Crust of accreting neutron stars

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A.I. Chugunov & N.N. Shchechilin, **MNRAS:Lett.**, 495, L32 (2020)
M.E. Gusakov & A.I. Chugunov, **Phys. Rev. Lett.**, 124, 191101 (2020)
M.E. Gusakov & A.I. Chugunov, **Phys. Rev. D:Lett.**, 103, L101301 (2021)
M.E. Gusakov, E.M. Kantor & A.I. Chugunov, **Phys. Rev. D:Lett.**, 104, L081301 (2021)
N.N. Shchechilin, M.E. Gusakov & A.I. Chugunov, **MNRAS**, 507, 3860 (2021)
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A.Y. Potekhin, M.E. Gusakov & A.I. Chugunov, **MNRAS**, 522, 4830 (2023)
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M.E. Gusakov & A.I. Chugunov, **Phys. Rev. D,** 109, 123032 (2024)

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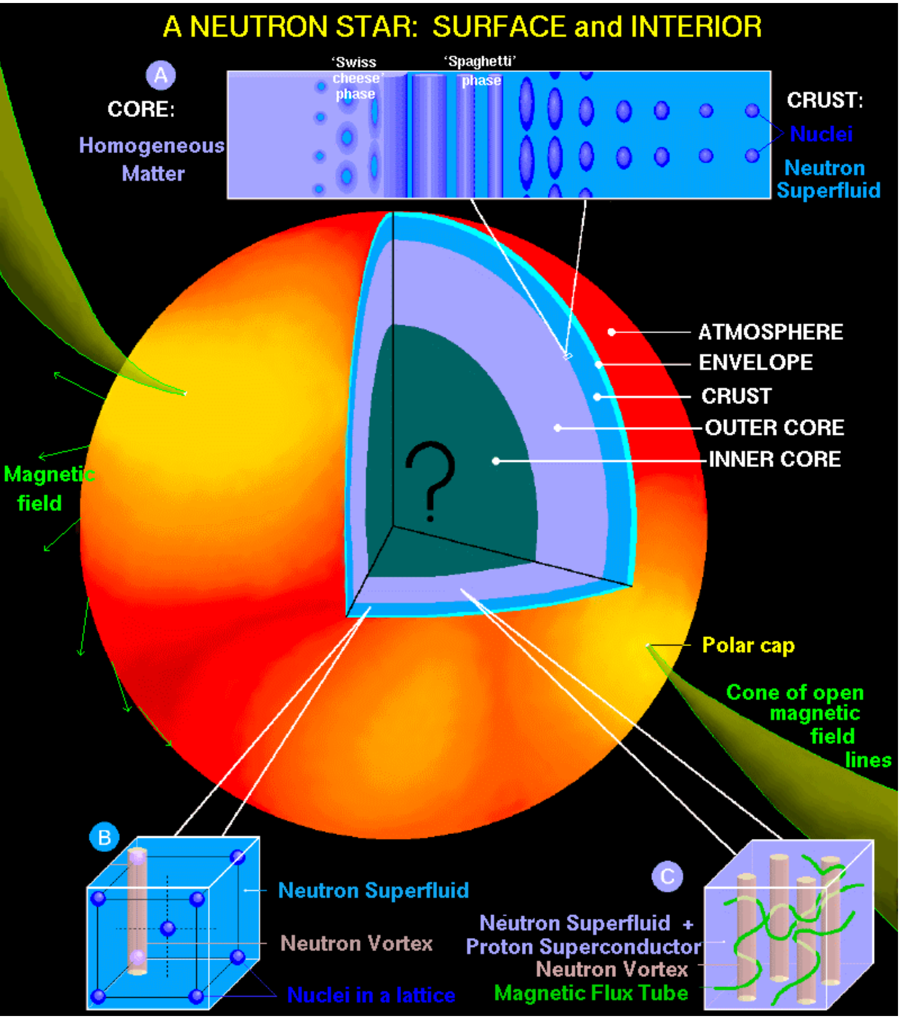
Motivation: neutron stars



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$R \sim 12\ \mathrm{km},\ M \sim 1.4 M_\odot$

$$\rho \sim 10^{15}\ \mathrm{g/cm^3}$$

$$T \lesssim 10^{9}\ \mathrm{K}$$

$$B \sim 10^{12}\ \mathrm{G}$$

$$g \sim 10^{14}\ \mathrm{cm/s^2}$$

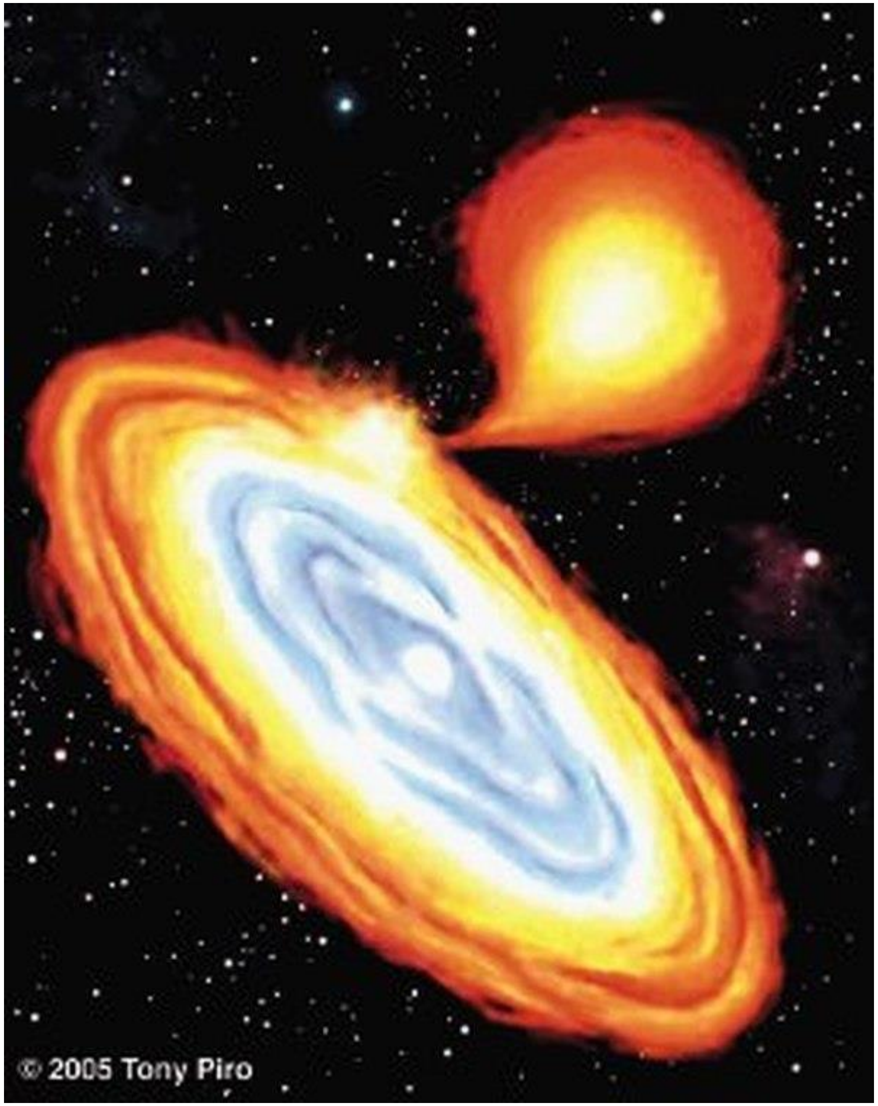
$$R \sim 2R_{\mathrm{g}} = 4GM/c^2$$

$$T_{\mathrm{cp}} \sim 10^{9}\ \mathrm{K}$$

$$T_{\mathrm{cn}} \sim 10^{8}\ \mathrm{K}$$

Observations of neutron stars allow to check theory of the dense matter

Motivation: accreting neutron stars



Many neutron stars accrete, i.e., have a closely located companion and matter flows from the companion to the neutron star.

