What lies beneath

Edward Brown, Michigan State University

A. Piro, Carnegie Obs.

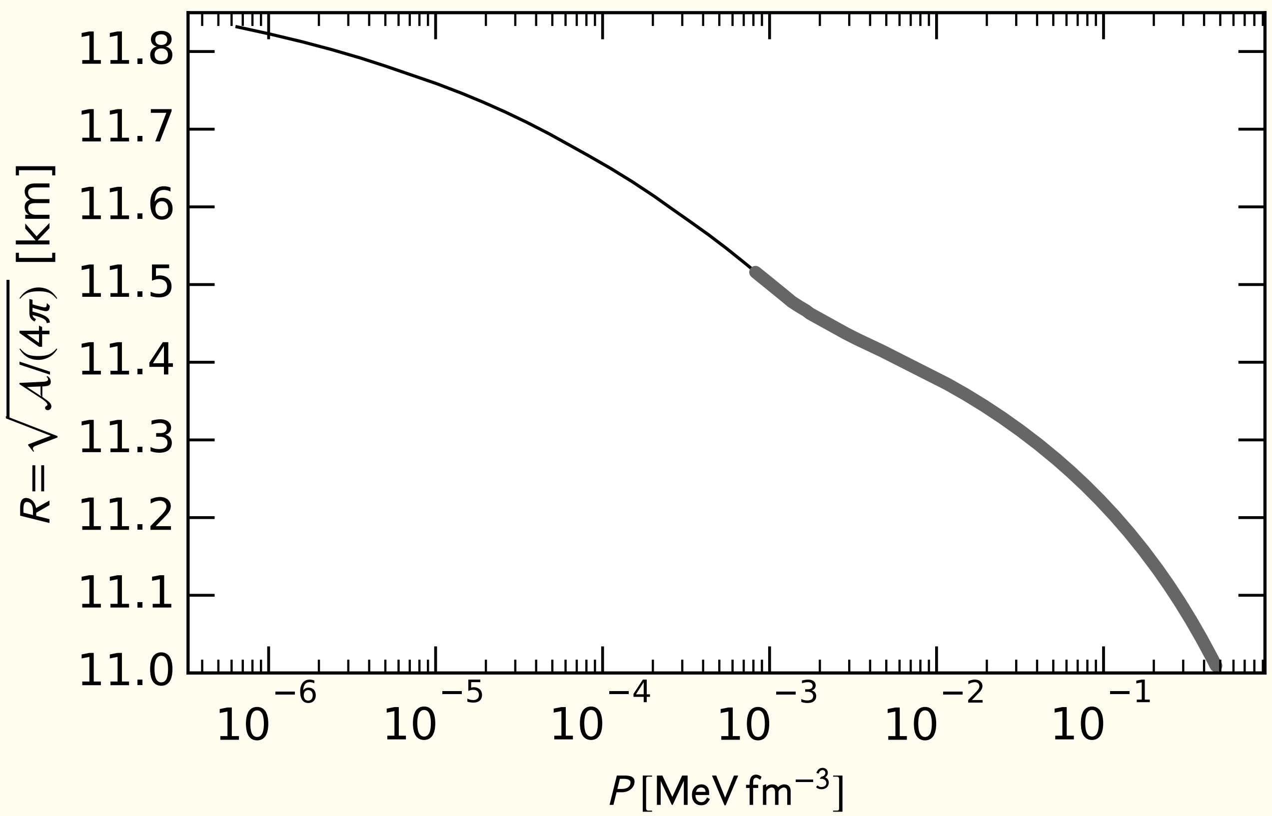
Neutron stars should have a km-thick crust composed of nuclei, electrons, and free neutrons.

Accretion pushes matter through this crust and induces nuclear reactions.

The heating from these reactions sets the ambient temperature (“Q_b”) for X-ray bursts and superbursts.

Observing the response of the star to these reactions allows us to infer the properties of matter in the deep crust and core.

Crust structure



$\mu_e \approx k_\mathrm{B} T$ ⟶

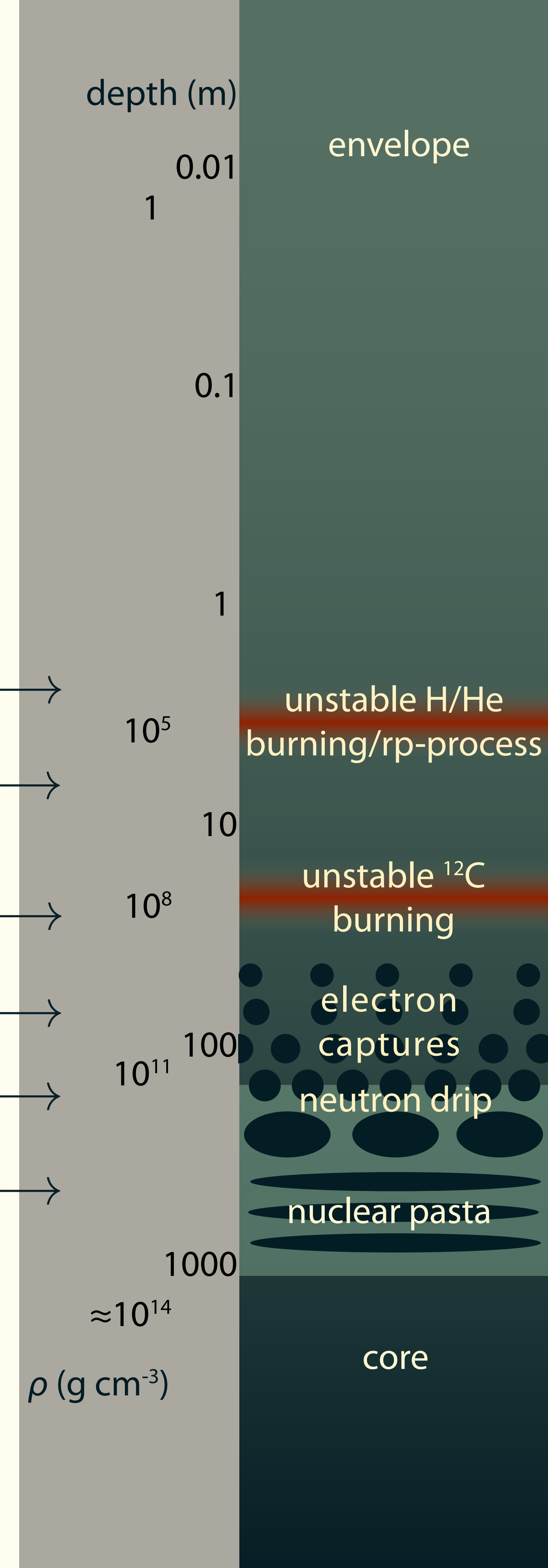
$\mu_e \approx m_e c^2$ ⟶

$\Gamma \equiv \dfrac{Z^2 e^2}{a k_\mathrm{B} T} > 175$ ⟶

$T \approx \Theta_\mathrm{D}$ ⟶

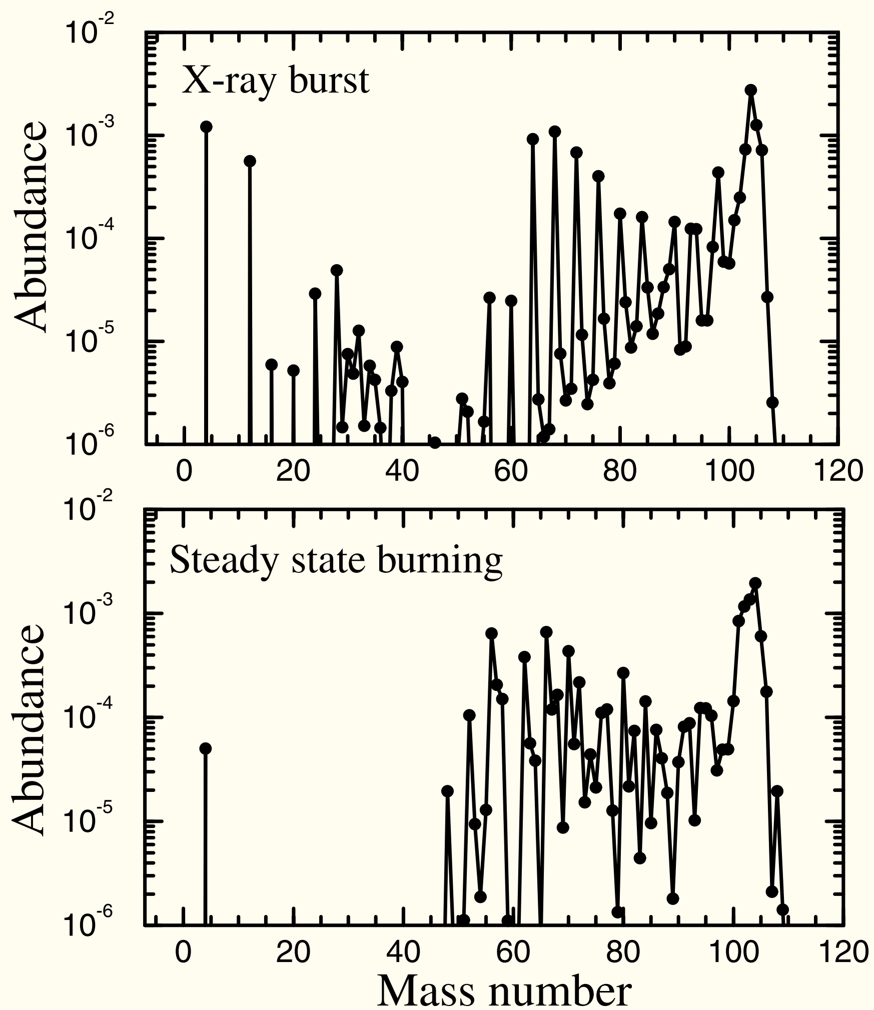
$\mu_e \approx 2a_V \approx 30\ \mathrm{MeV}$ ⟶

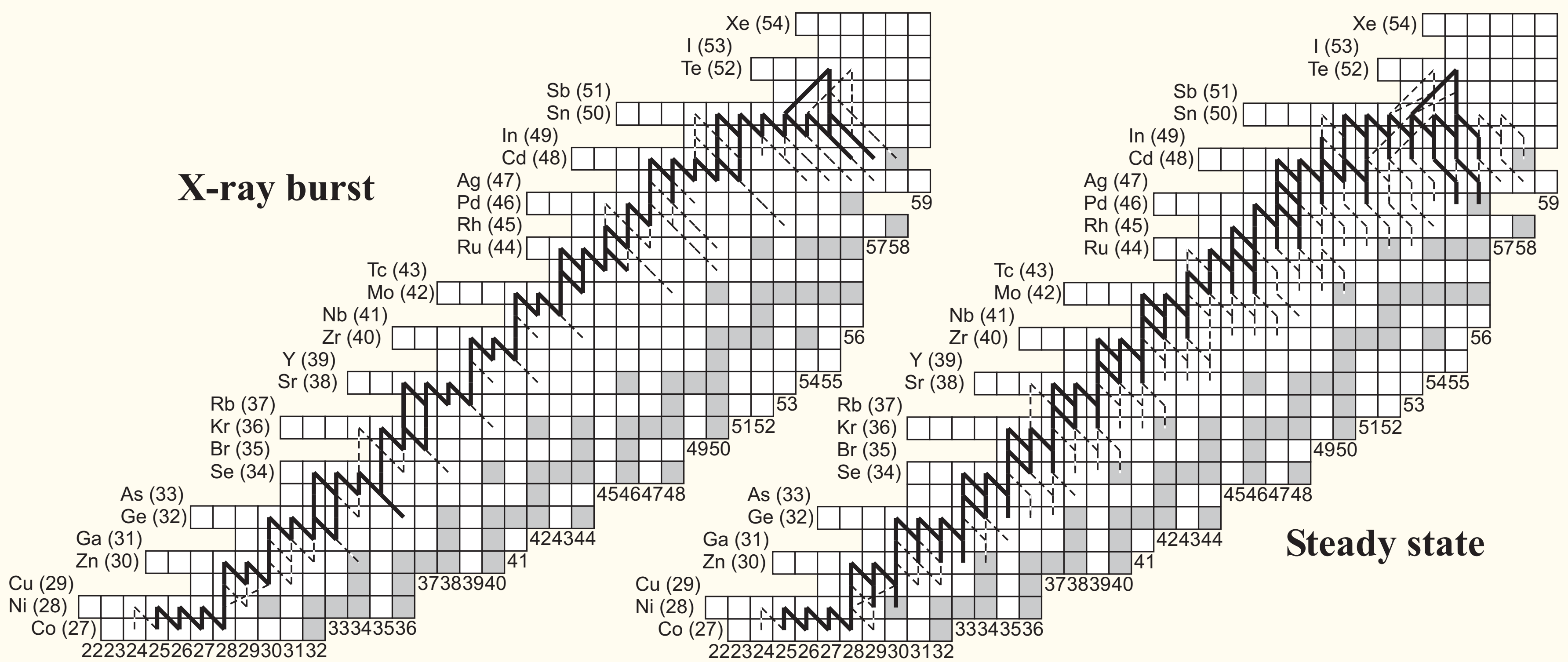
$r_\mathrm{N}^3 \approx \dfrac{a^3}{2}$ ⟶



Ashes of H, He burning

Schatz et al. '01



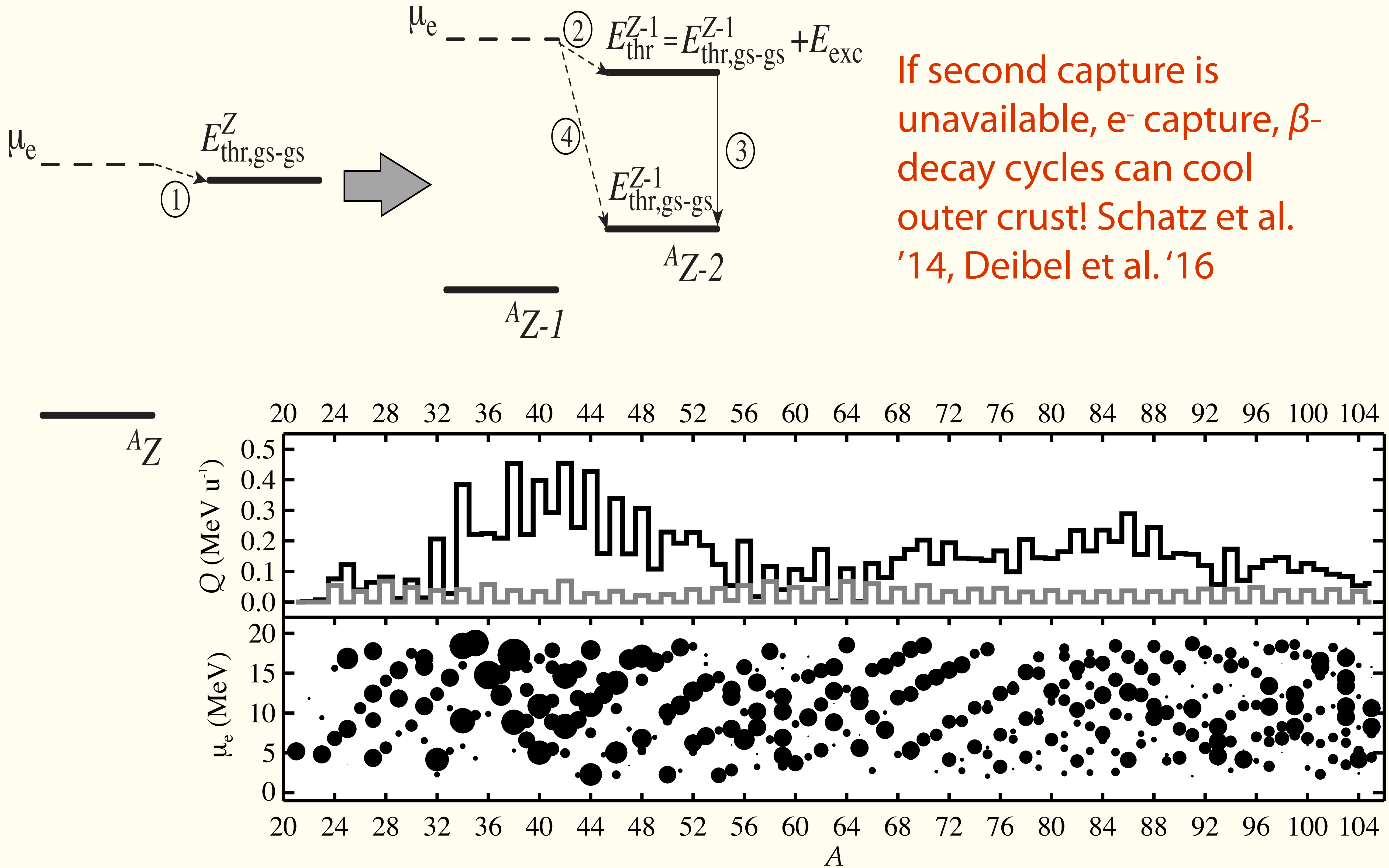


$$Q = \langle (Z - \langle Z \rangle)^2 \rangle \sim 100$$

See talk by Deibel

Heating from e⁻ captures into excited states

Gupta et al. 2007



If second capture is unavailable, e⁻ capture, β-decay cycles can cool outer crust! Schatz et al. '14, Deibel et al. '16

crust reactions | inner crust

NUCLEOSYNTHESIS IN SUPERNOVA OUTBURSTS AND THE CHEMICAL COMPOSITION OF THE ENVELOPES OF NEUTRON STARS

G. S. BISNOVATYI-KOGAN and V. M. CHECHETKIN
Institute of Applied Mathematics, U.S.S.R. Academy of Sciences, Moscow, U.S.S.R.

