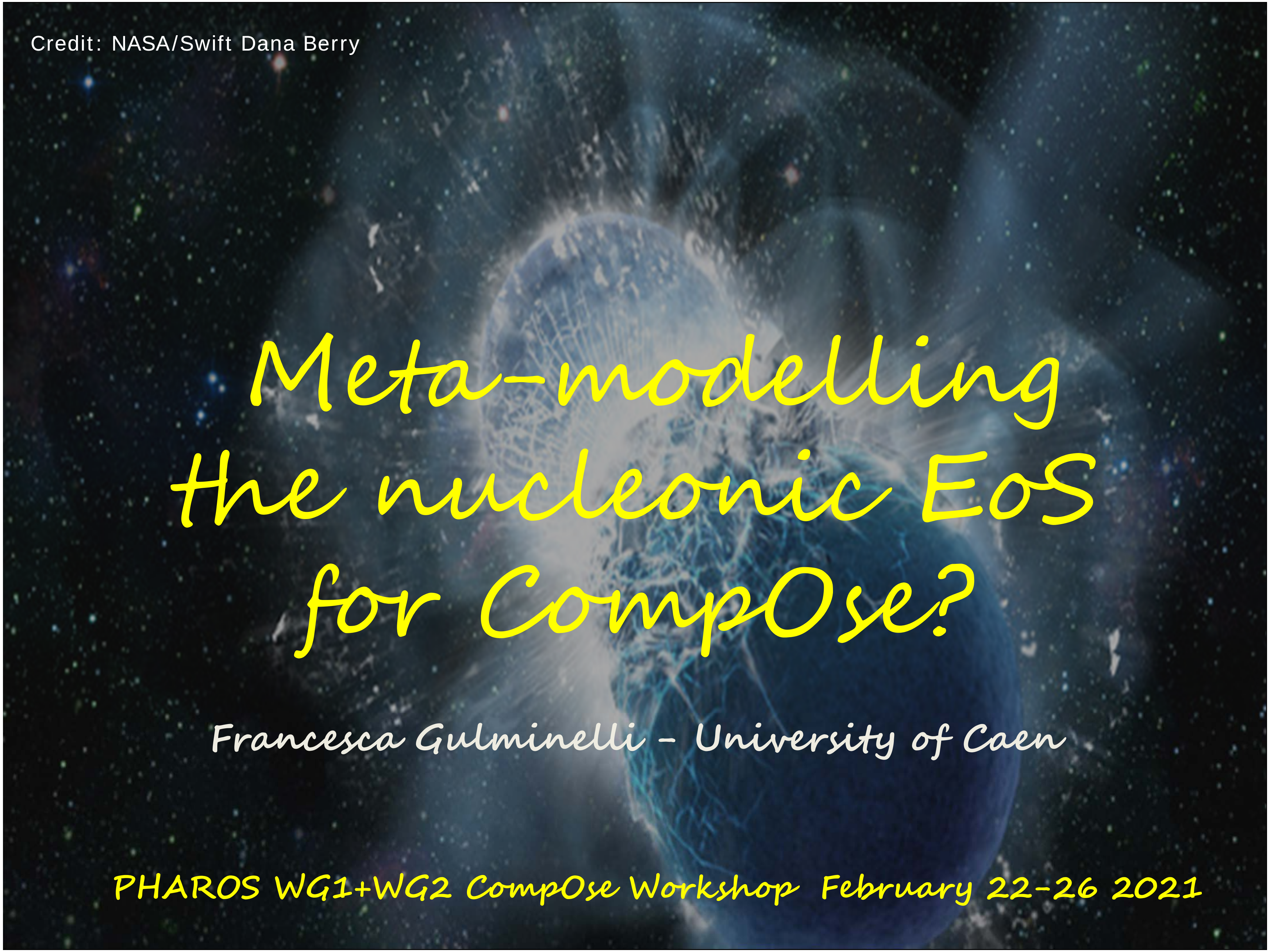


Credit: NASA/Swift Dana Berry

Meta-modelling the nucleonic EoS for CompOse?

Francesca Gulminelli - University of Caen

PHAROS WG1+WG2 CompOse Workshop February 22-26 2021

Master Project NewMAC

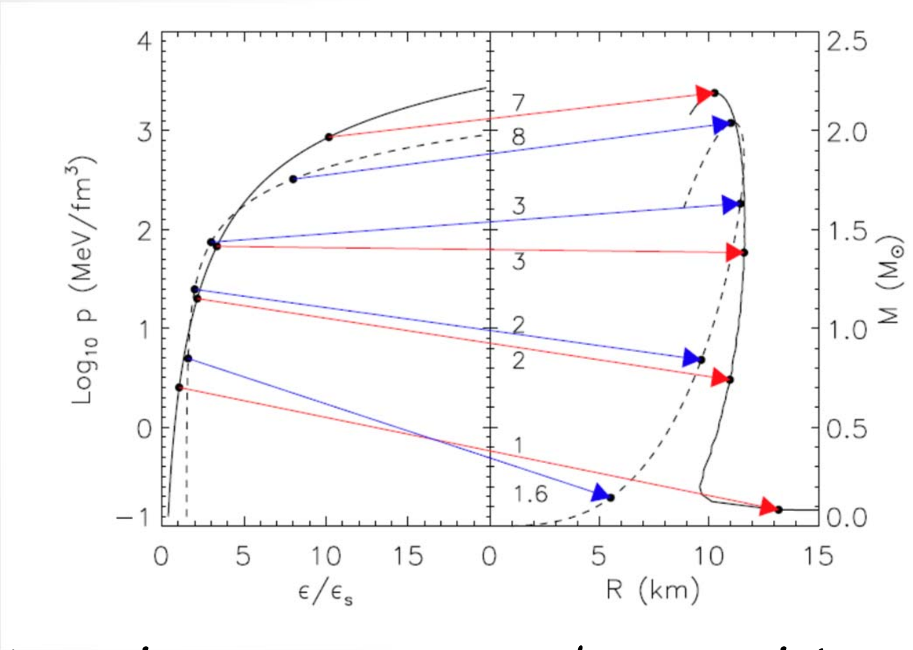
(CNRS-In2p3)

https://indico.in2p3.fr/event/21849/?view=standard
Contact: **MAC-L@IN2P3.fr**

- Caen (LPC/GANIL): H.Dinh Thi, A.F.Fantina, F.Gulminelli, C.Mondal
- Lyon (IP2I): G.Chanfray, G.Grams, H.Hansen, J.Margueron, A.Pfaff, R.Somasundaram
- Meudon (LUTH): J.Novak, M.Oertel, A.Pascal, L.Suleiman

