Neutron-star crust modelling and unified equations of state (ongoing projects)

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in collabaration with LPC Caen, LUTh-Meudon, IAA-ULB, Univ. Montreal, CAMK Warsow, …

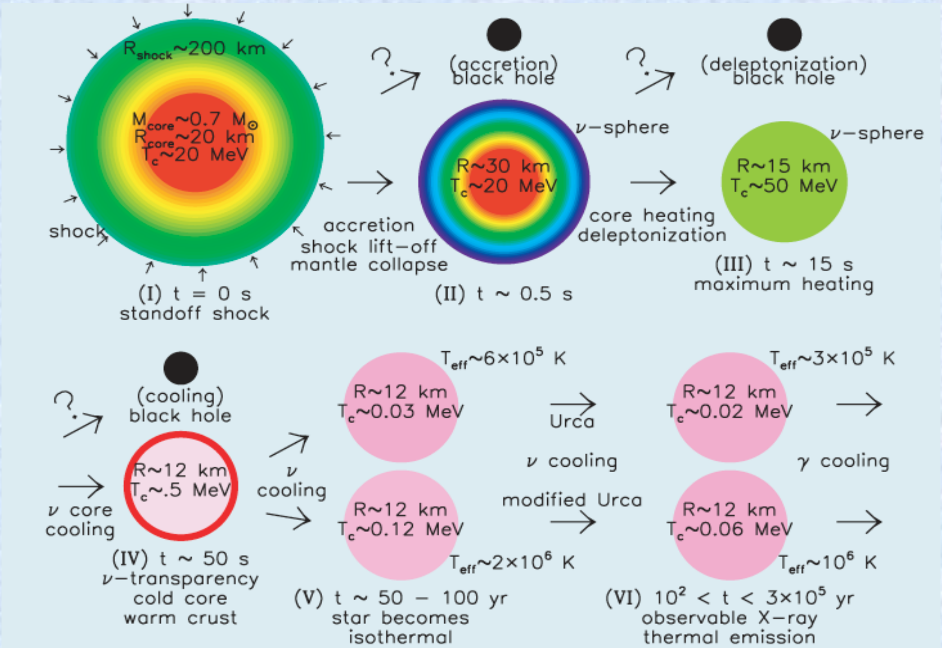
MAC meeting, 30-31 May 2024
IJCLab, Orsay, France

Outline

- Selected (ongoing) projects + outlooks
  - *Catalysed NSs* (T = 0, full equilibrium) → see P.J. Davis' talk
  - *Accreting NSs* (T = 0, crust out of equilibrium)
  - *Proto-neutron-star (PNS)* crust ($T \neq 0$, beta equilibrium)
  - *Supernova electron-capture rates*

NS (isolated): formation

after shock formation



Lattimer & Prakash, Science 304, 536 (2004)

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

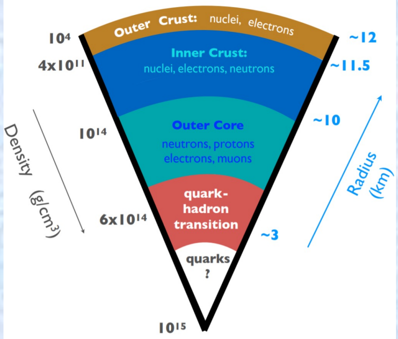


Image Credit: 3G Science White Paper

but: real picture can differ from cold catalysed one

⁎ Accretion of matter from companion (→ $\boldsymbol{P(n_B, Y_q)}$, *not full equilibrium*)

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

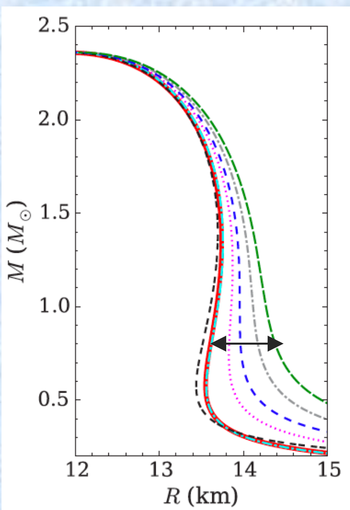
N.B.: *"General purpose" EoSs* $\boldsymbol{P(n_B, T, Y_q)}$ *& B effects not addressed here*

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

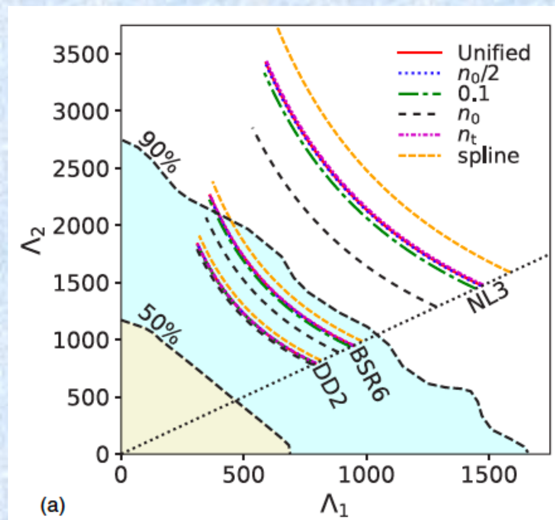
Why a <u>unified</u> treatment ?

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

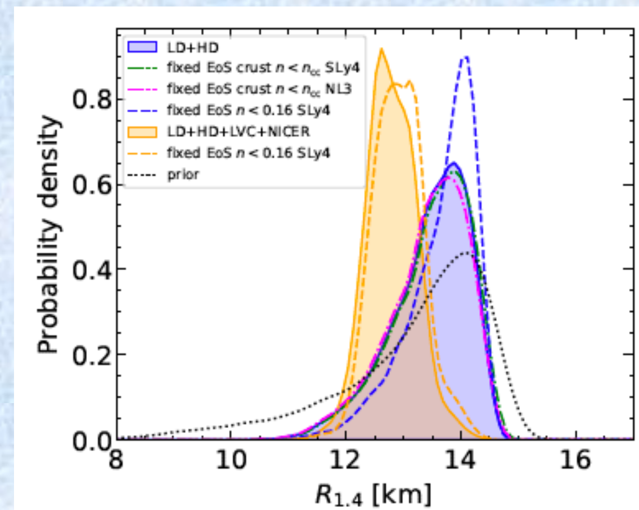
- Challenging because of wide range of thermodynamic conditions
- Challenging because different states of matter
- But: <u>essential to avoid spurious non-physical effects in numerical modelling</u>



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



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



Davis et al, A&A in press → P. Davis' talk

Aim: provide thermodynamically consistent and unified EoSs for astro modelling & inference analyses

EoS models used in our works

BSk + ETFSI

- **HFB mass model for outer crust**
- **ETFSI for inner crust**
- **Brussels-Montreal (BSk) EDFs**

MM + CLDM

- **CLDM for outer+inner crust**
- **meta-model (MM) for core**
  + also for bulk energy of ion

Unified EoSs

✓ Accurately calibrated Skyrme EDFs
  → study specific model dependence
  → benchmark calculations
✓ More microscopic
✗ No parameter-space exploration

➢ Ensemble of consistent nuclear inputs for astro models (e.g. *EoS, M(R), Λ(M),* but also nucl. masses, microscopic quantities like pairing gaps, *m**, etc.)

