Neutron star cooling and the symmetry energy

Questions from yesterday's discussion

- Why is R nearly constant?
- What would $R < 11$ km and $M_{max} > 2\ M_{sun}$ imply?

Cooling neutron stars

- Cooling with large and small proton fractions
- Isolated neutron stars
- Transient neutron stars

What EOS produces const. *R*? Newtonian version

For an equation of state

$$P = K\rho^{\gamma},$$

we can solve for the mass and pressure via

$$\frac{dm}{dr} = 4\pi r^2 \rho, \;\; \frac{dP}{dr} = -\rho \frac{Gm(r)}{r^2}.$$

This yields (can see this from dimensional analysis)

$$R \propto \mathcal{C}_\gamma K^{1/(3\gamma-4)} M^{(2-\gamma)/(4-3\gamma)}.$$

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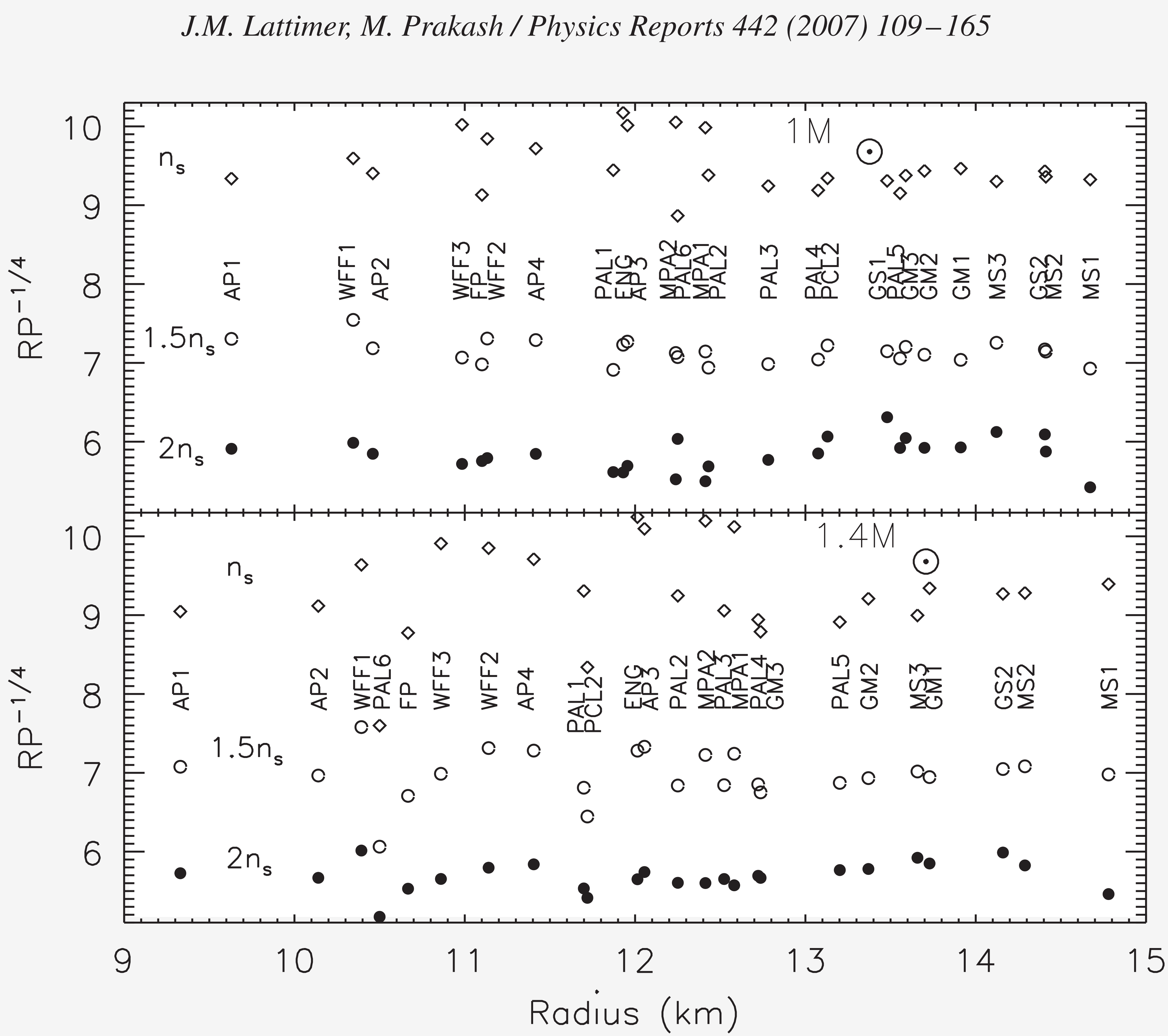
What EOS produces const. *R*? Relativistic version



Near saturation, $P \sim \rho^2$ and is dominated by L

As discussed yesterday, the energy per nucleon about ρ_0, $x = \rho_p/(\rho_n + \rho_p) = 1/2$ can be expanded as

$$E(\rho, x) = E_0 + \frac{K}{18}\left(\frac{\rho}{\rho_0} - 1\right)^2 + \left[S_0 + \frac{L}{3}\left(\frac{\rho}{\rho_0} - 1\right)\right](1-2x)^2.$$

Evaluating

$$P = \rho^2 \frac{\partial E}{\partial \rho}$$

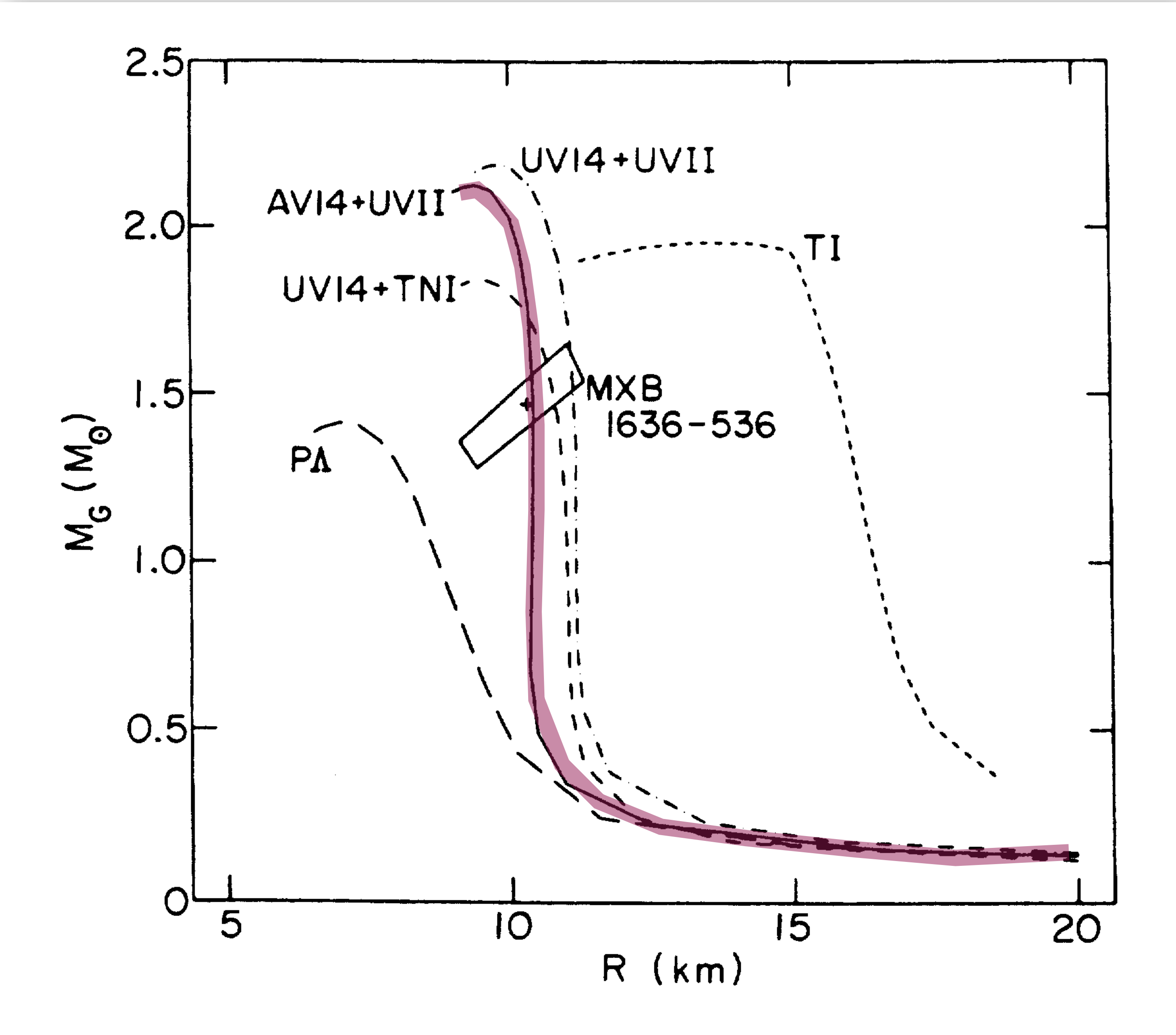
at $\rho \approx \rho_0$ and $x \ll 1$,

$$P(\rho \approx \rho_0, x \ll 1) \approx \frac{L}{3\rho_0}\rho^2.$$

Questions

1. A realistic $E(\rho,x)$ is fit to nuclear masses, scattering, etc. at ρ around ρ_0. How large a prior does this place on NS models? What happens if the $M_{\mathrm{max}} > 2.0\ M_{\mathrm{sun}}$ result is added?
2. If we want to have substantially smaller radii, how does $E\ (\rho,x)$ have to change? Is this in an experimentally accessible range?

