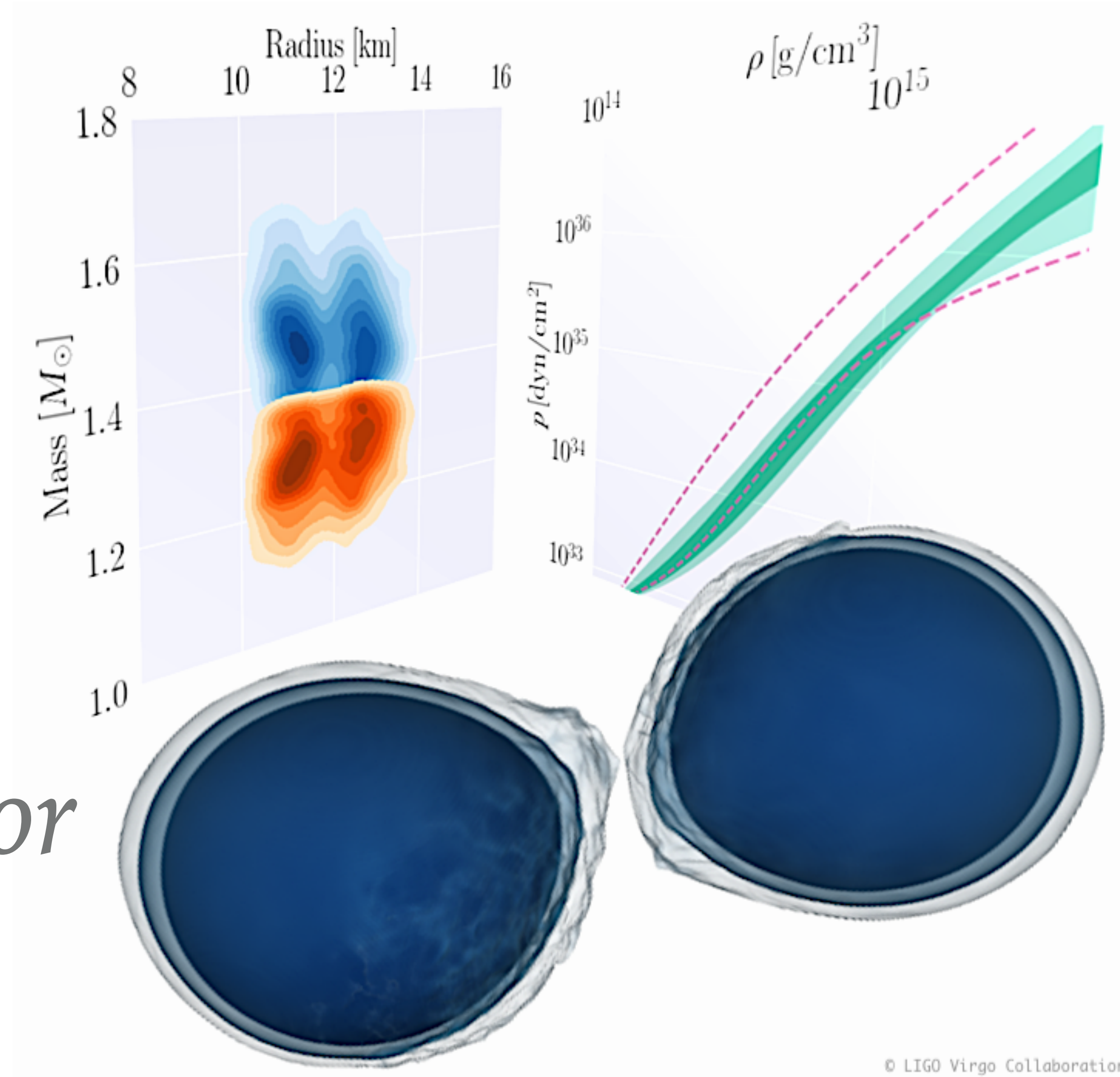


Gravitational Waves from Neutron-Star Mergers - Implications for Nuclear Physics and Cosmology

