Measuring the Specific Heat and Neutrino Emissivity of Neutron Stars

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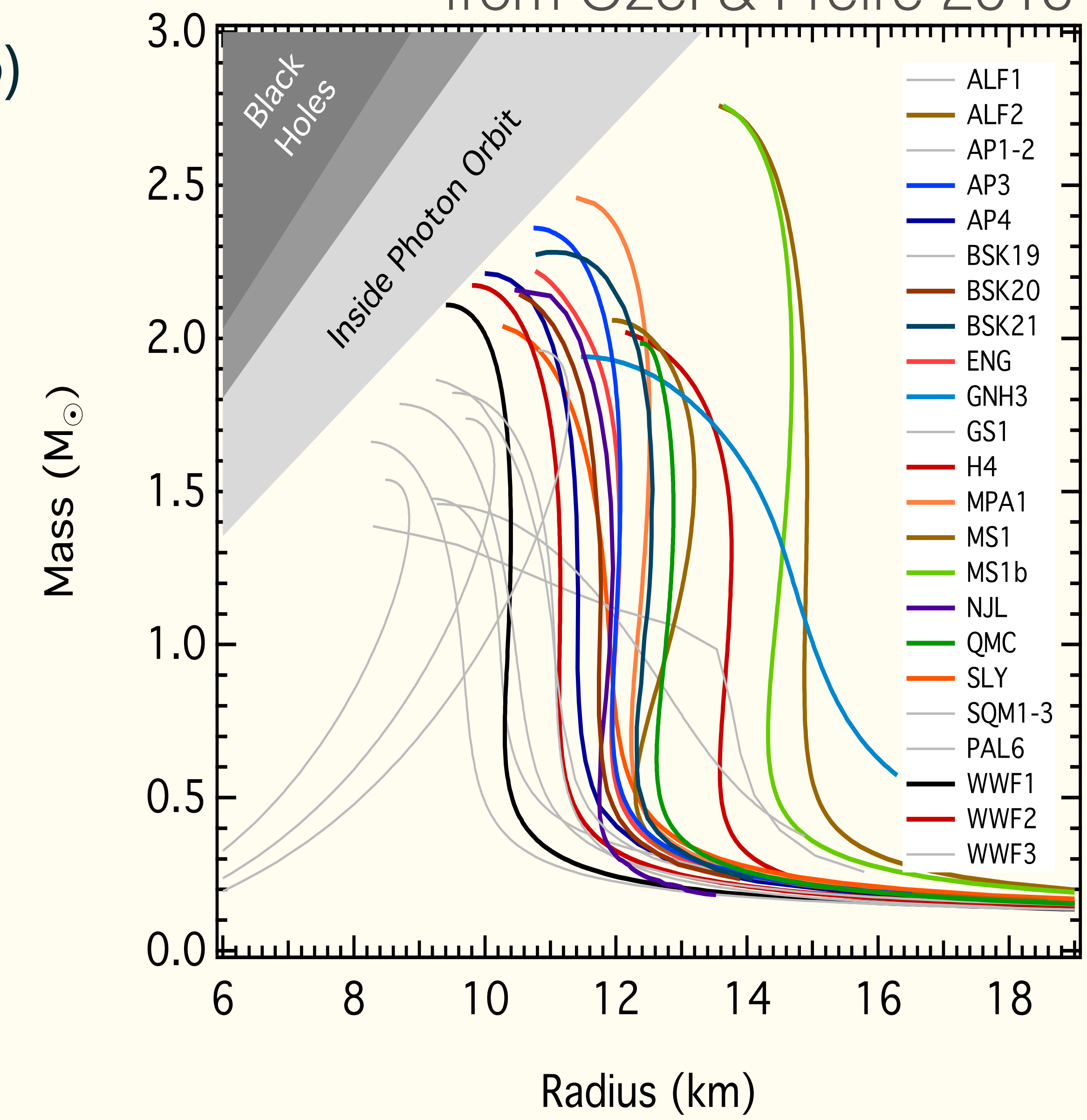
Cumming, Brown, Fattoyev, Horowitz, Page & Reddy 2017, PRC 95, 025806. arXiv: 1608.07532
Brown, Cumming, Fattoyev, Horowitz, Page & Reddy 2018, PRL 120, 182701. arXiv: 1801.00041

Measurements of *M*, *R*, *Λ* map onto the EoS *P*(*ρ*)

from Özel & Freire 2016



We have less information about transport in dense matter: 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

$$n \to p e \bar{\nu}_e \quad \text{and inverse}$$

direct Urca

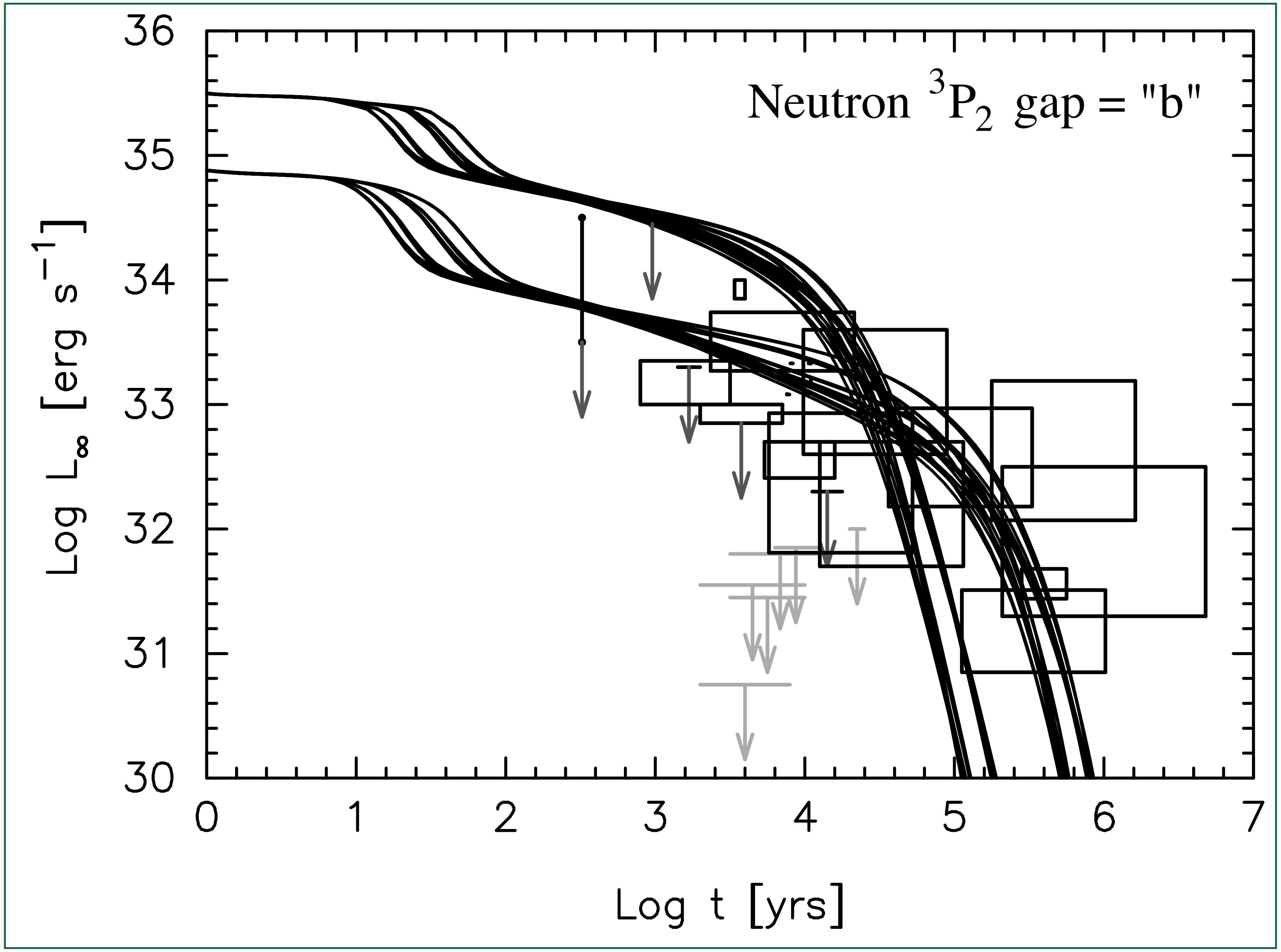
are blocked unless $n_p/n \gtrsim 0.11$; or other constituents (e.g., hyperons) are present.

conserve momentum, energy

Cooling isolated neutron stars

see reviews by Yakovlev & Pethick, Page et al.

