Neutron Star Cooling

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Measurements of M, R, Λ give us $P(\rho)$; but we don't know *what* is providing the pressure. Cooling neutron stars provide information on transport, namely

Specific heat—are the nucleons paired?

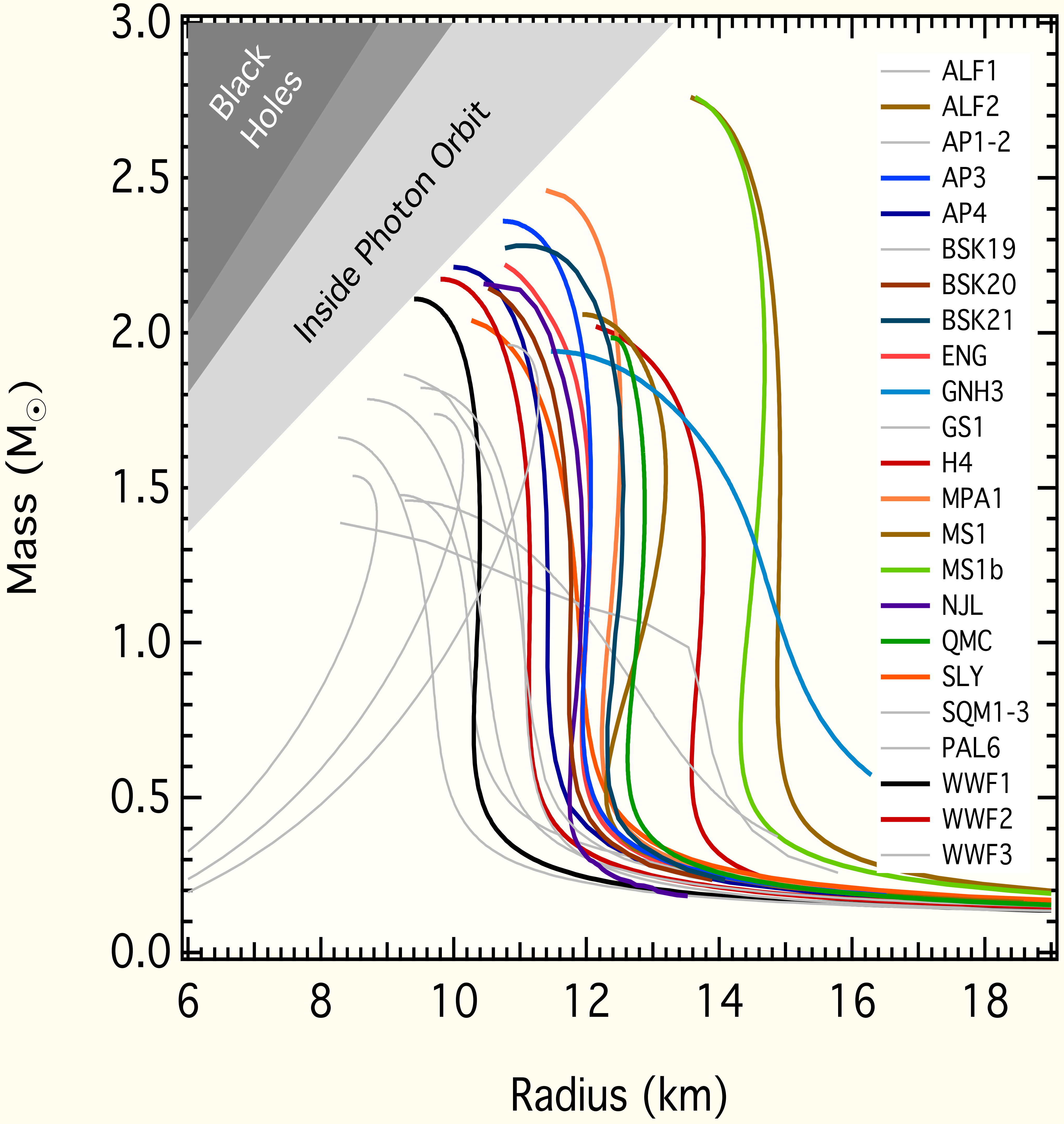
$$C \sim \left(\frac{T}{T_{\mathrm{F}}}\right) e^{-T_c/T}$$

Neutrino emissivity—can rapid cooling proceed?

The reactions $n \rightarrow p e \bar{\nu}_e$ and inverse (direct Urca) are blocked (conservation of momentum, energy) unless $n_p/n \gtrsim 0.11$; or other degrees of freedom (e.g., hyperons) are present.

$$\begin{aligned} L_{\nu,\mathrm{dU}} &= 6 \times 10^{38}\, \tilde{T}_8^6\ \mathrm{erg\ s}^{-1} \\ L_{\nu,\mathrm{mU}} &= 6 \times 10^{30}\, \tilde{T}_8^8\ \mathrm{erg\ s}^{-1} \end{aligned}$$

from Özel & Freire 2016



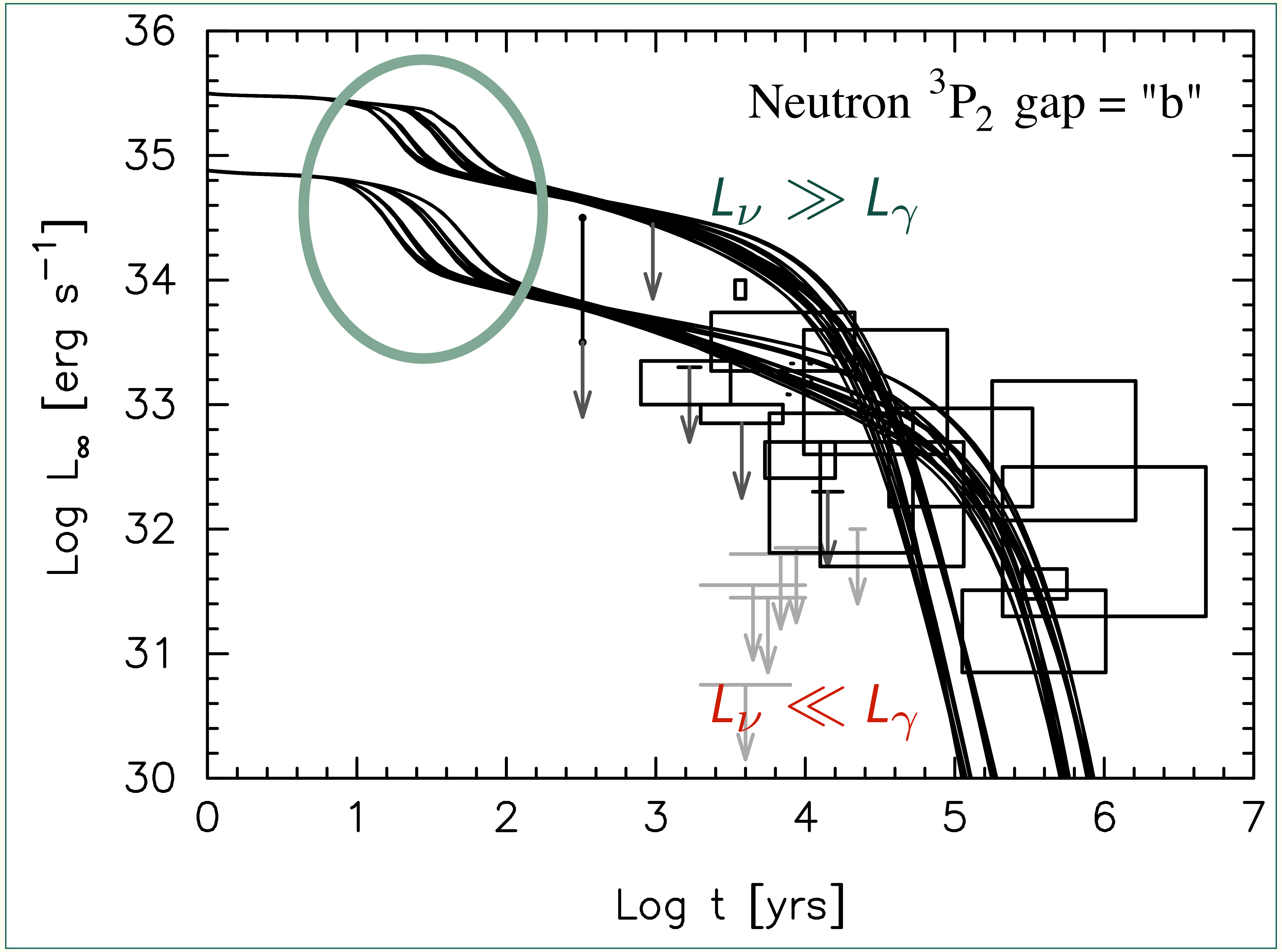
Cooling isolated neutron stars

see reviews by Yakovlev & Pethick, Page et al.

10+ years: star thermally relaxes, interior is mostly isothermal

Cooling via neutrinos from core, photons from surface

$$C(\tilde{T})\frac{d\tilde{T}}{dt} = -L_\nu(\tilde{T}) - L_\gamma(\tilde{T})$$



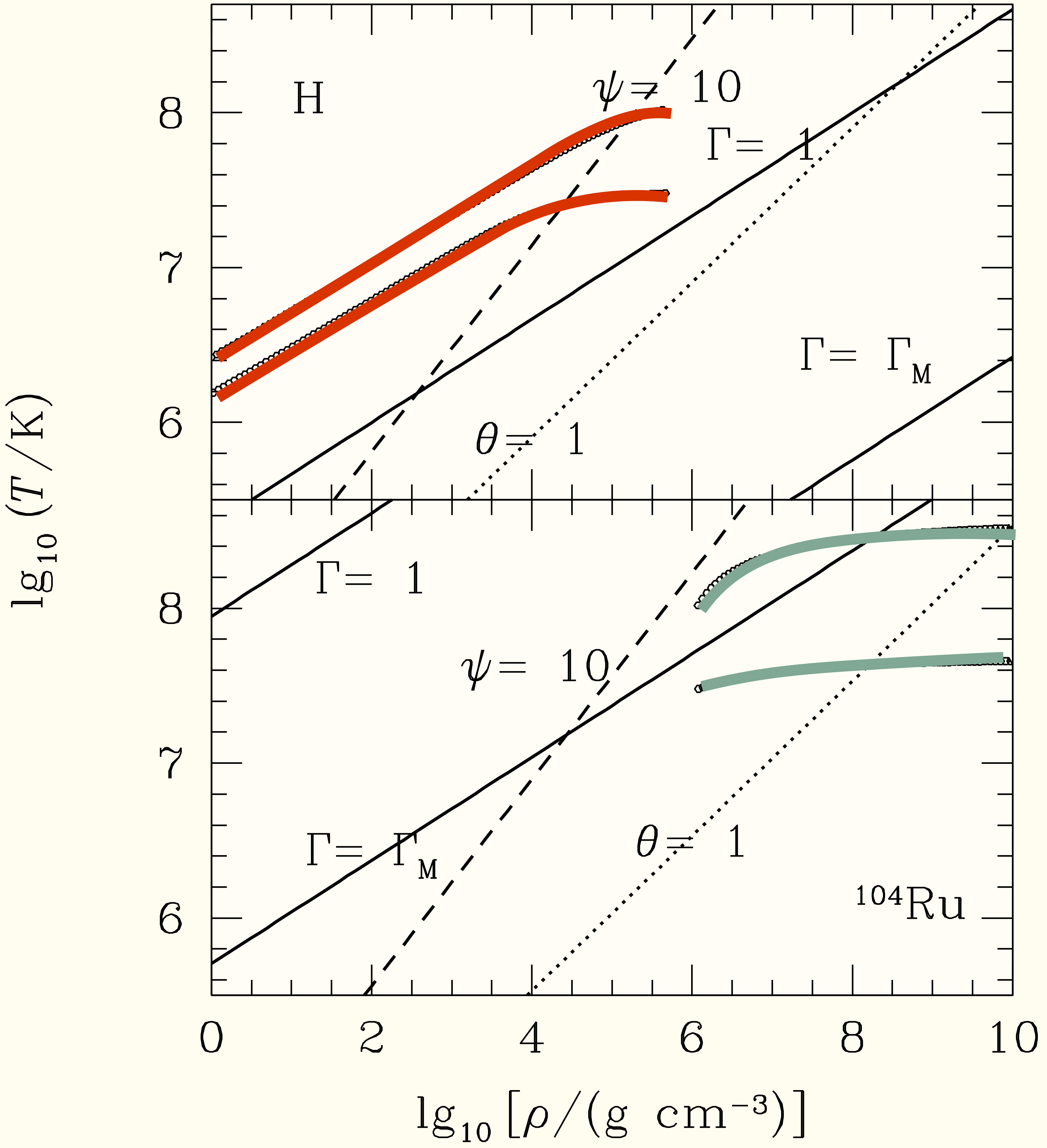
Page, Lattimer, Prakash, & Steiner 2009

The neutron star envelope | $F = \text{const.}$

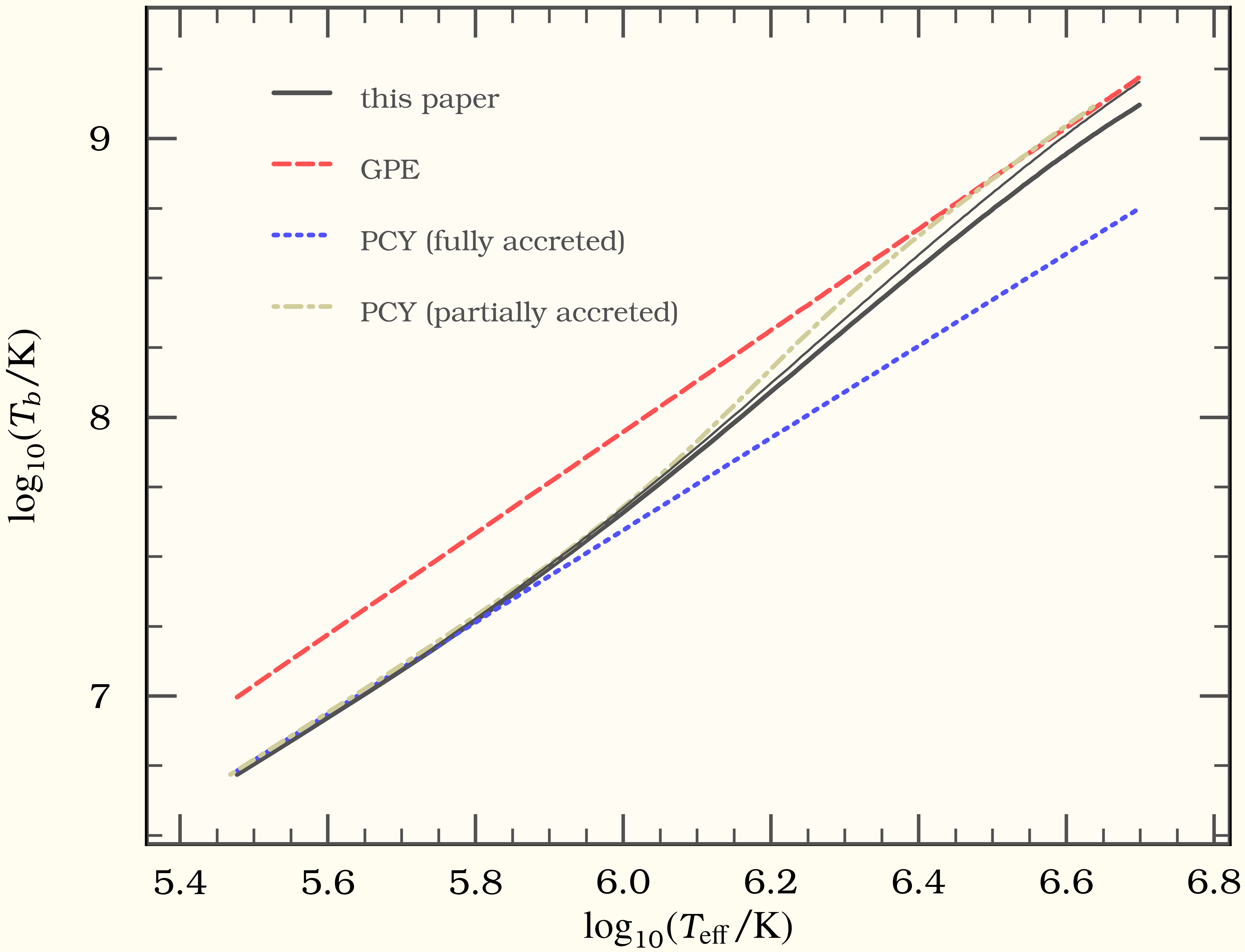
Envelope thermally relaxes in hours; flux is constant

$$\begin{aligned} F = \sigma_{\mathrm{SB}} T_{\mathrm{eff}}^4 &= -K\frac{\mathrm{d}T}{\mathrm{d}r} \\ \frac{\mathrm{d}P}{\mathrm{d}r} &= -\rho g \end{aligned}$$

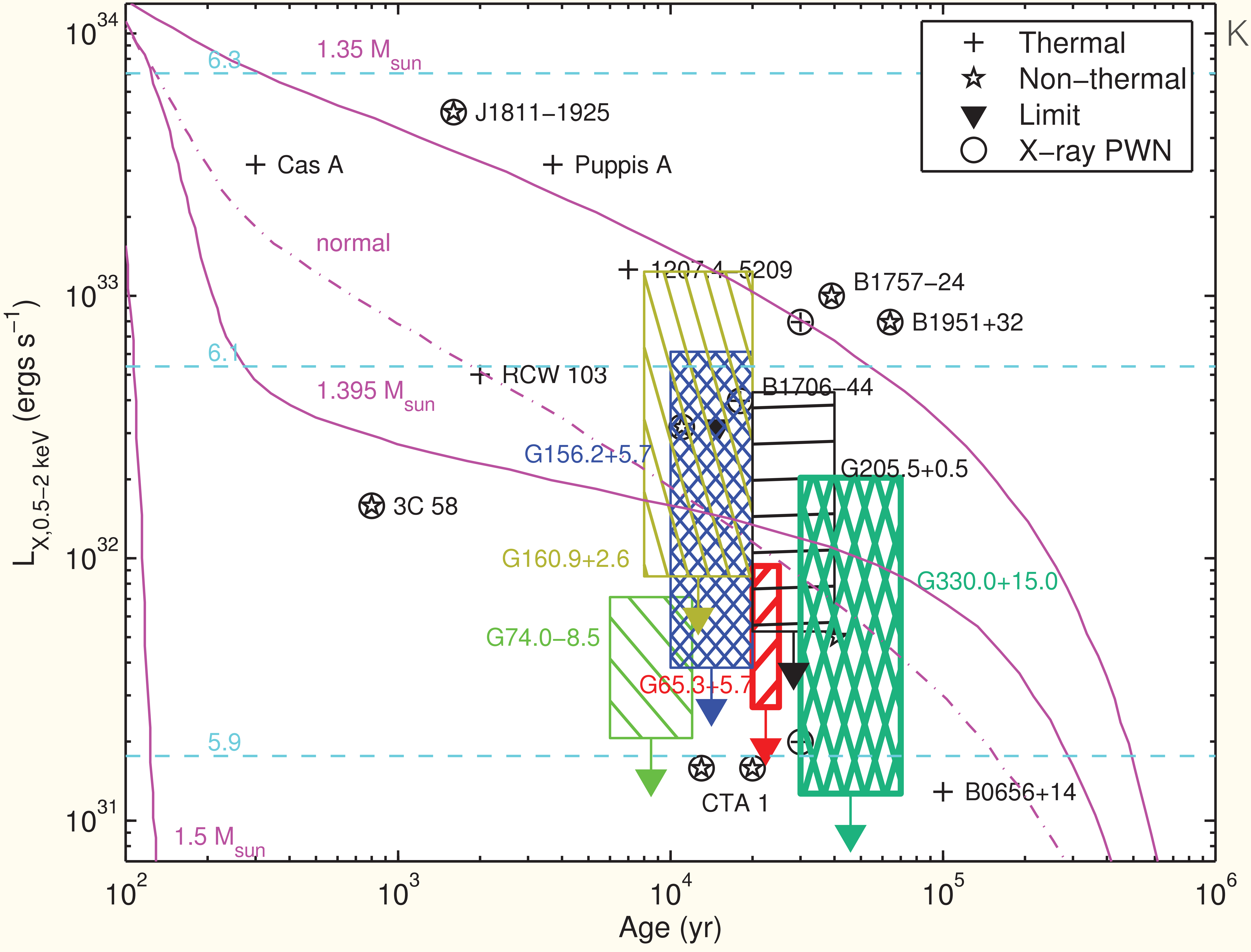
Flux carried by rad'n where electrons are non-degenerate; when electrons become degenerate, they carry heat, conductivity set by electron-ion scattering (Gudmundson et al. 1983; Potekhin et al. 1997).


