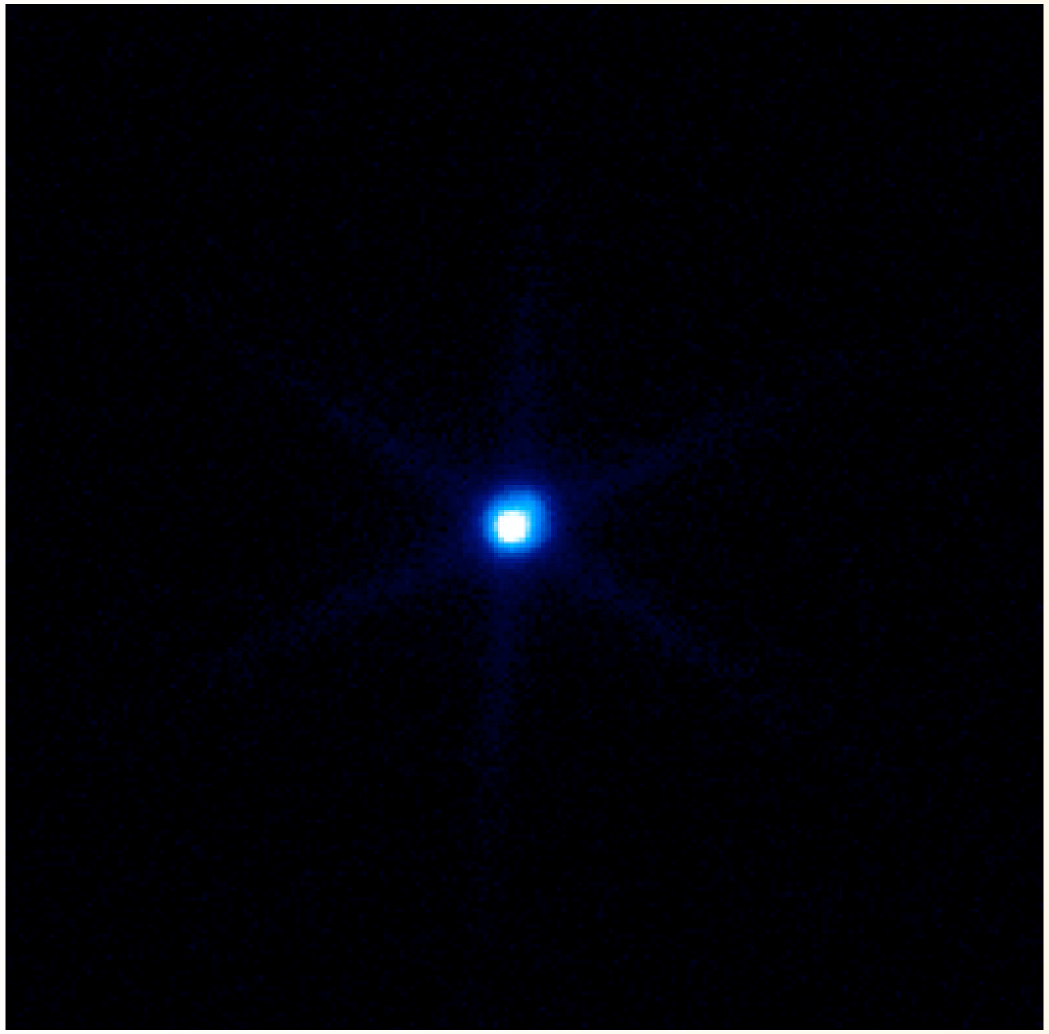
Crust electron captures

Edward Brown

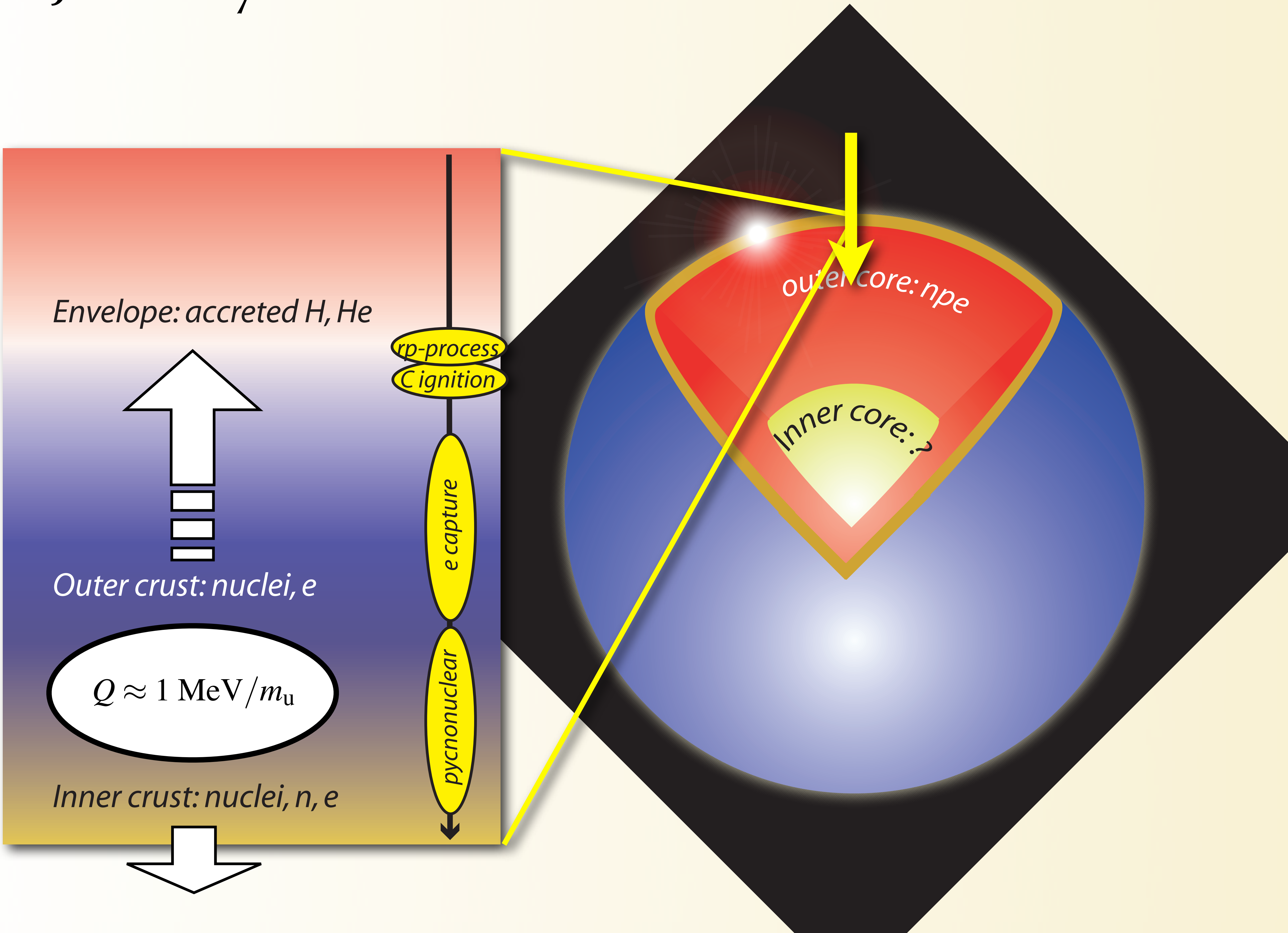
In this talk

KS 1731–260



- Review of deep crustal heating
- Connection to “surface” phenomena
- Electron captures in the outer crust with realistic nuclear physics
- Thermal conductivity & cooling timescales
- Next steps

Journey of an accreted fluid element



Envelope: accreted H, He

rp-process

C ignition

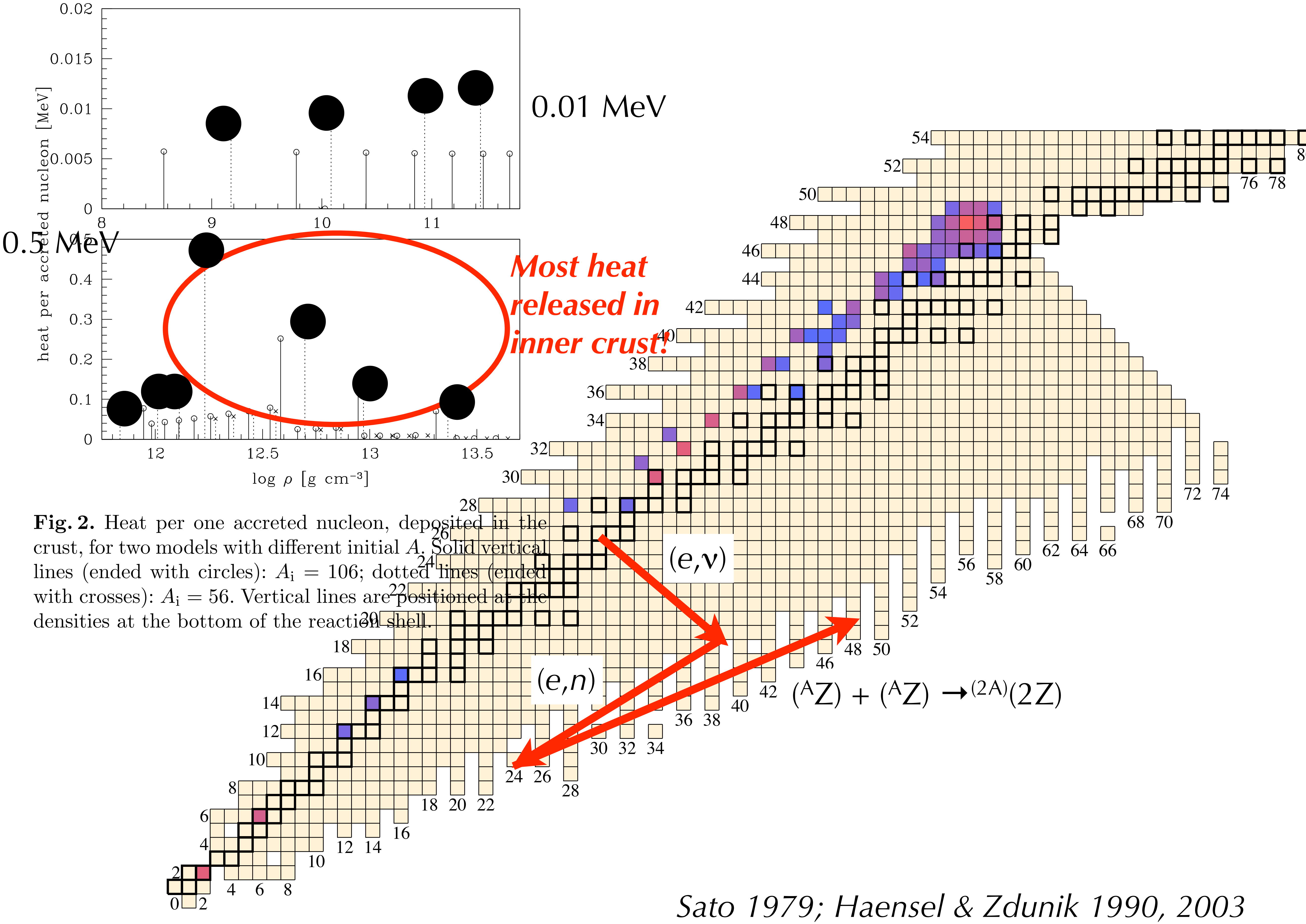
Outer crust: nuclei, e

e capture

$Q \approx 1\,\mathrm{MeV}/m_{\mathrm{u}}$

pycnonuclear

Inner crust: nuclei, n, e



0.01 MeV

0.5 MeV

Most heat released in inner crust!

(e,ν)

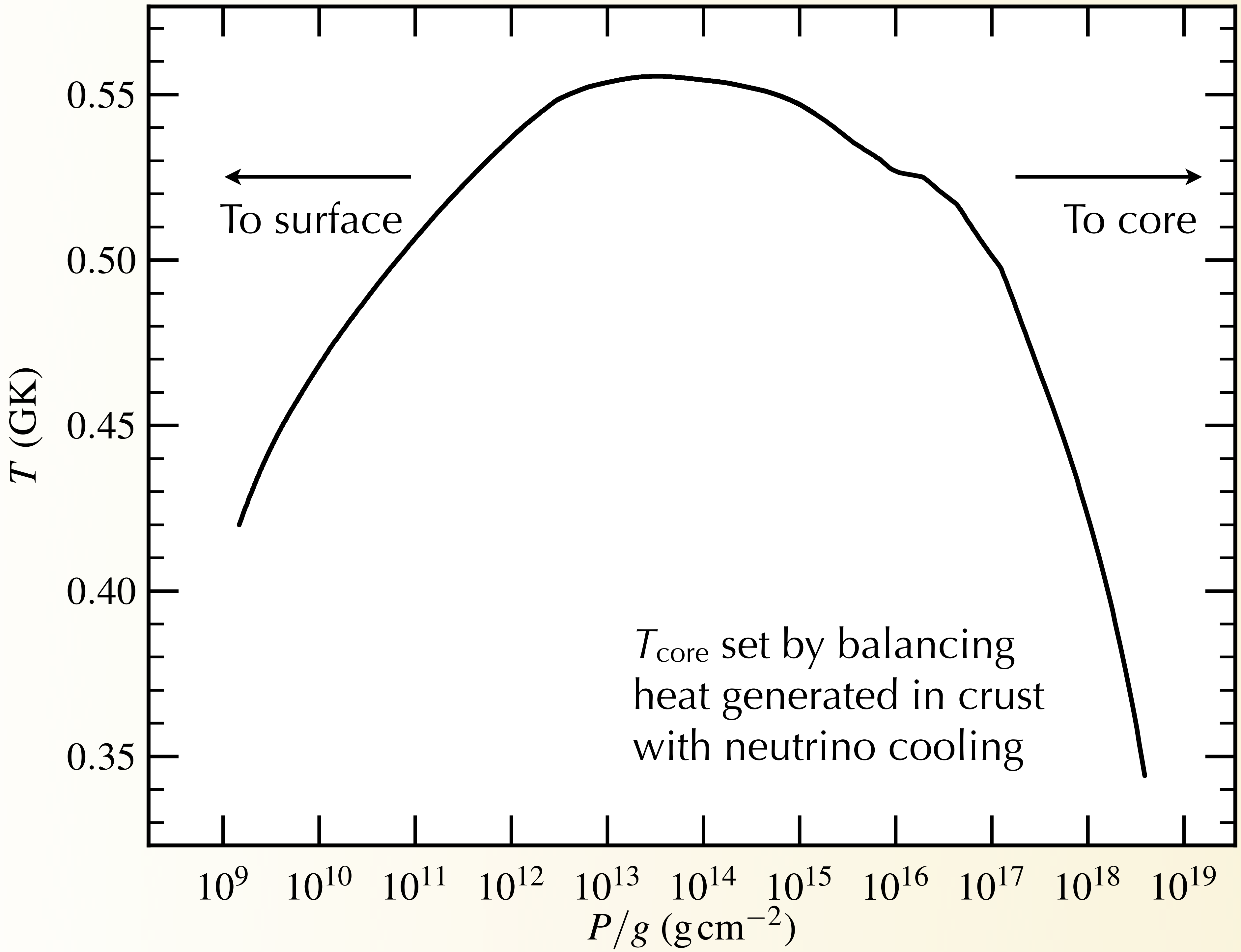
(e,*n*)

$(^{A}Z) + (^{A}Z) \rightarrow {}^{(2A)}(2Z)$

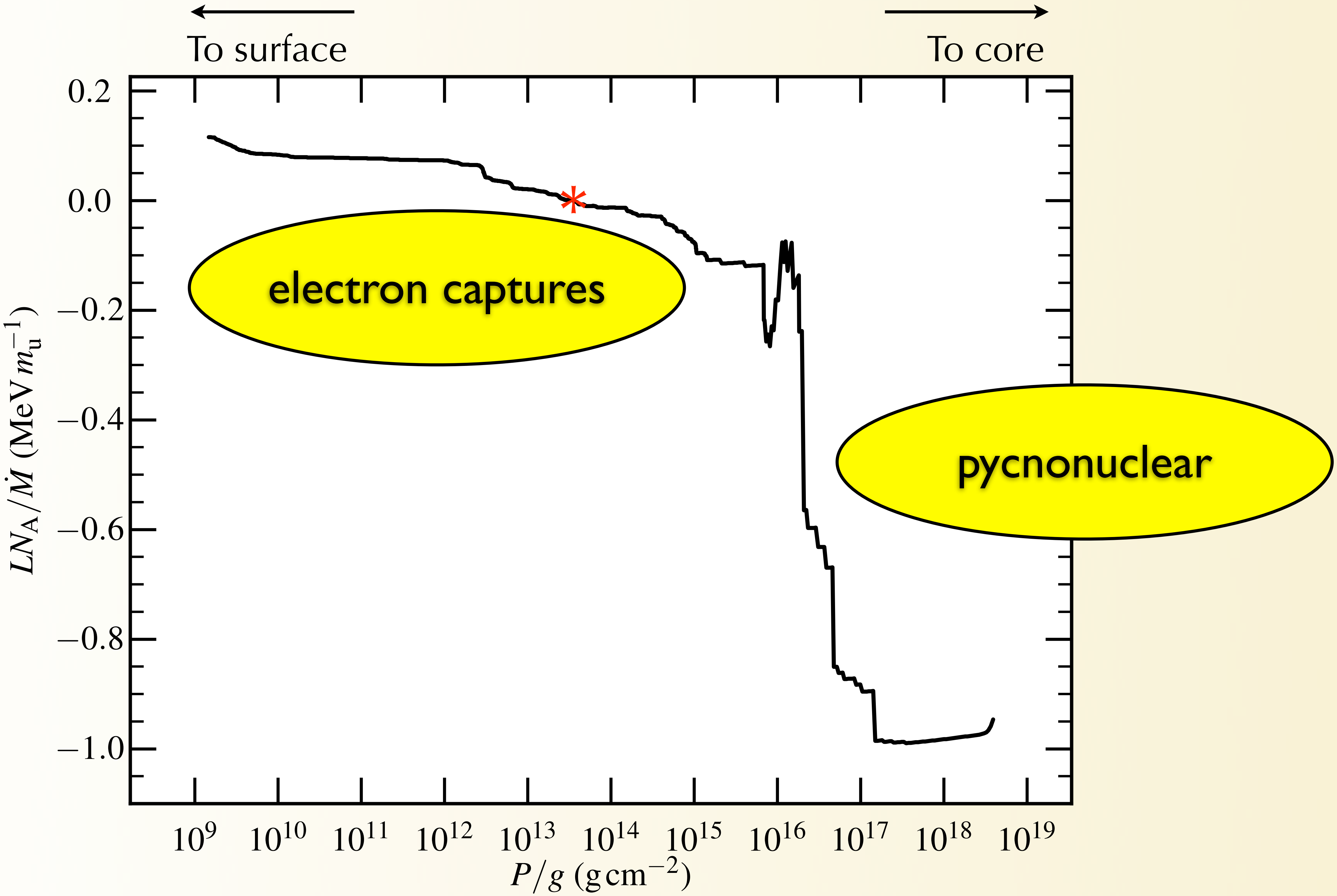
Fig. 2. Heat per one accreted nucleon, deposited in the crust, for two models with different initial A. Solid vertical lines (ended with circles): $A_{\rm i} = 106$; dotted lines (ended with crosses): $A_{\rm i} = 56$. Vertical lines are positioned at the densities at the bottom of the reaction shell.

