Providing crustal parameters for the NS cooling simulations

Nikolai Shchechilin

With N. Chamel, A.I. Chugunov, M.E. Gusakov, A.Y. Potekhin, W. Ryssens, J.M. Pearson

Université Libre de Bruxelles

EOS THE EXCELLENCE OF SCIENCE

ULB

fnrs LA LIBERTÉ DE CHERCHER

IReNA-INT Joint Workshop, Seattle 2024

On the way of providing crustal parameters for the NS cooling simulations

Nikolai Shchechilin

With N. Chamel, A.I. Chugunov, M.E. Gusakov, A.Y. Potekhin, W. Ryssens, J.M. Pearson

Université Libre de Bruxelles

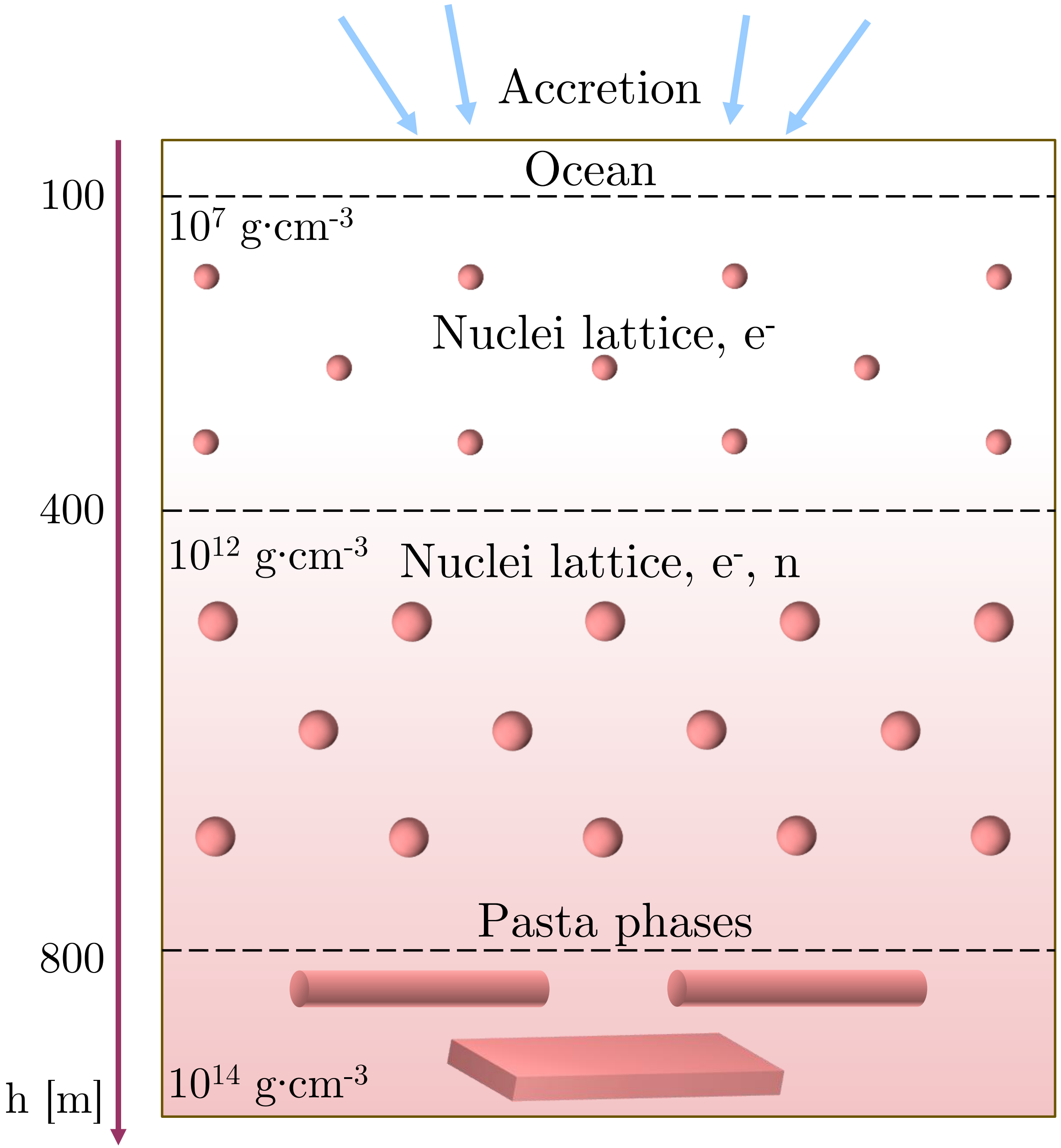
EOS
THE EXCELLENCE OF SCIENCE

ULB

fnrs
LA LIBERTÉ DE CHERCHER

IReNA-INT Joint Workshop, Seattle 2024

General paradigm of accreted crust



Envelope burning H/He → Fe/Pd

Shallow heating

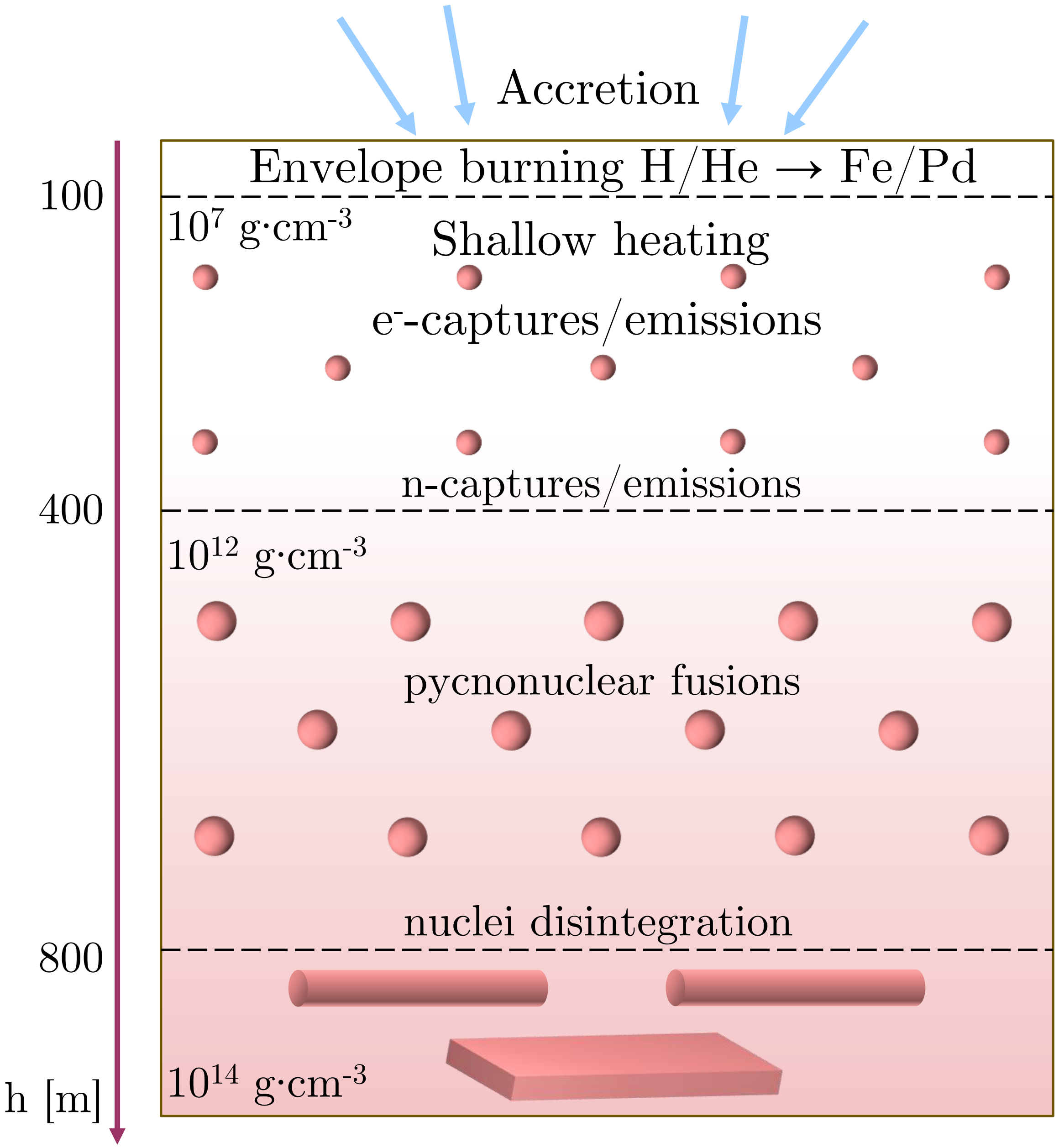
e$^-$-captures/emissions

n-captures/emissions

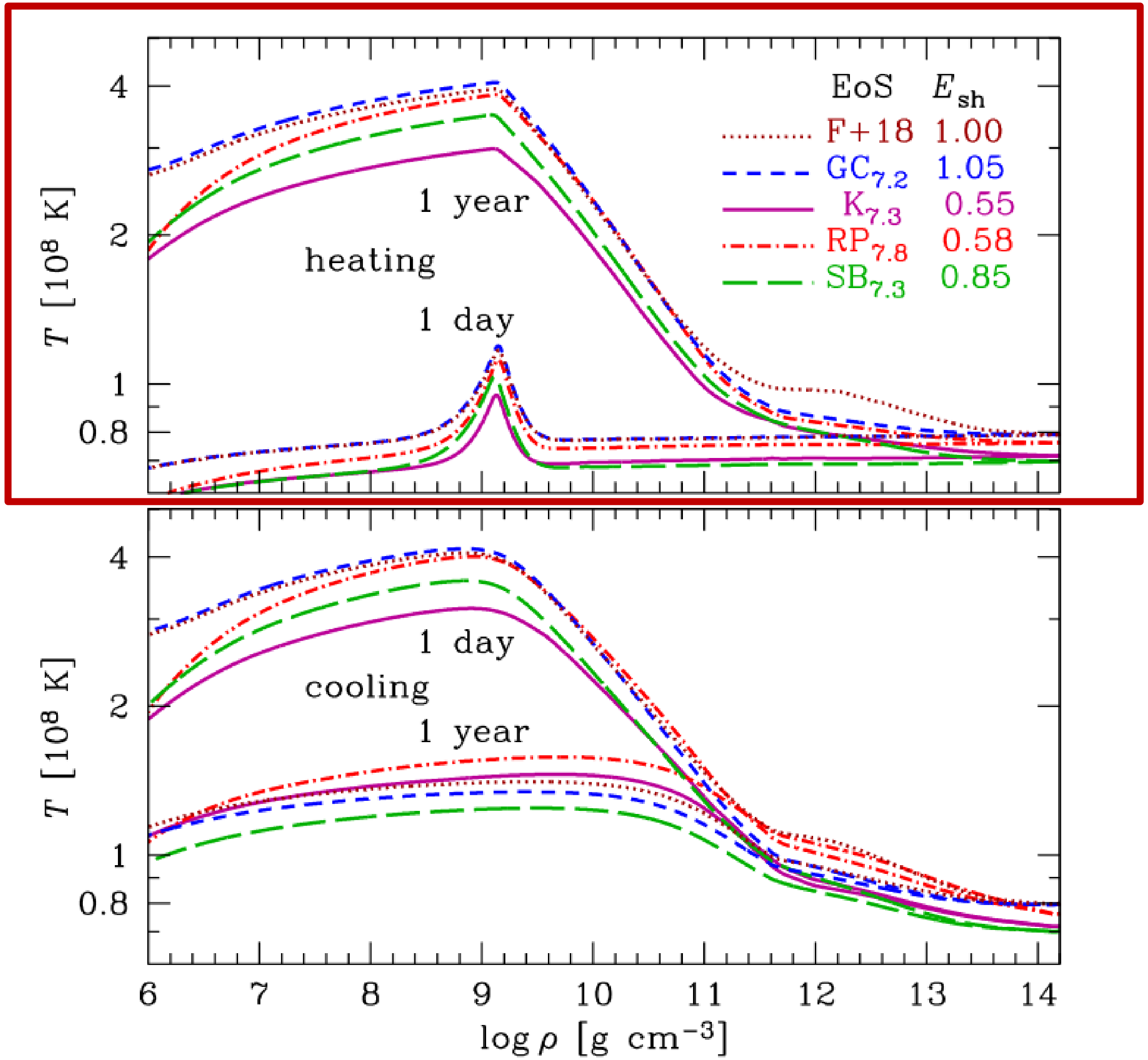
