Studying neutron star matter with gravitational waves in the multimessenger era

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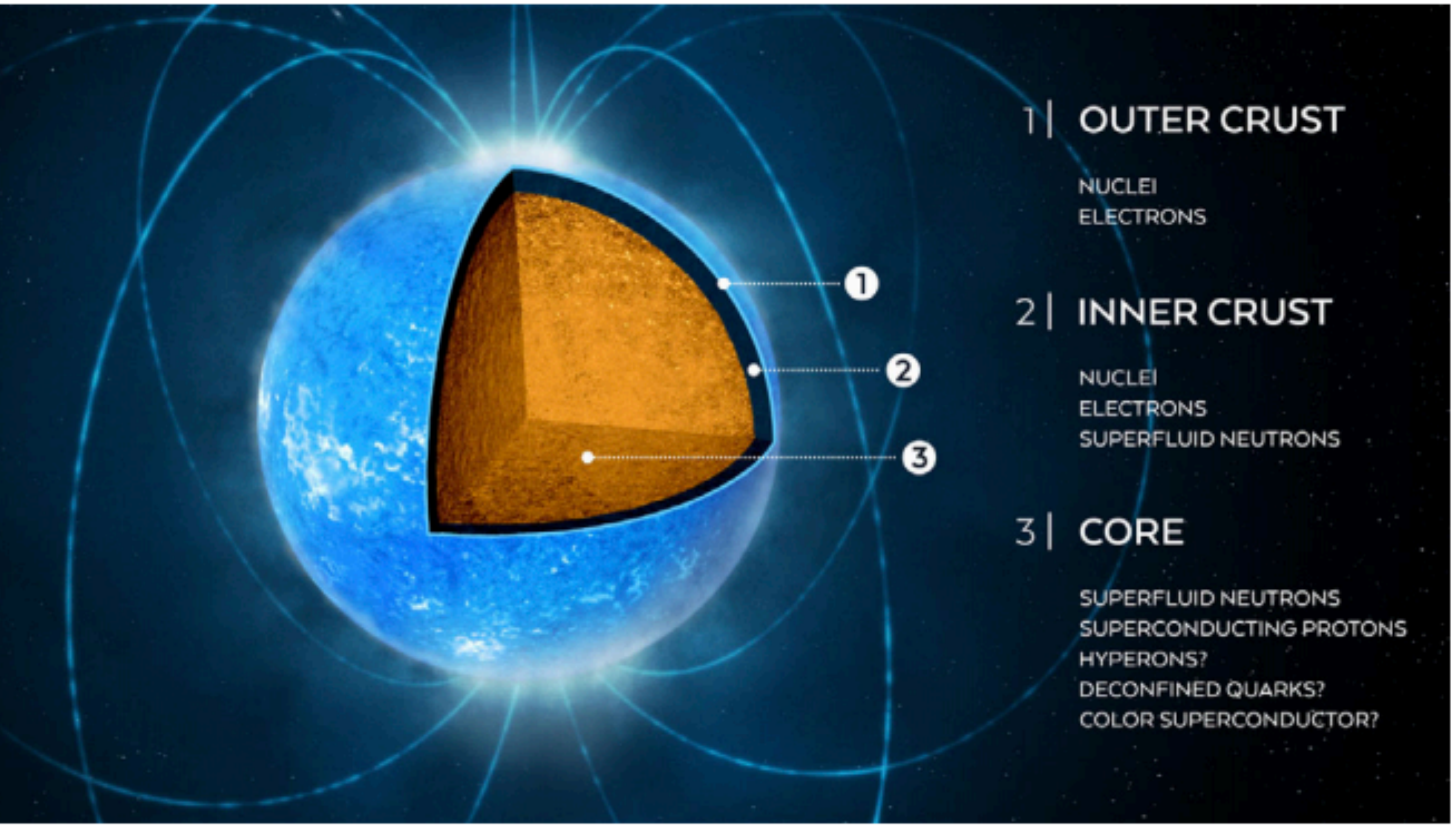
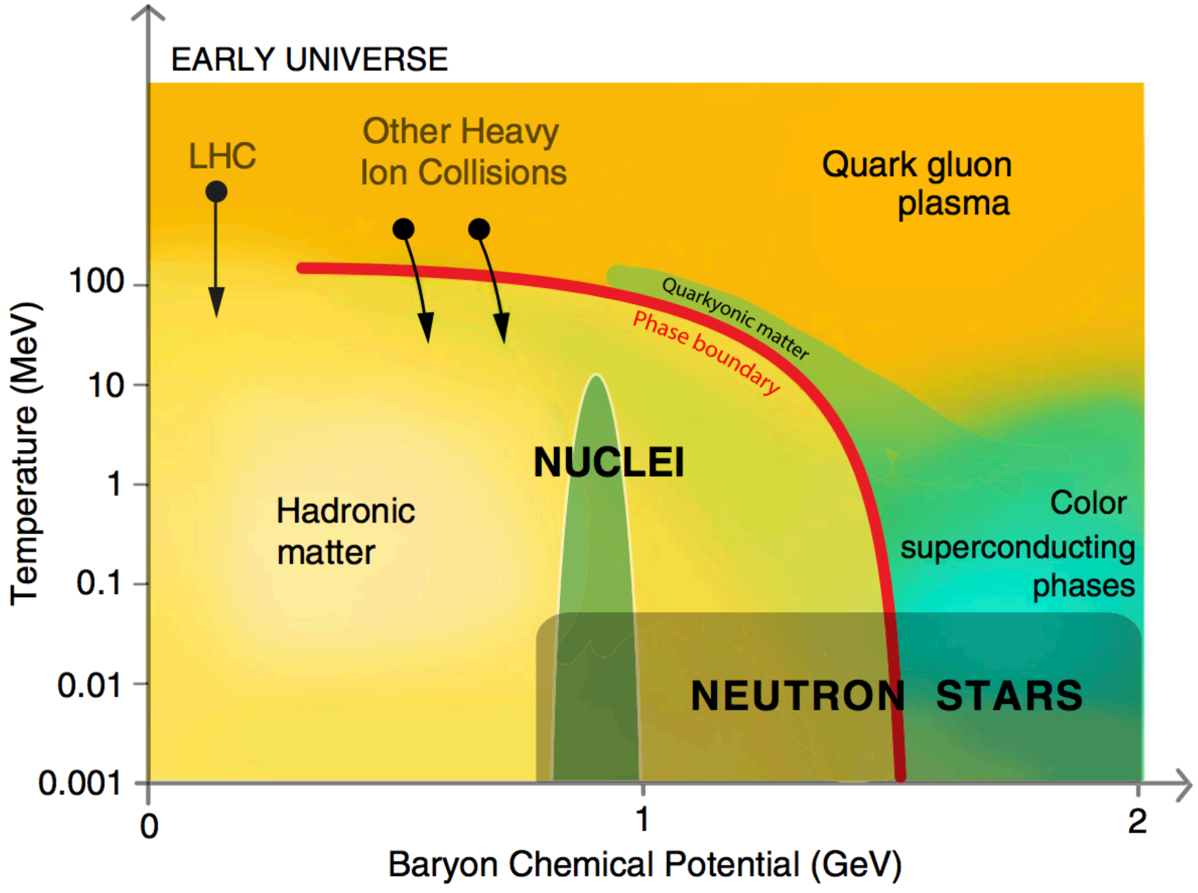
Neutron stars

The last frontier for stable matter

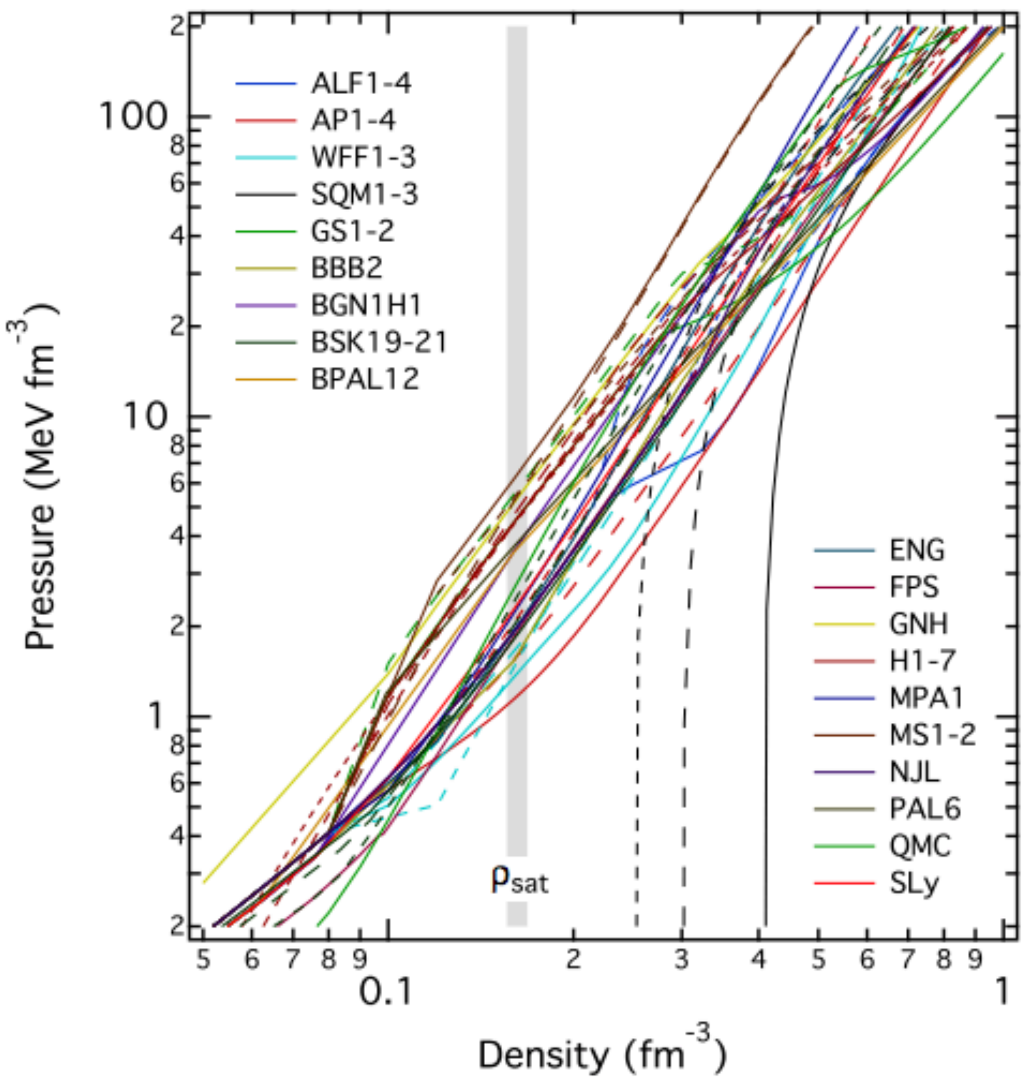




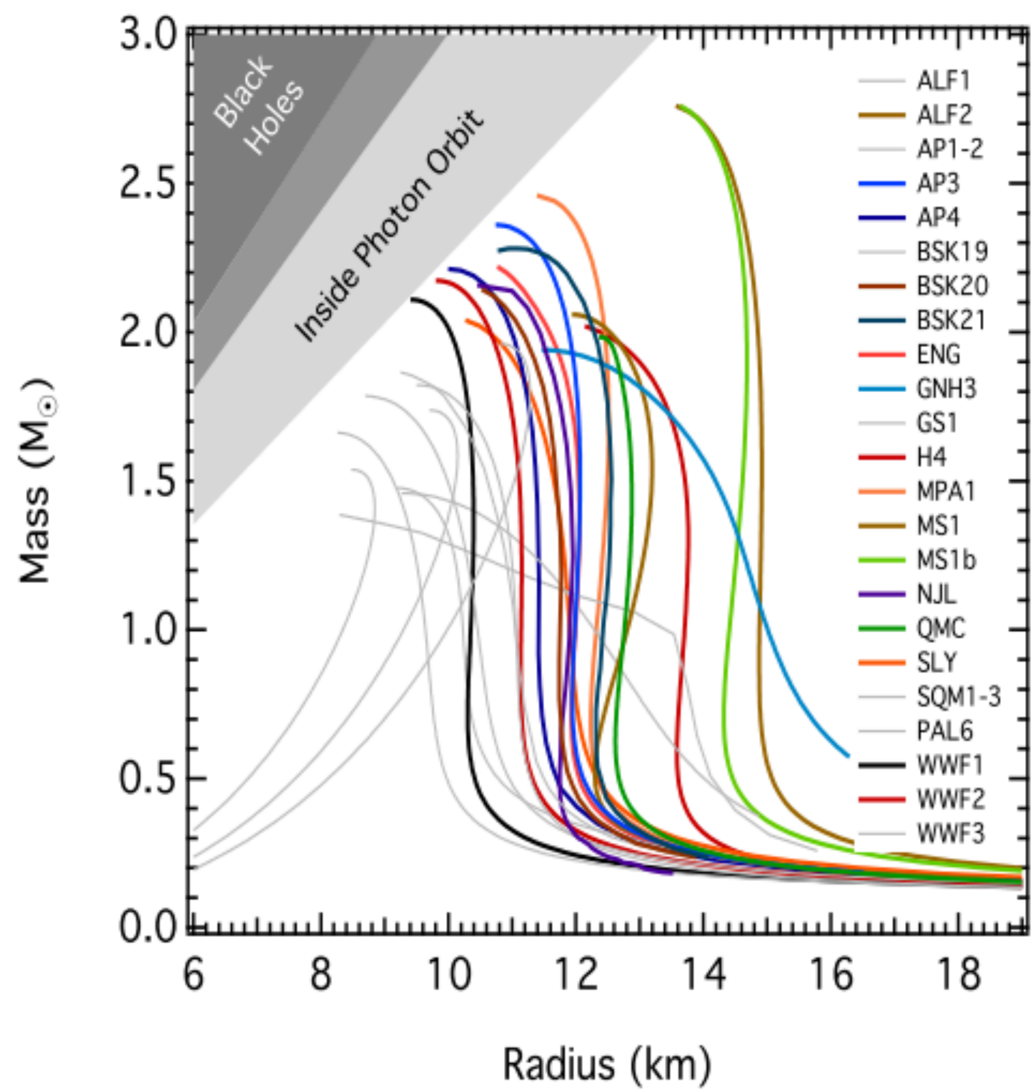
Watts+ (arxiv:1602.01081)

