} = \mathcal{R}_{\mathrm{GRB}}/(1-\cos\theta)$$

LIGO limits on GRB beaming



- LIGO S6/V2 didn't see any binaries: constrains beaming

How long will LIGO have to wait?



- First binary within ~6 months for LIGO (HL; Hanford + Livingston), ~1 month for LIGO + Virgo (HLV)
- Best estimate for LIGO detection rate!

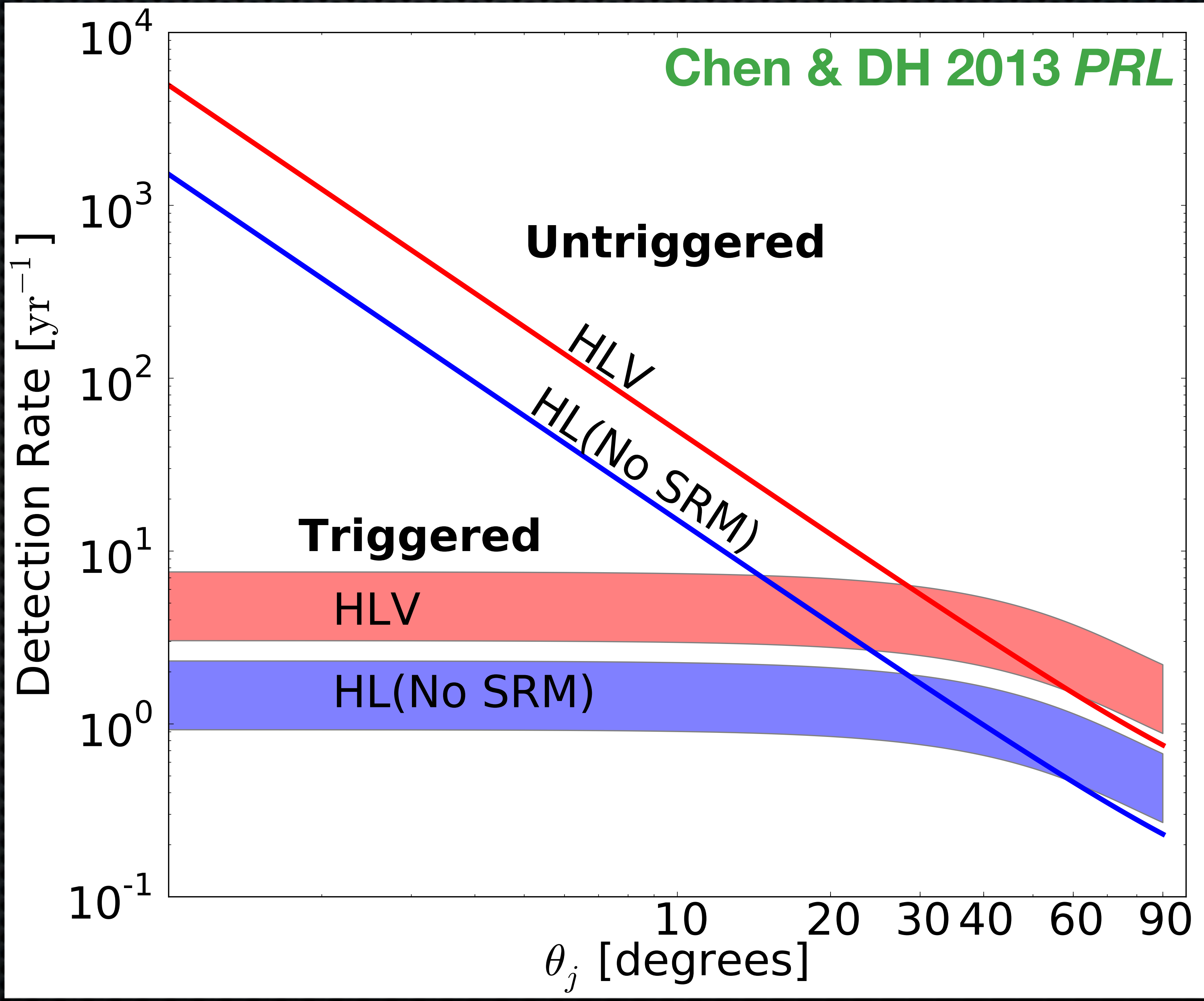
To trigger or not to trigger?

- Trigger: (see GRB and GWs at the same time)
  - provides time and sky position: drastic improvement in GW search algorithm, and hence lower detection threshold

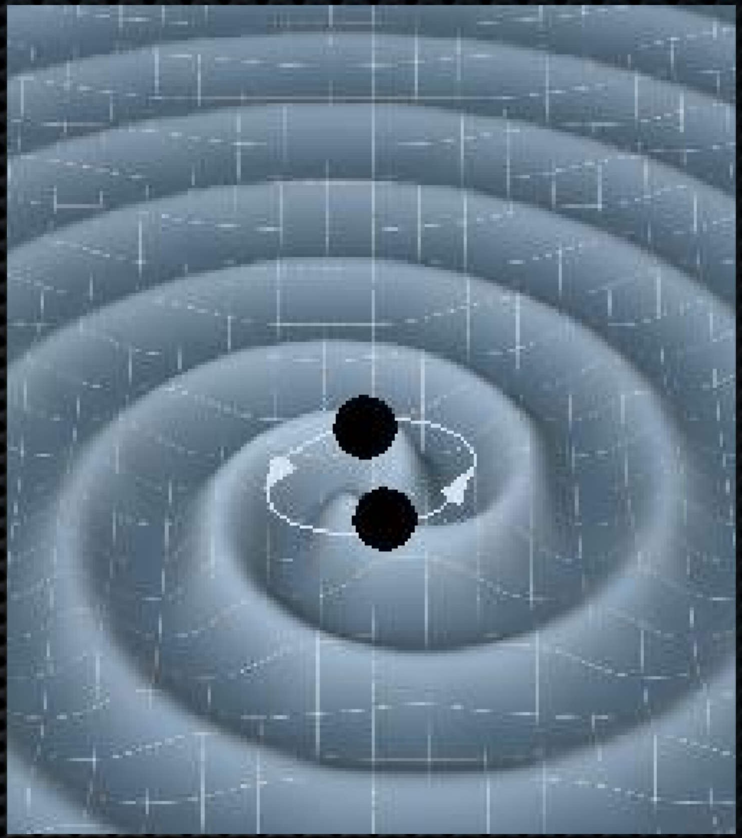
  - probably face-on, thus stronger signal
- Untriggered: (don't see GRB in EM spectrum)
  - don't need the gamma-rays to be pointing at us, so much higher space density

High rates. No trigger needed.

- Early sensitivity: ~10 events/year
- Mature sensitivity: ~50 events/year
- Will see untriggered before triggered



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, Nature
DH & Hughes 2005, ApJ
Dalal, DH, Hughes, & Jain 2006, PRD
Cutler and DH 2009, PRD
Nissanke et al. 2010, 2013, ApJ

GWs from binary systems

- Strongest harmonic (widely separated):
$$h(t) = \frac{M_z^{5/3} f(t)^{2/3}}{D_L} F(\text{angles}) \cos(\Phi(t))$$
- 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 $F(\text{angles})$
- (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

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

“Optical” counterpart?