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



Page, Lattimer, Prakash, & Steiner 2009

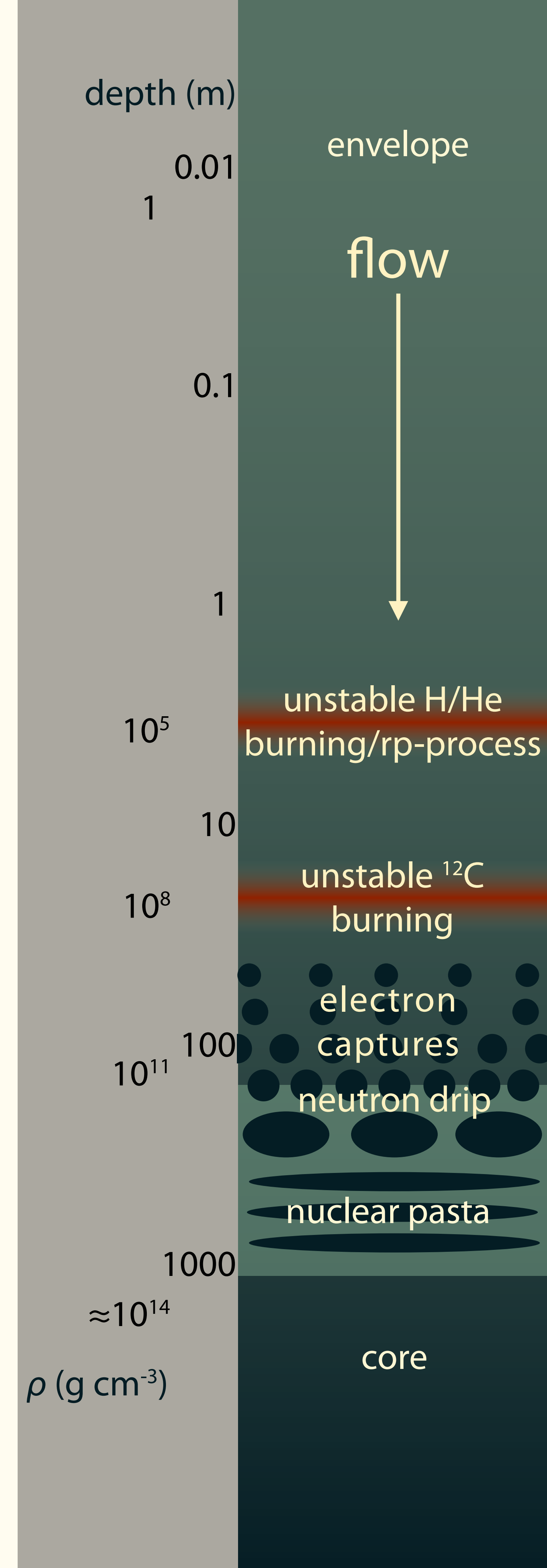
Many neutron stars accrete from a companion star

A. Piro, Carnegie Obs.

These neutron stars have a km-thick crust composed of nuclei, electrons, and free neutrons.

Accretion pushes matter through this crust and induces nuclear reactions that release ≈1–2 MeV/u.

Observing the response of the star to these reactions allows us to infer the properties of matter in the deep crust and core.



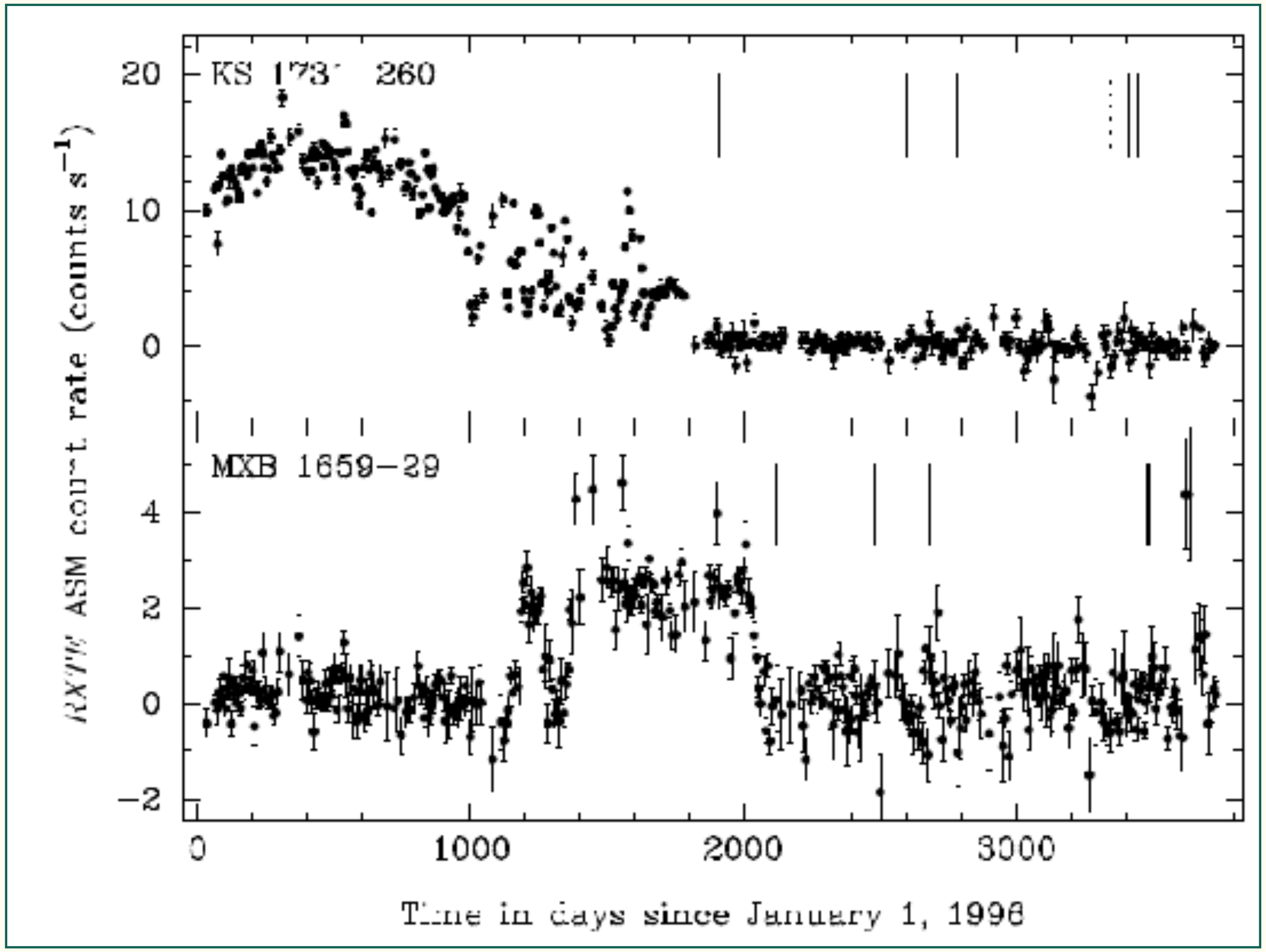
Quasi-persistent transients: long outburst and quiescent durations

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

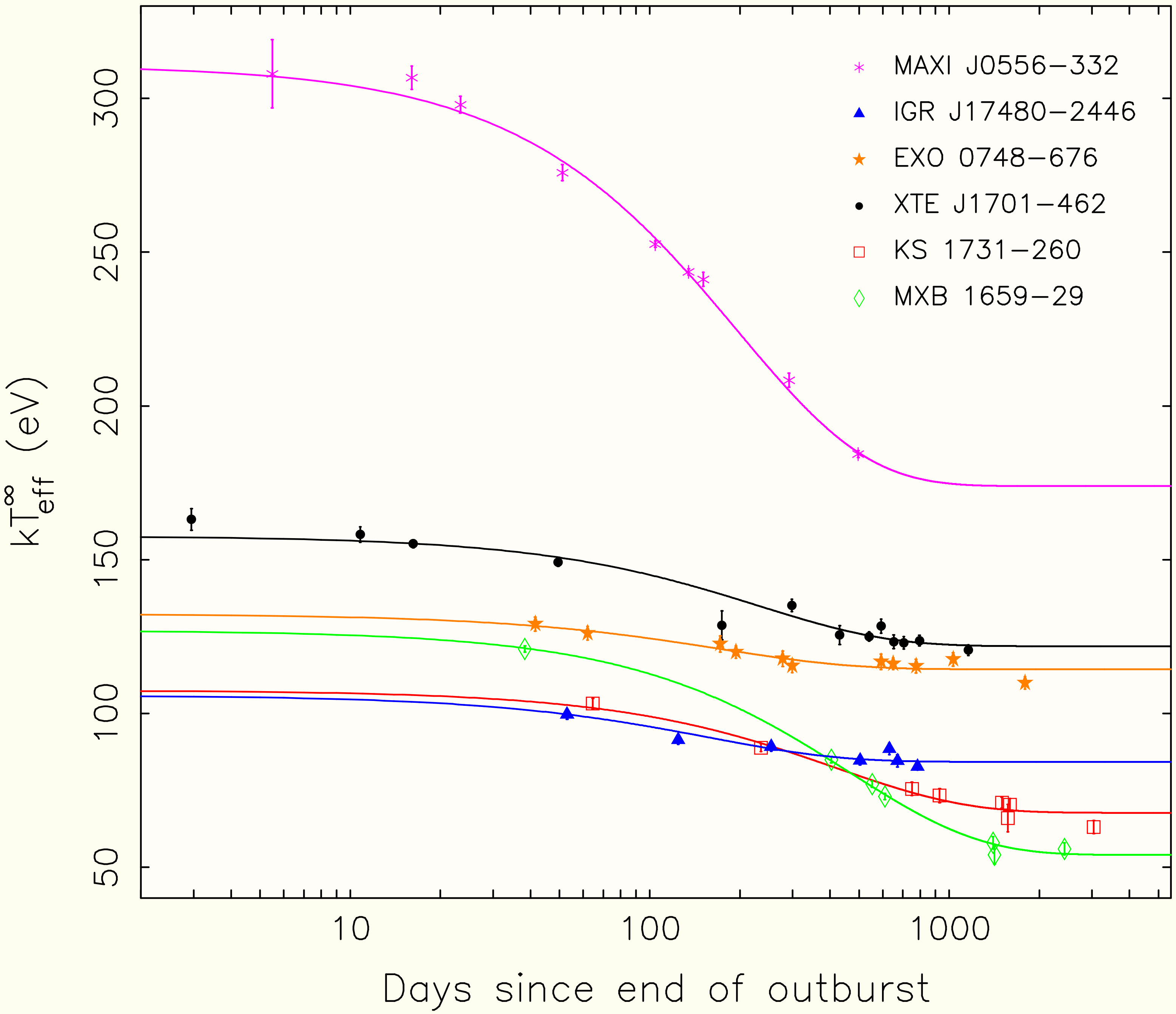
2002: Rutledge et al. suggest looking for crust thermal relaxation

