Hearing what gravitational wave standard sirens have to say

CaJAGWR - 24th March 2015

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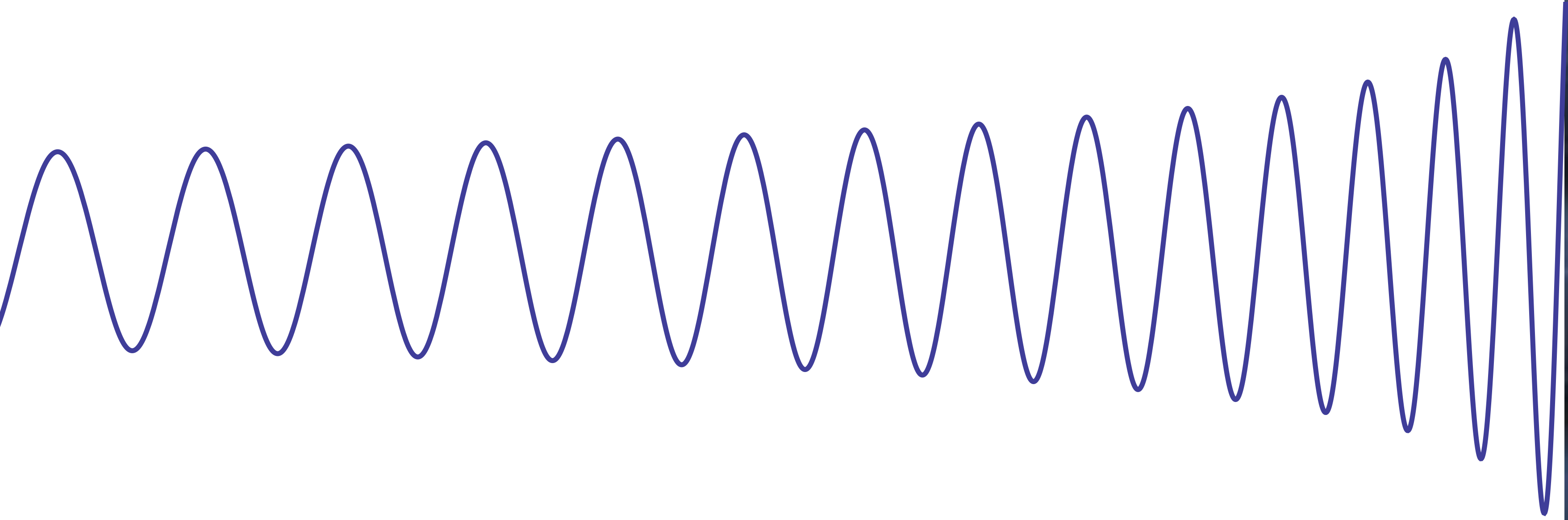
Talk outline

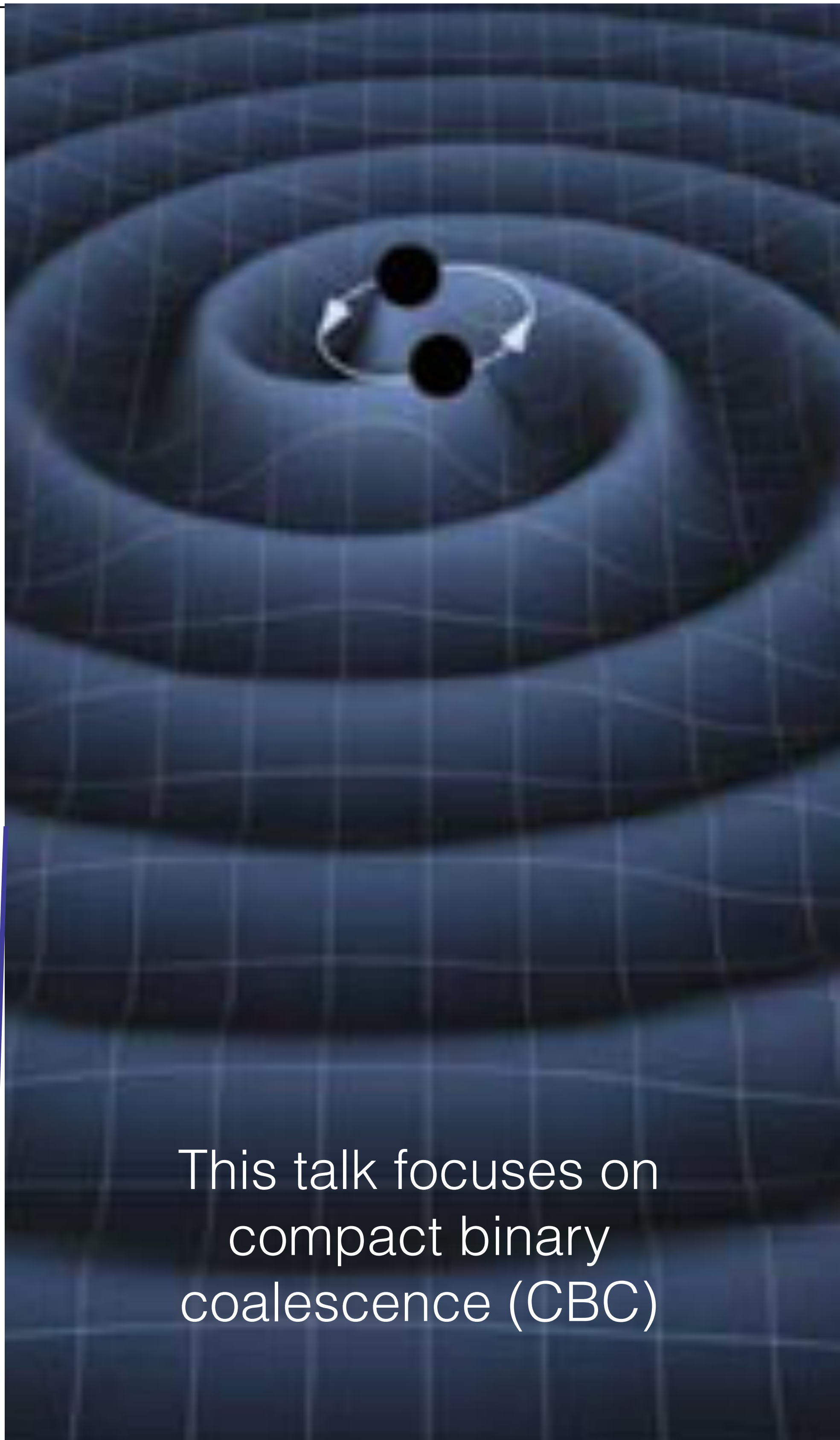
- Motivation
- Current state of knowledge
- The main ideas in GW cosmology
  - GW "standard sirens"
  - Statistical arguments
  - Space-based approaches
- Some recent ideas regarding neutron stars
  - Using tidal signatures
  - Using the hyper-massive NS
- Summary

Motivation

Gravitational waves

- Gravitational waves are propagating oscillations of the gravitational field.
- Travelling at the speed of light.
- Composed of 2 polarisations.
- Generated by time varying mass quadrupole (and higher) moment(s).

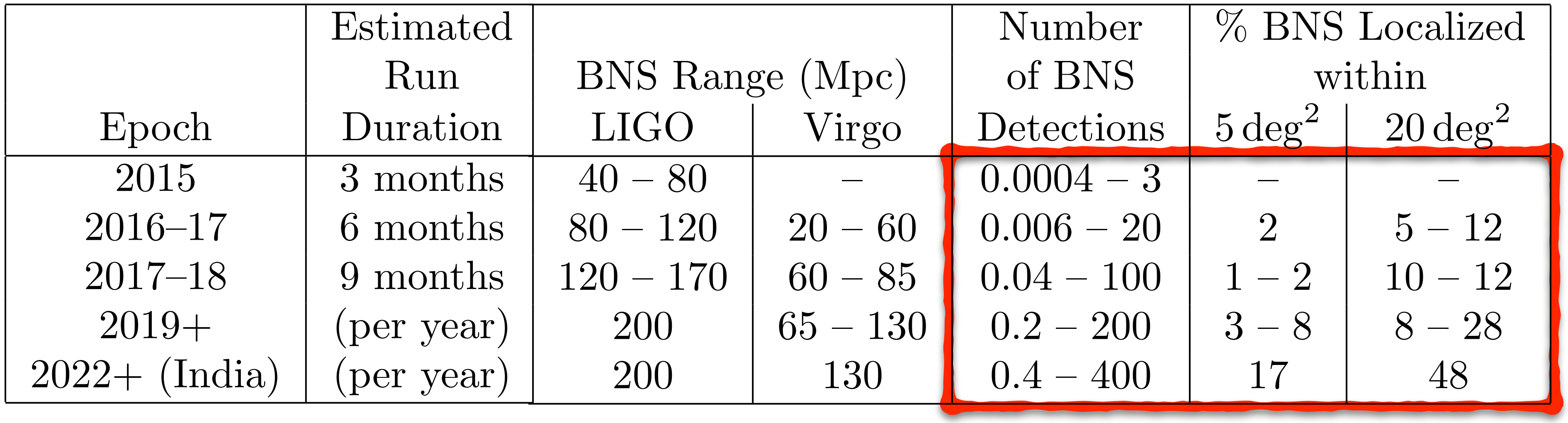




This talk focuses on compact binary coalescence (CBC)

Detection rates

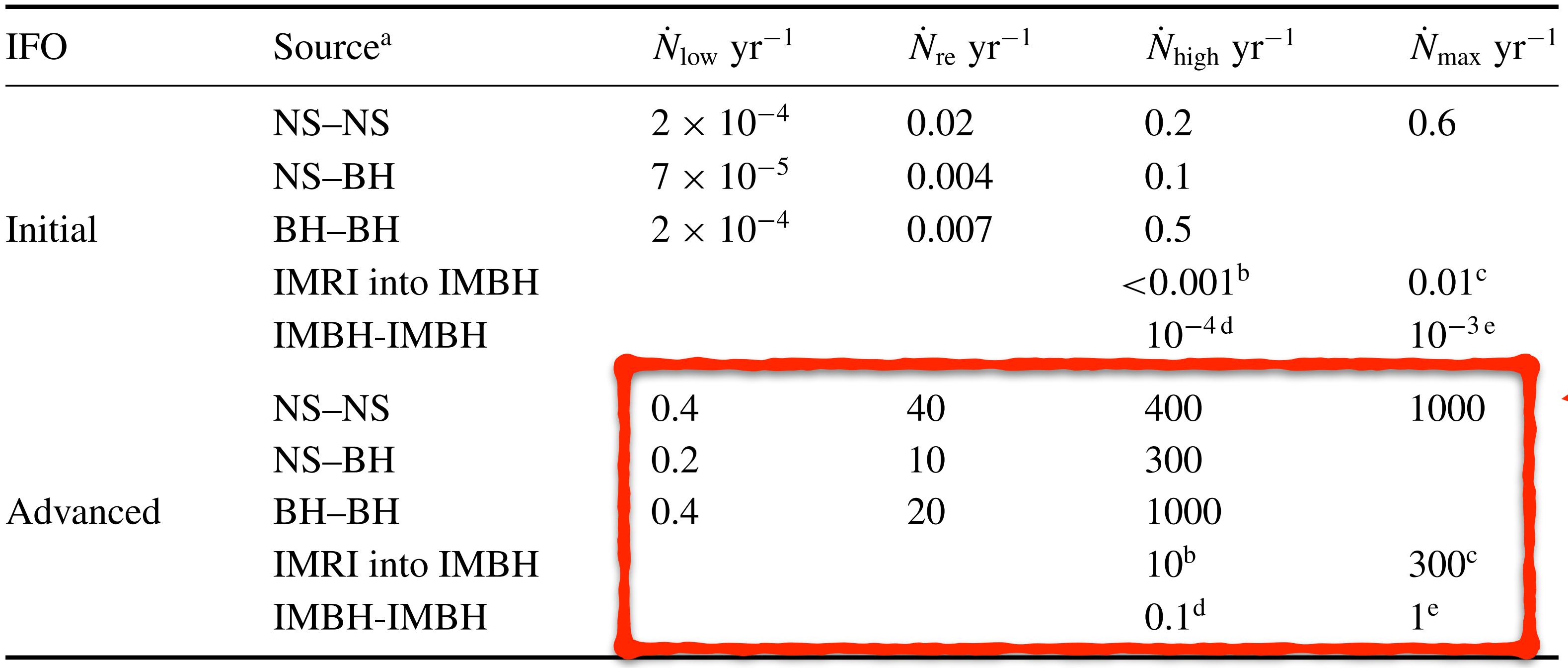
LIGO-Virgo Collaboration, arXiv:1304.0670 (2013)



Epoch	Estimated Run Duration	BNS Range (Mpc) LIGO	BNS Range (Mpc) Virgo	Number of BNS Detections	% BNS Localized within $5\,\mathrm{deg}^2$	% BNS Localized within $20\,\mathrm{deg}^2$
2015	3 months	40 – 80	–	0.0004 – 3	–	–
2016–17	6 months	80 – 120	20 – 60	0.006 – 20	2	5 – 12
2017–18	9 months	120 – 170	60 – 85	0.04 – 100	1 – 2	10 – 12
2019+	(per year)	200	65 – 130	0.2 – 200	3 – 8	8 – 28
2022+ (India)	(per year)	200	130	0.4 – 400	17	48

detection unlikely but not ruled out in 2015

Table 5. Detection rates for compact binary coalescence sources.



