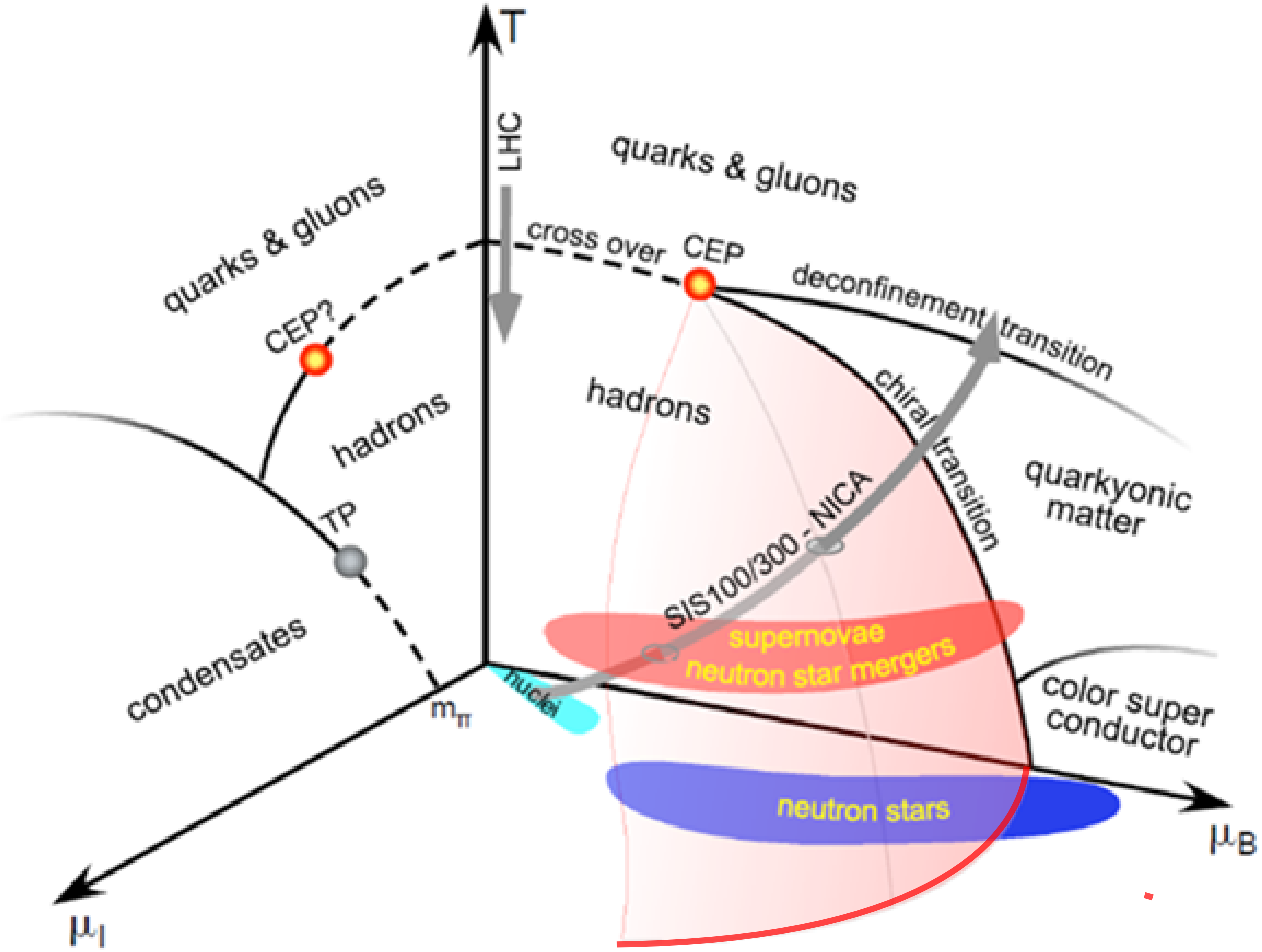
Detectability of a phase transition in neutron stars with third-generation interferometers

Based on:

C. Mondal, M. Antonelli,
F. Gulminelli, M. Mancini,
J. Novak, M. Oertel,
MNRAS 524 3 (2023)
[arxiv.org 2305.05999]



Marco Antonelli – antonelli@lpccaen.in2p3.fr
CNRS & Laboratoire de Physique Corpusculaire, Caen

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Meudon, October 17, 2023

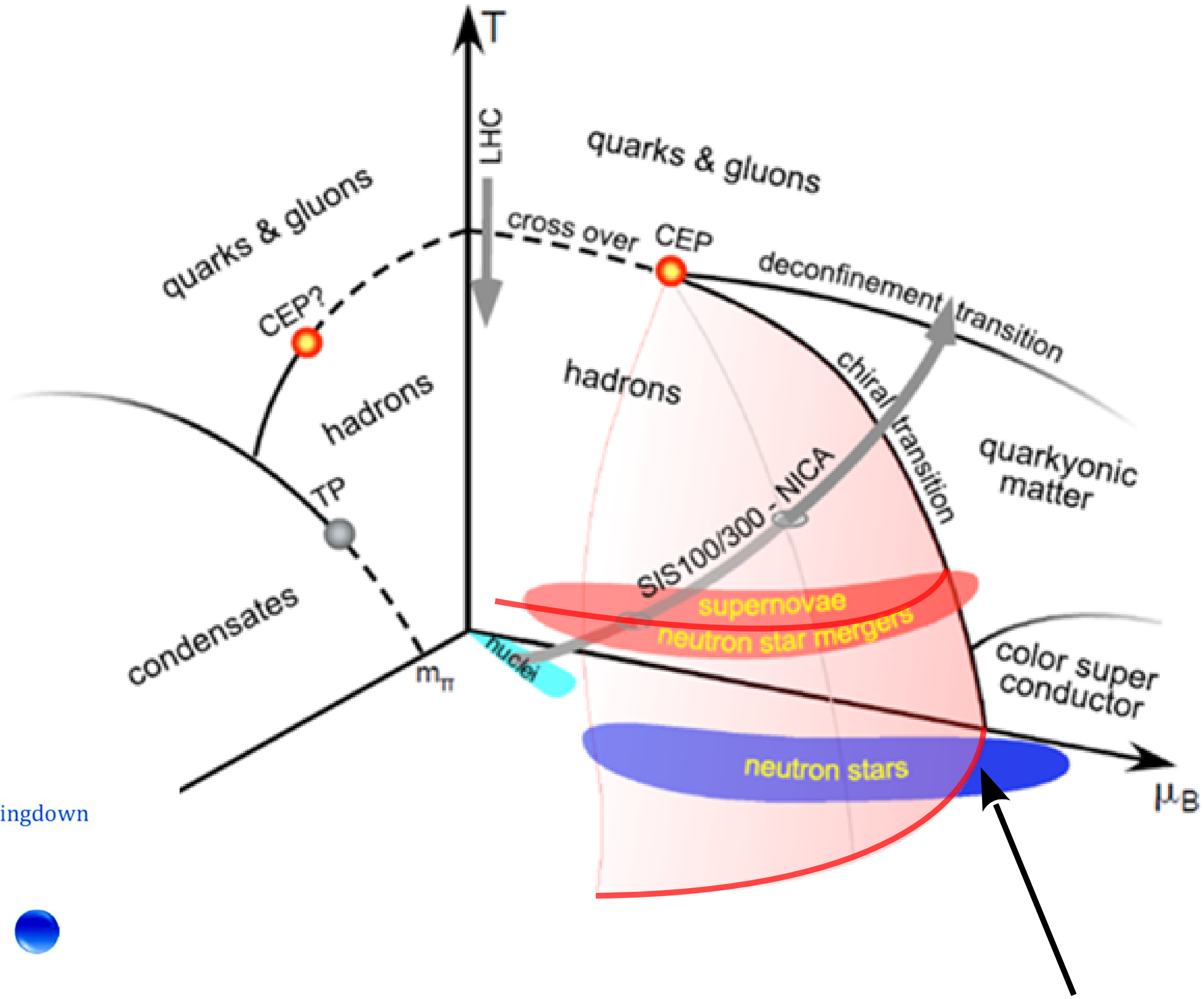
Motivation: signatures of phase transition in GW?