pycnonuclear fusions

nuclei disintegration

Crustal thermal evolution

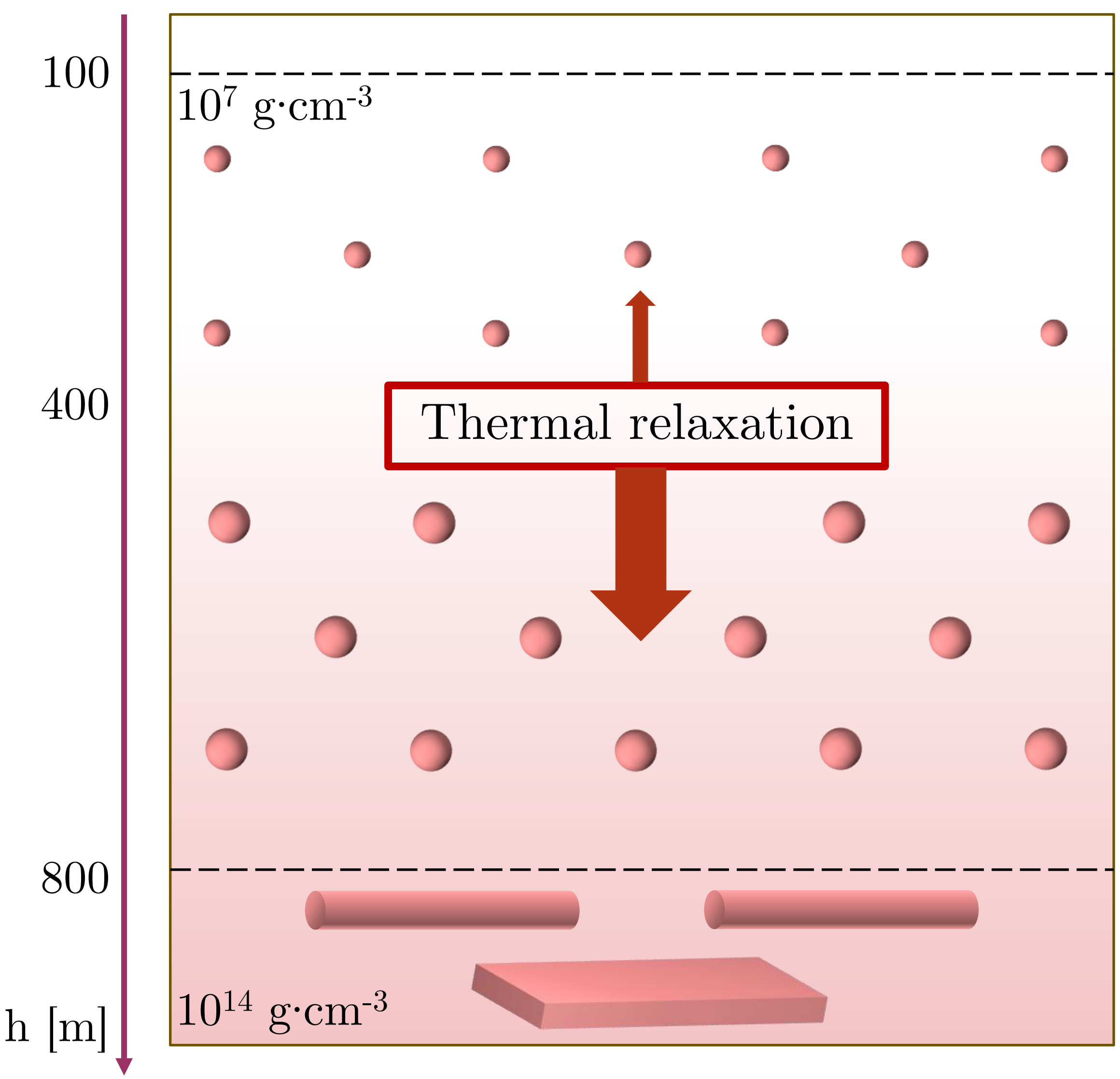


Temperature profiles in the crust

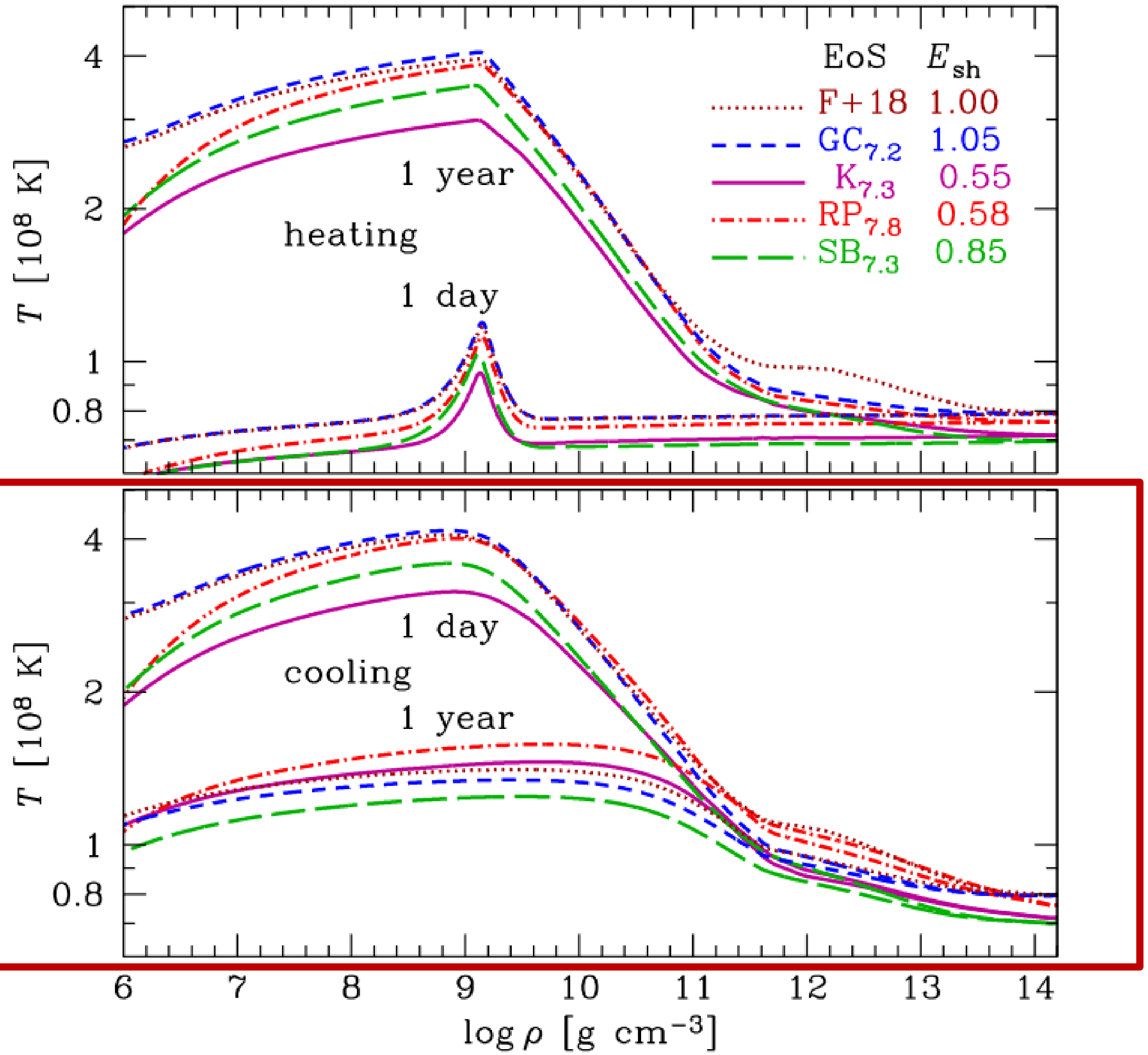


[Potekhin, Chugunov, NS, Gusakov '24]

Crustal thermal evolution



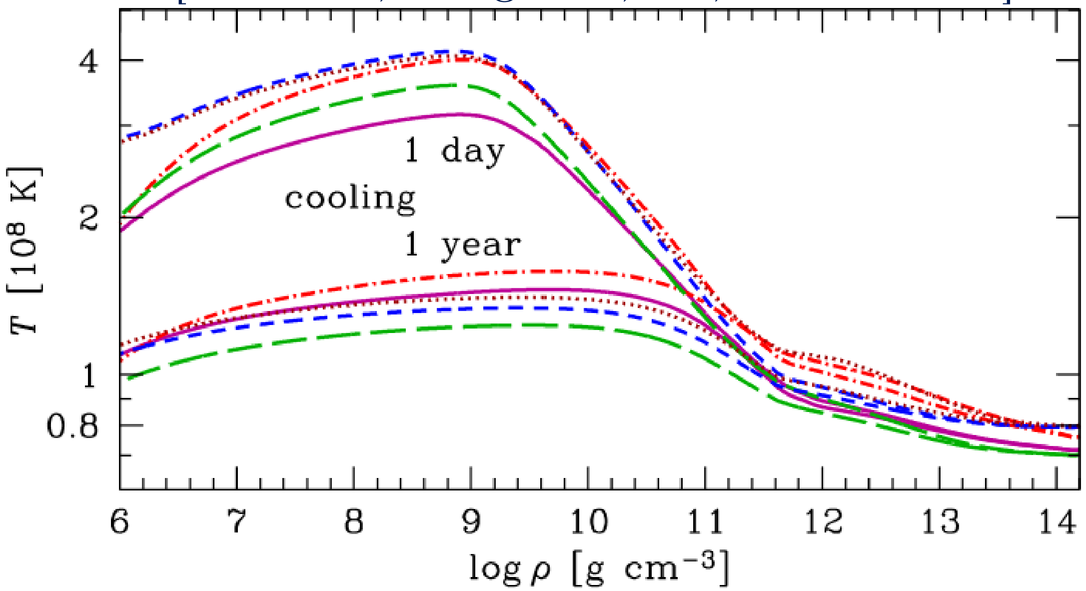
Temperature profiles in the crust



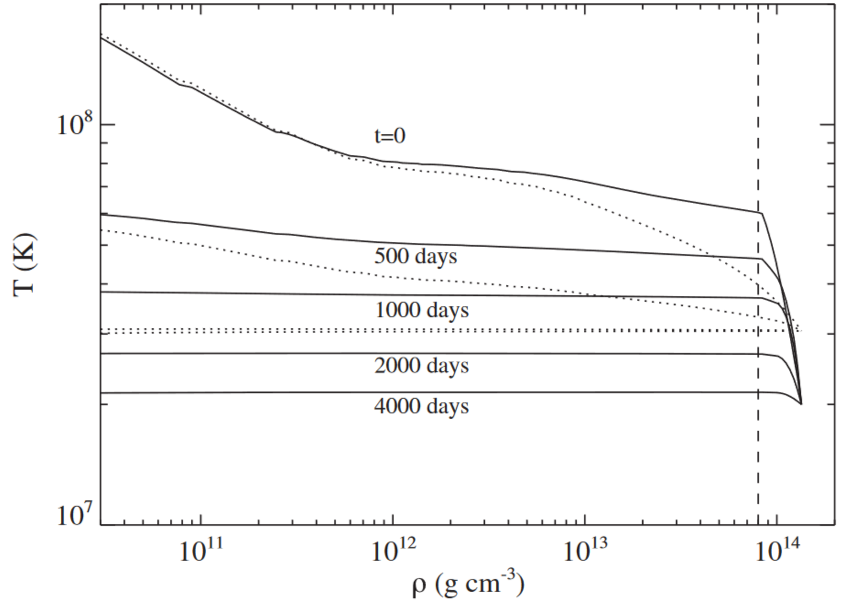
[Potekhin, Chugunov, NS, Gusakov '24]

Crustal thermal evolution

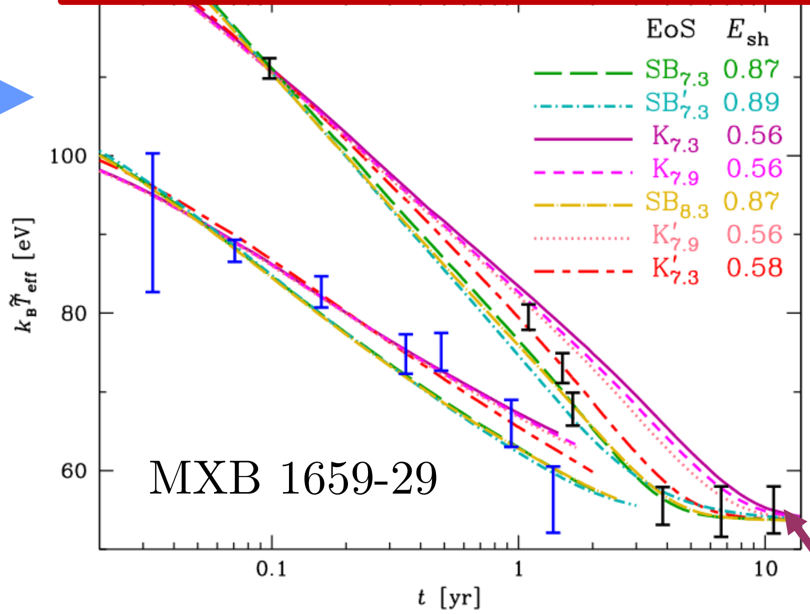
[Potekhin, Chugunov, NS, Gusakov '24]

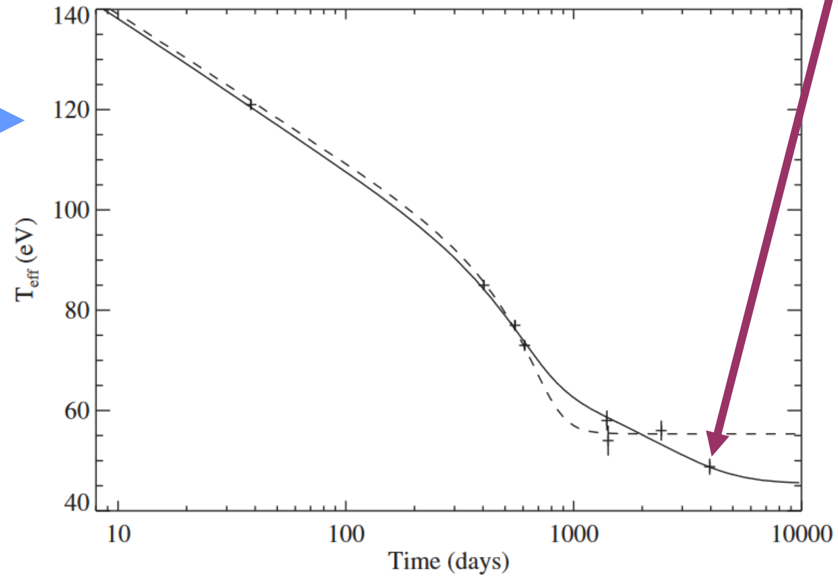


[Horowitz, Berry, Briggs, Caplan, Cumming, Schneider '15]



Cooling curves vs observations

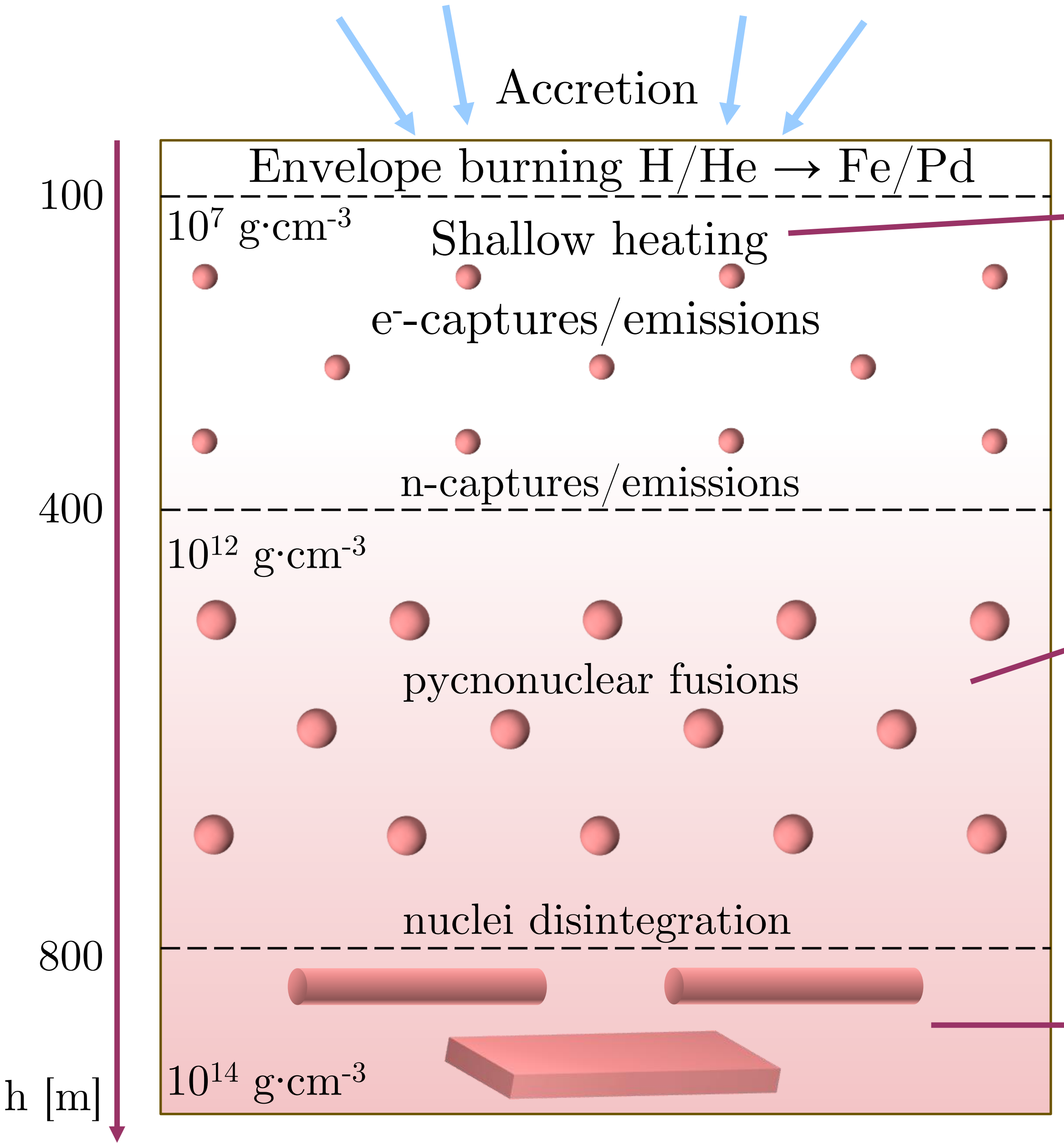


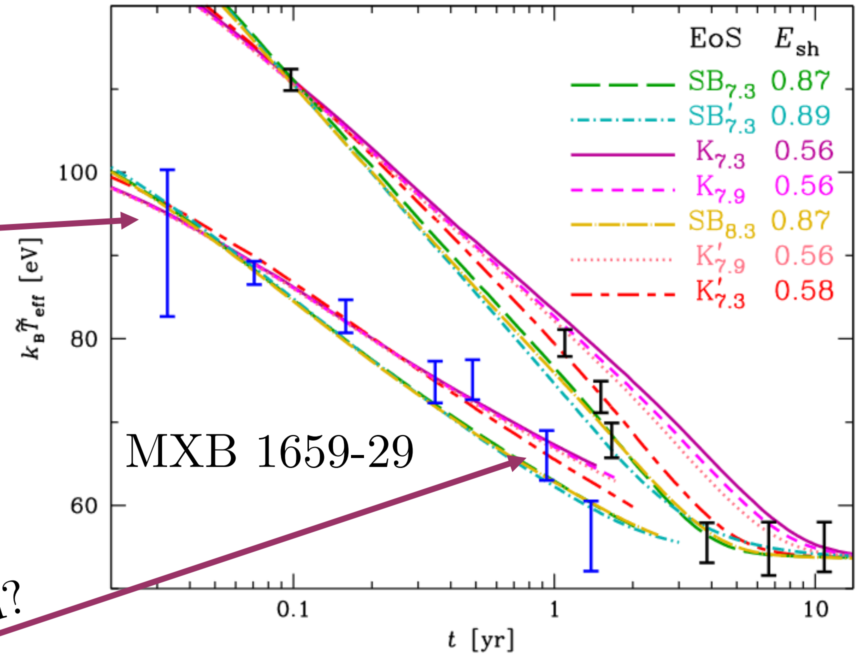


Depends on the spectral model [Cackett+ '13]

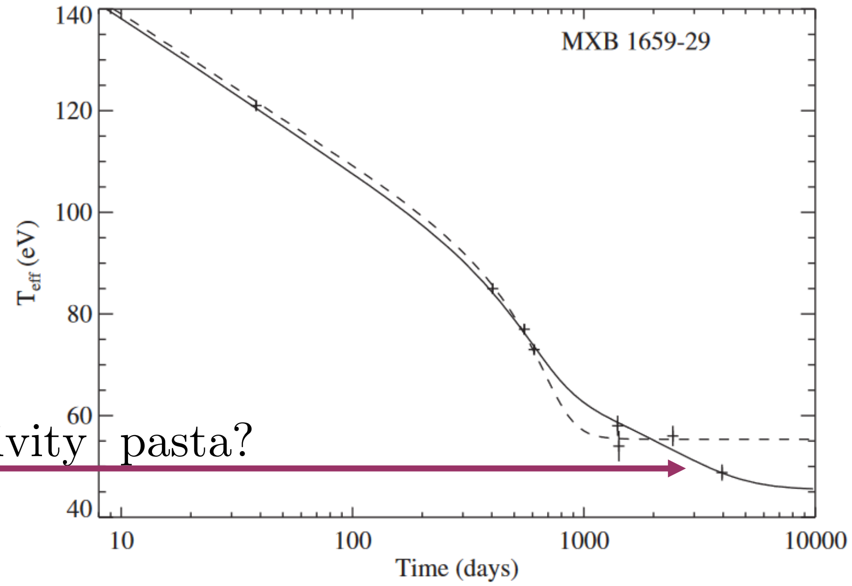
Crustal imprints

[Potekhin, Chugunov, NS, Gusakov ’24]





