Taking the temperature of accreting neutron stars

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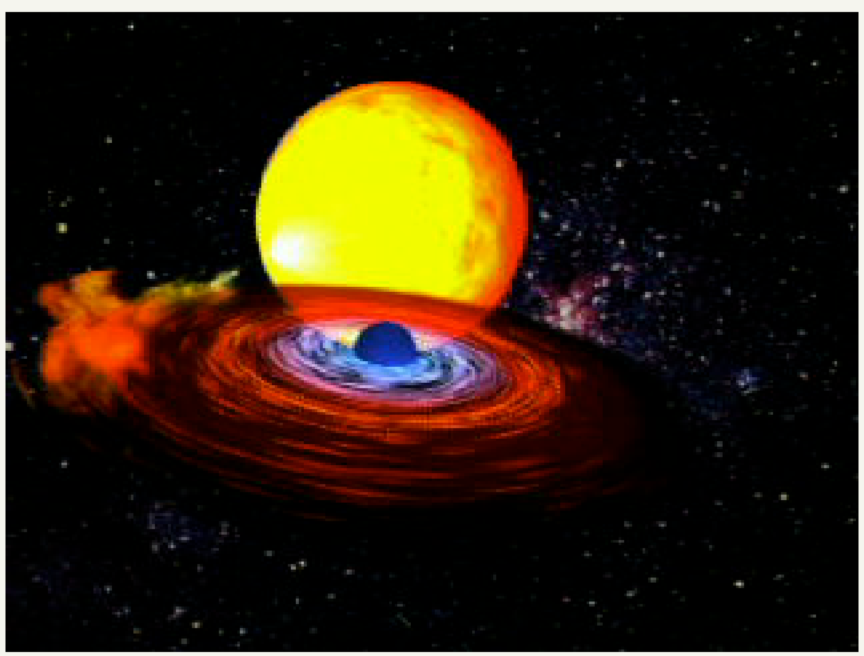
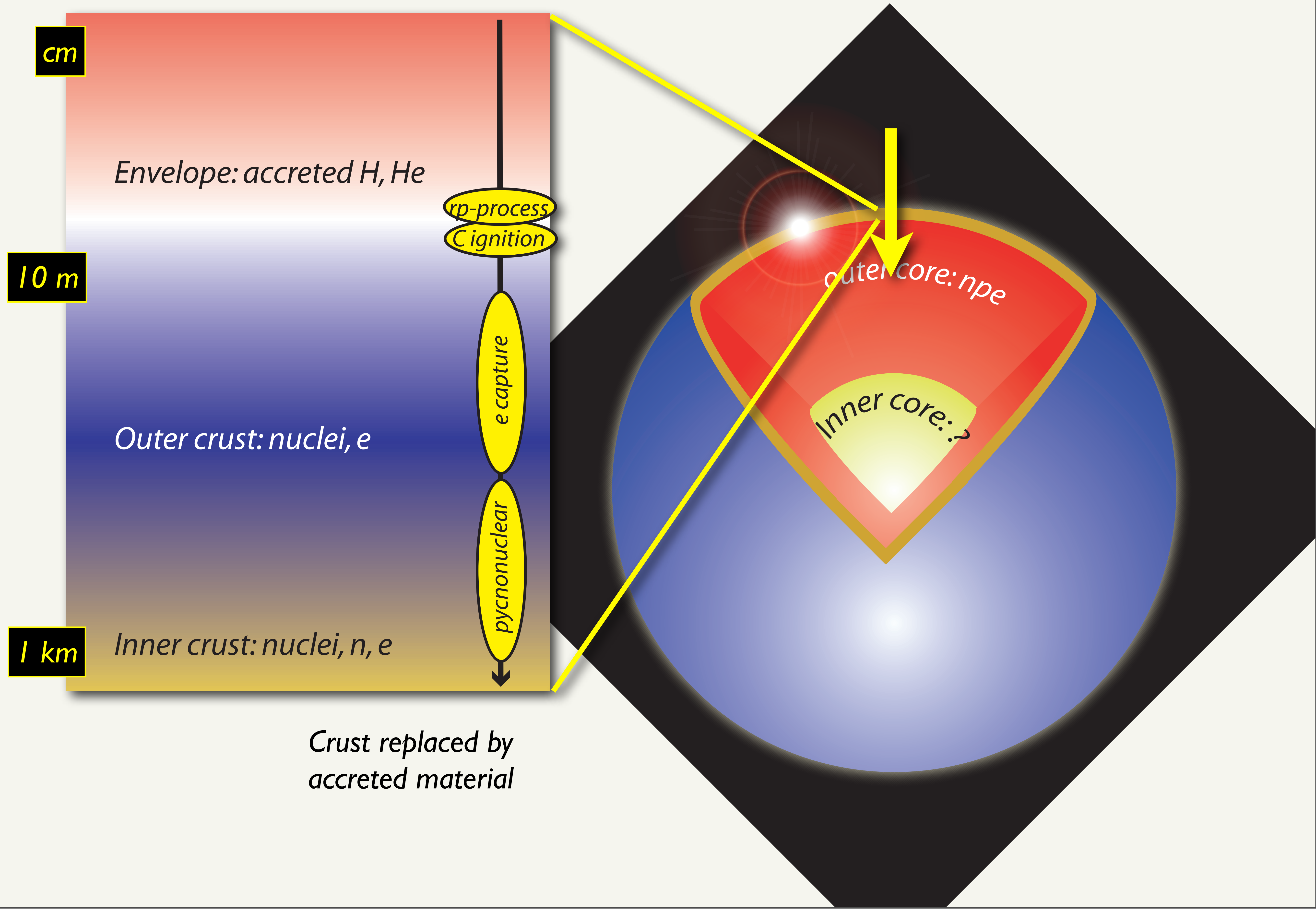


In this talk

- X-ray bursts, superbursts
    - Dependence on deep crustal heating
- Quasi-persistent transients
    - Crust cooling detected
    - Implications for crust structure
- Confrontation between these two methods

What can we learn?

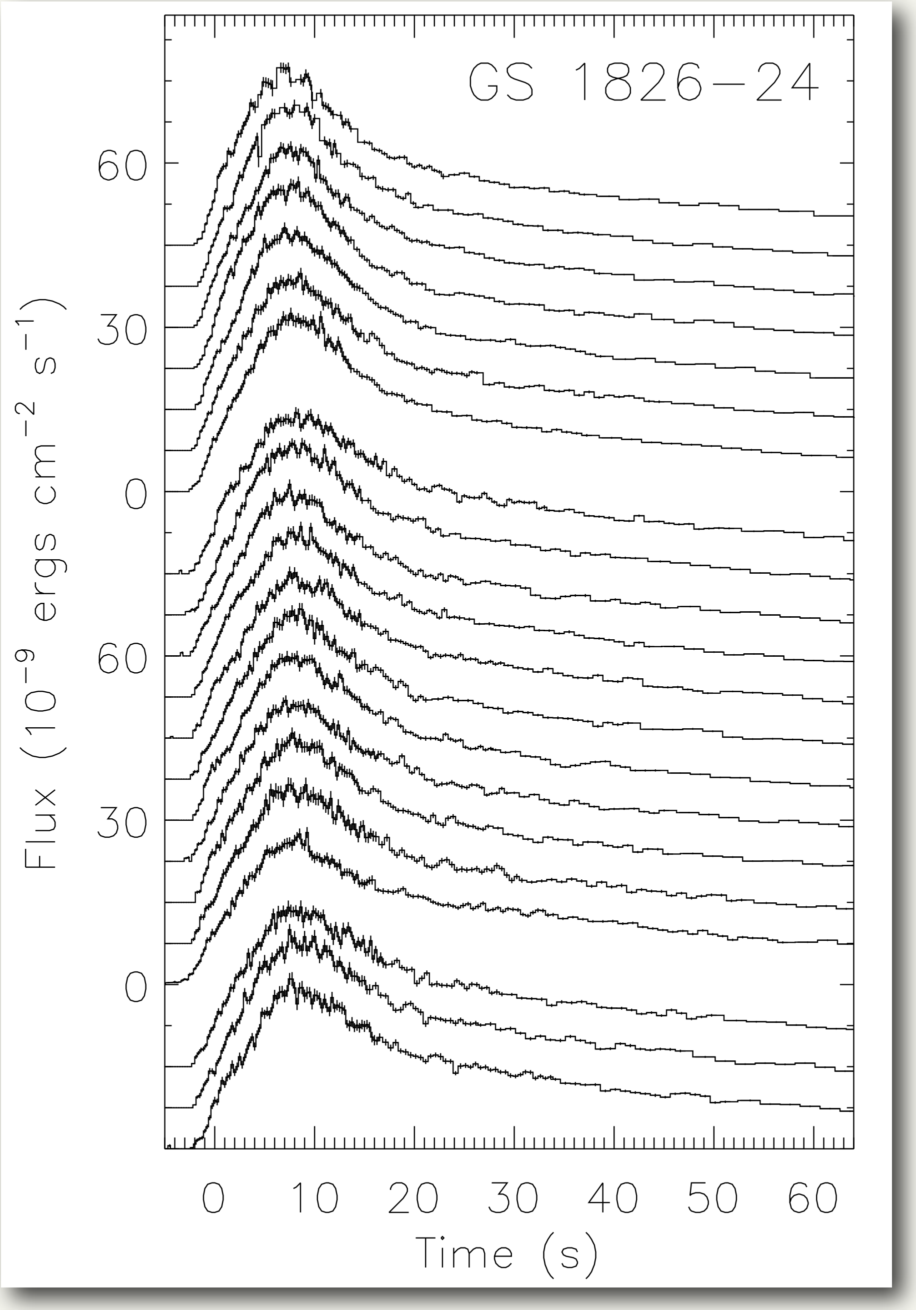
- Strength and distribution of crust heat sources
- Thermal properties of crust
  - composition
  - conductivity
- Bulk properties of neutron star (M, R)



