Probing the properties of dense matter with neutron stars

Anthea F. Fantina

Kick-off meeting of the IRL on Nuclear Physics and Astrophysics,
11 – 13 December 2023, East Lansing (USA)

Outline

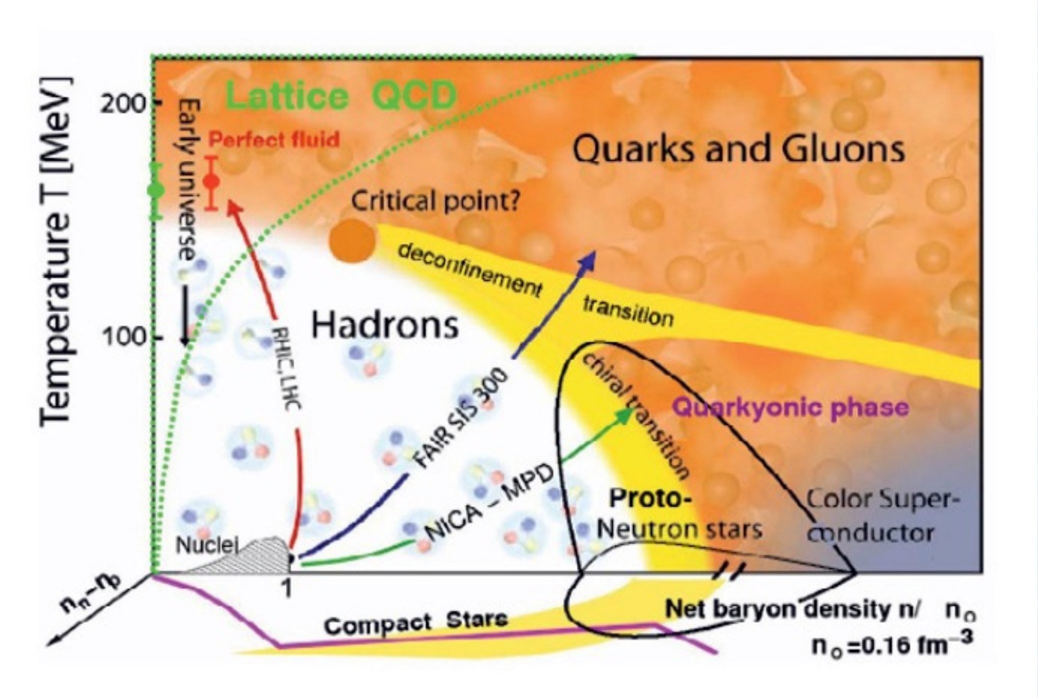
- Introduction
  - Neutron-star (NS) properties

- Equation-of-state (EoS) modelling
  - NS EoS & properties (catalysed matter, “T = 0”)
    - Constraints from nuclear physics
    - Bayesian analysis → quantify uncertainties
    - Perspectives

  - Proto-neutron stars (PNSs, $T \neq 0$)
    - Multi-component distributions & impurity factor
    - Perspectives

N.B.: In this talk, beta-equilibrated matter
NS static properties

Probing extreme conditions in NSs



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

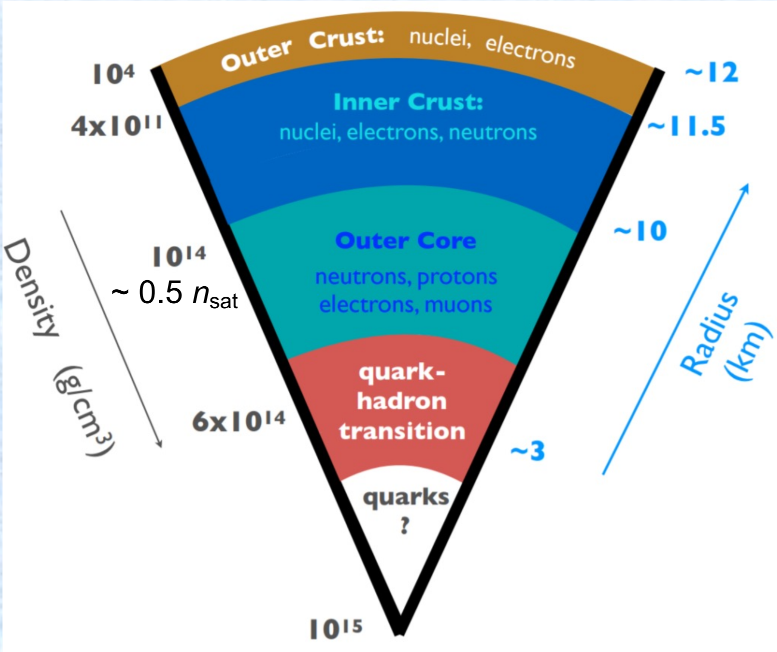


Image Credit: 3G Science White Paper

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 !

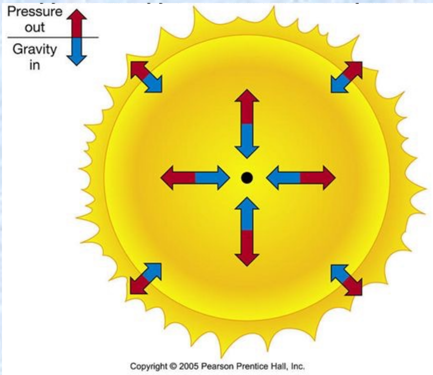
EoS ←→ NS (static) observables

- **TOV → *M*(*R*)** (Tolmann 1939; Oppenheimer&Volkoff 1939; see also Haensel, Potekhin, Yakovlev, Springer 2007)

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

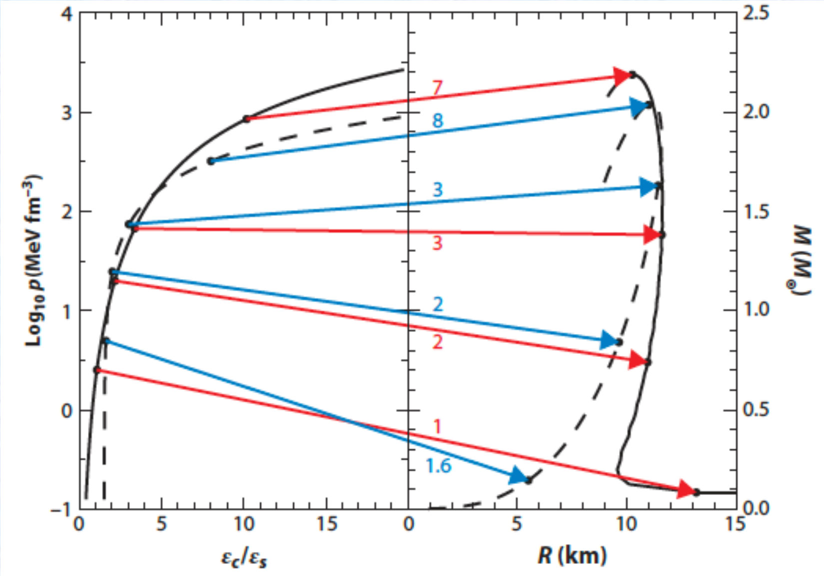
$$\mathcal{M}(r) = 4\pi\int_0^r \rho(r')r'^2\mathrm{d}r'$$

with b.c. $M(r=0) = 0$; $\rho(r=0) = \rho_c$



➡ only EoS $P(\rho)$ is needed !

➡ for each ρ_c (or equivalently P_c) → integration → R, $M(r = R)$



Lattimer, Annu. Rev. Part. Nucl. Sci. 62, 485 (2012)

➡ GR → direct correspondence EoS ←→ NS static properties

➡ for each ρ_c → **rayon *R*, masse *M***
→ **tidal deformability Λ**

N.B.: GR in slow rotation limit w/o magnetic field !