Detection of GW by LVC from NS mergers opens the possibility of probing the QCD phase diagram:

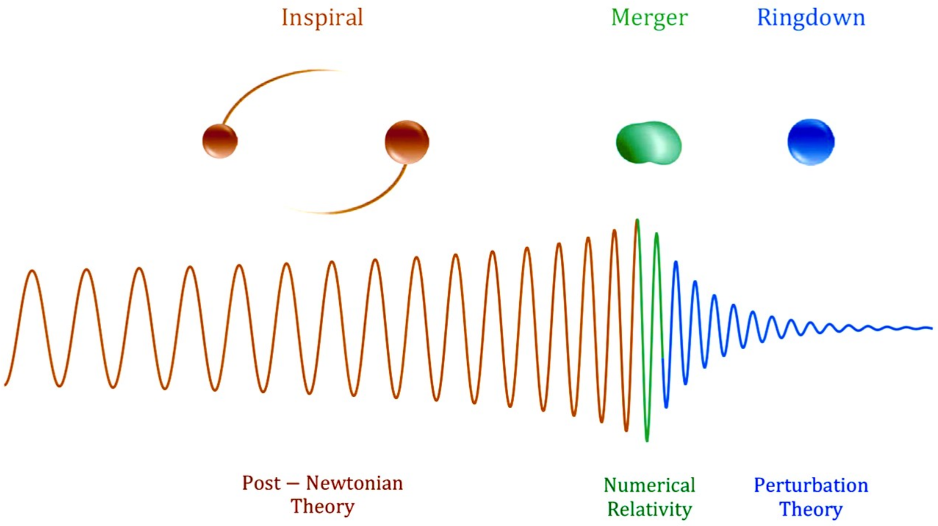
Late inspiral: static properties
→ “TOV” + “corrections”
→ the NSs are still cold

Merger: expensive NR simulations → big limitation

Post-merger: oscillation models of HMNS (hot, more difficult to detect)



Inspiral phase: cold neutron stars
→ T=0 & beta-equilibrium



Tidal deformability

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

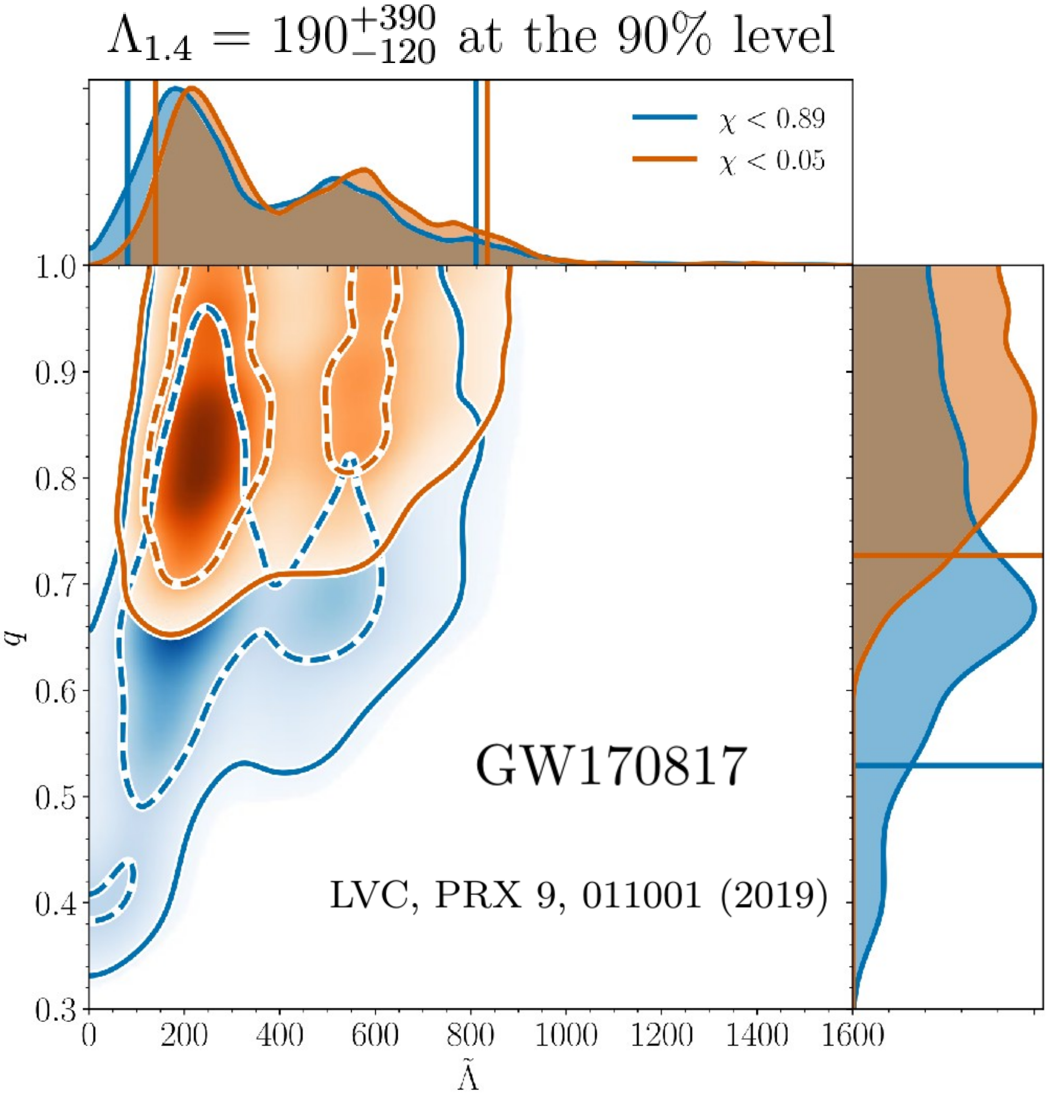
$$\Lambda = \frac{\lambda}{M^5}$$

Information from the inspiral:

- The joint tidal $\tilde{\Lambda}$ not Λ_1, Λ_2
- The chirp mass $\mathcal{M}_c$ not m_1, m_2

$$\mathcal{M} = \frac{(m_1 m_2)^{3/5}}{(m_1+m_2)^{1/5}} \qquad q = m_2/m_1$$

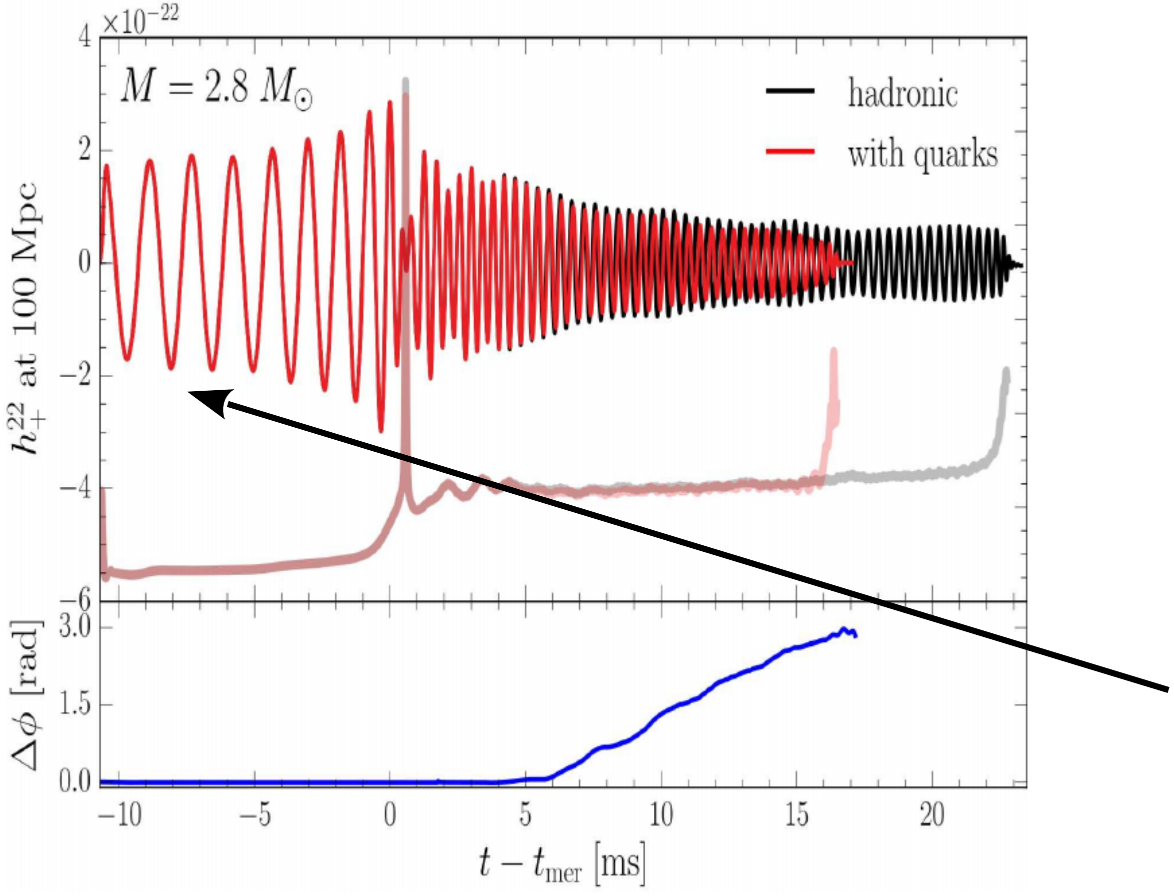
$$\tilde{\Lambda} = \frac{16}{13} \frac{(m_1 + 12 m_2) m_1^4 \Lambda_1 + (m_2 + 12 m_1) m_2^4 \Lambda_2}{(m_1+m_2)^{1/5}}$$



$\Lambda_{1.4} = 190^{+390}_{-120}$ at the 90% level

LVC, PRX 9, 011001 (2019)

Motivation: signatures of phase transition in GW?



Most *et. al.*, PRL 122, 061101 (2019)

- Deconfined quarks due to high temperatures and densities during the merger

- The ringdown of a hot quark core is shorter

Possible to see a signature of PT here?

It is worth to test a large EOS space
→ ***"metamodel"*** *needed*

Due to increased sensistivity of new GW interferometers more orbits will be available
→ ***reaslistic response of the detector*** *needed*

Nucleonic metamodel

(technical details: PRC 97, 025805, 2018)

- Flexible functional $e(n_n, n_p)$ able to reproduce existing effective nucleonic models and interpolate between them.

$$n = n_n + n_p \qquad \delta = (n_n - n_p)/n \qquad x = (n - n_{sat})/(3n_{sat})$$

$$e_{HM}^{N=2}(n,\delta) = E_{sat} + \frac{1}{2}K_{sat}x^2 + \delta^2(E_{sym} + L_{sym}x + \frac{1}{2}K_{sym}x^2)$$

Expansion at saturation…
…must be extended for NS!

- The energy per particle can be rewritten as,

$$\begin{aligned} e(n_n, n_p) &\simeq e_{\mathrm{SNM}}(n,0) + e_{\mathrm{sym}}(n)\delta^2 \\ e_{meta}(n_n, n_p) &= KE(n_n, n_p) + \sum_{\alpha \geq 0} \frac{1}{\alpha!}\left(v_\alpha^{is} + v_\alpha^{iv}\delta^2\right) x^\alpha \\ v_\alpha^{is(iv)} &\equiv f\left(E_{\mathrm{sat}}, K_{\mathrm{sat}} \cdots J_{\mathrm{sym}}, L_{\mathrm{sym}} \cdots\right) \end{aligned}$$

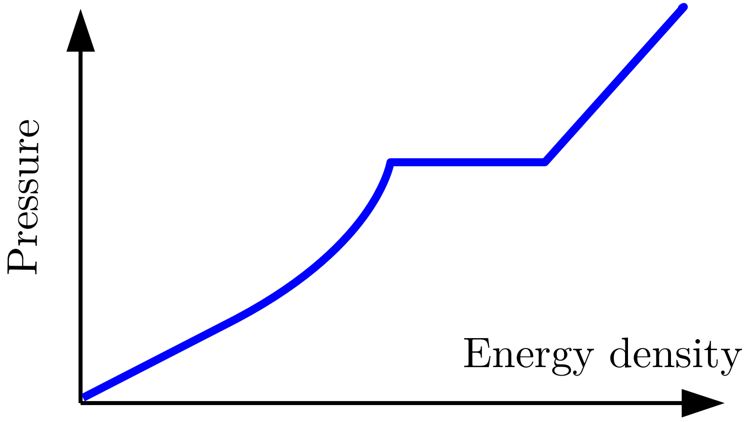
“Nuclear matter parameters” → some are
constrained by “laboratory nuclear physics” & “theory”

The idea in short: “metamodel” = the **most general EoS under the nucleonic hypothesis**.
The usual expansion at saturation is extended by including the **kinetic term** for
a **Fermi gas** (with effective masses) and a **higher-order polynomial**

Hybrid metamodel

(const. sound speed in the quark phase)

- Low density phase: nucleonic meta-modeling
- High density phase: constant sound speed
- Additional parameters: $n_{\mathrm{t}}, \Delta\varepsilon, \mathrm{c}_{\mathrm{s}}^2$



We consider three families of hybrid metamodels:

"PT03", "PT04", "PT05" based on the density at the onset of the nucleon-quark transition fixed to 0.3, 0.4, 0.5 fm^{-3}.