Crust replaced by accreted material

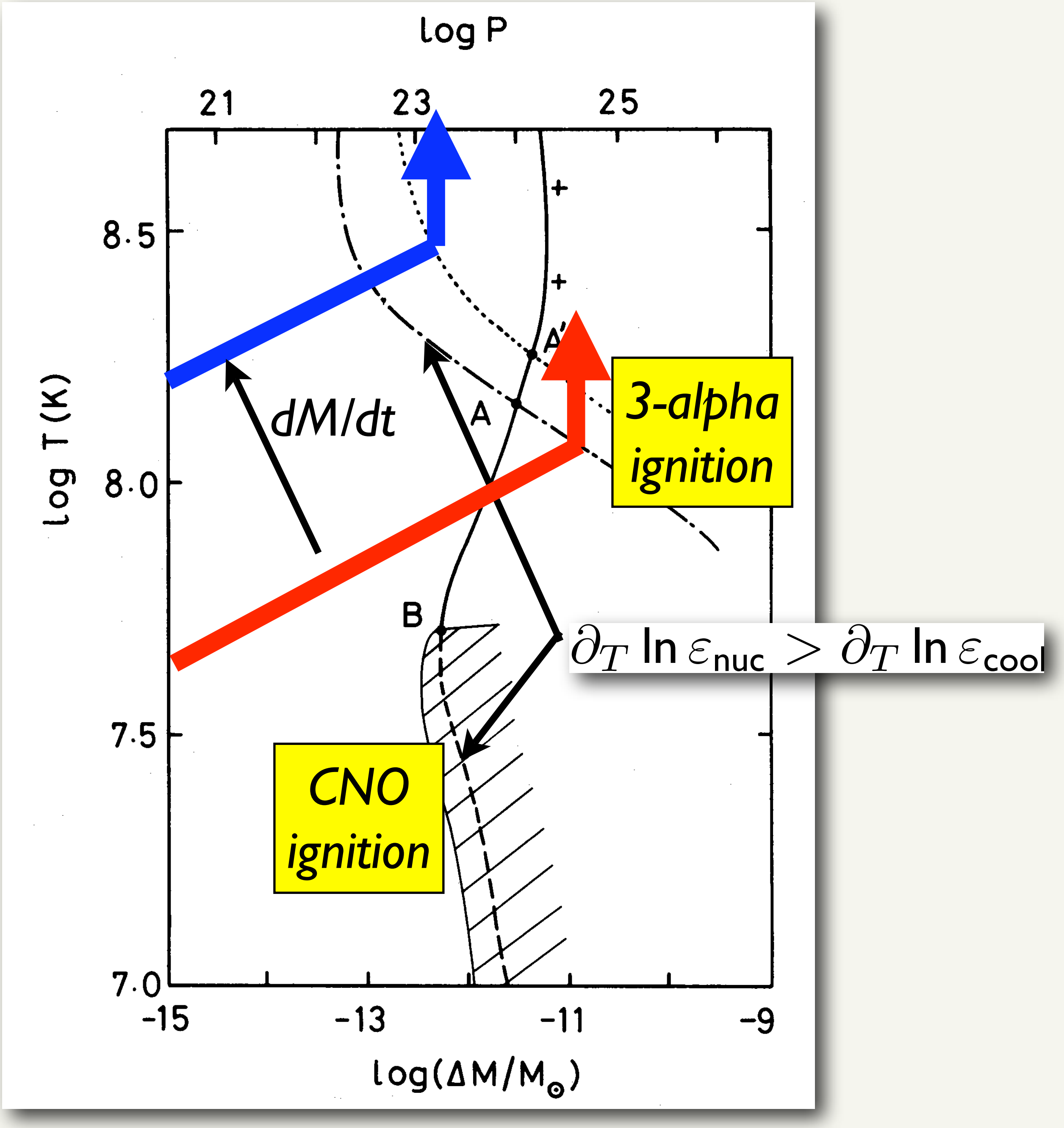
X-ray burst lightcurves

Galloway et al.



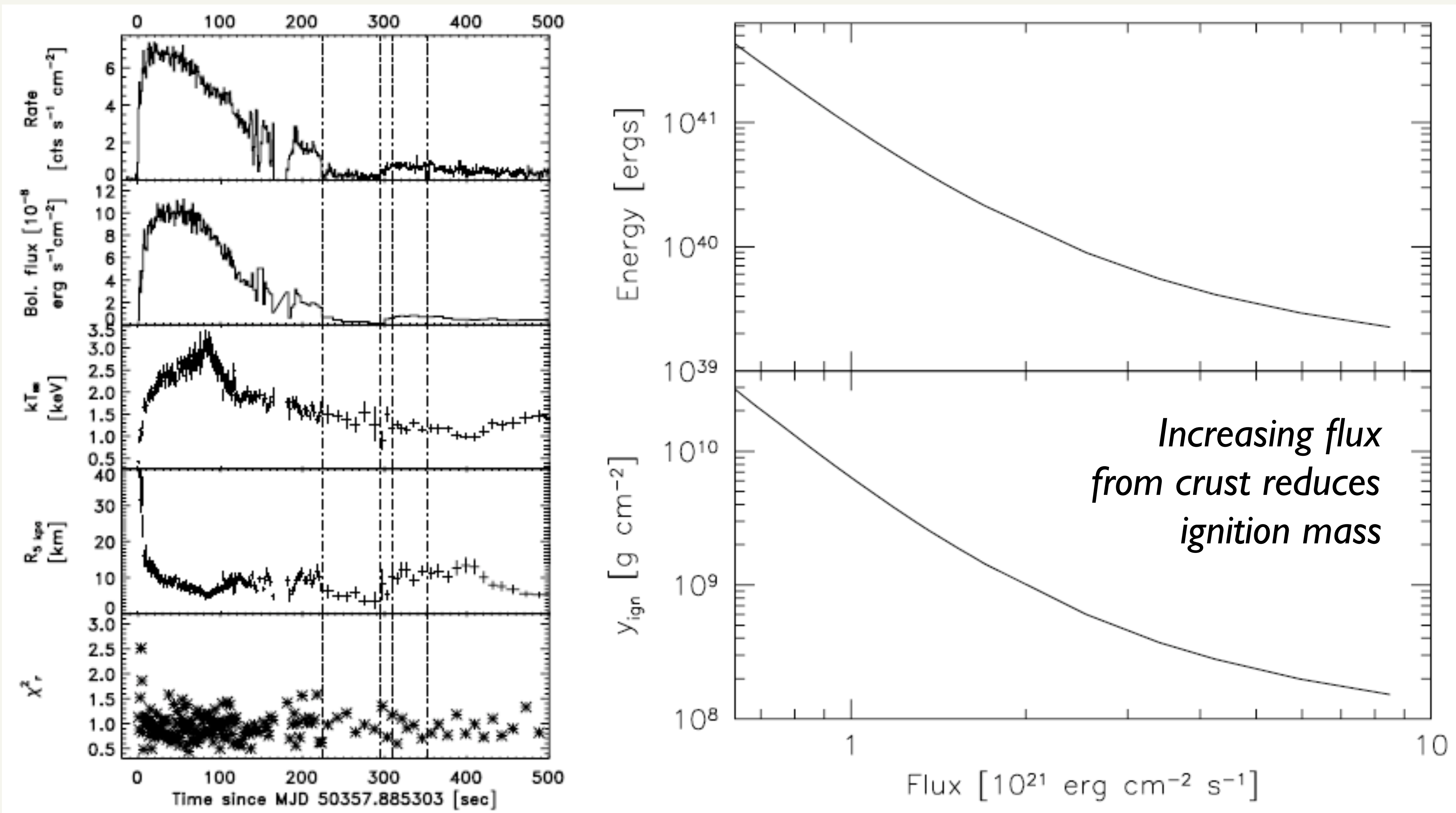
X-ray bursts

- Consumption of H regulated by β-decay of ^{14}O, ^{15}O
- time to deplete H is ≈18 hr
- temperature set by ≈7 MeV/u from H burning
- sensitive to temperature in deep crust if pure He accreted (next slide), or complete H burning prior to He ignition (SAX J1808.4–268; Galloway & Cumming 06)

