Probing properties of dense matter with neutron stars

Anthea F. Fantina (anthea.fantina[AT]ganil.fr)

QNP 2024,
08 – 12 July 2024, Barcelona (Spain)

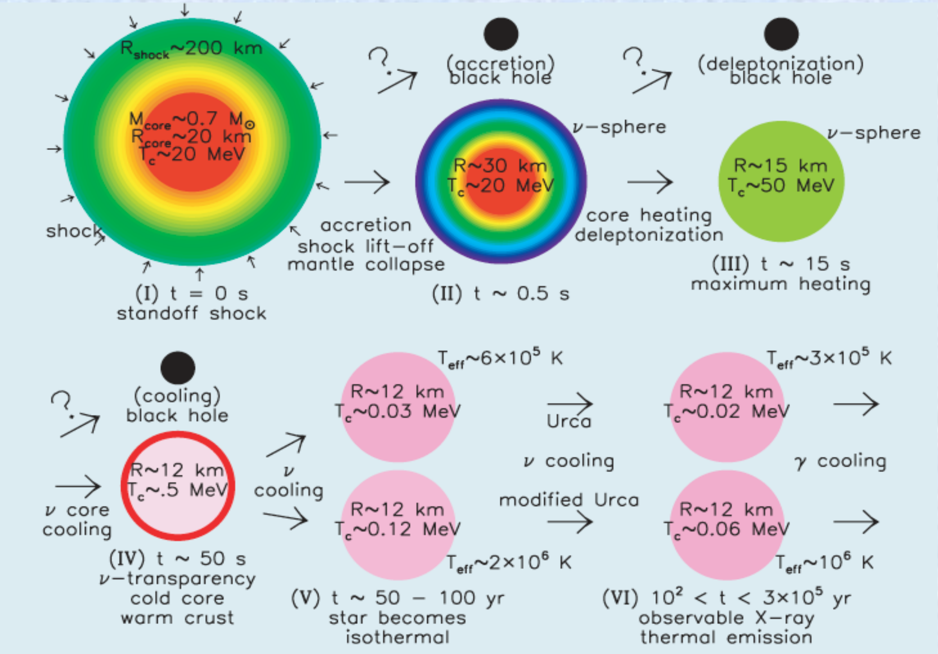
Outline

- ❖ Introduction:
  - ➢ Neutron-star (NS) properties and equation of state (EoS) modelling and constraints
- ❖ Selected results in :
  - ➢ Catalysed (“cold”) NSs ($T = 0$, full equilibrium)
    - → EoS and NS observables
  - ➢ Proto-neutron-star (PNS) crust ($T \neq 0$, beta equilibrium)
    - → multi-component plasma, impurity parameter
- ❖ Conclusions and open questions

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

NS (isolated): formation

after shock formation



Lattimer & Prakash, Science 304, 536 (2004)

- NS born hot, $T \sim 10^{10}$-10^{11} K ~ 1 – tens MeV
- after few tens of sec – mins
  → beta equilibrium (e.g. Camelio et al. 2017)
  → formation of crust (e.g. Pons&Viganò 2019)
  ($T < \sim 10^9 - 10^{10}$ K)
- cooling → $T < \sim 10^8$ K
  → **“cold catalysed”** (→ $T = 0$)
  full thermodynamic equilibrium, $\boldsymbol{P(n_B)}$

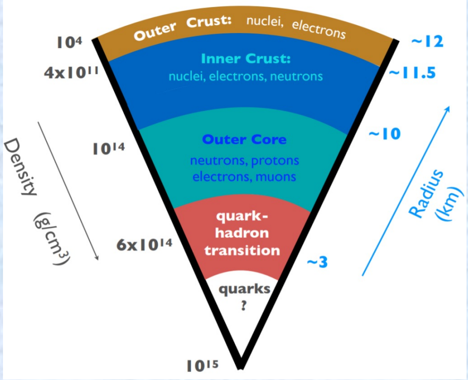
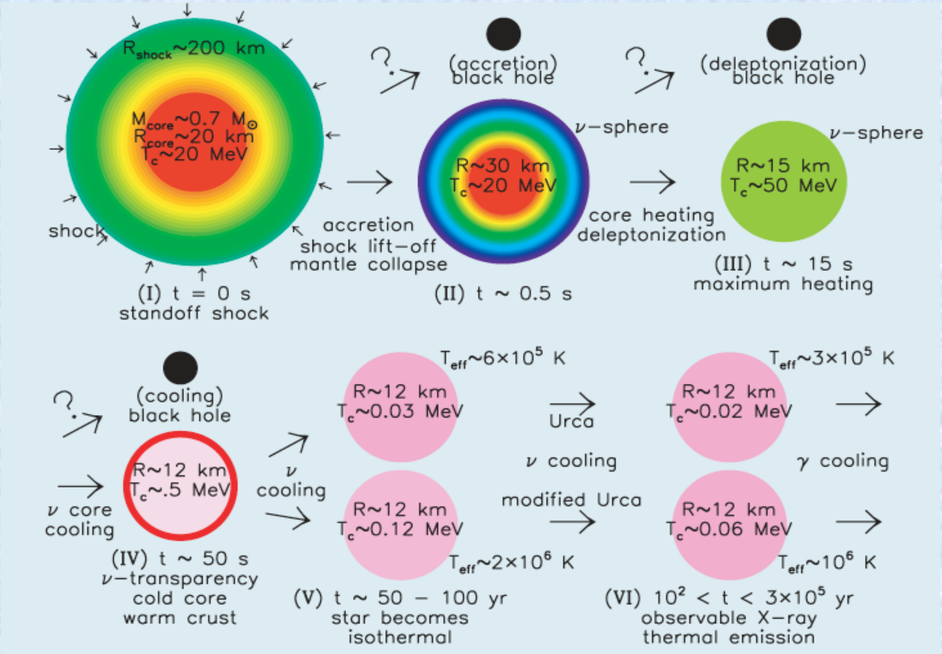


Image Credit: 3G Science White Paper

NS (isolated): formation

after shock formation



Lattimer & Prakash, Science 304, 536 (2004)

- NS born hot, $T \sim 10^{10}$-10^{11} K ~ 1 – tens MeV
- after few tens of sec – mins
  → beta equilibrium (e.g. Camelio et al. 2017)
  → formation of crust (e.g. Pons&Viganò 2019)
  ($T < \sim 10^9 – 10^{10}$ K)
- cooling → $T < \sim 10^8$ K
  → **"cold catalysed"** (→ $T = 0$)
  full thermodynamic equilibrium, $\boldsymbol{P(n_B)}$

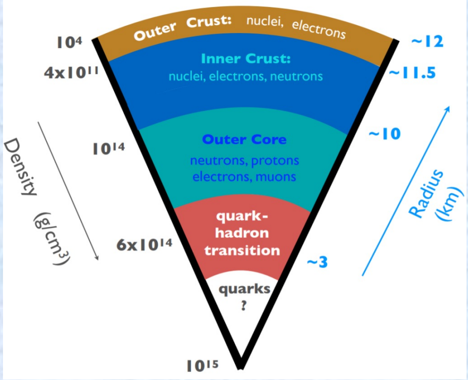


Image Credit: 3G Science White Paper

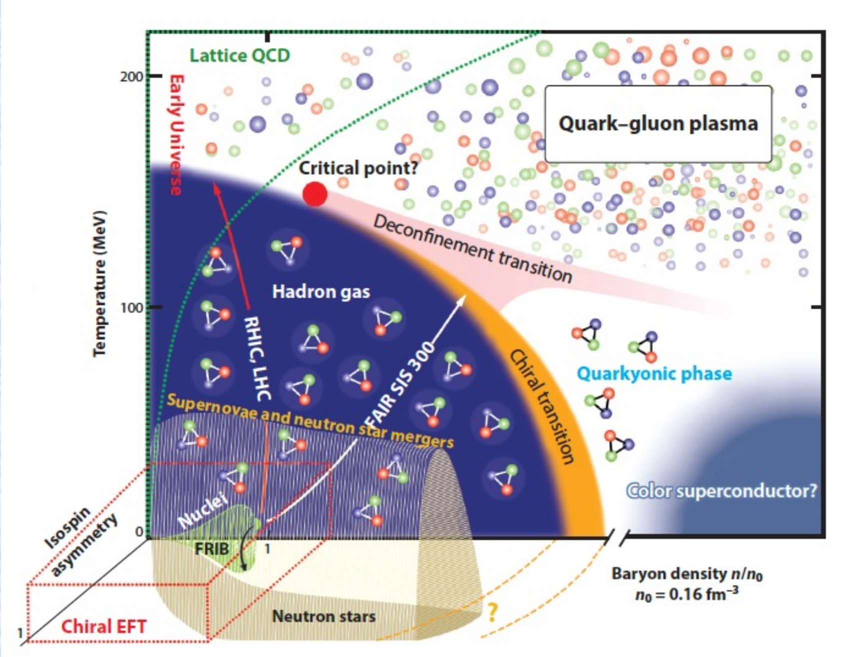
but: real picture can differ from cold catalysed one

⁎ **PNS** (→ $T > 0$, $\boldsymbol{P(n_B,T)}$) if beta equilibrium)

N.B.: *"General purpose" EoSs* $\boldsymbol{P(n_B,T,Y_q)}$, accretion *& B effects not addressed here*

(see e.g. Oertel et al., Rev. Mod. Phys. 2017; Burgio & Fantina, ASSL Springer 2018)

Probing extreme conditions in NSs



Drischler et al., Ann. Rev. Nucl. Part. Sci. 71, 403 (2021)

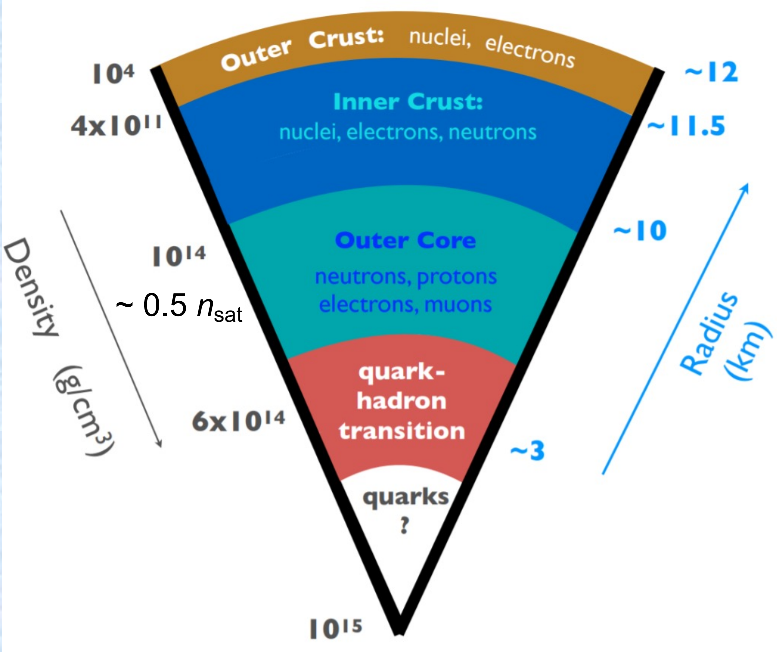


Image Credit: 3G Science White Paper

different states of matter spanned in NSs

→ inhomogeneous (crust), “pasta” phase, homogeneous (core), “exotic” particles (?)

+ superfluidity, (strong) magnetic field, etc.

