Constraining the neutron star equation of state with gravitational waves

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From heavy-ion collisions to neutron stars
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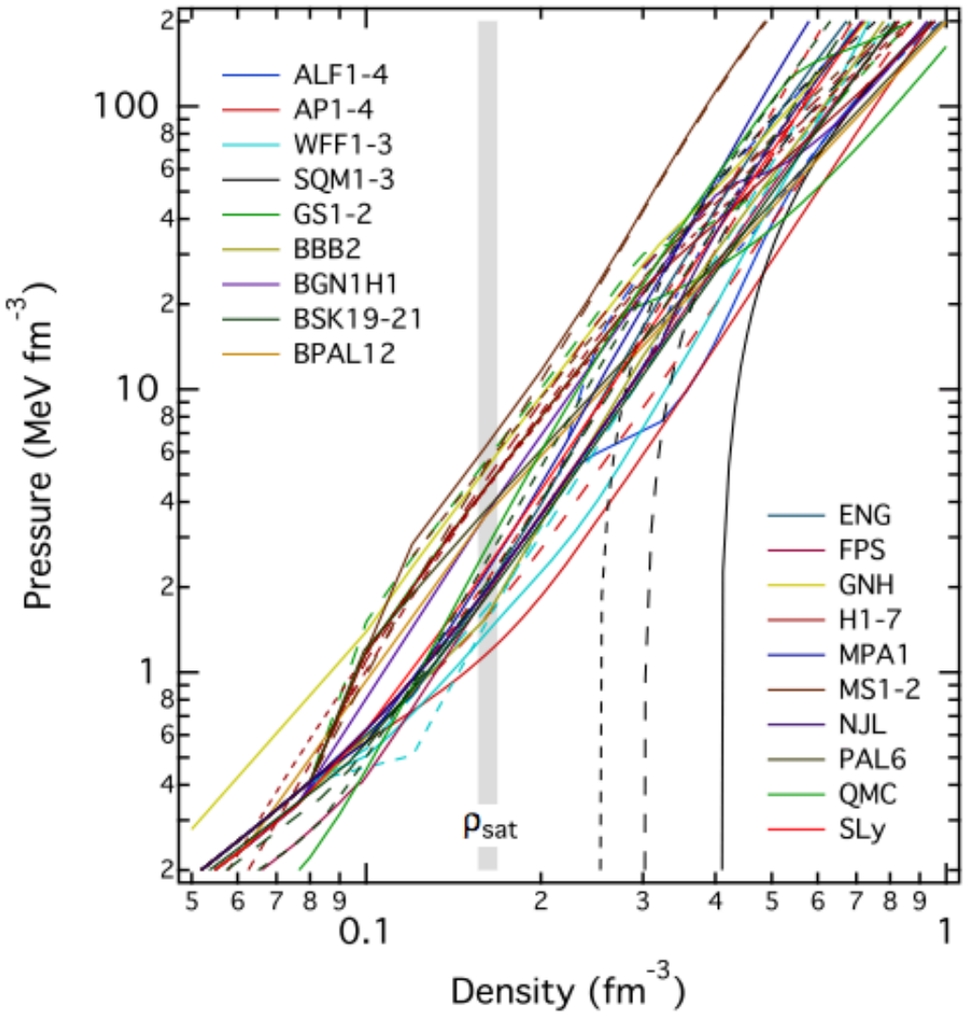
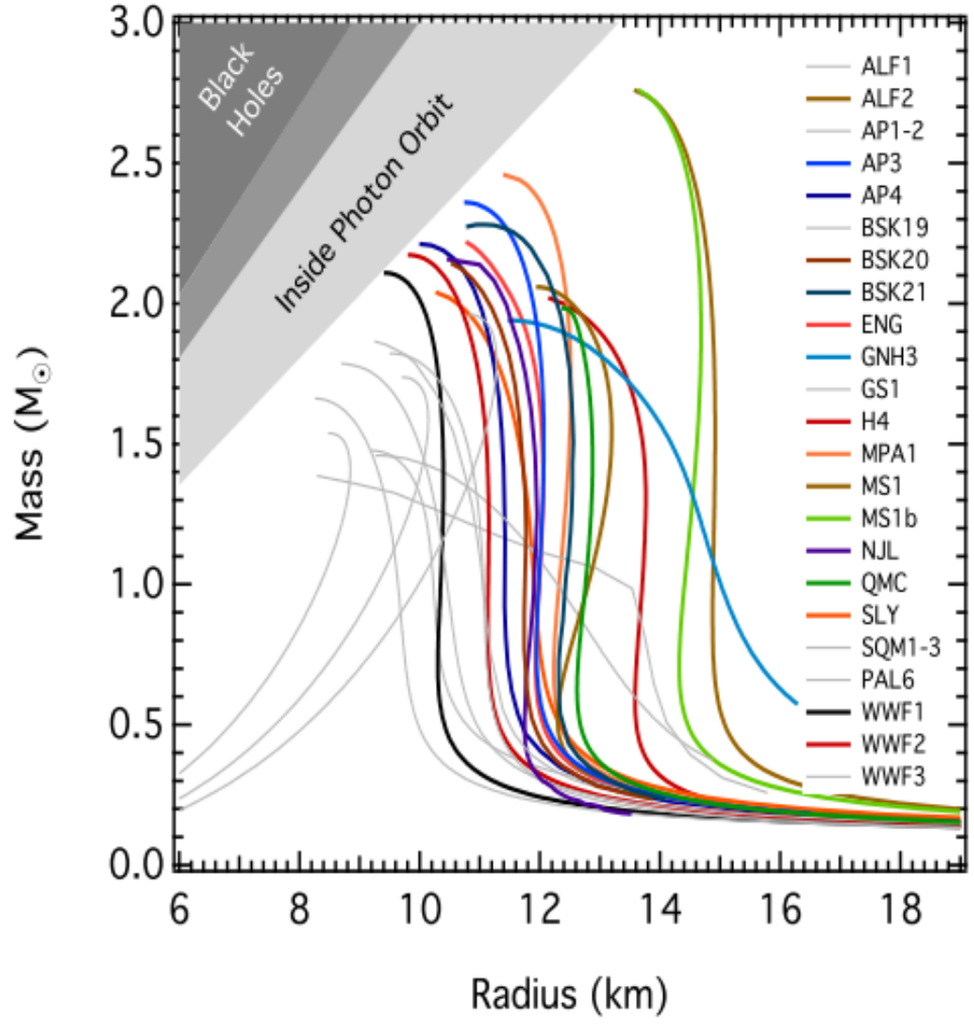
Neutron stars

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



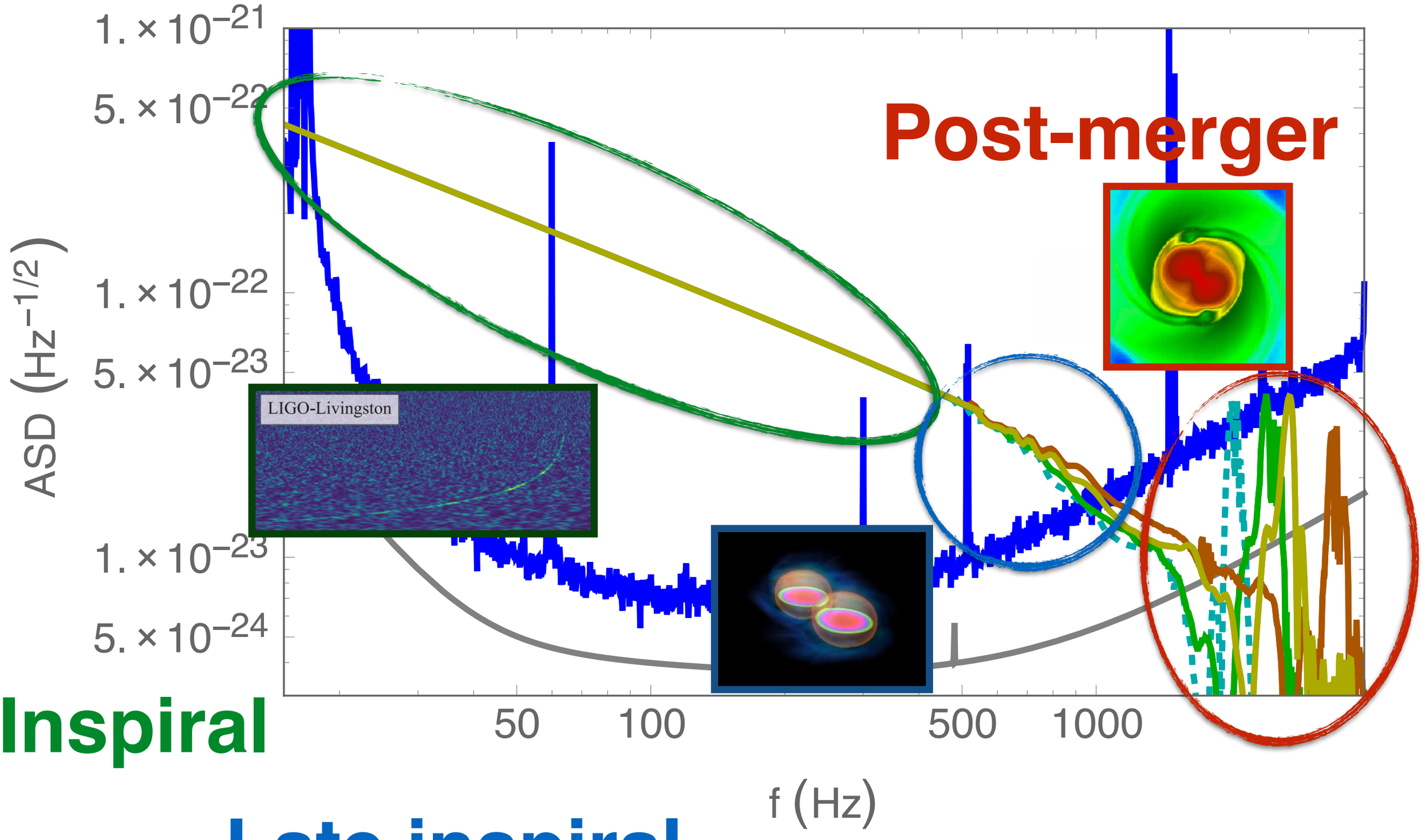
Macroscopic **properties of compact objects**



Joint study over 18 orders of magnitude

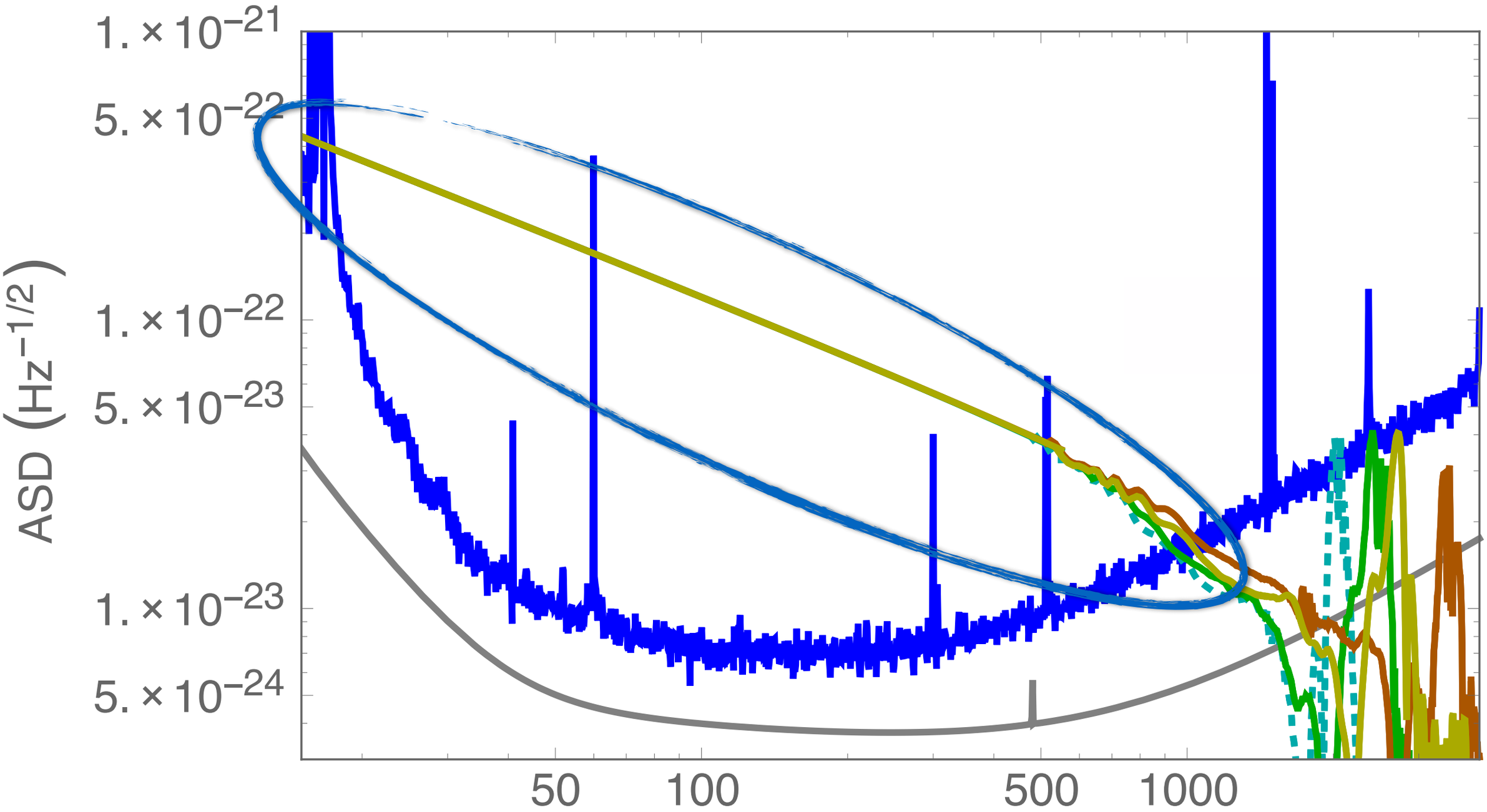
Ozel, Freire (arxiv:1603.02698)

