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Measuring the Specific Heat and the Neutrino Emissivity of Dense Matter

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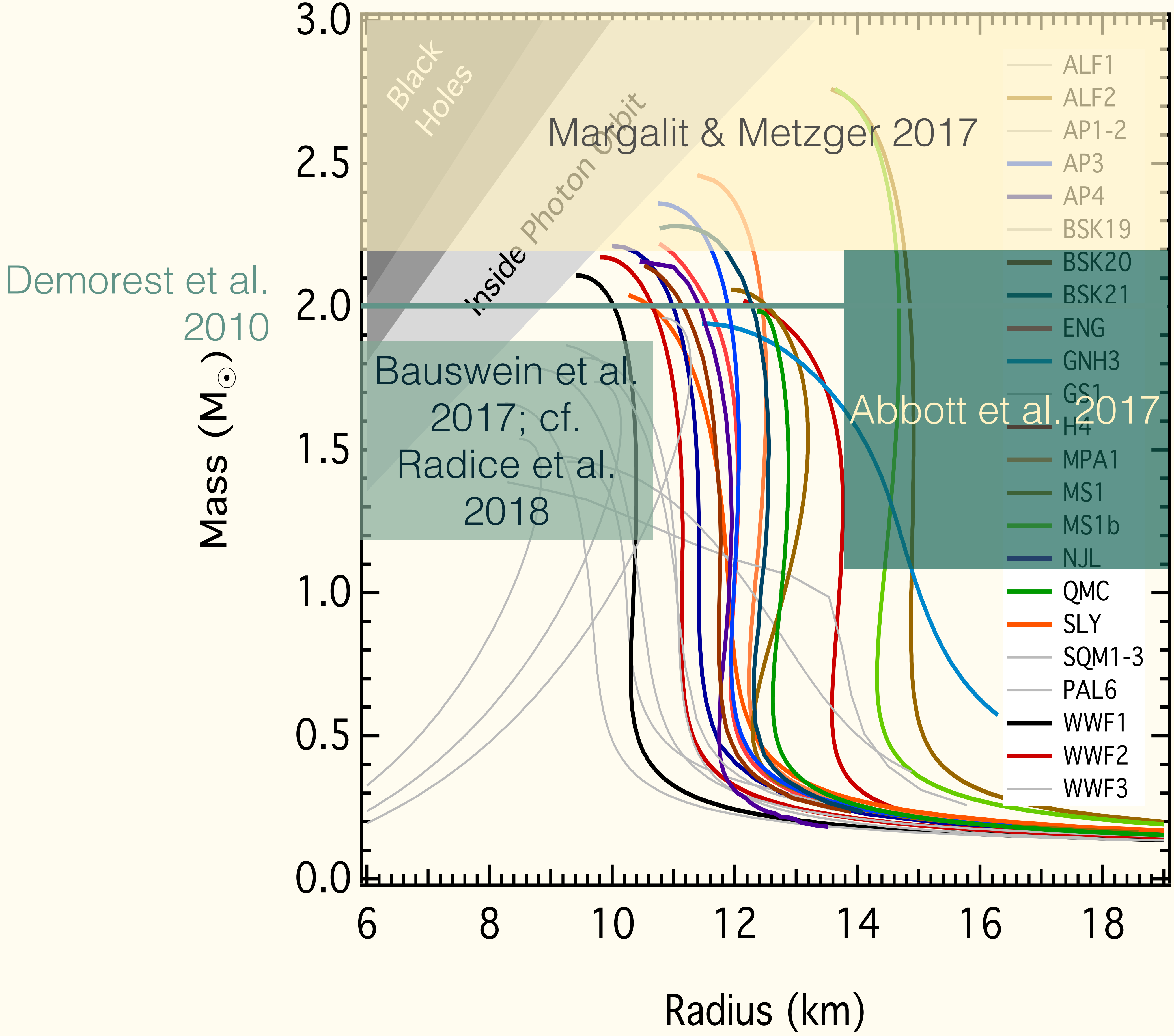
Cumming, Brown, Fattoyev, Horowitz, Page & Reddy 2017, PRC 95, 025806. arXiv: 1608.07532
Brown, Cumming, Fattoyev, Horowitz, Page & Reddy 2018, PRL, in press. arXiv: 1801.00041

from Özel & Freire 2016



Constraints on *M*, *R*, *Λ* map onto constraints on *P*(*ρ*)

We have less direct 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

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

direct Urca

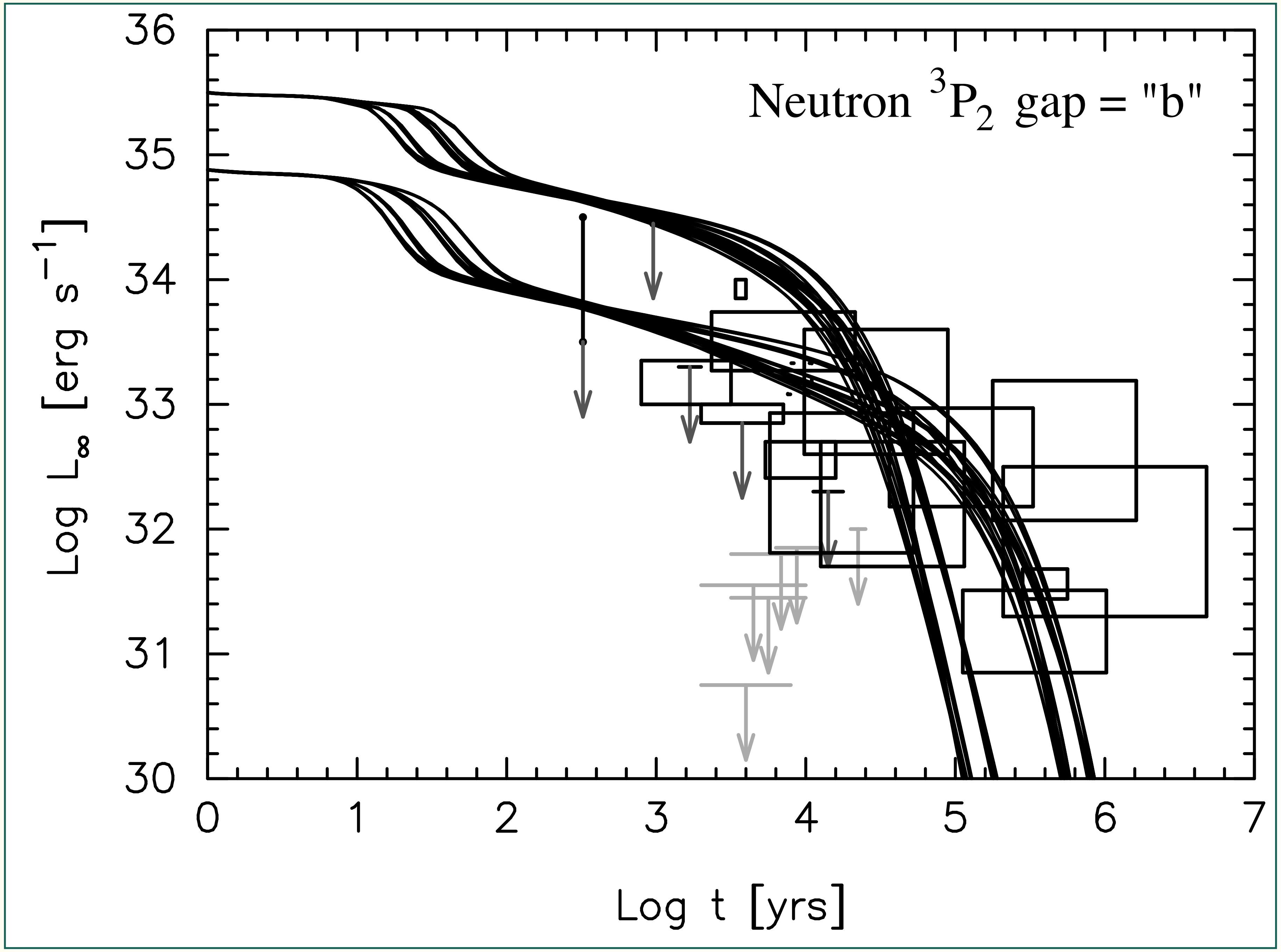
are blocked unless $n_p/n \gtrsim 0.11$; or other constituents (e.g., hyperons) are present.

