Measuring the Specific Heat of a Neutron Star

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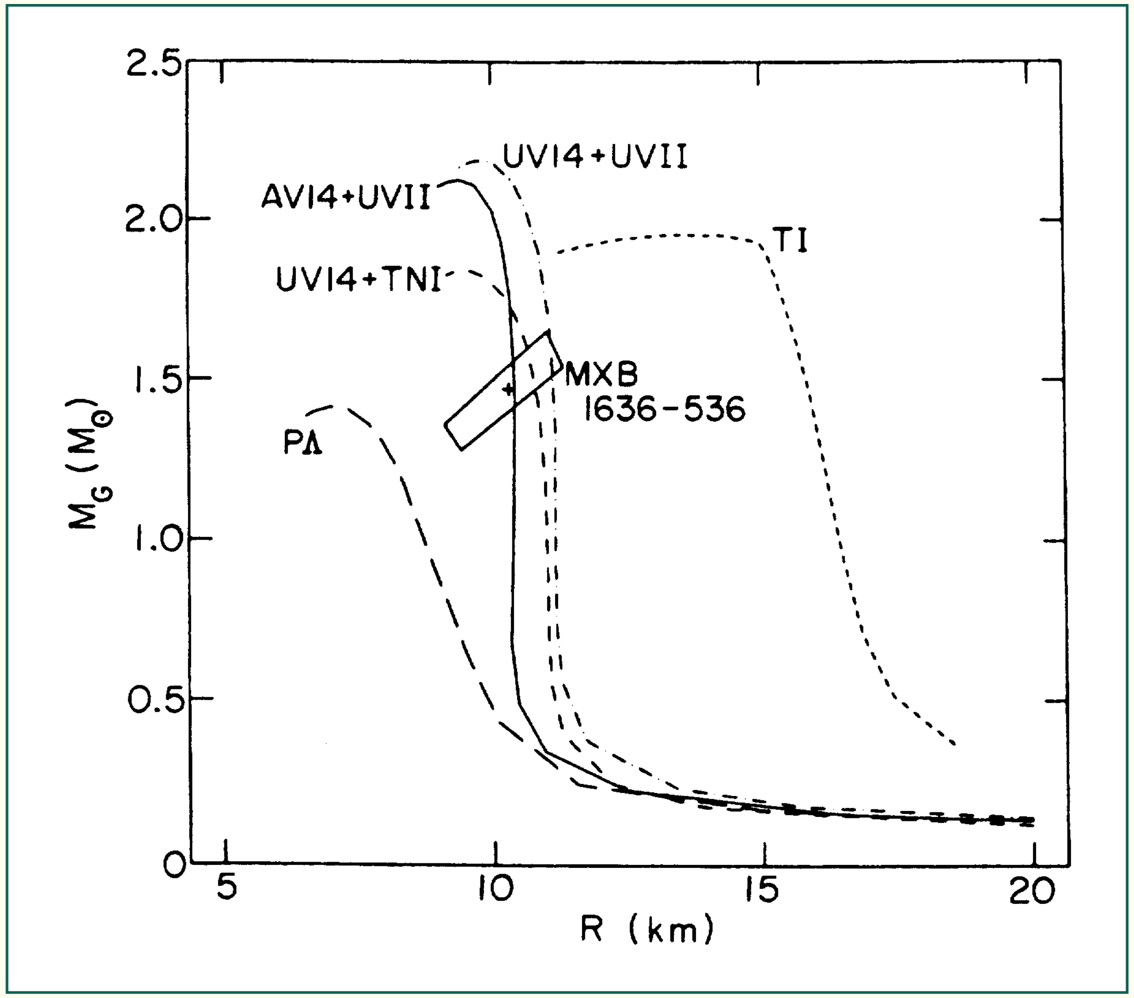
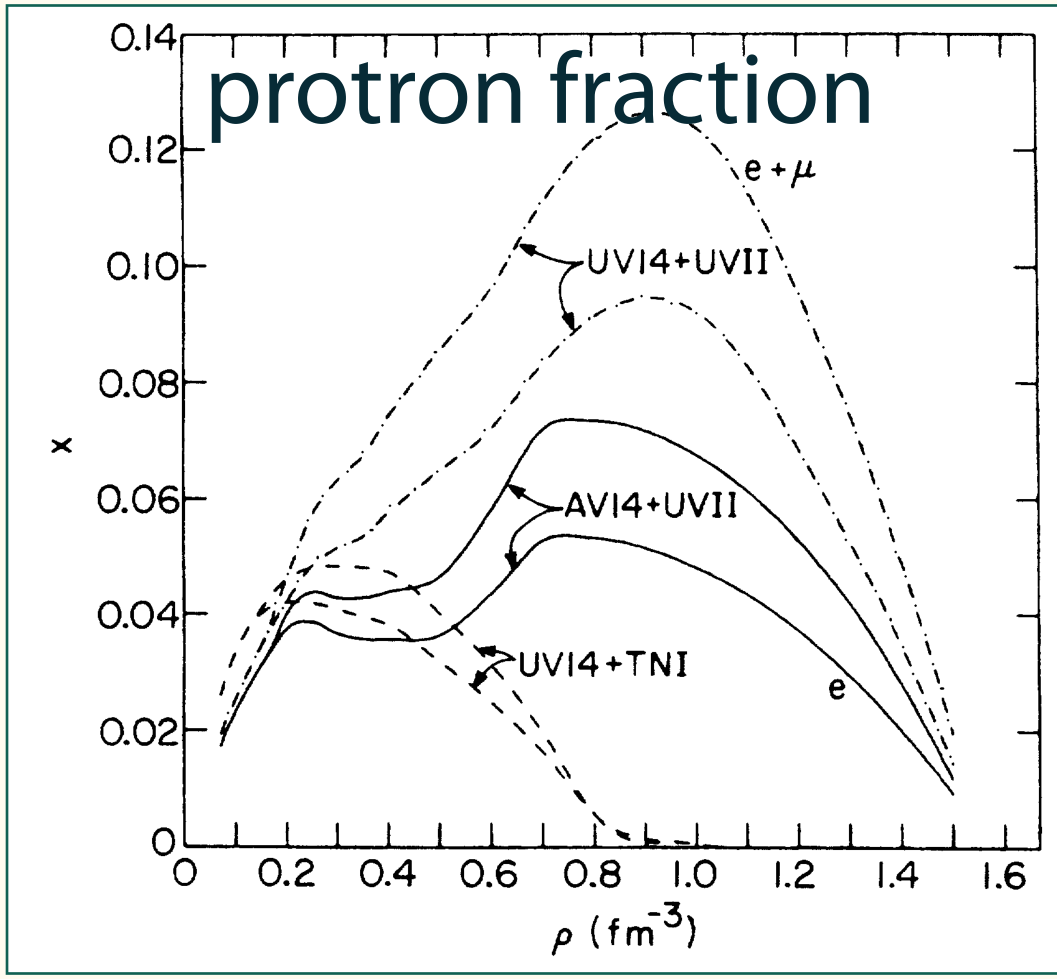
Cumming, Brown, Fattoyev, Horowitz, Page & Reddy 2017, in press. 1608.07532
Deibel, Cumming, Brown & Reddy 2017, submitted. 1609.07155

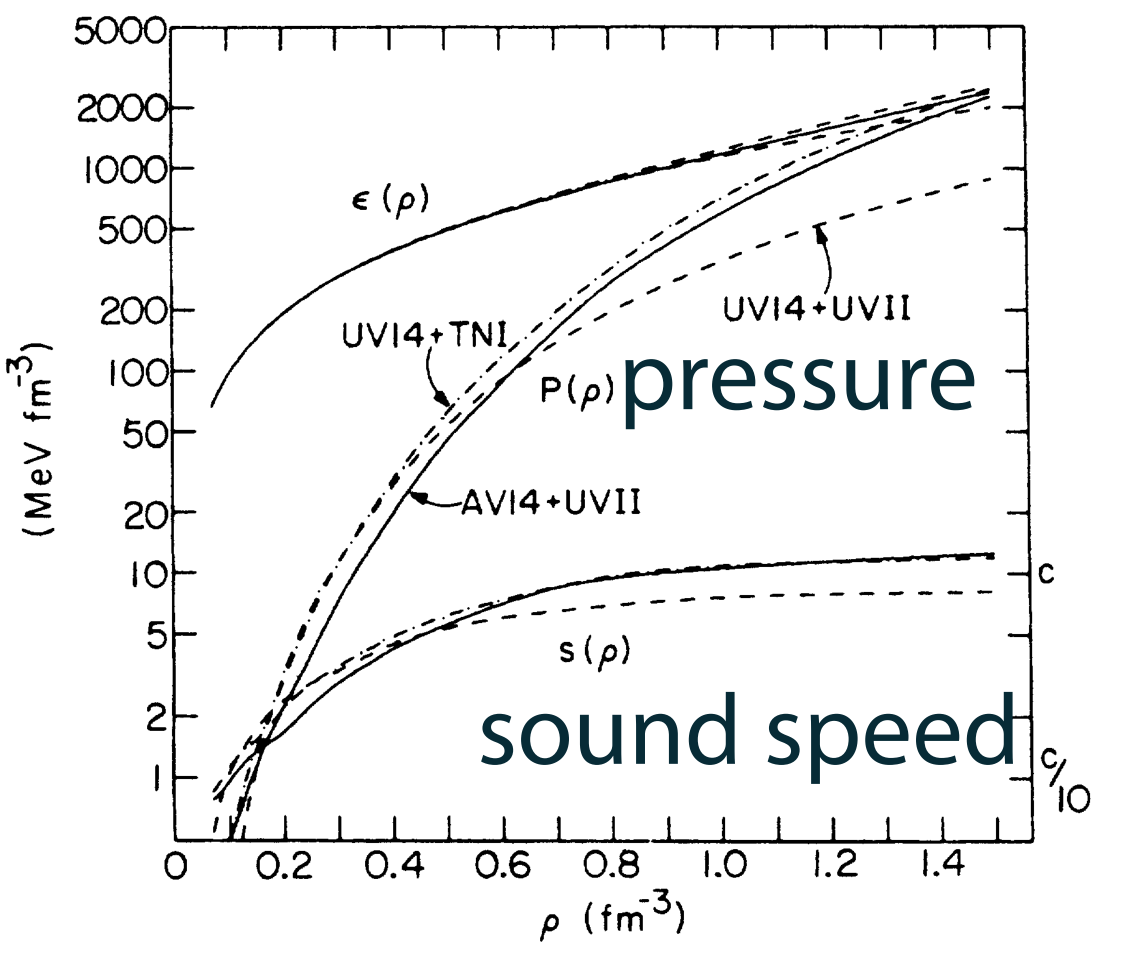
Three decades since supernova 1987a: detected with γ and ν



