Modelling dense matter at finite temperature in compact stars

Anthea F. Fantina (GANIL)
Francesca Gulminelli (LPC-Caen)
Micaela Oertel (LUTh-Obs. Paris)
Eric Bonnet (SUBATECH)

Atelier Physique Théorique des deux infinis
online, 7 – 8 June 2021

Outline

- Introduction and motivation
  - Treatment of clusters

- State-of-the-art & challenges for the (near) future *(selected examples)*
  - Clusters and in-medium effects
  - Cluster distributions in core-collapse supernova (CCSN)
  - Impurities in (proto-)neutron stars ((P)NS)
  - Accreting neutron-star (NS) crust

- Conclusions & outlooks

Microphysics inputs for compact stars

- Equation of state & composition:
  - sub-saturation density $T = 0$ → see M. Urban's talk
  - high density & GW → see J. Margueron's talk
  - **sub-saturation and $T \neq 0$ → this talk**
    → inhomogeneous matter at finite temperature (cluster distribution)
- Weak processes → see M. Oertel's talk
- Neutrino interactions / transport → see M. Oertel's talk

see

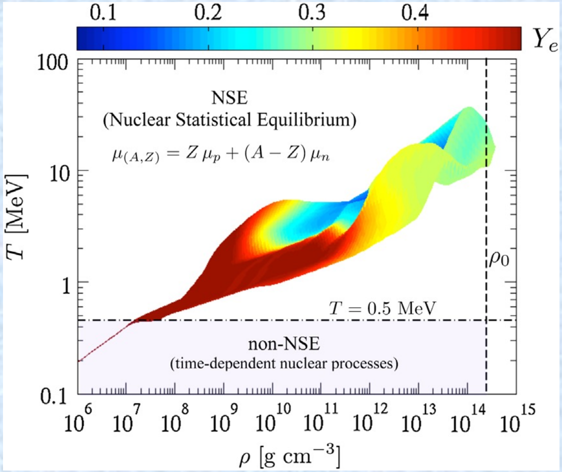
Nuclear physics experiments

F. Gulminelli's talk
at IN2P3 "perspectives"
(Jan. 2020)

Implementation in numerical simulations → see J. Guilet's talk
→ reliable interpretation of astrophysical observables

Inhomogeneous matter at finite T

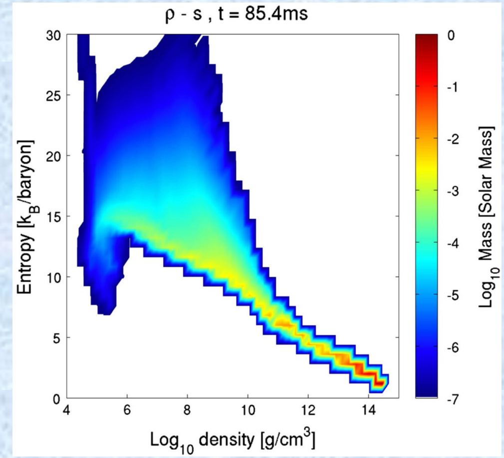
Core-collapse supernovae (SNe)



Simulation T. Fischer

Oertel et al., Rev. Mod. Phys. 89, 015007 (2017)

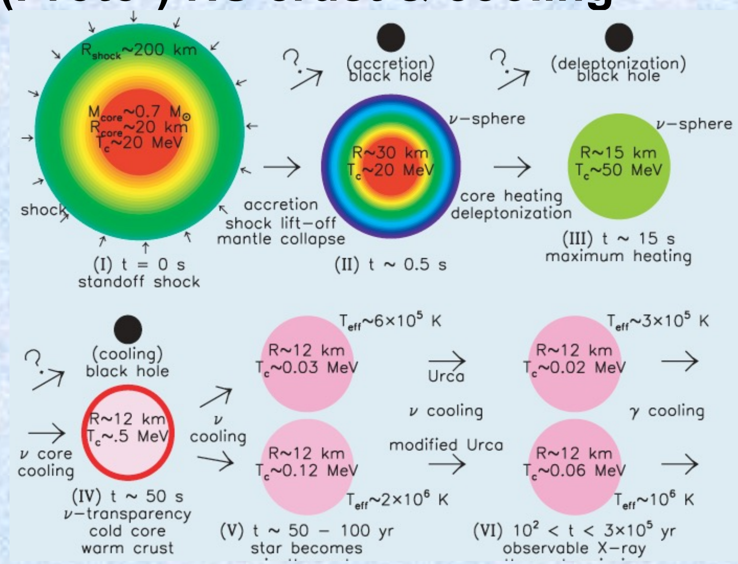
Binary neutron-star (NS) mergers



Simulation A. Perego

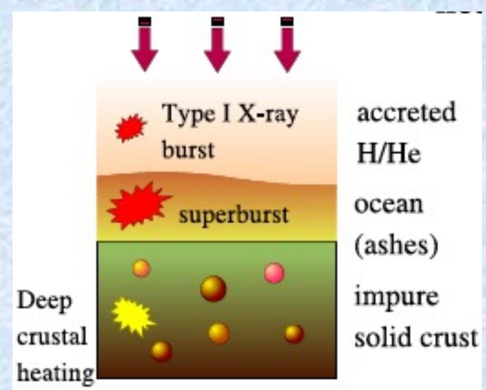
Oertel et al., Rev. Mod. Phys. 89, 015007 (2017)

