Darmstadt Lecture 15 – GW170817

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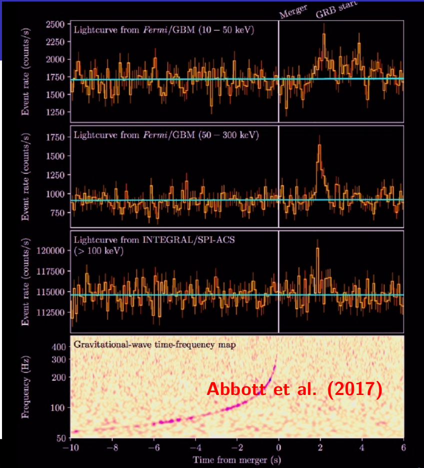
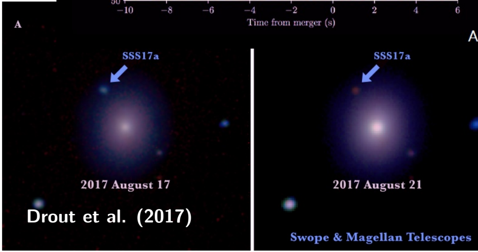
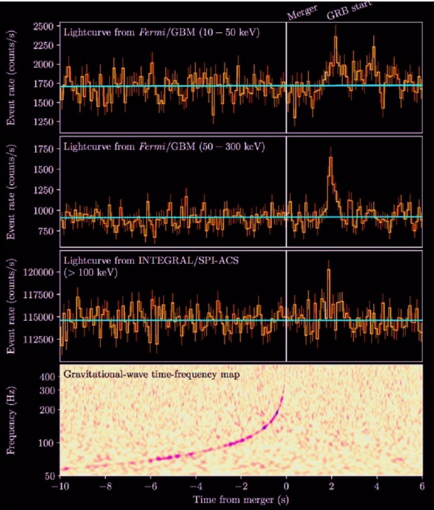
GW170817

- LIGO-Virgo (LVC) detected a signal consistent with a BNS merger, followed 1.7 s later by a weak sGRB.
- 16600 orbits observed over 165 s.
- $\mathcal{M} = 1.187 \pm 0.001 \ M_\odot$
- $M_{\rm T,min} = 2^{6/5}\mathcal{M} = 2.726 M_\odot$
- $E_{\rm GW} > 0.025 M_\odot c^2$
- $D_L = 40 \pm 10$ Mpc
- $75 < \tilde{\Lambda} < 560$ (90%)
- $M_{\rm ejecta} \sim 0.06 \pm 0.02 \ M_\odot$
- Blue ejecta: $\sim 0.01 M_\odot$
- Red ejecta: $\sim 0.05 M_\odot$
- Possible r-process production
- Ejecta + GRB: $M_{max} \lesssim 2.2 M_\odot$





The Appearance of a Short Gamma-Ray Burst

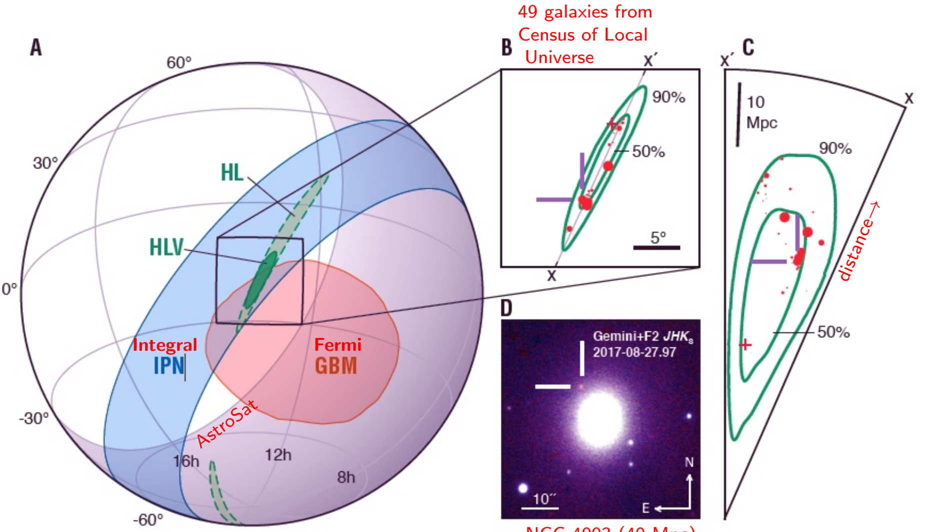


- The probability of a chance temporal and spatial association of GW170817 and GRB170817A is 5.0 x 10^{-8}
- We can confirm binary neutron stars as the progenitors of short, hard gamma-ray bursts
- The time delay between the end of the gravitational-wave signal and the start of the gamma-ray burst is 1.74 (+/- 0.05) s

Abbott,..., DAB et al. (LSC, Virgo, Fermi, Integral) ApJ **848** L13 (2017)

This observation also confirms that gravitational waves travel exactly at the speed of light; at most they lose 510,000 km after traveling 130 million light years.

The Discovery of the Host Galaxy, NGC 4993

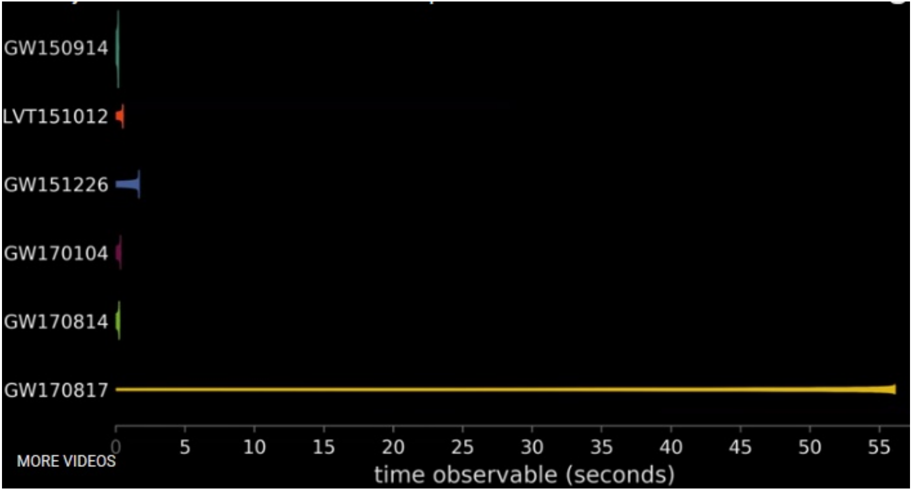


NGC 4993 (40 Mpc)

