Probing the Internal Temperature of an Accreting Neutron Star

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Cooling Neutron Stars

cf. talk by D. Page

- Star cools by ν-emission until $T_{\rm eff} \approx 10^5$–10^6 K
- ***Slow*** neutrino emission: modified Urca: e.g.,

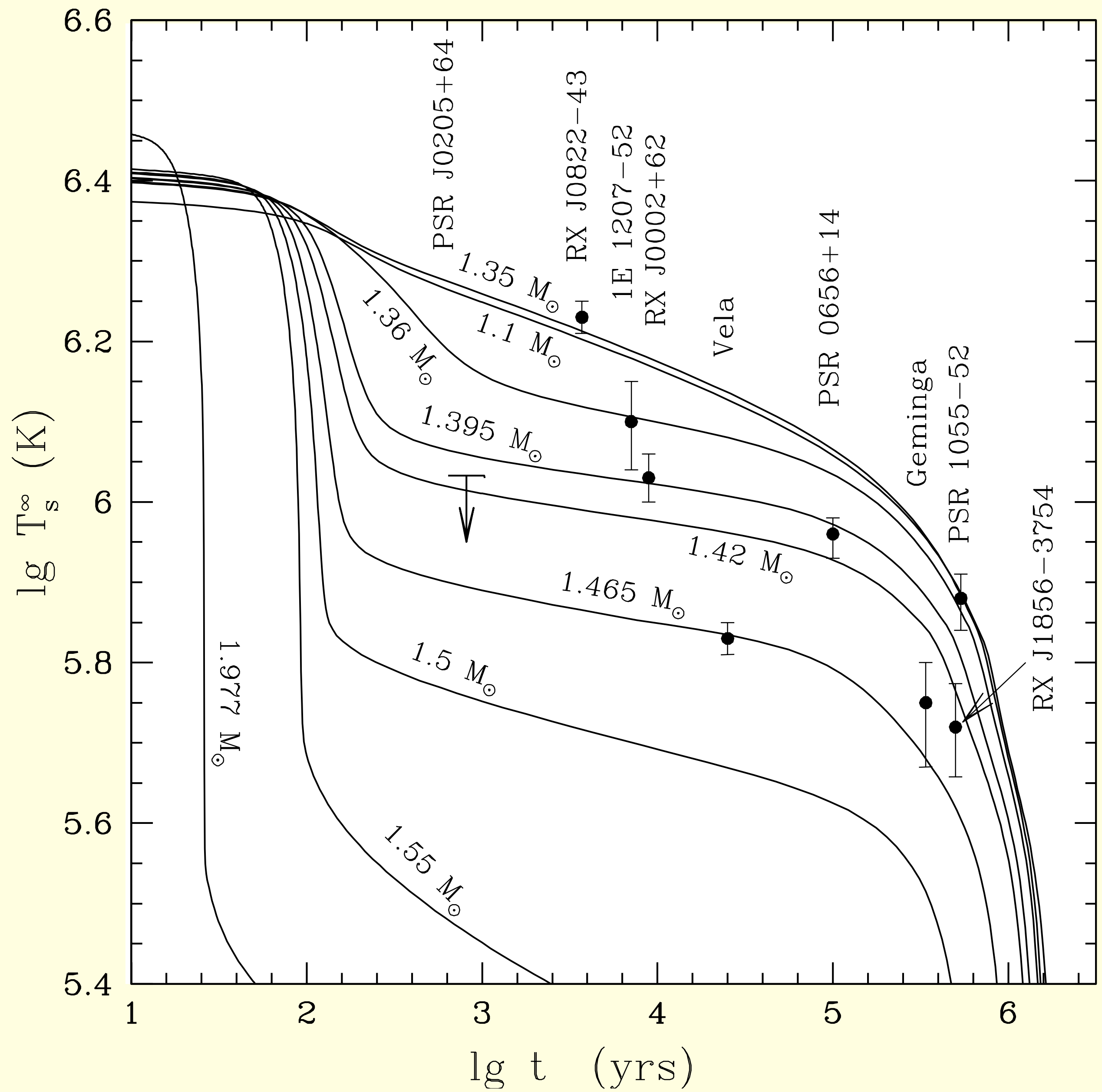
$$nn \to npe\bar{\nu}_e$$

$$\varepsilon_\nu \propto T^8$$

- ***Fast*** neutrino emission: e.g., direct Urca

$$n \to pe\bar{\nu}_e$$

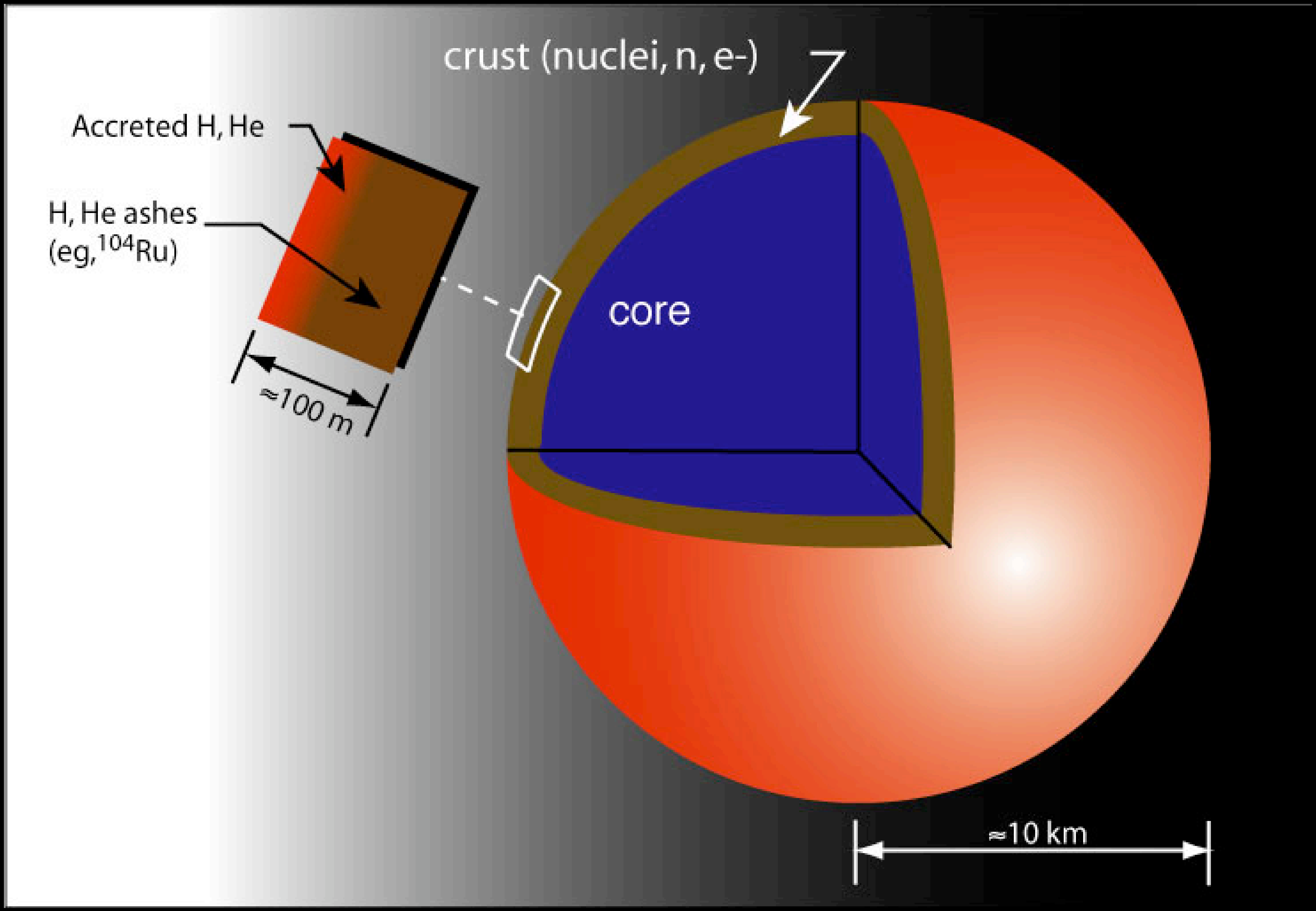
$$\varepsilon_\nu \propto T^6$$

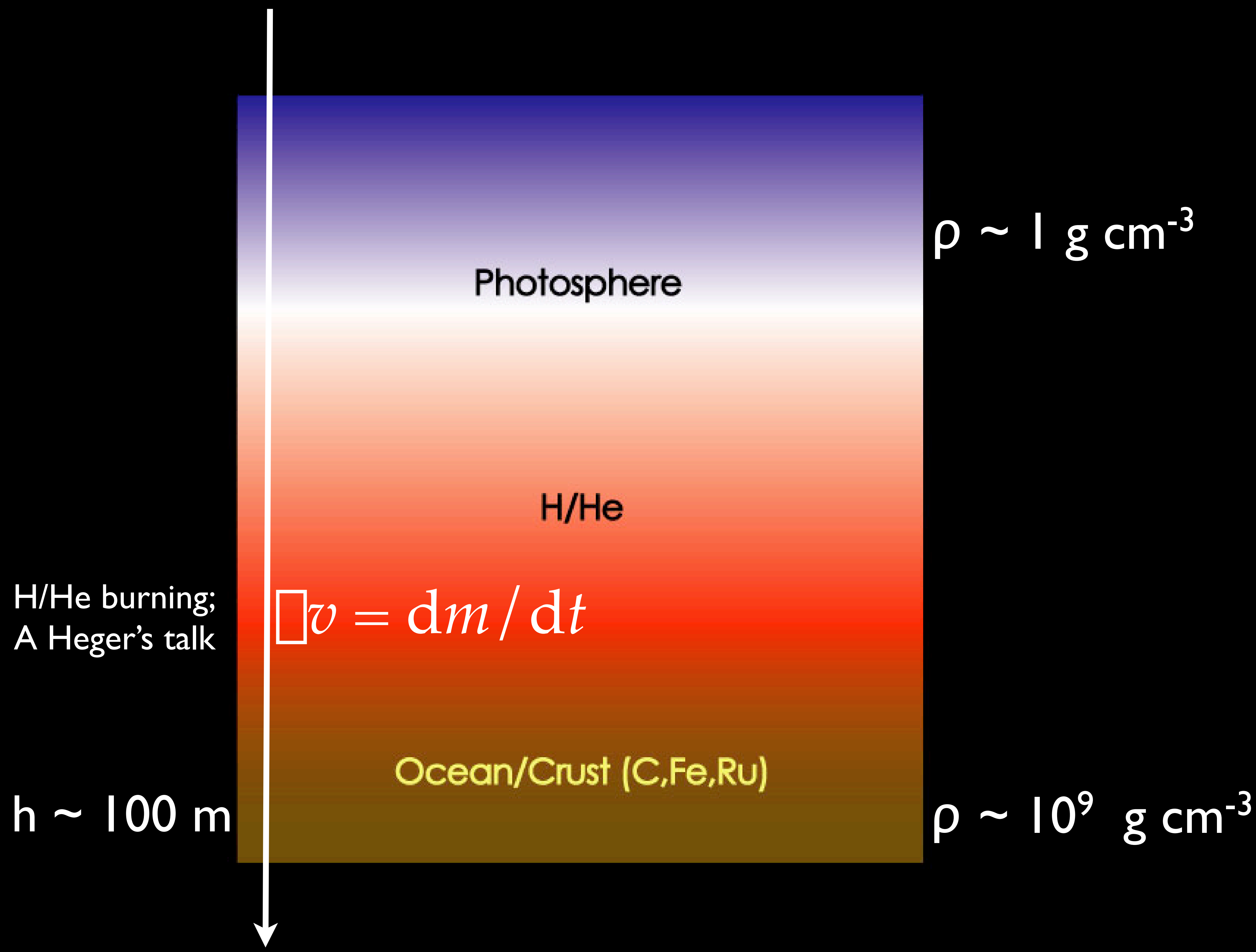


Yakovlev et al. 2002, following Kaminker et al. 2002

In This Talk

- The fate of accreted matter, and deep nuclear heating
- The thermal structure of an accreting neutron star
- Probing the internal structure of accreting neutron stars
  - Superbursts
  - Soft X-ray transients
- Constraints on r-modes