Anatomy of a BNS coalescence



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



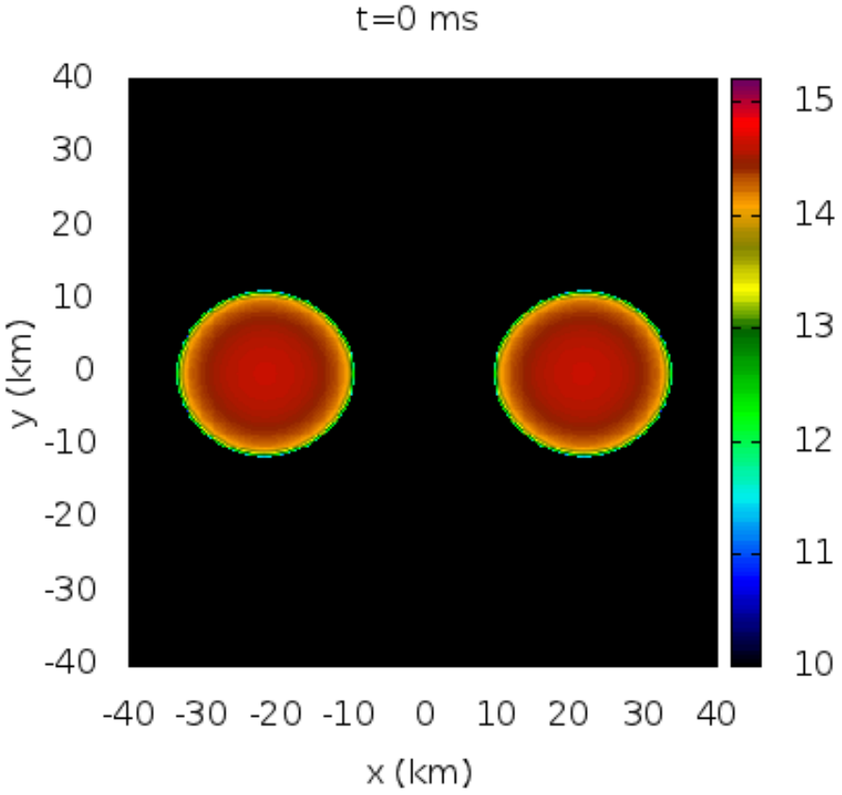
Inspiral+Late inspiral

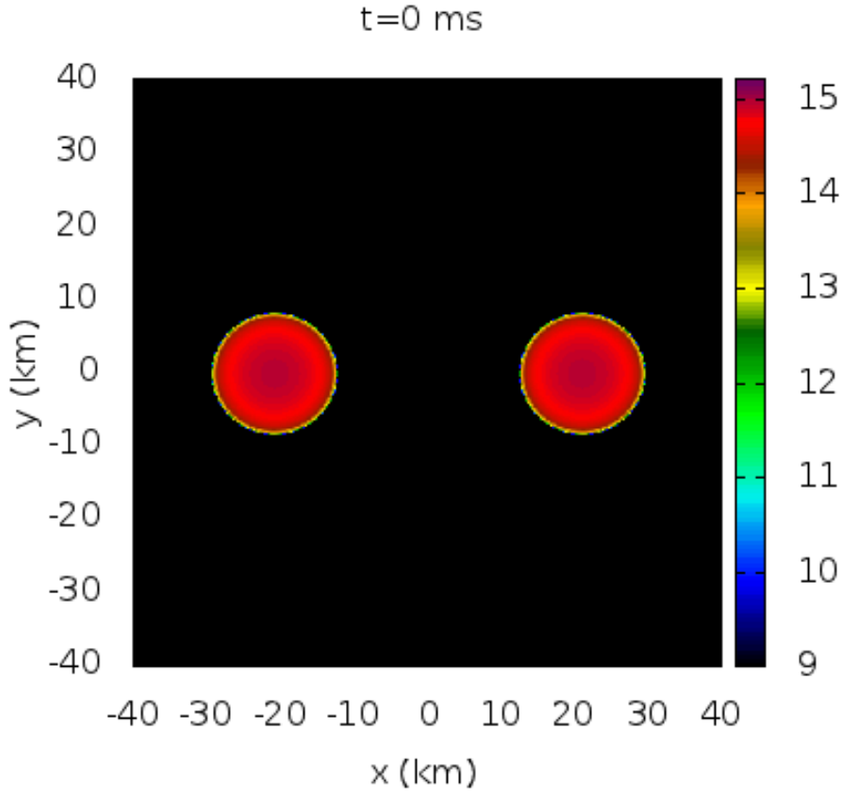
Data Visualization by J. Read
Numerical data by Tim Dietrich (AEI/FSU/BAM Collaboration)
PRD 95 124006, PRD 95 024029