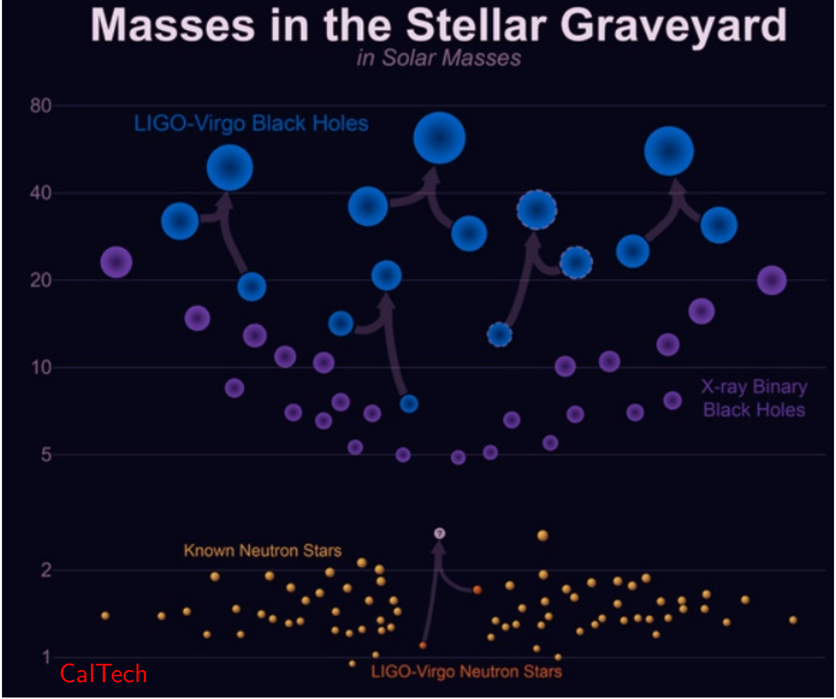
Kasliwal et al. (2017)

Comparison to Other Gravitational Wave Events

5 binary black hole mergers and 1 binary neutron star merger



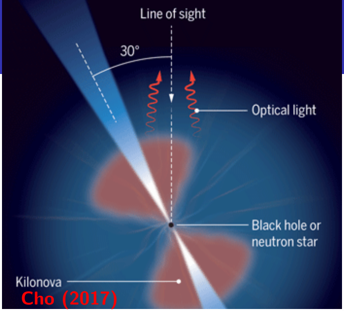
CalTech

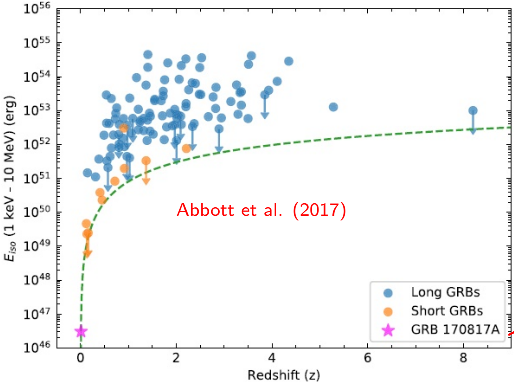

Masses in the Stellar Graveyard
in Solar Masses
80
40
20
10
5
2
1
LIGO-Virgo Black Holes
X-ray Binary
Black Holes
Known Neutron Stars
LIGO-Virgo Neutron Stars
CalTech

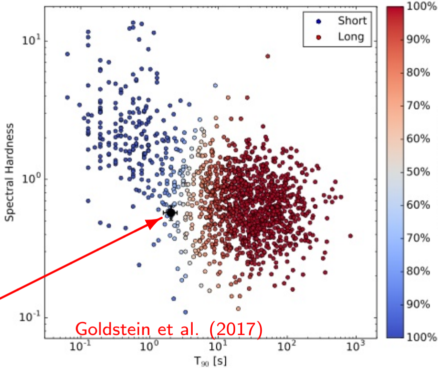
The Gamma-Ray Burst

It's classified as a short GRB.

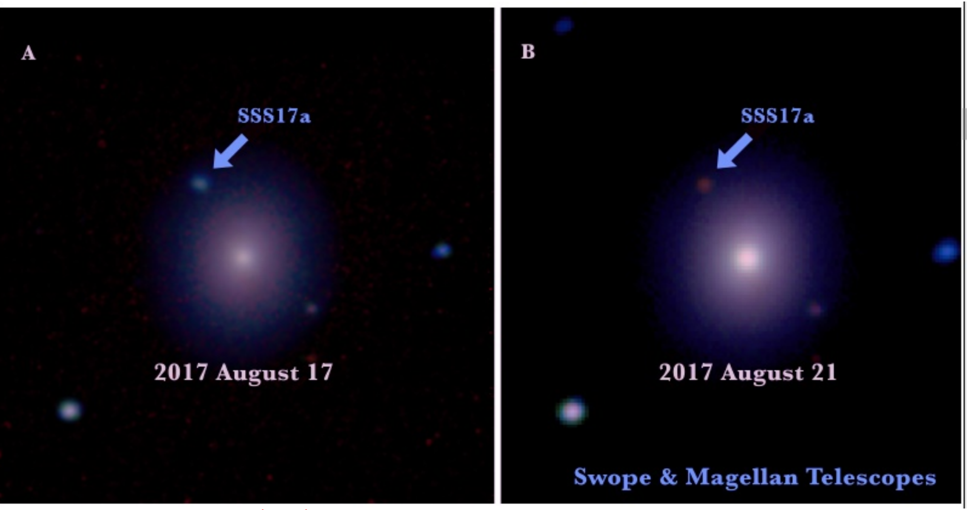
Its faintness may be due to being off-axis, or to obscuring matter; either explains the 2-week delay in detection of X-rays and radio.



