BNS and BHNS Mergers: Implications for Neutron Stars

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Main Topics

- Neutron Star Mass and Radius Estimates from Pulsar Timing and X-ray Observations
- GW170817 - Tidal Deformability, Mass and Radius Estimates From Compact Binary Mergers
  - Systematic Uncertainties in GW Radius Constraints
  - Refining Radius Constraints By Including Theoretical and Experimental Nuclear Physics Information
- Properties of Neutron Star-Black Hole Mergers and Gap Systems in O3

Nuclear Symmetry Energy and the Pressure

The symmetry energy is the difference between the energies of pure neutron matter ($x = 0$) and symmetric ($x = 1/2$) nuclear matter:

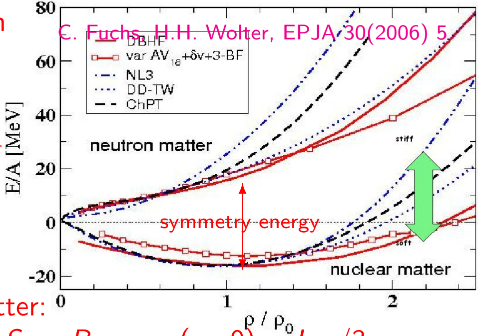
$$S(n) = E(n, x = 0) - E(n, x = 1/2)$$

Usually approximated as an expansion around the saturation density (n_s) and isopin symmetry ($x = 1/2$):

$$E(n,x) = E(n,1/2) + (1-2x)^2 S_2(n) + \dots$$

$$S_2(n) = \mathbf{S_v} + \frac{\mathbf{L}}{3}\frac{n-n_s}{n_s} + \dots$$

$$\mathbf{S_v} \simeq 31 \text{ MeV}, \quad \mathbf{L} \simeq 50 \text{ MeV}$$



Extrapolated to pure neutron matter:

$$E(n_s, 0) \approx S_v + E(n_s, 1/2) \equiv S_v - B, \qquad p(n_s, 0) = L n_s/3$$

Neutron star matter (beta equilibrium) is nearly neutron matter:

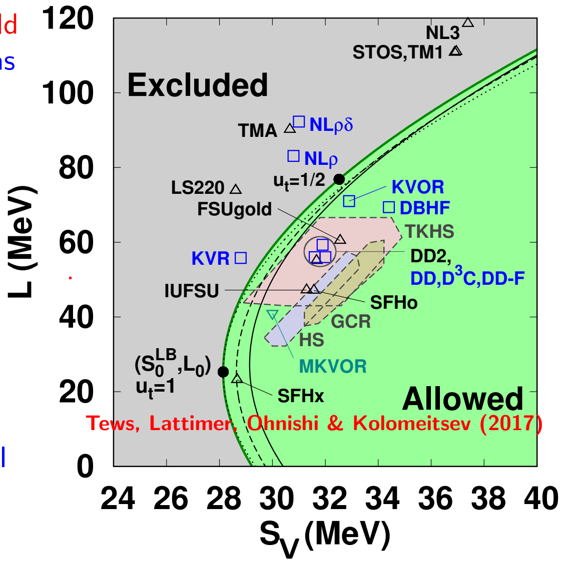
$$\frac{\partial(E + E_e)}{\partial x} = 0, \quad p(n_s, x_\beta) \simeq \frac{L n_s}{3}\left[1 - \left(\frac{4S_v}{\hbar c}\right)^3 \frac{4 - 3S_v/L}{3\pi^2 n_s}\right]$$

Unitary Gas Bounds

Neutron matter energy should be larger than the unitary gas energy $E_{UG} = \xi_0 (3/5) E_F$

$$E_{UG} = 12.6 \left(\frac{n}{n_s}\right)^{2/3} \mathrm{MeV}$$

The unitary gas refers to fermions interacting via a pairwise short-range s-wave interaction with an infinite scattering length and zero range. Cold atom experiments show a universal behavior with the Bertsch parameter $\xi_0 \simeq 0.37$.



$S_v \geq 28.6$ MeV; $L \geq 25.3$ MeV; $p_0(n_s) \geq 1.35$ MeV fm^{-3}

Theoretical and Experimental Constraints

H Chiral Lagrangian

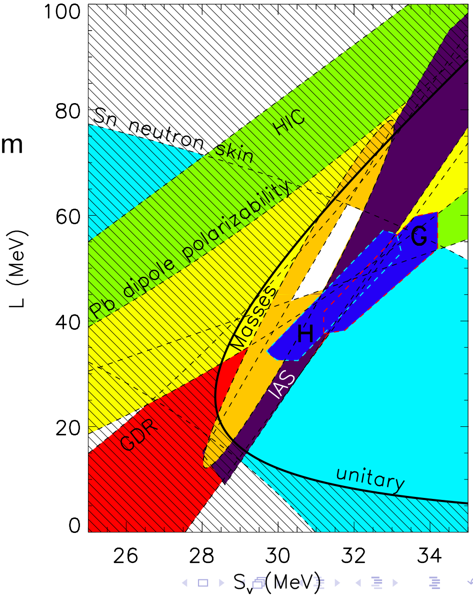
G: Quantum Monte Carlo

neutron matter calculations from Hebeler et al. (2012)

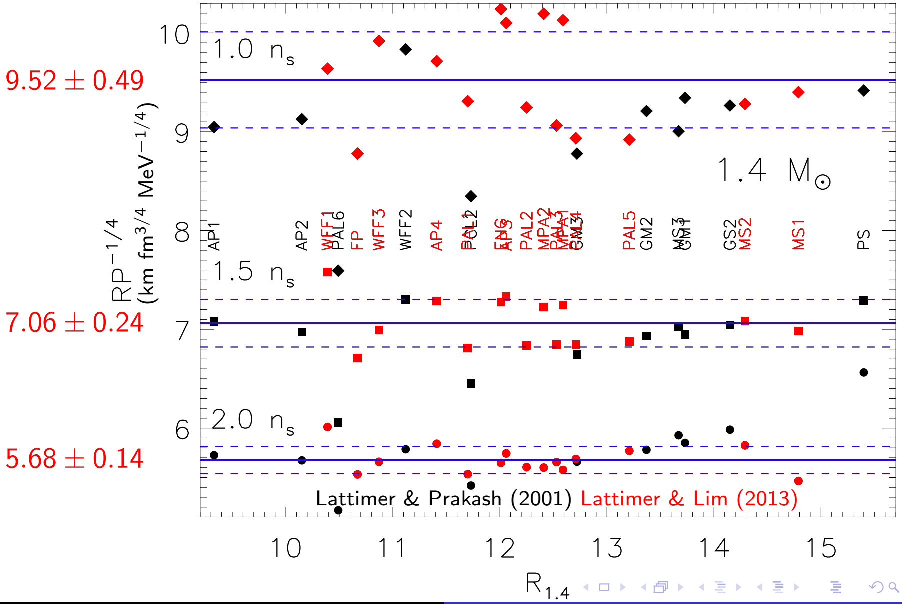
unitary gas constraints from Tews et al. (2017)

Combined experimental constraints are compatible with unitary gas bounds.

