Reanalysis of GW170817

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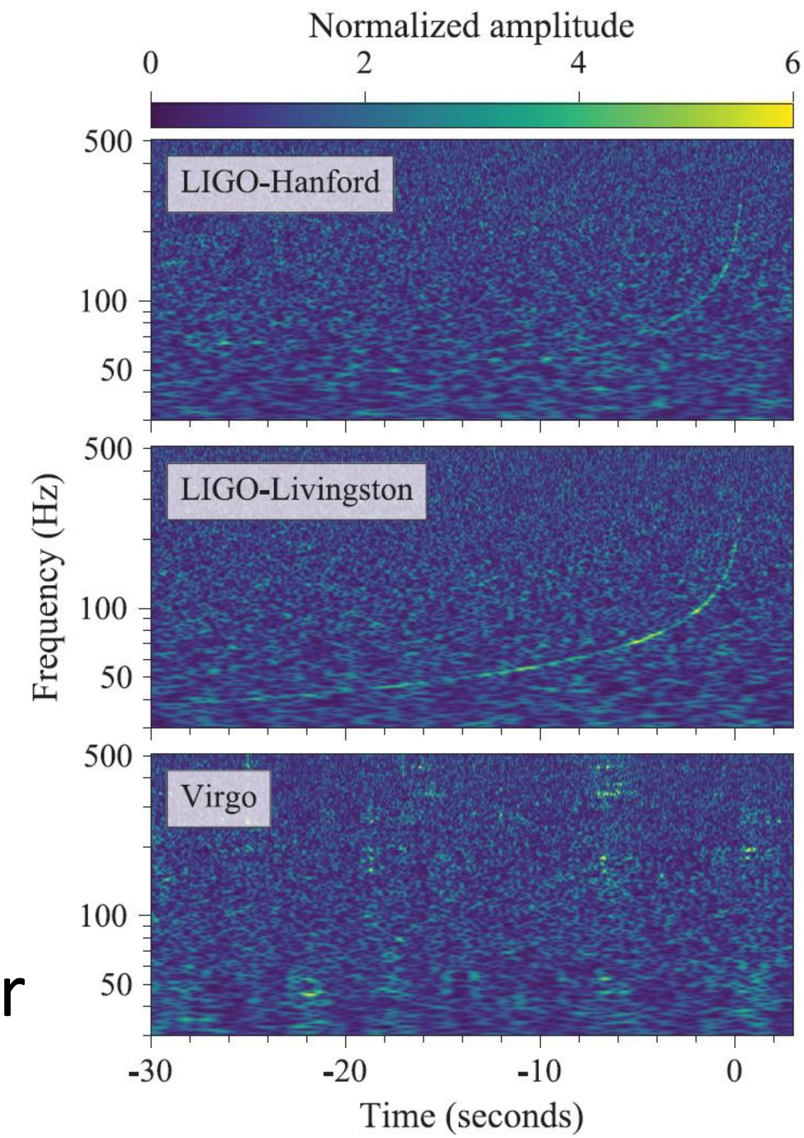
GW170817

The LIGO twins observed clear "chirp" signals, i.e., gravitational waves with increasing frequency and amplitude in time

But Virgo did not see… not useful for estimating binary's intrinsic parameter



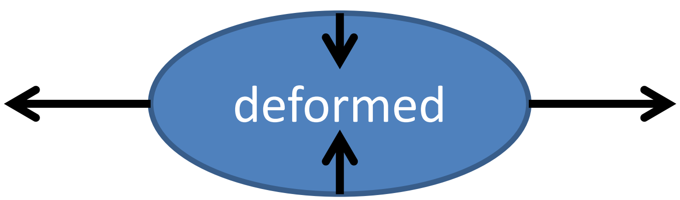
LIGO&Virgo (2017)

Quadrupolar tidal deformability

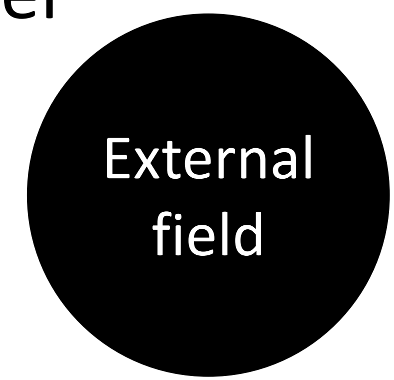
Leading-order finite-size effect on orbital evolution (strongly correlated with the neutron-star radius)

$$\Lambda = G\lambda \left(\frac{c^2}{GM} \right)^5 = \frac{2}{3} k \left(\frac{c^2 R}{GM} \right)^5 \propto R^5$$

$k \sim 0.1$: (second/electric) tidal Love number



$$\mathcal{Q}_{ij} = -\lambda \mathcal{E}_{ij}$$



$$\mathcal{Q}_{ij} \equiv \int \rho \left(x_i x_j - \frac{1}{3} x^2 \delta_{ij} \right) d^3x$$

$$\mathcal{E}_{ij} \equiv \frac{\partial^2 \Phi_{\rm ext}}{\partial x^i \partial x^j}$$

Particularly important parameters

Chirp mass $\mathcal{M} = \mu^{3/5} M^{2/5}$: accurately measured

- Total mass $M = m_1 + m_2$
- Reduced mass $\mu = m_1 m_2 / M$

Symmetric mass ratio $\eta = \mu / M$: not very accurate...

Binary tidal deformability ($m_1 \leq m_2$)

$$\tilde{\Lambda} = \frac{8}{13} [(1 + 7\eta - 31\eta^2)(\Lambda_1 + \Lambda_2) - \sqrt{1 - 4\eta}(1 + 9\eta - 11\eta^2)(\Lambda_1 - \Lambda_2)]$$

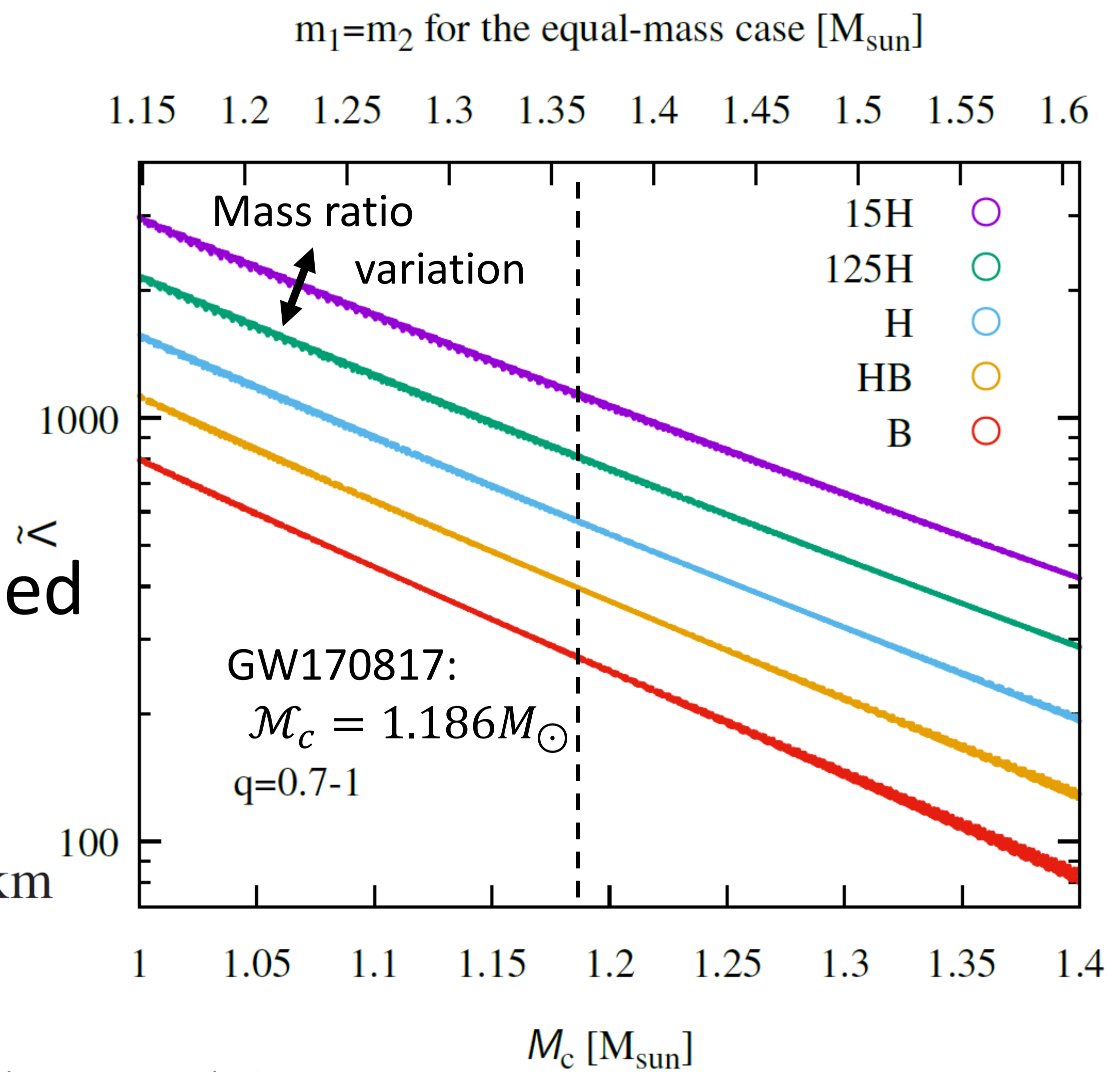
Tight correlation of $\tilde{\Lambda} - \mathcal{M}_c$

