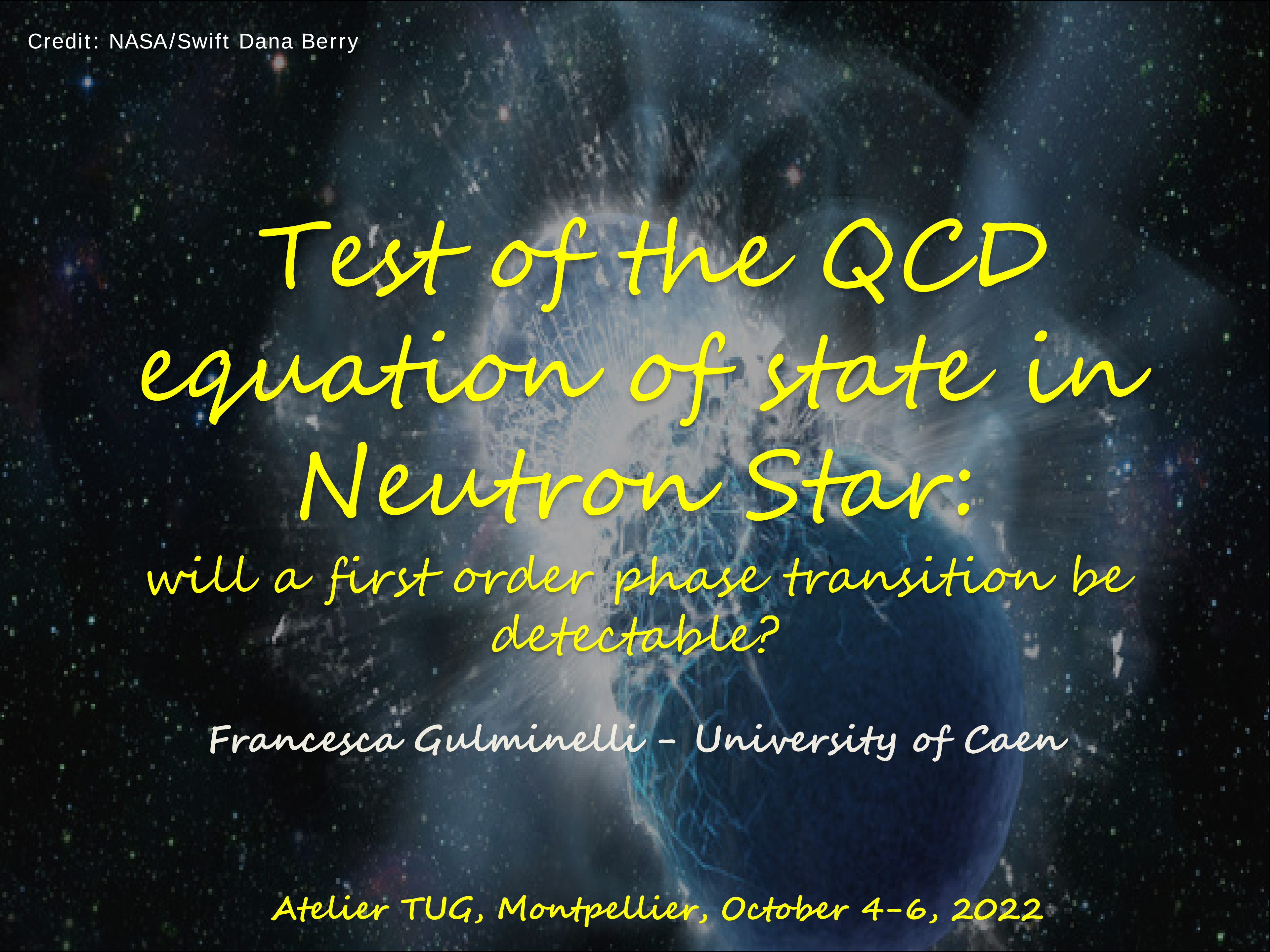


Credit: NASA/Swift Dana Berry

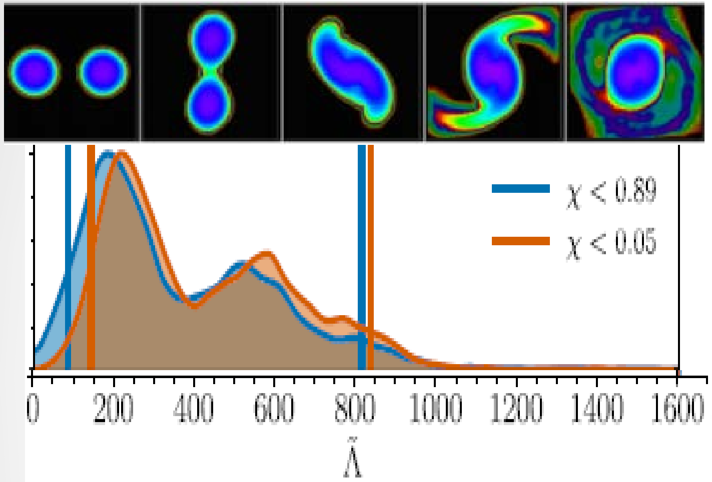
Test of the QCD equation of state in Neutron Star:

will a first order phase transition be detectable?

Francesca Gulminelli – University of Caen

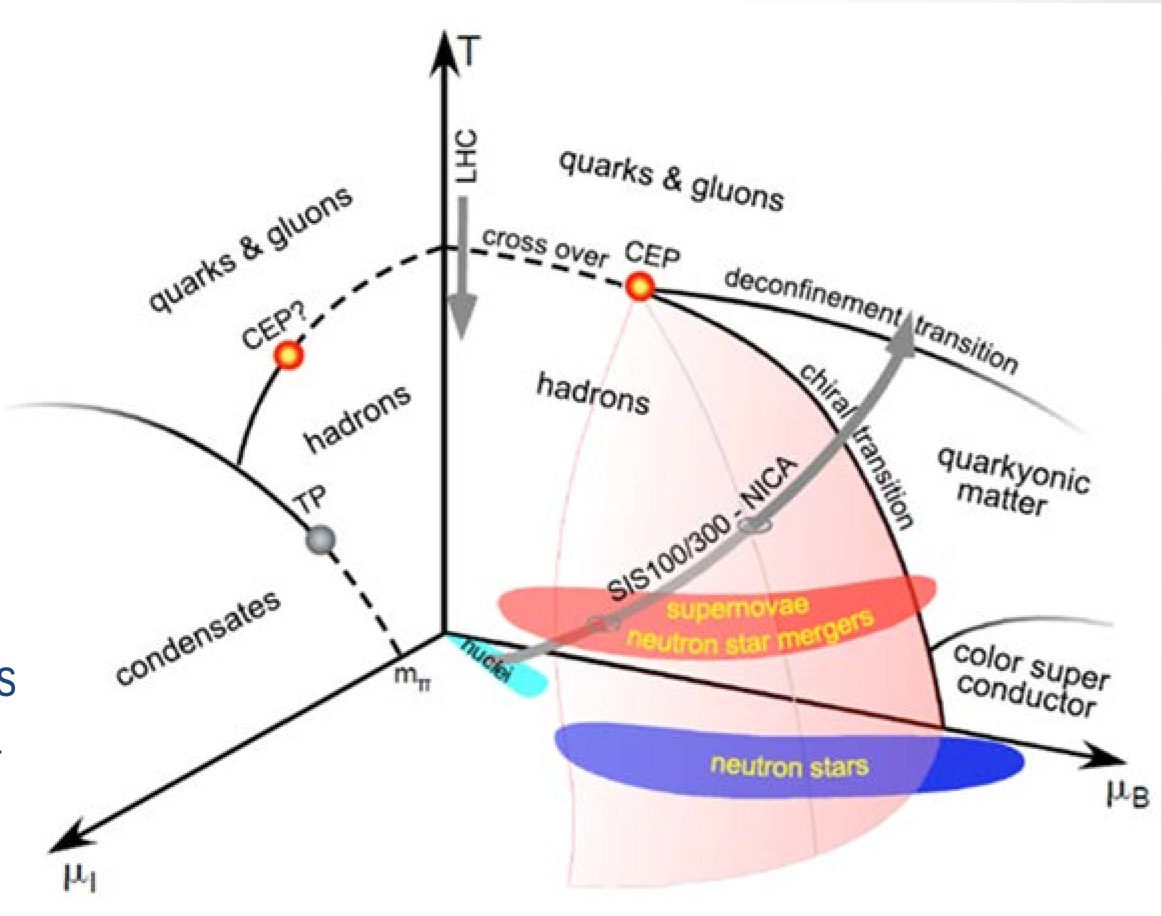
Atelier TUG, Montpellier, October 4-6, 2022

Motivation: GW and the phase diagram of QCD



LVC, PRX 9 (2019), 011001

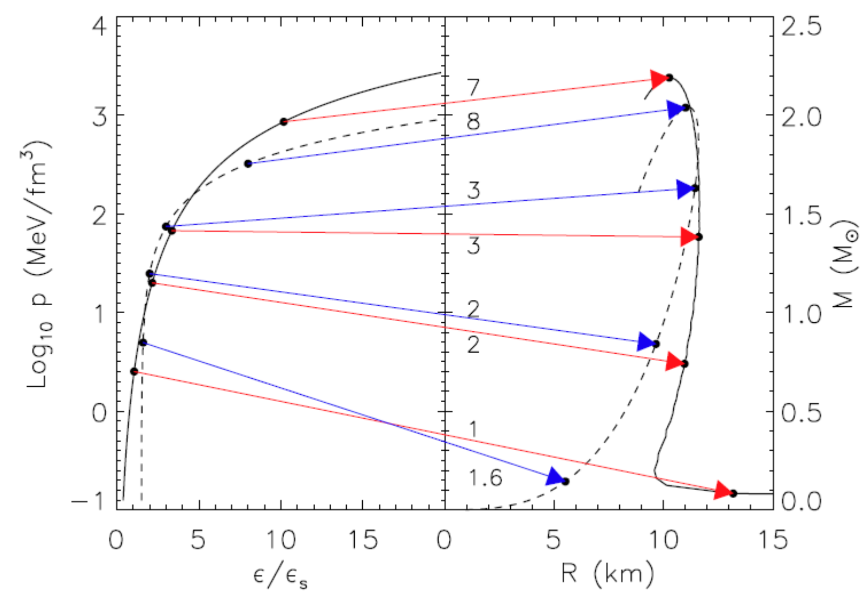
- The detection of GW by the LVC from NS mergers opens the possibility of a *DIRECT* measurement of the QCD phase diagram



NuPECC Long Range Plan 2017 "Perspectives for Nuclear Physics"

Motivation

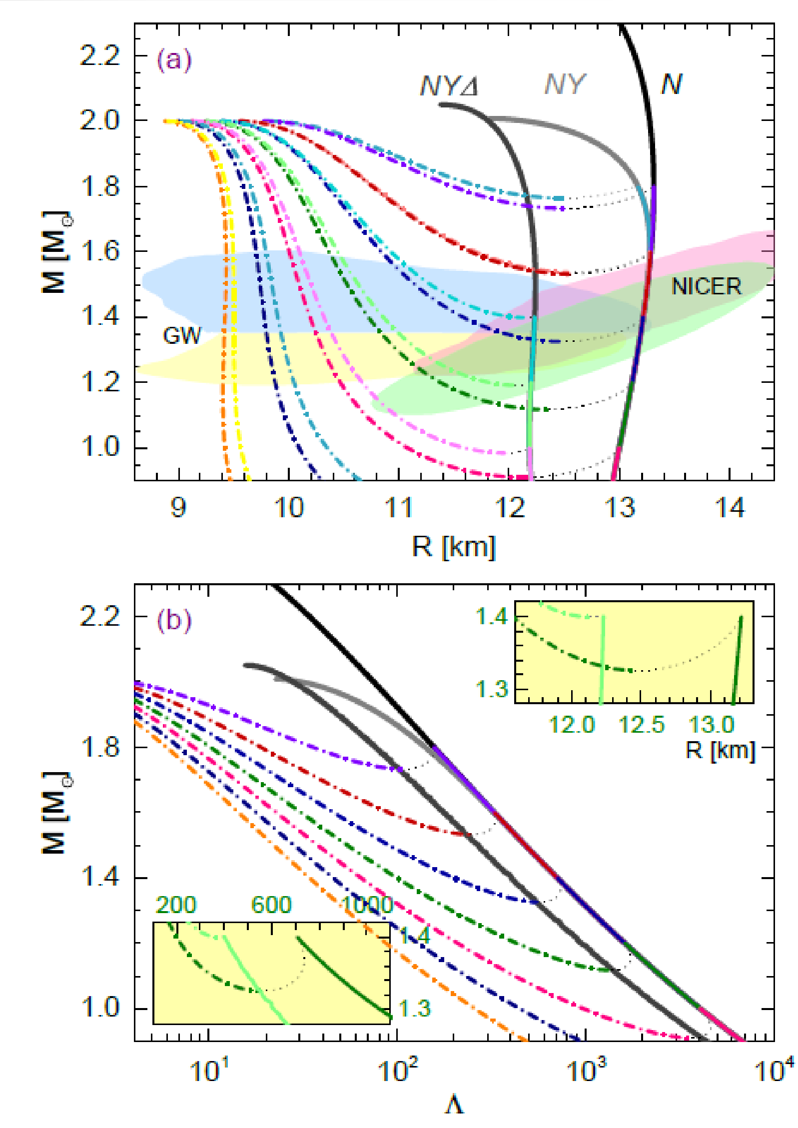
(T=0 – β eq. for this talk)



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

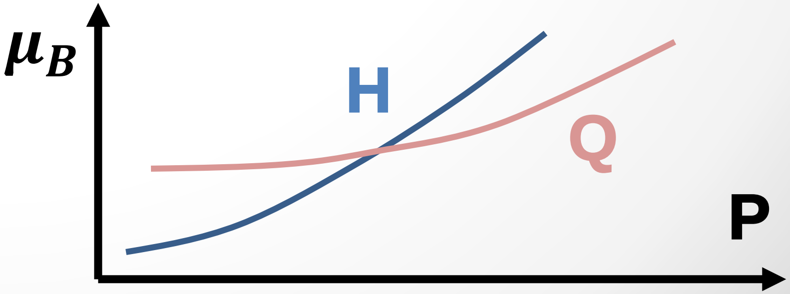
- Indeed, GR imposes a 1-to-1 correspondence between the nuclear EoS and static properties of NS (M(R)-M(Λ))
- Different compositions => different EoS => different gravitational signals!

Problem: no ab-initio theory of dense matter



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

- Hybrid stars: a first order phase transition ($\mu_B^H = \mu_B^Q$) between a nucleonic (RMF, Skyrme..) and a quark ((p)NJL, Bag,…) EoS
- Huge uncertainties on both sides!
- Still, the EoS is much better constrained on the H side



Nucleonic Meta-modeling

= the most general EoS *under the nucleonic hypothesis*

- Flexible functional $e[\rho_n, \rho_p, \nabla\rho_n, \nabla\rho_p, ..]$ able to reproduce existing effective nucleonic models and interpolate between them

$$\vec{X} = (\vec{X}_{bulk}, m^*, \Delta m^*, \vec{X}_{surf}) \sim 18 \text{ parameters}$$

=> Large flat prior $P(\vec{X}) = \prod_i P_i(X_i)$ spans the uncertainty of the nucleonic hyp.

- variational theory => both EoS and nuclear observables

$$\boldsymbol{M(A,Z)} \Leftarrow e(\rho_n, \rho_p, ..) \Rightarrow \mathbf{p}(\boldsymbol{\rho})$$

$\Rightarrow$ Posterior conditioned on astro AND finite nuclear observables

Nucleonic Meta-modeling

= the most general EoS *under the nucleonic hypothesis*

Posterior parameter distribution: $P\left(\vec{X}\middle|\vec{f}\right) = \frac{P(\vec{X})\prod_i P\left(f_i\middle|\vec{X}\right)}{P(\vec{f})}$

f_1. nuclear data (masses, radii)
f_2. ab-initio nuclear theory (MBPT)

Nuclear physics

f_3. max.mass from radio timing
f_4. tidal polarizability from GW
f_5. M(R) from X-ray

Astrophysics

(1) Huang et al, 2016 AME mass table, Angeli&Marinova, ADNDT 2013
(2) χEFT Drischler et al PRC 2016
(3) PSR J0348+0432 $M=2.01\pm0.04\ M_{\odot}$
(4) GW170817 $\widetilde{\Lambda}(M)$ LVK
(5) PSR J0030+0451, PSR J0740+6620 NICER

Nucleonic Meta-modeling

= **the most general EoS *under the nucleonic hypothesis***

Posterior parameter distribution: $P\left(\vec{X}\middle|\vec{f}\right) = \frac{P(\vec{X})\prod_i P\left(f_i\middle|\vec{X}\right)}{P(\vec{f})}$

f_1. nuclear data (masses, radii)
f_2. ab-initio nuclear theory (MBPT)

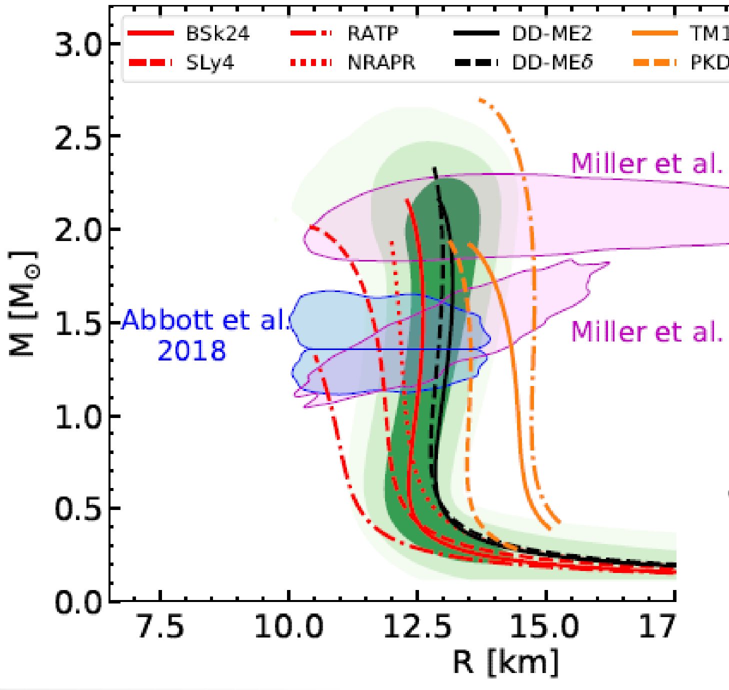
Nuclear physics

f_3. max.mass from radio timing
f_4. tidal polarizability from GW
f_5. M(R) from X-ray