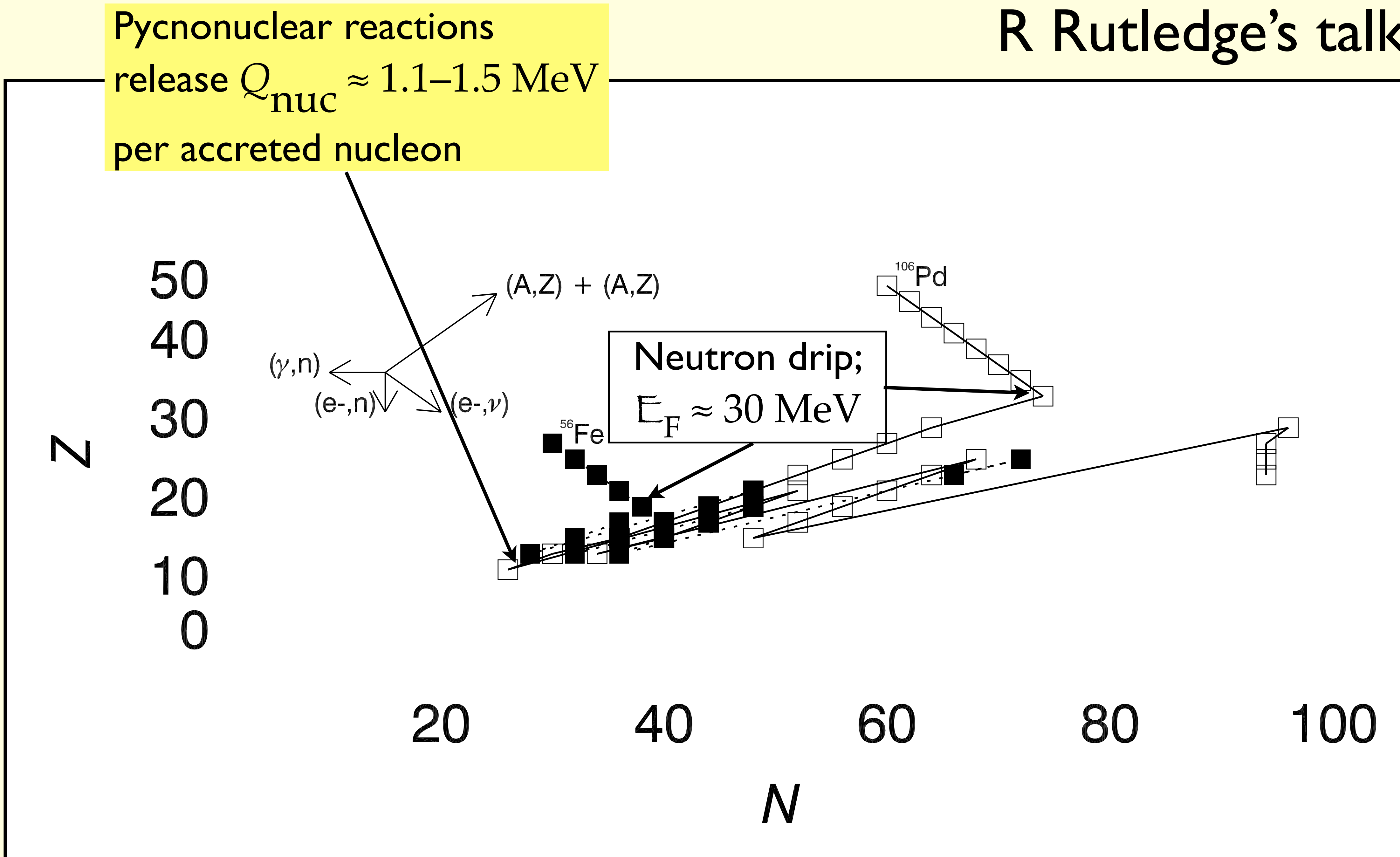

crust (nuclei, n, e-)
Accreted H, He
H, He ashes
(eg, ^{104}Ru)
core
≈100 m
≈10 km


Photosphere
ρ ~ 1 g cm-3
H/He
H/He burning;
A Heger's talk
□v = dm / dt
Ocean/Crust (C,Fe,Ru)
h ~ 100 m
ρ ~ 10^9 g cm-3

Deep Nuclear Heating

following Haensel & Zdunik 1990, 2003

R Rutledge's talk



A Steady-State Crust

$$\partial_r P = -\frac{Gm}{r^2}\square\left(1+\frac{P}{\square c^2}\right)\left(1+\frac{4\square r^3 P}{mc^2}\right)e^{2\square}$$

$$\partial_r \square = \frac{Gm}{r^2 c^2}\left(1+\frac{4\square r^3 P}{mc^2}\right)e^{2\square}$$

$$e^{-2\square}\partial_r\left(Le^{2\square}\right) = 4\square r^2 \square\left(\square_{\mathrm{N}} - \square_{\square}\right)e^{\square}$$

$$e^{-\square}\partial_r\left(Te^{\square}\right) = -\frac{L}{4\square r^2 \square}e^{\square}$$

$$e^{\square} = \left(1-\frac{2GM}{rc^2}\right)^{-1/2}$$

Thermal Conduction

$$K = \frac{\square^2}{3}\frac{n_e k^2 T}{m_e^*}\square$$

Wiedemann-Franz

$$\square_{\rm ph}^{-1} \approx \frac{\square kT}{\hbar}\square_{e,\rm ph}\left[1+\left(\frac{\square_{\rm Debye}}{3.5T}\right)^2\right]^{-1/2}$$

e⁻-phonon scattering

(Yakovlev & Urpin 1980)

Weakly dependent on (A, Z); $\square \sim T^{-1}$ *for* $T < \square$

$$\square_{\rm imp}^{-1} \approx \frac{4\square e^4}{p_{\rm F}^2 v_{\rm F}}\square N_{\rm A}\square_{e,\rm imp}\square_j \left(Z_j - \langle Z\rangle\right)^2 Y_j$$

e⁻-impurity scattering

(Itoh & Kohyama 1992)

Measures impurities, $\approx \square Z\square^2$ *for rp-process ashes*

For Steady, Rapid Accretion

Simple picutre

Crust reactions heat the core at a rate

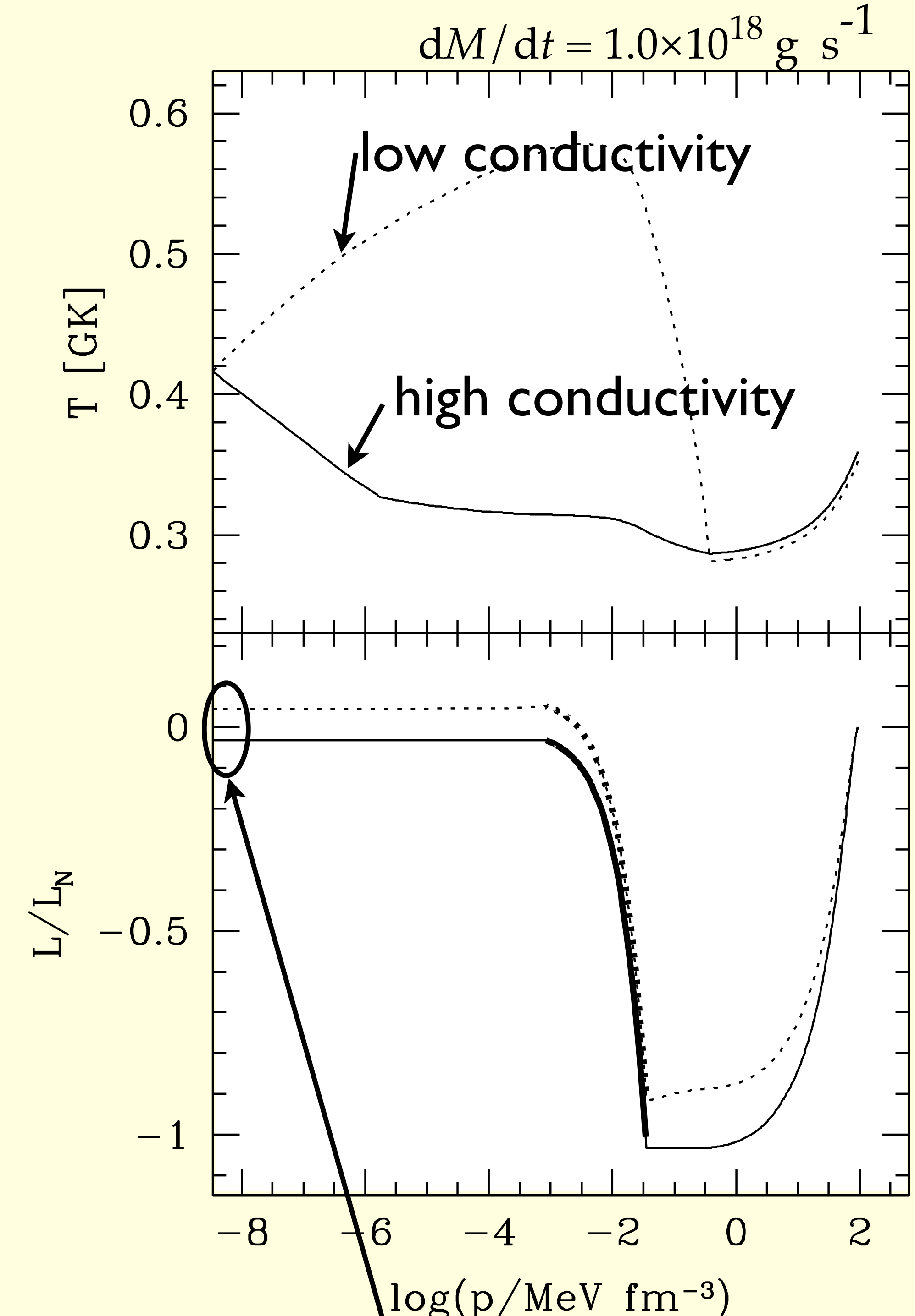
$$L_{\rm nuc} \approx \frac{Q_{\rm nuc}}{m_u}\dot{M}$$
$$\approx 10^{36}\left(\frac{\dot{M}}{10^{-8}\,M_\odot\,{\rm yr}^{-1}}\right)\,{\rm ergs\,s^{-1}}$$

for

$$Q_{\rm nuc} = 1.45\,{\rm MeV}$$

This heating is balanced by neutrino emission from the crust and core. For example, the modified Urca reaction, $nn \rightarrow npe\bar{\nu}_e$ gives