EoS ←→ NS (static) observables

- **TOV → *M*(*R*)** (Tolmann 1939; Oppenheimer&Volkoff 1939; see also Haensel, Potekhin, Yakovlev, Springer 2007)

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

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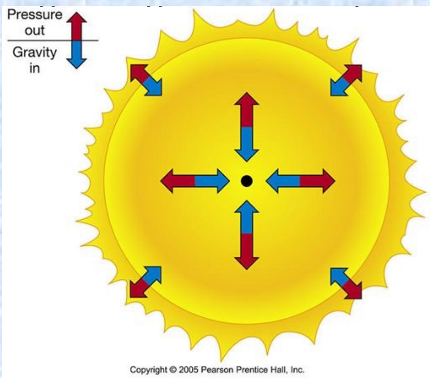

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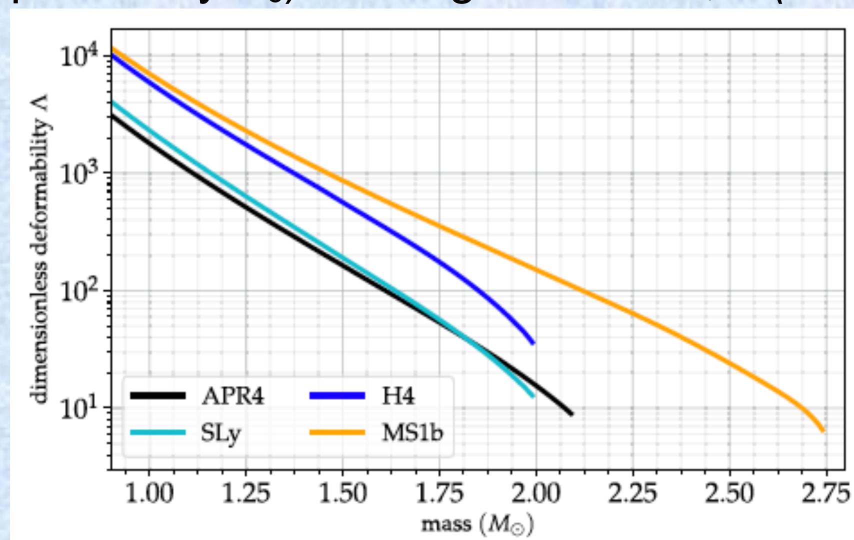


Dietrich et al., Gen. Rel. Gravit. 53, 27 (2021)

→ GR → direct correspondence
EoS ←→ NS static properties

→ for each ρ_c → **rayon *R*, masse *M***
→ **tidal deformability Λ**

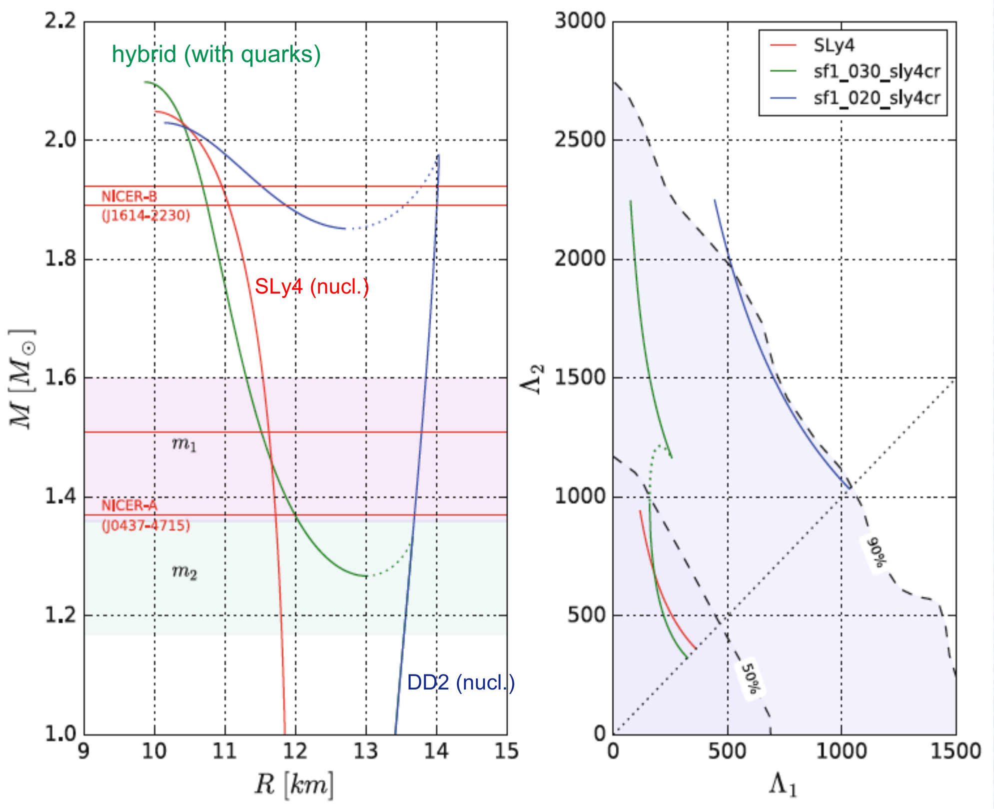
?
→ trace back to EoS and composition?

N.B.: GR in slow rotation limit w/o magnetic field !

High-density EoS → additional d.o.f.?

- Role of "exotic" degrees of freedom?
  Hyperons → softer EoS → lower M_{max}
  Quarks → not clear

- "Masquerade" effect



Blaschke & Chamel, ASSL 457, 337 (2018);
see also Li et al., PRD 101, 063022 (2020);
Somasundaram & Margueron, EPL 138, 14002 (2022)

High-density EoS → additional d.o.f.?

- Role of "exotic" degrees of freedom?
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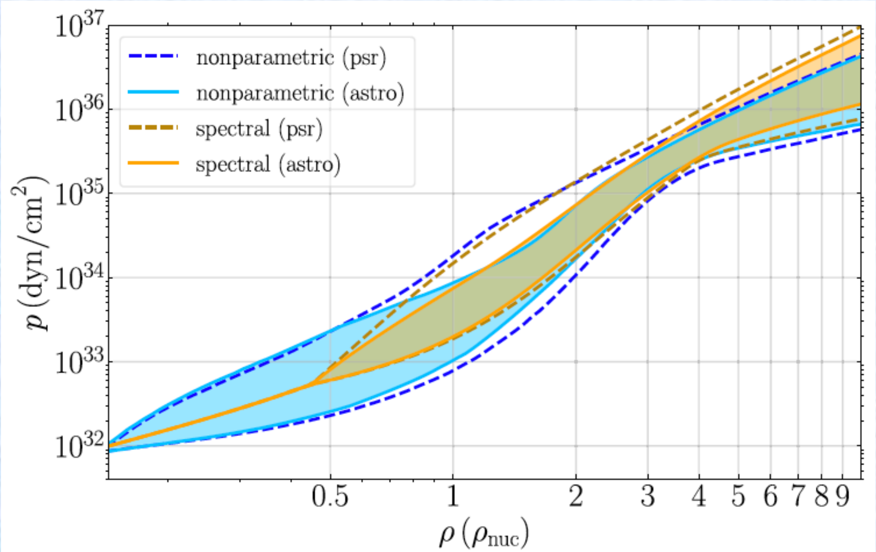
➢ *Agnostic* ("non-nuclear") approaches for NS core
(conditioned by astro)



Legred et al. PRD 105, 043016 (2022)

✓ poweful → no underlying hypotheses
✗ what about nuclear physics → composition ?
✗ often one low-density EoS → uncertainties underestimated

