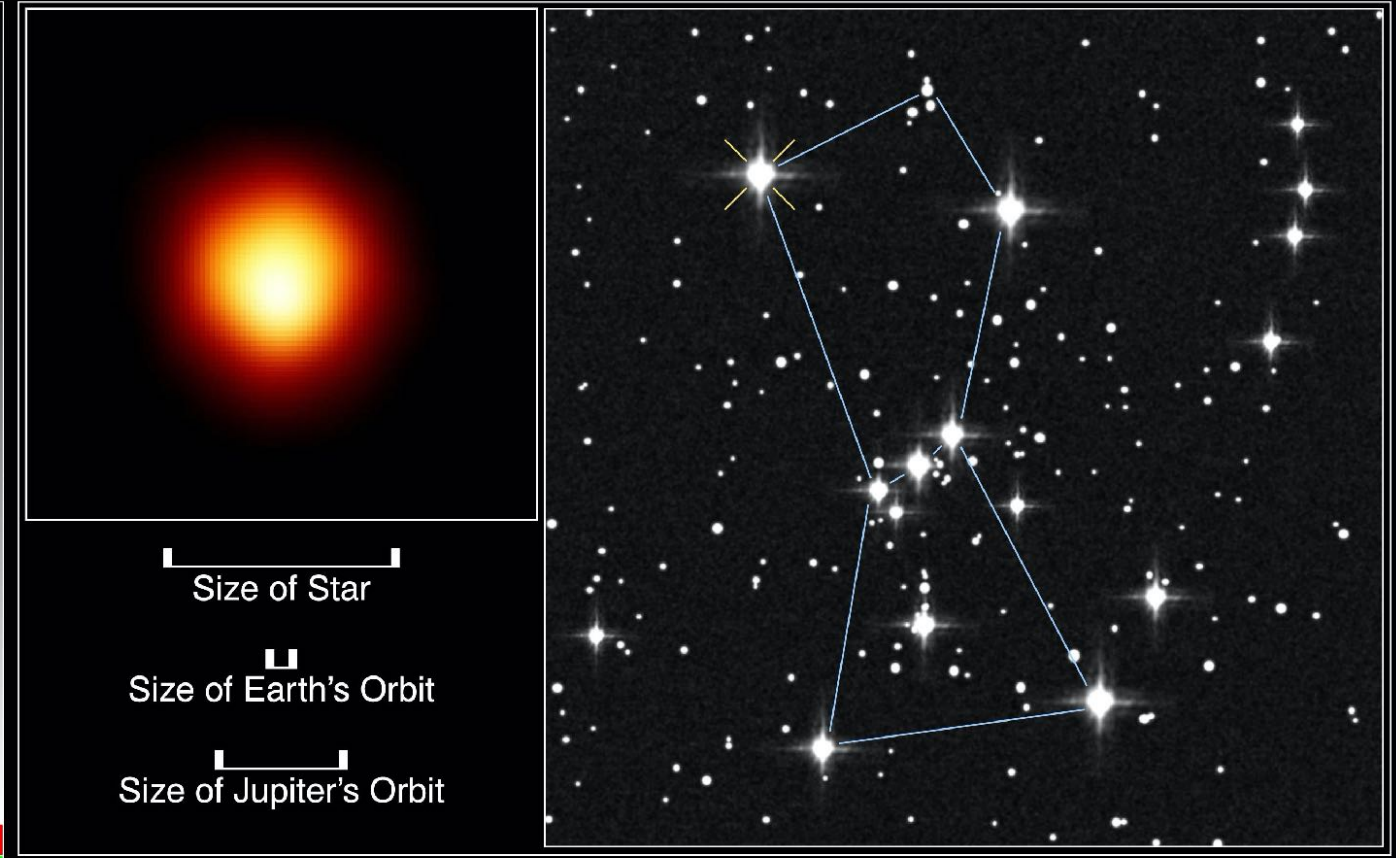
The Physics and Astrophysics of Accreting Neutron Stars

FRIB Theory Alliance
17 November 2020

Edward Brown (MSU), Andrew Cumming (McGill), Zach Meisel (Ohio University)

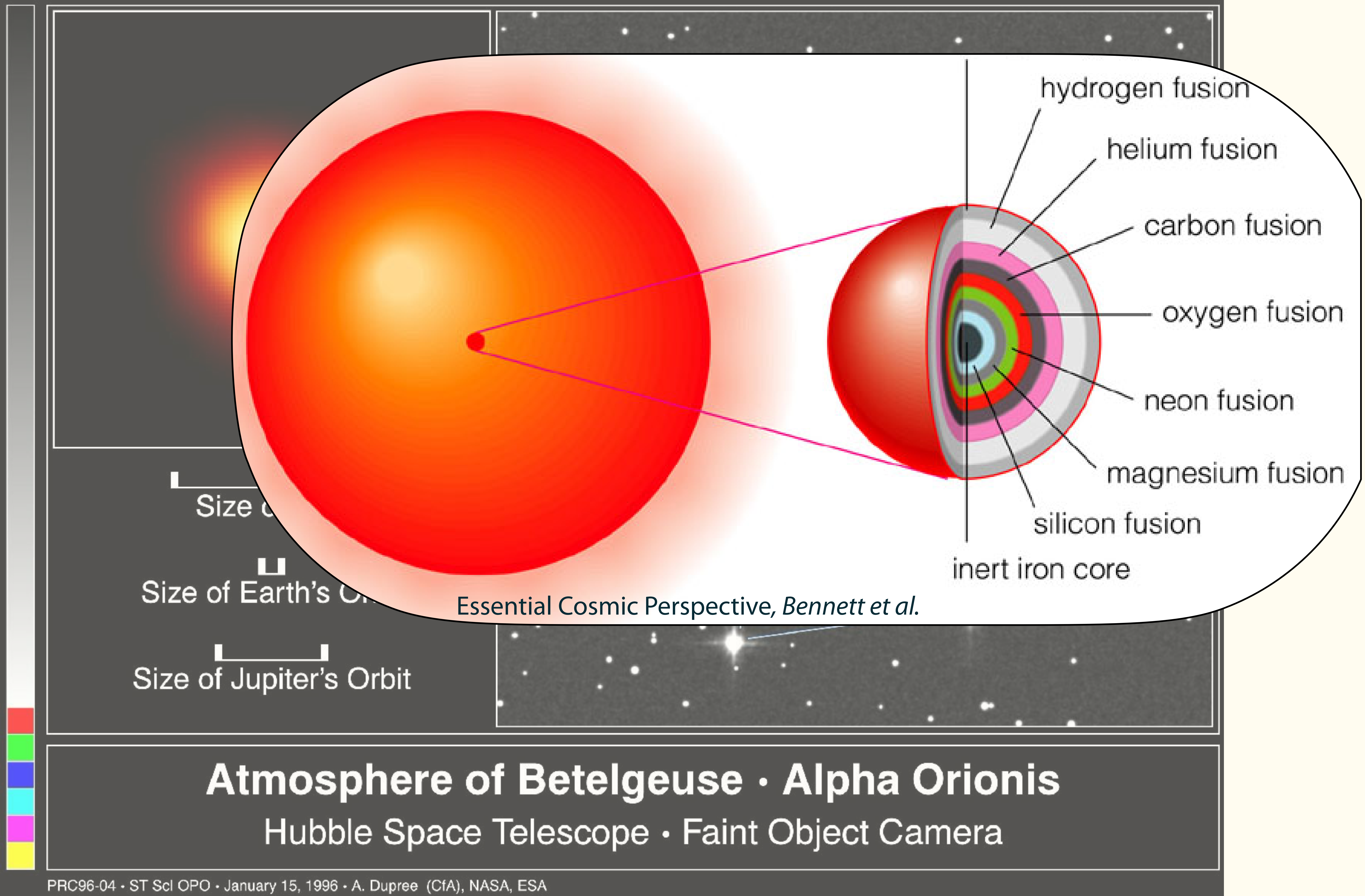
image credit: A Piro, Carnegie



Atmosphere of Betelgeuse • Alpha Orionis

Hubble Space Telescope • Faint Object Camera

PRC96-04 • ST ScI OPO • January 15, 1996 • A. Dupree (CfA), NASA, ESA



Essential Cosmic Perspective, *Bennett et al.*

SNe 1987a | neutrinos detected

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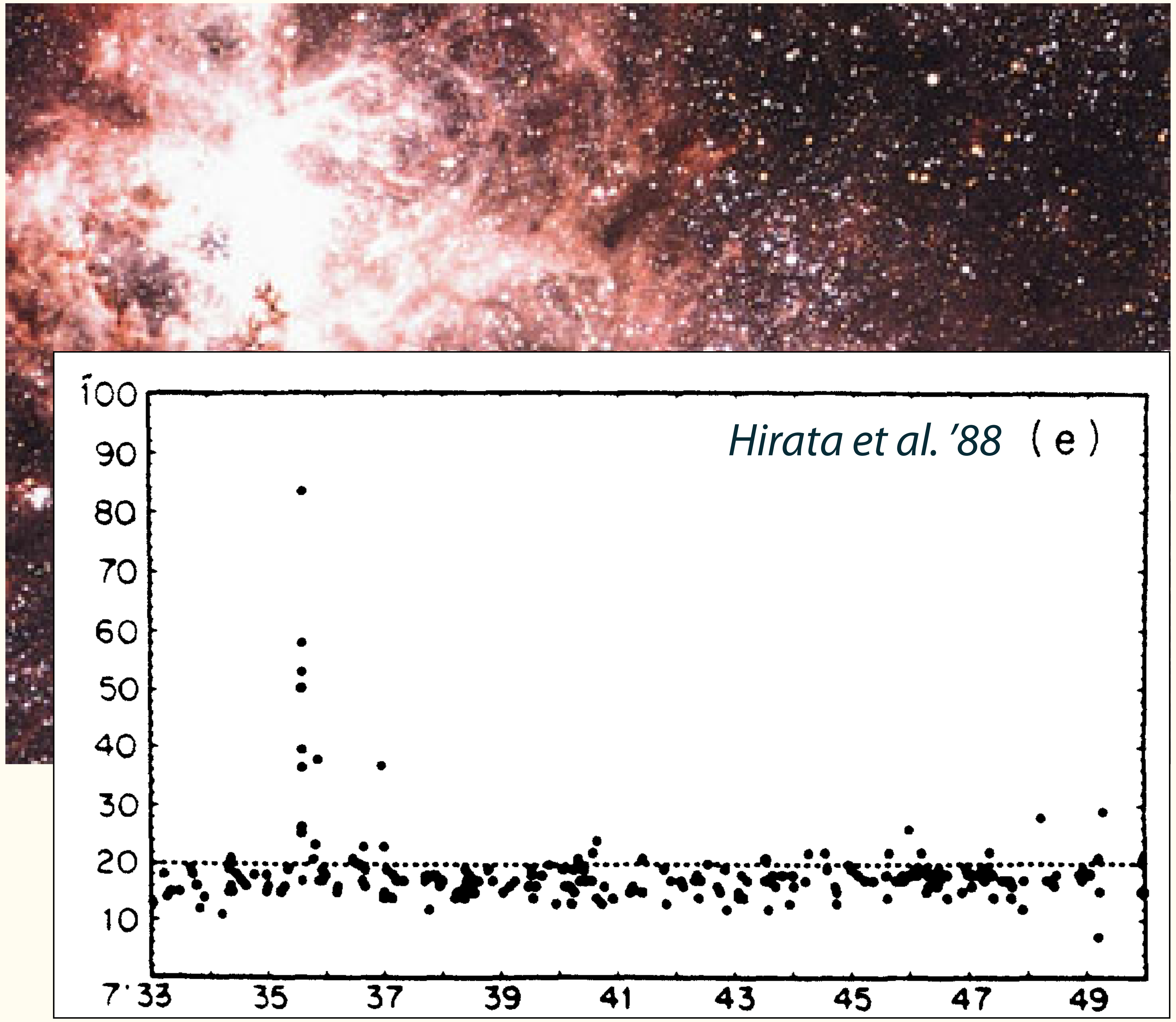
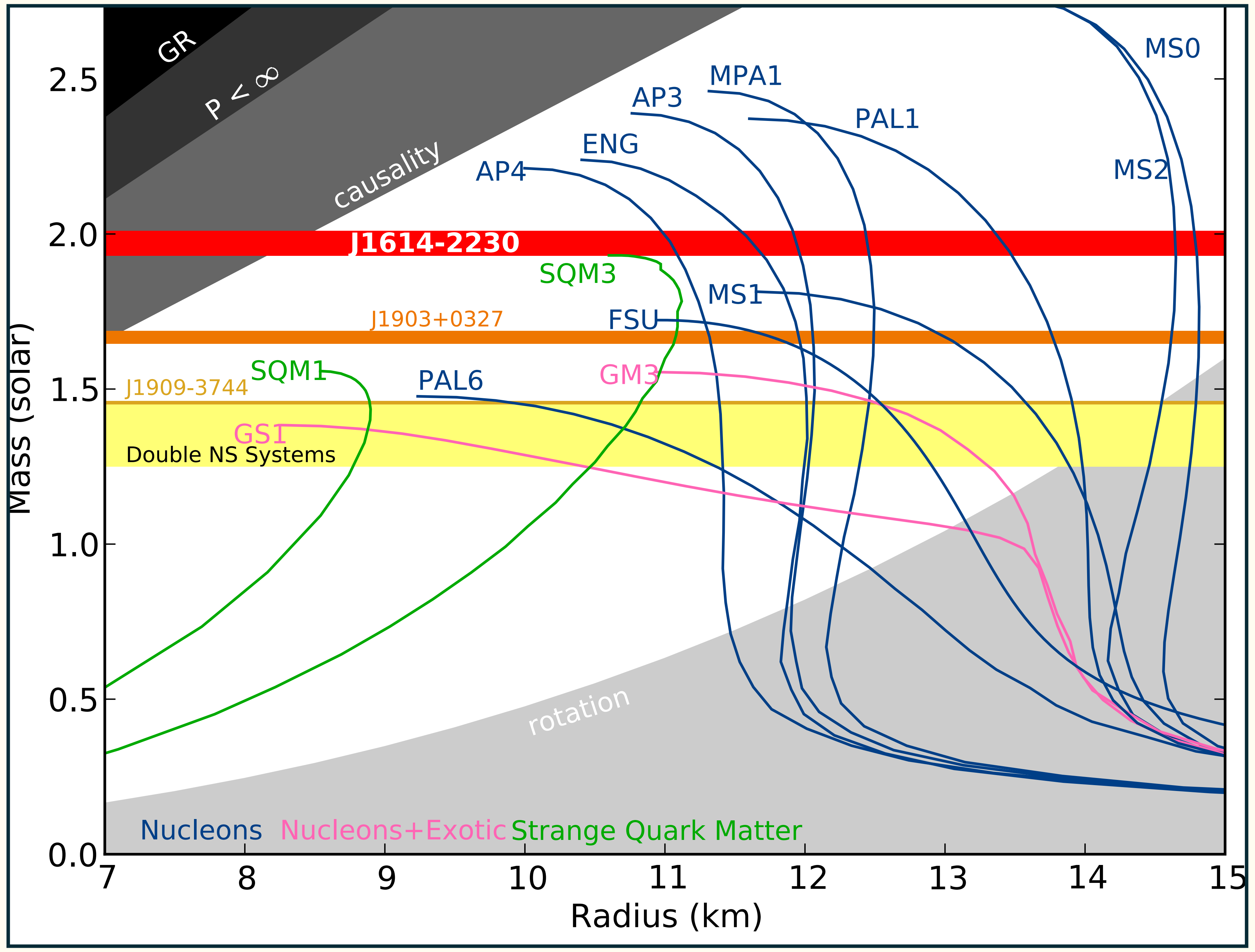


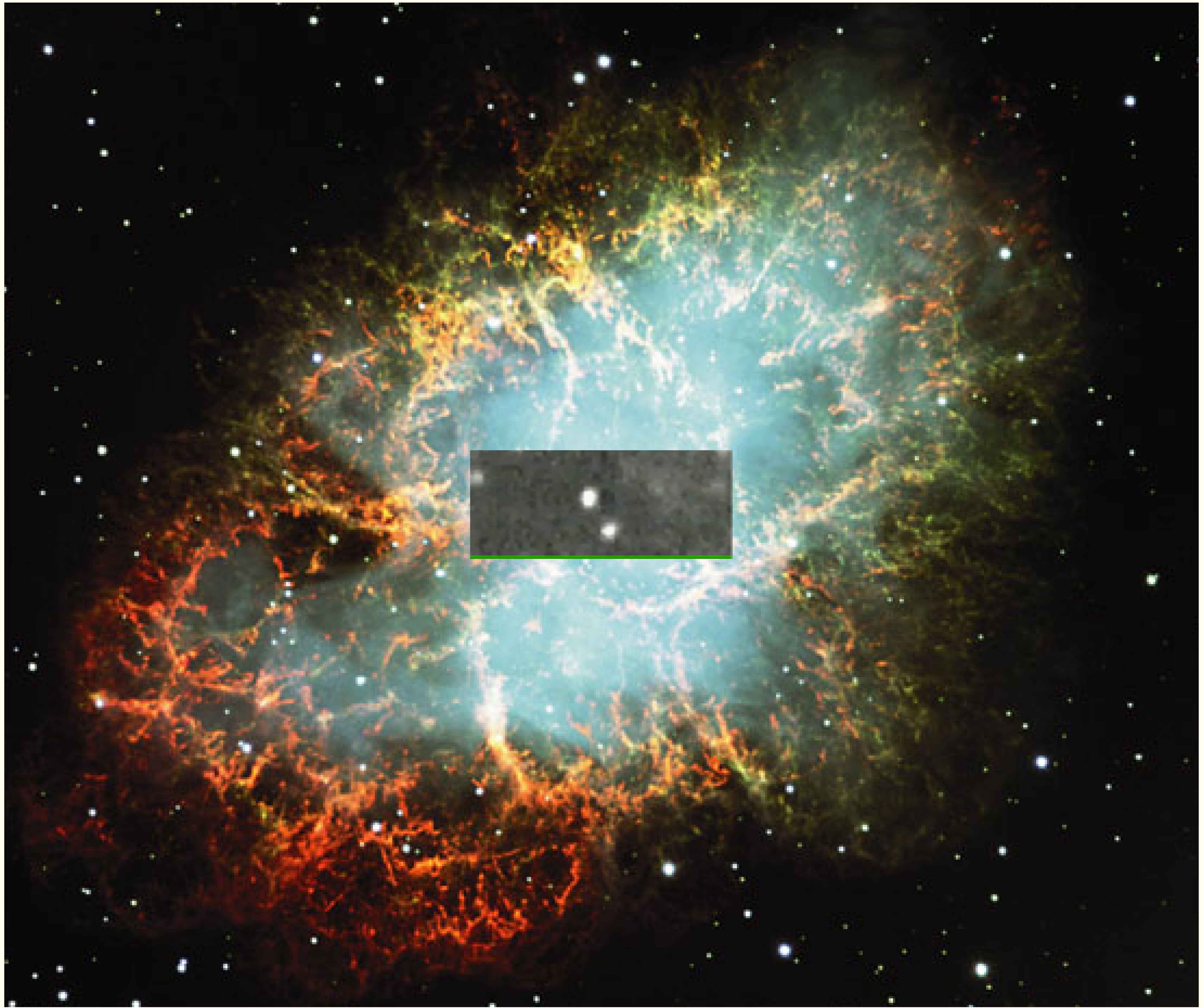

image courtesy NASA

detection | pulsars

Demorest et al. 2010



detection | pulsars



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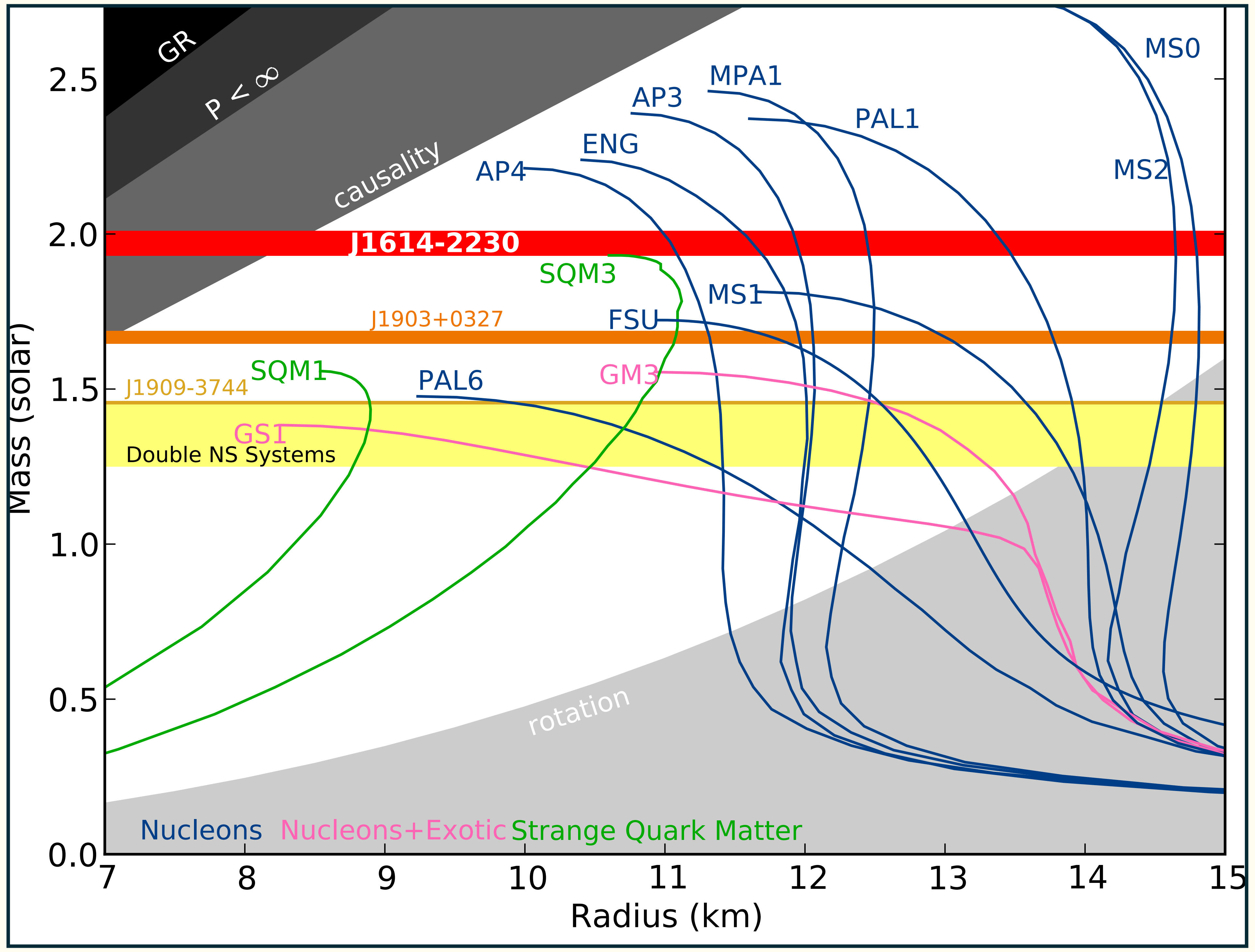