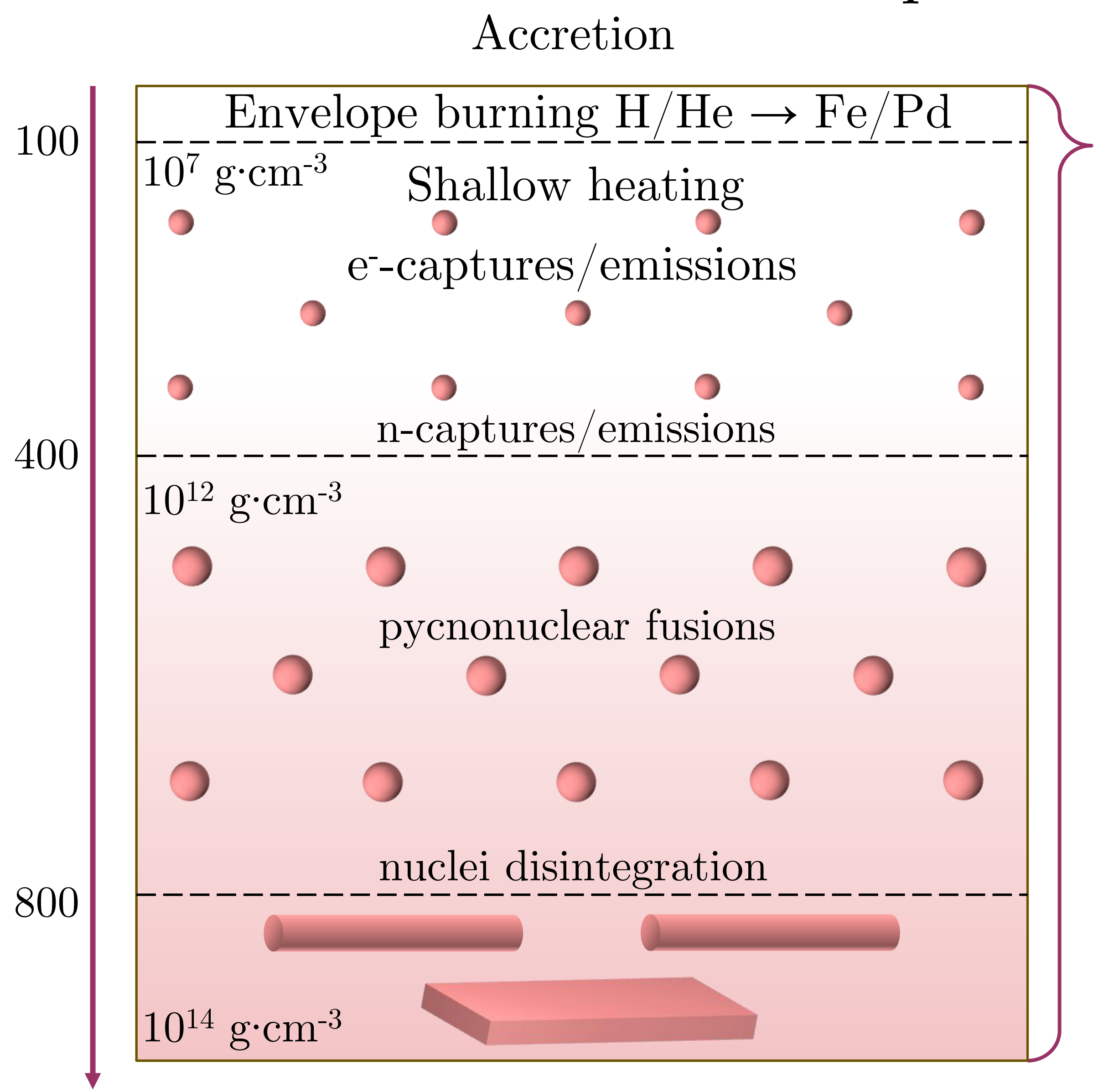
Pure crystal?



Low-conductivity pasta?

[Horowitz, Berry, Briggs, Caplan, Cumming, Schneider’15]

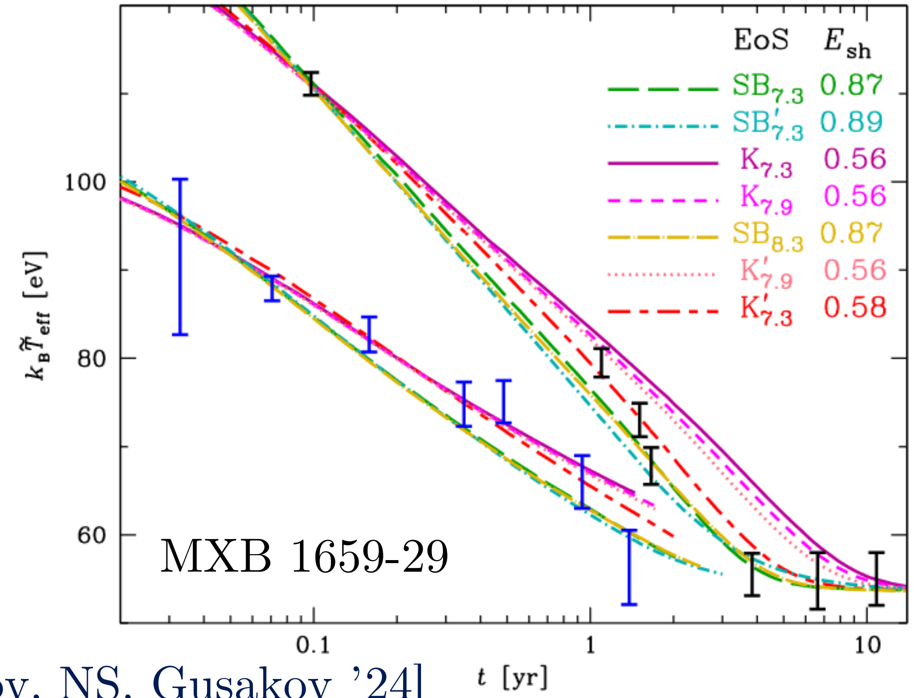
Crustal inputs for cooling simulations



Heating sources, composition, superfluidity model,

$\langle Z \rangle$, Q_{imp}, Δ_n

heat capacity, conductivity

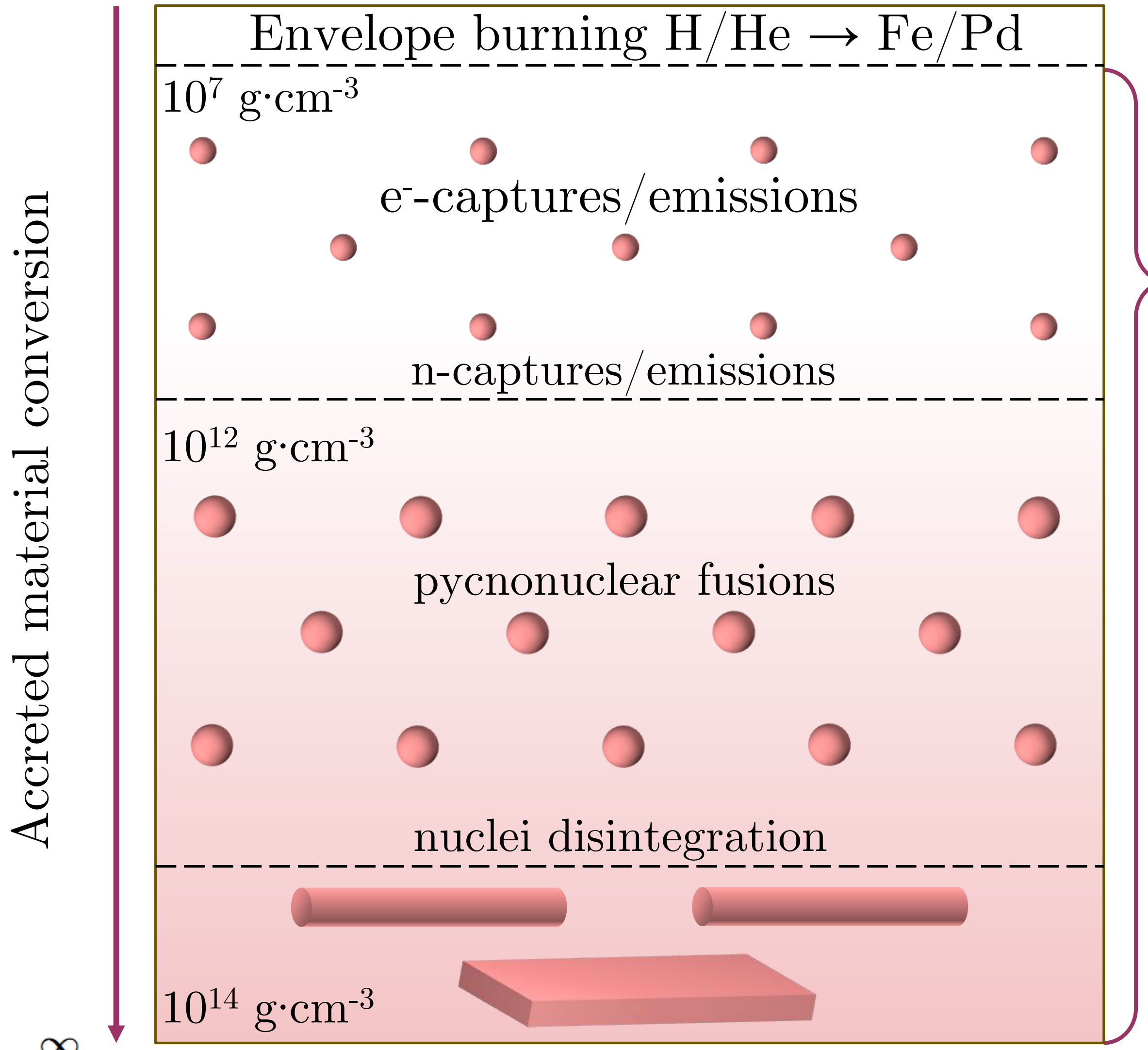


[Potekhin, Chugunov, NS, Gusakov '24]

Total heating: general considerations

$$Q_{\rm tot}^{\infty} = m_{\rm b,H} e^{\nu_{\rm s}/2} - \mu_{\rm b,core}^{\infty} =$$

$m_{\rm b,H} e^{\nu_{\rm s}/2}$



$\mu_{\rm b,core}^{\infty}$

redshift factor

$$(m_{\rm b,H} - m_{\rm b,ash}) e^{\nu_{\rm s}/2}$$

+

$$(m_{\rm b,ash} e^{\nu_{\rm s}/2} - \mu_{\rm b,core}^{\infty})$$

Heating in a “net” reaction

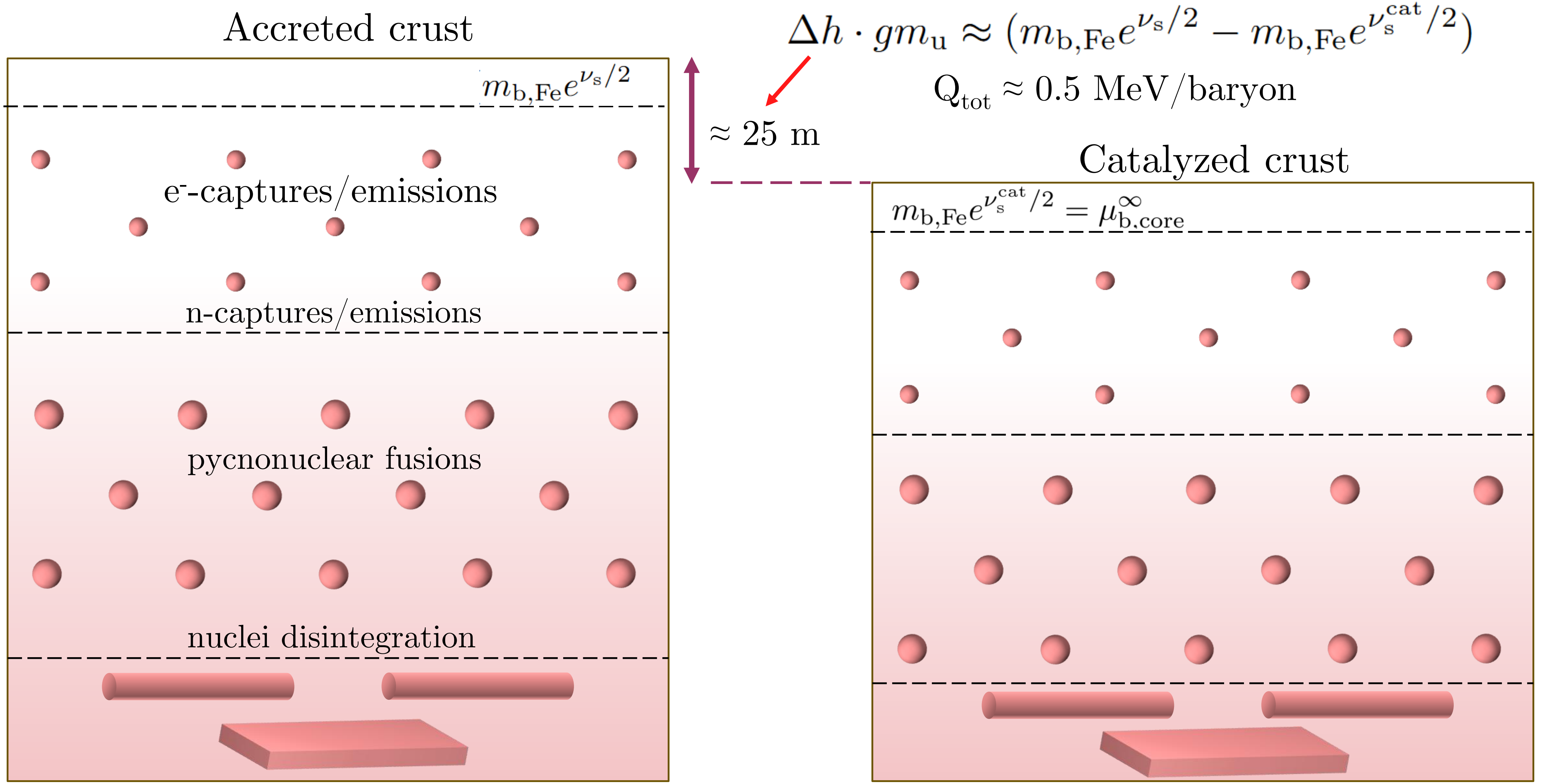
[Gusakov & Chugunov ’21]

Total heating: general considerations

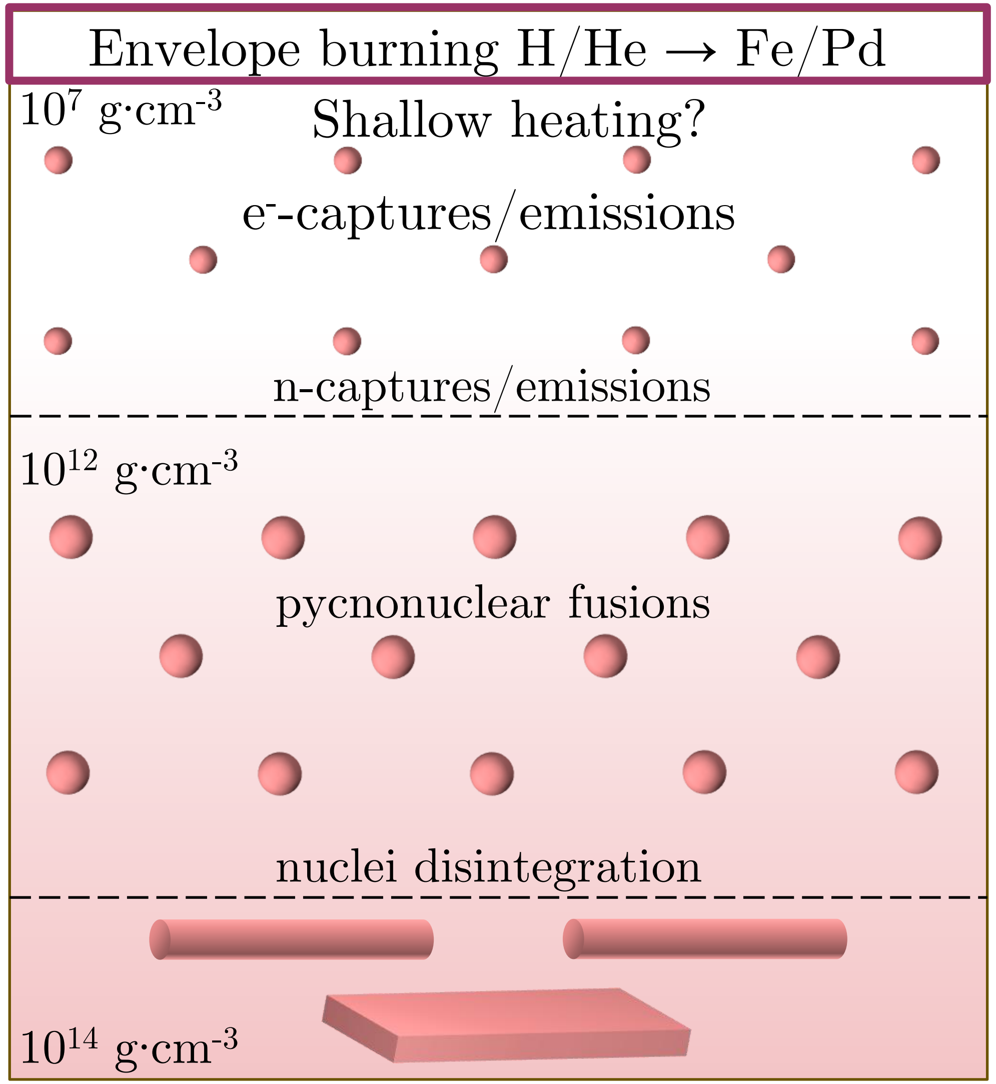
[Gusakov & Chugunov '21]