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

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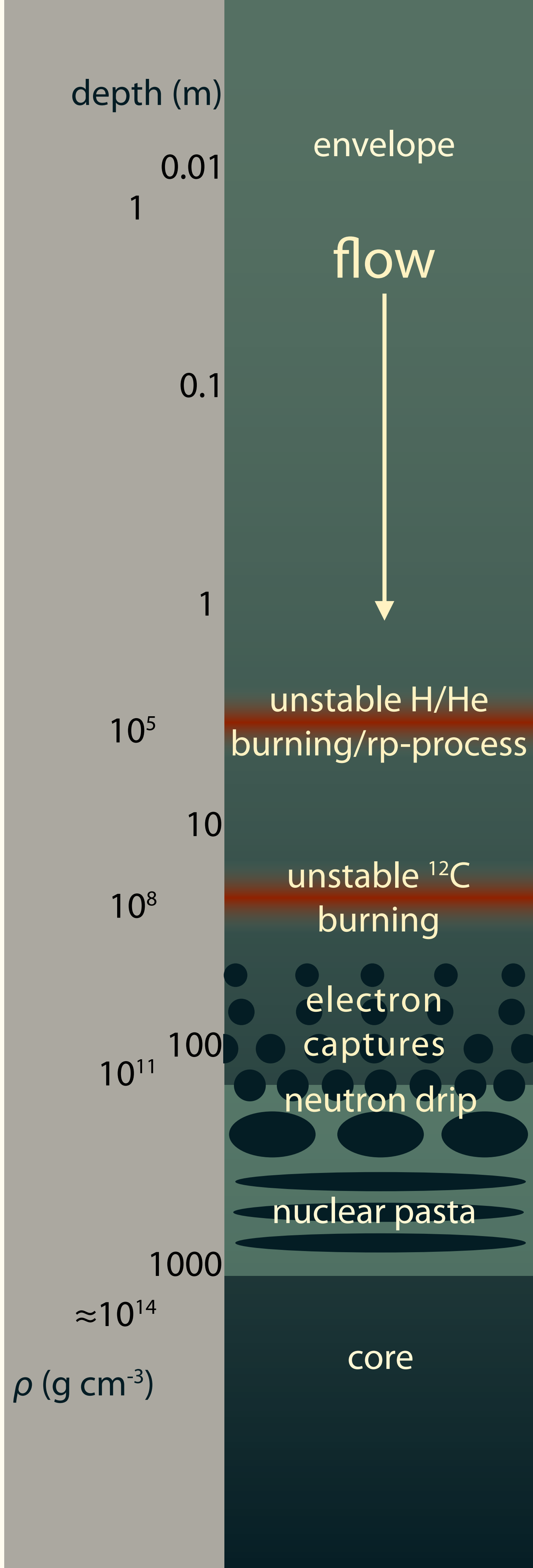
These neutron stars have a km-thick crust composed of nuclei, electrons, and free neutrons.

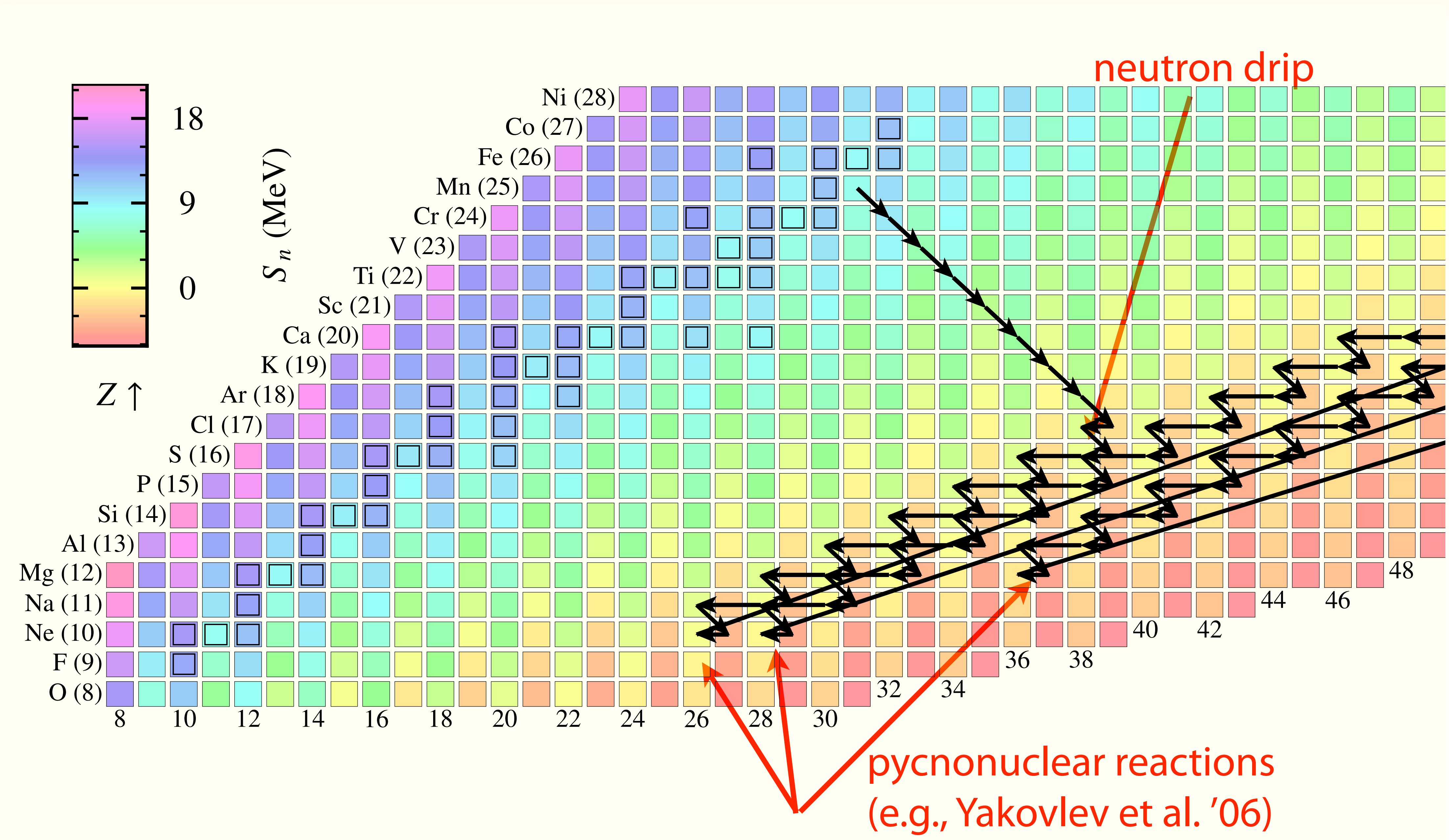
Accretion pushes matter through this crust and induces nuclear reactions.

