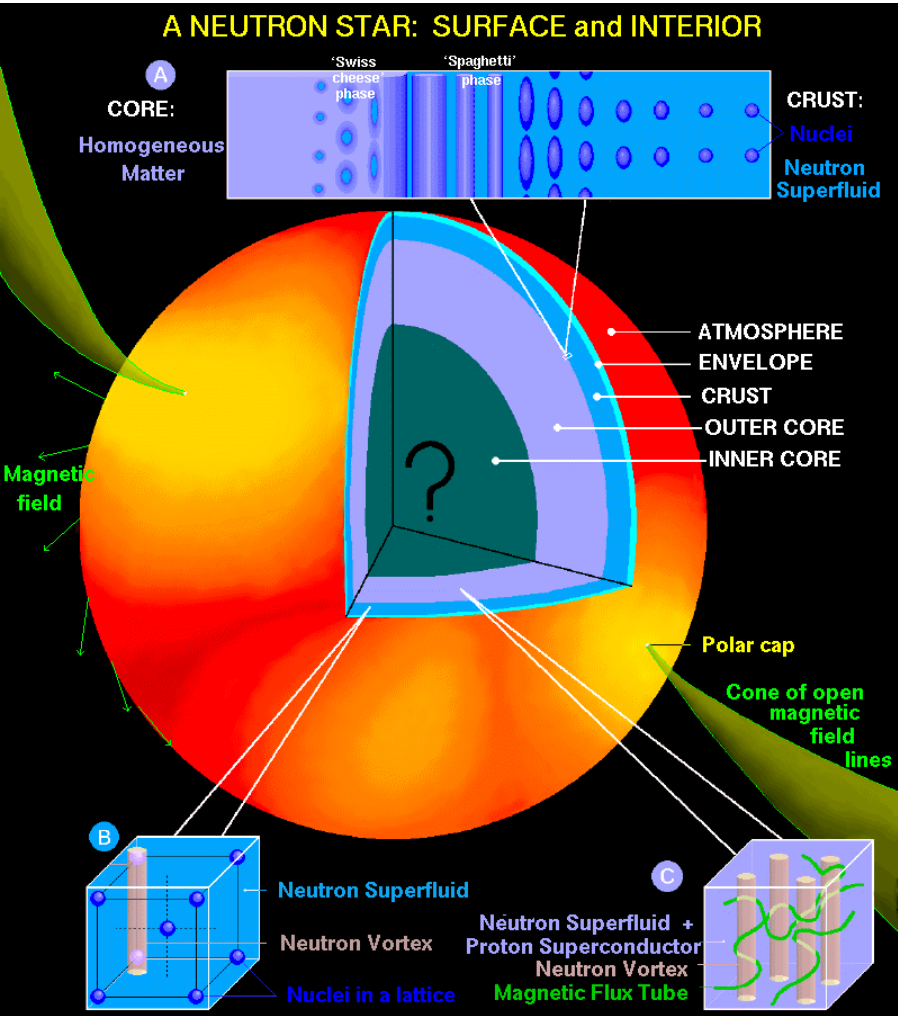
Кора аккрецирующих нейтронных звезд

А.И. Чугунов
М.Е. Гусаков, Н.Н. Щечилин, Е.М. Кантор
ФТИ им. А.Ф. Иоффе

Научный семинар ОЭПВАЯ НИИЯФ МГУ
и кафедры общей ядерной физики Физического факультета МГУ

22.09.2022

Motivation I: neutron stars and superdense matter

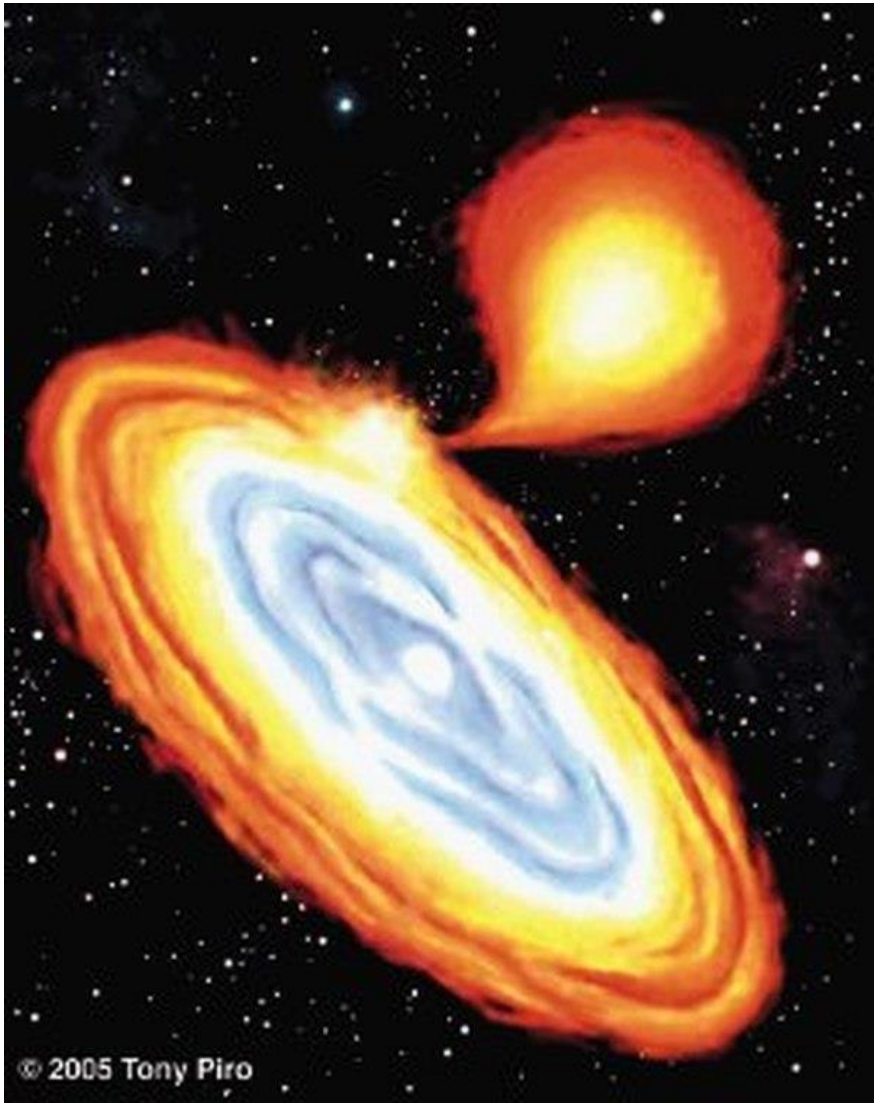


$$\rho \sim 10^{15}\ \mathrm{g/cm^3}$$
$$T \lesssim 10^9\ \mathrm{K}$$
$$B \sim 10^{12}\ \mathrm{G}$$
$$g \sim 10^{14}\ \mathrm{cm/s^2}$$
$$R \sim 2R_\mathrm{g} = 4GM/c^2$$
$$T_\mathrm{cp} \sim 10^9\ \mathrm{K}$$
$$T_\mathrm{cn} \sim 10^8\ \mathrm{K}$$

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

Information on the surface layers is required for correct interpretation of observations

Motivation II: accreting neutron stars



Many neutron stars are observed accreting, i.e. they are located in the close binary system with transfer of matter from (Roche-lobe overflow) companion star to the neutron star

- That happens with matter after accretion?
- How it affect observations?
- Which information on superdense matter can be inferred from these observations?