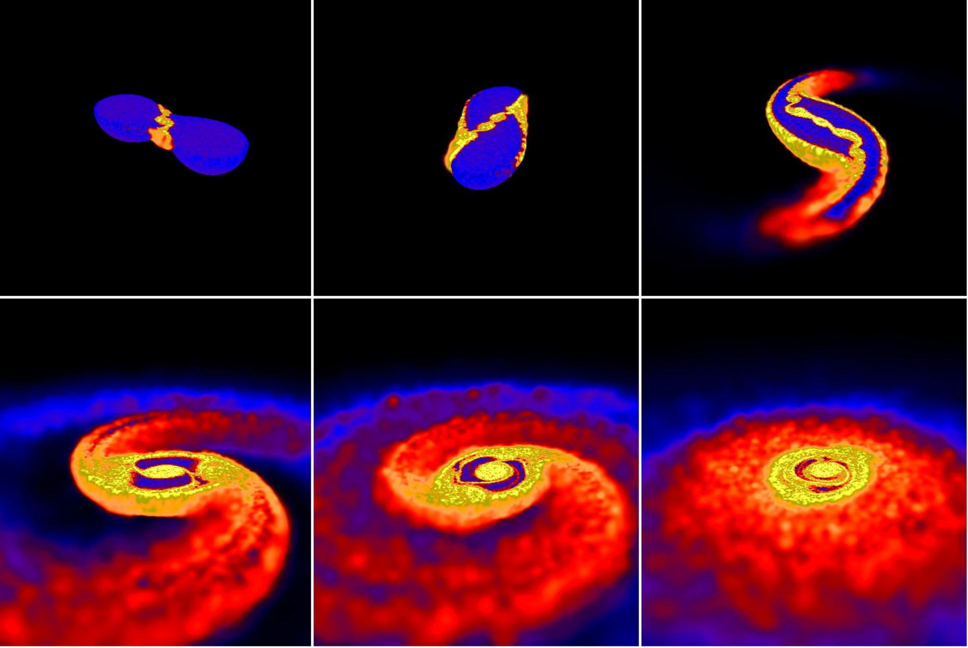




The Optical Afterglow

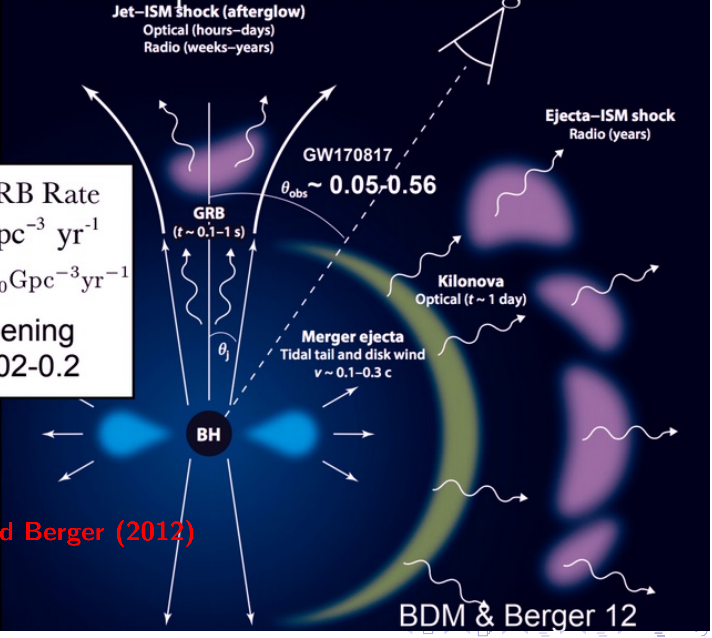


Drout et al. (2017)



Price & Rosswog (2006)

EM Counterparts of BNS Mergers



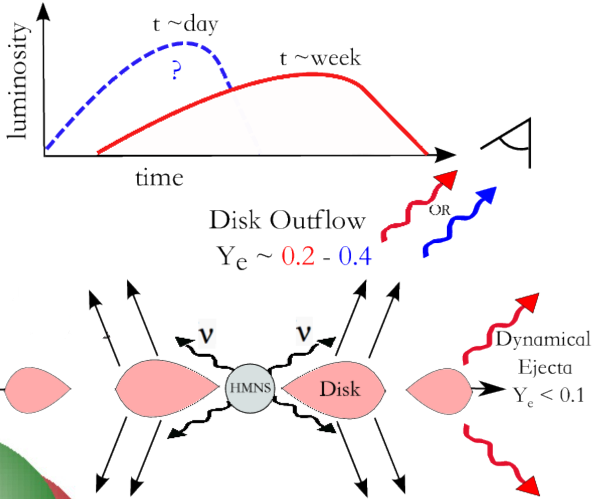
Luminous SGRB Rate

$R_{\rm SGRB} \sim 10$ Gpc^{-3} yr^{-1}

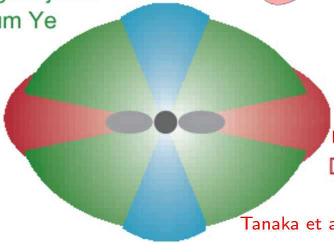
$\mathcal{R}_{\rm BNS} \approx 1540^{3200}_{-1220}\,{\rm Gpc}^{-3}{\rm yr}^{-1}$

=> jet half-opening angle Θ_j ~ 0.02-0.2

Metzger and Berger (2012)



blue = low opacity

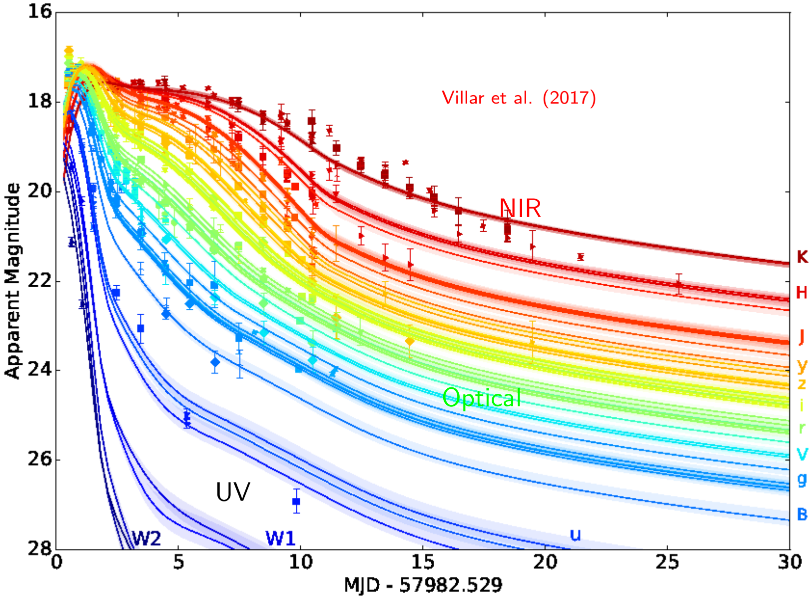


red = high opacity

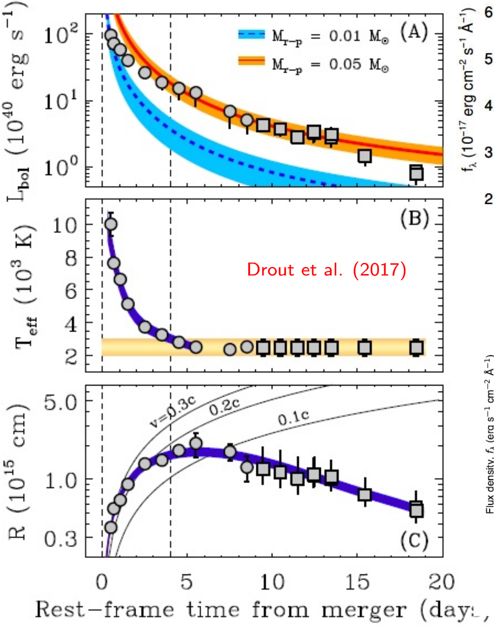
Metzger et al. (2012)

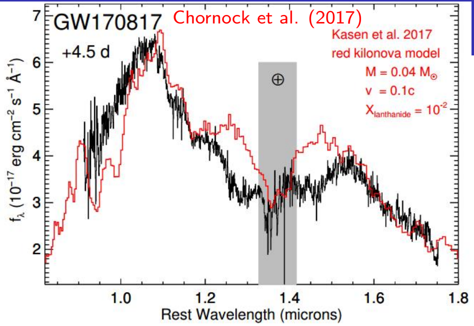
Tanaka et al. (2012)

