The Crusts of Accreting Neutron Stars

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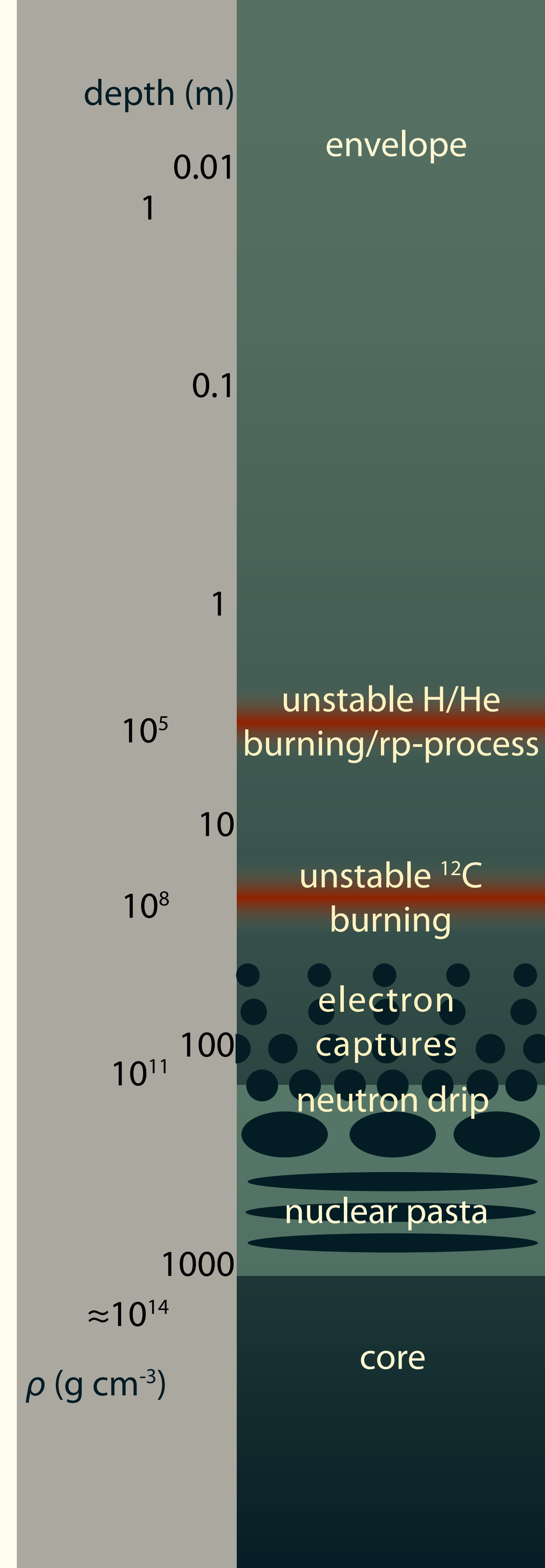
A. Piro, Carnegie Obs.

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

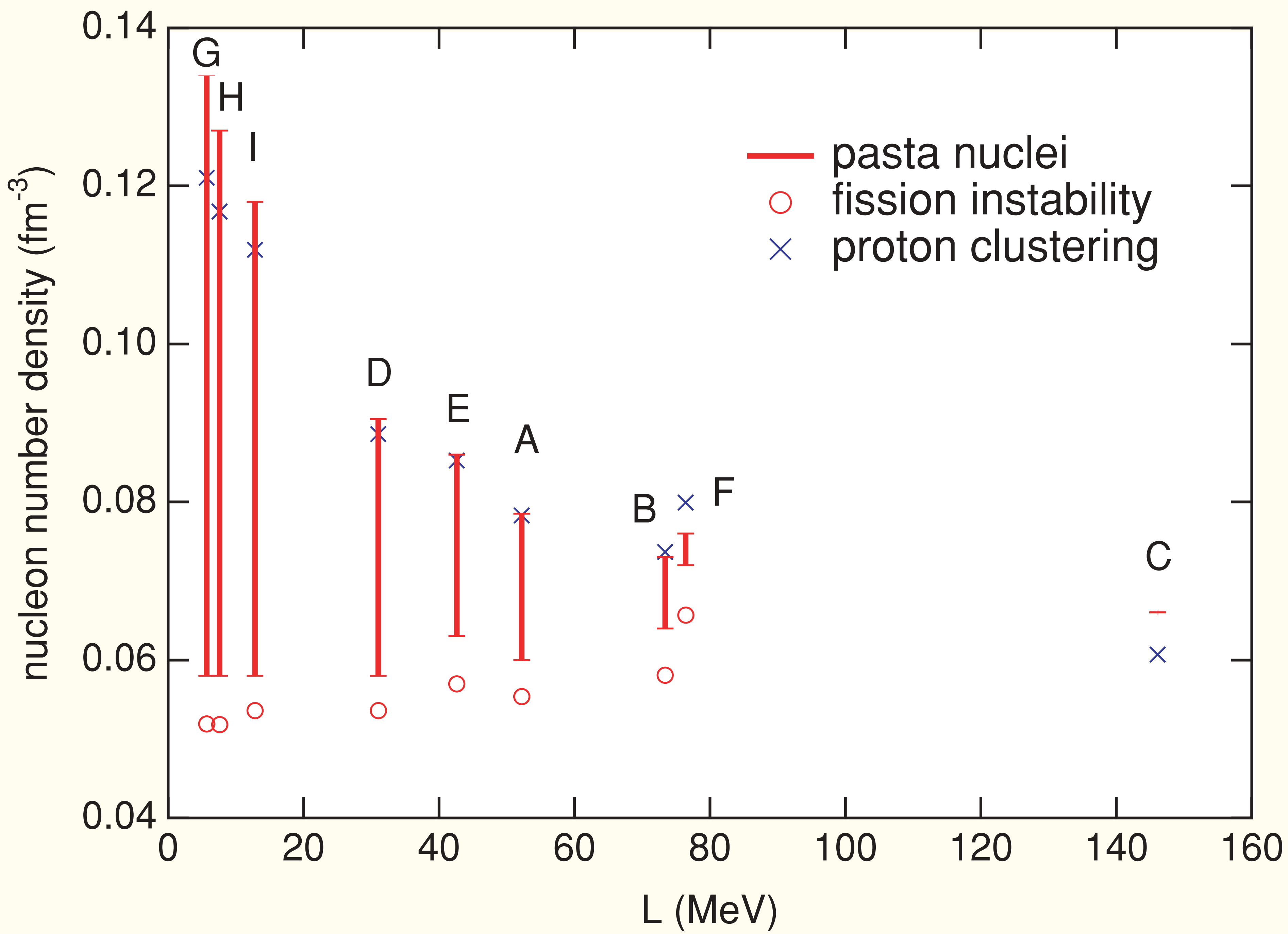
Accretion pushes matter through this crust and induces nuclear reactions.

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



Pasta and crust-core transition

Oyamatsu & Iida '07



schematic of Z, A in (outer) crust

$$B(Z,N) = a_V A - a_S A^{2/3} - a_A \frac{(N-Z)^2}{A} - a_C \frac{Z^2}{A^{1/3}}$$

start with a simple liquid drop

$$\mu_e = \mu_n - \mu_p$$

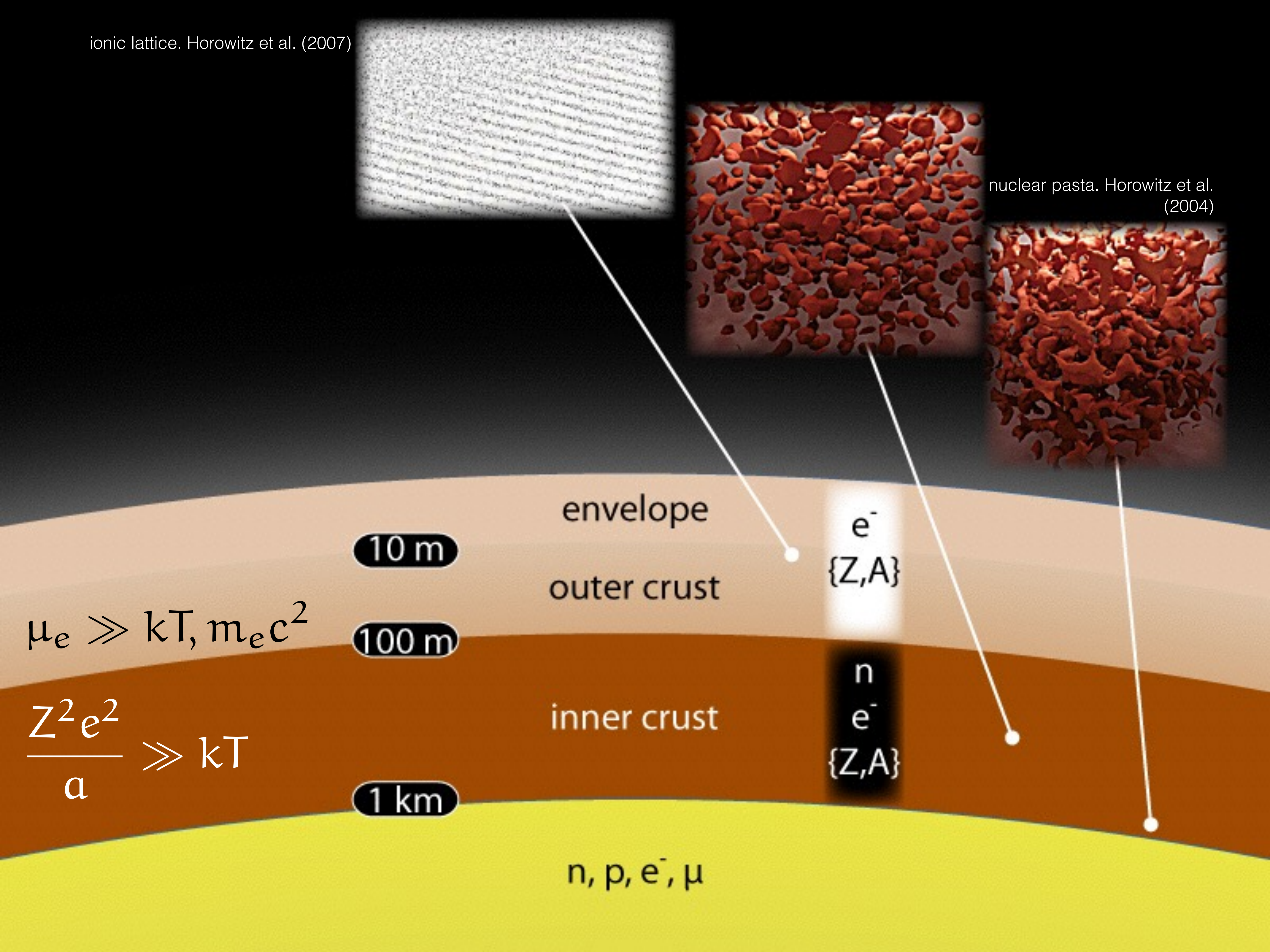
$$Y_e \approx \left(\frac{1}{2} - \frac{\mu_e}{8a_A}\right)\left(1 + \frac{a_C A^{2/3}}{4a_A}\right)^{-1}$$

enforce beta-equilibrium, charge neutrality: Y_e decreases linearly with rising electron chemical potential

$$S_n = \left(\frac{\partial B}{\partial N}\right)_Z = a_V - a_A\left(1 - 4Y_e^2\right) - \frac{1}{3} a_C Y_e^2 A^{2/3}$$

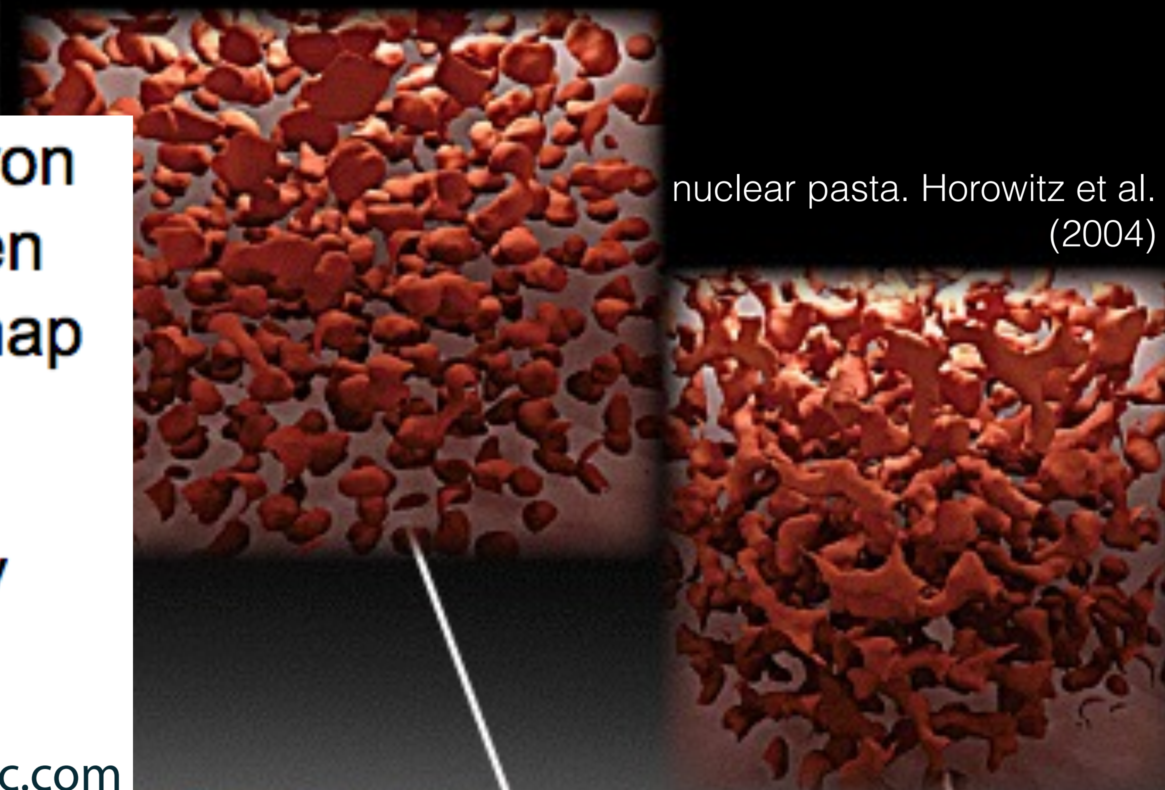
$$S_n \to 0 \implies \mu_e \approx 2a_V \approx 30\ \mathrm{MeV}$$

compute neutron separation energy S_n and set it zero to find density of neutron drip: $n_{\mathrm{drip}} \approx 0.001\ n_0$



ionic lattice. Horowitz et al. (2007)
nuclear pasta. Horowitz et al. (2004)
envelope
10 m
outer crust
100 m
inner crust
1 km
e^-
{Z,A}
n
e^-
{Z,A}
n, p, e^-, μ
$\mu_e \gg kT, m_e c^2$
$\frac{Z^2 e^2}{a} \gg kT$

ionic lattice. Horowitz et al. (2007)

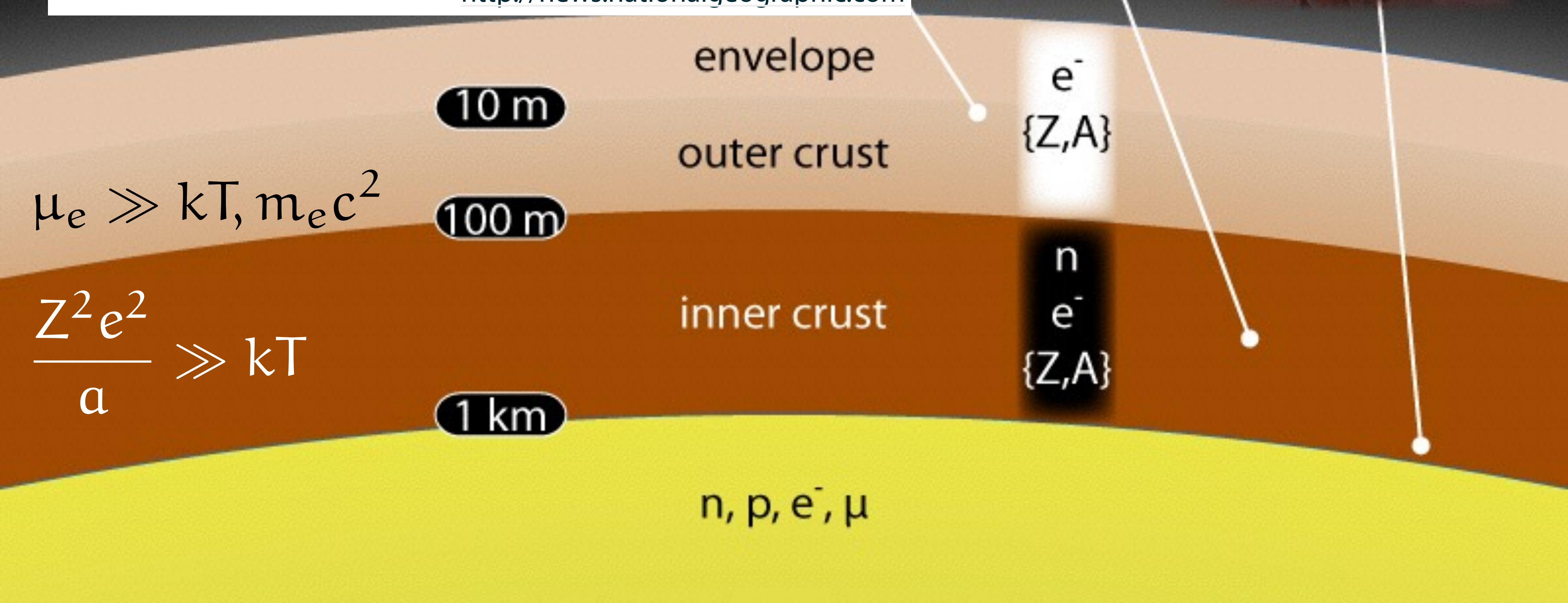


nuclear pasta. Horowitz et al. (2004)

The results showed that the crust of a neutron star can withstand a breaking strain up to ten billion times the pressure it would take to snap steel.