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Unified EoSs

✓ Accurately calibrated Skyrme EDFs
  → study specific model dependence
  → benchmark calculations
✓ More microscopic
✗ No parameter-space exploration

✓ Flexible, faster computation
  → Parameter-space exploration
  → Bayes analysis
✓ Multi-component plasma (MCP)
✗ Less microscopic

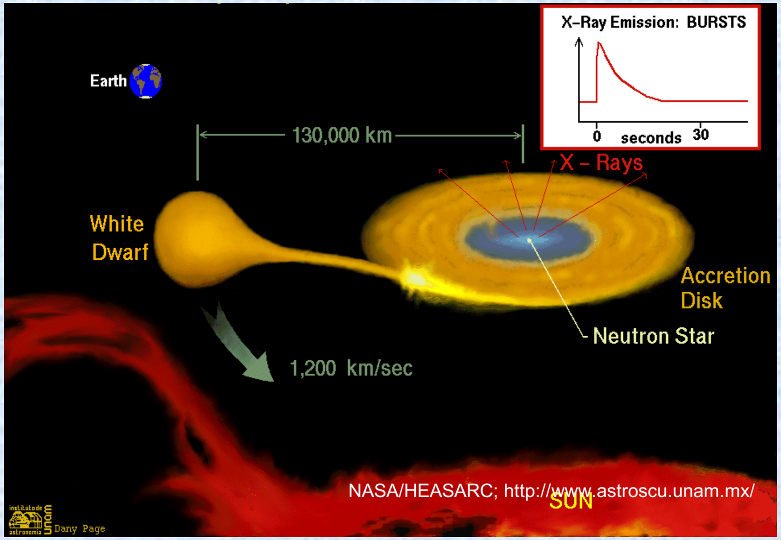
- MCP distributions *(e.g. PNS crusts)*
- Estimation of uncertainties in astro predictions/inference *(e.g. Bayesian)*

$$P(\mathbf{X}|\mathbf{c}) = \mathcal{N} P_{\rm prior}(\mathbf{X}) \prod_k P(c_k|\mathbf{X})$$

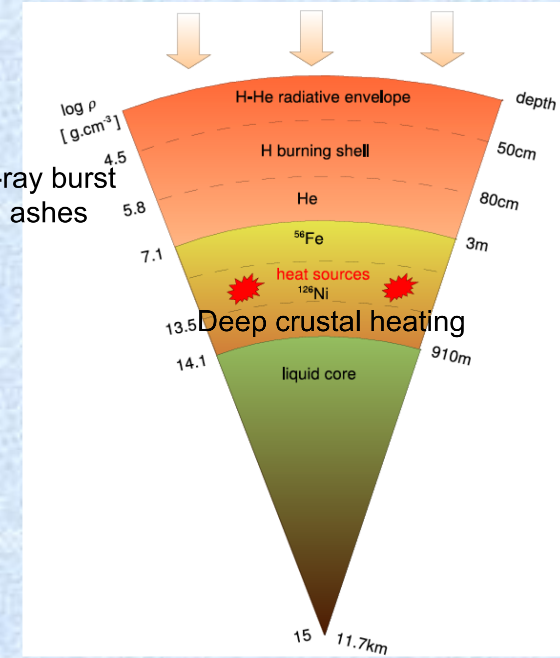
X = nucl. param.

$\prod_k P(c_k|\mathbf{X})$: nuclear+astro constraints

Accreting NS (Low-mass X-ray binary)



e.g. Soft X-ray transient (SXT)



Chamel & Haensel 2008

✧ **Electron captures + neutron emission** (inner crust):

$$(A,Z) + e^- \rightarrow (A, Z-1) + \nu_e$$

$$(A,Z-1) + e^- \rightarrow (A-k, Z-2) + kn + \nu_e + Q_c$$

✧ **Pycnonuclear** reactions:

$$(A,Z) + (A,Z) \rightarrow (2A, 2Z) + Q_p$$

✓ **matter off-equilibrium**
✓ reactions possible
→ **energy reservoir**
→ **deep crustal heating**

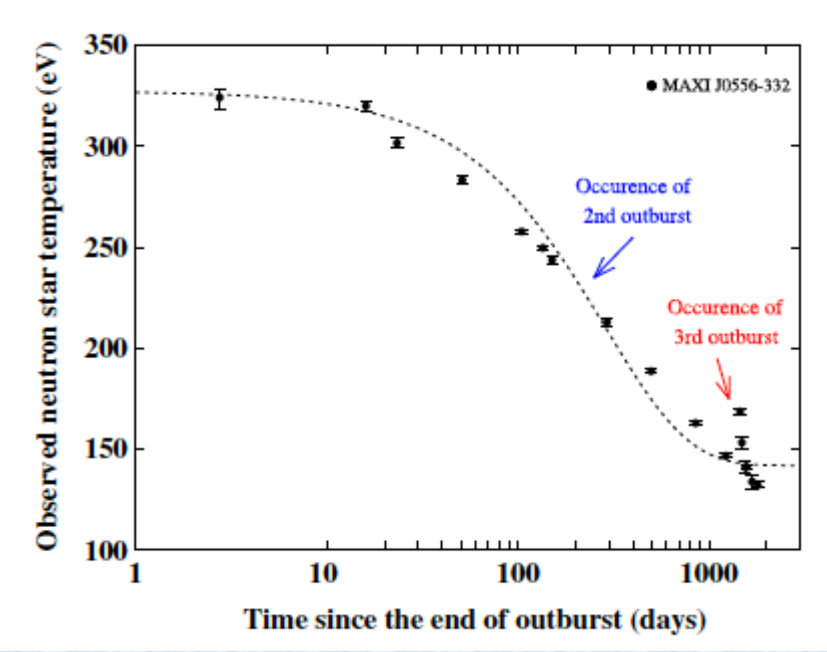
N.B.: uncertainties in pycno reactions → we assume it occurs when $Z = Z_{min} = 8$

see e.g. Chamel & Haensel, Living Rev. Relativ. 11, 10 (2008); Meisel et al., J. Phys. G, 45, 093001 (2018); Blaschke & Chamel, ASSL 457, 337 (2018); Haensel & Zdunik, A&A 1990, 2003, 2008

Accreting NS (SXT)

"**Deep crustal heating**" can explain thermal radiation in SXTs in quiescence

<u>but</u> : exceptions ! → *shallow heating* (additional sources in shallow layers)