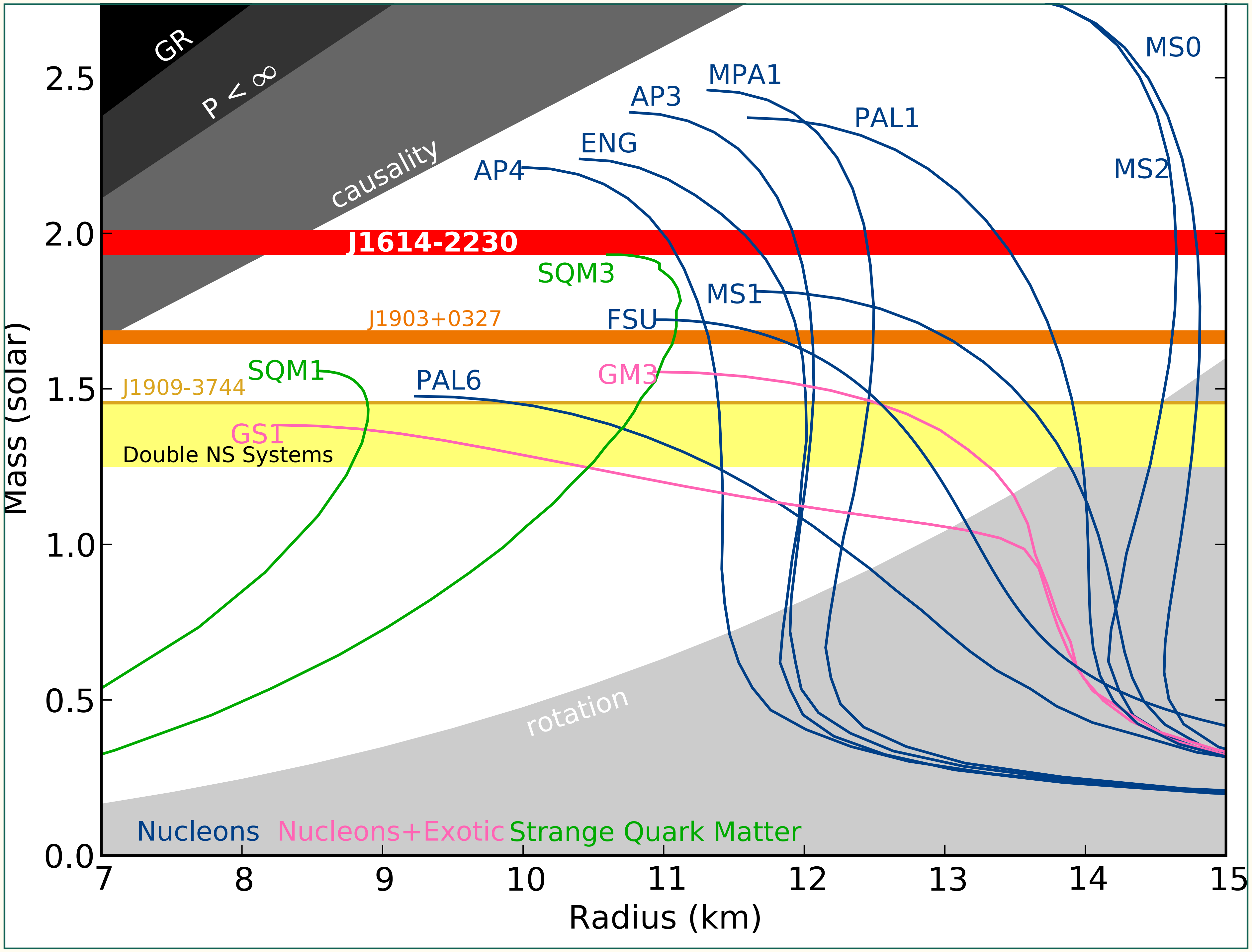
The structure of neutron stars depends on the EOS.

Example here from Wiringa, Fiks, & Fabrocini (1988)



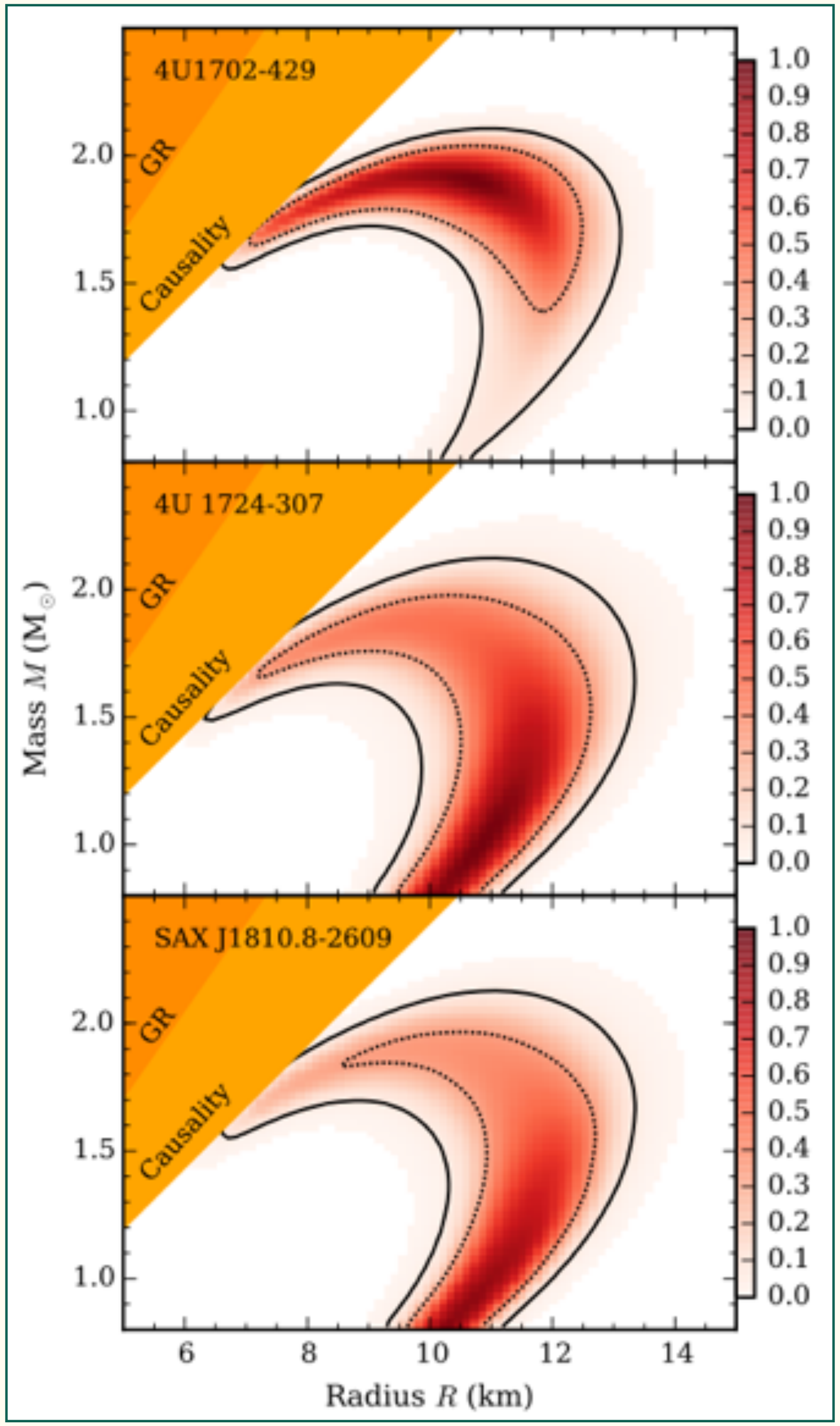


Neutron stars allow us to observe dense matter in the wild | masses

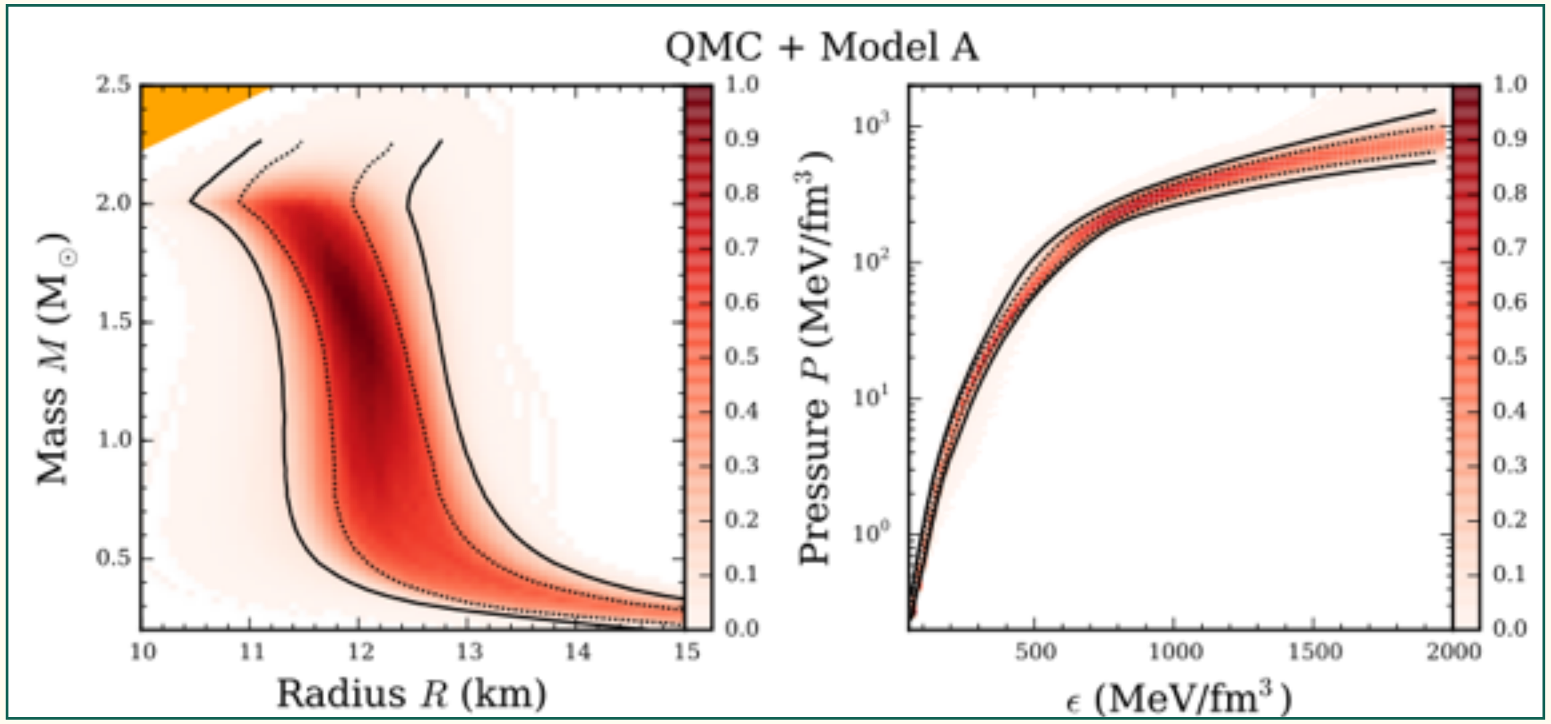


Demorest et al. ‘10

Neutron stars allow us to observe dense matter in the wild | radii



Nättilä et al. '16



Mass and radius constraints from spectroscopy of surface explosions: Özel, Suleimanov, Güver, Guillot, Steiner, Rutledge, …

