Probing the equation of state of dense matter with neutron stars: constraints from nuclear physics

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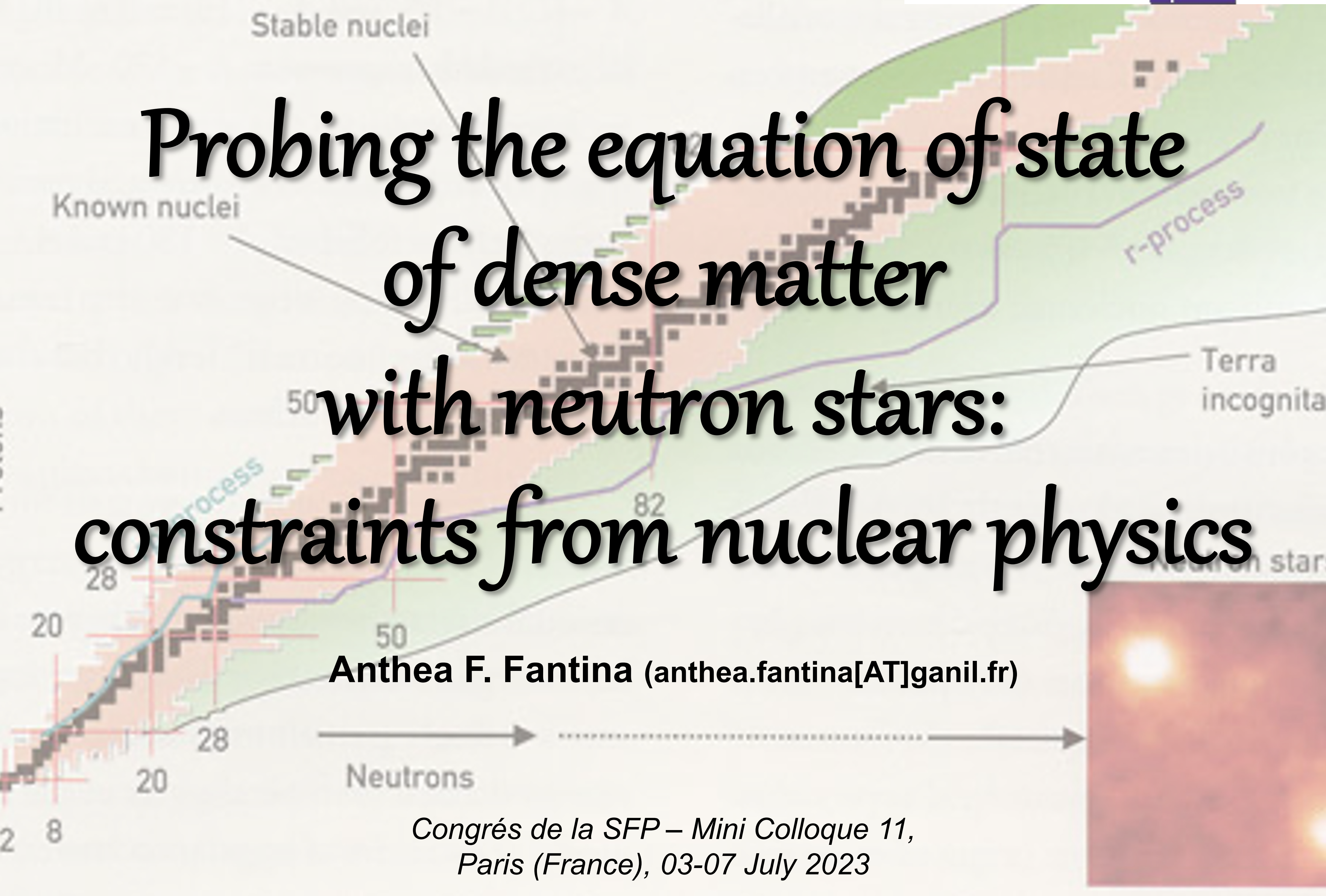


Outline

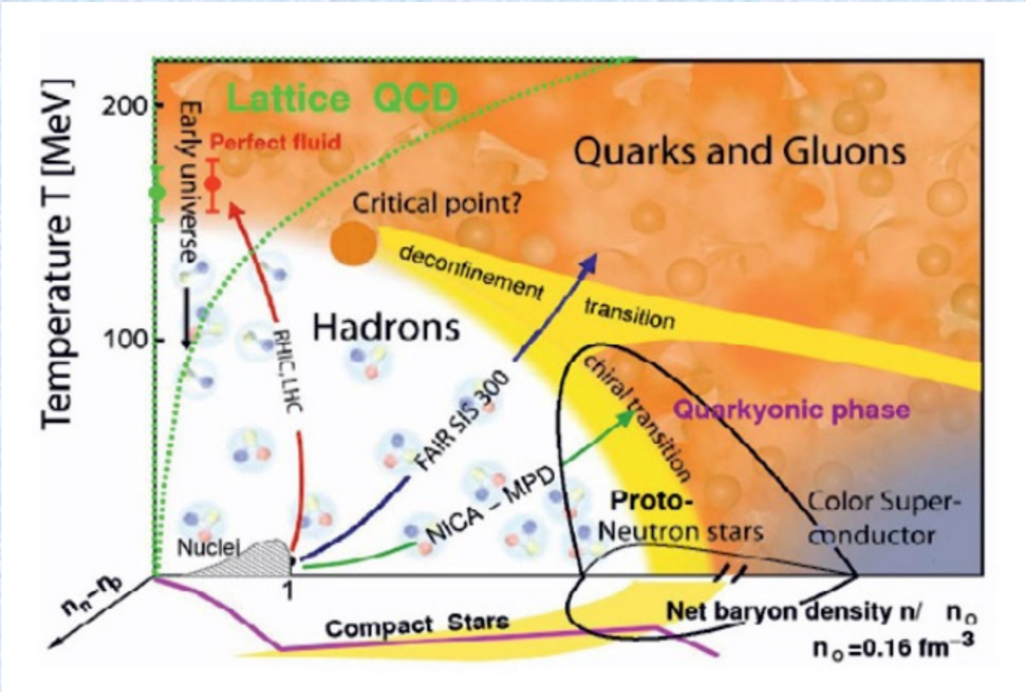
- Introduction: neutron stars (NSs)
- Equation-of-state (EoS) modelling
  - NS EoS
  - Constraints on the NS EoS from nuclear physics
  - EoS and neutron-star (NS) properties
- Conclusions and outlooks

N.B.: In this talk, $T = 0$ and beta-equilibrium matter, no magnetic field

see H. Dinh Thi’s talk for T>0, and L. Scurto’s talk for B field effects

see also F. Gulminelli’s talk

Probing extreme conditions in NSs



Kekelidze et al., EPJ Web of Conf. 70, 00084 (2014)