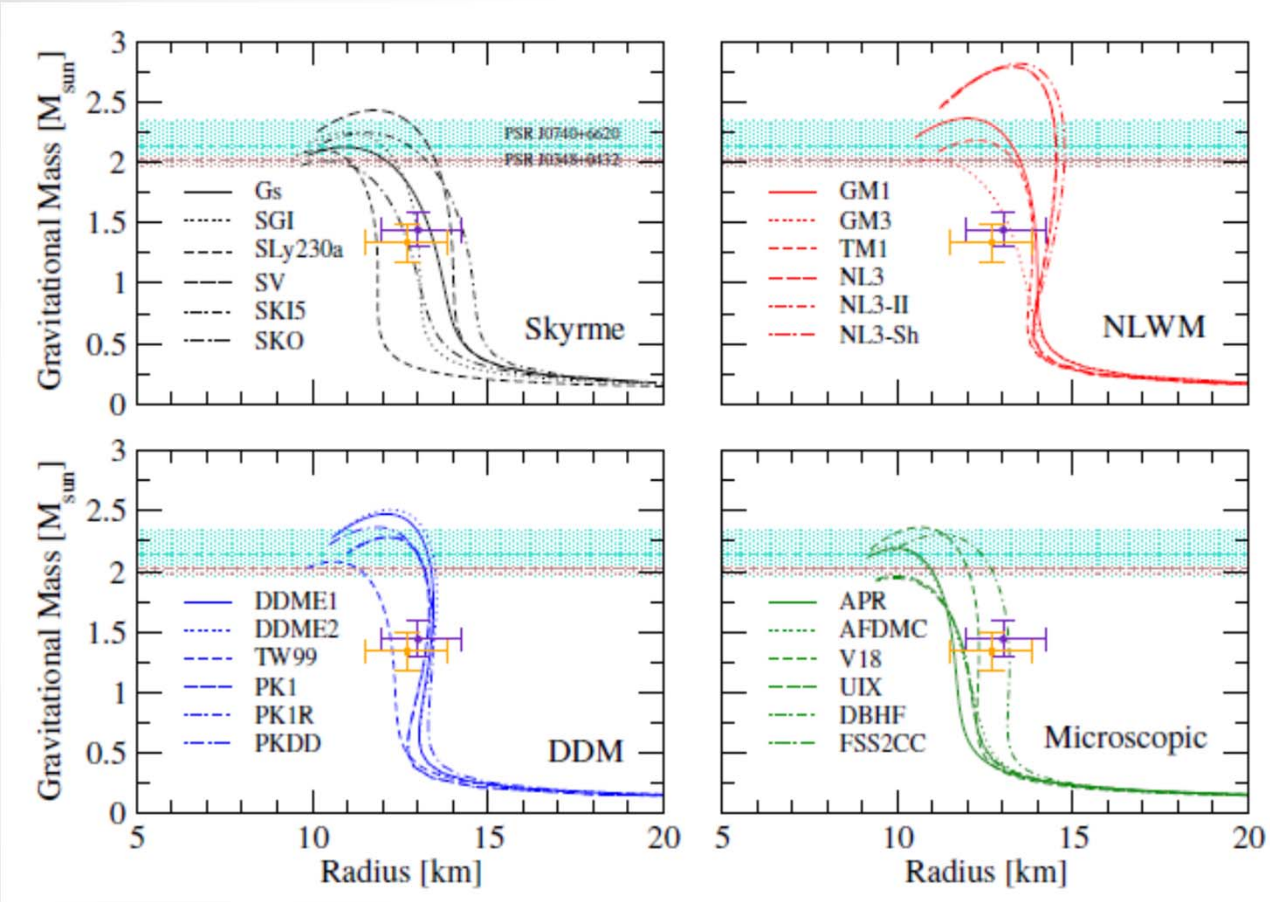
Motivation

(T=0 – β eq. only 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)*, Λ(R) *(LIGO/VIRGO)* M *(SKA)*
- But EoS is model dependent !



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

Max masses:

Demorest et al, Nature **2010**

Antoniadis et al, Science **2013**

Mass-radii:

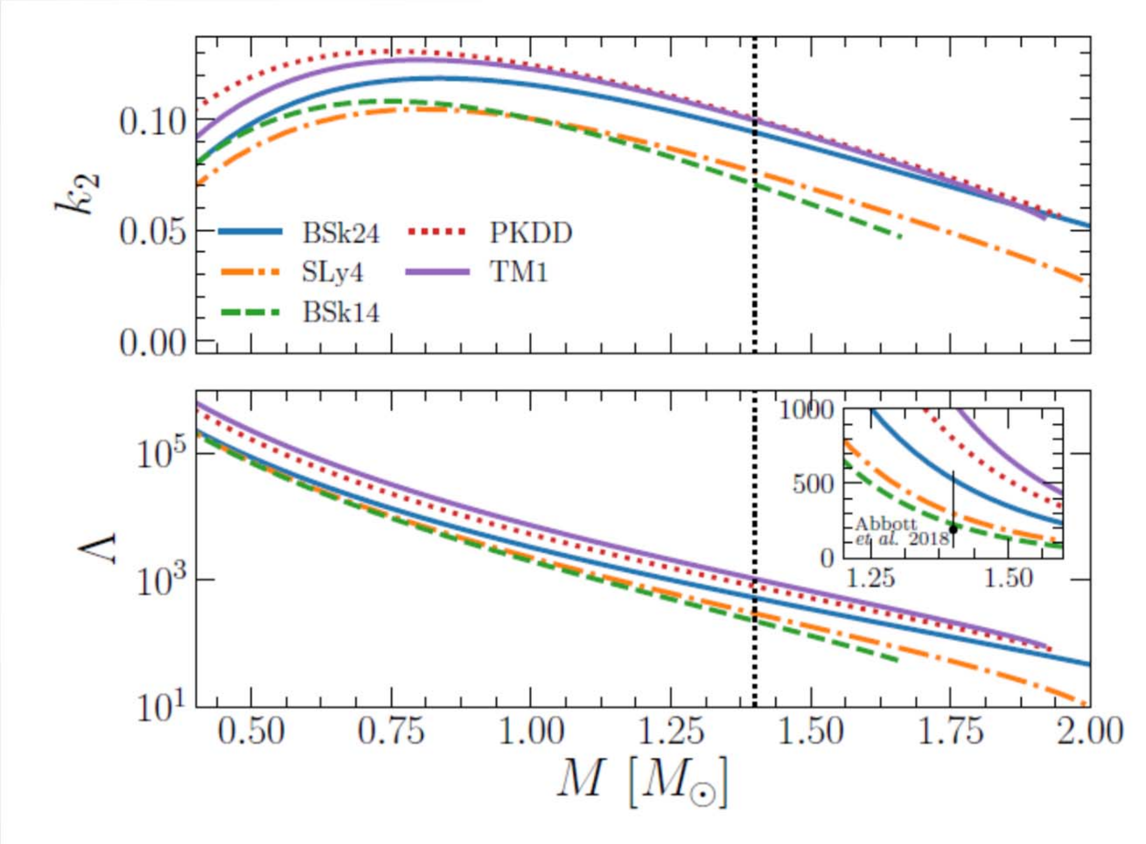
Riley et al, ApJ **2019**

Miller et al, ApJ **2019**

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

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

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



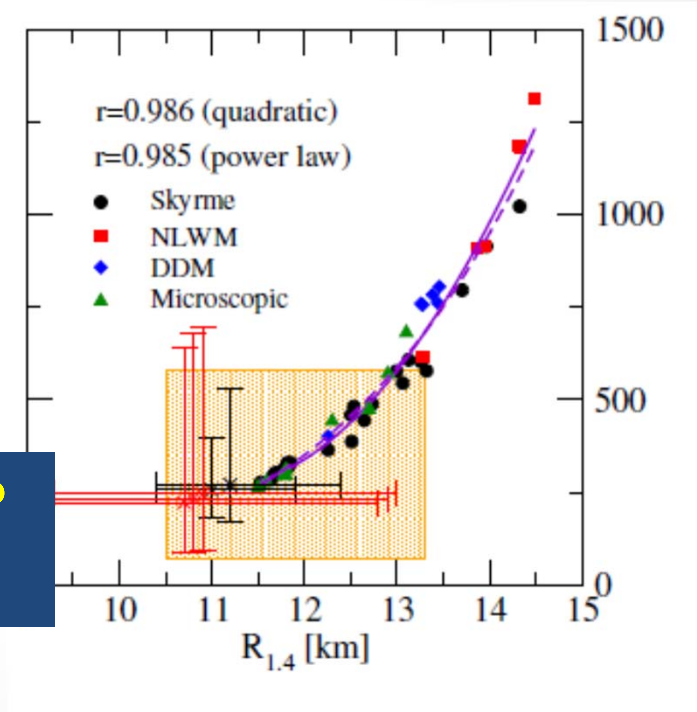
$\Lambda_{1.4}$

Abbott et al, PRL **2018**

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

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

De et al, PRL 2018

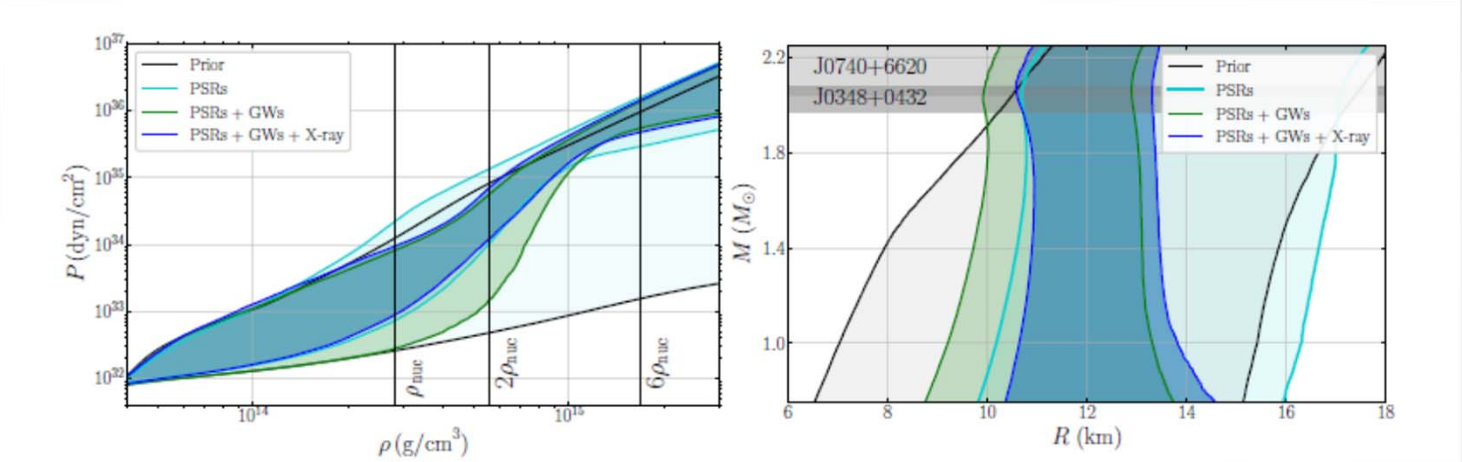


Which are the « good » models?