detection | X-rays

PHYSICAL REVIEW LETTERS

VOLUME 9 DECEMBER 1, 1962 NUMBER 11

EVIDENCE FOR X RAYS FROM SOURCES OUTSIDE THE SOLAR SYSTEM*

Riccardo Giacconi, Herbert Gursky, and Frank R. Paolini
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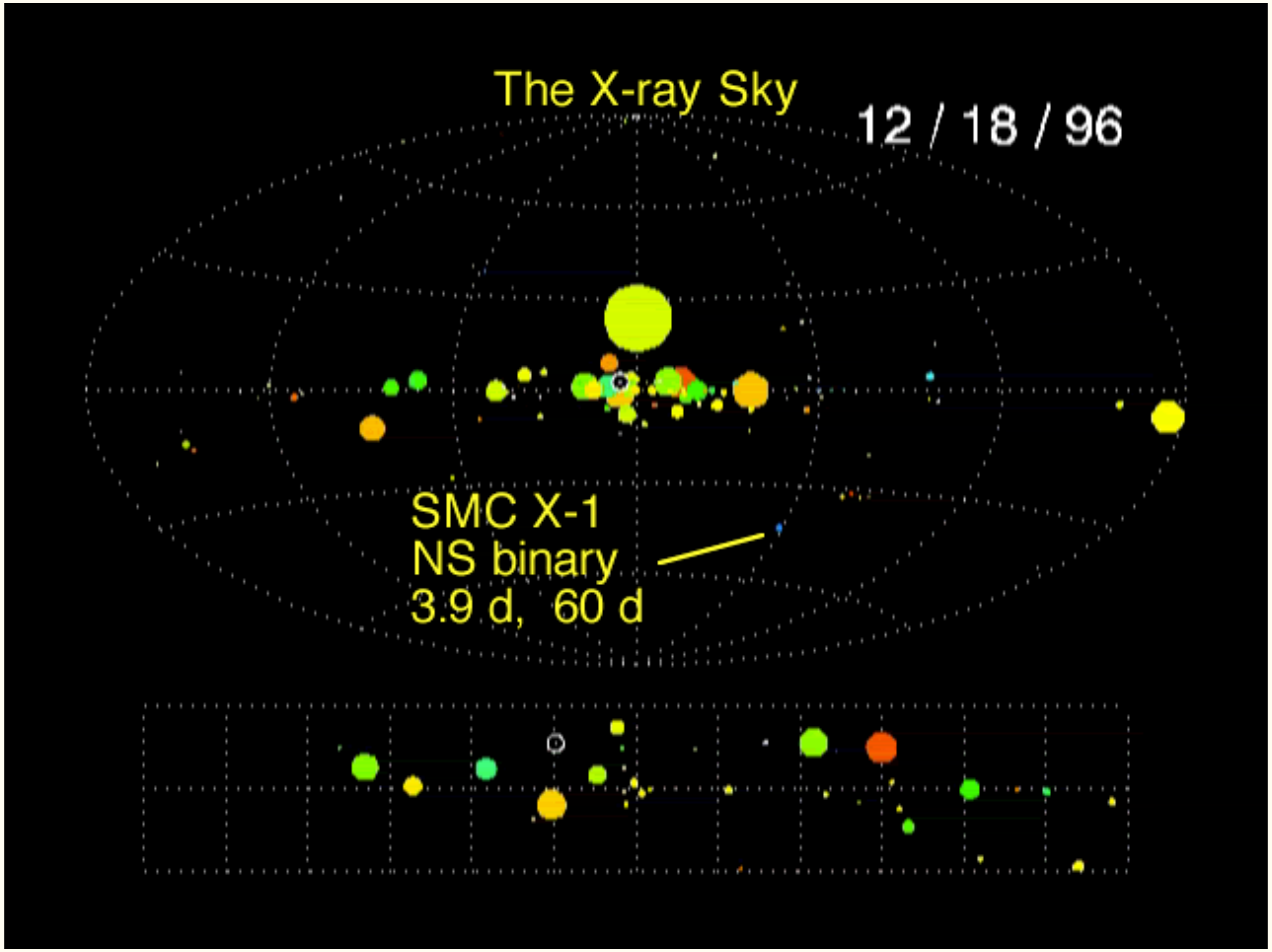
low-mass X-ray binaries



courtesy RXTE

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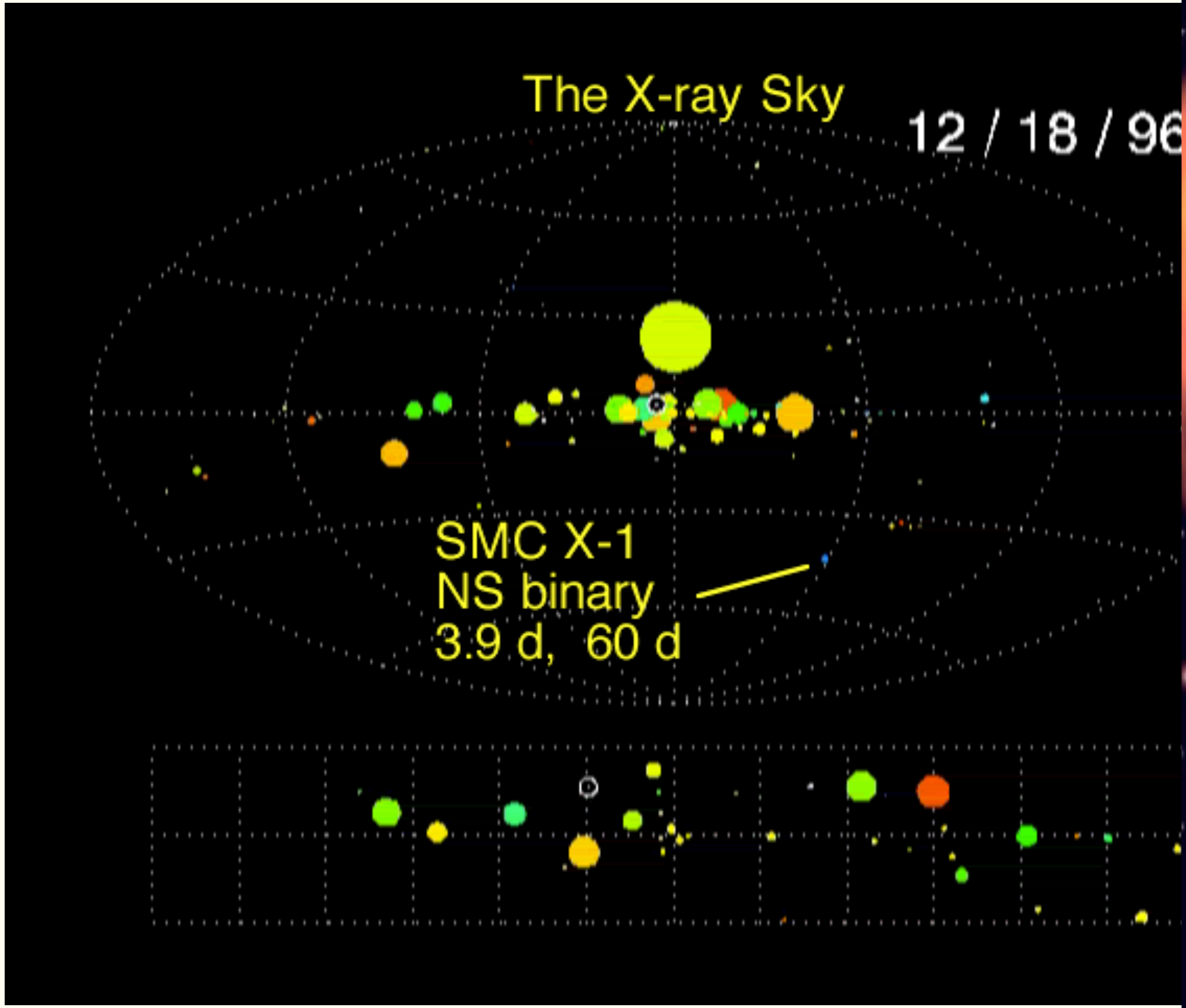

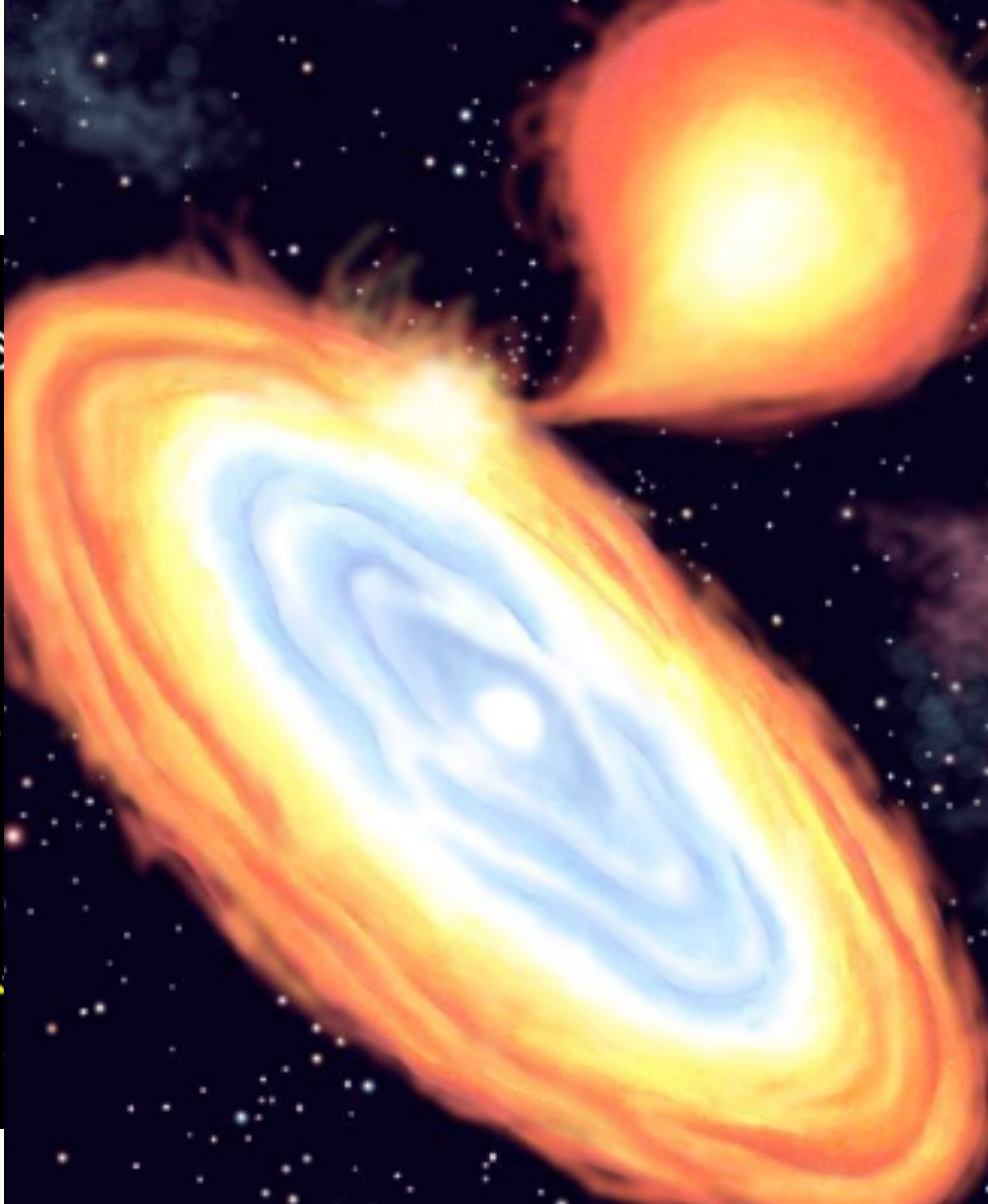

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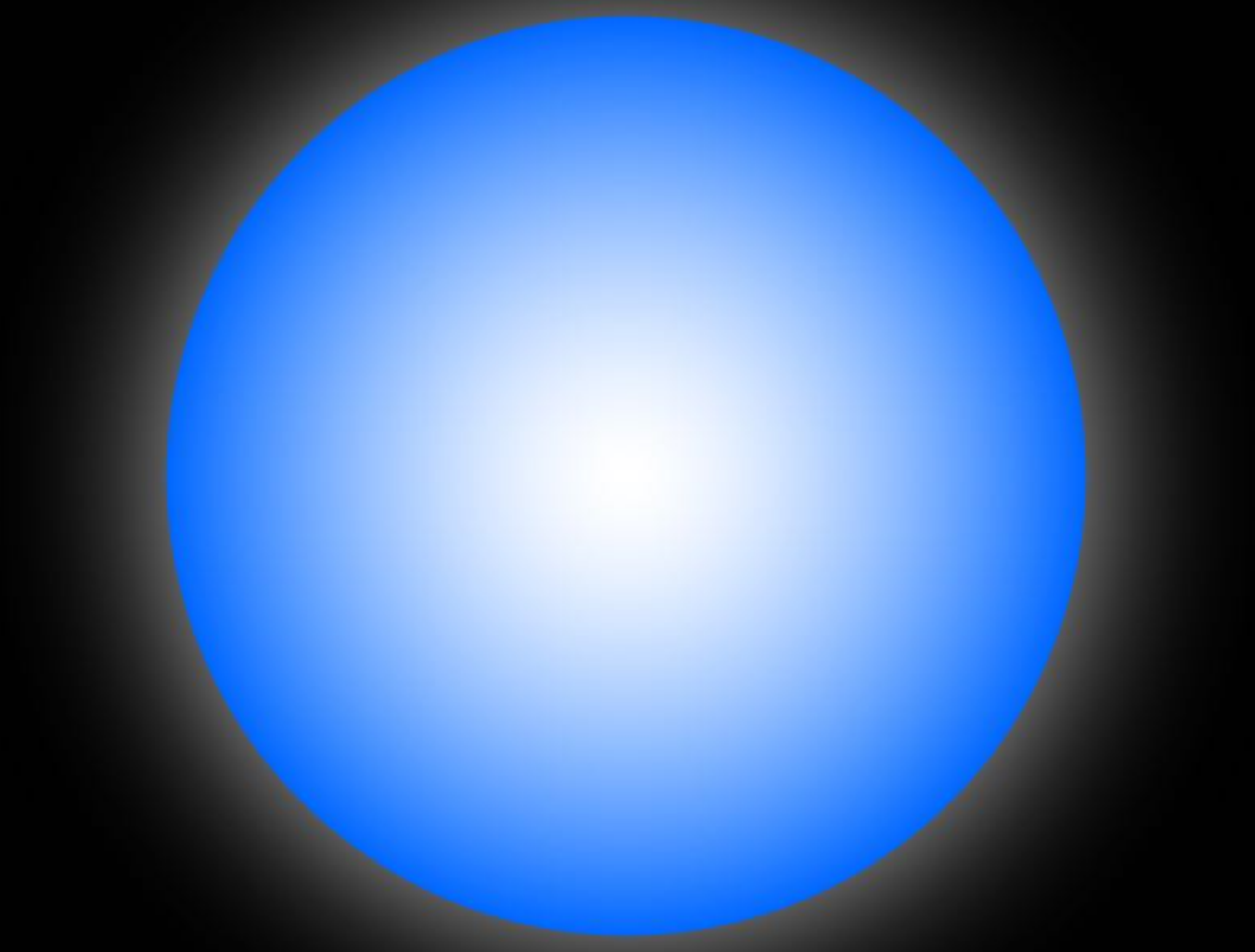
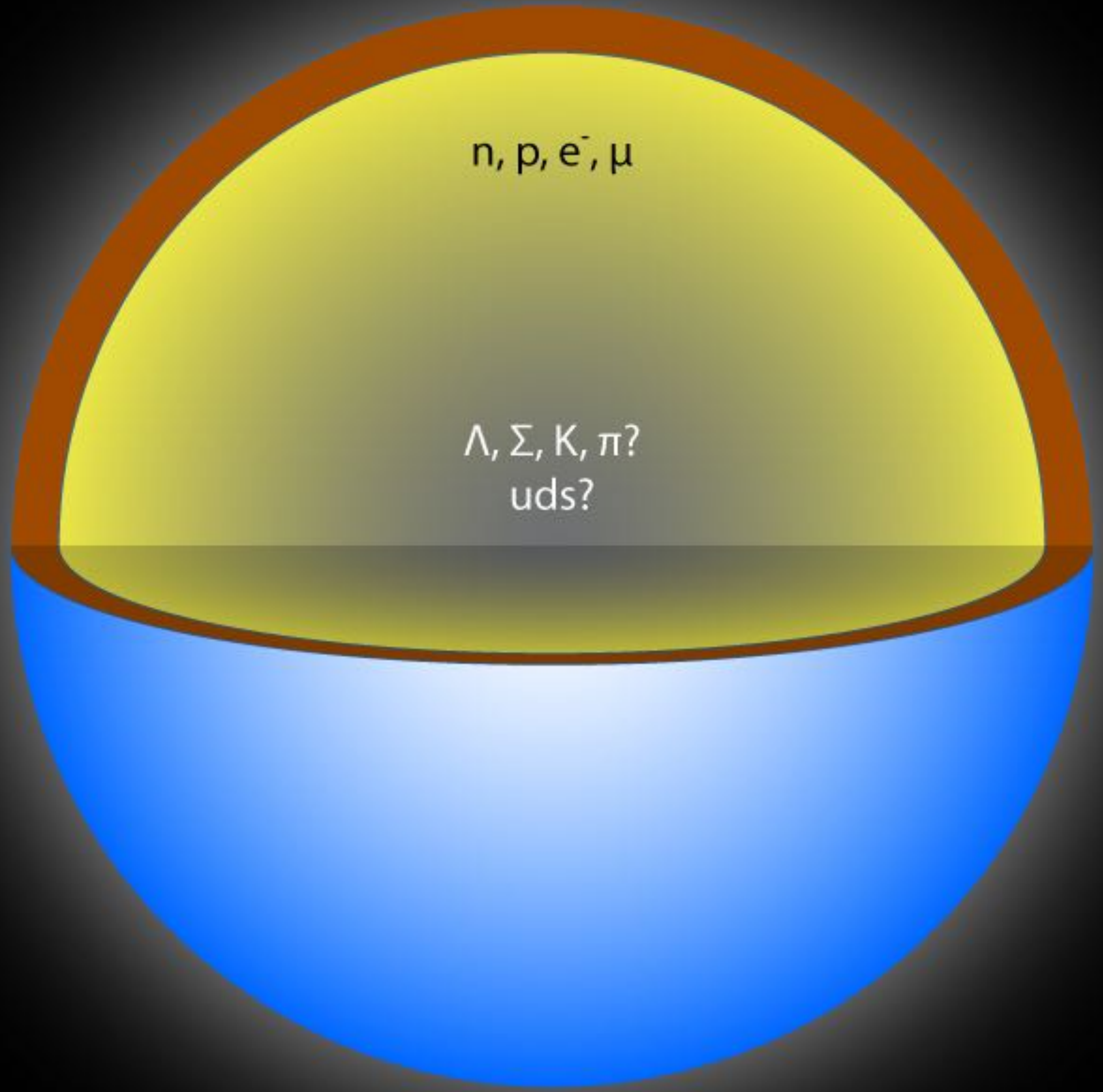



n, p, e$^-$, μ
Λ, Σ, K, π?
uds?

