# Tidal deformabilities and radii of Neutron Stars from multimessenger observations

**Soumi De**
Syracuse University

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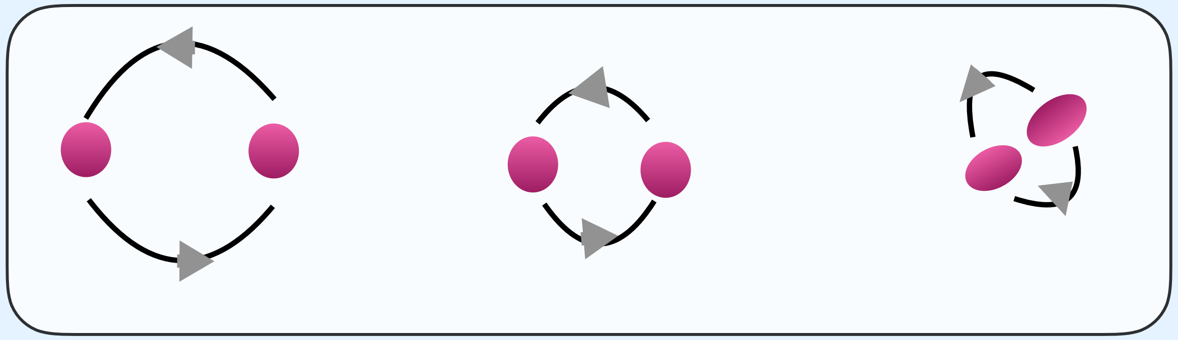
# Tidal deformations in binary neutron star inspirals



Neutron stars in binaries are deformed by the gravitational field of their companion towards the end of the inspiral

induced quadrupole moment

tidal deformability parameter

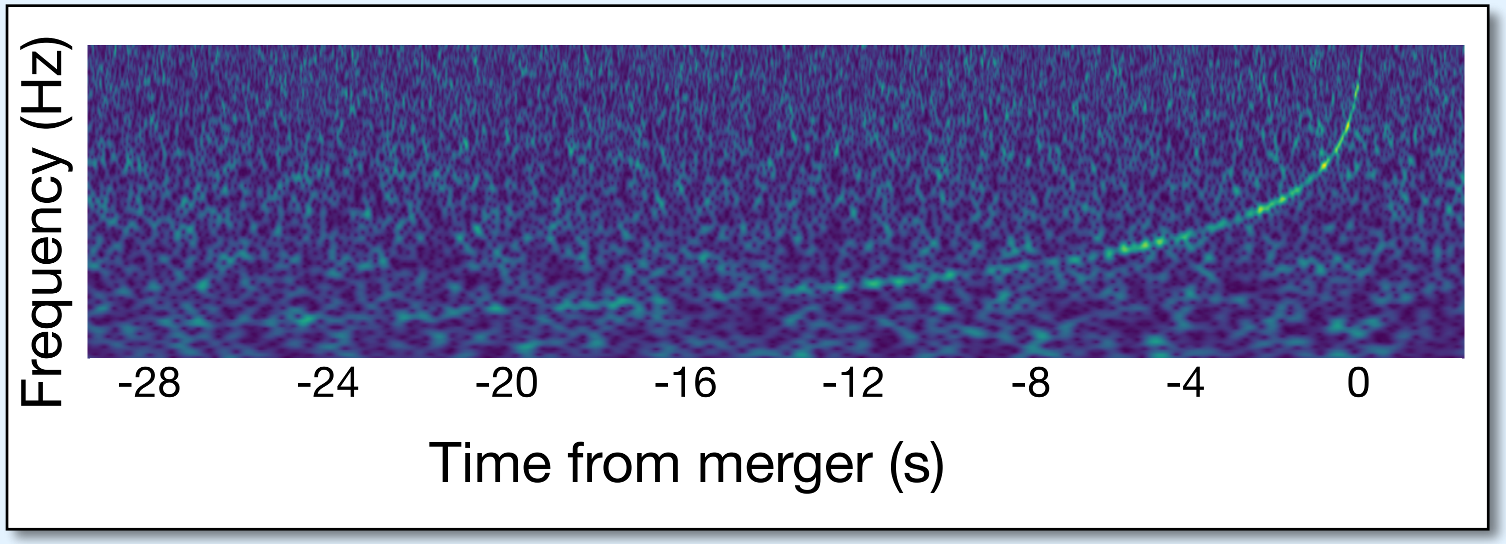
companion's gravitational field

$$Q_{i,j} = -\lambda \epsilon_{i,j}$$

$$\Lambda = \lambda / m^5$$

$$\Lambda = f(m, R, EOS)$$

# Effect of tidal deformability on gravitational waves from binary neutron stars

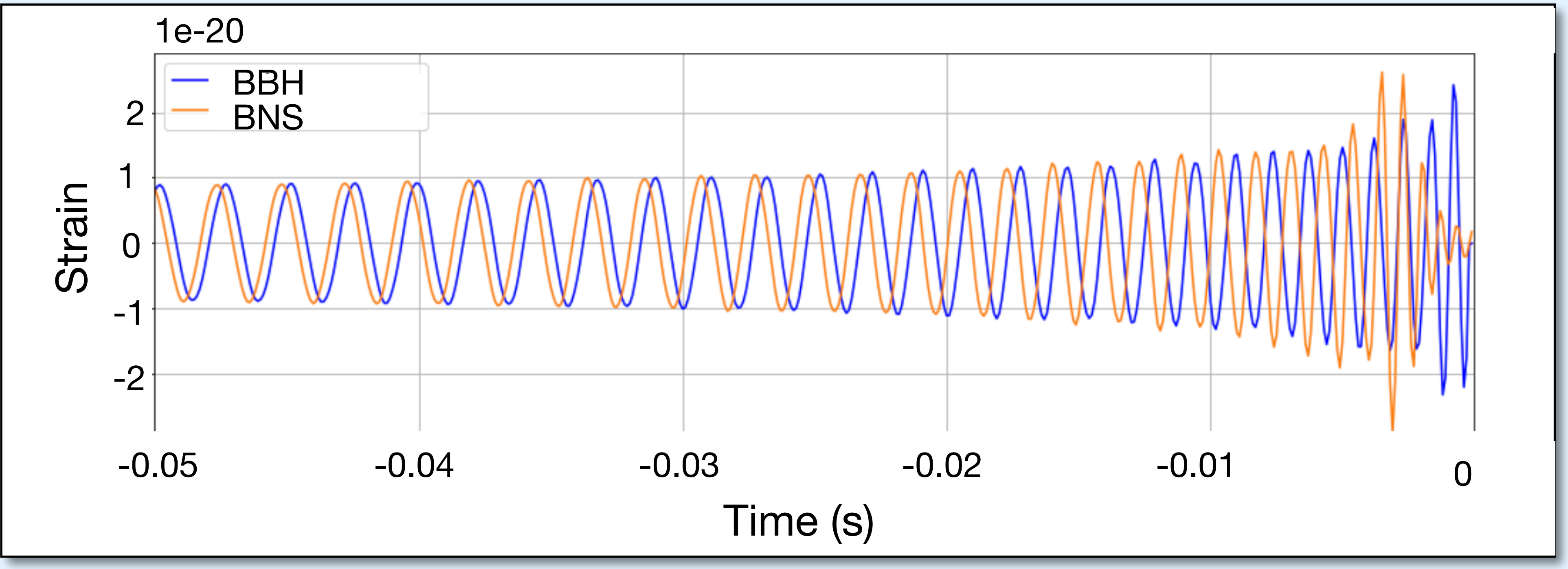


$$\tilde{\Lambda} = \frac{16}{13}\frac{(12q+1)\Lambda_1 + (12+q)q^4\Lambda_2}{(1+q)^5}$$

Enters into the phase of the emitted GW

$$\Phi(t) \sim \phi_0(\mathcal{M};t)\left[1 + \phi_1(\eta;t)\left(\frac{v}{c}\right)^2 + \right.$$

