cooling neutron star crusts

Edward Brown

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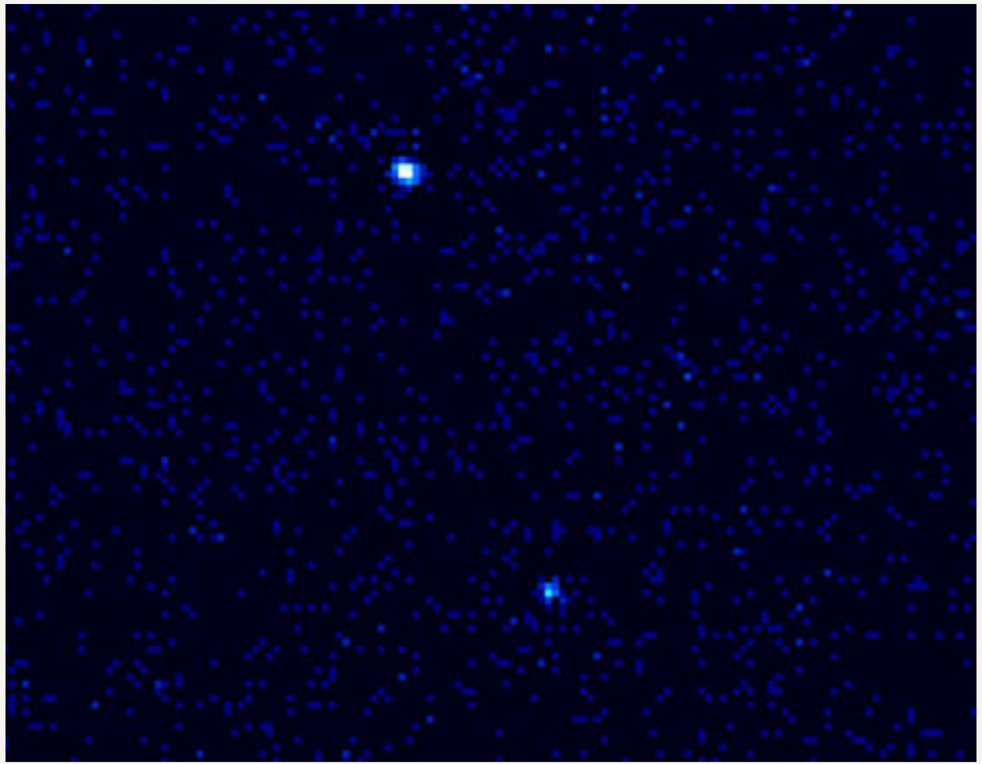
outline



Credit: NASA/CXC/Wijnands et al.

- motivation
- crust nuclear processes
- cooling crusts

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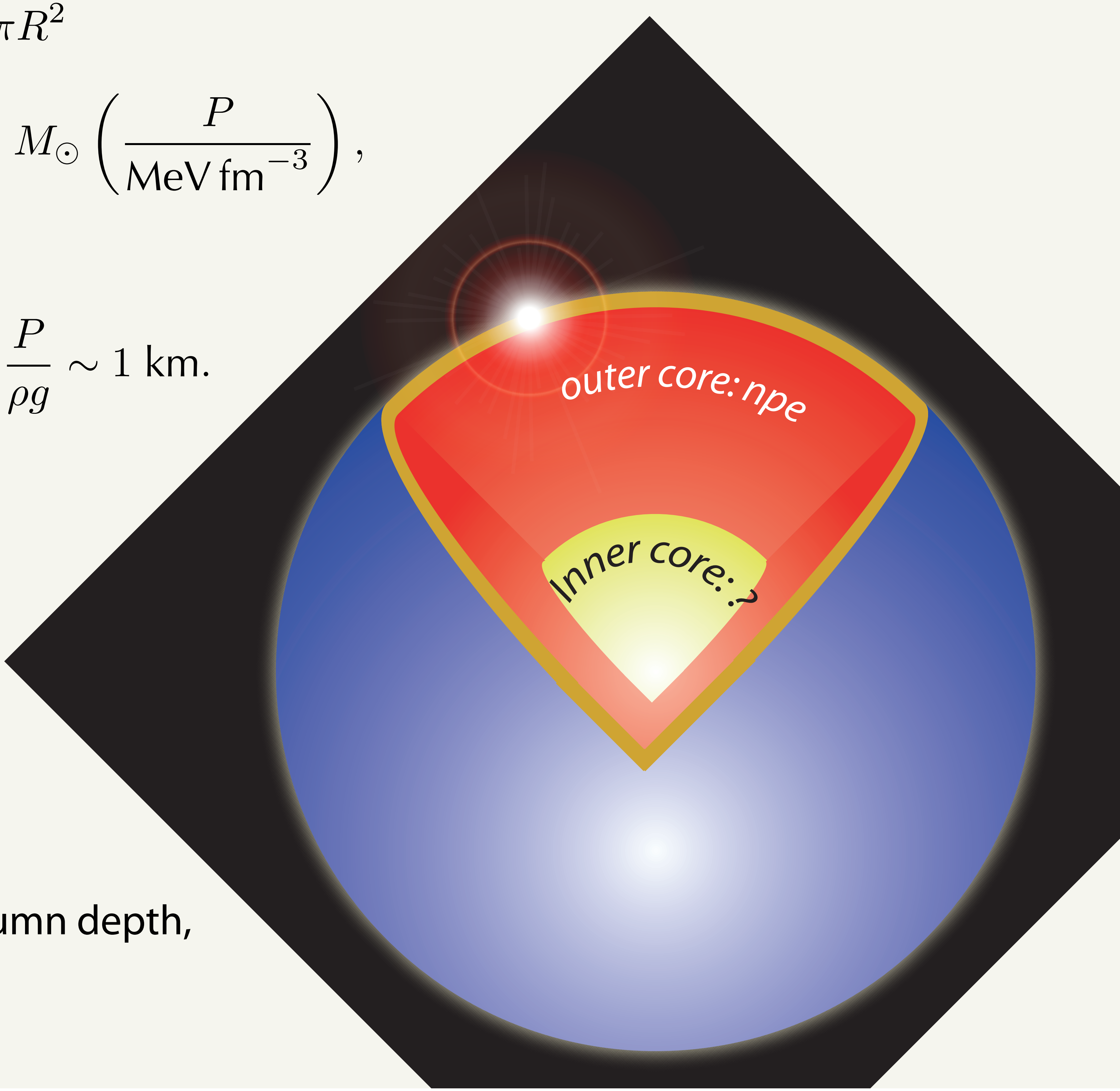
JINA

From hydrostatic equilibrium, $dP/dr = -\rho g$, the mass above an isobar is

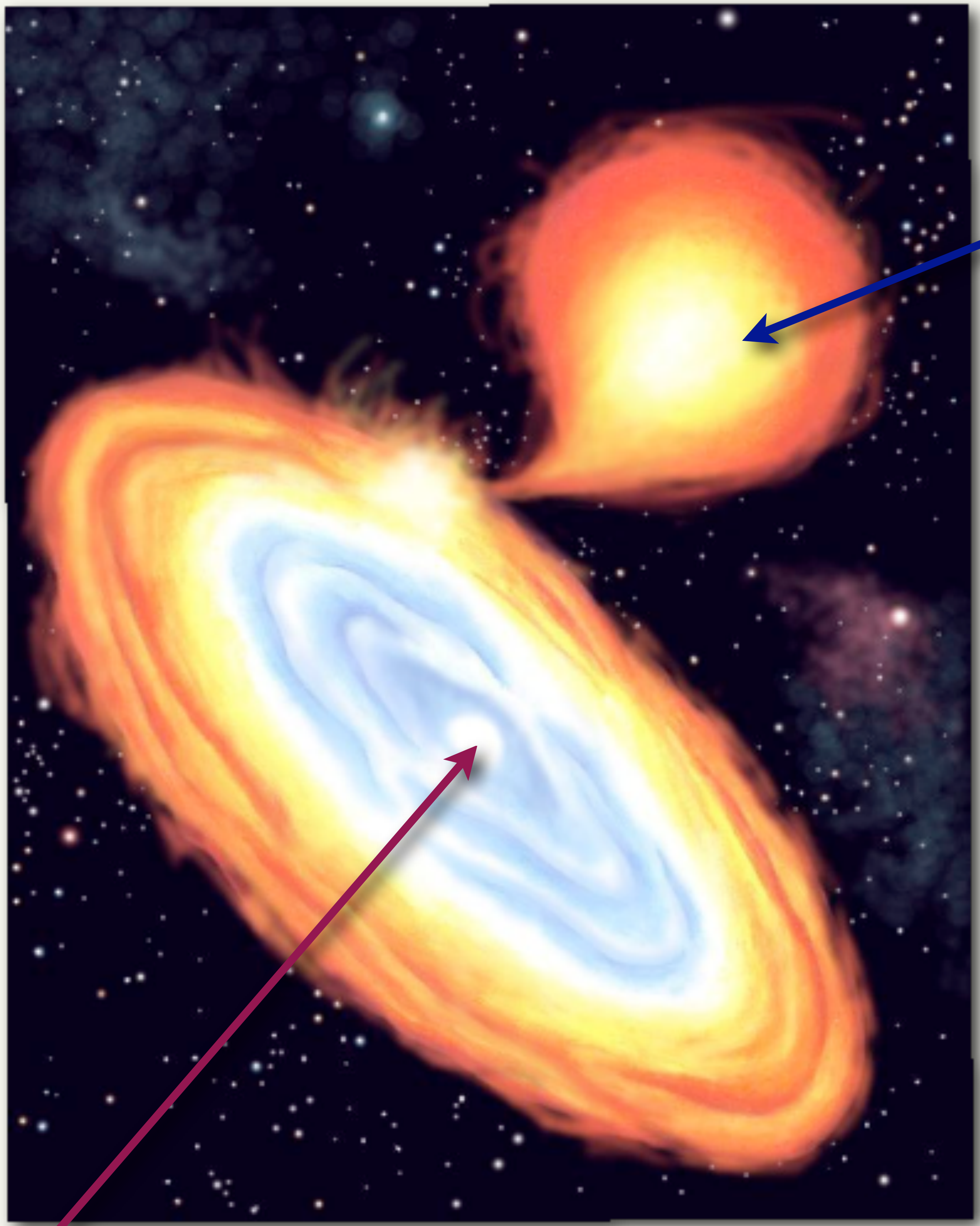
$$\begin{aligned}\Delta M &\approx \frac{P}{g} 4\pi R^2 \\ &\approx 0.05\ M_\odot \left(\frac{P}{\text{MeV fm}^{-3}}\right),\end{aligned}$$

and the thickness is

$$H_P = \frac{P}{\rho g} \sim 1\ \text{km}.$$



NB. *P/g* is roughly the column depth, defined as ∫ρ dz



Artwork courtesy T. Piro, UC-Berkeley

Each H atom accreted releases

$$E_{\text{grav}} \approx \frac{GMm_{\text{H}}}{R} \approx 200\,\text{MeV}.$$

Critical accretion rate: balance radiation, gravitational force to obtain *Eddington luminosity*

$$L_{\text{Edd}} = \frac{4\pi GMm_{H}c}{\sigma_{\text{T}}}.$$

This corresponds to a mass accretion rate of

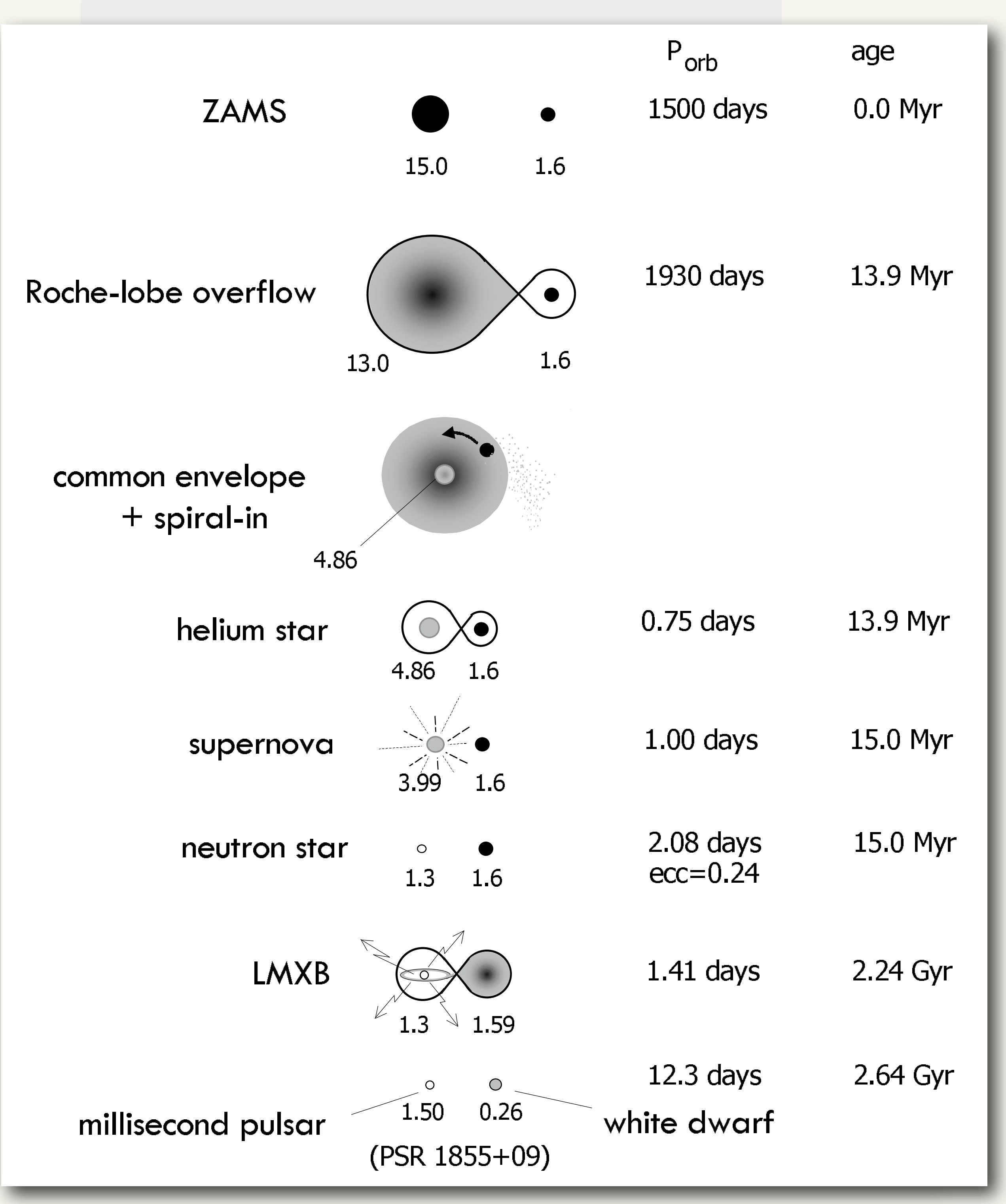
$$\dot{M} \approx 10^{-8}\ M_{\odot}\,\text{yr}^{-1}.$$