- Roughly 5% of the system’s mass is being released in gravitational waves (~$10^{52/58}$ ergs)
- Even if only 1 part in 10^{10} of this available energy is converted into photons, the source would be easily visible at high redshift
- Need fantastic efficiency to remain “dark”

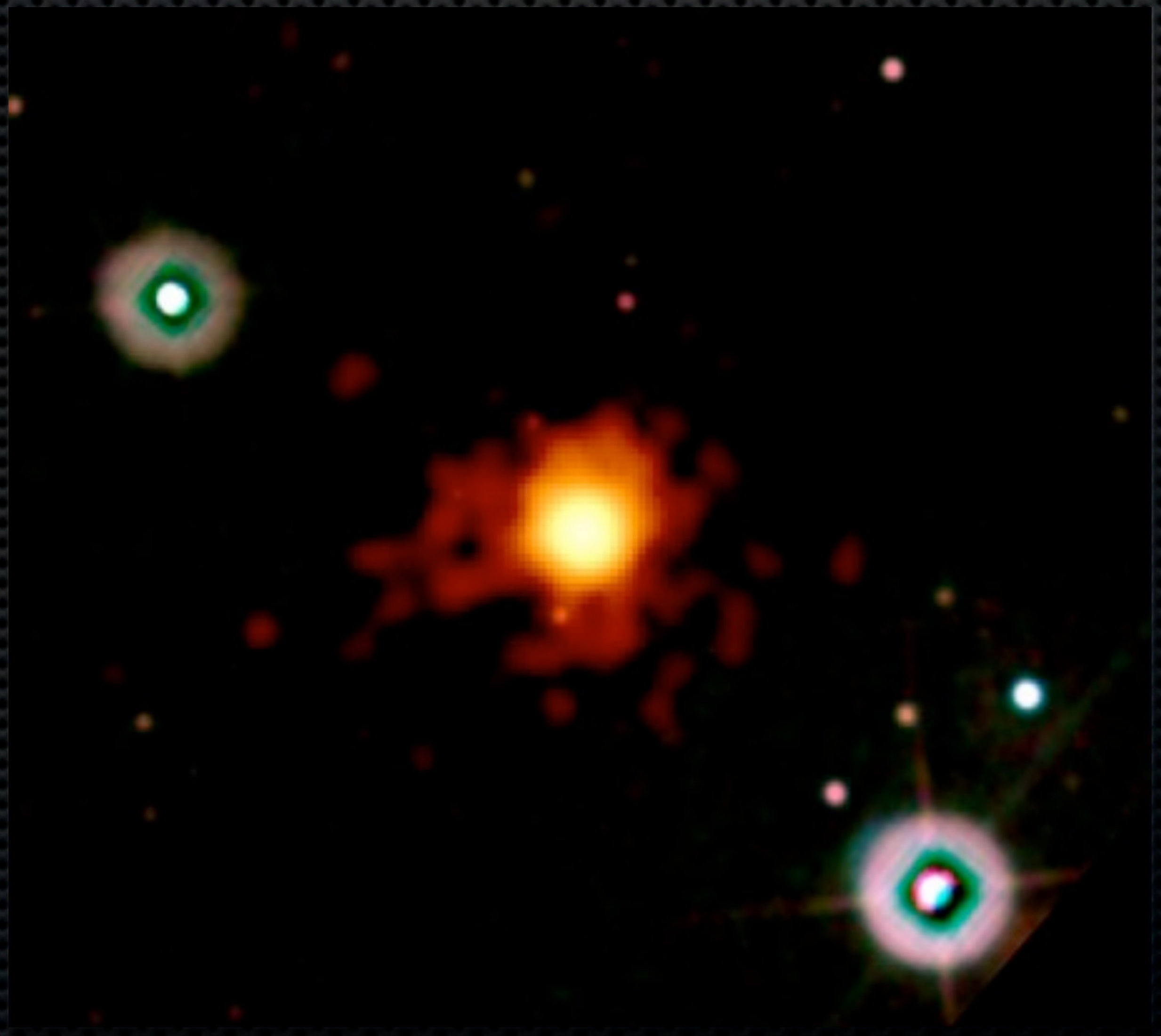
Potential standard sirens

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

LIGO standard sirens?:

LIGO standard sirens:

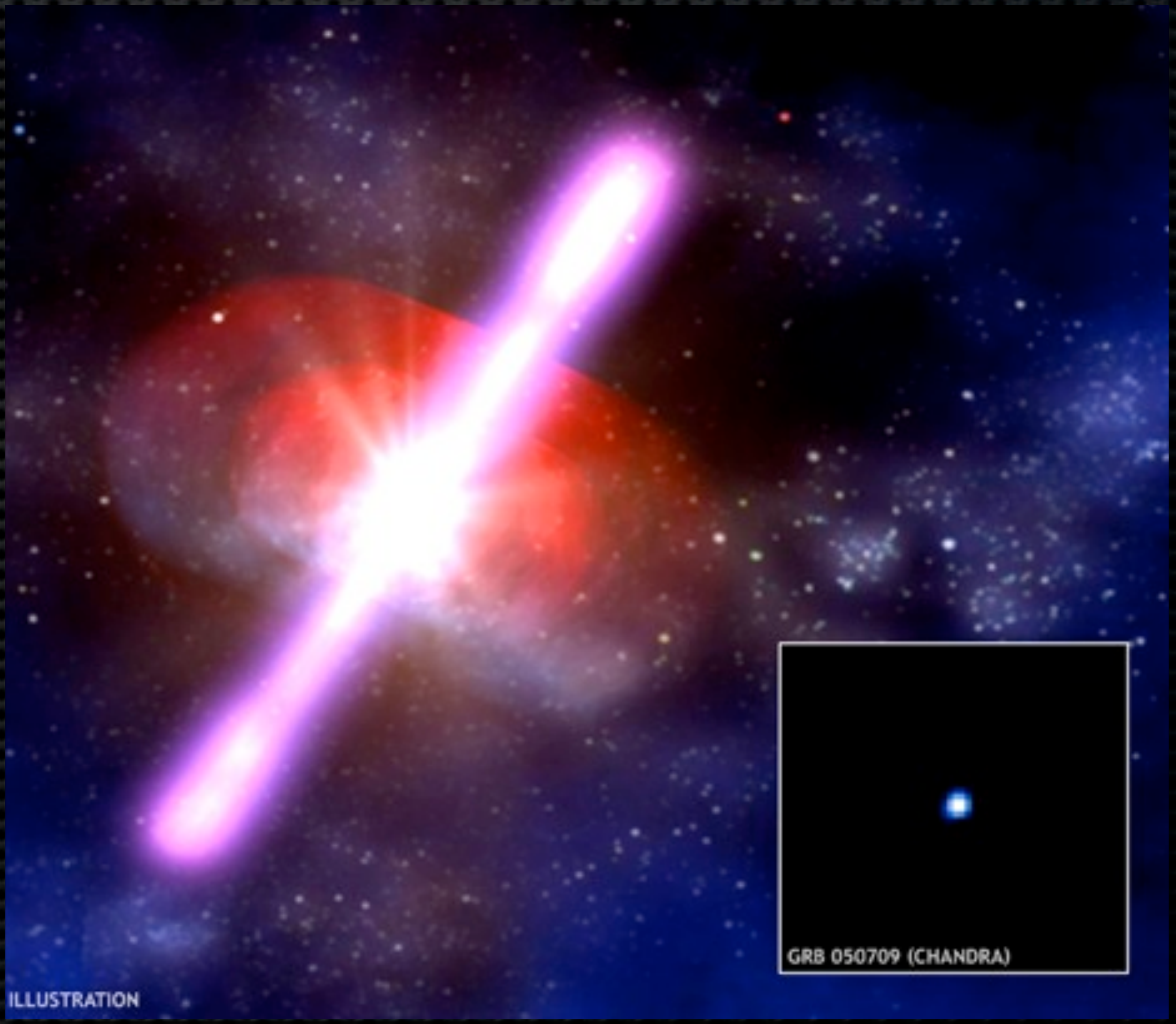
Short gamma-ray bursts!



Gamma-ray Burst Standard Sirens

- Short GRBs are known to occur at low redshift ($z < 0.2$)
- Short GRBs are thought to be the result of binary mergers (NS or BH)
- Will be seen by aLIGO. Perfect standard siren!