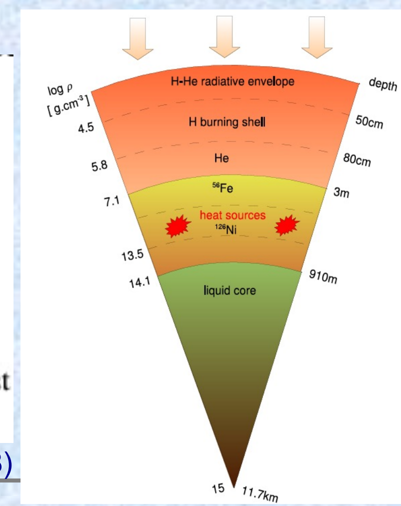
(Proto-) NS crust & cooling



Lattimer & Prakash, Science 304, 536 (2004)

Accreting NSs





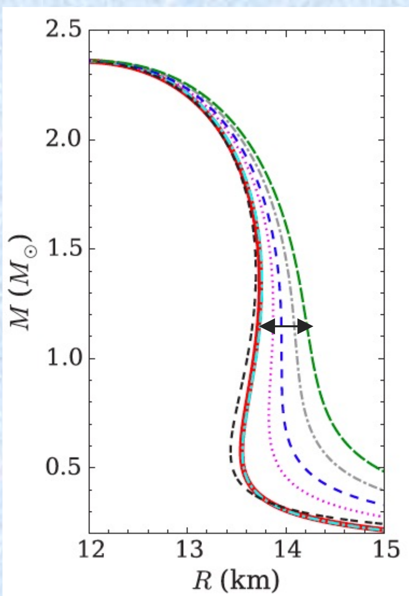
Chamel & Hansel, Liv. Rev. Relat. 11, 10 (2008)

N.B.: also off-(beta-) equilibrium !

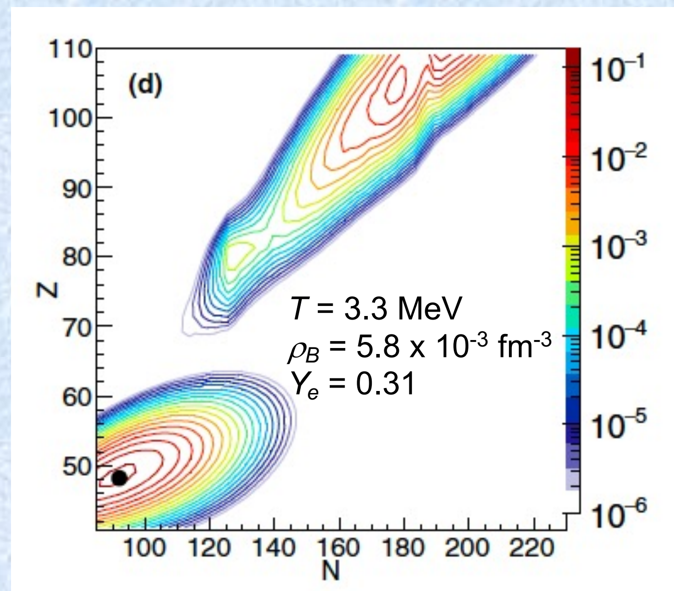
Why a <u>unified</u> treatment ?

Unified treatment of finite nuclei & infinite matter
→ same nuclear model employed in different regions of star

- Challenging because of wide range of density, temperature, isospin asymmetry
- Challenging because different states of matter (cluster, "pasta", homogeneous matter)
- But: <u>essential to avoid spurious non-physical effects in numerical modelling</u>



Fortin et al., PRC 94, 035804 (2016); T=0

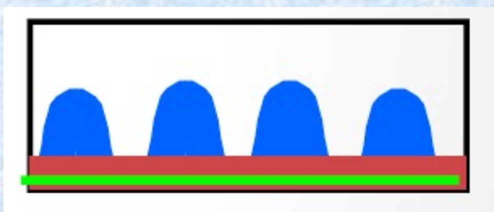


Grams et al., PRC 97, 035807 (2018); CCSN, $T\neq0$

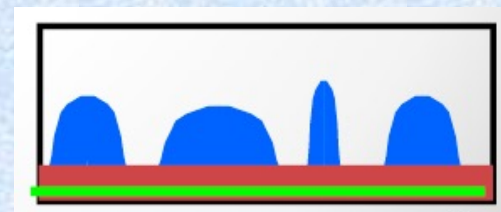
Which approach ?

- Which theoretical framework for clustered matter at finite *T* ?
  → *ab-initio methods*, but: not affordable for inhomogeneous matter
  → *phenomenological methods* → **Nuclear energy-density functional theory**

- <u>One-component (OCP) single-nucleus (SNA)</u> vs <u>**Multi-component (MCP)**</u>