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



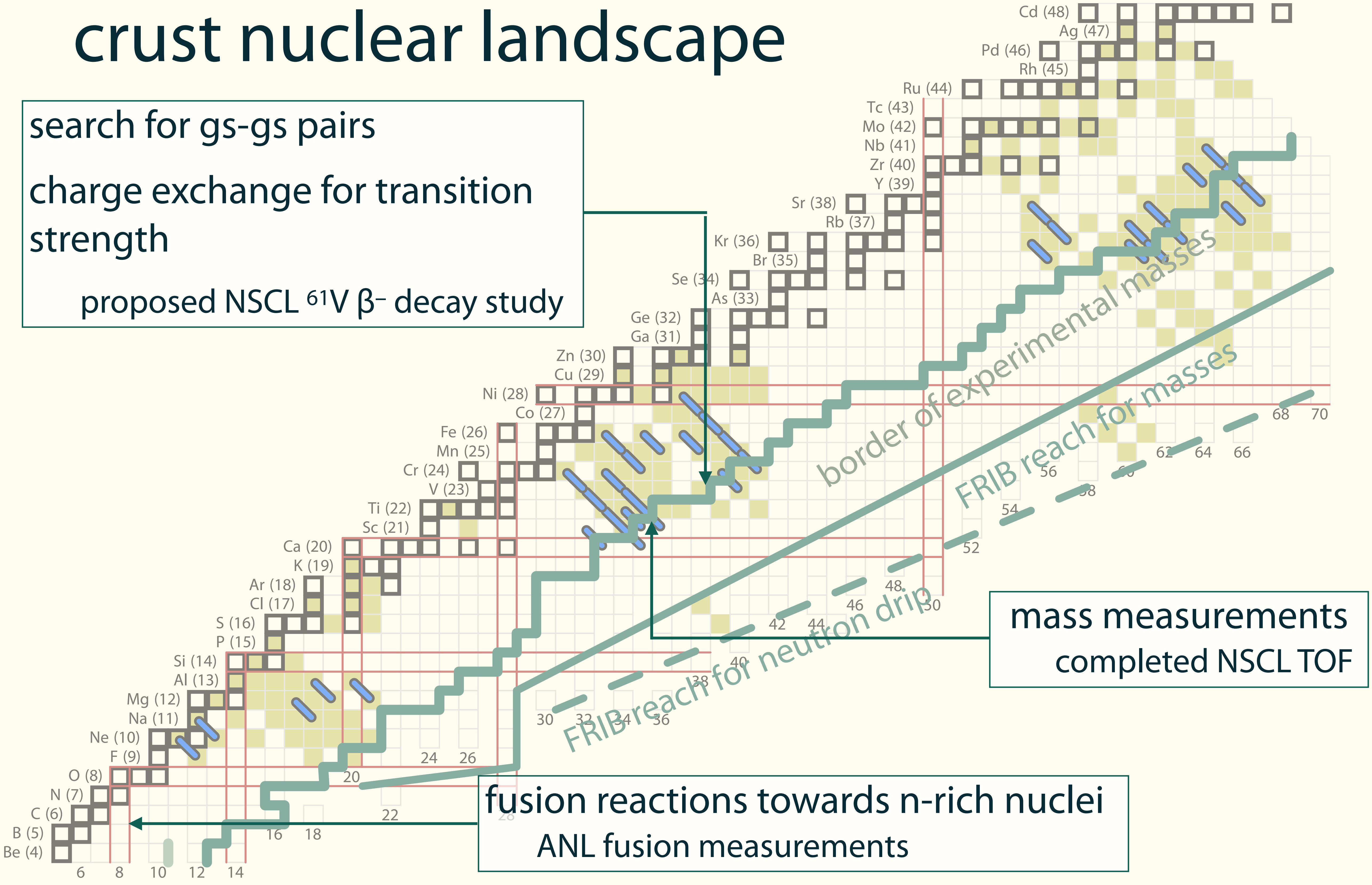
crust reactions release ≈1–2 Mev per accreted nucleon

Sato ’79; Haensel & Zdunk ’90; Gupta et al. ’07; Steiner ’12; Schatz et al. ‘13; Lau et al. ‘18



composition computed with a compressible liquid-drop model (Mackie & Baym ’77), following Haensel & Zdunik ’90

JINA/JINA-CEE experiments across the crust nuclear landscape



search for gs-gs pairs

charge exchange for transition strength

proposed NSCL ^{61}V β^- decay study

mass measurements

completed NSCL TOF

fusion reactions towards n-rich nuclei

ANL fusion measurements

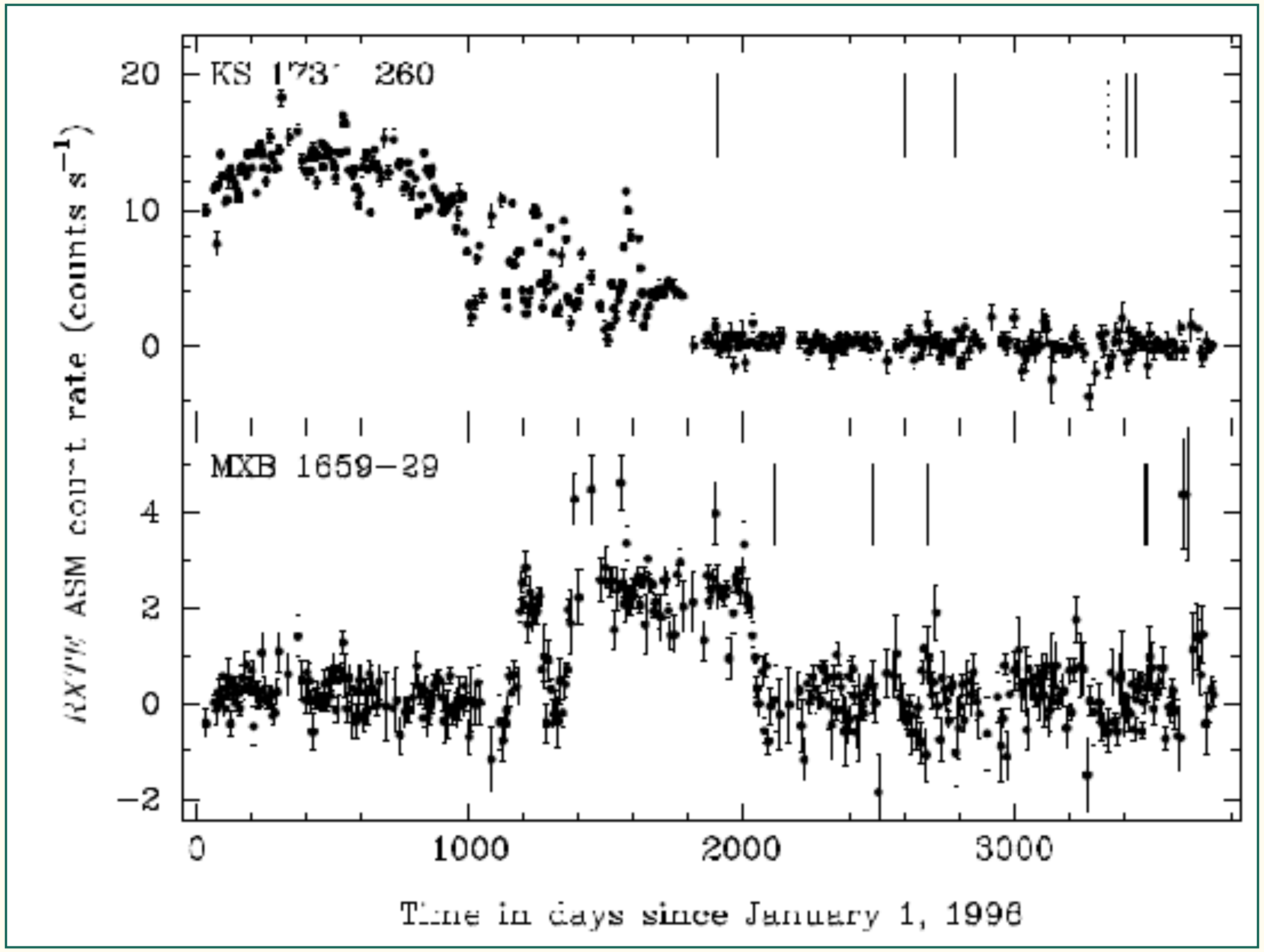
Quasi-persistent transients: long outburst and quiescent durations