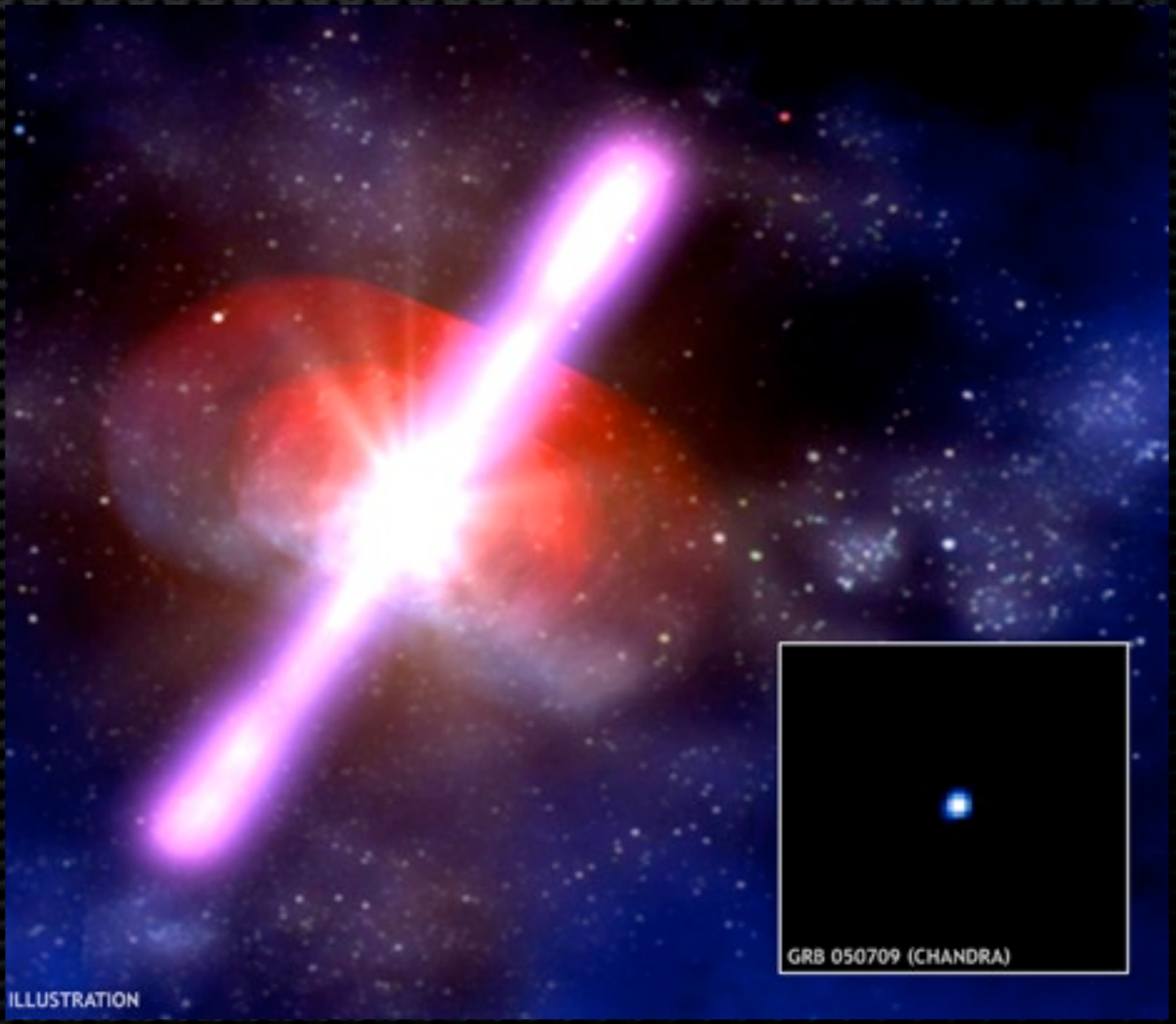
Systematic “free” absolute distance



Dalal, DH, Hughes, & Jain 2006, PRD
Nissanke et al. 2010, 2013 ApJ

Short gamma-ray bursts are perfect standard sirens

- Very bright in EM and GW
- Happen frequently
- Happen nearby
- Time of burst improves parameter estimation
- Can identify redshift from host galaxy



No distance ladder. Provides absolute distance

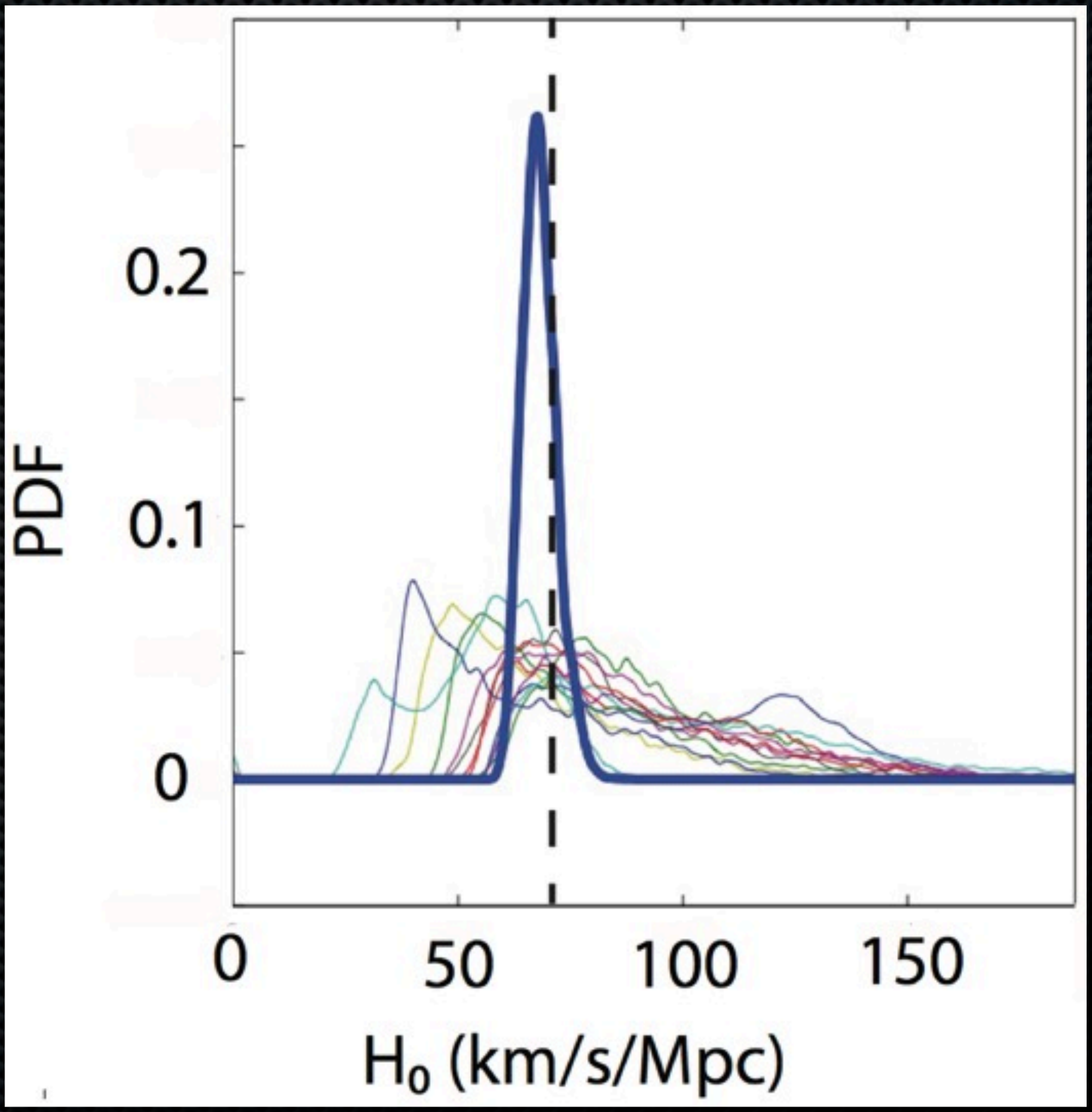
How well do GRB standard sirens measure distance?

- Markov-Chain Monte Carlo code
- Non-spinning restricted 3.5 post-Newtonian waveform
- Detection priors in population selection
- Independent interferometric noise realizations
- Advanced GW detector configurations

