Probing strong gravity & the densest objects in the cosmos with gravity's messengers

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[An artist's impression of LIGO-India]

Sukanta Bose

The main questions

1. How to distinguish neutron stars (NSs) from black holes (BHs) in gravitational waves (GWs) when the binary components are of low mass?

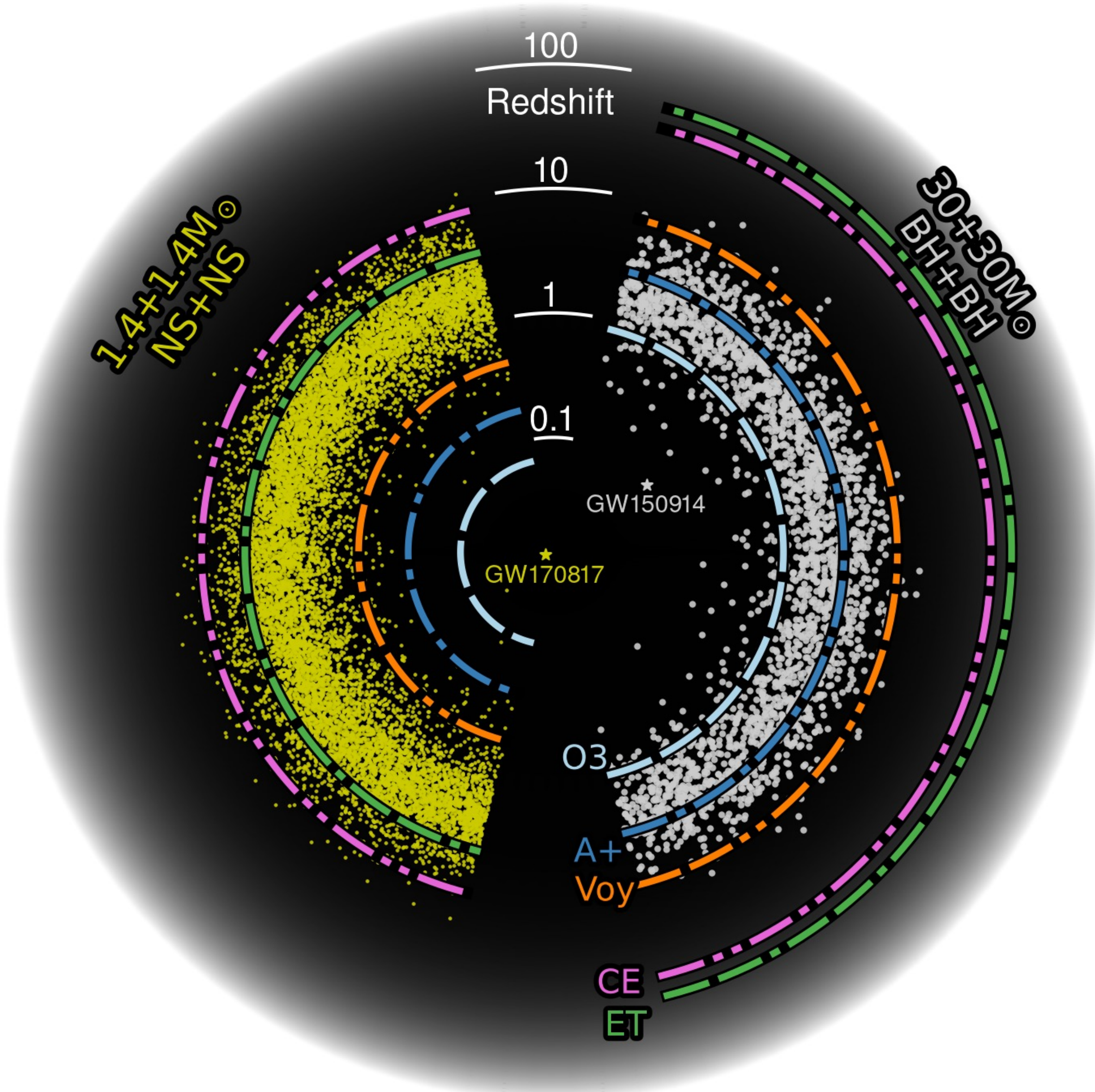
   a. How heavy / light can neutron stars be? (This probes nuclear physics.)

   b. How heavy / light can stellar-mass black holes be? (Probes stellar evolution, galactic dynamics, non-Gaussianities in primordial curvature fluctuations.)

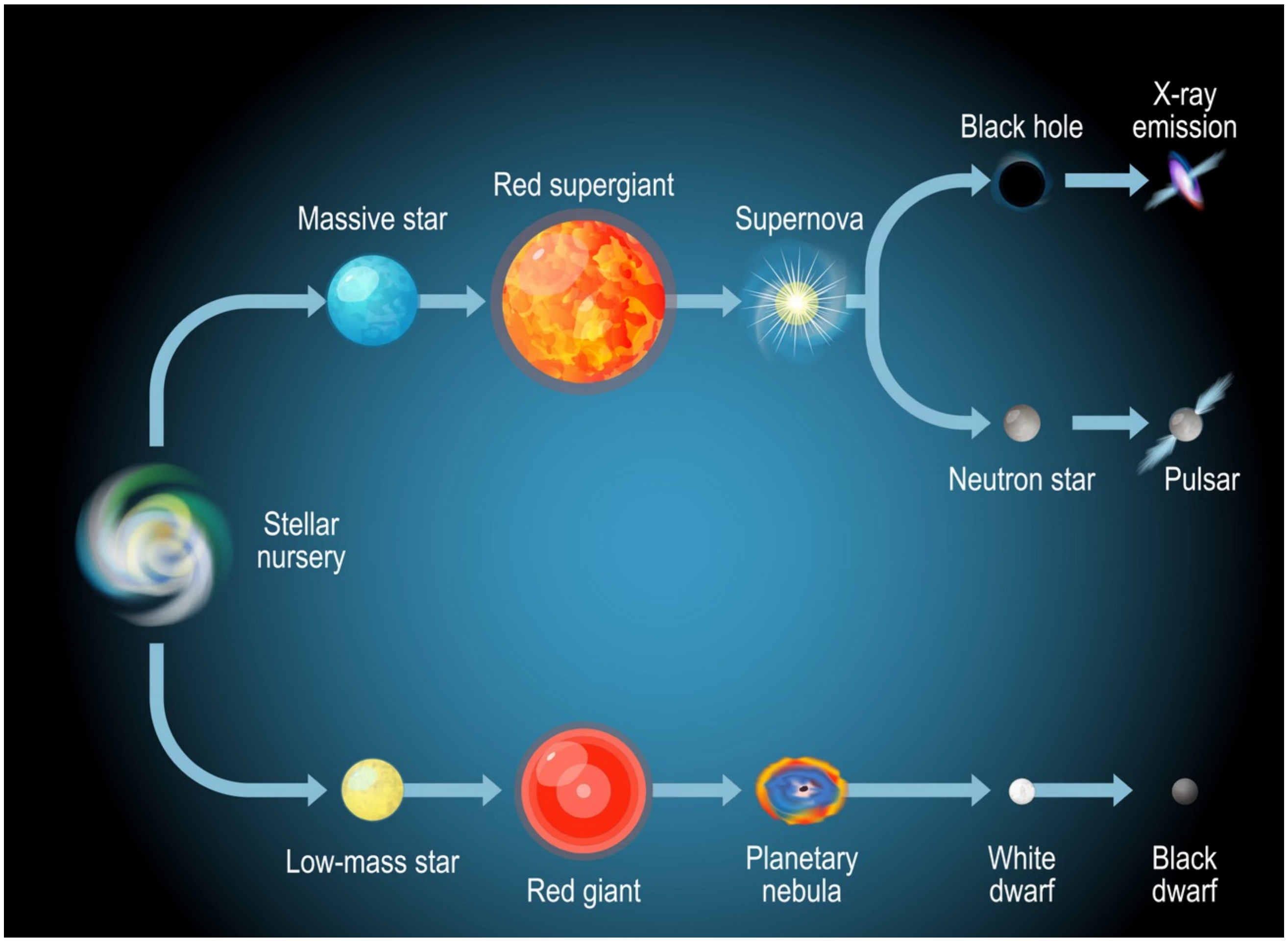
2. How to test if the high-mass GW sources are indeed black holes and not boson stars or BH mimickers? (Tests strong gravity.)

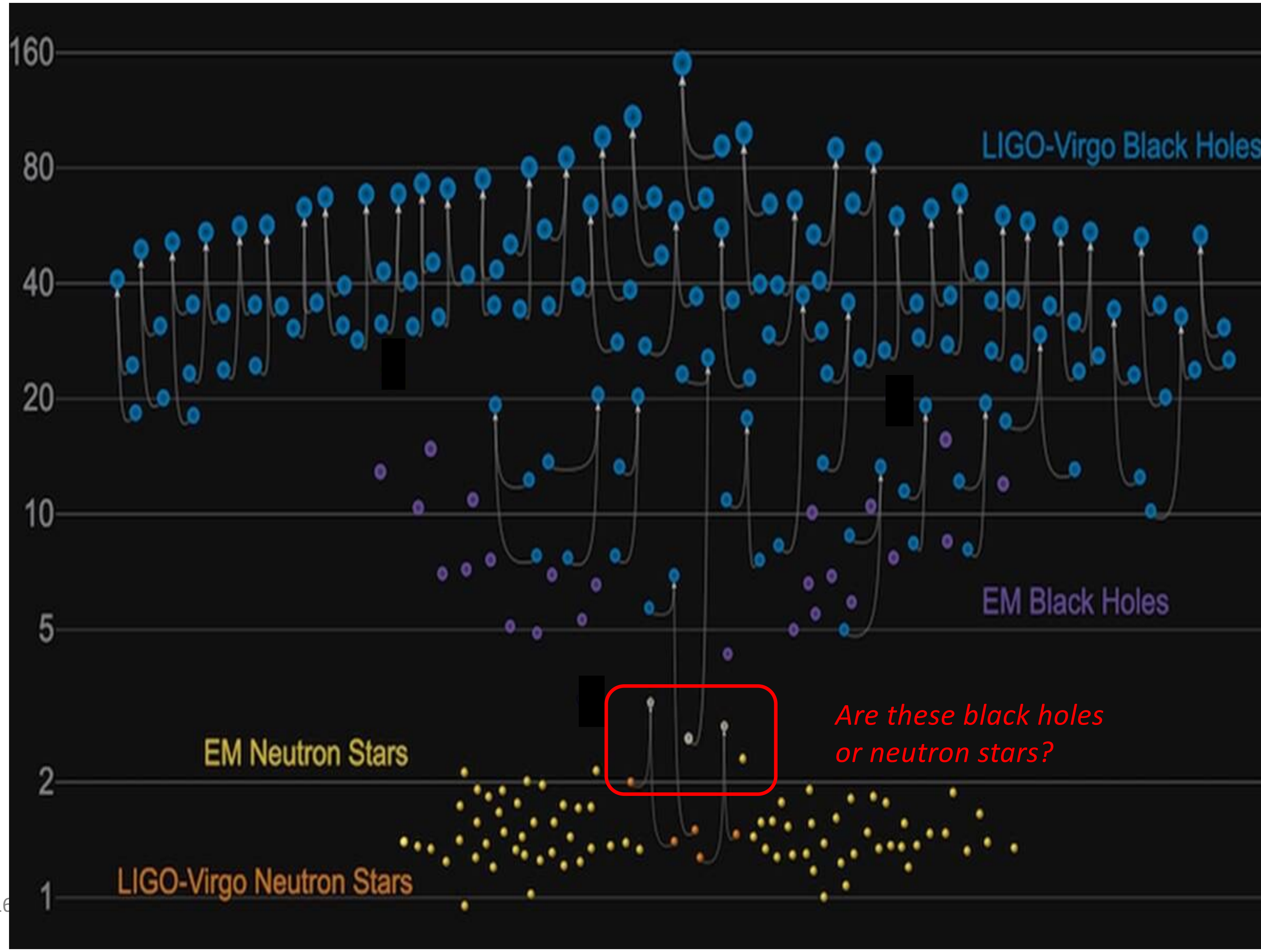
3. Can we measure the rate of cosmic expansion with GW binaries?

4. Are there other ways of testing General Relativity with these observations?



Stellar Evolution




160
80
40
20
10
5
2
1
LIGO-Virgo Black Holes
EM Black Holes
EM Neutron Stars
LIGO-Virgo Neutron Stars
Are these black holes
or neutron stars?