Mass transfer cycle of a LMXB

- 0.4 Gyr mass-transfer (LMXB) phase
- 0.2 Msun mass accumulated

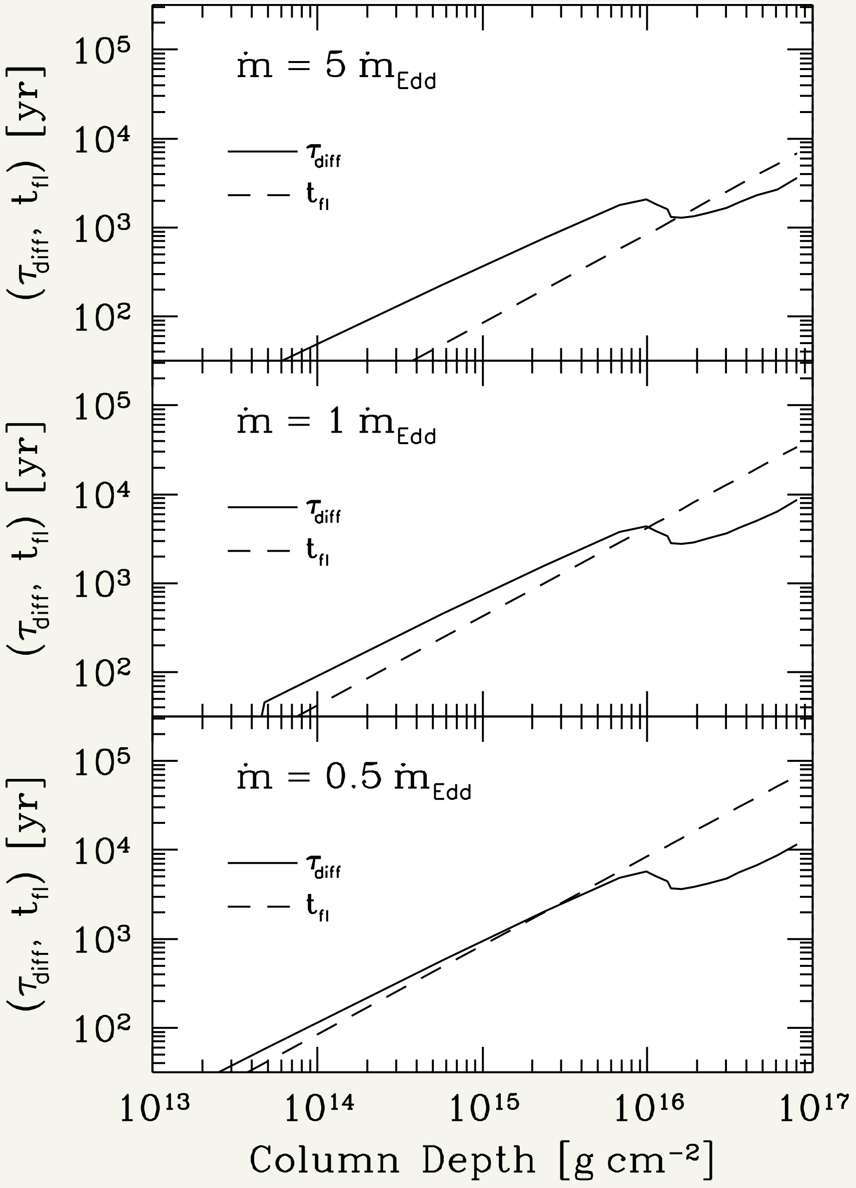
LMXBs replace their original crust

Tauris & van den Heuvel

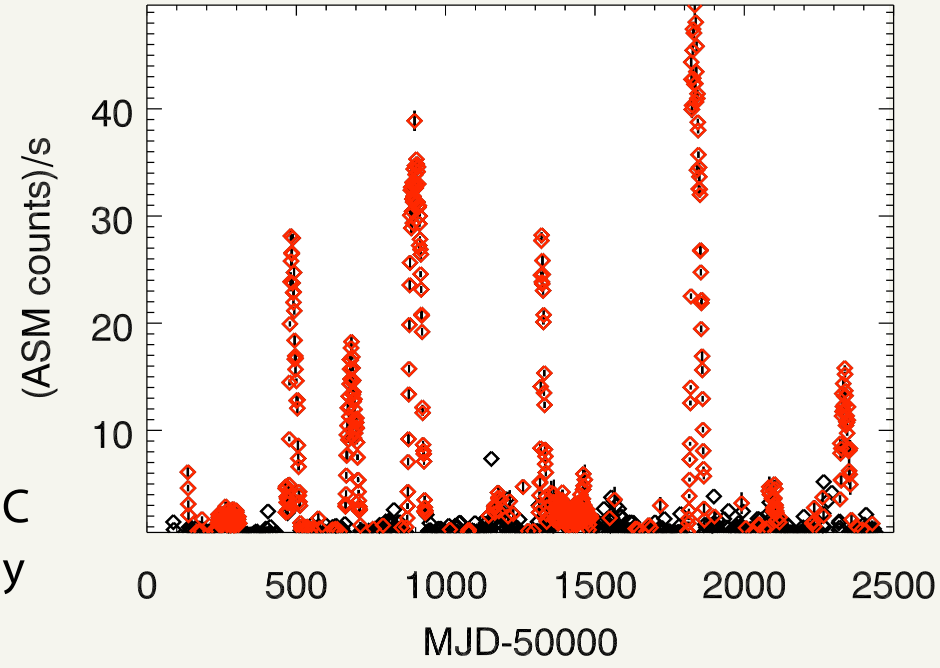


crust reactions important for...

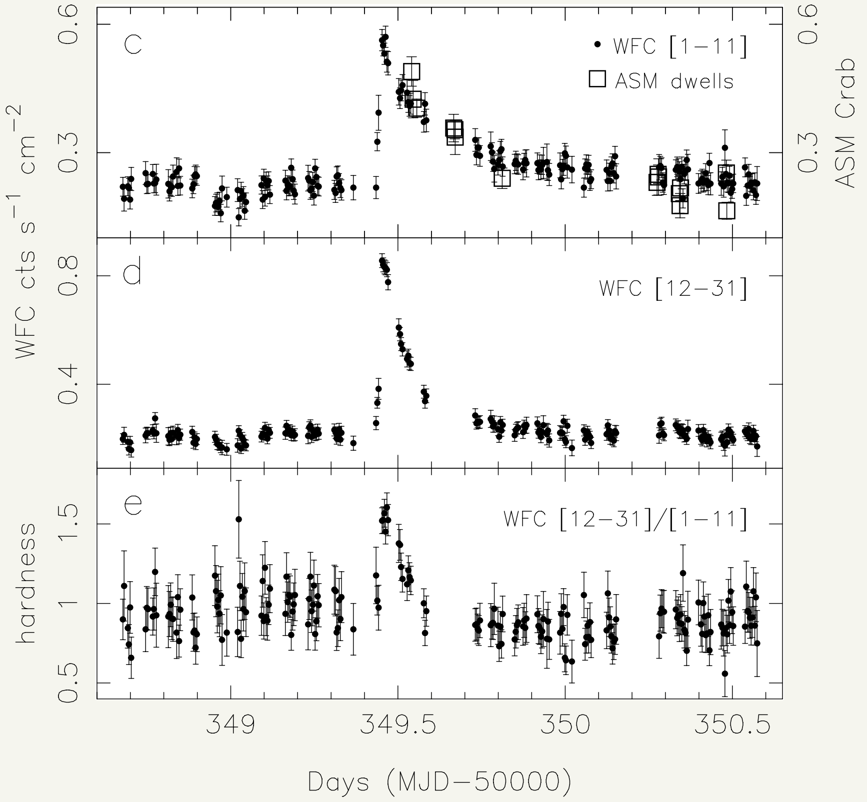
magnetic field evolution;
from Brown & Bildsten 98



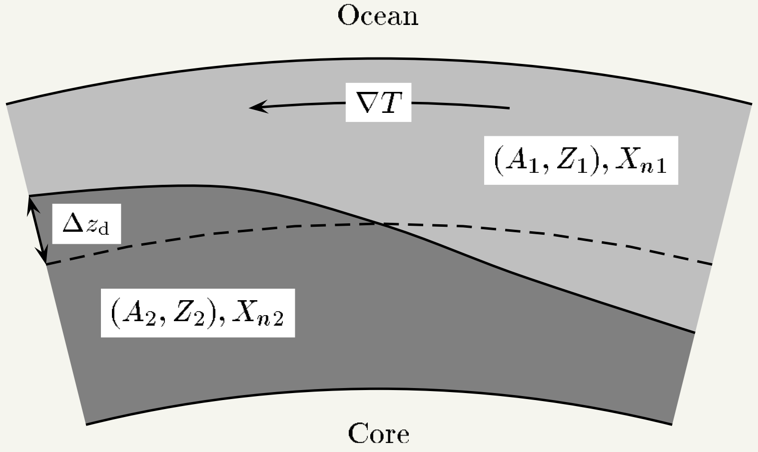
quiescent thermal
emission from transients



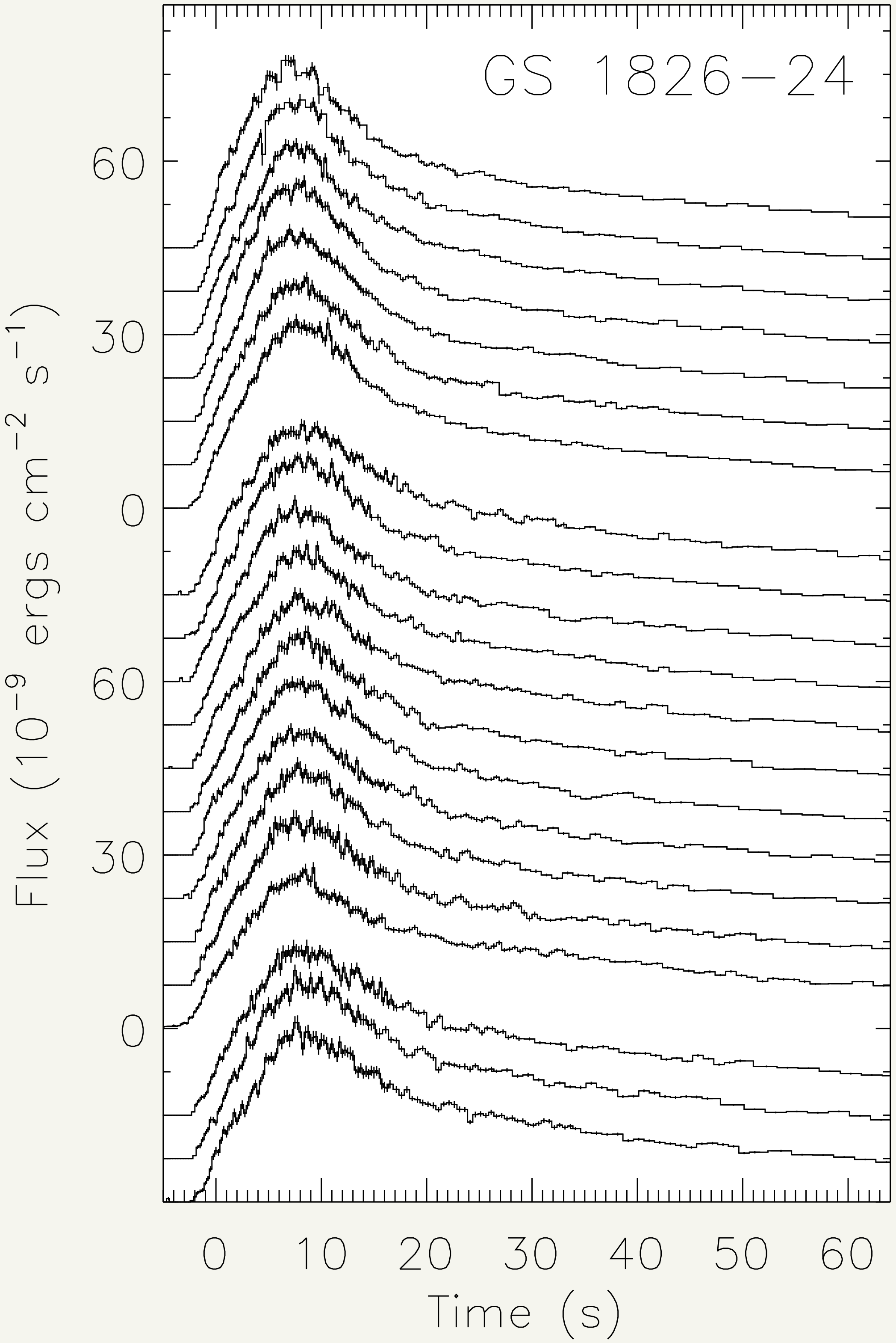
ignition depth of He, C
explosions (long X-ray
bursts);
from Kuulkers 01



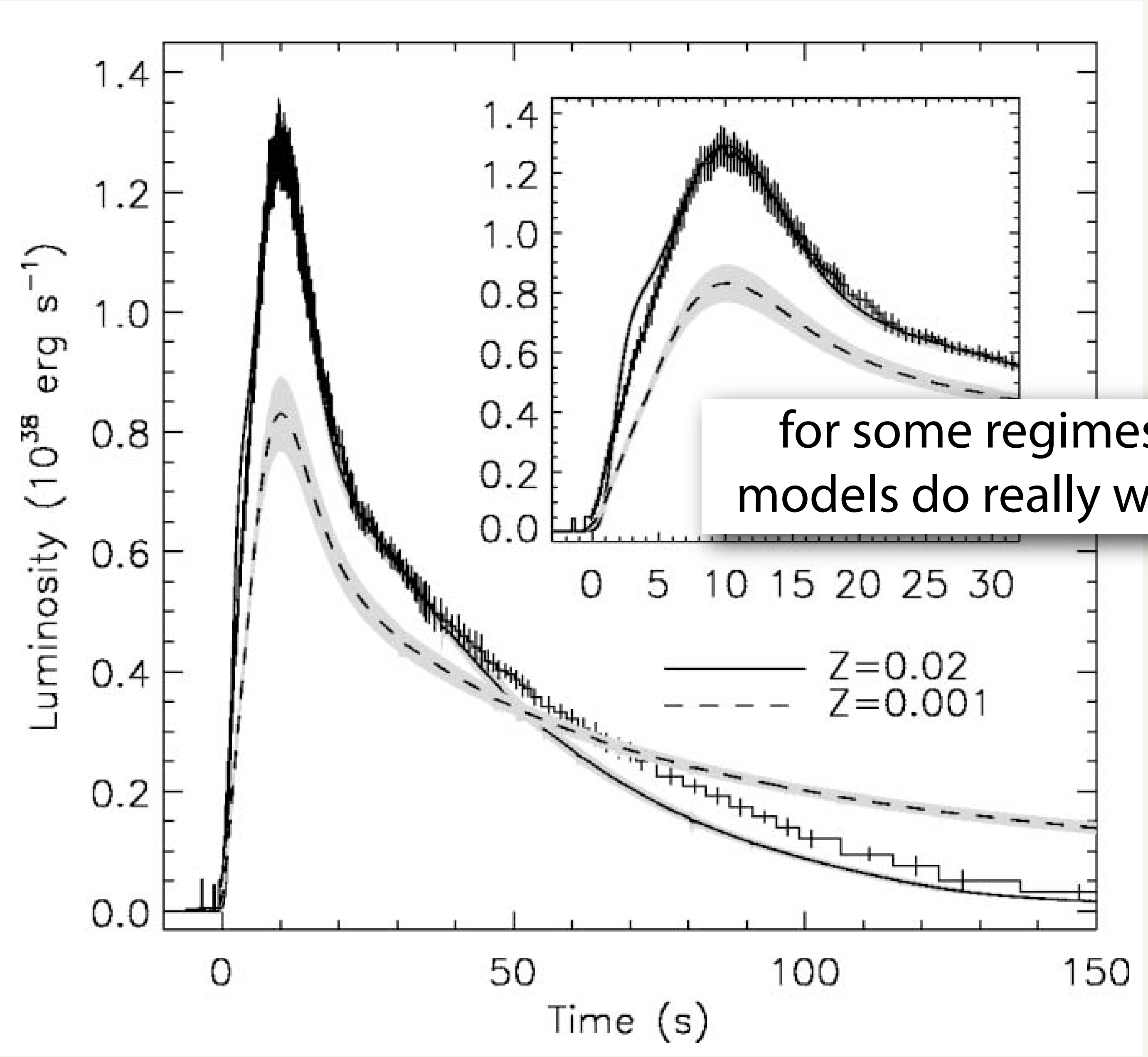
mountains (plot from
Ushomirsky et al. 00)
see talk by C. Horowitz



explosive H, He burning



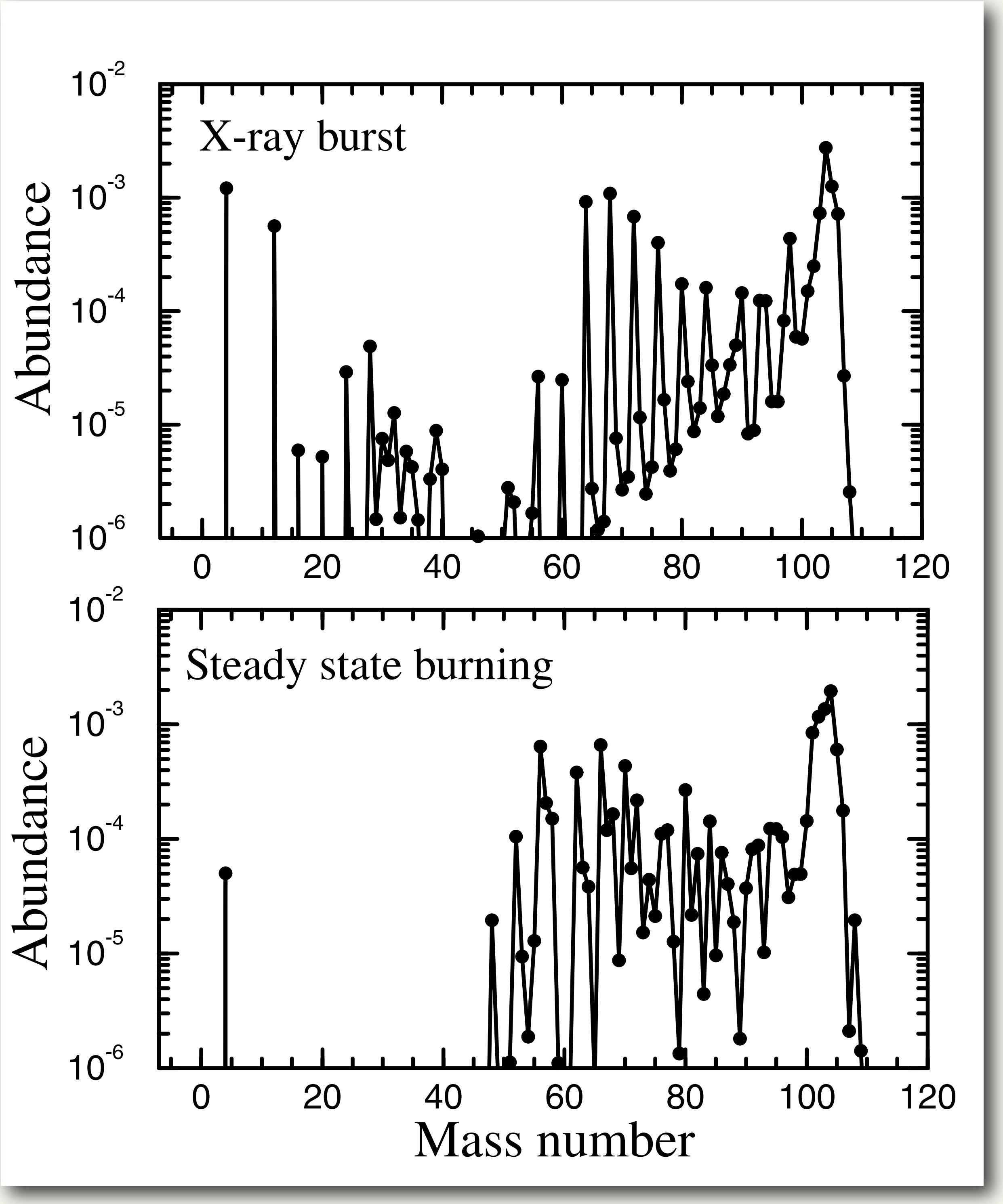
from Galloway et al.



