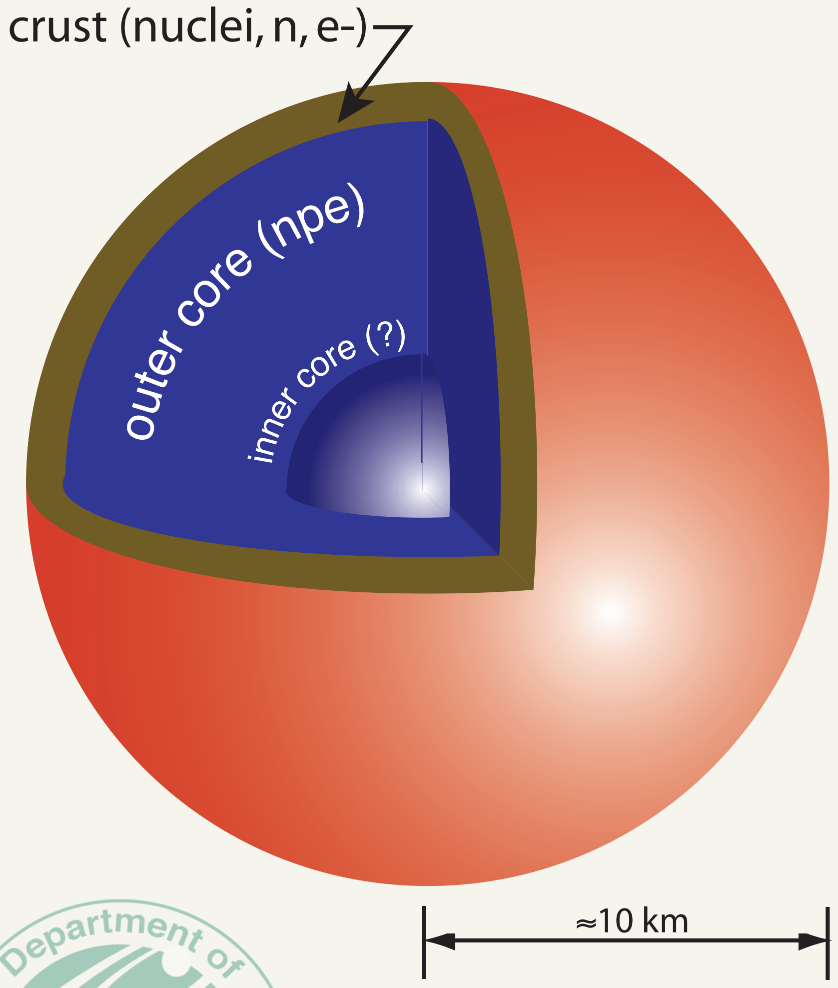
accreting neutron stars

edward brown



outline

- observations of cooling neutron star crusts
  - constraints on transport properties
  - core neutrino emissivity
  - nuclear reactions in outer crust

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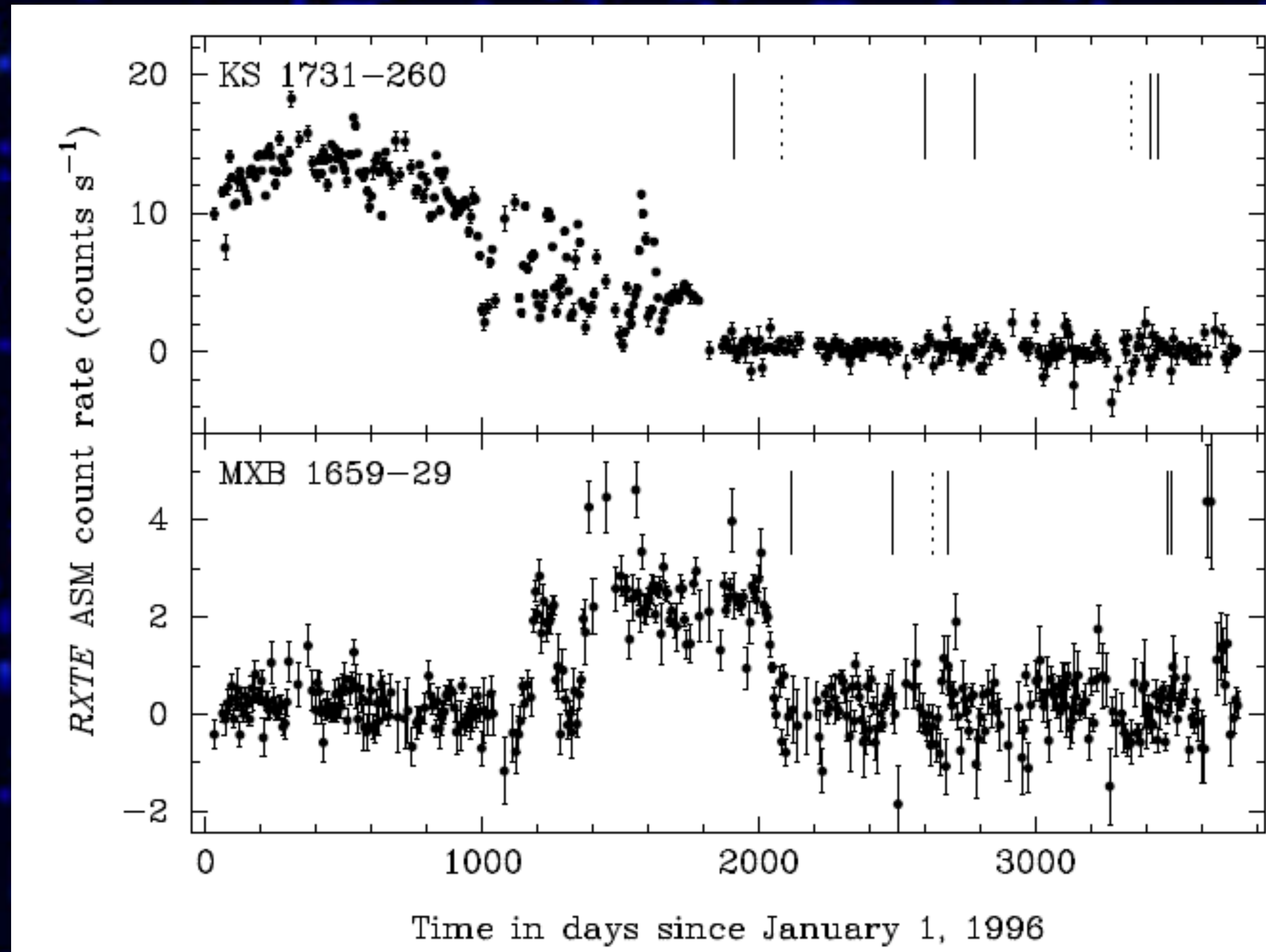
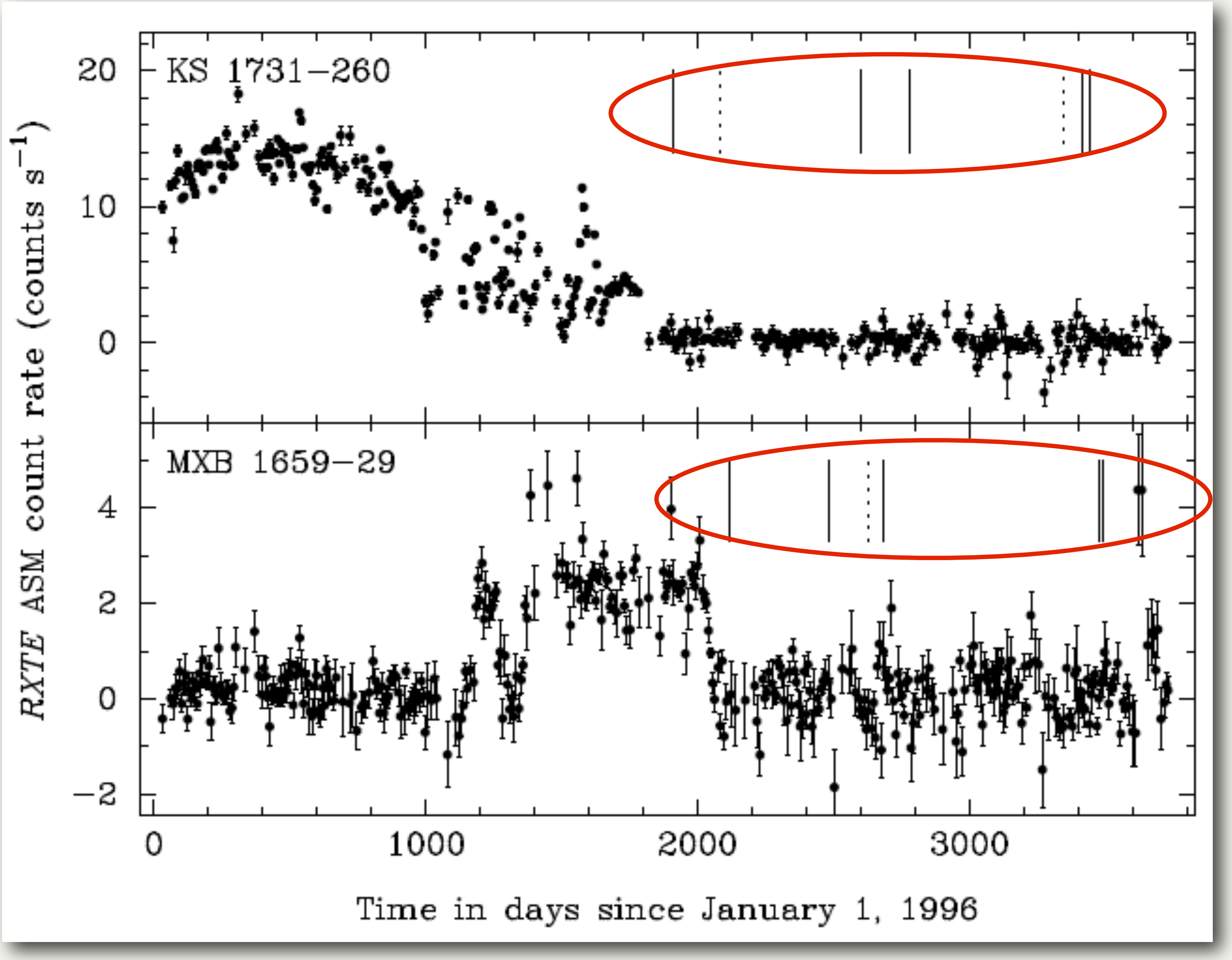
fig. from Cackett et al. '06