IFO	Source[a]	$\dot{N}_{\mathrm{low}}\ \mathrm{yr}^{-1}$	$\dot{N}_{\mathrm{re}}\ \mathrm{yr}^{-1}$	$\dot{N}_{\mathrm{high}}\ \mathrm{yr}^{-1}$	$\dot{N}_{\mathrm{max}}\ \mathrm{yr}^{-1}$
Initial	NS–NS	2×10^{-4}	0.02	0.2	0.6
	NS–BH	7×10^{-5}	0.004	0.1	
	BH–BH	2×10^{-4}	0.007	0.5	
	IMRI into IMBH			<0.001[b]	0.01[c]
	IMBH-IMBH			10^{-4}[d]	10^{-3}[e]
Advanced	NS–NS	0.4	40	400	1000
	NS–BH	0.2	10	300	
	BH–BH	0.4	20	1000	
	IMRI into IMBH			10[b]	300[c]
	IMBH-IMBH			0.1[d]	1[e]

older paper with slightly different assumptions

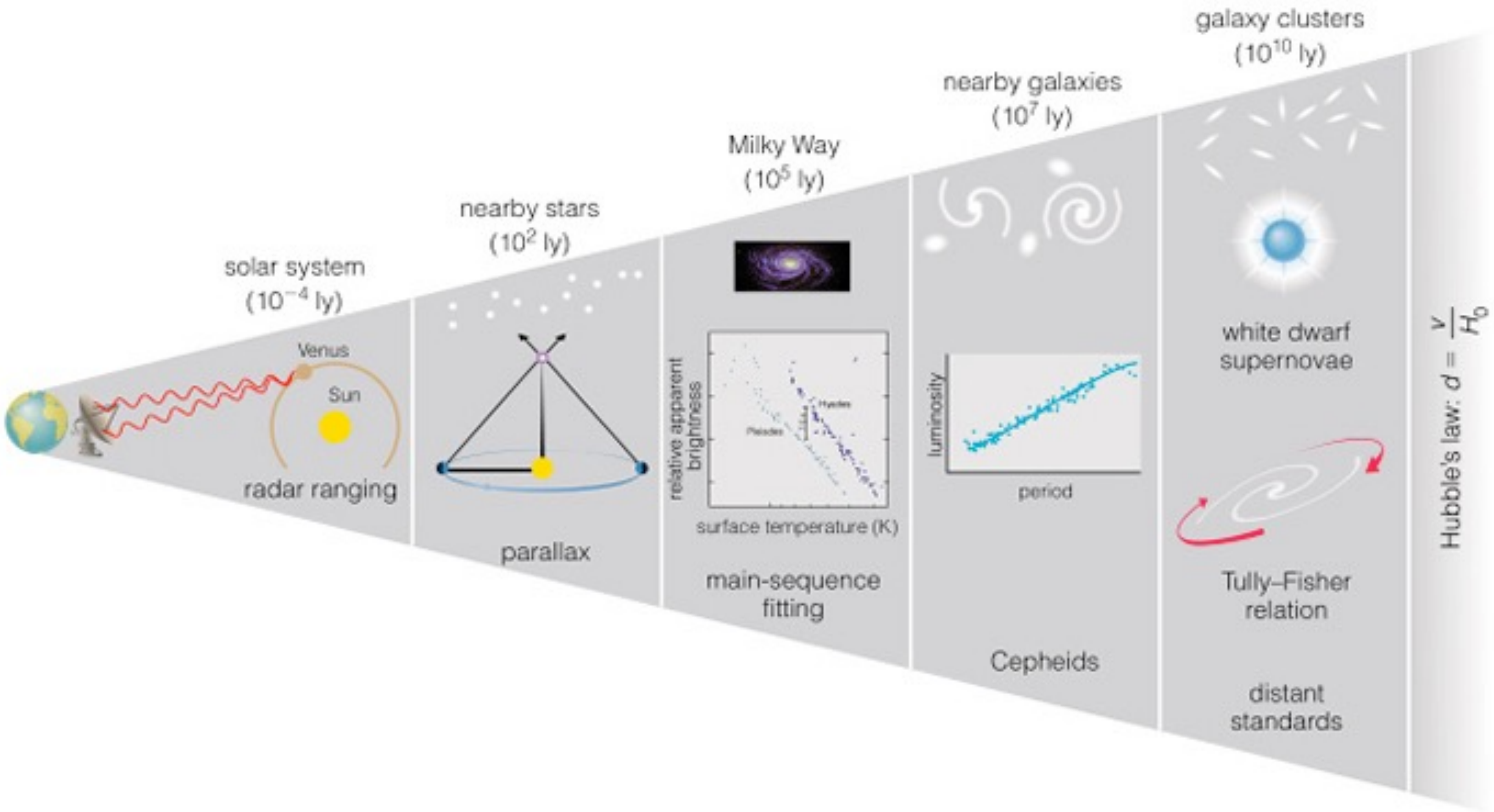
LIGO-Virgo Collaboration, CQG 27, 173001 (2010)

Motivation

- GW detection ***alone*** will be *pretty* good, *but…*
- The detection and characterisation of a ***population*** of GW sources will allow
    - the study of the large-scale structure of the Universe.
    - us to infer the formation history of the massive black hole population.
    - precision mapping of the expansion history of the Universe.
    - the use of cosmic distance markers (standard sirens).
    - provide a “powerful” probe of the dark energy content of the universe.

The current state of knowledge

Cosmic distance ladder



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- Nearby objects are used to calibrate more distant measurements.
- GW measurements would be **independent** of this ladder.

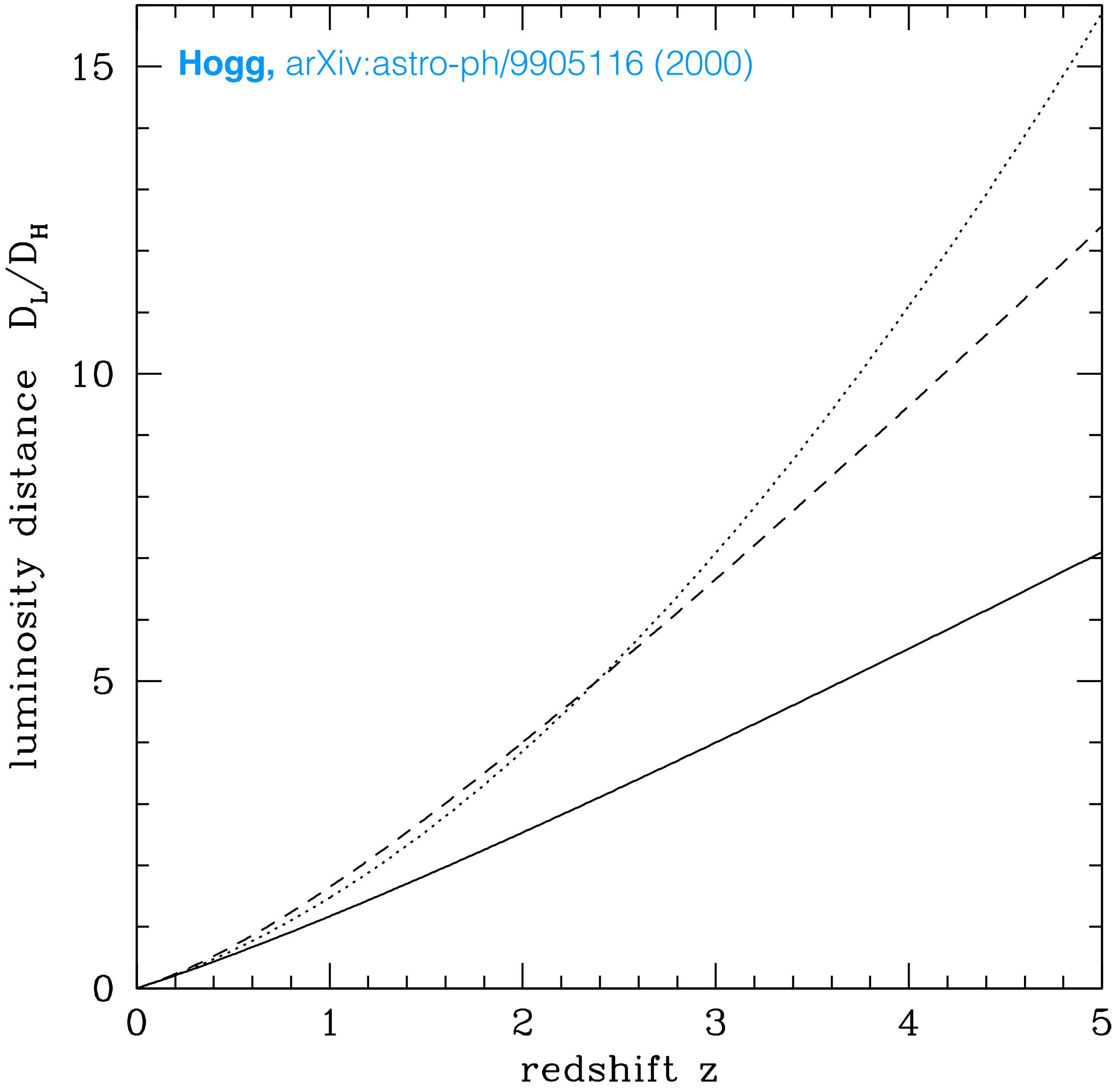
Hubble diagram

- Redshift $1+z=\sqrt{\frac{1+v/c}{1-v/c}}$

- Luminosity distance

$$D_{\mathrm{L}} = c(1+z)\int_0^z \frac{dz'}{H(z')}$$

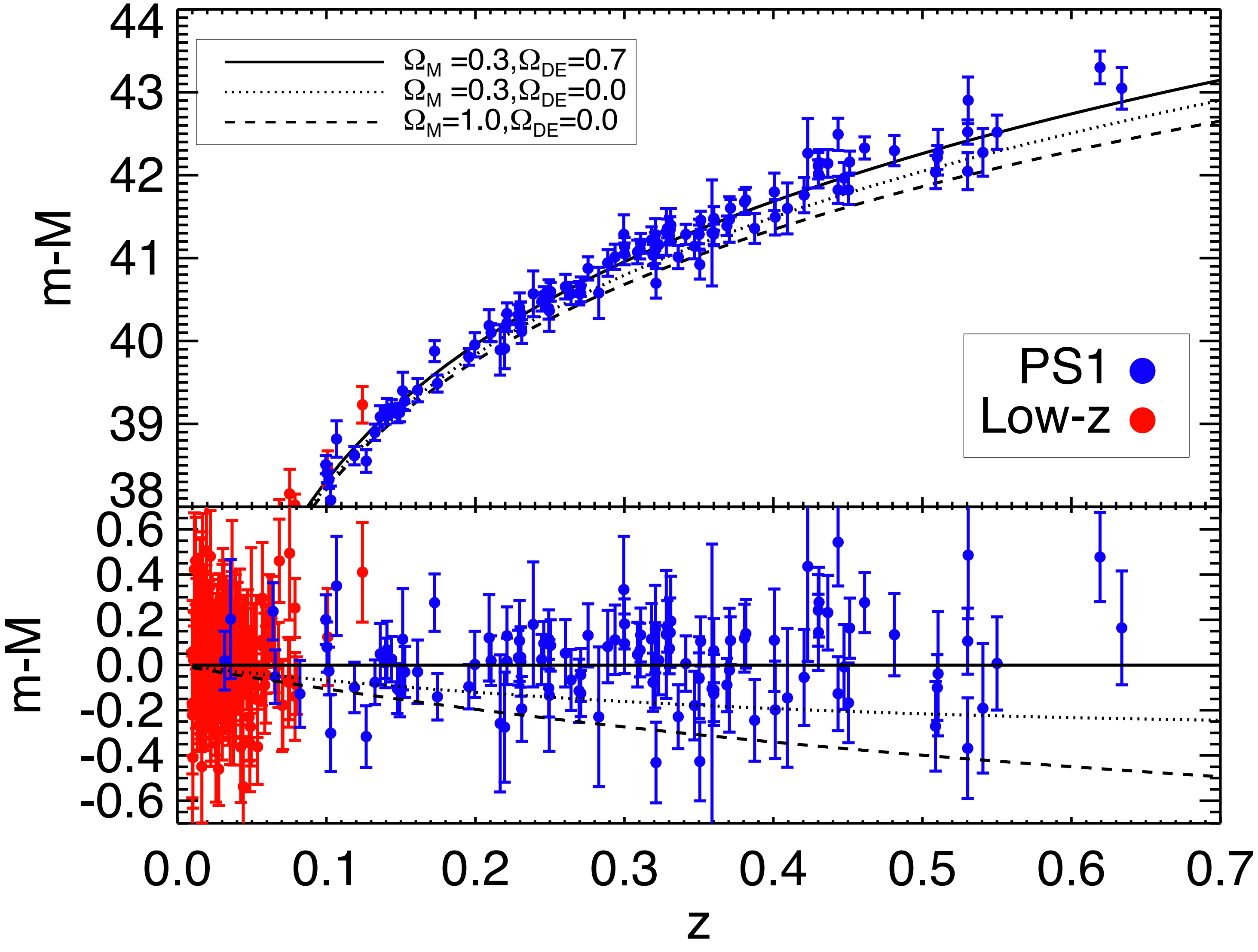
- Hubble parameter



$$H(z) = H_0\sqrt{\Omega_{\mathrm{M}}(1+z)^3 + \Omega_k(1+z)^2 + \Omega_\Lambda(1+z)^{3(1+w_0+w_a)}e^{-3w_a z/(1+z)}}$$

Standard Candles

- Type 1a supernovae progenitors are thought to be white dwarfs pushed over the Chandrasekhar limit.
- They act as standard candles" of *equal* luminosity (to ~15%).
- Calibration with Cepheids gives $H_0 = 73.8 \pm 2.4$ km s^{-1} Mpc^{-1} [**Riess** *et al*, ApJ (2011)]

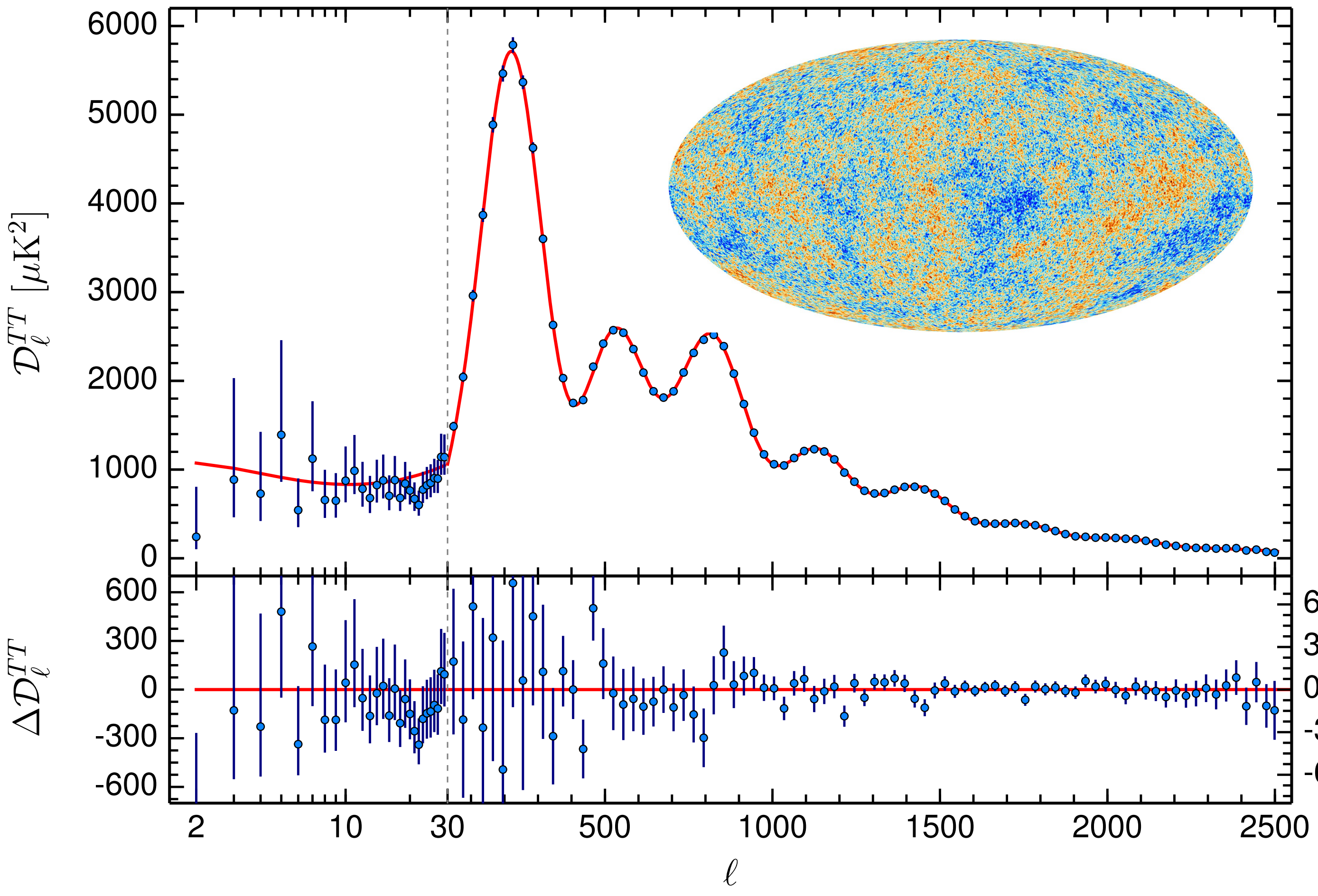


Rest *et al* arXiv:1310.3828 (2014)

Current knowledge

- The recently published Planck CMB results (combined with others) give the best constraints to date.
- Consistent with the standard ΛCDM model.
- Gives $H_0 = 67.8 \pm 0.9$ km s^{-1} Mpc^{-1}
- These (EM) results are likely to improve before GWs are competitive.