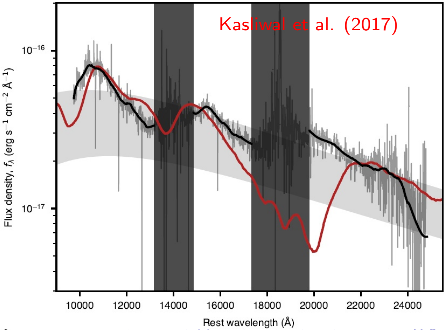
Light Curves



Ejecta Composition







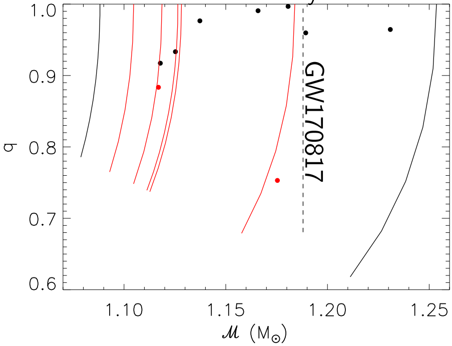
Properties of Known Double Neutron Star Binaries

- Both component masses are accurately measured (9)

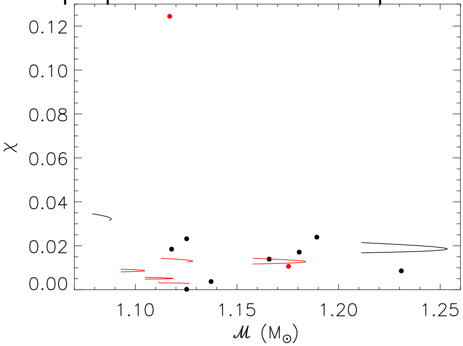
— Only the total binary mass is accurately measured (7)

Binaries with $\tau_{GW} > t_{\rm universe}$ (7)

$q = M_2/M_1$ is the binary mass ratio for a system



$\chi = cJ/(GM^2)$ is the dimensionless spin parameter for individual pulsars



$\mathcal{M} = (M_1 M_2)^{3/5}(M_1 + M_2)^{-1/5}$ is the chirp mass

Limits to $\mathcal{M}$ and q

Neutron stars have masses in the range $M_{min} \leq M \leq M_{max}$.

- $M_{min} \gtrsim 1.1 M_\odot$ from models of CCSNe models and ν-trapped remnants. Smallest well-measured mass is PSR J0453+1559 companion [Martinez et al. 2015] with $1.174 \pm 0.004 M_\odot$.
- $M_{max} \gtrsim 2 M_\odot$ from PSR J0348 + 0432 [Antoniadis et al. 2013] with $2.01 \pm 0.04 M_\odot$, PSR J0740 + 6620 [Cromartie et al. 2019] with $2.17^{+0.11}_{-0.10} M_\odot$, and PSR J2215-5135 [Linares et al. 2018] with $2.27^{+0.17}_{-0.15} M_\odot$. The first has smaller uncertainty, but involves white dwarf evolutionary assumptions; the second is a Shapiro-delay measurement; the third is a black widow like system with large companion modeling uncertainties.

$$2^{-1/5} M_{min} = 1.02 M_\odot < \mathcal{M} < 2^{-1/5} M_{max} = 1.89 M_\odot$$

GW170817: $\mathcal{M} = 1.187 M_\odot$; $q \geq 0.735$; $1.365 \leq M_1/M_\odot \leq 1.600$

Waveform Model Parameters

There are 13 wave-form free parameters including finite-size effects at third PN order $(v/c)^6$. LVC17 used a 13-parameter model; De et al. (2018) used a 9-10 parameter model.

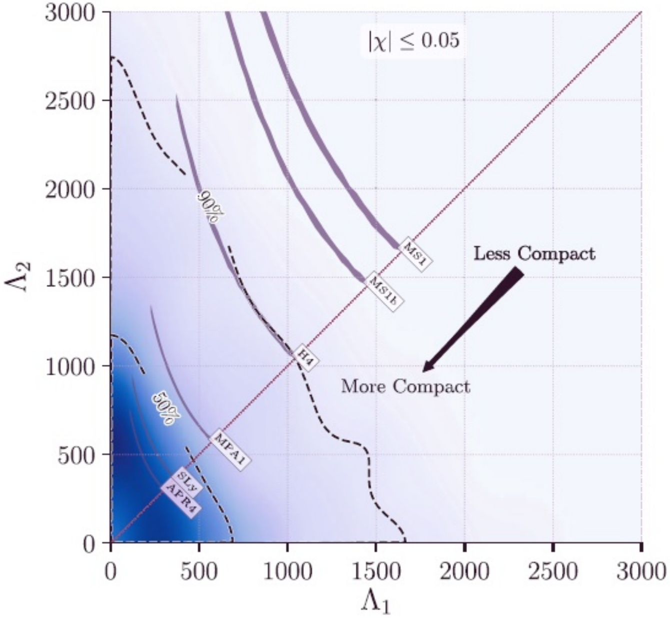
- Sky location (2) EM data
- Distance (1) EM data
- Inclination (1)
- Coalescence time (1)
- Coalescence phase (1)
- Polarization (1)

Extrinsic

- Component masses (2)
- Spin parameters (2)
- Tidal deformabilities (2) correlated with masses

Intrinsic

LVC GW170817 Tidal Deformability Constraints



LVC (2017)

Re-Analysis of GW170817 (De et al. 2018)

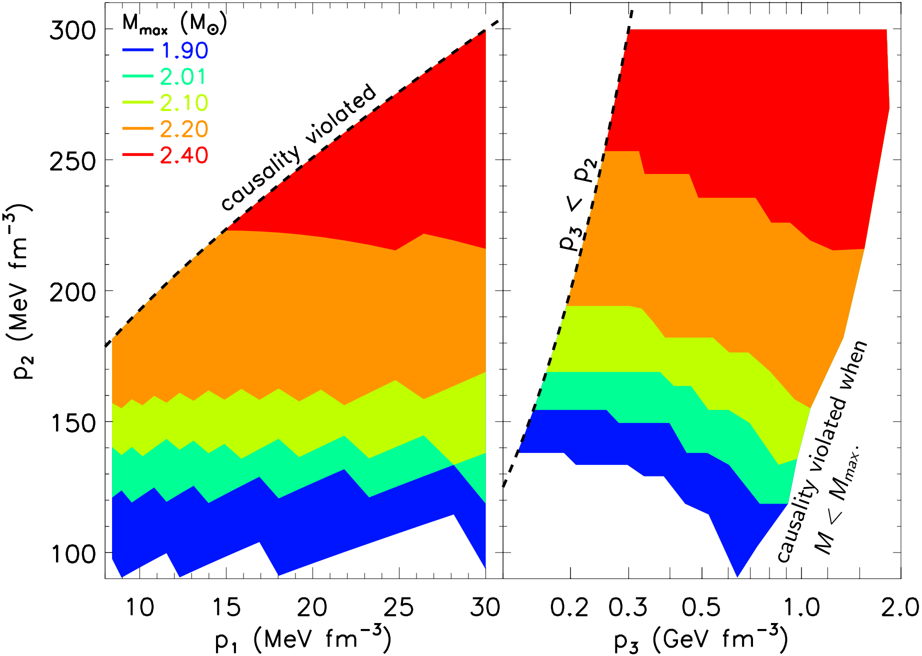
- De18 takes advantage of the precisely-known electro- magnetic source position (Soares-Santos et al. 2017).
- Uses existing knowledge of H_0 and the redshift of NGC 4993 to fix the distance (Cantiello et al. 2017).
- Assumes both neutron stars have the same equation of state, which implies $\Lambda_1 \simeq q^6 \Lambda_2$.
- Baseline model effectively has 9 instead of 13 parameters.
- Explores variations of mass, spin and deformability priors.
- Low-frequency cutoff taken to be 20 Hz, not 30 Hz as in LVC17, doubling the number of analyzed orbits.

