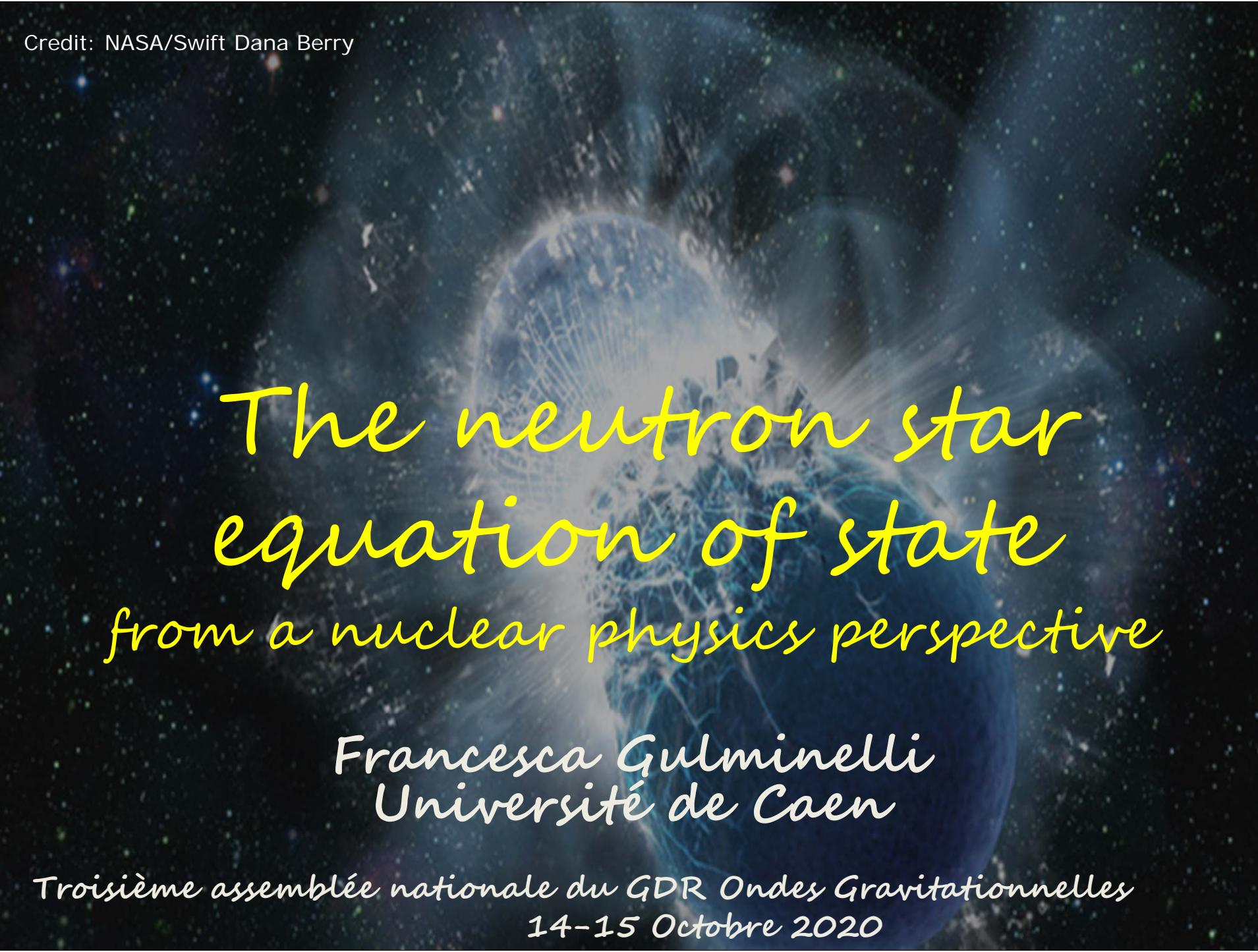


Credit: NASA/Swift Dana Berry

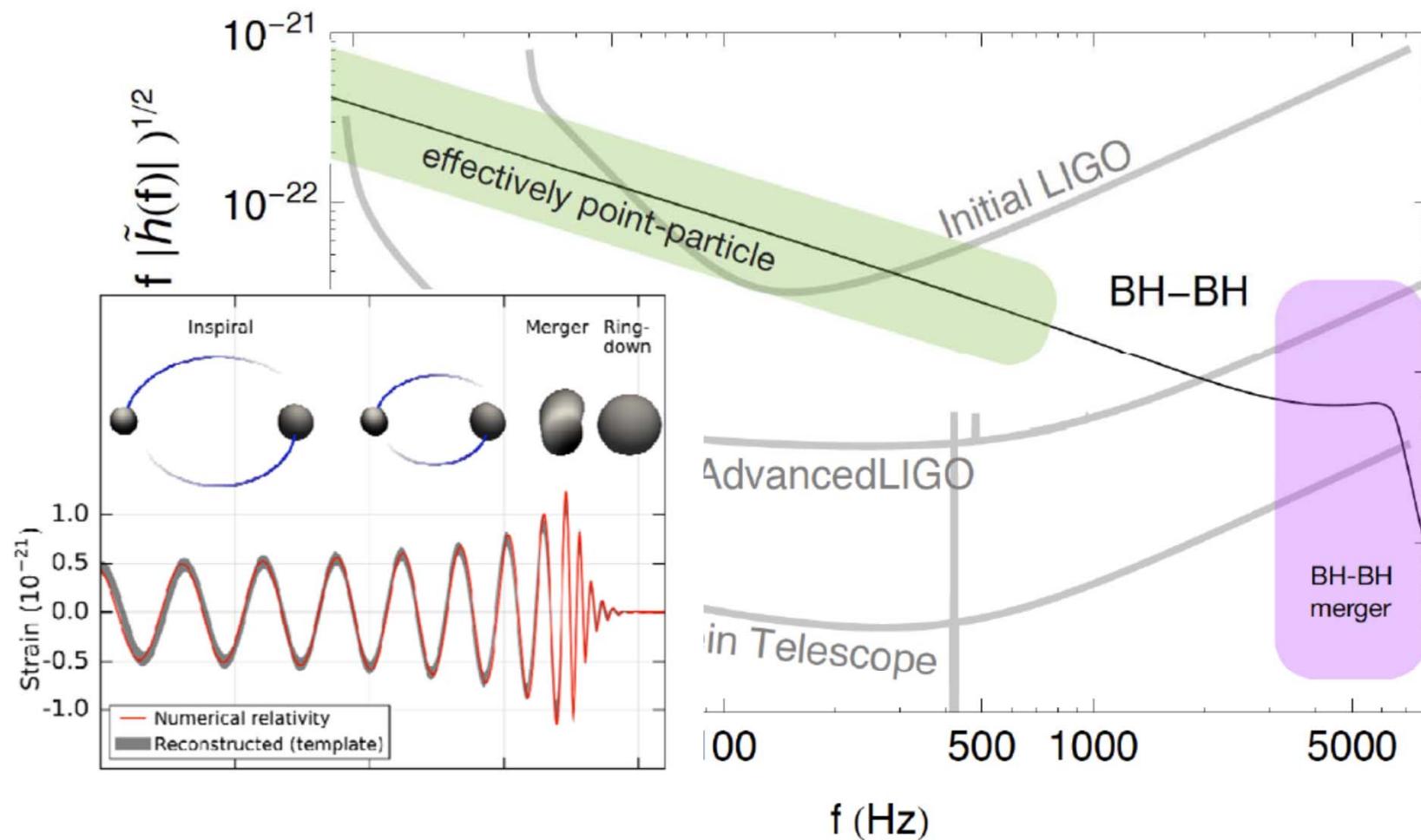


The neutron star equation of state from a nuclear physics perspective

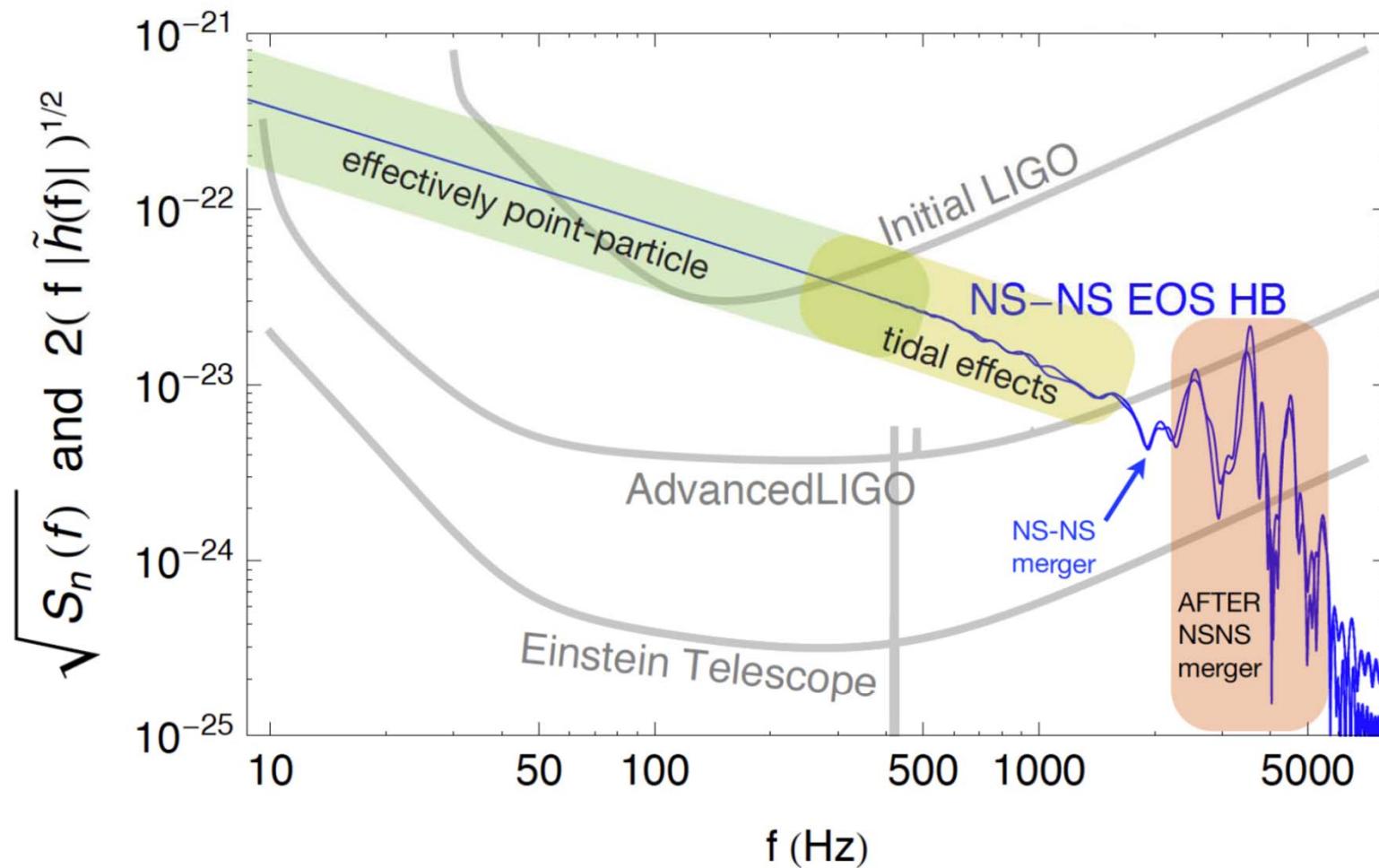
Francesca Gulminelli
Université de Caen

Troisième assemblée nationale du GDR Ondes Gravitationnelles
14-15 Octobre 2020

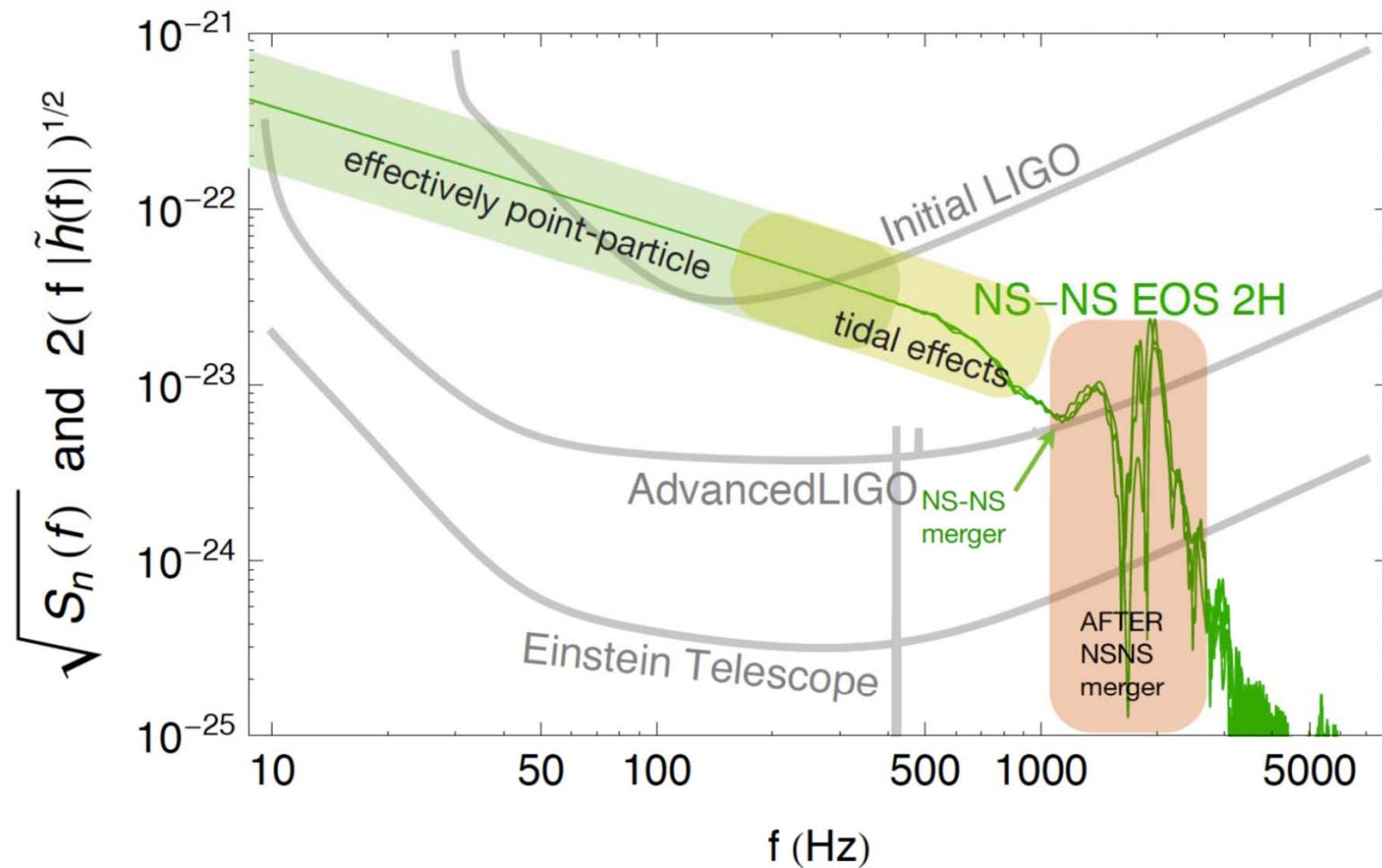
Spectrum of **BBH** inspiral, scale to 1.35-1.35, 45 Mpc



Spectrum of **NS-NS** inspiral, 1.35-1.35, 45 Mpc



Spectrum of **NS-NS** inspiral, 1.35-1.35, 45 Mpc



What is the EoS and why is it important?

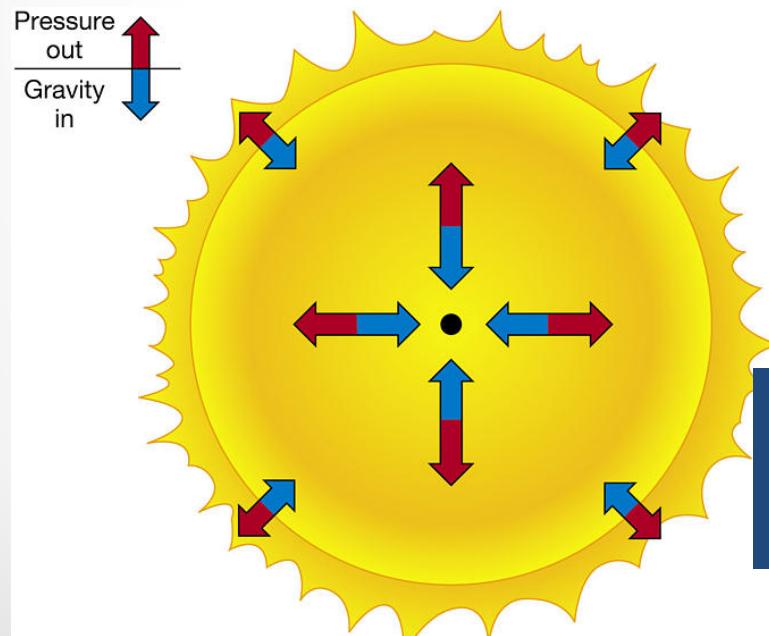
...

- How far can the EoS be constrained by nuclear physics ?

Modelling (Neutron) Stars

- Self-gravitation => Tolman Oppenheimer Volkoff (1939):

$$\frac{dP(\rho)}{dr} = -\frac{G}{r^2} \left[\rho(r) + \frac{P(\rho)}{c^2} \right] \left[m(r) + 4\pi r^3 \frac{P(\rho)}{c^2} \right] \left[1 - \frac{2Gm(r)}{rc^2} \right]^{-1}$$



$$\forall \rho_c \\ R=r(P=0) \\ M=m(r=R)$$

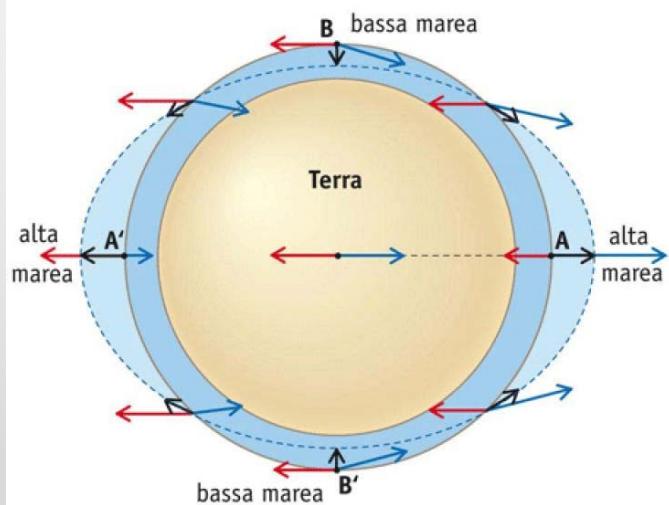
Mass and radius

Needs ONLY $P(\rho)$ of NS matter \Leftrightarrow EoS