Planck Collaboration arXiv:1310.3828 (2015)



GW standard sirens

Standard Candles

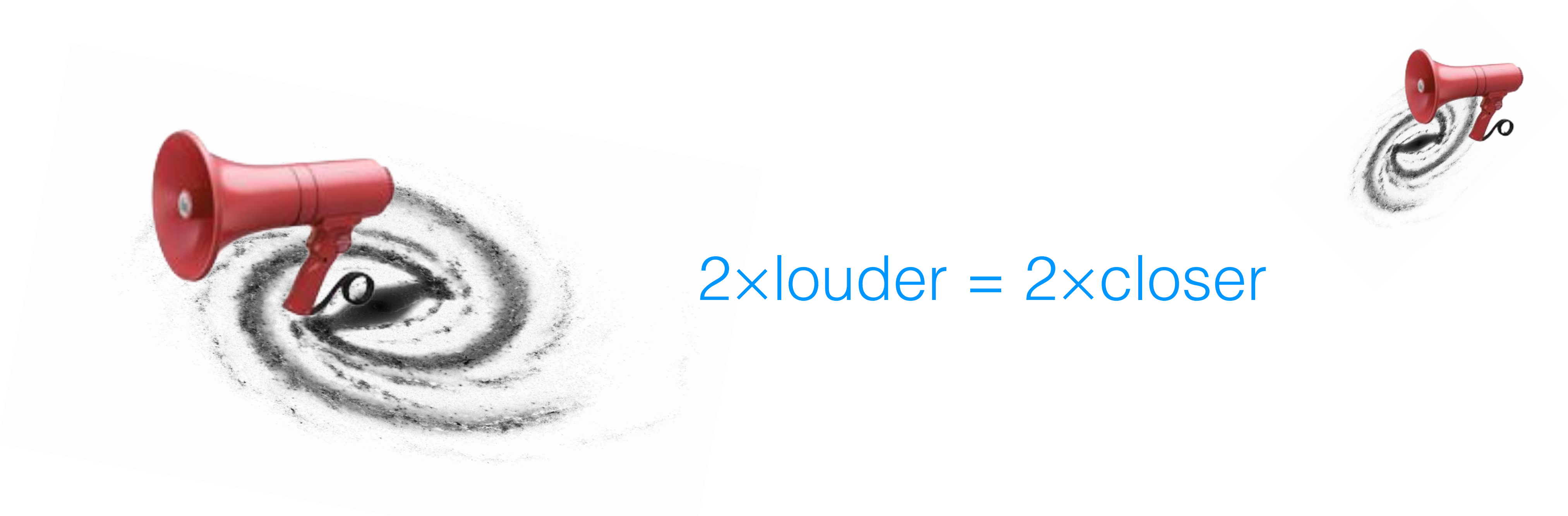
- The inverse square law relates the received flux to the distance
- All you need to know is that there are events/objects of equal intrinsic luminosity e.g. Type 1a Supernova

4×brighter = 2×closer

- Gives relative distances so still need calibration

GW standard sirens

- The inverse ~~square~~ law relates the received GW amplitude to the distance
- GW compact-binary-coalescences of neutron stars or black holes (of given mass) will produce identical signals.



2×louder = 2×closer

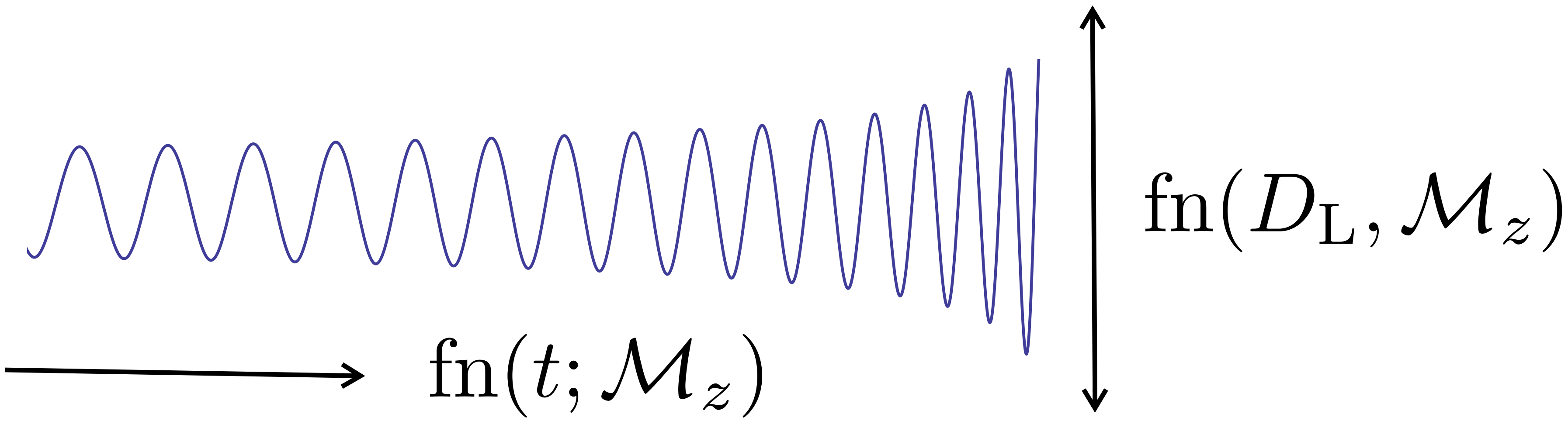
- Gives absolute distances so no *calibration* required

Schutz’s idea

- Schutz in 86’ proposed using compact-binary-coalescences as “standard sirens”[**Schutz,** Nature (1986)].
- Phase measurement gives redshifted chirp-mass $\mathcal{M}_z = \mathcal{M}(1+z)$

$$\mathcal{M} = M\eta^{3/5}$$

$$\eta = \frac{m_1 m_2}{M^2}$$



$\mathrm{fn}(D_\mathrm{L}, \mathcal{M}_z)$

$\mathrm{fn}(t; \mathcal{M}_z)$

- Amplitude gives ratio of redshifted chirp-mass$^{5/3}$ with luminosity distance D_L.
- “Self-Calibrating” sources but **no redshift**.

$\mathcal{M}, z$ degeneracy

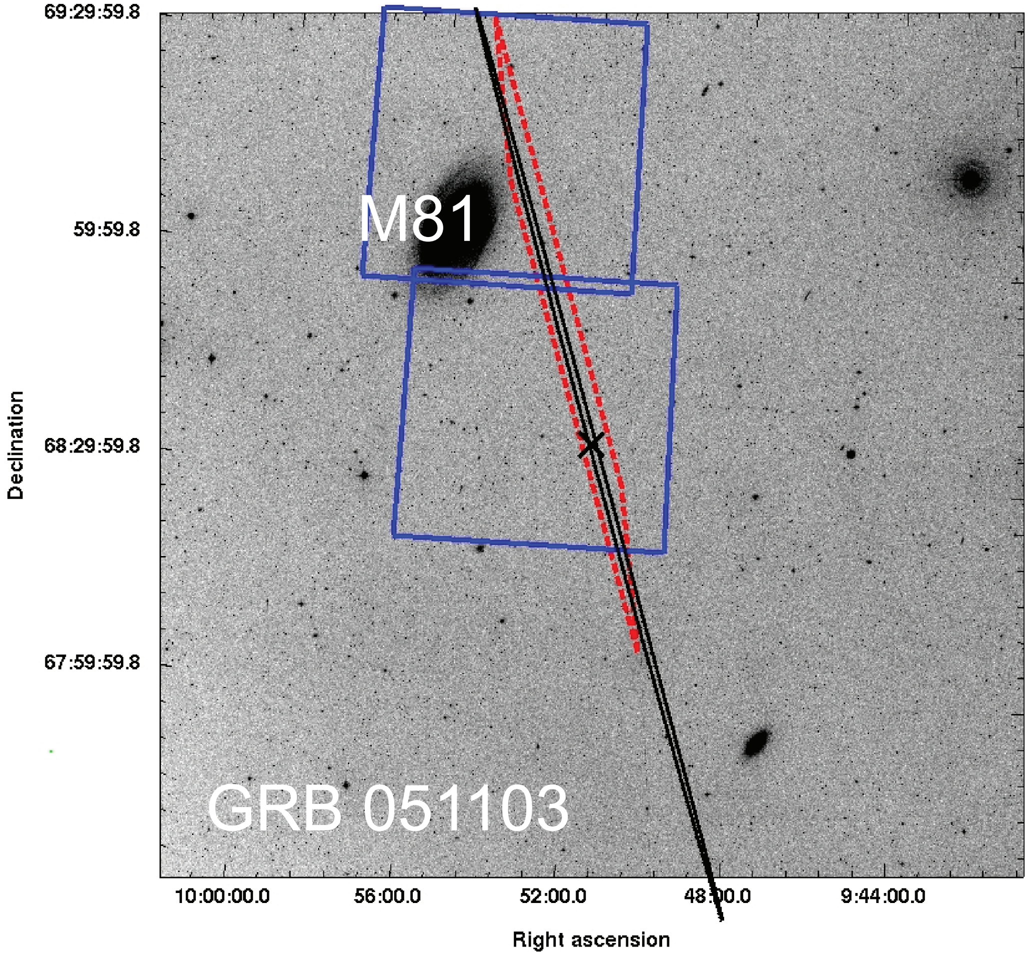
- The problem is that we only get D_L and the redshifted mass

$$\mathcal{M}_z = \mathcal{M}(1+z)$$

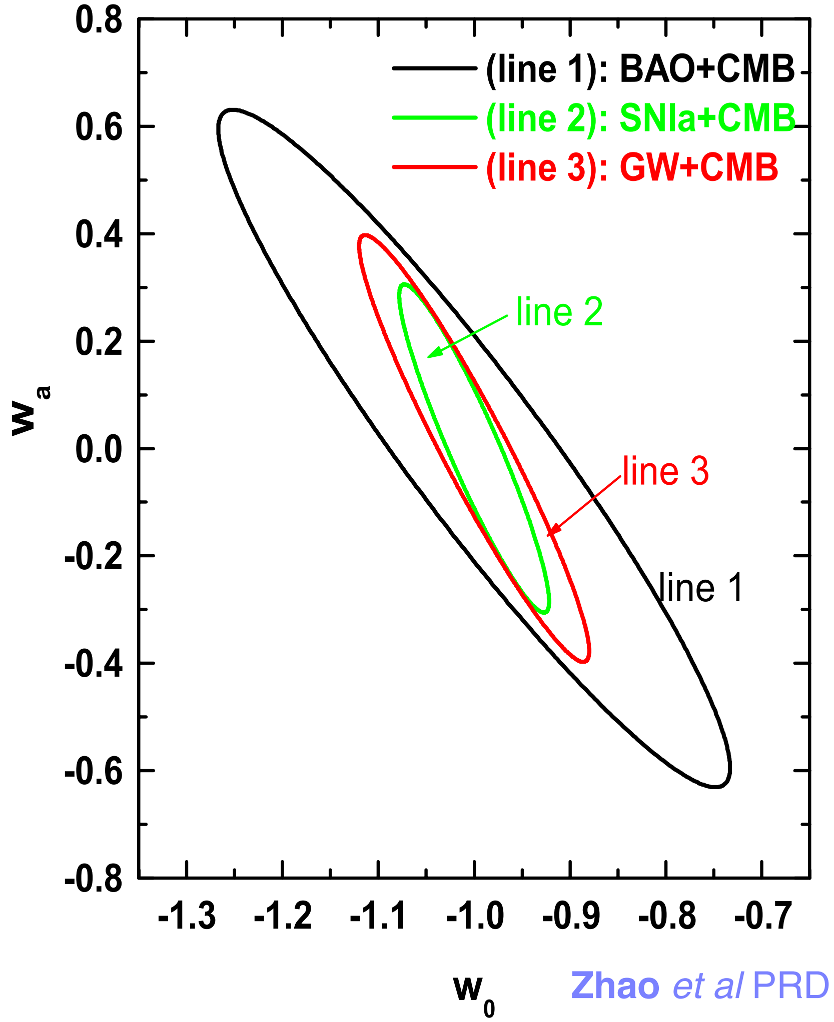
- We need EM measurements of redshift to break the degeneracy.
- Therefore we need host galaxy identification.

Gamma-ray bursts

- GRBs represent an EM counterpart with redshift obtained from the host galaxy. [**Dalal** *et al* PRD (2006), **Nissanke** *et al* ApJ (2010), **Zhao** *et al* PRD (2011)]

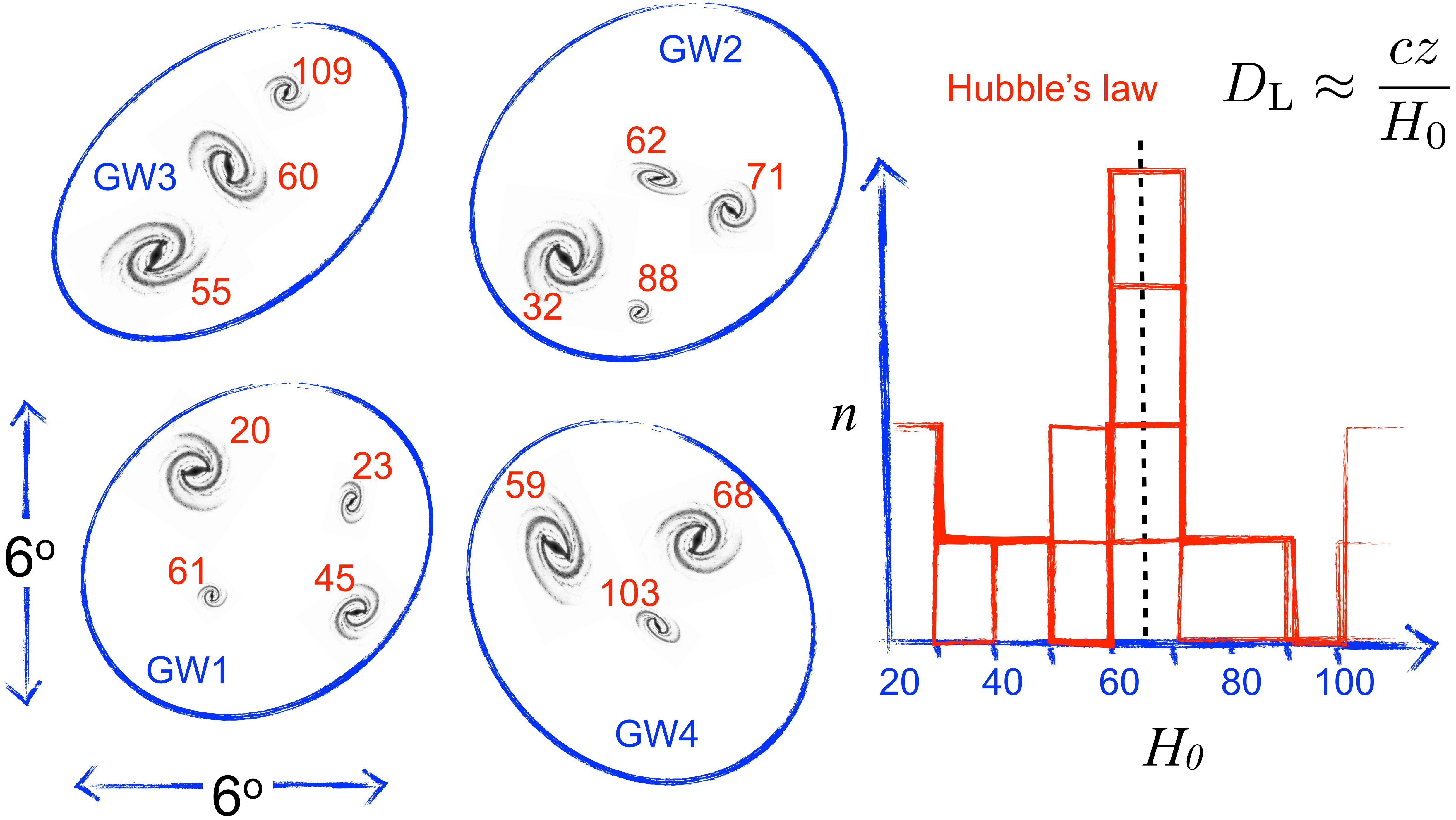


Hurley *et al* MNRAS (2010)