NON INFORMED PRIOR:

→ To build the prior for the **nucleonic** metamodel, 16 NMPs are varied randomly over a wide domain according to a flat distribution.

→ For all **hybrid** models "PT03", "PT04", "PT05", all the 18 parameters are "flat".

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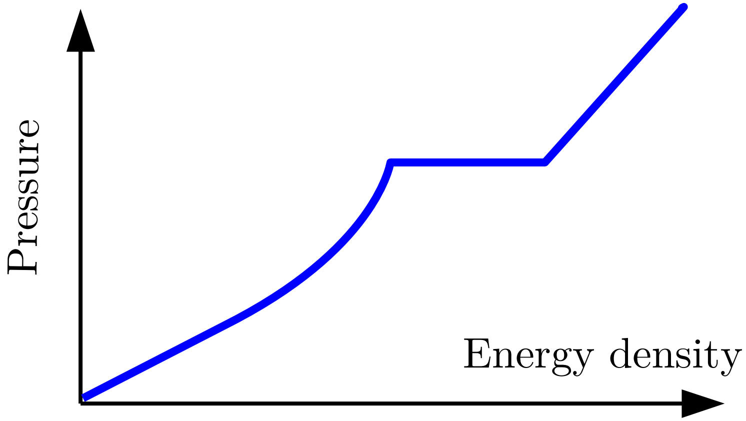

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Low-density filters:

→ meaningful reproduction of the whole AtomicMassEvaluation mass table (AME3016)
→ χ-EFT filter based on the constraints on SNM and PNM between 0.02-0.2 fm^{-3}

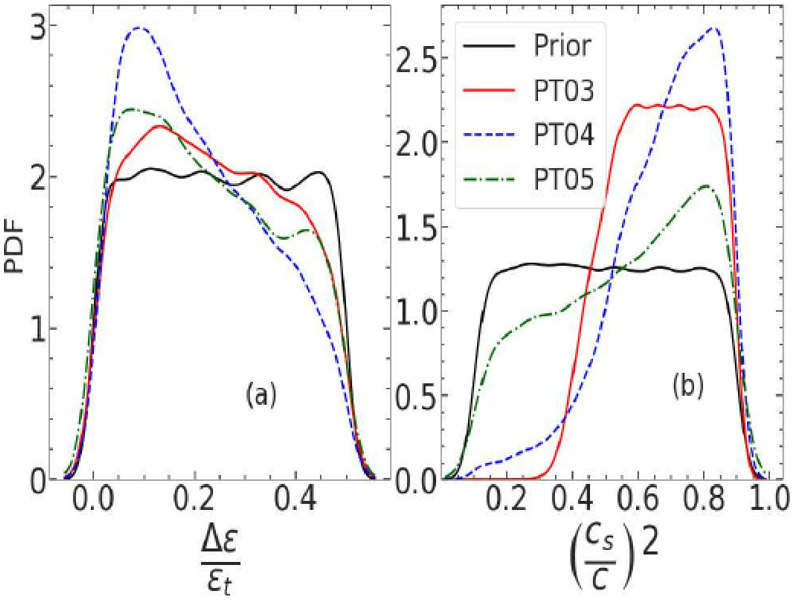
High-density filters:

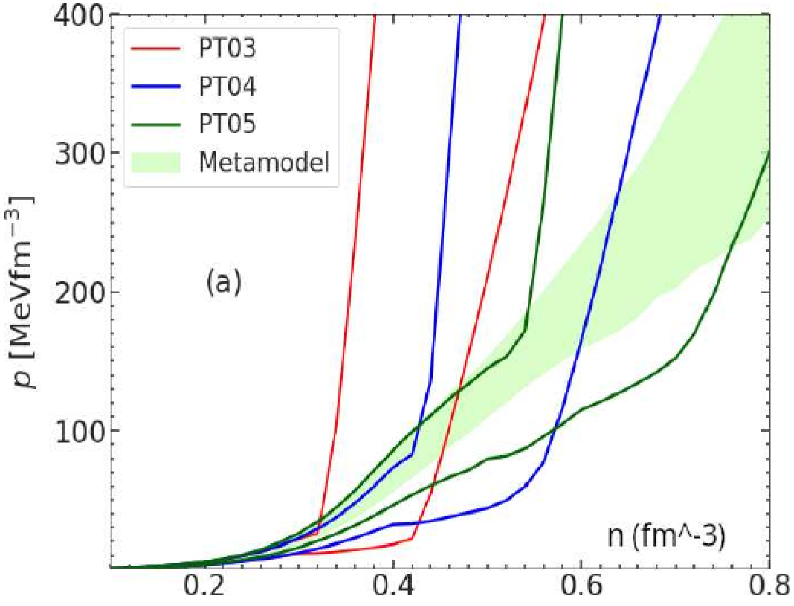
→ Maximum mass at least 2 M_Sun
→ the EOS must be able to reproduce a benchmark value for the $\tilde{\Lambda}$ of GW170817

Hybrid metamodel

- Low density phase: nucleonic meta-modeling
- High density phase: constant sound speed
- Additional parameters: $n_{\mathrm{t}}, \Delta\varepsilon, \mathrm{c}_{\mathrm{s}}^2$

Constraints in Bayesian studies:
χ-EFT, Finite nuclei, $\mathrm{M}_{\mathrm{max}}$, GW170817 *etc.*