observations

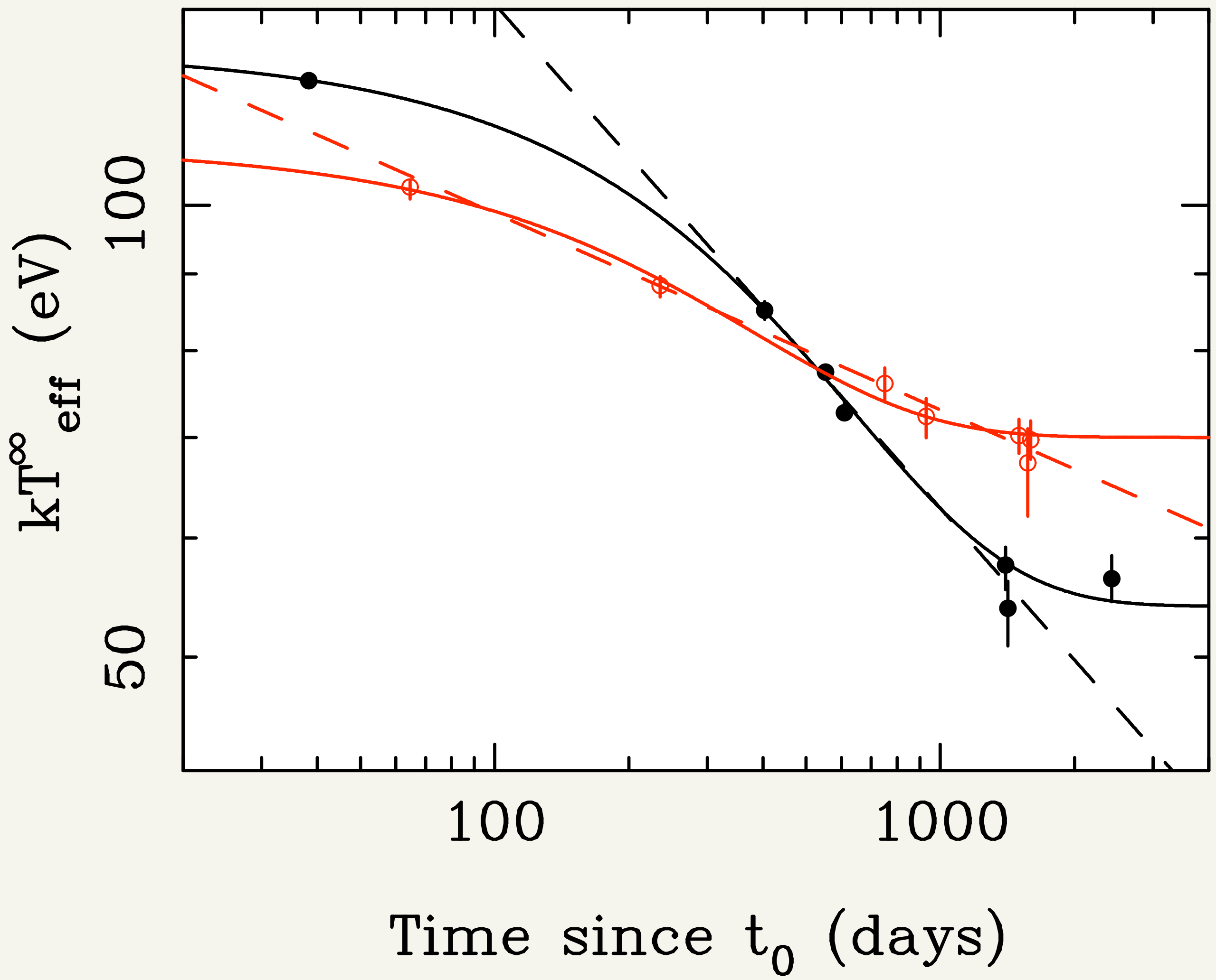
- *rxte* monitoring observations discover *quasi-persistent* transients
- rutledge et al. ’02 suggest looking for thermal relaxation of crust during quiescence
- observations (wijnands, cackett) detect this cooling



quiescent lightcurves

- Wijnands et al., Cackett et al. measured this cooling
- Shternin '07 suggested that crust must have a high thermal conductivity
- **This talk:** what we can learn from the lightcurve about the thermal state and transport properties of the neutron star crust (Brown & Cumming '08)

Cackett et al. '08



crust models

- hydrostatic structure
  - fixed core structure
  - APR eos
  - mass = 1.6 $M_{\rm sun}$
  - inner crust: Mackie & Baym neutron eos, relativistic deg. electrons
- solve time-dependent thermal equations on fixed hydrostatic grid

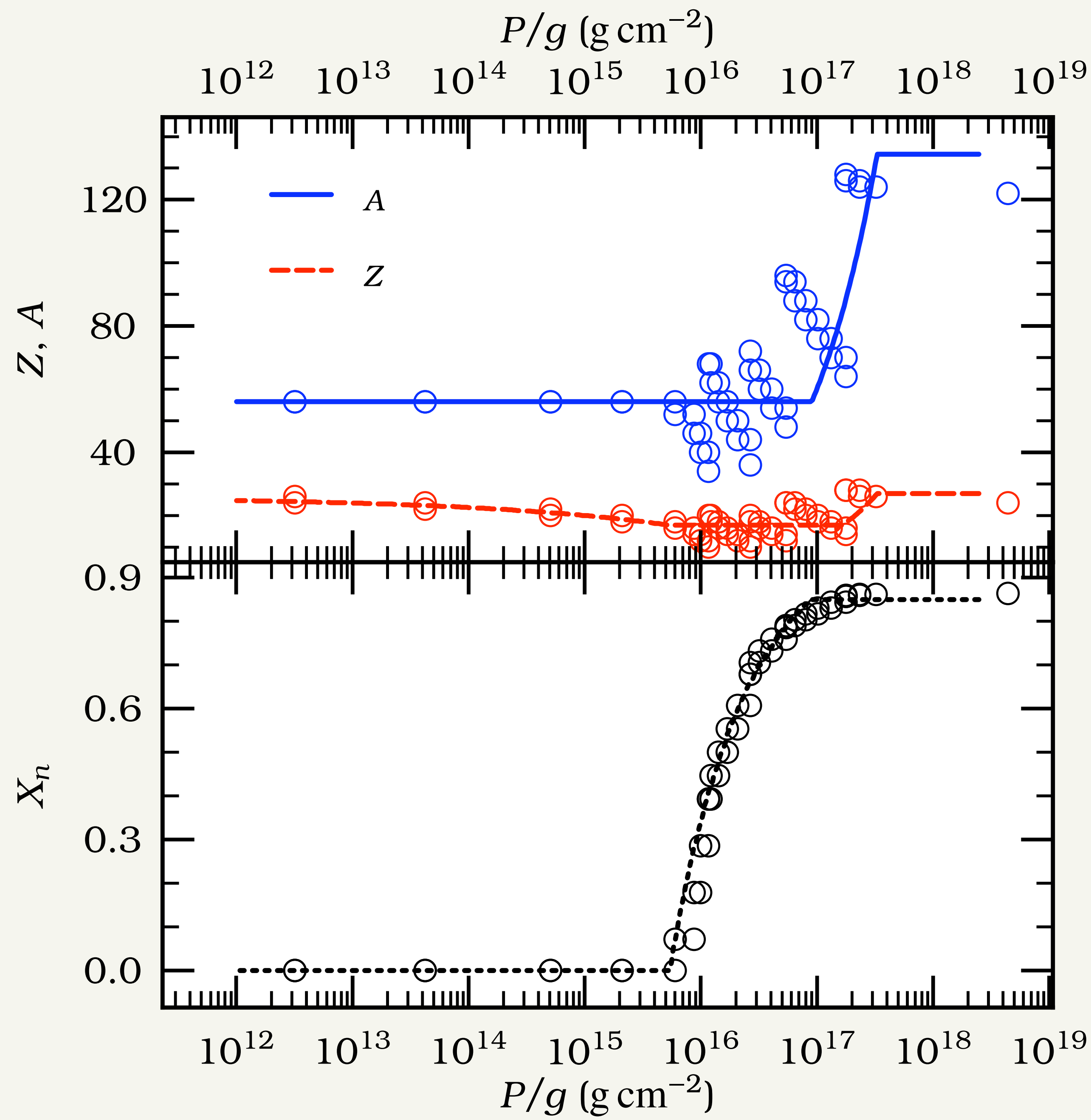
$$\frac{\mathrm{d}r}{\mathrm{d}\ln P} = -\frac{P}{\rho g}(1+z)^{-1},$$
$$\frac{\mathrm{d}M}{\mathrm{d}\ln P} = -4\pi r^2 \frac{P}{g},$$
$$\frac{\mathrm{d}\phi}{\mathrm{d}\ln P} = -\frac{P}{\rho}.$$

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

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

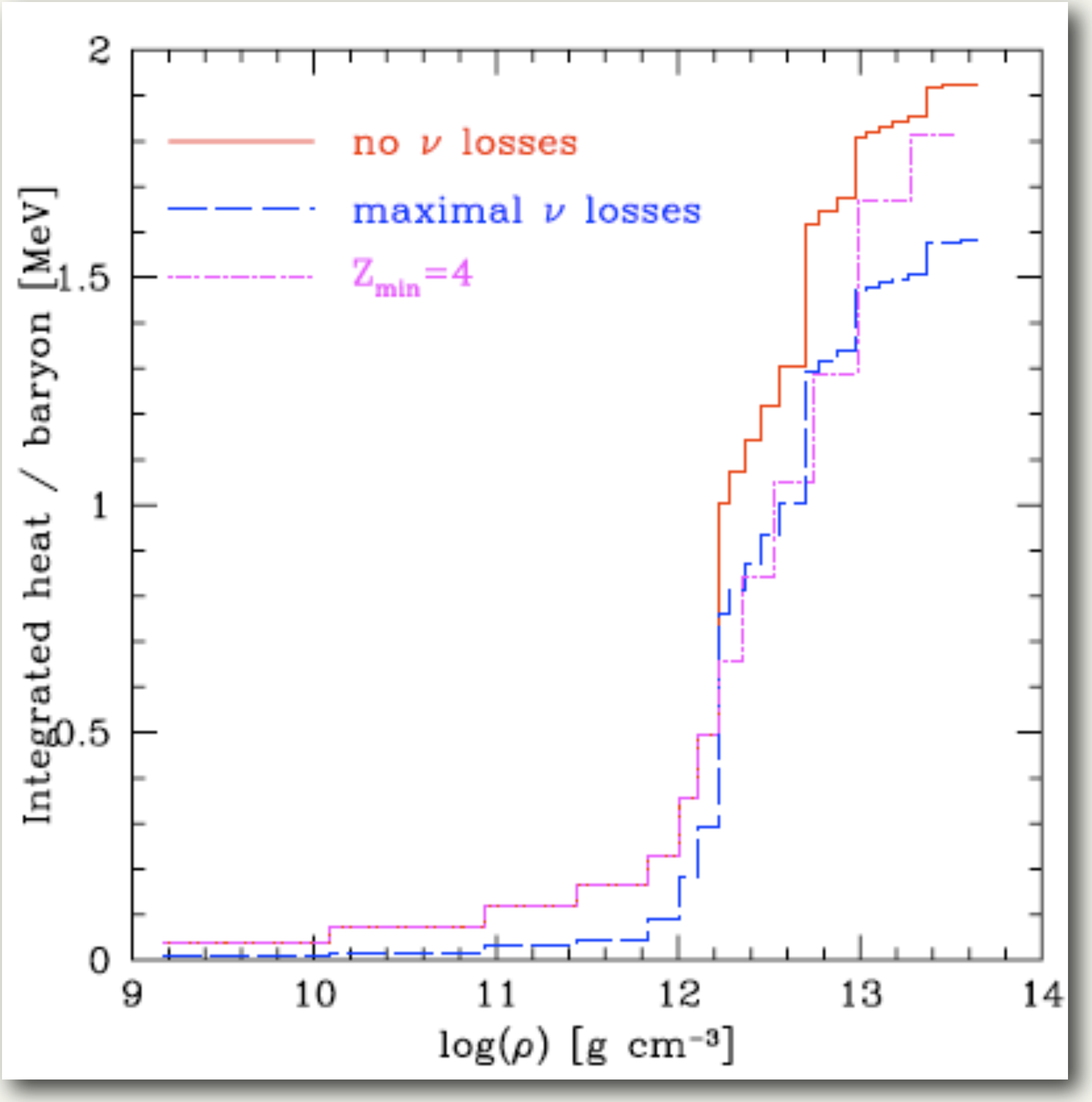
Crust composition

Haensel & Zdunik 08



Integrated heating, HZ08

- heating rate is proportional to *dM/dt*
- outer crust: electron captures
- inner crust: electron captures, neutron emissions, pycnonuclear reactions
- relatively insensitive to composition (but see Gupta et al. '07, '08)