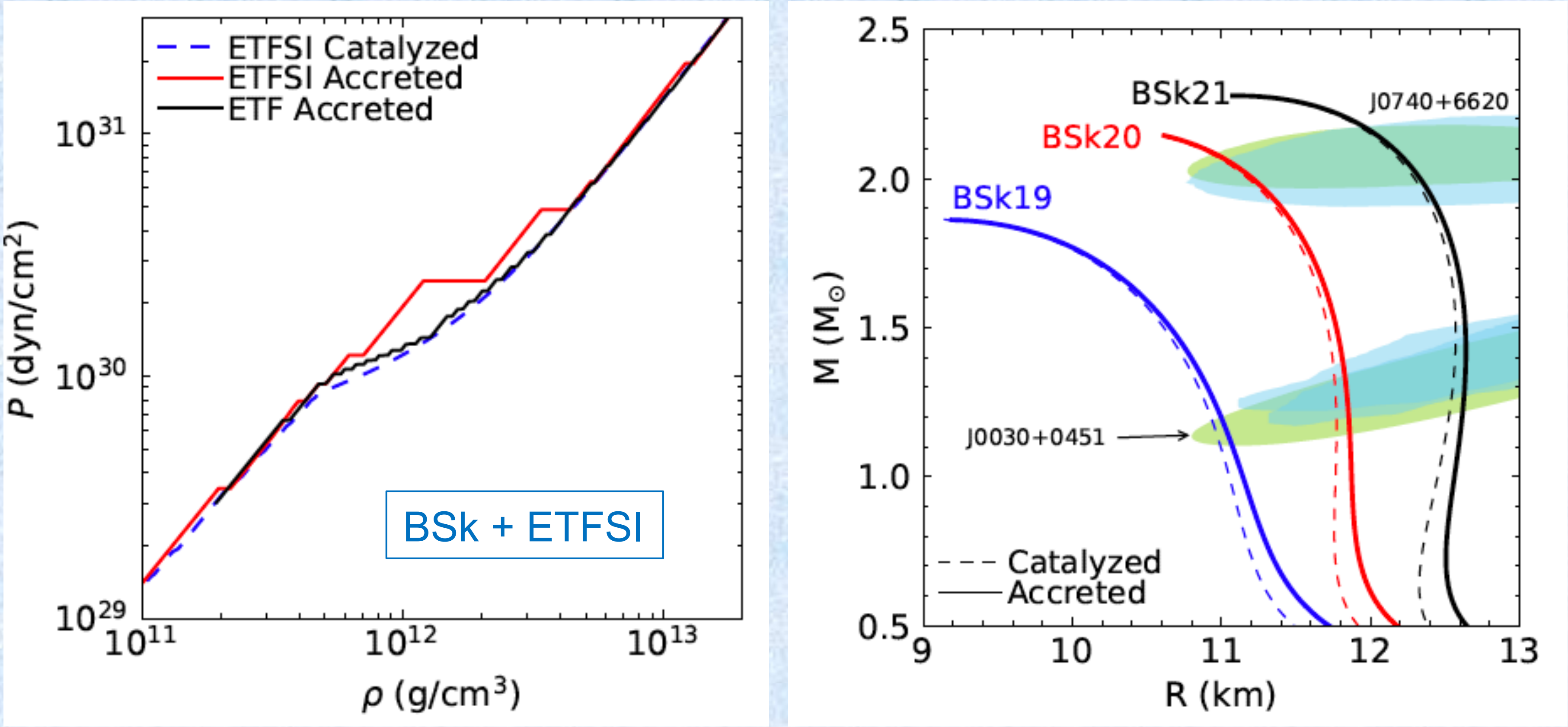
Wijnands et al., J. Astrophy. Astr. 38, 49 (2017)

Inputs to model relaxation / cooling :

- **Composition**
- **EoS**
- **Heat sources**
  → amount of heat and location

for a review: Chamel & Haensel, Living Rev. Relativ. 11, 10 (2008); Meisel et al., J. Phys. G, 45, 093001 (2018); Blaschke & Chamel, ASSL 457, 337 (2018)