Nissanke et al. 2010, 2011, 2013

Measuring the Hubble constant

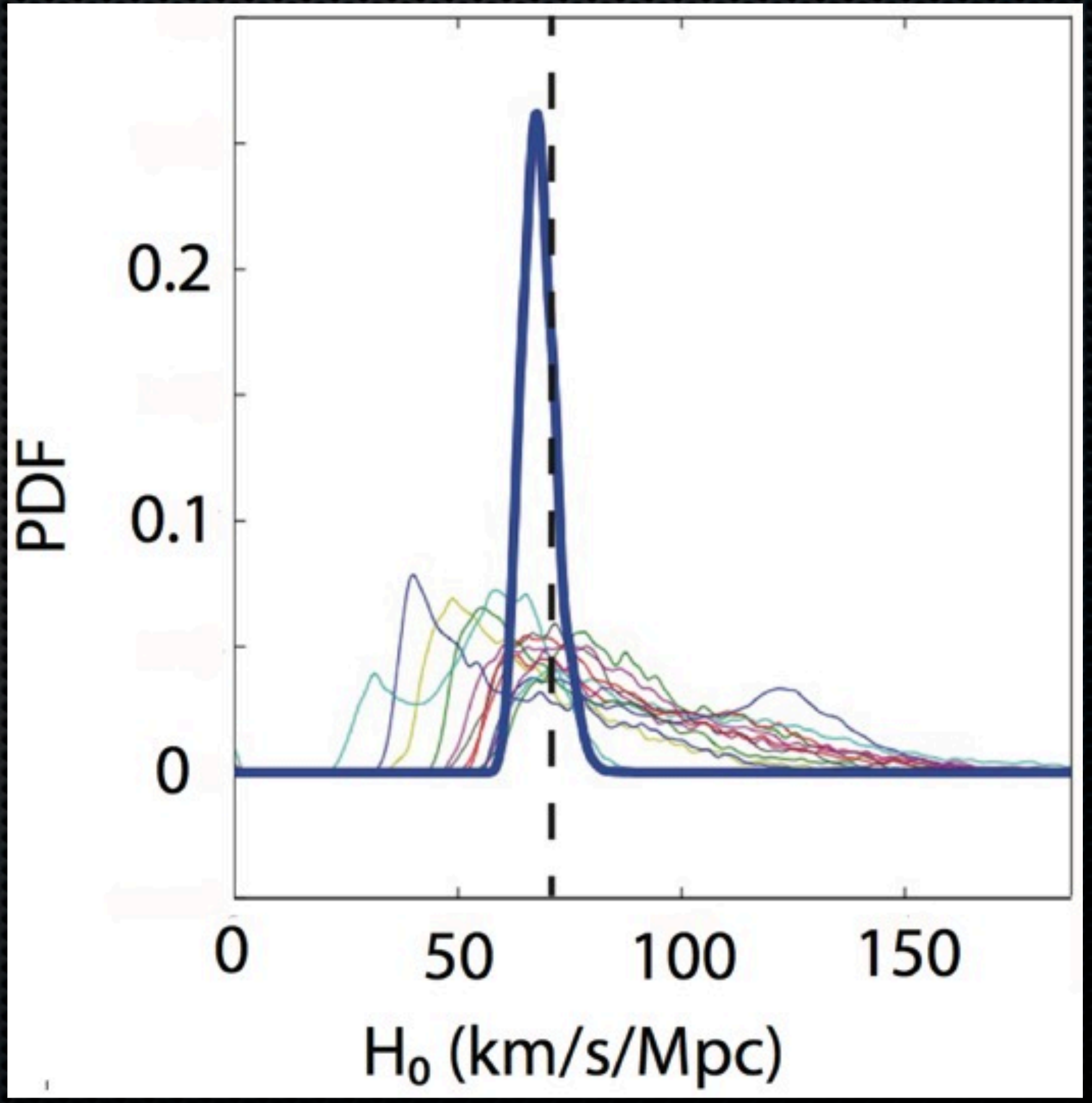
- Hubble: the overall scale of the Universe
- advanced LIGO/Virgo
- 15 isotropic NS-NS binaries
- assuming GW+EM: standard sirens
- distributions are non-Gaussian
- 3% measurement of H_0



Nissanke et al. 2013

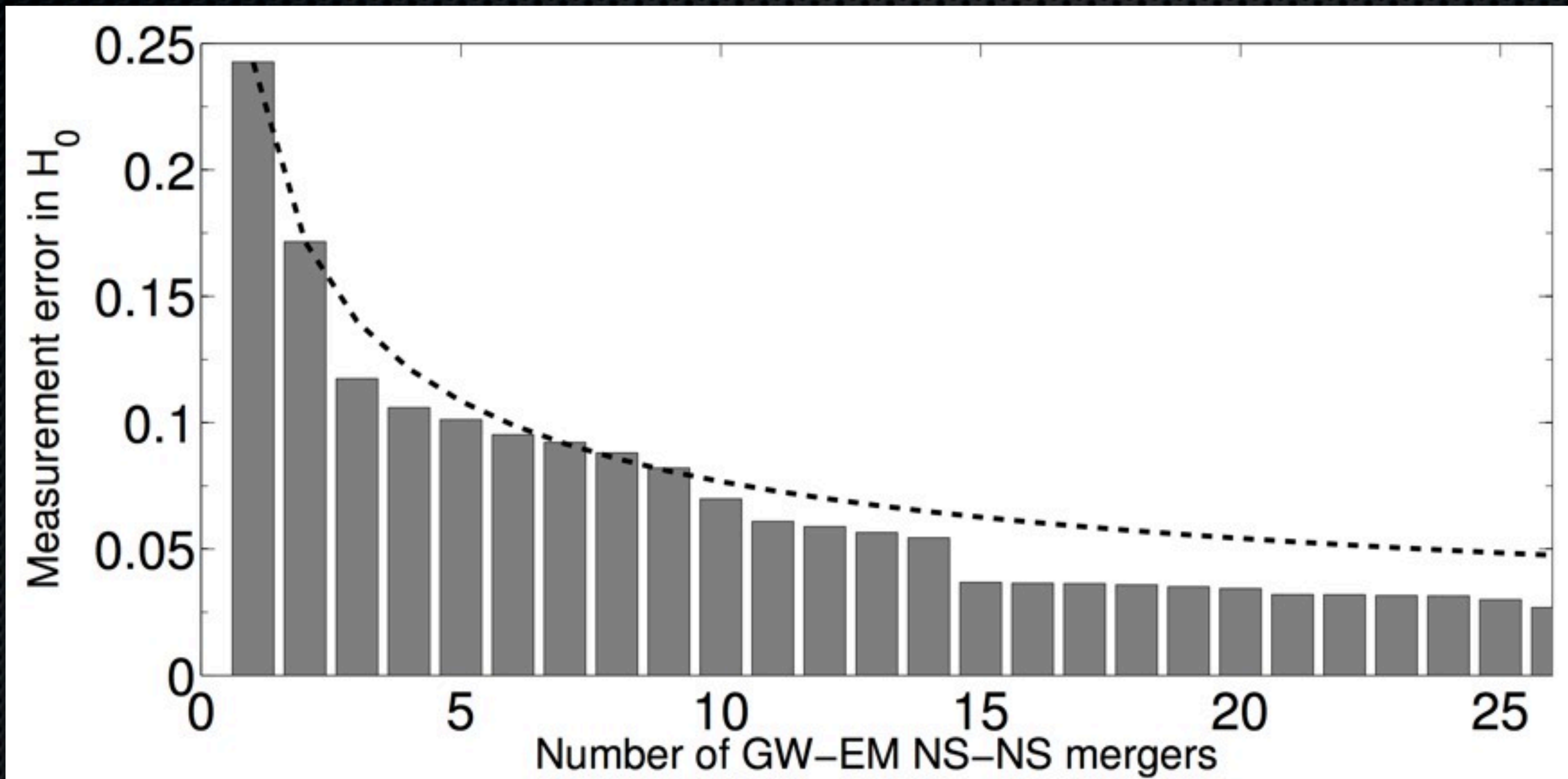
Measuring the Hubble constant

add Japan+India:
factor ~2
if GRBs are beamed:
factor >2
NS-NS->NS-BH:
factor ~4



Nissanke et al. 2013

Precision cosmology from GWs!

