# Cosmography with ground- and space-based detectors

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# Outline

- Cosmography with LISA
  - Difficulties and how we might mitigate some of them
- Cosmography with ground_based detectors
  - Measuring host redshifts from GW observations alone
  - Cosmography from a population of observed sources

# Why are inspirals standard sirens?

- Luminosity distance $D$ can be inferred if one can measure:
  - the flux of radiation $F$ and
  - absolute luminosity $L$

$$D_L = \sqrt{\frac{L}{4\pi F}}$$

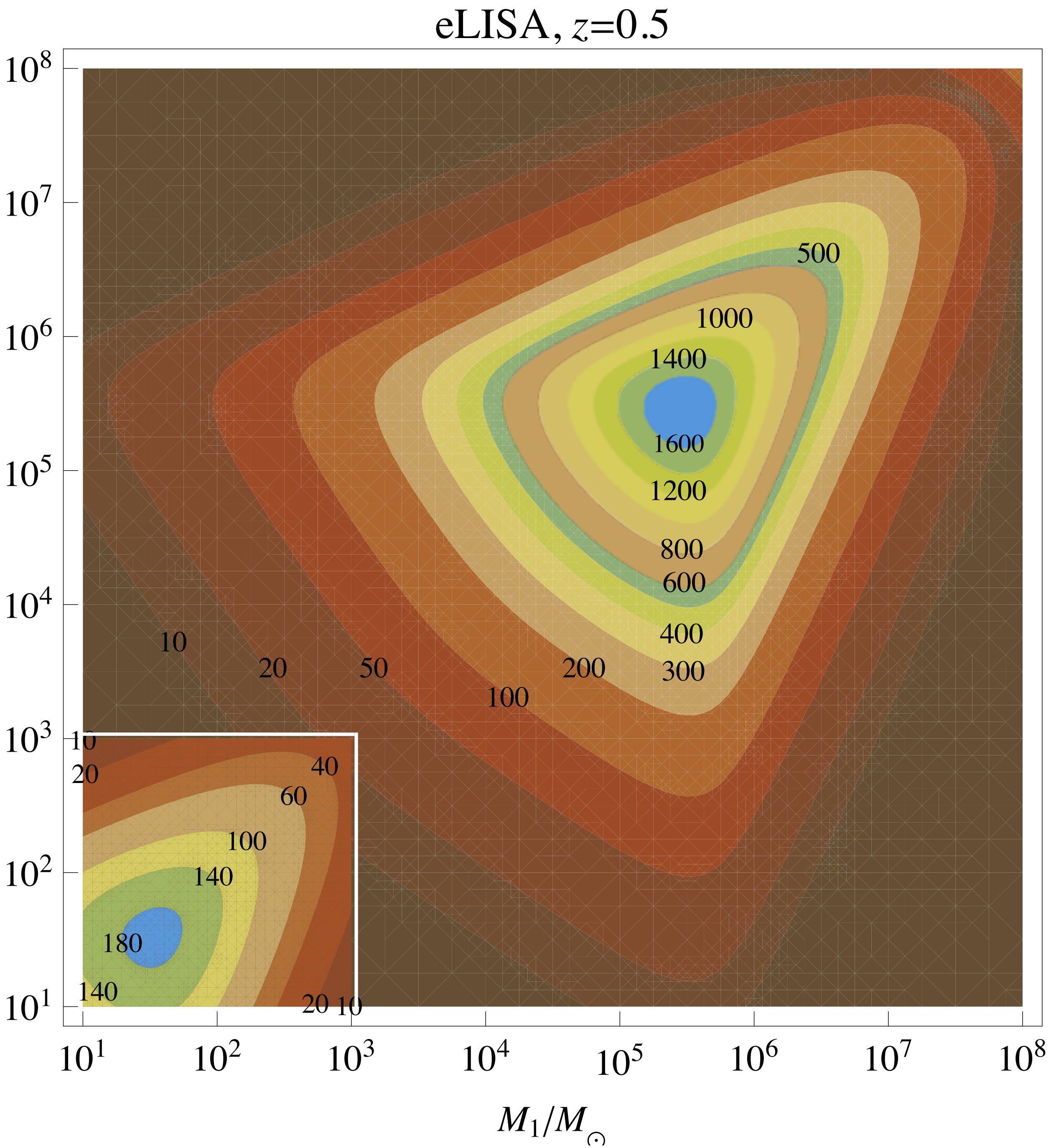
Schutz Nature1986

- Flux of gravitational waves determined by amplitude of gravitational waves measured by our detectors
- Absolute luminosity can be inferred from the rate $\dot{f}$ at which the frequency of a source changes
  - Not unlike Cephied variables except that $\dot{f}$ is completely determined by general relativity
- Therefore compact binaries are self_calibrating standard sirens

# Cosmography with LISA

# Cosmography from a single source

- Gravitational wave (GW) observations alone cannot measure the source's redshift
  - This is certainly true for binary black holes
  - For binary neutron stars it might be a different story
- If it is possible to identify the host galaxy then
  - can measure the source's redshift in addition to luminosity distance
  - An ideal tool for cosmography and synergy between EM and GW astronomy
- LISA can measure signals with a very high (amplitude) signal-to-noise ratio (~1000-10,000)
  - Should be possible to distinguish between different cosmological models with a high-SNR single event