AV14+UVII (Wiringa, Fiks, & Fabrocini 1988)



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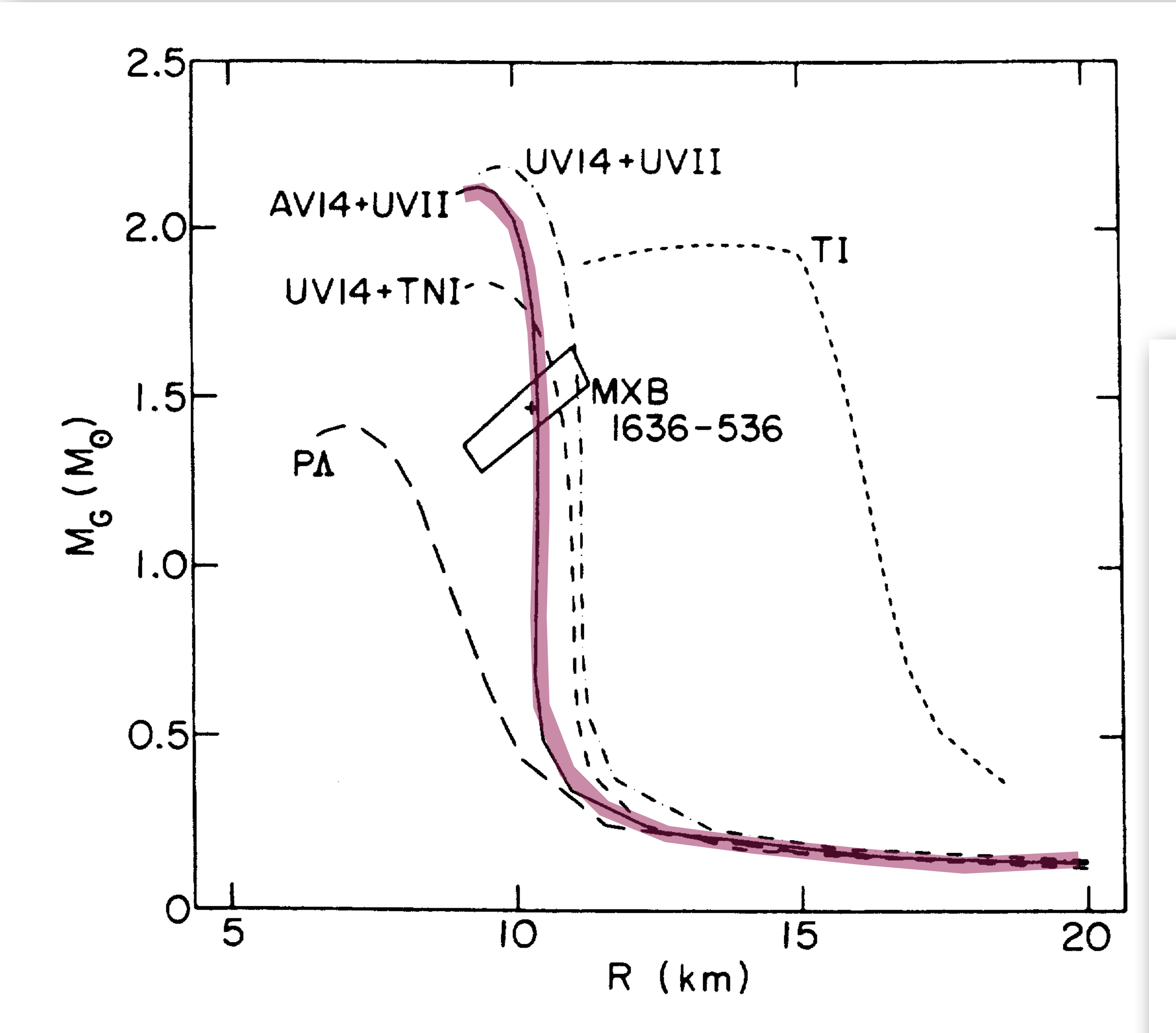
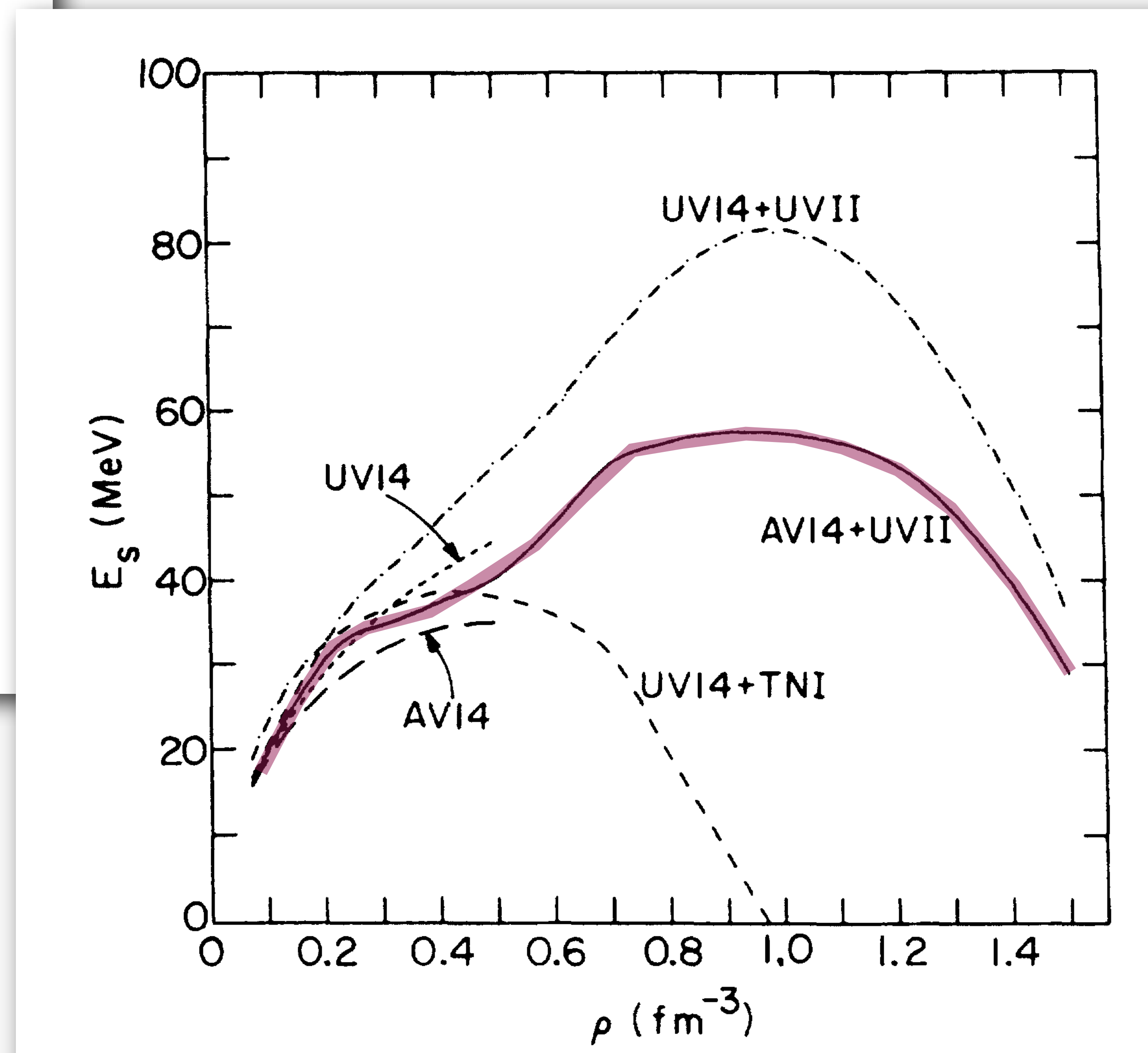
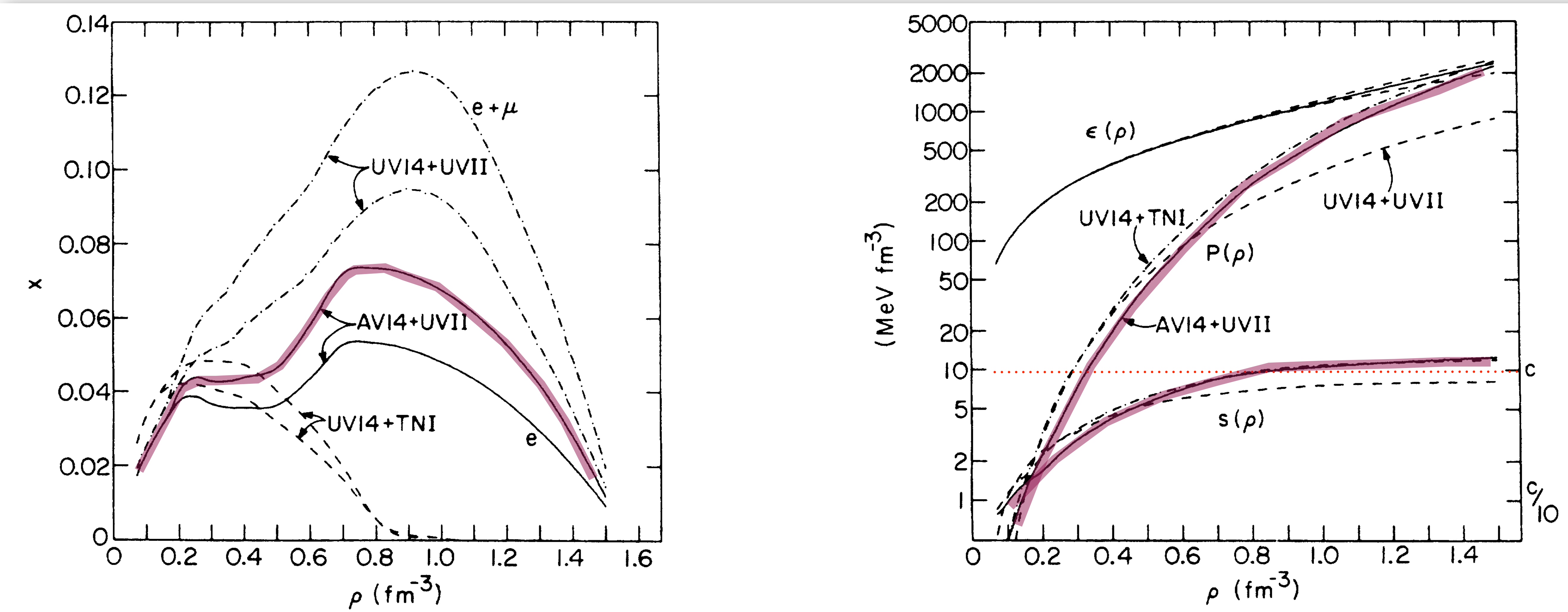




AV14+UVII (Wiringa, Fiks, & Fabrocini 1988): proton fraction and thermal properties



Cooling: the Urca (aka direct Urca, aka dUrca) process (just electron capture–β-decay equilibrium)

$$
\begin{aligned}
n &\rightarrow p + e + \bar{\nu}_e \\
p + e &\rightarrow n + \nu_e
\end{aligned}
$$

Integration over the phase space gives a T^6 dependence and the luminosity is large:

$$L_\nu(T) \sim 10^5\, L_\odot \left(\frac{T}{10^8\,\mathrm{K}}\right)^6 .$$

But this is blocked (Chiu & Salpeter, Bahcall & Wolff)...

momentum conservation	$p_{F,n} < p_{F,e} + p_{F,p}$,
β-equilibrium	$\mu_e = \mu_n - \mu_p$,
charge neutrality	$n_e = n_p$

cannot be simultaneously fulfilled unless

$$x > 0.11.$$

A large symmetry energy is indicated.