De18 find that including $\Lambda - M$ correlations

- establishes a lower 90% confidence bound to $\tilde{\Lambda}$ (which is above the causal minimum value), and
- reduces the upper 90% confidence bound to $\tilde{\Lambda}$ by 30%.

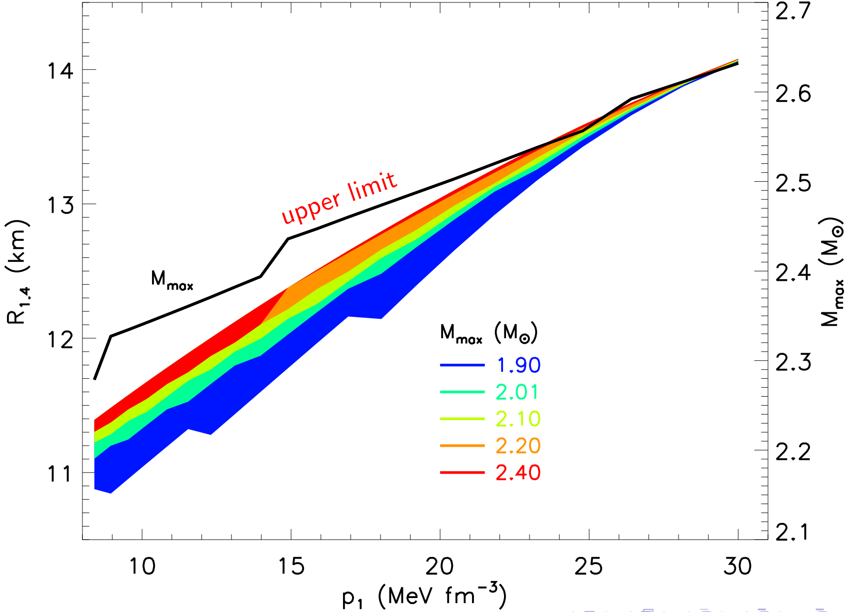
Piecewise Polytropic Equations of State

- For many reasons, it's believed neutron stars have hadronic crusts; the EOS is well-determined below $n_0 \sim 0.5 n_s$.
- $n_0 = n_s/2.7$, $p_0 = 0.2177$ MeV fm^{-3}, $\varepsilon_0 = 56.24$ MeV fm^{-3}.
- Read et al. found that $M - R$ is well-approximated with an EOS above n_0 containing as few as 3 polytropic segments.
- Read et al. found optimal upper boundaries (n_1, n_2, and $n_3 = 1.85 n_s$, $3.7 n_s$, and $7.4 n_s$) globally fit wide varieties of hadronic EOSs, leaving just 3 EOS parameters: p_1, p_2, and p_3.
- Neutron matter theory, nuclear experiment, and the unitary gas suggest that 8.4 MeV fm^{-3} $< p_1 <$ 20 MeV fm^{-3}, but we extend the upper limit to 30 MeV fm^{-3}. These limits imply $32 < S_v/\mathrm{MeV} < 38$ and $39 < L/\mathrm{MeV} < 85$.
- The parameters p_2 and p_3 are limited from above by causality and below by a maximum mass $1.9 M_\odot < M_{max} < 2.4 M_\odot$.
- The parameters p_1, p_2 and p_3 are uniformly sampled.

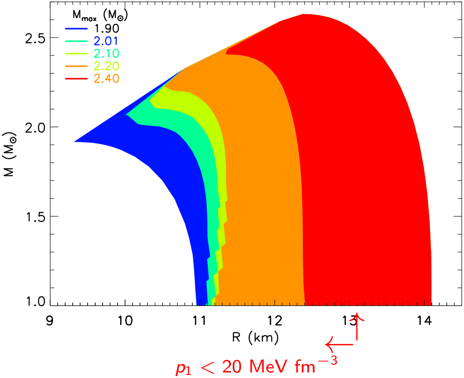


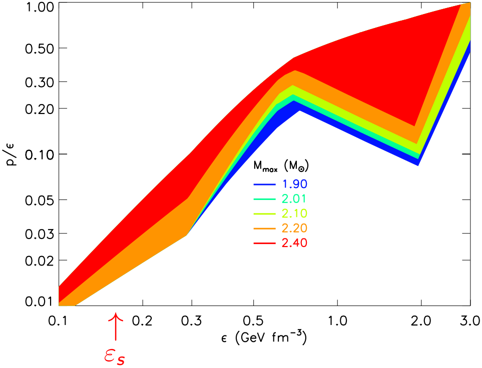
M_{max} ($M_\odot$)
1.90
2.01
2.10
2.20
2.40
causality violated
$p_3 < p_2$
causality violated when $M < M_{max}$.
p_2 (MeV fm^{-3})
p_1 (MeV fm^{-3})
p_3 (GeV fm^{-3})
300
250
200
150
100
10
15
20
25
30
0.2
0.3
0.5
1.0
2.0