FRIEDRICH-SCHILLER-UNIVERSITÄT JENA

KICC

UNIVERSITY OF CAMBRIDGE

Michalis Agathos

KICC10 Symposium
Cambridge 16-20 Sep 2019

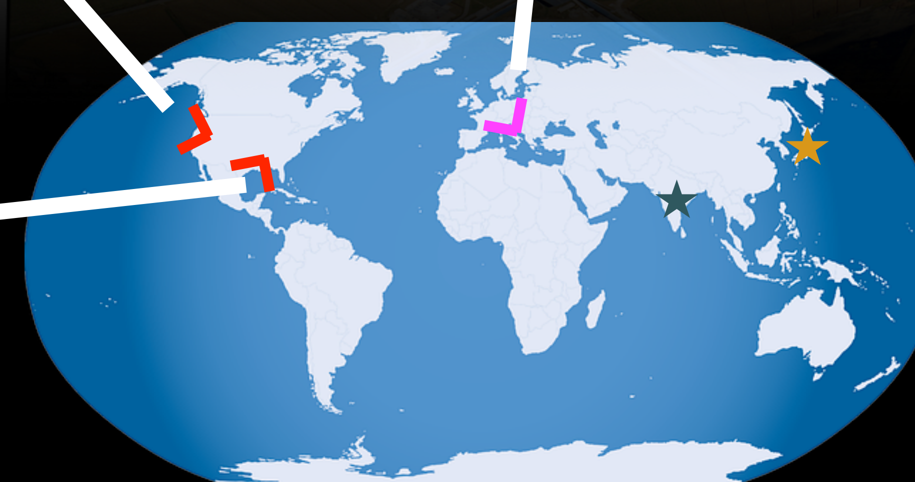
VIRGO

LSC LIGO Scientific Collaboration

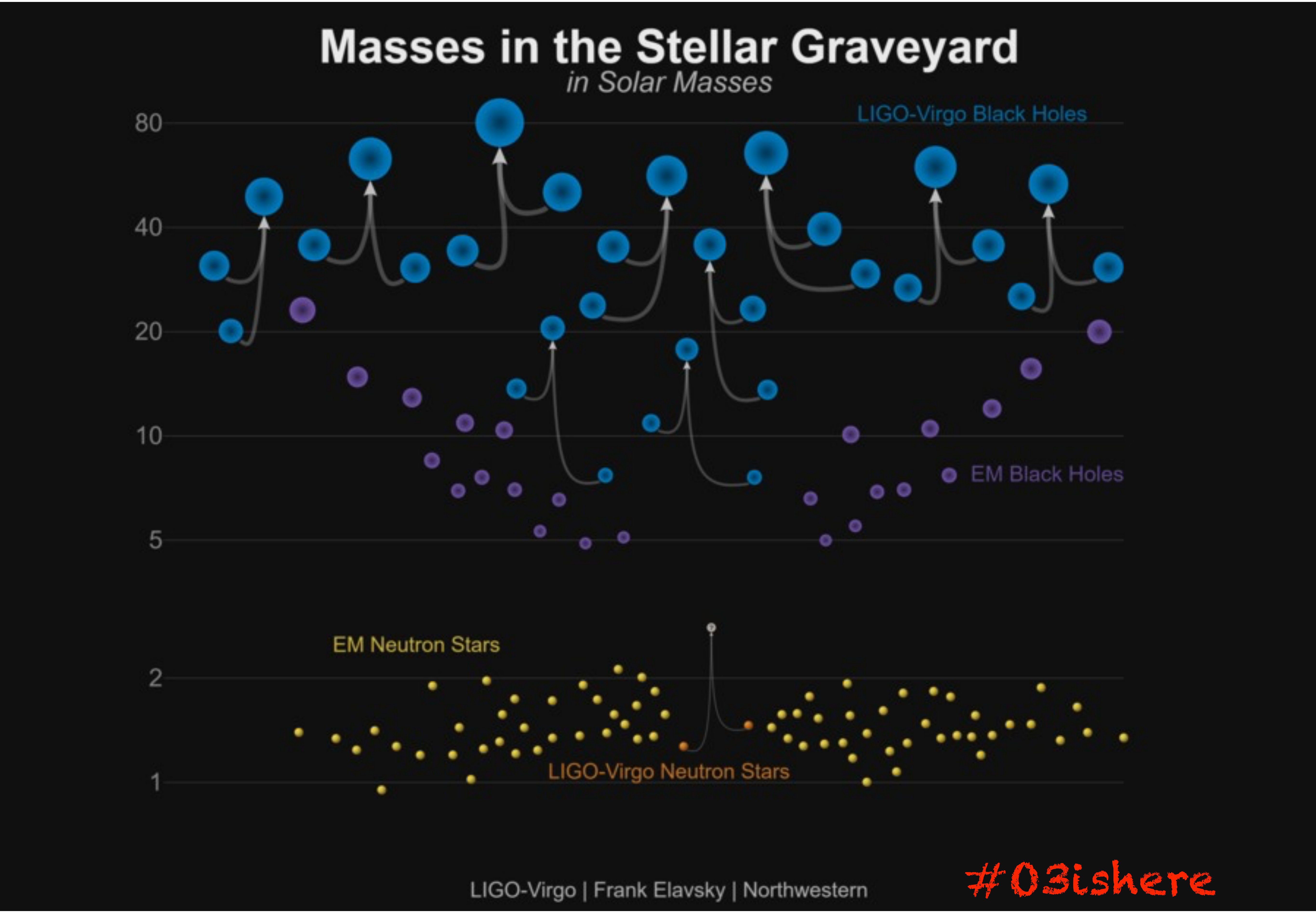
LIGO Hanford

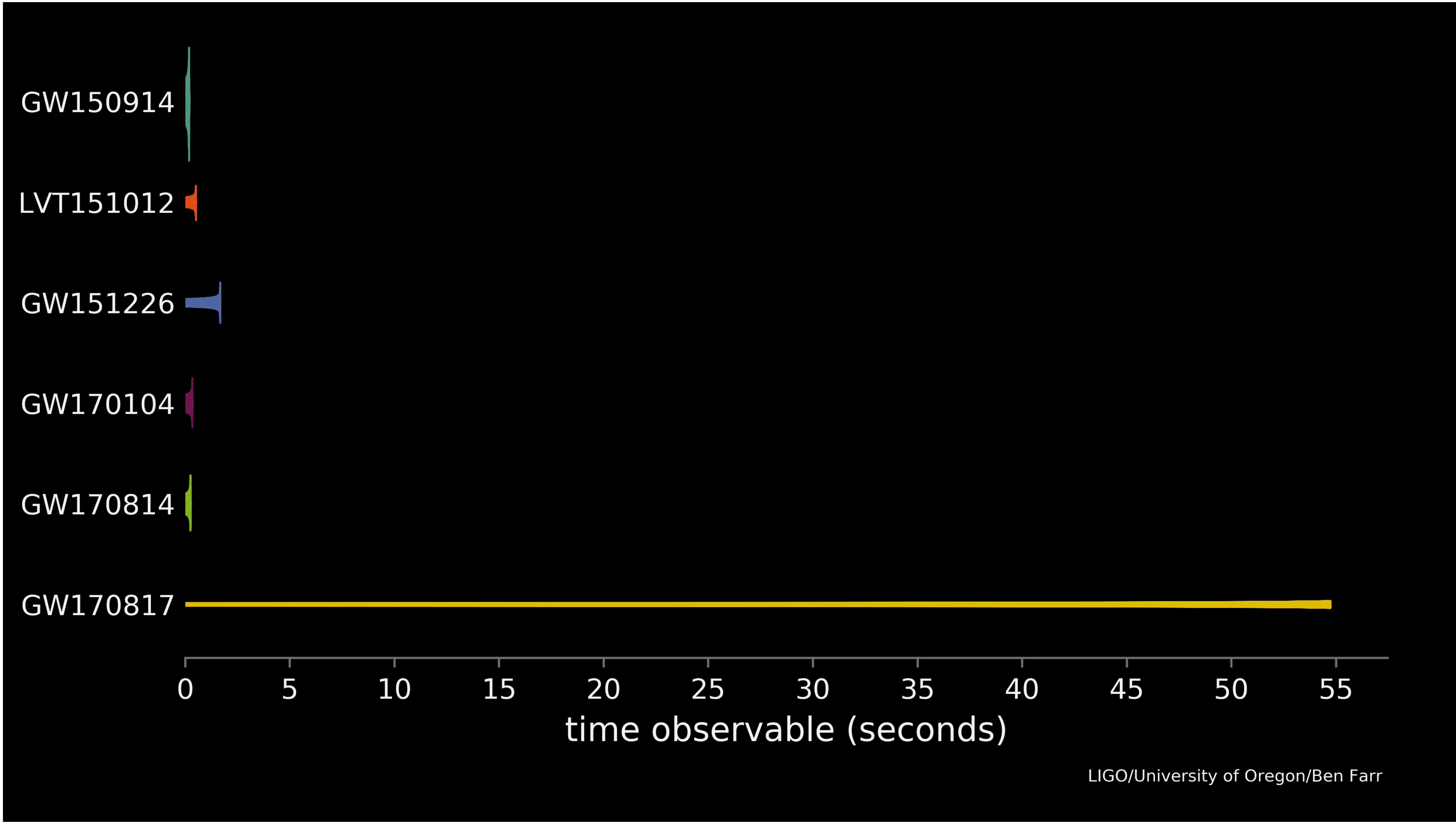
VIRGO

LIGO Livingston



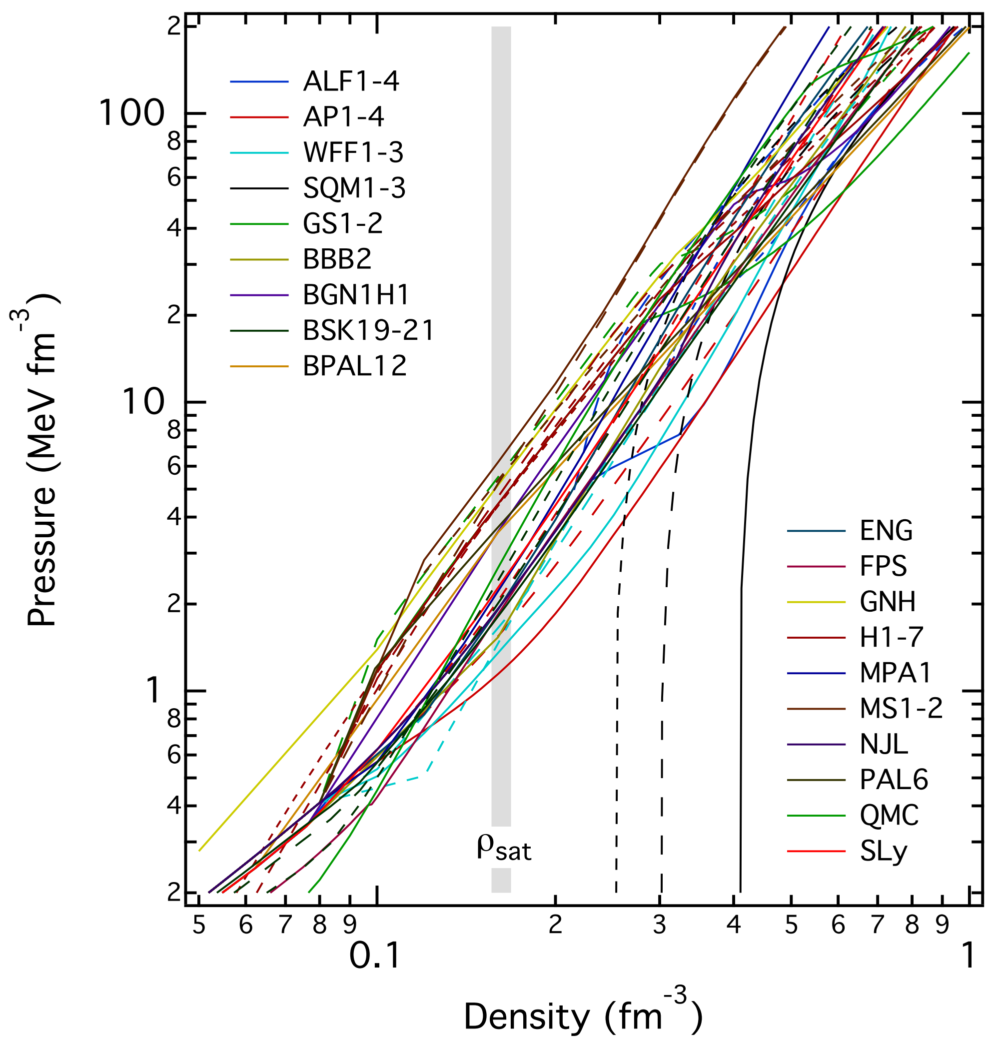
#O3ishere

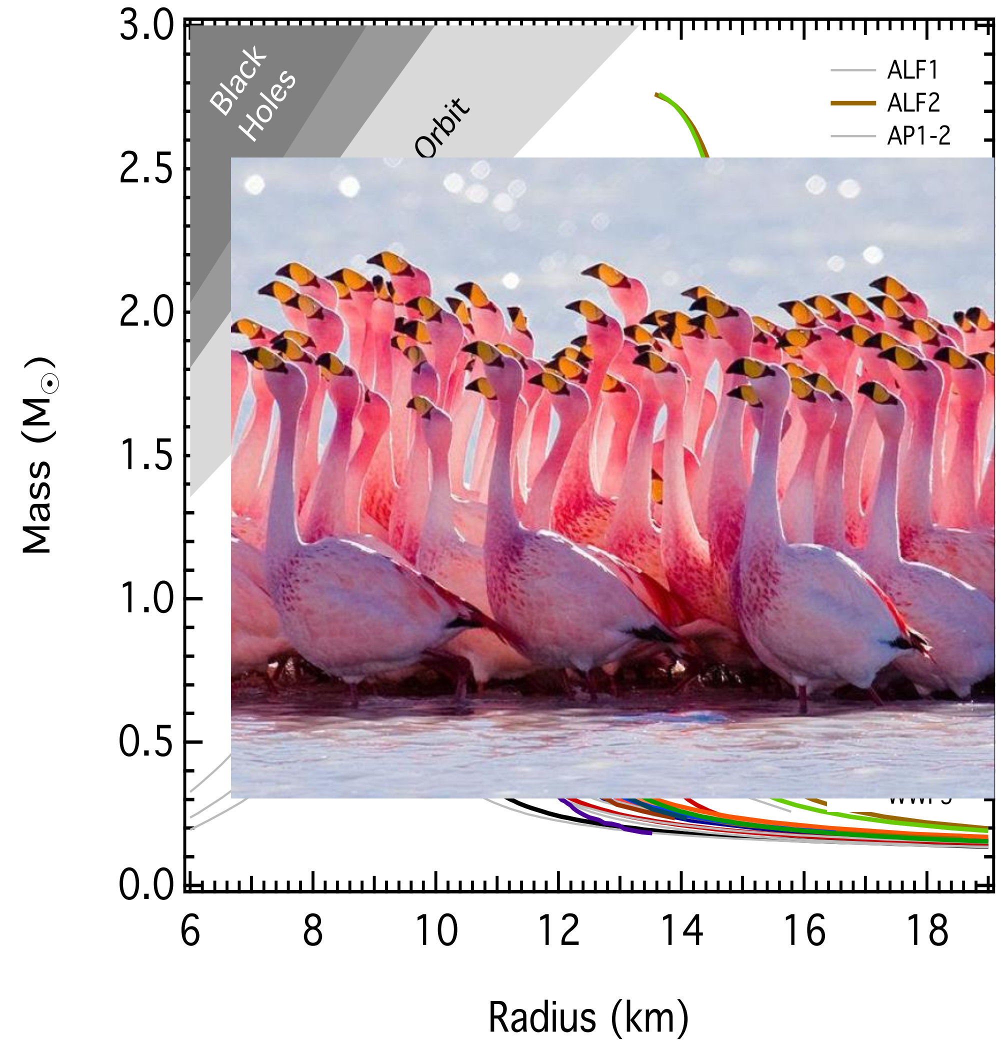

Masses in the Stellar Graveyard
in Solar Masses
80
40
20
10
5
2
1
LIGO-Virgo Black Holes
EM Black Holes
EM Neutron Stars
LIGO-Virgo Neutron Stars
LIGO-Virgo | Frank Elavsky | Northwestern
#O3ishere


GW150914
LVT151012
GW151226
GW170104
GW170814
GW170817
0
5
10
15
20
25
30
35
40
45
50
55
time observable (seconds)
LIGO/University of Oregon/Ben Farr

PROPERTIES OF NS MATTER

- Cold matter in the interior of NS reaches supra-nuclear densities
- Large uncertainties on matter properties; plethora of viable models



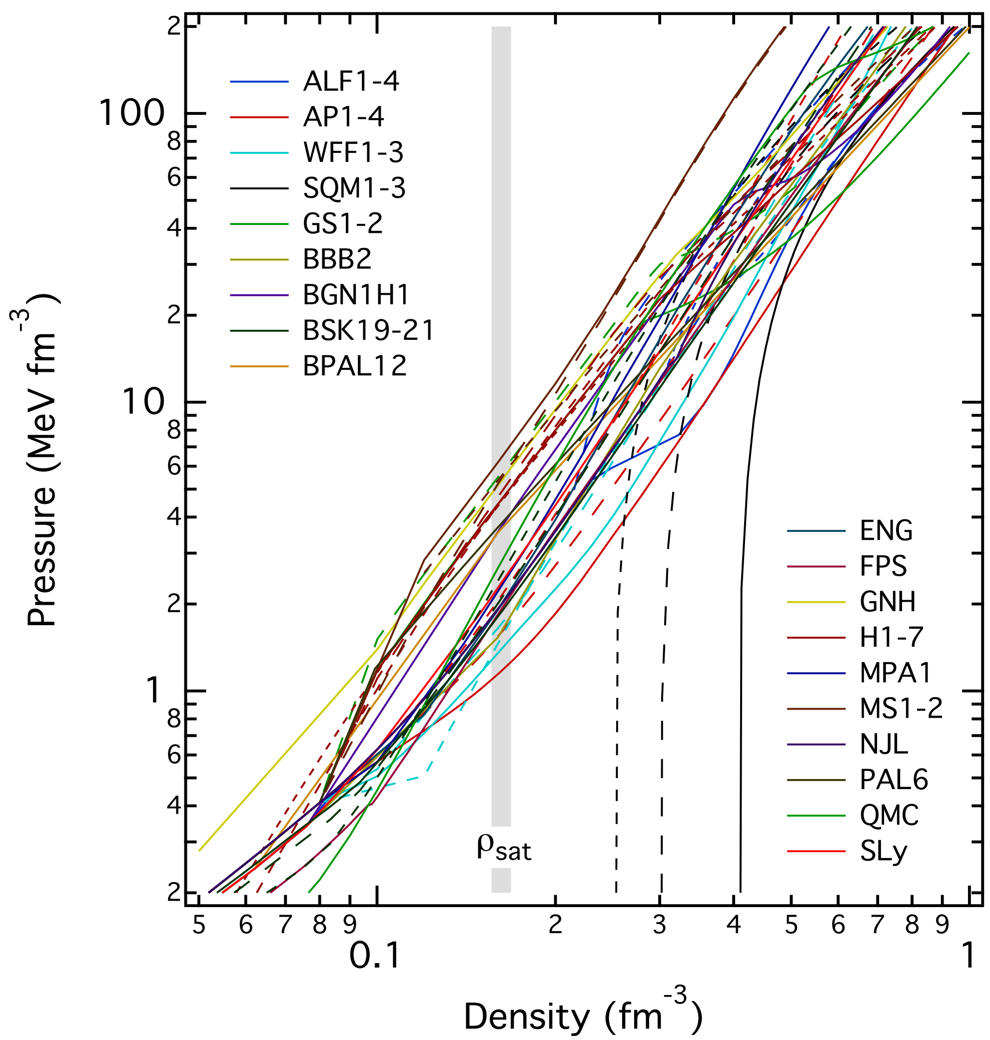


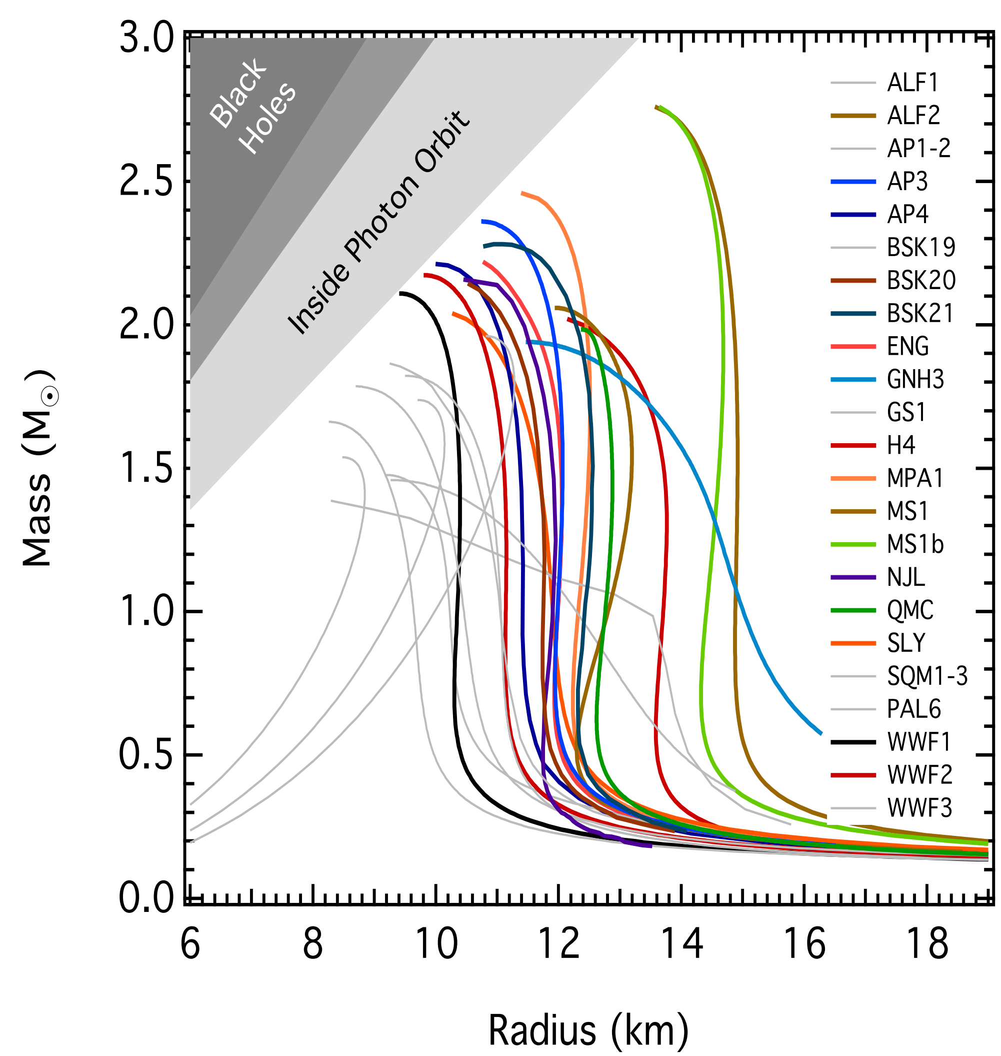
Özel & Freire [arXiv:1603.02698]

see also Lattimer [arXiv:1305.3510]

PROPERTIES OF NS MATTER

- Cold matter in the interior of NS reaches supra-nuclear densities
- Large uncertainties on matter properties; plethora of viable models

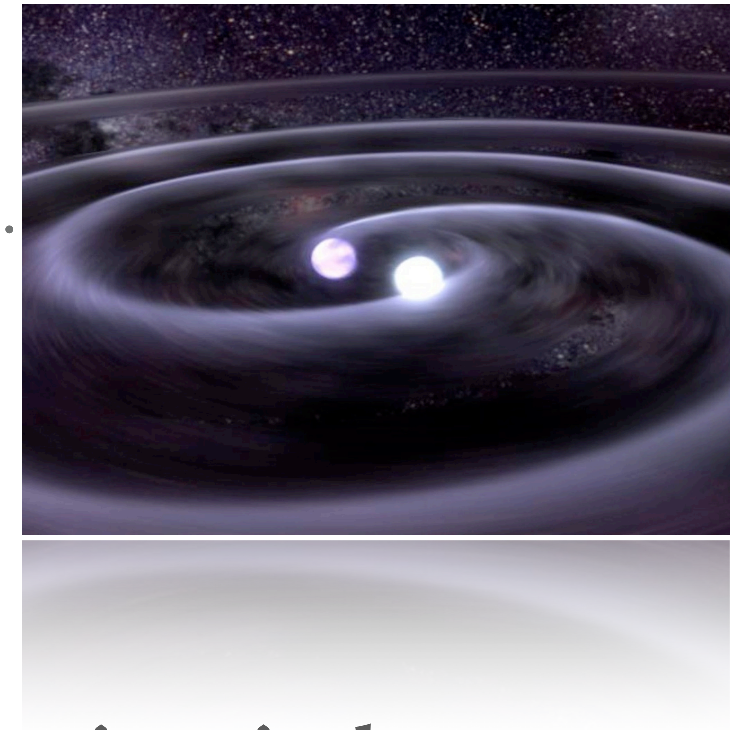




Özel & Freire [arXiv:1603.02698]

see also Lattimer [arXiv:1305.3510]

GW SOURCE MODELLING



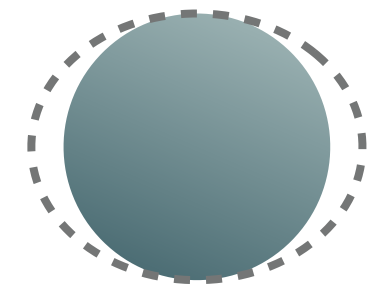
- The **post-Newtonian** (PN) expansion gives approximate solutions to the 2-body problem in GR
- Accurate analytic solution for the best part of the **inspiral stage**
- Simple frequency-domain waveform:

$$\tilde{h}(f) = \mathcal{A} f^{-7/6} \cos(2\Phi(f; m_1, m_2) + \phi_0) \qquad v = (\pi M f)^{1/3}$$

$$\Phi = \left(\frac{v}{c}\right)^{-5} \sum_{i=0}^{N} \left[\psi_i + \psi_i^{(l)} \ln \frac{v}{c}\right] \left(\frac{v}{c}\right)^i$$

- Alternative formulation uses **effective-one-body** (EOB) approach
- **Numerical Relativity** simulations complete the model close to/during merger, where perturbative expansions fail