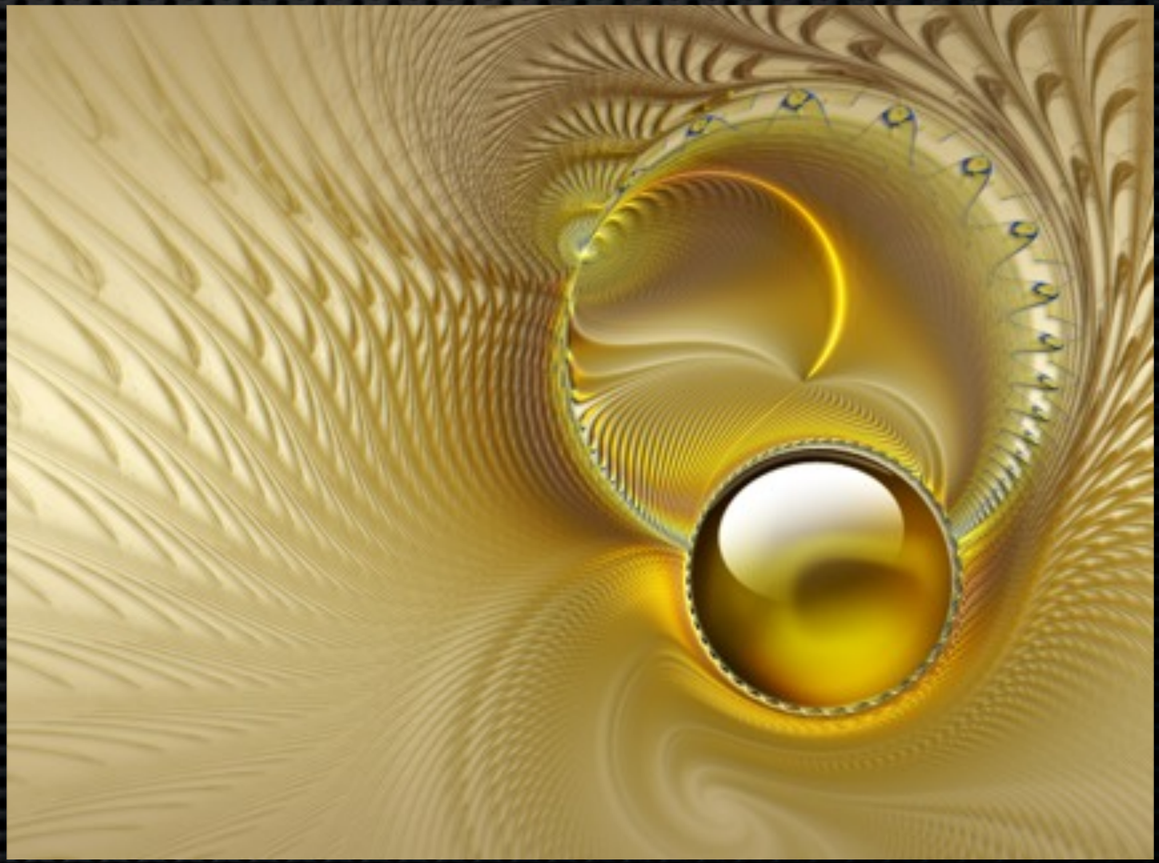


- Measure the Hubble constant to the few percent level

Nissanke et al. 2013

Golden binaries

- Most events are at detection threshold
- No extinction, obscuration, or evolution
- Can *predict* the full distribution of signal strengths
- Can *predict* the distribution of the strongest events



The loudest events provide the most physics!

GW strength in a LIGO detector

- Signal-to-noise ratio (restricted, first order, stationary phase):

$$\mathrm{SNR}^2 = 4\frac{\mathcal{A}^2}{{D_L}^2}\left[F_+^2(\theta,\phi,\psi)(1+\cos^2\iota)^2 + 4F_\times^2(\theta,\phi,\psi)\cos^2\iota\right] I_7$$

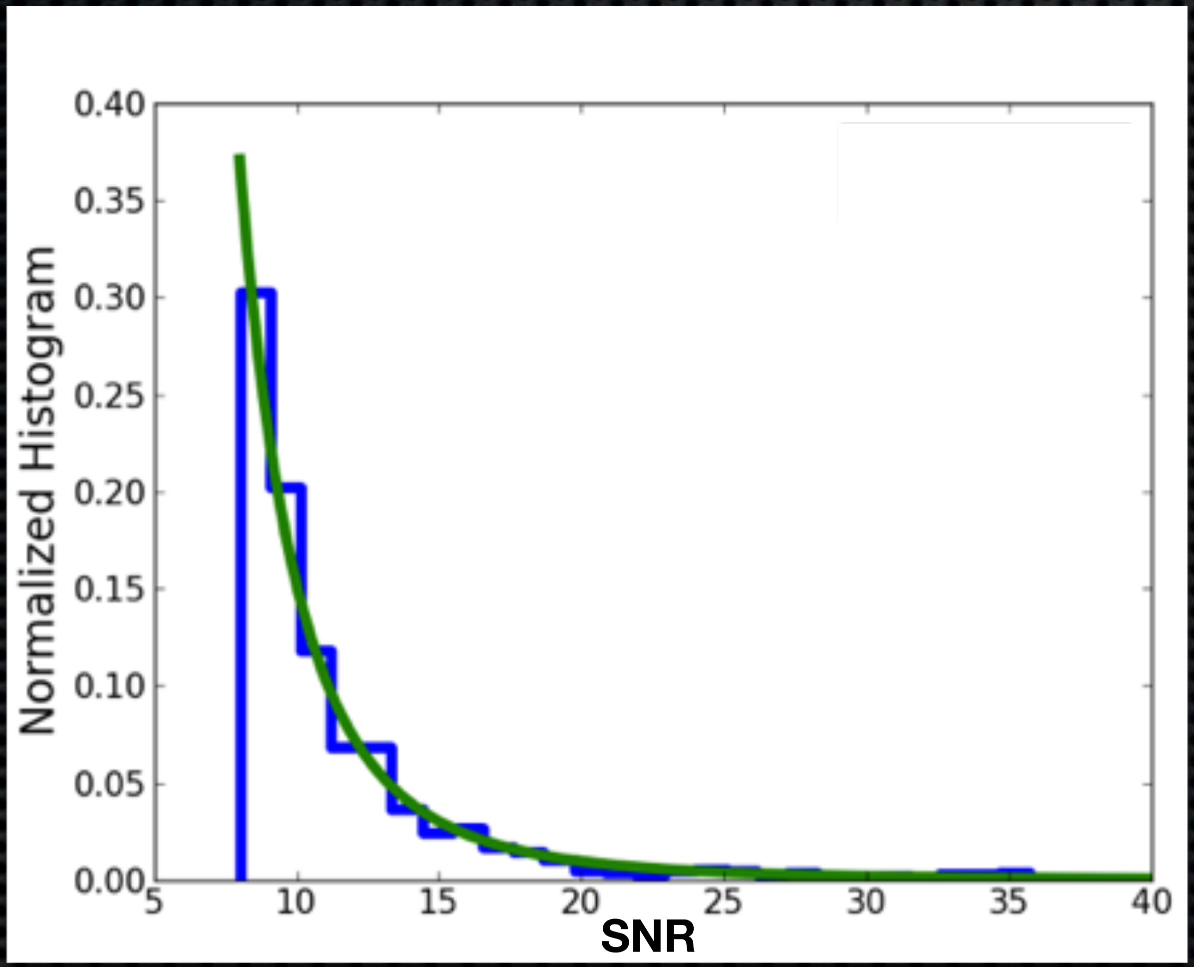
with (this color text doesn't show up?!!!):

$$\mathcal{A} = \sqrt{\frac{5}{96}}\frac{c}{\pi^{2/3}}\left(\frac{G\mathcal{M}_z}{c^3}\right)^{5/6} \qquad I_7 = \int_{f_\mathrm{low}}^{f_\mathrm{high}} \frac{f^{-7/3}}{S_h(f)}\,df$$

- sky position, orientation, inclination: $(\theta,\phi),\psi,\iota$
- luminosity distance: D_L
- antenna power patterns (2 polarizations): $F_+, F_\times$
- LIGO noise spectral density: $S_h(f)$
- (redshifted) chirp mass:

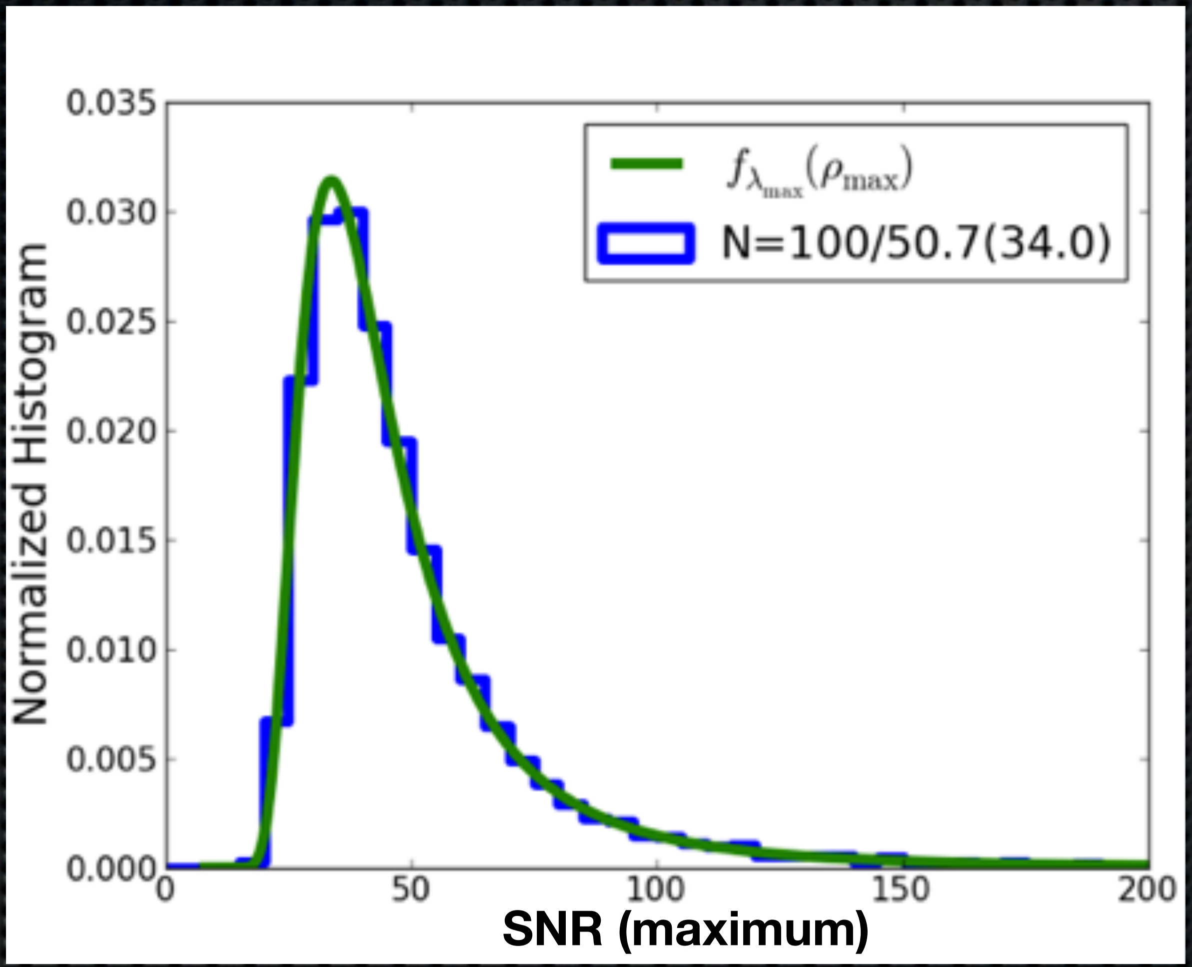
$$\mathcal{M} = (1+z)(m_1 m_2)^{3/5}/(m_1+m_2)^{1/5}$$

Universal distribution of SNR



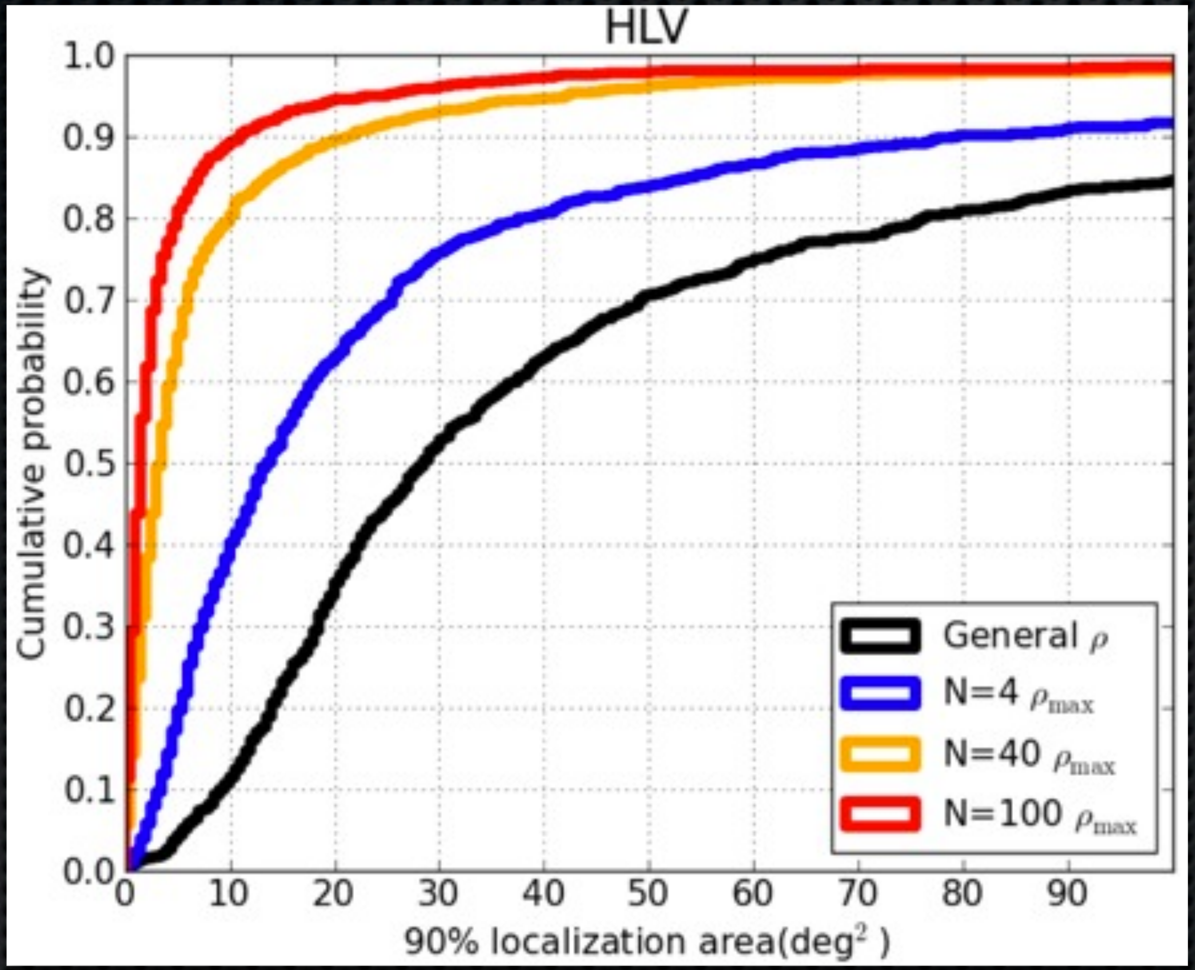
- Most events at detection threshold, with a tail to louder events
- Predictable, analytic, universal distribution