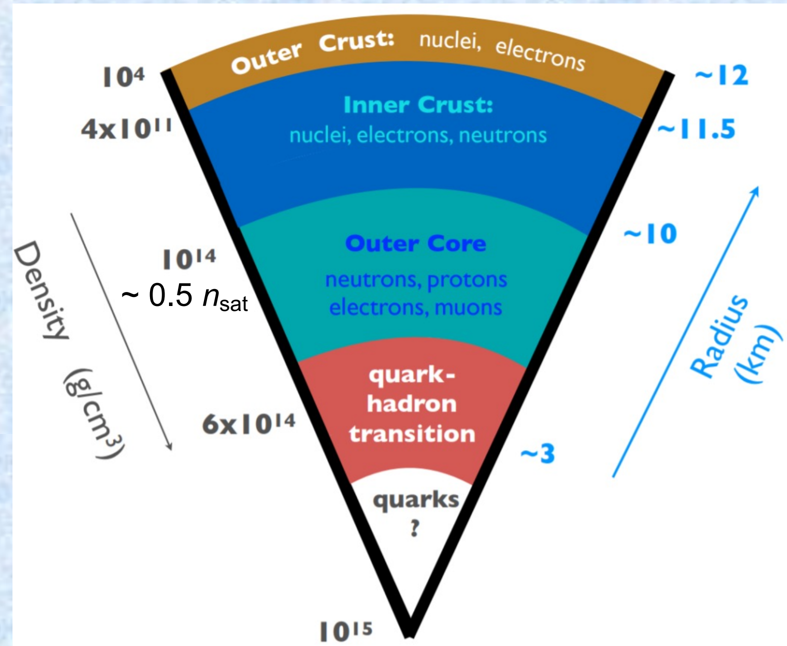
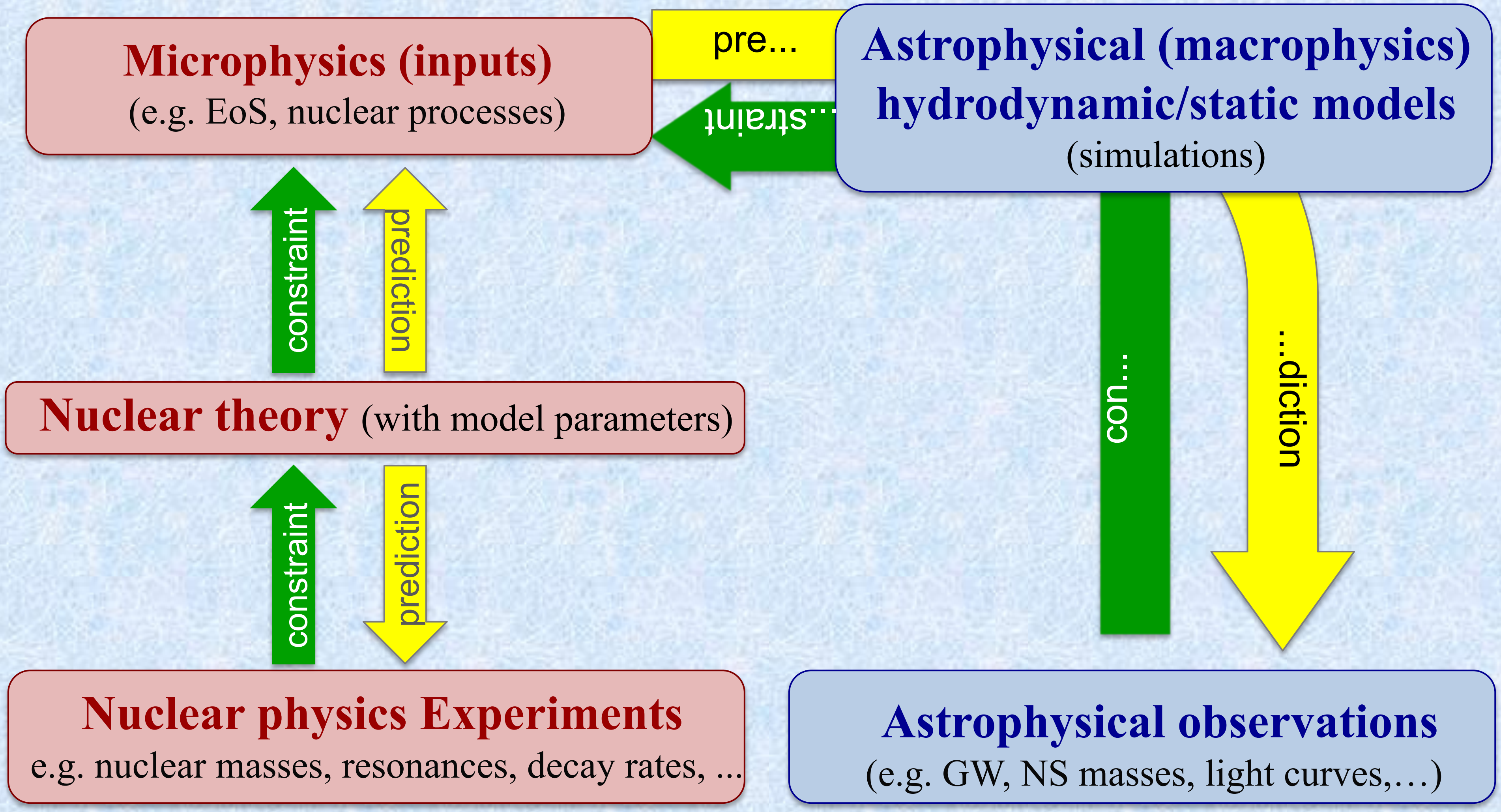


Image Credit: 3G Science White Paper

different states of matter spanned in NSs !
→ inhomogeneous, homogeneous, "exotic" particles (?)
+ superfluidity, magnetic field, etc.

→ not all conditions can be probed in terrestrial labs → theoretical models !

Micro to macro through modelling



Micro to macro through modelling

Microphysics (inputs)
(e.g. EoS, nuclear processes)

pre...

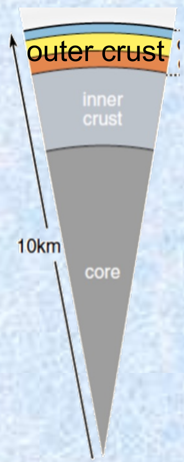
...straint

Astrophysical (macrophysics) hydrodynamic/static models
(simulations)

constraint

prediction

in outer crust !



con...

...diction

Nuclear physics Experiments
e.g. nuclear masses, resonances, decay rates, ...

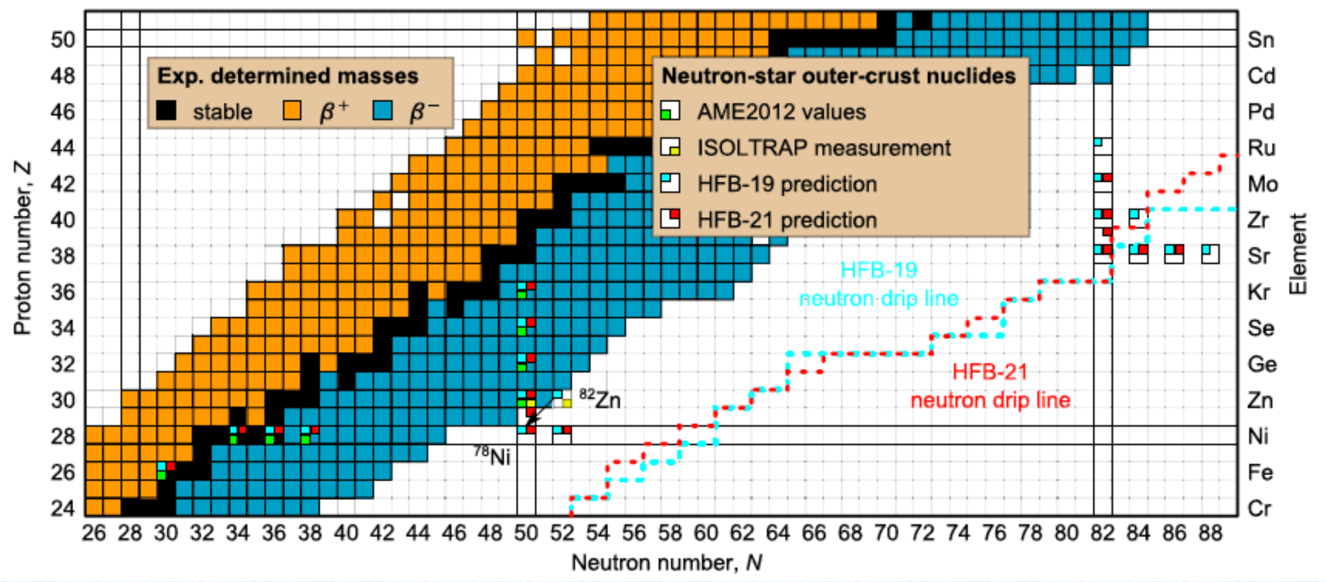
Astrophysical observations
(e.g. GW, NS masses, light curves,…)

NS outer crust: up to neutron drip (1)

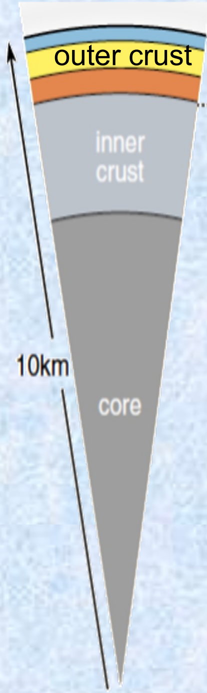
- Nuclei in bcc lattice + electrons: $\epsilon_{\rm WS}(n_B) = \dfrac{M(A,Z)c^2}{V_{\rm WS}} + \epsilon_e(n_e) + \epsilon_{\rm Coul}$

e-e and e-i int.