Last frontier for stable matter

***Microscopic* properties of dense matter in beta equilibrium**



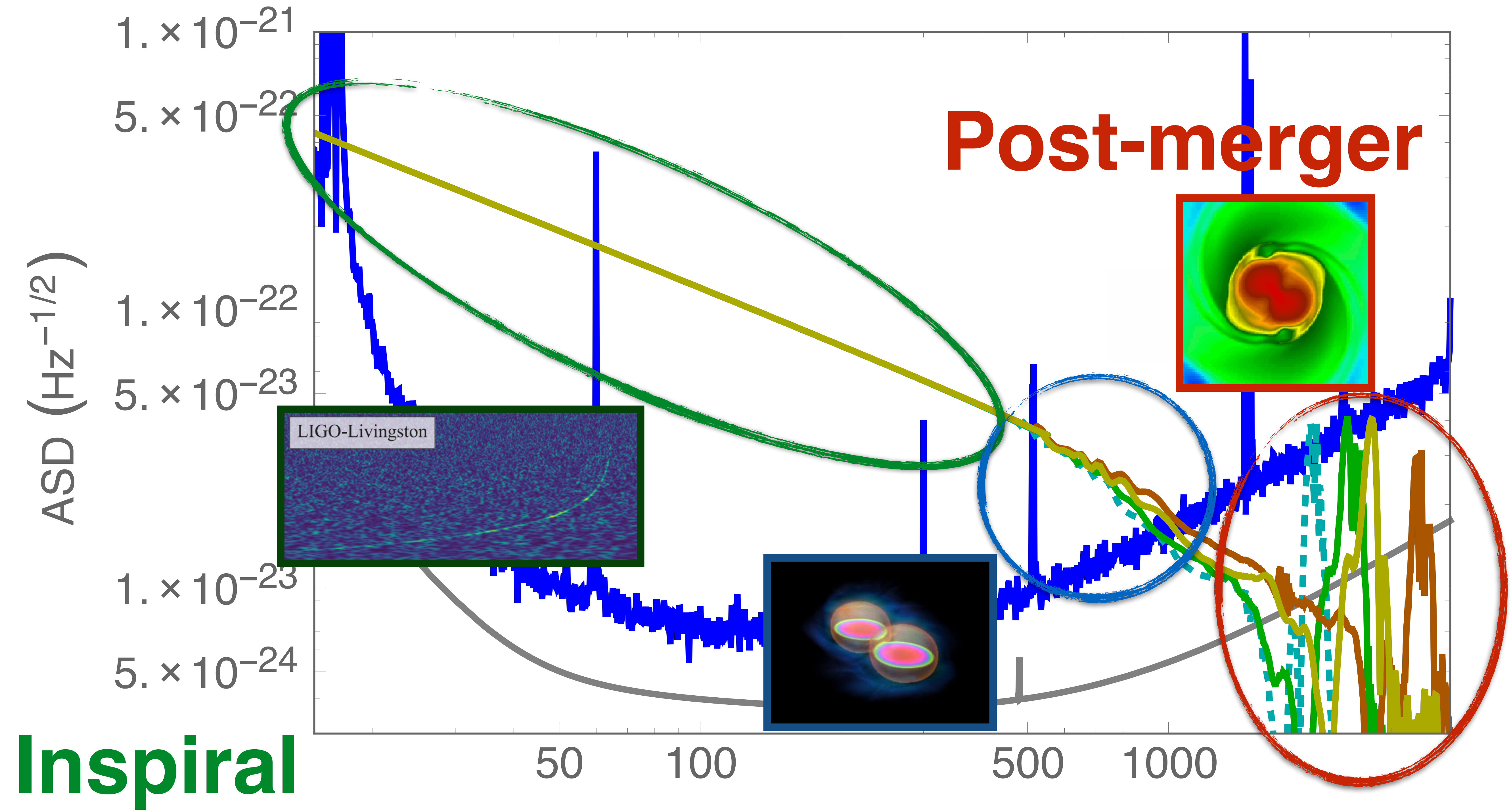
***Macroscopic* properties of compact objects**



Joint study over 18 orders of magnitude

Ozel, Freire (arxiv:1603.02698)

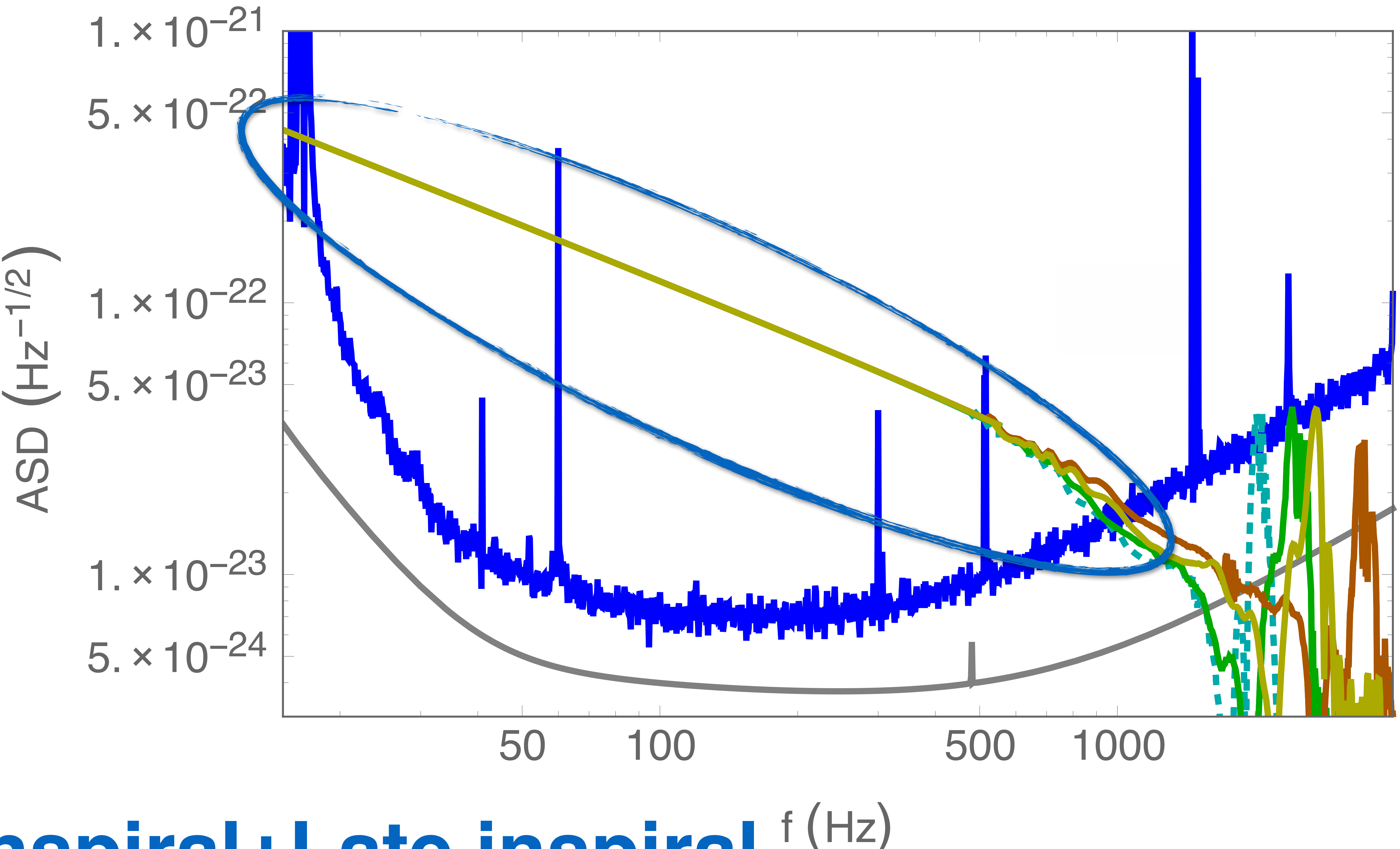
Anatomy of a BNS coalescence



Late inspiral

Data Visualization by J. Read
Numerical data by Tim Dietrich (AEI/FSU/BAM Collaboration)
PRD 95 124006, PRD 95 024029

Anatomy of a BNS coalescence: Late Inspiral



Inspiral+Late inspiral

Data Visualization by J. Read
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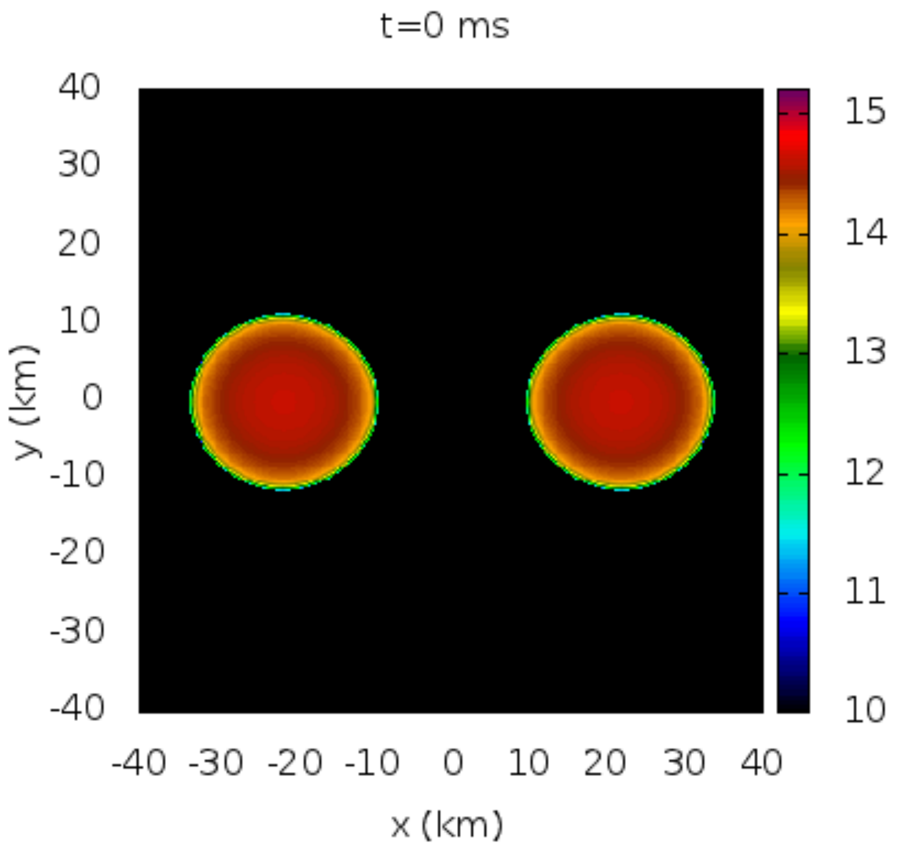
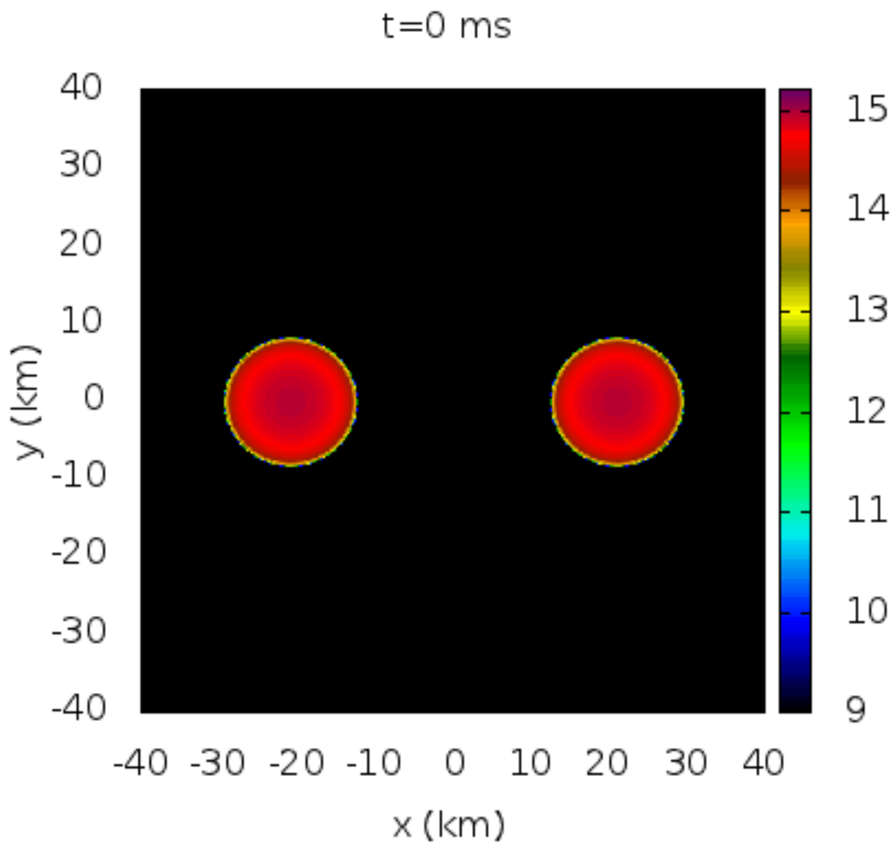
Effect of equation of state