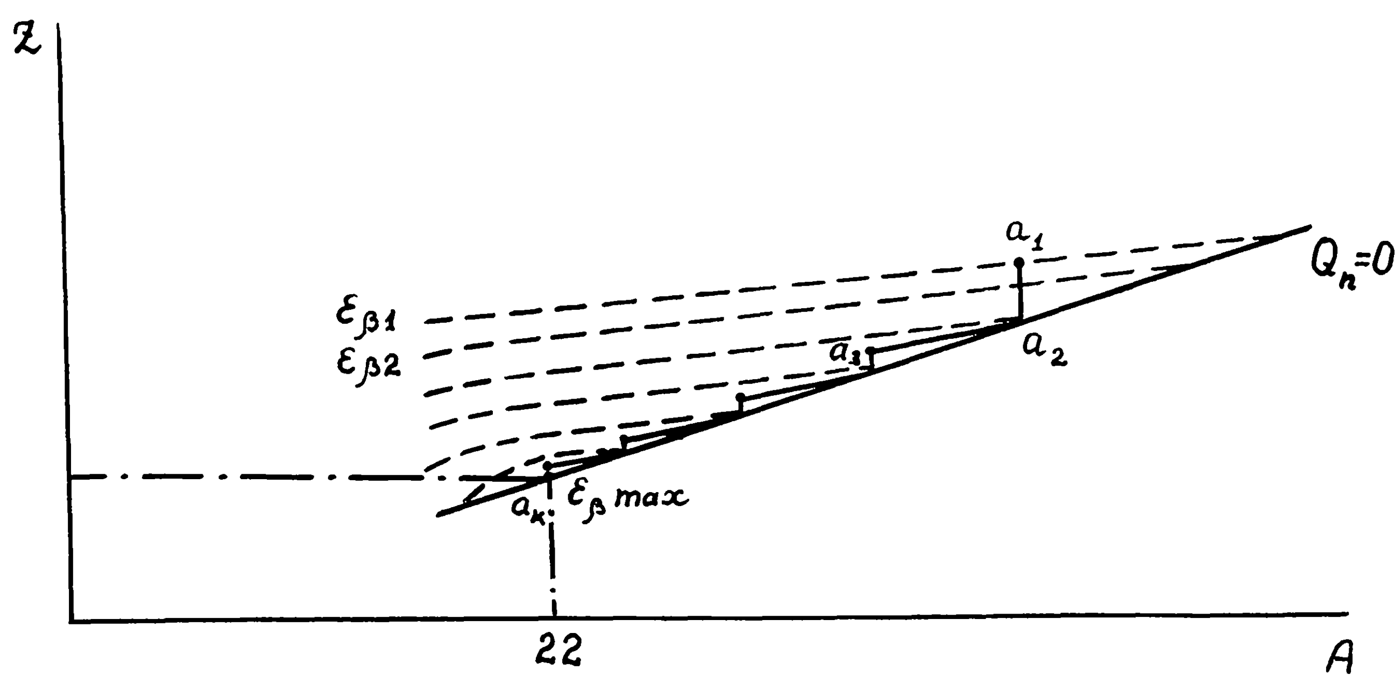
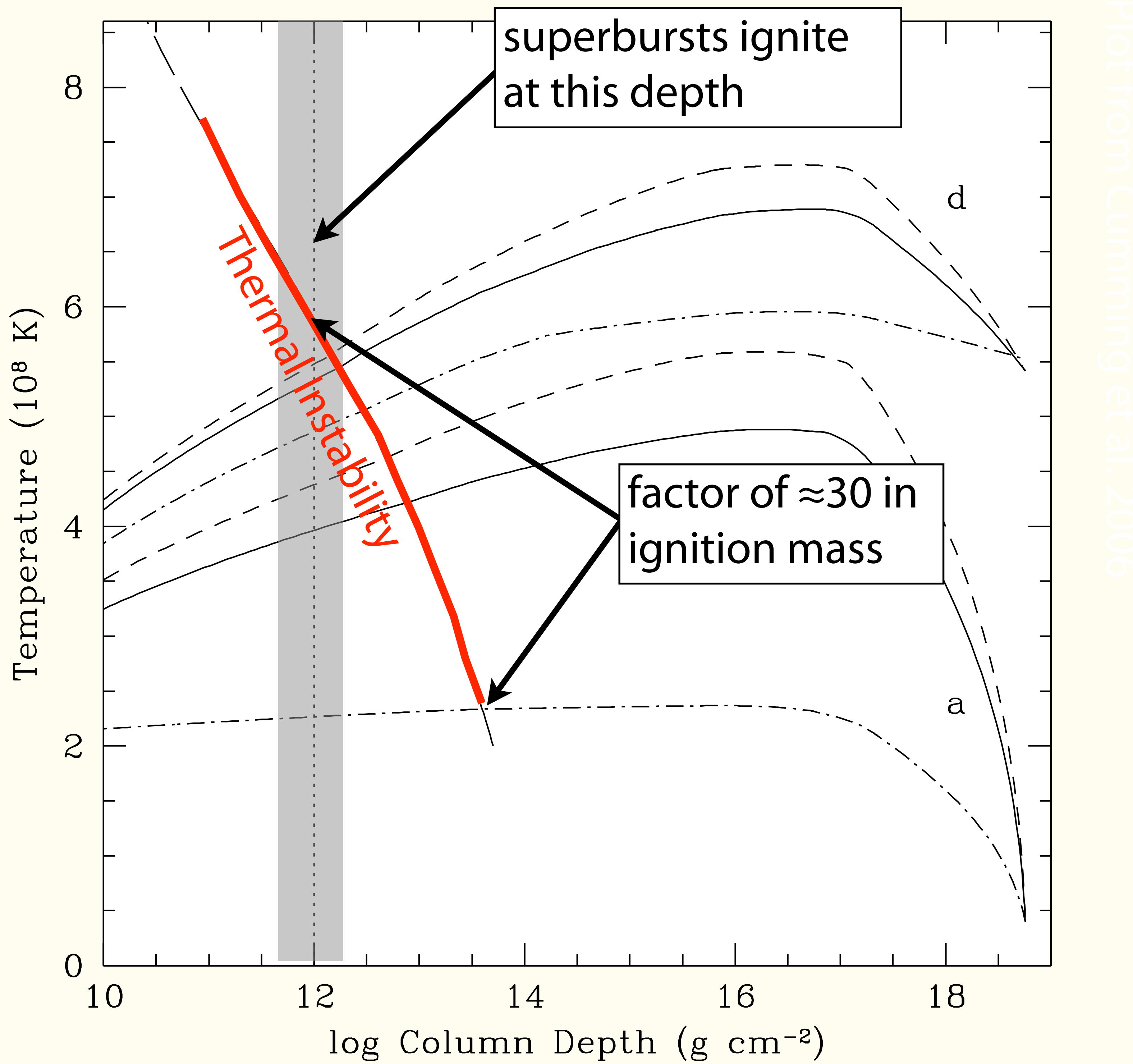


Fig. 2. Schematic representation of (A, Z). The curves of constant $\varepsilon_\beta = Q_p - Q_n$ have been indicated by dashed lines. The thick black line indicates the boundary of existence of a nucleus for which $Q_n = 0$. The step line $a_1 a_2 a_3 \ldots a_k$ correspond to variations of (A, Z) with increasing density of the cold material. At the point a_k, ε_β attains the maximum $\varepsilon_{\beta\max}$.

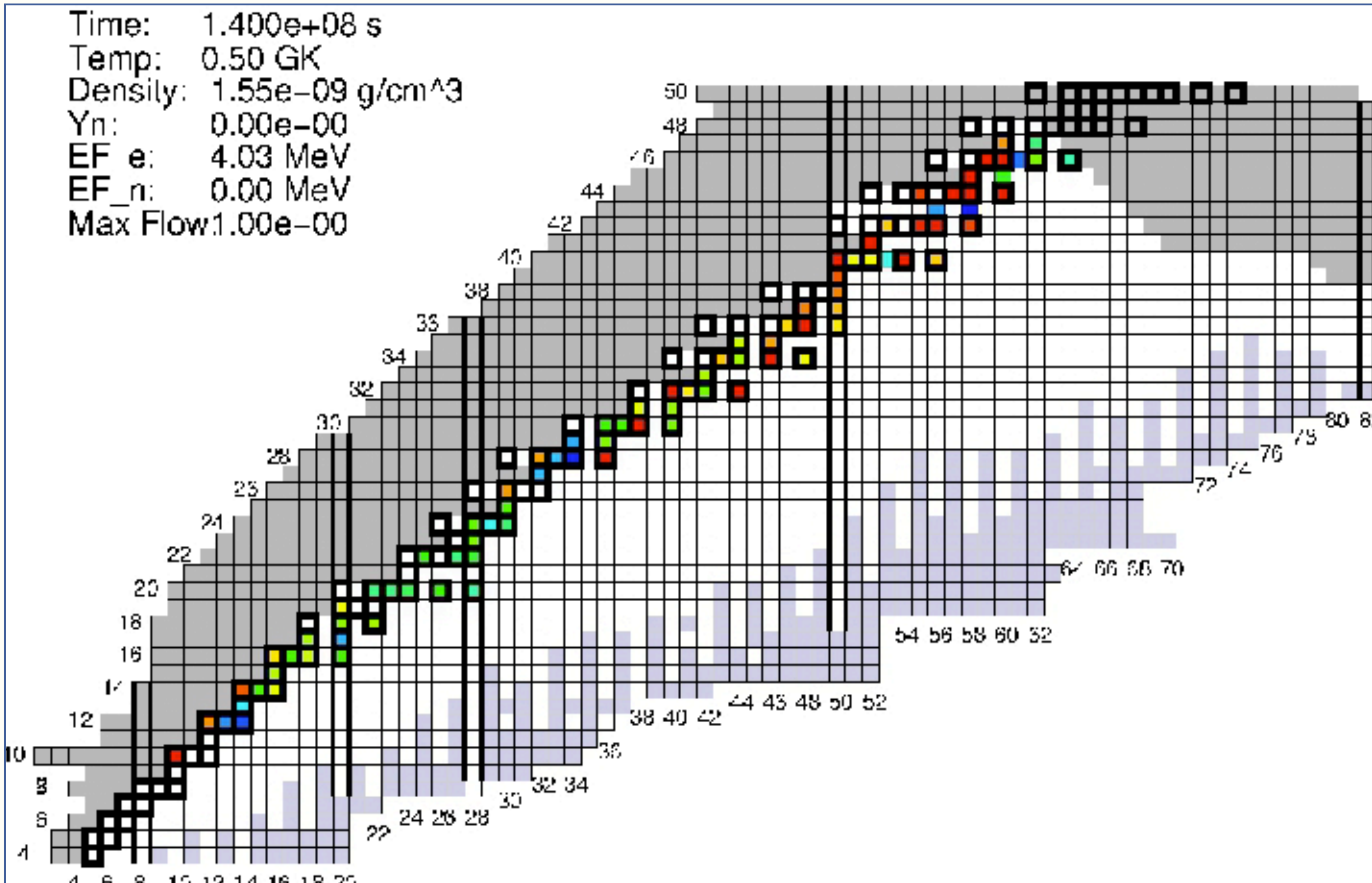
Heating can set ignition depth | e.g., ^{12}C ignition

Cumming & Bildsten 2001; Strohmayer & Brown 2002; Cooper & Narayan 2005; Cumming et al. 2006



Following reactions into the inner crust

MULTI-INSTITUTIONAL JINA/JINA-CEE EFFORT: **EC/β- strength**: QRPA (P. Moeller, S. Gupta, W. Hitt);**masses**: AME2012, FRDM (P. Moeller); **n-capture rates**: TALYS (S. Goriely, Y. Xu) with corrections from P. Shternin; **pycnonuclear fusion rates**: M. Beard, A. Afanasjev, L. Gasques, M. Wiescher, D. Yakovlev



Lau et al. 2018
arXiv:1803.03818

JINA-CEE
NSF Physics Frontier Center

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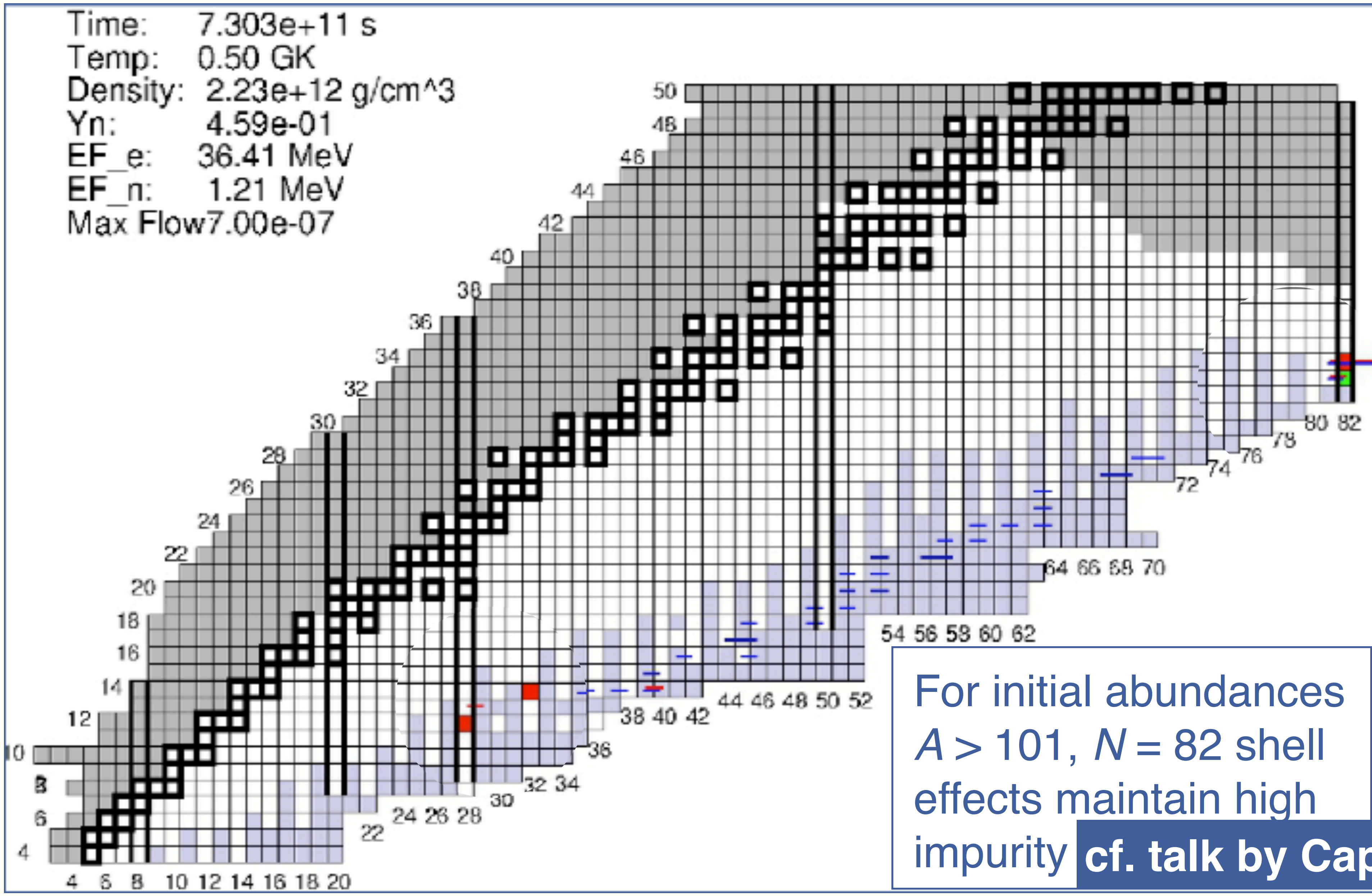