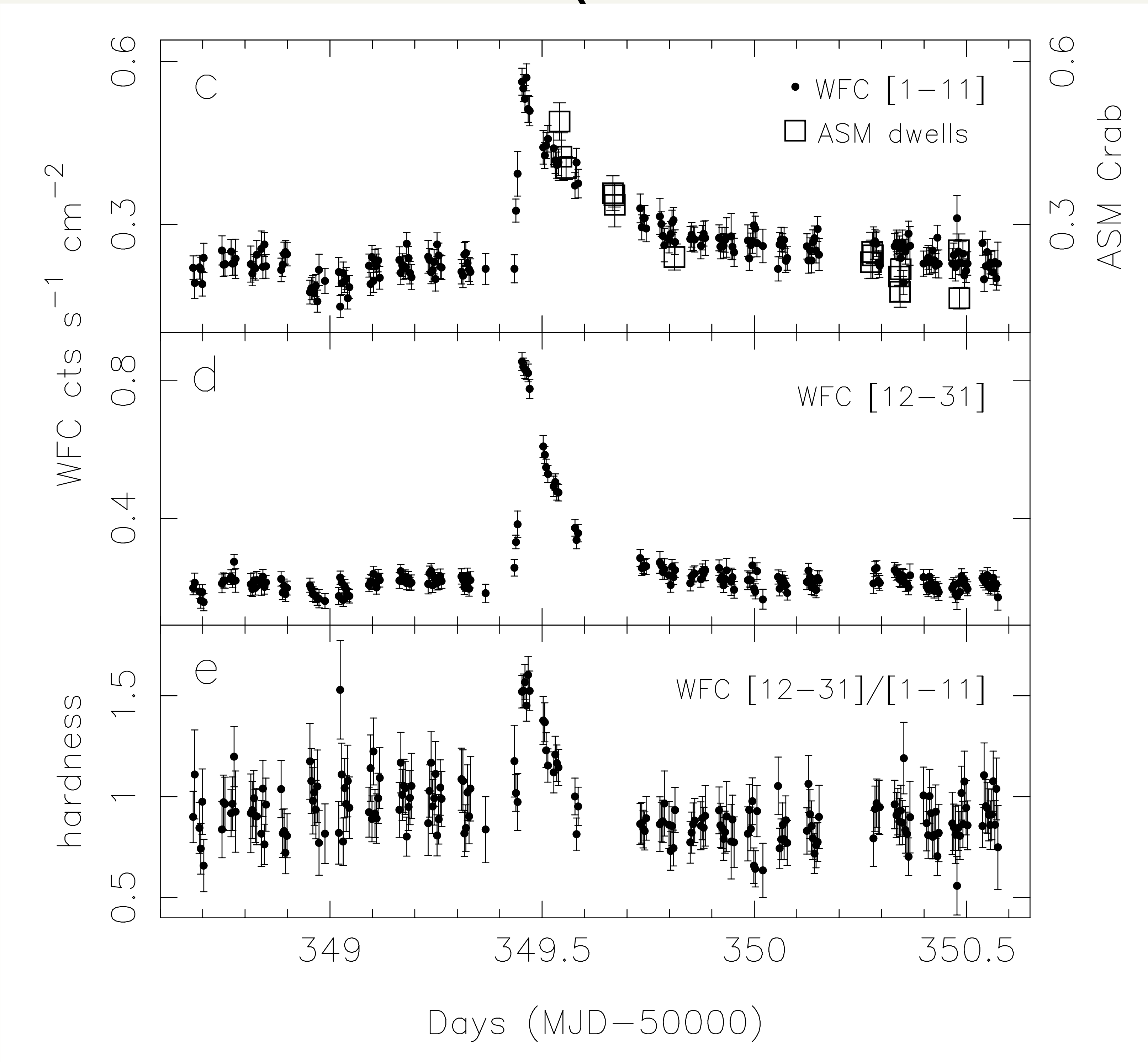


Fujimoto et al. 1981

Long (He) X-ray bursts in 2S 0918–549 (in 't Zand 05)



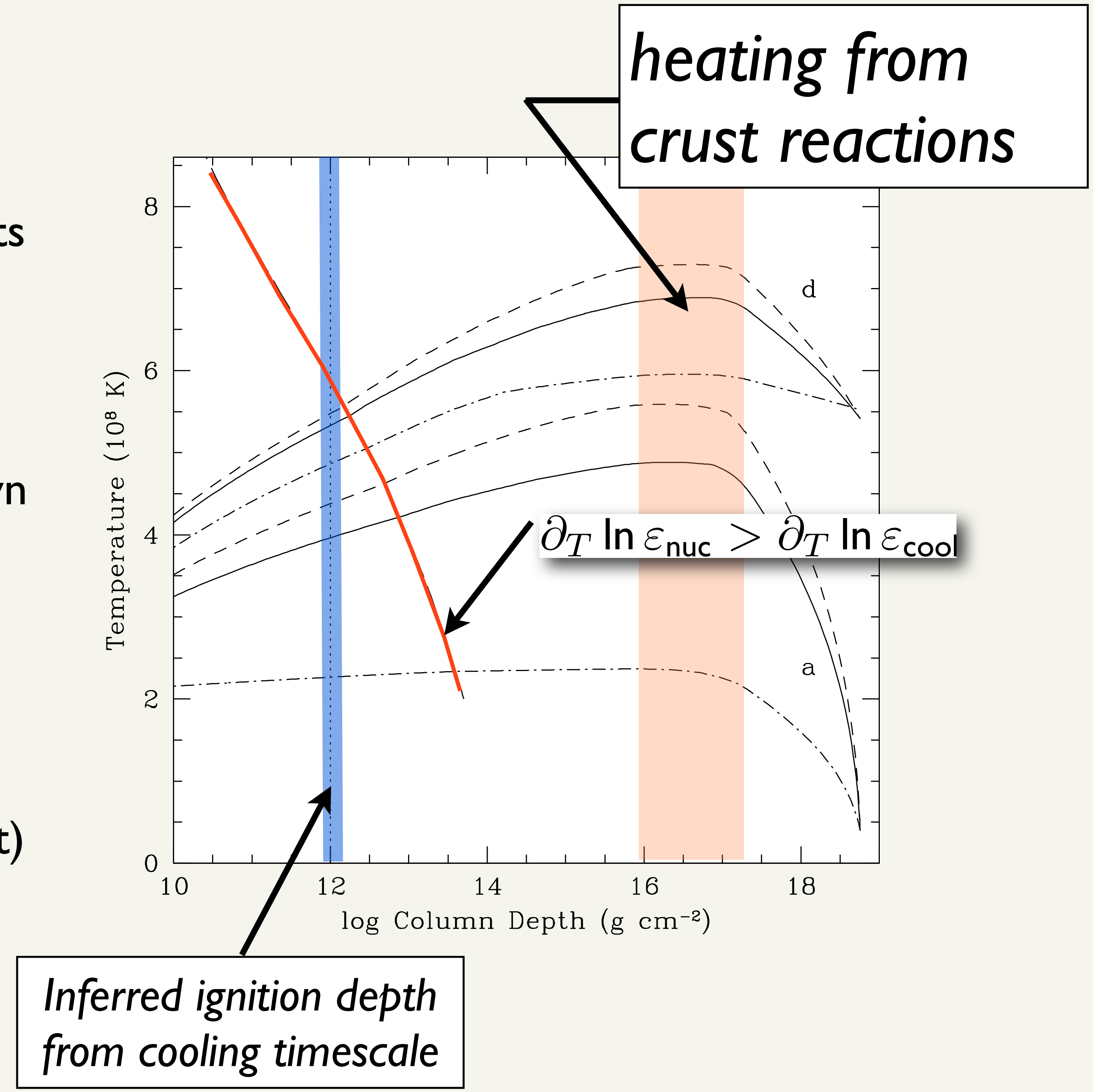
KS 1731–260 superburst (Kuulkers 2002)



- About 10^3 more energetic than type I XRB
- cooling time ~ hrs
- recurrence time ~ yrs