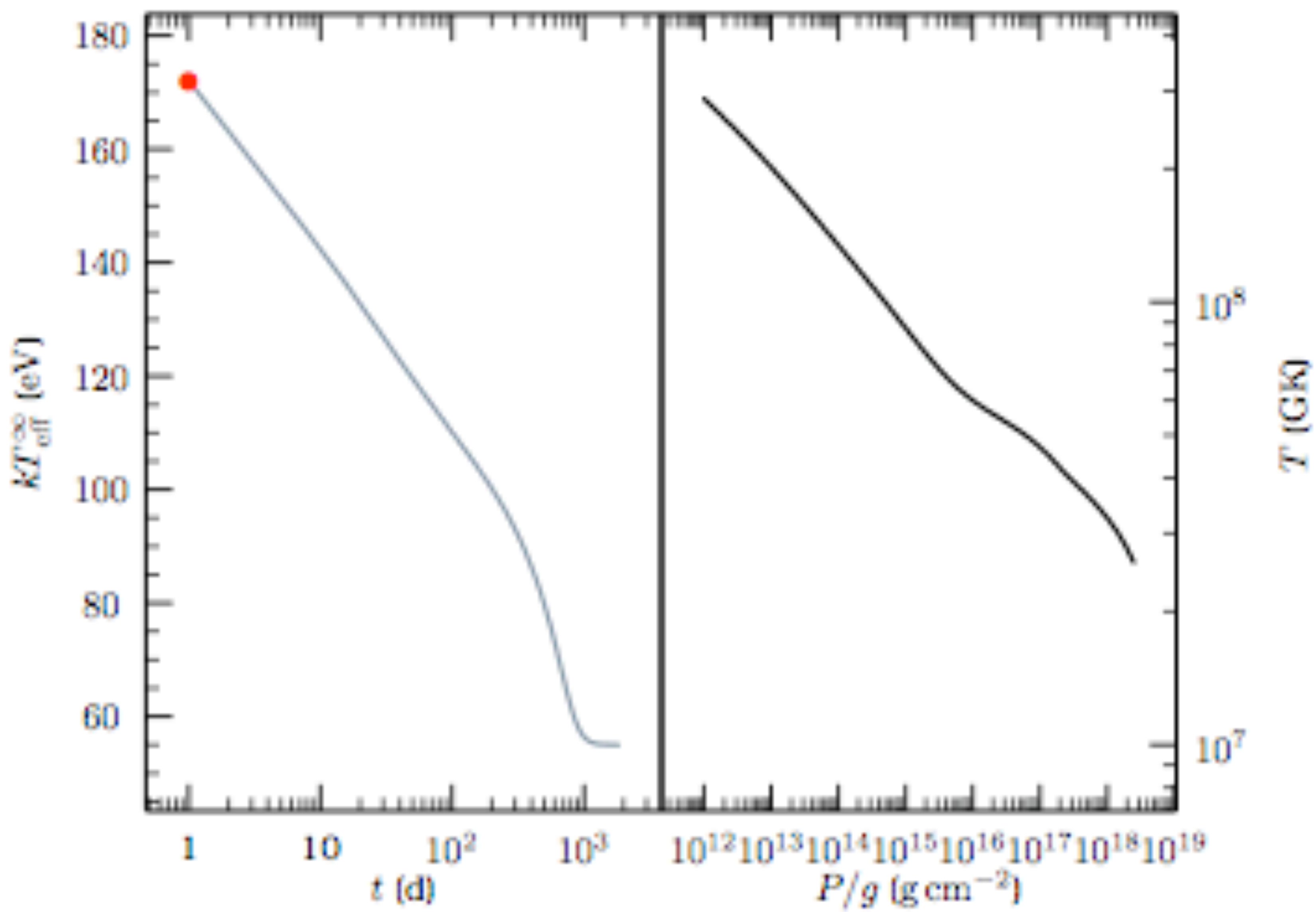
crust models

- 3 parameters that we adjust
  - T_{top}
  - T_{core}
  - Q_{imp}

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

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

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

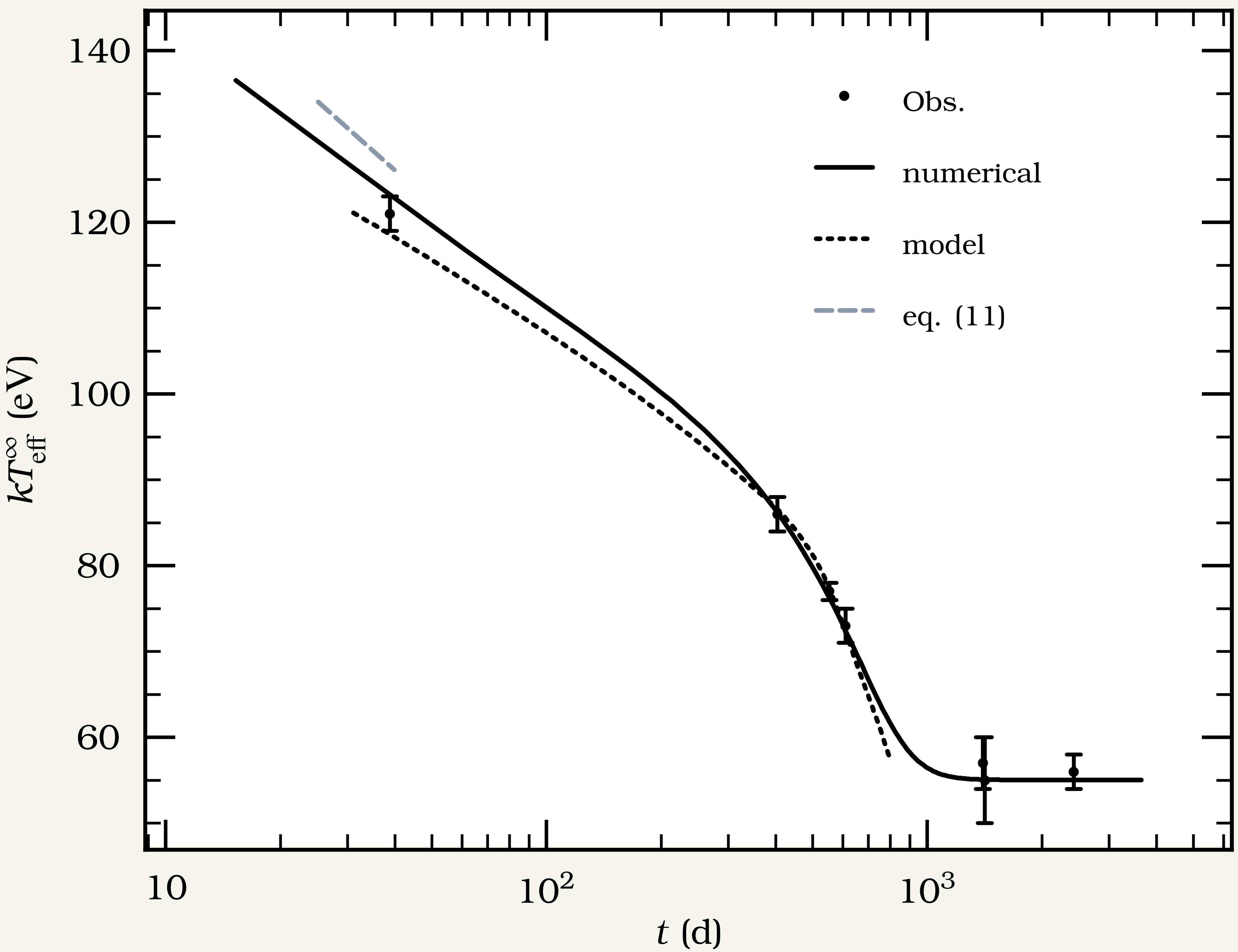


Cooling, MXB 1659–522

Brown & Cumming '08

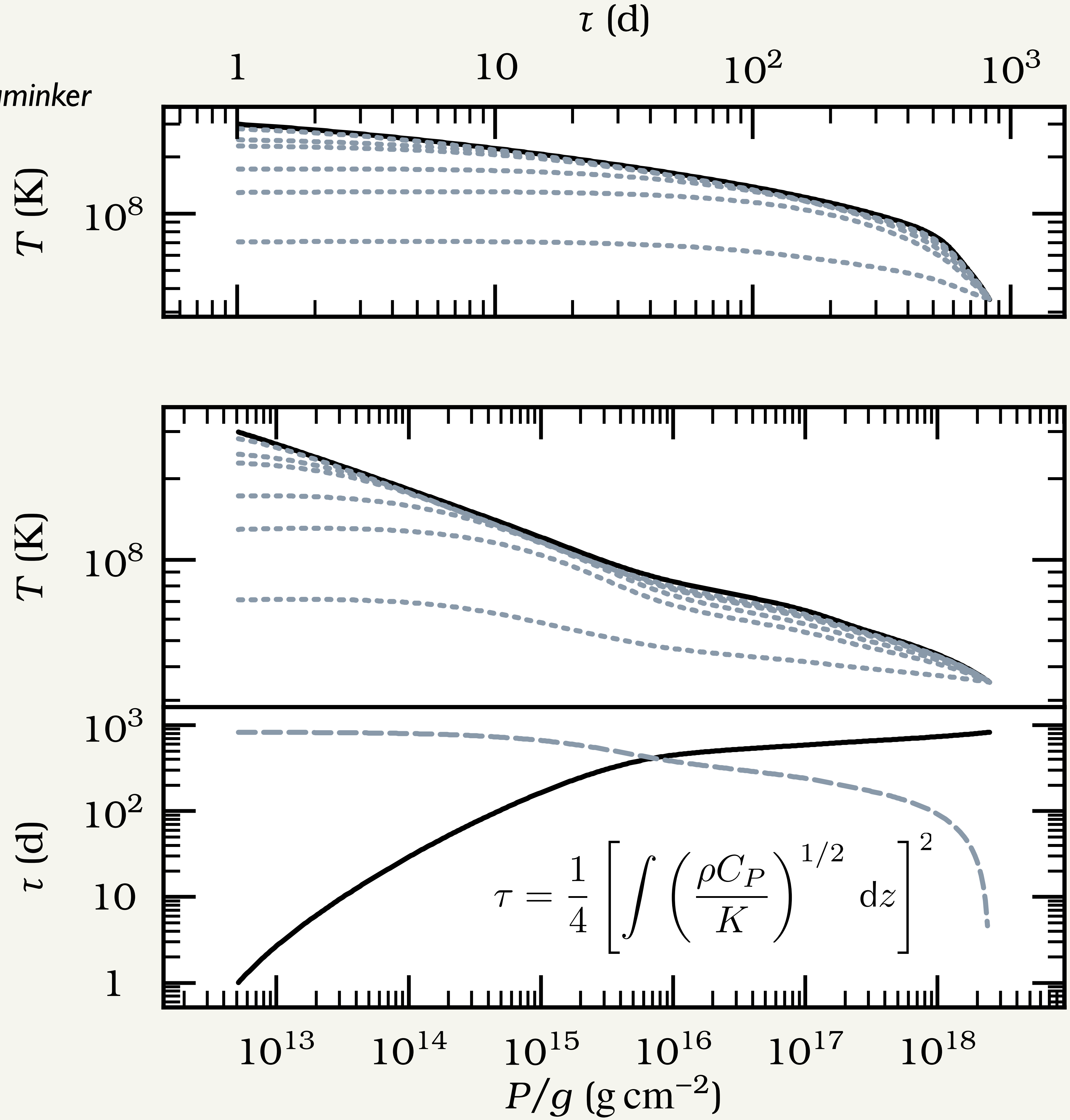