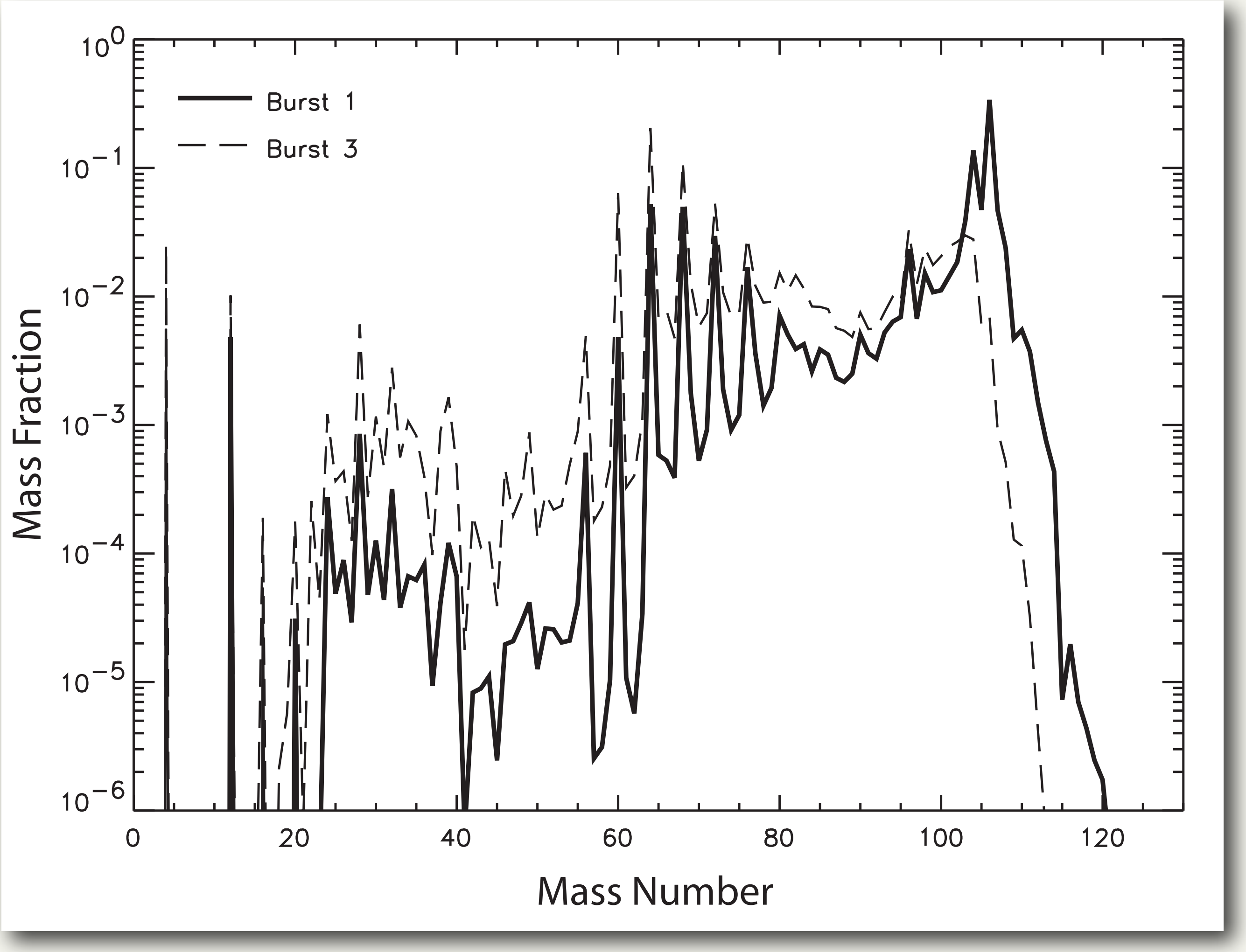
for some regimes, models do really well!

Heger et al. 07

ashes of H-He burning

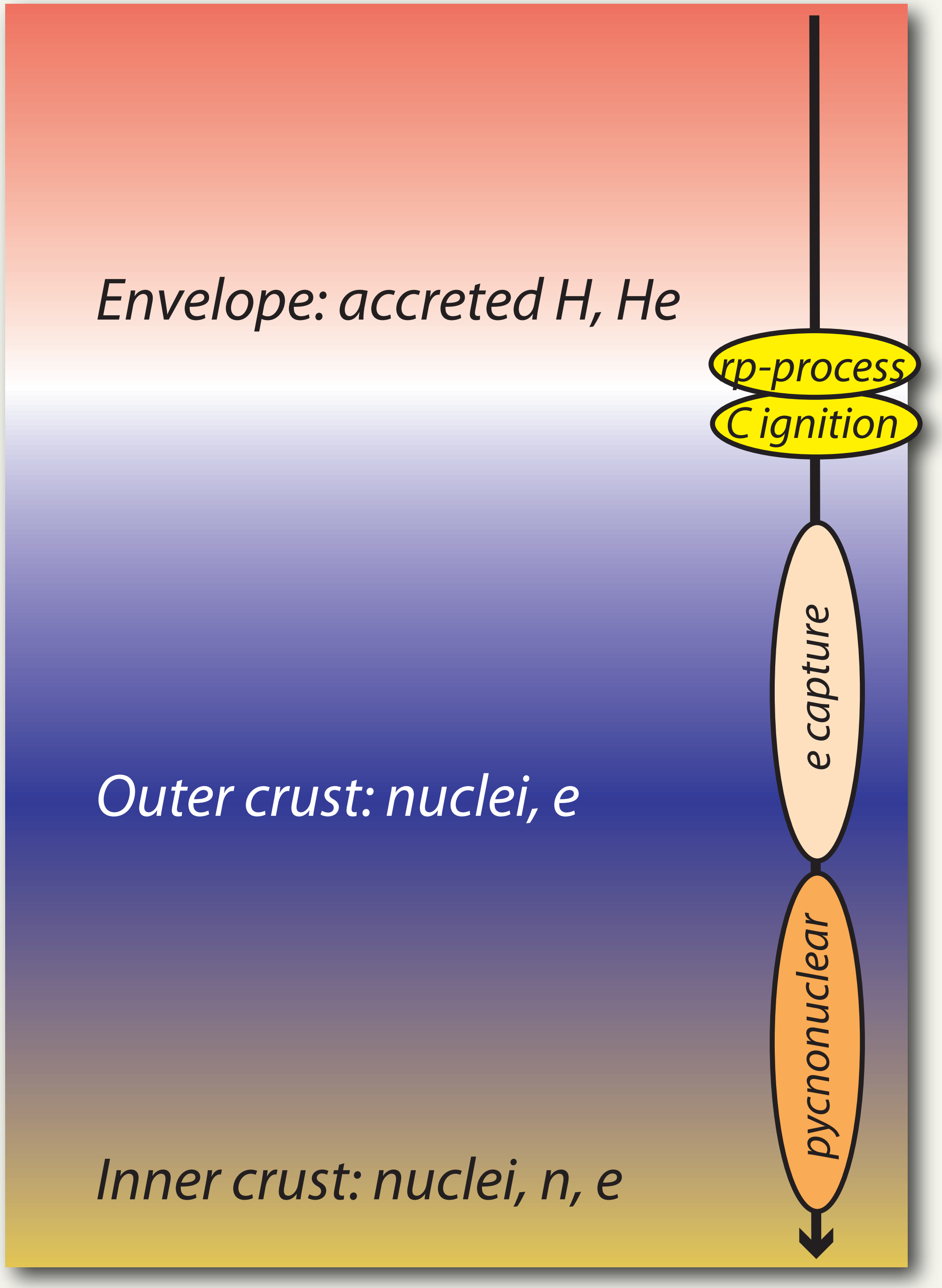


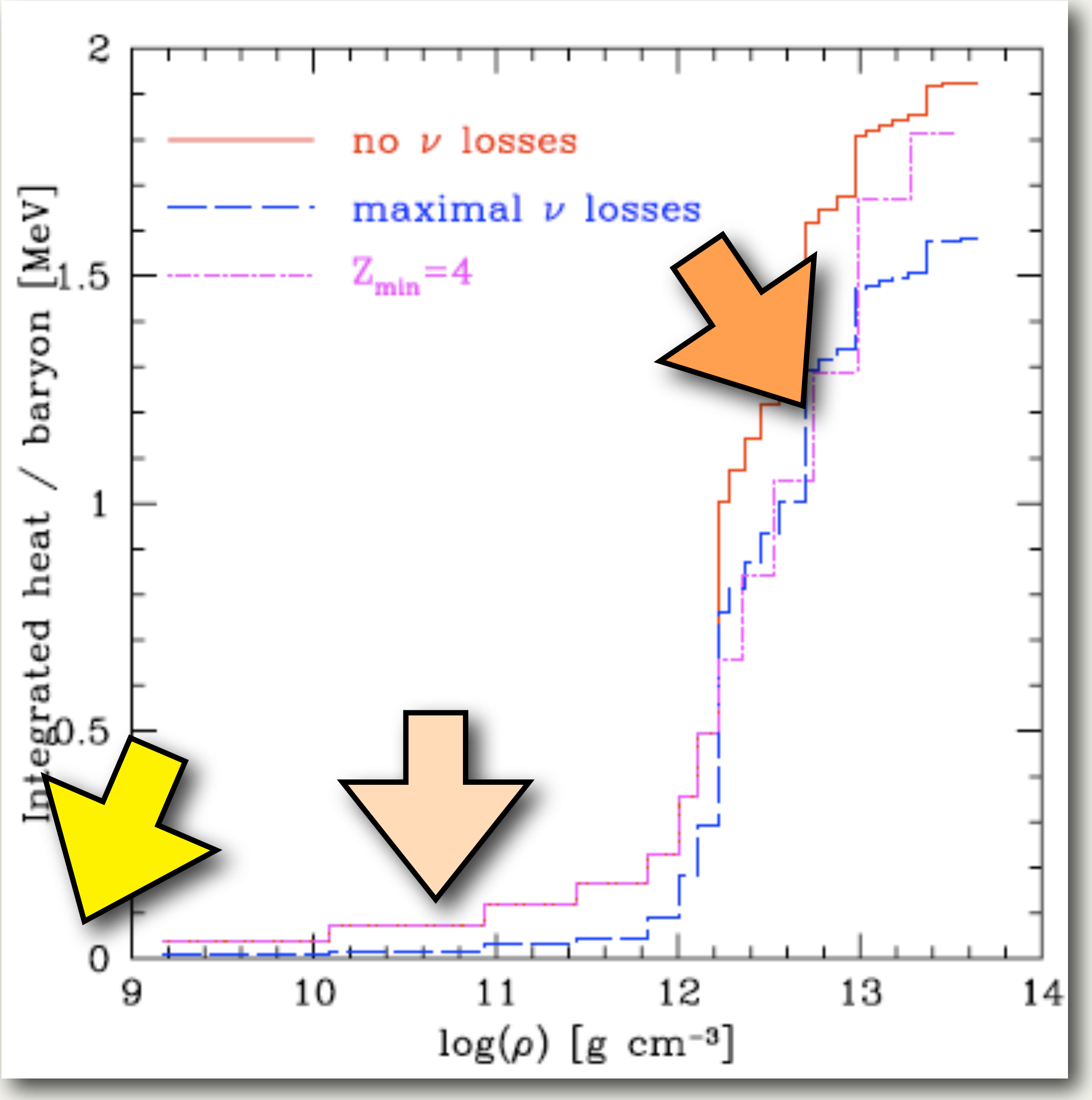
Woosley et al. 2004, ApJ



Schatz et al. 2001, PRL

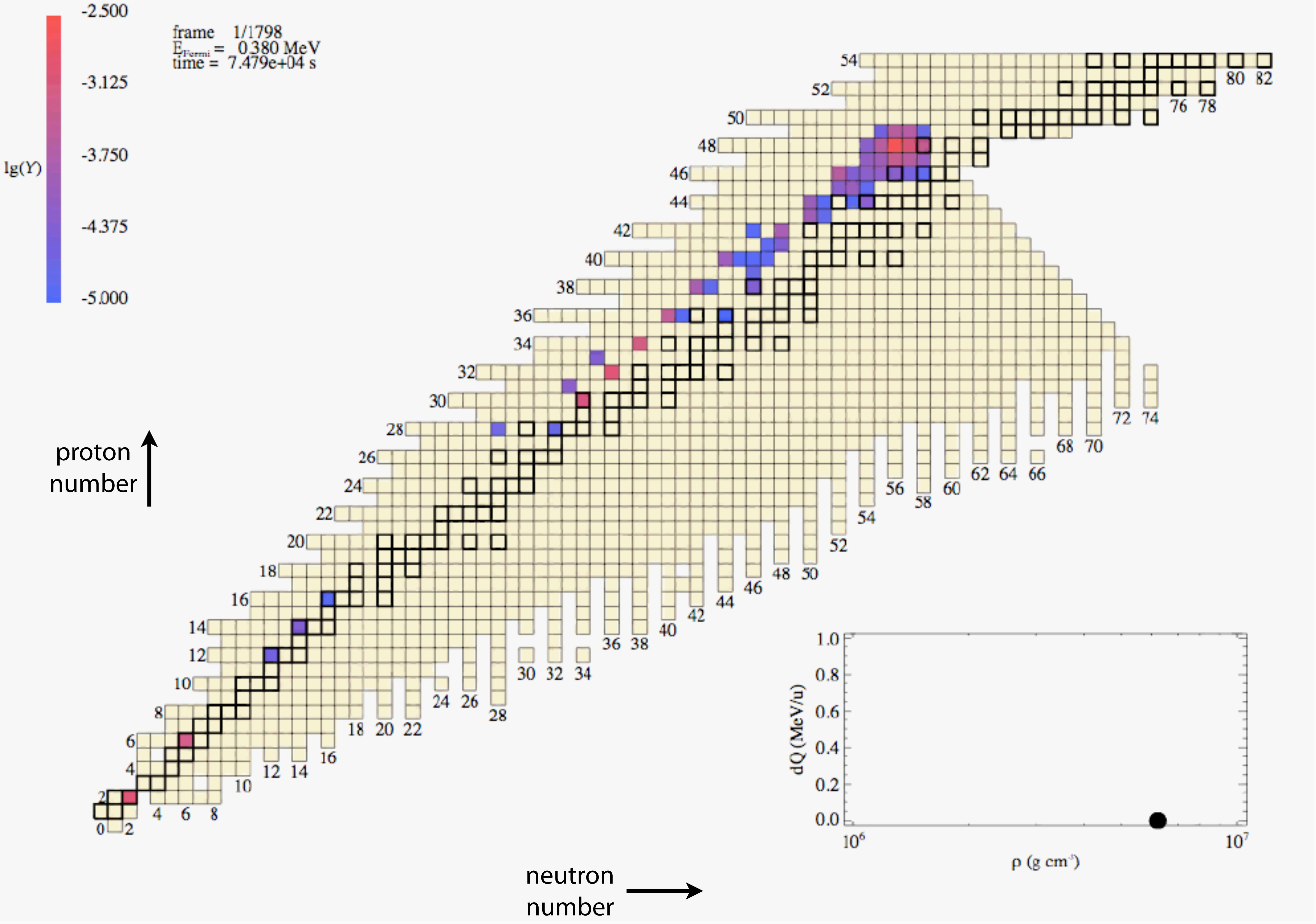
accretion-induced heating





Plot from Haensel & Zdunik '08;
see also Gupta et al. '07, '08

Gupta, Brown, Schatz, Möller, & Kratz (07)