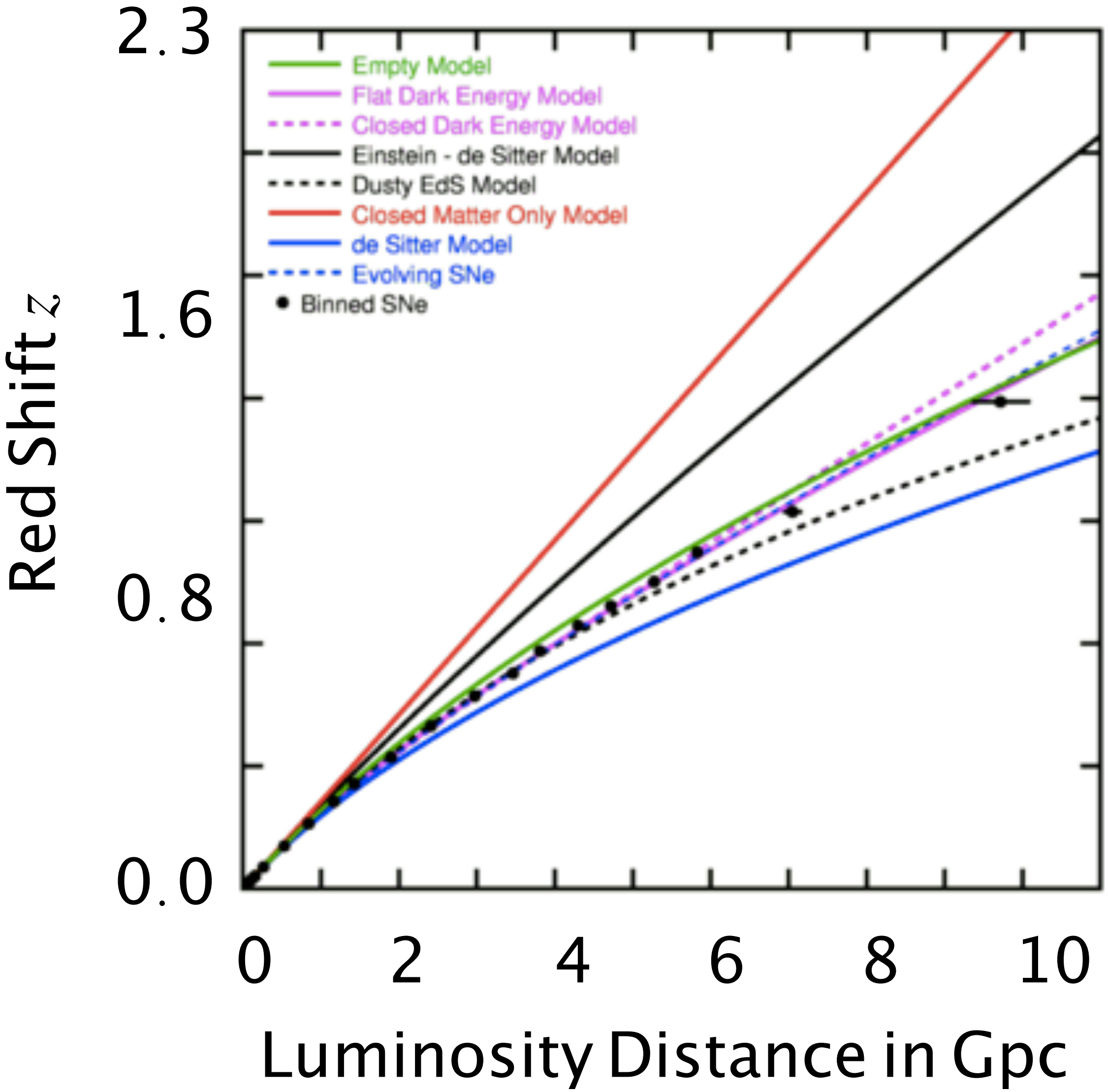


eLISA SNRs
Inset: ET SNRs
Inspiral signal only

Sathyaprakash and Schutz, LRR: 2014

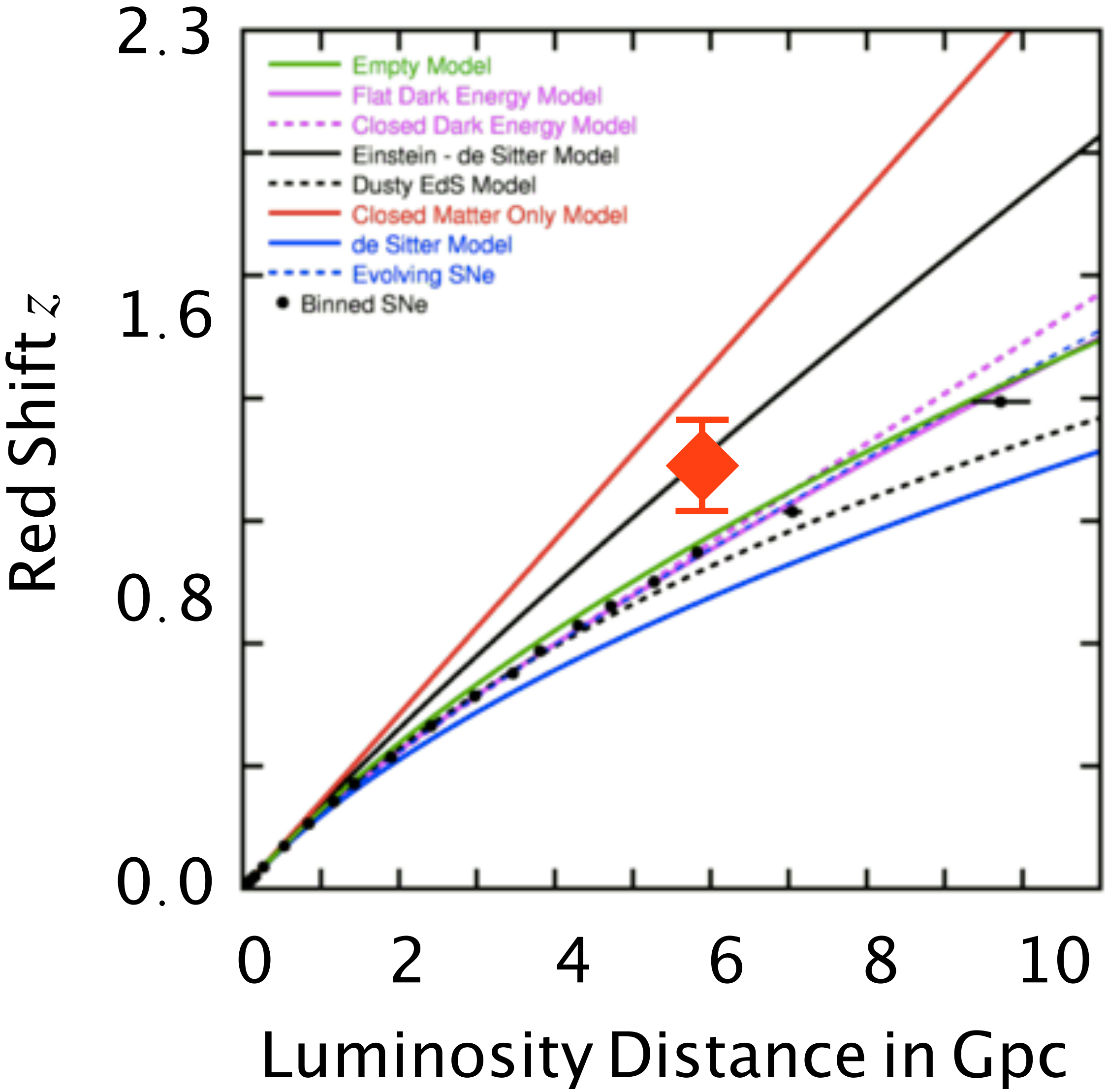
# Basic idea

Diagram:
Ned Wright: 2011



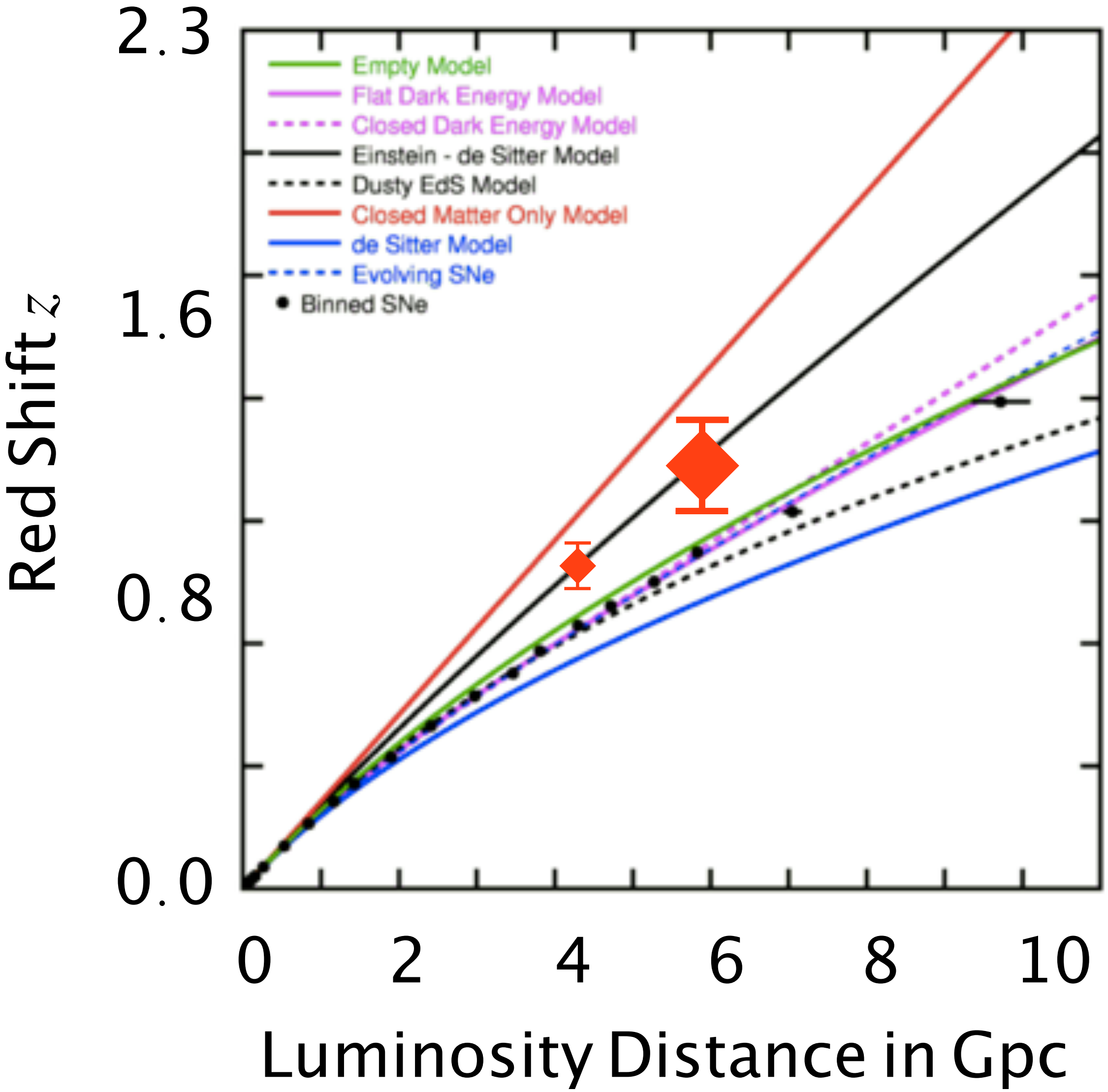
# Basic idea

Diagram:
Ned Wright: 2011



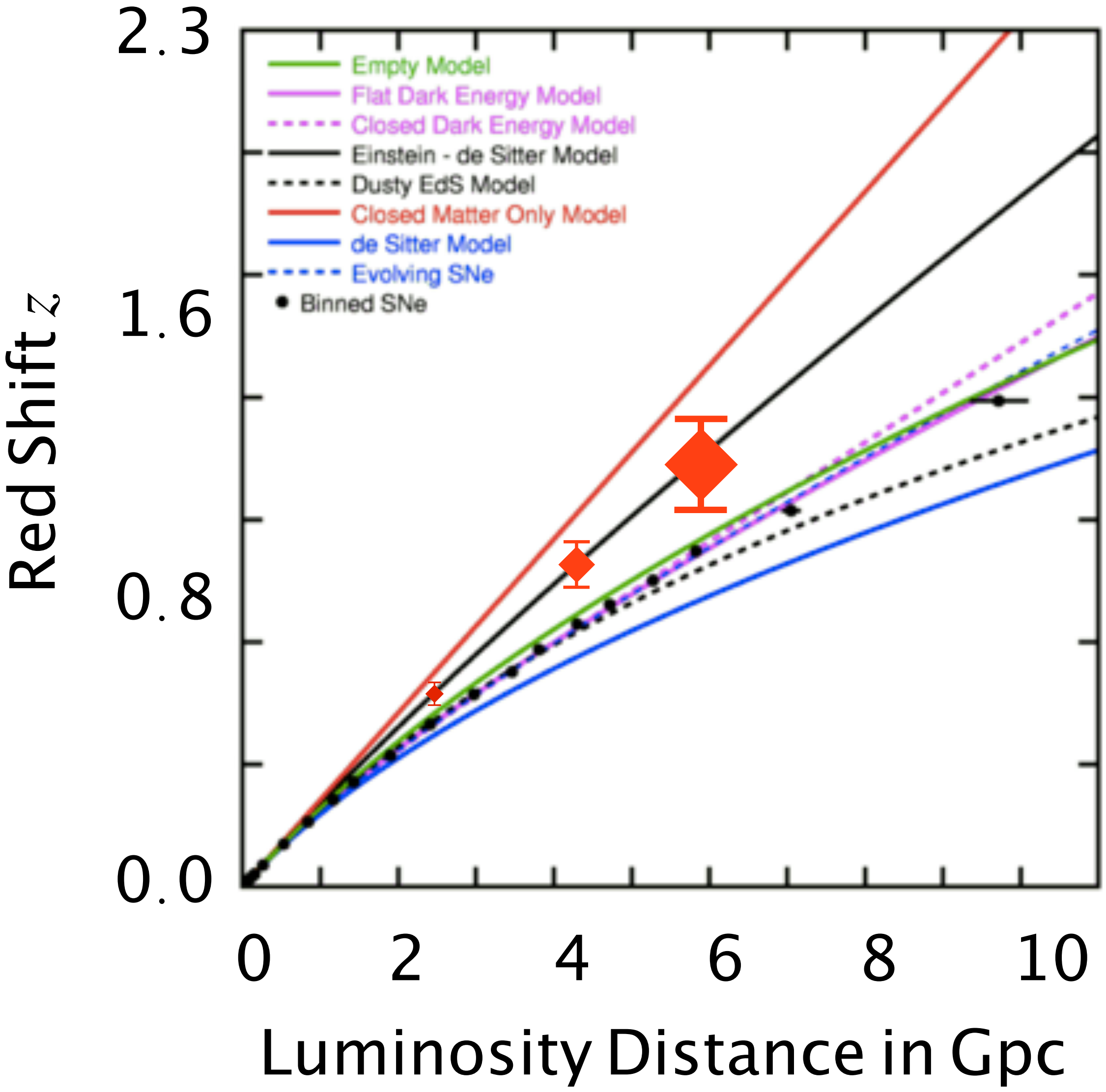
# Basic idea

Diagram:
Ned Wright: 2011



# Basic idea

Diagram:
Ned Wright: 2011



# But . . .

- We really only measure
  - The luminosity distance (redshifted comoving distance) and redshifted masses $$M_{\rm obs} = (1+z)M_{\rm intr},\, D_L = (1+z)D$$
- Cannot measure the source's redshift without EM identification but this is difficult since GW detectors have poor sky localization
  - at least that is what we thought until recently
- If we measure the source redshift we can deduce the intrinsic mass of the source and resolve redshift-mass degeneracy
- Distance measurement is corrupted by weak lensing

Holz and Hughes 2005; Van Den Broeck et al 2010

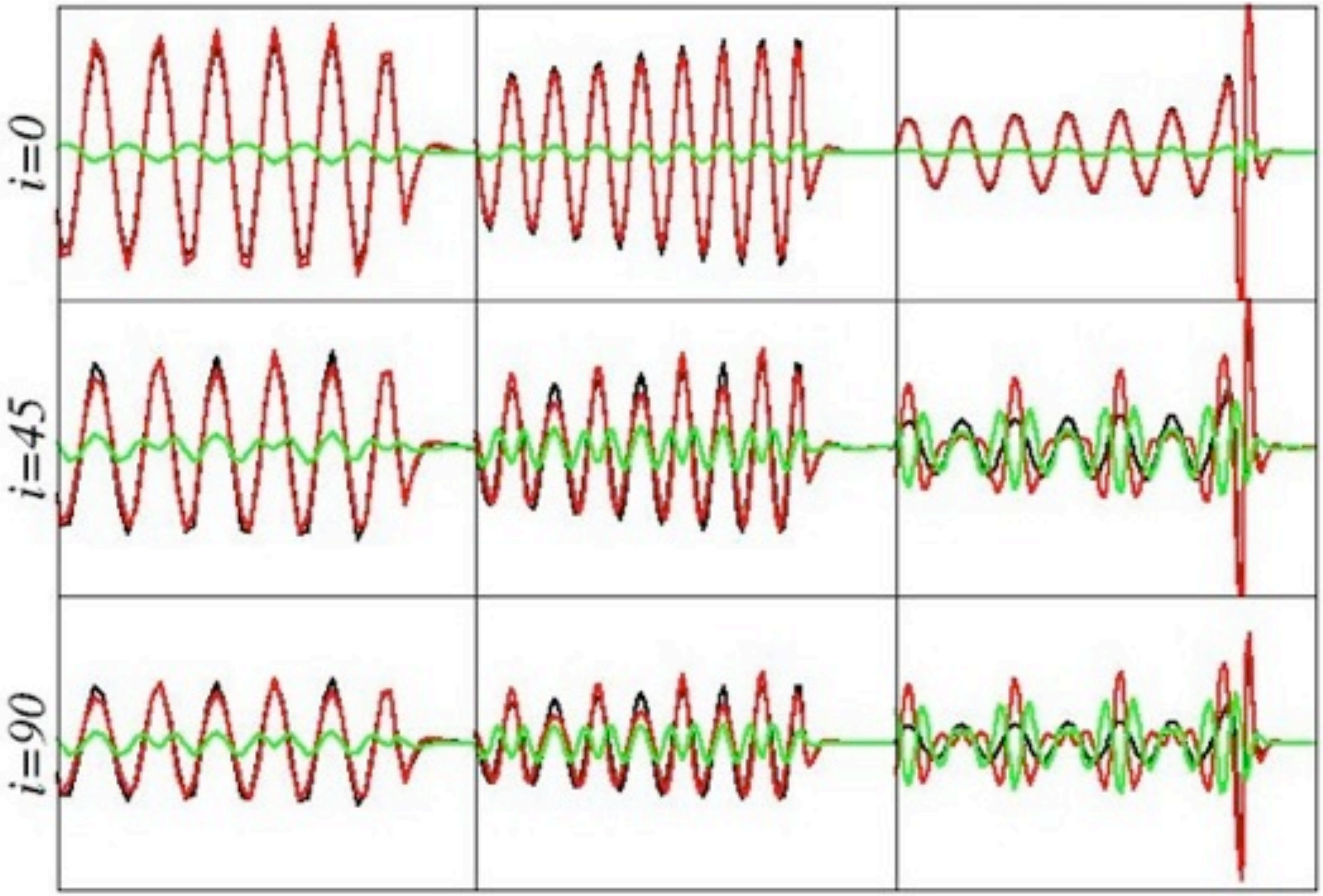
  - Correcting for or mitigating lensing would be important
- Distance is strongly correlated with the unknown orbital inclination of the source with respect to line-of-sight

Ajith and Bose 2009; Nissanke et al 2010

# Localization Question:
# Mitigated by Higher Signal Harmonics

Dominant radiation at twice the orbital frequency but radiation is emitted at all multiples of the orbital frequency

# Observed harmonics depend on the inclination of the binary



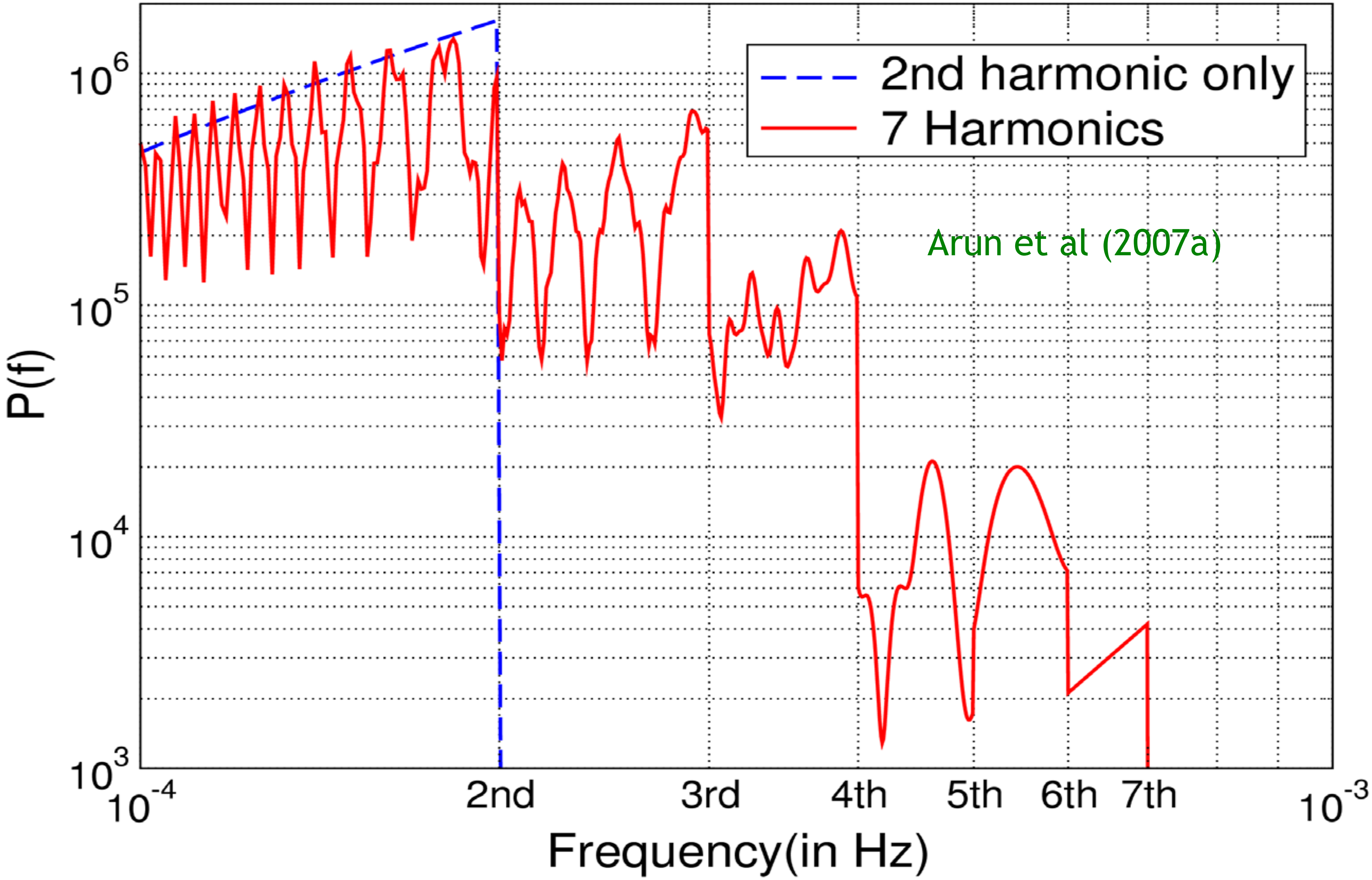
Pol angle=0, xy-scale same for given system