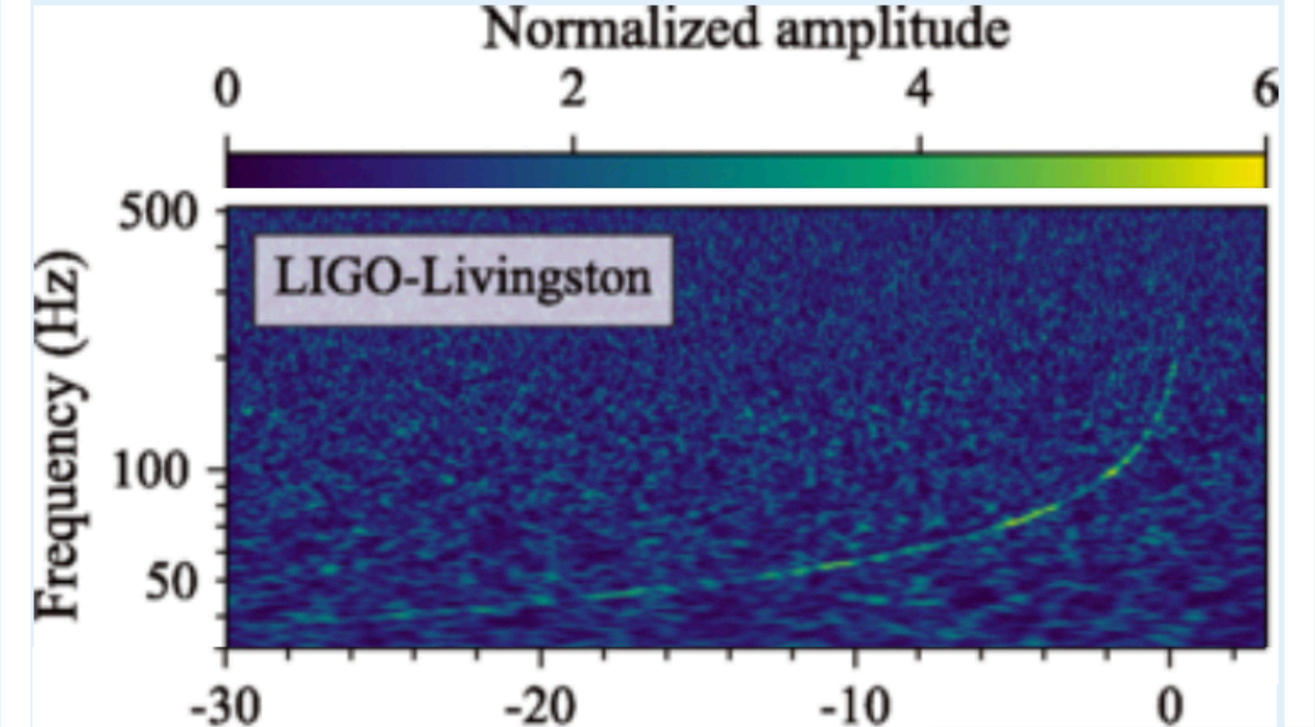
$$\left. ... + \phi_5(\tilde{\Lambda};t)\left(\frac{v}{c}\right)^{10}\right]$$

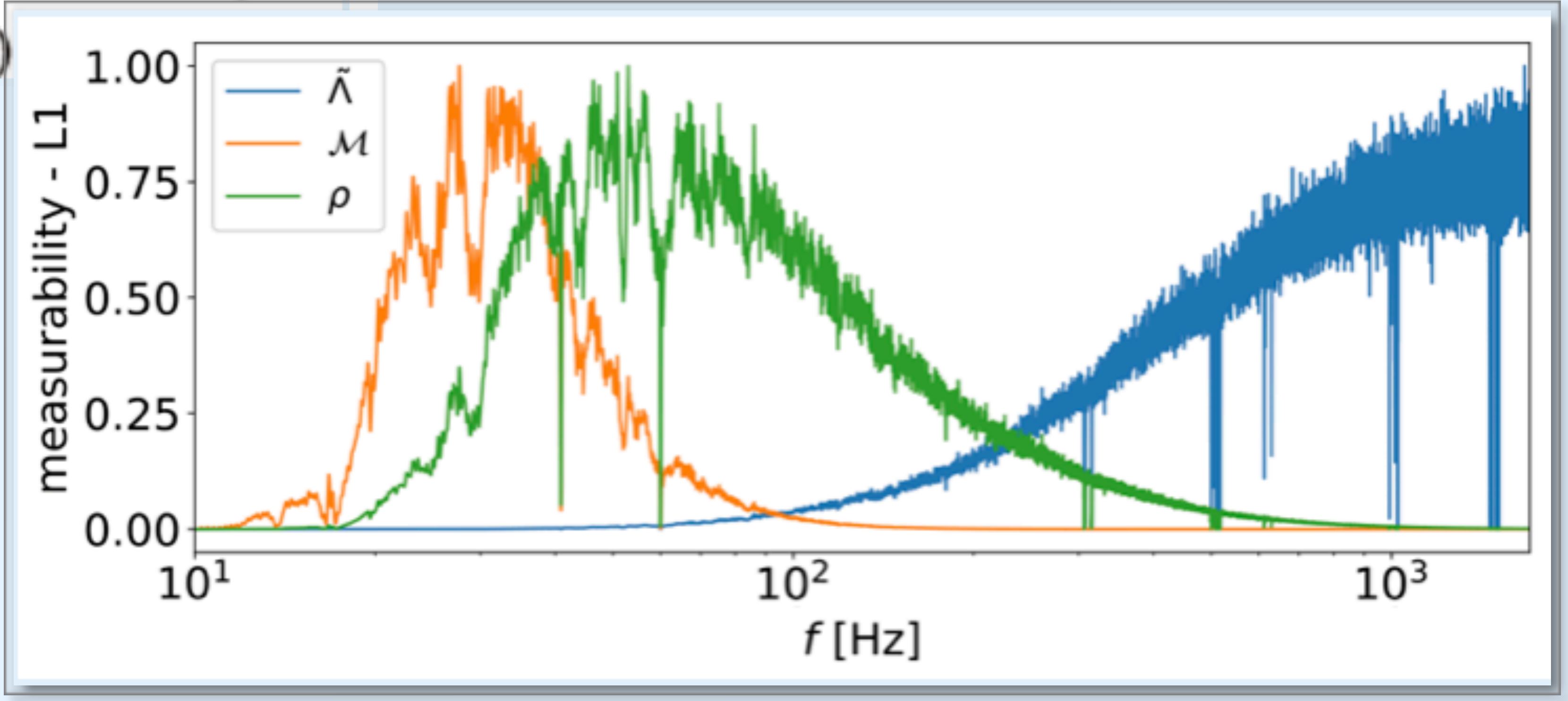


$$\Lambda_{1,2} = \frac{2}{3}k_2\left(\frac{R_{1,2}c^2}{Gm_{1,2}}\right)^5$$

$$q = \frac{m_2}{m_1}$$

# Measurabilities





De et al. Phys. Rev. Lett. **121**, 091102 (2018)

# Parameters of the gravitational waveform

**Parameter space** $\vec{\theta}$

- Component masses : $m_1, m_2$
- Component spins : $\vec{s}_1, \vec{s}_2$
- Distance to source : $d_{\mathrm{L}}$
- Source location and orientation : $\alpha, \delta, \psi, \iota$
- Coalescence time and phase : $t_c, \phi_c$
- Component tidal deformabilities : $\Lambda_1, \Lambda_2$

Bayesian inference analyses of GW data to extract these parameters

# Parameter estimation of the gravitational-wave data : Bayesian framework

prior

likelihood

$$p(\vec{\theta}|\vec{d}(t), H) = \frac{p(\vec{\theta}|H)p(\vec{d}(t)|\vec{\theta}, H)}{p(\vec{d}(t)|H)}$$

posterior

evidence

$\vec{d}(t)$ : gravitational-wave data from detectors

$\vec{\theta}$ : source parameters

$H$ : gravitational-wave model

$$d_i(t) = n_i(t) + s_i(t)$$

data

noise

signal

likelihood for a signal in stationary gaussian noise

$$\exp\left[-\frac{1}{2}\sum_{i=1}^{N}\langle\tilde{d}_i - \tilde{s}_i(\theta)|\tilde{d}_i - \tilde{s}_i(\theta)\rangle\right]$$

# Bayesian framework

$$p(\vec{\theta}|\vec{d}(t), H) = \frac{p(\vec{\theta}|H)p(\vec{d}(t)|\vec{\theta}, H)}{p(\vec{d}(t)|H)}$$

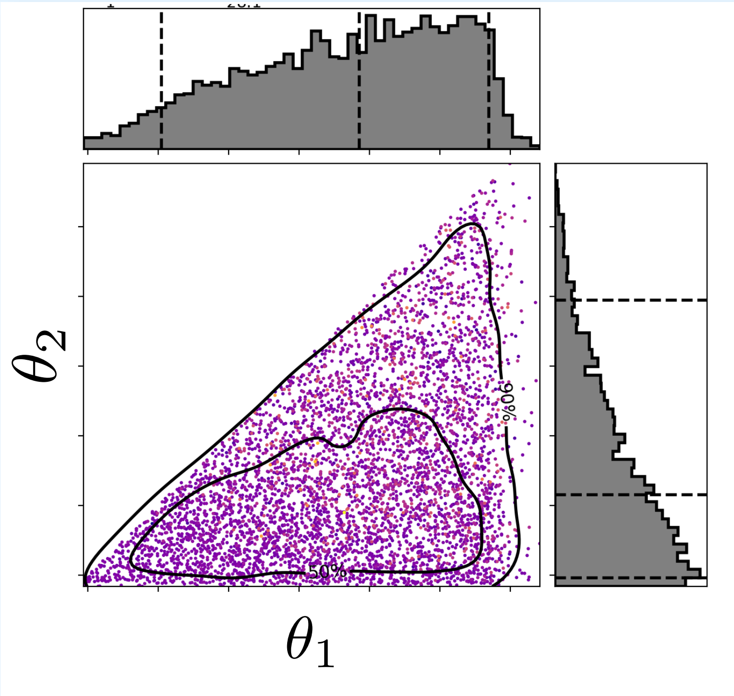
✓ Data $\vec{d}(t)$ from GW-Open Science Center

✓ Waveform model $h(t; \alpha, \delta, m_1, m_2, \vec{s}_1, \vec{s}_2, \Lambda_1, \Lambda_2, ...)$