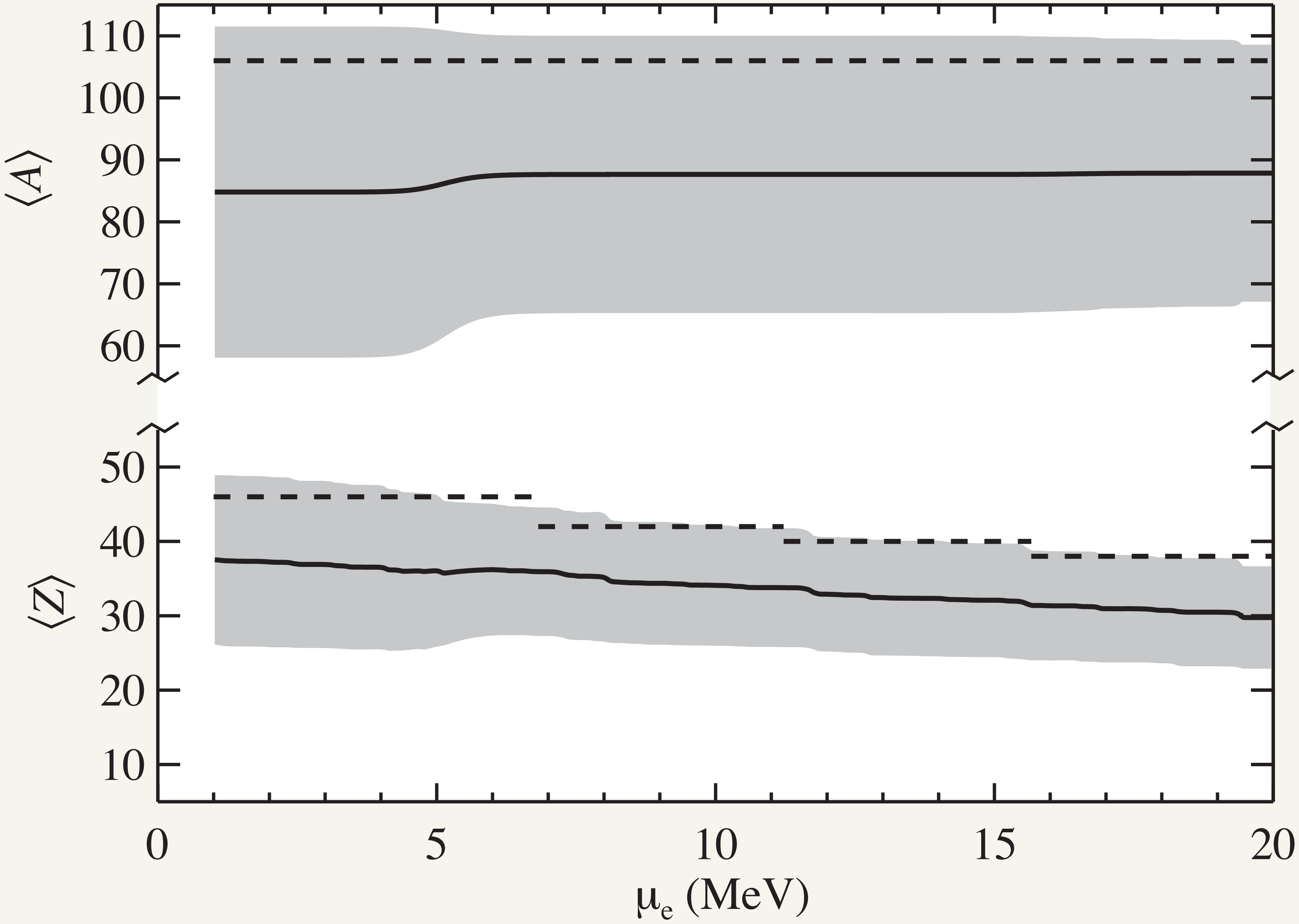
Consider the symmetry term in the mass formula,

$$\frac{E}{A} = -a_V + a_S A^{-1/3} + a_A \left(\frac{N-Z}{N+Z}\right)^2 + a_C \frac{Z^2}{A^{4/3}}.$$

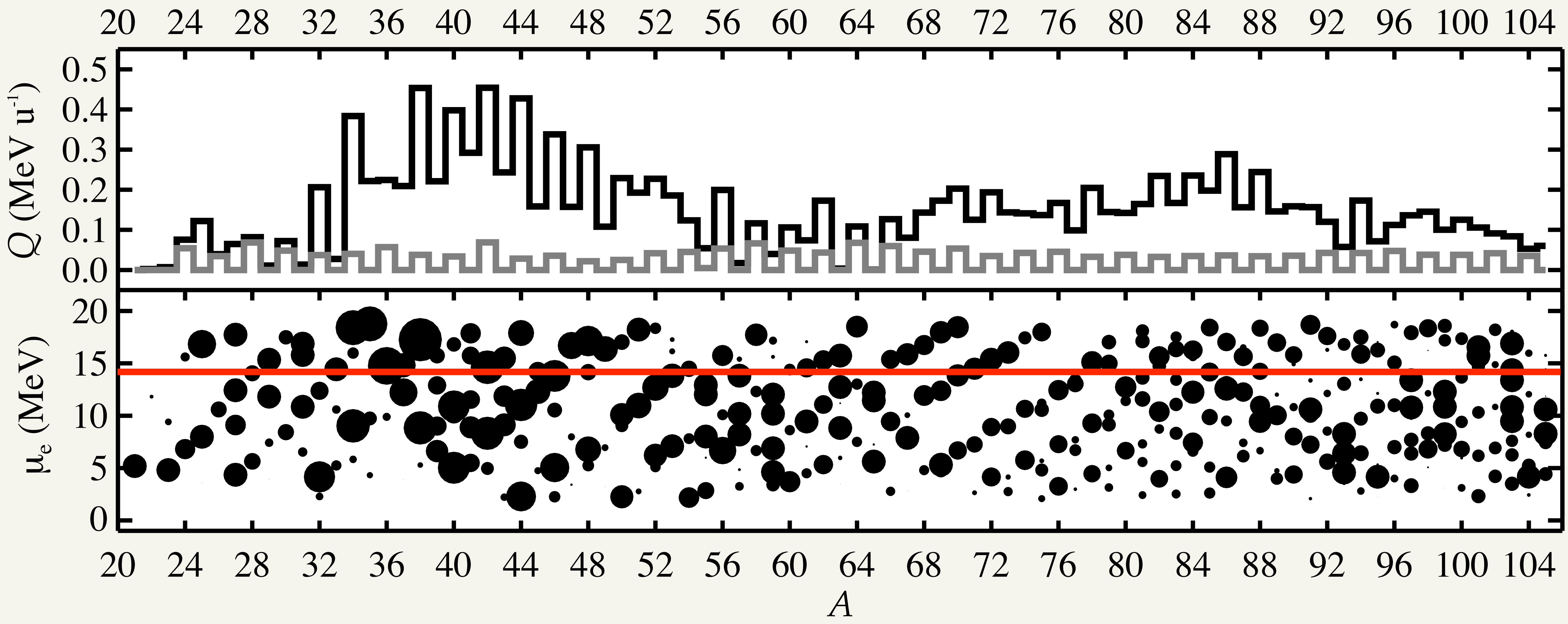
Minimize the Gibbs energy including the electron contribution $Y_e\mu_e$ to find

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

This is equivalent to demanding that $\mu_e = \mu_n - \mu_p$.



electron capture reactions, outer crust



mountains made by variations in composition
(Bildsten 98, Ushomirsky et al. 00)

Gupta et al. 07

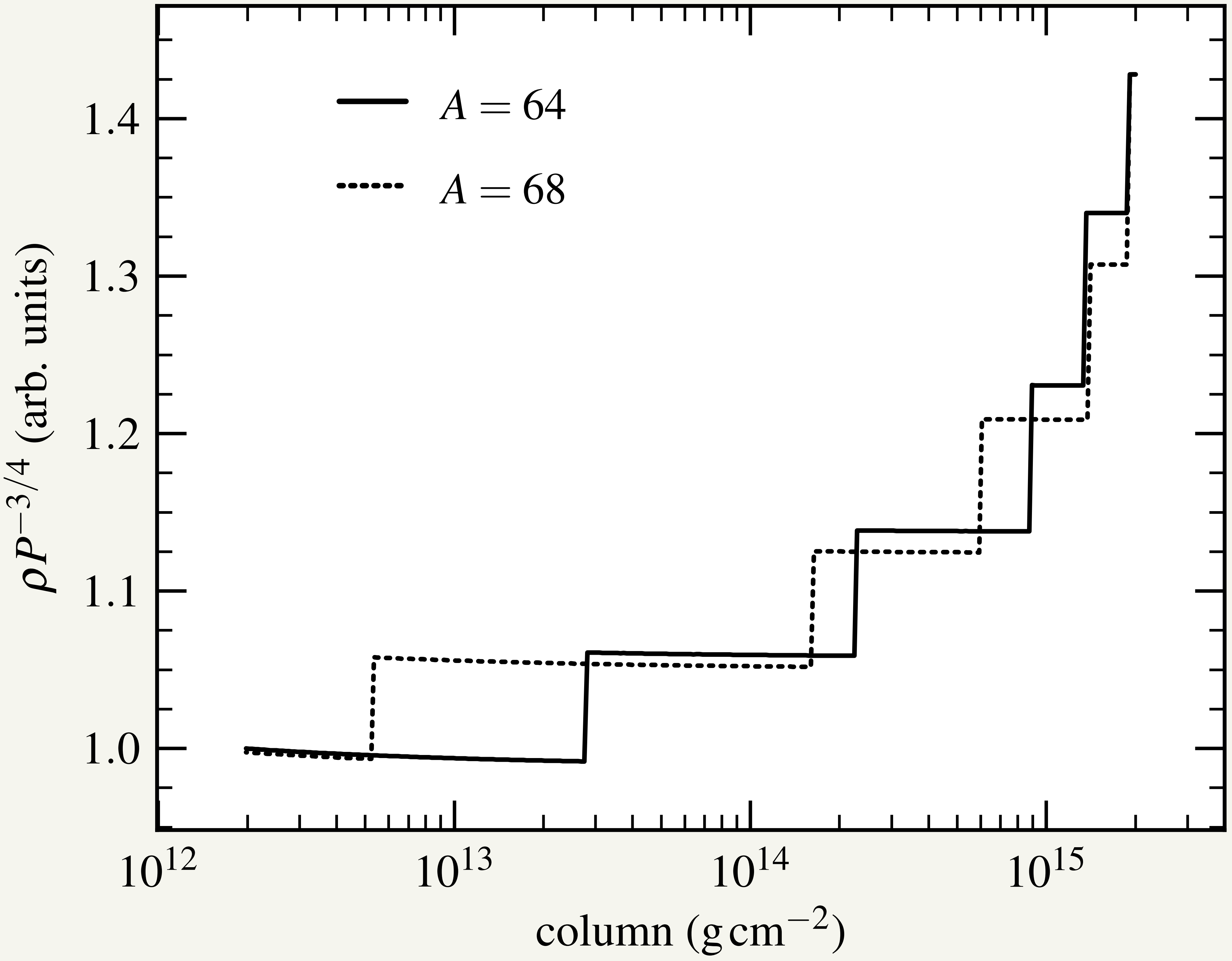
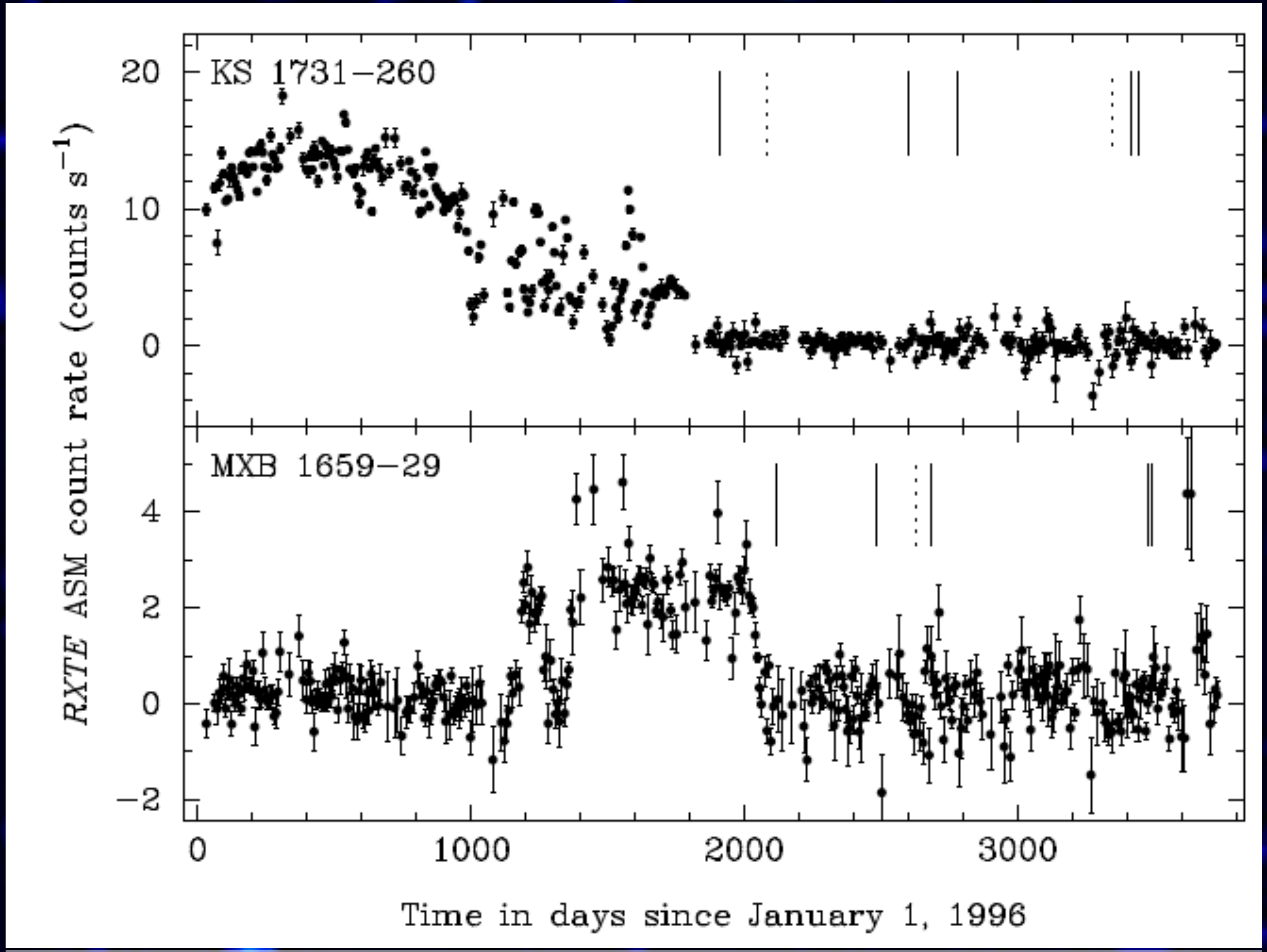
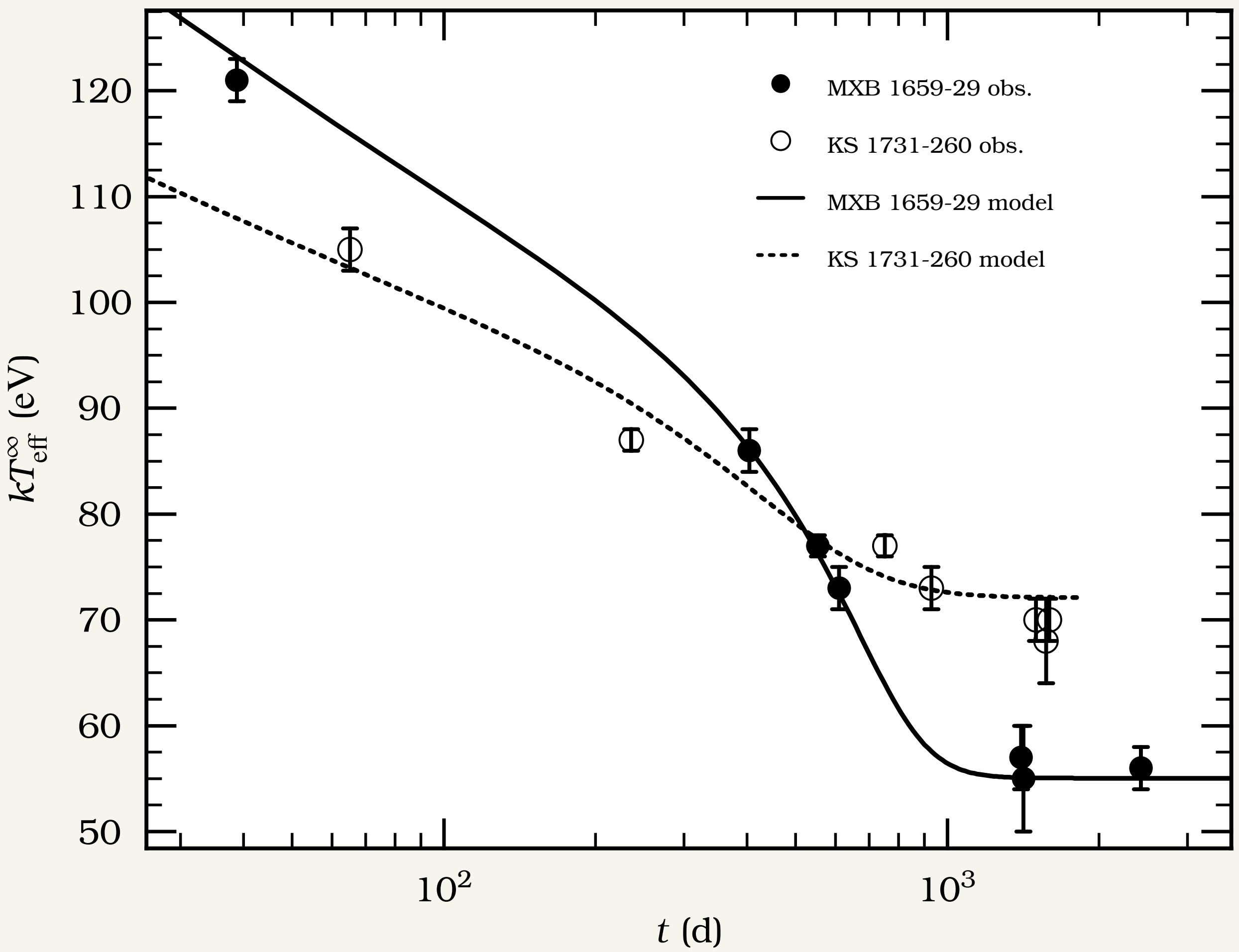