Modelling (Neutron) Stars

- Influence of a second body => Thorne and Campolattaro (1967):

$$\frac{d^2 H(r)}{dr^2} + \frac{dH(r)}{dr} \left[\frac{2}{r} + e^{\lambda(P(\rho))} \left(\frac{2m(r)}{r^2} + 4\pi r (P(\rho) - \rho(r)) \right) \right] + H(r)Q(P(\rho)) = 0$$



$$\forall \rho_c \quad \Lambda = \frac{2}{3} k_2 \left(\frac{H'(r=R)}{H(r=R)} \right) \left(\frac{c^2 R}{G M} \right)^5$$

Tidal polarizability



**Needs ONLY $P(\rho)$
of NS matter \Leftrightarrow EoS**

What is the EoS and why is it important?

...

The inspiral signal in a NS-NS merger only depends on general relativity+EoS

If EoS can be constrained by nuclear physics, GW from mergers could probe:

=> Exotica or deconfined matter

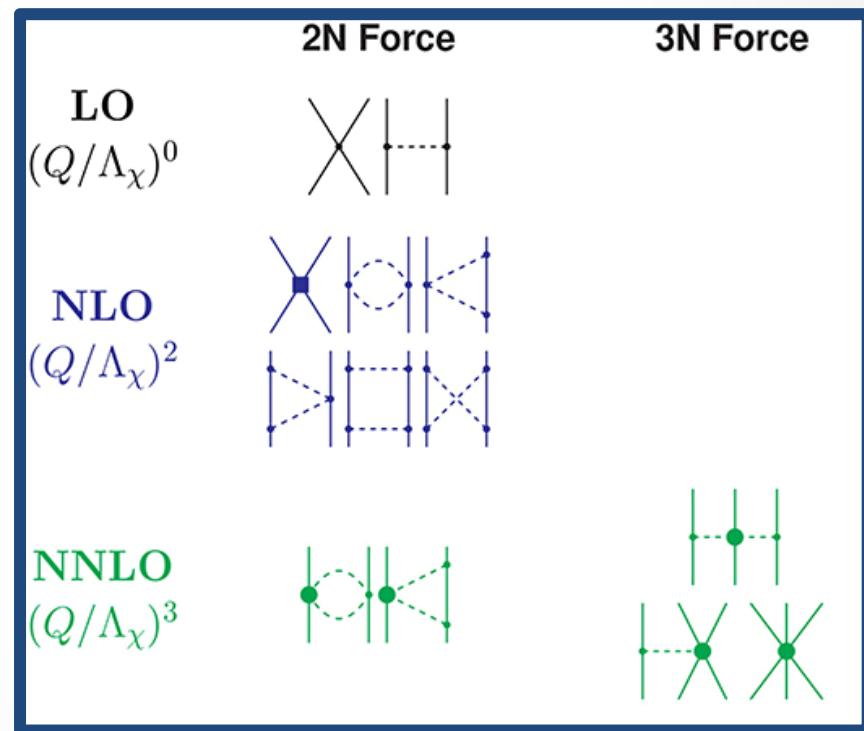
⇒ Nature of 190814 light object /mass gaps

EoS from nuclear physics ? « ab-initio »

- The core of a NS is an homogeneous distribution of leptons (~free particles) and baryons (protons & neutrons)
- Non-perturbative QCD domain for the baryons:
⇒ 2- and 3-body interactions from chiral perturbation theory
⇒ many-body problem by Monte Carlo