✓ Prior distribution

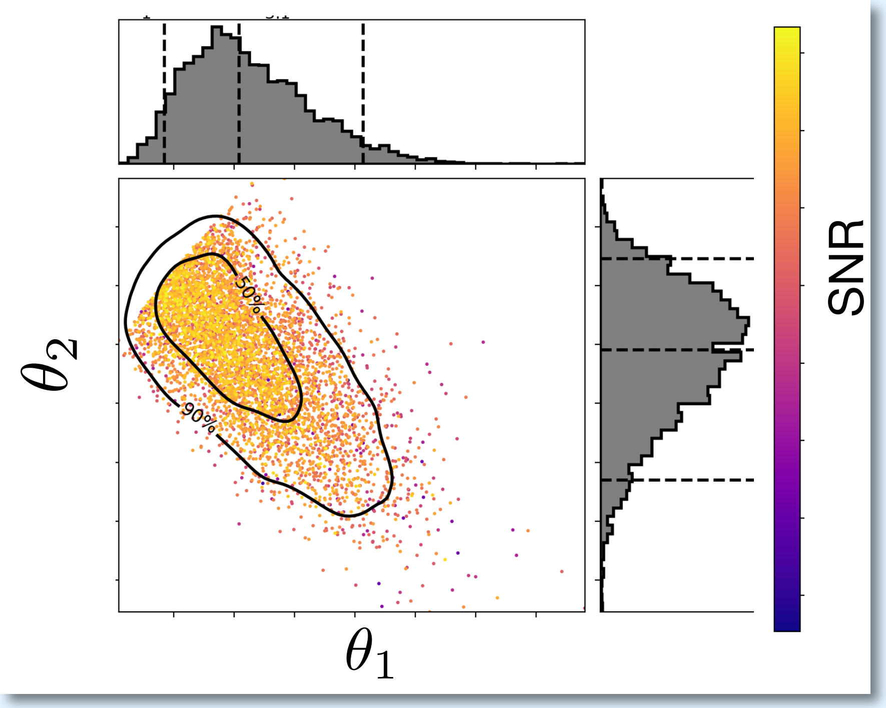
✓ Likelihood $p(\vec{d}(t)|\vec{\theta}, H)$

Prior $p(\vec{\theta}|H)$



Run sampler with Markov Chain Monte Carlo techniques to find the underlying distribution

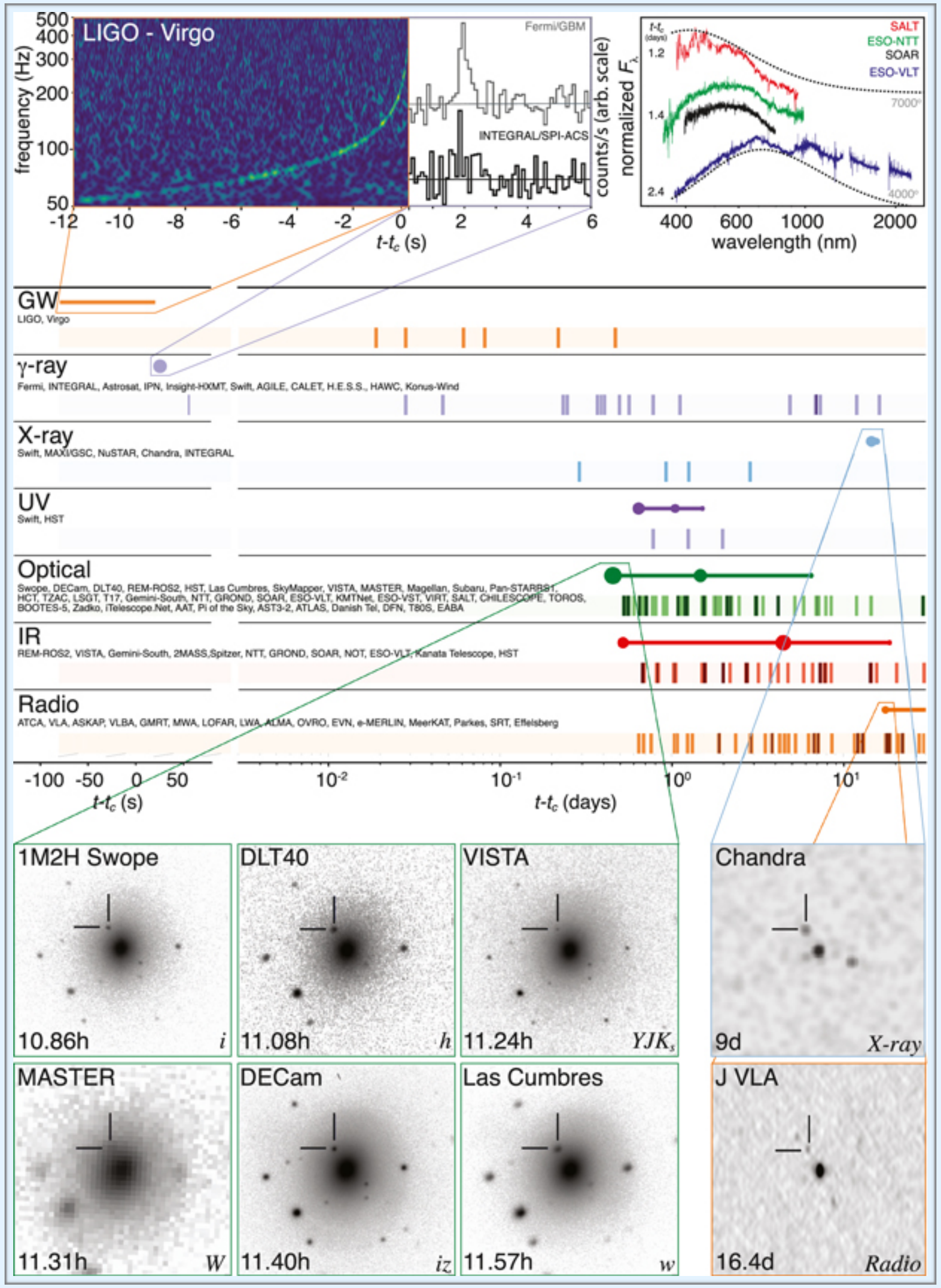
Posterior $p(\vec{\theta}|\vec{d}(t), H)$



✓ Marginalization to find parameter estimates

$$p(\theta_n|\vec{d}(t), H) \propto \int p(\vec{d}(t)|\vec{\theta}, H)p(\vec{\theta}|H)d\theta_1...d\theta_{n-1}$$

# Observation of GW170817



Abbott,…, SD et al. ApJL **848**, 2 (2017)

- Subsequent observation of gravitational waves and electromagnetic waves across the full spectrum

- Gave us the opportunity to use multimessenger observations to probe the physics associated with the event

# Analysis of GW170817 using multimessenger observations and chiral effective field theory

arXiv:1908.10352

Collin Capano, Ingo Tews, Stephanie Brown, Ben Margalit, Soumi De,
Sumit Kumar, Duncan Brown, Badri Krishnan, Sanjay Reddy (2019)

# What’s new in the analysis?

| **Chiral Effective Field** | + | **GW** | + | **EM** |
|---|---|---|---|---|
| theory constraints | | parameter estimation | | constraints |

# What's new in the analysis?

**Chiral Effective Field** + **GW** + **EM**

theory constraints

parameter estimation

constraints

accounts for density dependent uncertainties in the equation of state

sample directly over EoSs rather than sample over EoS related parameters

full set of EM information relating to binary parameters

# Equations of state from Chiral Effective Field theory

- Chiral Effective Field Theory at low density, provides a description of matter in terms of nucleons and pions

- It is expected to provide a good description of the equation of state of matter up to 1 - 2 $n_{\rm sat}$

- The equations of state constrained by the Chiral EFT are characterized by density-dependent theoretical uncertainty estimates

- The EoSs also ensure $c_{\rm sound} < c_{\rm light}$ and $M > 1.9 M_{\odot}$

# Gravitational wave parameter estimation method

Variable parameter space $\vec{\theta}$ in this analysis

- Component masses : $m_1, m_2$
- Component spins : $\vec{s}_1, \vec{s}_2$
- Distance to source : $d_\mathrm{L}$
- Source location and orientation : $\alpha, \delta, \psi, \iota$
- Coalescence time and phase : $t_c, \phi_c$