$A = 64$
$A = 68$
$\rho P^{-3/4}$ (arb. units)
1.0
1.1
1.2
1.3
1.4
10^{12}
10^{13}
10^{14}
10^{15}
column ($\mathrm{g\,cm^{-2}}$)

fig. from Cackett et al. '06

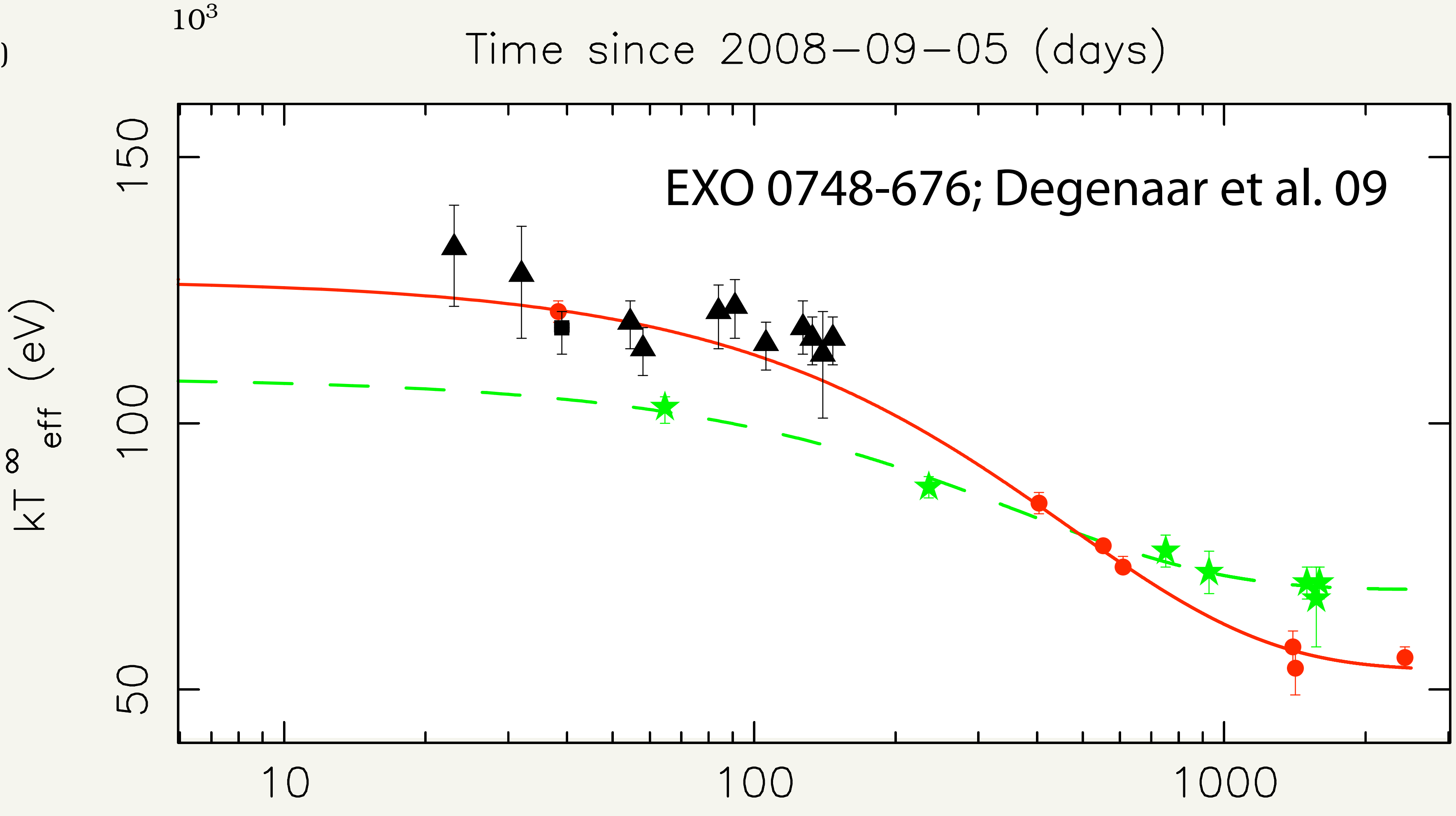


- *RXTE* monitoring observations discovered *quasi-persistent* transients
- Rutledge et al. '02 suggested looking for thermal relaxation of crust during quiescence
- observations (Wijnands, Cackett) detect this cooling



MXB 1659-29, KS 1731-260;
Cackett et al. 06, 08; fits from
Brown & Cumming 09

Cooling also
observed from
XTE J1701;
Homan et al., in
preparation



EXO 0748-676; Degenaar et al. 09

what can we learn from cooling transients?

Rutledge et al. '02,, Shternin et al. '07, Brown & Cumming '09

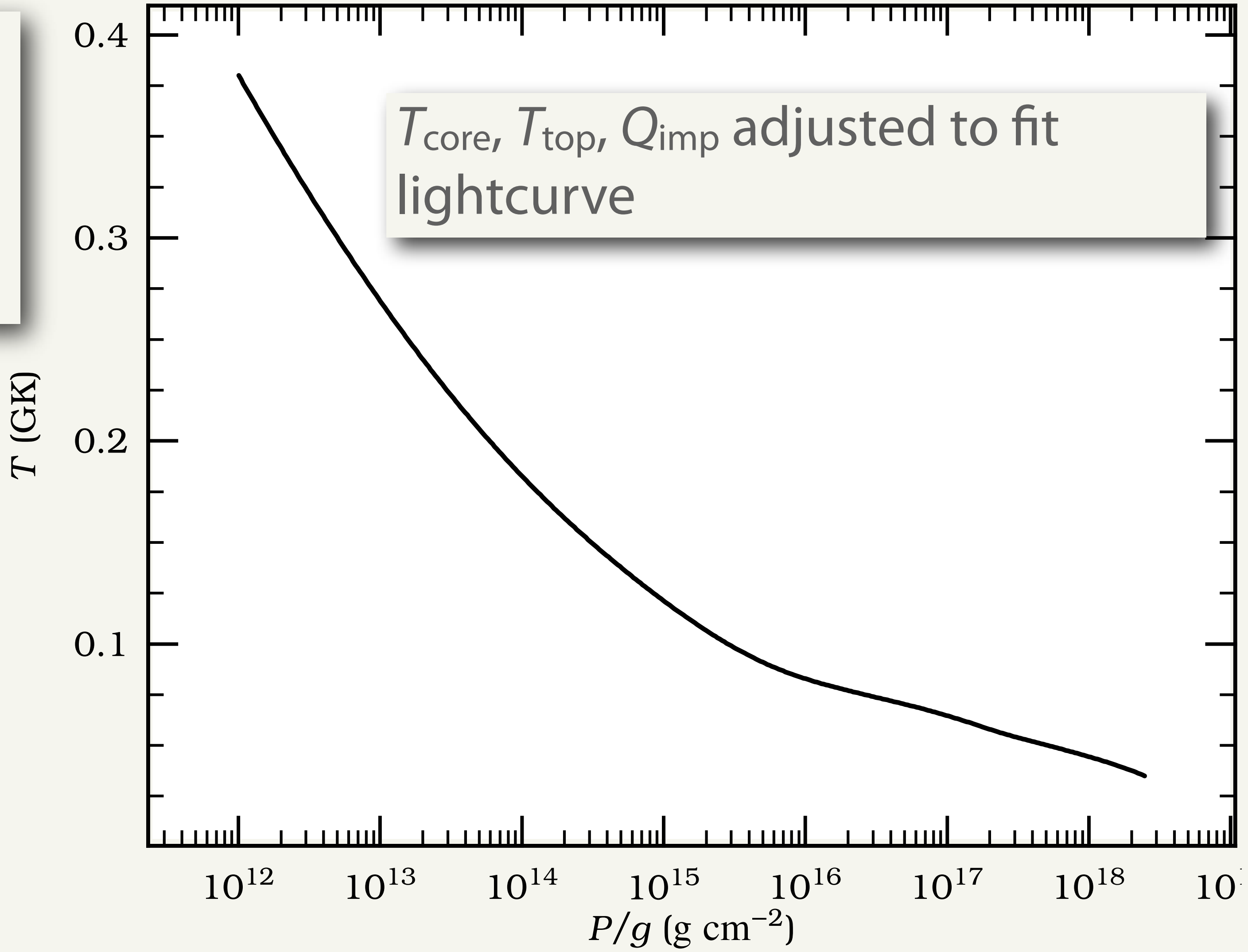
- core temperature
    - interpretation of neutrino cooling requires knowing the time-averaged *dM/dt*
- thermal timescale of crust
    - combination of conductivity, crust thickness, specific heat
- distribution of heat sources in the crust

crust models

solve thermal evolution equation on fixed hydrostatic grid

$$\frac{\partial}{\partial t}\left(Te^{\phi/c^2}\right) = e^{2\phi/c^2}\frac{\epsilon_{\mathrm{nuc}}-\epsilon_\nu}{C} - \frac{1}{4\pi r^2\rho C(1+z)}\frac{\partial}{\partial r}\left(Le^{2\phi/c^2}\right)$$

$$Le^{2\phi/c^2} = -\frac{4\pi r^2 K e^{\phi/c^2}}{1+z}\frac{\partial}{\partial r}\left(Te^{\phi/c^2}\right),$$



T_{core}, T_{top}, Q_{imp} adjusted to fit lightcurve

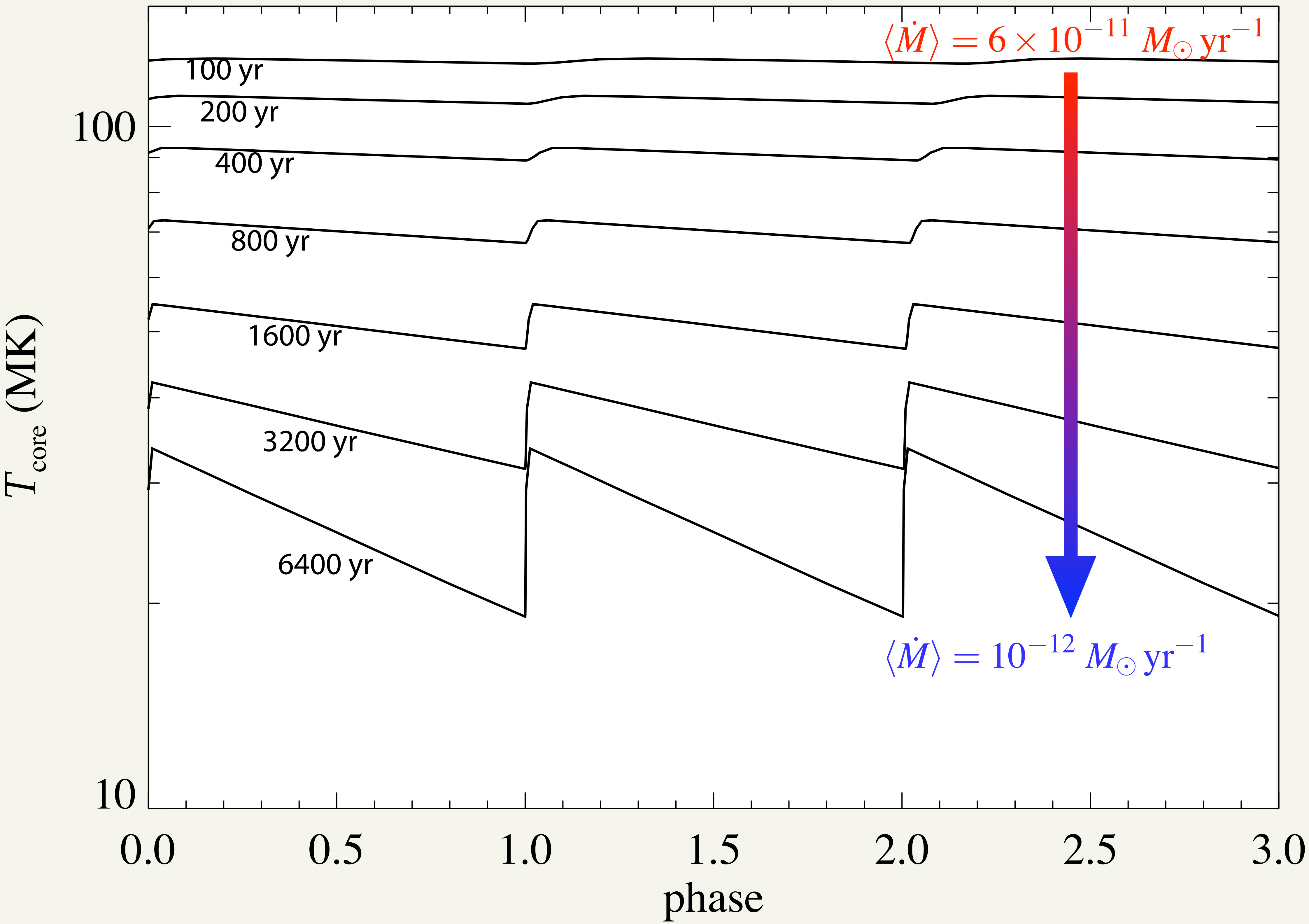
(depth) ⟶

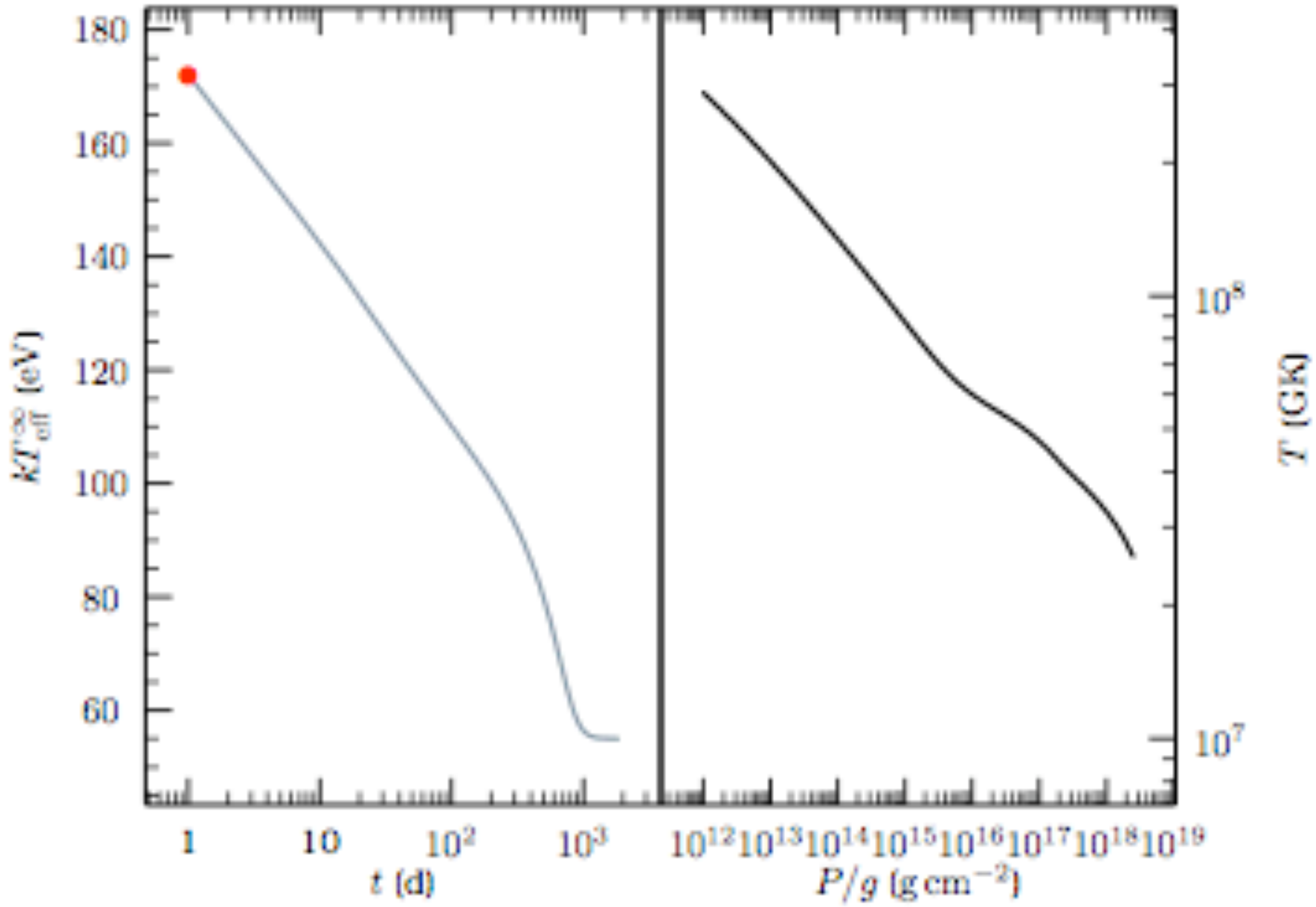
$$Q_{\mathrm{imp}} \equiv n_{\mathrm{ion}}^{-1}\sum_i n_i(Z_i - \langle Z\rangle)^2$$