Only microscopic inputs are **nuclear masses** → Experimental or mass models



Wolf *et al.*, PRL 110, 041101 (2013)



➢ very neutron-rich nuclei, imprint of shell structure

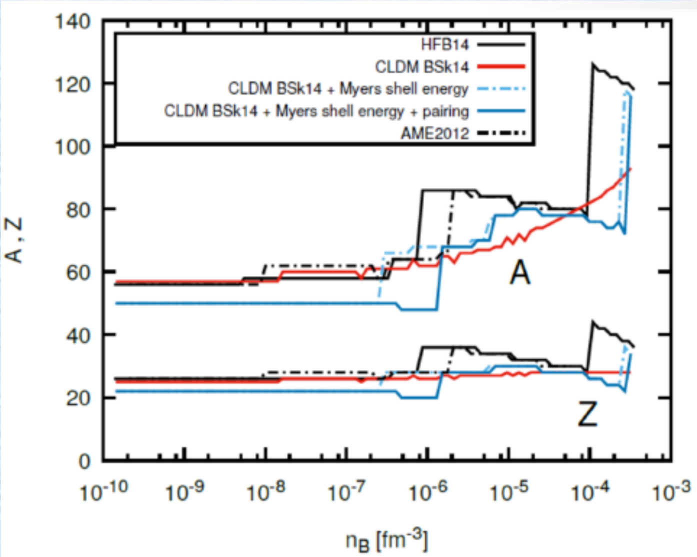
see e.g. Haensel et al. 2007 (Springer), Oertel et al., Rev. Mod. Phys. (2017), Burgio & Fantina, ASSL 457 (2018), Blaschke & Chamel, ASSL 457, 337 (Springer, 2018) for a review and refs. therein
for HFB models shown see also Goriely et al. 2010, 2016, Pearson et al., MNRAS 481, 2994 (2018)

NS outer crust: up to neutron drip (2)

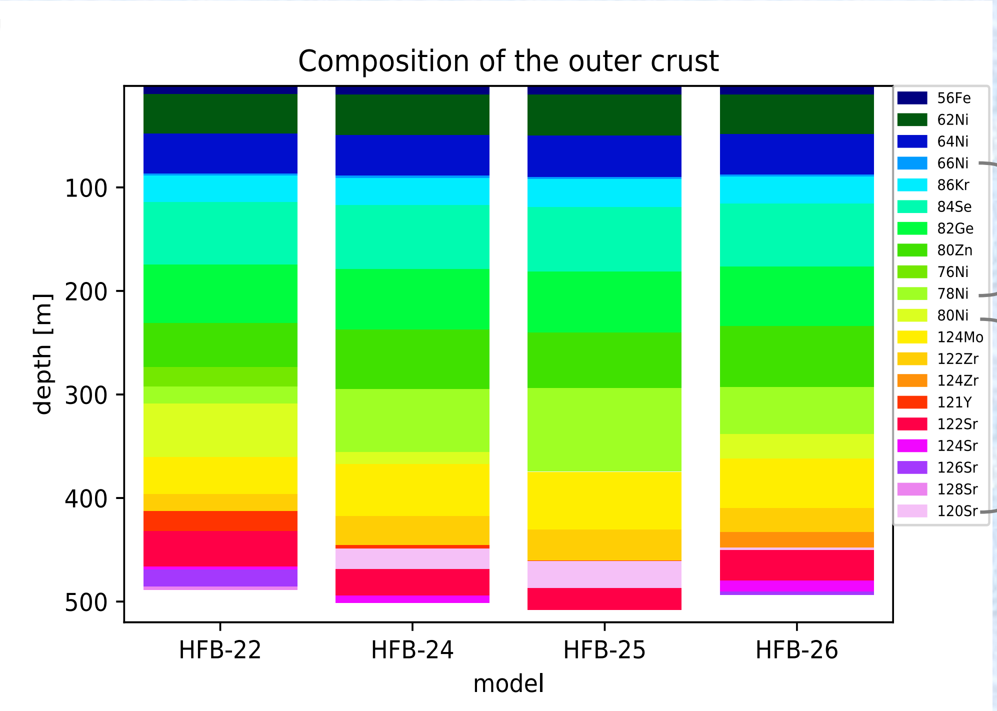
- Nuclei in bcc lattice + electrons: $\epsilon_{\rm WS}(n_B) = \dfrac{M(A,Z)c^2}{V_{\rm WS}} + \epsilon_e(n_e) + \epsilon_{\rm Coul}$

e-e and e-i int.

Only microscopic inputs are **nuclear masses** → Experimental or mass models



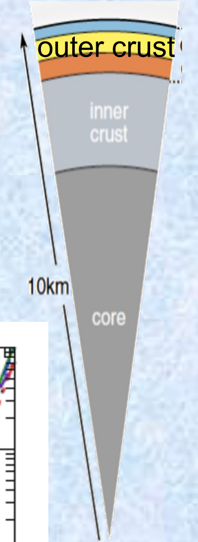
F. Gulminelli's talk @GMR workshop (2020)



➢ very neutron-rich nuclei, imprint of shell structure
➢ EoS relatively well constrained, dependence on many-body method

see e.g. Haensel et al. 2007 (Springer), Oertel et al., Rev. Mod. Phys. (2017), Burgio & Fantina, ASSL 457 (2018), Blaschke & Chamel, ASSL 457, 337 (Springer, 2018) for a review and refs. ttherein
for HFB models shown see also Goriely et al. 2010, 2016, Pearson et al., MNRAS 481, 2994 (2018)

NS inner crust: until cc transition



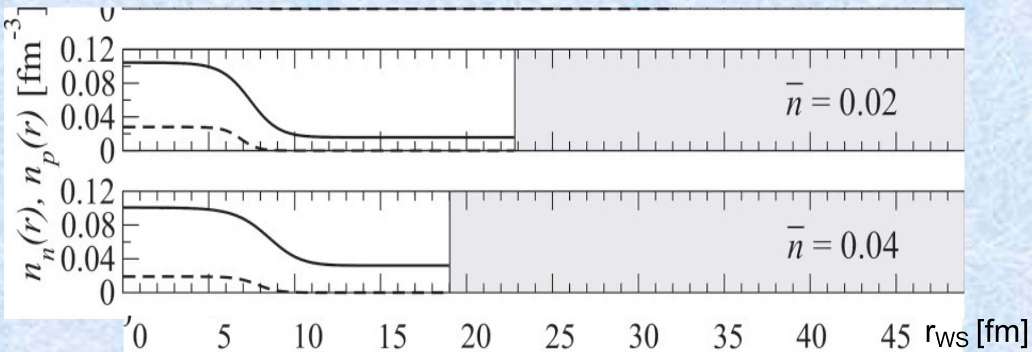
- Nuclei in bcc lattice + electrons + *"free" neutrons* → nuclear modelling

$$\epsilon_{\rm WS}(n_B) = \frac{M(A,Z)c^2}{V_{\rm WS}} + \epsilon_e(n_e) + \epsilon_{\rm Coul} + \epsilon(n_{gn}) + \epsilon_{\rm int}$$