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

fig. from Cackett et al. '06



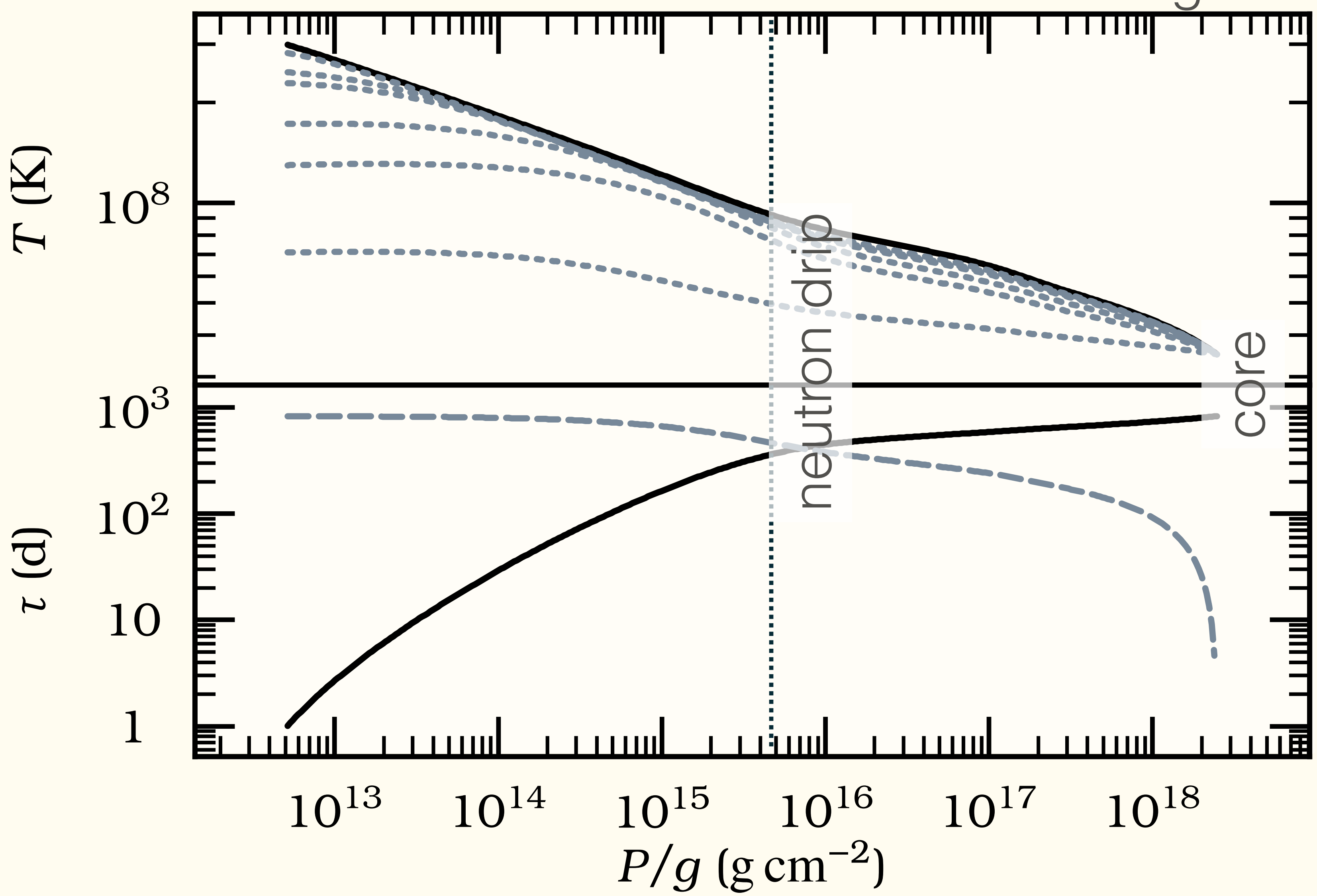
Many quasi-persistent transients are now being monitored



from Homan et al. (2014)

basic physics of the lightcurve

from Brown & Cumming '09



Thermal diffusion

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

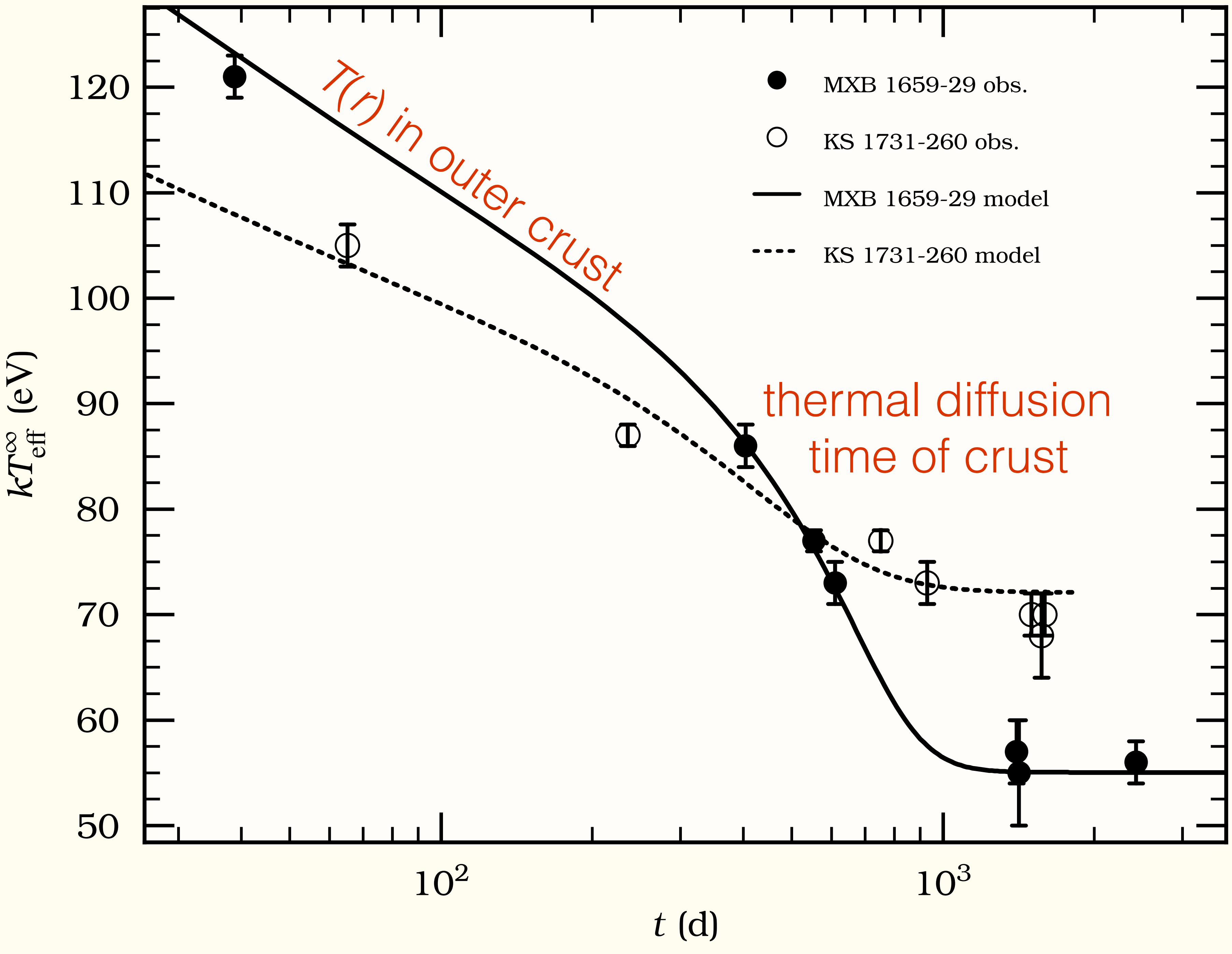
$$\tau = \frac{1}{4}\left[\int \left(\frac{\rho C}{K}\right)^{1/2} \mathrm{d}z\right]^2$$

depth→

Inferring crust properties from cooling

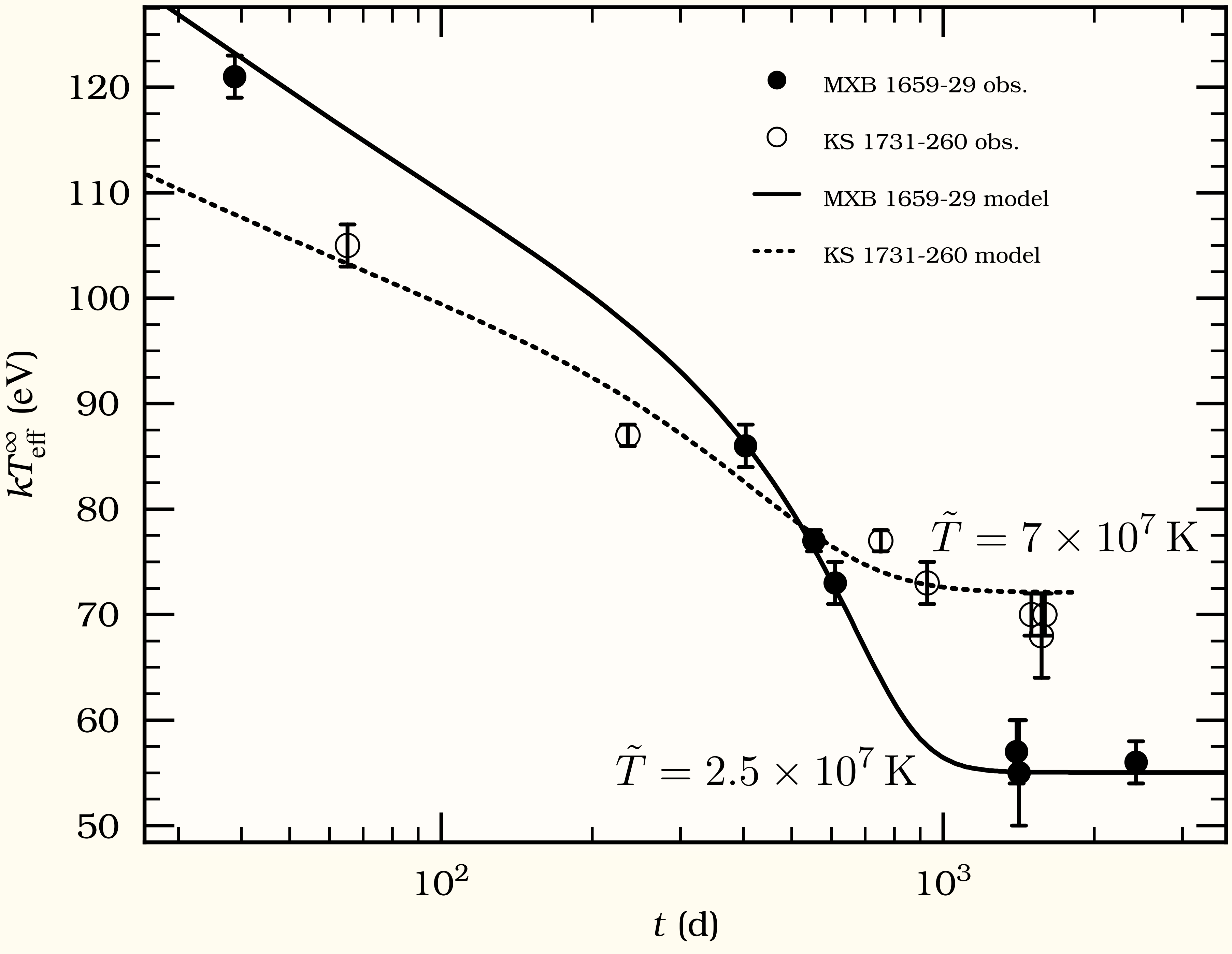
Ushomirsky & Rutledge, Shternin et al., Brown & Cumming, Page & Reddy, Turlione et al., Deibel et al., Merritt et al., Parikh et al.