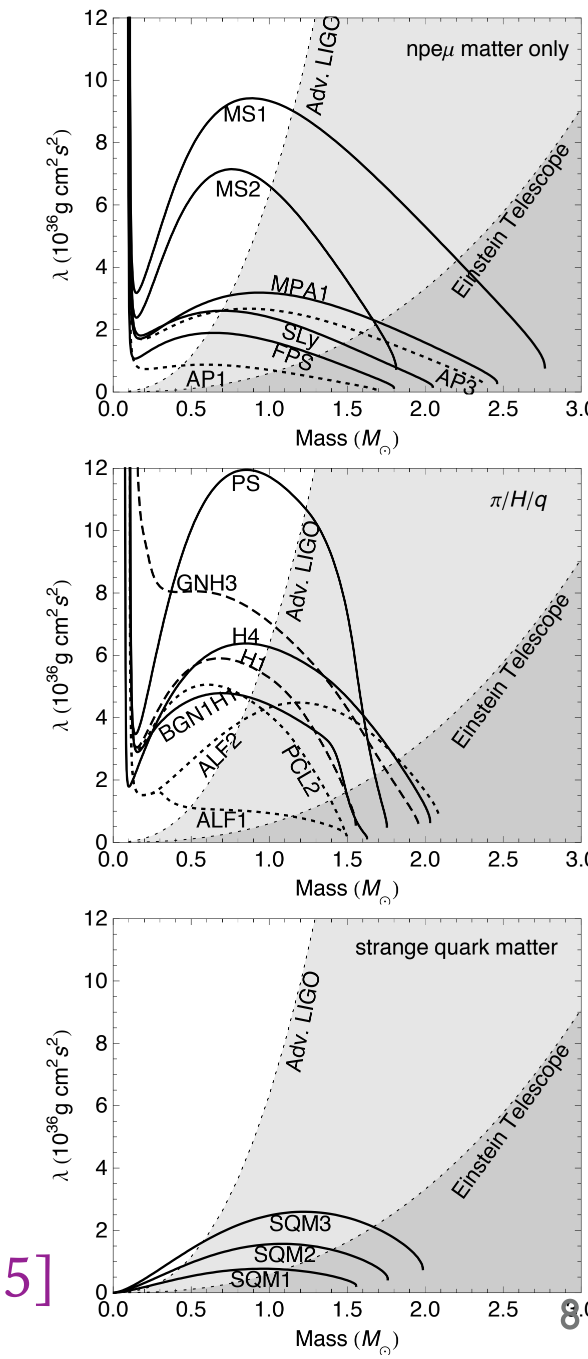
MATTER EFFECTS IN BINARY NEUTRON STARS



- Tidal gravitational field of each NS deforms companion

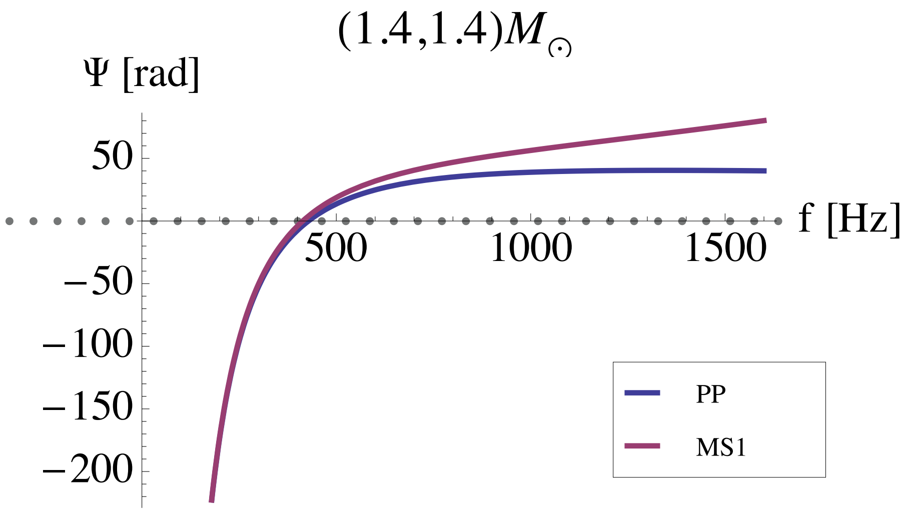
$$Q_{ij} = -\lambda(m)\mathcal{E}_{ij}$$

- Extra orbiting quadrupoles induced by NS spins
- **Tidal interactions** are the dominant matter effect for slow-spinning NSs for LIGO/Virgo BNS sources, where **spin-induced quadrupoles** are expected to be small
- In both cases, the effect magnitudes are determined by the **equation of state** (EoS) of NS matter
- **Post-merger** signal, lifetime and type of remnant (NS/BH) also depend on the "stiffness" of the EoS
- However, post-merger occurs at very high frequencies (>2 kHz), where detector sensitivities are still not good enough



[Hinderer+ arXiv:0911.3535]

TIDAL EFFECTS IN BNS



- Neutron stars are **not** point masses
- Strong tidal effects at the end of inspiral deform each NS:
- This tidal deformation affects binary orbital evolution (5PN+)

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

$$\Phi(f) = \Phi_{PP}(f) + \Phi_{tidal}(f)$$

5PN

$$\Phi_{tidal}(f) = (\pi M f)^{-\frac{5}{3}} \sum_{a=1,2} \frac{3\lambda_a}{128\eta M^5}\left[-\frac{24}{\chi_a}\left(1+\frac{11\eta}{\chi_a}\right)(\pi M f)^{10/3} - \frac{5}{28\chi_a}\left(3179 - 919\chi_a - 2286\chi_a^2 + 260\chi_a^3\right)(\pi M f)^{12/3} + \ldots\right]$$

[Flanagan & Hinderer 2008]

[Damour, Nagar, Villain 2012]

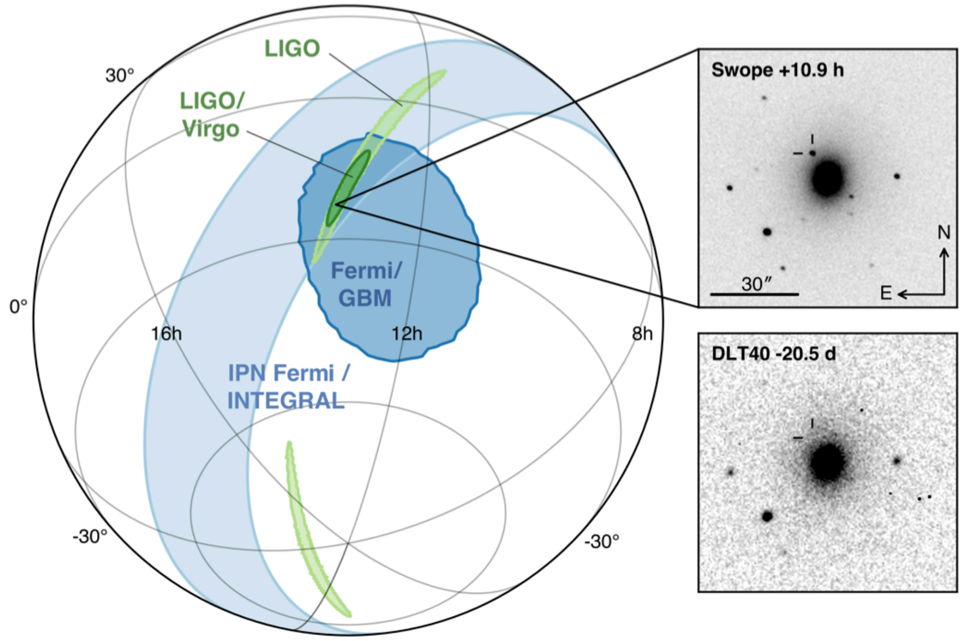
6PN ...7.5PN

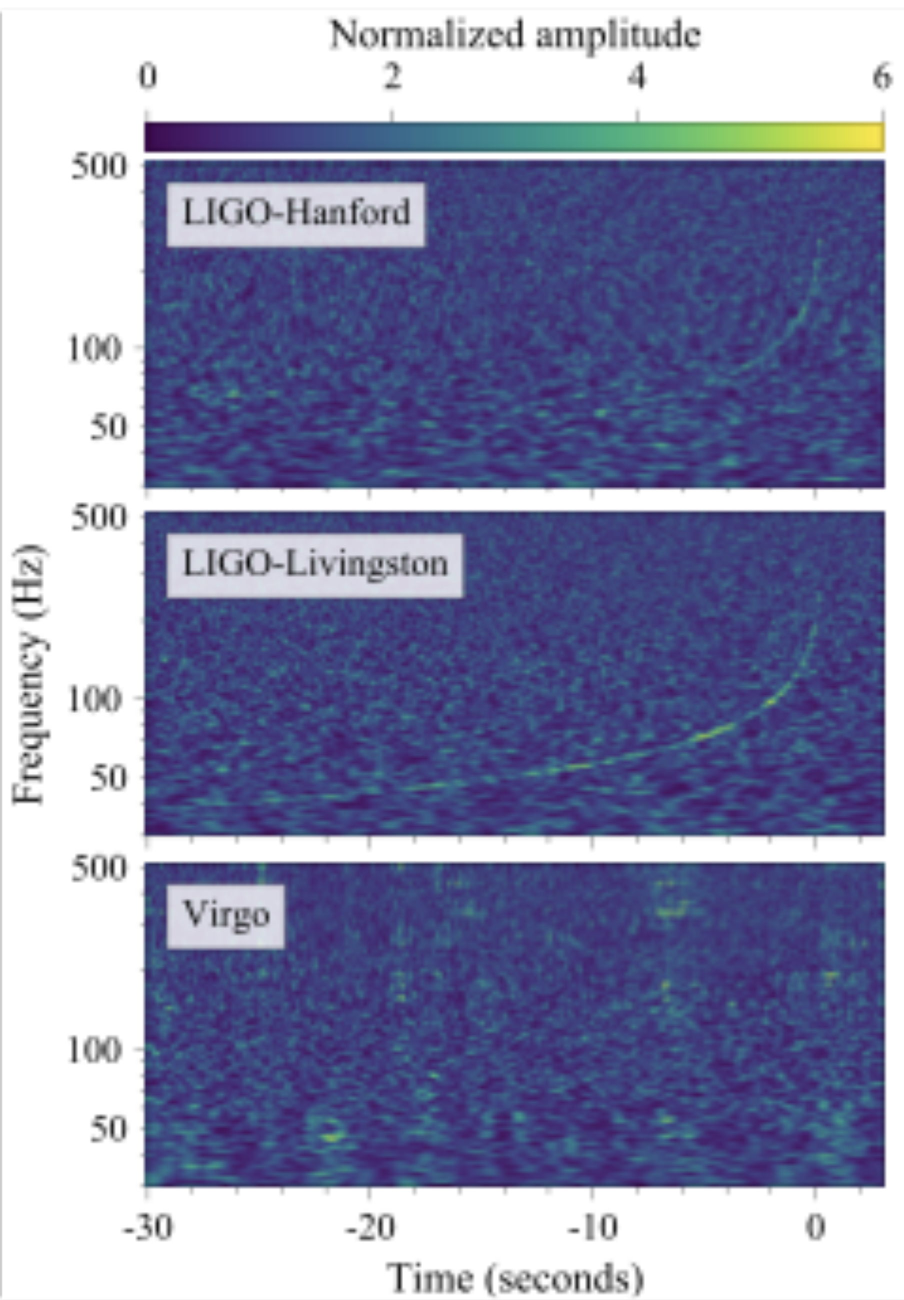
- Tidal deformability parameter λ depends on second Love number and radius:

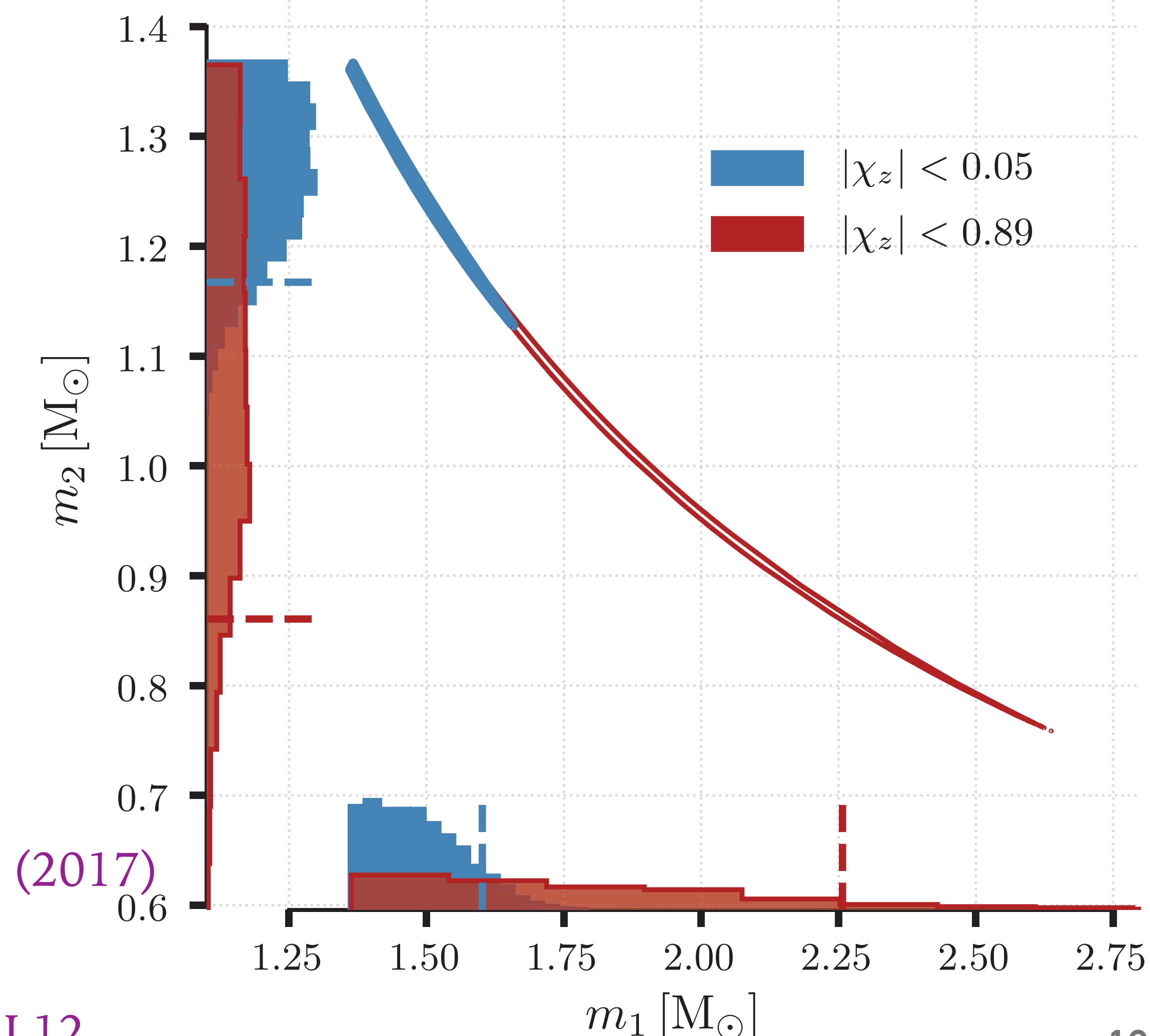
$$\lambda_a = \lambda(m_a) = \frac{2}{3}k_2 R^5(m_a) \qquad \Lambda_a = \lambda_a/m_a^5$$

GW170817: A BINARY NEUTRON STAR MERGER

- Coincident observation of GWs and EM signals across the spectrum
- Low-mass binary, consistent with NSs
- Host galaxy identified (NGC 4993)







LIGO-P170817
LVC PRL 119 161101 (2017)

