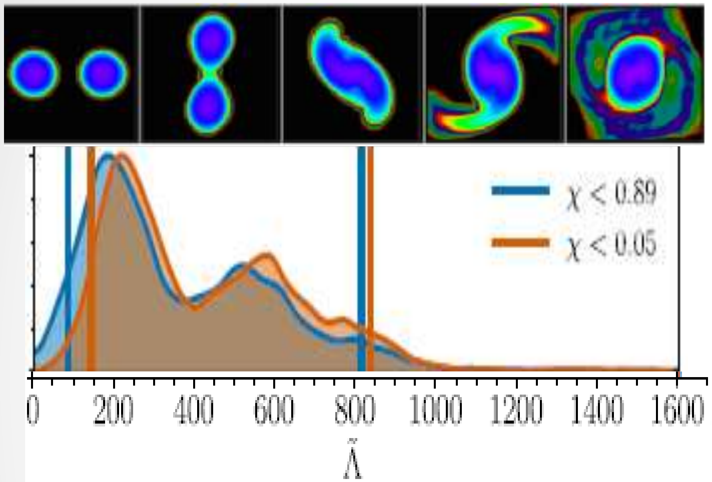
Credit: NASA/Swift Dana Berry

On the detectability of a 1st order phase transition

Francesca Gulminelli – University of Caen

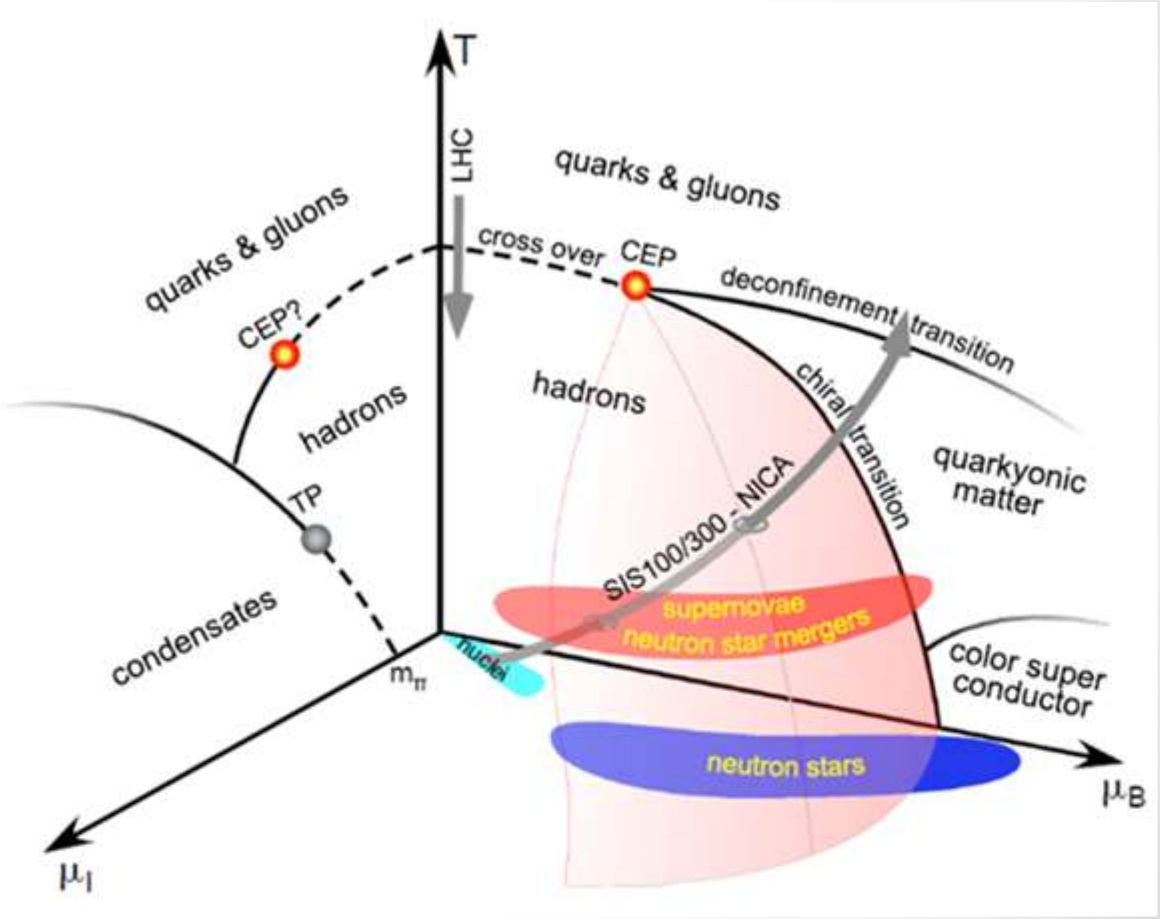
ECT* workshop
NEUTRON STARS AS MULTI-MESSENGER LABORATORIES FOR DENSE MATTER
June 20-24, 2022

Motivation: GW and the phase diagram of QCD



LVC, PRX 9 (2019), 011001

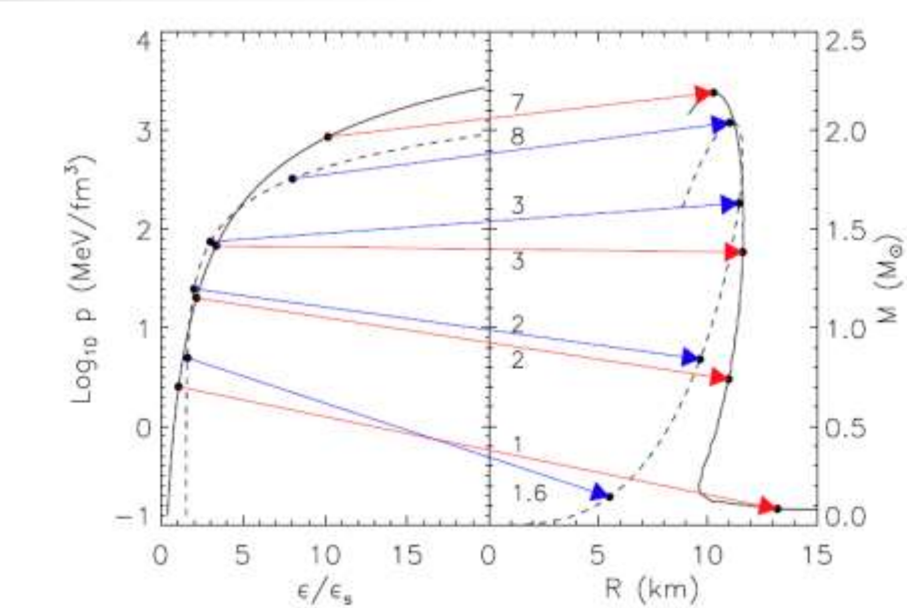
- The detection of GW by the LVC from NS merger opens the possibility of c *DIRECT* measurement of the QCD phase diagram



NuPECC Long Range Plan 2017 "Perspectives for Nuclear Physics"