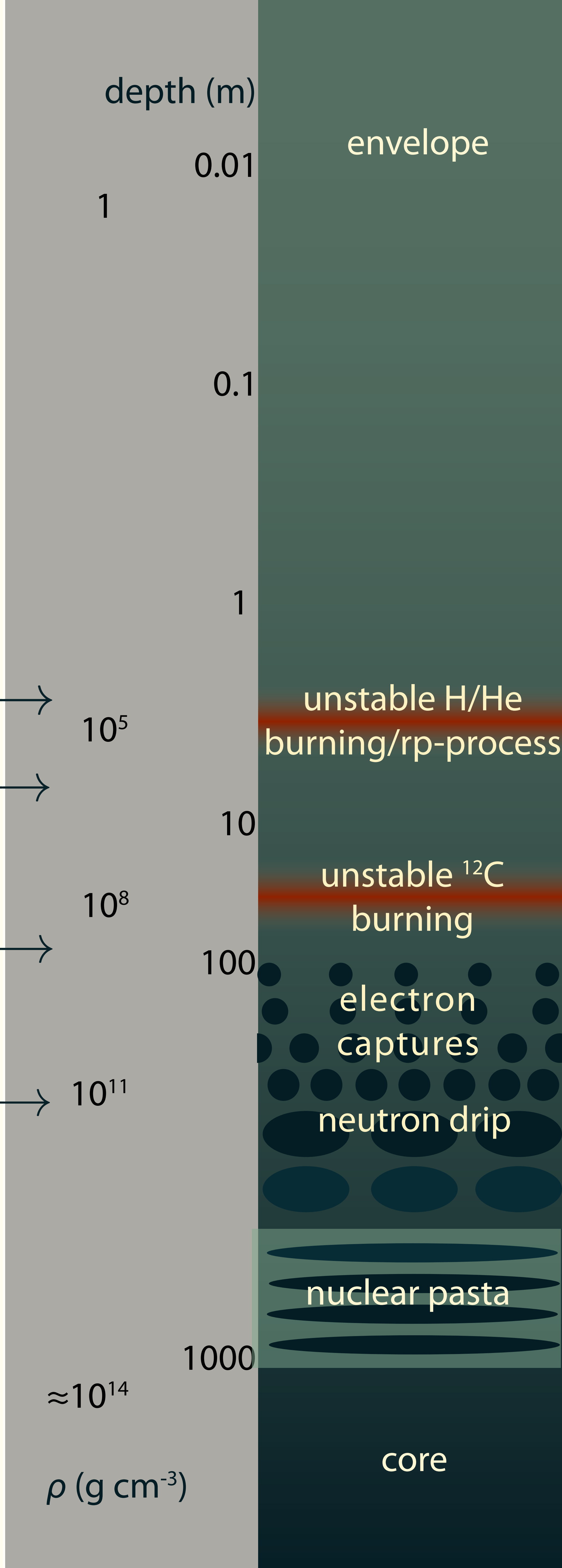
The neutron star crust

$$\mu_e \approx k_\mathrm{B} T \longrightarrow$$

$$\mu_e \approx m_e c^2 \longrightarrow$$

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

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



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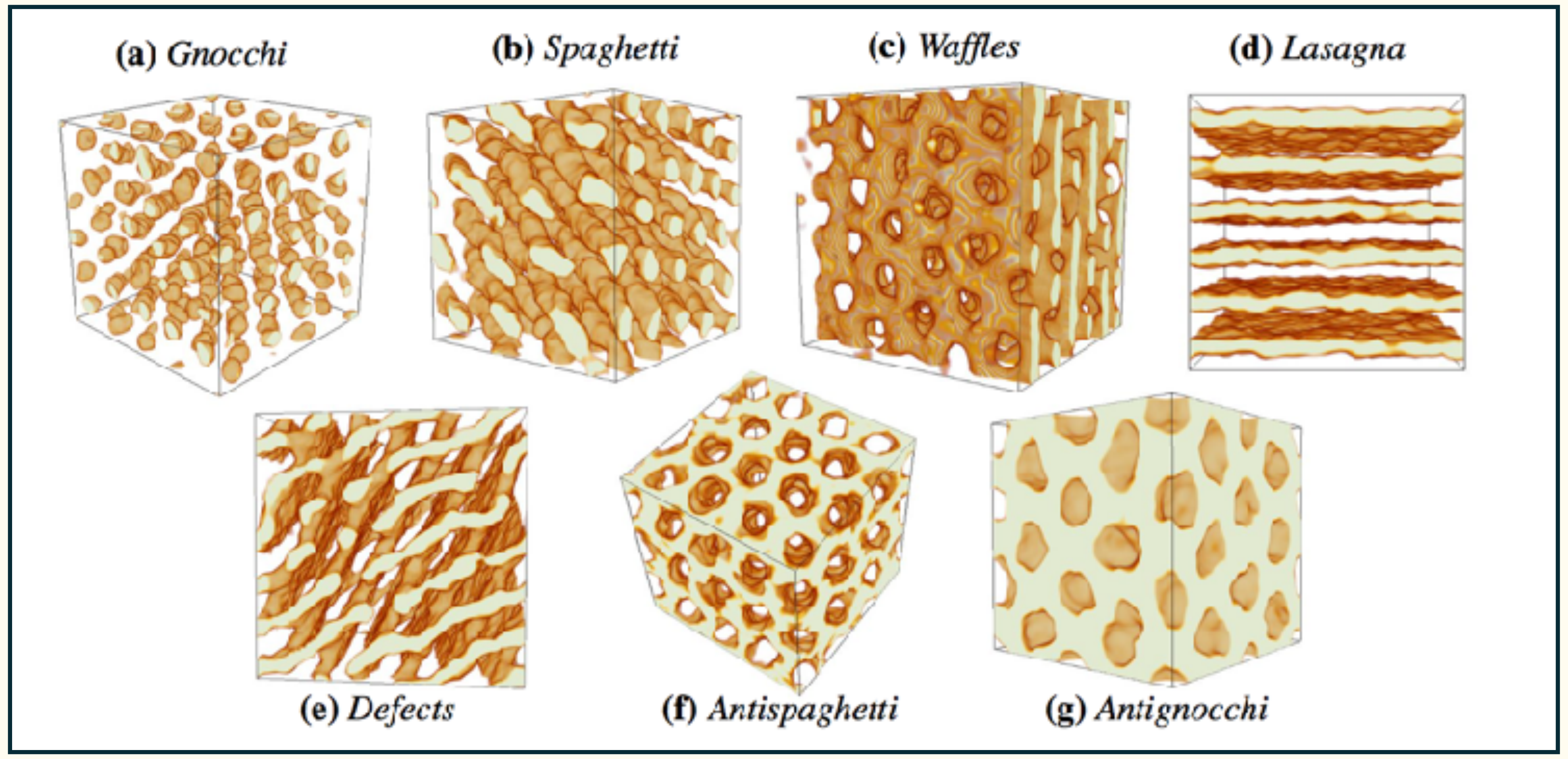
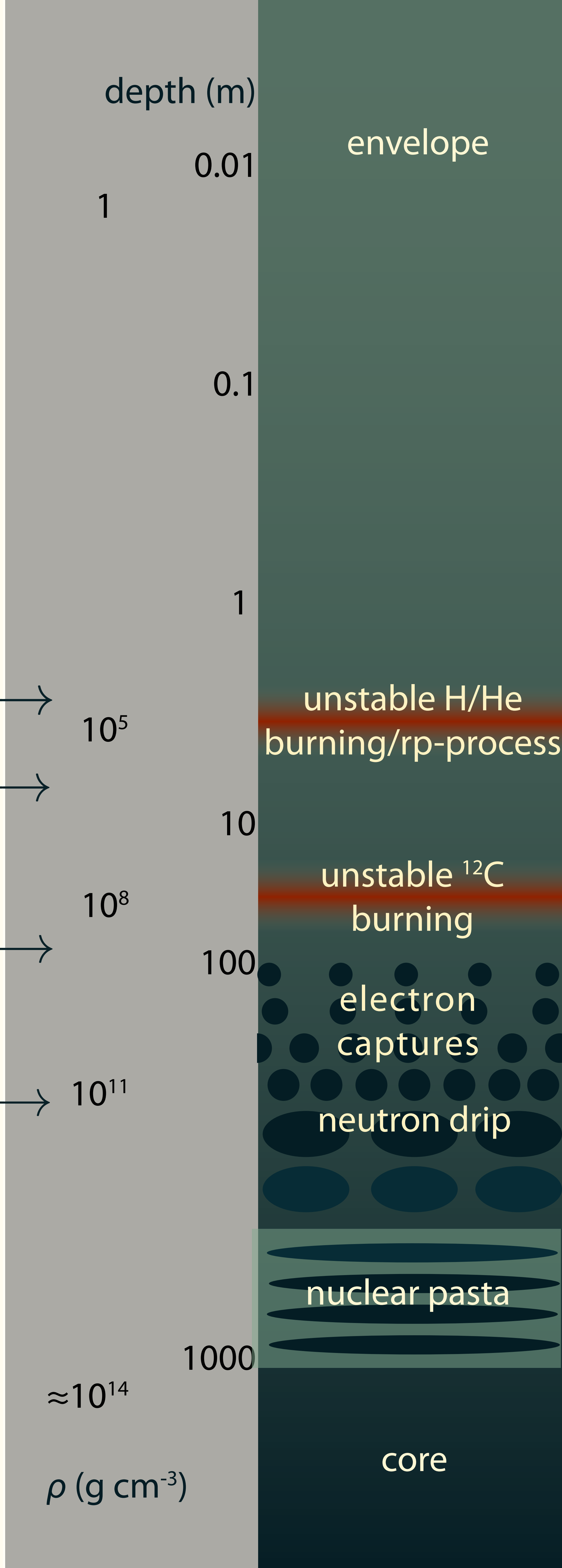
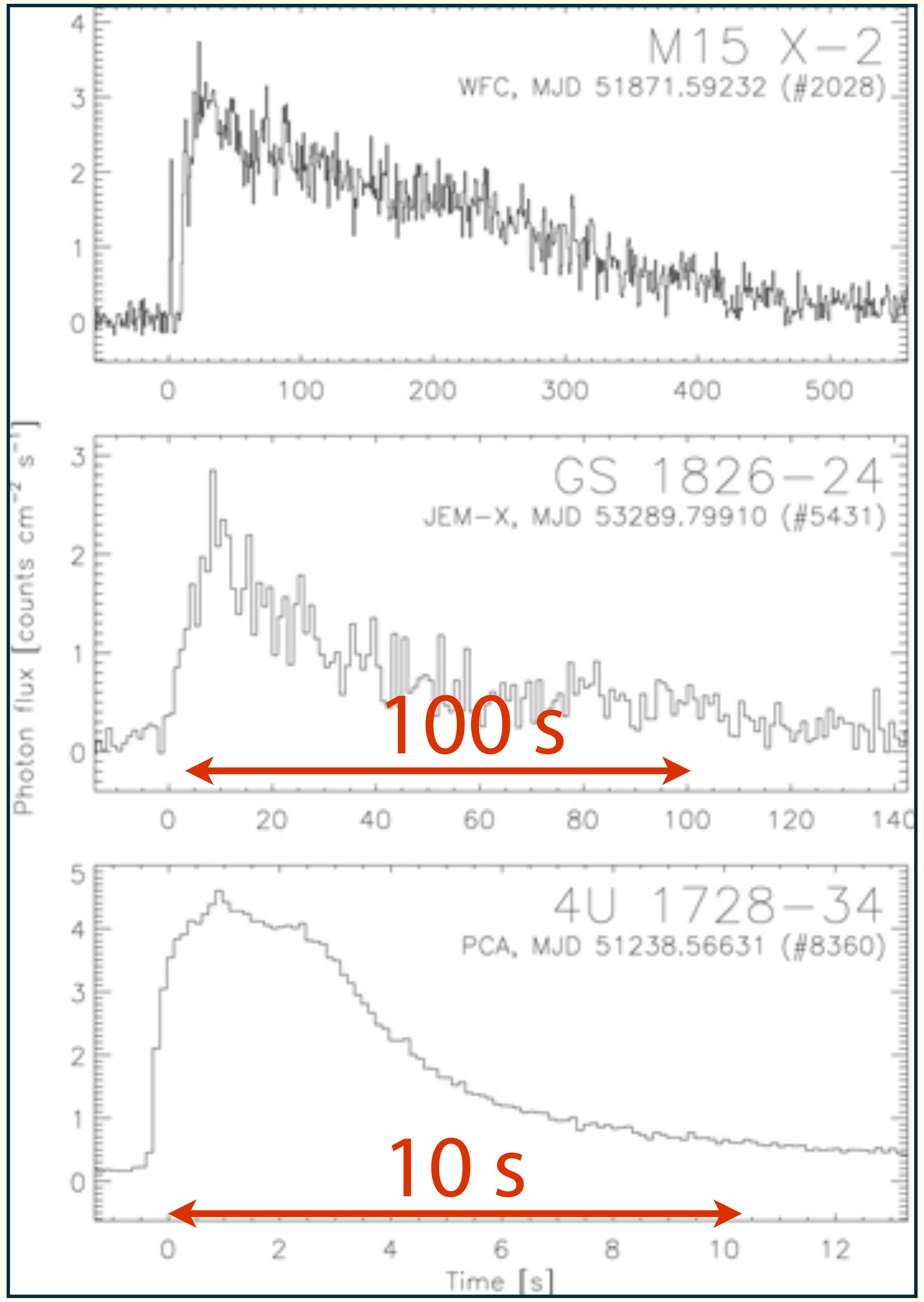
pasta menu courtesy M. Caplan



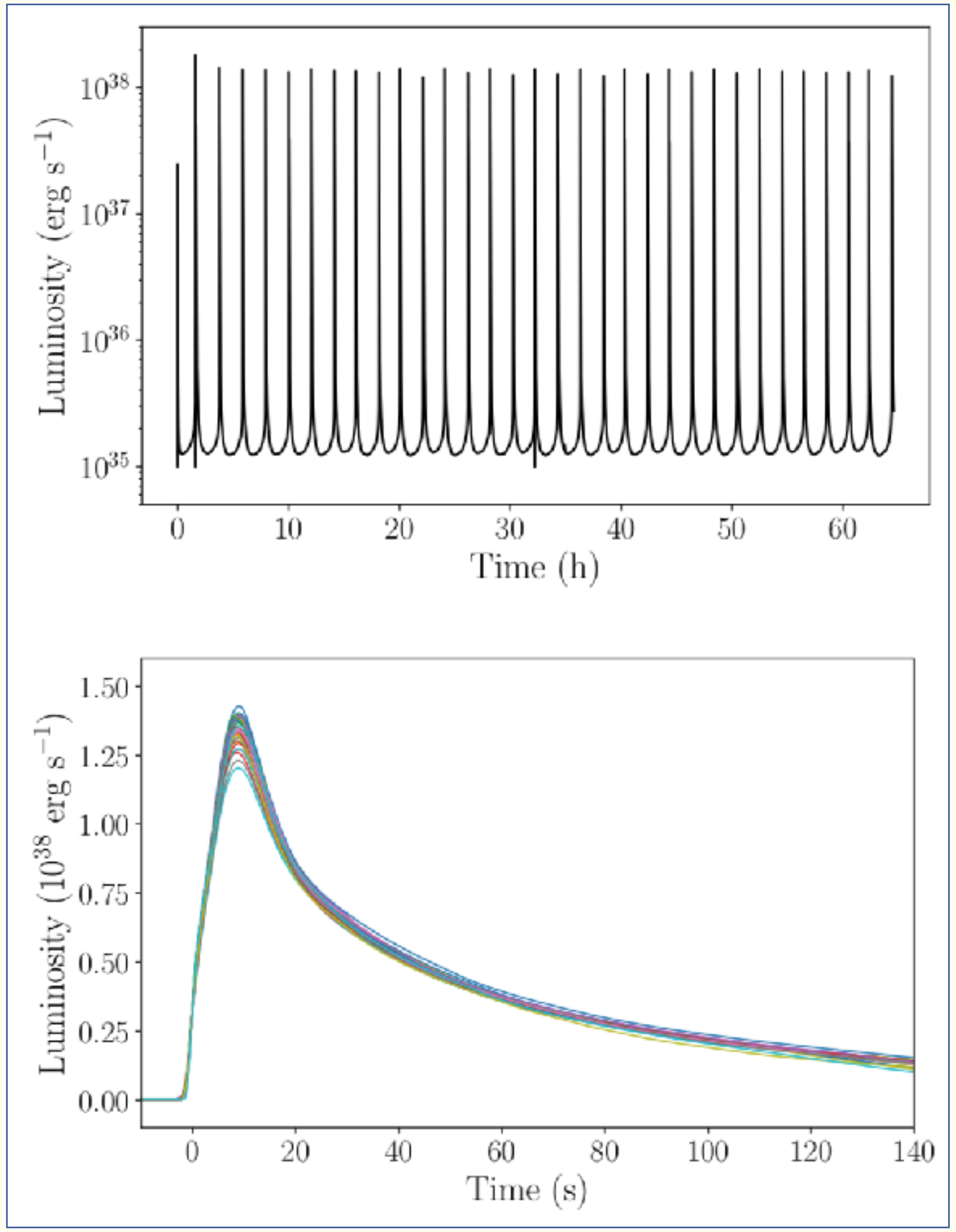


X-ray bursts | observations and models

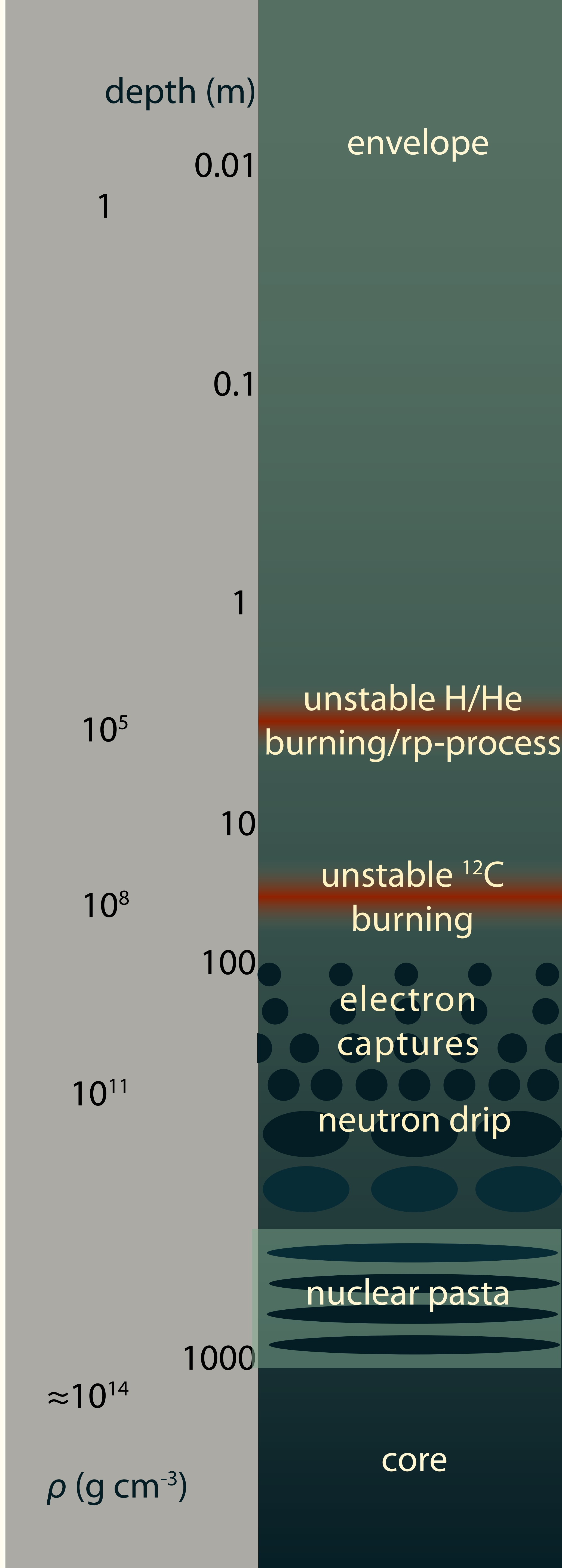


Galloway et al. 2020

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



Johnston, Heger & Galloway 2020



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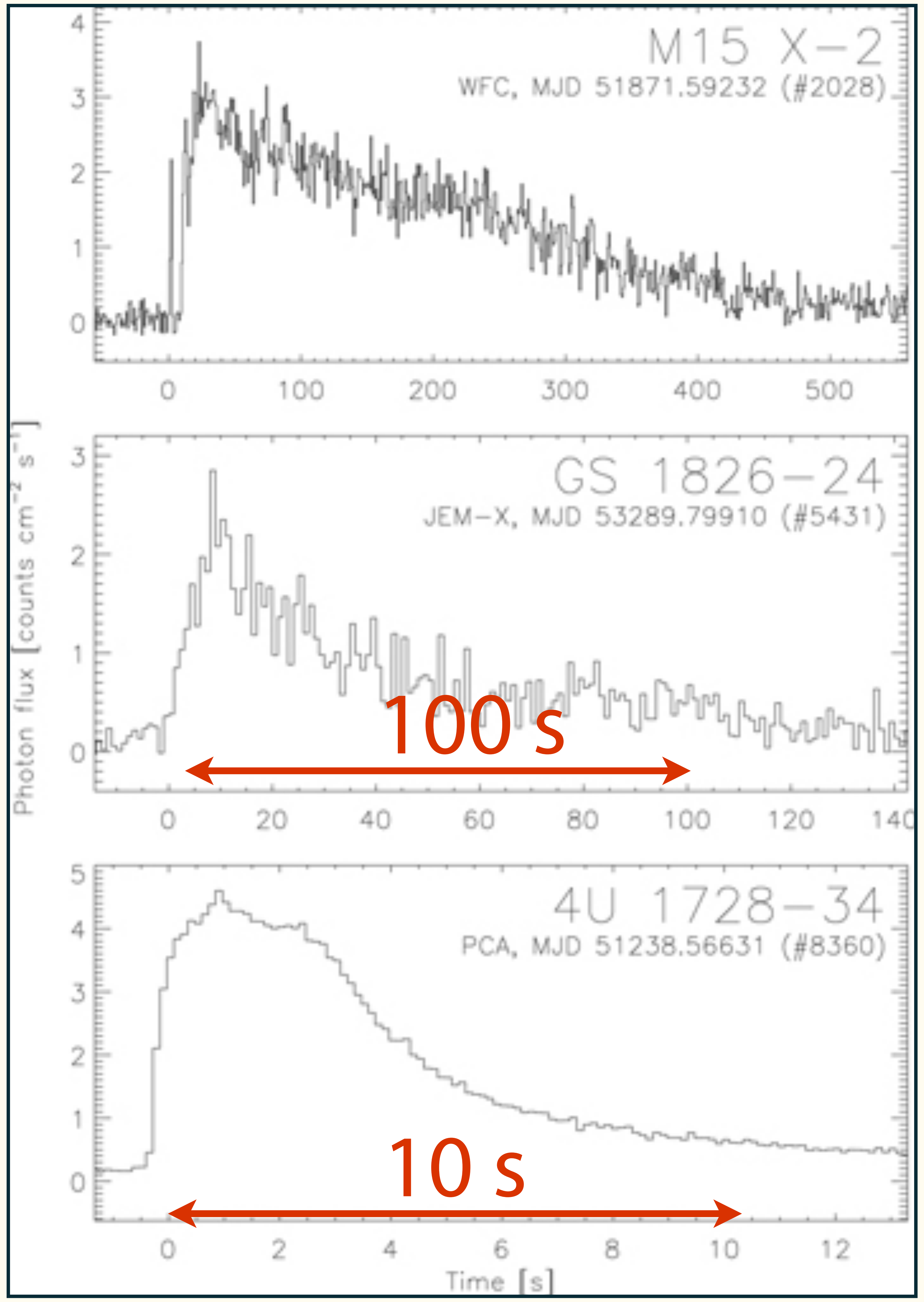

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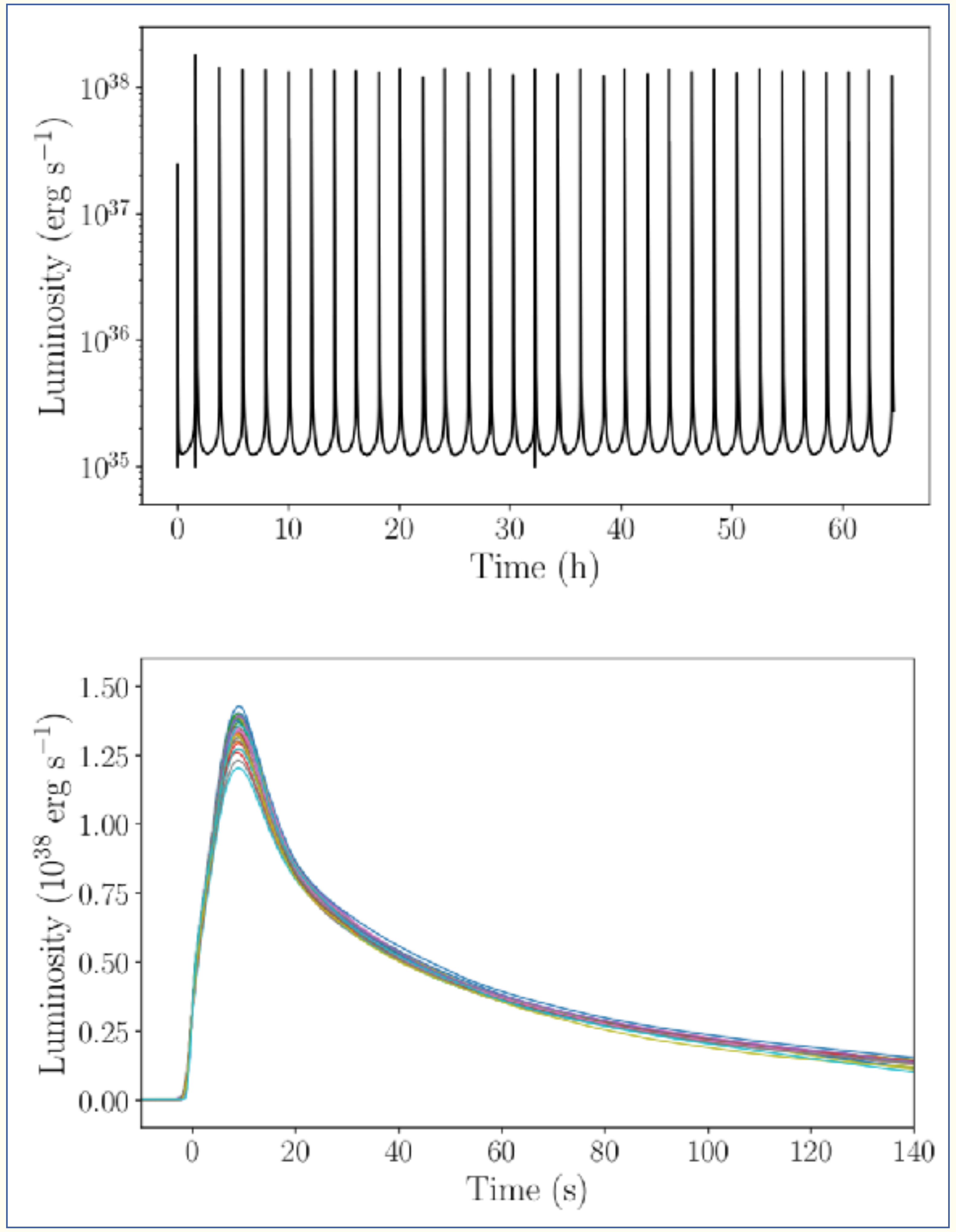

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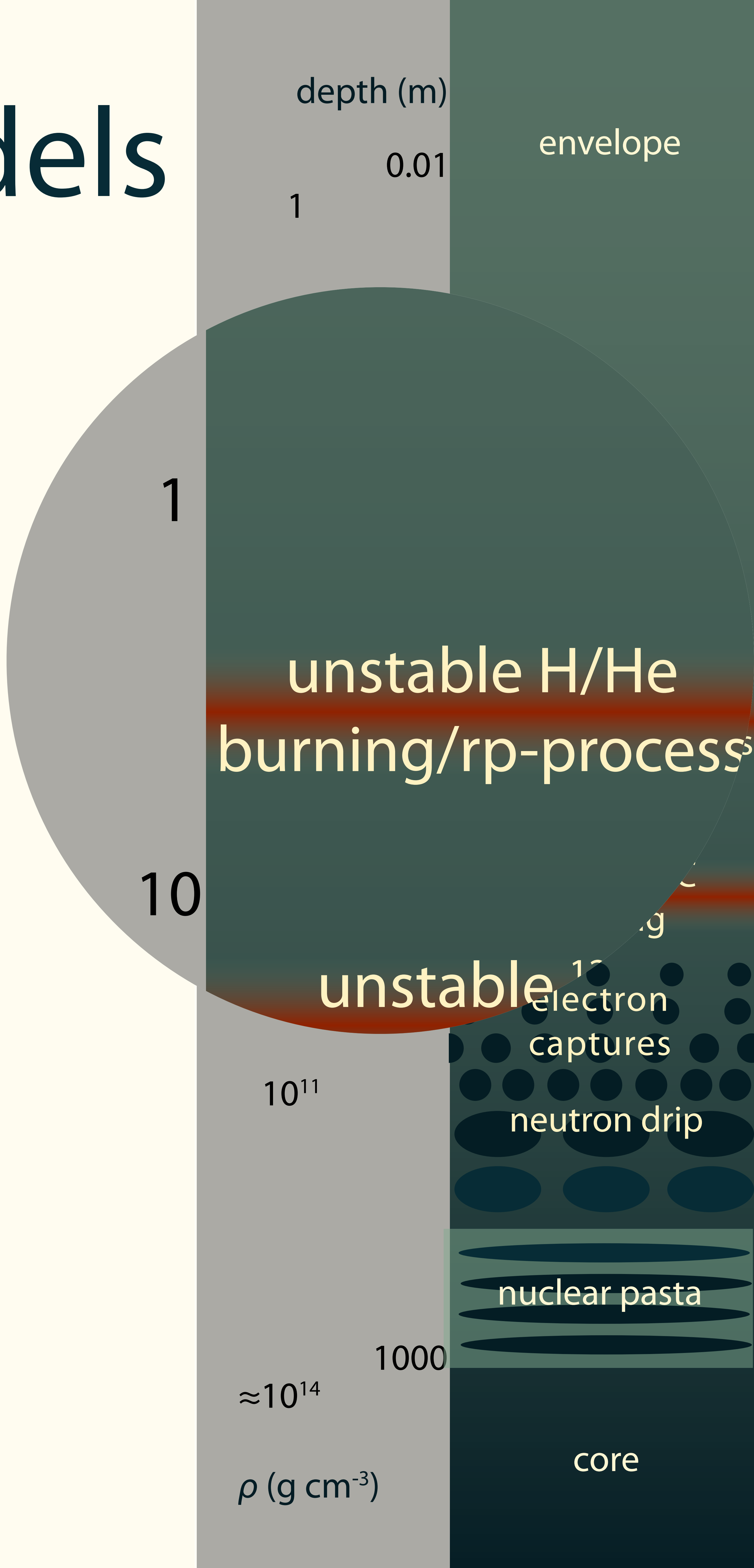
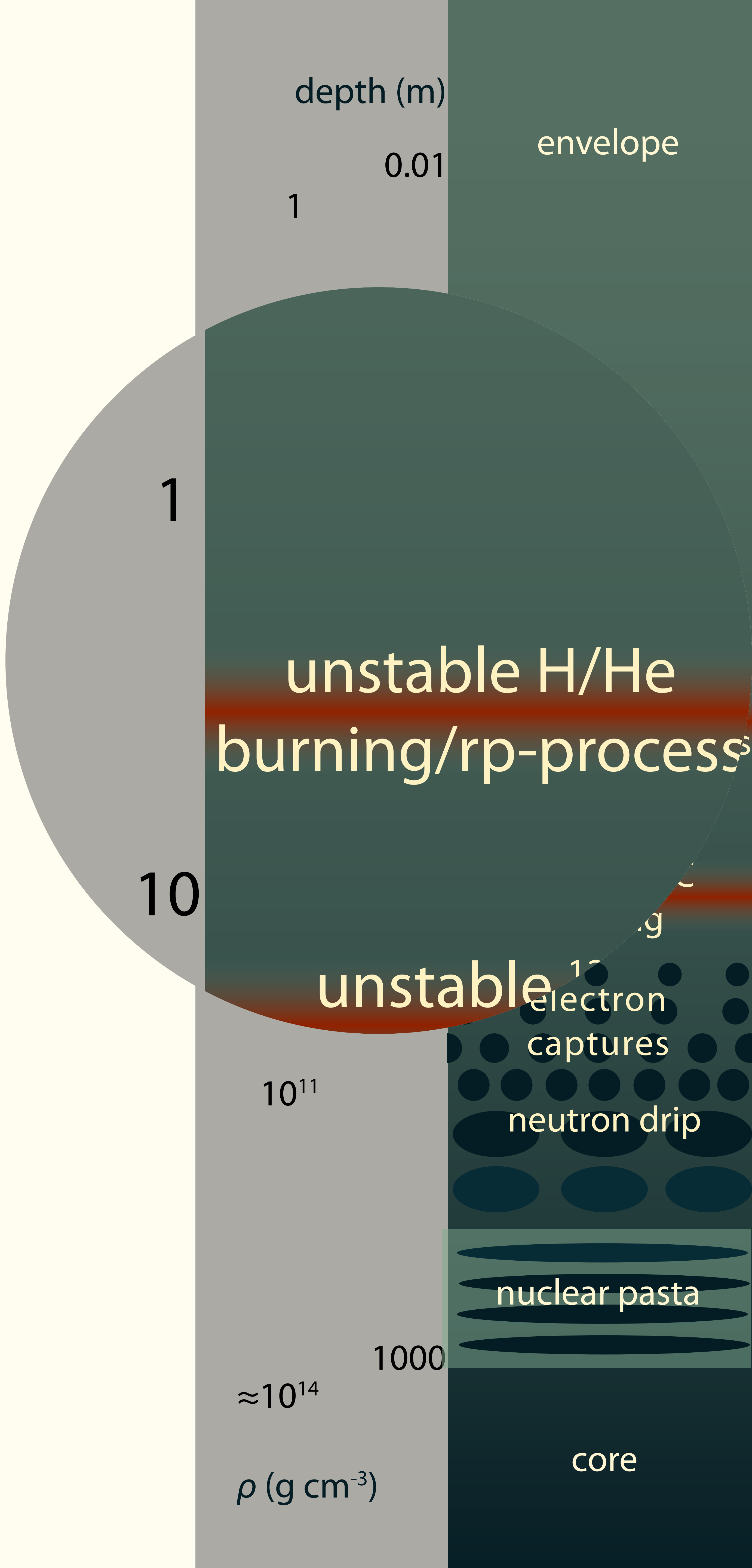