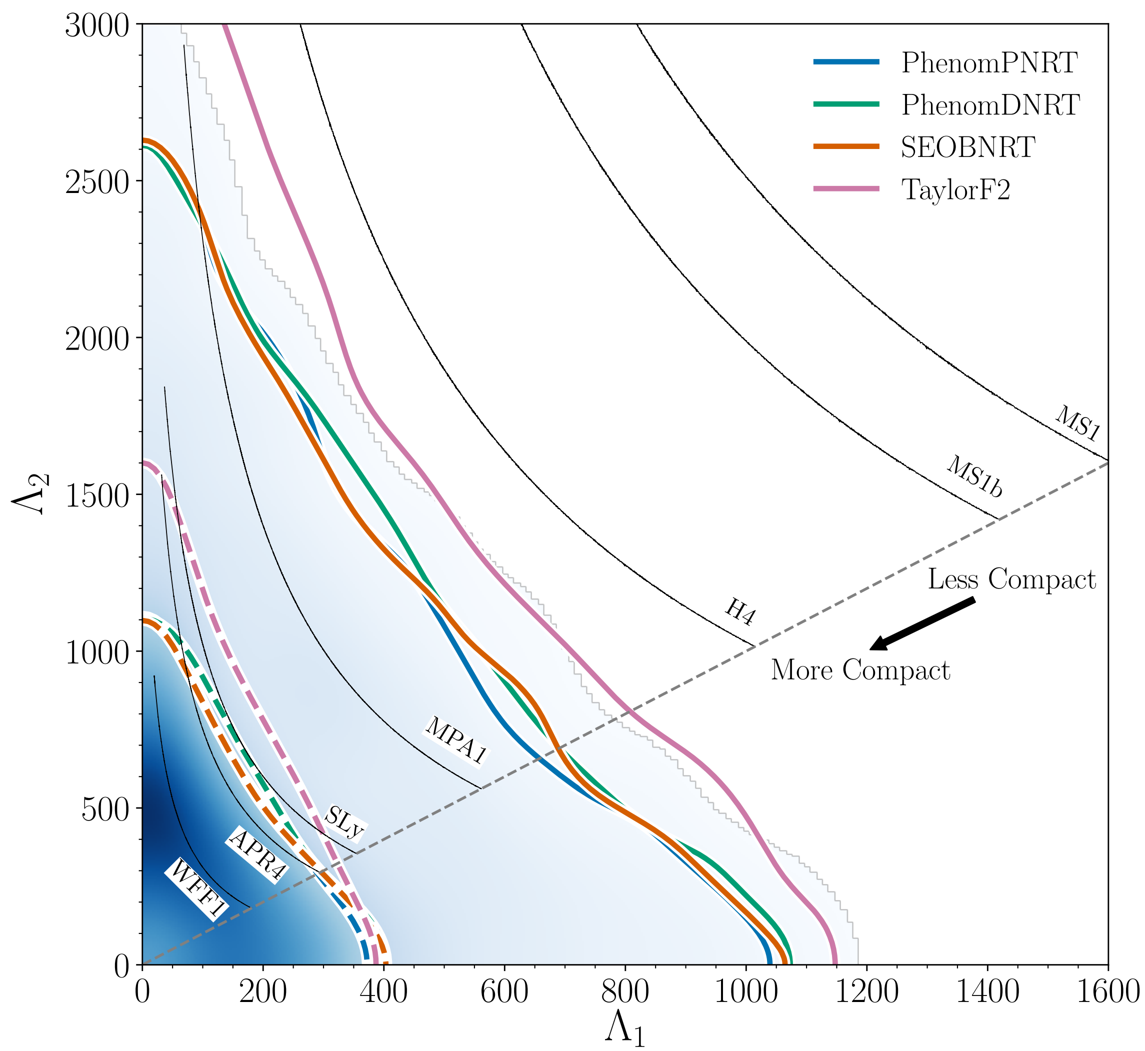
LIGO-P1700294
ApJ 848 (2017) no.2, L12

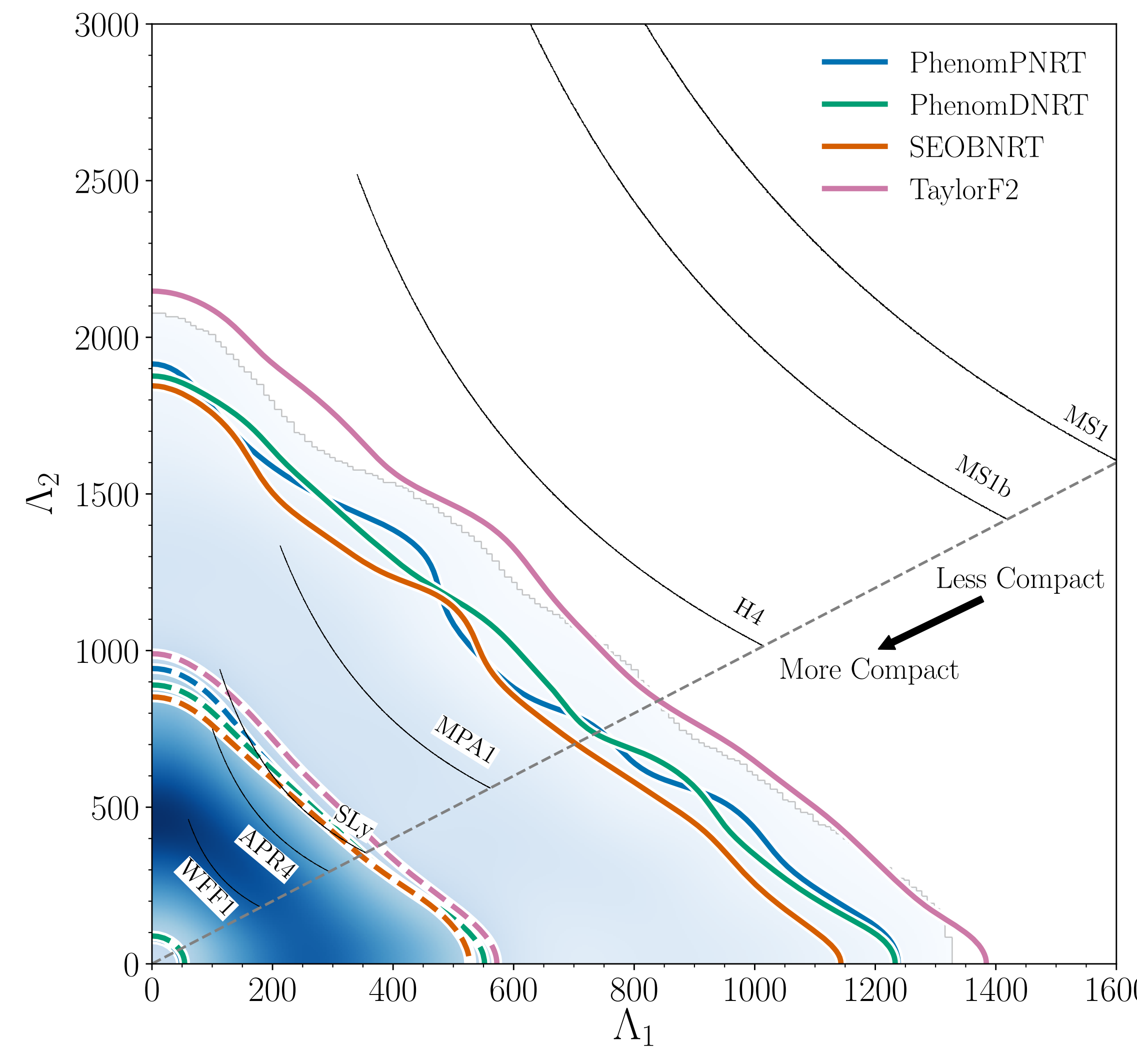
CONSTRAINTS ON TIDAL PARAMETERS

[LVC PRX 9, 011001 (2019)]

LIGO-P1800061

- Sky location fixed to identified EM source
- Two choices of spin priors, up to 0.05 and 0.89 resp.
- Low frequency down to 23 Hz
- Different BNS waveform models, including matter effects

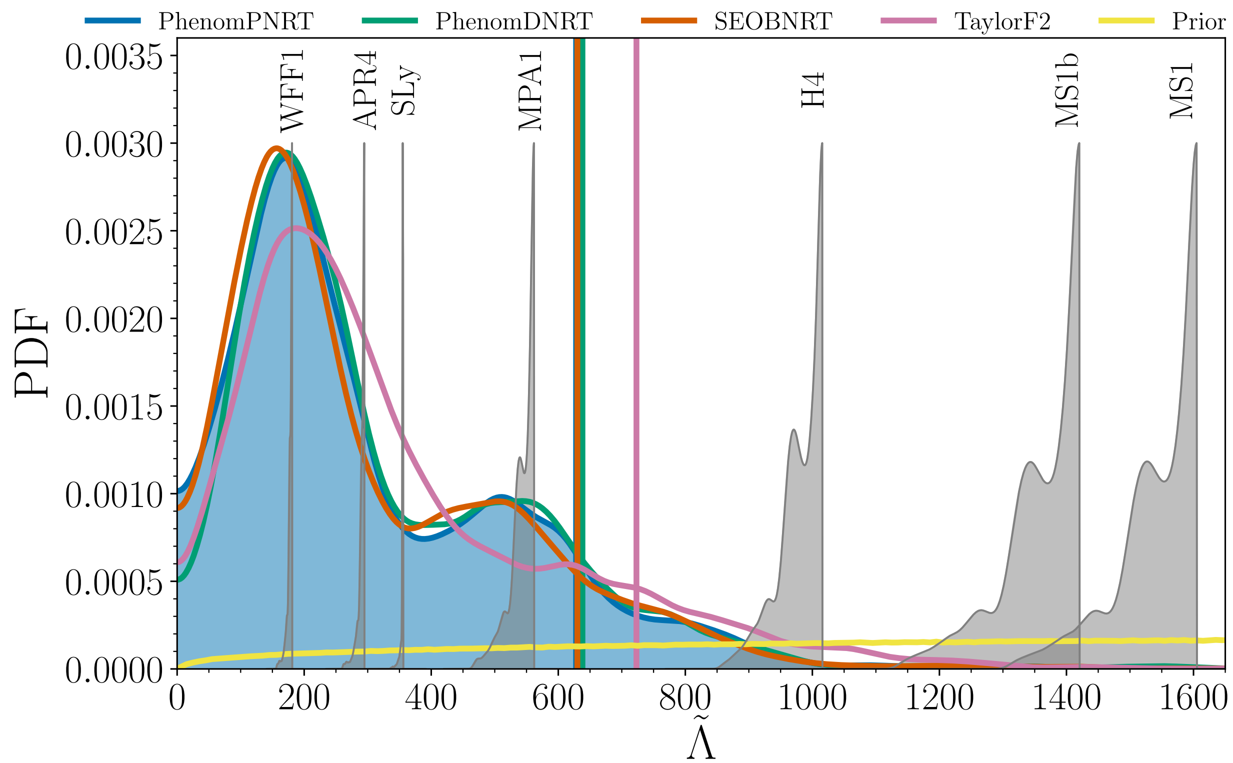


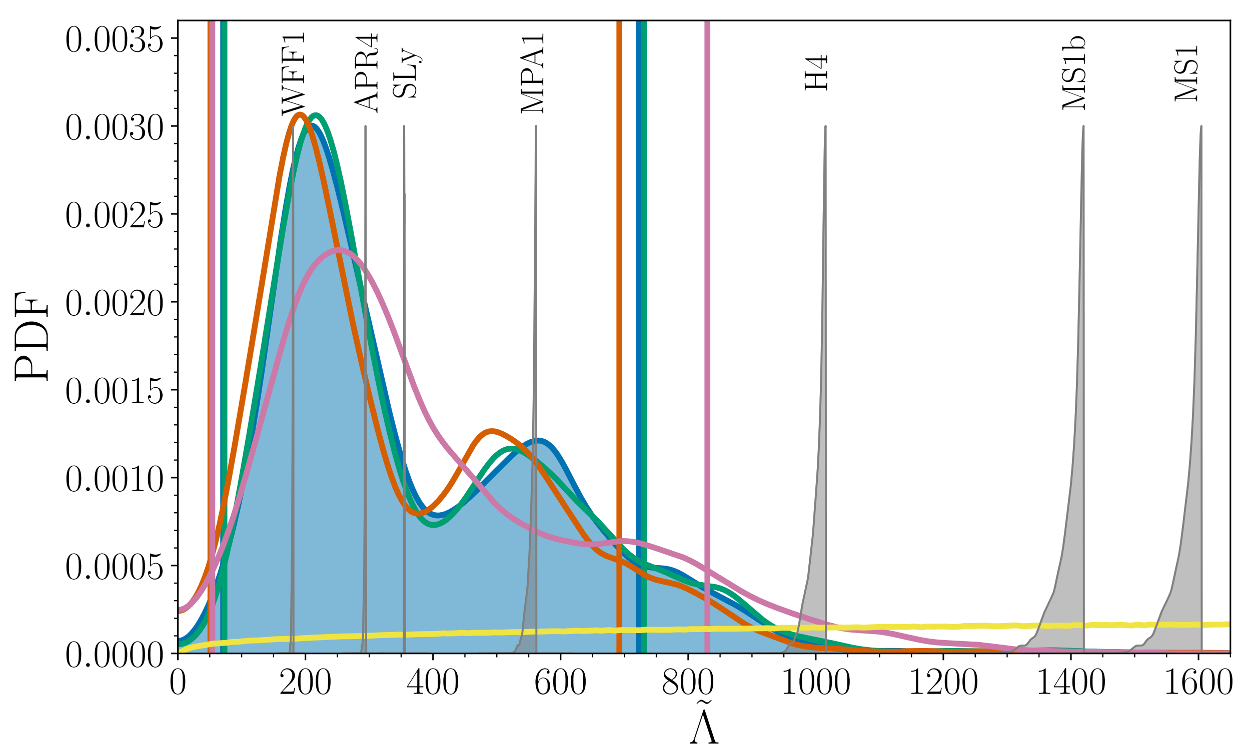


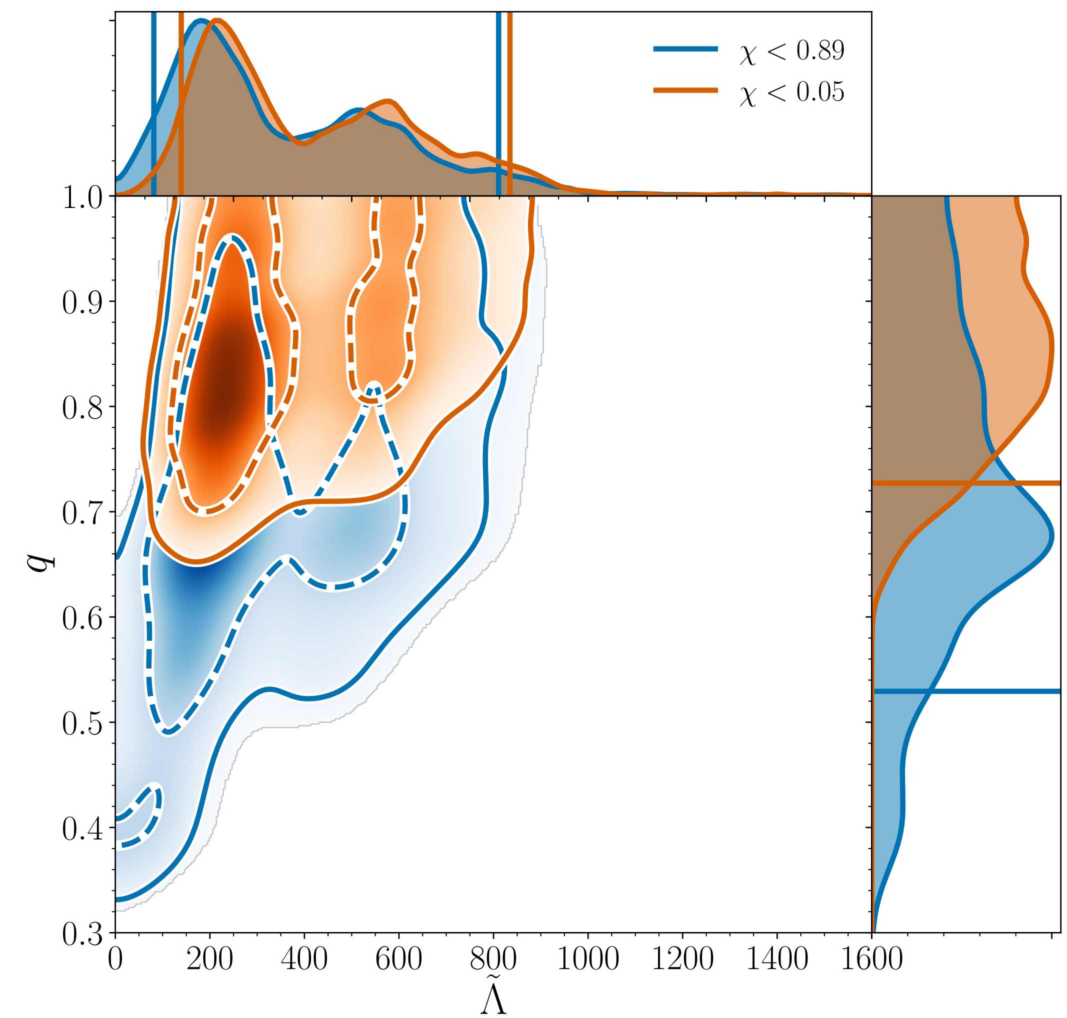
NEW IMPROVED CONSTRAINTS ON TIDAL PARAMETERS