GW-measured $\tilde{\Lambda}$ is tightly correlated w/ the chirp mass

$\Lambda(M = 2^{1/5}\mathcal{M}_c)$ is effectively constrained

Approximately

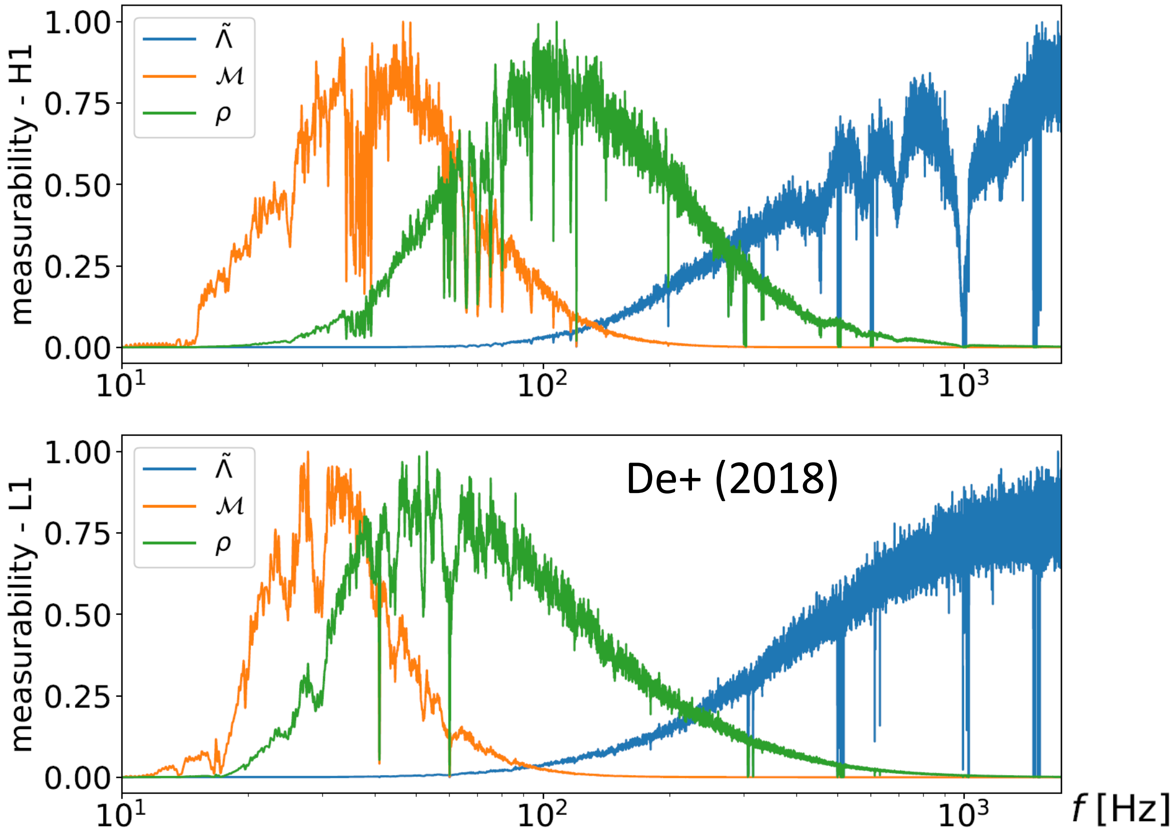
$$R_{1.4} \simeq (11.2 \pm 0.2) \frac{\mathcal{M}}{M_\odot} \left(\frac{\tilde{\Lambda}}{800}\right)^{1/6} \text{ km}$$



Important frequency range

$\mathcal{M}$: low frequency (many gravitational-wave cycles)

$\tilde{\Lambda}$: high frequency (closer orbit->large deformation)



Constraint on tidal deformability

Low-spin prior, $\chi_i \leq 0.05$	TaylorF2	SEOBNRT	PhenomDNRT
Binary inclination θ_{JN}	146^{+24}_{-28} deg	146^{+24}_{-28} deg	147^{+24}_{-28} deg
Binary inclination θ_{JN} using EM distance constraint [104]	149^{+13}_{-10} deg	152^{+14}_{-11} deg	151^{+14}_{-10} deg
Detector frame chirp mass $\mathcal{M}^{det}$	$1.1975^{+0.0001}_{-0.0001} M_\odot$	$1.1976^{+0.0001}_{-0.0001} M_\odot$	$1.1975^{+0.0001}_{-0.0001} M_\odot$
Chirp mass $\mathcal{M}$	$1.186^{+0.001}_{-0.001} M_\odot$	$1.186^{+0.001}_{-0.001} M_\odot$	$1.186^{+0.001}_{-0.001}$
Primary mass m_1	$(1.36, 1.61)\ M_\odot$	$(1.36, 1.59)\ M_\odot$	$(1.36, 1.60)\ M_\odot$
Secondary mass m_2	$(1.16, 1.36)\ M_\odot$	$(1.17, 1.36)\ M_\odot$	$(1.17, 1.36)\ M_\odot$
Total mass m	$2.73^{+0.05}_{-0.01} M_\odot$	$2.73^{+0.04}_{-0.01} M_\odot$	$2.73^{+0.04}_{-0.01} M_\odot$
Mass ratio q	(0.72, 1.00)	(0.74, 1.00)	(0.73, 1.00)
Effective spin χ_{eff}	$0.00^{+0.02}_{-0.01}$	$0.00^{+0.02}_{-0.01}$	$0.00^{+0.02}_{-0.01}$
Primary dimensionless spin χ_1	(0.00, 0.02)	(0.00, 0.02)	(0.00, 0.02)
Secondary dimensionless spin χ_2	(0.00, 0.02)	(0.00, 0.02)	(0.00, 0.02)
Tidal deformability $\tilde{\Lambda}$ with flat prior (symmetric/HPD)	$340^{+580}_{-240}/340^{+490}_{-290}$	$280^{+490}_{-190}/\ 280^{+410}_{-230}$	$300^{+520}_{-190}/\ 300^{+430}_{-230}$

Top: LIGO-Virgo (2018) / Bottom: De+ (2018)

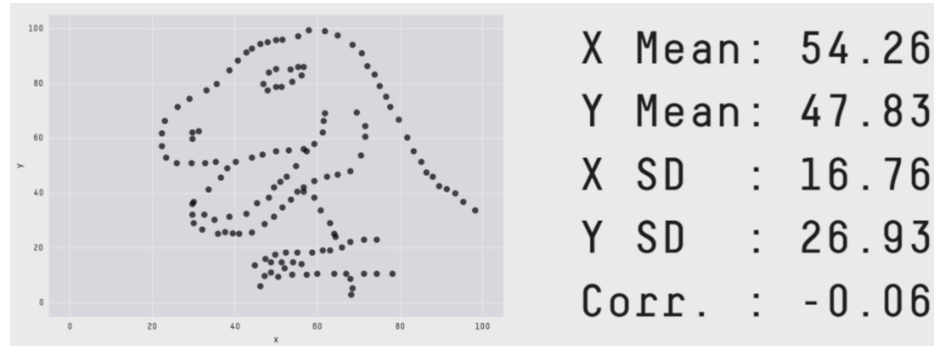
TaylorF2
Assume the EOS as common to both binary members