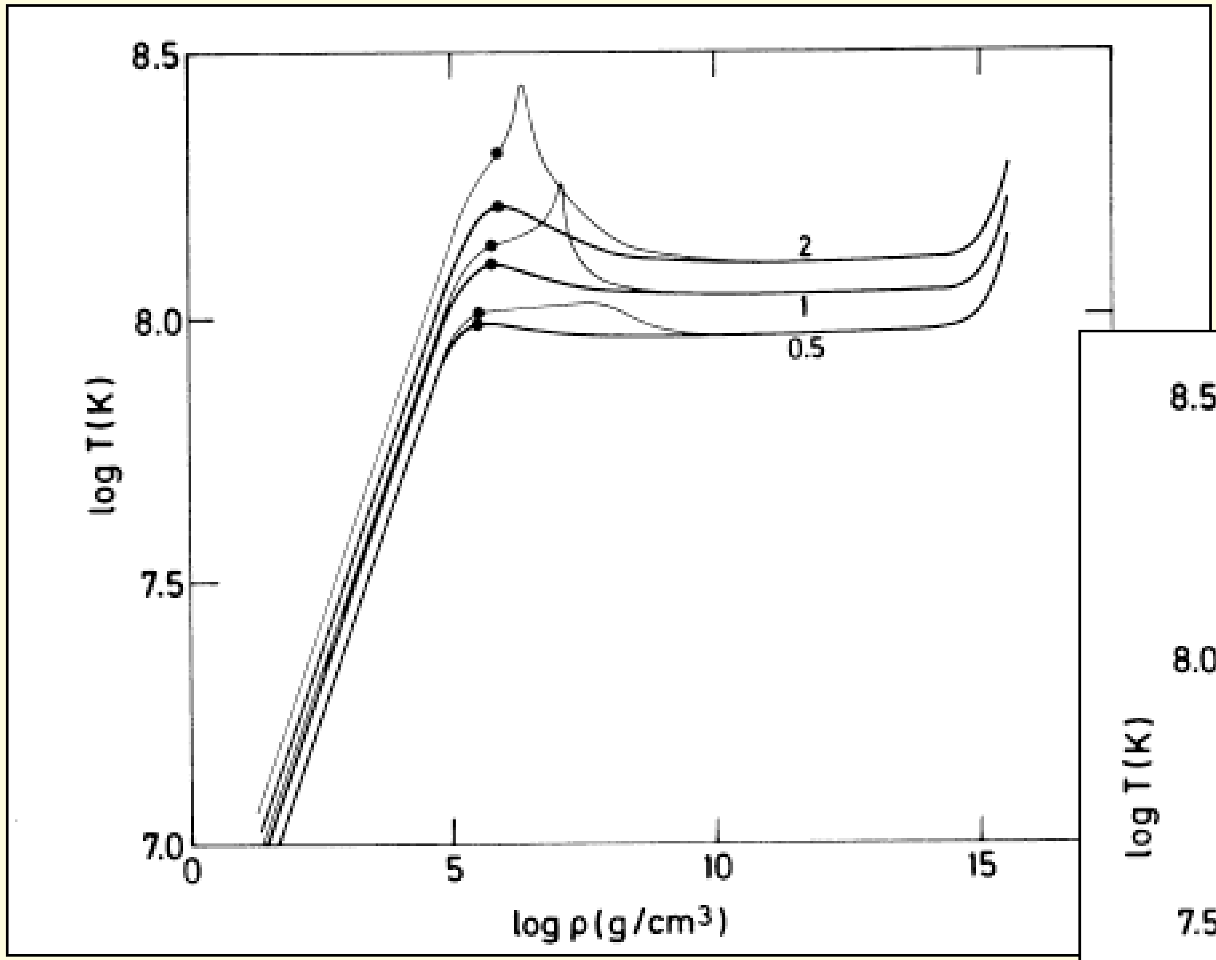
$$L_\nu \approx 2\times 10^{31}\,{\rm ergs\,s^{-1}}\,\left(\frac{T}{10^8\,{\rm K}}\right)^8$$

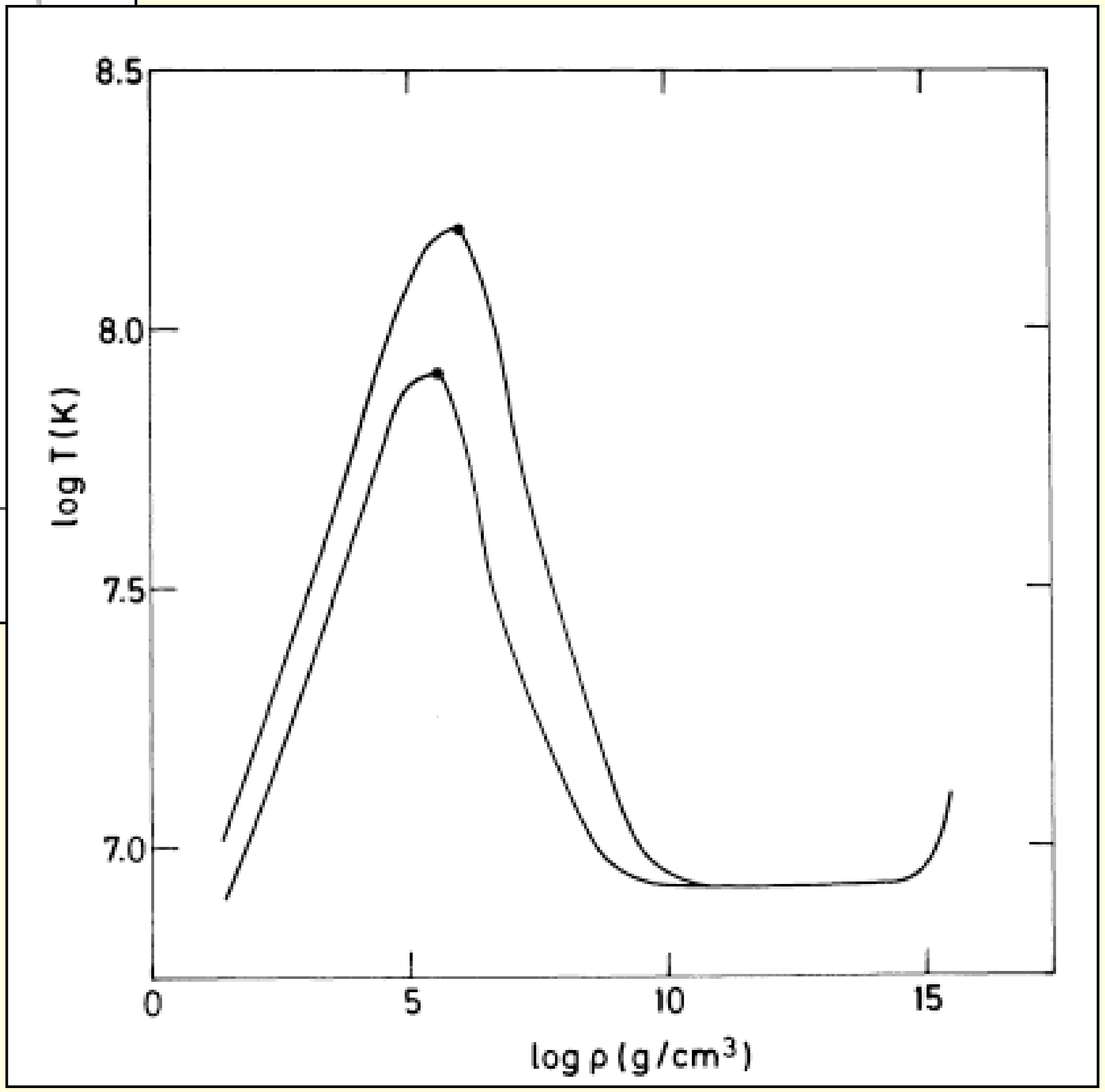


$$F \approx 0.05\,{\rm MeV}\;\dot{M}/m_{\rm u}$$

Brown 2000

Without deep heating...