Sato 1979; Haensel & Zdunik 1990, 2003

Crust thermal profile



Luminosity



To surface
To core
0.2
0.0
−0.2
−0.4
−0.6
−0.8
−1.0
$LN_A/\dot{M}$ (MeV m_u^{-1})
10^9
10^{10}
10^{11}
10^{12}
10^{13}
10^{14}
10^{15}
10^{16}
10^{17}
10^{18}
10^{19}
P/g (g cm^{-2})
*
electron captures
pycnonuclear

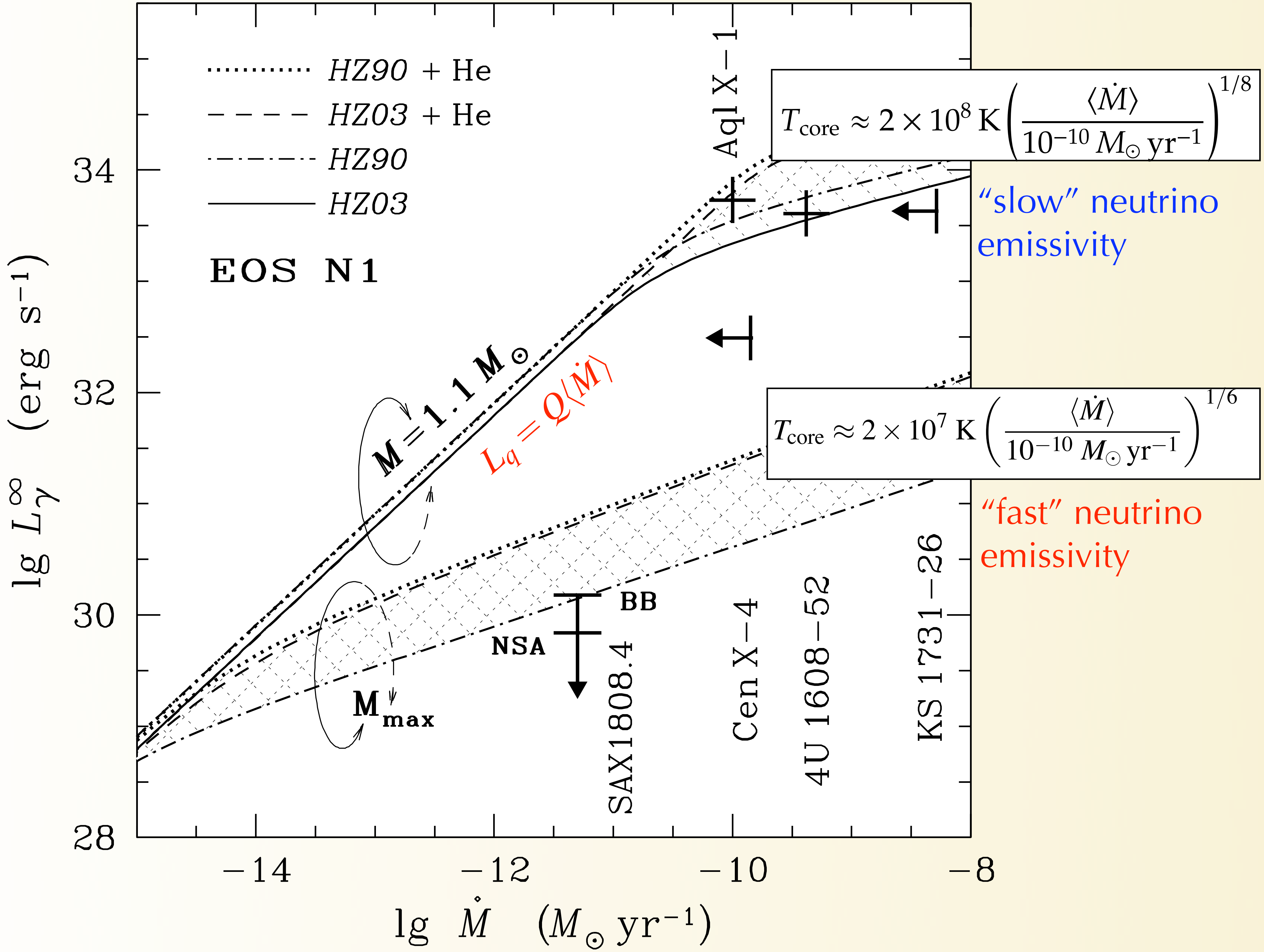
The heating sets

- the quiescent luminosity of transients (previous talks)
- ignition depth of superbursts (Brown, Cooper & Narayan, Cumming et al.)
- X-ray bursts at low accretion rates (Cumming et al., Peng et al.)

The composition sets

- transport properties
- mass quadrupole (Bildsten 1998, Ushomirsky et al. 2000, Haskell et al. 2006)

from Yakovlev et al. 2004, cf. update by Heinke



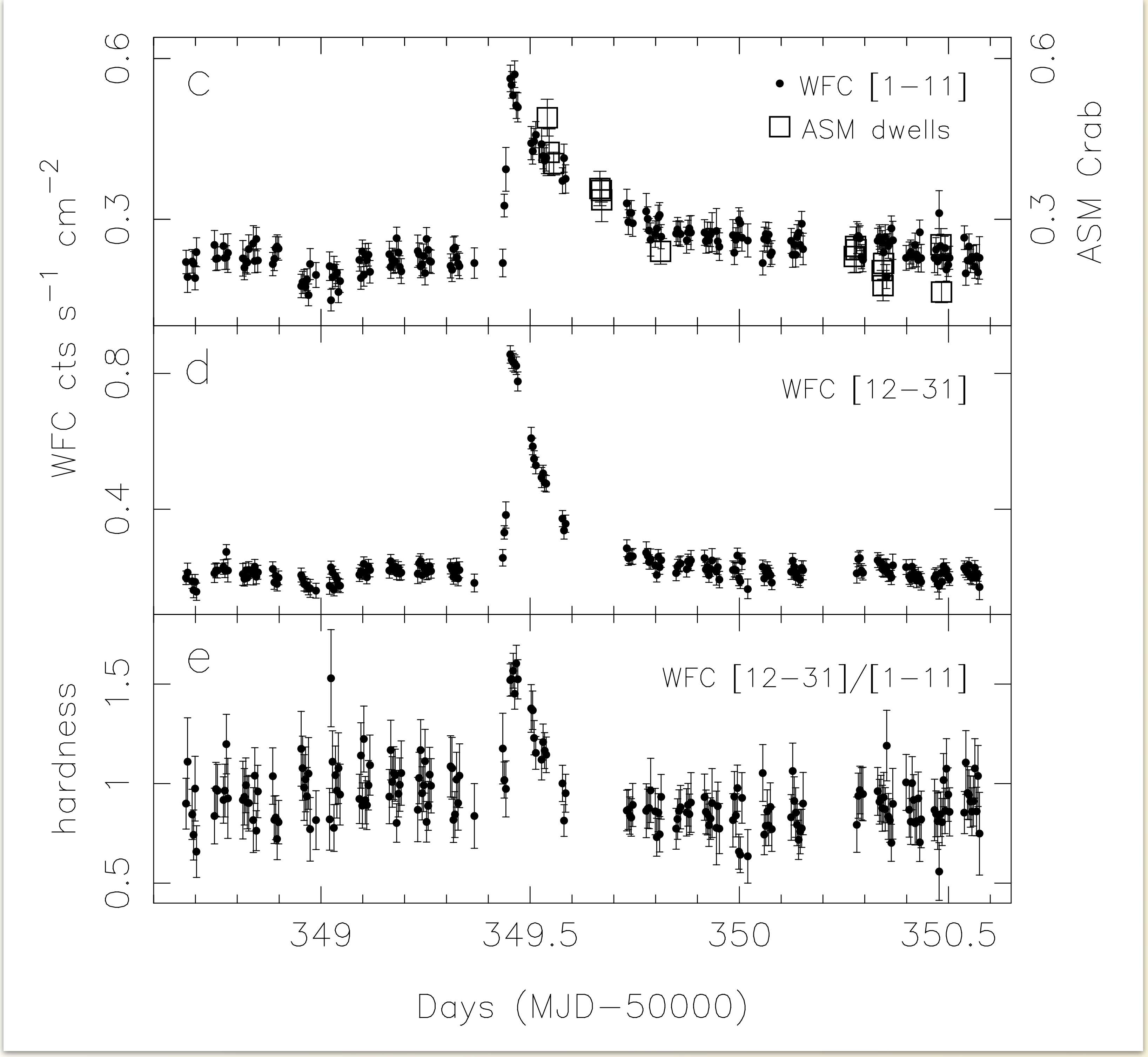
$$T_{\rm core} \approx 2 \times 10^8\,{\rm K} \left(\frac{\langle \dot{M} \rangle}{10^{-10}\, M_\odot\, {\rm yr}^{-1}} \right)^{1/8}$$

"slow" neutrino emissivity

$$T_{\rm core} \approx 2 \times 10^7\,{\rm K} \left(\frac{\langle \dot{M} \rangle}{10^{-10}\, M_\odot\, {\rm yr}^{-1}} \right)^{1/6}$$

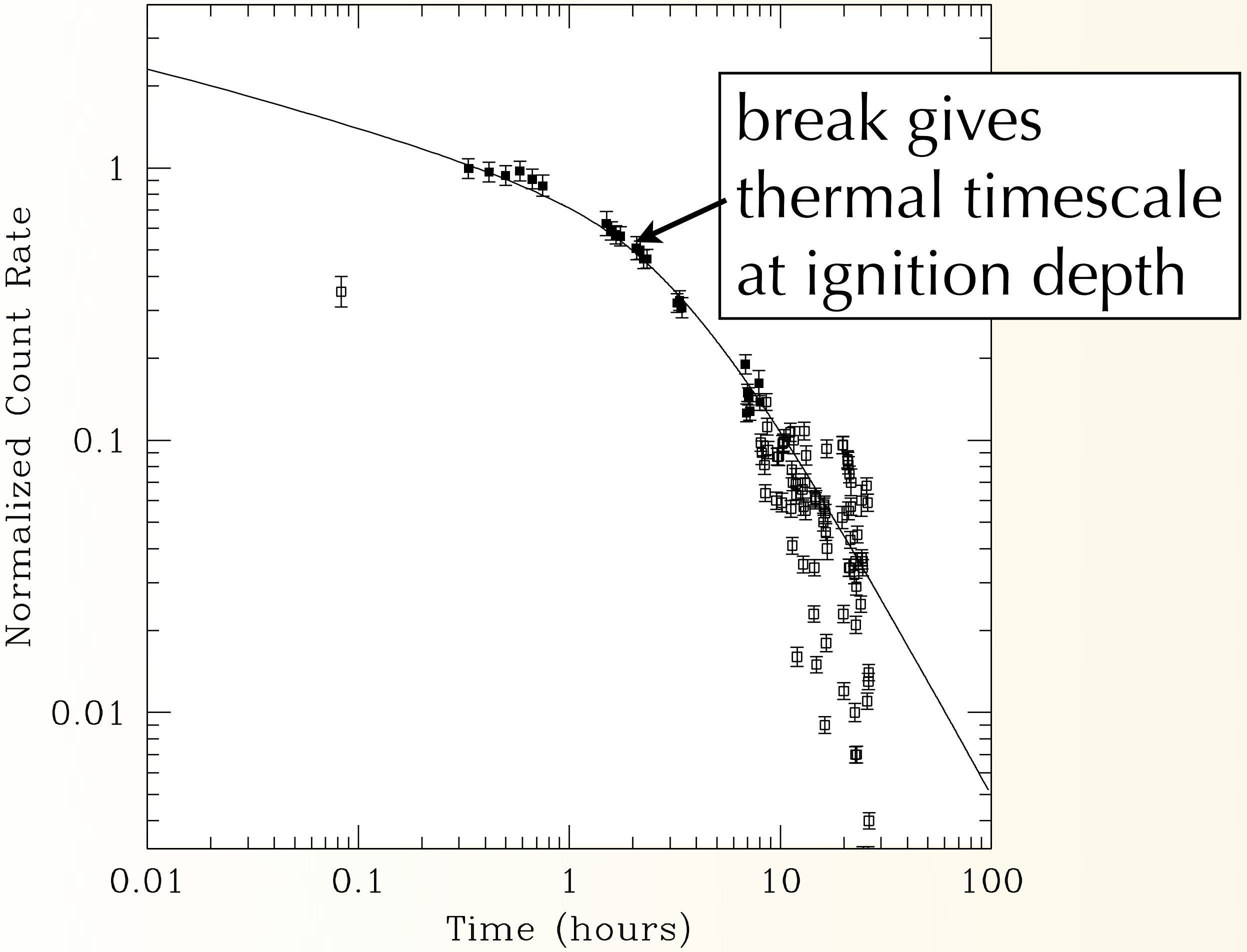
"fast" neutrino emissivity

KS 1731–260 superburst (Kuulkers 2002)



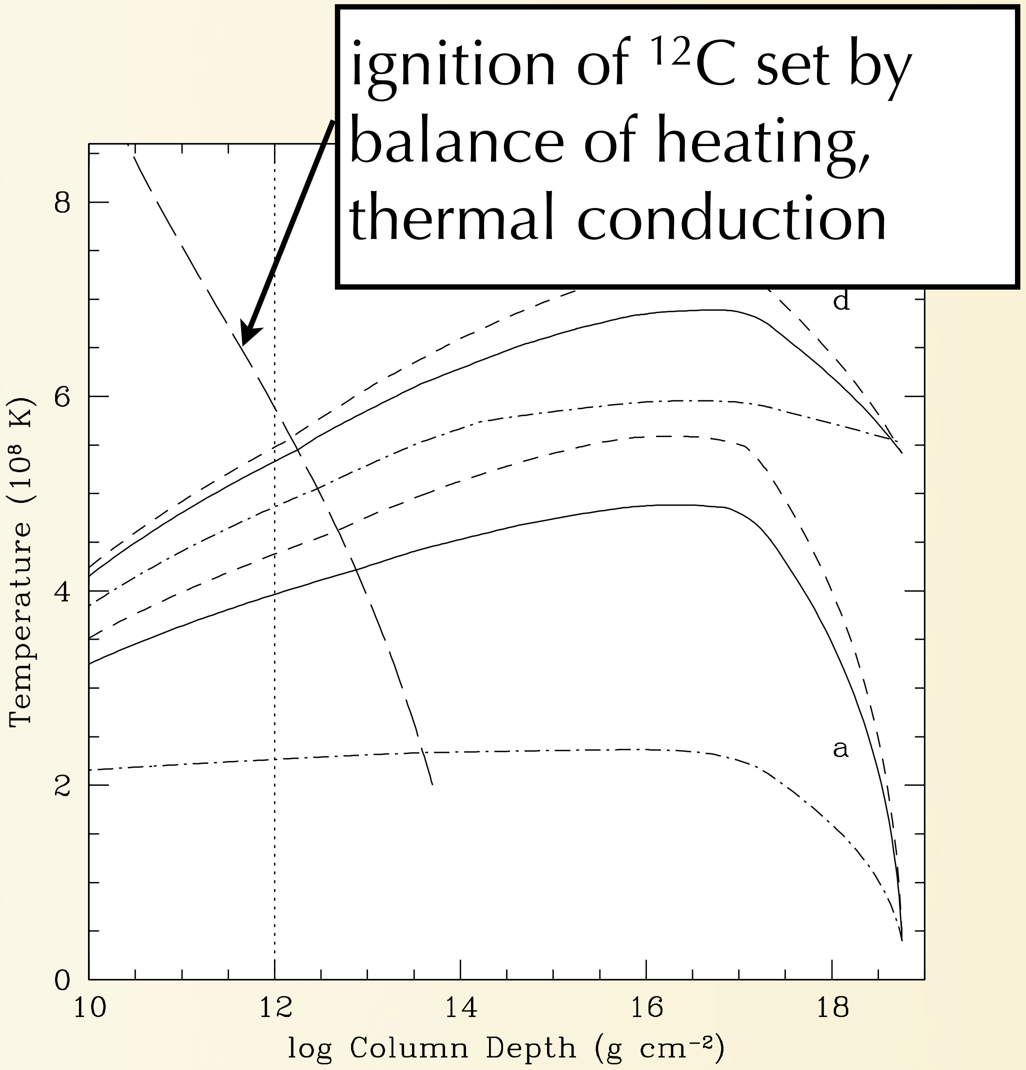
Superburst ignition wants a hot crust

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



break gives thermal timescale at ignition depth

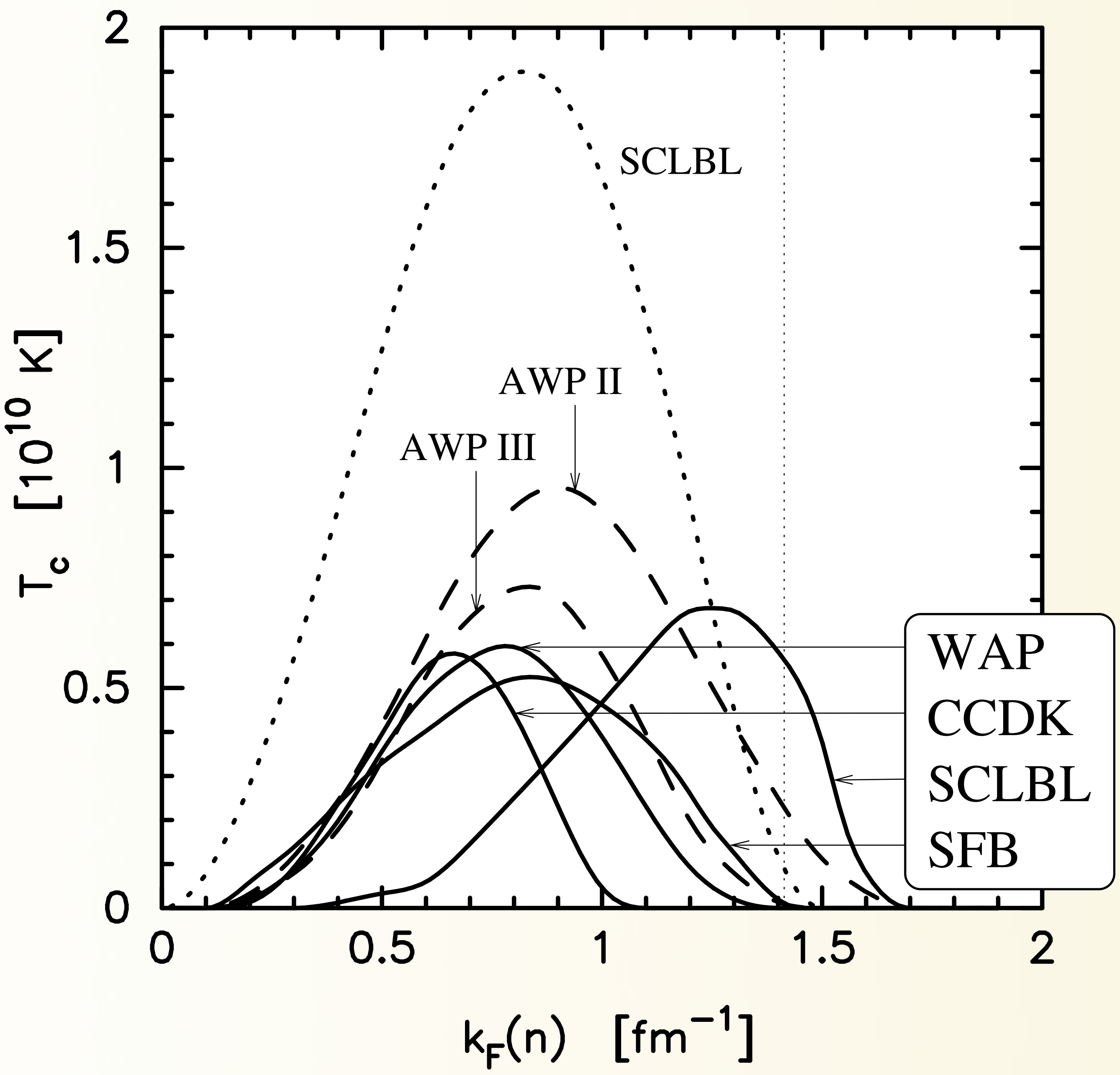
FIG. 5.— Fitted lightcurve for KS 1731-260, assuming the distance given in Table 1. Solid data points are included in the fit, open data points (with fluxes less than 0.1 of the peak flux) are not included.



