

Deep crustal heating for realistic compositions of thermonuclear ashes

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The Modern Physics of Compact Stars and Relativistic Gravity

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Introduction
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Initial conditions
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Nuclear evolution in the outer crust
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Low-mass X-ray binaries

- Roche-lobe mass transfer from a less compact star
- $M_{\text{comp}} \lesssim M_{\odot}$
- $B_{\text{NS}} \sim 10^{10} \text{ G}$
- Non-stationary accretion (disk instabilities)
- $t_{\text{acc}} \sim \text{months}$
- $t_{\text{q}} \sim \text{years}$
- $\langle \dot{M} \rangle \sim 10^{-10} M_{\odot} \text{ yr}^{-1}$
- $L_{\text{acc}}^{\text{edd}} \sim 10^{38} \text{ Erg s}^{-1}$,
- $L_{\text{q}} \sim 10^{33} \text{ Erg s}^{-1}$
- $T_{\text{crust}} \lesssim 5 \cdot 10^8 \text{ K}$
- $\gtrsim 30$ systems known

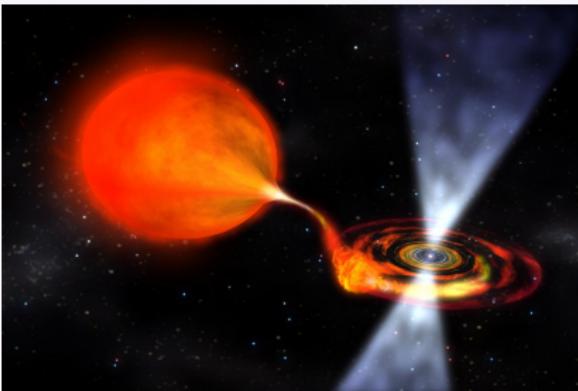


Figure: LMXB (astronomy.com).

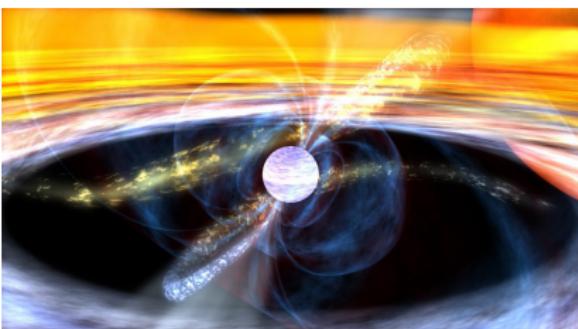
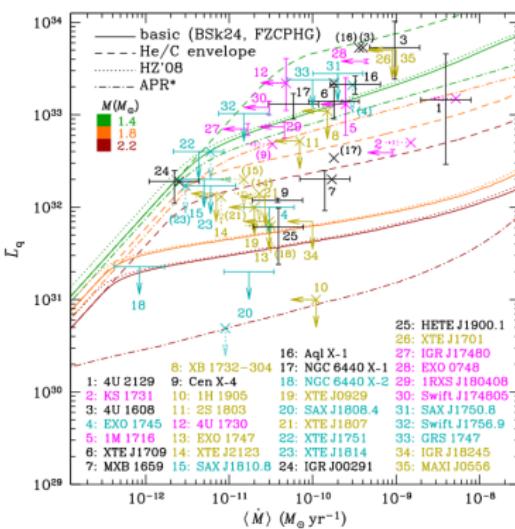
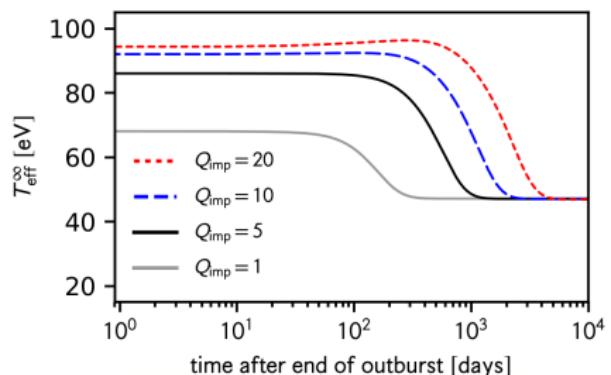


Figure: Artist view of accretion (nasa).