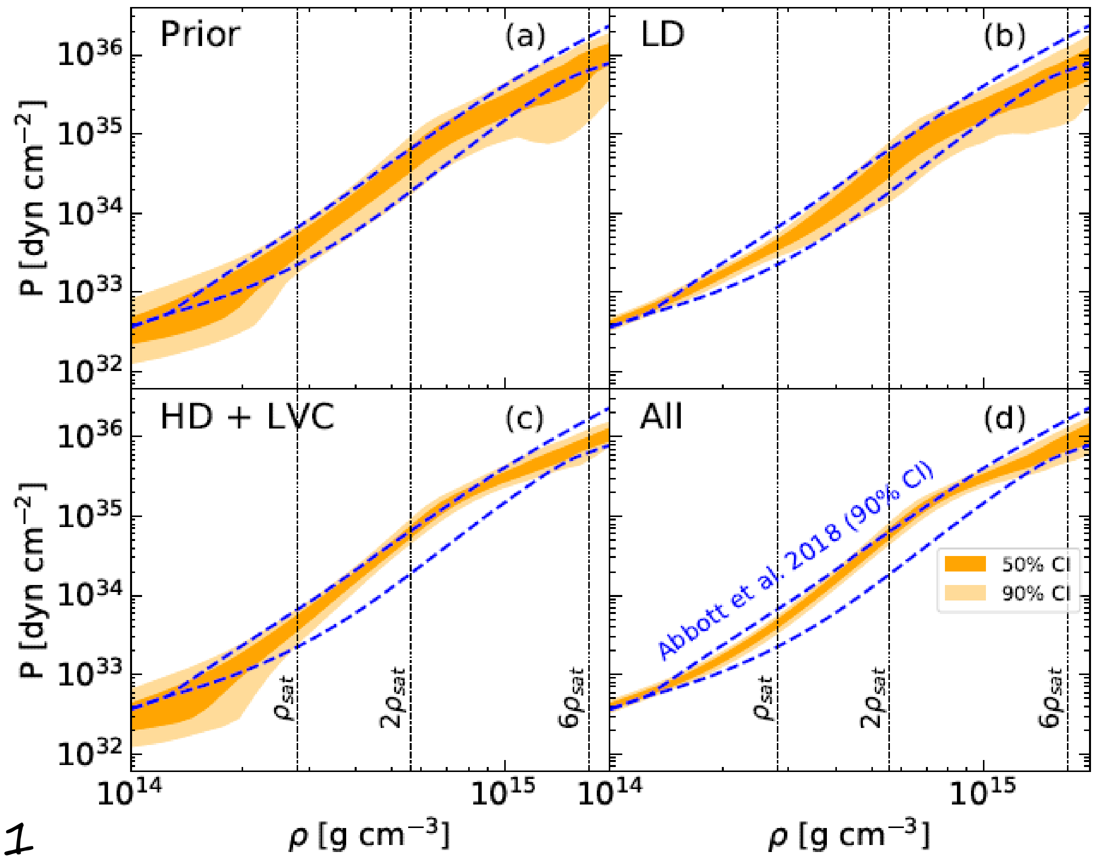
Astrophysics

=> A null hypothesis for exotic degrees of freedom

The nucleonic hypothesis

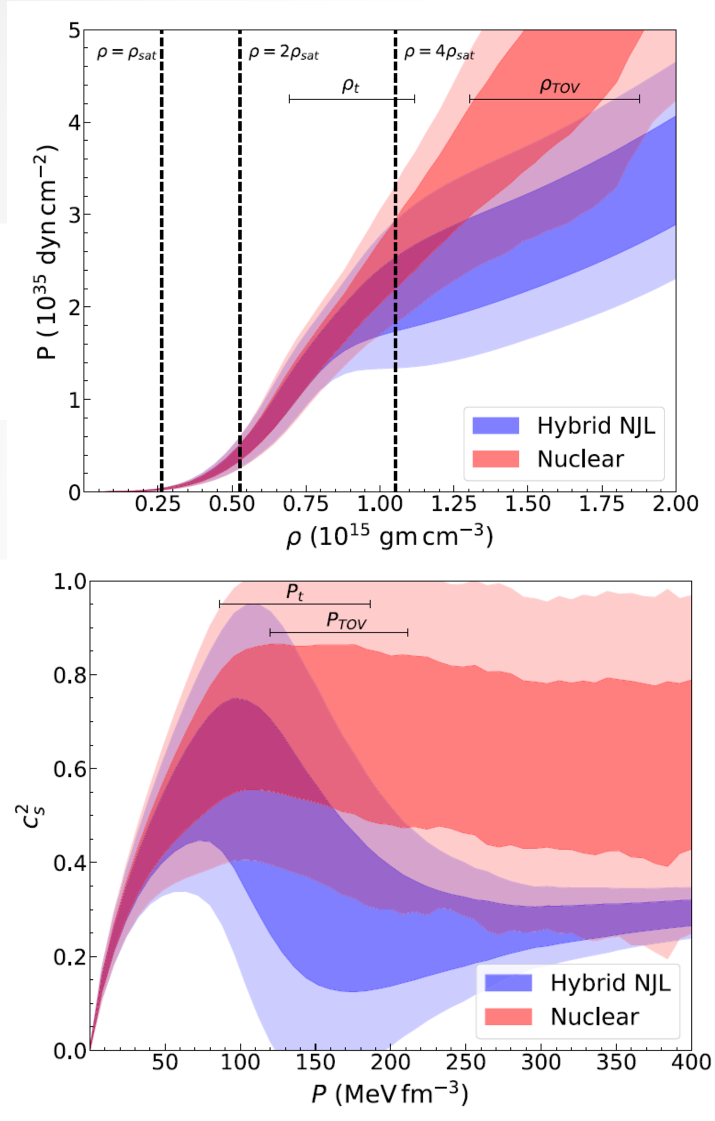


- Nucleonic hypothesis compatible with all observations



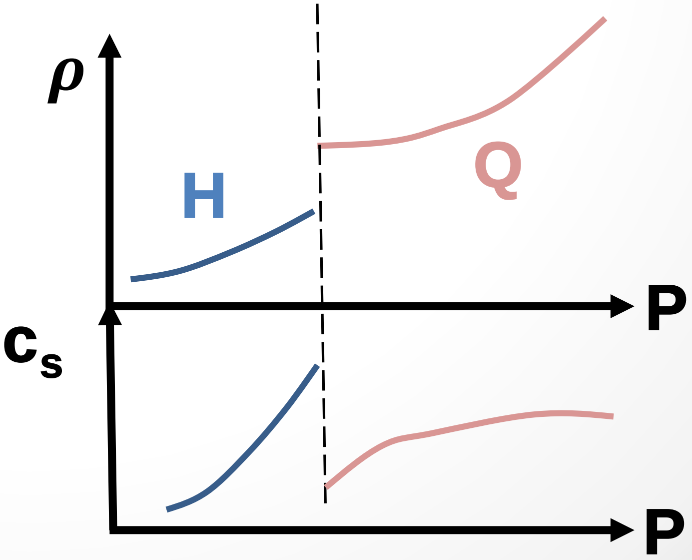
H.Dinh Thi et al, A&A 2021

Challenging the nucleonic hypothesis with GW



- 1st order transition: density jump => discontinuity in the sound speed

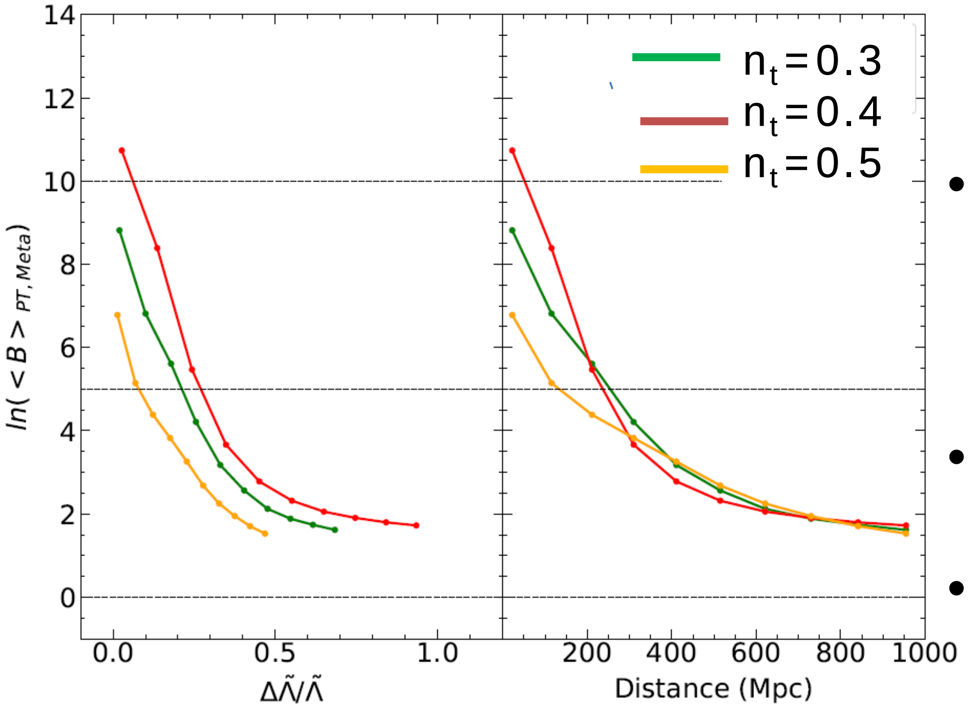
- Can the observation be precise enough to recognize the phase transition from the PN(5) waveform analysis?



A.Pfaff, H.Hansen,F.G.,PRC 2022

Challenging the nucleonic hypothesis with GW

Cosmic Explorer sensitivity

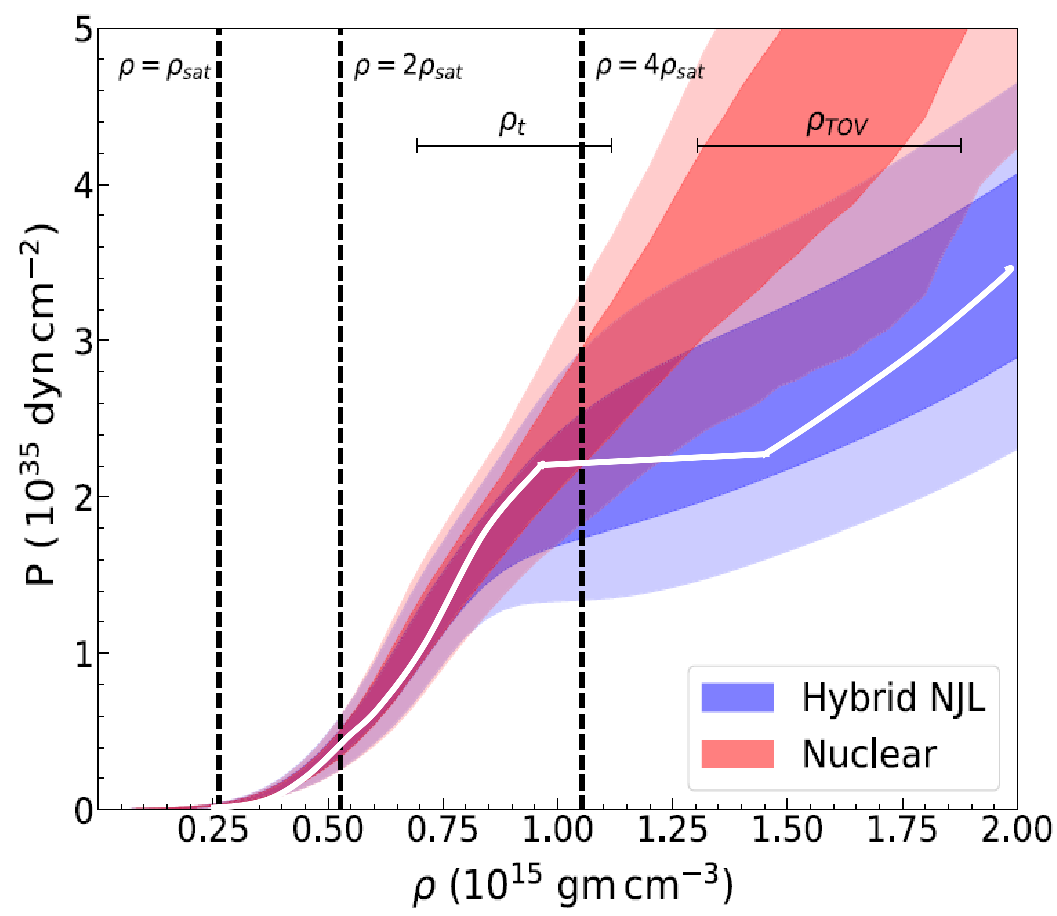


- Take an hypothetical event similar to GW170817 $(\mathcal{M}_0, q_0, d)$ producing $\tilde{\Lambda}$
- For this event the nucleonic metamodel predicts $P_0^{nucl}(\tilde{\Lambda})$, while the PT at a baryonic density n_t implies $P_0^{n_t}(\tilde{\Lambda})$
- Interferometer sensitivity => $\Delta\tilde{\Lambda}, \Delta q$ gitlab.com/sborhanian/gwbench
- The « true » $\tilde{\Lambda}$ gets distorted into $P_0^{GW}(\tilde{\Lambda})$

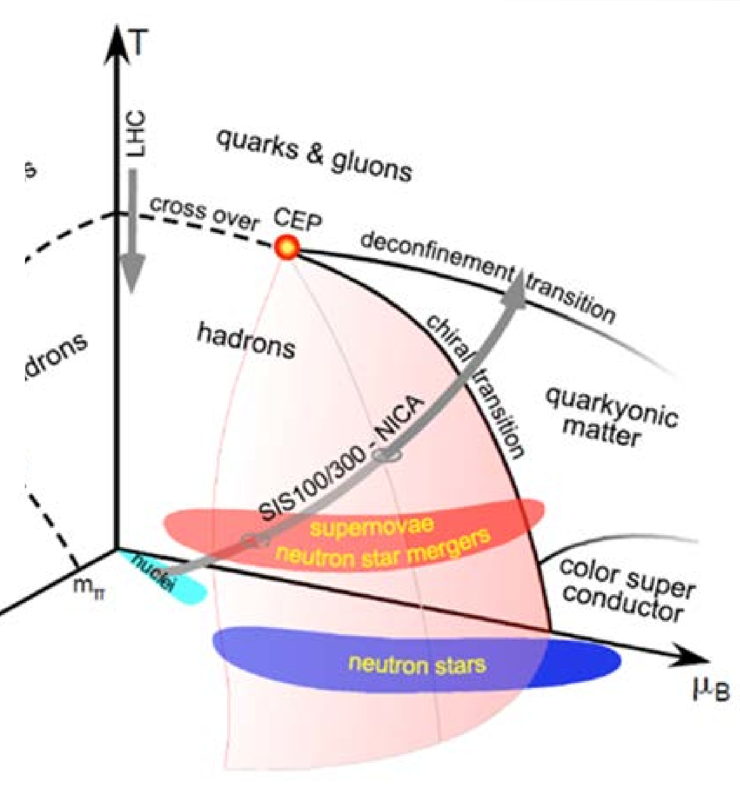
$$\boxed{log\left(\langle B\rangle_{PT,nucl}^{\mathcal{M}_0,q_0}\right) = \int d\tilde{\Lambda}\, P_0^{GW}(\tilde{\Lambda}) log\left[\frac{P_0^{n_t}(\tilde{\Lambda})}{P_0^{nucl}(\tilde{\Lambda})}\right]}$$

=> High detectability potential of a density jump with G3 detectors

Do we really expect a density jump?



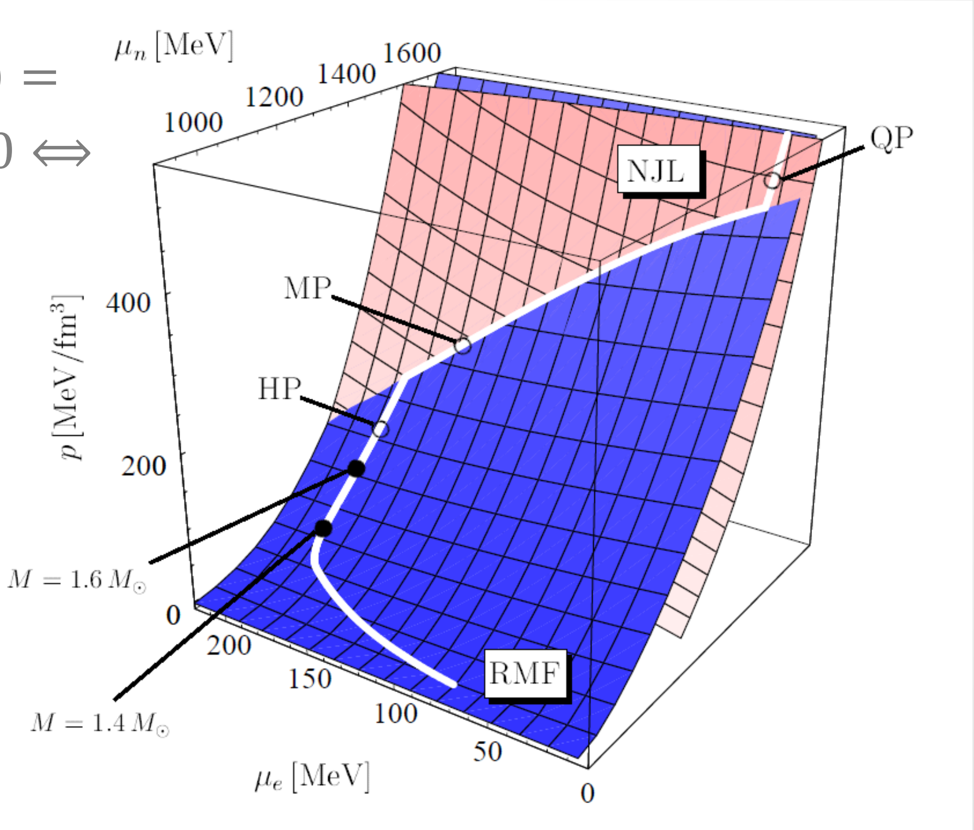
First order transition=order parameter jump?