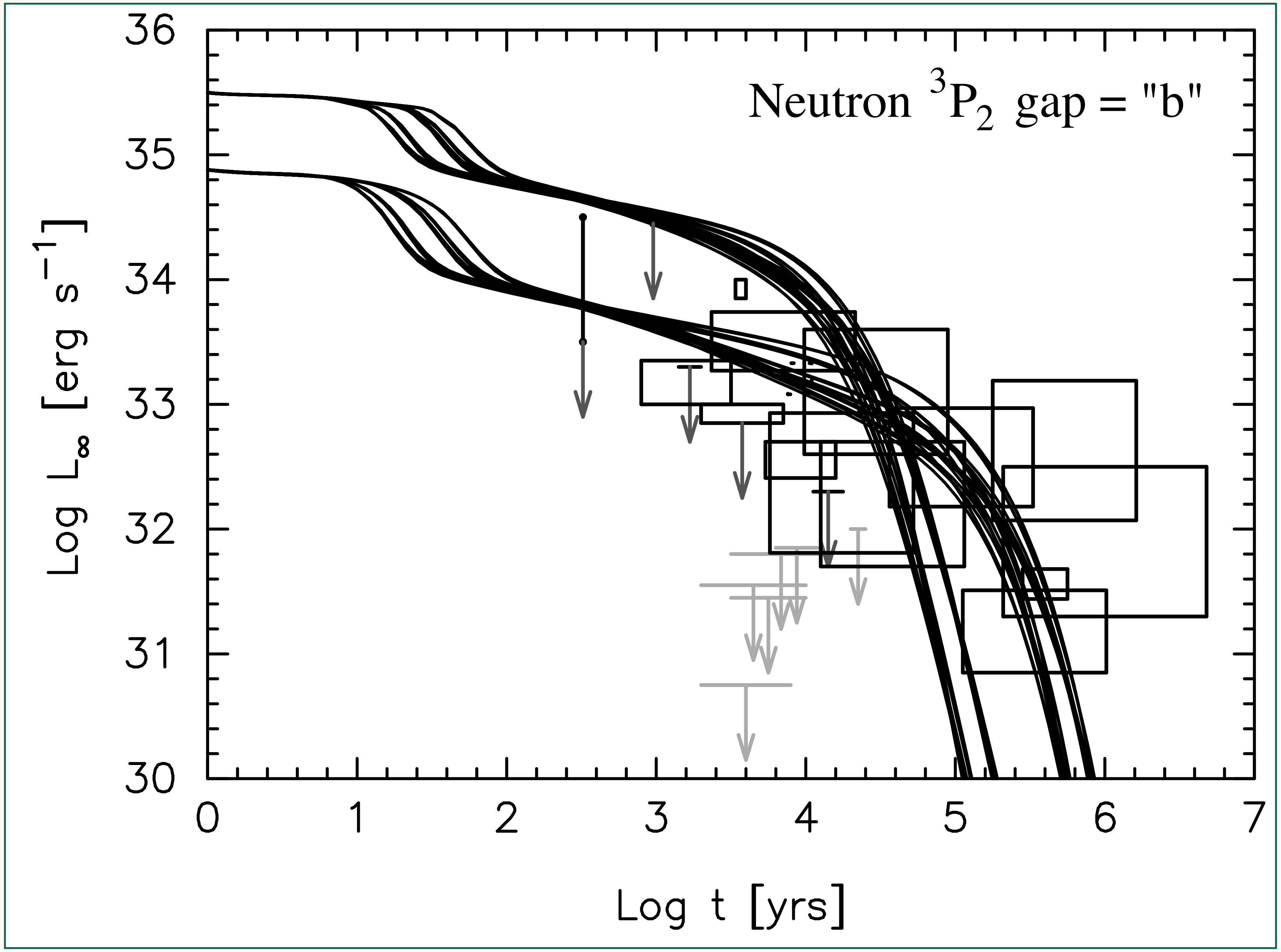
More observations coming (NICER, LIGO)

We have less direct information about transport in dense matter: namely,

- Specific heat
- Thermal conductivity
- Neutrino emissivity

Cooling isolated neutron stars

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



Page, Lattimer, Prakash, & Steiner 2009

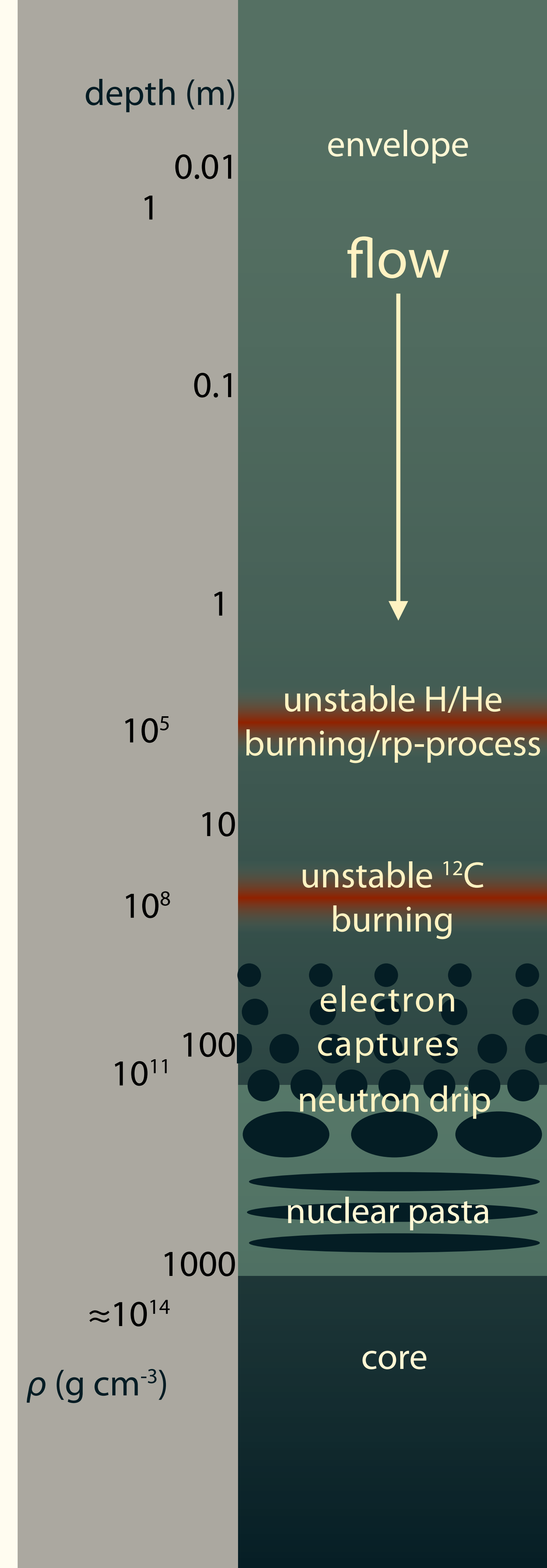
Many neutron stars accrete from a companion star

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.

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.