- ~~Component tidal deformabilities : $\Lambda_1, \Lambda_2$~~

- Equation of state constrained by Chiral EFT, indexed by : $i$ + $m_1, m_2$

Each EoS is described by a (m, R, $\Lambda$) dataset

↓

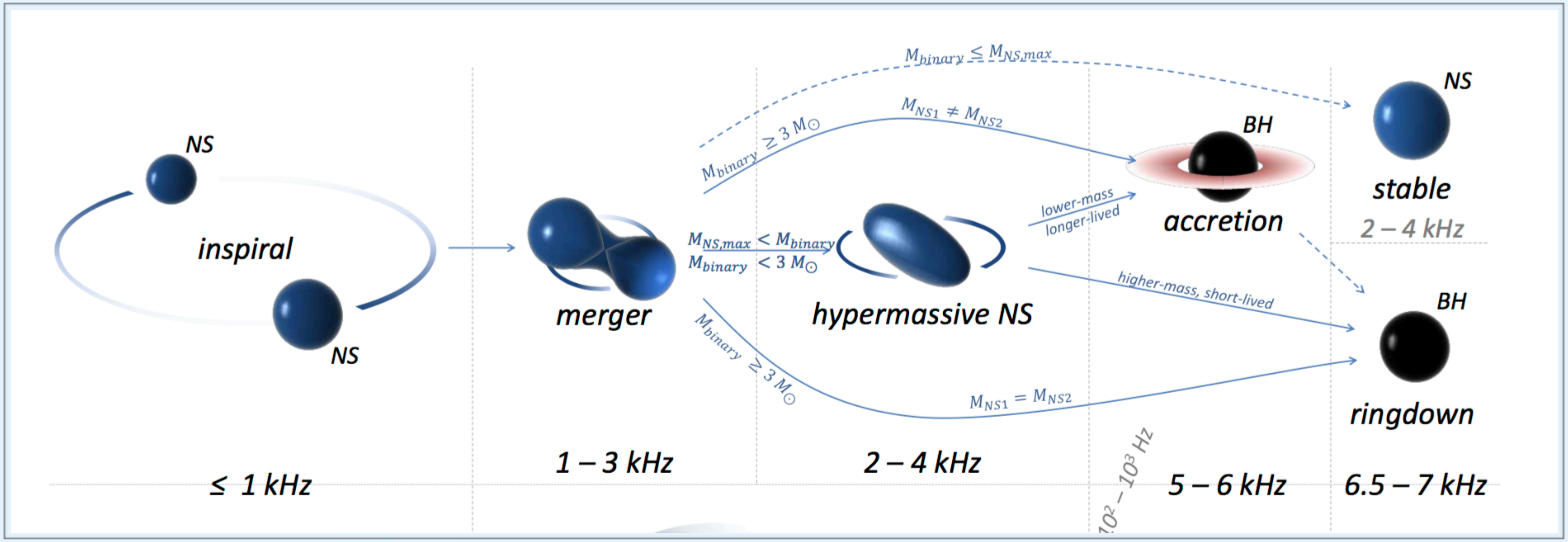
$R_1, R_2$ and $\Lambda_1, \Lambda_2$

by-passes the need of a universal relation

# Gravitational wave parameter estimation method

- Analyzed GW data between 20 - 2048 Hz
- Used TaylorF2 waveform model (Better waveform models did not produce an significant difference in results)
- Assumed low spins $\chi < 0.05$
- Performed Bayesian inference analysis using two families of EoSs generated with a uniform prior on $R_{1.4M_\odot}$ using Chiral EFT

# Constraints from electromagnetic observations of GW170817



Bartos et al. (2013) CQG 30, 123001

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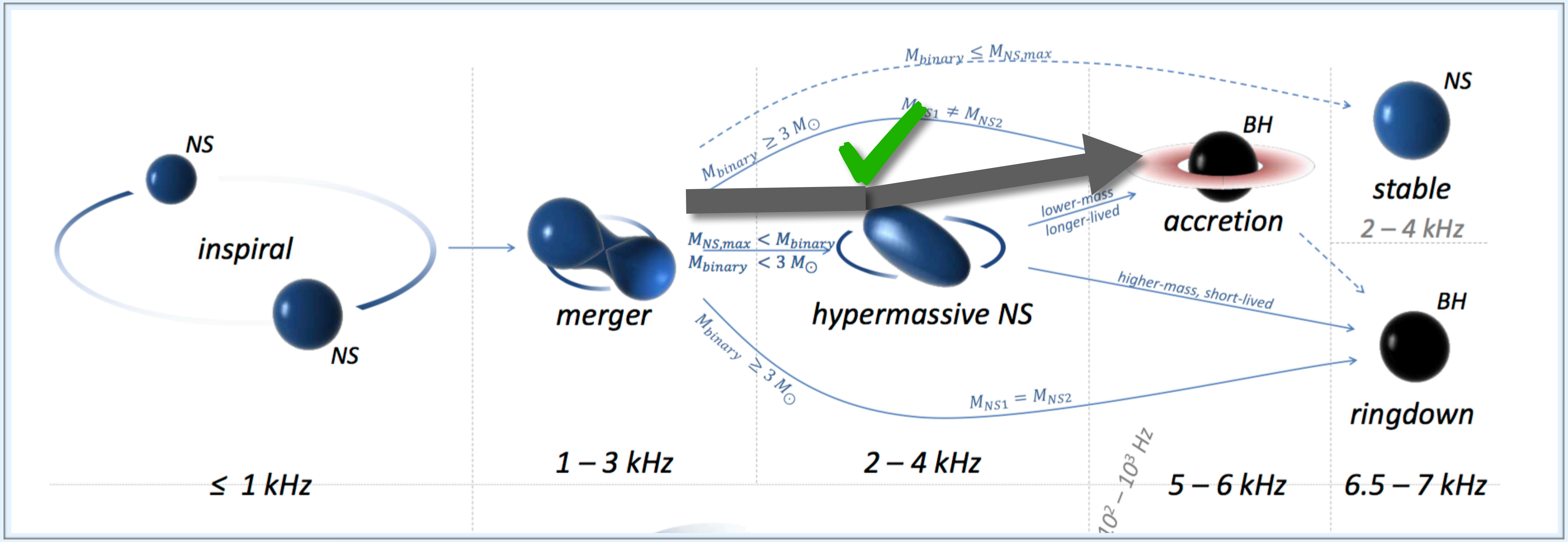

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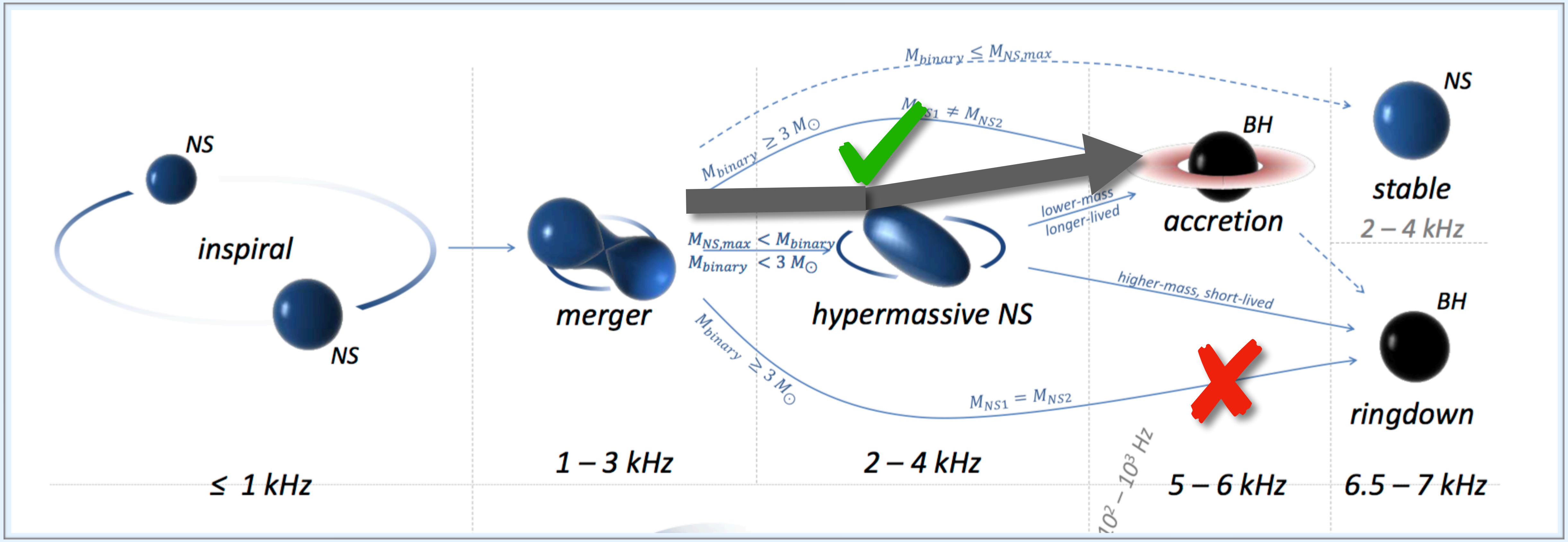