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



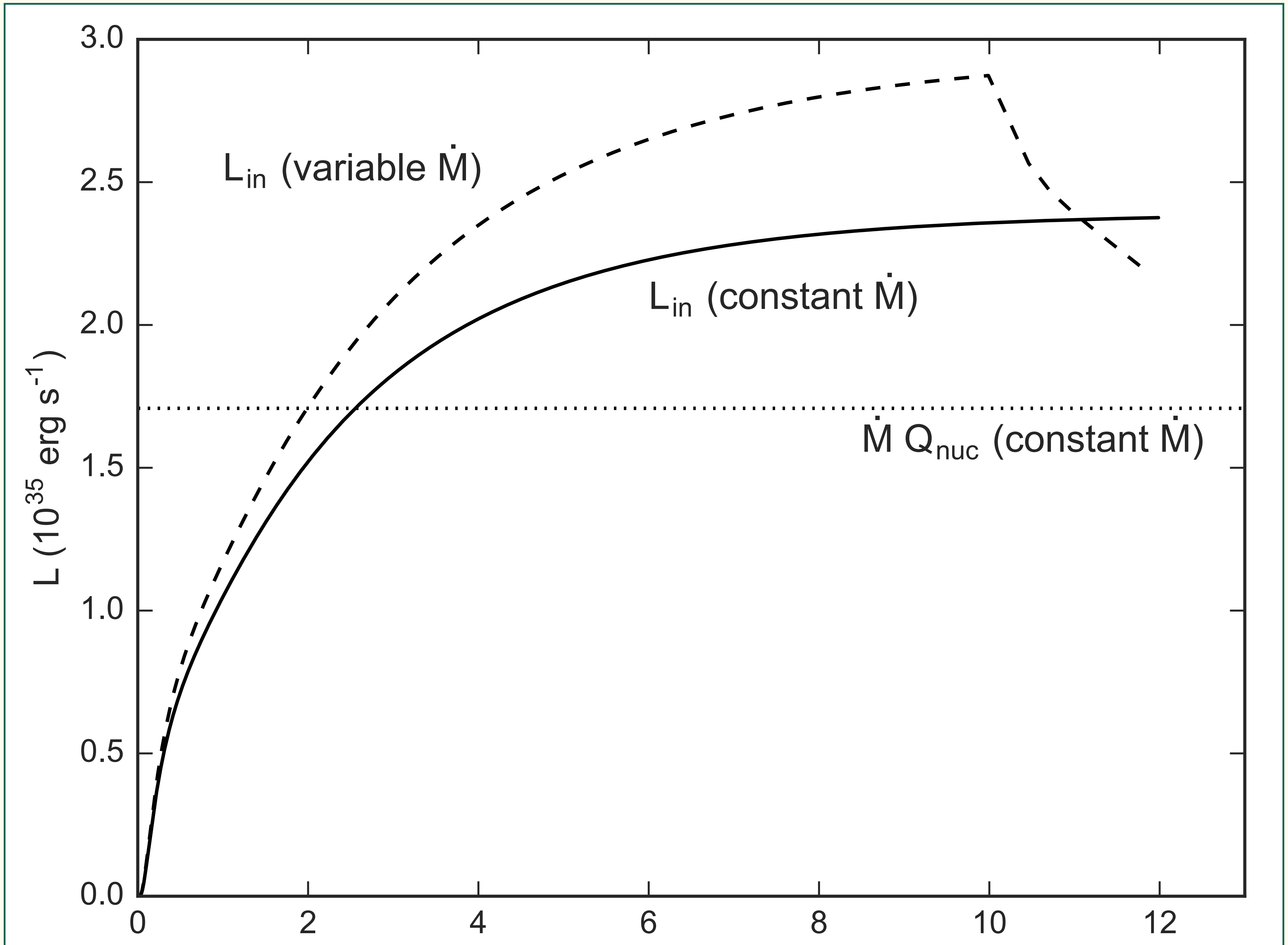
Models also give us the total energy deposited into the core and its temperature: calorimetry!

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



For KS 1731-260, $\approx 6 \times 10^{43}$ ergs deposited into the core

Cumming et al. '17



time in outburst (yrs)

Suppose core cools completely between outbursts and neutrino cooling is weak

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

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

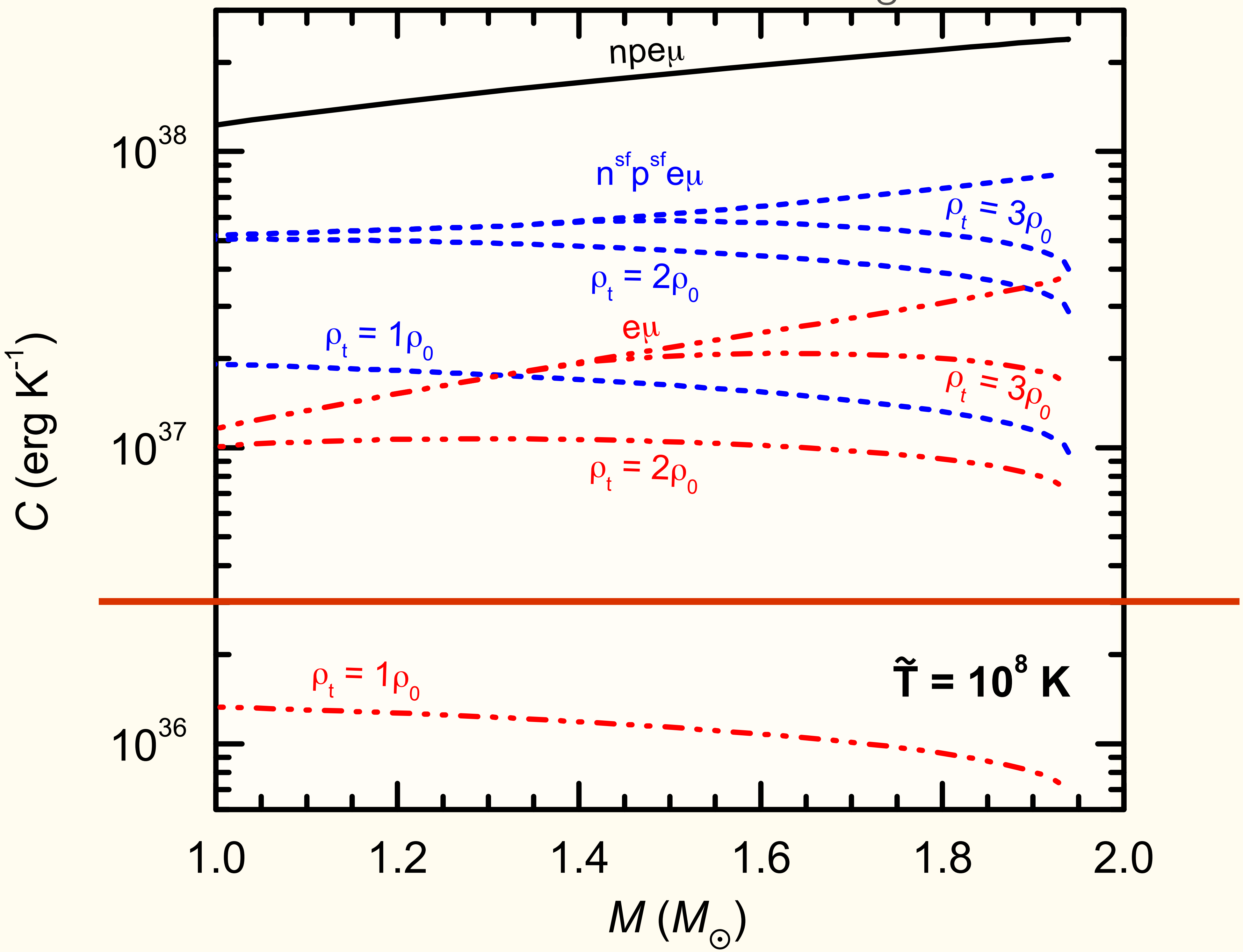
since $C \sim T$

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

The specific heat must be larger than this!