Is the ensemble exhaustive?

Agnostic non-parametric EoS inference

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



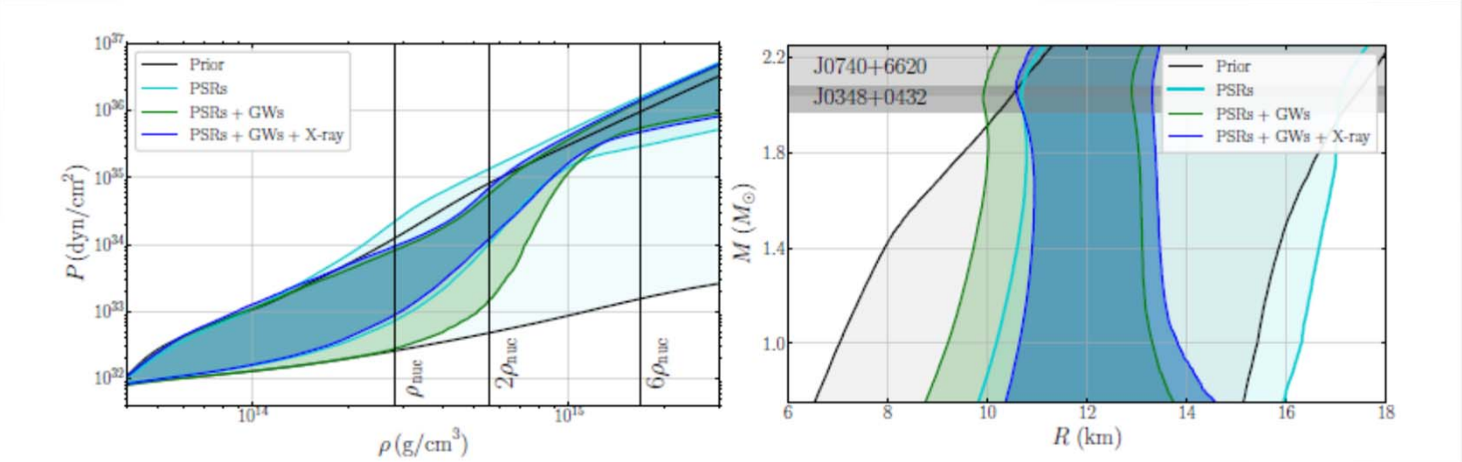
P.Landry, R.Essick, K.Chatziioannou, ArXiV 2003.04880

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.Chatziioannou, ArXiV 2003.04880

- 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….

Nucleonic Meta-modeling

- 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 $\vec{X}$ - flat prior

  (BUT: beta equilibrium !)
- Our choice: expansion around ρ_0 :

Symmetric matter $\rho_n = \rho_p$

Symmetry energy

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

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

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

A.Bulgac et al, PRC 2018

J.Margueron, R.Casali FG PRC 2018

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

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 (chiral)
f_2. empirical uncertainties on $\vec{X}$
f_3. nuclear masses

} **Nuclear physics**

J.Margueron, R.Casali FG PRC 2018

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=> Predict astro observables with controlled uncertainty intervals within the nucleonic hypothesis
=> Quantify the reliability of the different models (figures of merit)

J.Margueron, R.Casali FG PRC 2018

Nucleonic Meta-modeling

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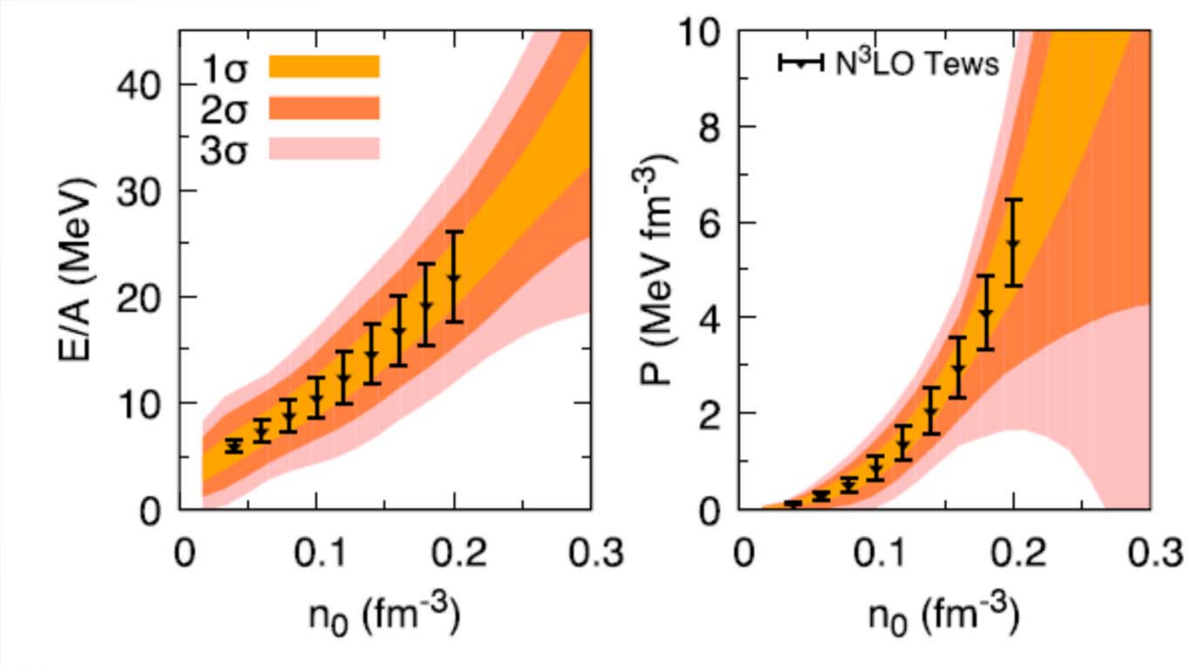
f$_3$. nuclear masses

} **Nuclear physics**

J.Margueron, R.Casali FG PRC 2018

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

Pure neutron matter



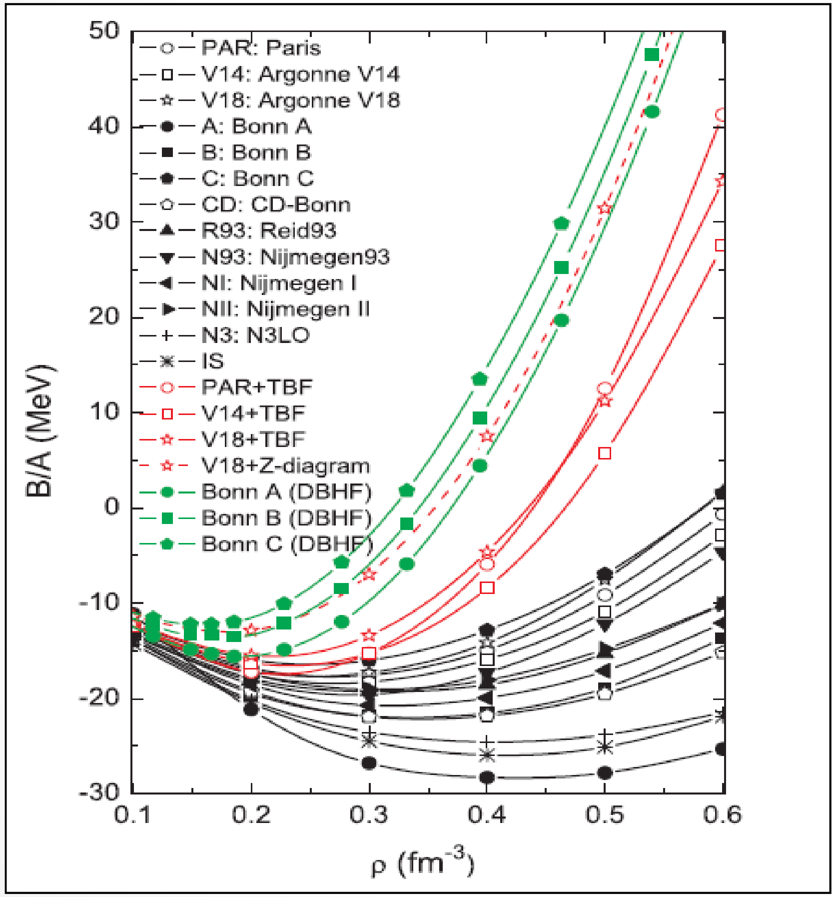
- **Diagrammatic expansion: controlled uncertainties!**
- **Power counting & regularization valid only up to ~ 1,5ρ_0**