Neutron matter calculations are compatible with both.



The Radius – Pressure Correlation



Theoretical and Experimental Constraint Summary

$$R_{1.4} = (9.52 \pm 0.49) \left(\frac{p_s}{\mathrm{MeV\ fm}^{-3}} \right)^{1/4} \mathrm{km}$$

$$p_s \simeq n_s L/3$$

$$30\ \mathrm{MeV} \lesssim L \lesssim 70\ \mathrm{MeV}:$$

$$10.9\ \mathrm{km} \lesssim R_{1.4} \lesssim 13.1\ \mathrm{km}$$

Causality and $M_{max} \gtrsim 2.0 M_\odot$: $R_{1.4} \gtrsim 8.2$ km
Imposing the unitary gas conjecture: $R_{1.4} \gtrsim 9.7$ km

How to Measure Neutron Star Masses and Radii

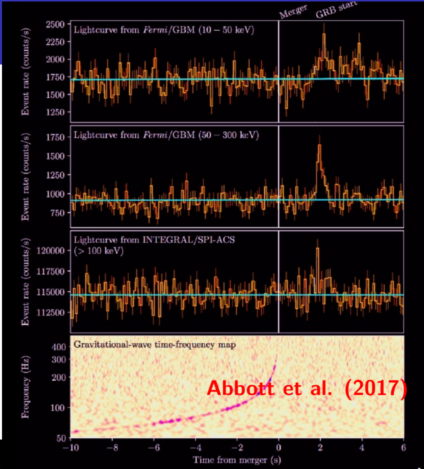
- Pulsar timing can accurately ($\gtrsim 0.0001 M_\odot$) measure masses.

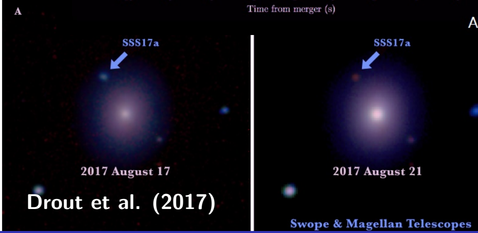
  Most are between $1.2 M_\odot$ and $1.5 M_\odot$; lowest is $1.174 \pm 0.004 M_\odot$ (J1453+1559), highest are $2.14^{+0.10}_{-0.09} M_\odot$ (J0740+6620) and $2.01 \pm 0.04 M_\odot$ (J0438+0432). Higher estimates exist, but have large uncertainties.
- Thermal, pulse profile and bursting observations of X-rays yield radii, but uncertainties are currently a few km.
  - Quiescent sources in globular clusters
  - Thermonuclear explosions on accreting neutron stars
  - Pulse profile modeling of hot spots on rapidly rotating neutron stars (NICER experiment)
- Gravitational waves from merging neutron stars measure masses and tidal deformabilites. Radius uncertaintes from GW170817 are a few km.

There is no tension between theoretical/experimental expectations and astrophysical measurements.

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: $M_{max} \lesssim 2.2 M_\odot$





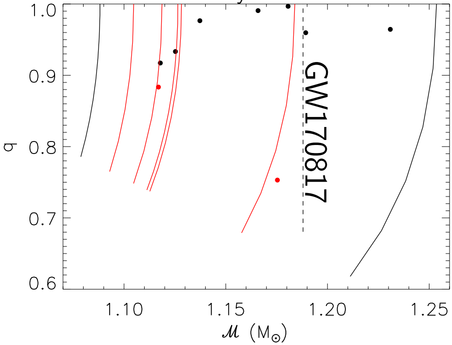
Properties of Known Double Neutron Star Binaries

- Both component masses are accurately measured (9)

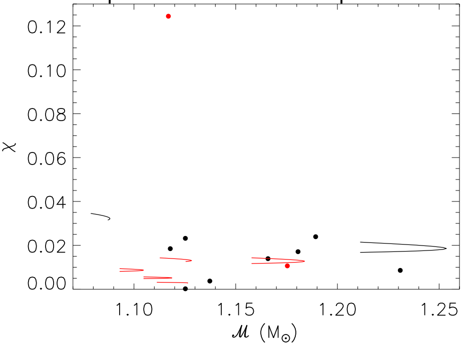
— Only the total binary mass is accurately measured (7)

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 $M_{min} \le M \le M_{max}$.

- $M_{min} \gtrsim 1.1 M_\odot$ 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 $2.14^{+0.10}_{-0.09} M_\odot$, 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 companion modeling uncertainties.

$$2^{-1/5} M_{min} = 0.96 M_\odot < \mathcal{M} < 2^{-1/5} M_{max} = 1.83 M_\odot$$

GW170817: $\mathcal{M} = 1.187 M_\odot$; $q \ge 0.65$; $1.365 \le M_1/M_\odot \le 1.692$

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.

Extrinsic:

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

Intrinsic:

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

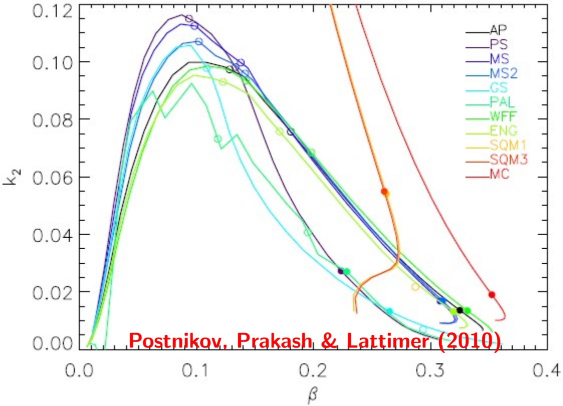
Tidal Deformability

The tidal deformability λ is the ratio of the induced dipole moment Q_{ij} to the external tidal field E_{ij}, $Q_{ij} \equiv -\lambda E_{ij}$.