The Radius-Pressure-M_{max} Correlations

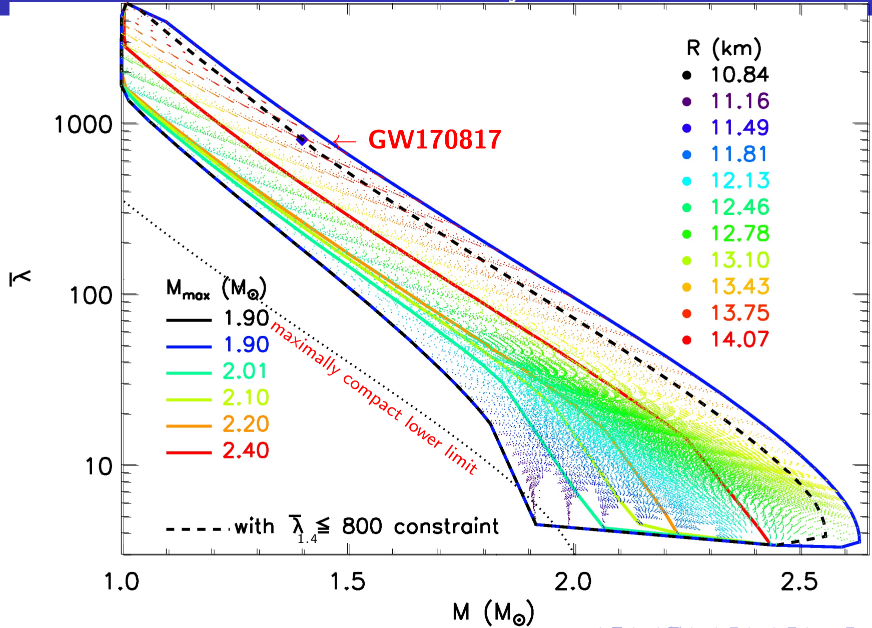


$M - R$ and EOS Constraints

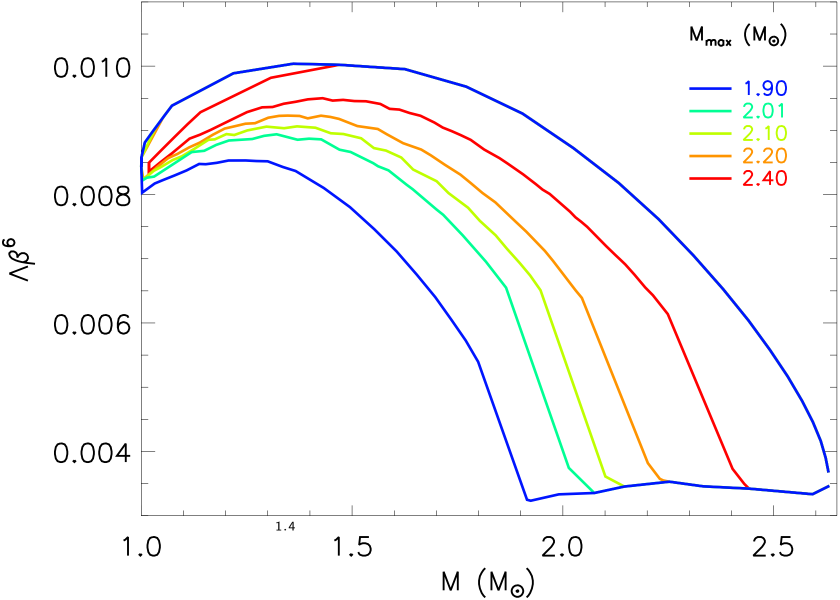




Dimensionless Tidal Deformability



Dimensionless Tidal Deformability



$\Lambda \propto \beta^{-6}$ and $R_1 = R_2$ Correlations

In the GW170817 mass range, $1.1 < m/M_\odot < 1.6$, $k_2 \propto \beta^{-1}$, and $\Lambda \simeq a\beta^{-6}$. Piecewise polytropes give $a = 0.0093 \pm 0.0007$.

Furthermore, in this mass range, R is insensitive to m. For $M_{max} \gtrsim 2M_\odot$, $<\Delta R>= -0.07$ km and $\sqrt{<(\Delta R)^2>} = 0.11$ km, where $\Delta R = R_{1.6} - R_{1.1}$.

With the assumptions $\Lambda = a\beta^{-6}$ and $R(m) = R_{1.4}$, one finds

$$\Lambda_2 = q^{-6}\Lambda_1,$$

$$\bar\Lambda = \frac{16a}{13}\left(\frac{R_{1.4}c^2}{G\mathcal{M}}\right)^6 \frac{q^{8/5}}{(1+q)^{26/5}}(12 - 11q + 12q^2),$$

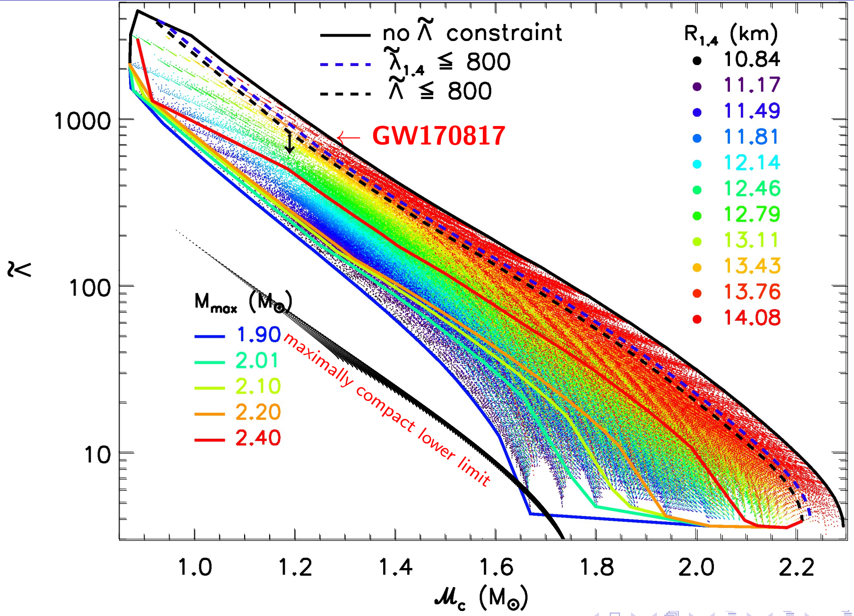
which is remarkably insensitive to q:

$$\frac{\partial\bar\Lambda}{\partial q} = \frac{16a}{65}\left(\frac{R_{1.4}c^2}{G\mathcal{M}}\right)^6 \frac{(1-q)q^{3/5}}{(1+q)^{31/5}}(96 - 263q + 96q^2)$$

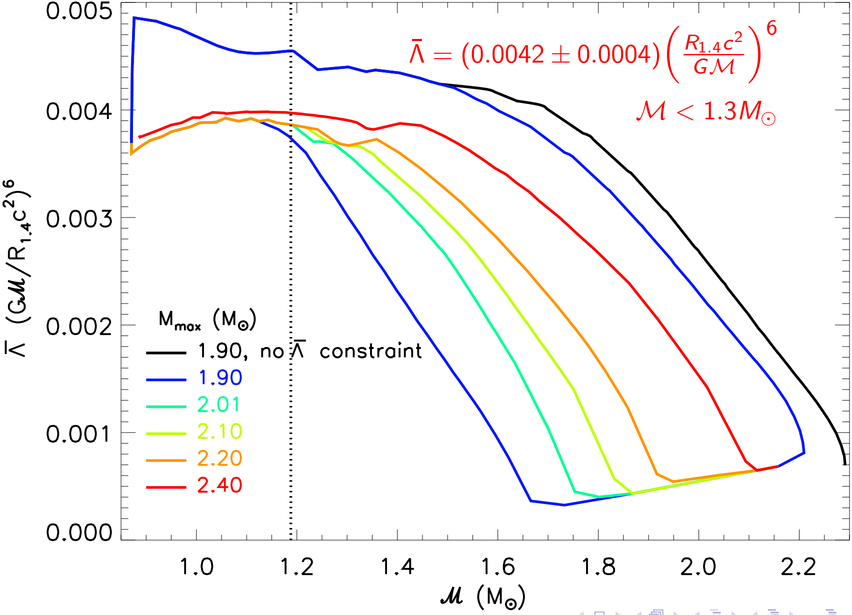
vanishes when $q = 1$. $\bar\Lambda(q = 0.75)/\bar\Lambda(q = 1) = 1.02$.

We now find that $\bar\Lambda(\Lambda_1, \Lambda_2)$ and $q(\Lambda_1, \Lambda_2)$.