→ energy minimisation gives favoured *cluster (A,Z)*



→ energy minimisation gives favoured *cluster distribution*

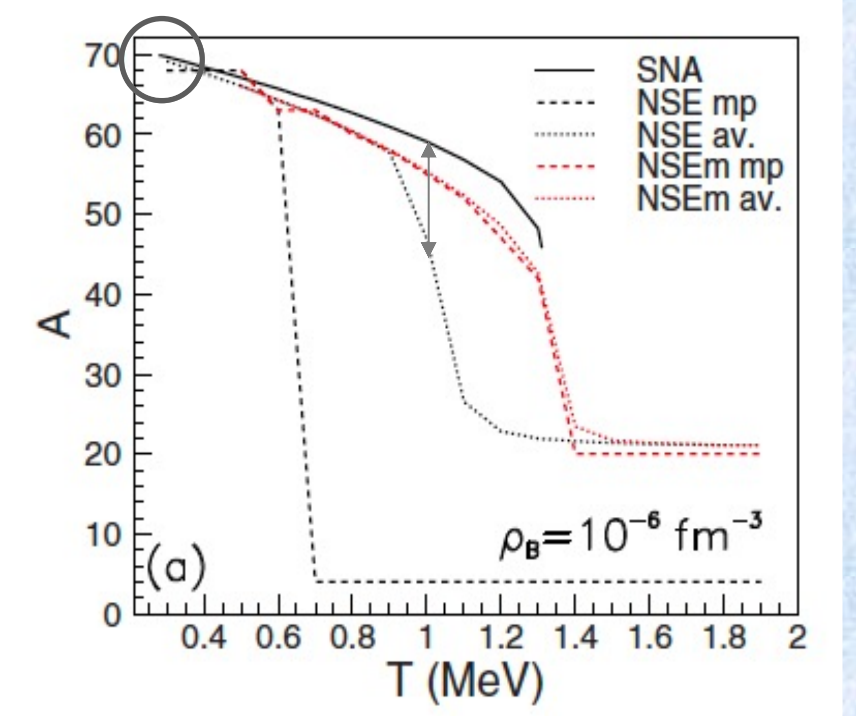
$$p(A,Z) \propto \exp\left[-(k_B T)^{-1}\left(F_N + \delta\Omega - \mu_n N - \mu_p Z\right)\right]$$

✓ OCP OK for thermodynamic quantities and faster computationally
✗ but: at finite *T* more microstates populated → nuclear distributions
✗ MCP needed to compute reaction (electron-capture) rates (CCSN, cooling, …)

Treatment of clusters

→ Need to go beyond the standard Wigner-Seitz (one-component) approximation

- Possible strategies:
  1. Micro calculations (MD, TDHF)
     → computationally expensive
     (e.g. Sebille et al., 2009, 2011;
     Nandi & Schramm 2018, …)
  2. **Statistical (NSE) models**
     → cluster degrees of freedom
     → more flexible but more difficult to treat
     beyond mean-field effects
     (e.g. Gullminelli & Raduta 2015,
     Grams et al. 2018, Pais et al. 2020, …)

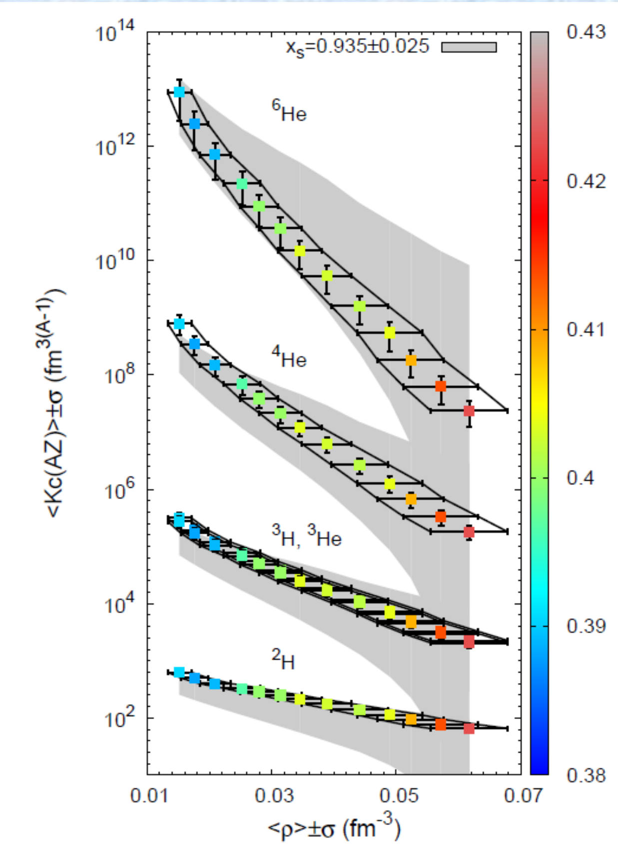


Gulminelli & Raduta, PRC 92, 055803 (2015)

for a review: Oertel et al., Rev. Mod. Phys. 89, 015007 (2017);
Burgio & Fantina, Astrophys. Space Sci. Lib. 457, 255 (2018)

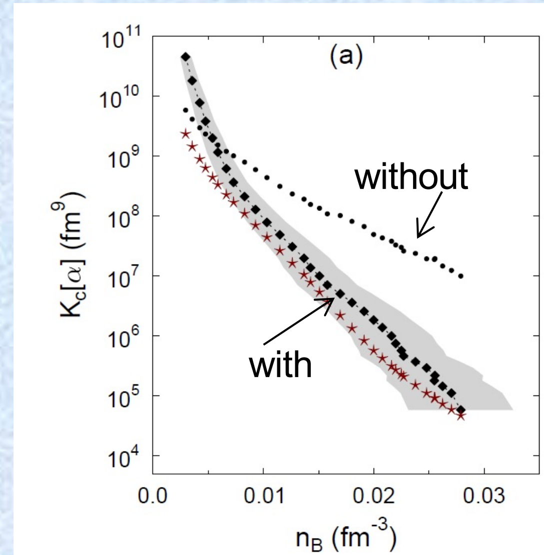
Clusters and in-medium effects

In-medium effects on SN matter composition from multi-fragmentation:
Calibration of the low-density equation of state