During the "quiescence" period, thermal emission is observed (from some of these neutron stars); it is possible to track the thermal evolution in real time!!!

Information on the properties of neutron star matter

Motivation: the crustal models are crucial

To calculate thermal evolution one needs:

- Heating power and its distribution
- Thermal conductivity
- Specific heat
- Structure (thickness of the crust)
- …

Crustal models
(heating and profile, composition, …)
is a key to interpret thermal emission,
observed from accreting neutron stars

Motivation

Crustal models
(heating and profile, composition, …)
is a key to interpret thermal emission,
observed from accreting neutron stars

The essence of the work

- The previously used (1979+) approach to crustal modeling neglects an essential phenomenon (neutron redistribution between crustal layers), which means that the results obtained with its help may be incorrect (use of incorrect results may lead to errors in interpretation of observations).
- An approach, allowing for redistribution of neutrons is formulated, respective models are constructed
- It is shown that the physical processes occurring in the crust are qualitatively different from the previous works

What happens to matter after accretion?

Traditional approach: nuclear reactions driving by compression

$^{56}\mathrm{Fe}, \quad e^-$
$^{56}\mathrm{Cr}, \quad e^-$
$^{56}\mathrm{Ti}, \quad e^-$
$^{56}\mathrm{Ca}, \quad e^-$
$^{56}\mathrm{Ar}, \quad e^-$
$^{52}\mathrm{S}, \quad e^-, \quad n$
$^{46}\mathrm{Si}, \quad e^-, \quad n$

1. Thermonuclear reactions in the surface layers lead to the formation of heavy elements ("ashes")
2. Continued accretion compresses the underlying matter
3. Compression leads to beta-captures

$$^{A}_{Z}X + e^- \rightarrow ^{A}_{Z-1}X + \nu_e$$

4. Beta captures increase fraction of neutrons
5. At a certain pressure, beta-capture leads to neutron emission

$$^{A}_{Z}X + e^- \rightarrow ^{A-1}_{Z-1}X + n + \nu_e$$

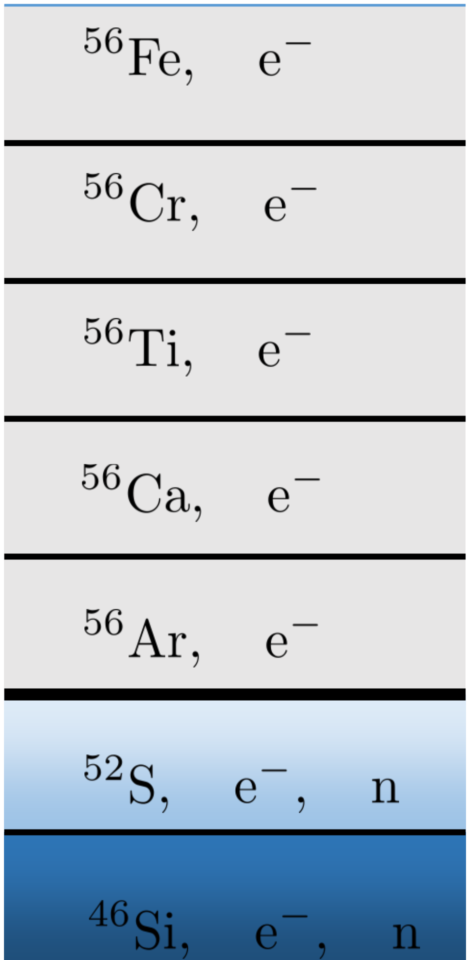
6. Fully accreted crust consists of matter at different stages of compression

Initial problem: Initial composition (ashes) determine whole evolution

Transition to inner crust is determined by neutron drip $P_{\mathrm{oi}} = P_{\mathrm{drip}}$

Что происходит с веществом после аккреции?

Традиционный подход: ядерные реакции при сжатии вещества



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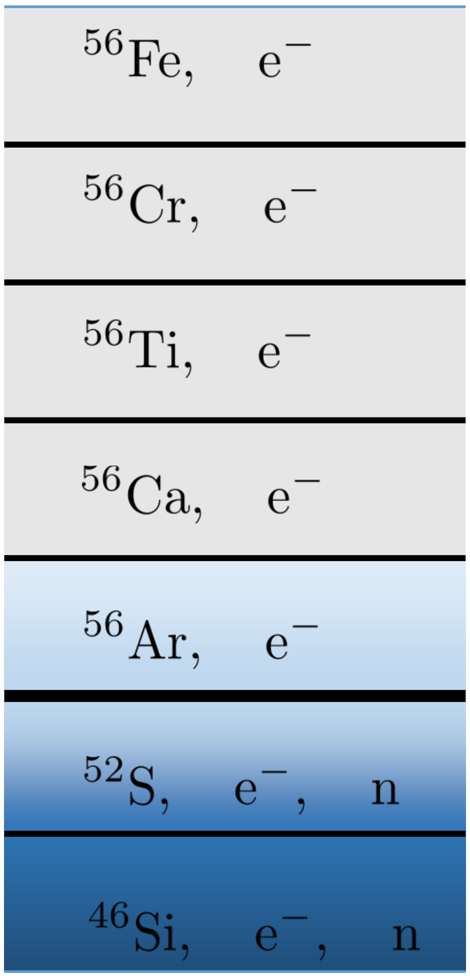
Unbound neutrons are not in equlibrium in the inner crust
Redistribution between layers is energetically favourable

Что происходит с веществом после аккреции?

Традиционный подход: ядерные реакции при сжатии вещества



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A.I. Chugunov & N.N. Shchechilin, **MNRAS:Lett.**, 495, L32 (2020)

Even if traditional crust is constructed ‘by hands’, neutrons start to move and redistribute themselves. The structure of the crust will be changed.

Where does accreted crust end? At the instability!