Work with the dimensionless quantity

$$\Lambda = \frac{\lambda c^{10}}{G^4 M^5} \equiv \frac{2}{3} k_2 \left(\frac{Rc^2}{GM} \right)^5$$

k_2 is the dimensionless Love number.

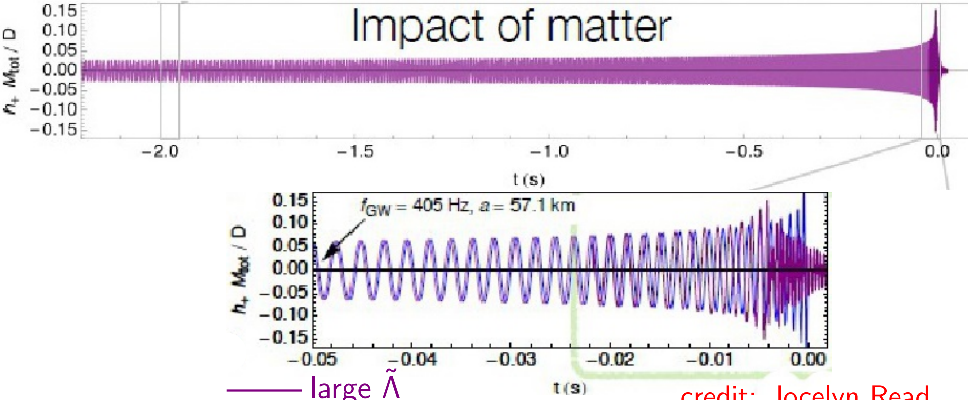


For a neutron star binary, $\tilde{\Lambda}$ is the relevant quantity:

$$\tilde{\Lambda} = \frac{16}{13} \frac{(1+12q)\Lambda_1 + (12+q)q^4\Lambda_2}{(1+q)^5}, \qquad q = M_2/M_1 \leq 1$$

The Effect of Tides

Tides accelerate the inspiral and produce a phase shift compared to the case of two point masses.



large $\tilde{\Lambda}$

small $\tilde{\Lambda}$

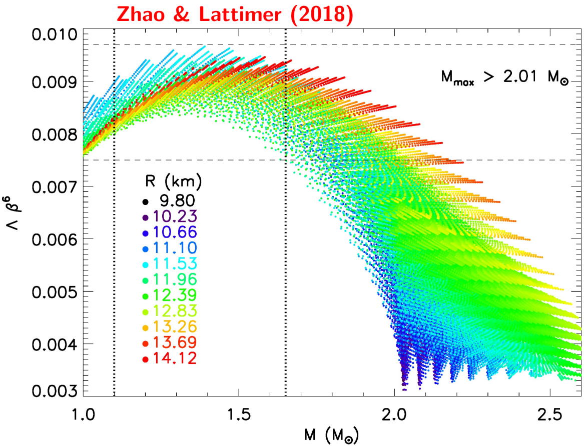
credit: Jocelyn Read

$$\delta\Phi_t = -\frac{117}{256}\frac{(1+q)^4}{q^2}\left(\frac{\pi f_{GW} G\mathcal{M}}{c^3}\right)^{5/3}\tilde{\Lambda} + \cdots .$$

Λ is Highly Correlated With M and R

- $\Lambda = a\beta^{-6}$
  $\beta = GM/Rc^2$

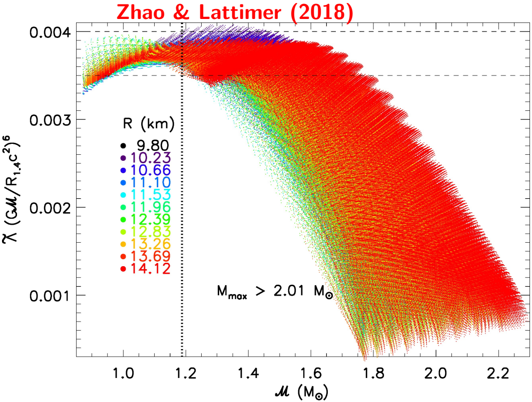
  $a = 0.0086 \pm 0.0011$
  for
  $M = 1.35 \pm 0.25\ M_\odot$
- If $R_1 \simeq R_2 \simeq R_{1.4}$
  it follows that
  $\Lambda_2 \simeq q^{-6}\Lambda_1$.



Binary Deformability and the Radius

$$\tilde{\Lambda}=\frac{16}{13}\frac{(1+12q)\Lambda_1+q^4(12+q)\Lambda_2}{(1+q)^5}\simeq\frac{16a}{13}\left(\frac{R_{1.4}c^2}{G\mathcal{M}}\right)^6\frac{q^{8/5}(12-11q+12q^2)}{(1+q)^{26/5}}$$

- $\tilde{\Lambda}=a'(R_{1.4}c^2/G\mathcal{M})^6$
  $a'=0.0035\pm0.0006$
  for
  $\mathcal{M}=1.2\pm0.2\ M_\odot$
- GW10817:
  $a'=0.00375\pm0.00025$
- $R_{1.4}=$
  $11.5\pm0.3\ \frac{\mathcal{M}}{M_\odot}\left(\frac{\tilde{\Lambda}}{800}\right)^{1/6}$ km
- GW10817:
  $R_{1.4}=13.4\pm0.1\ \left(\frac{\tilde{\Lambda}}{800}\right)^{1/6}$ km



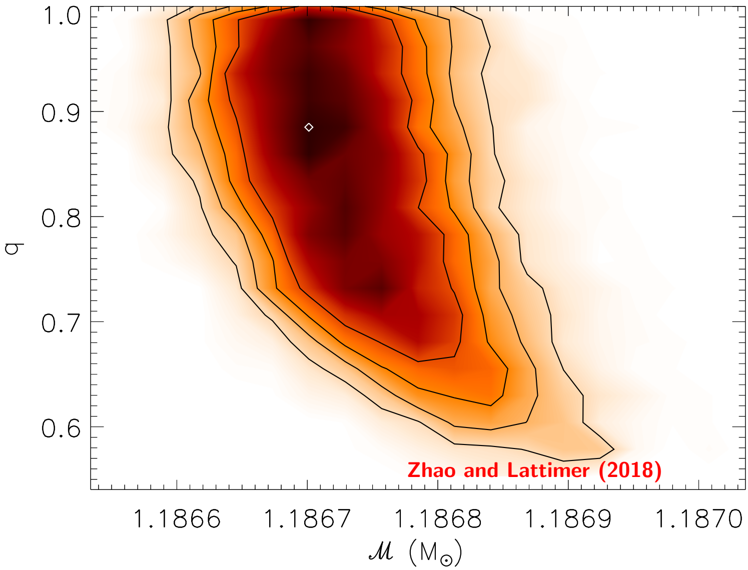
Re-Analysis of GW170817 (De et al. 2018)