Accreting NS crusts: EoS

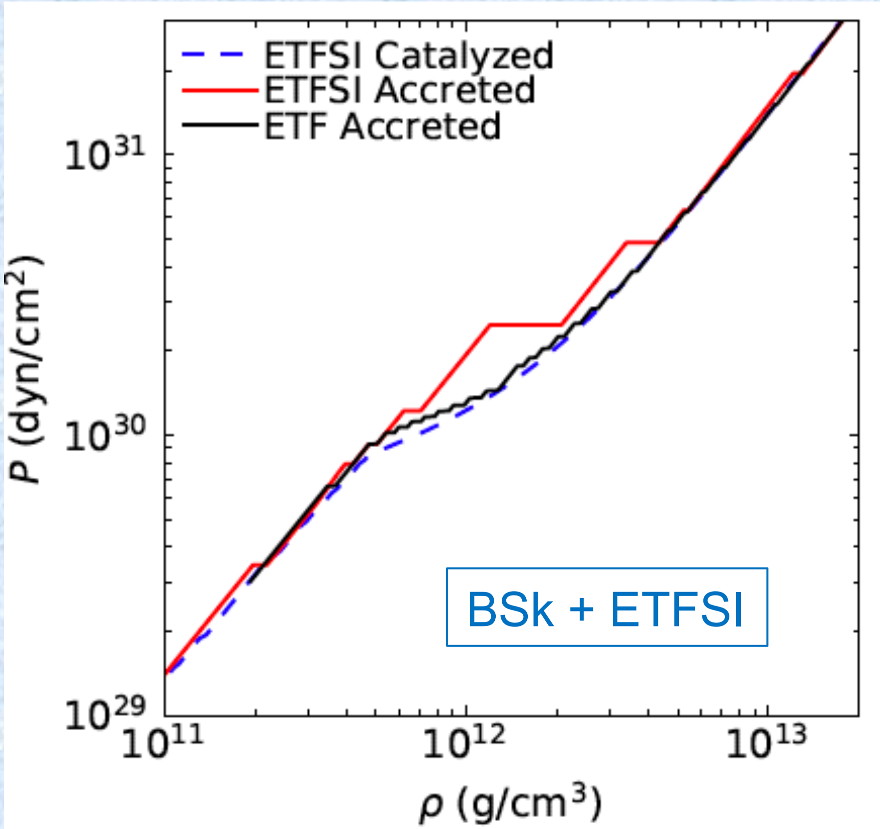


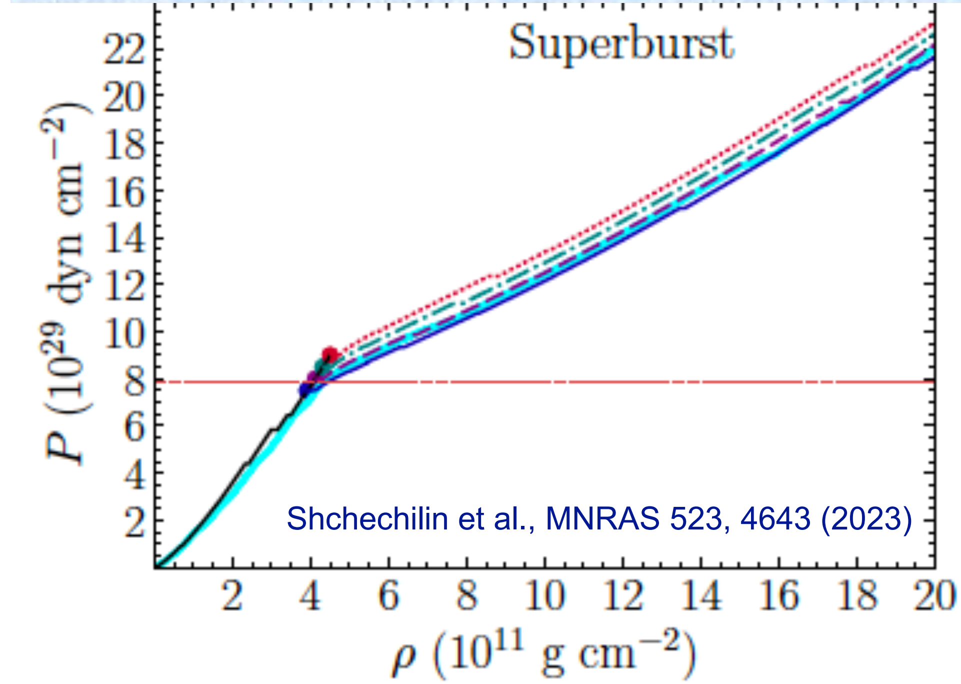
Fantina et al., A&A 665, A74 (2022)

➢ Accreting crust EoS stiffer than catalysed one → larger radii

✗ but: difference still smaller than observation uncertainties

Accreting NS crusts: EoS





- ➢ Accreting crust EoS stiffer than catalysed one → larger radii
- ✗ but: difference still smaller than observation uncertainties
- ✗ EoS closer to catalysed EoS if *n* diffusion (Gusakov & Chugunov 2020; Shchechilin et al. 2023)
  → to be investigated (e.g. Allard&Chamel, PRL 2024)

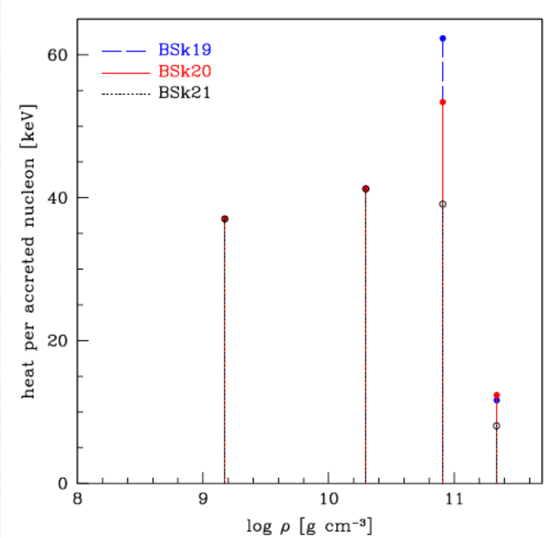
Accreting NS crusts: heat sources

heat sources

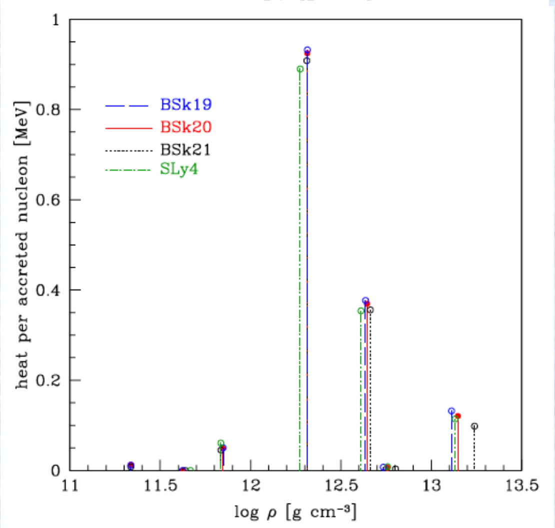
BSk + ETFSI

total heat

Outer crust (starting from ^{56}Fe)



Inner crust

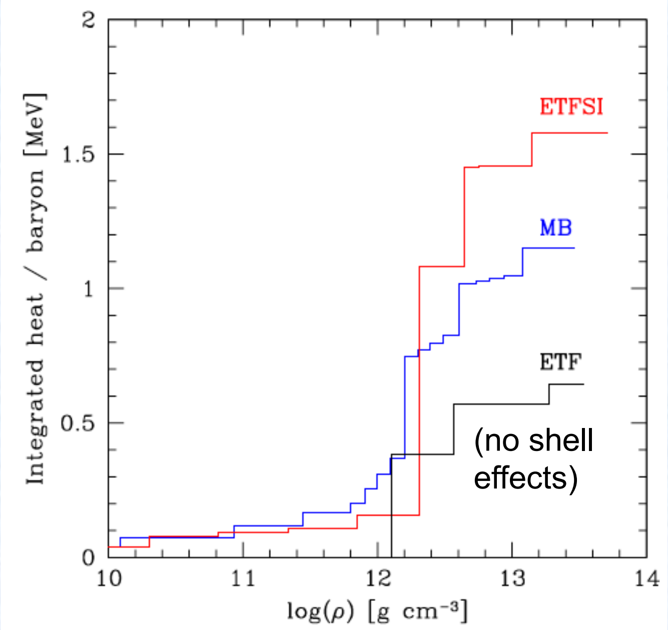


Fantina et al., A&A 620, A105 (2018)

- ➢ Importance of shell effects
- ➢ Q_{tot} = ~1.5–1.6 MeV/nucl.
- ➢ Pycnonuclear main sources in inner crust

✗ but: OCP (^{56}Fe)

- ✳ Q_{tot} comparable with reaction networks
- ✳ Heat for different ashes higher (Chamel, Fantina, et al. 2020)



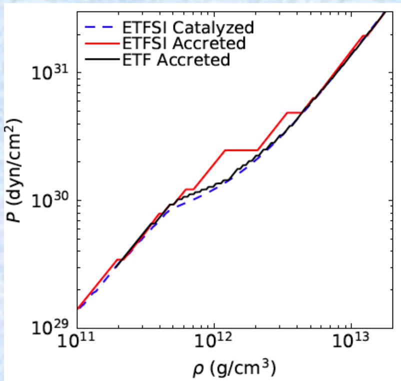
→ MCP ?