This could change T_{core} significantly

Cumming et al. 2017



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

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

$$L_{\nu,\mathrm{dU}} = 6 \times 10^{38}\, \tilde{T}_8^6\, \mathrm{erg\,s^{-1}} \qquad n \rightarrow pe\nu$$

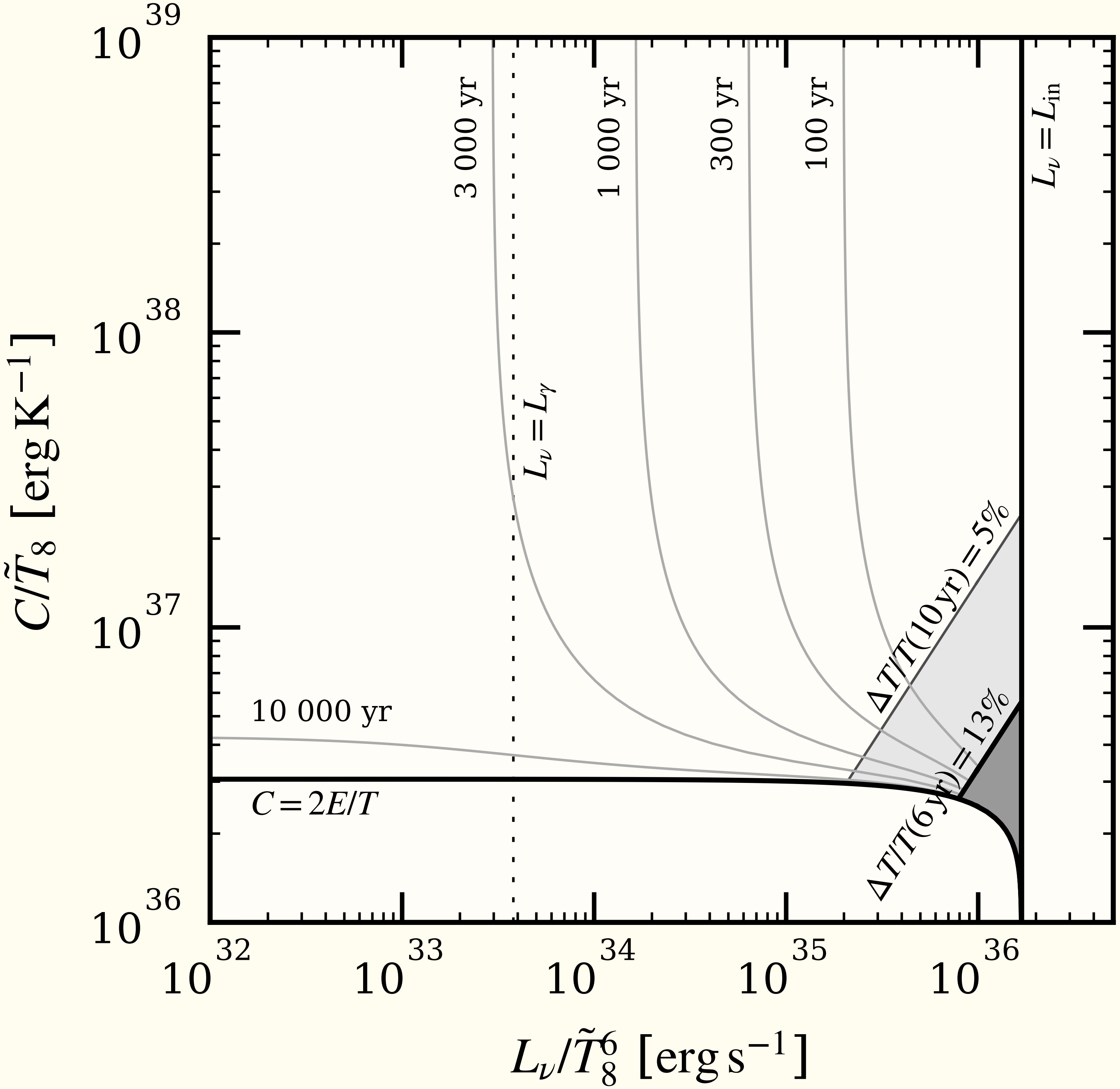
$$L_{\nu,\mathrm{mU}} = 6 \times 10^{30}\, \tilde{T}_8^8\, \mathrm{erg\,s^{-1}} \qquad nn \rightarrow npe\nu$$

The neutrino luminosity cannot exceed the heating rate, however:

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

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

Phase diagram for KS 1731–260



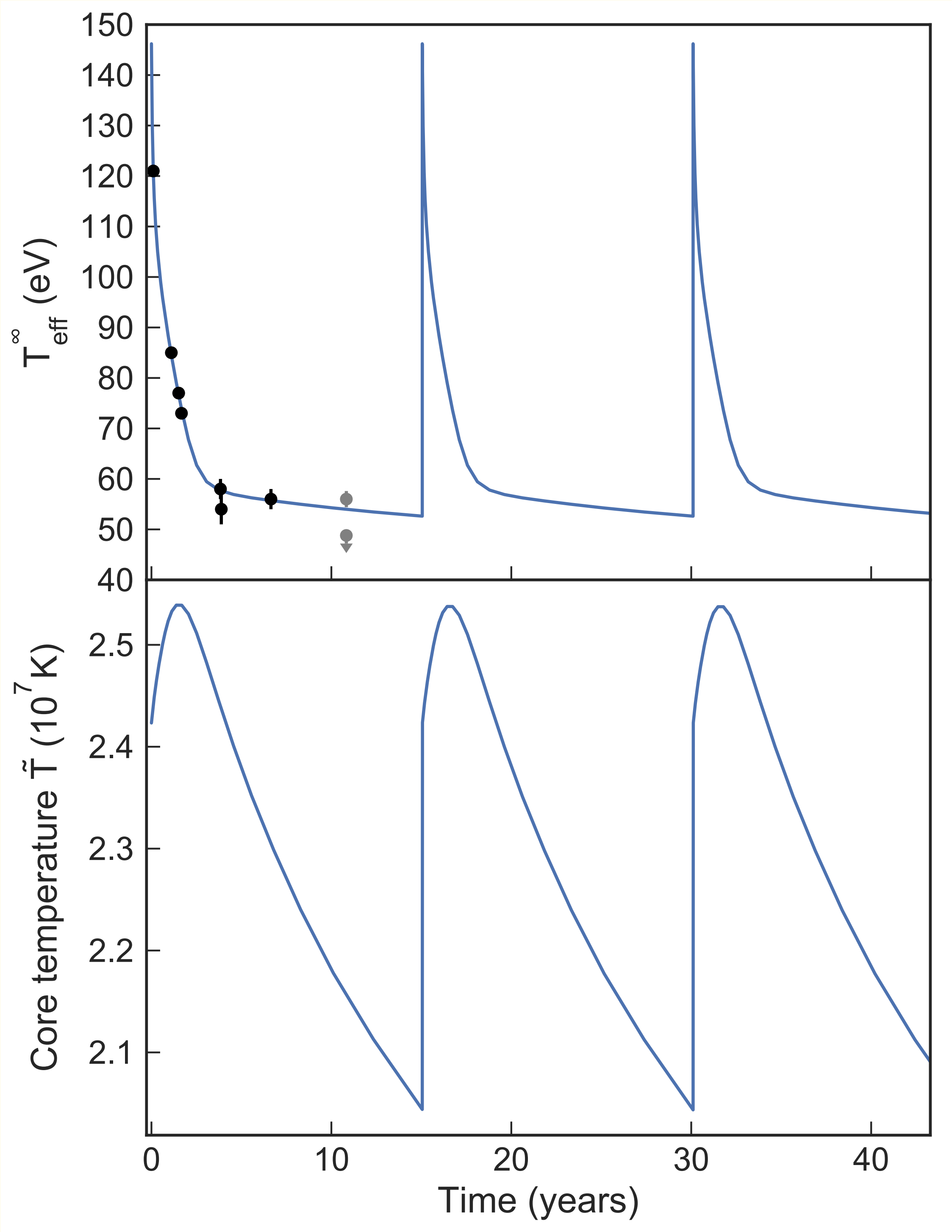
MXB 1659-29: 3 outbursts since 1978 (it finished an outburst mid-2017 and is in quiescence again)

Thermal time of core (at average cooling luminosity $L \approx 4 \times 10^{34}\,\mathrm{erg\,s^{-1}}$) is

$$\tau \approx 660\,\mathrm{yr}\left(\frac{C/\tilde{T}_8}{10^{38}\ \mathrm{erg\ K^{-1}}}\right)\left(\frac{\tilde{T}_8}{0.25}\right)^2$$