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

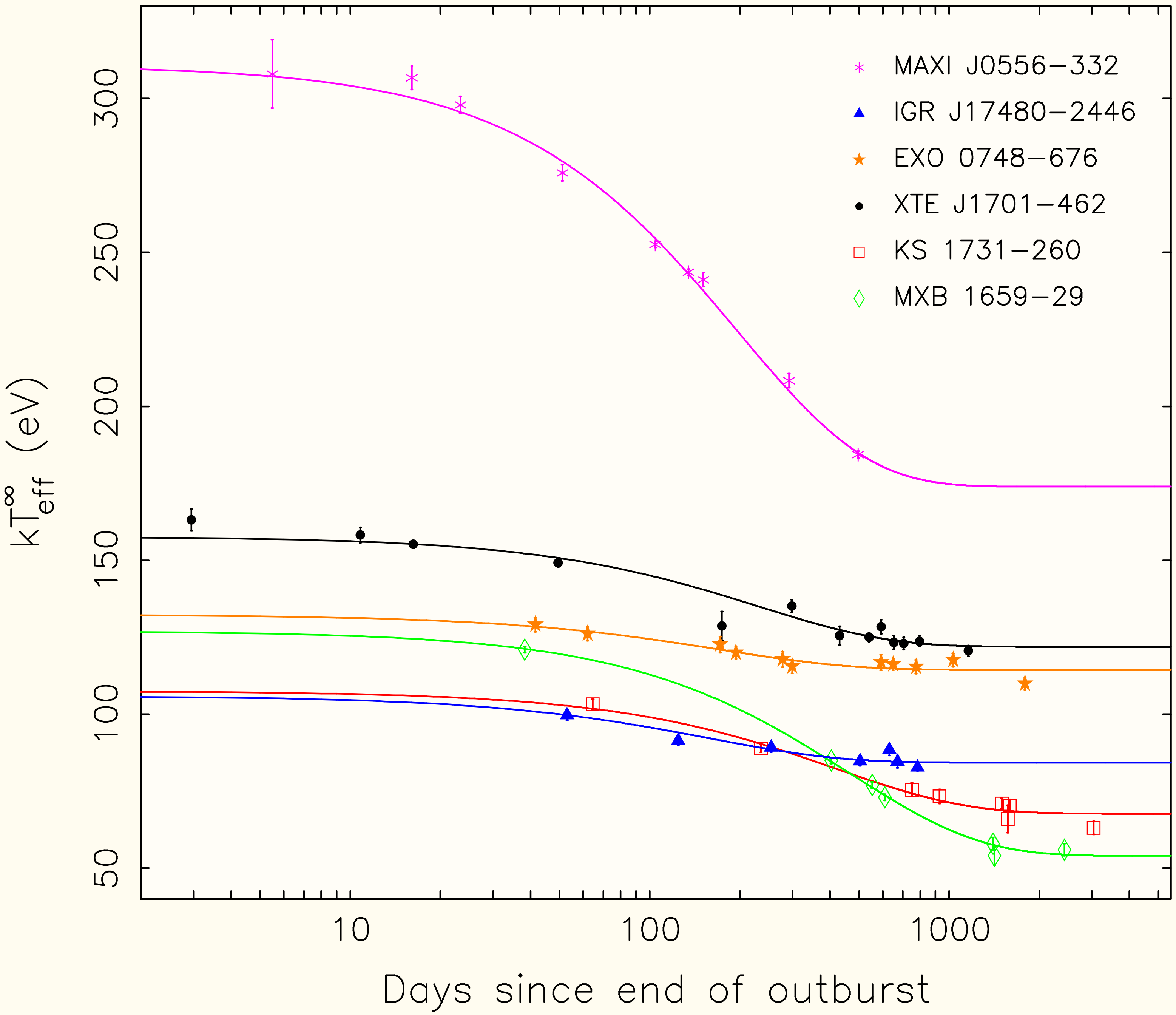
2002: Rutledge et al. suggest looking for crust thermal relaxation

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

fig. from Cackett et al. ‘06



Many quasi-persistent transients are now being monitored



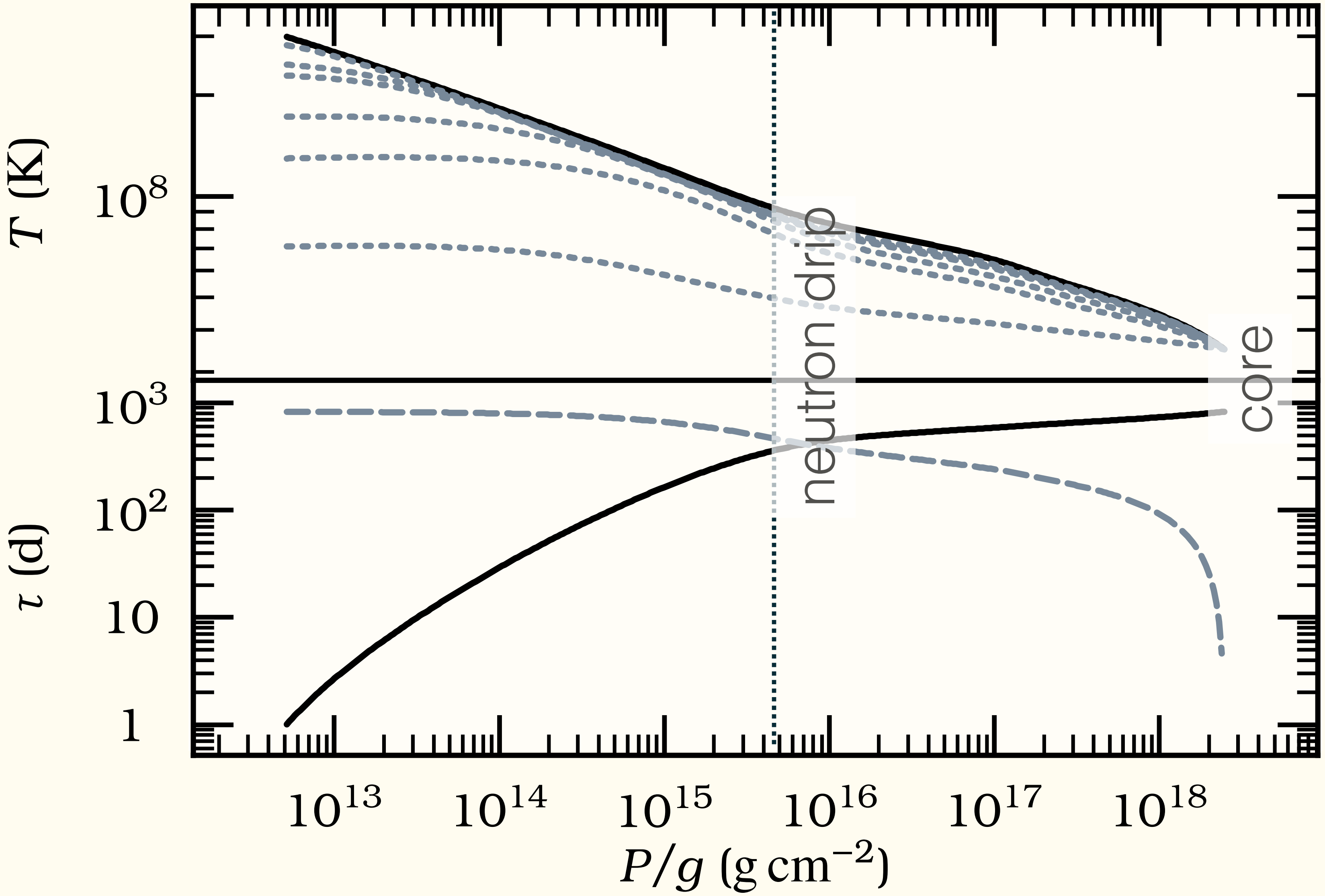
from Homan et al. (2014)