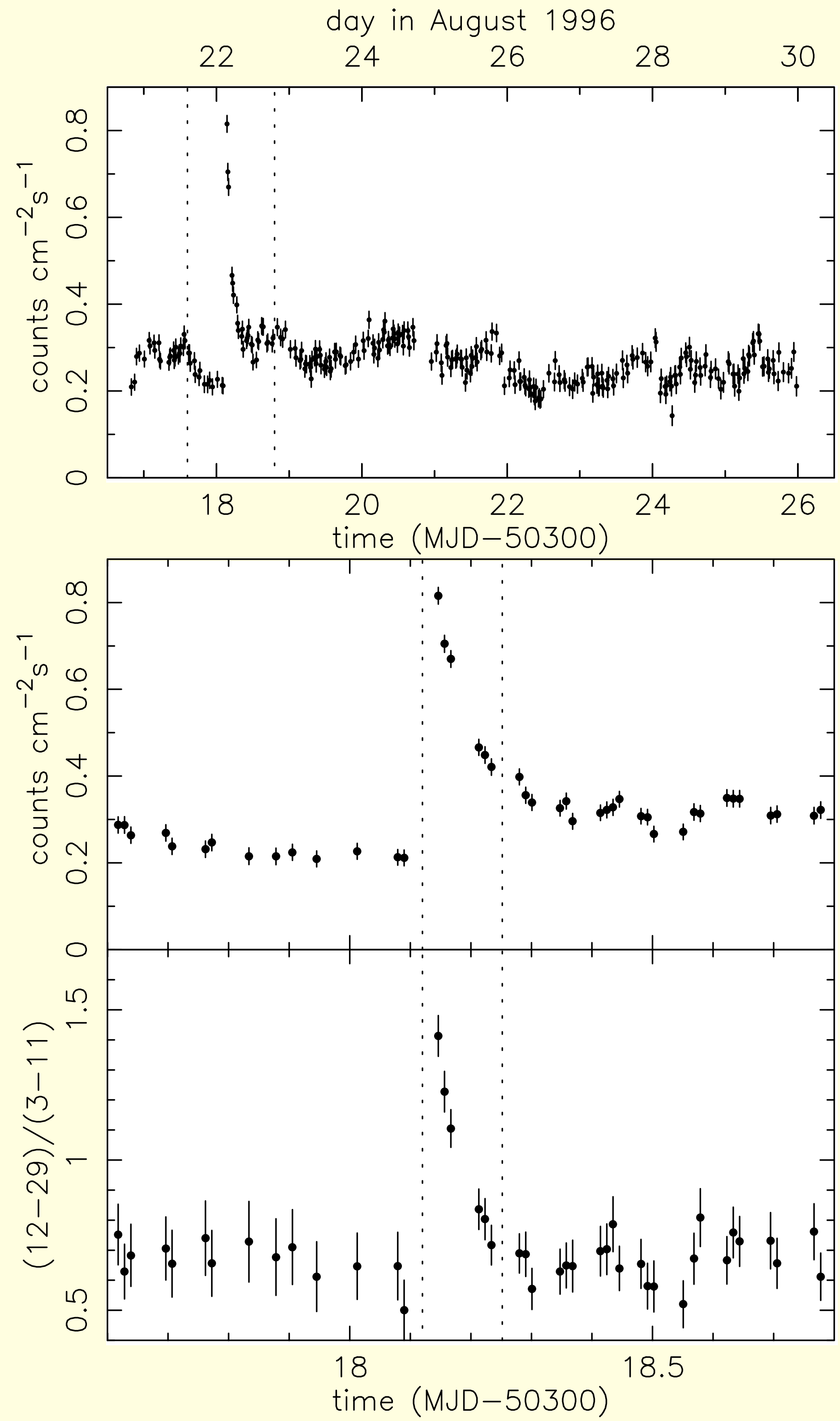


eg, Fujimoto et al. 1987

Superbursts

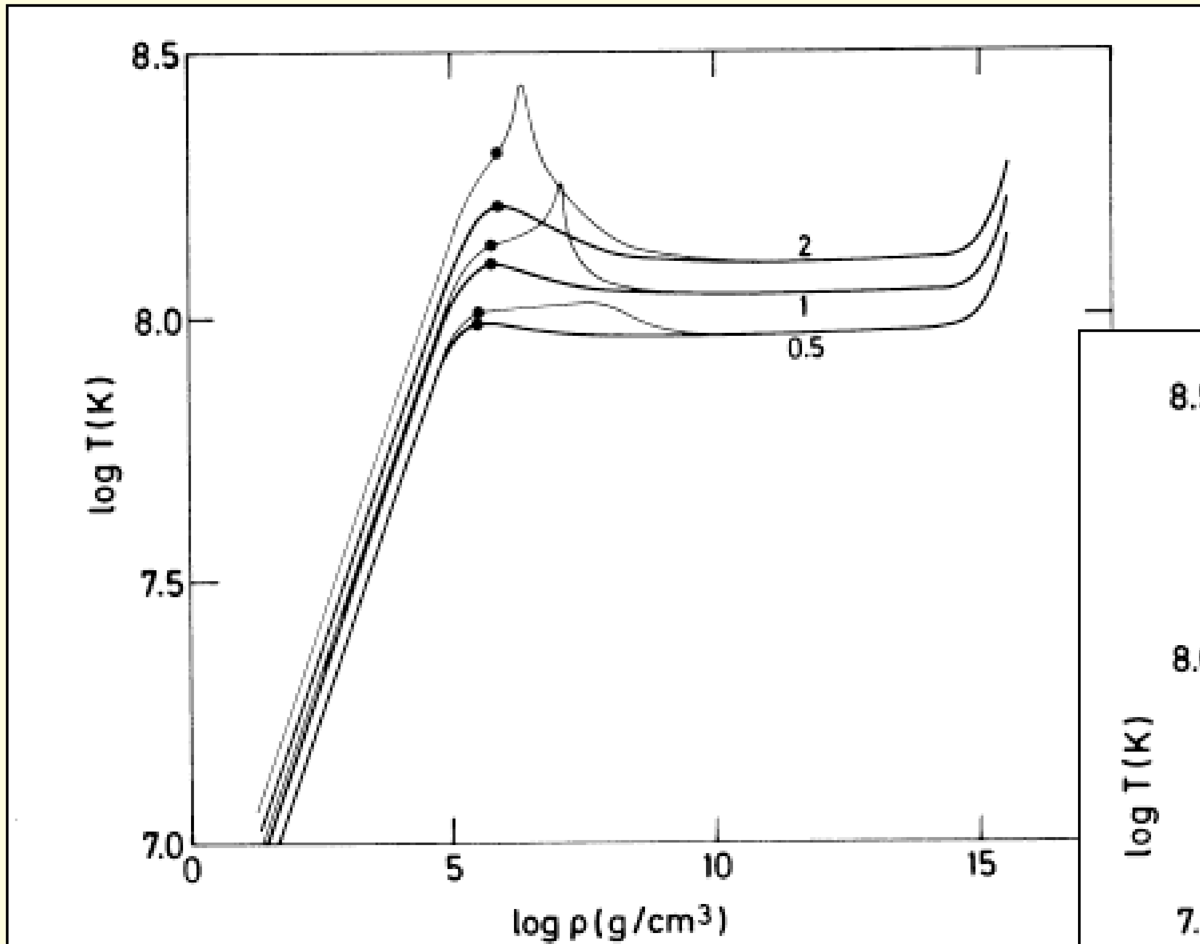
Talks by T Strohmayer, A Cumming

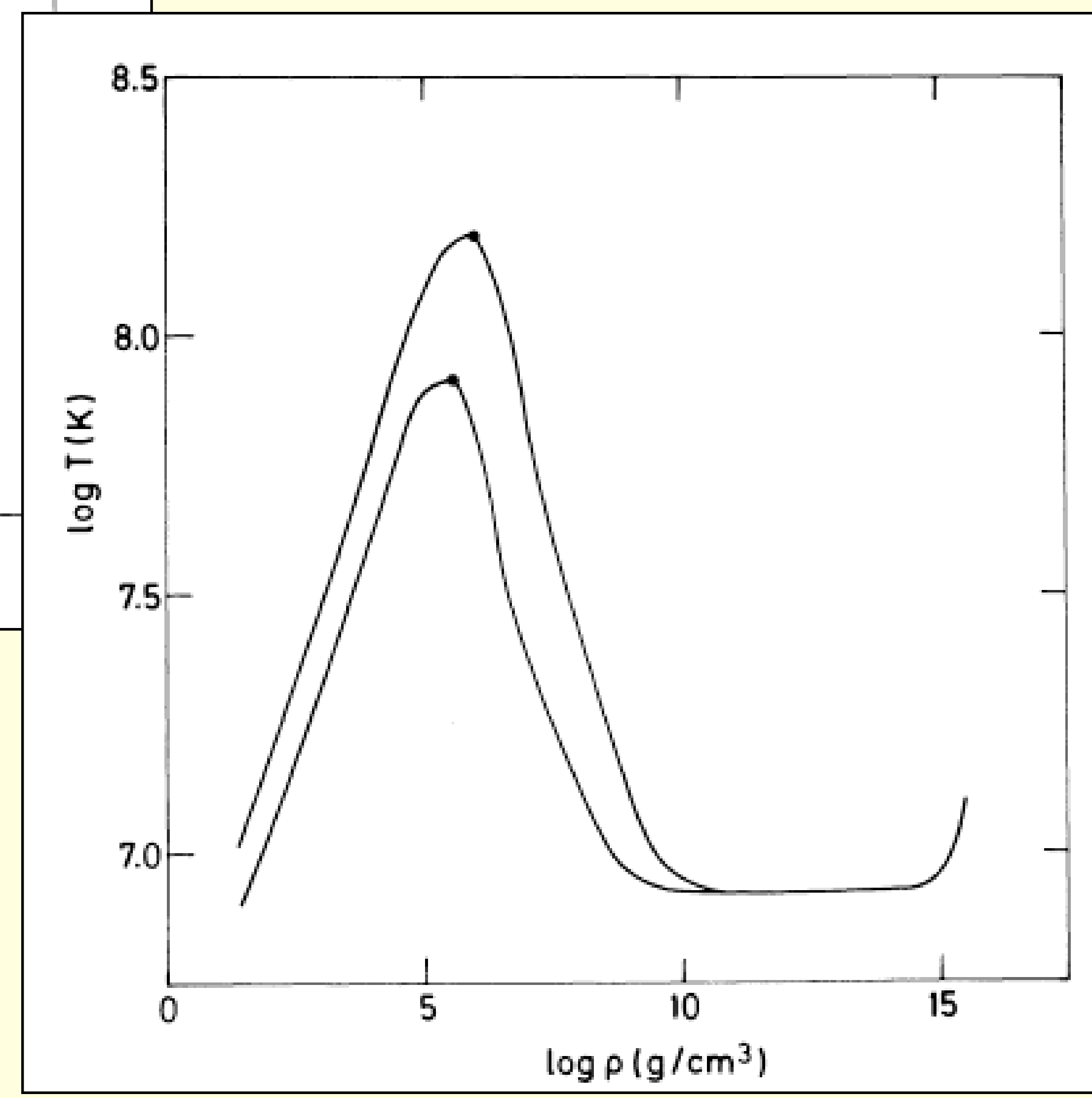
- 7 bursts seen from 6 sources
- 1 measured recurrence time: 4.7 years (Wijnands 2001)
- Duration: 2–12 hrs (Kuulkers et al. 2002)
- Energetics: $E \sim 10^{42}$ ergs
- Fuel:
  - photodisintegration of heavy nuclei (Schatz et al. 2003), triggerered by ^{12}C ignition (Cumming & Bildsten 2001).
  - burning of ^{12}C-rich matter (Strohmayer & Brown 2001);



Cornelisse et al. 2000

Without deep heating...





eg, Fujimoto et al. 1987

Effects of Crust Heating, Neutrino Cooling on Superbursts

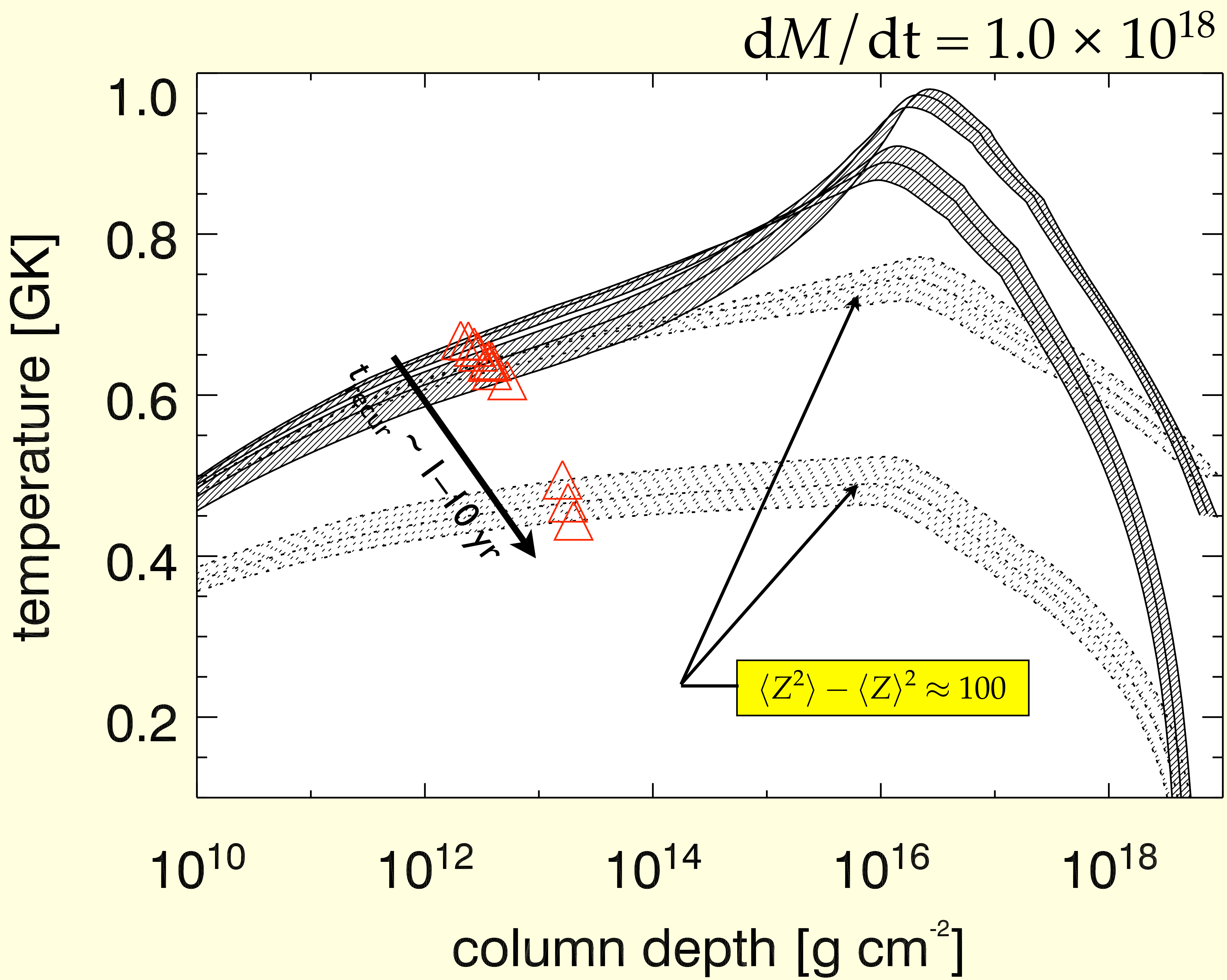
- Toy model of core (Yakovlev, Levinfish, & Haensel 2003; Lattimer & Prakash 2001; Tolman 1939)

$$\rho = \rho_0 \left[1 - \left(\frac{r}{R}\right)^2\right]$$

$$\begin{aligned} \rho\epsilon_\nu &= Q_s T_9^8, \quad \rho < \rho_s \\ &= Q_f T_9^6, \quad \rho > \rho_f \end{aligned}$$