=> *constrain low order parameters*

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



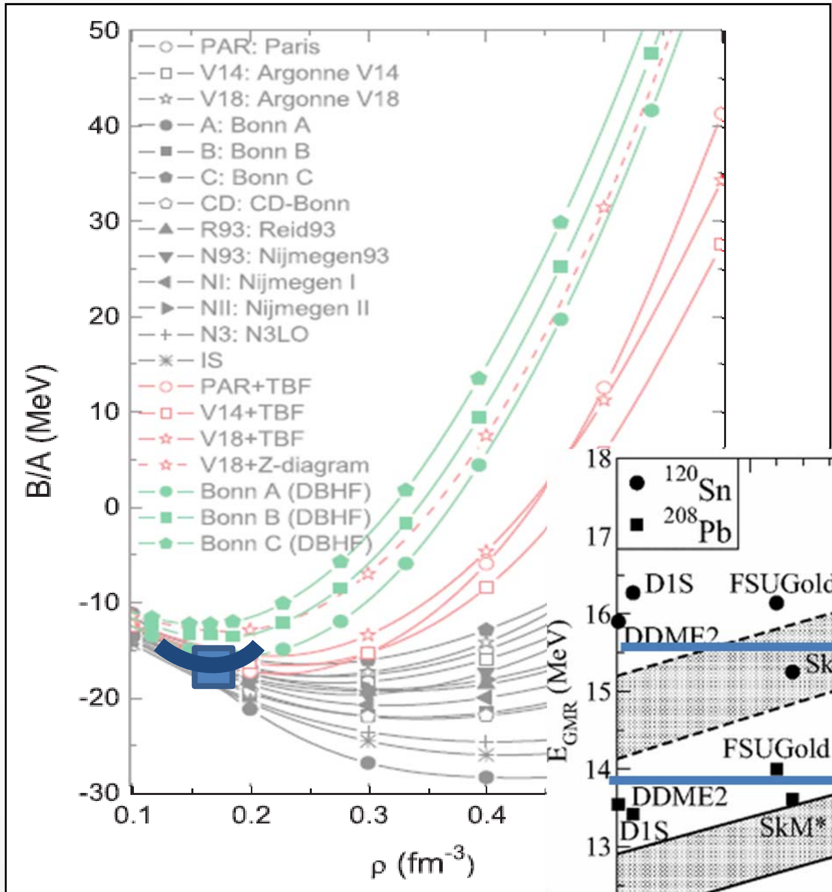
Z.H.Li et al, PRC 74(06) 047304

- **Many different observables: masses, radii, skins, collective modes, polarizability, IAS, flows .....**
- **Also sensitive to low densities up to ~ ρ_0**