Effect of equation of state

Larger NSs emit energy faster, accelerating the inspiral

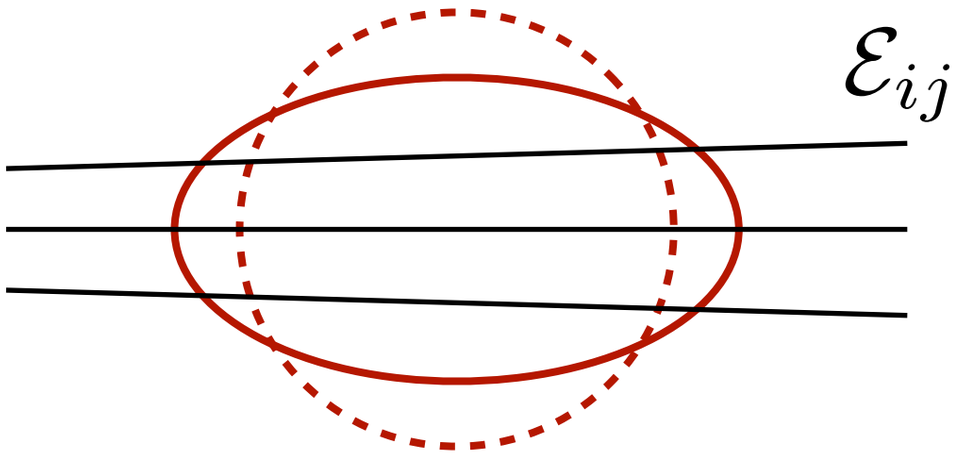
Smaller NSs take longer to merge





Simulations by Kenta Hotokezaka

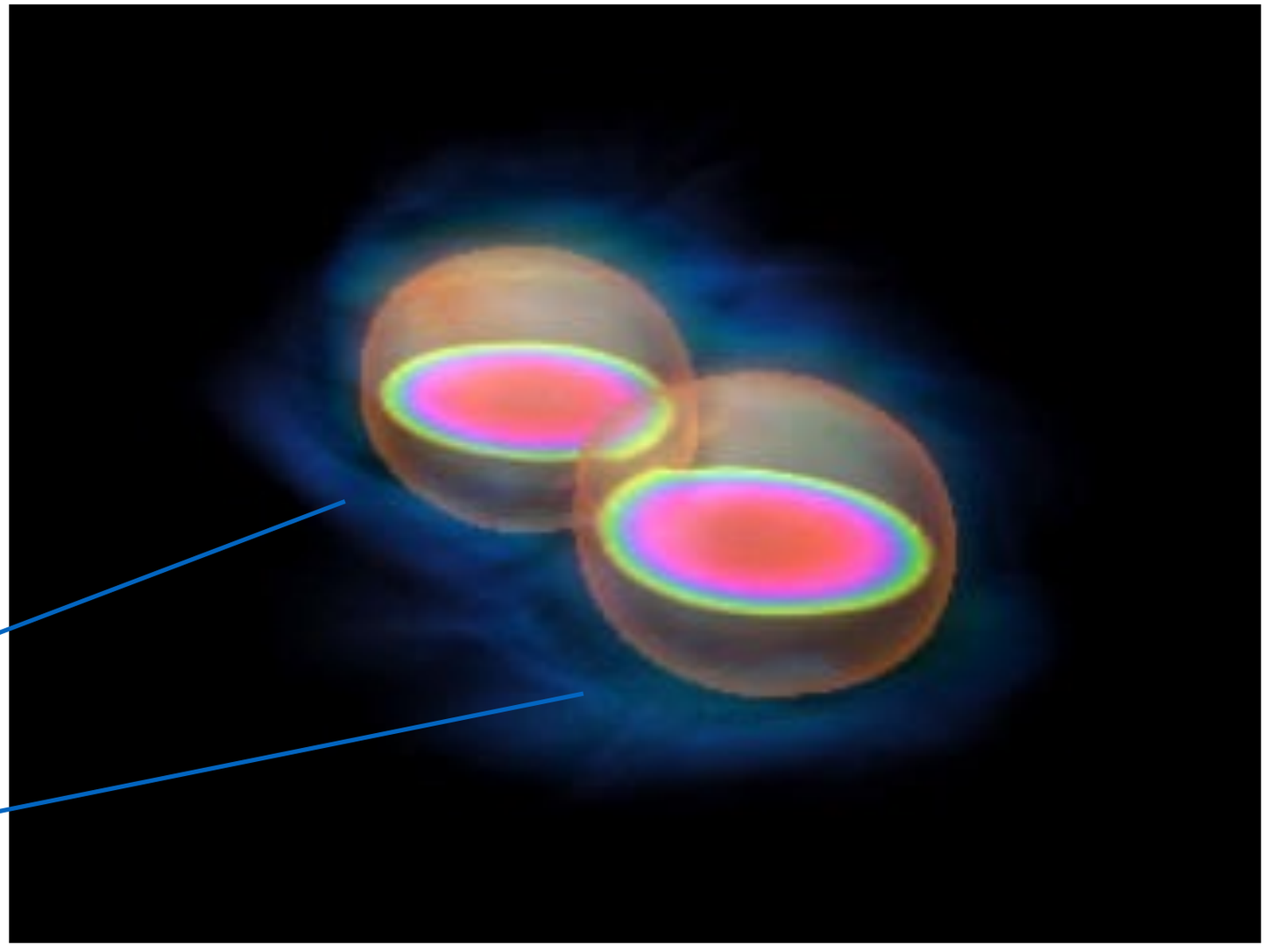
Tidal interactions



Credit: Aaron Zimmerman

Tidal deformability

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



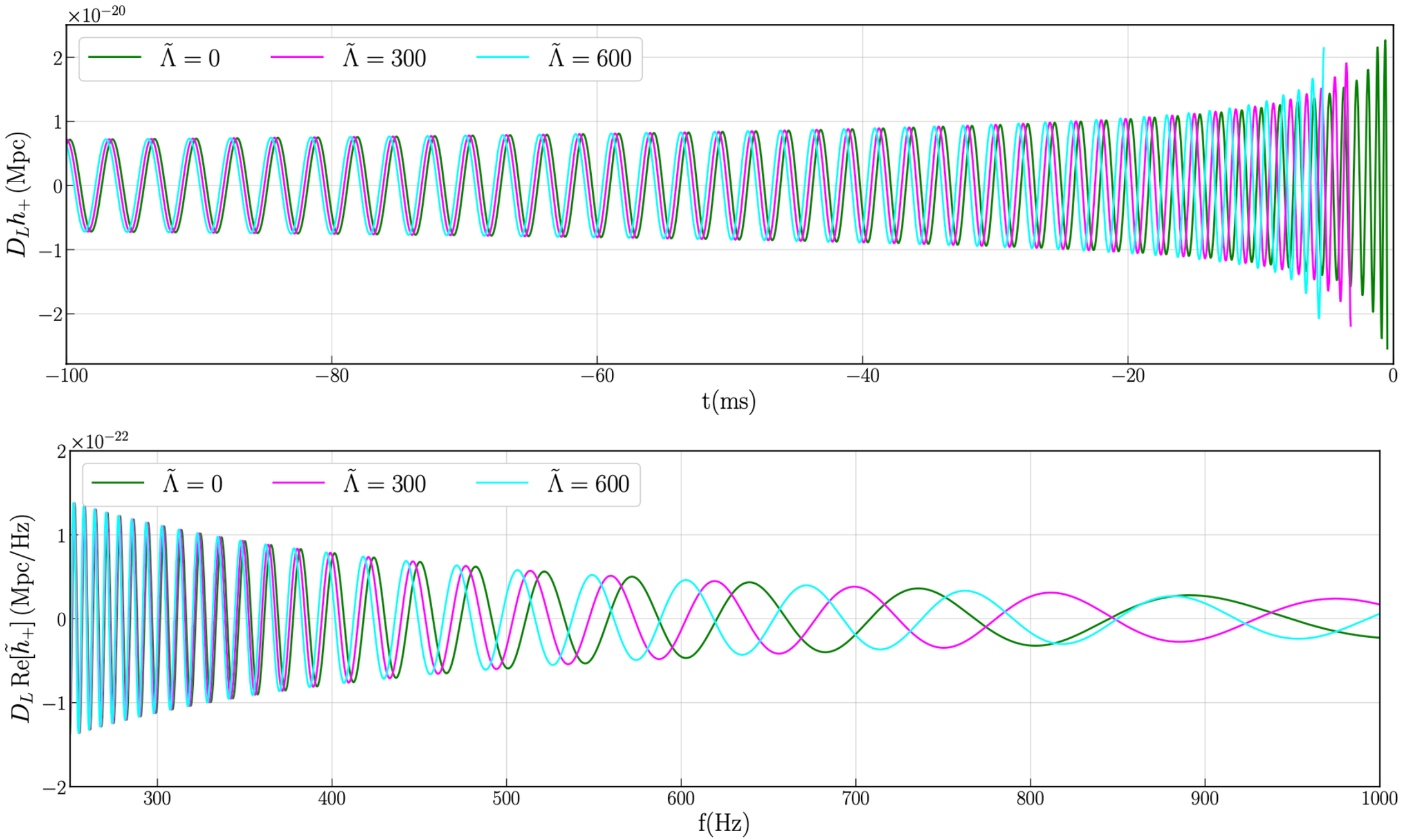
Calder

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)

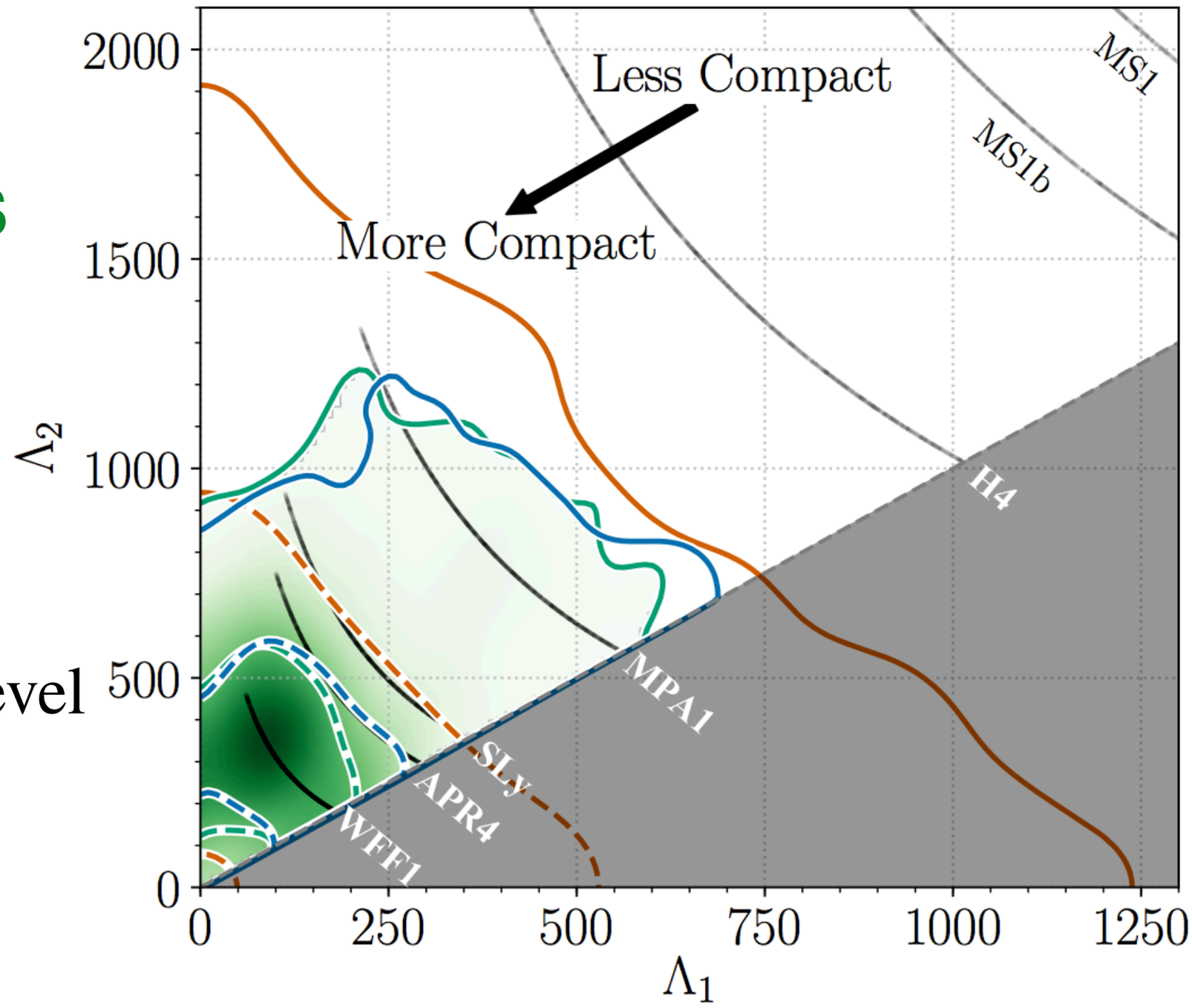
Waveform: Dietrich+ (arxiv:1804.02235)