X-ray bursts

How does the burning spread over the surface? How do multi-dimensional effects change the burst ashes?
see Cavecchi et al. 2017, 2020; Eidan et al. 2020

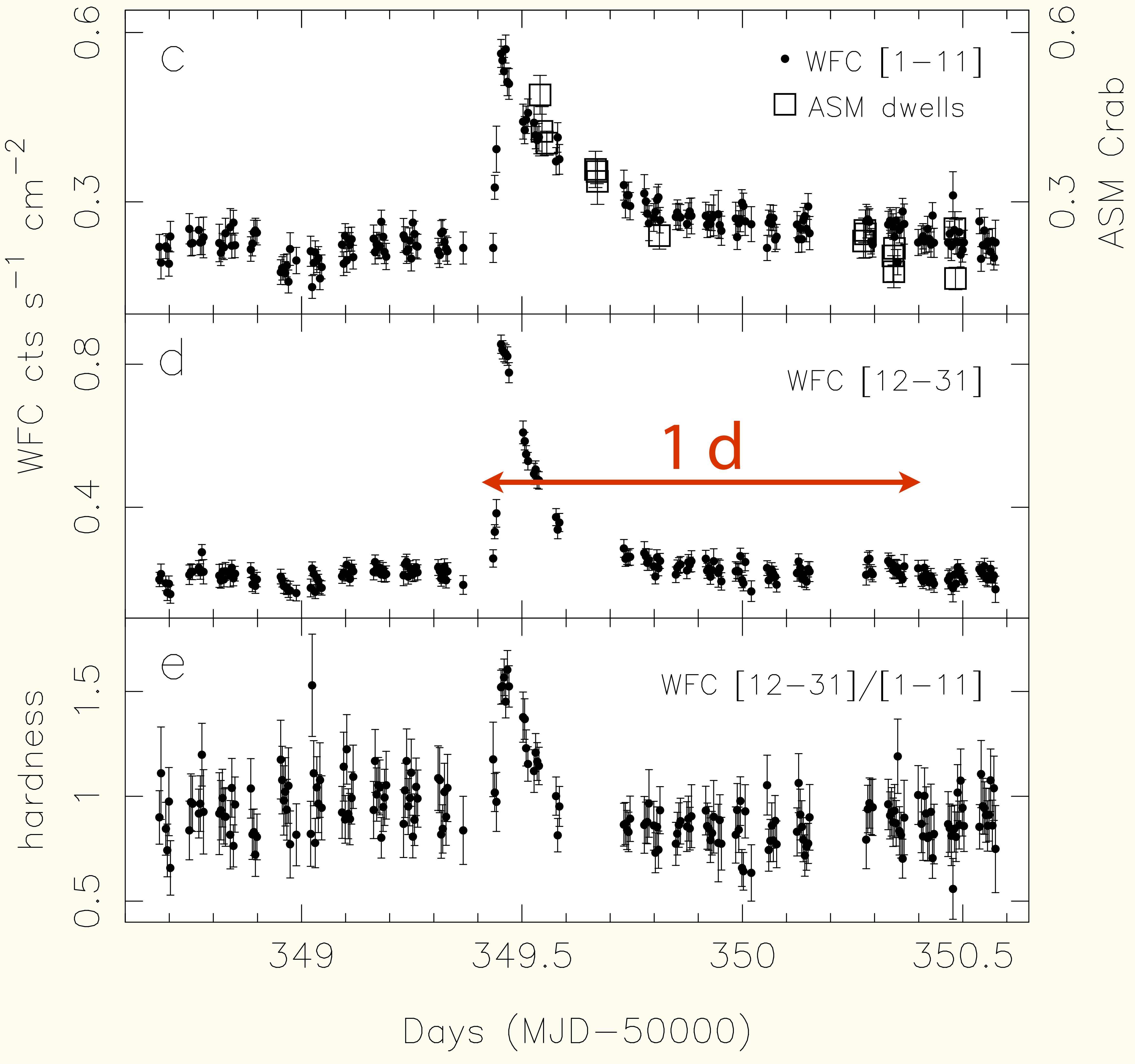
Can we do neutron star "meteorology"?

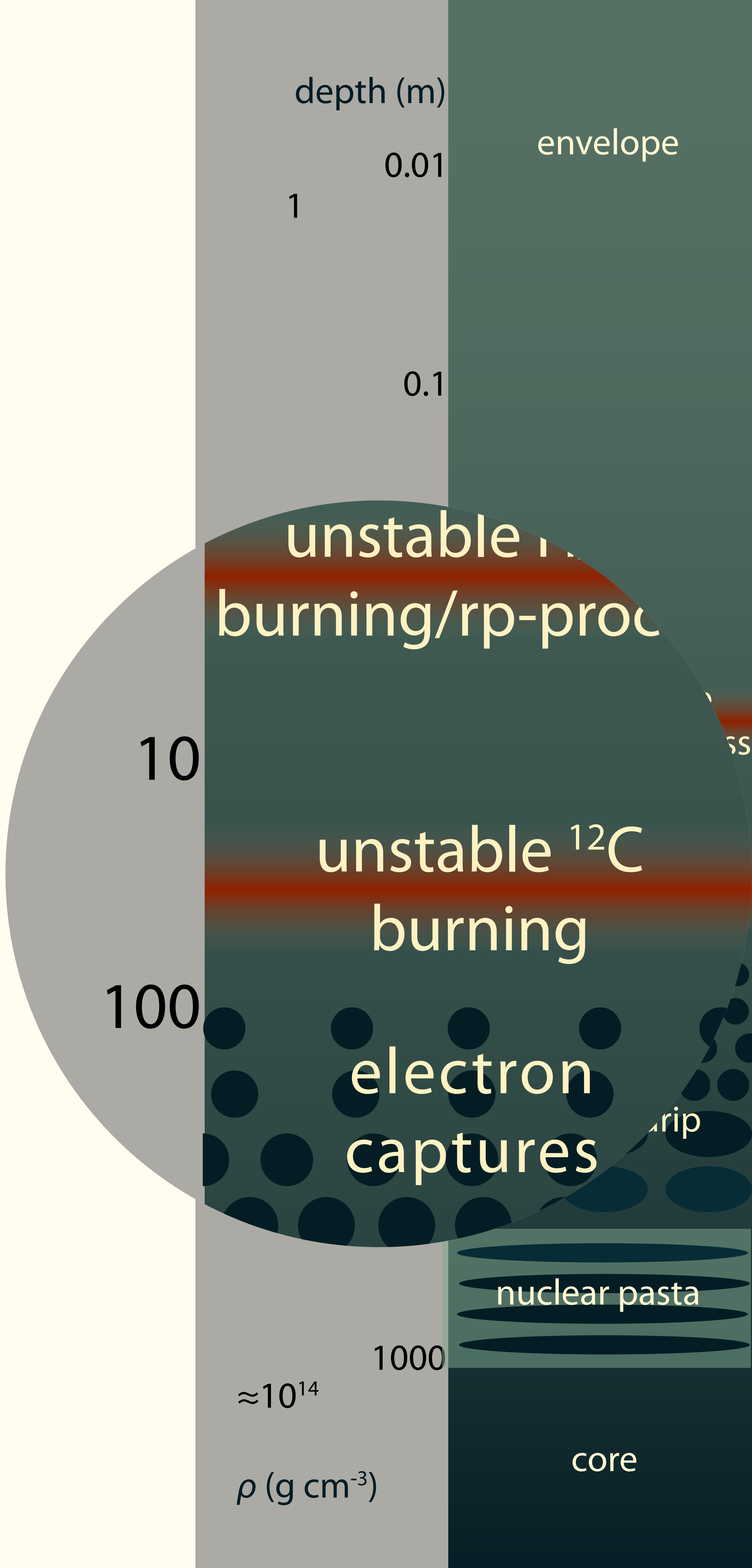
Can we understand the spectra of X-ray bursts enough to constrain neutron star masses and radii?
see Nättilä et al. 2016



Superbursts

Kuulkers et al. 2002





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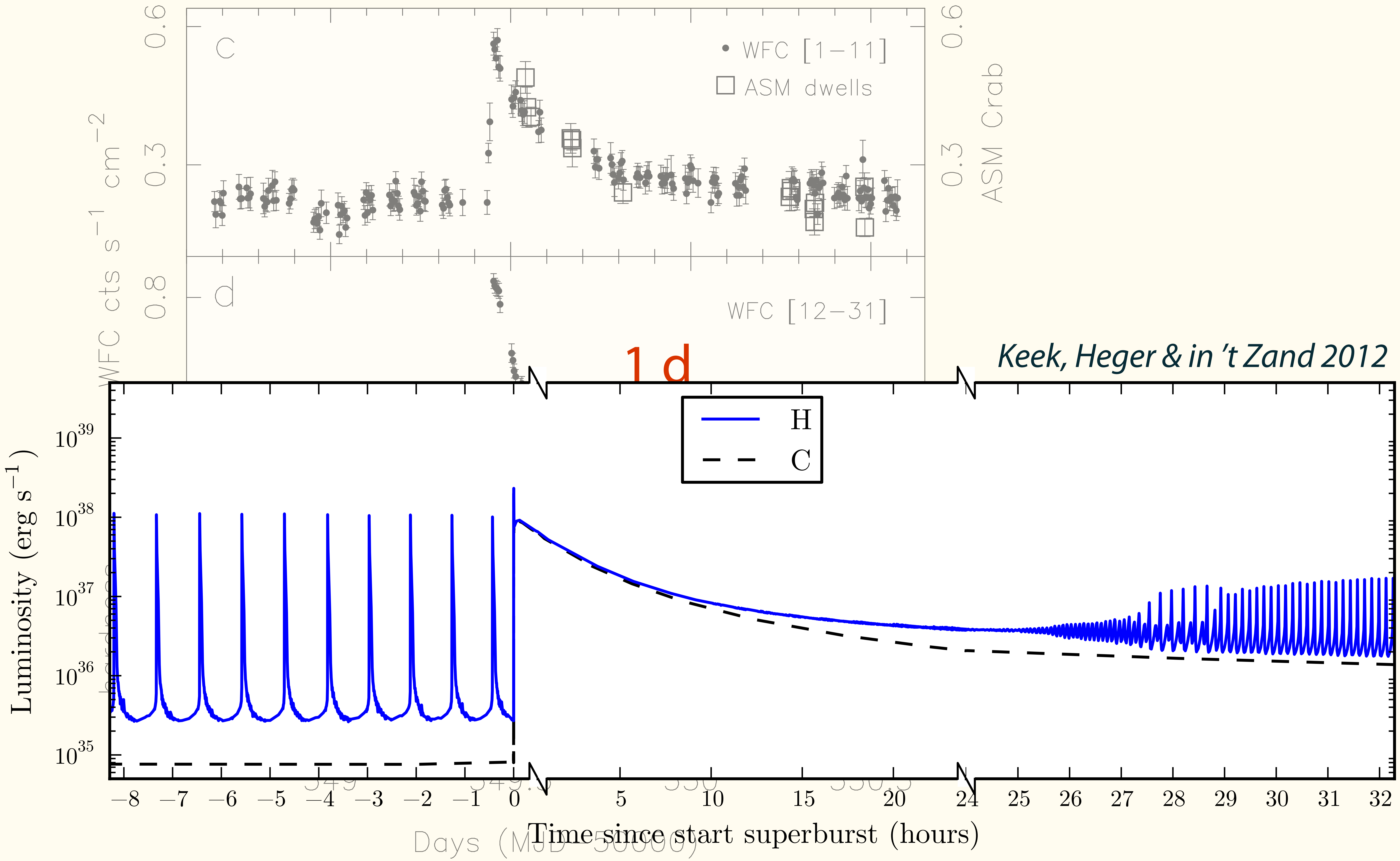
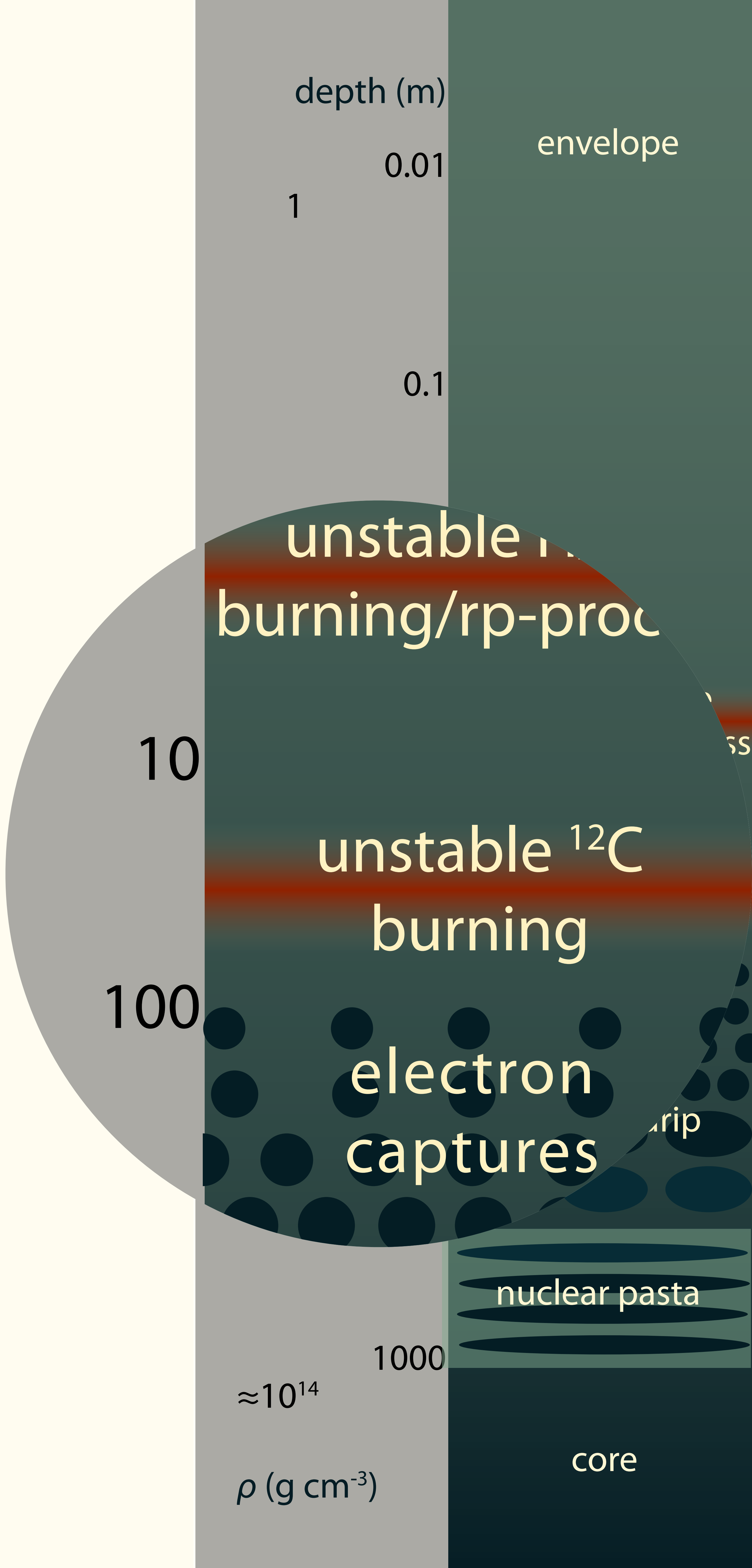


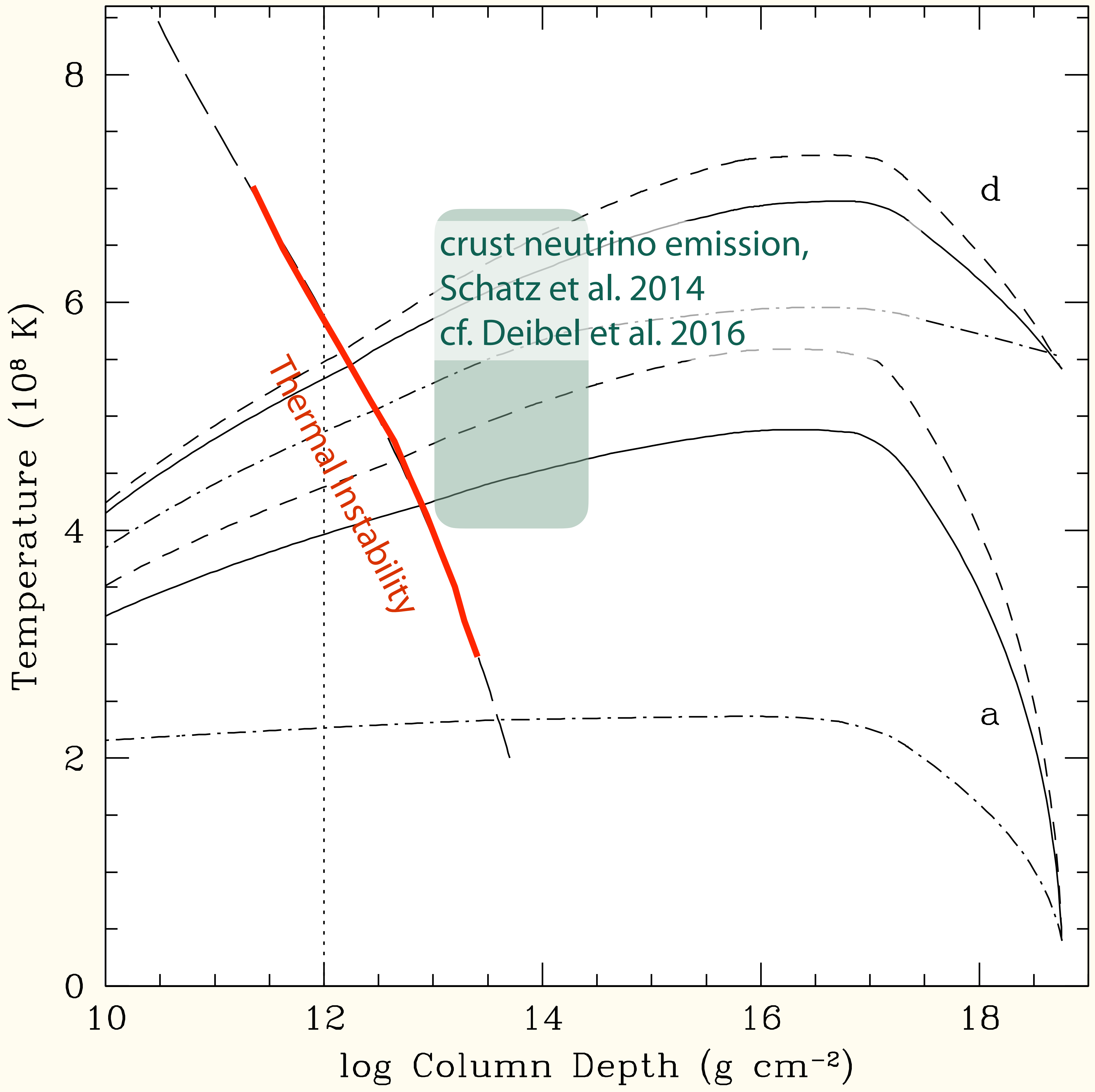


Superbursts

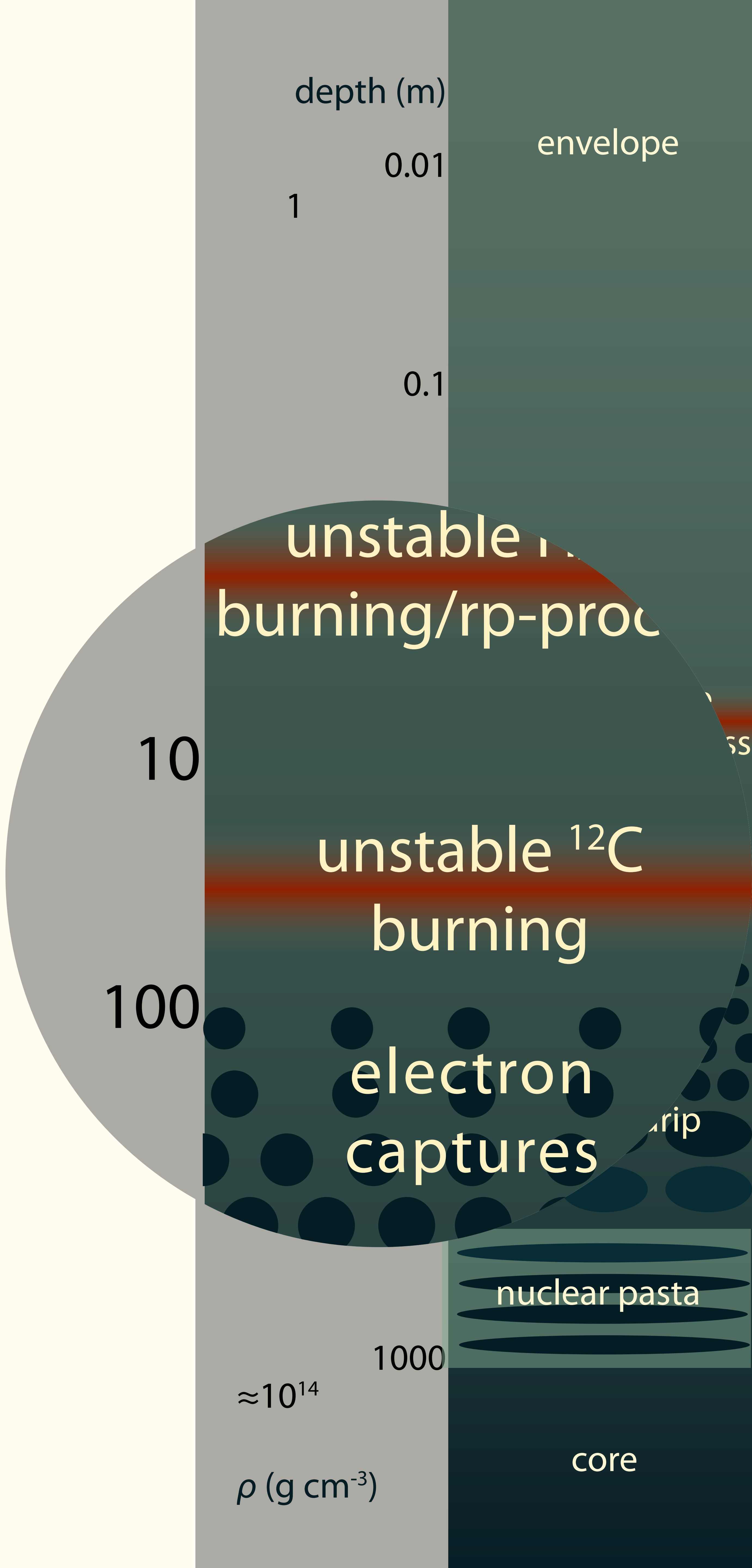
How to produce sufficient ^{12}C?
Stevens et al. 2014