Imprints of the nature of compact objects on GWs

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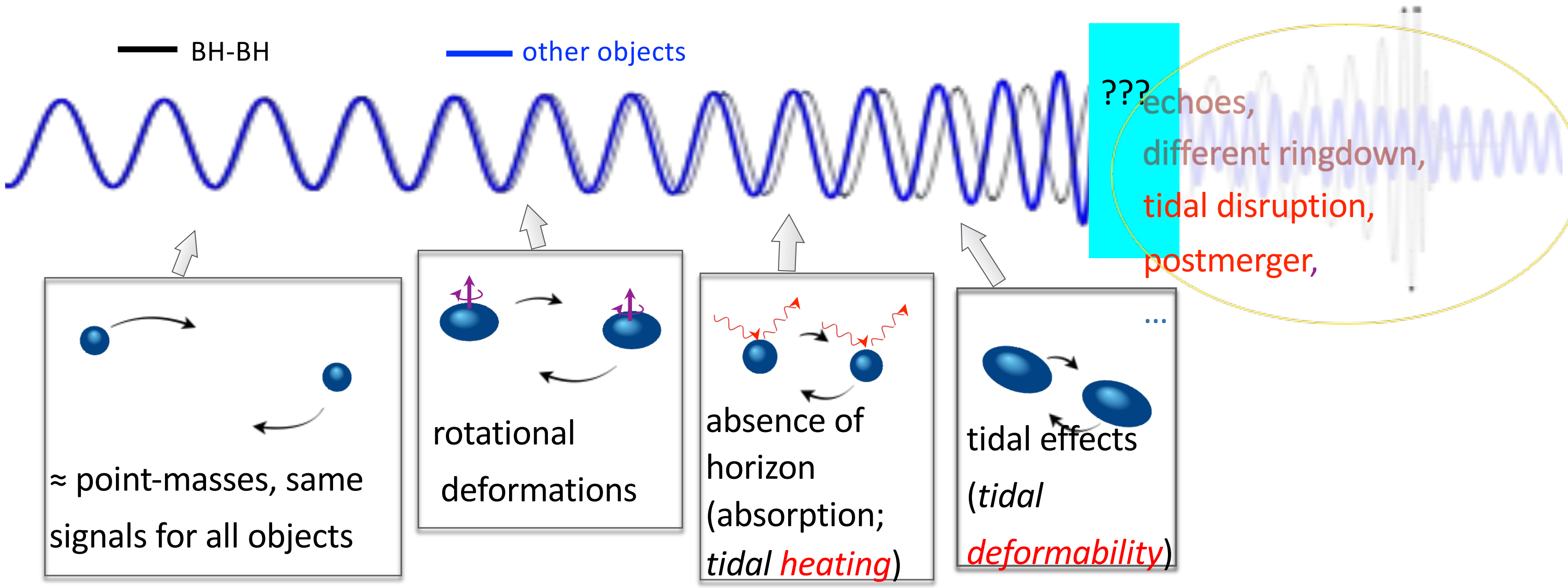
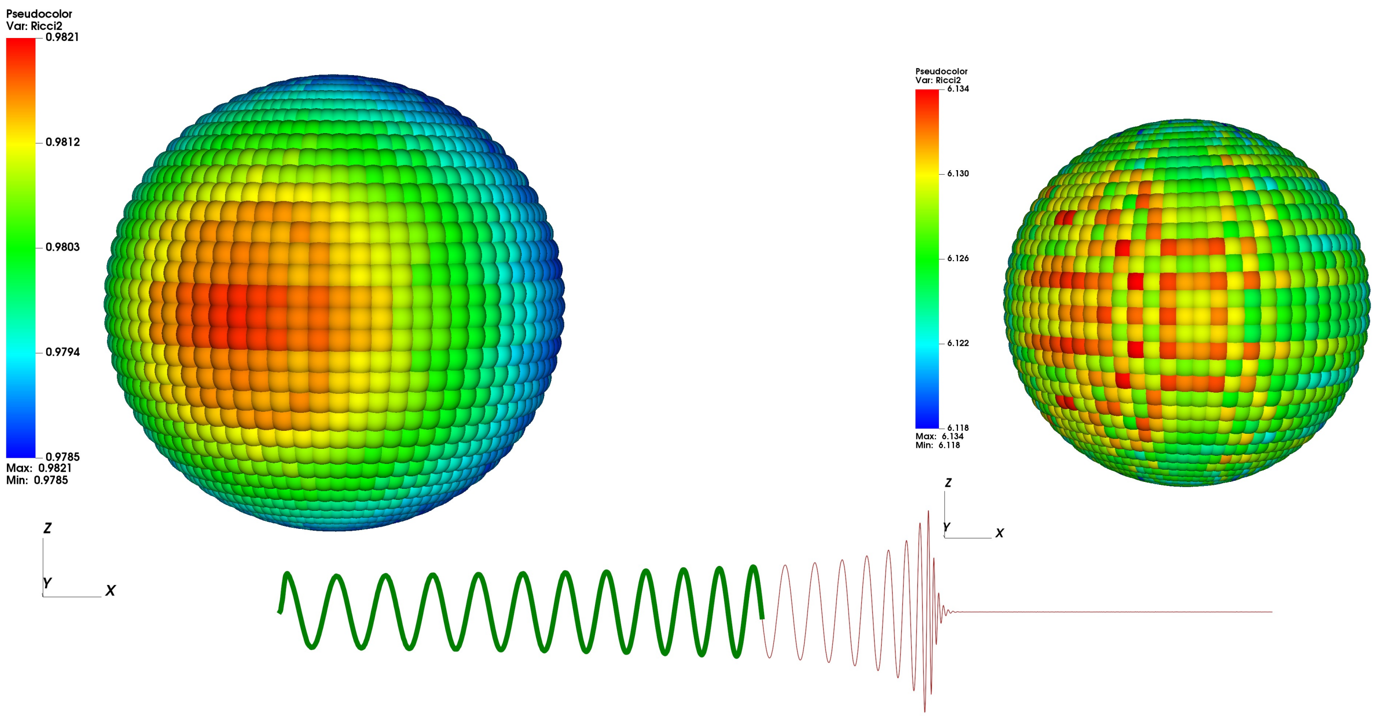


[≳10³ cycles for BNSs at f_{GW}≳10Hz]

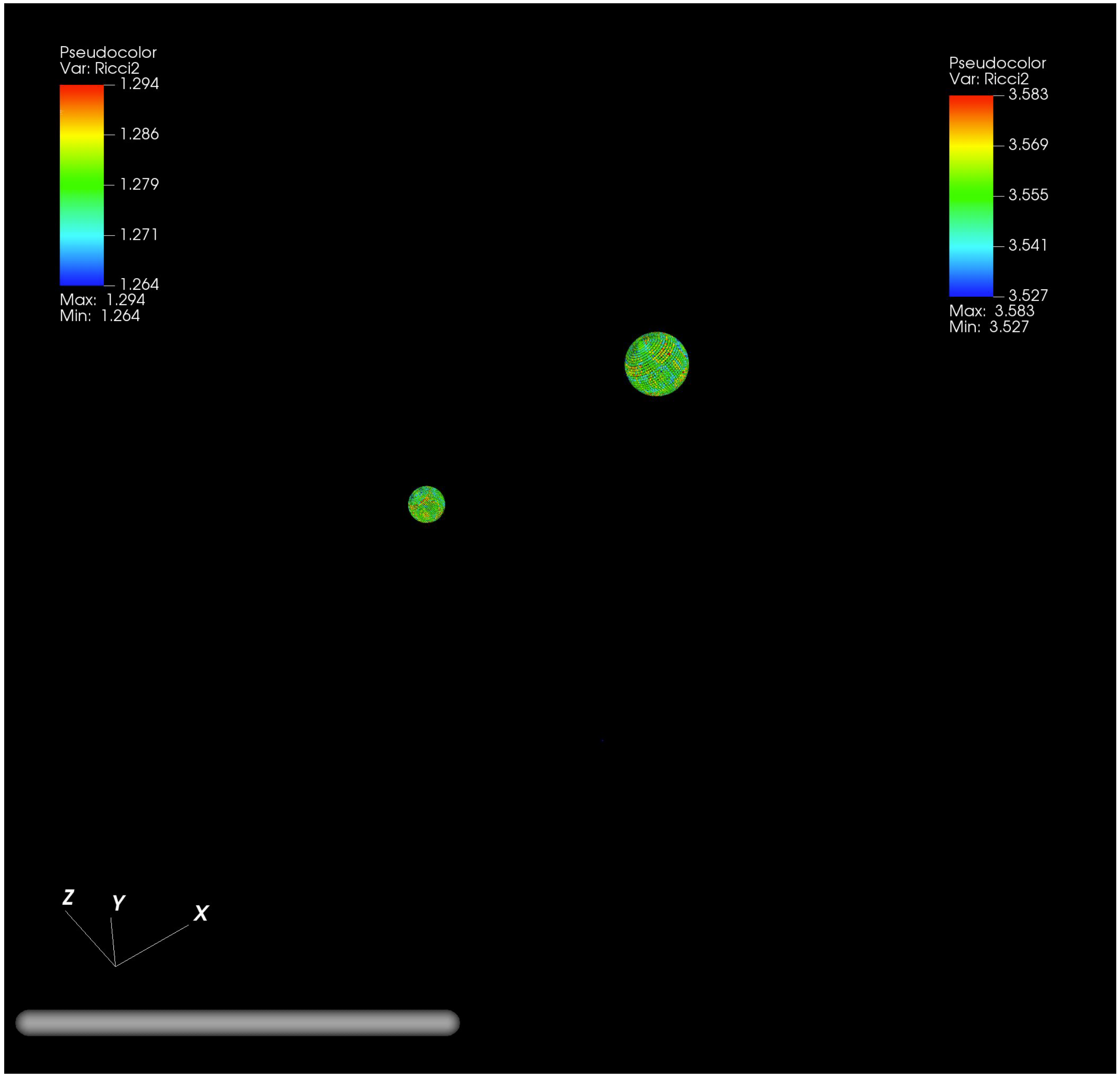
tidal excitation of various oscillation modes

[Slide courtesy: Tanja Hinderer]

Evolution of perturbed horizons in BBHs: Tidal heating



Prasad+, arxiv:2106.02595 (2021).



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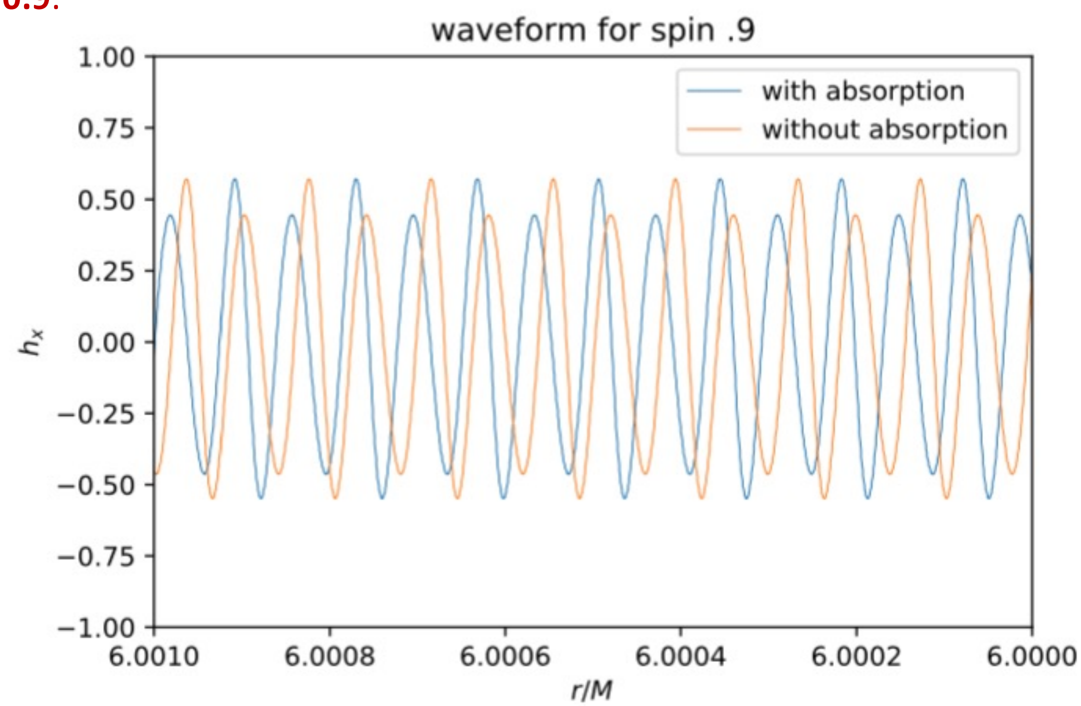
Lack of horizon-absorption in extreme mass-ratio inspirals (EMRIs) causes GW dephasing

Spin (χ) = **0.9**.



Distance →

Sayak Datta, R. Brito, *SB*,
P. Pani, S. Hughes, arxiv:1910.07841.

Testing blackhole-ness

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- Point-particle contribution to the waveforms determines the component masses and spins but not the presence of horizons.

- Test based on finite-size contributions
    1. Tidal heating (TH): Much strong in black holes than in neutron stars
    2. Tidal deformation (TD): Much stronger in (low mass) neutron stars than BHs.

Black holes exchange energy with orbit. If the bodies are (at least partially) absorbing, they back-react on the orbit, exchanging their energy and angular momentum with the orbit. This effect is tidal heating.

[Datta, Phukon, SB, PRD (2021)]

Tidal *deformability*: Measuring neutron star compactness

- How stiff or soft the NS EOS is determines how much the NS will flex (with quadrupole moment Q_{ij}) in an external tidal field, E_{ij} .

The EOS parameter to be measured is λ,

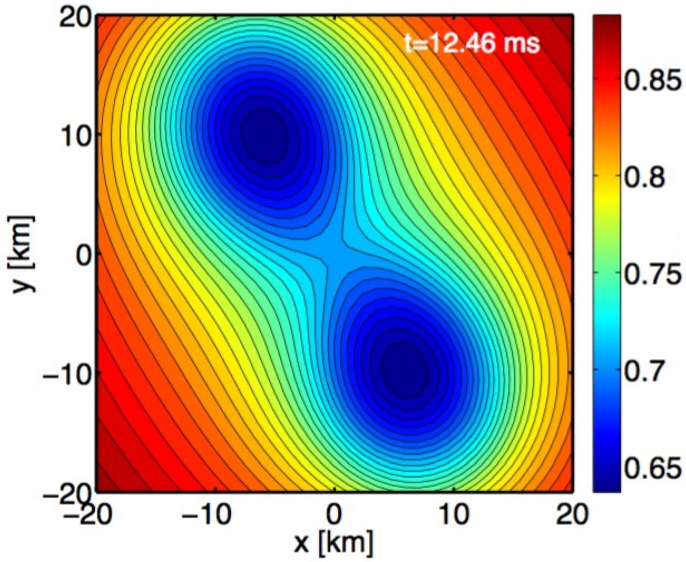
where $Q_{ij} = -\lambda E_{ij}$, and

$$\frac{\lambda}{M^5} = \frac{2}{3} k_2 \left(\frac{R}{M}\right)^5 \approx 10^2 - 10^5 \quad = \Lambda$$

k_2 is the "second Love number".

It is bigger for stiffer EOS.

- The flexing of a neutron star affects the GW emitted by it.



[Bauswein+, arxiv:1508.05493]

What is the densest form of matter?

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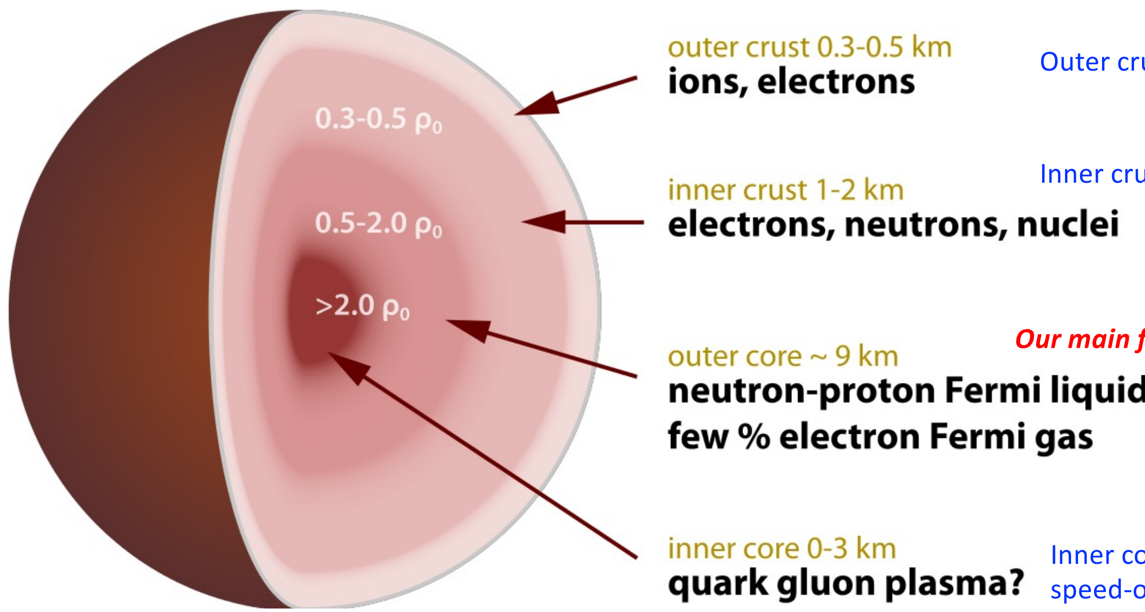