Brown, Bildsten & Chang (2002)

Envelope sets mapping between surface and interior temperatures



from Brown & Cumming '09



Kaplan et al. 2006

Accreting neutron stars

Bright when accreting

Different population than merging neutron stars: potentially wider mass range

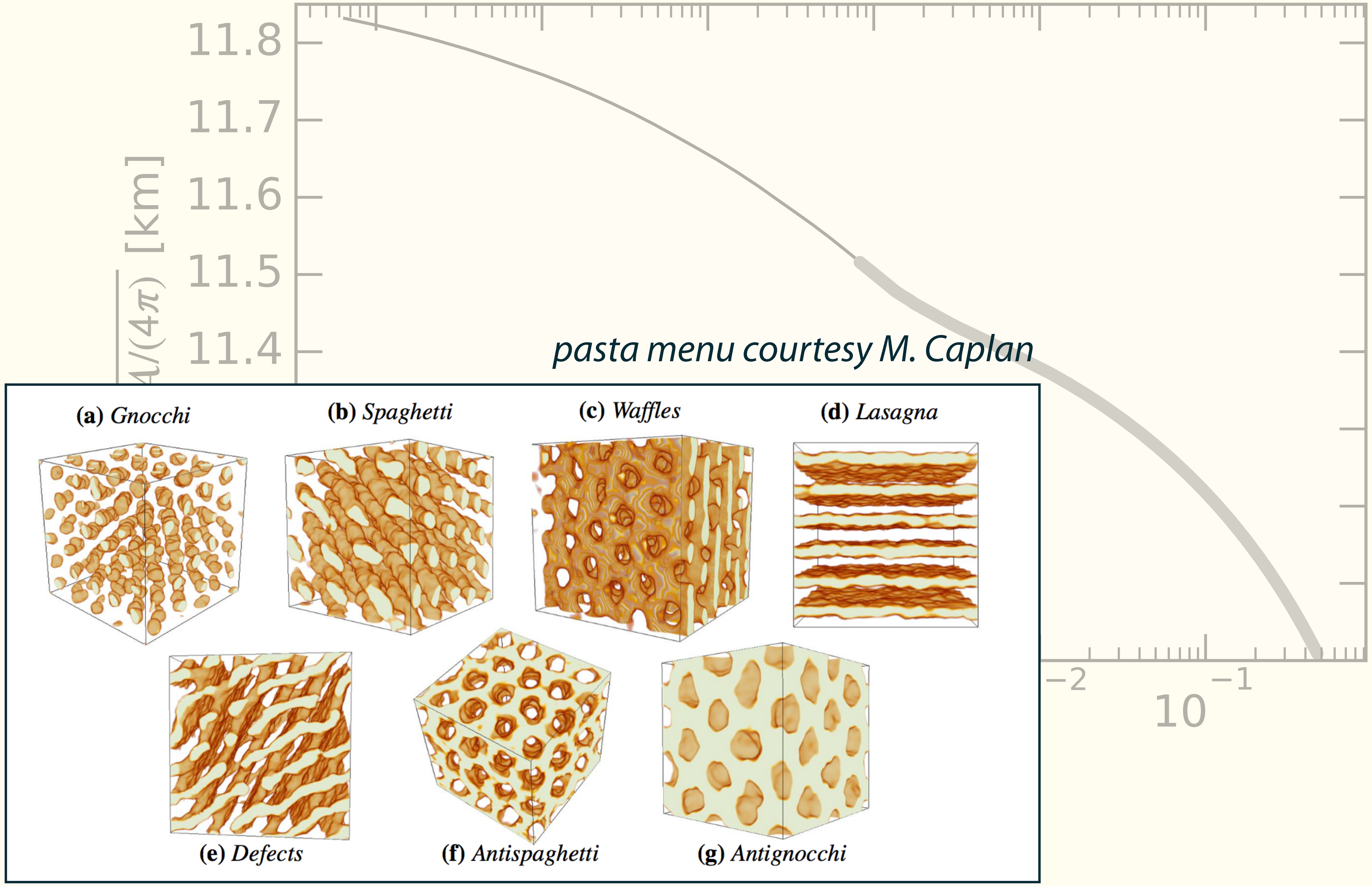
Sample range of heating rates, interior temperatures

Non-symmetric: good for mountain-building

Diverse nuclear-powered phenomena probe ambient conditions over a wide range of densities throughout crust