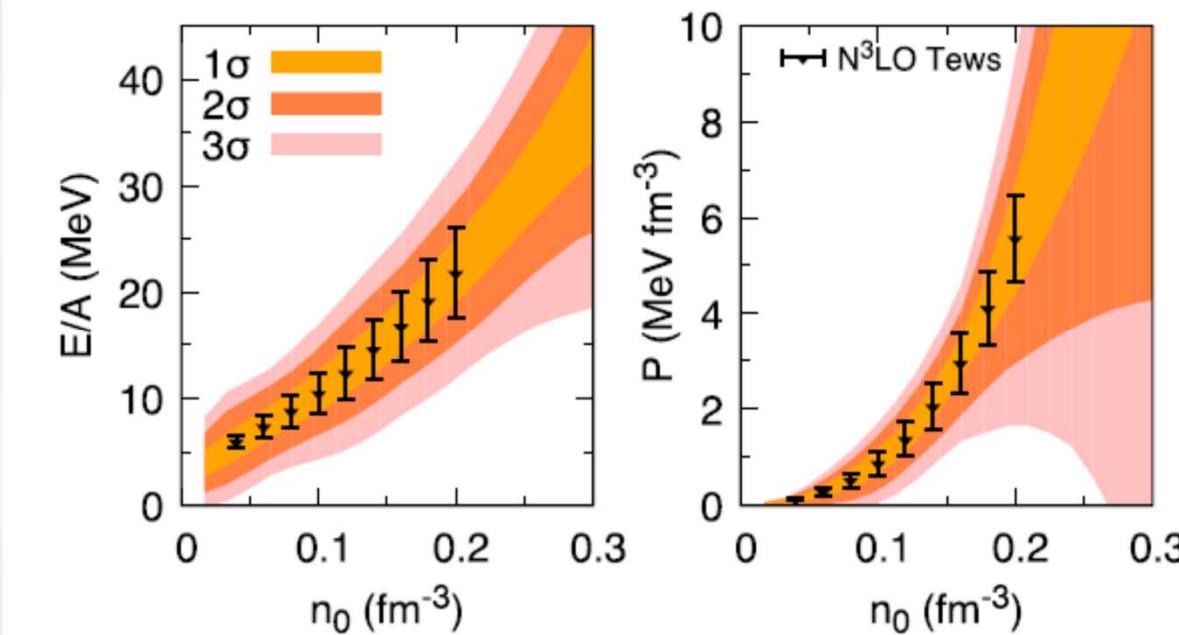
Machleidt R., Int J Mod Phys. (2017)

- Diagrammatic expansion: controlled uncertainties!



EoS from nuclear physics ? « ab-initio »

Pure neutron matter



- Power counting & regularization valid only up to $\sim 1,5\rho_0$
 - Central densities in NS up to $\sim 5\rho_0$
- => Extrapolations needed

I. Tews, T. Krüger, K. Hebeler, and A. Schwenk, [Phys. Rev. Lett. 110, 032504 \(2013\)](#).
C. Drischler, K. Hebeler, and A. Schwenk, [Phys. Rev. C 93, 054314 \(2016\)](#).

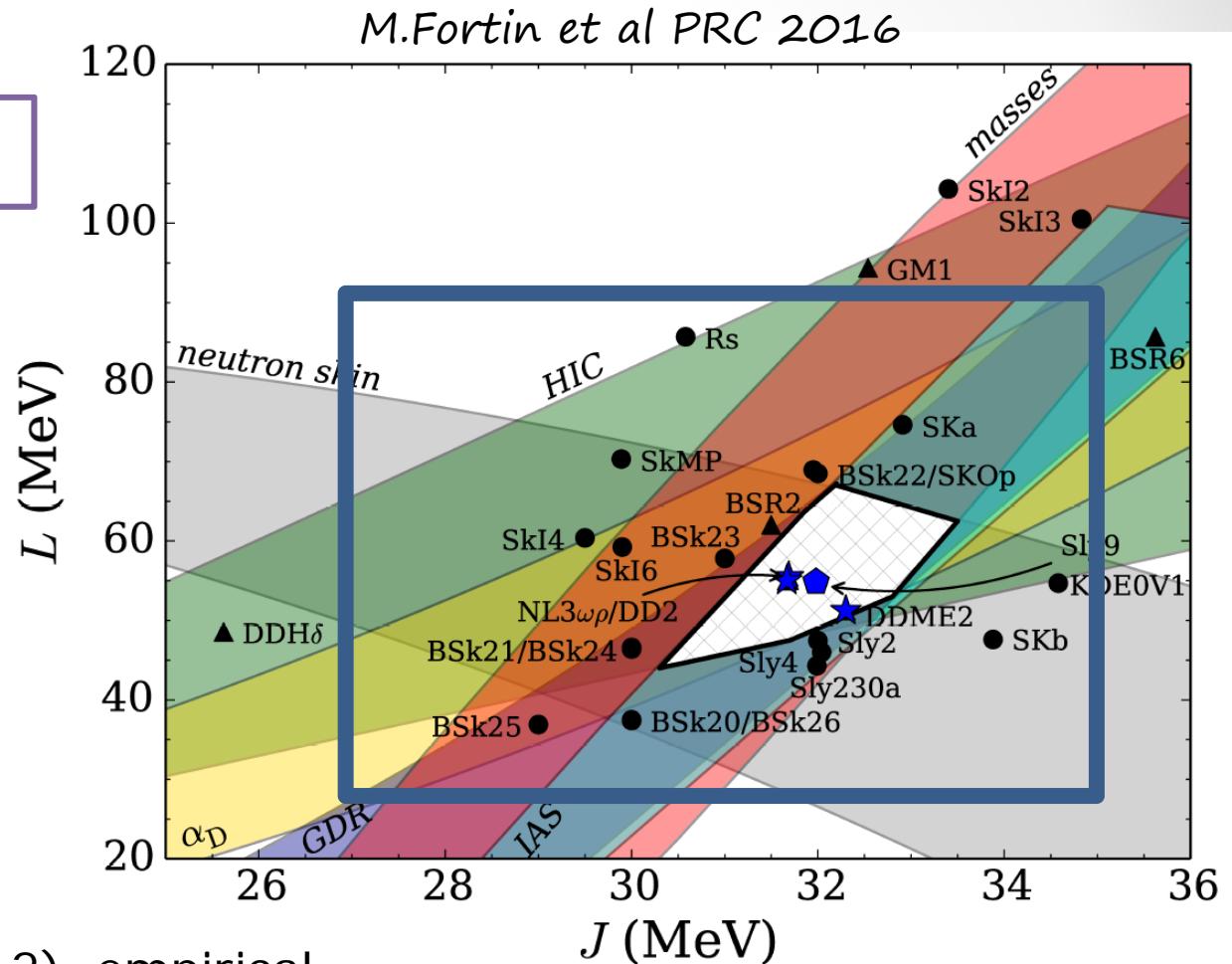
EoS from nuclear physics ? « Empirical »

Symmetric matter
 $\rho_n = \rho_p$

Symmetry energy
 $e(\rho_n, \rho_p) = e_0 + e_{sym} \delta^2$

$$X_k = \frac{d^k e_0(sym)}{d\rho^k} |_{\rho=\rho_0}$$

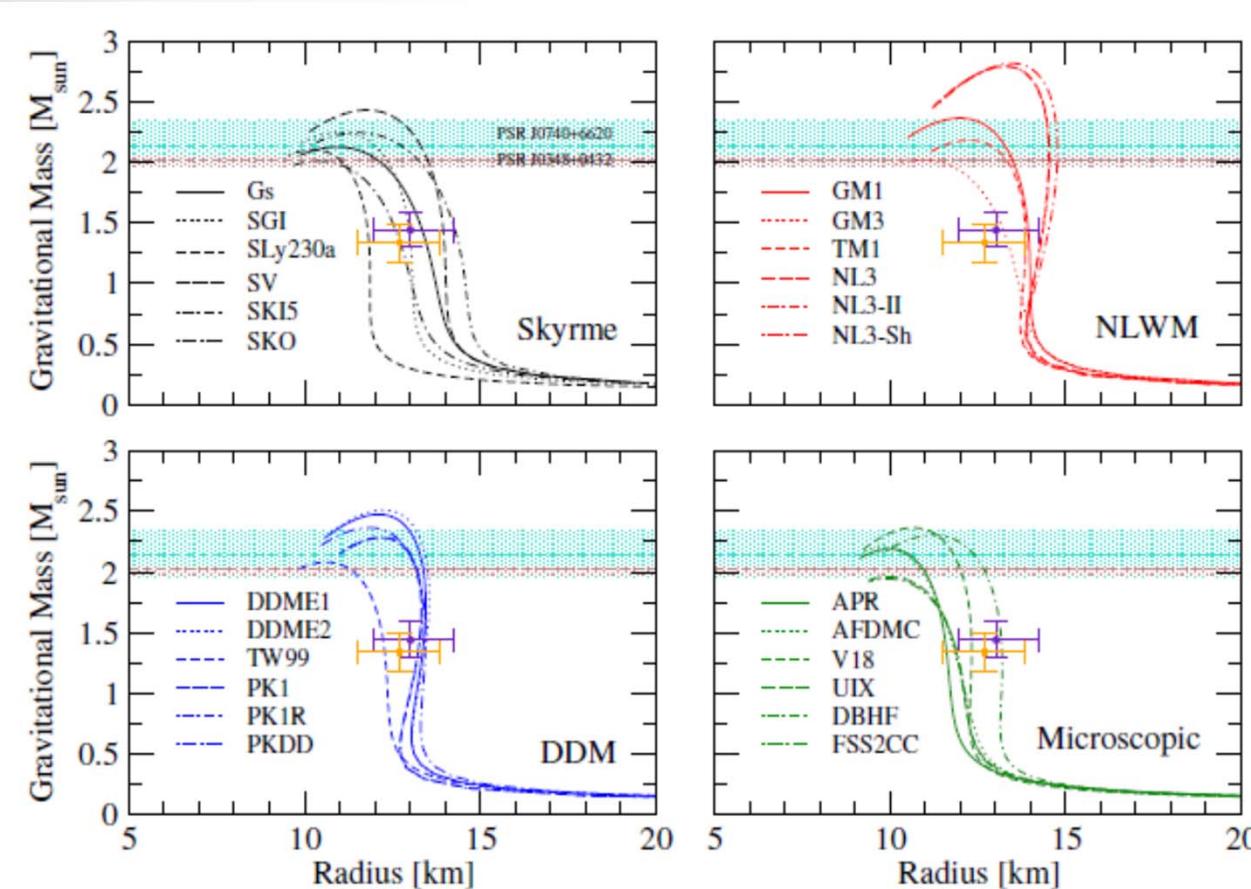
$$\vec{X} = (E_0, K_0, J, L, K_{sym}, \dots)$$



The lowest order ($k=0,1,2$) empirical parameters X_k can be extracted from nuclear experiments. But the high order ones are unknown

EoS from nuclear physics ? « Effective »

- **Nuclear density functionals**
- **Effective single particles:** $e_q(k) = \sqrt{m_q^*{}^2 + k^2} + V_q(\rho_q, \rho_{q'})$
⇒ m_q^* , V_q from a **phenomenological** Hamiltonian (Skyrme, Gogny, M3Y..) or Lagrangian (RMF)
⇒ Coupling constants fitted on nuclear data and/or ab-initio
⇒ $e(\rho_B, \rho_L, \rho_S)$ $P(\rho) = -\rho_B^2 \frac{\partial e}{\partial \rho_B} \Big|_{\mu_L=0, \mu_S=0}$
- **Model dependence: choice of functional form (Lagrangian versus Hamiltonian), fitting protocol, d.o.f. (exotics?) lead to different EoS => different predictions**