basic physics of the lightcurve

Thermal diffusion

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

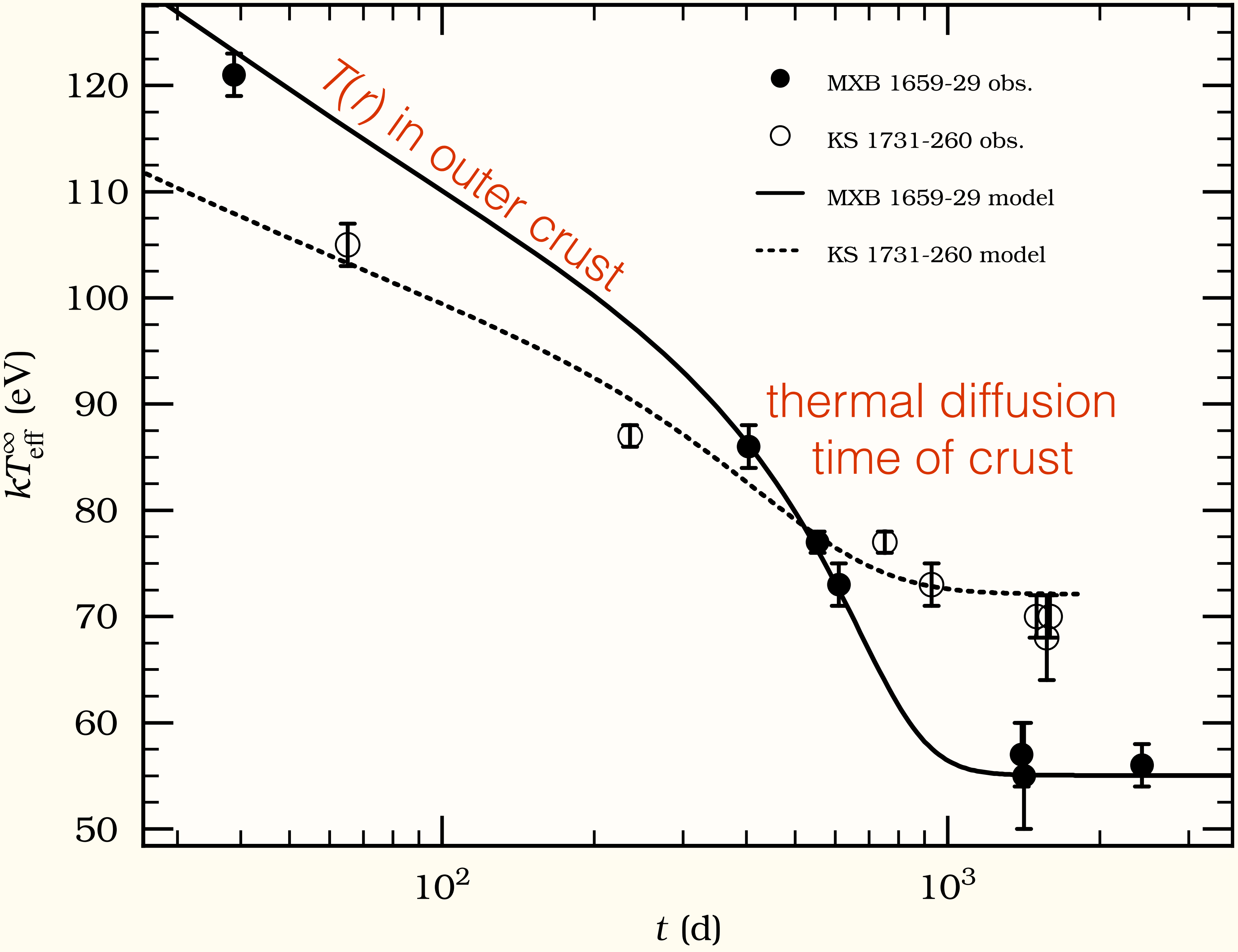
$$\tau = \frac{1}{4}\left[\int \left(\frac{\rho C}{K}\right)^{1/2} \mathrm{d}z\right]^2$$