If it's blocked the modified Urca (mUrca) can still proceed

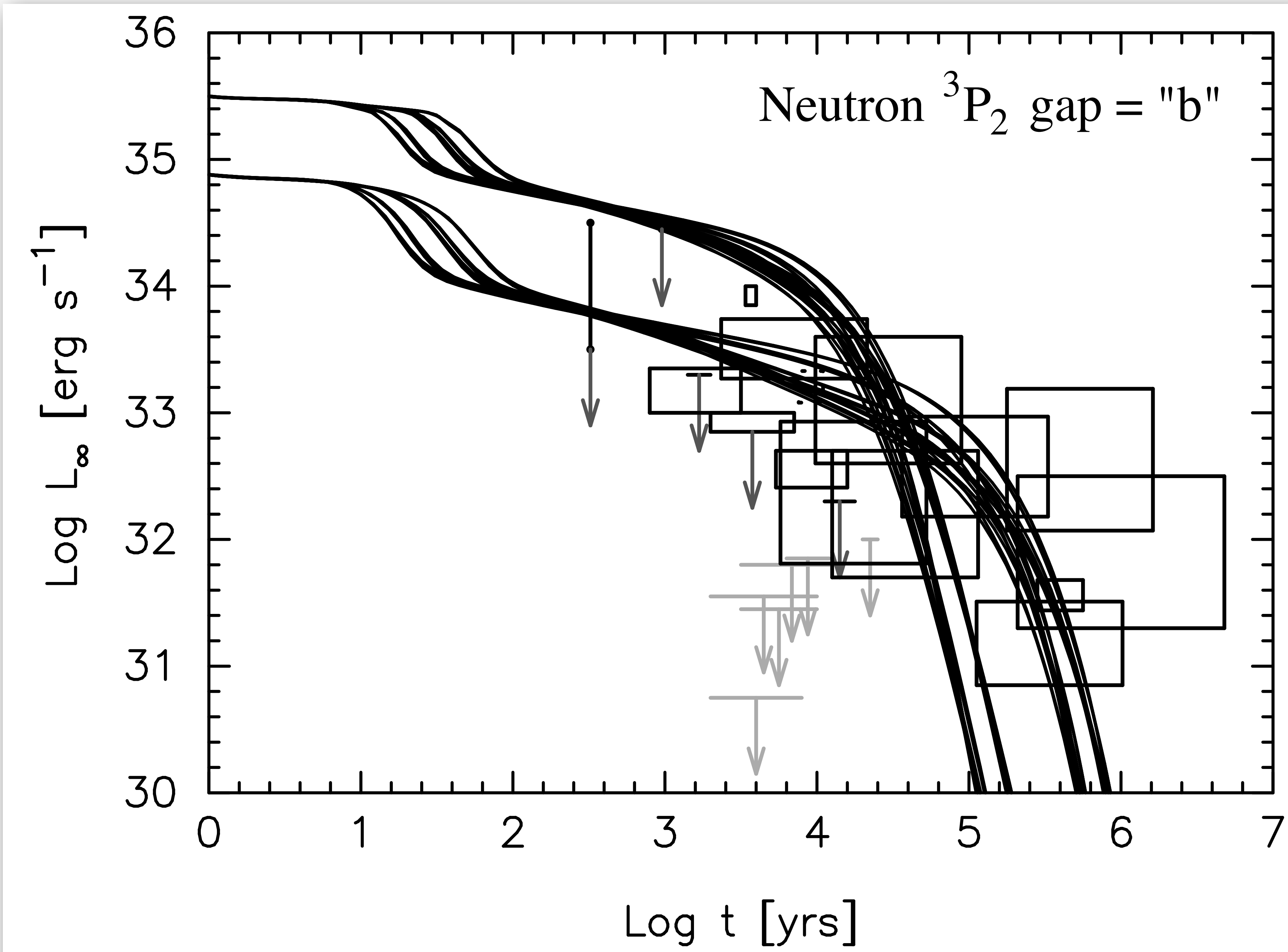
$$\begin{aligned} n + n &\rightarrow n + p + e + \bar{\nu}_e \\ n + p + e &\rightarrow n + n + \nu_e \end{aligned}$$

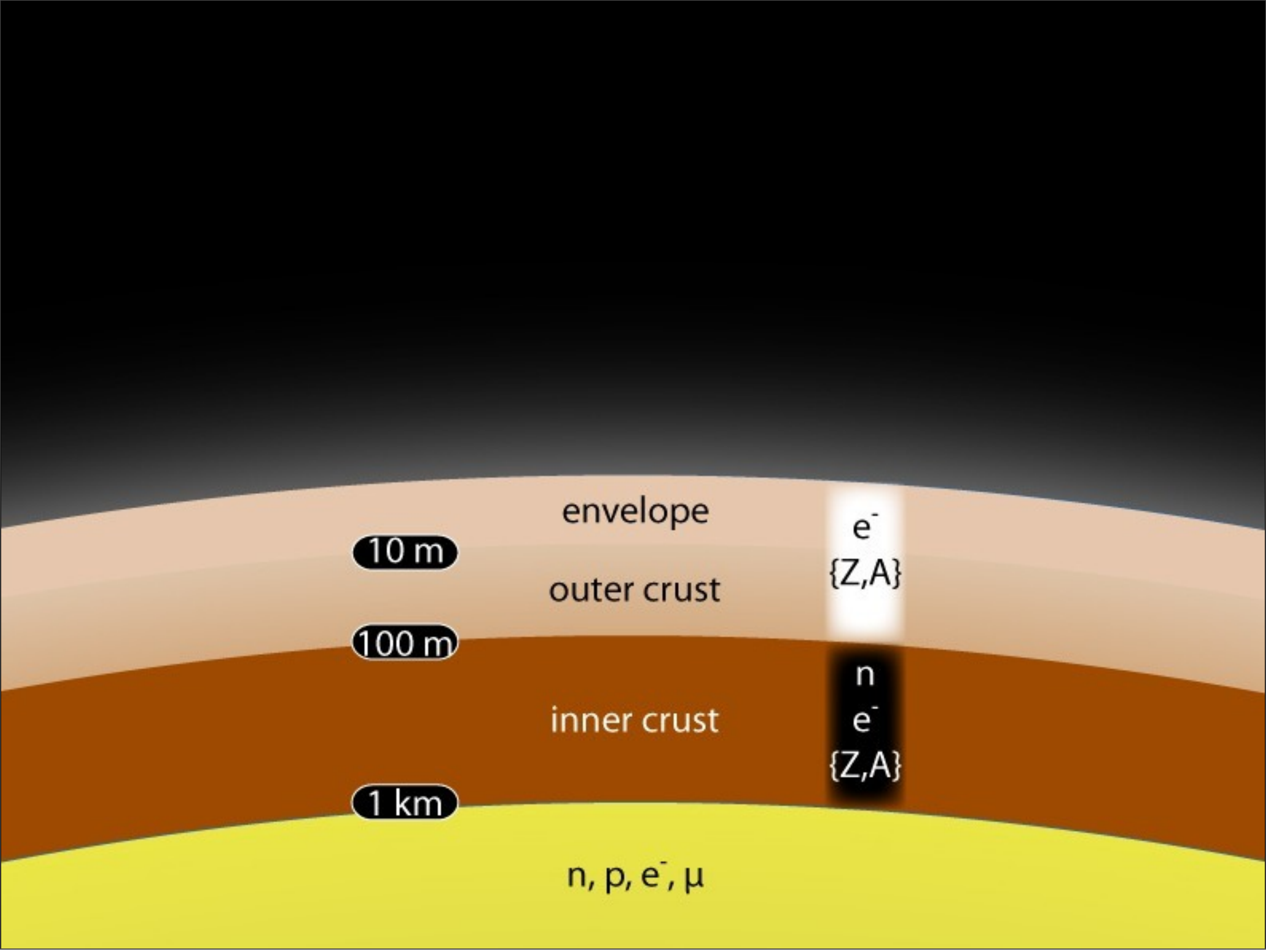
Integration over the phase space gives a T^8 dependence and the luminosity is not so large:

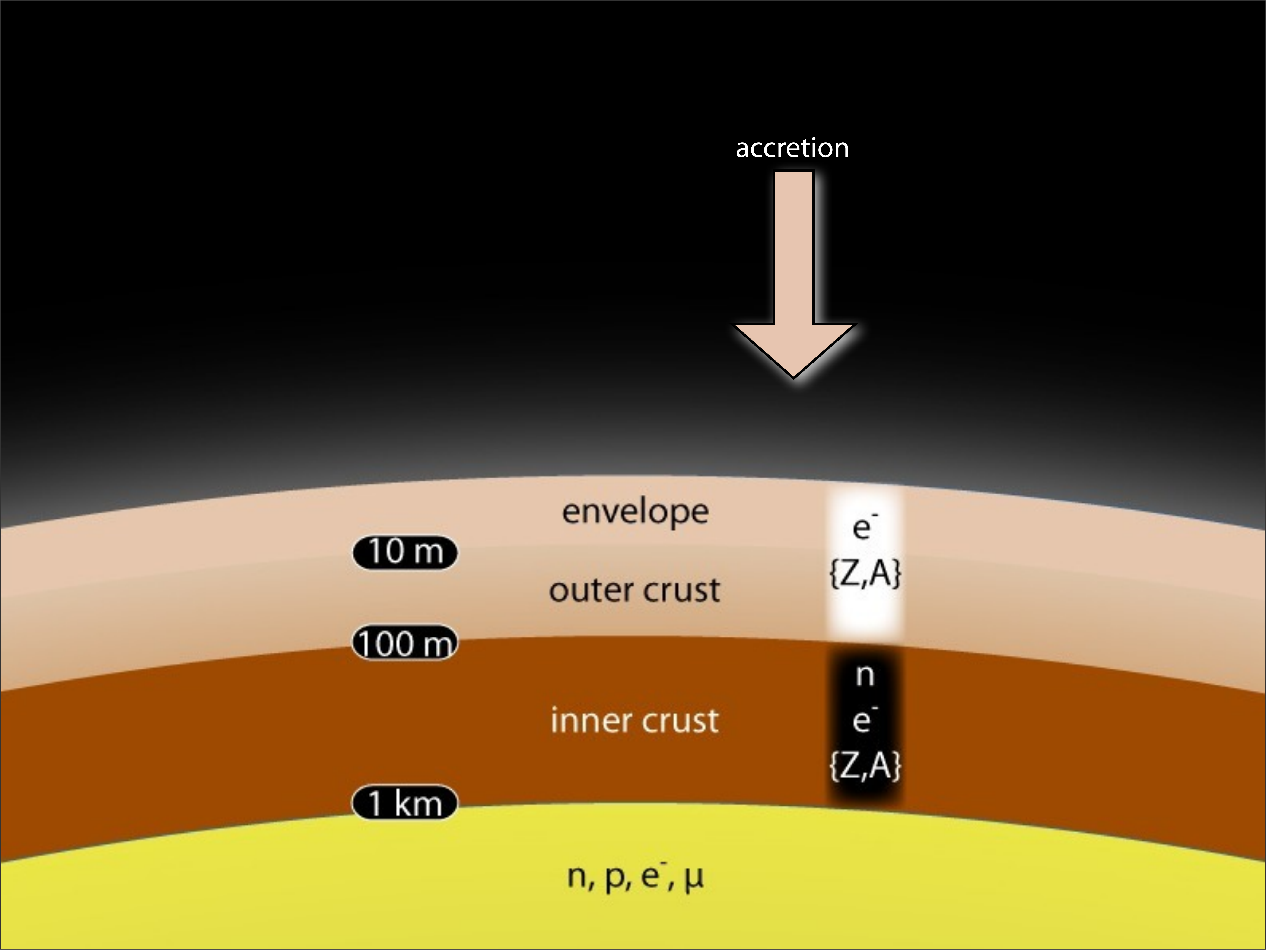
$$L_\nu(T) \sim 10^{-2}\, L_\odot \left(\frac{T}{10^8\,\mathrm{K}}\right)^8 .$$

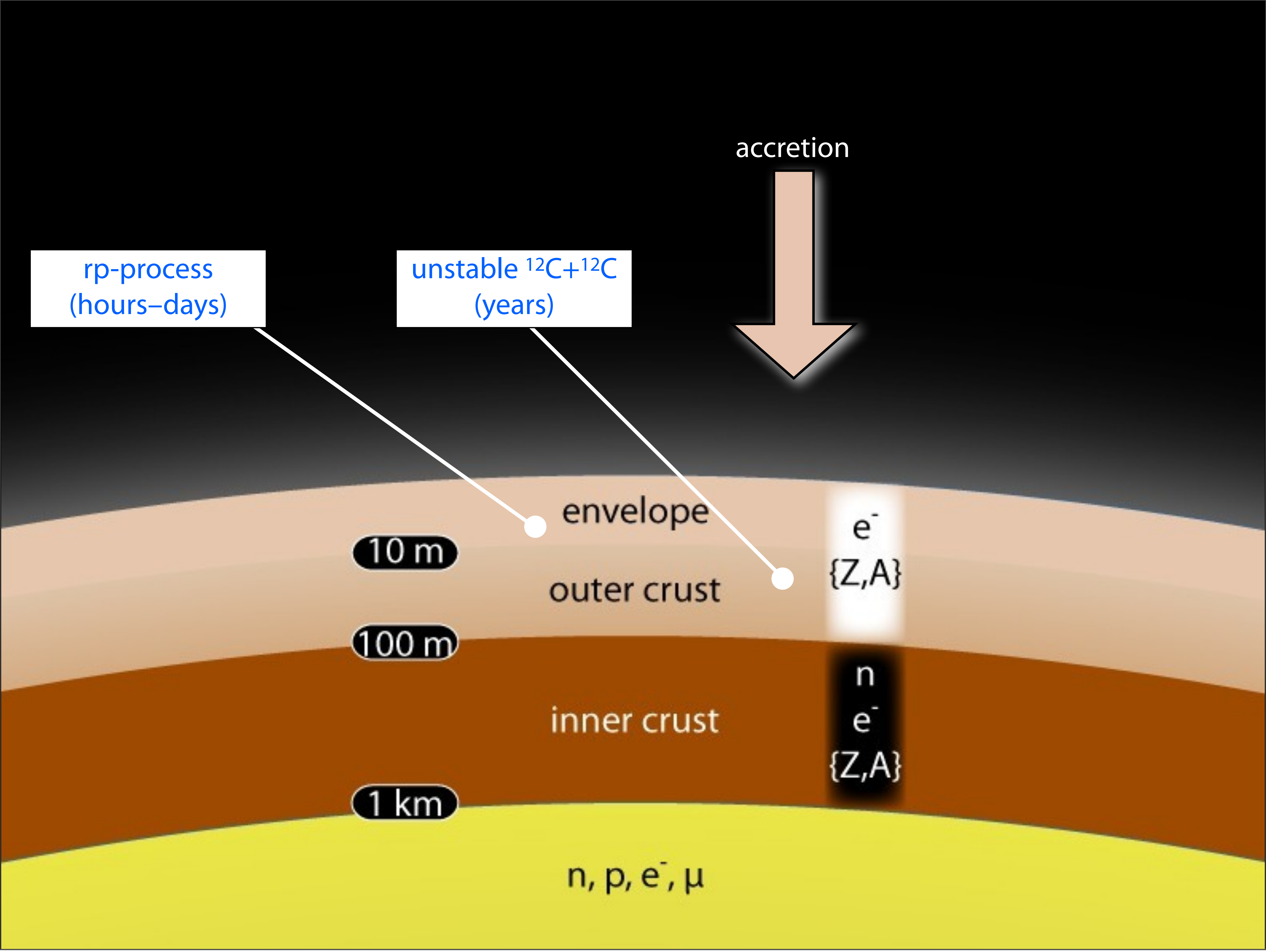
Bremsstrahlung and pair-breaking-formation processes can also occur.

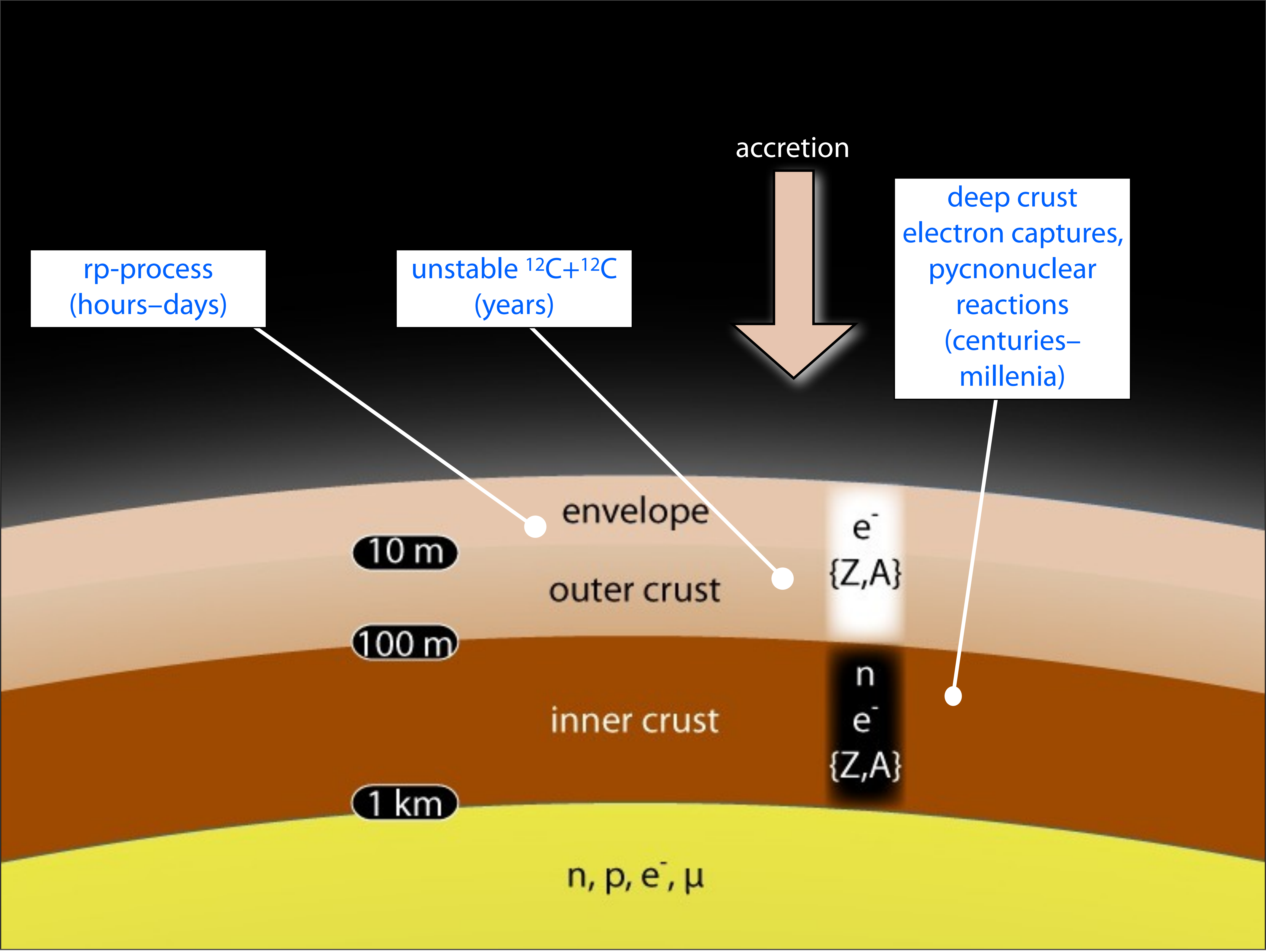
Isolated neutron stars: no enhanced cooling in models
Page, Lattimer, Prakash, & Steiner 2009