Motivation III: transiently accreting neutron stars

Compression of accreted matter → Nuclear reactions → Heating → Thermal emission (detected!!!)

Thermal emission just after accretion episode (crust)

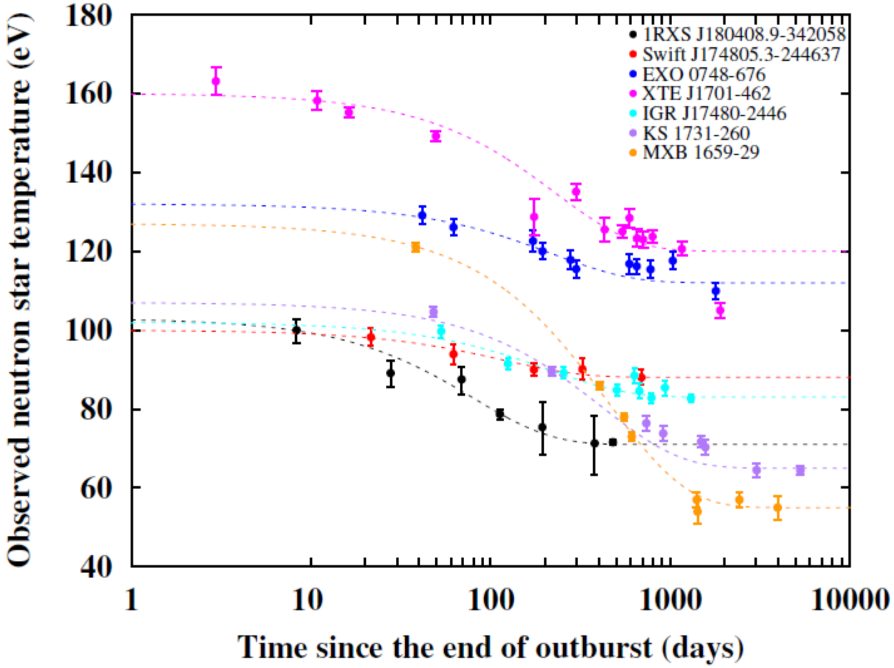


Figure from Wijnands et al. 2017

After thermal relaxation of the crust (the NS core)

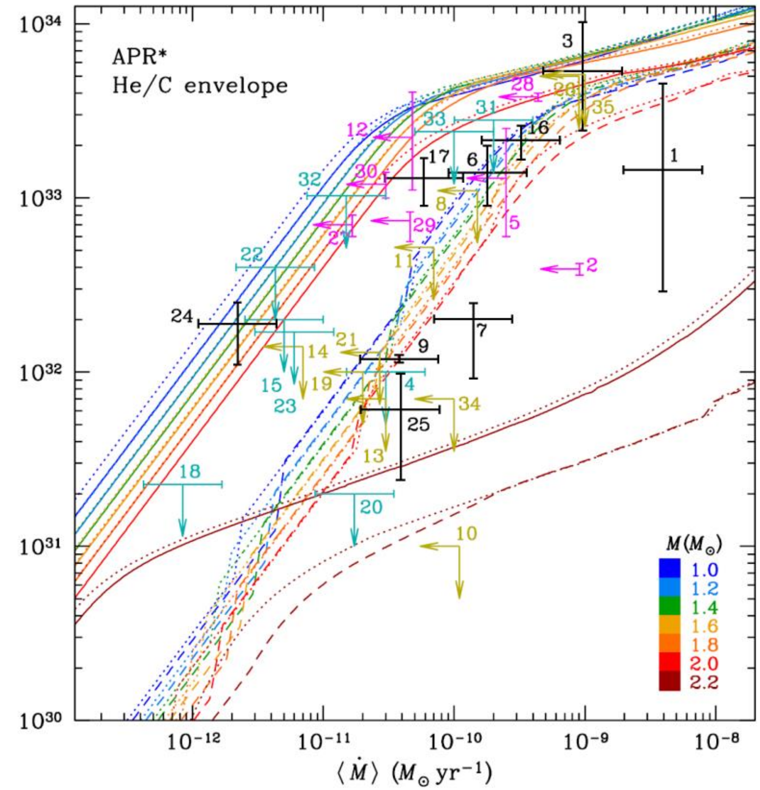


Figure from Potekhin et al. 2019

$$L^{\rm tot} = L_\nu + L_{\rm ph} = \langle Q \rangle$$

The plan of the talk

- Traditional model and its inconsistency

[AIC & N.N. Shchechilin, MNRAS 495, L32 (2020)]

- Thermodynamically consistent model

neutron Hydrostatic/Diffusion equilibrium (nHD)

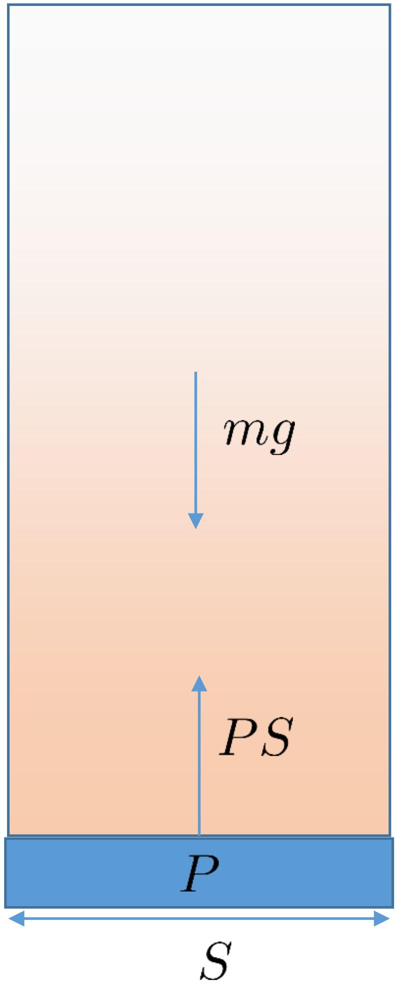
[M.E. Gusakov & AIC, Phys. Rev. Lett. 124, 191101 (2020),
M.E. Gusakov, E.M. Kantor & AIC, Phys. Rev. D, 104, L081301 (2021),
N.N. Shchechilin, M.E. Gusakov & AIC, MNRAS (2021-….)]

- Heating of the neutron star crust

[M.E. Gusakov and AIC, Phys. Rev. D, 103, L101301 (2021) ,
M.E. Gusakov, E.M. Kantor & AIC, Phys. Rev. D, 104, L081301 (2021),
N.N. Shchechilin, M.E. Gusakov & AIC, MNRAS (2021-….)]

That happens with matter after accretion?