Inferring crust properties from cooling

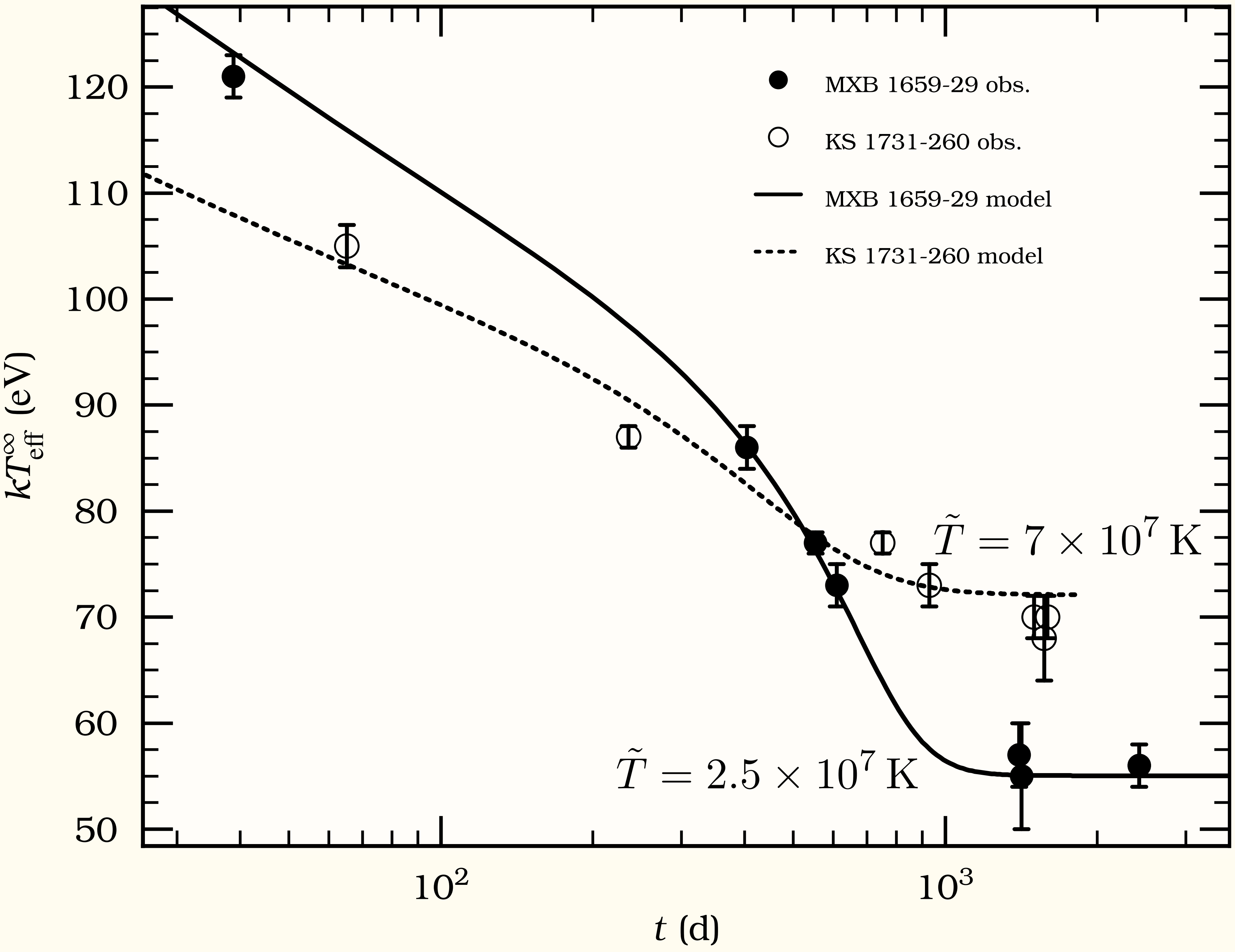
Ushomirsky & Rutledge, Shternin et al., Brown & Cumming, Page & Reddy, Turlione et al., Deibel et al., Merritt et al., Parikh et al.

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

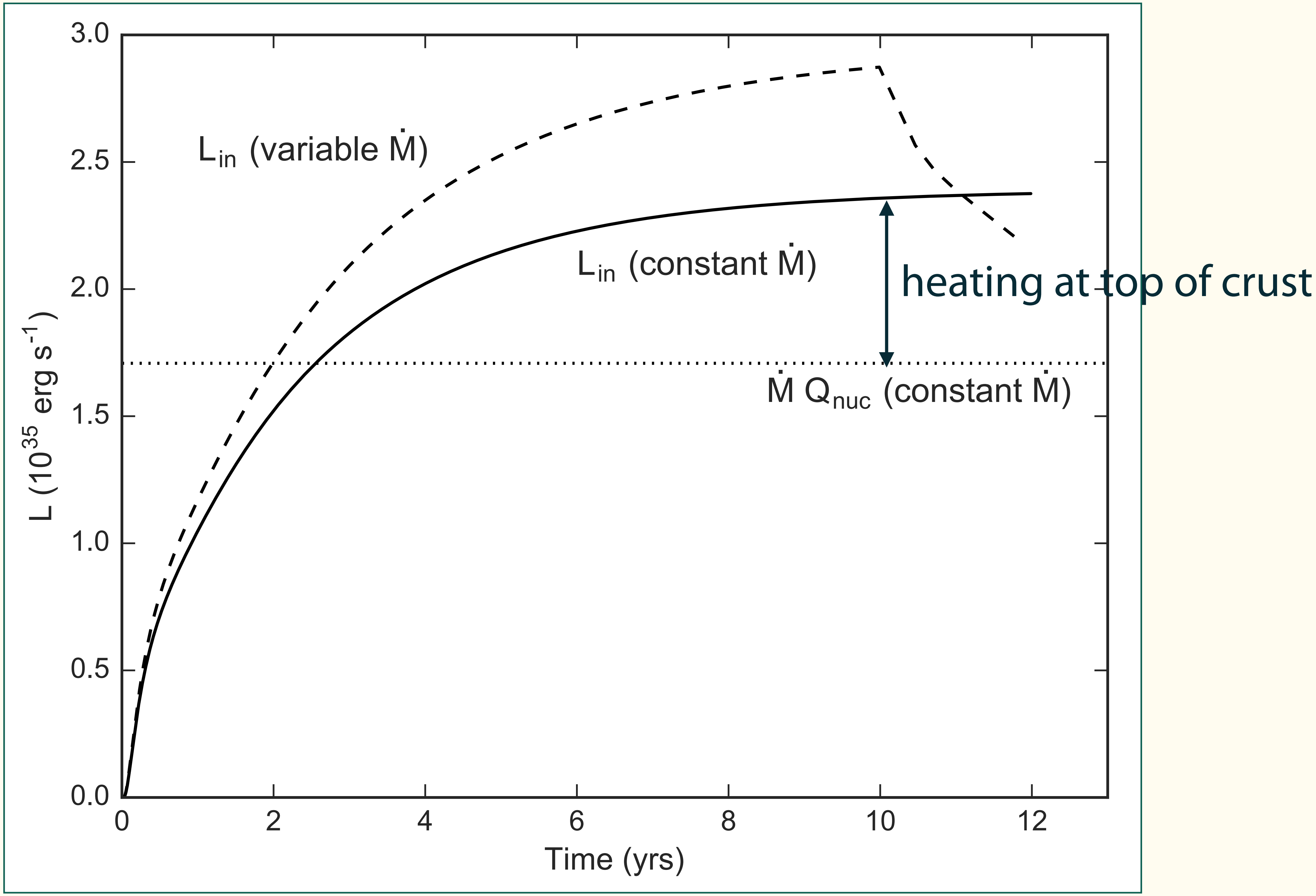


Models also give us the total energy deposited into the core and its temperature: calorimetry!