$$K = \frac{\pi^2}{3}\frac{n_e k_{\mathrm{B}}^2 T}{m_e^\star \nu},$$

$$\nu_{eQ} = \frac{4\pi Q_{\mathrm{imp}} e^4 n_{\mathrm{ion}}}{p_F^2 v_F}\Lambda_{\mathrm{imp}},$$

Core temperature during outburst, recurrence cycle (1H1905)





Lightcurve from cooling crust

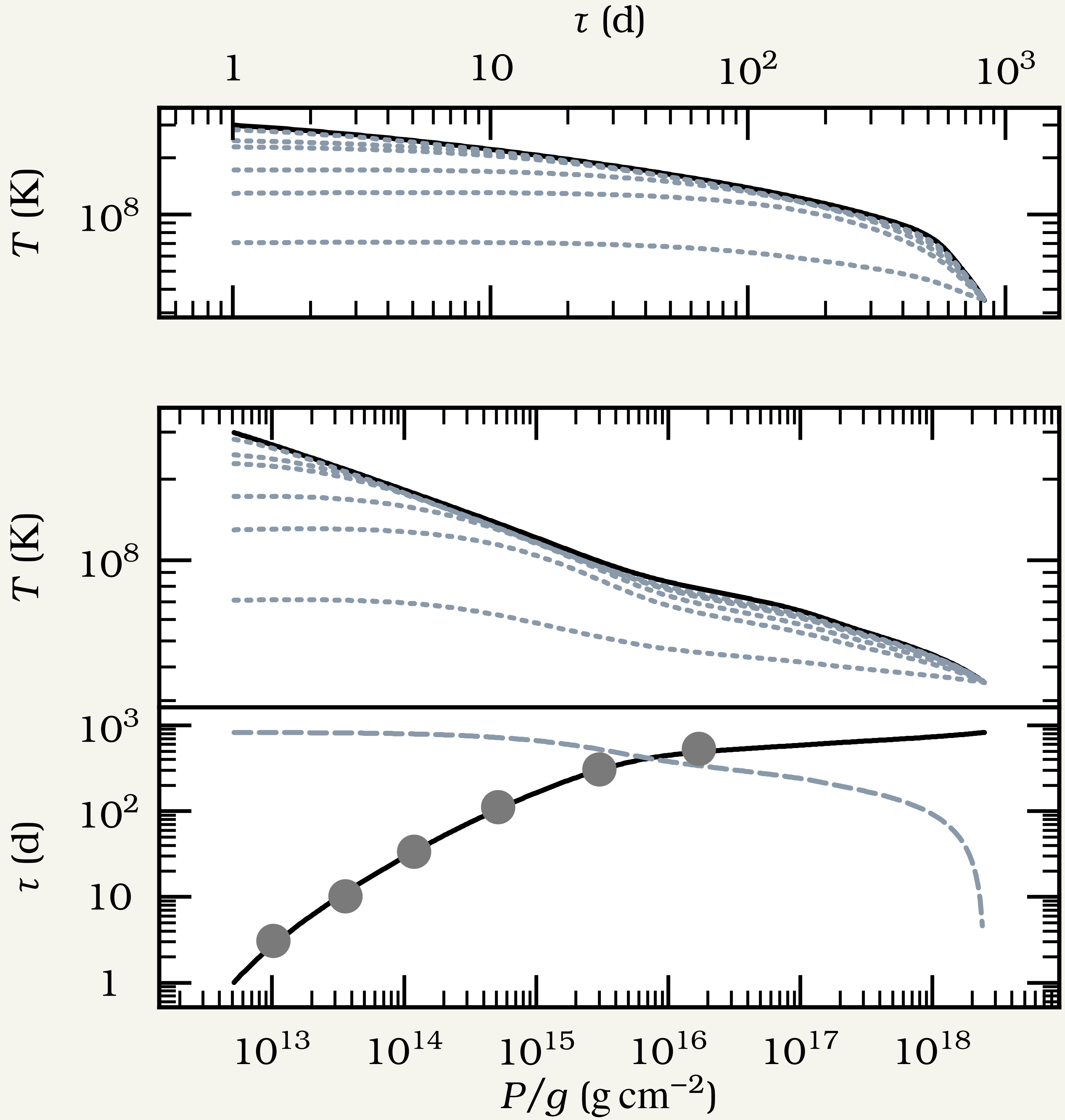
Brown & Cumming '09

For a cooling crust,

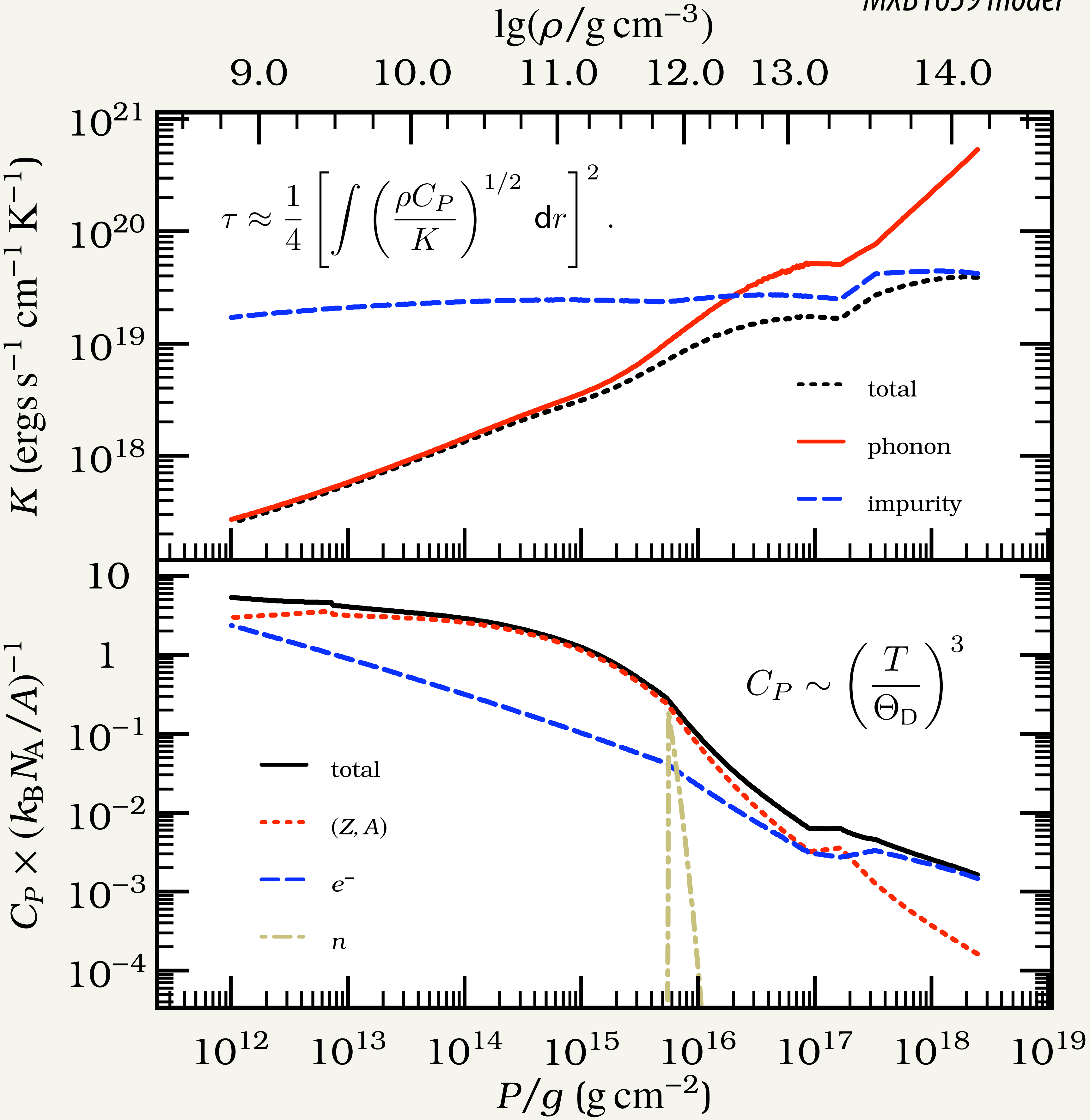
$$\rho C_P \frac{\partial T}{\partial t} = \frac{\partial}{\partial r}\left(K \frac{\partial T}{\partial r}\right),$$

and a cooling front propagates into crust on a timescale

$$\tau \approx \frac{1}{4}\left[\int \left(\frac{\rho C_P}{K}\right)^{1/2} \mathrm{d}r\right]^2 .$$

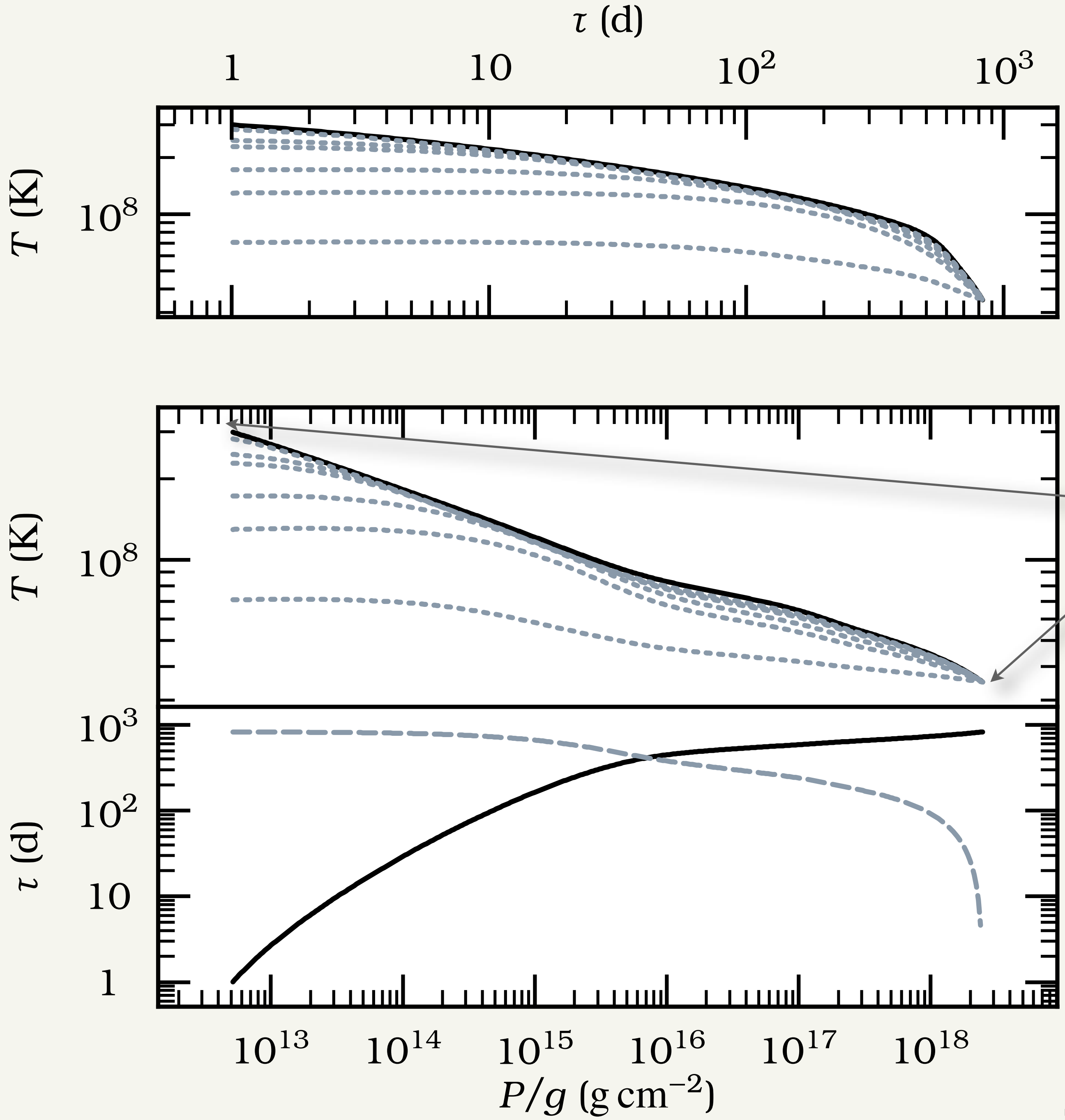


MXB1659 model

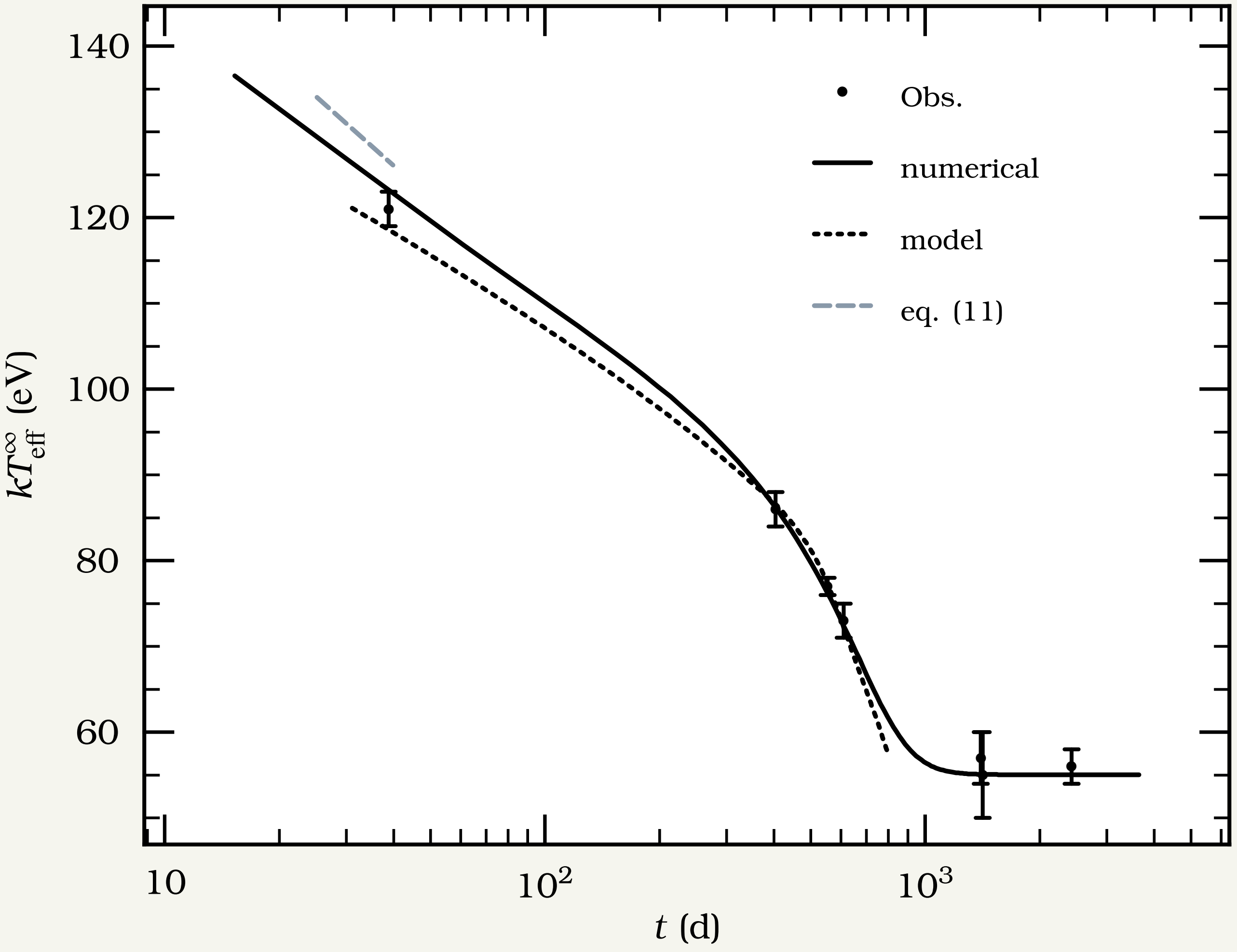


$$\tau \approx \frac{1}{4}\left[\int \left(\frac{\rho C_P}{K}\right)^{1/2} \mathrm{d}r\right]^2 .$$