(the traditional approach)



Force balance for the accreted column

$$mg = P\,S$$

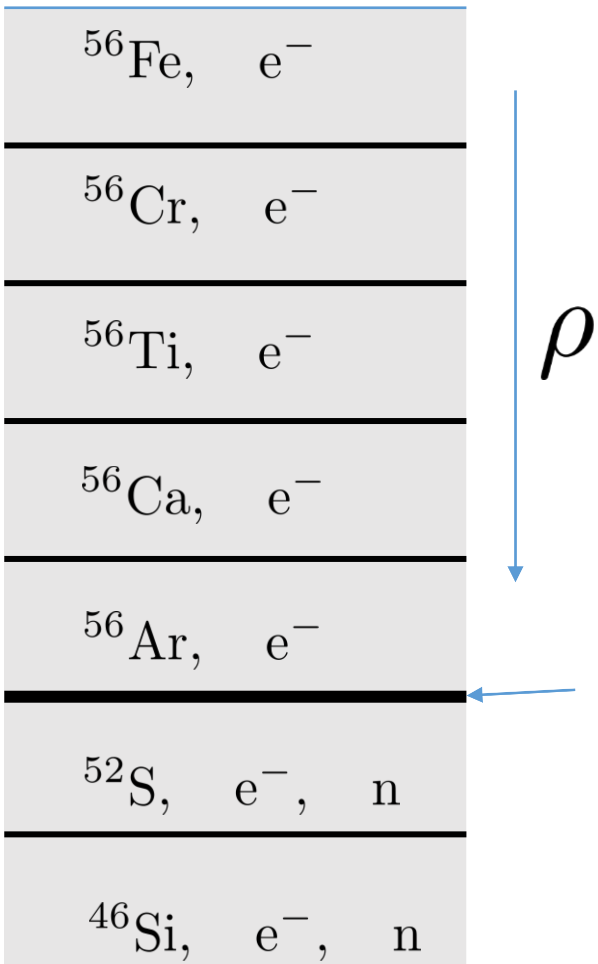
Accretion supplies matter to the stellar surface
=> The mass of accreted column increases
=> The pressure is growing

$$\dot{P} = \frac{\dot{m}g}{S}$$

<u>Traditional apporach [Sato 1979, Haensel&Zdunik 1990,....]:</u>
Consider nuclear reaction on course of compression (increase of the pressure)

That happens with matter after accretion?

(the traditional approach)



$\rho < 10^8 \mathrm{g/cm}^3$:

Complicated thermonuclear reactions produce heavy nuclei

$\rho > 10^8 \mathrm{g/cm}^3$:

Increase of electron chemical potential leads to electron captures

$$\mathrm{d}P \approx n_e \mathrm{d}\mu_e$$

$$^A_Z X + e^- \rightarrow {}^A_{Z-1} X + \nu_e$$

The electron captures are typically paired due to pairing effect

Neutronization

ρ $(\mathrm{g\ cm}^{-3})$	Process
1.49×10^9	$^{56}\mathrm{Fe} \rightarrow {}^{56}\mathrm{Cr} - 2e^- + 2\nu_e$
1.11×10^{10}	$^{56}\mathrm{Cr} \rightarrow {}^{56}\mathrm{Ti} - 2e^- + 2\nu_e$
7.85×10^{10}	$^{56}\mathrm{Ti} \rightarrow {}^{56}\mathrm{Ca} - 2e^- + 2\nu_e$
2.50×10^{11}	$^{56}\mathrm{Ca} \rightarrow {}^{56}\mathrm{Ar} - 2e^- + 2\nu_e$
6.11×10^{11}	$^{56}\mathrm{Ar} \rightarrow {}^{52}\mathrm{S} + 4n - 2e^- + 2\nu_e$
9.075×10^{11}	$^{52}\mathrm{S} \rightarrow {}^{46}\mathrm{Si} + 6n - 2e^- + 2\nu_e$

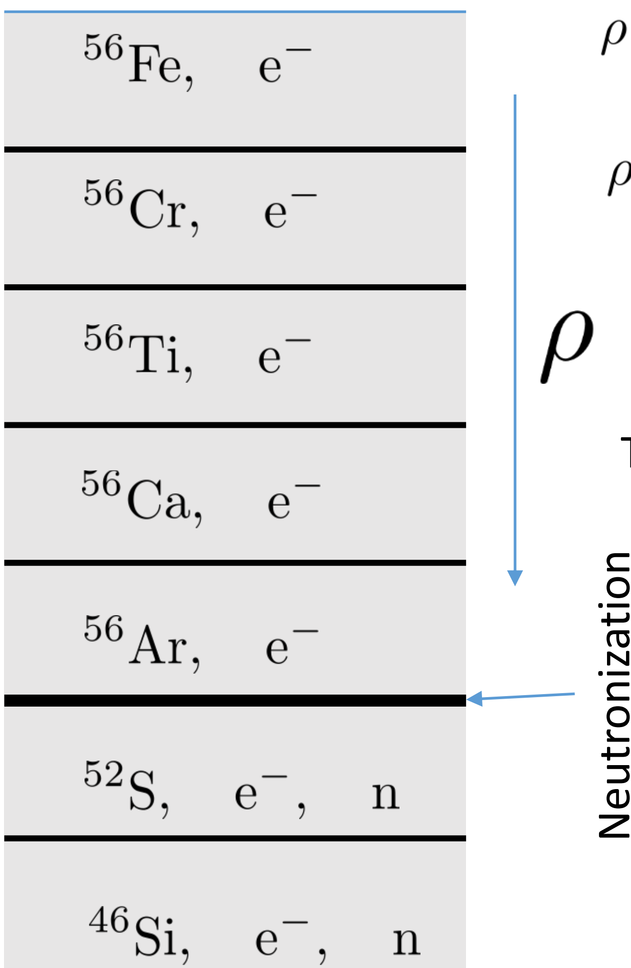
[From Haensel&Zdunik 2007]

Neutronization is associated with neutron drip, induced by beta-capture

$$P_{\mathrm{oi}} = P_{\mathrm{drip}}$$

That happens with matter after accretion?

(the traditional approach)



$\rho < 10^8 \mathrm{g/cm^3}$:

Complicated thermonuclear reactions produce heavy nuclei

$\rho > 10^8 \mathrm{g/cm^3}$:

Increase of electron chemical potential leads to electron captures

$$\mathrm{d}P \approx n_e \mathrm{d}\mu_e$$

$$^A_Z X + e^- \rightarrow {}^A_{Z-1} X + \nu_e$$

The electron captures are typically paired due to pairing effect

ρ ($\mathrm{g\ cm^{-3}}$)	Process
1.49×10^9	$^{56}\mathrm{Fe} \rightarrow {}^{56}\mathrm{Cr} - 2e^- + 2\nu_e$
1.11×10^{10}	$^{56}\mathrm{Cr} \rightarrow {}^{56}\mathrm{Ti} - 2e^- + 2\nu_e$
7.85×10^{10}	$^{56}\mathrm{Ti} \rightarrow {}^{56}\mathrm{Ca} - 2e^- + 2\nu_e$
2.50×10^{11}	$^{56}\mathrm{Ca} \rightarrow {}^{56}\mathrm{Ar} - 2e^- + 2\nu_e$
6.11×10^{11}	$^{56}\mathrm{Ar} \rightarrow {}^{52}\mathrm{S} + 4n - 2e^- + 2\nu_e$
9.075×10^{11}	$^{52}\mathrm{S} \rightarrow {}^{46}\mathrm{Si} + 6n - 2e^- + 2\nu_e$

[From Haensel&Zdunik 2007]

Strong diffusion currents should arise in the crust, as it is predicted by the traditional approach. These currents rapidly modify crust structure and can not be neglected

Thermodynamically consistent model: neutron Hydrostatic/Diffusion equilibrium (nHD)

The statement of problem is crucially modified in the inner crust (=region, where free neutrons exist):

Instead of considering of nuclear reactions in compressing volume element one should consider whole inner crust, accounting for redistribution of neutrons between the layers

<u>Two conditions:</u>

Newtonian gravity

General hydrostatic equation

$$\nabla P = \rho \boldsymbol{g}$$

---

neutron Hydrostatic/Diffusion equilibrium

$$\nabla \mu_n = m_n \mathbf{g}$$

Transfer of a neutron from one layer to another does not lead to any energy gain

Thermodynamically consistent model: neutron Hydrostatic/Diffusion equilibrium (nHD)

The statement of problem is crucially modified in the inner crust (=region, where free neutrons exist):

Instead of considering of nuclear reactions in compressing volume element one should consider whole inner crust, accounting for redistribution of neutrons between the layers

Two conditions:

General hydrostatic equation

General relativity

$$P' = -\frac{P+\epsilon}{2}\nu'$$

---

neutron Hydrostatic/Diffusion equilibrium

$$\mu_n' = -\frac{\mu_n}{2}\nu' = \frac{\mu_n}{P+\epsilon}P'$$

$$\boxed{\mu_n^\infty = \mu_n \mathrm{e}^{\nu/2} = \mathrm{const}}$$

Transfer of a neutron from one layer to another does not lead to any energy gain

Modeling of accreted crust (schematically)

Traditional approach

(Haensel & Zdunik 1990, ….)