Motivation

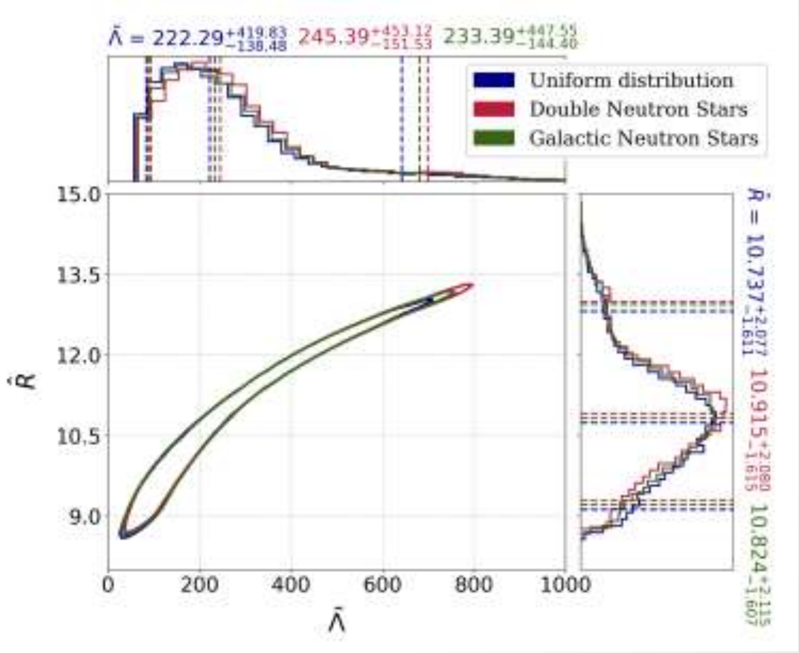
(T=0 – β eq. for this talk)



J.Lattimer Ann.Rev.Nucl.Part.Sci (2012)

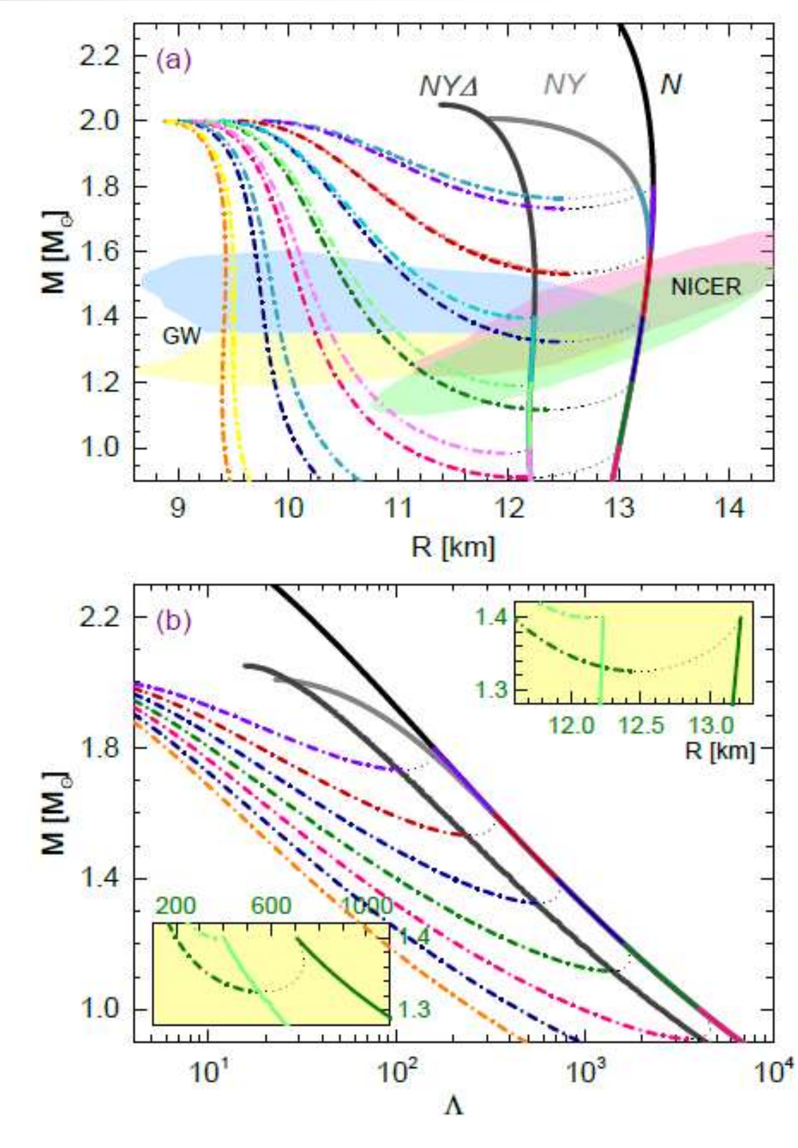
- Different compositions => different EoS => different gravitational signals!

- Indeed, GR imposes a 1-to-1 correspondence between the nuclear EoS and static properties of NS (M(R)- M(Λ))



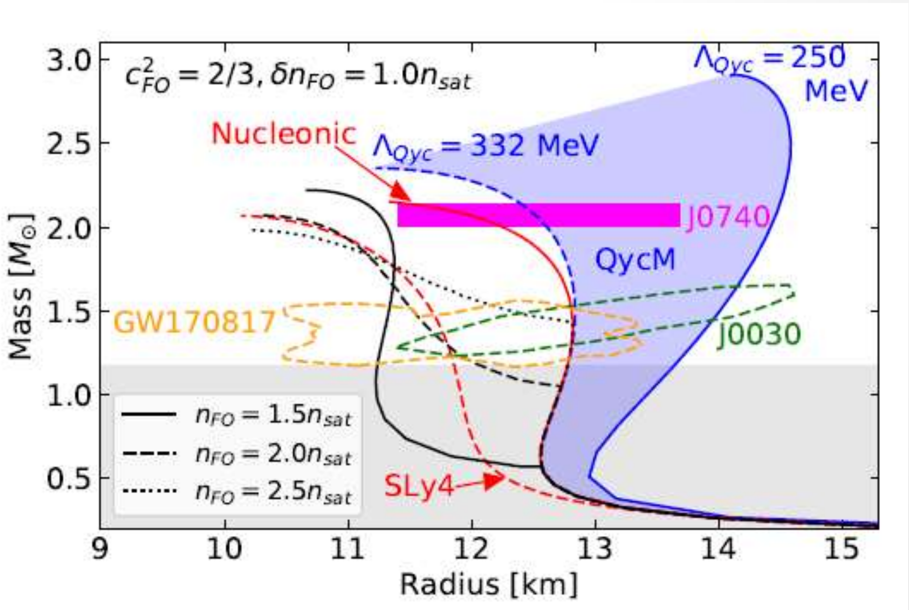
S.De et al, Phys. Rev. Lett. 121, 091102 (2018)