ignition of ^{12}C set by balance of heating, thermal conduction

Plots from Cumming et al. 2006

$^1S_0$ Critical temperatures for n-matter

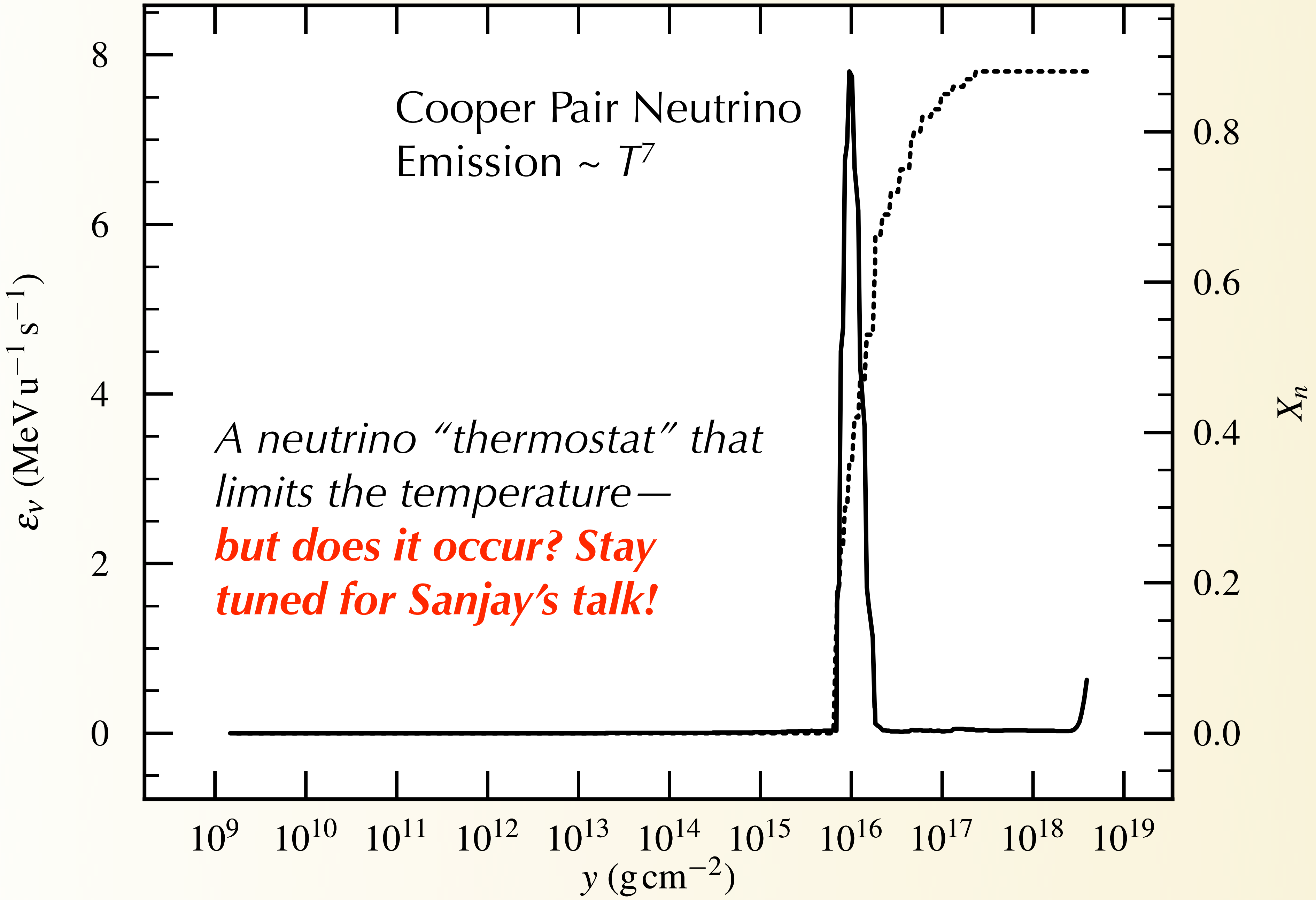


For $T < T_{\rm crit}$, formation & breaking of Cooper pairs emits neutrinos more efficiently than modified Urca

$$\rho\varepsilon_\nu \approx 10^{22} f(T/T_{\rm crit}) T_{\rm GK}^7 \,\mathrm{ergs\,cm^{-3}s^{-1}}$$

Compilation from Page et al. 2004

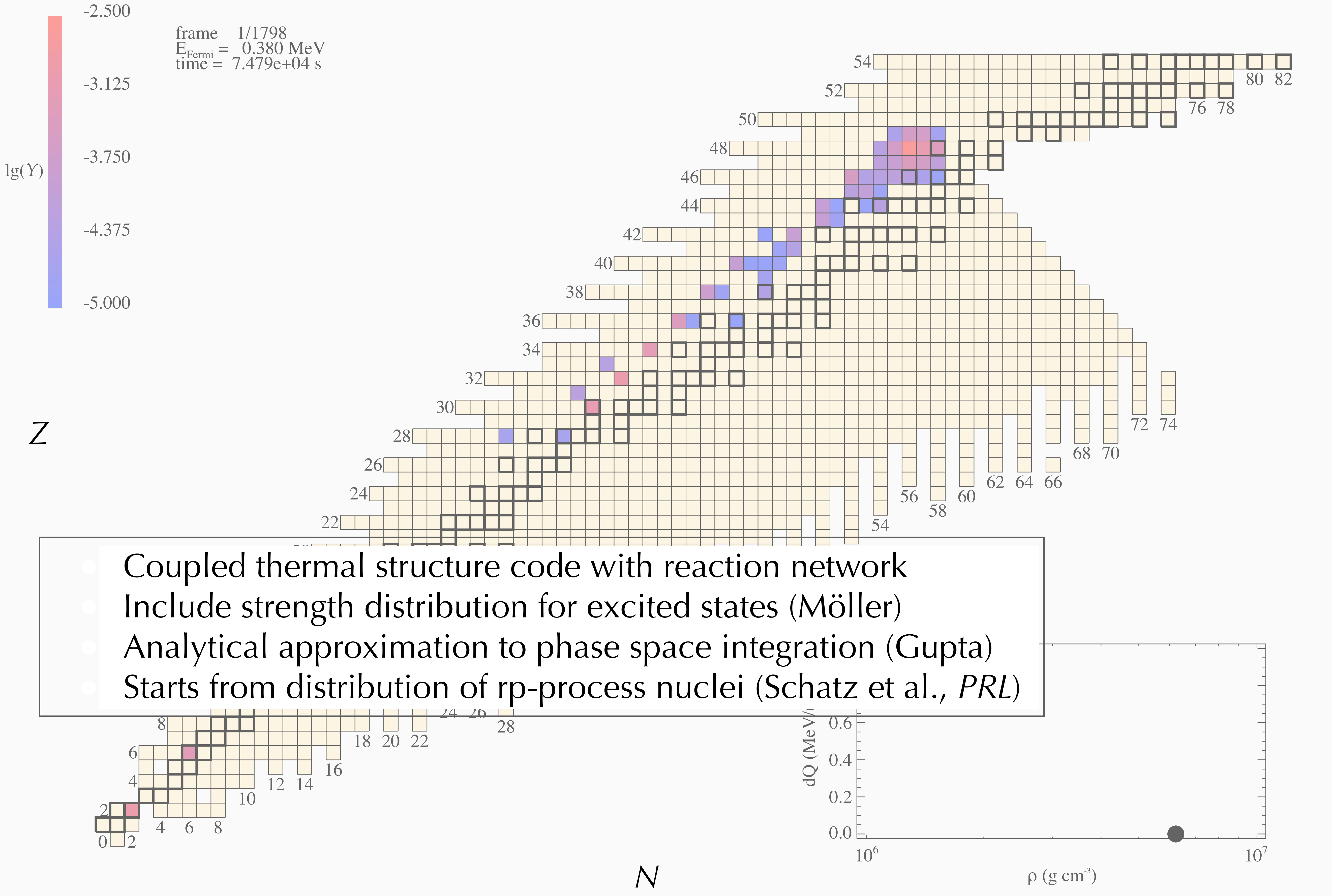
Neutrino emissivity in the crust



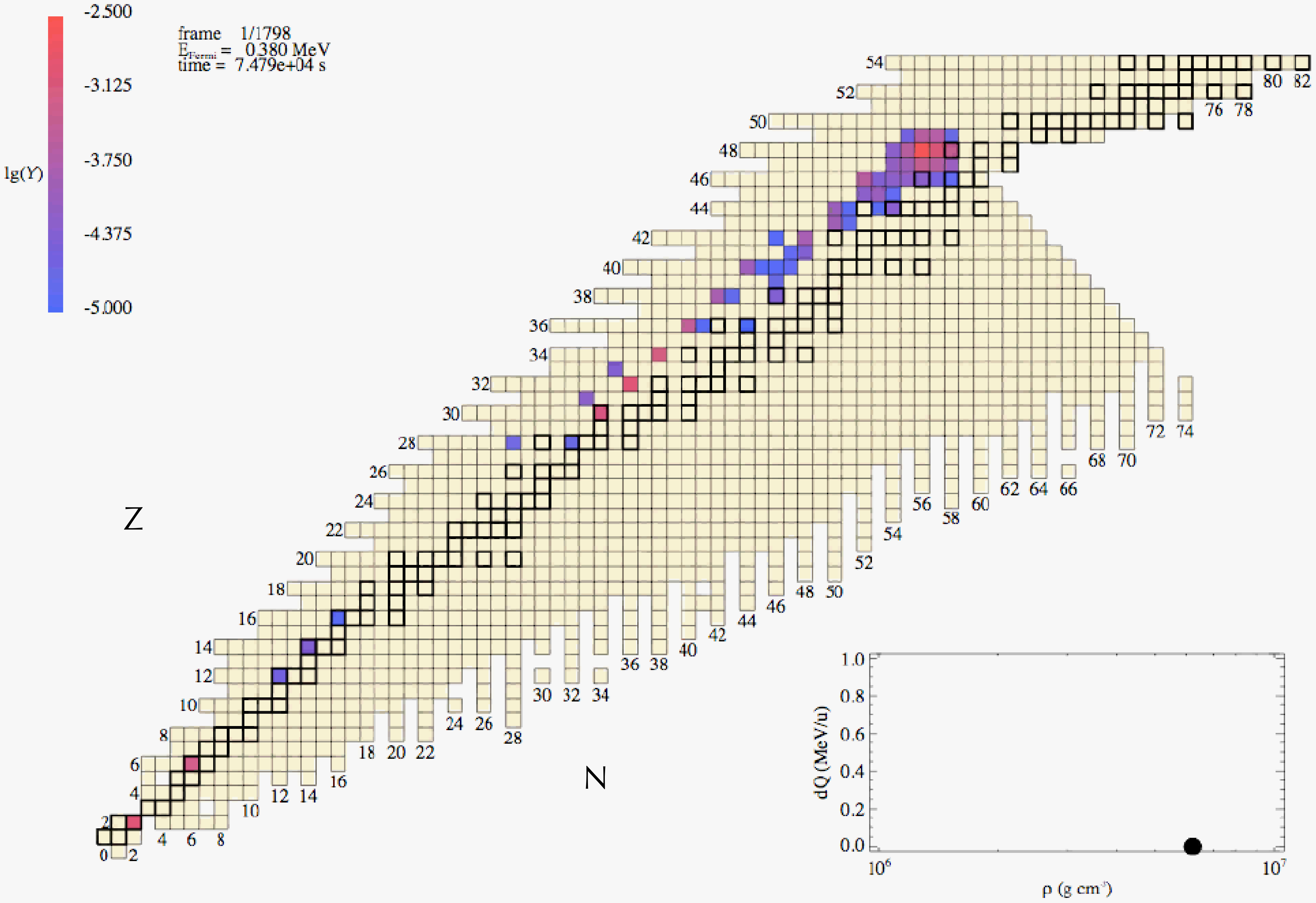
Cooper Pair Neutrino Emission ~ T^7

A neutrino “thermostat” that limits the temperature— ***but does it occur? Stay tuned for Sanjay’s talk!***

Gupta, Brown, Schatz, Möller, & Kratz (2007)



- Coupled thermal structure code with reaction network
- Include strength distribution for excited states (Möller)
- Analytical approximation to phase space integration (Gupta)
- Starts from distribution of rp-process nuclei (Schatz et al., *PRL*)


-2.500
-3.125
-3.750
-4.375
-5.000
lg(Y)
frame 1/1798
E_Fermi = 0.380 MeV
time = 7.479e+04 s
Z
N
54
52
50
48
46
44
42
40
38
36
34
32
30
28
26
24
22
20
18
16
14
12
10
8
6
4
2
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
32
34
36
38
40
42
44
46
48
50
52
54
56
58
60
62
64
66
68
70
72
74
76
78
80
82
dQ (MeV/u)
1.0
0.8
0.6
0.4
0.2
0.0
10^6
10^7
ρ (g cm^-3)

Composition set by rising Fermi energy

Consider the symmetry term in the mass fmla.,

$$\frac{E}{A} = \ldots + E_s\left(\frac{N-Z}{N+Z}\right)^2 = \ldots + E_s(1-2Y_e)^2.$$

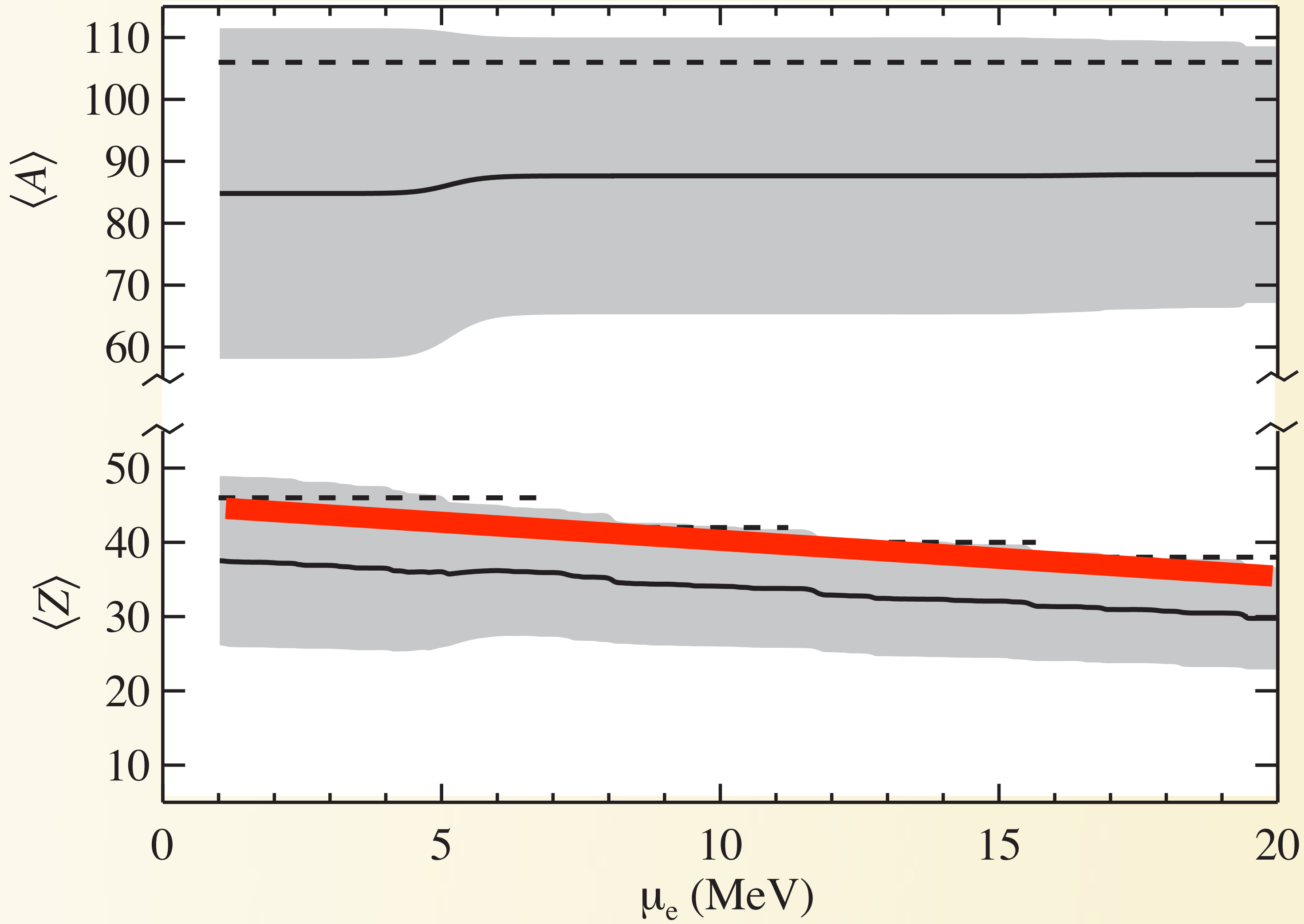
The electron Gibbs energy, per nucleon is

$$\frac{1}{n_b}(E+PV) = Y_e\mu_e$$

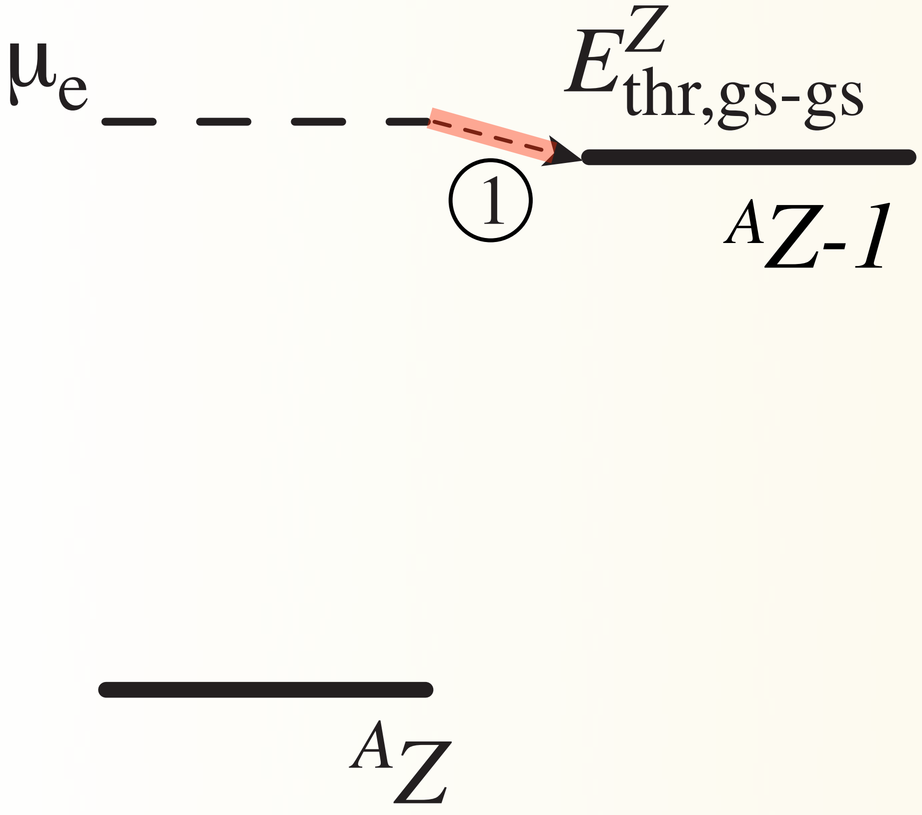
and minimizing the total energy with respect to Y_e gives