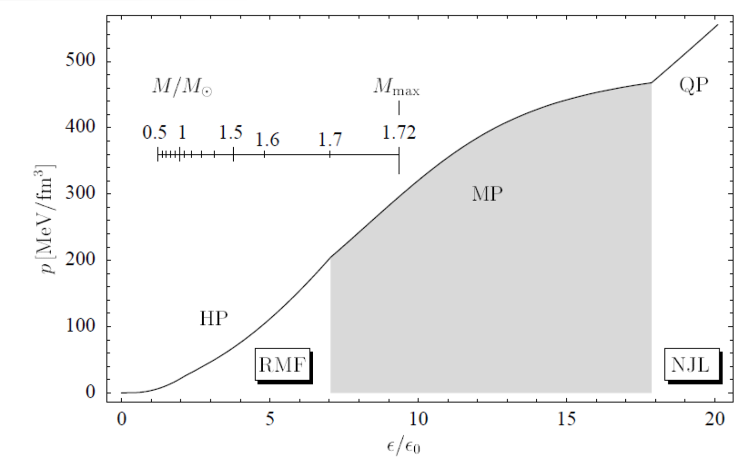


Do we really expect a density jump?

- 1st order Φ trans. with more than one conserved charges => Gibbs construction
- $\varepsilon(n_B, n_C, n_S, n_L) \Leftrightarrow \bar{\varepsilon}_{\mu_S,\mu_L}(n_B, n_C) = \varepsilon - \mu_S n_S - \mu_L n_L$ with $\mu_S = \mu_L = 0 \Leftrightarrow$ 2D phase diagram
- The mixed phase follows coexistence=> no pressure plateau ?

$(n_B, n_C) \Leftrightarrow (\mu_n, \mu_e)$



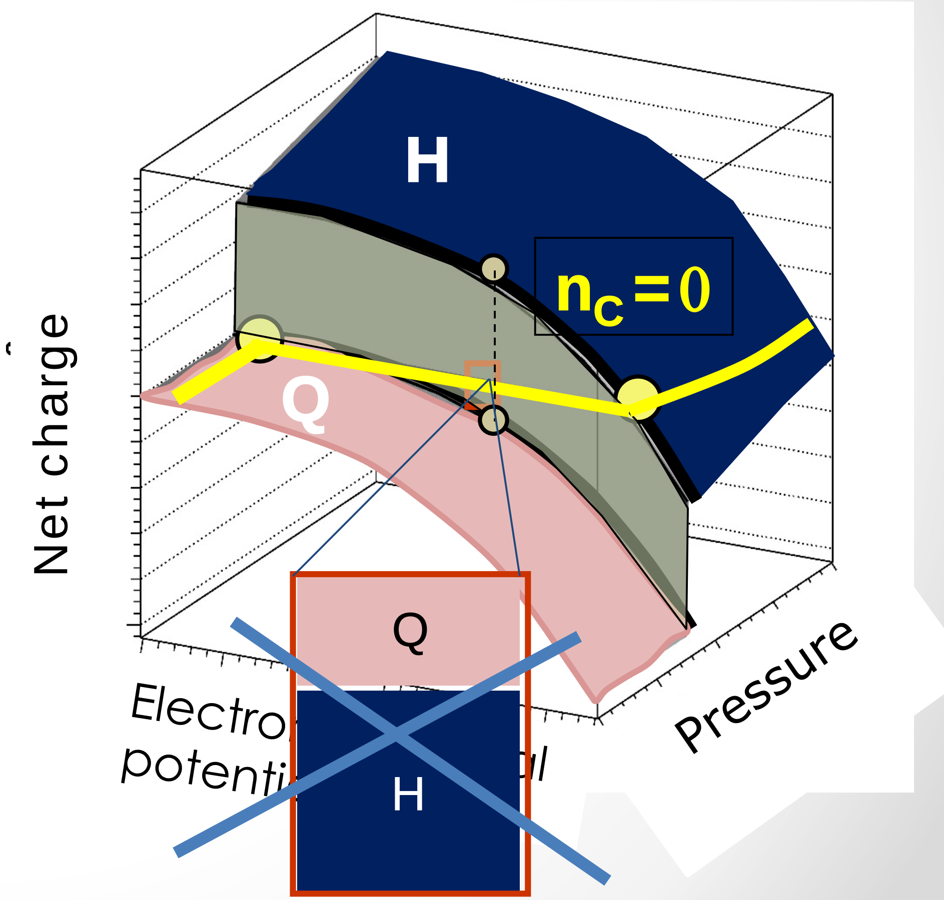


K.Schertler, S.Leupold, J.Schaffner-Bielich,
PRC 1999

Do we really expect a density jump?

- n_C order parameter: but a macroscopic charge gradient cannot exist at equilibrium => n_C=0 in each phase **if macroscopic**

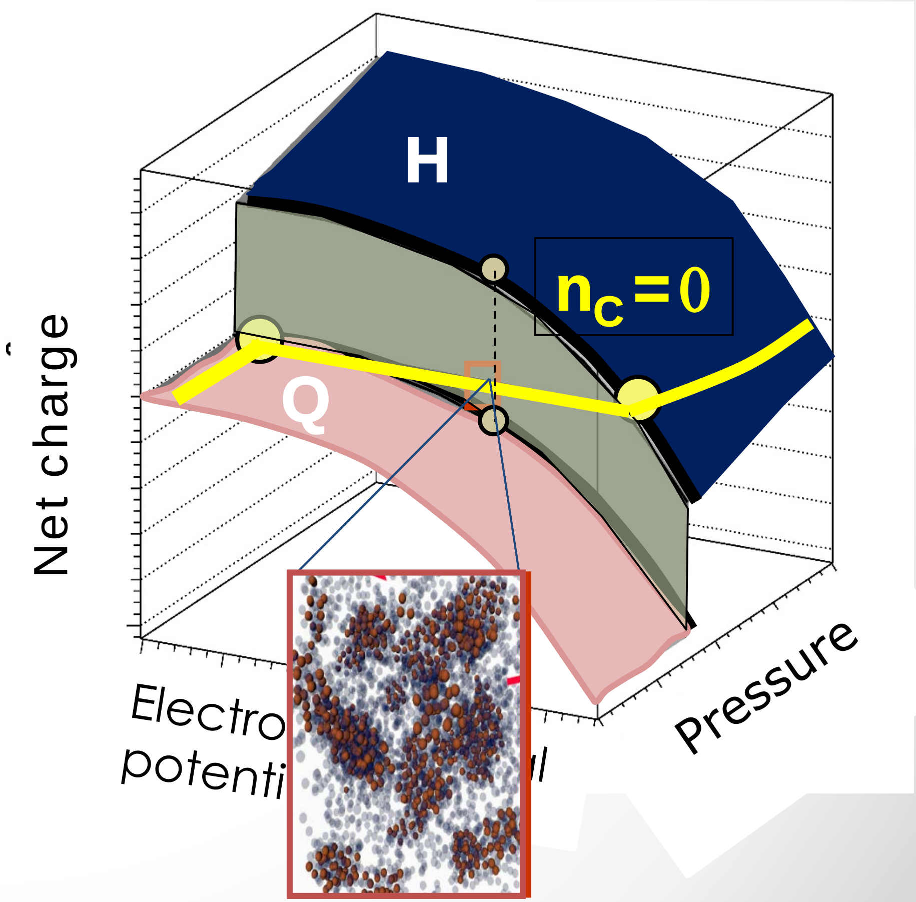
C.Ducoin, Ph.Chomaz, F.G, PRC 2007



Do we really expect a density jump?

- n_C order parameter: but a macroscopic charge gradient cannot exist at equilibrium => n_C=0 in each phase **if macroscopic**
- Density fluctuations can only appear at the **microscopic** level
- The H-Q transition passes through an inhomogeneous phase in stellar matter!
- The size of fluctuations depends on the interplay between surface and Coulomb

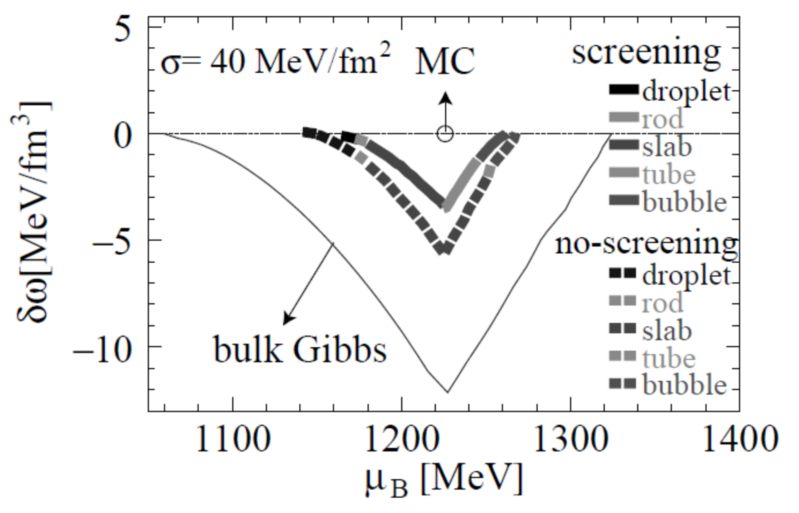
C.Ducoin, Ph.Chomaz, F.G, PRC 2007



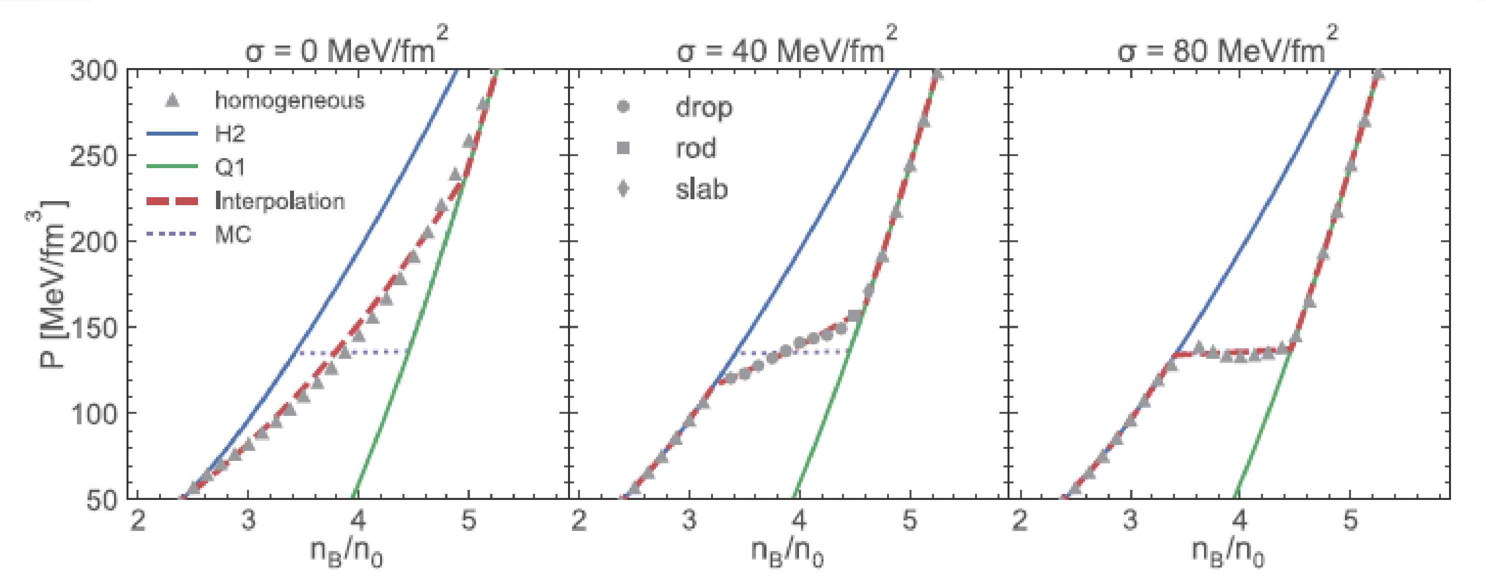
Do we really expect a density jump?

- Microscopic inhomogeneities: deconfined clusters in hadronic matter
- Energy gain depends on the (unknown) surface tension between the two phases
- Behavior intermediate between Maxwell and Gibbs

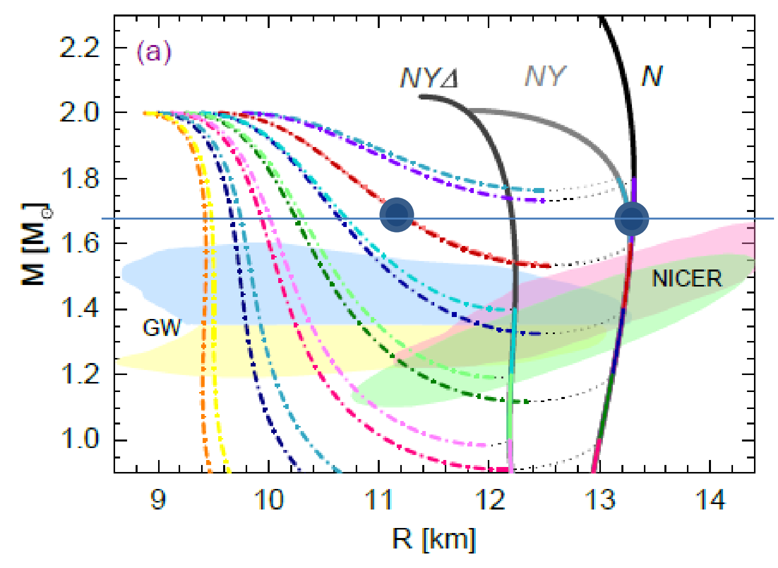
=> No density discontinuity



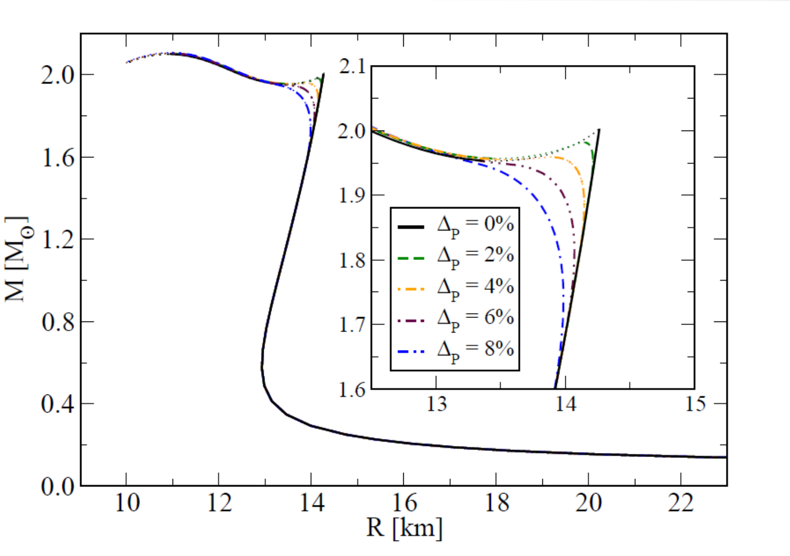
T.Endo at al, Prog.Th.Phys. 2006
K.Maslov et al, PRC 2019



A third family of NS?



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



D.Blaschke et al,
“Topics on Strong Gravity"
World Scientific (2020), pp. 207-256

No third family is we account for the mixed phase!

Summary & Conclusions

- How to (dis)prove the existence of deconfined matter in the core of neutron stars?
- A null hypothesis: the nucleonic meta-modelling technique allows predictions with controlled uncertainties within the hypothesis of nucleonic matter

  => No present indication of exotic degrees of freedom
- Relatively tight observable prediction within the nucleonic hypothesis

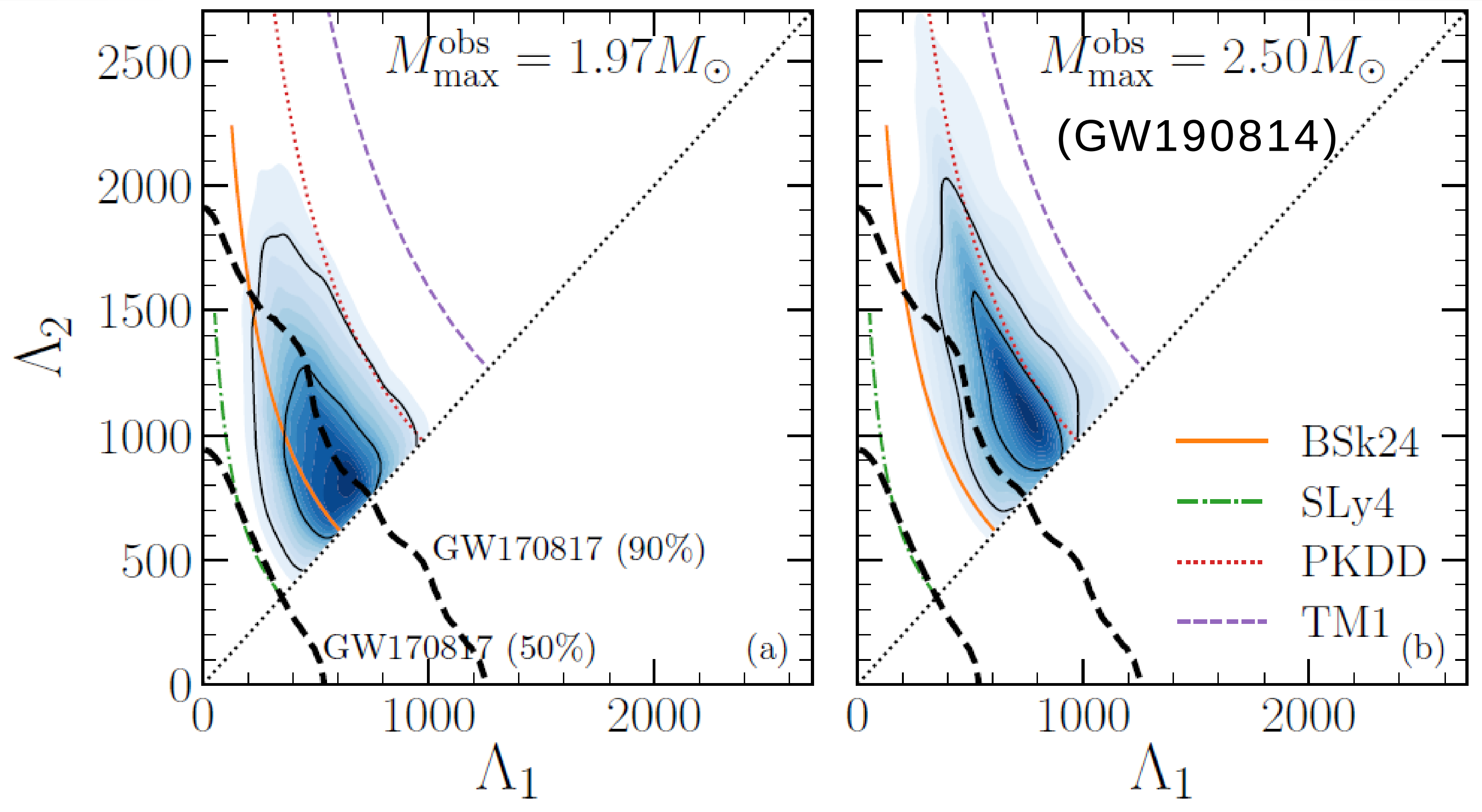
  => A density jump can in principle be detectable with post O5 and 3G interferometers
- But what is the smoking gun for a first order H-Q phase transition?

