

Credit: NASA/Swift Dana Berry

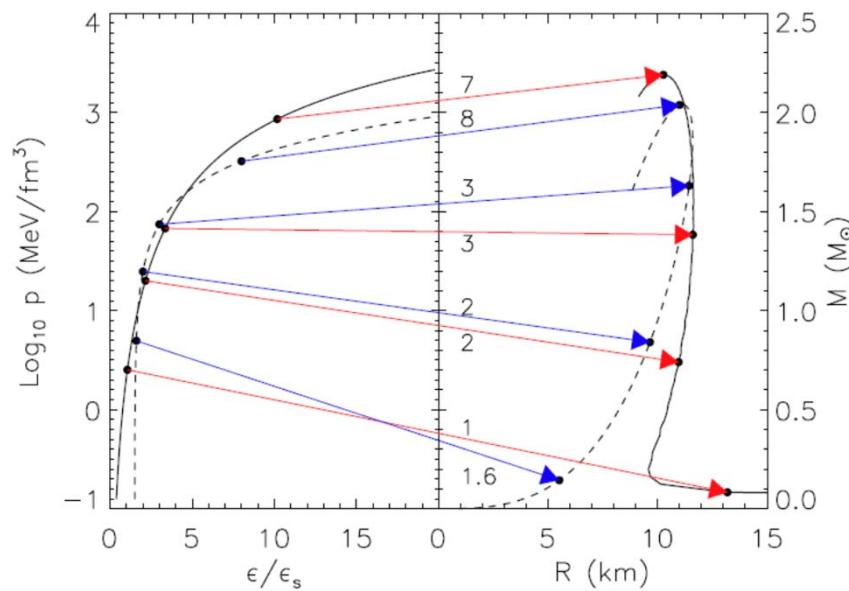
The EoS of dense matter & nuclear physics constraints

Francesca Gulminelli - University of Caen

IWM-EC International conference
November 23-26 2021

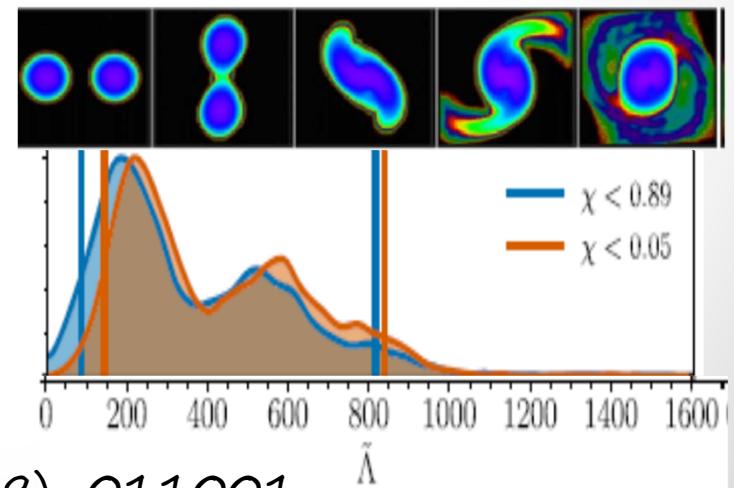
Motivation

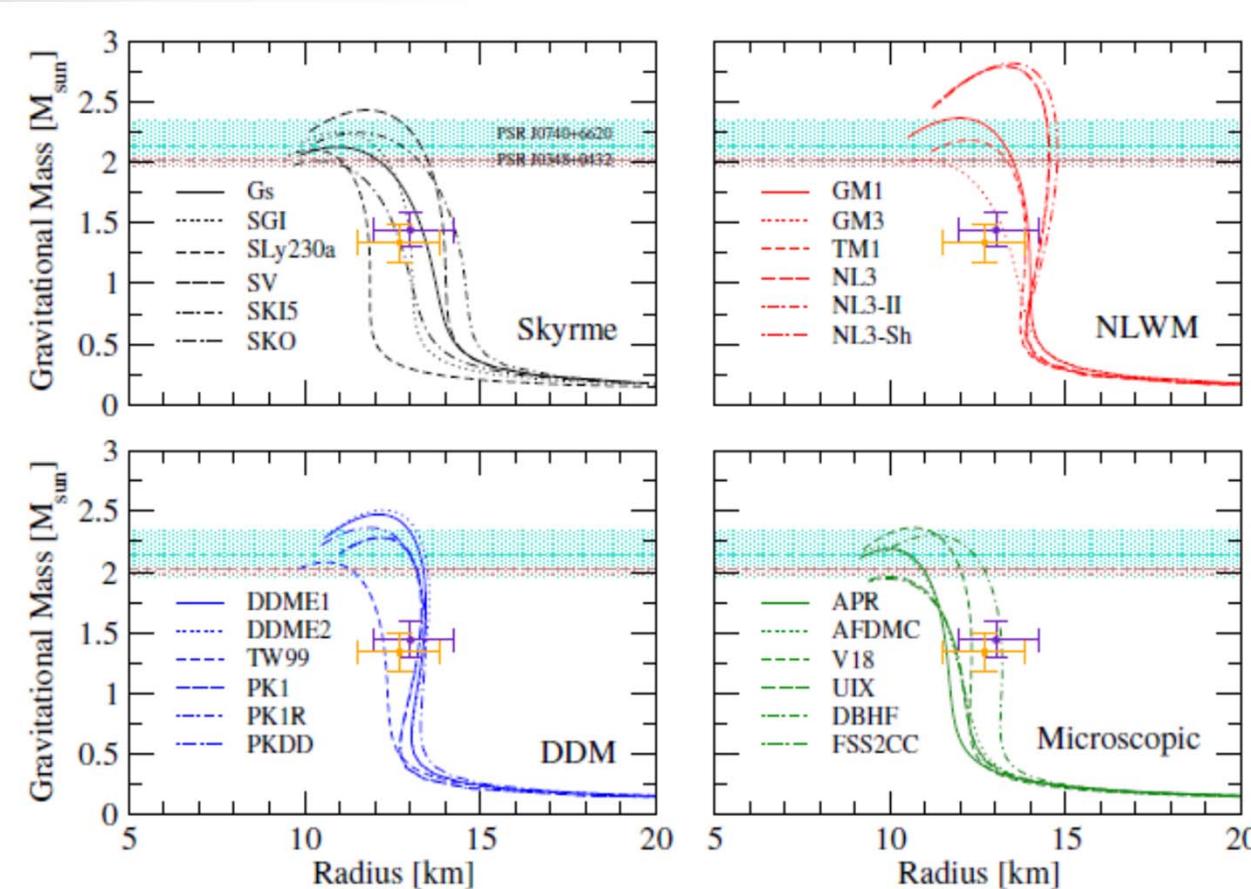
($T=0 - \beta$ eq. for this talk)



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

- GR imposes a 1-to-1 correspondence between the nuclear EoS and static properties of NS
- $M(R)$ (*NICER*), $\Lambda(R)$ (*LVK*) M (*SKA*)
- But EoS is model dependent !