- Set z, R: vary mass to get range of core temperatures

^{12}C Ignition, X_{12} = 0.1



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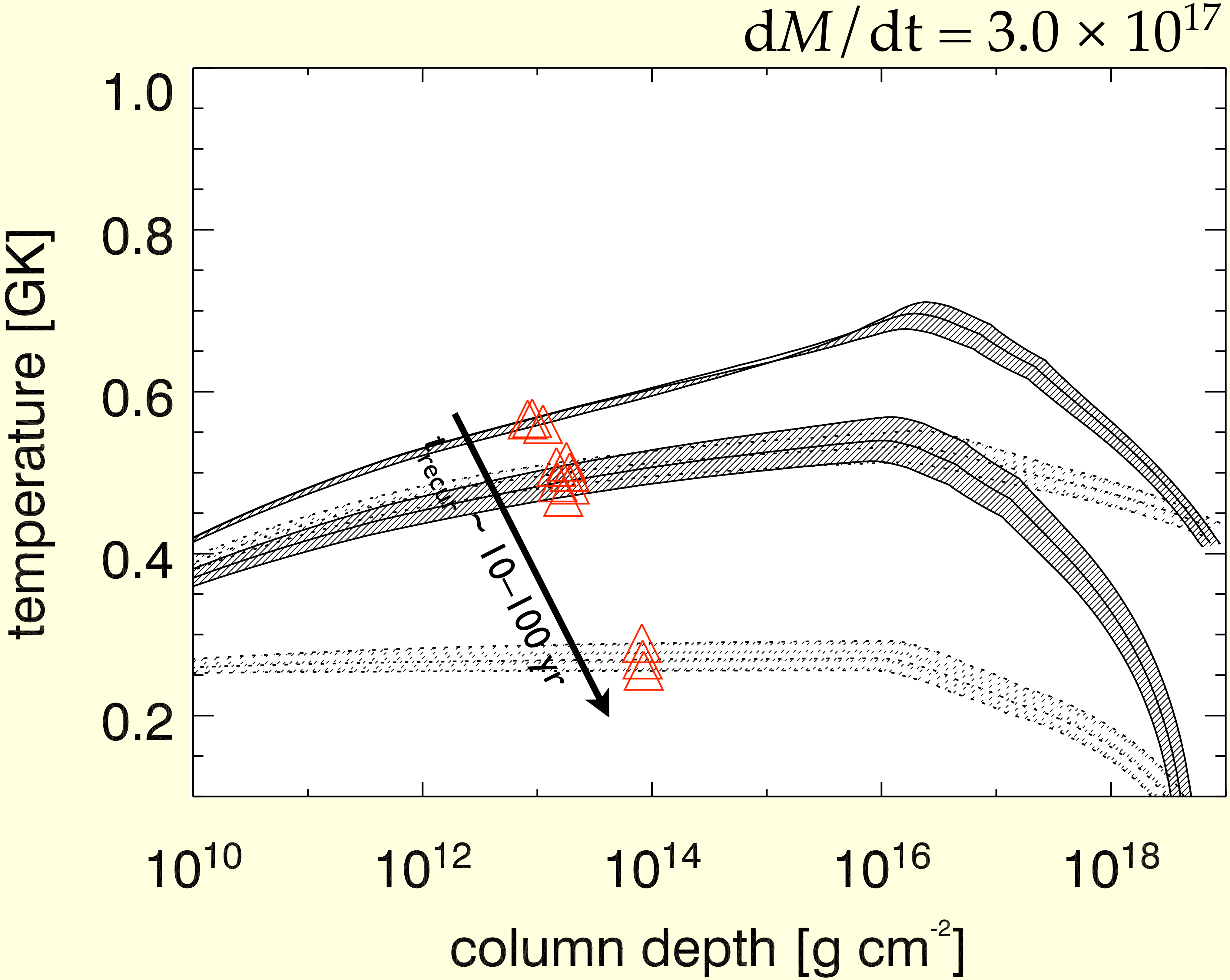

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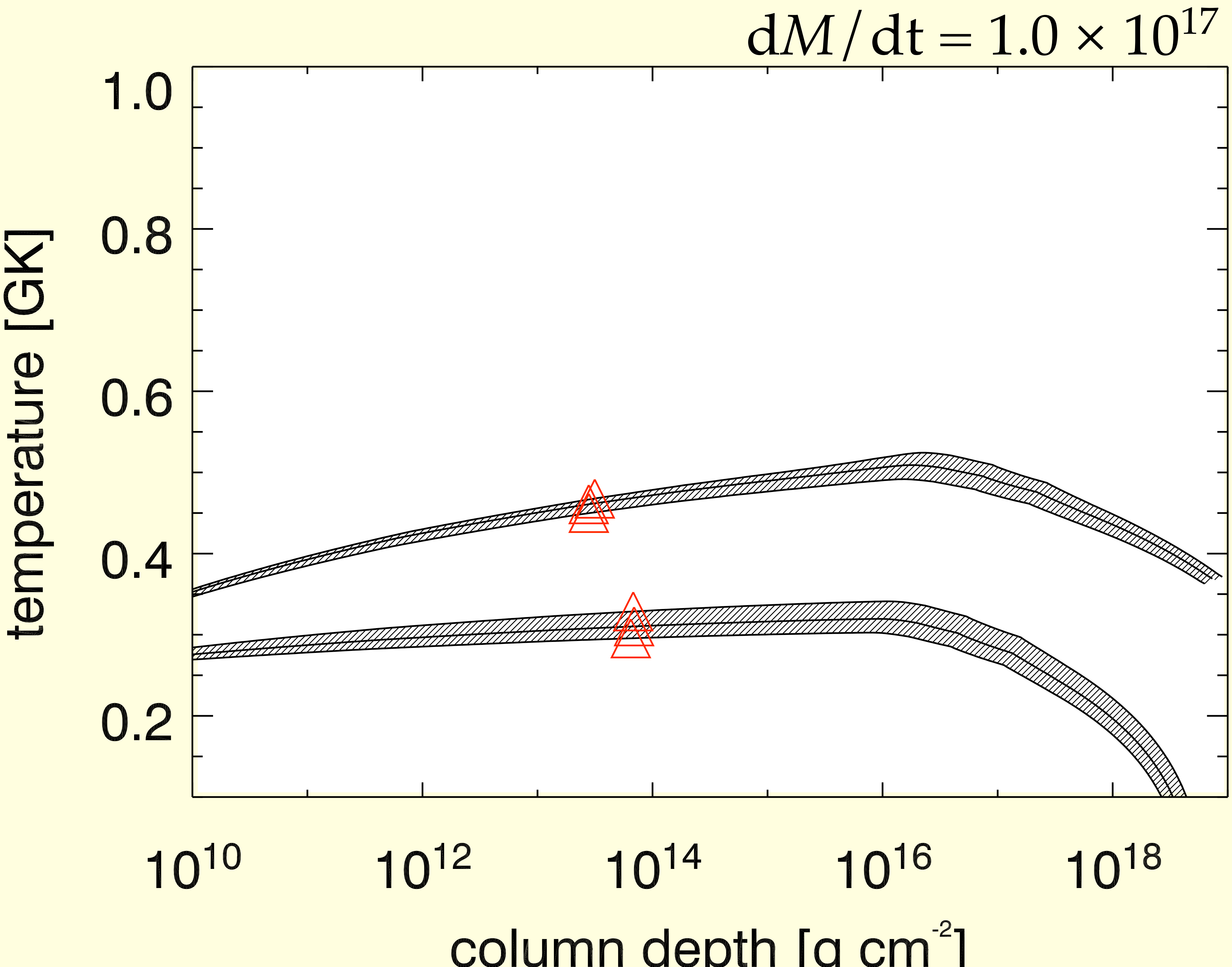
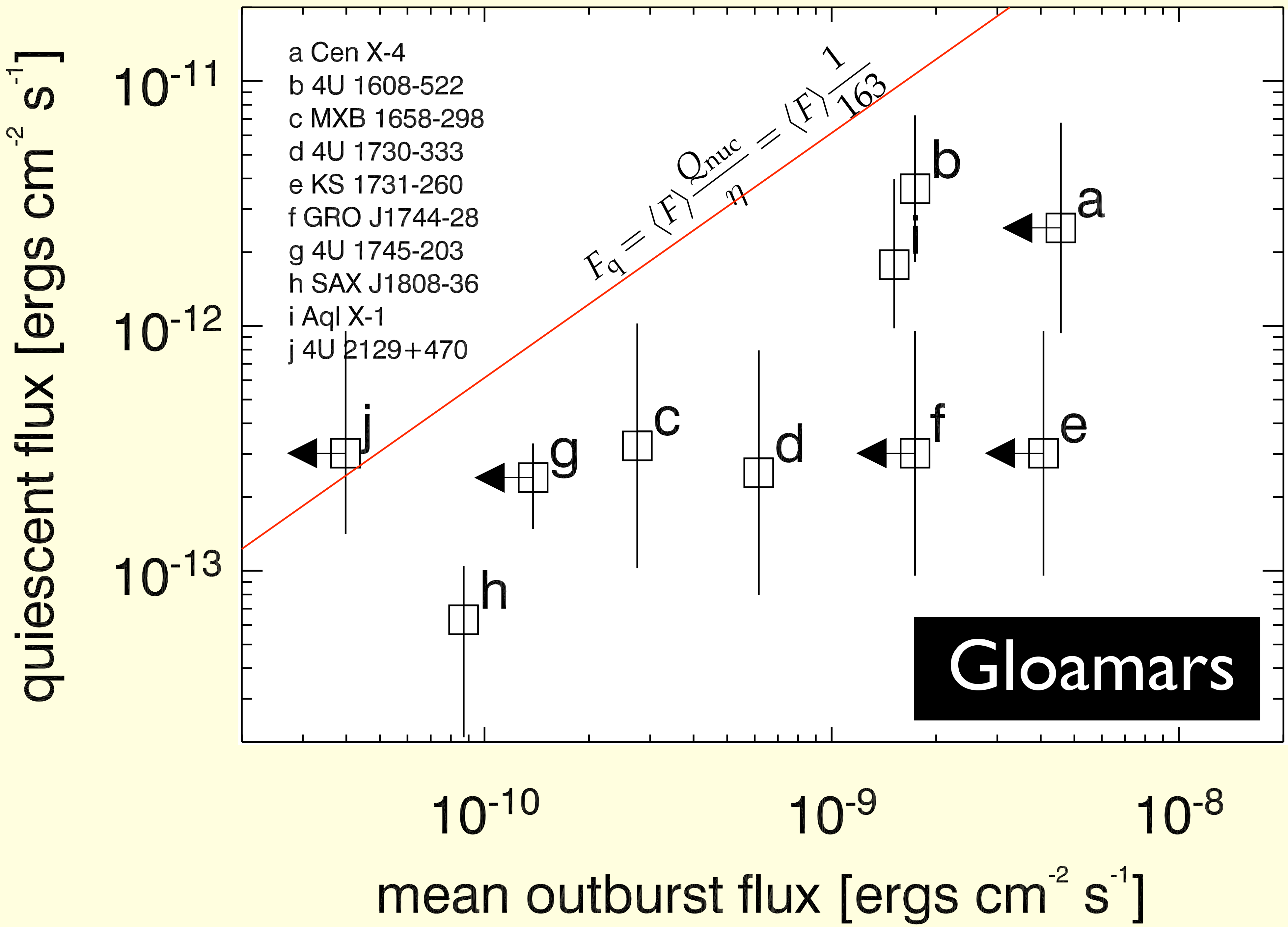


Neutron Star Transients

Flux-flux plot is independent of distance!