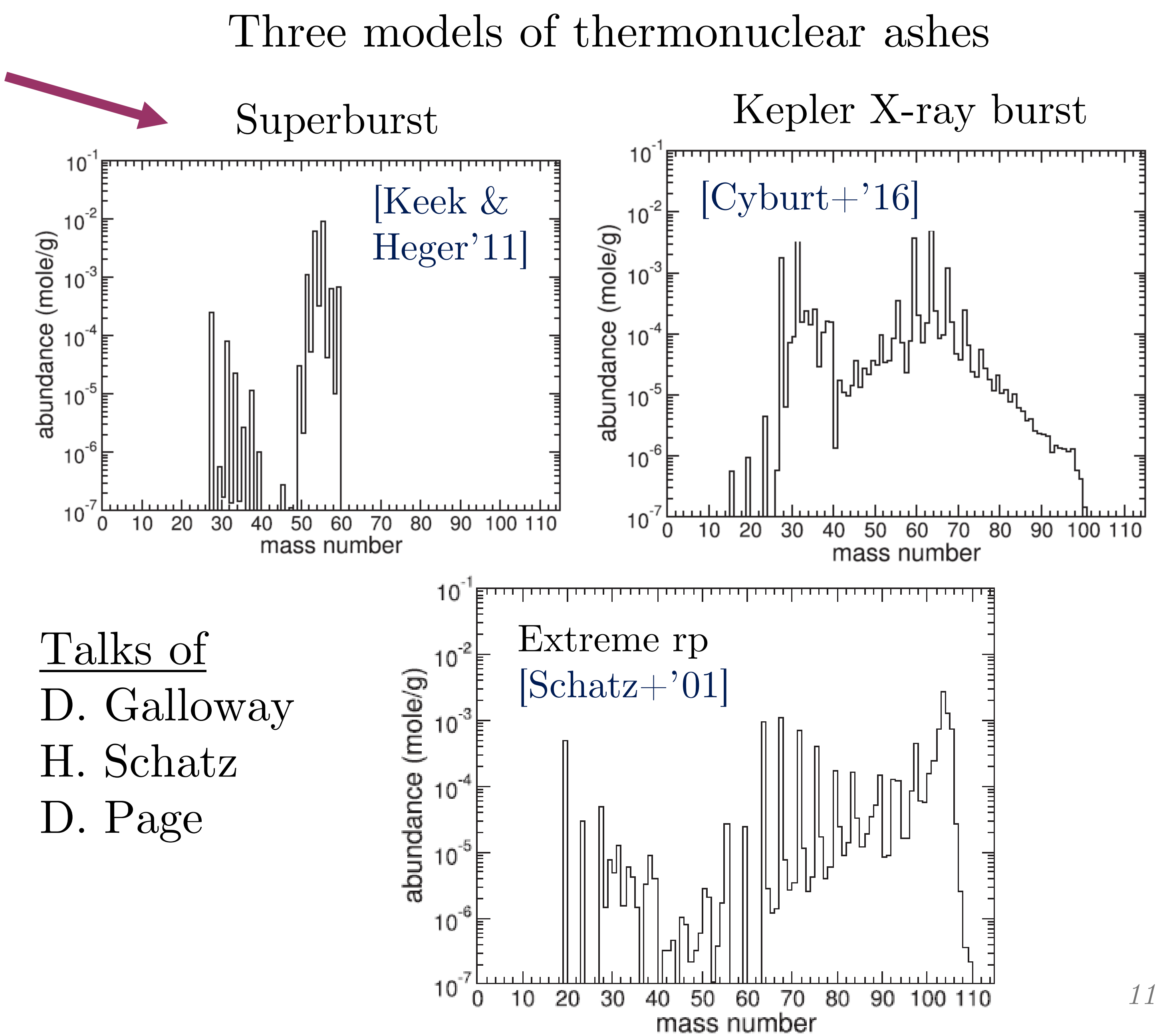
$$\Delta h \cdot g m_u \approx (m_{b,Fe} e^{\nu_s/2} - m_{b,Fe} e^{\nu_s^{cat}/2})$$

$Q_{tot} \approx 0.5$ MeV/baryon



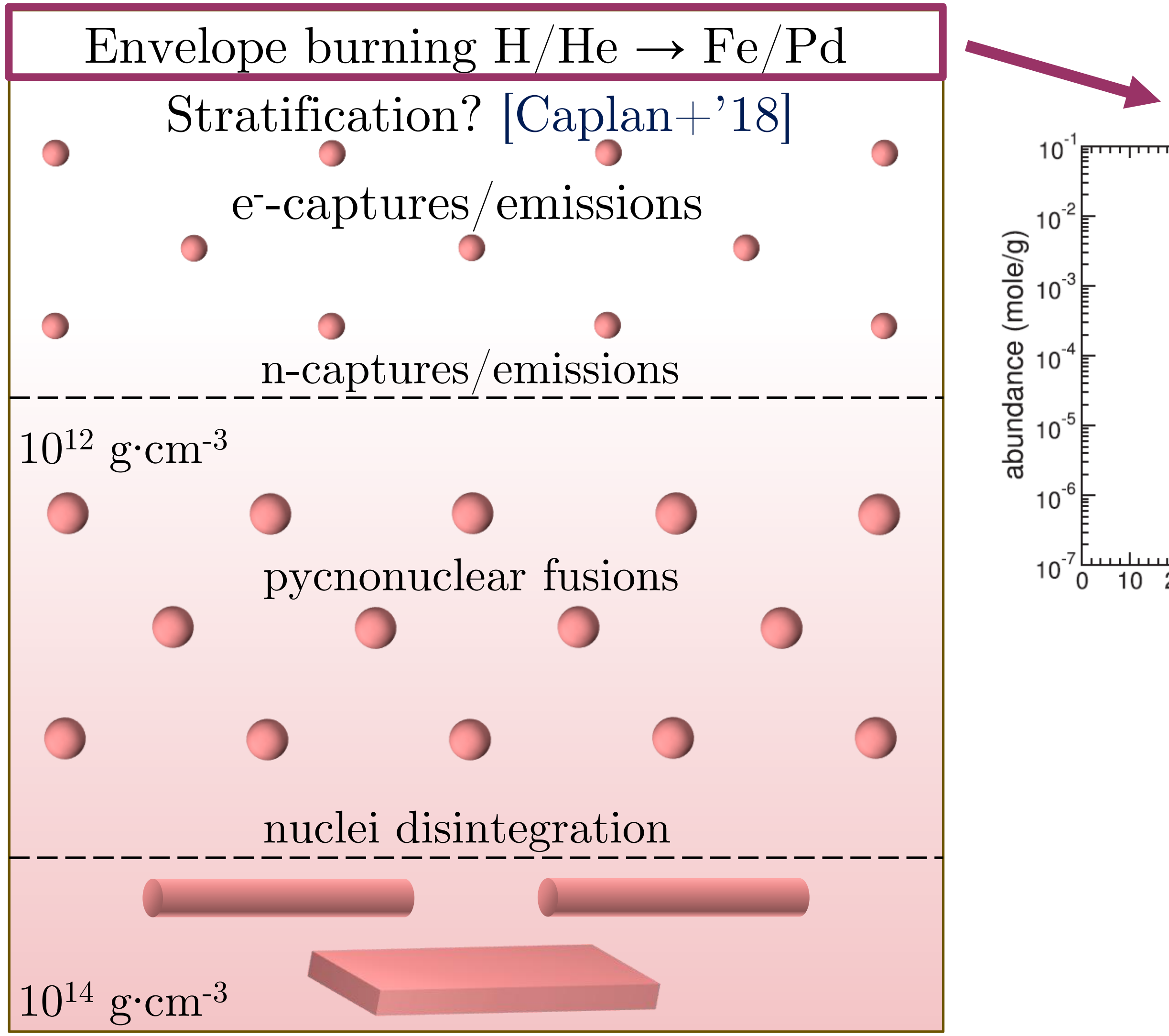
Initial composition for the crustal simulations





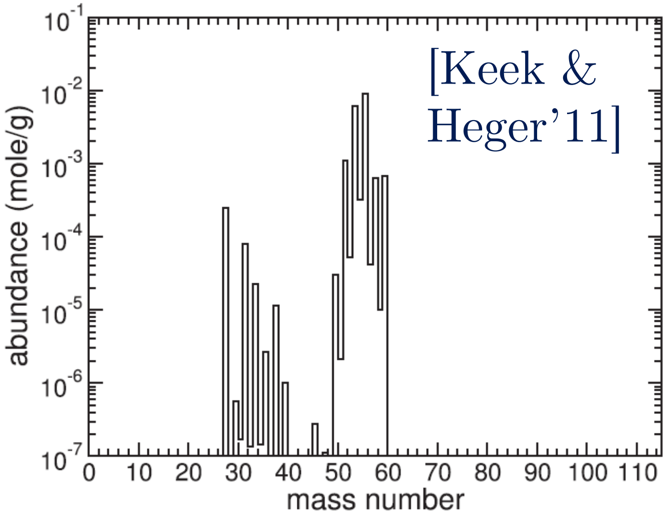
Talks of
D. Galloway
H. Schatz
D. Page

Initial composition for the crustal simulations

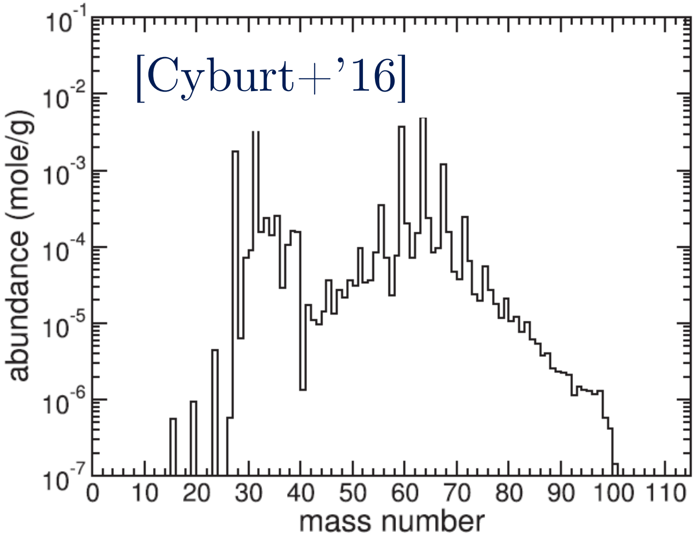


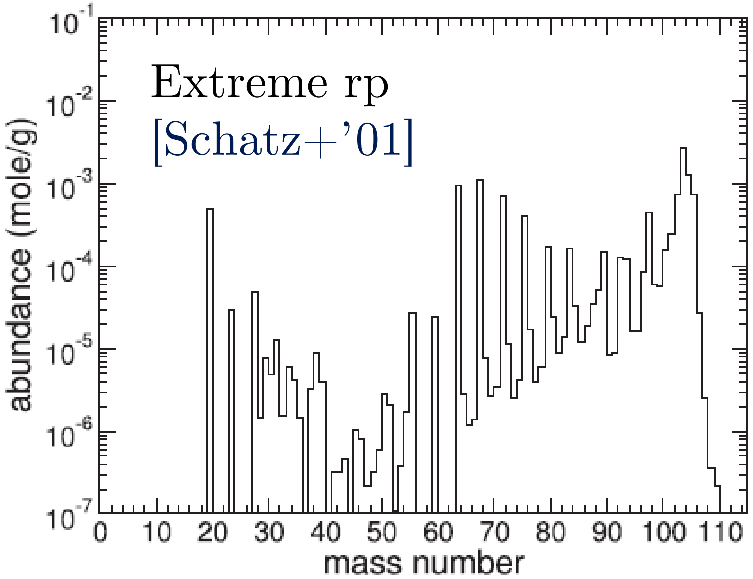
Three models of thermonuclear ashes

Superburst

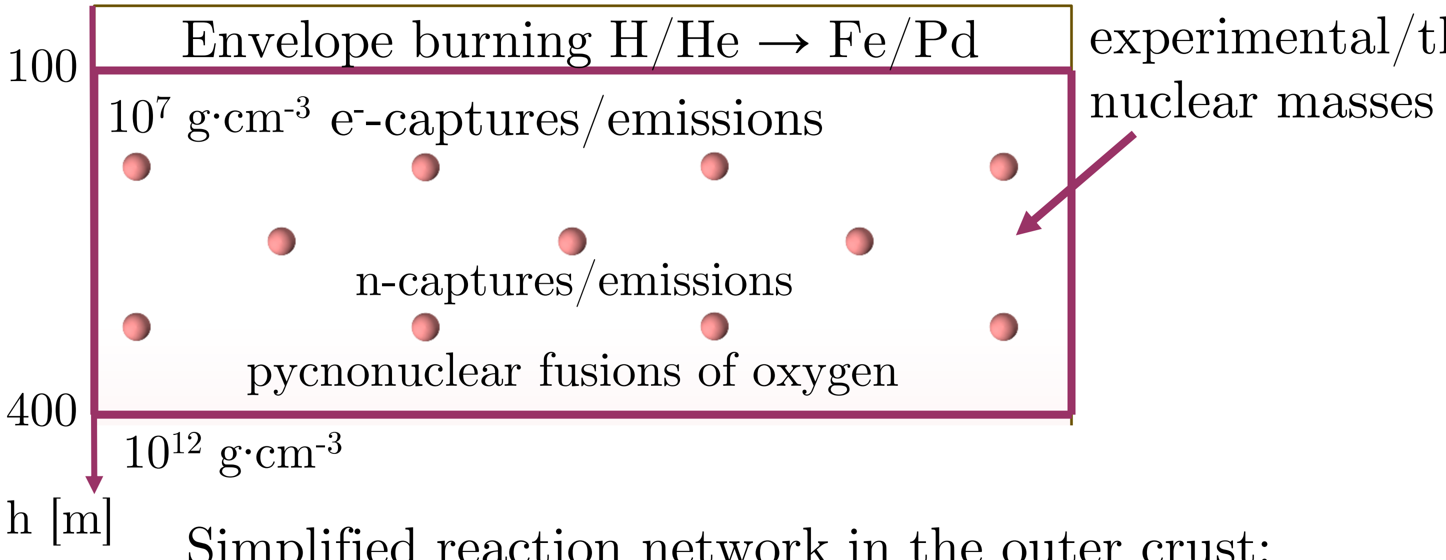


Kepler X-ray burst



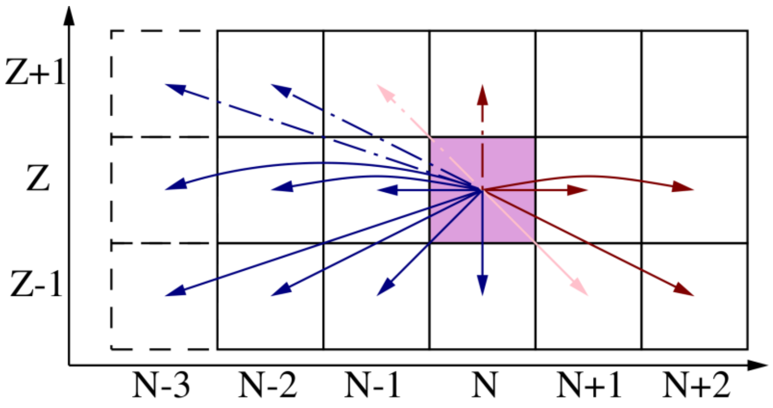


Evolution in the outer crust

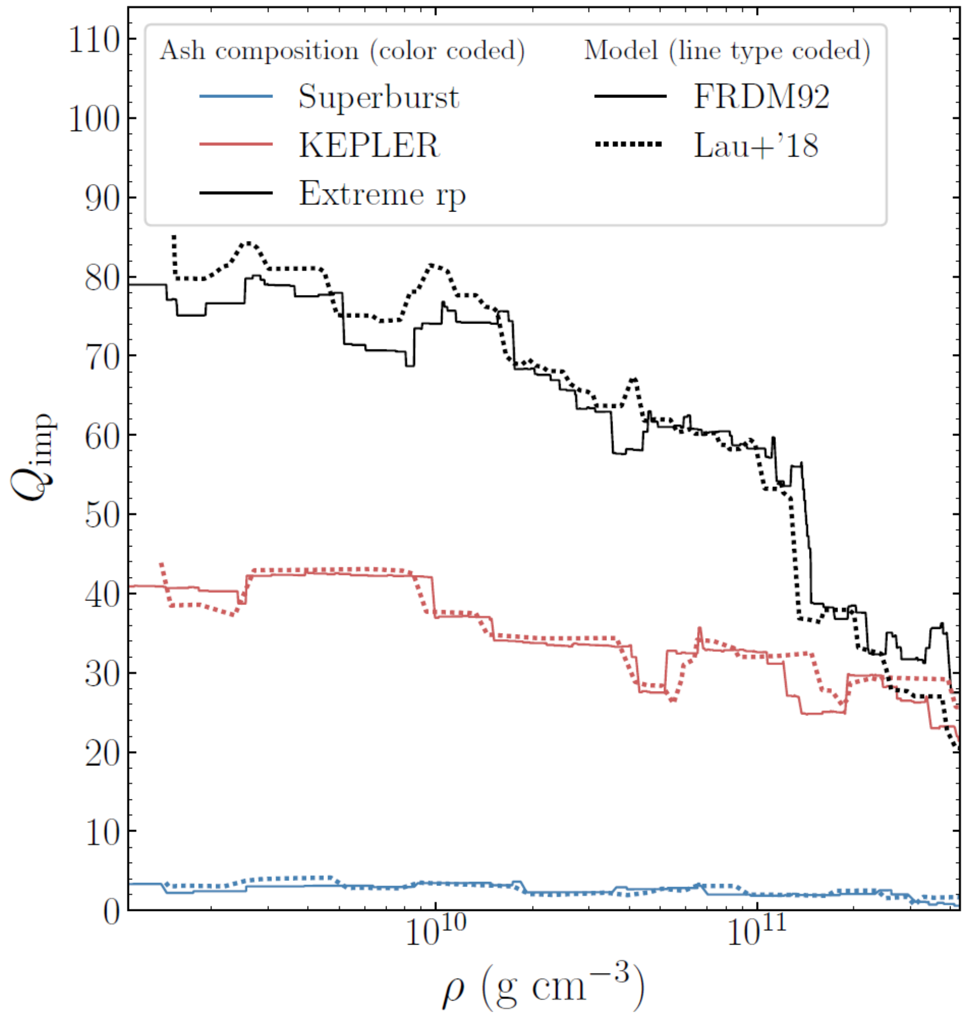


Simplified reaction network in the outer crust:

- Check for allowed reactions (min Gibbs energy)
- Small part of nuclei reacting according to the priority rules (based on τ_{reac})
- Increase the pressure



Comparison with [Lau+'18]



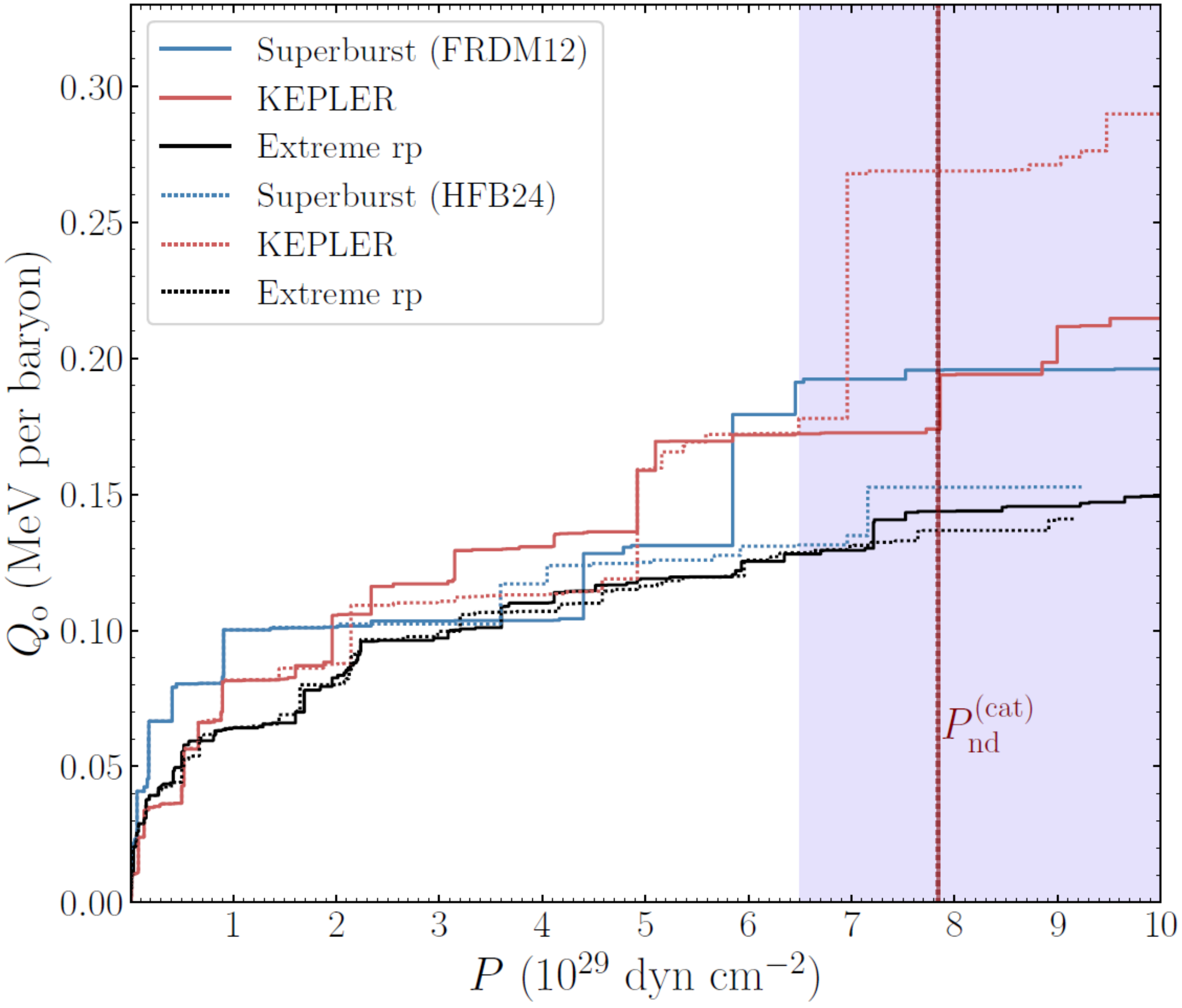
[NS, Gusakov, Chugunov'21]

Heating in the outer crust

Total accumulated heat in the **outer crust** with experimental masses AME2020 plus HFB24/FRDM12 theoretical mass evaluations

- Superburst $Q_o \approx$ **0.15-0.20** MeV/baryon
- Kepler $Q_o \approx$ **0.17-0.26** MeV/baryon
- Extreme rp $Q_o \approx$ **0.12-0.15** MeV/baryon

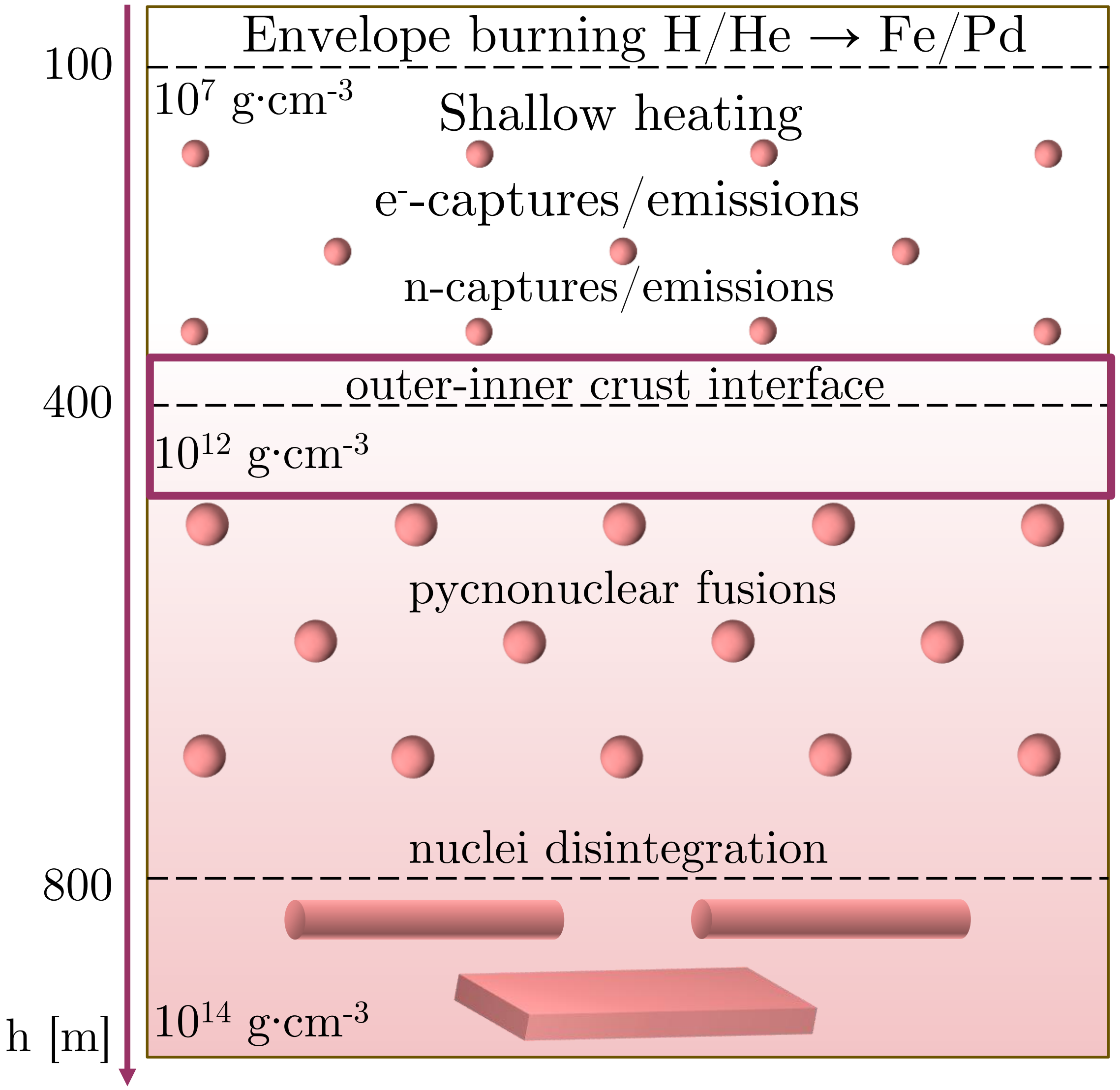
Heat distribution in the outer crust



<u>Without neutrino cooling and shallow heating!</u>

[NS, Gusakov, Chugunov'21]

Transition to the inner crust



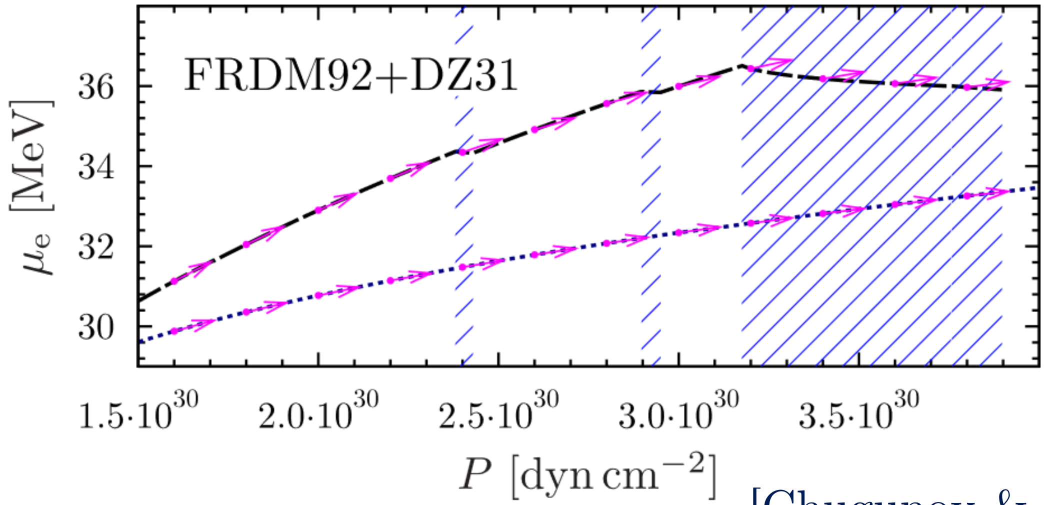
Traditional approach

- Compression till neutrons become abundant (not captured by the neighboring nuclei)
- Keeping neutrons in the compressed volume

Such crust can not exist!

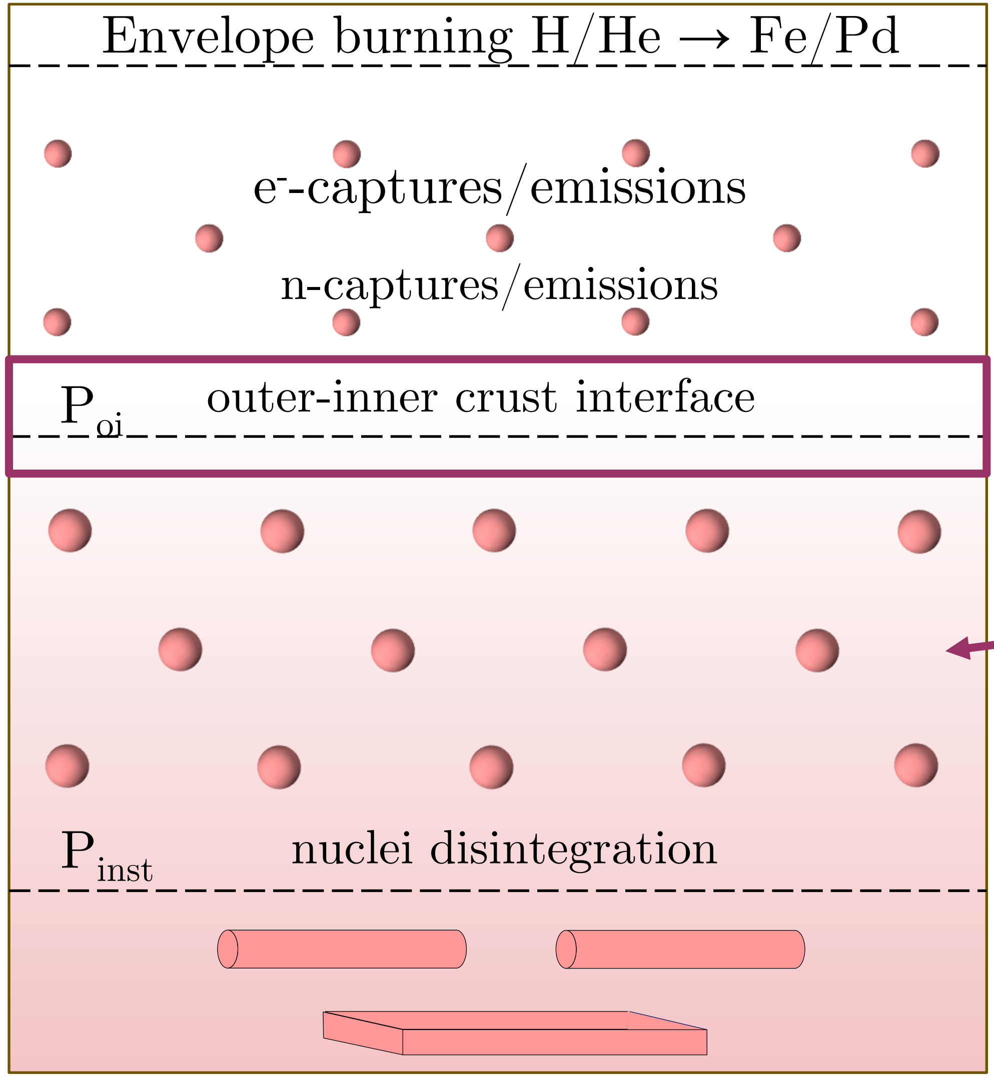
In the regions of active neutron emission electron chemical potential decreases violating the force balance

$$Z\nabla\mu_e\downarrow - m_i g \neq 0$$



[Chugunov & NS'20]

Transition to the inner crust



$\mu_n^\infty = m_n e^{\nu_{oi}/2}$

$\mu_n^\infty = \mu_{b,core}^\infty$

Neutron Hydrostatic and Diffusion (nHD) equilibrium superfluidity/rapid diffusion allows considering static picture in the limit of fast redistribution of neutrons

$$\mu_n^\infty = const$$

Unbound neutrons form a 'sea'