What is the $^{12}C+^{12}C$ cross-section at low energies?
Tumino et al. 2018; cf. Tan et al. 2019, Li et al. 2020

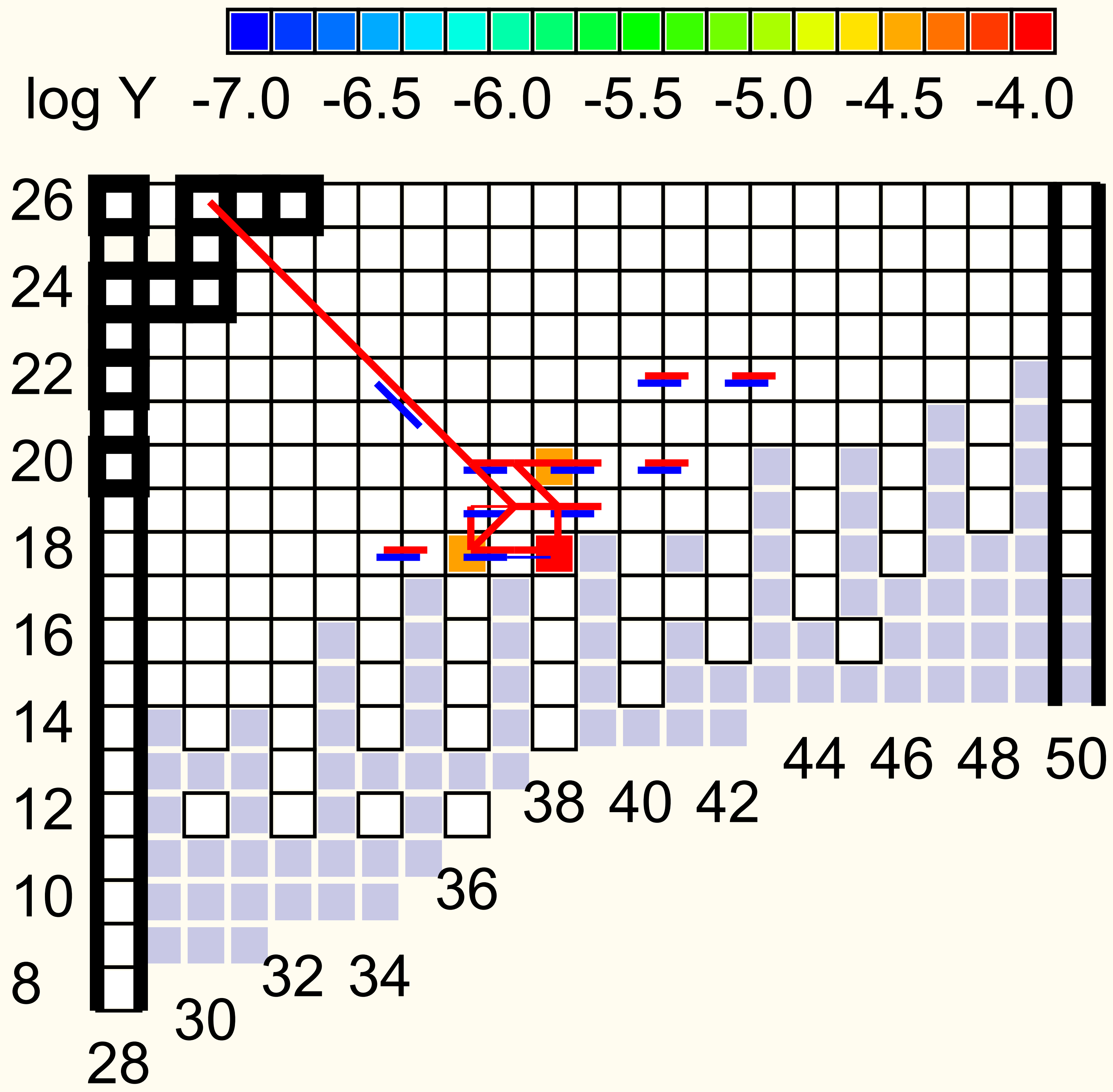
How do we heat the ocean to ignition temperature?
Cumming et al. 2006; Cooper et al. 2009