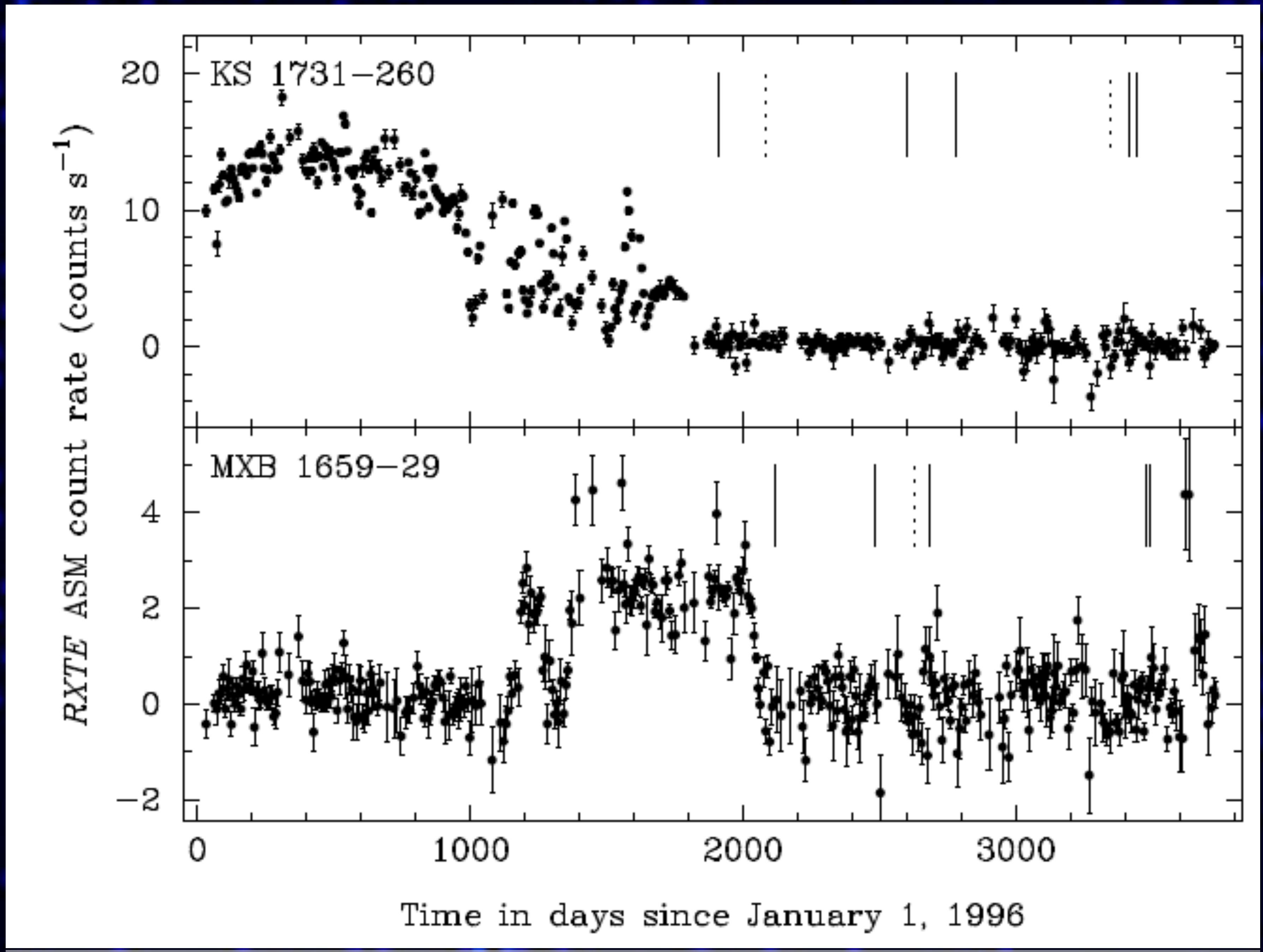
Superburst ignition

- ^{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)