Outer crust: BPS

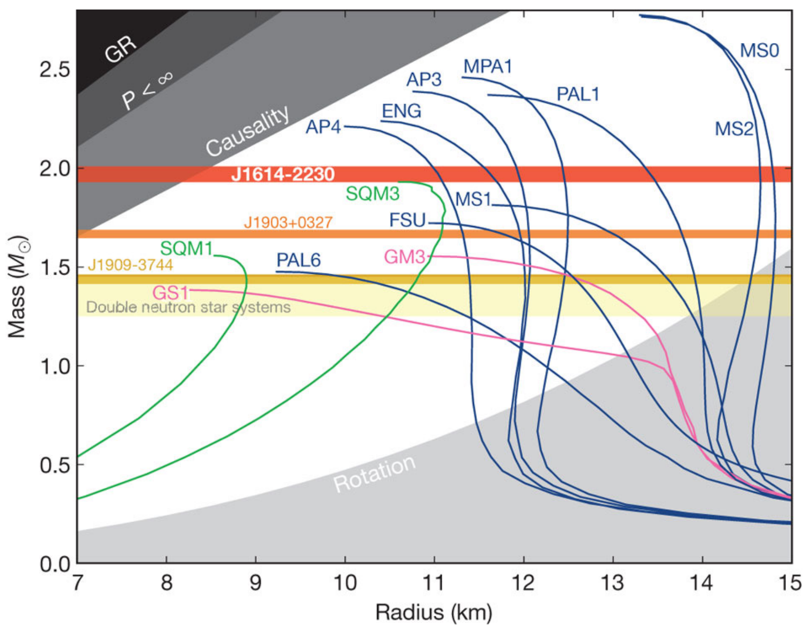
Inner crust: CLDM

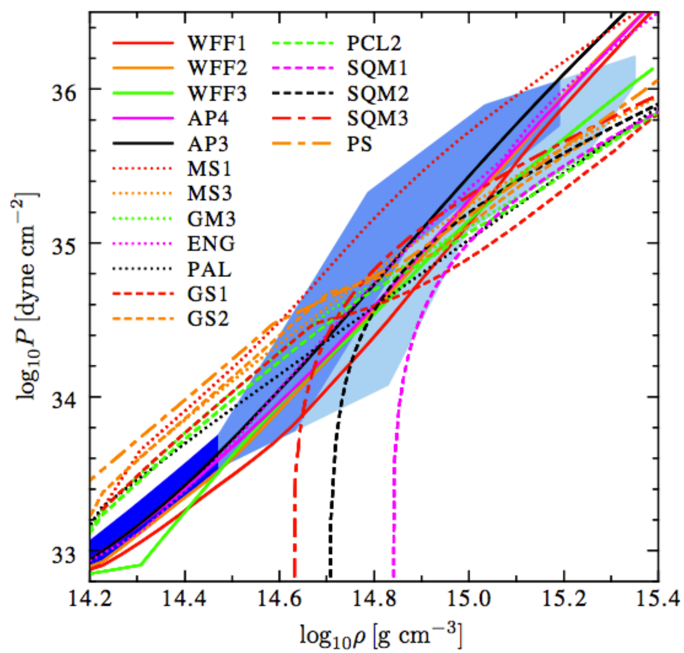
Our main focus here

Inner core: A speed-of-sound parameterization

[Credit: Wikipedia Commons / Robert Schulze.]

If the object is a BNS, then what? *Neutron star EoS*





J. Lattimer, ApJ 2012.

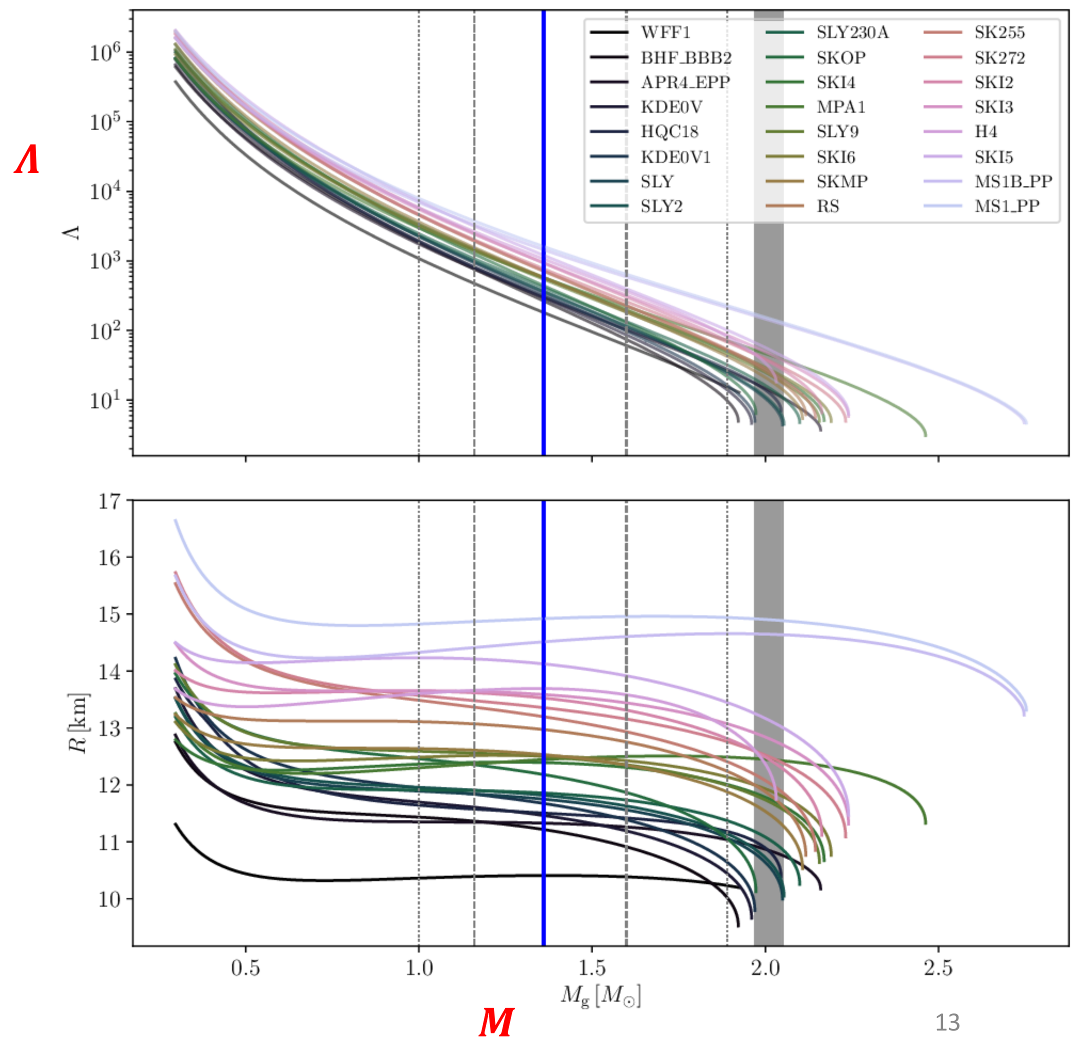
Breaking the mass-redshift degeneracy using NS EoS

- We measure the detector-frame mass of neutron stars, which is the redshifted mass $m_z \equiv m(1+z)$. Here, m is the source-frame mass, which is what we are targeting to obtain the inherent NS mass distribution.

- Use the measured Λ to break the $m - z$ degeneracy:

Λ (or the NS EoS) gives us the source-frame mass.

That mass and m_z give us the source redshift!



NS tide in the pre-merger phase

Total phase = Point-particle phase + Tidal phase-correction.

Point-particle phase has non-spinning and spinning (aligned or anti-aligned) terms up to 3.5pN. We add test-particle non-spinning corrections for 4pN to 6pN to bridge the gap up to the terms where tidal corrections are present (5pN and 6pN).

Tidal phase-correction is:

$$\Phi_{\text{tidal}} = \sum_{i=1}^{2} \frac{3\lambda_i}{128\eta M^5}\left[\begin{array}{l} -\frac{24}{\chi_i}\left(1+\frac{11\eta}{\chi_i}\right)\left(\frac{v}{c}\right)^5 \\ -\frac{5}{28\chi_i}\left(3179-919\chi_i-2286\chi_i^2+260\chi_i^3\right)\left(\frac{v}{c}\right)^7 \end{array}\right],$$

[Vines, Flanagan, Hinderer, arXiv:1101.1673v1.; Damour, Nagar, Villain, PRD85, 123007 (2012).

where $v=(M\omega)^{1/3}$, $\chi_i = m_i / M$ and "i" is binary component index.

$M = m_1 + m_2$ and $\eta = m_1 m_2 / M^2$.

GW170817's Implications on *Equation of State:* from *inspiral* part of waveform

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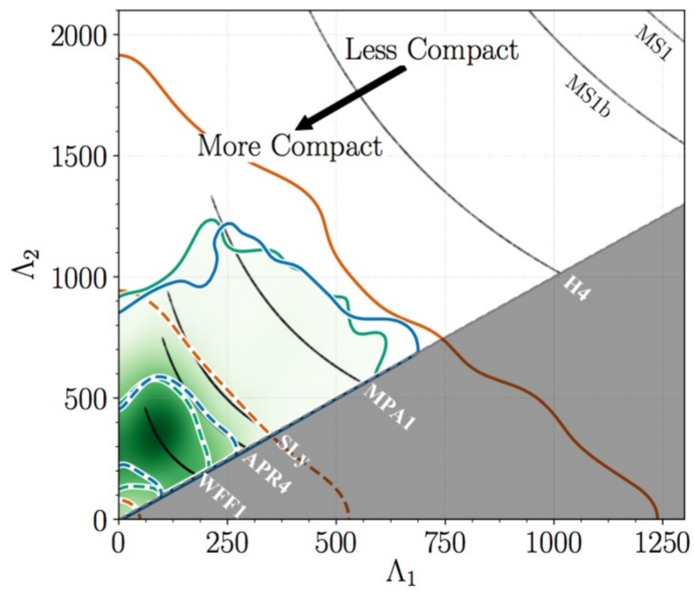
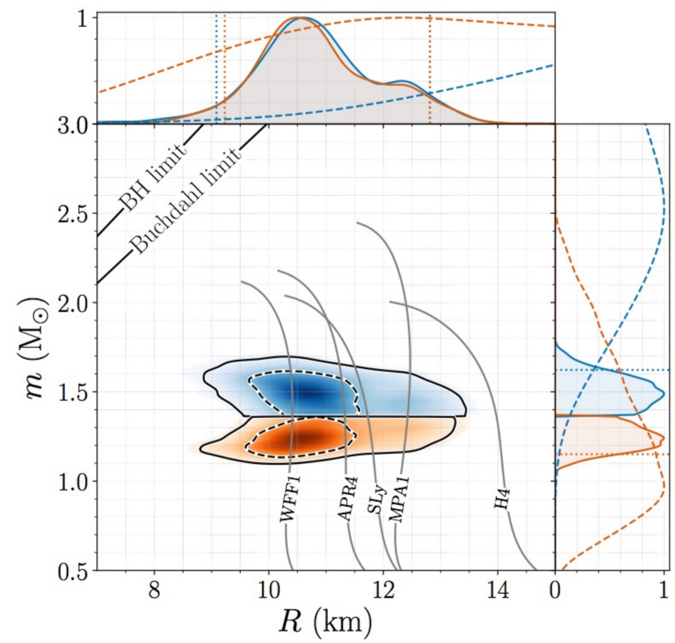


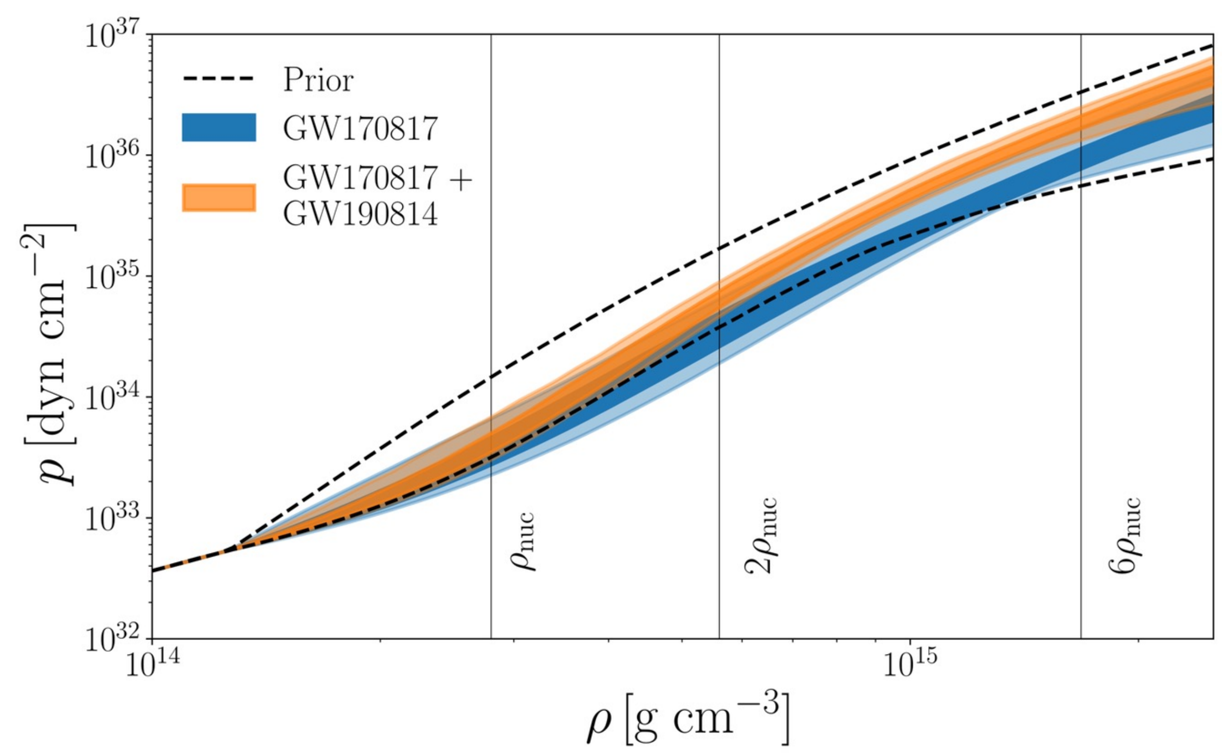
Tidal deformability: $\boldsymbol{\Lambda_{1.4}} = 190^{+390}_{-120}$ (90%).