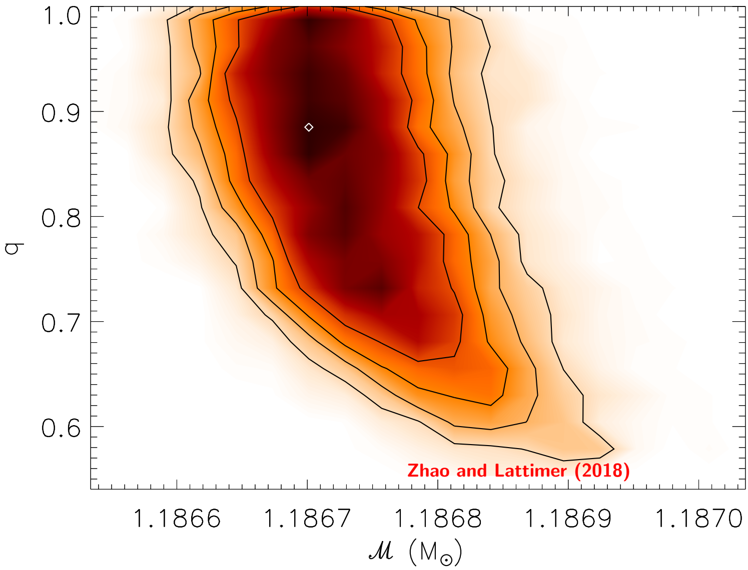
Dimensionless Binary Tidal Deformability

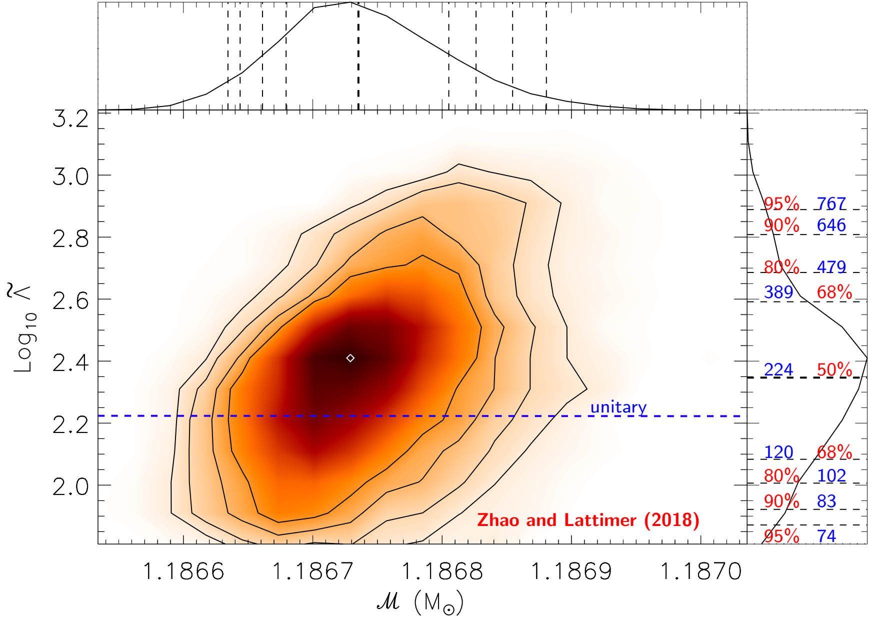


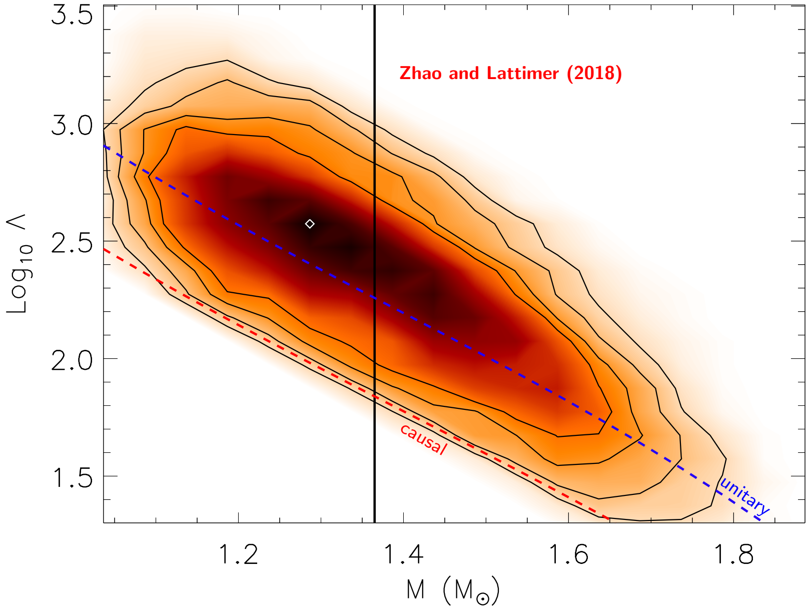
Dimensionless Binary Tidal Deformability