[LVC PRX 9, 011001 (2019)]

LIGO-P1800061







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

ADDITIONAL BNS ASSUMPTIONS

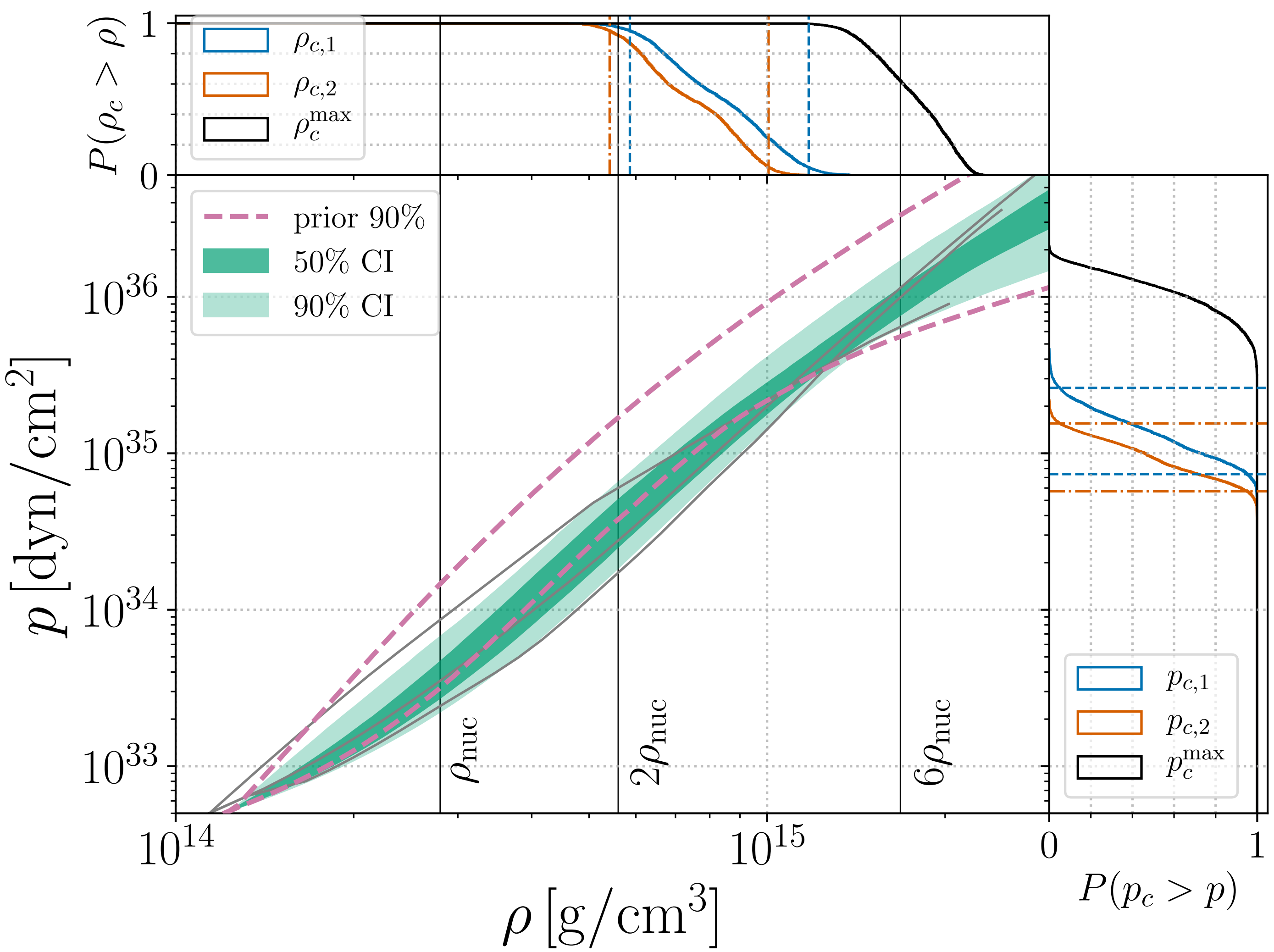
[LVC PRL 121 161101 (2018)]
LIGO-P1800115

- Work under the additional assumption that GW170817 is a BNS
- Both NSs obey the same EOS
- Implement this in two independent ways:
  - Sample P(ρ) function directly and integrate TOV equations to get macroscopic properties
  - Sample Λ and use approximately universal relations between macroscopic NS properties: Λ, Q, C, as well as correlation between Λ_1, Λ_2, q (binary-Λ relation) Yagi-Yunes [arXiv:1608.02582], Chatziioannou-Haster-Zimmerman [arXiv:1804.03221]

SPECTRAL PARAMETERIZATION OF P(\RHO)

[LVC PRL 121 161101 (2018)]
LIGO-P1800115

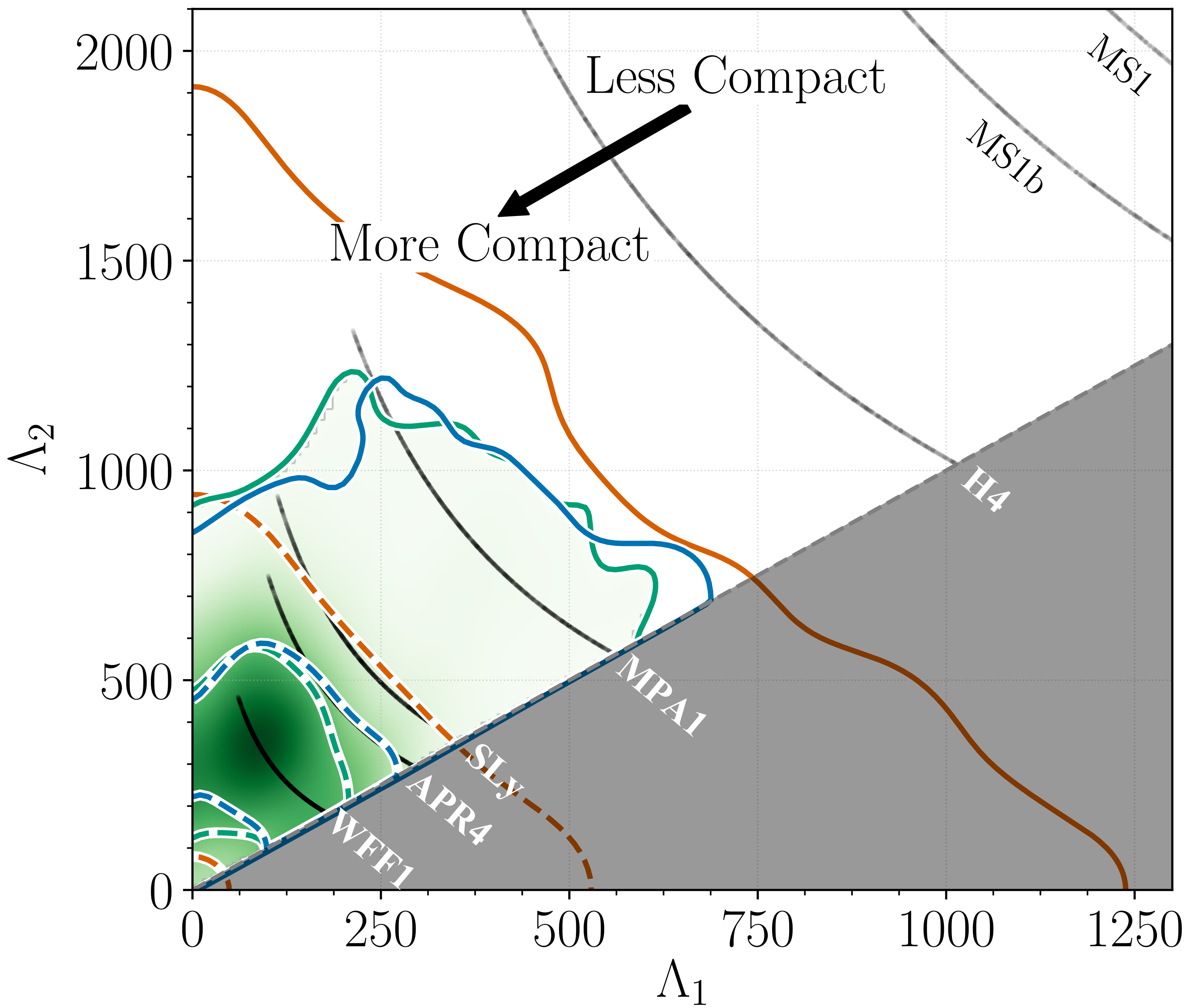
- Samples the EoS directly as in Carney-Wade-Irwin [arXiv:1805.11217], based on spectral parametrization of Lindblom [arXiv:1009.0738]
- Constraints on P(ρ) function assuming a realistic 4-dim family of EoS
  $P(\rho) \sim \rho^{\Gamma}$
  $\Gamma = \Gamma(P; \gamma_i)$, $\gamma_i = (\gamma_1, \gamma_2, \gamma_3, \gamma_4)$
- Constraints at 90% CL:
  - $P(2\rho_{sat}) \sim 3.5 \times 10^{34}$ dyn/cm2
- Stiff EoS region excluded



MEASUREMENT OF TIDAL DEFORMATIONS

[LVC PRL 121 161101 (2018)]

LIGO-P1800115

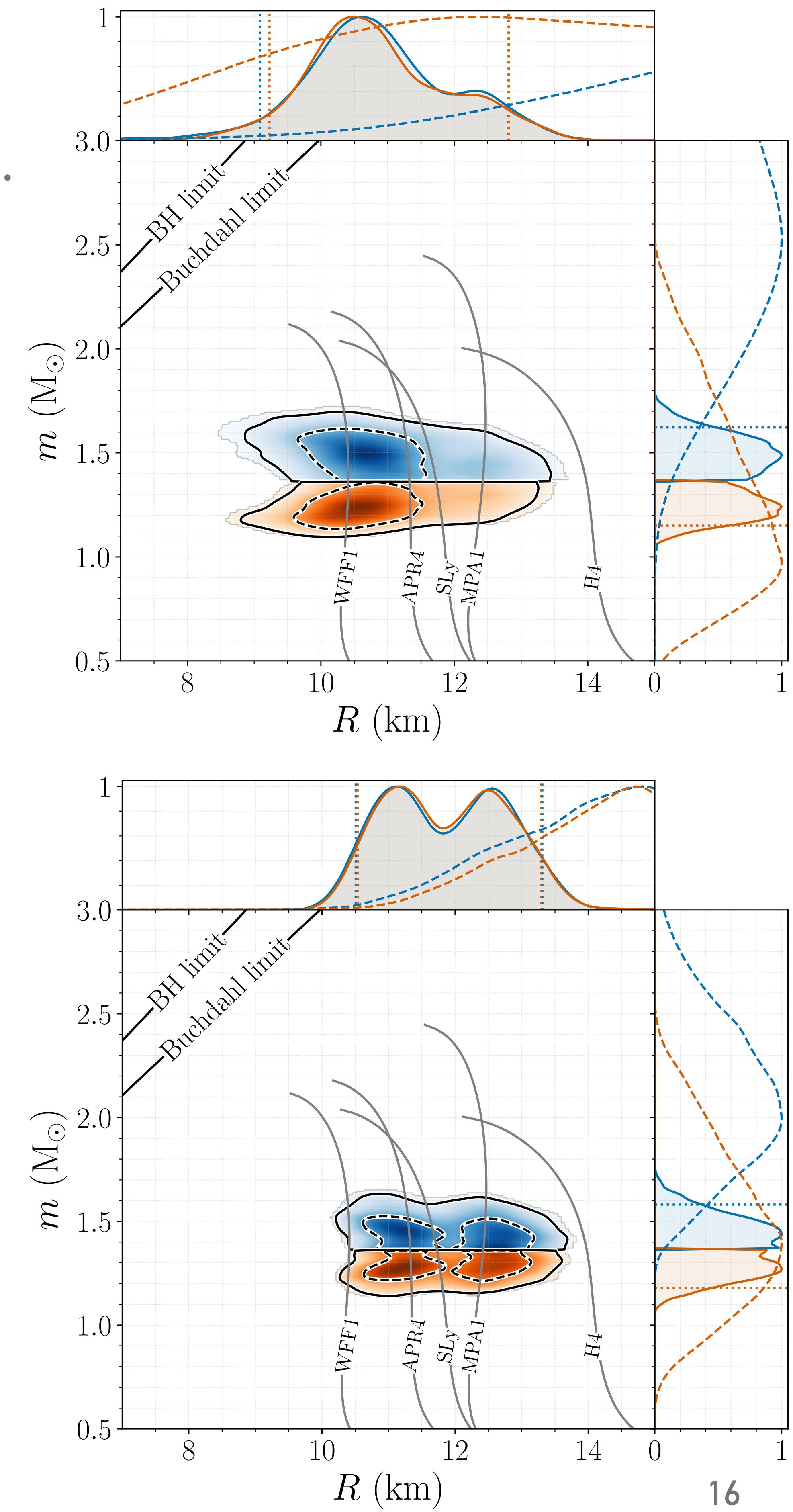


MASS-RADIUS USING BOTH METHODS

- Radius-mass posteriors are produced by either
    - using Λ - C relation:
      $R_1 = 10.8^{+2.0}_{-1.7}$, $R_1 = 10.7^{+2.1}_{-1.5}$
      or
    - integrating TOV eqns and imposing EoS support at 1.97 Msun (most massive observed NS):
      $R_1 = 11.9^{+1.4}_{-1.4}$, $R_2 = 11.9^{+1.4}_{-1.4}$
- Parametrized-EoS method cuts out low radii (too soft to support 1.97 Msun)