(MCP models exist, e.g. Lau et al. 2018 but only for outer / low-density inner crust)

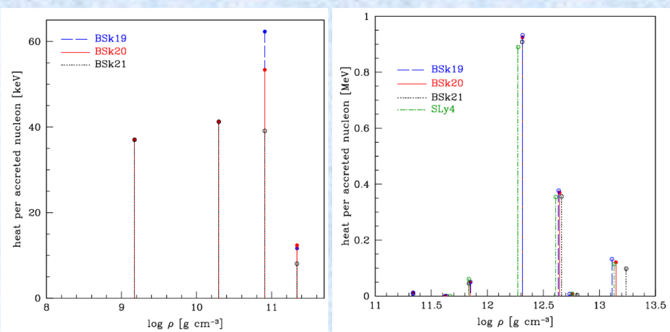
N.B.: heat sources also in magnetar's crusts (Chamel, Fantina, et al. 2021; Chamel & Fantina 2022)

Accreting NSs: thermal evolution

BSk + ETFSI



EoS + heat sources



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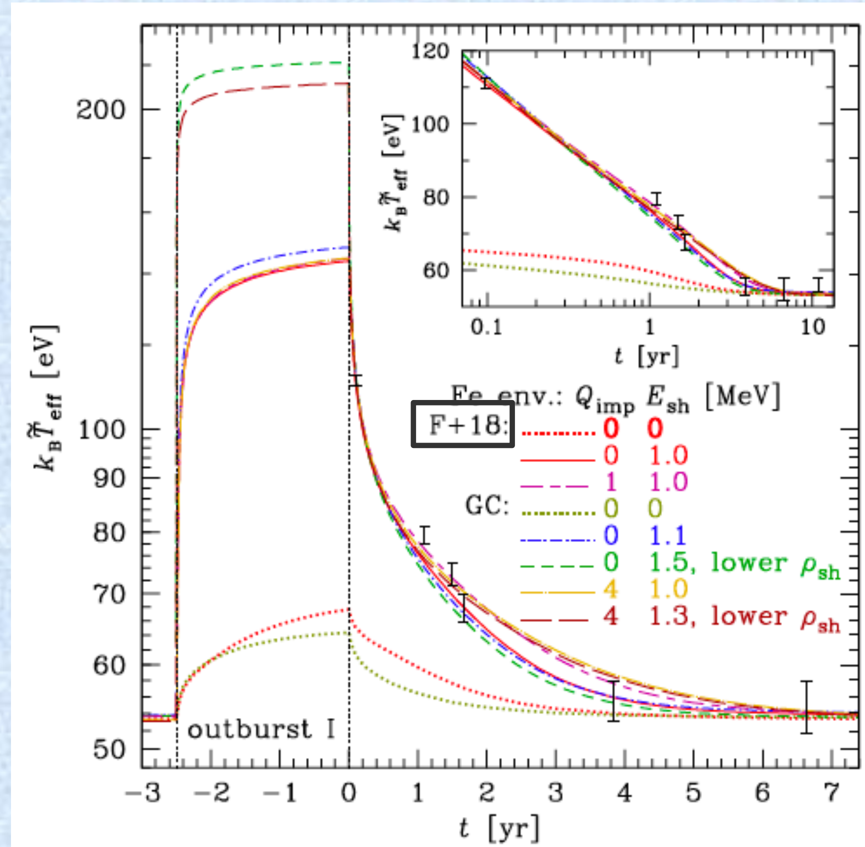


Potekhin et al., MNRAS 522, 4830 (2023)

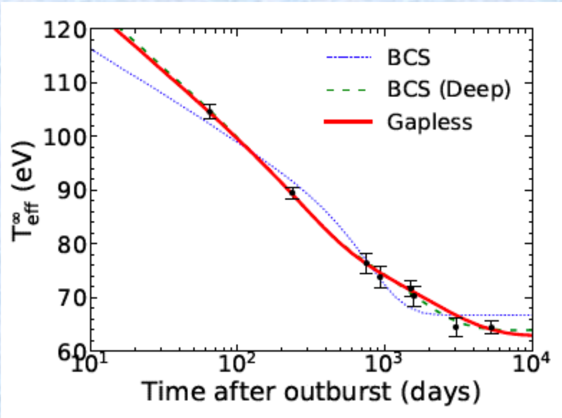
- ➢ Observations can be reproduced by models (with tuning)
- ✗ but: difficult to discriminate models
  → other parameters (Q_{imp}, shallow heating, …) play a role

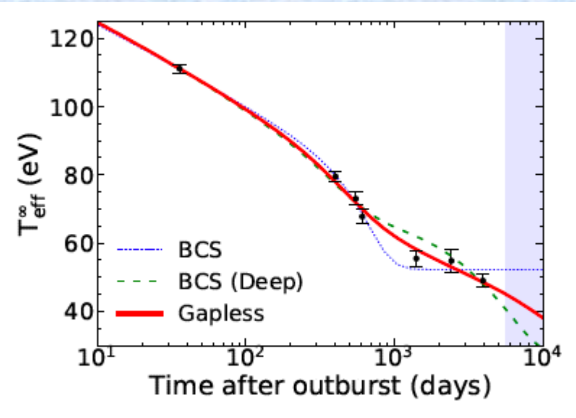
Accreting NSs: outlooks

Unified EoS + heat released
data publicly available (tables on CDS, Zenodo* for magnetar's crusts)

- Accreted crust ≠ catalysed crust → importance of nuclear shell effect
  - Inclusion of neutron diffusion ? (Gusakov & Chugunov 2020, 2021, Shchechilin et al. 2022, 2023)
  - OCP vs MCP to be explored → Q_{imp}, transport coeff. → *impact on light curves / cooling*
  - Partially accreted crust (e.g. Suleiman et al. 2022)