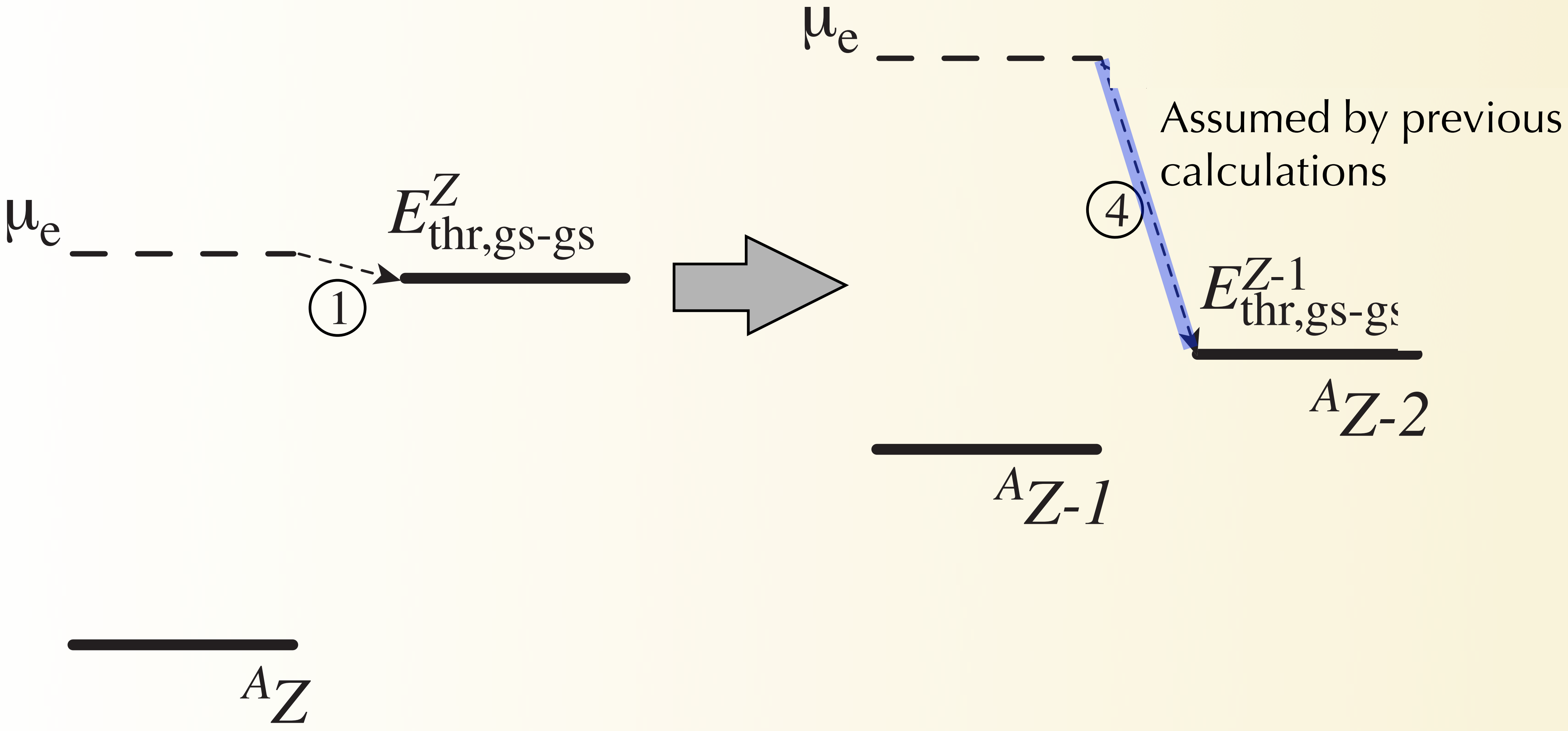
$$Y_e \approx \frac{1}{2} - \frac{\mu_e}{8E_s}.$$

NB. This fmla. also follows from $\mu_\mathrm{e} = \mu_\mathrm{n} - \mu_\mathrm{p}$

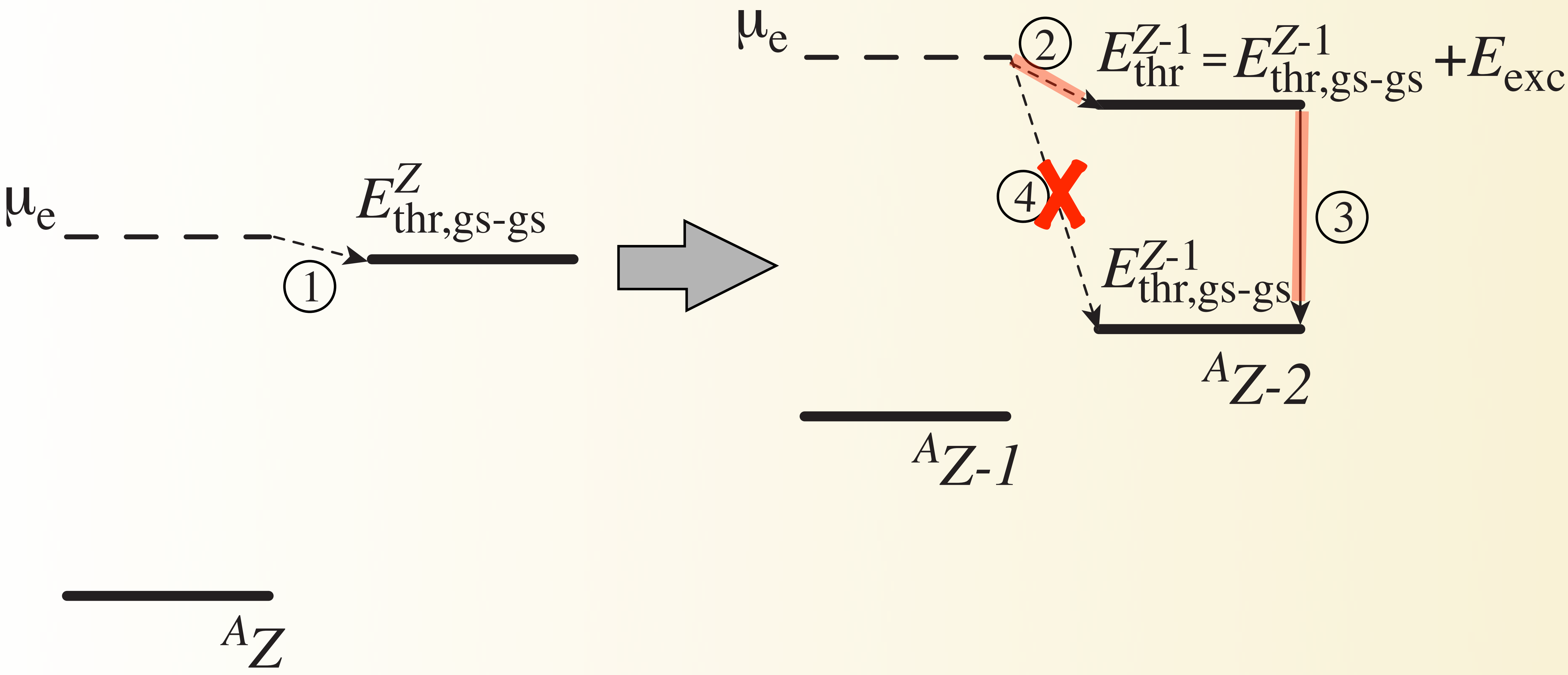


$\mu_e \propto P^{1/4}$

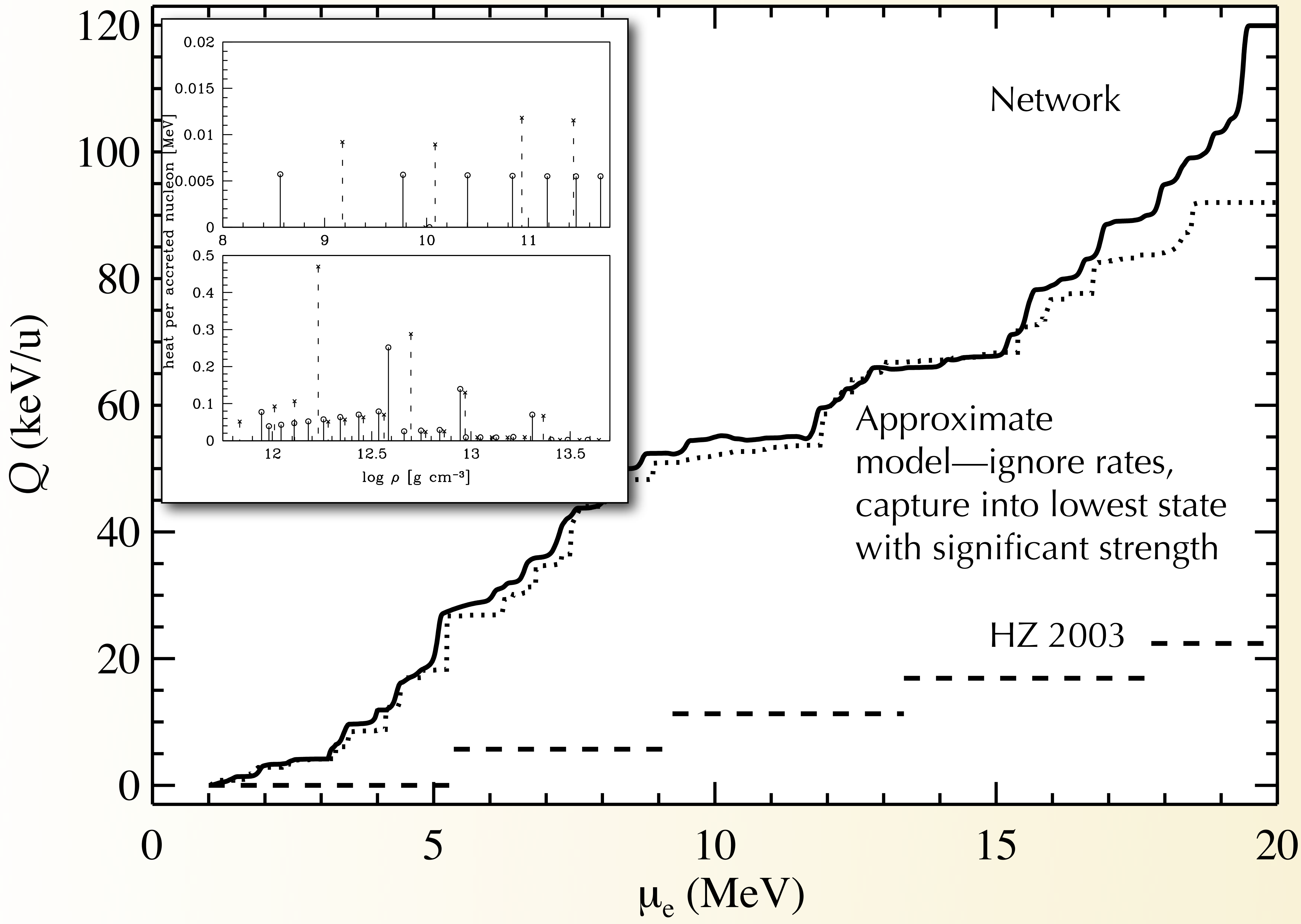




Assumed by previous calculations

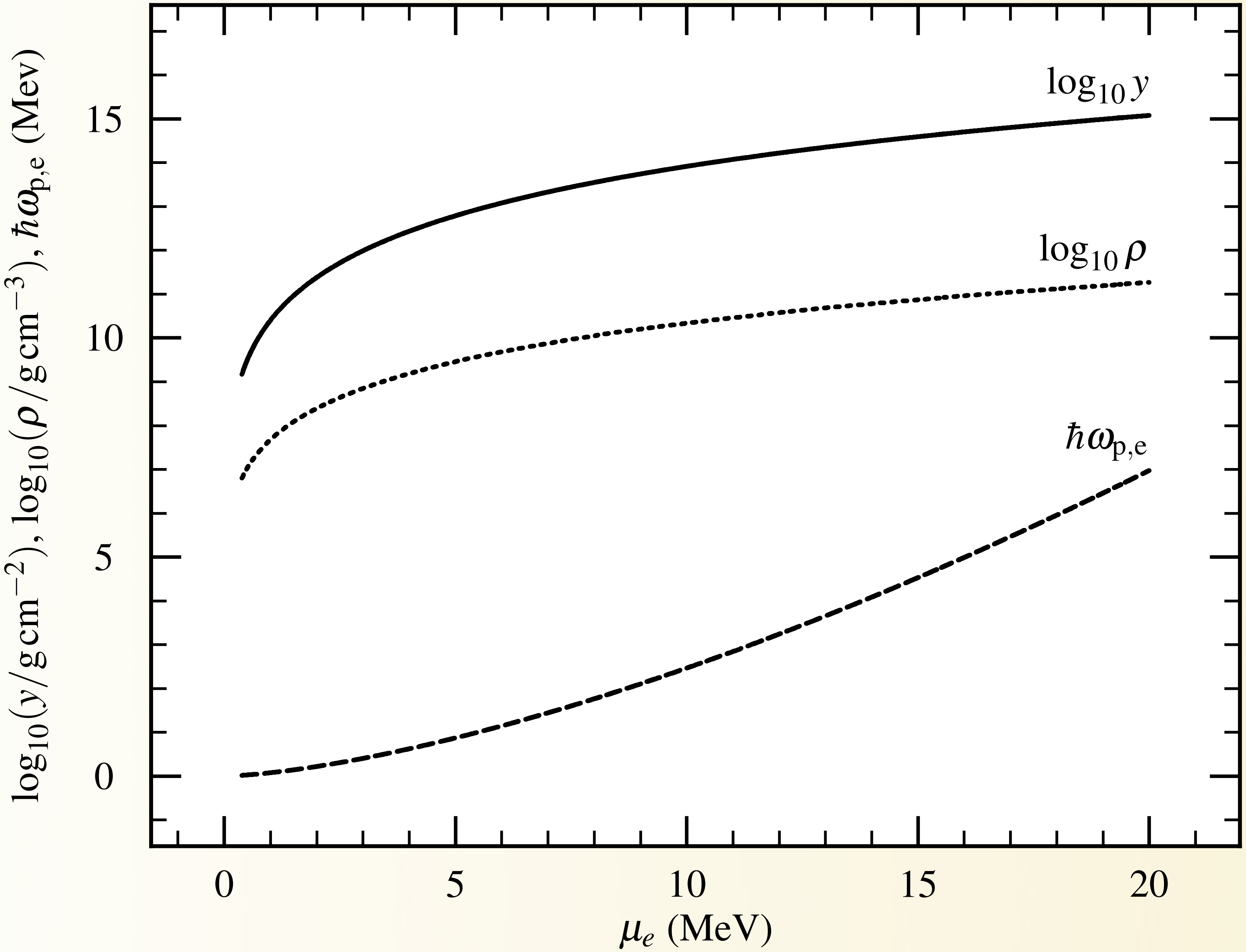

μ_e
①
$E^{Z}_{\text{thr,gs-gs}}$
^{A}Z
μ_e
②
$E^{Z\text{-}1}_{\text{thr}} = E^{Z\text{-}1}_{\text{thr,gs-gs}} + E_{\text{exc}}$
④
③
$E^{Z\text{-}1}_{\text{thr,gs-gs}}$
$^{A}Z\text{-}2$
$^{A}Z\text{-}1$

With captures into excited states

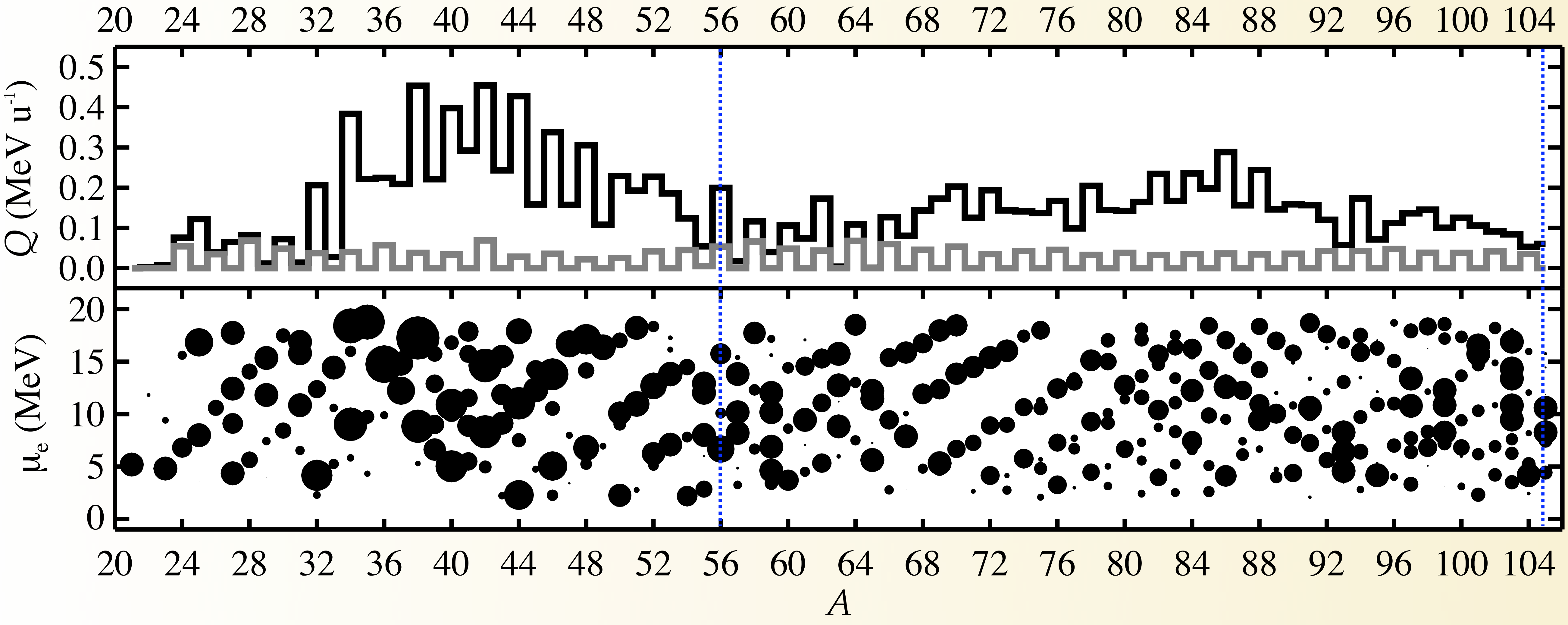


Approximate model—ignore rates, capture into lowest state with significant strength