Larger NSs emit energy faster, accelerating the inspiral

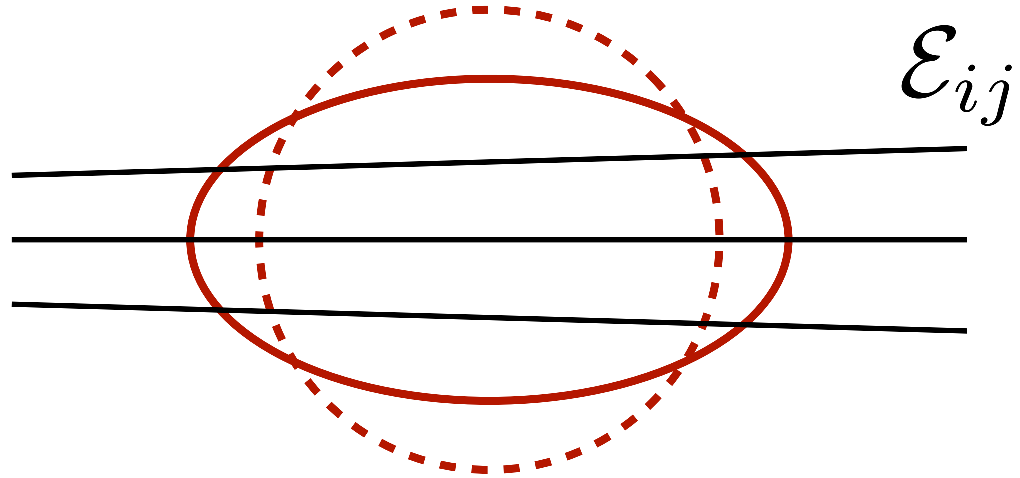
Smaller NSs take longer to merge



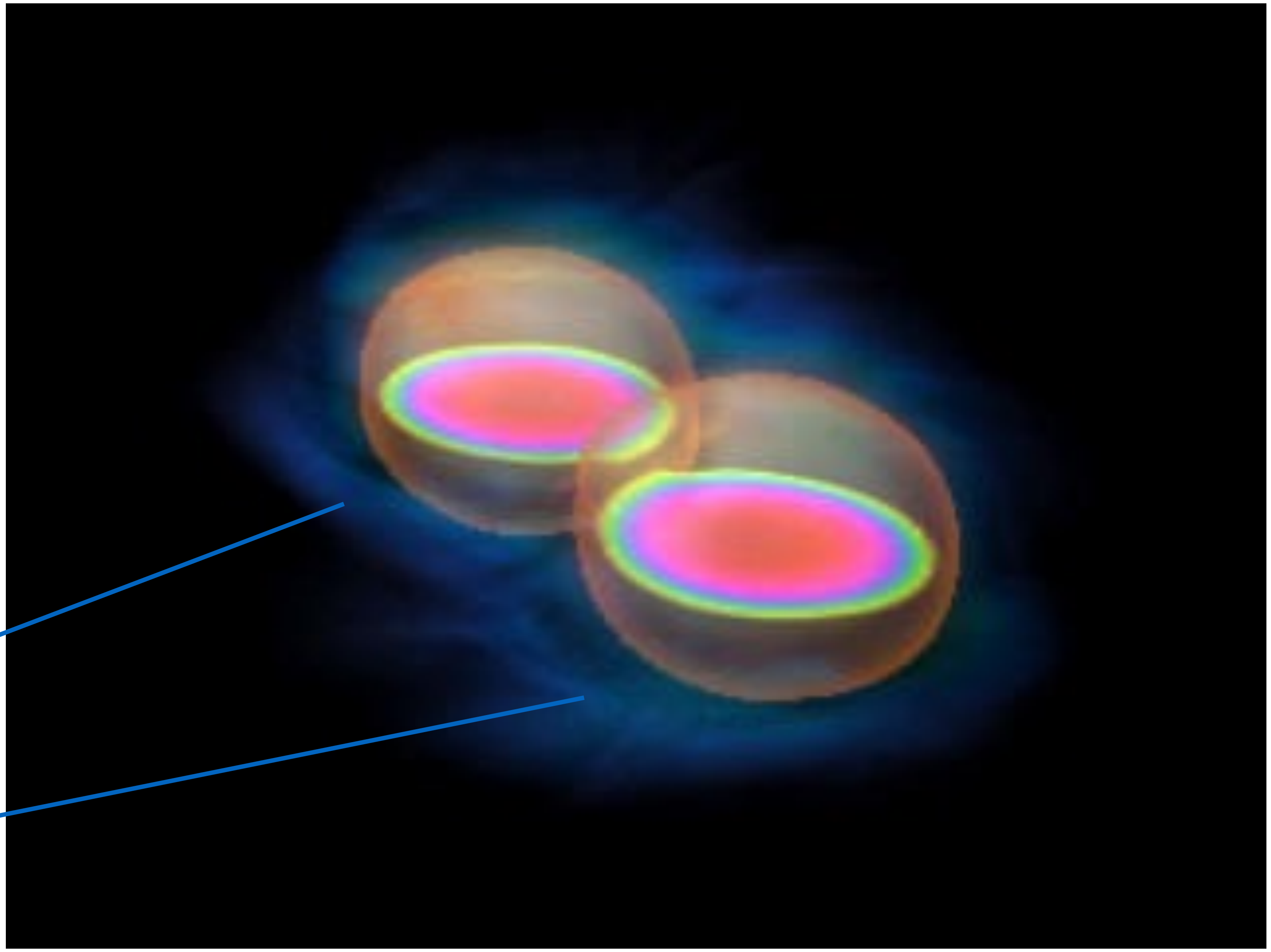


Simulations by Kenta Hotokezaka

Tidal interactions



Credit: Aaron Zimmerman



Calder

Tidal deformability

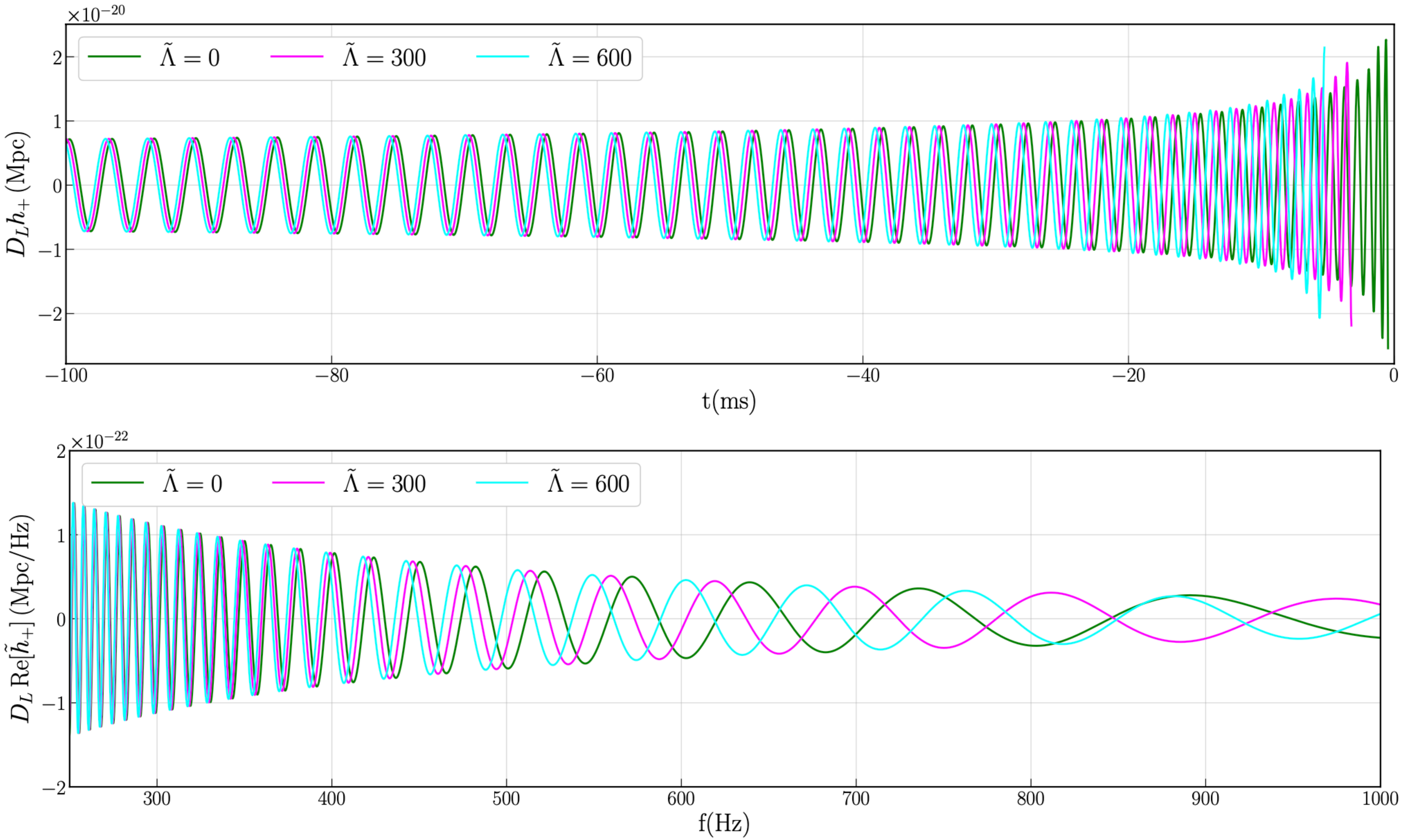
$$Q_{ij} = -\lambda \mathcal{E}_{ij}$$

The tidal deformation speeds up the inspiral (observable) and it depends on the EoS

Tidal interactions

In practice with current sensitivity we only measure:

$$\tilde{\Lambda} \equiv \frac{16}{13} \frac{(m_1 + 12m_2)m_1^4\Lambda_1 + (m_2 + 12m_1)m_2^4\Lambda_2}{(m_1 + m_2)^5}$$



Chatziioannou+ (arxiv:2006.03168)

Waveform: Dietrich+ (arxiv:1804.02235)