Problem: no ab-initio theory of dense matter



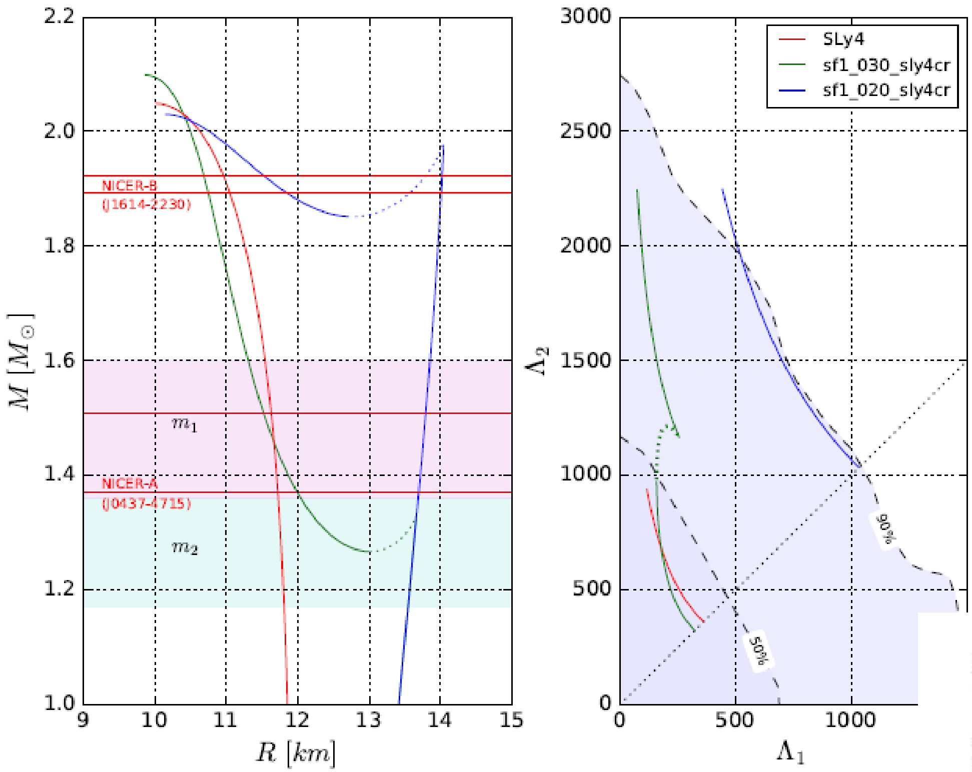
- Even qualitatively, the effect of quark dof is not clear

R.Somasundaram, J.Margueron
ArXiv 2104.13612



- J.J.Li, A.Sedrakian, M.Alford, PRD101 (2020) 063022

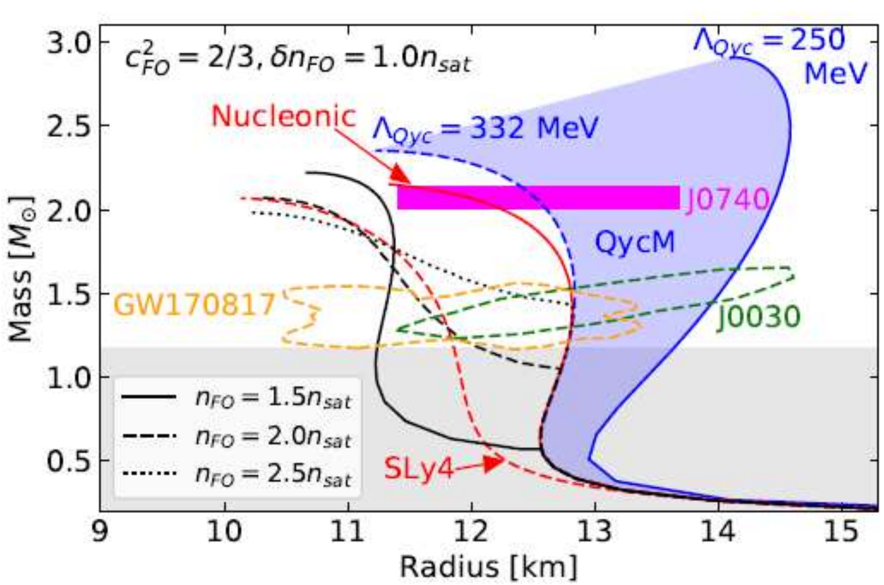
Problem: no ab-initio theory of dense matter



D.Blaschke, N.Chamel, in "The Physics and Astrophysics of Neutron Stars" Springer 2019

- Even qualitatively, the effect of quark dof is not clear
- Masquerade: different compositions may lead to the same EoS

R.Somasundaram, J.Margueron ArXiv 2104.13612



- Nuclear matter modelling is (much!) better constrained by theory&experiment in the nucleonic regime

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$\Rightarrow$ **A null hypothesis for exotic degrees of freedom**

Nucleonic Meta-modeling

= the most general EoS *under the nucleonic hypothesis*

- Flexible functional $e(\rho_n, \rho_p)$ able to reproduce existing effective nucleonic models and interpolate between them
- Parameter space = empirical parameters that can be constrained by experiment (fixed N/Z)
- NS EoS via beta equilibrium imposed $\forall\rho$ $\quad e(\rho_n, \rho_p) \Rightarrow \mathbf{p}(\boldsymbol{\rho})$

$\Rightarrow$ **Physical correlations between isoscalar and isovector sector**

A.Bulgac et al, PRC 2018
J.Margueron et al, PRC 2018
T.Carreau et al, EPJA 2019
H.Gil et al, PRC 2019
I.Tews et al, EPJA 2019
H.Guven et al, PRC 2020
R.Essick et al, PRC 2021
S.Ghosh et al, EPJA 2022
H.Dinh Thi et al, A&A 2021
H.Dinh Thi et al, Universe 2021
……………………………………

Nucleonic Meta-modeling

= the most general EoS *under the nucleonic hypothesis*

- Our choice: expansion around ρ_0 :
- $m_q^*(\rho)$ and $\delta^{2/3}$ terms included
- Unified treatment of the inhomogeneous crust
- Flat prior $P(\vec{X})$

Symmetric matter $\rho_n = \rho_p$

Symmetry energy

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

$$X_k^{bulk} = \frac{d^k e_{0(sym)}}{d\rho^k}\Big|_{\substack{\rho=\rho_0 \\ \delta=0}}$$

$E_0, K_0, J, L, K_{sym}, ..$

$\sigma_0, \sigma_c, ..$

$$\vec{X} = \left(\vec{X}_{bulk}, \vec{X}_{surf}, m^*, \Delta m^*\right) \quad \sim 15\ parameters$$

Nucleonic Meta-modeling

= the most general EoS *under the nucleonic hypothesis*

Filters: $P(\vec{X}|\vec{f}) = \dfrac{P(\vec{X}) \prod_i P(f_i|\vec{X})}{P(\vec{f})}$

f_1. ab−initio EoS (MBPT)
f_2. empirical uncertainties on $\vec{X}_{bulk}$
f_3. nuclear masses