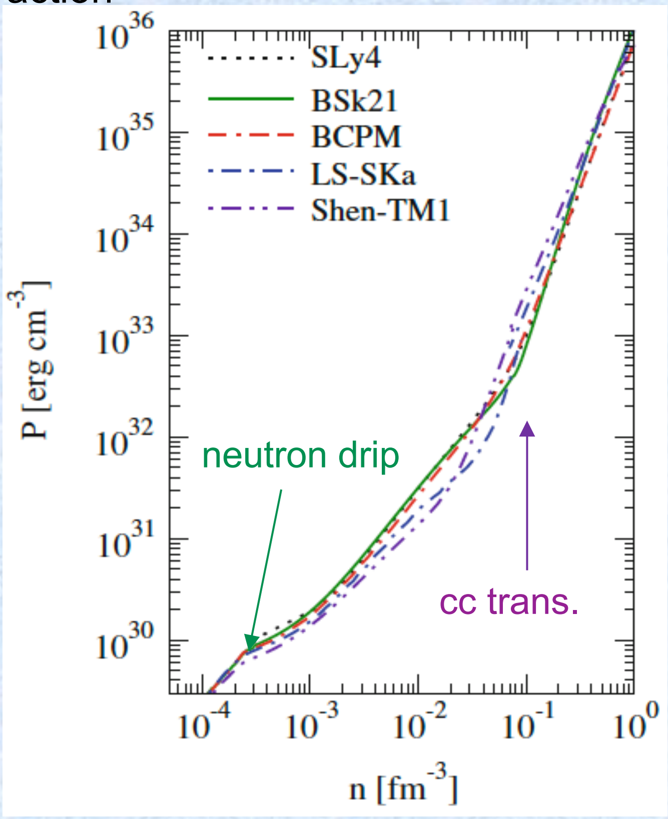
exp./theo masses

Coulomb interaction

nucleus-gas interaction



Pearson et al., PRC 85, 065803 (2012)



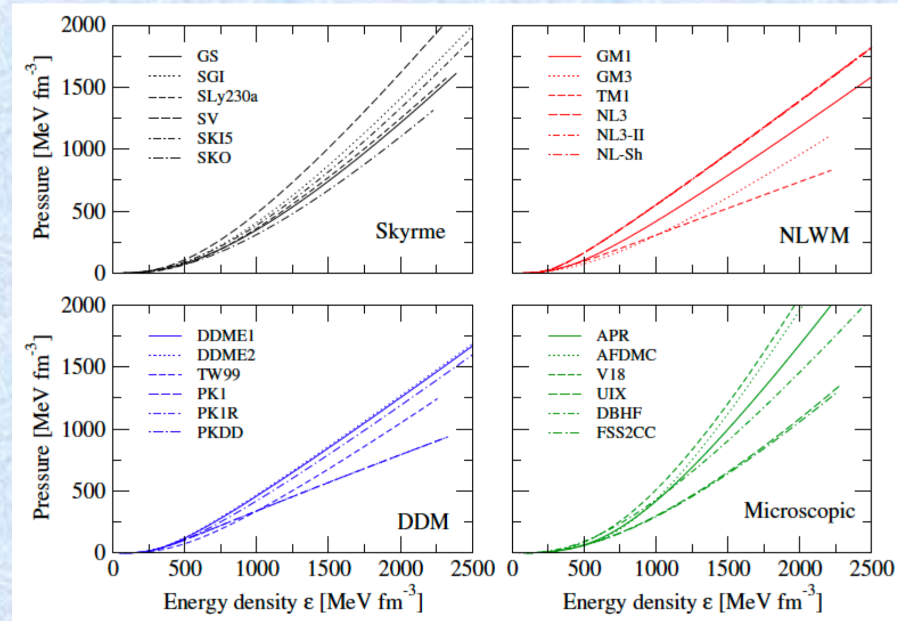
➢ higher uncertainties
→ model-dependence in the functional
→ model-dependence in many-body method

Burgio & Fantina, ASSL 457 (2018)

 see e.g. Haensel et al. 2007 (Springer), Oertel et al., Rev. Mod. Phys. (2017), Burgio & Fantina, ASSL 457 (2018), Blaschke & Chamel, ASSL 457, 337 (Springer, 2018) for a review and refs. therein

NS core: homogeneous matter

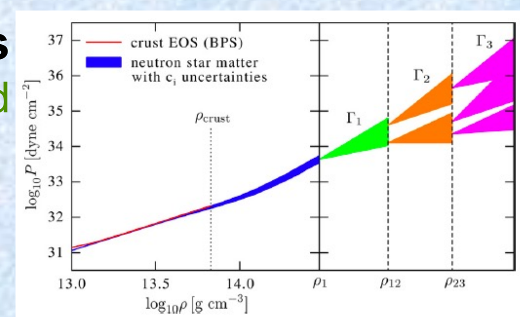
- **Ab-initio ("microscopic") approaches**
  e.g. variational methods, (D)BHF, chiral EFT, Monte-Carlo, Green's func.,….)
- **Phenomenological approaches**
  e.g. EDF e.g. Skyrme/Gogny, meta-models, …

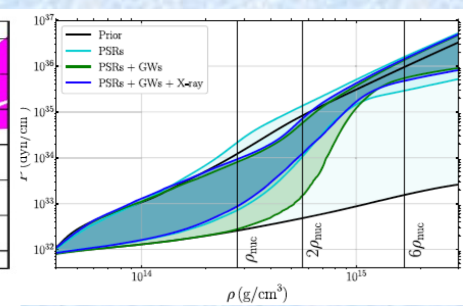


> ➢ higher uncertainties in the functional
>   → extrapolation
> ➢ + additional particles ?

Burgio & Vidana, Universe 6, 119 (2020)

- **Agnostic (non-parametric) approaches**
  e.g. Piecewise polytropes (PP), Speed-of-sound models (CSM), Spectral functions (SF), Gaussian processes (GP)
  → but what about nuclear physics?

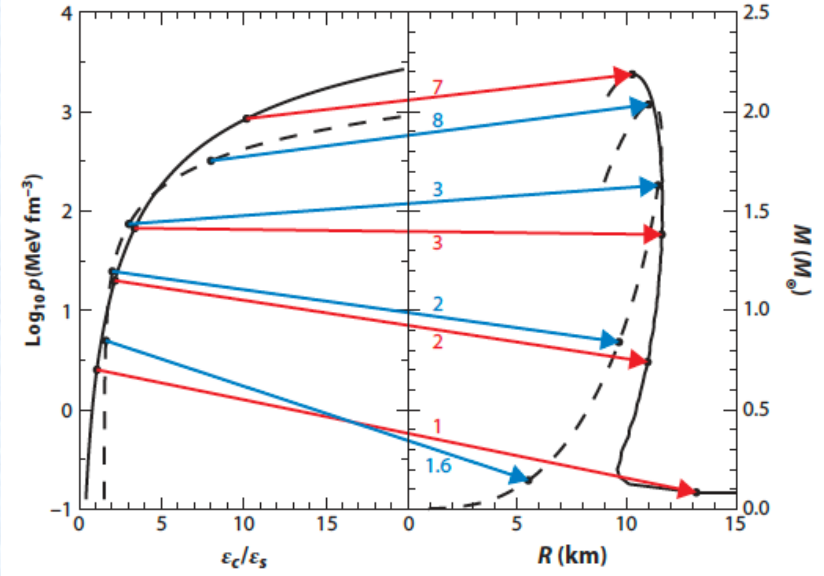




Hebeler et al., ApJ 773, 11 (2013)   Landry et al. PRD 101, 123007 (2020)

for a review see e.g. Haensel et al. 2007 (Springer), Oertel et al., Rev. Mod. Phys. (2017), Burgio & Fantina, ASSL 457 (2018)
Agnostic approaches, e.g. PP: Reed et al. PRD 2009, Hebeler et al. ApJ 2013, Annala et al. PRL 2018, …; CSM: Tews et al. ApJ 2018, Tan et al. PRL 2020; Somasundaram et al., PRC 2023; SF: Lindblom 2010, Lindblom & Indik 2014, …; GP: Landry et al. PRD 2020, Essick et al. PRD 2020; Legred et al. PRD 2021, PRD 2022, …

EoS ←→ NS (static) observables (1)



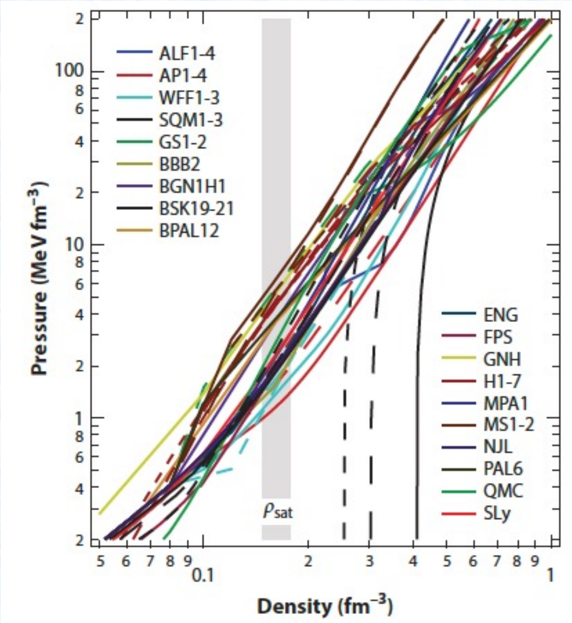
Lattimer, Annu. Rev. Part. Nucl. Sci. 62, 485 (2012)
see also F. Gulminelli's talk