"It sounds dramatic, but it's true," said study team member Charles Horowitz of Indiana University.

http://news.nationalgeographic.com

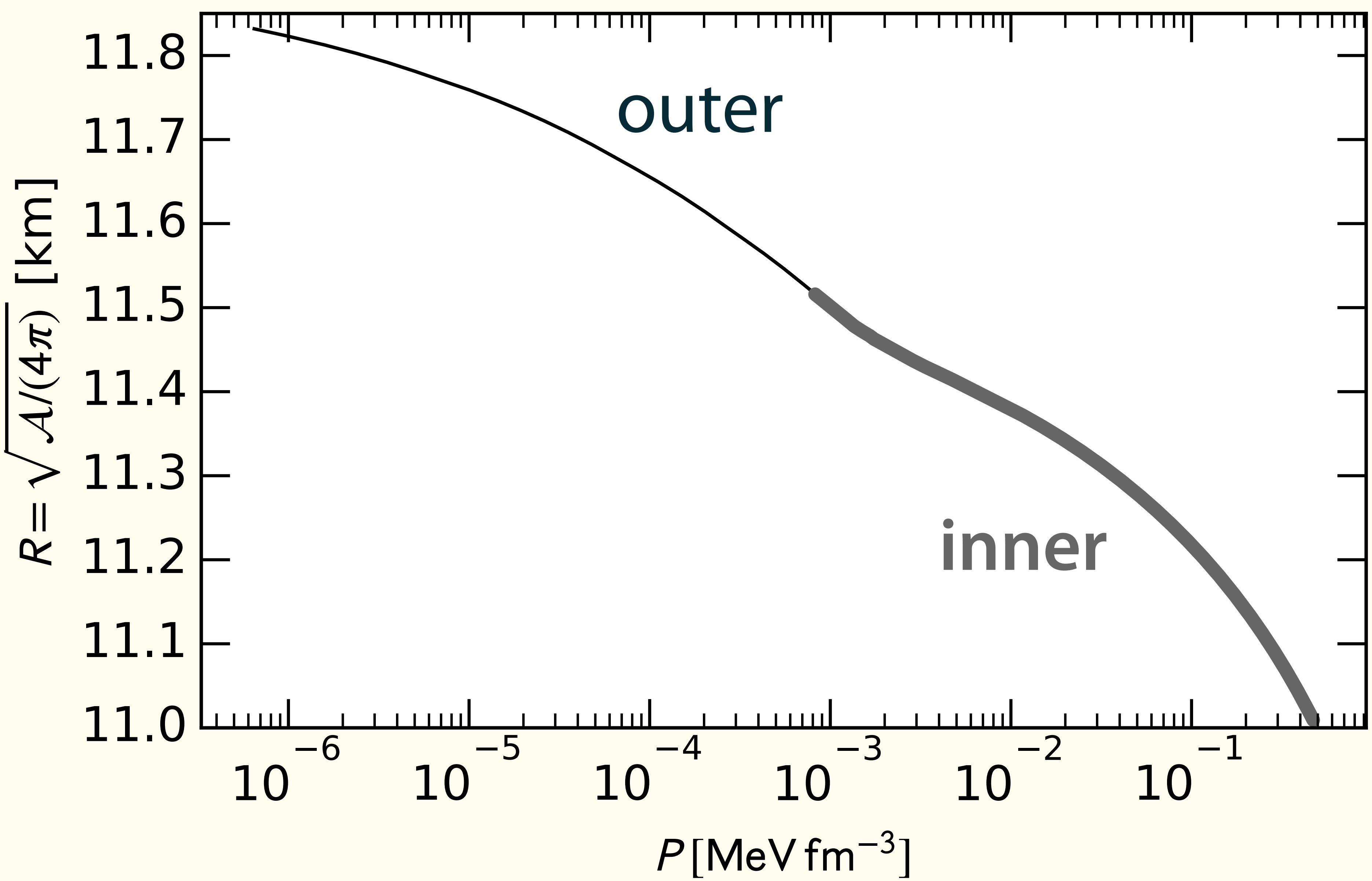


$$\mu_e \gg kT, m_e c^2$$

$$\frac{Z^2 e^2}{a} \gg kT$$

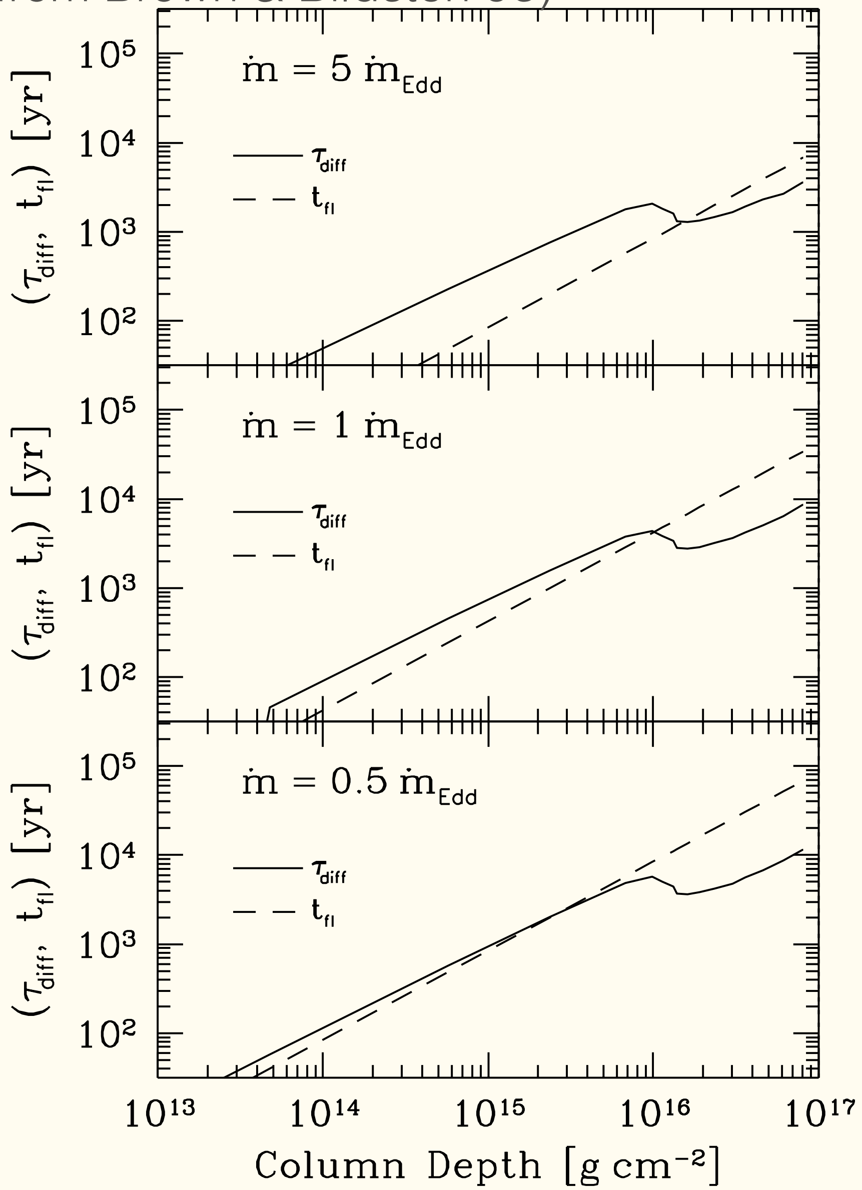
structure of crust

$R_{\mathrm{core}} = 11$ km, $M_{\mathrm{core}} = 1.6\,M_{\mathrm{sun}}$, accreted composition

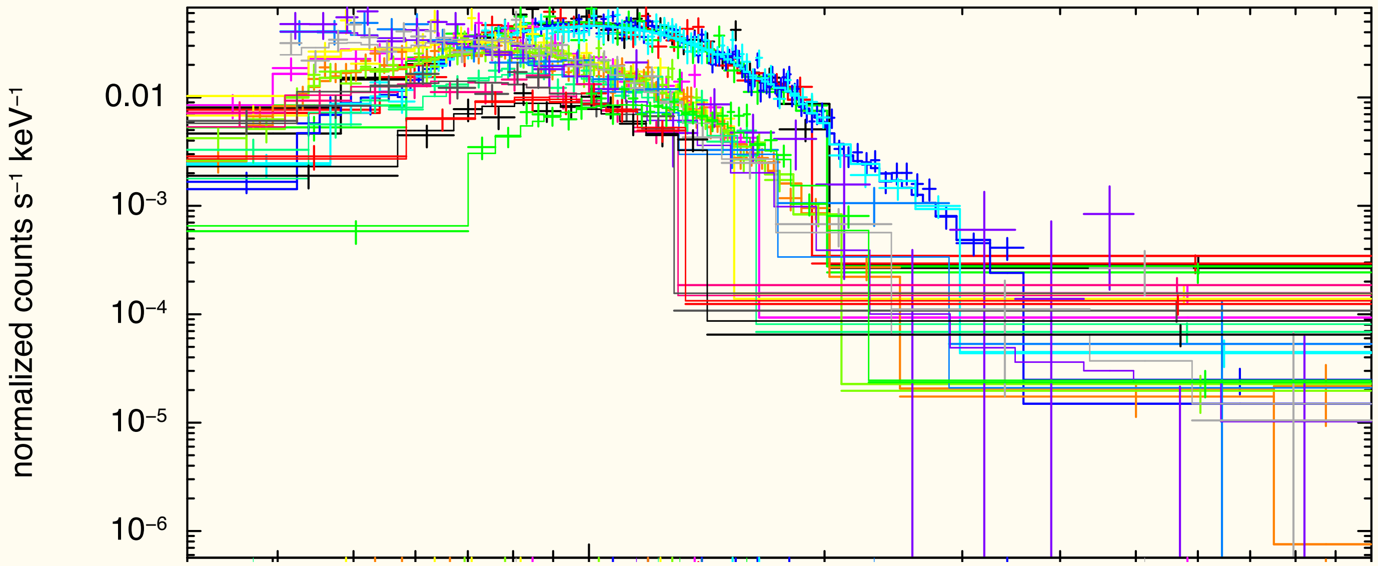


crust | observables

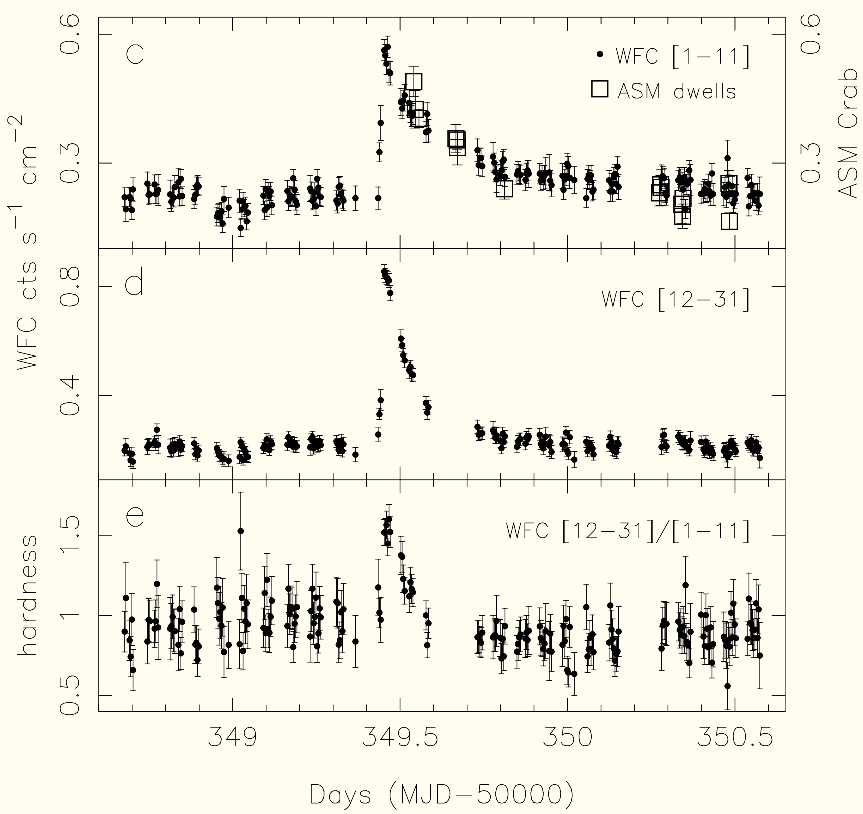
magnetic field evolution
(from Brown & Bildsten 98)



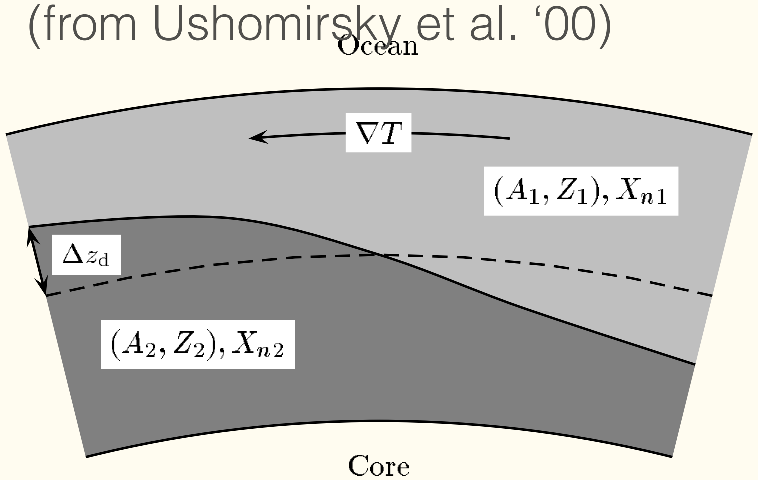
quiescent thermal emission from transients
(from Guillot et al. '13)



ignition of long X-ray bursts
(from Kuulkers '01)



crust mountains
(from Ushomirsky et al. '00)