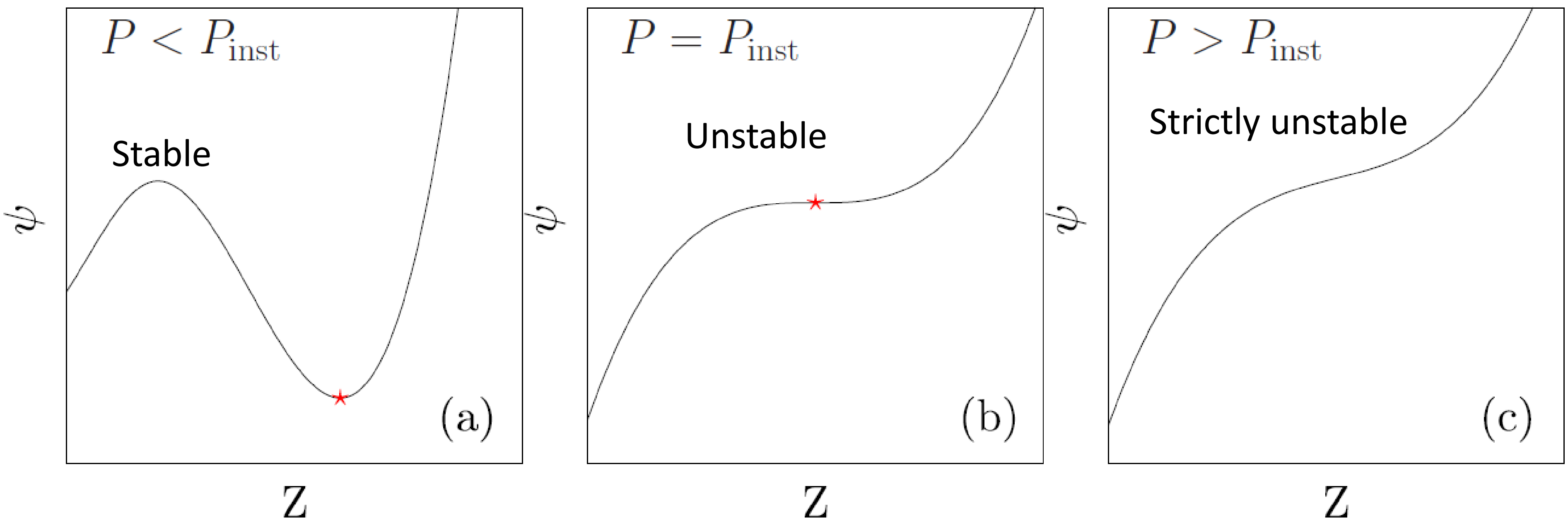
<u>Construction of the crust within nHD approach:</u>

Increase P and μ_n + minimization of the appropriate thermodynamic potential Ψ

One component example:

$\psi(Z)$ with grow of P

Can be minimized | Can not be minimized | Can not be minimized



Instability:

Nuclei dissociation as a result of beta-capture/neutron emission sequence

Similar instability without neutrons:
G. S. Bisnovatyi-Kogan&V. M. Chechetkin, Astrophys. Space Sci. 26, 25 (1974).

How to chose P_{oi}?

M.E. Gusakov & A.I. Chugunov, **Phys. Rev. Lett.**, 124, 191101 (2020)

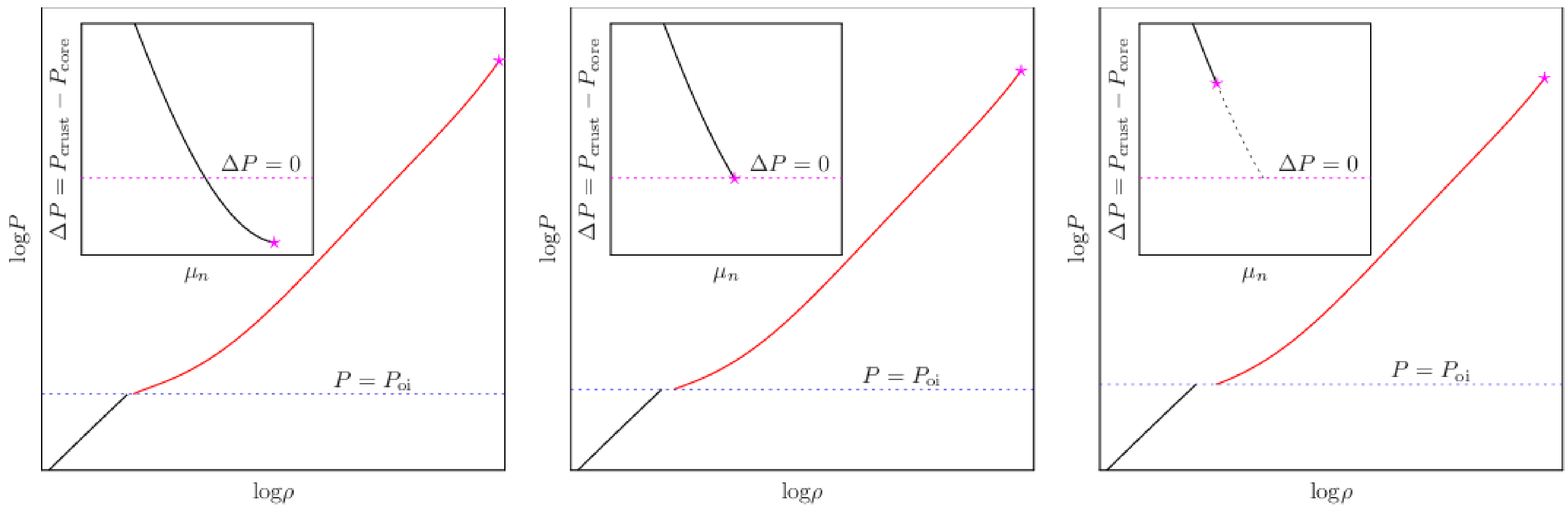
- Accretion supply nuclei into the crust
- Instability dissociate nuclei => stationary structure is possible
- We need to describe neutron star: a boundary between crust and the core should be thermodynamically stable (continuous pressure and neutron chemical potential)

Formation of fully accreted crust:

- Instability is active (and compensate nuclei supply by accretion)
- Crust is thermodynamically consistent with the core

Construction of FAC EOS via shooting method

Depend on nuclear physics of innermost crustal layers. Example: (smooth) SLY4 case



<u>Can not be FAC state</u>

The instability does not take place in the crust

P_{oi} is too low

<u>The FAC state</u>

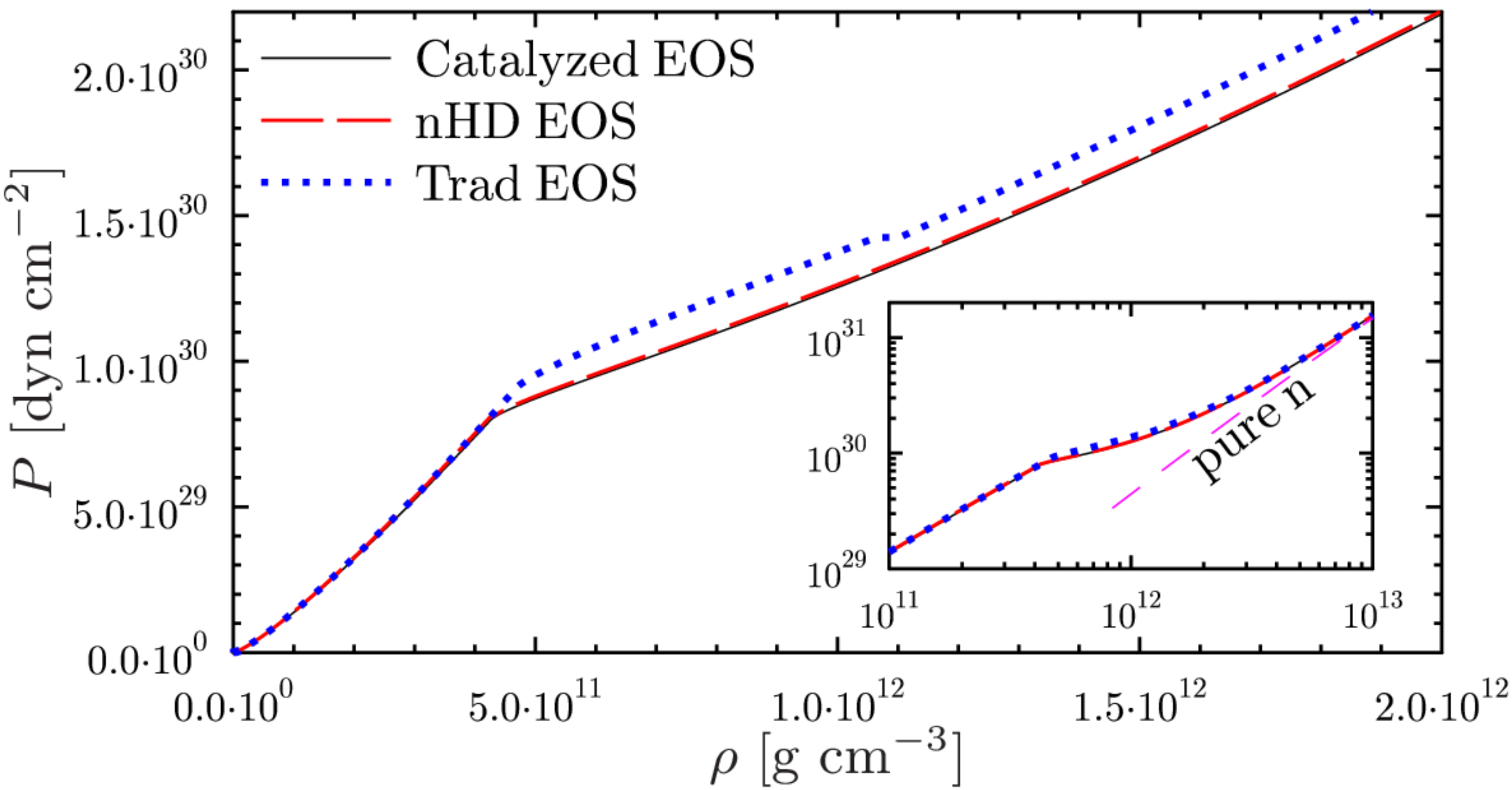
The instability take place exactly at the crust-core boundary