On course of accretion nuclei sink in the sea of neutrons

Thermodynamic analyses [Gusakov & Chugunov'24] shows

$$P_{oi} \lesssim P_{nd}^{(cat)}$$

Evolution in the upper layers of the inner crust

Nuclei sink in the sea of neutrons

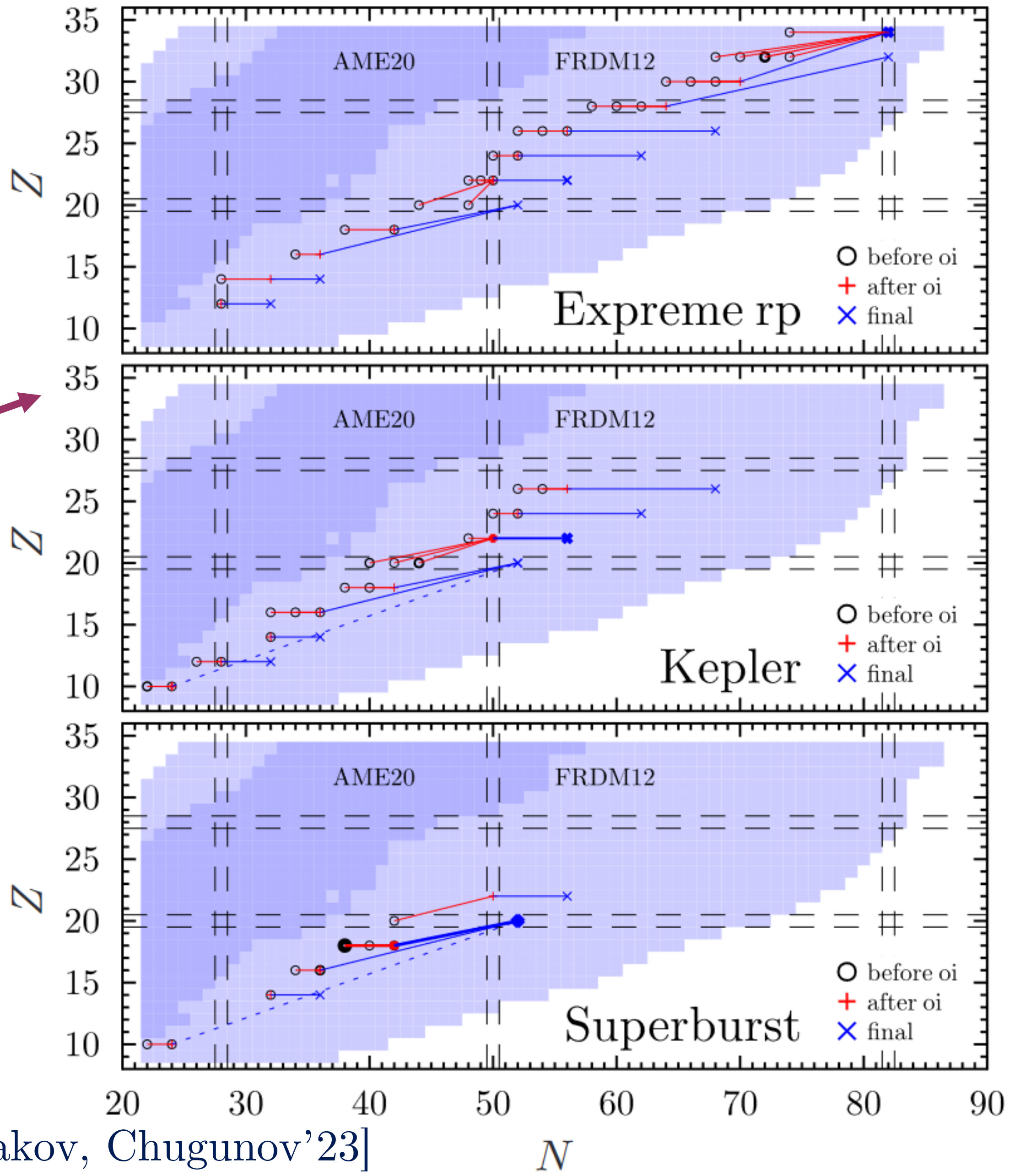
Main reactions at the oi interface:

- neutron captures
- electron emissions

In this shallow layers nuclei mass tables are still applicable [Lau+'18]

Catalyzed crust nuclei have Z ≈ 40

<u>In contrast to the traditional approach, for which reverse reactions dominate</u>



[NS, Gusakov, Chugunov'23]

Evolution in the upper layers of the inner crust

Simplified reaction network in the inner crust:

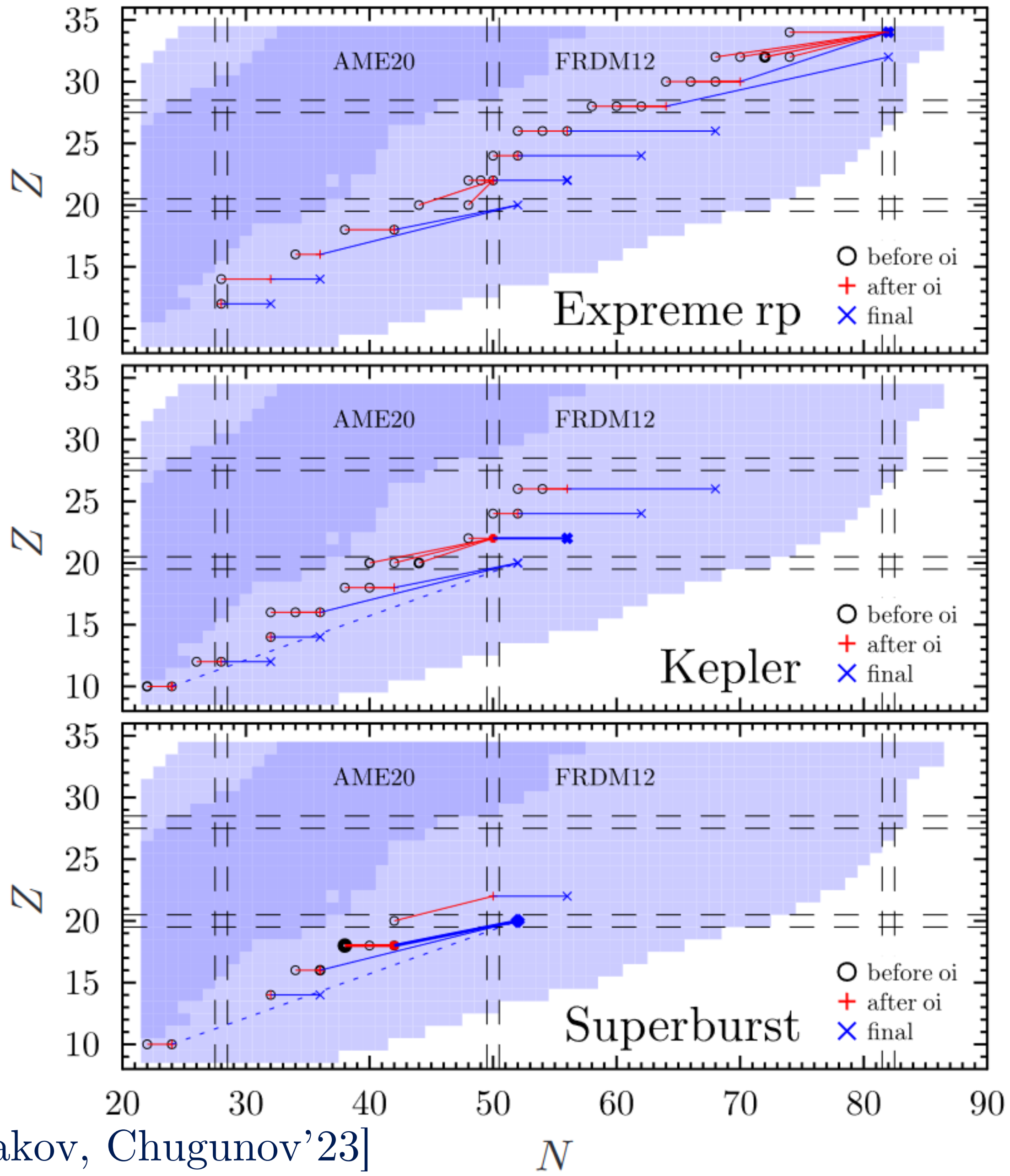
- Check for allowed reactions, which minimize $\Psi = G - \mu_n N_b$

  [Gusakov, Kantor, Chugunov'21]
- Small part of nuclei reacting according to the priority rules (based on τ_{reac})
- Increase the pressure and μ_n

Main reactions at the oi interface:
- neutron captures
- electron emissions

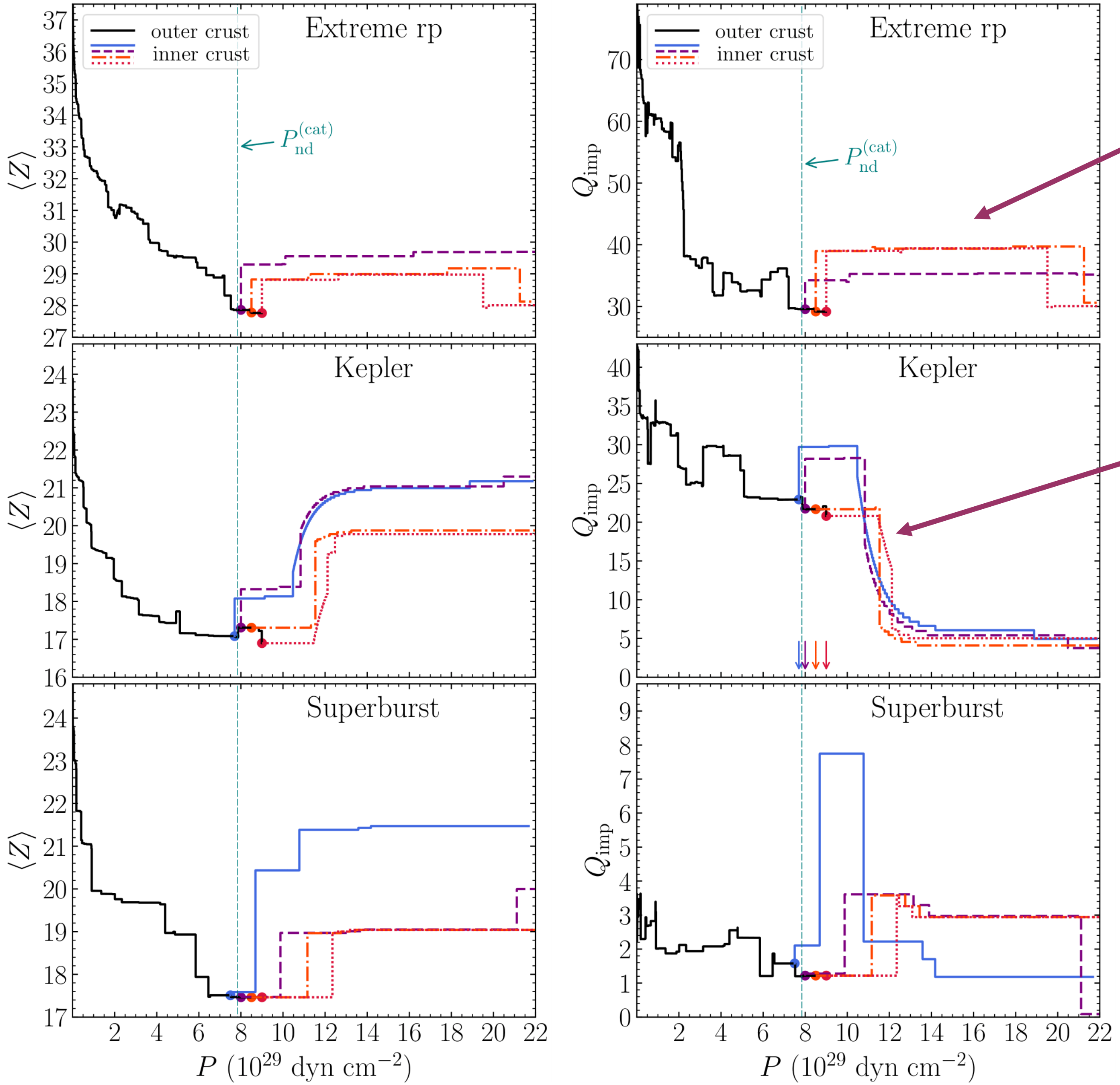
Pycnonuclear fusions play some role only for Kepler ashes

<u>In contrast to the traditional approach, for which reverse reactions dominate</u>



[NS, Gusakov, Chugunov'23]

Evolution in the upper layers of the inner crust

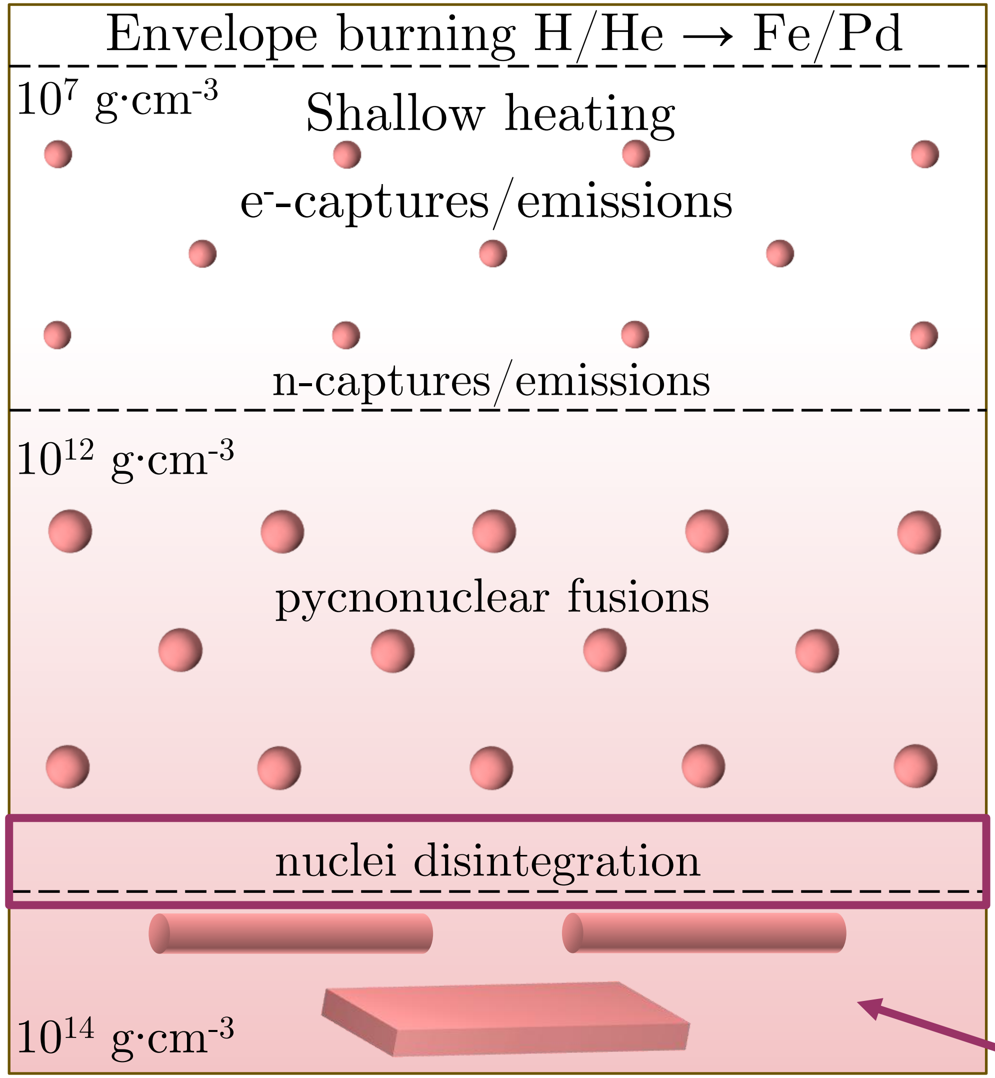


For Extreme rp ashes Q_{imp} stays high

Pycnonuclear fusions purify the crust only for Kepler ashes

[NS, Gusakov, Chugunov'23]

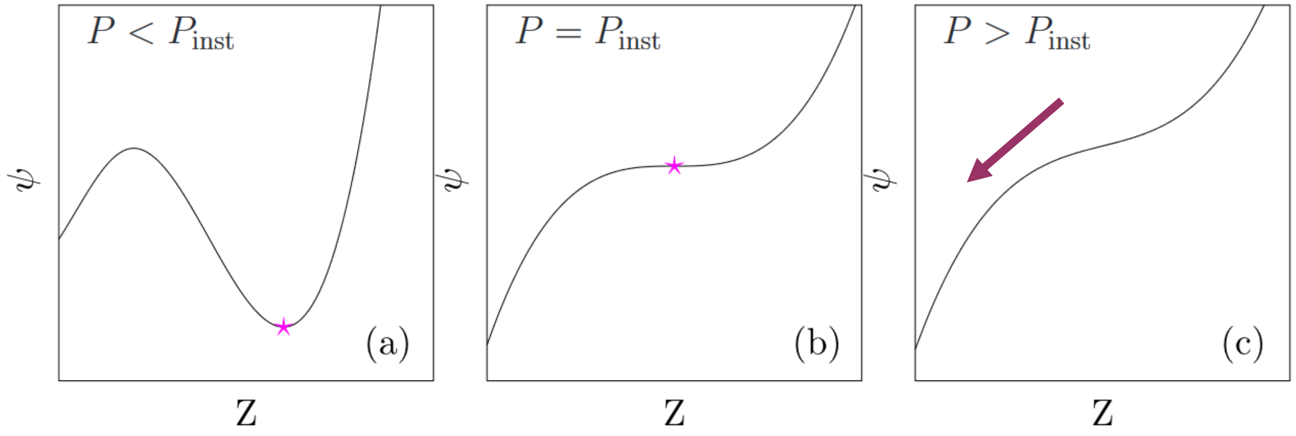
Transition to the core



P_{oi}

P_{inst}

Absence of minimum in potential ψ signals instability



[Gusakov &Chugunov'24]

Nuclei are converted into the *npe* matter by unstoppable electron capture cascades (and possible pycnonuclear fusions)