[LIGO-Virgo Collab, arxiv:1805.11681]



Radius $R = 11.9^{+1.4}_{-1.4}$ km (90%)

Neutron star (NS) equation of state (EOS) from GWs (agnostic priors)



LIGO-Virgo, arxiv: 2006.12611

Empirical EoS parameterization

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pressure as a function of energy

energy per particle of nuclear matter

$$p(\rho, \delta) = \rho^2 \frac{d}{d\rho}(e_0(\rho, \delta))$$

symmetric nuclear matter

symmetry energy

$$e_0(\rho, \delta) \approx e_0(\rho) + e_{sym}\delta^2$$

$$e_0(\rho) = e_0(\rho_0) + \frac{K_0}{2}\chi^2 + \frac{J_0}{6}\chi^3$$

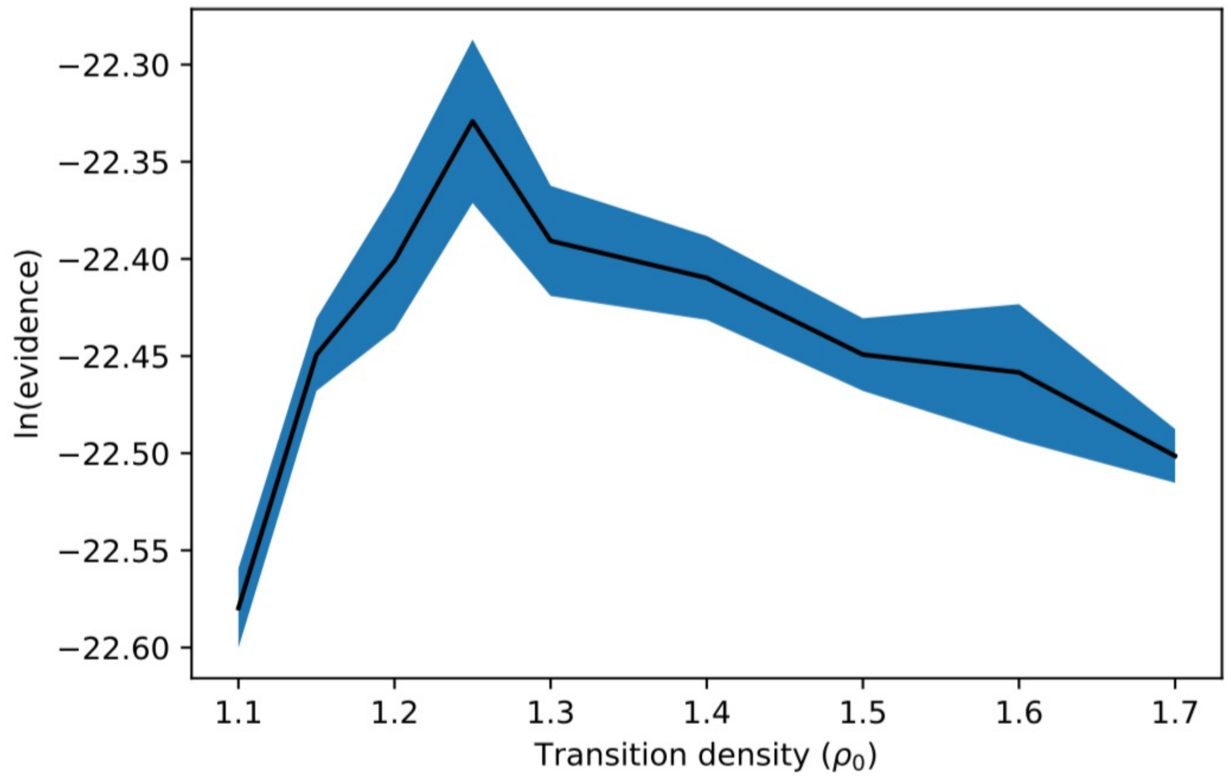
$$e_{sym}(\rho) = e_{\rm sym}(\rho_0) + L\chi + \frac{K_{\rm sym}}{2}\chi^2 + \frac{J_{\rm sym}}{6}\chi^3$$

$$\delta = \text{"symmetry parameter"} = (\rho_{\rm n} - \rho_{\rm p})/\rho,$$
$$\chi = (\rho - \rho_0)/3\rho_0$$

EoS model:
a hybrid nuclear ($\rho < 1.25\rho_0$)
+ Piecewise Polytrope

Biswas, Char, Nandi, Bose, arxiv 2020.

Transition density:
From nuclear to core polytrope



Astro evidence for transition from nuclear to first polytrope, around 1.25 times nucl. saturation density.

Biswas, Char, Nandi, Bose, PRD, arXiv:2008.01582.

Neutron star EoS posteriors from data

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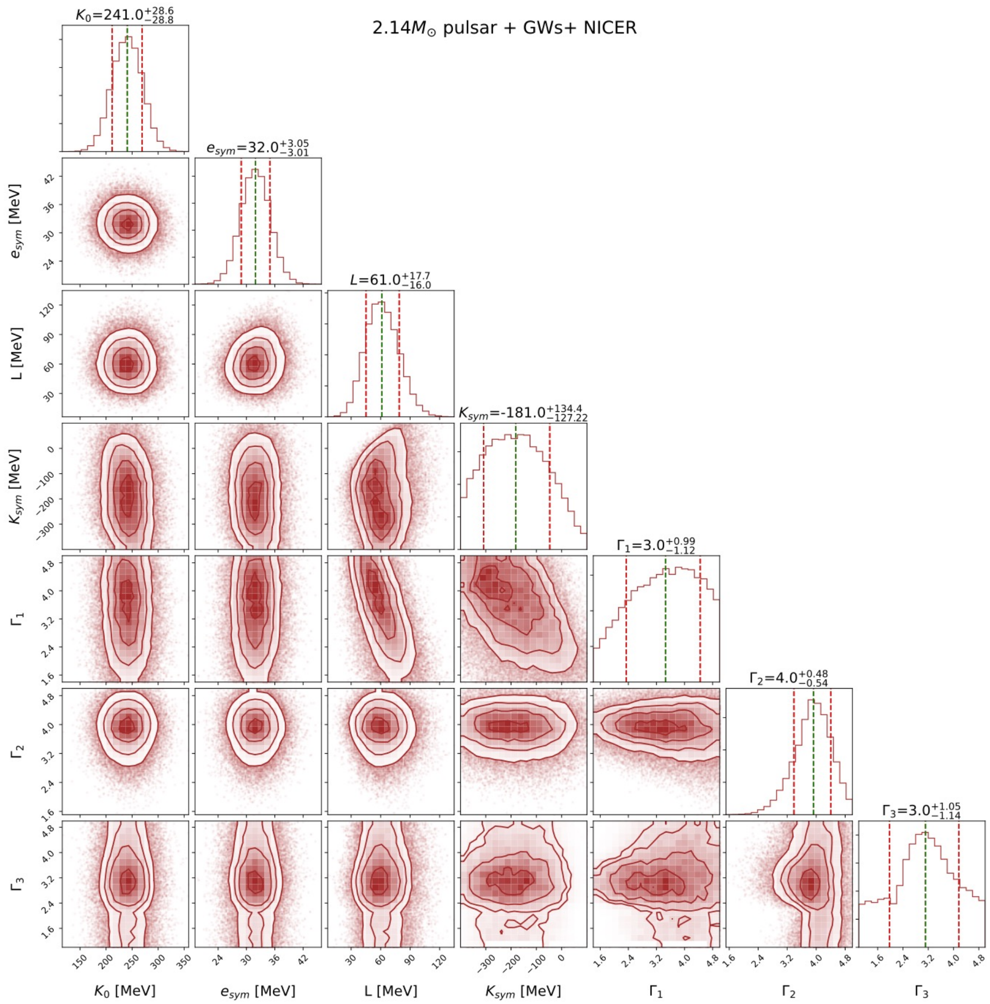


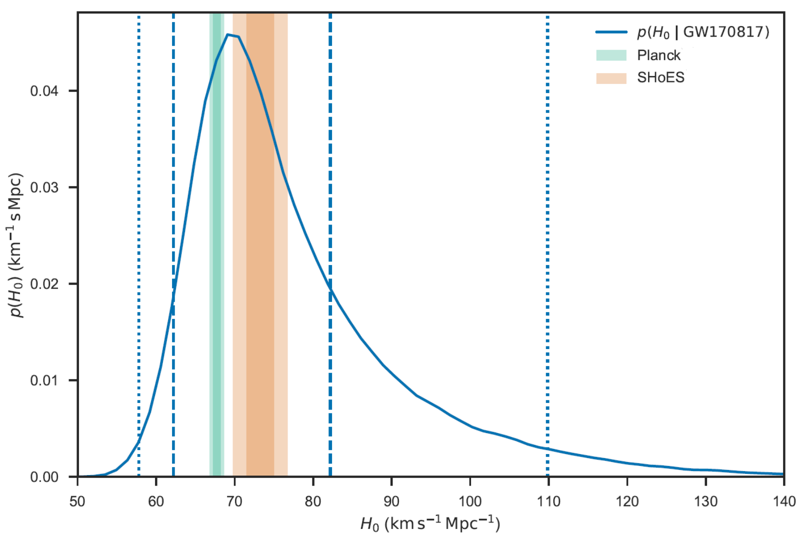
Maximum non-spinning NS mass ~ 2.16 $M_\odot$.

Rezzolla+, ApJL, 2018;
Biswas+, MNRAS 2021.

150 200 250 300 350 24 30 36 42 30 60 90 120 −300 −200 −100 0 1.6 2.4 3.2 4.0 4.8 1.6 2.4 3.2 4.0 4.8 1.6 2.4 3.2 4.0 4.8

K_0 [MeV] e_{sym} [MeV] L [MeV] K_{sym} [MeV] Γ_1 Γ_2 Γ_3

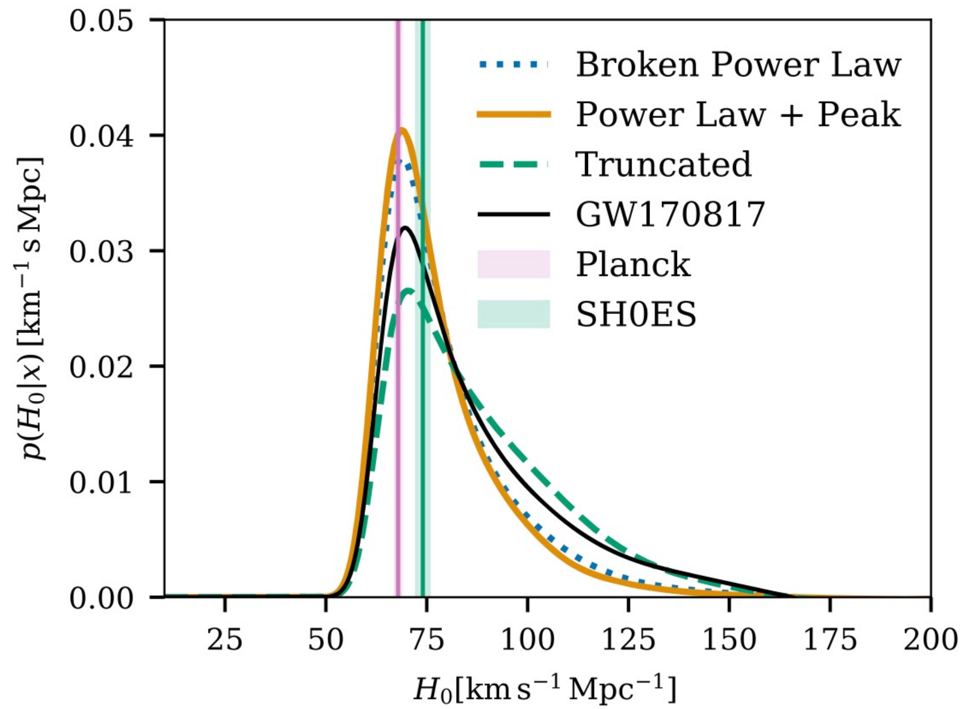
The Hubble parameter from dark sirens + *GW170817*



Without any prior on inclination angle:

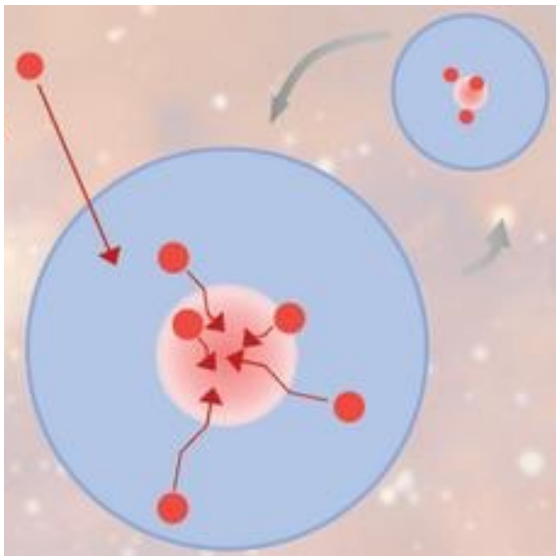
$H_0 = 70^{+12}_{-8}$ km/s/Mpc (68%).

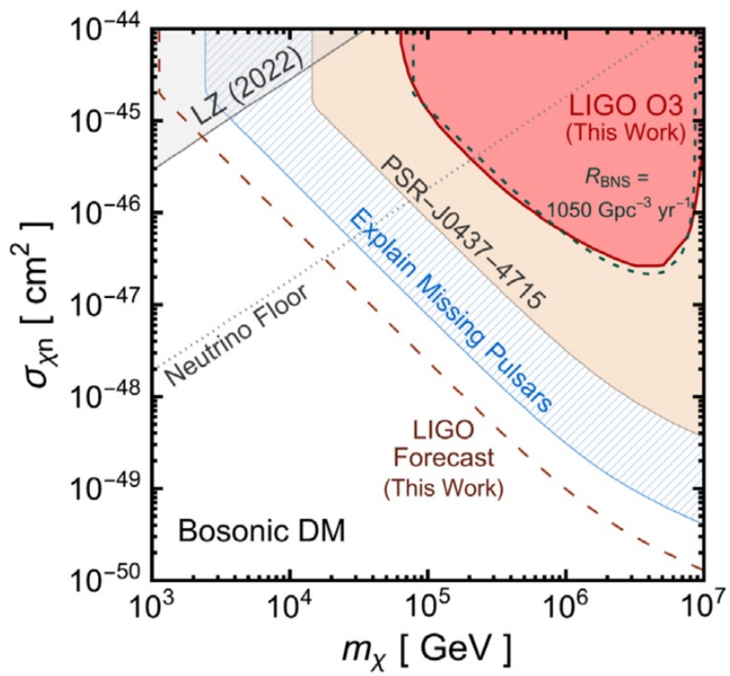
[LIGO-Virgo+EM partners, Nature 2017]

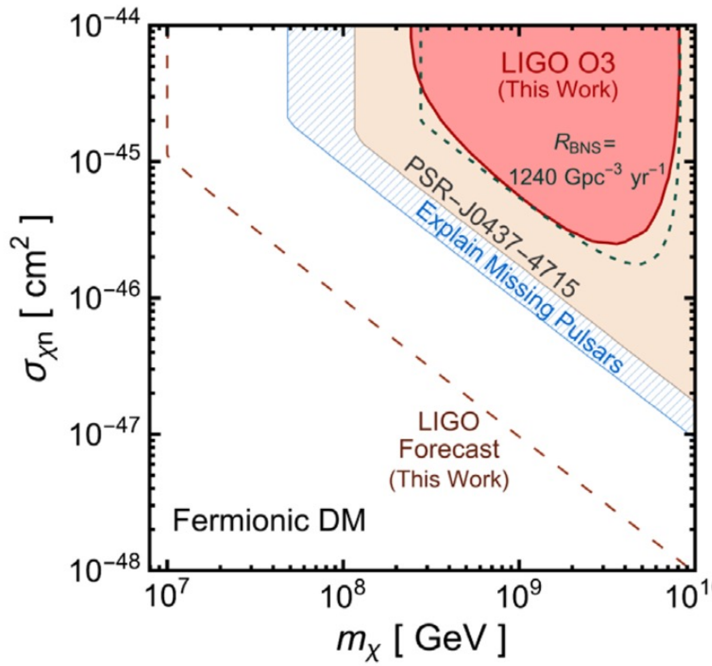


[LIGO-Virgo, ApJ 2023]