For initial abundances $A > 101$, $N = 82$ shell effects maintain high impurity

cf. talk by Caplan

Lau et al. 2018
arXiv:1803.03818

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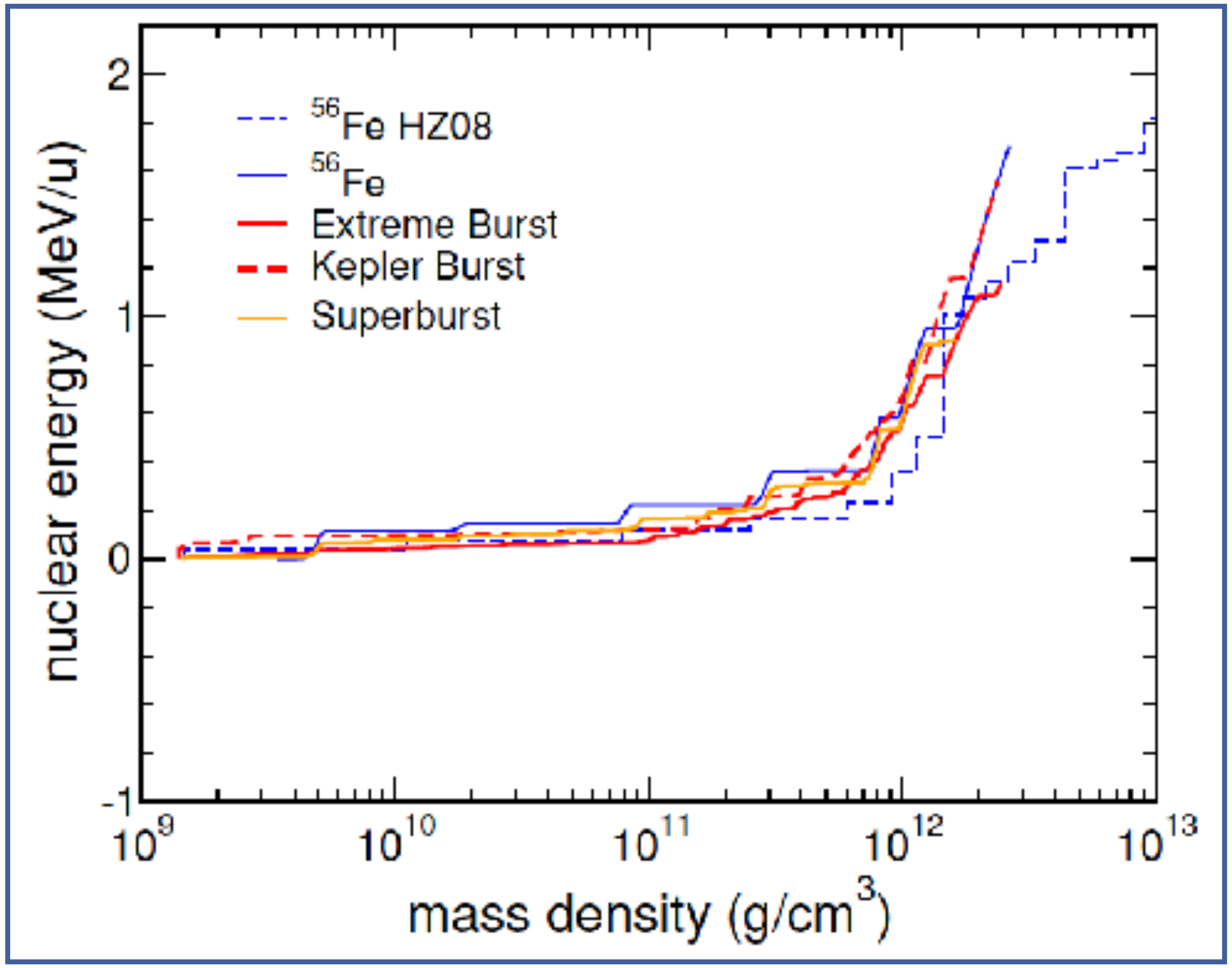
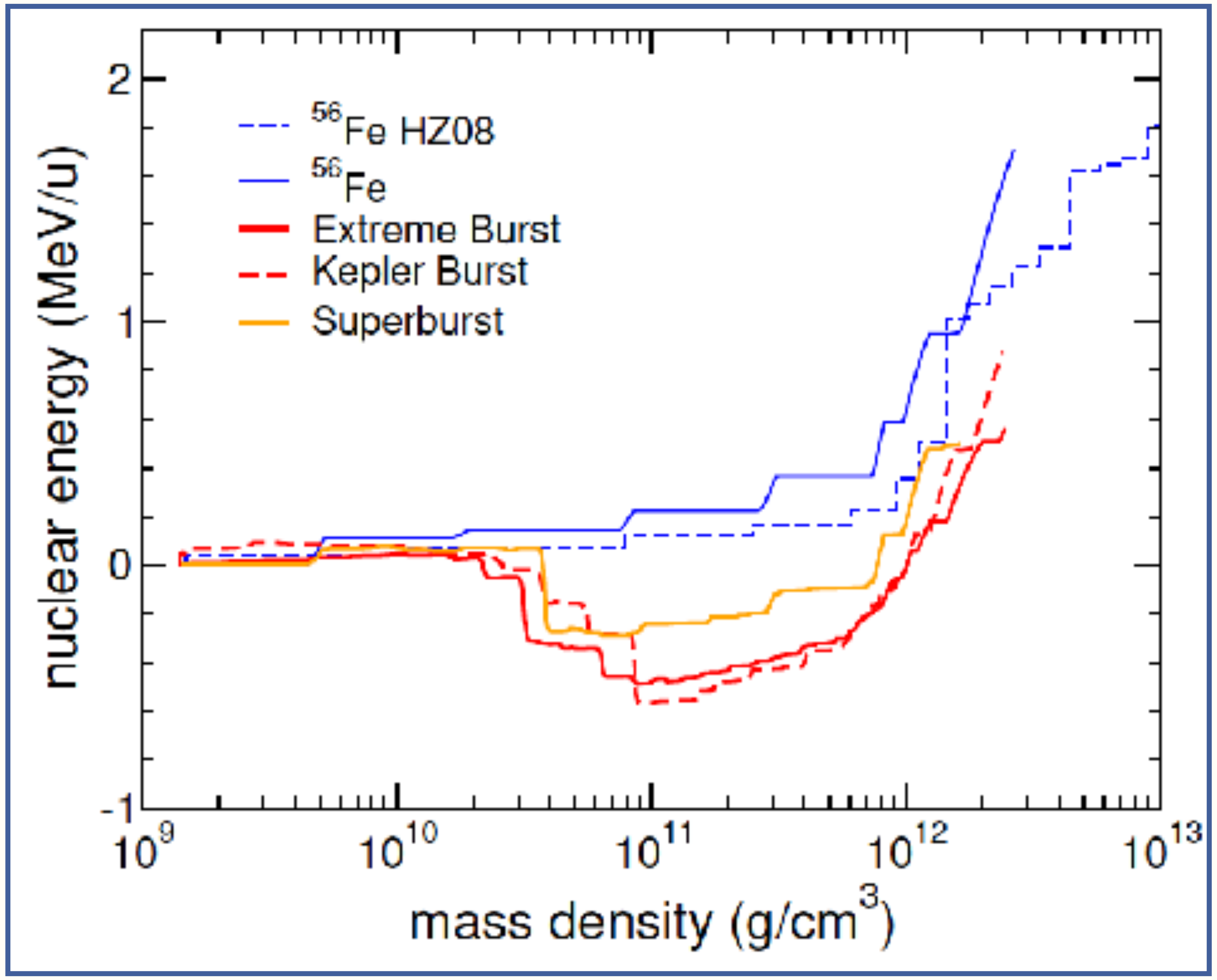
Nuclear Energy Deposition in the Crust for Different Initial Compositions



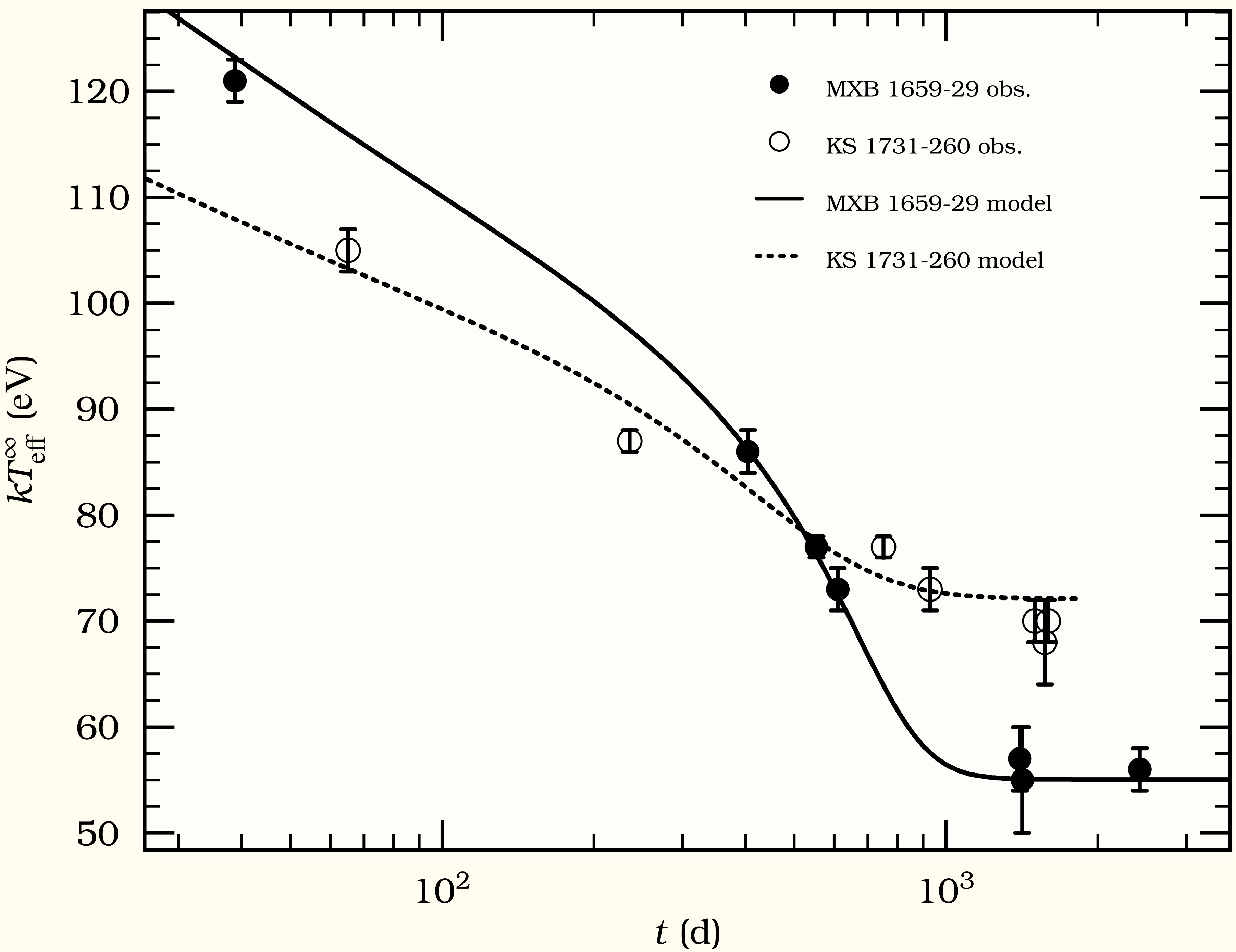
heating only

with neutrino cooling

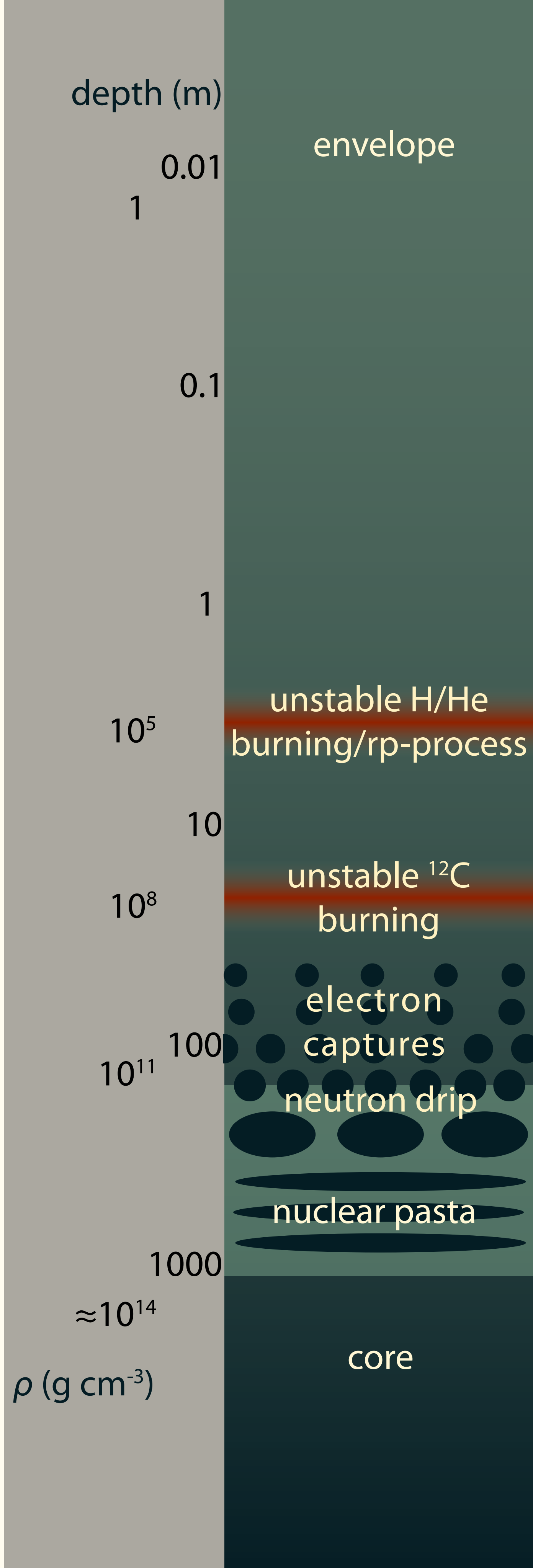


Inferring crust properties from cooling

Ushomirsky & Rutledge, Shternin et al., Brown & Cumming, Page & Reddy, Turlione et al., Deibel et al., Merritt et al., Parikh et al., Ootes et al.



data from Cackett et al. 2008
fits from Brown & Cumming 2009



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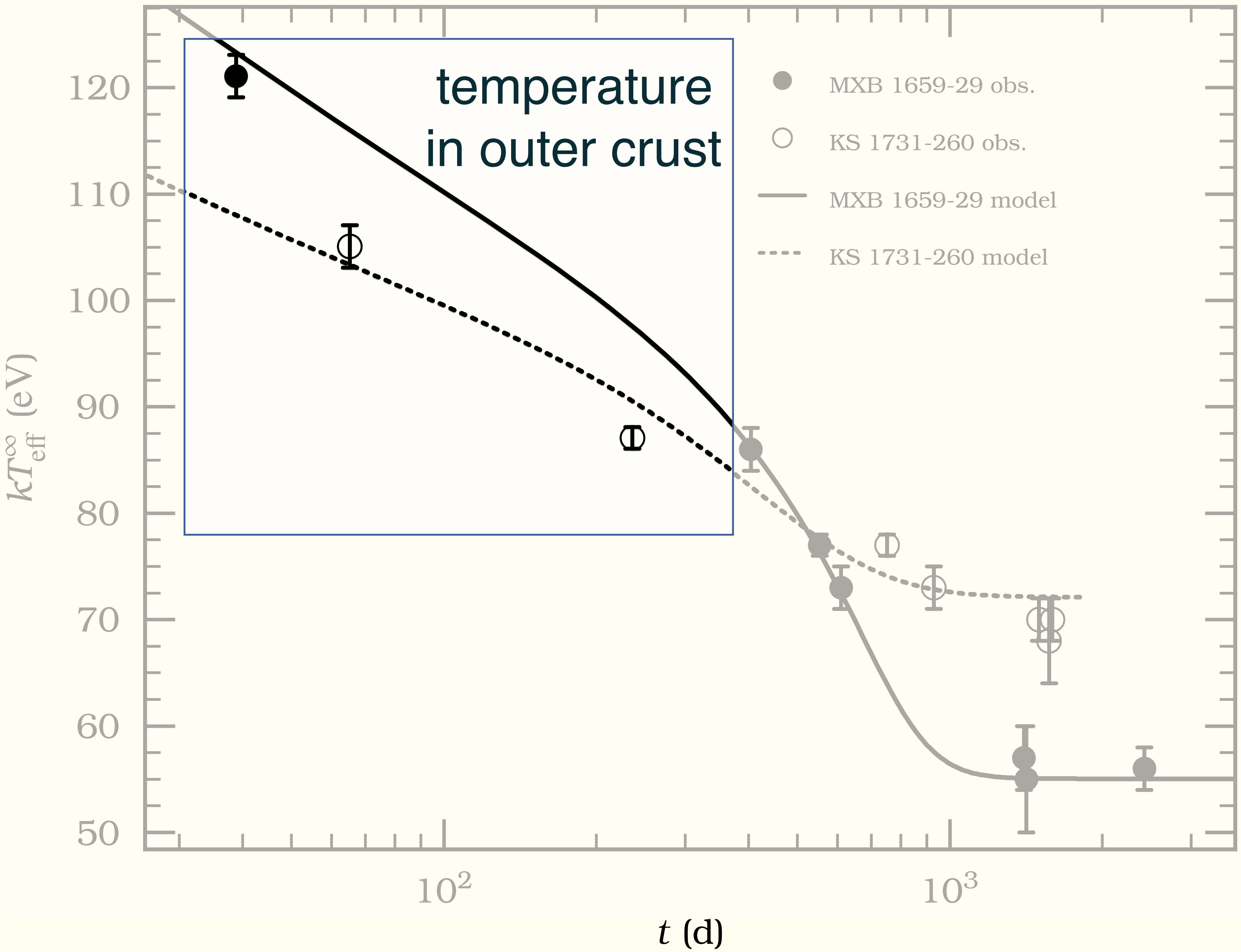