Black: Dominant harmonic

Red: Dominant harmonic

Green: Difference All-Dominant

# Higher Signal Harmonics: Spectrum



Arun et al (2007a)

# Signal Harmonics and Sky Localization

- Sky localization is improved by higher signal harmonics that were neglected in earlier studies
- Why does sky localization improve due to signal harmonics?
    - Observed harmonics depend strongly on the inclination of the binary
    - Inclination is strongly correlated with sky position
    - Harmonics help break distance–inclination and inclination–sky position degeneracy

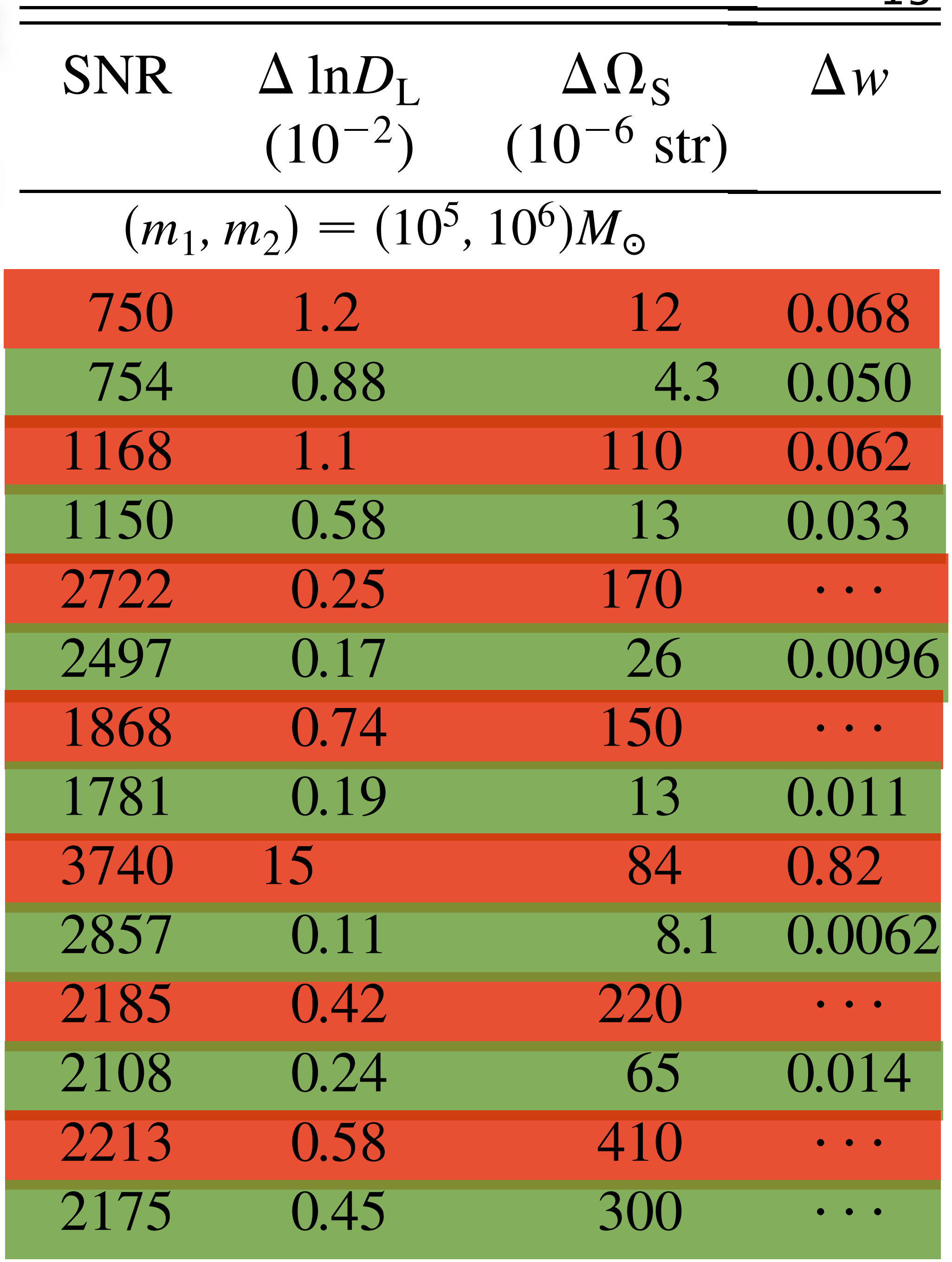
# Level of Improvement

- SNR doesn’t change much
- Distance improves by a factor of 2
- Angular resolution improves by a factor of 10 or larger
- Entries correspond to different orientations

🟥 **Uses only the dominant harmonic**

🟩 **Uses all known harmonics**

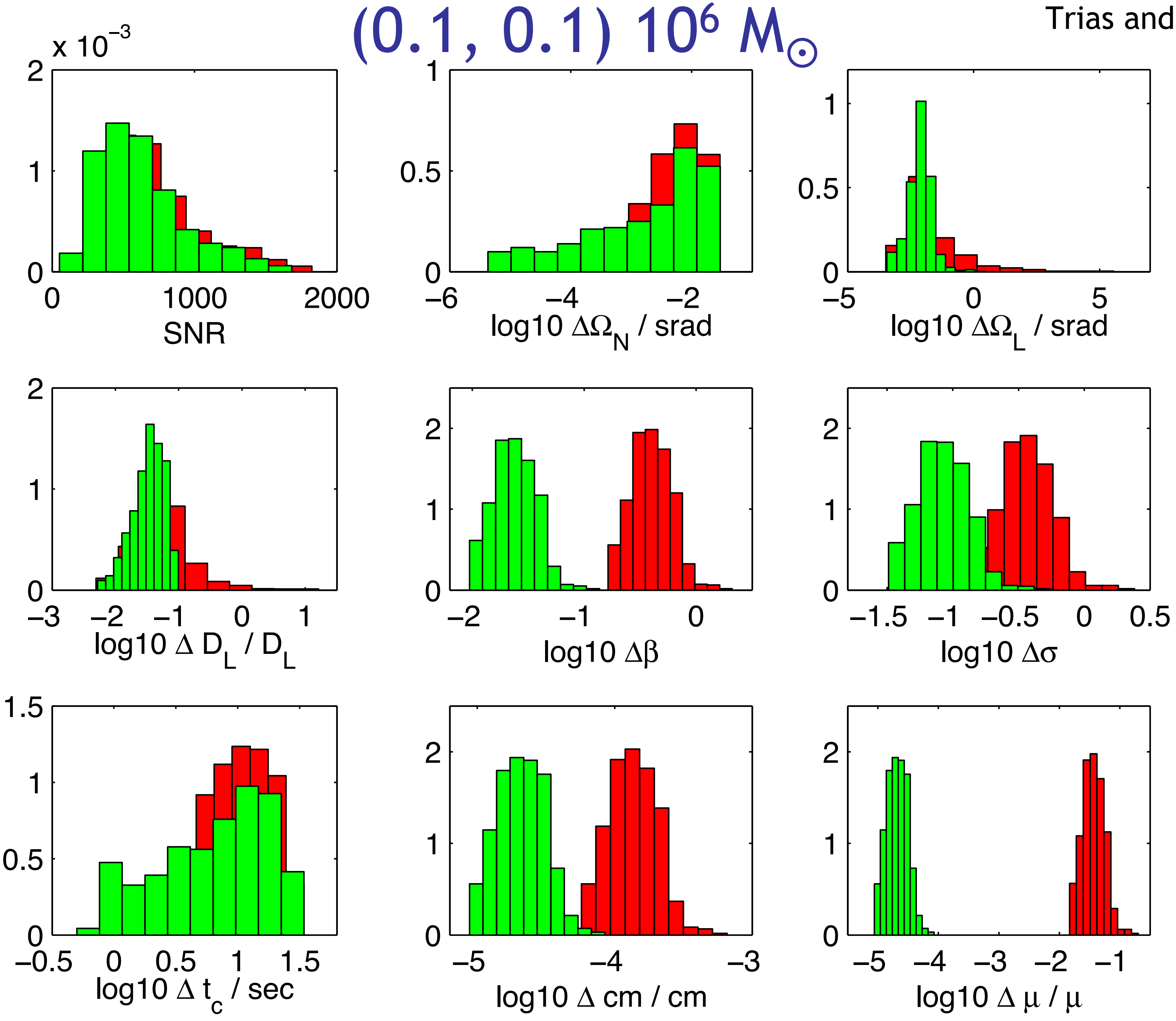
Table from
Arun et al: 2007



| SNR | $\Delta \ln D_L$ ($10^{-2}$) | $\Delta\Omega_S$ ($10^{-6}$ str) | $\Delta w$ |
|---|---|---|---|
| $(m_1, m_2) = (10^5, 10^6)M_\odot$ | | | |
| 750 | 1.2 | 12 | 0.068 |
| 754 | 0.88 | 4.3 | 0.050 |
| 1168 | 1.1 | 110 | 0.062 |
| 1150 | 0.58 | 13 | 0.033 |
| 2722 | 0.25 | 170 | $\cdots$ |
| 2497 | 0.17 | 26 | 0.0096 |
| 1868 | 0.74 | 150 | $\cdots$ |
| 1781 | 0.19 | 13 | 0.011 |
| 3740 | 15 | 84 | 0.82 |
| 2857 | 0.11 | 8.1 | 0.0062 |
| 2185 | 0.42 | 220 | $\cdots$ |
| 2108 | 0.24 | 65 | 0.014 |
| 2213 | 0.58 | 410 | $\cdots$ |
| 2175 | 0.45 | 300 | $\cdots$ |