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



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



Cumming et al. ‘17

Suppose core cools completely between outbursts and neutrino cooling is off

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

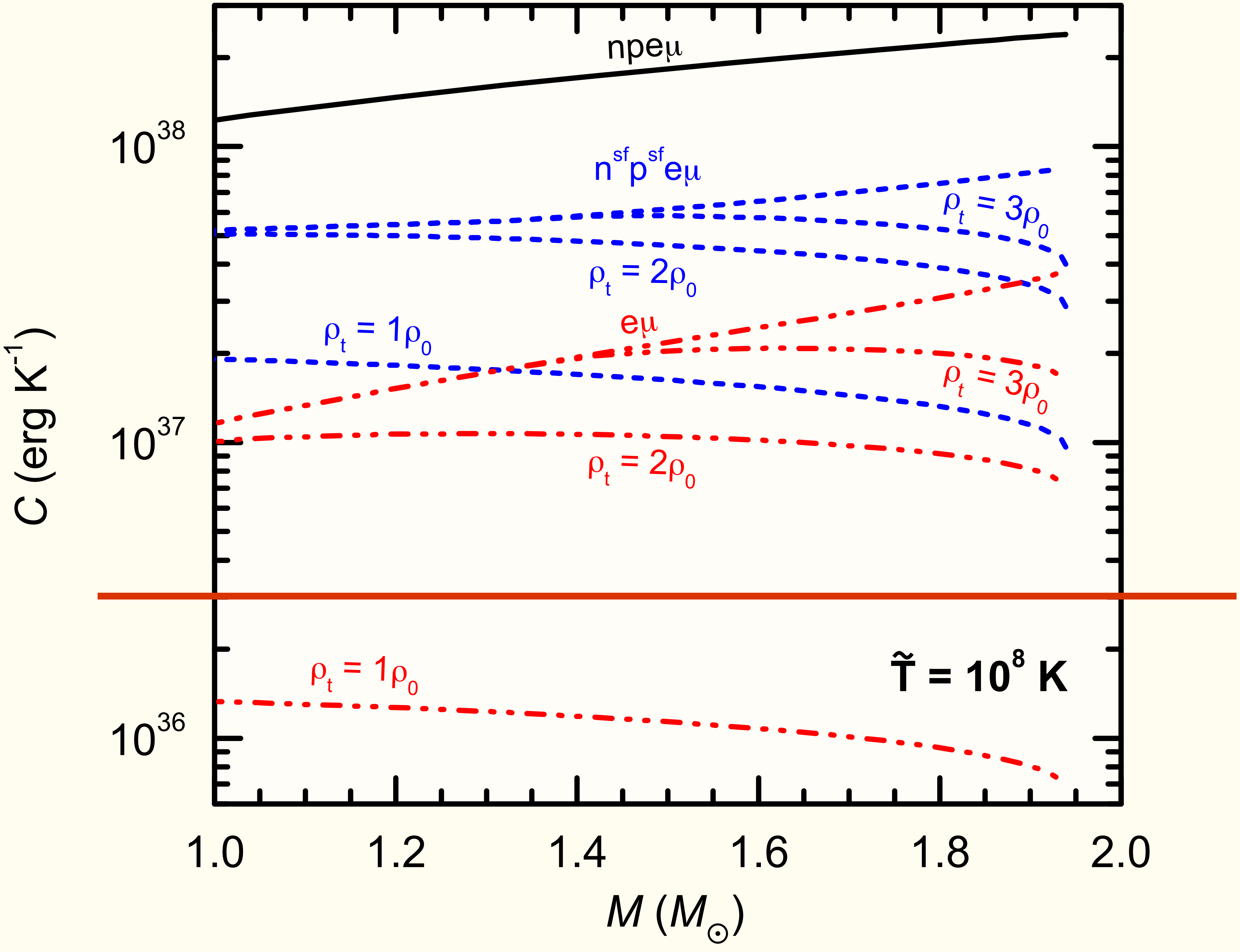
$$C > \frac{2E}{\tilde{T}_f} \quad \text{with} \quad E = \int L_{\mathrm{in}}\, dt$$

since $C \sim T$

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

The specific heat must be larger than this!

This could change T_{core} significantly



At the other limit, suppose the core temperature saturates because of neutrino emission:

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

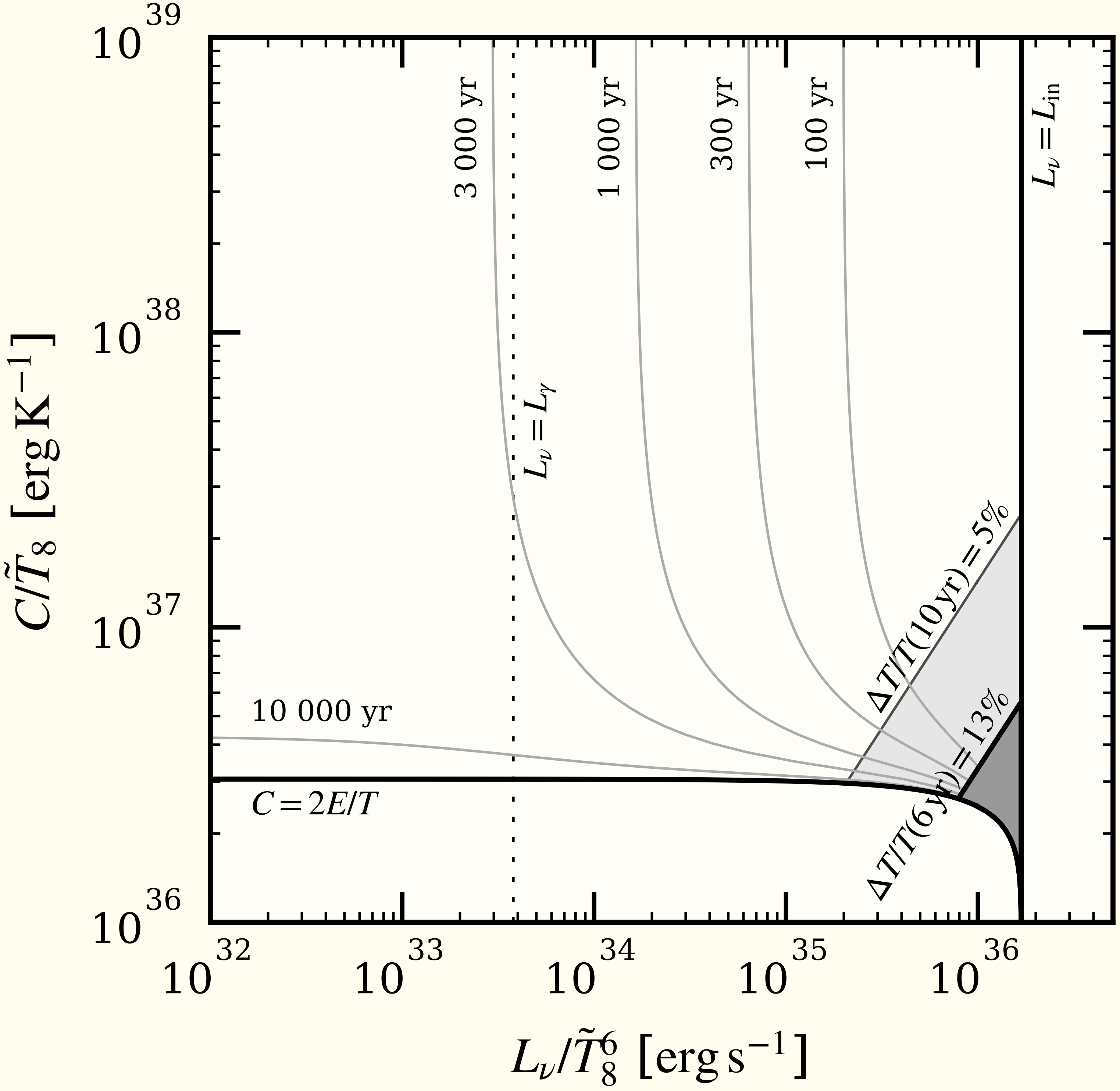
$$\begin{aligned} L_{\nu,\text{dU}} &= 6 \times 10^{38}\, \tilde{T}_8^6\, \text{erg s}^{-1} & \qquad n &\rightarrow pe\nu \\ L_{\nu,\text{mU}} &= 6 \times 10^{30}\, \tilde{T}_8^8\, \text{erg s}^{-1} & \qquad nn &\rightarrow npe\nu \end{aligned}$$

The neutrino luminosity cannot exceed the heating rate, however:

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

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

Phase diagram for KS 1731–260



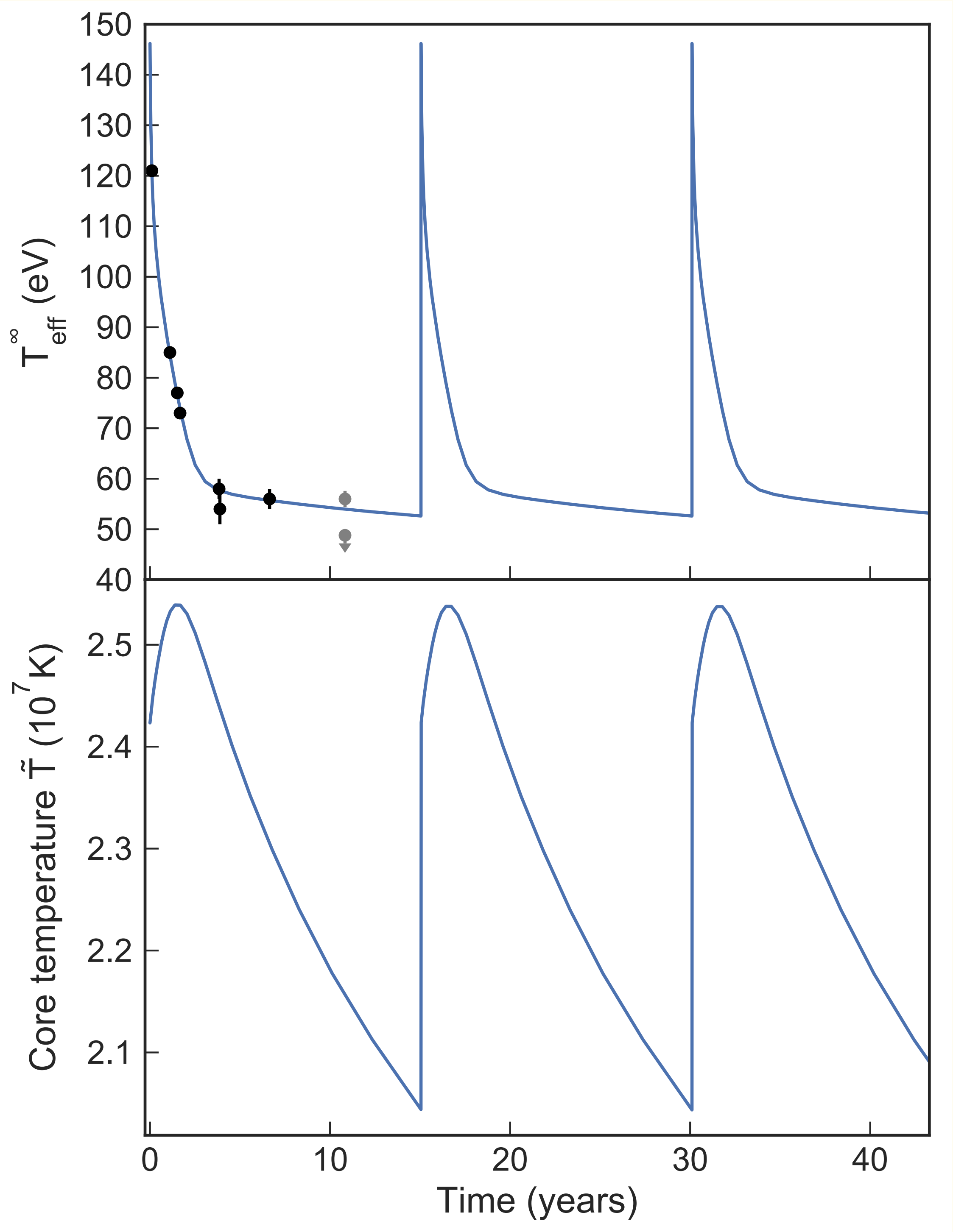
MXB 1659-29: 4 outbursts since 1978 (it finished an outburst mid-2017 and is in quiescence again)

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

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

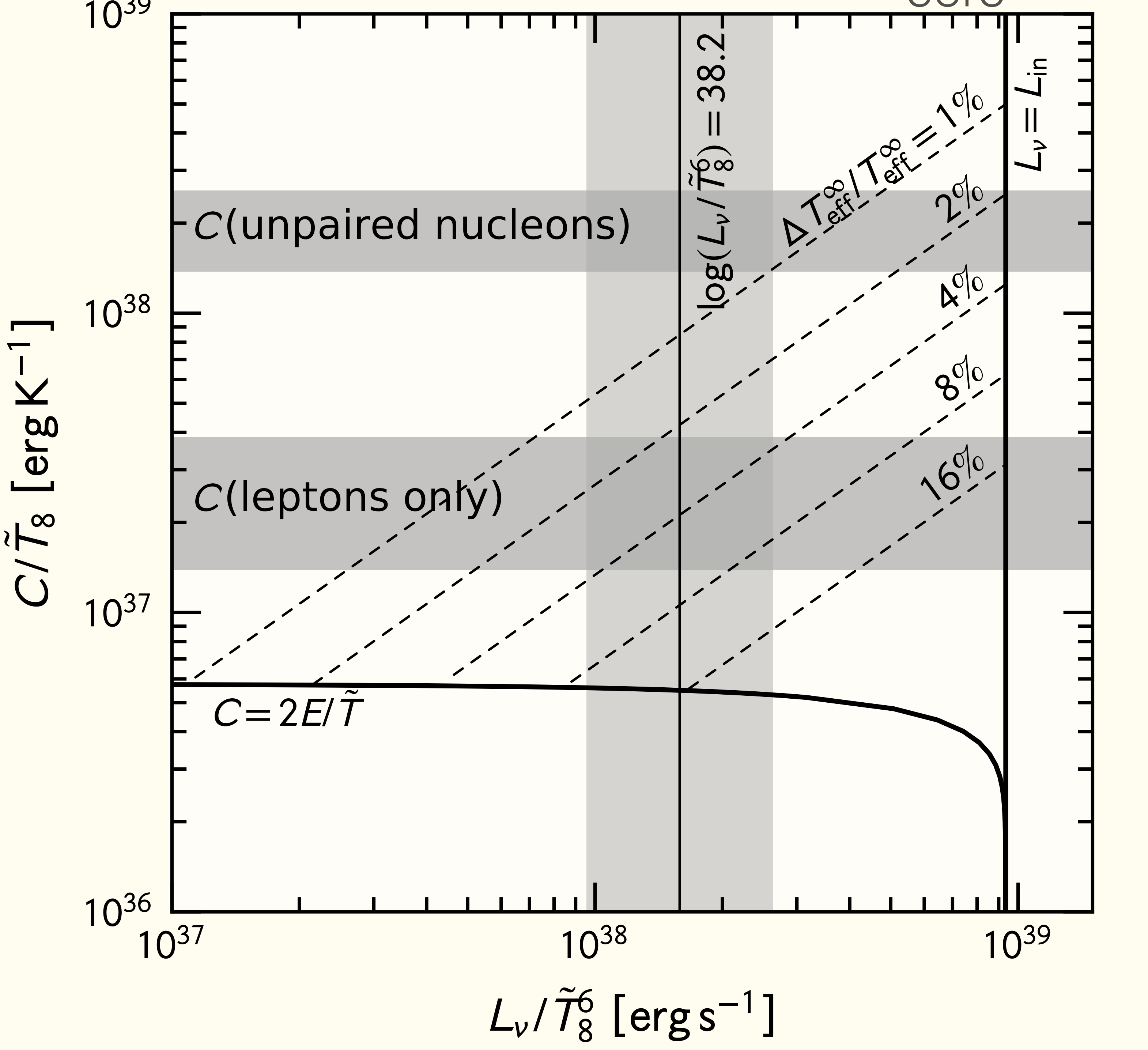
Low core temperature implies strong neutrino cooling,

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



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, or constraints on the recurrence duration, will improve constraints.