EoS ←→ nuclear matter parameters

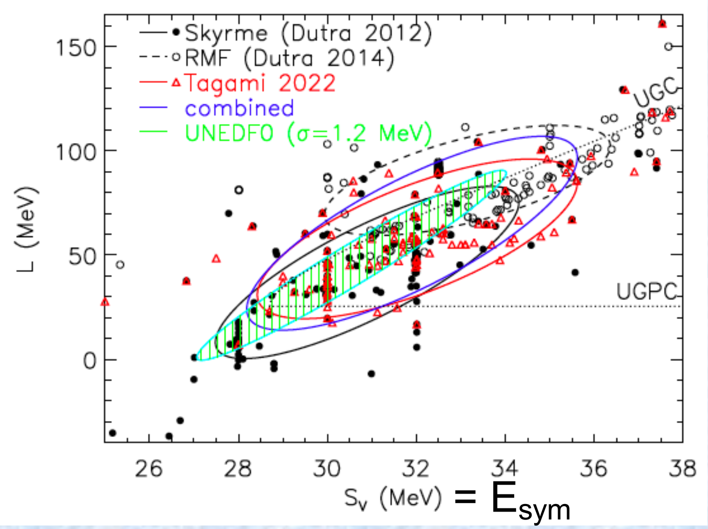
- Expansion in density and asymmetry around $n_{\rm sat}$ and $\delta = 0$

$$x = (n - n_{\rm sat})/3n_{\rm sat}$$
$$\delta = (n_n - n_p)/n$$

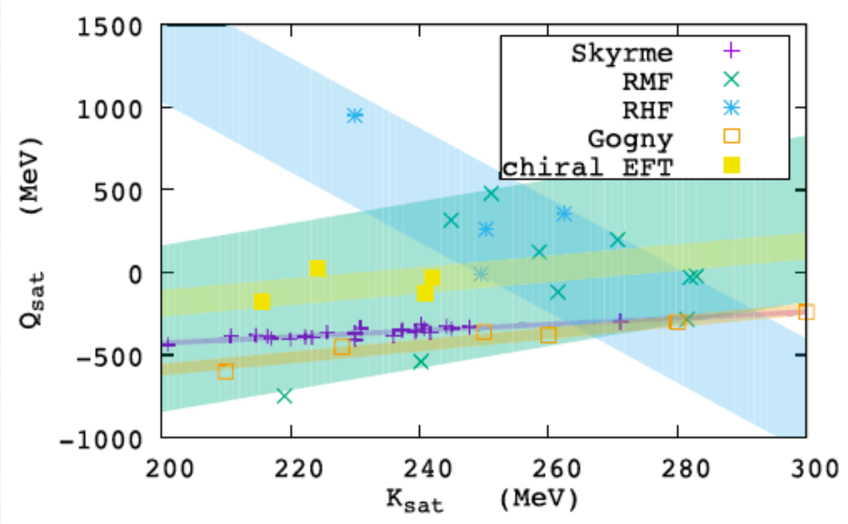
$$e_{\rm is} = E_{\rm sat} + \frac{1}{2}K_{\rm sat}x^2 + \frac{1}{6}Q_{\rm sat}x^3 + \ldots$$ → $e_{\rm sat}(n,\delta=0)$

$$e_{\rm iv} = E_{\rm sym} + L_{\rm sym}x + \frac{1}{2}K_{\rm sym}x^2 + \frac{1}{6}Q_{\rm sym}x^3 + \ldots$$ → $e_{\rm sym}(n)=e(n,\delta=1) - e(n,\delta=0)$

→ Empirical parameters (bulk) $\boldsymbol{X}_{\rm sat,sym}$ = $E_{\rm sat}$, $K_{\rm sat}$, $Q_{\rm sat}$, …, $E_{\rm sym}$, $L_{\rm sym}$, $K_{\rm sym}$, $Q_{\rm sym}$, …



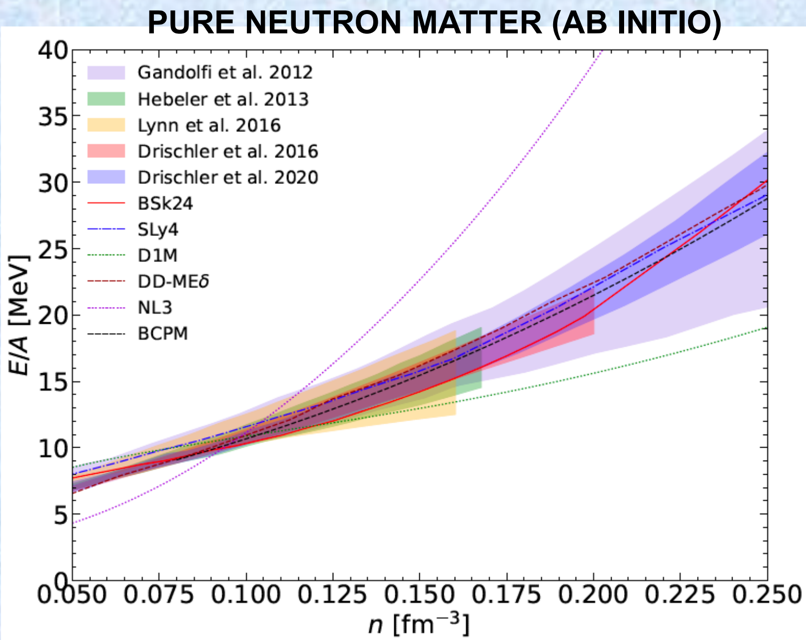
Lattimer, Particles 6, 30 (2023)



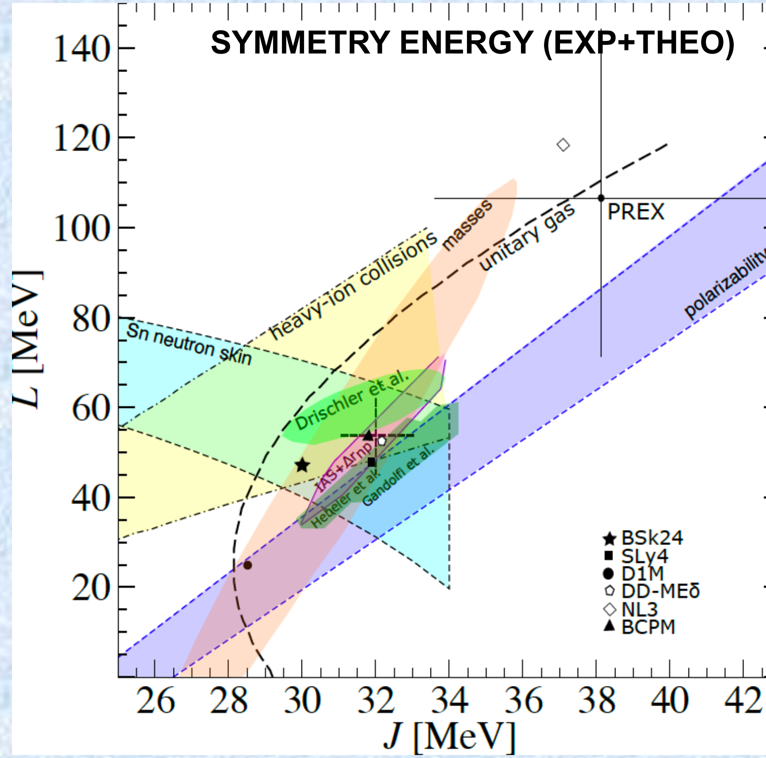
Margueron et al., PRC 97, 025805 (2018)

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), …

Constraints from nuclear physics



Fantina & Gulminelli, J.Phys. Conf. Ser. 2586, 012112 (2023);
see also Oertel et al., Rev. Mod. Phys. 89, 015007 (2017)



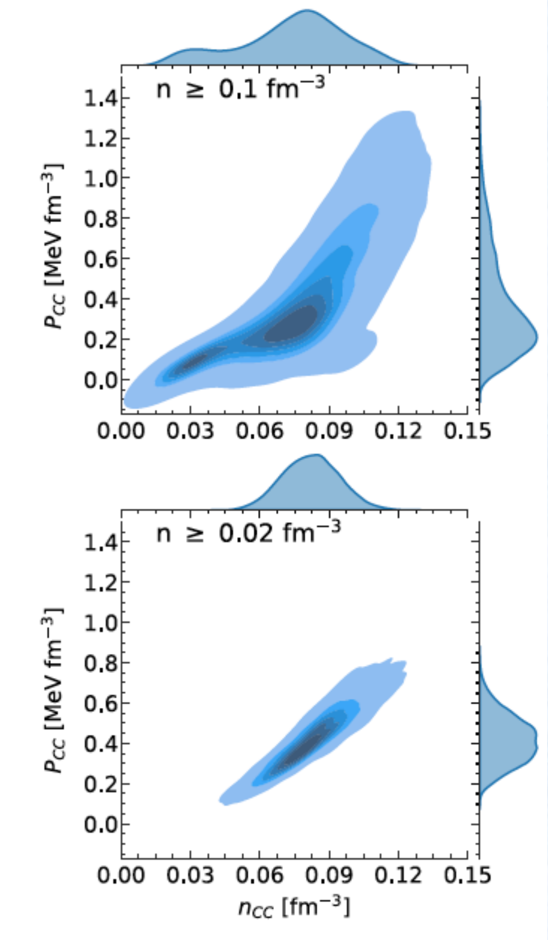
Gulminelli&Fantina, Nucl. Phys. News 31, 9 (2021);
Fantina&Gulminelli, J.Phys.Conf.Ser. 2586, 012112 (2023)

→ PNM calculations benchmark / constraints
→ not all popular models agree with ab-initio constraints!