$\Big\}$ **Nuclear physics**

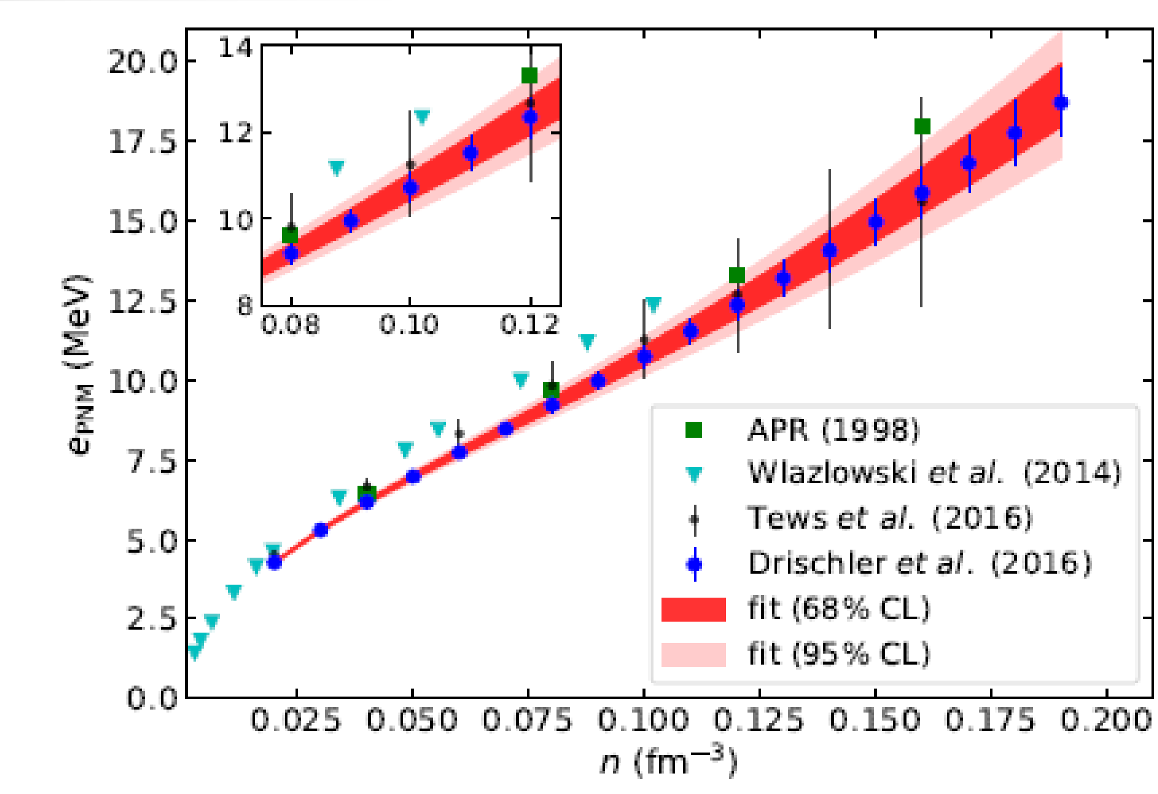
f_4. max.mass from radio timing*
f_5. tidal polarizability from GW**
f_6. M(R) from X-ray***

$\Big\}$ **Astrophysics**

* PSR J0348+0432 M=2.01±0.04 M_O
** GW170817 $\tilde{\Lambda}(M)$ LVK
*** PSR J0030+0451, PSR J0740+6620 NICER

EoS Constraints from nuclear physics (1): « ab-initio »

Pure neutron matter



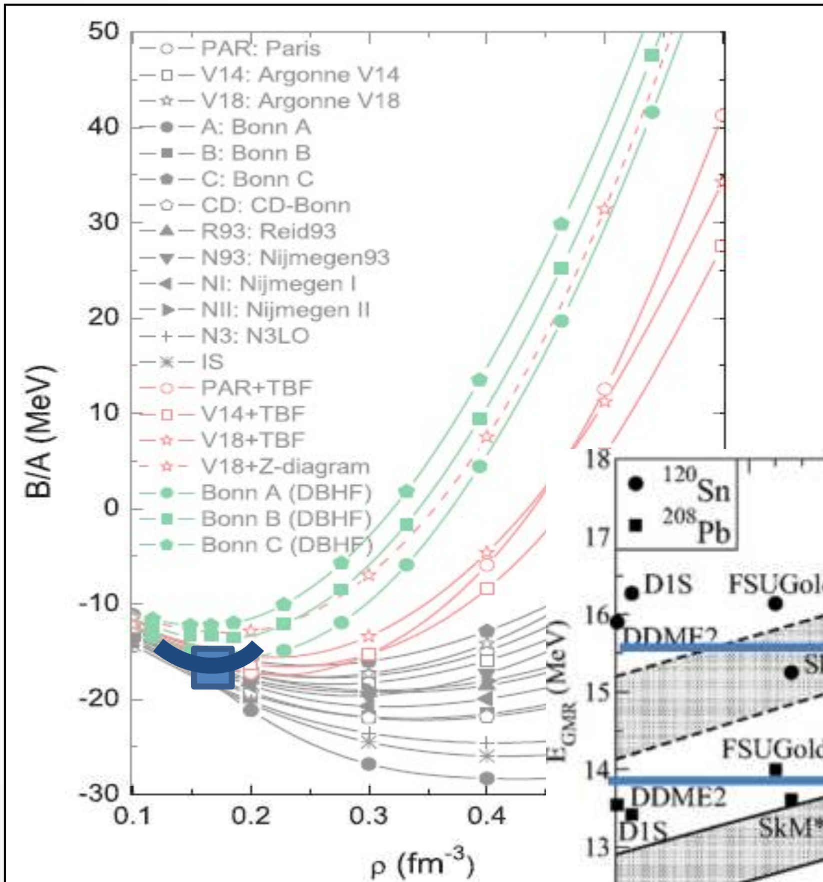
- **Diagrammatic expansion: controlled uncertainties!**
- **Power counting & regularization valid only up to ~ 1,5ρ_0**

=> constrain low order parameters

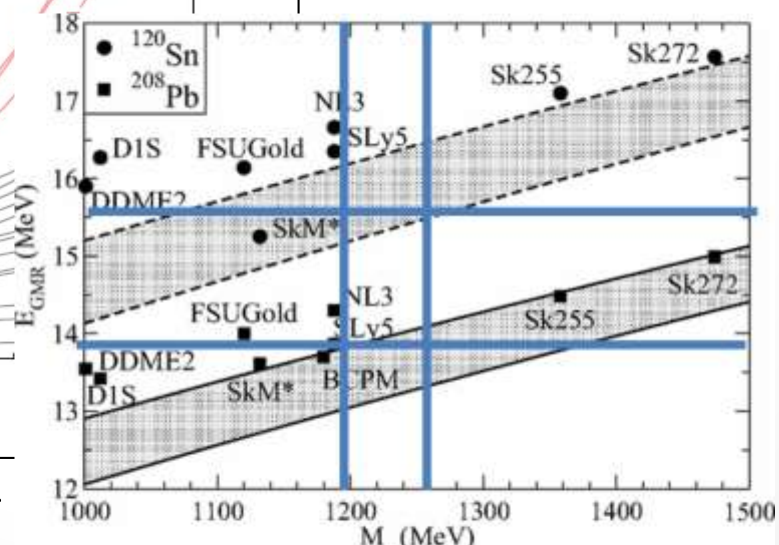
R.Somasundaram et al, Phys.Rev.C 103, 045803 (2021).
I. Tews, T. Krüger, K. Hebeler, and A. Schwenk, Phys. Rev. Lett. **110**, 032504 (2013).
C. Drischler, K. Hebeler, and A. Schwenk, Phys. Rev. C **93**, 054314 (2016).