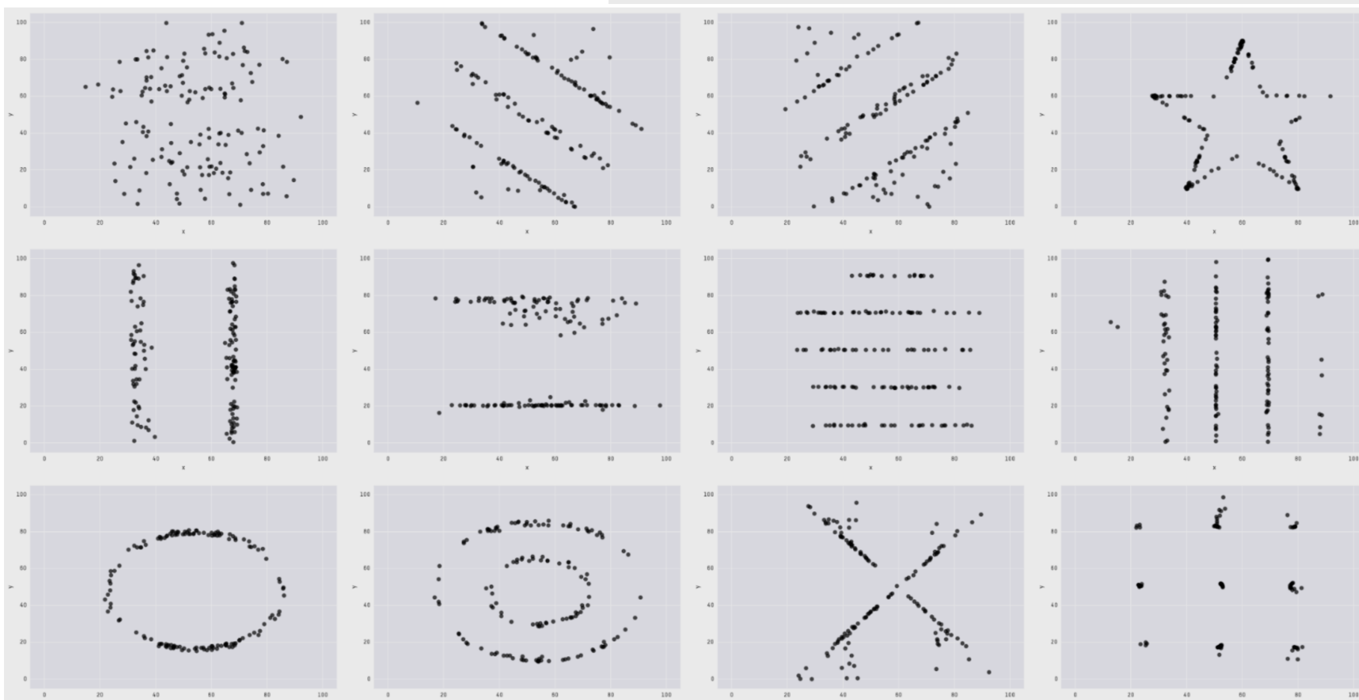
Mass prior	$\tilde{\Lambda}$	$\hat{R}$ (km)	$\mathcal{B}$	$\tilde{\Lambda}_{90\%}$
Uniform	222^{+420}_{-138}	$10.7^{+2.1}_{-1.6} \pm 0.2$	369	< 485
Double neutron star	245^{+453}_{-151}	$10.9^{+2.1}_{-1.6} \pm 0.2$	125	< 521
Galactic neutron star	233^{+448}_{-144}	$10.8^{+2.1}_{-1.6} \pm 0.2$	612	< 516

Never skip looking at the distribution

See also

Anscombe's quartet



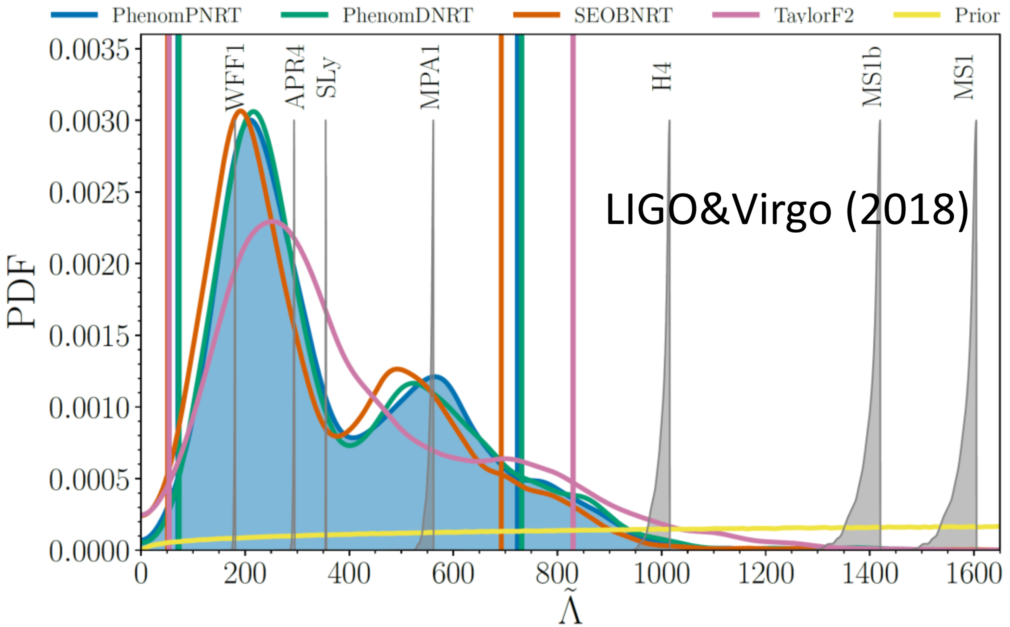


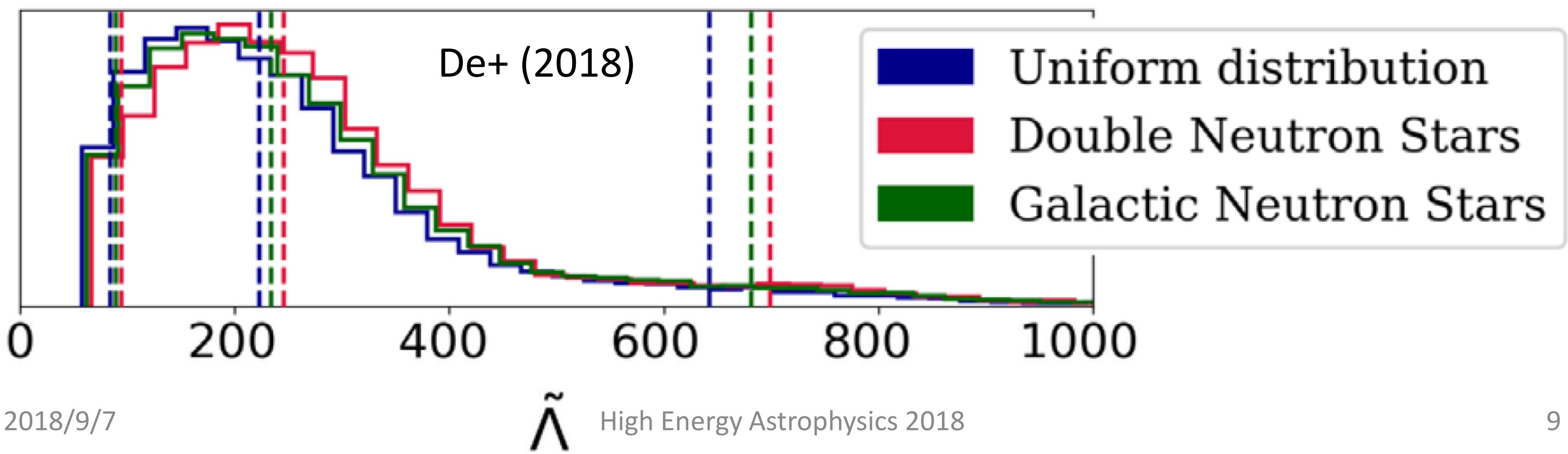
https://www.autodeskresearch.com/publications/samestats