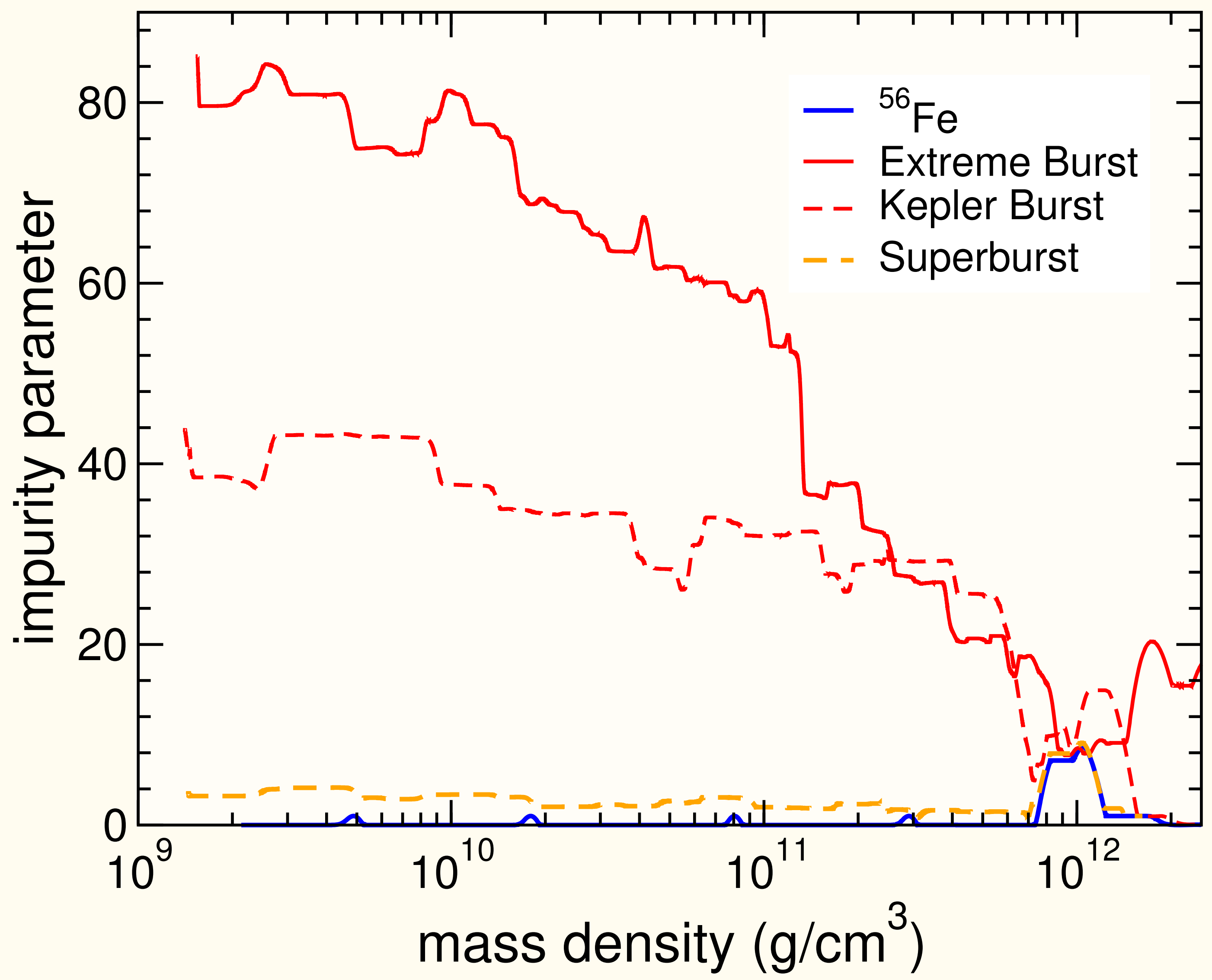


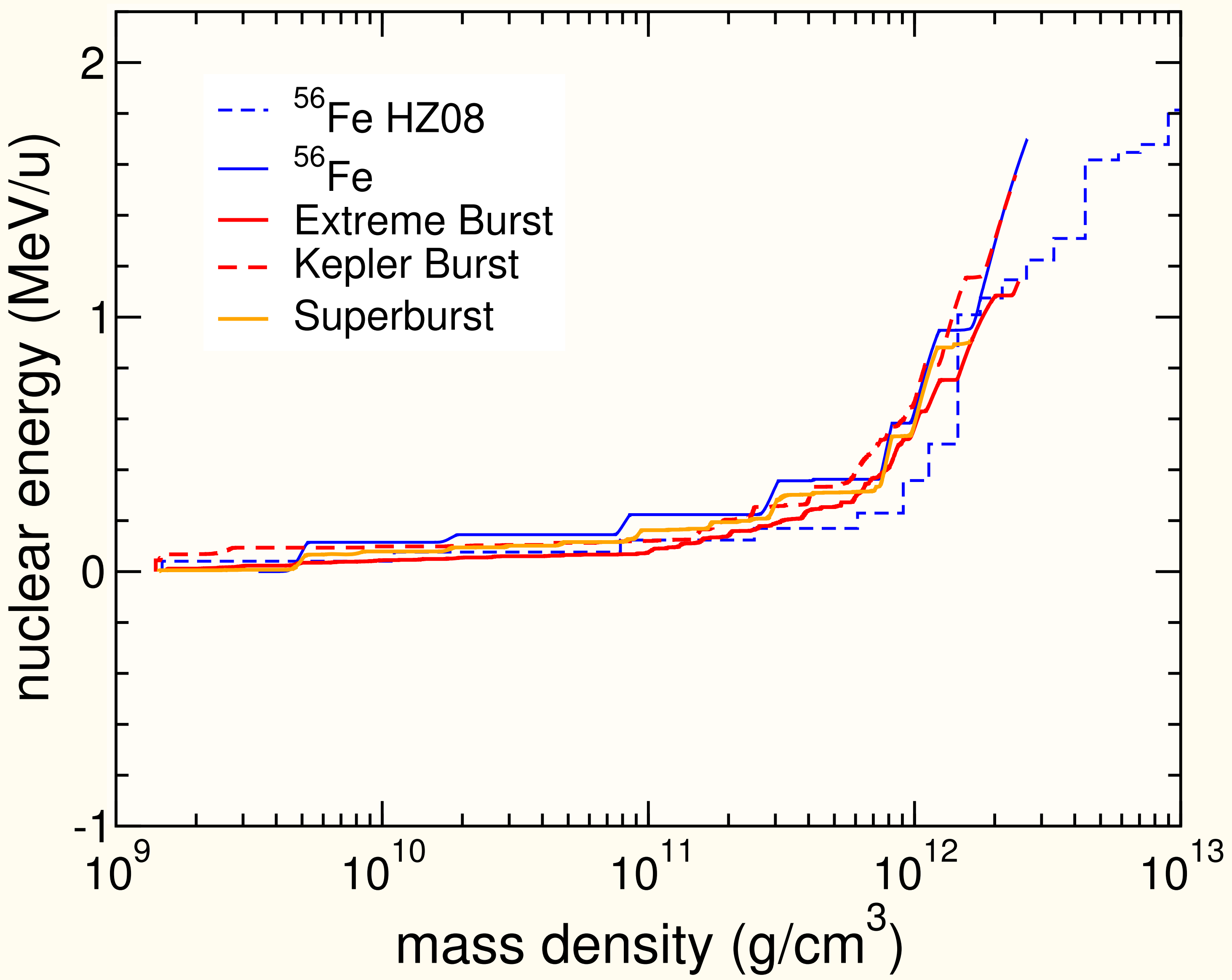
Cumming et al. 2006



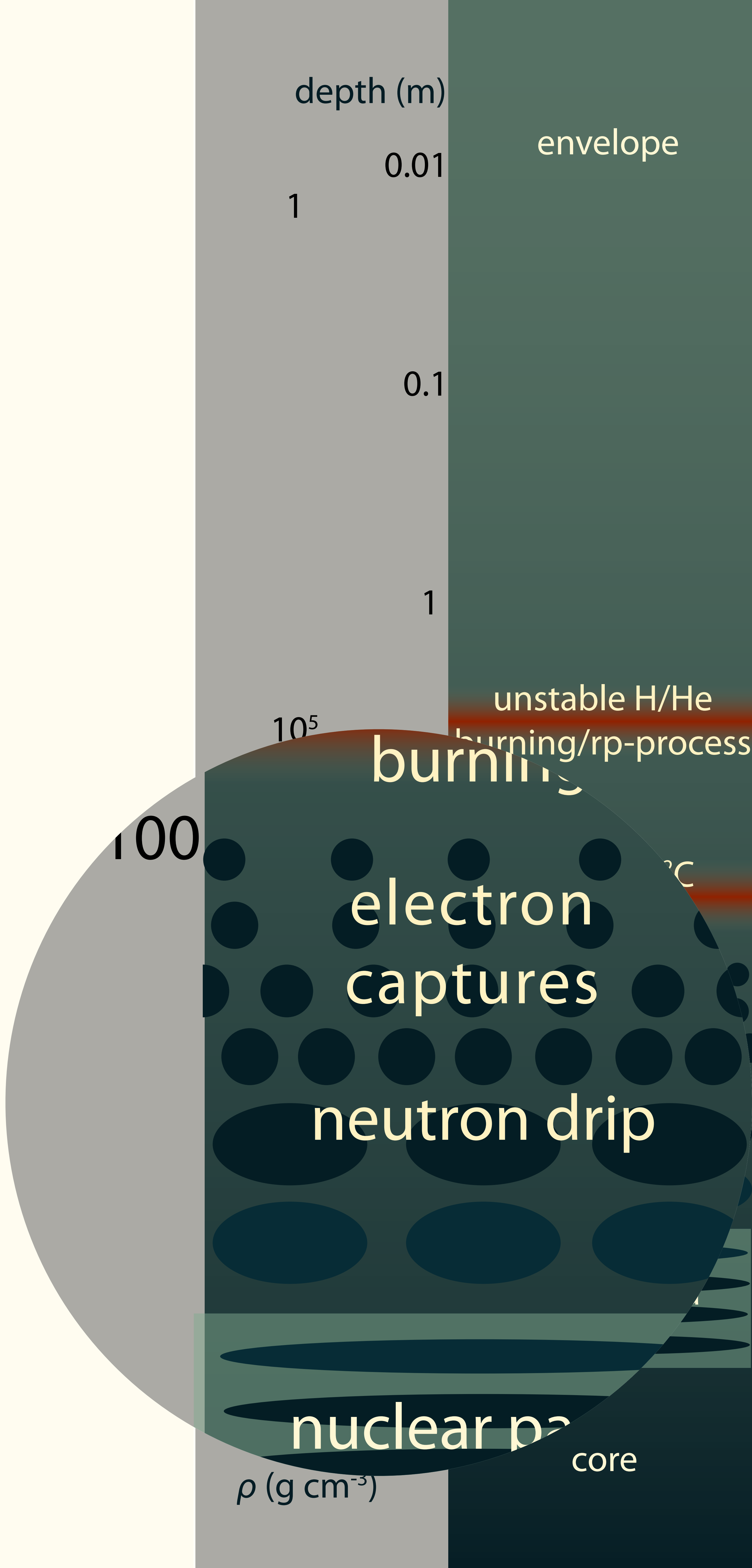
Heating in the deep crust



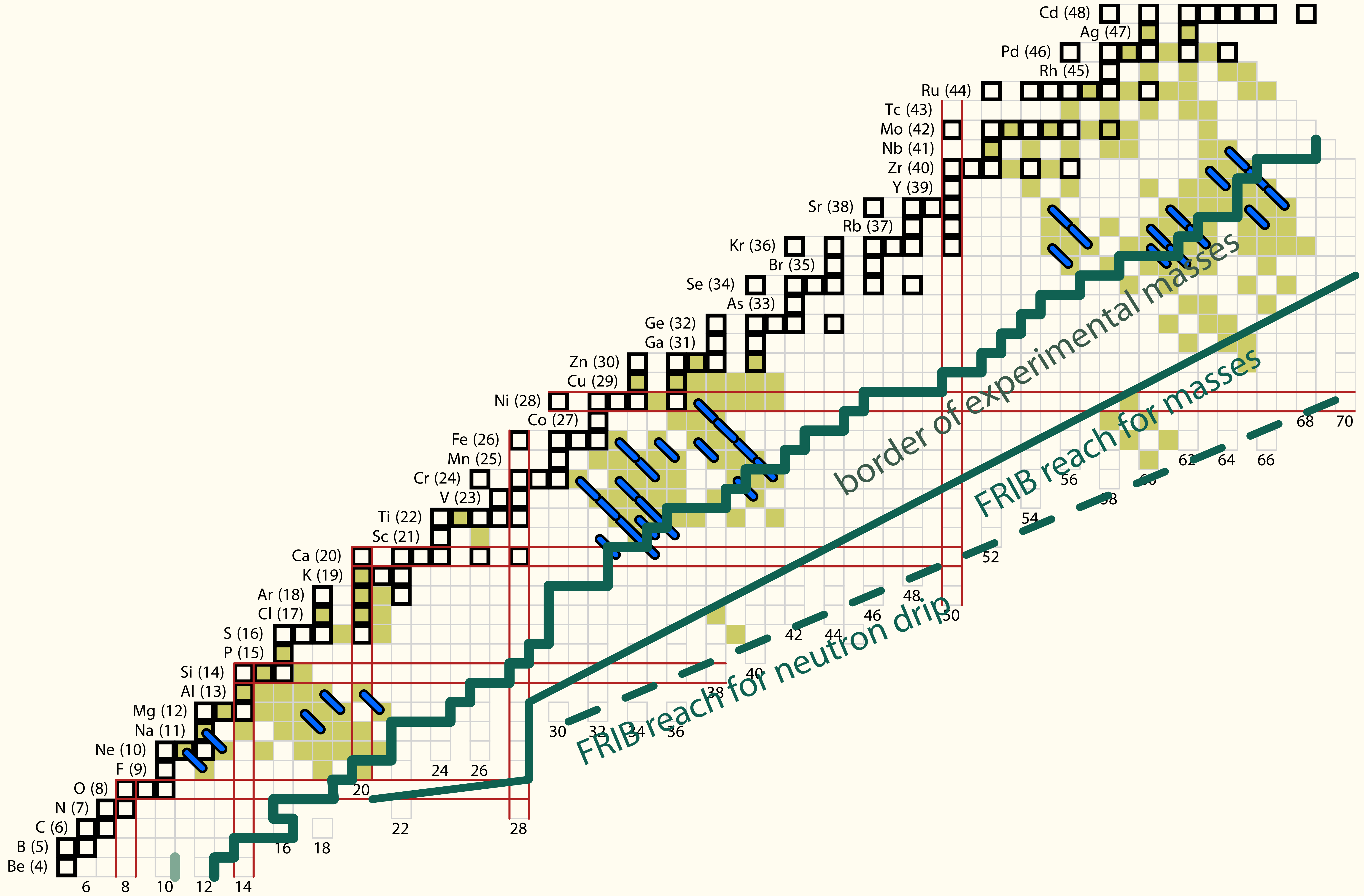


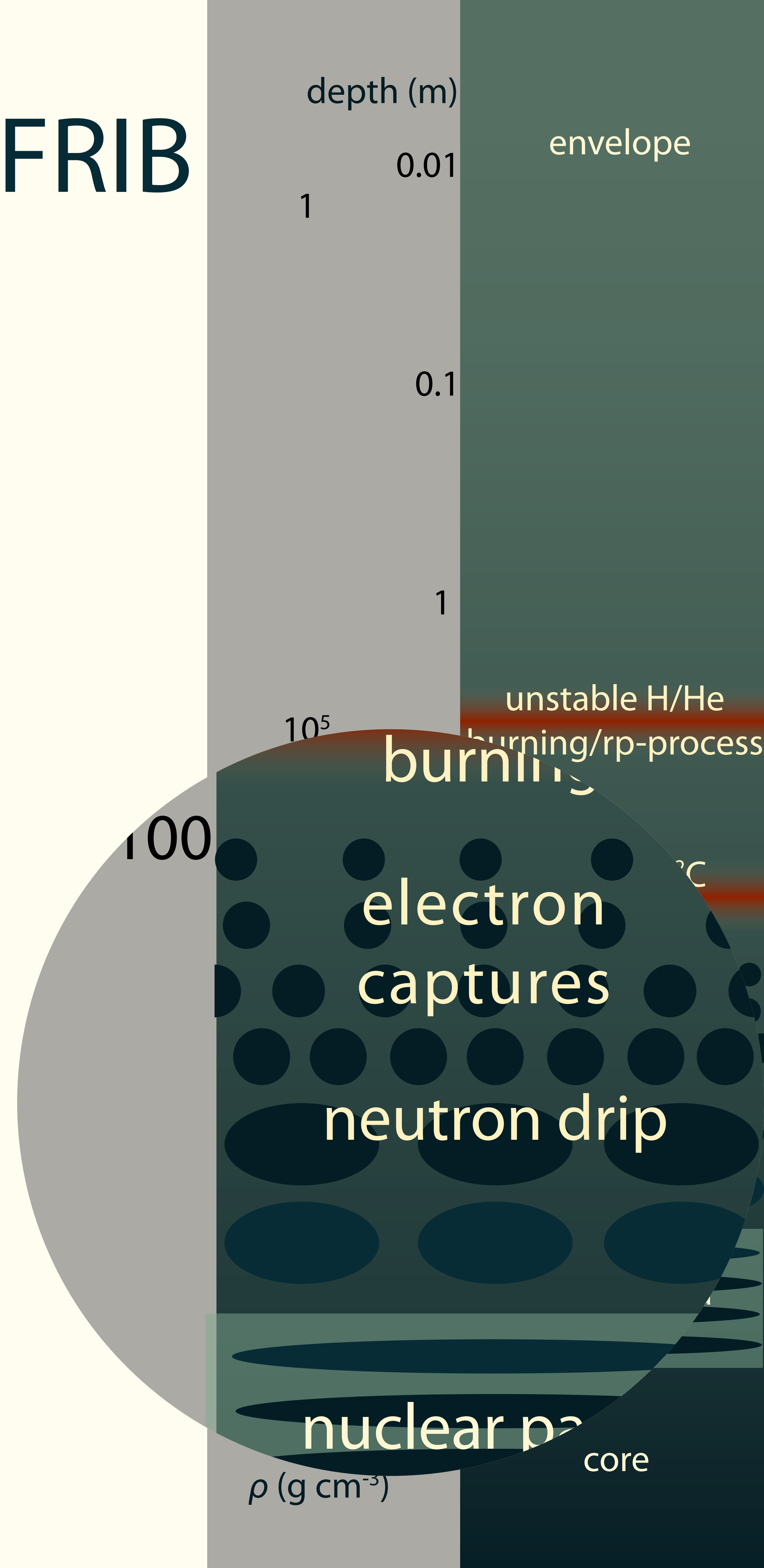


Lau et al. 2018



Much of the outer crust is accessible with FRIB

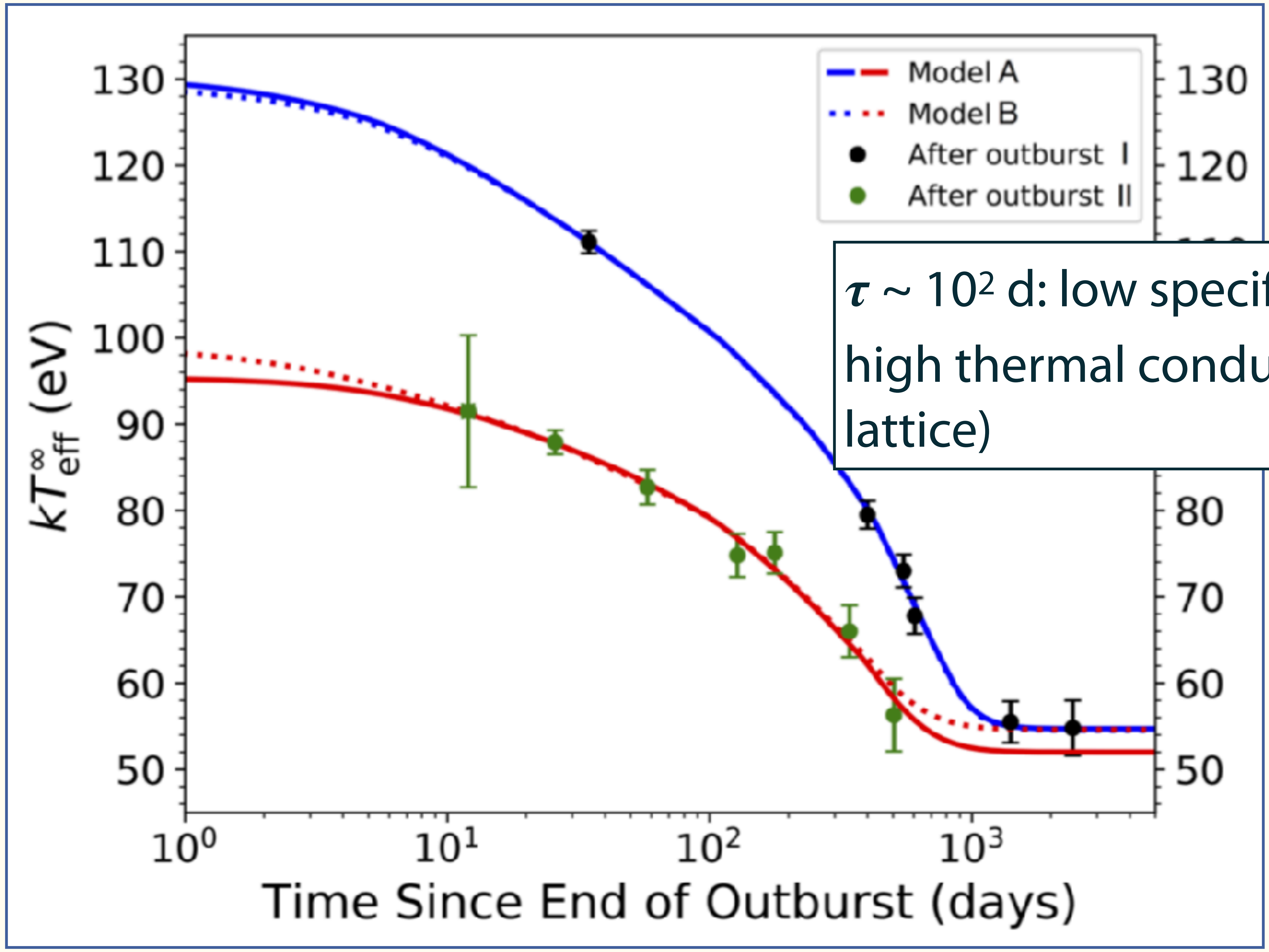




Transient neutron stars in quiescence

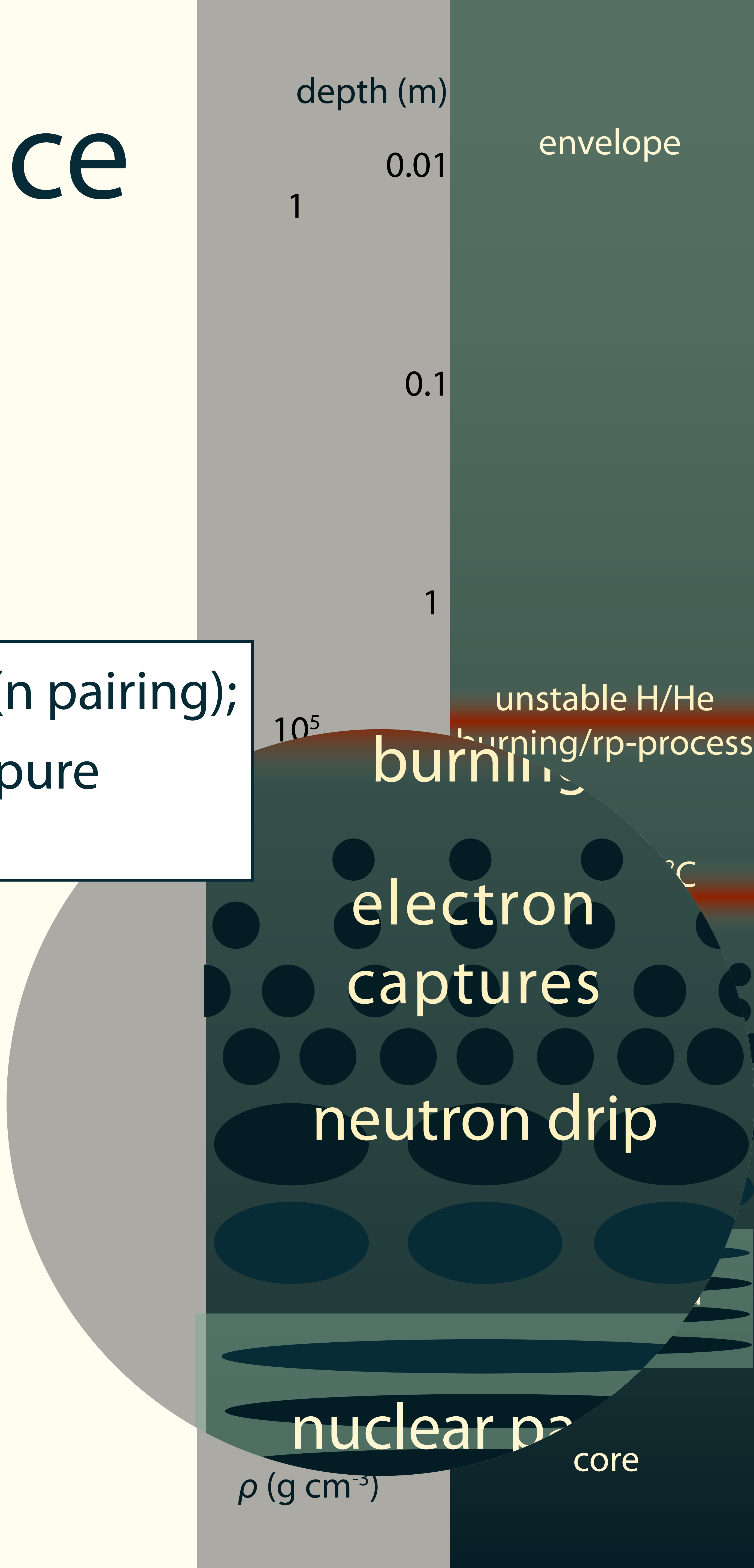
MXB 1659-29

Parikh et al. 2019



$\tau \sim 10^2$ d: low specific heat (n pairing); high thermal conductivity (pure lattice)

see Shternin et al. '07; Brown & Cumming '09; Degenaar '11, '13, '15; Page & Reddy '13; Turlione '13; Deibel et al. '17; Merritt et al. '16; Waterhouse et al. '16; Parikh et al. '17, '19



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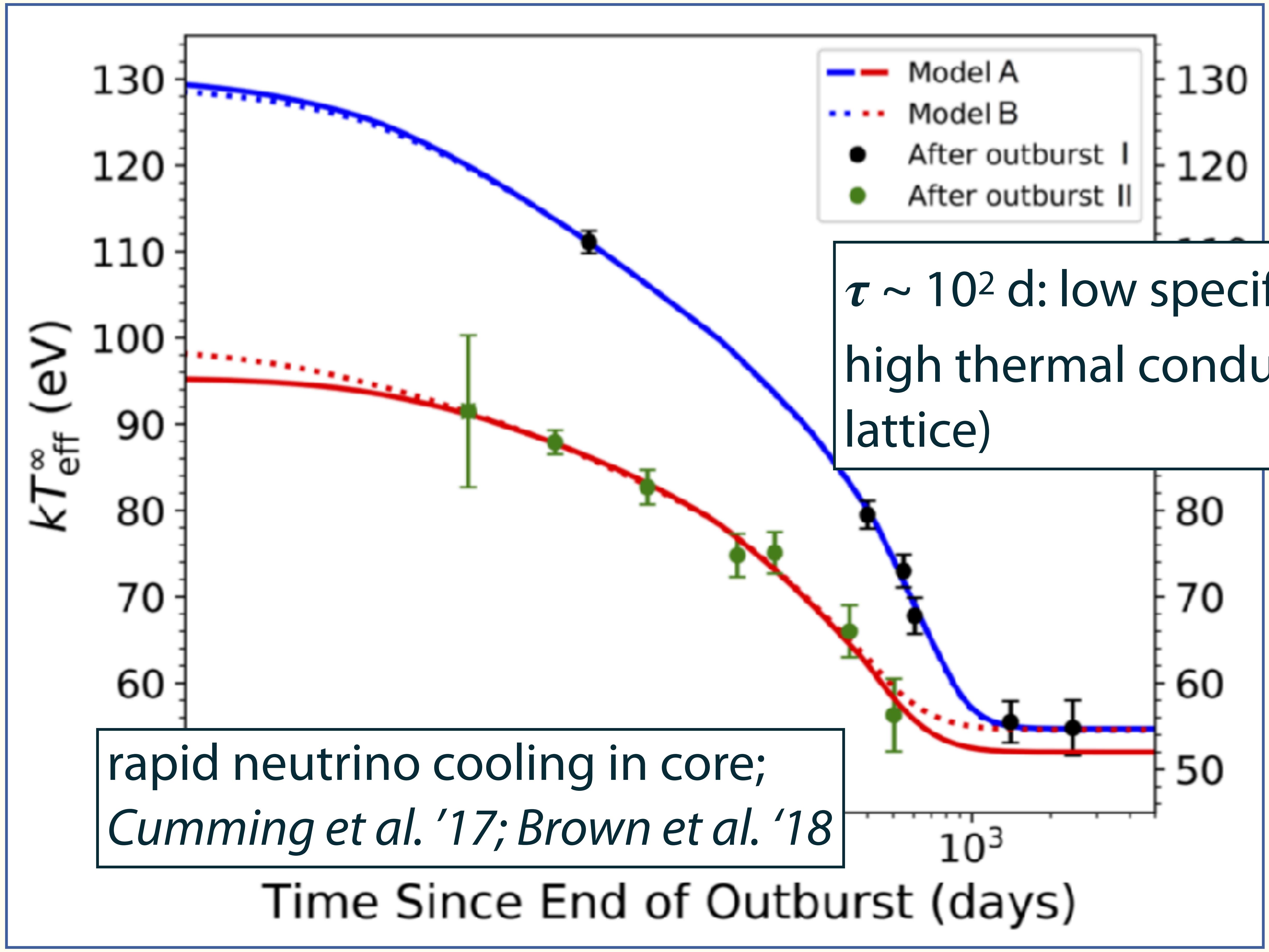

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rapid neutrino cooling in core; *Cumming et al. '17; Brown et al. '18*

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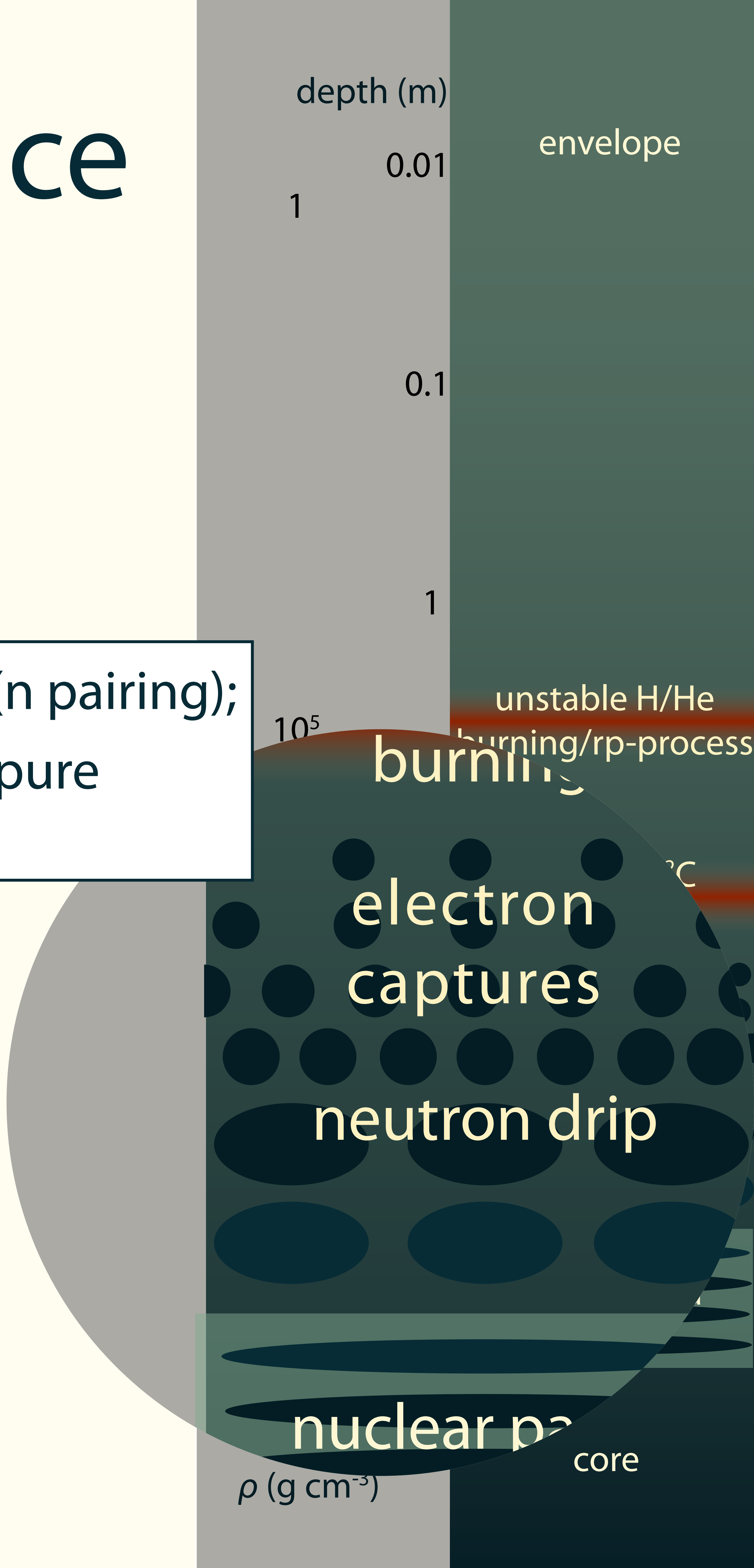

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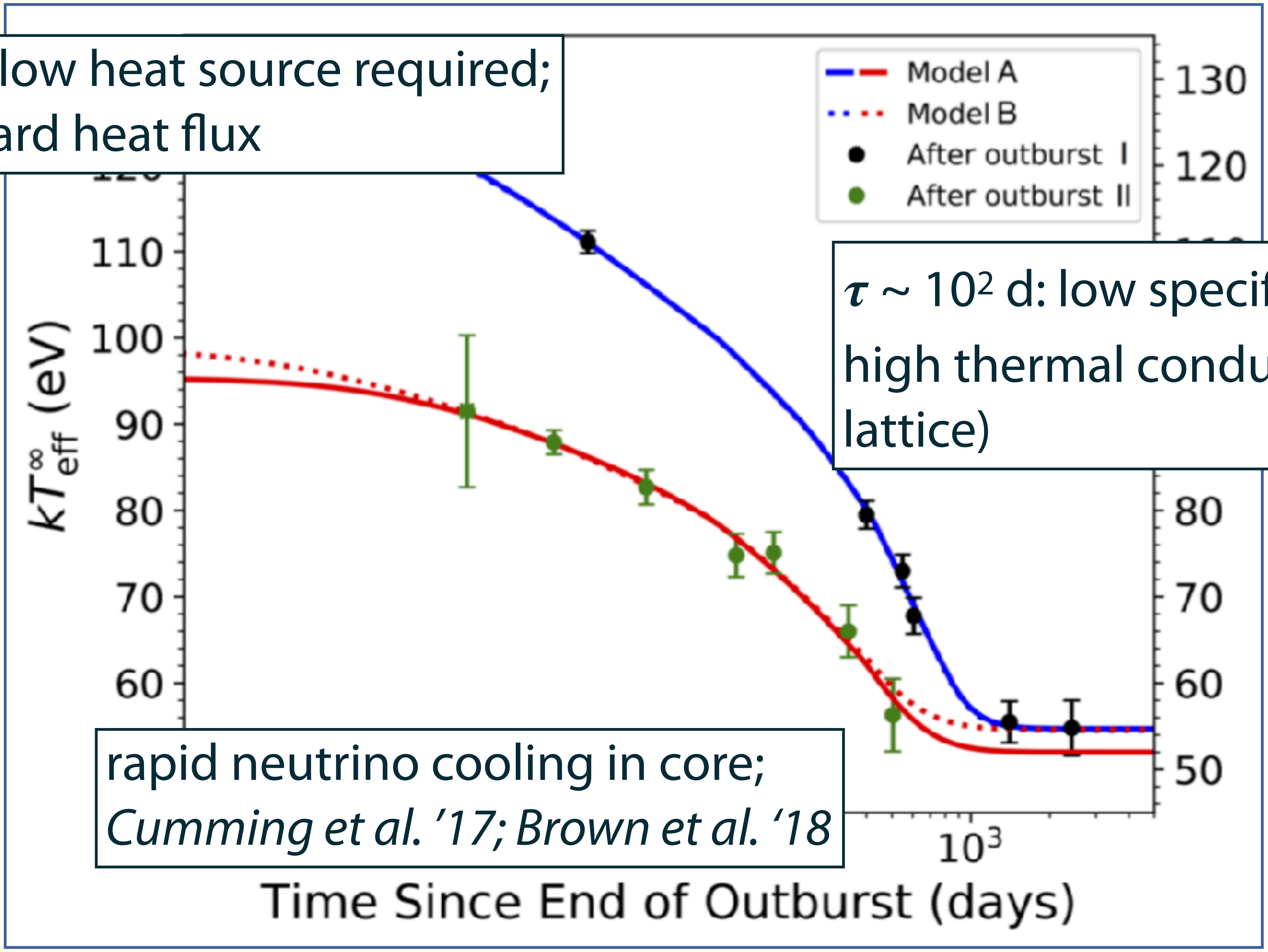