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

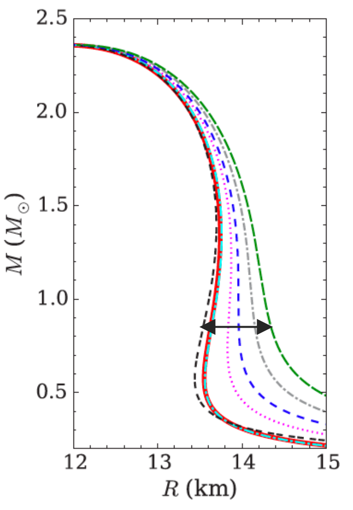
→ Consistent description very challenging

N.B.: T = 0 picture OK for cold isolated NSs and binary (pre-merger) NSs

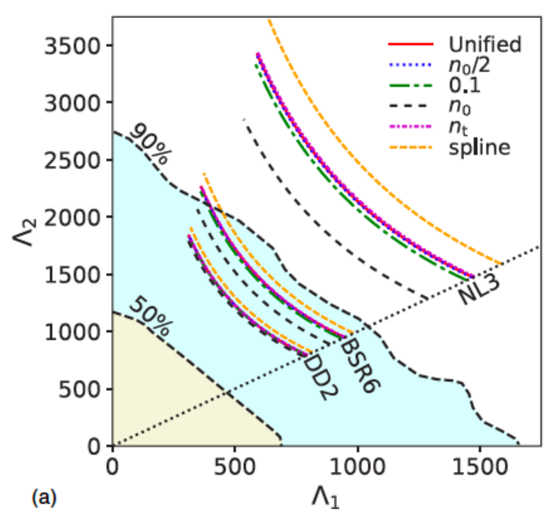
Why a unified treatment ?

Unified treatment of inhomogeneous & homogeneous matter
→ same nuclear model employed in different regions of star

- Challenging because of wide range of thermodynamic conditions
- Challenging because different states of matter
- But: essential to avoid spurious non-physical effects in numerical modelling



Fortin et al., PRC 94, 035804 (2016)

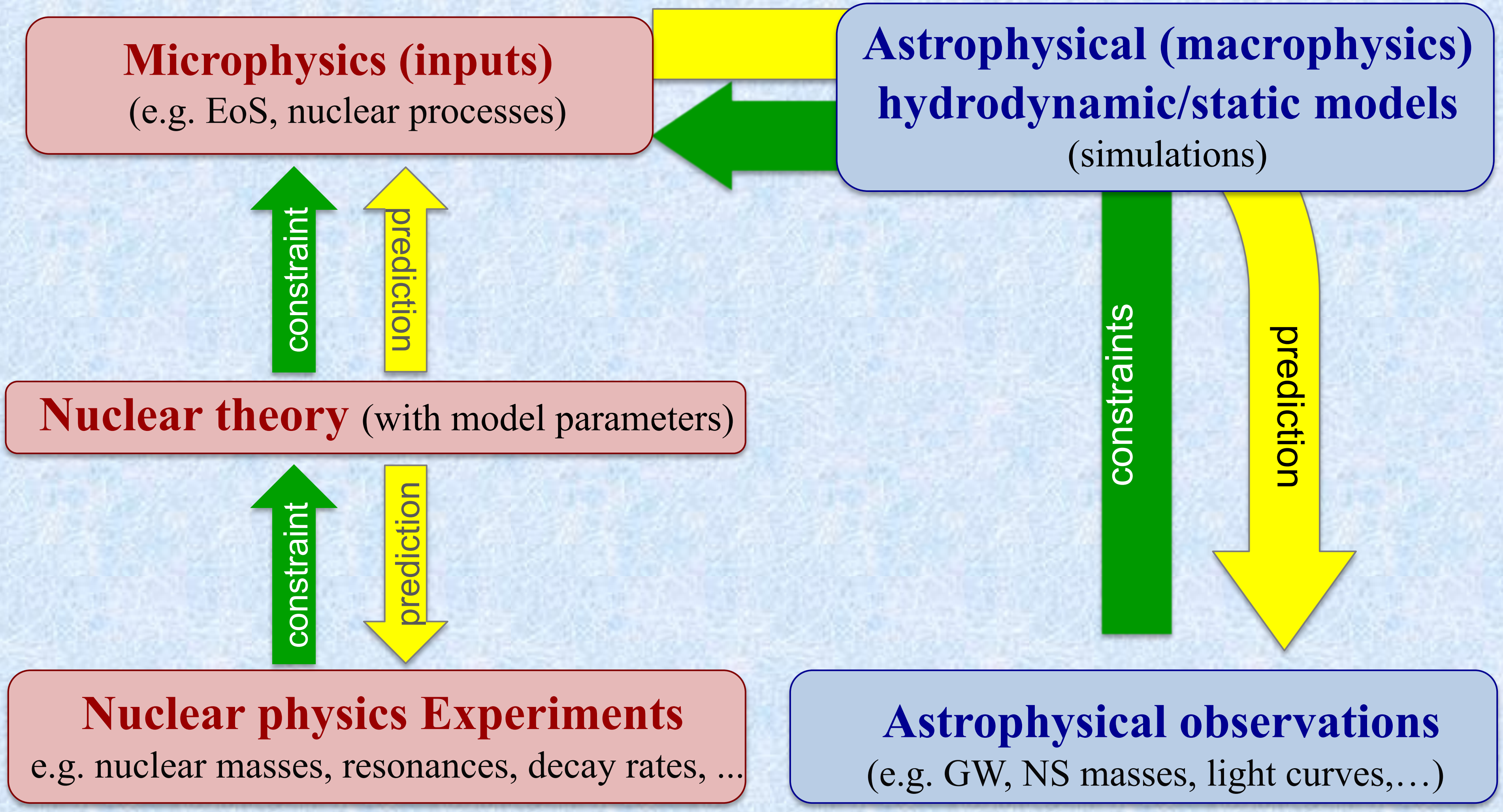


Suleiman et al., PRC 104, 015801 (2021)

see also Ferreira&Providençia 2020

➡ **Thermodynamically consistent and unified EoSs for astro modelling & inference analyses** (but not many available, e.g. Douchin&Haensel 2001; Fantina et al. 2013; Raduta&Gulminelli 2015; Viñas et al. 2021; Pearson et al. 2018; Grams et al. 2022; Xia et al. 2022; Scurto et al. 2024; see CompOSE database)

Micro to macro through modelling



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

Astrophysical (macrophysics) hydrodynamic/static models
(simulations)

Nuclear theory (with model parameters)

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

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

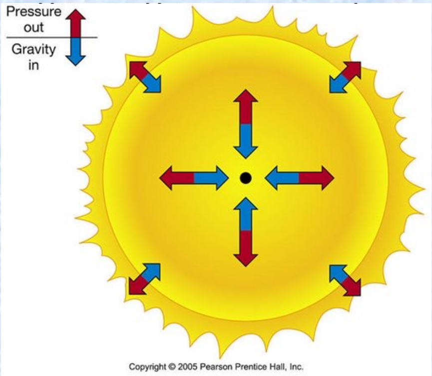
EoS ←→ NS (static) observables (1)

- **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. $M(r=0) = 0$; $\rho(r=0) = \rho_c$



Copyright © 2005 Pearson Prentice Hall, Inc.

only EoS $P(\rho)$ is needed !

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

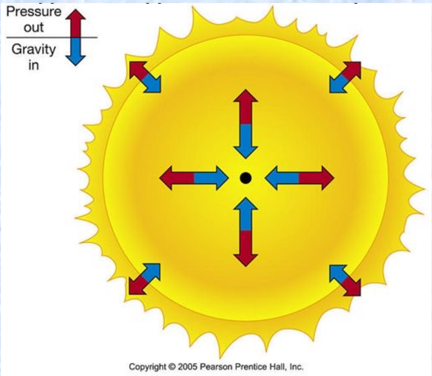
N.B.: GR in slow rotation limit w/o magnetic field !

EoS ←→ NS (static) observables (1)

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

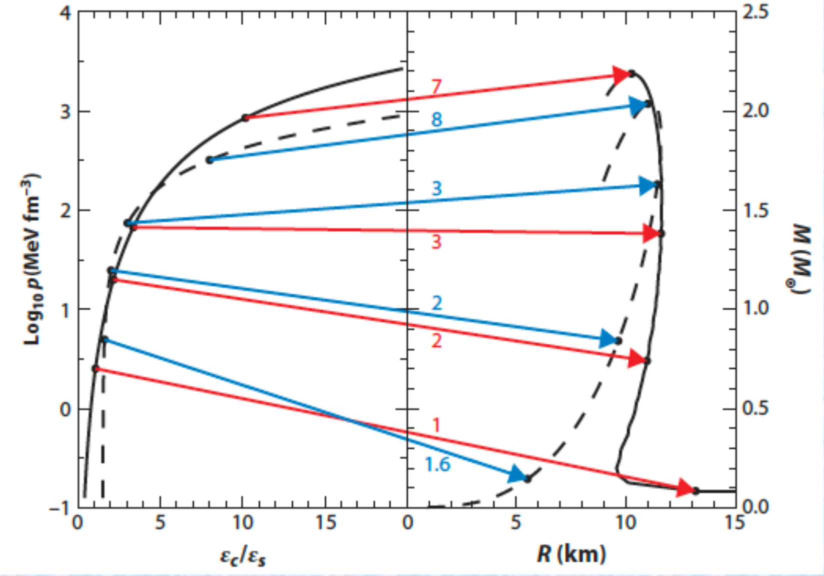
$$\frac{\mathrm{d}P(r)}{\mathrm{d}r} = -\frac{G\rho(r)\mathcal{M}(r)}{r^2}\left[1+\frac{P(r)}{c^2\rho(r)}\right]\left[1+\frac{4\pi P(r)r^3}{c^2\mathcal{M}(r)}\right]\left[1-\frac{2G\mathcal{M}(r)}{c^2 r}\right]^{-1}$$

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

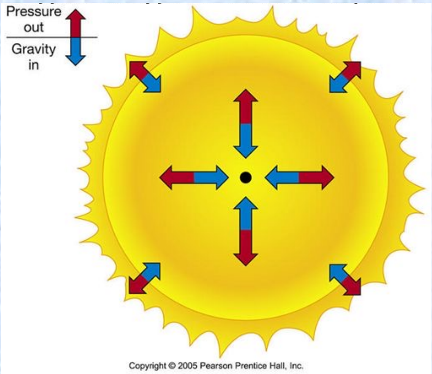
EoS ←→ NS (static) observables (1)

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

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

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

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



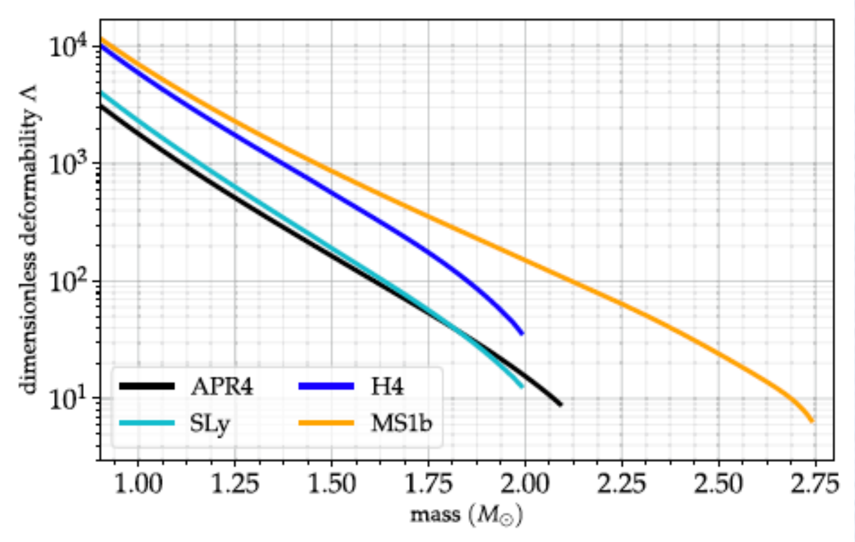
→ only EoS $P(\rho)$ is needed !