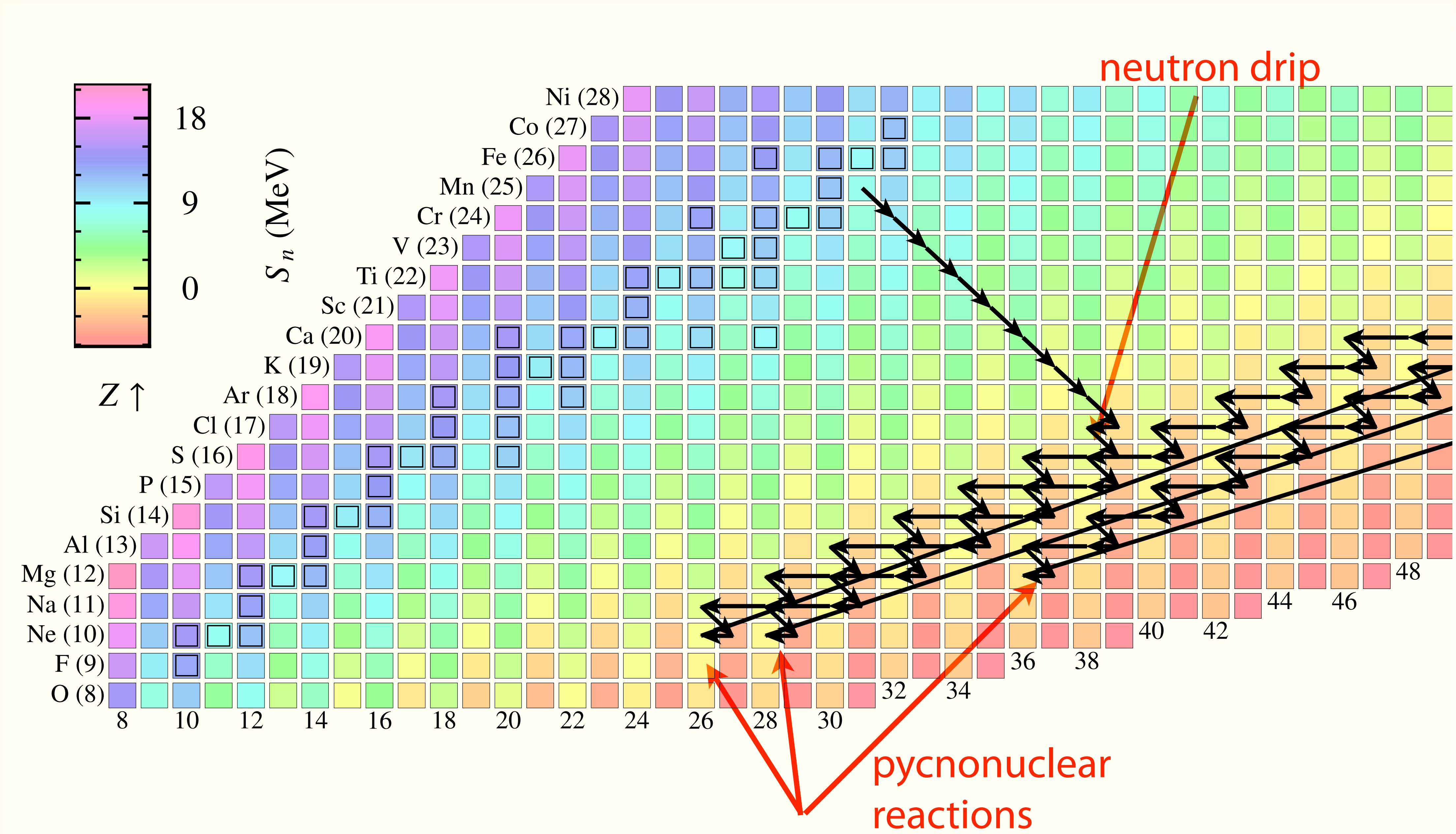
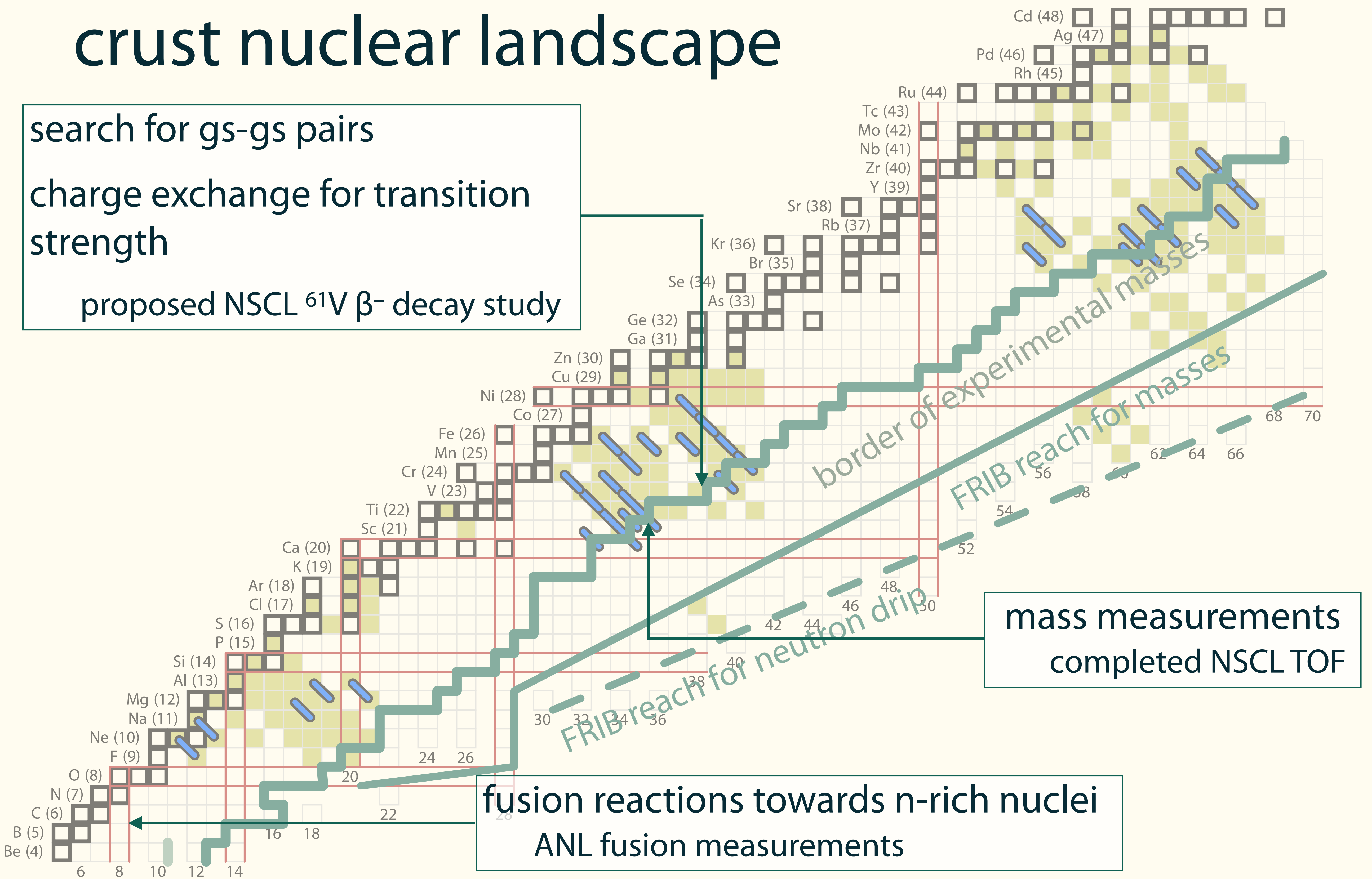


illustration with a simple liquid-drop model (Mackie & Baym ’77, following Haensel & Zdunik ’90)

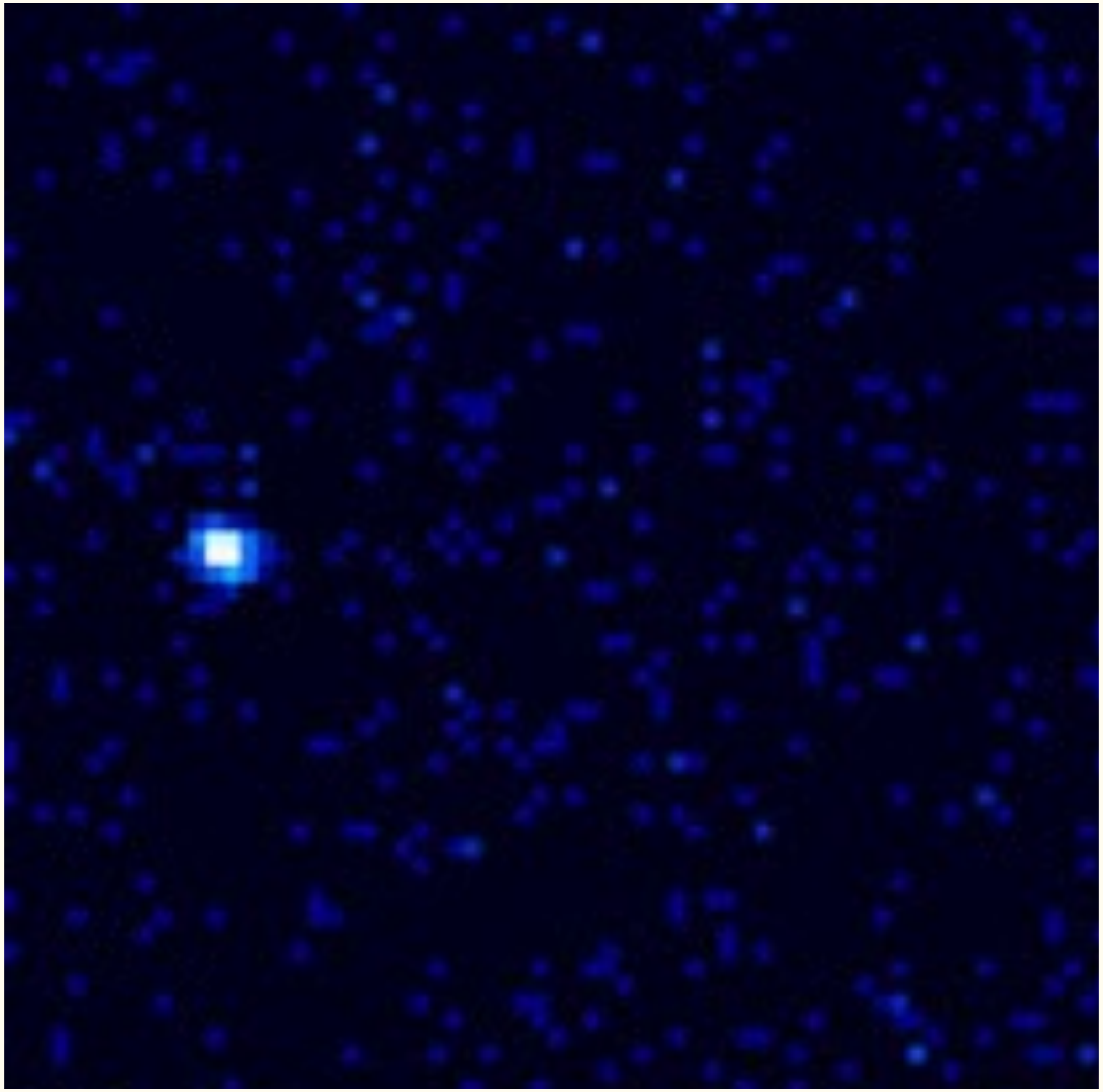
Crust reactions can be studied at the **F**acility for **R**are **I**sotope **B**eams at Michigan State University