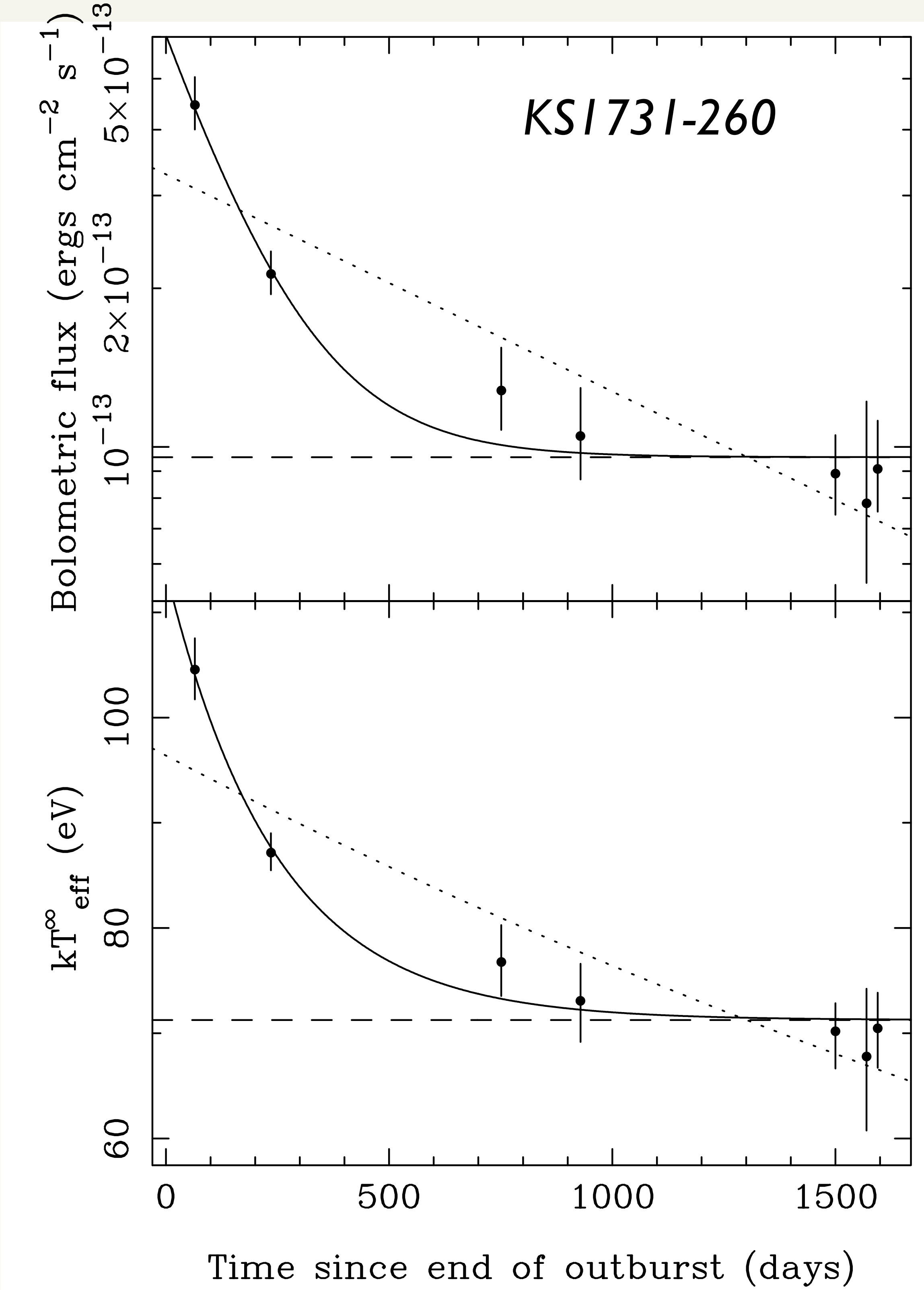


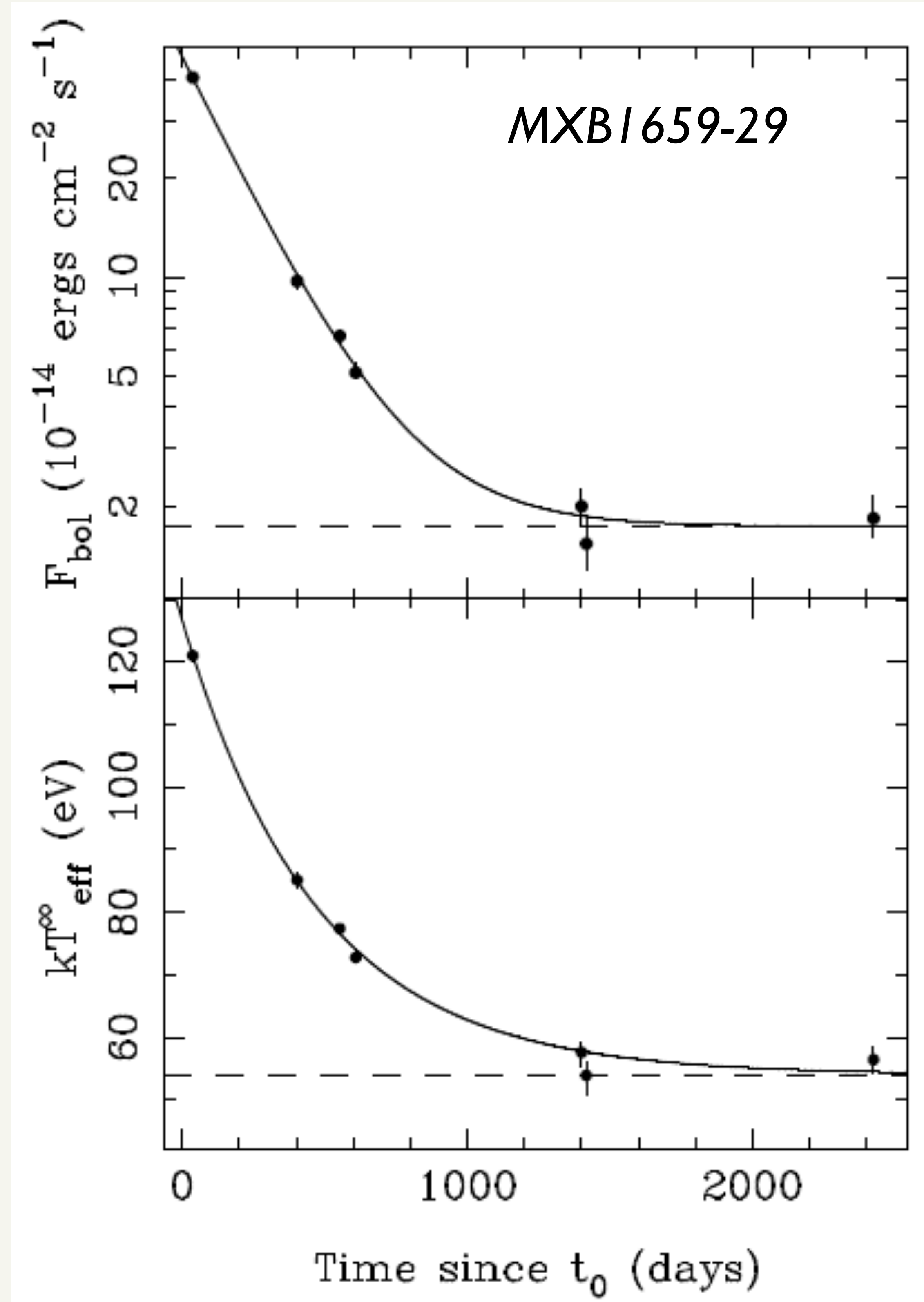
Plot from Cumming et al. 06

Rutledge et al. 02 suggested looking for post-outburst thermal relaxation of crust for transients with extended outbursts



quiescent lightcurves



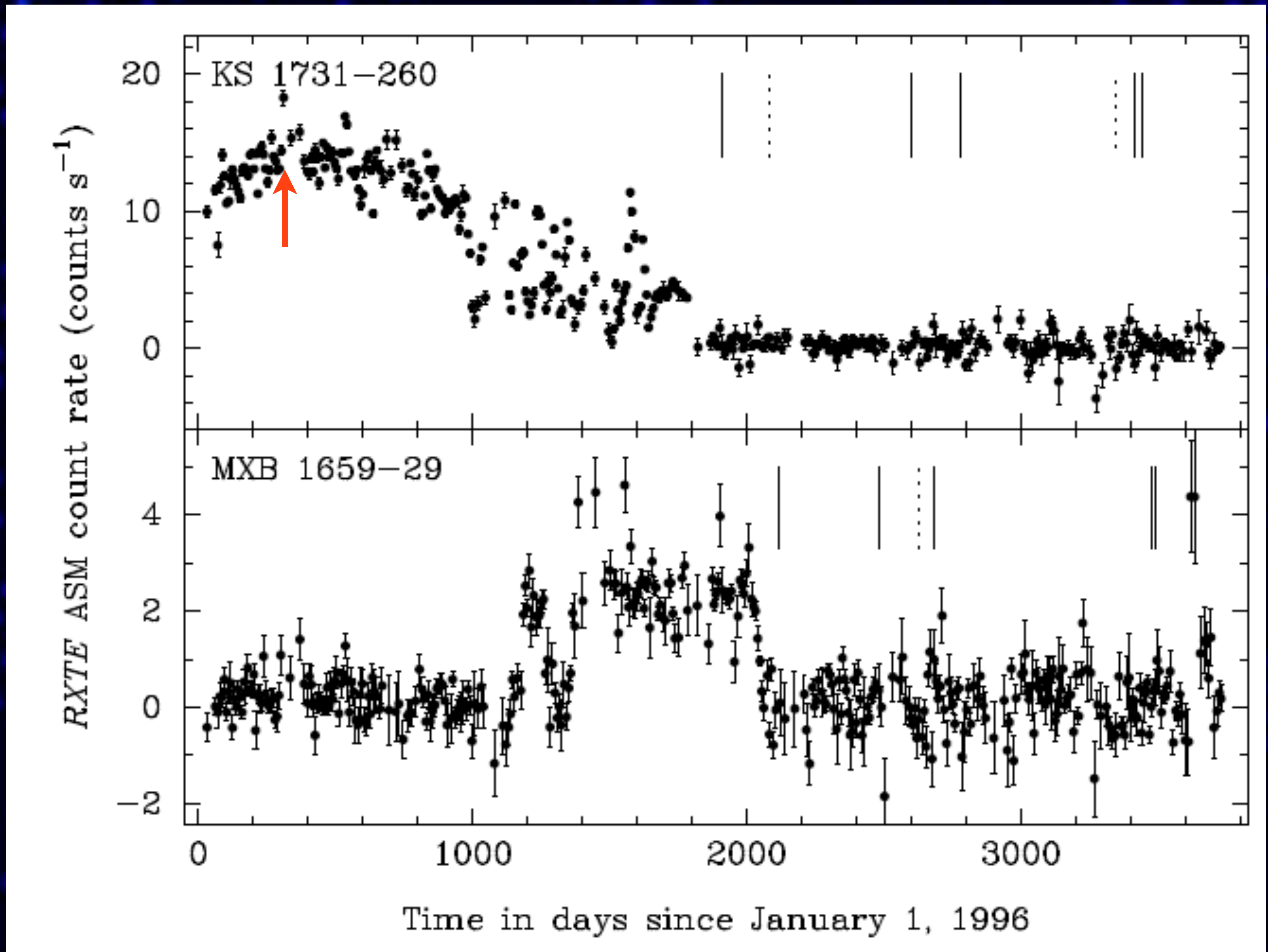


Cackett et al. 06, 08

Rutledge et al. 02 suggested looking for post-outburst thermal relaxation of crust