Transients evolution

Combining theory and observations \Rightarrow
properties of a superdense matter
(talk by M. Beznogov)



Problem formulation

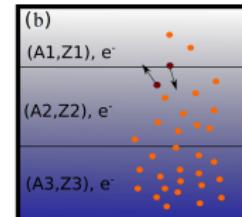
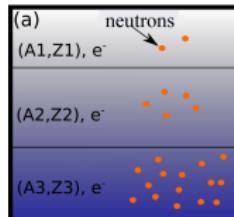
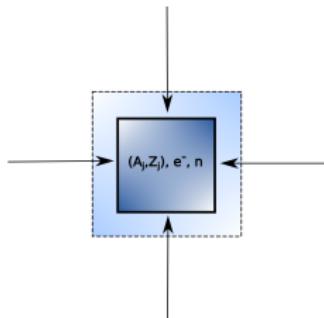
- Nuclear evolution of matter during compression from $\rho_{\text{in}} \approx 10^9 \text{ g cm}^{-3}$
- Initial composition – thermonuclear burning ashes in the envelope

Traditional approach

- Sato'79,
Haensel&Zdunik'90, ...,
Lau+'18, Fantina+'18
- $A_{\text{cell}} = \text{const}$
- Outer crust (N, e^-) ✓
- Inner crust (+n) ✗

Thermodinamically consistent approach

- Gusakov&Chugunov'20
- Accounting for neutron hydrostatic/diffusion equilibrium ($\mu_n^\infty = \text{const}$)
- Fully accreted crust: $N_{\text{nuclei}} = \text{const}$, nuclei disintegration into npe -matter

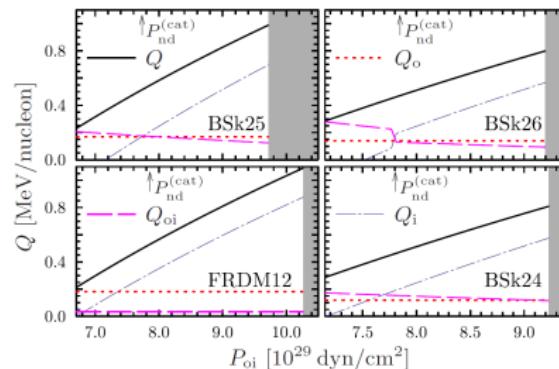


Inner crust of the NS

- Neutrons are not attached to the nuclear clusters
- Problems of HFB calculation: boundary conditions, neutron pairing, artificial shell effects, numerically costly.

Gusakov&Chugunov'21

- One-component CLD model with shell corrections
- Result: $P_{\text{oi}} \approx P_{\text{nd}}^{(\text{cat})}$ (nuclear uncertainties and unknown crust evolution)
- $Q^\infty \simeq \bar{m}_{\text{b,ash}} e^{\nu_s/2} - \mu_{\text{b,core}}^\infty \simeq \underbrace{Q_o}_{\text{trad}} e^{\nu_{\text{oi}}/2} + \underbrace{[\mu_b(P_{\text{oi}}) - m_n]}_{\text{det at oi interface}} e^{\nu_{\text{oi}}/2}$



Ash composition

- depends on:
 - accreted matter composition
 - accretion rate
 - and actually on Q
- Usually used: pure ^{56}Fe