JINA/JINA-CEE experiments across the crust nuclear landscape



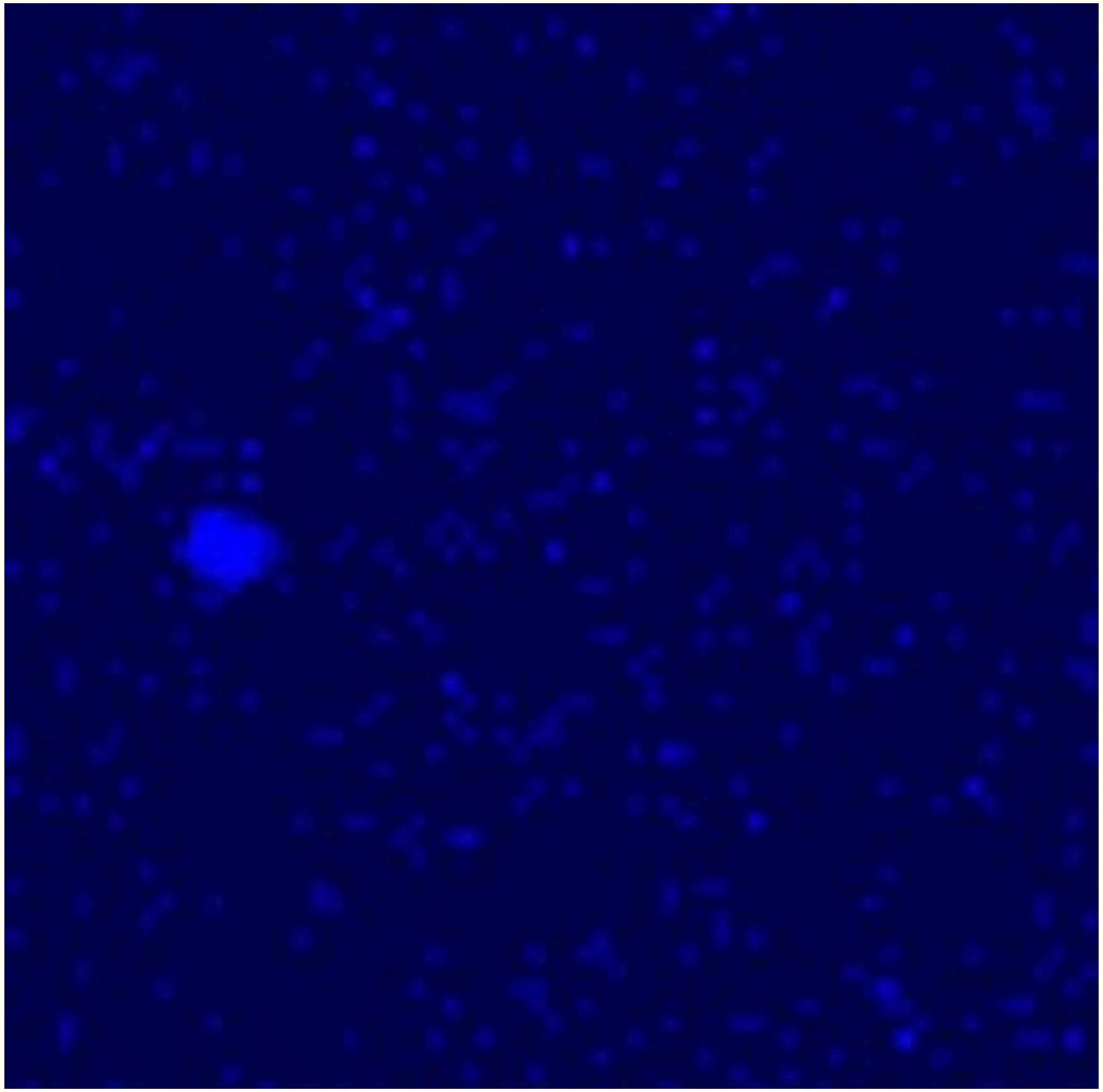
Many accreting neutron stars are transients: for example, KS1731-260

Image credit: NASA/Chandra/Wijnands et al.



Many accreting neutron stars are transients: for example, KS1731-260

Image credit: NASA/Chandra/Wijnands et al.



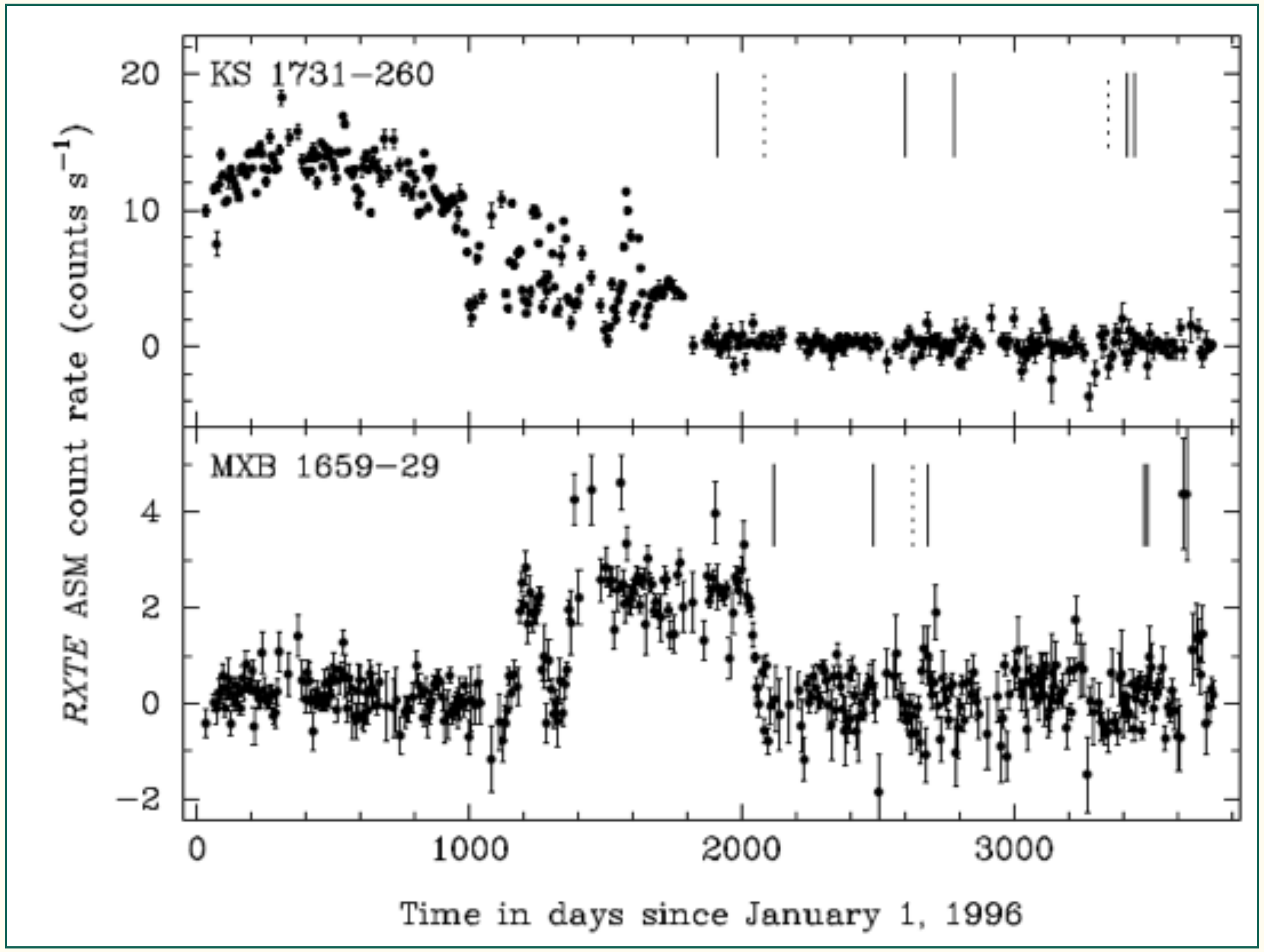
Many accreting neutron stars are transients

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)