Zhao *et al* PRD (2010)

Schutz's method



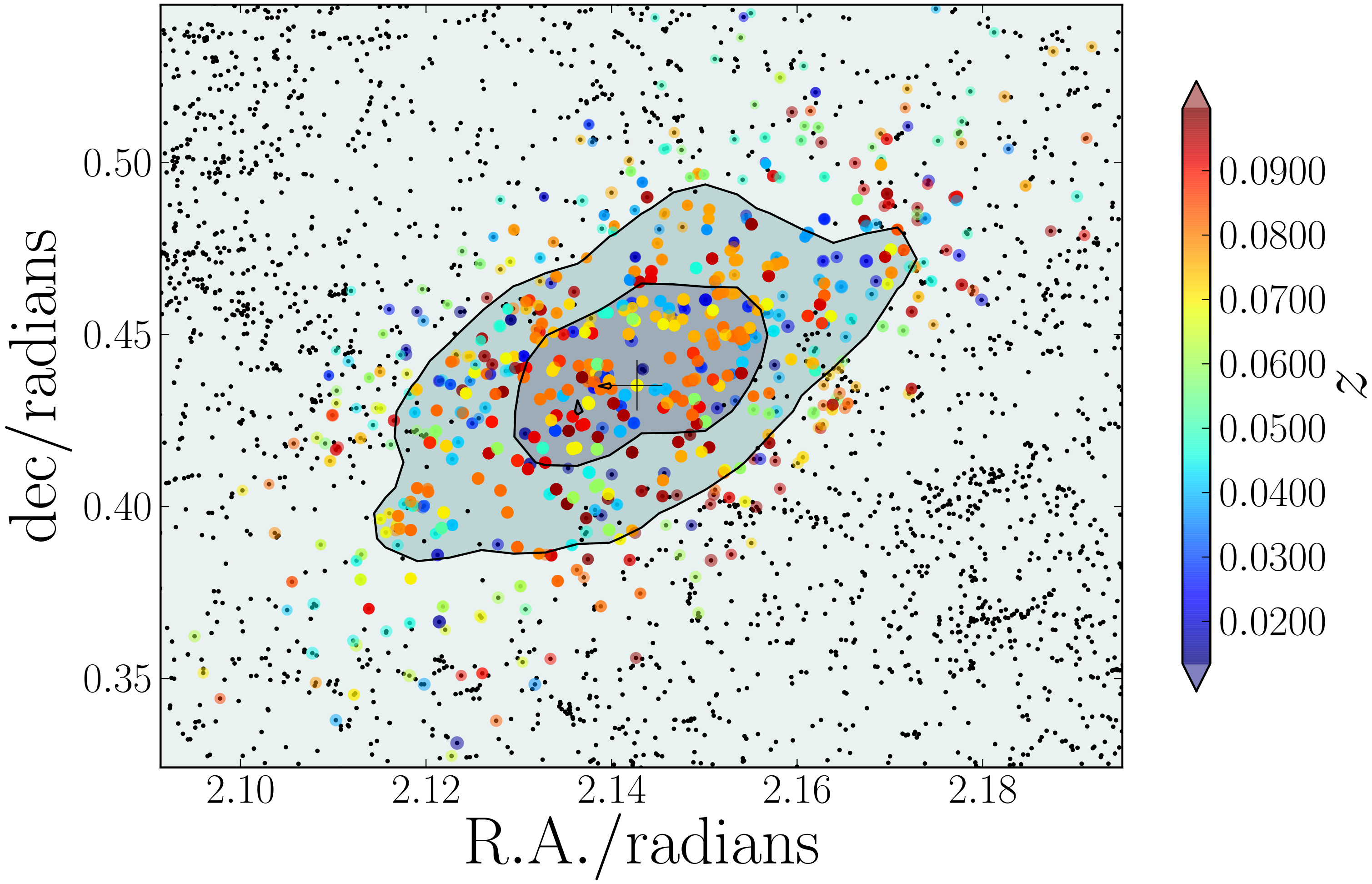
Hubble's law

$$D_{\rm L} \approx \frac{cz}{H_0}$$

Galaxy catalogues

- Del Pozzo extended the Schutz idea to make use of galaxy catalogues to identify hosts [**Del Pozzo** PRD (2012)].
- The redshift can then be obtained.
- Any confusion on between host galaxies is averaged out with many sources.

H_0 to ~few% with 50 sources

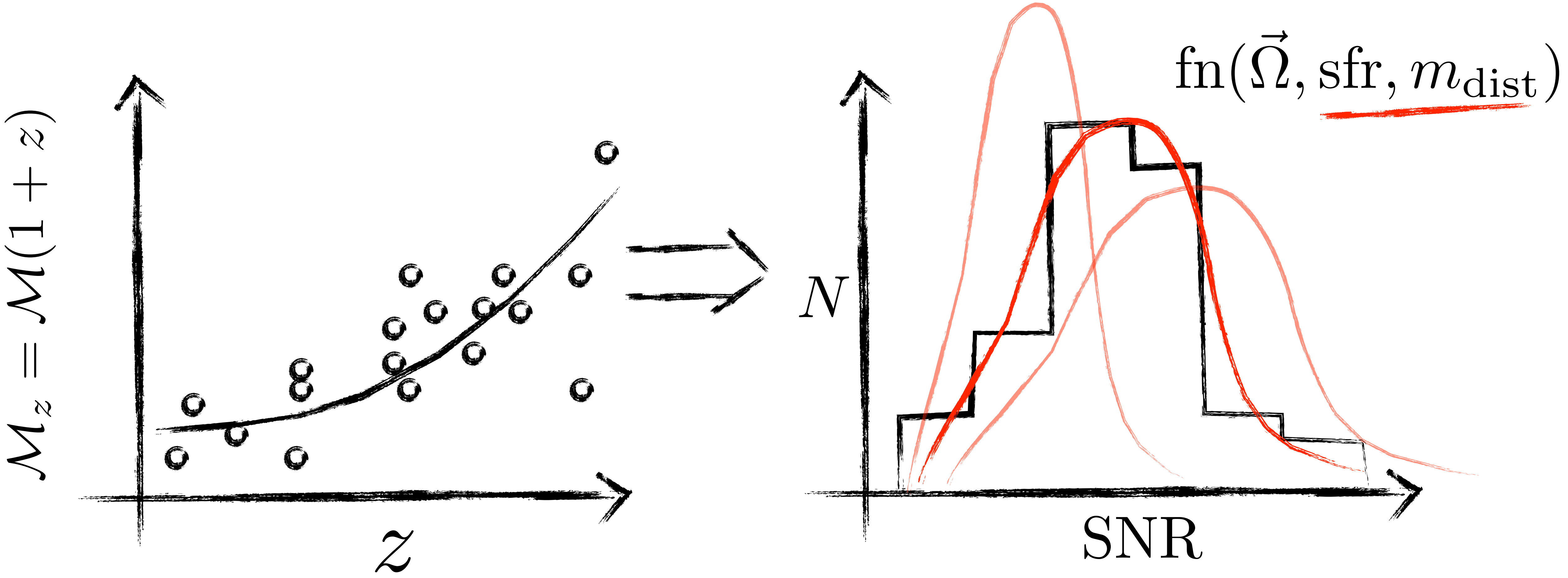


Del Pozzo PRD (2012)

Statistical arguments

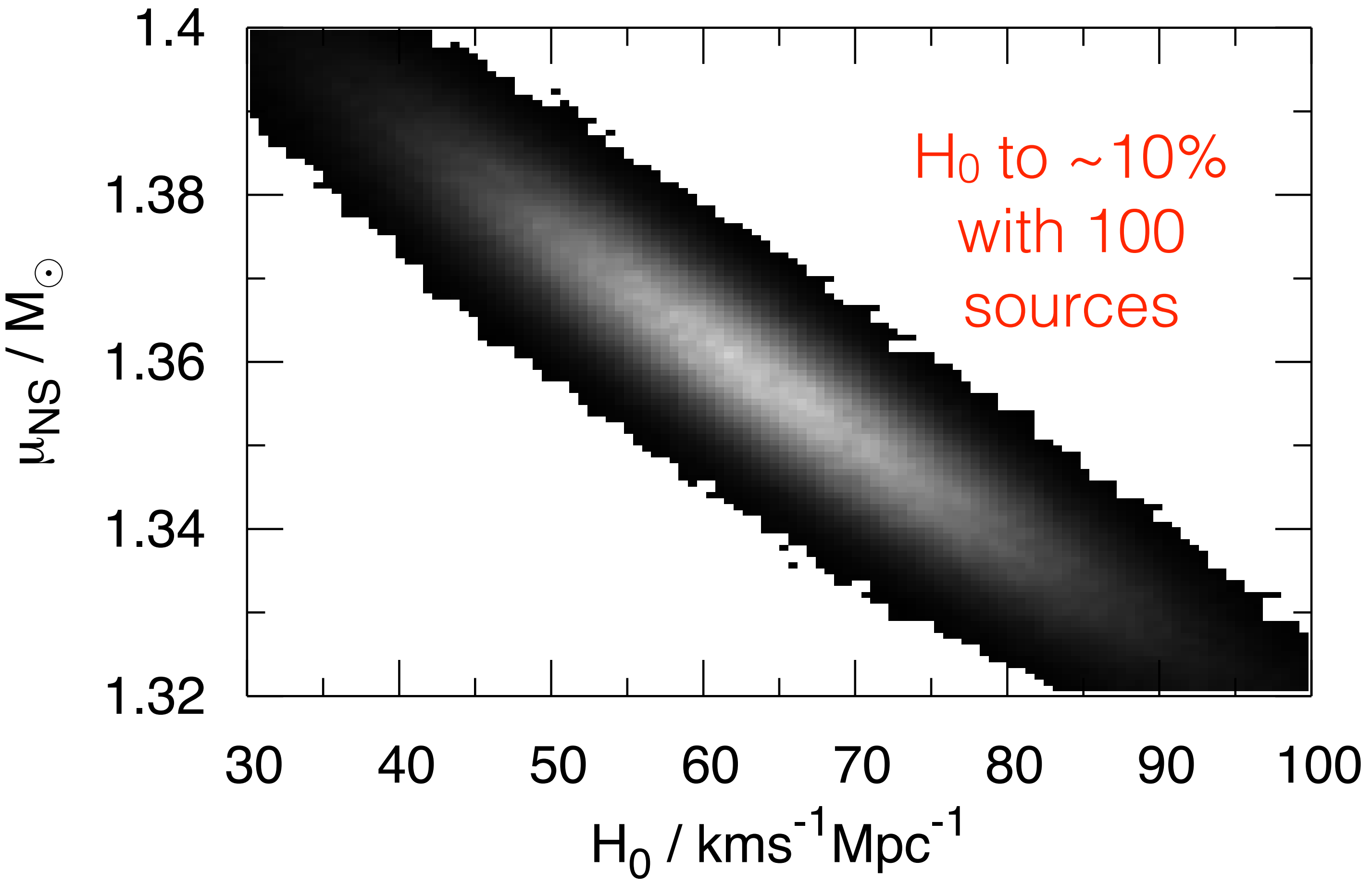
Statistical properties

- Idea first proposed by Marković 93’ and Finn & Chernoff 93’ to use the distribution of measured SNRs. [**Markovic** PRD (1993), **Finn & Chernoff** ApJ (1993), **Finn** PRD (1996)]



Statistical properties

- The idea was expanded upon by Taylor *et al* 2011 [**Taylor** *et al* PRD (2011), **Taylor** *et al* PRD (2012)]
- Where the mass distribution and star formation rate are included in the model.



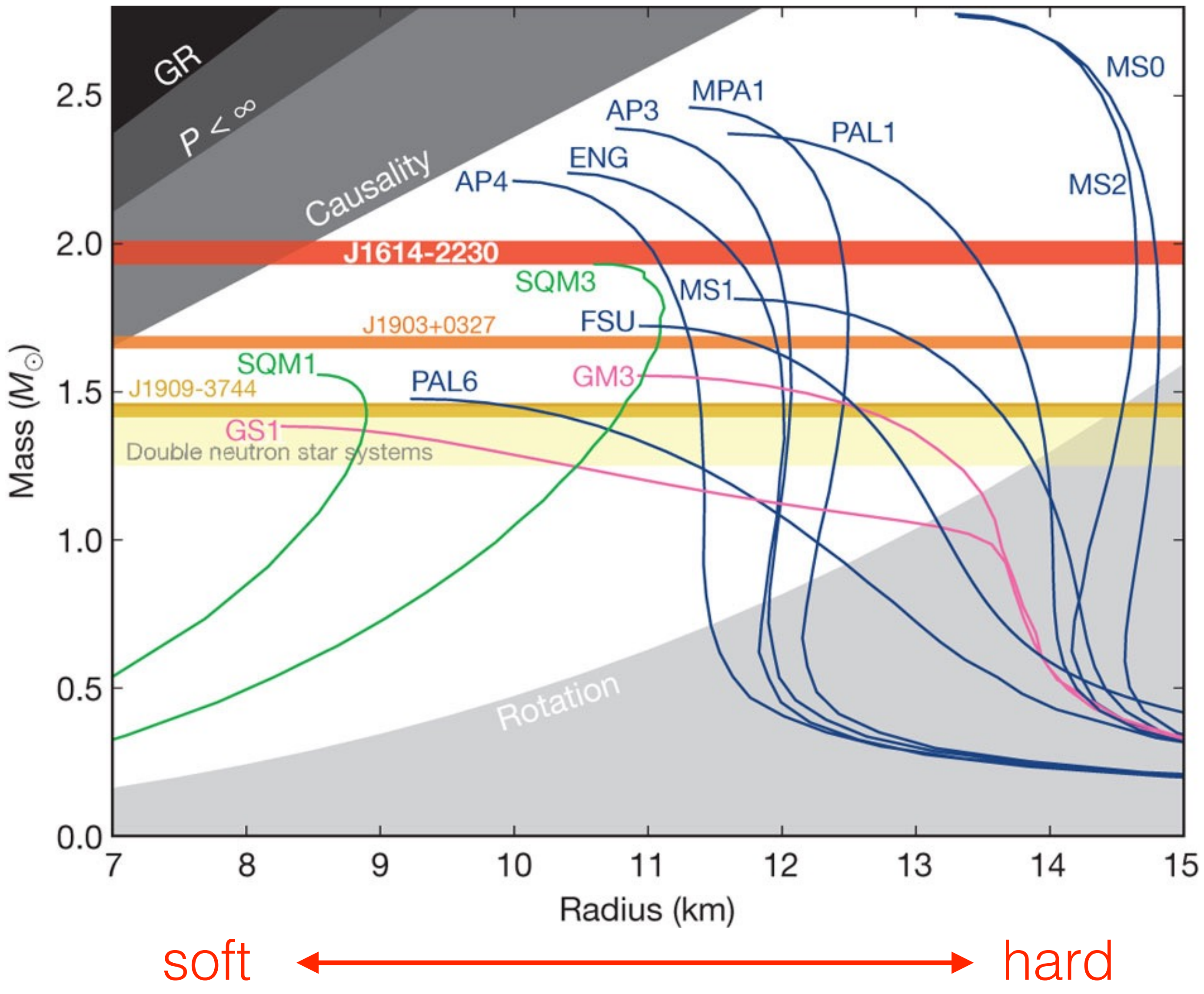
Taylor *et al* PRD (2012)