shallow heat source required; inward heat flux

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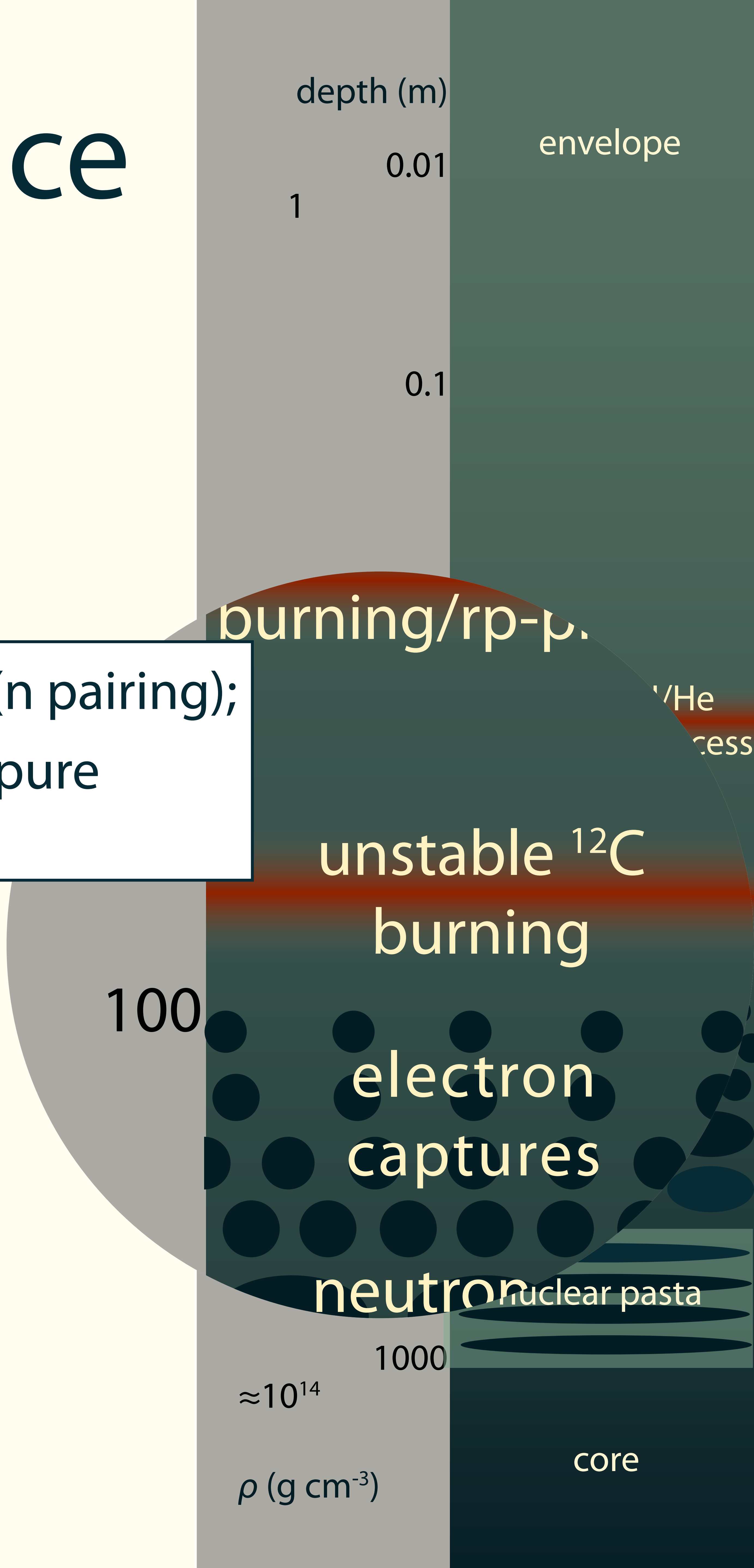
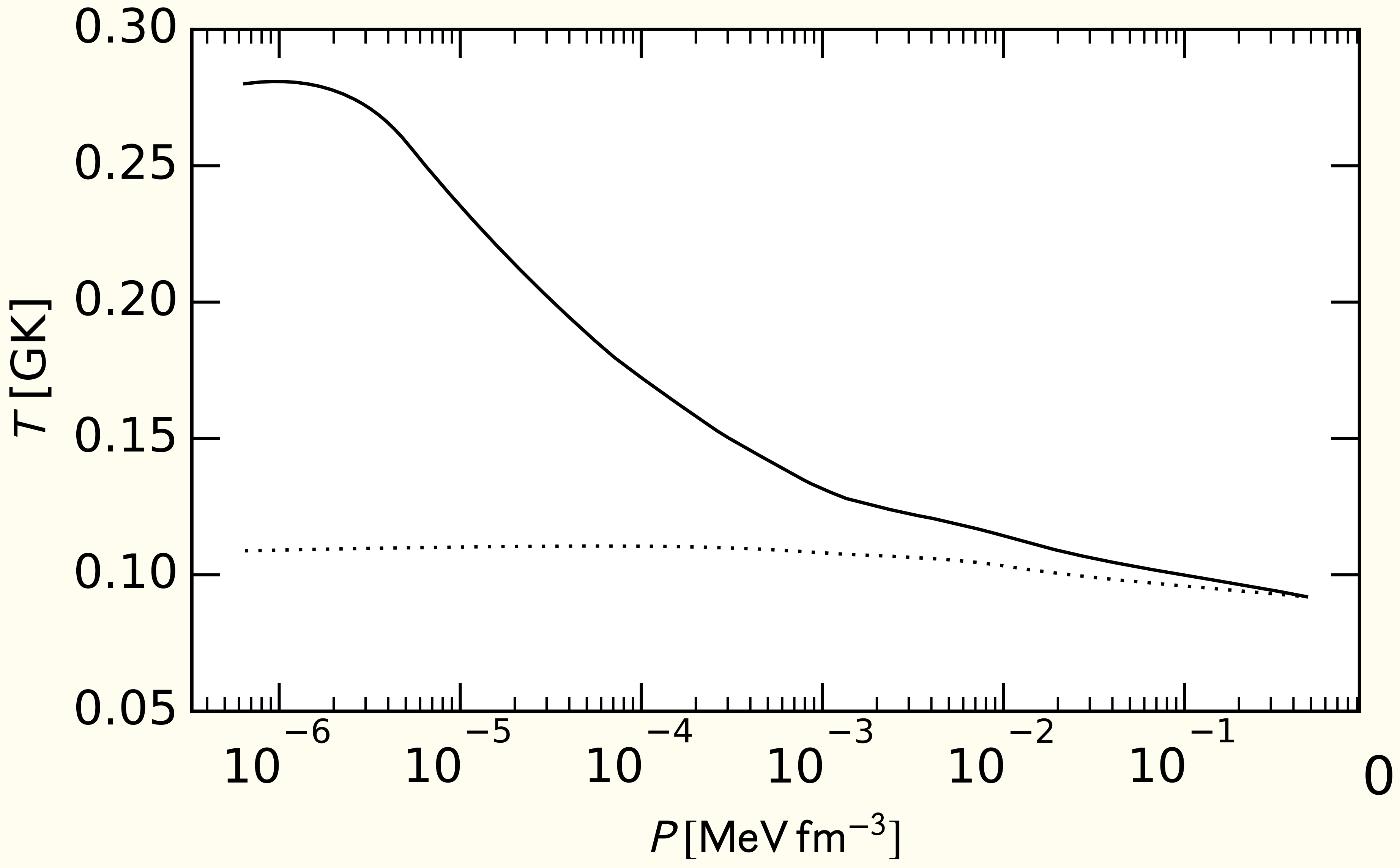
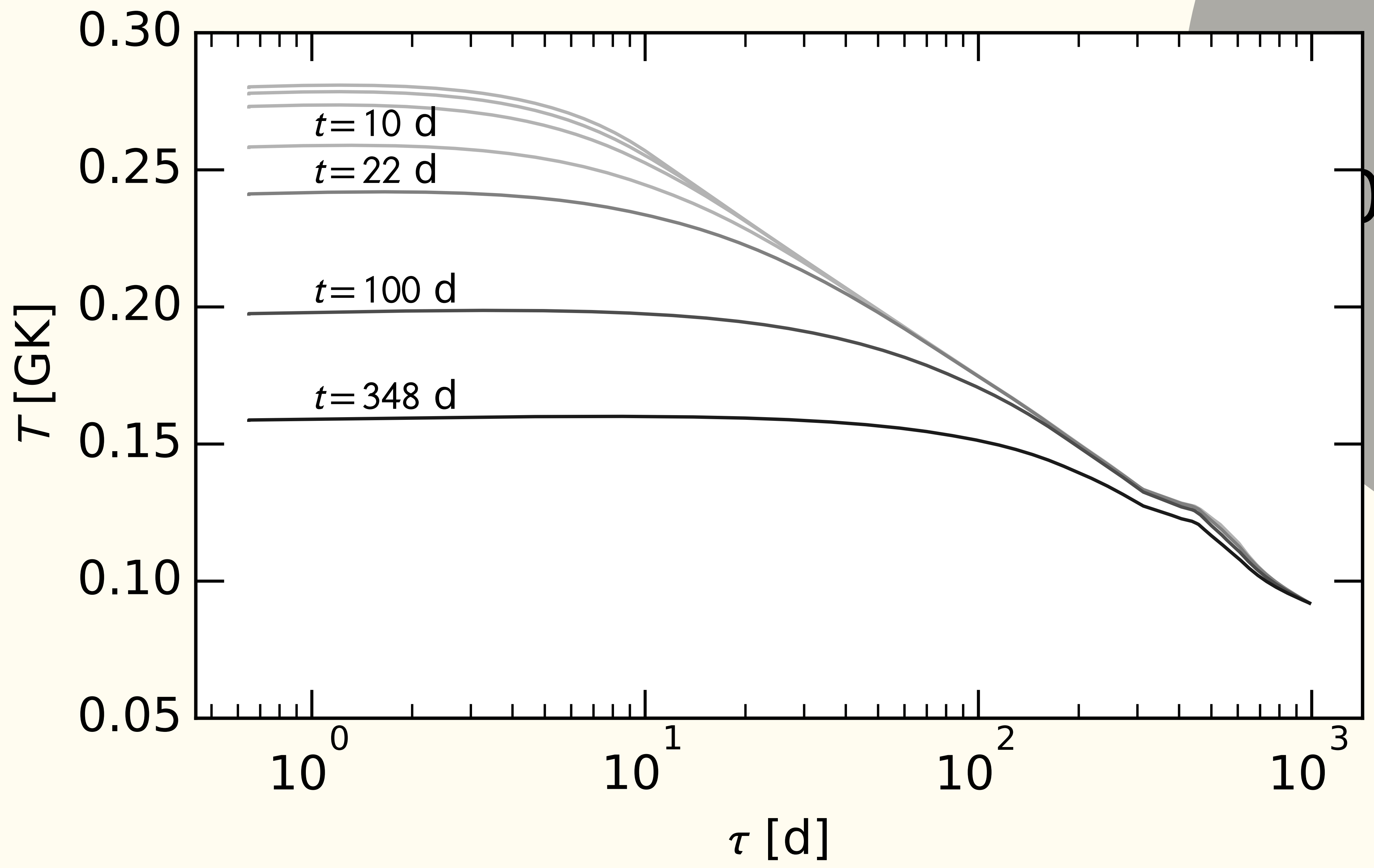
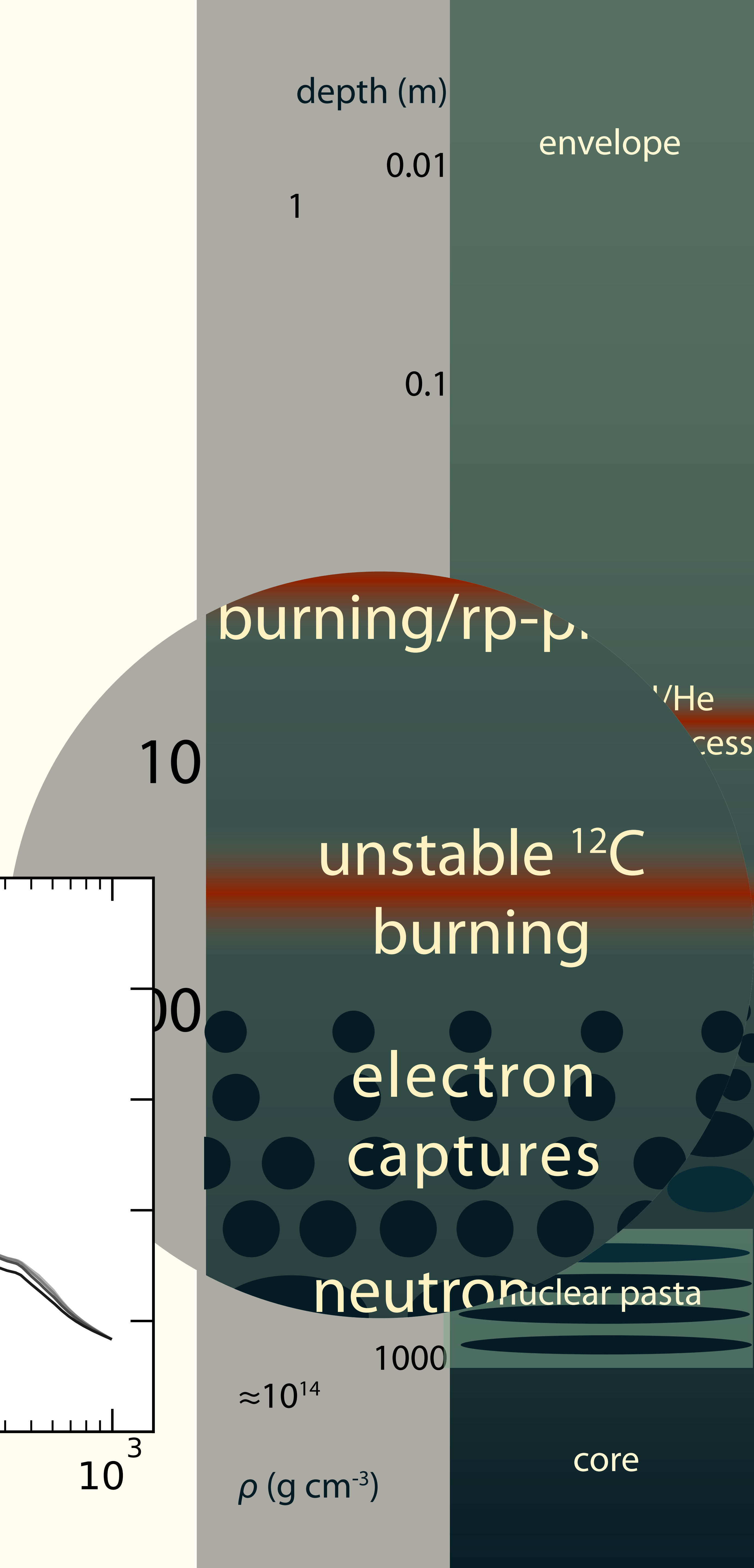


Effect of shallow heating



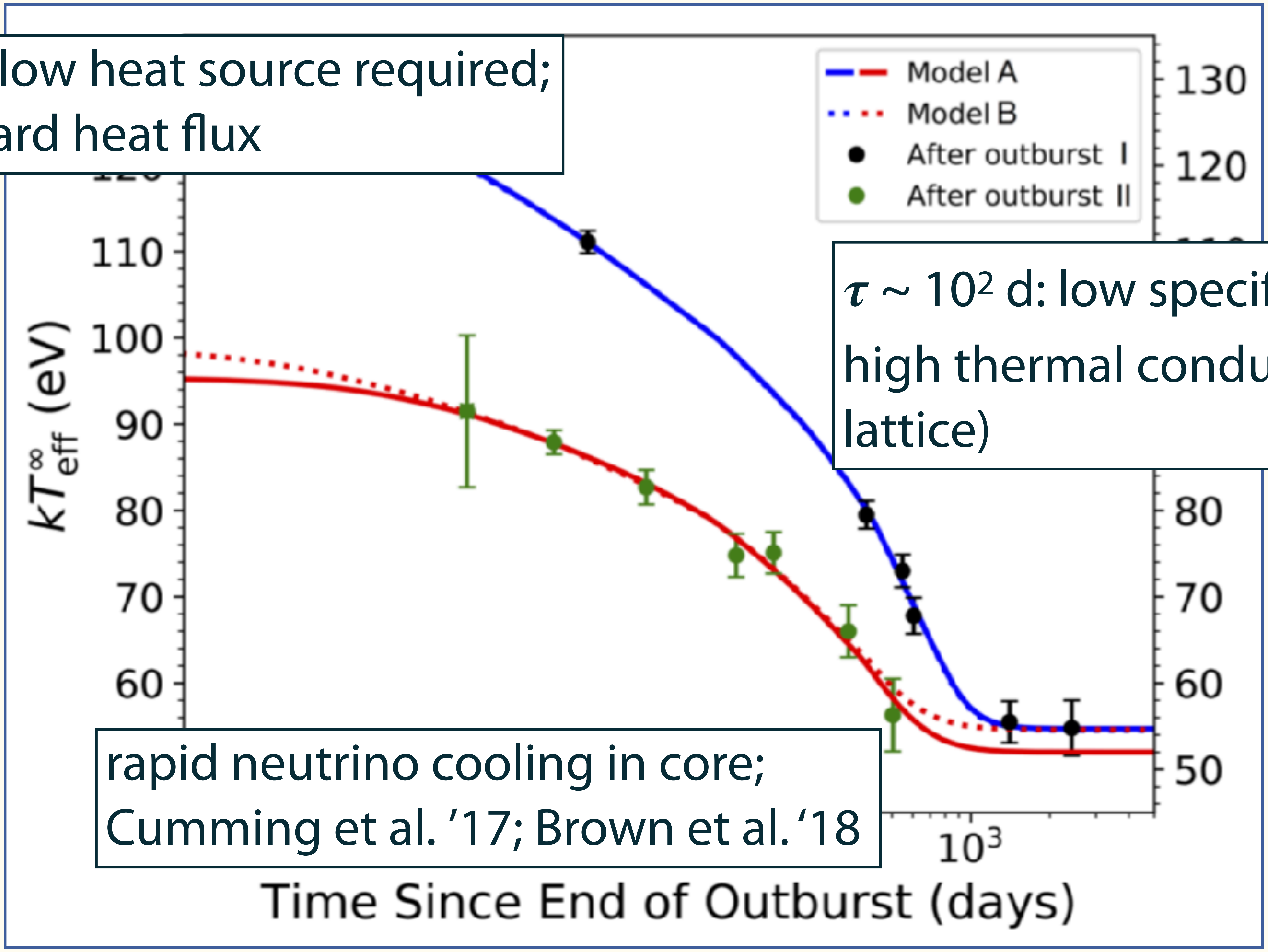




Transient neutron stars in quiescence

MXB 1659-29

Parikh et al. 2019



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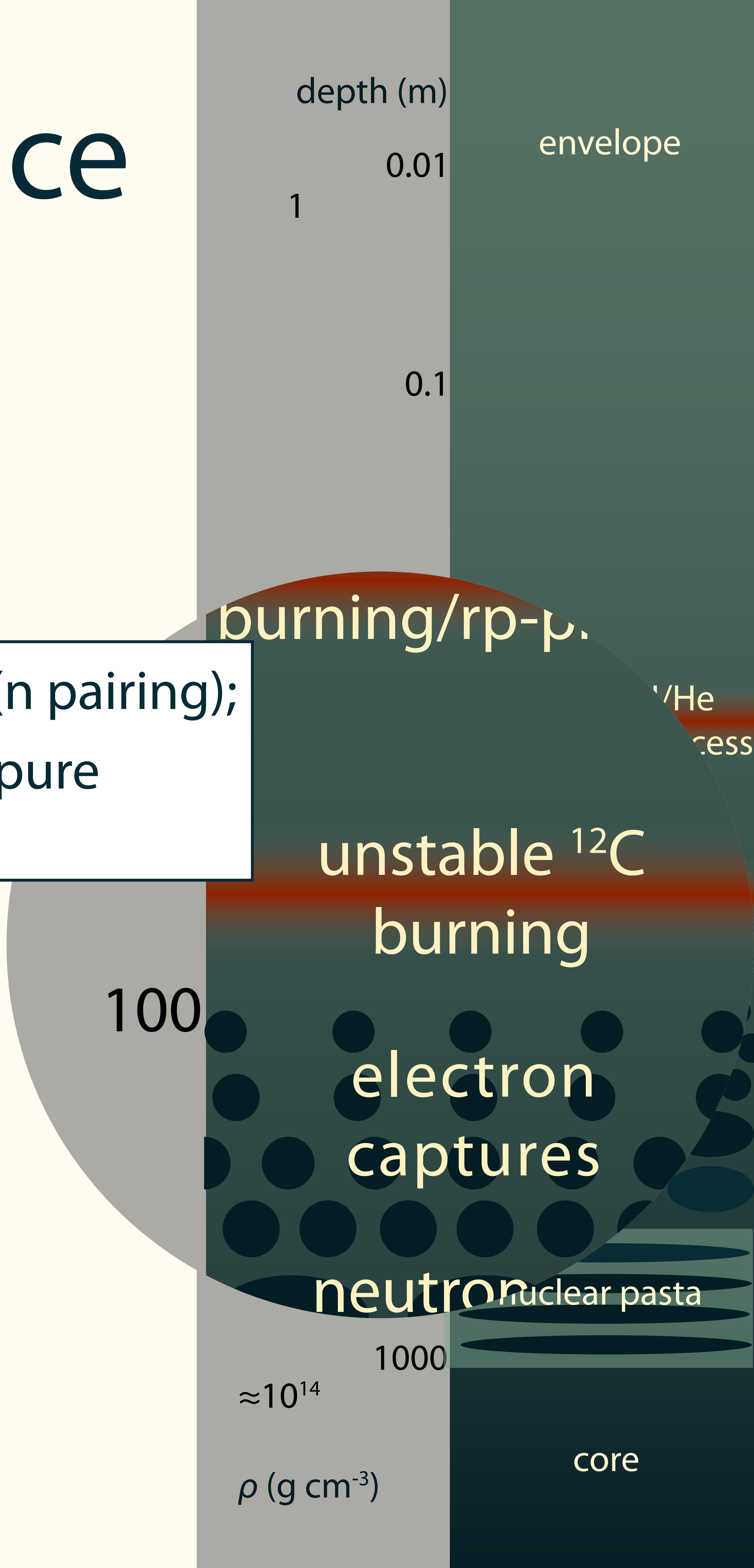


The deep crust

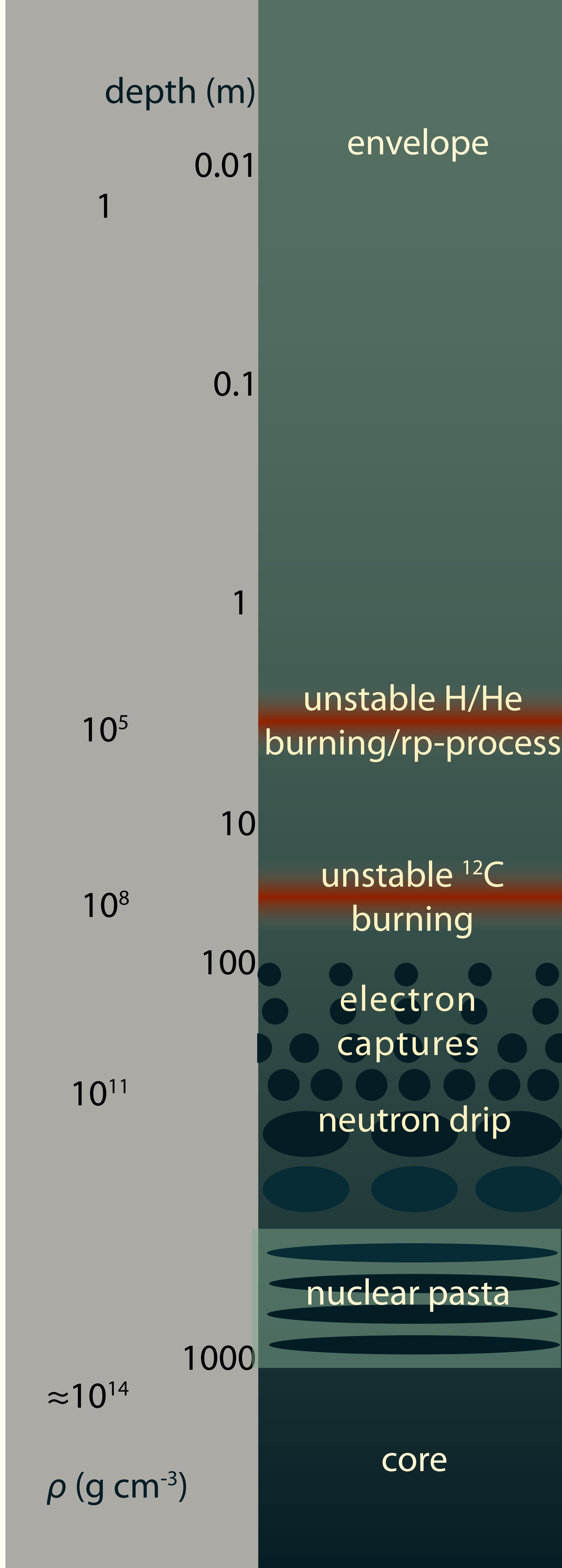
What is the source of the shallow heating? How much does it vary? *Degenaar et al. 2019*

At what point does the composition relax to its ground state?

How does diffusion of superfluid neutrons change the heating and composition? *Gusakov & Chuganov 2020*

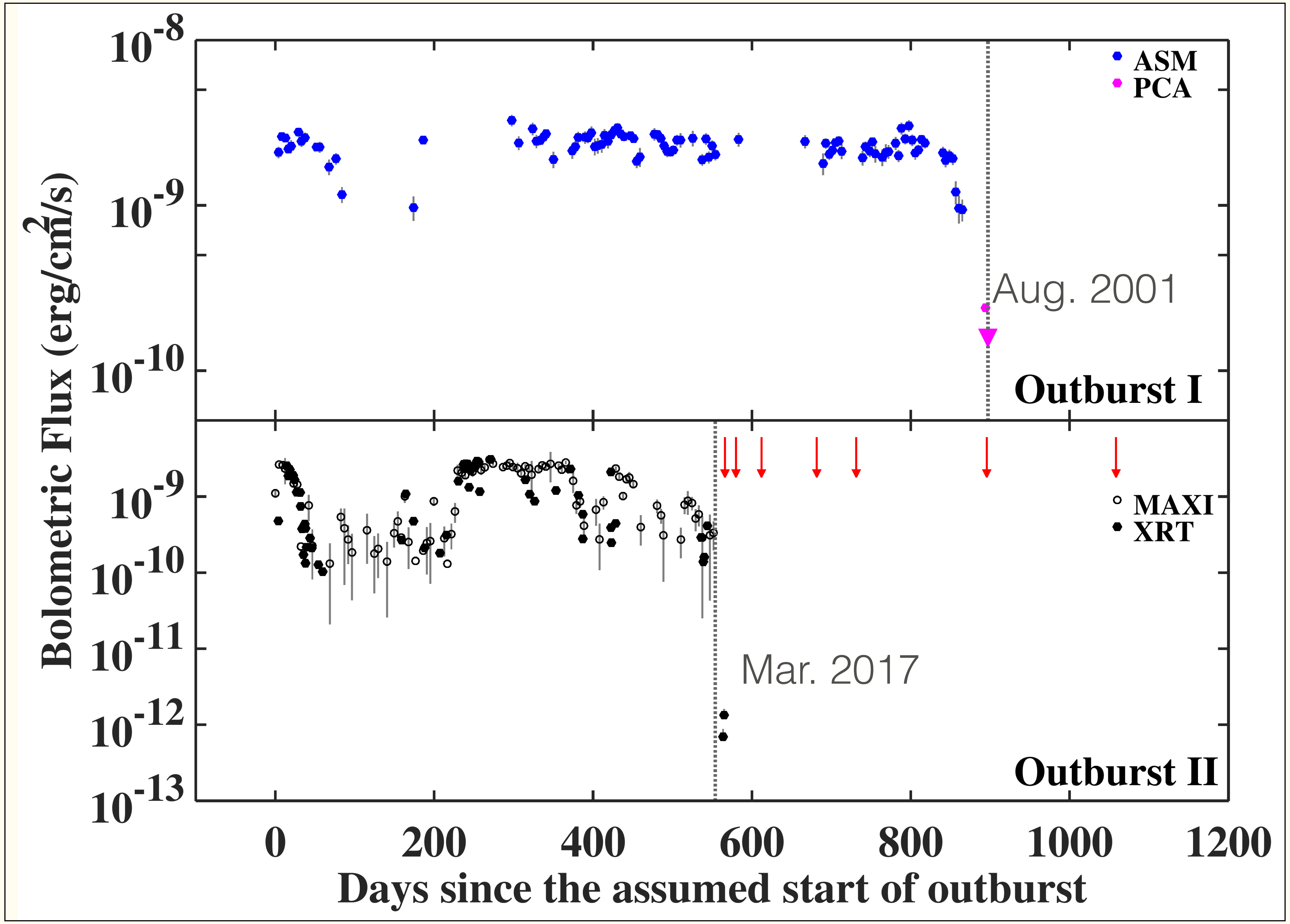
Can we find an unambiguous signature of pasta?
see Deibel et al. 2017

What will further observations of transients reveal about the core specific heat and neutrino emissivity?