Double peak/high-$\tilde{\Lambda}$ tail

Posterior distribution is far from Gaussian in LVC/non-LVC analysis

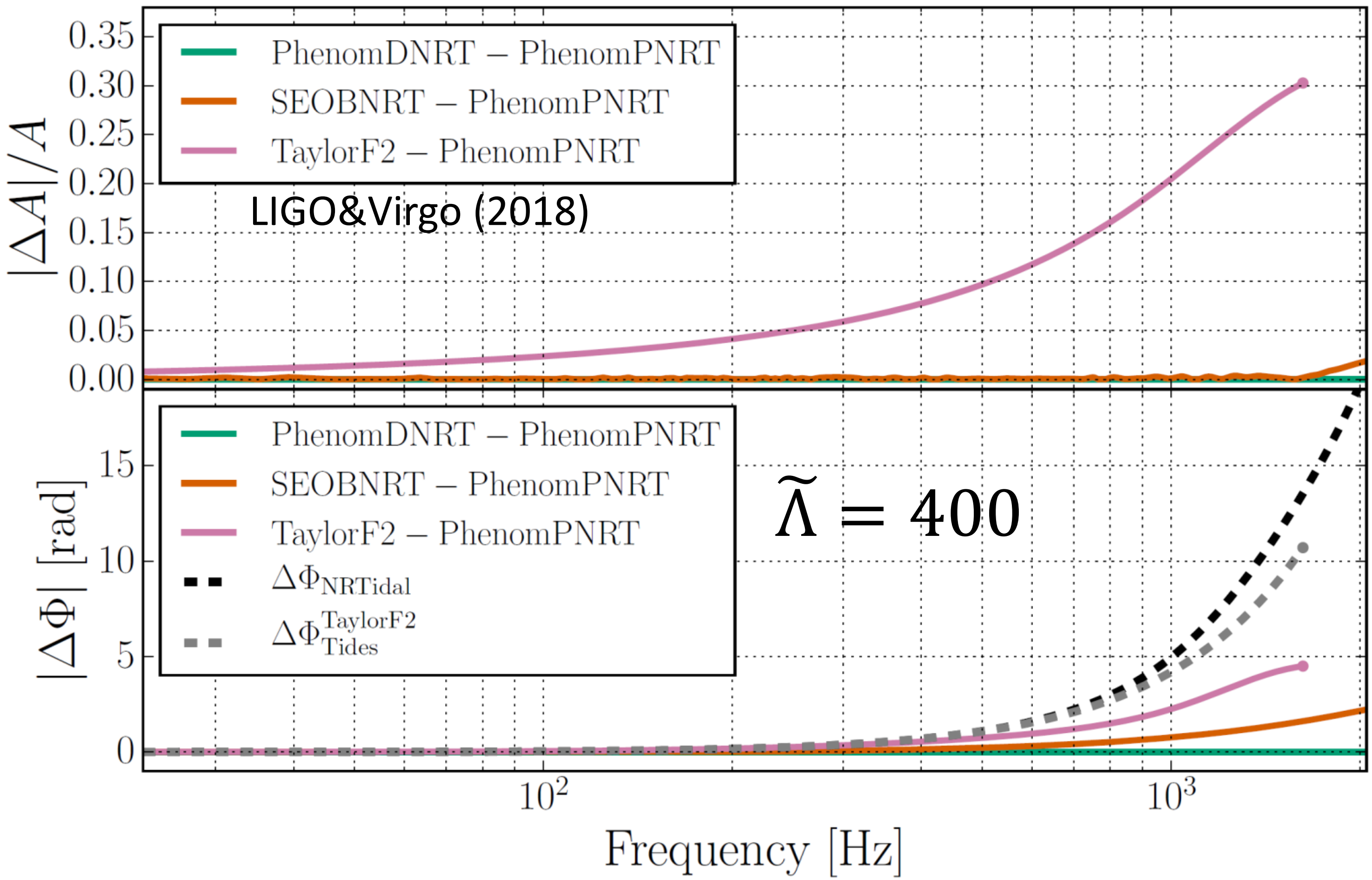
Moderate dependence on waveform models





Waveform model dependence

O(1)rad phase differences are not very comfortable



Kyoto model

TaylorF2: Post-Newton phase $\left(x \propto f^{2/3}\right)$

$$\Psi_{\rm tidal}^{\rm 2.5PN} = \frac{3}{128\eta}\left(-\frac{39}{2}\tilde{\Lambda}\right)x^{5/2}\left[1+\frac{3115}{1248}x-\pi x^{3/2}+\frac{28024205}{3302208}x^2-\frac{4283}{1092}\pi x^{5/2}\right]$$

\+ insignificant correction terms associated with η

We introduce a nonlinear-in-$\tilde{\Lambda}$ term (empirically)

$$-\frac{39}{2}\tilde{\Lambda}(1+12.55\tilde{\Lambda}^{2/3}x^{4.240})$$

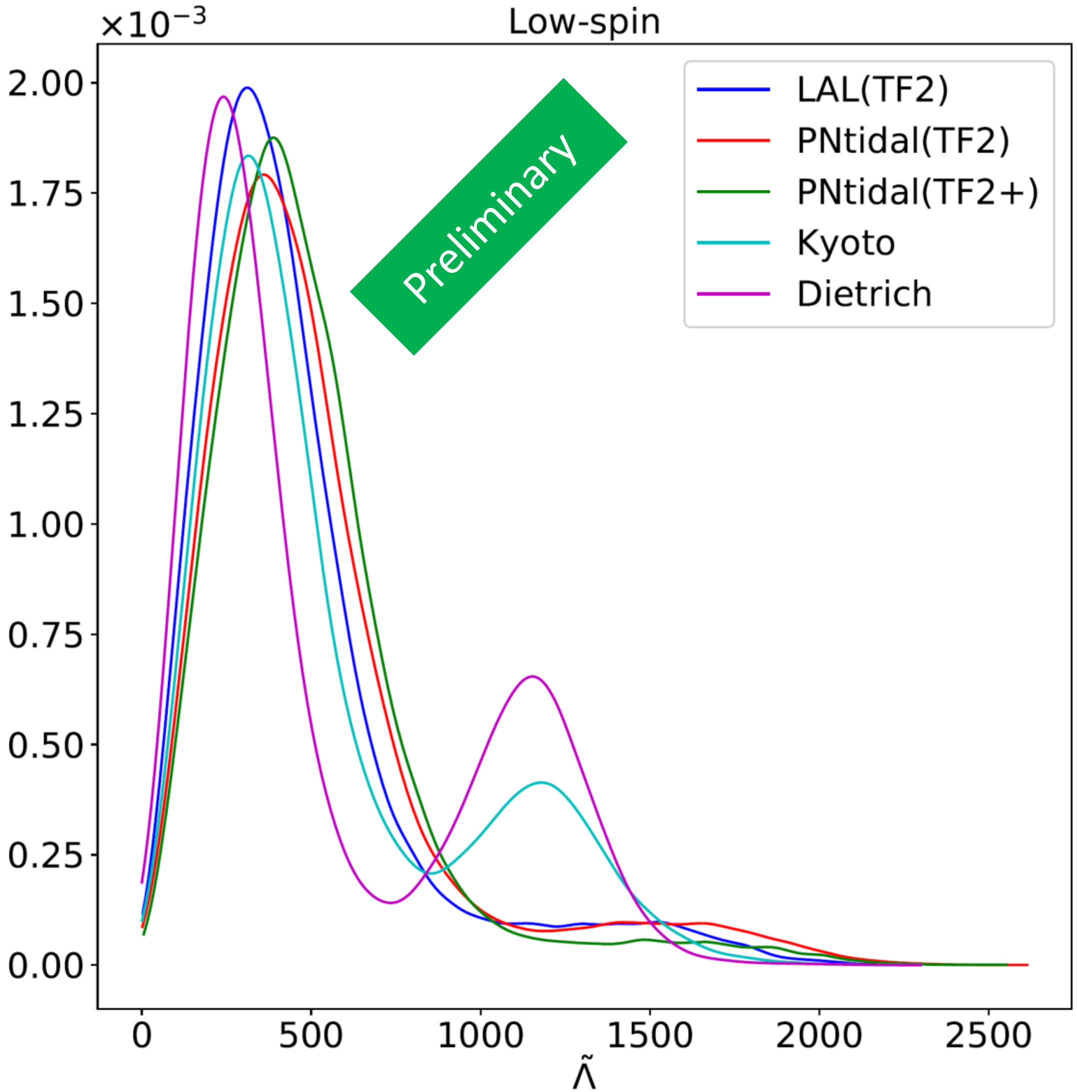
Another model Pade-resums the post-Newton part

$$\frac{1+\tilde{n}_1 x+\tilde{n}_{3/2}x^{3/2}+\tilde{n}_2 x^2+\tilde{n}_{5/2}x^{5/2}}{1+\tilde{d}_1 x+\tilde{d}_{3/2}x^{3/2}}$$