Hybrid metamodel

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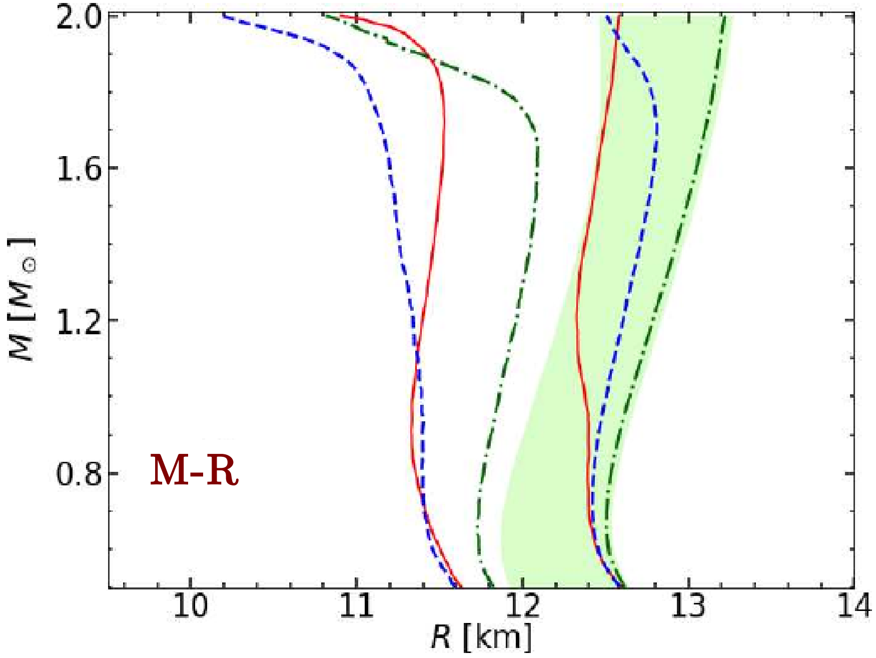
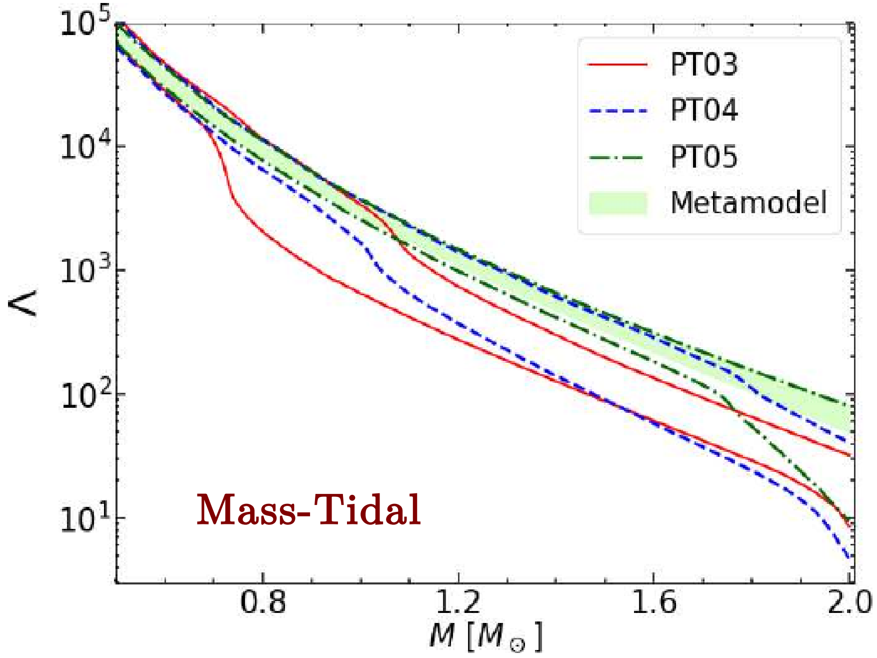




Detector’s response & procedure

To assess the uncertainty in the parameter estimation associated with future observations, we make use of the publicly available Python package “GWBENCH”, https://gitlab.com/sborhanian/gwbench

To simulate an event, GWBENCH needs:

- Chirp mass
- Reduced mass
- 2 spins
- Luminosity distance
- Inclination angle of orbital plane
- Tidal deformabilities of both stars

$$\left(\mathcal{M}_c, \eta, \vec{\chi}_1, \vec{\chi}_2, \mathcal{D}_L, \iota, \tilde{\Lambda}, \delta\tilde{\Lambda}\right)$$

$$\chi_1 = 0.01, \; \chi_2 = 0.005, \; \iota = 45^\circ$$

→ Detector network: triangle configuration for Einstein Telescope, two detectors Cosmic Explorer

→ For a selection of GW detectors (“network”) and given a waweform model, GWBENCH can compute: “+” and “x” polarizations of the WF, detector PSD, detector responses, detector and network signal to noise ratios…

Bayesian framework to quantify the compatibility of a **simulated observation** with a purely nucleonic and/or a hybrid (nucleons+quarks) neutron star.

→ We supply m1 & m2 and their tidal deformabilities for a given EOS (“**injection**”) → $\tilde{\Lambda}_0(\mathcal{M}_c^0, q_0)$

$$\text{BNS coalescing event specified by } \{\mathcal{M}_c^0, q_0, \tilde{\Lambda}_0\}$$

→ GWBench returns the posterior “**observational**” distribution

$p^0_{GW}(\mathcal{M}_c, q, \tilde{\Lambda})$ and the marginalized $p^0_{GW}(\tilde{\Lambda})$ $p^0_{GW}(q)$

$$p^{(1)}_{meta}(\tilde{\Lambda}) \equiv p\left(\tilde{\Lambda} \,|\, meta, BI = \mathcal{M}_c^0, p^0_{GW}(q)\right) \qquad p^{(1)}_{PT}(\tilde{\Lambda}) \equiv p\left(\tilde{\Lambda} \,|\, PT, BI = \mathcal{M}_c^0, p^0_{GW}(q)\right)$$

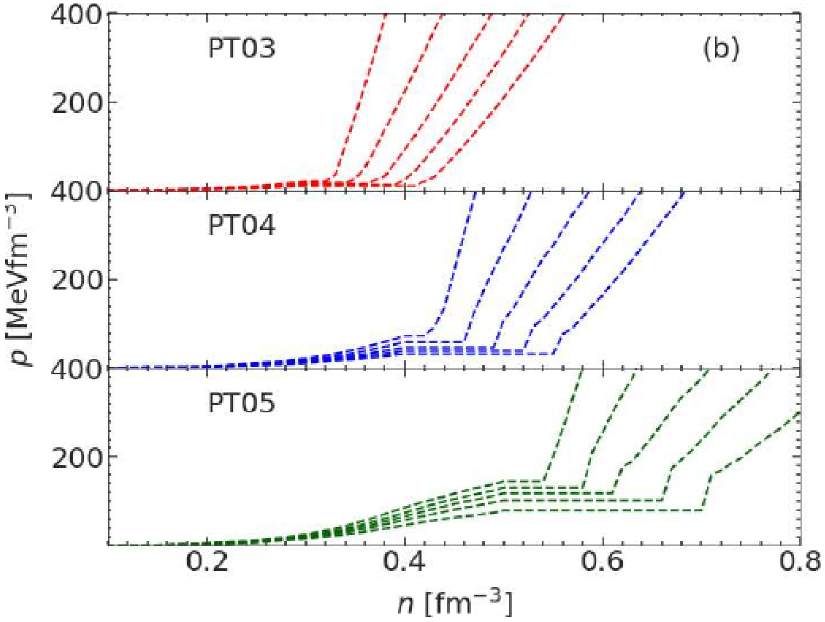
Simulated observations with GWBench

$$p^{(1)}_{meta}(\tilde{\Lambda}) \equiv p\left(\tilde{\Lambda} \,|\, meta, BI = \mathcal{M}^0_c, p^0_{GW}(q)\right)$$
$$p^{(1)}_{PT}(\tilde{\Lambda}) \equiv p\left(\tilde{\Lambda} \,|\, PT, BI = \mathcal{M}^0_c, p^0_{GW}(q)\right)$$