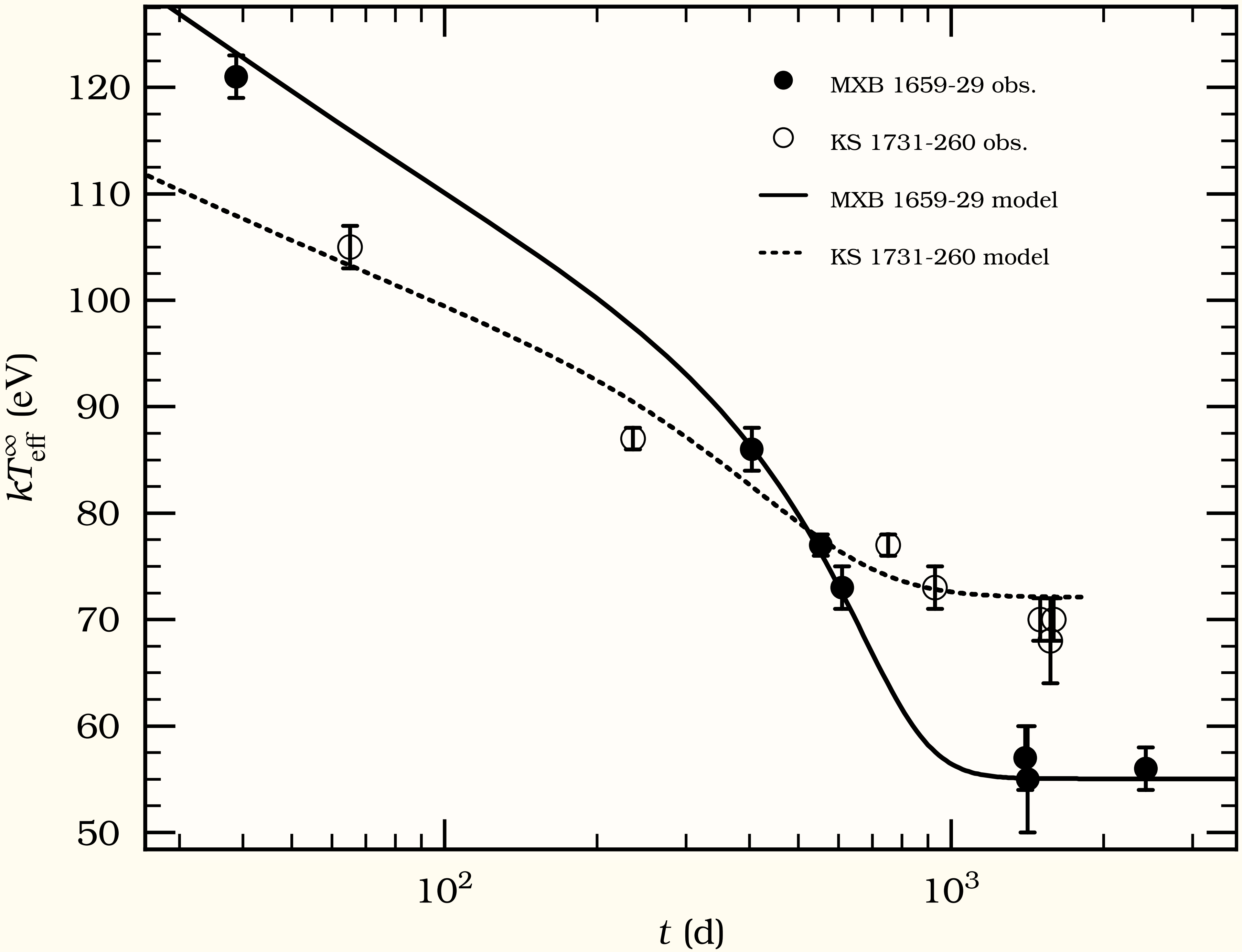
fig. from Cackett et al. '06



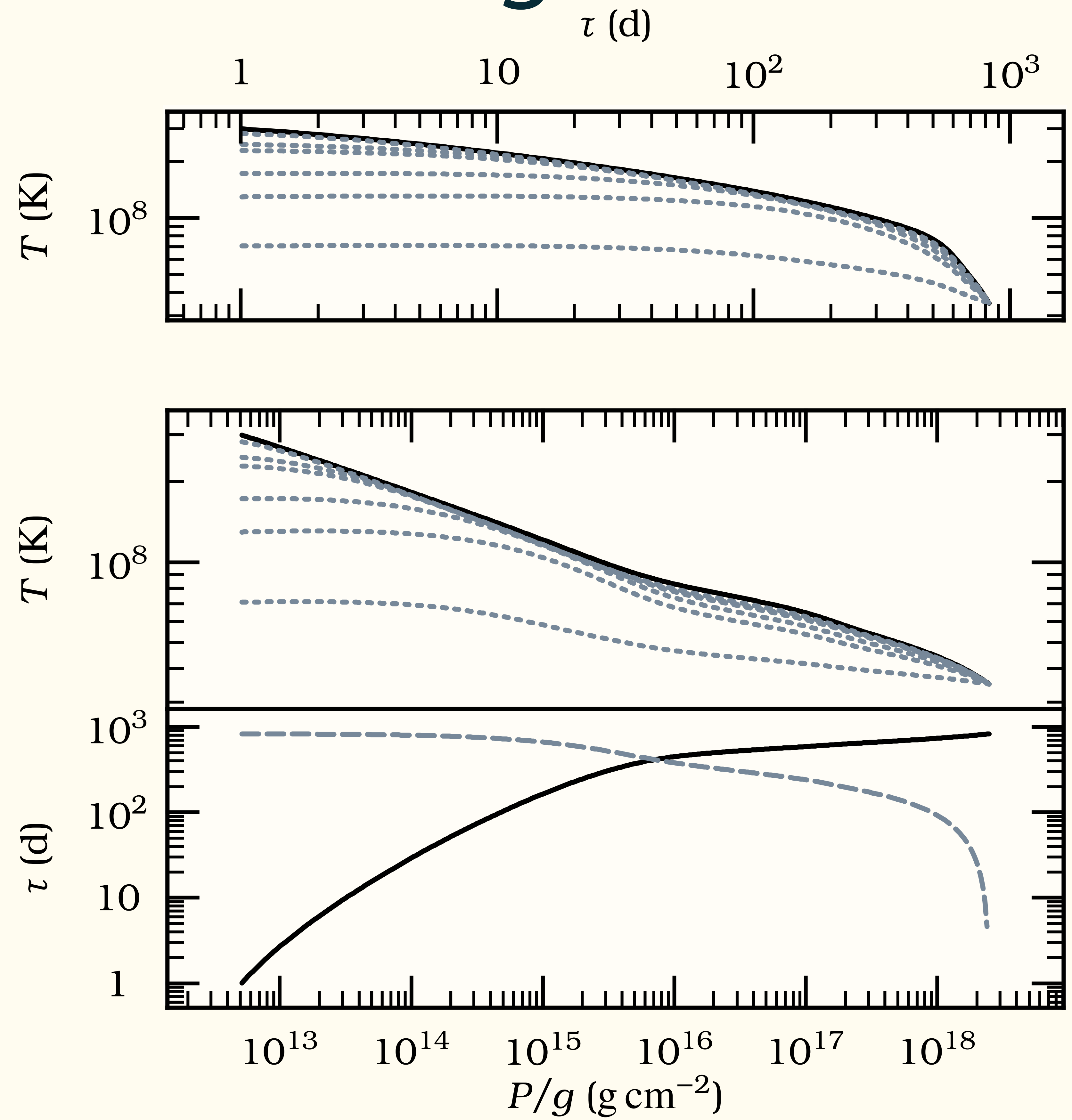
Inferring crust properties from cooling

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

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



basic physics of the lightcurve



Thermal diffusion

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

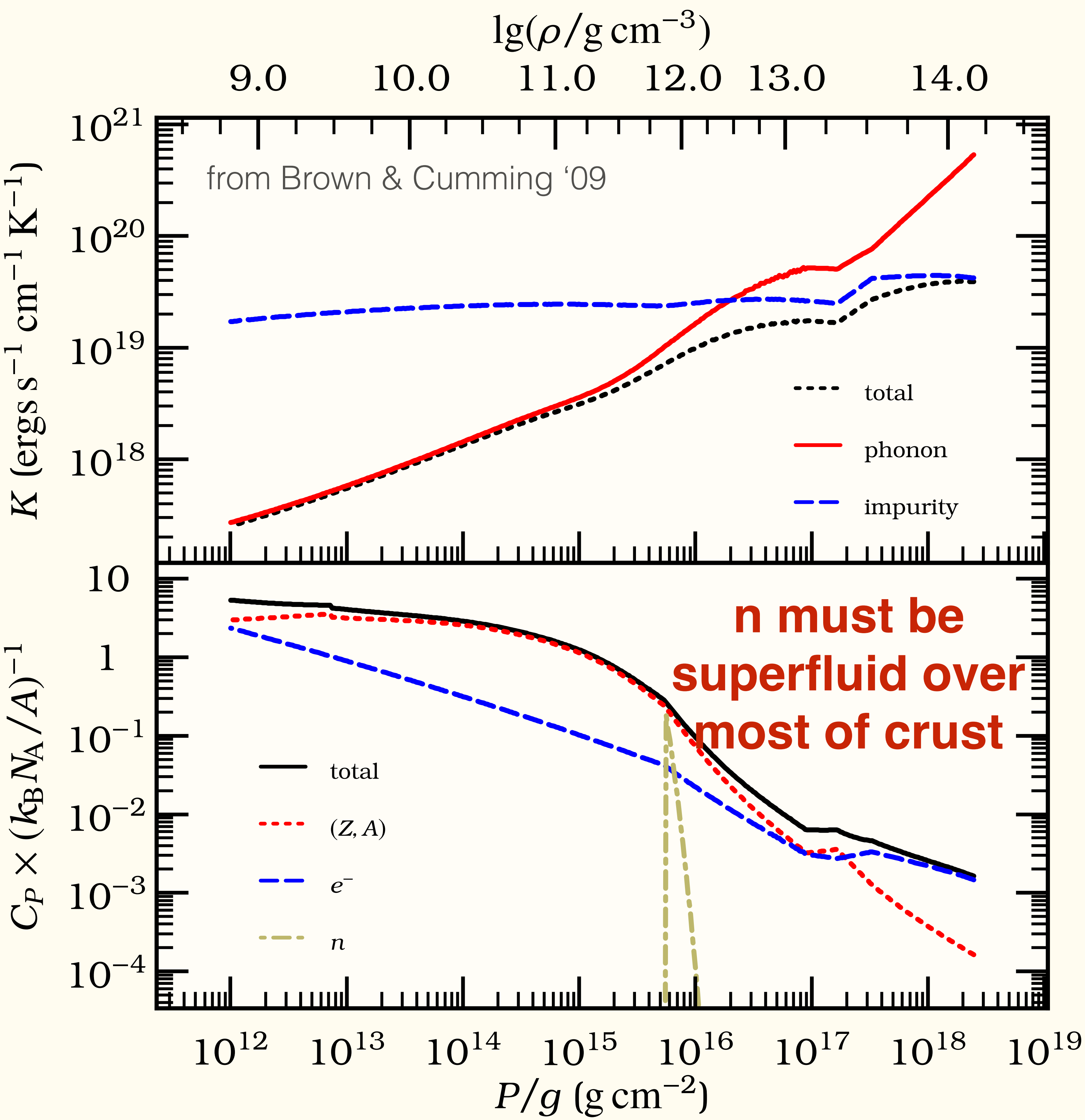
$$\tau = \frac{1}{4}\left[\int \left(\frac{\rho C}{K}\right)^{1/2} dz\right]^2$$