envelope
10 m
outer crust
100 m
inner crust
1 km
n, p, e$^-$, μ
e$^-$
{Z,A}
n
e$^-$
{Z,A}


accretion
envelope
10 m
outer crust
100 m
inner crust
1 km
e^-
{Z,A}
n
e^-
{Z,A}
n, p, e^-, μ


accretion
rp-process
(hours–days)
unstable $^{12}C+^{12}C$
(years)
envelope
10 m
outer crust
e^-
{Z,A}
100 m
inner crust
n
e^-
{Z,A}
1 km
n, p, e^-, μ

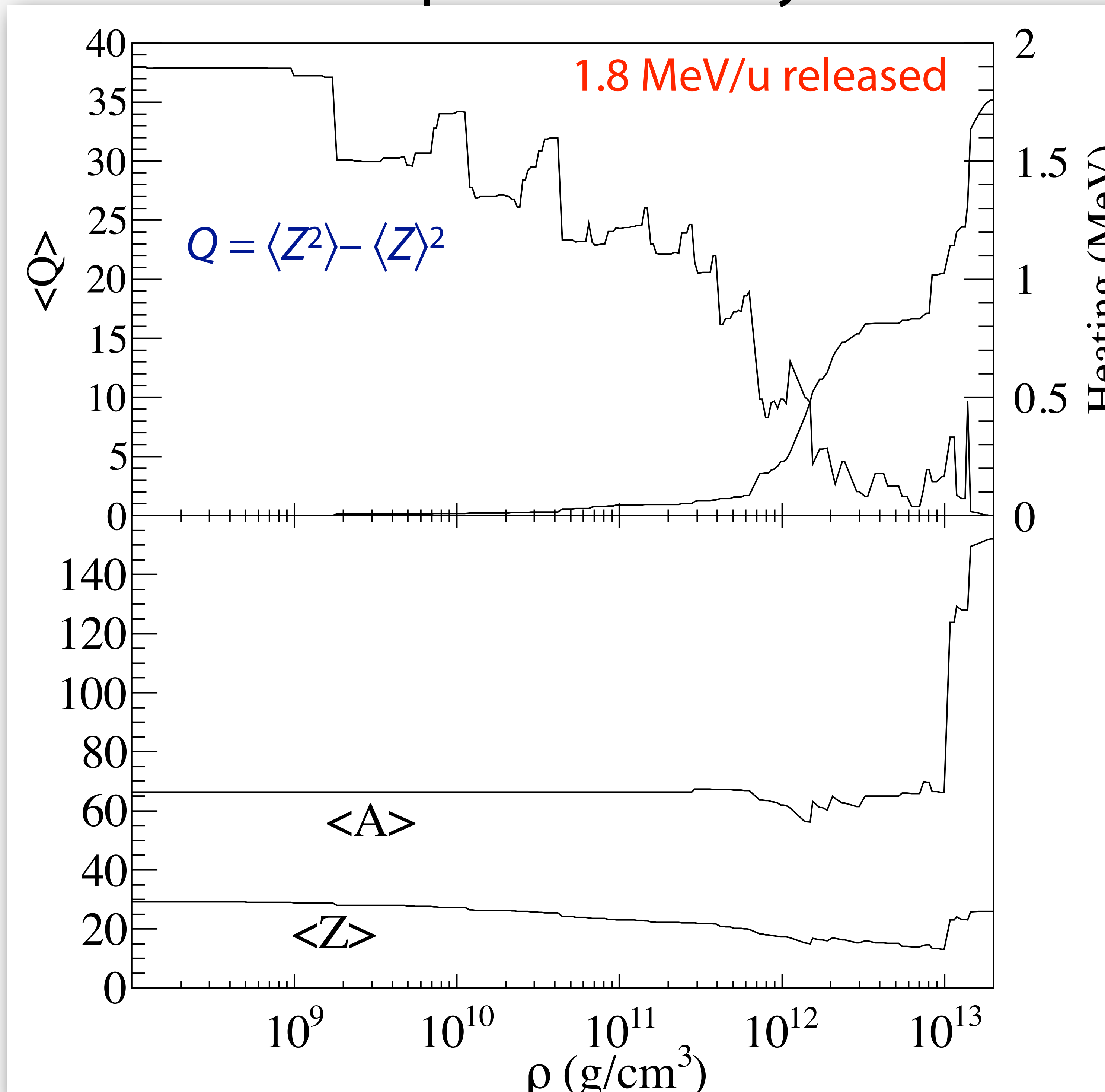

accretion
rp-process (hours–days)
unstable $^{12}C+^{12}C$ (years)
deep crust electron captures, pycnonuclear reactions (centuries–millenia)
envelope
10 m
outer crust
100 m
inner crust
1 km
e^-
{Z,A}
n
e^-
{Z,A}
n, p, e^-, μ

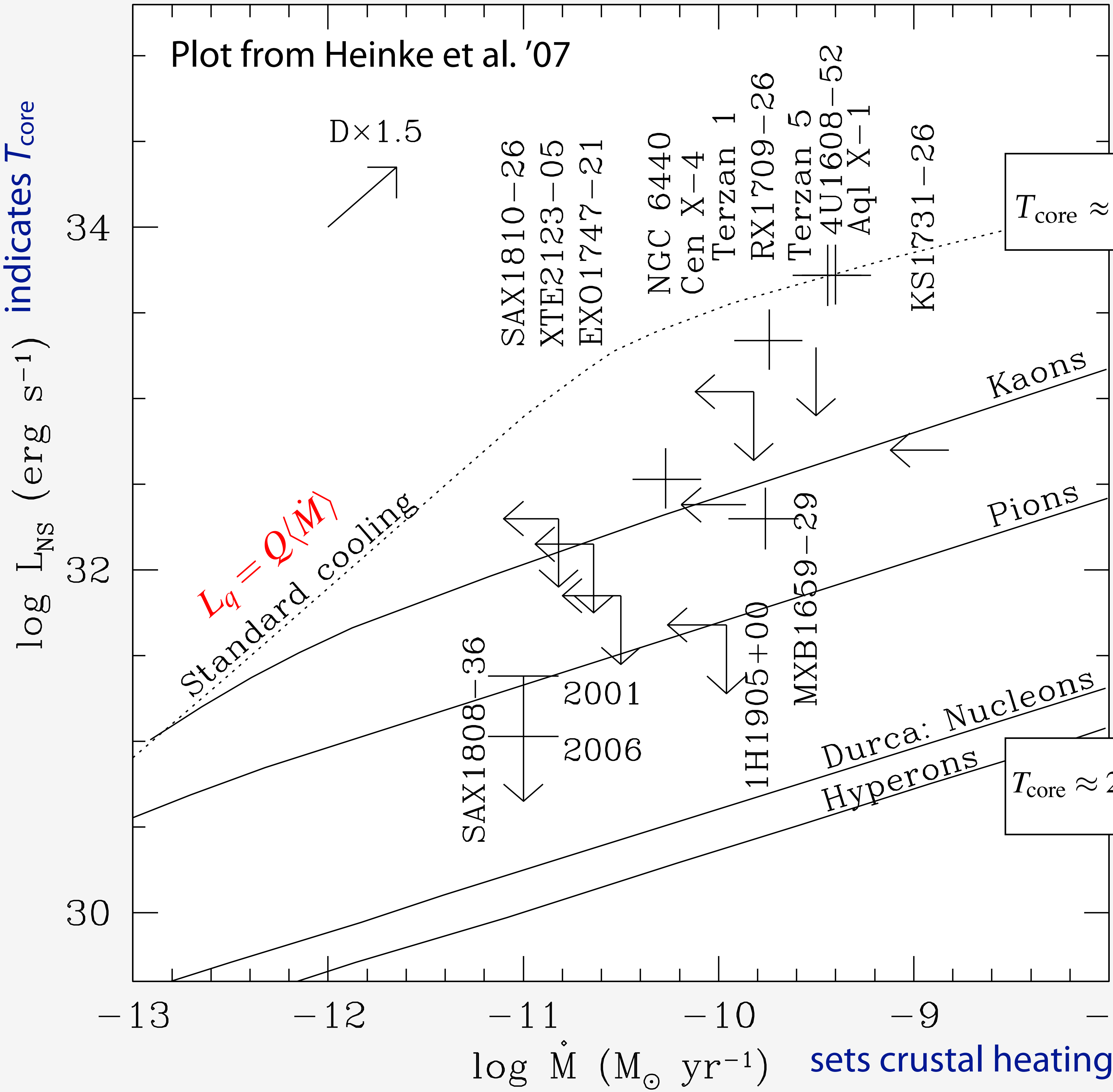
plot courtesy A. Steiner

deep crustal heating

crust reactions deposit ≈ 2 MeV/u in the inner crust (Sato, Haensel & Zdunik, Gupta et al., Steriner)