Max masses:

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

Mass-radii:

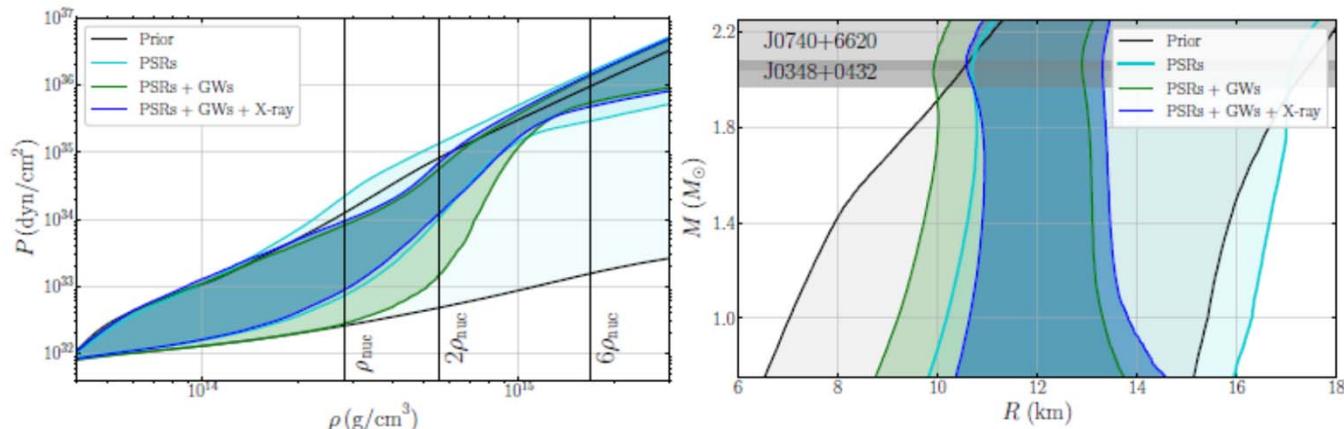
Riley et al, ApJ 2019
Miller et al, ApJ 2019

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

Which are the « good » models?
Is the ensemble exhaustive?

Agnostic non-parametric EoS inference

Max masses
& $\Lambda_{1.4}$
& Mass-radii:



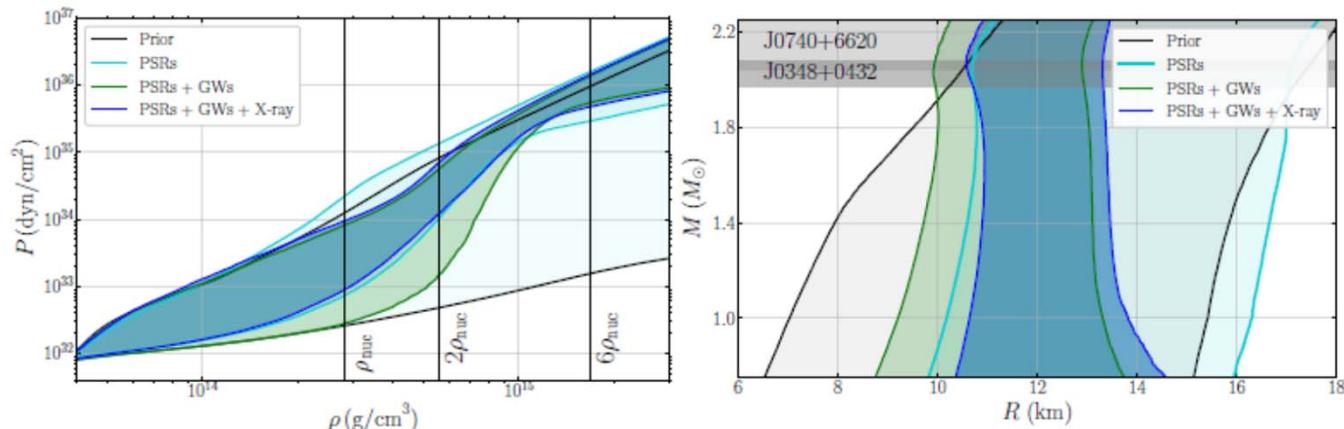
P.Landry, R.Essick, K.Chaudhuri, PRD 101 (2020) 123007

Many popular alternative techniques

- **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.....
-

Agnostic non-parametric EoS inference

Max masses
& $\Lambda_{1.4}$
& Mass-radii:



P.Landry, R.Essick, K.Chaudhuri, PRD 101 (2020) 123007

- Model independent prediction of static astro observables
- Consistency check of the different observations
- But we do not learn much about the properties, structure and composition of dense matter....

$$e(\rho_n, \rho_p) \Rightarrow p(\rho)$$

$$\frac{\partial e}{\partial \rho_n} - \frac{\partial e}{\partial \rho_p} = \mu_e + \Delta m$$

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
- Expansion in powers of the Fermi momentum or of the density
- Parameter space = expansion parameters \vec{X}
 - => « agnostic »: spurious correlations of Skyrme or RMF avoided
- Beta equilibrium imposed $\forall \rho$
 - ⇒ Physical correlations between isoscalar and isovector sector
 - ⇒ Composition available beside pressure
 - ⇒ A null hypothesis for non-nucleonic degrees of freedom

A.Bulgac et al, PRC 2018

J.Margueron et al, PRC 2018

T.Carreau et al, EPJA 2019

R.Essick et al, ArXiv:2107.05528

S.Ghosh et al, ArXiv:2107.09371

H.Dinh Thi et al, A&A 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 $P(\vec{X})$

$$\begin{array}{c} \text{Symmetric matter} \\ \rho_n = \rho_p \end{array} \quad \downarrow \quad e(\rho_n, \rho_p) = e_0 + e_{sym}(\delta)\delta^2$$
$$\begin{array}{c} \text{Symmetry energy} \end{array} \quad \downarrow$$

$$X_k^{bulk} = \frac{d^k e_0(sym)}{d\rho^k} |_{\rho=\rho_0, \delta=0}$$

$E_0, K_0, J, L, K_{sym}, \dots$

$\sigma_0, \sigma_c, \dots$

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

Nucleonic Meta-modeling

= the most general EoS *under the nucleonic hypothesis*

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

f_1 . ab-initio EoS (MBPT)

f_2 . empirical uncertainties on \vec{X}_{bulk}

f_3 . nuclear masses

f_4 . max.mass from radio timing*

f_5 . tidal polarizability from GW**

f_6 . M(R) from X-ray***

Nuclear physics
« LD »

Astrophysics
« HD »

* PSR J0348+0432 $M=2.01\pm0.04 M_\odot$

** GW170817 $\tilde{\Lambda}(M)$ LVK

*** PSR J0030+0451, PSR J0740+6620 NICER

Nucleonic Meta-modeling

= the most general EoS *under the nucleonic hypothesis*

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

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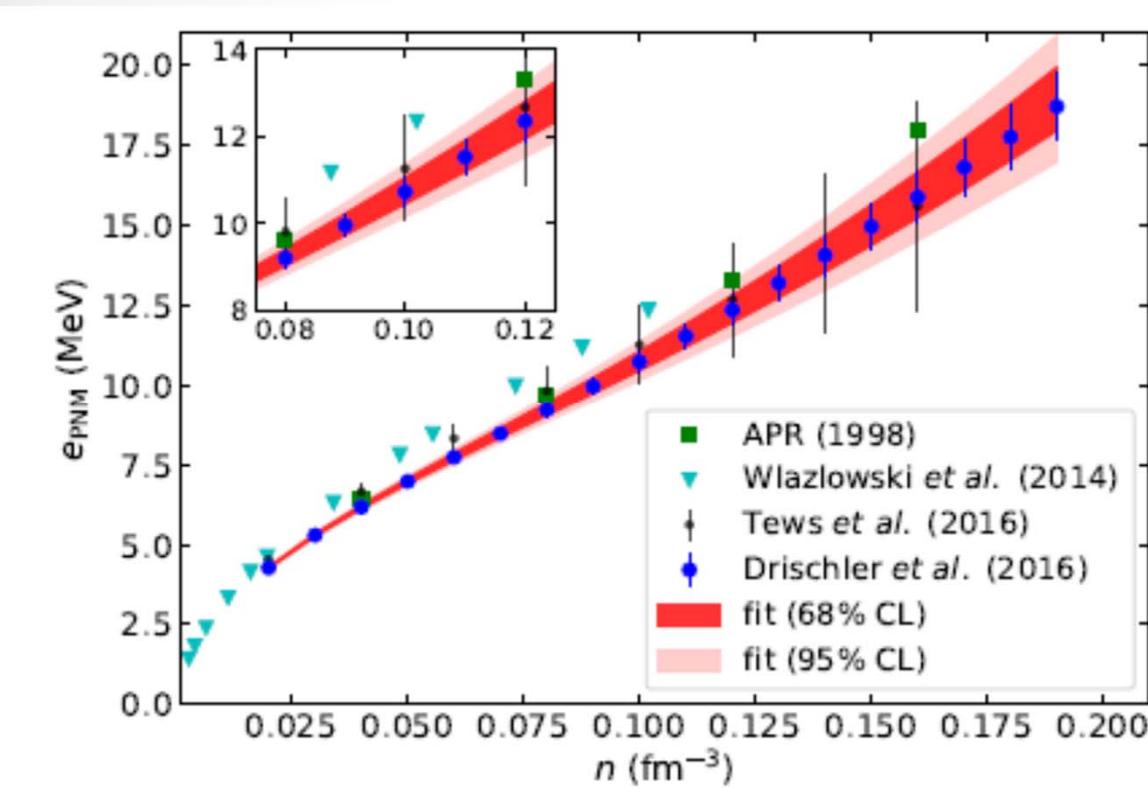
Nuclear physics
« LD »