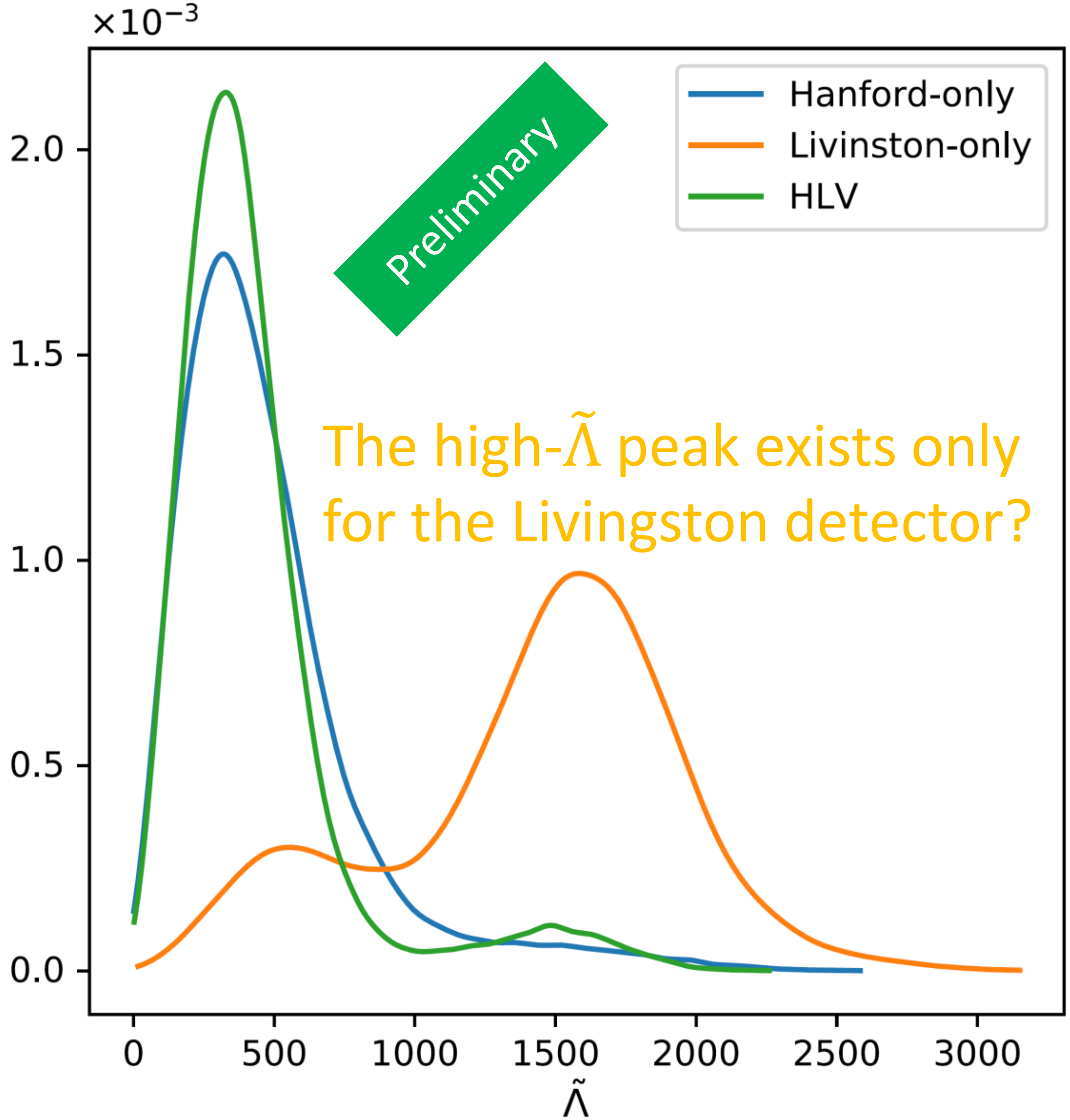
Our independent analysis

So far, differences associated with waveform models may be minor

Double peaks remain particularly for sophisticated models



Discrepancy of the LIGO twins



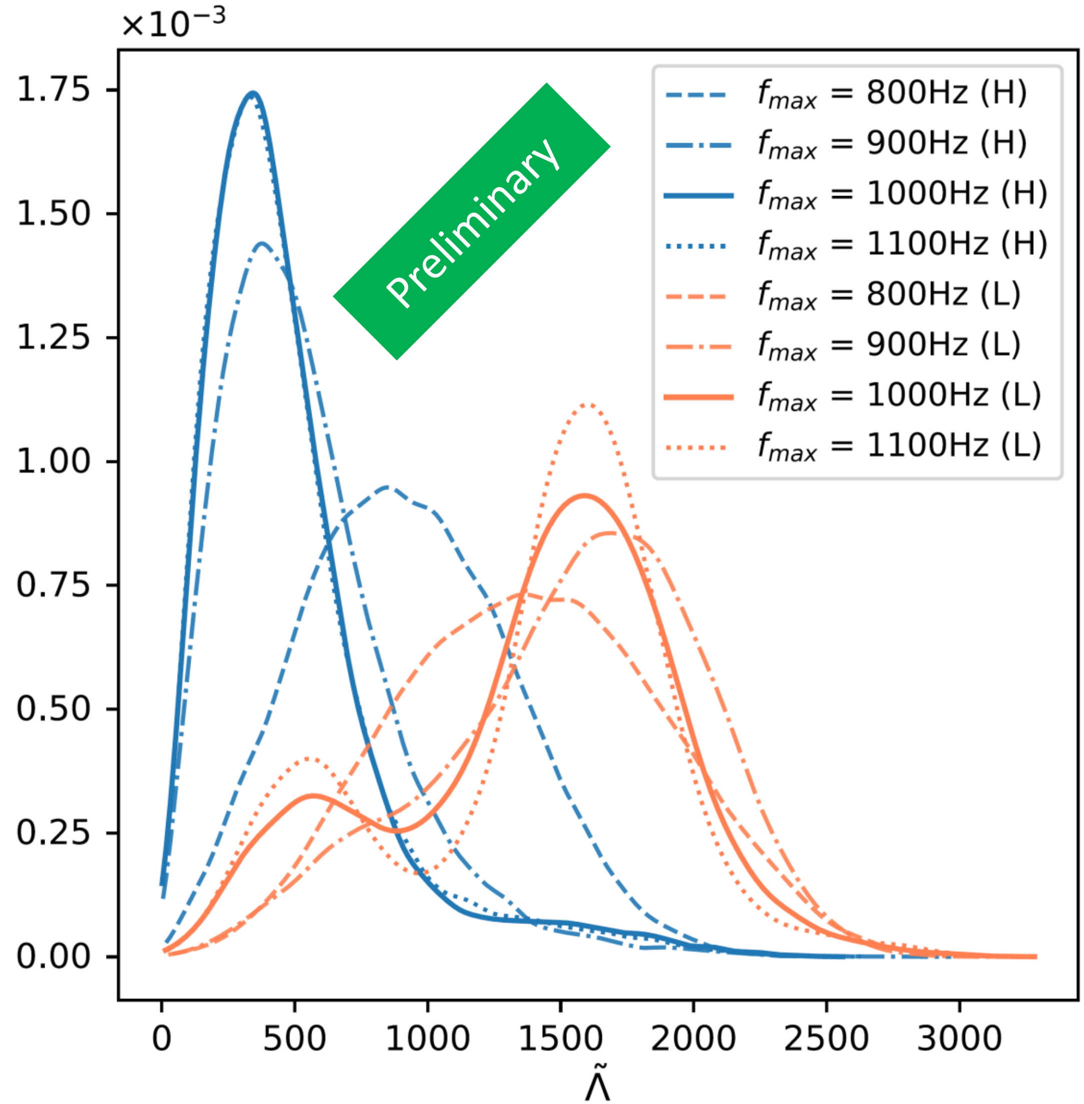
Dependence on high-frequency cutoff

Hanford detector:

- single (low) peak
- converge smoothly w.r.t $f_{\max}$ change

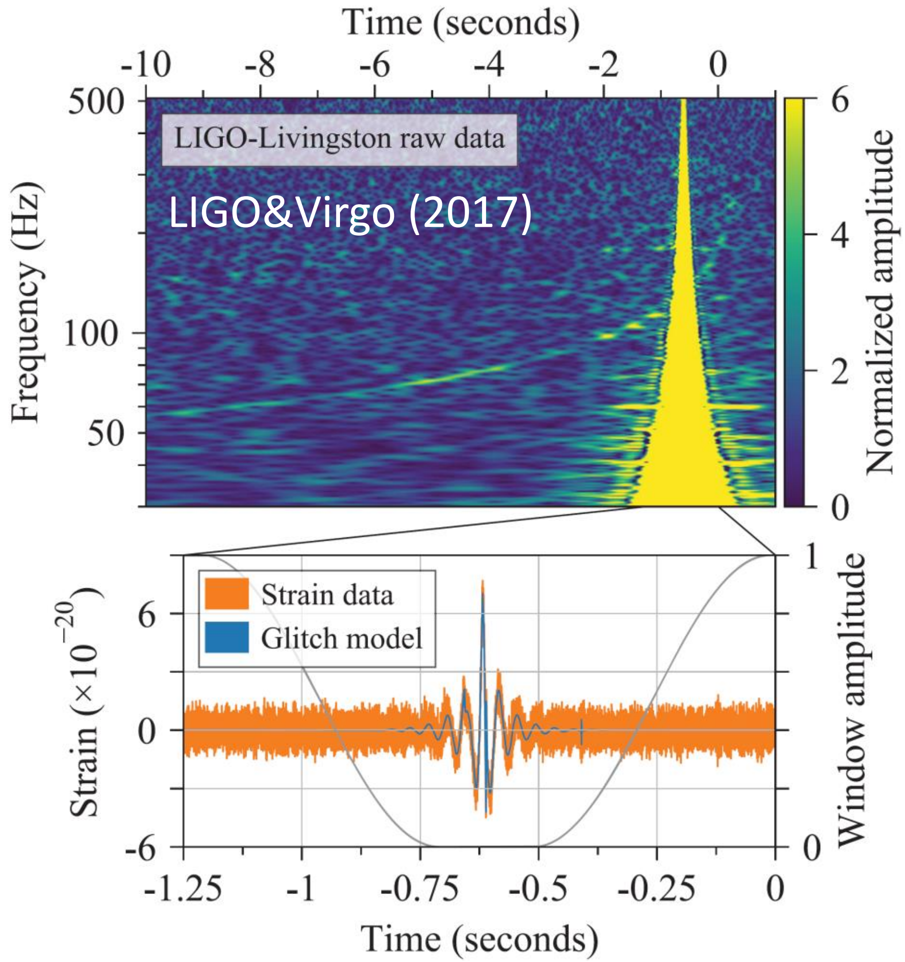
Livingston detector:

- double peak
- irregular variation w.r.t $f_{\max}$ change



Random noise or specific component?

E.g., a glitch and incomplete subtraction thereof (this is just an example!)