Using tidal signatures

Neutron star Equation of State

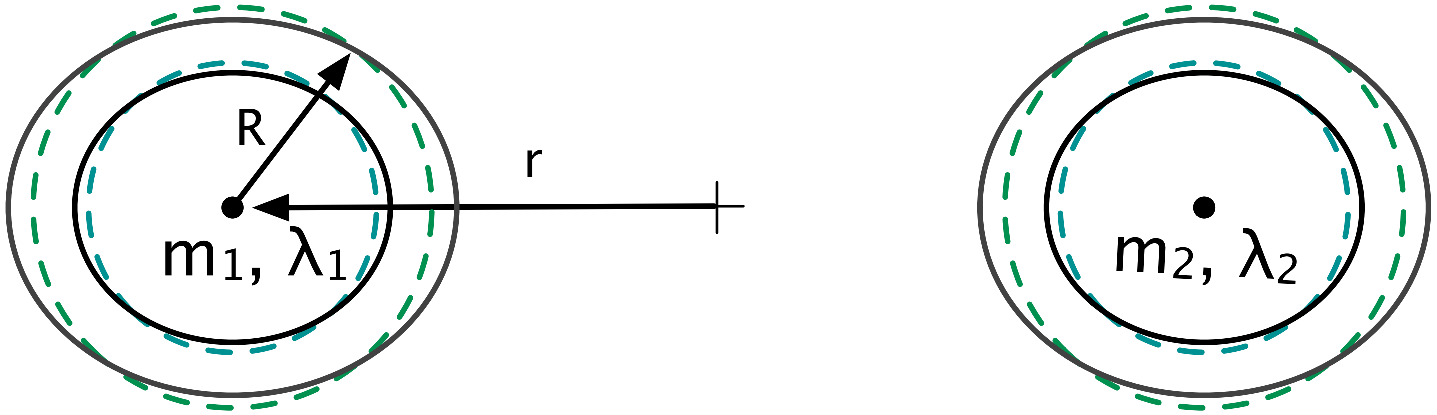
- The equation of state (EOS) specifies the pressure of neutron star matter at a given density.
- Expect a single equation of state to describe all (cold) neutron stars
- It's not crazy to think that the Neutron-star EOS will be well-understood in the era of third-generation GW detectors [**Del Pozzo** *et al* PRL (2013)].

Demorest *et al*, Nature (2010)



Tidal deformation

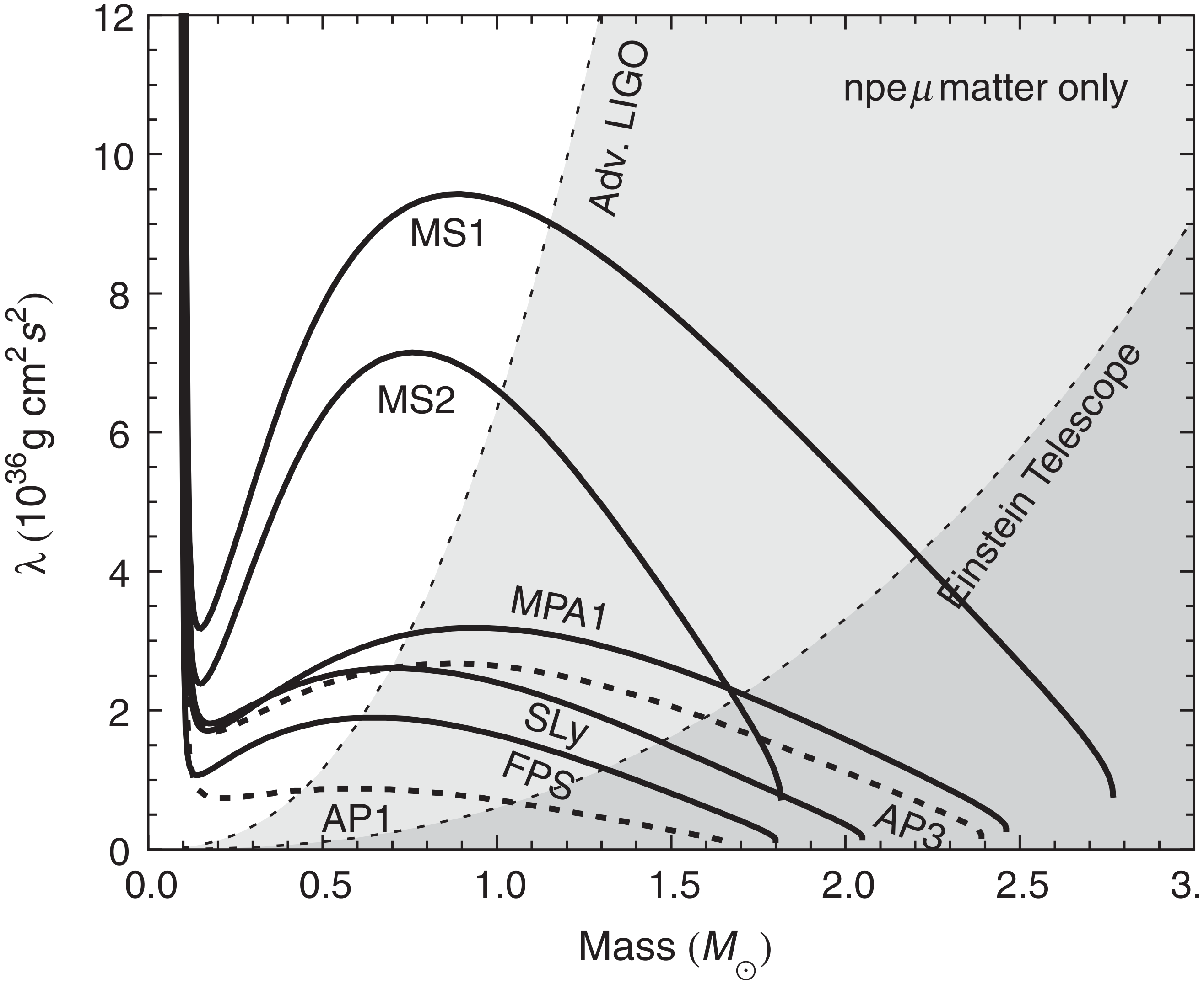
- Each neutron star’s tidal field deforms the other star.
- The EOS sets how a neutron star of given mass responds.
- Tidal deformation modifies orbital energy and GW luminosity, contributing to the GW phase evolution:



$$\Phi(f)_{\mathrm{tidal}} = \frac{3}{128\eta}(\pi M f)^{5/3}\left(-\frac{24}{M^5}\left(\frac{M+11m_1}{m_2}\lambda_1 + \frac{M+11m_2}{m_1}\lambda_2\right) + \ldots\right)$$

Tidal deformation

- Each EOS will provide a different level of deformation.
- Hence a different level of GW phasing.
- Also a different dependence on NS mass
- Tidal deformability is a function of the Love number k_2

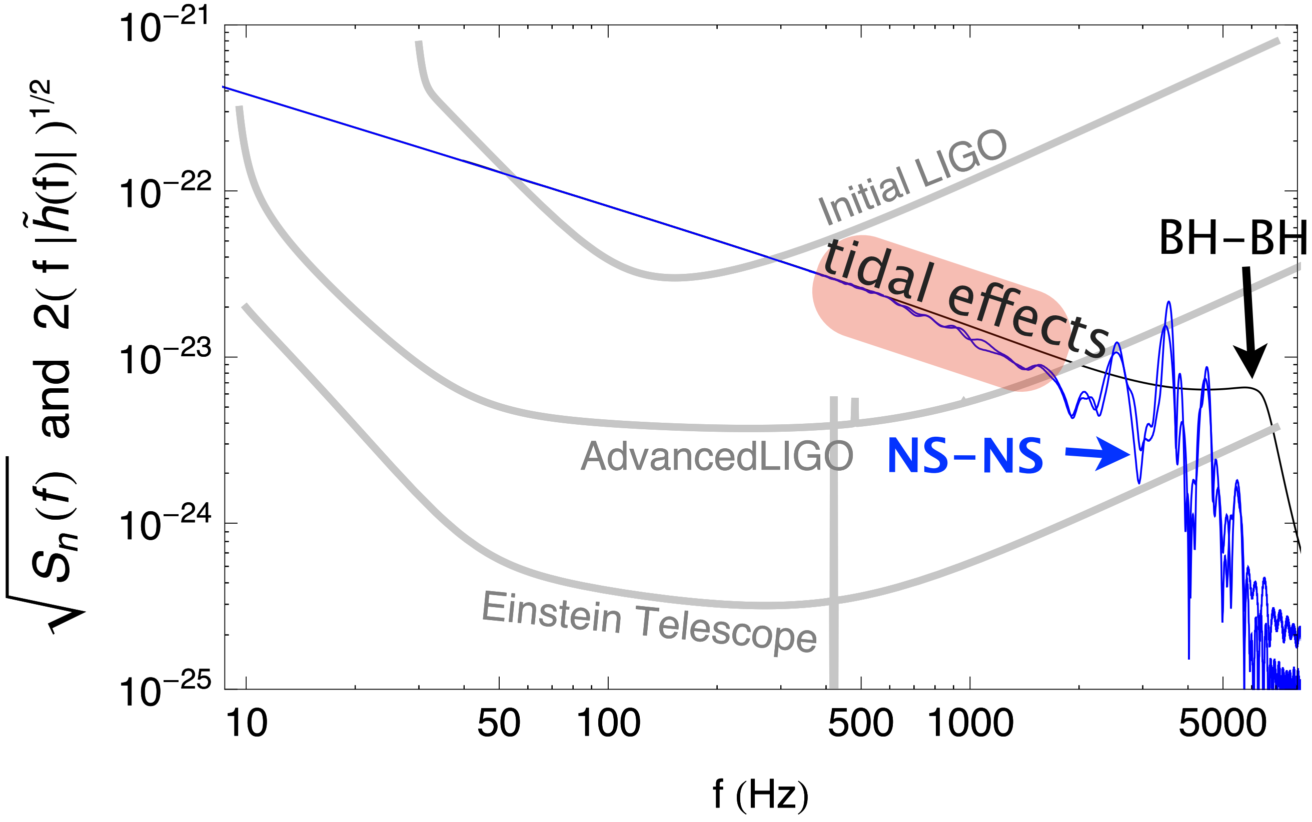


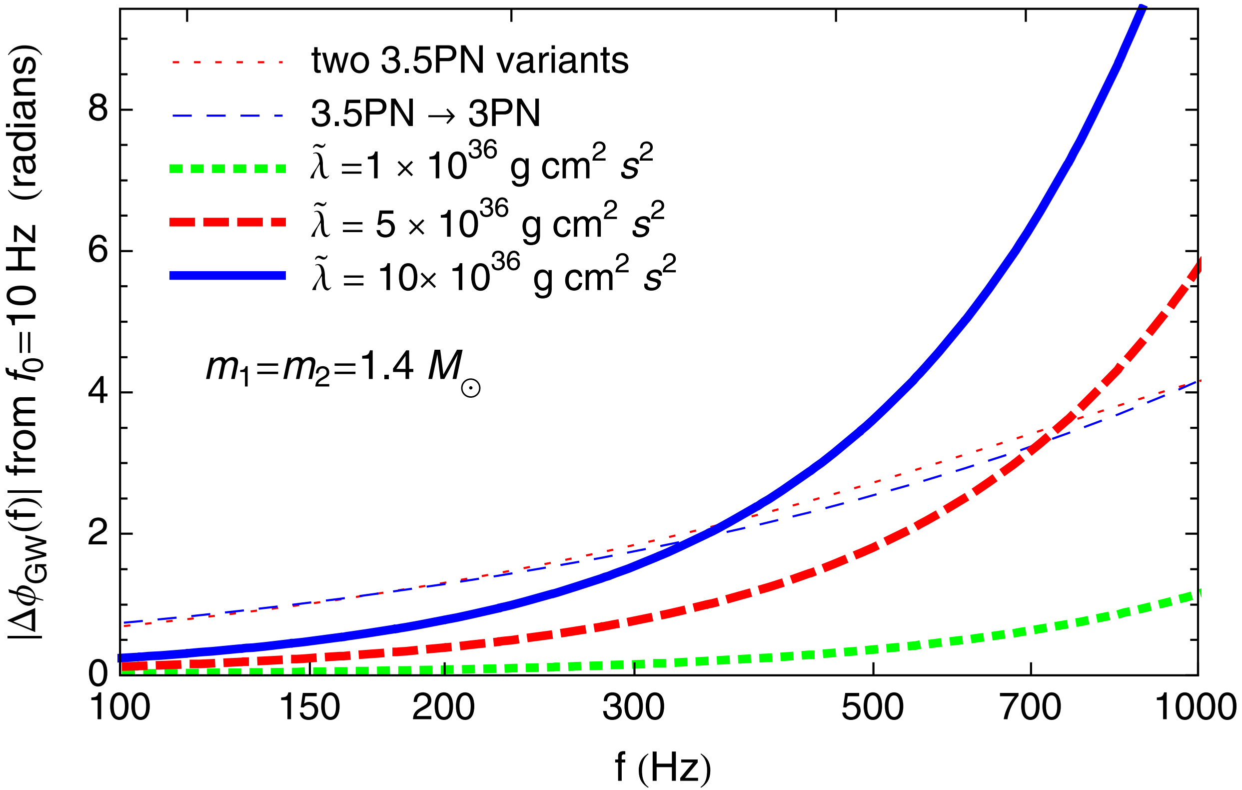
Hinderer *et al* PRD (2010)

$$\lambda(m) = (2/3)k_2R^5(m)$$

EOS effect on waveforms

- The presence of matter modifies the late-inspiral, merger, and post-merger GW signals: the high-frequency part of the coalescence.