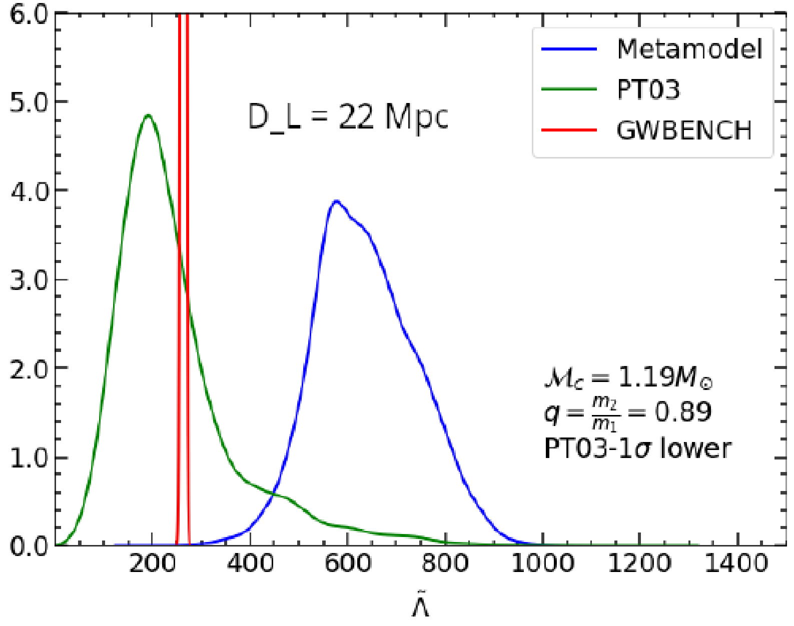
“**observational**” distribution

$$p^0_{GW}(\tilde{\Lambda})$$

Injection models with PT



$\tilde{\Lambda}$ distribution



Example with PT03

“Near” event (22 Mpc)

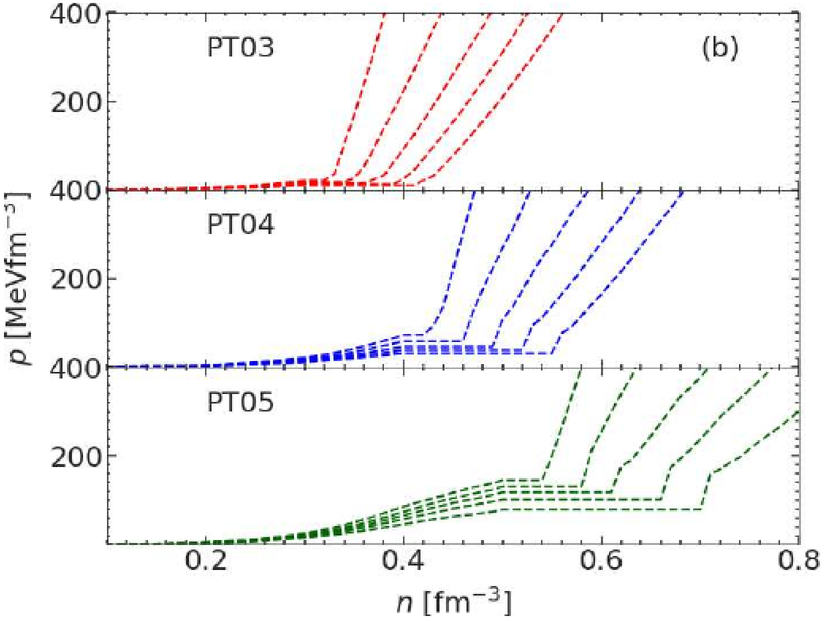
Simulated observations with GWBench

$$p^{(1)}_{meta}(\tilde{\Lambda}) \equiv p\left(\tilde{\Lambda} \,|\, meta, BI = \mathcal{M}^0_c, p^0_{GW}(q)\right)$$
$$p^{(1)}_{PT}(\tilde{\Lambda}) \equiv p\left(\tilde{\Lambda} \,|\, PT, BI = \mathcal{M}^0_c, p^0_{GW}(q)\right)$$

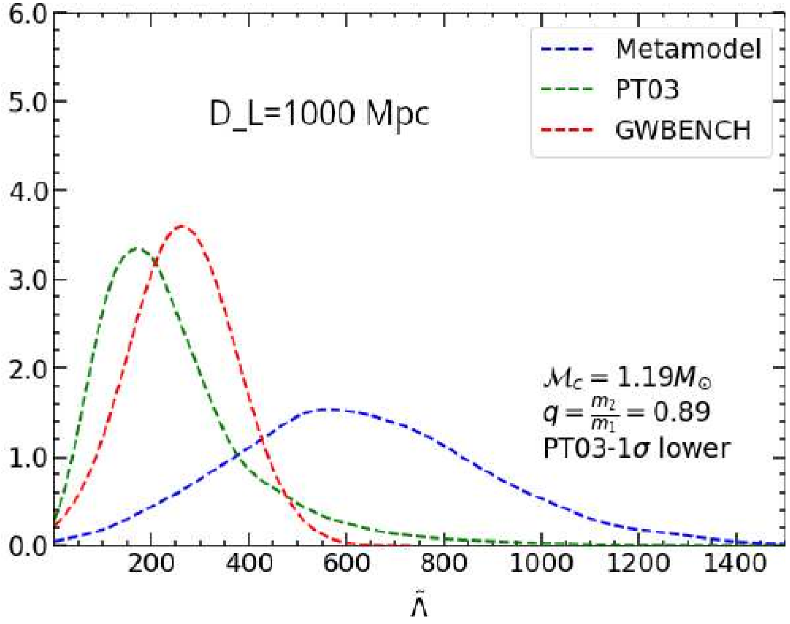
"**observational**" distribution

$$p^0_{GW}(\tilde{\Lambda})$$

Injection models with PT



$\tilde{\Lambda}$ distribution



Example with PT03

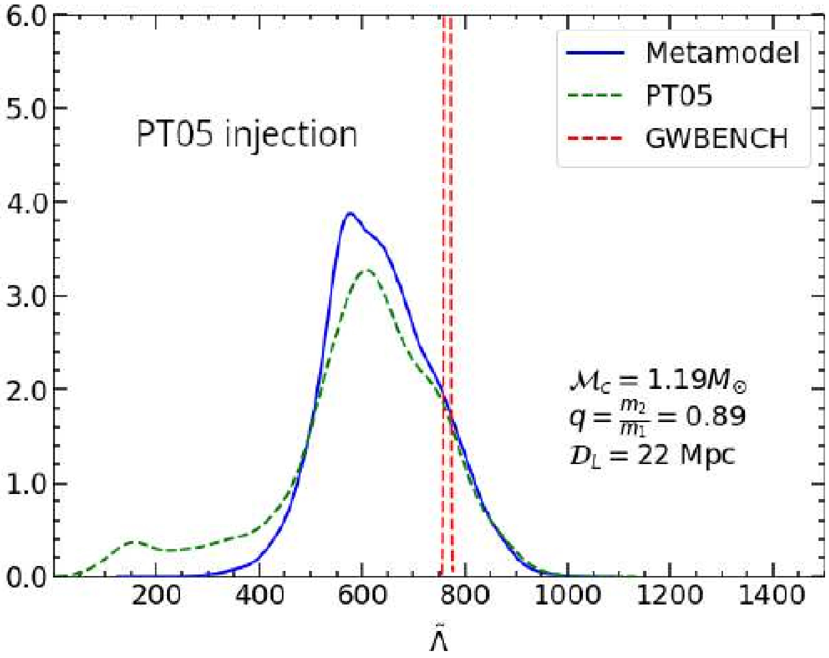
"Distant" event (1000 Mpc)