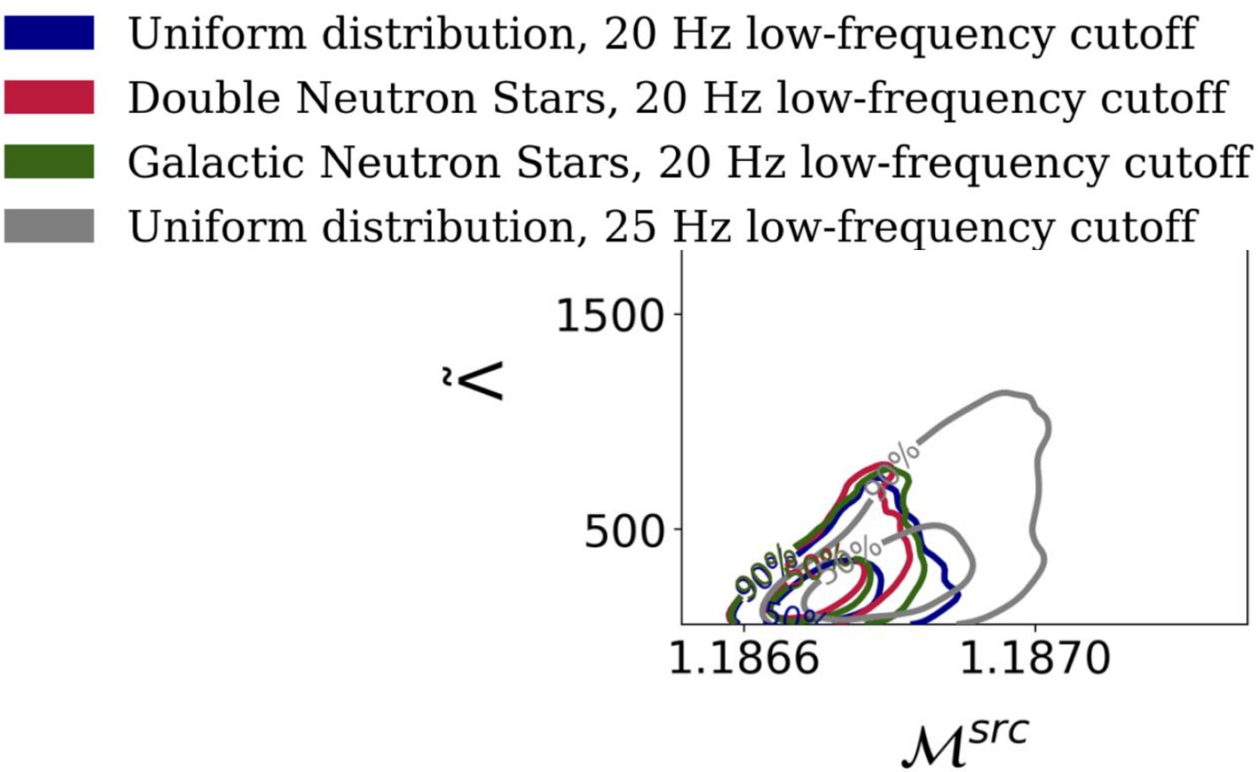
If the “second” peak is associated with noises that do not average out, future results will be biased

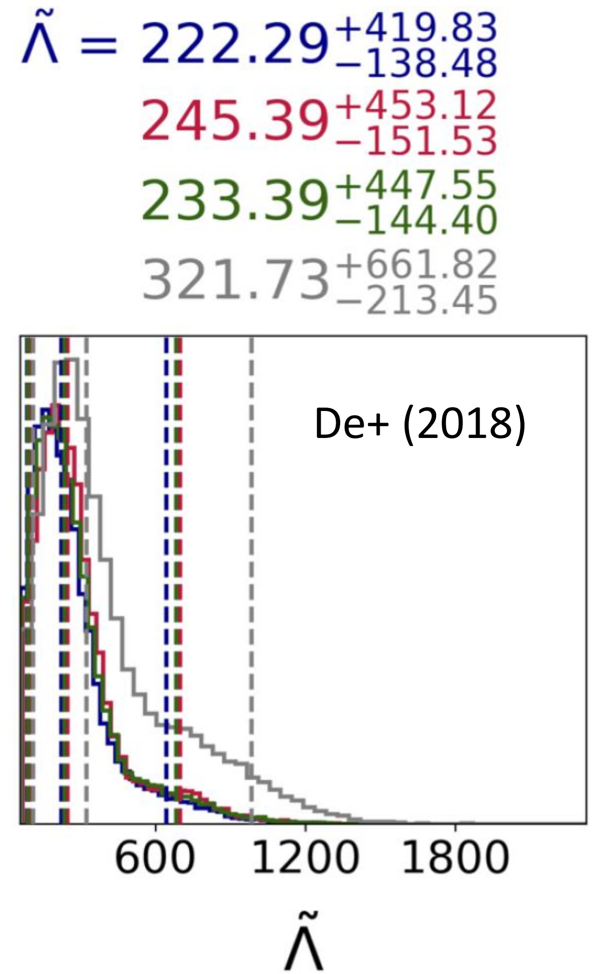
-> noise hunting warranted

Low-frequency cutoff?

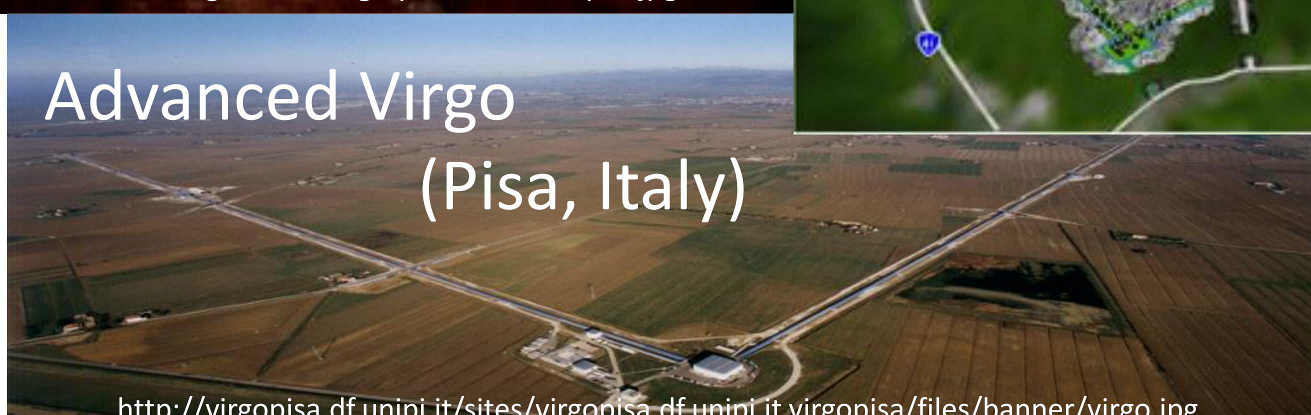
Degeneracy can be solved

and constraints become tight





More than 3 detectors preferable



Summary

- We have independently analyzed LIGO-Virgo data of GW170817 using our waveform models.
- Constraints on tidal deformability are similar to those obtained by other analysis, that is, the posterior probability distribution exhibits a double peak structure.
- The second peak exists only for Livingston and behaves irregularly with respect to changes of the high-frequency cutoff (<-> Hanford).