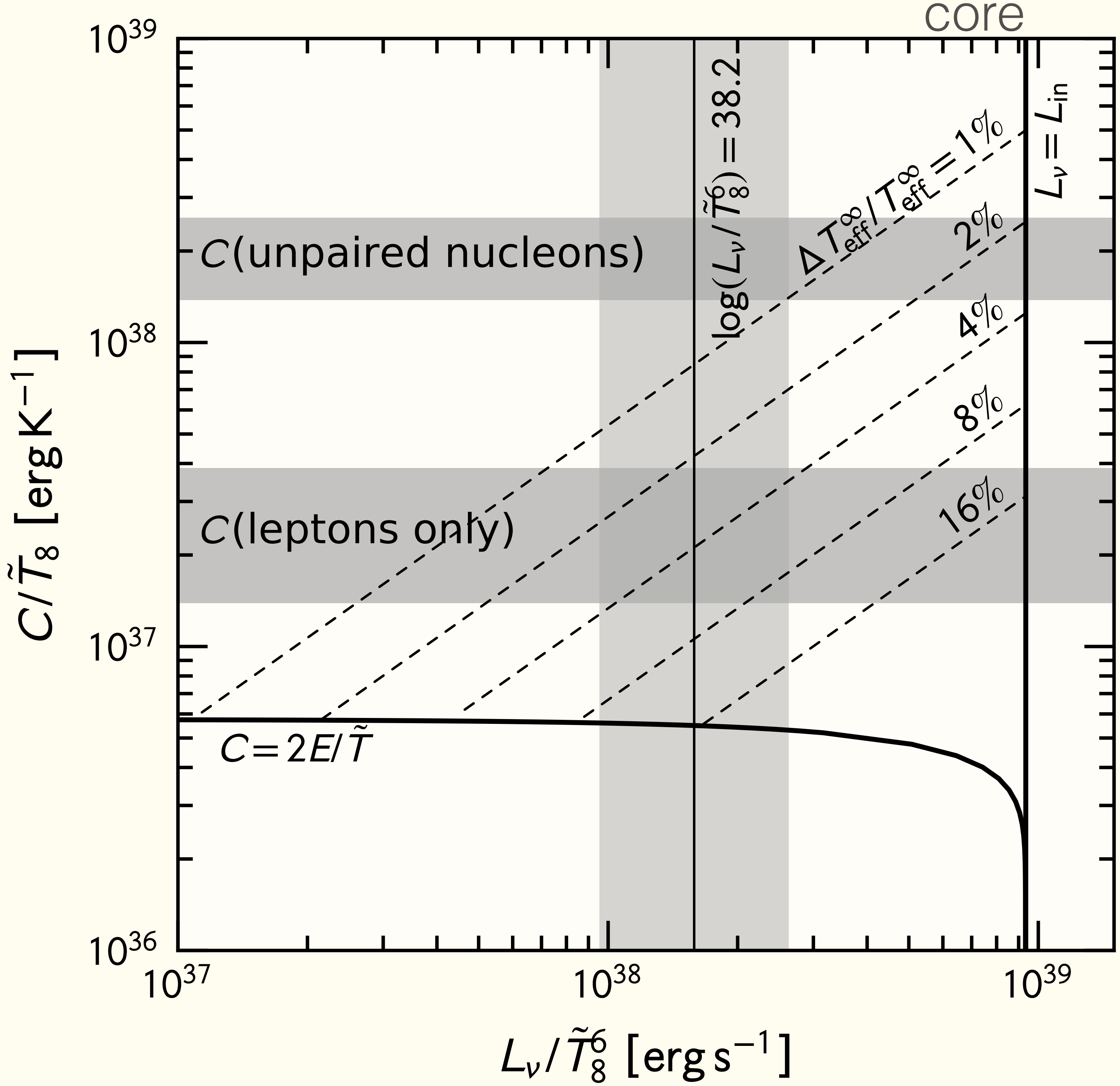
Low core temperature implies strong neutrino cooling,

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



Phase diagram for MXB 1659-29

L_ν consistent with dUrca 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.

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

For KS1731, $C > 3 \times 10^{36} \tilde{T}_8$
Its neutrino luminosity is < 10^{-3} that of direct Urca.

SAX J1808.4-3658 has an even colder core

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

Further monitoring of variations in the core temperature will improve constraints on the core specific heat.

Example of stellar volume above dUrca threshold

Fattoyev et al., in prep.

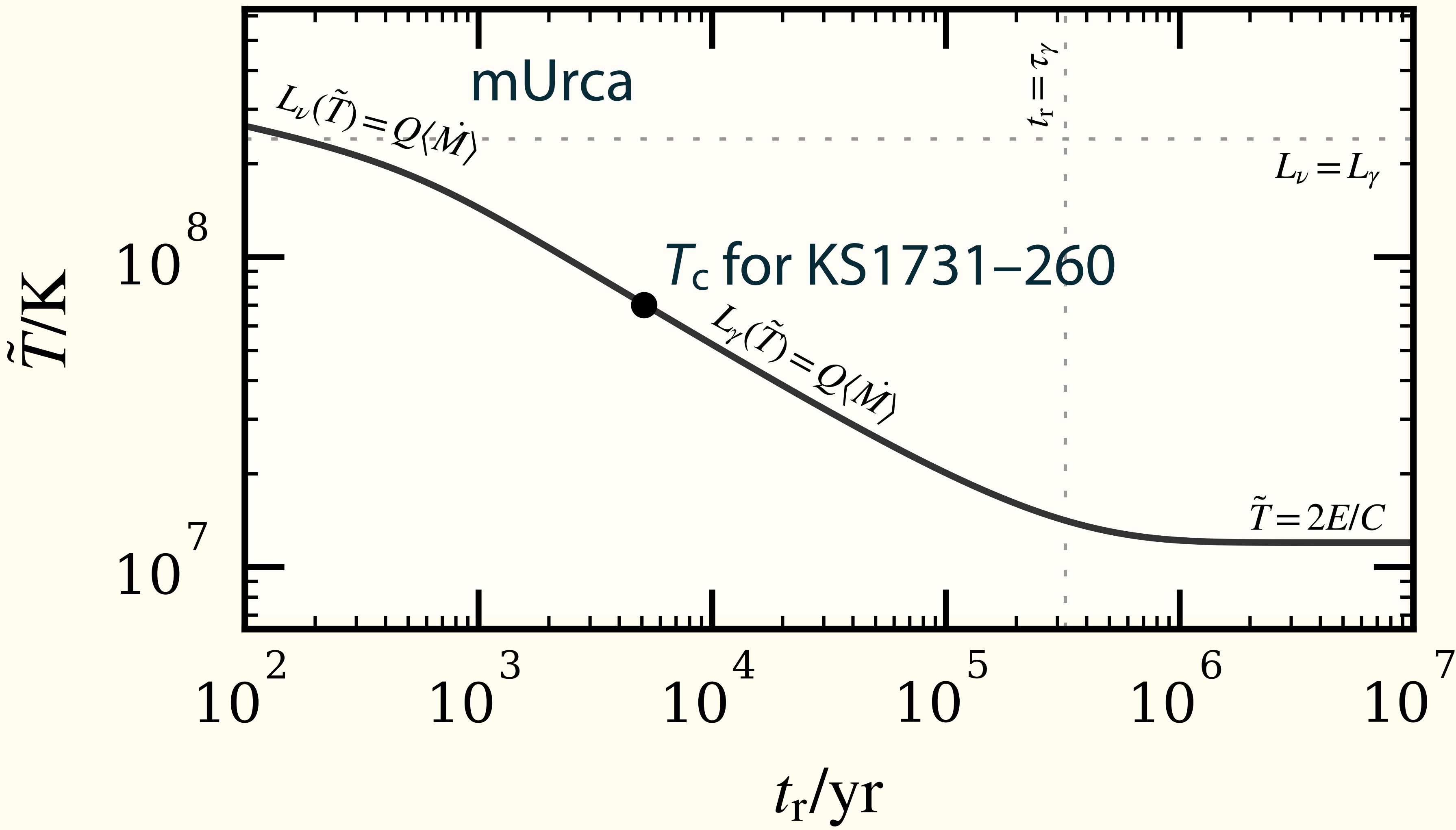
M [Msun]	V_DU,eff/V_tot
1.591	0
1.715	5%
1.788	10%
1.897	20%
2.024	45%

The general case

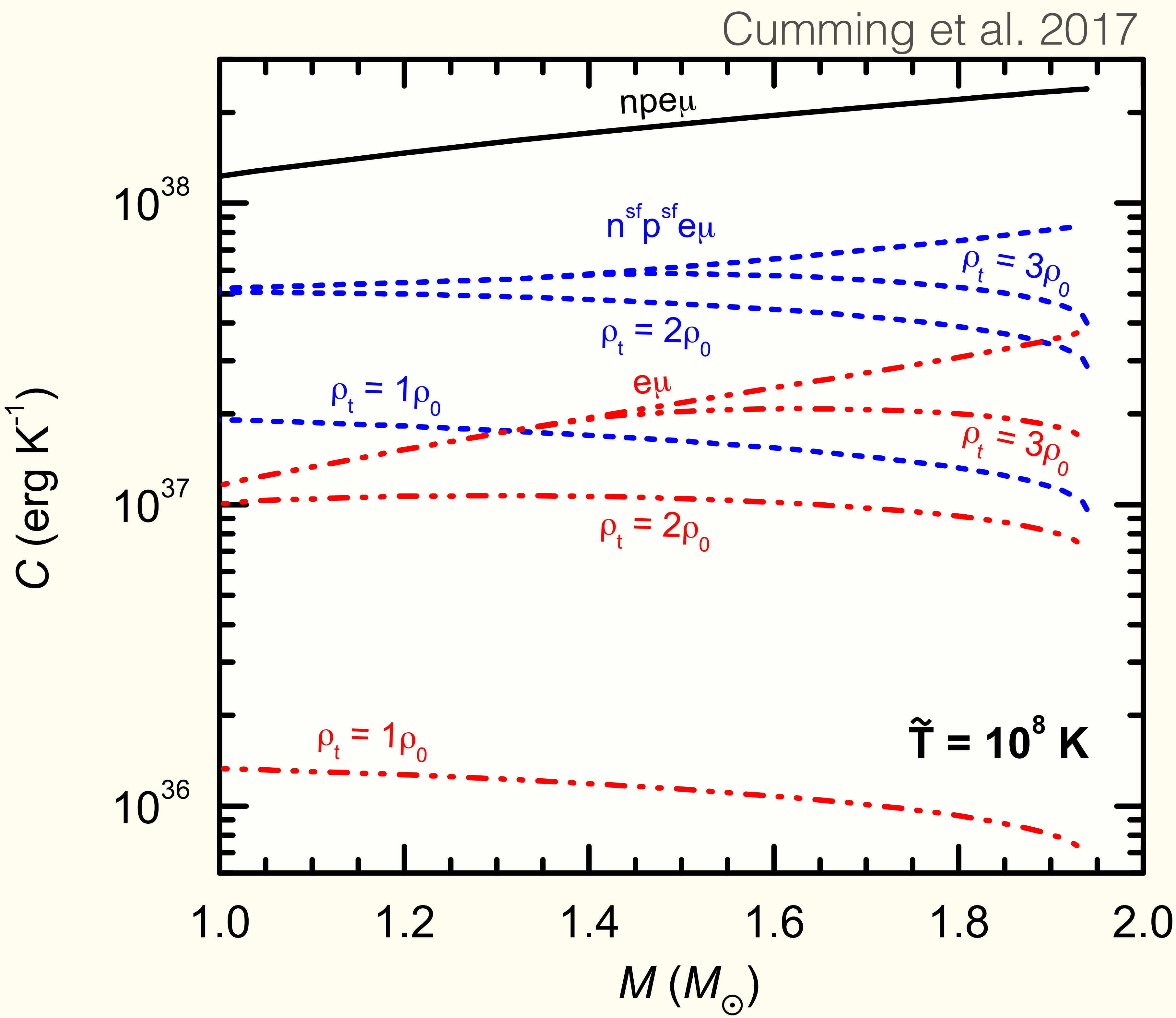
$$C\frac{d\tilde{T}}{dt} = -L_\gamma(\tilde{T}) - L_\nu(\tilde{T}) + L_{\text{in}},$$