Path to neutron drip

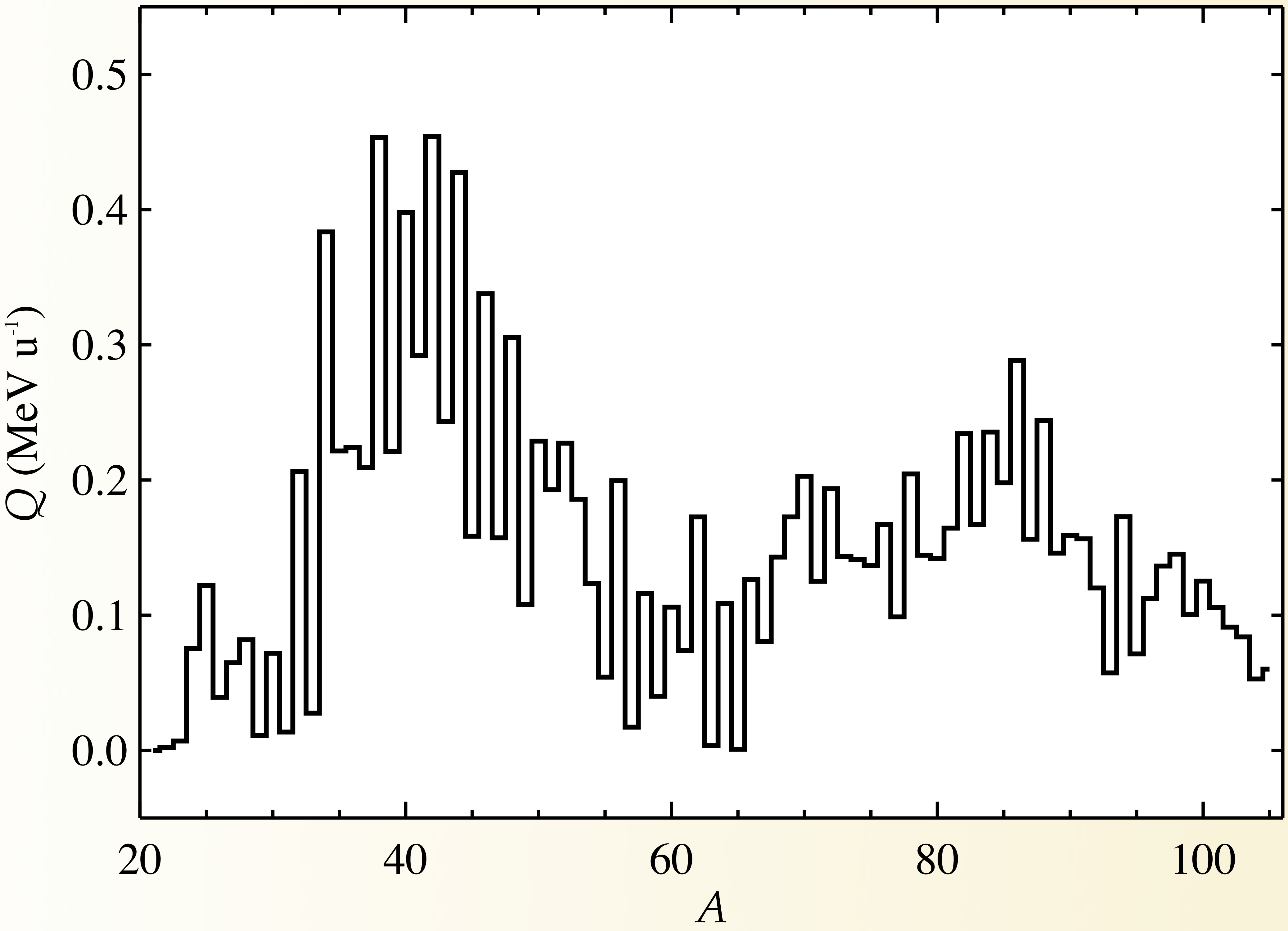


Electron capture reactions, outer crust

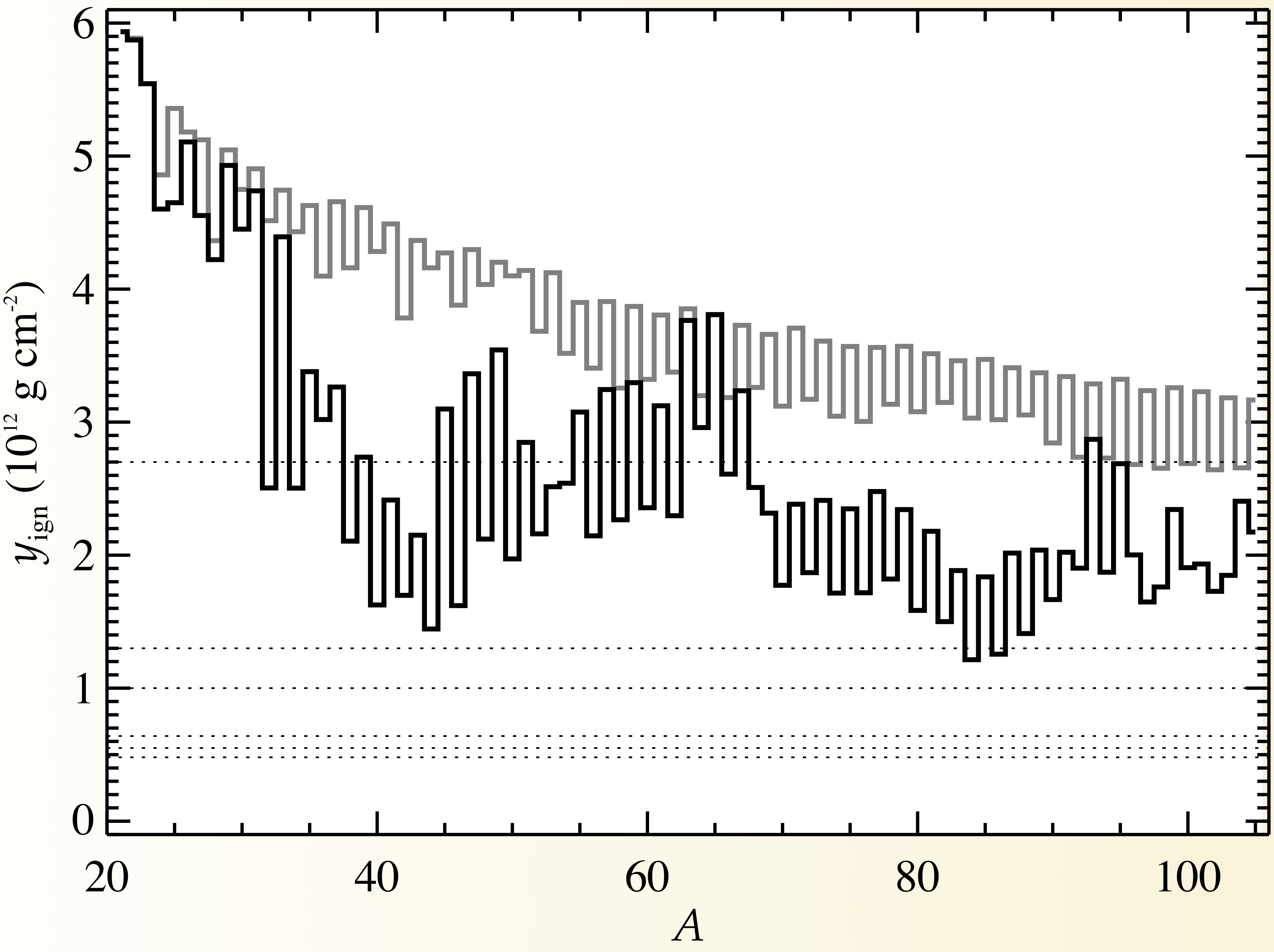


Composition matters!

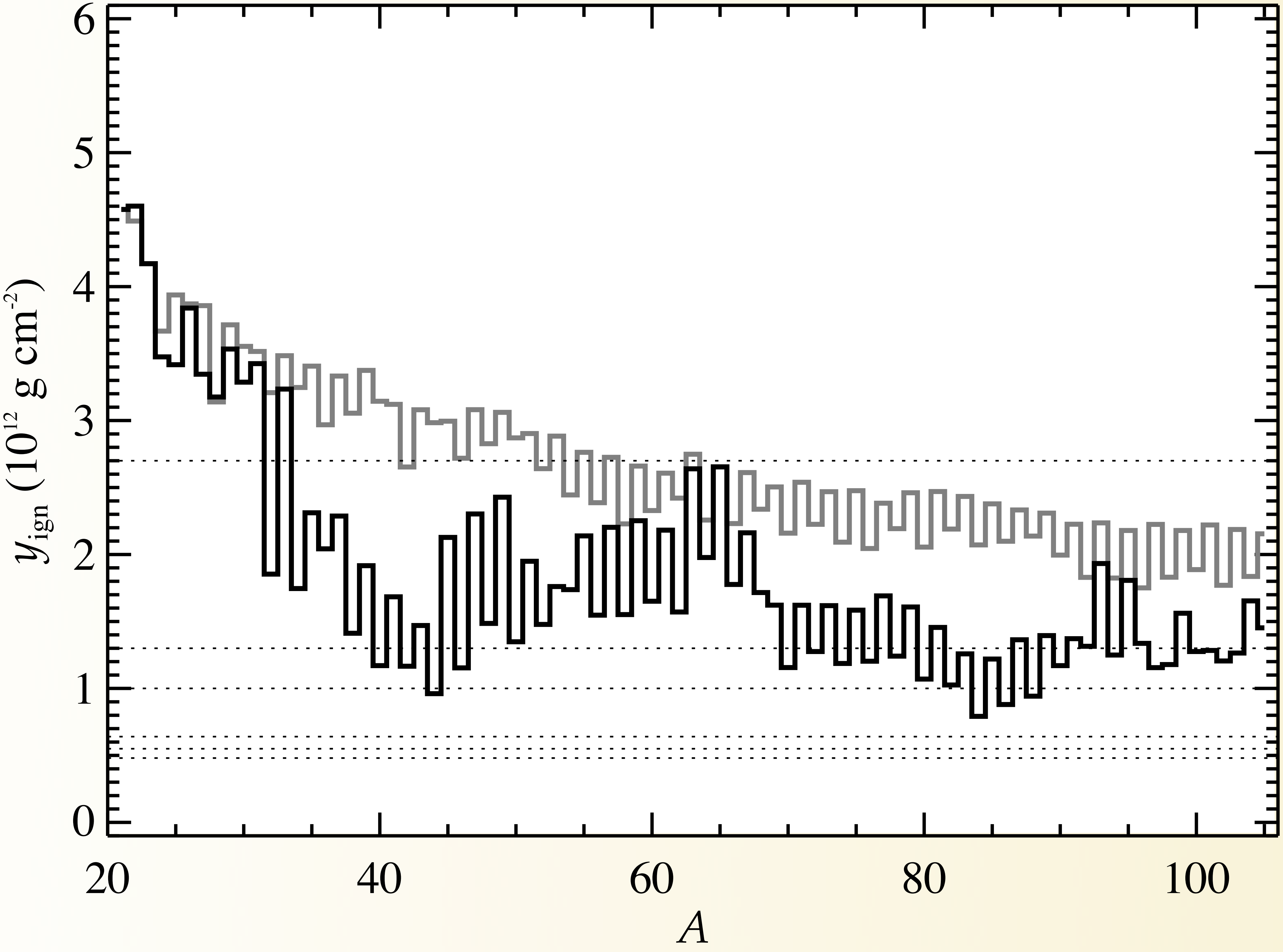
Total heat deposited into outer crust



Ignition column

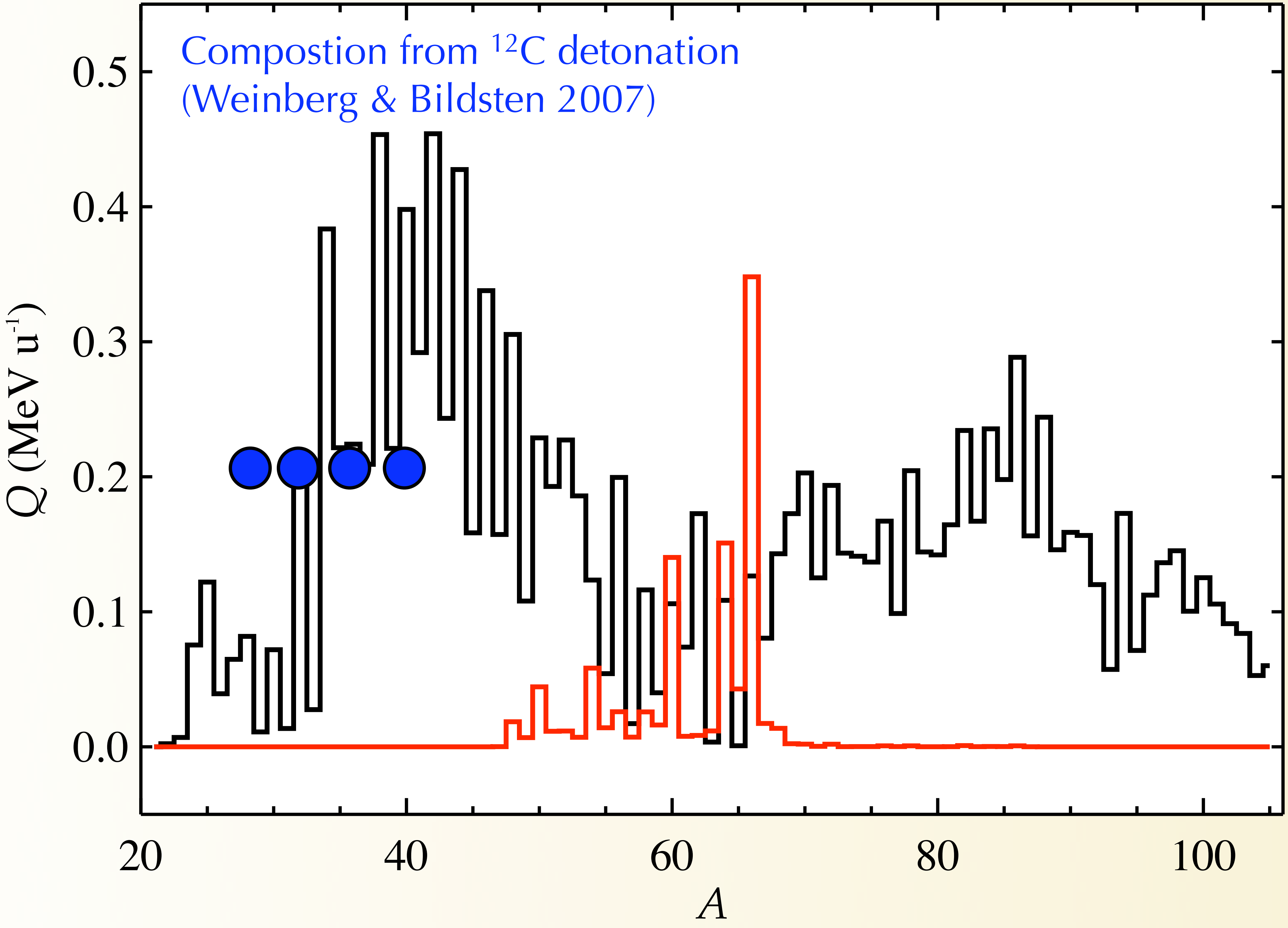


Ignition column—Cooper pairing suppressed

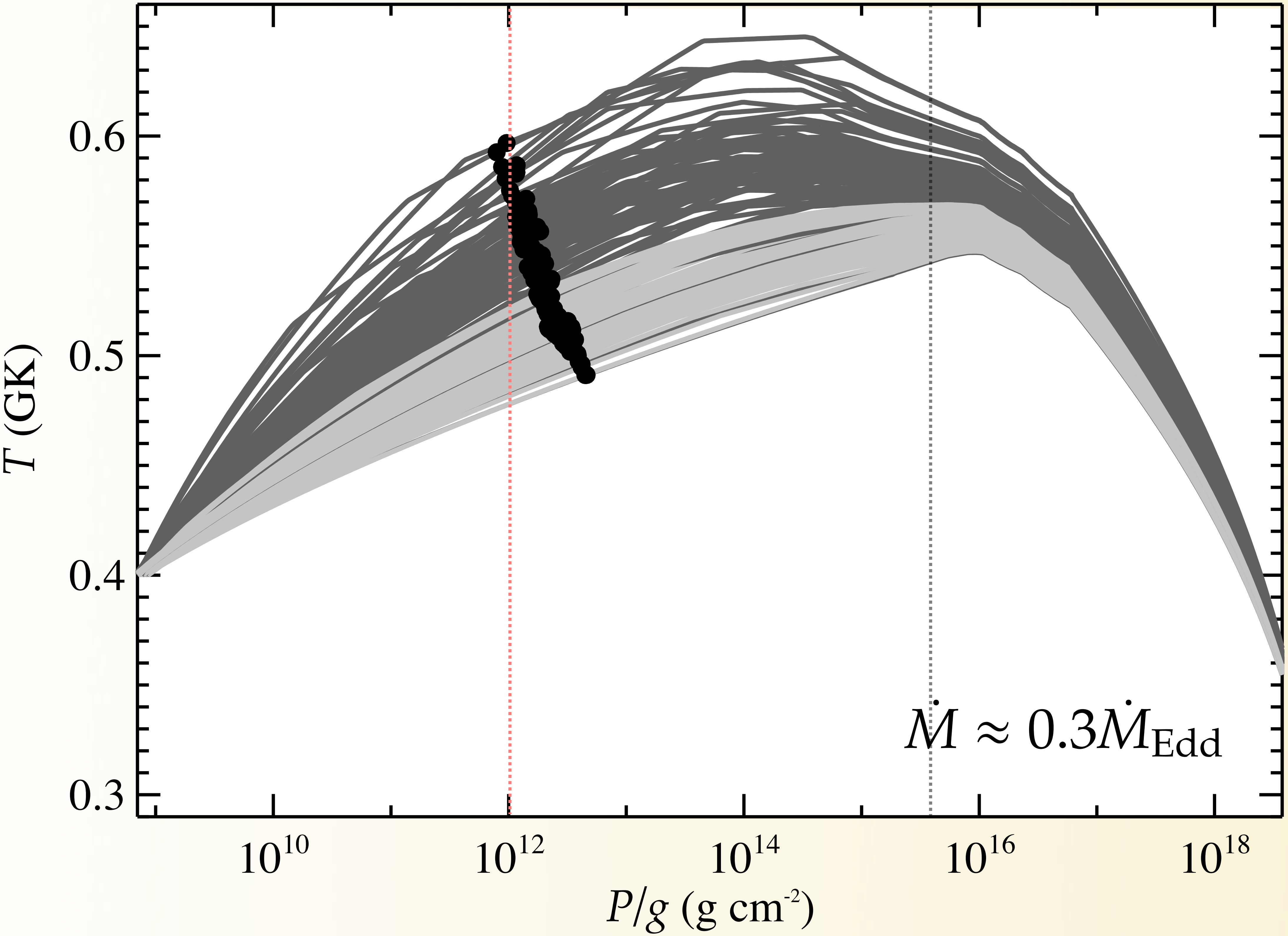


With superburst ashes (dissociation of rp-process material)

Composition from Schatz, Bildsten & Cumming (2003)