Astrophysics
« HD »

=> Predict astro observables with controlled uncertainty intervals
within the nucleonic hypothesis

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

Pure neutron matter



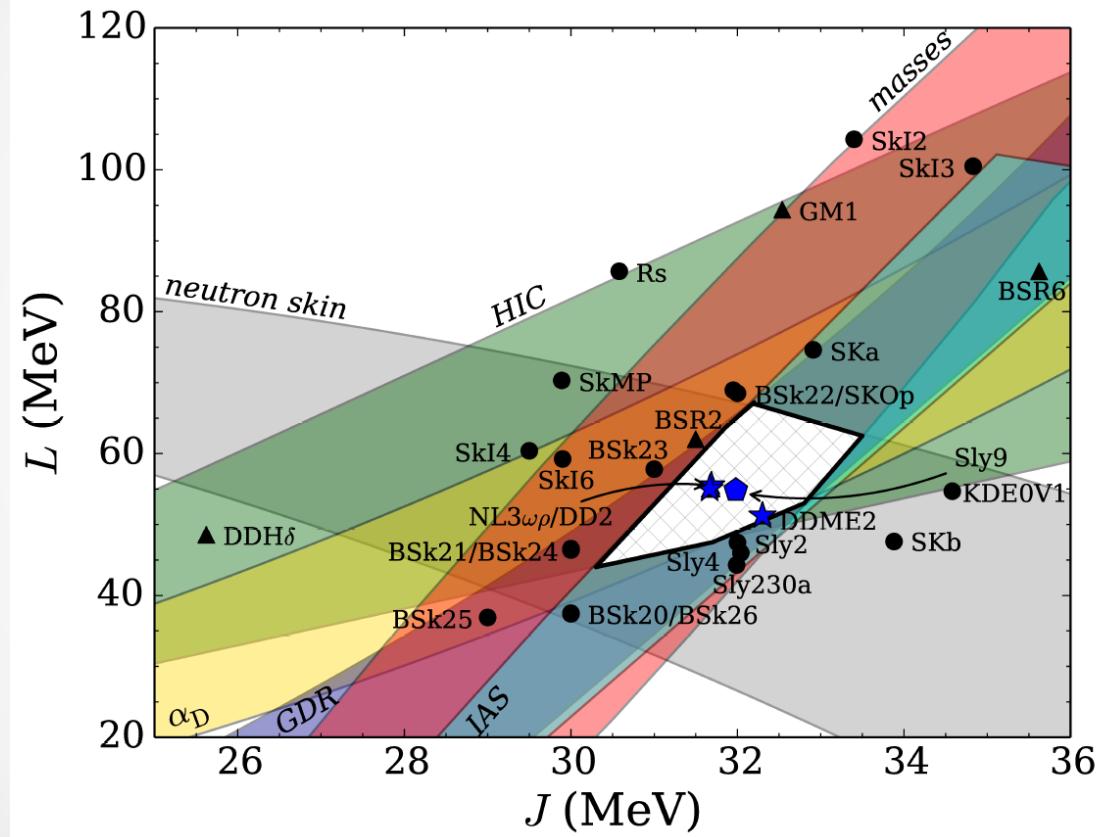
- **Diagrammatic expansion: controlled uncertainties!**
- **Power counting & regularization valid only up to $\sim 1.5\rho_0$**
=> constrain low order parameters

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

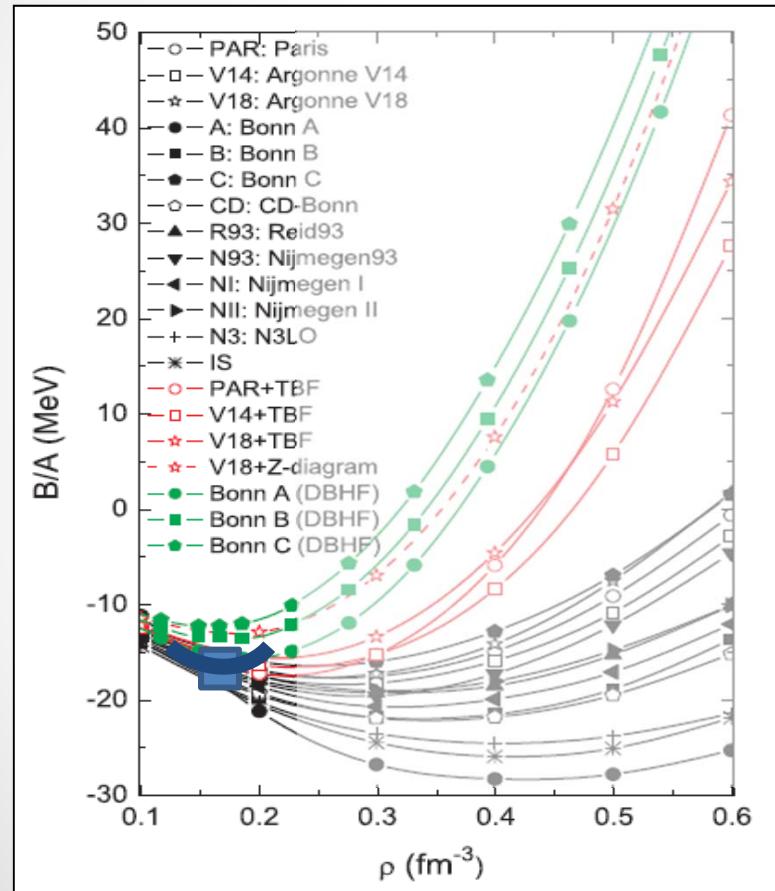


- **Many different observables: masses, radii, skins, collective modes, polarizability, IAS, flows**
- **Also sensitive to low densities up to $\sim \rho_0$**
=> constrain low order parameters

M.Fortin et al PRC 2016

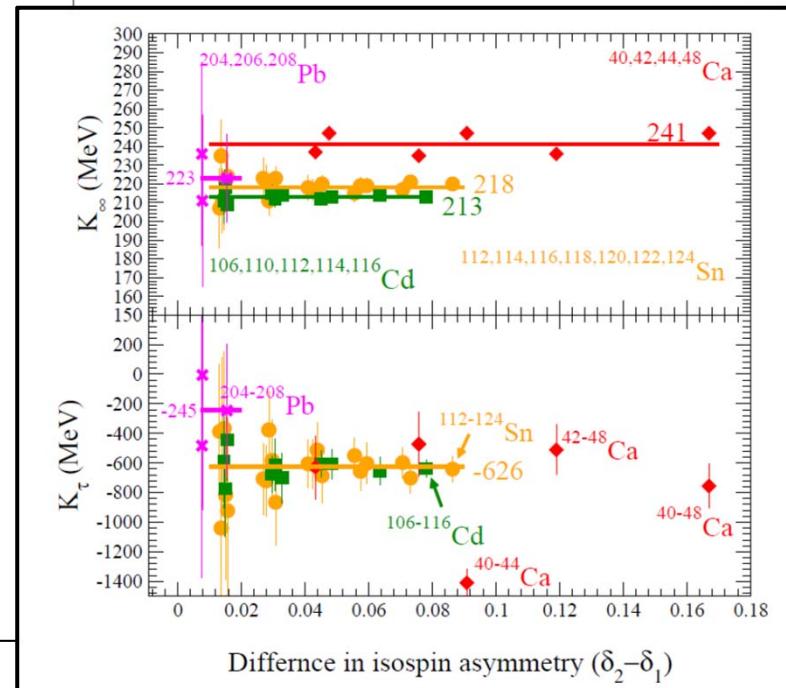
EoS Constraints from nuclear physics (2): experiments