Max masses:

Demorest et al, Nature 2010
Antoniadis et al, Science 2013

Mass-radii:

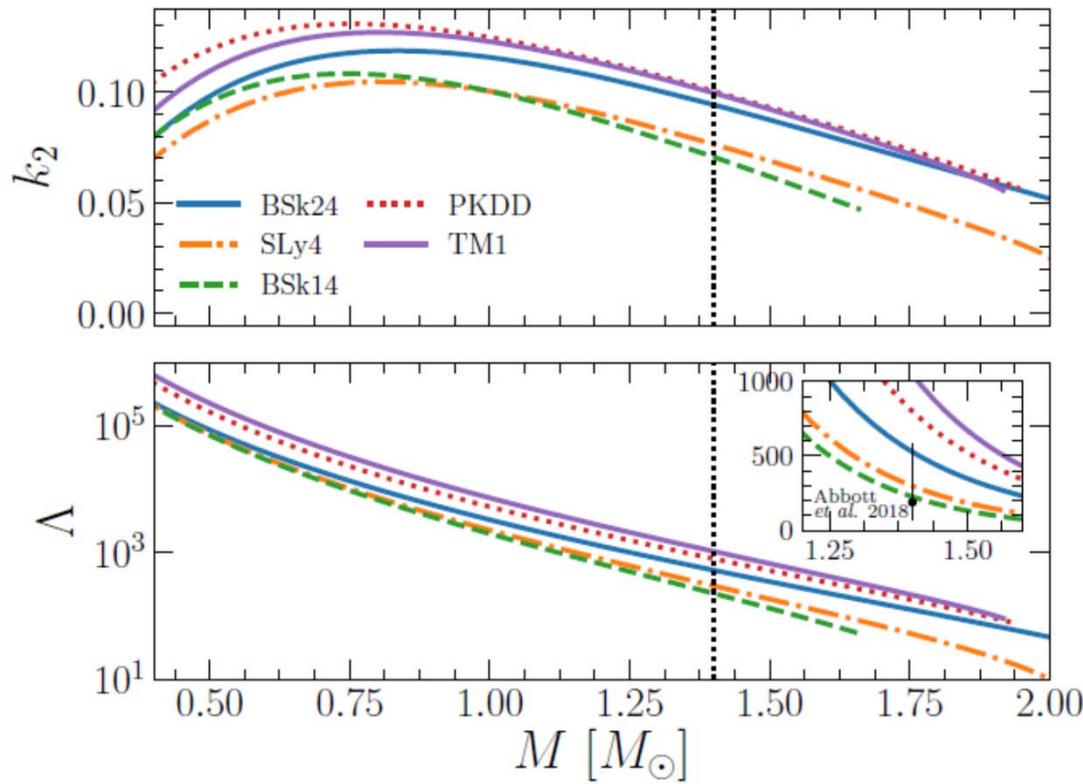
Riley et al, ApJ 2019
Miller et al, ApJ 2019

F.Burgio, I.Vidana, Universe 2020, 6, 119

Which is the correct model?
Is the ensemble exhaustive?

F.Burgio, I.Vidana, Universe **2020**, 6, 119

T.Carreau et al, PRC **2020**, 100, 055853



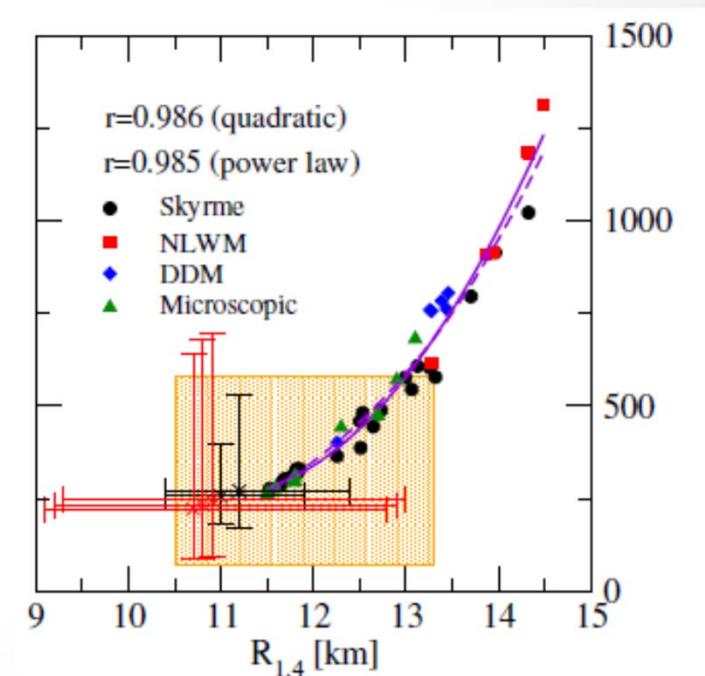
$\Lambda_{1.4}$

Abbott et al, PRL **2018**

$\Lambda_{1.4} - R_{1.4}$

Capano et al, Nat.Astron.**2020**

De et al, PRL 2018



Which is the correct model?
Is the ensemble exhaustive?

Meta-modeling

- Flexible functional $e(\rho_n, \rho_p)$ able to reproduce existing effective models and interpolate between them
- Parameter space: empirical parameters \vec{X}
- Prior $P(\vec{X})$: uncorrelated flat distribution
 - Filters:

1. ab-initio EoS

2. empirical uncertainties on \vec{X}

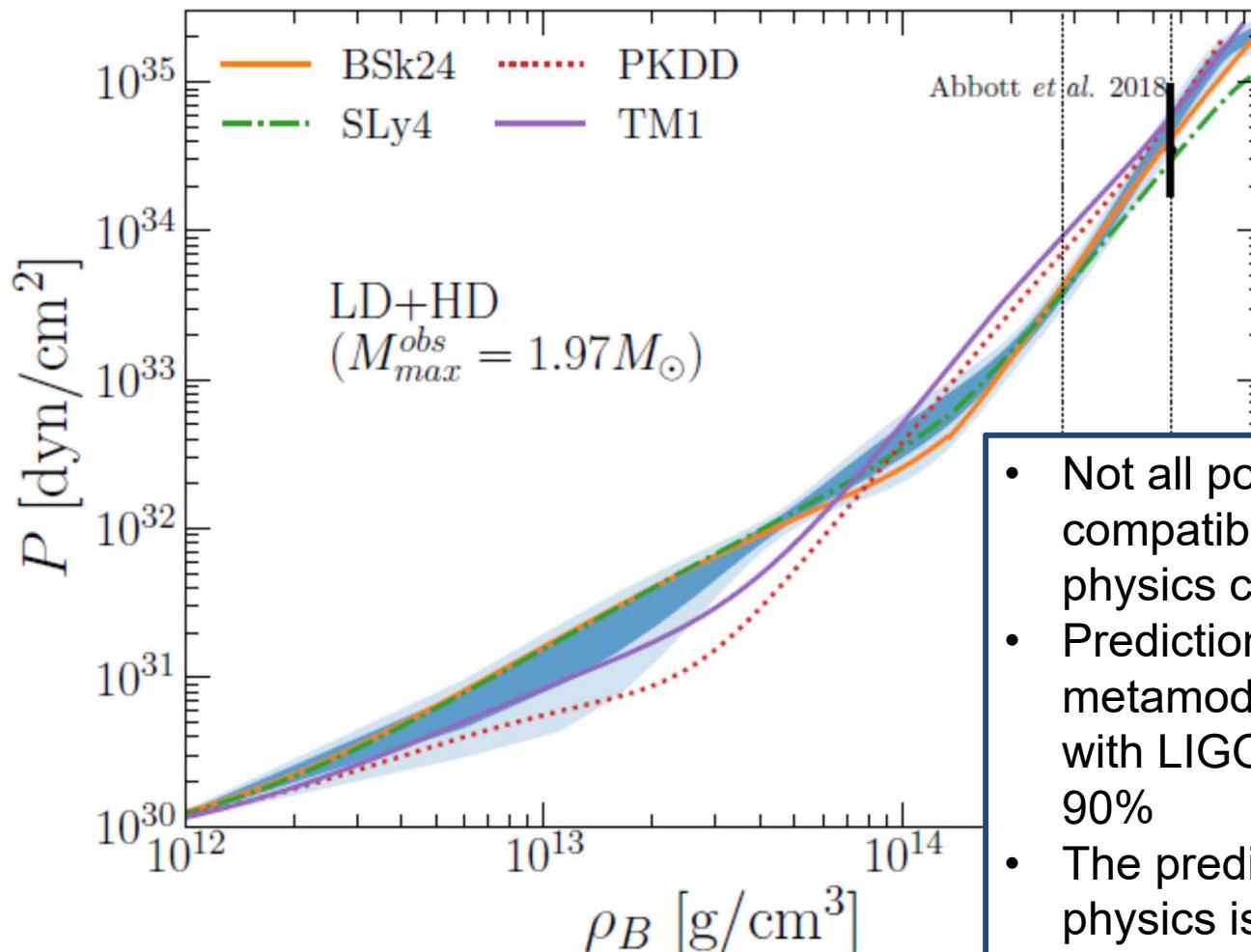
=> Predict astro observables with controlled uncertainty intervals

3. astro constraints (maximal mass, radius, tidal ...)