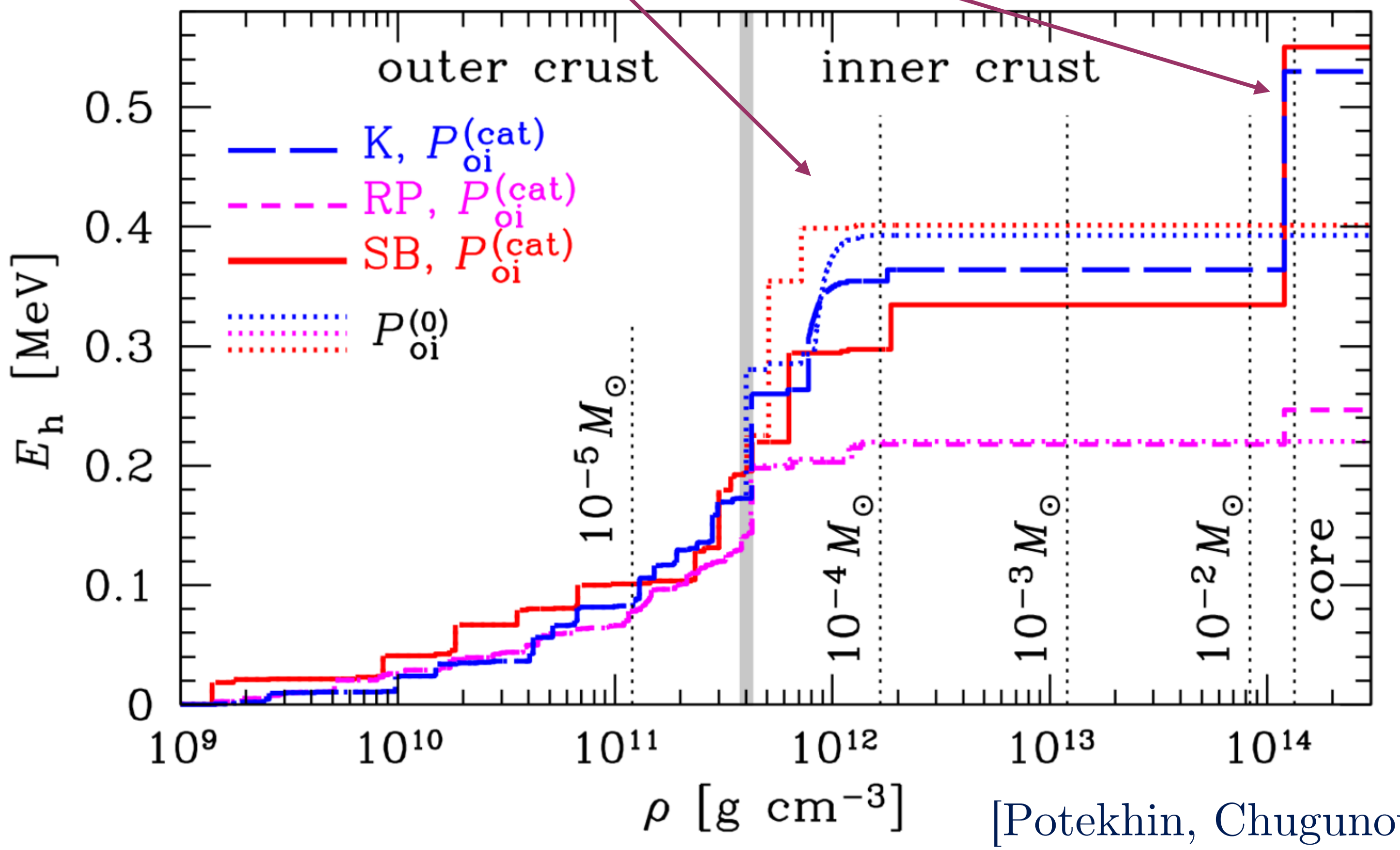
[Gusakov & Chugunov'24]: most of the heat in the inner crust is released at the instability point $Q_{inst} \gtrsim 0.05$ MeV per baryon

Some relic layer consisting of nuclear pasta can survive?

Heat profile in the crust

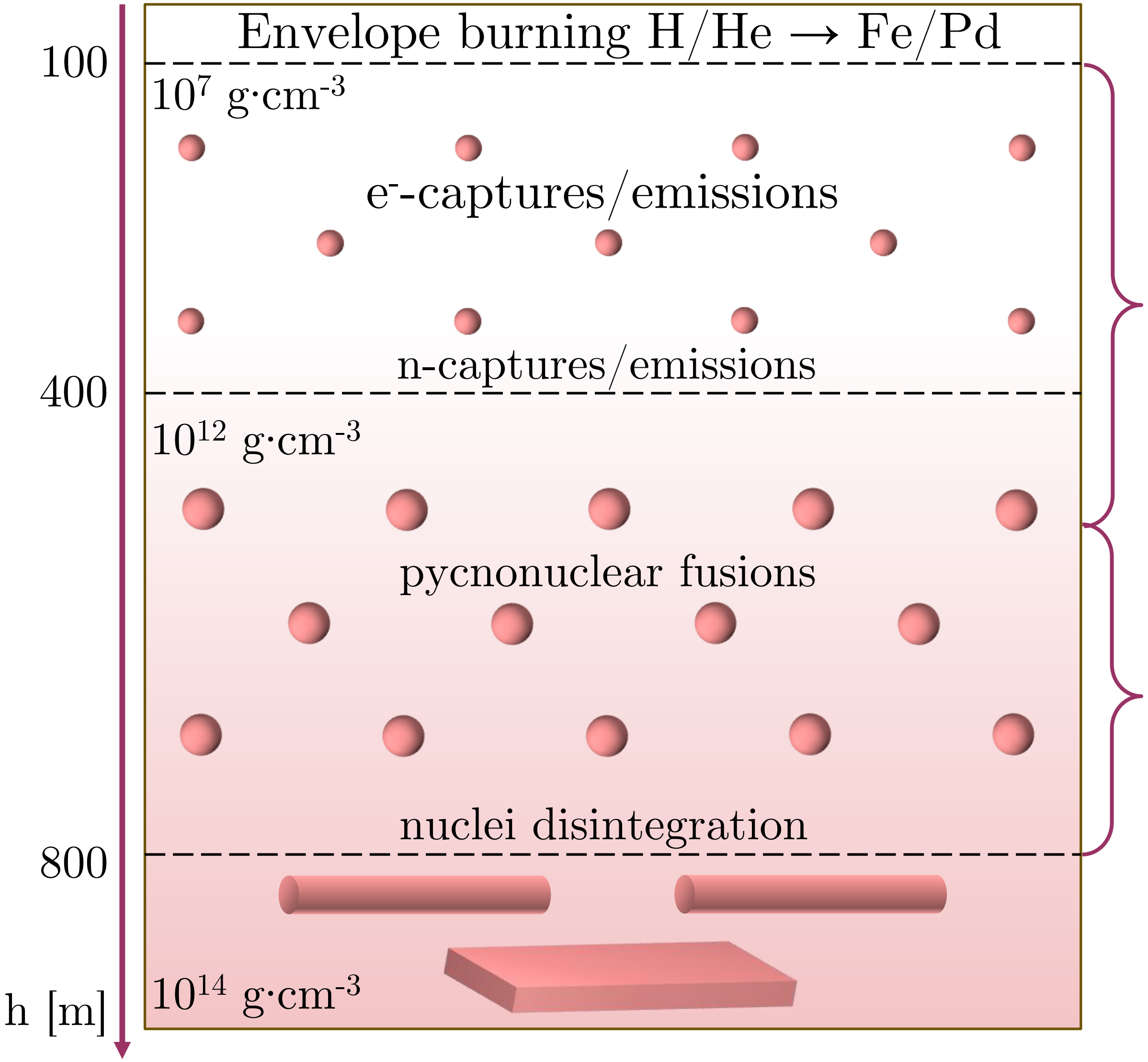
Main reactions are near the outer-inner crust transition and at the crust-core interface

Total heat release
- Kepler and Superburst ashes $Q_{tot} \approx$ **0.5** MeV/baryon
- Extreme rp $Q_{tot} \approx$ **0.2** MeV/baryon



[Potekhin, Chugunov, NS, Gusakov'24]

Accreted crust models



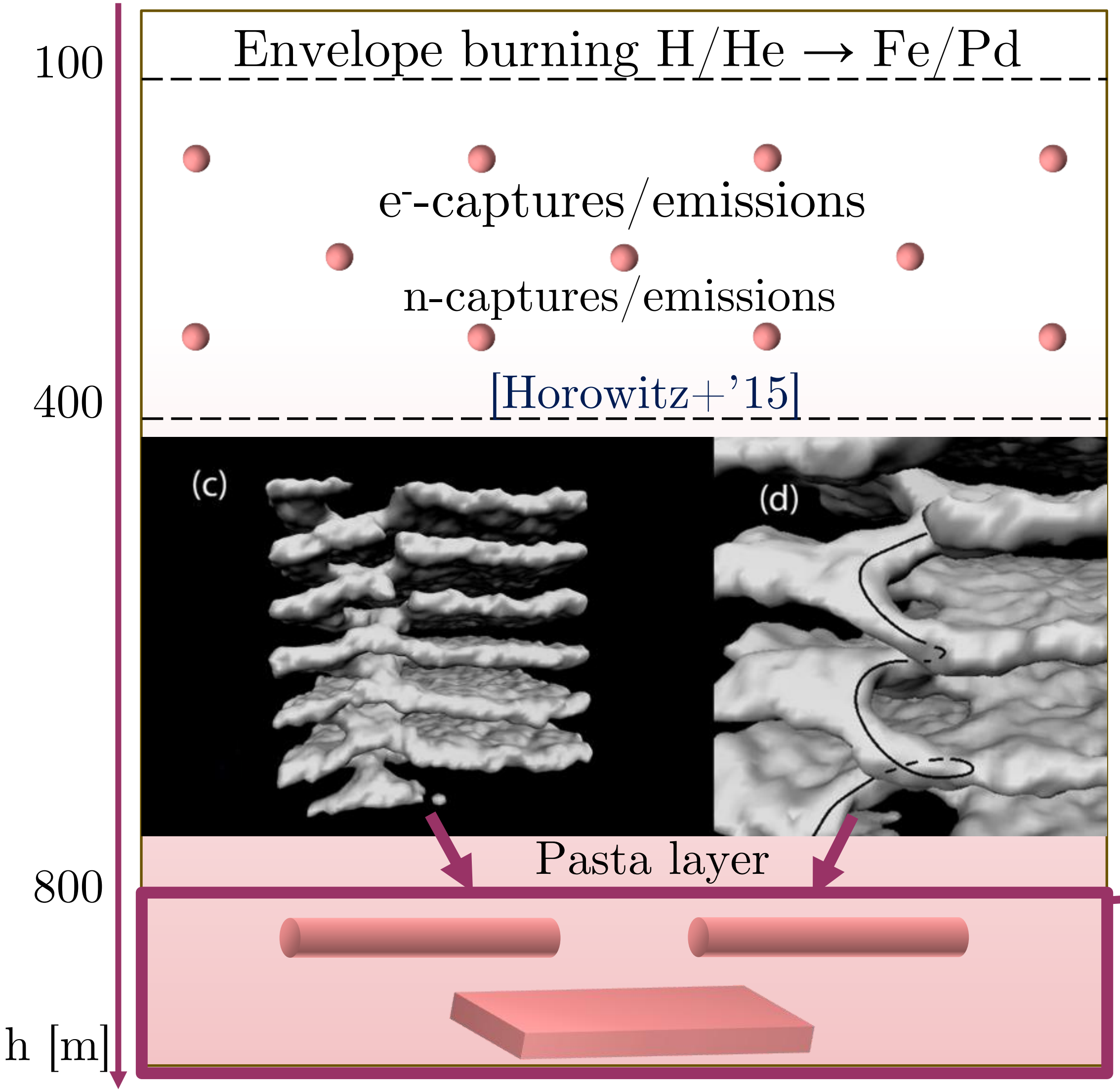
Evolution of multicomponent composition with FRDM12 and heating sources are available at https://www.ioffe.ru/astro/NSG/accrust/

[NS, Gusakov, Chugunov '21,22,23]

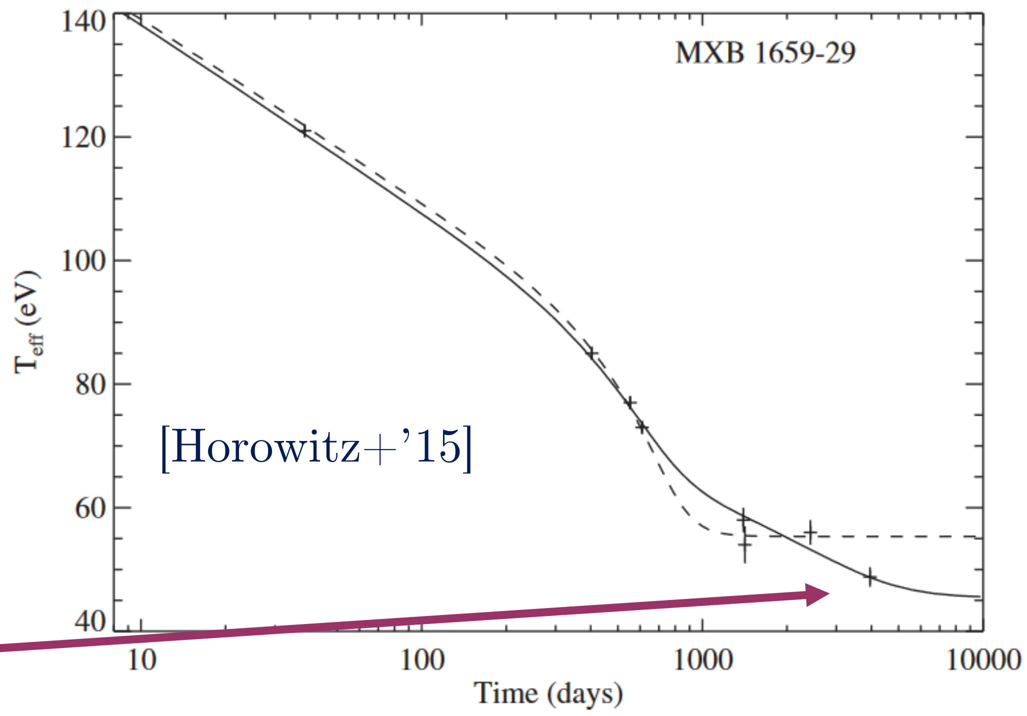
One-component CLDM+Shell effects

[Gusakov & Chugunov '24]

Pasta imprints on the cooling curve



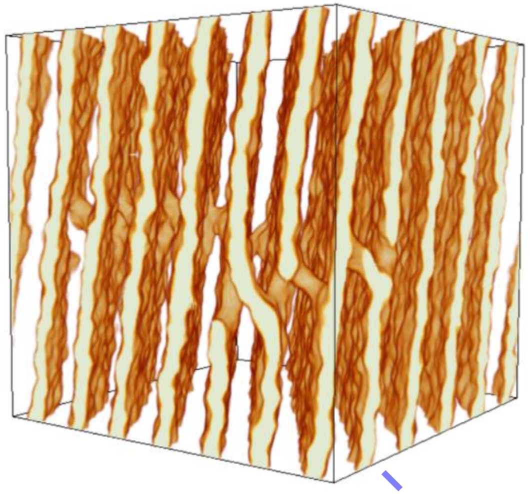
Topological defects in molecular dynamic simulations point towards low-conductivity layer in the crust bottom (typically modelled with $Q_{imp} \approx 40$)

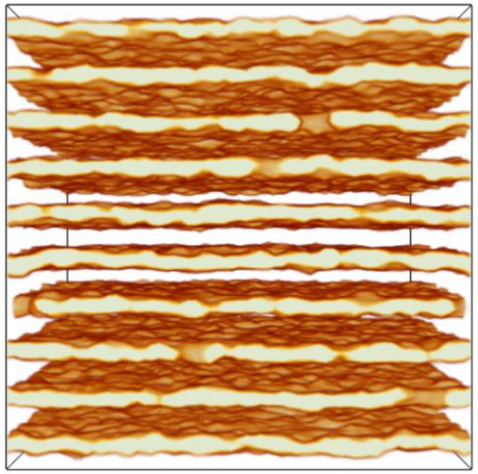


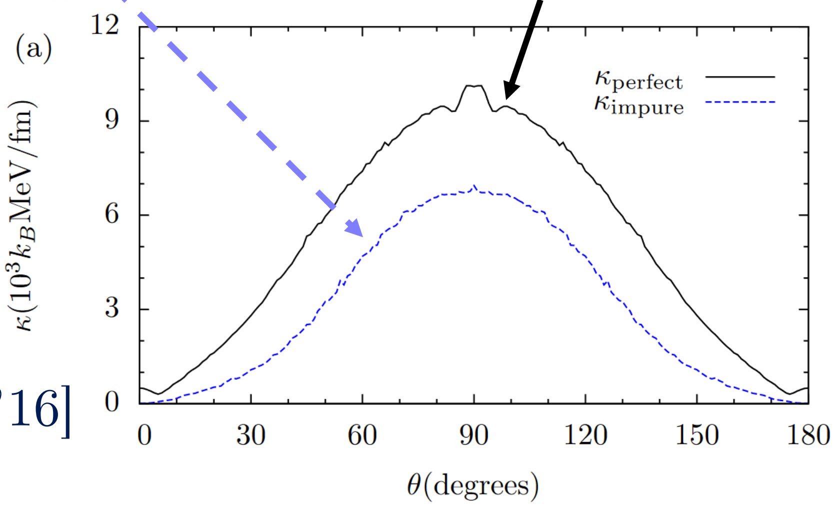
Talk of N. Chamel for explanation with gapless superfluidity

Do pasta have lower conductivity?