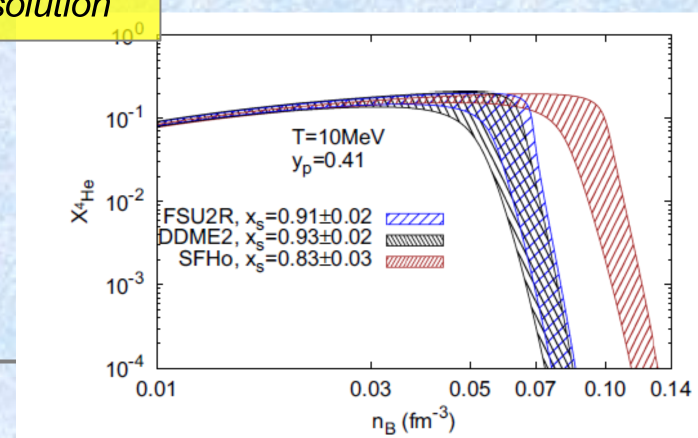


Pais et al., PRL 125, 012901 (2020)

- **Clusters as quasi-particles in an effective RMF formalism**
  - ✓ *modified scalar and vector meson couplings produce clusters binding energy shifts*
- **Observable: chemical constants from HI collisions**
  - ✓ *high sensitivity to in-medium effects*
- **New consistent analysis of INDRA data**
  - ✓ *collaboration theory-experiment*
- **Calibration of couplings on exp.data**
  - ✓ *residual model dependence on the Mott density of cluster dissolution*

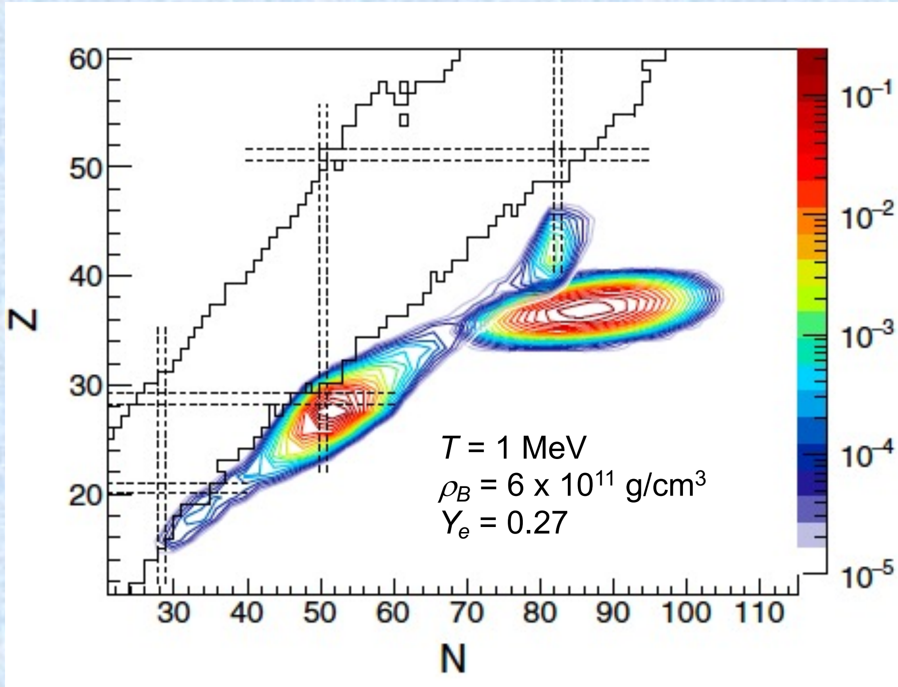


Qin et al., PRL 108, 172701 (2012)



Custodio et al., EPJA 56, 295 (2020)

Cluster distributions in CCSN

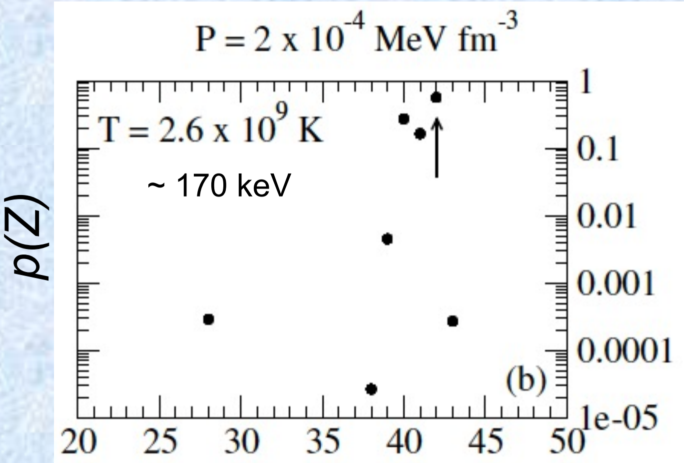


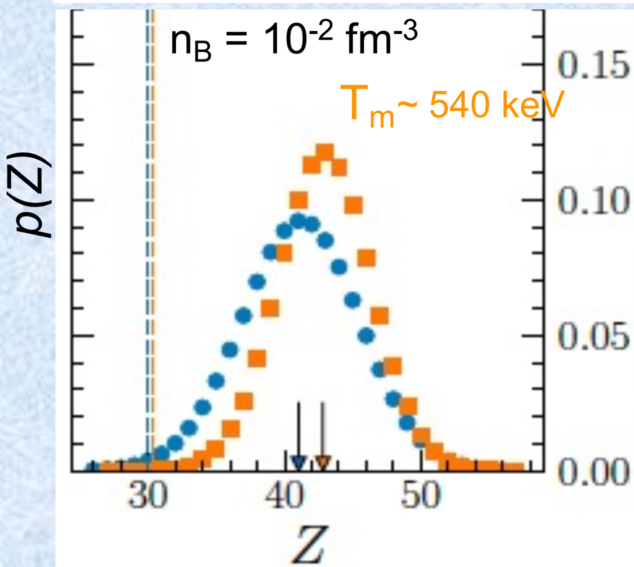
Pascal et al., PRC 101, 015803 (2020)