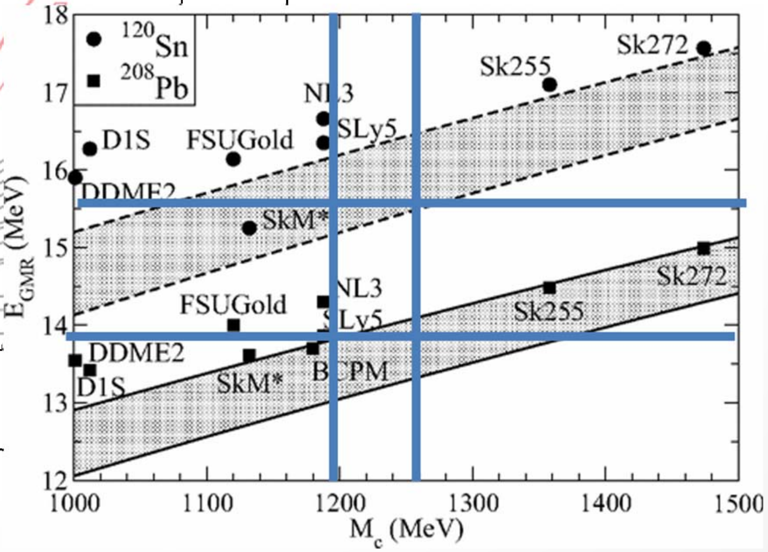
=> constrain low order parameters

EoS Constraints from nuclear physics (2): experiments

Symmetric matter



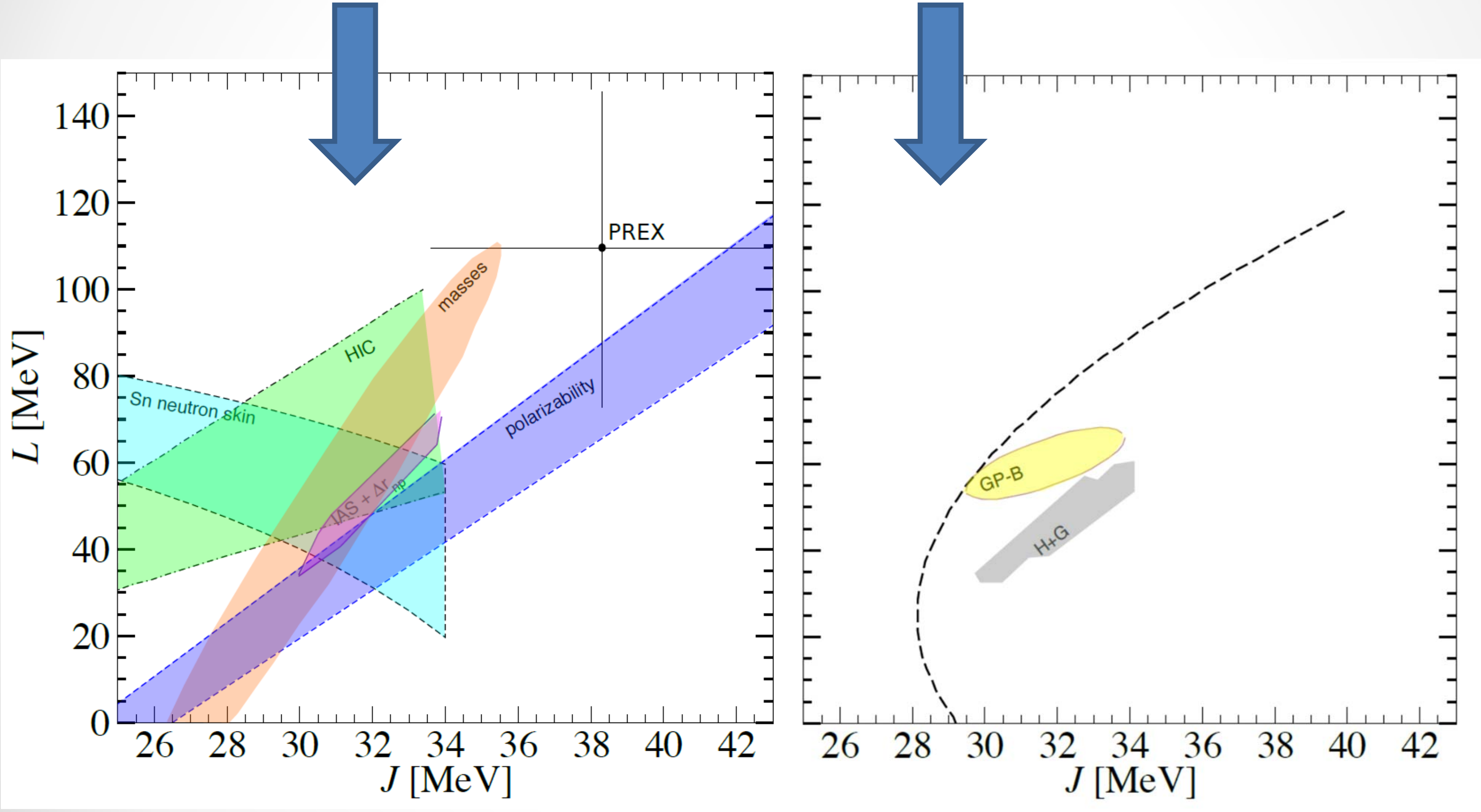
Z.H.Li et al, PRC 74(06) 047304



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

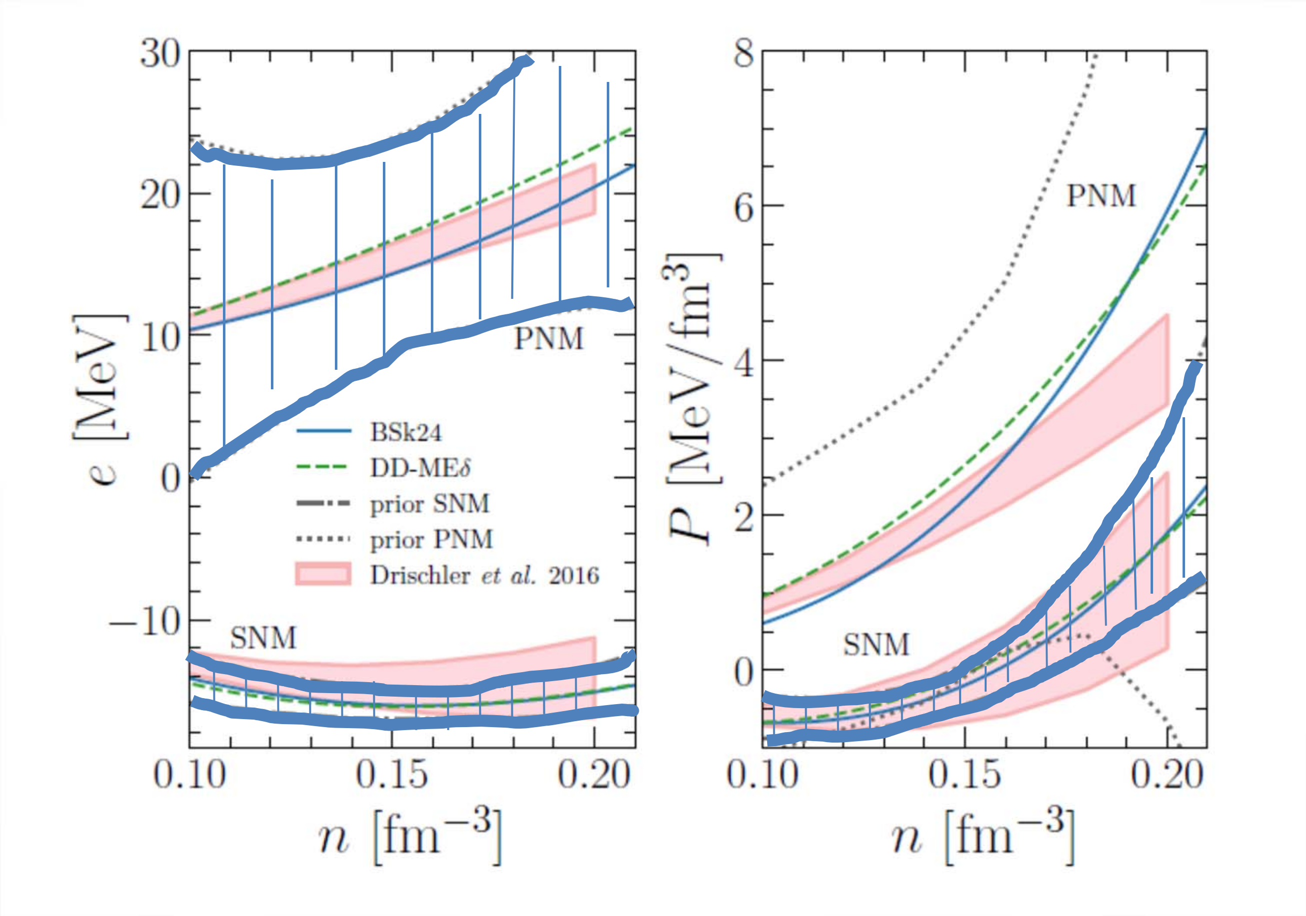
- **Many different observables: masses, radii, skins, collective modes, polarizability, IAS, flows .....**

Experimental versus theoretical constraints



Courtesy A.F.Fantina

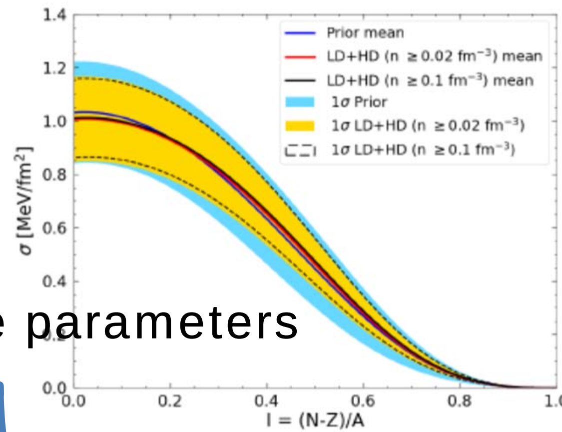
Experimental versus theoretical constraints



EoS Constraints from nuclear physics (3): masses

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

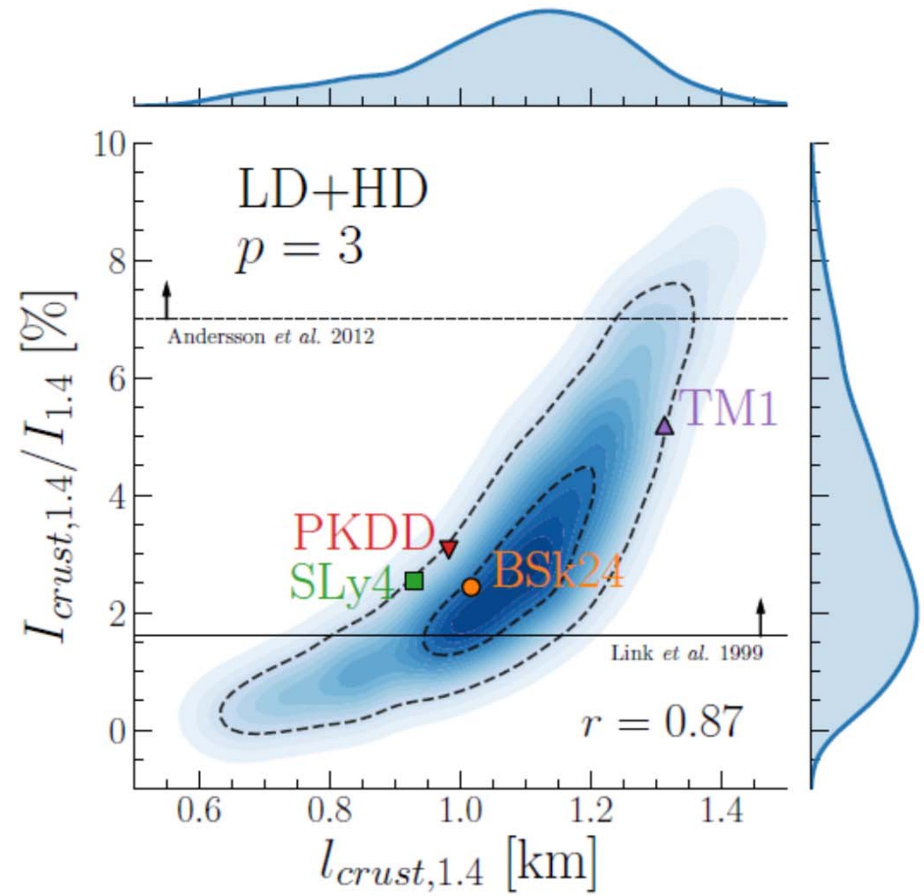
=> sub-saturation EoS



	Bulk parameters										Surface parameters			
	E_{sat}	n_{sat}	K_{sat}	Q_{sat}	Z_{sat}	E_{sym}	L_{sym}	K_{sym}	Q_{sym}	Z_{sym}	σ_0	b_s	σ_{0c}	β
n_{CC}	-0.10	-0.05	0.16	-0.06	-0.03	-0.32	-0.68	-0.22	0.51	-0.17	0.12	0.44	-0.18	-0.12
n_{pasta}	-0.88	0.20	0.35	-0.28	0.03	0.35	-0.20	-0.27	0.20	-0.02	0.89	0.61	-0.75	-0.86
M_{pasta}	0.88	-0.27	-0.28	0.21	-0.05	-0.61	-0.31	0.08	0.16	-0.06	-0.88	-0.35	0.68	0.84
I_{pasta}	0.89	-0.27	-0.28	0.21	-0.05	-0.61	-0.30	0.09	0.15	-0.06	-0.88	-0.35	0.68	0.84
R_{pasta}	0.75	-0.22	-0.21	0.19	-0.06	-0.46	-0.45	-0.10	0.22	-0.05	-0.75	-0.36	0.63	0.70