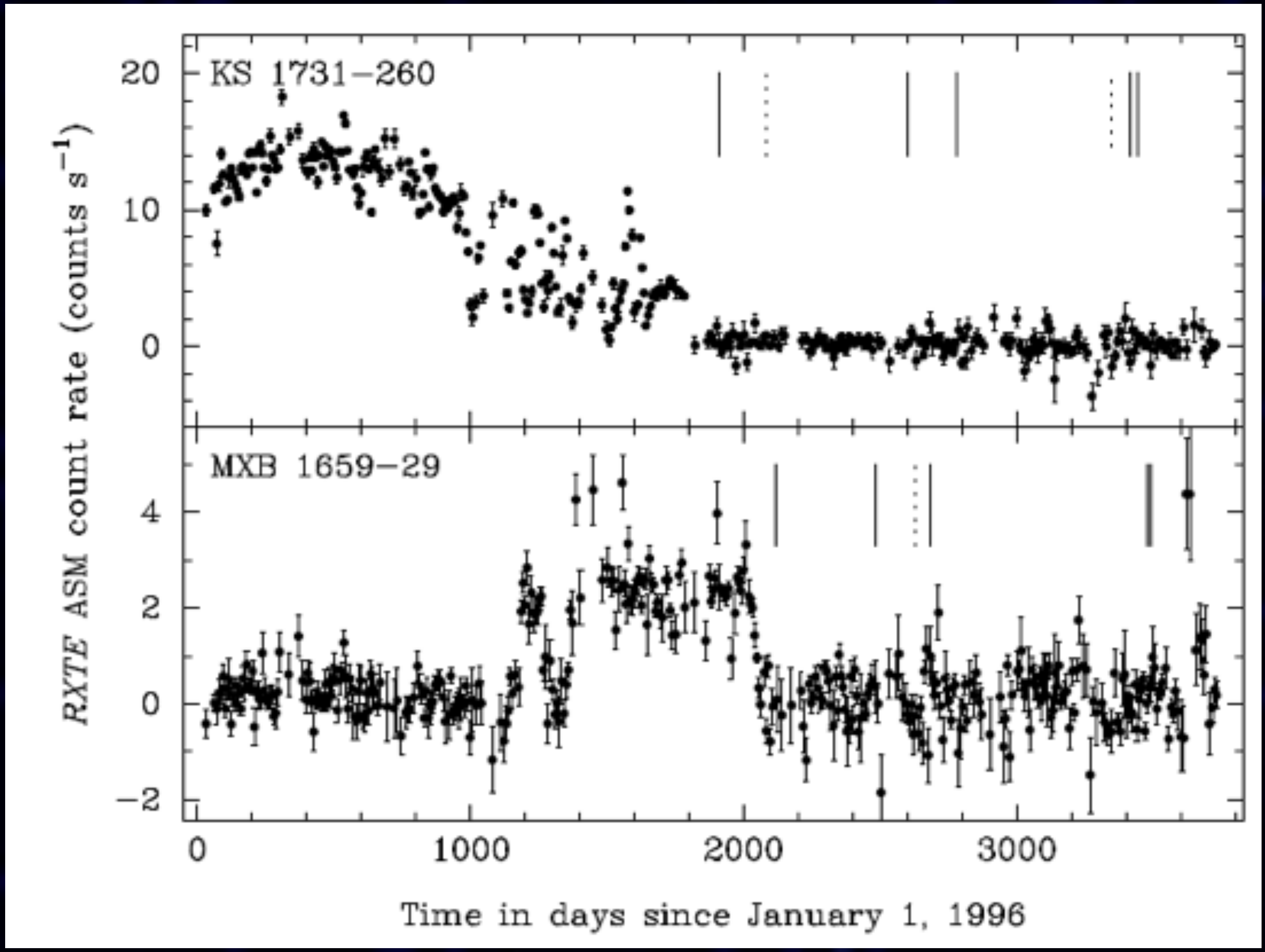
transients

2001: RXTE discovers quasi-persistent transients

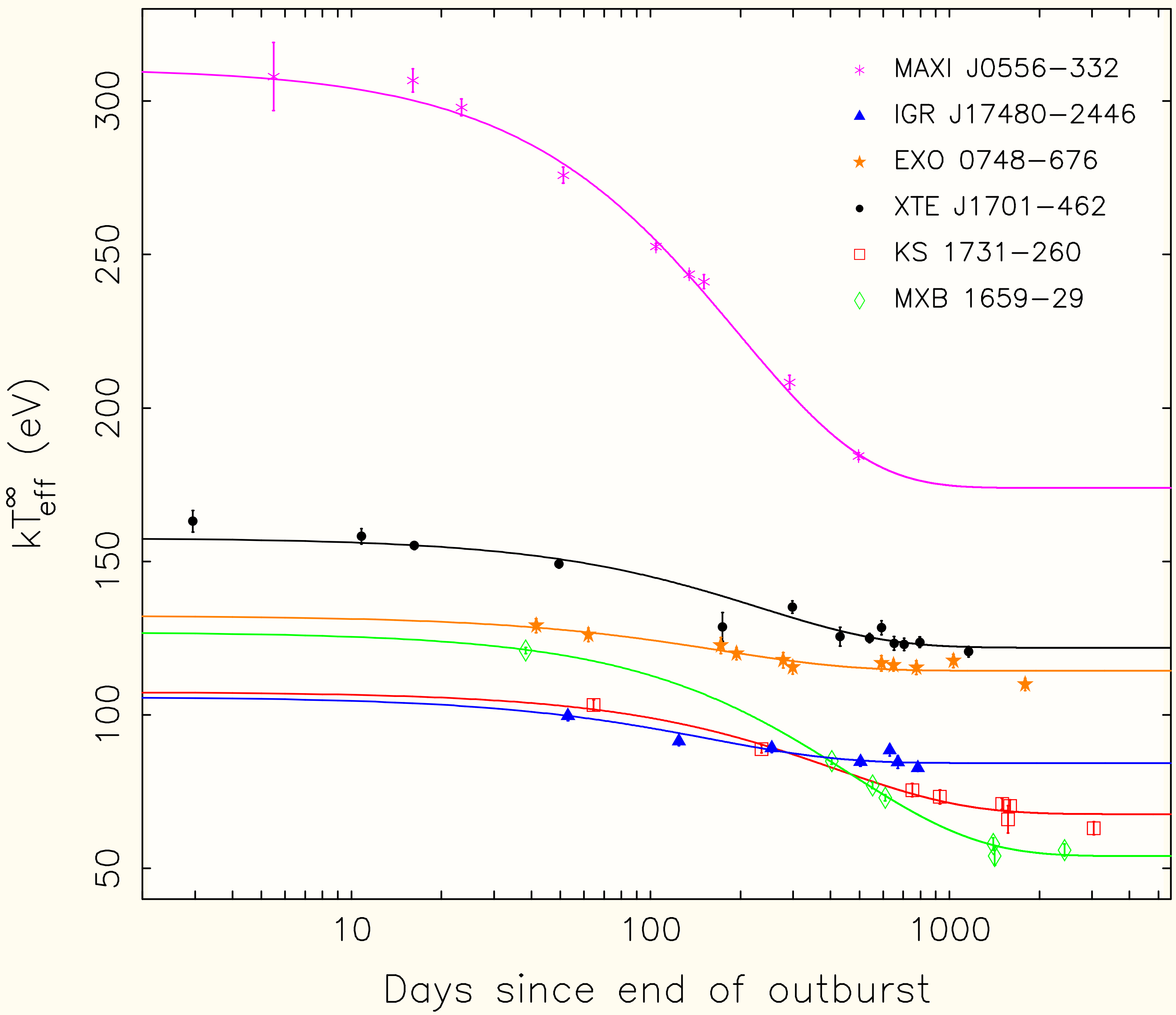
2002: Rutledge et al. suggest looking for crust thermal relaxation

2002–: cooling detected! (many: Wijnands, Cackett, Degenaar, Fridriksson)

fig. from Cackett et al. '06



observed cooling of transients post-outburst

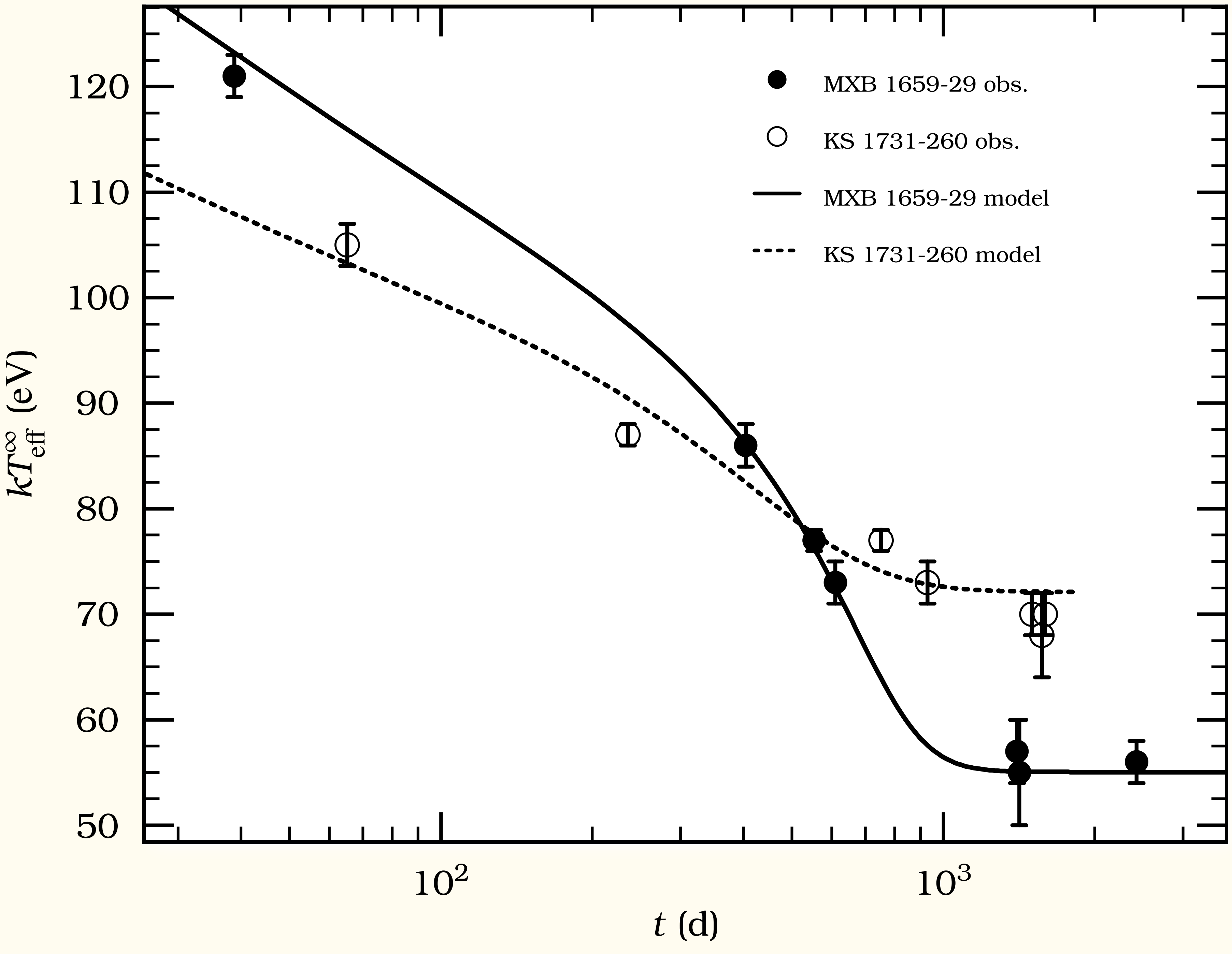


Homan et al. '14

Infer crust properties from cooling

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

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

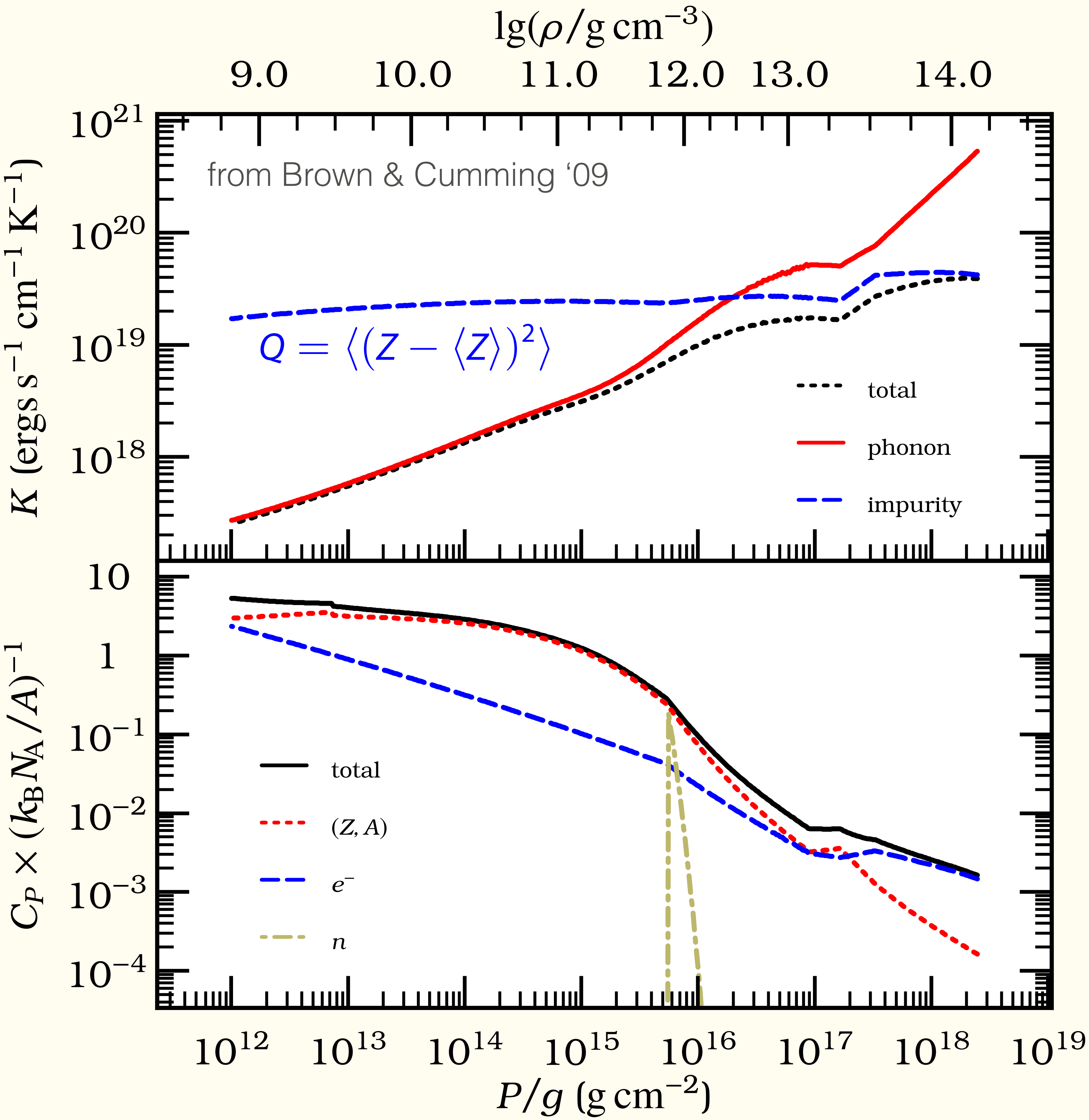


cooling timescale

Thermal diffusion

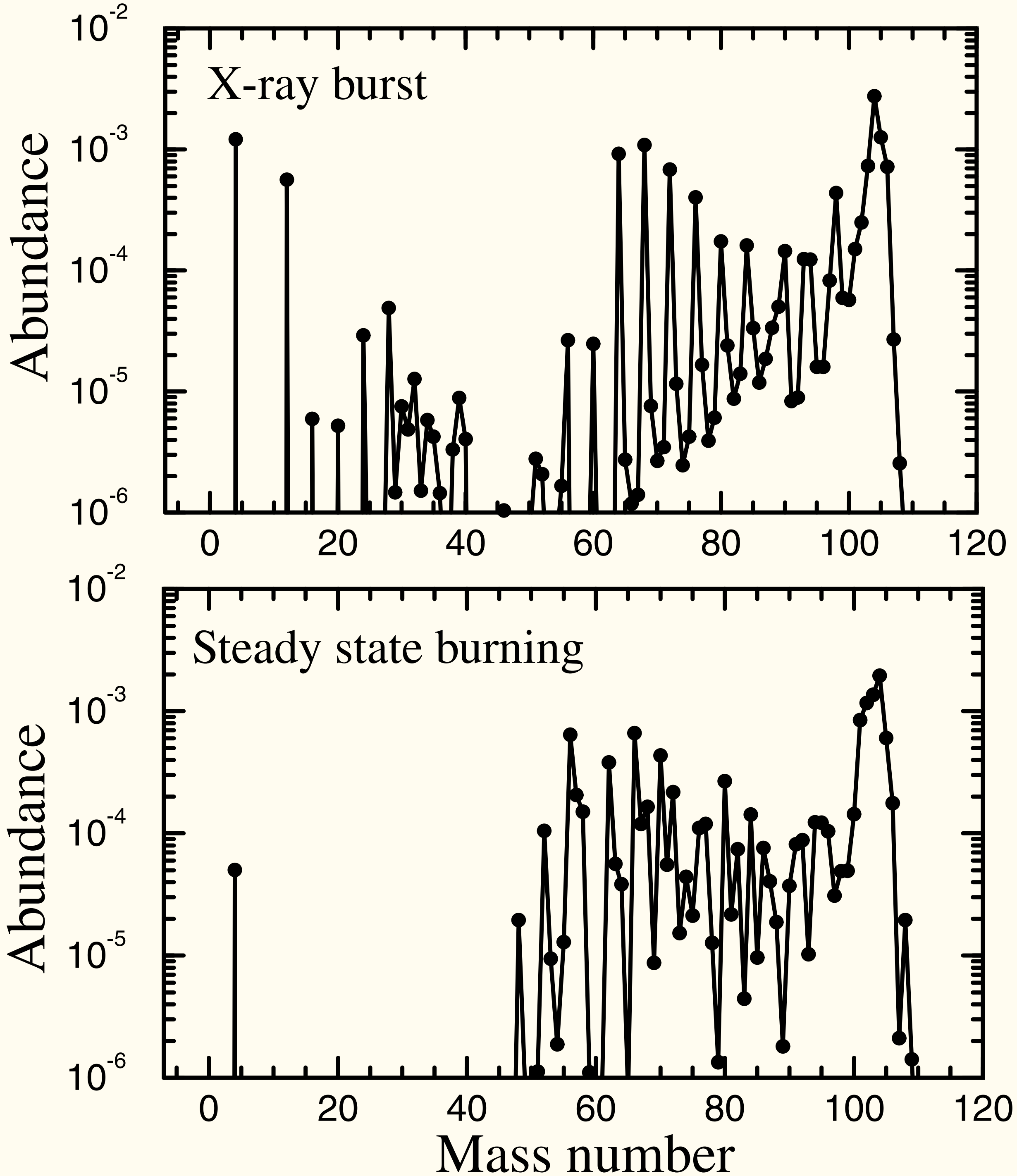
$$\rho C \frac{\partial T}{\partial t} = \nabla \cdot (K \boldsymbol{\nabla} T)$$