  => The answer is not clear, both Maxwell and Gibbs are not correct

Strong challenge for future observation

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

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



The importance of lab constraints:

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

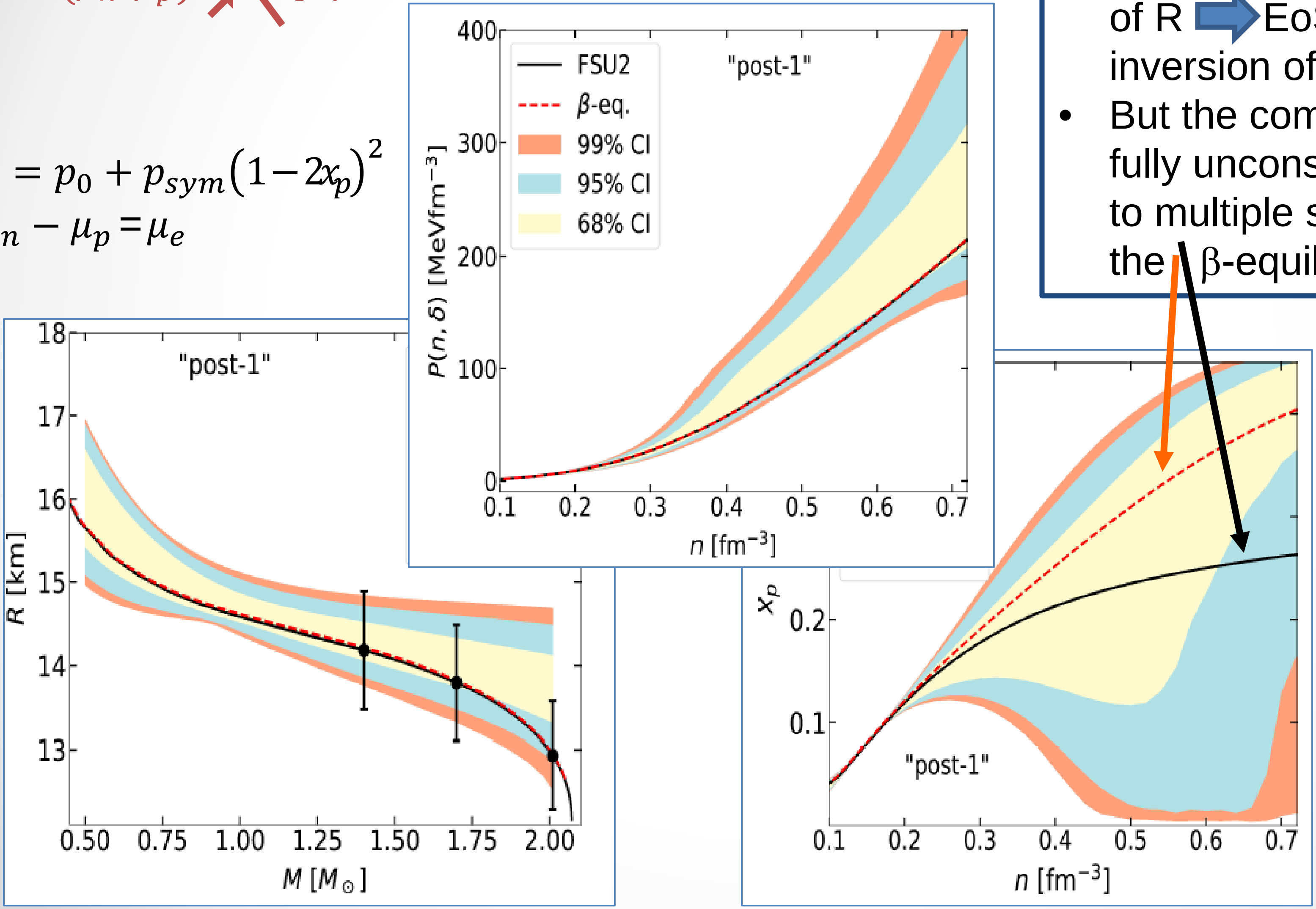
$e(\rho_n,\rho_p) \cancel{\Leftarrow} p(\rho)$

(1) high density

- precise measurements of R ⇒ EoS via inversion of the TOV
- But the composition if fully unconstrained due to multiple solutions of the β-equilibrium eq.

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

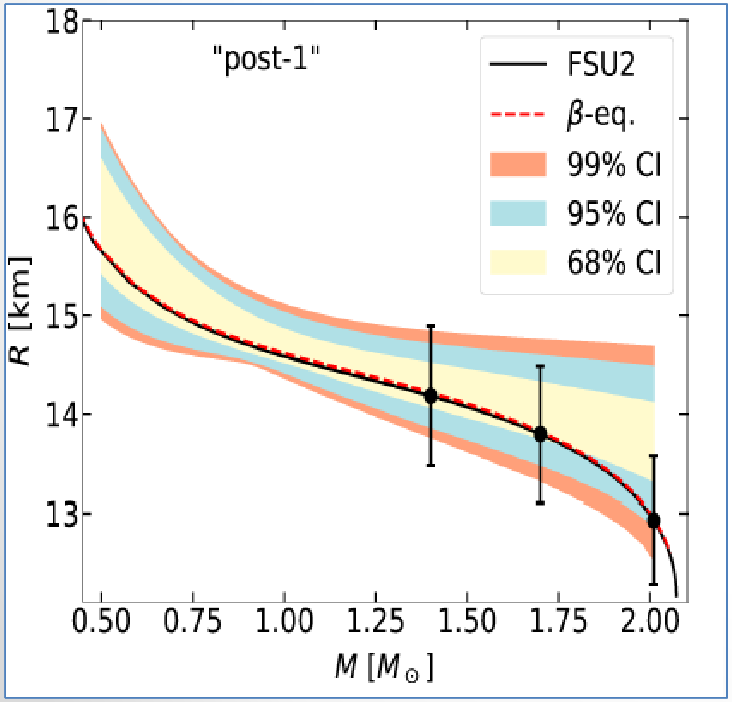
$$\mu_n - \mu_p = \mu_e$$

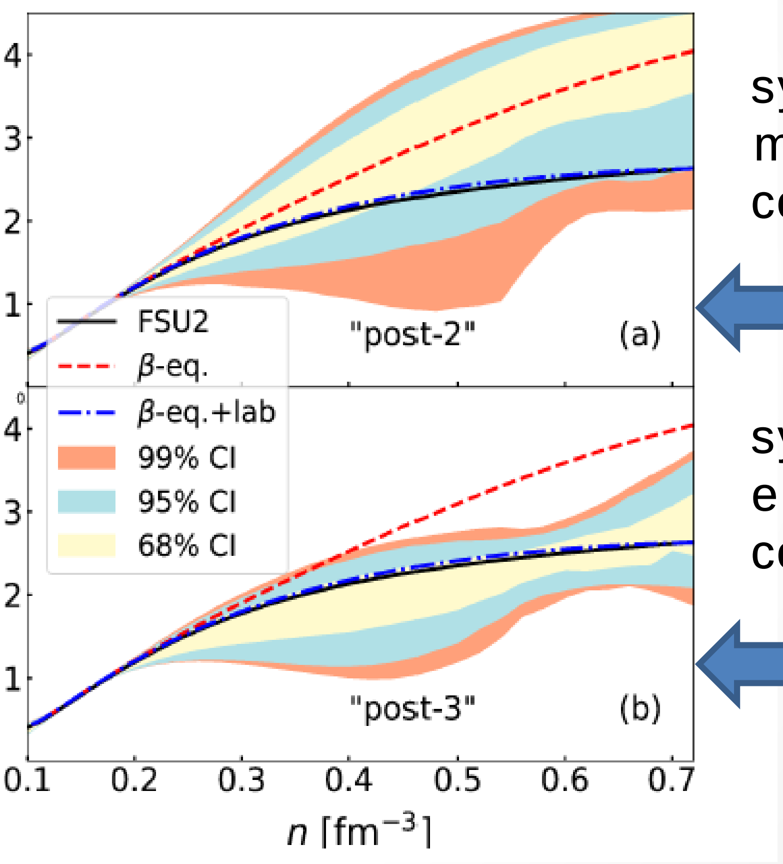


The importance of lab constraints:

(1) high density

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





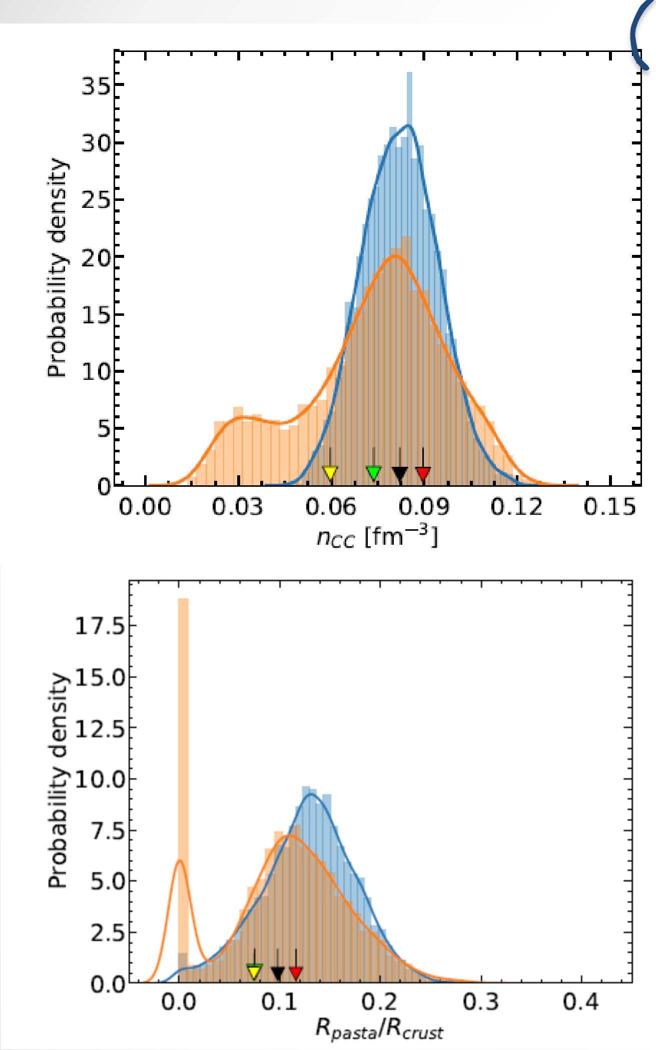
symmetric matter constraint

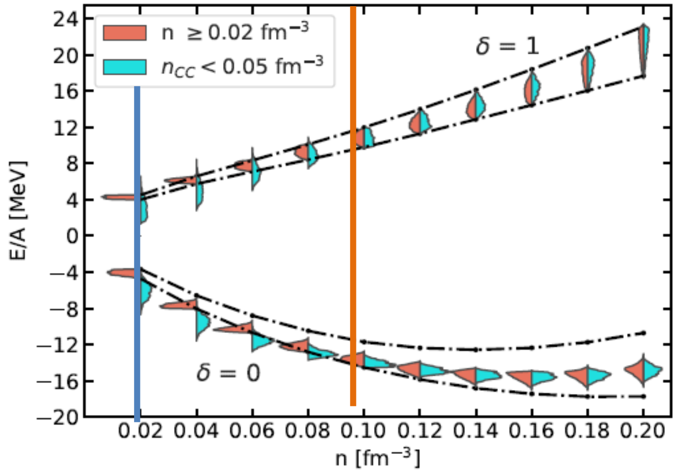
symmetry energy constraint

C.Mondal and F.G,arXiv:2111.04520v1

The importance of lab constraints:

(2) low density

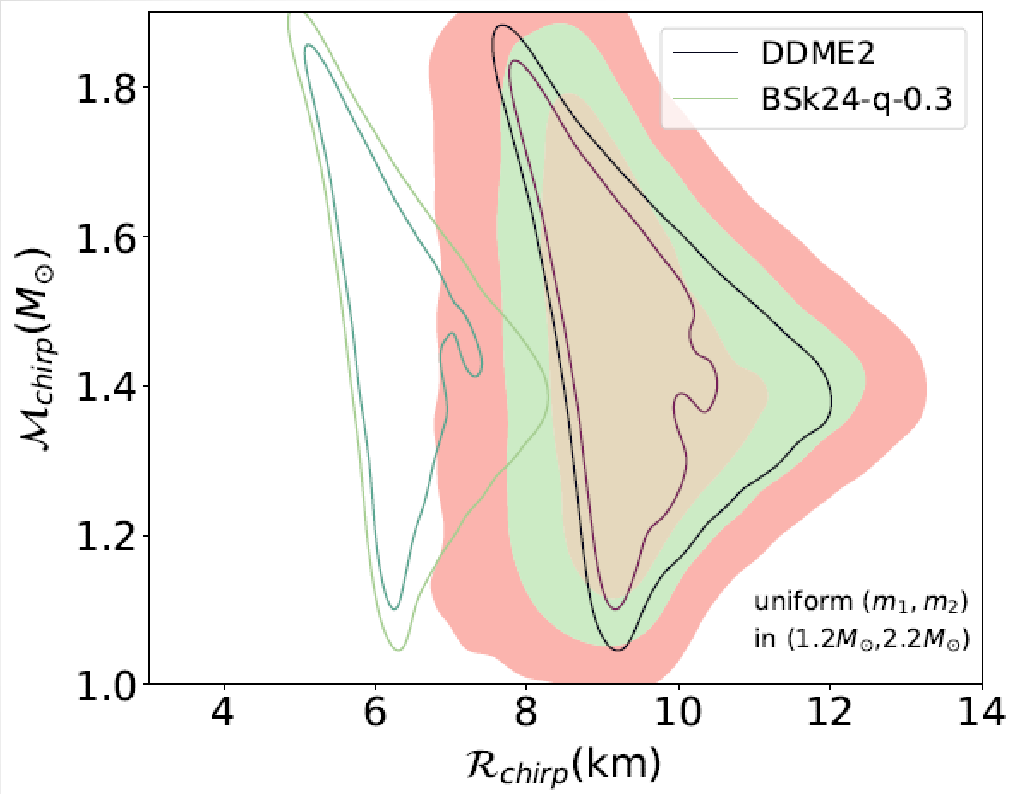




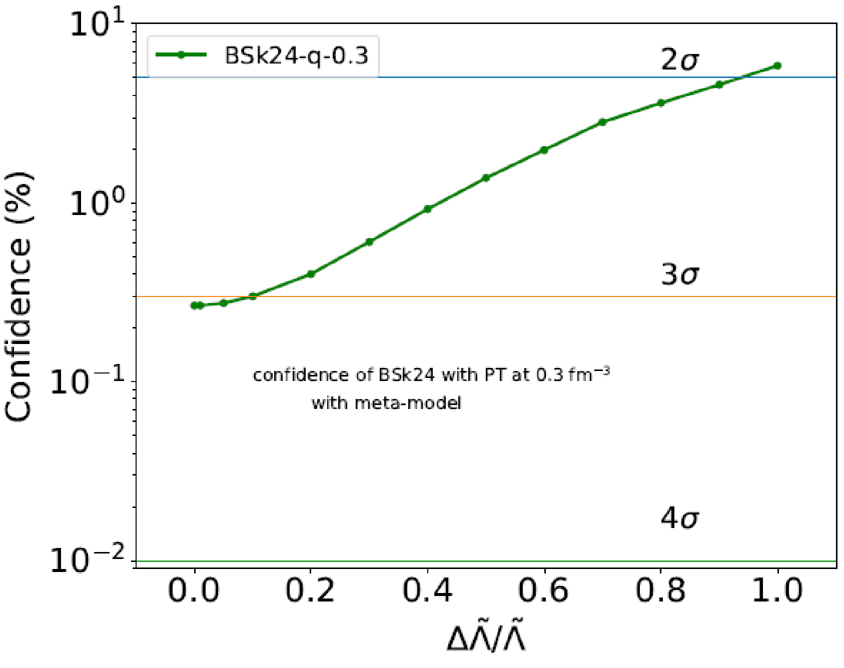
- If the chiral constraint is only applied from n=0.1 models with thin crust and no pasta cannot be excluded
- Crustal properties crucially depend on the very low density EoS

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



C.Mondal, M.Oertel, F.G., in preparation

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

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

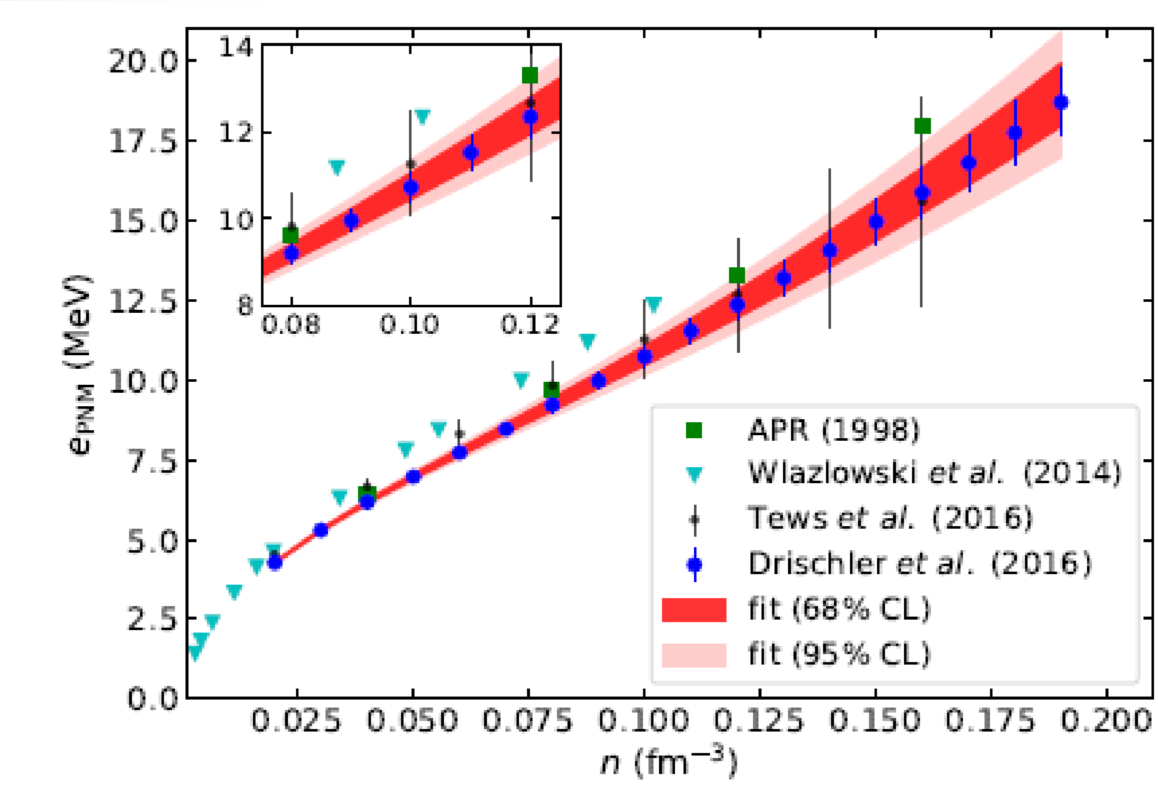
(CNRS-In2p3)