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

→ GR → direct correspondence
EoS ←→ NS static properties

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

?
→ trace back to EoS and composition?



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

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

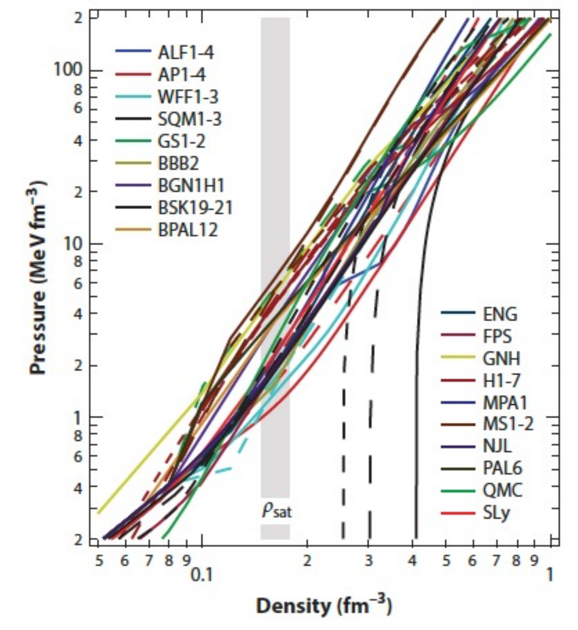
EoS ←→ NS (static) observables (2)

but:

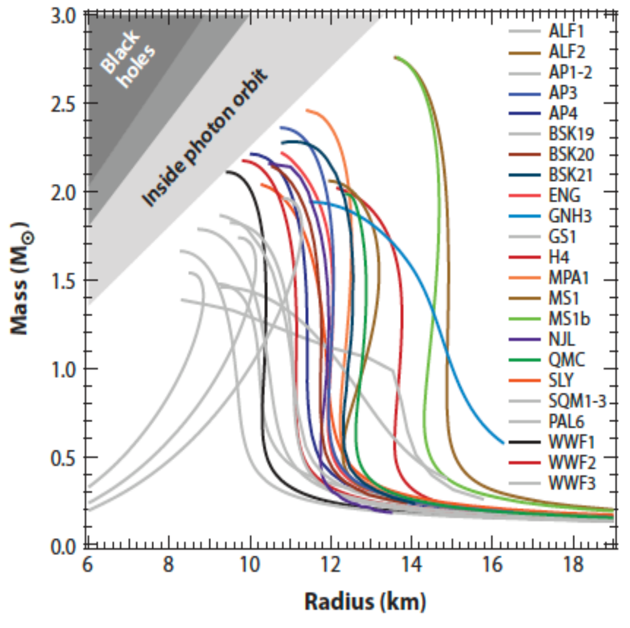
✗ EoS model dependent !

✗ no ab-initio dense-matter calculations in all regimes → phenomenological models

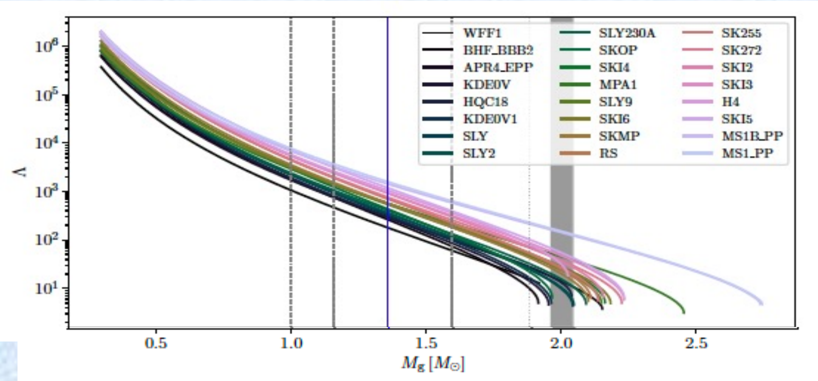
✗ composition ←→ EoS → $M(R)$?



Ozel & Freire, ARAA 54, 401 (2016)



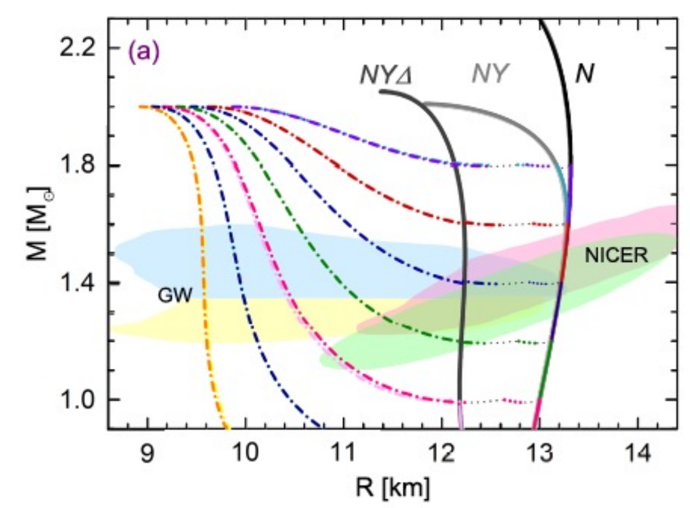
Ozel & Freire, ARAA 54, 401 (2016)



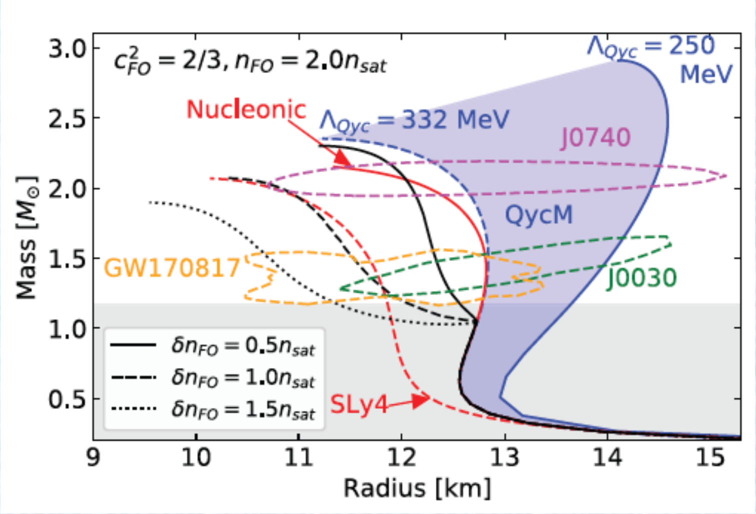
Abbott et al., Class. Quantum Grav, 37, 045006 (2020)

High-density EoS → additional d.o.f.?

- Role of “exotic” degrees of freedom? *(not addressed in this talk, see talks Mon, session H)*
  Hyperons → softer EoS → lower $M_{\max}$ (+ reduction of R and Λ for intermediate-mass)
  Quarks → not clear



Li et al., PRD 101, 063022 (2020)

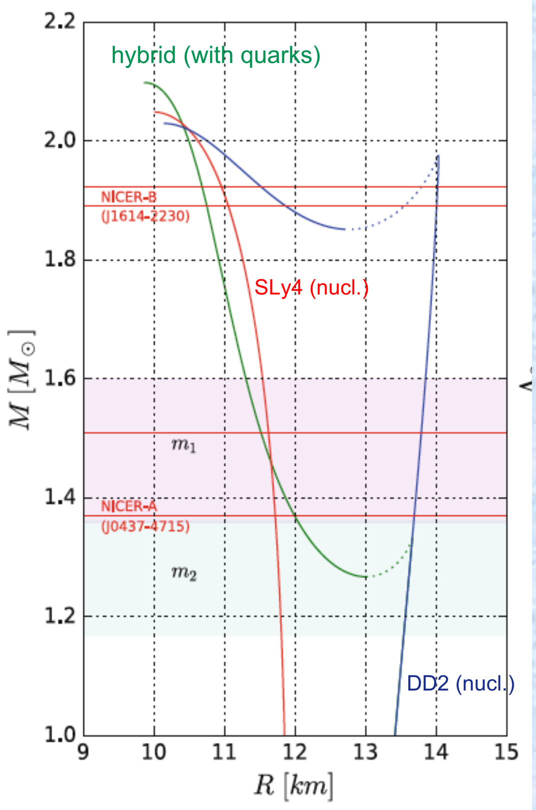


Somasundaram & Margueron, EPL 138, 14002 (2022)

High-density EoS → additional d.o.f.?

- Role of “exotic” degrees of freedom? *(not addressed in this talk, see talks Mon, session H)*
  Hyperons → softer EoS → lower M_{max} (+ reduction of R and Λ for intermediate-mass)
  Quarks → not clear

- “Masquerade” effect



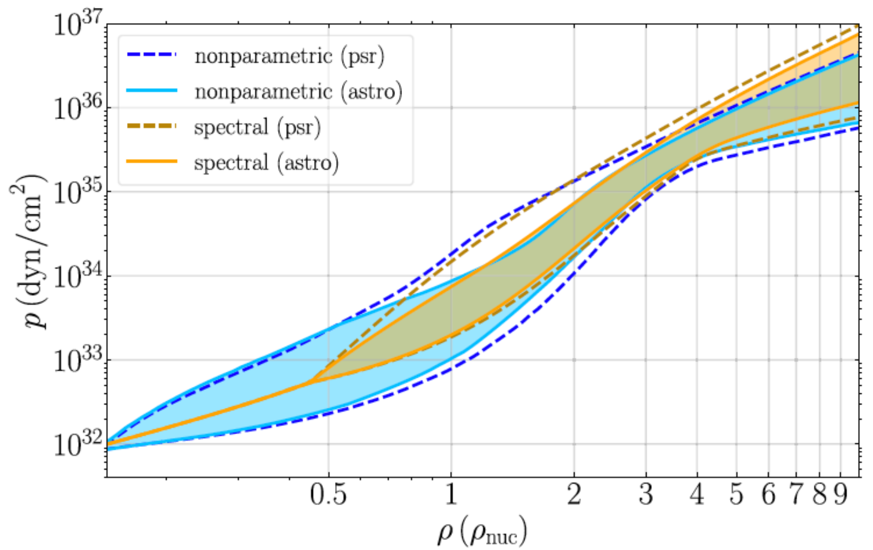
Blaschke & Chamel, ASSL 457, 337 (2018);

High-density EoS → additional d.o.f.?