- ✓ GR → one-to-one correspondence
  EoS ←→ NS static properties $M(R)$, $\Lambda(M)$…
  (non-rotating mature NS)
- ✓ Different EoSs ←→ different NS properties
  ←→ different GW signals
  ?
  → trace back to EoS and composition ?

$$\frac{\mathrm{d}P(r)}{\mathrm{d}r} = -\frac{G\rho(r)\mathcal{M}(r)}{r^2}\left[1+\frac{P(r)}{c^2\rho(r)}\right]\left[1+\frac{4\pi P(r)r^3}{c^2\mathcal{M}(r)}\right]\left[1-\frac{2G\mathcal{M}(r)}{c^2 r}\right]^{-1}$$

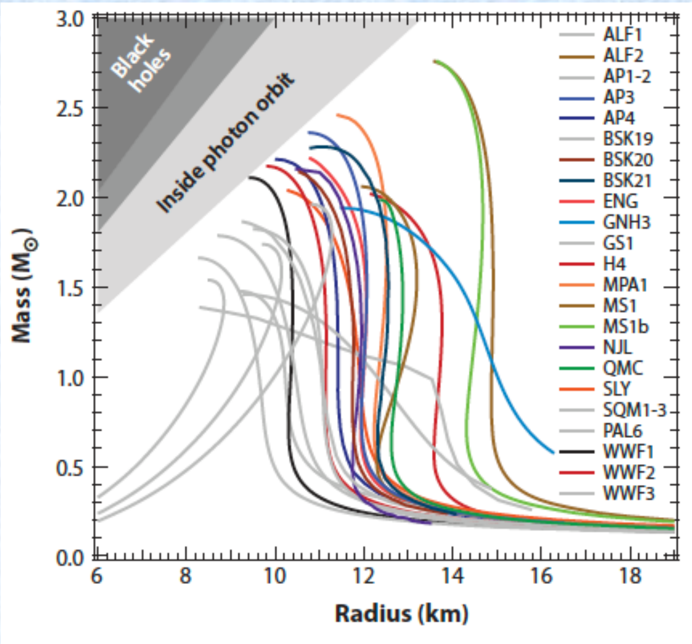
$P(\rho)$ → EoS

EoS ←→ NS (static) observables (2)



Ozel & Freire, ARAA 54, 401 (2016)

- ✓ GR → one-to-one correspondence EoS ←→ NS static properties $M(R)$, $\Lambda(M)$… (non-rotating mature NS)
- ✓ Different EoSs ←→ different NS properties ←→ different GW signals
  ? → trace back to EoS and composition ?



Ozel & Freire, ARAA 54, 401 (2016);
see also Burgio & Fantina, ASSL 457, 255 (2018)

but:

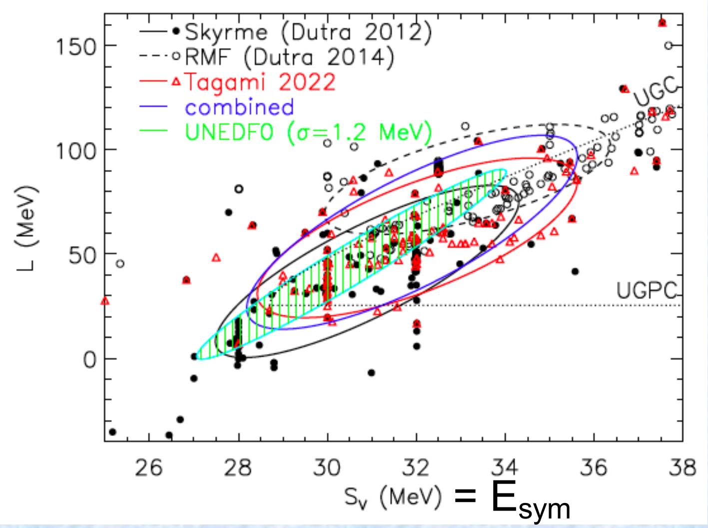
- ✗ EoS model dependent !
- ✗ no ab-initio dense-matter calculations in all regimes
  → phenomenological models
- ✗ composition ←→ EoS → $M(R)$?
- ✗ role of additional d.o.f. ?

EoS ←→ nuclear matter parameters

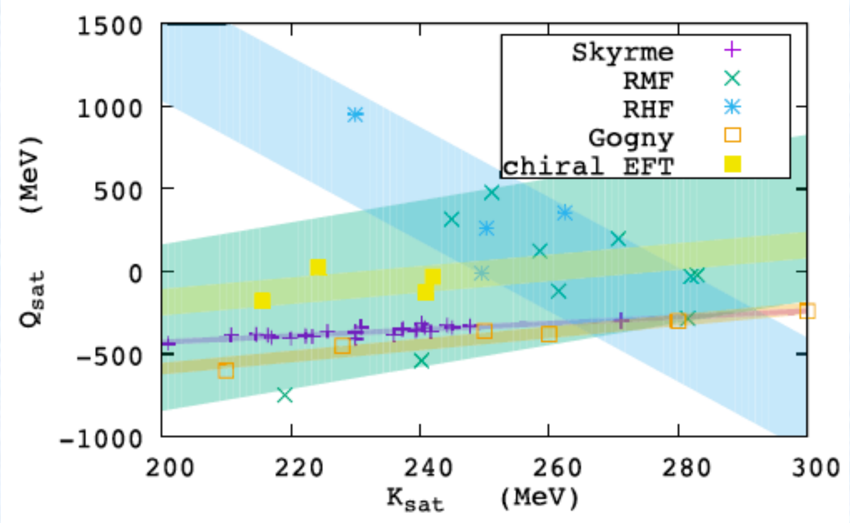
- Expansion in density and asymmetry around n_{sat} and $\delta = 0$

$$\epsilon_B(n,\delta) \approx n \sum_{m=0}^{N} \frac{1}{m!} \left(\left.\frac{d^m e_{sat}}{dx^m}\right|_{x=0} + \left.\frac{d^m e_{sym}}{dx^m}\right|_{x=0} \delta^2 \right) x^m \qquad x = (n - n_{sat})/3n_{sat} \quad \delta = (n_n - n_p)/n$$

Empirical parameters (<u>bulk</u>) $\boldsymbol{X}_{sat}$ = E_{sat}, K_{sat}, Q_{sat}, …
$\boldsymbol{X}_{sym}$ = E_{sym}, L_{sym}, K_{sym}, Q_{sym}, …



Lattimer, Particles 6, 30 (2023)



Margueron et al., PRC 97, 025805 (2018)

see e.g. Bulgac et al., PRC 97, 044313 (2018), Margueron et al., PRC 97, 025805 (2018), Carreau et al, EPJA 55, 188 (2019), Tews et al., EPJ A 55, 97 (2019), Dinh Thi et al., A&A 654, A114 (2021), Dinh Thi et al., EPJA 57, 296 (2021); Essick et al., PRC 104, 065804 (2021), …

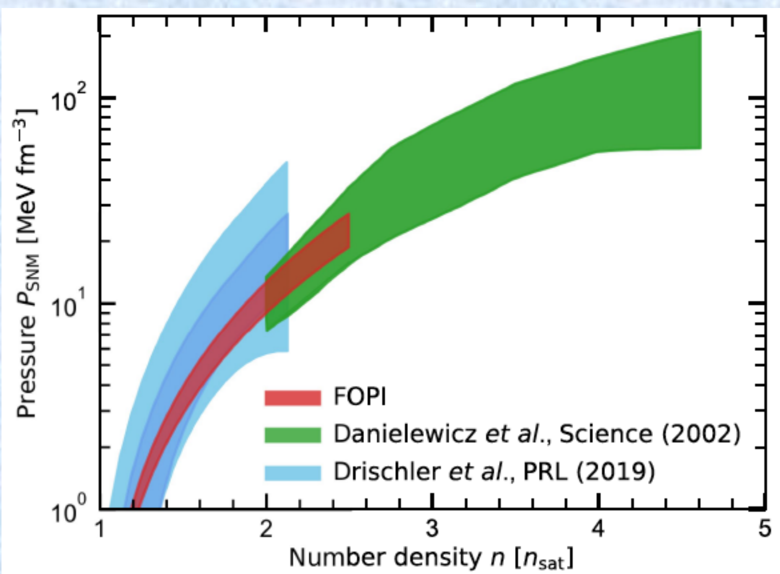
How can we get constraints?