Switch to the next, *j*+1, layer:

Increase of pressure

$$P_{j+1} = P_j + \Delta P$$

Determine composition of this layer, specified by pressure P

Minimization of the Gibbs potential Φ

$$\delta Q^{\infty} = \Phi_j^{\infty} - \Phi_{j+1}^{\infty}$$

nHD approach (for $P>P_{\rm oi}$)

(Gusakov&AIC, Gusakov, Kantor&AIC)

Switch to the next, *j*+1, layer:

Increase of pressure

$$P_{j+1} = P_j + \Delta P$$

and neutron chemical potential $\mu_{\rm n}$

$$\mu_{n,j+1} = \mu_{n,j} + \frac{\mu_n}{\epsilon + P}\Delta P$$

$$\frac{\mathrm{d}\mu_n}{\mu_n} = \frac{\mathrm{d}P}{\epsilon + P}$$

TOV equation

+ nHD condition

Determine composition of this layer, specified by pressure P

and neutron chemical potential $\mu_{\rm n}$

Minimization of the appropriate thermodynamic potential Ψ

$$\delta Q^{\infty} = \Psi_j^{\infty} - \Psi_{j+1}^{\infty}$$

Family of models, parametrized by $P_{\rm oi}$

Thermodynamics of nHD inner crust

Gusakov, Kantor, AIC (2021)

In the fully accreted inner crust nuclear reactions take place at the conditions, specific for a given layer:

- Pressure (hydrostatic equilibrium with overlying layers) P
- Neutron chemical potential (nHD condition) $\mu_{\rm n}$

Appropriate thermodynamic potential is **not the Gibbs energy** Φ, but:

$$\boxed{\Psi = \Phi - \mu_{\rm n} N_b = E + PV - \mu_{\rm n} N_b - TS}$$

Total number of baryons (beta equilibrium is assumed)

The heat release equals to the decrease of thermodynamic potential

$$\boxed{Q = \Psi_{\rm before} - \Psi_{\rm after}}$$

(see GKA21 for 'textbook' proof)

Ground state:

$\Psi = 0$

Minimization of thermodynamic potential: Simplified reaction network

- Only energetically favorable reactions
- Reaction at fixed *P* and μ_{n}
- Reactions by chunks, ordered by the priority rules

  (a) emission/capture of neutrons

  (b) electron emission/capture plus emission/capture of neutrons

  (c) (pycnonuclear) fusion

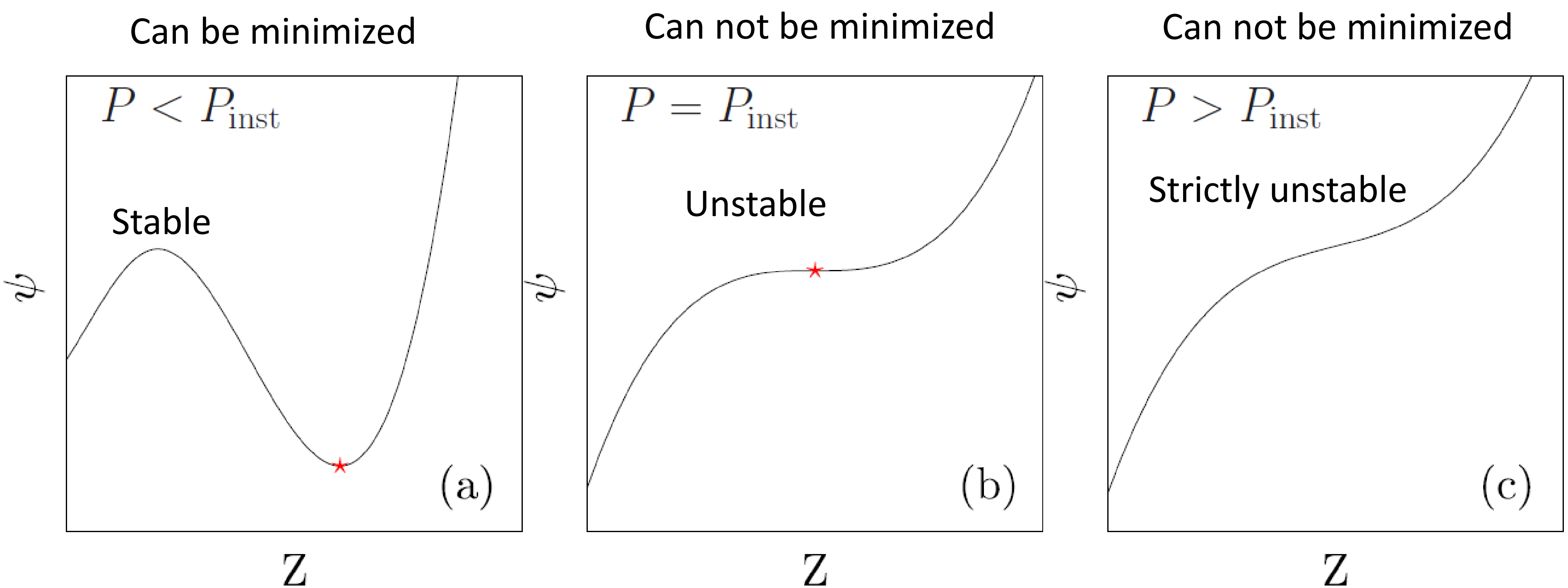
Where does accreted crust end? At the instability!

Construction of the crust within nHD approach:

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

One component example:

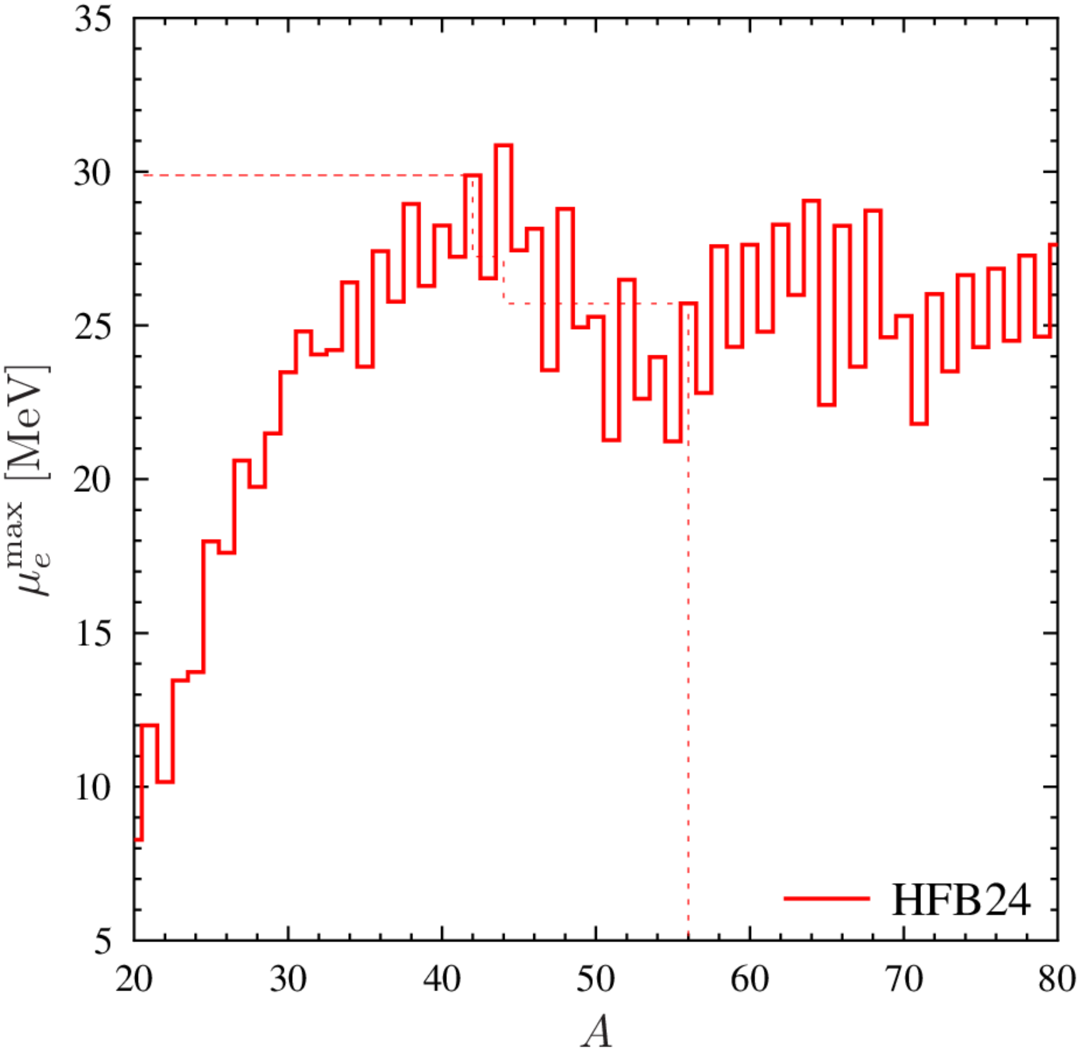
$\psi(Z)$ with grow of P



Instability:

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

Similar instability in absence of neutrons ($\mu_n < m_n$)



None of the nuclei before neutron drip line can survive at

$$\mu_e > 31 \text{ MeV}$$

(for HFB24 model)

See also
G. S. Bisnovatyi-Kogan &
V. M. Chechetkin,
Astrophys. Space Sci. 26, 25 (1974).

How to choose P_{oi}? Fully accreted crust state

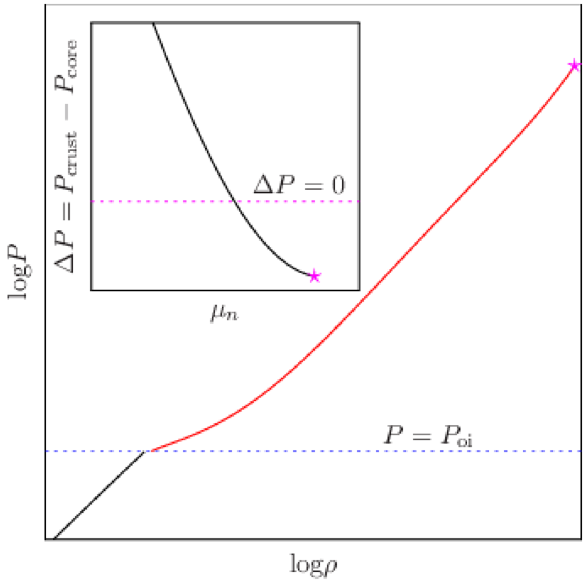
- Accretion supply nuclei to the crust
- Instability can destroy nuclei => stationary state can exist
- We need to describe neutron star: the crust should be connected to the core in a thermodynamic consistent way (continuous pressure and neutron chemical potential)

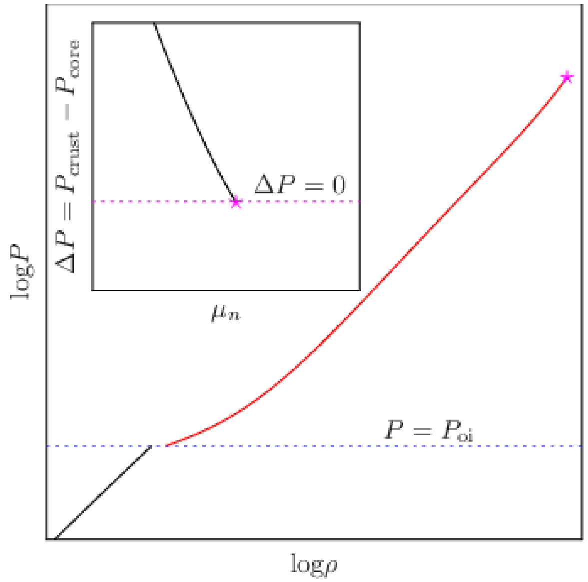
Accretion leads to formation of Fully Accreted Crust (FAC) state, where

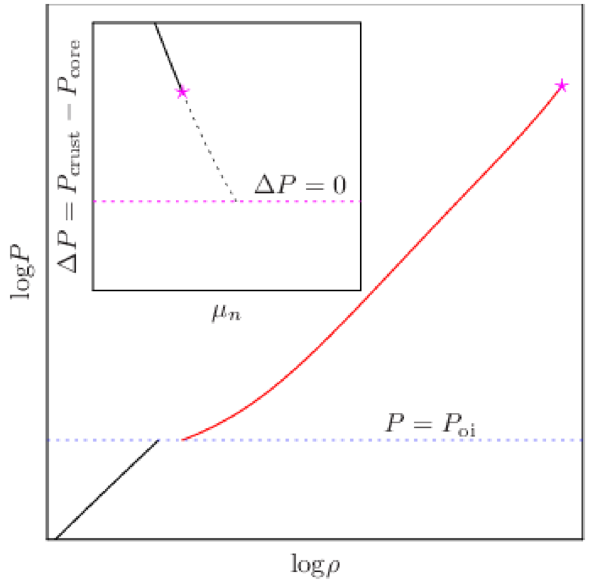
- Instability is active (and compensate nuclei supply by accretion)
- Crust is connected to the core

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

nHD accreted crust

<u>(almost) Everything is not as it was generally believed before</u>

- Outer-inner crust interface is not associated with neutron drip.
- Nuclei capture neutrons at this interface
- There are a diffusion/superfluid flow of neutrons in upward direction
- There are an instability region at the inner crust, which allows dissociation of nuclei (as a sequence of beta-captures and neutron emissions). This instability is required to keep static crustal structure (avoid accumulation of nuclei)
- It is onset of the instability, which determines position of the outer-inner crust interface in FAC state.

(Sorry, it is not end of the talk. The remaining part is about energetics)

Motivation III: transiently accreting neutron stars

Compression of accreted matter → Nuclear reactions → Heating → Thermal emission (detected!!!)