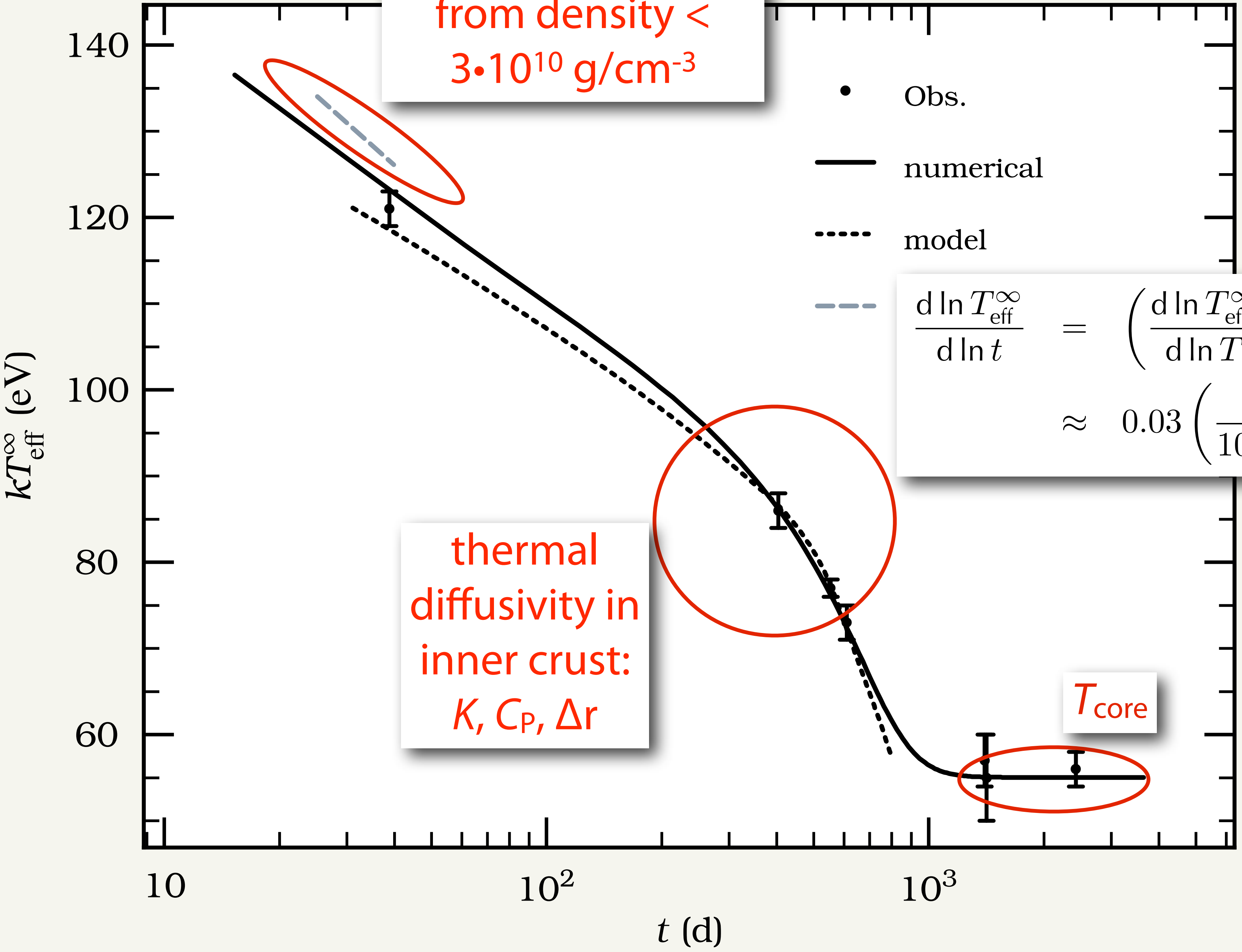
$$C_P \sim \left(\frac{T}{\Theta_\mathrm{D}}\right)^3$$



$T_{\rm core}$, $T_{\rm top}$ adjusted to fit lightcurve



power-law cooling similar to other cases:
white dwarfs in DN (Piro et al. 05)
superbursts (Cumming et al. 06),
magnetars (Eichler & Cheng 89,
Kaminker et al. 07)



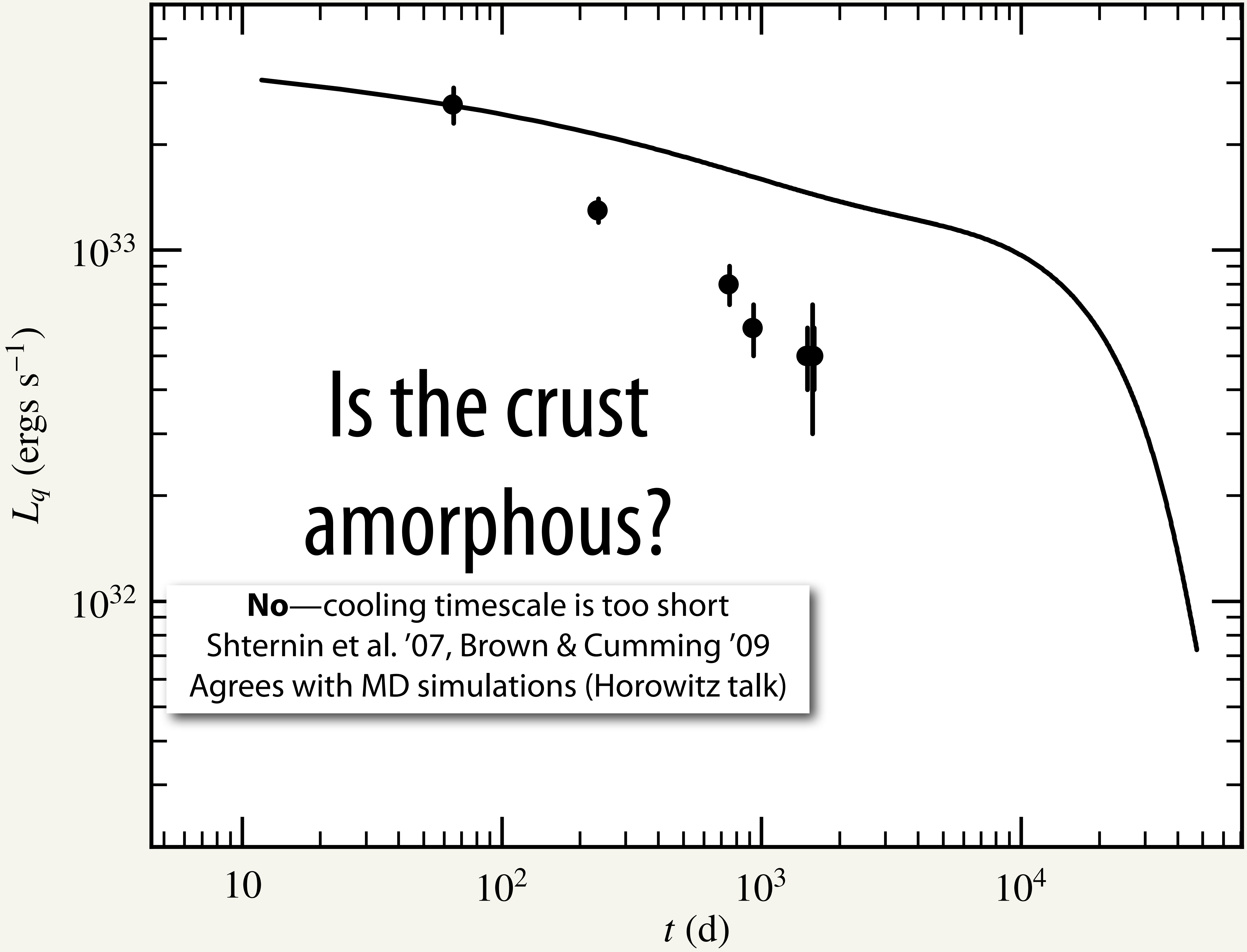
heat flux in outer crust ≈0.5 MeV/u•dM/dt from density < $3 \cdot 10^{10}$ g/cm^{-3}

$$\frac{\mathrm{d}\ln T_{\mathrm{eff}}^{\infty}}{\mathrm{d}\ln t} = \left(\frac{\mathrm{d}\ln T_{\mathrm{eff}}^{\infty}}{\mathrm{d}\ln T}\right)\left(\frac{\mathrm{d}\ln T}{\mathrm{d}\ln y}\right)\left(\frac{\mathrm{d}\ln y}{\mathrm{d}\ln \tau}\right) \approx 0.03\left(\frac{F}{10^{21}\ \mathrm{ergs\,s^{-1}\,cm^{-2}}}\right),$$

thermal diffusivity in inner crust: K, C_P, Δr

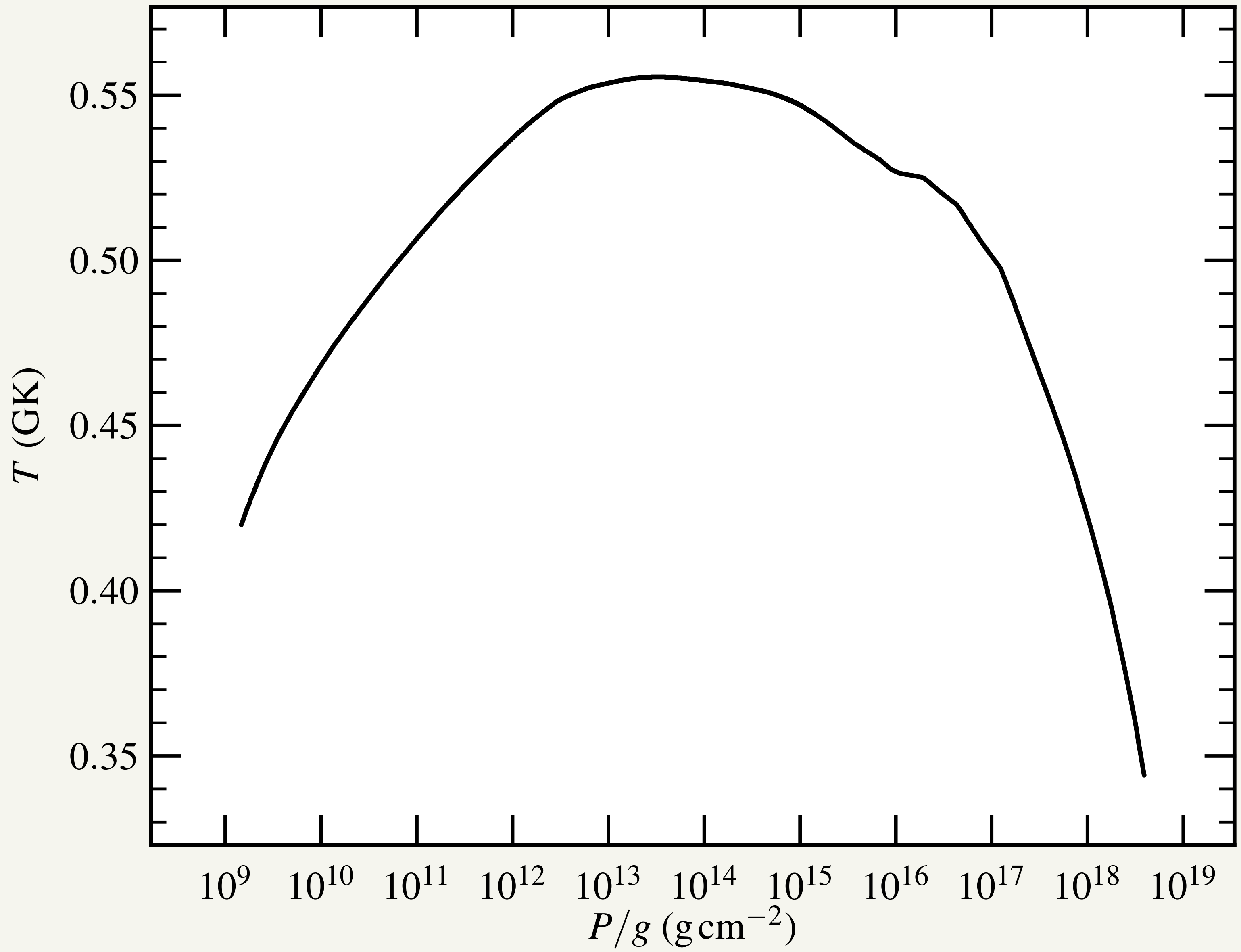
T_{core}

KS1731 data



Is the crust amorphous?

No—cooling timescale is too short
Shternin et al. ’07, Brown & Cumming ’09
Agrees with MD simulations (Horowitz talk)