Appendix

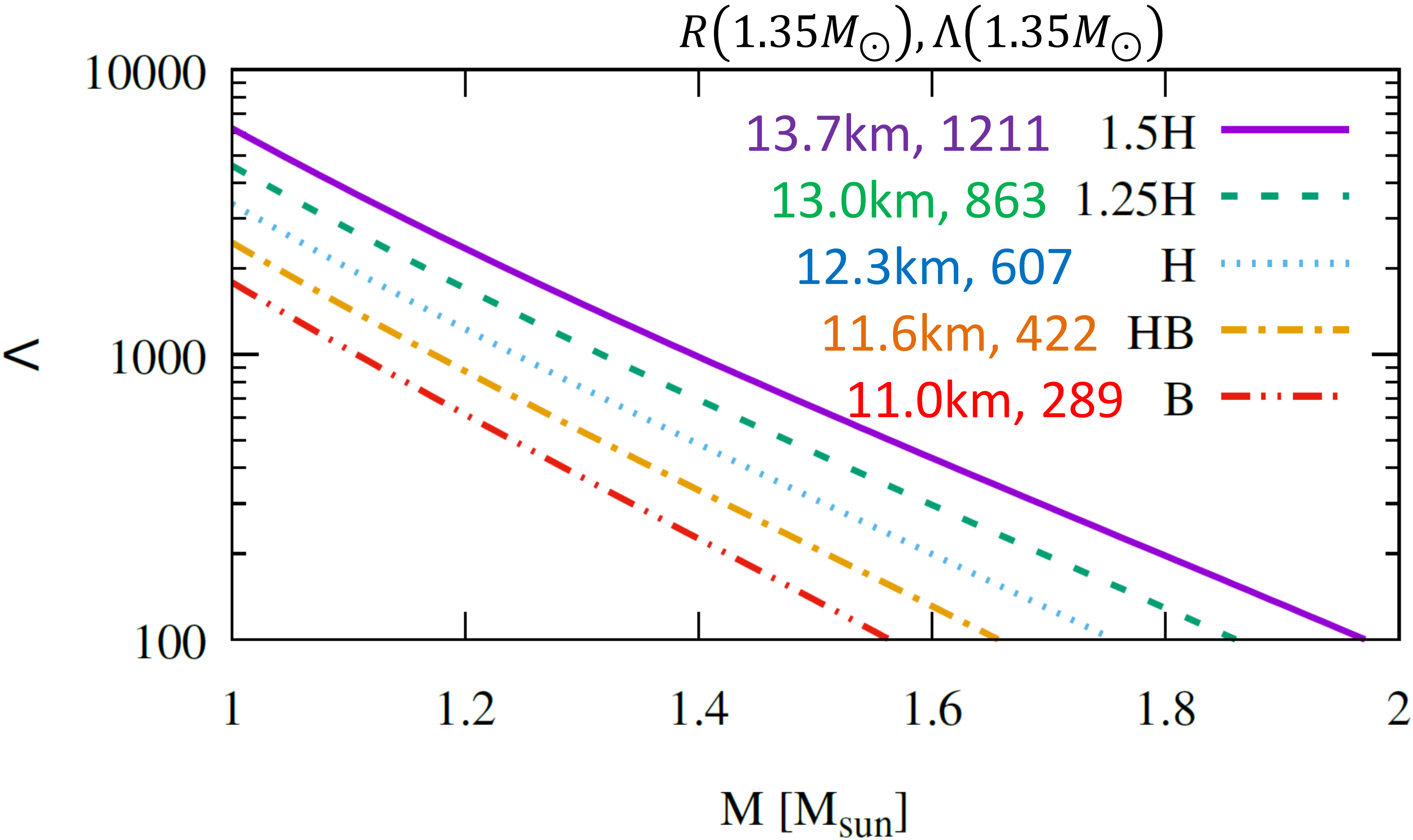
Parameters of GW170817

Low-spin: limiting to spin values observed for Galactic binary neutron stars that merge within the Hubble time (with some safe margins)

High-spin: as far as GW models may be applicable

LIGO&Virgo (2017)	Low-spin priors ($|\chi| \leq 0.05$)	High-spin priors ($|\chi| \leq 0.89$)
Primary mass m_1	1.36–1.60 $M_\odot$	1.36–2.26 $M_\odot$
Secondary mass m_2	1.17–1.36 $M_\odot$	0.86–1.36 $M_\odot$
Chirp mass $\mathcal{M}$	$1.188^{+0.004}_{-0.002} M_\odot$	$1.188^{+0.004}_{-0.002} M_\odot$
Mass ratio m_2/m_1	0.7–1.0	0.4–1.0
Total mass m_{tot}	$2.74^{+0.04}_{-0.01} M_\odot$	$2.82^{+0.47}_{-0.09} M_\odot$
Radiated energy E_{rad}	$> 0.025 M_\odot c^2$	$> 0.025 M_\odot c^2$
Luminosity distance D_{L}	40^{+8}_{-14} Mpc	40^{+8}_{-14} Mpc
Viewing angle Θ	$\leq 55°$	$\leq 56°$
Using NGC 4993 location	$\leq 28°$	$\leq 28°$
Combined dimensionless tidal deformability $\tilde{\Lambda}$	≤ 800	≤ 700
Dimensionless tidal deformability $\Lambda(1.4 M_\odot)$	≤ 800	≤ 1400

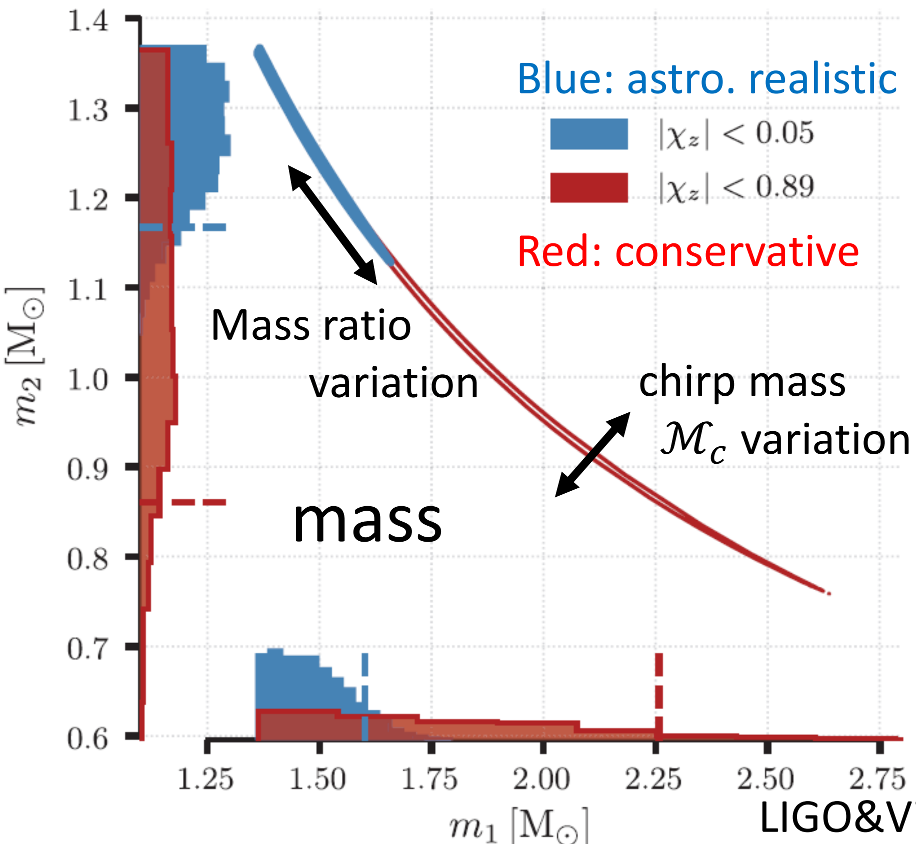
Representative example of EOSs

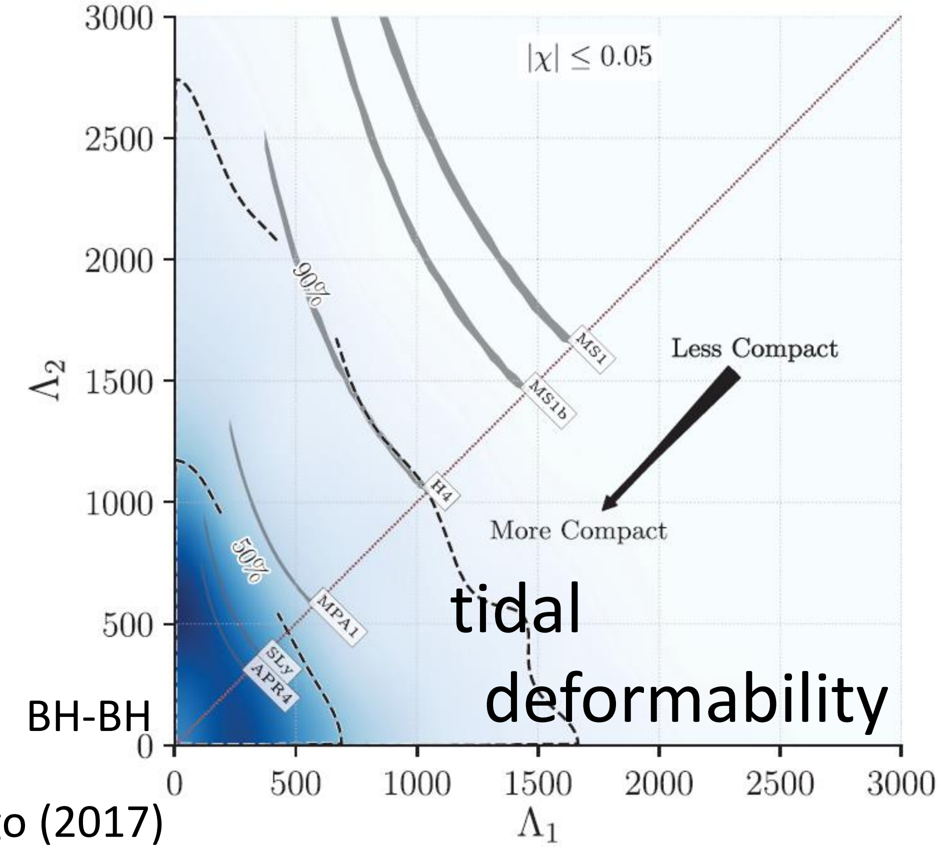


Constraints on parameters

The NS radius may be smaller than ~13-14km

- this can be made tighter with better waveforms





LIGO&Virgo (2017)

Shape of mass constraints

Gravitational waves tightly constrain the chirp mass

$$\mathcal{M} = \frac{m_1^{3/5} m_2^{3/5}}{(m_1 + m_2)^{1/5}} = \mu^{3/5} M^{2/5}$$