=> Quantify the reliability of the different models

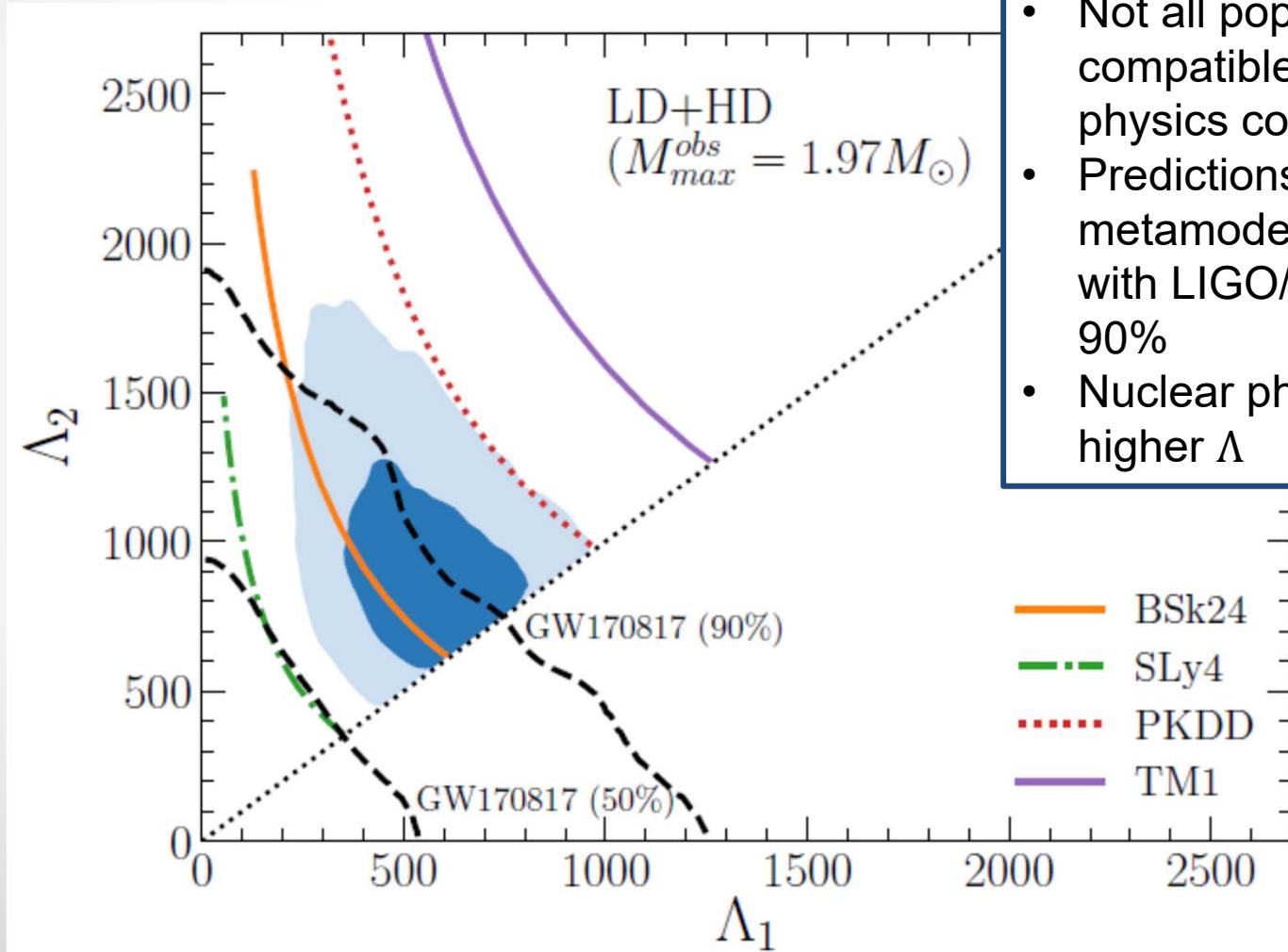


Application: nuclear physics => EoS



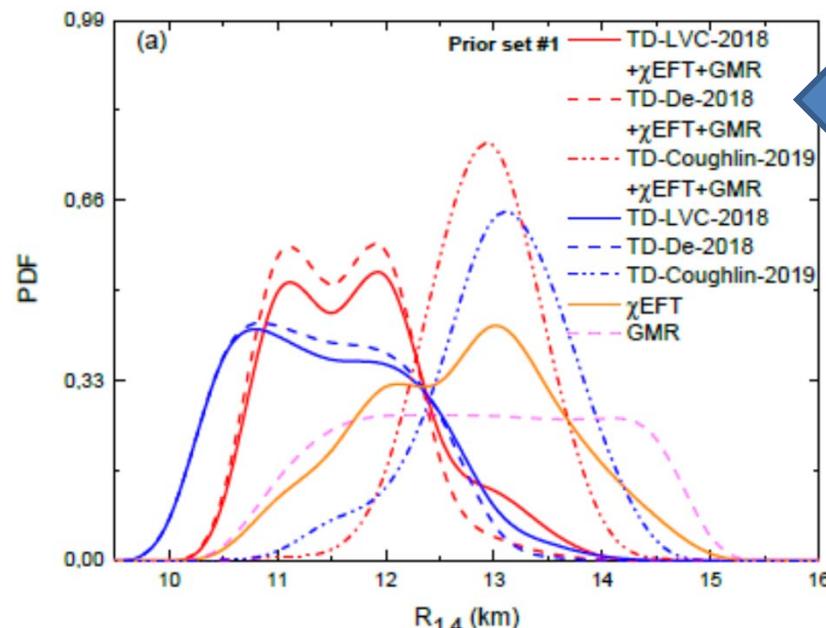
- Not all popular models are compatible with nuclear physics constraints
- Predictions from metamodeling (blue) agree with LIGO/VIRGO (black) at 90%
- The prediction from nuclear physics is more constraining

Application: nuclear physics $\Rightarrow \Lambda$

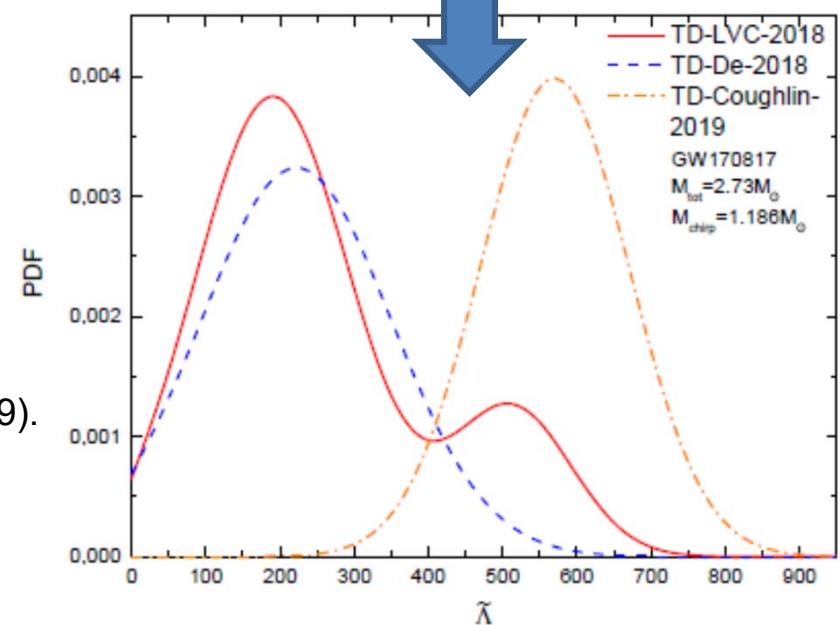


- Not all popular models are compatible with nuclear physics constraints
- Predictions from metamodelling (blue) agree with LIGO/VIRGO (black) at 90%
- Nuclear physics « prefers » higher Λ

Application: nuclear physics + $\Lambda \Rightarrow$ radius



- A tension between LIGO/VIRGO (TD-LVC 2018, TD-DE 2018) and nuclear physics (χ EFT) on the NS radius
- reflects a tension between the Λ estimation from GW and EM+GRB (TD-Coughlin 2019)



TD-DE: S. De et al PRL 121, 091102 (2018).

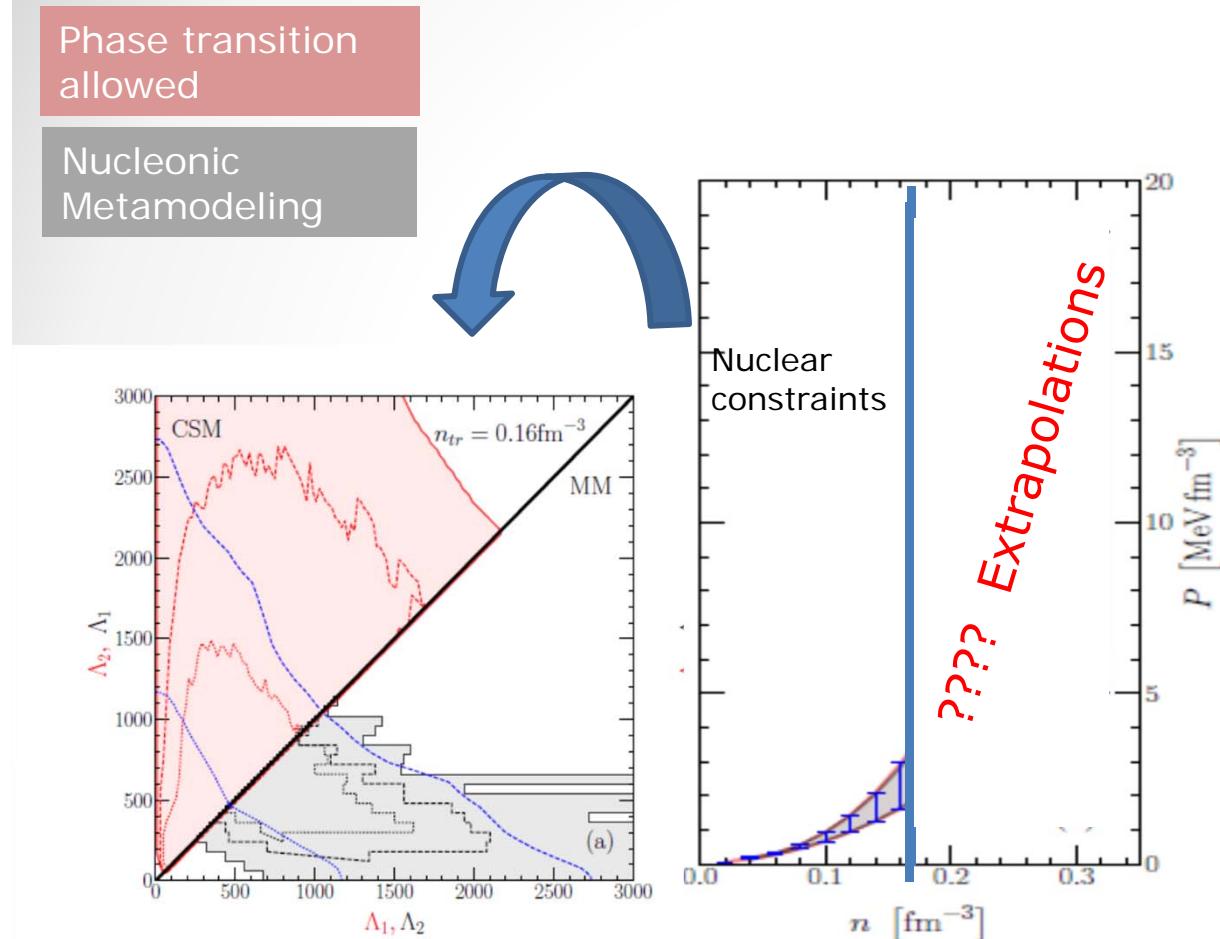
TD-LVC: B.P.Abbott et al, PRX 9, 011001 (2019)

TD-Coughlin: M. W. Coughlin et al MNRAS 489, L91 (2019).

Meta-modeling : the limitations

- Constraints from nuclear physics (empirical+ab-initio) come from densities \leq normal nuclear density ρ_0
- The metamodeling assumes that the behavior is analytic at all densities: no extra degrees of freedom, no phase transition
- If this is not the case, more general (and agnostic) forms should be used
 - **piecewise polytropes** J.S.Read 2009, Steiner 2013,
E.Annala 2018, T.E.Riley 2018....
 - **spectral functions** L.Lindblom 2010,
L.Lindblom&N.M.Indik 2014...
 - **parameterized c_s^2 functions** M.G.Alford 2015, I.F.Ranea 2016
I.Tews 2018, H.Tan 2020.....