H.Dinh Thi et al, in preparation

Application: crustal moment of inertia

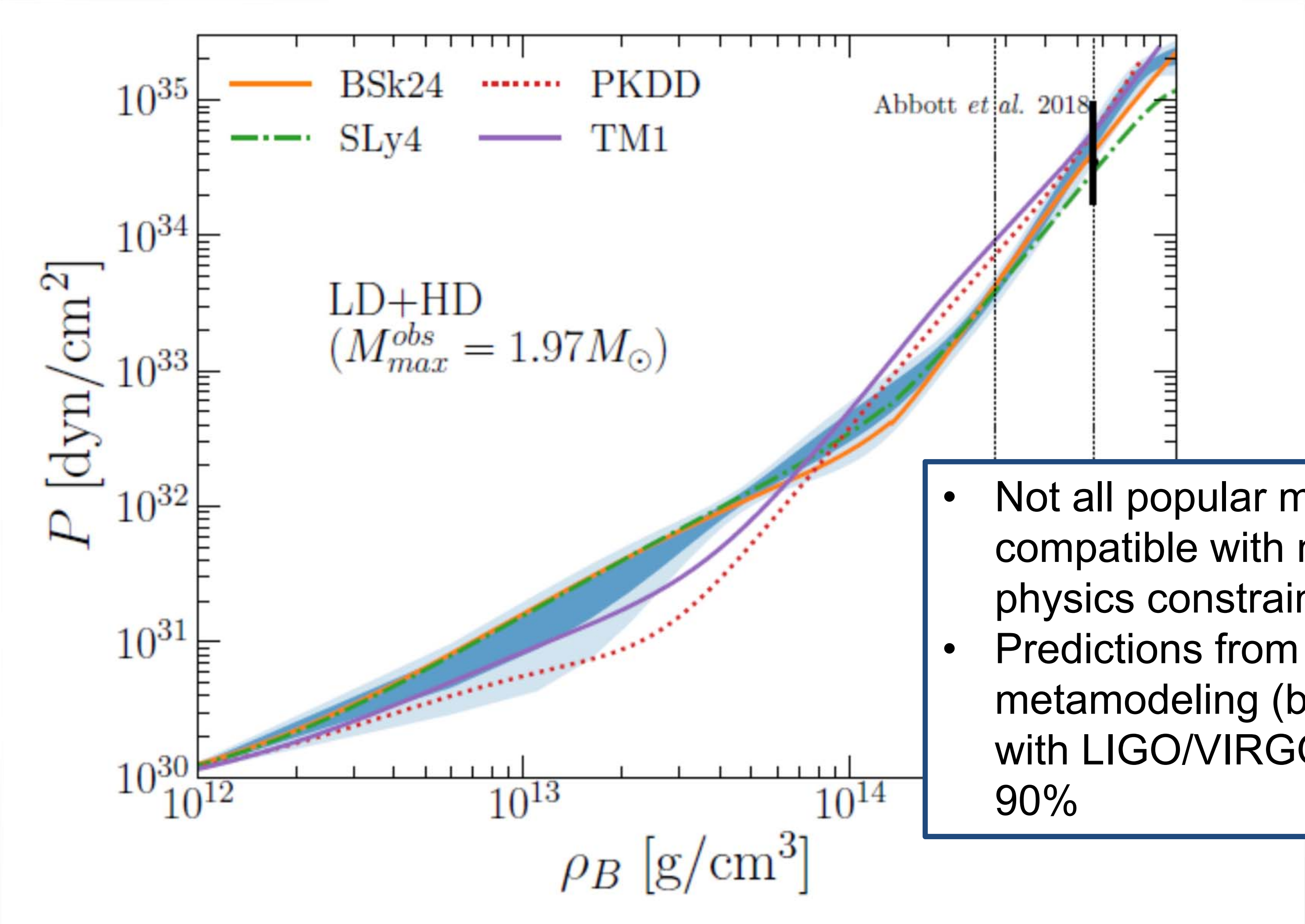


- An extra superfluid core component is needed to explain the strongest Vela glitch if entrainment is considered

T.Carreau et al, PRC 2019

T.Carreau et al, PRC 2019

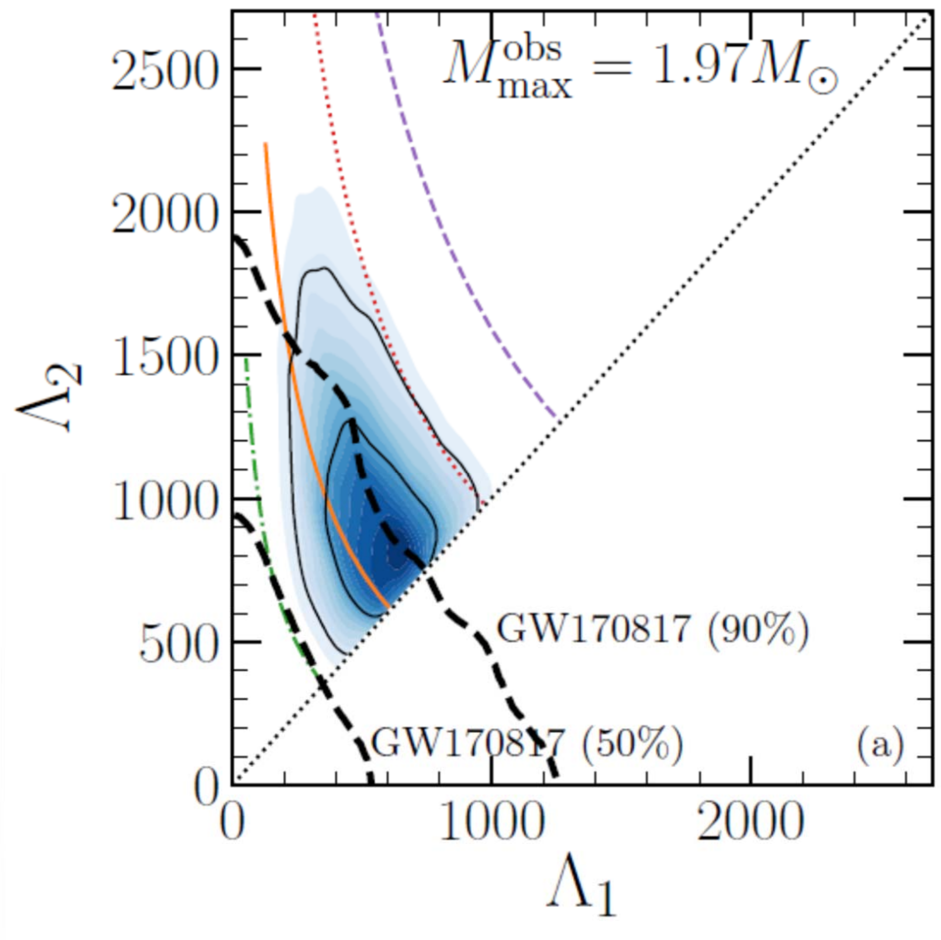
Application: EoS



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

T.Carreau et al, PhD Thesis 2020

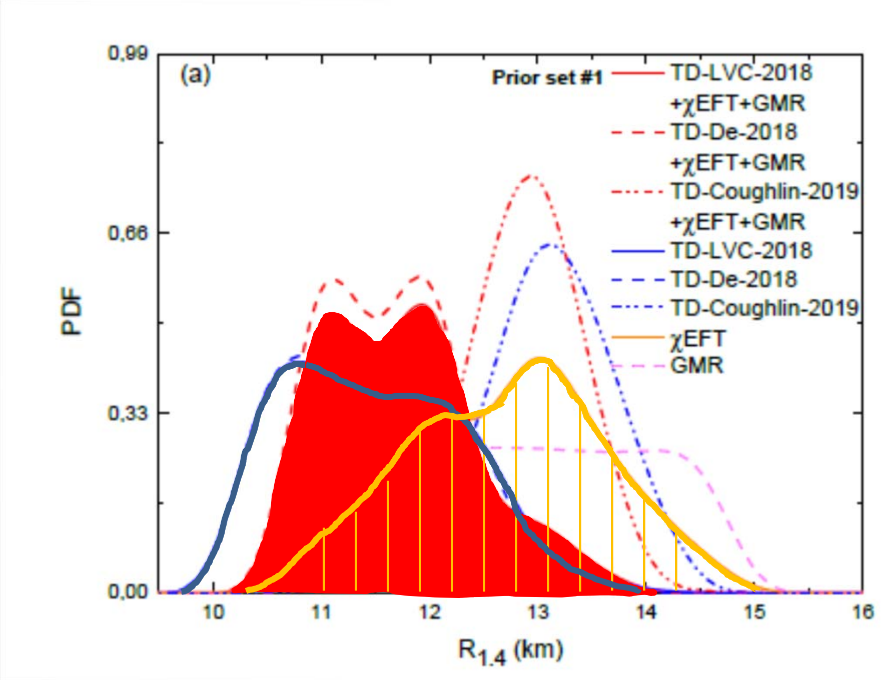
Application: Λ



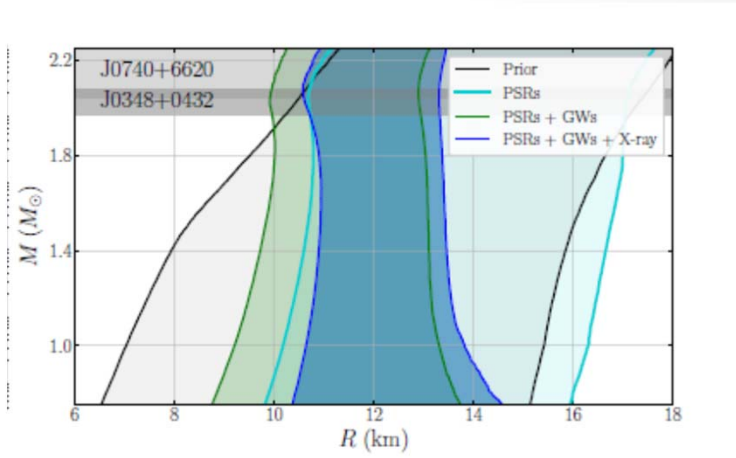
- Not all popular models are compatible with nuclear physics constraints
- Predictions from metamodelling (blue) agree with LIGO/VIRGO (black) at 90%
- Nuclear physics « prefers » higher Λ

H.Guven et al Phys. Rev. C 102, 015805 (2020)