→ Exp. constraints at “lower” densities & more symmetric matter
→ not always “clear” constraints → “tension” (data + modelling)

Crustal properties

CRUST-CORE TRANSITION



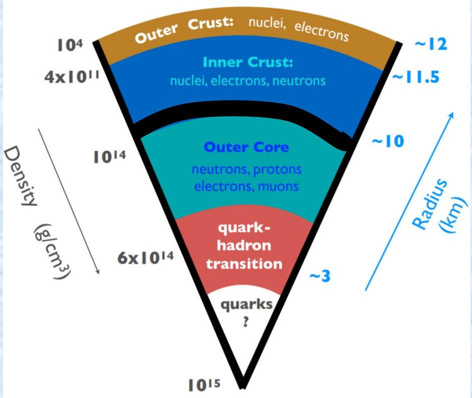


Image Credit: 3G Science White Paper

n_{CC}

	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	p
LD+HD ($n \geq 0.02$ fm^{-3})	-0.04	-0.07	0.11	-0.05	-0.02	-0.30	-0.57	-0.15	0.45	-0.15	0.05	0.52	-0.15	-0.04	0.51
LD+HD ($n \geq 0.1$ fm^{-3})	-0.06	-0.06	0.33	-0.46	0.17	-0.15	-0.29	-0.10	0.39	-0.16	0.06	0.34	-0.11	-0.08	0.33
Prior	0.14	0.09	0.13	-0.18	0.02	0.08	-0.56	0.11	0.20	-0.05	-0.17	0.07	0.29	0.18	0.18

bulk (E_{sat} … Z_{sym}) surface (σ_0 … p)

→ importance of low-density EoS

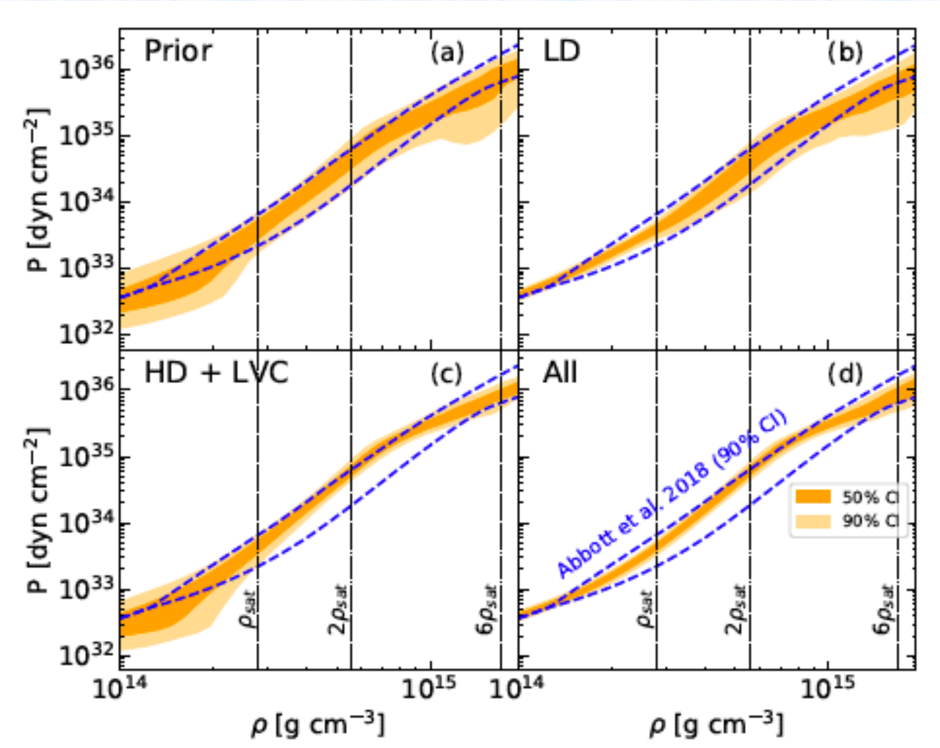
→ importance of parameters (*bulk* + *surface*)

→ importance of higher-order parameters

Dinh Thi et al., A&A 654, A114 (2021); EPJA 57, 296 (2021)

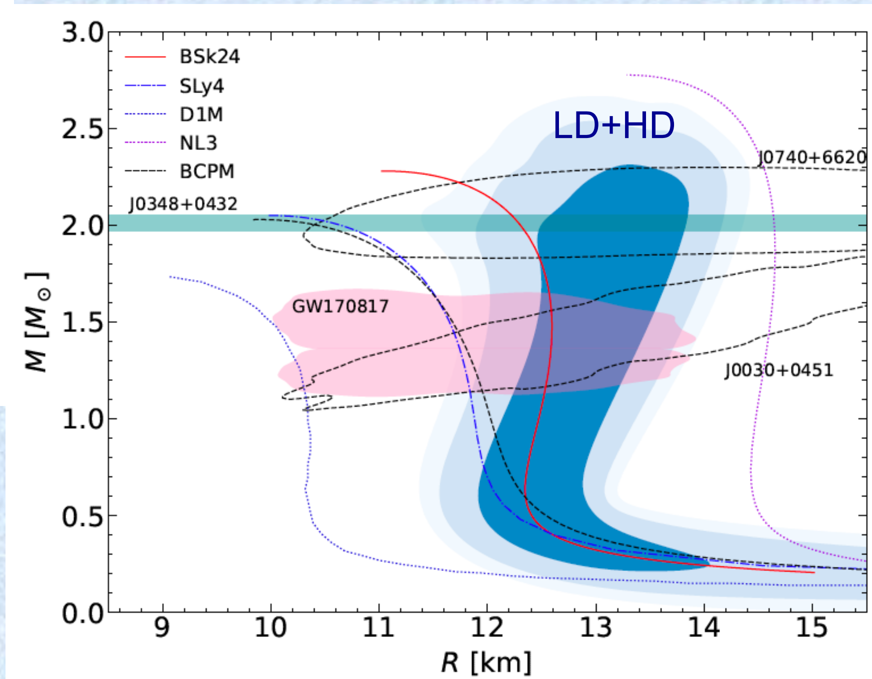
see also Balliet et al., ApJ 918, 79 (2021); Carreau et al., PRC 100, 055803 (2019)

EoS : effect of LD/HD constraints



Dinh Thi et al., Universe 7, 373 (2021)

LD (EFT calc.) → low-density (nucl.phys.)
HD → high-density (astro: causality, M_{max})
All → LD+HD+NICER+GW



→ filters reduce uncertainties
→ posterior compatible with observations
but: some popular models are not !