Independent EoSs

Same hadronic EoS

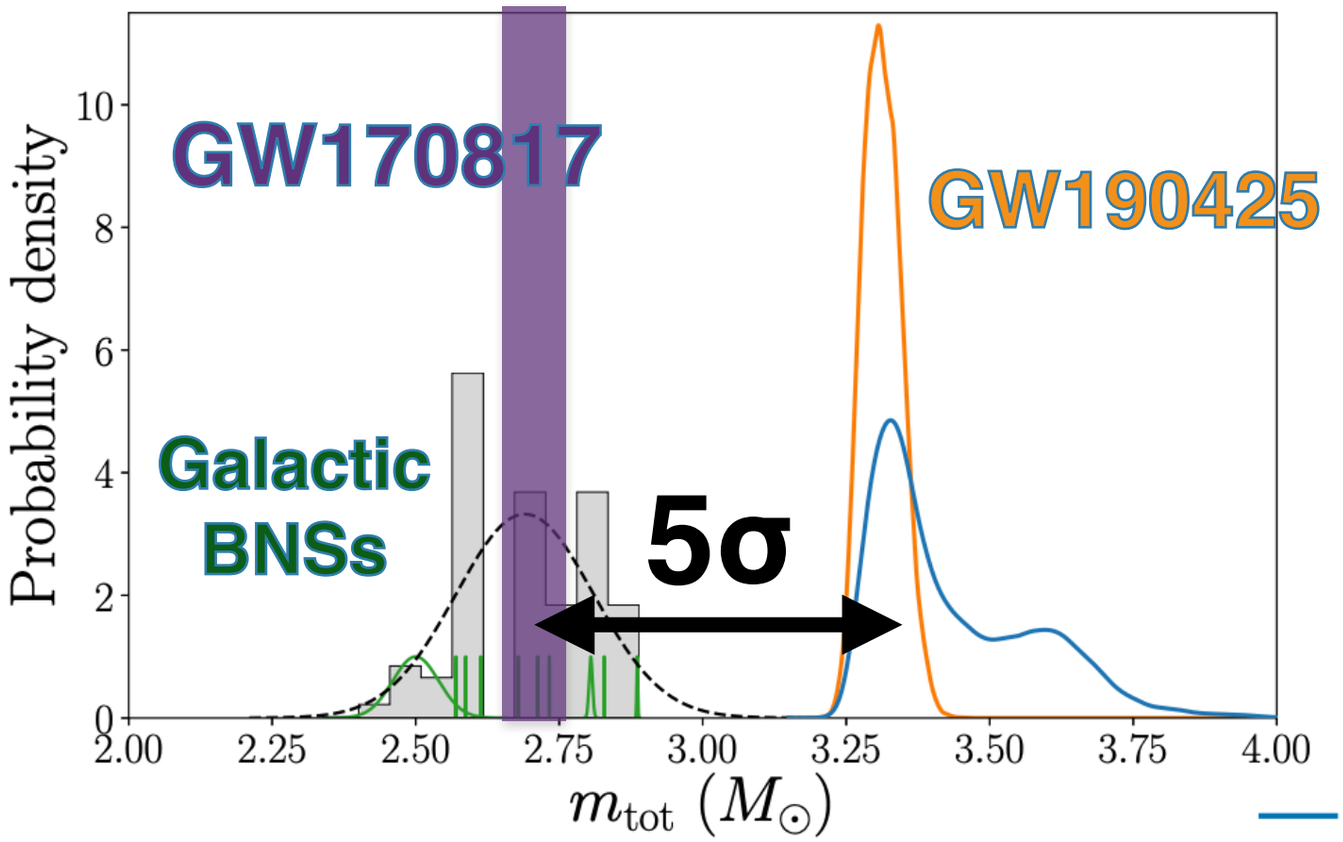
Spectral EoS parametrization

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

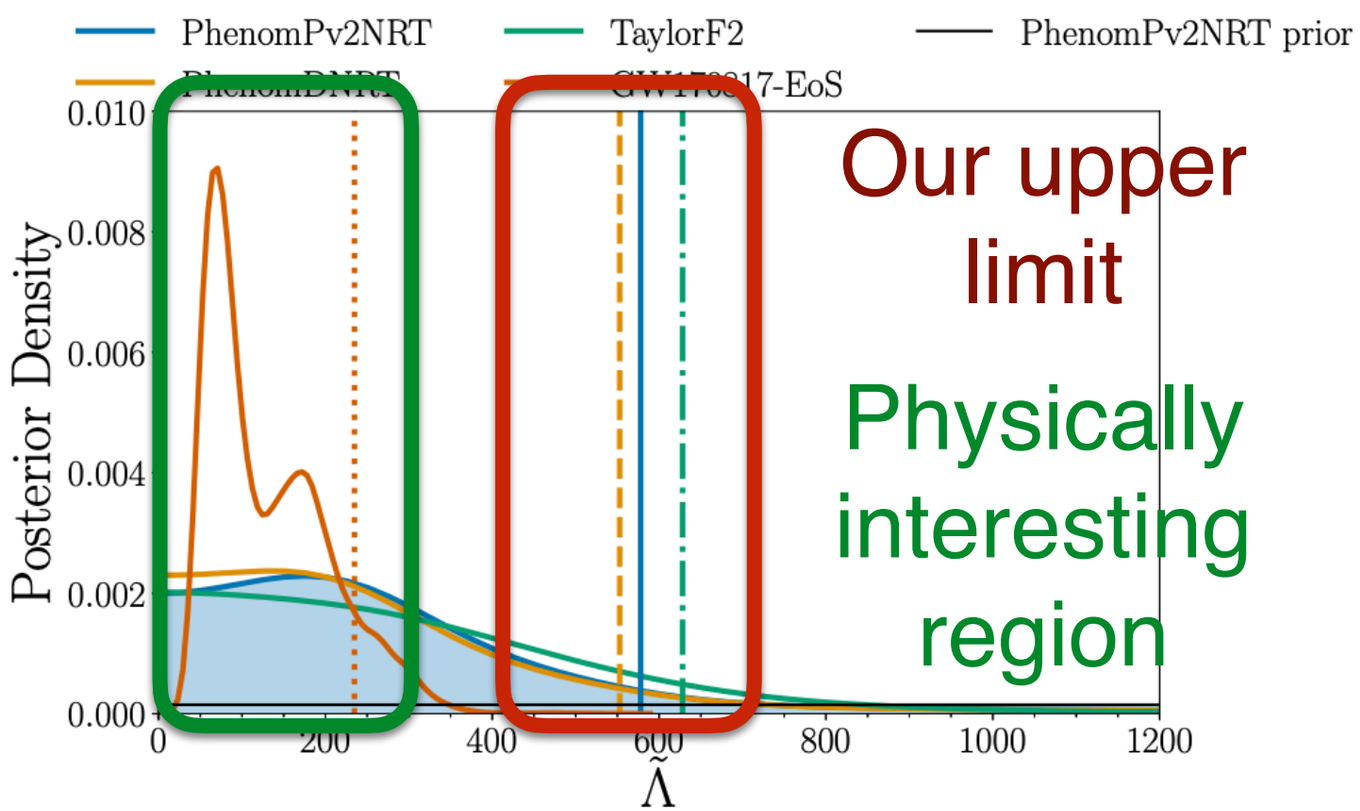


LVC (arxiv:1805.11581)
PE: Veitch+ (arxiv:1409.7215)
Waveform: Dietrich+ (arxiv:1804.02235)
Universal relations: Yagi and Yunes (arxiv:1512.02639), Chatziioannou+ (arxiv:1804.03221)
EoS Parametrization: Lackey and Wade (arxiv:1410.8866), Carney+ (arxiv:1805.11217)

GW190425



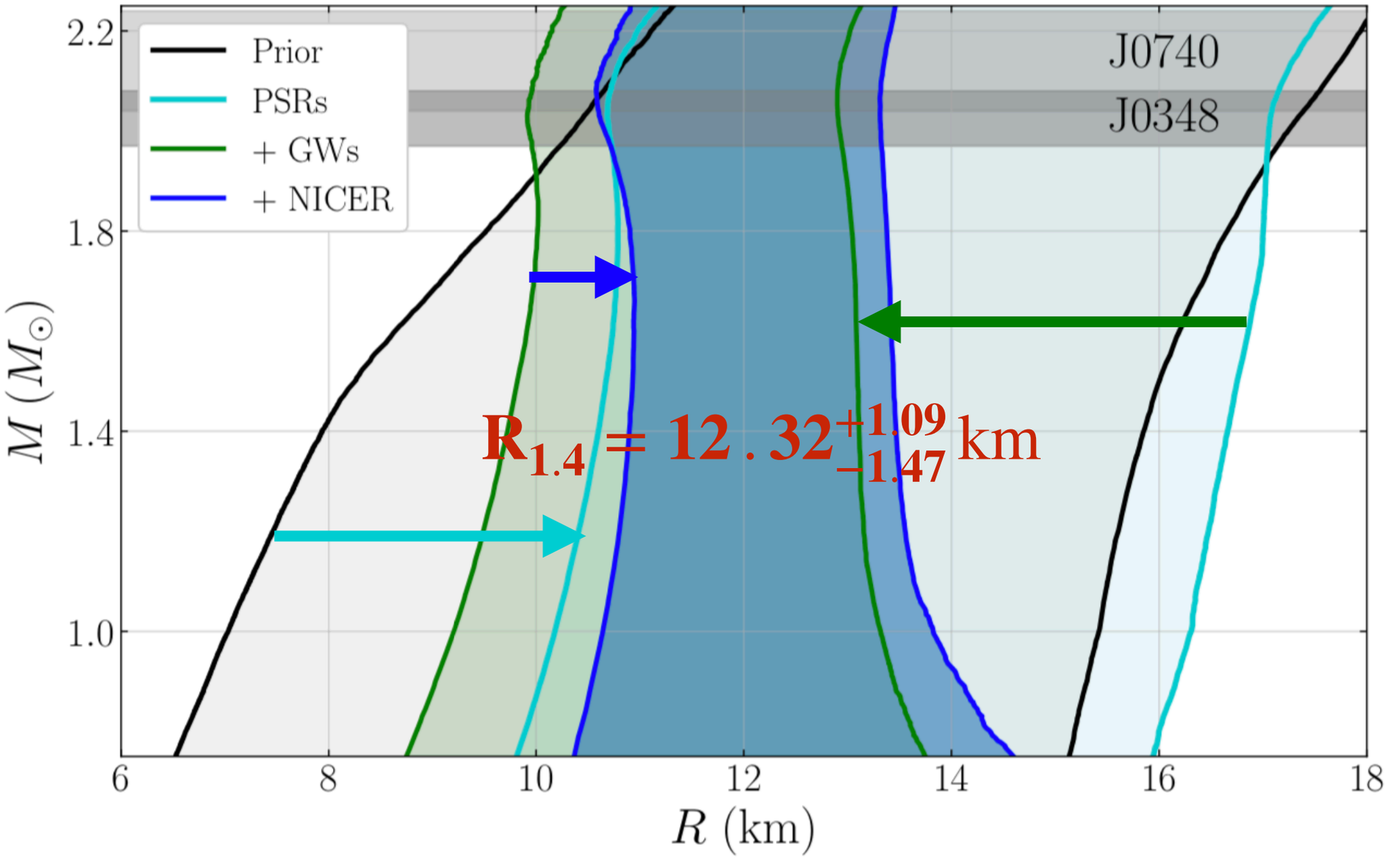
Pro: massive NSs form binaries and merge
Con: tidal interactions are intrinsically weaker



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

Non parametric constraints

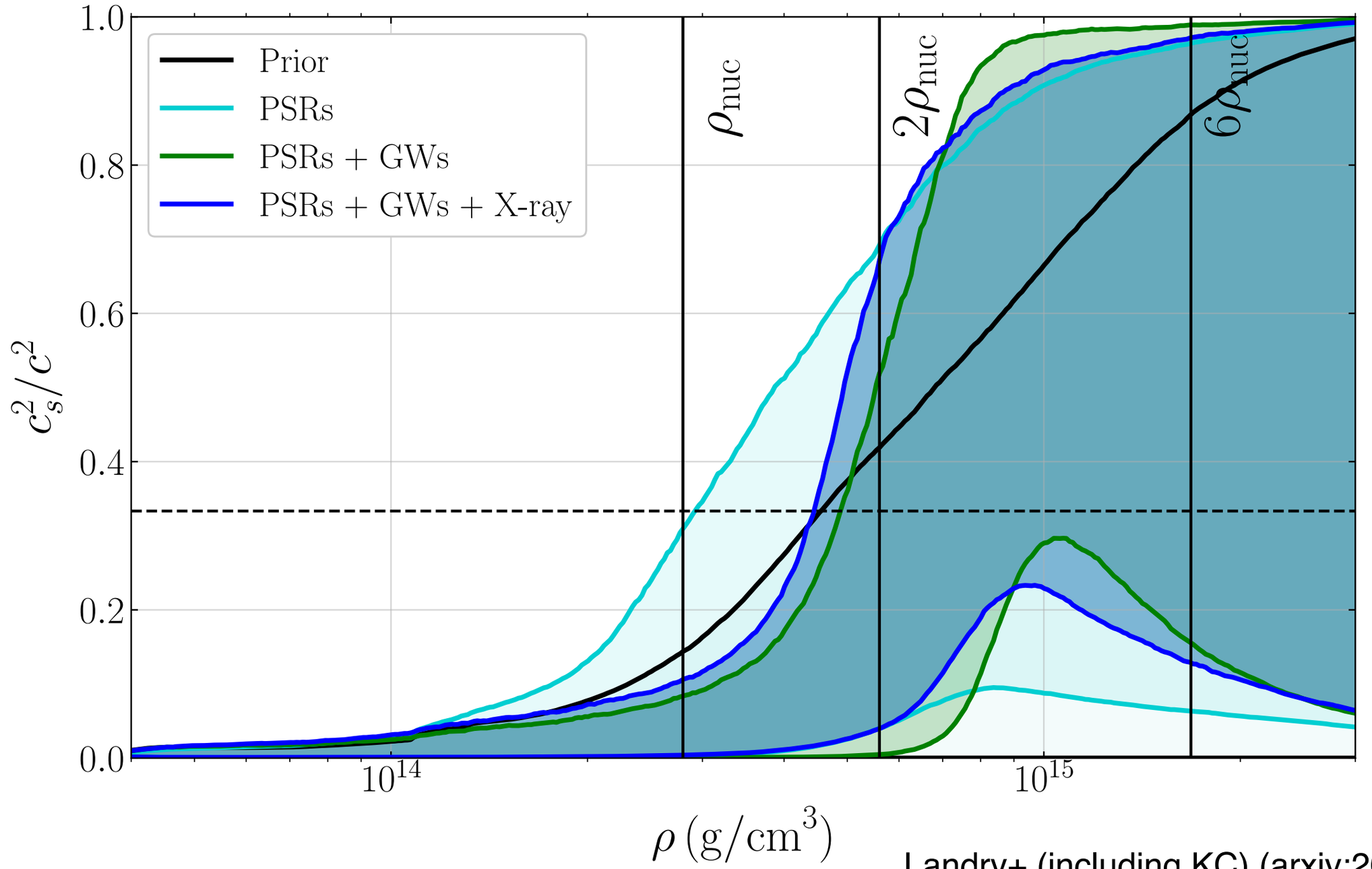
EoS prior based on a gaussian process conditioned on existing nuclear EoS models of different compositions



Landry+ (including KC) (arxiv:2003.04880)