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

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



This could change T_{core} significantly



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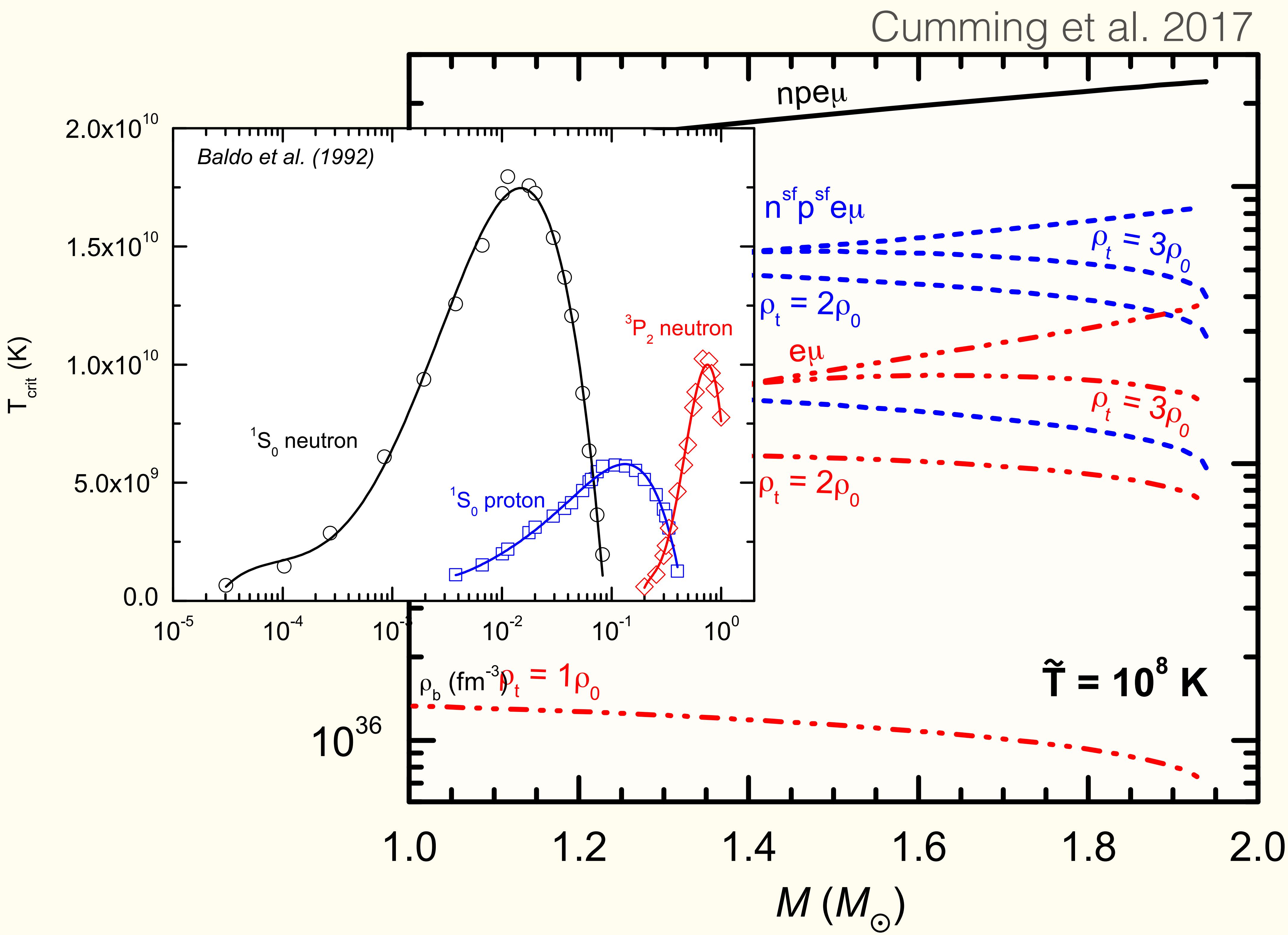