EoS Constraints from nuclear physics (2): experiments

Symmetric matter



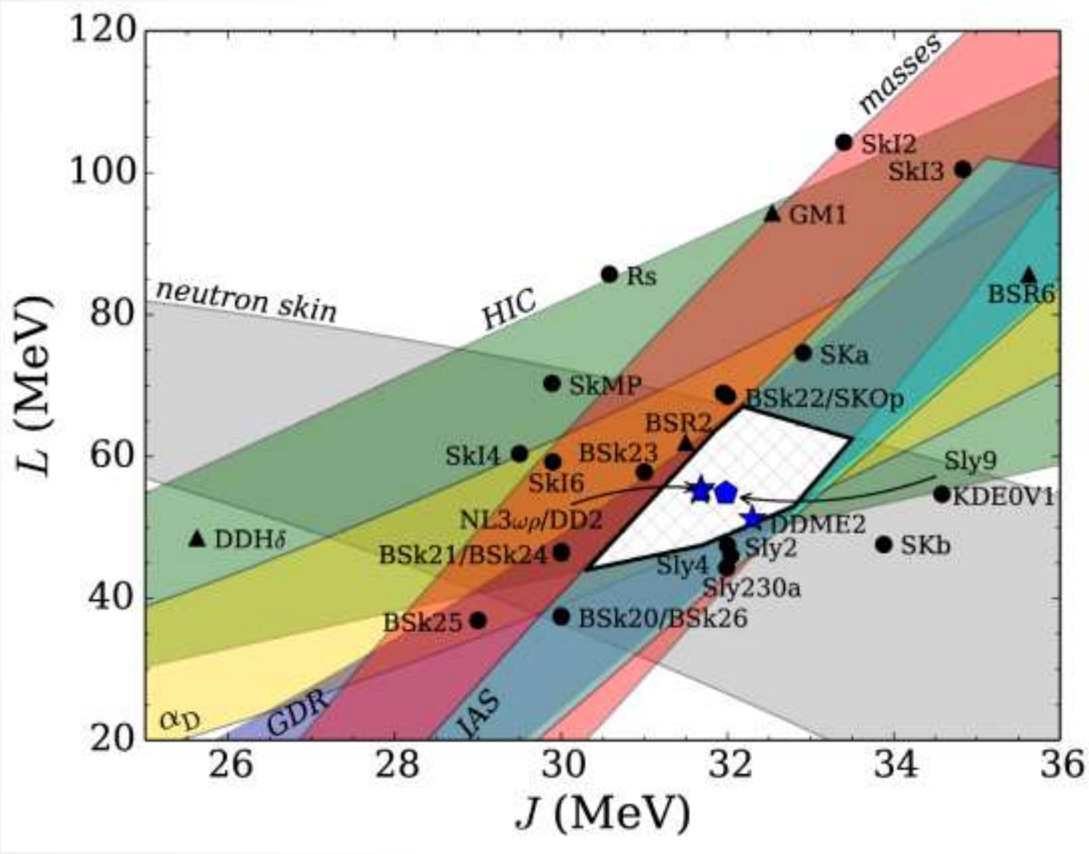
Z.H.Li et al, PRC 74(06) 047304



E.Khan et al, PRL 109(12) 092501

- **Many different observables: masses, radii, skins, collective modes, polarizability, IAS, flows .....**

EoS Constraints from nuclear physics (2): experiments



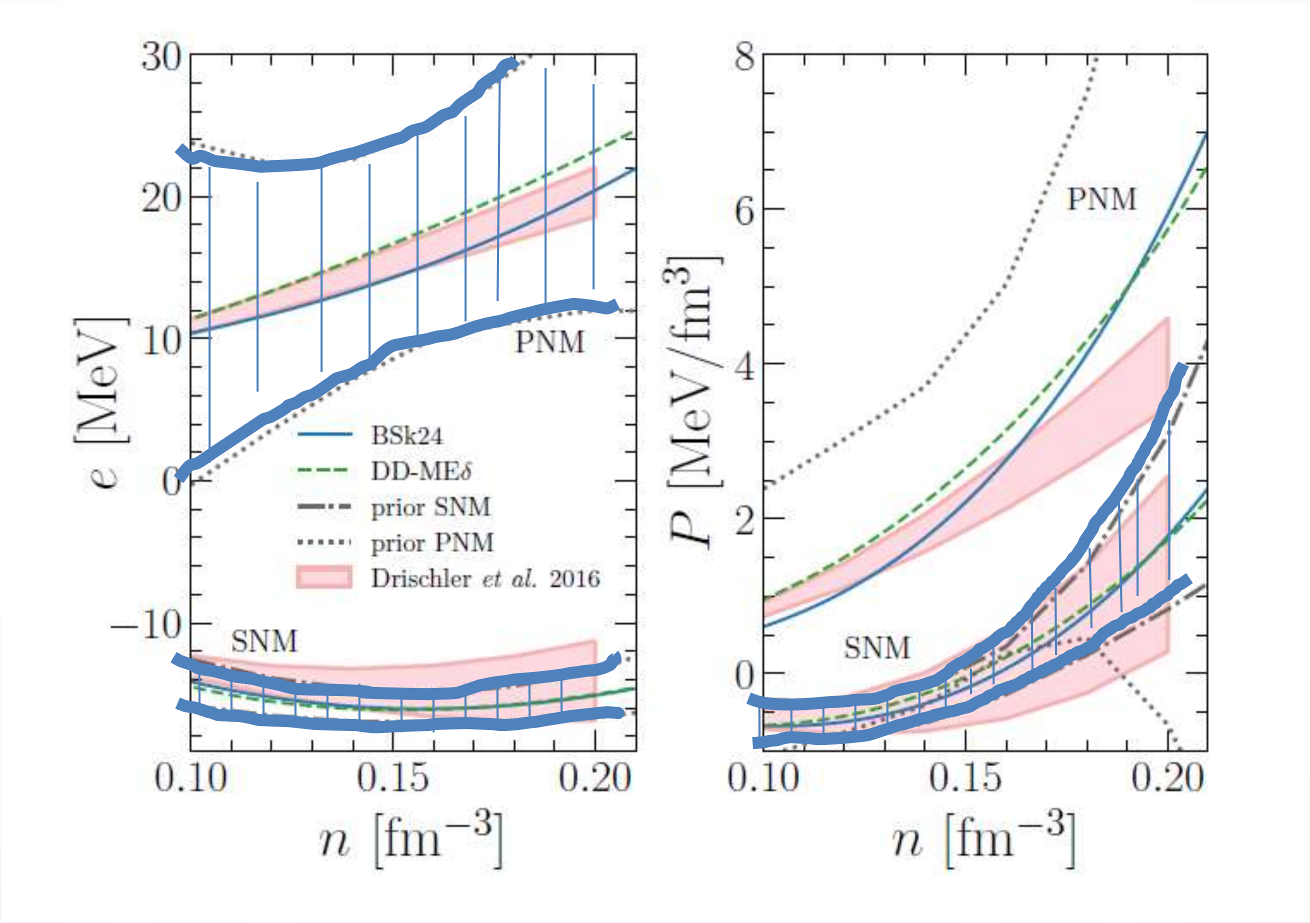
- **Many different observables: masses, radii, skins, collective modes, polarizability, IAS, flows .....**