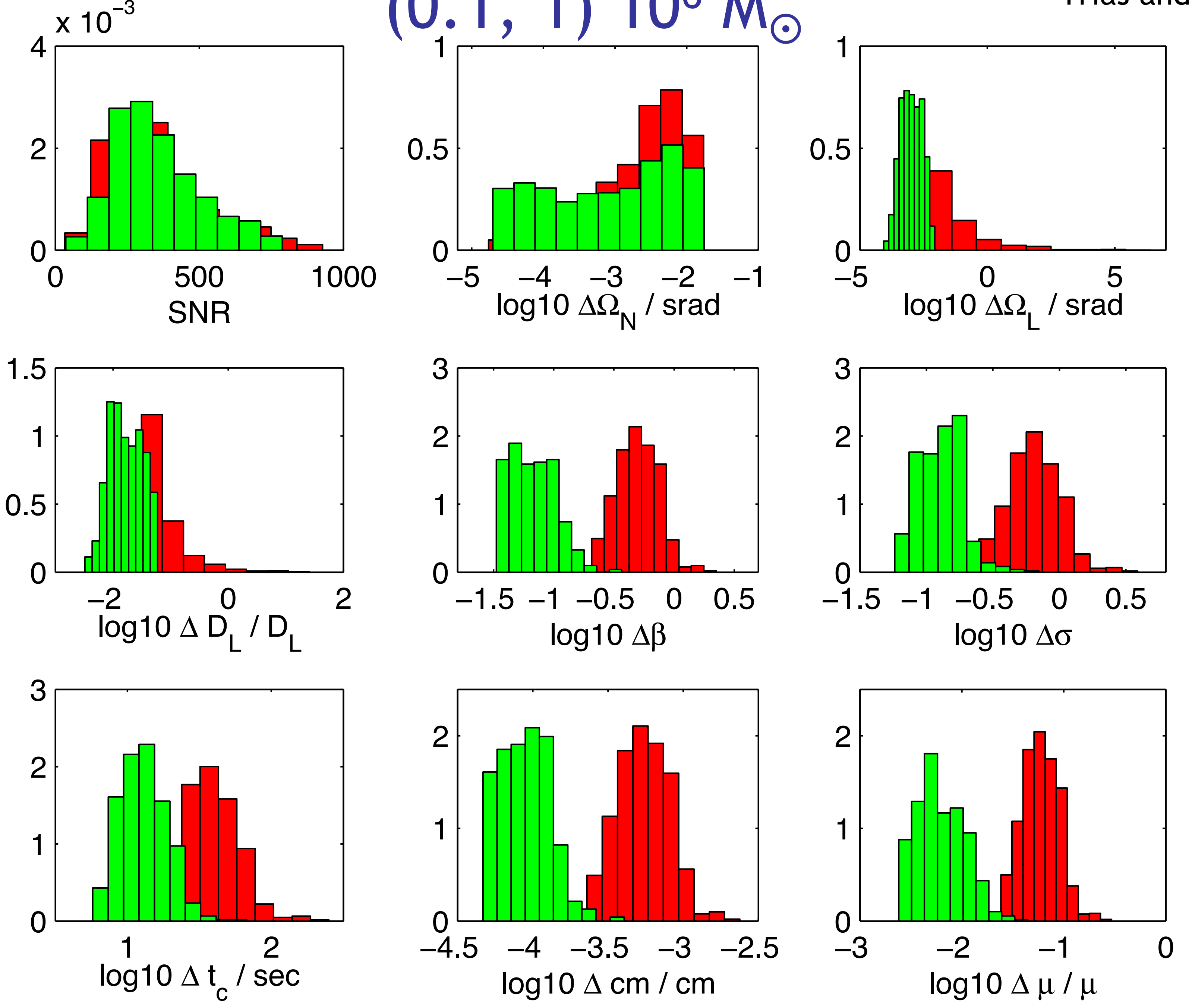
# (0.1, 0.1) $10^6\ M_\odot$

Trias and Sintes



# $(0.1, 1)\ 10^6\ M_\odot$

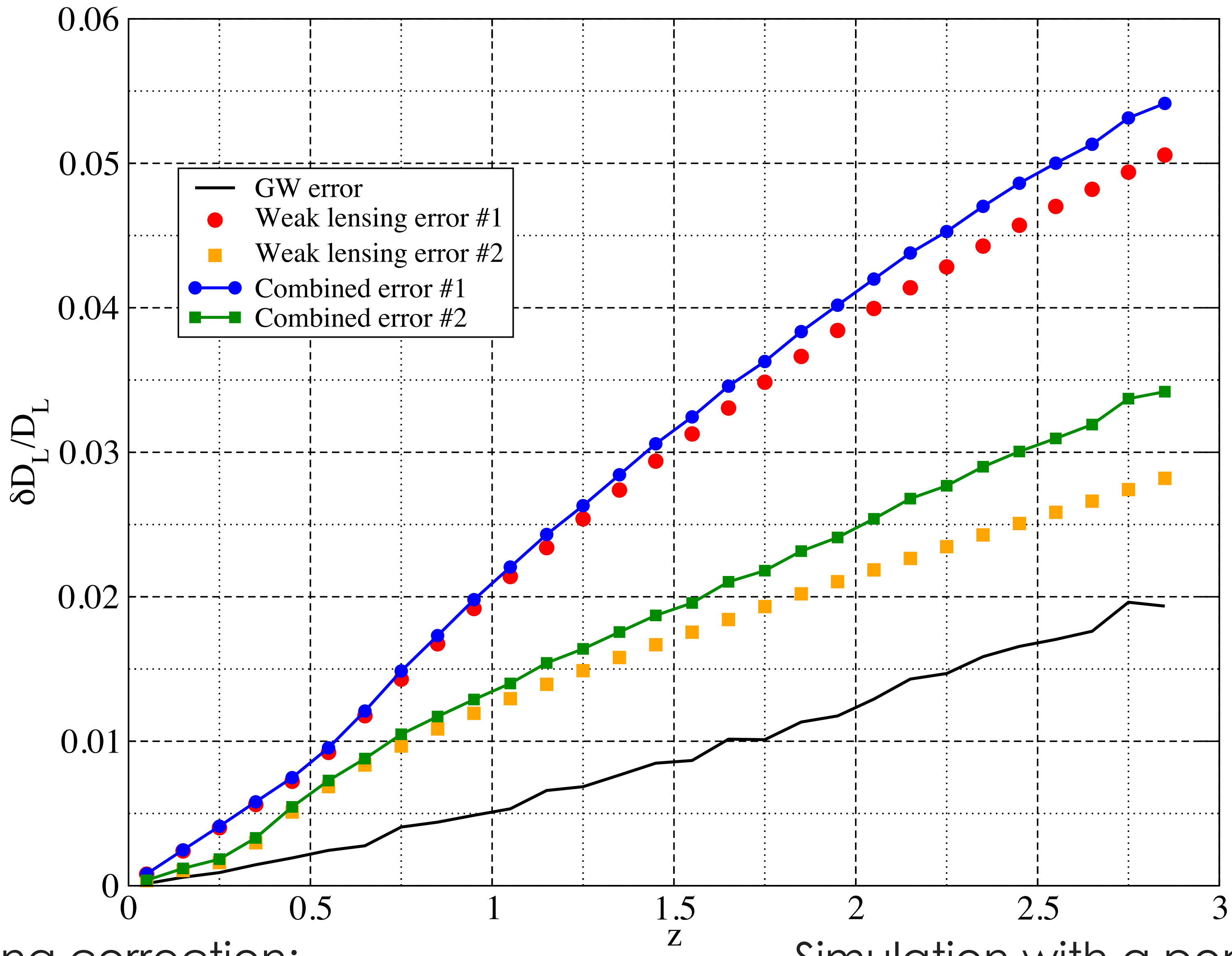
Trias and Sintes



# Addressing Weak Lensing

Correct for weak lensing by mapping the sky in the direction of the source AND assume LISA will see many sources

# Distance Measurement: Dominated by Lensing

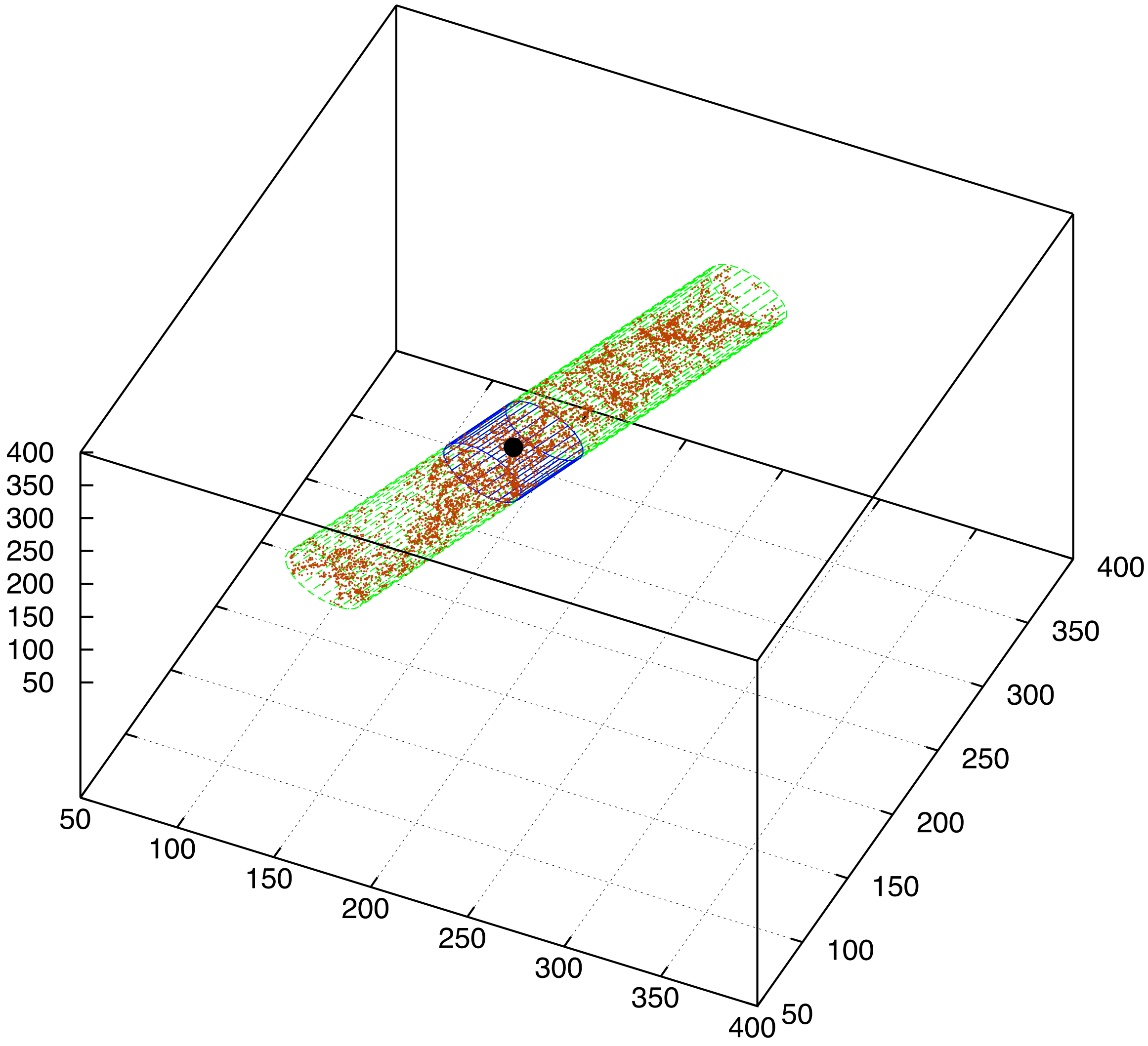


Lensing correction:
Shapiro et al 2010

Simulation with a population
Petiteau, Babak, Sesana: 2011

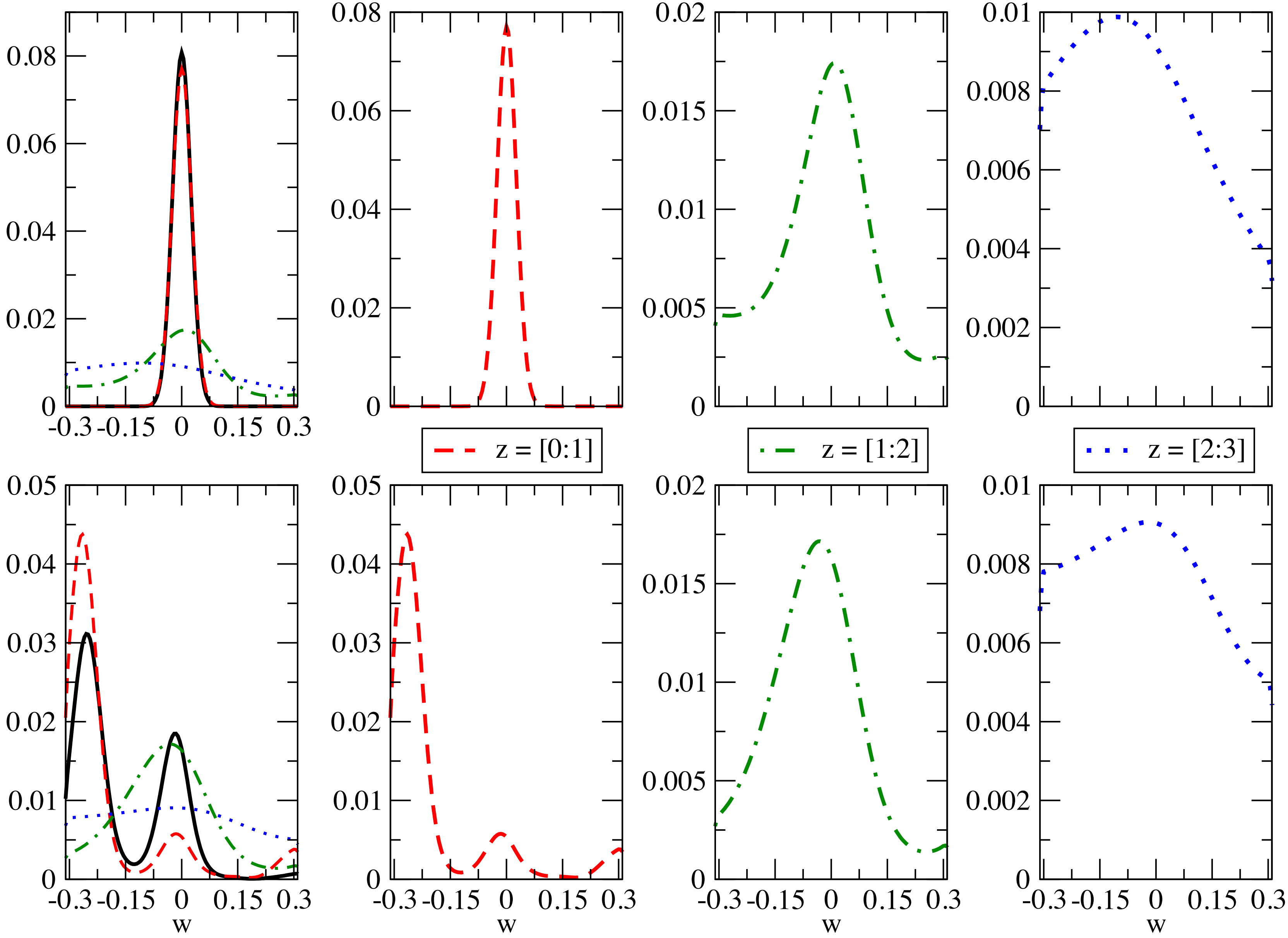
# Mitigating Lensing: Safety in Numbers

- If LISA detects ~ 30 events weak lensing might be mitigated
- Use the original Schutz idea of not depending on EM identification



Petiteau, Babak, Sesana: 2011

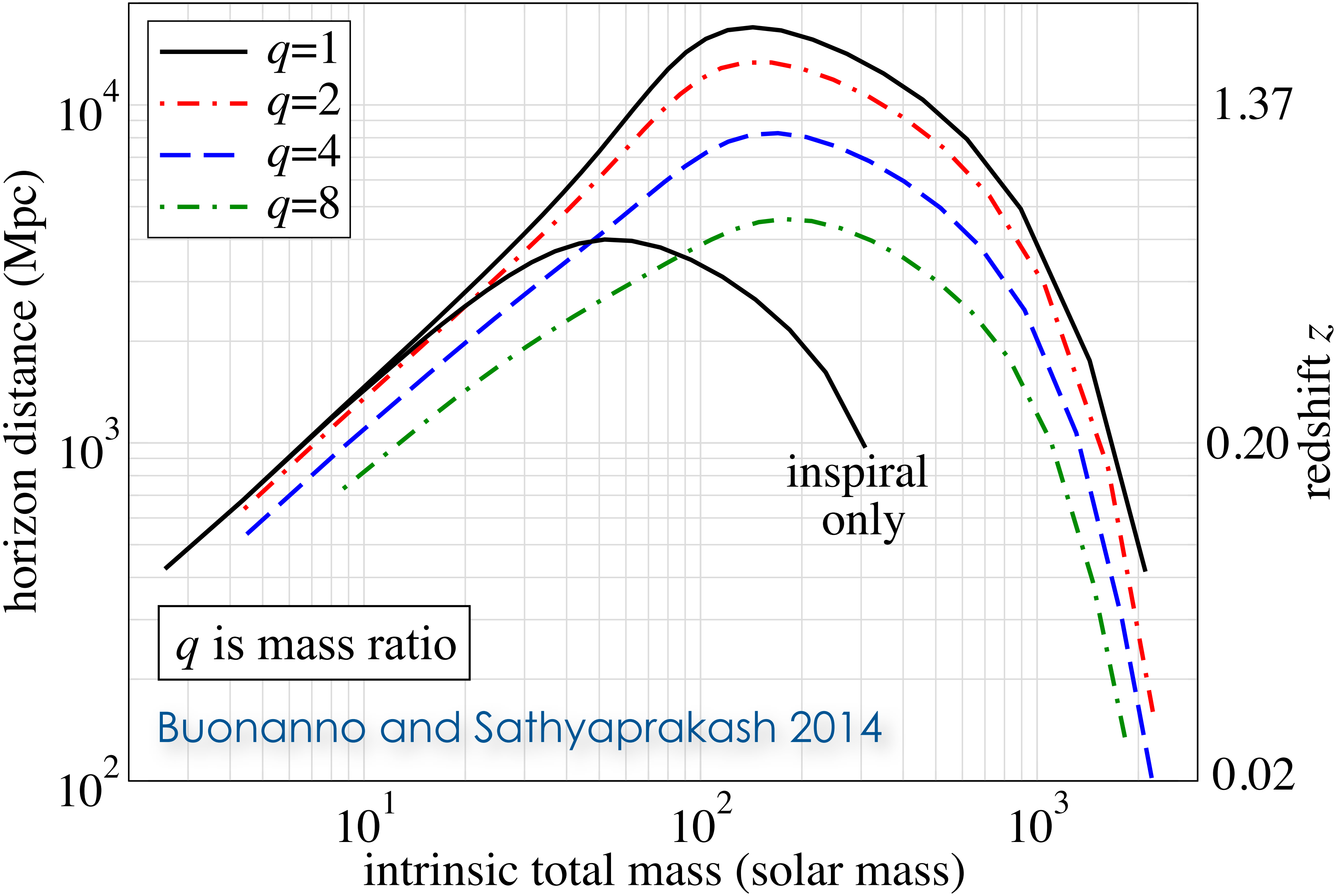
# Posteriors on $w$: Two Different Realisations