Talks by R Rutledge, C Heinke



Brown & Rutledge (2003)

Time-averaged flux $\langle F \rangle$ measured with *RXTE*/ASM where possible

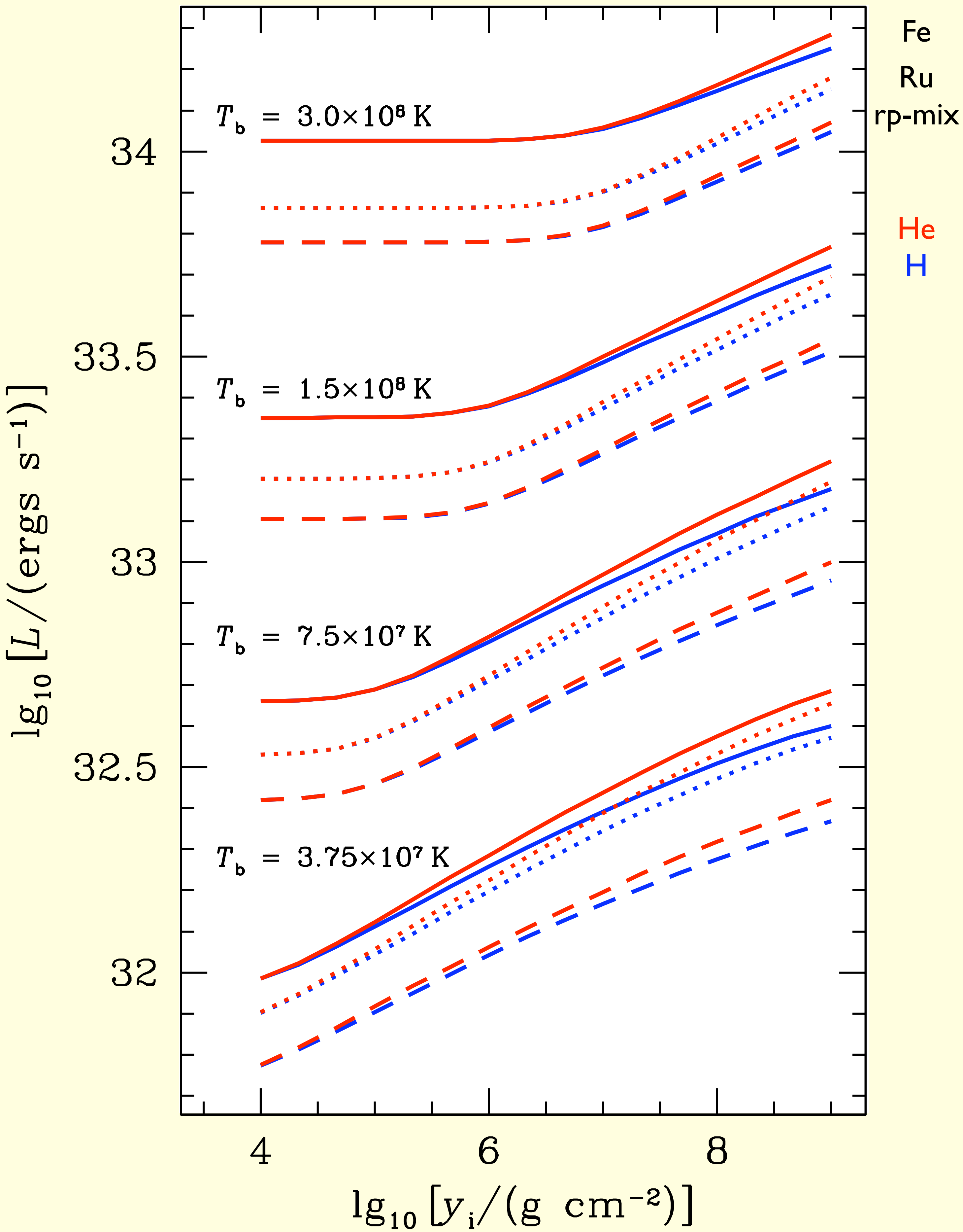
$$\frac{\mathrm{d}}{\mathrm{d}y}\left(\frac{T}{T_{\mathrm{eff}}}\right)^4 = \frac{3}{4}\kappa$$

$$y = \int \rho\, \mathrm{d}z$$

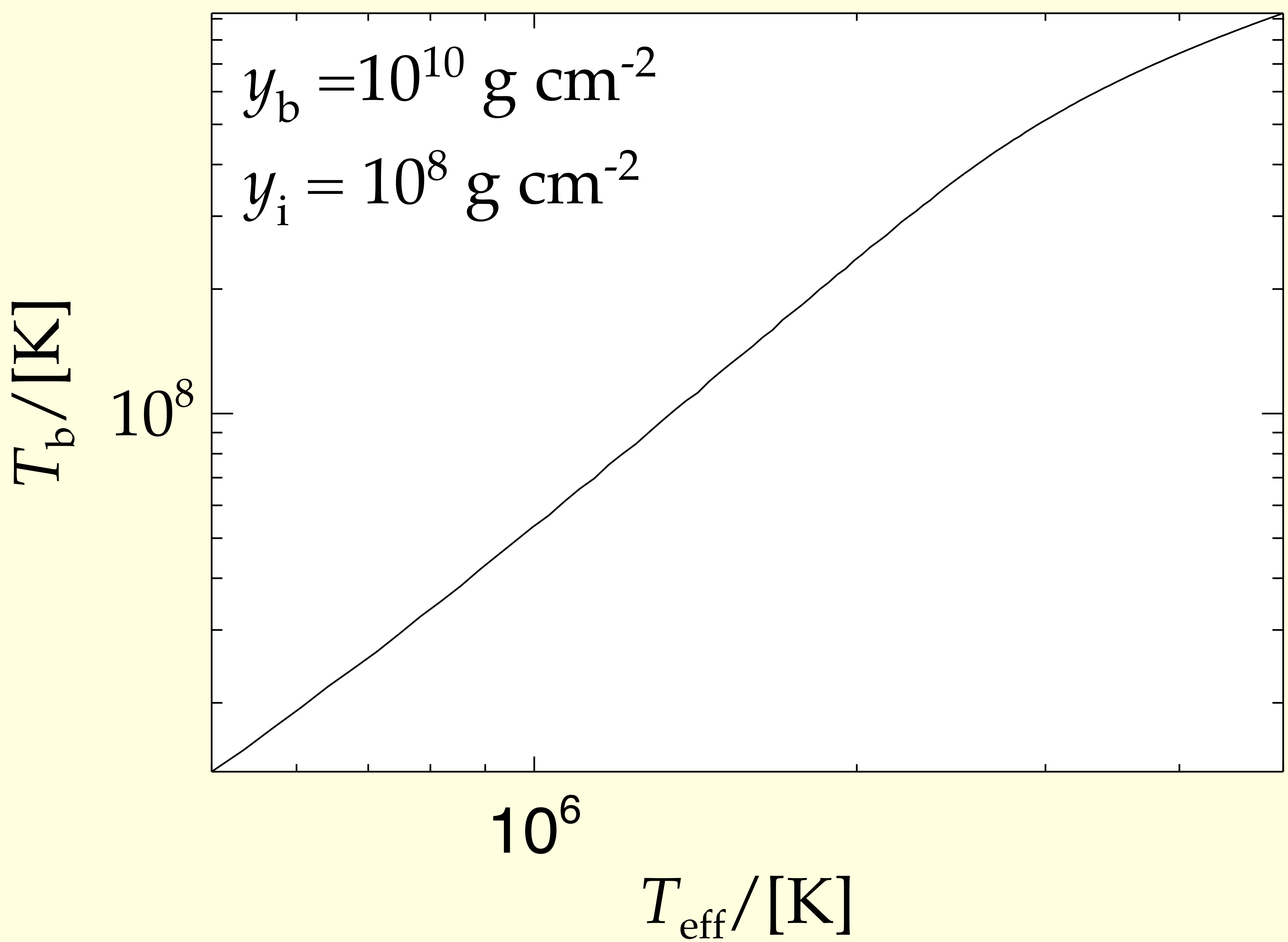
$$\kappa^{-1} = \kappa_{\mathrm{rad}}^{-1} + \kappa_{\mathrm{cond}}^{-1}$$