The cooling timescale

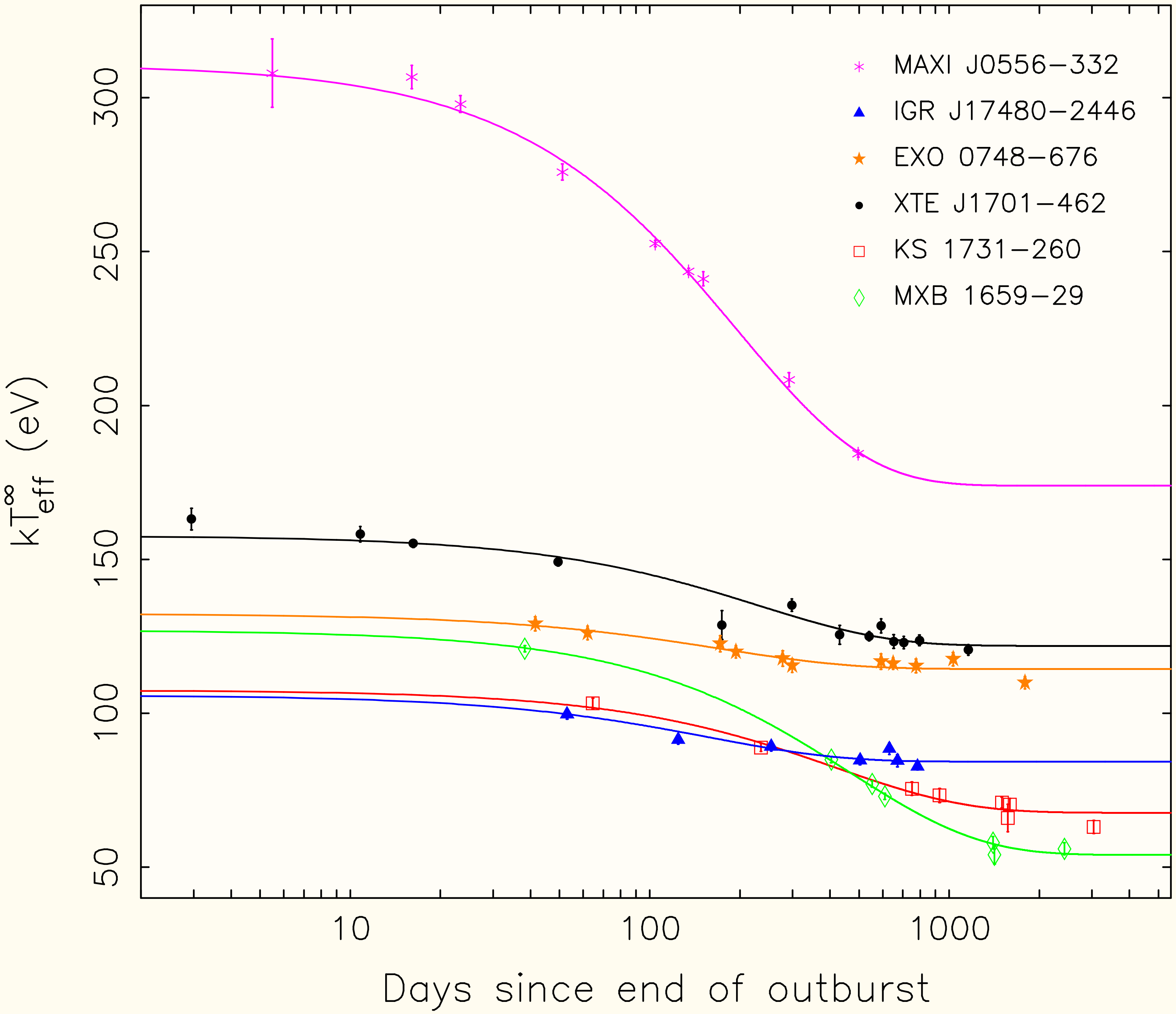
Thermal diffusion

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

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

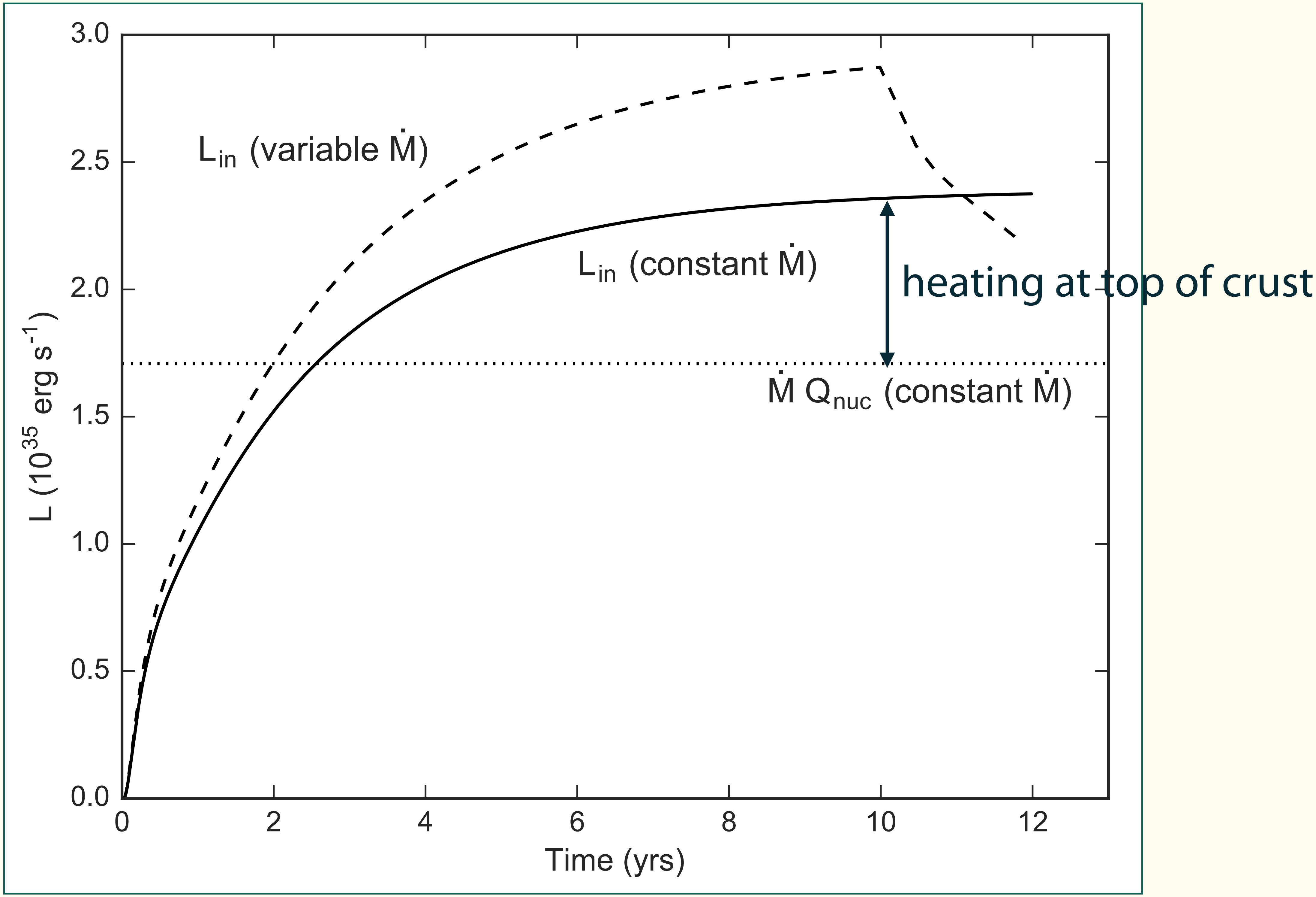


Many quasi-persistent transients are now monitored



from Homan et al. (2014)

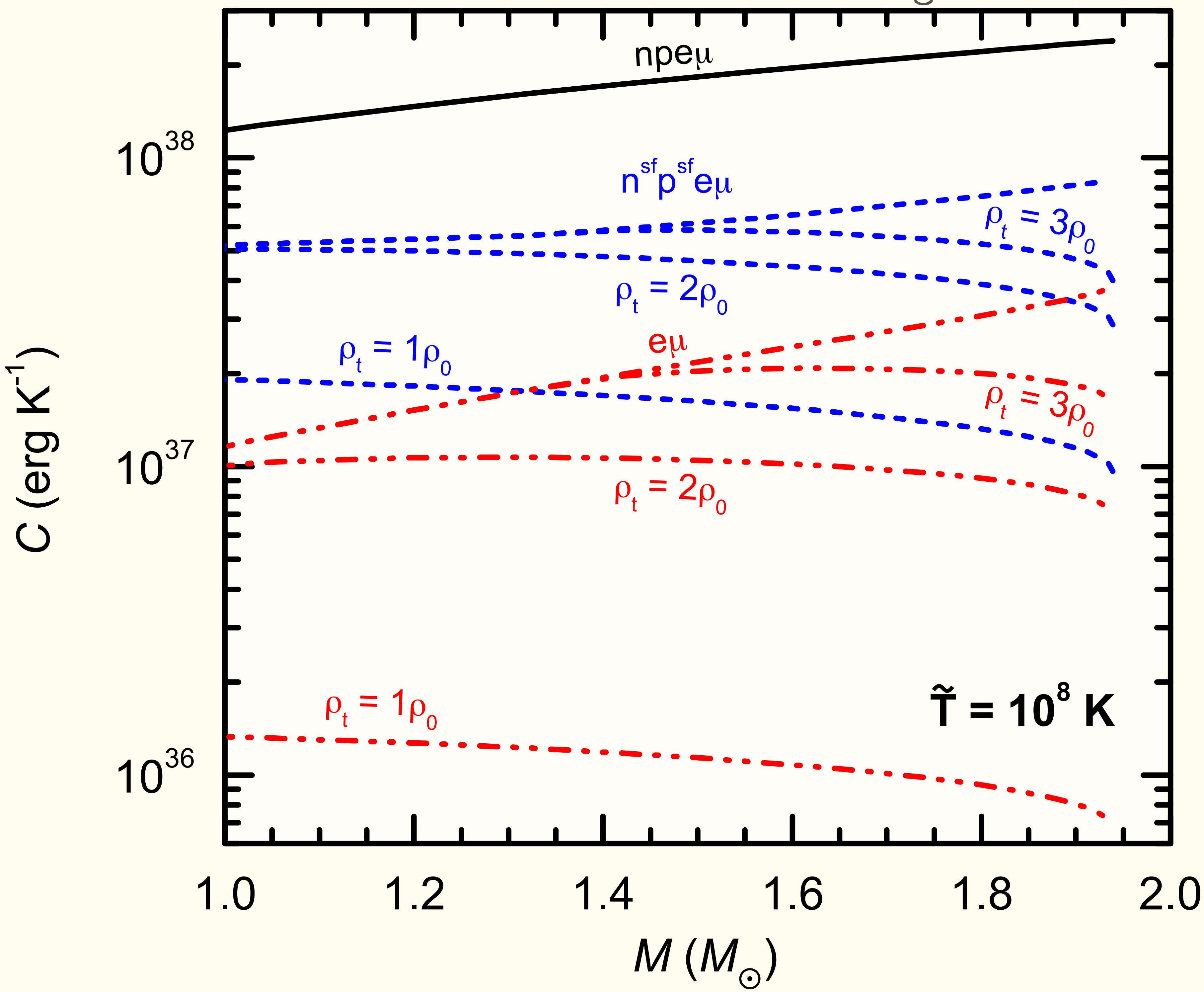
For KS1731, $E \approx 6 \times 10^{43}$ ergs deposited into the core



Cumming et al. '17

This could change T_{core} significantly

Cumming et al. 2017



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!