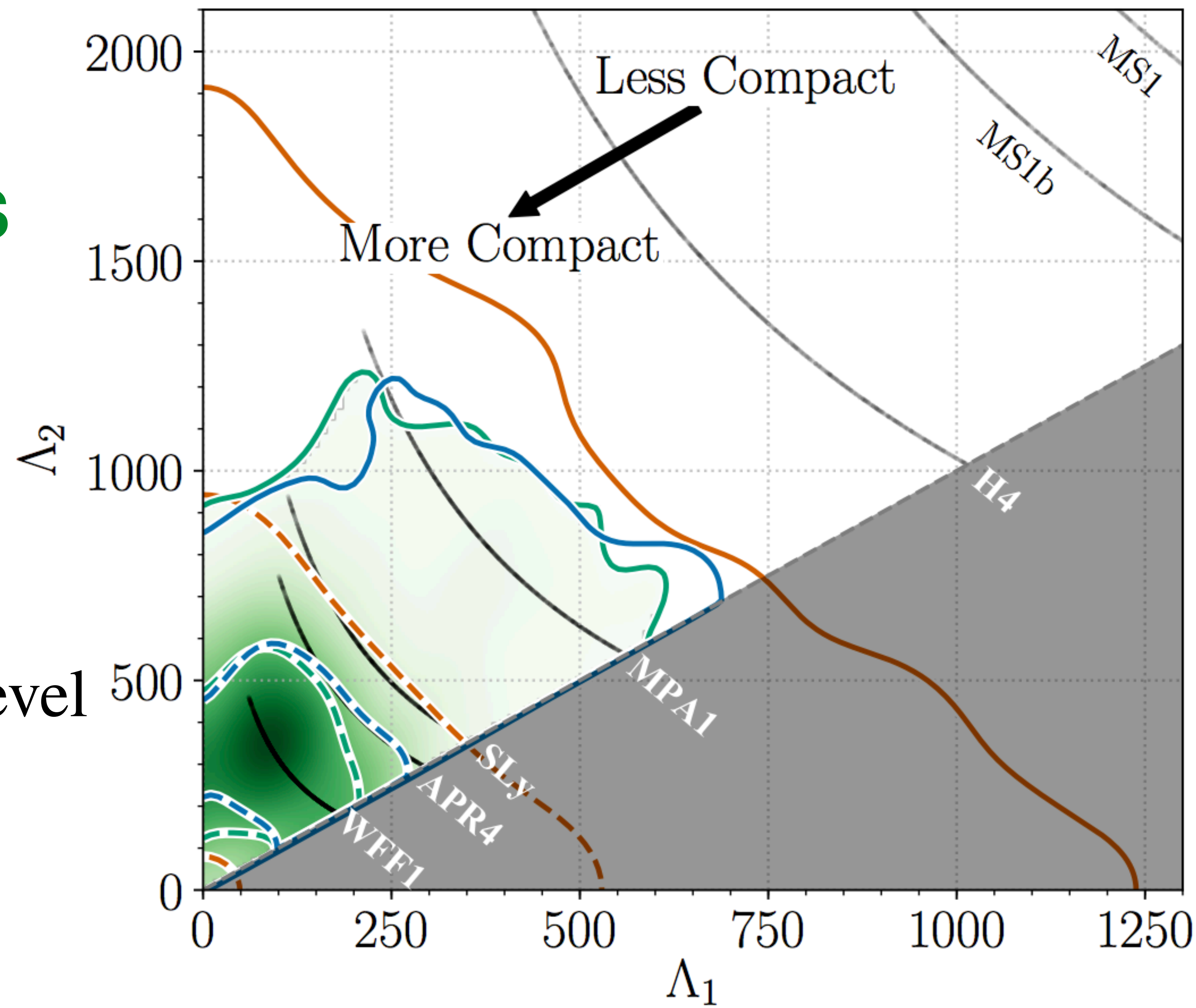
GW170817 tides

Independent EoSs

Same hadronic EoS

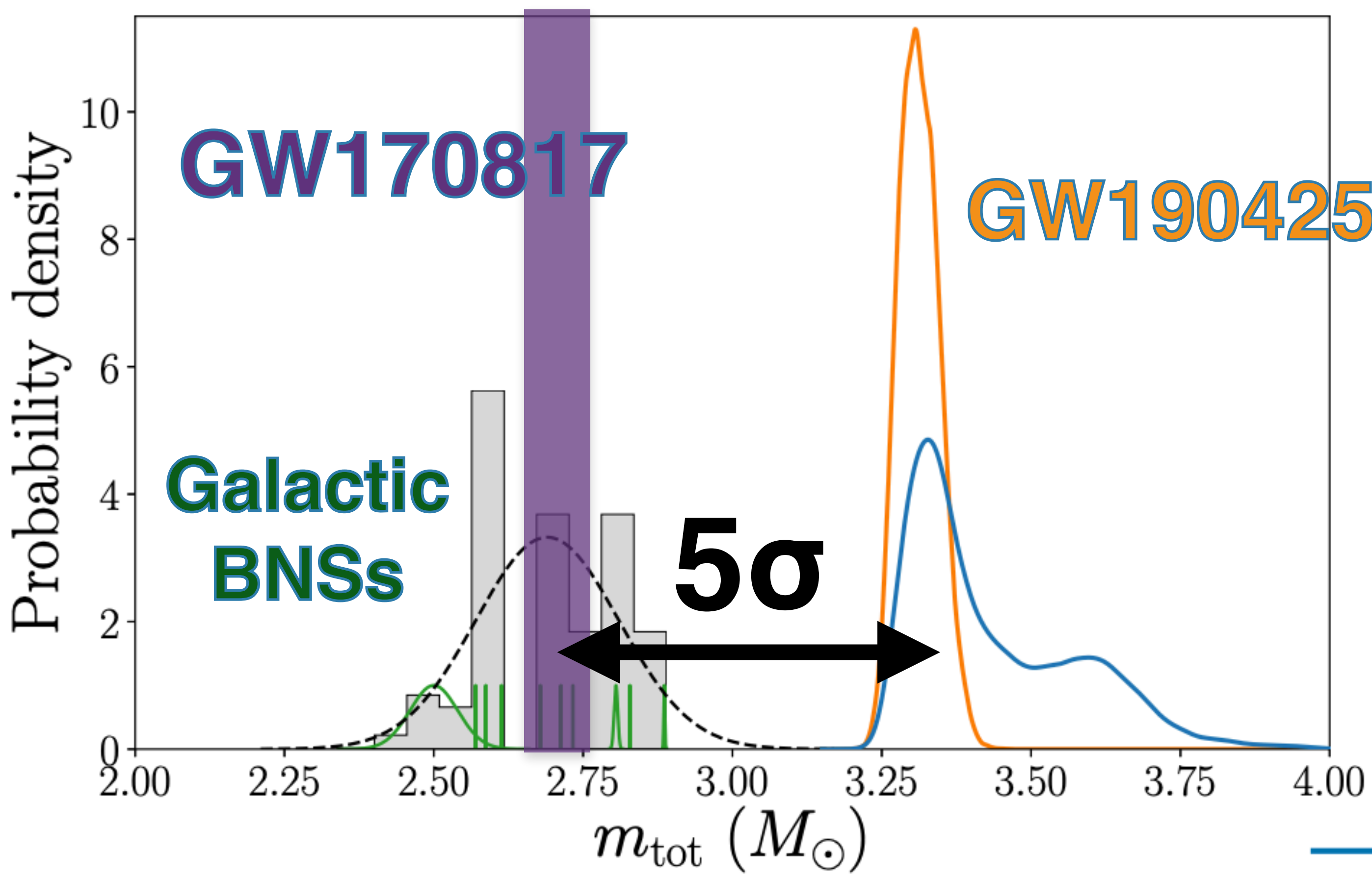
Spectral EoS parametrization

$\tilde{\Lambda} \lesssim 700$ at the 90 % level

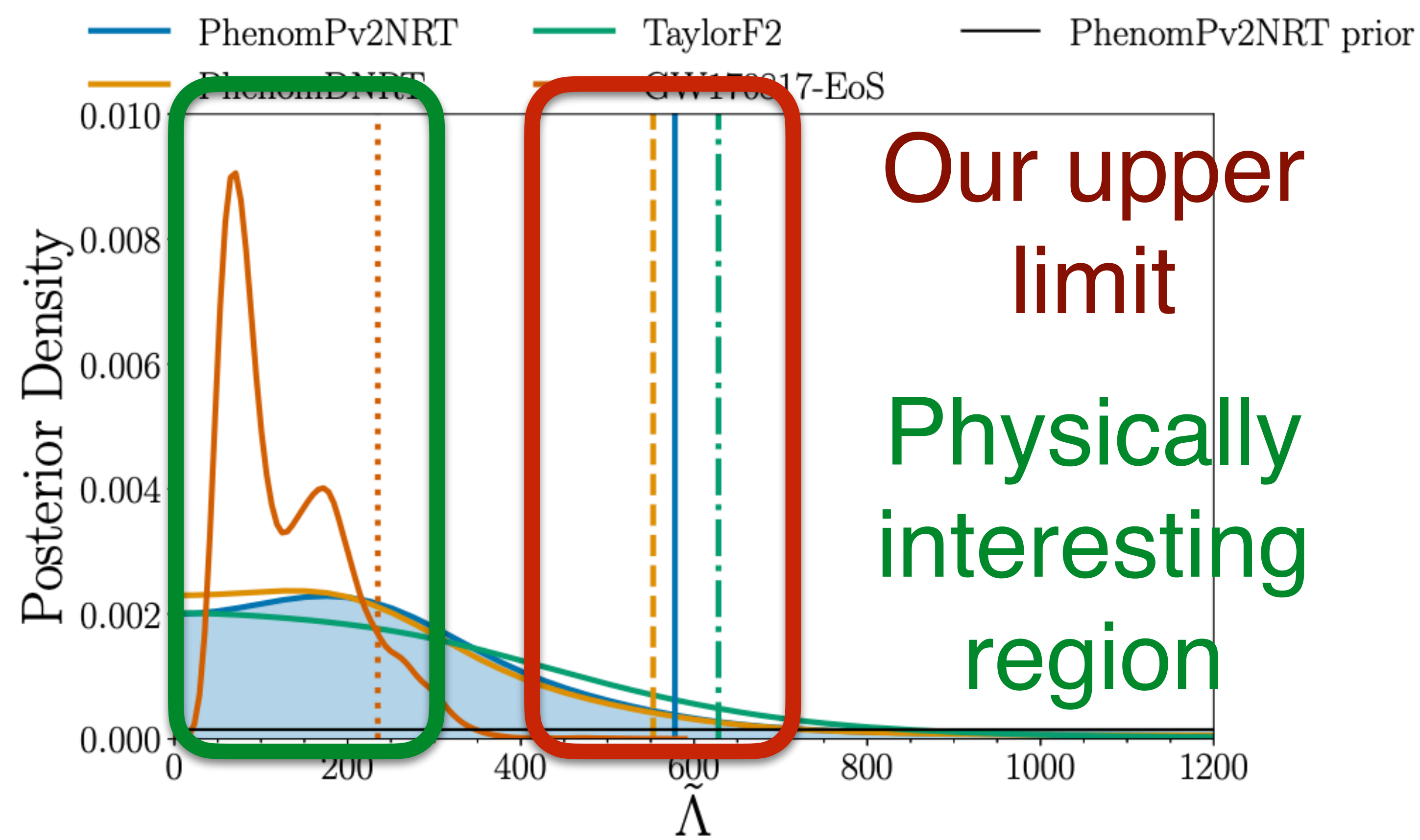


LVC (arxiv:1805.11581)
PE: Veitch+ (arxiv:1409.7215)
Waveform: Dietrich+ (arxiv:1804.02235)
Universal relations: Yagi and Yunes (arxiv:1512.02639), Chatziioannou+ (arxiv:1804.03221)
EoS Parametrization: Lackey and Wade (arxiv:1410.8866), Carney+ (arxiv:1805.11217)

GW190425

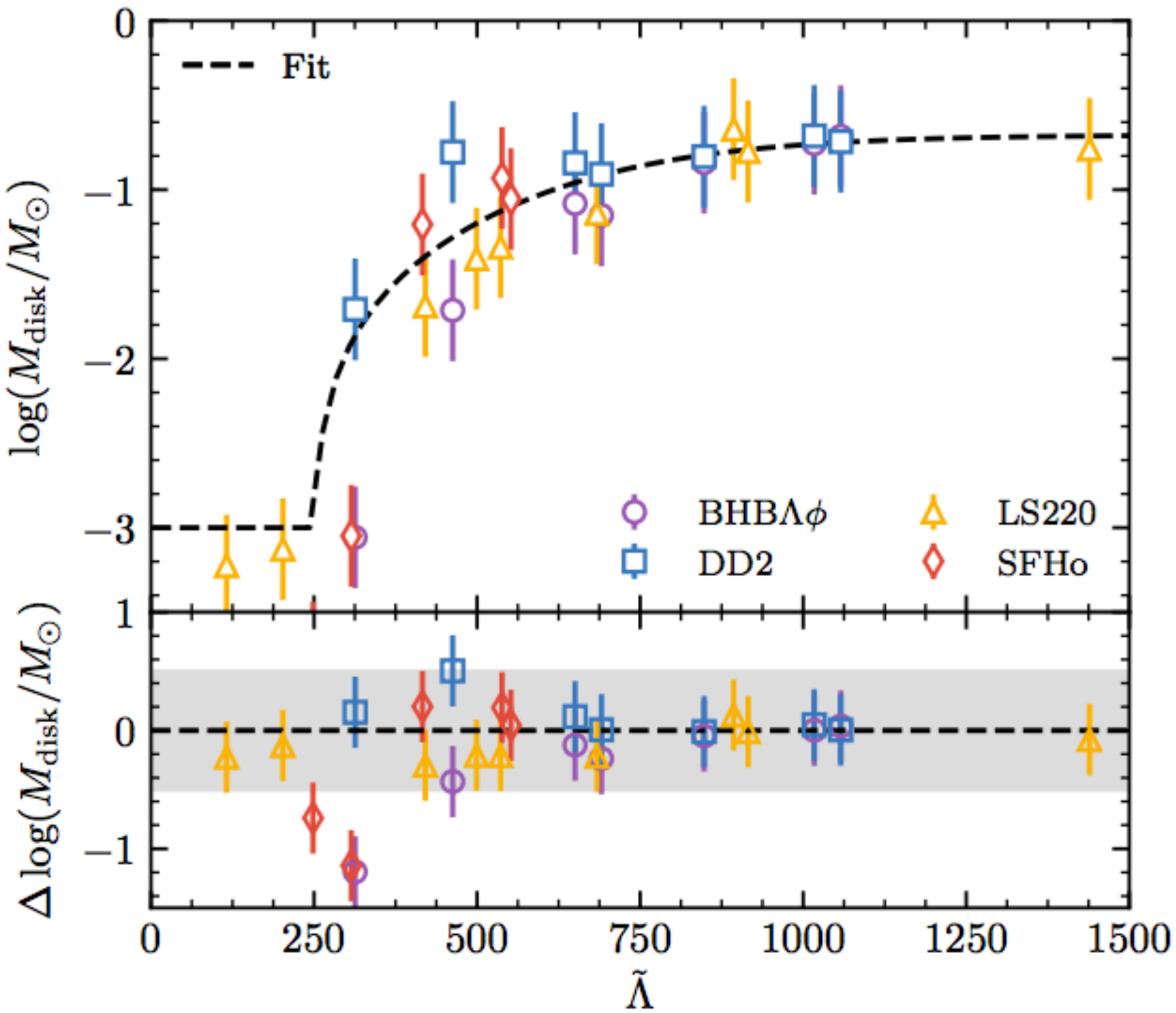


Pro: massive NSs form binaries and merge
Con: tidal interactions are intrinsically weaker