Nuclear physics exp./ theory

- Measure of **nuclear properties**:
  - masses and radii of nuclei
  - collective modes, polarizability
  - neutron skins, HIC, flows

  etc …
- **ab-initio calculations**

→ **"low" density** (better in nucleonic sector)



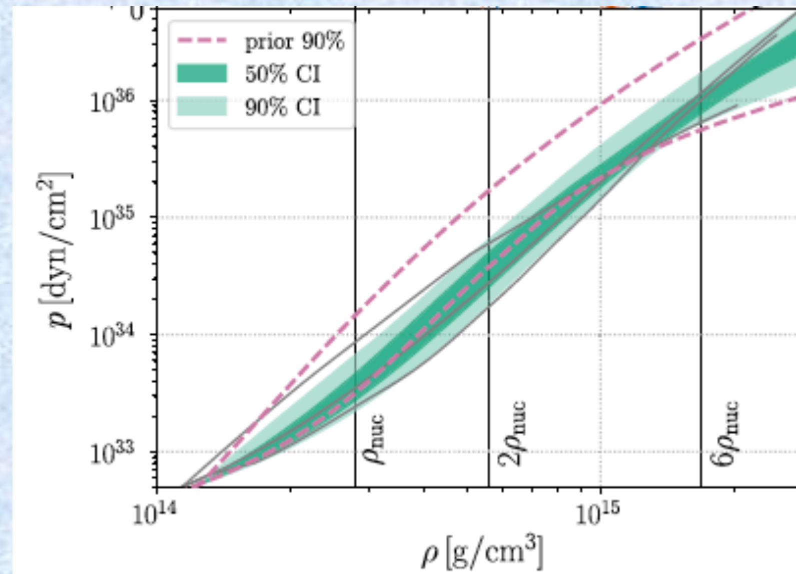
Huth et al., Nature 606, 276 (2022)

Astrophysical observations

- Measure of **NS properties:**
  - **-** NS masses and radii
  - rotational frequency, oscillation modes
  - cooling, moment of inertia

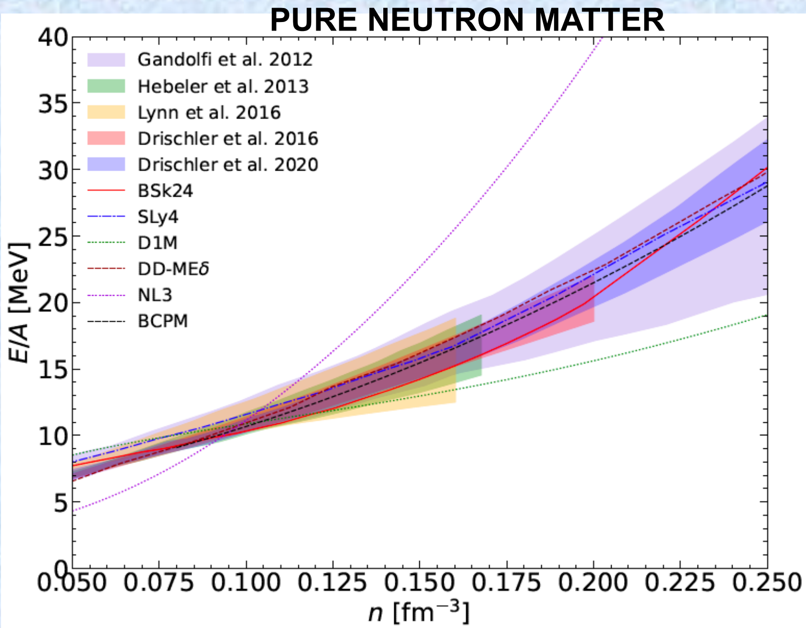
  etc …
- **Gravitational waves**

→ **"high" density**

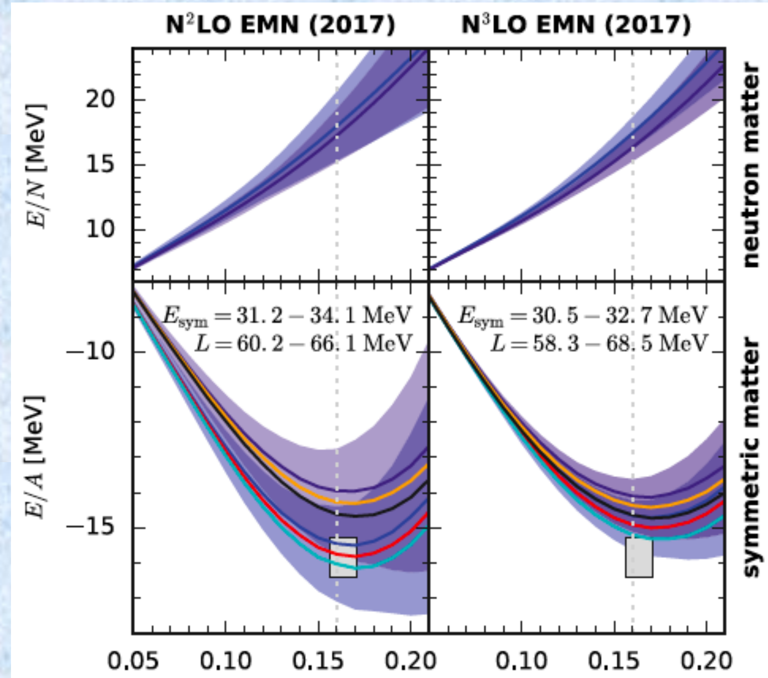


Abbott et al., PRL 121, 161101 (2018)

Constraints from nucl. phys.: theo



Fantina & Gulminelli, J.Phys. Conf. Ser. (submitted 2022);
see also Oertel et al., Rev. Mod. Phys. 89, 015007 (2017)



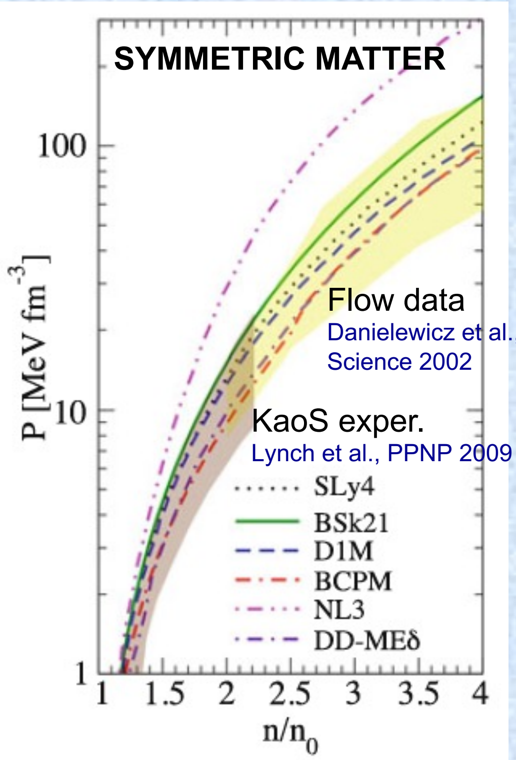
Drischler et al., PPNP 121, 103888 (2021)

→ Not all popular models agree with ab-initio constraints!