best fit, MXB1659

Brown & Cumming '08

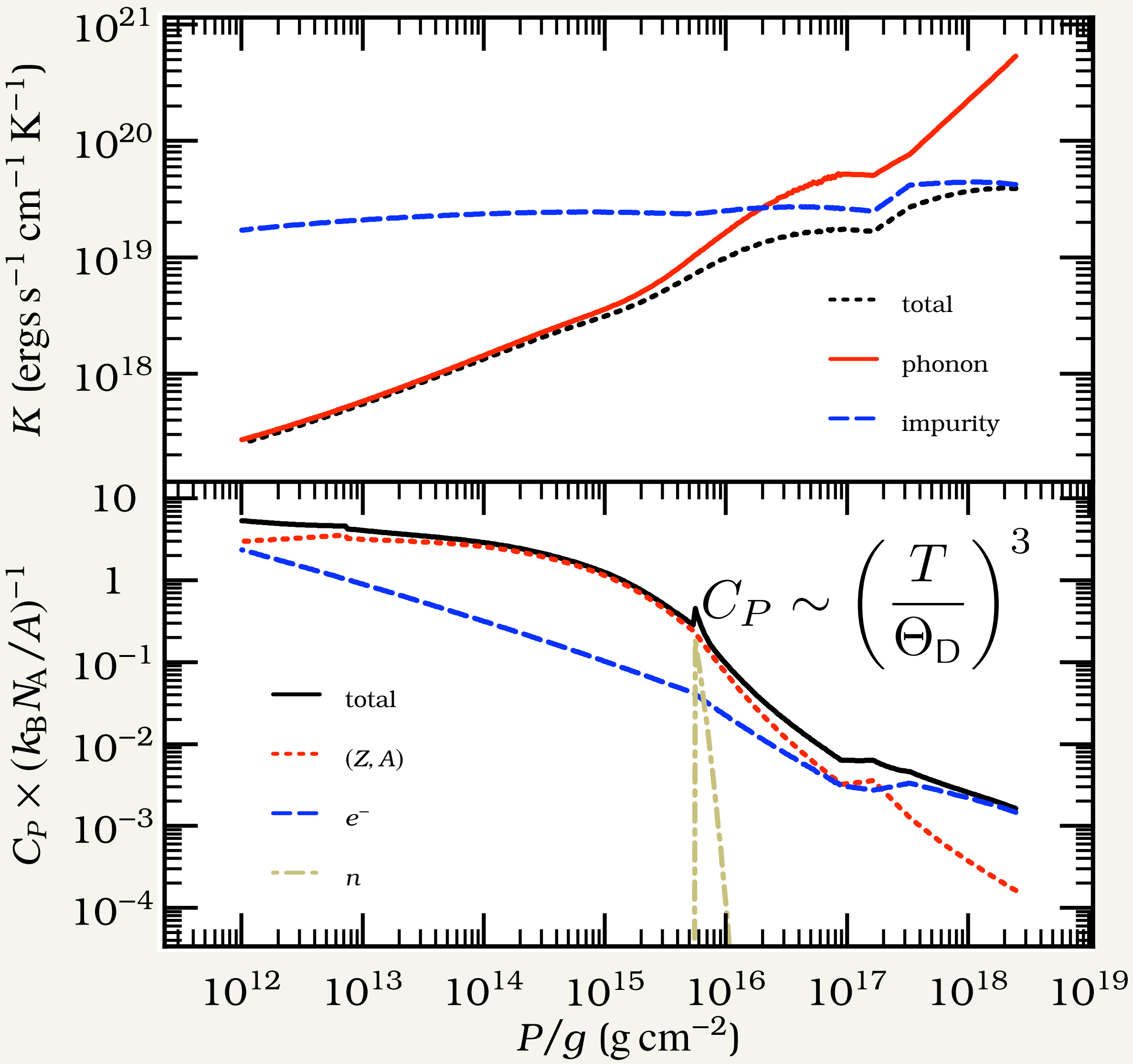


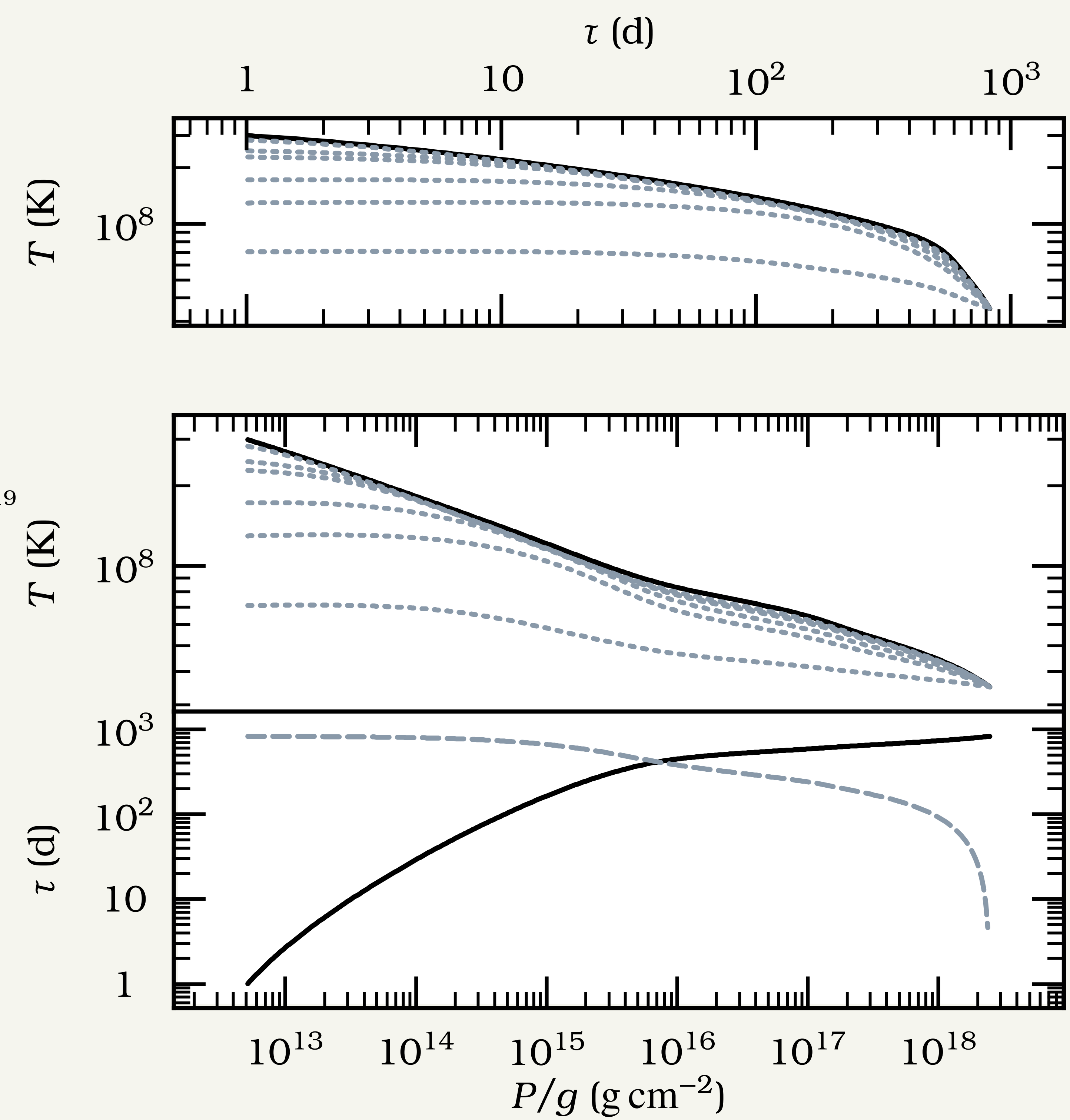
power-law cooling similar to other cases: white dwarfs in DN (Piro et al. 05) superbursts (Cumming et al. 06), magnetars (Eichler & Cheng 89, Kaminker et al. 07)

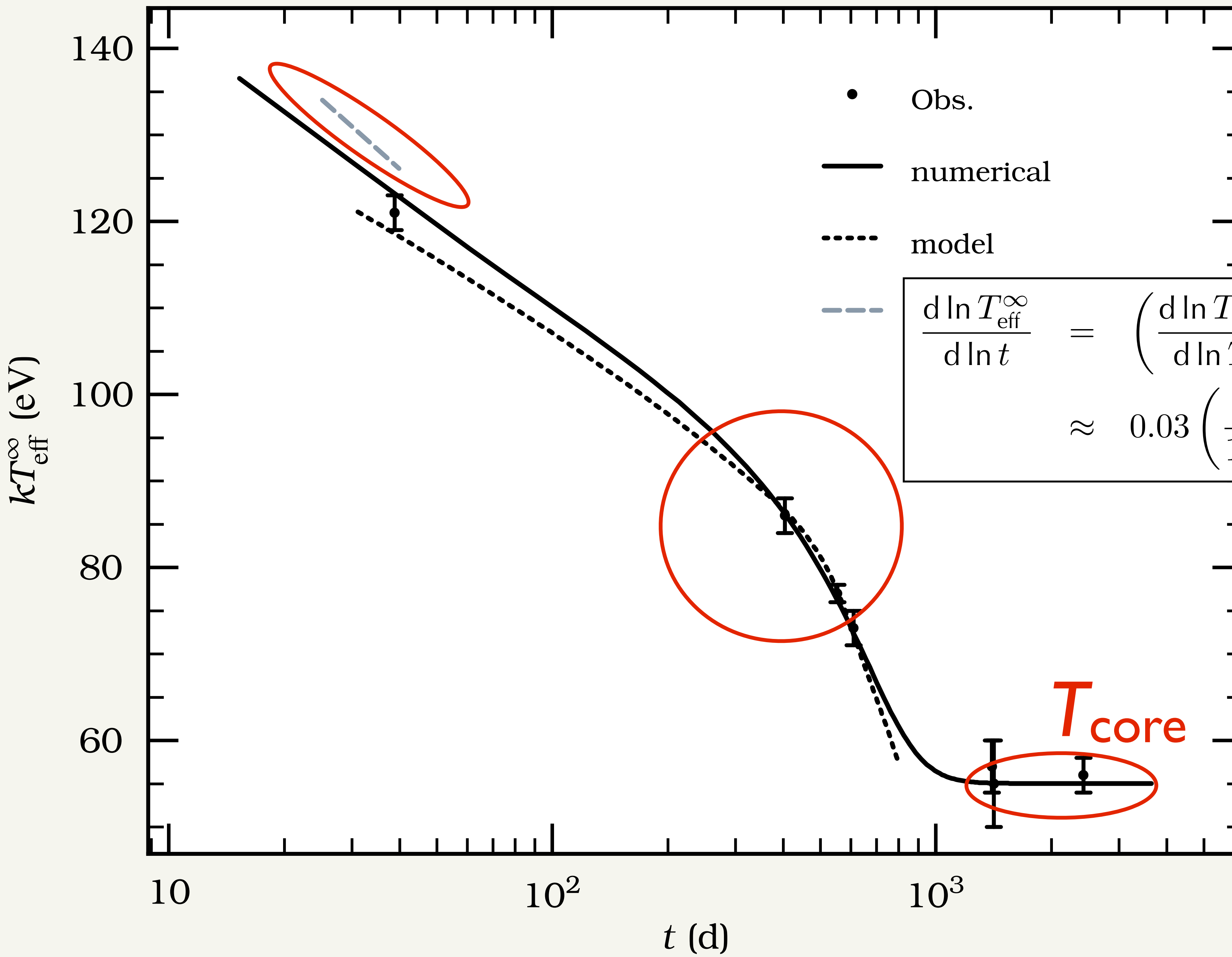
Can "invert" the lightcurve to infer the temperature profile