Hinderer *et al* PRD (2010)

Breaking M-z degeneracy

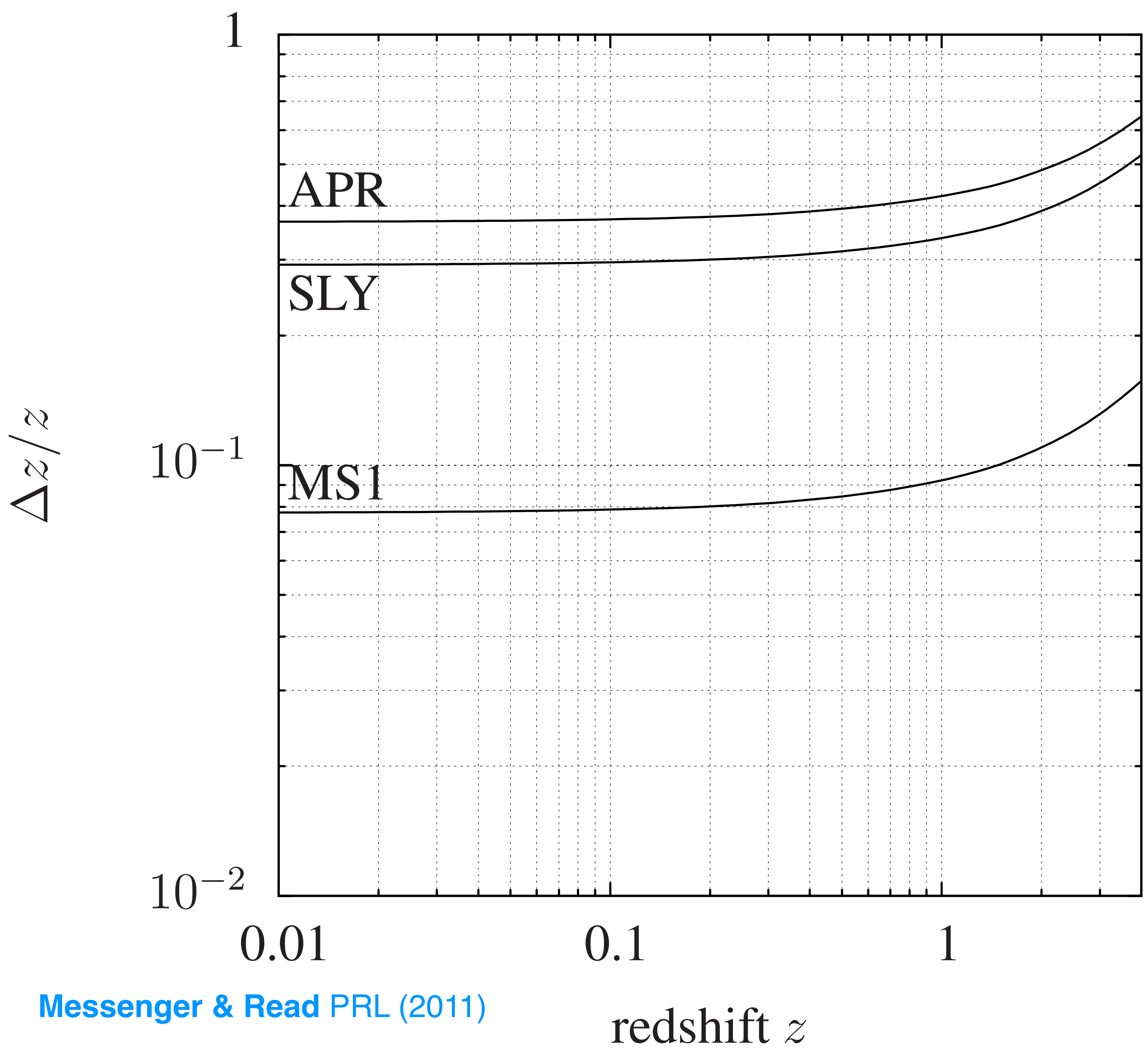
- Rest-frame waveform phase evolution with tidal contributions: (leading order, equal mass system)
- Tidal terms are formally 5 and 6PN order

$$\Phi(f) = \Phi_{\mathrm{PN}} - \frac{117}{8\eta}(\pi M(1+z)f)^{5/3}\frac{\lambda_1(\mathrm{EOS}; m)}{M^5}$$

These mass-dependent terms are not paired
with a redshift factor

- Inference on the detected waveform allows us to estimate M and z.

Redshift measurement

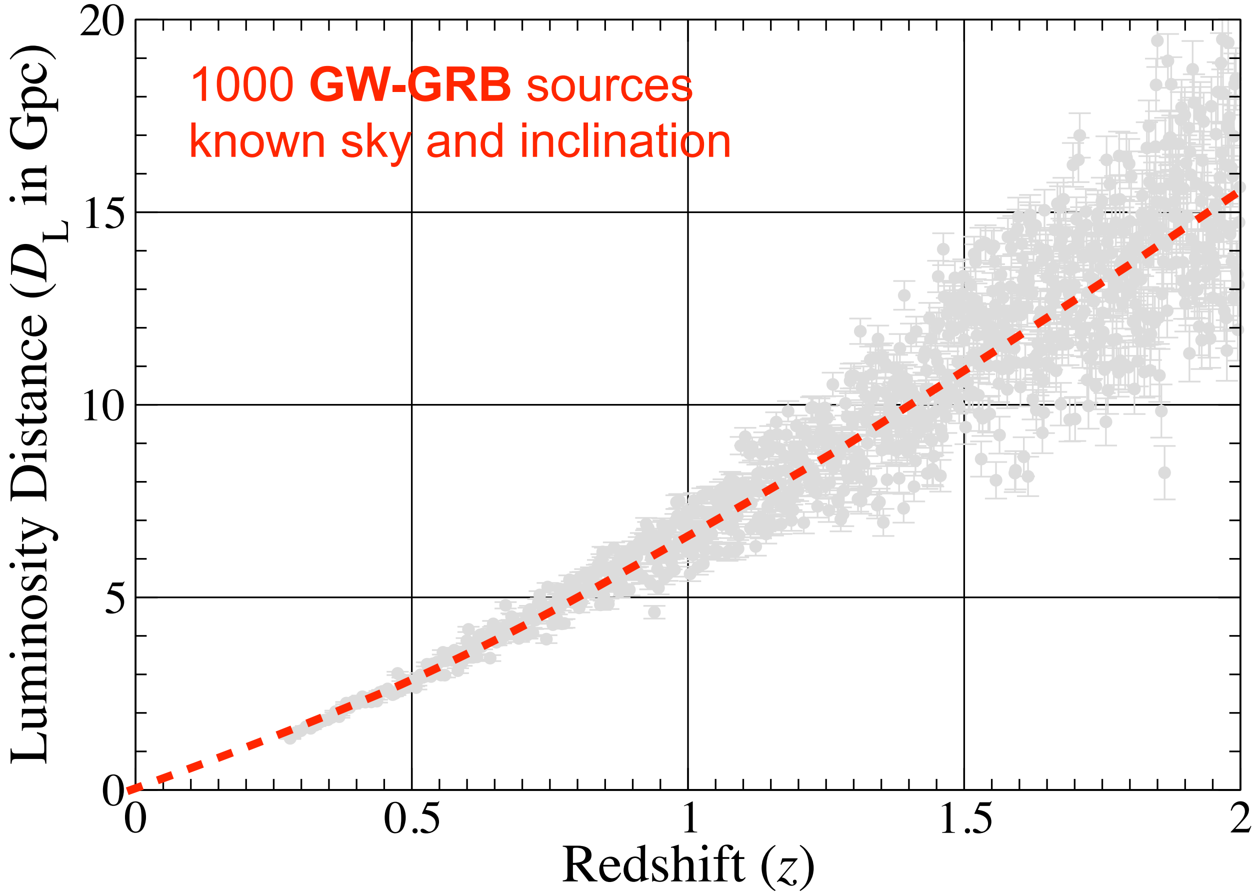


Messenger & Read PRL (2011)

- For 3rd generation detectors the GW signal **alone** can be used to determine the redshift of the source.
- Even in the worst case, redshift uncertainties can be constrained to ~40% at z < 1 and in the best case ~8%.

Cosmological implications

- The uncertainty we predict for the redshift is O(10s%) for all sources, but we will have O(10^3 - 10^7) sources!
- Independent of the cosmic distance ladder so immune to its potential systematic errors.
- We will have our own issues with relation to calibration.

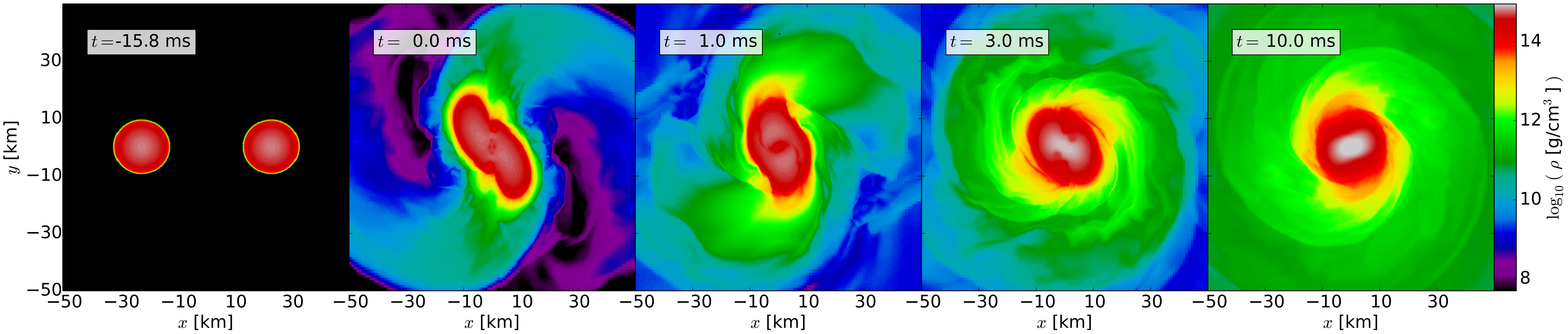


Sathyaprakash *et al* CQG (2010)

Using the hyper-massive NS

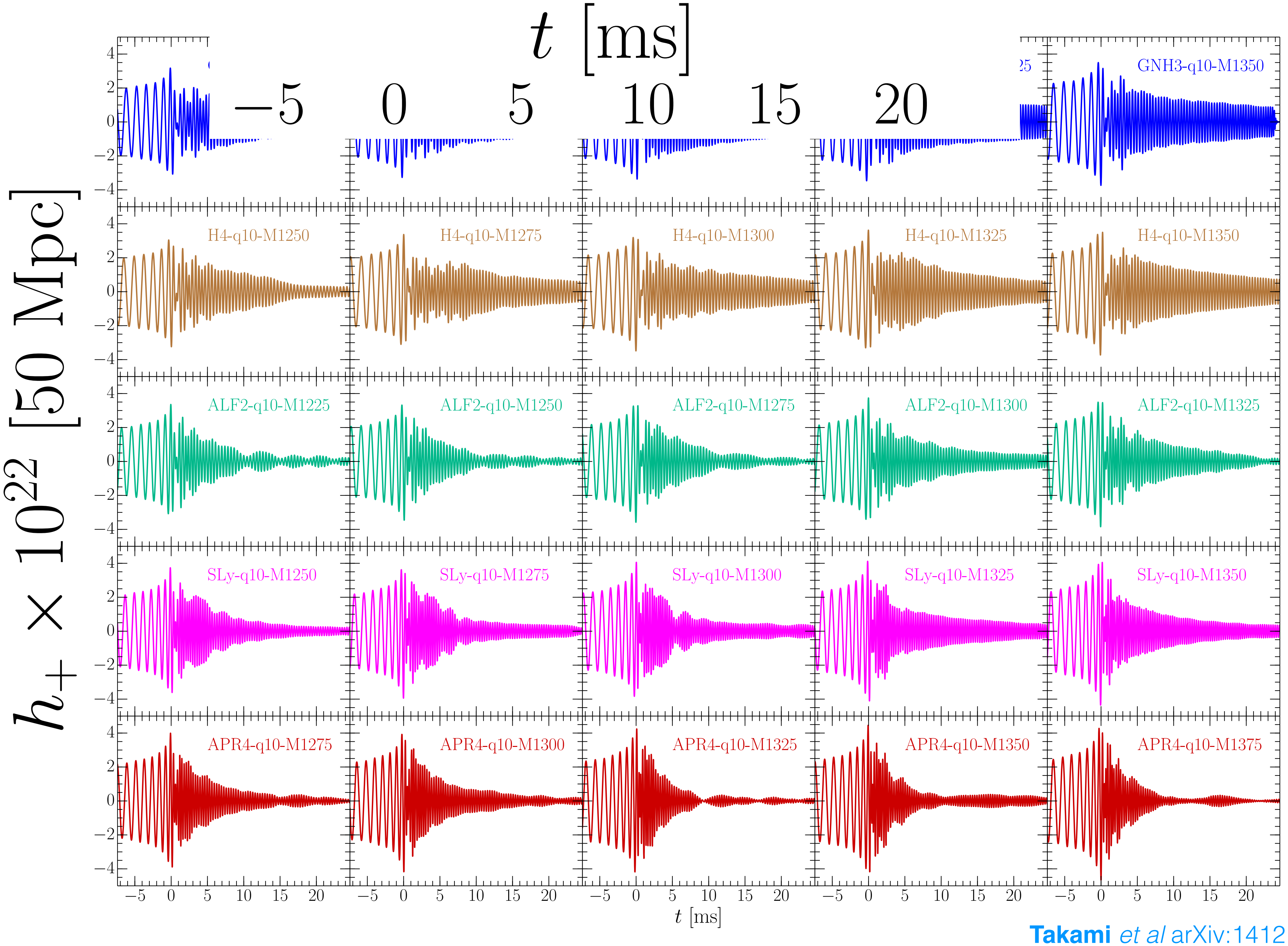
Post-Merger

- When 2 NSs merge after the inspiral they **briefly** form an unstable hyper-massive NS (if the EOS is not too soft).
- Such an object will survive for O(10s) milliseconds before collapsing into a black-hole.
- The GW waveform contains signatures of the EOS encoded in multiple frequency components.