T. Piro, Carnegie Obs.

The neutron star crust



pasta menu courtesy M. Caplan

$\mu_e \approx k_\mathrm{B} T$ →

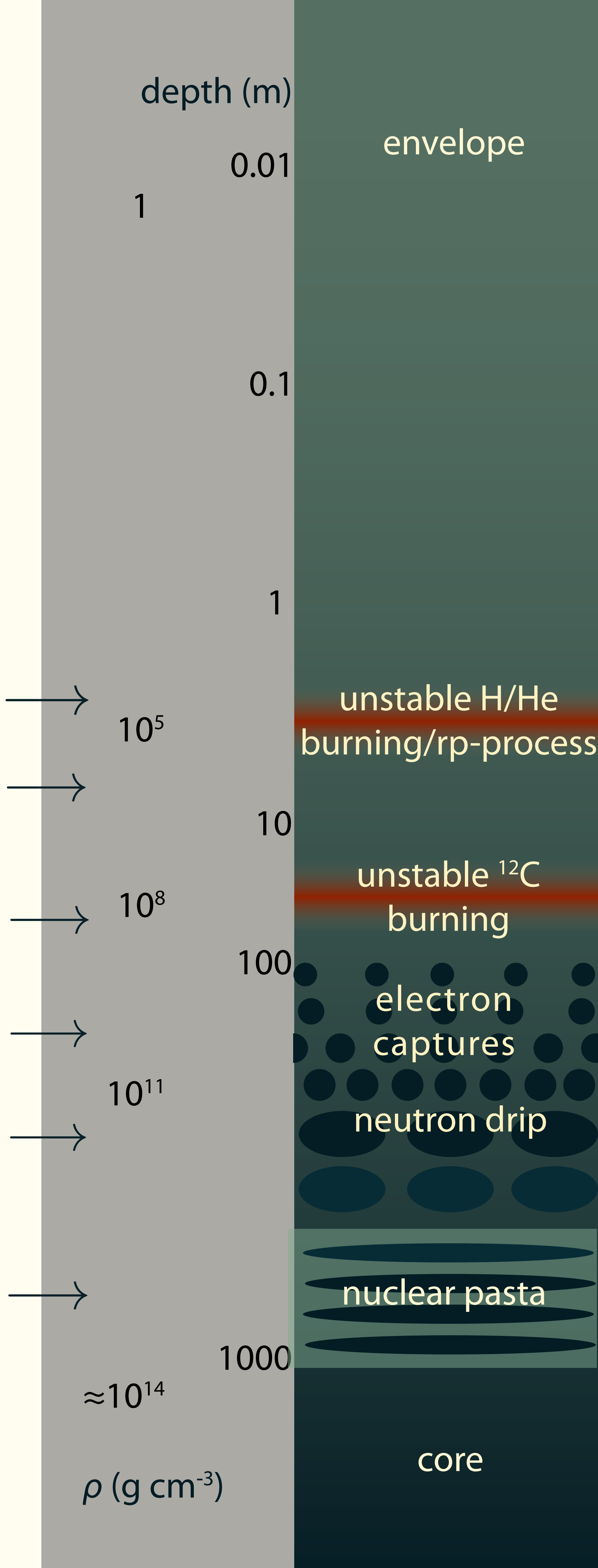
$\mu_e \approx m_e c^2$ →

$\Gamma \equiv \dfrac{Z^2 e^2}{a k_\mathrm{B} T} > 175$ →

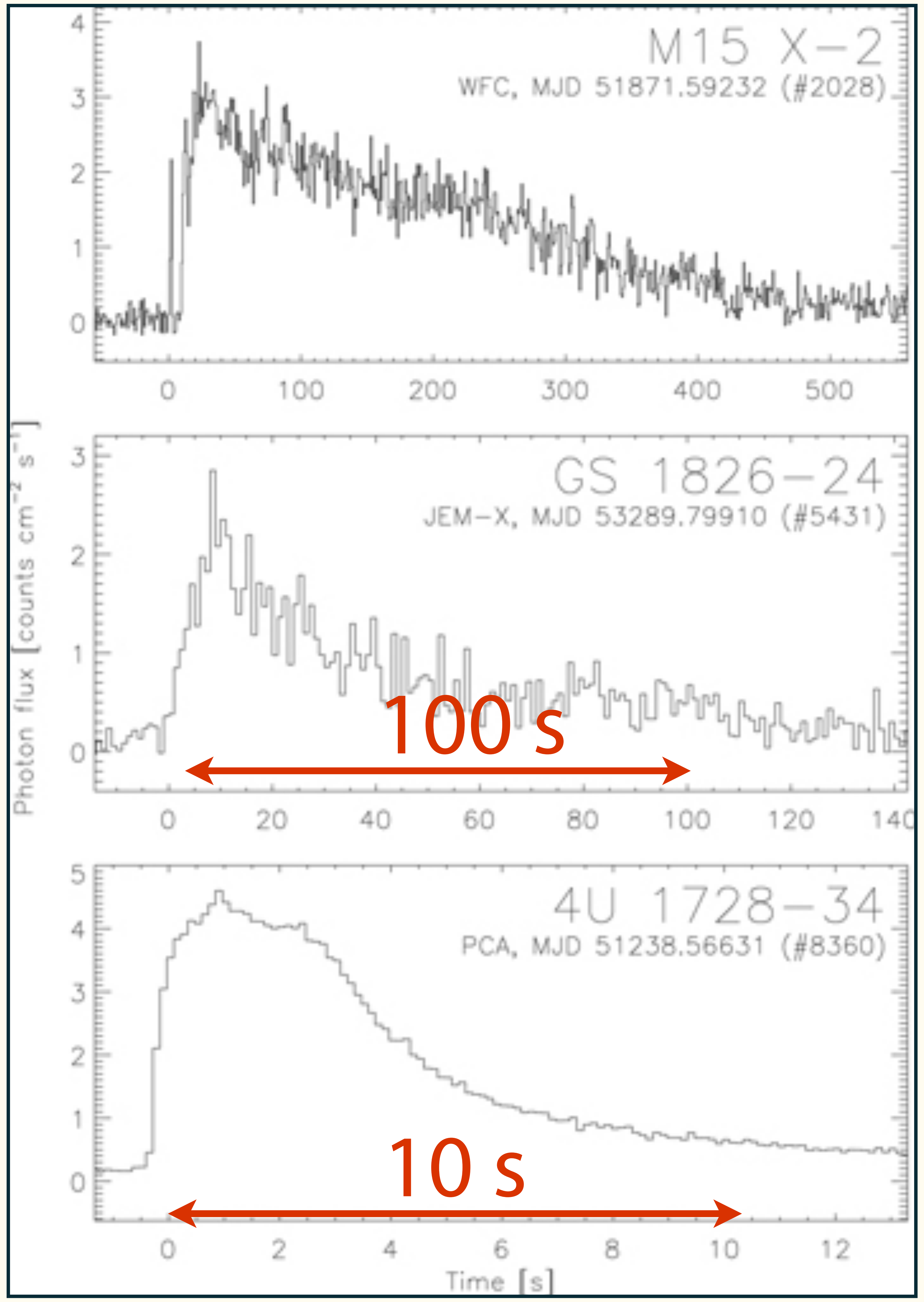
$T \approx \Theta_\mathrm{D}$ →

$\mu_e \approx 2a_V \approx 30\ \mathrm{MeV}$ →

$r_\mathrm{N}^3 \approx \dfrac{a^3}{2}$ →

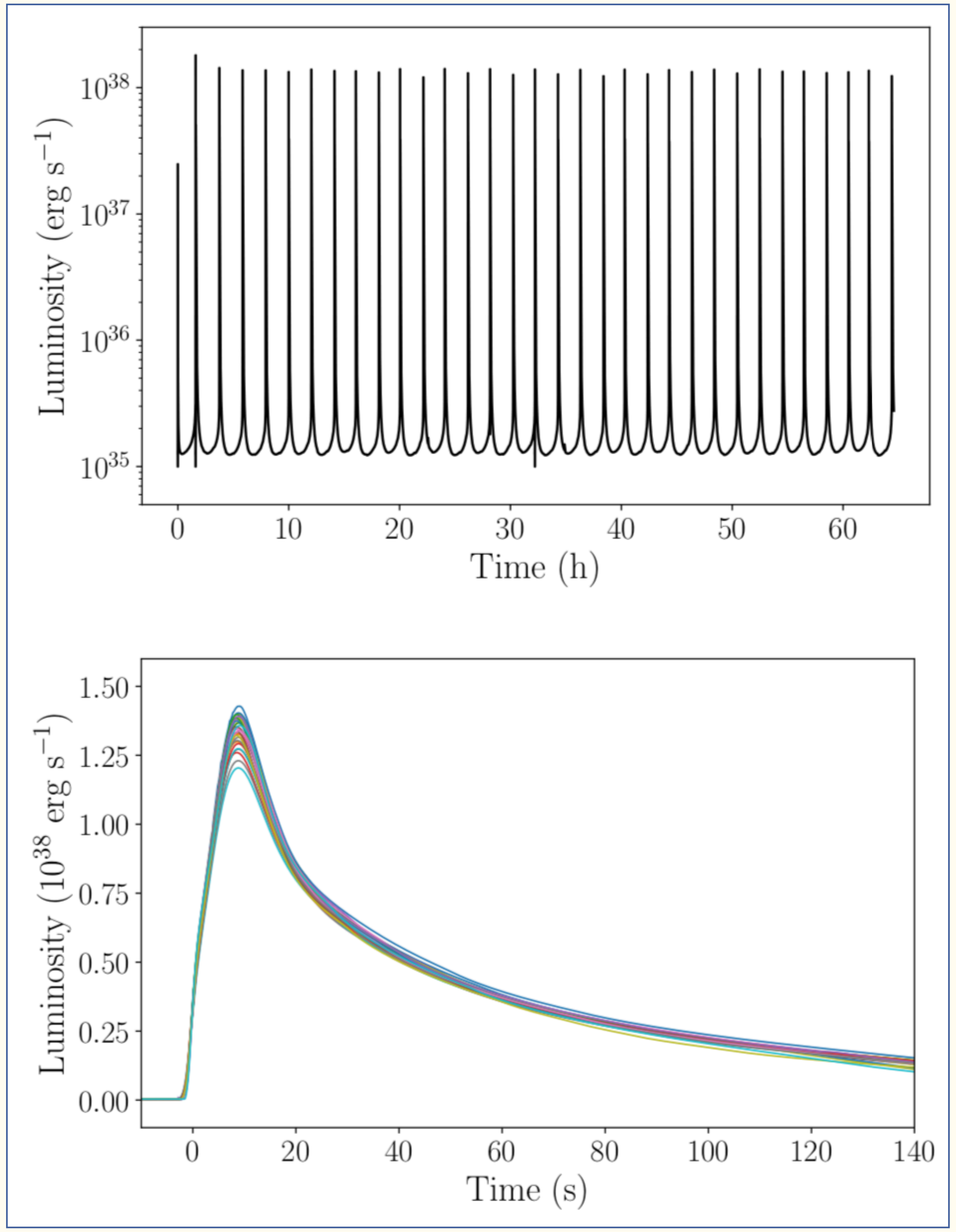


Nuclear-powered variability | X-ray bursts

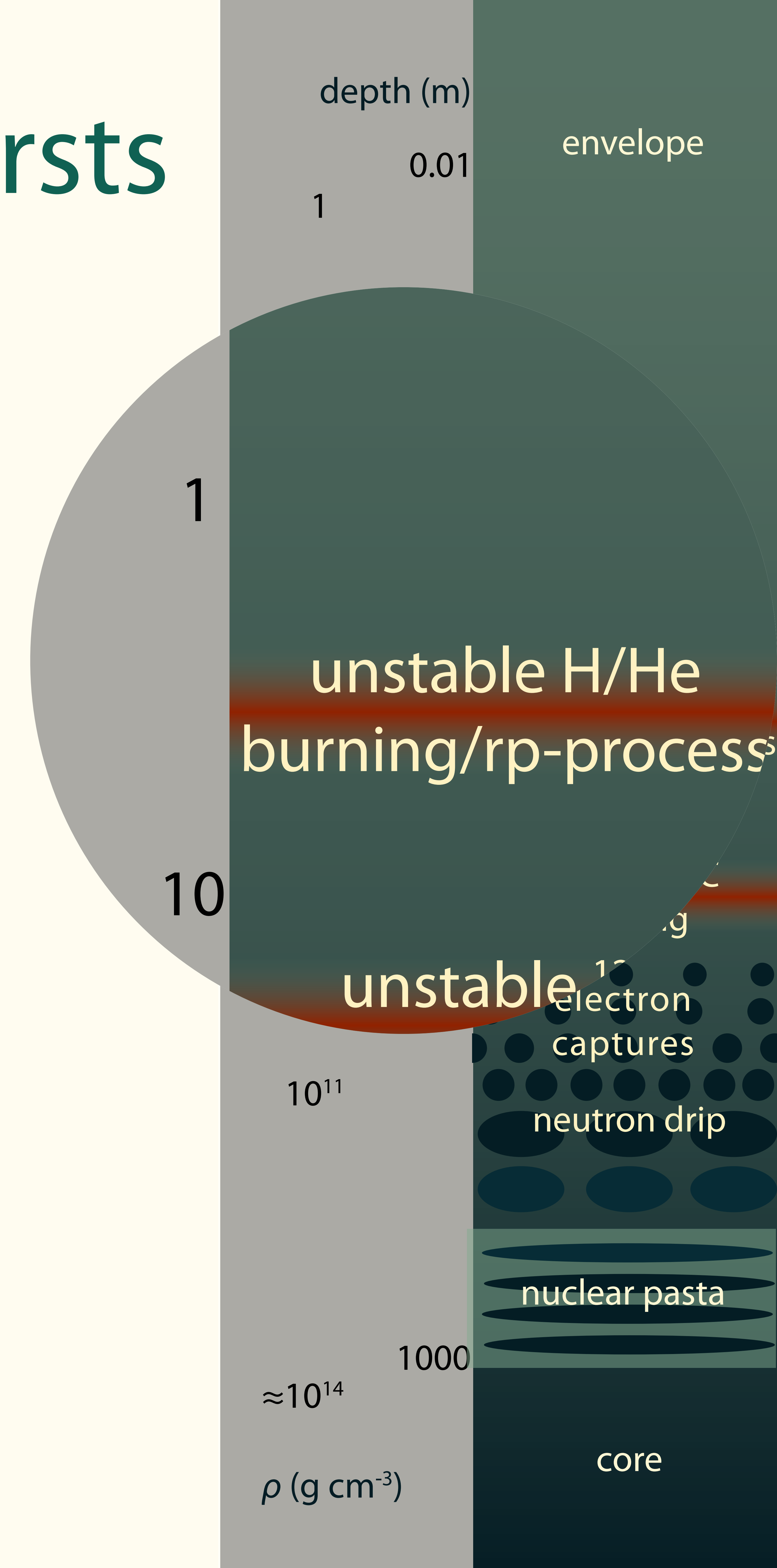


Galloway et al. 2020

https://burst.sci.monash.edu/minbar/

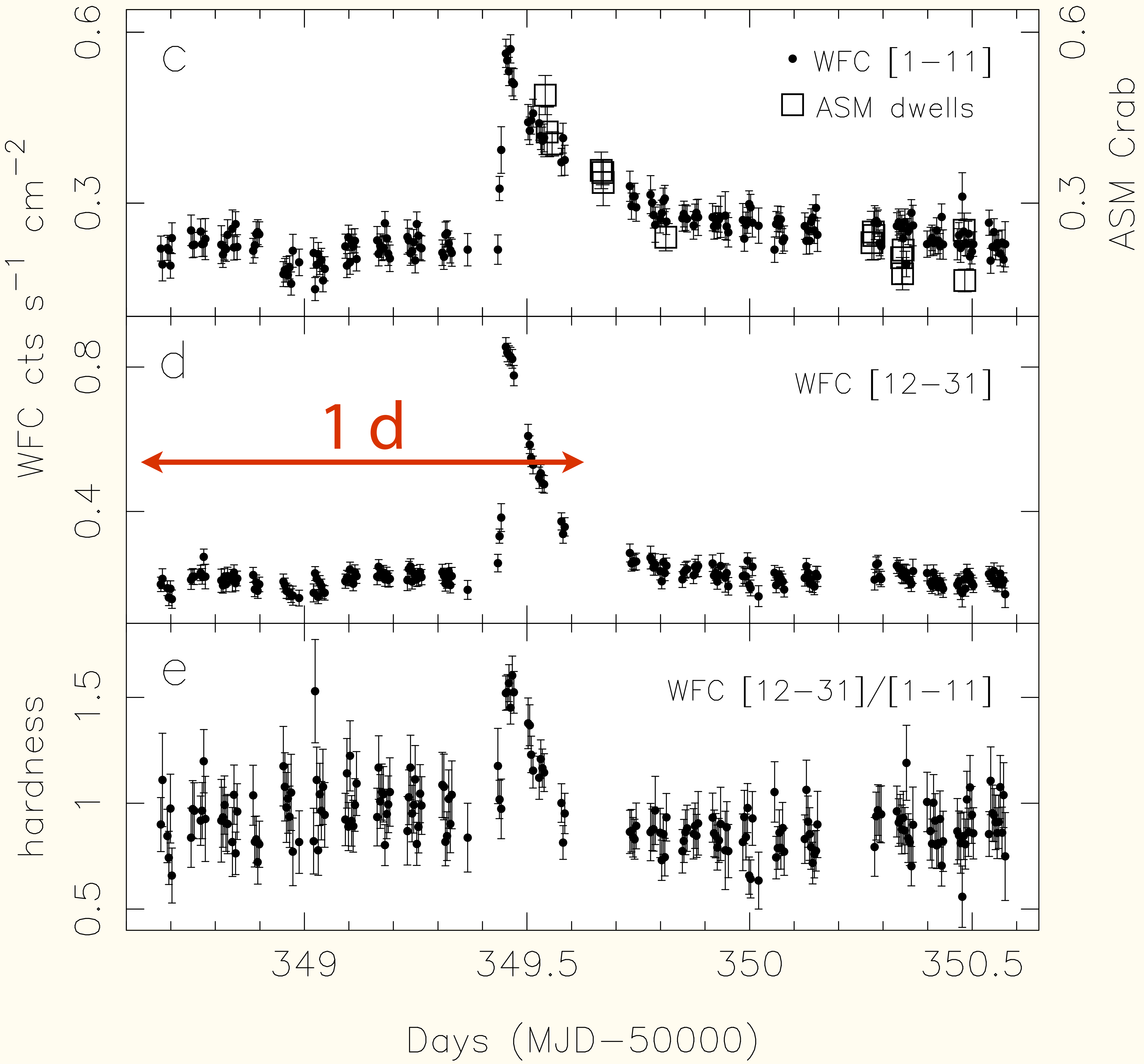


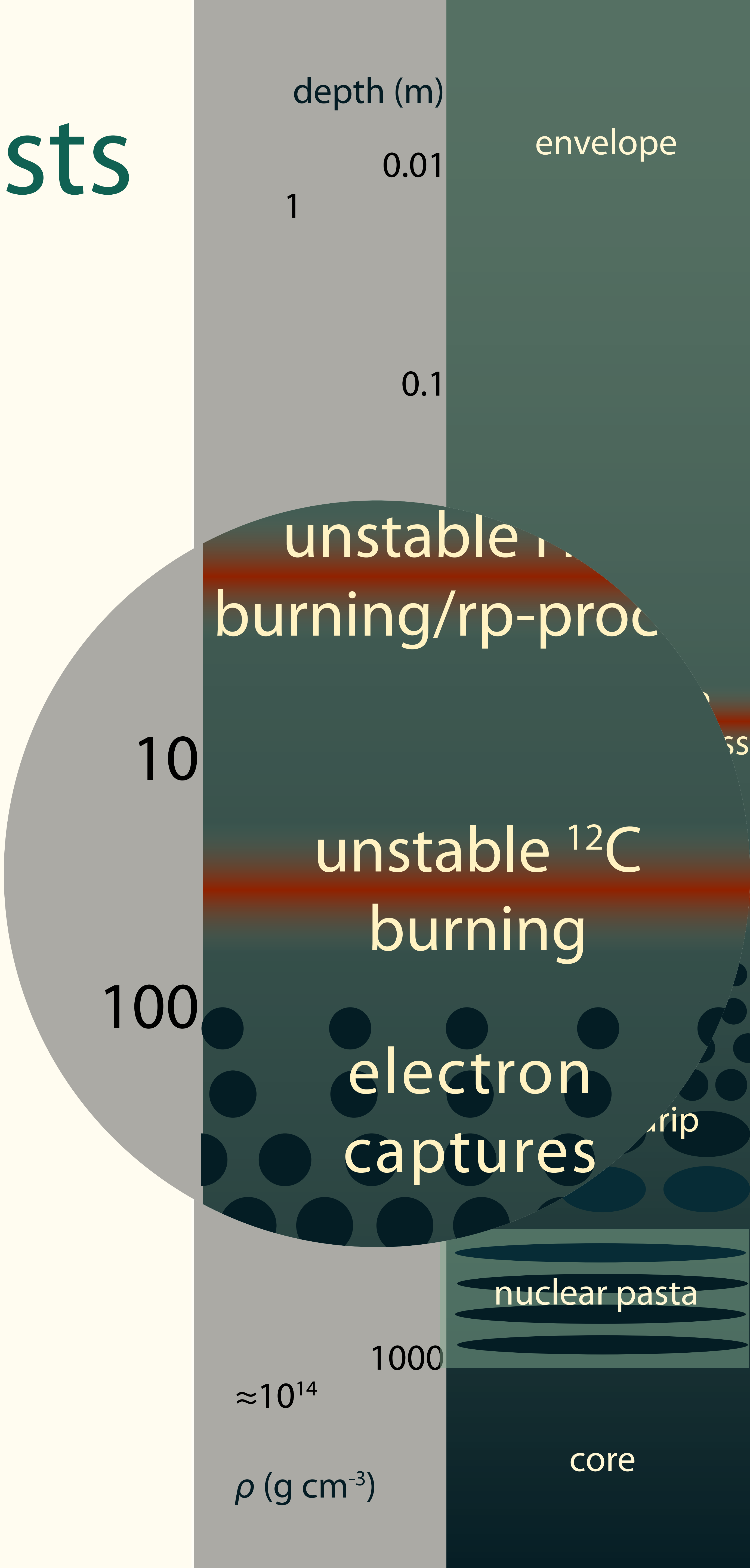
Johnston, Heger & Galloway 2020



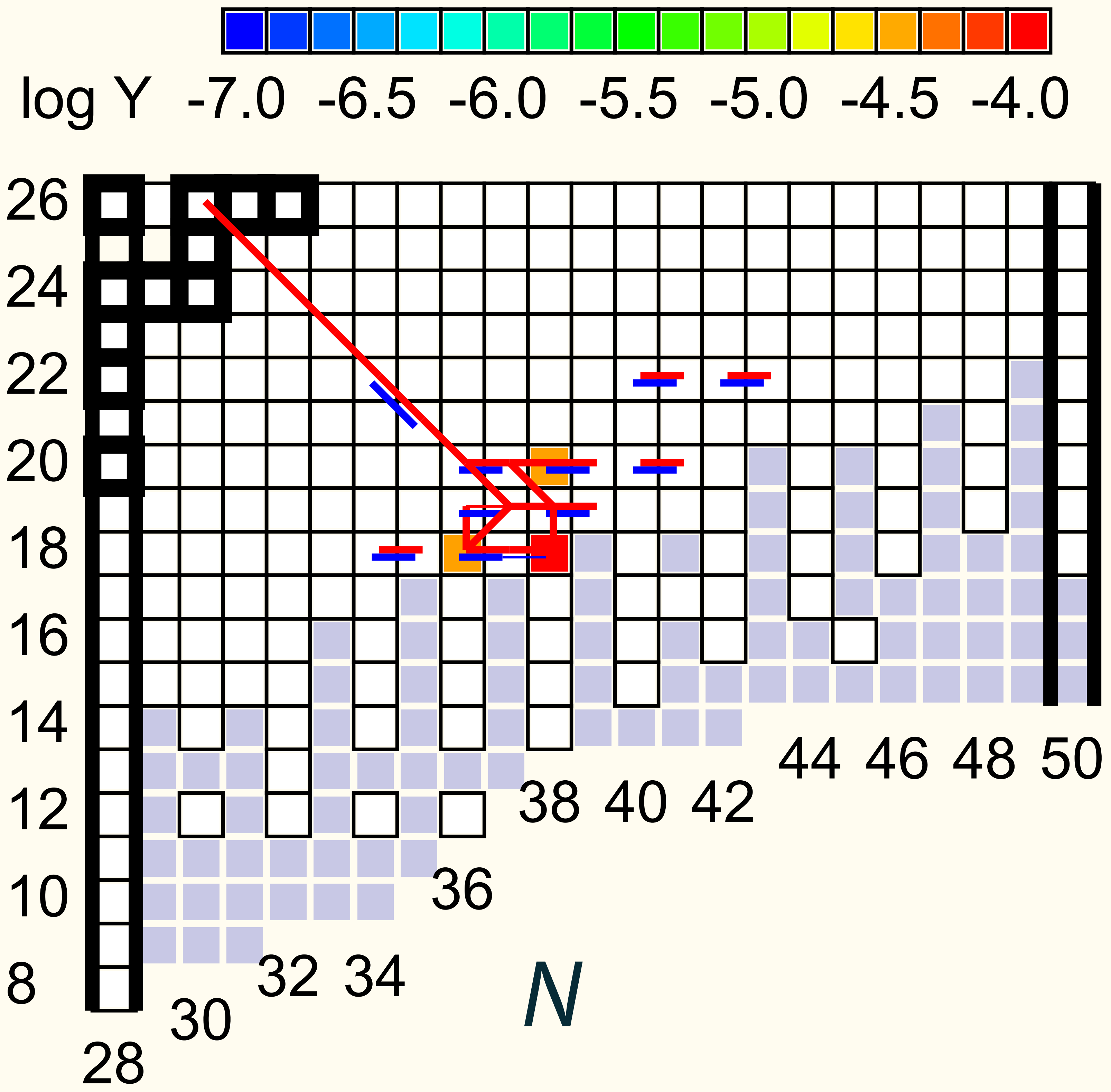
Nuclear-powered variability | Superbursts