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



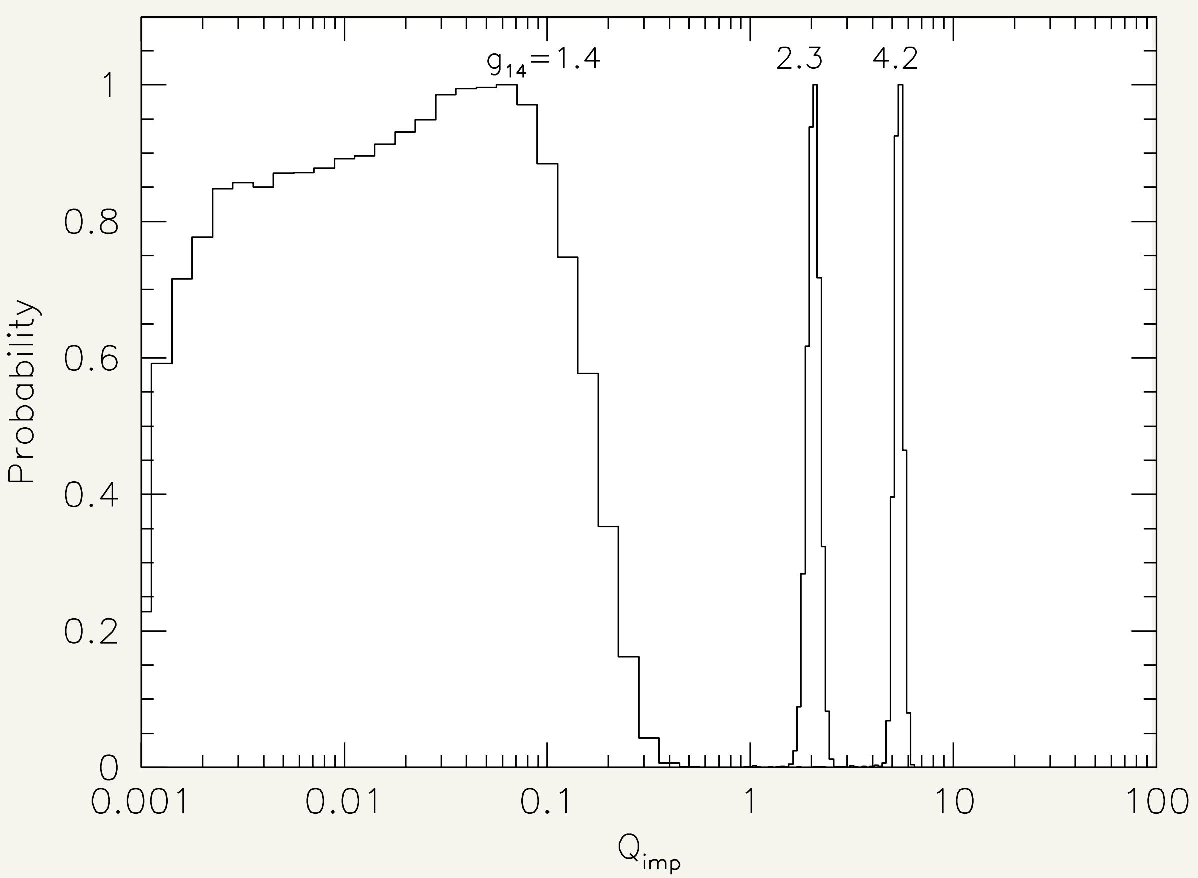




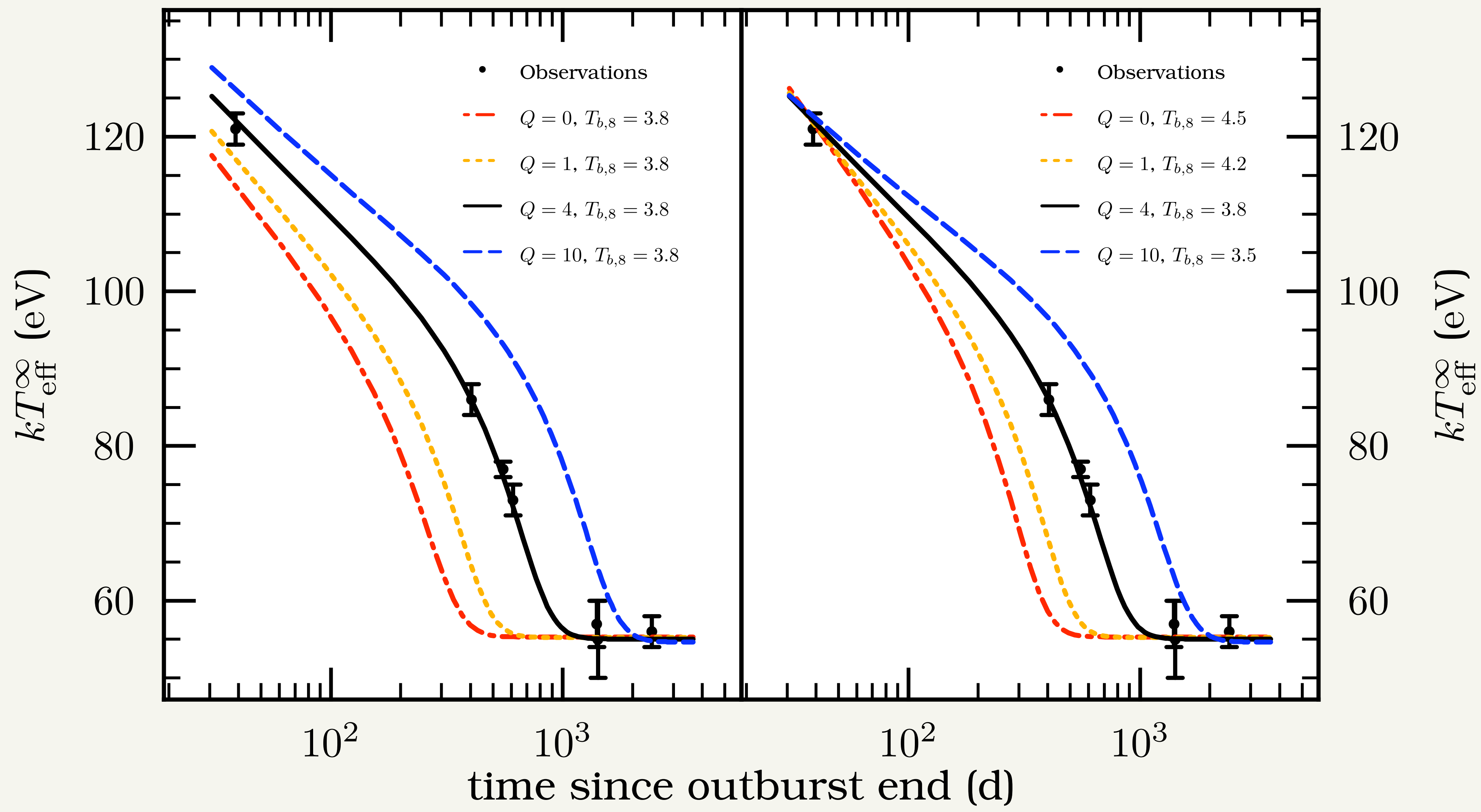
$$\frac{d\ln T_{\rm eff}^{\infty}}{d\ln t} = \left(\frac{d\ln T_{\rm eff}^{\infty}}{d\ln T}\right)\left(\frac{d\ln T}{d\ln y}\right)\left(\frac{d\ln y}{d\ln \tau}\right) \approx 0.03\left(\frac{F}{10^{21}\ {\rm ergs\,s^{-1}\,cm^{-2}}}\right),$$

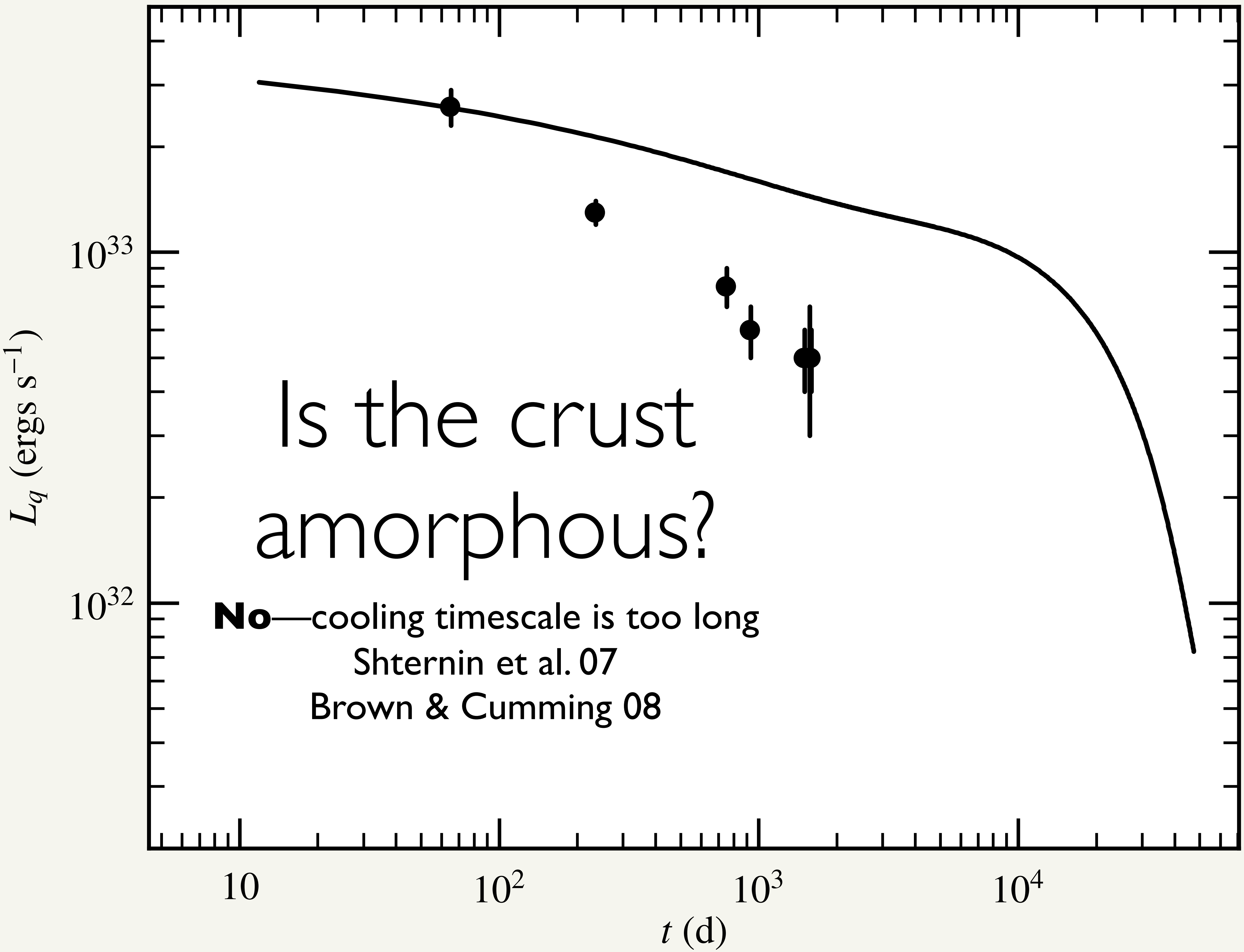
monte carlo using approximate model

- observations fix thermal conductivity of inner crust
  - $Q_{imp} < 10$
  - agrees with Shternin et al. ’08
  - degenerate with gravity, accretion rate
    - crust thickness (Lattimer et al. ’94)
    - $\tau \propto (\Delta r)^2 (1+z)^3$