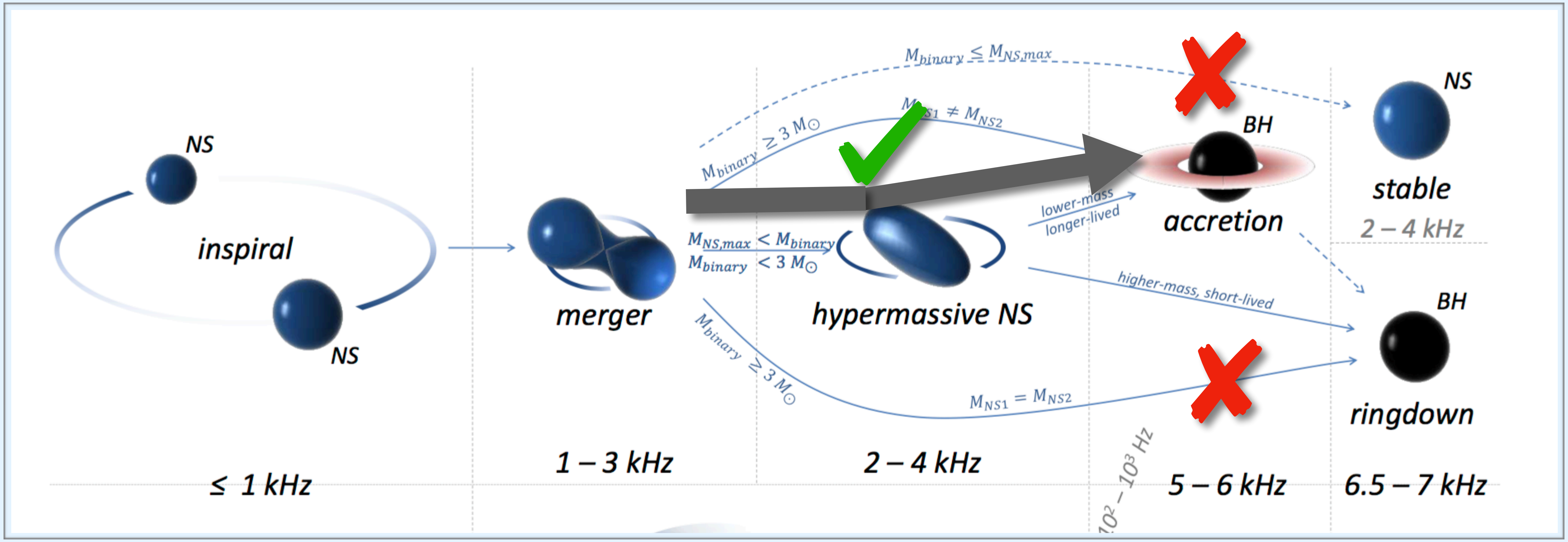
Bartos et al. (2013) CQG 30, 123001

- Total mass in agreement with **No prompt collapse to BH**

$$M_{\rm total} < M_{\rm thres} \approx M_{\rm max}\left(2.380 - 3.606\frac{GM_{\rm max}}{c^2 R_{1.6M_\odot}}\right) \pm 0.05 M_\odot$$

Bauswein et al. PRL 111, 131101 (2013)

# Constraints from electromagnetic observations of GW170817



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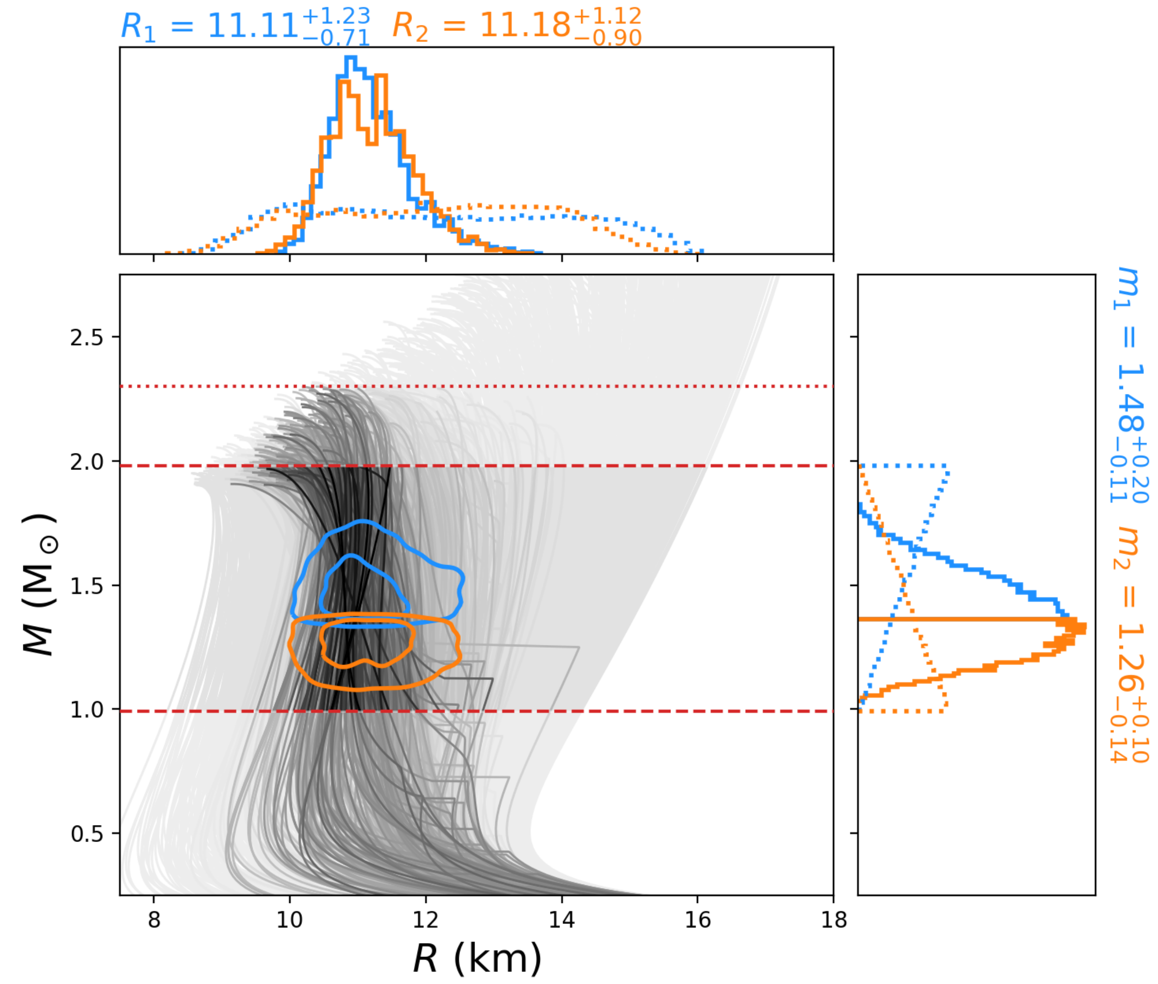
Bauswein et al. PRL 111, 131101 (2013)