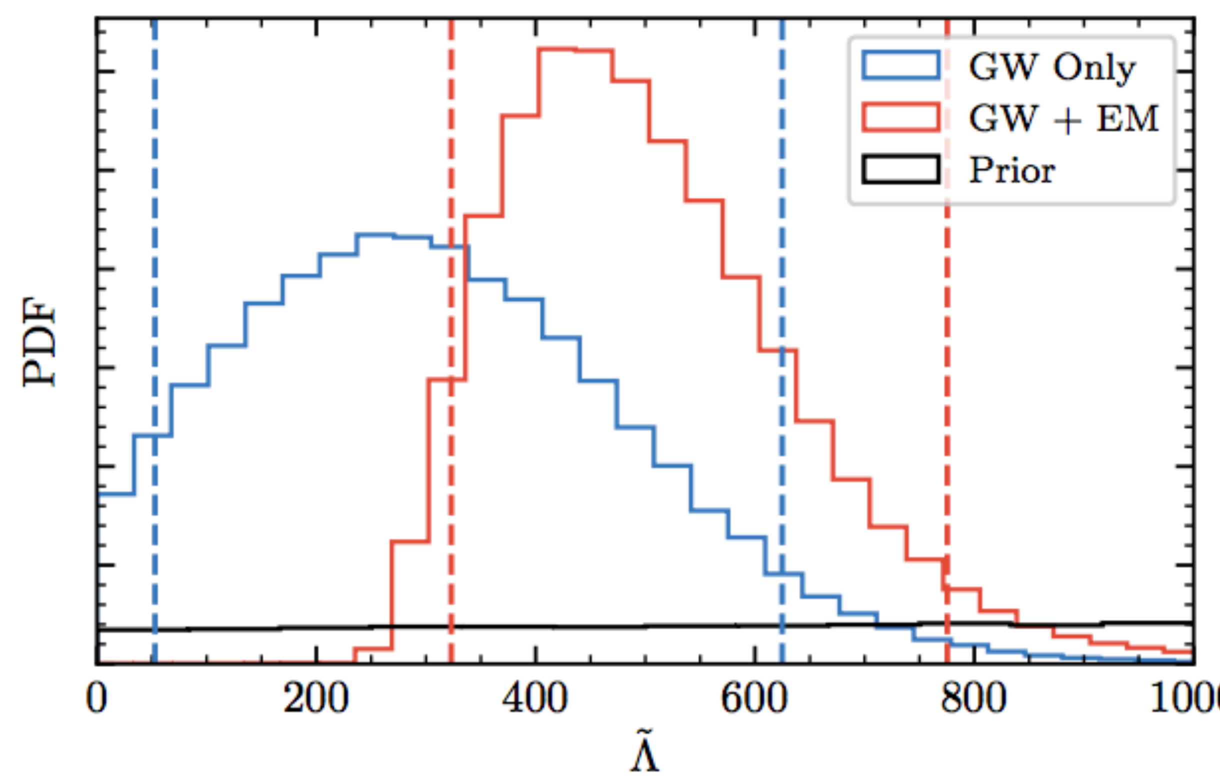
LVC (arxiv:2001.01761)
PE: Veitch+ (arxiv:1409.7215)
Waveform: Dietrich+ (arxiv:1804.02235)

Kilonova - disk mass



$$\log\left(\frac{M_{\rm disk}}{M_\odot}\right) \simeq \Phi(\tilde{\Lambda}) := \max\left\{-3, \log\left[\alpha + \beta \tanh\left(\frac{\tilde{\Lambda}-\gamma}{\delta}\right)\right],\right\}$$

Employing a relation between the disk mass and the tidal parameter, fitted from numerical simulations



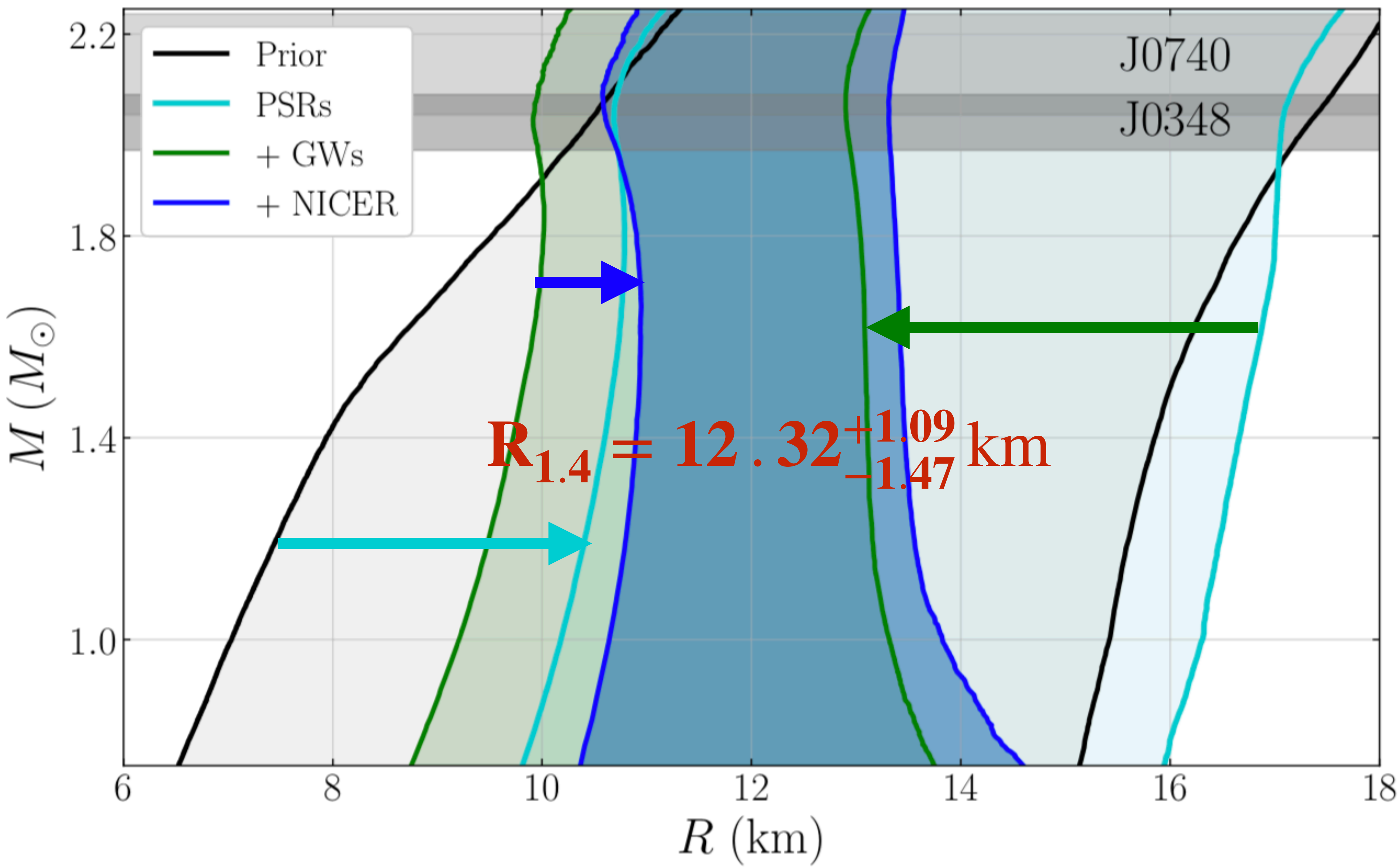
Radice+ (arxiv:1810.12917)

Similar results using the ejecta rather than the disk mass

Coughlin+ (arxiv:1812.04803)

Non parametric constraints: NICER

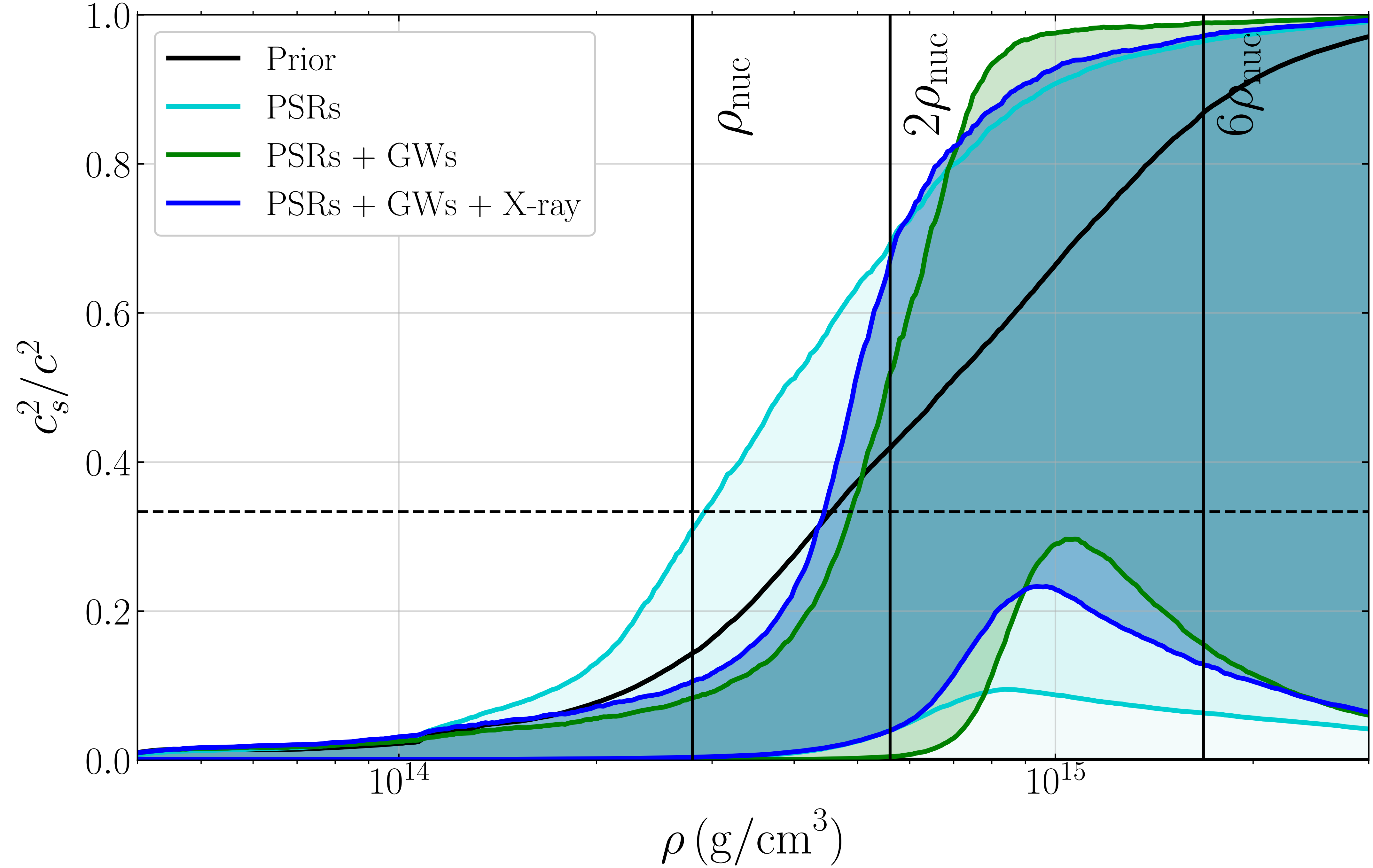
EoS prior based on a gaussian process conditioned on existing nuclear EoS models of different compositions



Landry+ (including KC) (arxiv:2003.04880)