- Role of "exotic" degrees of freedom? *(not addressed in this talk, see talks Mon, session H)*
  Hyperons → softer EoS → lower $M_{\max}$ (+ reduction of R and Λ for intermediate-mass)
  Quarks → not clear

- "Masquerade" effect

➢ *Agnostic* ("non-nuclear") approaches for NS core (e.g. piecewise polytropes, c_s models,…) (conditioned by astro)



Legred et al. PRD 105, 043016 (2022)

✓ poweful → no underlying hypotheses
✗ what about nuclear physics → composition ?
✗ often unique (non-consistent) low-density EoS → uncertainties underestimated

EoS ←→ nuclear matter parameters

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

$$\delta = (n_n - n_p)/n$$

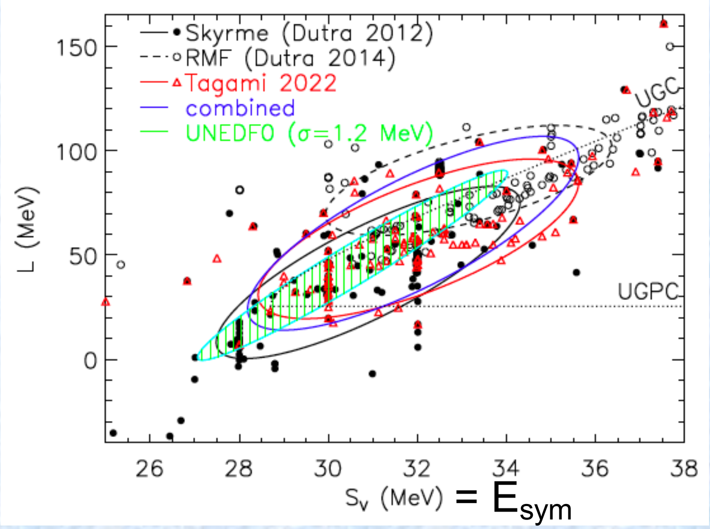
- Expansion in density and asymmetry around $n_{\rm sat}$ and $\delta = 0$

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

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

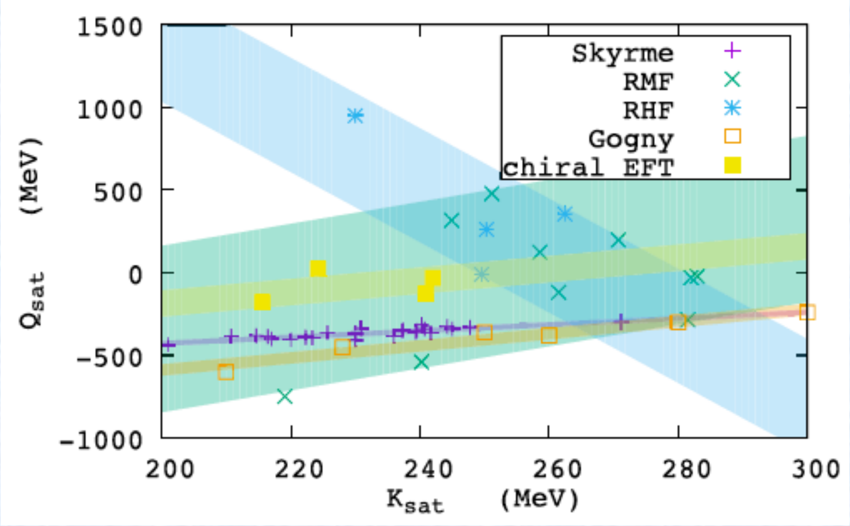
→ Nuclear empirical parameters (NEP, bulk)

$\boldsymbol{X}_{\rm sat,sym} = E_{\rm sat}, K_{\rm sat}, Q_{\rm sat}, \ldots, E_{\rm sym}, L_{\rm sym}, K_{\rm sym}, Q_{\rm sym}, \ldots$



= $E_{\rm sym}$

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), …

A semi-agnostic approach: meta-model

- **Meta-model (MM)** (Margueron et al., PRC 97, 025805 (2018); also e.g. Lim&Holt 2019, Tsang et al. 2020) → EDF-based but flexible. Based on a Taylor expansion in density and asymmetry.

$$\mathcal{E}_B(n_B,\delta) = \mathcal{E}_{\mathrm{kin}}(n_B,\delta) + \mathcal{V}(n_B,\delta)$$

$$\mathcal{V}(n_B,\delta) = \sum_{k=0}^{N} \frac{n_B}{k!}(v_k^{\mathrm{is}} + v_k^{\mathrm{iv}}\delta^2)x^k u_k(x)$$

functions of NEP

zero-density limit

  - For application of MM to NS crust → CLDM

    e.g. Carreau et al., EPJA 2019; Dinh Thi et al., A&A 2021; Grams et al., EPJA 2022; Mondal et al., MNRAS 2023; Davis et al., A&A 2024 (for relativistic version, see Char et al., PRD 2023)

✓ Vary NEP → parameter exploration (without a priori correlations)
→ statistical (Bayesian) analysis (see Mon-Wed talks, session H)

$$p_{\mathrm{post}}(\vec{X}) = \mathcal{N}\, p_{\mathrm{prior}}(\vec{X})\, e^{-\chi^2(\vec{X})/2}\, w_{\mathrm{LD}}(\vec{X}) w_{\mathrm{HD}}(\vec{X})$$

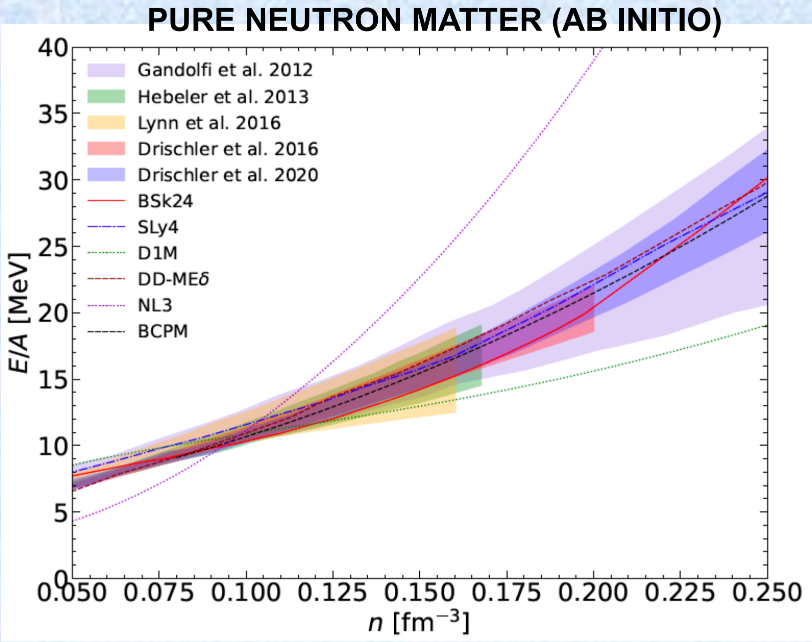
flat non-informative prior
→ large parameter space

nuclear masses
(AME)

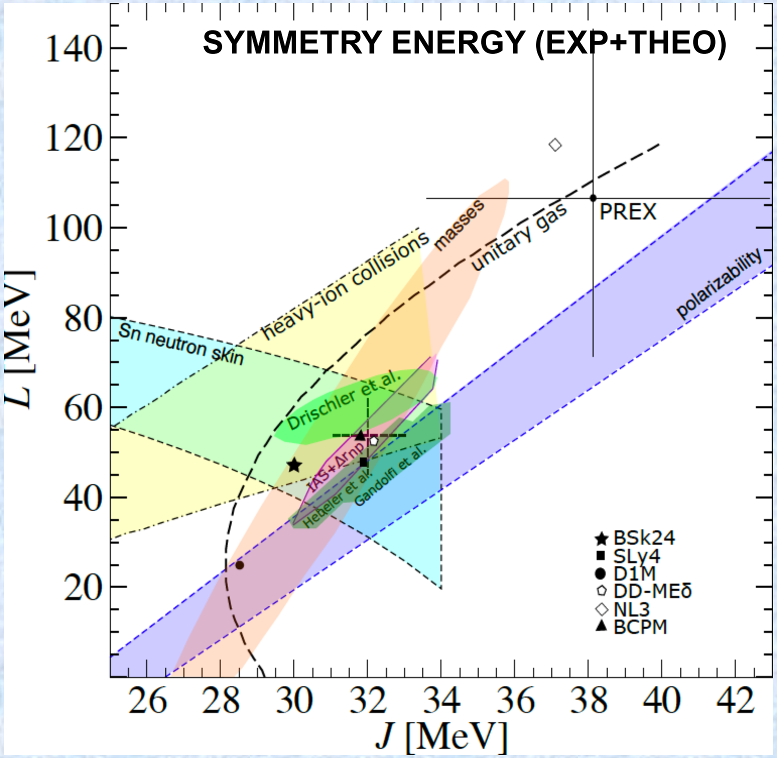
Low-Density filters
→ ab-initio (EFT)

High-Density filters
→ causality, stability,
$M_{\mathrm{NS,max}}$ (+ NICER, GW)

Constraints from nuclear physics



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



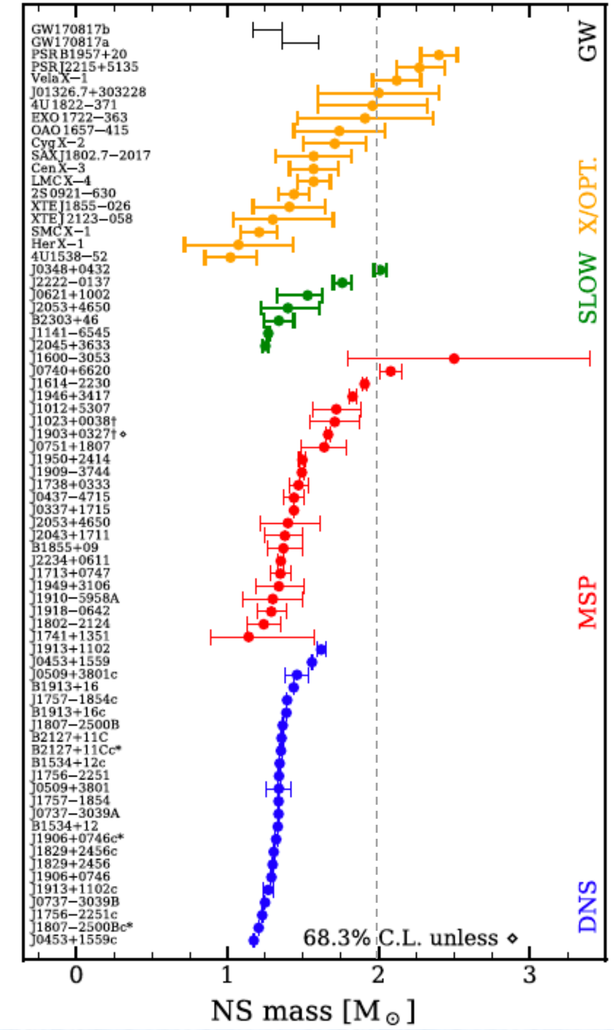
Gulminelli&Fantina, Nucl. Phys. News 31, 9 (2021);
Fantina&Gulminelli, J.Phys.Conf.Ser. 2586, 012112 (2023)

→ 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)