Universal distribution of loudest events



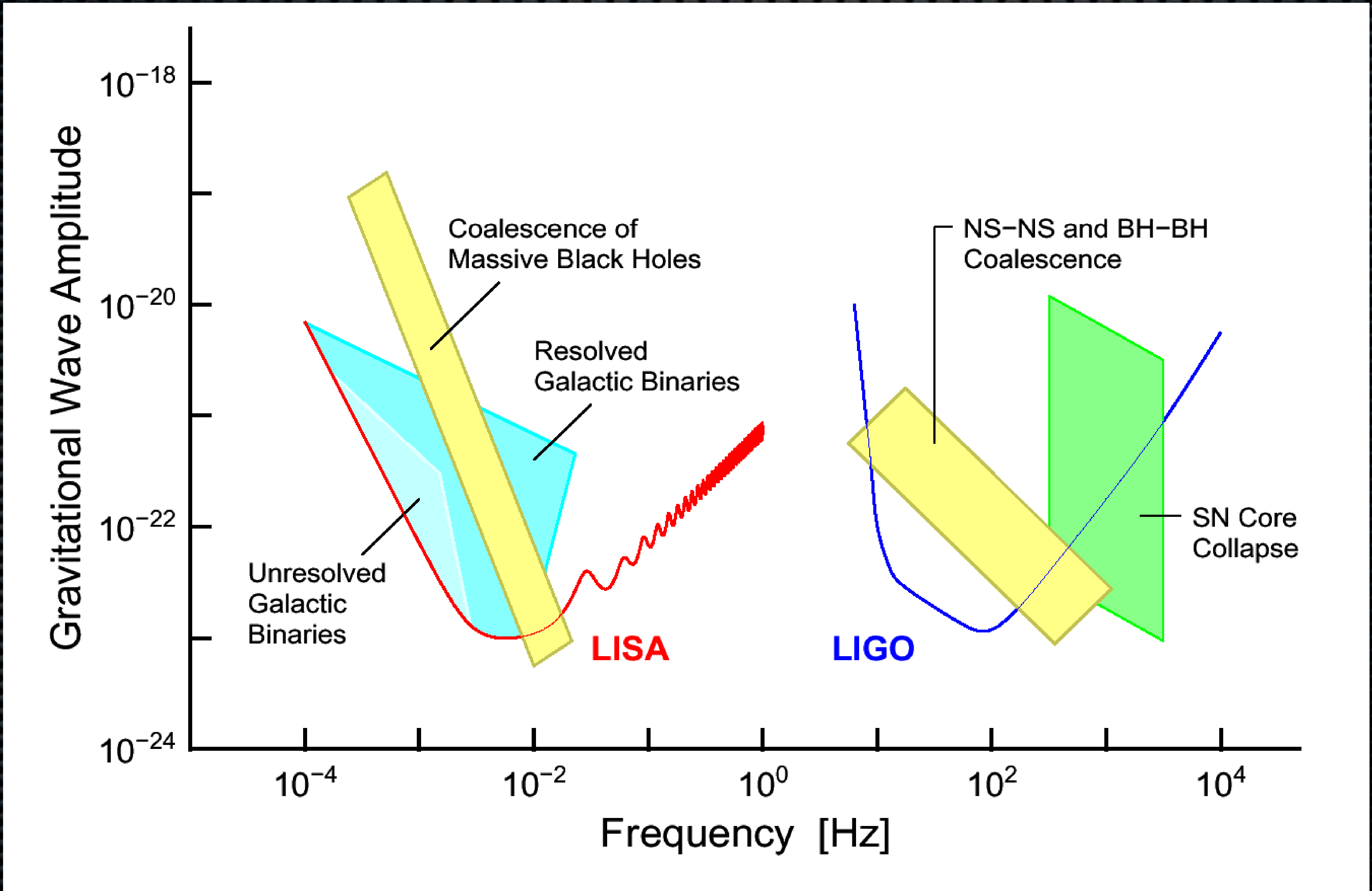
- Predictable, analytic, universal distribution. Independent of all details of source population. Extreme value statistics.
- For 4 events, loudest has SNR>14.5 (for threshold =12; 90% likelihood). SNR>31 for 40 events.
  SNR>42 for 100 events.

The louder, the better

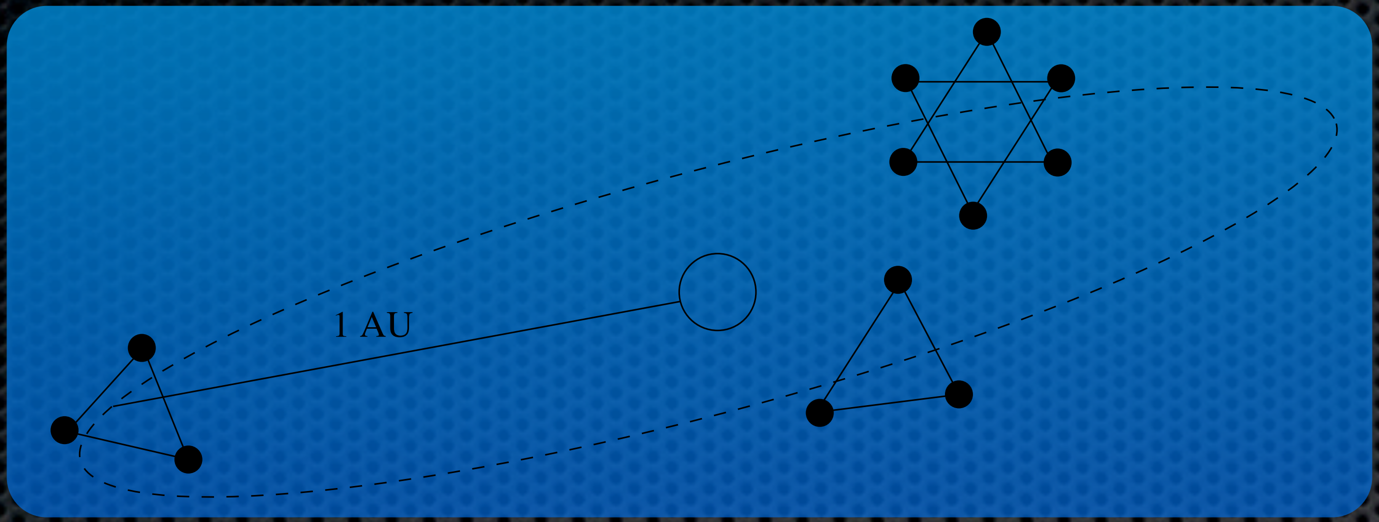


- Larger SNR means better parameter estimation
- The best out of 4 events reduces the sky localization from ~30 deg^2 to ~15 deg^2. Out of 40 events, the best one is localized to better than ~2 deg^2
- Probability of finding counterparts increases dramatically