Simulated observations with GWBench

$$p^{(1)}_{meta}(\tilde{\Lambda}) \equiv p\left(\tilde{\Lambda}\,|\,meta, BI = \mathcal{M}^0_c, p^0_{GW}(q)\right)$$
$$p^{(1)}_{PT}(\tilde{\Lambda}) \equiv p\left(\tilde{\Lambda}\,|\,PT, BI = \mathcal{M}^0_c, p^0_{GW}(q)\right)$$

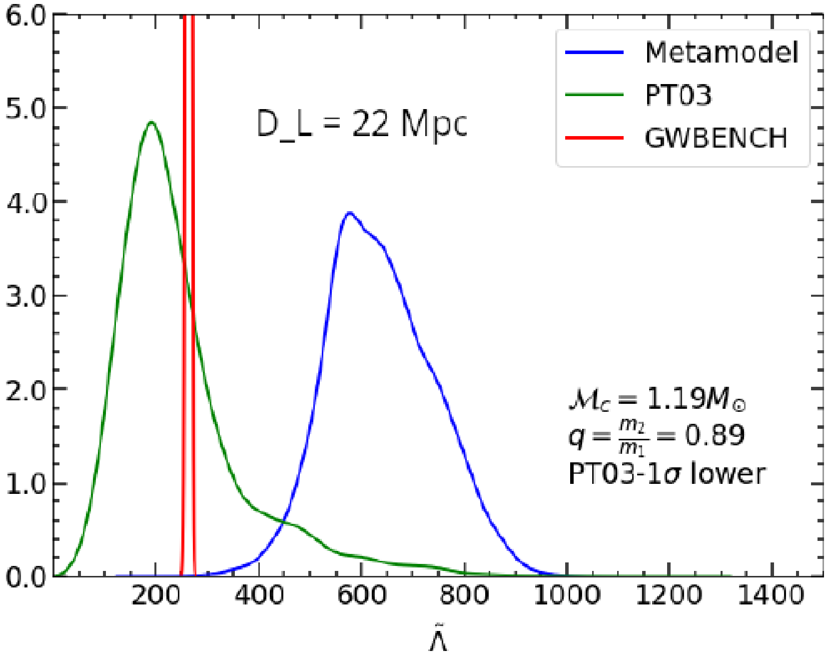
"**observational**" distribution

$$p^0_{GW}(\tilde{\Lambda})$$



"Near" event & PT05 "injection"

Late phase transition



"Near" event & PT03 "injection"

Early phase transition

Simulated observations with GWBench

Different choices for $\mathrm{q}, \mathcal{M}_{\mathrm{c}}, \mathcal{D}_{\mathrm{L}}$ and PT injection models.

To distinguish the nucleonic metamodel and the hybrid metamodels, we use the Bayes factors.

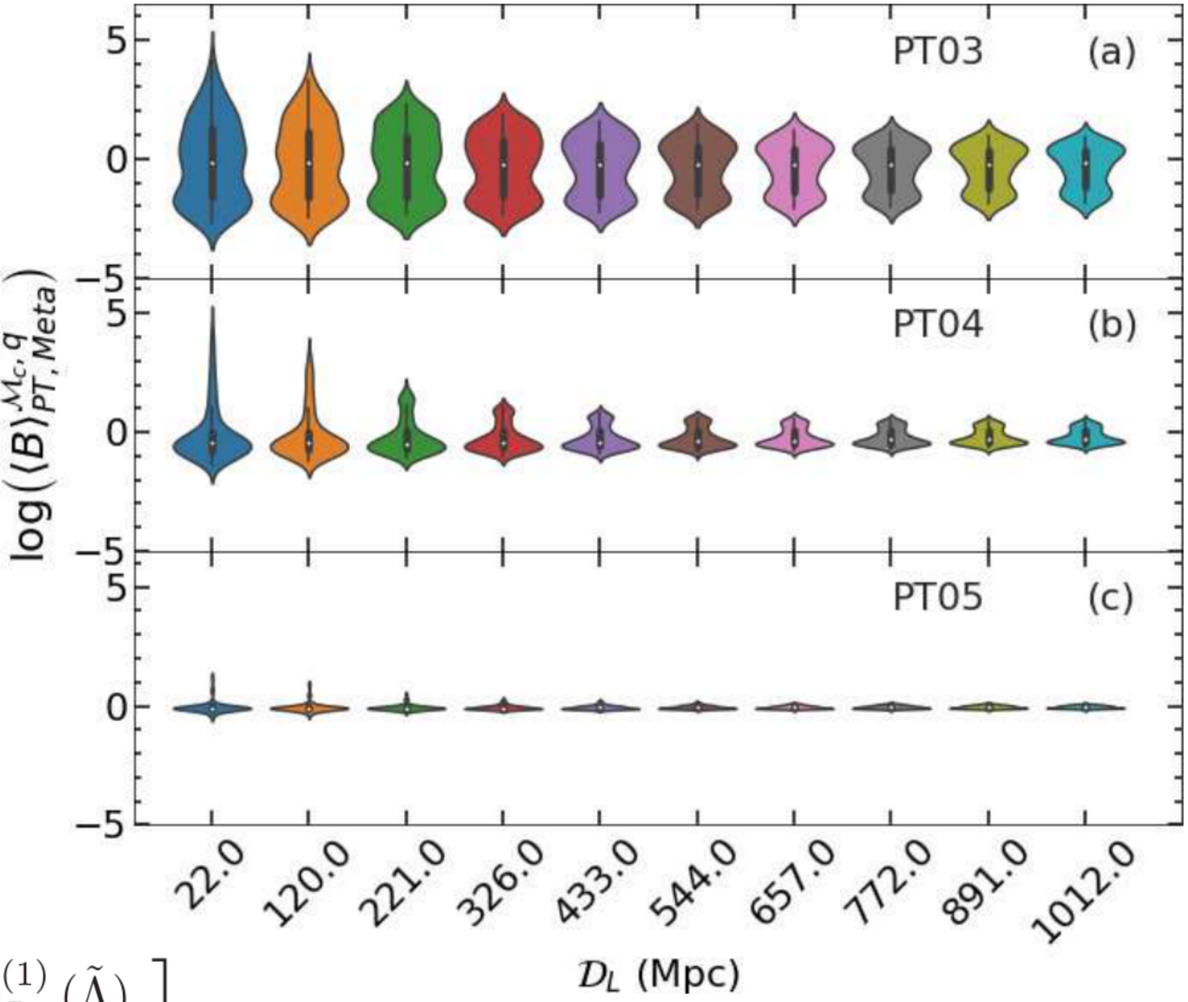
Given a precise measurement of the tidal deformability, the Bayes factor can be defined as

$$B_{PT,meta}(\tilde{\Lambda}) = \frac{p^{(1)}_{PT}(\tilde{\Lambda})}{p^{(1)}_{meta}(\tilde{\Lambda})}$$

However, the tidal has an uncertainty (in the form of distribution), so we consider an opportune average of the Bayes factors.

It seems possible to infer the presence of a PT at low densities (PT03) with B~100

$$\log\left(\langle B\rangle^{\mathcal{M}^0_c,q_0}_{PT,meta}\right) = \int d\tilde{\Lambda}\; p^0_{GW}(\tilde{\Lambda}) \log\left[\frac{p^{(1)}_{PT}(\tilde{\Lambda})}{p^{(1)}_{meta}(\tilde{\Lambda})}\right]$$



Distributions of Bayes factors due to different injected masses (chirp mass, q)

Summary

- A possible mechanism to detect the signature of 1st order phase transition was proposed.