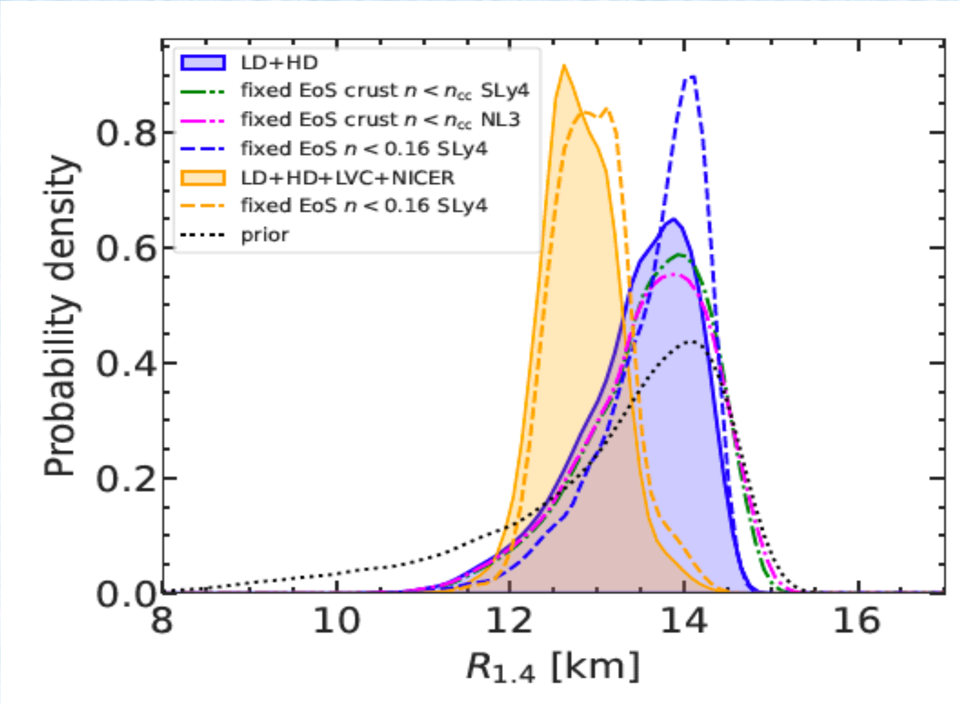
→ nucleonic hp compatible with observations
→ observations not yet enough constraining!

Fantina & Gulminelli, J.Phys.Conf.Ser. 2586, 012112 (2023)
see also Dinh Thi et al., A&A 654, A114 (2021)

similar conclusions in Malik&Providencia, PRD 2022, Lim&Holt, EPJA 2019, Malik et al., ApJ 2022

Effect of the (non-unified) crust

RADIUS



Davis et al., A&A submitted (2023)

→ **CUTER** code to reconstruct a *thermodynamically consistent and unified* low-density EoS from a beta-equilibrium EoS

(available for LIGO-Virgo-KAGRA collab.)

→ use of unique crust does not change much averages (~ few %)

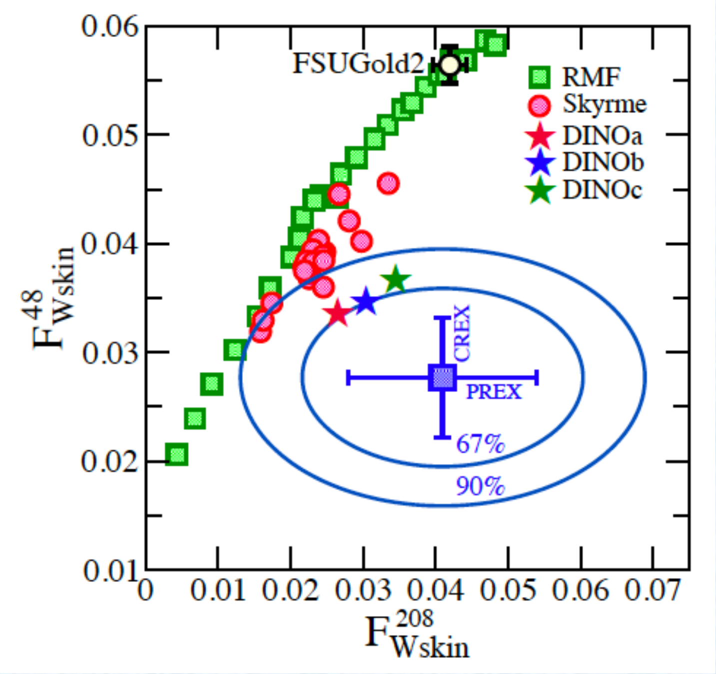
(see also Gamba et al., Class. Quant. Grav. 37, 025008 (2020) → ~ 3%)

→ variance larger in consistent approach → underestimation of uncertainties

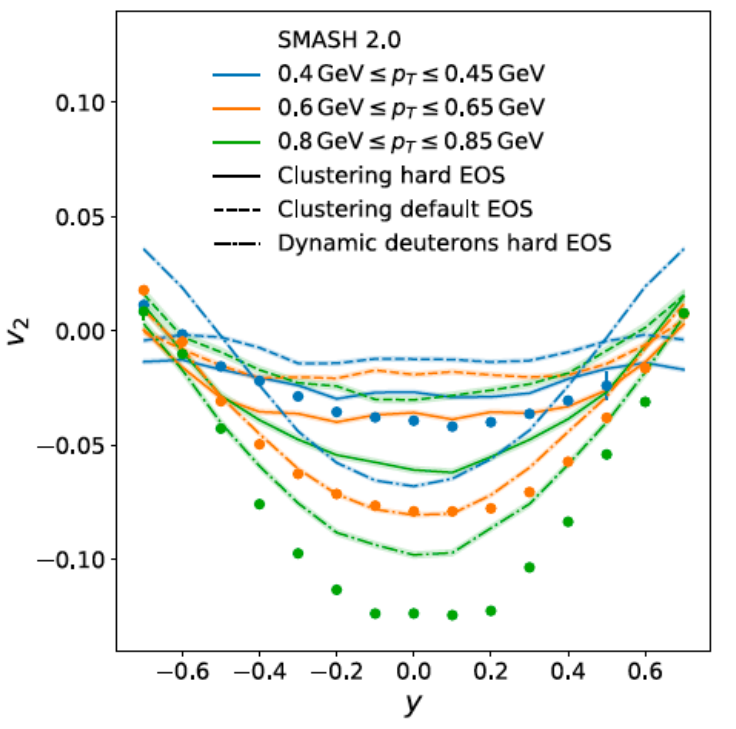
→ quantitative error bars on NS properties can be addressed

Additional constraints ? (exp)

- More constraints from nuclear physics experiments (some examples)
  → reduced error bars e.g. in n skin → low-order parameters in isospin sector
  → constraints at high-density (~ 2 n_{sat}) e.g. elliptic flow → "higher"-order parameters in isoscalar sector



Reed et al., arXiv:2305.19376 (2023)

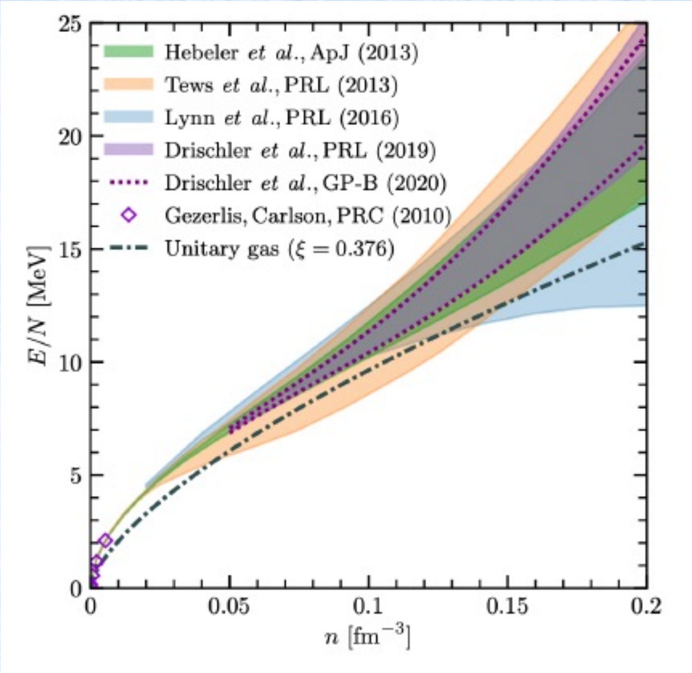


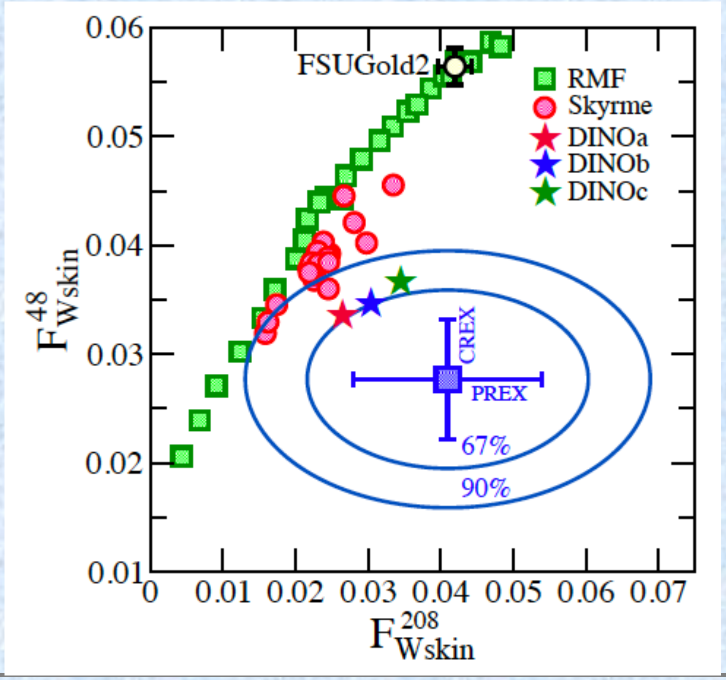
Mohs et al., PRC 105, 034906 (2022)