Petiteau, Babak, Sesana: 2011

# Cosmography with Ground_Based Detectors

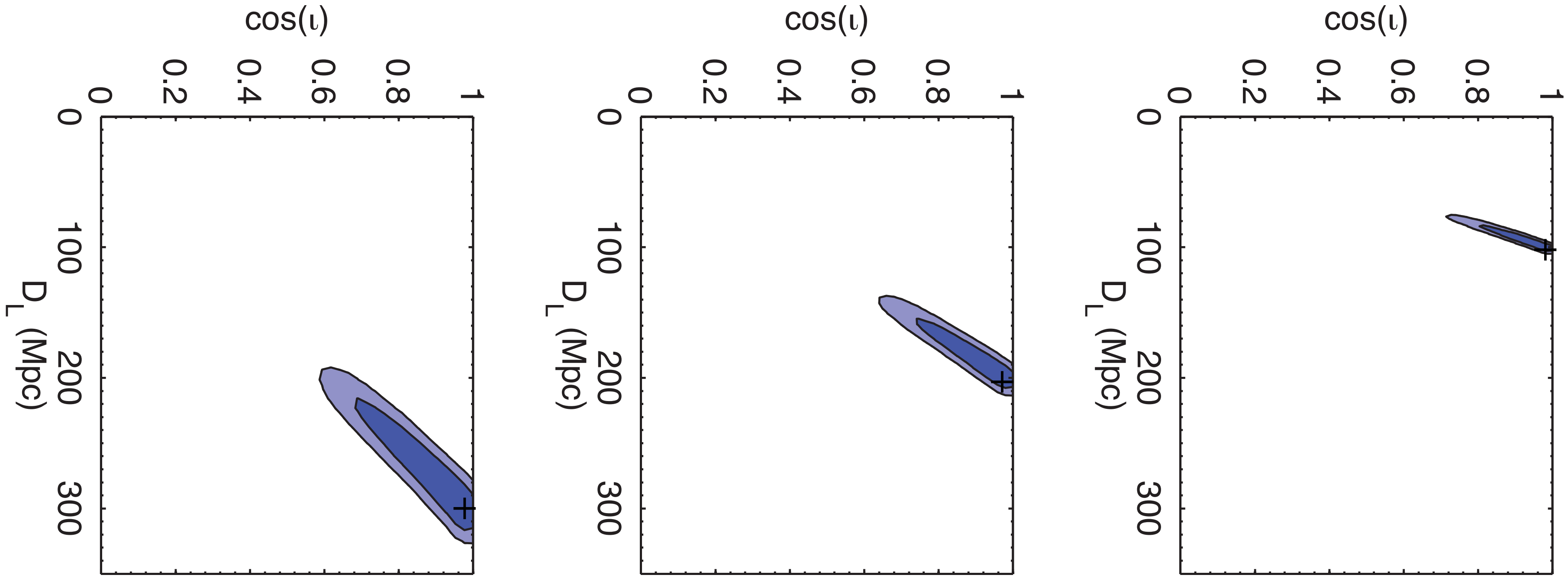
# Advanced LIGO Distance Reach to Binary Coalescences



Buonanno and Sathyaprakash 2014

# Hubble Constant from Advanced Detectors Assuming short_hard_GRBs are binary neutron stars

we find that *one* year of observation should be enough to measure $H_0$ to an accuracy of $\sim 1\%$ if SHBs are dominated by beamed NS-BH binaries using the "full" network of LIGO, Virgo, AIGO, and LCGT—admittedly,



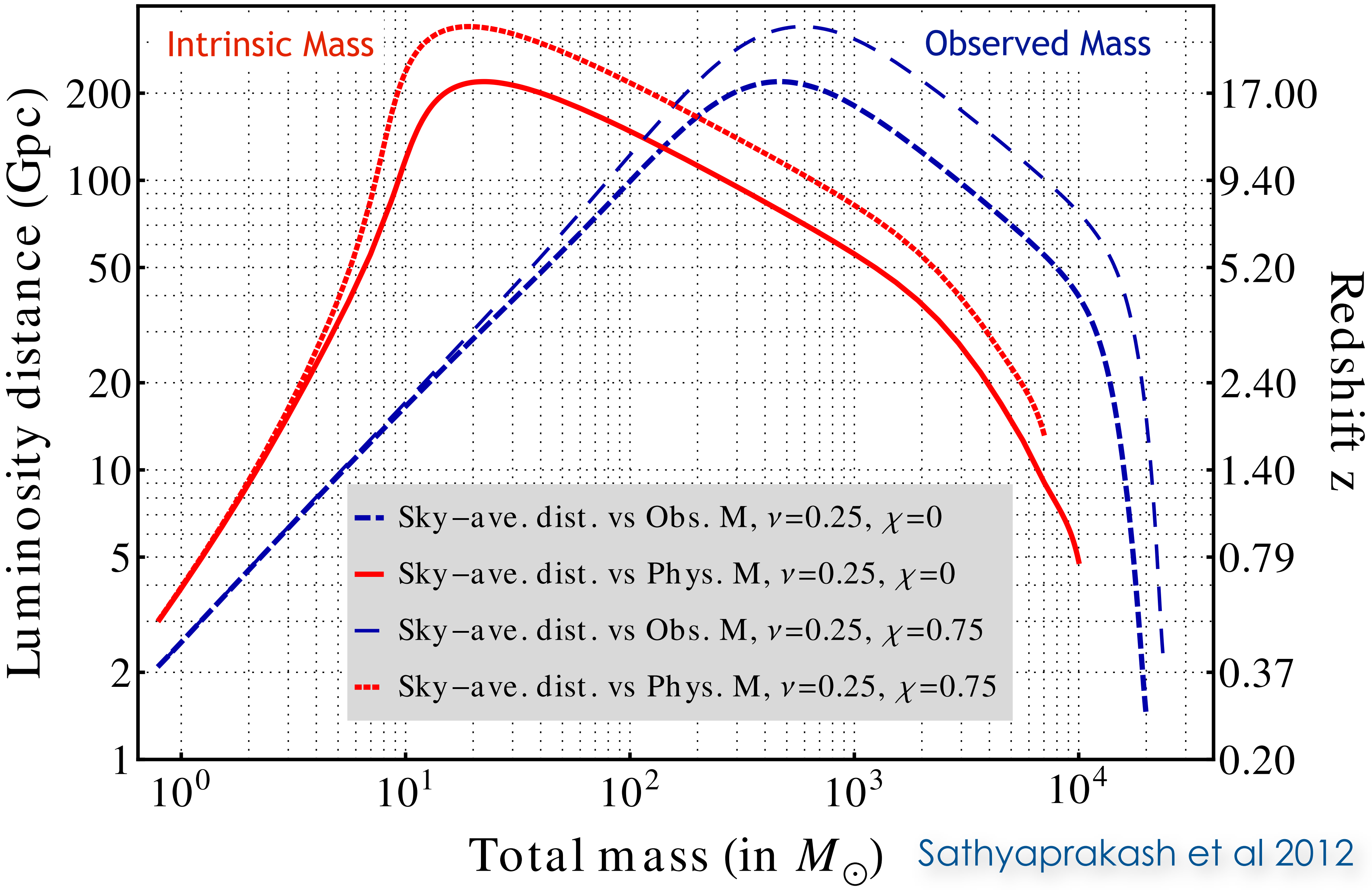
Nissanke et al 2009

# Hubble Constant from Advanced Detectors without EM counterparts

- 25 events:
  - $H_0$= 69 ± 3 km $s^{-1}$ $Mpc^{-1}$ (~4% at 95% confidence)
- 50 events:
  - $H_0$= 69 ± 2 km $s^{-1}$ $Mpc^{-1}$ (~3% at 95% confidence)
- WMAP7+BAO+SnIa (Komatsu et al.,2011):
  - $H_0$= 70.2 ± 1.4 km $s^{-1}$ $Mpc^{-1}$ (~2% at 68% confidence)

Del Pozzo, 2011

# ET Distance Reach to Coalescing Binaries



Sathyaprakash et al 2012

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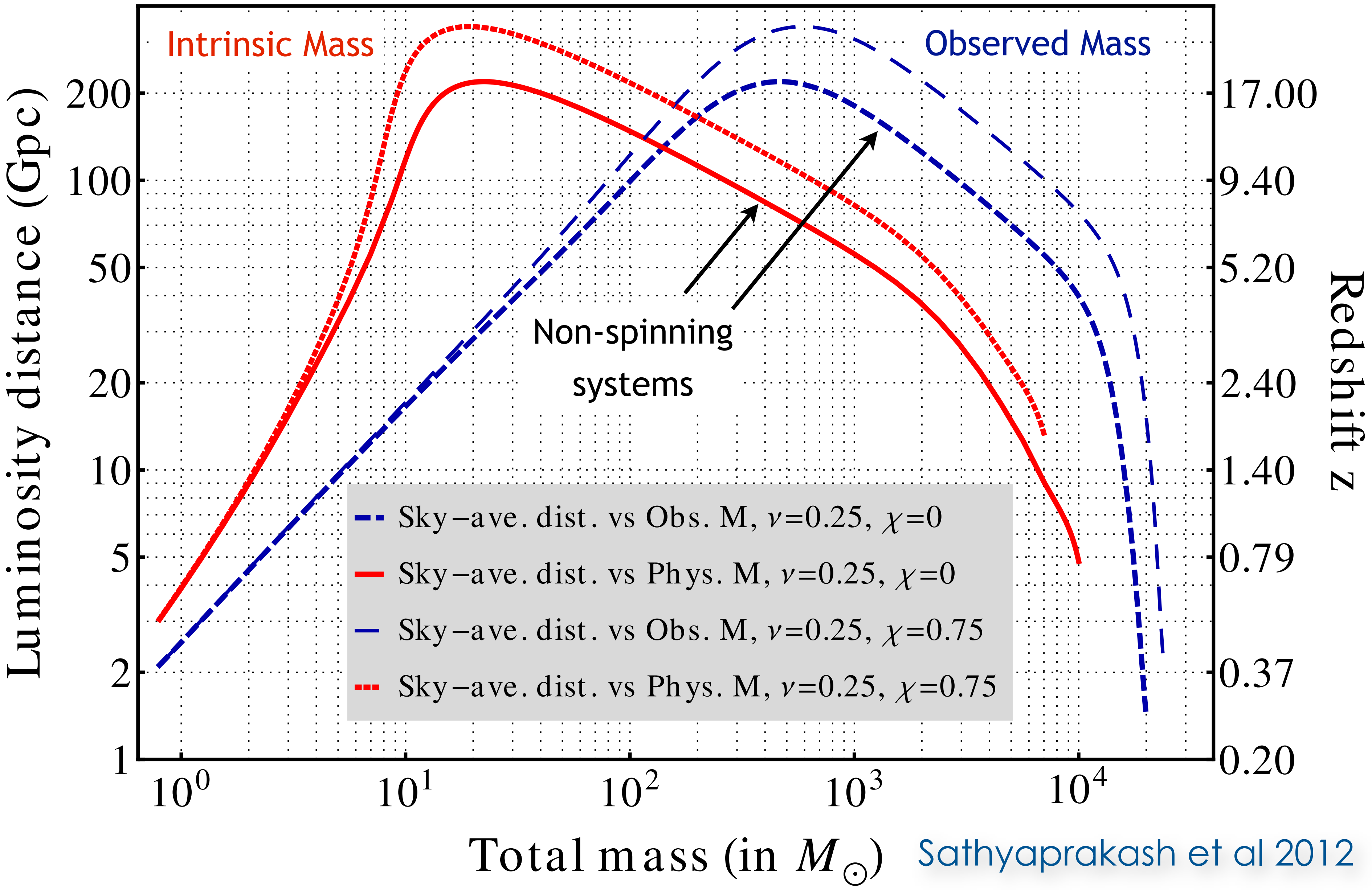