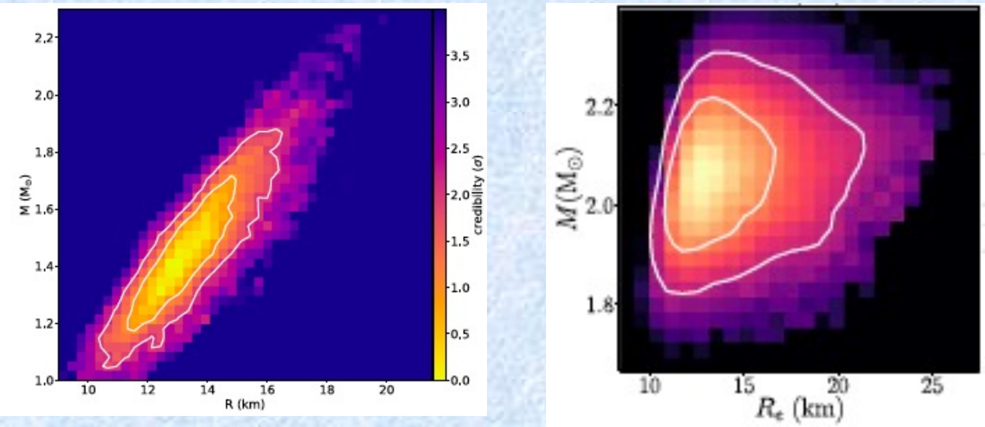
Constraints from astrophysics

MASSES



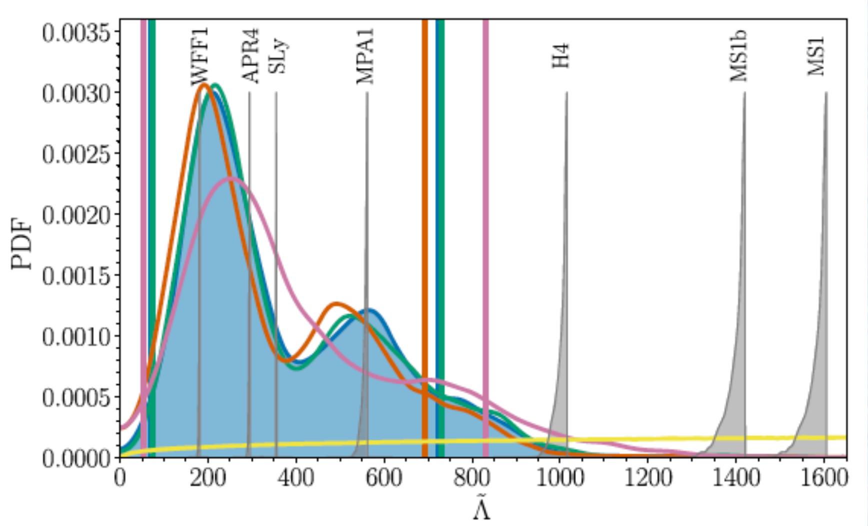
Suleiman et al., PRC 104, 015801 (2021)

RADII



Miller et al., ApJL 887, L24 (2019); ApJL 918, L28 (2021); see also Riley et al., ApJL 2019, 2021

TIDAL DEFORMABILITY



Abbott et al., PRX 9, 011001 (2019)

<u>NB</u>: most are inferred, not “direct” observations, so model dependent !

Outline

- Introduction:
  - Neutron-star (NS) properties and equation of state (EoS) modelling and constraints

- Selected results in :
  - Catalysed ("cold") NSs (*T* = 0, full equilibrium)

    → EoS and NS observables

  - Proto-neutron-star (PNS) crust (*T* ≠ 0, beta equilibrium)

    → multi-component plasma, impurity parameter

- Conclusions and open questions

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

Catalysed NSs: crustal properties

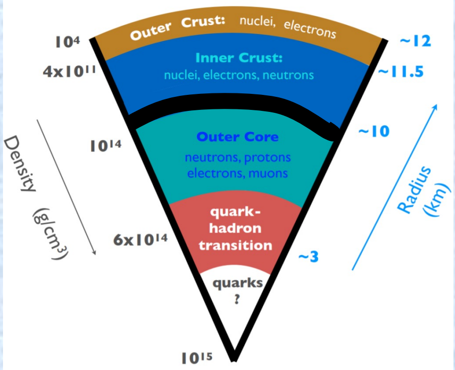
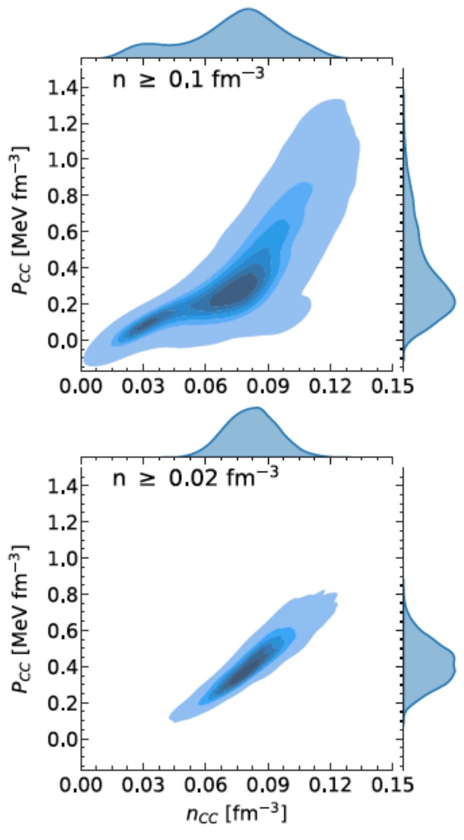
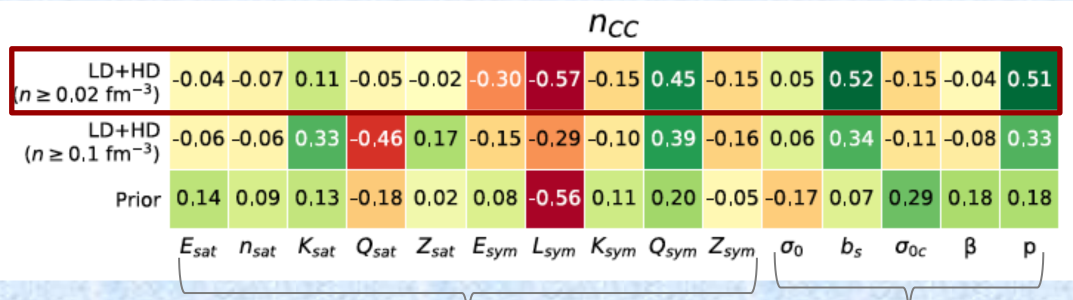


Image Credit: 3G Science White Paper

CRUST-CORE TRANSITION

Meta-model + CLDM for crust





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

surface

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

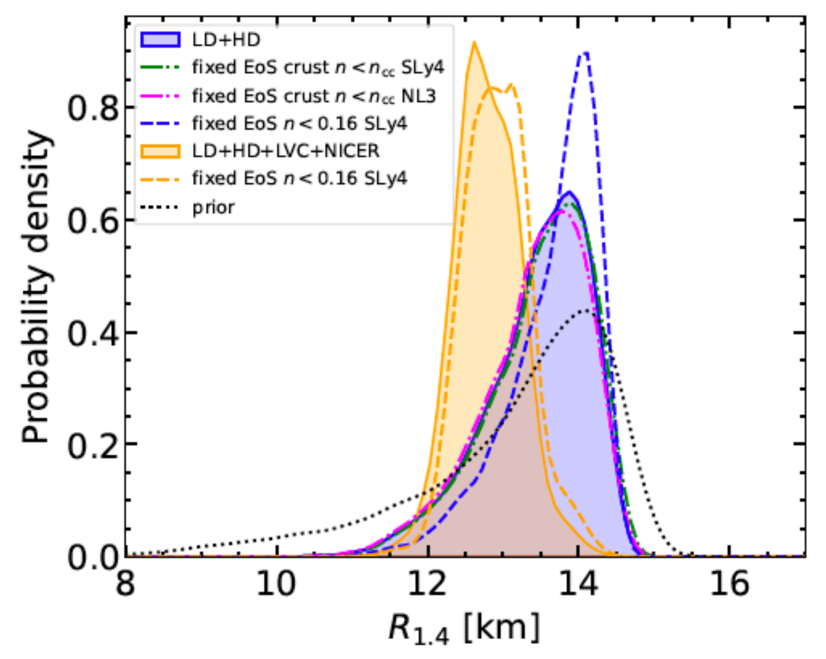
→ importance of
low-density EoS

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

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

Effect of the (non-unified) crust

RADIUS



Davis, Dinh Thi, Fantina, et al., A&A 687, A44 (2024)

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

(available for LIGO-Virgo-KAGRA collab. and publicly available on Zenodo)

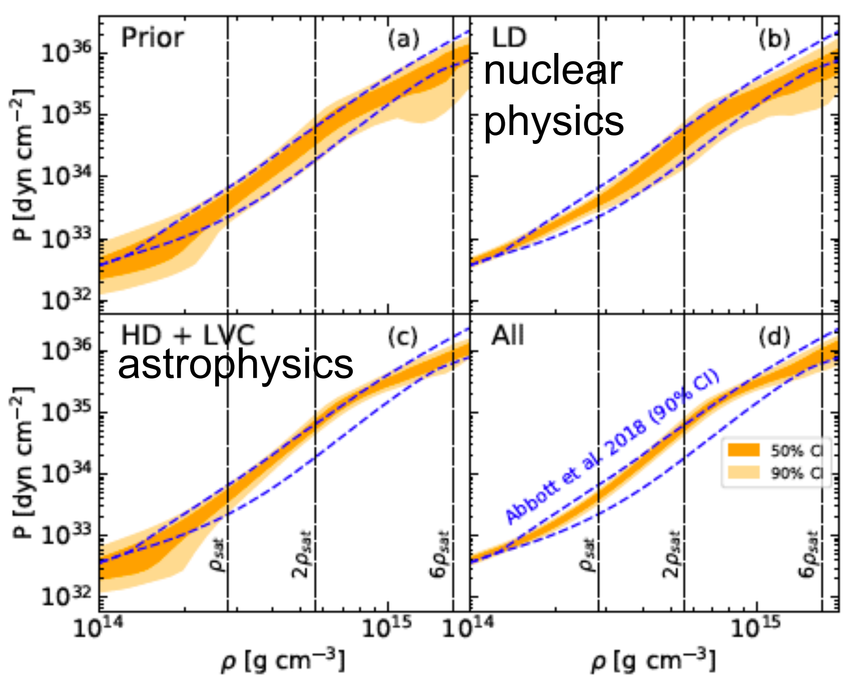
→ use of unique crust does not change much averages (~ few %)
→ ok for current GW detectors, but next generation ?
(see also Gamba et al., Class. Quant. Grav. 37, 025008 (2020) → ~ 3%)

→ underestimation of uncertainties in non-consistent approach

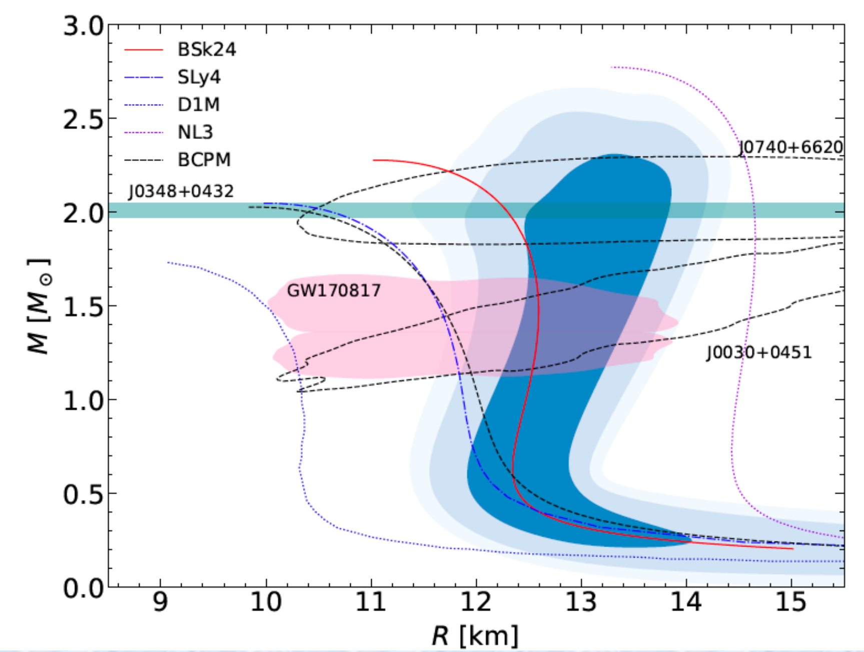
→ quantitative error bars on NS properties can be addressed

`CUTER` = Crust Unified Tool for Equation-of-state Reconstruction

Catalysed NSs: observables



Dinh Thi et al., Universe 7, 373 (2021);
Dinh Thi et al., A&A 654, A114 (2021)



Gulminelli & Fantina, NPN 31, 9 (2021);
Fantina & Gulminelli, J.Phys. Conf.Ser. 2596, 012112 (2023)

→ posterior compatible with observations, but: some popular models are not !