Kuulkers et al. 2002

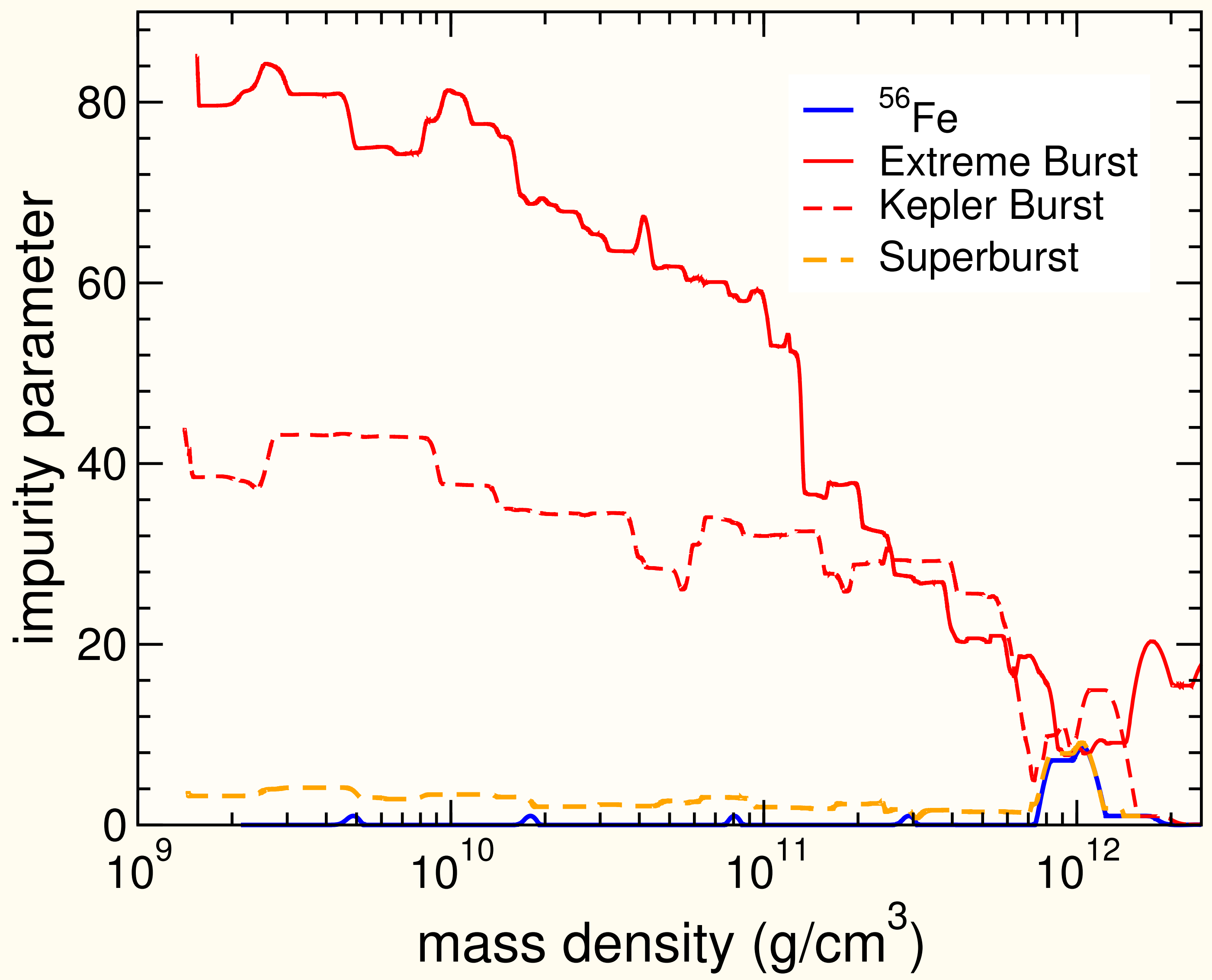


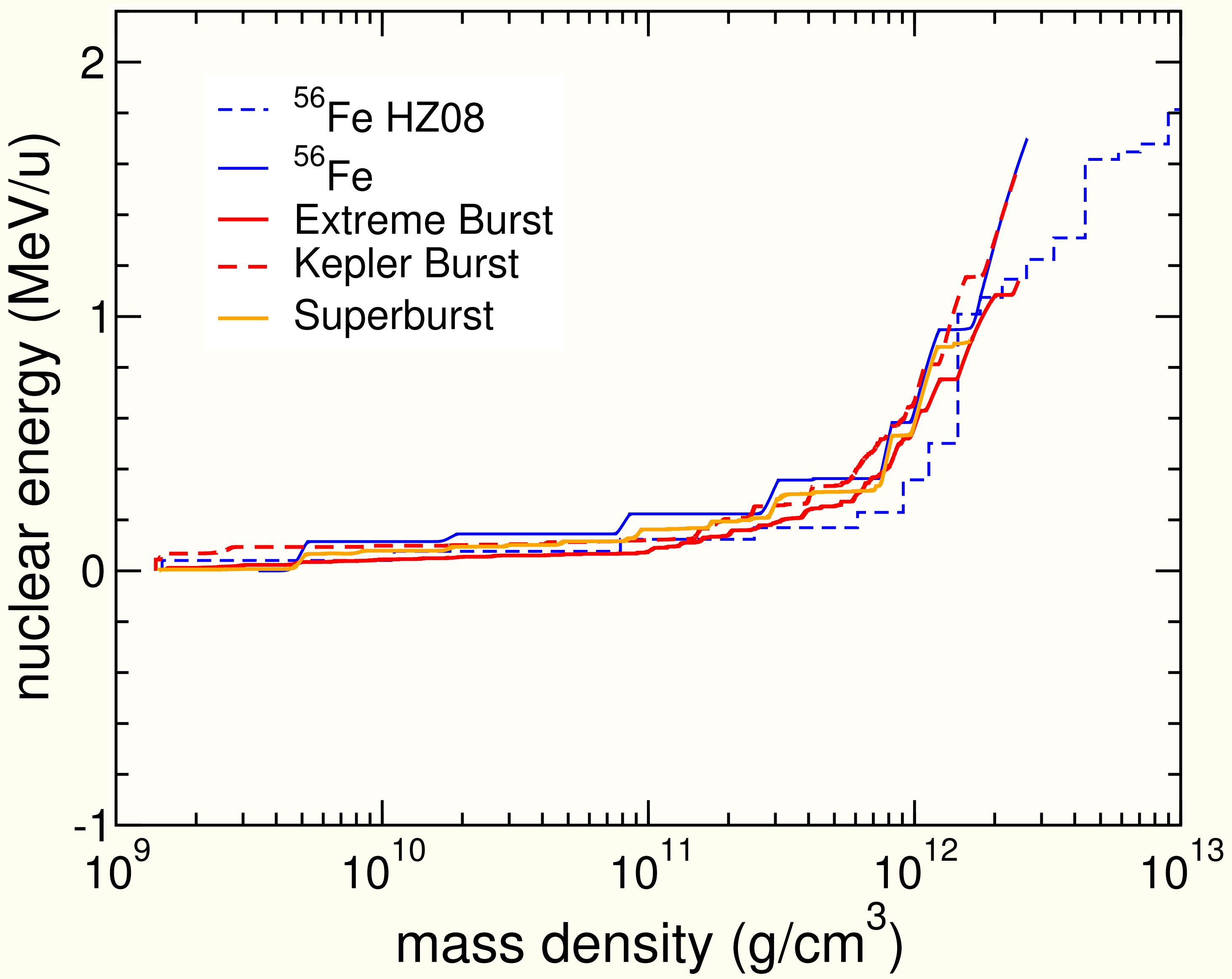


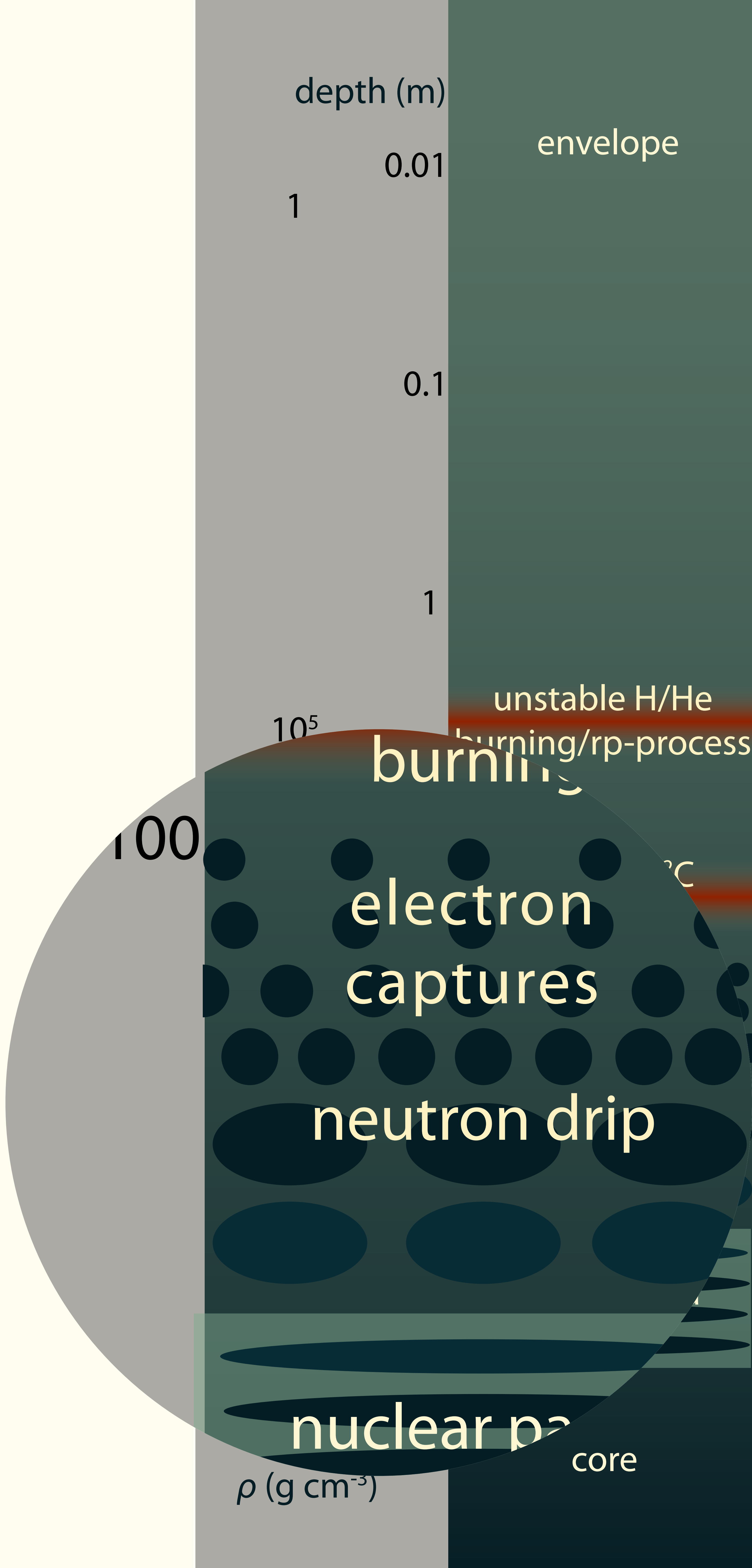
Heating in the deep crust



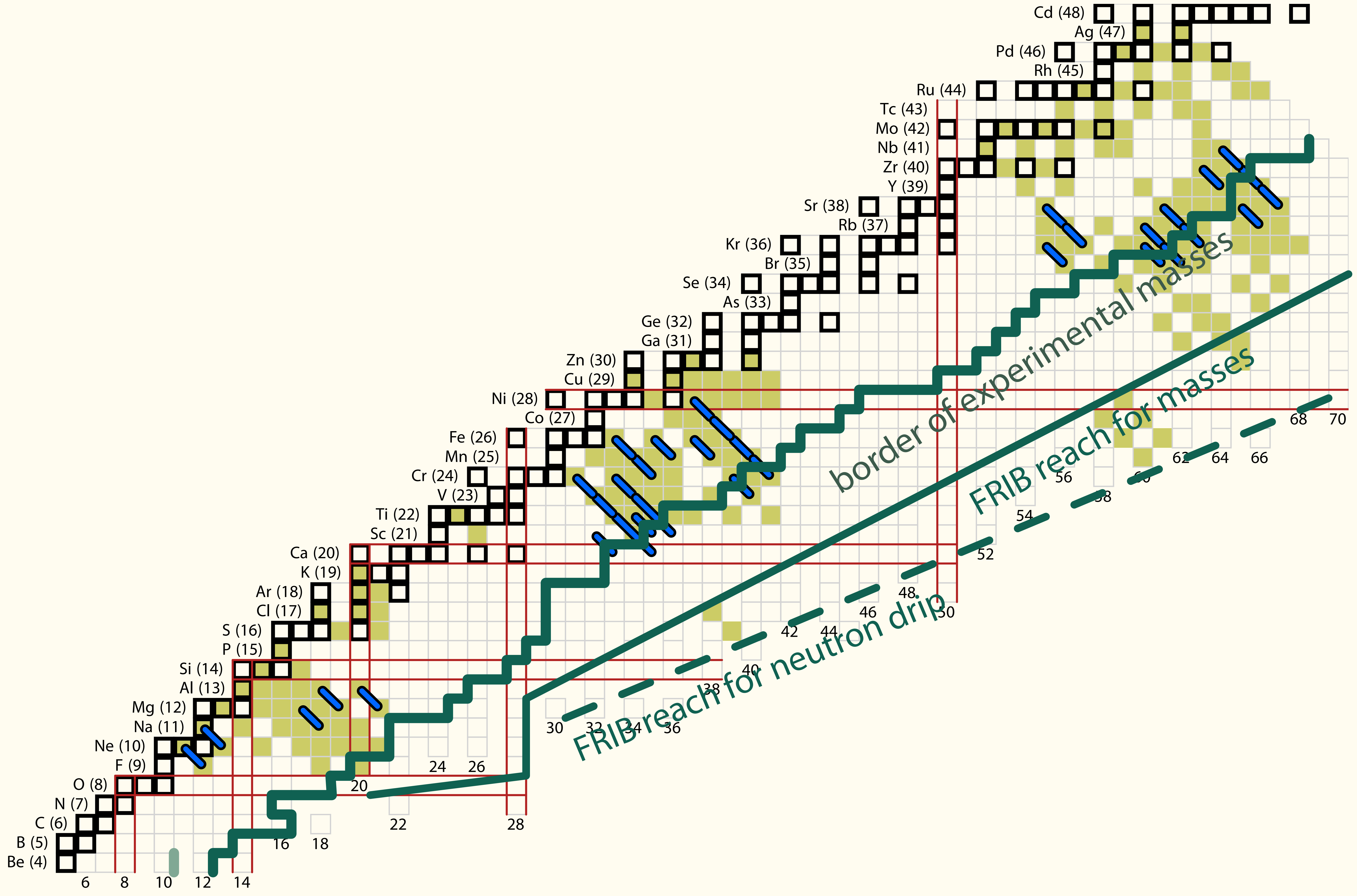
Lau et al. 2018

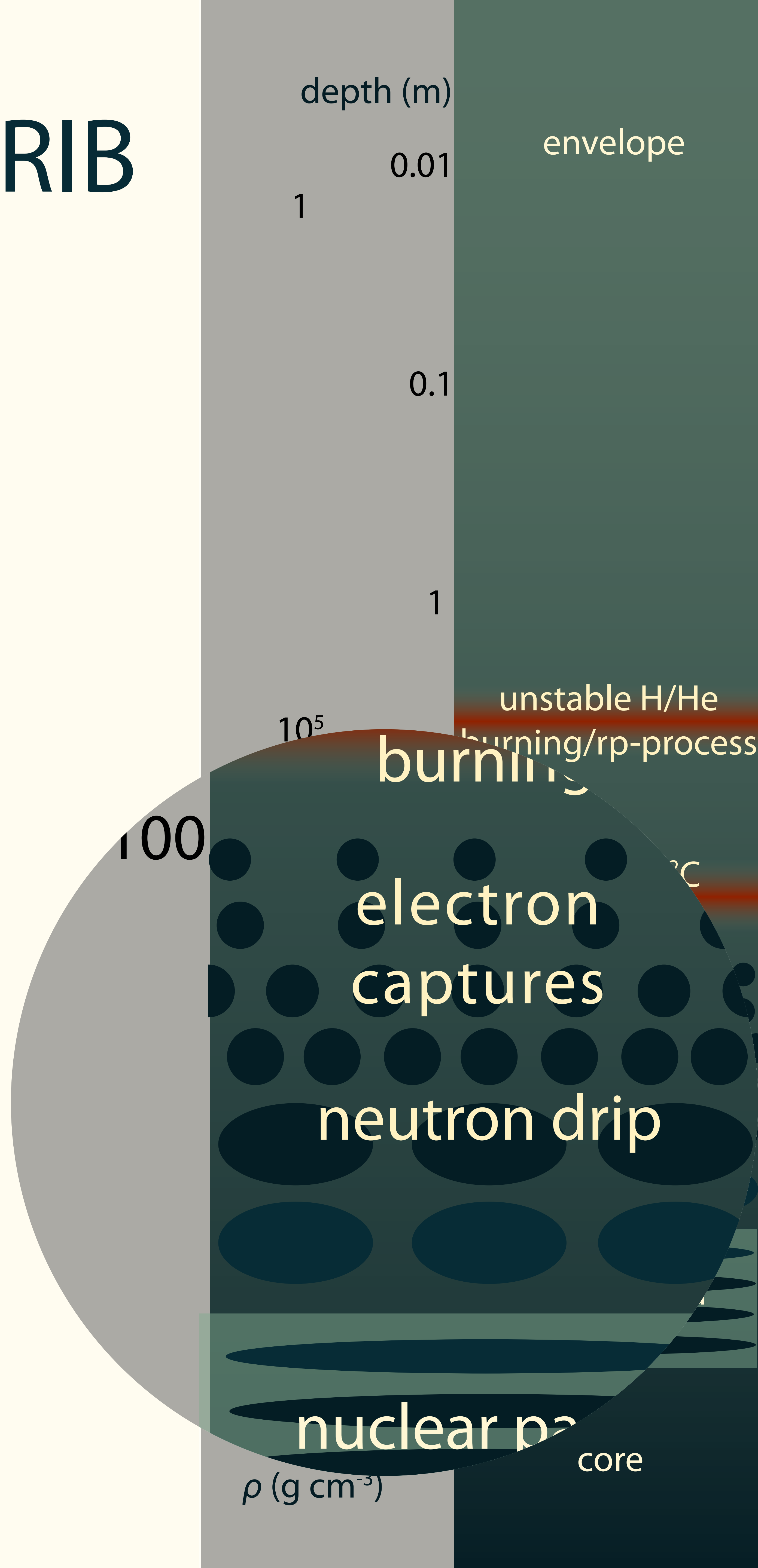






Much of the outer crust is accessible with FRIB





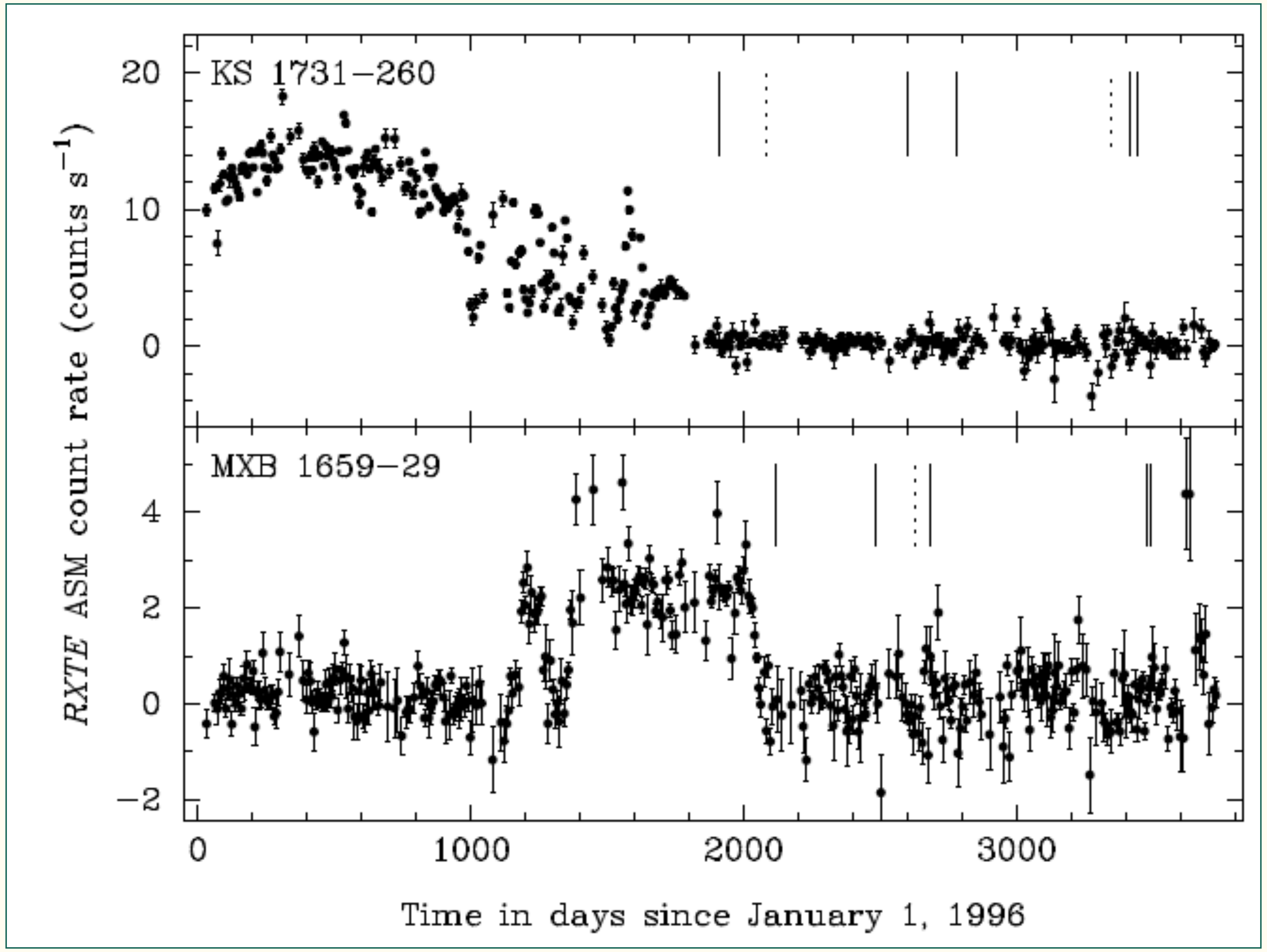
Quasi-persistent transients: long outburst and quiescent durations

2001: quasi-persistent transients discovered (Wijnands, using the Rossi X-ray Timing Explorer)