- ✓ Magic nuclei dominate trajectory of CCSN
- ✓ Distribution during collapse large wrt OCP

→ impact on (electron-capture) rates, L_ν
→ Collaboration theory-experiment

Impurities in the (P)NS crust





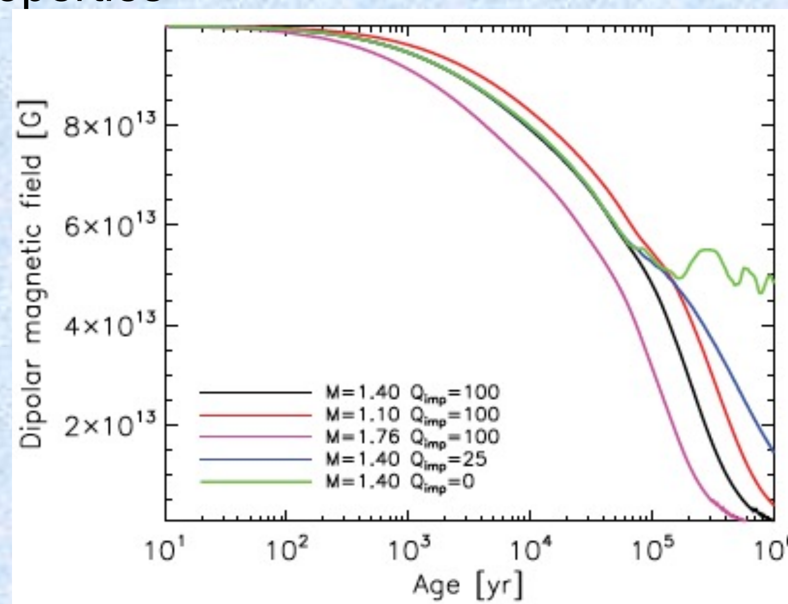
Fantina et al., A&A 633, A149 (2020)
Carreau et al., A&A 640, A77 (2020)

Co-existence of nuclear species

→ **"impurity factor"**
(usually free parameter adjusted on cooling data)

$$Q_{\rm imp} = \sum_j p(Z^{(j)})(Z^{(j)} - \langle Z \rangle)^2$$

→ impact dynamic, magneto-rotational, and transport properties

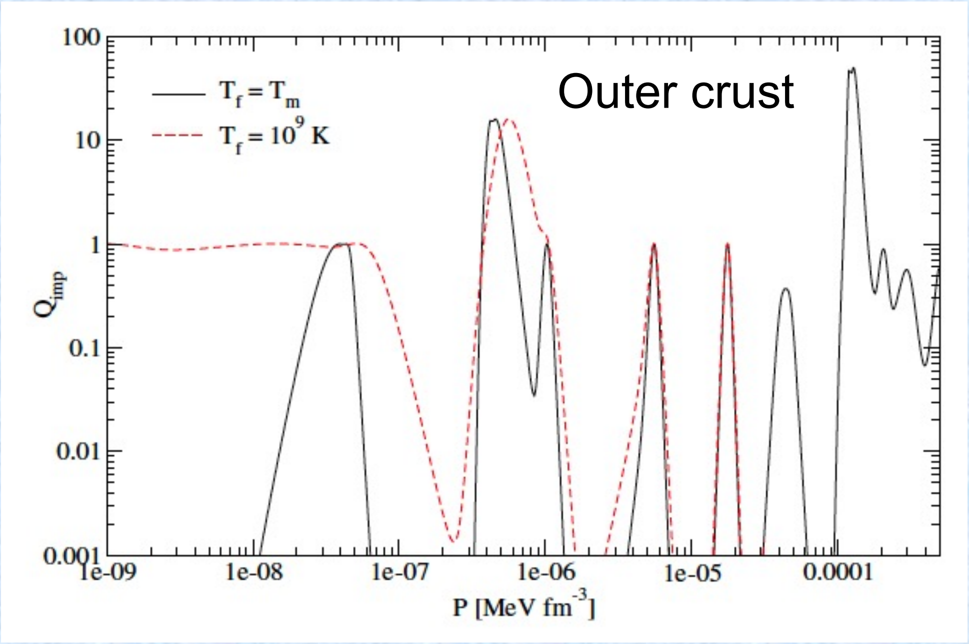


Viganò et al., MNRAS 434, 123 (2013)