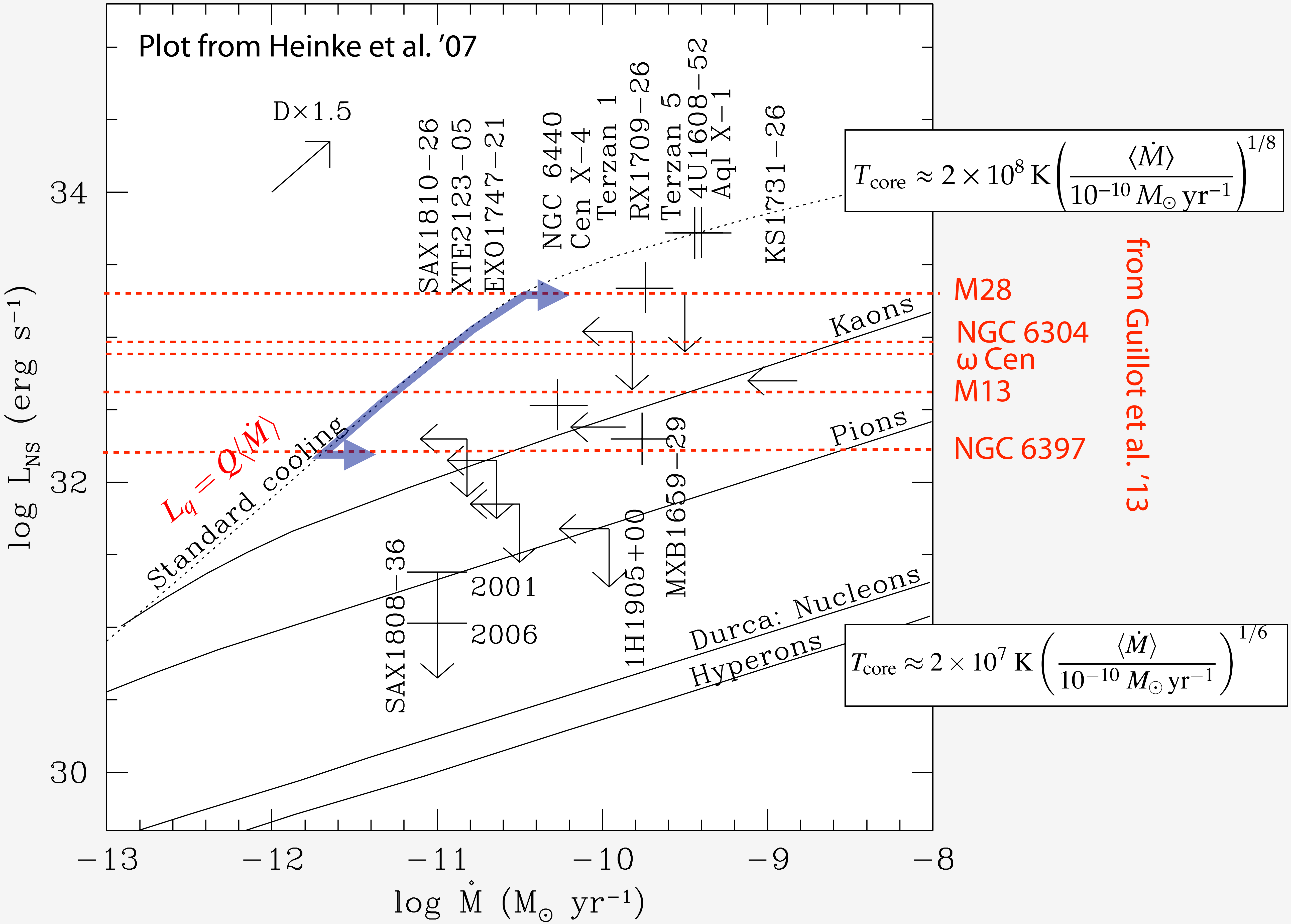
1. core temperature set by balance of heating, neutrino cooling
2. crust is not in thermal equilibrium with core





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

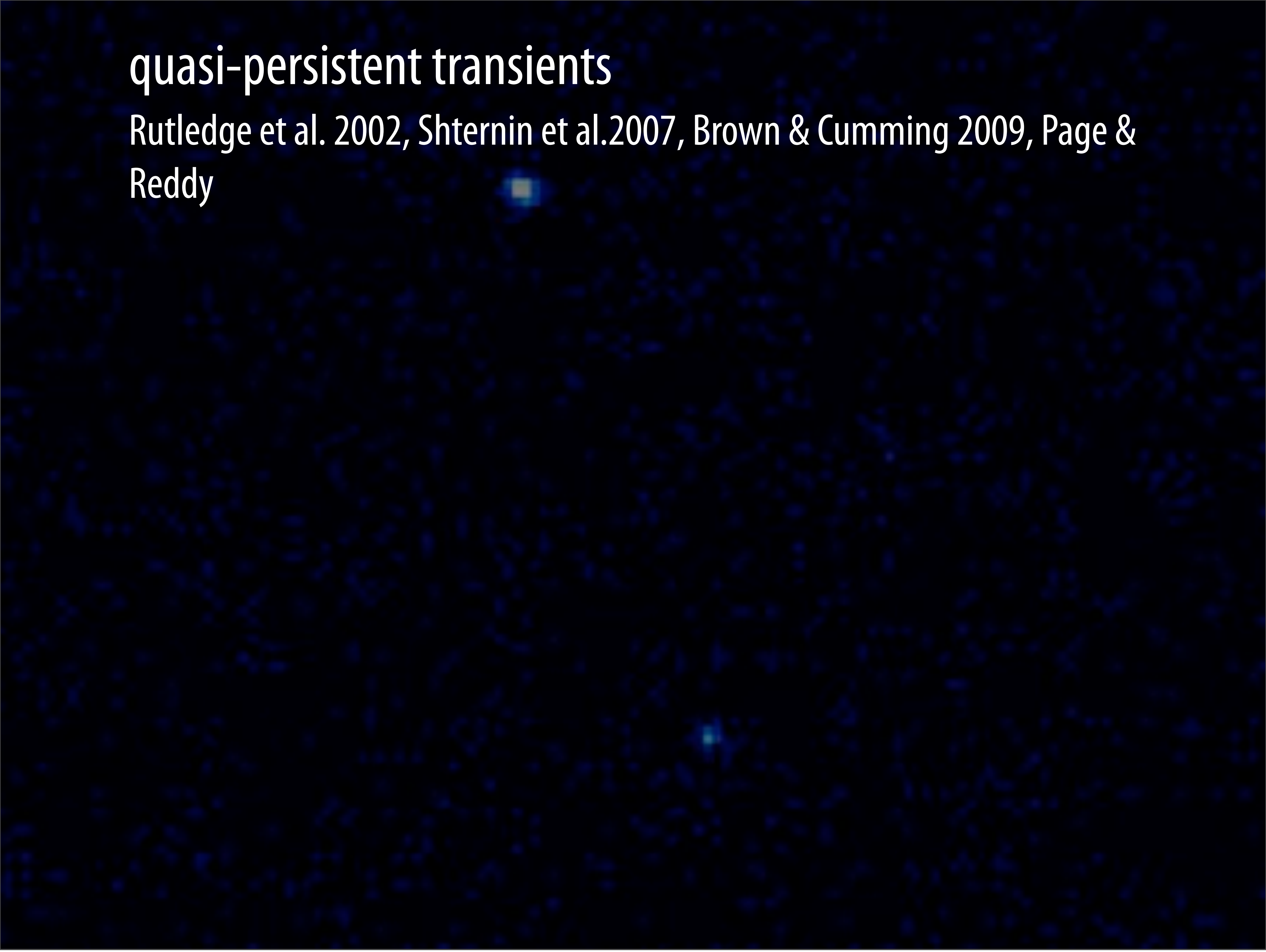
$$T_{\rm core} \approx 2\times 10^{7}\,{\rm K}\left(\frac{\langle \dot M\rangle}{10^{-10}\,M_{\odot}\,{\rm yr}^{-1}}\right)^{1/6}$$



Plot from Heinke et al. '07
D×1.5
SAX1810−26
XTE2123−05
EXO1747−21
NGC 6440
Cen X−4
Terzan 1
RX1709−26
Terzan 5
4U1608−52
Aql X−1
KS1731−26
$T_{\rm core} \approx 2\times10^8\,{\rm K}\left(\frac{\langle \dot M\rangle}{10^{-10}\,M_\odot\,{\rm yr}^{-1}}\right)^{1/8}$
M28
NGC 6304
ω Cen
M13
NGC 6397
from Guillot et al. '13
Kaons
Pions
$L_q = Q\langle \dot M\rangle$
Standard cooling
SAX1808−36
2001
2006
1H1905+00
MXB1659−29
Durca: Nucleons
Hyperons
$T_{\rm core} \approx 2\times10^7\,{\rm K}\left(\frac{\langle \dot M\rangle}{10^{-10}\,M_\odot\,{\rm yr}^{-1}}\right)^{1/6}$
log L_{NS} (erg s^{-1})
34
32
30
−13
−12
−11
−10
−9
−8
log $\dot M$ ($M_\odot$ yr^{-1})