[LVC PRL 121 161101 (2018)]

LIGO-P1800115



LIGO-VIRGO OPEN SCIENCE

GW170817 data is available in GWOSC

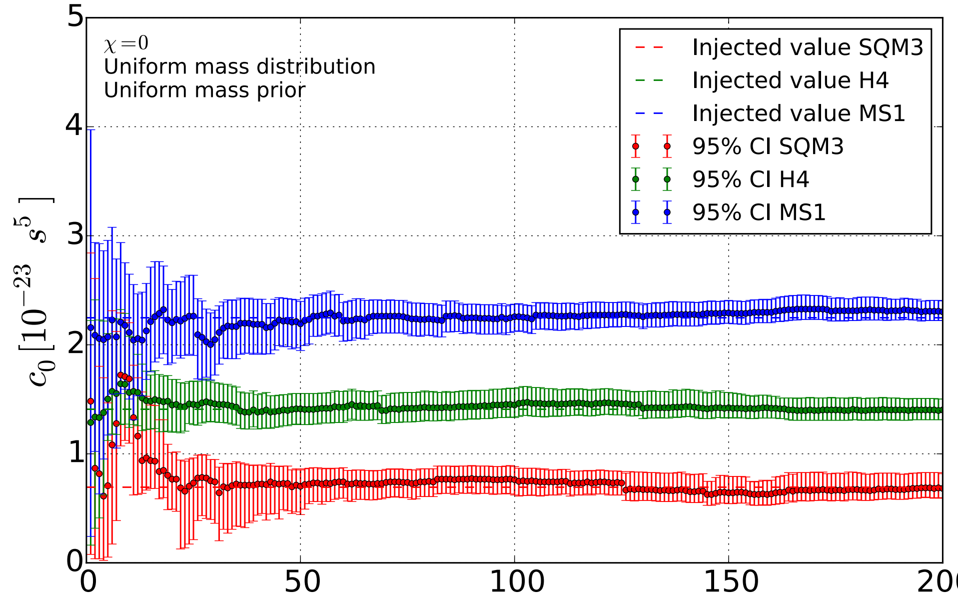
https://www.gw-openscience.org/

Results and posterior samples publicly available at

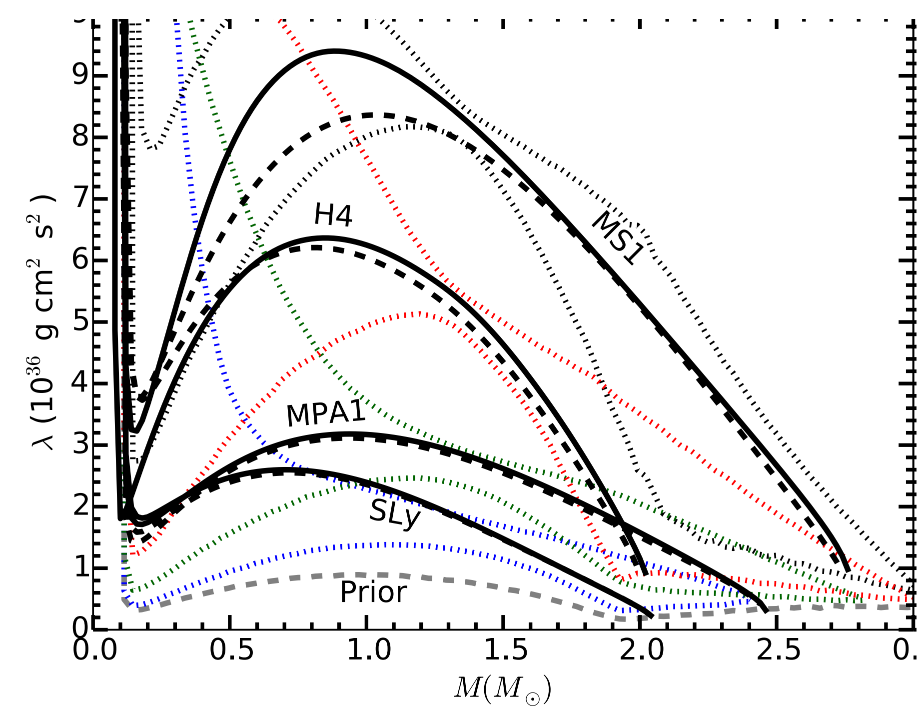
https://dcc.ligo.org/LIGO-P1800115/public

IMPROVING CONSTRAINTS WITH MANY BNS EVENTS #O3ishere

- Need to remove apparent source-dependence from parametrization of matter effects
- Choice of parameterisation (or not):
  - Phenomenological approach: parameterise effects that enter the gravitational waveform model, see Del Pozzo, MA+2013, MA+2015
  - Fundamental approach: parameterise EOS of NS matter, then GW observables are derived quantities, see Lackey & Wade 2014, Carney+ 2018
  - Nonparametric approach: recover functional dependence P(ρ) or λ(m) (Landry & Essick 2018, MA in prep)
- Need very high accuracy in **both**
  - point-mass (PM) baseline model and
  - matter effects in the GW waveform



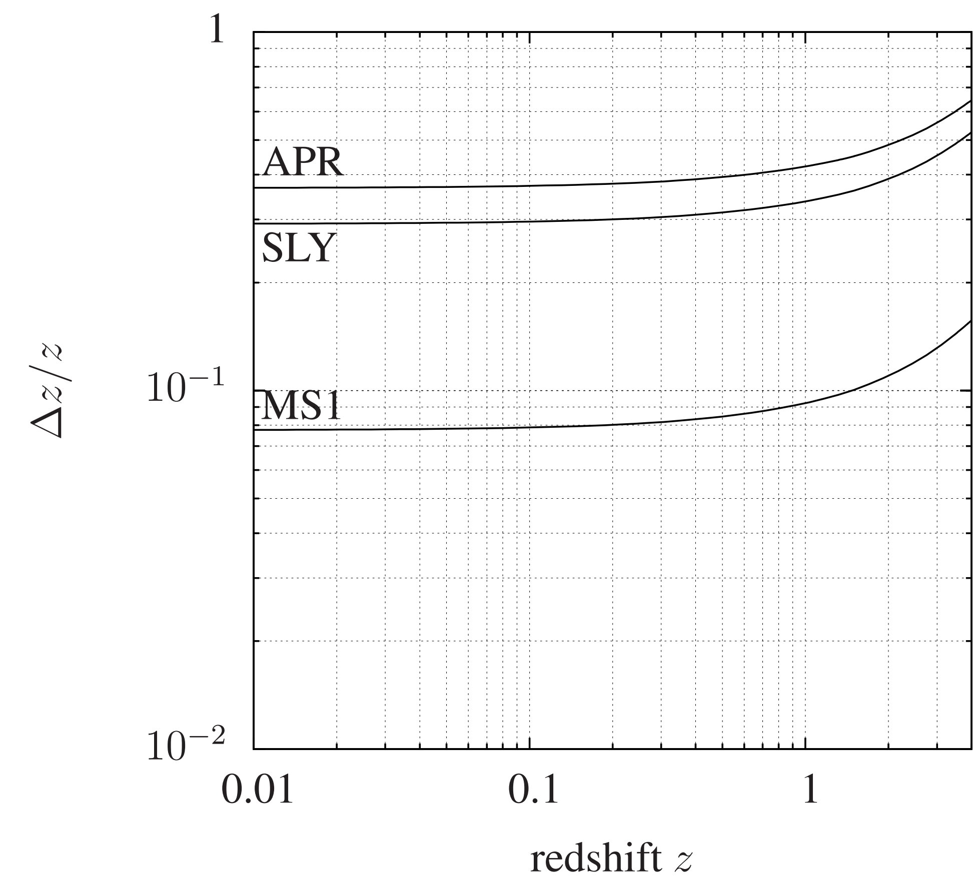
[MA+ PRD 92, 023012 (2015)]



[Lackey & Wade PRD 91, 043002 (2015)]

A DIFFERENT STANDARD SIREN MEASUREMENT

- Like BBH, BNS mergers are standard sirens
- Unlike BBH, BNS spacetimes are not "scale-symmetric"
  - In BBH, the effect of redshift is degenerate with a mass rescaling
  - In BNS, matter properties introduce additional scale that breaks the degeneracy
- Only works if we know the EOS (or measure everything together)
- Independent EOS measurement with NICER?

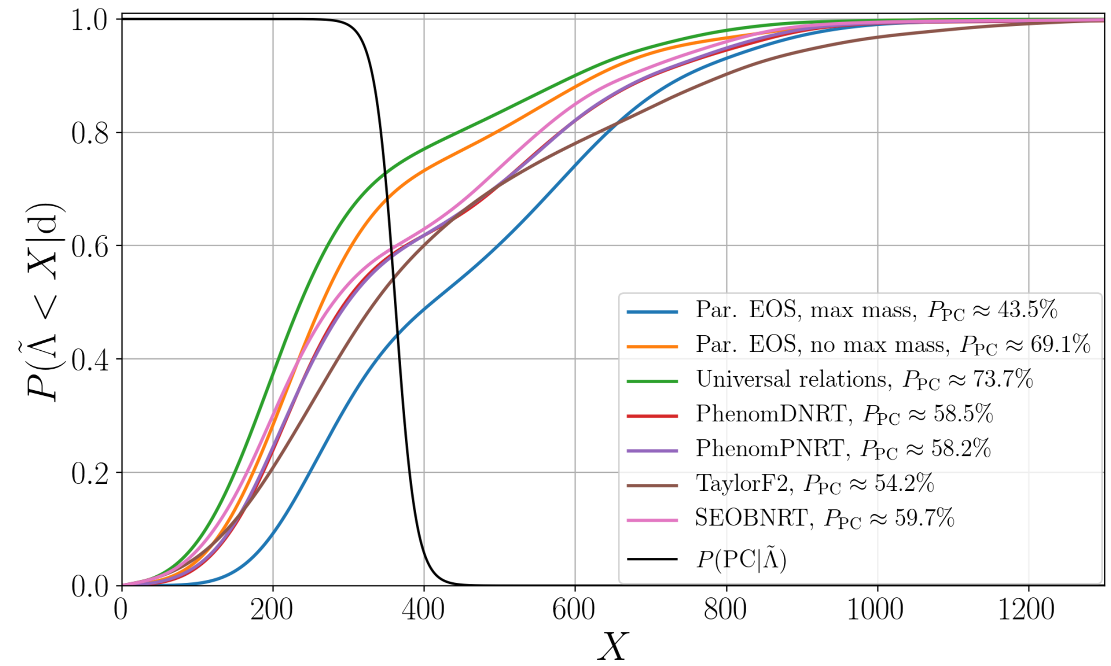


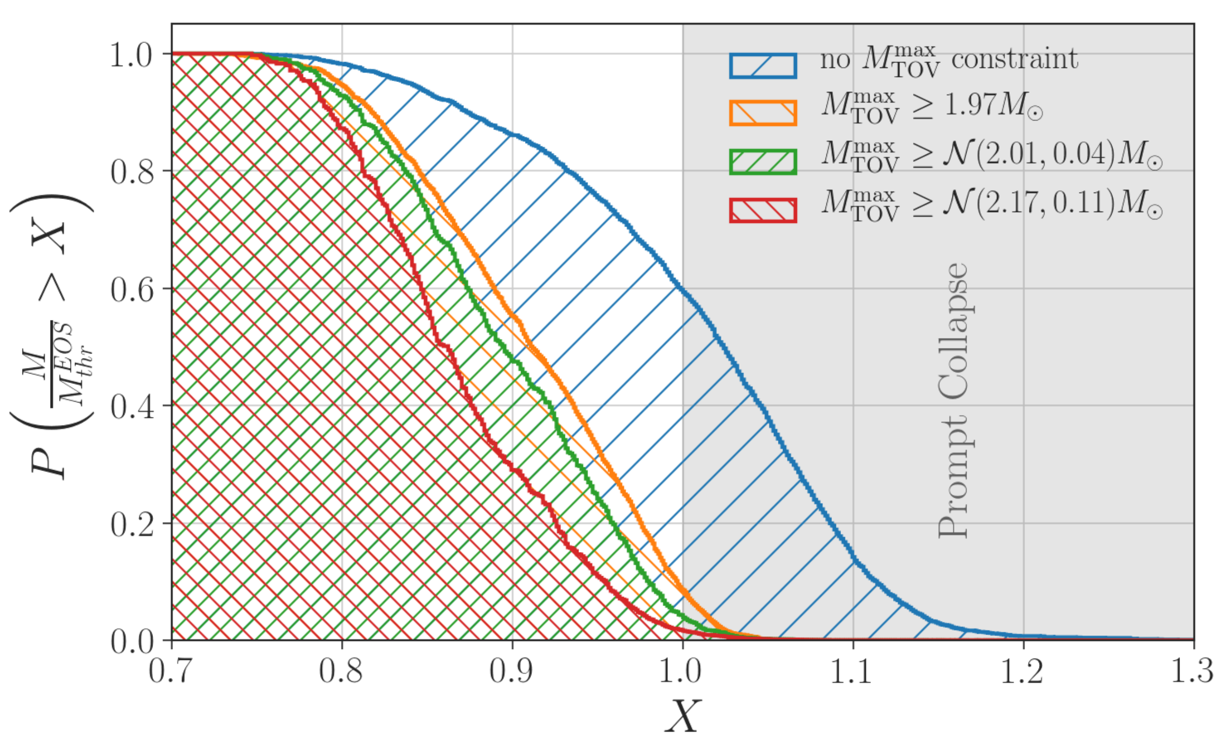
[Messenger & Read PRL **108** 091101 (2012)]

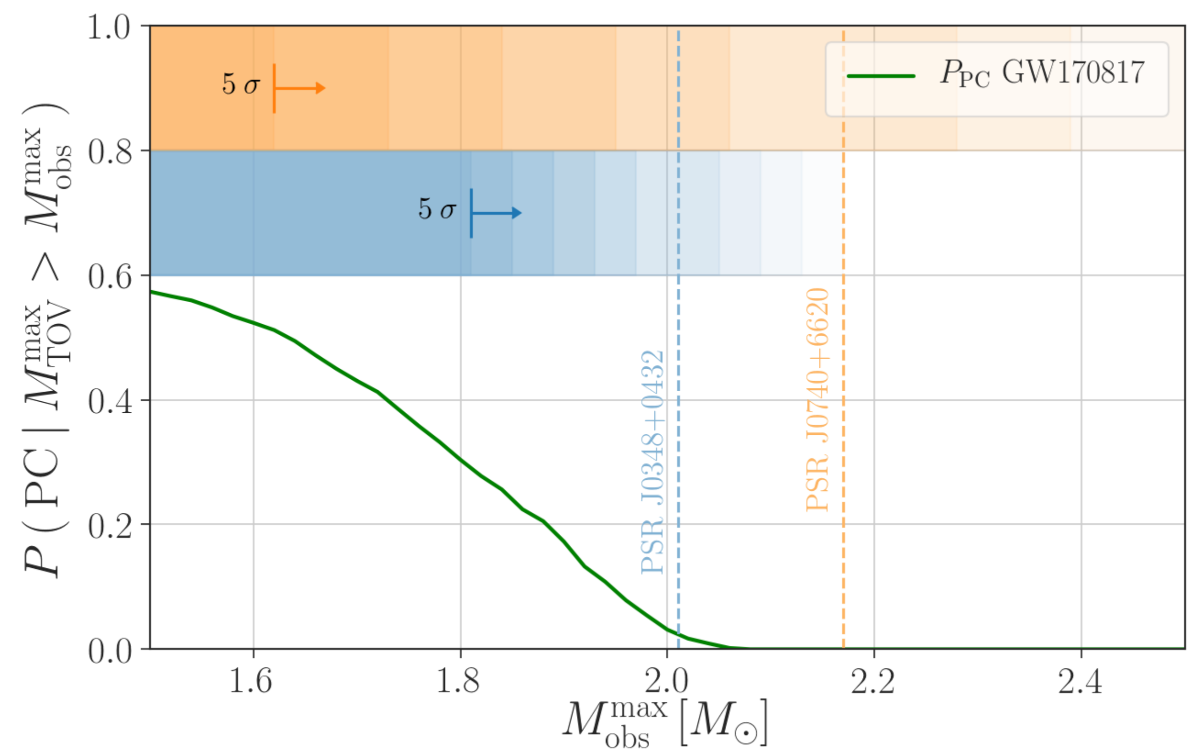
DID GW170817 PROMPTLY COLLAPSE TO A BH?