Variation of crust temperature–no Cooper



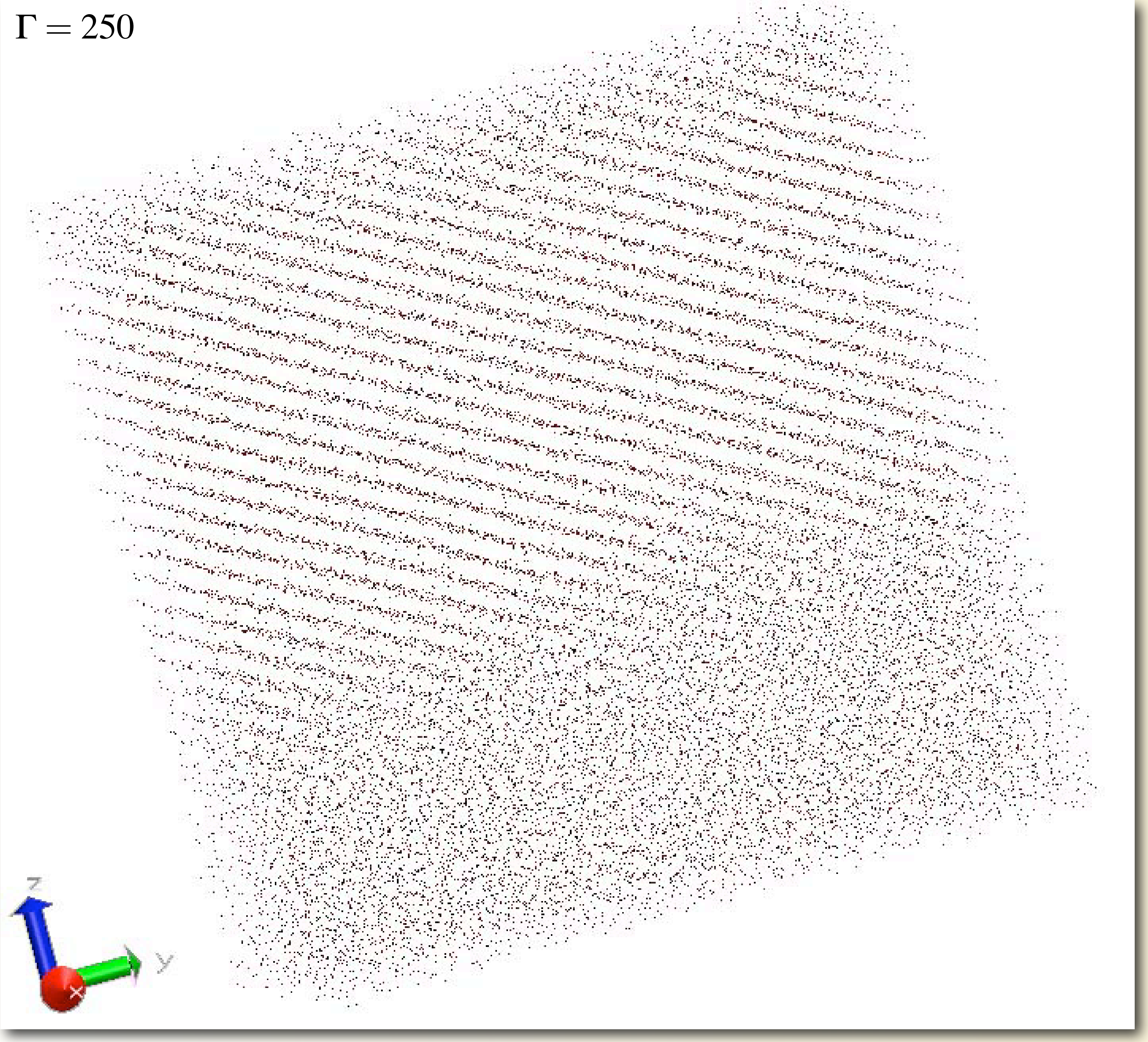
An Amorphous Crust

- Crust unlikely to be a pure lattice
  - Different phases of nuclear matter may coexist in inner crust (Magierski & Heenan 2002)
  - Fluctuations in composition during cooling from birth (Jones 2004)
  - Distribution of isotopes from burning of H, He
- Estimate relaxation time by setting structure factor to unity (as for a liquid)

$$\tau_{\mathrm{amp}}^{-1} \approx \frac{4\pi e^4}{p_{\mathrm{F}}^2 v_{\mathrm{F}}} \rho N_{\mathrm{A}} \Lambda \langle Z^2 \rangle$$

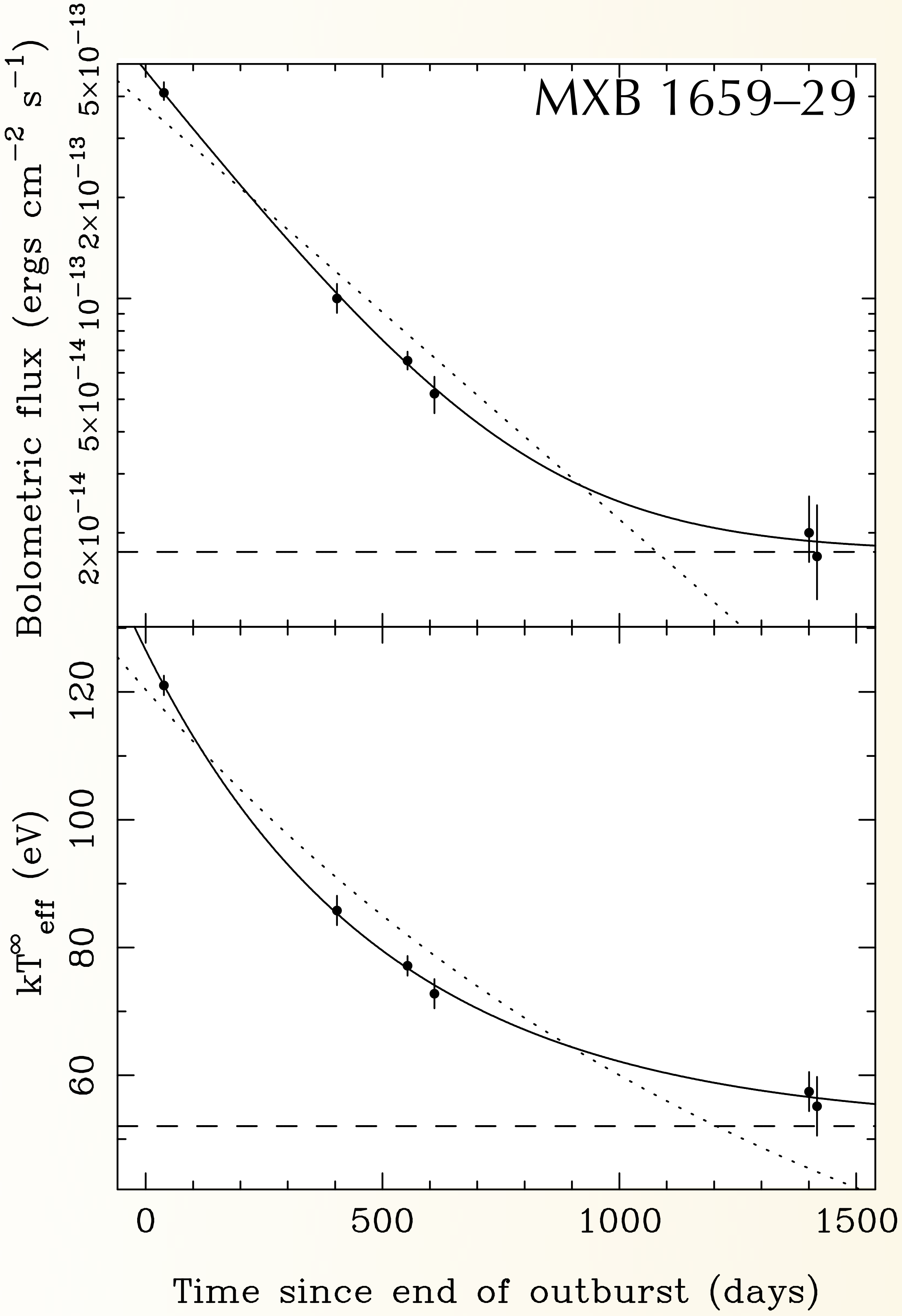
- Cf. estimate of Jones (2004, *PRL*)
- Neglects phonon transport, transport by superfluid protons
  - May be important in the inner crust

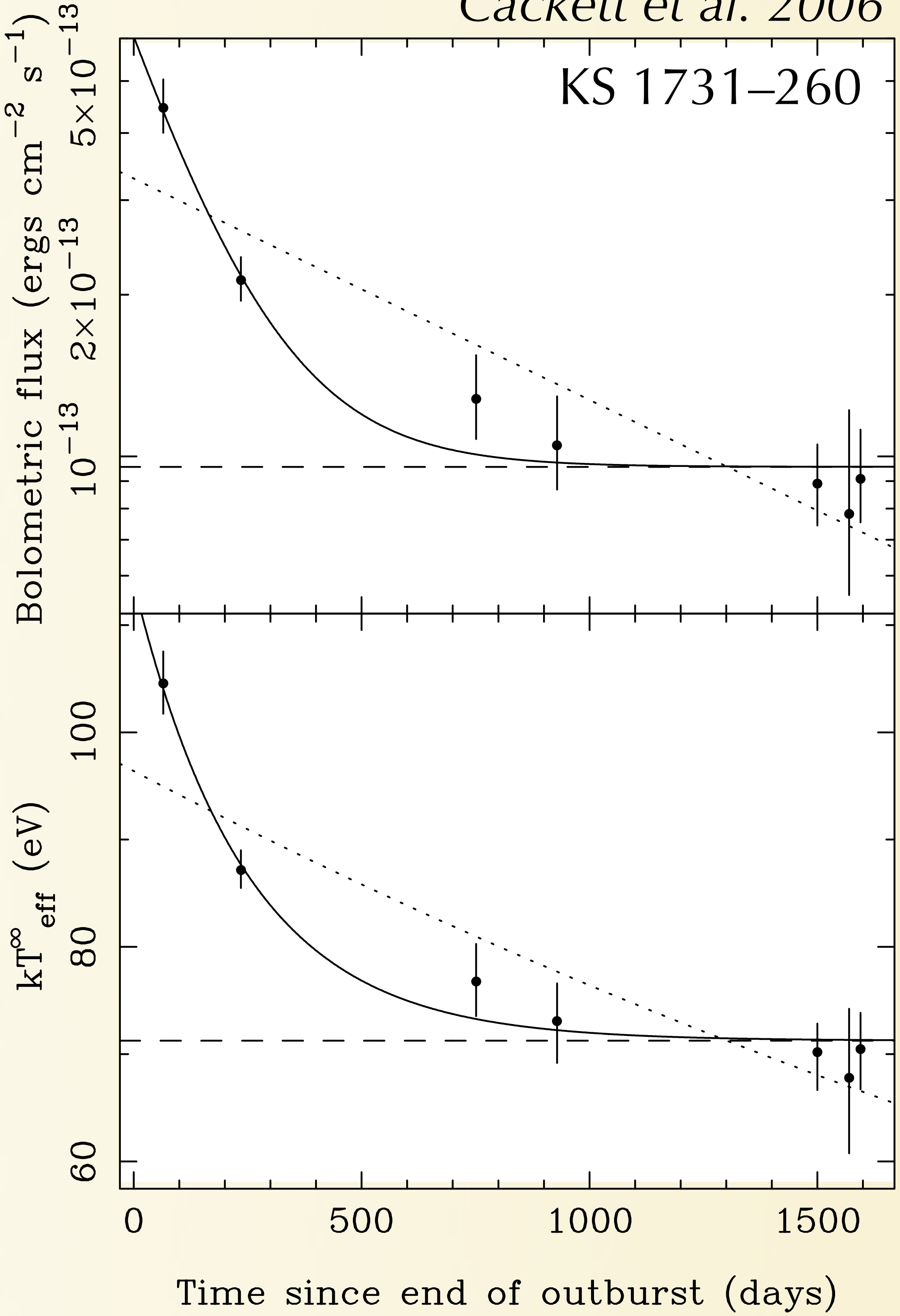
Horowitz, Berry, & Brown 2007



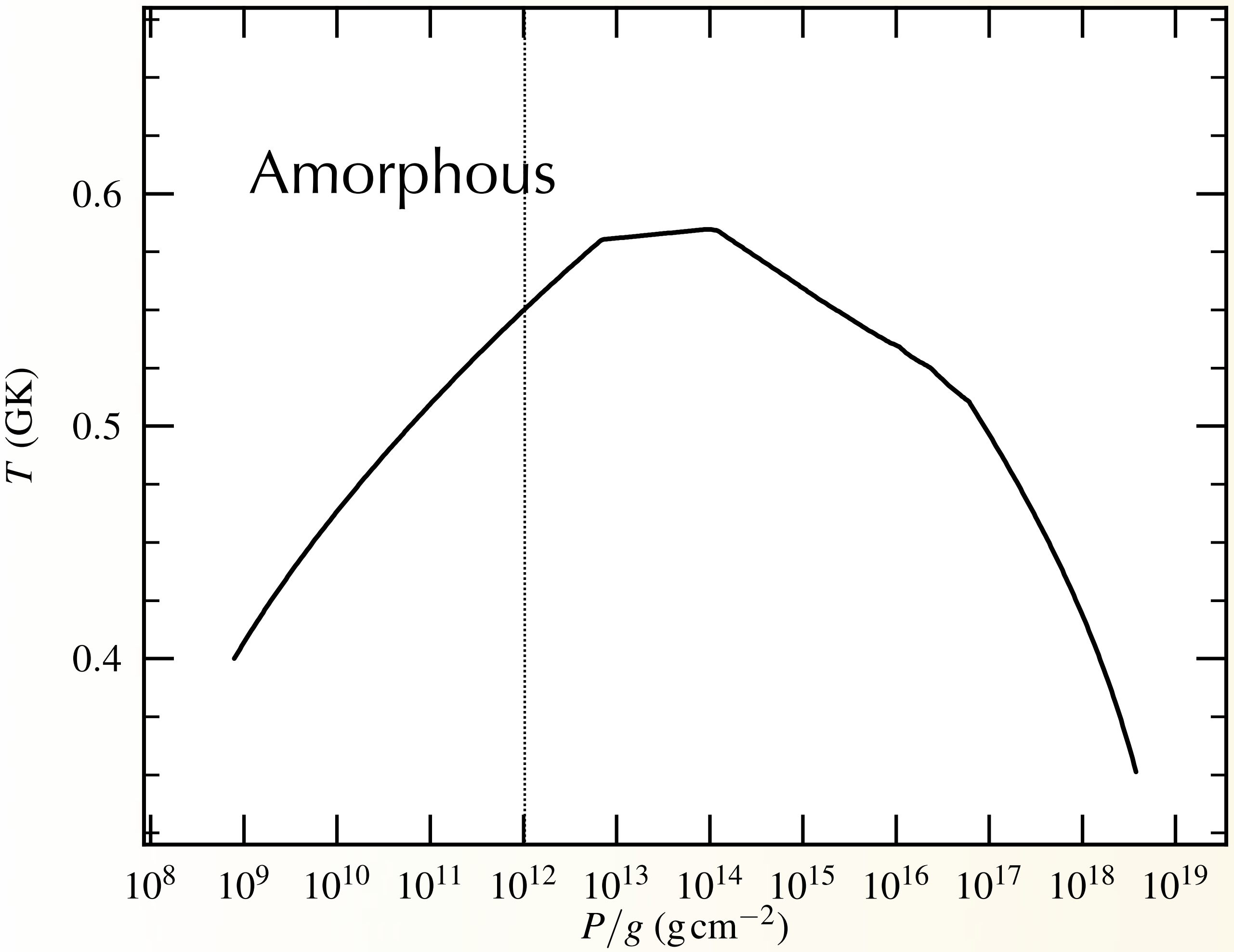
Crust cooling observed!