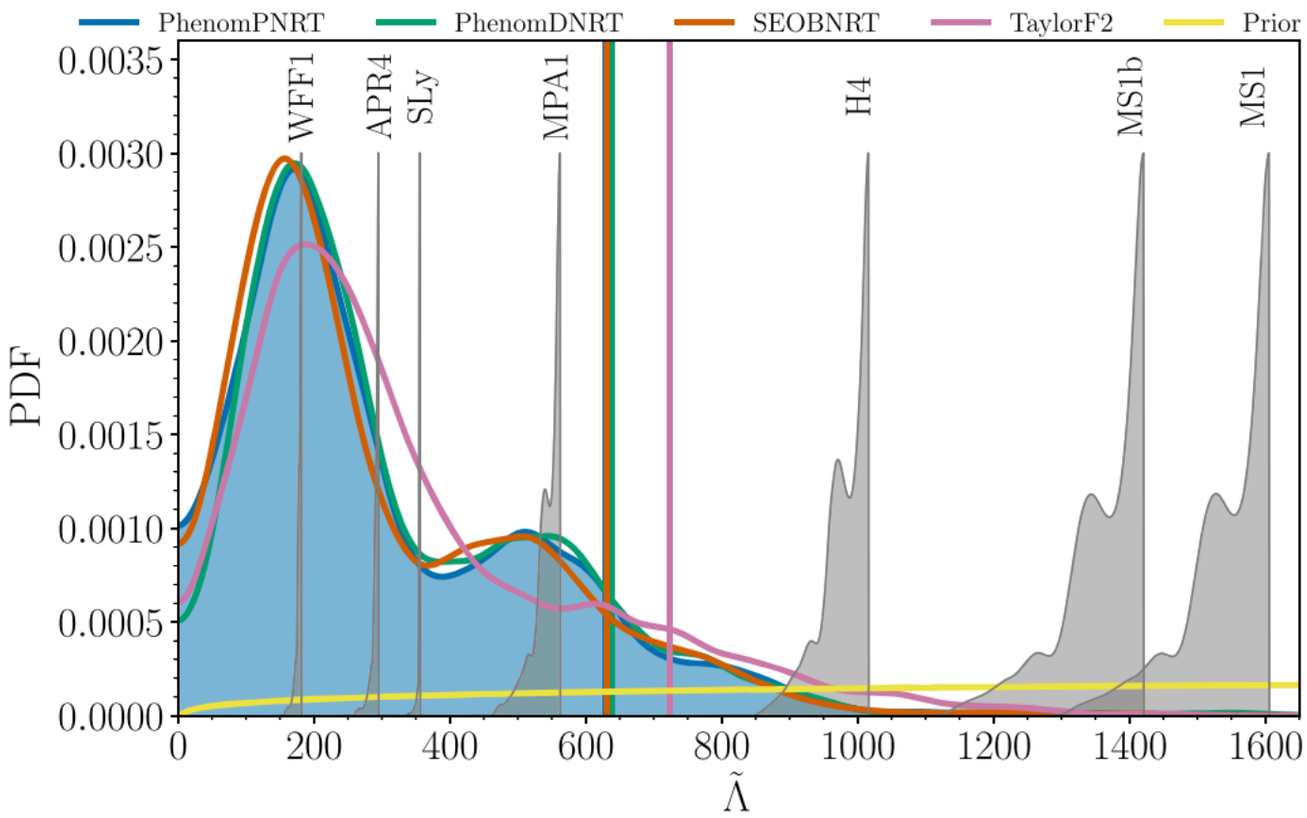
Speed of sound

soft at low densities (GW170817) +
stiff at high densities (Heavy PSRs) =
$c_s^2 > 1/3$



Landry+ (including KC) (arxiv:2003.04880)

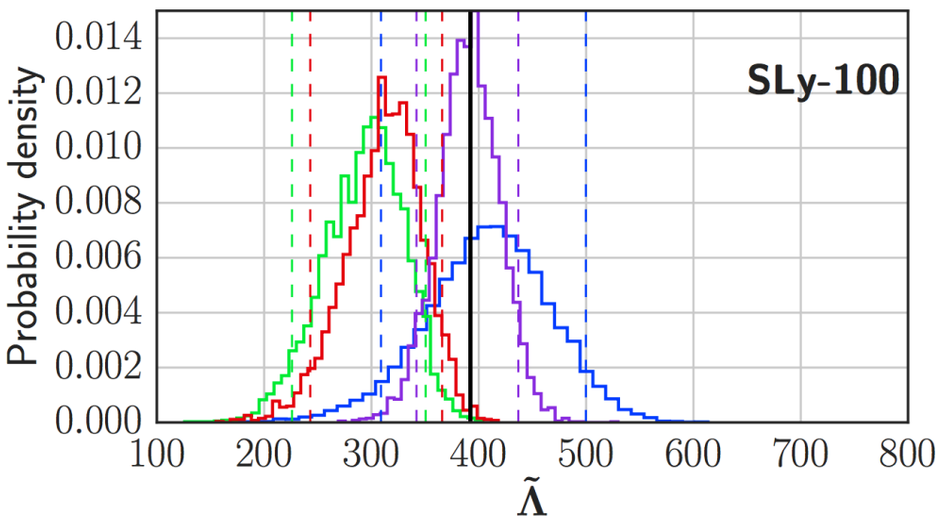
Going forward: Waveform systematics

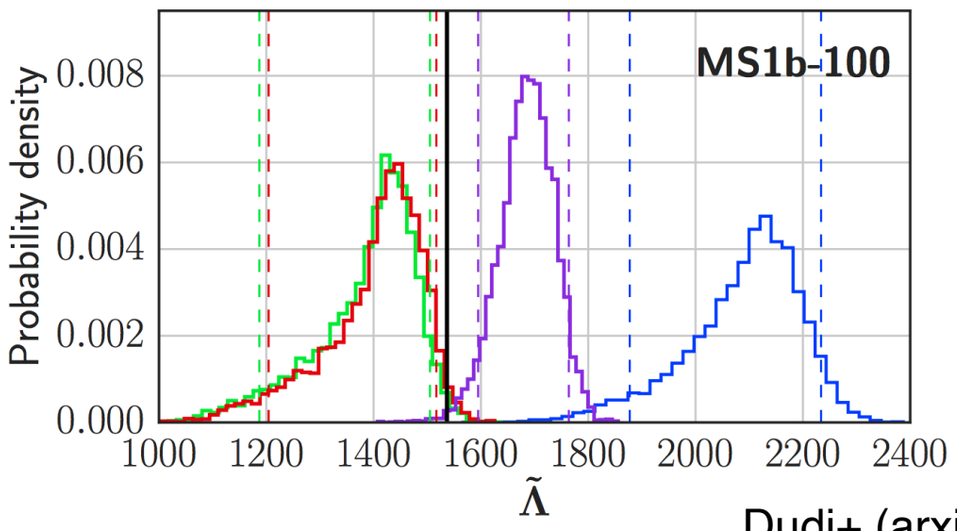


GW170817 tidal measurement with different waveform models

LVC (arxiv:1805.115)
PE: Veitch+ (arxiv:1409.7215)
Waveforms: Dietrich+ (arxiv:1804.02235)

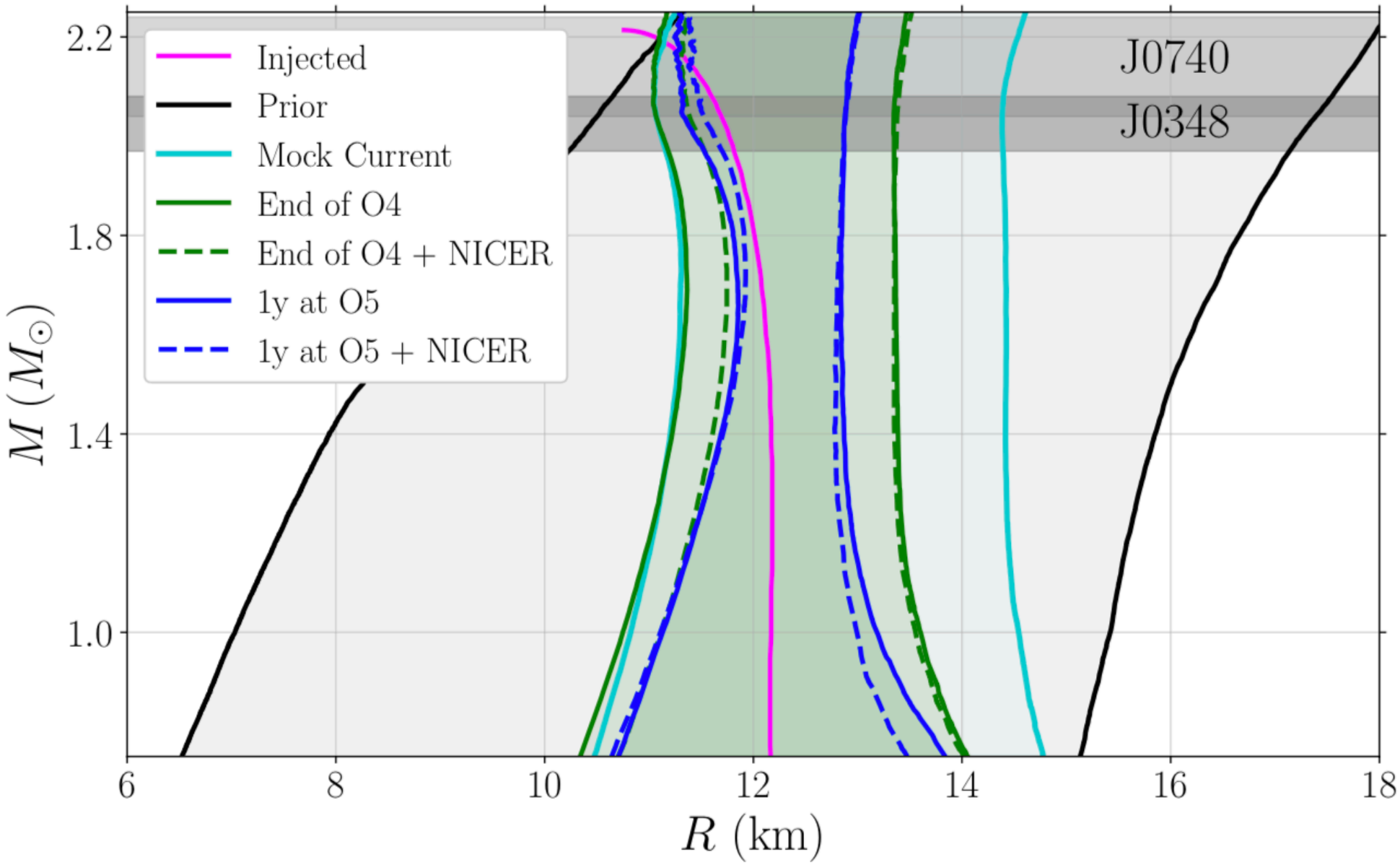
GW170817 at design sensitivity (in a few years) would be dominated by systematic errors





Dudi+ (arxiv:1808.09749)

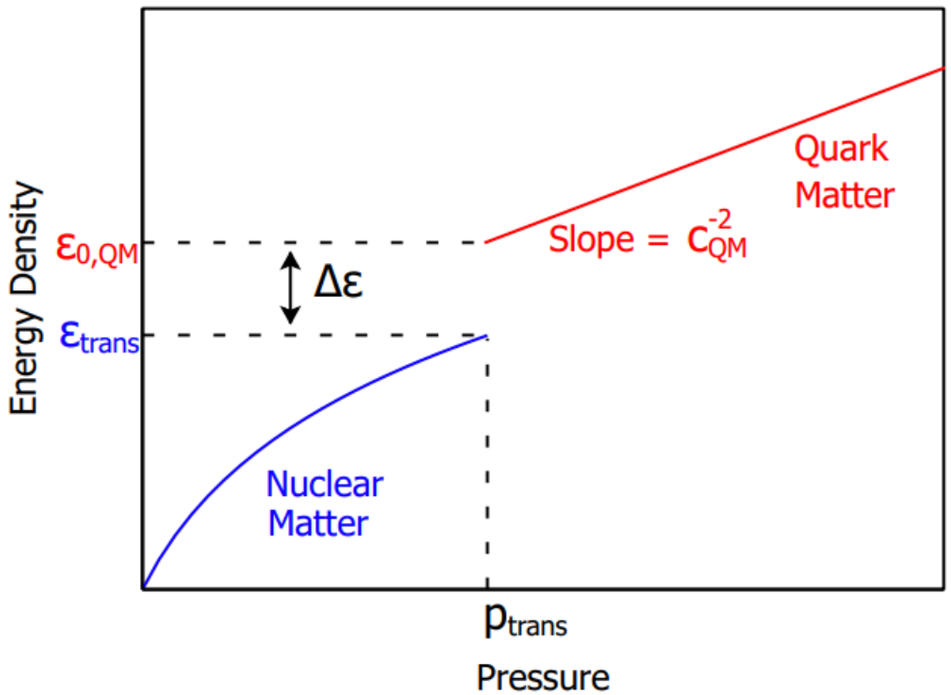
Going forward: More observations

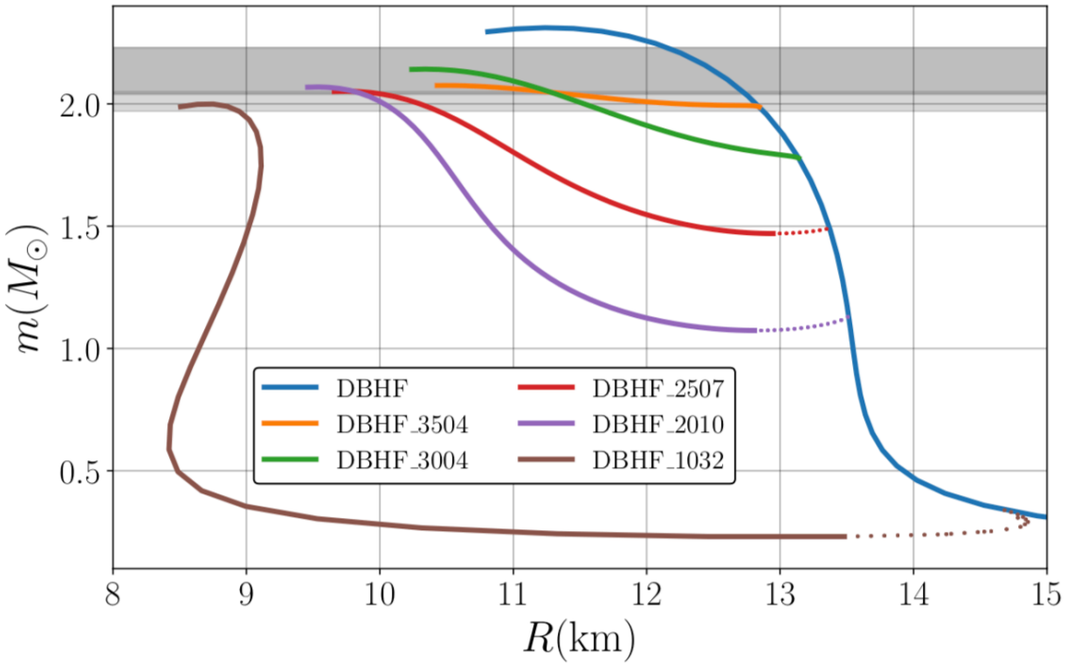


O(1km) radius determination in the coming years

Landry+ (including KC) (arxiv:2003.04880)