$$\tau = \frac{1}{4}\left[\int \left(\frac{\rho C}{K}\right)^{1/2} dz\right]^2$$



bury the ashes of H, He burning

Schatz et al. '01

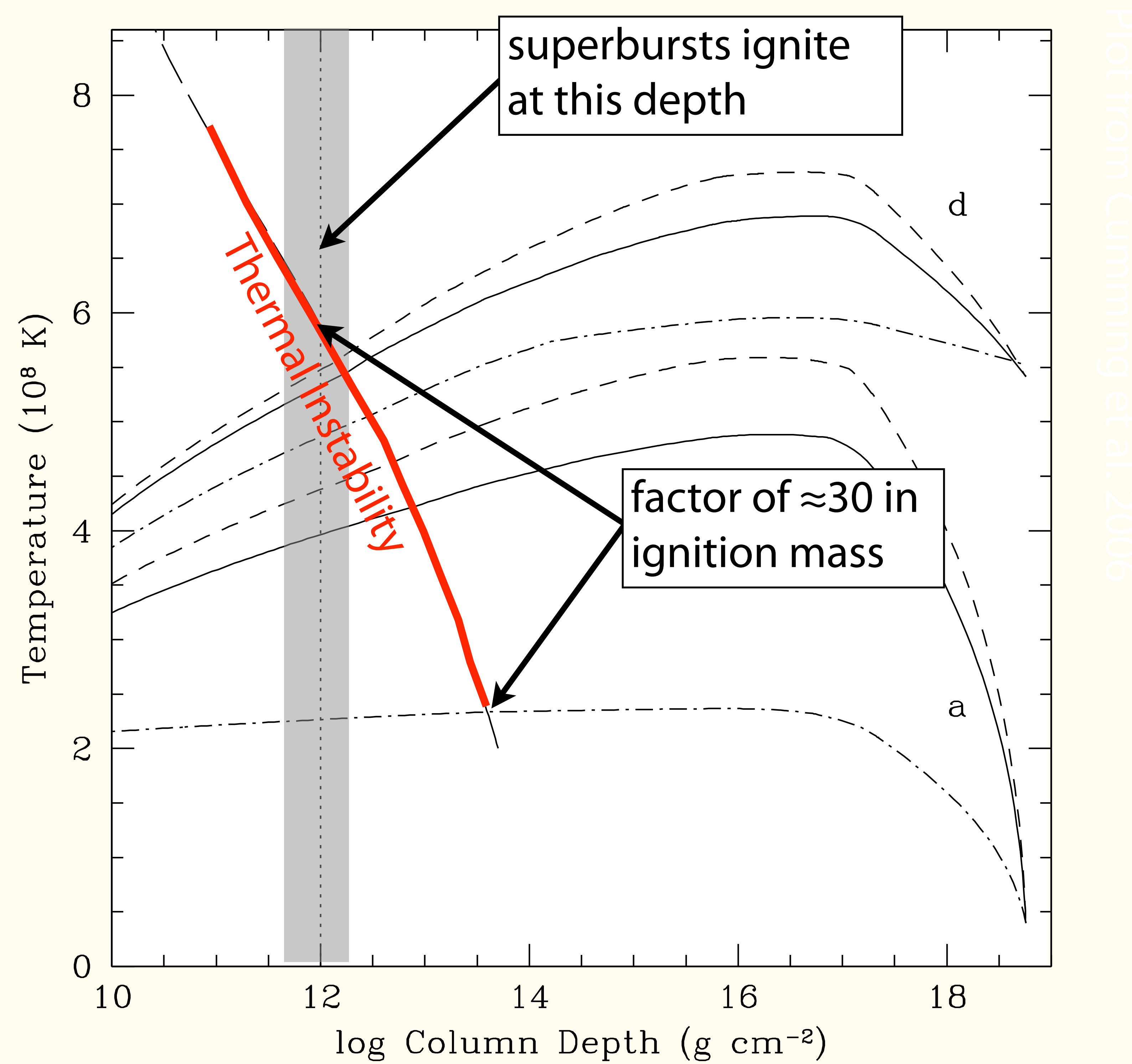


This makes a really dirty crust

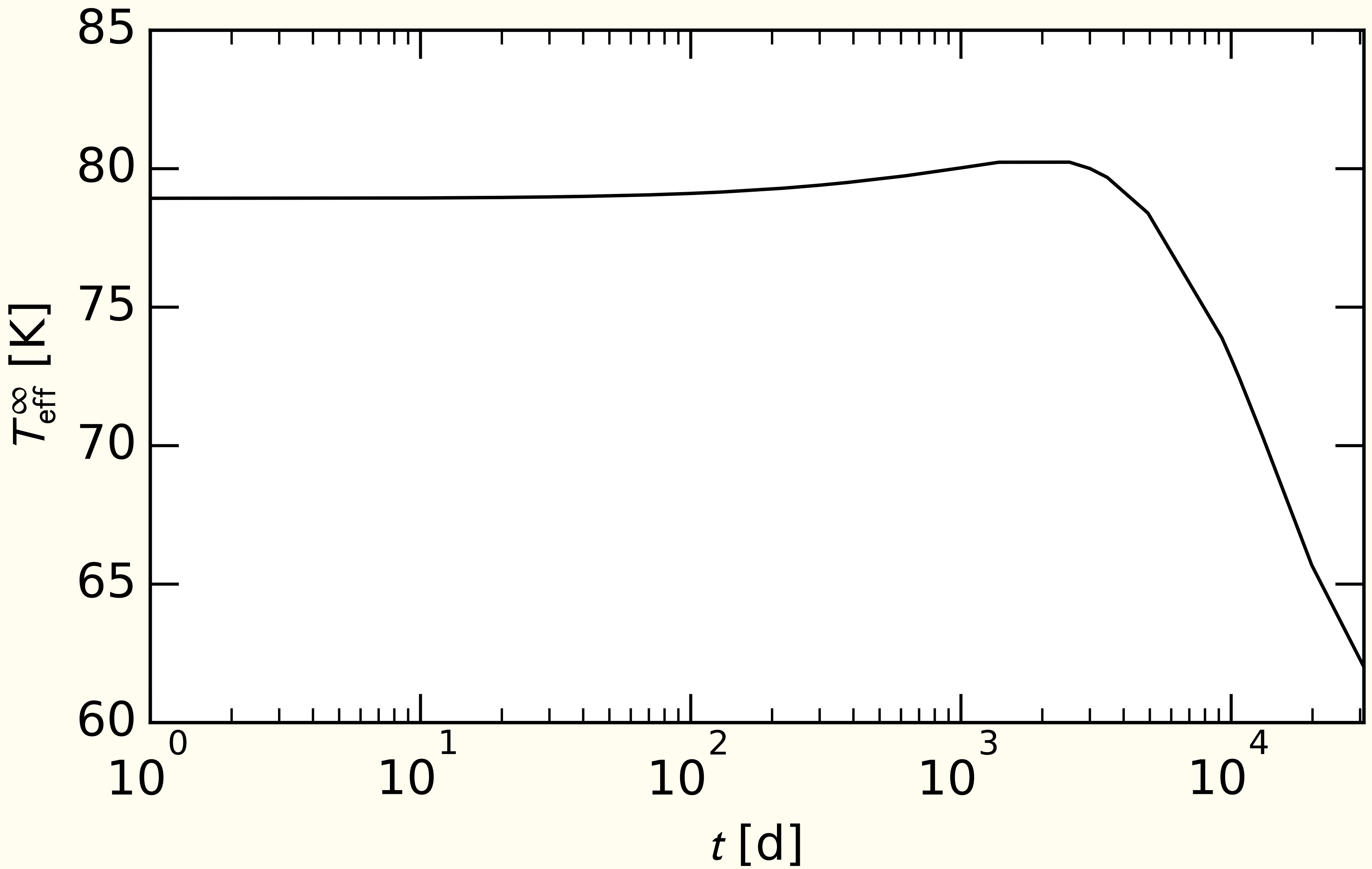
$$Q = \langle (Z - \langle Z \rangle)^2 \rangle \sim 100$$

^{12}C ignition requires high crust temperatures

Brown 2004, Cooper & Narayan 2005, Cumming et al. 2006



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).

code to generate plots is posted at https://github.com/nworbde/dStar

Branch: master ▾ dStar / README.md Find file Copy path

nworbde shout-out to INT talk 342383d just now

1 contributor

79 lines (50 sloc) 4.52 KB Raw Blame History

dStar

A collection of modules for computing neutron star structure and evolution.

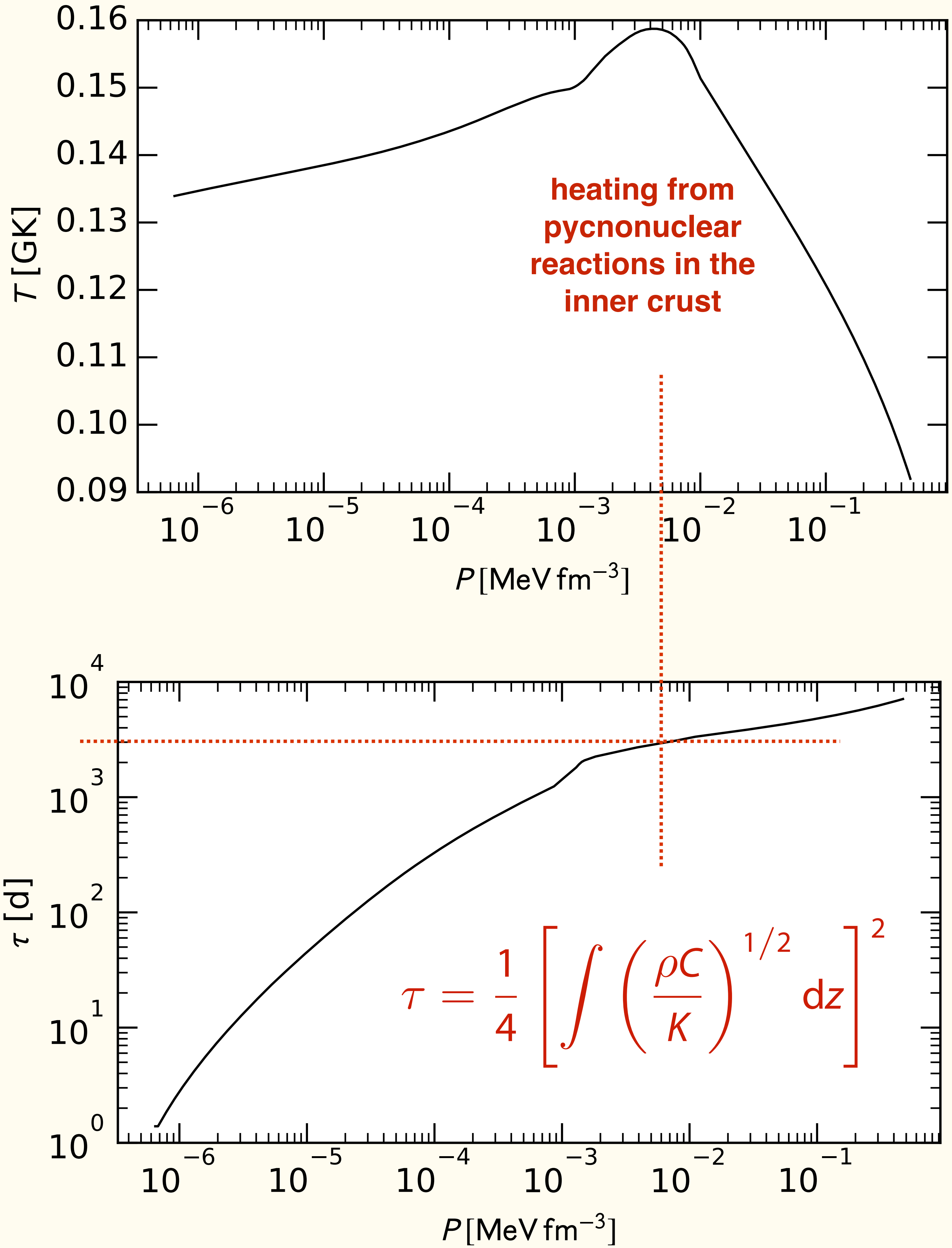
What's new

A tutorial on crust cooling

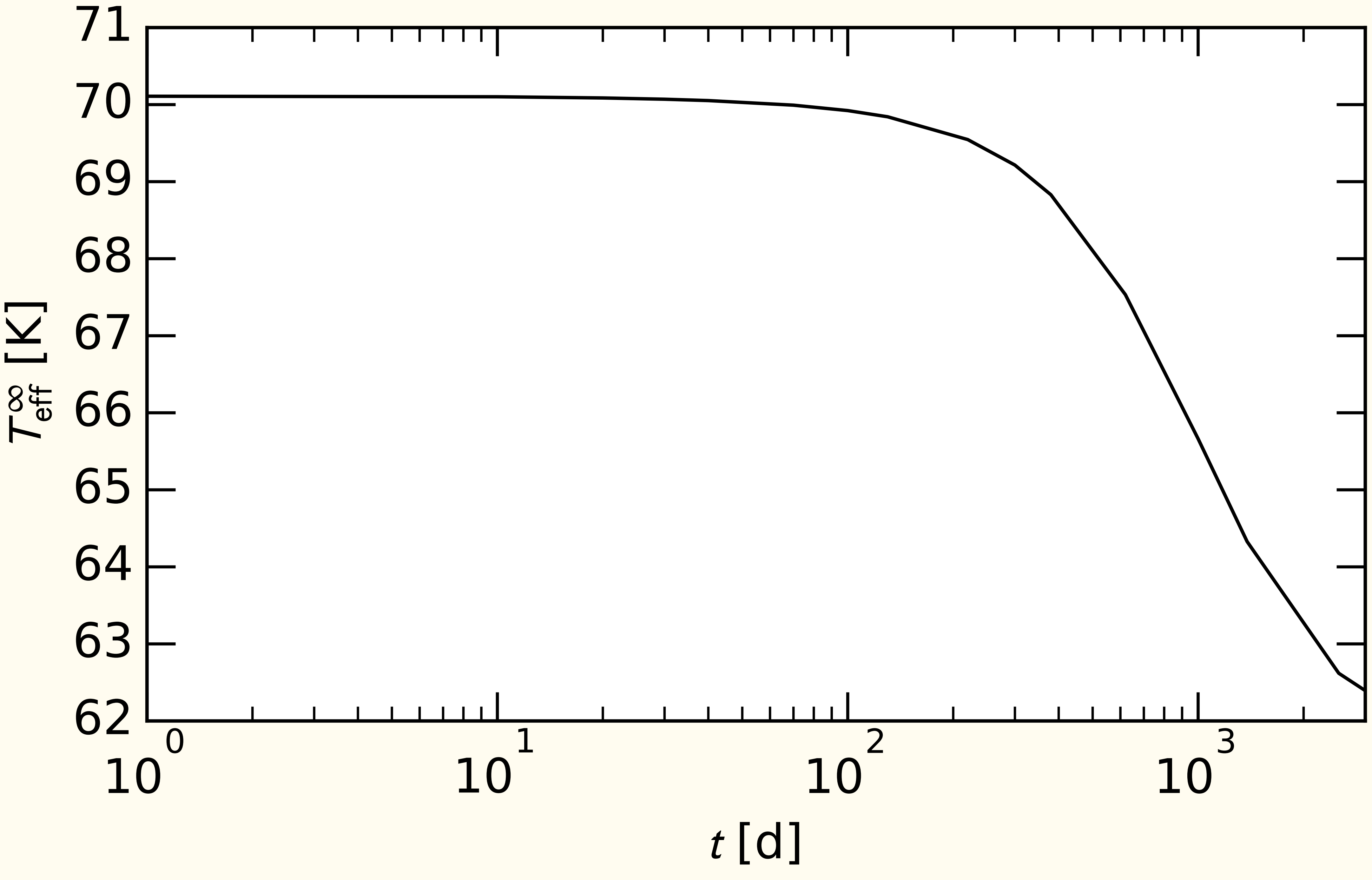
Look in the `examples/INT-16-2b-demo` directory for a demonstration of using this code that was presented in a talk given at the INT workshop 16-2b, "Phases of Dense Matter". See the `README.md` file in that directory for instructions.