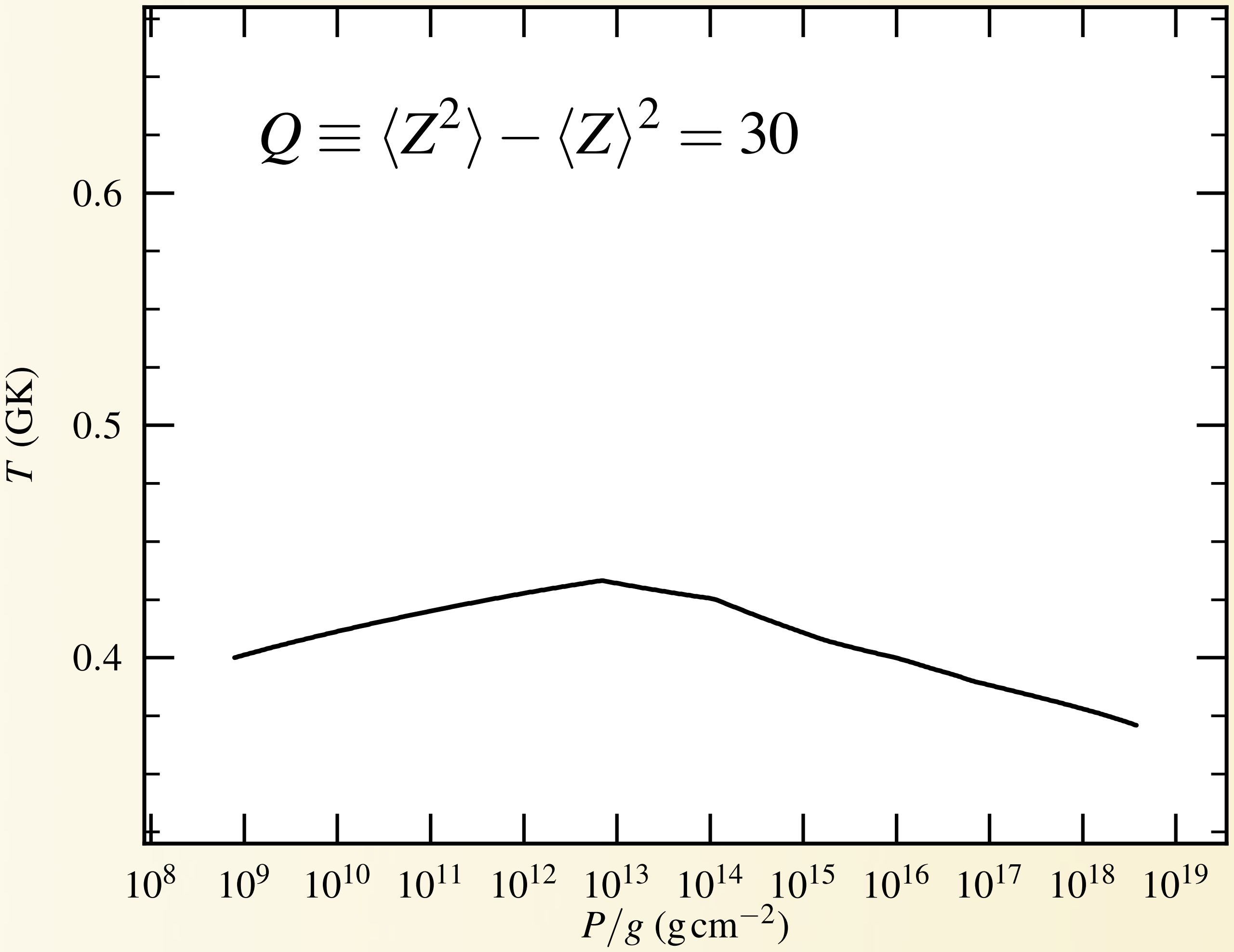
Cackett et al. 2006





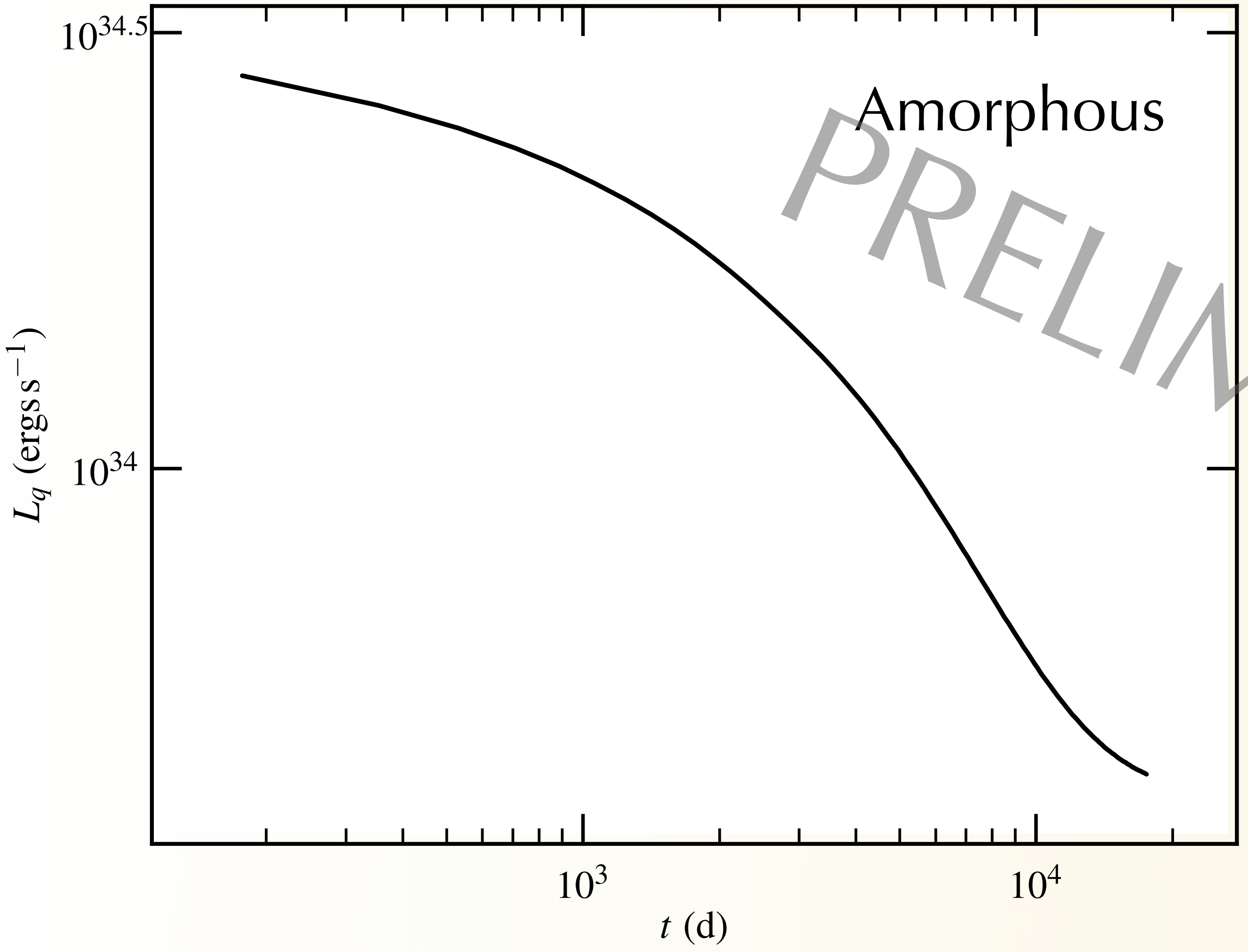
Impact of thermal conductivity

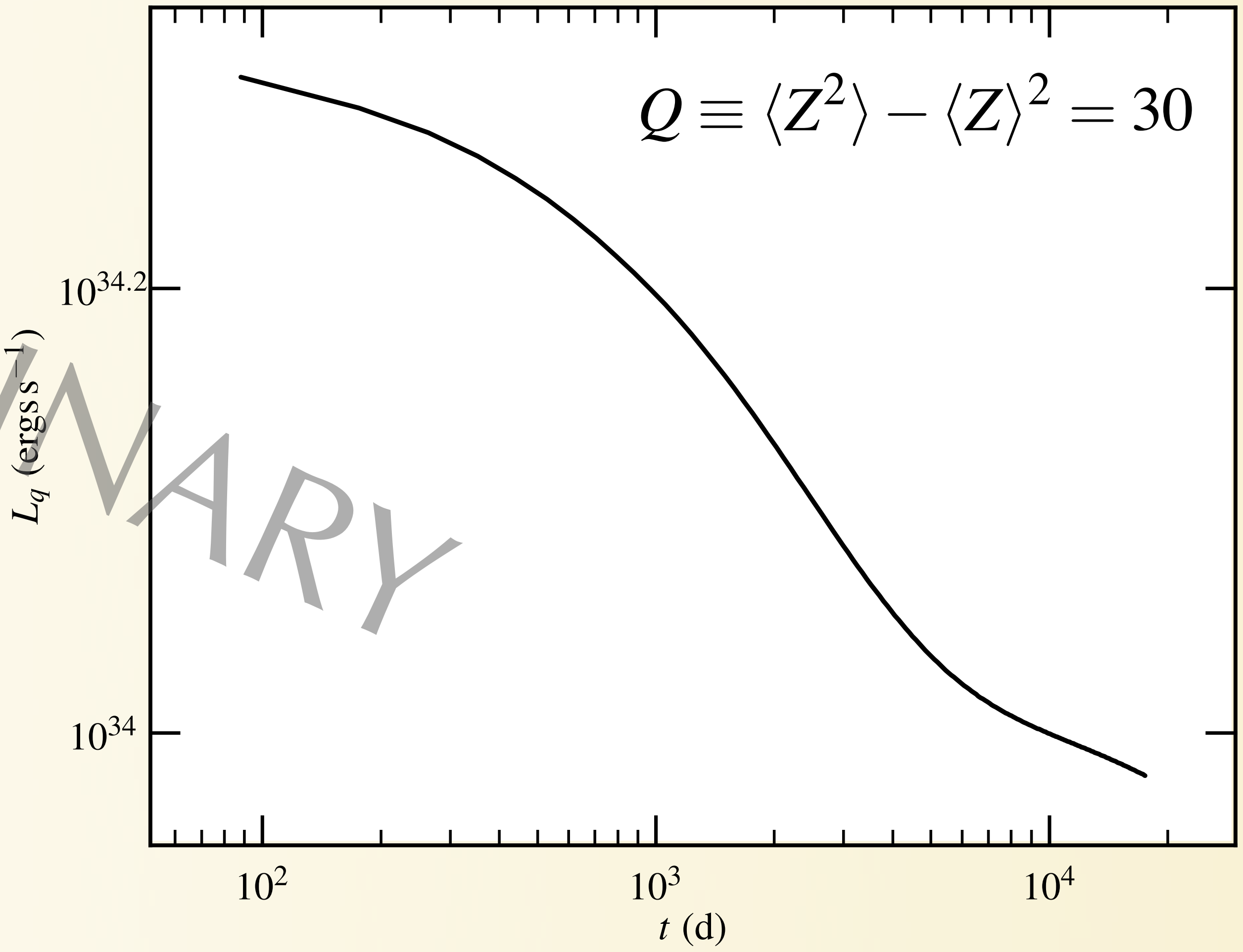




Important! What is the thermal conductivity of pasta?

Compare with cooling timescale

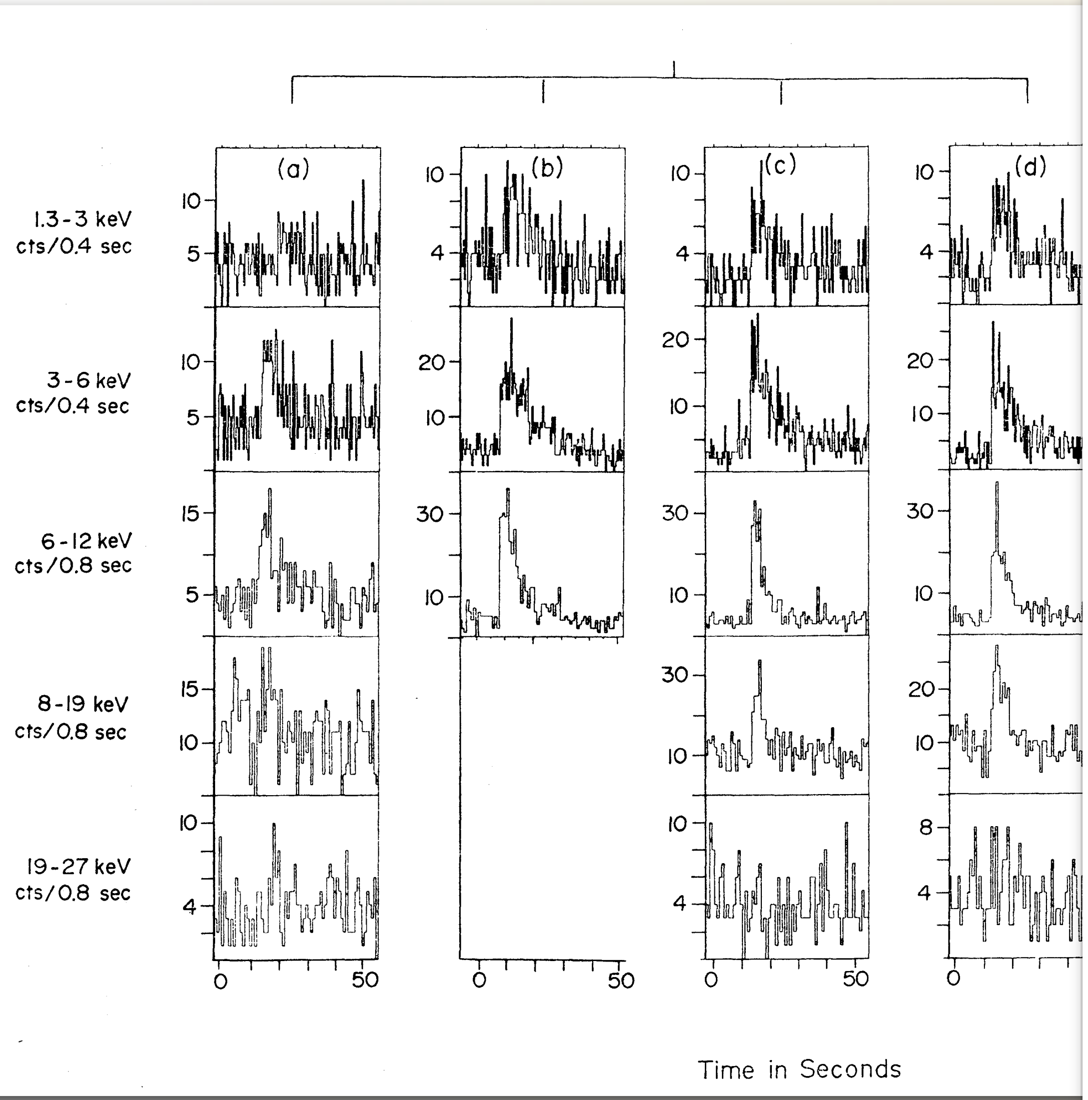




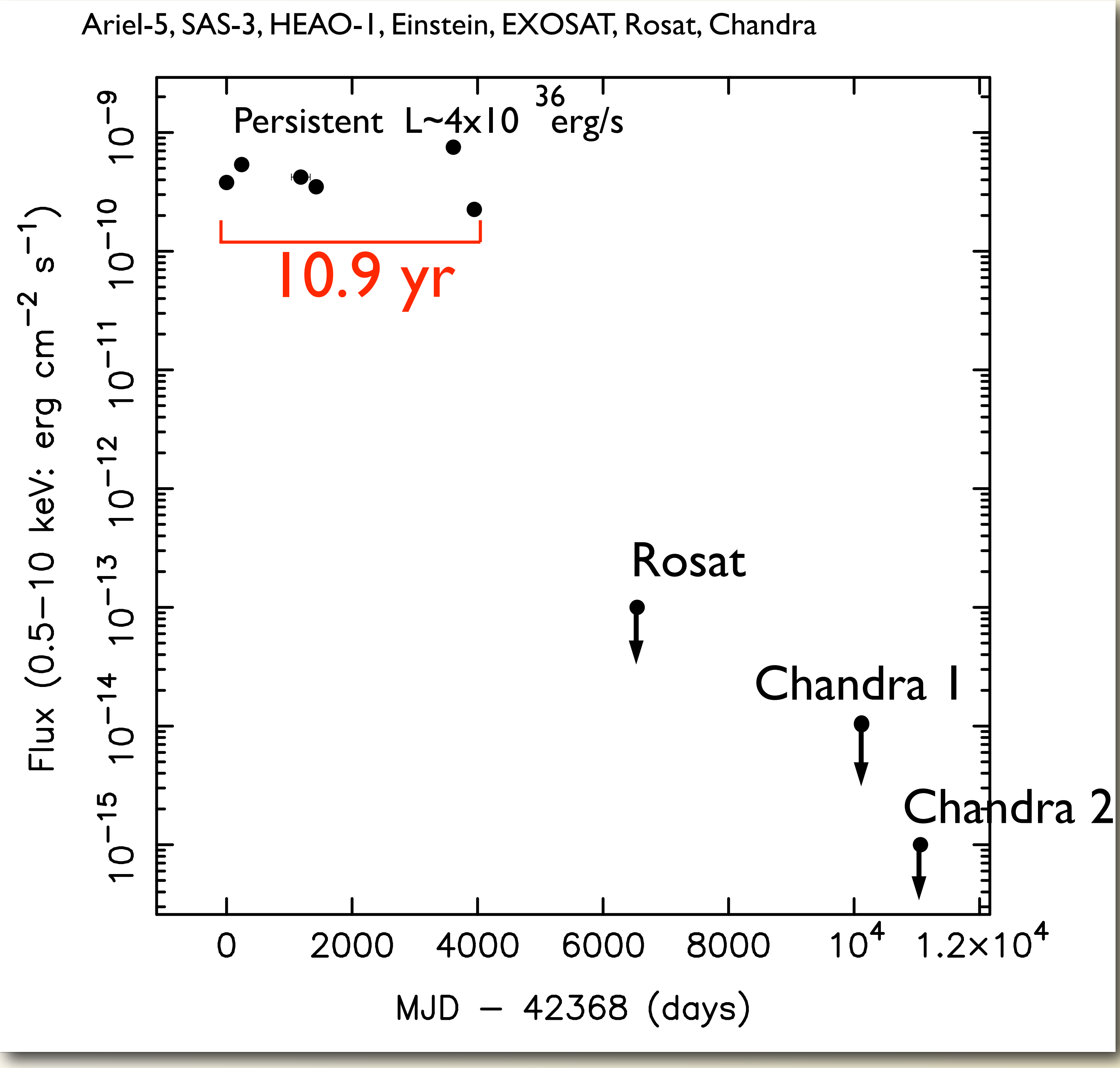
Brown, Degenaar, Steiner, in preparation; cf. Lattimer et al. 1994

1H 1905+000

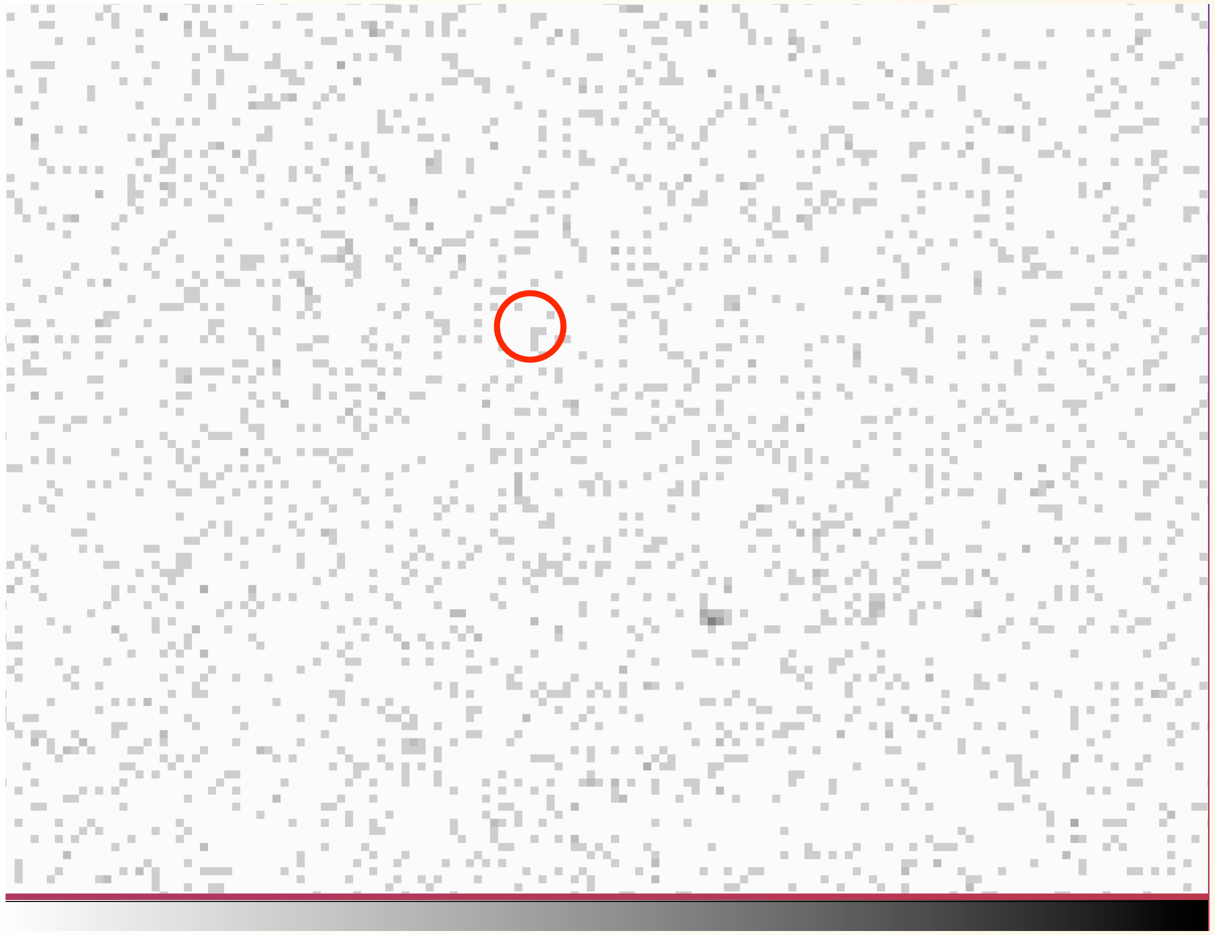
Jonker et al. 2006



X-ray bursts—it is a neutron star
Lewin et al. 1976



The $3,000,000 photon!



From a 300 ks *Chandra* observation (Jonker, Steeghs, Chakrabarty, et al. in prep.), 95% confidence upper limit:

$$L_X < 2 \times 10^{30}\,\mathrm{ergs\,s^{-1}} \left(\frac{d}{10\,\mathrm{kpc}}\right)^2$$

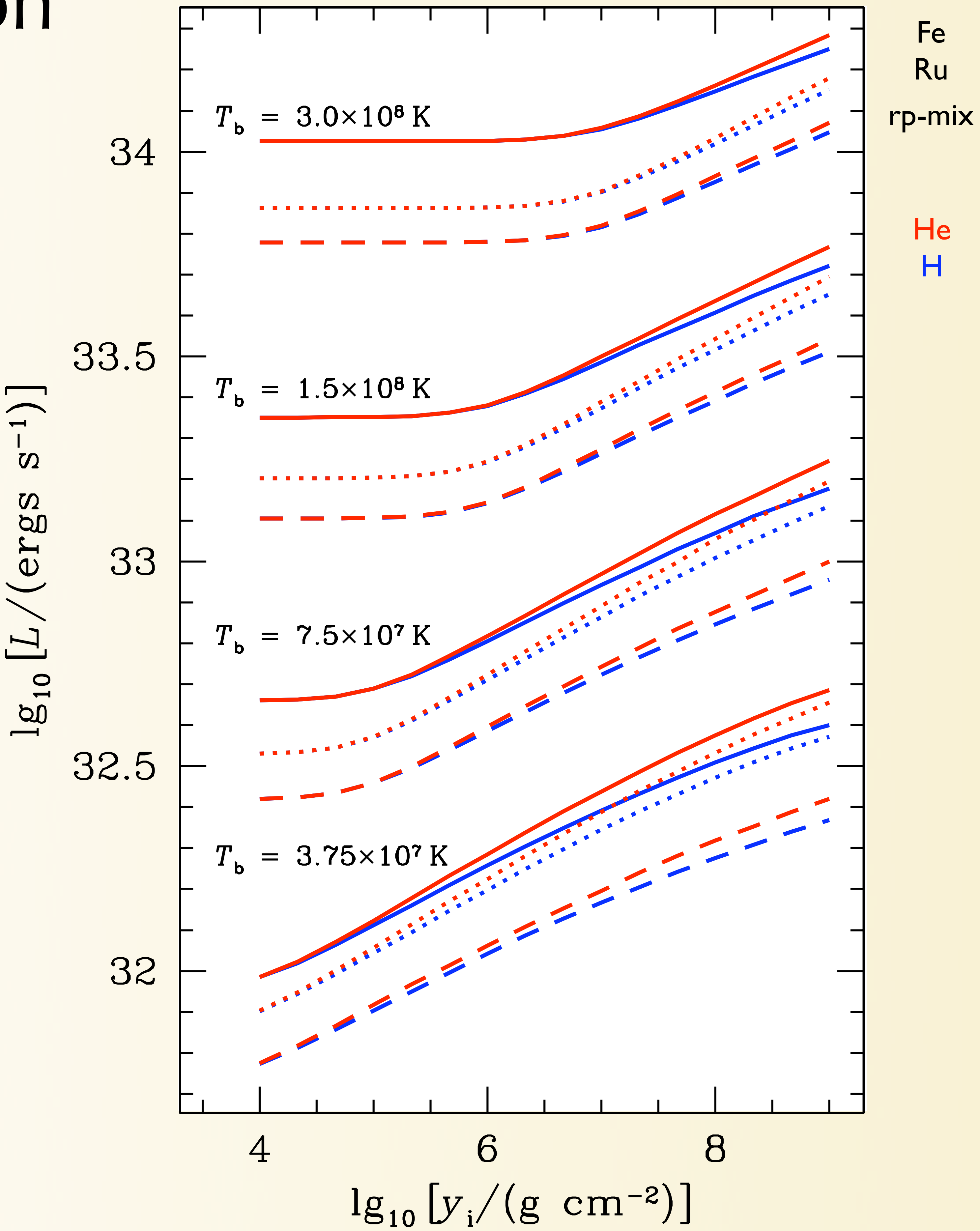
with

$$T_{\mathrm{eff}}^{\infty} < 3.6 \times 10^5\ \mathrm{K}$$

What does this say about enhanced neutrino cooling?
What is different about this binary?
Is the telescope pointed at the right place?