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

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

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

Pure neutron matter

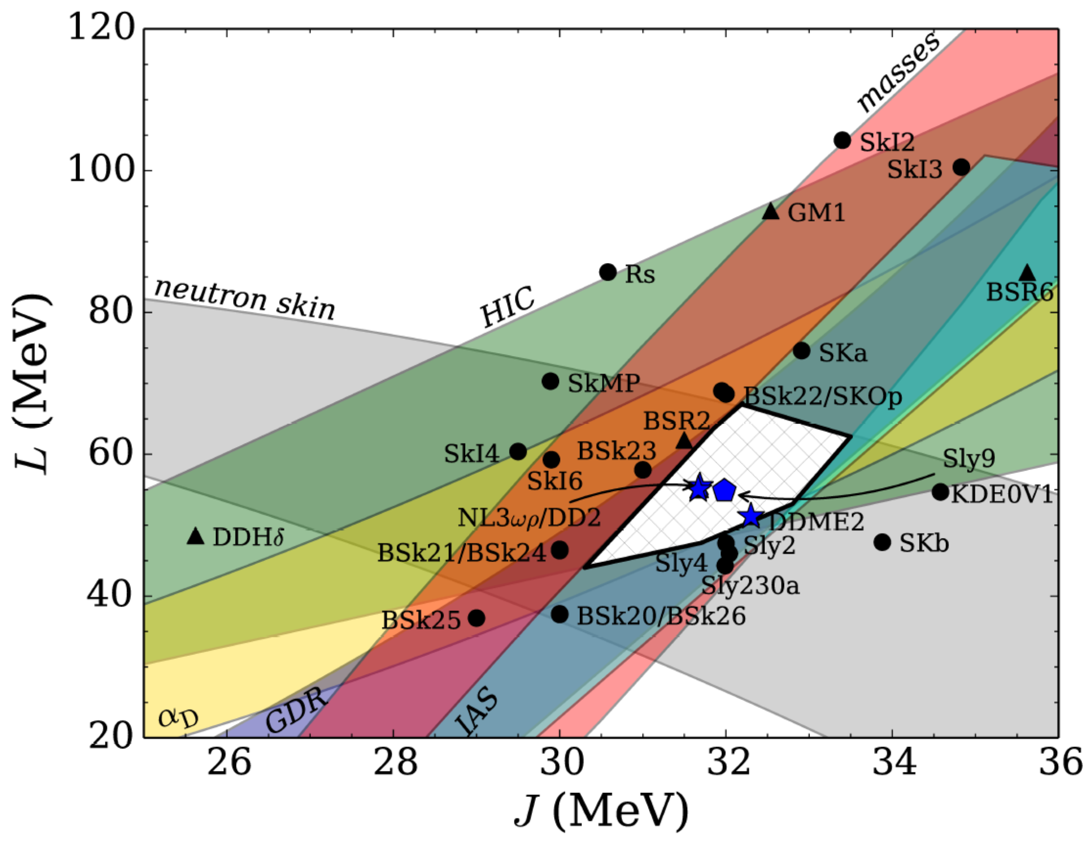


- **Diagrammatic expansion: controlled uncertainties!**
- **Power counting & regularization valid only up to ~ 1,5ρ_0**

=> 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



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

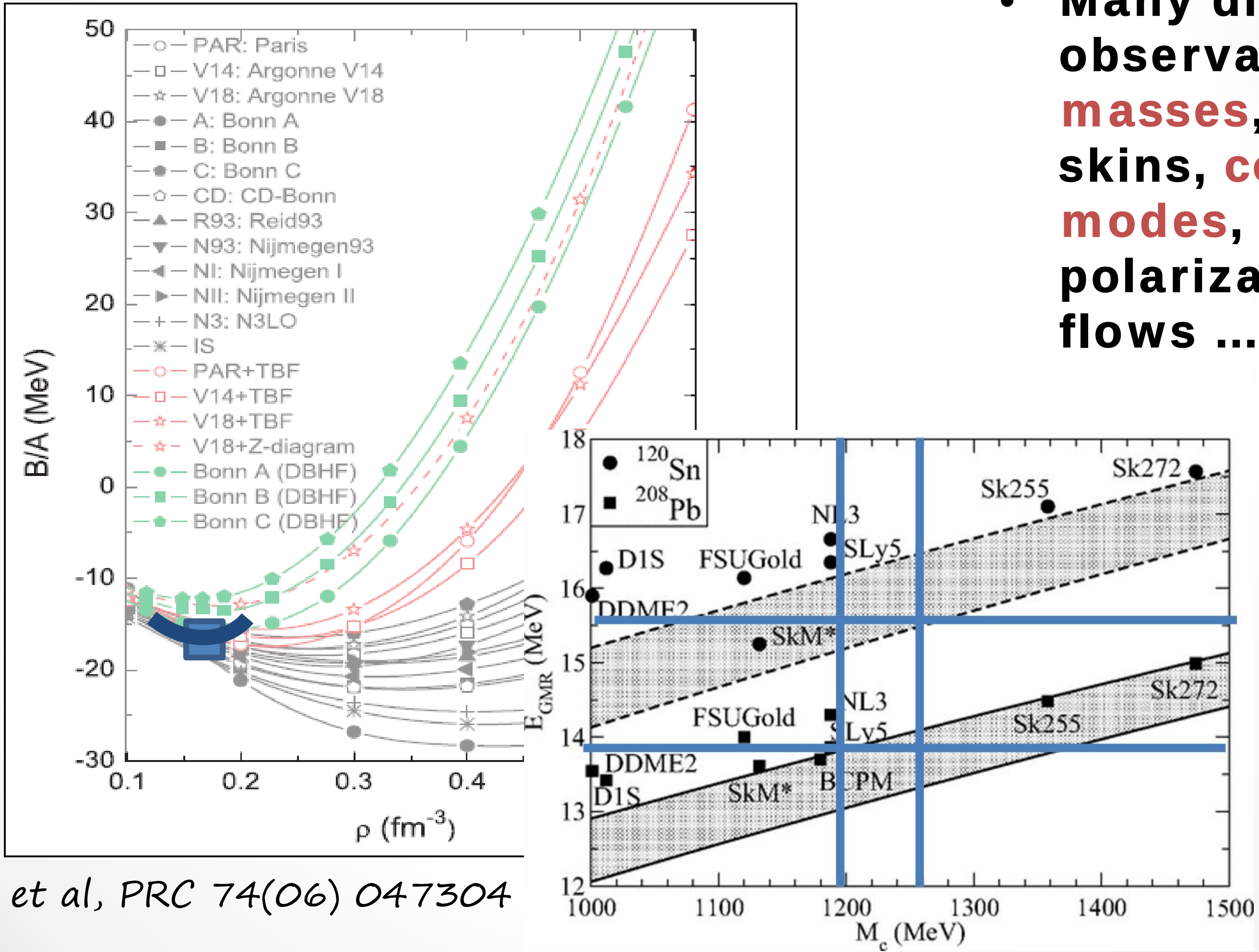
- **Also sensitive to low densities up to ~ ρ_0**

=> constrain low order parameters

M.Fortin et al PRC 2016

EoS Constraints from nuclear physics (2): experiments

Symmetric matter

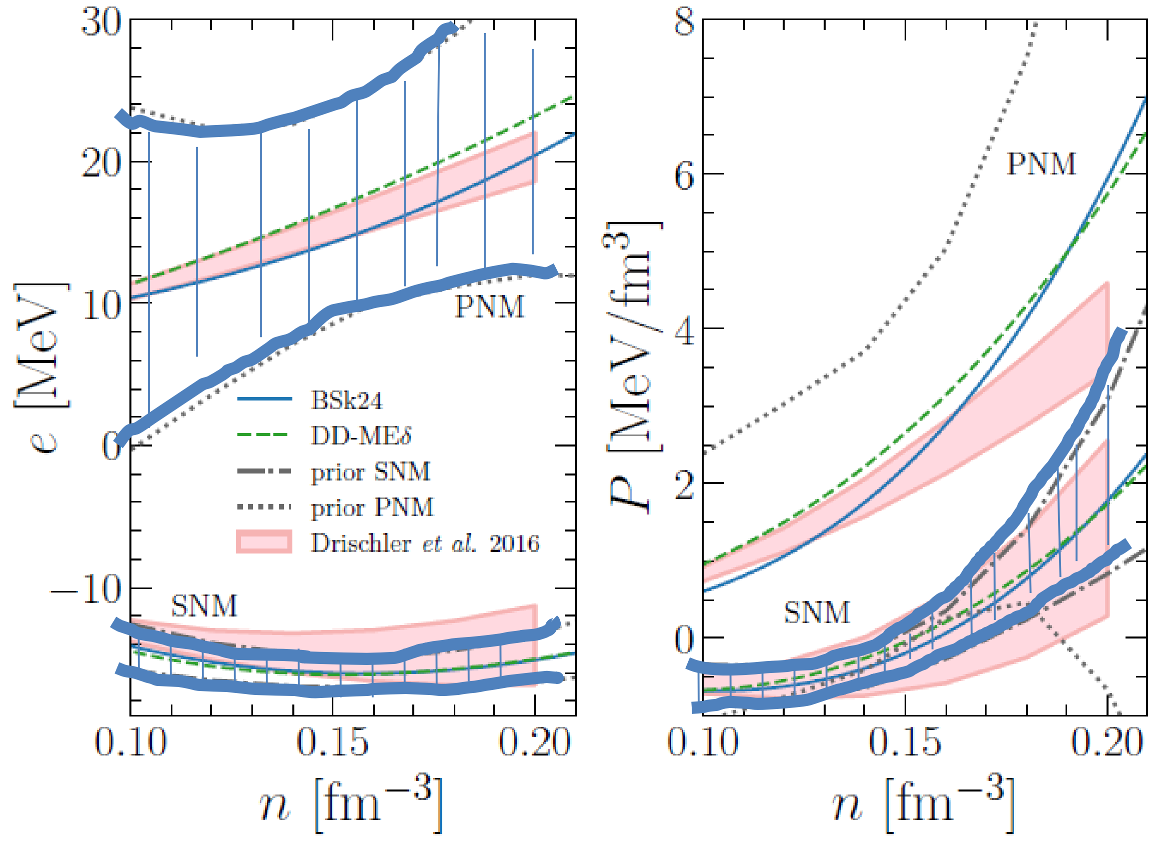


Z.H.Li et al, PRC 74(06) 047304

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

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

Experimental versus theoretical constraints

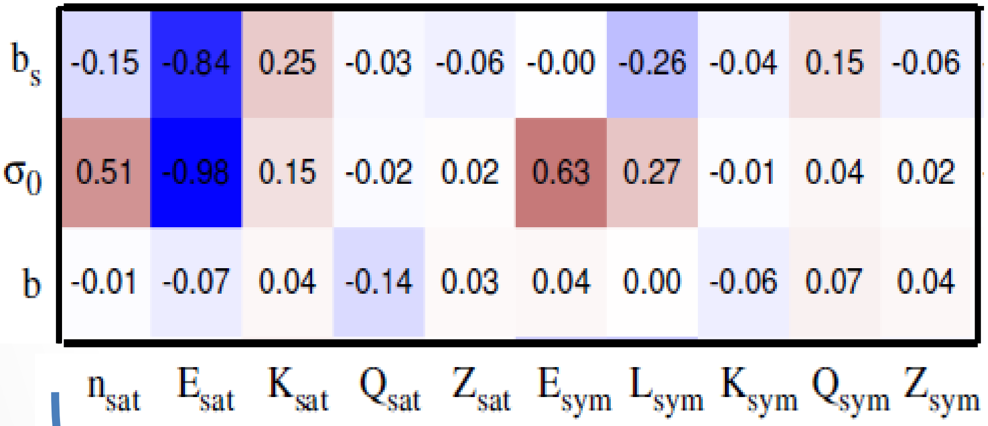


EoS Constraints from nuclear physics (3): masses

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

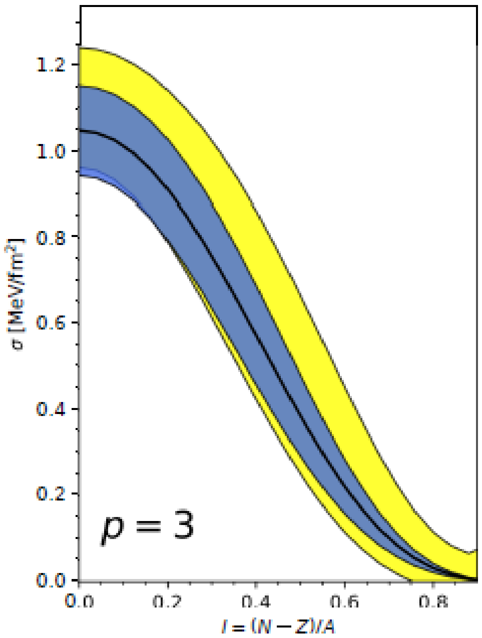
=> sub-saturation EoS

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



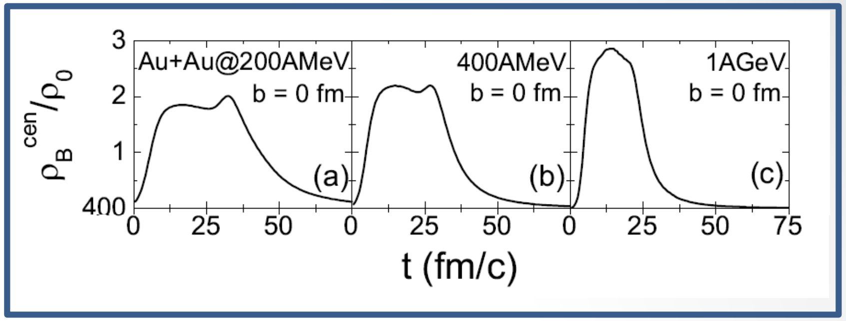
$$P(M|\vec{X}) = exp - \left(\sum_i^{AME} \frac{\left(M_i^{exp} - M_i(\vec{X})\right)^2}{2\sigma_i^2} \right)$$

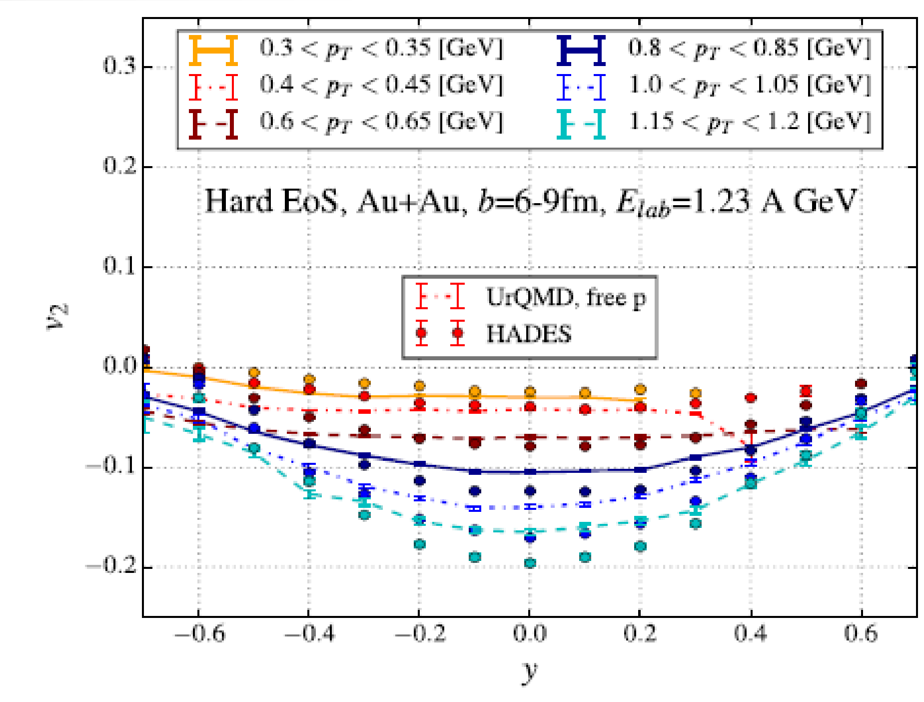
T.Carreau et al, EPJA 2019, PRC 2019

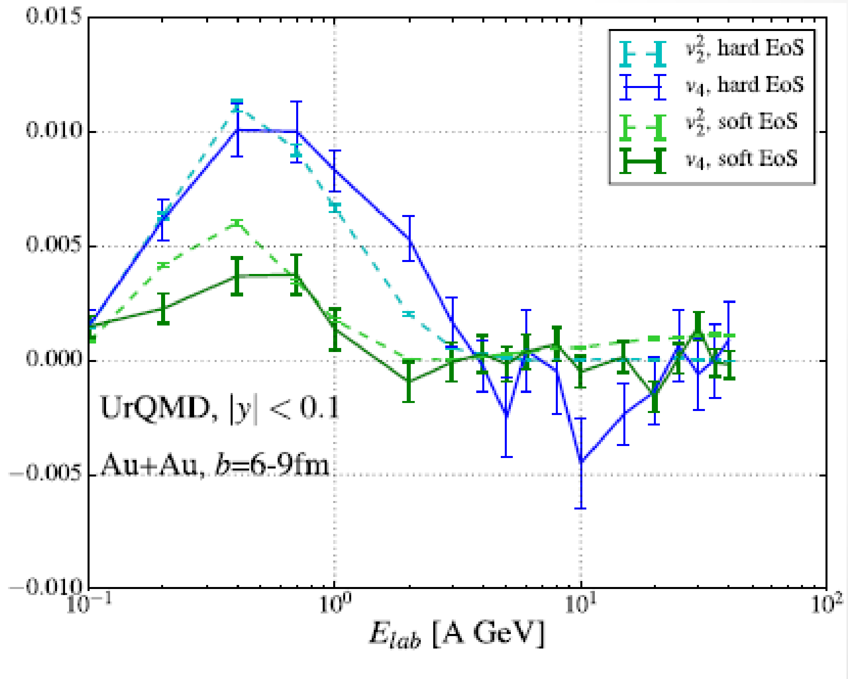
Tighter constraints from high energy experiments ?