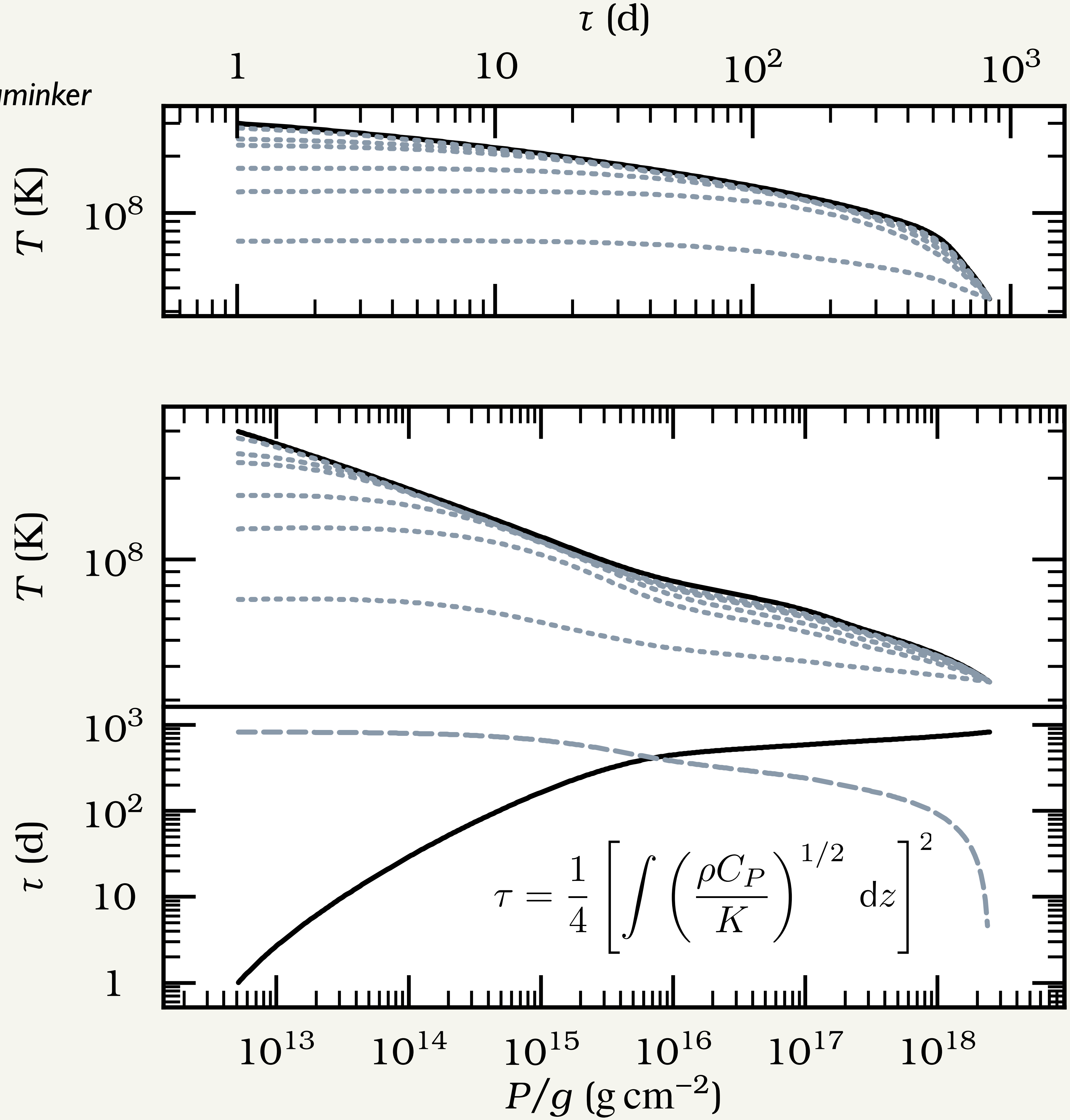
Observations (Wijnands et al., Cackett et al.) detected this cooling

Shternin et al. 2007 fit KS 1731 lightcurve, suggest crust has high thermal conductivity



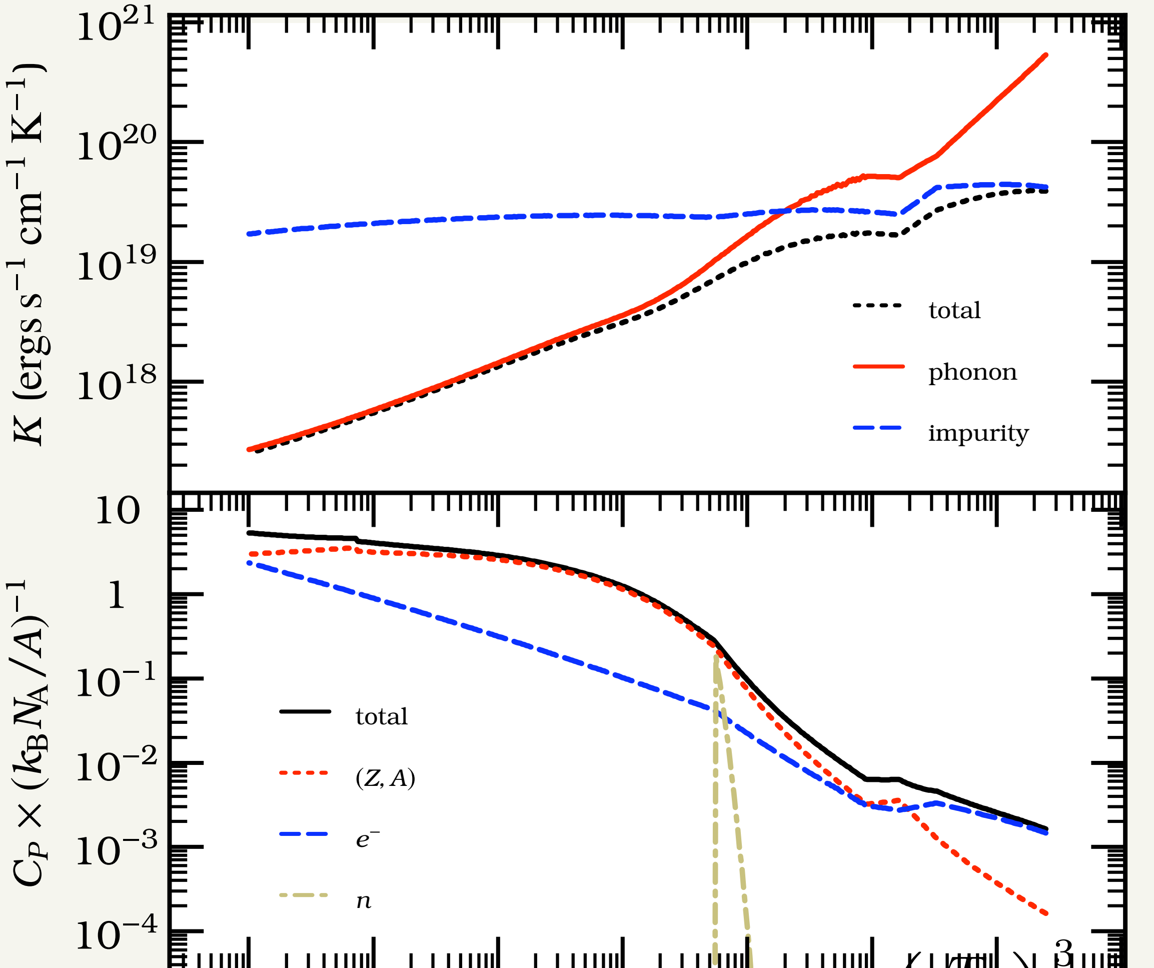
This talk: what we can learn from lightcurve (Brown & Cumming 08)

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)