Sathyaprakash et al 2012

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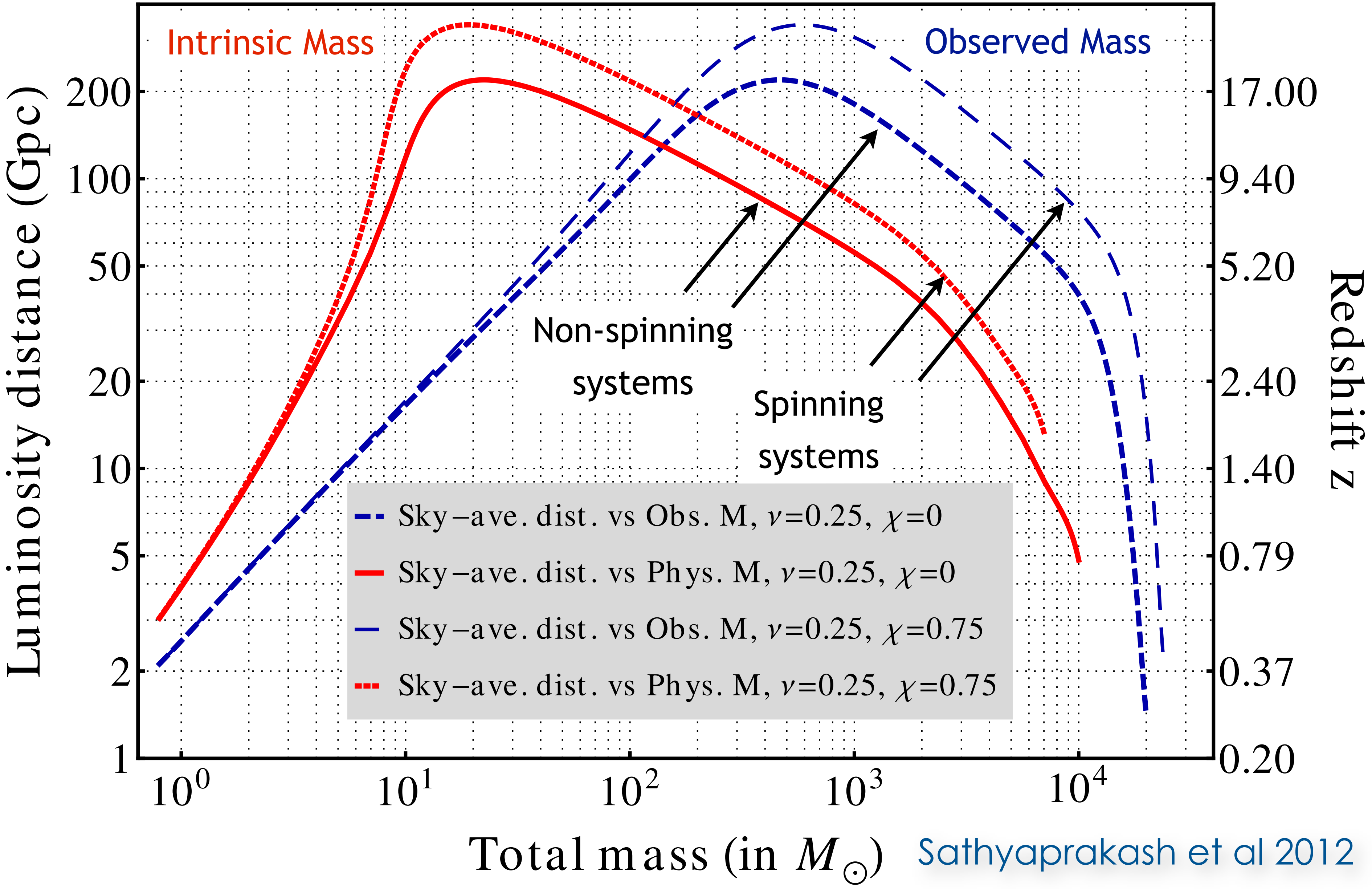
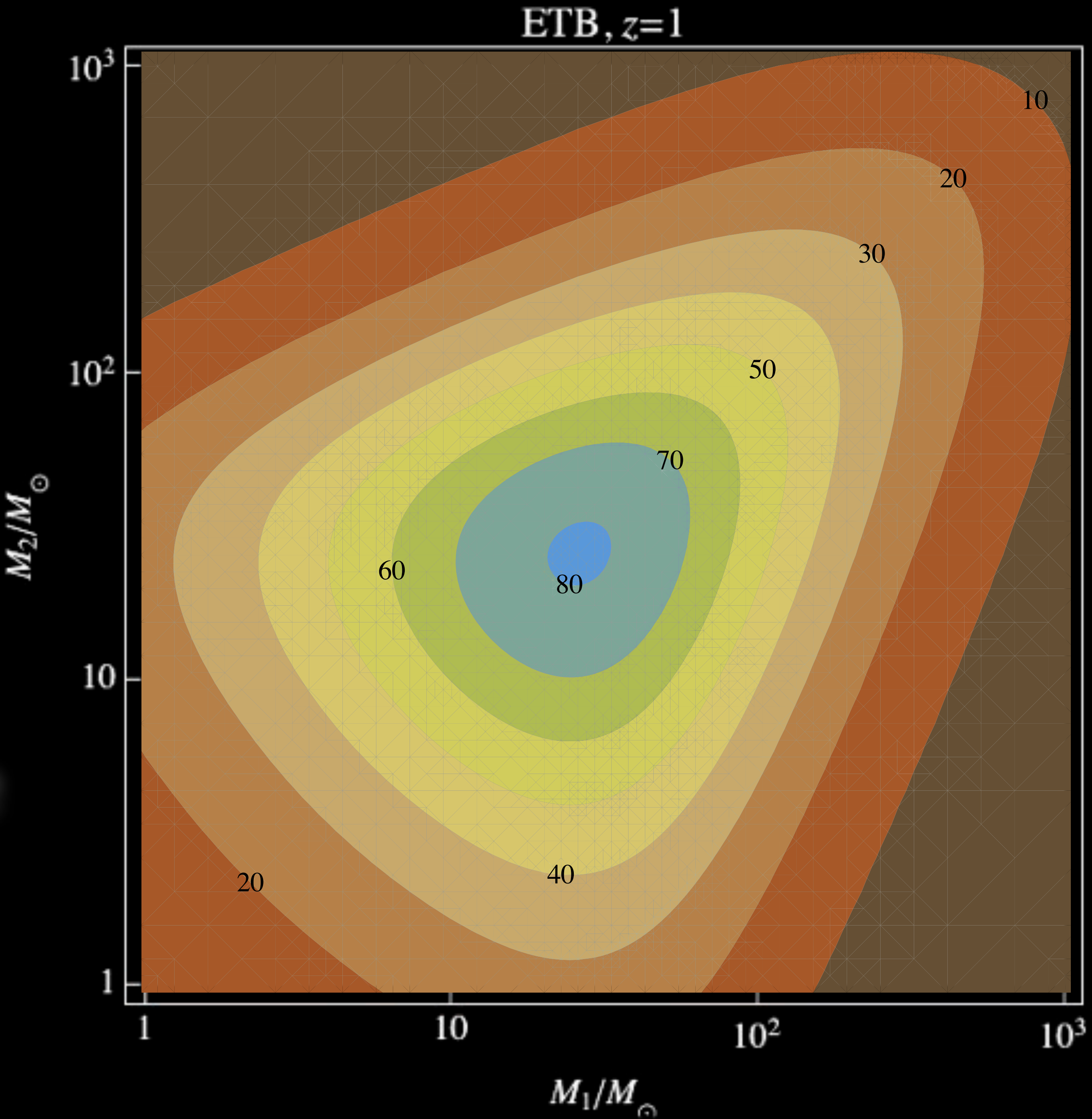


Sathyaprakash et al 2012

# Visibility of Binary Inspirals in Einstein Telescope

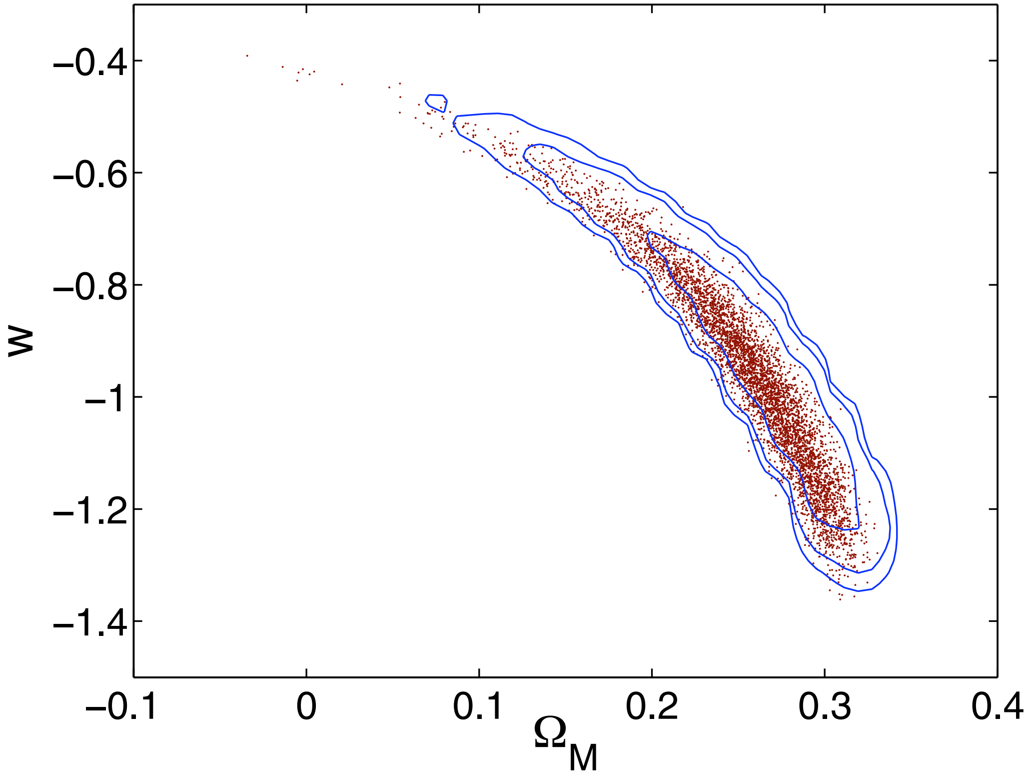


# ET: Measuring Dark Energy and Dark Matter

- ET will observe 100's of binary neutron stars and GRB associations each year
- GRBs could give the host location and red-shift, GW observation provides $D_L$

Class. Quantum Grav. **27** (2010) 215006

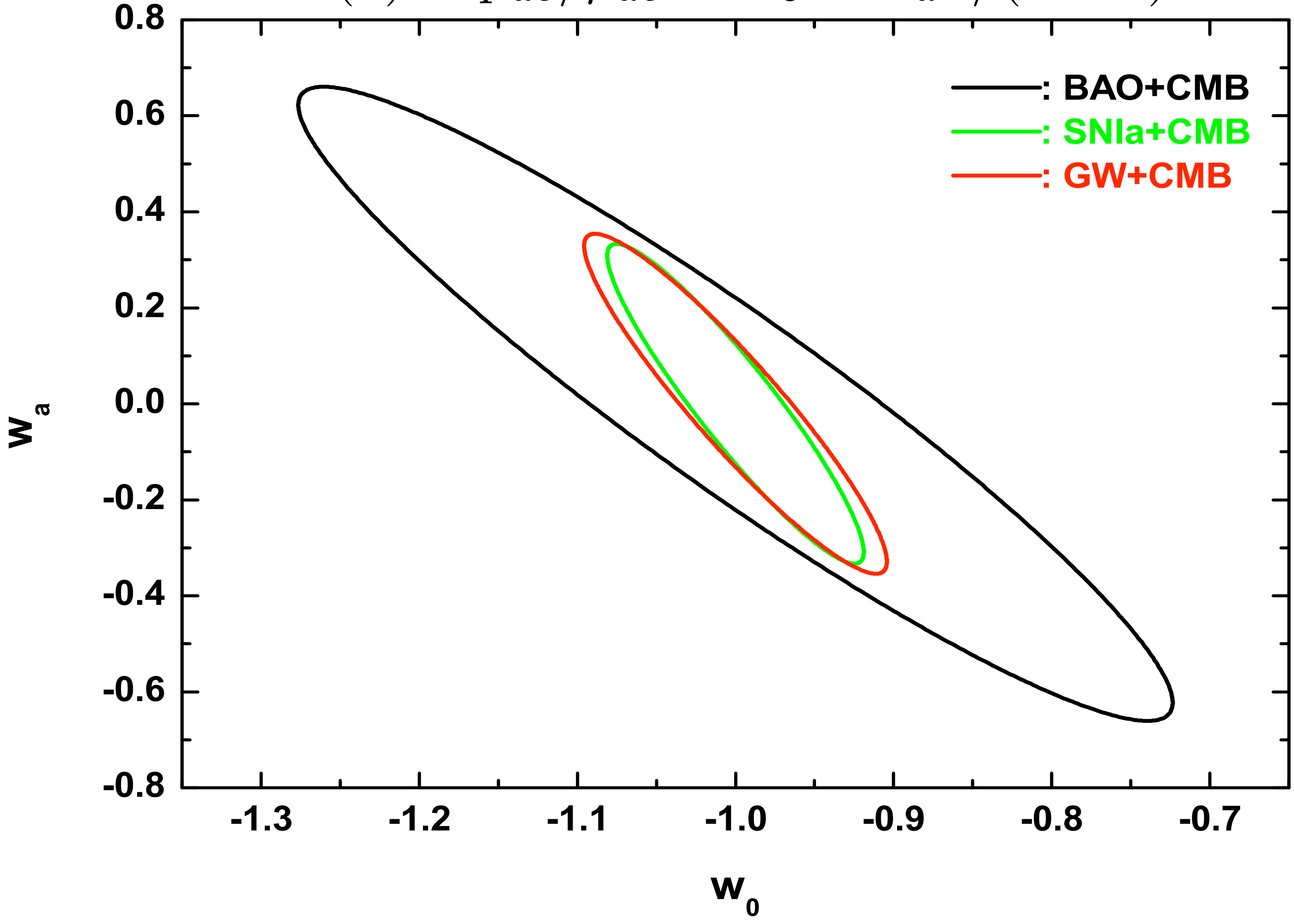
Sathyaprakash et al 2010



# Measuring *w* and its variation with *z*

Baskaran, Van Den Broeck, Zhao, Li, 2011

$$w(z) \equiv p_{de}/\rho_{de} = w_0 + w_a z/(1+z)$$



# GW cosmography without EM counterparts

- Measure redshift from gravitational wave observations alone
- Use a population of sources to statistically infer cosmological parameters

# Messenger–Read Method:
# Make use of the post–Newtonian Tidal Term

K. G. Arun, B. R. Iyer, B. S. Sathyaprakash, and P. A. Sundararajan, Phys. Rev. D, **71**, 084008 (2005), arXiv:gr-qc/0411146.

$$\Psi_{PP}(f) = 2\pi f t_c - \phi_c - \frac{\pi}{4} + \frac{3}{128\eta x^{5/2}} \sum_{k=0}^{N} \alpha_k x^{k/2}$$