Elliptic flow @ HADES:
Transport model versus data

J.Xu, PRC 2013







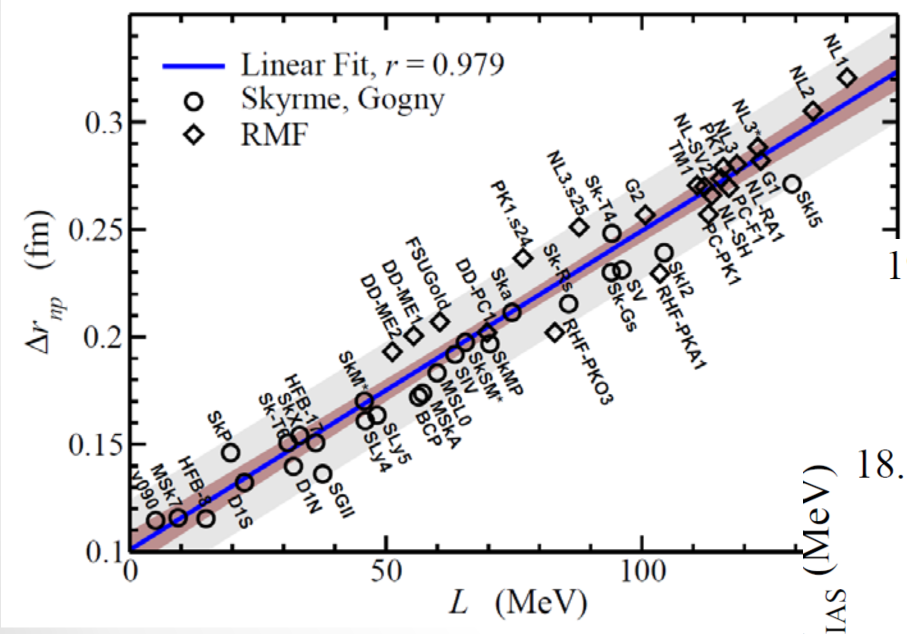
P.Hillmann et al., JPG 47 (2020) 055101

Strategy II: high precision

Isovector probes with stable nuclei:

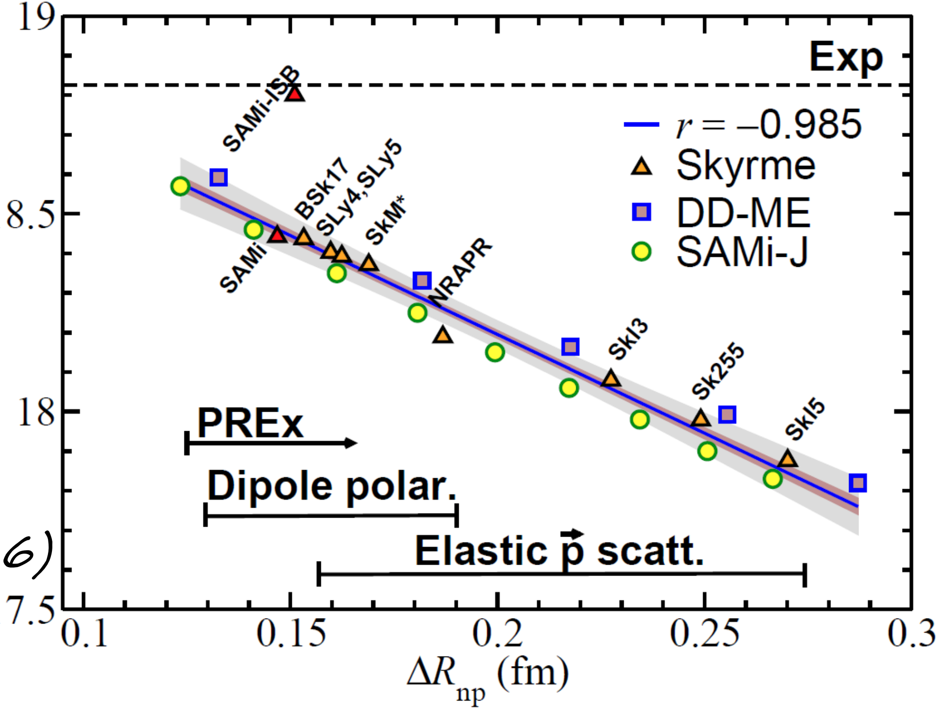
- Skin
- IAS
- GDR response
- Isospin transport in HIC (INDRA/FAZIA)

Exp: Δr_{np}= 0,1318-0,3072



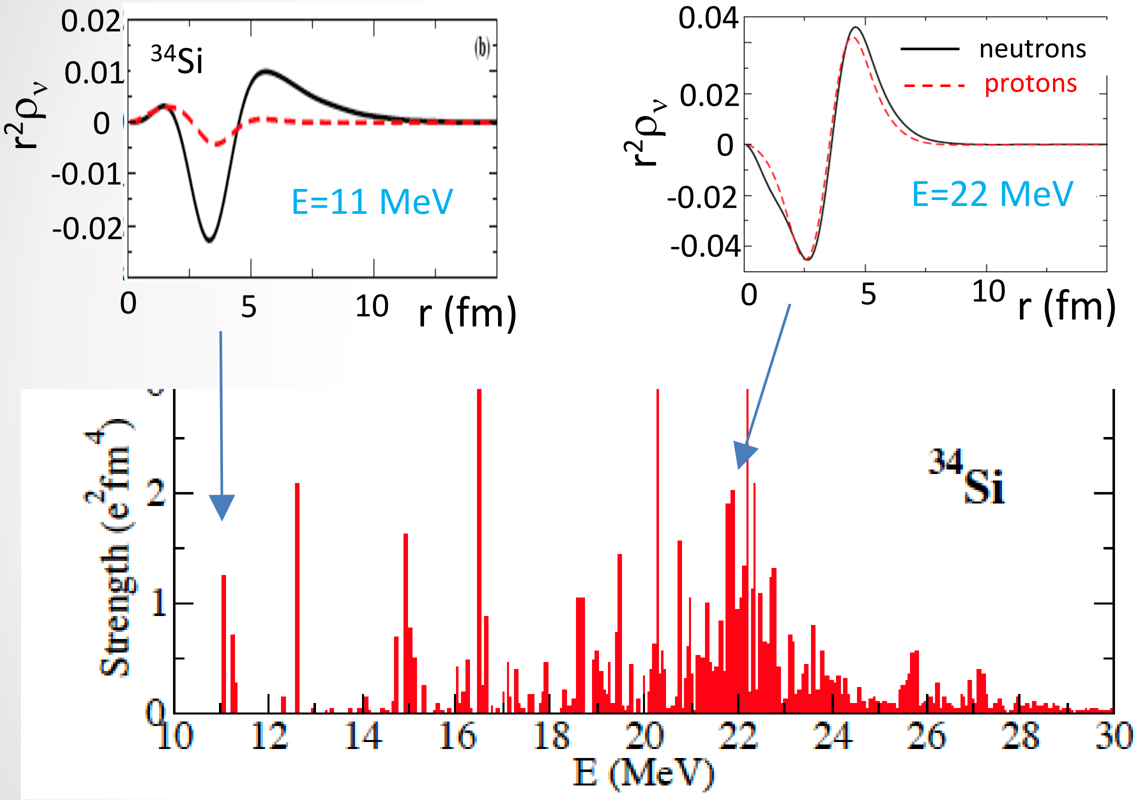
X.Vinas et al (2014)
P.G.Reinhard, W.Nazarewicz (2016)
J.Yang, J.Piekarewicz (2017)

X.Roca-Maza, G.Colo, H.Sagawa (2018)



Strategy III: new probes

SSRPA calculations

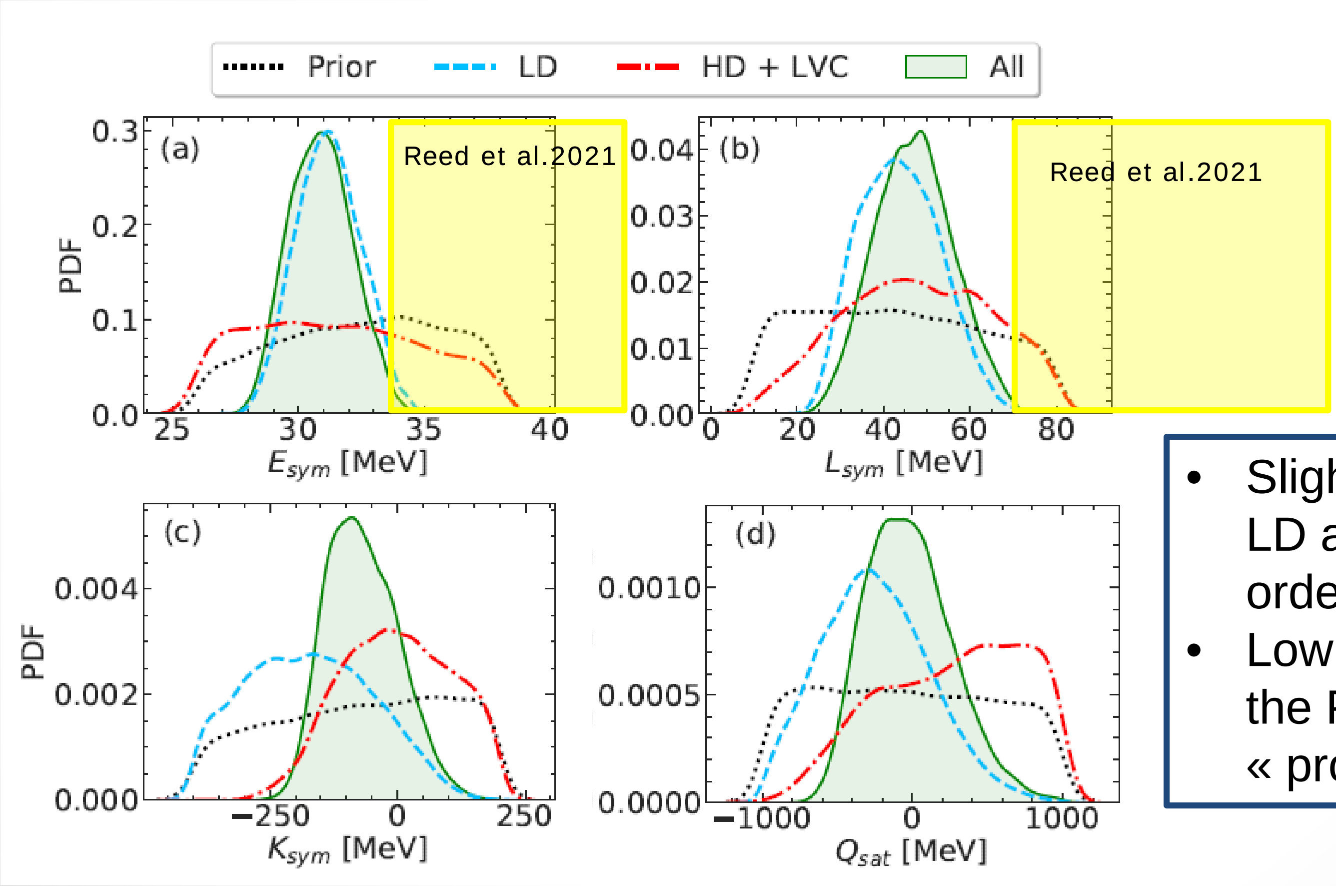


Isoscalar probes in exotic nuclei:

- Soft monopole

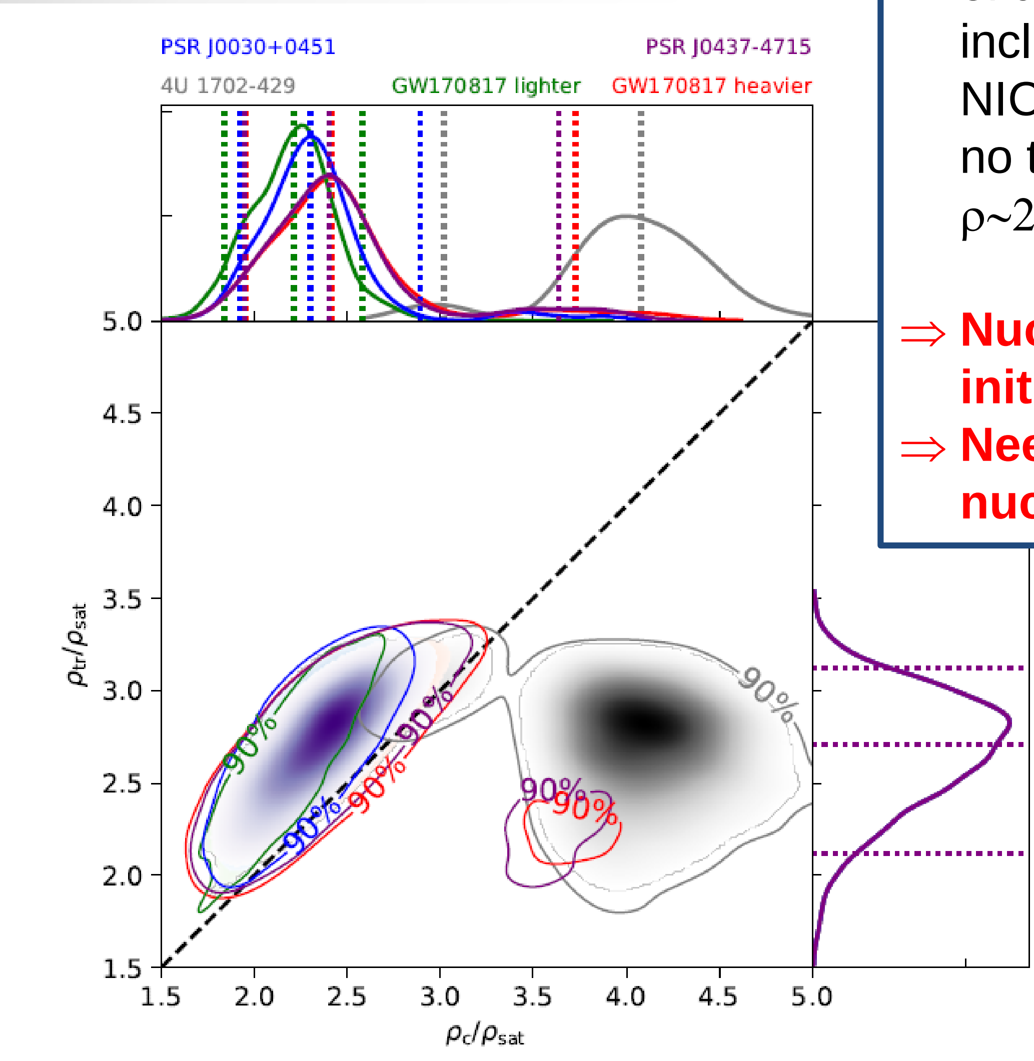
D.Gambacurta, Phys. Rev. C ***100****, 014317 (2019)*

Tensions in the empirical parameters?