$$\kappa \propto \frac{Z^2}{A}$$

NB. $y \approx M/(4\pi R^2)$

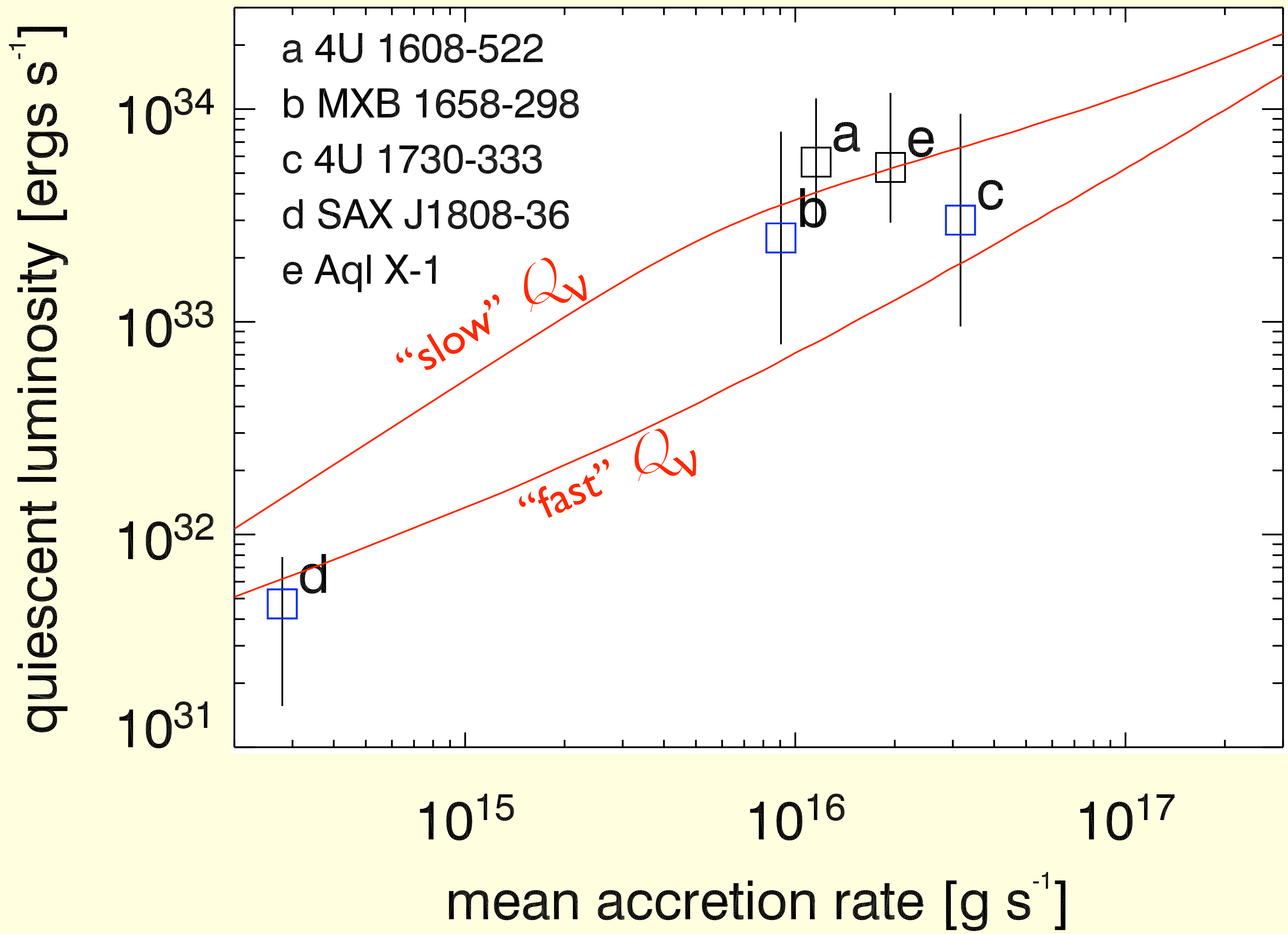


Brown, Bildsten, & Chang 2002; cf. Gudmundsson et al, Charbrier et al.



$y_b = 10^{10}$ g cm^{-2}
$y_i = 10^8$ g cm^{-2}
10^8
T_b/[K]
10^6
T_{eff}/[K]

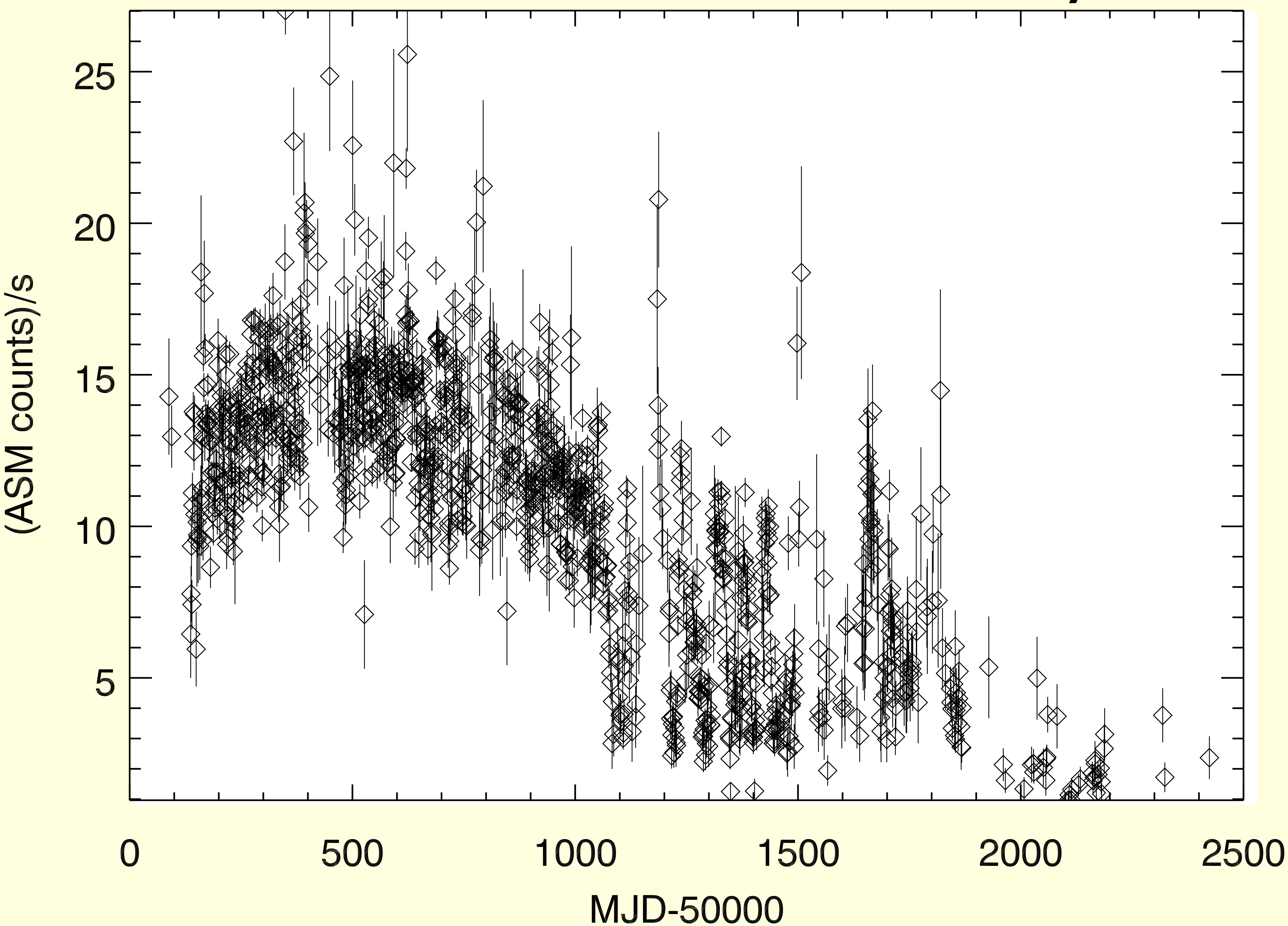
Measuring ν-cooling with neutron star transients