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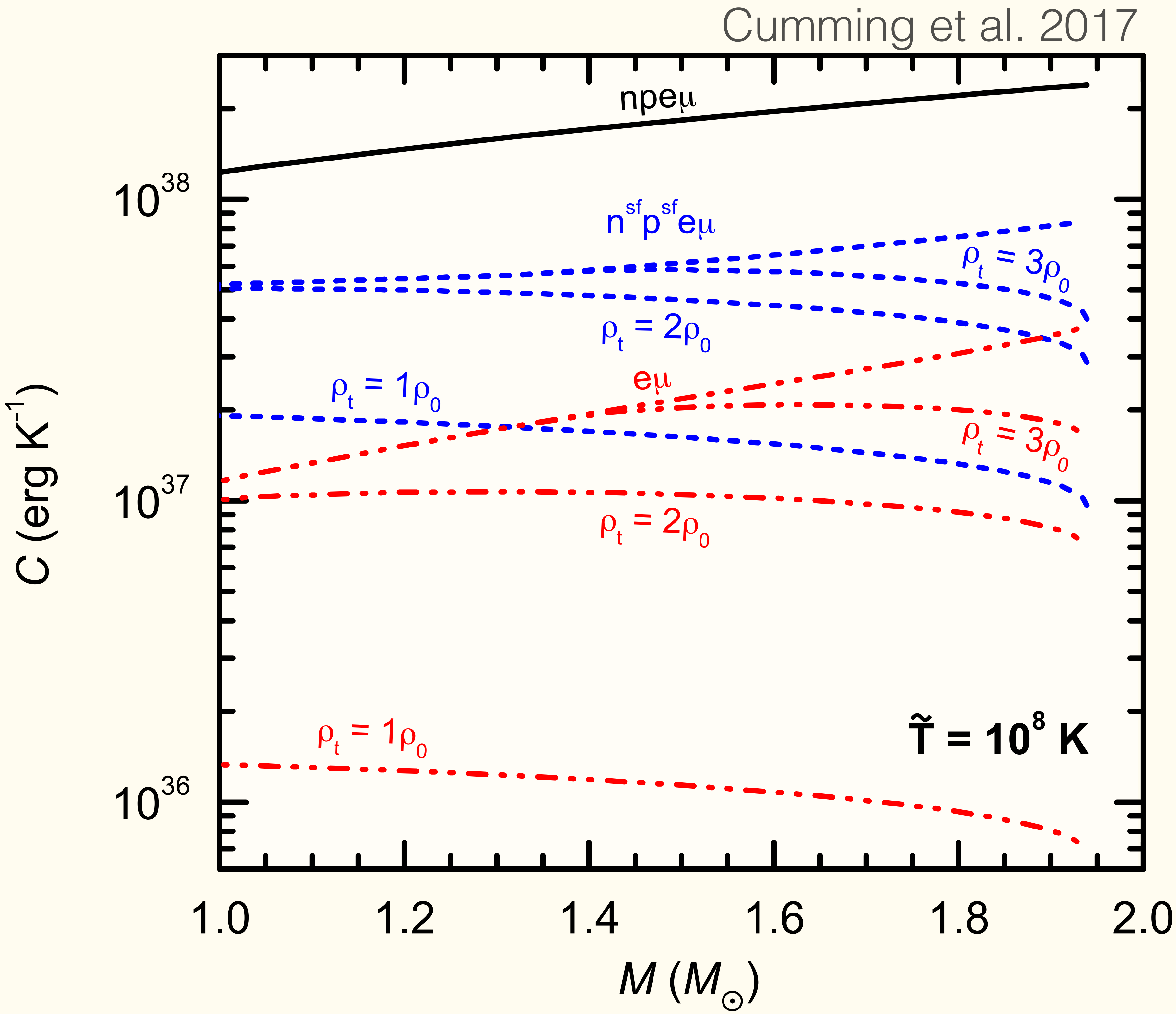
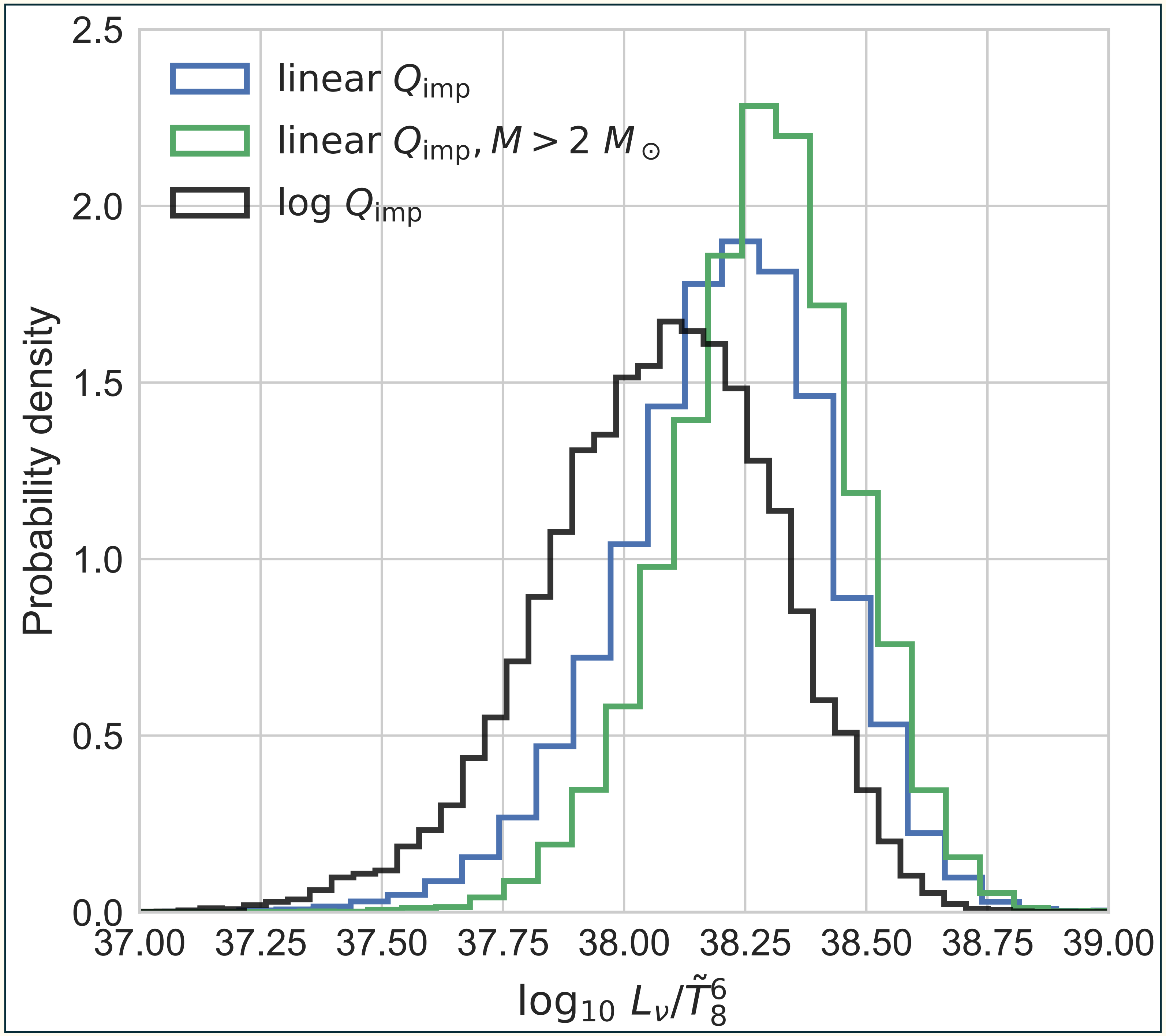
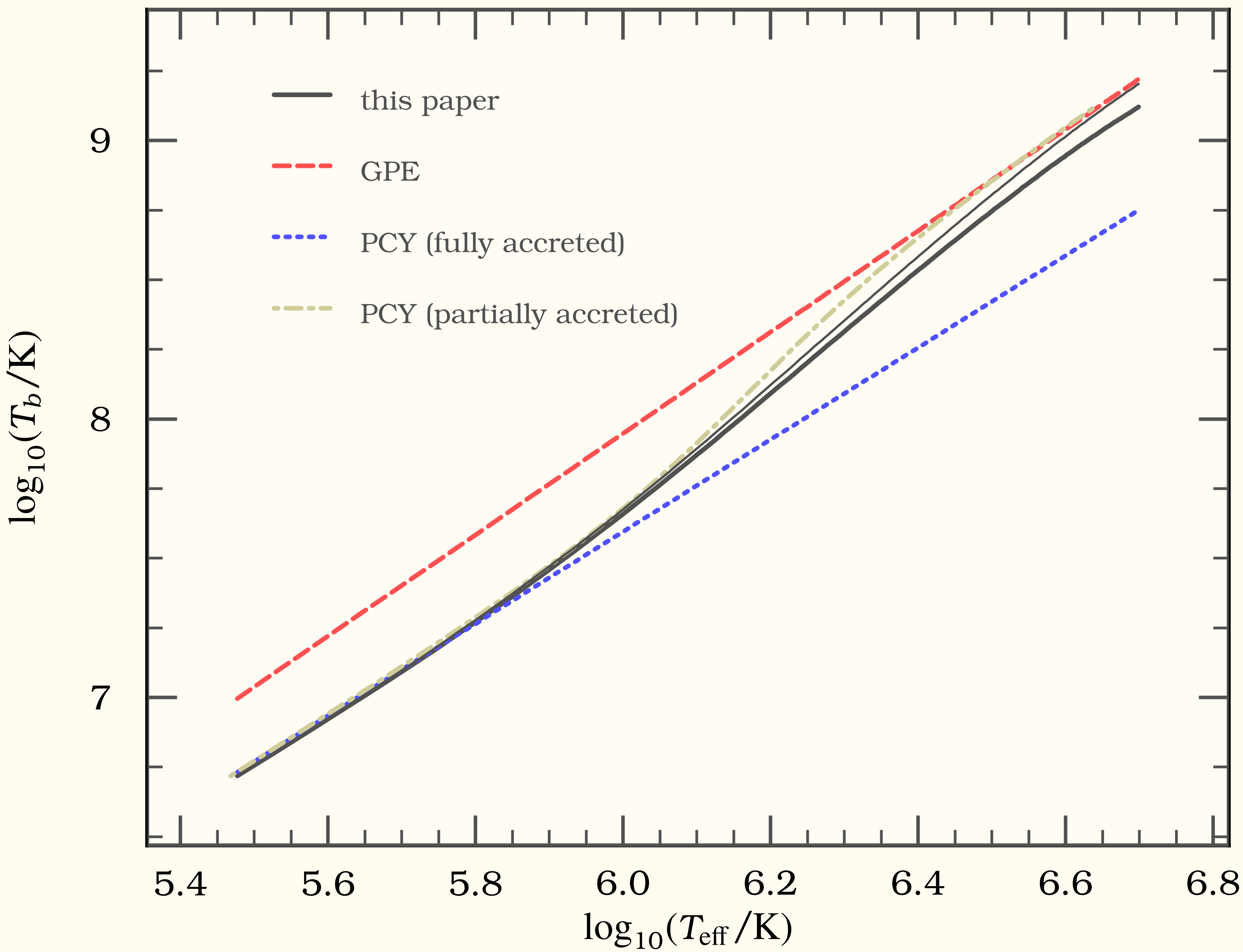


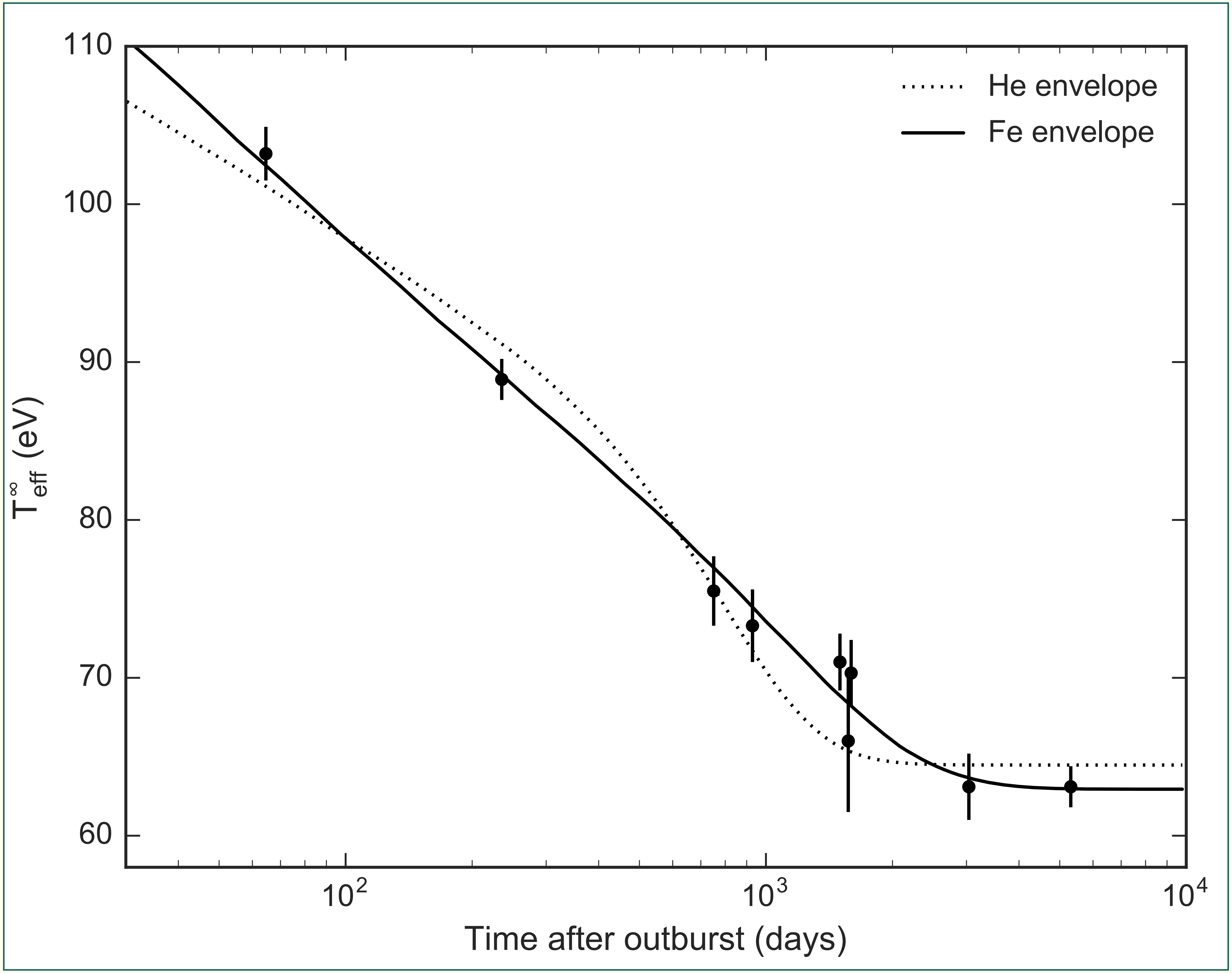
Neutrino luminosity, MXB1659-29



Envelope sets mapping between surface and interior temperatures



from Brown & Cumming '09



He envelope
Fe envelope
110
100
90
80
70
60
T_{eff}^{∞} (eV)
10^2
10^3
10^4
Time after outburst (days)