2002: Rutledge et al. suggest looking for crust thermal relaxation

2002–: cooling detected! (many: Wijnands, Cackett, Degenaar, Fridriksson, Homan, Ootes, Parikh)

fig. from Cackett et al. '06



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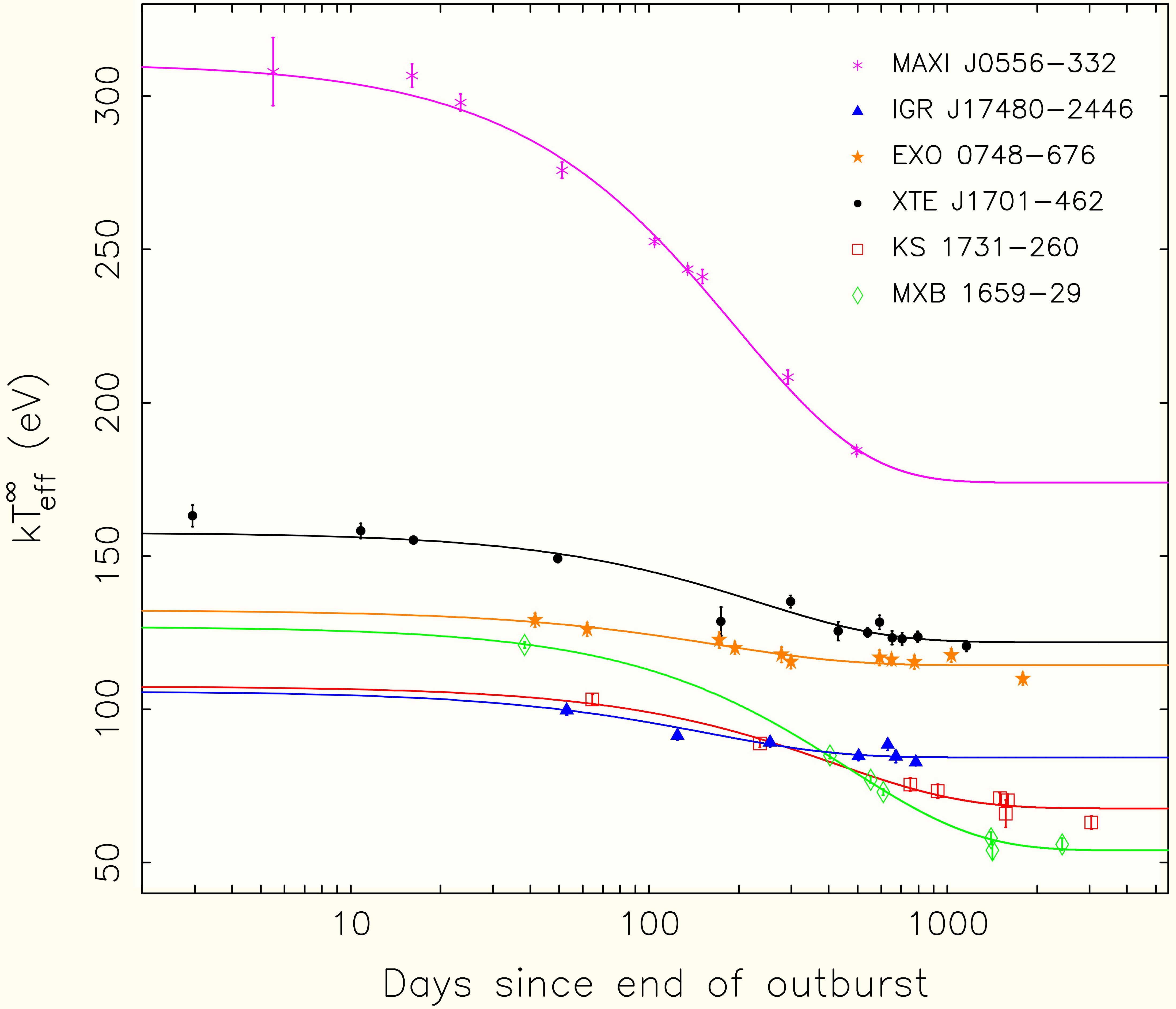
from Homan et al. (2014)



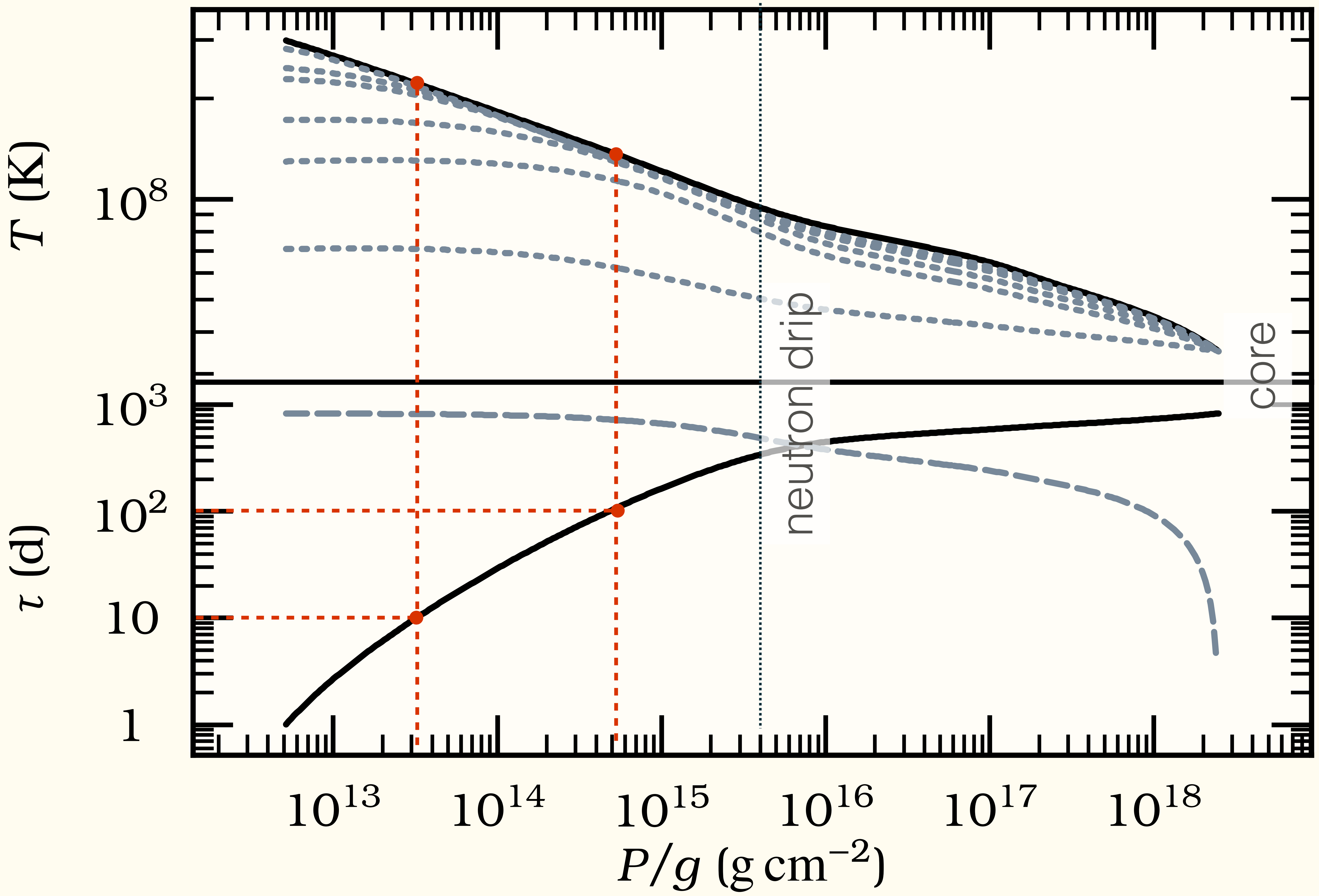
Cooling lightcurve

Thermal diffusion

$$\rho C \frac{\partial T}{\partial t} = \nabla \cdot (K \boldsymbol{\nabla} T)$$

$$\tau = \frac{1}{4}\left[\int \left(\frac{\rho C}{K}\right)^{1/2} dz\right]^2$$

Brown & Cumming 2009

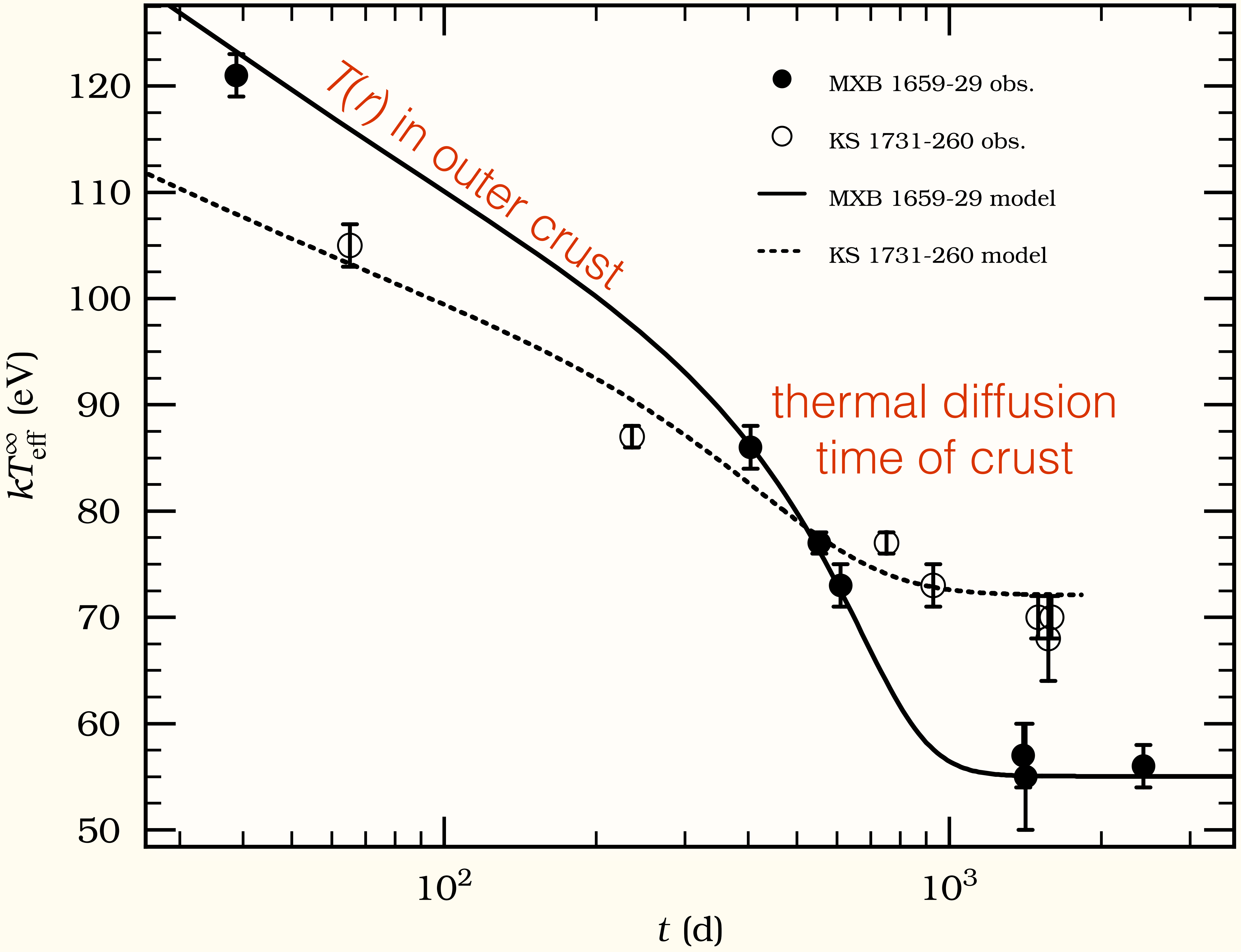


`dStar`: open-source crust thermal evolution code

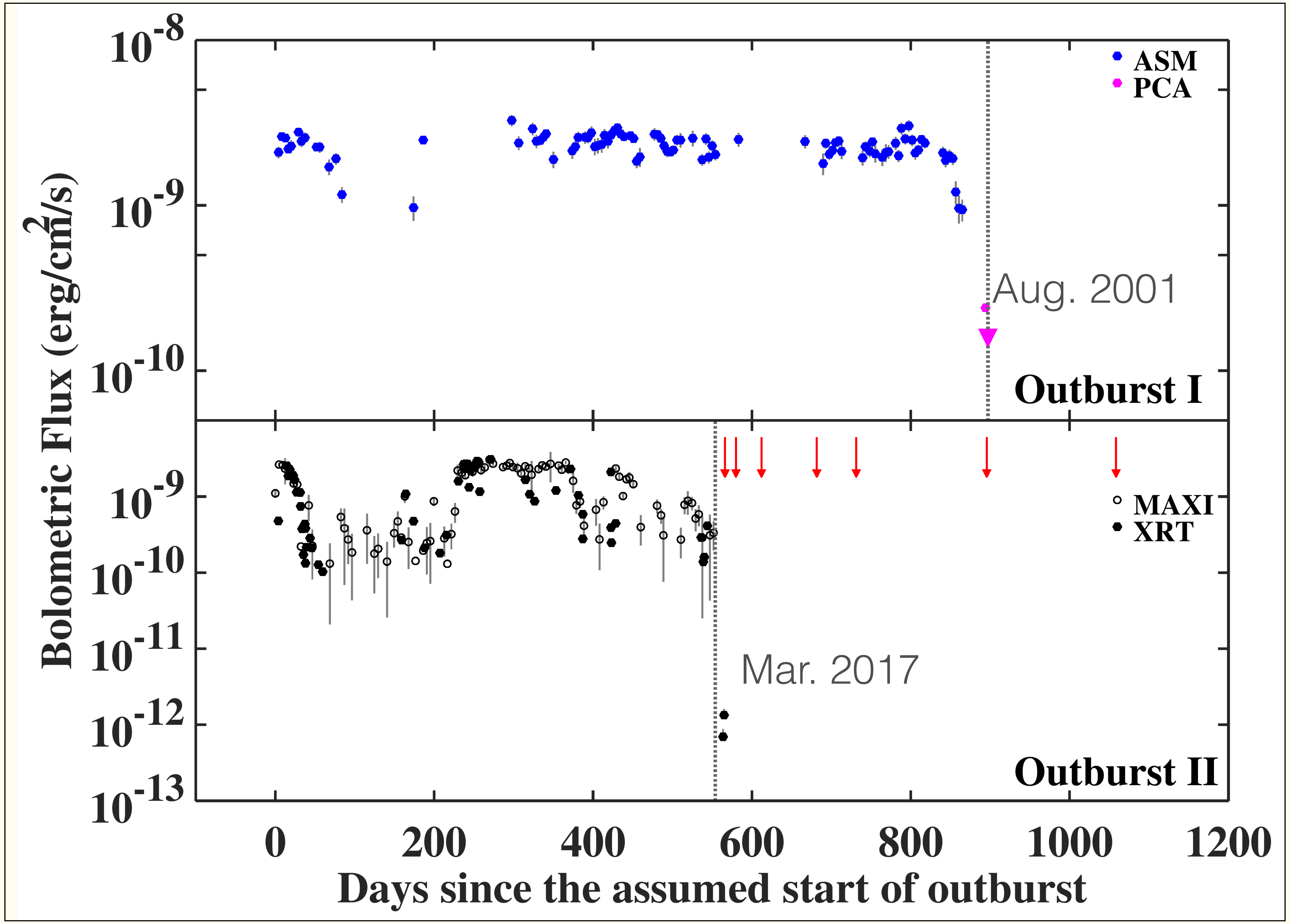
Inferring crust properties from cooling

Ushomirsky & Rutledge, Shternin et al., Brown & Cumming, Page & Reddy, Turlione et al., Deibel et al., Merritt et al., Parikh et al.

data from Cackett et al. 2008
fits from Brown & Cumming 2009



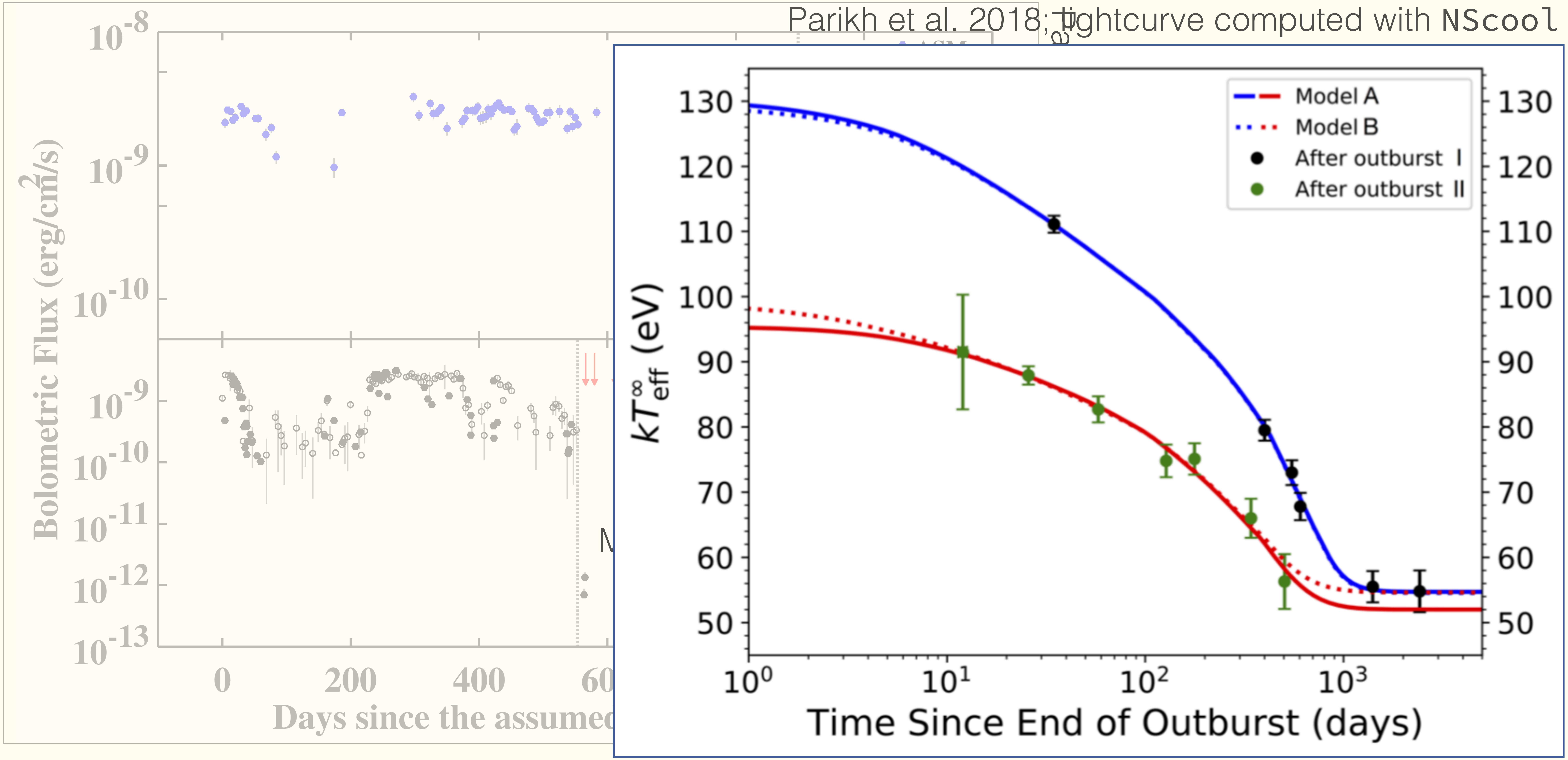
Cooling of MXB1659-29 following outburst ending 2017