Application: nuclear physics + Λ =>radius



- A tension between LIGO/VIRGO (TD-LVC 2018, TD-DE 2018) and nuclear physics (χEFT) on the NS radius
- Not sufficient to exclude the nucleonic hypothesis



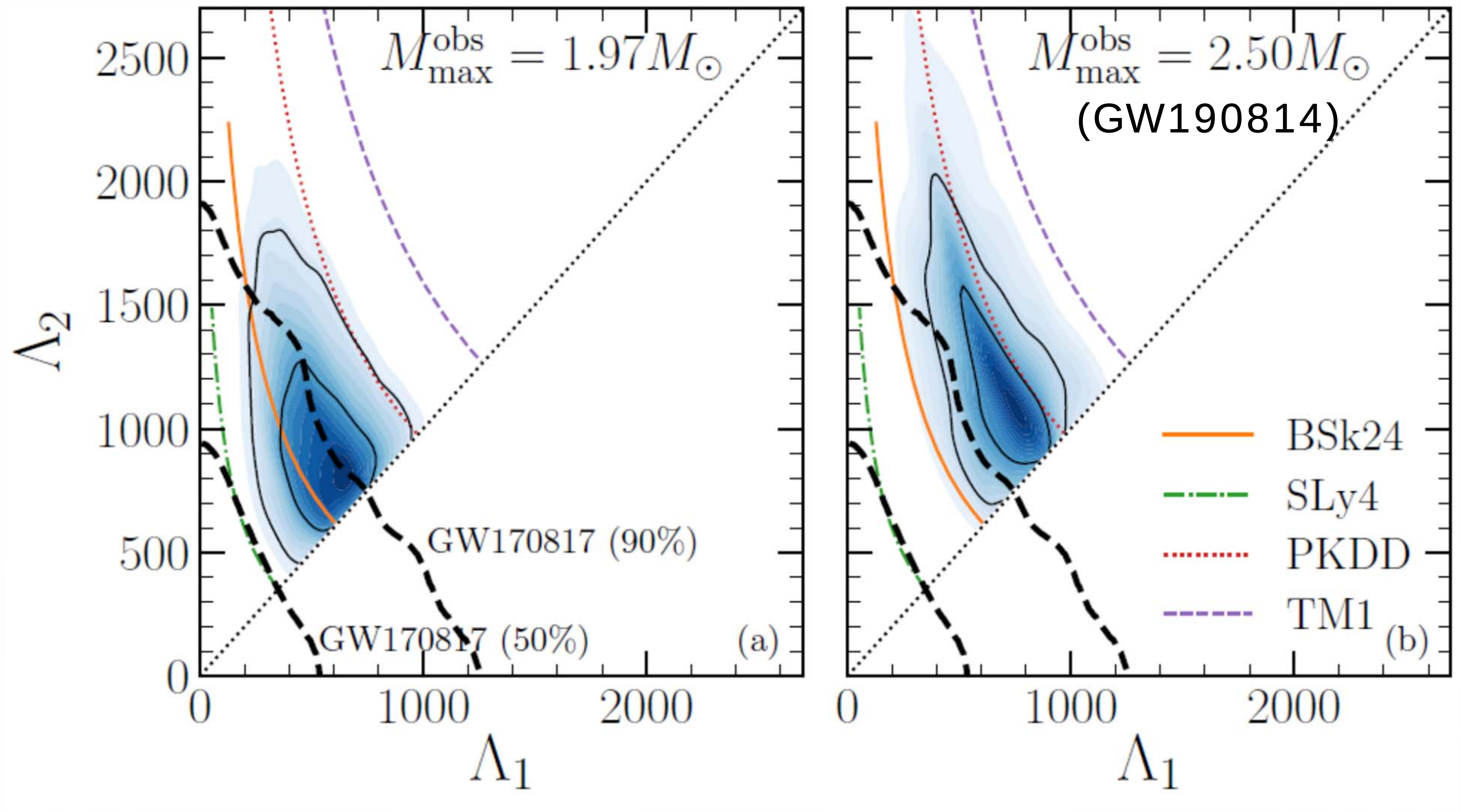
TD-DE: S. De et al PRL 121, 091102 (2018).
TD-LVC: B.P.Abbott et al, PRX 9, 011001 (2019)
TD-Coughlin: M. W. Coughlin et al MNRAS 489, L91 (2019).

P.Landry, R.Essick, K.Chatziioannou, ArXiV 2003.04880

T.Carreau et al, PhD Thesis 2020

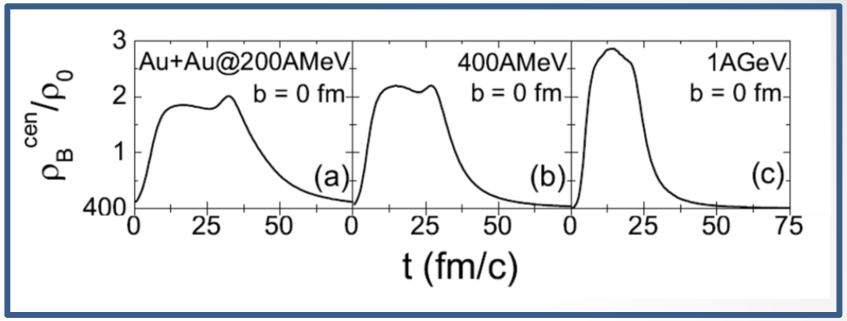
Application: Λ

- To (in)validate the nucleonic hypothesis : new observations **and/or tighter nuclear constraints for $\rho_0 < \rho < 2\rho_0$**