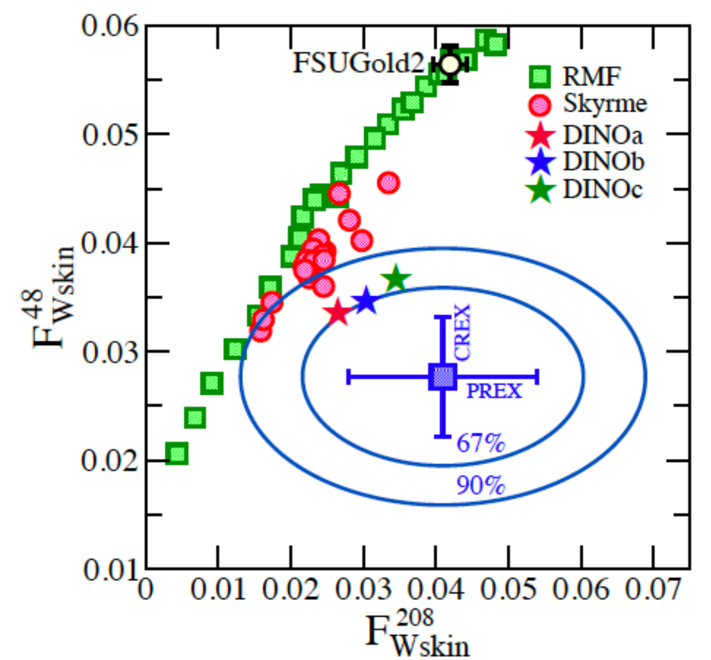
→ nucleonic hp compatible with observations → observations not yet enough constraining!

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

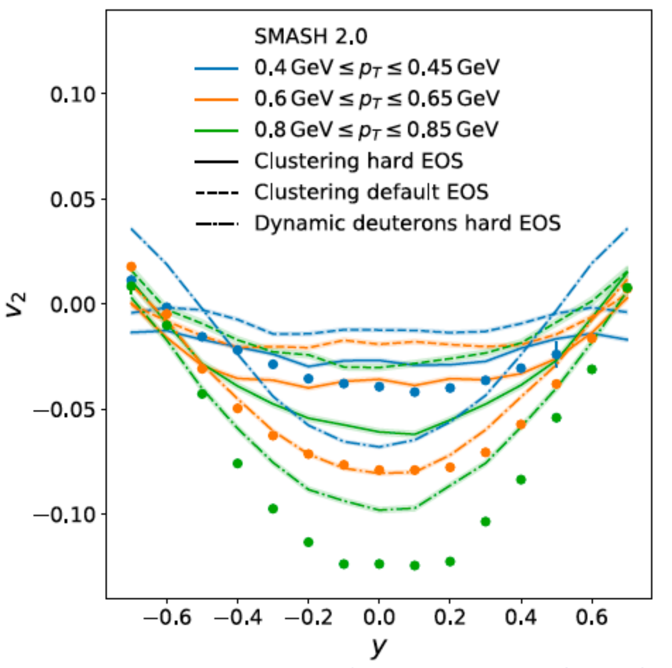
N.B.: Many works within Bayesian analysis trying to constrain NEP
see also Beznogov & Raduta, PRC (2023); Ghosh et al., EPJA (2022); Char et al., PRD (2023); Imam et al., PRD (2024);
Zhu et al., ApJ (2023); Huang et al., arXiv:2303.17518, …. + see talks on Mon, Wed, session H

How to discriminate models? (exp)

- ***Nuclear physics (theory + experiments)*** → information up to ~ 1.5 – 2 n_{sat}
  - *reduced error bar in neutron skin measurements (e.g. PREX/CREX)*
    → constraints on low-order parameters in isospin sector
  - *constraints at high density e.g. HADES collaboration (transport model vs data)*
    → constraints on higher order parameters



Reed et al., arXiv:2305.19376 (2023)



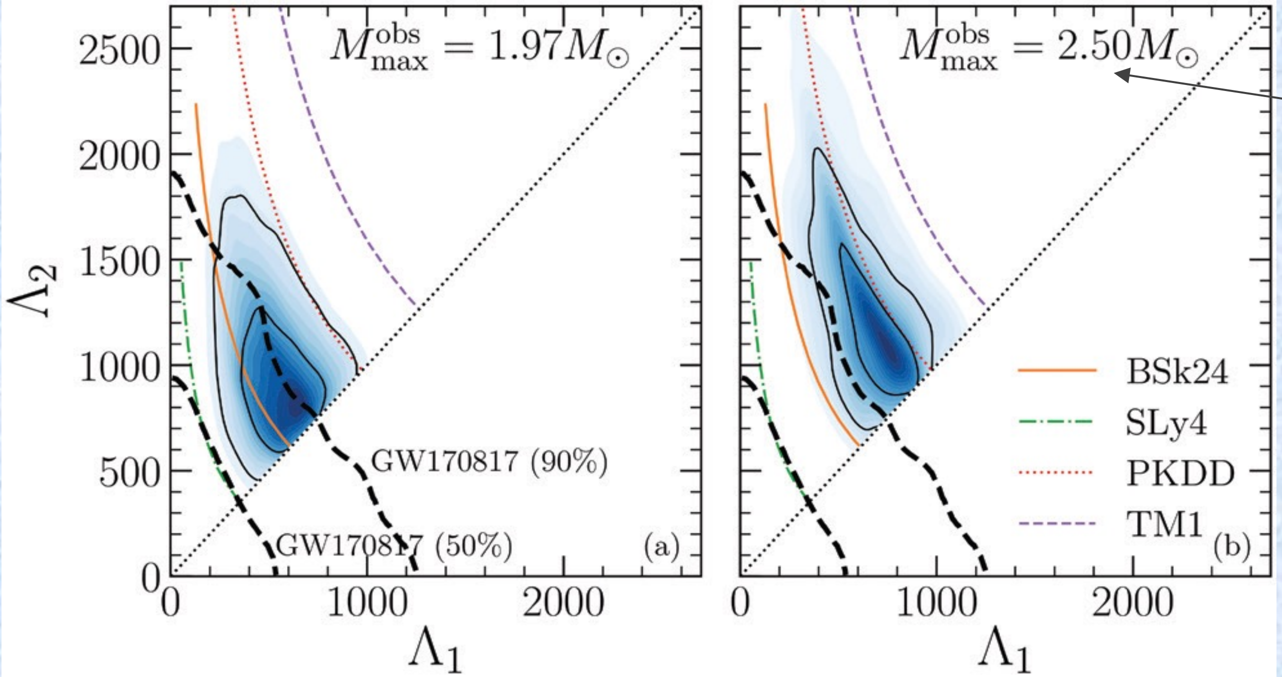
Mohs et al., PRC 105, 034906 (2022)

→ Better extrapolation of models

How to discriminate models ? (astro 1)

❖ ***Astrophysical observations (multi-messenger)***

➢ “Smoking gun” observation



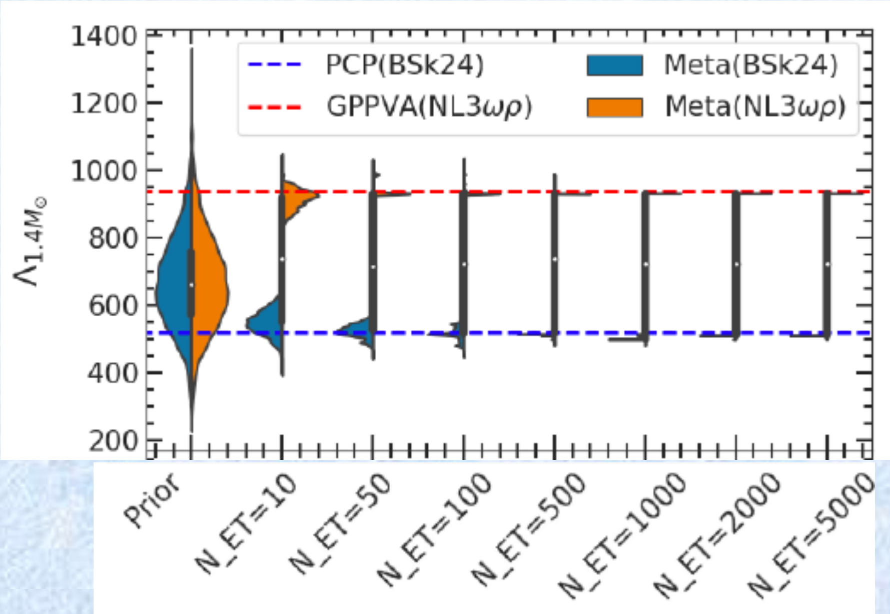
GW190426 ?

Gulminelli & Fantina, Nucl. Phys. News 31, 2 (2021); T. Carreau, PhD Thesis (2020)

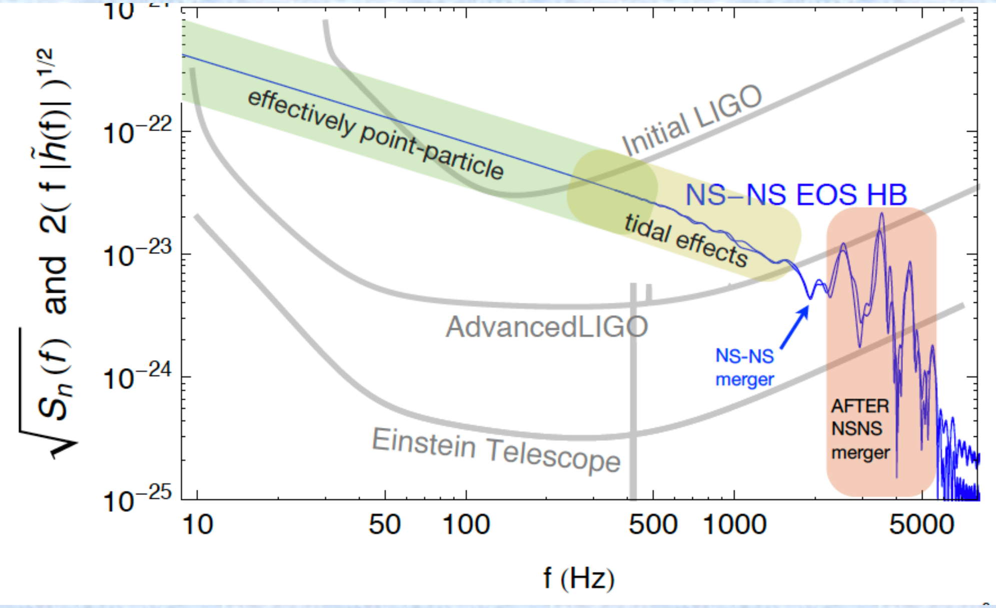
→ posterior (nucleonic matter) compatible with observations
but: if $M_{\rm max}$ ~ 2.5 $M_{\rm sun}$ → challenge for nucleonic hypothesis ! → exotica !
→ Nucleonic hp can be used as null hp

How to discriminate models? (astro 2)

- ➢ more and more precise data (e.g. M, R, Λ, ...)
- ➢ more sensitive detectors → new generation (ET, CE) → post-merger



Iacovelli et al., PRD 2023



Read, CGWAS lecture (2015)

- ➢ More reliable prediction / interpretation of astrophysical observations
- ➢ Better knowledge of dense matter in compact stars :
  Phase transition to deconfined matter (quarks, …) ?
- ➢ Astrophysical sites of nucleosynthesis ?