- **Also sensitive to low densities up to ~ ρ_0**

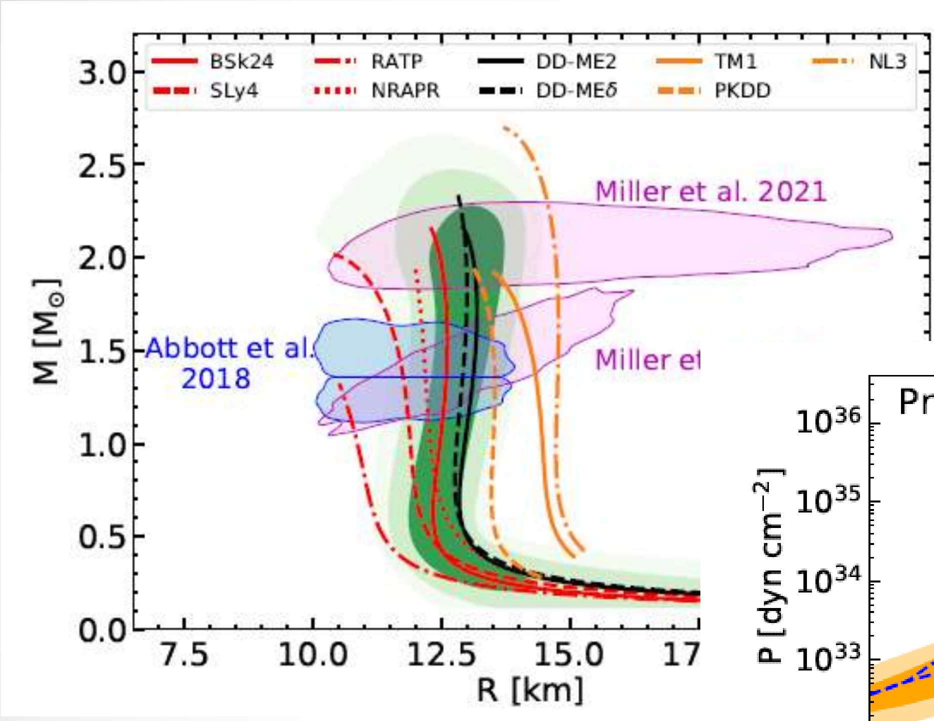
=> *constrain low order parameters*

M.Fortin et al PRC 2016

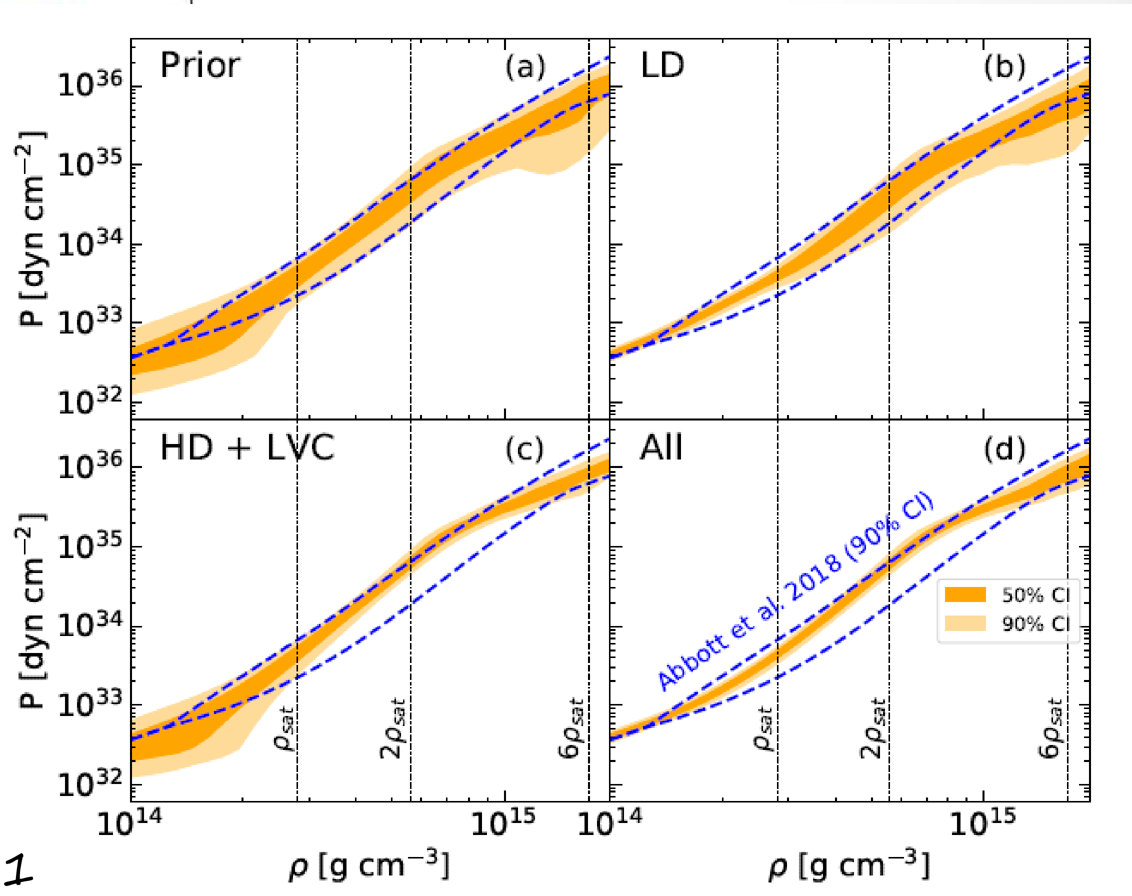
Experimental versus theoretical constraints



Strong challenge for nuclear models



- Nucleonic hypothesis compatible with all observations
- Many popular models do not satisfy the constraints