Symmetric matter



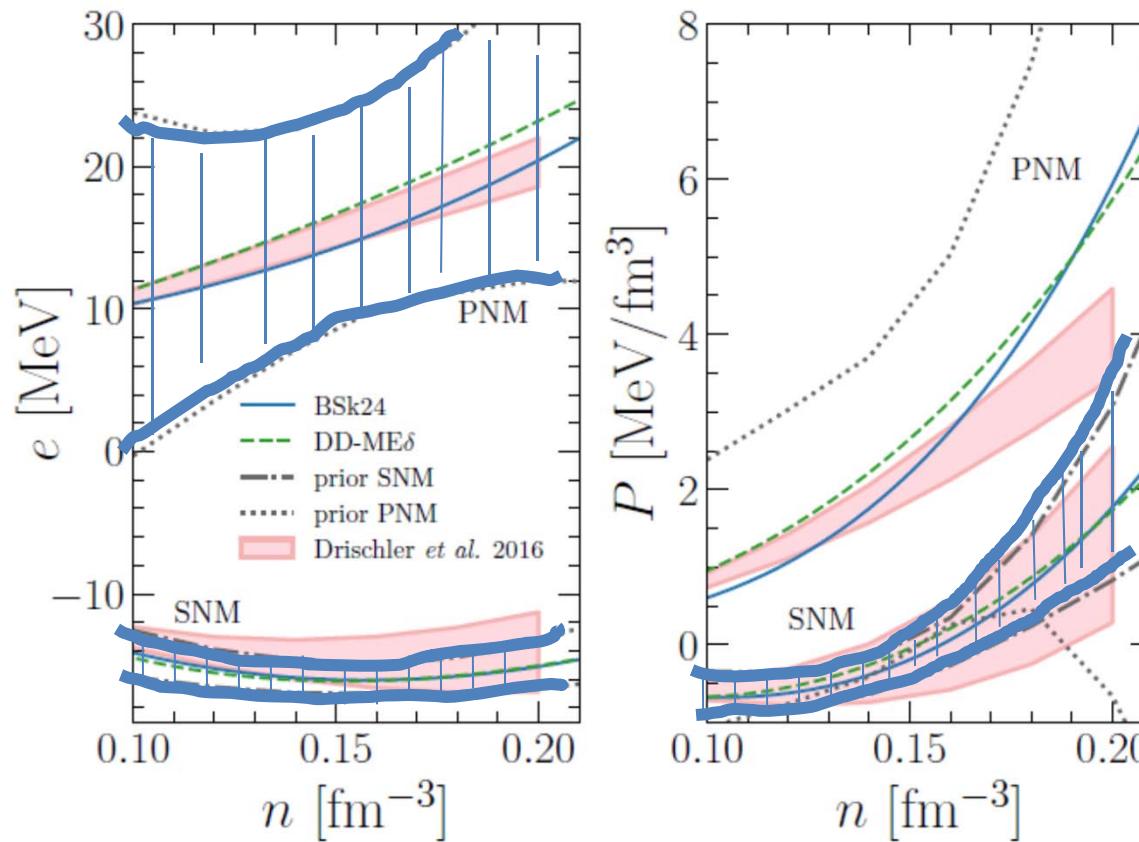
Z.H.Li et al, PRC 74(06) 047304

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



B.A.Li, W.J.Xie PRC 104(21) 034610

Experimental versus theoretical constraints



EoS Constraints from nuclear physics (3): masses

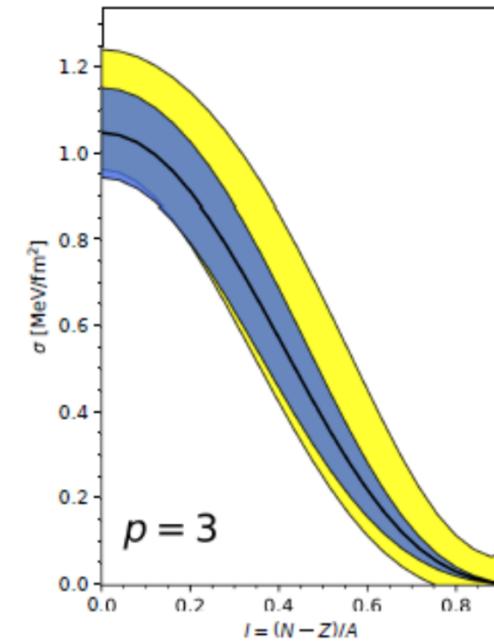
$$M(A, Z) = Am + E_{bulk} + E_{surf}$$

=> sub-saturation EoS

Surface parameters	n_{sat}	E_{sat}	K_{sat}	Q_{sat}	Z_{sat}	E_{sym}	L_{sym}	K_{sym}	Q_{sym}	Z_{sym}
b_s	-0.15	-0.84	0.25	-0.03	-0.06	-0.00	-0.26	-0.04	0.15	-0.06
σ_0	0.51	-0.98	0.15	-0.02	0.02	0.63	0.27	-0.01	0.04	0.02
b	-0.01	-0.07	0.04	-0.14	0.03	0.04	0.00	-0.06	0.07	0.04

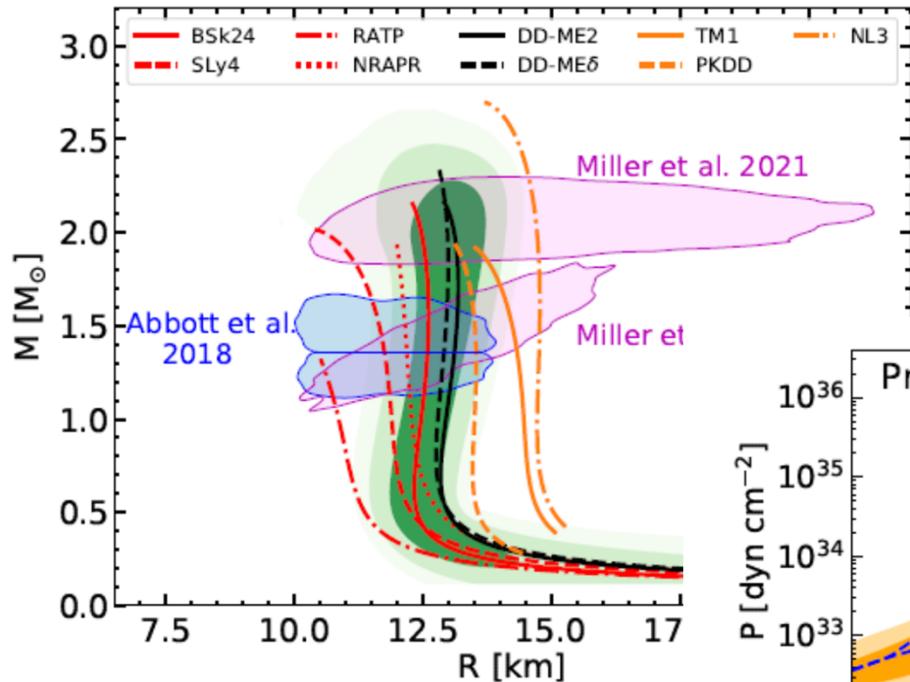
Bulk parameters

$$P(M|\vec{X}) = \exp - \left(\sum_i^{AME} \frac{(M_i^{exp} - M_i(\vec{X}))^2}{2\sigma_i^2} \right)$$