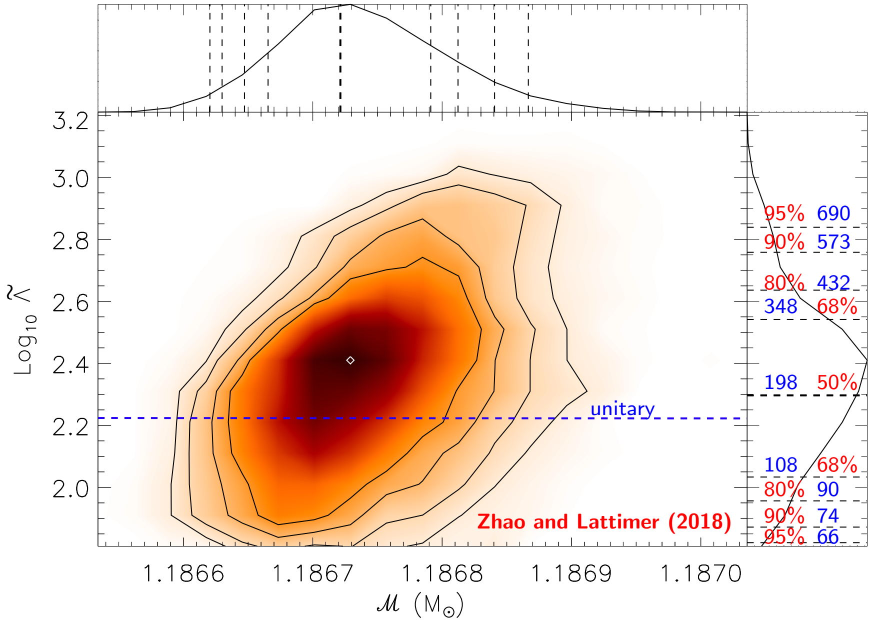
- De18 takes advantage of the precisely-known electromagnetic source position (Soares-Santos et al. 2017).
- Uses existing knowledge of H_0 and the redshift of NGC 4993 to fix the distance (Cantiello et al. 2017).
- Assumes both neutron stars have the same equation of state, which implies $\Lambda_1 \simeq q^6 \Lambda_2$.
- 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.

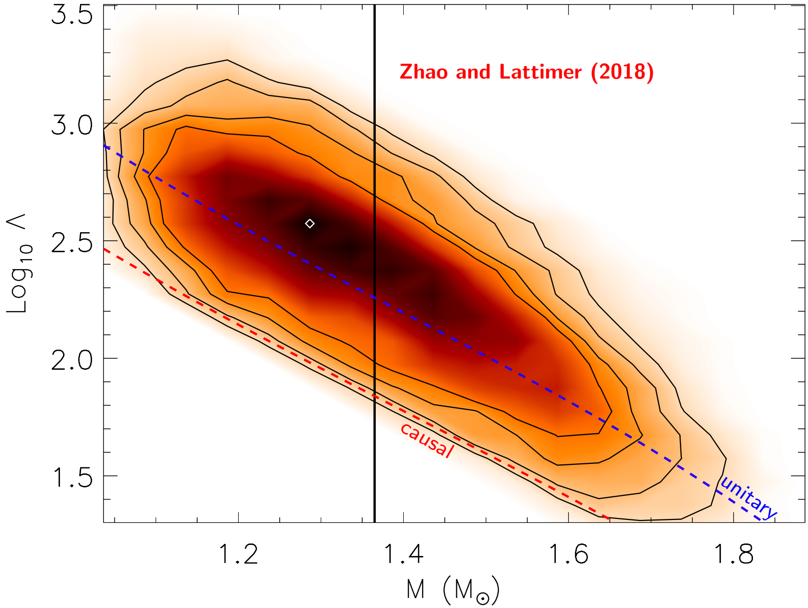
De18 find that including $\Lambda - M$ correlations

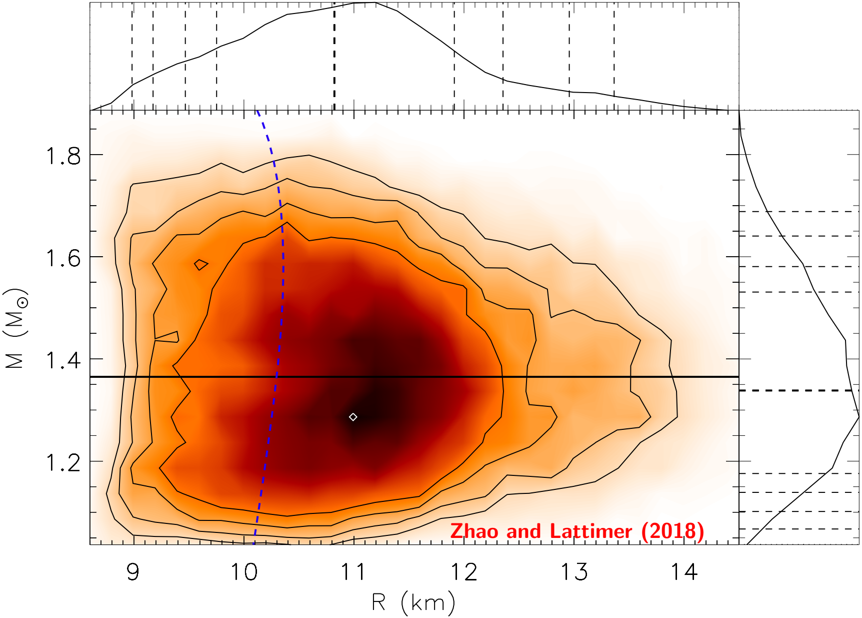
- establishes a lower 90% confidence bound to $\tilde{\Lambda}$ (which is above the causal minimum value), and
- reduces the upper 90% confidence bound to $\tilde{\Lambda}$ by 30%.