<u>Can not be FAC state</u>

The instability takes place, but crust EOS can not be connected with core

P_{oi} is too high

Equation of state of fully accreted crust



M.E. Gusakov & A.I. Chugunov, **Phys. Rev. Lett.** 124, 191101 (2020)

Accreted neutron star crust

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(almost) everything is not as it was generally believed

- Boundary of outer and inner crust is not associated with neutron emission
- The main reactions in outer layers of inner crust is electron emission and neutron capture
- There is an upward flow of neutrons (to compensate neutron capture)
- Stationary structure of the crust is supported by instability

(sorry, it’s not the end. The remaining part is about energetics)

Heating power

M.E. Gusakov & A.I. Chugunov, **Phys. Rev. D:Letters**, 103, L101301 (2021)

$$\langle H \rangle = \frac{q}{m_u} \langle \dot{M} \rangle$$

<u>«Book-keeping» approach:</u>
(previously applied)

Total heating
=
Sum of the heat in each reaction

$$q = \sum_i q_i$$

Require detailed information on all reactions

<u>Thermodynamic approach</u>

To assumptions:

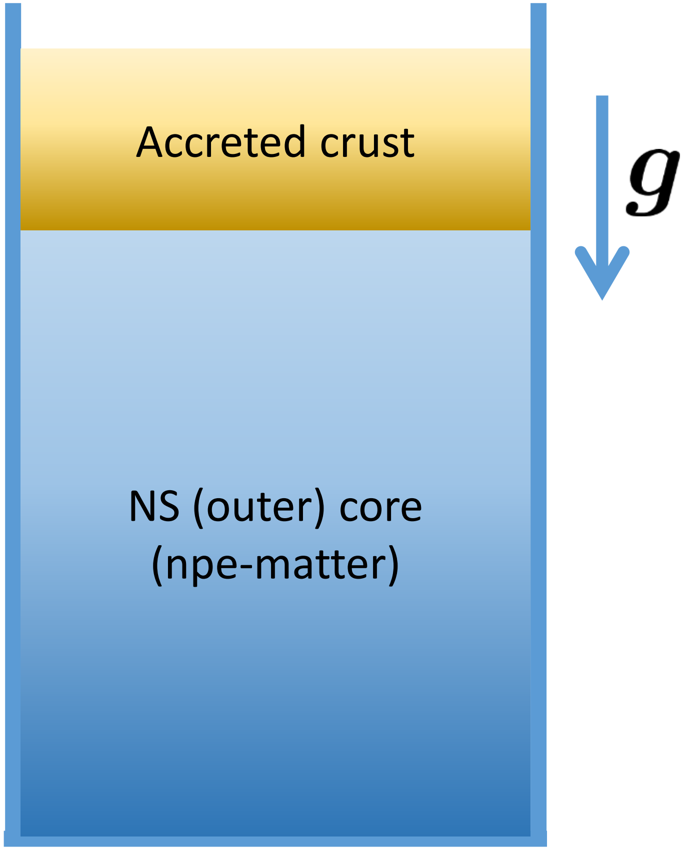
- *Equilibrium composition of the core*
- *Stationary structure of the crust*

$$q^{\infty} \quad = \quad \mu_{b,\mathrm{H}}\, e^{\nu_{\mathrm{s}}/2} - \mu^{\infty}_{b,\mathrm{core}}$$

Detailed information on kinetics is not required

Agrees with «book-keeping» approach

Heating efficiency: general consideration



Plane-parallel consideration (to simplify presentation)

Thought experiment I:
«The accretion process»

a) Let us add δN_b baryons (in form of hydrogen) to the surface and keep them there `by hands'.
The energy of the system is

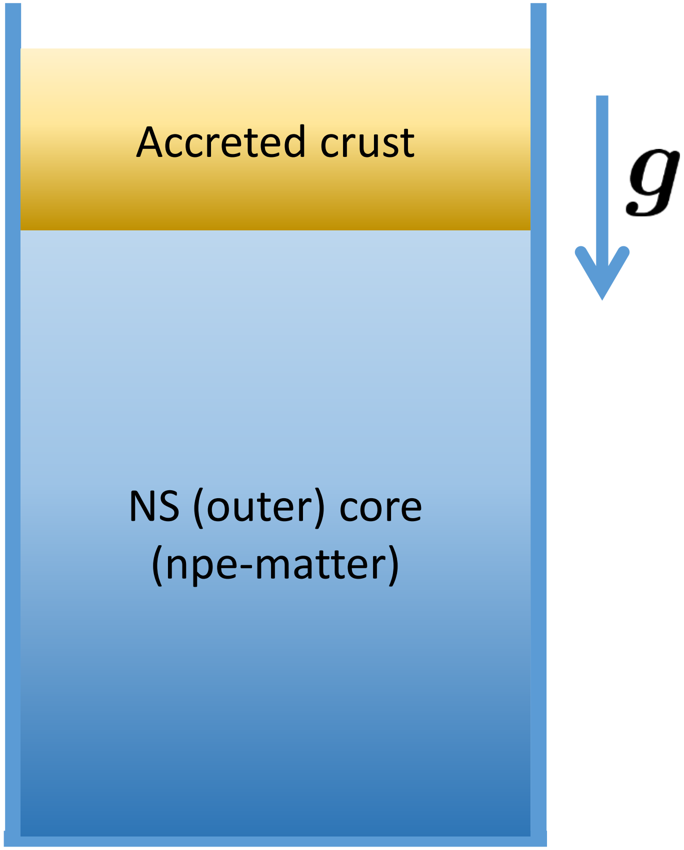
$$E(N_b) + \mu_{b,\,\mathrm{H}}^{\infty} \delta N_b$$