Parikh et al. 2018

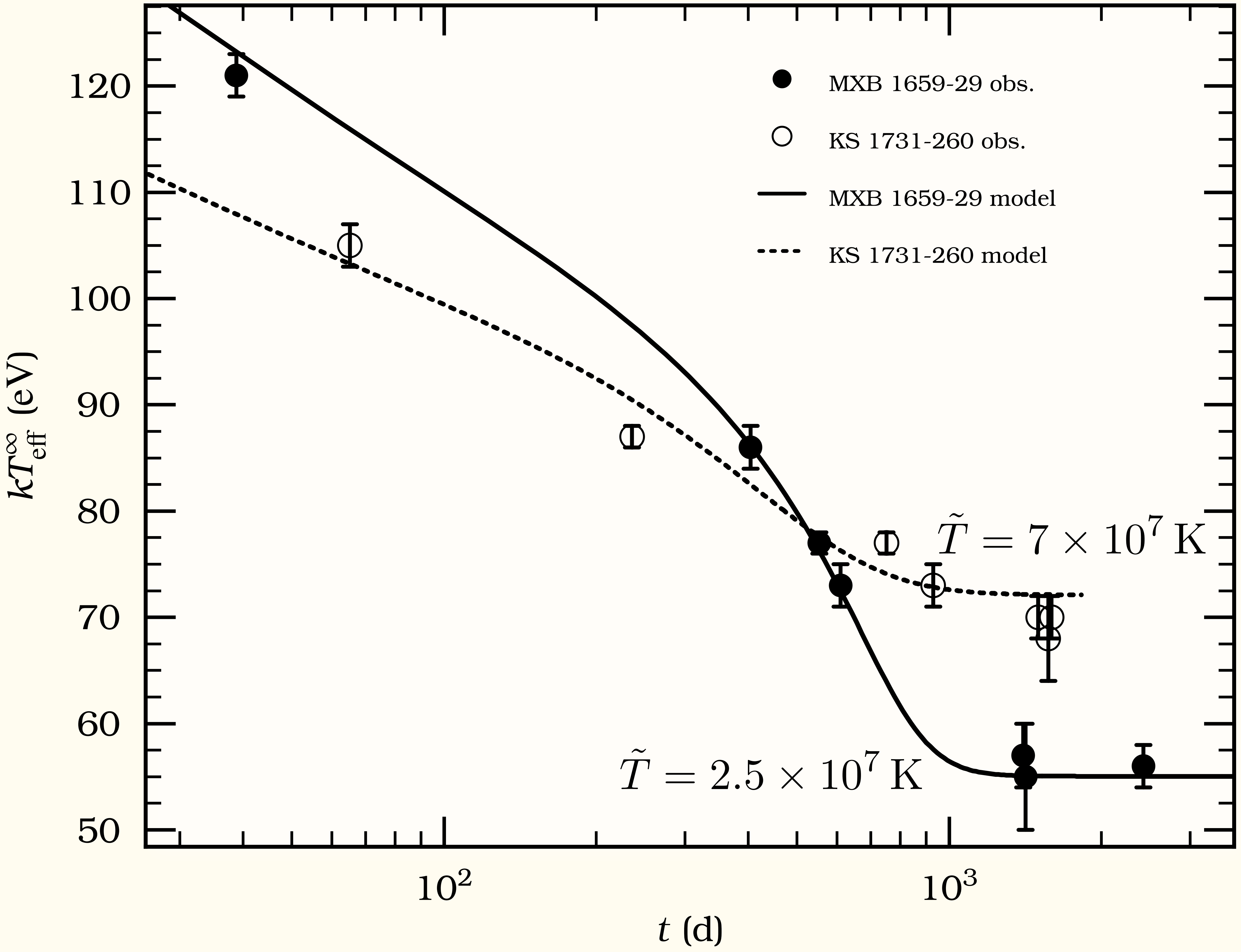
Cooling of MXB1659-29 following outburst ending 2017

Parikh et al. 2018; lightcurve computed with `NScool`

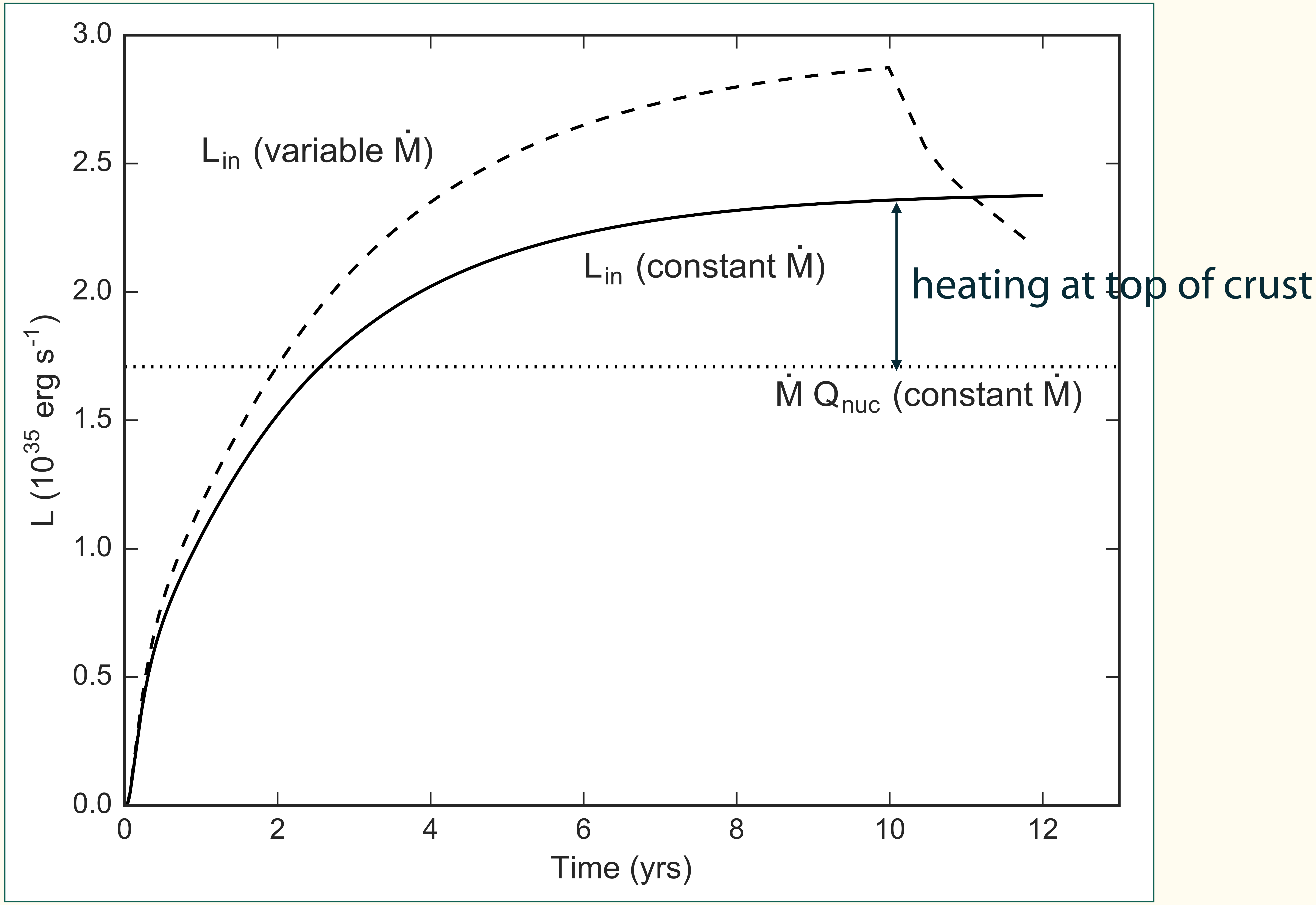


Models also give us the total energy deposited into the core and its temperature

data from Cackett et al. 2008
fits from Brown & Cumming 2009

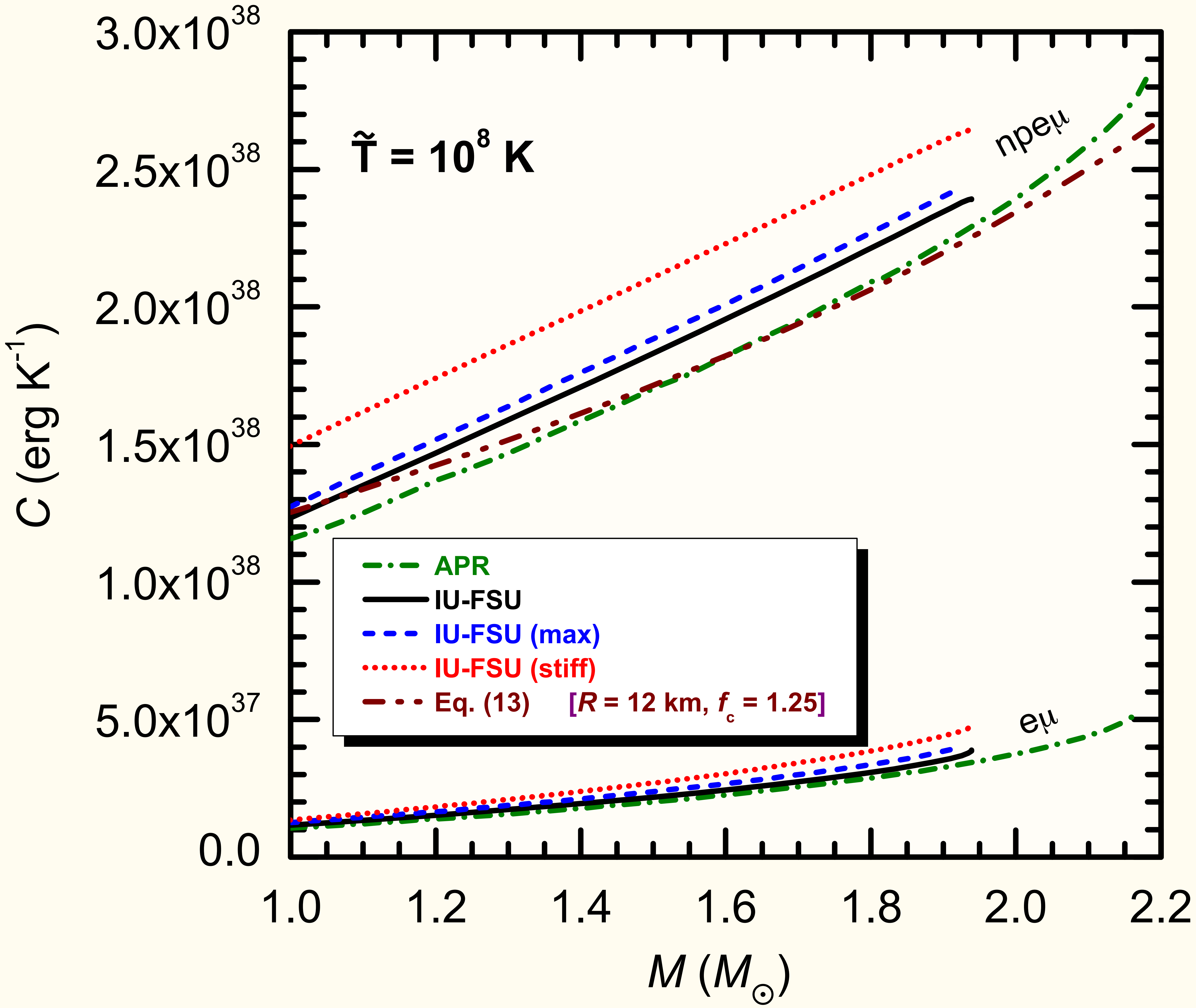


For KS 1731-260, ≈ 6×10^{43} ergs deposited into the core



Cumming et al. ‘17

There is sufficient heating during outburst to change $T_{\rm core}$ significantly



Cumming et al. ‘17

Suppose core cools completely between outbursts and neutrino cooling is weak

$$C\frac{d\tilde{T}}{dt} = -\cancel{L_\nu} - \cancel{L_\gamma} + L_{\mathrm{in}}$$

during outburst

$$C > \frac{2E}{\tilde{T}_f} \quad \text{with} \quad E = \int L_{\mathrm{in}}\, dt$$

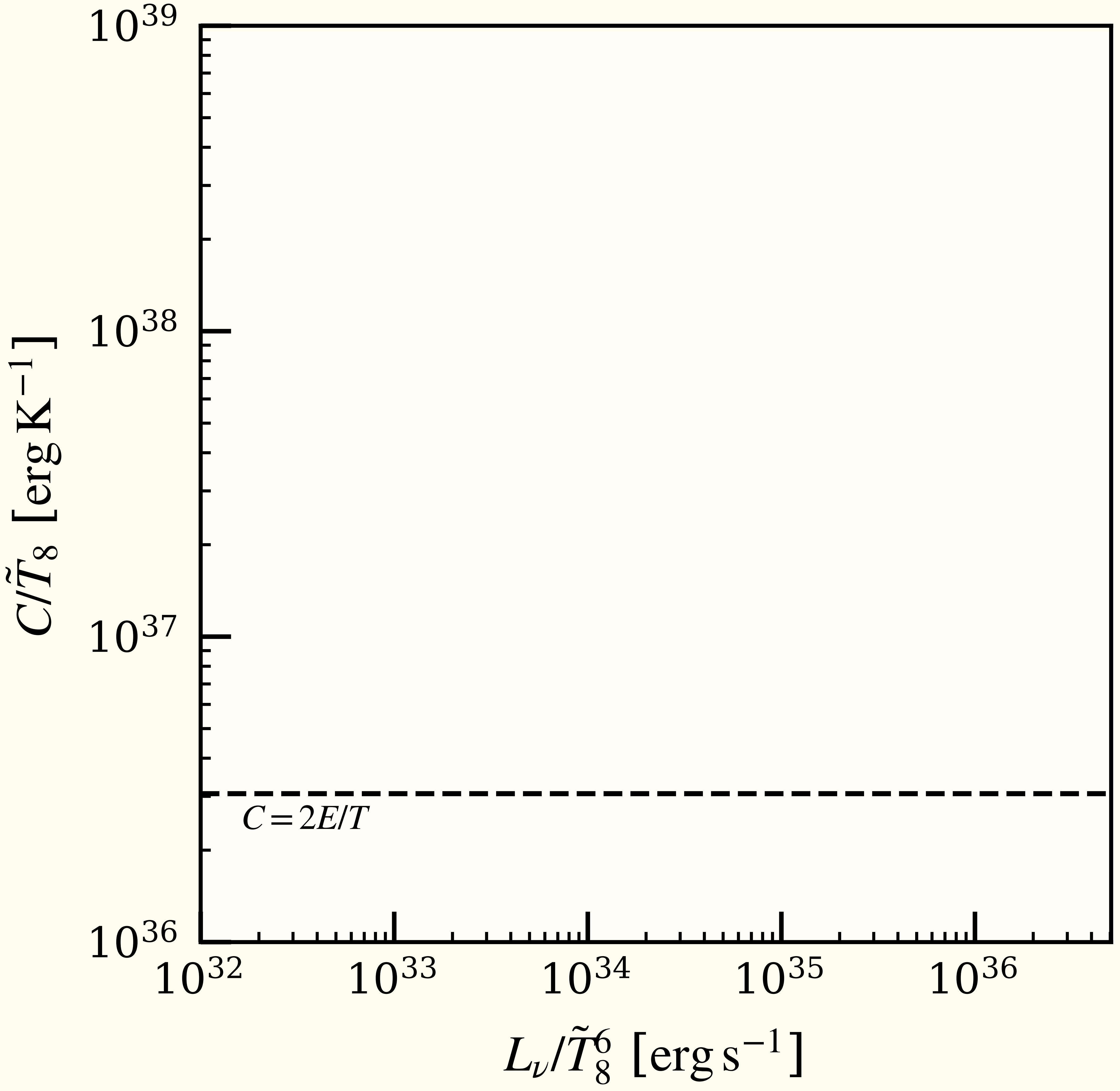
since $C \sim T$

For KS1731, $C > 3 \times 10^{36} \tilde{T}_8$

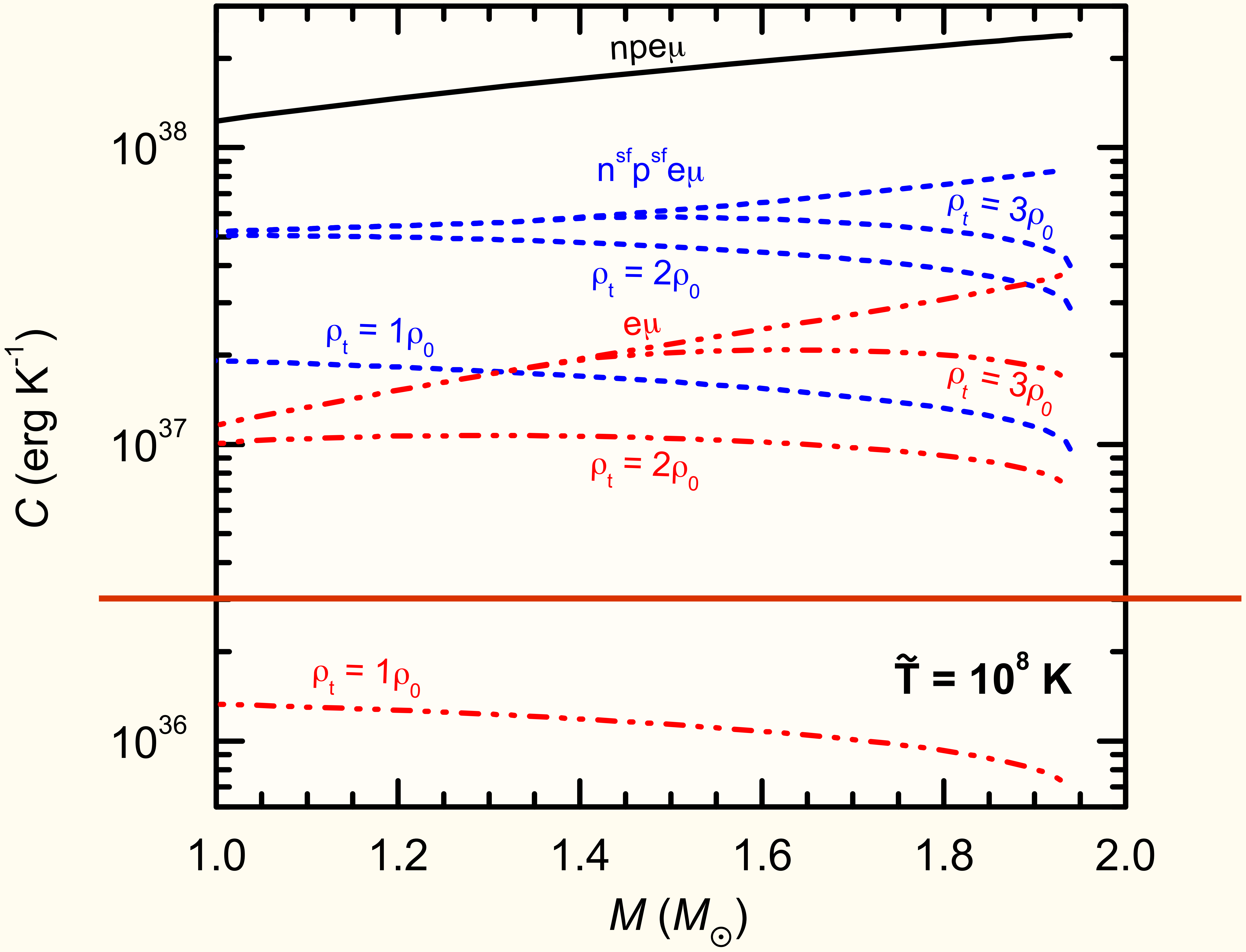
The specific heat must be larger than this!