Thermal emission just after accretion episode (crust)

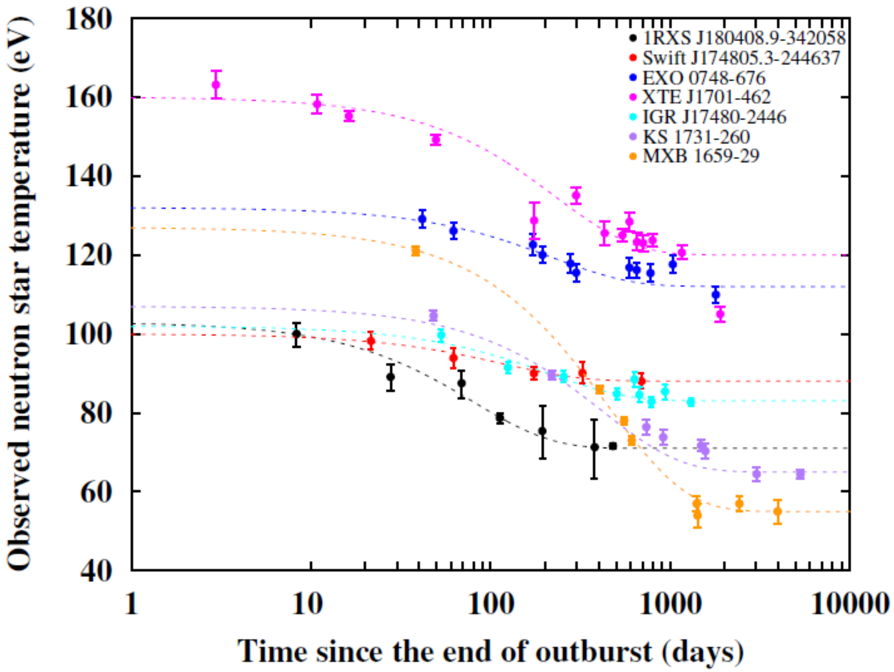


Figure from Wijnands et al. 2017

After thermal relaxation of the crust (the NS core)

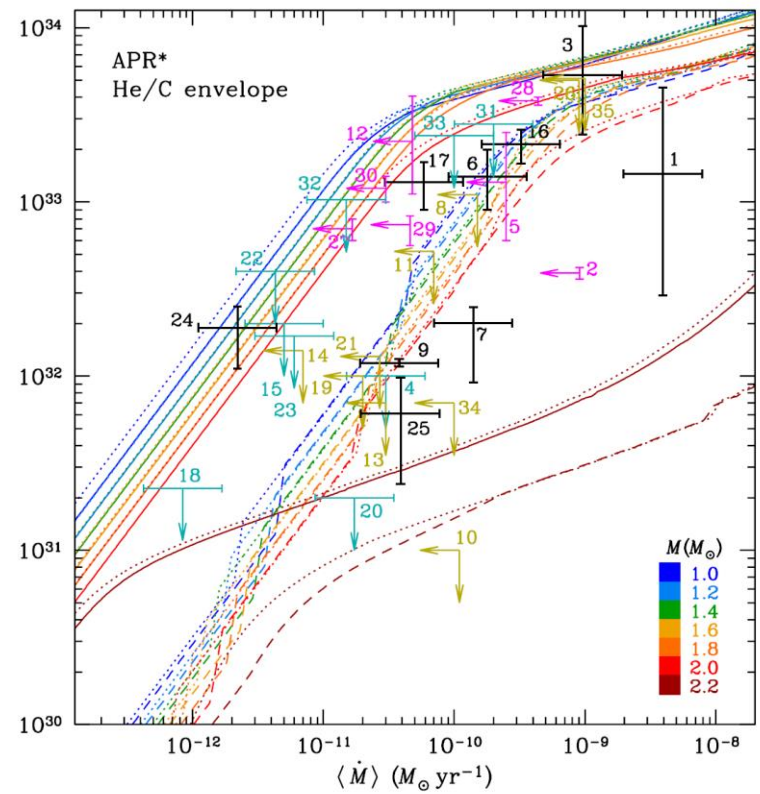


Figure from Potekhin et al. 2019

$$L^{\rm tot} = L_\nu + L_{\rm ph} = \langle Q \rangle$$

Efficiency of the deep crustal heating

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

<u>Straightforward approach:</u>
(applied previously)

Sum of the heat release over reactions:

$$q = \sum_i q_i$$

Detailed information on the reaction kinetics is required

<u>Thermodynamic approach</u>
(here)

Two assumptions:

- *Equilibrium composition of NS core*
- *Fully accreted crust (stationary structure)*

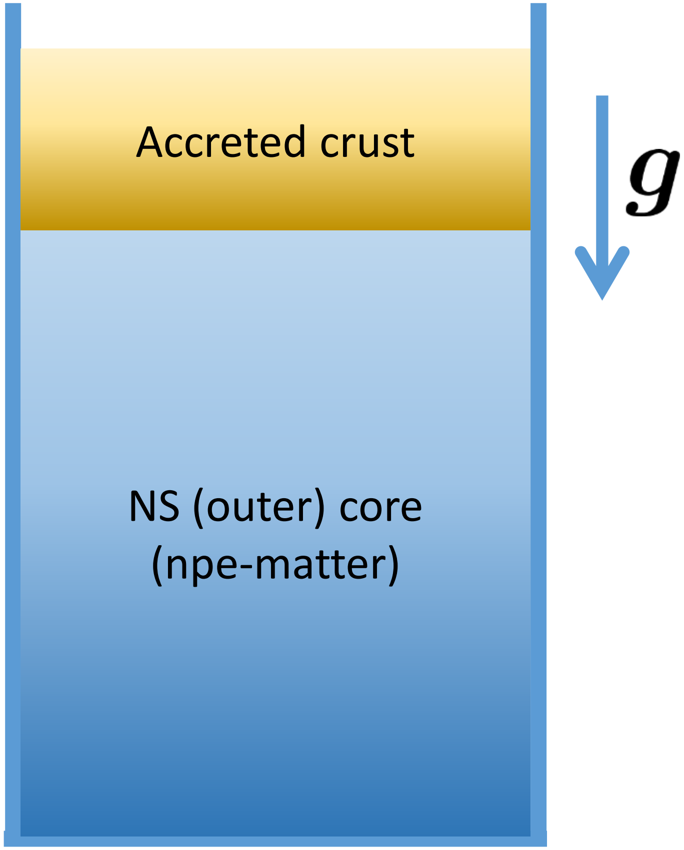
$$q^{\infty} \quad = \quad \overline{m}_{b,\mathrm{ash}}\, e^{\nu_{\mathrm{s}}/2} - \mu^{\infty}_{b,\mathrm{core}}$$

Almost no information on the reaction kinetics

Neutrino energy is included into the heating

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

Heating efficiency: general consideration



Plane-parallel consideration (to simplify presentation)