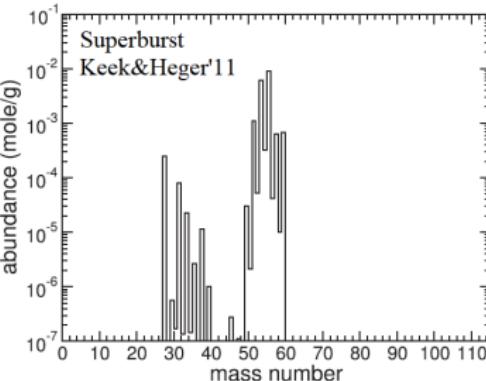
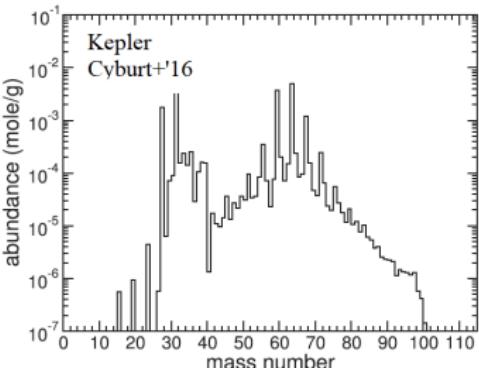
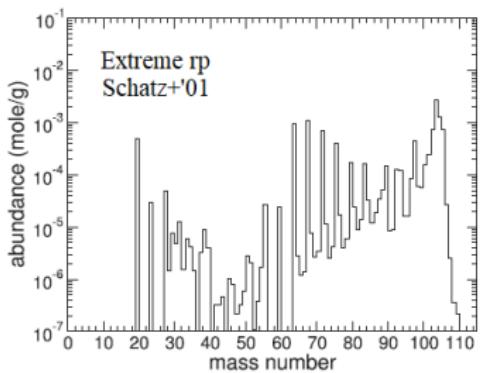


Figure: Lau+'18.

Nuclear physics input

- AME20 – experimental data compilation by Wang+ '21
- FRDM92(12) – finite-range droplet models of Moller+'95('16)
- HFB24 – Hartree-Fock-Bogoliubov calculations of Goriely+'13

rms with AME ≈ 0.6 MeV,
however $\Delta M_j^{\text{th}} \lesssim 10$ MeV

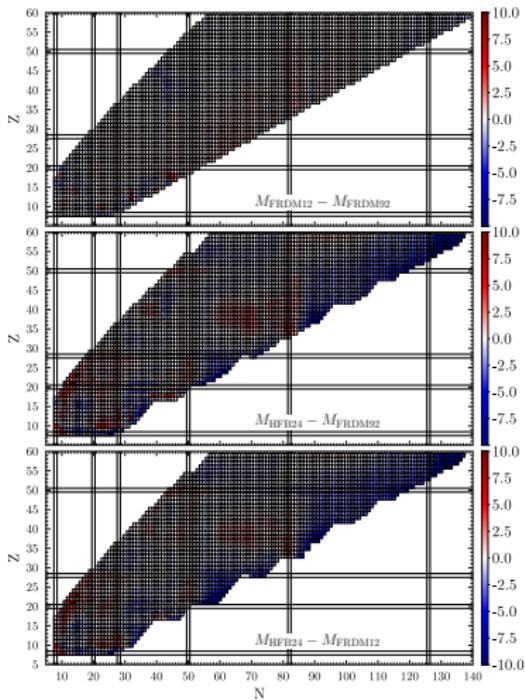
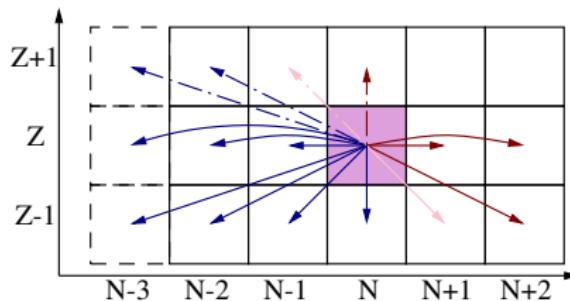


Figure: Mass differences.

details	model
matter	multicomponent
formalism	Gibbs energy minimization
reaction scheme	simplified reaction network, based on τ_{reac}
transitions	ground state \rightarrow ground state, no Q_{ν_e}
thermal corrections	$T = 0$
pycnonuclear reactions	Yakovlev+06 Afanasjev+12 $T = 0.5 \text{ GK}$