- The nucleonic metamodelling is used as a “null hypothesis” in a Bayesian framework.

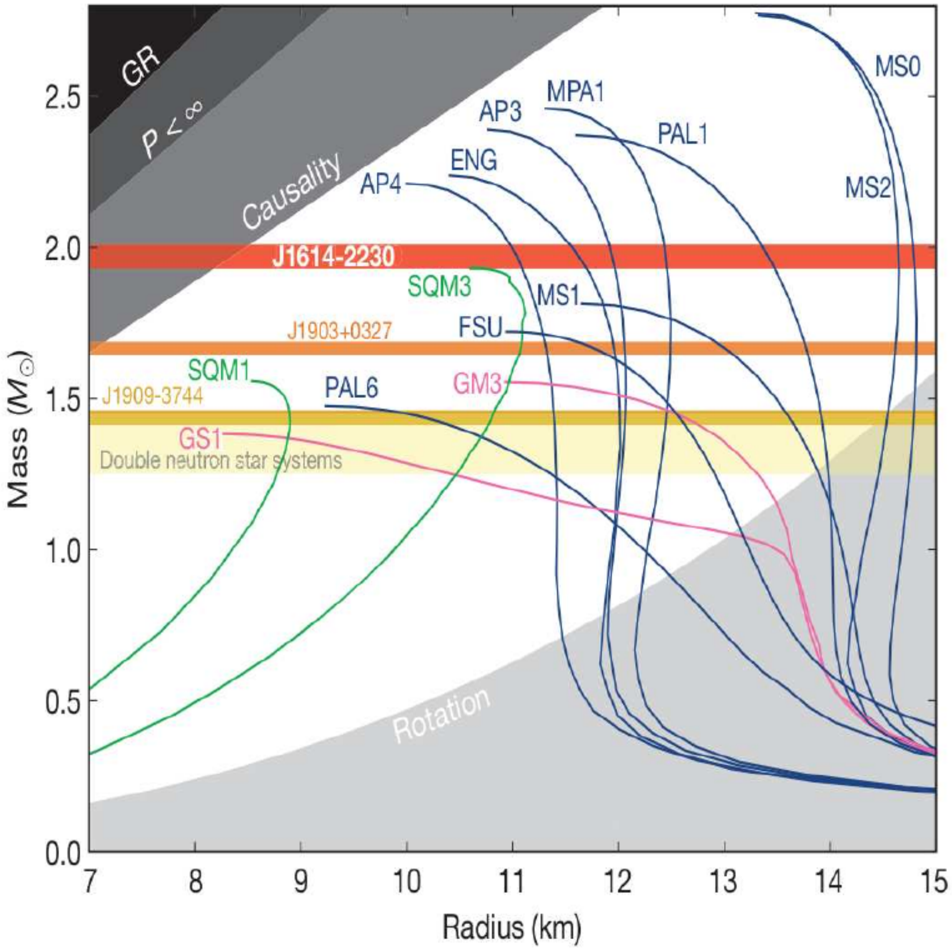
- Detection of a PT depends on many things (astro parameters, detector’s response, PT itself).
  In principle, it is possible to detect a low density PT with 3rd gen. interferometers (1 loud event):

We considered a **single detection**, and compared different chosen cases corresponding to different masses of Nss, located at different distances, and using injection models which include first-order phase transition.

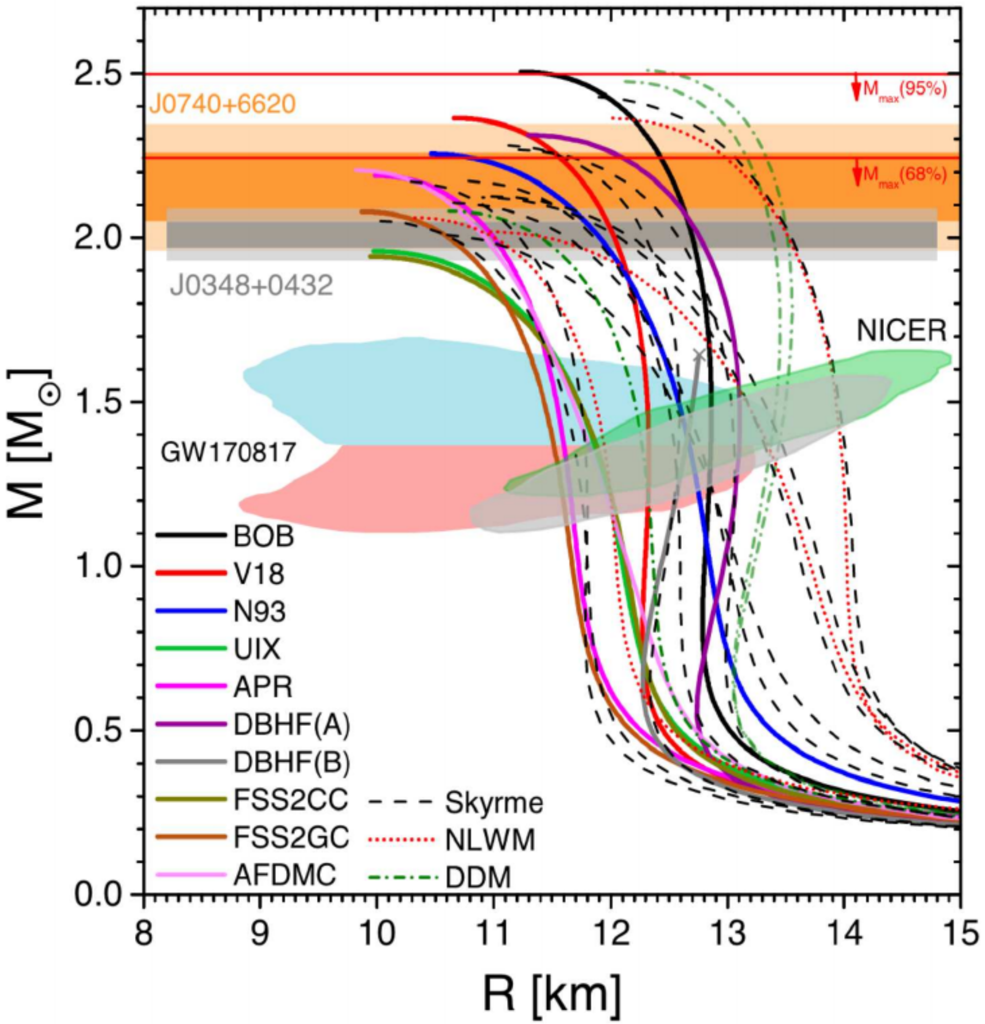
→ Mass ratio does not play a significant role in the Bayes factors.
→ Higher chirp mass, smaller luminosity distances, early phase transition with strong first-order effect: facilitate possible identification of phase transition
→ If phase transition at higher densities (~3 sat. den. “PT05”): most likely to be masked

Realistic **population** models to be incorporated → Analysis based on many events on the way

Astro constraints



Demorest *et. al.* (2010)



Burgio *et. al* (2021)