Effect of a phase transition at $\rho > \rho_0$



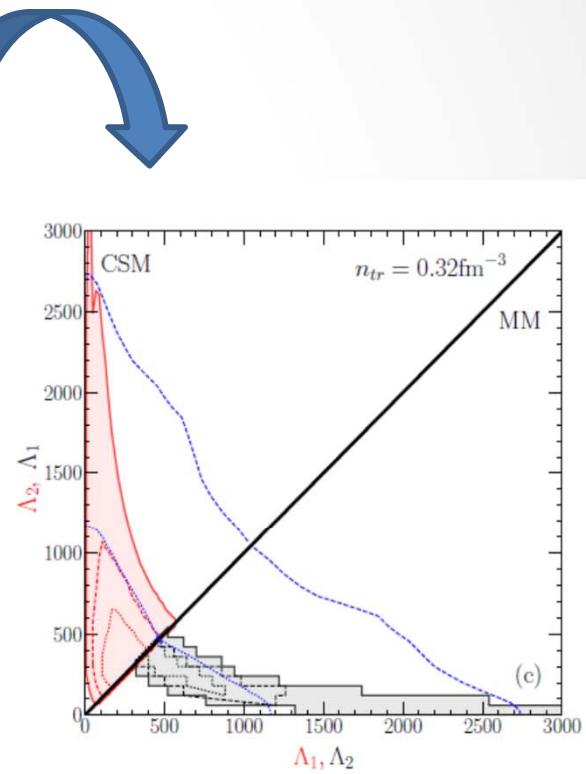
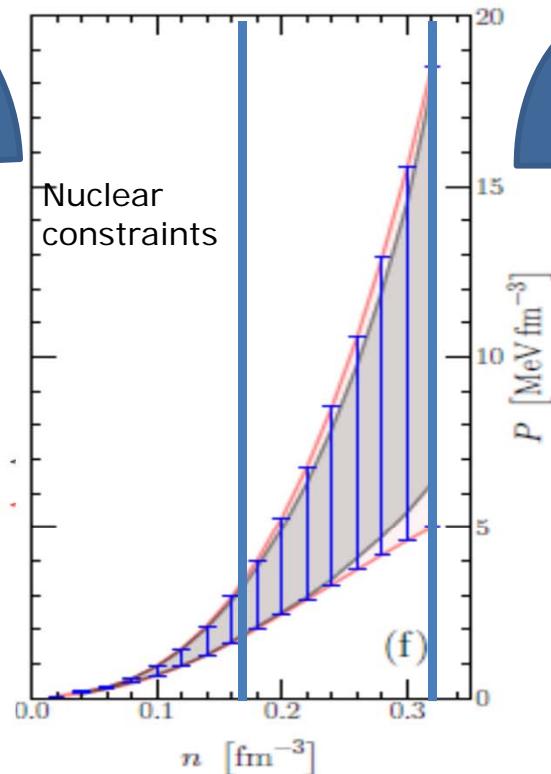
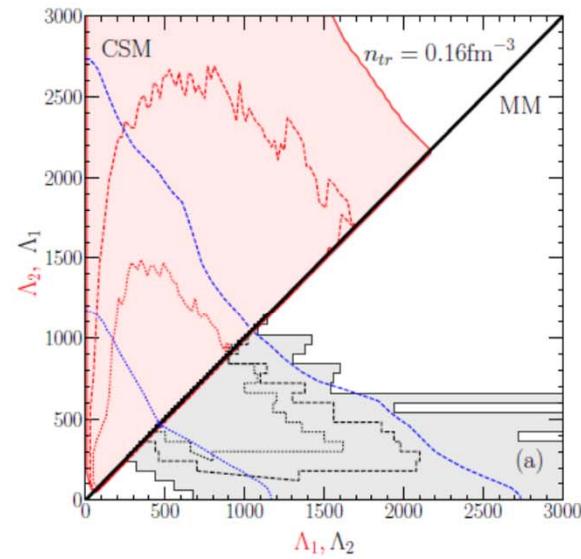
I.Tews, J.Margueron, S.Reddy, PRC (2018)

If we cannot trust nuclear physics beyond ρ_0 ,
LIGO/VIRGO data are a constraint for nuclear physics

Effect of a phase transition at $\rho > 2\rho_0$

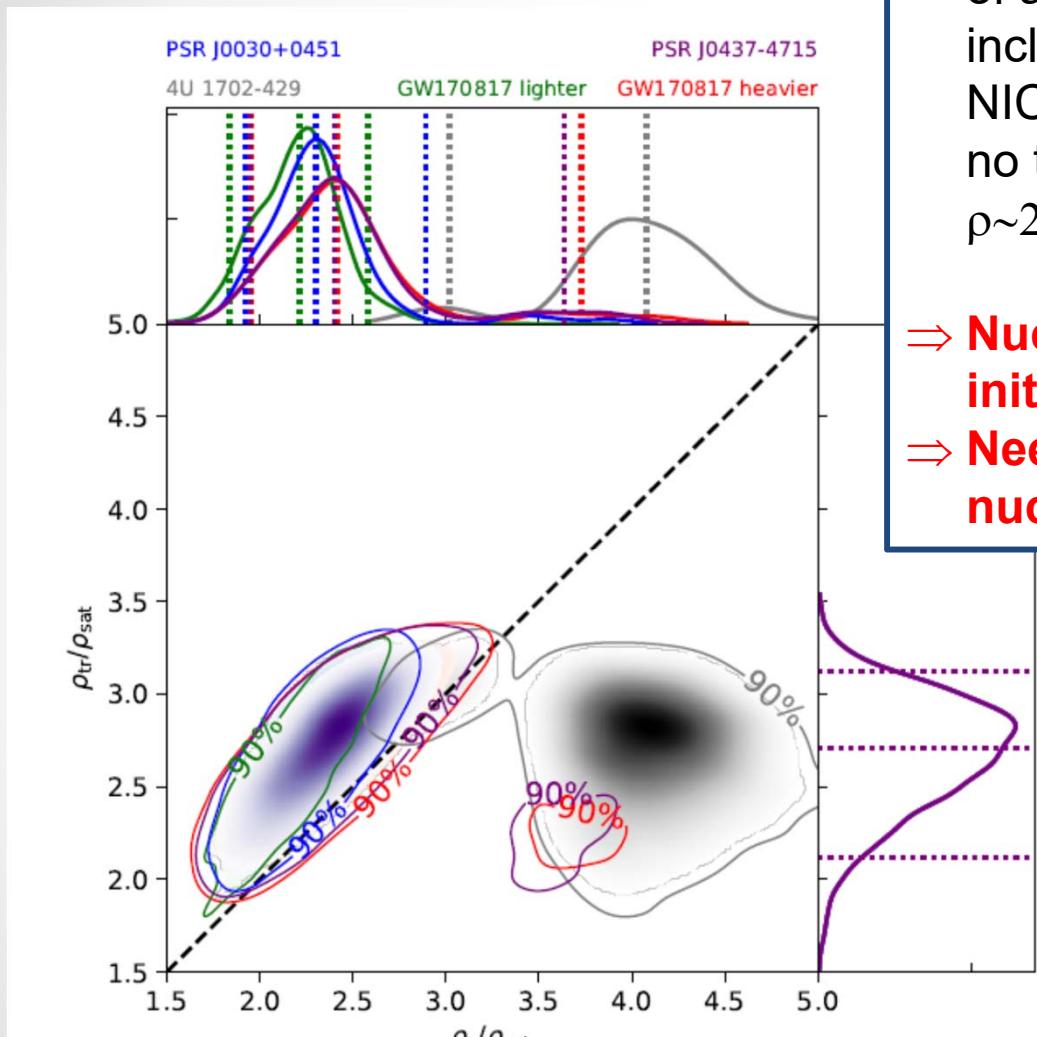
Phase transition allowed

Nucleonic Metamodeling



I.Tews, J.Margueron, S.Reddy, PRC (2018)

- If we can extend nuclear knowledge up to $2\rho_0$, nuclear physics is a constraint for GW analysis

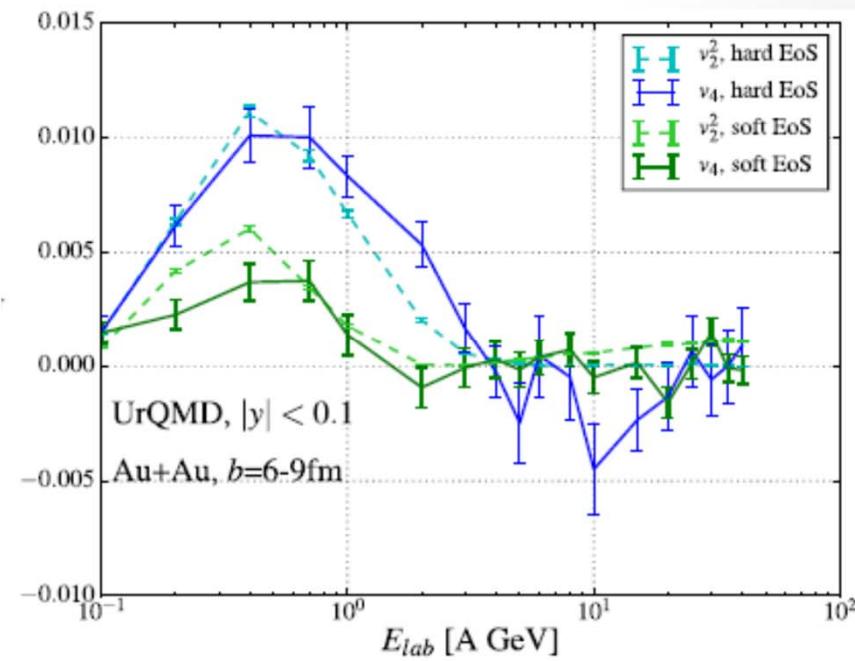
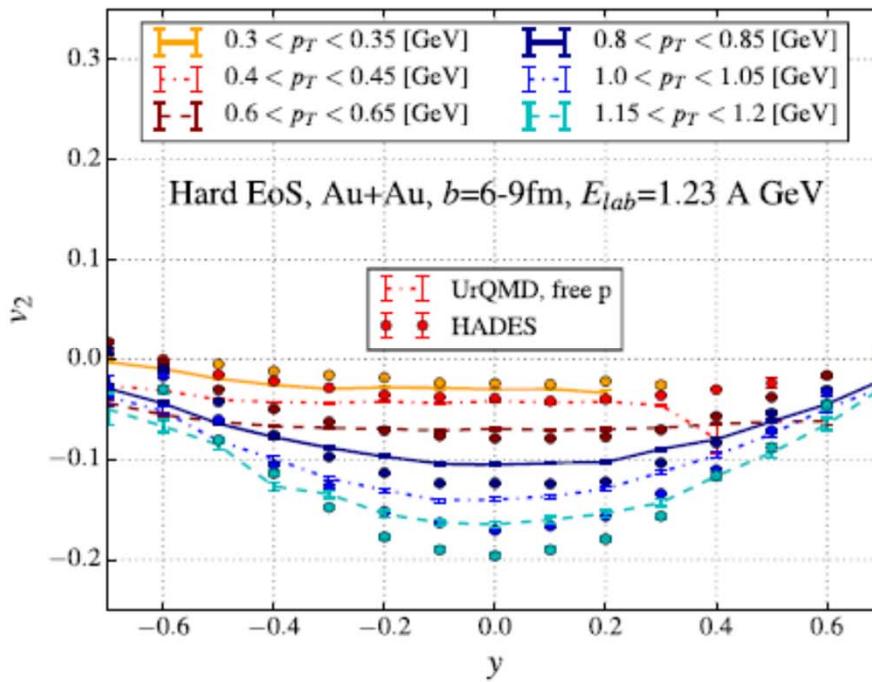
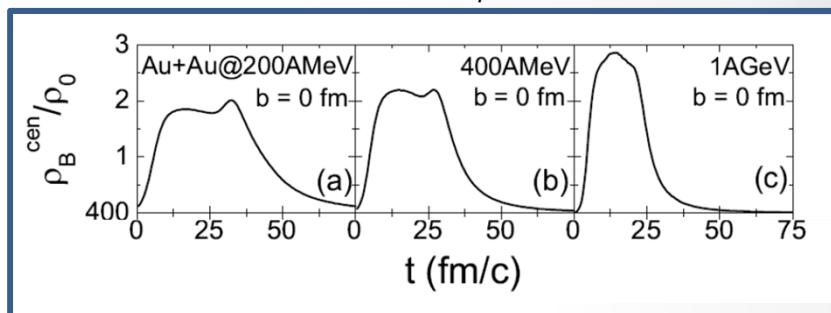