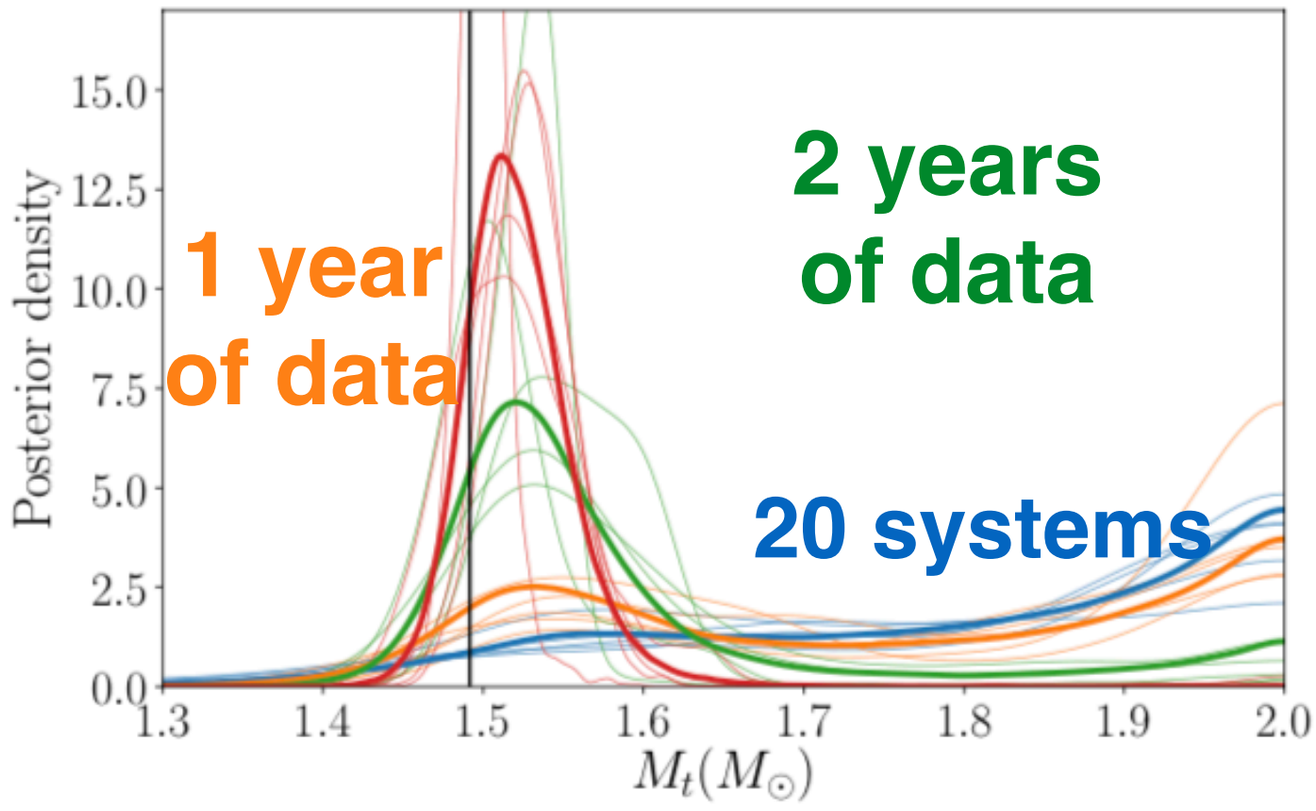
Going forward: Quark matter





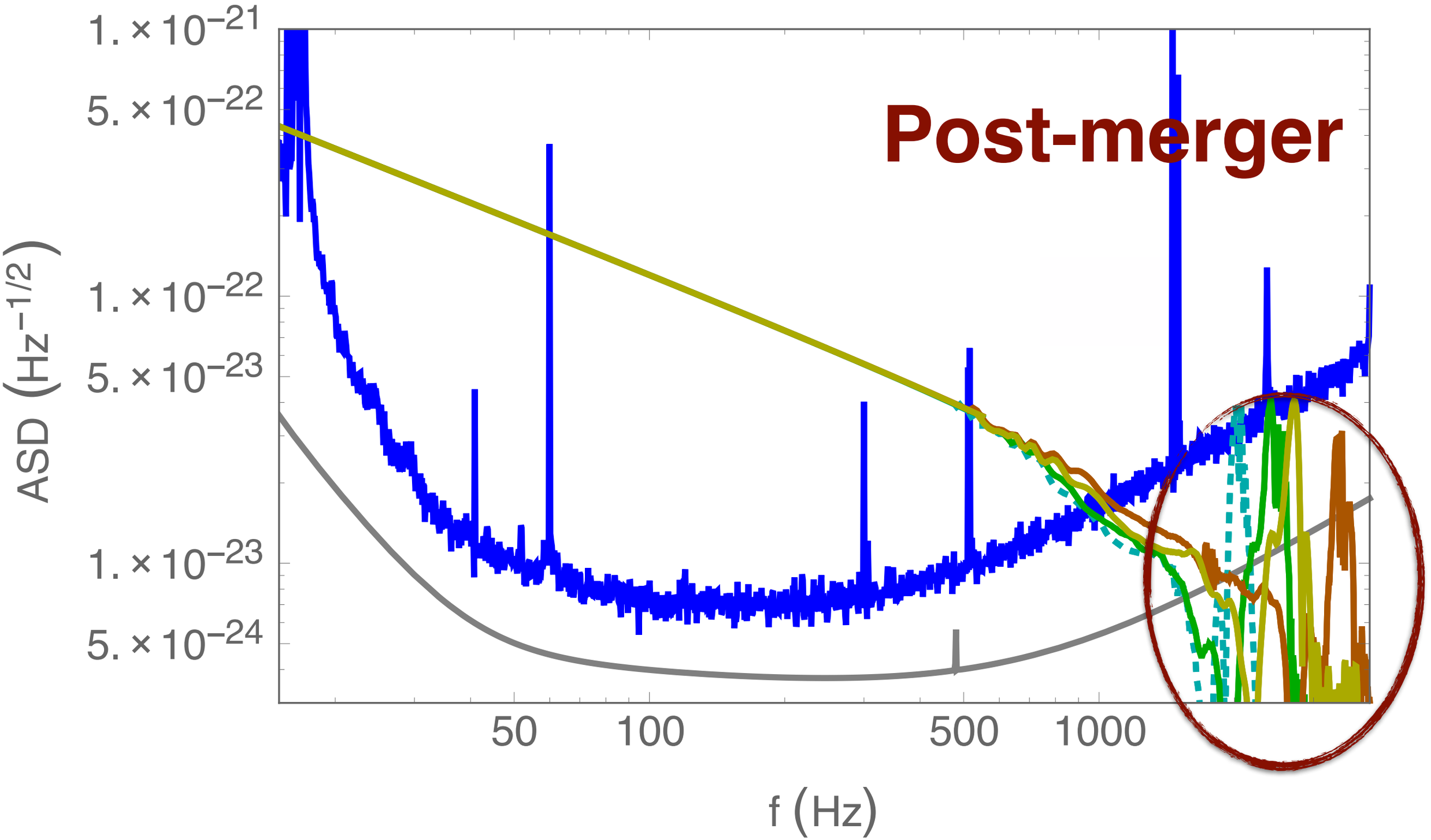
Han and Steiner (arxiv:1810.10967)

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



Chatziioannou and Han (arxiv:1911.07091)

Anatomy of a BNS coalescence: post-merger



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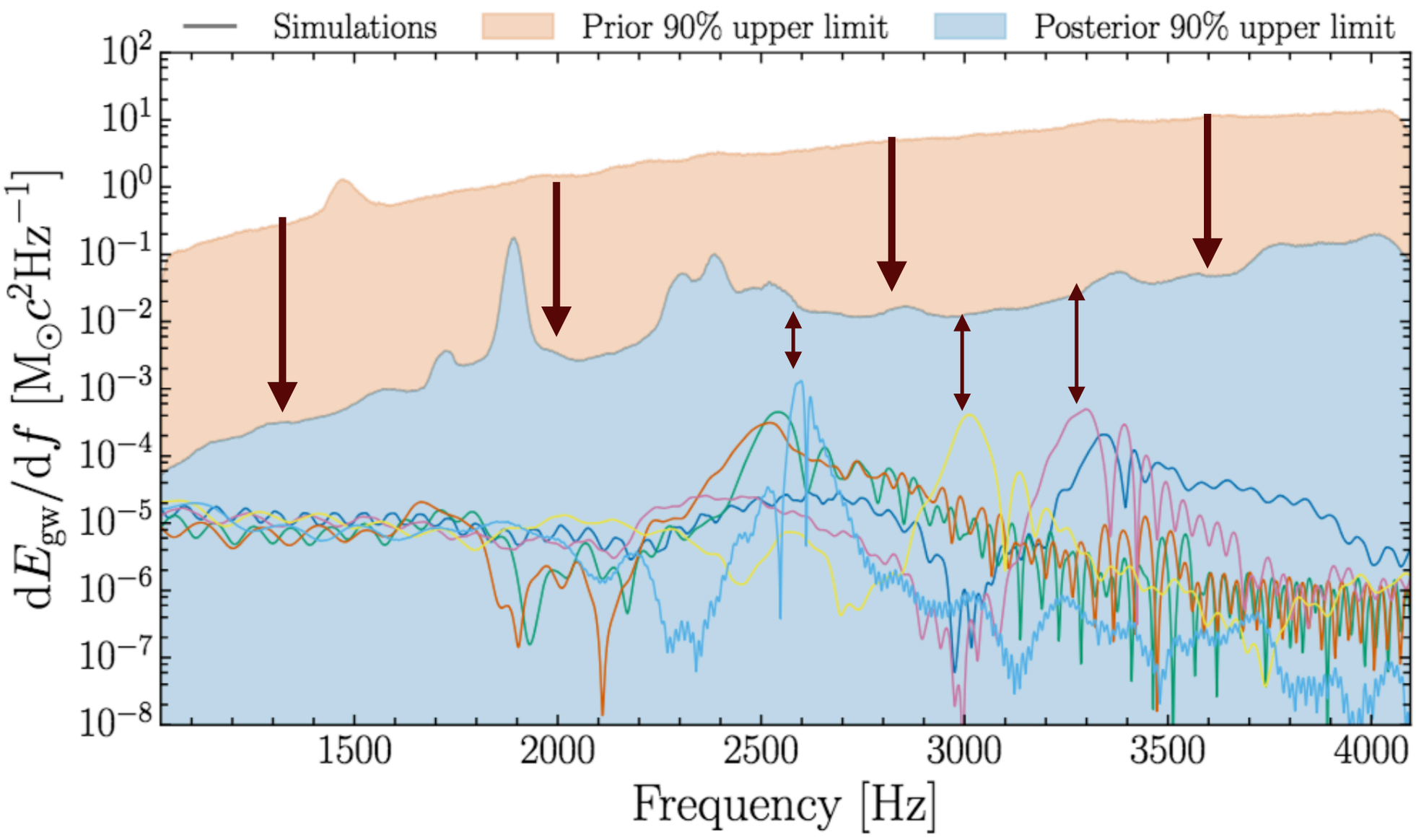
PRD 95 124006, PRD 95 024029