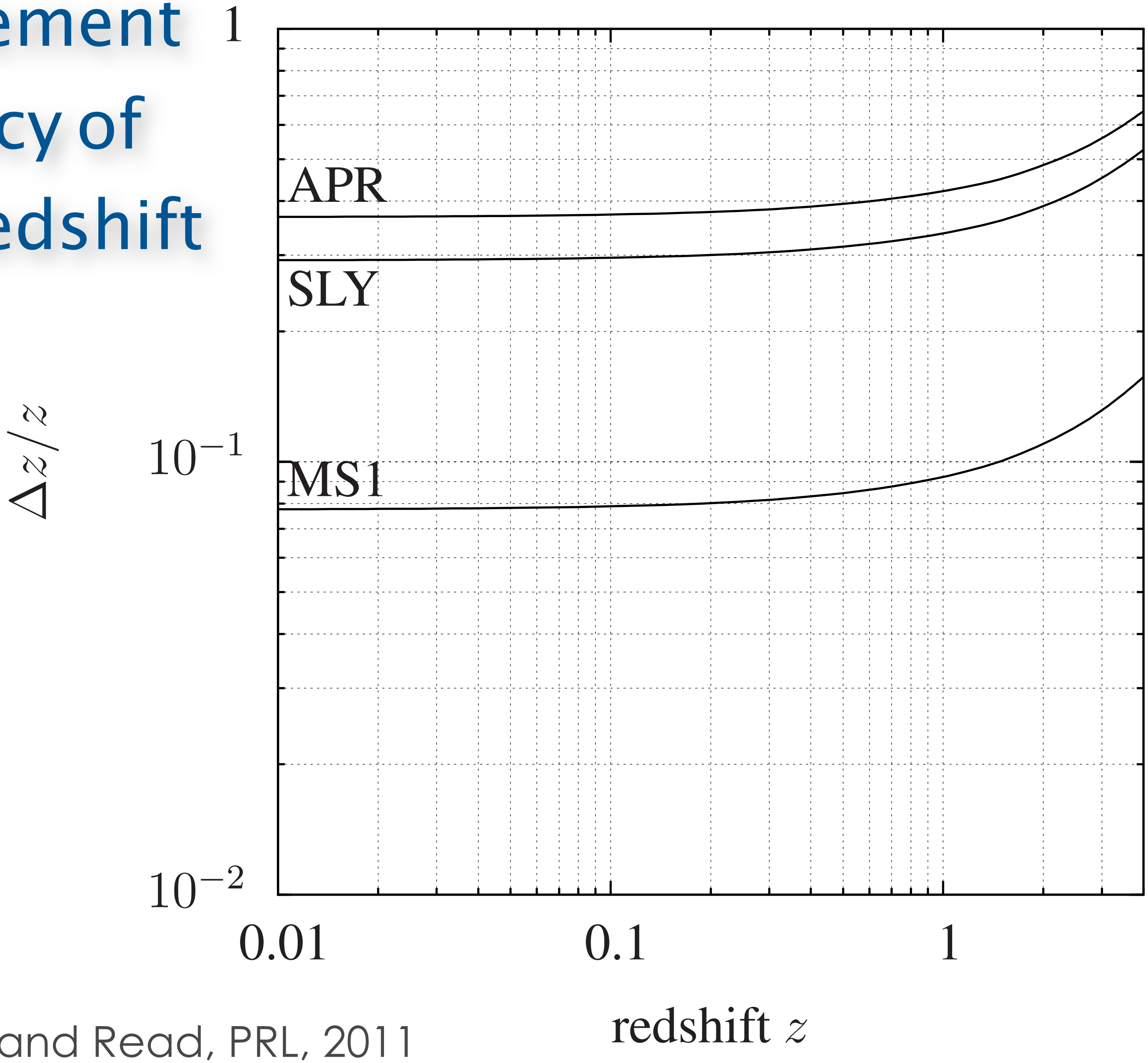
T. Hinderer, B. D. Lackey, R. N. Lang, and J. S. Read, Phys. Rev. D, **81**, 123016 (2010), arXiv:0911.3535 [astro-ph.HE].

$$\Psi^{\rm tidal}(f) = \sum_{a=1,2} \frac{3\lambda_a}{128\eta}\left[-\frac{24}{\chi_a}\left(1+\frac{11\eta}{\chi_a}\right)\frac{x^{5/2}}{M^5} - \frac{5}{28\chi_a}\left(3179 - 919\chi_a - 2286\chi_a^2 + 260\chi_a^3\right)\frac{x^{7/2}}{M^5}\right] \quad (3)$$

$$x = (\pi M f)^{2/3}$$

$$\lambda = (2/3) R_{\rm ns}^5 k_2$$

# Measurement accuracy of source redshift

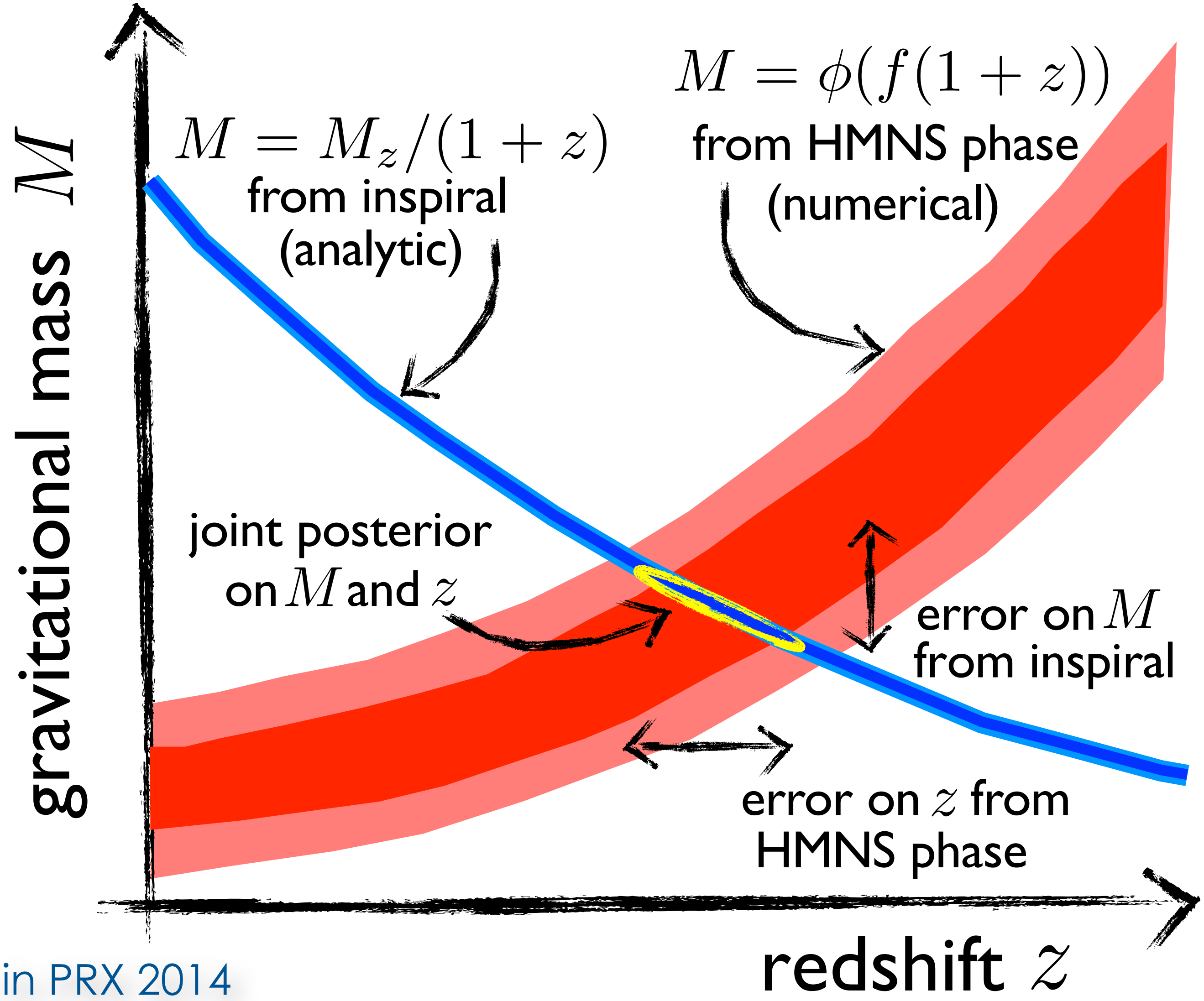


Messenger and Read, PRL, 2011

# Host redshifts from gravitational wave observations

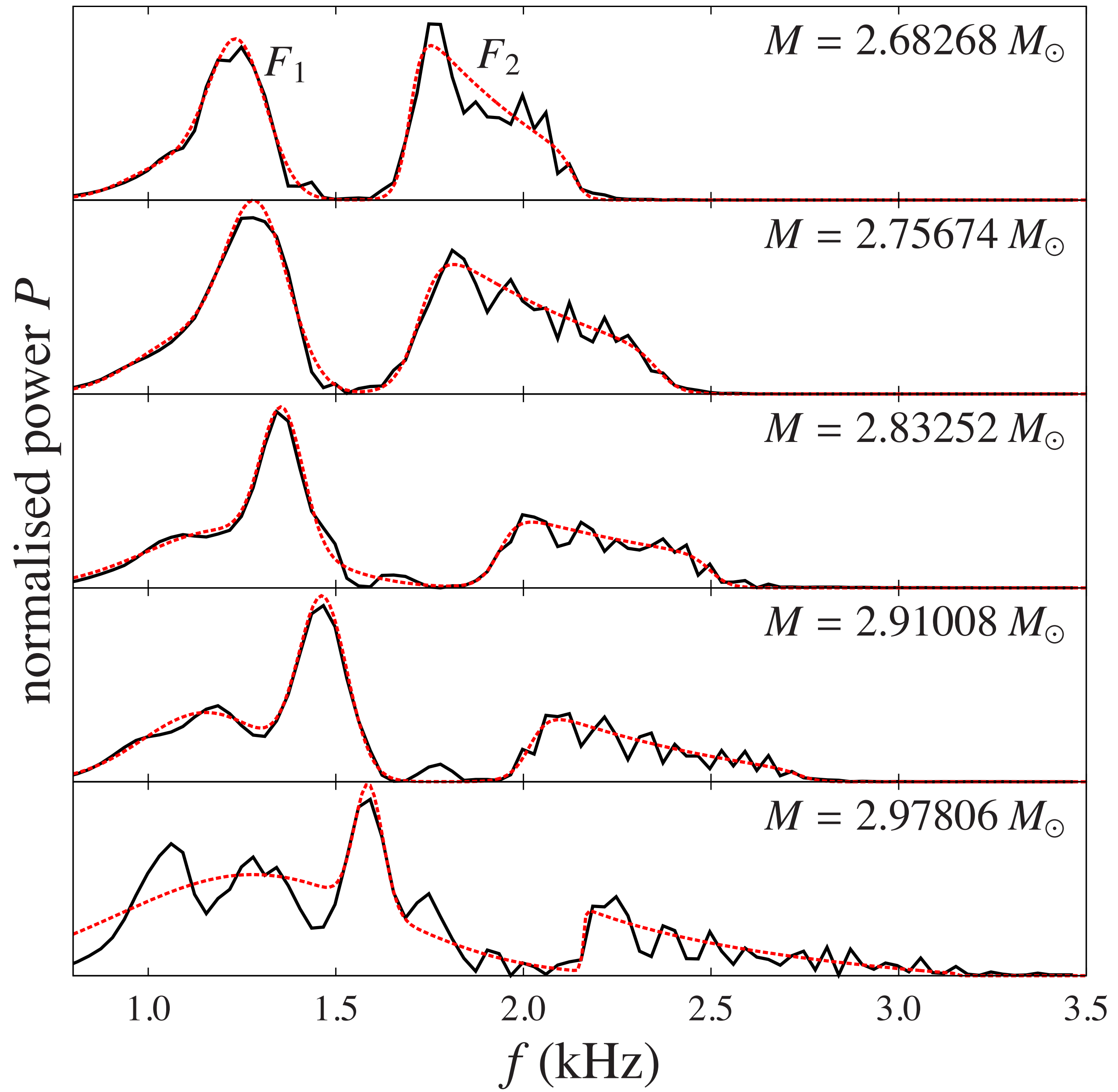
## Host-galaxy redshifts from gravitational-wave observations of binary neutron star mergers