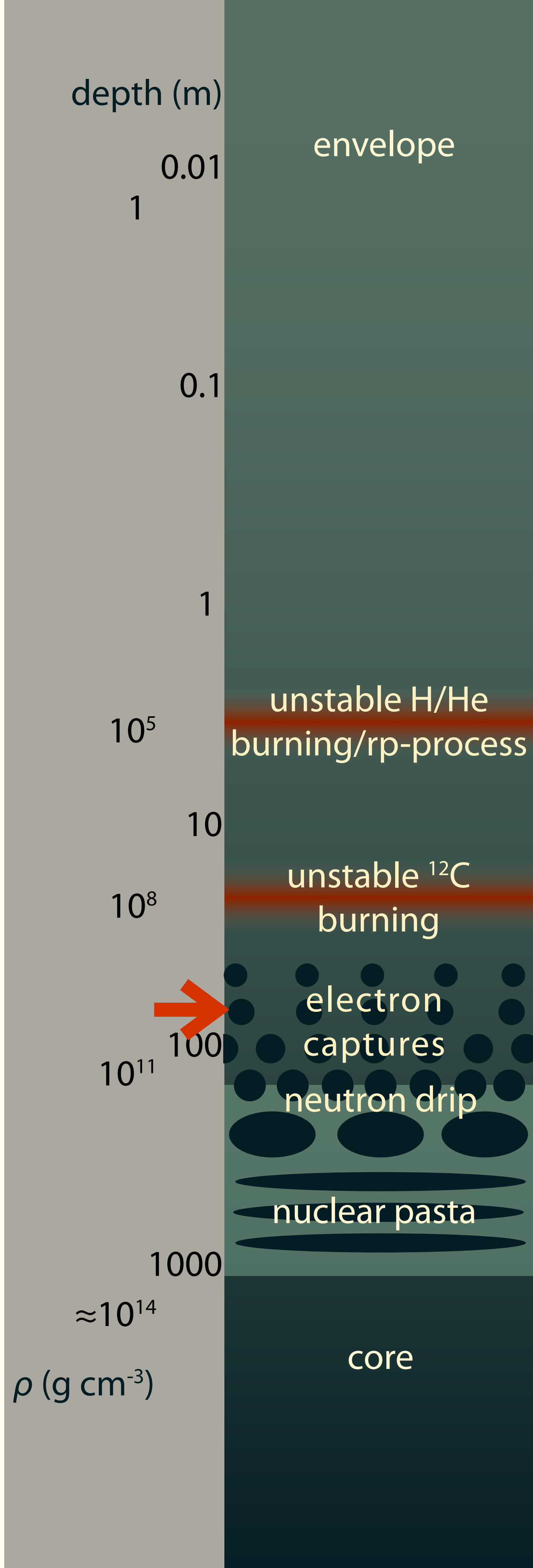

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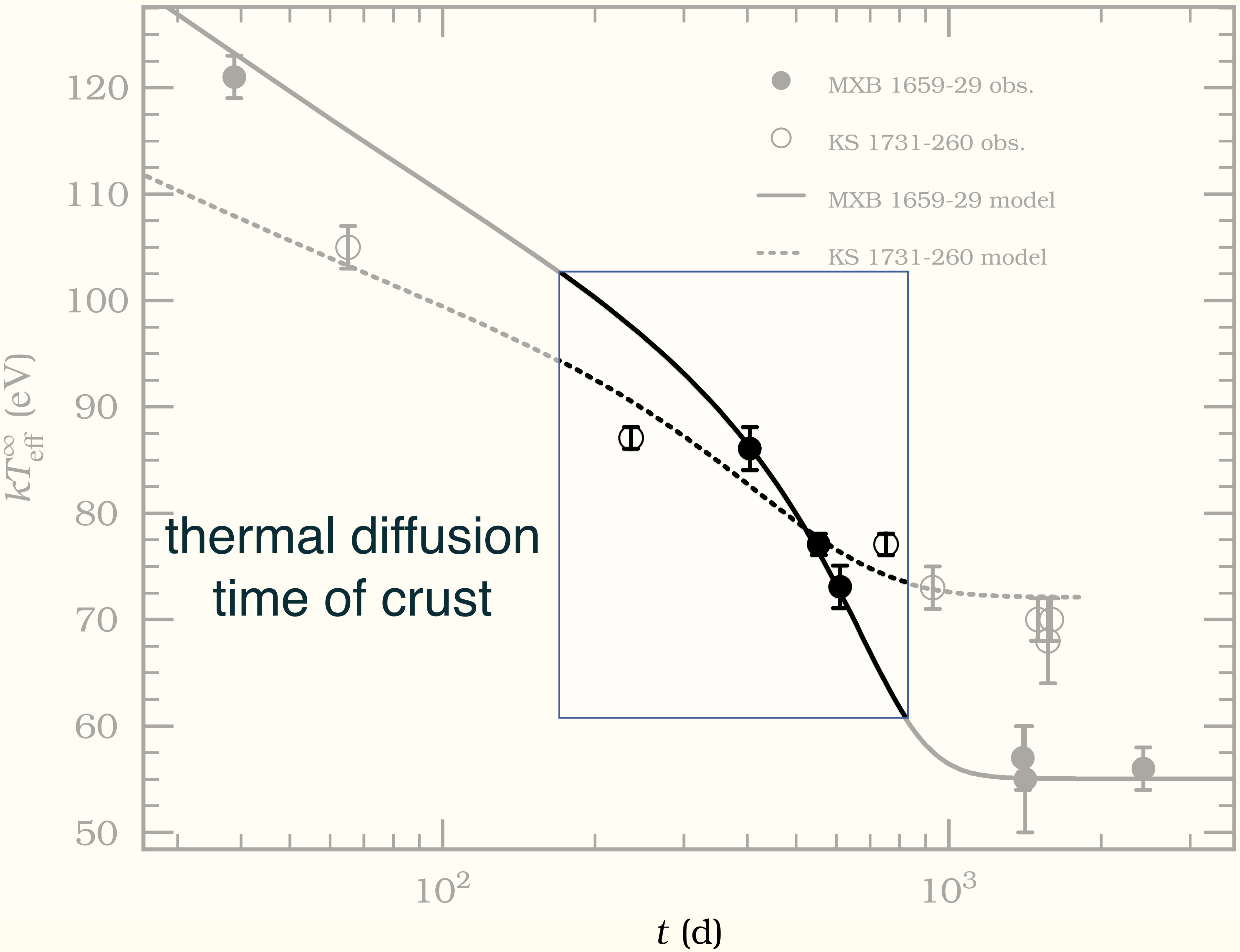