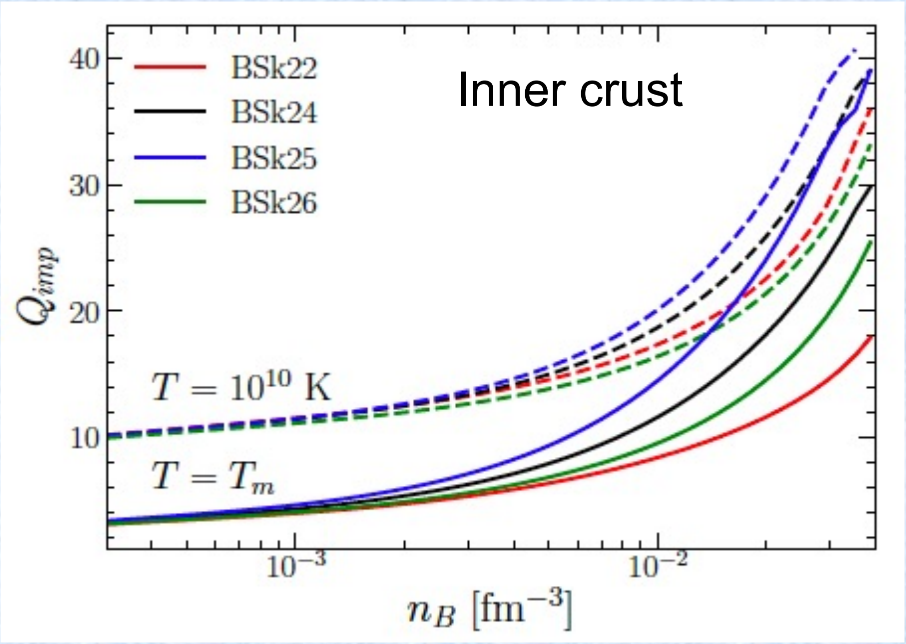
for a review see e.g. Schmidt & Shternin, ASSL 457, 455 (2018)

Impurities in the (P)NS crust

✓ First self-consistent (microscopic) calculation of $Q_{\rm imp} = \sum_j p(Z^{(j)})(Z^{(j)} - \langle Z \rangle)^2$



Fantina et al., A&A 633, A149 (2020)

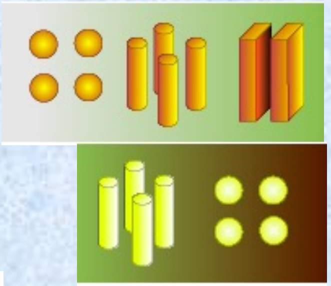


Carreau et al., A&A 640, A77 (2020)

What next ?

- ➢ consistent calculations of transport coefficients/properties needed
- ➢ implementation in numerical simulations of (P)NS cooling → freeze-out time
- ➢ determine crystallization in MCP approach → phase equilibrium in MCP

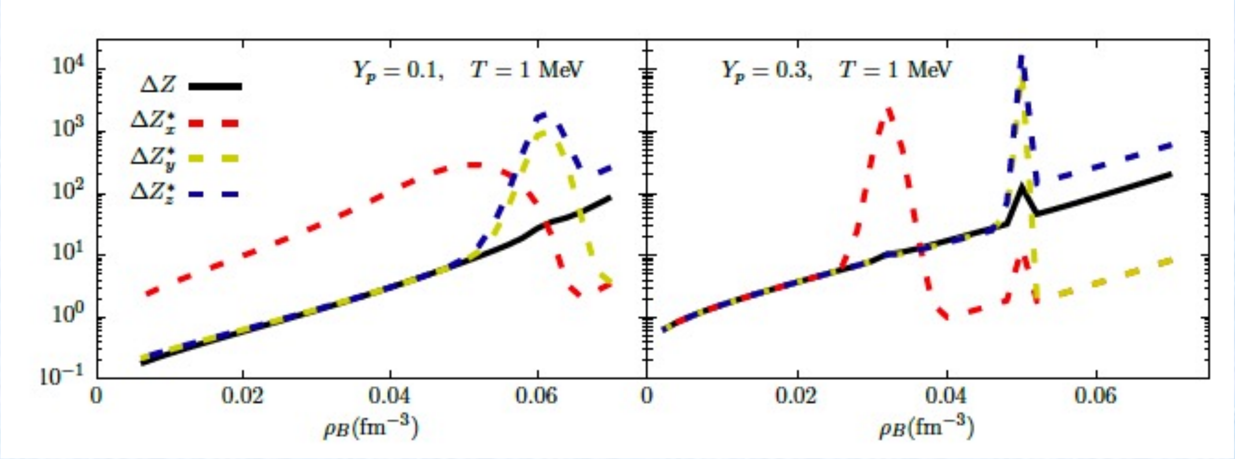
Impurities in the (P)NS crust & pasta



What about non-spherical nuclei/clusters (**“pasta” phases**) ?

$$p(A,Z) \propto \exp\left[-(k_B T)^{-1}\left(F_{N,d} + \delta\Omega_d - \mu_n N - \mu_p Z\right)\right]$$

✓ Calculations at finite *T* exist



Pelicer et al., arXiv:2105.03318 (RMF models)