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

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

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

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

The neutrino luminosity cannot exceed the heating rate, however:

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

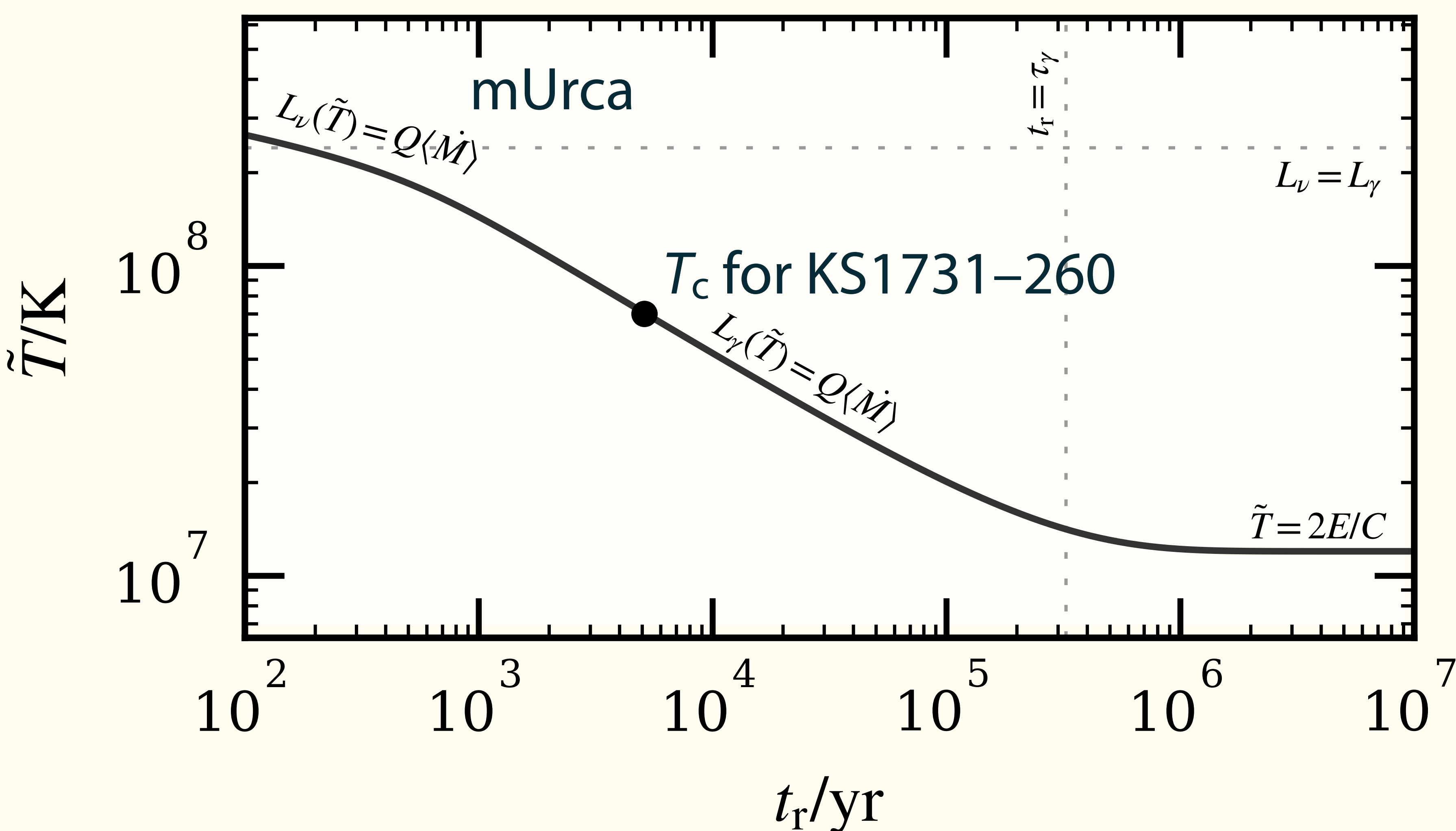
for KS1731. If a *fast* process is present, its strength is $< 10^{-3}$ of direct Urca.

The general case

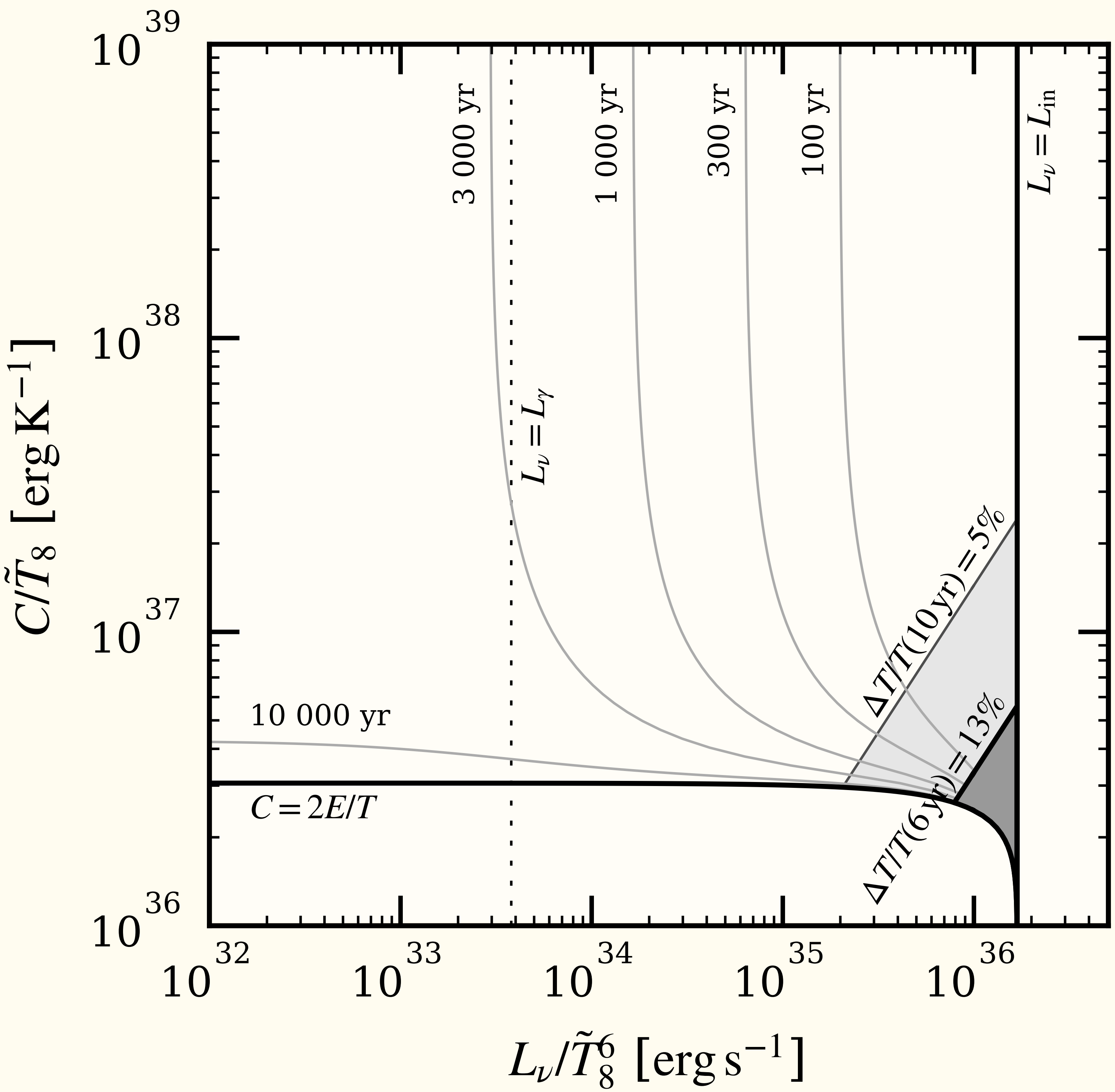
$$C\frac{d\tilde{T}}{dt} = -L_\gamma(\tilde{T}) - L_\nu(\tilde{T}) + L_{\rm in},$$

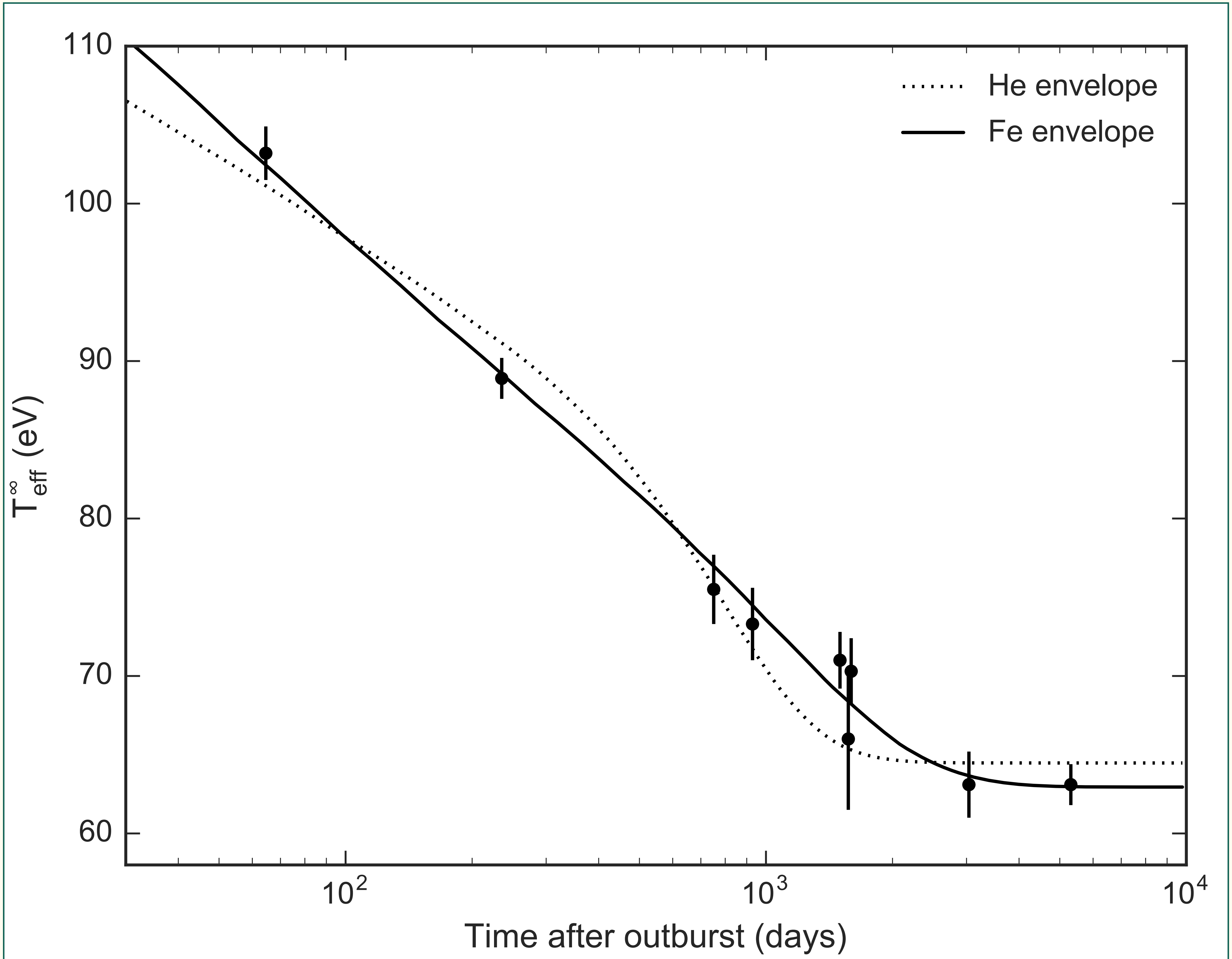
where $L_{\rm in} = 0$ during quiescence

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.



Putting everything together: a “phase diagram” for KS1731–260





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

In summary,

Cooling neutron star transients probe the transport properties of matter and 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.

Further monitoring of variations in the core temperature, or constraints on the recurrence duration, will improve constraints.