- EM indicates: probably not!
- What can we say with GW signal alone?
  - Threshold-Λ analysis: sample Λ directly
  - Threshold-mass analysis: sample EoS, derive Λ, M_{max} , M_{thr} ; can impose mass constraints

[MA+ arXiv:1908.05442]



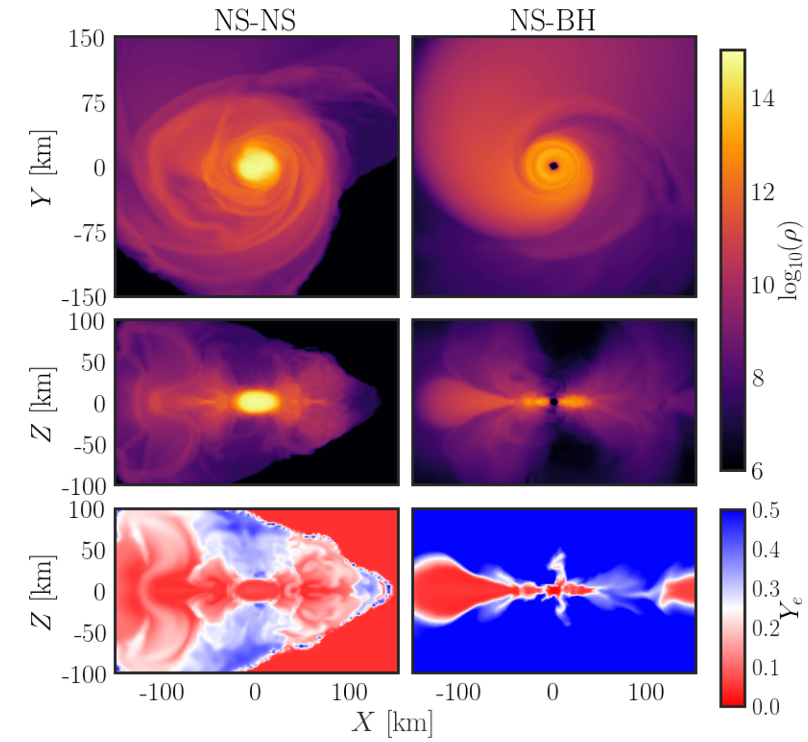


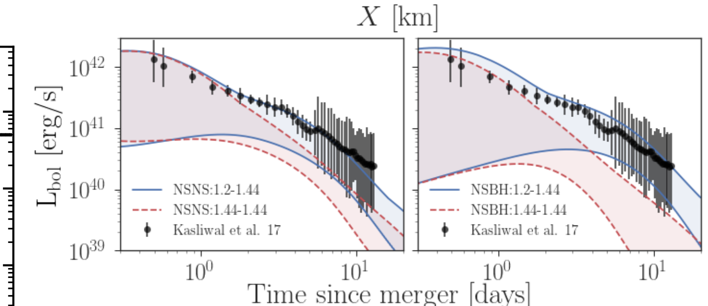


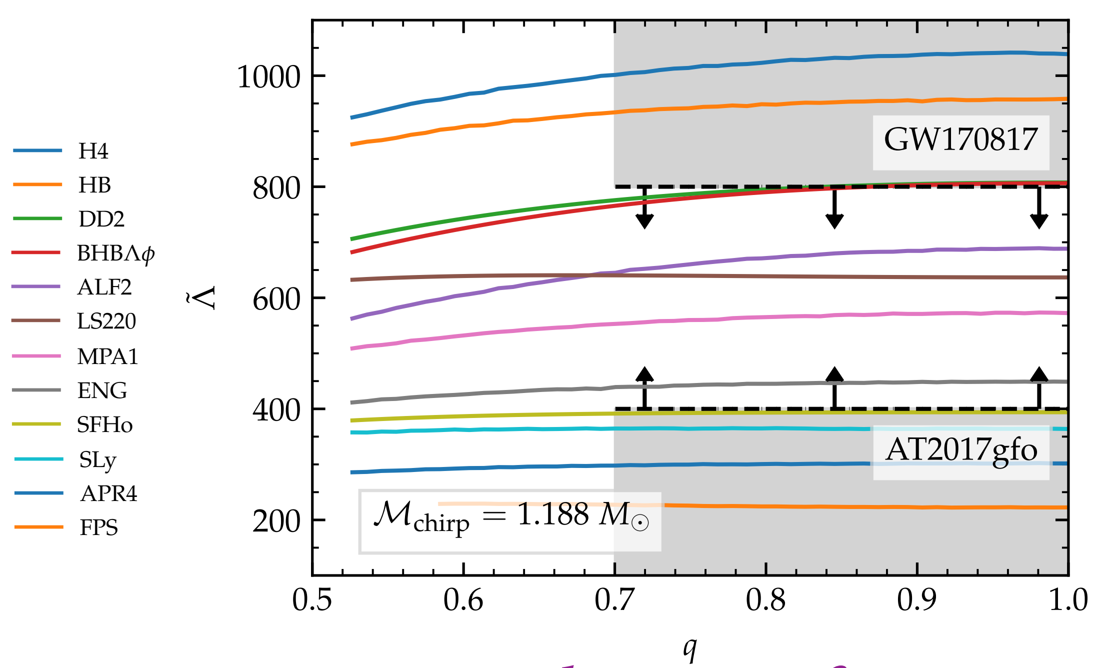
MULTIMESSENGER STUDIES WITH BNS MERGERS

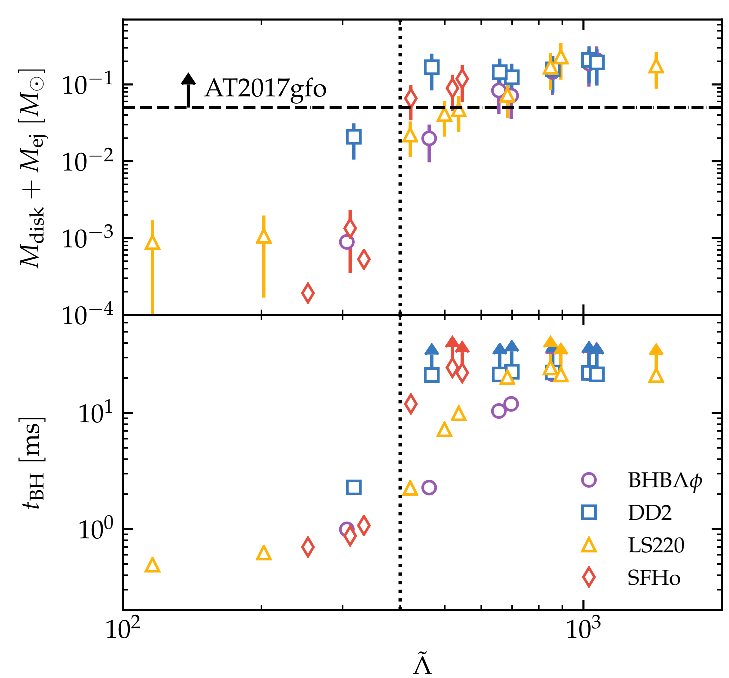
- GW + EM coincident detection (e.g. GW170817) should lead to GW + EM coherent data analysis
- Identification of EM source -> fixed sky location, constr. distance
- EM spectrum -> inclination, intr. source properties
- Modelling via high-res NR simulations w/ microphysics
- e.g. Λ-M_{disk} correlation Radice+ ApJL 852:L29 (2018)

[Hinderer, Nissanke+ arXiv:1808.03836]





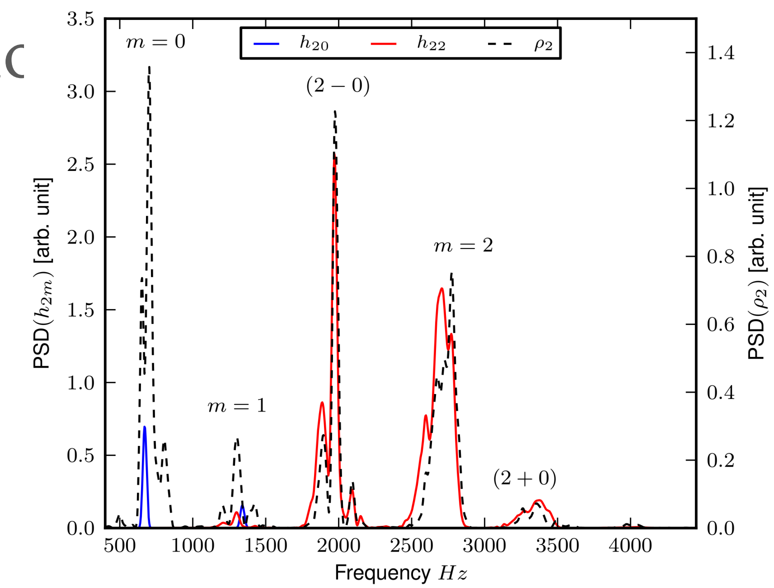




EoS cannot be too soft!

INFORMATION FROM THE MERGER AND BEYOND

- PM inspiral+matter effects: clean perturbative formulatic
- Violent merger of relativistic balls of matter at supra-nuclear densities: not so clean… NR input is crucial!
- Characteristic peaks in post-merger
- Modeling post-merger signal is an active research field



[Bernuzzi+ PRD **89** 104021 (2014)]

[Bernuzzi+ PRL **115**, 091101 (2015)]

[Bauswein+ PRL **108** 011101 (2012)]

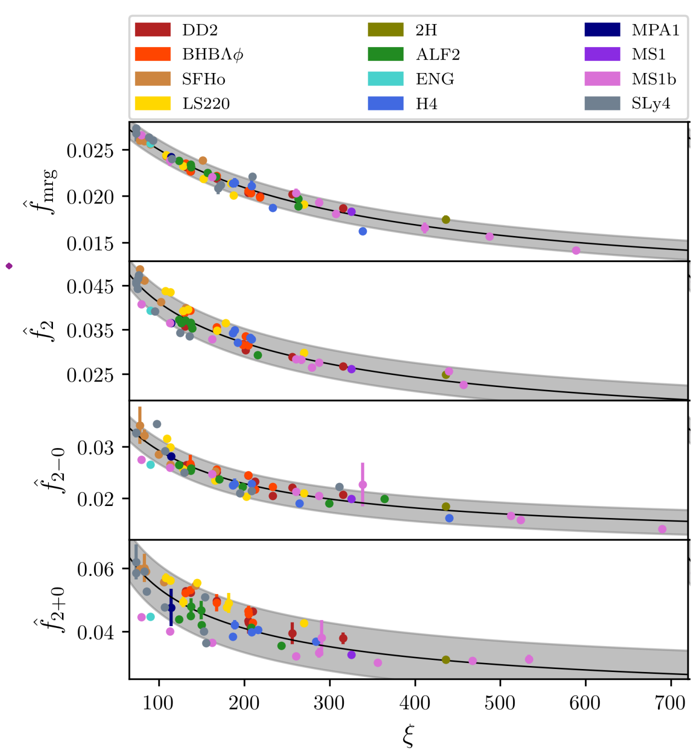
[Takami+ PRD **91** 064001 (2015)]

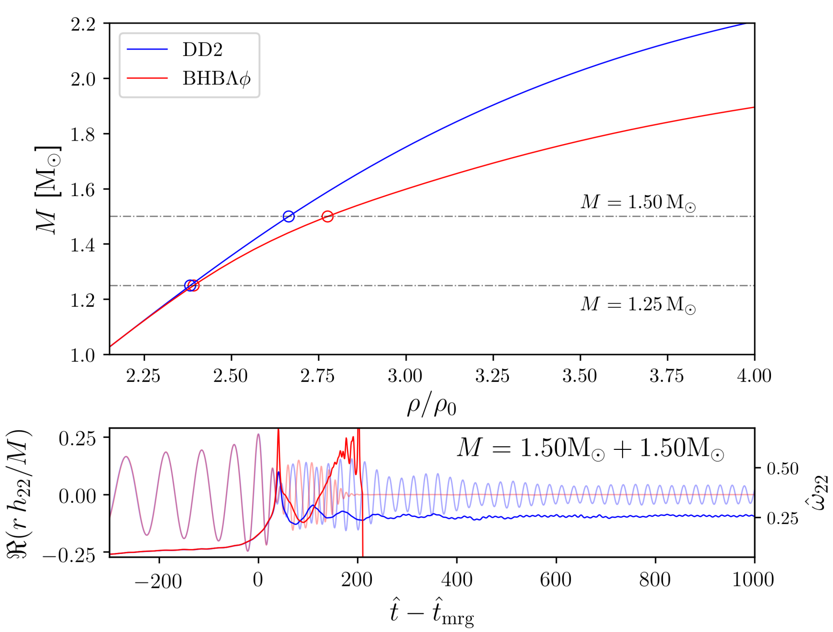
[Del Pozzo, Nagar PRD 95 124034 (2017)]

[Dudi+ PRD 98 084061 (2018)]

[Chatziioannou+ PRD 96, 124035 (2017)]