Outlooks

- Quantitative estimations of probability distributions from nuclear physics
  → theory : probability distribution of ab-initio constraints ?
  N.B. very-low density important for crustal properties
  → experiment : constraints on isoscalar/isovector parameters
  consistent treatment of different observables

➡ Implementation of consistent constraints in astro predictions / inference
→ discussion on EoS constraints already ongoing with E. Litvinova (WMU/MSU)



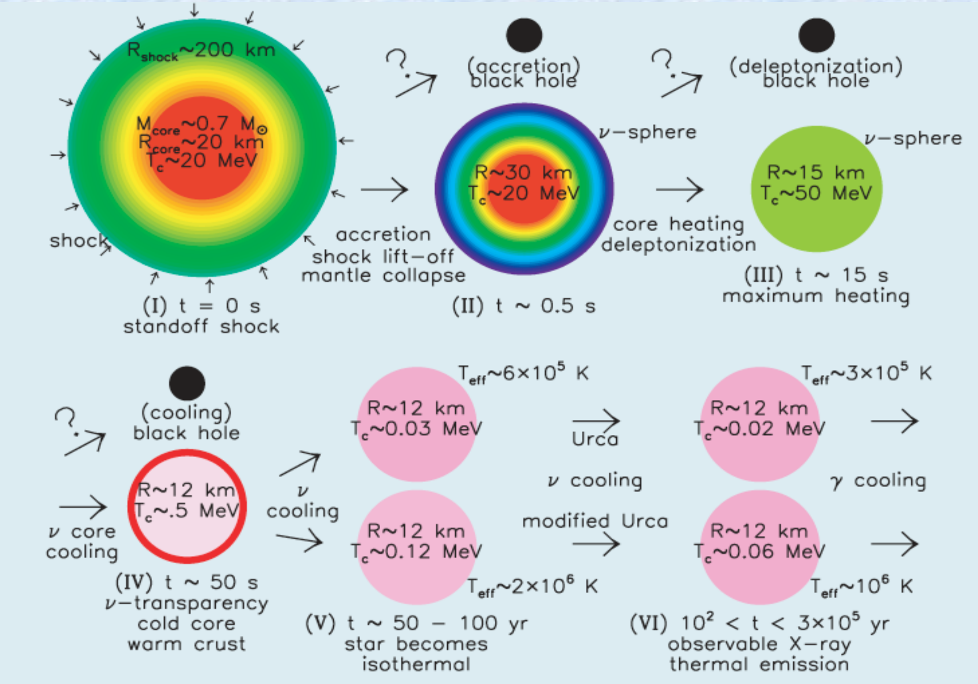


Hebeler, talk @MICRA2023;
see also Huth et al., Nature 606, 276 (2022)

Reed et al., arXiv:2305.19376 (2023)

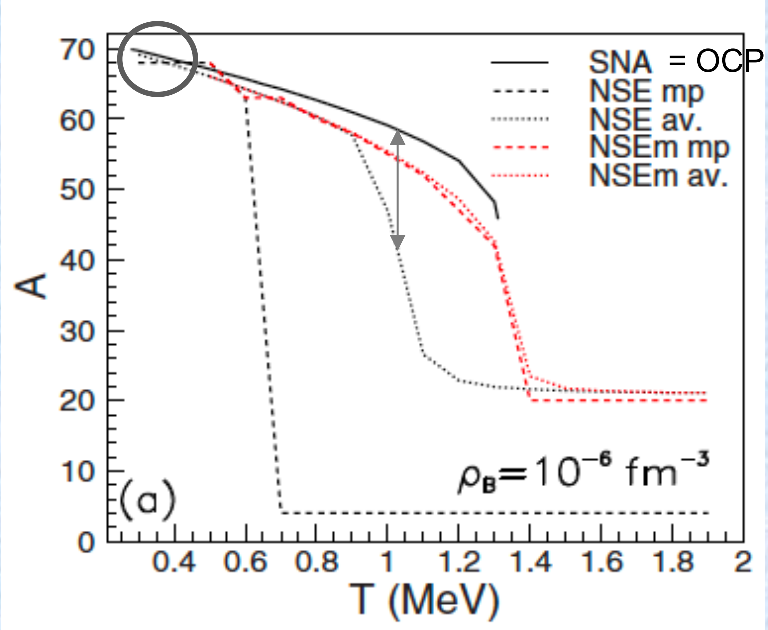
Proto-NS (finite temperature)

NS formation from CCSN



Lattimer & Prakash, Science 304, 536 (2004)

At finite T → need to go beyond OCP



Gulminelli & Raduta, PRC 92, 055803 (2015)

→ NS are born hot (*T* > 1 MeV) → ensemble of nuclei (MCP) expected

→ NS crust crystallises at T_m ~ 0.1 – 1 MeV → composition of the crust "frozen"

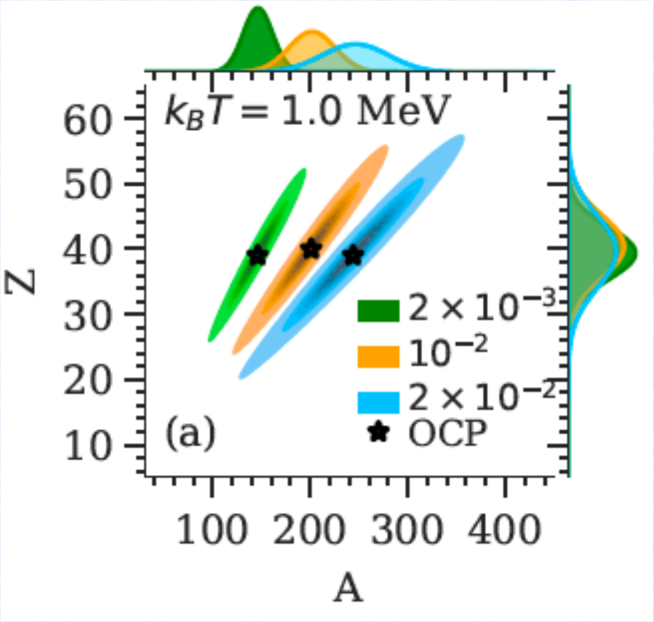
but: - depending on cooling timescales, composition can be frozen at $T > T_m$
(e.g. Goriely et al., A&A 531, A78 (2011))

- other reactions possible below T_m ? (e.g. Potekhin & Chabrier, A&A 645, A102 (2021))

for a review, see Haensel, Potekhin, Yakovlev (Springer 2007)