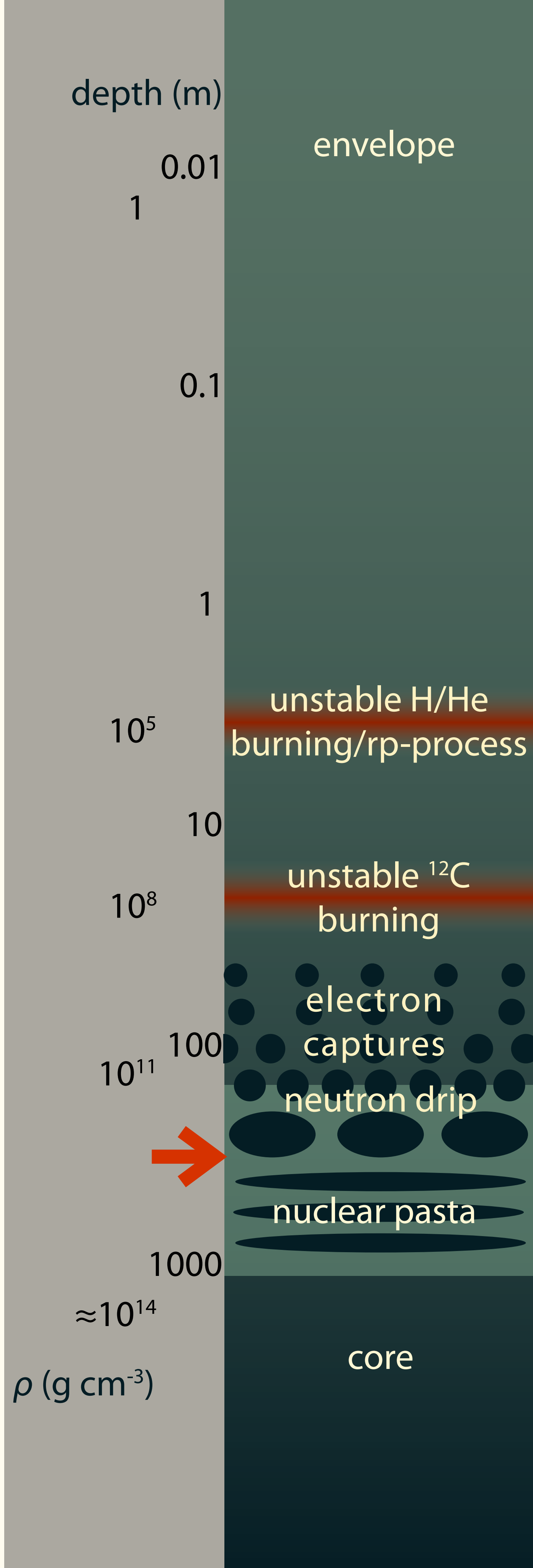

Inferring crust properties from cooling

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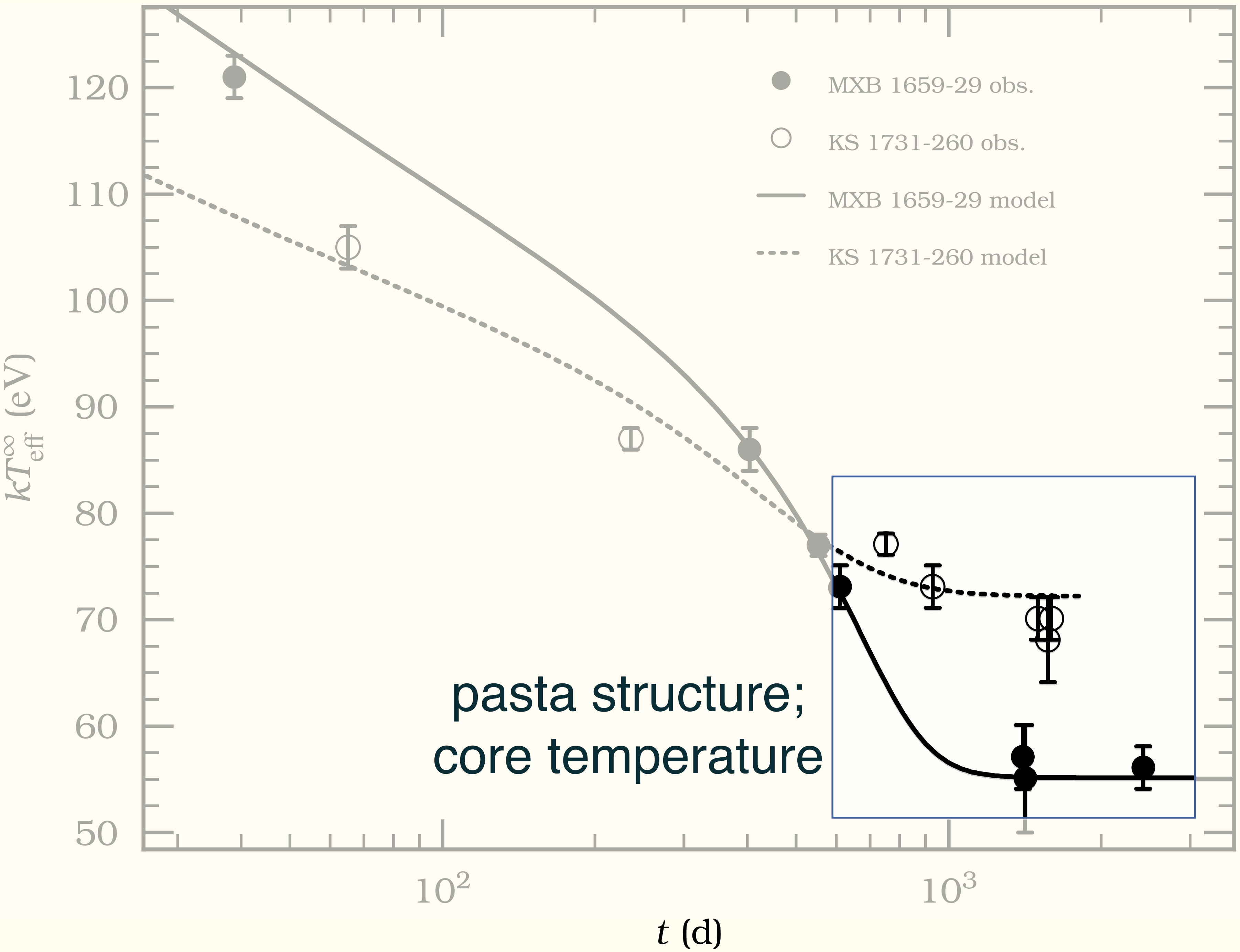
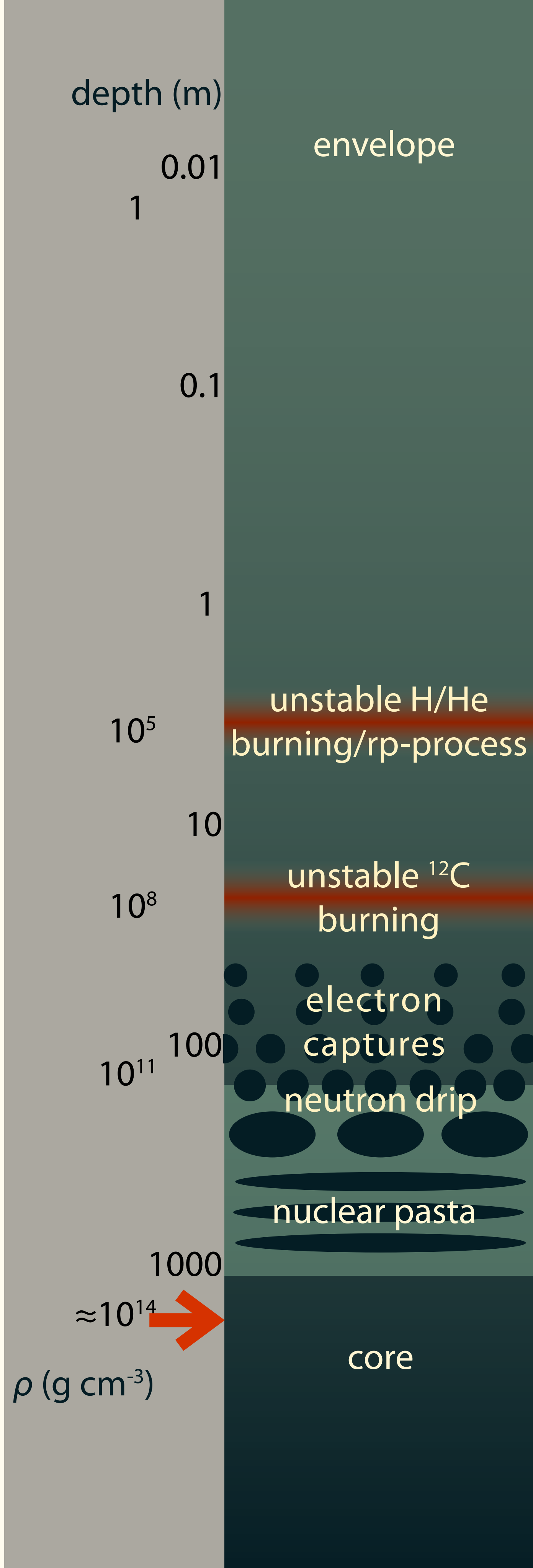
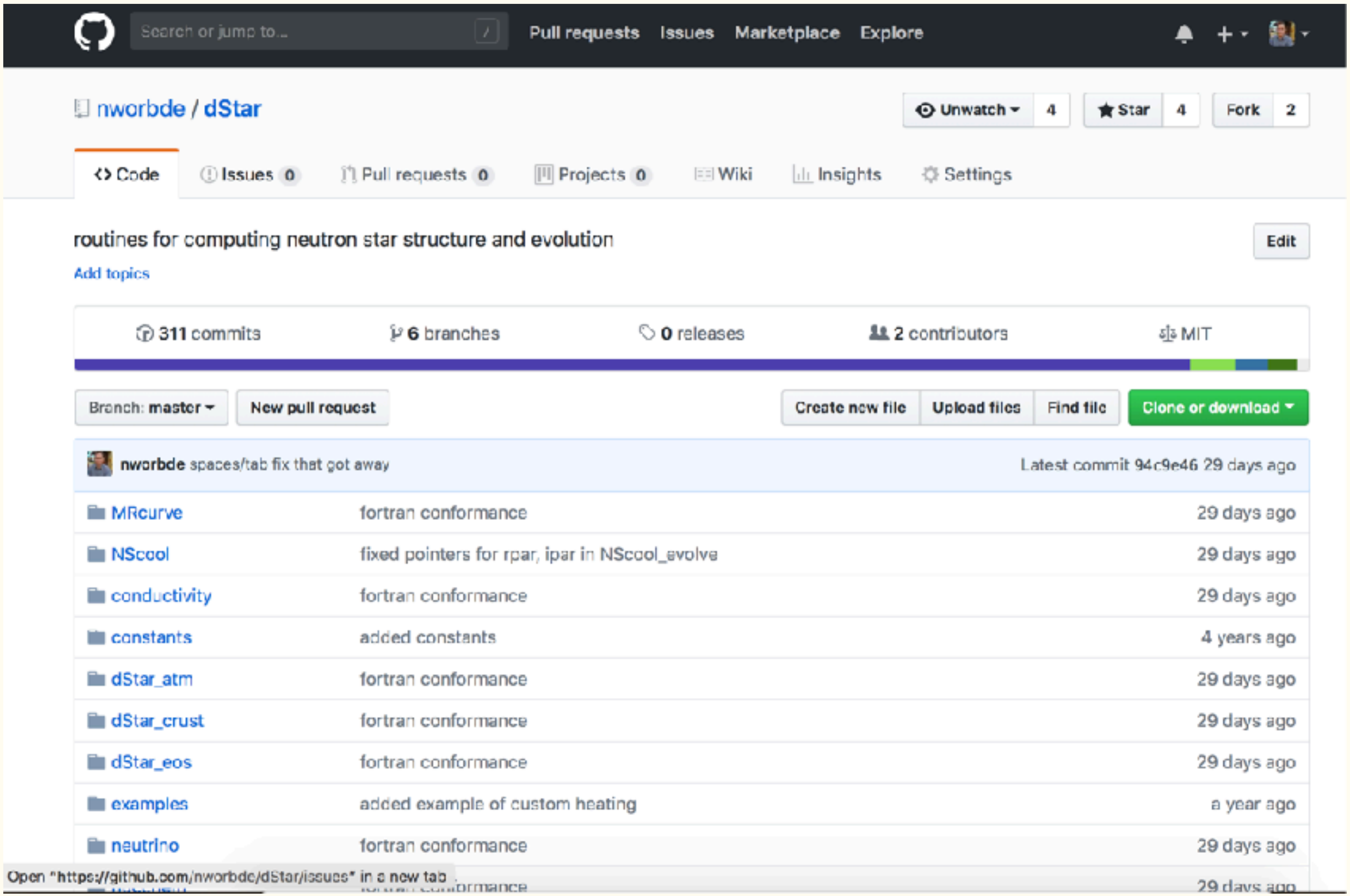
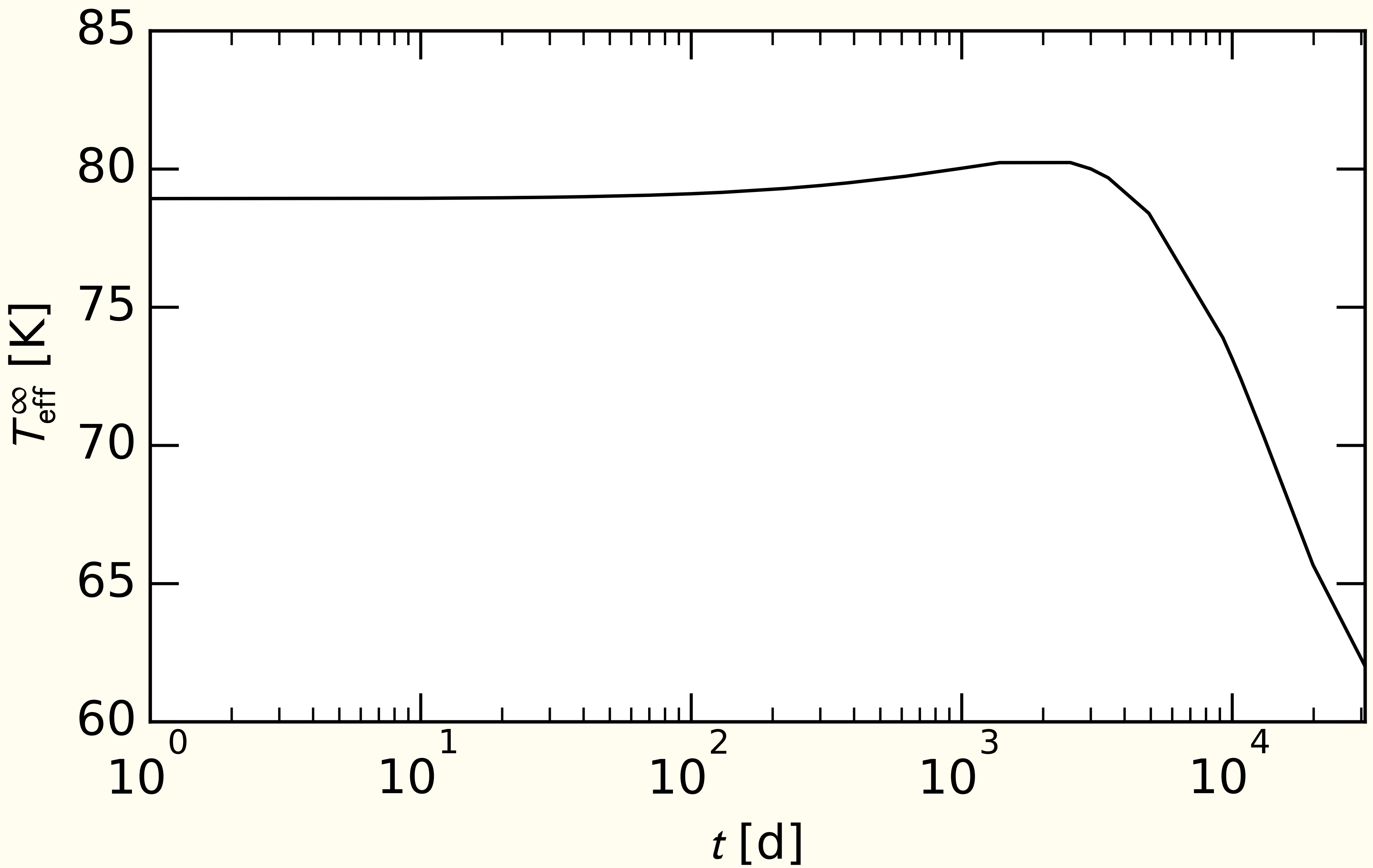




`dStar`: Open-source neutron star cooling



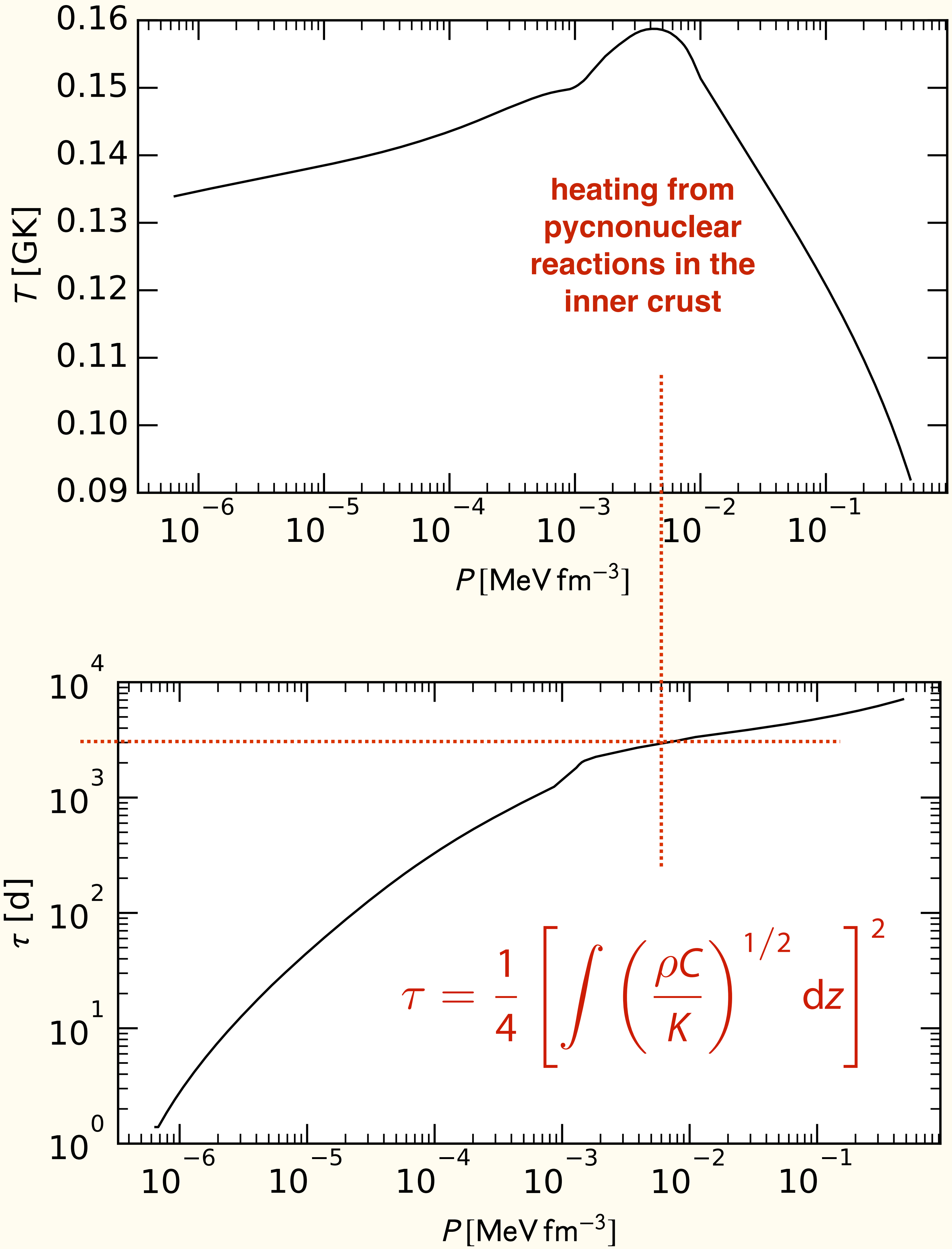
crust cooling | surface temperatures after a 12 yr accretion outburst



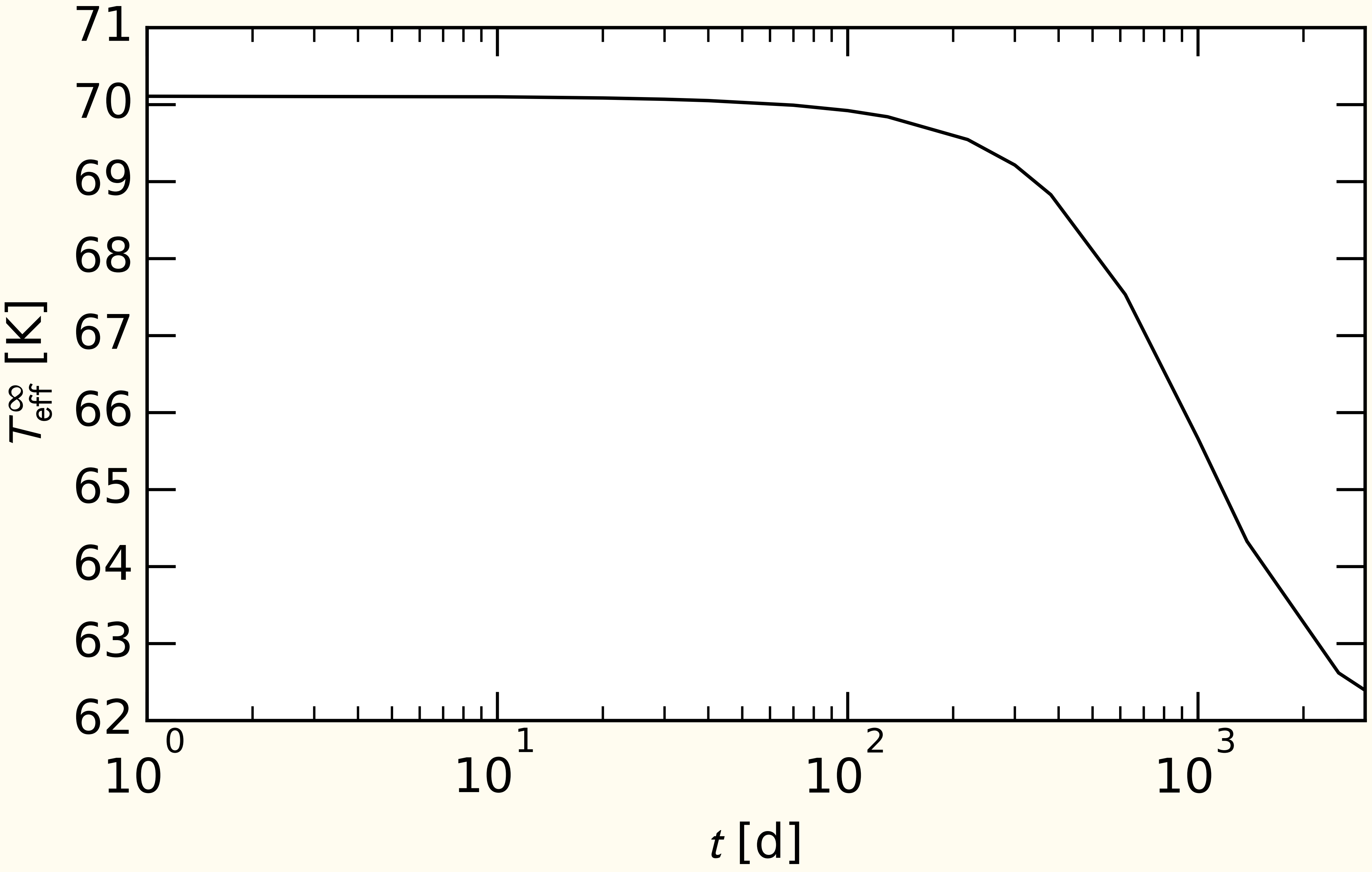
The following 8 slides were made using the open-source code *dStar* (https://github.com/nworbde/dStar).