Hydrogen energy per baryon, including gravitational energy

b) Release the baryons
The baryons compress the crust and core, initiate reactions, but total energy should be conserved

$$E_I(N_b + \delta N_b) = E(N_b) + \mu_{b,\,\mathrm{H}}^{\infty} \delta N_b$$

Heating efficiency: general consideration



Plane-parallel consideration (to simplify presentation)

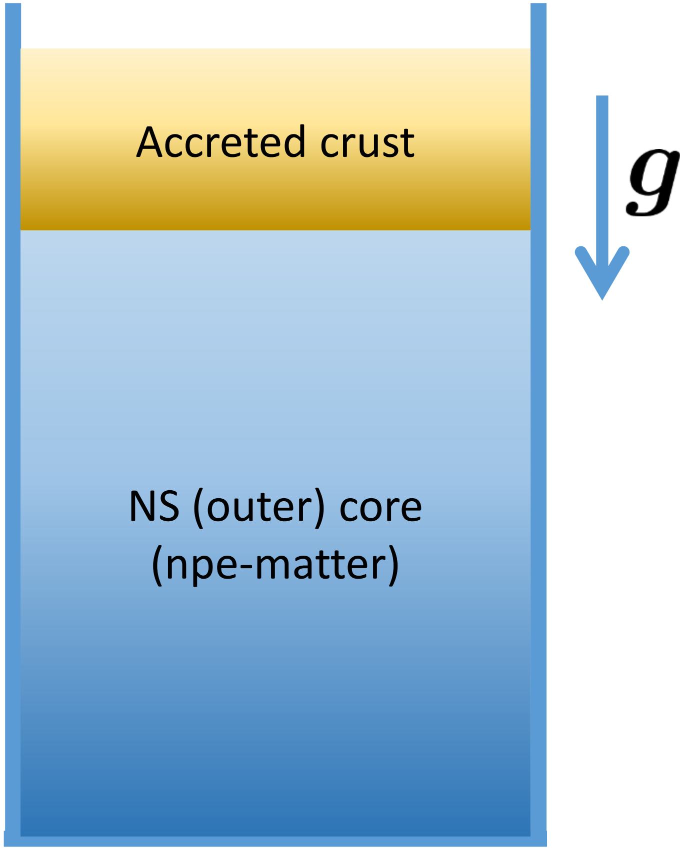
<u>Thought experiment II:</u>

«The result of accretion»

- For fully accreted crust the EOS is fixed
  - $\Rightarrow$ the number of baryons in the crust is fixed
  - $\Rightarrow$ Additional δN_b baryons appear in the core of NS
- The core is in equilibrium, thus the change of the energy is

$$E_{II}(N_b + \delta N_b) = E(N_b) + \mu^{\infty}_{b,\,\mathrm{core}} \delta N_b$$

Heating efficiency: general consideration



Plane-parallel consideration (to simplify presentation)

<u>Thought experiment I:</u>

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$$E_I(N_b + \delta N_b) = E(N_b) + \mu^{\infty}_{b,\,\mathrm{H}} \delta N_b$$

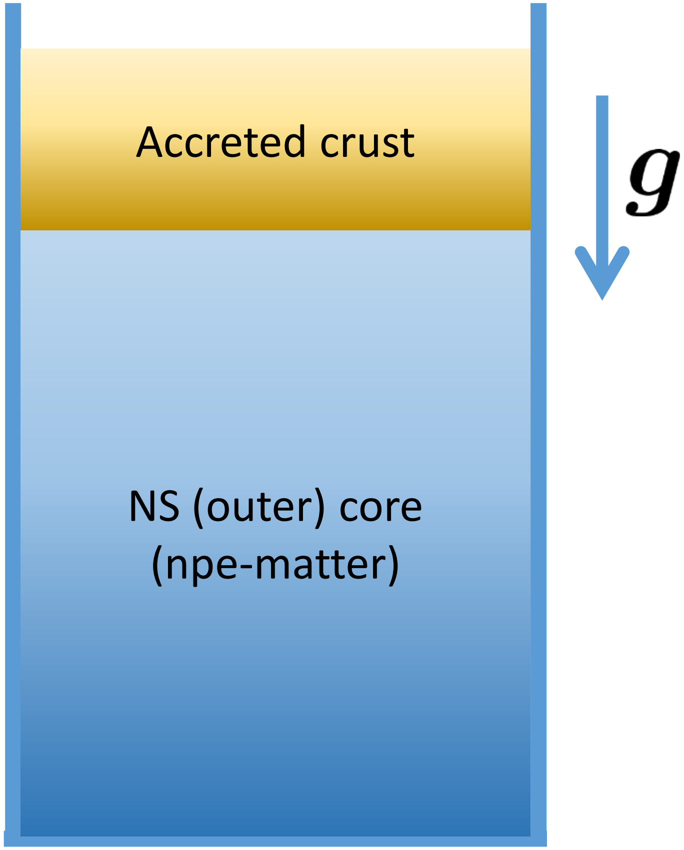
<u>Thought experiment II:</u>

«The result of accretion»

$$E_{II}(N_b + \delta N_b) = E(N_b) + \mu^{\infty}_{b,\,\mathrm{core}} \delta N_b$$

Which answer is the correct one?

Heating efficiency: general consideration



Plane-parallel consideration (for simplicity of the talk)

<u>Thought experiment I:</u>

«The accretion process»

$$E_I(N_b + \delta N_b) = E(N_b) + \mu^{\infty}_{b,\,\mathrm{H}}\delta N_b$$

<u>Thought experiment II:</u>

«The result of accretion»

$$E_{II}(N_b + \delta N_b) = E(N_b) + \mu^{\infty}_{b,\,\mathrm{core}}\delta N_b$$

Which answer is the correct one?

Both are accurate!!!

The heat was released in the first experiment!

$$Q = E_I(N_b + \delta N_b) - E_{II}(N_b + \delta N_b) = \left(\mu^{\infty}_{b,\,\mathrm{H}} - \mu^{\infty}_{b,\,\mathrm{core}}\right)\delta N_b$$

Heating efficiency: general consideration

The result is the same for a spherical general relativistic star

M.E. Gusakov & AIC [Phys. Rev. D:Letters, 103 (2021), L101301]

$$\mu^{\infty}_{b,\mathrm{H}} = m_{b,\mathrm{H}}\, e^{\nu_\mathrm{s}/2}$$

$$\mu^{\infty}_{b,\,\mathrm{core}} = m_{b,\mathrm{Fe}}\, e^{\nu_\mathrm{s}^{(\mathrm{cat})}/2}$$