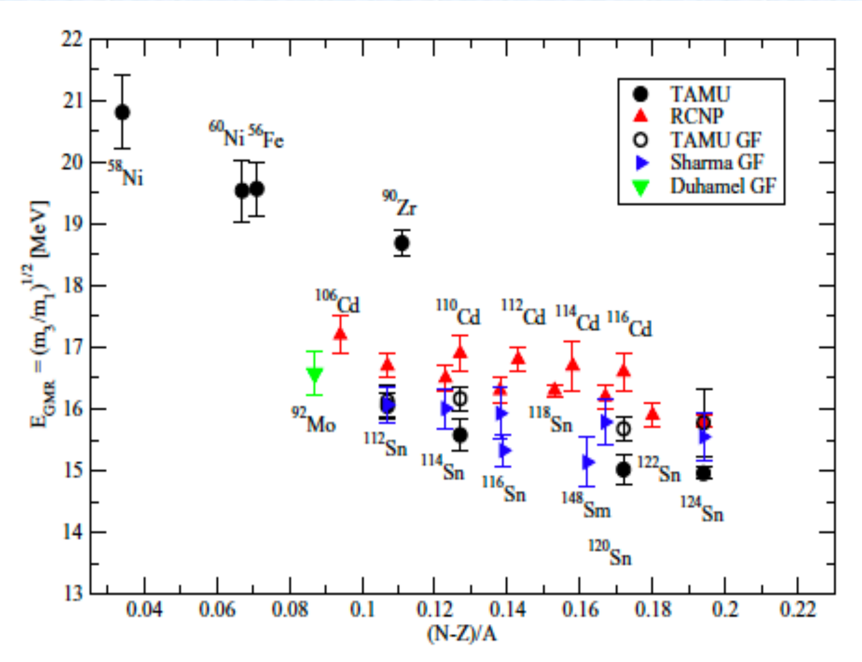
→ Reasonable agreement of ab-initio (PNM) up to ~ saturation density
→ PNM calculations benchmark for phenomenological models

N.B.: for symmetric matter (ab-initio): (i) saturation point difficult to obtain ; (ii) larger uncertainties ; (iii) cluster formation at subsaturation

Constraints from nucl. phys.: exp (1)



Burgio&Fantina, ASSL 457, 255 (2018)



Stone et al., PRC 89, 0044316 (2014)

→ Constraints at "low" densities → low-order parameters
→ Constraints more on "symmetric" matter

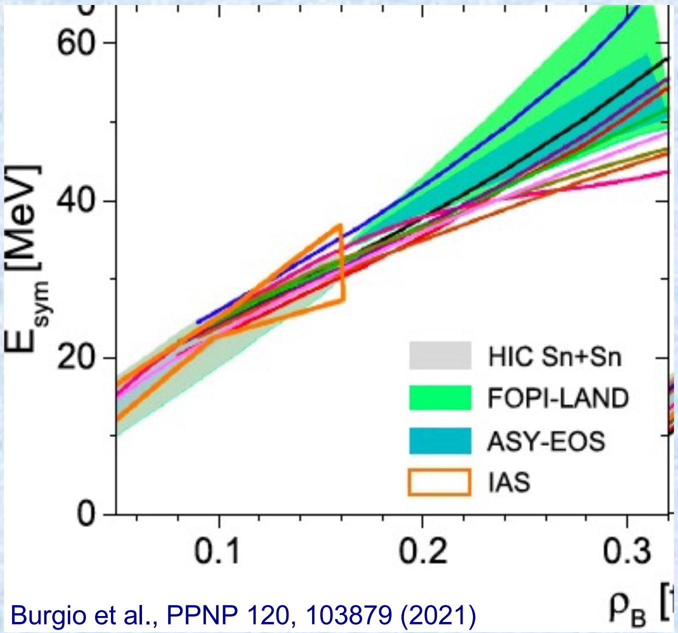
N.B.: deduced constraints are often *not* raw data, but combined with models
→ model dependence of constraints !

see also Margueron et al., PRC 97, 025805 (2018) for a compilation

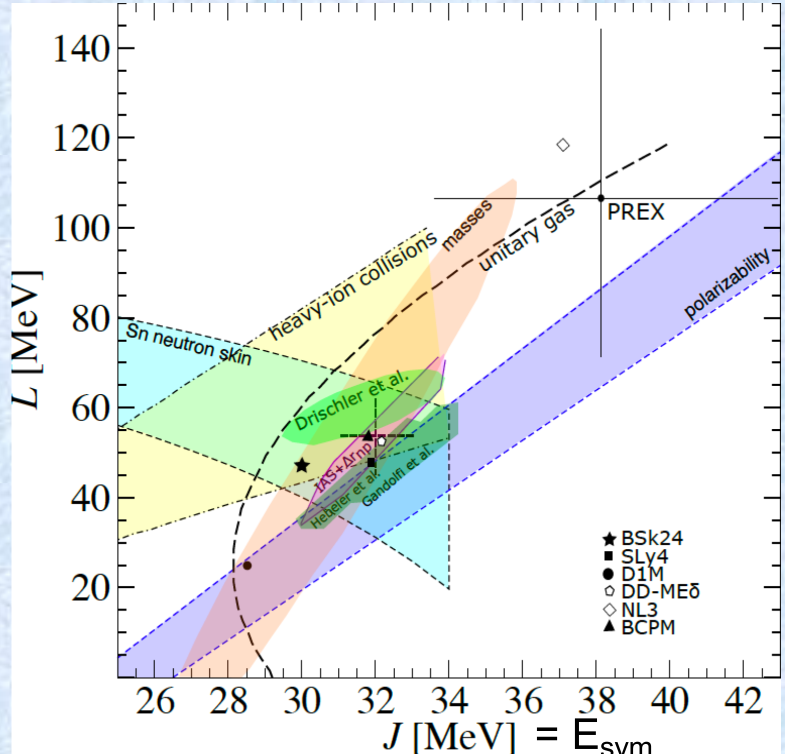
see also D. Gruyer's and R. Bougault's talks

Constraints from nucl. phys.: exp (2)

SYMMETRY ENERGY



Burgio et al., PPNP 120, 103879 (2021)
see also Burgio&Fantina, ASSL 457, 255 (2018)



Gulminelli&Fantina, Nucl. Phys. News 31, 9 (2021); Fantina&Gulminelli, submitted (2022)

→ Constraints at "low" densities → low-order parameters
→ Constraints more on "symmetric" matter
→ Not always "clear" constraints → "tension"

N.B.: deduced constraints are often *not* raw data, but combined with models
→ model dependence of constraints !

see also Margueron et al., PRC 97, 025805 (2018) for a compilation

see also D. Gruyer's and R. Bougault's talks

NS properties : which nuclear parameters matter ?

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

CRUST-CORE TRANSITION

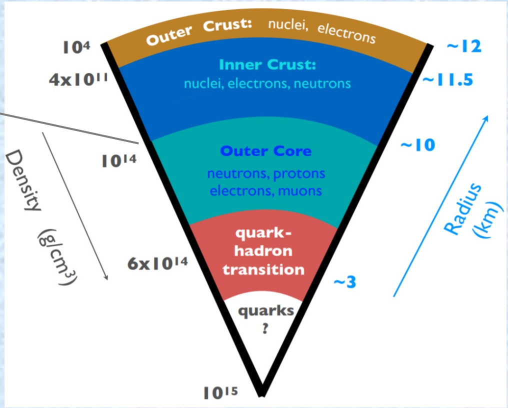


Image Credit: 3G Science White Paper

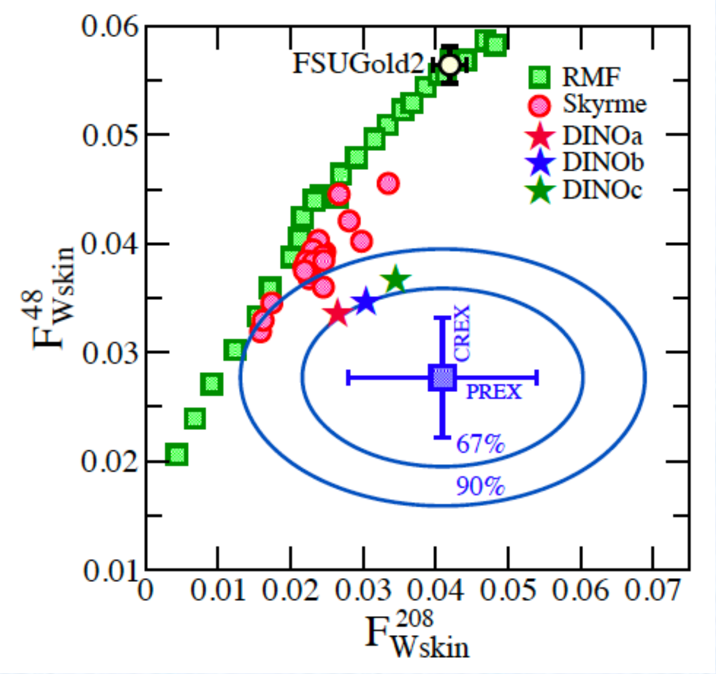
→ importance of *higher-order* parameters