Colpi et al. 2001; Yakovlev et al. 2003; Brown & Rutledge 2003

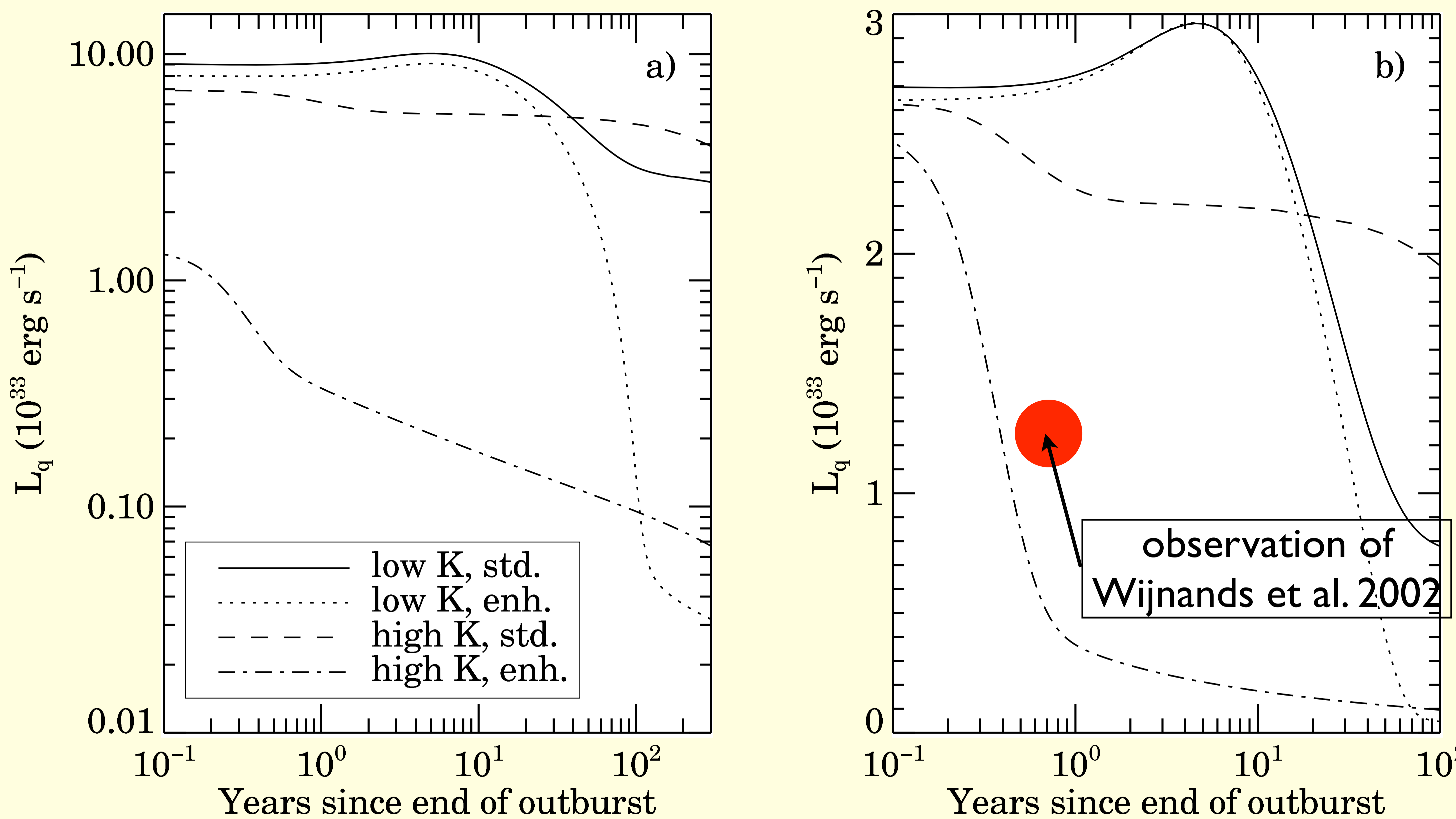
KS 1731-260

Crust thermally relaxes



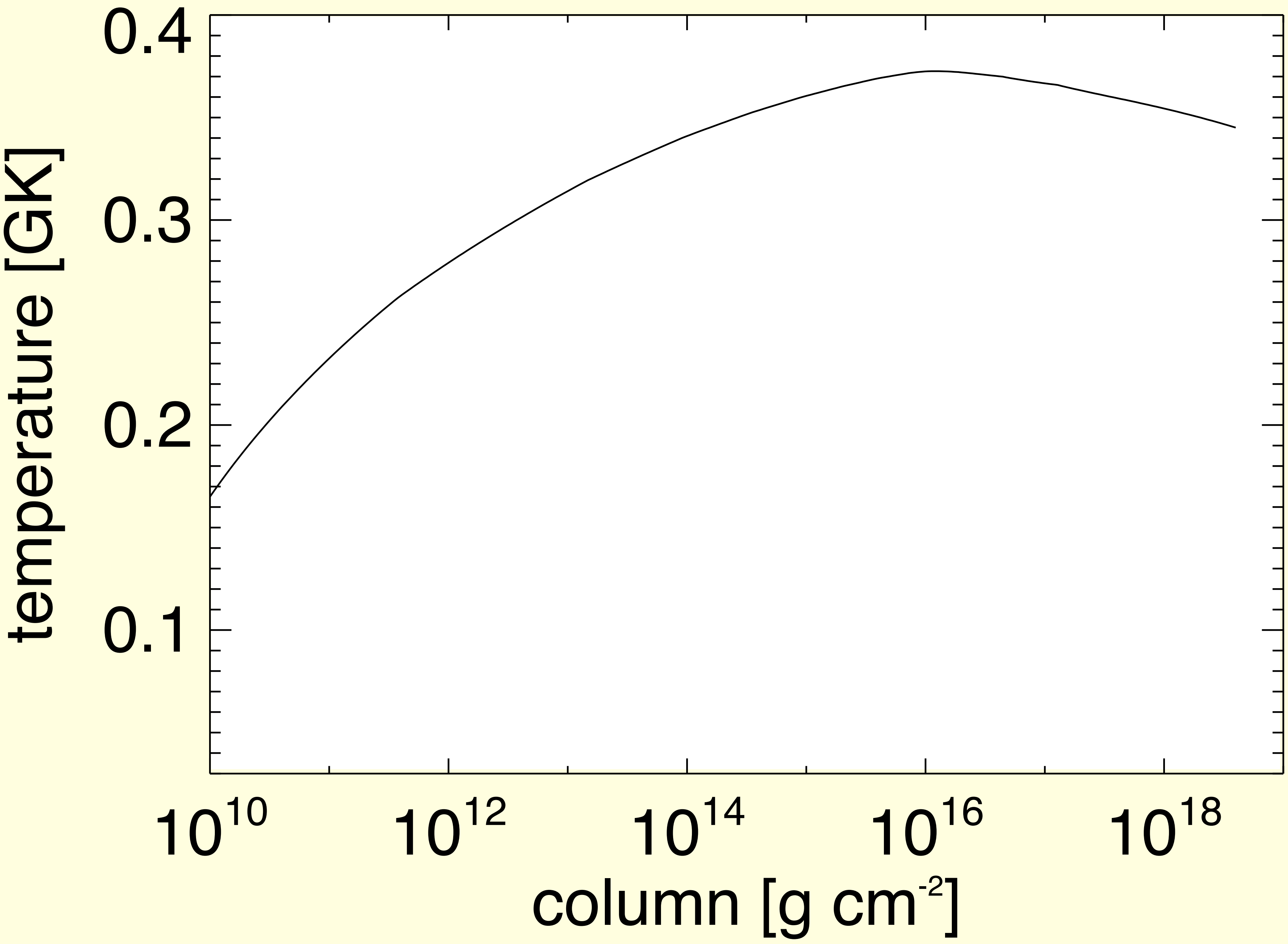
Luminosity Evolution, KS 1731–260

Rutledge et al. 2002, following Ushomirsky & Rutledge 2001



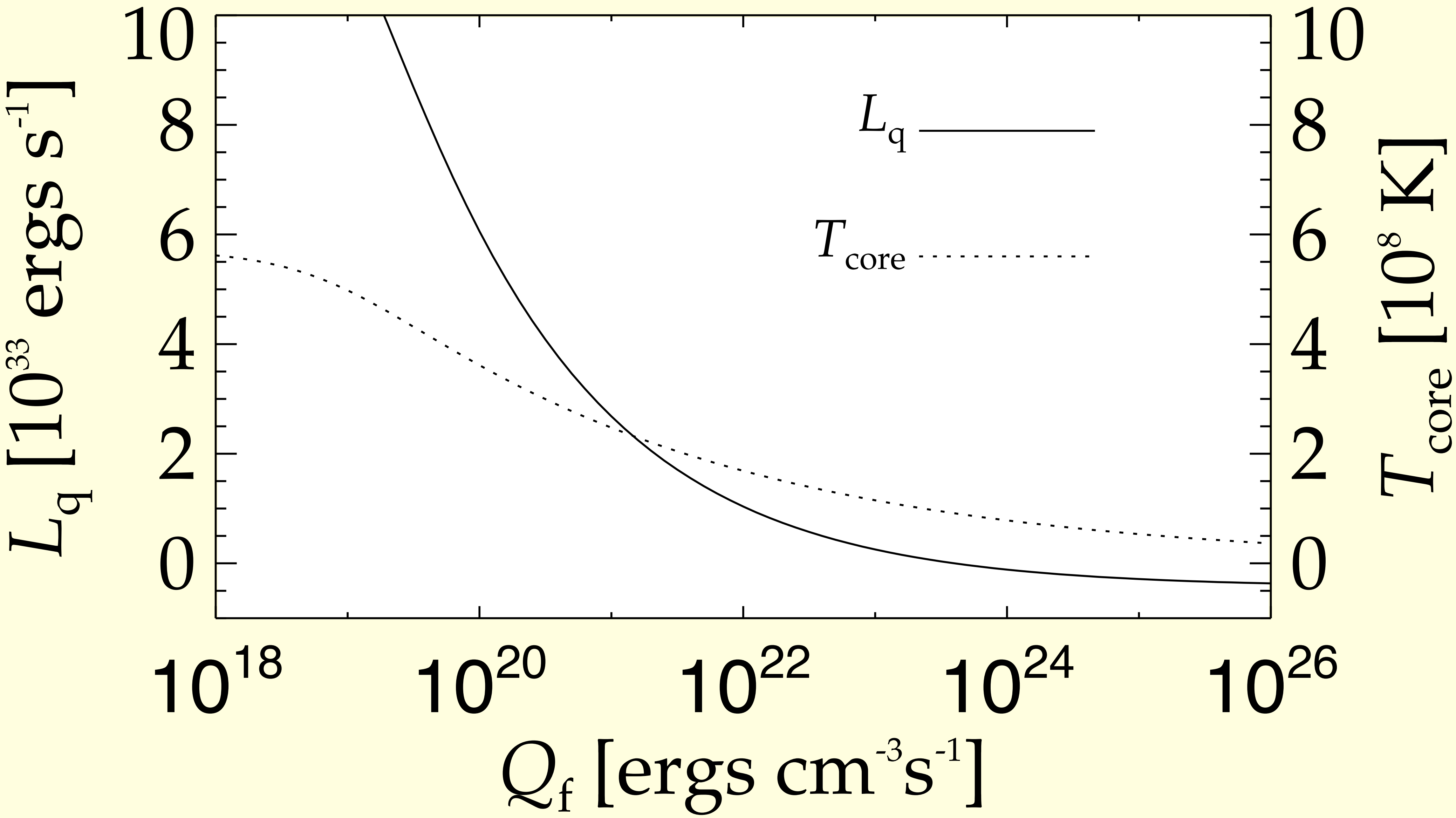
Favors enhanced □-emission, high K

Crust Temperature, Aql X-1

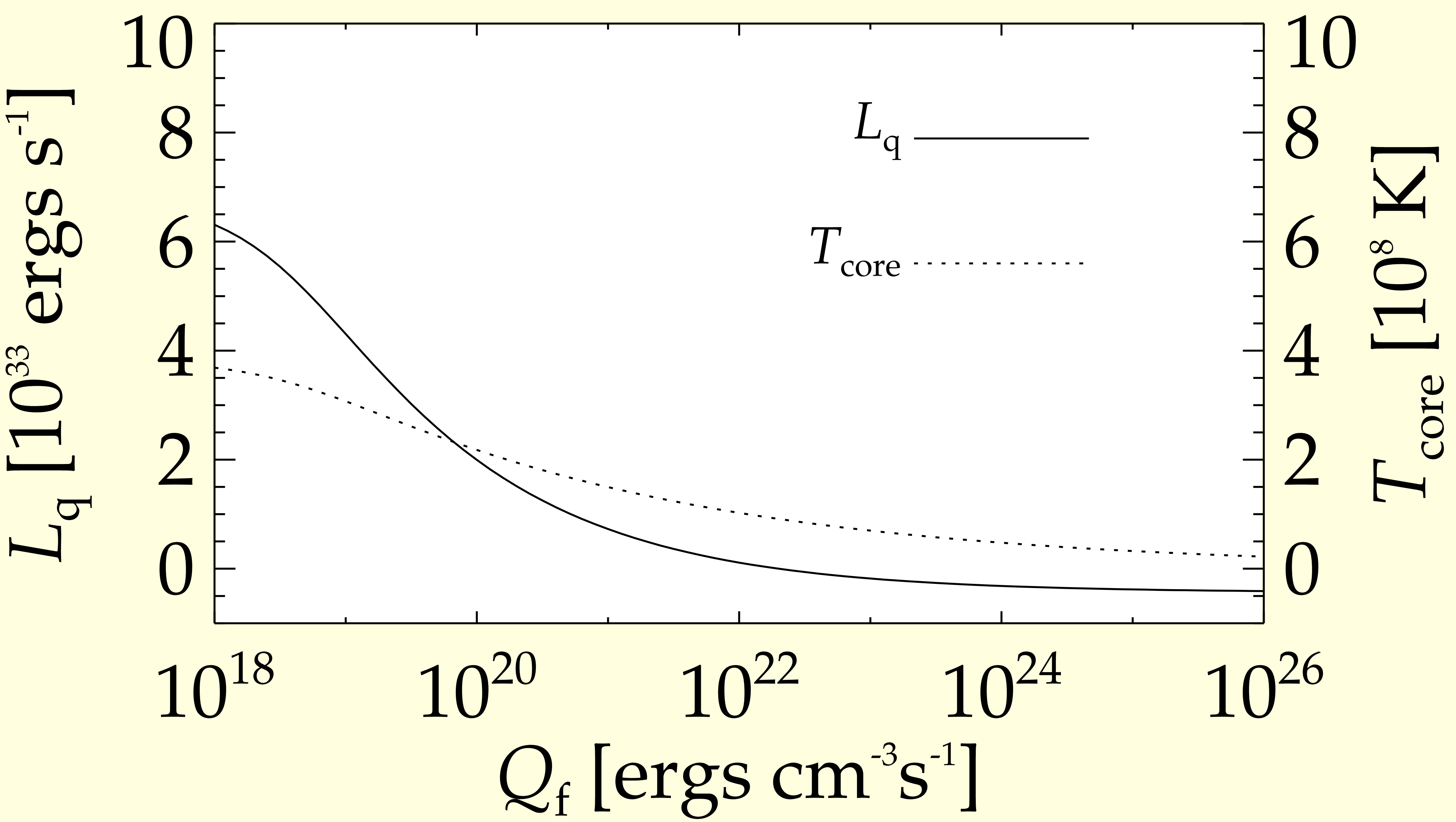


Quiescent Luminosity, Aql X-1

With r-mode heating (Brown & Ushomirsky 2000); talks by N Andersson, A Reisenegger



Quiescent Luminosity, Aql X-1



Summary

- Electron captures, neutron emission, pycnonuclear reactions heat the neutron star's interior
  - Observed from neutron star transients
  - Affects recurrence times of superbursts—but need to know accretion rate
- Measurements can constrain crust, core physics (P Arras's talk); compare with observations of isolated neutron stars
- Measured temperatures and spins inform r-mode calculations