In this case, crust takes decades to cool

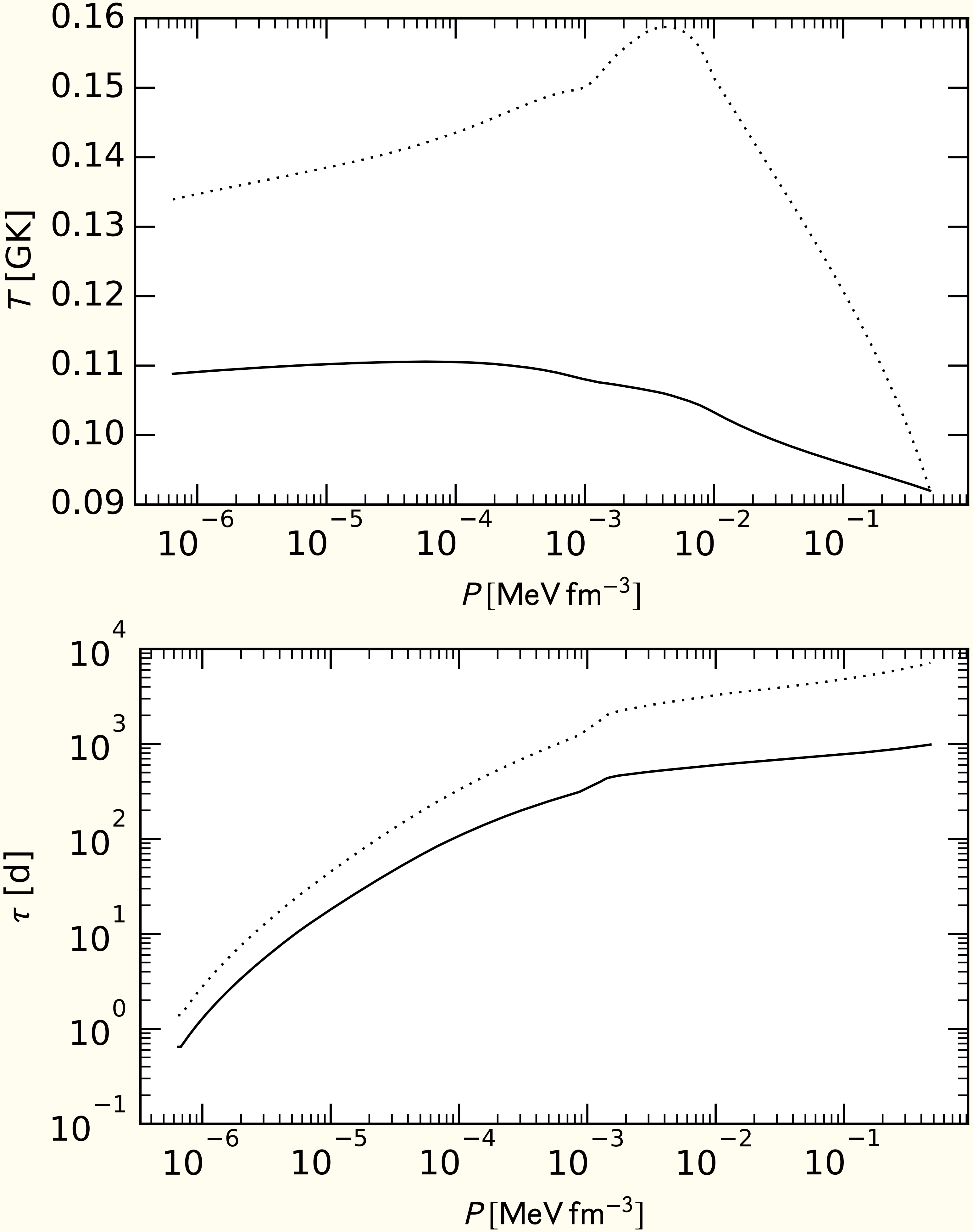
Ushomirsky & Rutledge '01



set $Q = 4$

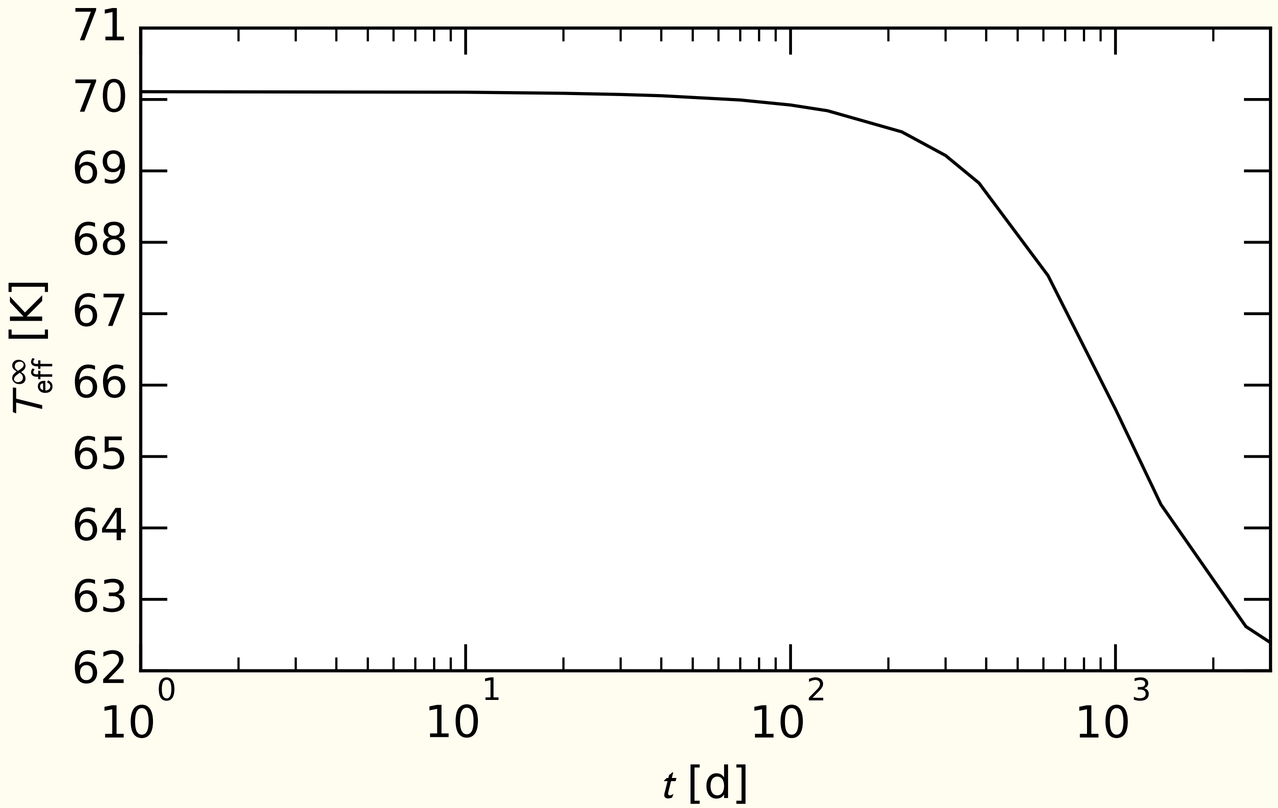


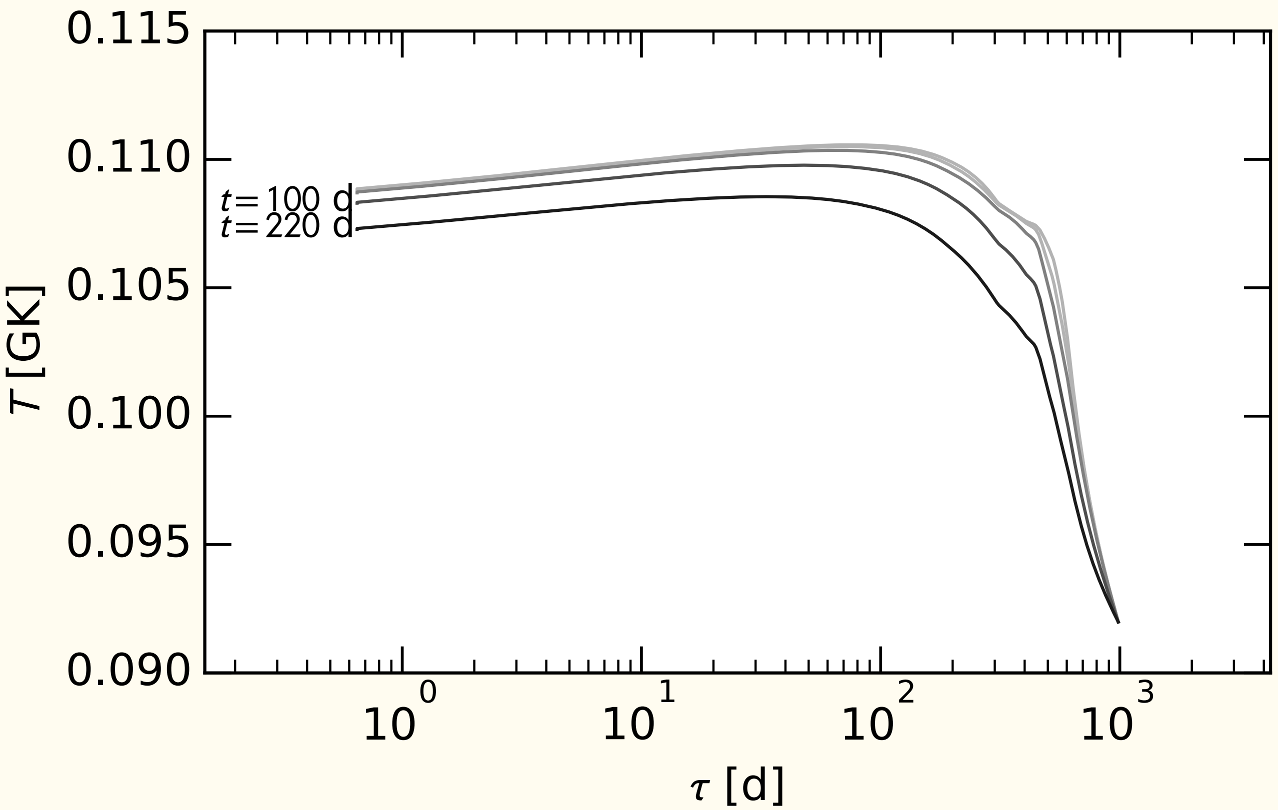
71
70
69
68
67
66
65
64
63
62
$T_{\mathrm{eff}}^{\infty}$ [K]
10^0
10^1
10^2
10^3
t [d]

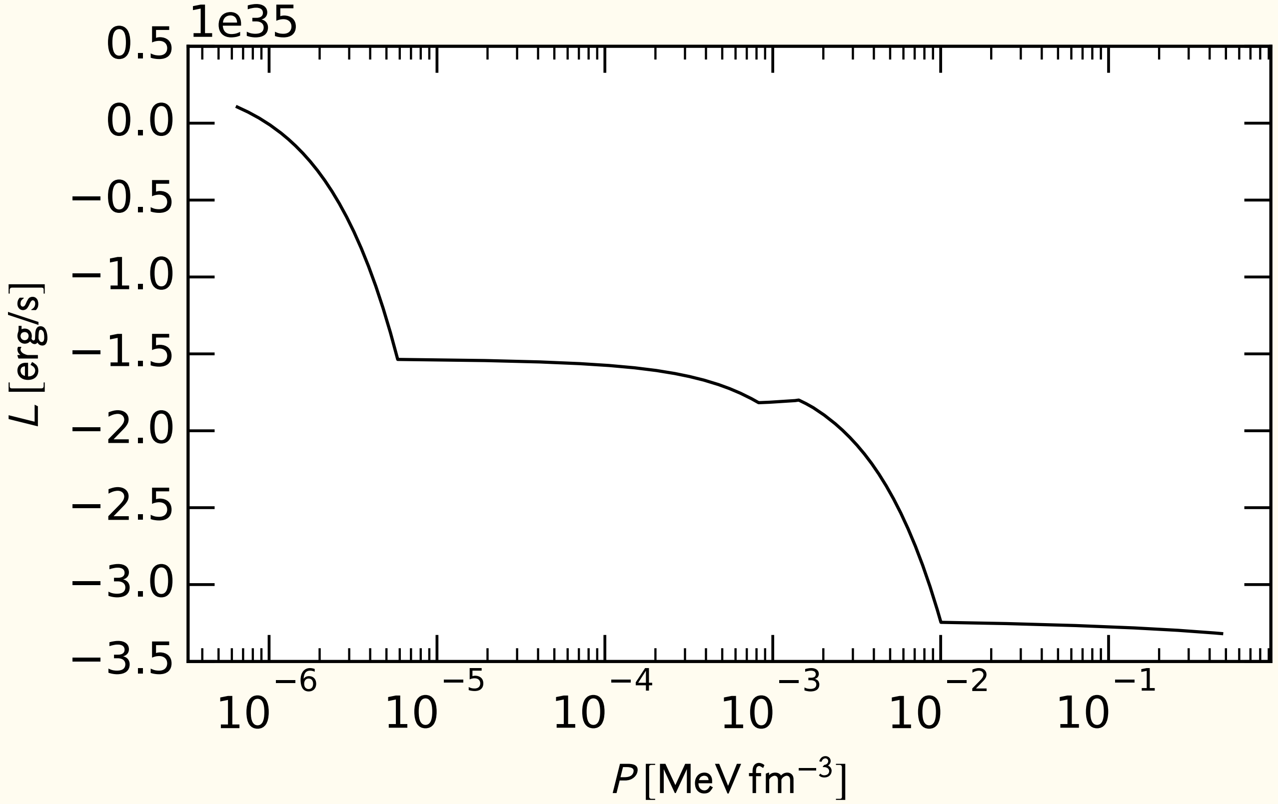


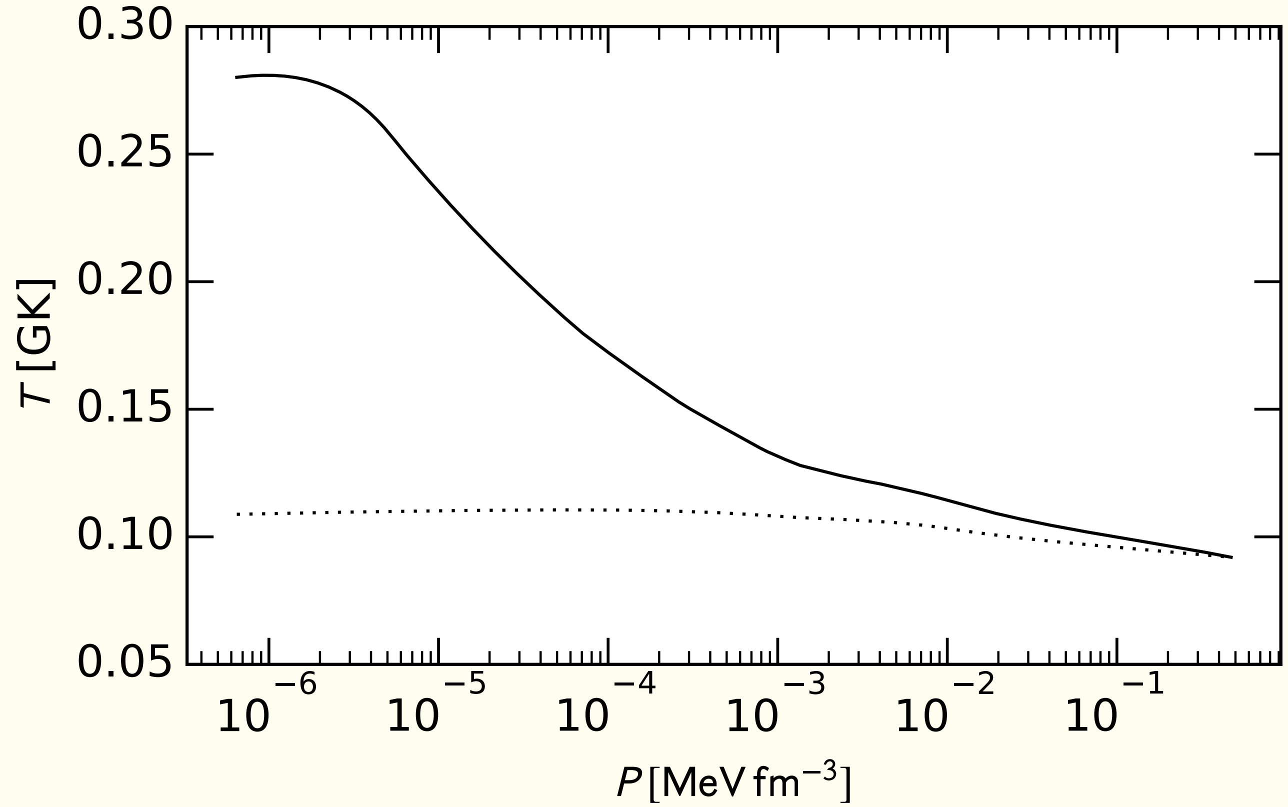
Crust cools in a few years; temperature rise is less pronounced after outburst