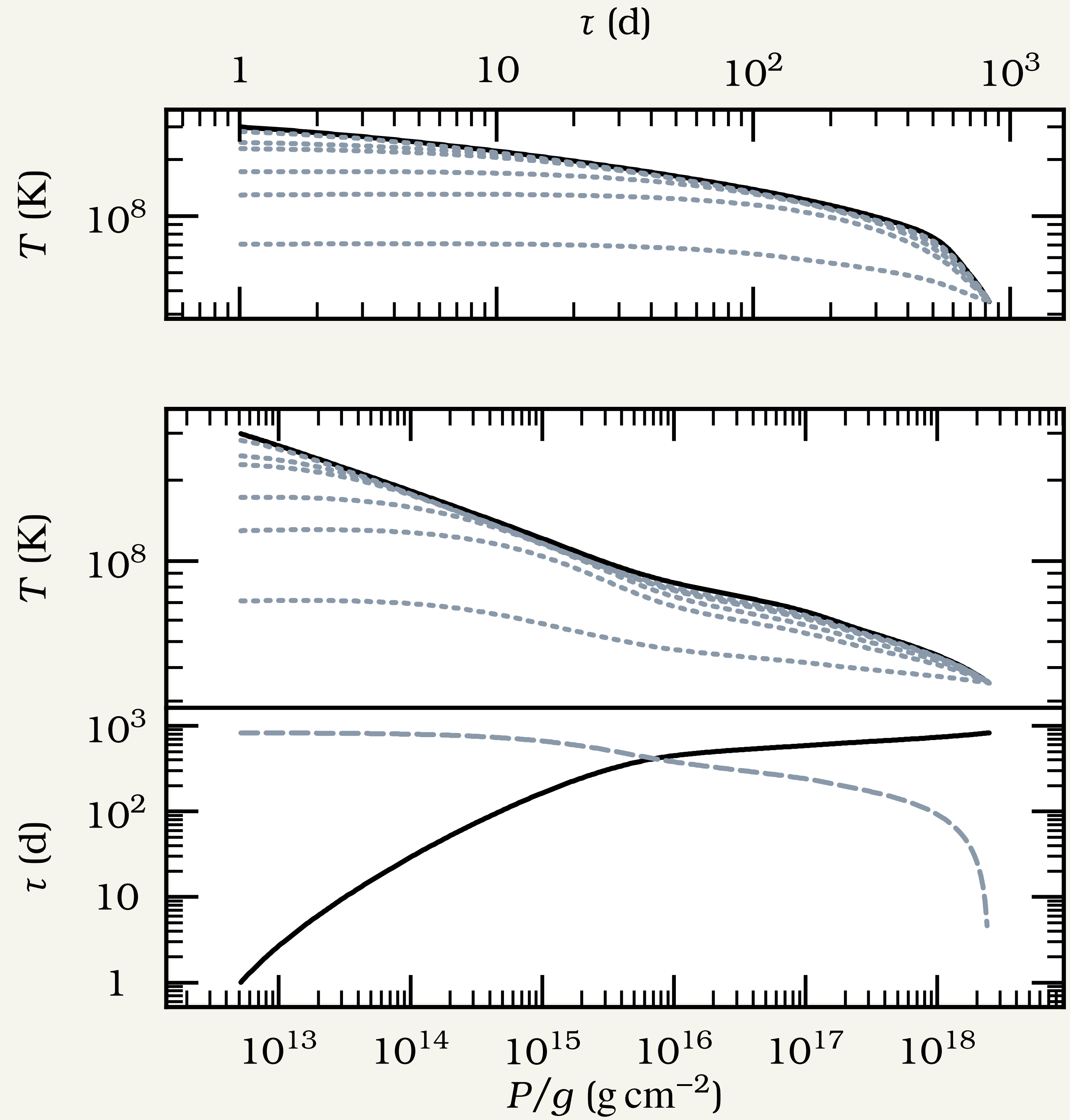


Can "invert" the lightcurve to infer the temperature profile

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

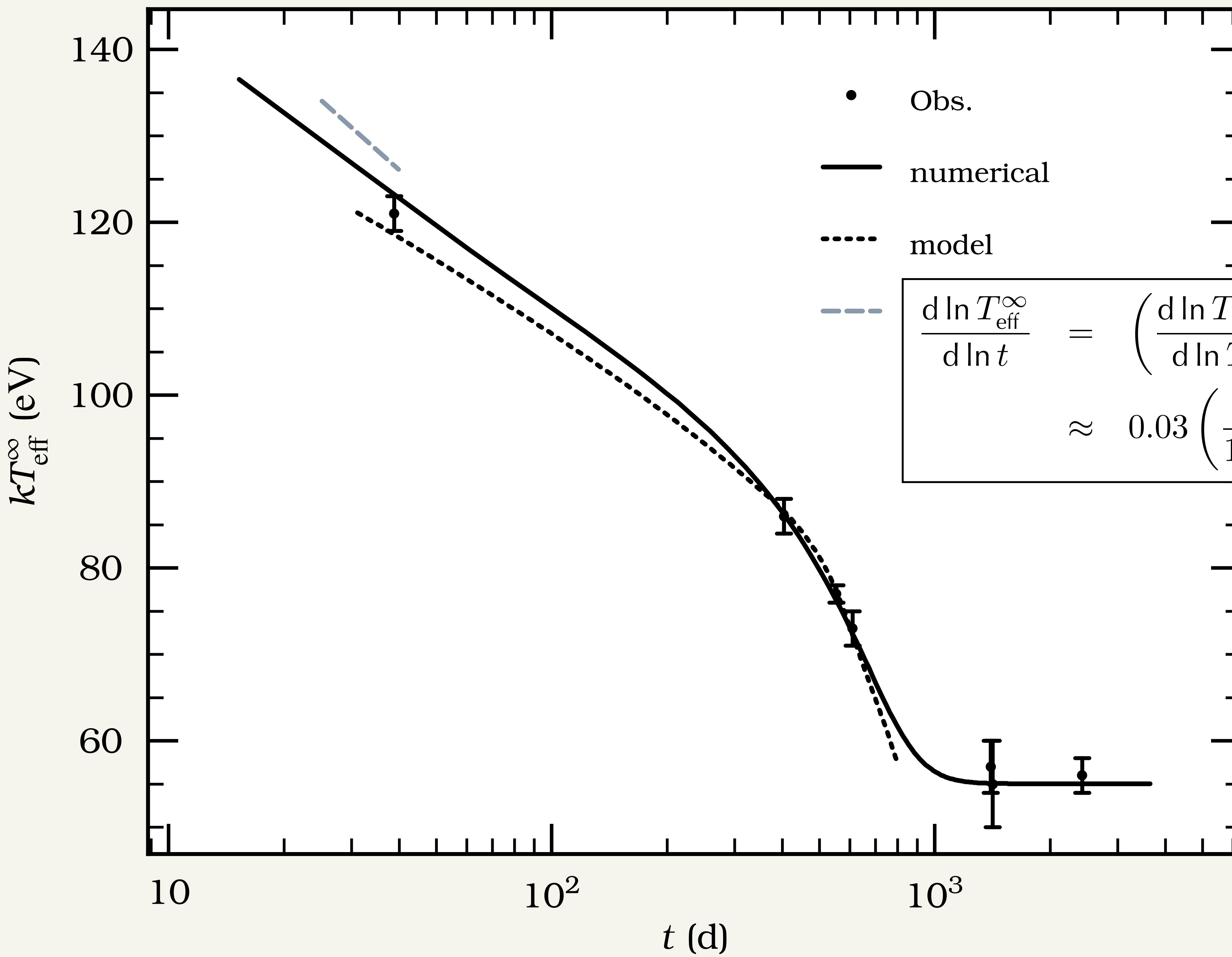


$$C_P \sim \left(\frac{T}{\Theta_D}\right)^3$$



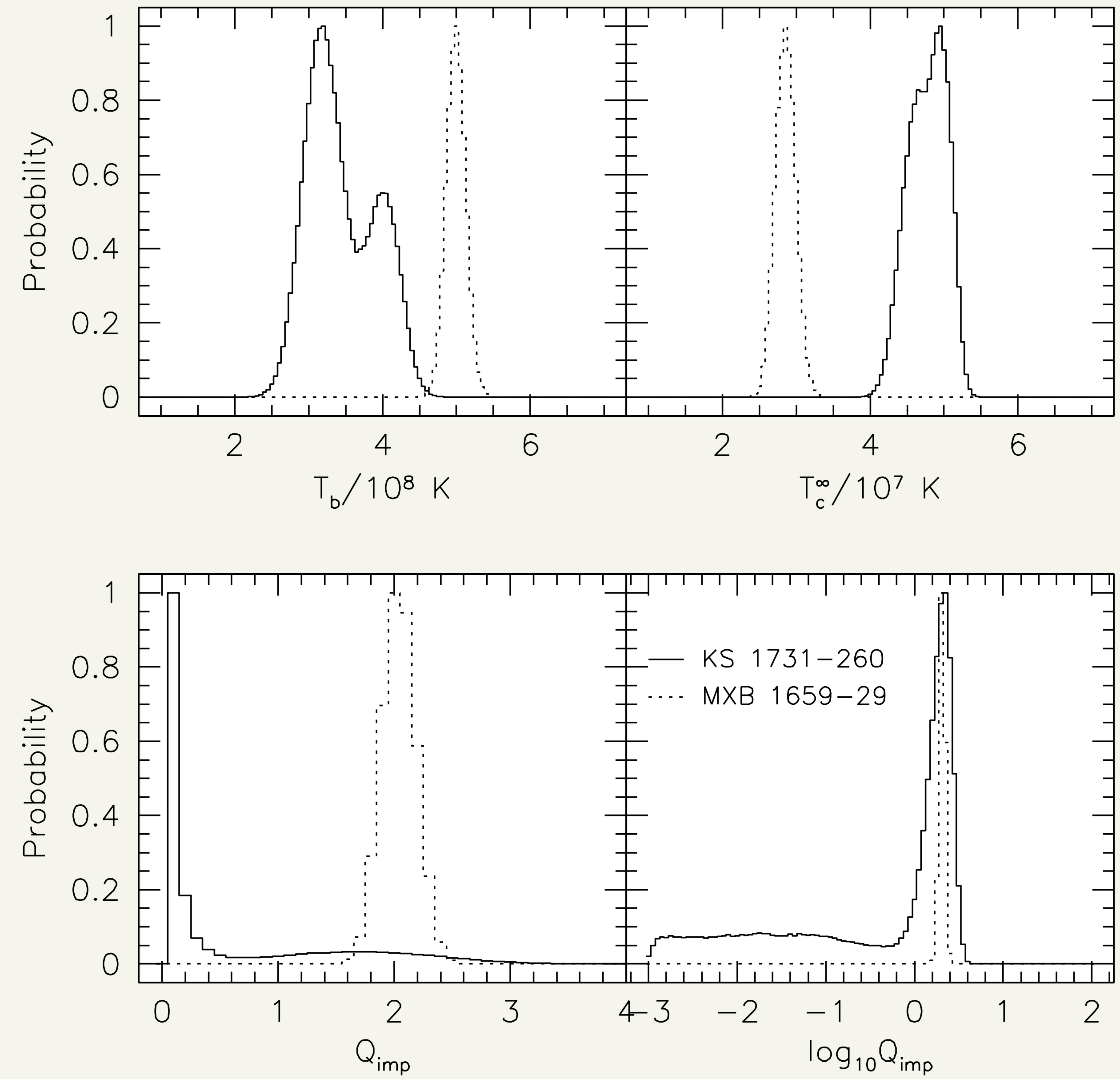
Timescale also depends on crust thickness (Lattimer et al. 94)