[Breschi, MA+ arXiv:1908.11418 (2019)], …





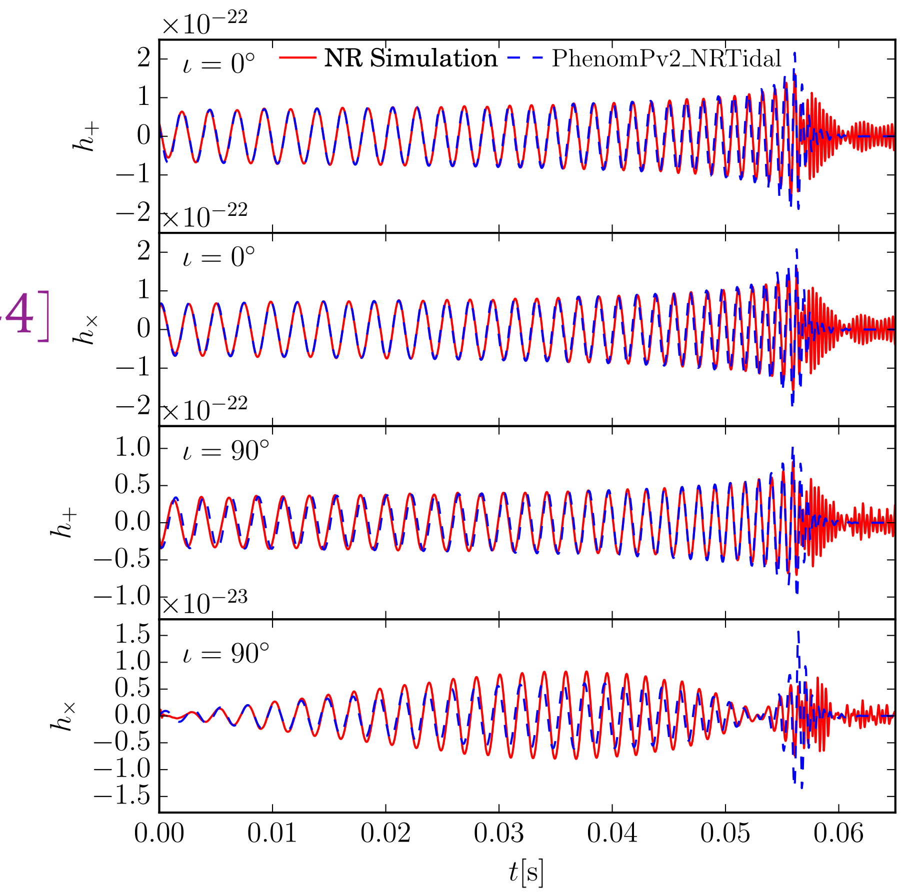
CONCLUSIONS

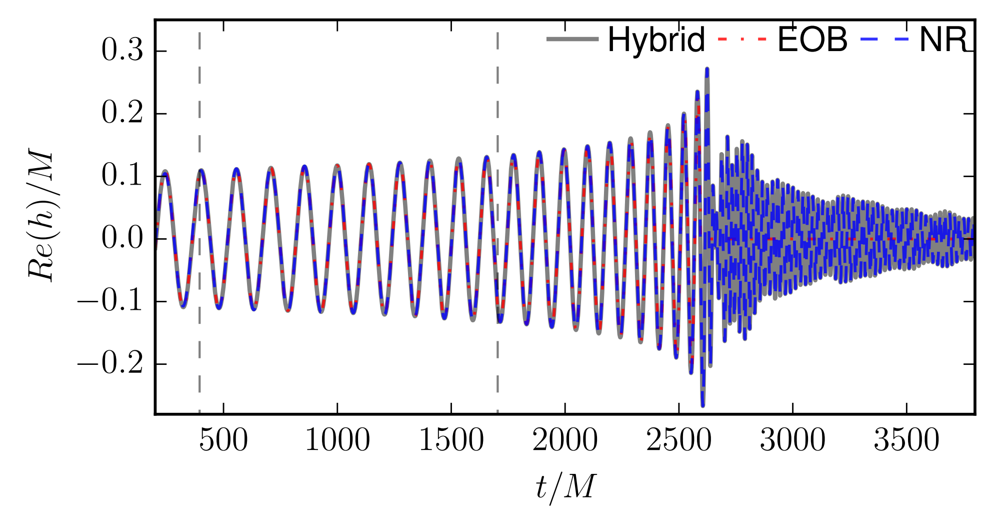
- BNS detections can probe properties of cold matter at supranuclear densities
- **GW170817** already gave very interesting results
- Making use of the assumption that NSs obey the same EoS further improves measurements
- Continuously **improving waveform models** with matter effects (TEOBResumS)
- Need high-quality **input from NR** simulations with matter
- Matter breaks scale-invariance and allows for new **standard-siren cosmography**
- Further gain if information from **EM observations** is folded in (coherently and robustly)
- **Many more BNS** detections in O3 and beyond will improve constraints
- Looking forward to results from NICER!
- We are officially in the era of GW astrophysics & cosmology (and even GW nuclear physics?). Posterior samples available online!

#O3ishere

MODELLING MATTER EFFECTS IN THE WAVEFORM

- Point-Mass baseline: IMRPhenomPv2 [Schmidt+ arXiv:1408.1810]
  - Post-Newtonian inspiral+ fit to EOB/NR
  - intermediate post-inspiral and merger-ringdown fit to EOB/NR [Taracchini+ arXiv:1311.2544]
  - spins w/ one-parameter precession effects
- Matter effects
  - PN: Hinderer+, Flanagan+, Poisson+, Ferrari+, Gualtieri+, …
  - EOB: Damour+, Nagar+, Buonanno+, …
  - NR simulations: Bernuzzi+, Read+, Rezzolla+, Hotokezaka+, Dietrich+, …
- **NRTidal:** NR-tuned **tidal** & **spin-Q** effects [Dietrich+ arXiv:1712.02992, arXiv:1804.02235]

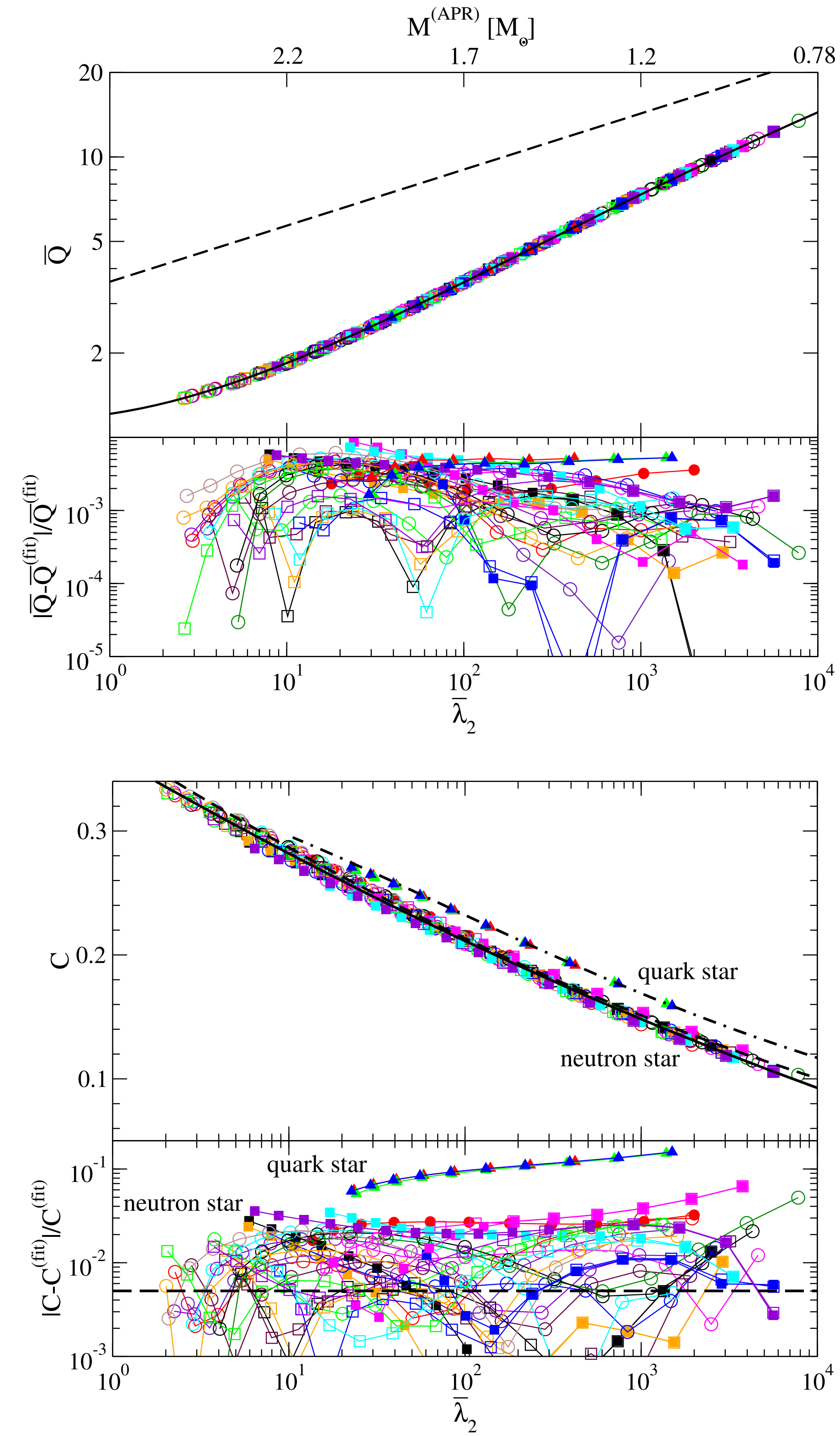




"I-LOVE-Q" RELATIONS

[Yagi & Yunes arXiv:1608.02582]

- NS assumption allows us to make use of known "universal" relations between NS properties
- These reduce the dimensionality of parameter space
- Λ — Q relation
  Yagi-Yunes [arXiv:1302.4499]
- Λ — C relation
  Maseli+ [arXiv:1304.2052],
  Urbanec+ [arXiv:1301.5925],
  Yagi-Yunes [arXiv:1608.02582]

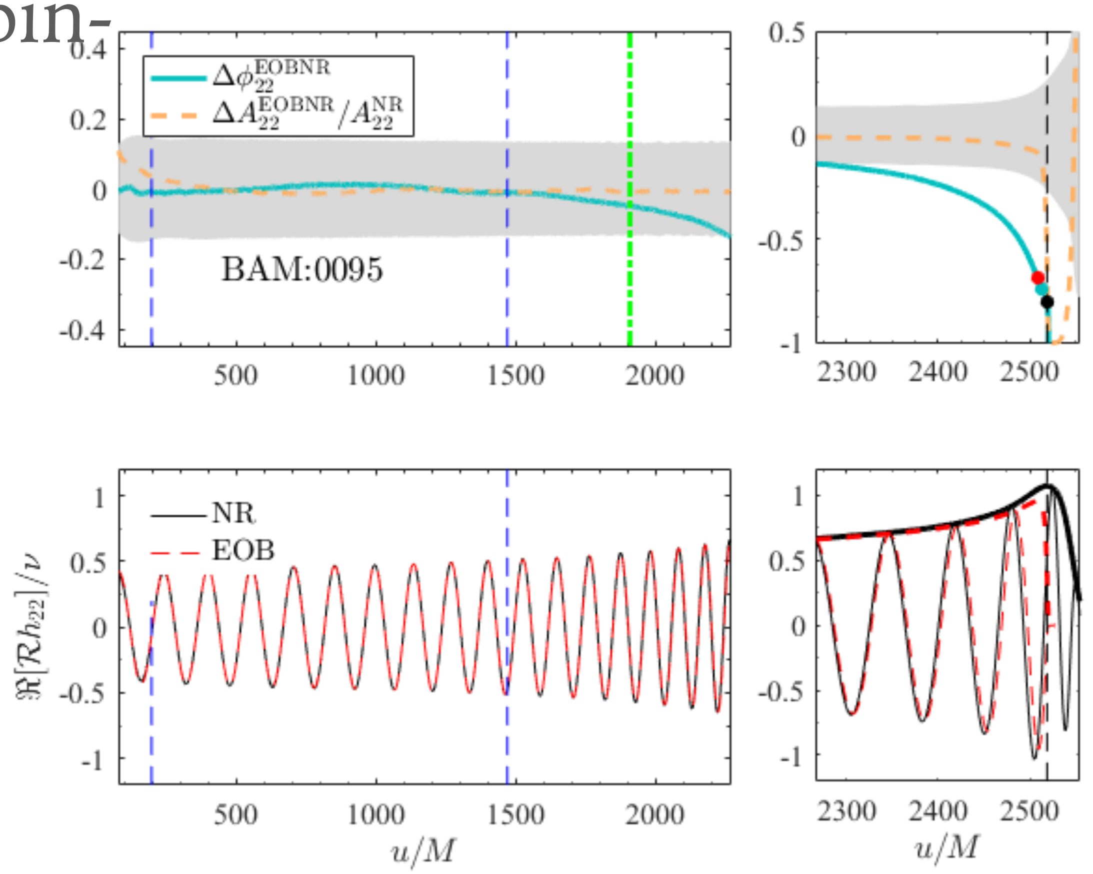


TOWARDS A BETTER WAVEFORM MODEL

[Nagar+ PRD 98, 104052 (2018)]

[Nagar&Retegno PRD 99 021501 (2019)]

- New model: **TEOBResumS**
- PM baseline:
  - EOB, resummed PN expansion of binary dynamics, w/ spin-orbit & spin-spin interactions to high order
  - reliable up to merger
  - higher order modes
  - next-to-quasi-circular corrections
  - Post-adiabatic inspiral (speed-up)



Code publicly available (+examples): **https://bitbucket.org/eob_ihes/teobresums**

TOWARDS A BETTER WAVEFORM MODEL

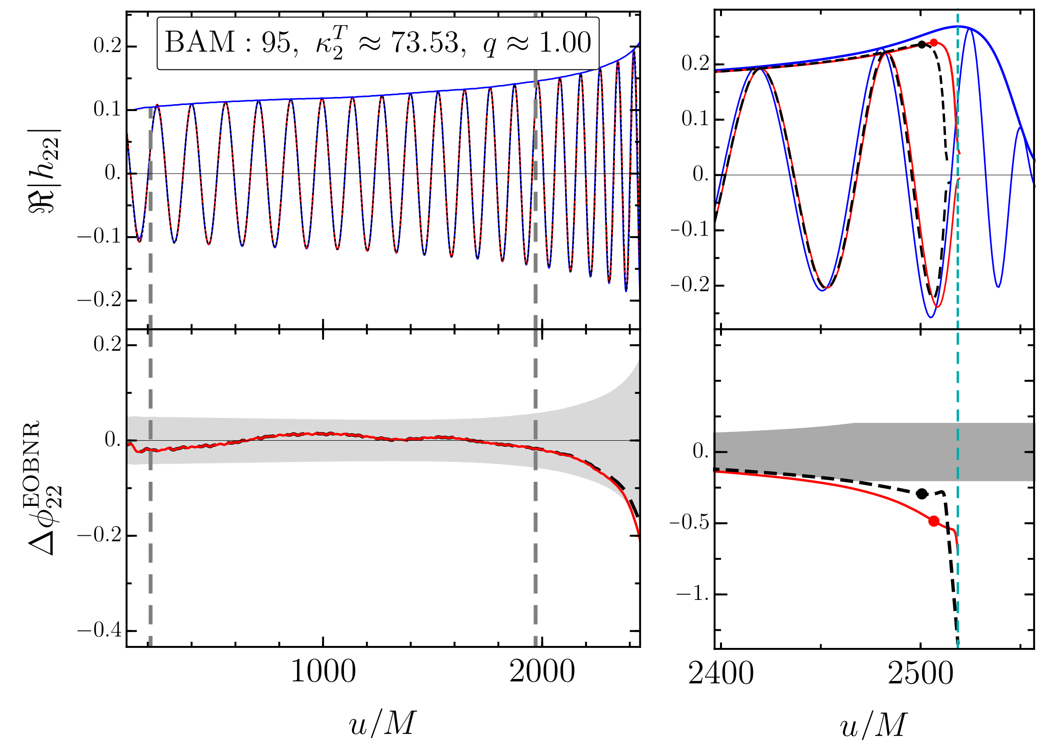
- New model: **TEOBResumS**
- Matter sector:
  - GSF-resummed potential with tides to high order
  - Spin-induced effects in resummed form at NNLO
  - l=2,3,4 tidal polarizability
  - LO gravitomagnetic tides resummed
  - Universal fits for relations between multipole Love parameters [Yagi PRD 89, 043011 (2014)]

[Nagar+ PRD 98, 104052 (2018)]

[Nagar&Retegno PRD 99 021501 (2019)]

[Akcay+ PRD 99, 044051 (2019)]

[Bernuzzi+ PRL 114, 161103 (2015)]



Code publicly available (+examples): **https://bitbucket.org/eob_ihes/teobresums**