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

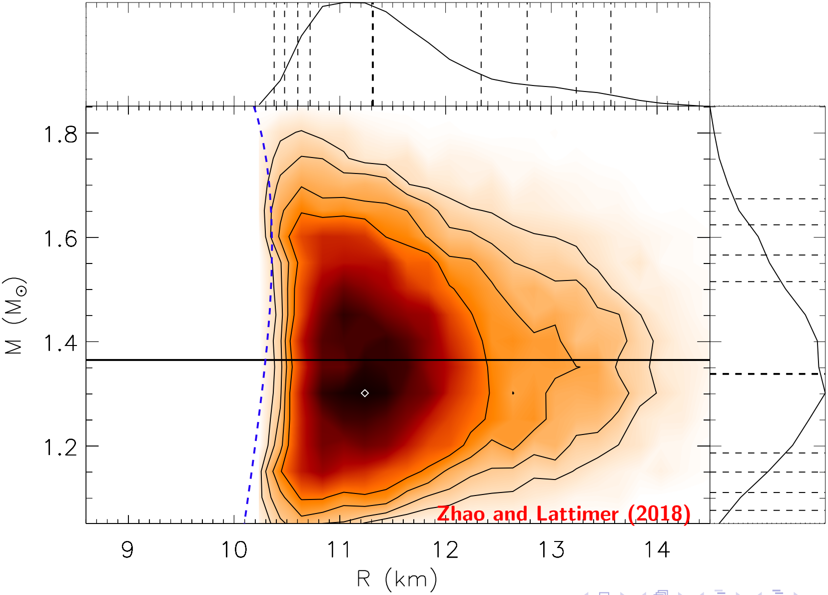



3.2
3.0
2.8
2.6
2.4
2.2
2.0
$\mathrm{Log}_{10}\,\tilde{\Lambda}$
1.1866
1.1867
1.1868
1.1869
1.1870
$\mathcal{M}$ ($M_\odot$)
unitary
Zhao and Lattimer (2018)
95% 690
90% 573
80% 432
348 68%
198 50%
108 68%
80% 90
90% 74
95% 66


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


1.8
1.6
1.4
1.2
M (M⊙)
9
10
11
12
13
14
R (km)
Zhao and Lattimer (2018)

$M - R$ With Unitary Gas Limit Imposed



Systematic Uncertainties From Prior Choices

LVC and De et al. (2018) assumed uniform prior in Λ_1 and Λ_2, or $\tilde{\Lambda}$.

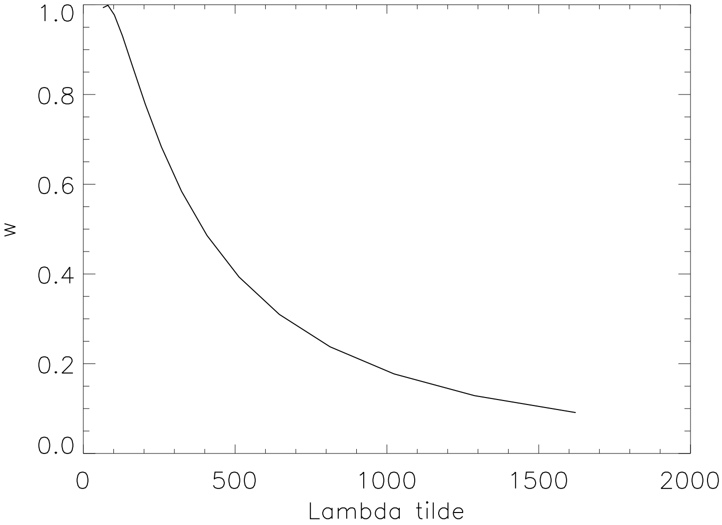
Capano et al. (2019) claim to reduce GW-inferred R uncertainty by 50%: 90% confidence upper limit decreased by ~ 1 km using nuclear theory constraints on neutron matter energy, 90% confidence lower limit raised by $\sim$1 km using Bauswein et al. (2017) lower limit to neutron star radius for remnant formation in BNS mergers.

Net effect is a 50% decrease in uncertainty in R estimate.

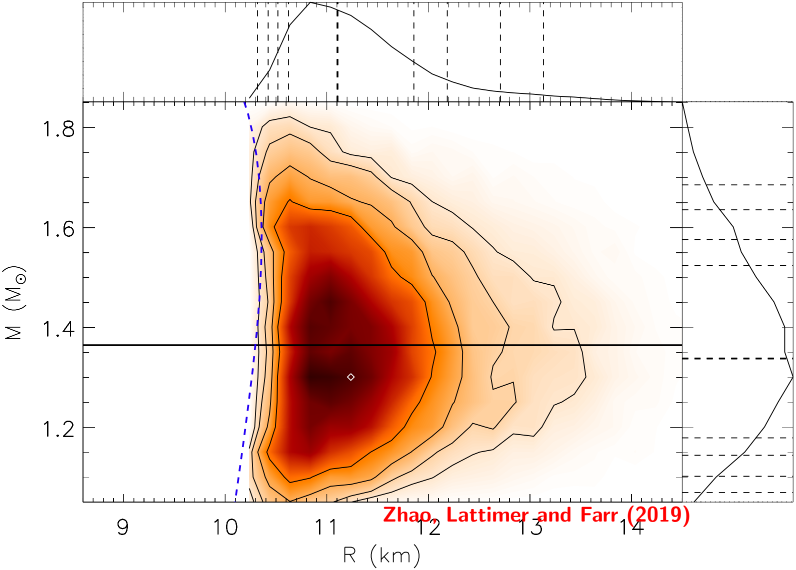
However, Capano et al. (2018) analyzed GW data using a Λ prior generated from a distribution of EOS's giving a uniform R distribution.

Coincidentally, *unitary gas conjecture* bound to $\tilde{\Lambda}$ predicts a similar lower limit $R \gtrsim 10.5$ km as Bauswein et al. (2017).