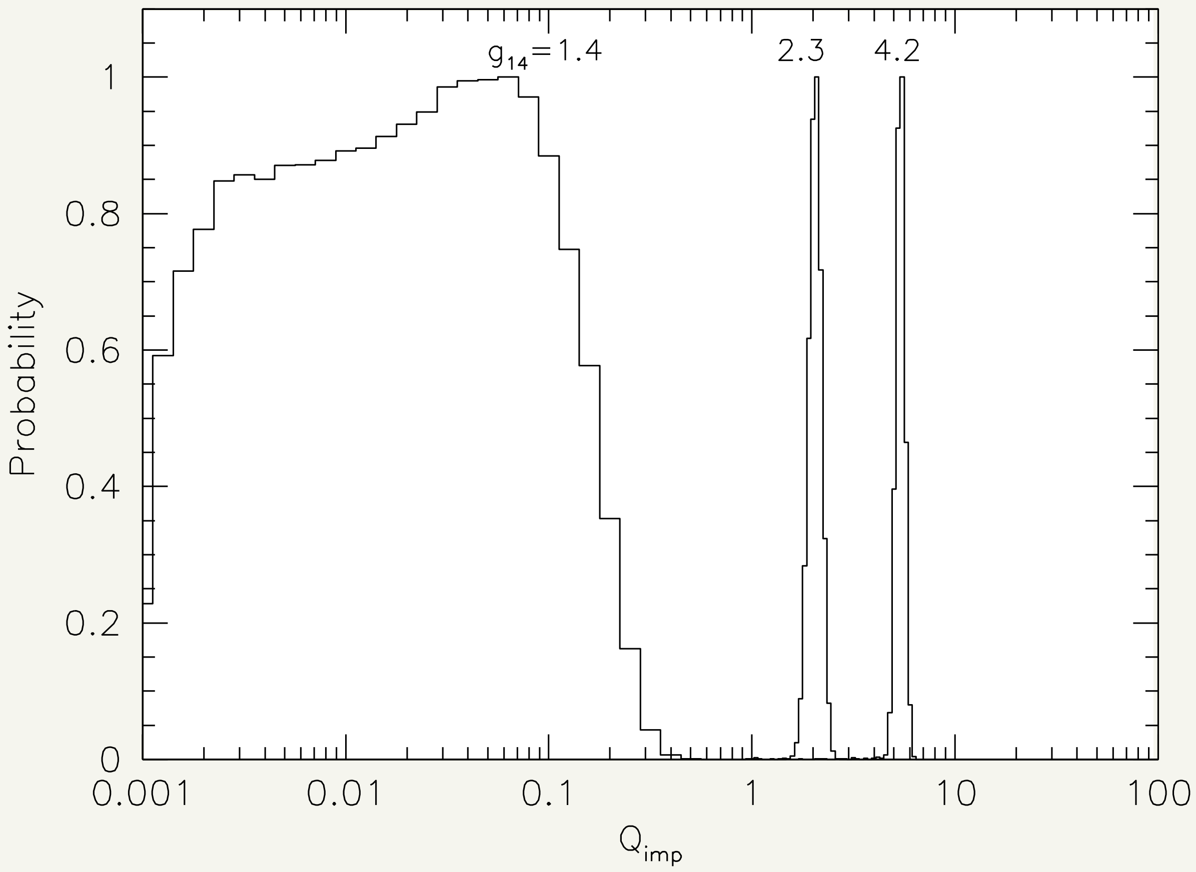
thermal profile, amorphous crust

constraints on $Q_{\rm imp}$

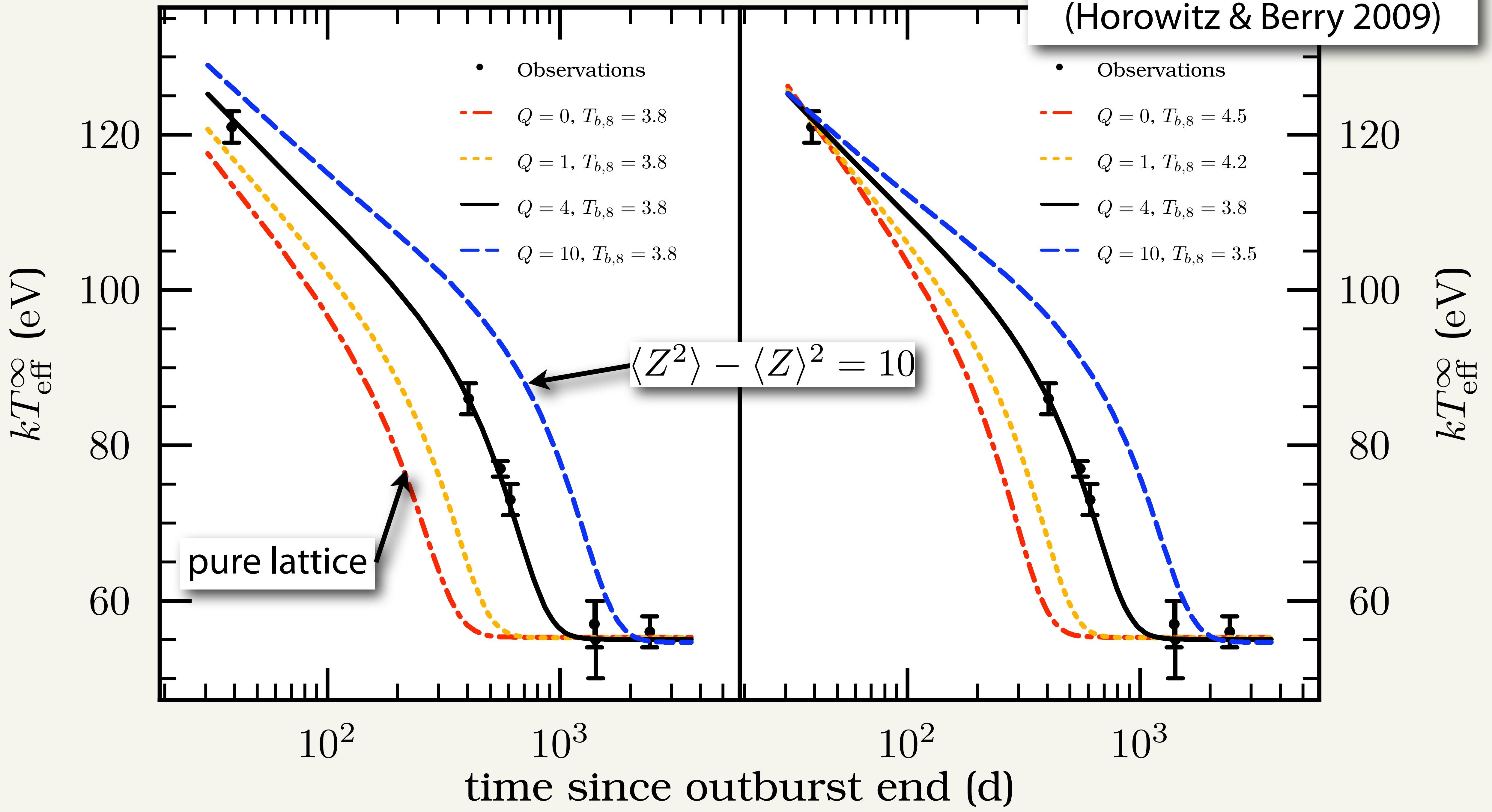
- use approximate model in Markov Chain Monte Carlo
    - $Q_{\rm imp} < 10$
    - agrees with Shternin et al. '08
    - degenerate with gravity, accretion rate
        - crust thickness (Lattimer et al. '94)

$$\tau \propto \left(\frac{R^2}{GM}\right)^2 \left(1 - \frac{2GM}{Rc^2}\right)^{1/2}$$

Brown & Cumming 09



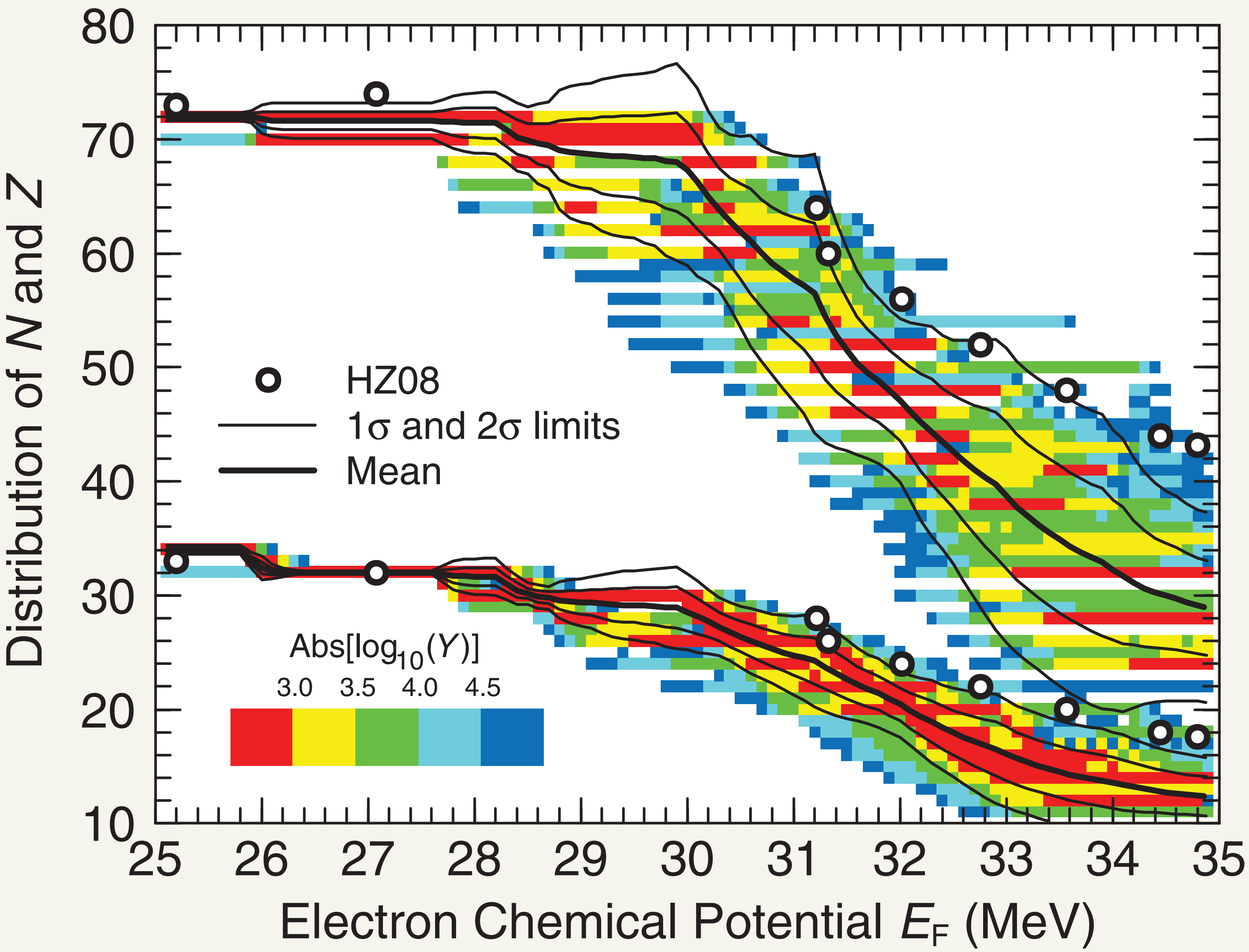
crust impurities



rp-process ashes: $Q_{\rm imp} \approx 23$
(Horowitz & Berry 2009)

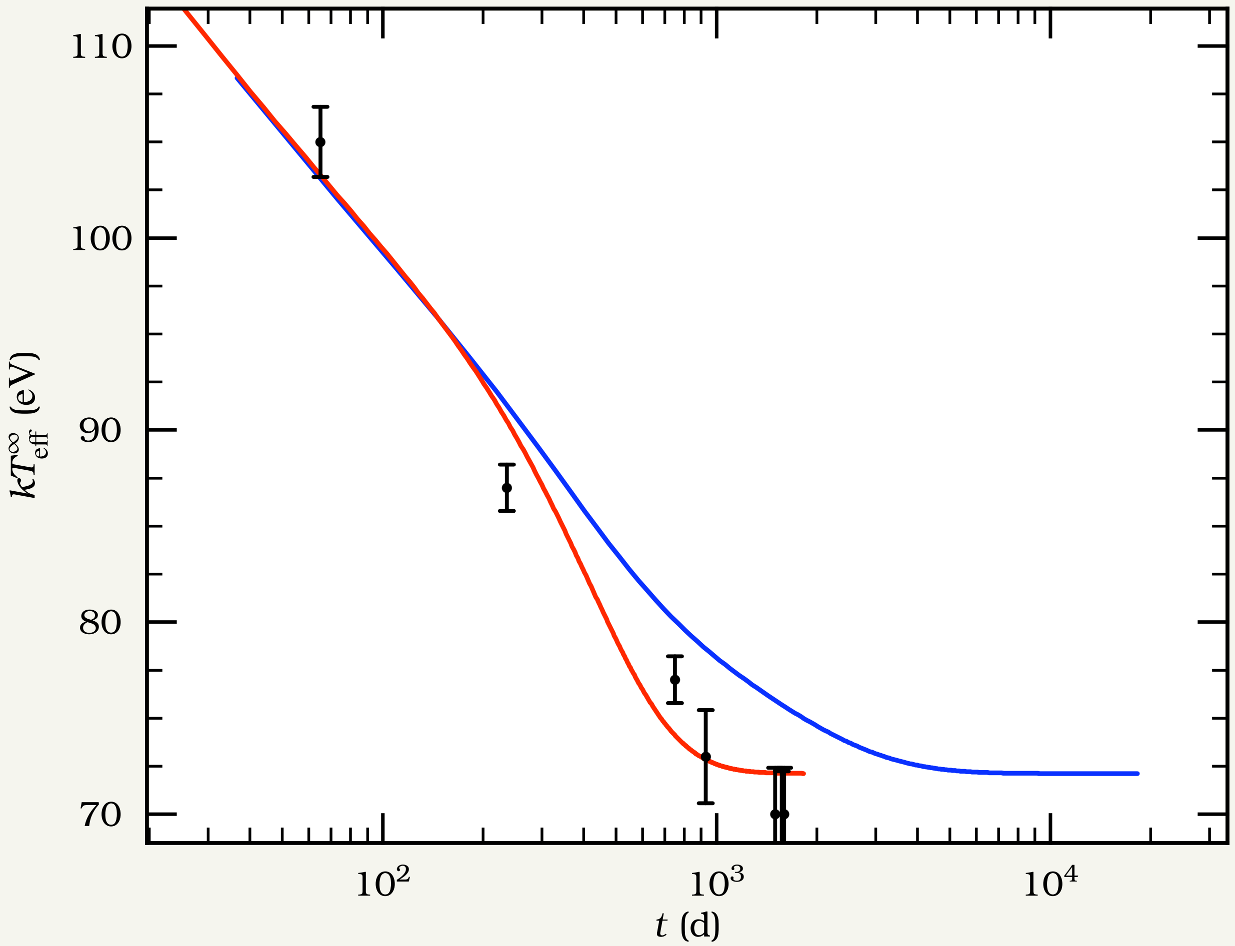
$\langle Z^2\rangle - \langle Z\rangle^2 = 10$

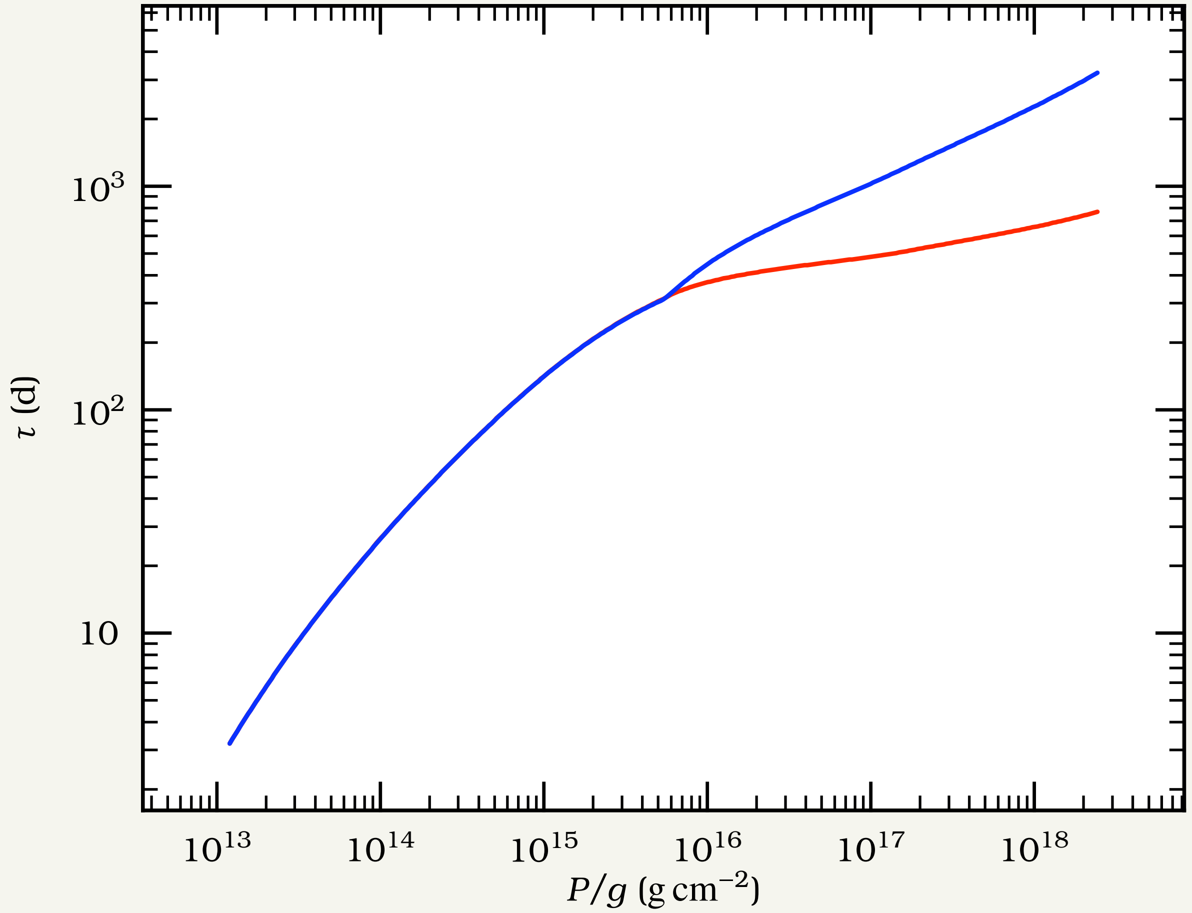
pure lattice



Reactions post-neutron drip; Gupta et al. 08

superfluid n in inner crust





- If crust *n* are not superfluid
- greater C_P lengthens diffusion timescale

Ushomirsky & Rutledge '01, Shternin et al. '07, Brown & Cumming '09

summary

- observations of neutron star transients provide information on core temperature, crust conductivity & thickness, and crust heating
  - consistent with regular lattice with low Q_{imp} in inner crust
  - do nuclear processes in the inner force low Q_{imp}? does it follow that all neutron stars have identical inner crusts?
  - implications for raising mountains in the crust (Bildsten 98, Ushomirsky 00, Haskell 06)
- much progress is being made on modeling the composition from photosphere to core