- Max NS mass in agreement with **No long-lived NS**

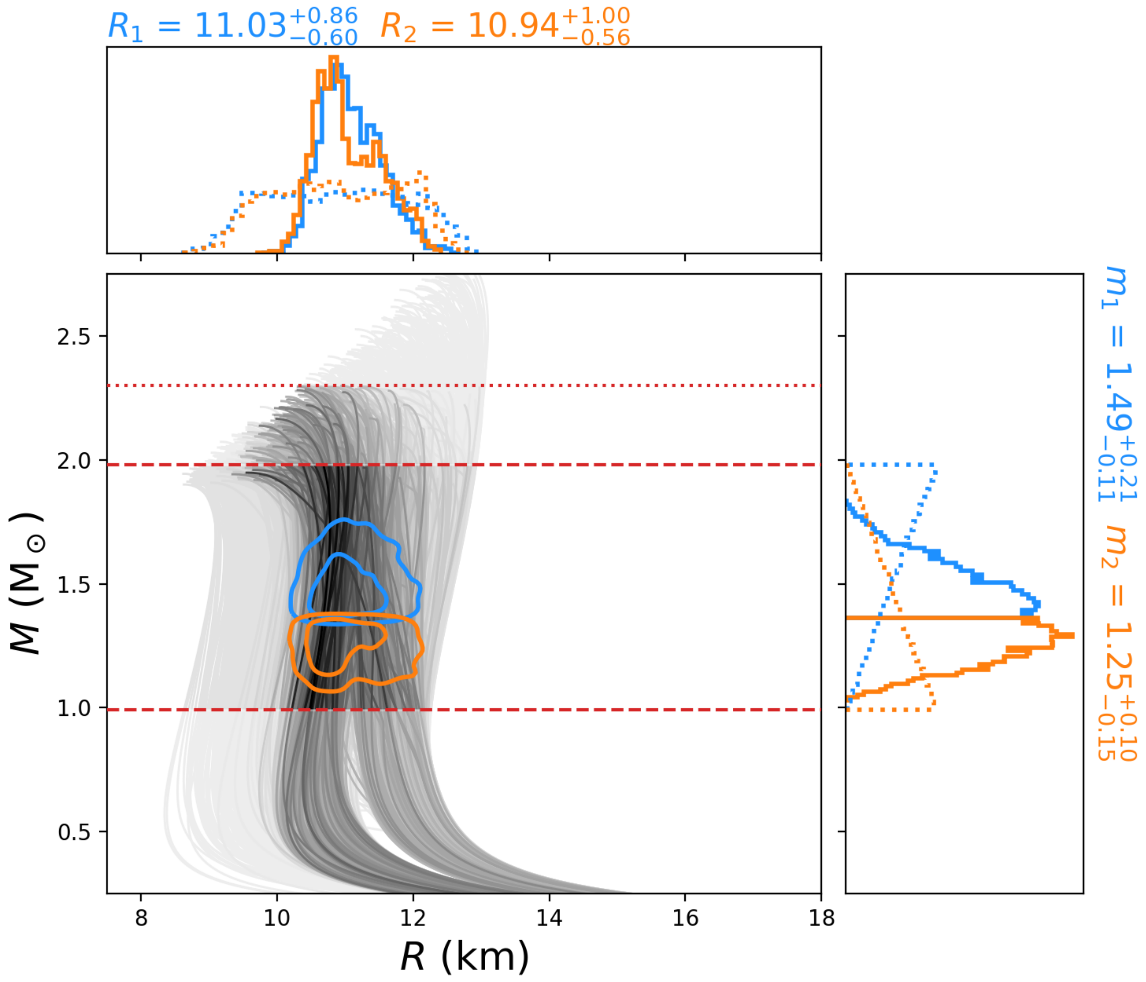
$$M_{\rm max} < 2.3M_\odot$$

# Analysis of GW170817

Constrained till $n_{\text{sat}}$

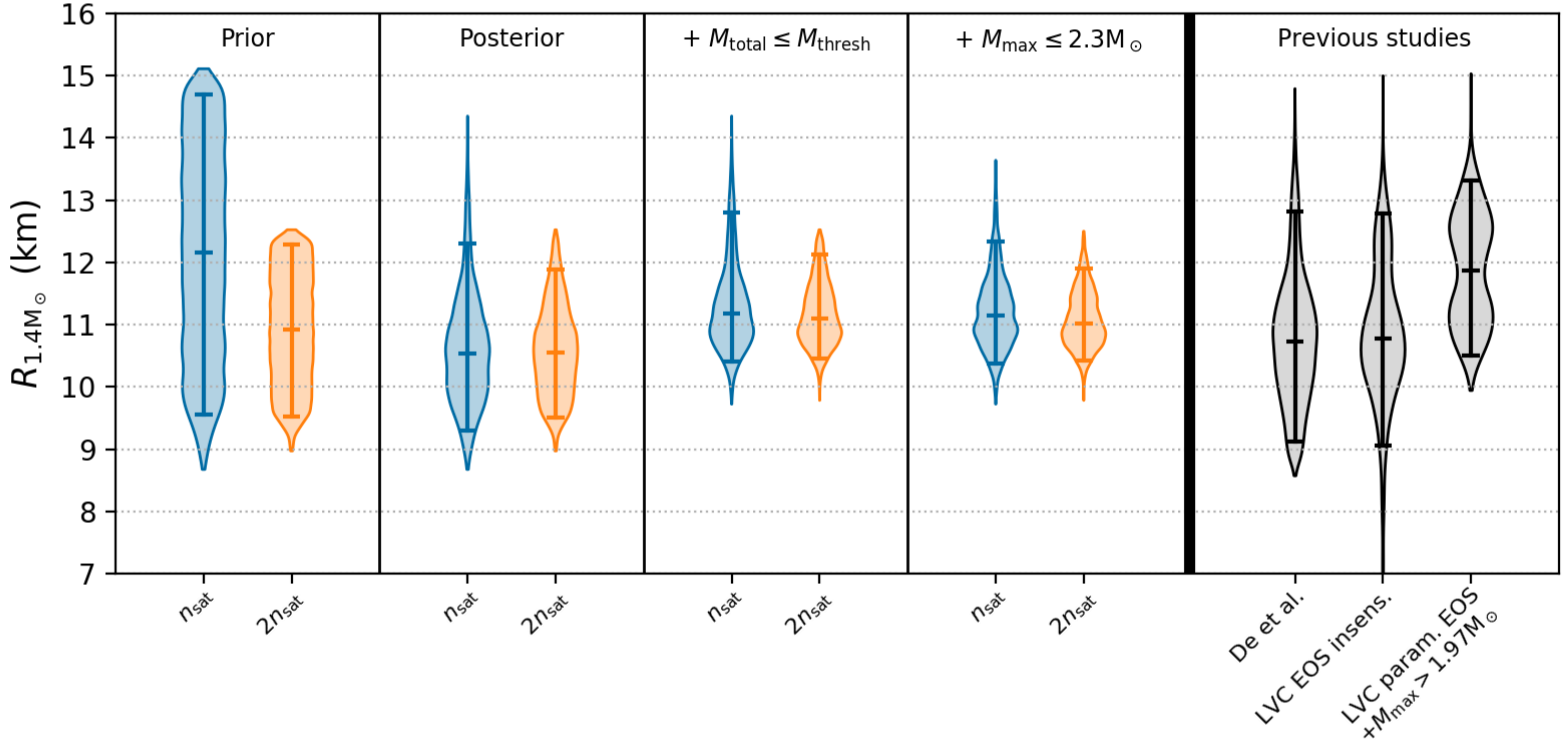


Constrained till $2n_{\text{sat}}$



Capano, Tews, Brown, Margalit, **SD** et al (2019), arXiv:1908.10352

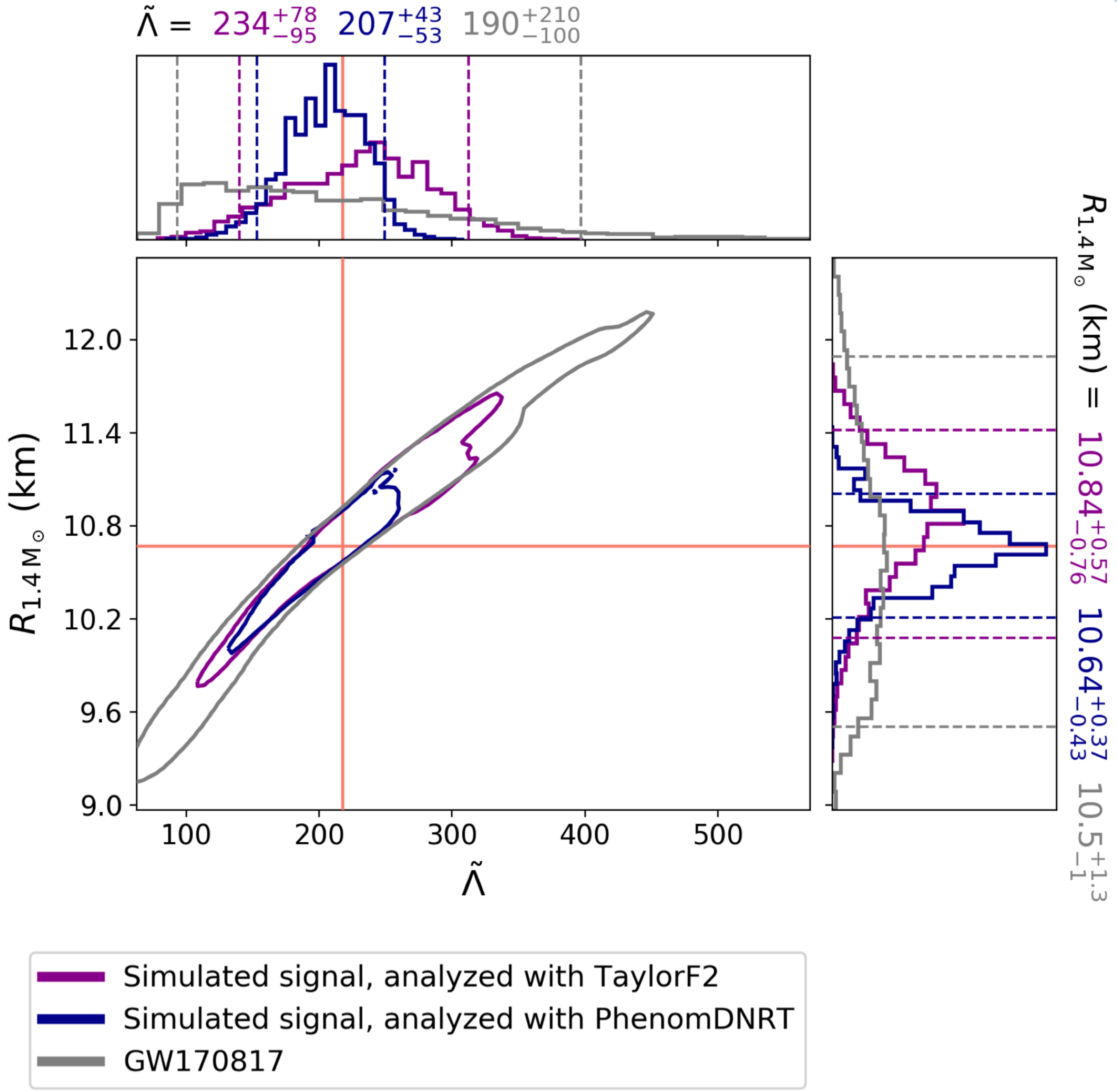
# Radius measurements from analyses of GW170817



Capano, Tews, Brown, Margalit, **SD** et al (2019), arXiv:1908.10352

Posterior samples available at https://github.com/sugwg/gw170817-eft-eos

# Prospects for improving measurements



- Using simulated signals at SNR ~100 we find ~2.9x improvement in measurement uncertainty
- Better waveform models further improves the measurements by 2x
- Gravitational waves alone will be able to constrain upper and lower bounds of tidal deformability and radii for loud SNR signals
- Low SNR signals would need combination of information from GW + EM + nuclear theory

# Astrophysical source distinguishability using gravitational waves

- Perform Bayesian Inference analyses with BNS and BBH template waveforms models

- Compute Evidence for each model marginalizing over the full parameter space

$$\mathcal{Z} = \int p(\vec{d}(t)|\vec{\theta}, H)p(\vec{\theta}|H)d\theta_1 ... d\theta_n$$

- Compute Bayes factor comparing BNS to BBH model $\mathcal{B} = \mathcal{Z}_{\mathrm{BNS}}/\mathcal{Z}_{\mathrm{BBH}}$

$\mathcal{B}$ ~ 1.0 for GW170817. The event cannot distinguish between BNS and BBH mergers

$\mathcal{B}$ ~ $10^5$ for simulated GW170817 in aLIGO design sensitivity, SNR~100. Gravitational waves can reliably distinguish between BNS and BBH mergers for high-SNR observations.