extra slides

Update: Cooling of MXB1659-29 following outburst ending 2017



Parikh et al. 2018

Suppose core cools completely between outbursts and neutrino cooling is off

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

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

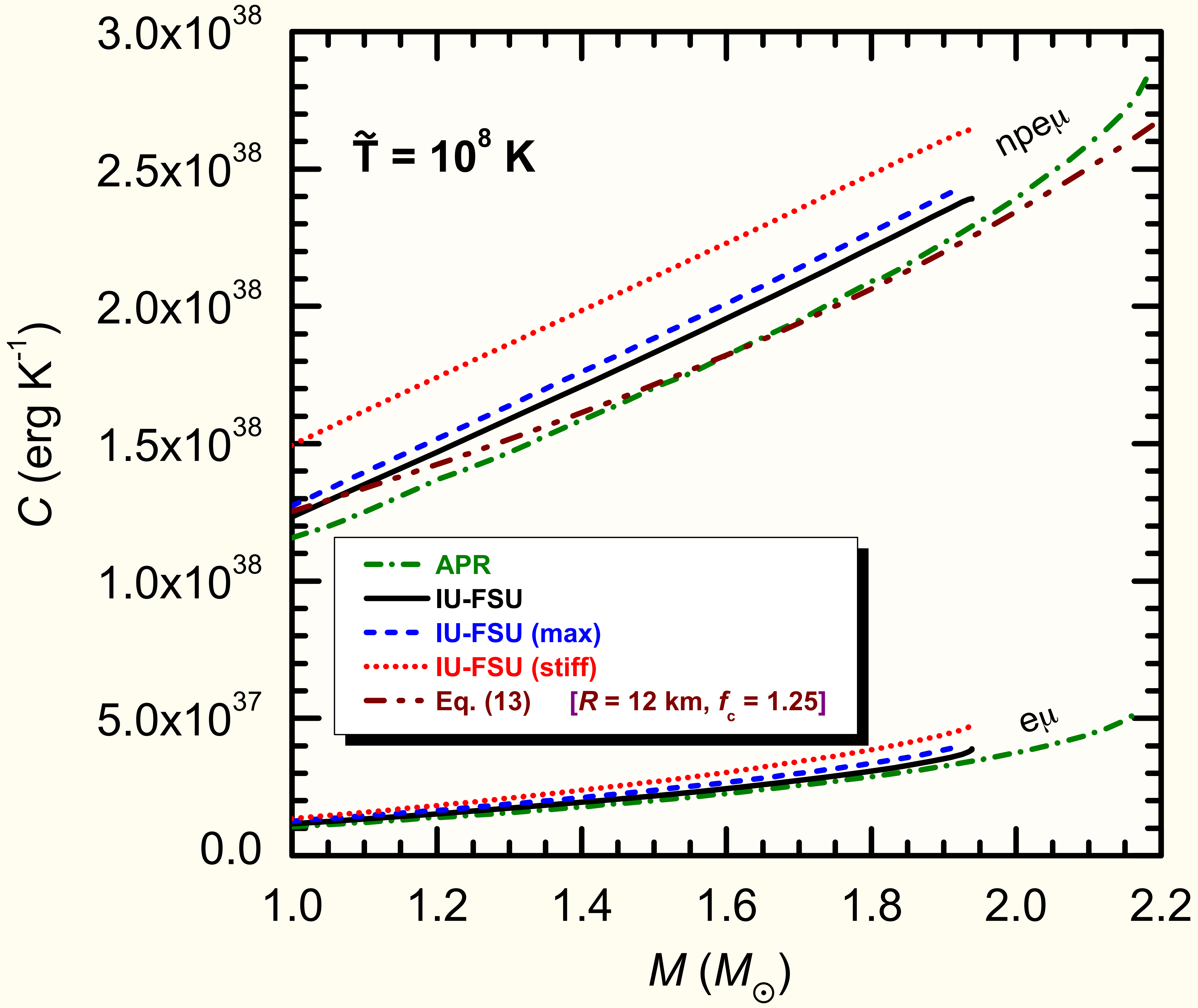
$$C > \frac{2E}{\tilde{T}_f} \quad \text{with} \quad E = \int L_{\rm in}\, dt$$

since $\quad C \sim T$

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

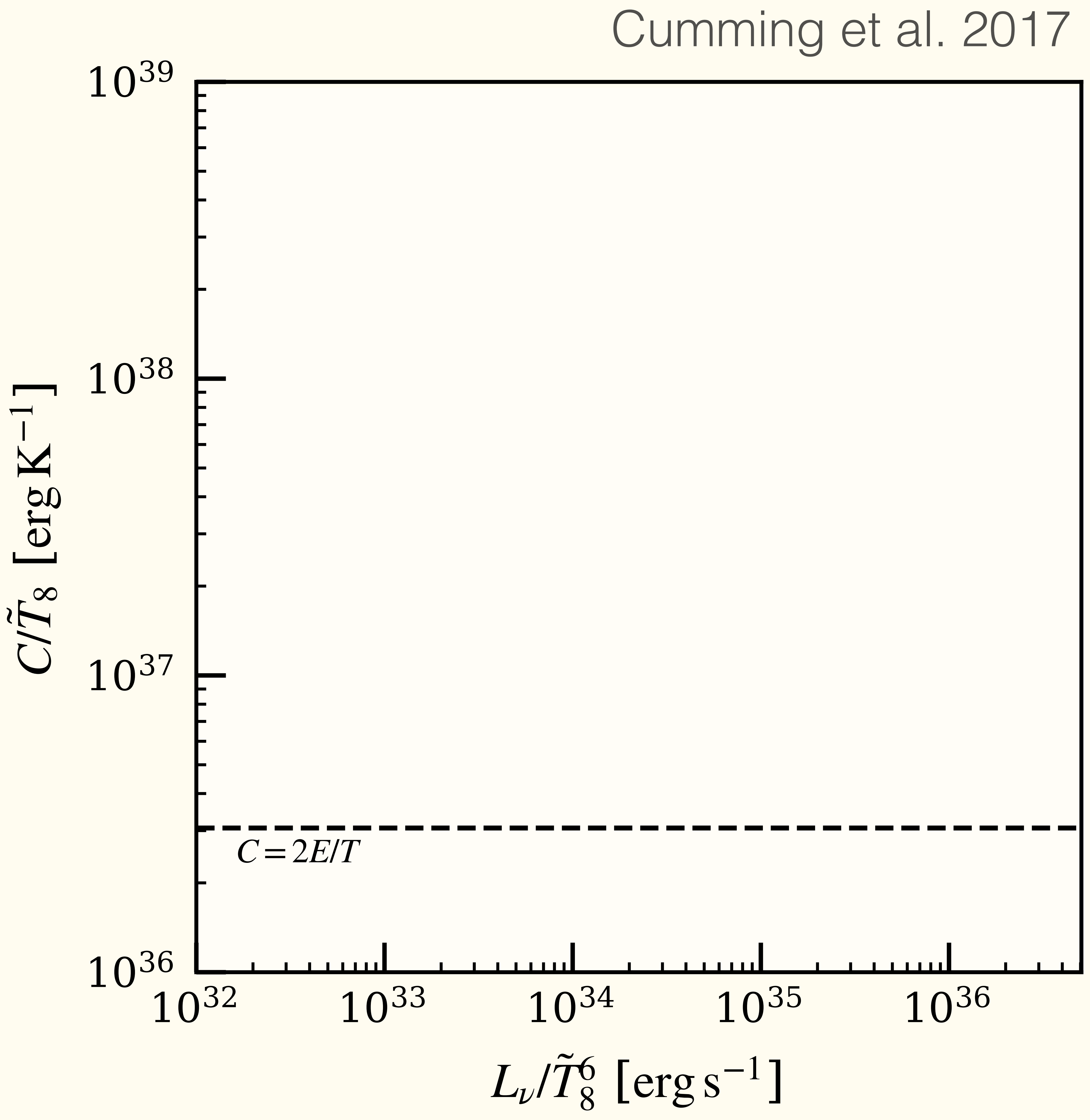
The specific heat must be larger than this!

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

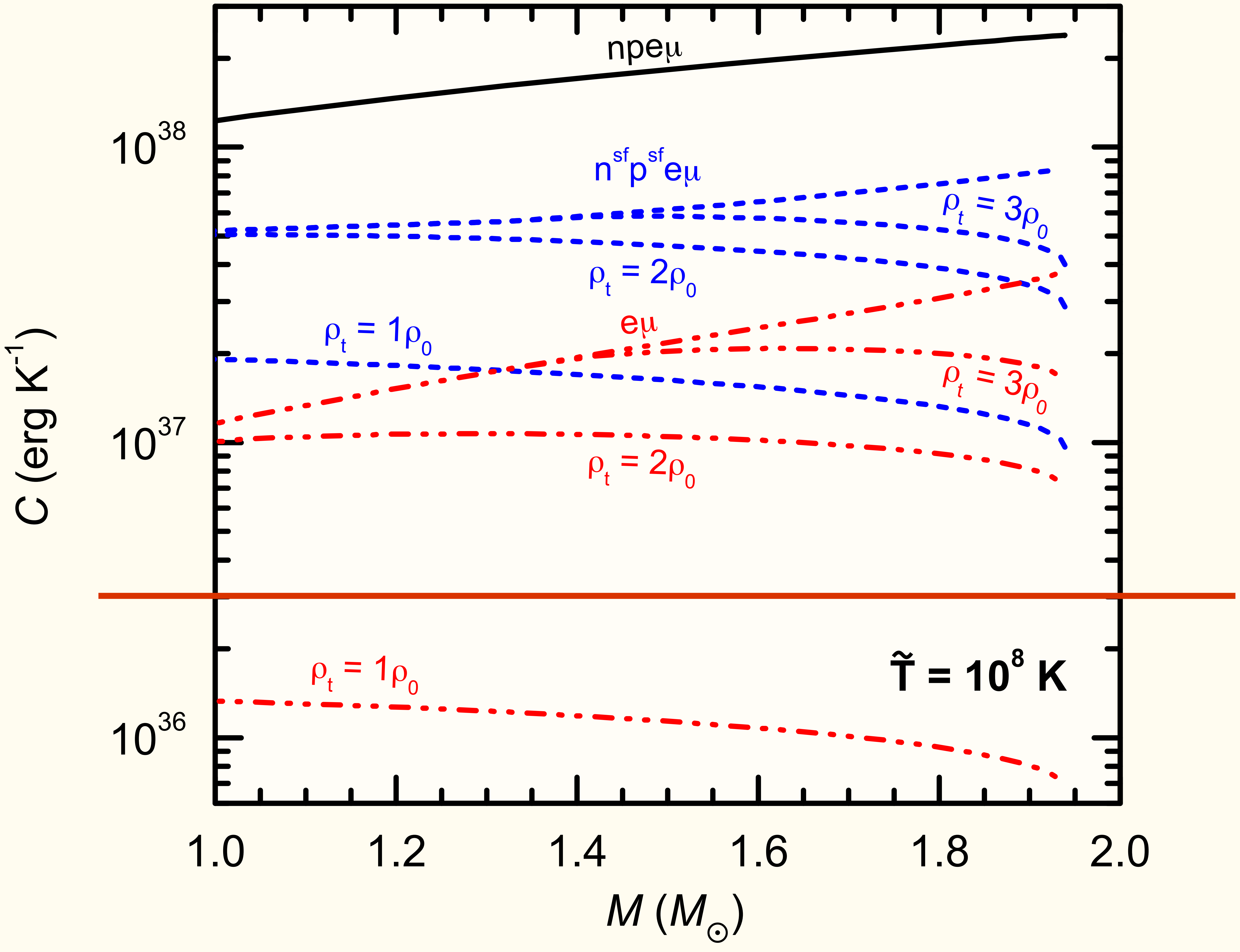


Cumming et al. '17

Minimum specific heat for KS 1731–260



Measured temperature is incompatible with a quark CFL phase throughout core



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

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

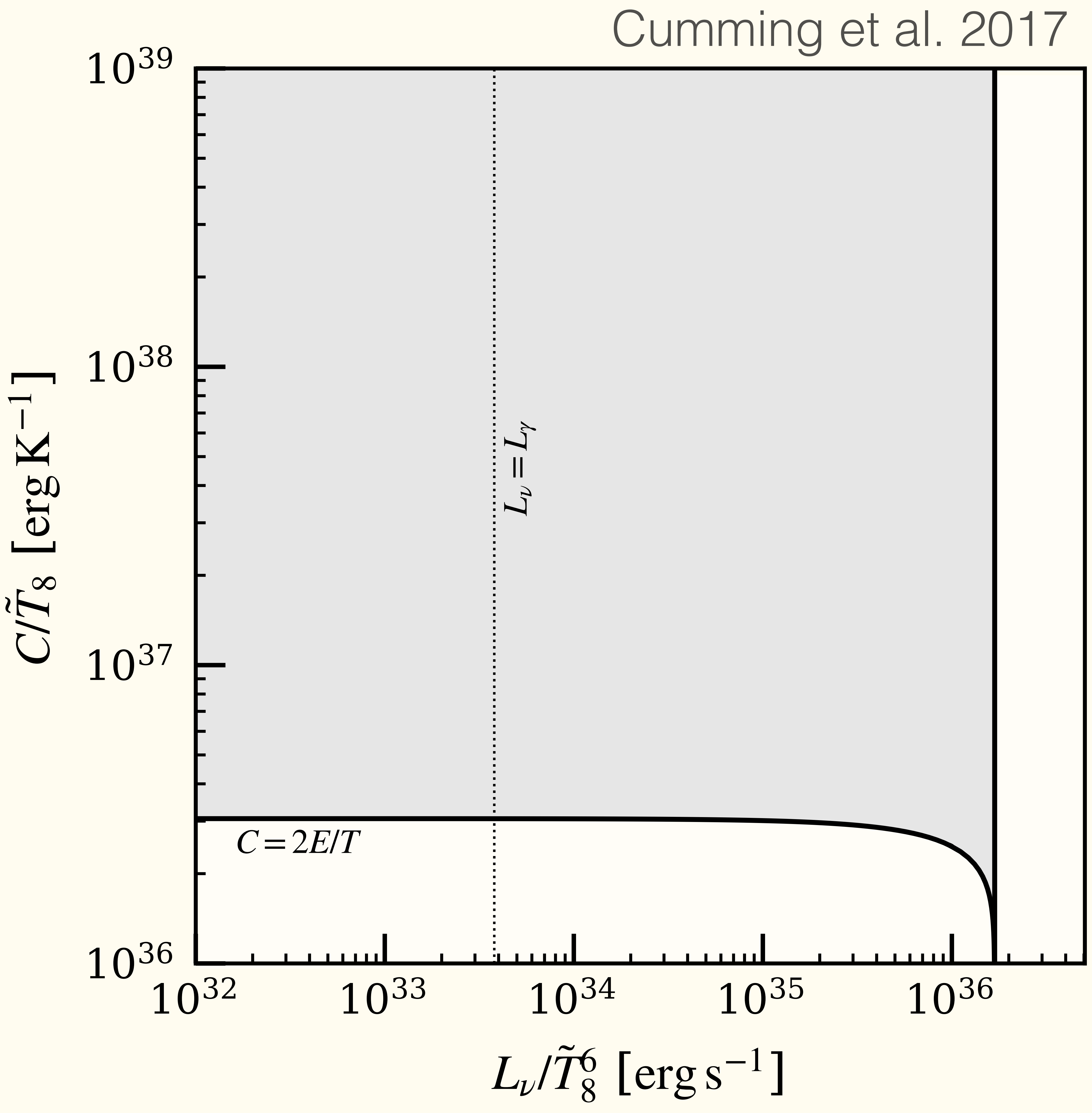
$$\begin{aligned} L_{\nu,\mathrm{dU}} &= 6 \times 10^{38}\, \tilde{T}_8^6\, \mathrm{erg\ s^{-1}} & n &\to pe\nu \\ L_{\nu,\mathrm{mU}} &= 6 \times 10^{30}\, \tilde{T}_8^8\, \mathrm{erg\ s^{-1}} & nn &\to npe\nu \end{aligned}$$

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.

Maximum neutrino luminosity for KS 1731–260

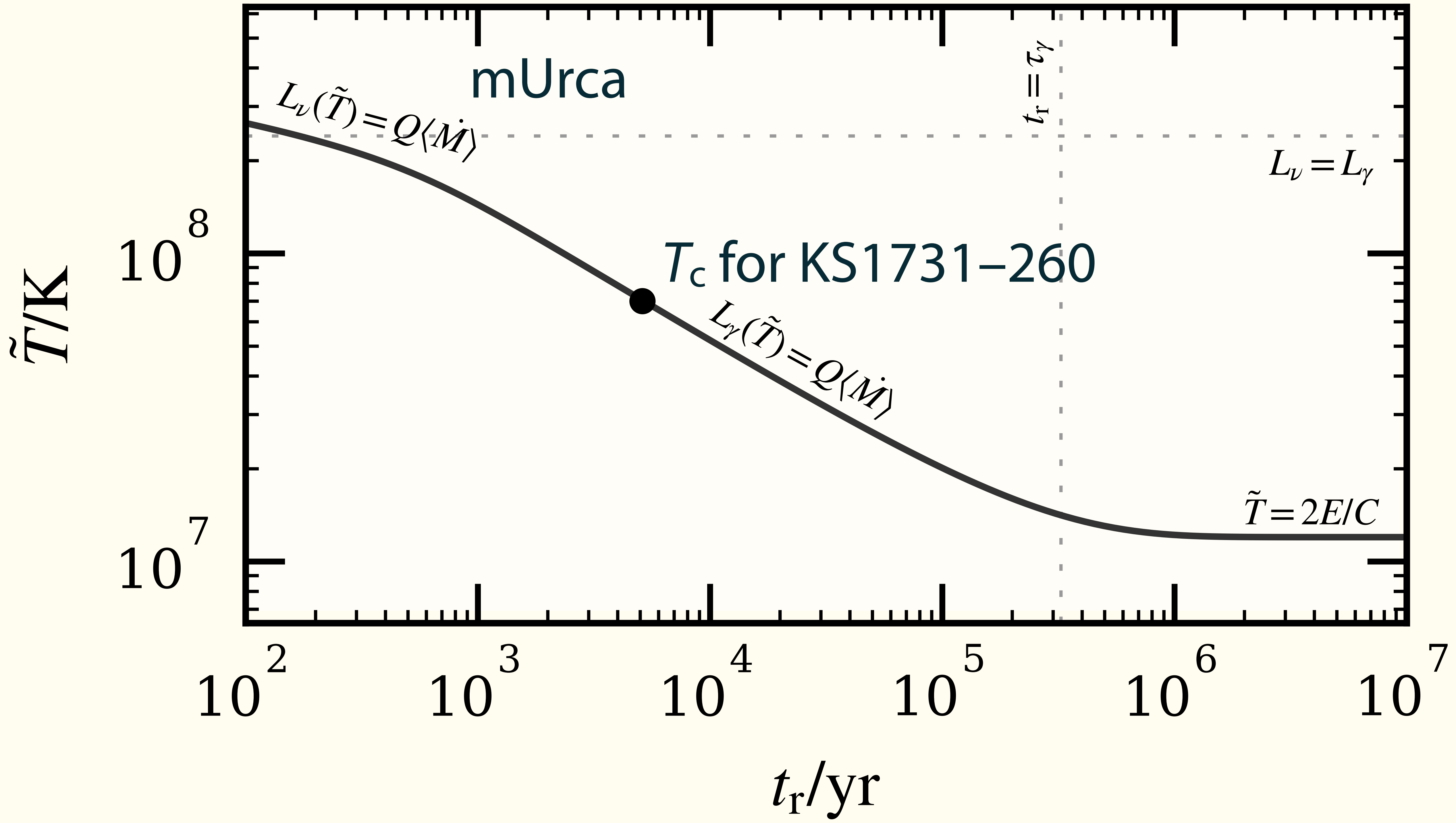


The general case

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

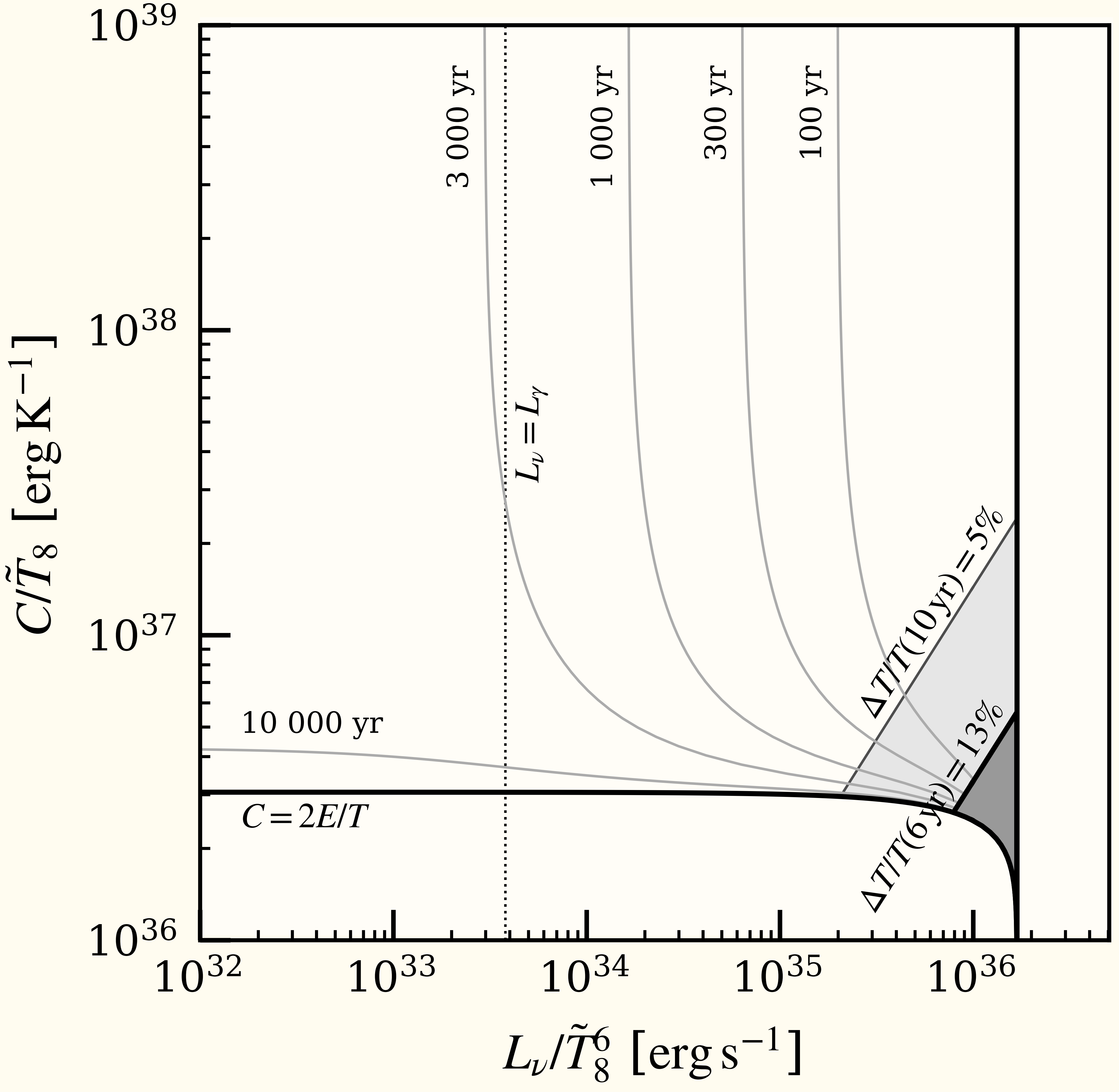
where $L_{\mathrm{in}} = 0$ during quiescence

In this plot the specific heat is fixed, $C/\tilde{T}_8 = 10^{38}$ 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 just finished an outburst and is back in quiescence again)

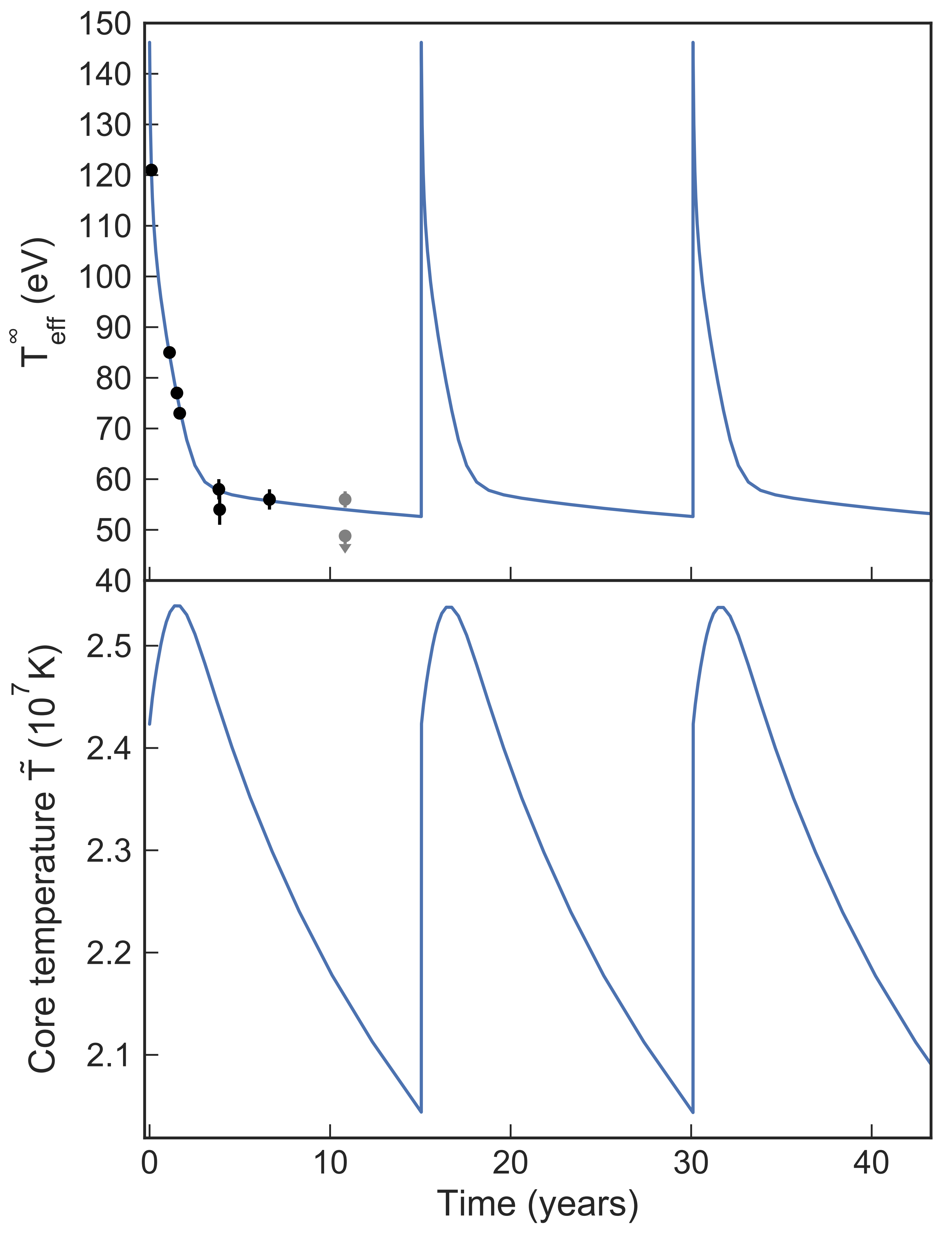
Thermal time of core (at average cooling luminosity $L \approx 4 \times 10^{34}\,\mathrm{erg\,s^{-1}}$) is

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

Low core temperature implies strong neutrino cooling,

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

Brown et al. 2018, *PRL*
arXiv: 1801.00041



Phase diagram for MXB 1659-29

L_ν consistent with direct Urca over ≈1% of core