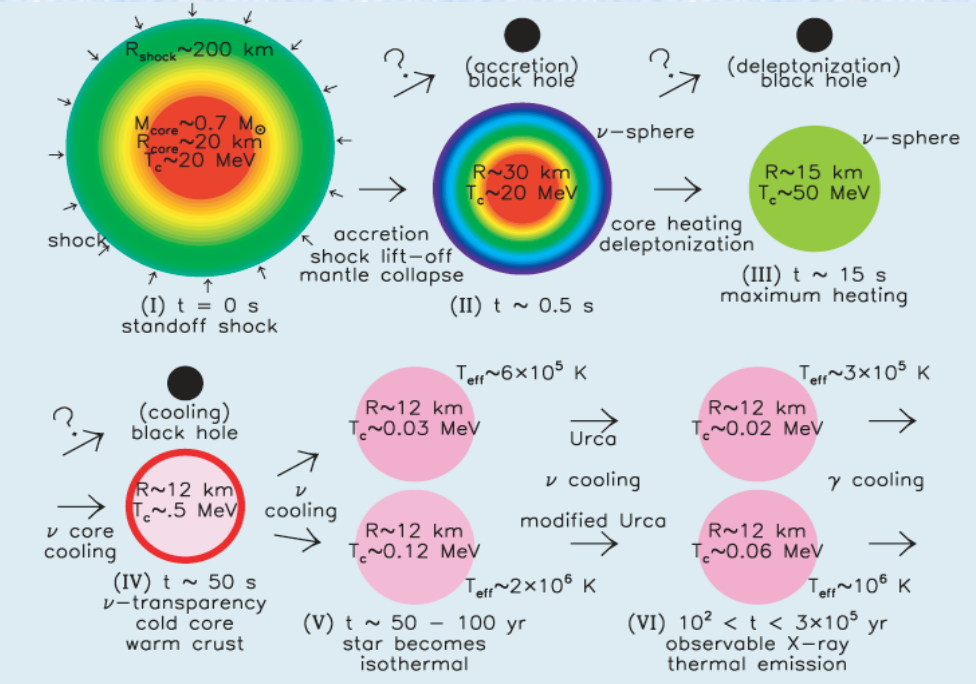
Outline

- Introduction:
  - Neutron-star (NS) properties and equation of state (EoS) modelling and constraints
- Selected results in :
  - Catalysed (“cold”) NSs (T = 0, full equilibrium)
    → EoS and NS observables
  - Proto-neutron-star (PNS) crust ($T \neq 0$, beta equilibrium)
    → multi-component plasma, impurity parameter
- Conclusions and open questions

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

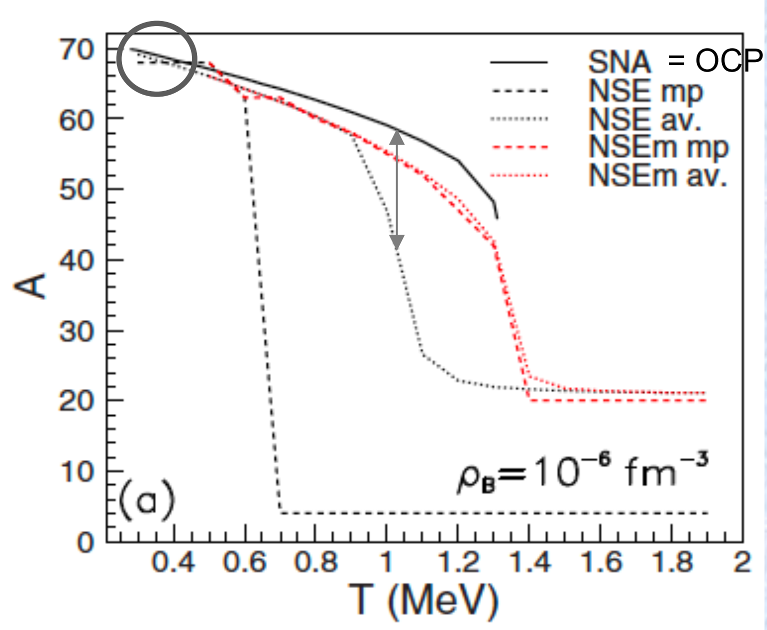
Proto-NS (finite temperature)

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 $T > T_m$

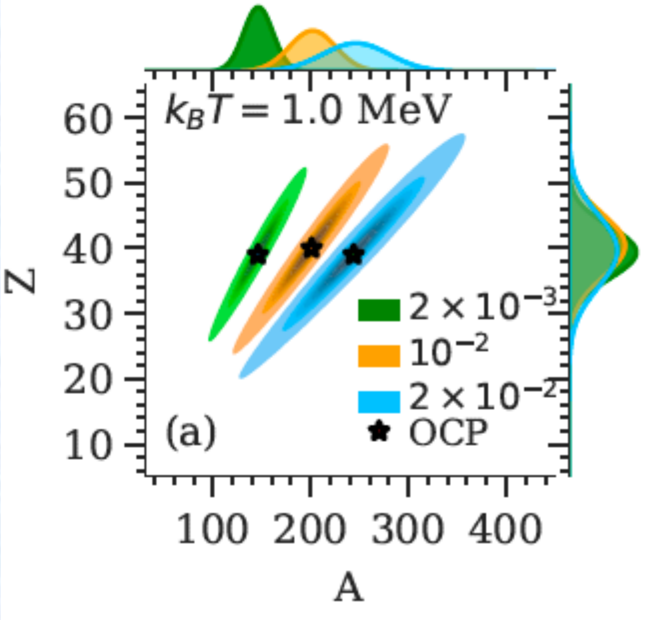
(e.g. Goriely et al., A&A 531, A78 (2011)) or other reactions possible below T_m ?

(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 !

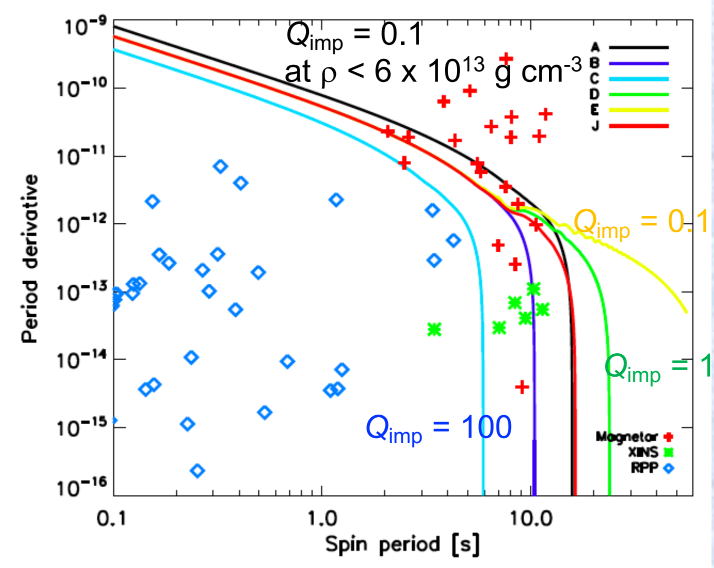


Dinh Thi et al., A&A 677, A174 (2023)
see also Fantina et al., A&A 633, A149 (2020);
Carreau et al., A&A 640, A77 (2021)

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



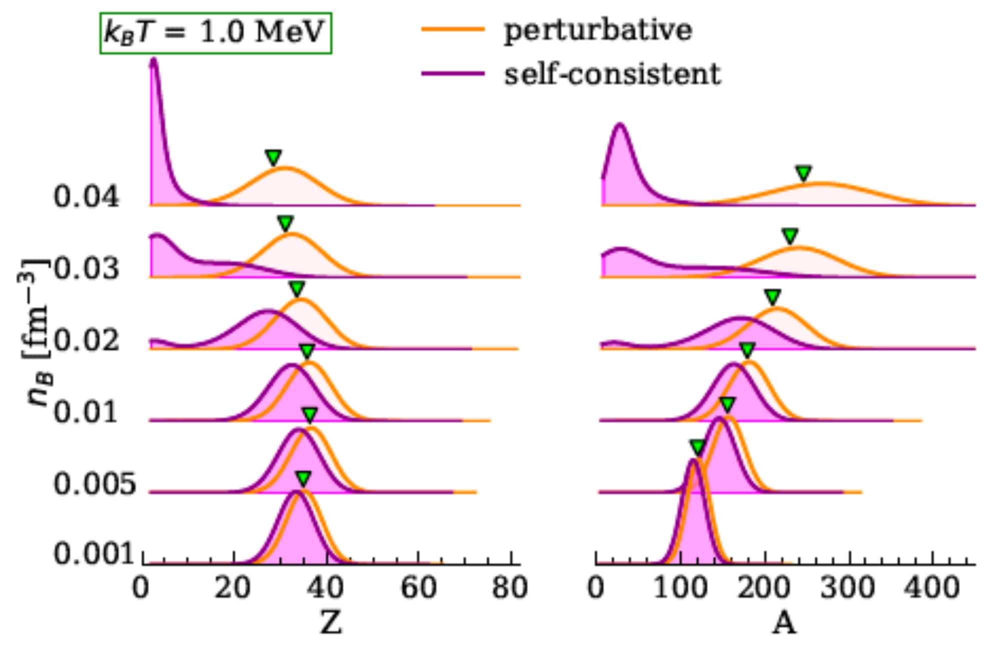
Pons et al., Nature Phys., 9, 431 (2013)
(see also Viganò et al., MNRAS 2013)