# Summary

- We analyzed GW170817 combining GW and EM observations and Chiral Effective Field theory

- We have provided the most stringent constraints on radii of neutron stars to date

- With Advanced LIGO design sensitivity
    - there are prospects of improving the current constraints by more than two times using gravitational waves alone
    - gravitational waves can be used to distinguish between BNS and BBH events

Thank you for your attention!

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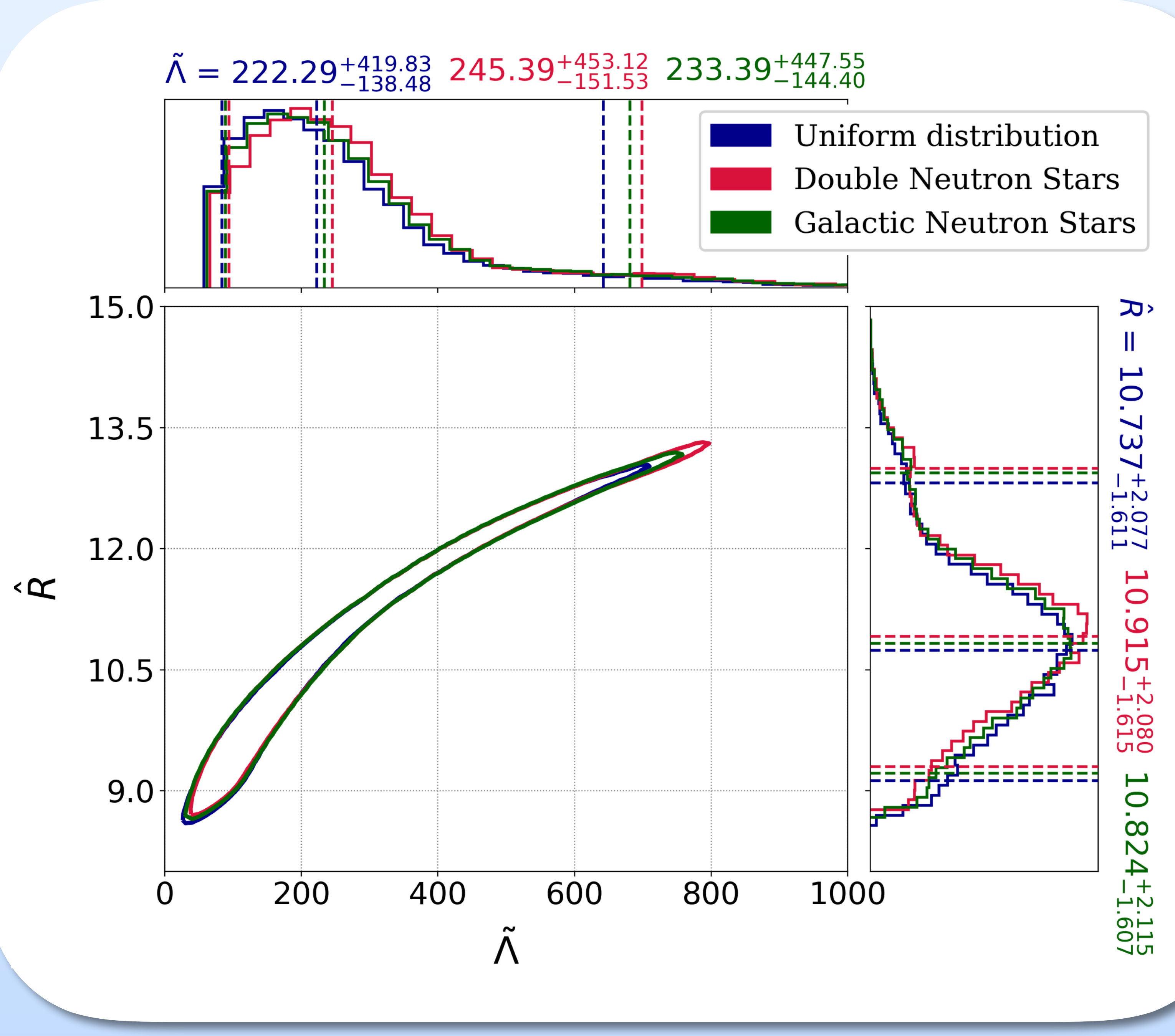
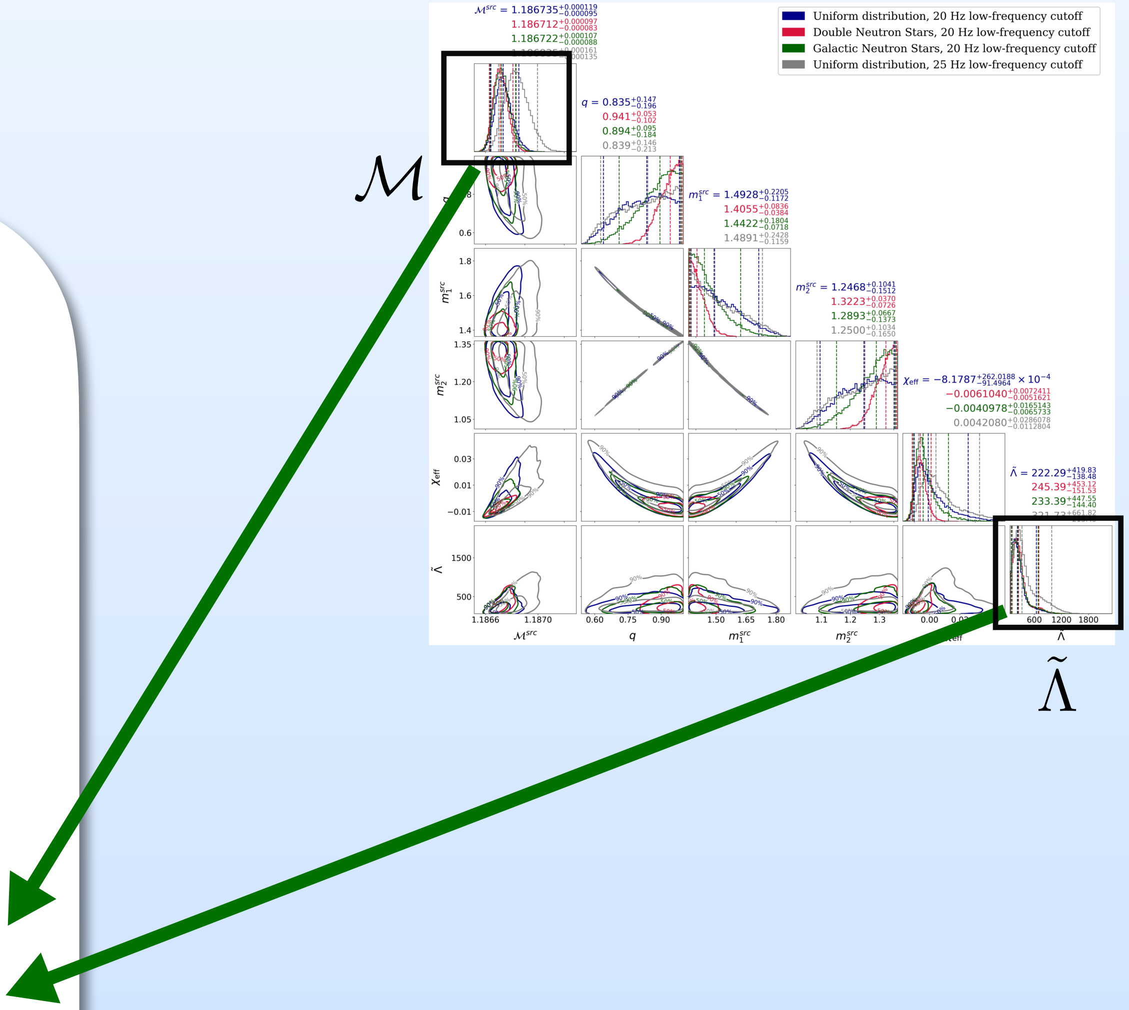
# Extra Slides

# Measurement of the neutron star radius (1)

*De, Finstad, Lattimer, Brown, Berger, Biwer (2018)*





$$\hat{R} = (11.2 \pm 0.2)\frac{\mathcal{M}}{M_\odot}\left(\frac{\tilde{\Lambda}}{800}\right)^{1/6}$$