Dark matter accretion in neutron stars



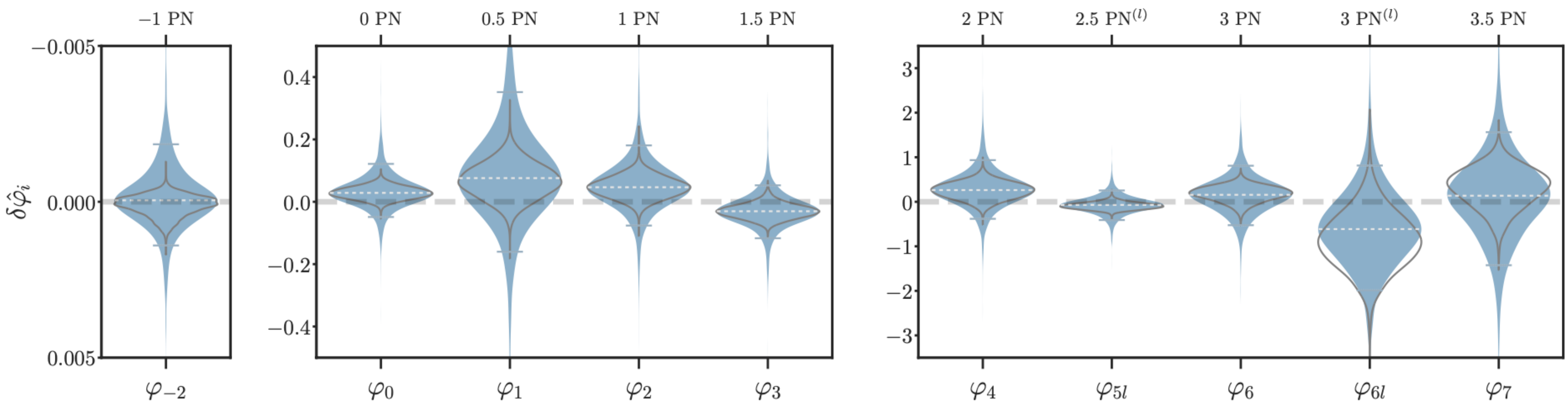




[Bhattacharya+, PRL (2023)]

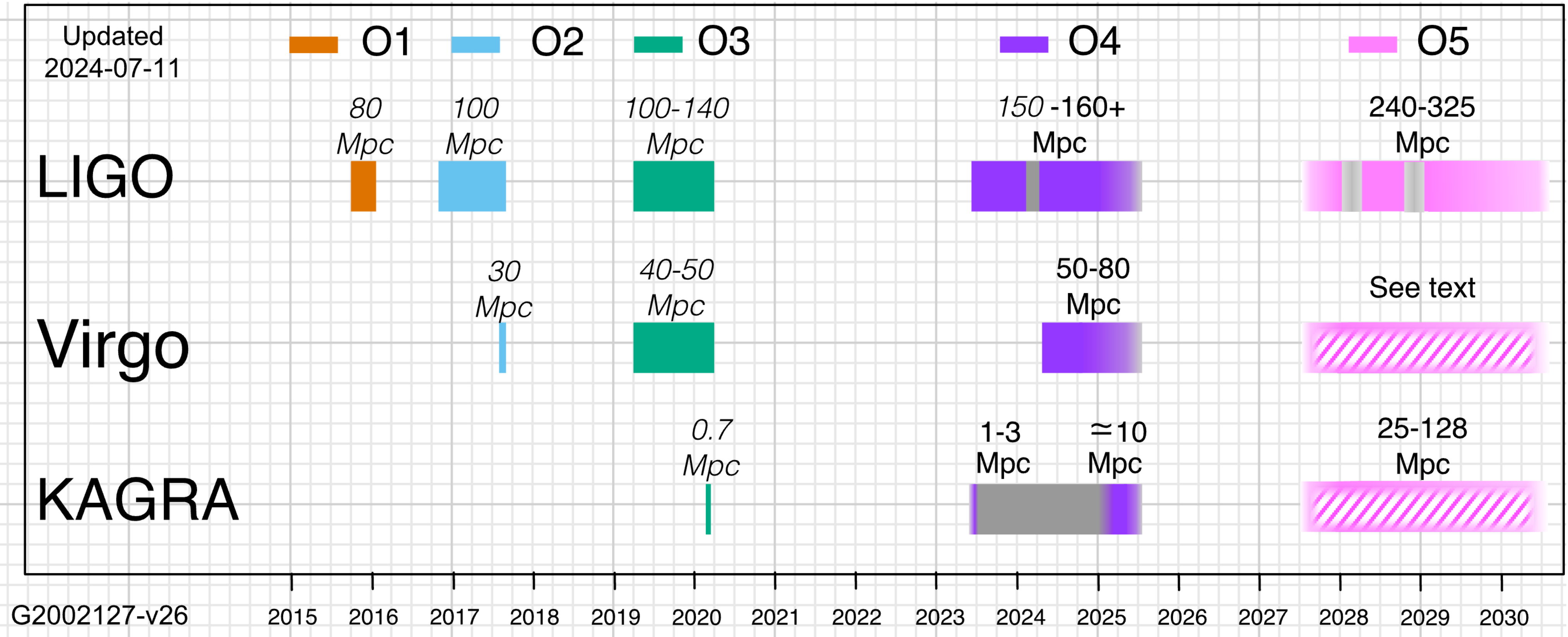
Testing General Relativity via addition of deviation terms in waveform phase

$$\varphi_{\rm PN}(f) = 2\pi f t_{\rm c} - \varphi_{\rm c} - \frac{\pi}{4} + \frac{3}{128\eta}\left(\pi \tilde{f}\right)^{-5/3} \sum_{i=0}^{7} \left[\varphi_i + \varphi_{i\,l} \log(\pi \tilde{f})\right] \left(\pi \tilde{f}\right)^{i/3}$$



 [LIGO-Virgo, Tests of GR with GWTC3, arXiv:2112.06861v1]

GW observing scenario



Take-away messages

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1. The maximum mass of a stable non-spinning (TOV) neutron star estimated to be ~ 2.16 $M_\odot$, with R = $11.9^{+1.4}_{-1.4}$ km and densities at least a few times nuclear saturation density. Several stiff equations of state have been ruled out.

2. Heavier compact objects are presumably black holes, with those in [2.16, 4] $M_\odot$ most likely being merger remnants. Not clear if stellar collapse can produce such remnants.

3. Challenging to distinguish neutron stars from black holes in the lower-mass gap unless their signals are O(10) times stronger. Tidal heating in next generation detectors can confirm presence of horizons in nearby black hole binaries, individually.

4. H_0 estimation set to get more precise with O5.

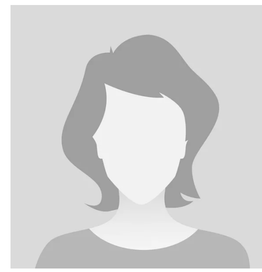
5. GW signals from neutron star and black hole binaries may be able to constrain certain non-annihilating dark matter candidates, but the jury is still out.

Collaborators


Sayak Datta


Khun Sang Phukon


Vaishak Prasad


Anshu Gupta


Badri Krishnan


Samanwaya Mukherjee


Shristi Tiwari


Tathagata Ghosh


Bhaskar Biswas


Shasvath Kapadia

GW observing scenario

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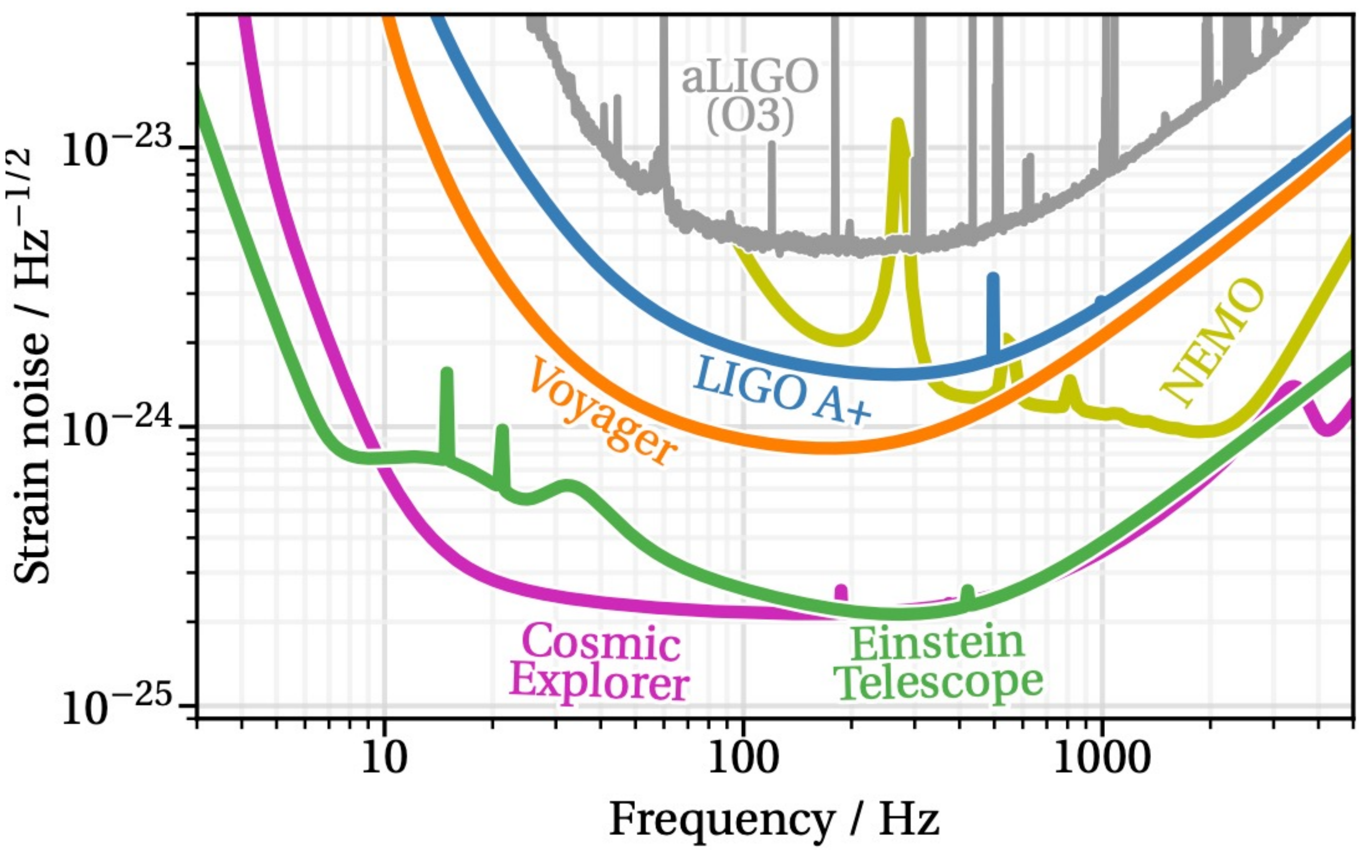


O4 alerts so far

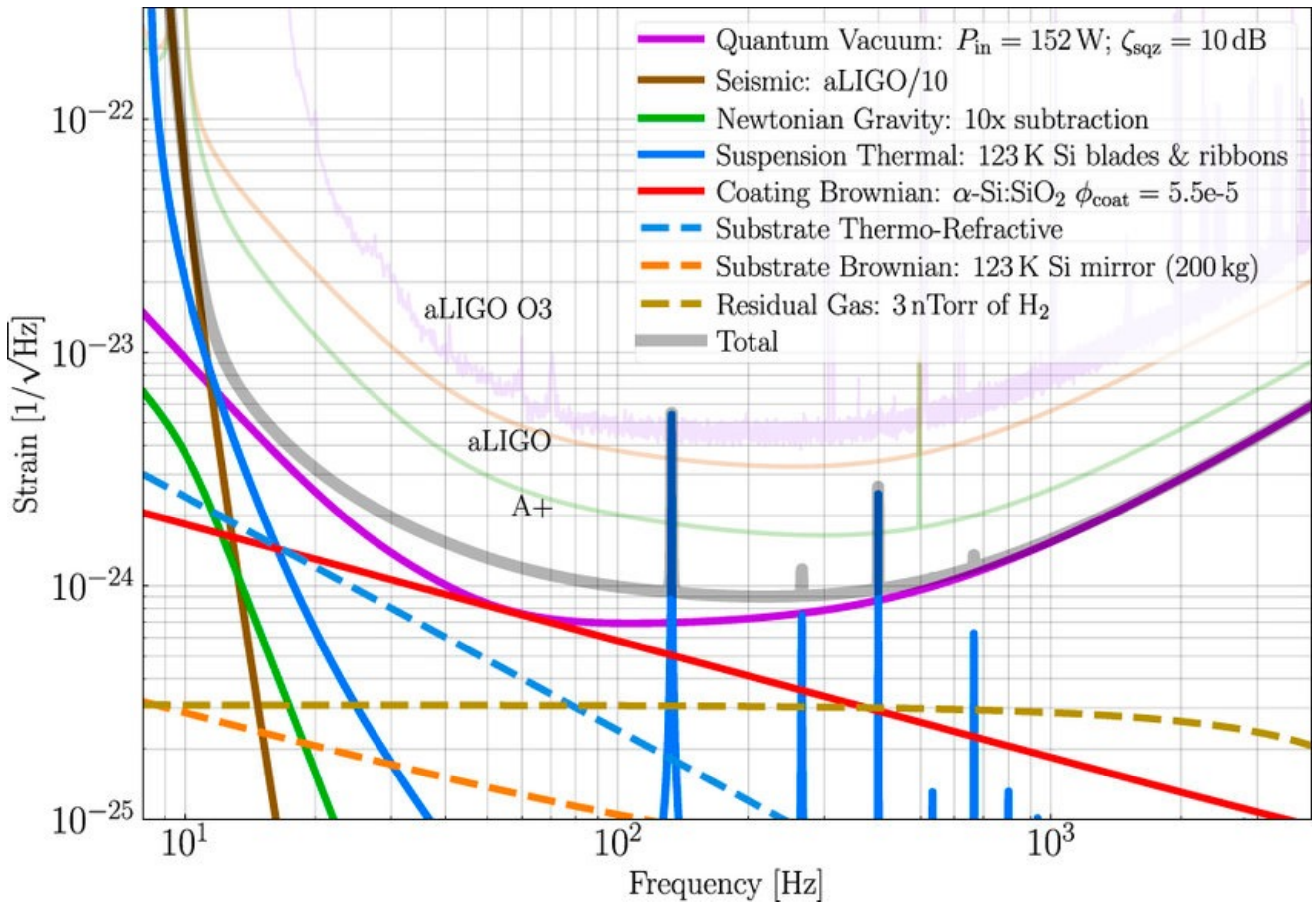
O4a Significant Detection Candidates: **81** (92 Total - 11 Retracted)
O4a Low Significance Detection Candidates: **1610** (Total)

O4b Significant Detection Candidates: **61** (66 Total - 5 Retracted)
O4b Low Significance Detection Candidates: **872** (Total)

Published NSBH: O4a, GW230529: masses: $m_1 = 2.5 - 4.5\ M_\odot$, $m_2 = 1.2 - 2.0\ M_\odot$

O4b NSBH alert:
S240422ed $m_1 = 3.89\ M_\odot$, $1.07\ M_\odot$

GW observing scenario



Adhikari+, CQG (2020)