Effect of impurity parameter Q

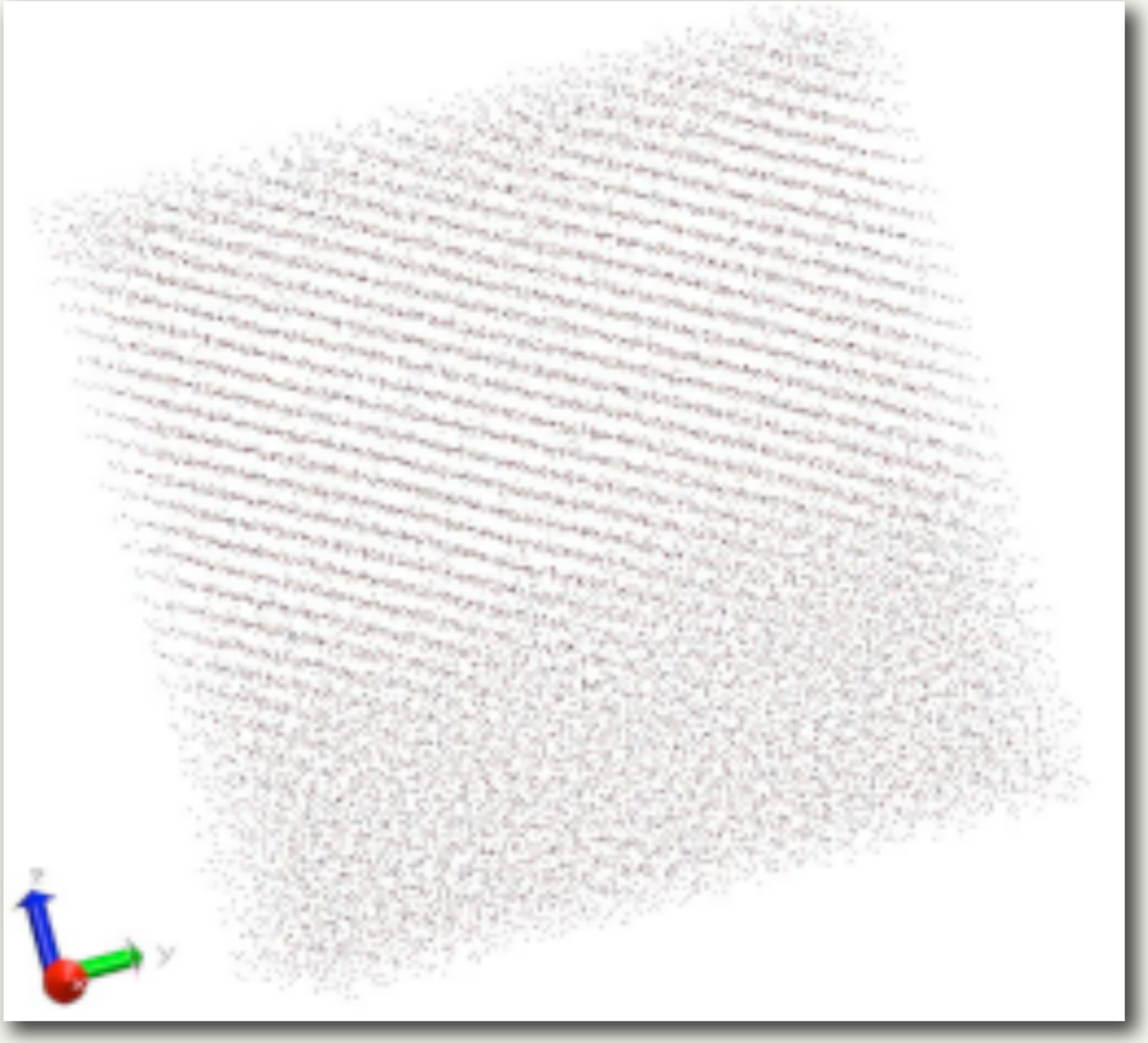


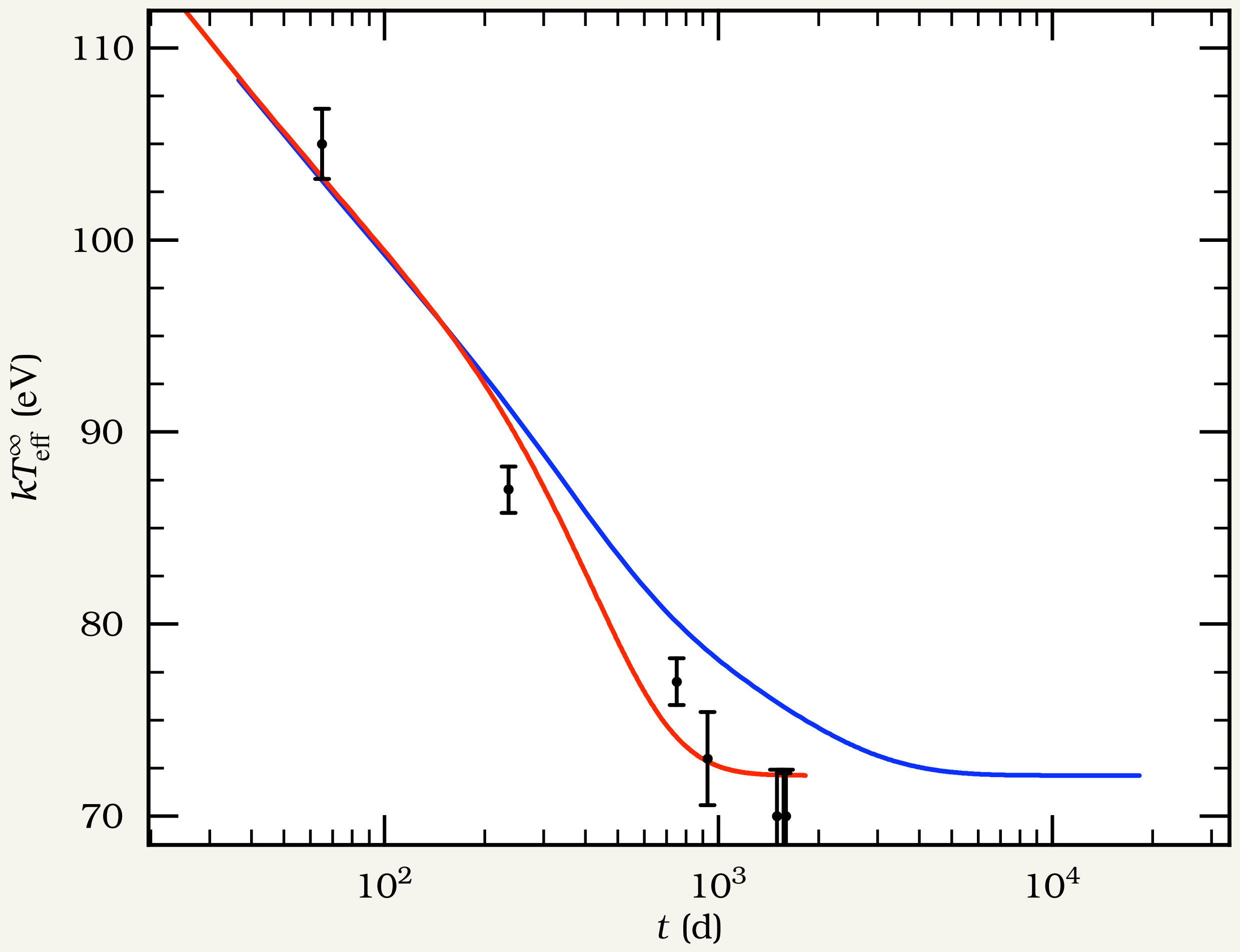


Is the crust amorphous?
No—cooling timescale is too long
Shternin et al. 07
Brown & Cumming 08
L_q (ergs s^{-1})
10^{33}
10^{32}
10
10^2
10^3
10^4
t (d)

Implications

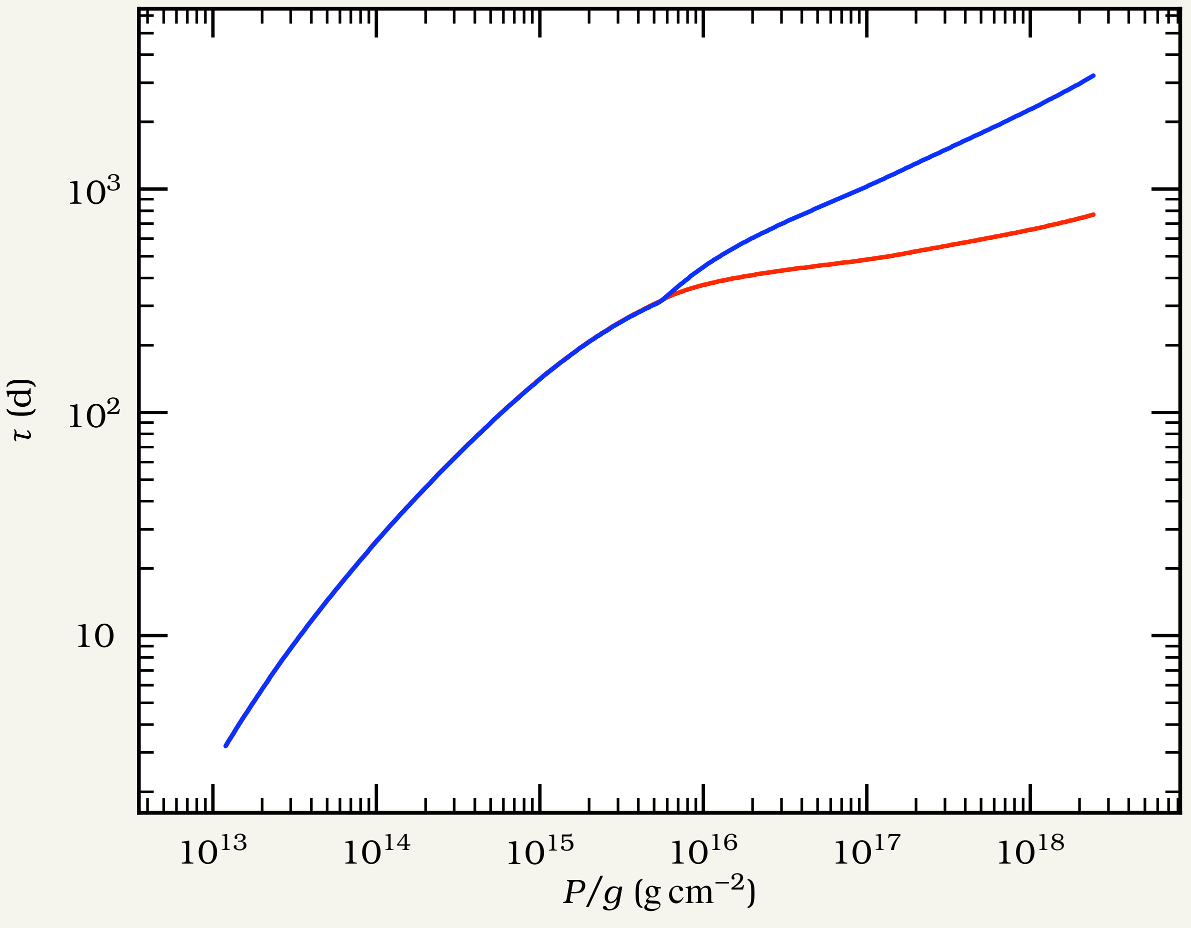
- Crust has high thermal conductivity (**not amorphous**)—agrees with MD simulations (Horowitz et al. 07, 08); cf. Shternin et al. (07)





If crust *n* are not superfluid

greater C_P lengthens diffusion timescale



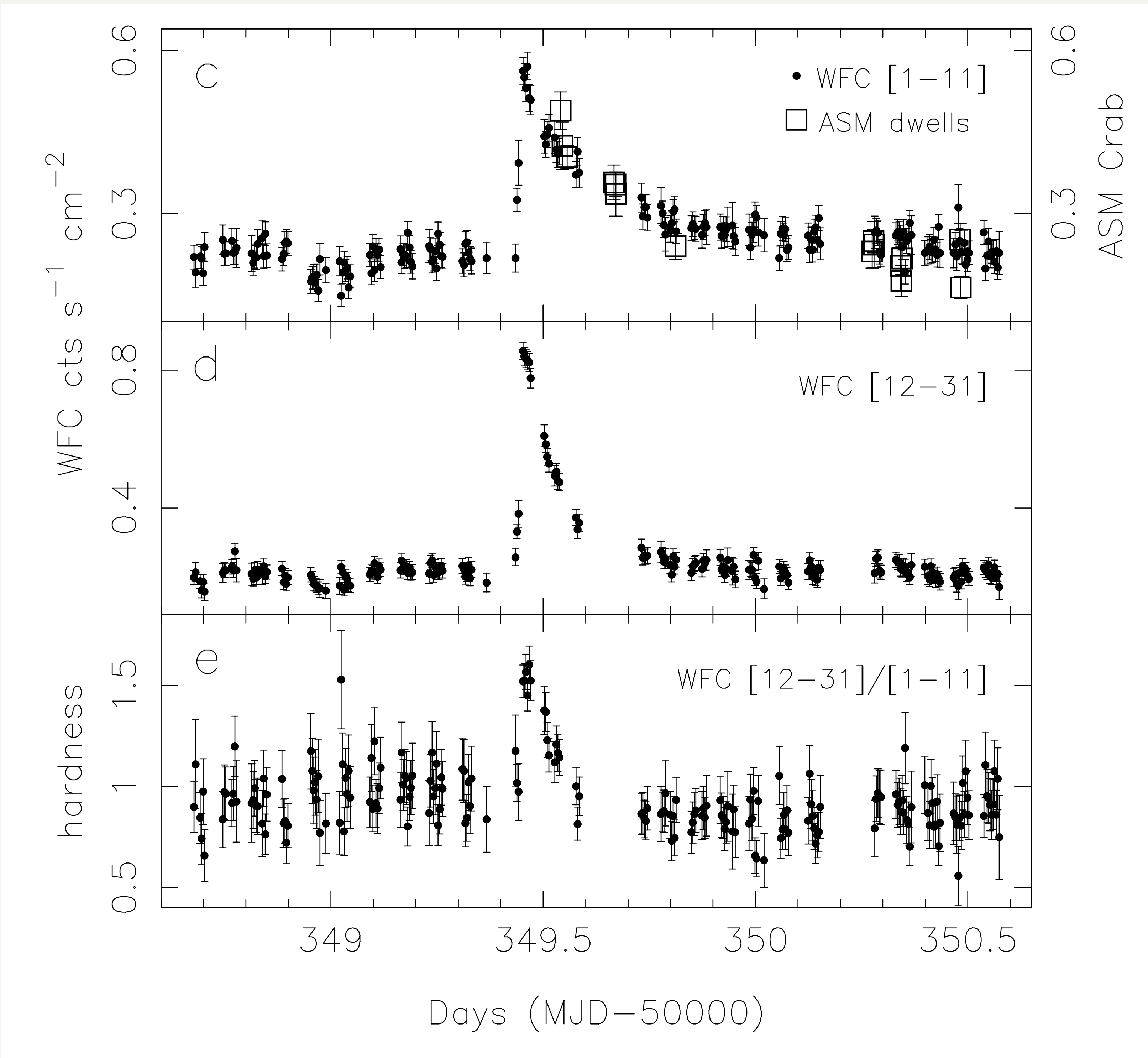
what can we learn from cooling transients?