C. Messenger,[1] Kentaro Takami,[2,3] Sarah Gossan,[4] Luciano Rezzolla,[3,2] and B. S. Sathyaprakash[5]

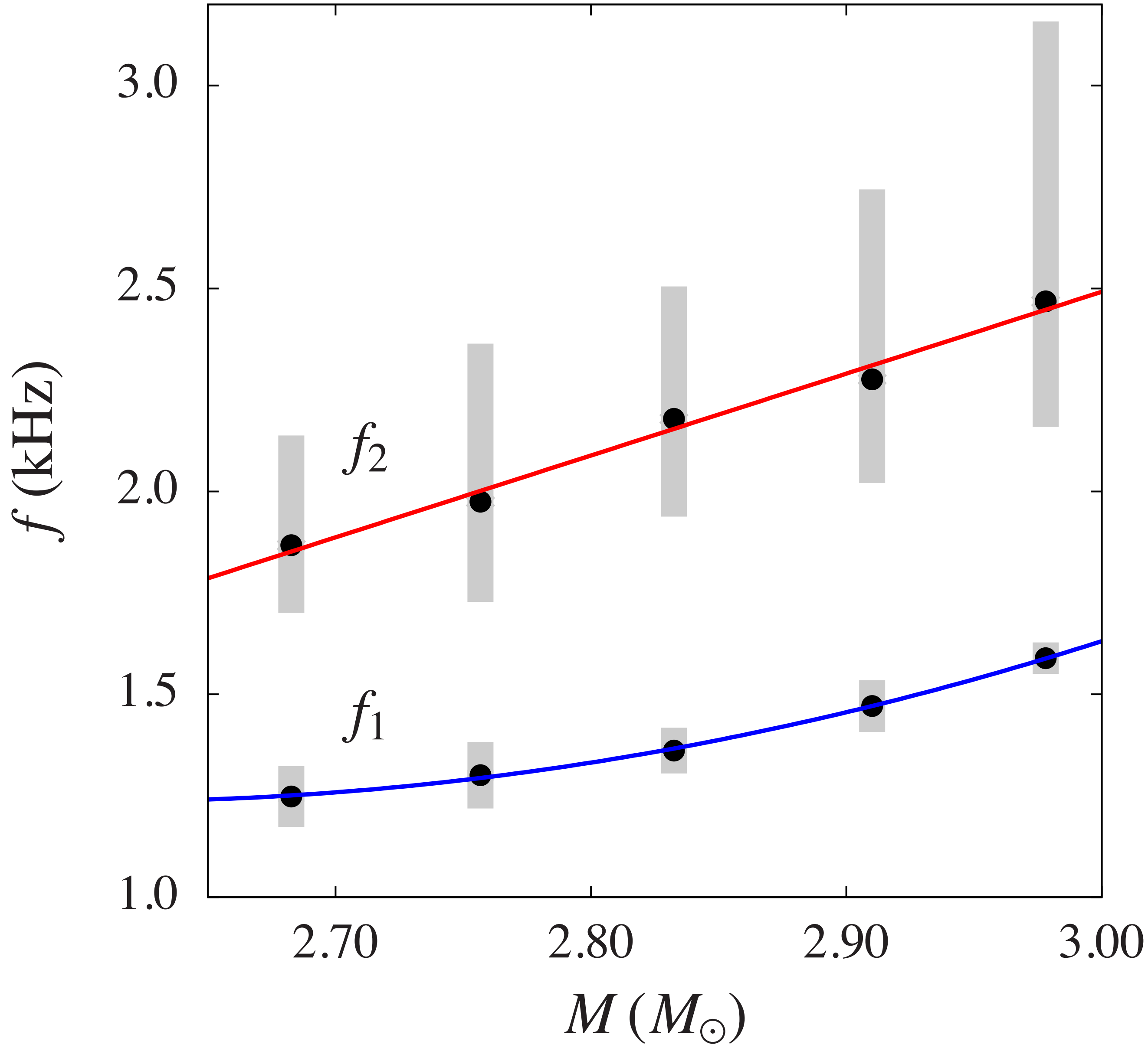


to appear in PRX 2014

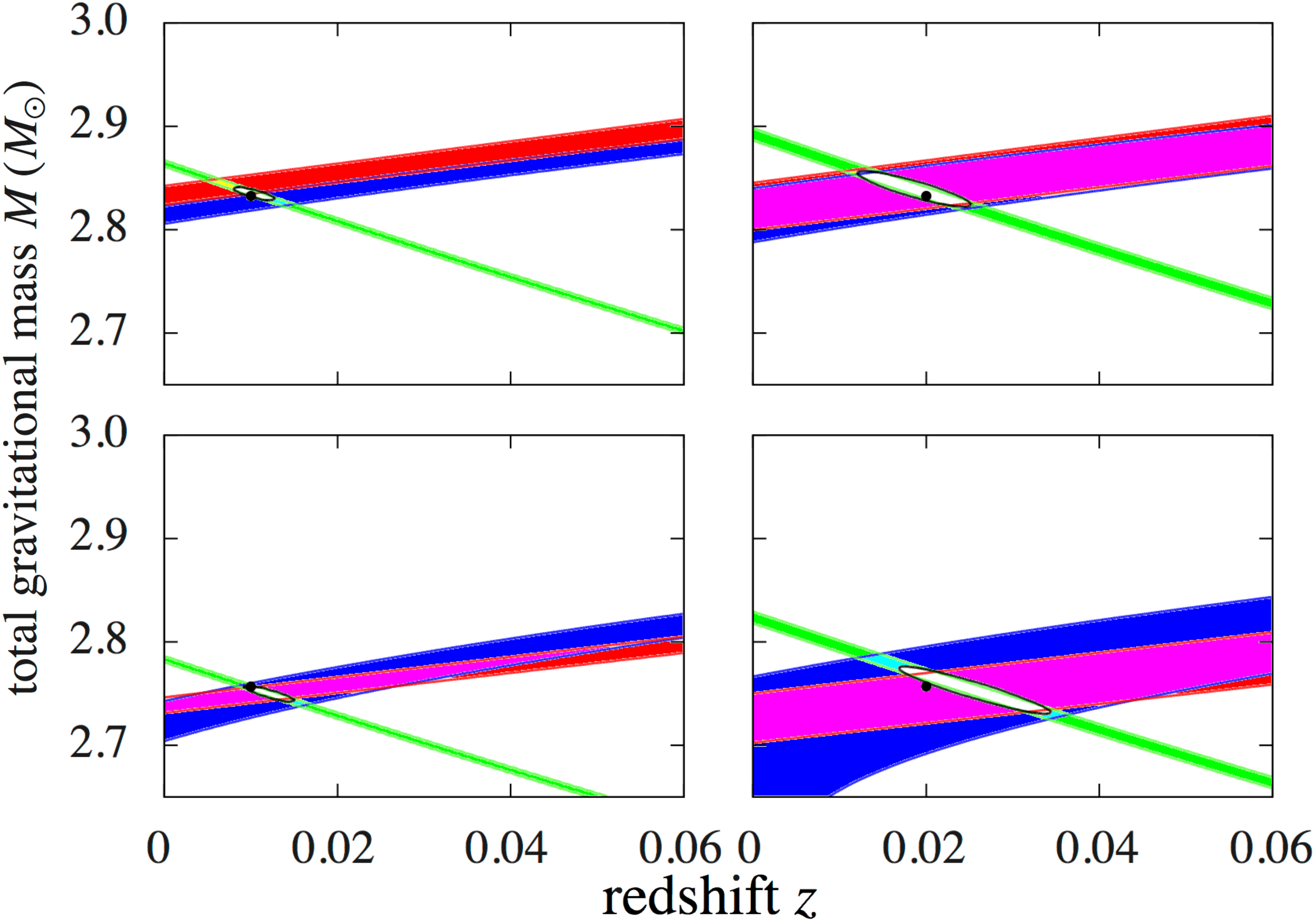
# Binary Neutron Star GW Spectrum – post Merger

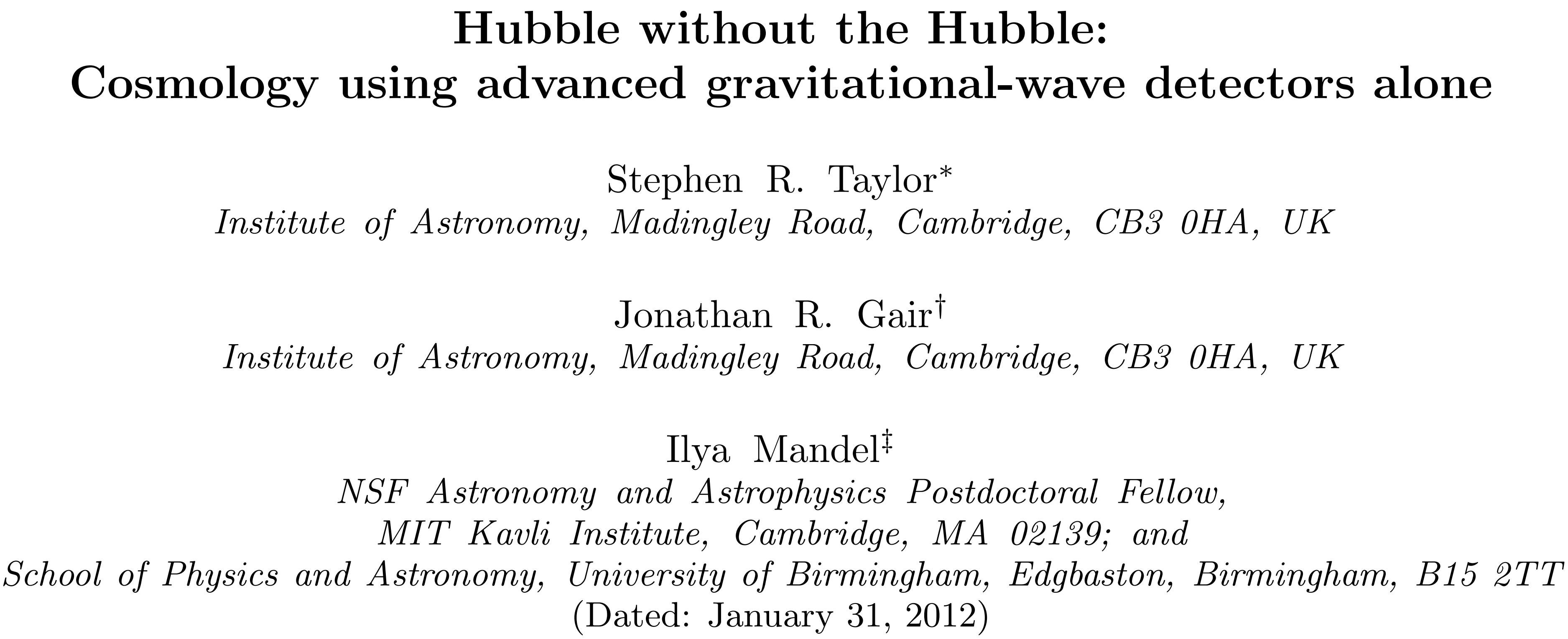


# Measurement Accuracies of Char. Frequencies



# How well can we measure z?





# Hubble without the Hubble: Cosmology using advanced gravitational-wave detectors alone

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*Institute of Astronomy, Madingley Road, Cambridge, CB3 0HA, UK*

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Ilya Mandel‡
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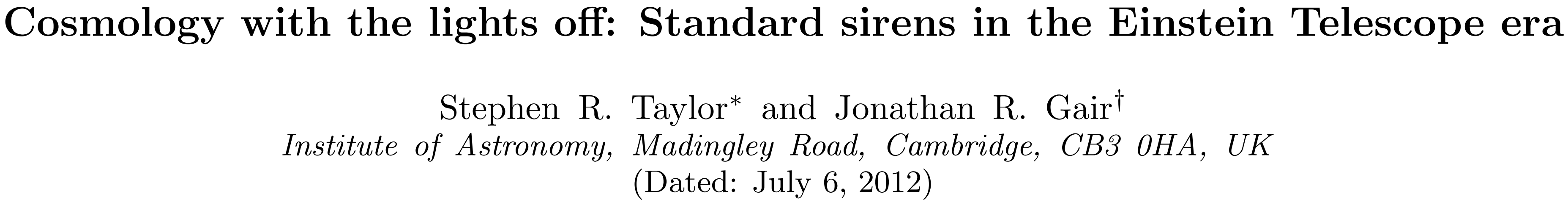
*School of Physics and Astronomy, University of Birmingham, Edgbaston, Birmingham, B15 2TT*

(Dated: January 31, 2012)



# Cosmology with the lights off: Standard sirens in the Einstein Telescope era

Stephen R. Taylor* and Jonathan R. Gair†
*Institute of Astronomy, Madingley Road, Cambridge, CB3 0HA, UK*

(Dated: July 6, 2012)

# Cosmology without EM Counterparts

- Distribution of Chirp Mass

$$\mathcal{M} \sim N(\mu_c, \sigma_c^2),$$

$$\mu_c \approx 2(0.25)^{3/5}\mu_{\rm NS}, \quad \sigma_c \approx \sqrt{2}(0.25)^{3/5}\sigma_{\rm NS},$$

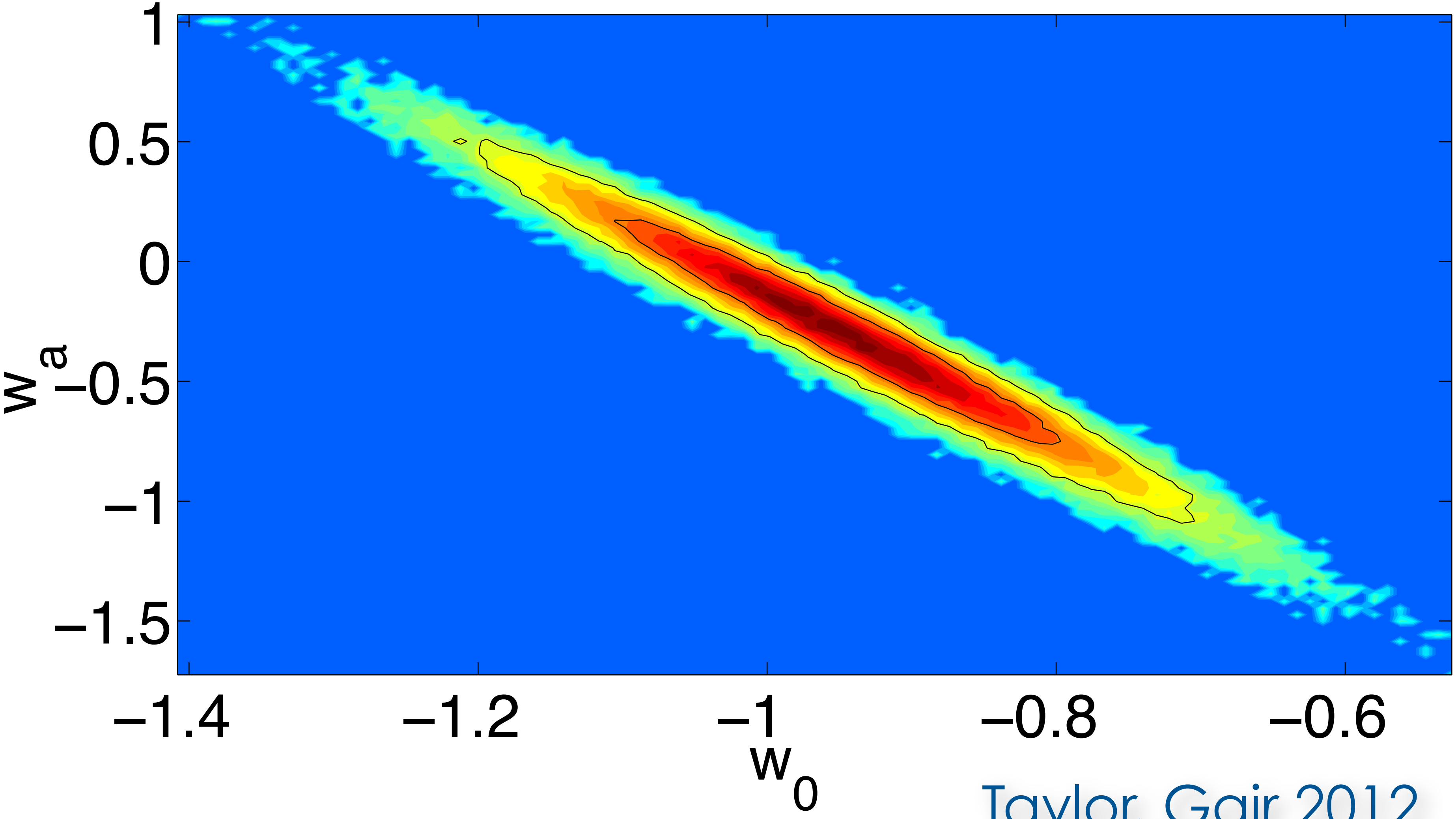
$$\mu_{\rm NS} \in [1.0, 1.5]M_\odot, \; \sigma_{\rm NS} \in [0, 0.3]M_\odot$$

$$w(a) = w_0 + w_a(1-a),$$

$$w(z) = w_0 + w_a\left(\frac{z}{1+z}\right).$$

Taylor, Gair 2012

# Measuring dark energy EoS and its variation with redshift



Taylor, Gair 2012

# Conclusions

- LISA observations alone could measure cosmological parameters, but …
  - A lot depends on the true event rate
  - Also, will it really be possible to correct for weak lensing
  - Measurement errors achieved in the end are not really comparable to what can be done by other means
- Ground–based detectors are in a good shape for cosmography
  - A population of sources helps mitigate weak lensing
  - Statistical approaches work pretty well

# Determining the Large Scale Structure