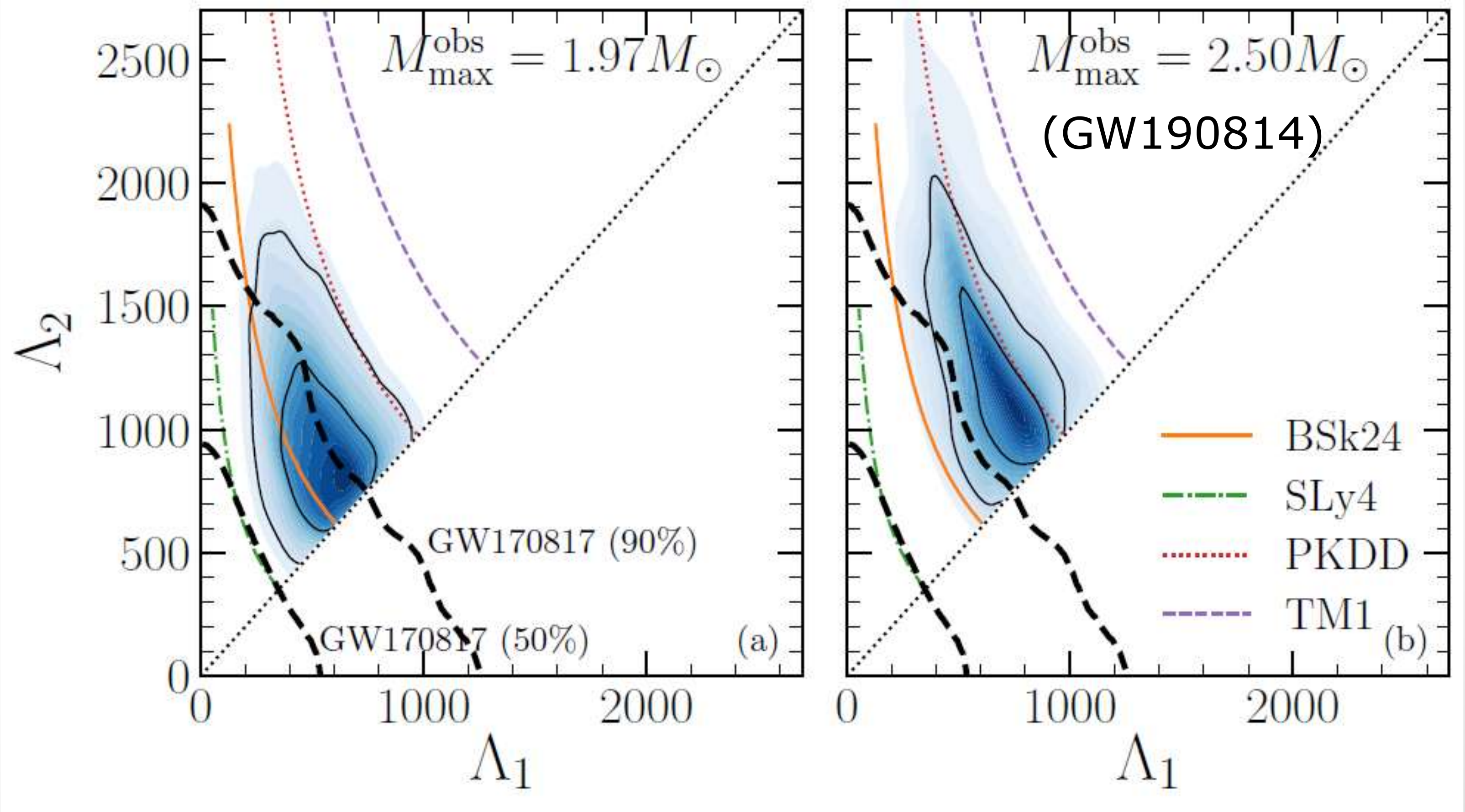


H.Dinh Thi et al, A&A 2021

Strong challenge for future observation

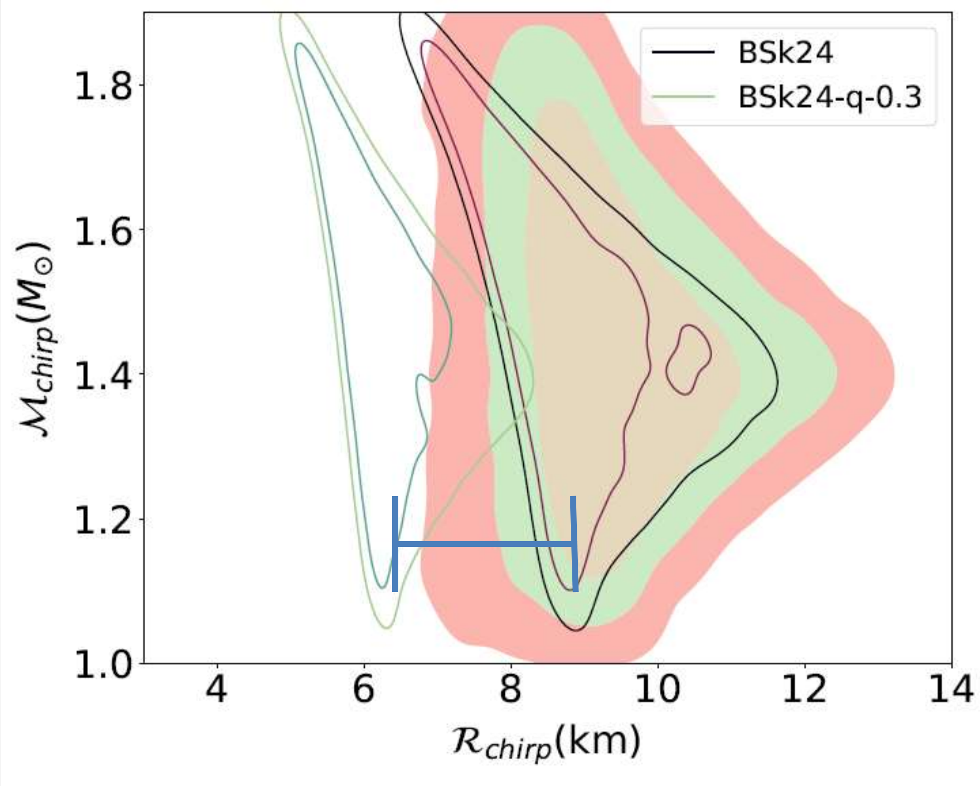
- Nucleonic hypothesis compatible with all observations
- But potential challenge with upcoming measurements

F.G., A.F.Fantina,NPN 2021



Strong challenge for future observation

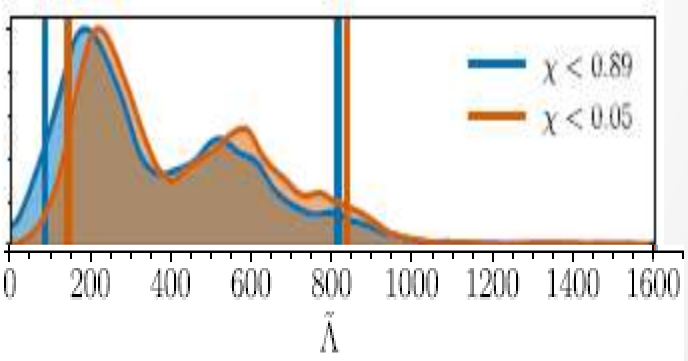
C.Mondal et al., in preparation



$$\mathcal{R}_{chirp} = 2\mathcal{M}_{chirp}\tilde{\Lambda}^{1/5}$$

- Nucleonic hypothesis compatible with all observations
- But potential challenge with upcoming measurements

If $\tilde{\Lambda}$ could be very precisely measured, an (early) 1st order phase transition would be detectable