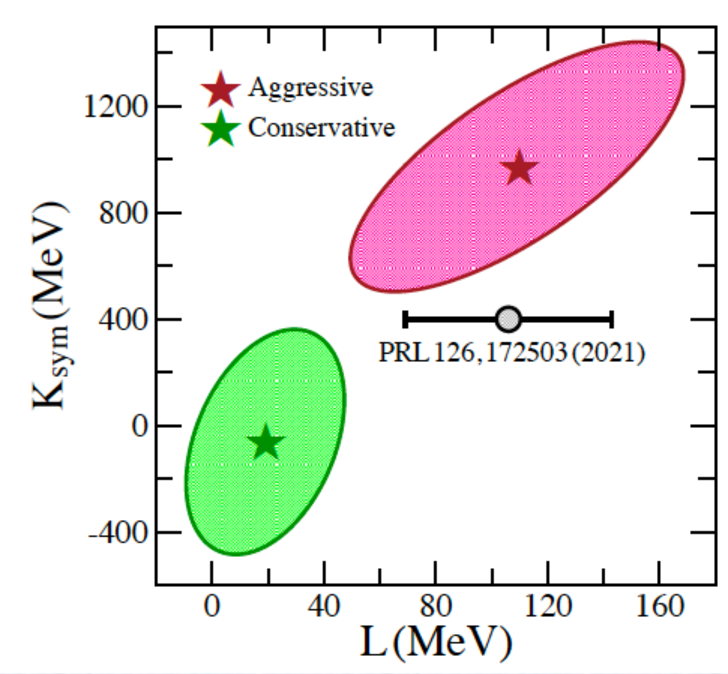
Dinh Thi et al., A&A 654, A114 (2021); EPJA 57, 296 (2021); Universe 7, 00373 (2021) within meta-model approach

see also Balliet et al., ApJ 918, 79 (2021)

How to discriminate models ? (exp 1)

- More constraints from nuclear physics experiments
  → e.g. reduced error bar in neutron skin measurements (e.g. PREX/CREX)
  → constraints on low-order parameters in isospin sector

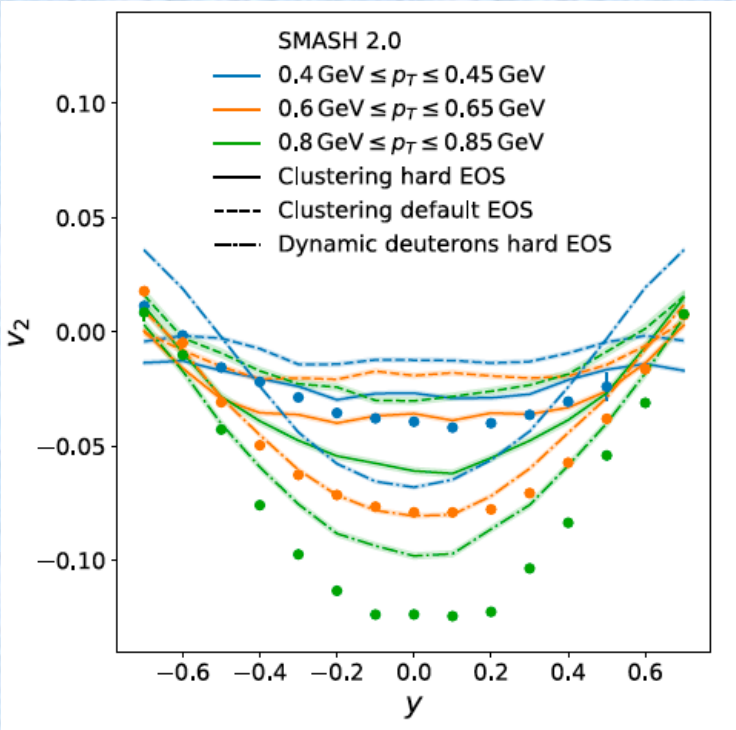




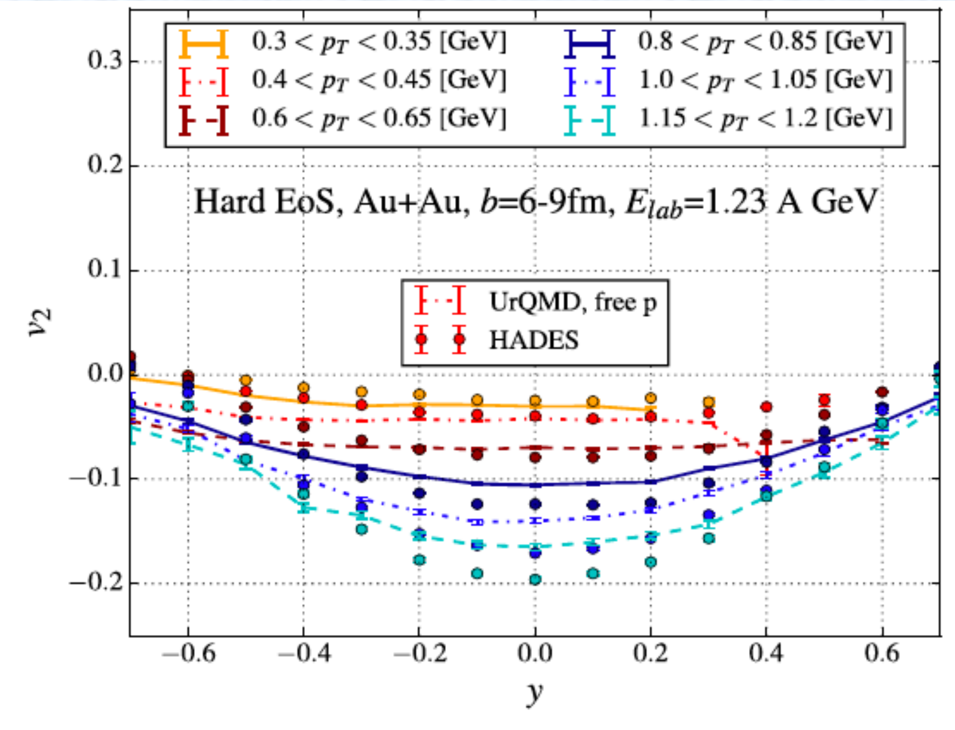
Reed et al., arXiv:2305.19376 (2023)

How to discriminate models ? (exp 2)

- More constraints from nuclear physics at high density (~ 2 n_{sat})
  - → e.g. HADES collaboration; elliptic flow: transport model vs data
  - → constraints "higher"-order parameters in isoscalar sector



Mohs et al., PRC 105, 034906 (2022)



Hillman et al., J. Phys. G 47, 055101 (2020)

Conclusions & open questions

- Nuclear inputs needed for neutron-star modelling
  → extrapolations of data & theoretical models needed

- Nuclear physics + astrophysics → constraints on EoS

- Uncertainties in nuclear data → impact astro observables

  ⇨ ✓ need of (microscopic) reliable theoretical model when no data
  ✓ need of experimental data to calibrate the models
  ✓ need of astrophysical observations

- Extrapolation from raw data → **model dependence of the constraints**

- Lab experiments mostly "low" density (~ saturation density), low *T* probed; matter in astro sites different from lab → **extrapolation to astro conditions (high *T* and density, asymmetry, charge neutral) ?**

- Astro simulations vs microphysics inputs → **uncertainties in nuclear / astro**, **consistency of inputs** and relative **effects of microphysics inputs in astro modelling** ? → systematic studies / bayesian analysis needed


Thank you