- thermal timescale in the "outer" inner crust
  - combination of conductivity, crust thickness, specific heat
- core temperature
  - interpretation of neutrino cooling requires knowing the time-averaged *dMdt*
- distribution of heating in the crust

Is the heating consistent with other phenomena?

- Look to unstable nuclear burning in the neutron star atmosphere
  - temperature sensitive ignition
  - temperature in NS atmosphere, ocean depends on thermal flux if no other heat sources (H fusion)

KS 1731–260 superburst (Kuulkers 2002)



- About 10^3 more energetic than type I XRB (H, He burning)
- cooling time ~ hrs
- recurrence time ~ yrs

Determining ignition mass

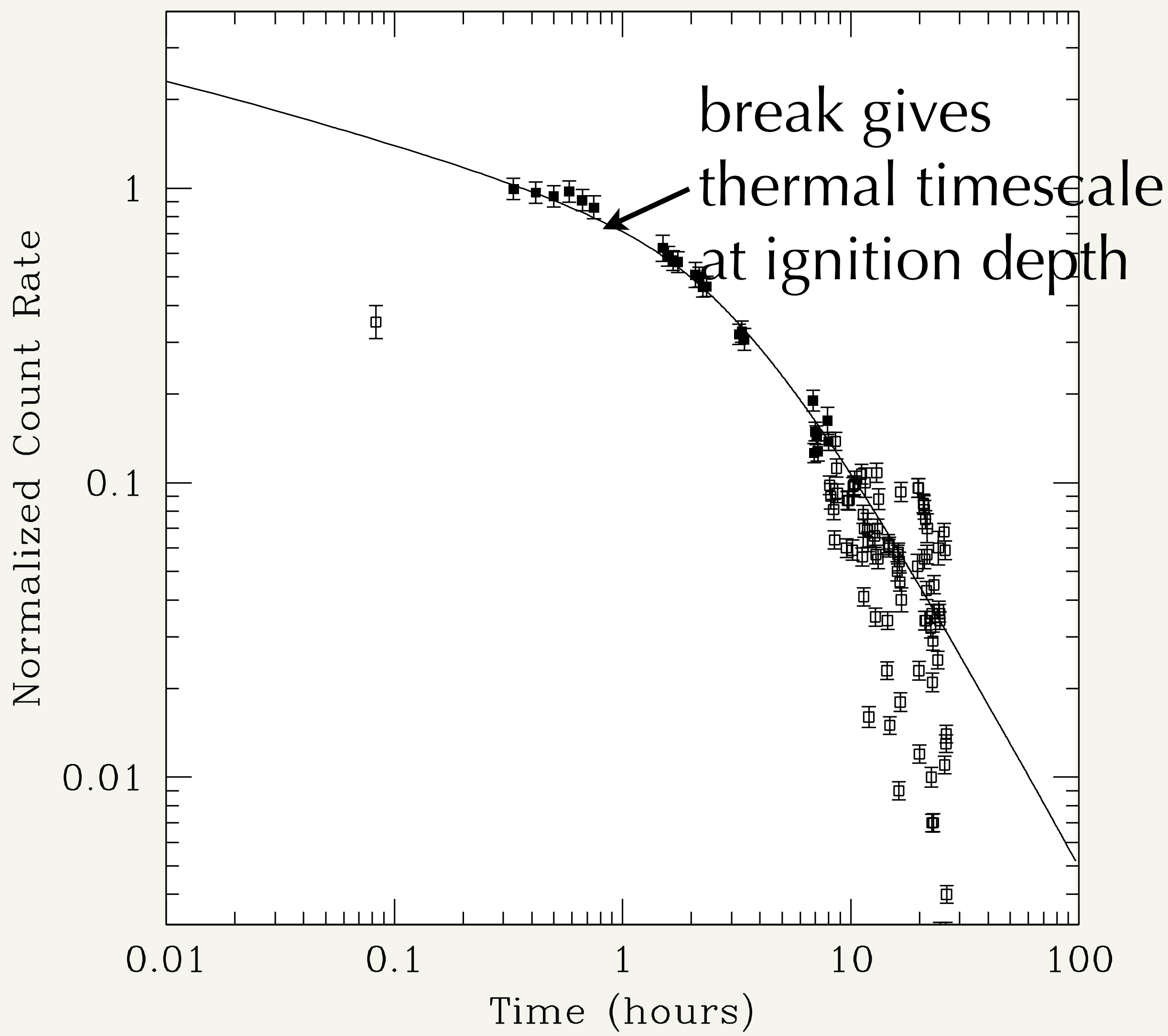


FIG. 5.— Fitted lightcurve for KS 1731-260, assuming the distance given in Table 1. Solid data points are included in the fit, open data points (with fluxes less than 0.1 of the peak flux) are not included.

- Can't use total energetics because of significant neutrino emission; (Strohmayer & Brown 02, Schatz et al. 03)
- Cooling follows broken power-law, with change of slope at thermal timescale at ignition depth (Cumming et al. 07)

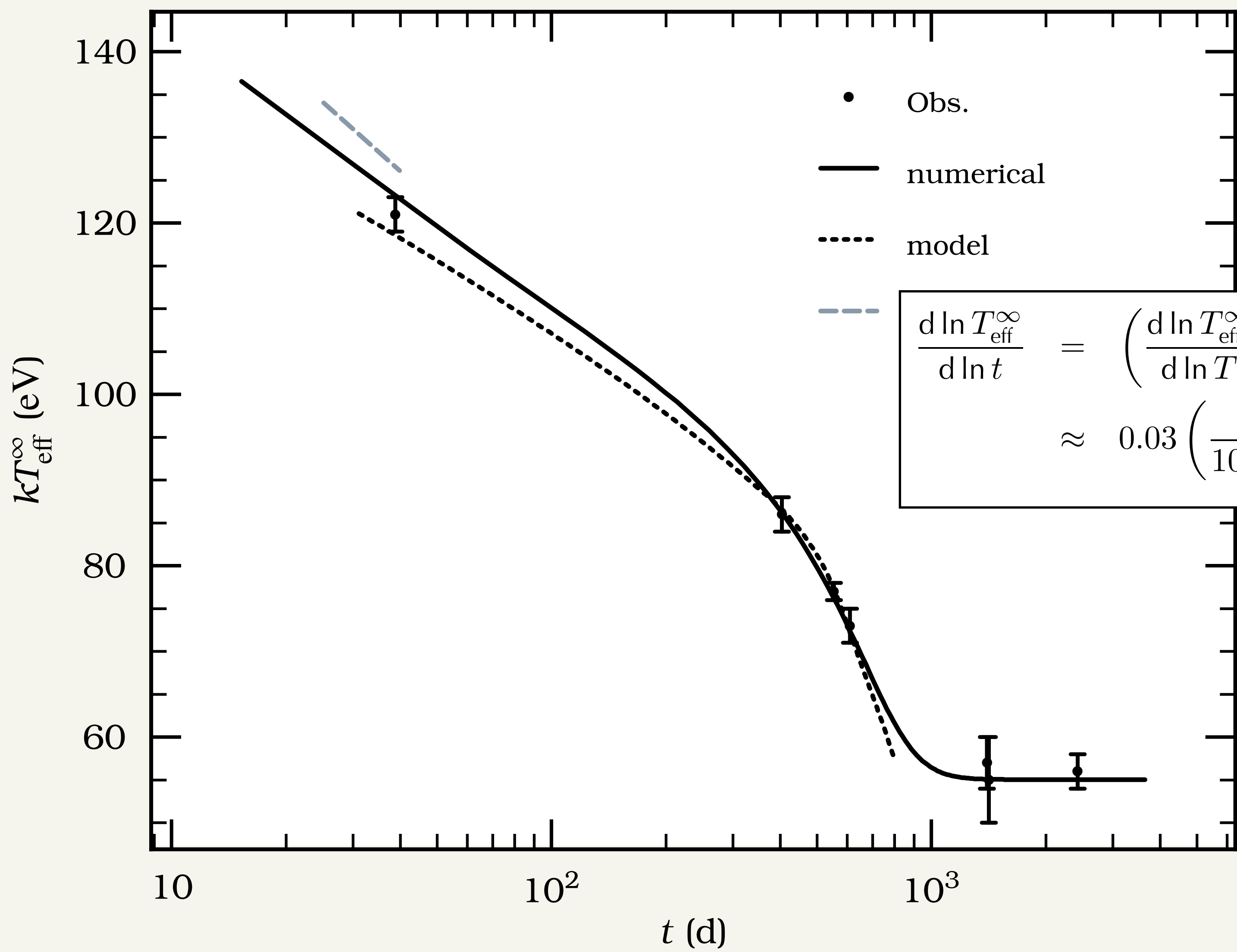
TABLE 1
FITS TO SUPERBURST LIGHTCURVES

Source	f_{peak} [a]	d/R [b]	E_{17} [c]	y_{12} [c]
4U 1254-690	0.22	13	1.5	2.7
4U 1735-444	1.5	8	2.6	1.3
KS 1731-260	2.4	4.5	1.9	1.0
GX 17+2 burst 2	0.8	8	1.8	0.64
Ser X-1	1.9	6	2.3	0.55
4U 1636-54	2.4	5.9	2.6	0.48

[a] Observed peak flux in units of 10^{-8} erg cm^{-2} s^{-1}.
[b] Adopted distance in units of kpc/10 km.
[c] The fitted parameters scale roughly as $E_{17} \propto (d/R)^{8/7}$ and $y_{12} \propto (d/R)^{10/7}$ (see text). For a 50% distance uncertainty, the uncertainties in E_{17} and y_{12} are 60% and 70% respectively (see also Fig. 4).

From Cumming et al. 07

shallow crustal heating?