N.B. very recent results on cooling of SXTs with "gapless" superfluidity



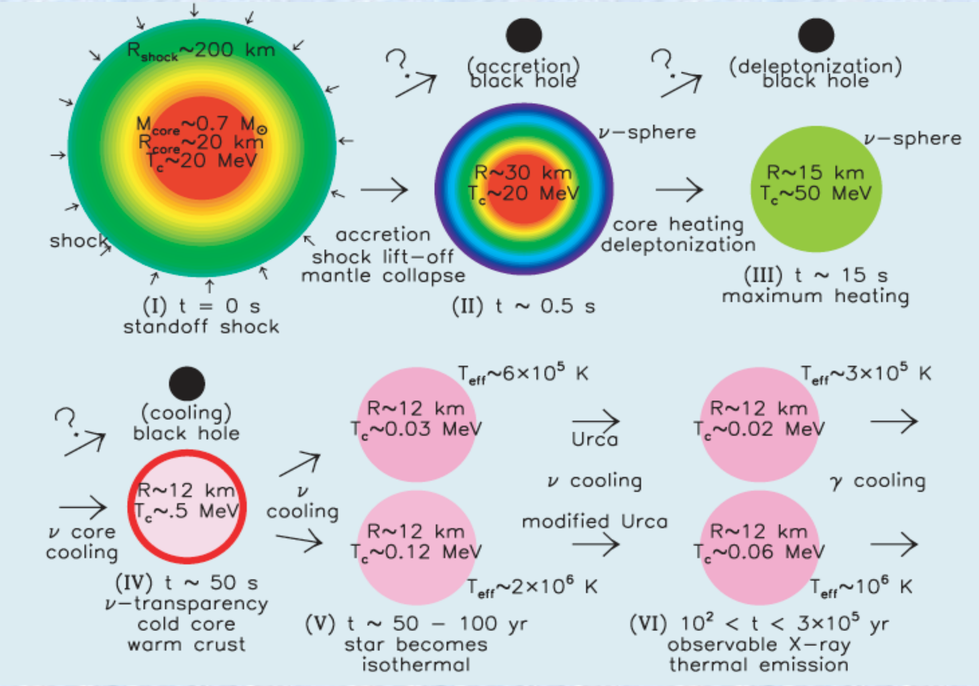


Allard & Chamel, PRL 132, 181001 (2024)

(*) http://cdsarc.u-strasbg.fr/viz-bin/cat/J/A+A/, https://zenodo.org/

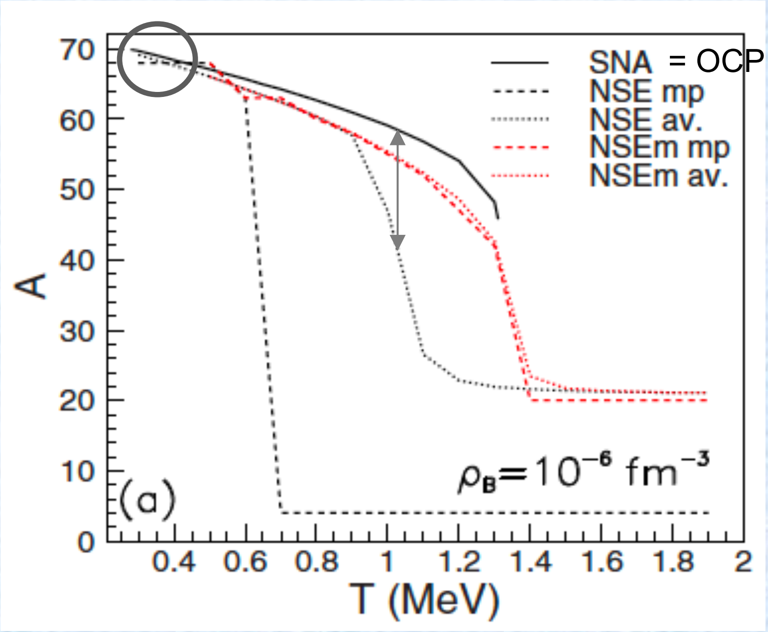
Proto-NS (finite temperature)

NS formation from CCSN



Lattimer & Prakash, Science 304, 536 (2004)

At finite T → need to go beyond OCP



Gulminelli & Raduta, PRC 92, 055803 (2015)

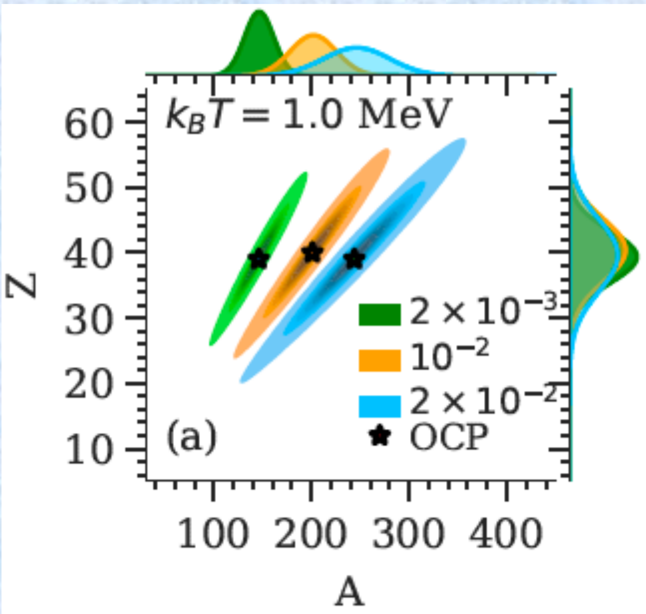
→ NS are born hot ($T > 10^{10}$ K ~ 1 MeV) → ensemble of nuclei (MCP) expected

→ NS crust crystallises (liquid → solid) at T_m ~ 0.1–1 MeV → crust composition "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 & impurities

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

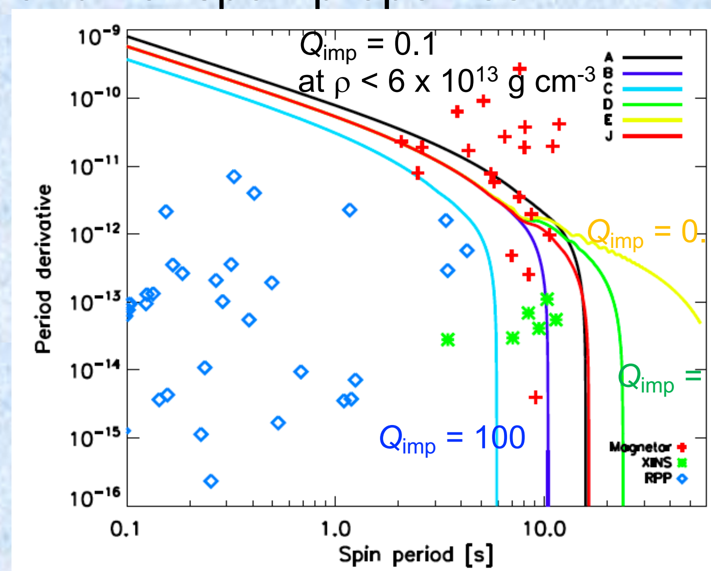


Dinh Thi et al., A&A 677, A174 (2023)
see also Fantina et al., A&A 633, A149 (2020);
Carreau et al., A&A 640, A77 (2021)