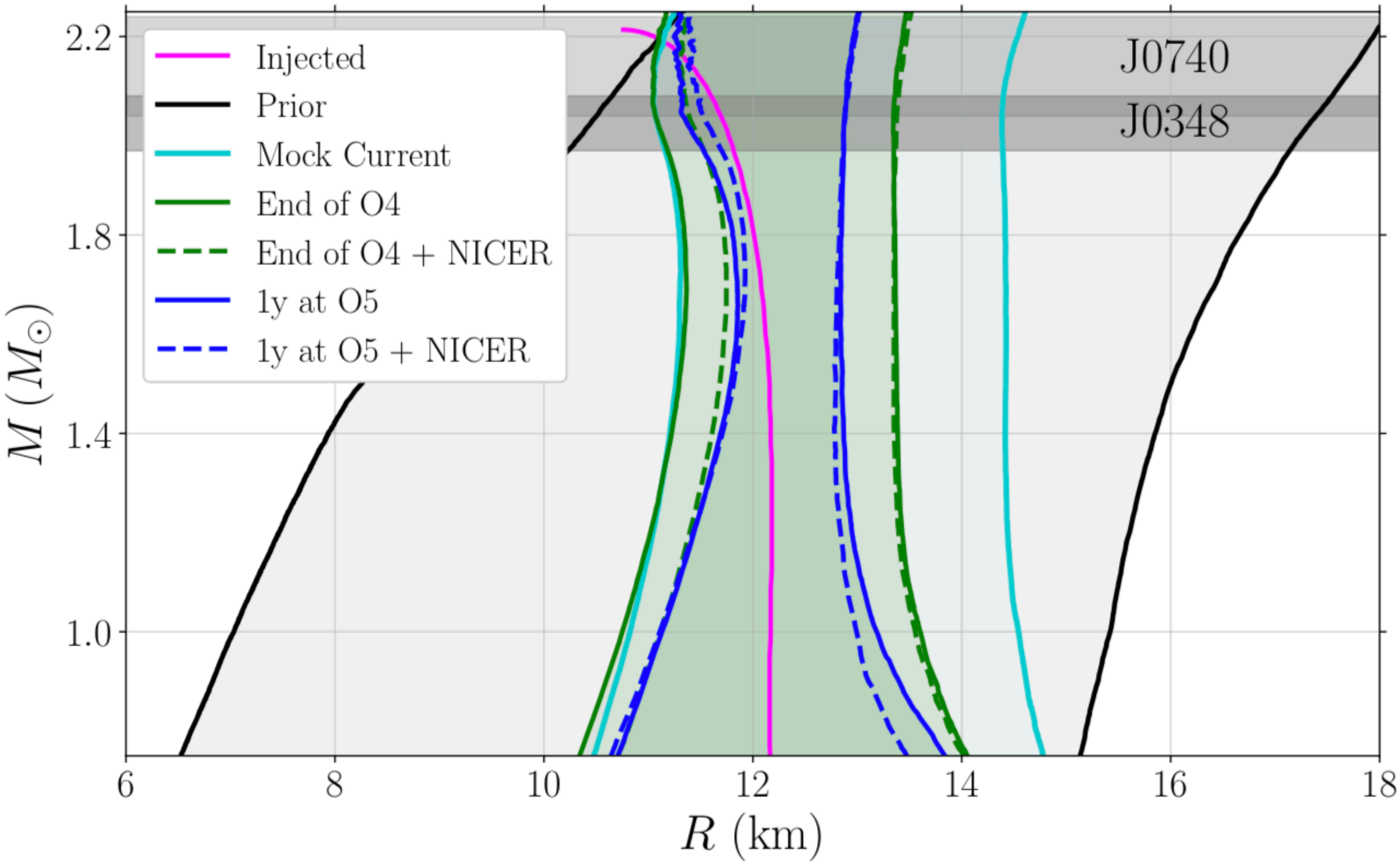
Non parametric constraints

EoS prior based on a gaussian process conditioned on existing nuclear EoS models of different compositions



Landry+ (including KC) (arxiv:2003.04880)

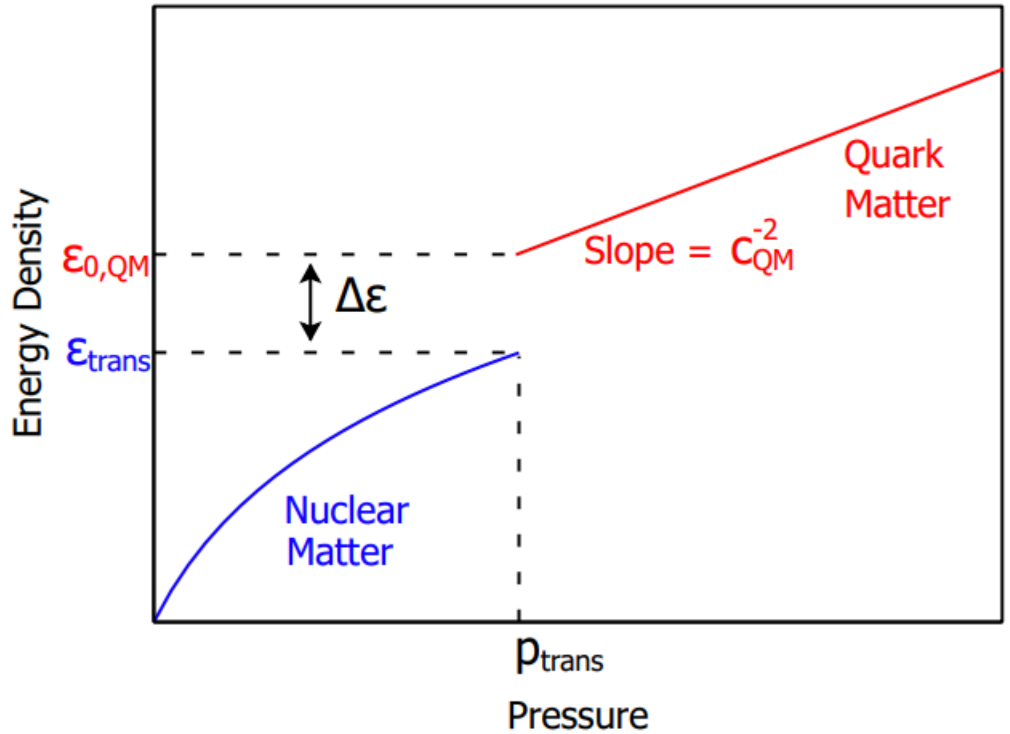
Going forward: More observations



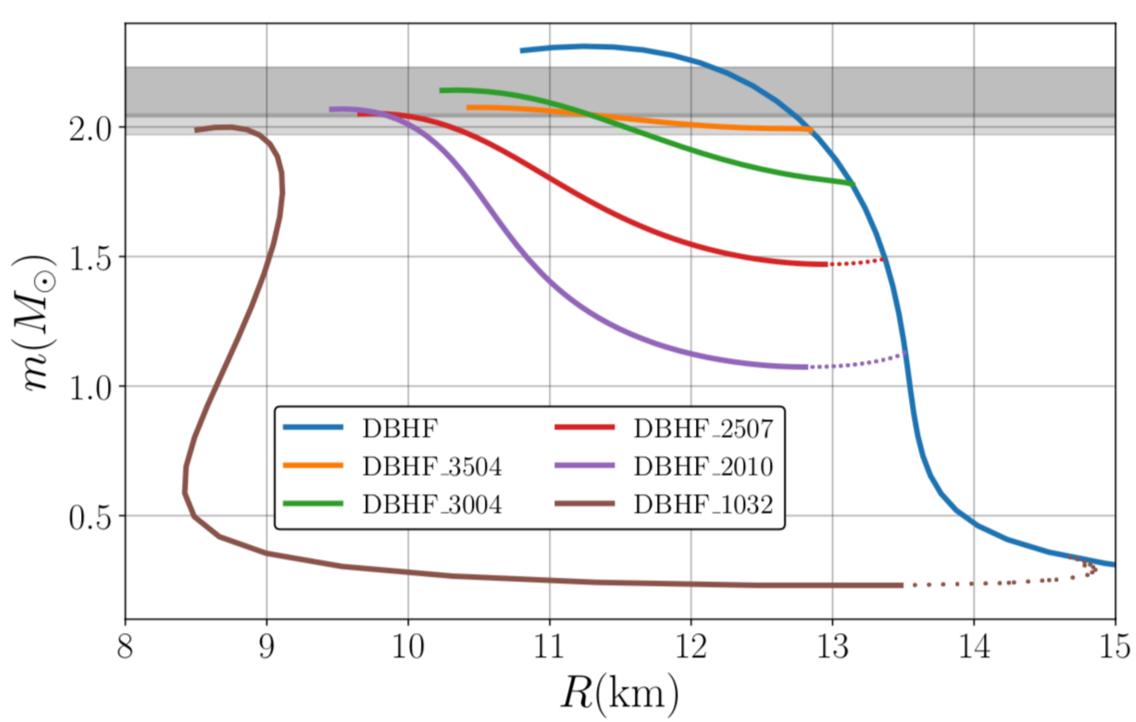
O(1km) radius determination in the coming years

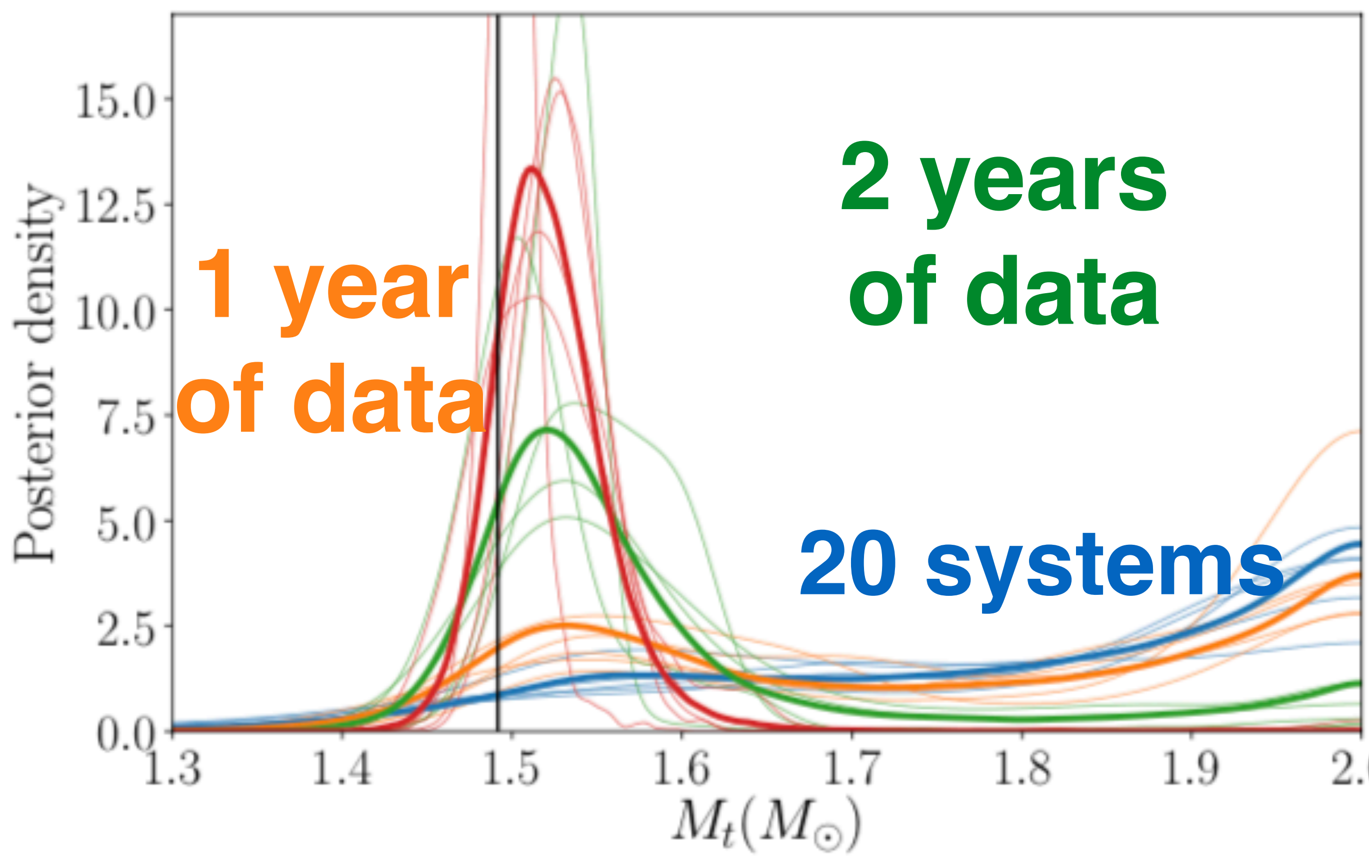
Landry+ (including KC) (arxiv:2003.04880)

Going forward: Quark matter



A population of BNSs can lead to constraints on the properties of a phase transition in dense matter