<u>Thought experiment I:</u>

«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

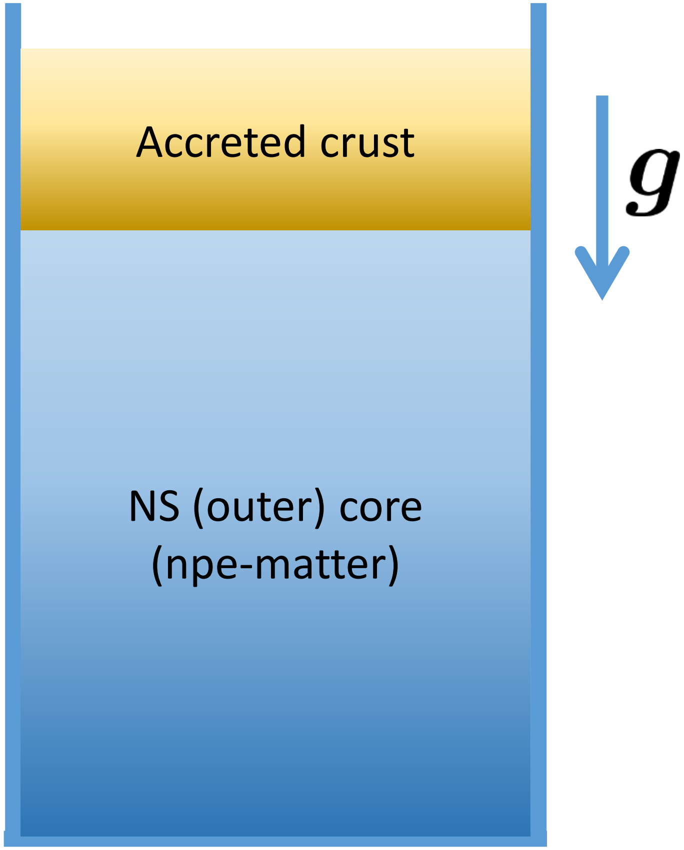
$$E(N_b) + \mu_{b,\,\mathrm{H}}^{\infty} \delta N_b$$

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>

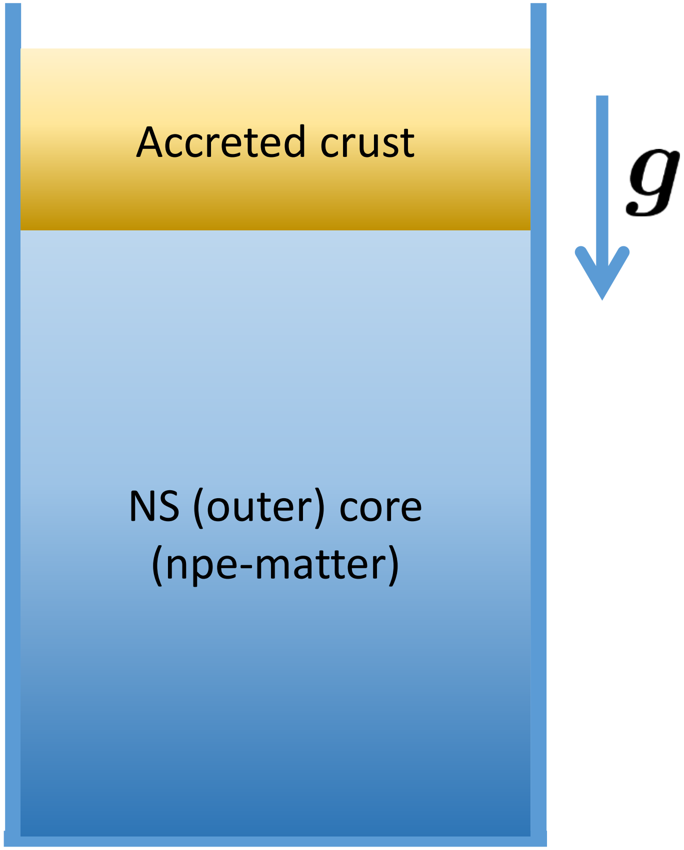
«The result of accretion»

- 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>

«The accretion process»

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

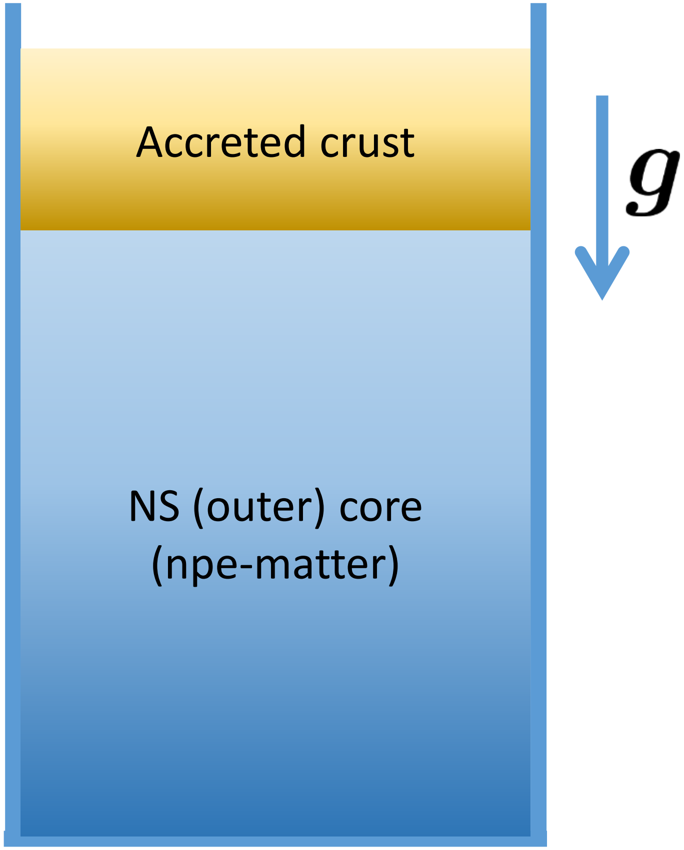
<u>Thought experiment II:</u>

«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?

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]

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

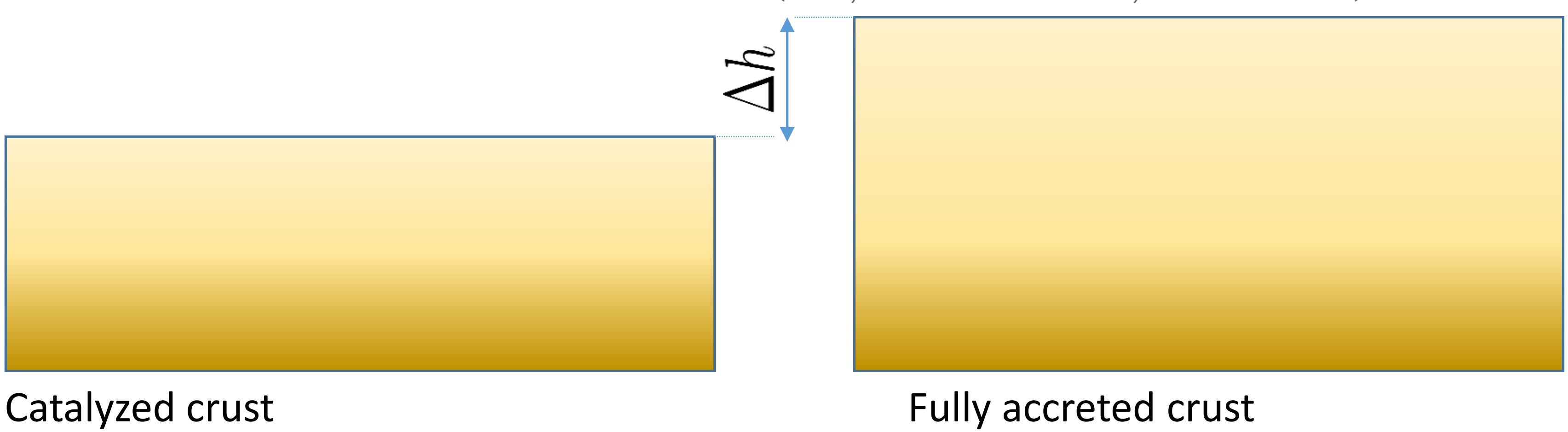
$$\mu^{\infty}_{b,\,\mathrm{core}} = m_{b,\mathrm{Fe}}\, e^{\nu_{\mathrm{s}}^{(\mathrm{cat})}/2}$$

$$\begin{aligned} q^{\infty}_{\mathrm{tot}} &\equiv Q/N_{\mathrm{b}} = m_{b,\mathrm{H}} e^{\nu_{\mathrm{s}}/2} - \mu^{\infty}_{b,\mathrm{core}} \\ &= \boxed{\left(m_{b,\mathrm{H}} - \overline{m}_{b,\mathrm{ash}}\right) e^{\nu_{\mathrm{s}}/2}} + \boxed{\left(\overline{m}_{b,\mathrm{ash}}\, e^{\nu_{\mathrm{s}}/2} - \mu^{\infty}_{b,\mathrm{core}}\right)} \end{aligned}$$