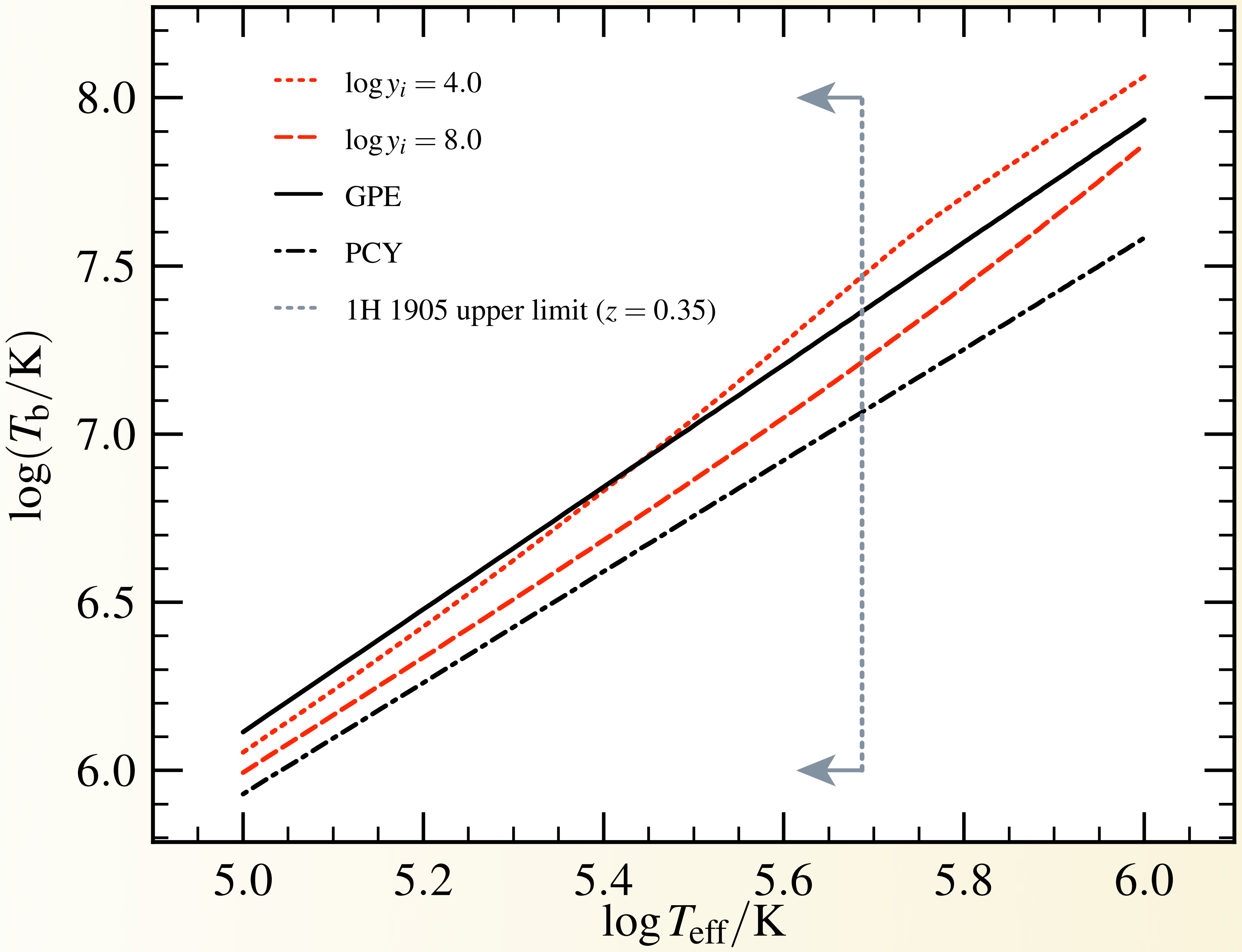
$T_{\rm eff} - T_{\rm core}$ relation

Potekhin et al. 1998;
Brown, Bildsten & Chang 2002



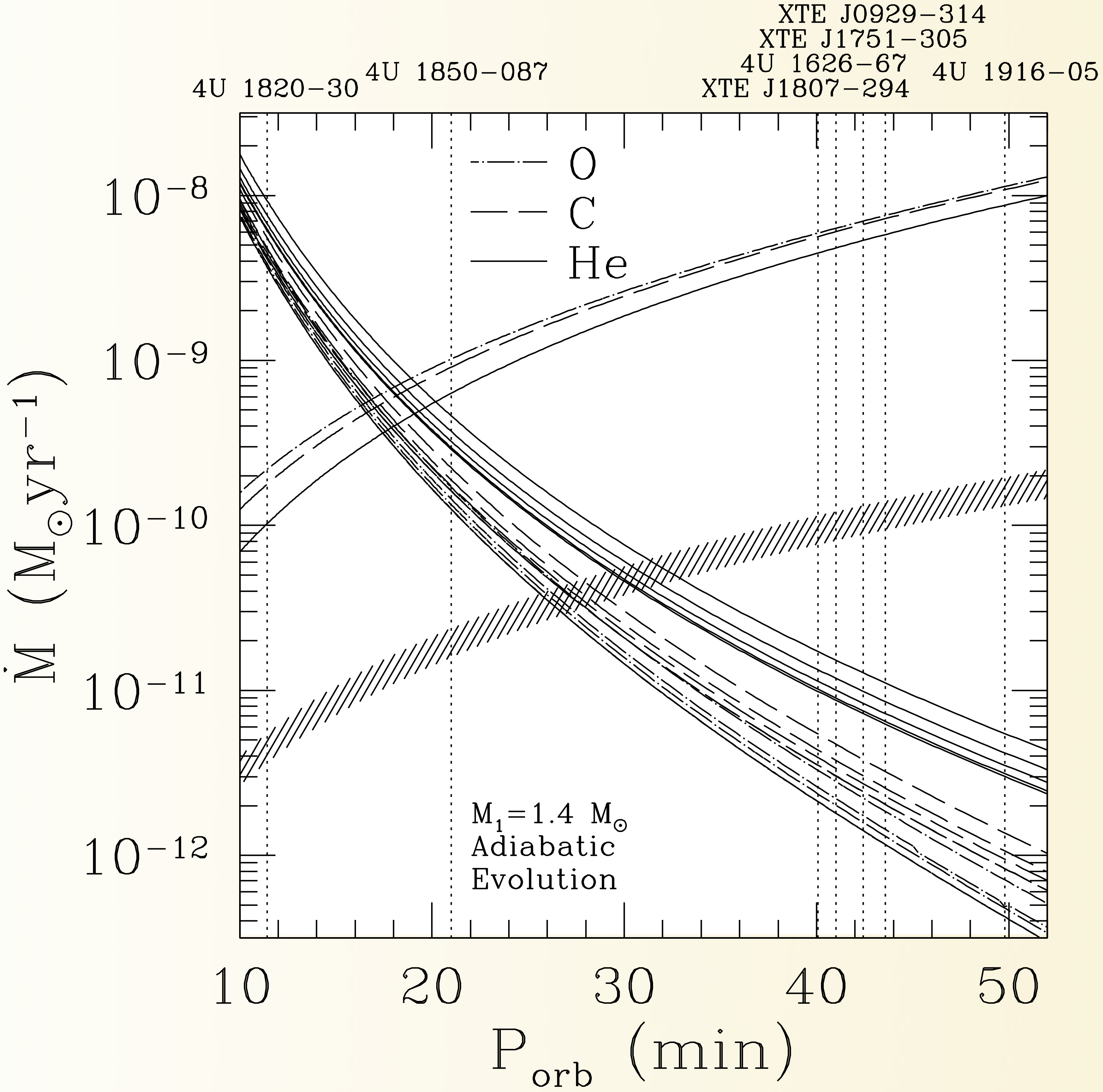
Infer the core temperature
from the asymptotic
effective temperature

Interior temperature, 1H 1905+000

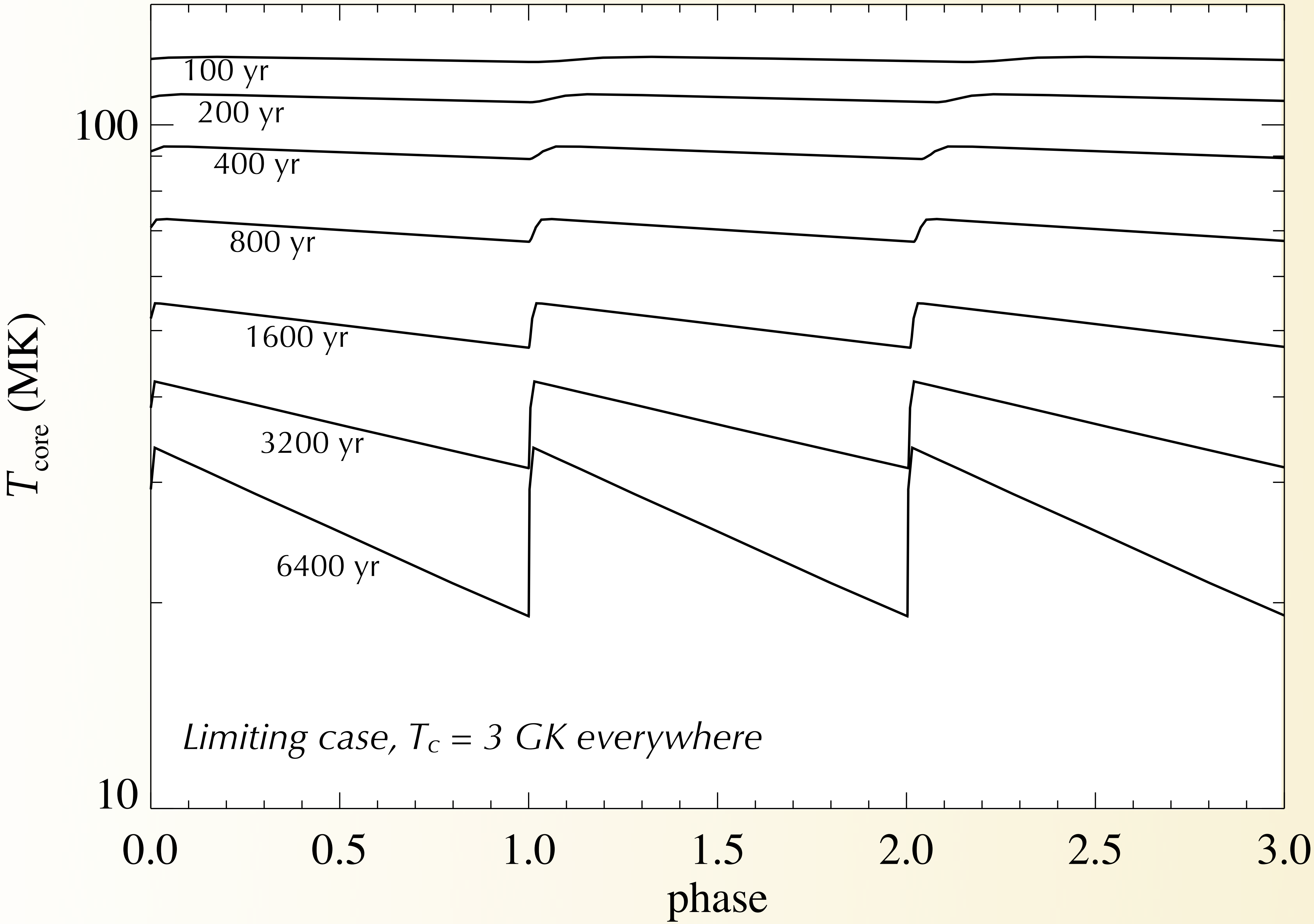


Evolution of *dM/dt*

Deloye & Bildsten 2003



Core temperature evolution



Evolution of core temperature

The heating is described by

$$C(T)\frac{dT}{dt} = Q\frac{\dot{M}}{m_{\rm u}},$$

and the cooling by

$$C(T)\frac{dT}{dt} = -\tilde{L}T^{\alpha}$$

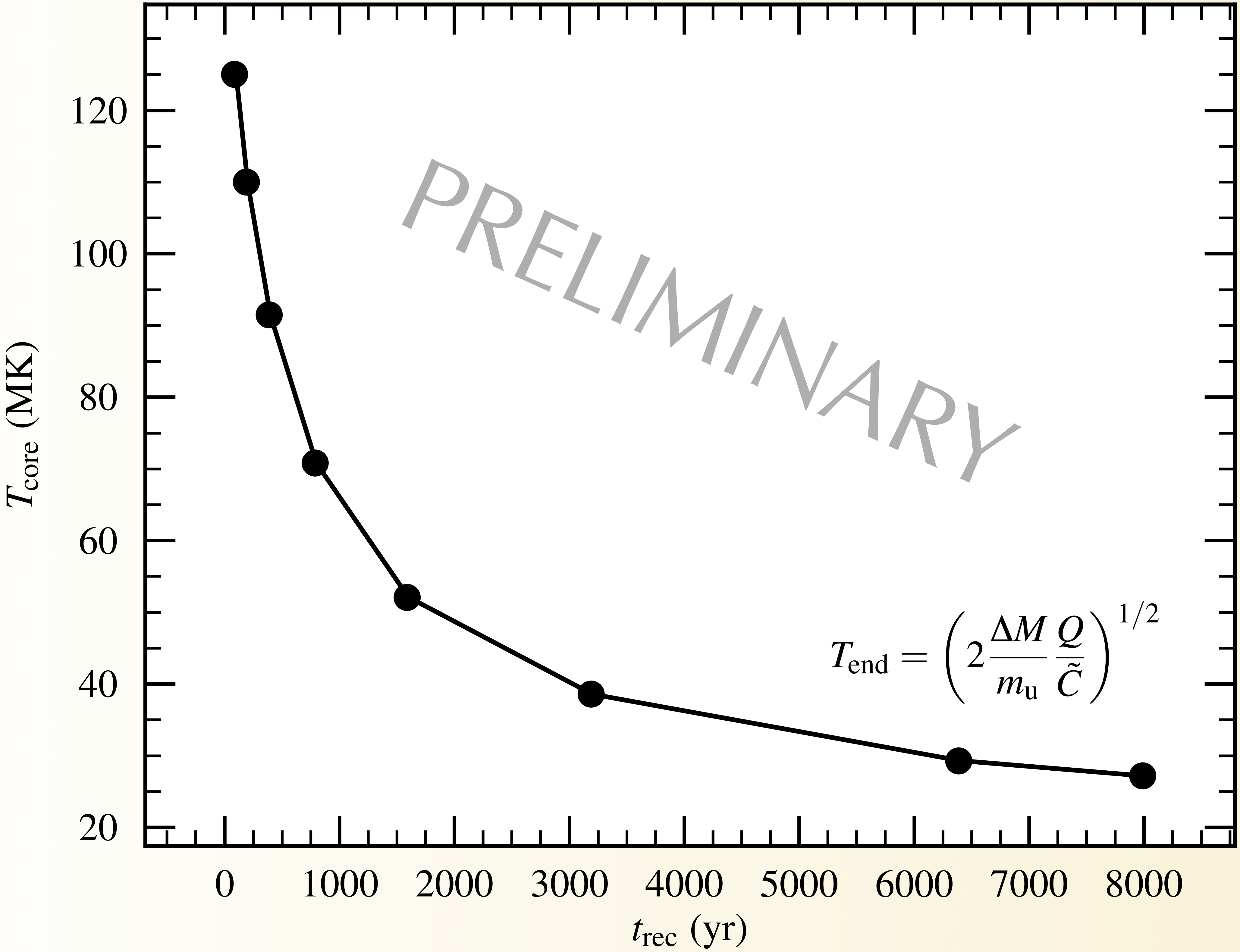
with $\alpha \approx 2.2$. Defining the cooling timescale of the core as

$$\tau \equiv \frac{E_{\rm core}}{L_{\gamma}} = \frac{1}{2}\tilde{C}T_{\rm end}^{2}(\tilde{L}T_{\rm end}^{\alpha})^{-1},$$

and the temperature at the end of the outburst is

$$T_{\rm end}^{2} = \left(2\frac{\Delta M}{m_{\rm u}}\frac{Q}{\tilde{C}}\right)\left[1-\left(1+\frac{\alpha-2}{2}\frac{t_{\rm recur}}{\tau}\right)^{-2/(\alpha-2)}\right]^{-1}.$$

Core temperatures following end of 15 yr outburst



$$T_{\mathrm{end}} = \left(2\frac{\Delta M}{m_{\mathrm{u}}}\frac{Q}{\tilde{C}}\right)^{1/2}$$

Summary

- Observations of thermal relaxation of neutron star crusts
  - Cooling timescale sensitive to NS mass, crust composition
  - Suggestion of high thermal conductivity—at odds with superburst ignition?
- First calculation of heating in the outer crust with realistic nuclear physics
  - Potentially much more heating than previously predicted
  - Amount of heating depends strongly on composition
  - Ignition of superbursts, long X-ray bursts (Cumming et al. 2006, Peng et al. 2007)
- Calculations still overpredict the ignition depth of superbursts? Does this imply another source of heating?

Future work

- Reactions in the inner crust
    - Pathway to equilibrium nuclei (Jones 2005)?
    - Composition
    - Heating
- Applications to quasi-persistent transients (Cackett's talk)

The Bob Questions

- Nuclear physics
    - Transport properties: what is the thermal conductivity of pasta (and sauce)—are there reasonable upper & lower limits?
    - Better understanding of the transition between crust & core
- Astrophyscs
    - Larger sample of superbursts & bursts at low accretion rates
    - Synthesis of disparate observations: isolated cooling neutron stars, magnetars, X-ray bursters, & X-ray transients share the same nuclear physics.