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

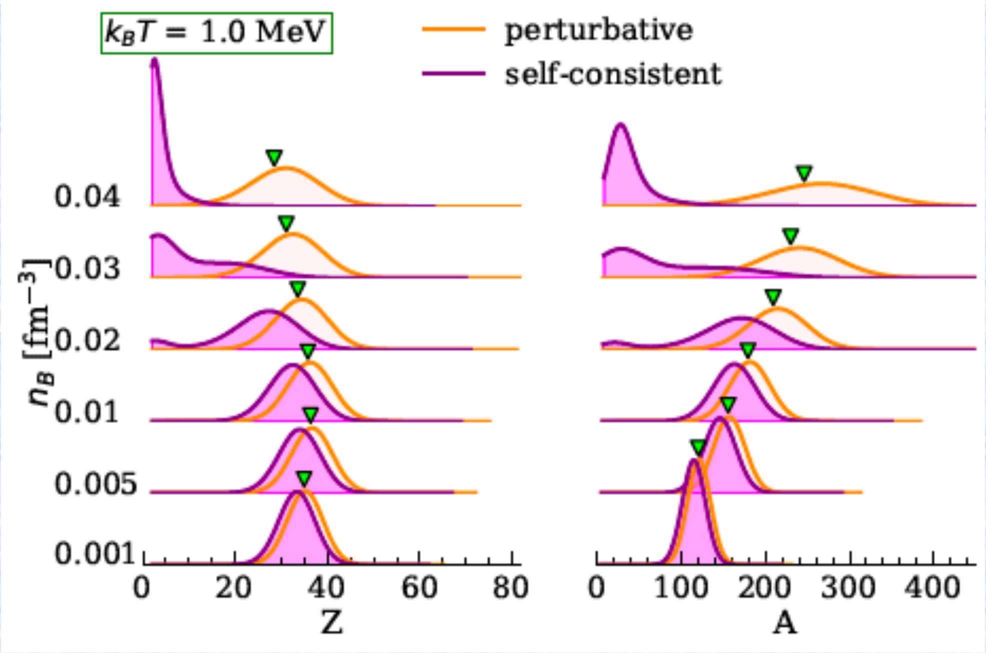


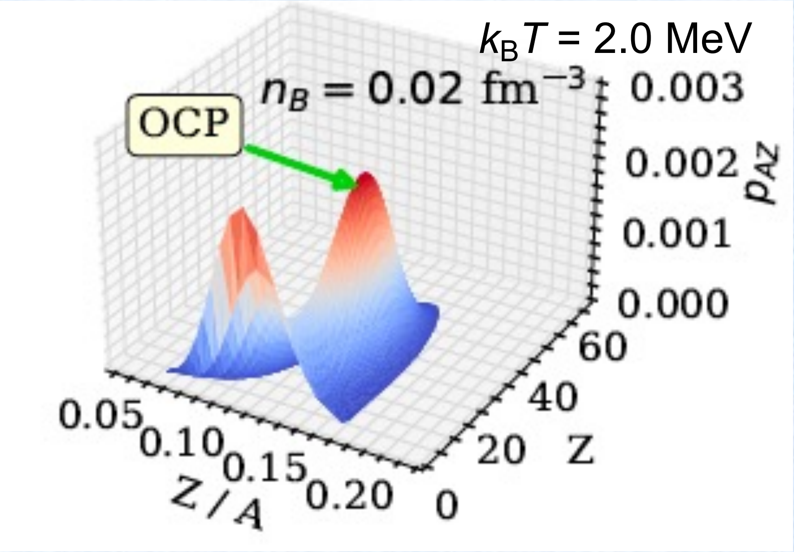
Pons et al., Nature Phys., 9, 431 (2013)
(see also Viganò et al., MNRAS 2013)

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)

PNS crust (MCP): perturb. vs consistent

MM + CLDM





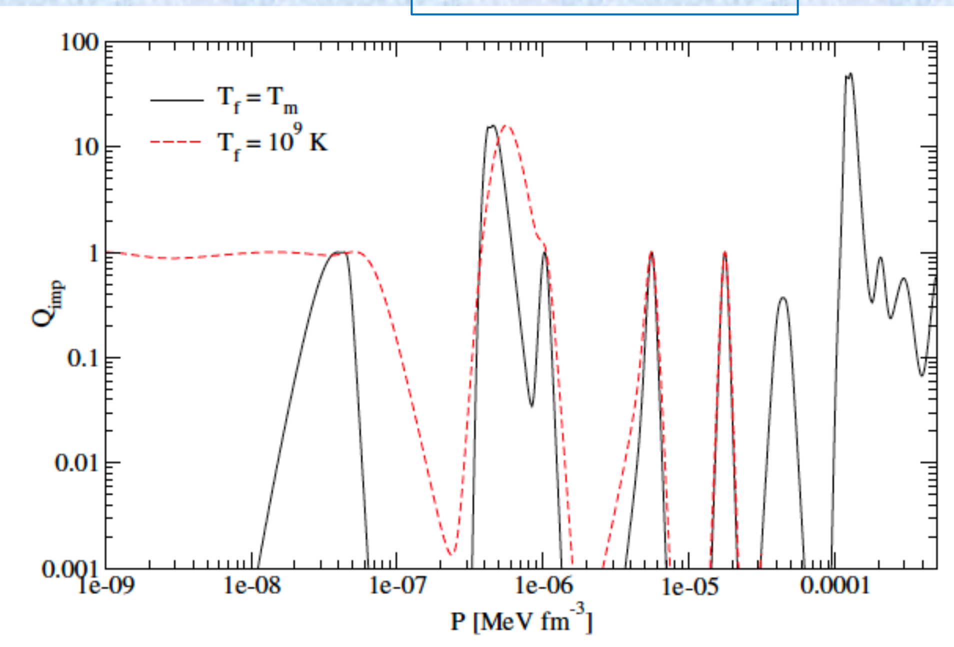
Dinh Thi et al., A&A 677, A174 (2023) – CLDM with BSk24

- 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

PNS crust (MCP): impurities

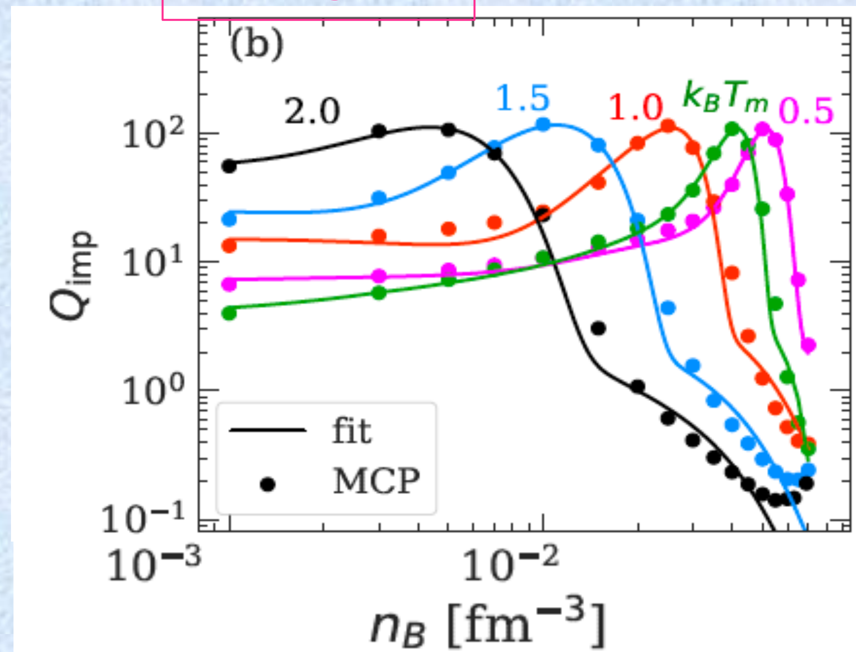
✓ Self-consistent calculations of $Q_{\rm imp} = \langle Z^2 \rangle - \langle Z \rangle^2$