- Slight tension between LD and HD in the high order parameters
- Low order parameters: the PREX-2 « problem »

H.Dinh Thi et al, Universe 2021

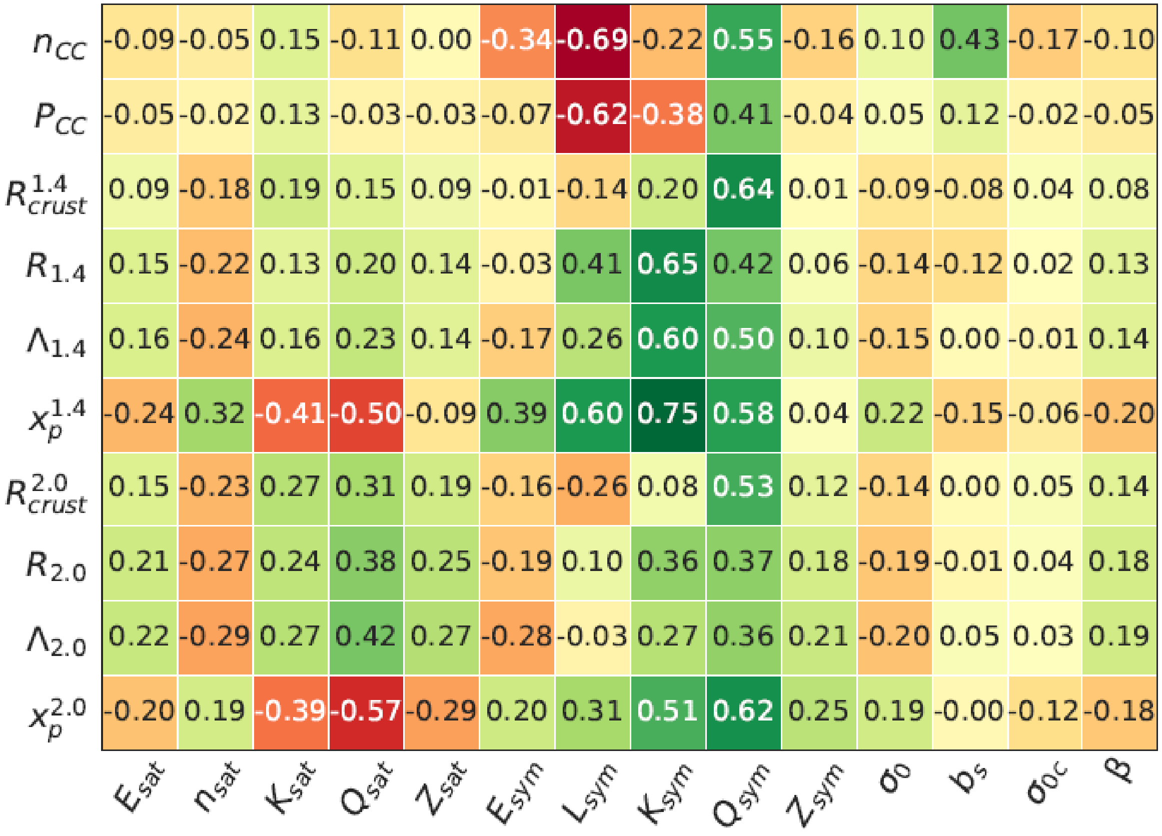


- « Reasonable » agnostic modeling of a 1st order phase transition including both LIGO/VIRGO and NICER data as constraints, predicts no transitions below densities $\rho \sim 2,5\rho_0$

⇒ Nuclear physics is valid, but ab-initio modeling is not…

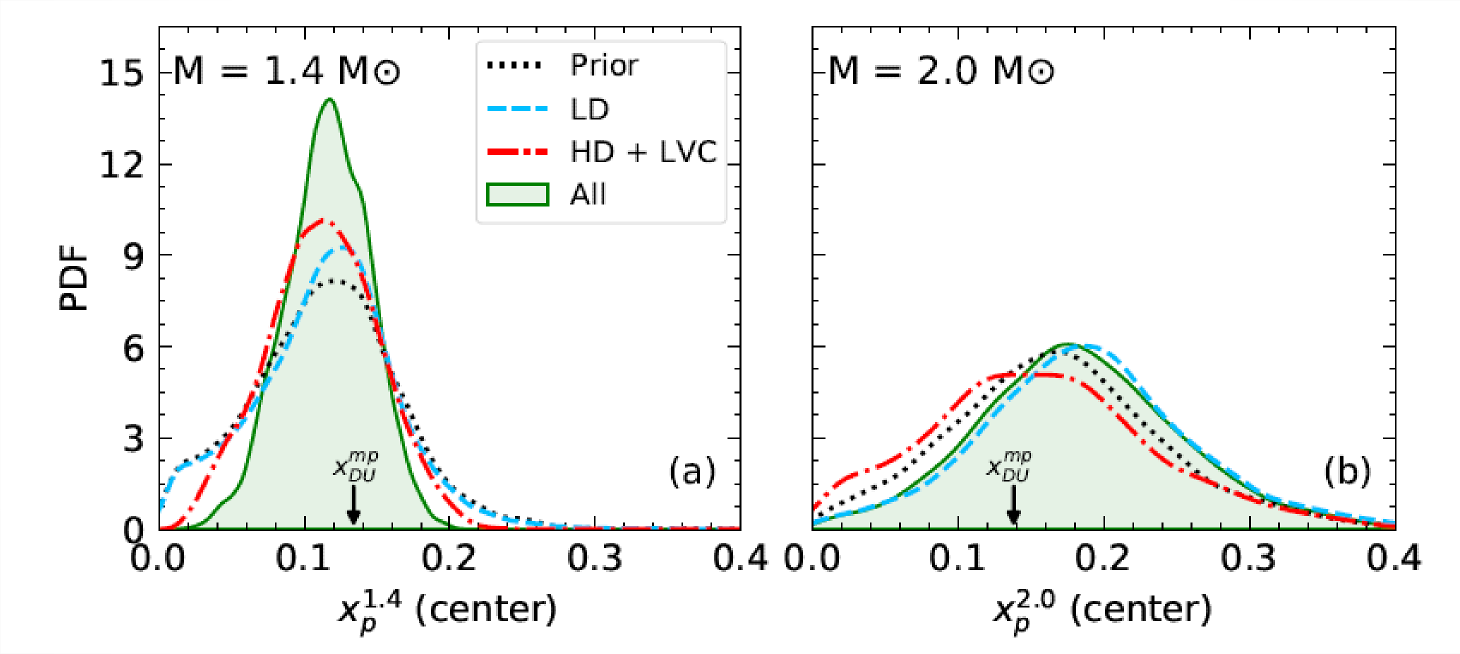
⇒ Need of more constraining nuclear data for $\rho_0 < \rho < 2\rho_0$

S.P.Tang et al., arXiv:2009.05719v1



	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}	-0.09	-0.05	0.15	-0.11	0.00	-0.34	-0.69	-0.22	0.55	-0.16	0.10	0.43	-0.17	-0.10
P_{CC}	-0.05	-0.02	0.13	-0.03	-0.03	-0.07	-0.62	-0.38	0.41	-0.04	0.05	0.12	-0.02	-0.05
$R^{1.4}_{crust}$	0.09	-0.18	0.19	0.15	0.09	-0.01	-0.14	0.20	0.64	0.01	-0.09	-0.08	0.04	0.08
$R_{1.4}$	0.15	-0.22	0.13	0.20	0.14	-0.03	0.41	0.65	0.42	0.06	-0.14	-0.12	0.02	0.13
$\Lambda_{1.4}$	0.16	-0.24	0.16	0.23	0.14	-0.17	0.26	0.60	0.50	0.10	-0.15	0.00	-0.01	0.14
$x_p^{1.4}$	-0.24	0.32	-0.41	-0.50	-0.09	0.39	0.60	0.75	0.58	0.04	0.22	-0.15	-0.06	-0.20
$R^{2.0}_{crust}$	0.15	-0.23	0.27	0.31	0.19	-0.16	-0.26	0.08	0.53	0.12	-0.14	0.00	0.05	0.14
$R_{2.0}$	0.21	-0.27	0.24	0.38	0.25	-0.19	0.10	0.36	0.37	0.18	-0.19	-0.01	0.04	0.18
$\Lambda_{2.0}$	0.22	-0.29	0.27	0.42	0.27	-0.28	-0.03	0.27	0.36	0.21	-0.20	0.05	0.03	0.19
$x_p^{2.0}$	-0.20	0.19	-0.39	-0.57	-0.29	0.20	0.31	0.51	0.62	0.25	0.19	-0.00	-0.12	-0.18

Composition: xp and DURCA

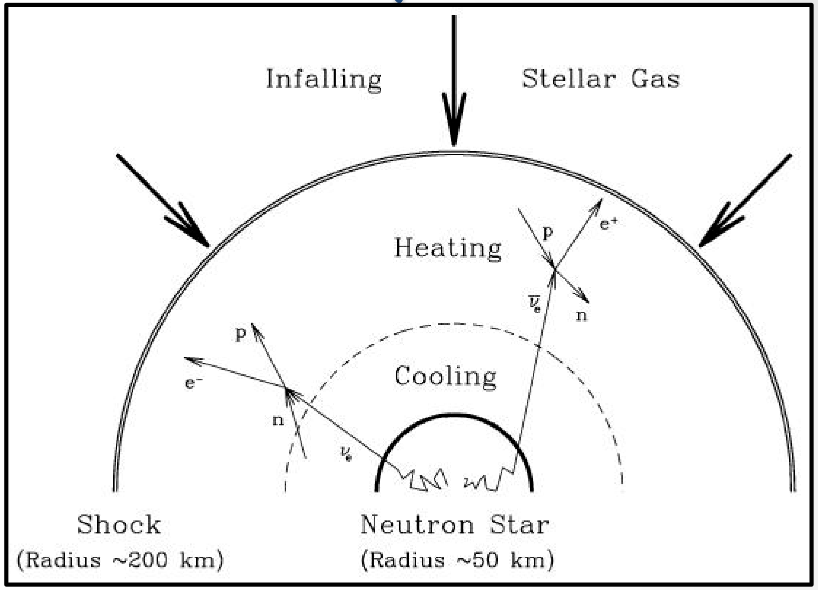


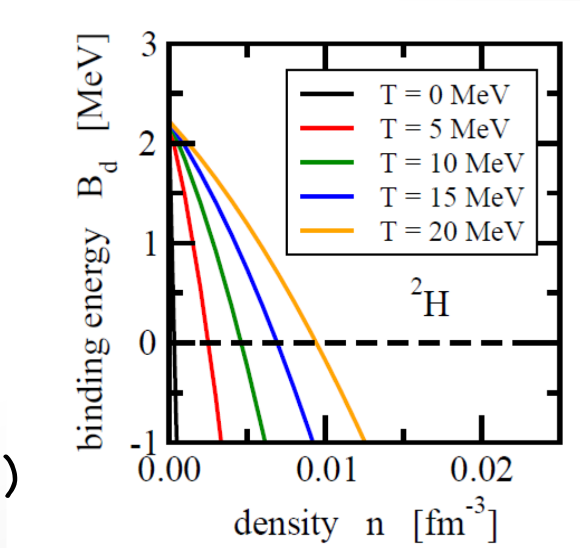
- Nucleonic hypothesis compatible with all observations
- But potential challenge with upcoming measurements

H.Dinh Thi et al, Universe 2021

3) SN explosion and r-process seeds: matter composition at the ν–sphere

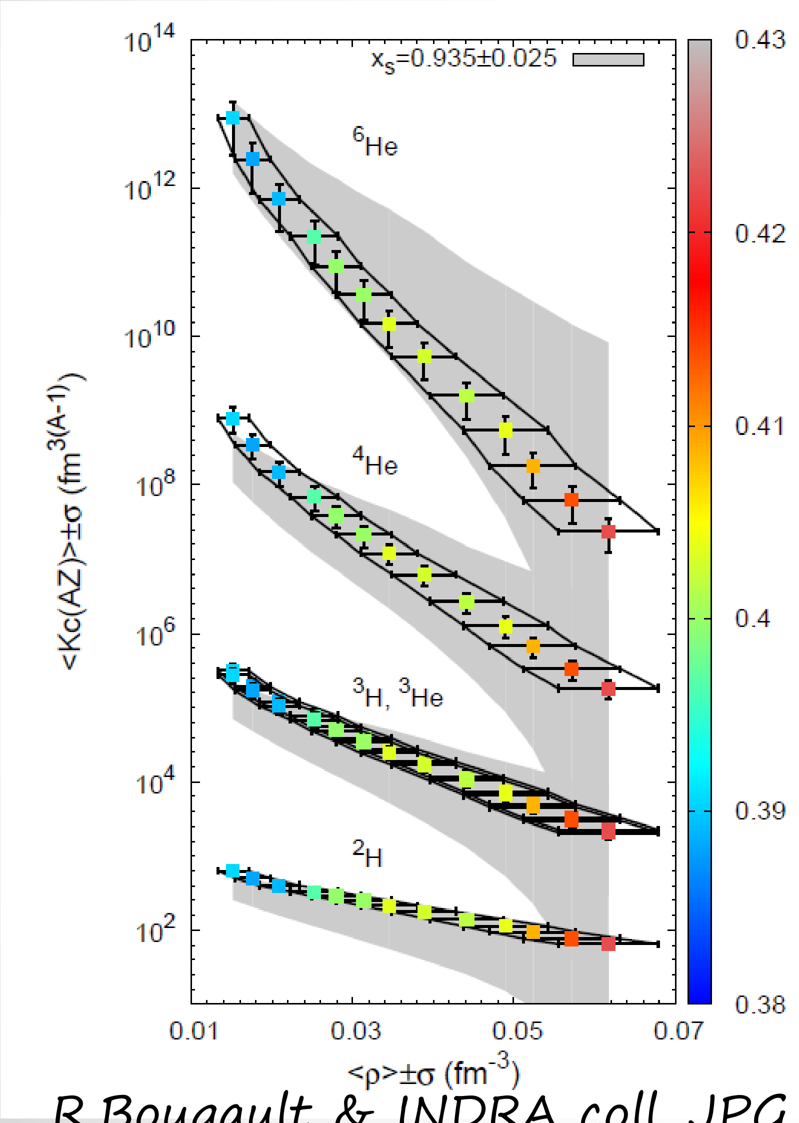
- The energy deposition in the gain region depends on the position of the ν–sphere
- Coherent scattering off nuclei is a crucial source of opacity
- Composition depends on the in-medium modifications to the binding energy





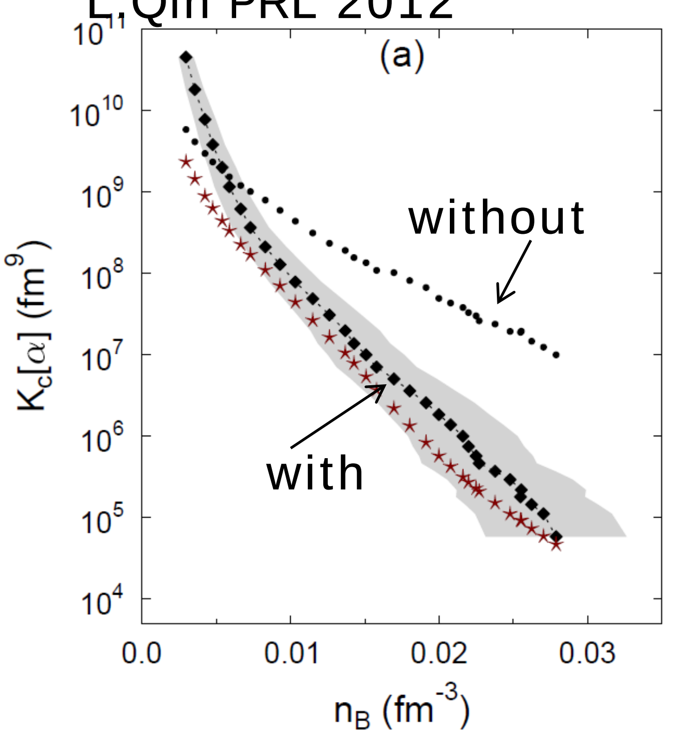
S.Typel NPA (2009)

Chemical constants from multi-fragmentation



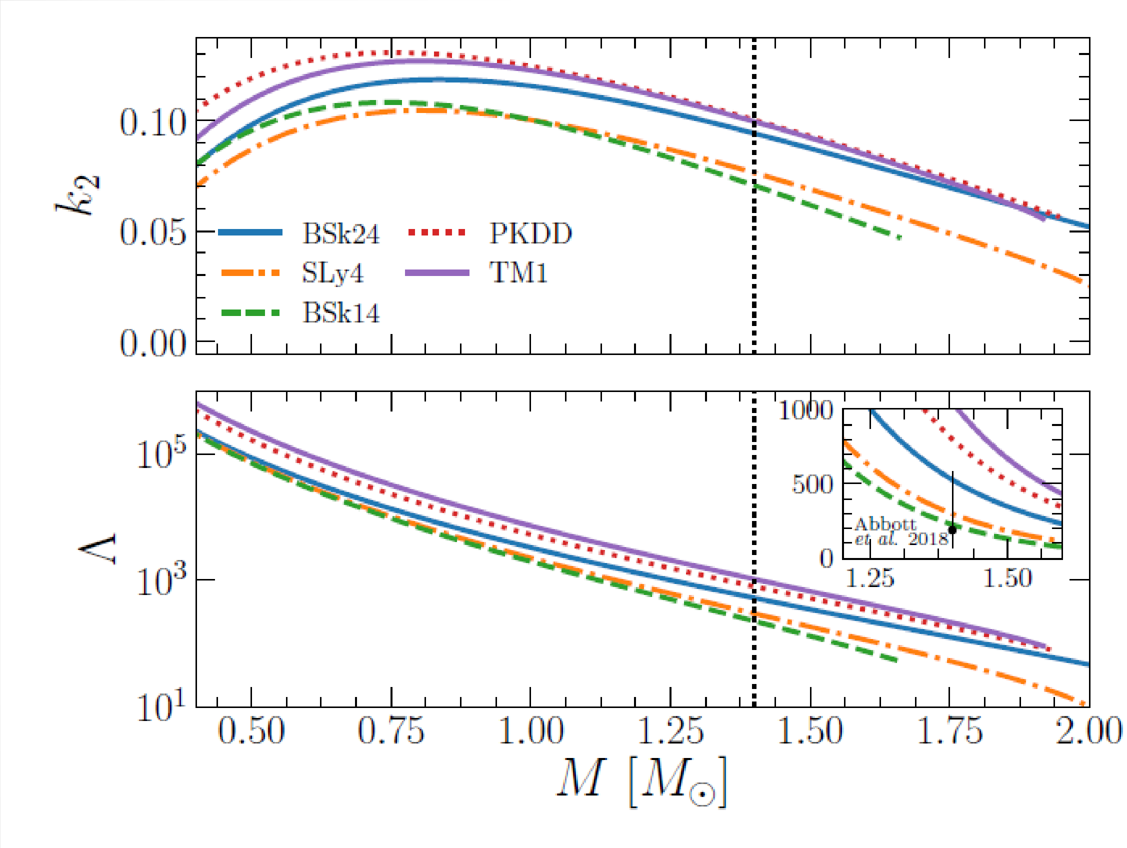
$$K_c(A,Z) = \frac{\rho_{pa}(A,Z)}{\rho_{pa}(1,1)^Z \ \rho_{pa}(1,0)^N}$$

L.Qin PRL 2012

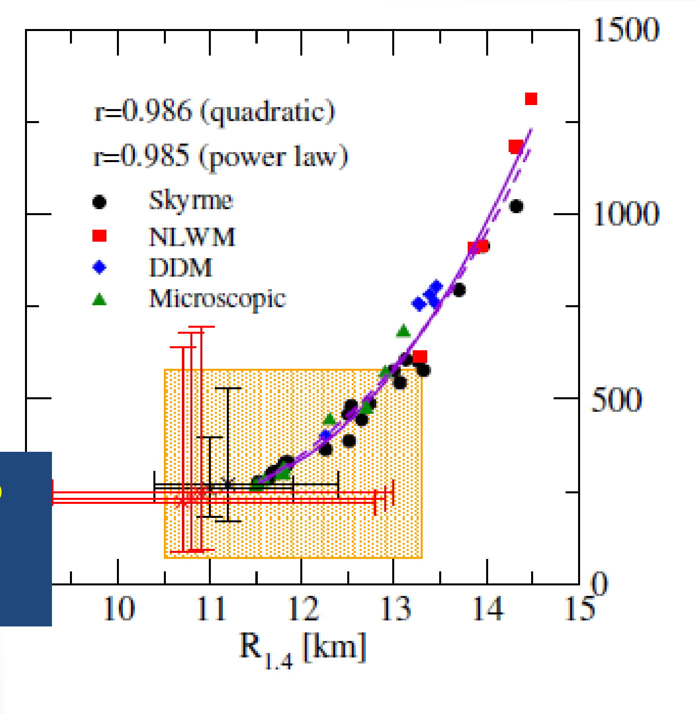


R.Bougault & INDRA coll. JPG (2019)
H.Pais & INDRA coll. PRL (2020)