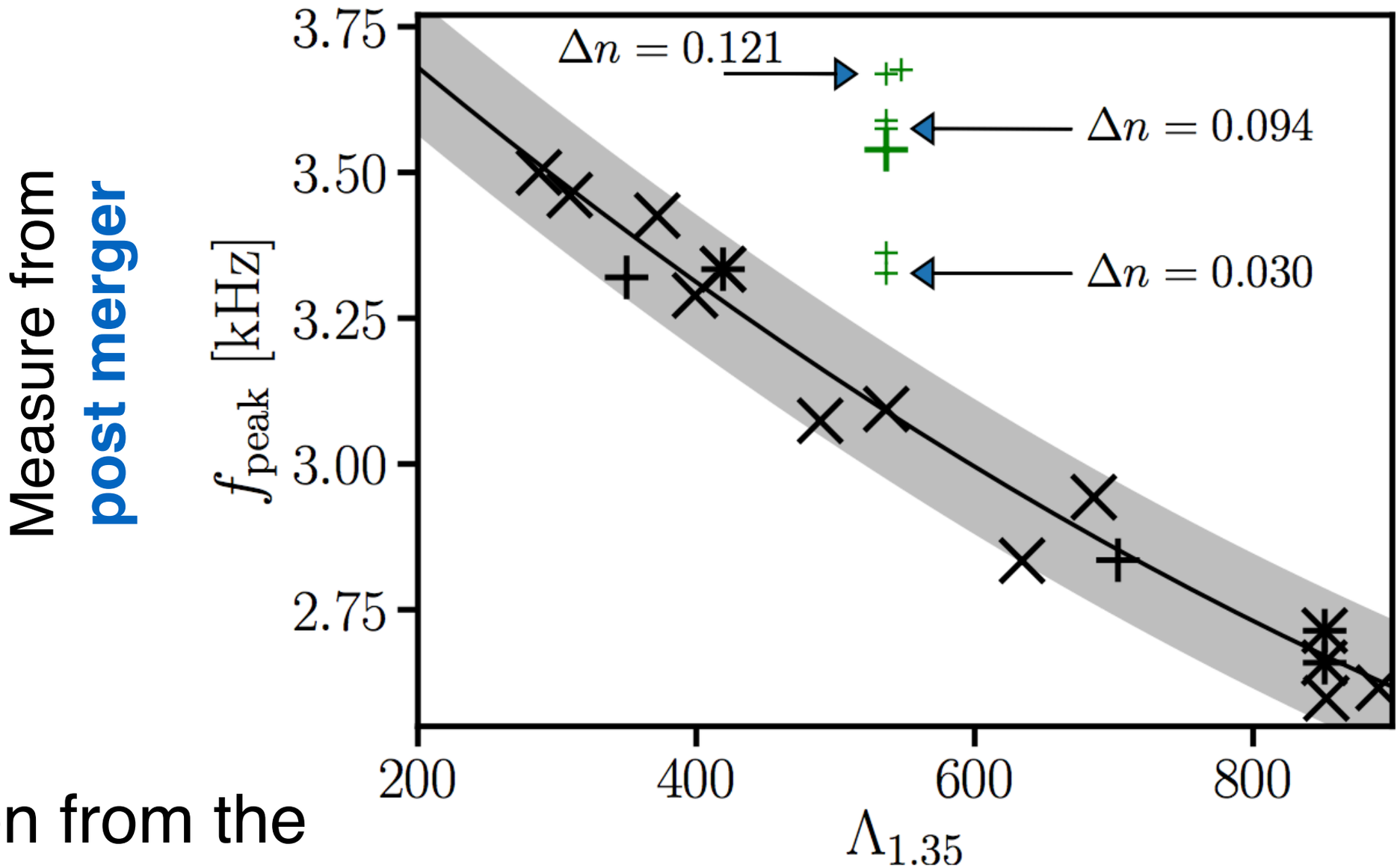
No detectable post-merger emission, upper limits



LVC (arxiv:1805.11579)
Analysis: Chatziioannou+ (arxiv:1711.00040)
Simulations: Bauswein+ (arxiv:1204.1888)

Complementary information

Measure from **post merger**

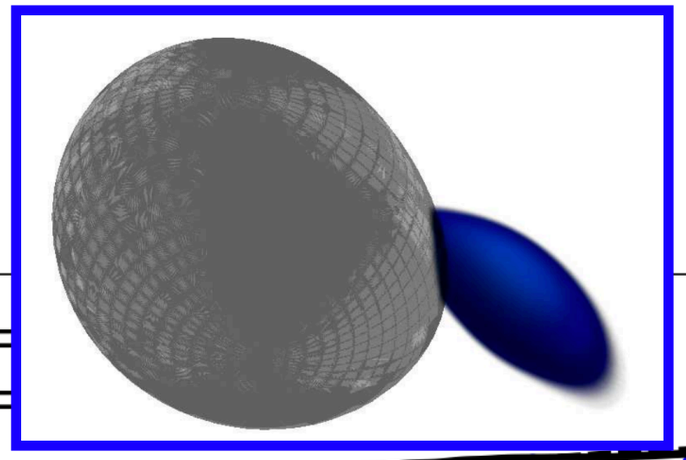


Information from the pre-merger phase breaks the degeneracy

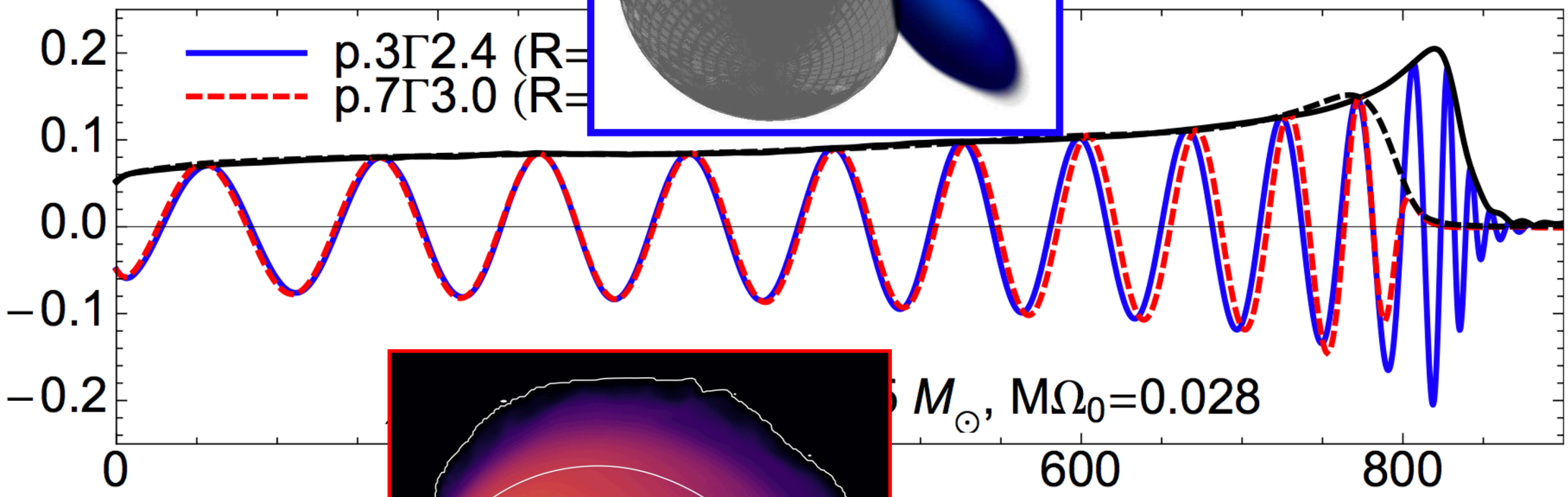
Measure from **pre merger**

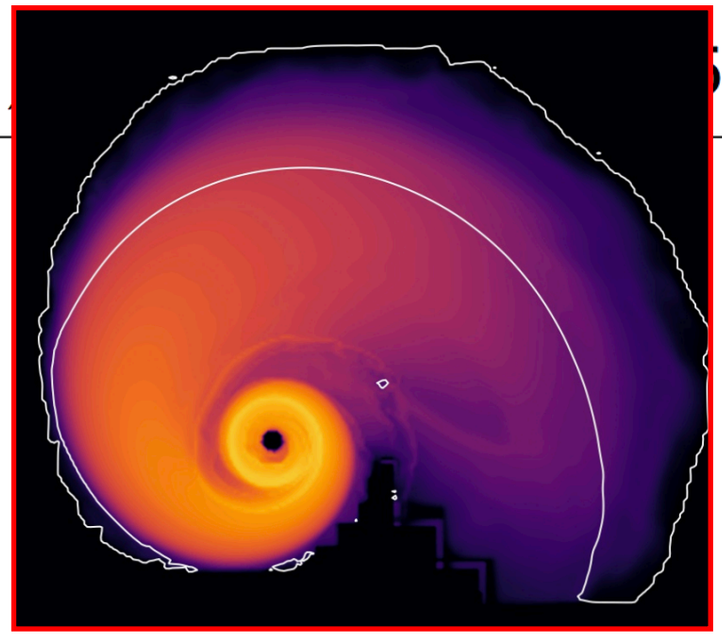
Bauswein+ (including KC) (arxiv:1809.01116)