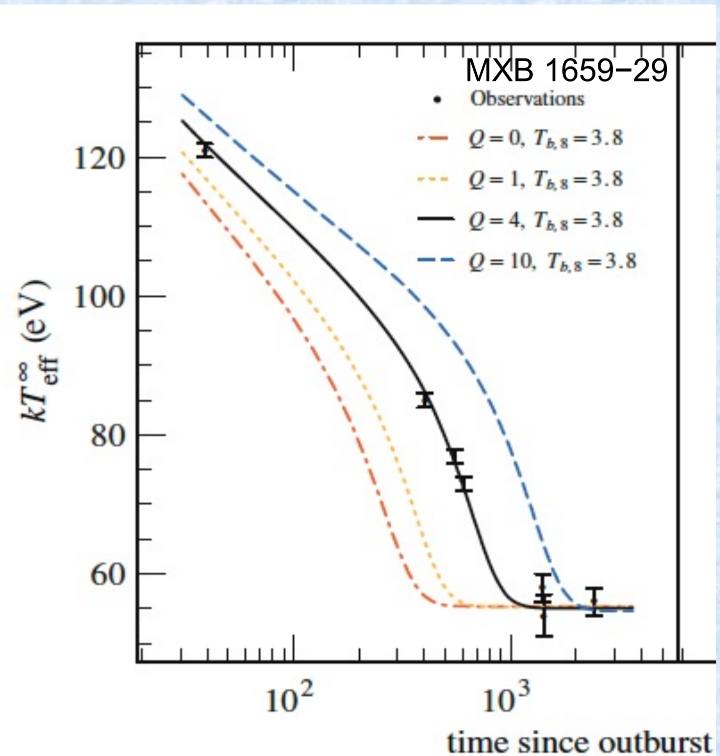
✓ and are under way (Dinh Thi, PhD thesis)

What next ?

- calculation of the static/dynamic structure factor (3D)
- calculation of associated transport coefficients
- implementation in numerical simulations of (P)NS cooling

Accreting NS crusts

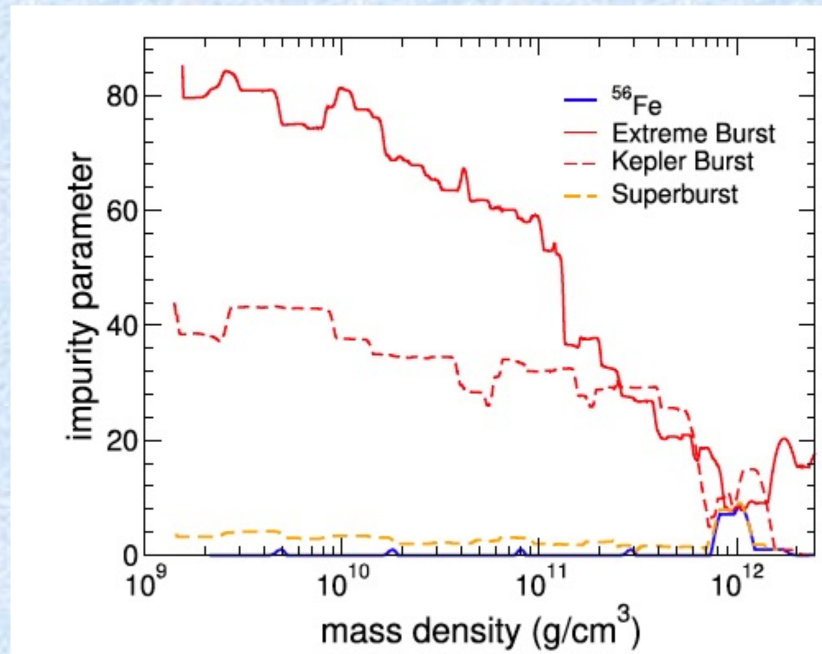
To model relaxation / cooling we need
- EoS + composition (Q_{imp})
- heat sources (→ nuclear process)
  → amount of heat and location



Brown & Cumming, ApJ 698, 1020 (2009)

✓ Calculations of Q_{imp} (and heat sources) within MCP / reaction network exist *(mainly outside France)*

✗ but : - computationally expensive
- usually less micro nuclear models
- restricted to outer /start of inner crust



Lau et al., ApJ 859, 62 (2018)

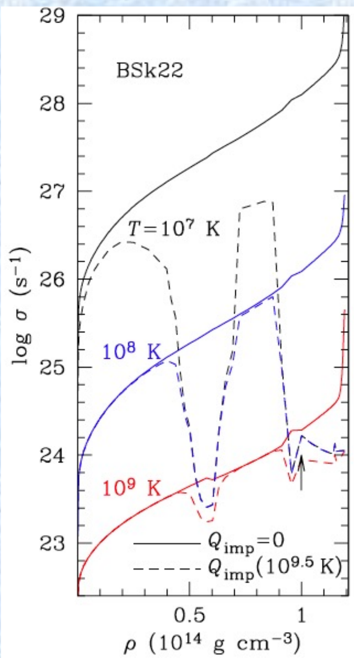
for a review see e.g. Meisel et al., J. Phys. G, 45, 093001 (2018)

Accreting NS crusts

✓ Recent calculations of crustal heating employ more microscopic models for outer & inner crust