PNS: composition and impurities

1. Composition can be different from $T = 0$ & OCP one !

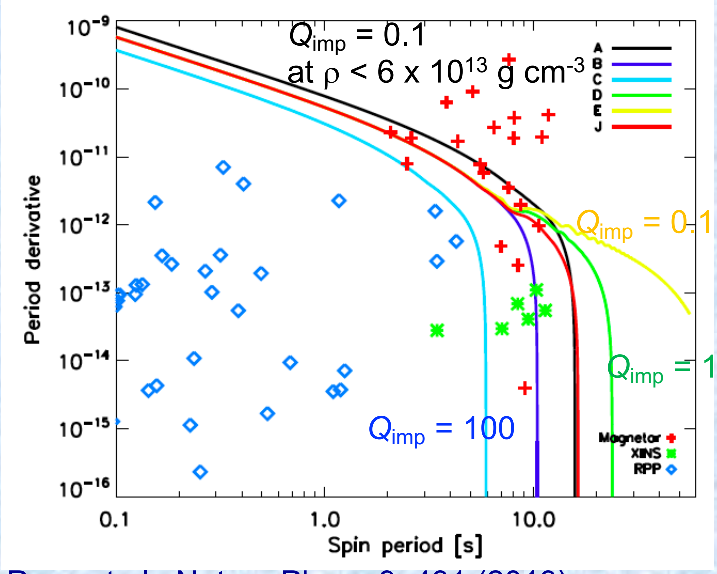


Dinh Thi et al., A&A 677, A174 (2023)
see also Fantina et al., A&A 633, A149 (2020);
Carreau et al., A&A 640, A77 (2021)

2. Co-existence of nuclear species
→ **"impurity factor"** (usually free parameter adjusted on cooling data)

$$Q_{\rm imp} = \langle Z^2 \rangle - \langle Z \rangle^2$$

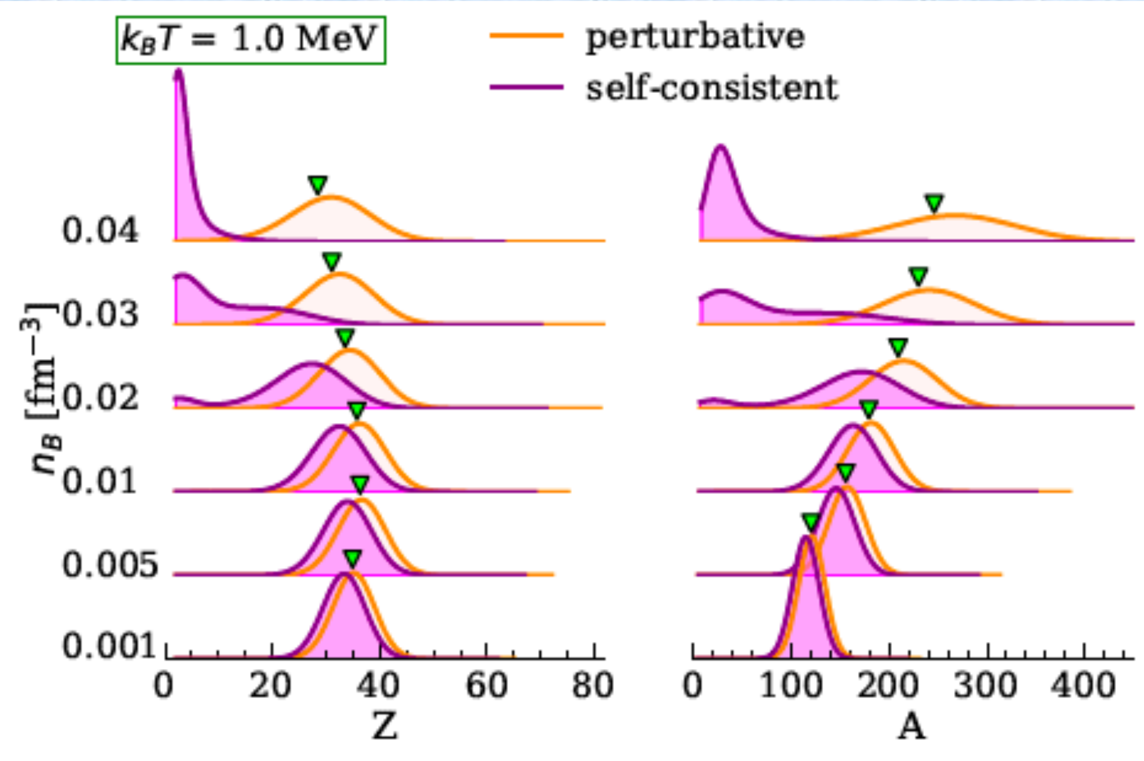
→ impact dynamic, magneto-rotational and transport properties



Pons et al., Nature Phys., 9, 431 (2013)
(see also Viganò et al., MNRAS 2013)

see e.g. Schmidt&Shternin, ASSL 457, 455 (2018) for a review; Jones, PRL 83, 3589 (1999), MNRAS 321, 167 (2001), PRL 93, 221101 (2001); Pons et al., Nat. Phys. 9, 431 (2013)

(P)NS crust: composition



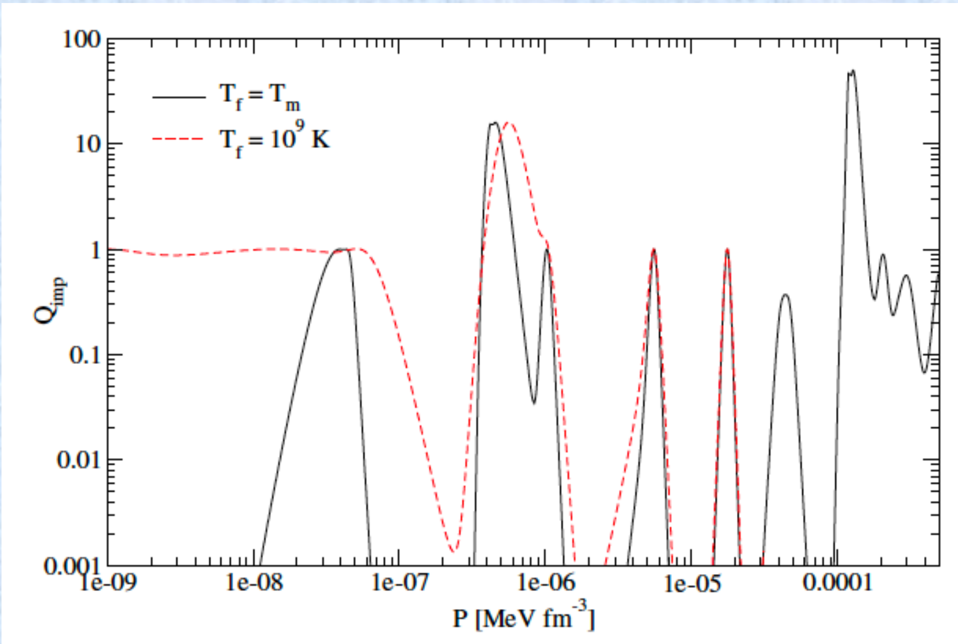
Dinh Thi et al., A&A 677, A174 (2023)

- OCP less reliable at higher density and temperature
  → (self-consistent) MCP needed for composition
- appearance of bi-modal distribution → light clusters !

(P)NS crust: impurities

✓ Self-consistent calculations of $Q_{\mathrm{imp}} = \langle Z^2 \rangle - \langle Z \rangle^2$