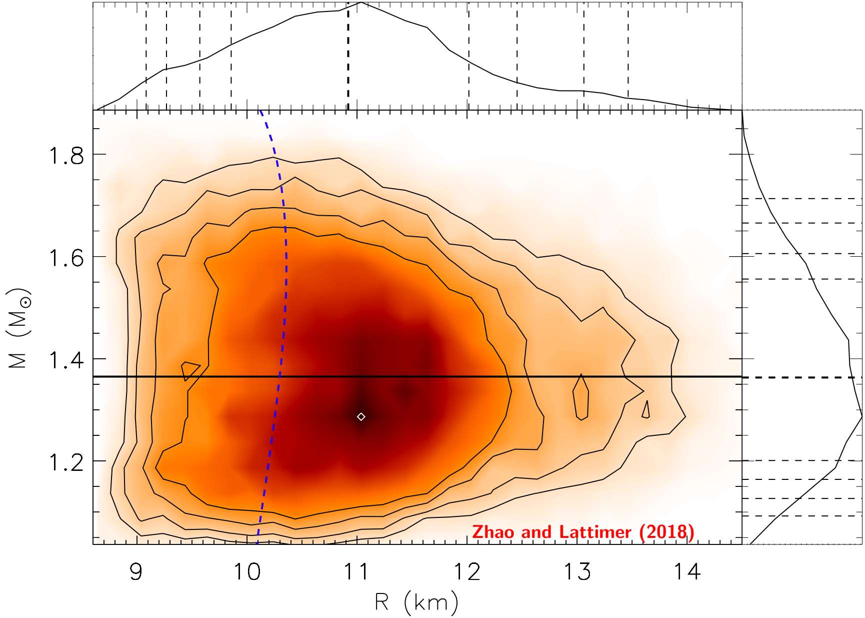


68%, 80%, 90% and 95% Confidence Bounds

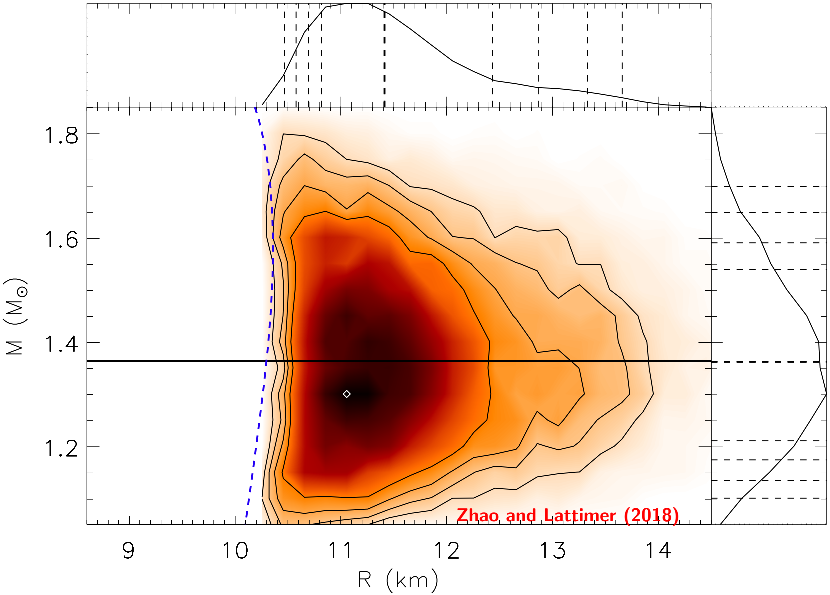



3.2
3.0
2.8
2.6
2.4
2.2
2.0
$\mathrm{Log}_{10}\,\tilde{\Lambda}$
1.1866
1.1867
1.1868
1.1869
1.1870
$\mathcal{M}$ ($M_\odot$)
unitary
Zhao and Lattimer (2018)
95% 767
90% 646
80% 479
389 68%
224 50%
120 68%
80% 102
90% 83
95% 74

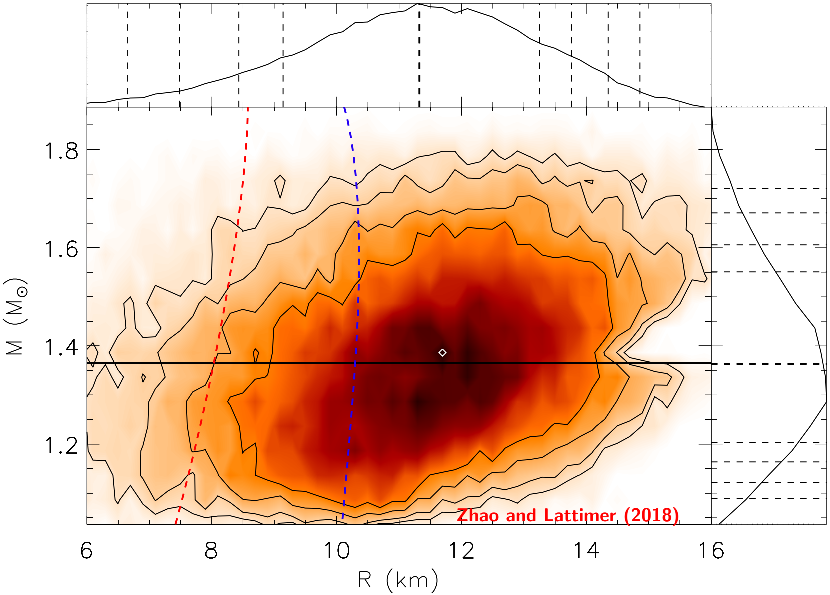

Zhao and Lattimer (2018)
causal
unitary
$\mathrm{Log}_{10}\,\Lambda$
$M\ (M_\odot)$
3.5
3.0
2.5
2.0
1.5
1.2
1.4
1.6
1.8


1.8
1.6
1.4
1.2
M (M$_\odot$)
9
10
11
12
13
14
R (km)
Zhao and Lattimer (2018)

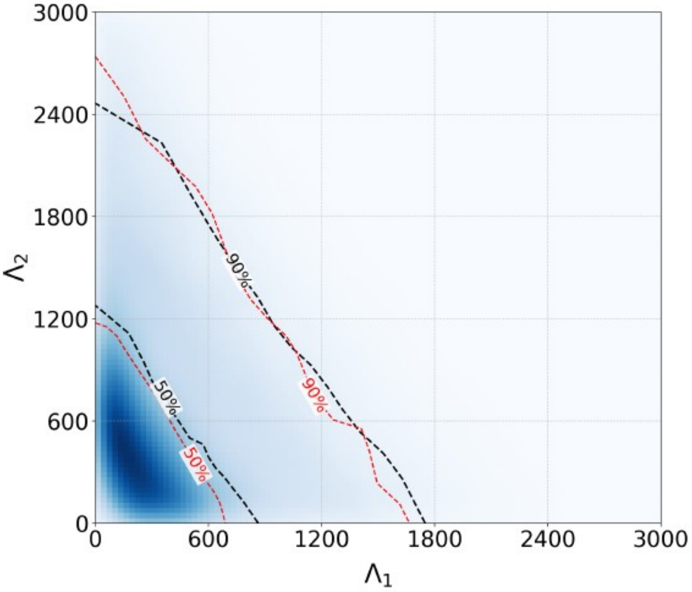
$M - R$ With Unitary Gas Limit Imposed



$M - R$ With No $\Lambda - M$ Correlations



Comparison with LVC Assuming Uncorrelated Λ's



Maximum Mass Constraint From GW170817

- Pulsar observations imply that slowly rotating neutron stars have a maximum mass $M_{max} \gtrsim 2M_\odot$.
- Initially, the remnant is differentially rotating, but quickly (~ 0.1s) uniformizes its rotation.
- Differentially-rotating stars likely have $M_{max,d} \gtrsim 1.5M_{max}$.
- Maximally uniformly rotating stars have $M_{max,u} = \xi M_{max}$ with $1.17 \lesssim \xi \lesssim 1.21$.
- *Hypermassive* stars, with $M > M_{max,u}$, promptly collapse to a BH.
- *Supermassive* stars, with $M_{max} \leq M \leq M_{max,u}$, are metastable but have much longer lifetimes.
- Inspiralling mass $M_T = M_1 + M_2 = \mathcal{M} q^{-3/5}(1+q)^{6/5}$ is between $2.73M_\odot$ ($q = 1$) and $2.78M_\odot$ ($q = 0.7$).
- Whether or not a supermassive star promptly collapses depends on M_T and binding energy; use baryon masses.

Maximum Mass Constraint

- Define BE$= M^b - M$,

$$\frac{\mathrm{BE}}{M} \simeq (0.058 \pm 0.006M) + (0.013 \pm 0.001)M^2 = aM + bM^2.$$

- Define $M^b_{max,u}/M^b_{max} = \xi_b$.
- If $M^b_T > M^b_{max,d}$, remnant promptly collapses to a BH before a gamma-ray burst or radio jets can form or disc ejecta occurs (which were observed).
- If $M^b_T < M^b_{max,u}$, remant will be indefinitely stable, but disc ejecta likely poisioned by neutrinos which de-neutronize it and destroy the r-process.
- $M^b_{max,u} < M^b_T < M^b_{max,d}$, modulo ejecta $\Delta \gtrsim 0.05 M_\odot$.
- $\xi_b M^b_{max} < M^b_T - \Delta$ is a cubic equation for M_{max}, with approximate solution

$$M_{max}/M_\odot < 2.18 + 0.52(1-q)^2 \simeq 2.18 - 2.25.$$