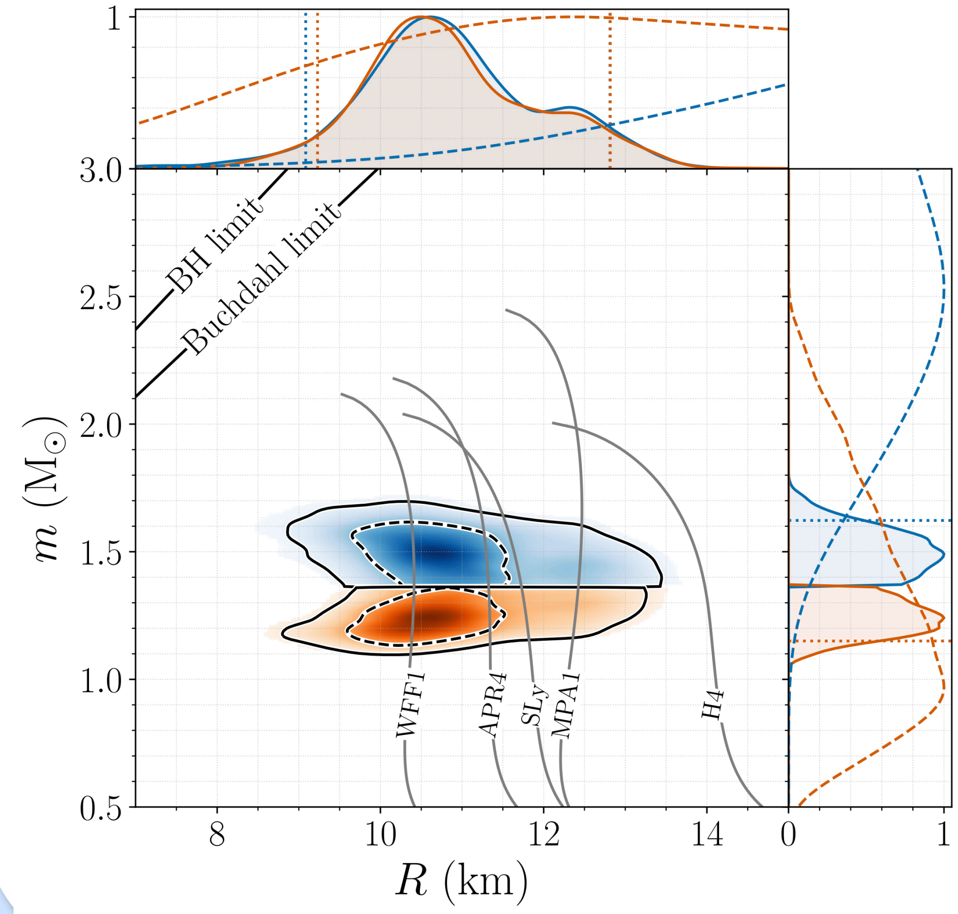
Soumi De (Syracuse Univ.)

# Measurement of the neutron star radius (2)

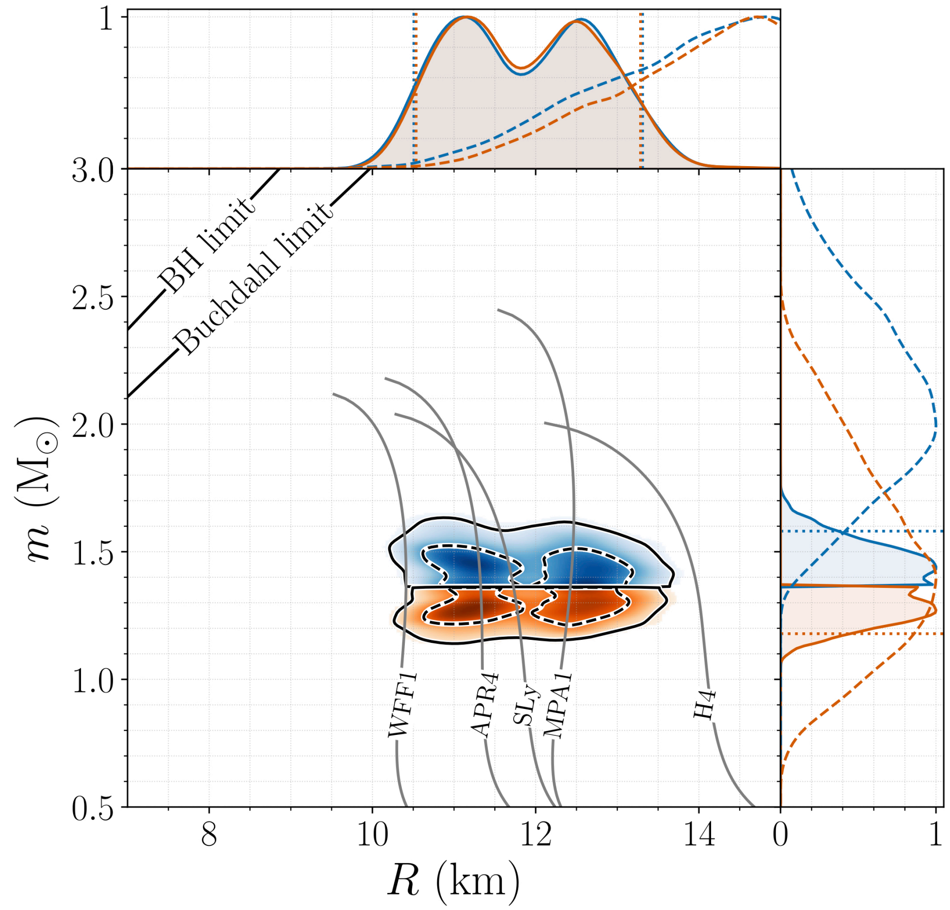
*LIGO-Virgo Collaboration (2018)*

**EOS-insensitive relations :**

**Parameterized EOS :**



$$(R_1, R_2) = (10.8^{+2.0}_{-1.7}, 10.7^{+2.1}_{-1.5})$$



$$(R_1, R_2) = (11.9^{+1.4}_{-1.4}, 11.9^{+1.4}_{-1.4})$$

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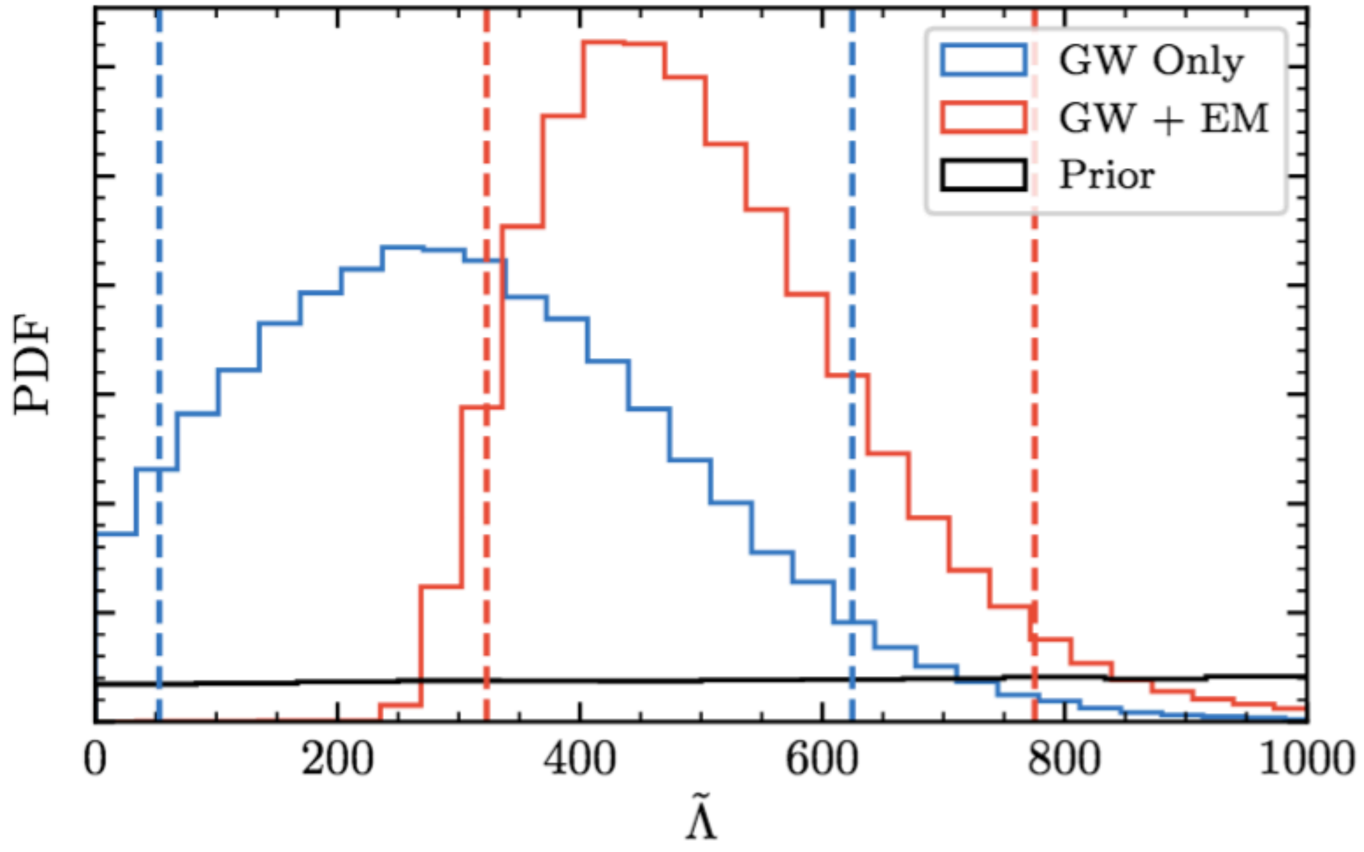
# Measurement of the neutron star radius (3)

*Radice, Dai (2018)*



- EM data incorporation showed $\tilde{\Lambda} < 300$ excluded
- Used $\hat{R}(\mathcal{M}, \tilde{\Lambda})$ expression from De et al to get

GW : $R_{1.4} = 11.3^{+1.5}_{-2.8} \pm 0.2$ km

GW + EM : $R_{1.4} = 12.2^{+1.0}_{-0.8} \pm 0.2$ km

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