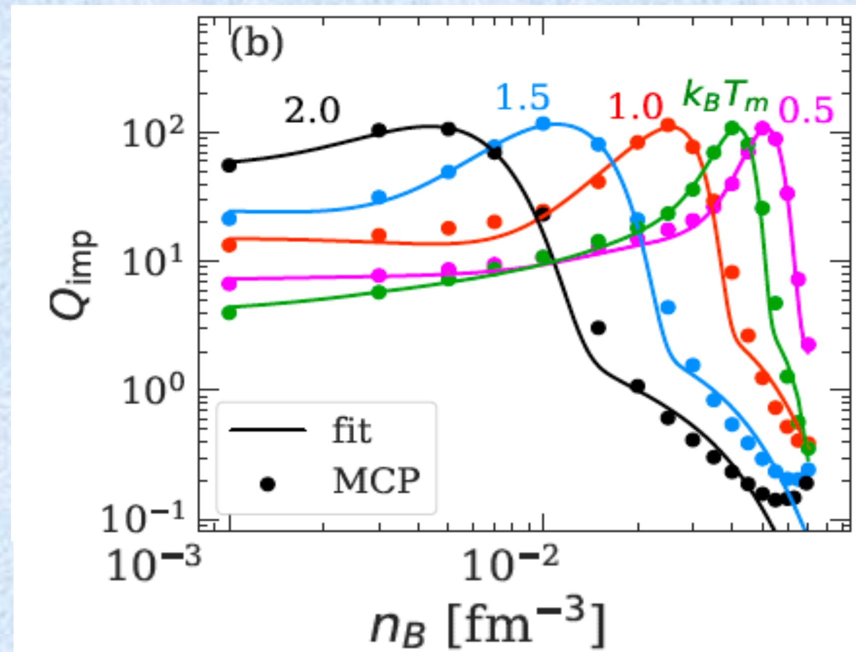
Outer crust



Fantina et al., A&A 633, A149 (2020) + data on CDS

BSk24 functional

Inner crust



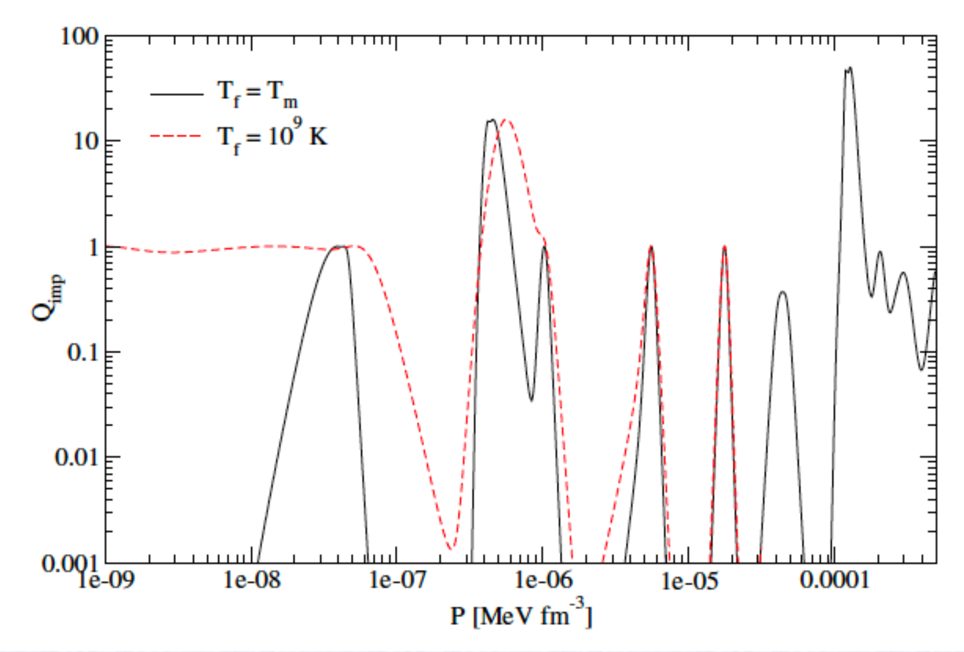
Dinh Thi et al., A&A 677, A174 (2023); see also Carreau et al., A&A 640, A77 (2020) + data on CDS

➢ consistent calculations of Q_{imp} throughout the crust
→ impact on transport coefficient/properties

(P)NS crust: impurities

✓ Self-consistent calculations of $Q_{\mathrm{imp}} =$

Outer crust



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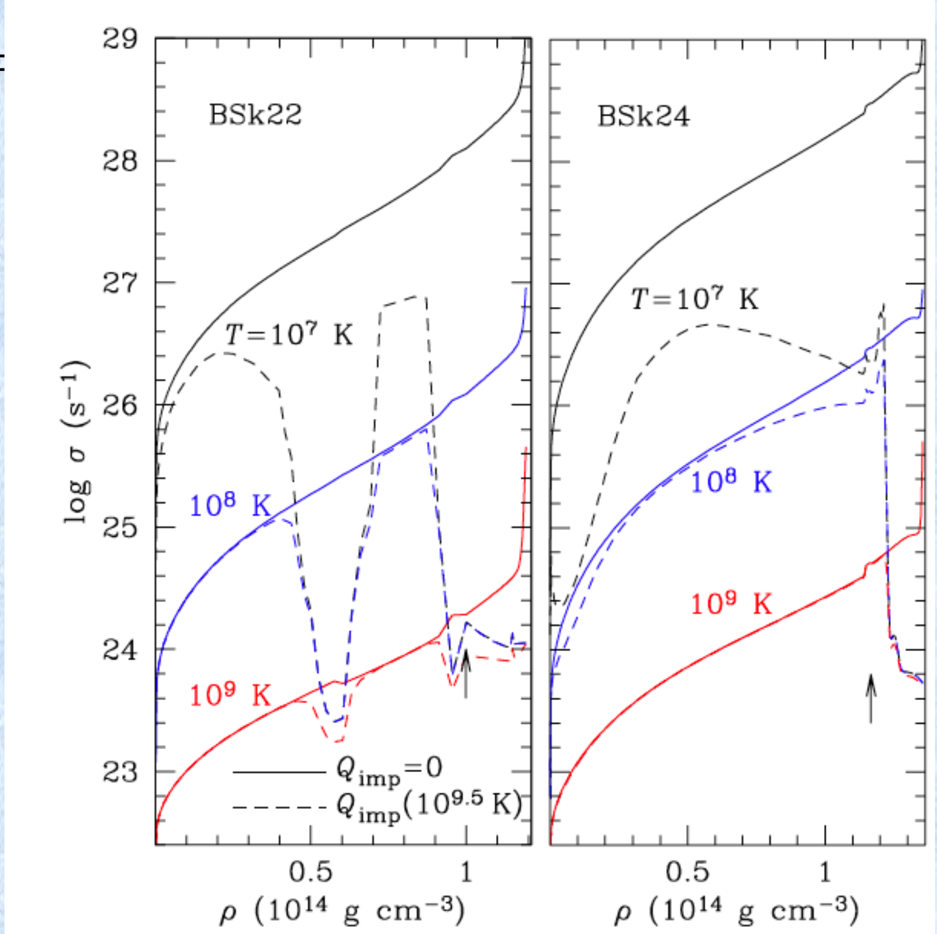

Potekhin & Chabrier, A&A 645, A102 (2021)

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Outlooks

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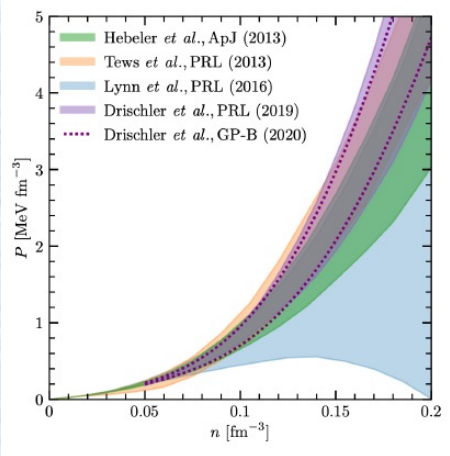
  → theory : probability distribution of ab-initio constraints ?
  N.B. very-low density important for crustal properties
  → experiment : constraints on isoscalar/isovector parameters
  consistent treatment of different observables

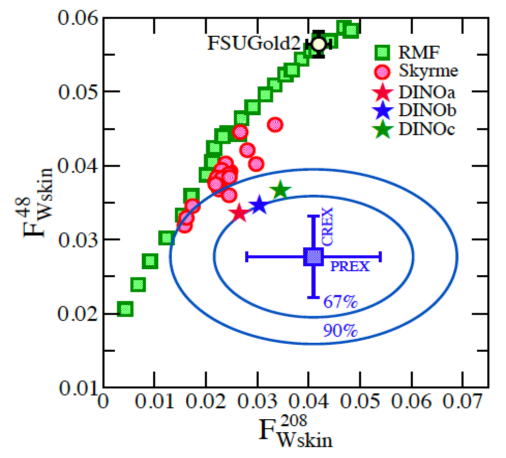
➡ Implementation of consistent PDF constraints in astro predictions / inference

- Ab initio predictions on derived quantities
  → not only E/A but also e.g. P, μ → propagation of uncertainties

➡ Better constraints on the (more phenomenological) functionals



Hebeler, talk @MICRA2023



Reed et al., arXiv:2305.19376 (2023)

Thank you