- « Reasonable » agnostic modeling of a 1st order phase transition including both LIGO/VIRGO and NICER data as constraints, predicts no transitions below densities $\rho \sim 2,5\rho_0$
- ⇒ Nuclear physics is valid, but ab-initio modeling is not...
- ⇒ Need of more constraining nuclear data for $\rho_0 < \rho < 2\rho_0$

Strategy I: high energy experiments

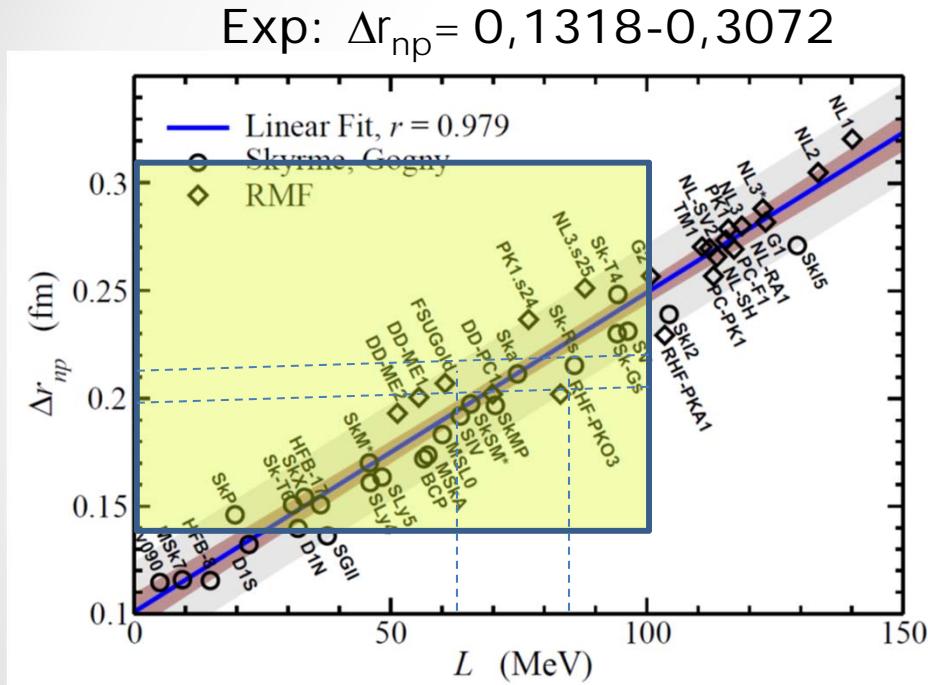
J.Xu, PRC 2013

**Elliptic flow @ HADES:
Transport model versus data**



Strategy II: high precision

Neutron skin of ^{208}Pb : effective models versus data



X.Vinas et al (2014)

P.G.Reinhard, W.Nazarewicz (2016)

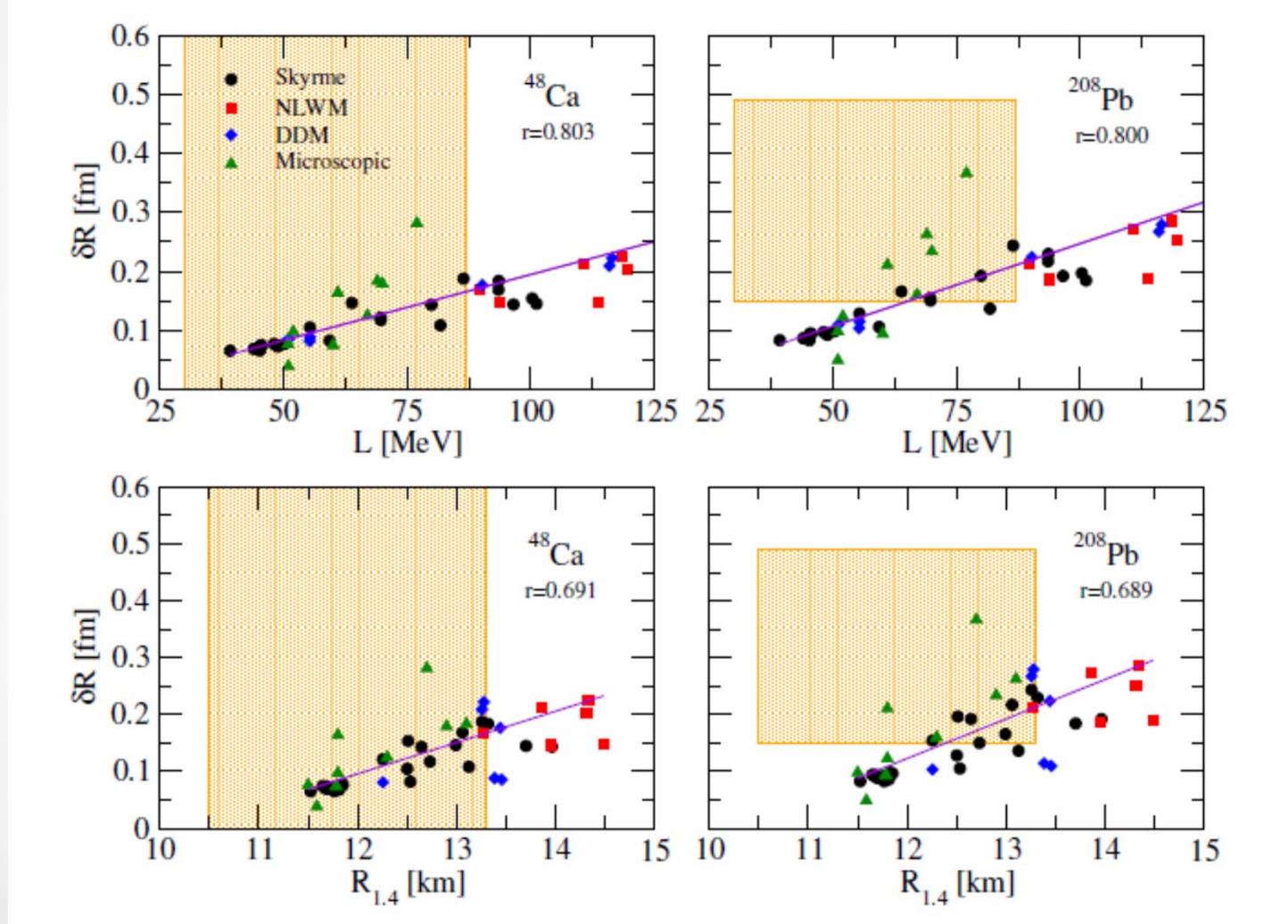
J.Yang, J.Piekarewicz (2017)

- An improved measurement of the skin would greatly reduce the present uncertainty on the EoS empirical parameters => more reliable extrapolations

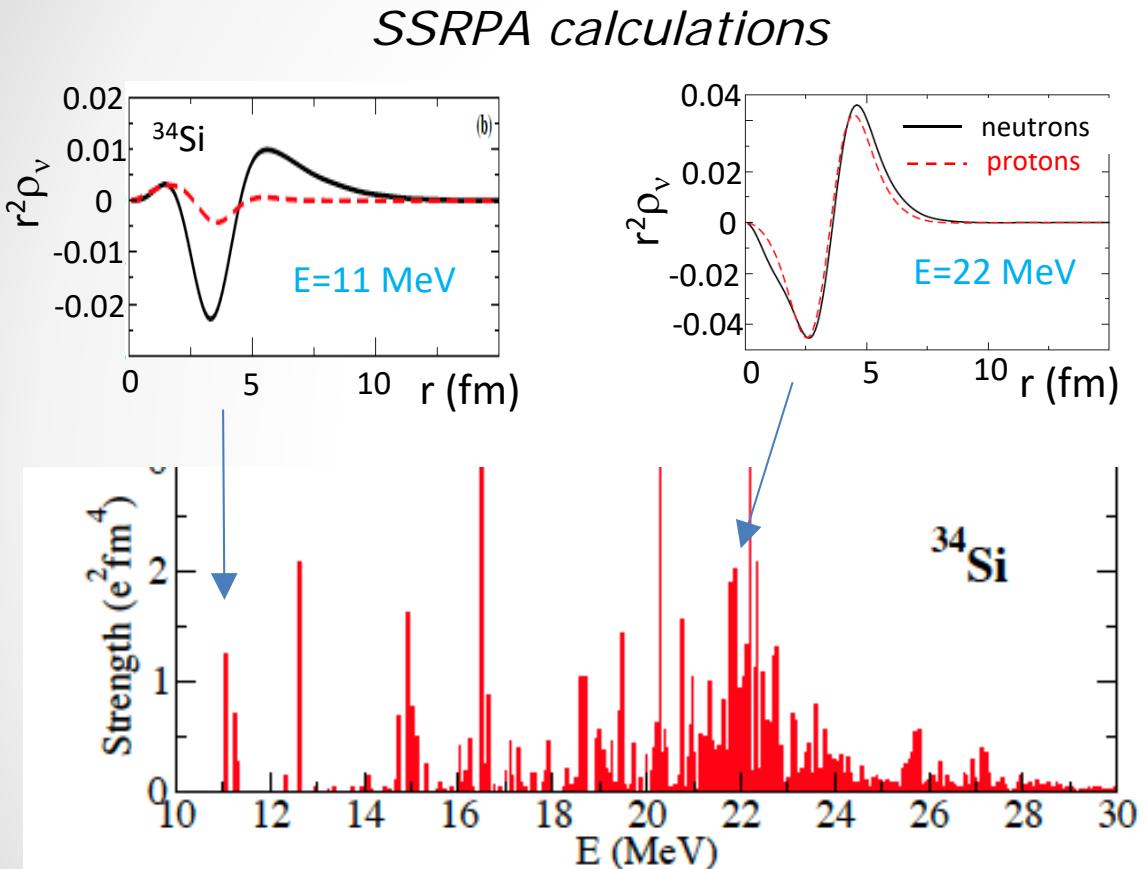
Conclusions

- The description of neutron stars static observables only needs general relativity + the nuclear EoS
- Many models! But the metamodeling technique allows predictions with controlled uncertainties
- Astrophysical and nuclear physics constraints can be treated on the same footing => could be used to generate realistic prior distributions for the waveforms
- **If nuclear constraints can be applied above normal density the inspiral GW signal of NS mergers will give hints on the presence of deconfined matter in NS and/or alternative gravity**
- Interesting perspectives from upcoming nuclear physics experiments