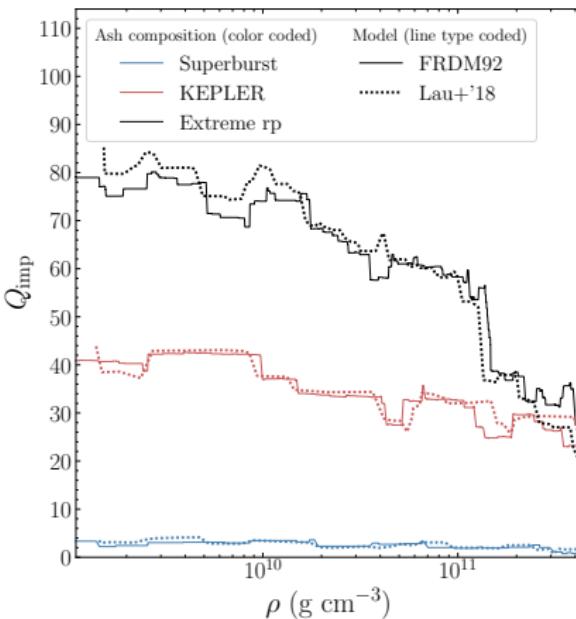


reaction order: $-xn, +n, \pm e - xn, \pm e + n, +2n$, pycnonuclear fusion.

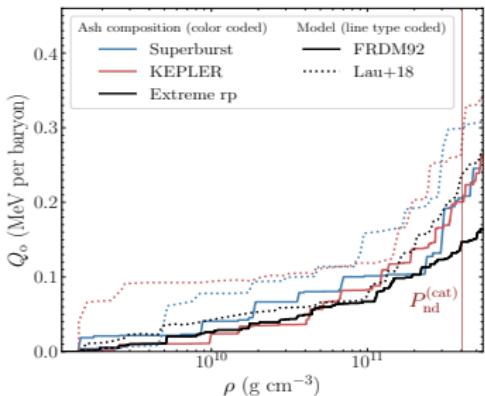
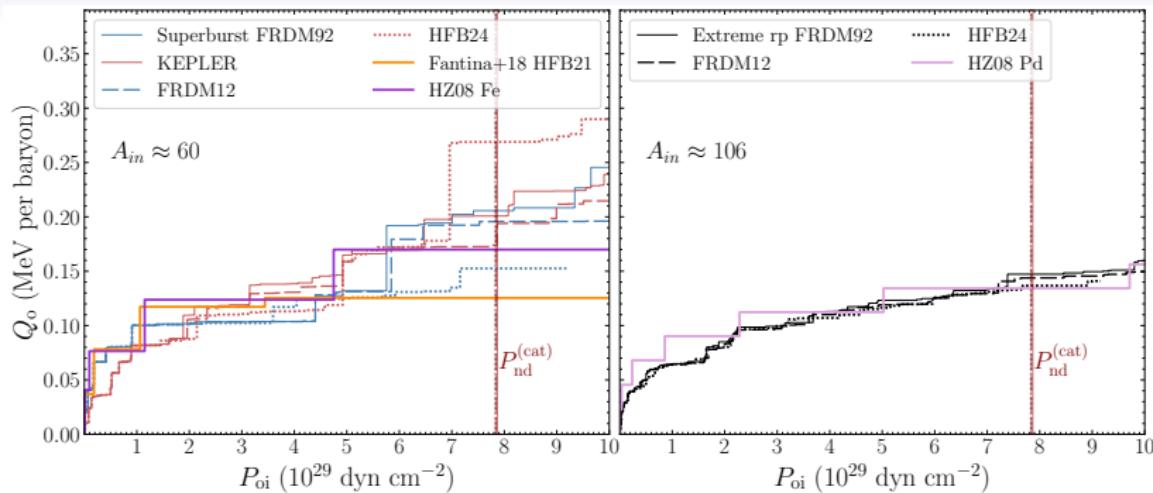
Comparison with Lau+'18