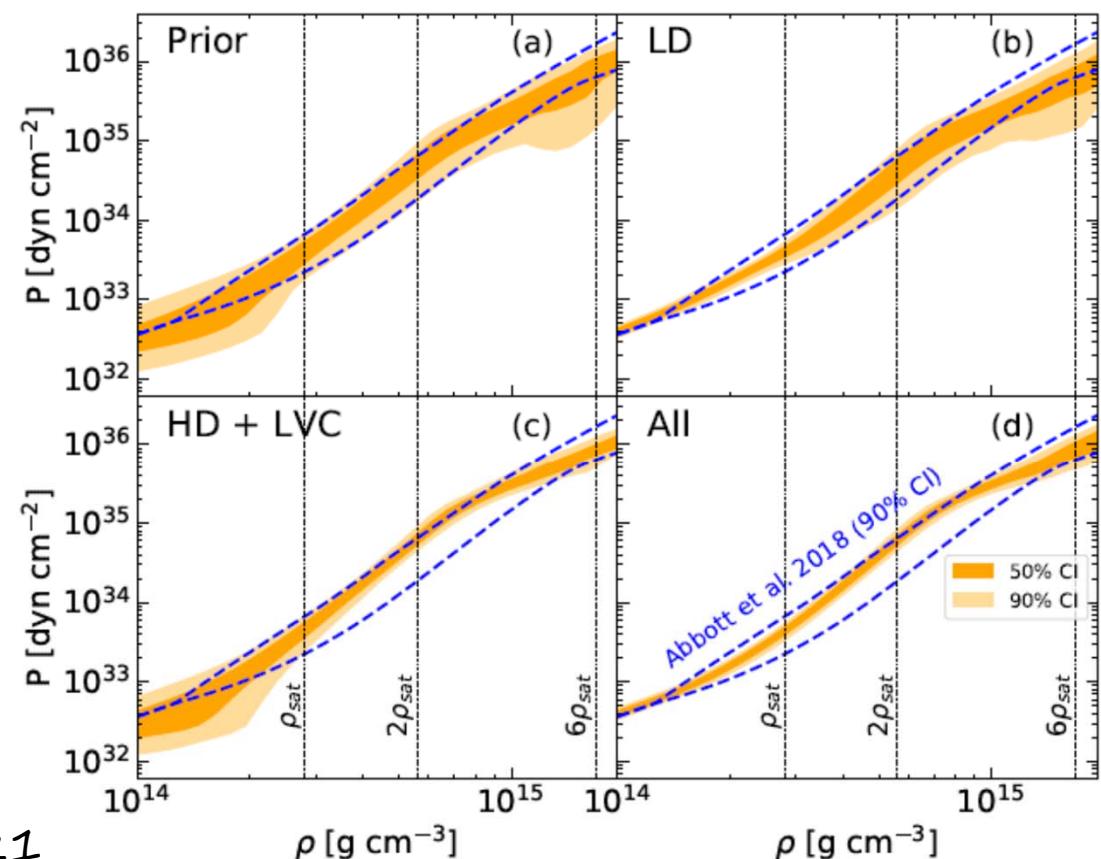


- T.Carreau et al, EPJA 2019

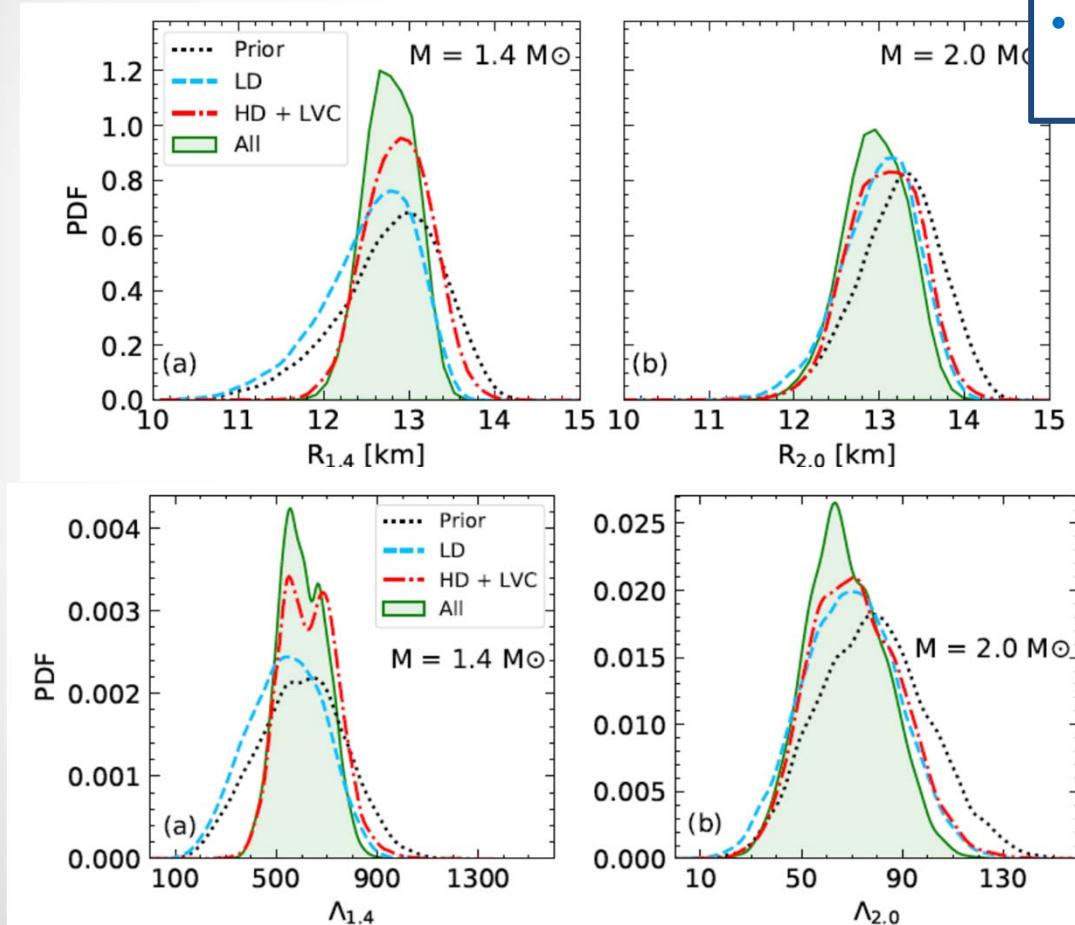
Strong challenge for nuclear models



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



Strong challenge for nuclear models

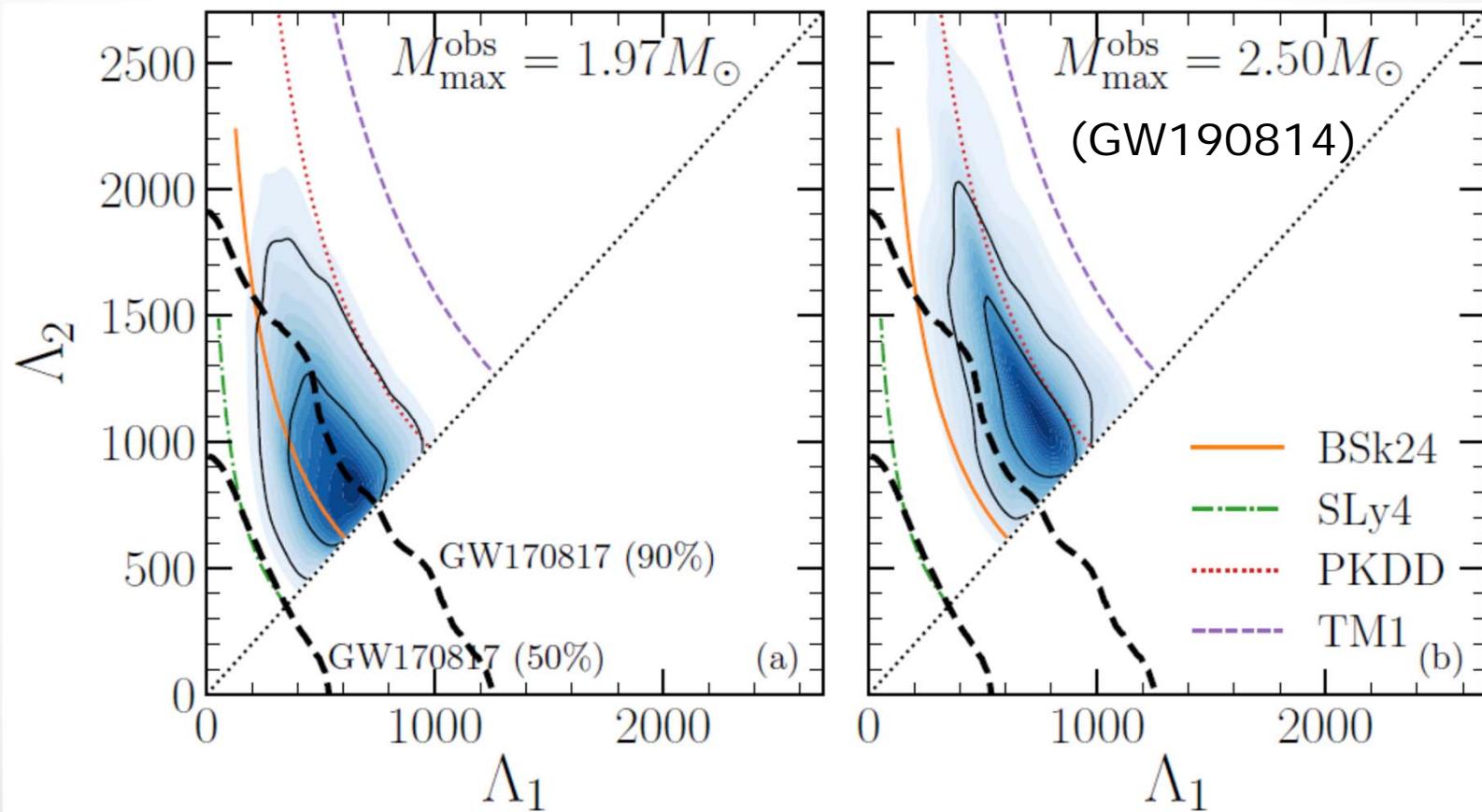


- Nucleonic hypothesis compatible with all observations
- But potential challenge with upcoming measurements

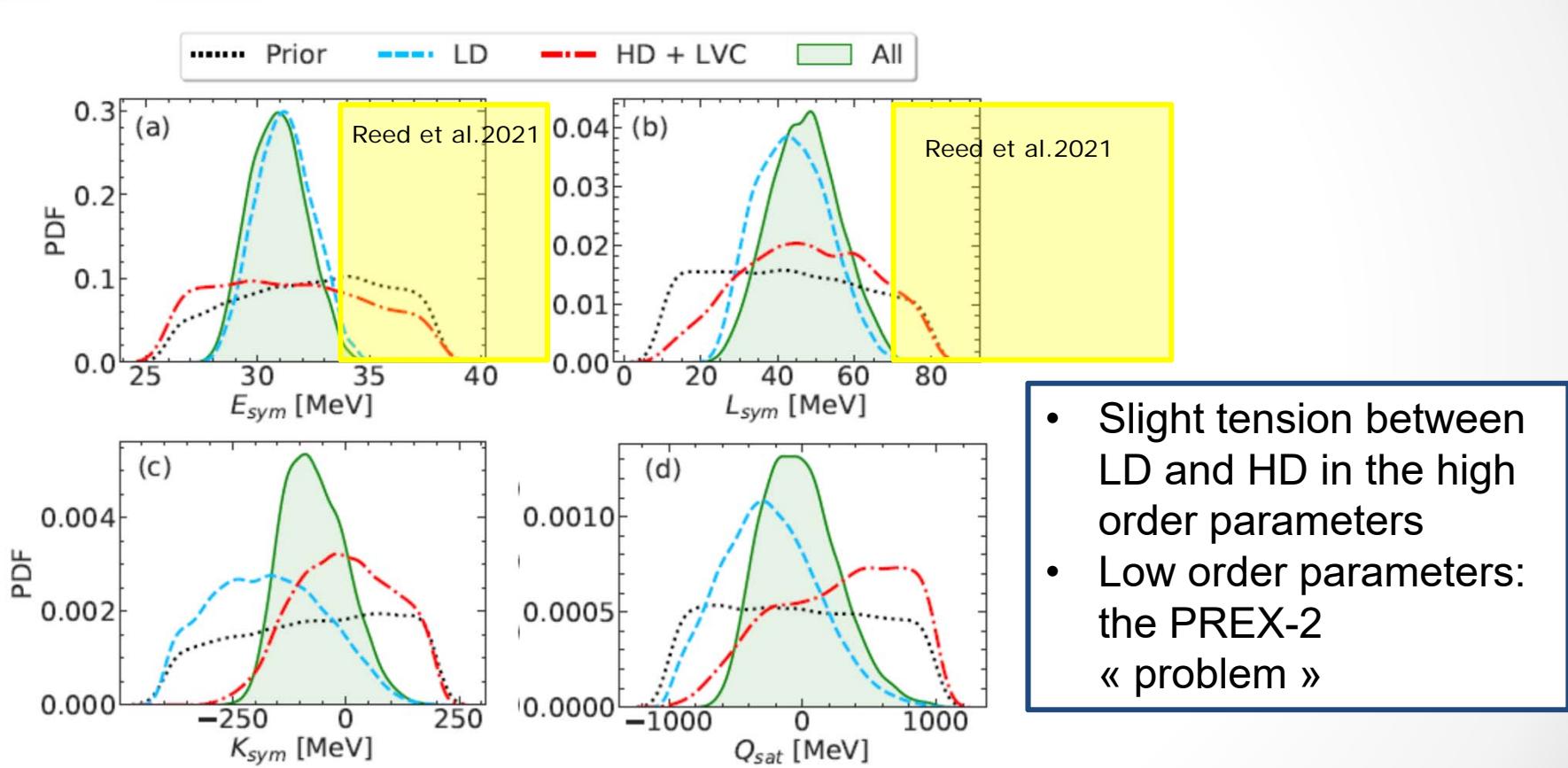
Strong challenge for nuclear models

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