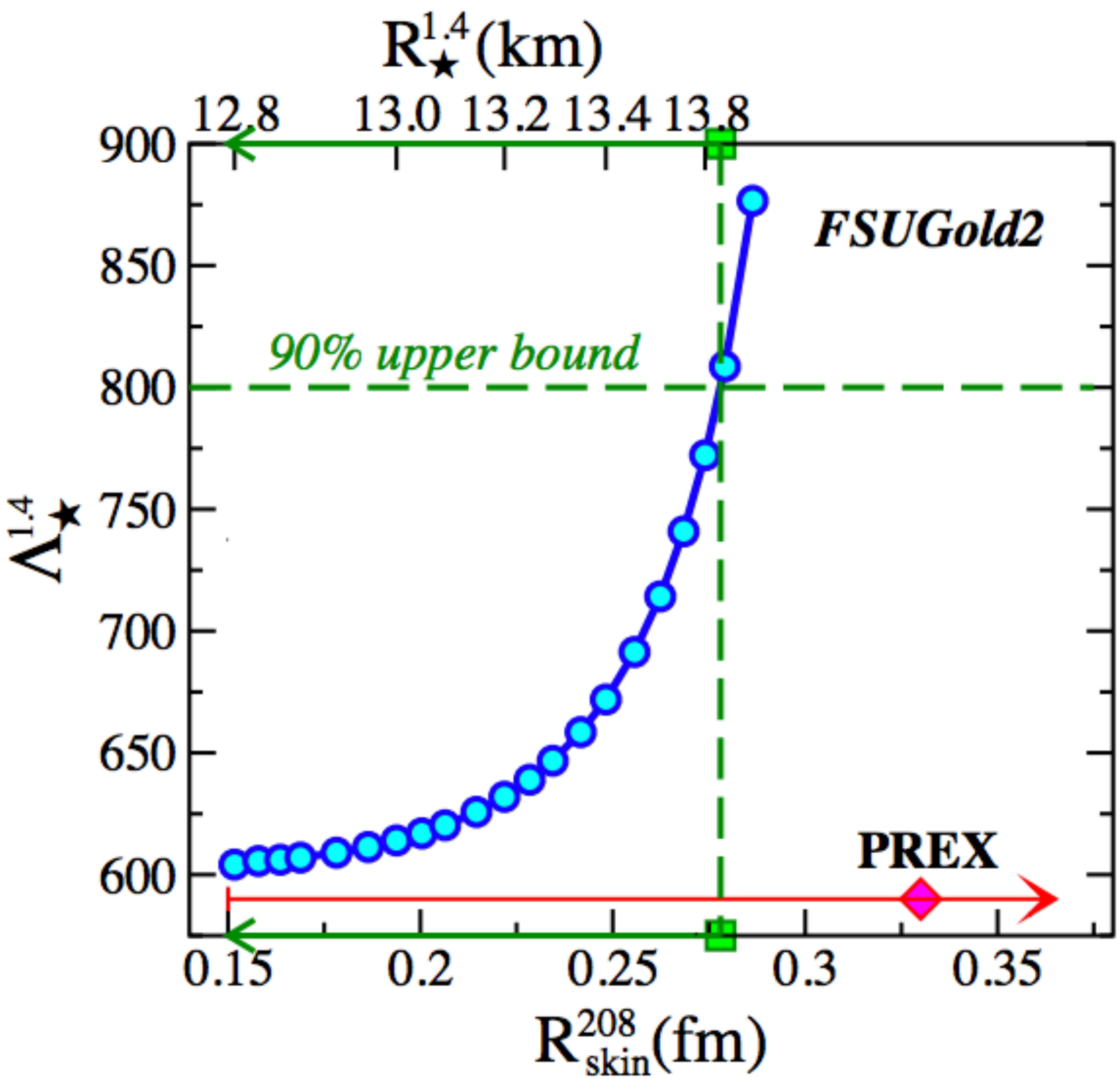




Han and Steiner (arxiv:1810.10967)

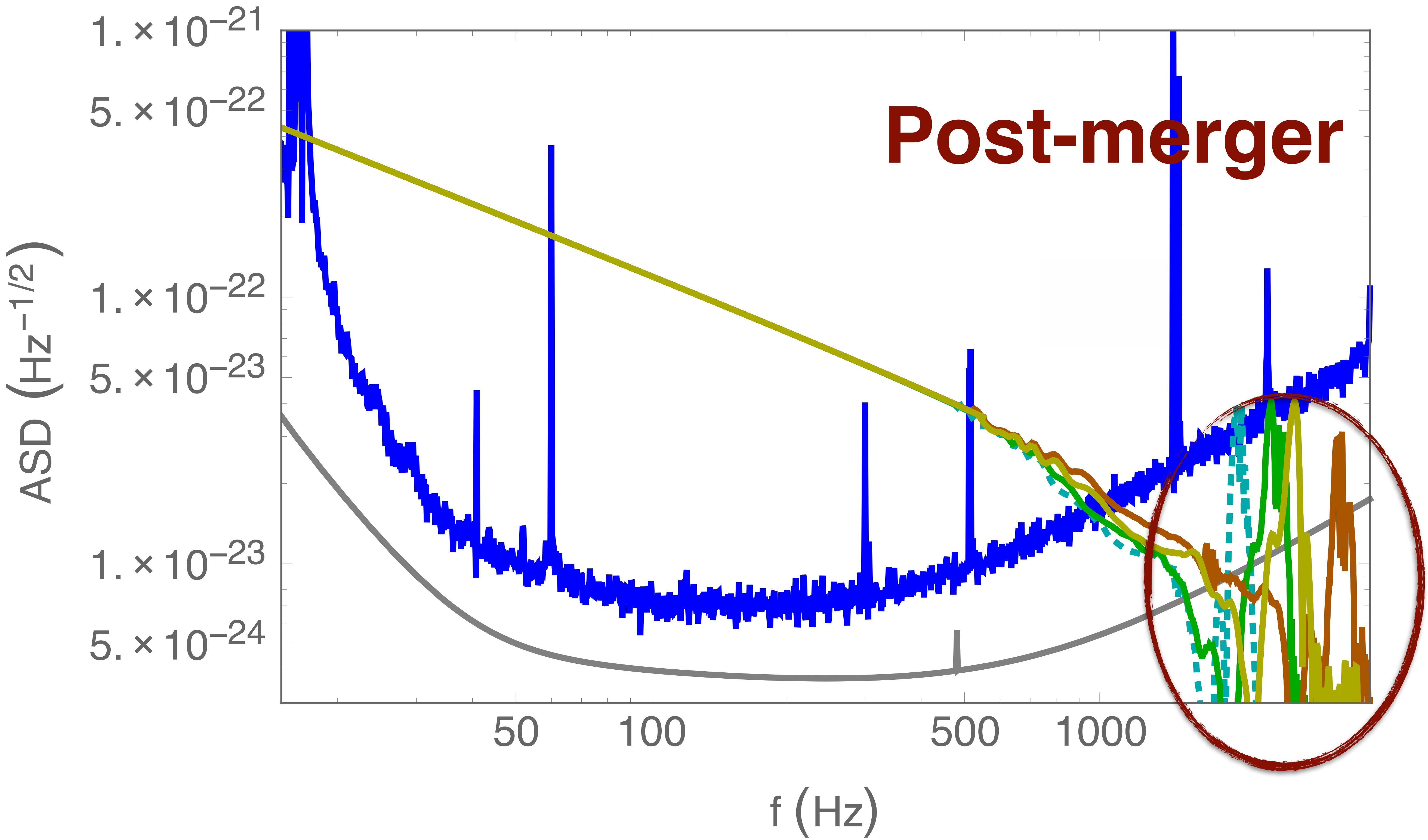
Chatziioannou and Han (arxiv:1911.07091)

Going forward: Nuclear experiment



Fattoyev+ (arxiv:1711.06615)

Anatomy of a BNS coalescence: post-merger



Data Visualization by J. Read
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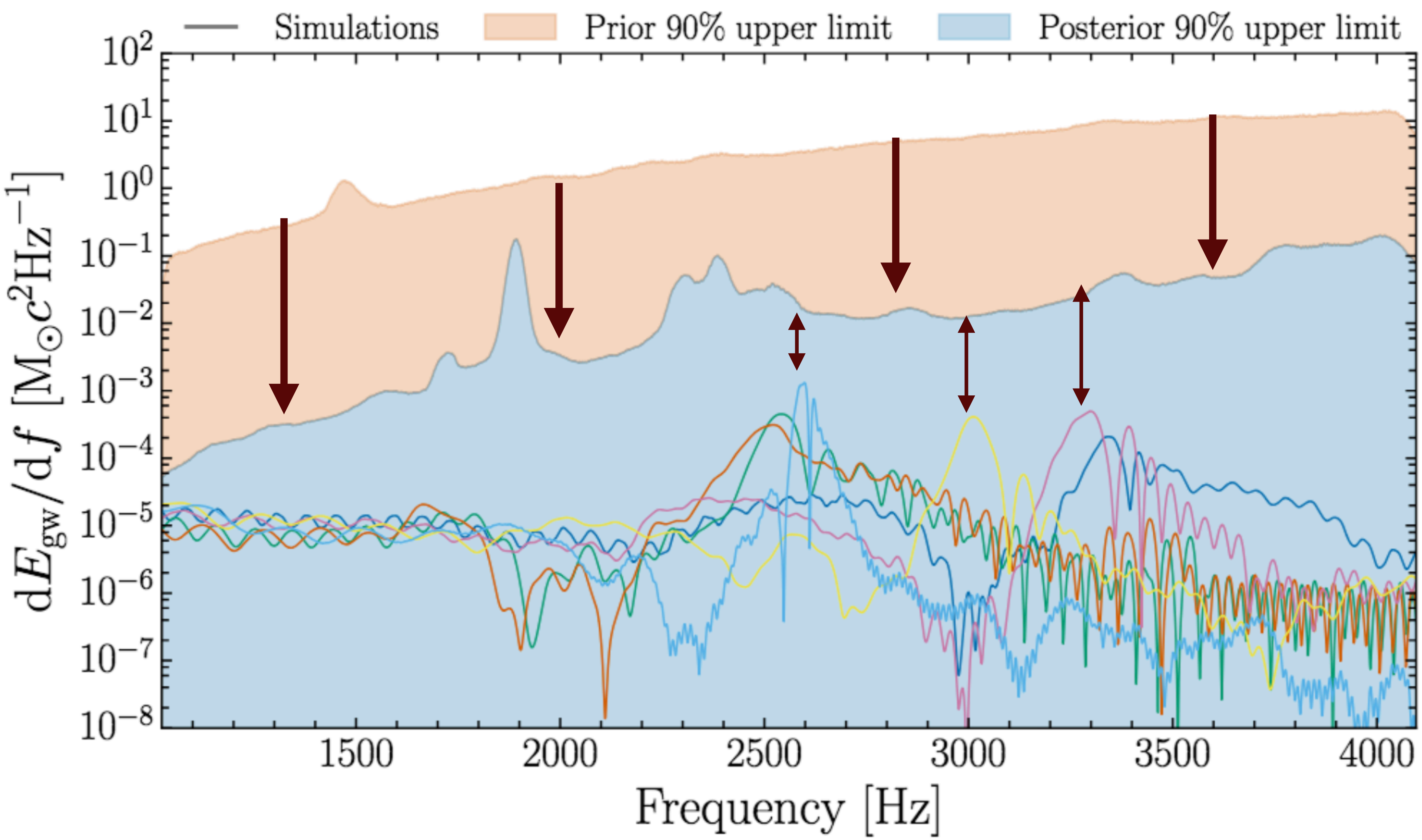
No detectable post-merger emission, upper limits



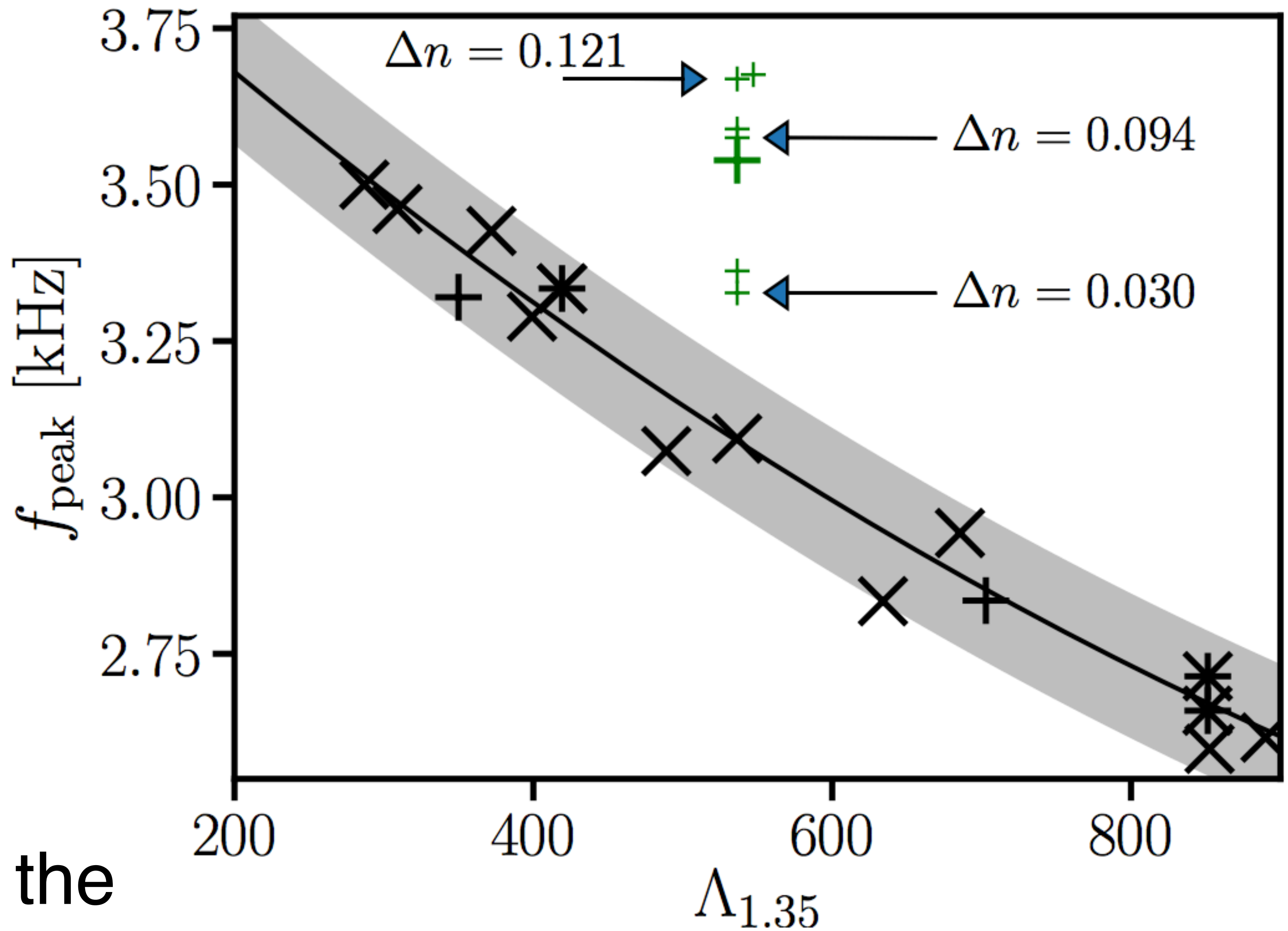
LVC (arxiv:1805.11579)