$$\tau \propto (\Delta r)^2 (1+z)^3$$



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

Probability distribution of parameters



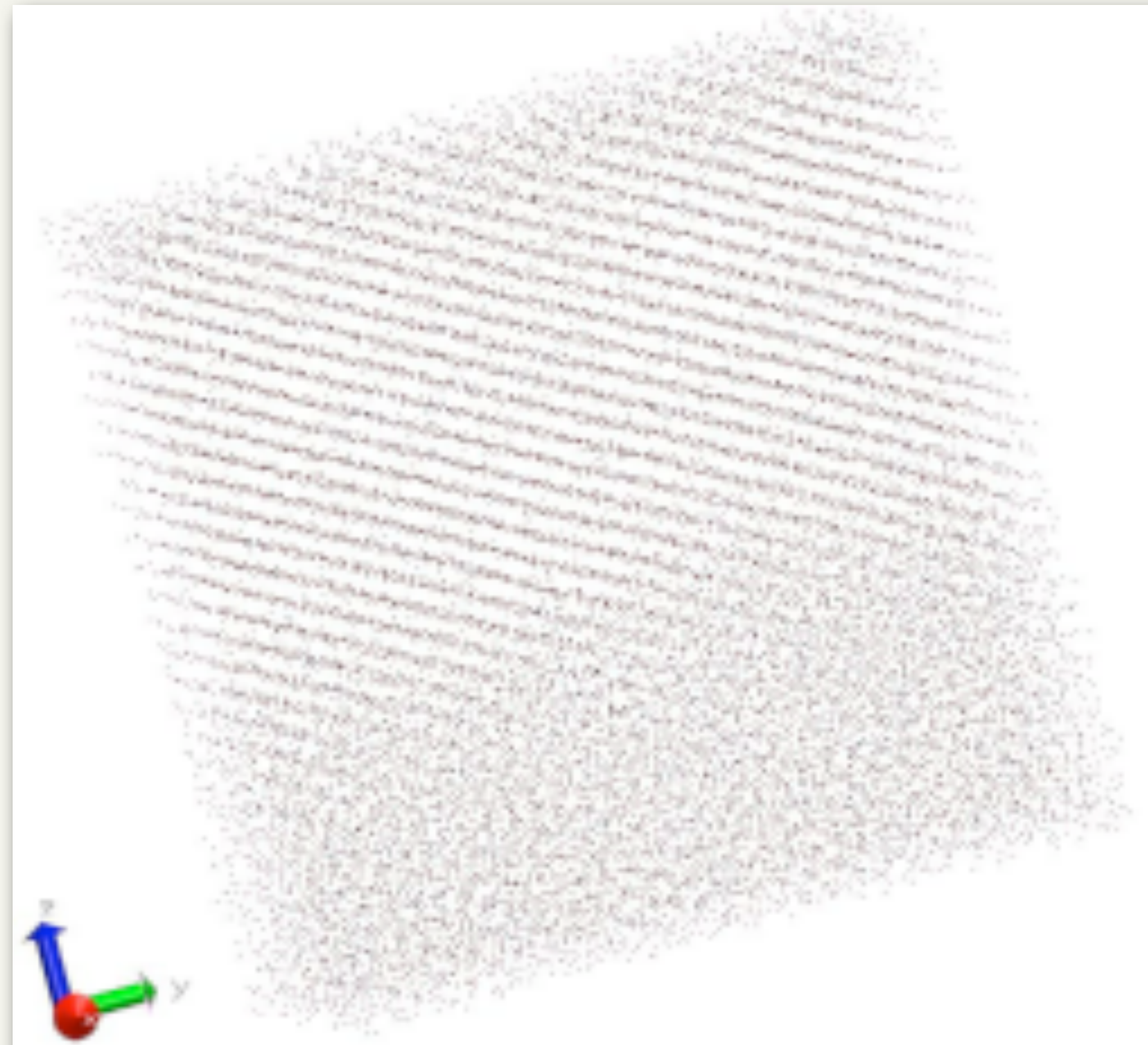
- Monte Carlo runs using simple model of lightcurve
  - 3 parameters: $Q_{\rm imp}$, $T_{\rm top}$, $T_{\rm core}$

$$Q_{\rm imp} \equiv n_{\rm ion}^{-1} \sum_i n_i (Z_i - \langle Z \rangle)^2 \lesssim 10$$

- Confirm with numerical cooling calculations

Implications

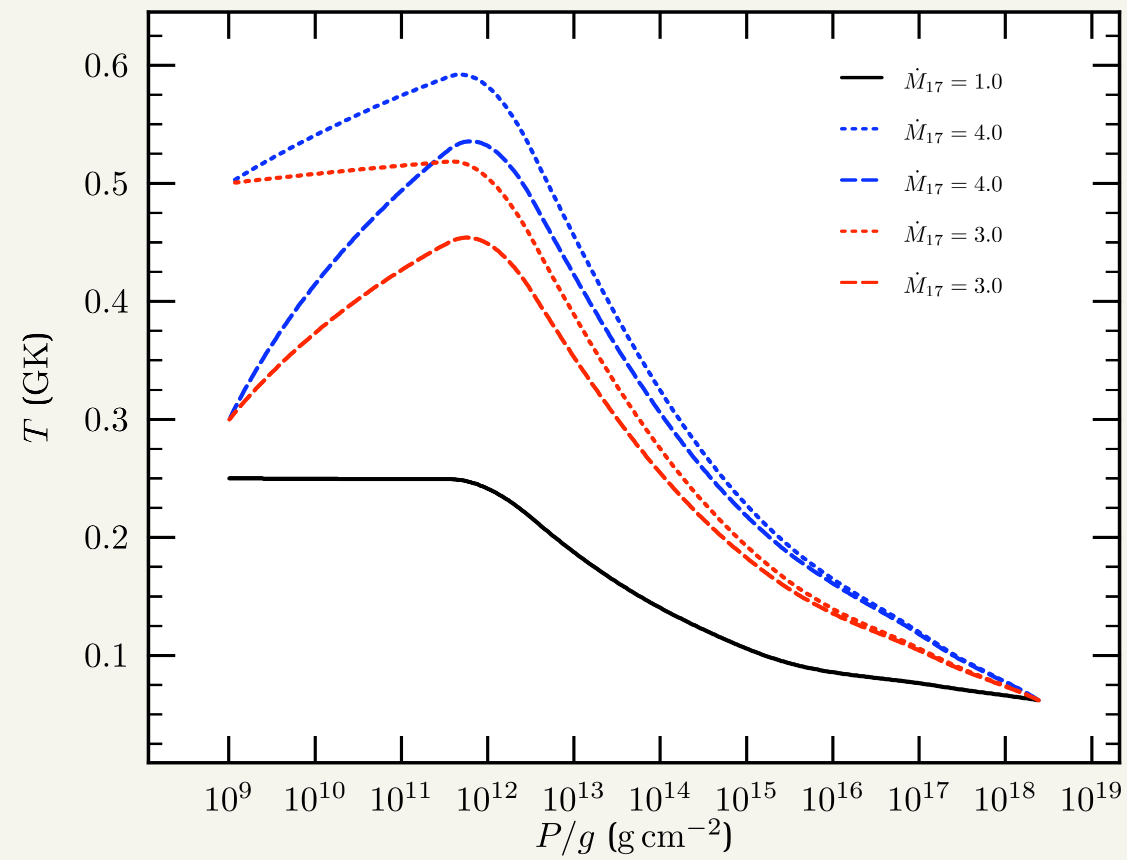
- Crust has high thermal conductivity (**not amorphous**)—agrees with MD simulations (Horowitz et al. 07, 08); cf. Shternin et al. (07)
- Inward-directed flux from shallow depth ≈ 0.5 MeV/u • (dM/dt)



Horowitz et al. 07; note the crystalline planes!

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!



summary

- deep crustal heating
  - sets ignition conditions of superbursts, X-ray bursts where stable H burning is unimportant
  - observations of quasi-persistent transients in quiescence
    - crust has high thermal conductivity (agree with Shternin et al. 07)
    - need shallow heat source to fit early part of lightcurve—what is this heating? (pycnonuclear reactions [Horowitz et al. 08]?; other light element reactions?)