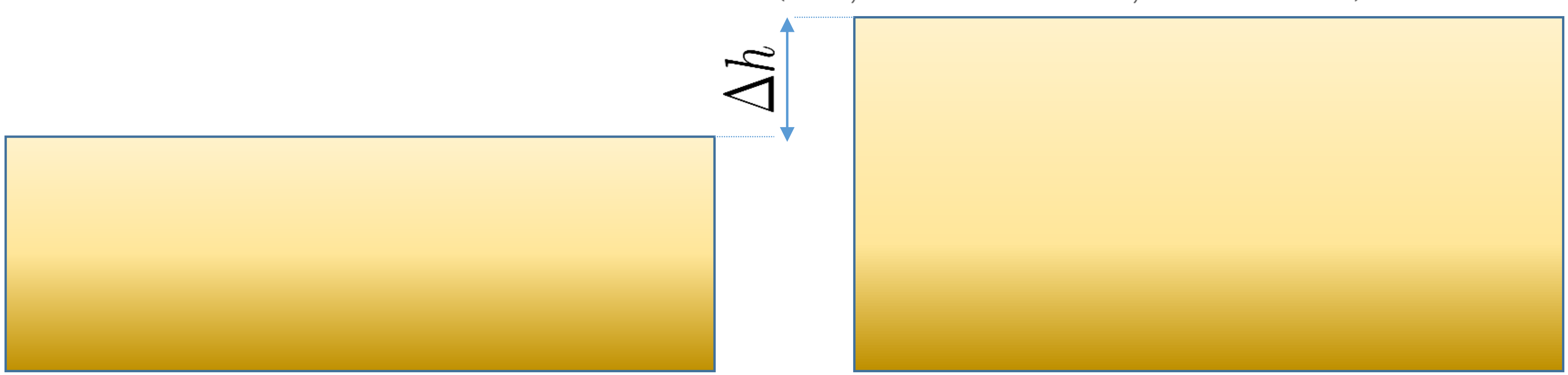
$$q^{\infty}_{\mathrm{tot}} \equiv Q/N_\mathrm{b} = m_{b,\mathrm{H}} e^{\nu_\mathrm{s}/2} - \mu^{\infty}_{b,\mathrm{core}}$$

$$= \left(m_{b,\mathrm{H}} - \overline{m}_{b,\mathrm{ash}}\right) e^{\nu_\mathrm{s}/2} + \left(\overline{m}_{b,\mathrm{ash}}\, e^{\nu_\mathrm{s}/2} - \mu^{\infty}_{b,\mathrm{core}}\right)$$

The «nuclear» part, associated with thermonuclear burning to the ashes (≈ ^{56}Fe).
Released from the surface, does not heat up the NS core

The gravitational energy, associated with larger thickness of the accreted crust. Released in the depths of the crust, heats up NS core

$$\left(m_{b,\mathrm{Fe}}\, e^{\nu_\mathrm{s}/2} - m_{b,\mathrm{Fe}}\, e^{\nu_\mathrm{s}^{(\mathrm{cat})}/2}\right) \approx m_U\, g\, \Delta h$$



Catalyzed crust

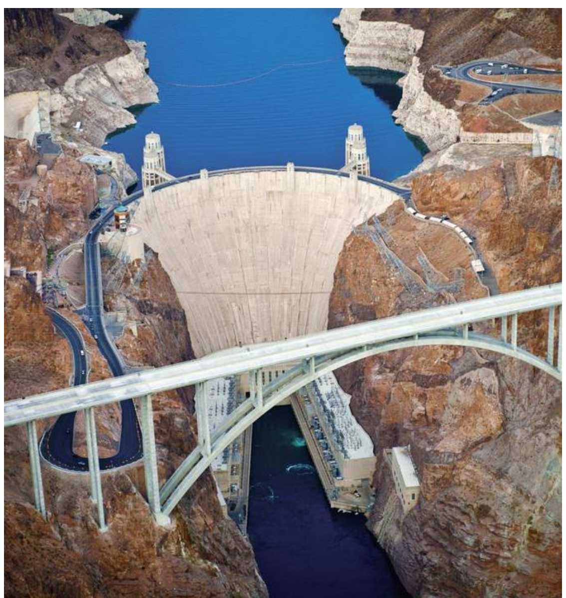
Fully accreted crust

Heating efficiency: general consideration

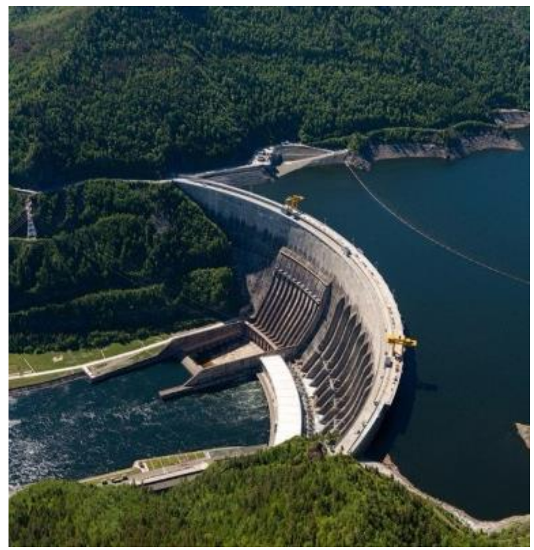
$$q \approx m_u \, g \, \Delta h \Rightarrow \Delta h \approx 25 \text{ m} \frac{q}{0.5 \ \frac{\text{MeV}}{\text{nucleon}}} \left(\frac{g}{2 \times 10^{14} \ \frac{\text{cm}}{\text{s}^2}} \right)^{-1}$$

Within traditional one component approach derived by Zdunik et al. [A&A, 599 (2017), 119]

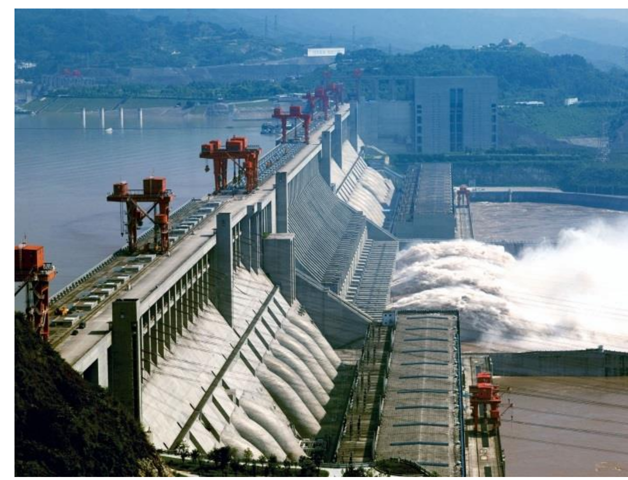
Deep crustal heating: conversion of the gravitational energy into the heat
(in some sense similar to the gravity dams)



Hoover dam
221 m



Sayano-Shushenskaya Dam
242 m



Three Gorges Dam
181 m

Heating efficiency: nHD crust

$$q^{\infty} = \overline{m}_{b,\mathrm{ash}}\, e^{\nu_{\mathrm{s}}/2} - \mu^{\infty}_{b,\mathrm{core}}$$

$$\mu^{\infty}_{b,\mathrm{core}} = \mu_b e^{\nu_{\mathrm{cc}}/2} = \mu_n e^{\nu_{\mathrm{cc}}/2} = m_n e^{\nu_{\mathrm{oi}}/2}$$

$$q^{\infty} = \boxed{\overline{m}_{b,\mathrm{ash}}\, e^{\nu_{\mathrm{s}}/2} - \mu_{b,\mathrm{o}}(P_{\mathrm{oi}})\, e^{\nu_{\mathrm{oi}}/2}} + \mu_{b,\mathrm{o}}(P_{\mathrm{oi}})\, e^{\nu_{\mathrm{oi}}/2} - \mu_n\, e^{\nu_{\mathrm{oi}}/2}$$

q^{∞}_{o}

Baryon chemical potential at the bottom of outer crust

$$q^{\infty} = e^{\nu_{\mathrm{oi}}/2} \left\{ q_{\mathrm{o}} + \left[\mu_{b,\mathrm{o}}(P_{\mathrm{oi}}) - m_n \right] \right\}$$