quasi-persistent transients

Rutledge et al. 2002, Shternin et al.2007, Brown & Cumming 2009, Page & Reddy



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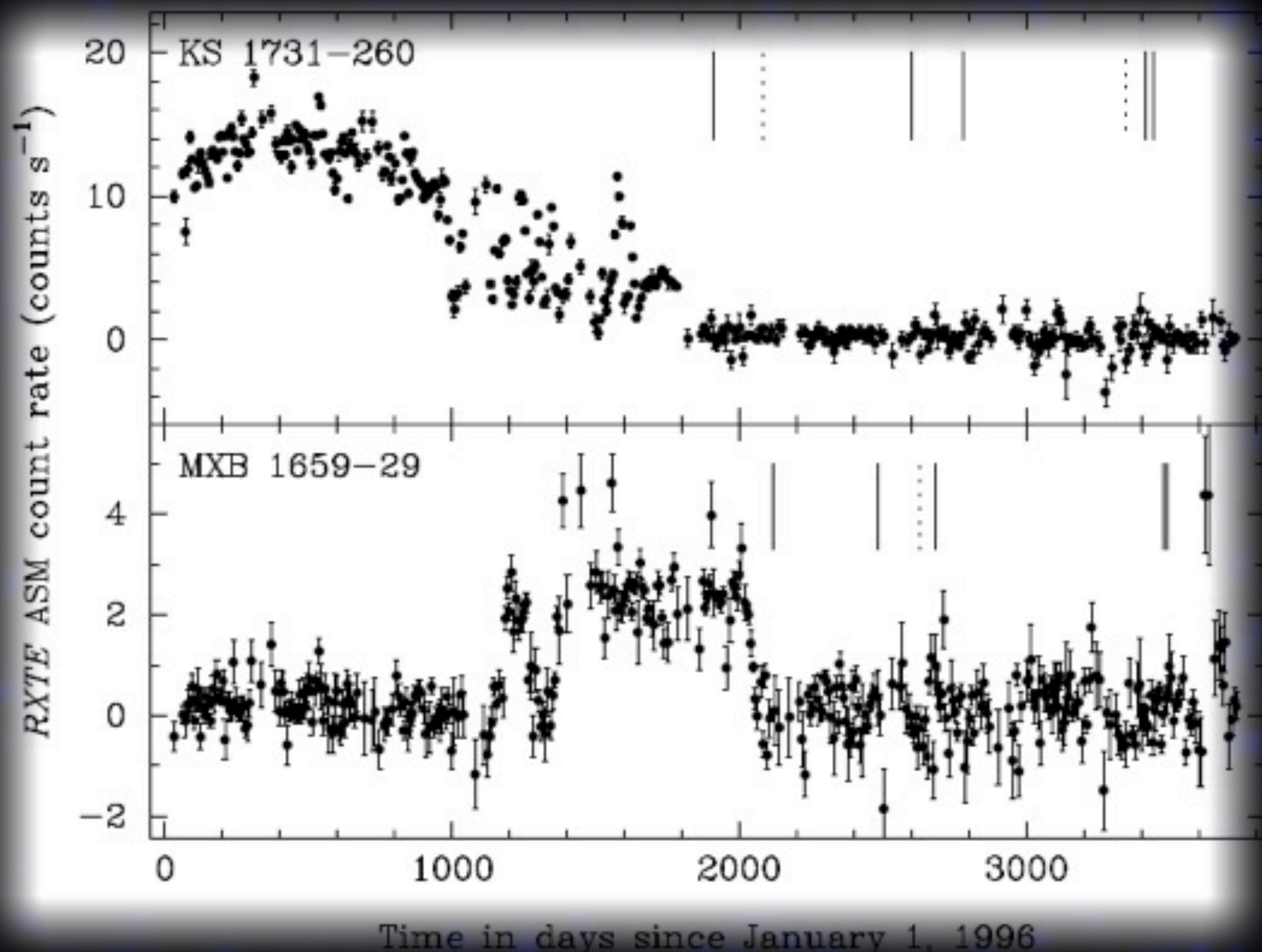

quasi-persistent transients

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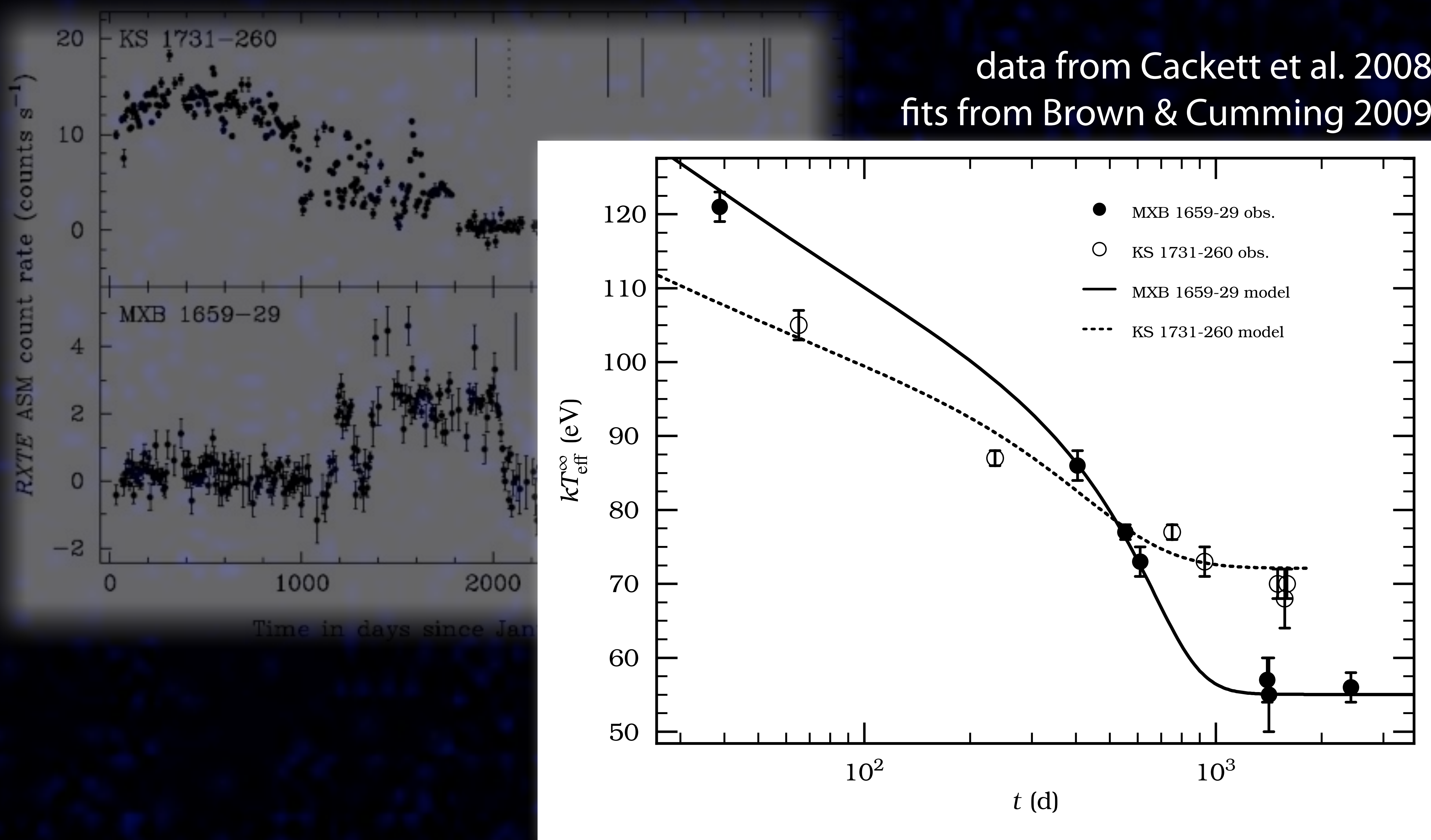
data from Cackett et al. 2008
fits from Brown & Cumming 2009



Why is cooling a broken power-law in time? Consider a cooling slab

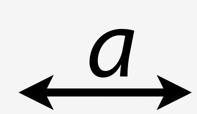
For

$$\frac{\partial T}{\partial t} = D\,\frac{\partial^2 T}{\partial x^2},$$

the flux at $D = 0$ is

$$\propto \left(\frac{\tau}{t}\right)^{1/2}\left[1 - \exp\left(-\frac{\tau}{t}\right)\right],$$

where $\tau = a^2/(4D)$.



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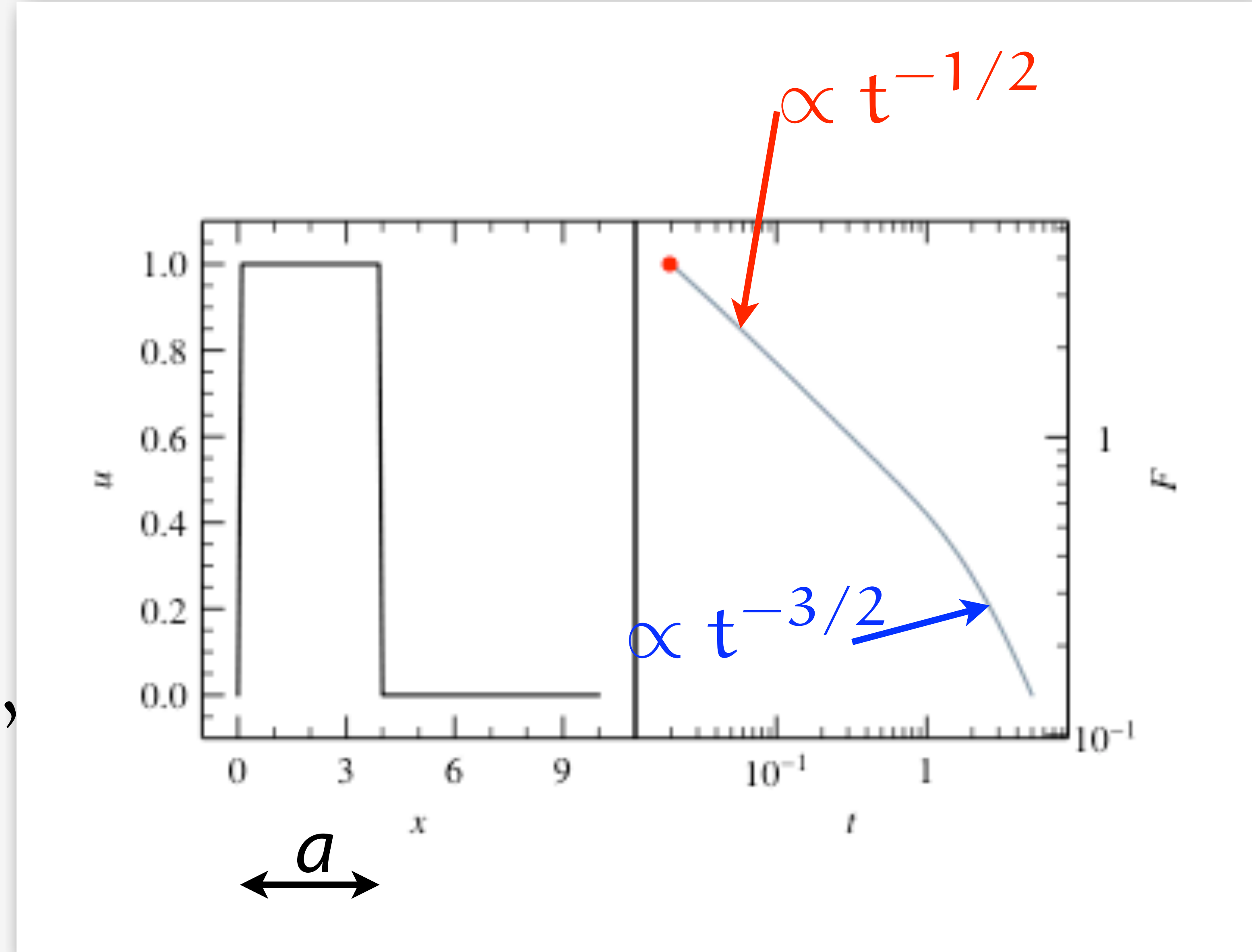