Lau+'18 model

- Detailed reaction network
- AME12+FRDM92
- Thermal effects, $T = 0.5$ GK
- Theoretical nuclei levels
- ↳ separately $\pm n, \pm e$

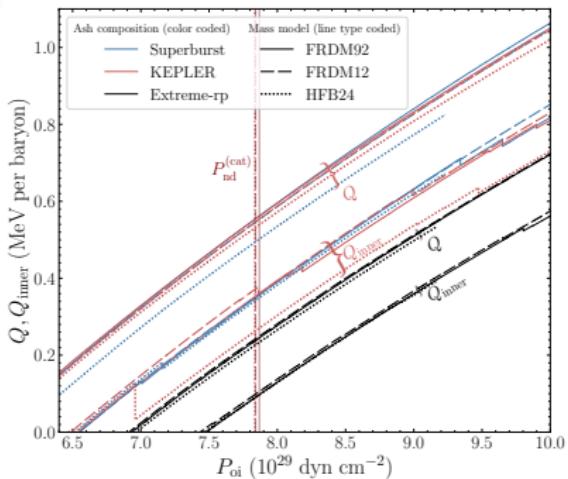
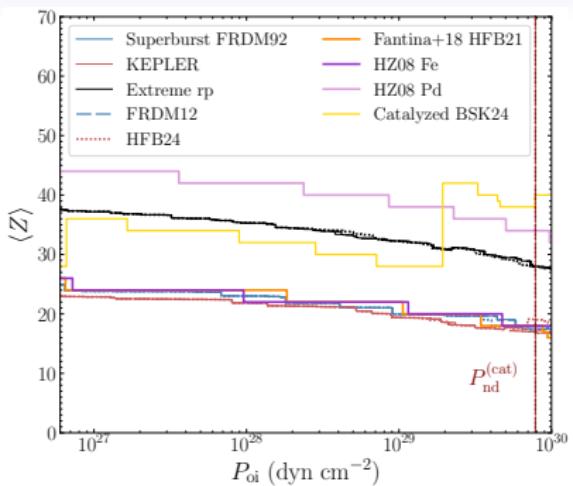


Our simplified reaction network produces composition profile in reasonable agreement with Lau+'18 \Rightarrow reliable $\mu_b(P_{\text{oi}})$.



	FRDM92	FRDM12	HFB24
Superburst	0.21	0.20	0.15
Kepler	0.20	0.17	0.27
Extreme rp	0.15	0.14	0.14

Table: Outer crust energy release (MeV per baryon) at $P_{oi} \approx P_{nd}^{(cat)}$.



	FRDM92	FRDM12	HFB24
Superburst	0.56	0.55	0.49
Kepler	0.56	0.55	0.52
Extreme rp	0.25	0.24	0.23

Deep crustal heating at $P_{oi} \approx P_{nd}^{(\text{cat})}$.

$$Q_{\text{in}} = \mu_{\text{b},\text{oi}} - m_{\text{n}}$$

at $Q_{\text{in}} \geq 0, P_{oi}^{\text{sb,kep}} \geq 6.5 \times 10^{29} \text{ dyn cm}^{-2}, P_{oi}^{\text{rp}} \geq 7.4 \times 10^{29} \text{ dyn cm}^{-2}$.