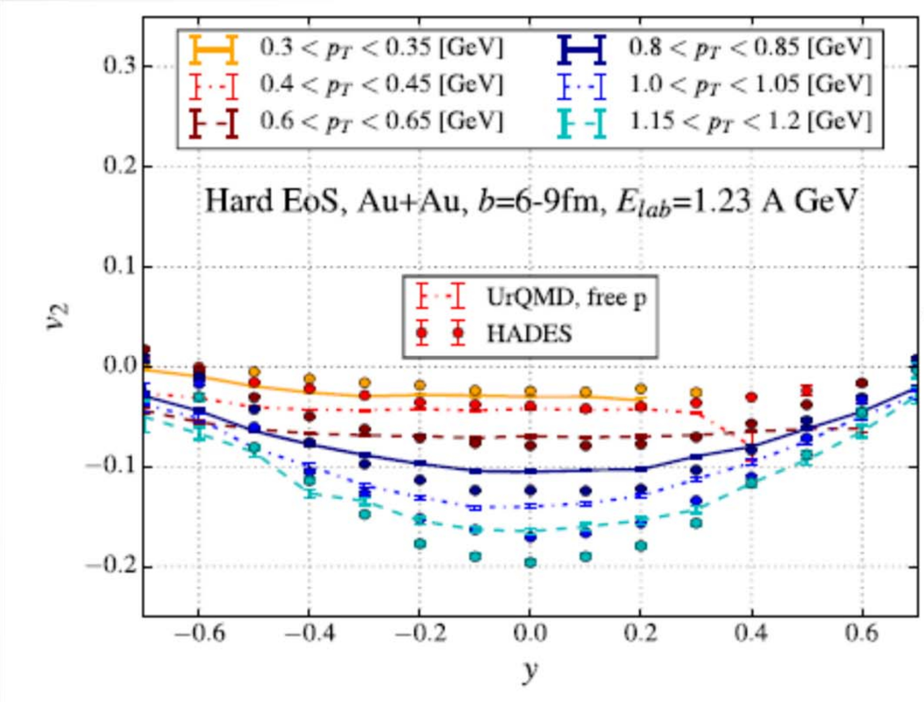


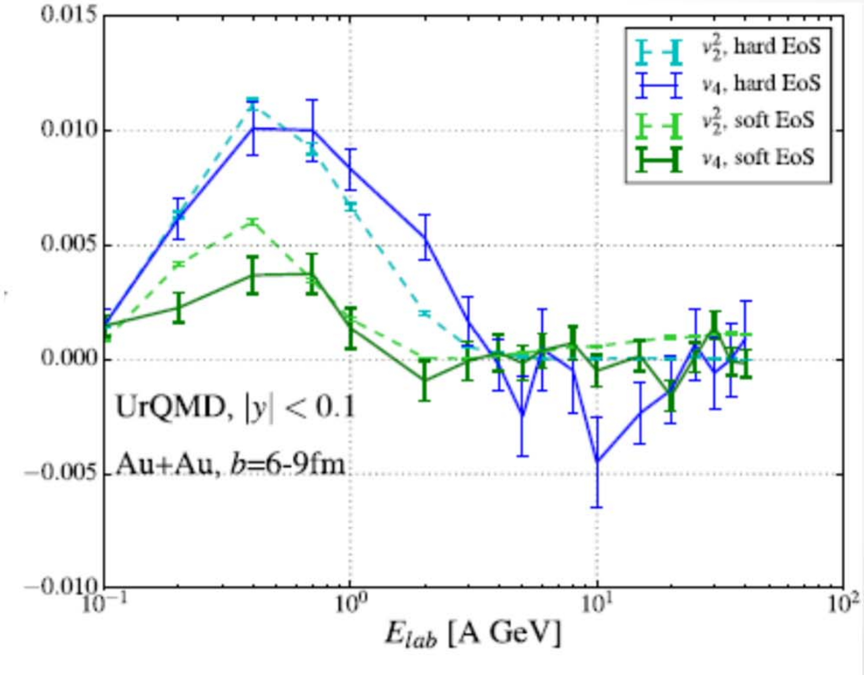
Strategy I: high energy experiments

J.Xu, PRC 2013



Elliptic flow @ HADES:
Transport model versus data

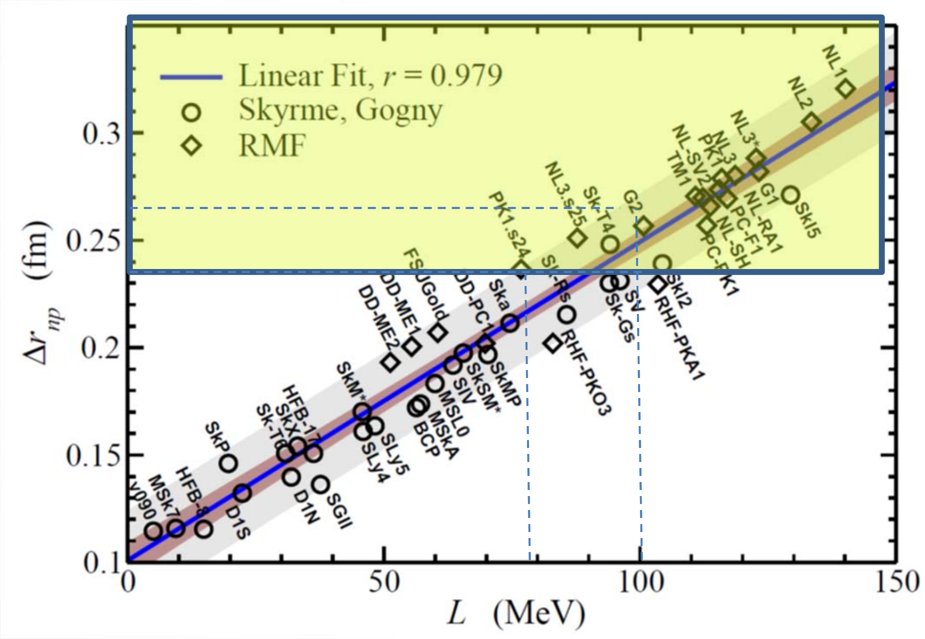




P.Hillmann et al., JPG 47 (2020) 055101

Strategy II: high precision

Exp: Δr_{np}= 0,1318-0,3072
PREX (**arXiv:2011.11125**): 0,22-0,36



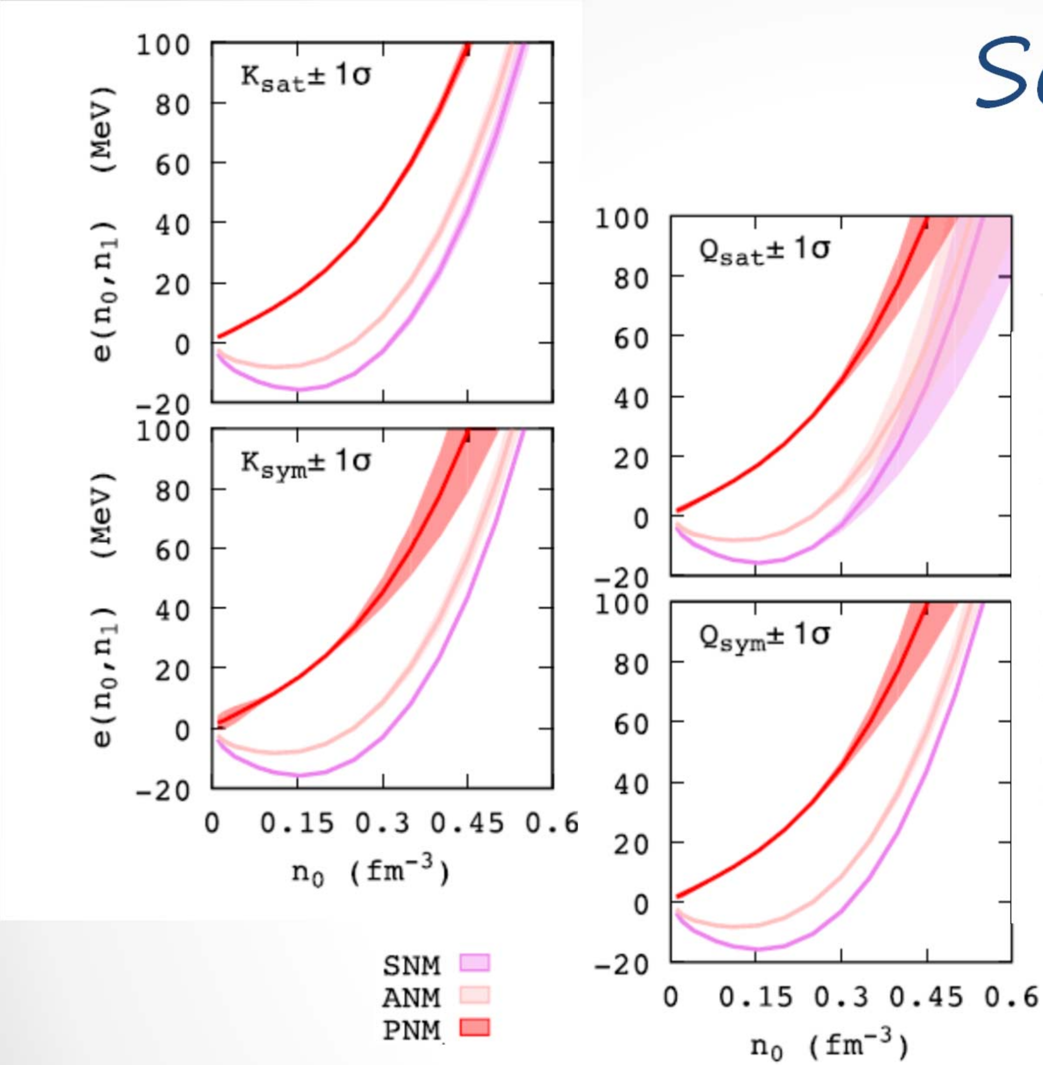
Neutron skin of ^{208}Pb: effective models versus data

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

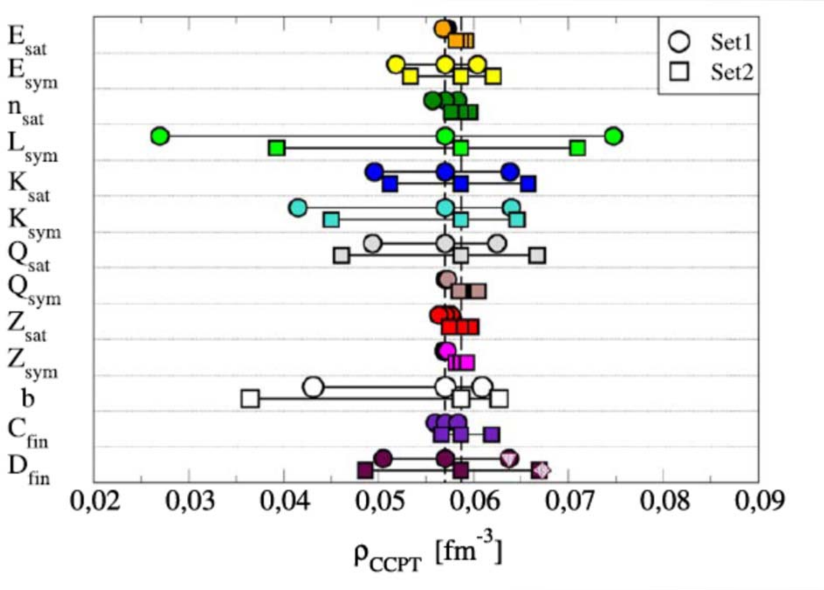
X.Vinas et al (2014)
P.G.Reinhard, W.Nazarewicz (2016)
J.Yang, J.Piekarewicz (2017)

Sensitivity study

(slide for Davide Radice)



J.Margueron, H.Casali, FG, PRC97 (2018) 025805



S.Antic et al, J.Phys.G 46 (2019) 065109

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 **within the hypothesis of nucleonic degrees of freedom**
- Astrophysical and nuclear physics constraints can be treated on the same footing
- **More stringent extrapolations above normal density might give hints on the presence of deconfined matter in NS**
- Interesting perspectives from upcoming nuclear physics experiments
- **Practical implementation in CompOse (including T>0 extension) to be discussed**