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

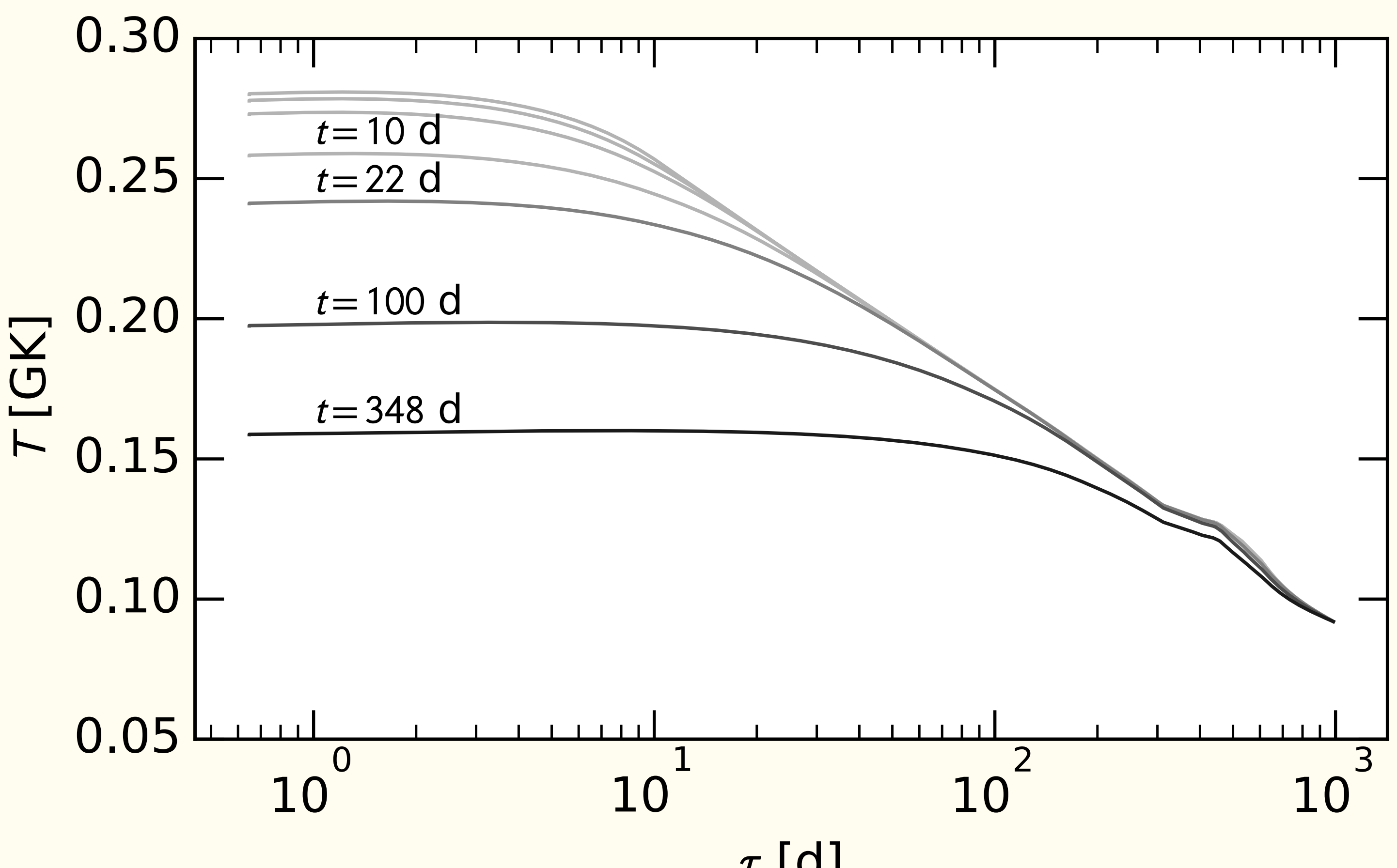


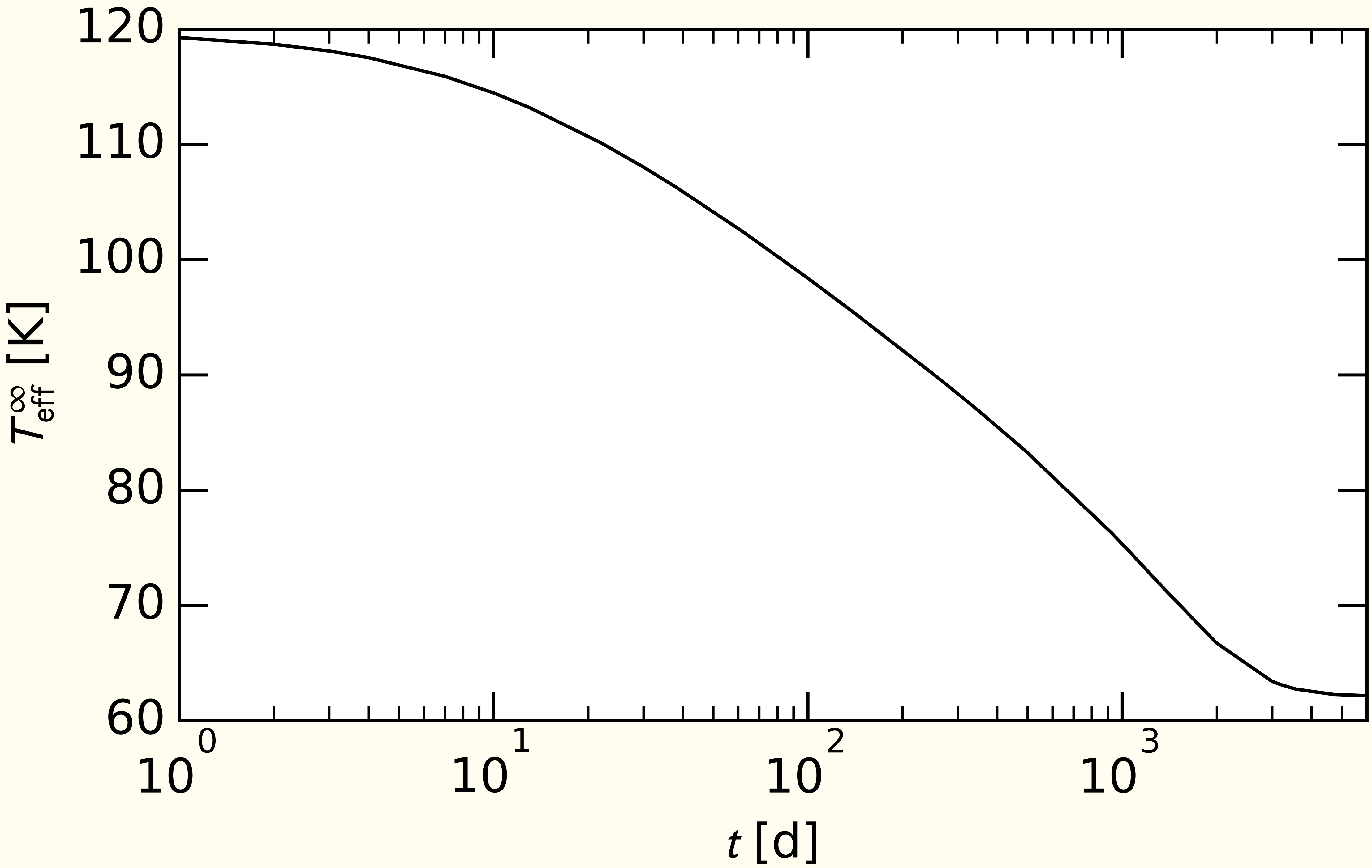






Add a heat source,
$L = 1.7$ MeV · d*M*/d*t*

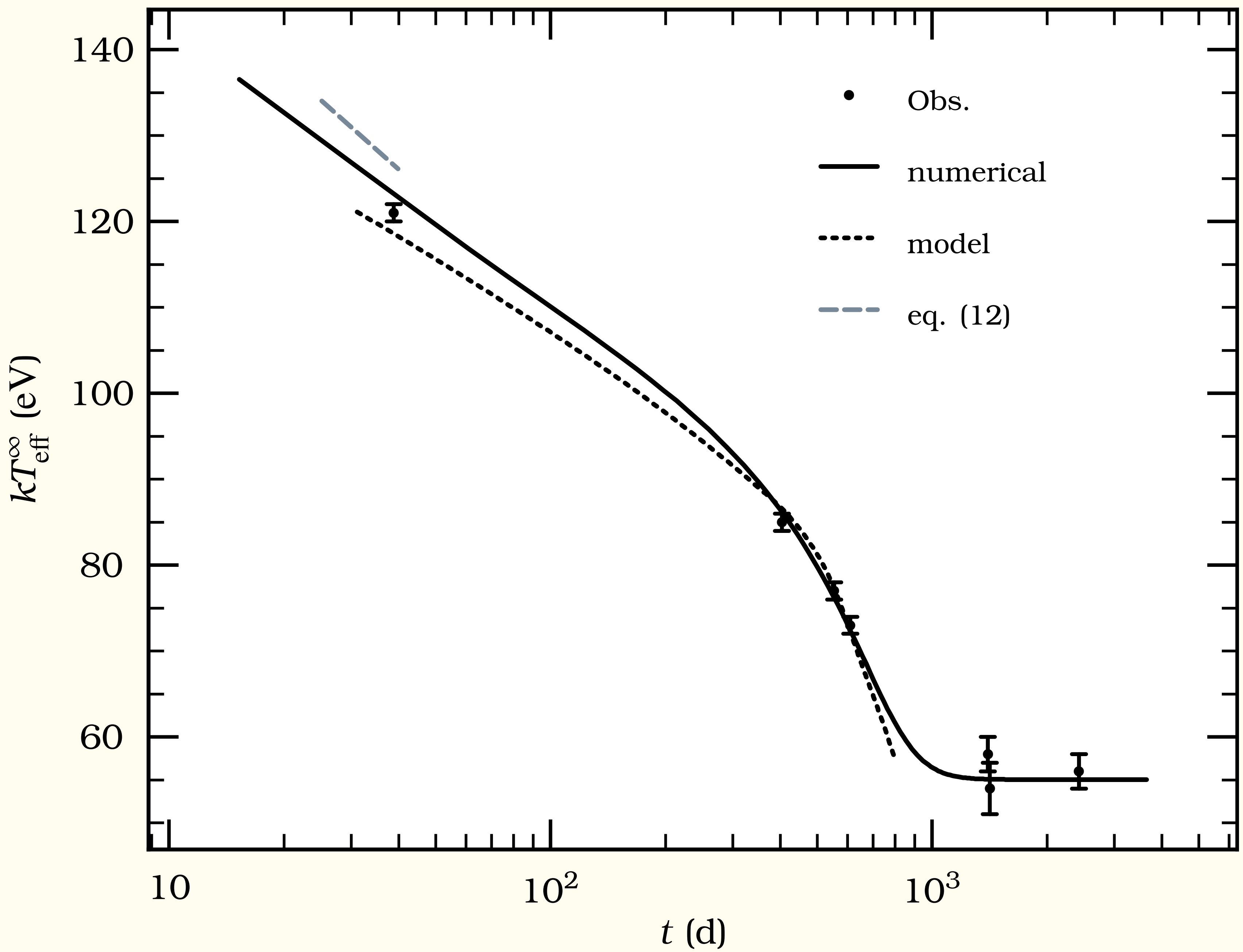




120
110
100
90
80
70
60
$T_{\rm eff}^{\infty}$ [K]
10^0
10^1
10^2
10^3
t [d]

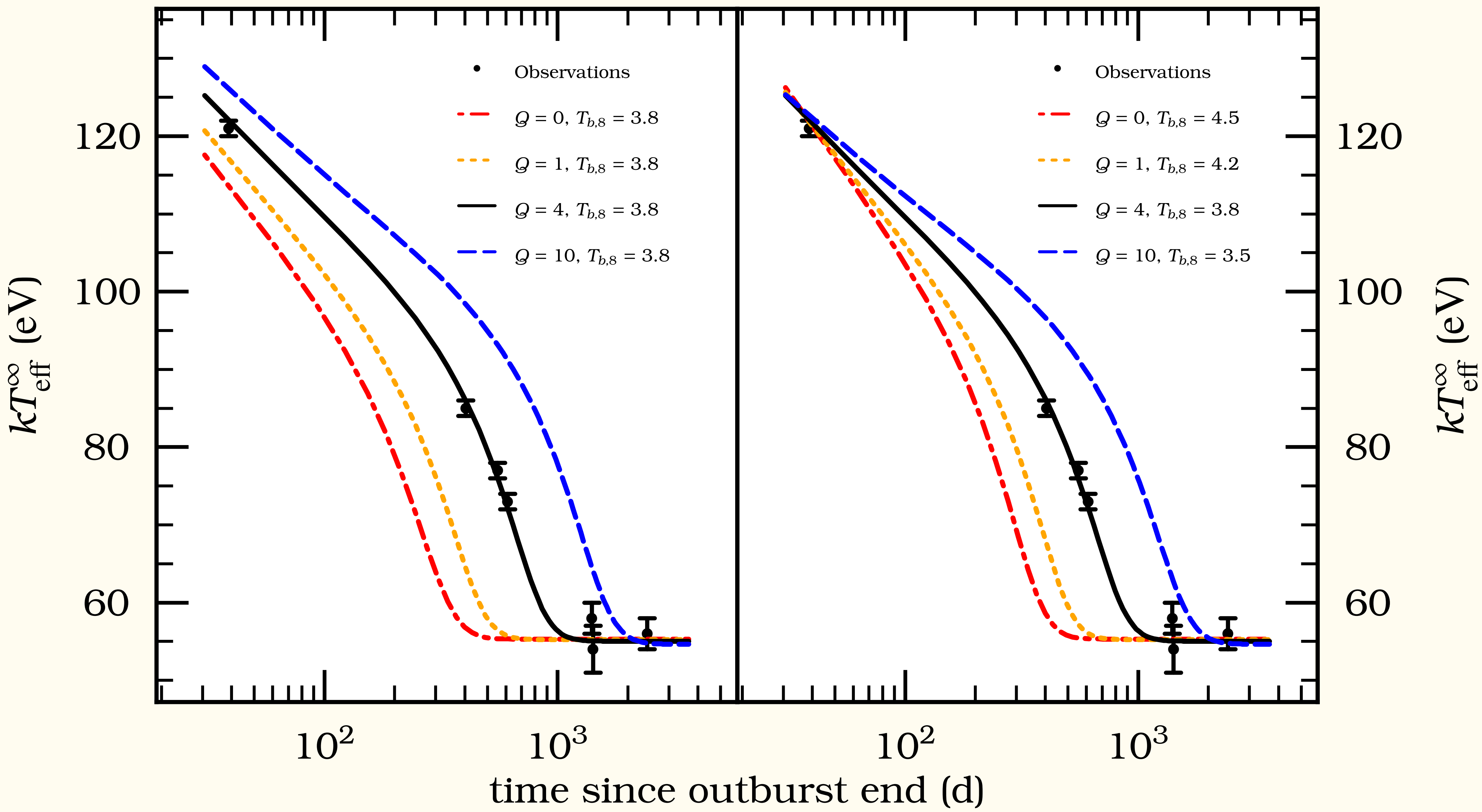
Fit to MXB 1659

Brown & Cumming '09



How impure is the crust? $Q < 10$

Shternin et al. 2007; Brown & Cumming 2009



what have we learned?

Neutron stars have crusts (including the inner part)

These crusts are good conductors of heat

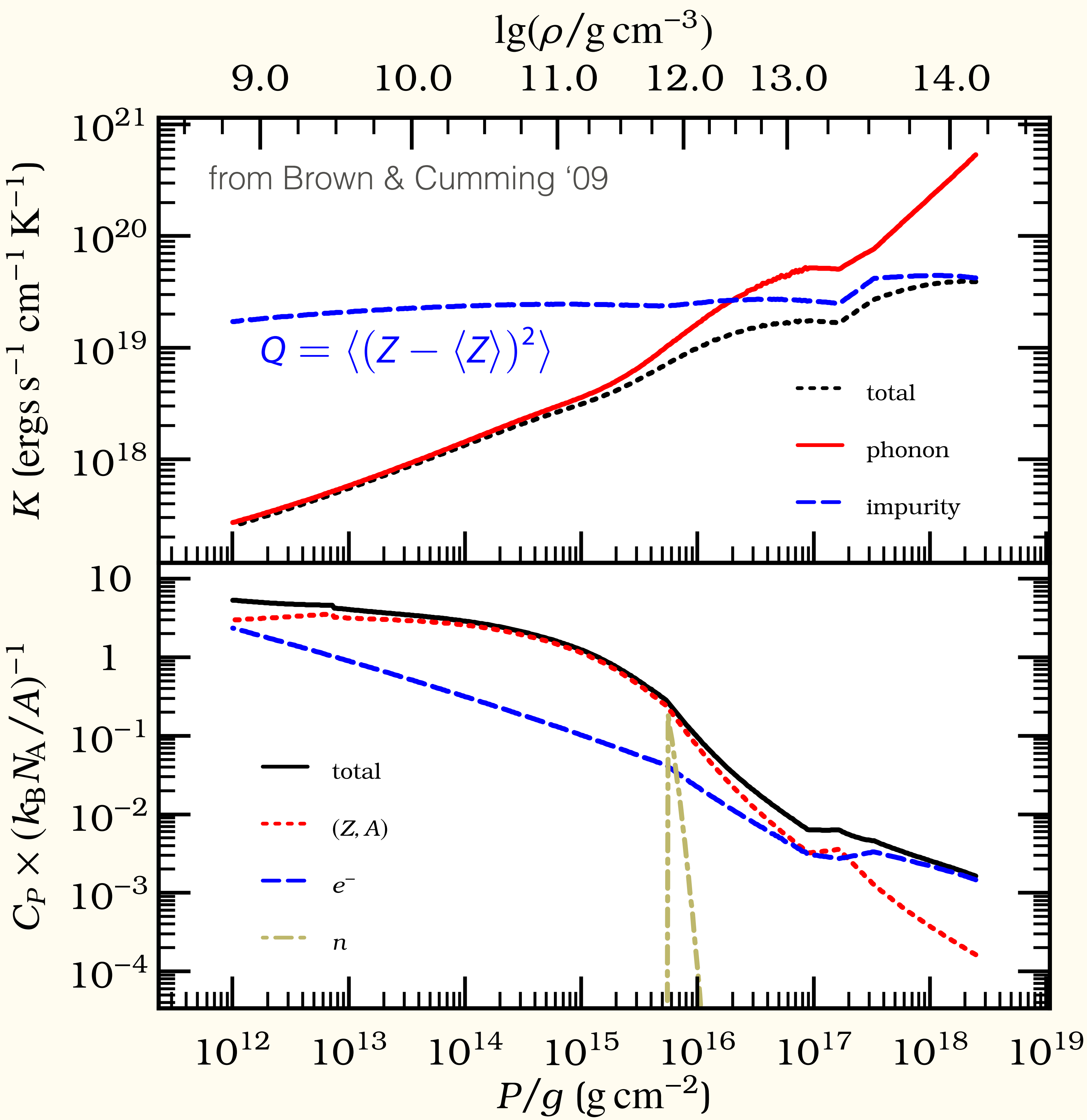
The neutrons must be superfluid

cooling timescale

Thermal diffusion

$$\rho C \frac{\partial T}{\partial t} = \nabla \cdot (K \boldsymbol{\nabla} T)$$

$$\tau = \frac{1}{4} \left[\int \left(\frac{\rho C}{K} \right)^{1/2} dz \right]^2$$



what have we learned?

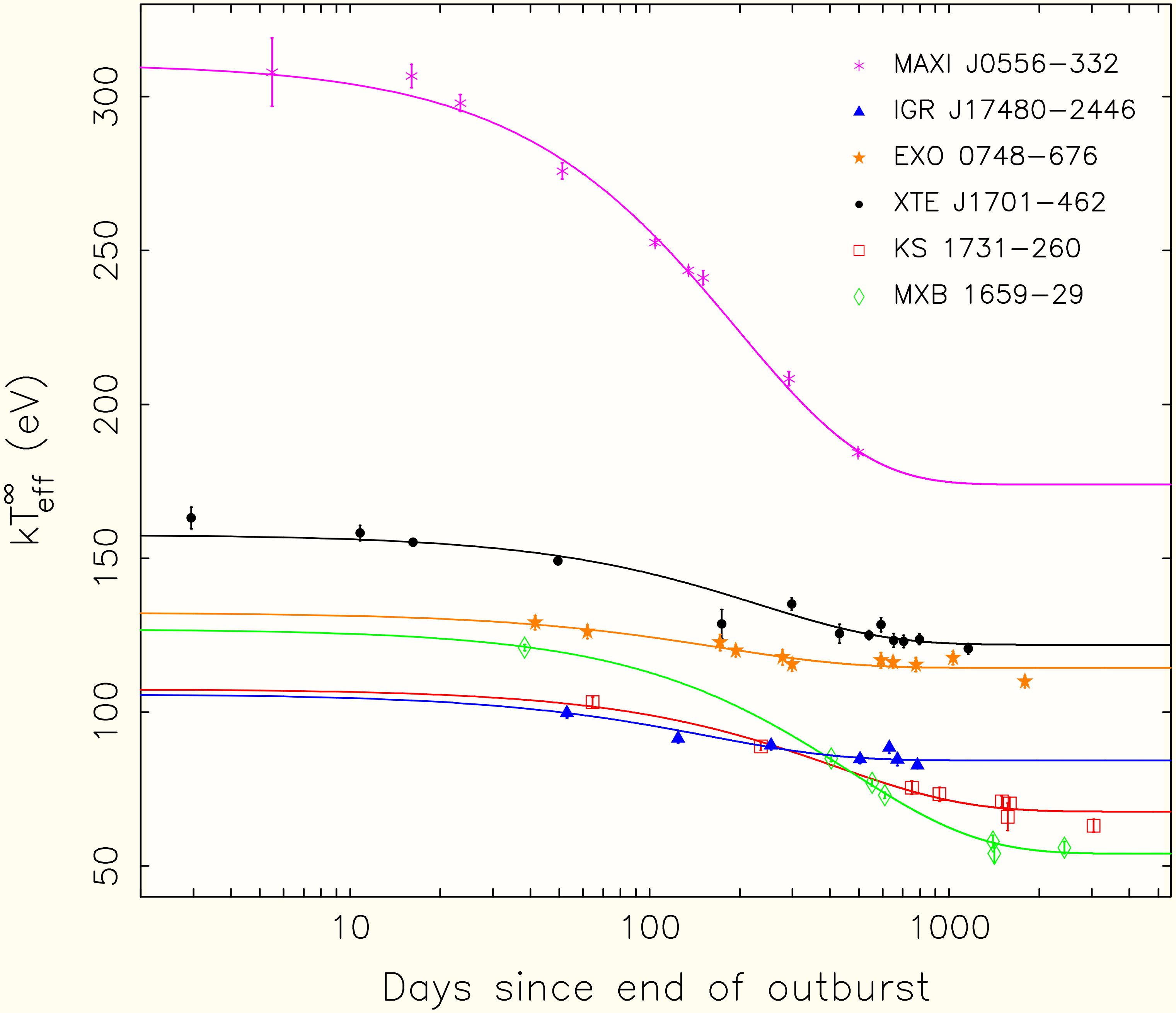
Neutron stars have crusts (including the inner part)

These crusts are good conductors of heat

The neutrons must be superfluid

There appears to be additional heating

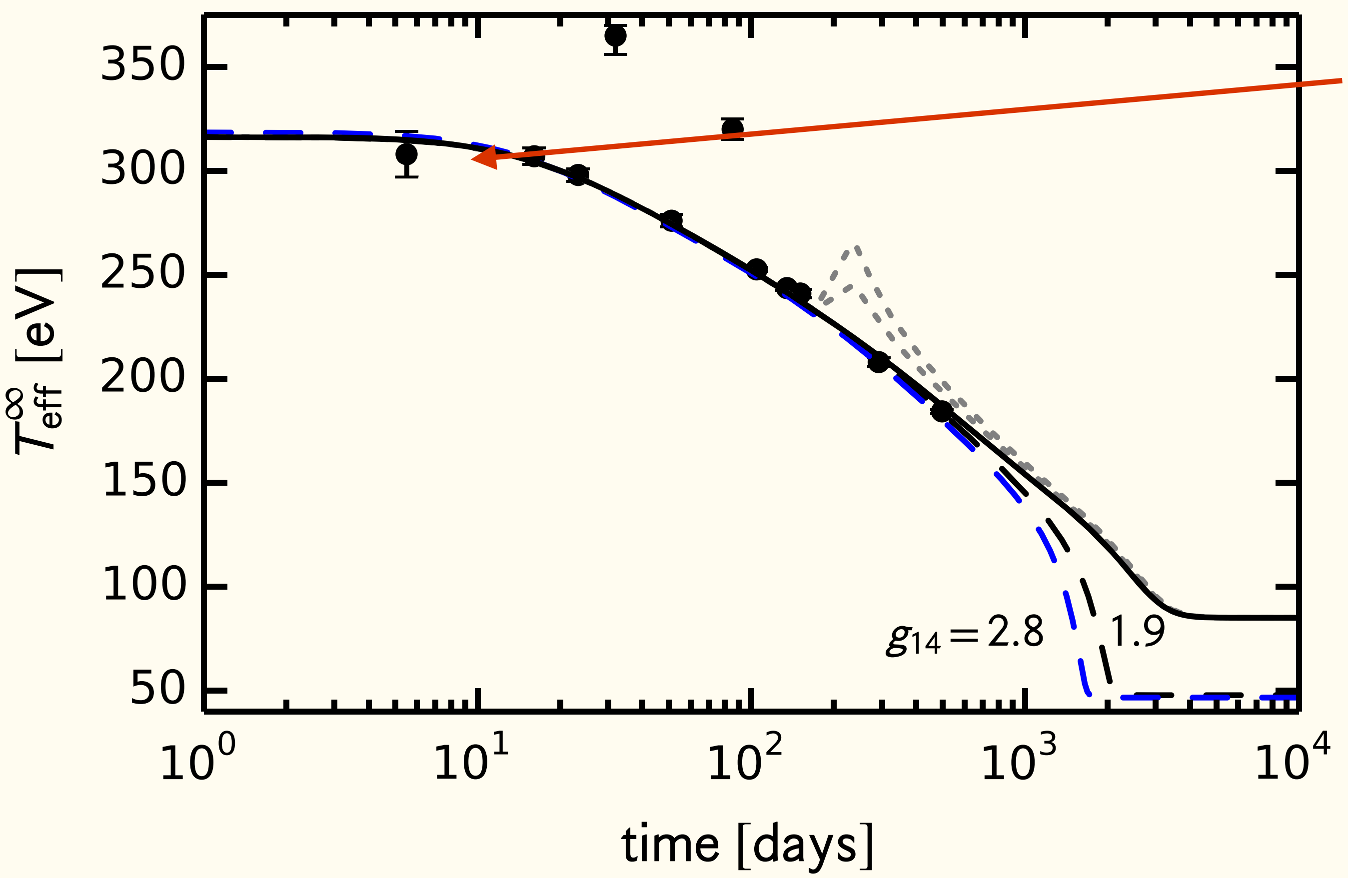
observed cooling of transients post-outburst