Results [Summary of Part I]

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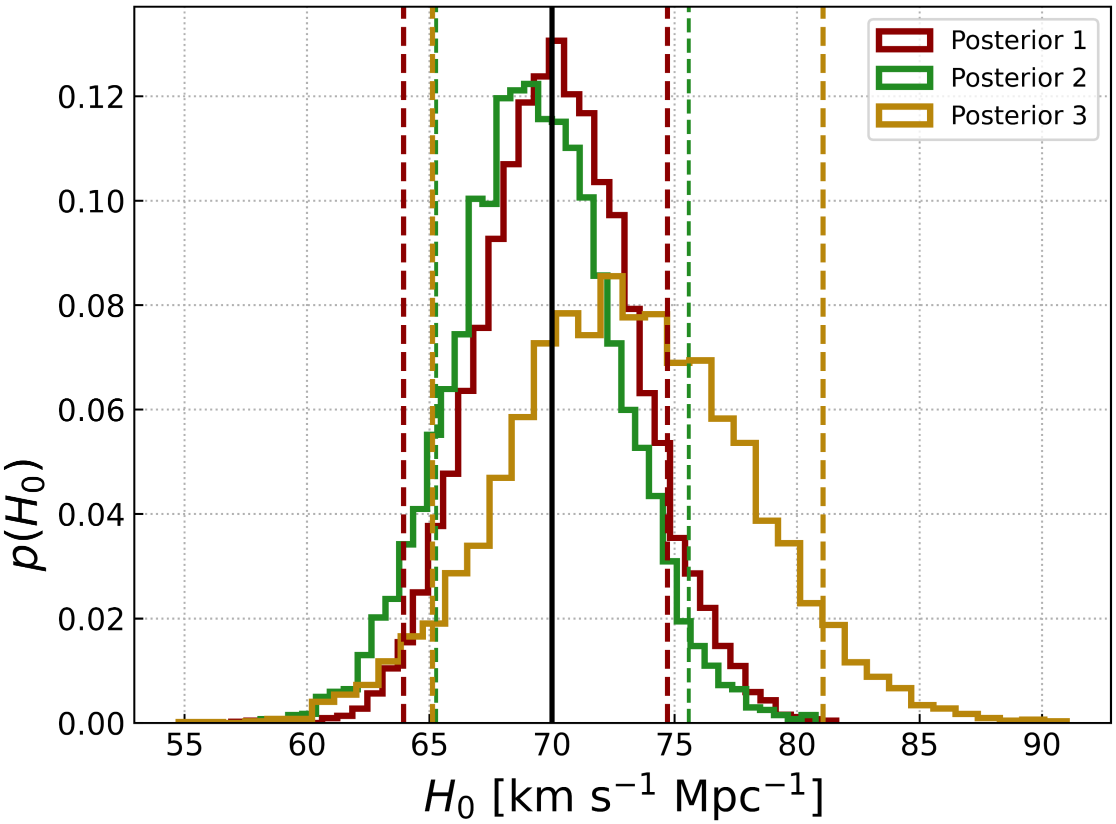


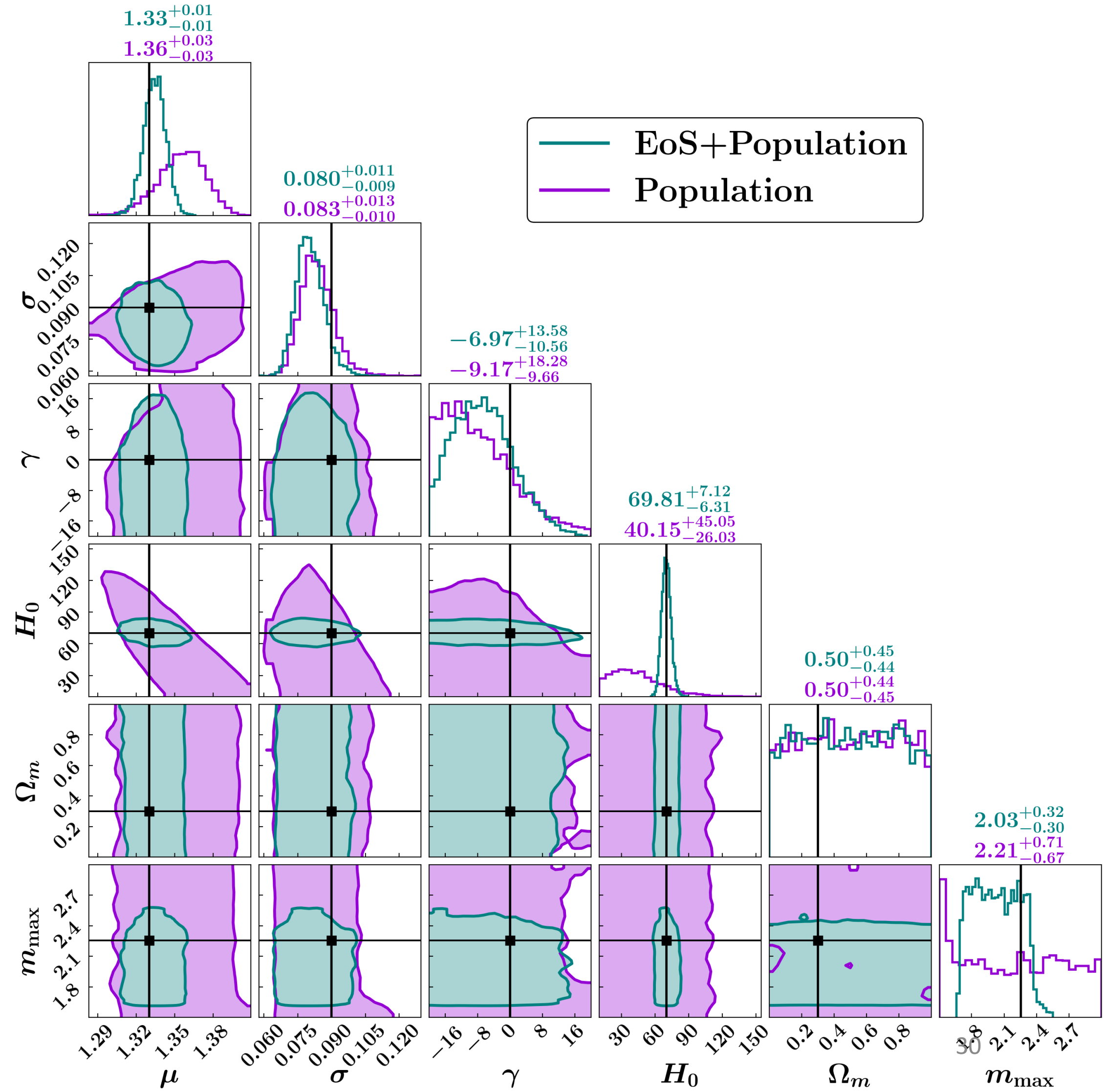
Error at ~15-20% for the first two priors (at 90% CI), but will drop to 3-5% when scaled to 1000 sources.

Ref.: Ghosh et al. (2022)

Results

(Gaussian mass distribution)

- ***50 Events***
- Redshift Distribution: Power Law
  - $\gamma = 0.$
- Mass Distribution: ***Gaussian***
  - $m_{\min} = 1\ M_{\odot}, m_{\max} = 2.25\ M_{\odot},$
  - $\mu = 1.33\ M_{\odot}, \sigma = 0.09\ M_{\odot}.$
- 90% credible interval.



Results

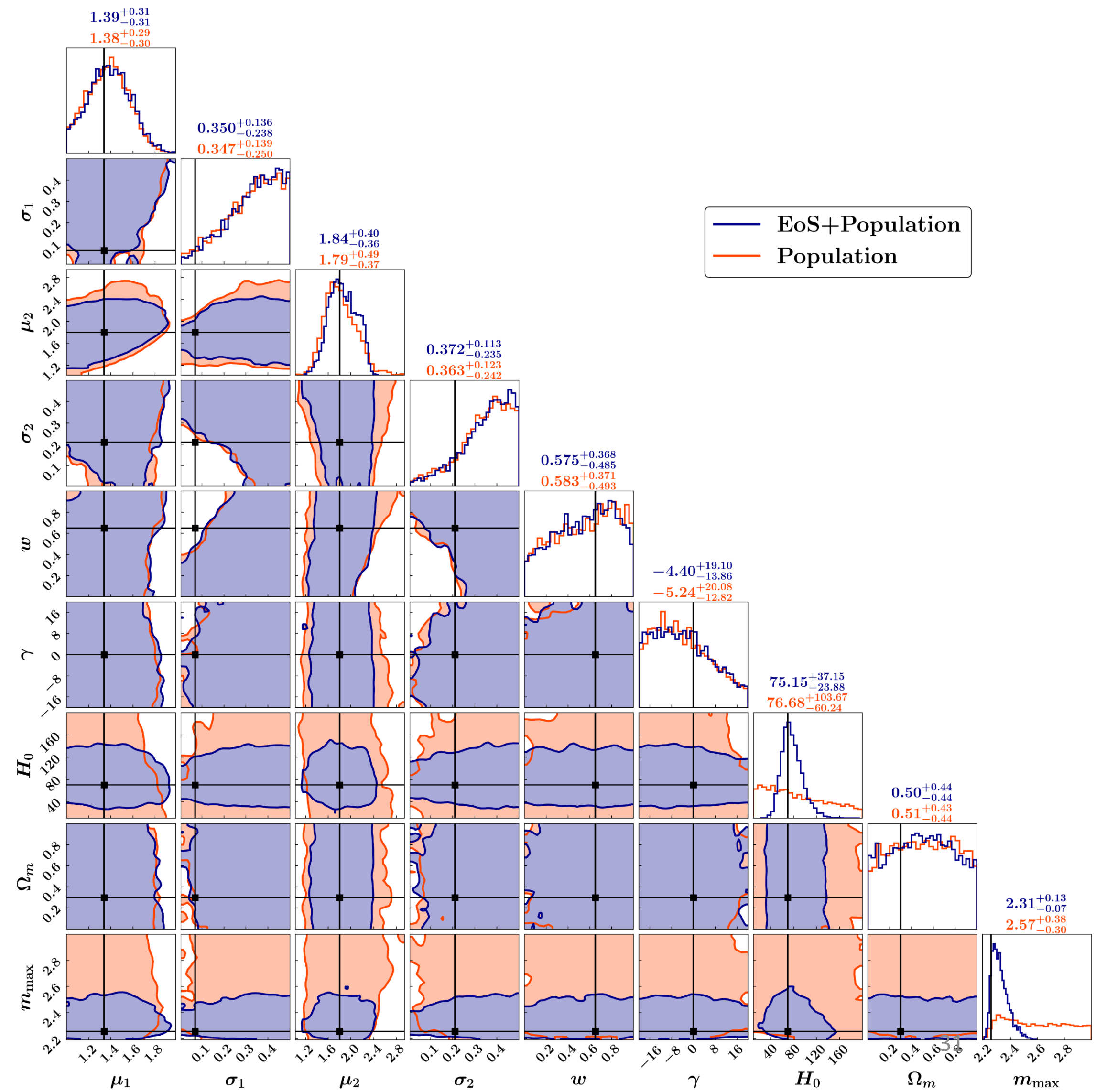
(double-Gaussian mass distrib.)

- ***5 Events***

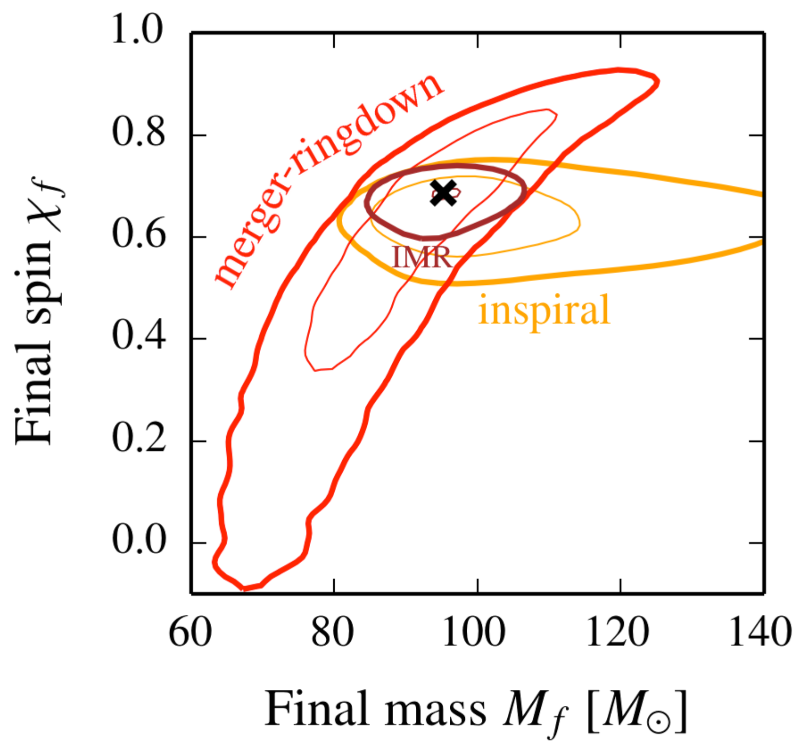
- Redshift Distribution: Power Law
  - $\gamma = 0.$

- Mass Distribution: ***Double Gaussian***
  - $= wG_1 + (1-w)G_2,$
  - $m_{\min} = 1\ M_{\odot}, m_{\max} = 2.25\ M_{\odot},$
  - G_1: $\mu_1 = 1.34\ M_{\odot}, \sigma_1 = 0.07\ M_{\odot},$
  - G_2: $\mu_2 = 1.8\ M_{\odot}, \sigma_1 = 0.21\ M_{\odot},$
  - $w = 0.65.$

- 90% credible interval.



Testing GR: Consistency of binary black hole *inspiral* & *"ringdown"* waveforms



Abhirup Ghosh et al., PRD 2016.