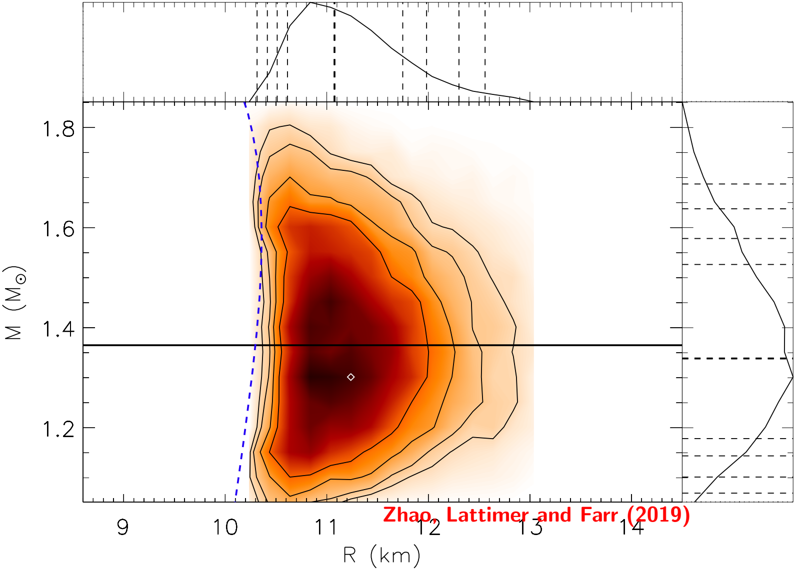
Implied $\tilde{\Lambda}$ Prior From Uniform M and R Priors



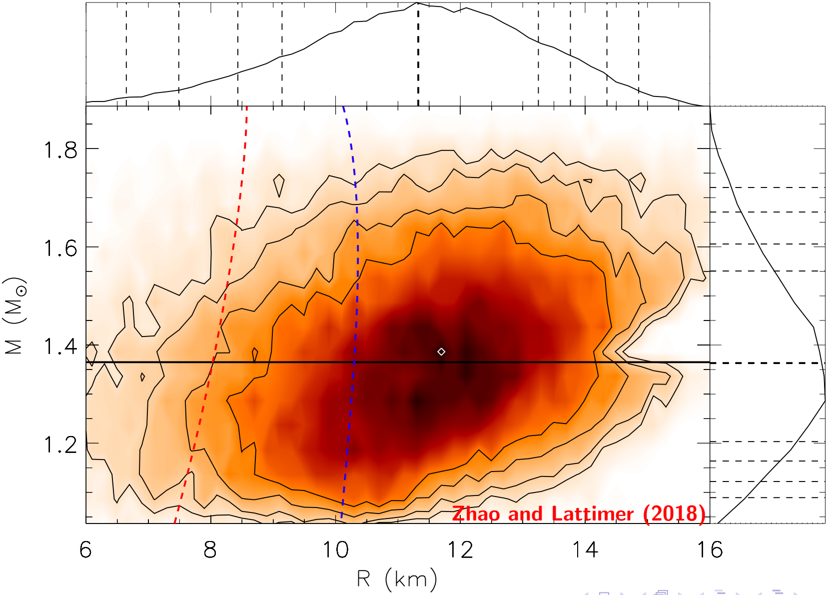
$M - R$ With UG and Uniform R Priors



$M - R$ With UG, NMT and Uniform R Priors



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



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 $M > M_{max,u}$, should 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$= M^b - M$,

$$\frac{\mathrm{BE}}{M} \simeq (0.058 \pm 0.006)\frac{M}{M_\odot} + (0.013 \pm 0.001)\left(\frac{M}{M_\odot}\right)^2 .$$

- 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 sufficient disc is ejected (not observed).
- If $M^b_T < M^b_{max,u}$, remant indefinitely stable, but possibly no GRB and disc ejecta poisoned 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 an upper limit to M_{max}, with approximate solution

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

LVC O3 Detections To Date (6 Months)

22 binary black hole systems, of which 1 is marginal

4 binary neutron star systems, of which 2 are marginal, $p_{\rm BNS} = 1$

- S190425z (156 ± 41 Mpc, FAR $= 4.5 \cdot 10^{-13}$)
- S190510g (1331 ± 341 Mpc, FAR $= 8.8 \cdot 10^{-10}$)
- S190901ap (241 ± 79 Mpc, FAR $= 7.0 \cdot 10^{-9}$)
- S190910h (241 ± 89 Mpc, FAR $= 3.6 \cdot 10^{-8}$)

5 black hole-neutron star systems, of which 2 are marginal, $p_{\rm NS} = 1$

- S190426c (377 ± 100 Mpc, FAR $= 1.9 \cdot 10^{-8}$) $p_{\rm BHNS} = 0.6$, $p_{\rm gap} = 0.25$, $p_{BHNS} = 0.15$
- S190814bv (267 ± 52 Mpc, FAR$=2.0 \cdot 10^{-33}$) $p_{\rm BHNS} = 0.998$, $p_{\rm gap} = 0.002$
- S190910d (632 ± 186 Mpc, FAR $= 3.7 \cdot 10^{-9}$) $p_{\rm BHNS} = 1.000$
- S190923y (438 ± 133 Mpc, FAR $= 4.8 \cdot 10^{-8}$) $p_{\rm BHNS} = 1.000$
- S190930t (108 ± 38 Mpc, FAR $= 1.5 \cdot 10^{-8}$) $p_{\rm BHNS} = 1.000$

2 mass gap systems, $p_{\rm gap} = 1$

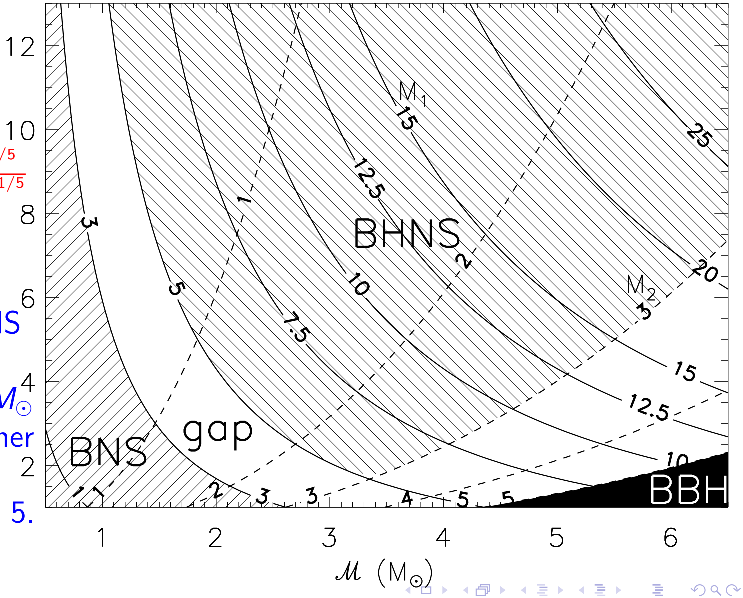
- S190924h (548 ± 112 Mpc, FAR $= 8.9 \cdot 10^{-19}$) $p_{\rm NS} = 0.297$
- S190930s (752 ± 224 Mpc, FAR $= 3.0 \cdot 10^{-9}$) $p_{\rm NS} = 0.0$

LVC Classifications

$q = \frac{M_1}{M_2} > 1$

$\mathcal{M} = \frac{(M_1 M_2)^{3/5}}{(M_1+M_2)^{1/5}}$

LVC defines NS if $M \leq 3M_\odot$, BH if $M \geq 5M_\odot$ and gap if either mass satisfies $3 < M/M_\odot < 5$.