Minimum specific heat for KS 1731–260

Cumming et al. 2017



Measured temperature is incompatible with a quark CFL phase throughout core



Now suppose neutrino emission is strong, so the core temperature saturates during outburst:

$$\cancel{C\frac{d\tilde{T}}{dt}} = -L_\nu + L_{\rm in},$$

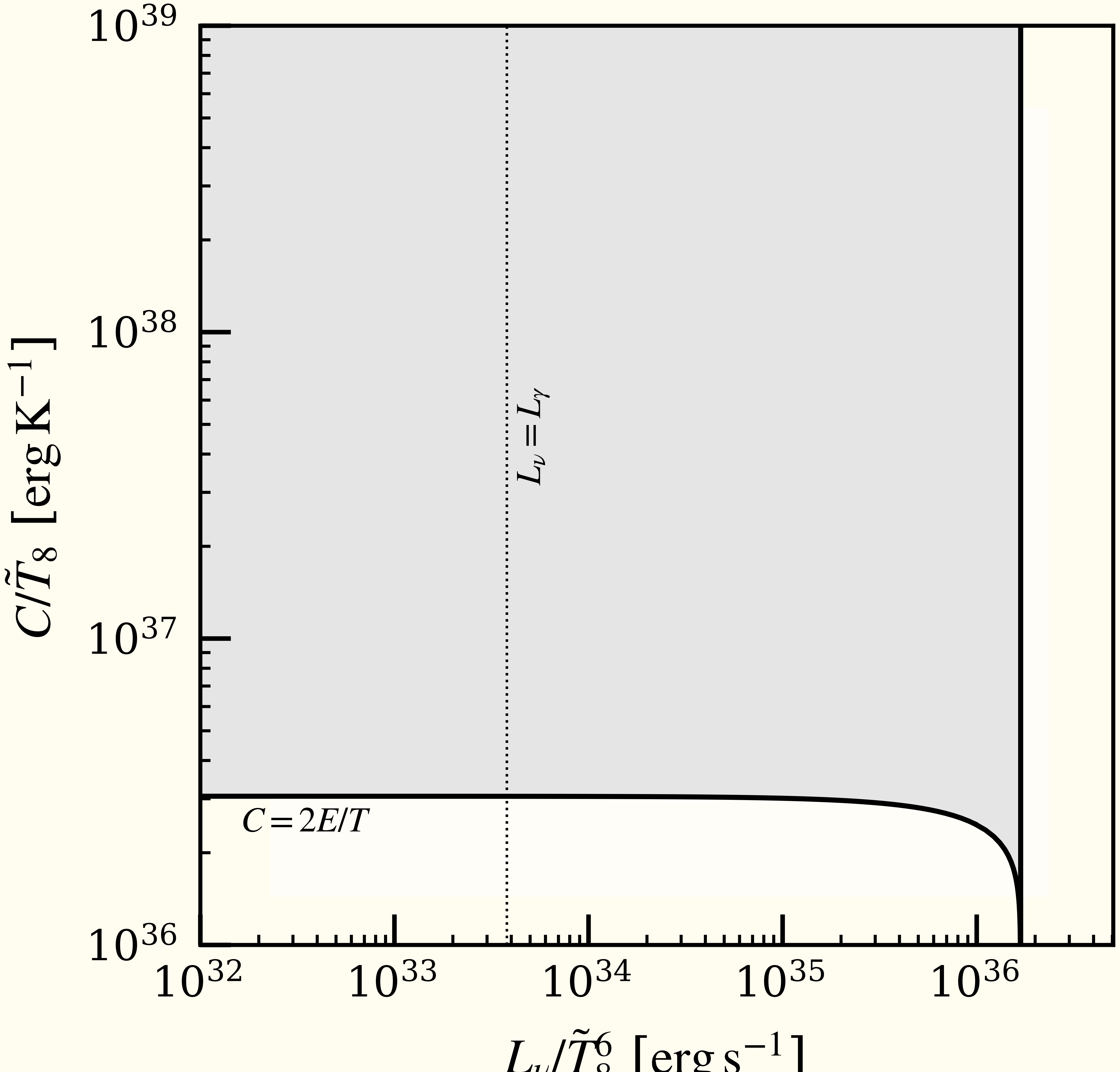
$$\begin{aligned} L_{\nu,\rm dU} &= 6\times 10^{38}\,\tilde{T}_8^6\,\mathrm{erg\,s^{-1}} & n &\rightarrow pe\nu \\ L_{\nu,\rm mU} &= 6\times 10^{30}\,\tilde{T}_8^8\,\mathrm{erg\,s^{-1}} & nn &\rightarrow npe\nu \end{aligned}$$

The neutrino luminosity cannot exceed the heating rate, however:

$$L_\nu < L_{\rm in} \approx 2\times 10^{35}\,\mathrm{erg\,s^{-1}}$$

for KS1731. If a *fast* process is present, its strength is $< 10^{-3}$ of direct Urca.

Maximum neutrino luminosity for KS 1731–260



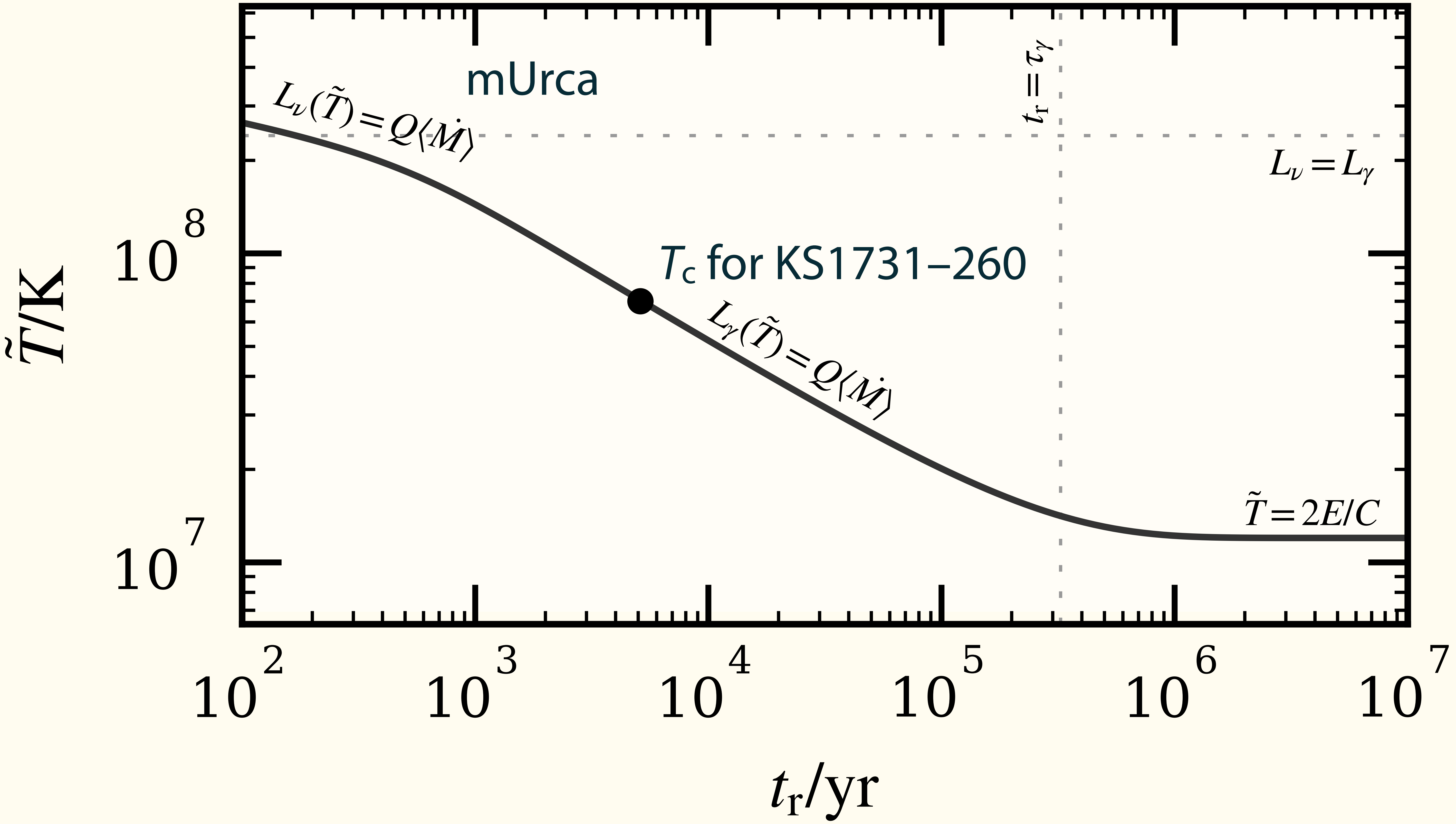
Cumming et al. 2017

The general case

$$C\frac{d\tilde{T}}{dt} = -L_\gamma(\tilde{T}) - L_\nu(\tilde{T}) + L_{\rm in},$$

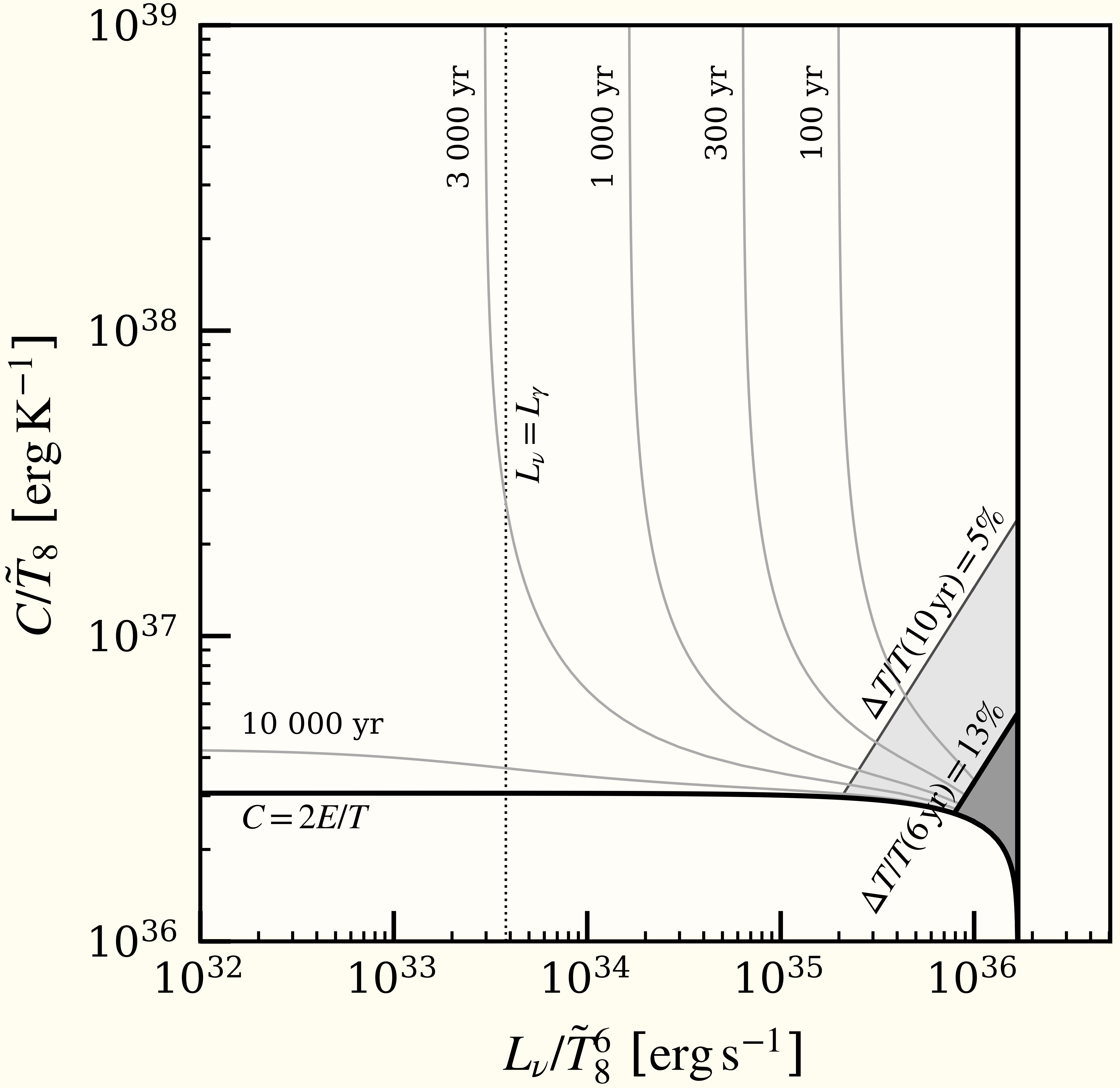
where $L_{\rm in} = 0$ during quiescence

In this plot the specific heat is fixed, $C/\tilde{T}_8 = 10^{38}\ {\rm erg\ K^{-1}}$, and we vary the recurrence time t_r.



Phase diagram for KS 1731–260

Cumming et al. 2017



MXB 1659-29: 3 outbursts since 1978 (it finished an outburst mid-2017 and is in quiescence again)

The core is likely in steady-state: the thermal time of the core (at an average cooling luminosity $L_\nu \approx 4 \times 10^{34}\ \mathrm{erg\,s^{-1}}$ is

$$\tau \approx 700\ \mathrm{yr} \left(\frac{C/\tilde{T}_8}{10^{38}\ \mathrm{erg\,K^{-1}}}\right)\left(\frac{\tilde{T}_8}{0.25}\right)^2$$

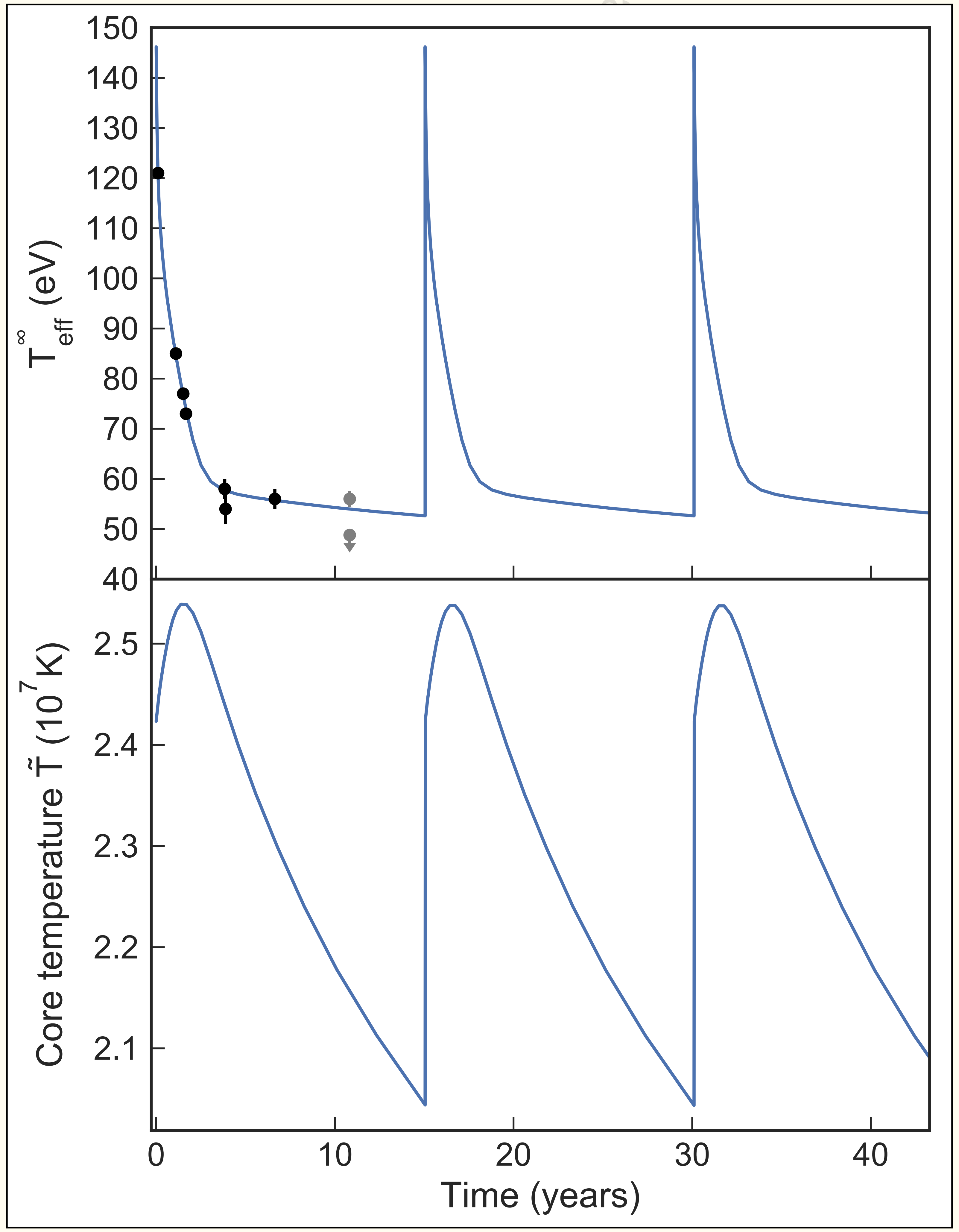
The low core temperature implies that strong neutrino cooling is present:

$$L_\nu \approx 10^{38}\ \mathrm{erg\,s^{-1}}\tilde{T}_8^6.$$

This is consistent with direct Urca over a small fraction ($\sim 1\%$) of the core.