AME20 vs AME16

Recent update in the experimental data

Decrease of the difference between the lines with various models

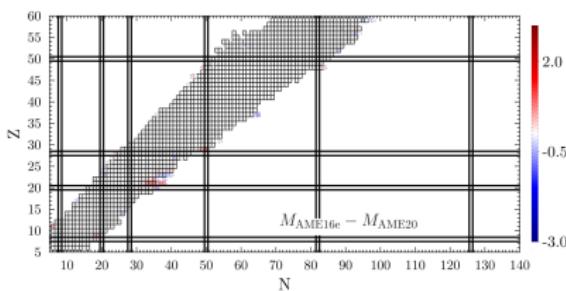
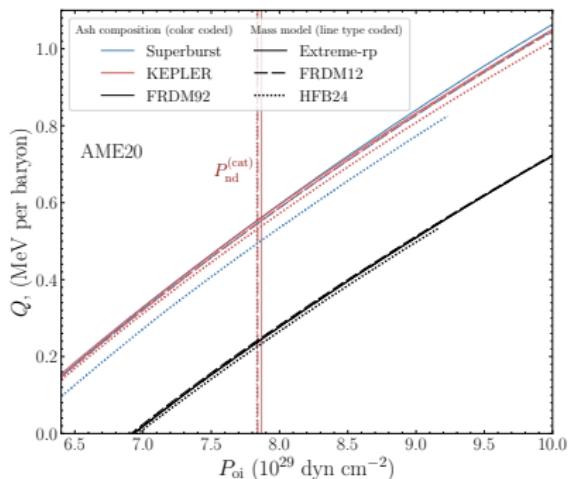


Figure: Experimental mass differences.

Figure: Energy release with AME20.

AME20 vs AME16

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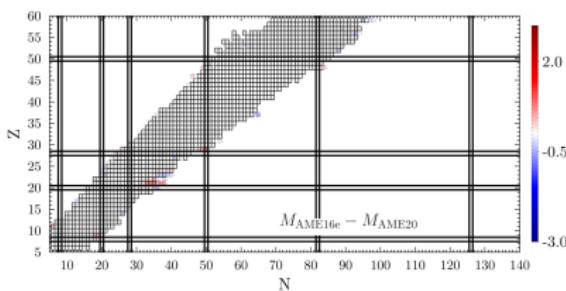
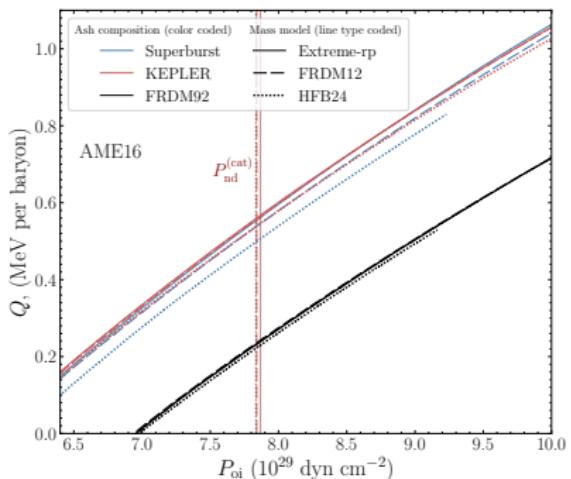


Figure: Experimental mass differences.

Figure: Energy release with AME16.

Summary

Results

- We apply a simplified reaction network to model nuclear evolution of multi-component thermonuclear burning ashes in the outer crust.
- We calculate the deep crustal heating energy release Q , parametrized by the pressure at the outer-inner crust interface, P_{oi} .
 - At $P_{\text{oi}} \approx P_{\text{nd}}^{(\text{cat})}$, $Q \approx 0.24$ MeV per baryon for Extreme rp ashes, and $Q \approx 0.54$ MeV for Kepler and Superburst ashes.

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Future work

- Extend our model to the upper layers of the inner crust, where approach alters, however theoretical mass tables still applicable.
- Preliminary calculations. For $Q \geq 0$ in any region of the crust:

$$\begin{aligned}P_{\text{oi}}^{\text{sb,kep}} \geq 0.94 P_{\text{nd}}^{(\text{cat})} &= 7.4 \times 10^{29} \text{ dyn cm}^{-2}, \\P_{\text{oi}}^{\text{rp}} \geq 1.02 P_{\text{nd}}^{(\text{cat})} &= 8.0 \times 10^{29} \text{ dyn cm}^{-2}.\end{aligned}$$