Classical molecular dynamics (point-like particles) **VS** **Quantum molecular dynamics** (Gaussian wave-packets)

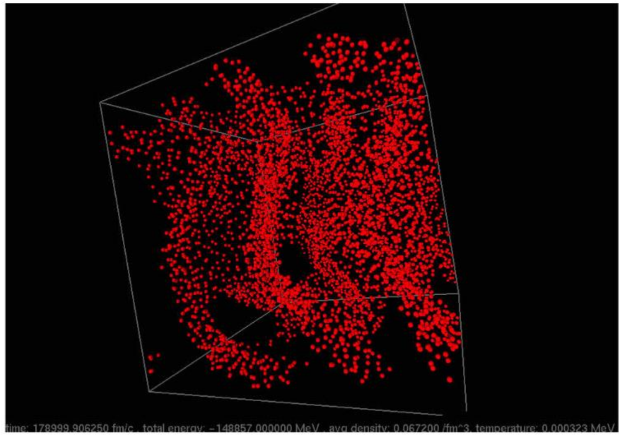


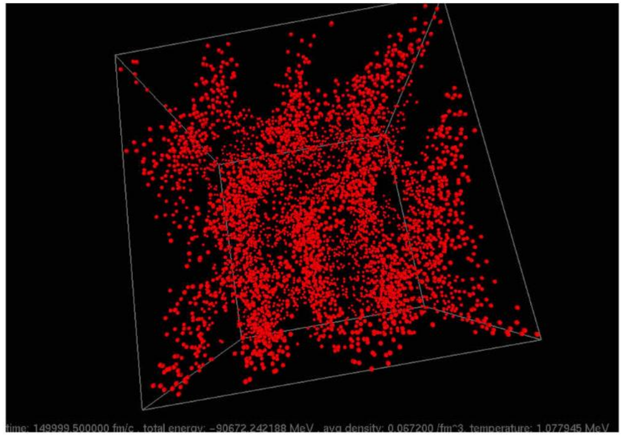




[Schneider+'16]

Suppressed conductivity for impure lasagna,
$n_b = 0.05$ fm^{-3}, T= 1 MeV, $Y_p = 0.4$, N ≈ $4{\cdot}10^5$





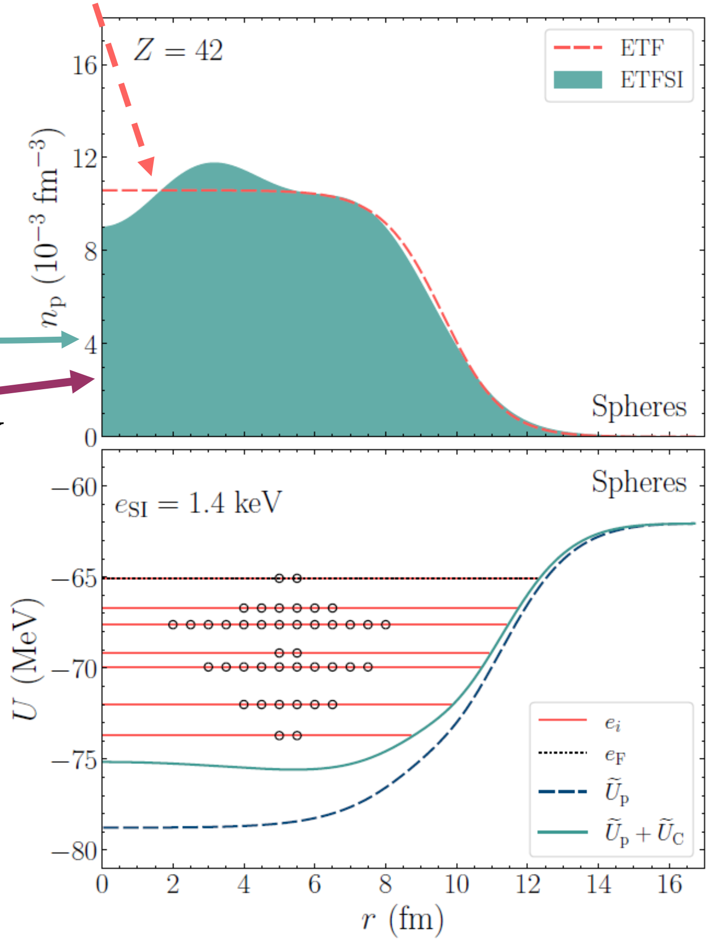
$n_b = 0.064$ fm^{-3}, T= 0,1 MeV, $Y_p = 0.3$, N ≈ $1.6{\cdot}10^4$

[Nandi & Schramm '18] the effect of pasta is not dramatic for the transport properties

Do we have sizable amount of **pasta at all**?

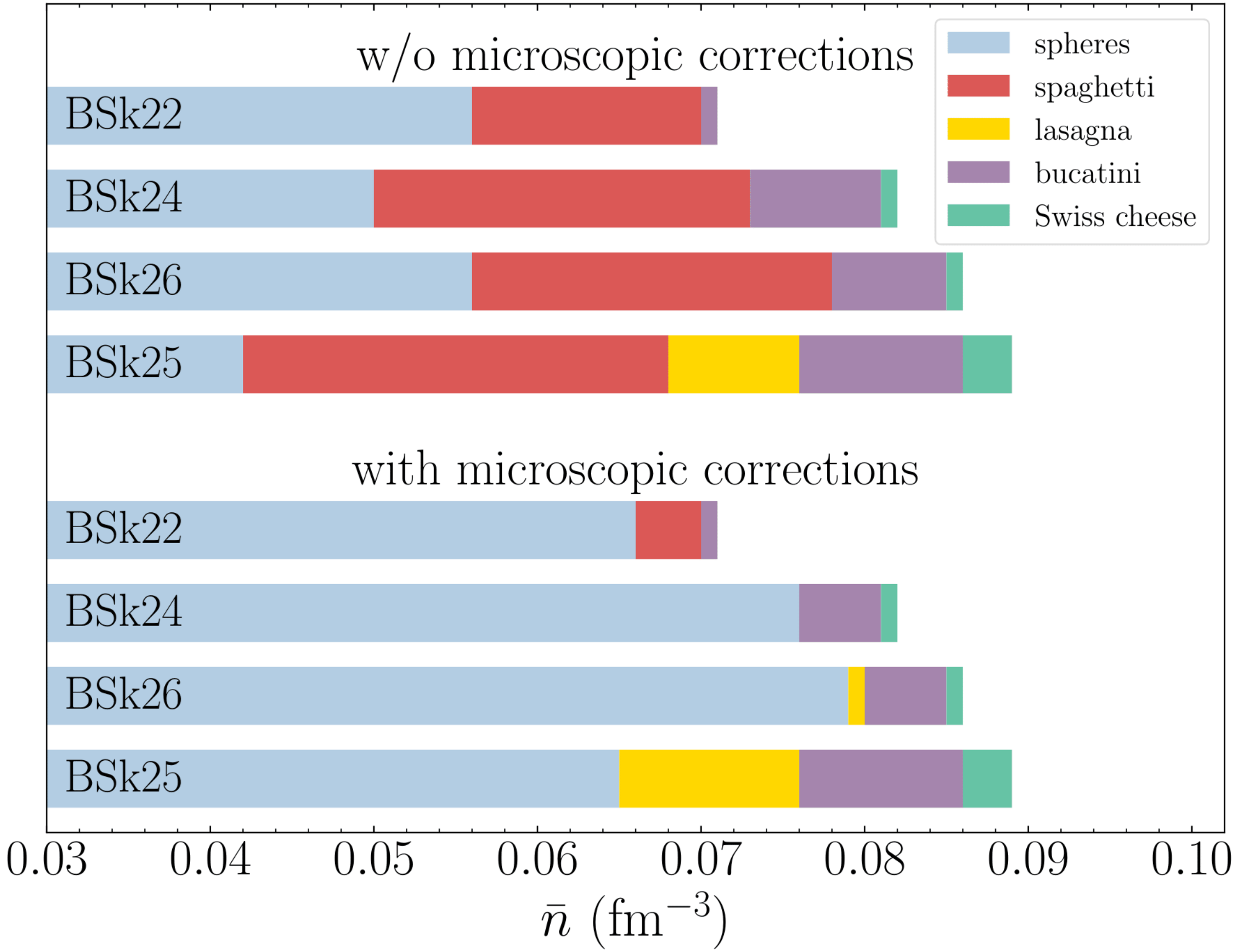
With perturbative method for adding microscopic (shell + pairing) corrections on top of semi-classical calculations

Proton density distribution



[NS, Chamel, Pearson, Chugunov, Potekhin '24]

Shrinking of pasta layer with microscopic corrections



Pasta sequence in the mantle

[NS, Chamel, Pearson '23]

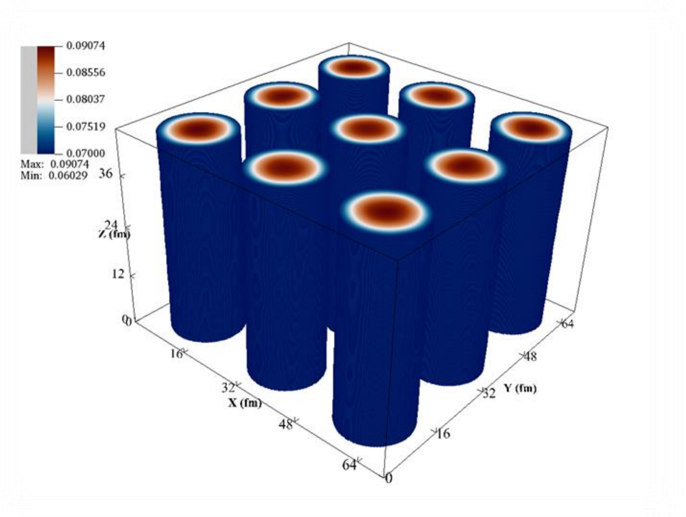
3D HF+BCS in the mantle

In attempt to **systematically study pasta phases in large domains within fully microscopic framework** we generalize 3D HFB code MOCCa [Ryssens, Heenen, Bender '15]

Proof of principle example:
Iterative procedure for calculating spaghetti shape using ETFSI solution as a guide

n_b=0.07 fm^{-3}, N=16164, Y_p=0.033

Preliminary



[NS, Ryssens, Chamel]

Using spatial symmetries

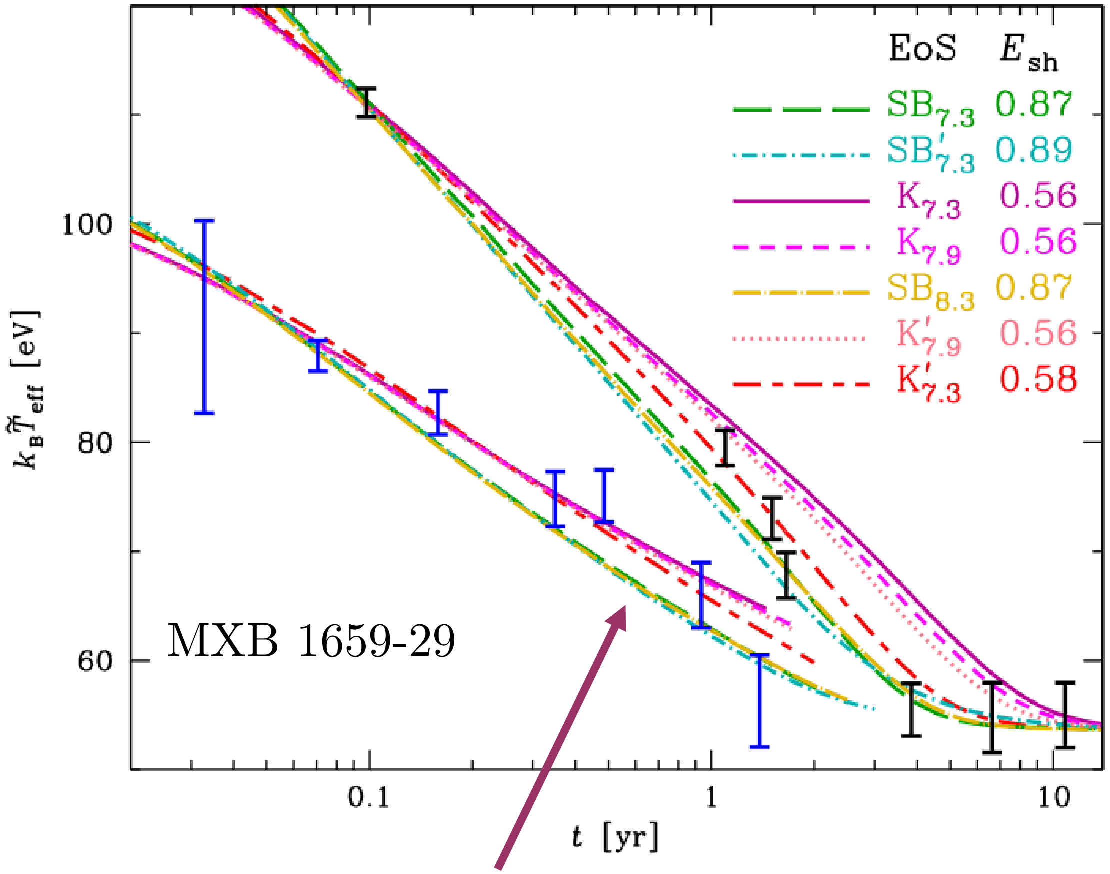
Conclusions

- We developed multicomponent simplified reaction network for the accreted crust considering **neutron hydrostatic and diffusion equilibrium** condition.
  In contrast to the traditional approach:
  - Total deep crustal heating amounts only to **0.2-0.5 MeV** per baryon
  - Outer-inner crust transition and equation of state is close to the catalyzed crust
  - Pycnonuclear reactions purify the composition only if initial ashes were abundant in light elements (A $\approx$ 30)

- It is **uncertain whether the pasta** layer possesses **reduced thermal conductivity** and whether it **exists at all**. To provide more definitive answer within **fully microscopic framework** at large scales we generalized 3D HFB code MOCCa and made **proof-of-principle calculations**. More results are coming...

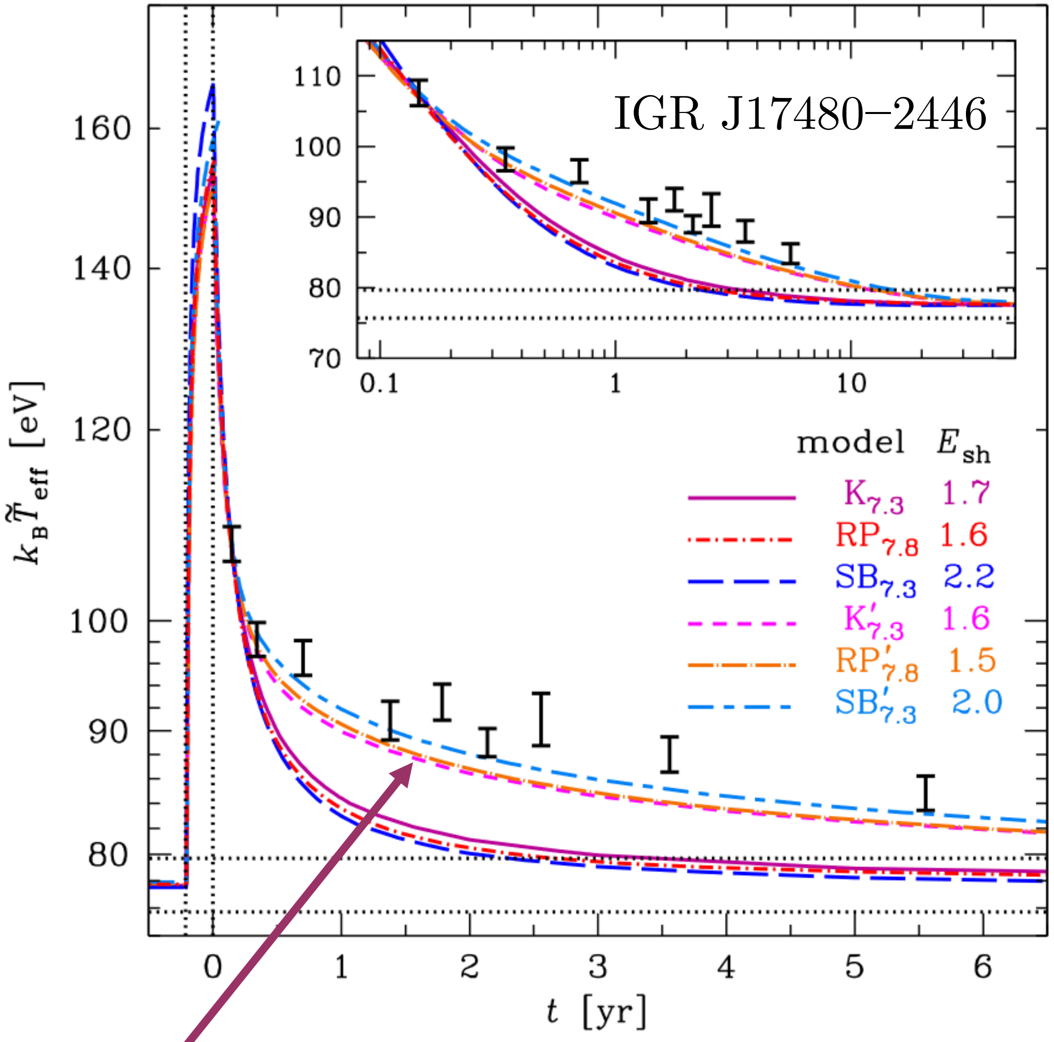
Cooling with realistic crust composition and heating

[Potekhin, Chugunov, NS, Gusakov'24]



Explained with pure ashes

- superburst?
- partially accreted crust?



Disordered layer is required with $Q_{imp} = \langle Z \rangle^2$