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



Tensions in the empirical parameters?



Partial conclusion

- - ⇒ No present indication of exotic degrees of freedom
 - ⇒ Relatively tight observable prediction within the nucleonic hypothesis: potential challenge with upcoming observations!
 - ⇒ Is it worthwhile to further constrain the nucleonic EoS from nuclear physics ?
 - (1) The importance of high density constraints at fixed N/Z
 - (2) The importance of low density constraints at fixed N/Z
-

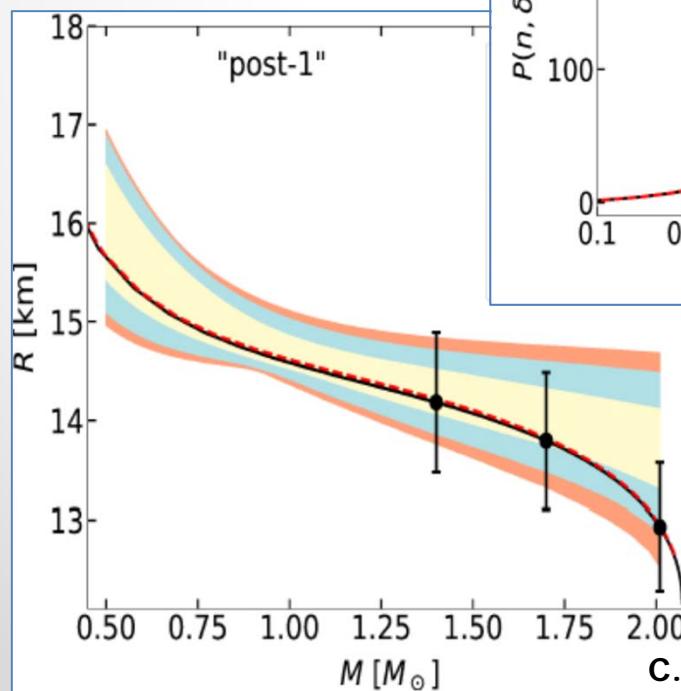
The importance of lab constraints:

$$e(\rho_n, \rho_p) \xrightarrow{\quad} p(\rho)$$

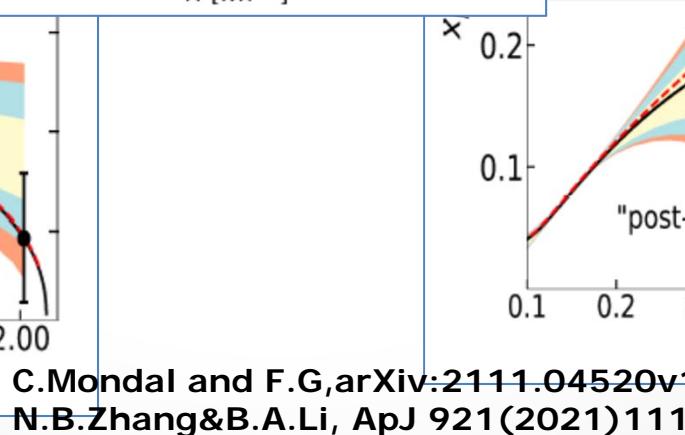
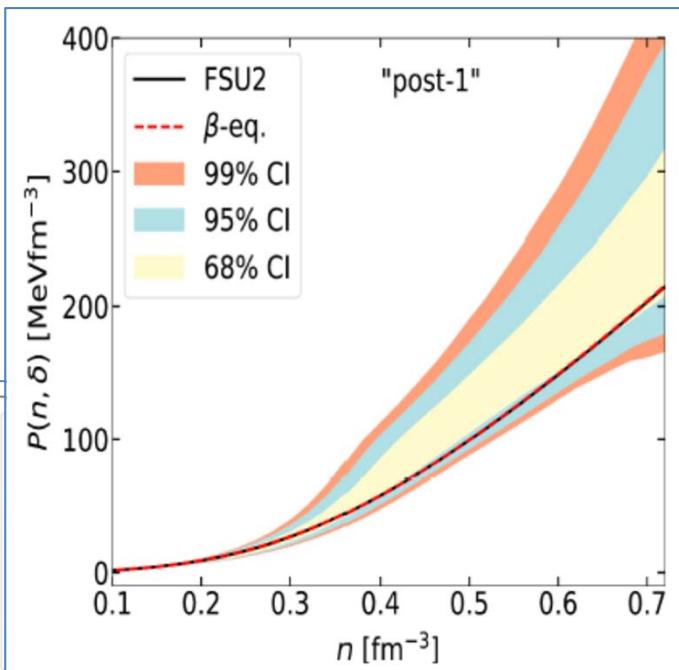
$$e(\rho_n, \rho_p) \xleftarrow{\quad} p(\rho)$$

$$p = p_0 + p_{sym}(1 - 2x_p)^2$$

$$\mu_n - \mu_p = \mu_e$$



(1) high density

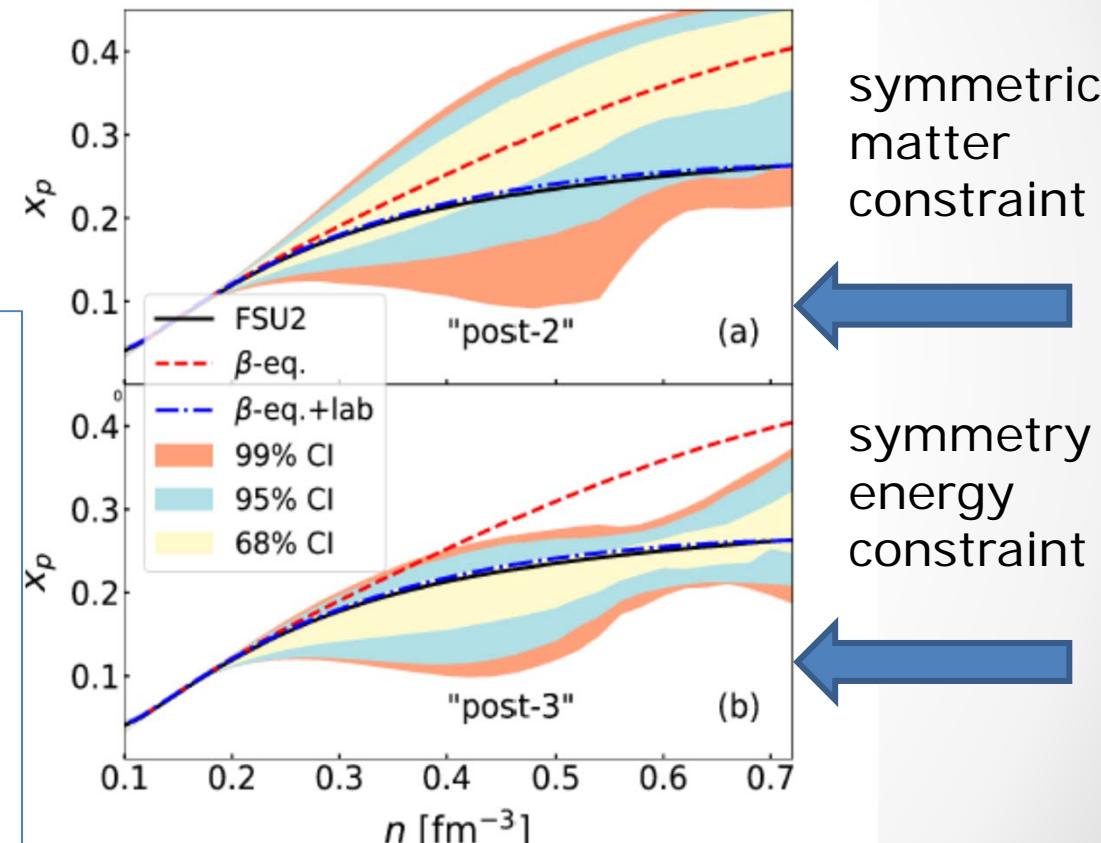
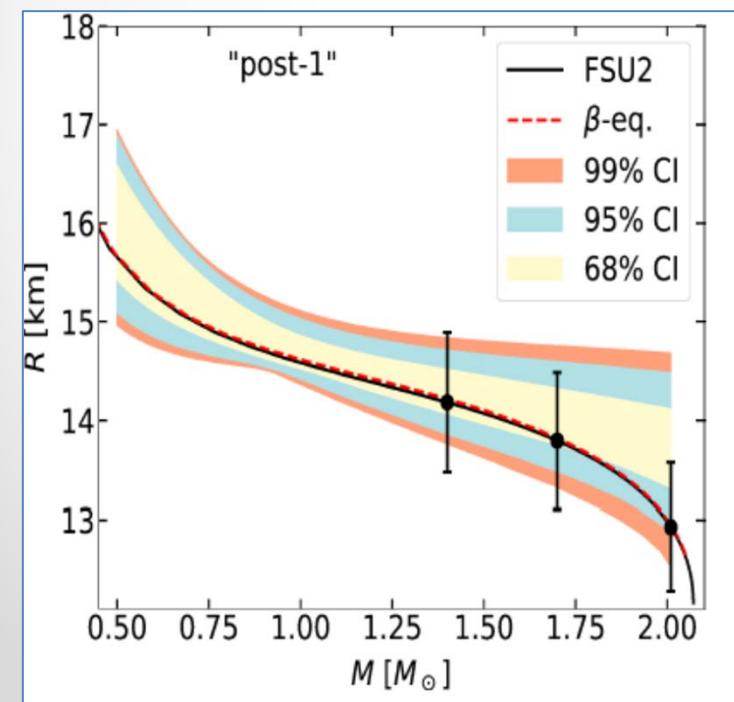


- precise measurements of $R \rightarrow$ EoS via inversion of the TOV
- But the composition is fully unconstrained due to multiple solutions of the β -equilibrium eq.