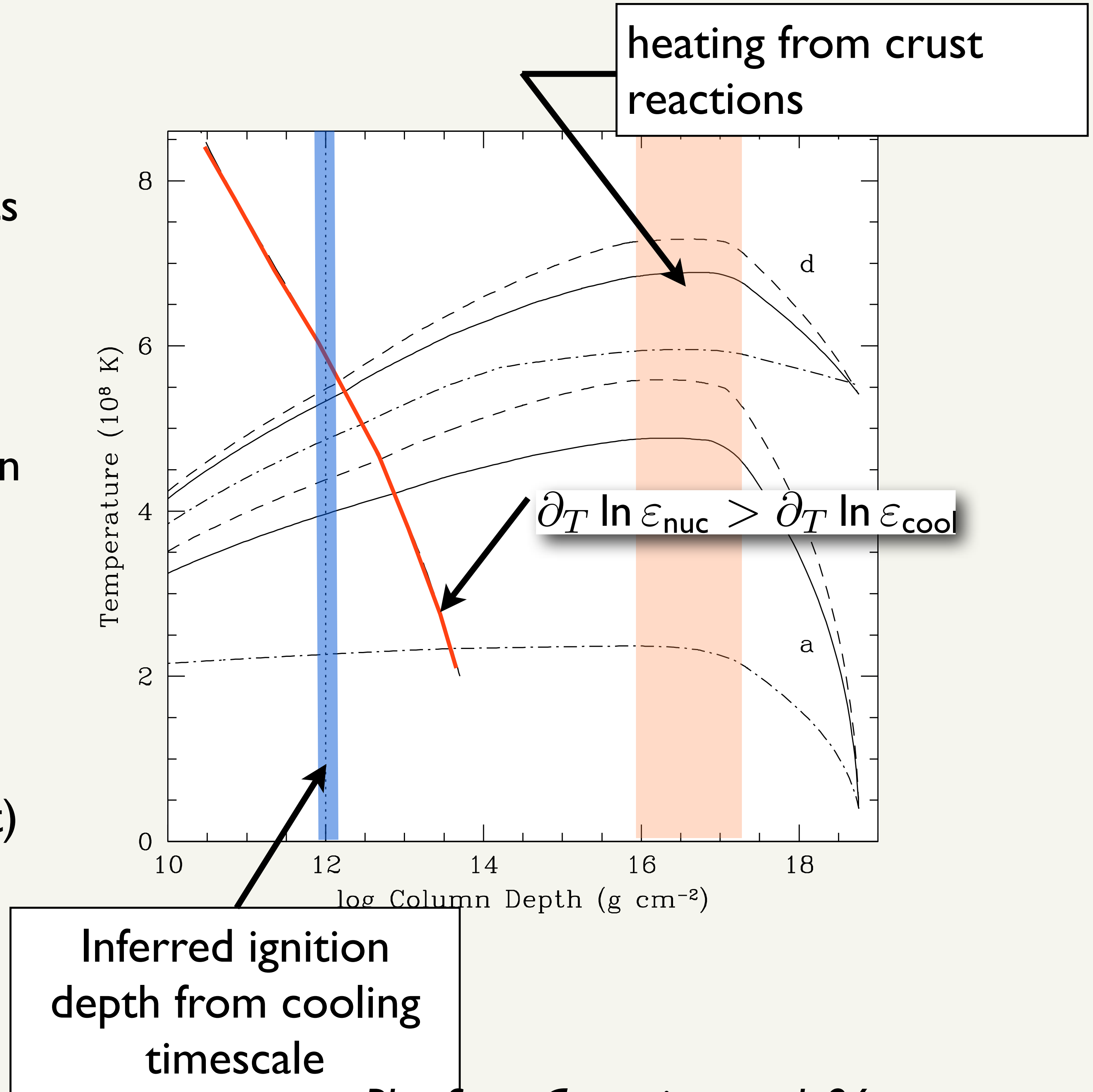


$$
\begin{aligned}
\frac{\mathrm{d}\ln T_{\rm eff}^{\infty}}{\mathrm{d}\ln t} &= \left(\frac{\mathrm{d}\ln T_{\rm eff}^{\infty}}{\mathrm{d}\ln T}\right)\left(\frac{\mathrm{d}\ln T}{\mathrm{d}\ln y}\right)\left(\frac{\mathrm{d}\ln y}{\mathrm{d}\ln \tau}\right) \\
&\approx 0.03\left(\frac{F}{10^{21}\ \mathrm{ergs\,s^{-1}\,cm^{-2}}}\right),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

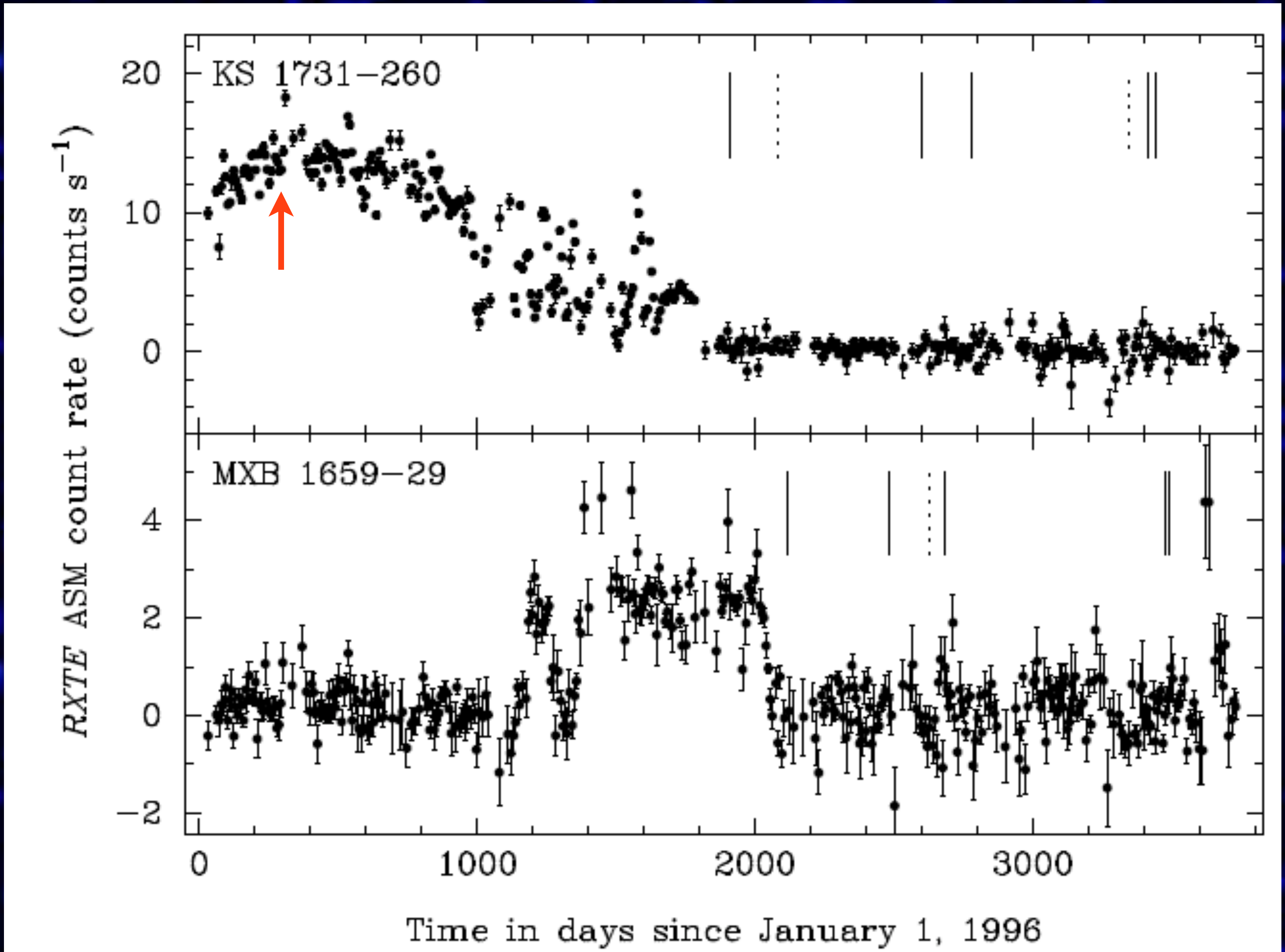
- Best-fits have “inverted temperature profile”
  - inward-directed heat flux
  - requires heat source at place where thermal diffusion time < 30 d

superburst ignition

- ^{12}C likely cause of superbursts (Cumming & Bildsten 01, Strohmayer & Brown 02)
- Hot crust required to match inferred ignition depth (Brown 04; Cooper & Narayan 05; Cumming et al. 06)
  - No enhanced cooling
  - low thermal conductivity (impure, amorphous crust)

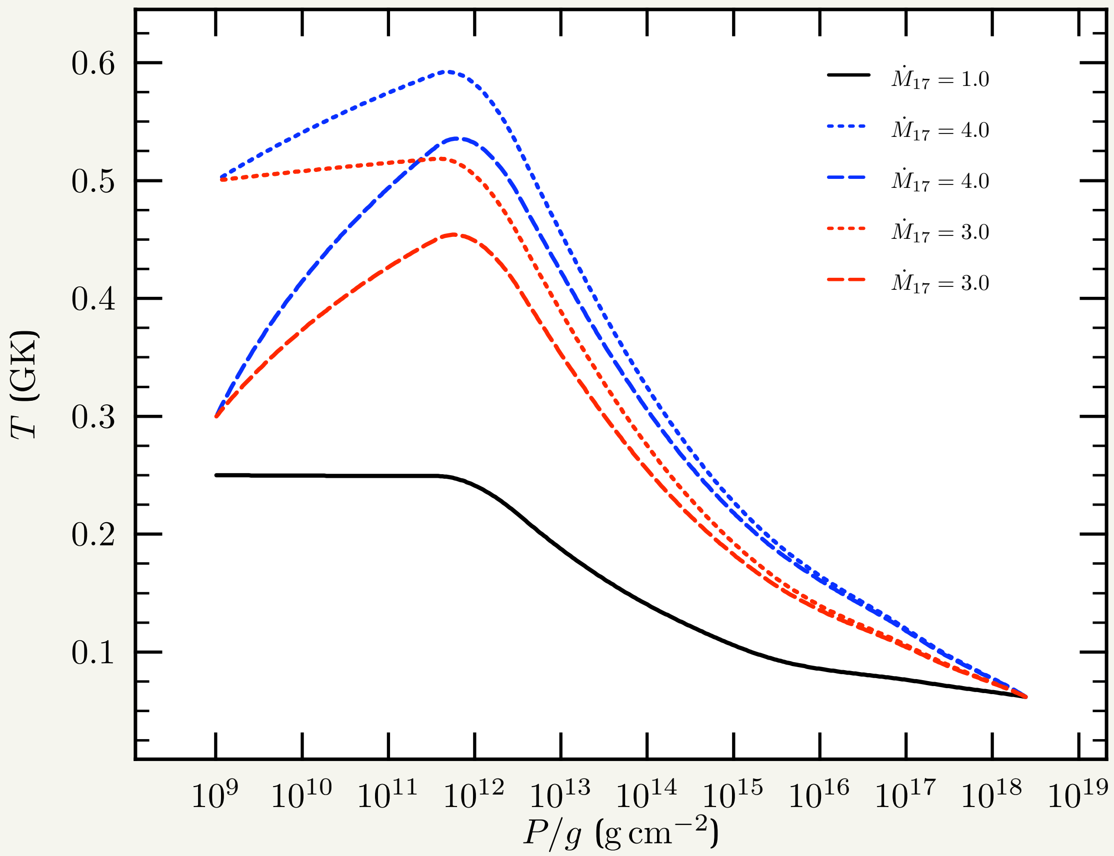


Plot from Cumming et al. 06


KS 1731−260
MXB 1659−29
RXTE ASM count rate (counts s⁻¹)
Time in days since January 1, 1996
20
10
0
4
2
0
−2
0
1000
2000
3000

Shallow Crustal Heating?

- Introduce shallow heat source
  E_{nuc} = 0.5 MeV/u • (dM/dt)
- Could this explain superburst ignition when accretion rate was higher?
- Observations within 10 days post-outburst could confirm existence of this heating!



What's the heat source?

questions for discussion

- what are the differences (*K*, *C*) between
  - pasta
  - what is non-pasta: couscous? gruel?
- should we worry about domains—phase separated composition (Horowitz et al. '08)?
- what can FRIB, PREX do to constrain the composition in the outer, inner crust?