S190426c: First Black Hole-Neutron Star Merger?

Information from LVC indicates a marginal case, with 14% chance of being 'terrestrial anomaly' (now revised to 58%).

Assuming it is cosmic, GCN circular 24411 stated $p_{\rm BHNS} = 0.60, p_{\rm gap} = 0.35, p_{\rm BNS} = 0.15, p_{\rm BBH} < 0.01,$ $p_{\rm HasNS} > 0.99$ and $p_{\rm rem} = 0.72$.

LVC will not release the chirp mass $\mathcal{M}$ (even though it is known relatively well), the mass ratio $q = M_1/M_2 > 1$ or the spin parameter χ of the BH (both known much less precisely).

But it is possible to recover $\mathcal{M}, M_1, M_2$ and χ in cases where $p_{\rm BHNS}, p_{\rm gap}$, p_{BNS} and/or $p_{\rm rem}$ are nonzero.

Technique: choose $\sigma_{\mathcal{M}}$ and σ_q as variables, and reverse-engineer probabilities.

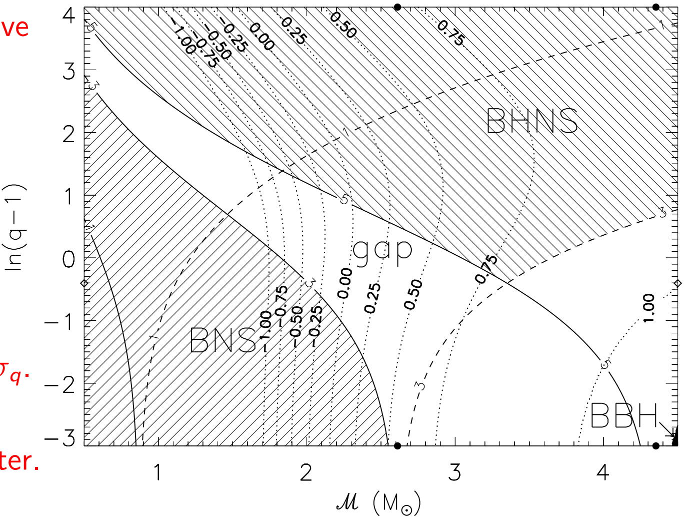
Suitable Variables

$\mathcal{M}$ assumed to have relatively small uncertainty $\sigma_{\mathcal{M}}$.

q has large uncertainty, but $q \in [1, \infty]$.

$\bar{q} = \ln(q-1)$ has $\bar{q} \in [-\infty, \infty]$ and large uncertainty σ_q.

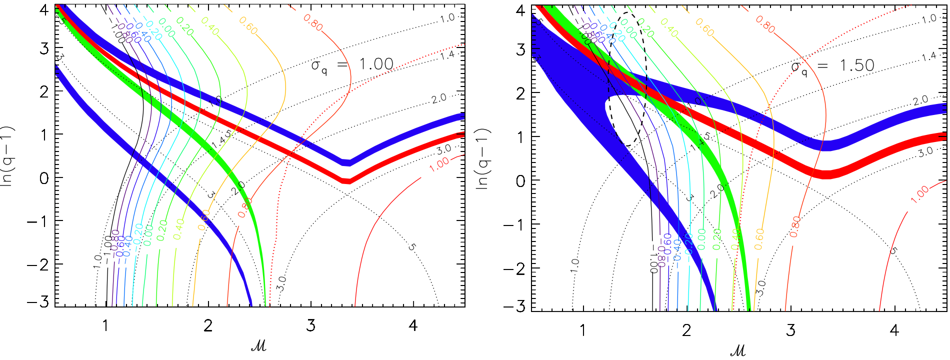
σ_q is the most important parameter.

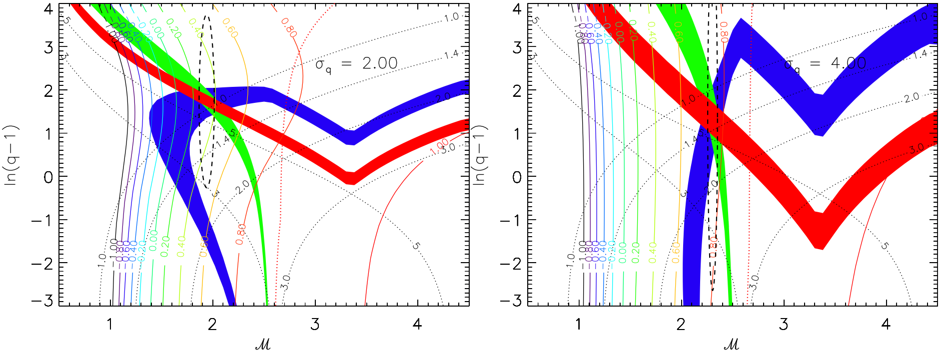


Probabilities

Assume

$$\frac{d^2p}{d\mathcal{M}d\bar{q}} = \frac{1}{2\pi\sigma_{\mathcal{M}}\sigma_q}\exp\left[-\frac{(\mathcal{M}-\mathcal{M}_0)^2}{2\sigma_{\mathcal{M}}^2}-\frac{(\bar{q}-\bar{q}_0)^2}{2\sigma_q^2}\right].$$




σq = 2.00
σq = 4.00
ln(q−1)
𝓜
4
3
2
1
0
−1
−2
−3
1
2
3
4

Spin

LVC uses model of Foucart et al. (2012, 2018) to determine mass M_d remaining outside the remnant more than a few ms after a BHNS merger:

$$M_d/M^b_{\rm NS} \simeq \alpha'\eta^{-1/3}(1-2\beta) - \hat{R}_{\rm ISCO}\beta\beta'\eta^{-1} + \gamma',$$

$\beta = GM_{\rm NS}/R_{\rm NS}c^2$, $\eta = q(1+q)^{-2}$ and
$\hat{R}_{\rm ISCO} = R_{\rm ISCO}c^2/GM_{\rm BH}$. $\alpha' \simeq 0.406$, $\beta' \simeq 0.139$, $\gamma' = 0.255$.