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

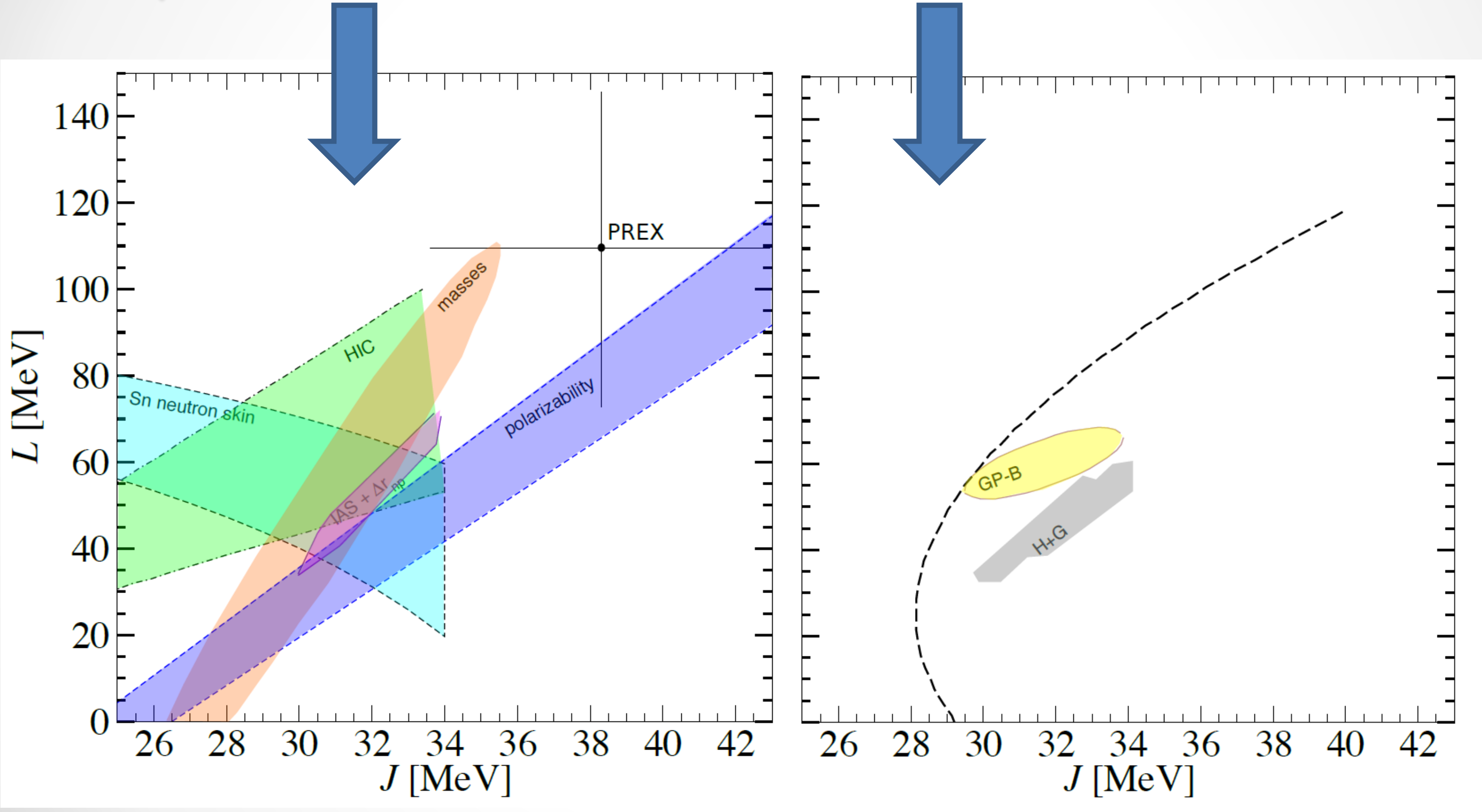


$\Lambda_{1.4}$
Abbott et al, PRL **2018**
$\Lambda_{1.4} - R_{1.4}$
Capano et al, Nat.Astron.**2020**
De et al, PRL 2018



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

Experimental versus theoretical constraints



Courtesy A.F.Fantina

Quarkyonic matter

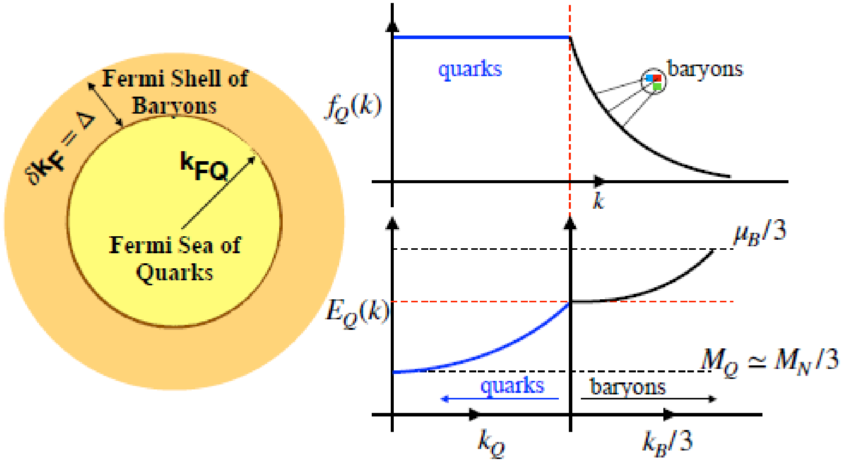
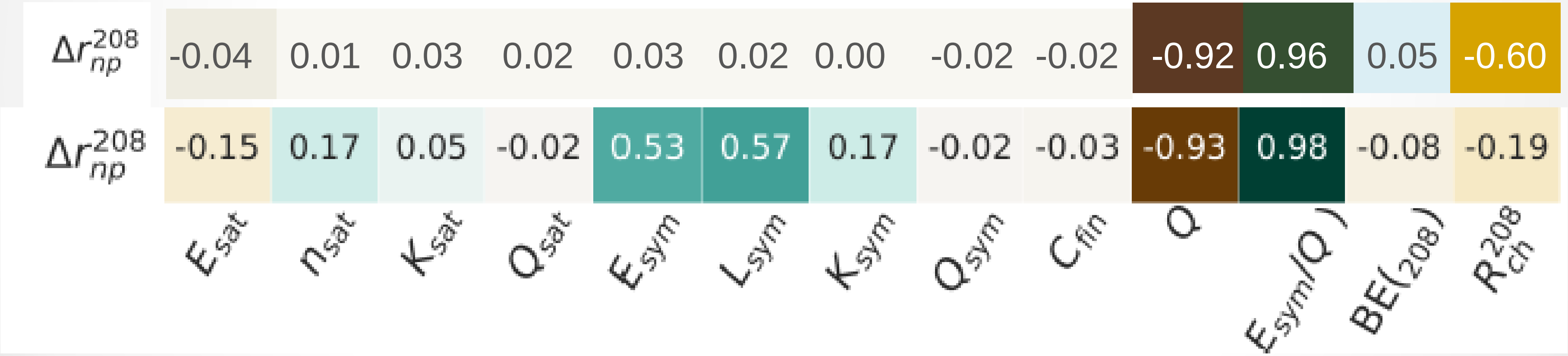


FIG. 1. The schematic shows the distribution of momentum and energy of quarks and baryons. The diffuse distribution of quarks in the right upper graph indicates they are confined inside baryons.

L.MacLerran and S.Reddy Phys. Rev. Lett. 122, 122701 (2019)

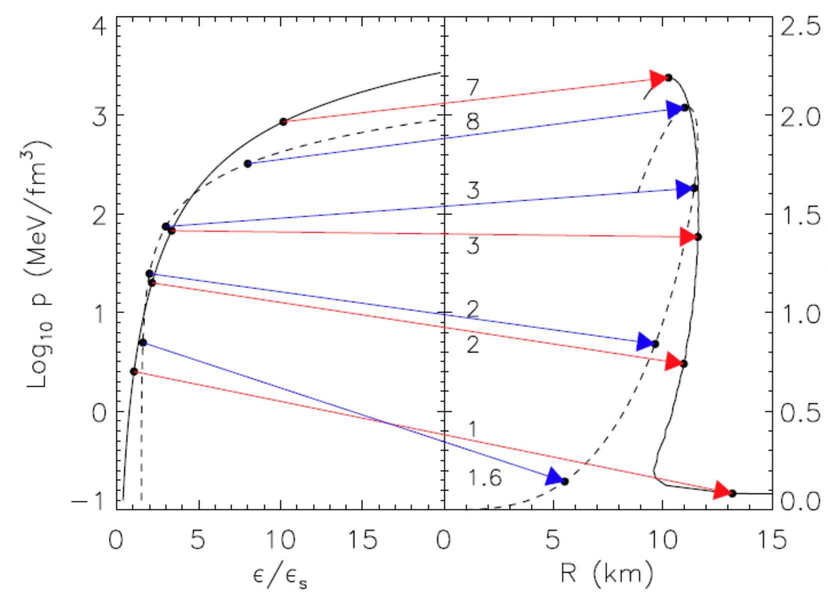


	E_{sat}	n_{sat}	K_{sat}	Q_{sat}	E_{sym}	L_{sym}	K_{sym}	Q_{sym}	C_{fin}	Q	E_{sym}/Q)	BE(208)	R_{ch}^{208}
Δr_{np}^{208}	-0.04	0.01	0.03	0.02	0.03	0.02	0.00	-0.02	-0.02	-0.92	0.96	0.05	-0.60
Δr_{np}^{208}	-0.15	0.17	0.05	-0.02	0.53	0.57	0.17	-0.02	-0.03	-0.93	0.98	-0.08	-0.19

- Nuclear data well constrain low order isoscalar parameters
- Natural surface-bulk correlation from mass constraint

Motivation

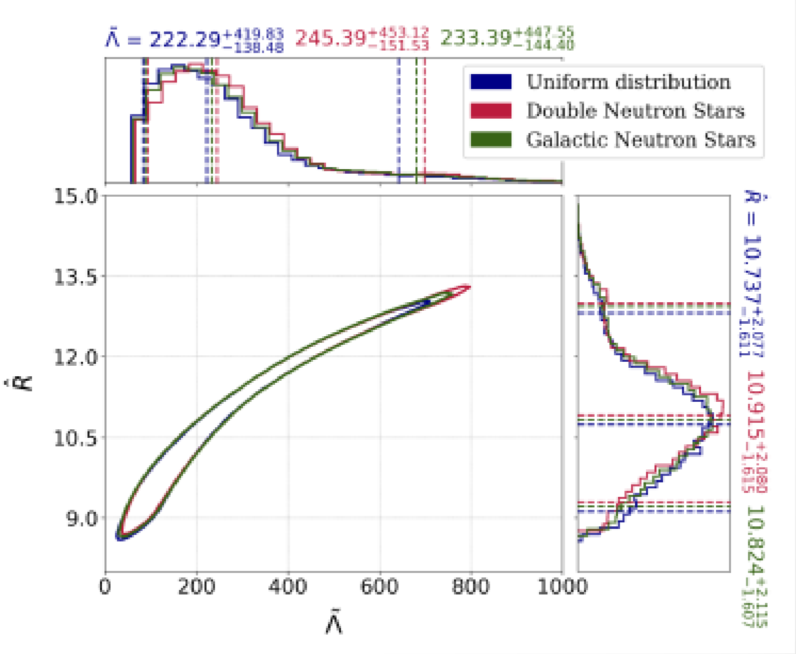
(T=0 – β eq. for this talk)



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

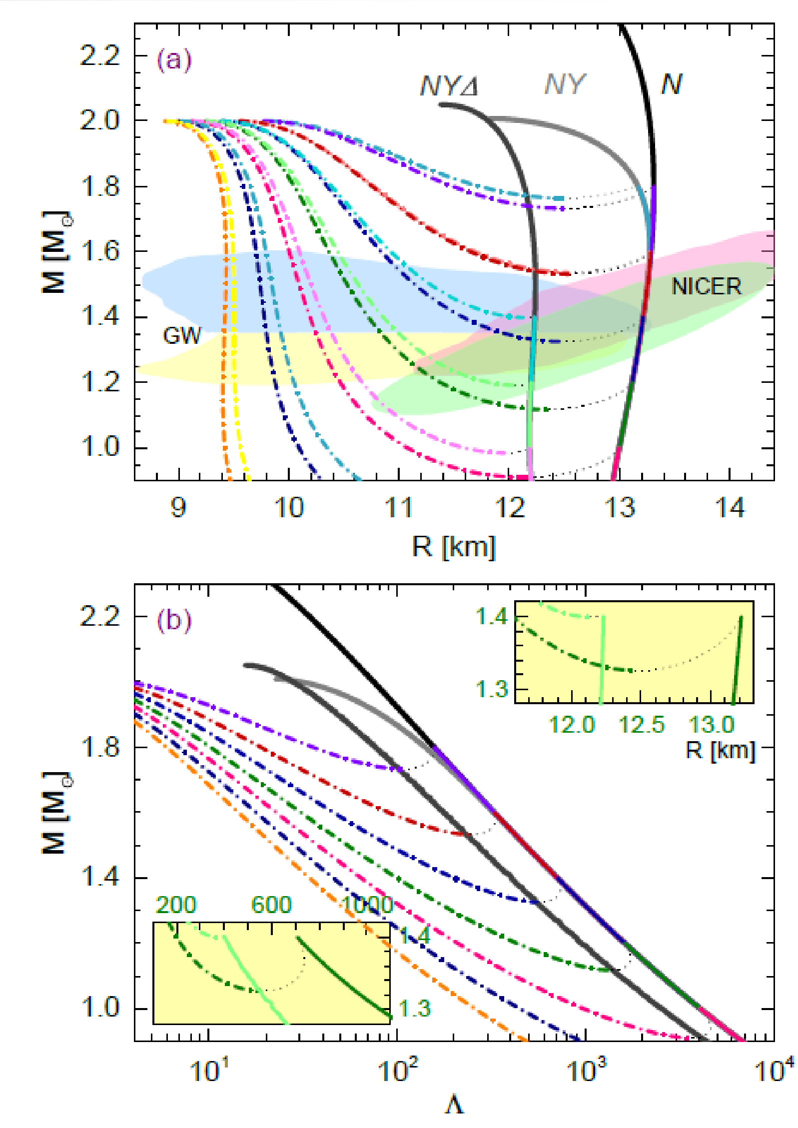
- Different compositions => different EoS => different gravitational signals!

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



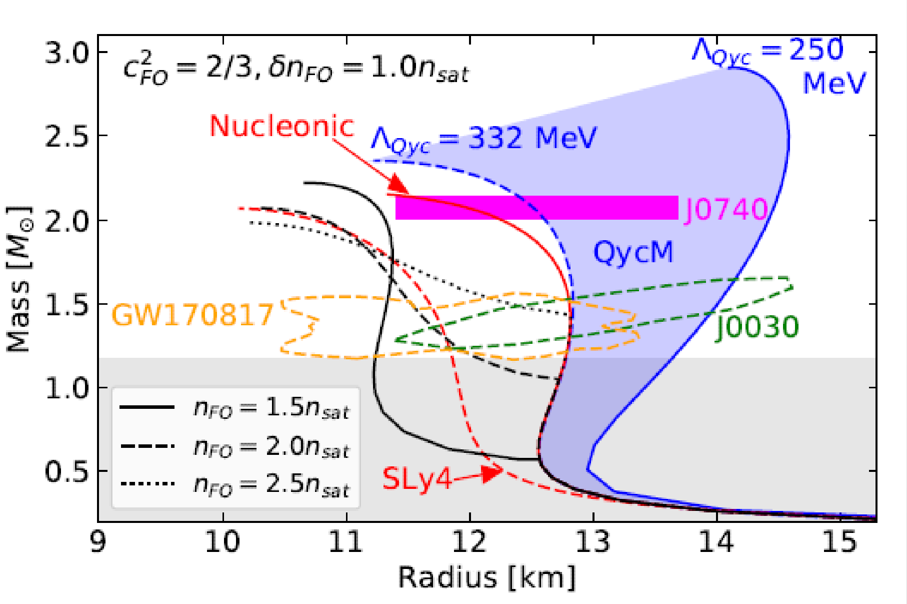
S.De et al, Phys. Rev. Lett. 121, 091102 (2018)

Problem: no ab-initio theory of dense matter



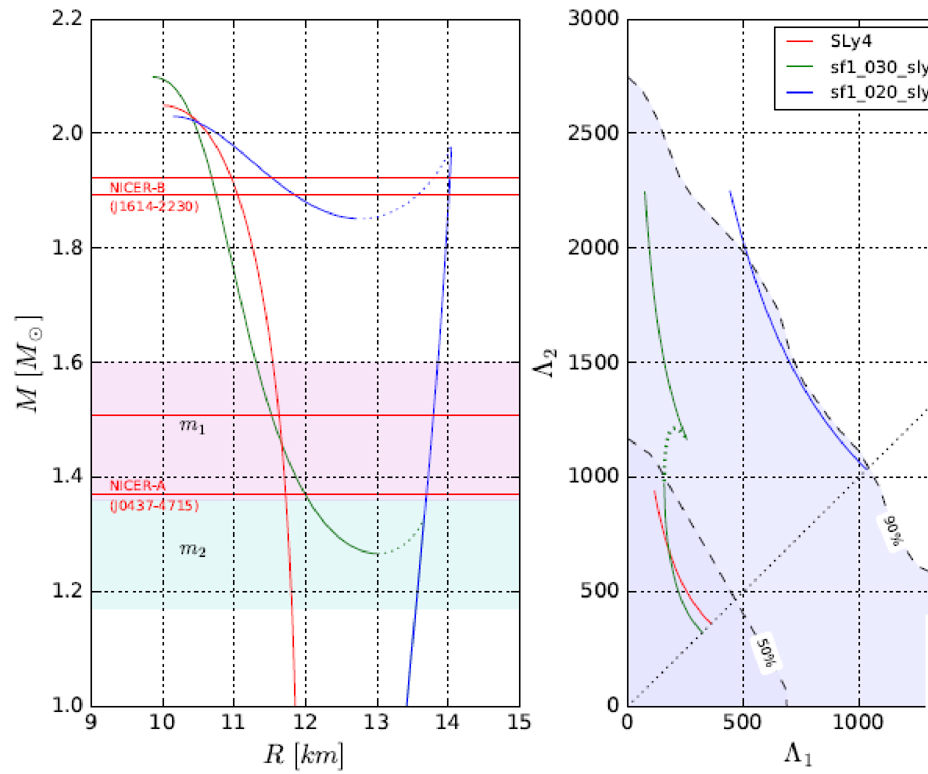
- Even qualitatively, the effect of quark dof is not clear

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