Takami *et al* arXiv:1412:3240 (2014)

Post-Merger waveforms



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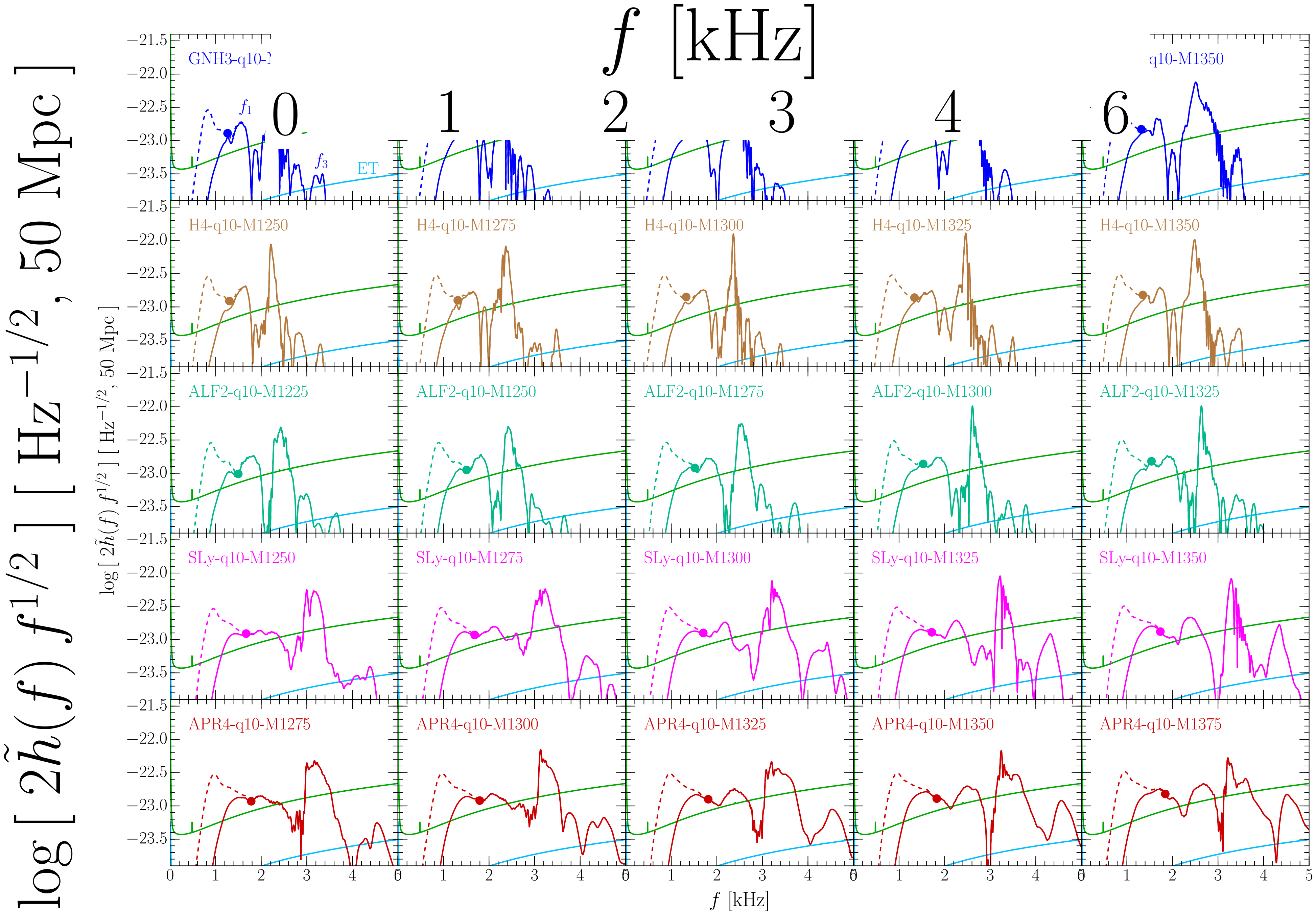
Post-Merger waveforms

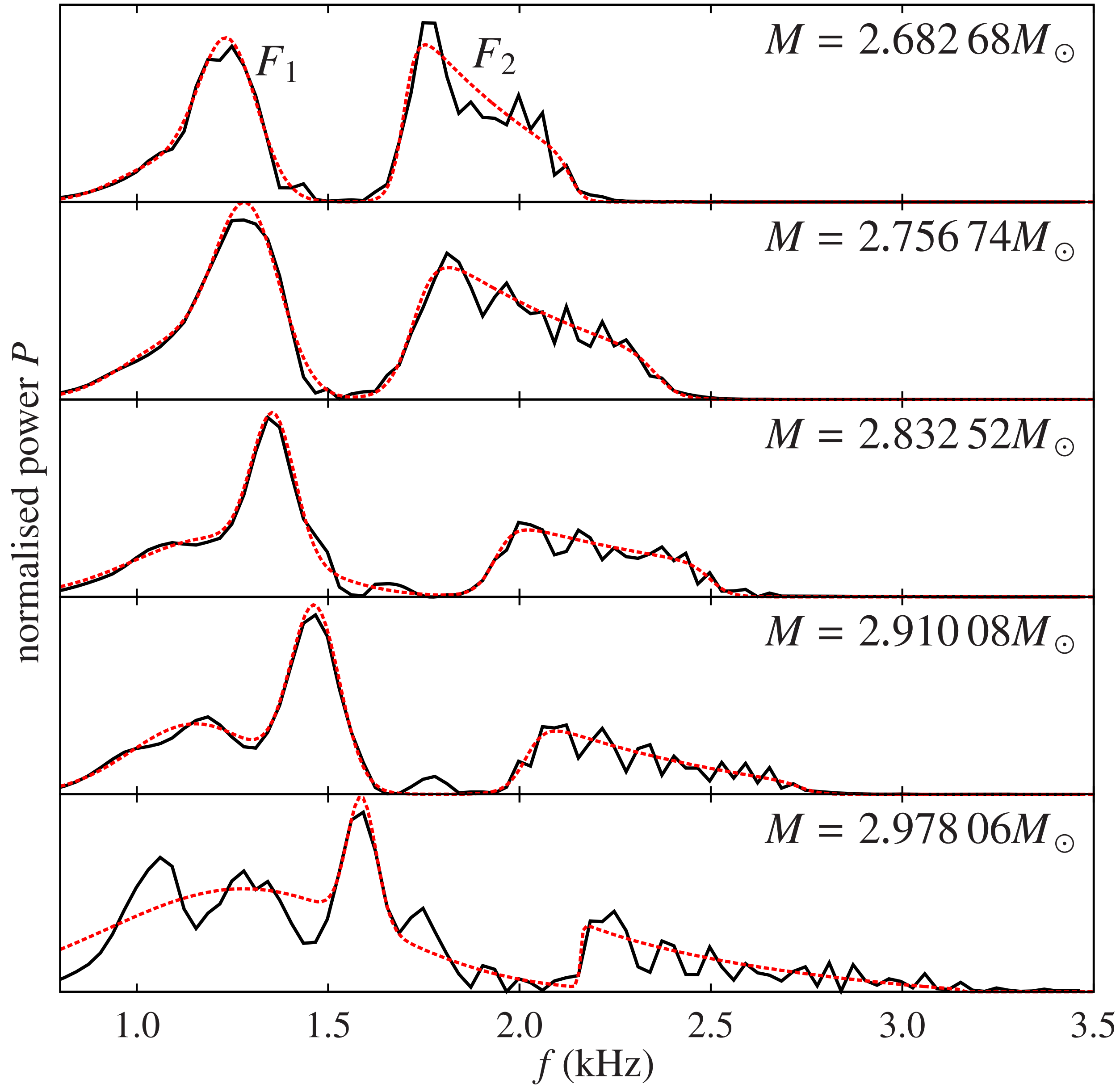


Takami *et al* arXiv:1412:3240 (2014)

Dependence on mass

- The frequency features correlate positively with mass.
- This is expected since heavier NSs are smaller → characteristic frequencies are higher.

$$\boxed{R \propto M^{-1/3}}$$

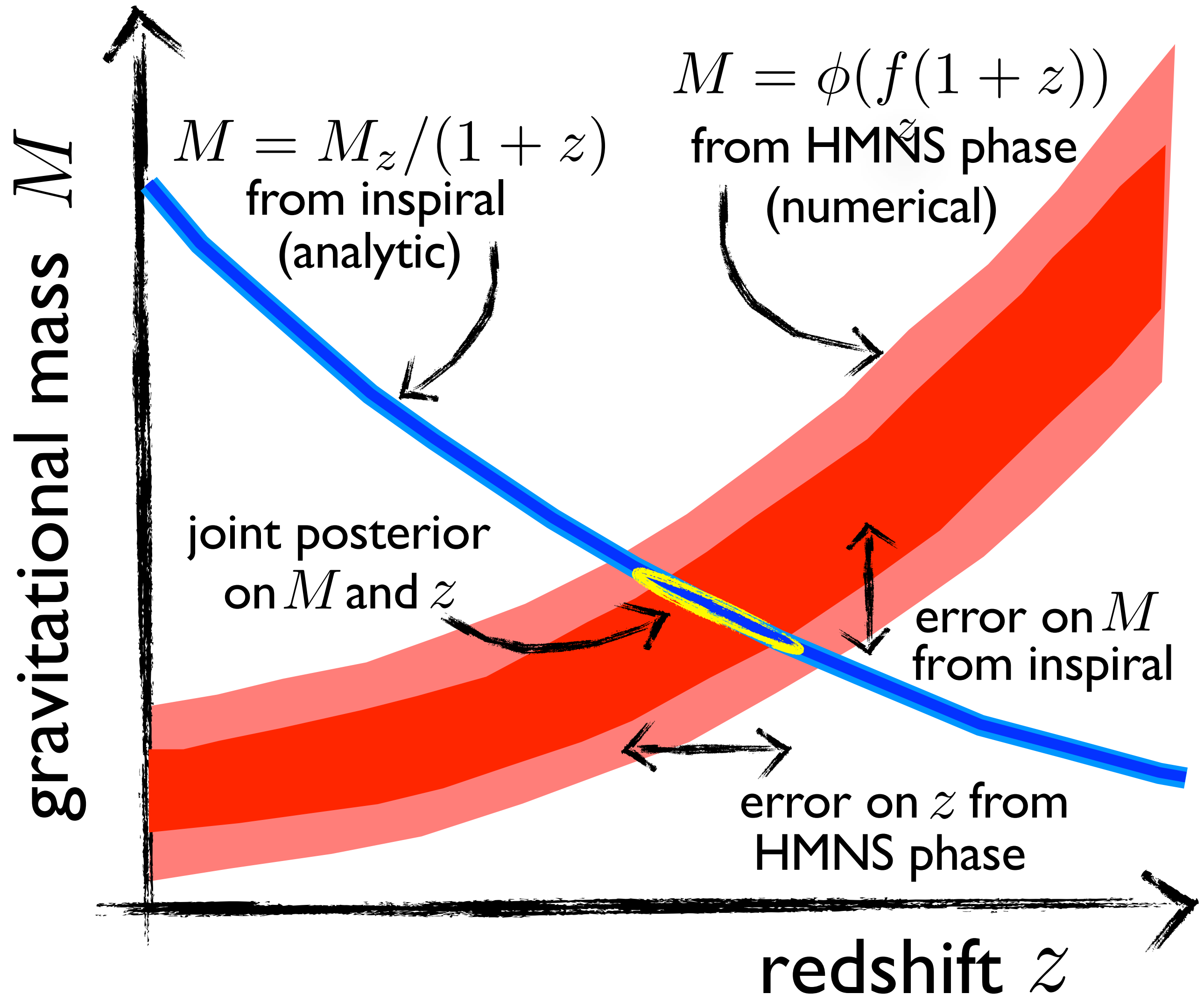


This work uses 5 waveforms from the same polytropic EOS

Messenger *et al*, PRX (2014)

The idea

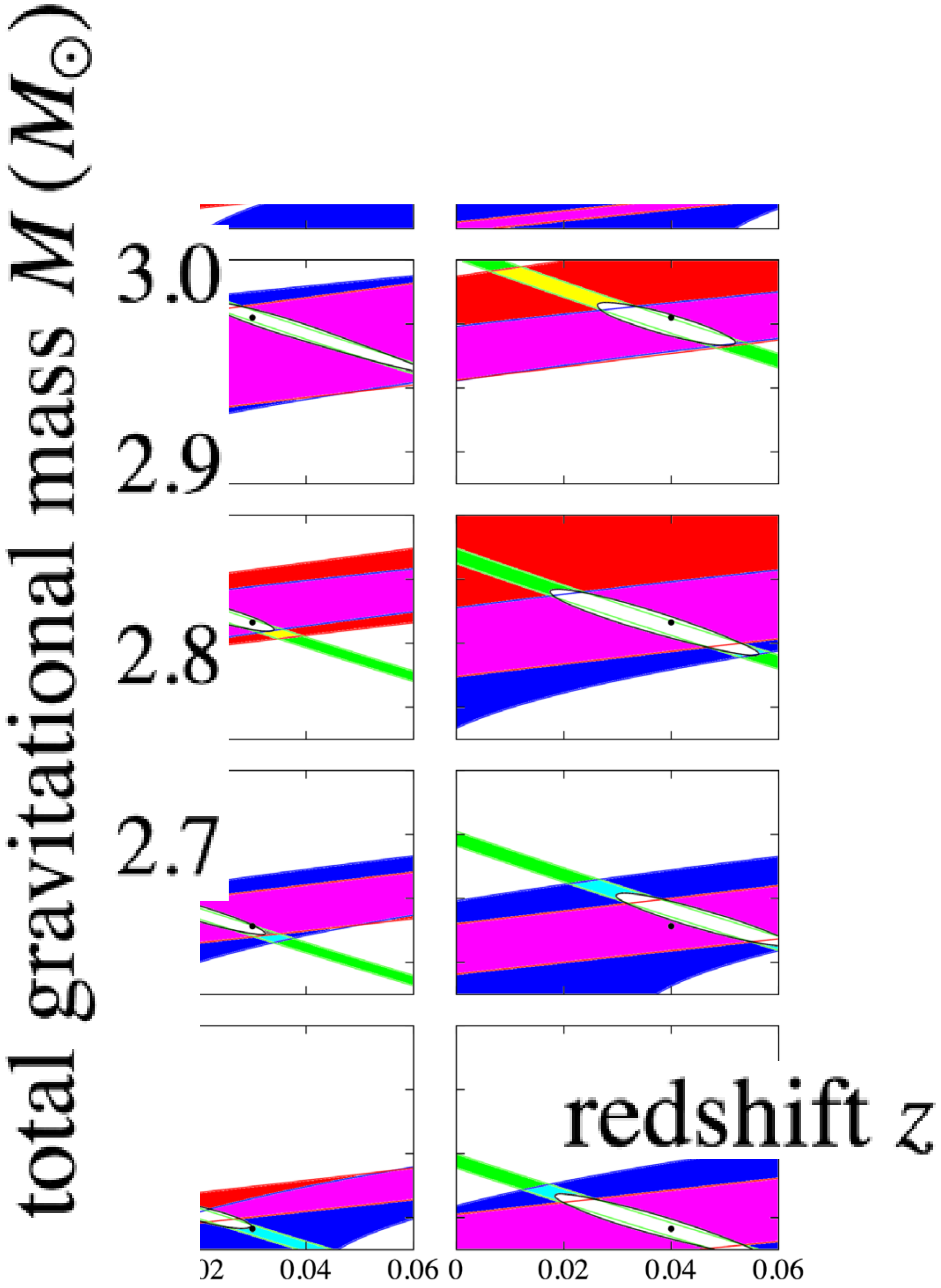
- First detect the inspiral and accurately measure the redshifted mass.
- Then analyse the post-merger signal and measure the redshifted frequency feature(s).
- Their different dependence on redshift allows us to break the degeneracy.



Messenger *et al* PRX (2014)

Redshift measurements

- Nice but despite the huge SNR in the inspiral, the post-merger has low SNR.
- Hence currently only applicable to nearby sources (Adv detector distances).
- However, still independent of EM observations.



Summary

- GW sources are (will be) very useful cosmological probes.
- They will provide measurements **independent** of the “cosmic distance ladder”.
- We have a number of different methods with and without EM counterparts.
- Calibration may end up being a limiting systematic factor.
- We need to compare our potential sensitivities to future EM experiments.
- Focus **right now** is on first direct detection.