Anatomy of a NSBH coalescence



BBH-like signal



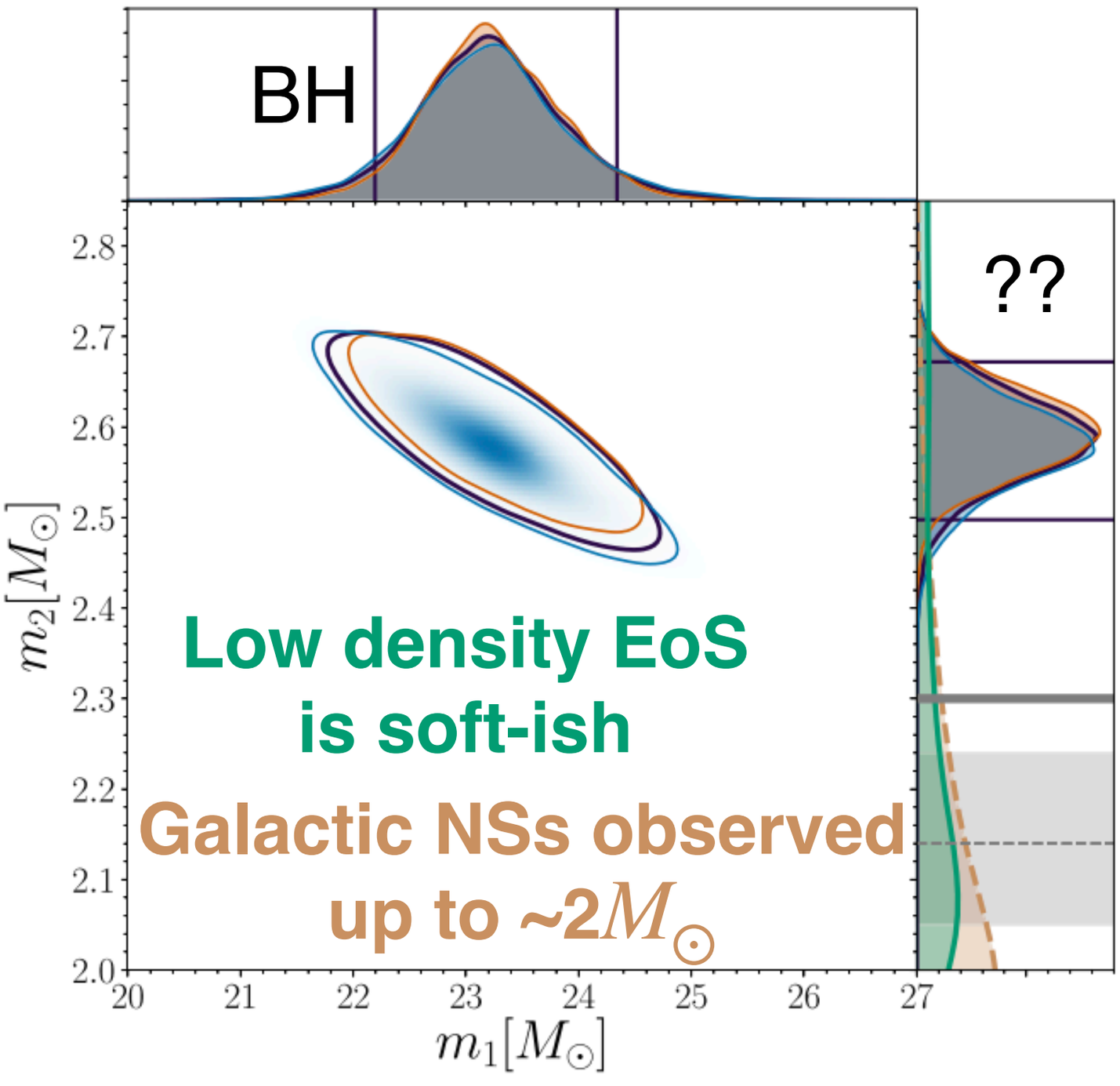


Signal shuts off

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



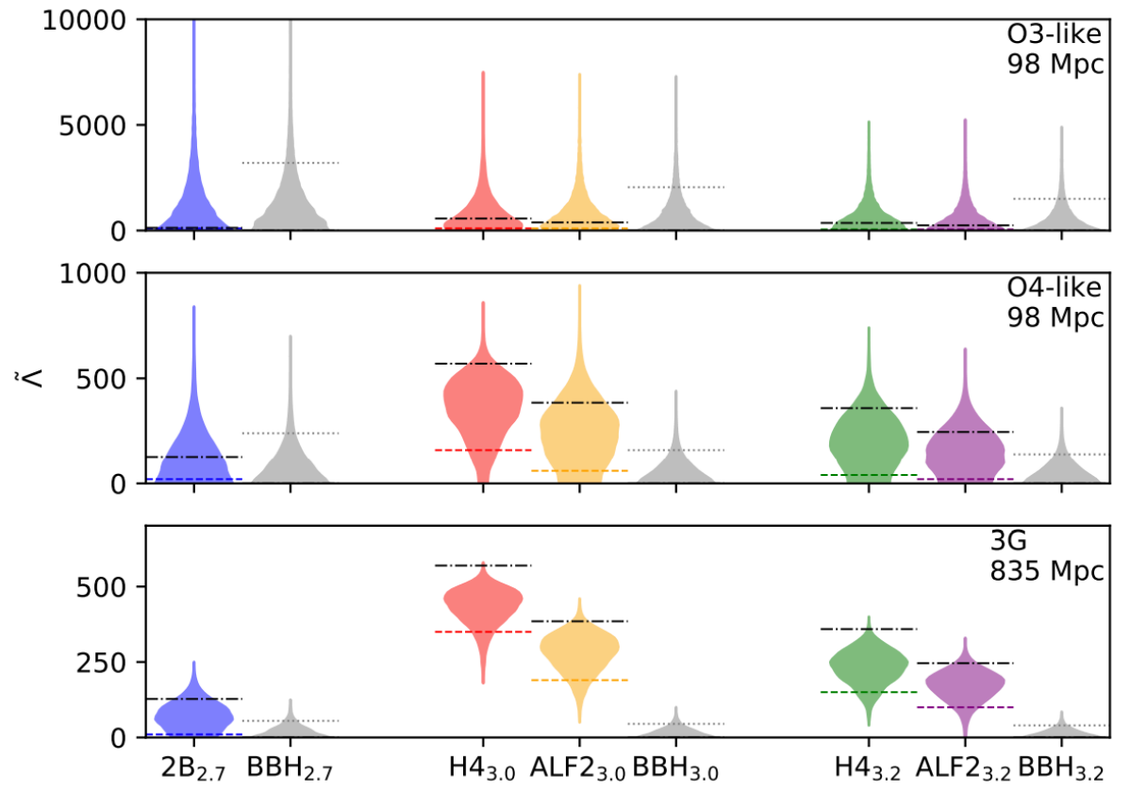
LVC (arxiv:2006.12611)

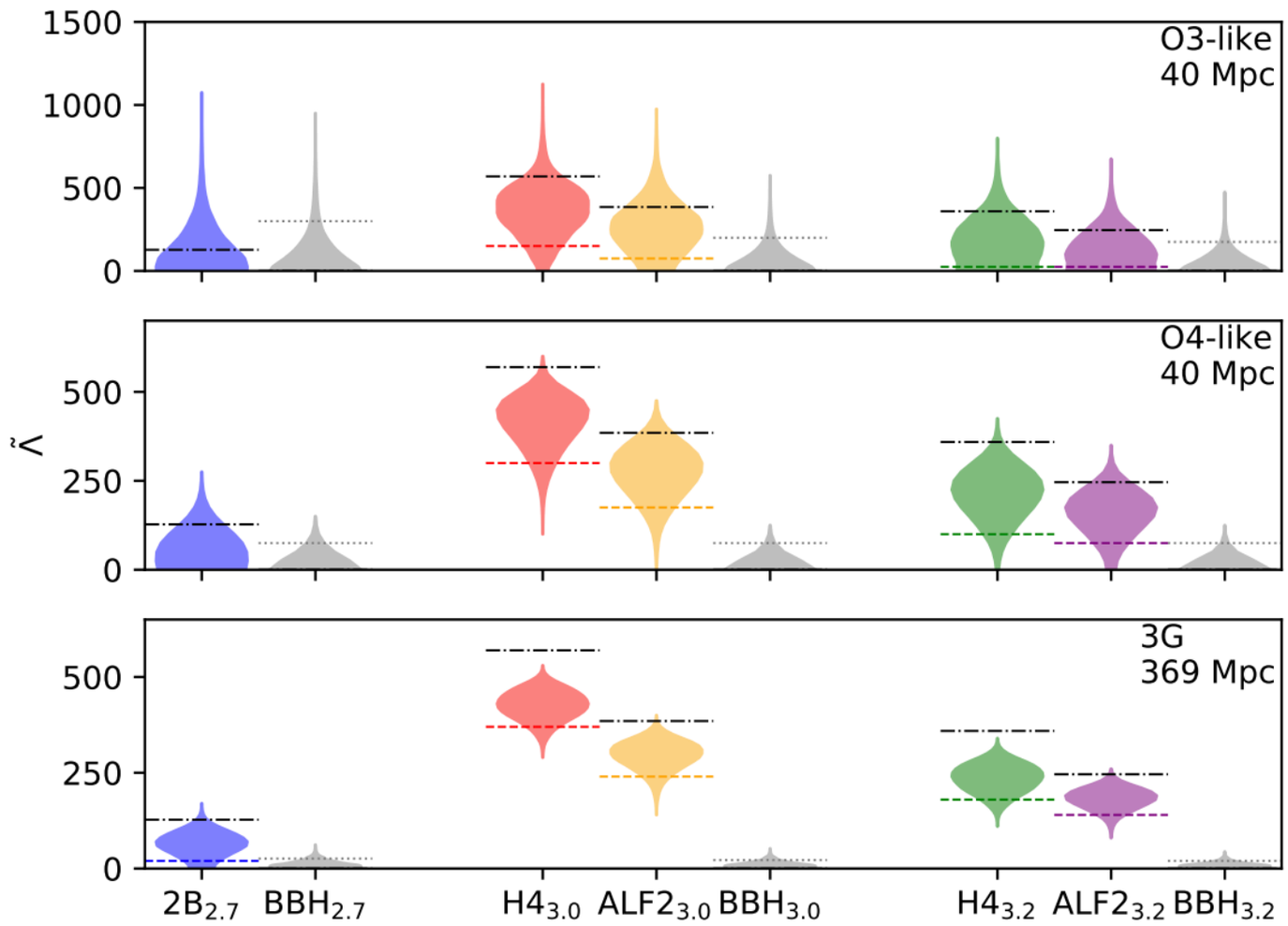
Ongoing efforts to study the nature of the secondary object

- 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)

Going forward: High mass events



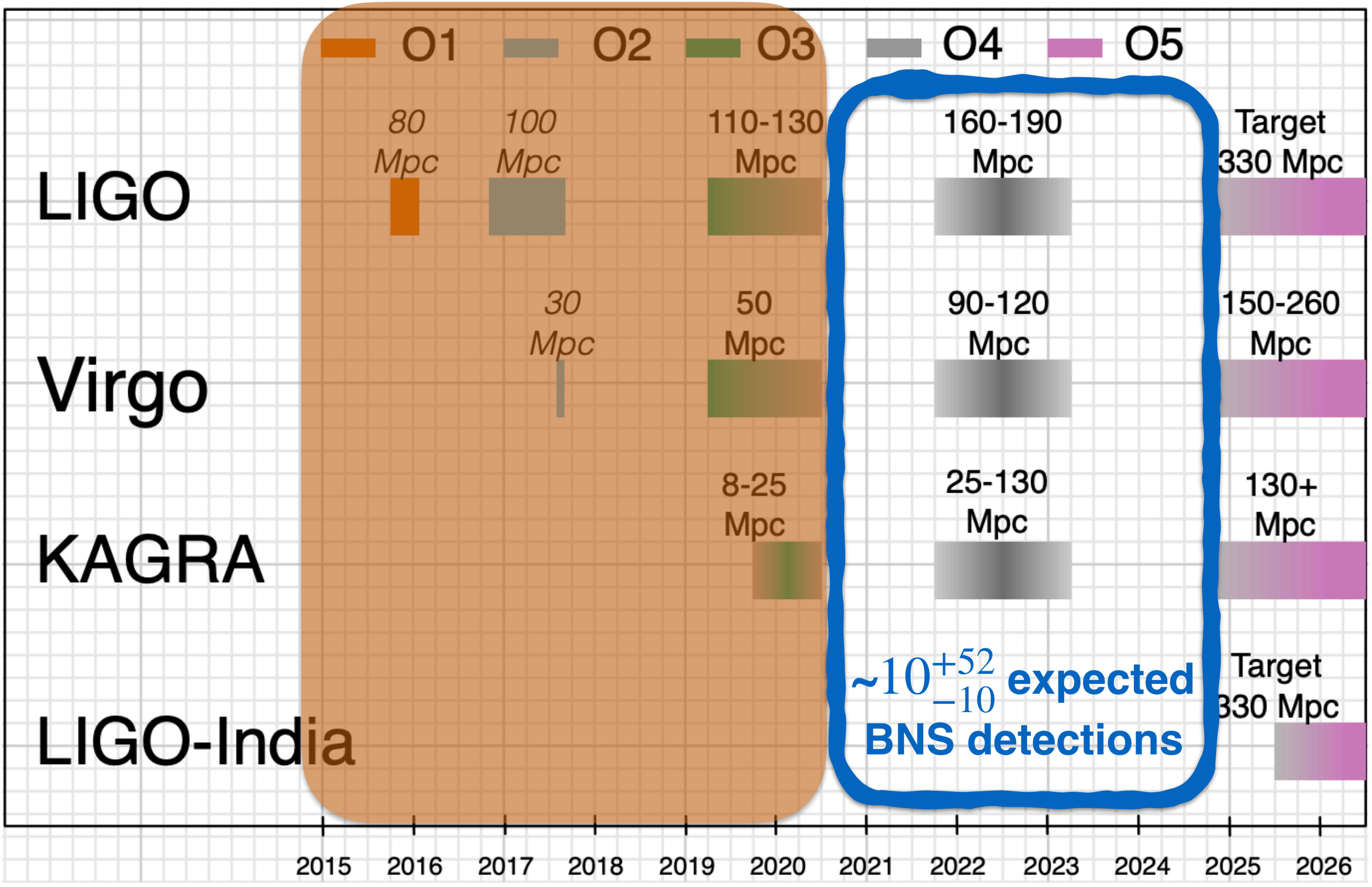


Chen+ (arxiv:2001.11470)

A non zero tidal parameter proves the existence of one NS. Up to what mass are we confident about the NS nature of the body? Can we use external information?

Essick and Landry (arxiv:2007.01372)

The next steps



LVC (arxiv:1304.0670)