Compositional variation with NS mass

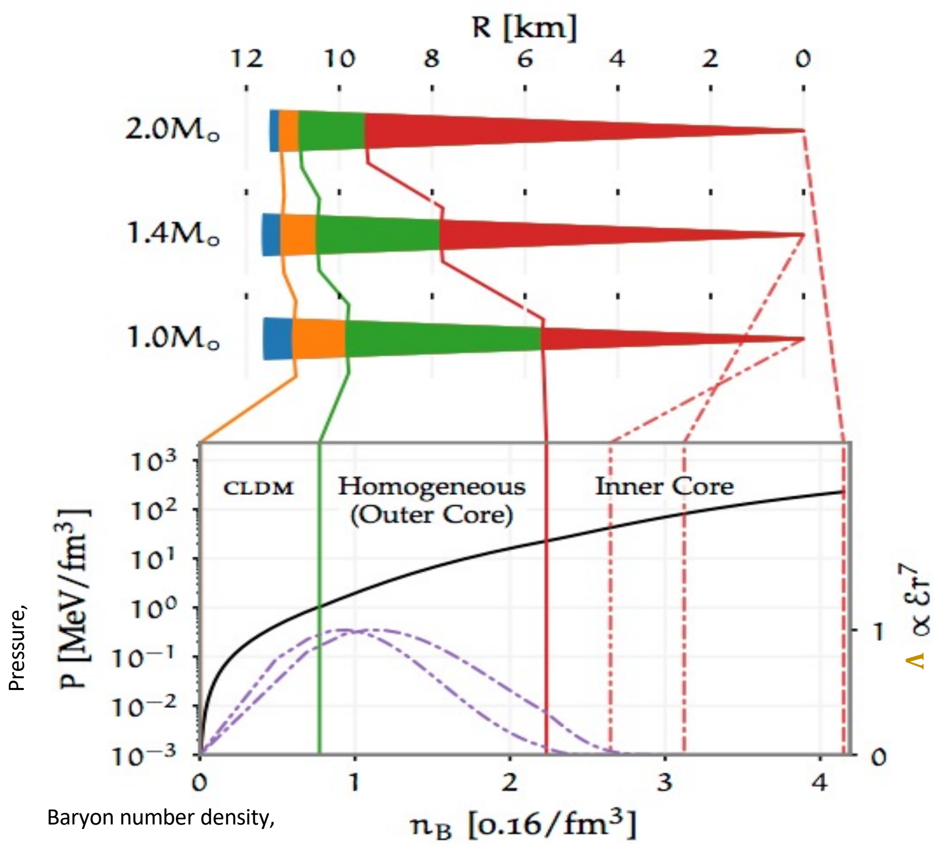
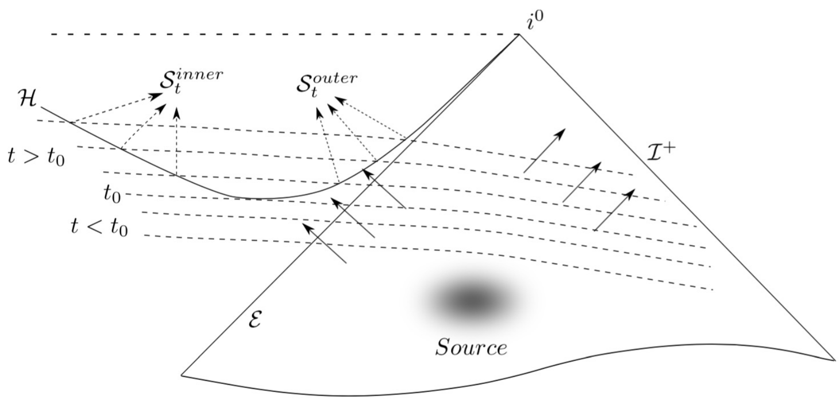


Fig. Compositions of NSs with 3 different masses for what we term as our Central EOS. Lighter stars allow probing the neutron matter EOS (outer core) better than heavier stars. Outer crust is taken as BPS.

[M. Forbes, SB, S. Reddy, D. Zhou, A. Mukherjee, S. De, PRD 2019; arxiv:1904.04233.]

How does GW know about tidal heating?



$$\frac{dE_{orb}}{dt} = -\frac{dE_{GW}}{dt} - \frac{dM_1}{dt} - \frac{dM_2}{dt}.$$

1. Orbital / rotational motion feeds GW emission (via time-varying quadrupole) and tidal heating (TH)

2. For tidal heating: Calculate energy flux through the horizon; a Weyl tensor projection at the horizon carries this information. Results in mass (and spin) change.

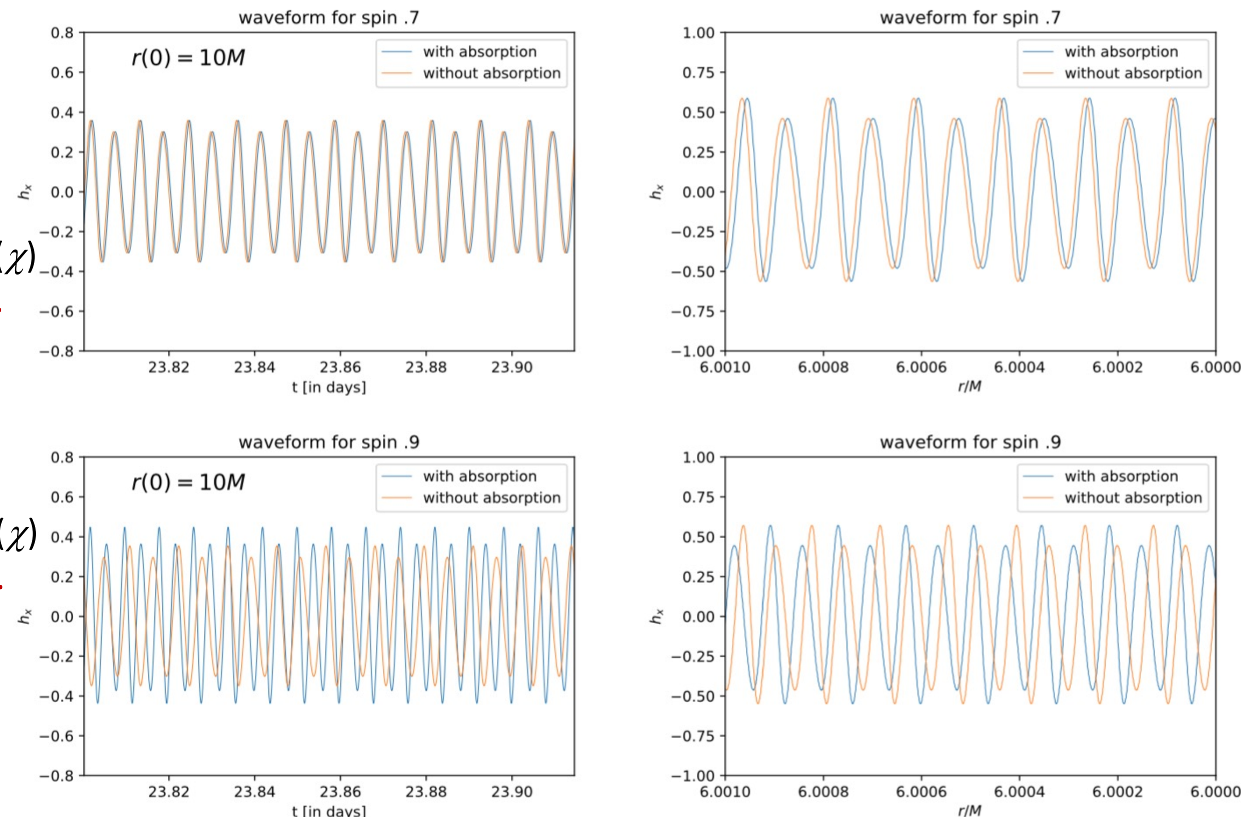
3. The energy equation relates the GW phasing to tidal heating.

Hartle, PRD 8, 1010 (1973),
Hughes, PRD 64, 064004 (2001).
Brito, Cardoso, Pani, arxiv:1501.06570.

GW dephasing for different central object spins

Spin (χ)
= **0.7**.

Spin (χ)
= **0.9**.

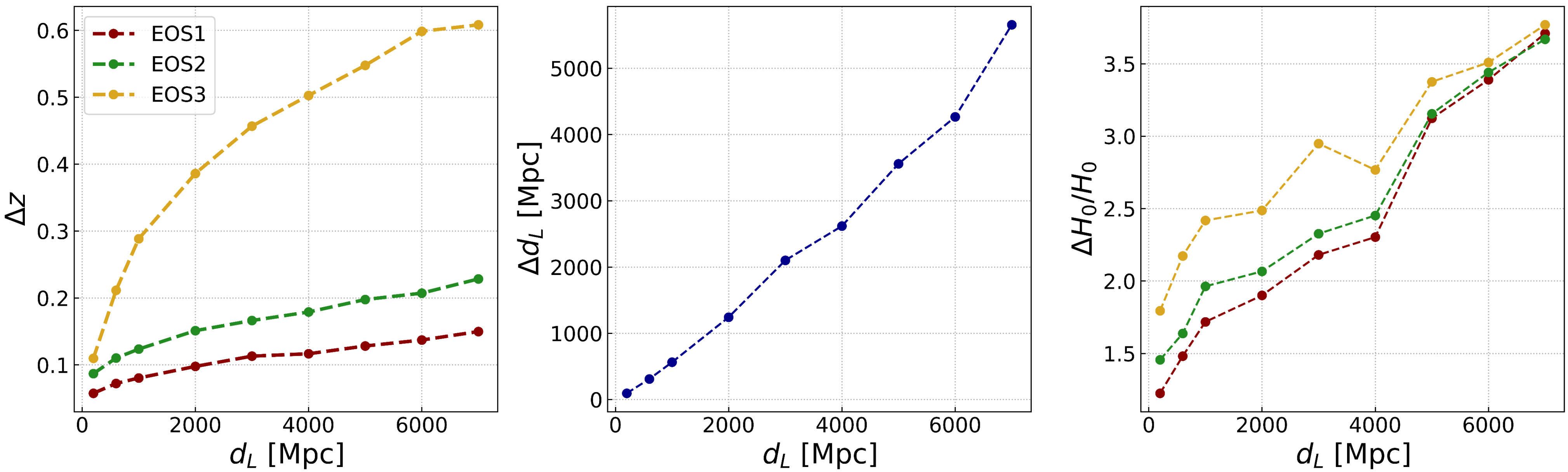


Time →

Distance →

Sayak Datta, R. Brito, *SB*,
P. Pani, S. Hughes, arxiv:1910.07841.

Results [Summary of Part I]



Ref.: Ghosh et al. (2022)

Correlation between physics @ horizon and that at infinity

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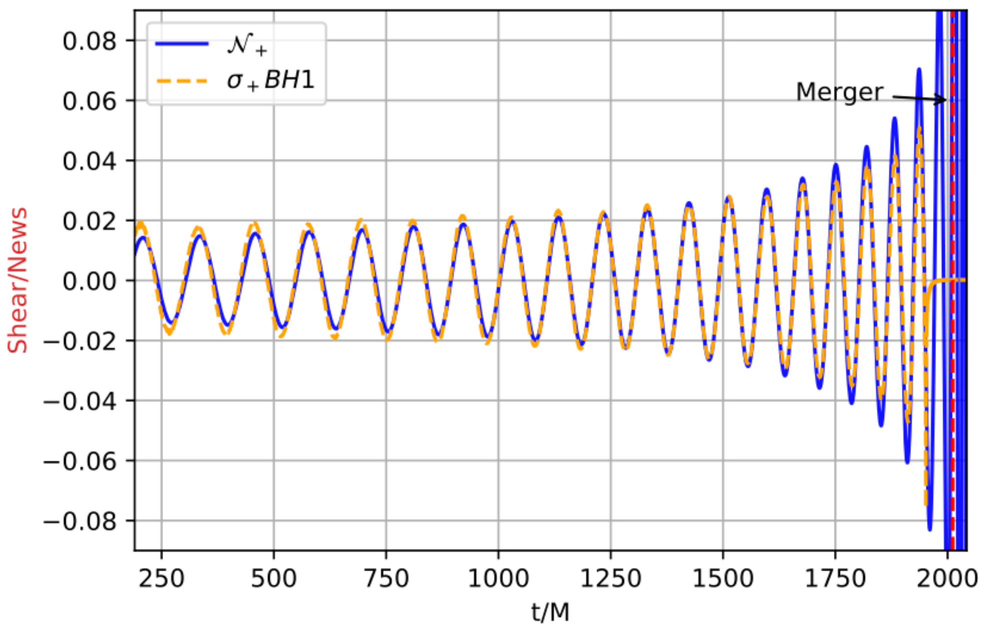

Prasad, Gupta, SB, Krishnan, Schnetter, PRL (2020).

Empirical relation of news and shear:

$$|\mathcal{N}| \approx 0.5(1+q)M_1\,|\sigma_1|$$

$$\frac{M_2\sigma_2}{M_1\sigma_1} \approx q^{-0.7}$$

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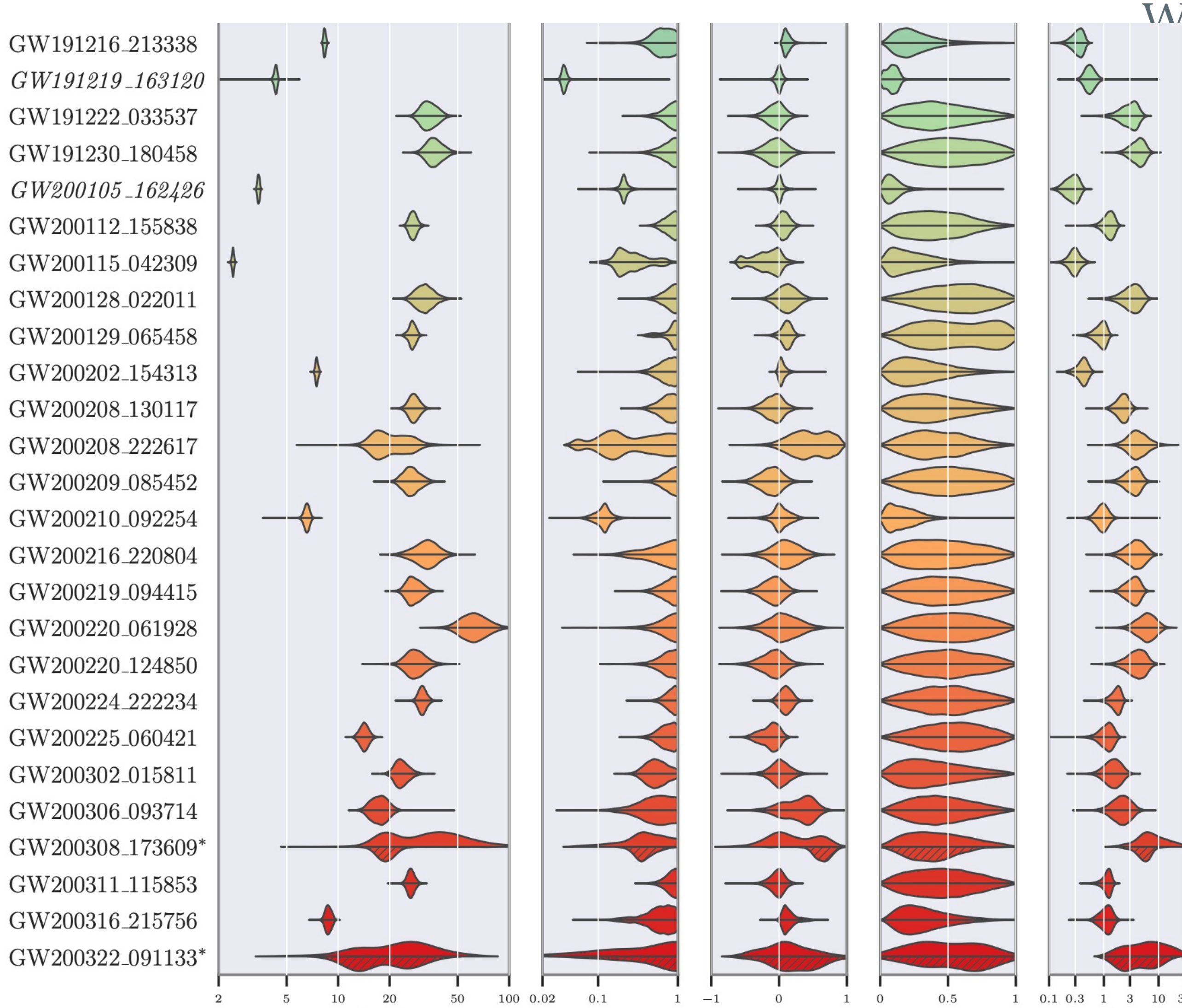
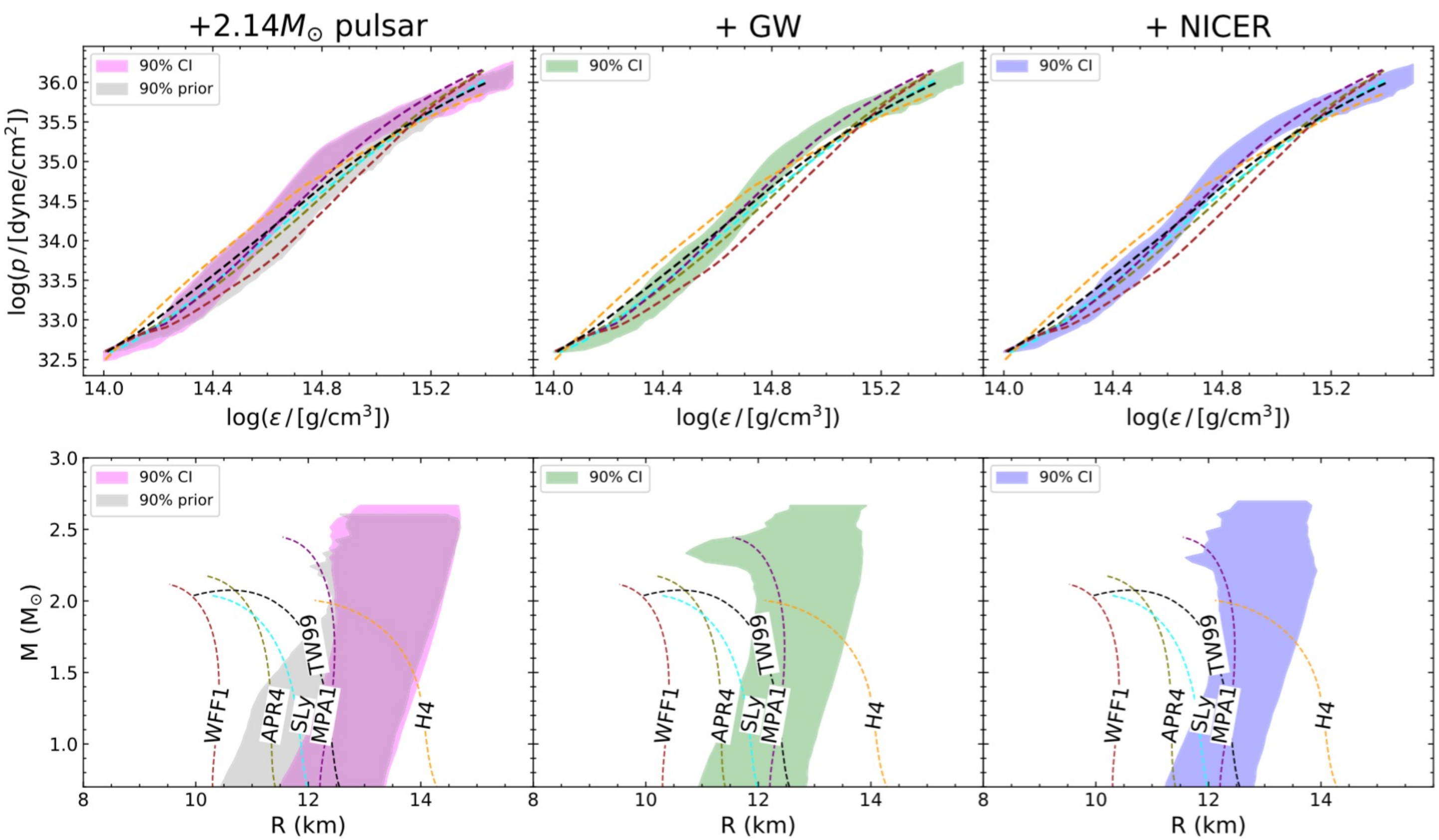
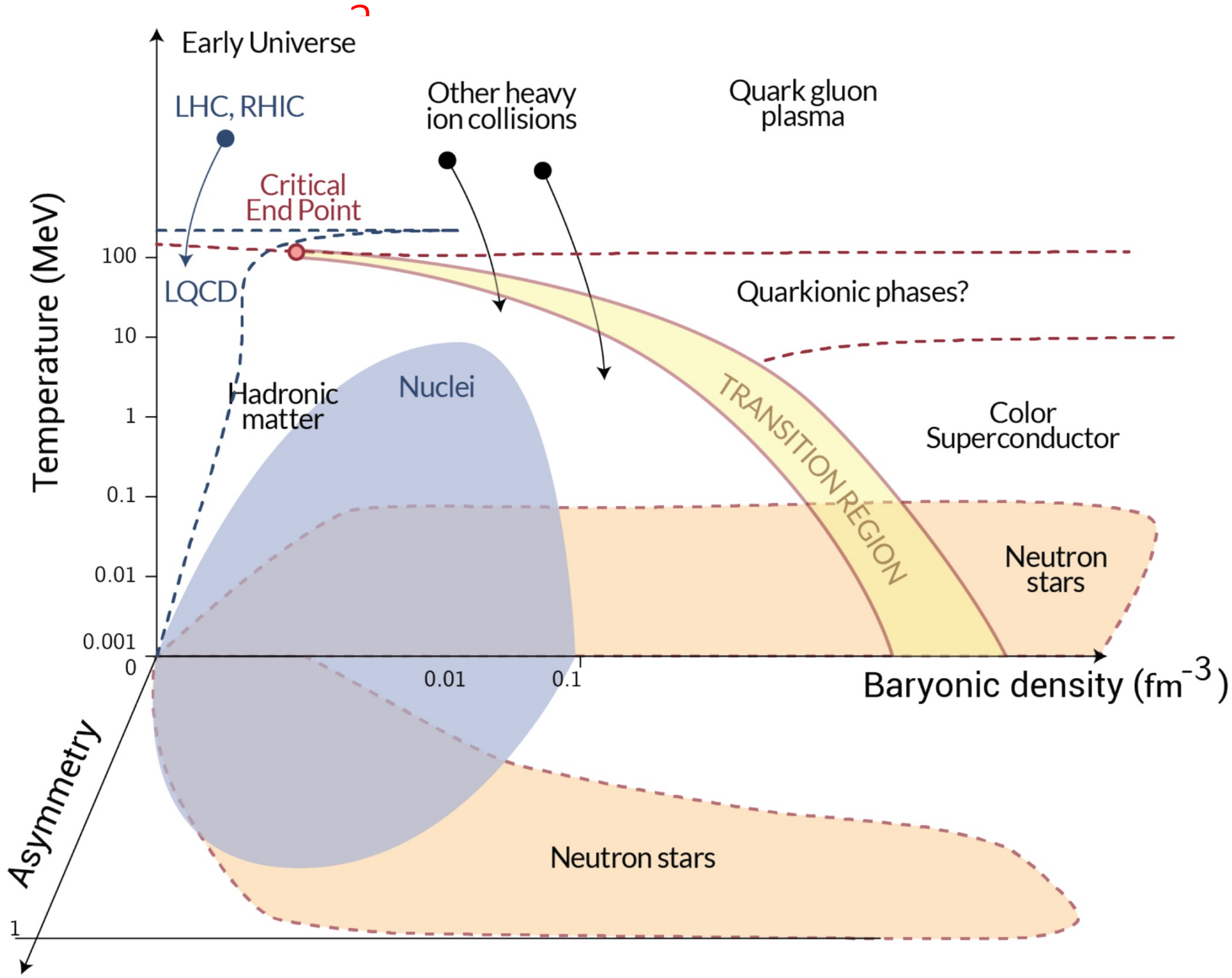


Nuclear-only EOS model: Posteriors from astro data



Supports stiffer EOS than PP.

Biswas, Char, Nandi, Bose, PRD, arXiv:2008.01582.



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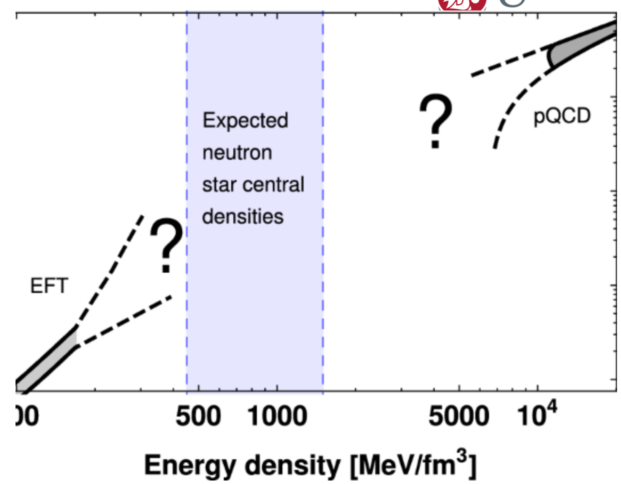
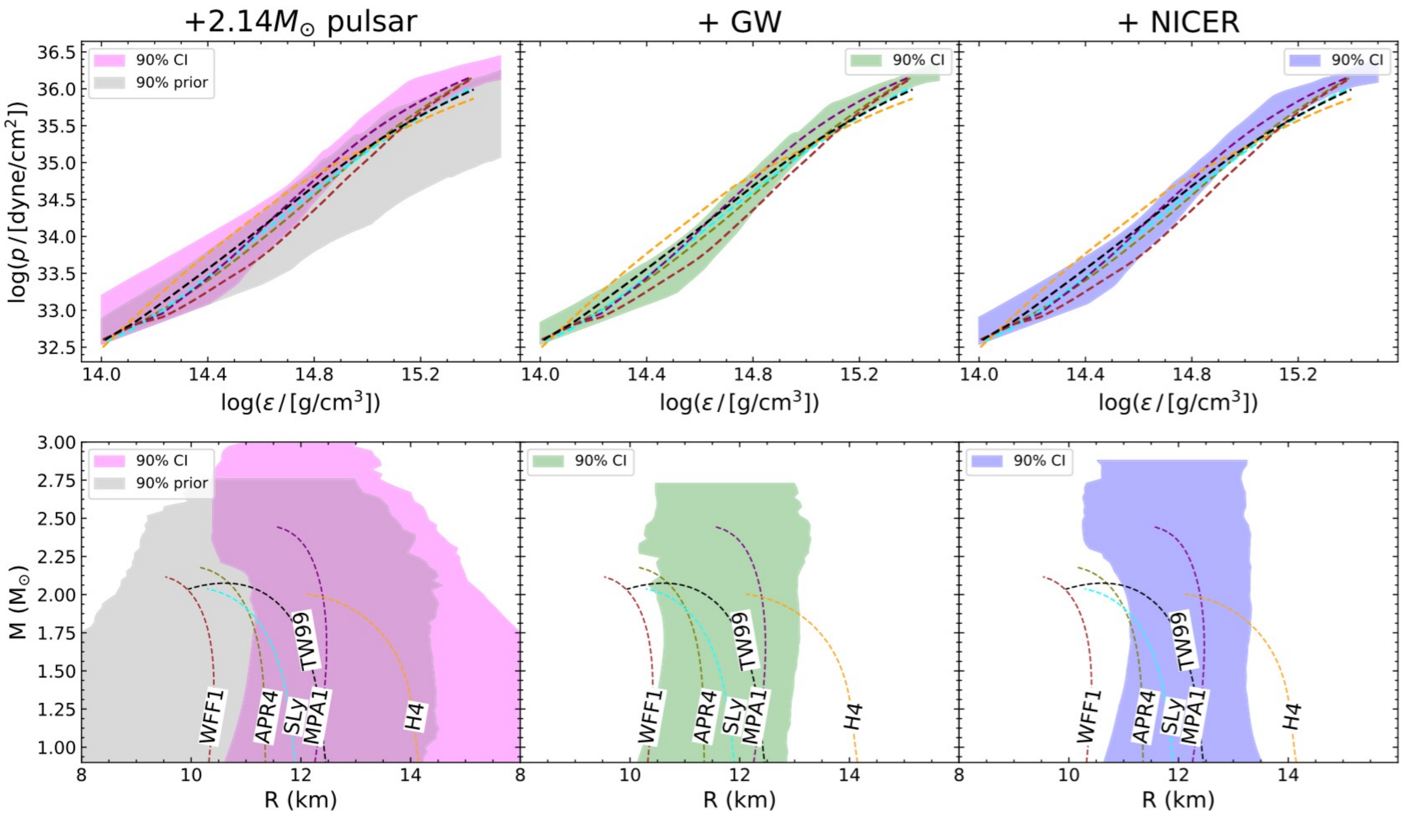


Piecewise-polytrope only (PP) EOS model: Posteriors from astro data

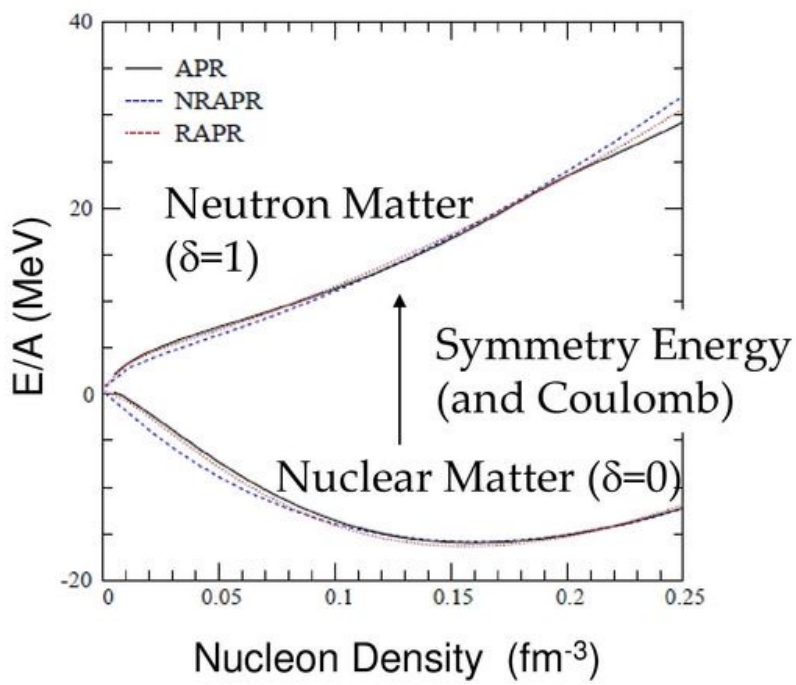
NICER: PSR J0030 + 0451
Riley+ ApJL (2019);
Miller+ ApJL (2019).



PP suggests softer stars compared to rel. EOSs.

Biswas, Char, Nandi, Bose, PRD, arXiv:2008.01582.

Modeling neutron matter



Steiner et al., Phys. Rep. 411 325(2005)

Isospin asymmetry:

$$\delta \equiv \frac{n_n - n_p}{n_n + n_p} .$$

Deviation from nuclear saturation density:

$$\chi = (\rho - \rho_0)/3\rho_0$$

Tracking the redshift evolution

- An example of a redshift distribution of binary black holes

$$m_z \equiv m(1+z)$$