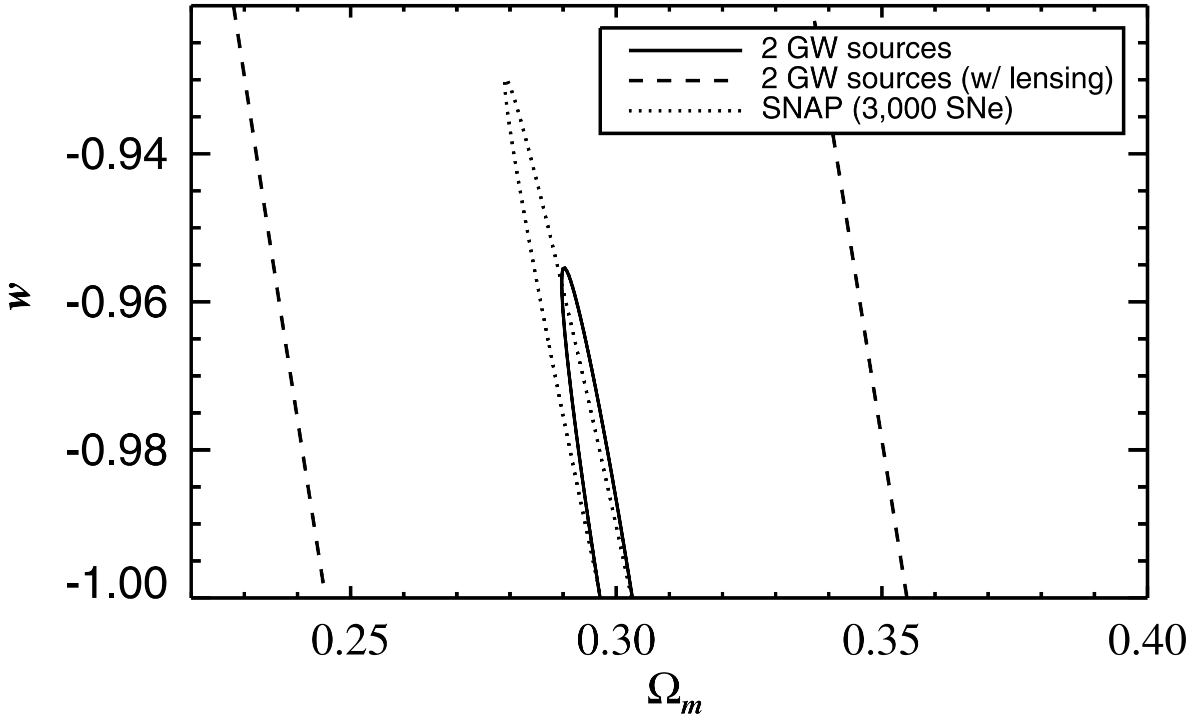
Thanks

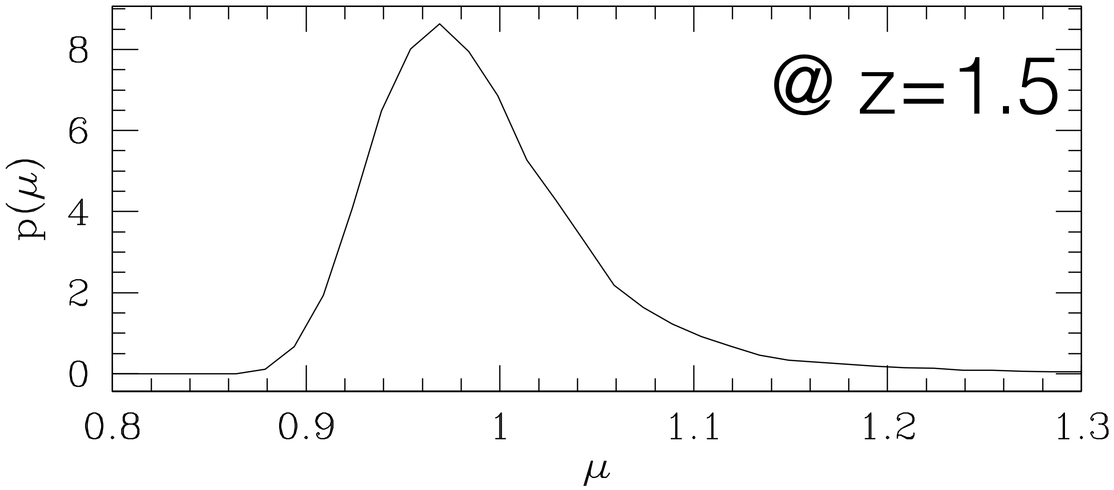
Extra slides

Super-Massive binary black-holes

- D_L,z relation investigated for LISA by Holz & Hughes 2005. [**Holz & Hughes** 2005 ApJ]
- Statistical approach taken by Petiteau *et al* 2011. [**Petiteau** *et al* 2011 ApJ]
- Good localisation makes host identification tractable.
- Weak gravitational lensing is a limiting factor in estimating luminosity distance.

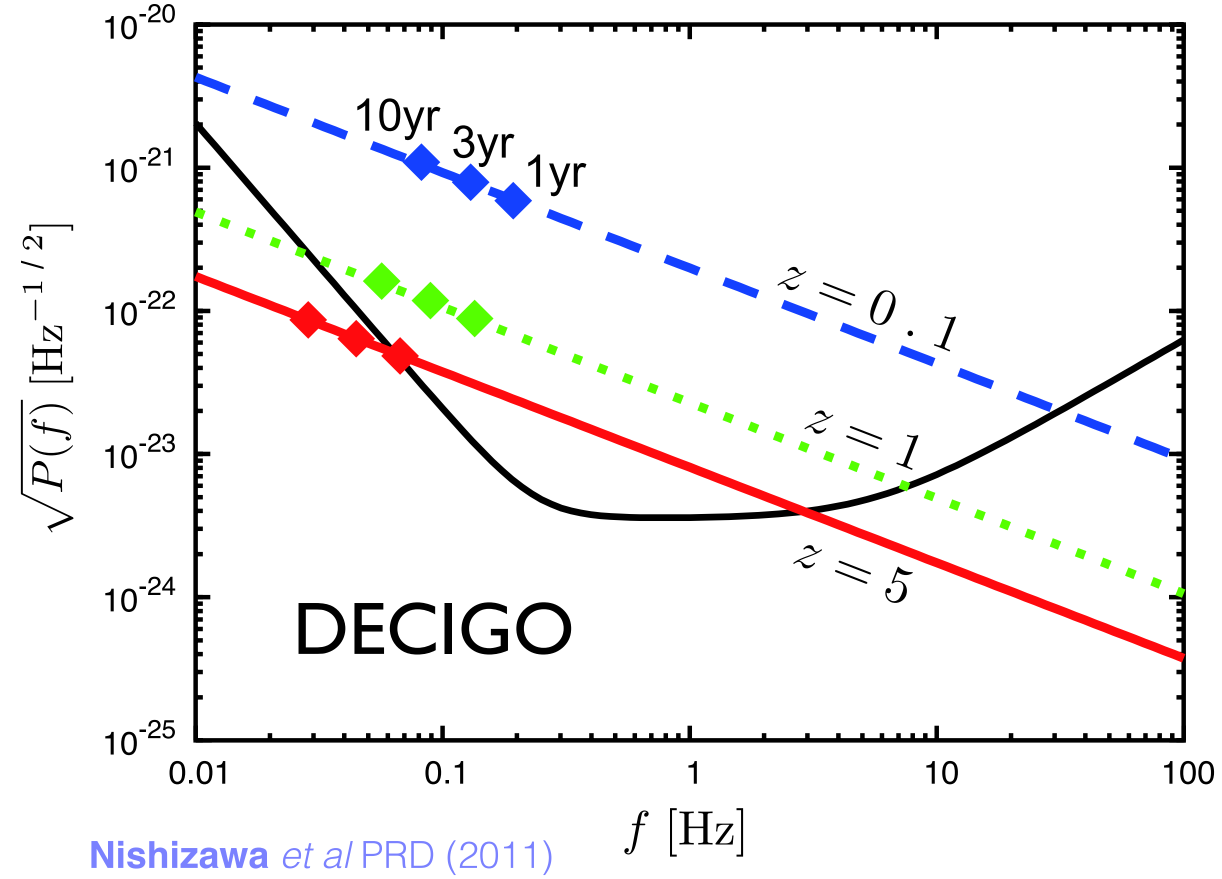
Holz & Hughes ApJ (2005)



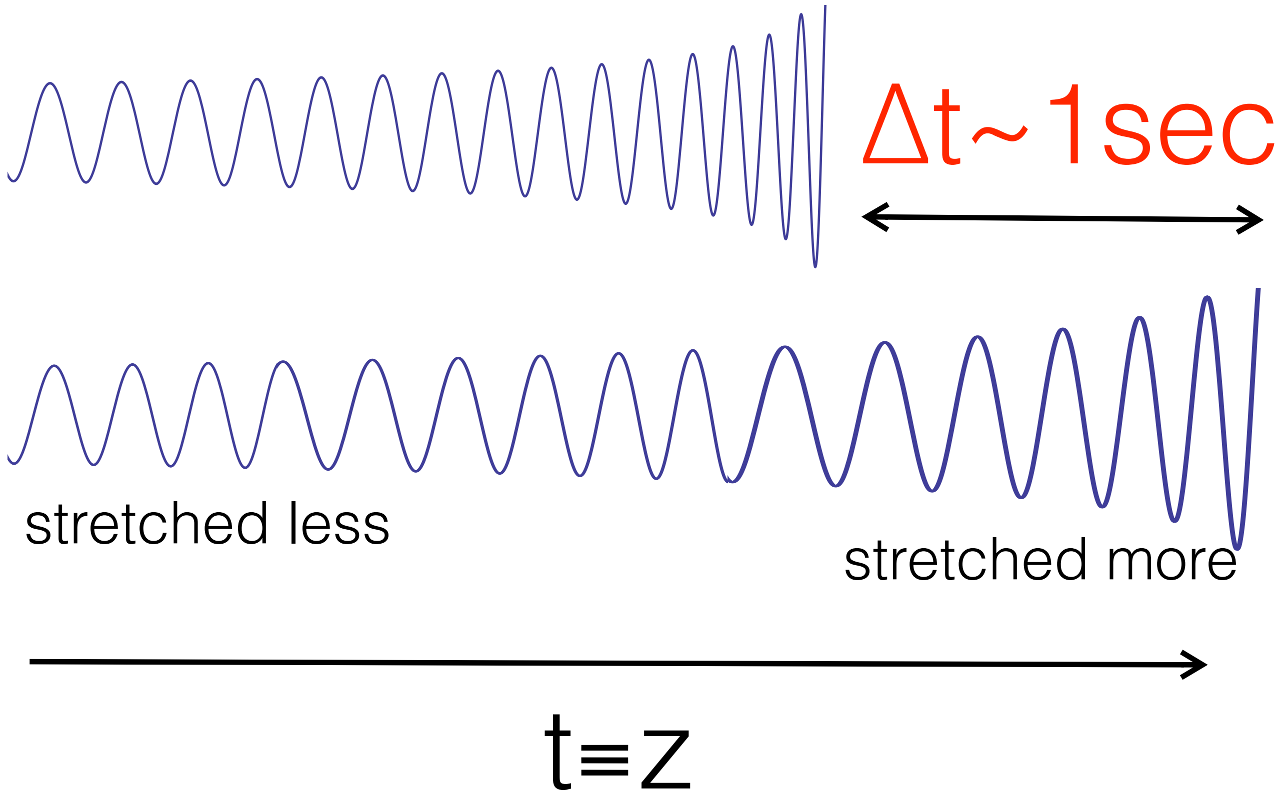


Expansion acceleration

- Directly measuring the expansion of the universe during a GW event [**Seto** *et al* 2001 PRL].
- Observe for long enough to see an object's changing redshift.



Nishizawa *et al* PRD (2011)



Δt~1sec

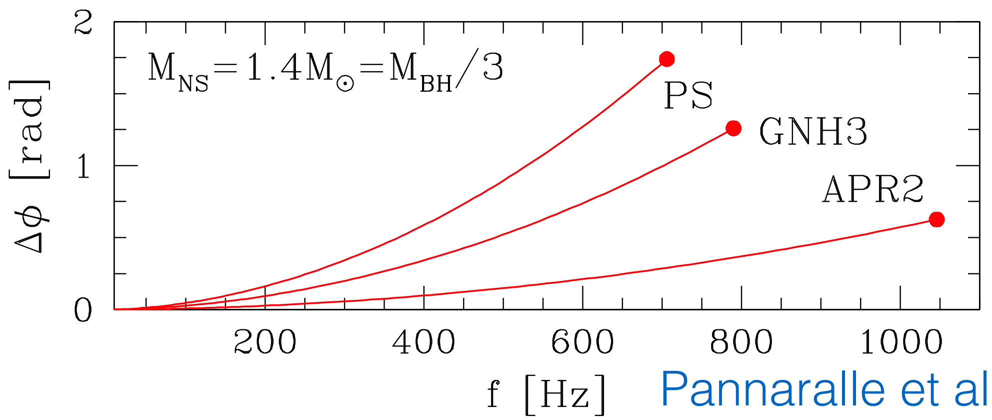
stretched less

stretched more

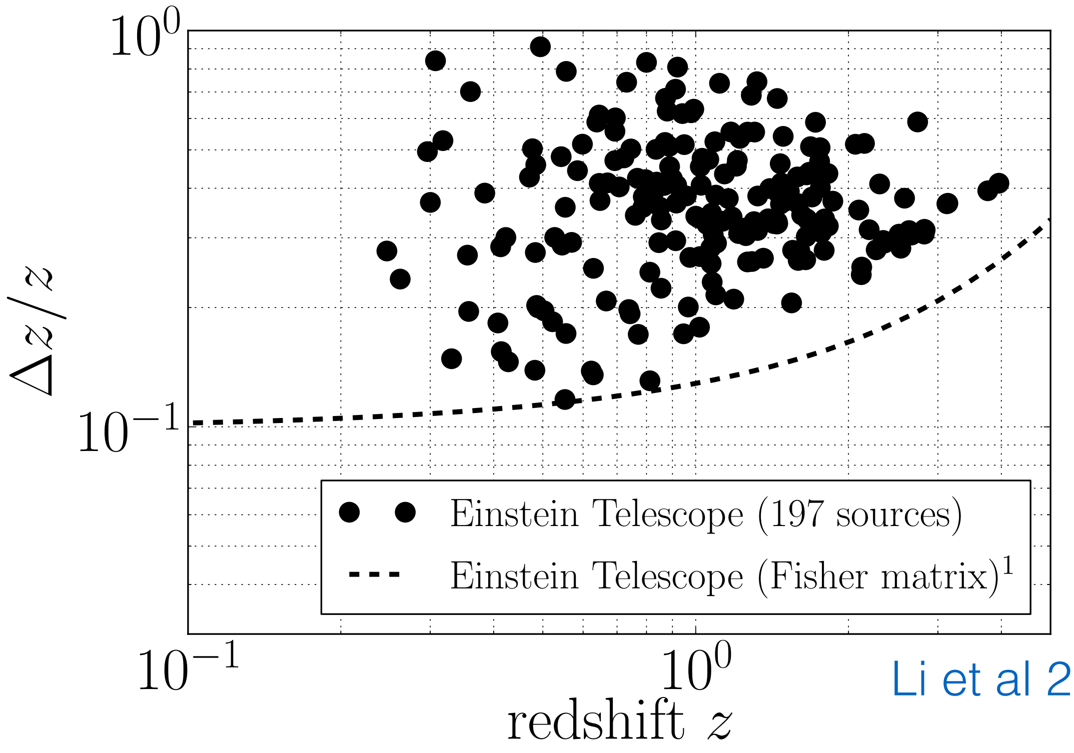
t≡z

NS tidal effects

- CM & Read discovered that tidal effects in NS binaries break the M,z degeneracy. [Messenger & Read 2012 PRL, Li et al 2013]
- The additional phase contribution is a function of the intrinsic mass!
- So you get the redshift without an EM observation.



Pannaralle et al 2011



Li et al 2013