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

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

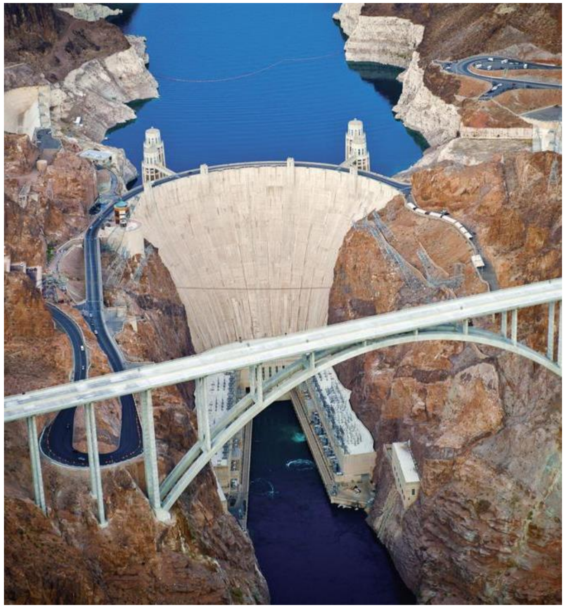


Heating efficiency: general consideration

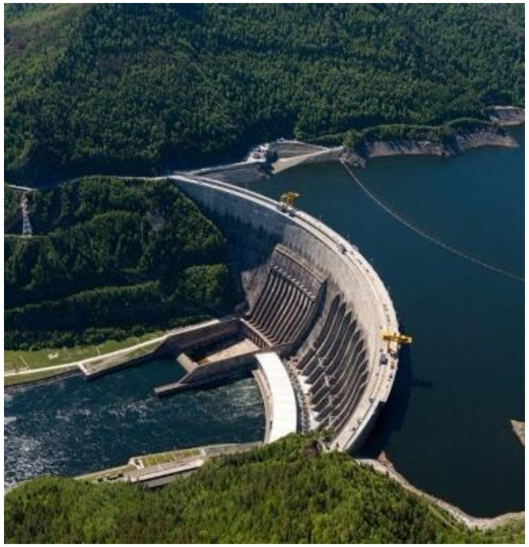
$$q \approx m_u \, g \, \Delta h \Rightarrow \Delta h \approx 25 \text{ m} \, \frac{q}{0.5 \, \frac{\text{MeV}}{\text{nucleon}}} \, \left(\frac{g}{2 \times 10^{14} \, \frac{\text{cm}}{\text{s}^2}} \right)^{-1}$$

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

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

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

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

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

Structure and heating profile of nHD crust

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

Details on the nuclear reaction kinetics at the inner crust are not important for the net efficiency of deep crustal heating (all encoded into $P_{\rm oi}$),

but

It is the kinetics that determines
the structure of accreted crust and heating profile in real accreting NS
(in particular, location of outer-inner crust interface – the pressure $P_{\rm oi}$)

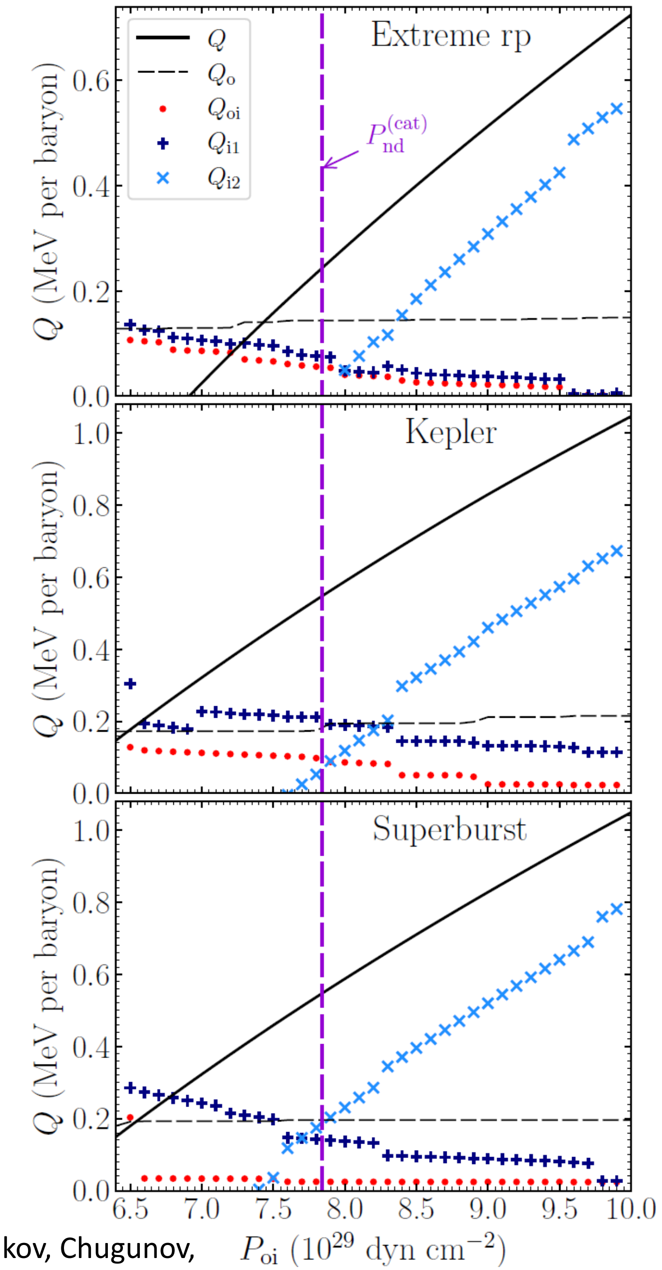
⬇

We need to study kinetics of nuclear reactions to determine structure of fully accreted crust and heating release profile in our models. To do so we perform following steps (~Shooting method):

1. Construct a family of nHD models, parametrized by the pressure $P_{\rm oi}$
2. Analyze this family to constrain $P_{\rm oi}$ by applying following criteria:

- ➢ Stationary structure => Nuclei, provided by accretion, should desintegrate
- ➢ Crust should be connected with the core in thermodynamically consistent way

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

Results and conclusions

- One should account for nHD condition while constructing accreting neutron star models

- Crust evolve to stationary FAC state, where instability in the depths of inner crust compensate nuclei supply by accretion

<u>Construction of FAC model</u>

- It is instructive to construct a set of 'candidate' FAC models, parametrized by the pressure at the outer-inner crust interface $P_{\rm oi}$.

- We derive simple, physically transparent formula for efficiency of deep crustal heating. It allows to calculate total energy release for each of candidate model without considering of the inner crust. This information can be applied to analyze thermal evolution of accreting NSs

- To determine $P_{\rm oi}$ and choose correct FAC model inner crust layers should be modeled. Observational constraints are also possible

- A lot should be done: accurate reaction network, improve of the nuclear physics (shell models) for inner crust…