GW science reach



Big Bang Observer

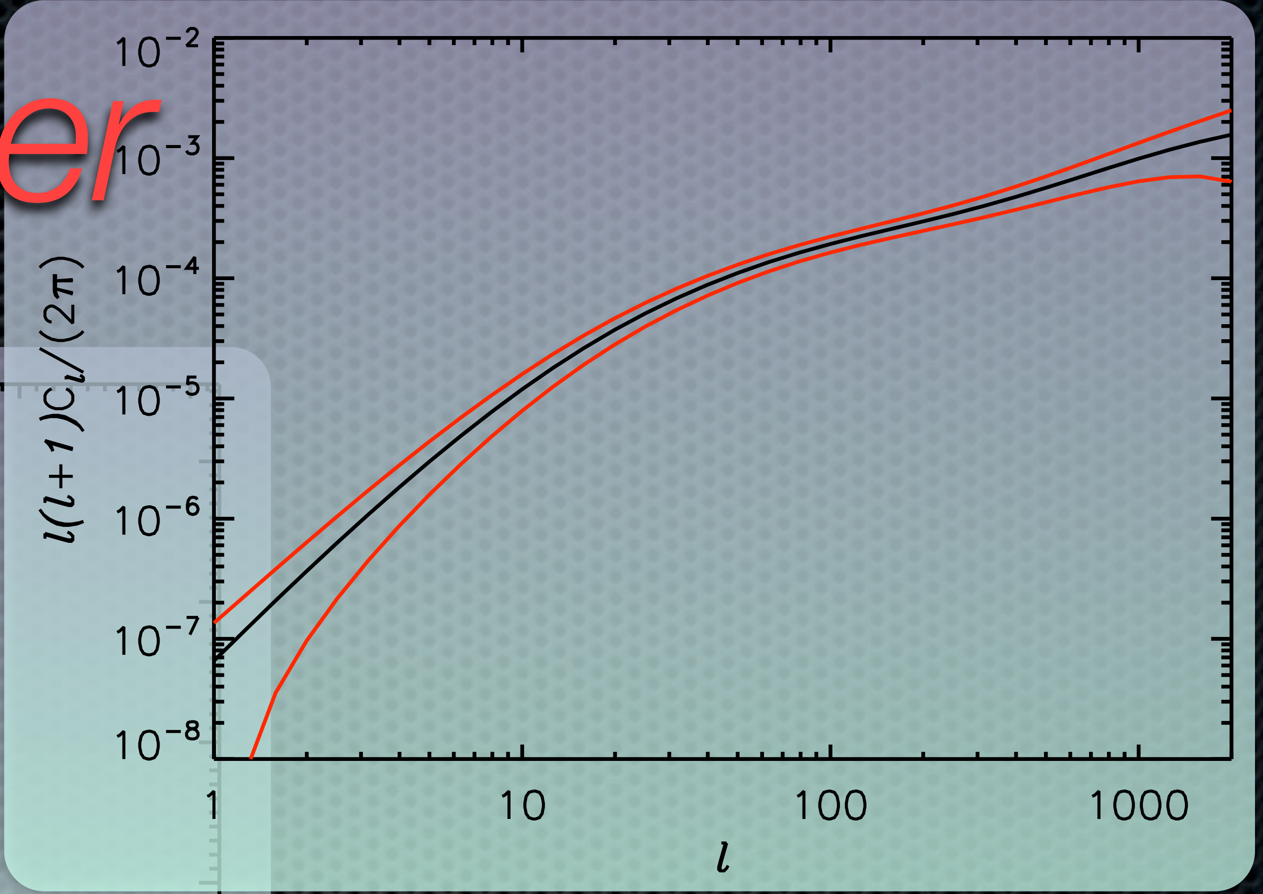


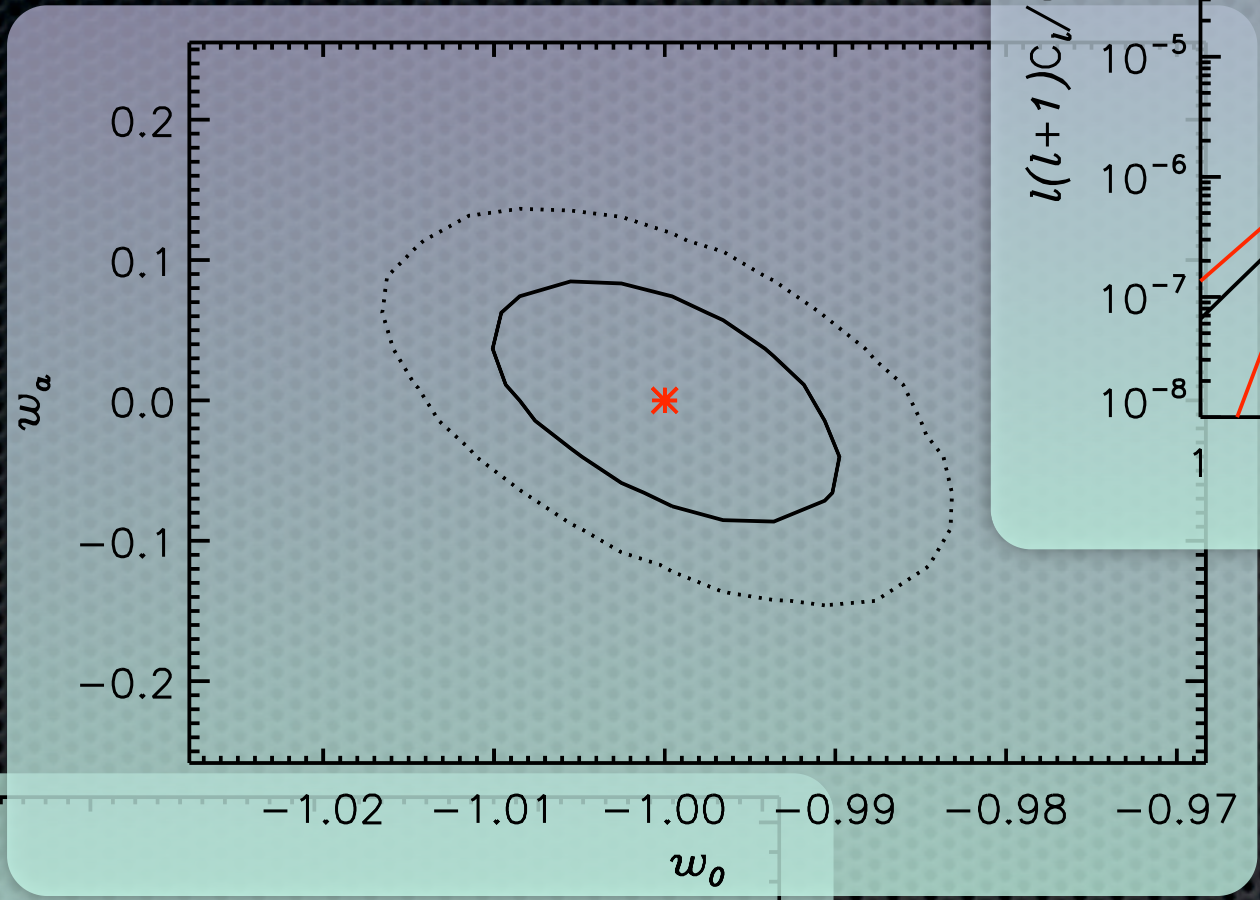
- BBO sees $\sim 10^5$ NS-NS binaries to $z \sim 5$
- BBO sky localization uniquely identifies host
  - Extraordinary measurement of luminosity distance-redshift relation
  - Extraordinary measurement of gravitational lensing (and hence structure formation)

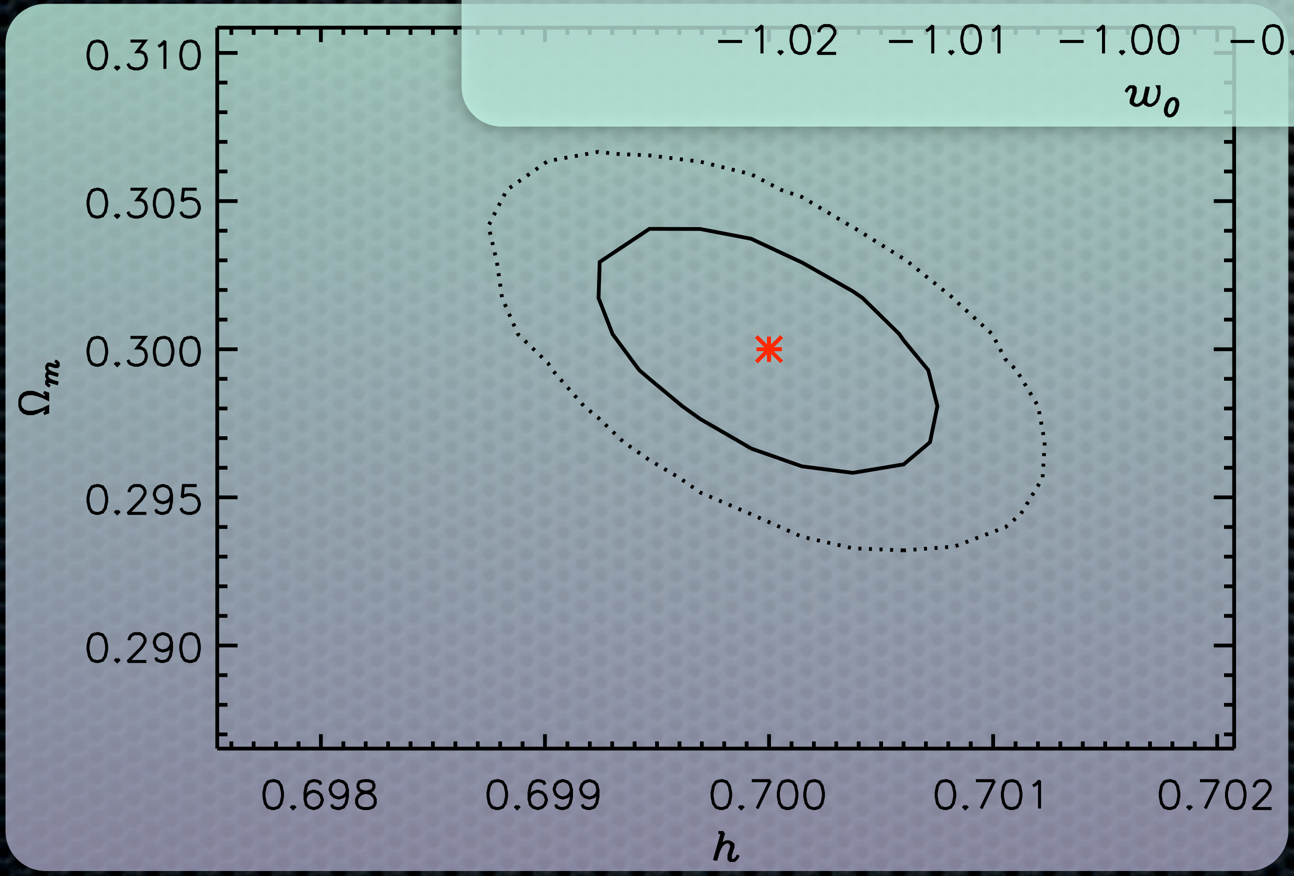
Ultra-precise cosmology

Cutler & DH 2009

Big Bang Observer







BBO is a fantastic cosmological probe

Thunder and lightning

Thus far we've only seen the Universe (and 95% of it is dark: dark matter and dark energy).

In the the next few years we will finally be able to listen to the Universe.

This will be revolutionary!