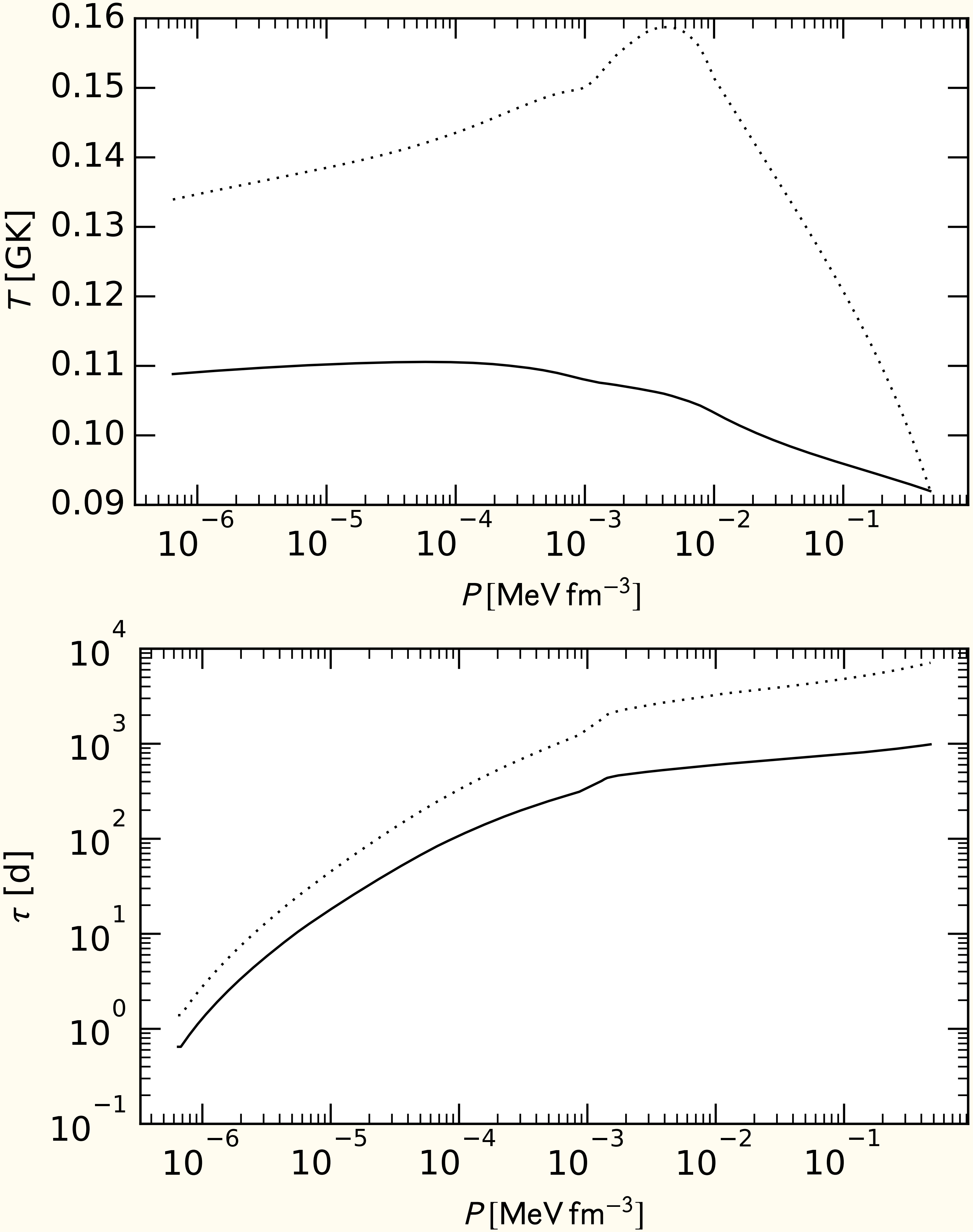
In this case, crust takes decades to cool

Ushomirsky & Rutledge '01



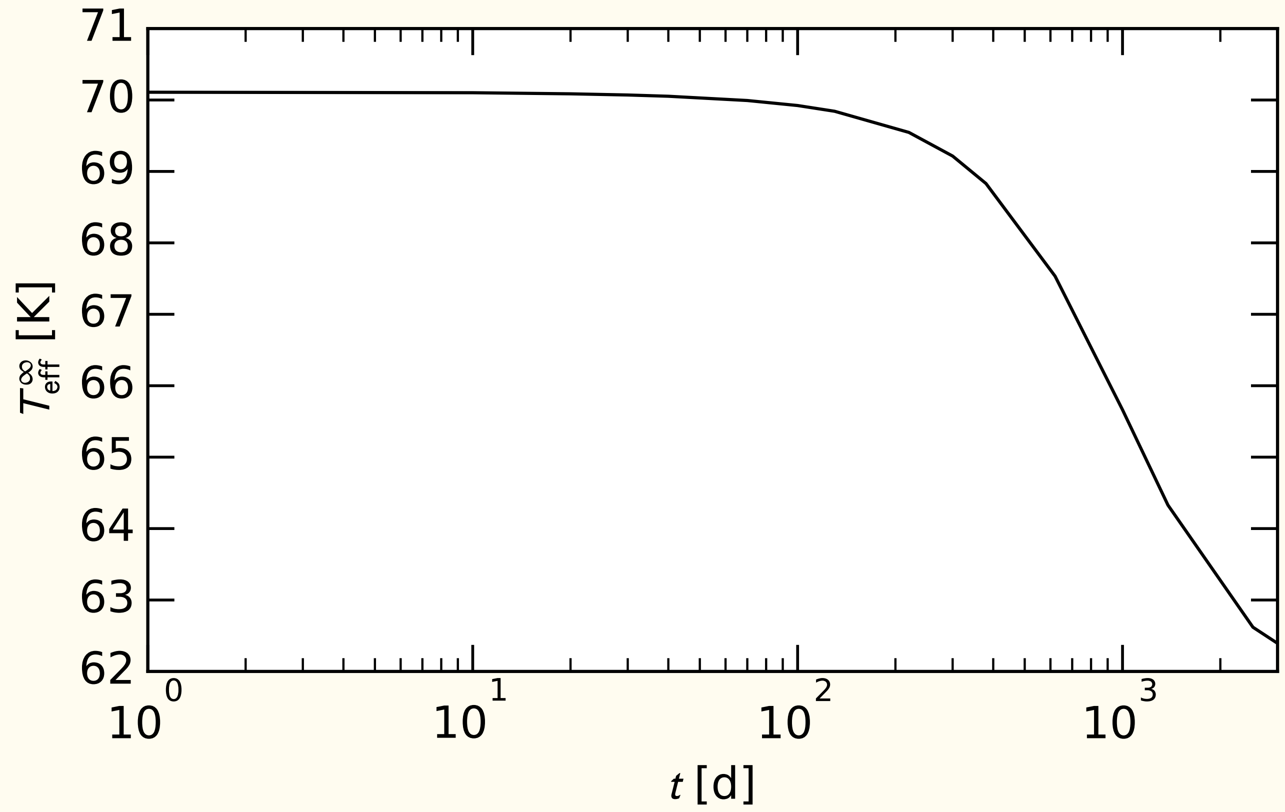
set $Q_{imp} = 4$

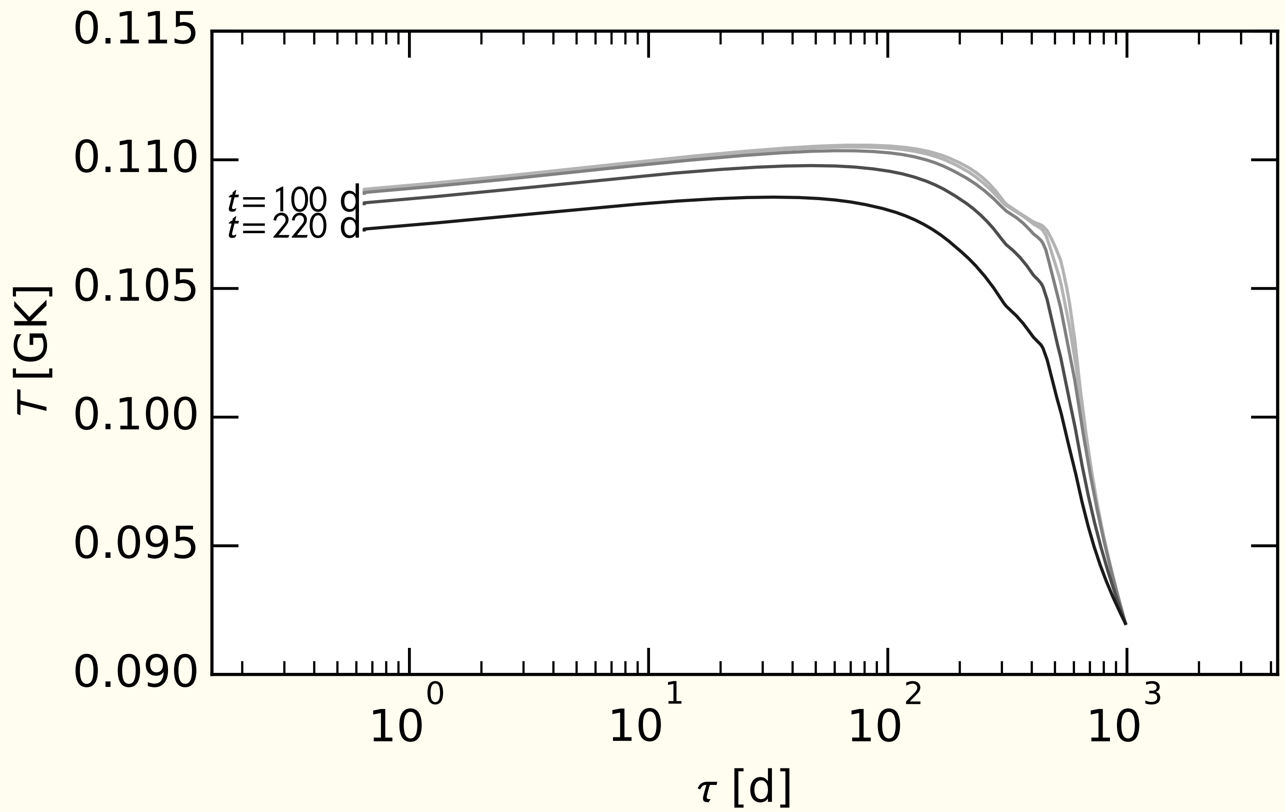


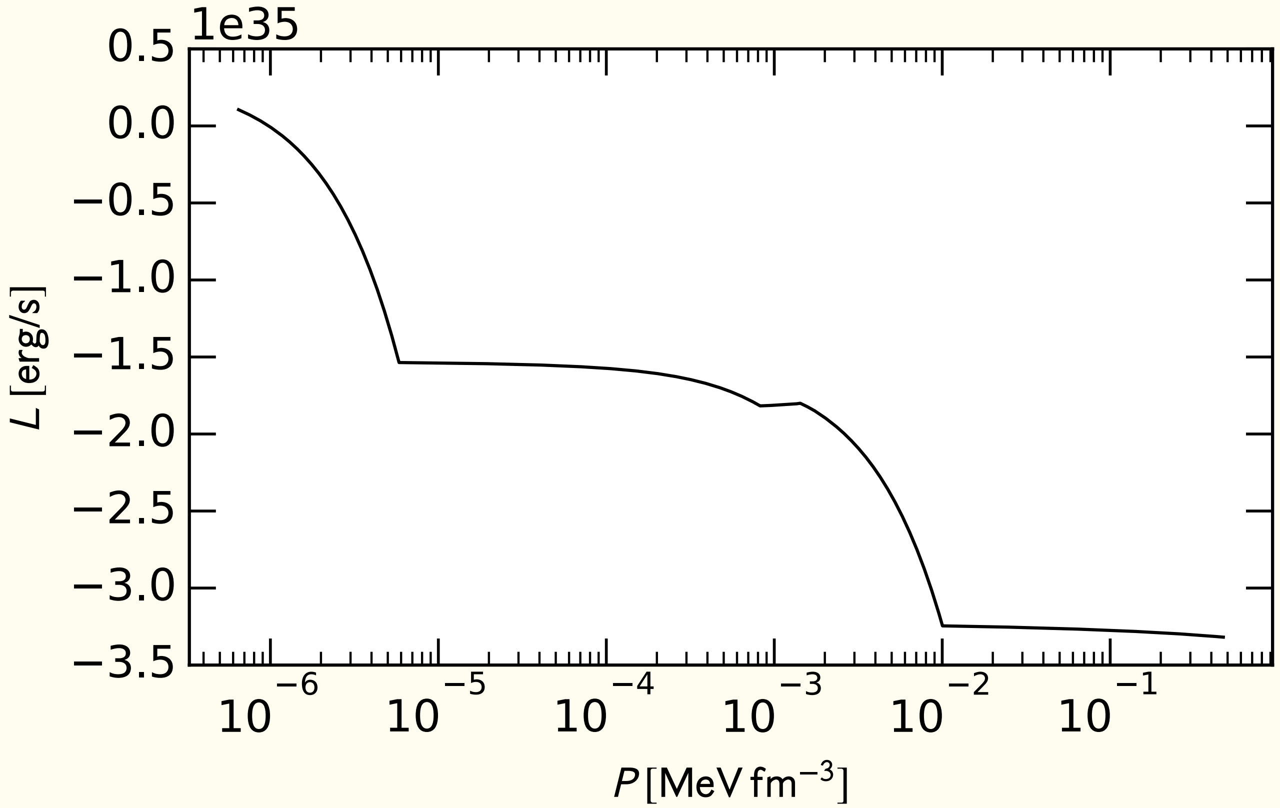


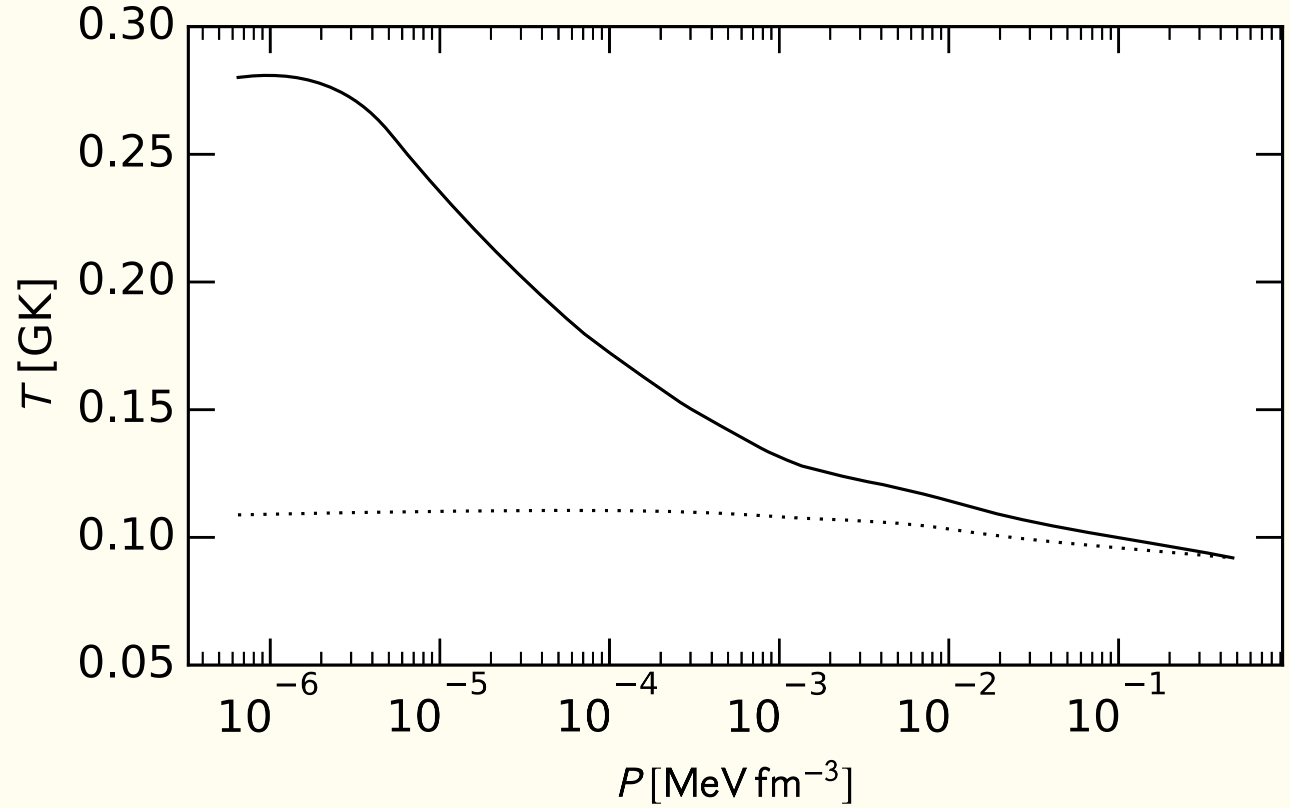
Crust cools in a few years; temperature rise is less pronounced after outburst

Very little evolution of surface temperature until cooling front reaches inner crust.