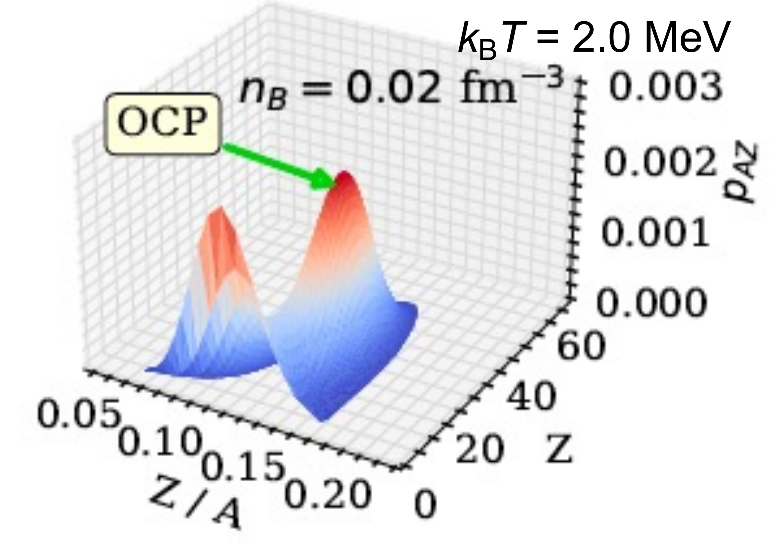
---

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)

PNS crust (MCP): composition

MM + CLDM





Dinh Thi et al., A&A 677, A174 (2023) – CLDM with BSk24

- OCP less reliable at higher density and temperature
  → (self-consistent) MCP
- appearance of bi-modal distribution → light clusters !
  → importance of light cluster already highlighted, e.g. Typel et al., PRC 2010; Hempel et al., PRC 2011

(P)NS crust: impurities

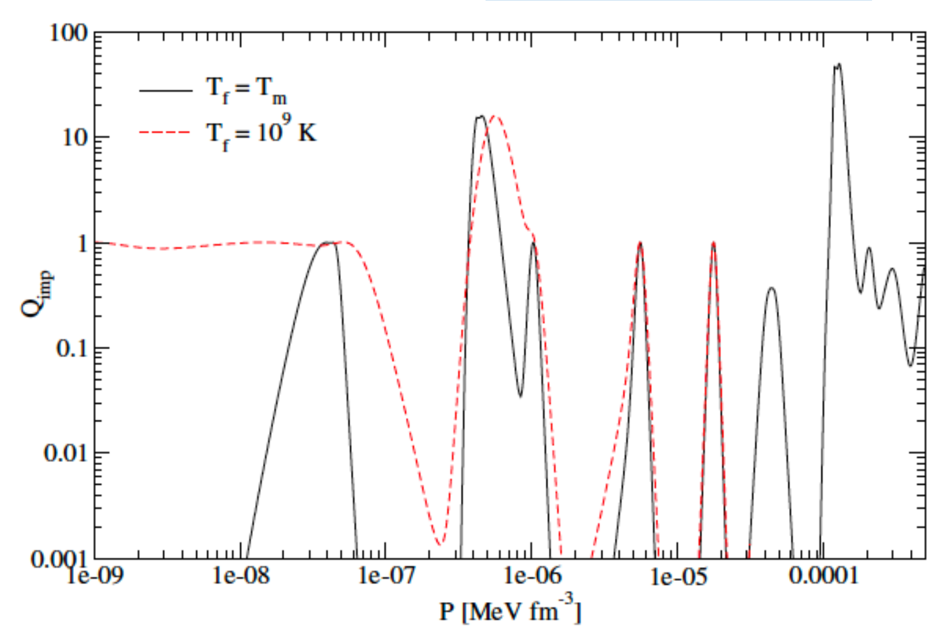
✓ Self-consistent calculations of $Q_{\rm imp} = \langle Z^2 \rangle - \langle Z \rangle^2$

Outer crust

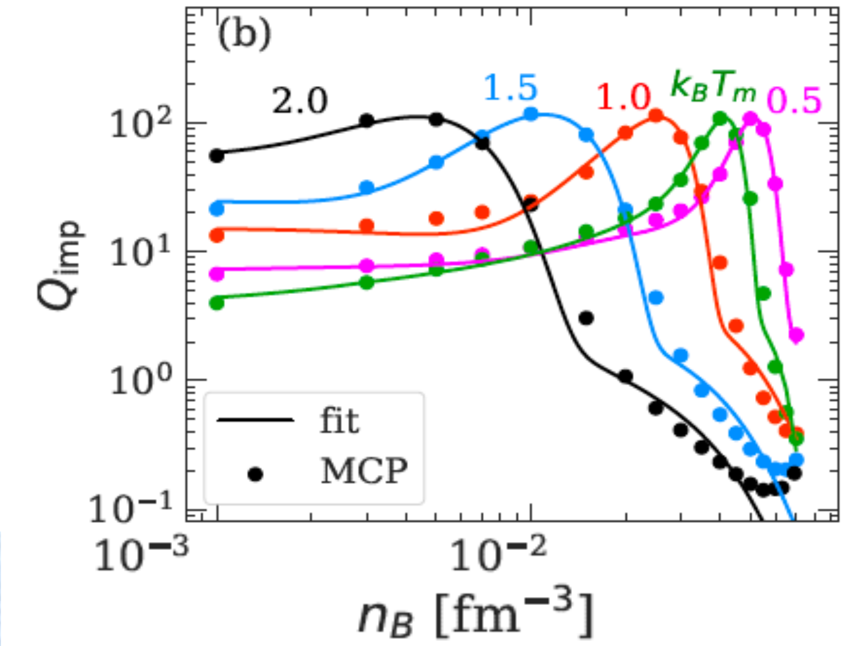
HFB-24 masses

MM + CLDM

Inner crust



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

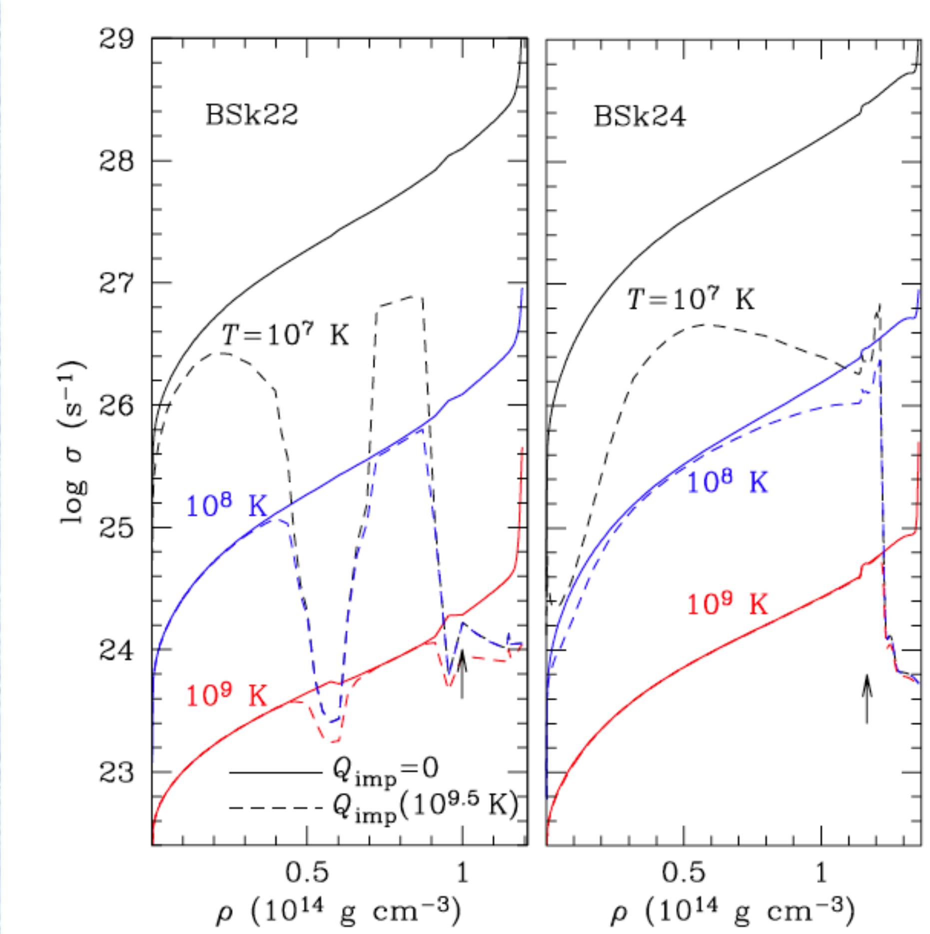


Dinh Thi et al., A&A 677, A174 (2023); see also Carreau et al., A&A 640, A77 (2020) + data on CDS

- ➢ consistent calculations of $Q_{\rm imp}$ throughout the crust (data available)

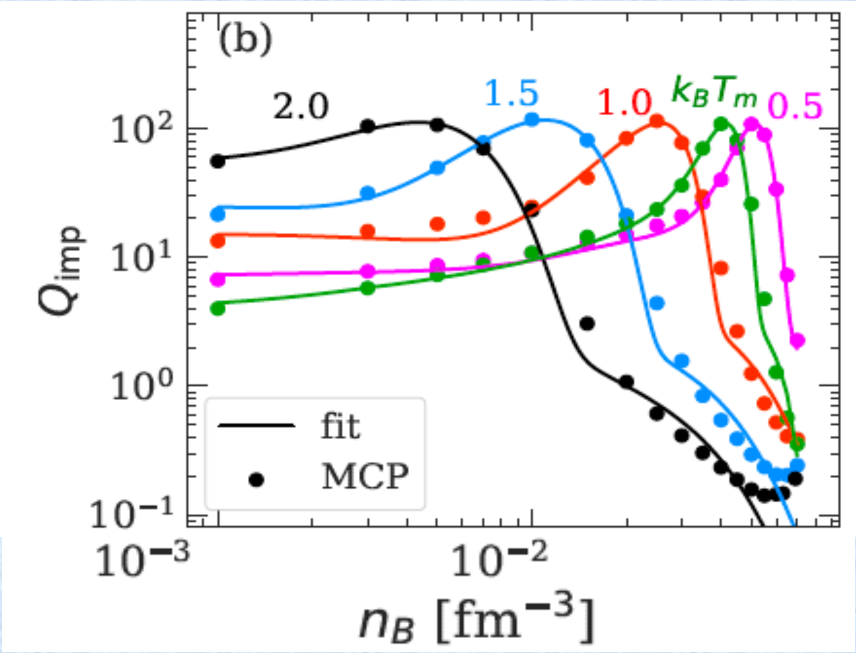
(P)NS crust: impurities

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



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

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 $Q_{\rm imp}$ throughout the crust
  → impact on transport coefficient/properties

Conclusions & open questions

❖ Nuclear inputs needed for neutron-star modelling → extrapolation of data / theory

❖ Nuclear physics + astrophysics → constraints on EoS but still hard to discriminate

- ✓ need of (microscopic) reliable theoretical model when no data
- ✓ need of experimental data to calibrate the models
- ✓ need of (more precise / numerous) astrophysical observations

❖ Importance of MCP treatment at finite temperature

Conclusions & open questions

- Nuclear inputs needed for neutron-star modelling → extrapolation of data / theory
- Nuclear physics + astrophysics → constraints on EoS but still hard to discriminate
  - ✓ need of (microscopic) reliable theoretical model when no data
  - ✓ need of experimental data to calibrate the models
  - ✓ need of (more precise / numerous) astrophysical observations
- Importance of MCP treatment at finite temperature

- Extrapolation from raw data → **model dependence of the constraints**
- Lab. exper. 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) ?**
- Uncertainties in high-density EoS → **blurring of different effects ?**
- Astro simulations vs microphysics inputs → **uncertainties**, **consistency of inputs** and relative **effects of microphysics inputs in astro modelling** ?
  → systematic studies / bayesian analysis needed

Thank you

NASA - X-ray: CXC, Optical: STSCI, Infrared: JP