Analysis: Chatziioannou+ (arxiv:1711.00040)

Simulations: Bauswein+ (arxiv:1204.1888)

Complementary information

Measure from **post merger**



Measure from **pre merger**

Information from the pre-merger phase breaks the degeneracy

Bauswein+ (including KC) (arxiv:1809.01116)

Remnant fate

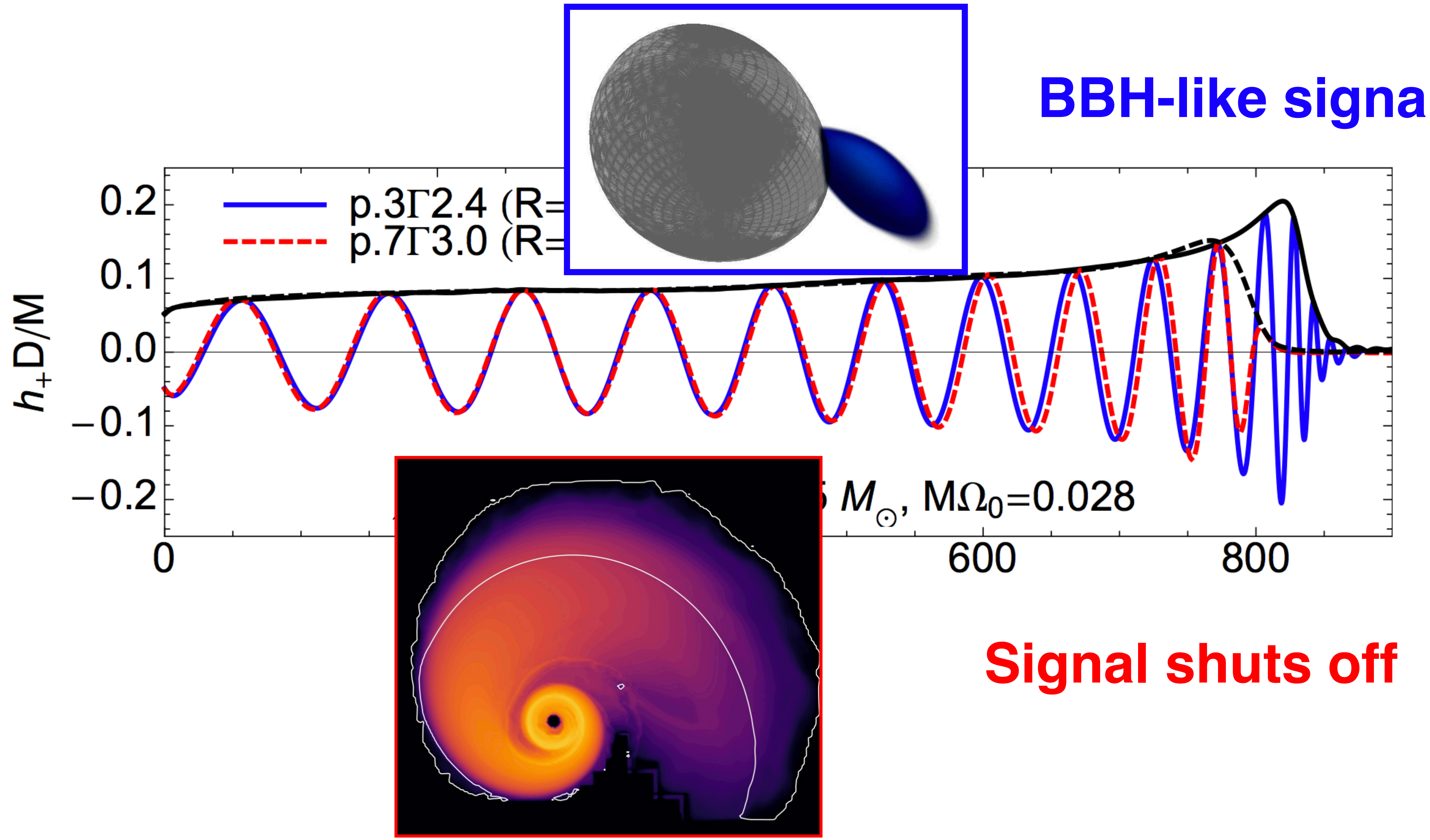
Information about the fate of the remnant might be extracted from modeling the EM emission

Total mass (GW) + requirement for a HMNS (EM) suggests

$$M_{max} \lesssim 2.3 M_{\odot}$$

Margalit+ (arxiv:1710.05938)

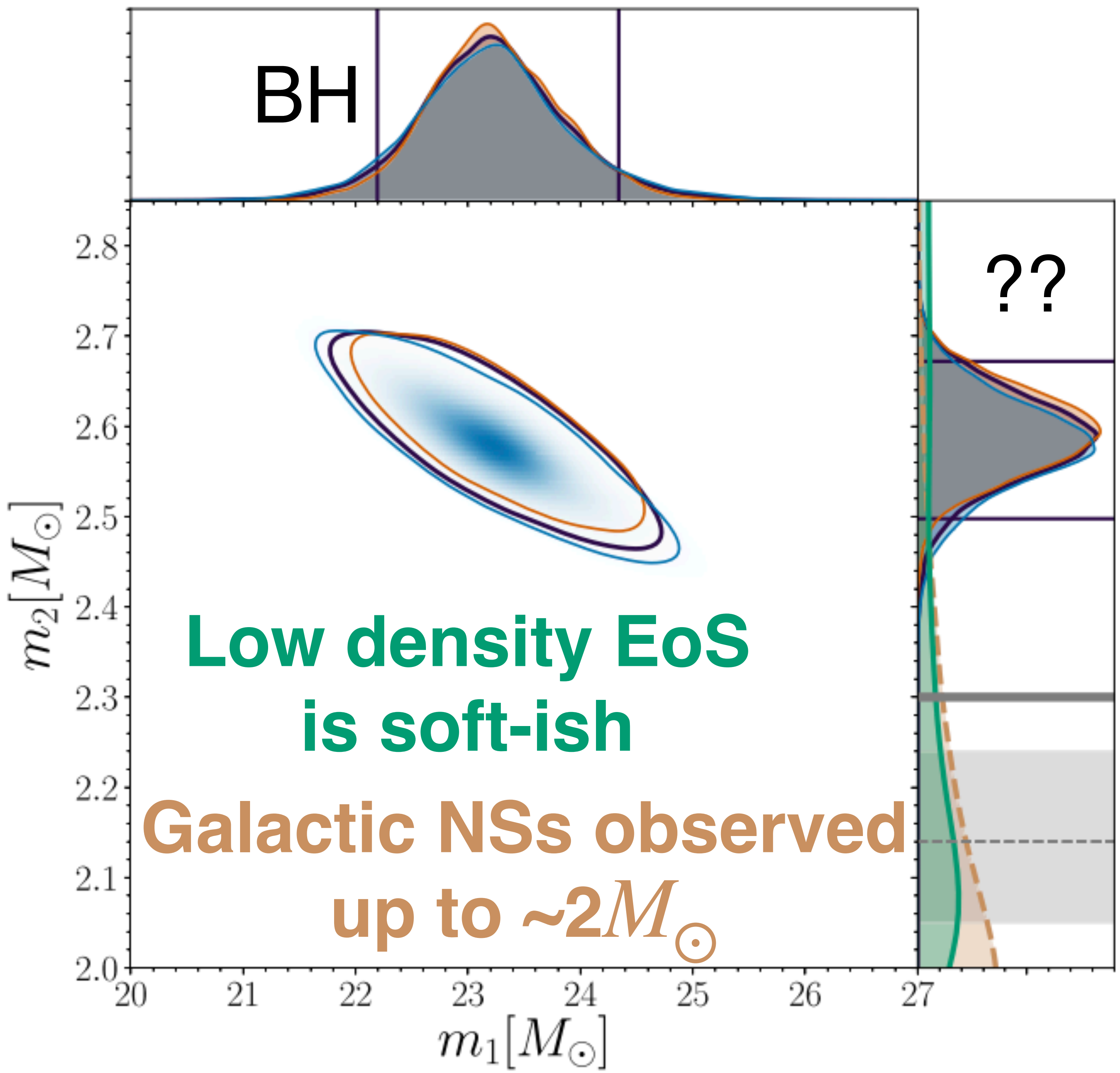
Anatomy of a NSBH coalescence



Relation between the disruption radius and the "plunge" radius

Lackey+ (arxiv:1303.6298)
Foucart+ (arxiv:1307.7685)
Foucart+ (arxiv:1807.00011)

GW190814: a ~2.6$M_\odot$ object



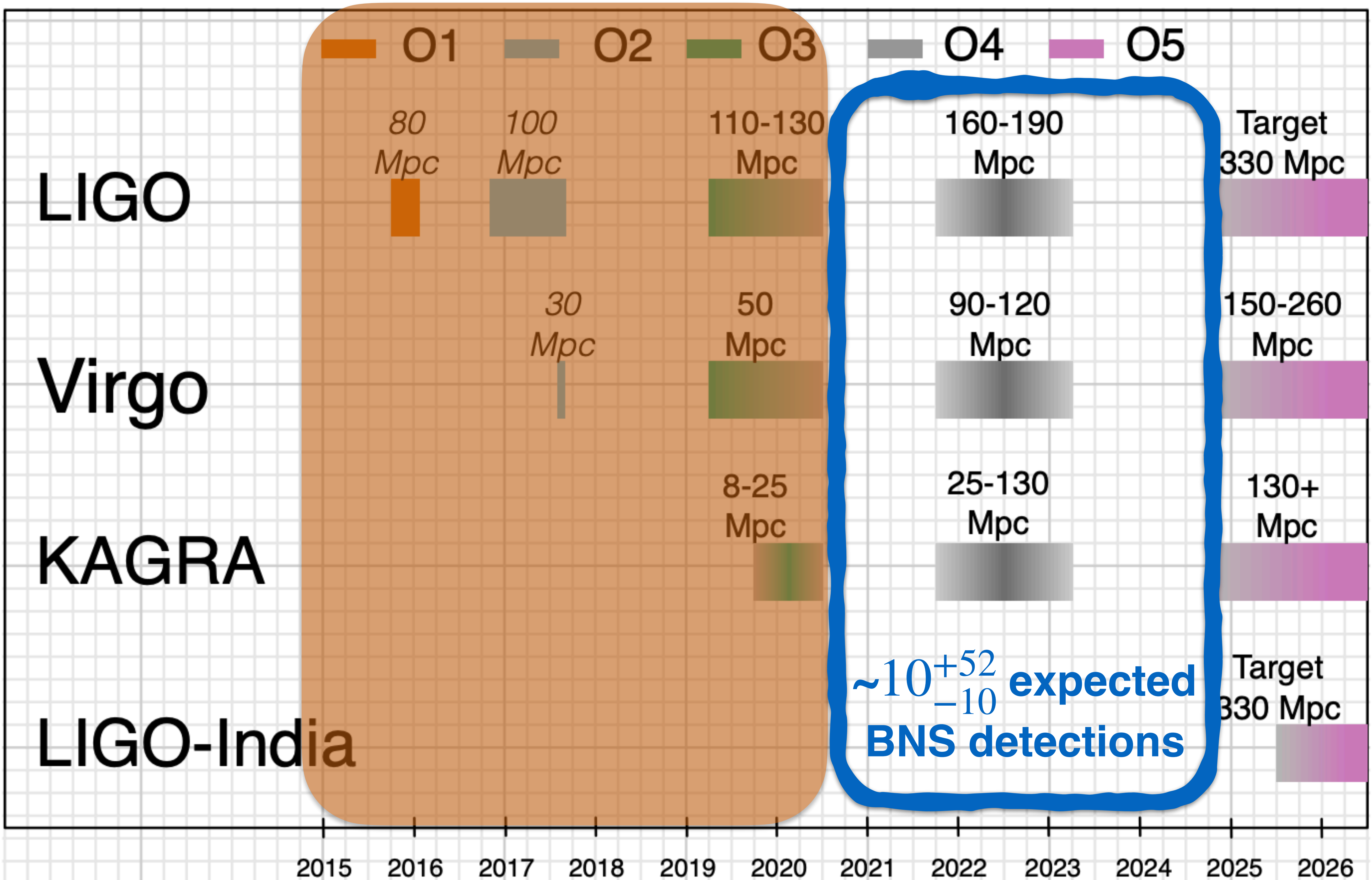
LVC (arxiv:2006.12611)

Ongoing efforts to study the nature of the secondary object

- BH
- Spinning NS
- Phase transitions
- Statistical outlier
- …

Tan+ (arxiv:2006.16296)
Essick+ (arxiv:2007.01372)
Dexheimer+ (arxiv:2007.08493)
Tews+ (arxiv:2007.06057)
Fattoyev+ (arxiv:2007.03799)

The next steps



LVC (arxiv:1304.0670)