The importance of lab constraints:

- The « true » functional is pinned down if the info of a **high density point** (symmetric matter or symmetry energy) is added (blue lines)

(1) high density

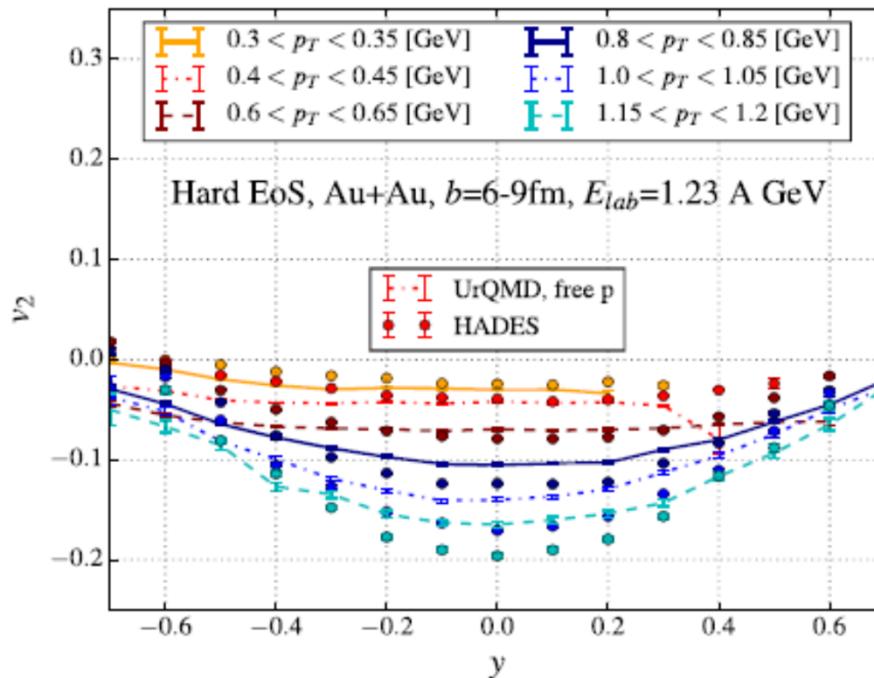


Tighter constraints from high energy experiments ?

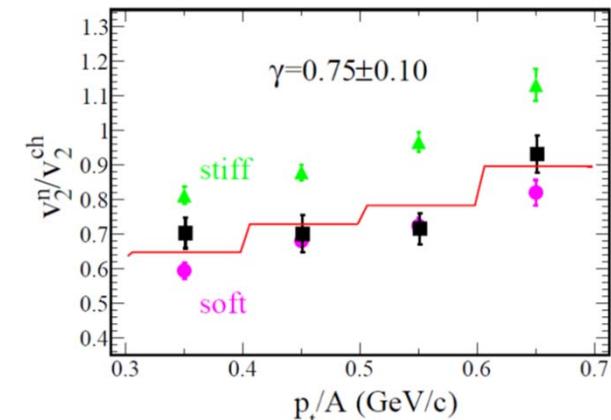
ASY-EoS@GSI:

P.Russotto et al, Phys. Rev. C 94, 034608 (2016)

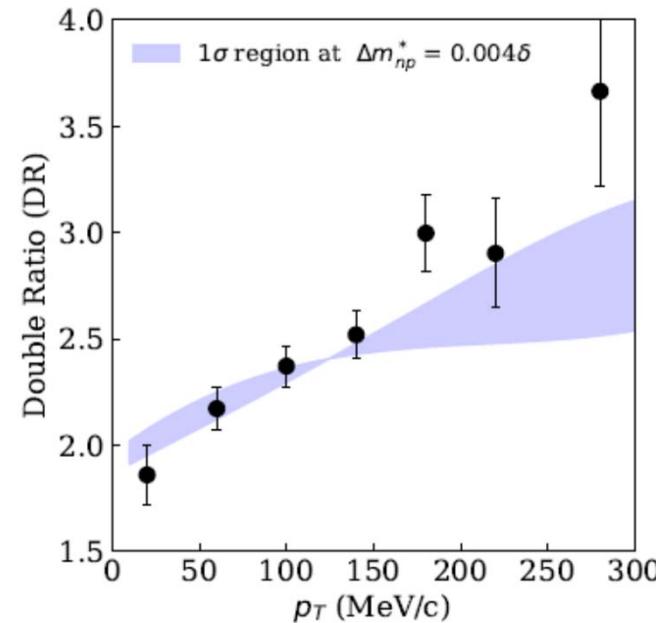
Elliptic flow @ HADES:



P.Hillmann et al., JPG 47 (2020) 055101



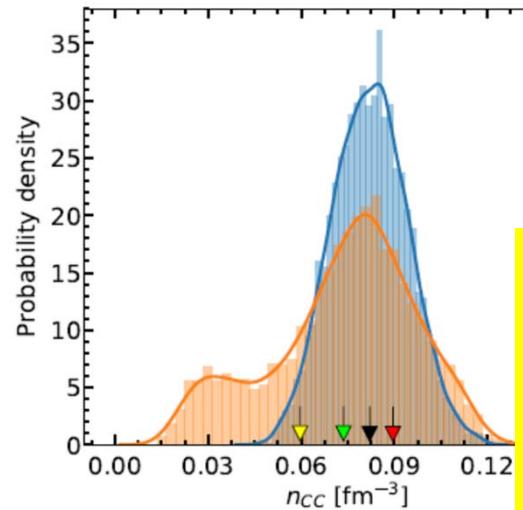
Double pion ratio @ RIBF:



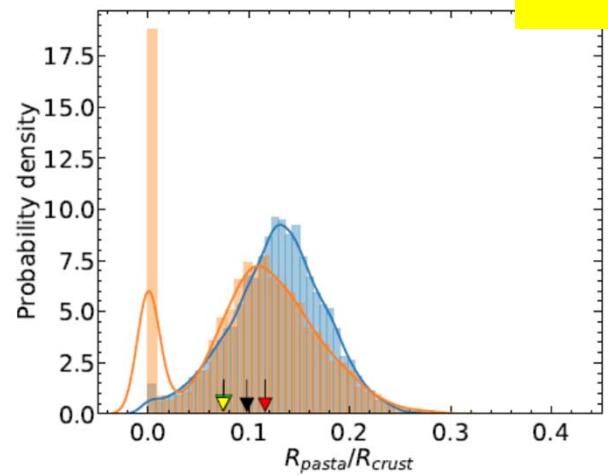
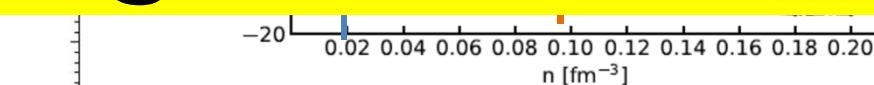
J.Estee et al., PRL 126 (2021) 162701

The importance of lab constraints:

(2) low density



See Hoa's talk
right now!



- If the chiral constraint is only applied from $n=0.1$ models with thin crust and no pasta cannot be excluded
- Crustal properties crucially depend on the very low density EoS

Conclusions & outlooks

- 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 **within the hypothesis of nucleonic matter**
- Astrophysical and nuclear physics constraints can be treated on the same footing

=> **No present indication of « exotic » degrees of freedom**

- Upcoming observations might give hints on the presence of deconfined matter in NS
- Measurements of high density matter with controlled isospin (HIC) are essential to pin down the composition of dense matter
- Modeling and measurements at very low density crucial for the inner crust



Collaboration:Master Project NewMAC



(CNRS-In2p3)

<https://indico.in2p3.fr/event/21849/>

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- Lyon (IP2I): G.Grams, H.Hansen, J.Margueron, A.Pfaff, R.Somasundaram
- Meudon (LUTH): J.Novak, M.Oertel, G.Servignat, L.Suleiman

Collaboration:Master Project NewMAC



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