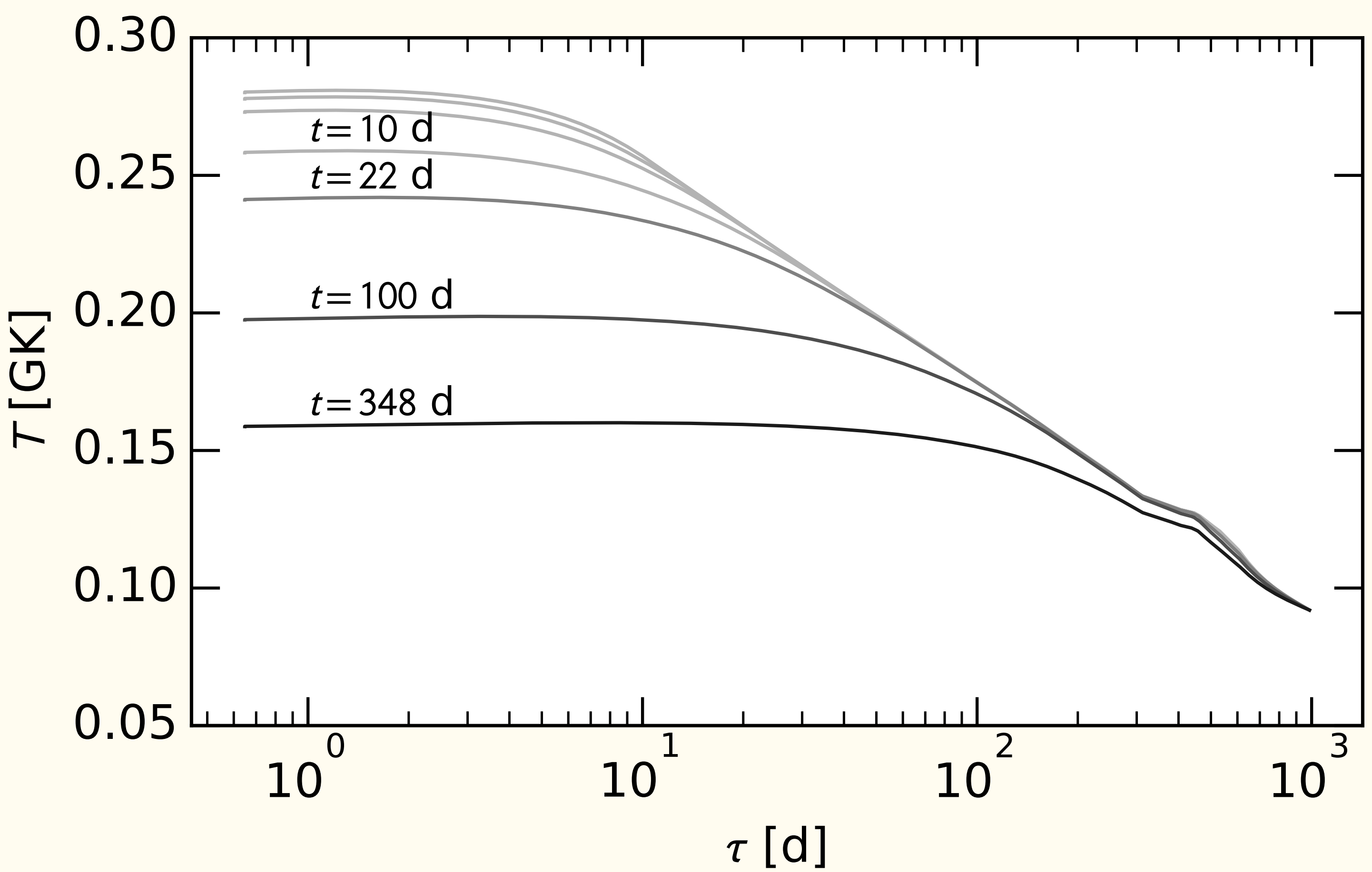


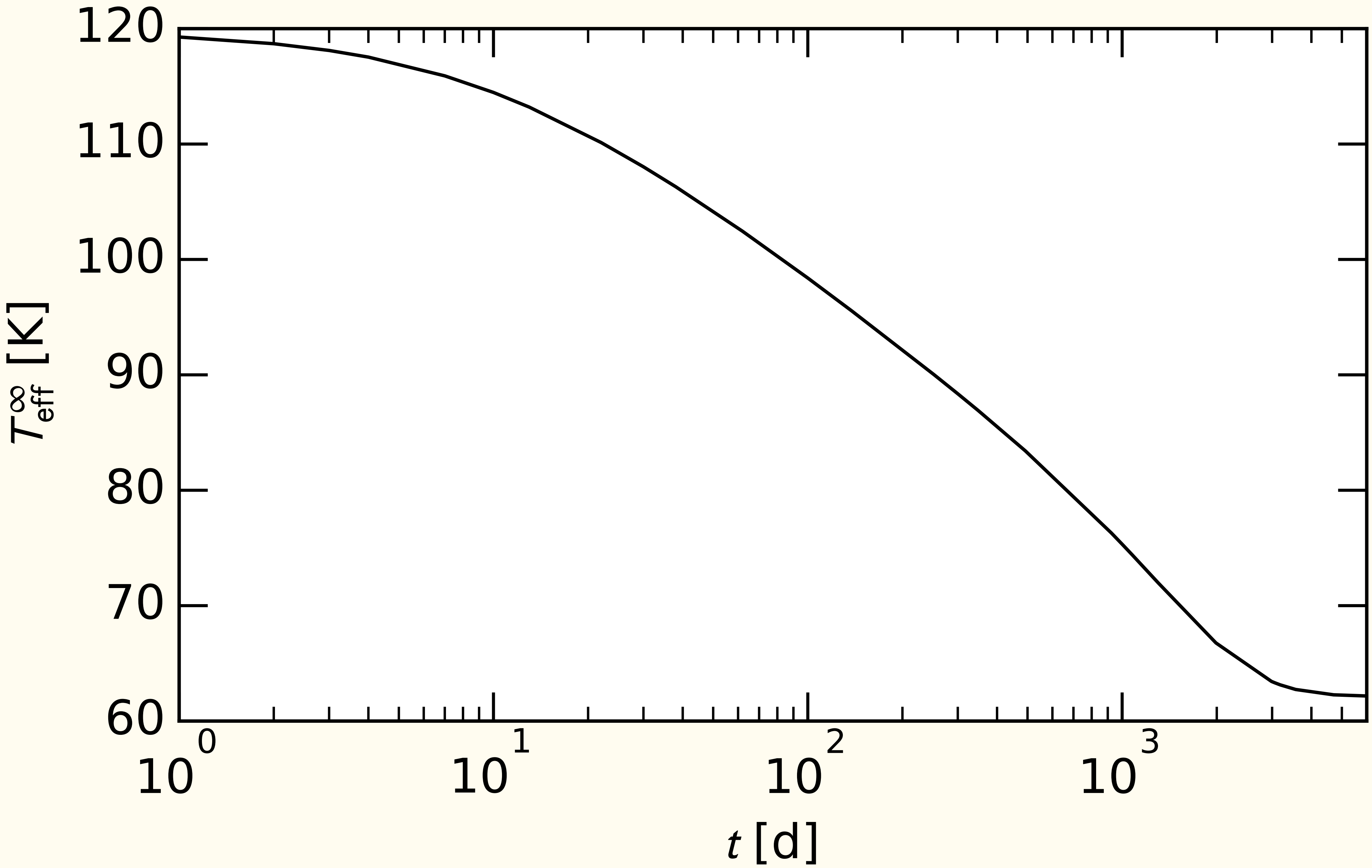






Add a heat source,
$L = 1.7$ MeV · d*M*/d*t*



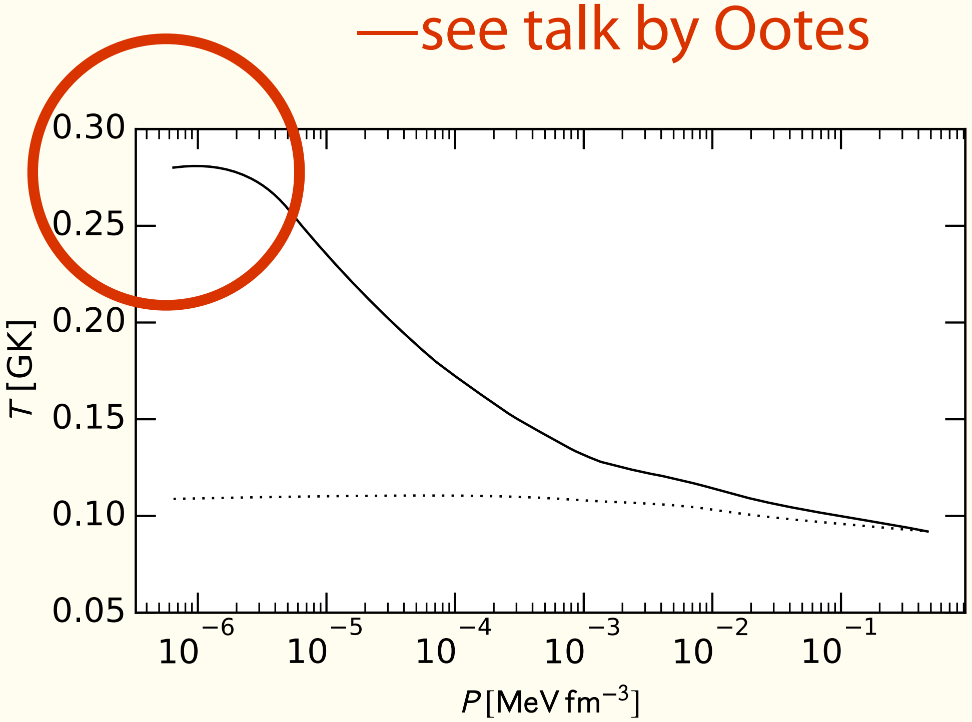


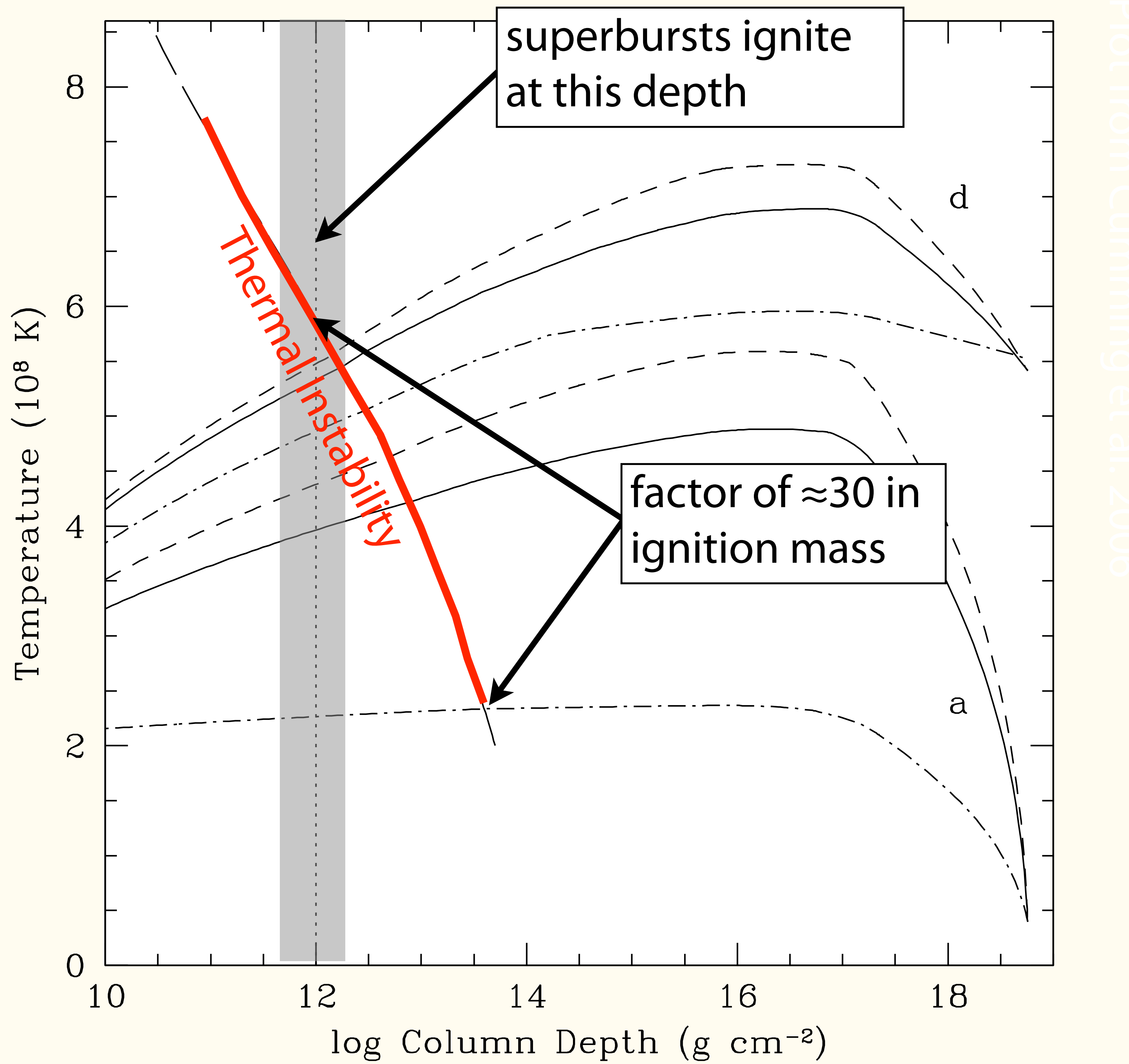
120
110
100
90
80
70
60
$T_{\rm eff}^{\infty}$ [K]
10^0
10^1
10^2
10^3
t [d]

^{12}C ignition

Cumming & Bildsten 2001; Strohmayer & Brown 2002; Cooper & Narayan 2005; Cumming et al. 2006

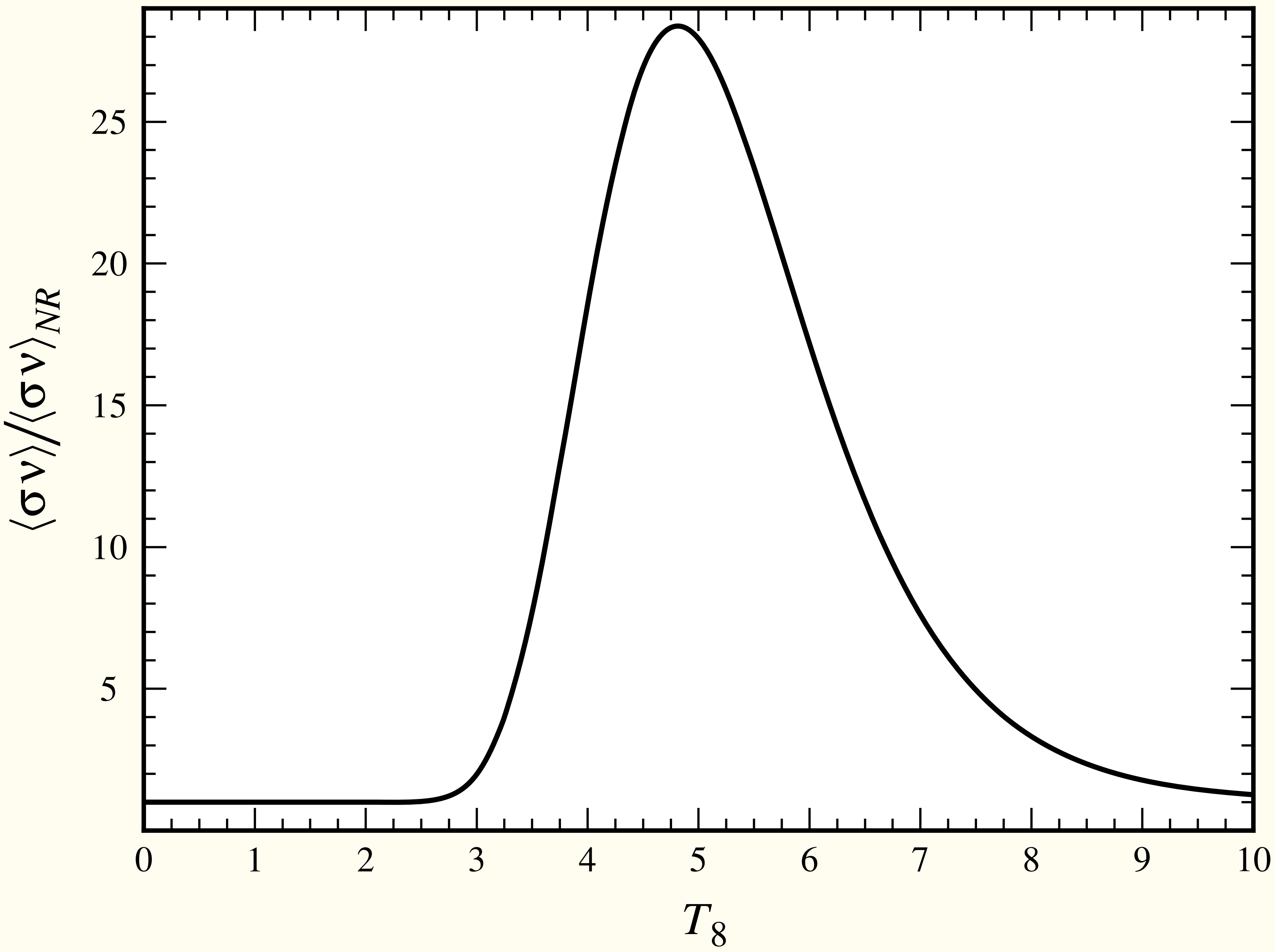
This is for mean outburst d*M*/d*t*
—see talk by Ootes