LVC, PRX 9 (2019), 011001

Strong challenge for future observation

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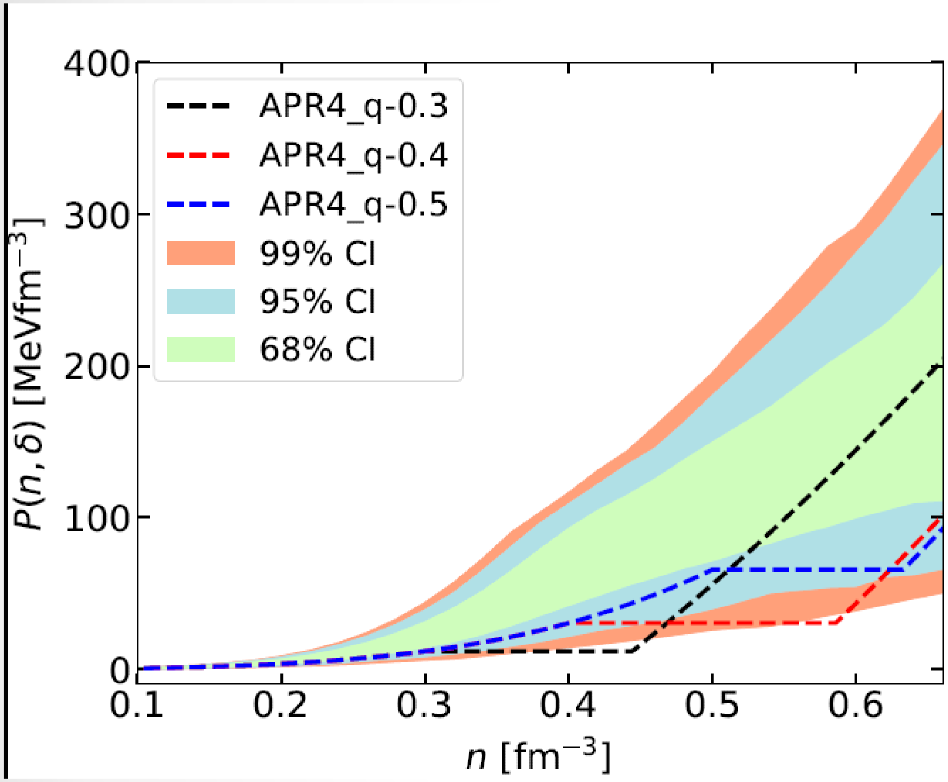
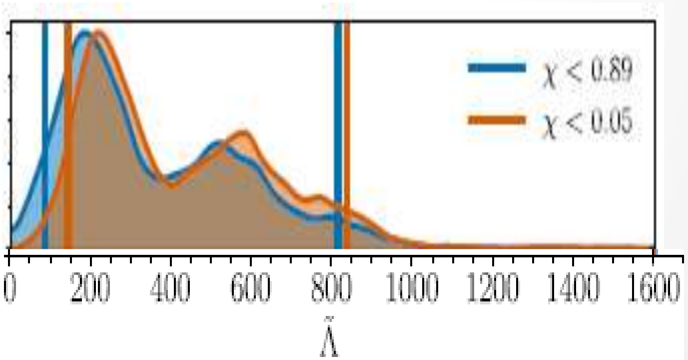


- Nucleonic hypothesis compatible with all observations
- But potential challenge with upcoming measurements

How precise should be the observation to recognize the phase transition from the PN(5) waveform analysis?



LVC, PRX 9 (2019), 011001

Strong challenge for future observation

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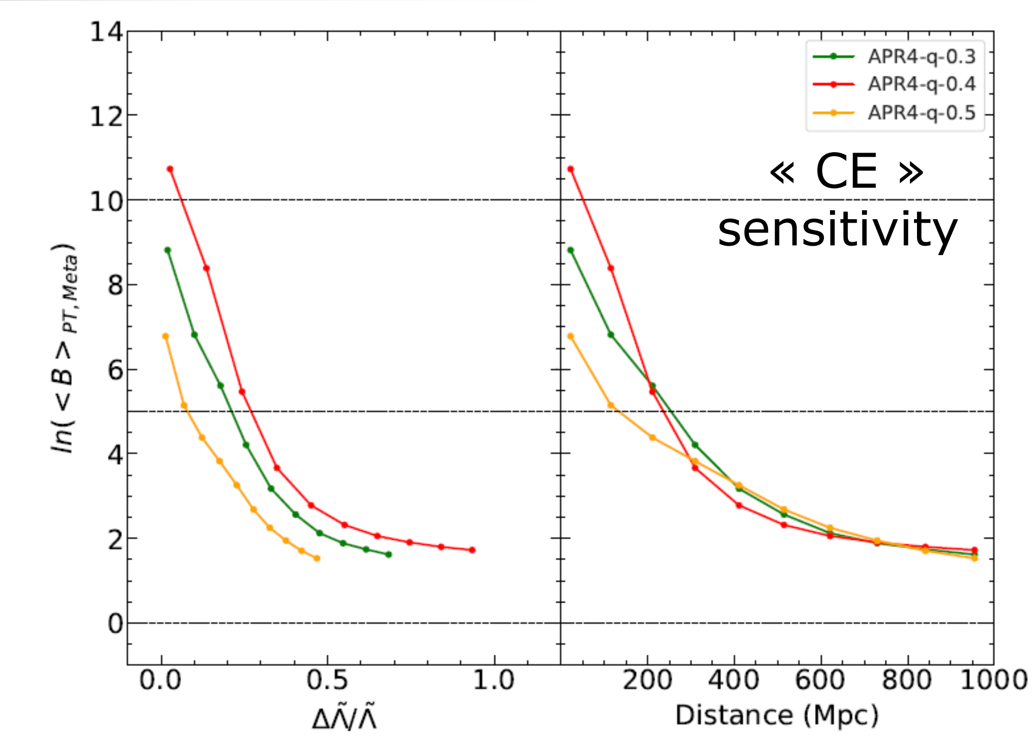

- Nucleonic hypothesis compatible with all observations
- But potential challenge with upcoming measurements

- We suppose the real EoS has an early PT
- An hypothetical physical event $(\mathcal{M}_0, q_0, d)$ detected by next gen. interferometers $(\Delta\tilde{\Lambda}, \Delta q)$ $p^0_{PT}(\tilde{\Lambda}) \leftrightarrow p^0_{GW}(\tilde{\Lambda})$

https://gitlab.com/sborhanian/gwbench

$$log\left(\langle B\rangle^{\mathcal{M}_0,q_0}_{PT,nucl}\right) = \int d\tilde{\Lambda}\, p^0_{GW}(\tilde{\Lambda}) log\left[\frac{p^0_{PT}(\tilde{\Lambda})}{p^0_{nucl}(\tilde{\Lambda})}\right]$$

=> High detectability potential with G3 detectors!

Summary & Conclusions

- The metamodeling technique allows predictions with controlled uncertainties **within the hypothesis of nucleonic matter**
- Astrophysical and nuclear physics constraints can be treated on the same footing

$\Rightarrow$ **No present indication of exotic degrees of freedom**

$\Rightarrow$ **Relatively tight observable prediction within the nucleonic hypothesis: potential challenge with post-O5 and 3G detectors!**

Collaboration: Caen-LUTH Virgo group

- Caen (LPC/GANIL): M.Antonelli, Ph.Davis, H.Dinh Thi, A.F.Fantina, F.Gulminelli, C.Mondal
- Meudon (LUTH): J.Novak, M.Oertel, G.Servignat, L.Suleiman