Strategy II: high precision



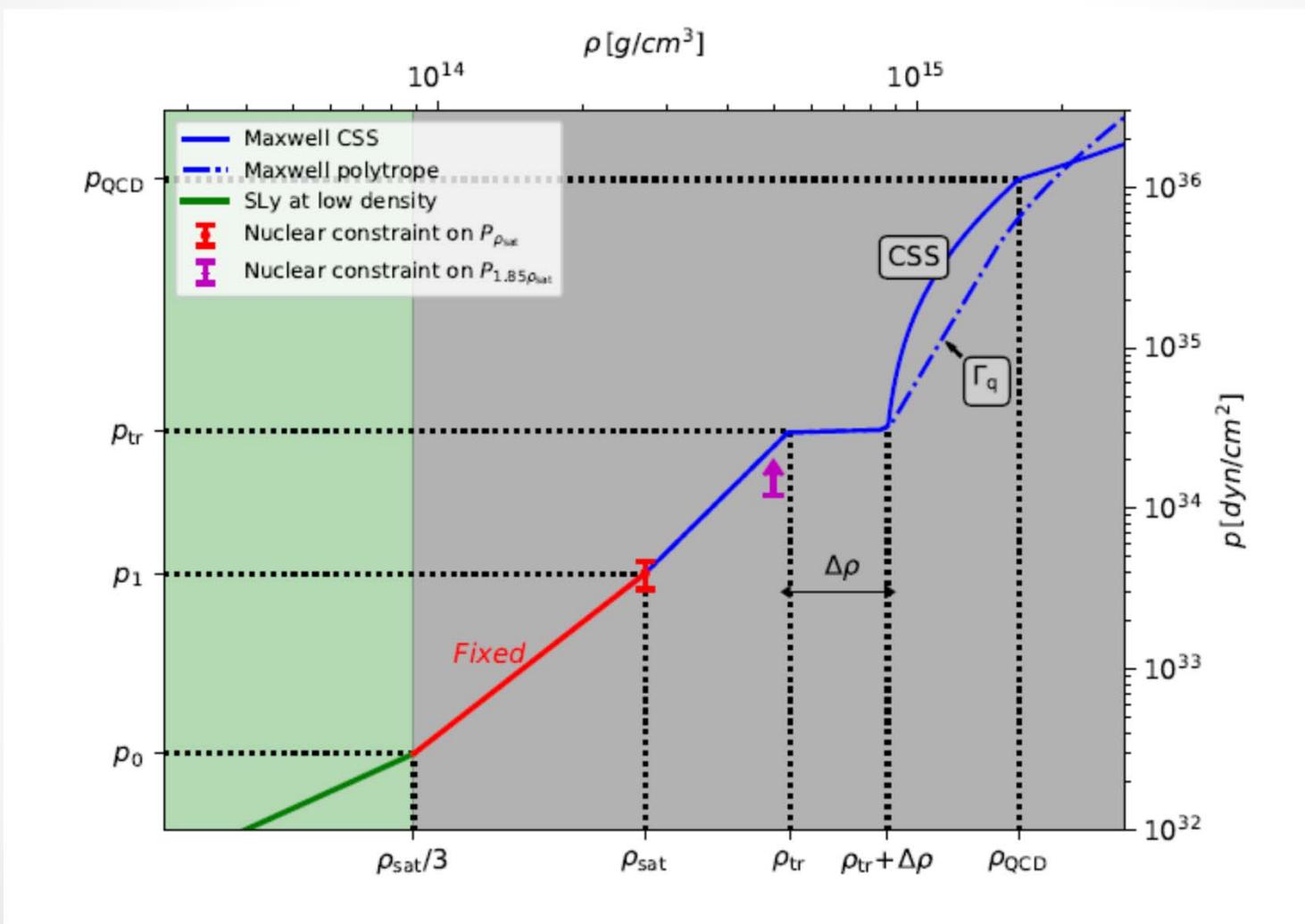
Strategy III: new probes

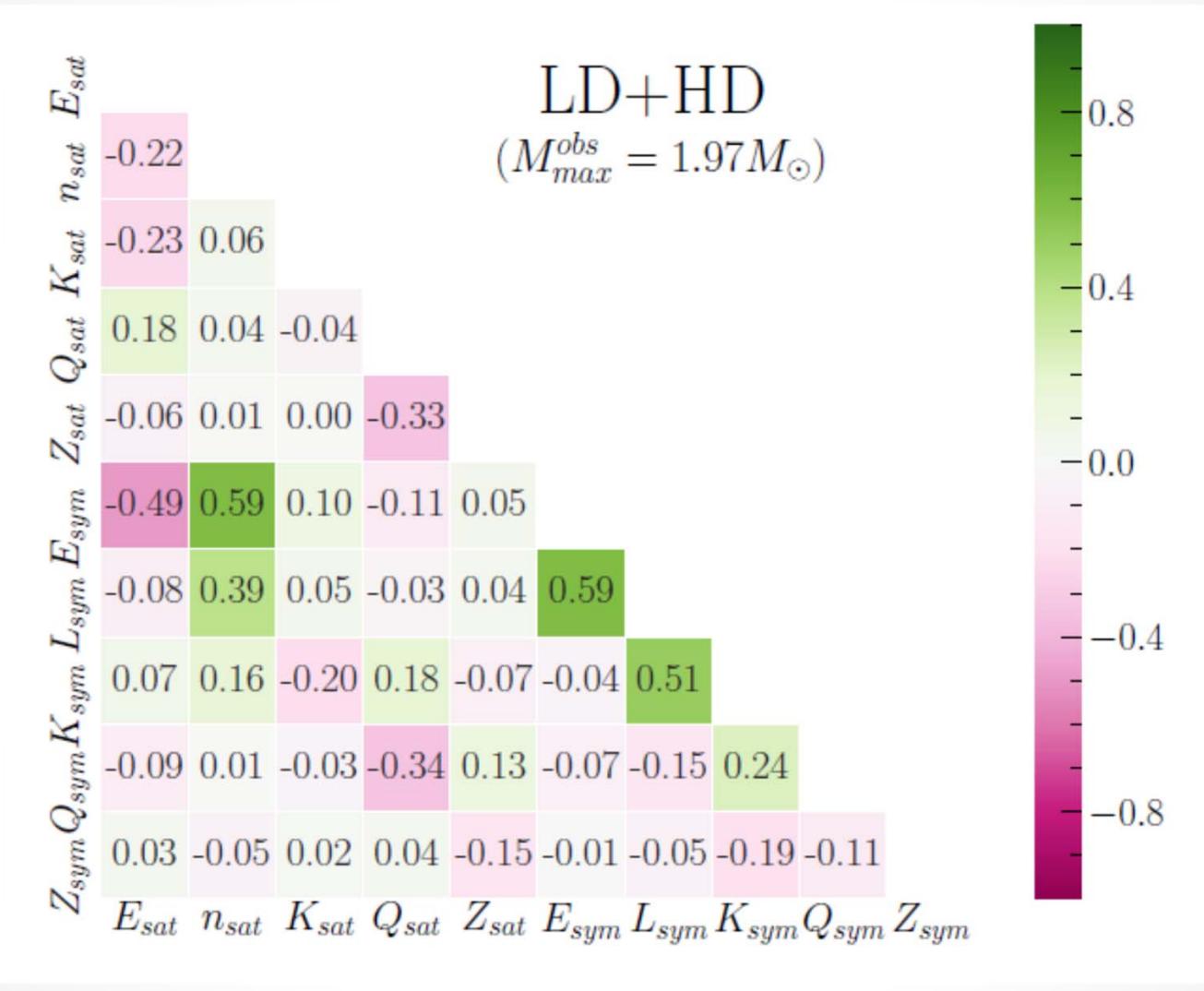


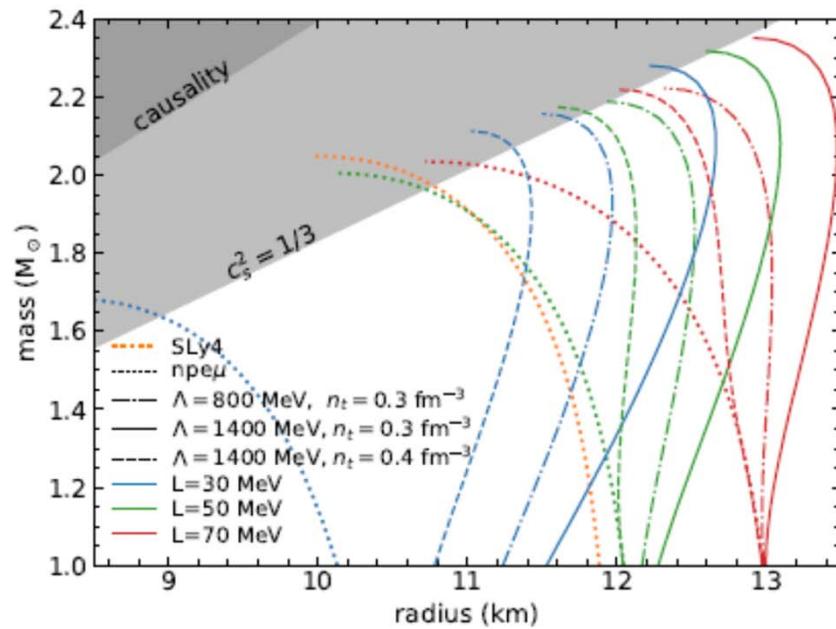
Isoscalar probes in exotic nuclei:

- Soft monopole

D.Gambacurta, Phys. Rev. C 100, 014317 (2019)

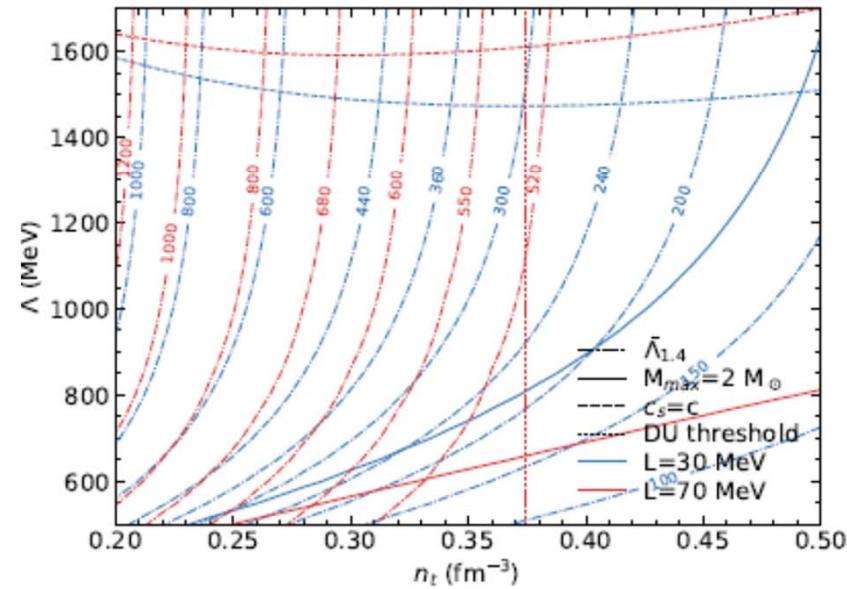






Quarkyonic matter

Zhao&Lattimer 2020



Tews, Carlson, Gandolfi, Reddy 2018