For the Kerr metric

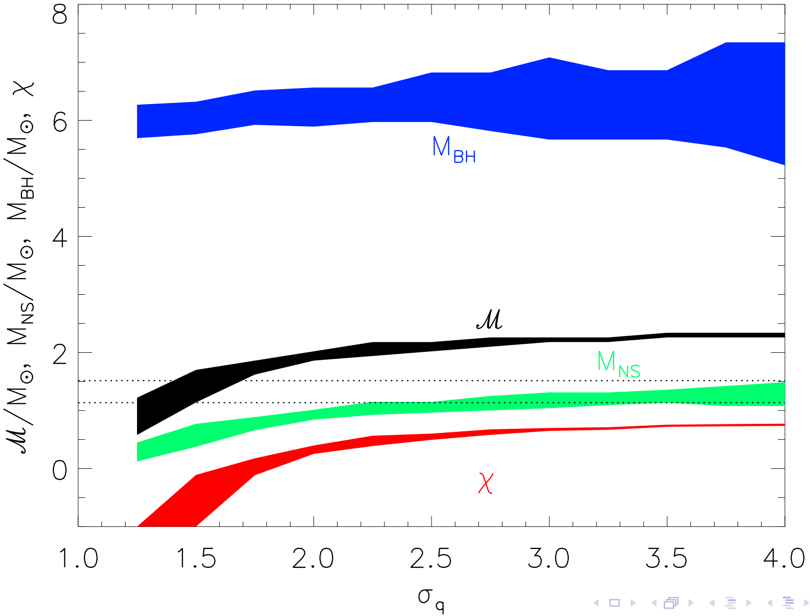
$$\chi = \sqrt{\hat{R}_{\rm ISCO}}\left(4/3 - \sqrt{\hat{R}_{\rm ISCO}/3 - 2/9}\right).$$

$M_d = 0$ implies

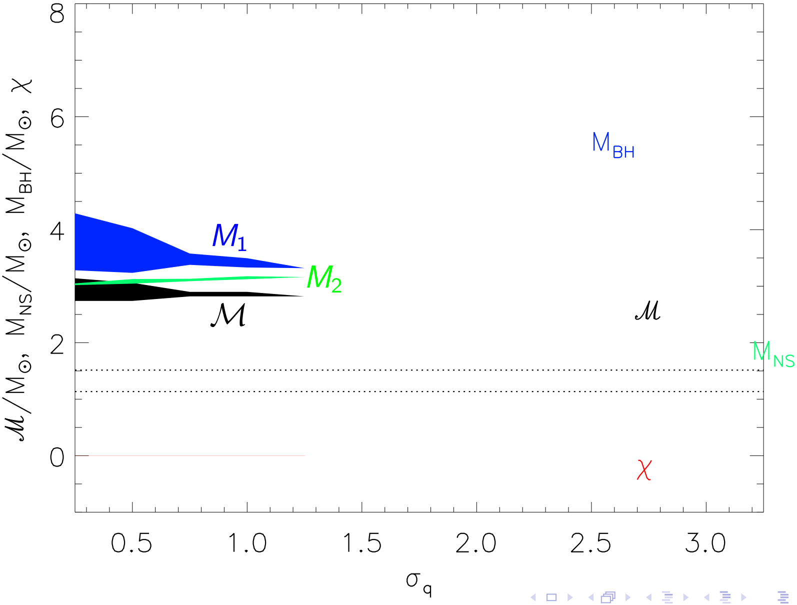
$$\hat{R}_{\rm ISCO} = (\beta'\beta)^{-1}(\alpha'\eta^{2/3}(1-2\beta) + \gamma'\eta).$$

χ is found from $p_d = \int\int_{M_d\geq 0} \frac{d^2p}{d\mathcal{M}d\bar{q}} d\mathcal{M}d\bar{q}$.

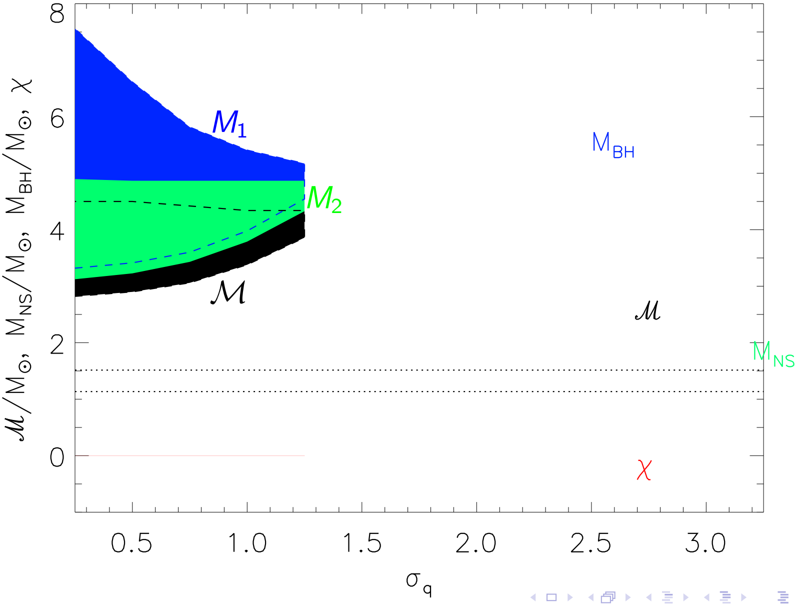
Convergence For Large σ_q



S190924h – A Gap Event



S190930s – A Gap Event



Summary

- GW170817 provided R and EOS information compatible with expectations from nuclear theory, experiment and other astrophysical observations, but still has a large systematic uncertainty from assumed Λ priors.
- GW170817 also hints that M_{max} is not far above the minimum provided by pulsar timing.
- NICER should soon provide complementary radius information from X-ray sources.
- Future GW measurements of BNS should be additive if sources are similar.
- A potential BHNS candidate seems to have $M_{\rm BH} \simeq 6 M_\odot$, $M_{\rm NS} \simeq 1.2 M_\odot - 1.4 M_\odot$ and $\chi \gtrsim 0.3$.