For nHD crust the energy release is given by

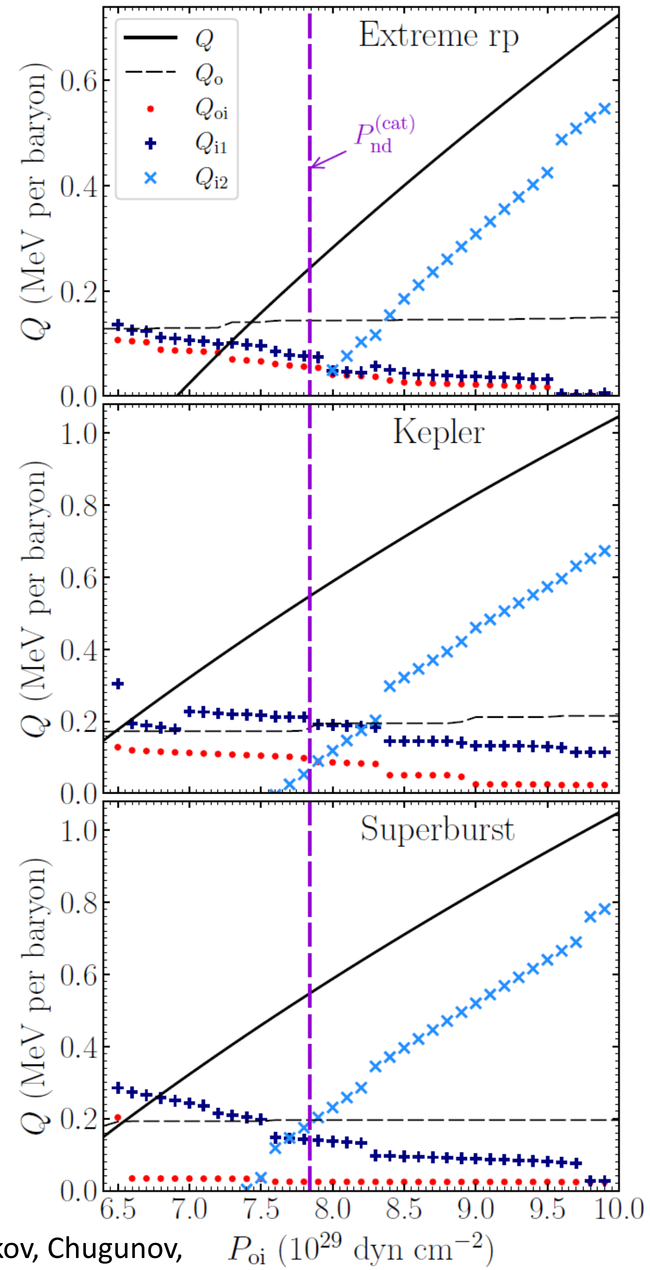
- EOS in the **outer** crust
- Pressure at the outer-inner crust interface P_{oi}

Heating efficiency: nHD crust

$$q \lesssim 0.5 \frac{\text{MeV}}{\text{nucleon}}$$

Deep crustal heating is factor of few less efficient,

than it was supposed in traditional models!



Shchechilin, Gusakov, Chugunov, *MNRAS: Letters*, 515 (2022), L6

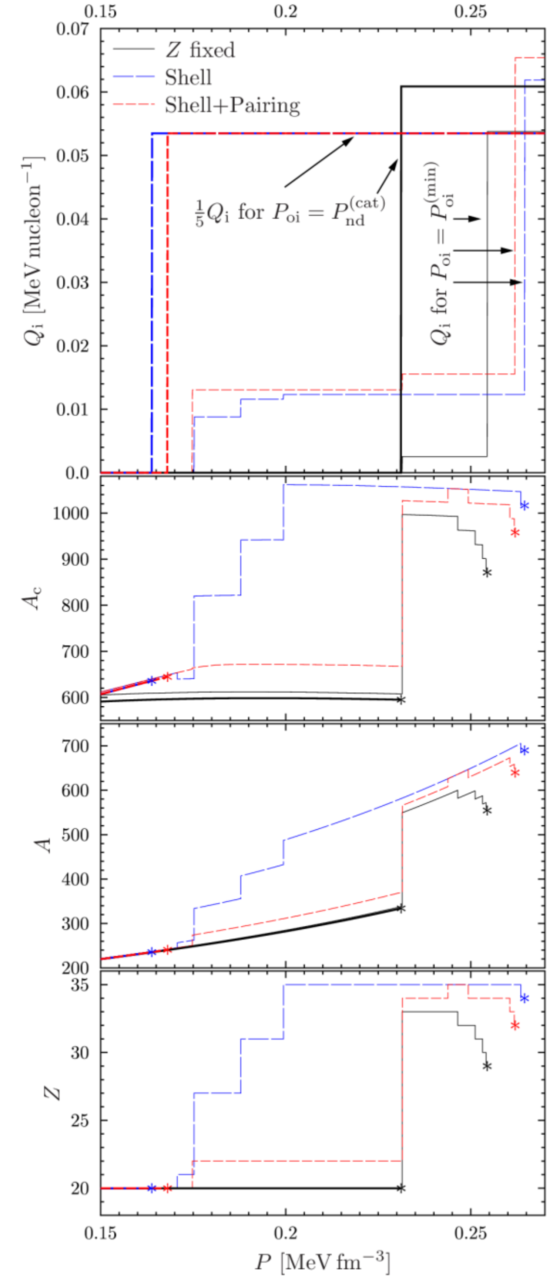
Dependence on the shell model

Shell effects in the inner crust are crucial:

In major part of the inner crust:

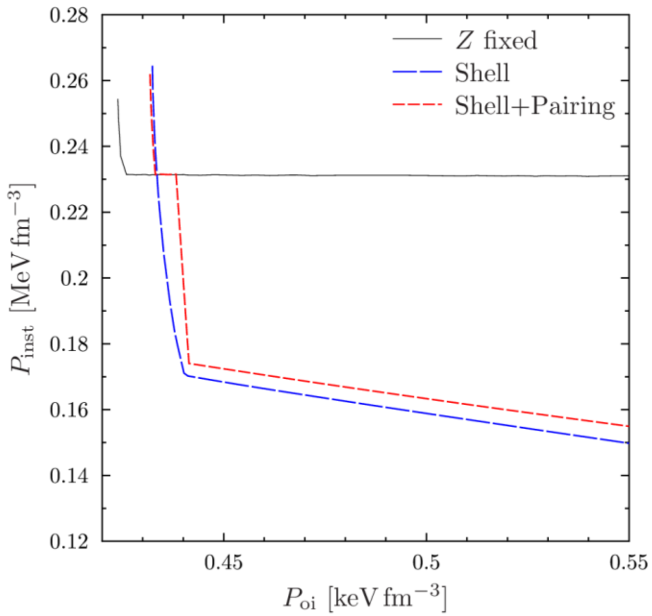
- ➢ Z=20
- ➢ No energy release

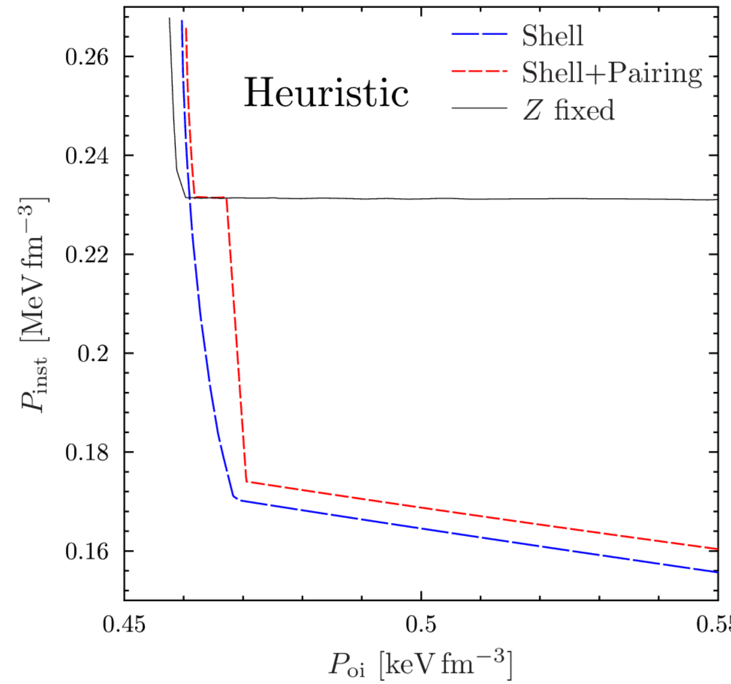
Details of nuclei evolution (composition) in innermost layers of inner crust depends on the model