Outer crust HFB-24 masses



Fantina et al., A&A 633, A149 (2020) – HFB-24
+ data on CDS

MM + CLDM Inner crust



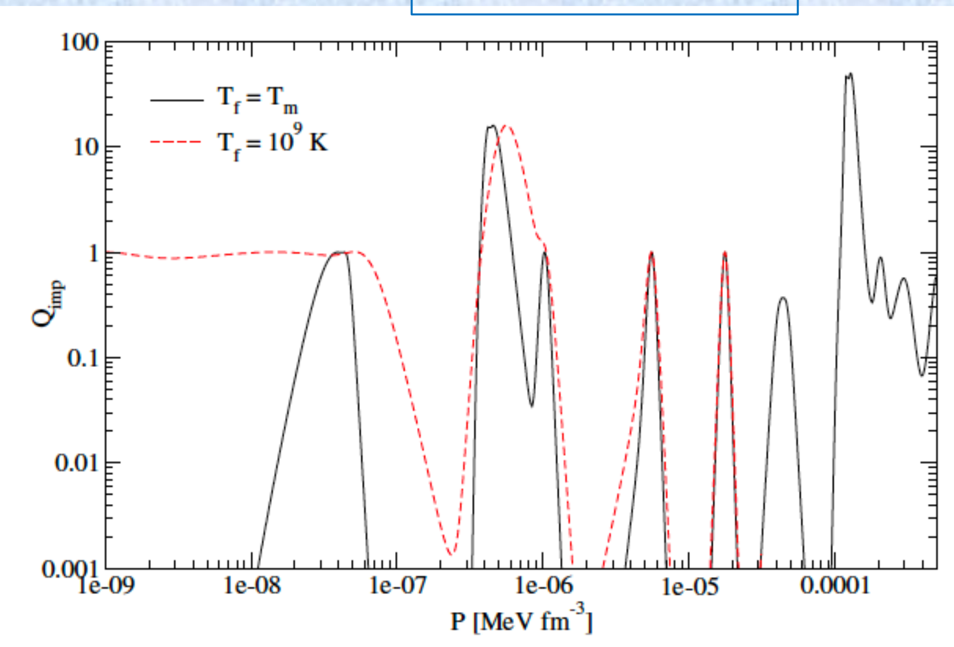
Dinh Thi et al., A&A 677, A174 (2023); see also Carreau et al., A&A 640, A77 (2020) – CLDM with BSk24
+ data on CDS

➢ consistent calculations of $Q_{\rm imp}$ throughout the crust
→ impact on transport coefficients / properties

PNS crust (MCP): impurities

✓ Self-consistent calculations of Q_{imp} =

Outer crust — HFB-24 masses



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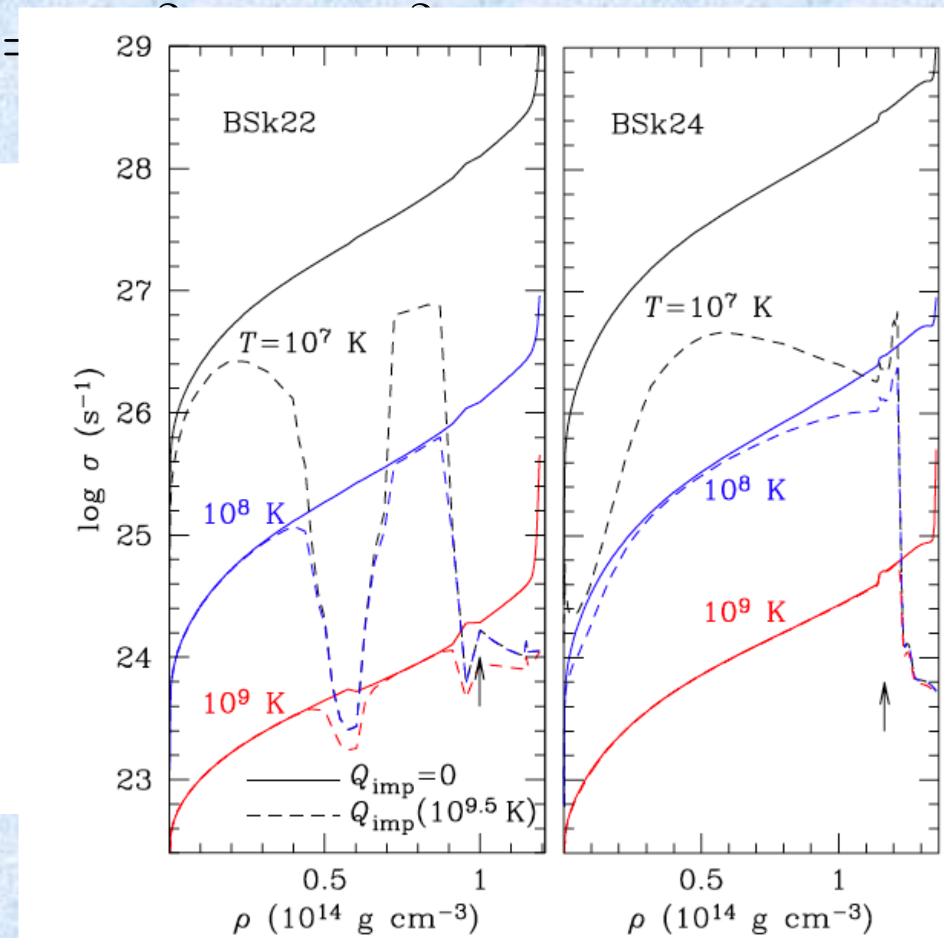

Potekhin & Chabrier, A&A 645, A102 (2021)

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

PNS crust: outlooks

- Crystallisation of (P)NS crust + (perturbative) MCP
- Liquid (P)NS crust in self-consistent MCP → Q_{imp} (publicly available)

- Self-consistent MCP needed at higher ρ,T
  - Inclusion of pasta phase to be done (e.g. Pelicer et al. 2021)
  - Q_{imp} → transport coeff. → impact on cooling (e.g. Pelicer et al. 2023)
- T-dependent parametrisation of surface energy
  - Neutron “skin”, finite T → benchmark / fit with more microscopic calculations (collab. ETFSI IAA-ULB)