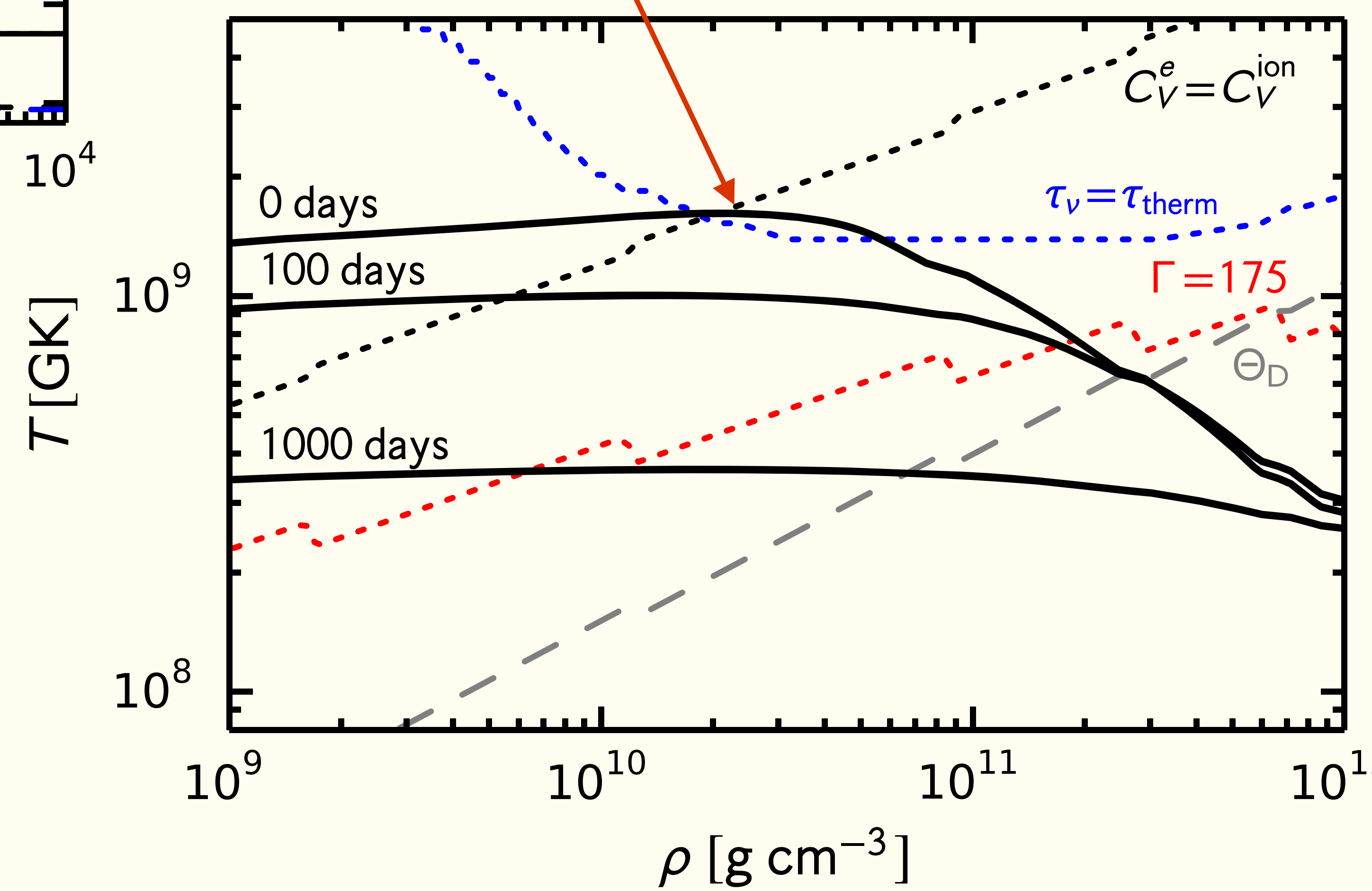
Homan et al. '14

Shallow Heating in MAXI J0556-332

Deibel et al. '15



break in light curve gives depth of shallow heating (4–10 MeV per accreted nucleon!)



$$\tau = \frac{1}{4}\left[\int \left(\frac{\rho C}{K}\right)^{1/2} dz\right]^2$$

Questions

Is there residual accretion during quiescence?

What causes the shallow heating?

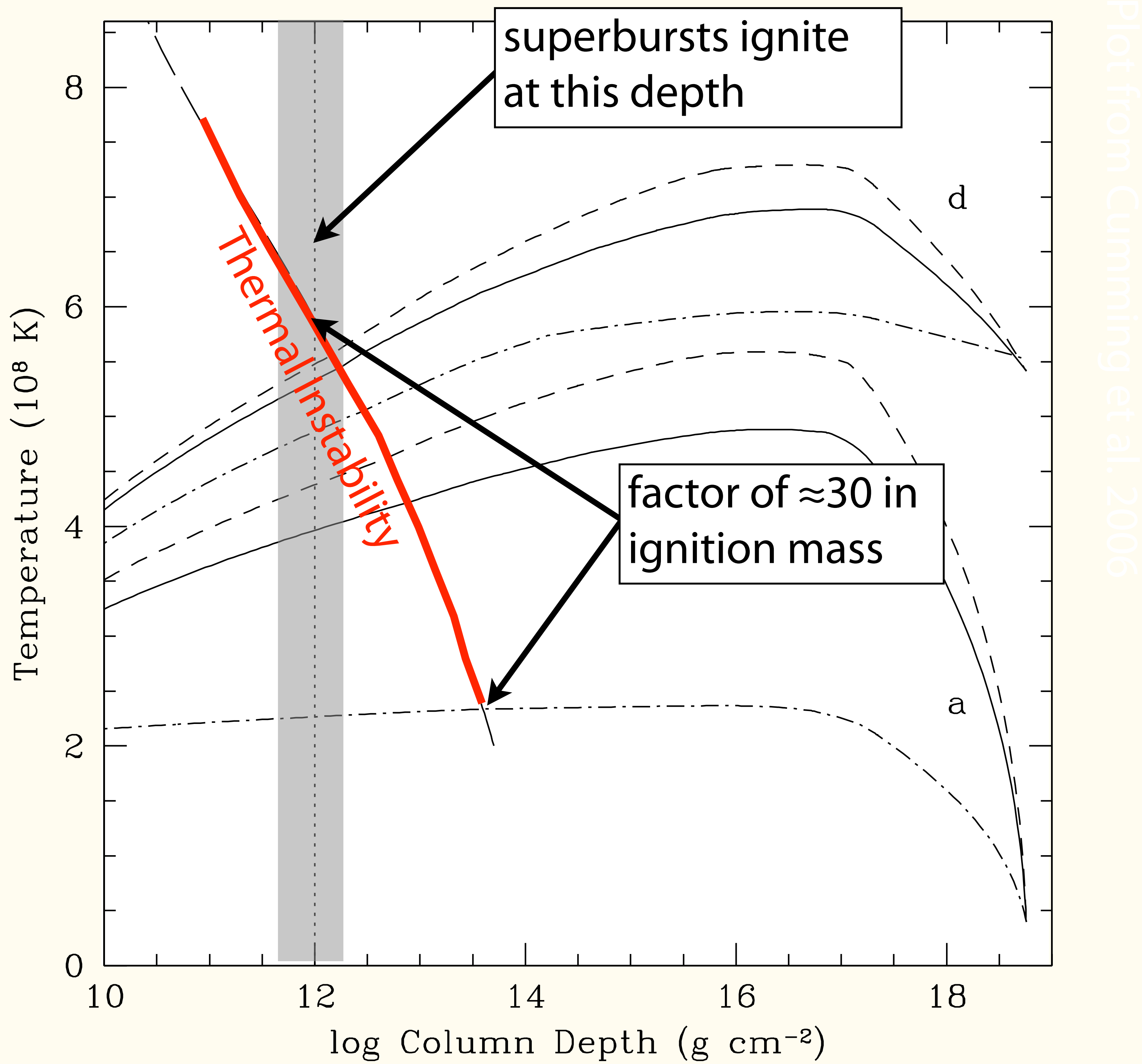
Why is the inner crust so nearly pure?

How quickly does pasta cool?

What do the inferred core temperatures imply?

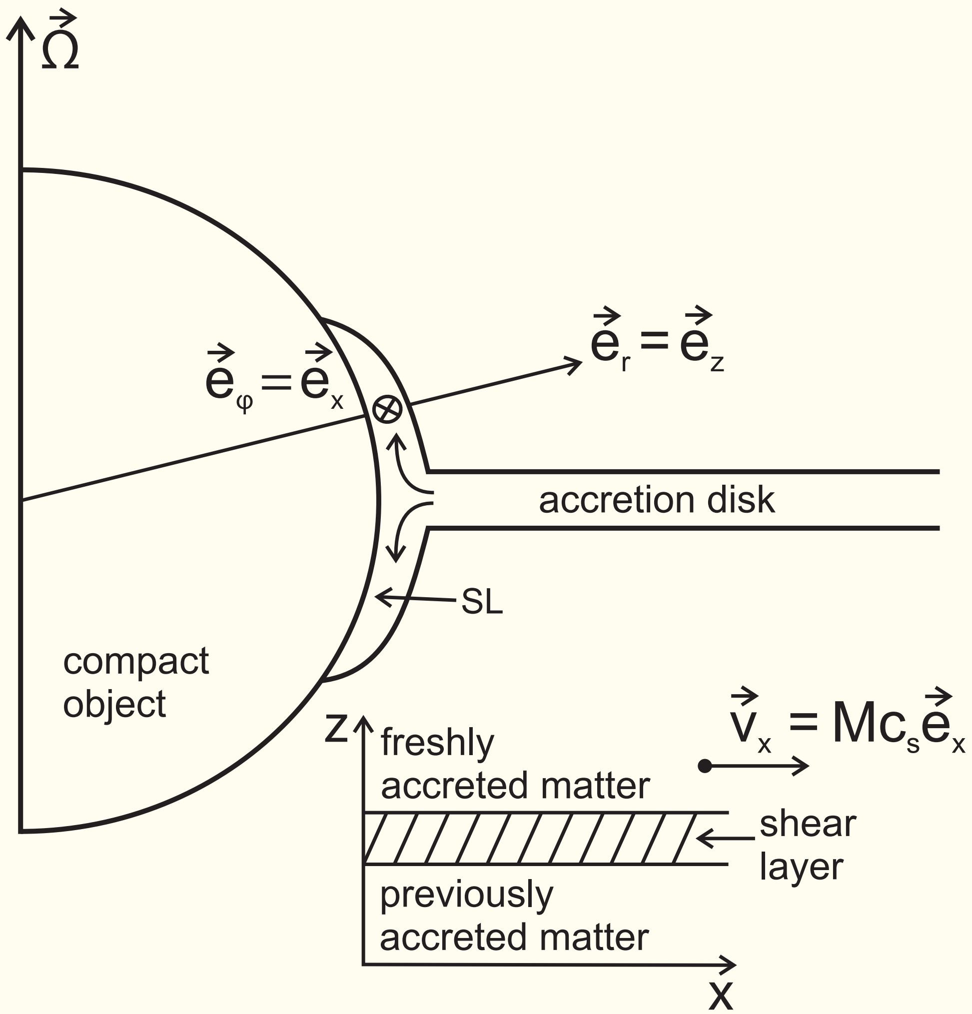
^{12}C ignition requires high crust temperatures

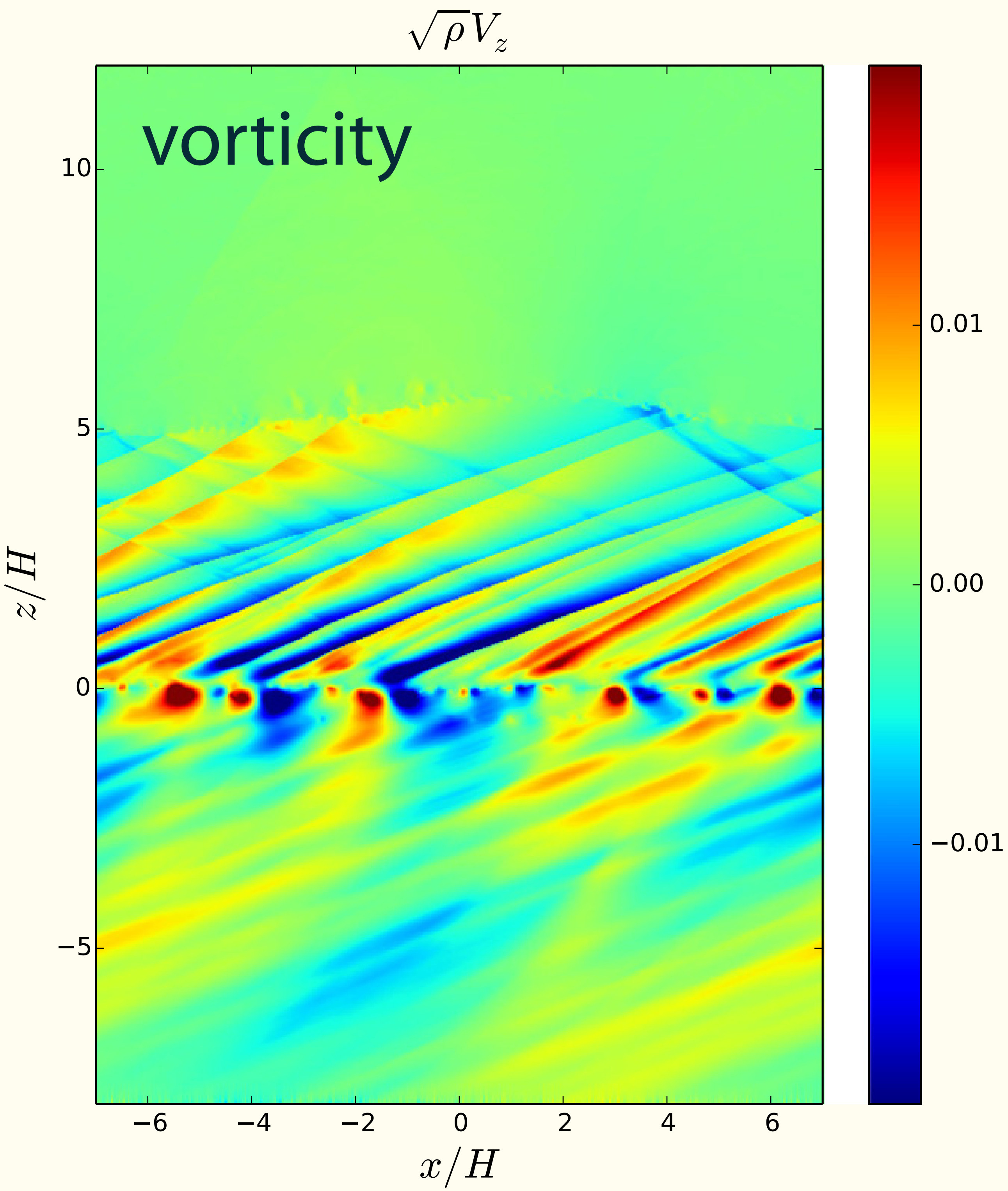
Brown 2004, Cooper & Narayan 2005, Cumming et al. 2006