✗ but OCP approximation

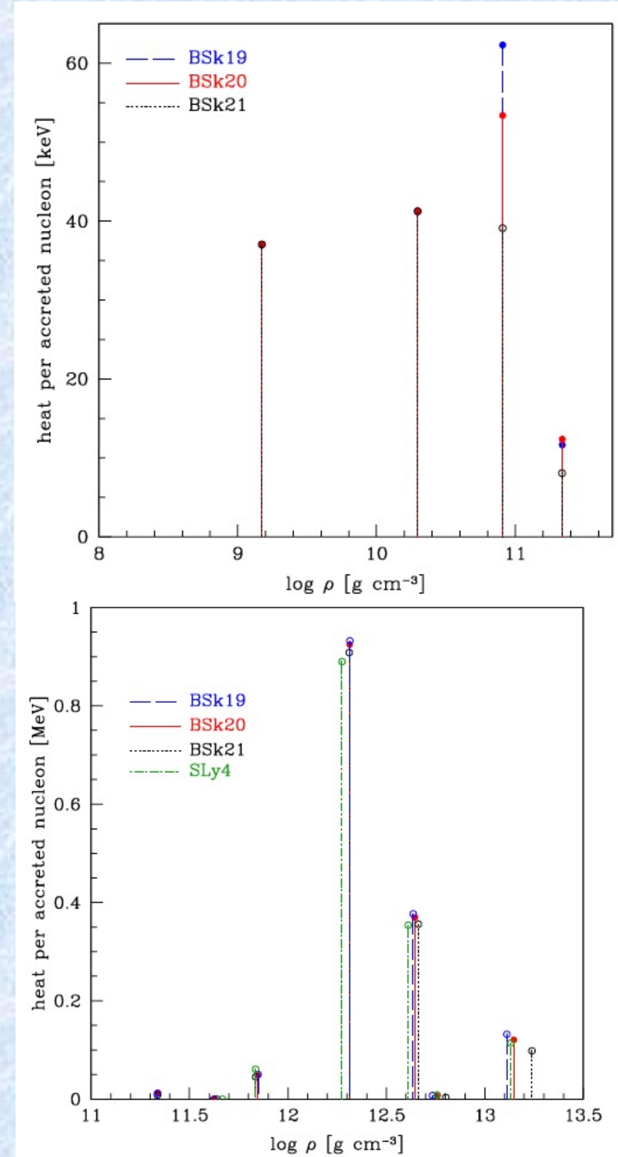
✗ even with more micro models shallow heating remains a puzzle



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

<u>What next</u> ?

- MCP approach and up-to-date nuclear model
- calculation of the Q_{imp} → transport coefficients
- implementation in numerical simulations (cooling, relaxation)



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

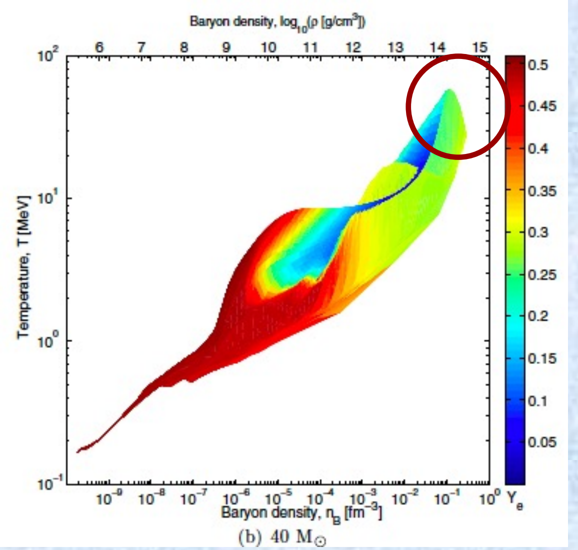
Finite *T* – high-density regime

✓ Finite *T* and high density met in **CCSN & BNS mergers**
→ additional degrees of freedom ? Effect on dynamics ?

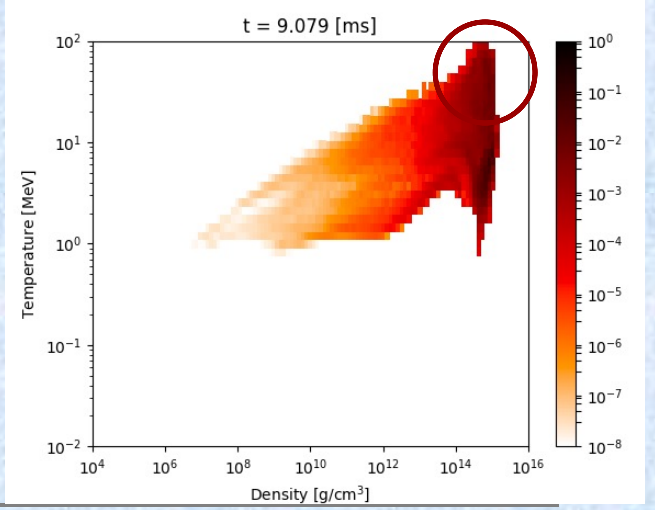
Temperature	$0\ \mathrm{MeV} \leq T < 150\ \mathrm{MeV}$
Baryon number density	$10^{-11}\ \mathrm{fm}^{-3} < n_B < 10\ \mathrm{fm}^{-3}$
Electron fraction	$0 < Y_e < 0.6$

✗ Consistent treatment of phase transitions challenging
✗ Extension of many-body methods and extrapolation of predictions not trivial (e.g. parameters of EDF usually fitted at *T*=0)

➢ Need of a *unified* "general purpose" EoS (and composition) in very wide thermodynamic conditions
➢ Implementation in numerical simulations



Fischer et al., ApJSS 194, 39 (2011)



Perego et al., EPJA 55, 124 (2019)

for a review e.g. Oertel et al., Rev. Mod. Phys. 89, 015007 (2017); Burgio&Fantina, ASSL 457, 255 (2018)

Conclusions & outlooks

- ❖ Modelling of clustered matter at finite temperature challenging
  but important for description of different compact-object properties / observables

- ❖ Strongly interdisciplinary field
  → collaboration nuclear physicist + astrophysicists (IN2P3 + non-IN2P3 labs)

- ❖ Collaborations already exist (national & international)
  → strengthen & extend cross-field collaborations

- ❖ Advances in the field need *consistent* implementation of **microphysics inputs** in **macroscopic simulations** and/or **analysis of observational data**
  → collective effort to improve and promote *open-access repository*
  (e.g. CompOSE(*) database)

(*) https://compose.obspm.fr

Thank you