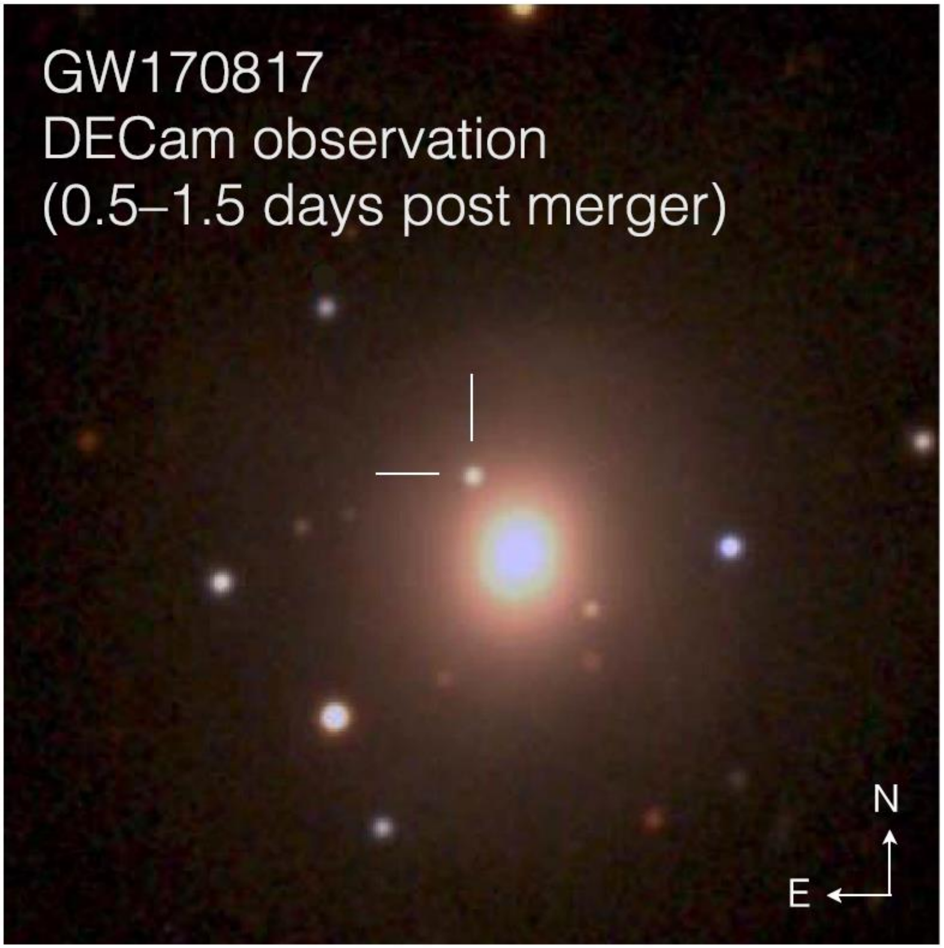
But the mass ratio (e.g., $q = m_2/m_1 < 1$) tends to be degenerated with the spin of components,

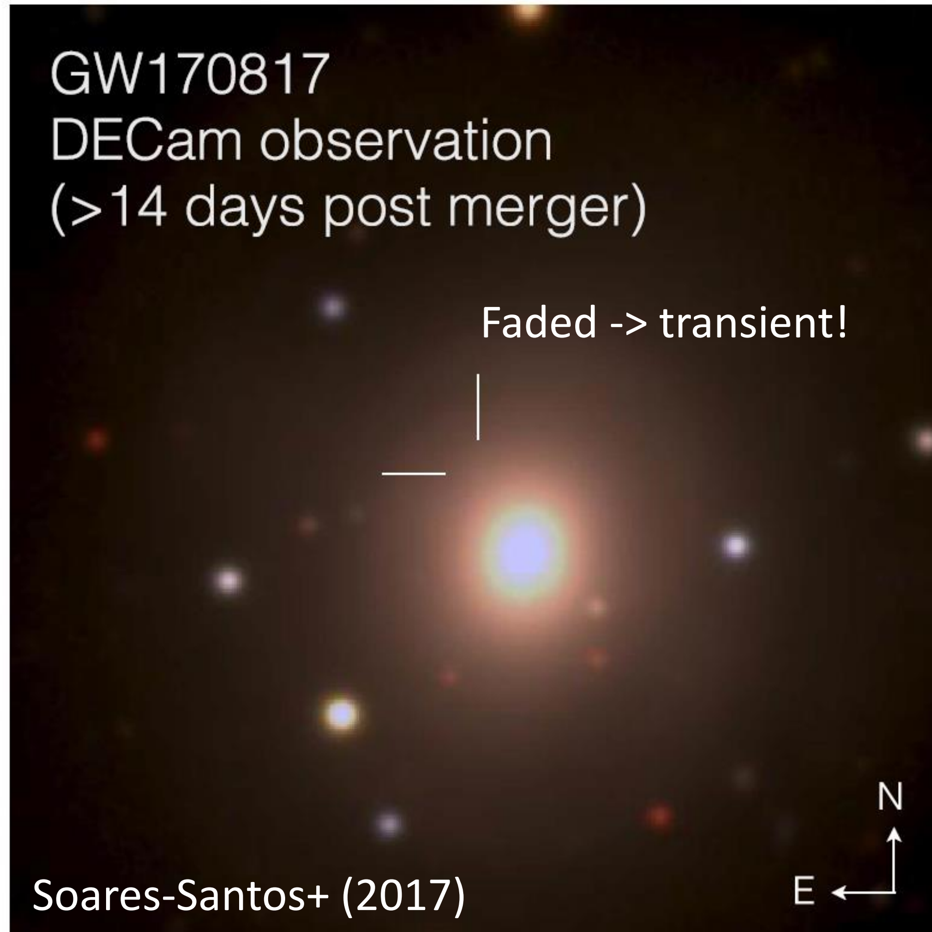
$$\chi_i = \frac{cS_i}{Gm_i^2} \quad (i = 1,2)$$

The error in q appears large particularly for nearly equal-mass systems like binary neutron stars

Transient and host galaxy

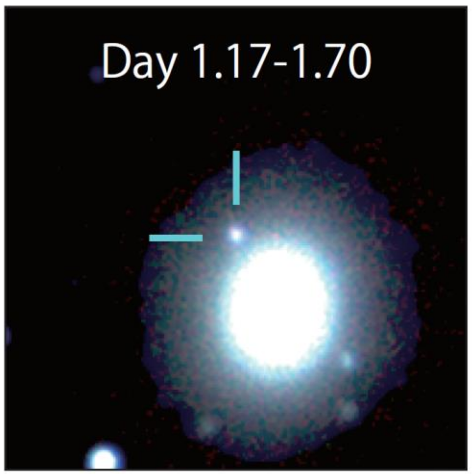
First found by Swope Supernova Survey (not this)

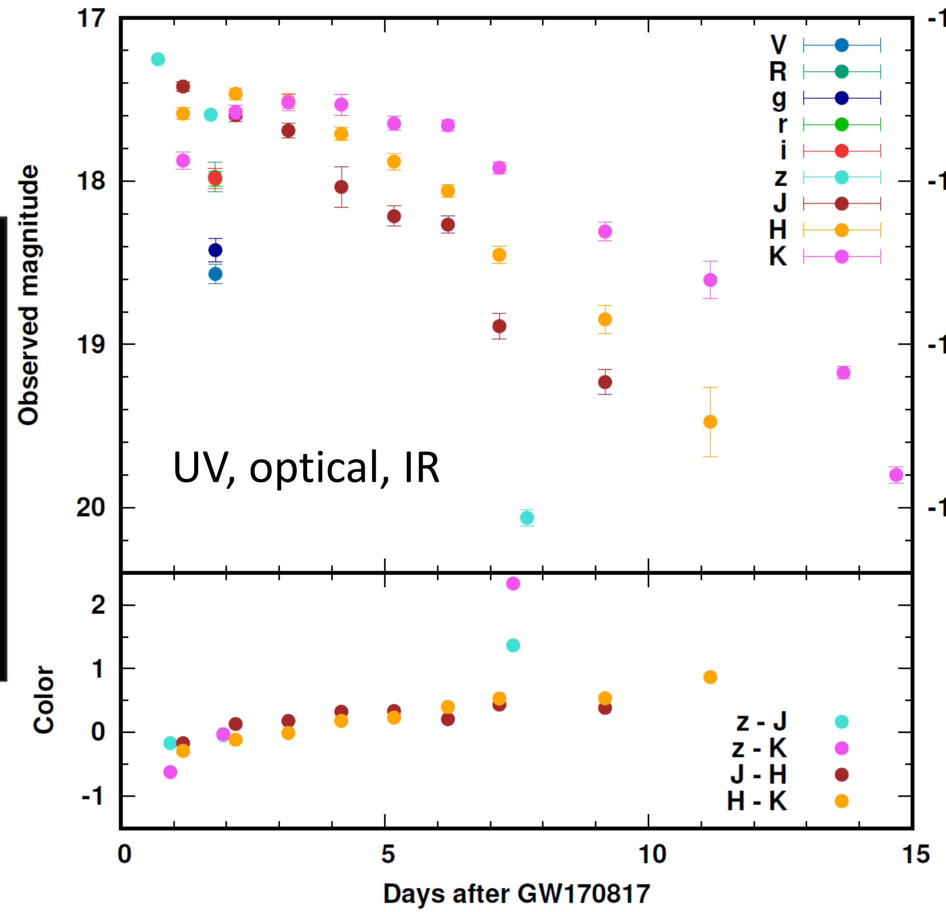




J-GEM observation

Japanese observatories, for example Subaru/HSC, took well-sampled images





Utsumi+ (2017)

Stacking estimation

~tidal deformability