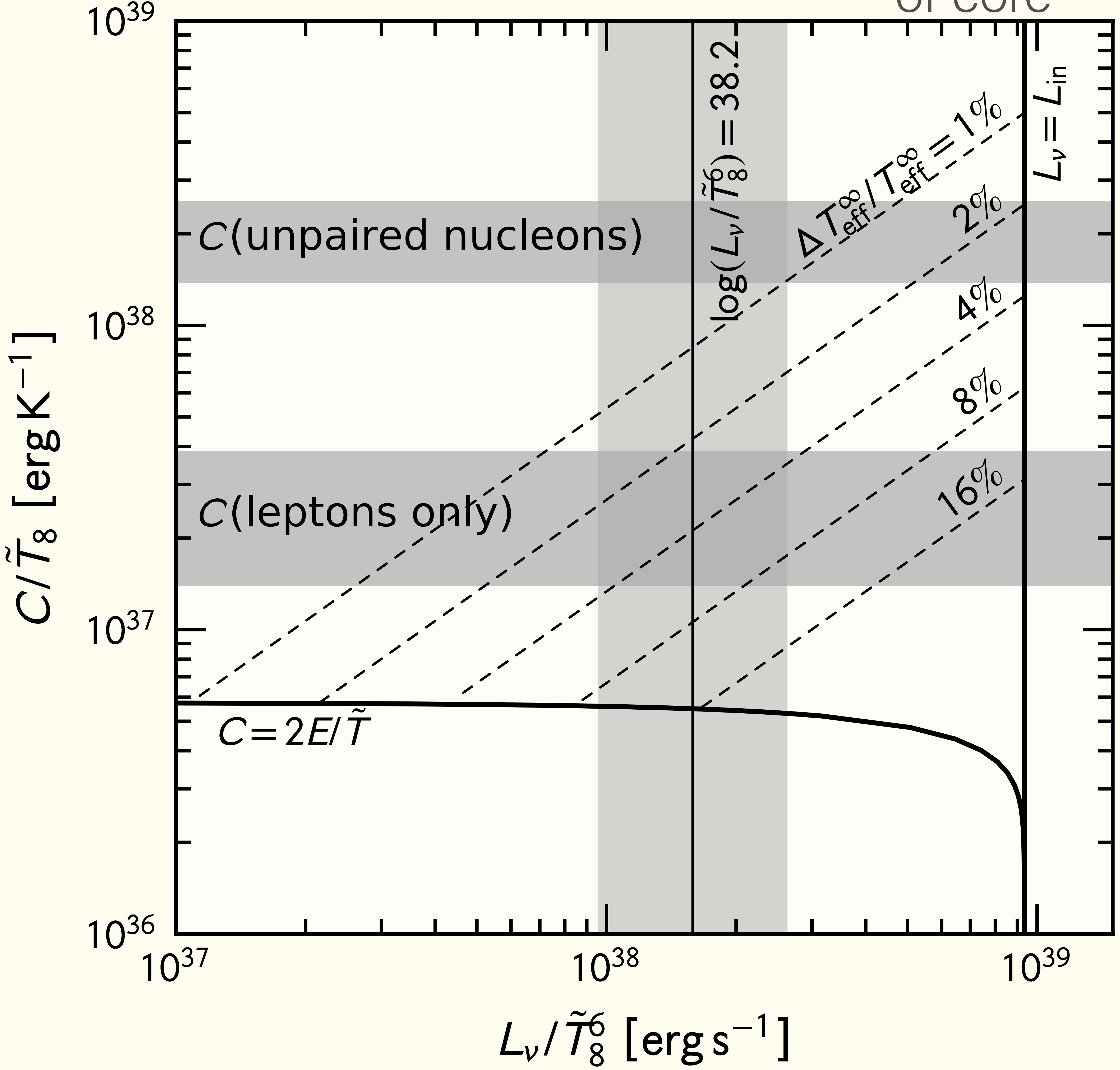
Note: here we assume outburst of 1999 is typical.

Brown et al. 2018



Phase diagram for MXB 1659-29

L_ν consistent with
direct Urca over ≈1%
of core



In summary,

Cooling neutron star transients probe the transport properties of matter at near-saturation density.

Transients with long outbursts deposit enough heat in the core to potentially raise the core temperature. Observations following crust relaxation measure this temperature.

For KS1731, $C > 3 \times 10^{36}\tilde{T}_8$

Its neutrino luminosity is $< 10^{-3}$ that of direct Urca.

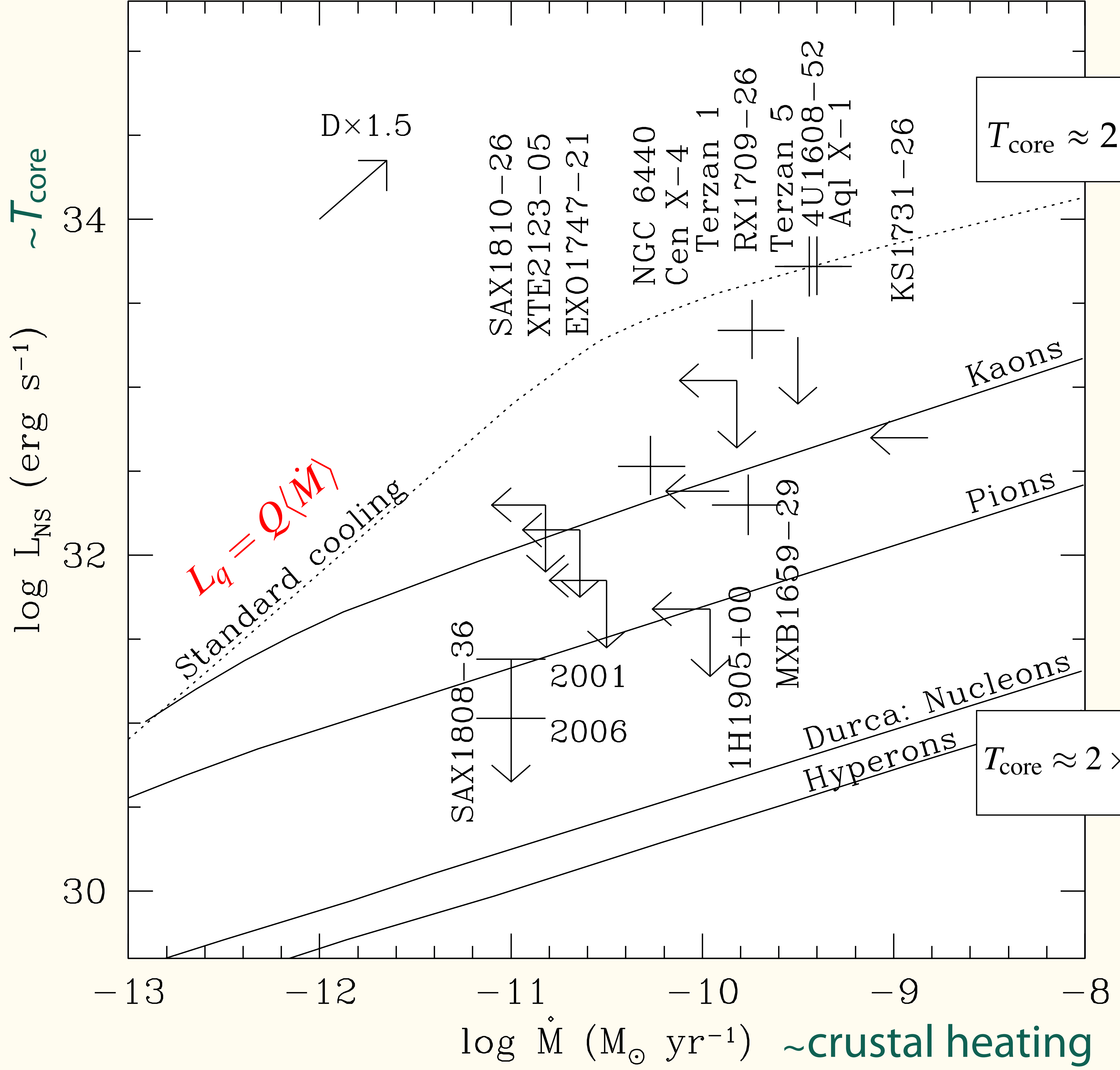
implies $M_{\mathrm{MXB}} > M_{\mathrm{KS}}$

For MXB 1659, neutrino luminosity is ≈1% of direct Urca

SAX J1808.4-3658 has an even colder core

Further monitoring of variations in the core temperature will improve constraints on the core specific heat, superfluid gaps (cf. Mendes et al. 2021)…

Heinke et al. 2007, following Yakovlev et al. 2004



$$T_{\rm core} \approx 2\times10^{8}\,{\rm K}\left(\frac{\langle\dot{M}\rangle}{10^{-10}\,M_\odot\,{\rm yr}^{-1}}\right)^{1/8}$$

$$T_{\rm core} \approx 2\times10^{7}\,{\rm K}\left(\frac{\langle\dot{M}\rangle}{10^{-10}\,M_\odot\,{\rm yr}^{-1}}\right)^{1/6}$$

Composition in the outer crust

decrease e^-

start with a simple liquid drop

$$B(Z,N) = a_V A - a_S A^{2/3} - a_A \frac{(N-Z)^2}{A} - a_C \frac{Z^2}{A^{1/3}}$$

enforce beta-equilibrium, charge neutrality: electron abundance Y_e decreases linearly with rising electron chemical potential

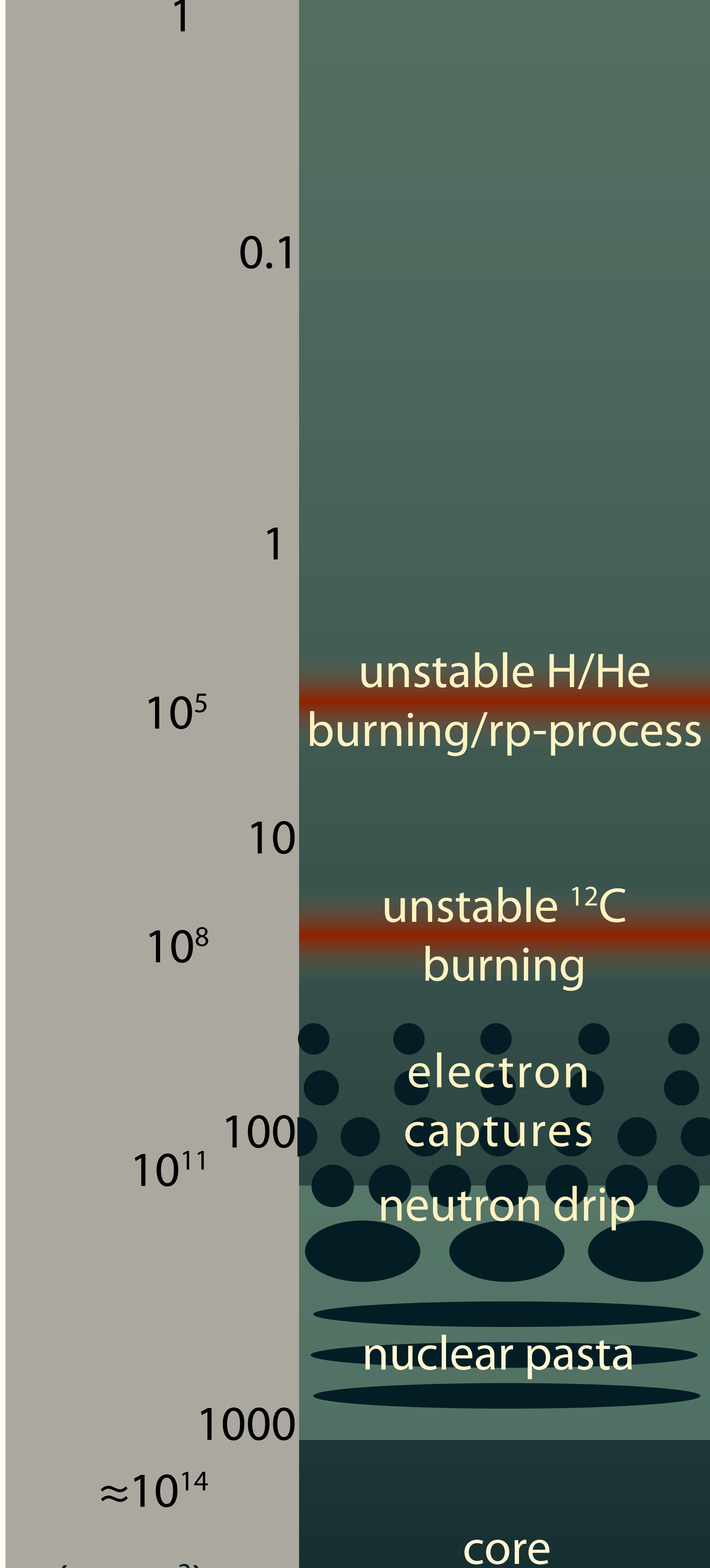
$$\mu_e = \mu_n - \mu_p$$

$$Y_e \approx \left(\frac{1}{2} - \frac{\mu_e}{8a_A}\right)\left(1 + \frac{a_C A^{2/3}}{4a_A}\right)^{-1}$$

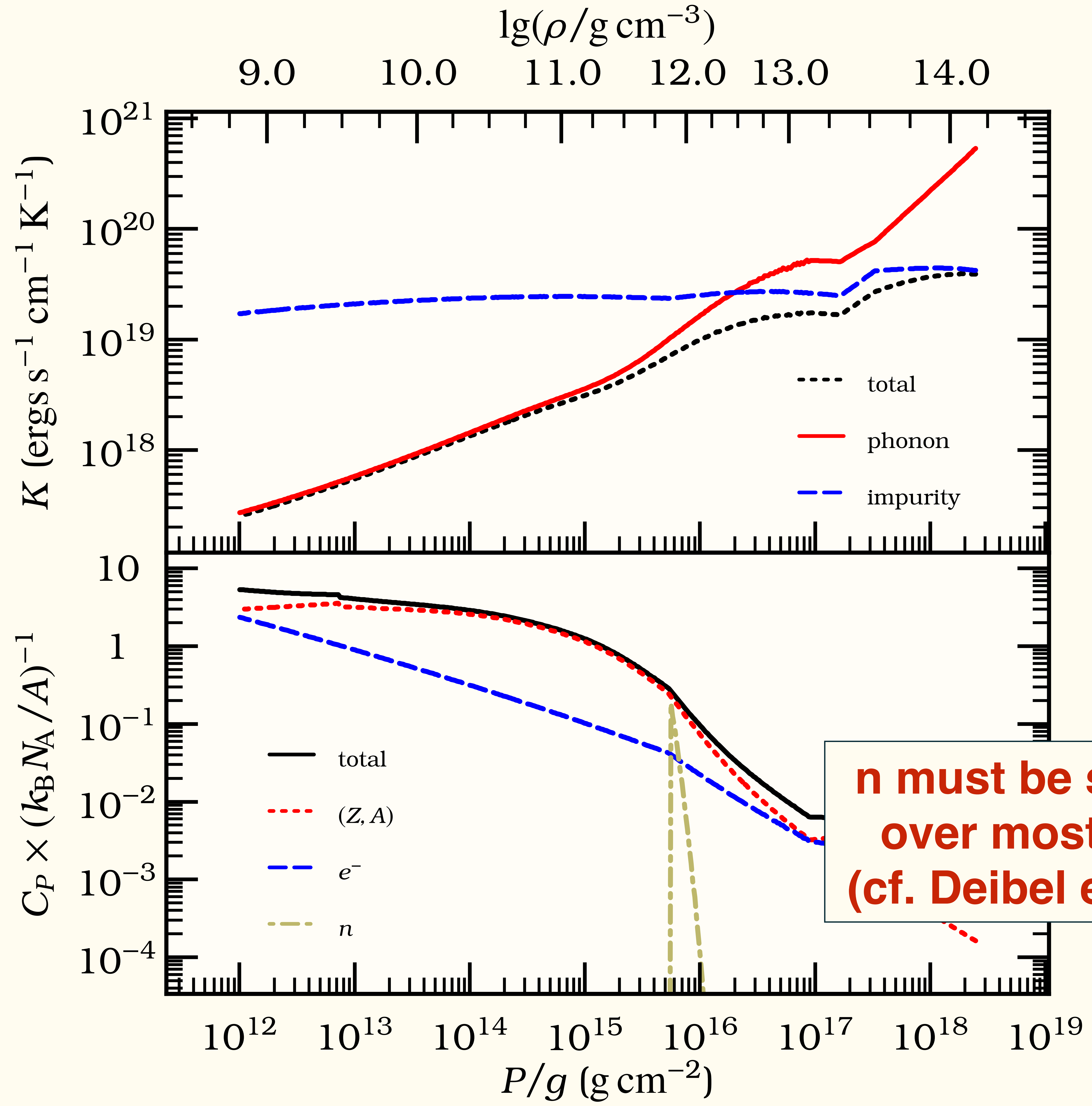
compute neutron separation energy S_n and find density of neutron drip, where $S_n = 0$: $n_{\mathrm{drip}} \approx 0.001\ n_0$

$$S_n = \left(\frac{\partial B}{\partial N}\right)_Z = a_V - a_A\left(1 - 4Y_e^2\right) - \frac{1}{3}a_C Y_e^2 A^{2/3}$$

$$S_n \to 0 \implies \mu_e \approx 2a_V \approx 30\,\mathrm{MeV}$$



The cooling timescale



n must be superfluid over most of crust (cf. Deibel et al. 2017)

from Brown & Cumming ‘09

$$\Gamma \equiv \frac{Z^2 e^2}{a k_B T} > 175 \longrightarrow$$

$$T \approx \Theta_D \longrightarrow$$