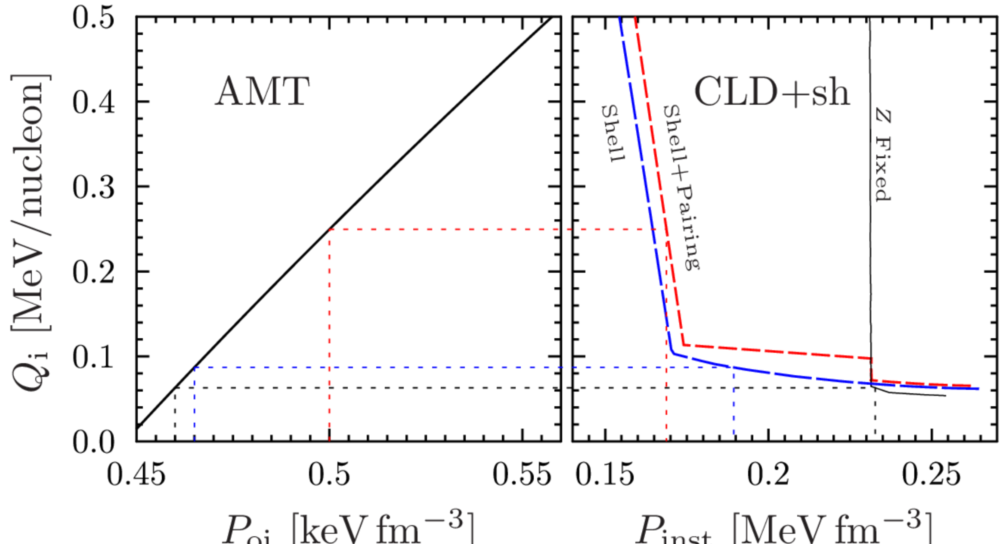


M.E. Gusakov & AIC, **Phys. Rev. D,** 109, 123032 (2024)

Universal relations based on energy conservation







Some dependence on the shell effect in major part of inner crust can be compensated

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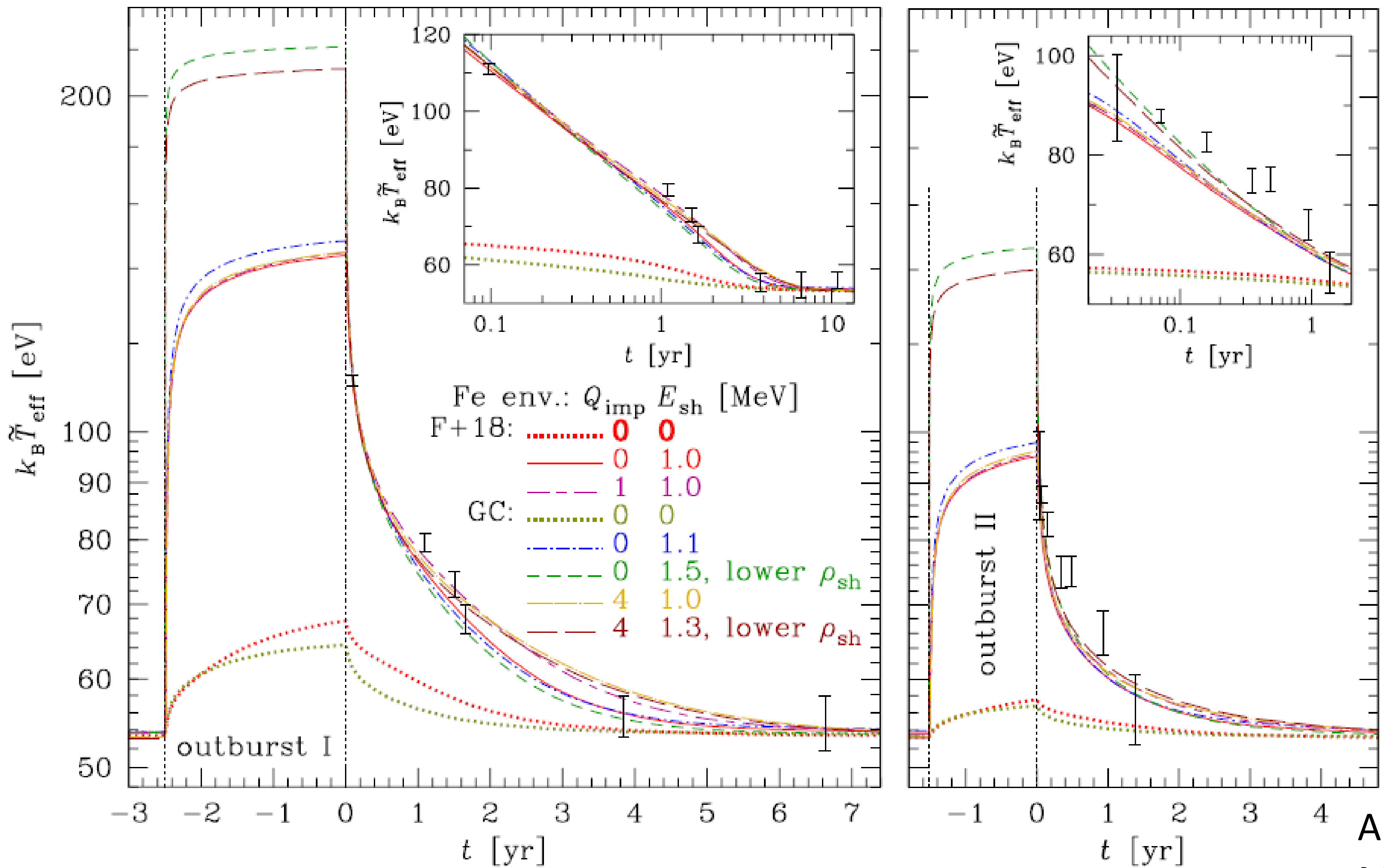
Thermal evolution (example MXB 1659-20)



- Additional heating is required

A.Y. Potekhin,
M.E. Gusakov,
AIC, MNRAS,

522, 4830 (2023)

Summary

- It is shown that neutron redistribution in the inner crust have a crucial role
- First nHD models are constructed. They qualitatively differ from the traditional ones.
- Nuclei shell effects are crucial.
- Stationary structure of the crust is supported by nuclei dissociation by instability in inner layers
- Observations of accreting neutron stars require additional shallow heating source (as in traditional models). The nature of this source is unknown…

To do list

- Improve of nuclear physical model (currently: CLDM + tabulated Strutinsky corrections; [Carreau et al., A&A 635, A84 (2020)]).
- Partially accreted crust
- *Mystery of the shallow heating source*

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