Possible resonance in ^{12}C

Cooper, Steiner, & Brown 2009, following Perez-Torres et al. 2006



Nine years later…

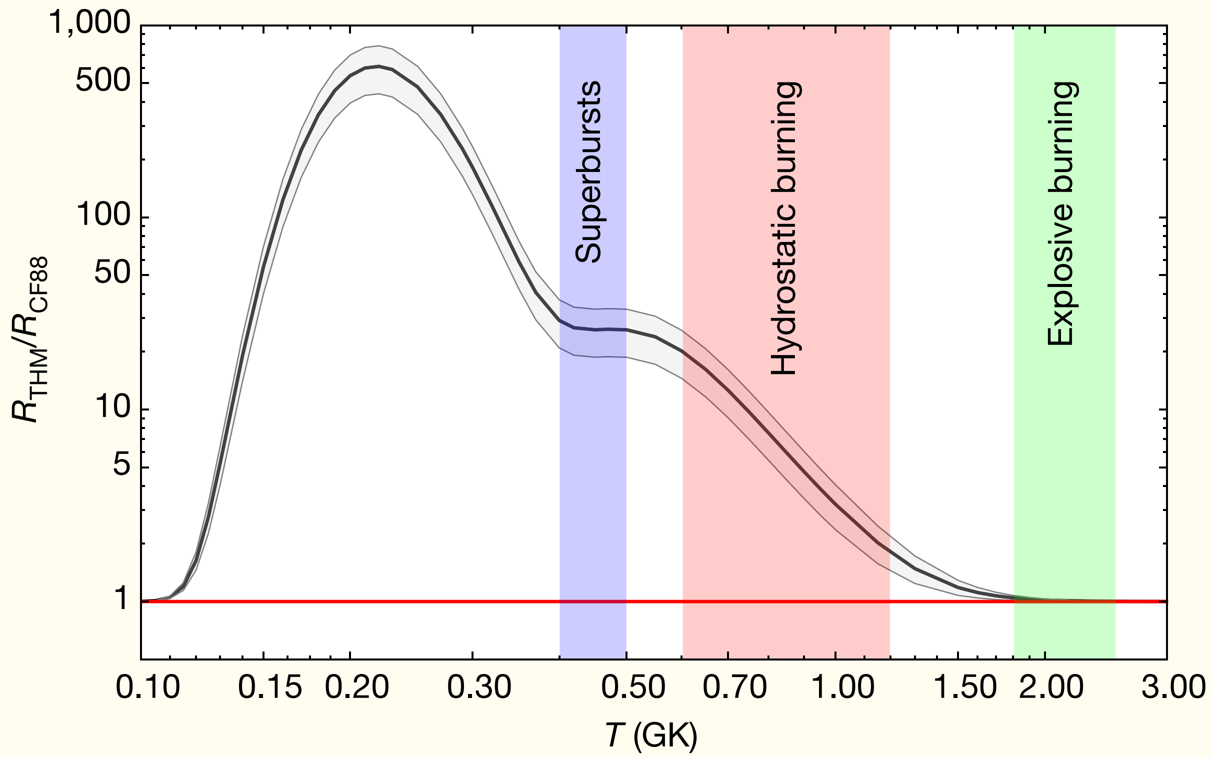
LETTER

https://doi.org/10.1038/s41586-018-0149-4

An increase in the $^{12}C + {}^{12}C$ fusion rate from resonances at astrophysical energies

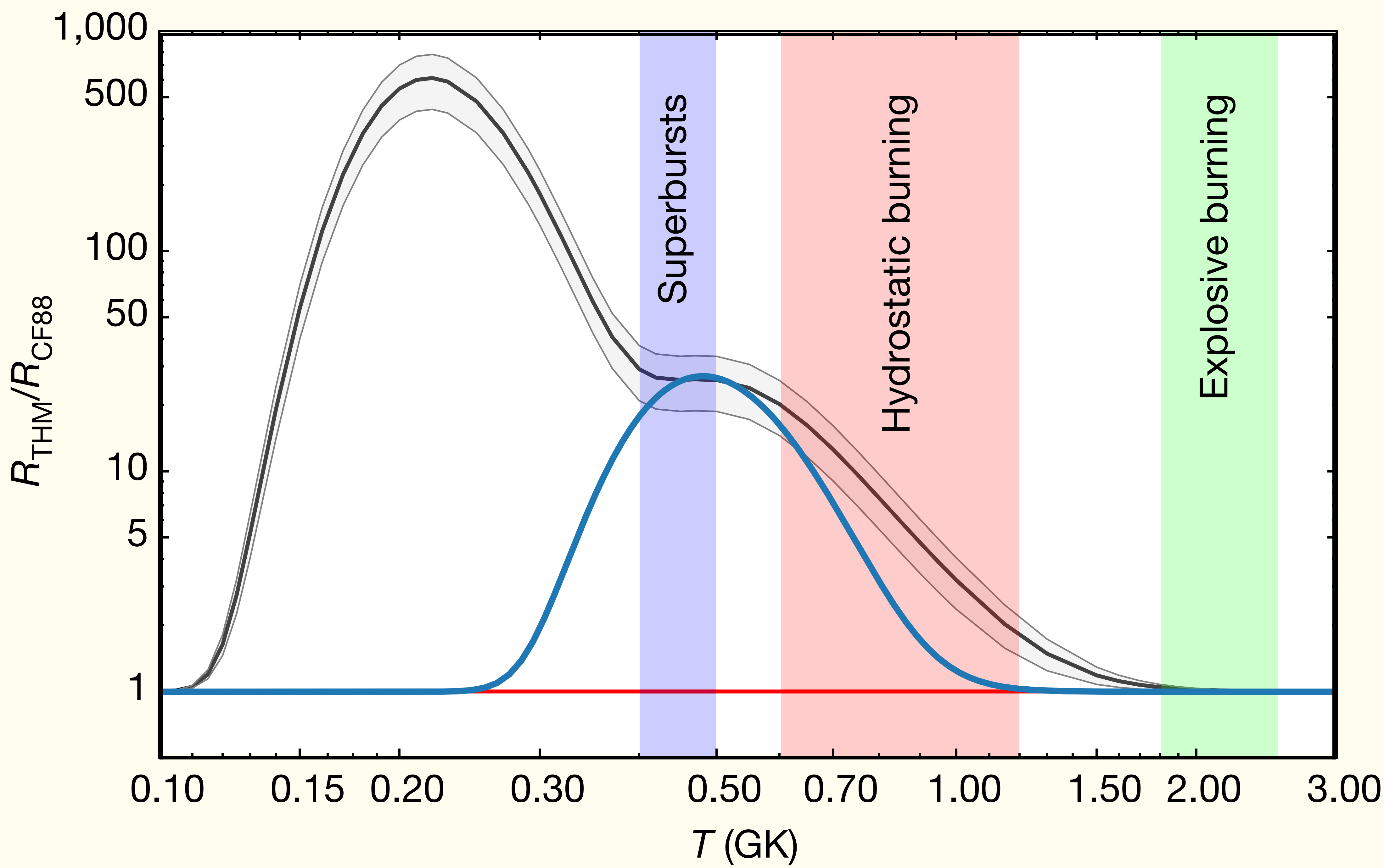
A. Tumino[1,2]*, C. Spitaleri[2,3], M. La Cognata[2], S. Cherubini[2,3], G. L. Guardo[2,4], M. Gulino[1,2], S. Hayakawa[2,5], I. Indelicato[2], L. Lamia[2,3], H. Petrascu[4], R. G. Pizzone[2], S. M. R. Puglia[2], G. G. Rapisarda[2], S. Romano[2,3], M. L. Sergi[2], R. Spartá[2] & L. Trache[4]

$^{12}C(^{14}N, \alpha^{20}Ne)^{2}H$ and $^{12}C(^{14}N, p^{23}Na)^{2}H$



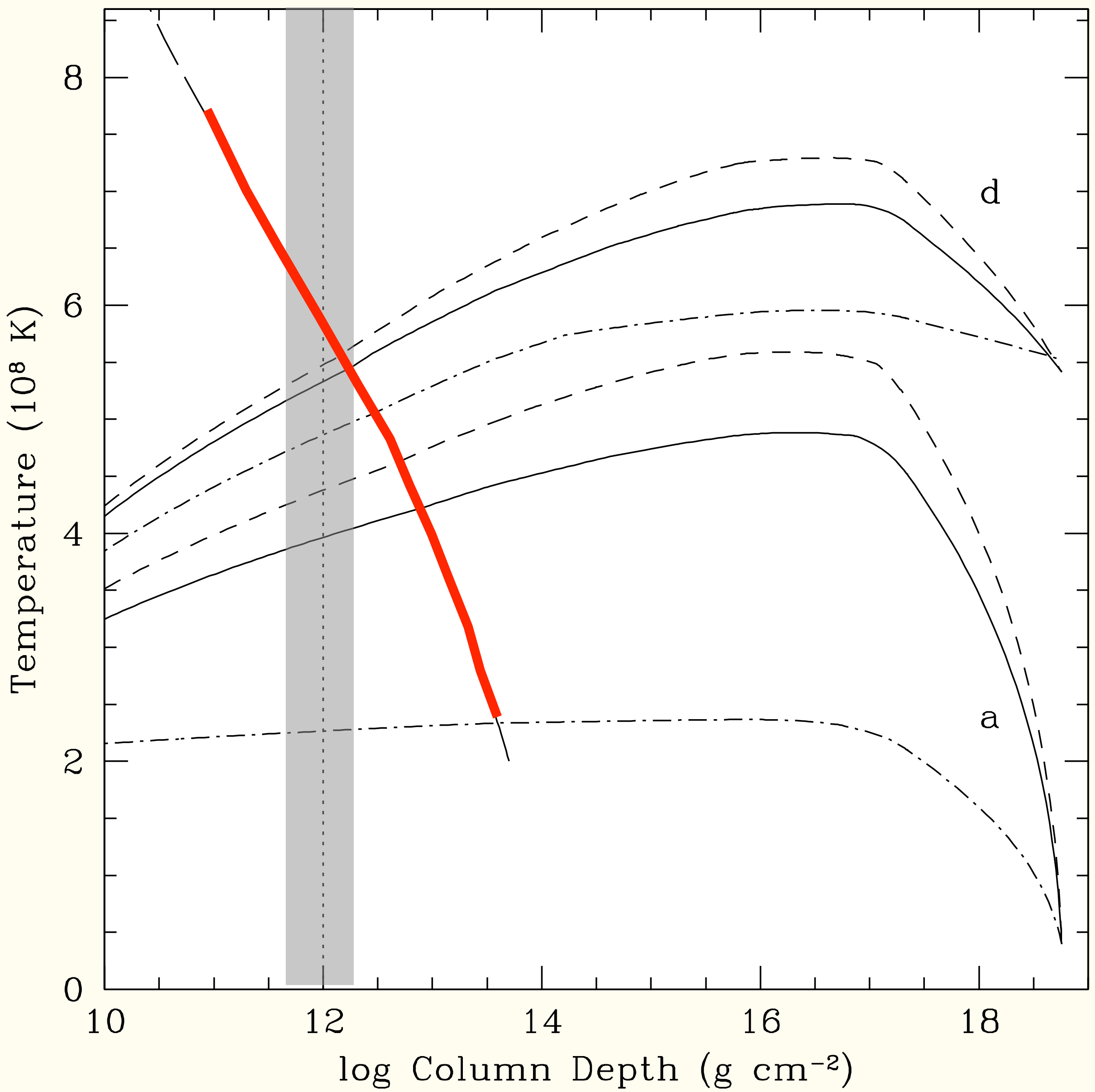
The Procession of the Trojan Horse into Troy
Giovanni Domenico Tiepolo
ca. 1760

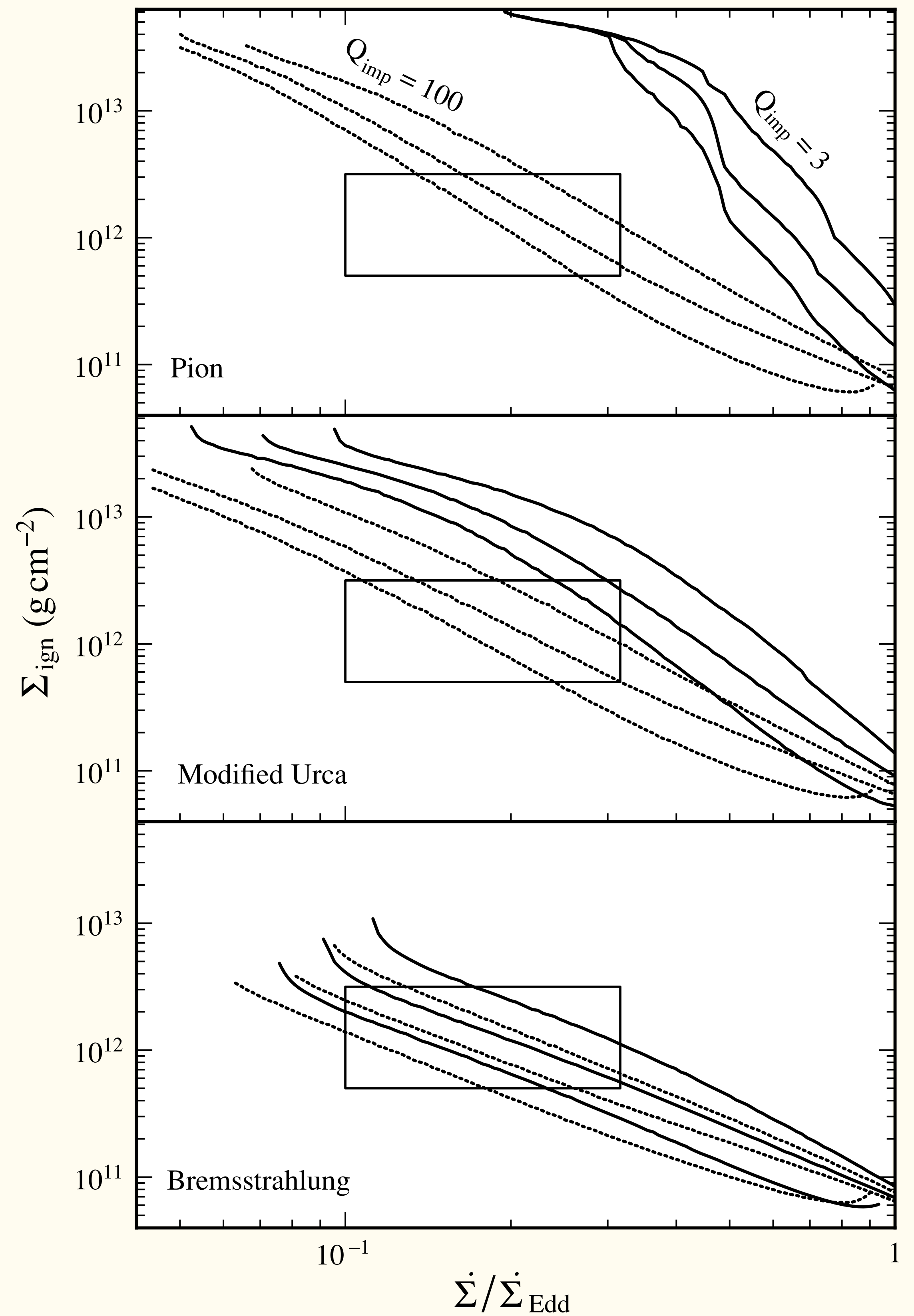
Nine years later…



^{12}C ignition

Cumming & Bildsten 2001; Strohmayer & Brown 2002; Cooper & Narayan 2005; Cumming et al. 2006





Tasks

- KS1731–26: bursts (with oscillations), superbursts, crust cooling: can we make a consistent model?
  Talks by Ootes, Meisel

- What produces shallow heating?

- Compositional domains in crust: extend reaction network calculations to include neutron diffusion—is the inner crust unique?
  Talks by Caplan, Deibel