Heating by acoustic modes

Philippov et al. ’16; Inogamov & Sunyaev ‘10





figures from Philippov et al. ‘16

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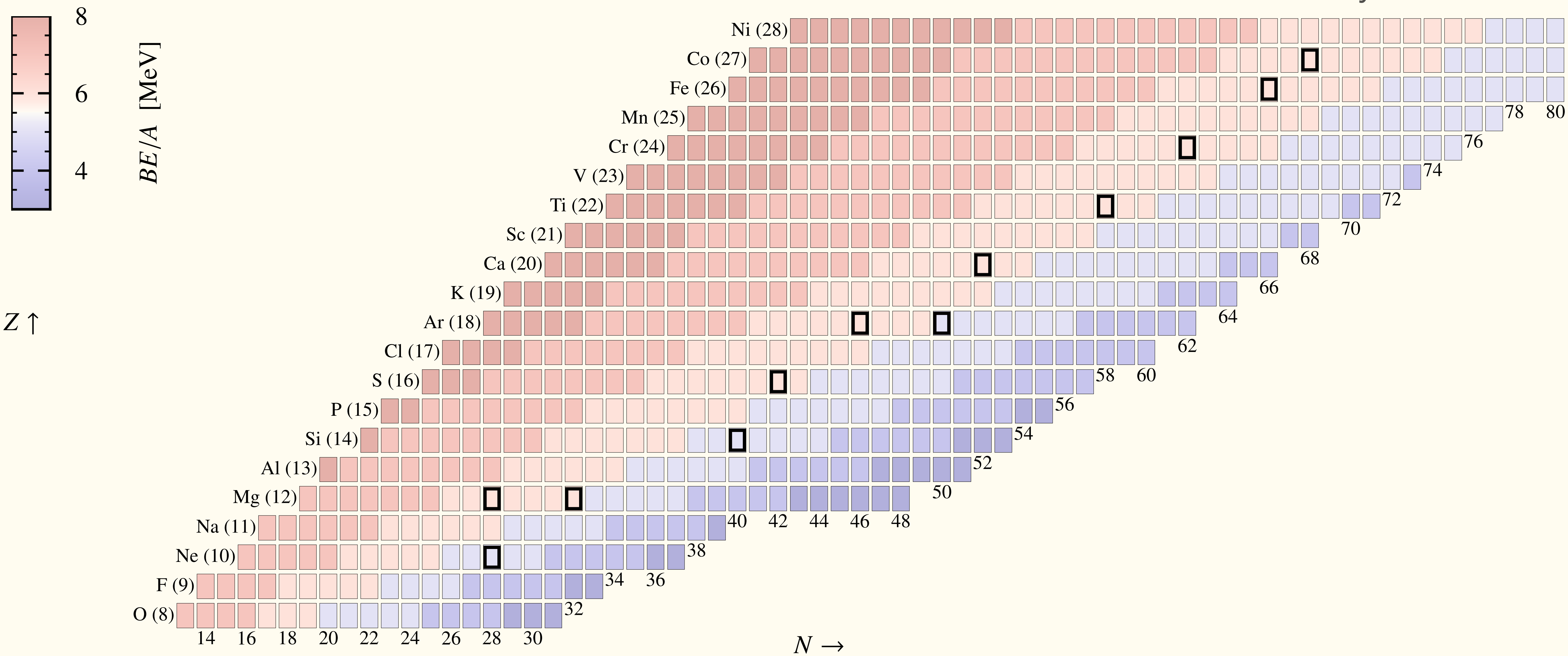
stable nuclei at 6×10^{12} g cm^{-3}

courtesy A. Deibel



Facility for Rare Isotope Beams at Michigan State University

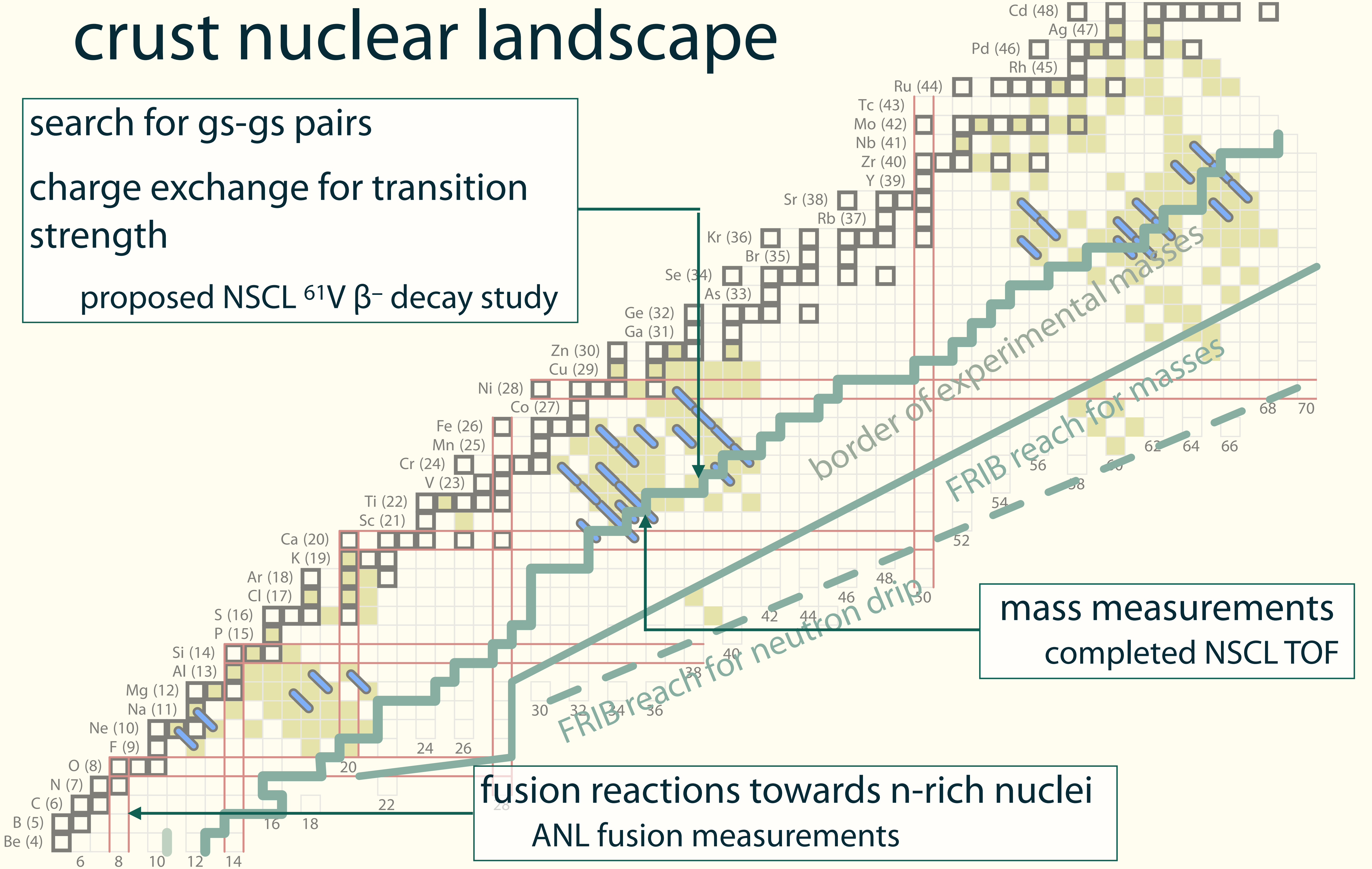
Facility for Rare Isotope Beams at Michigan State University

JINA/JINA-CEE experiments across the crust nuclear landscape

search for gs-gs pairs

charge exchange for transition strength

proposed NSCL ^{61}V β^- decay study



mass measurements

completed NSCL TOF

fusion reactions towards n-rich nuclei

ANL fusion measurements

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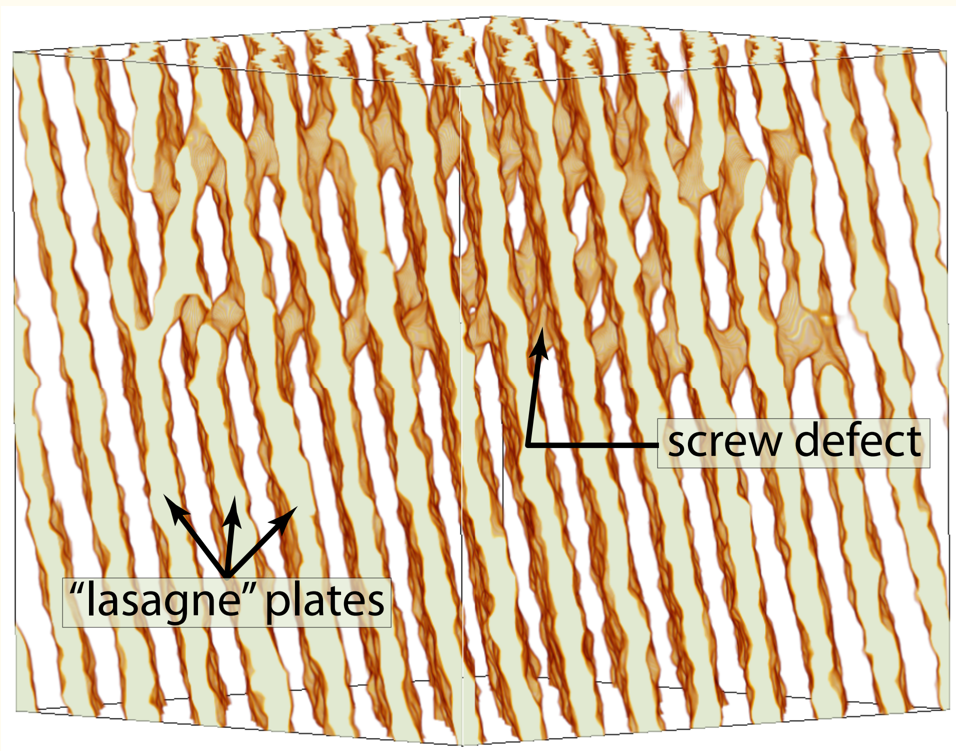
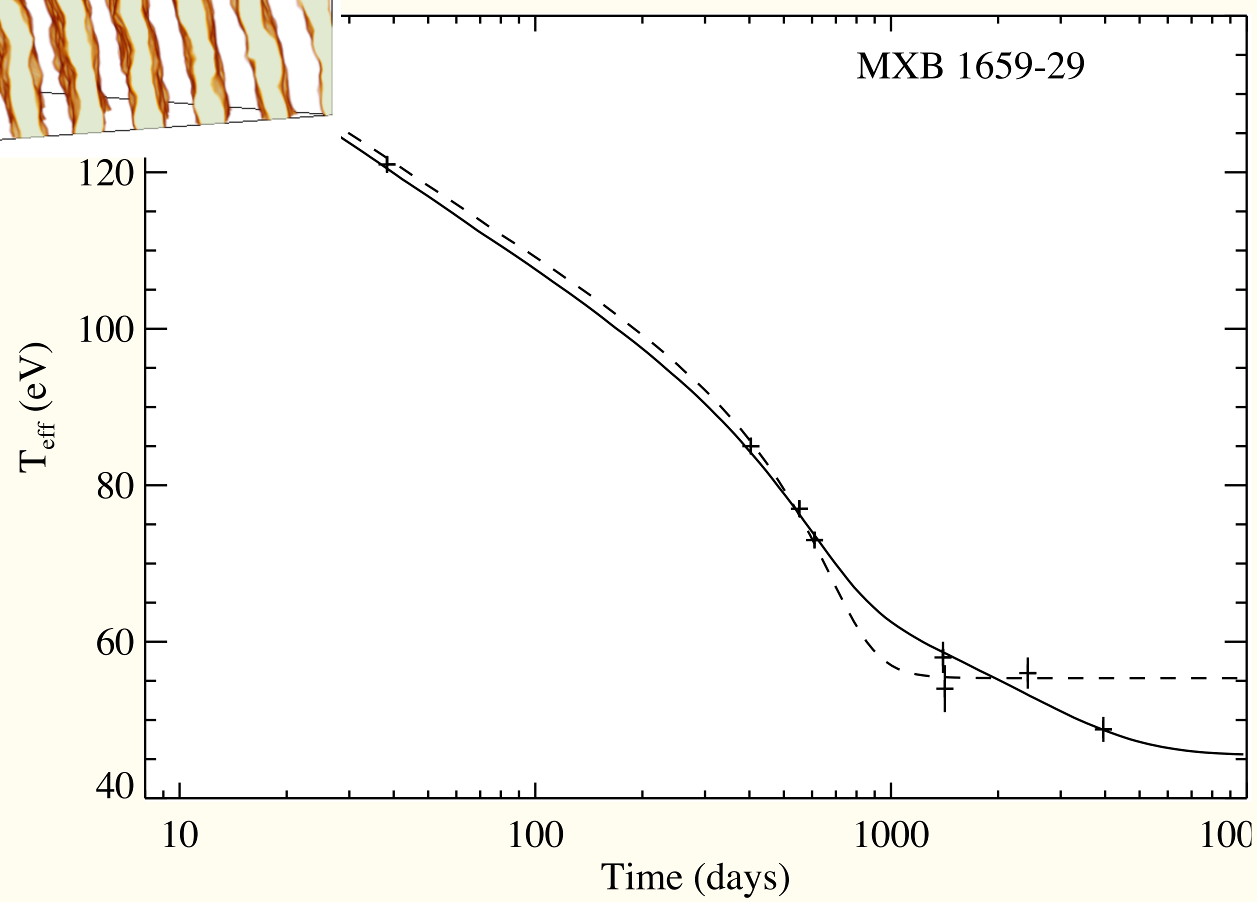
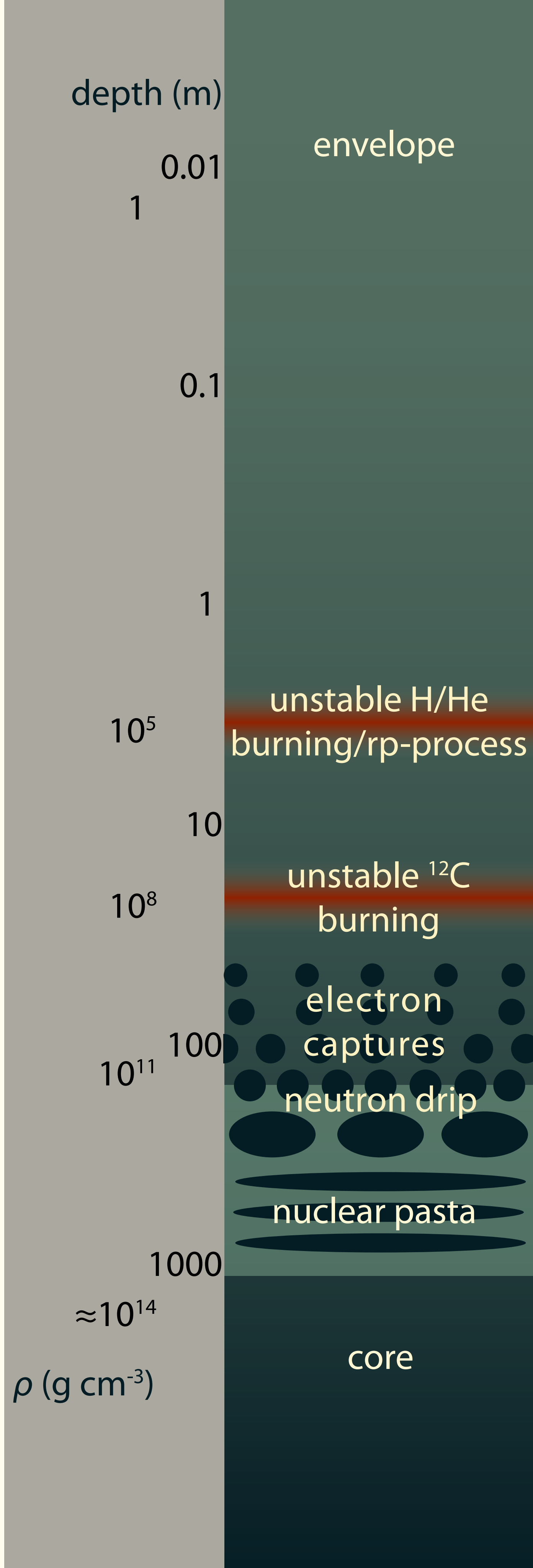
Pasta delays late-time cooling

Horowitz et al. ‘15







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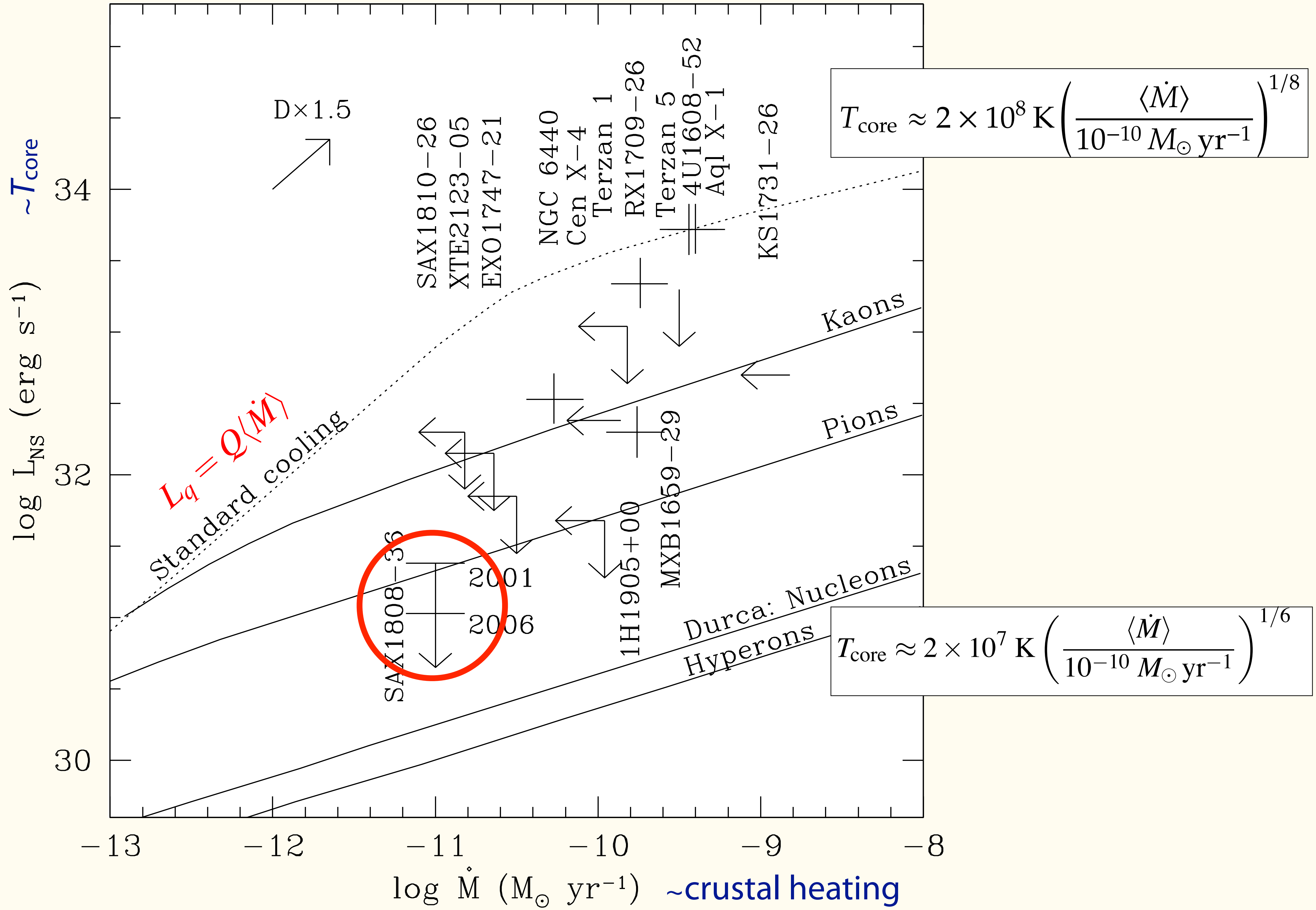
Heinke et al. 2007, following Yakovlev et al. 2004



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