basic physics of the lightcurve

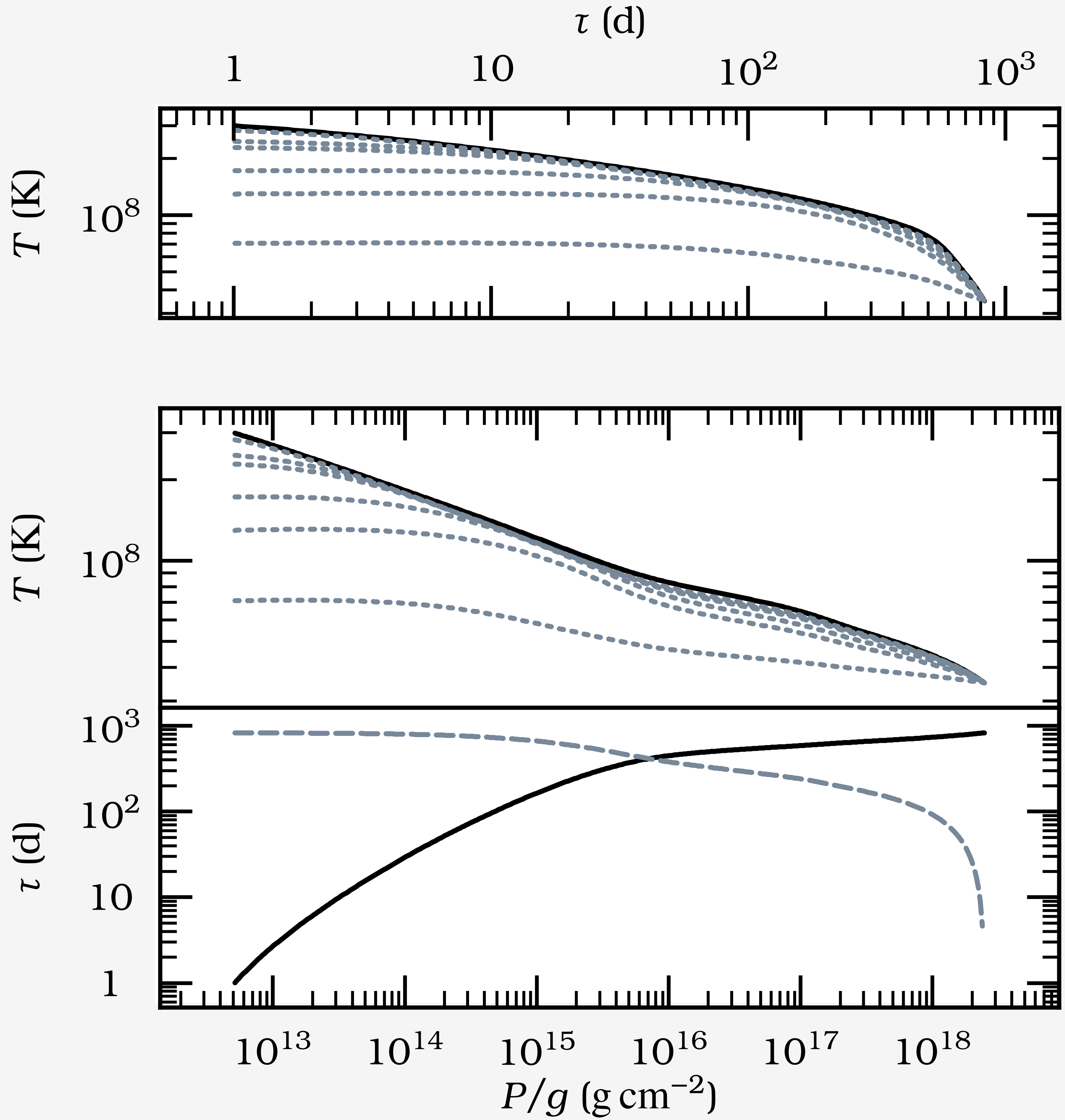
For a cooling crust,

$$\rho C_P \frac{\partial T}{\partial t} = \frac{\partial}{\partial r}\left(K \frac{\partial T}{\partial r}\right),$$

and a cooling front propagates into crust on a timescale

$$\tau \approx \frac{1}{4}\left[\int \left(\frac{\rho C_P}{K}\right)^{1/2} \mathrm{d}r\right]^2 .$$

$$\tau \propto \left(\frac{R^2}{GM}\right)^2 \left(1 - \frac{2GM}{Rc^2}\right)^{1/2}$$



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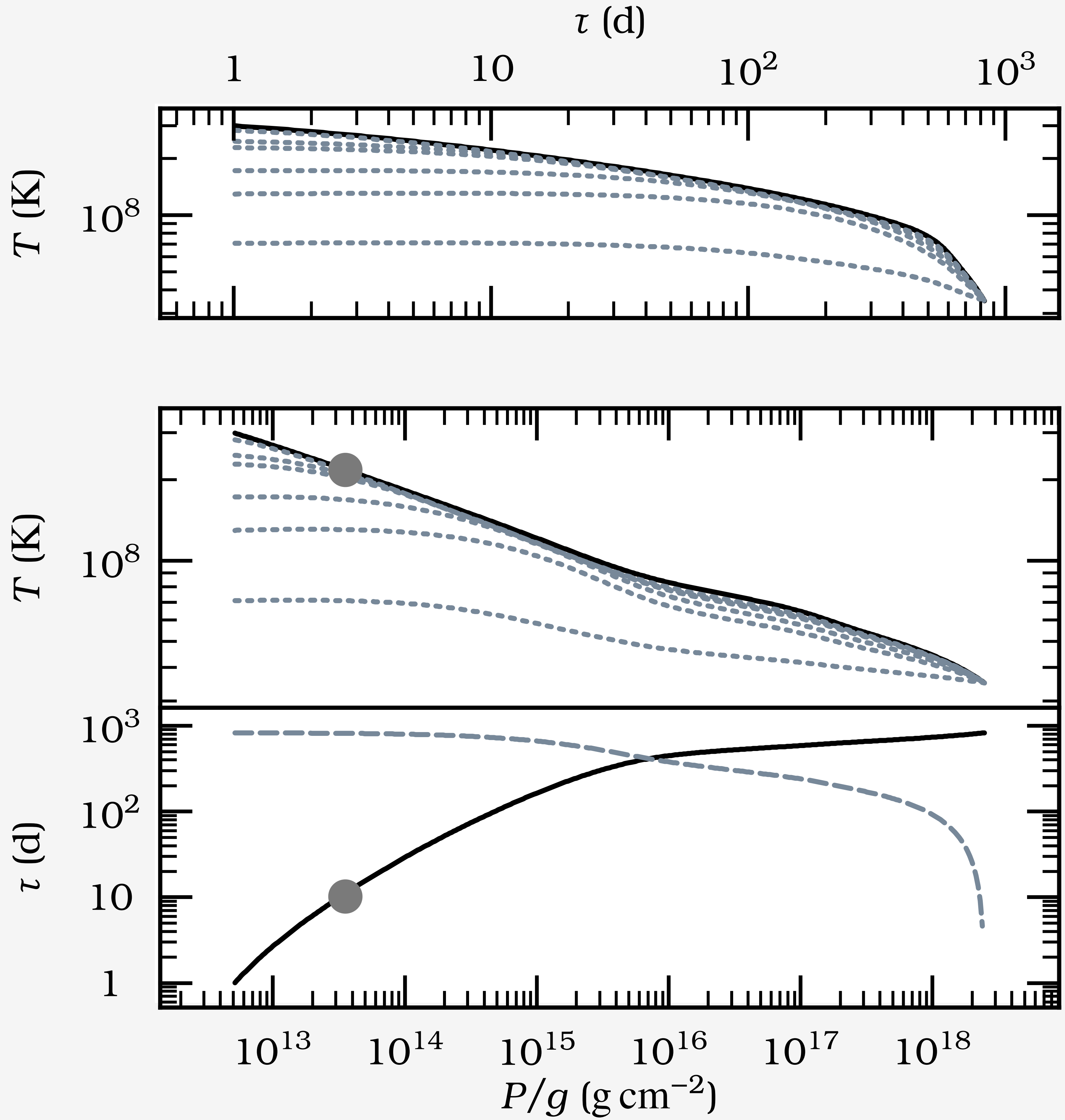

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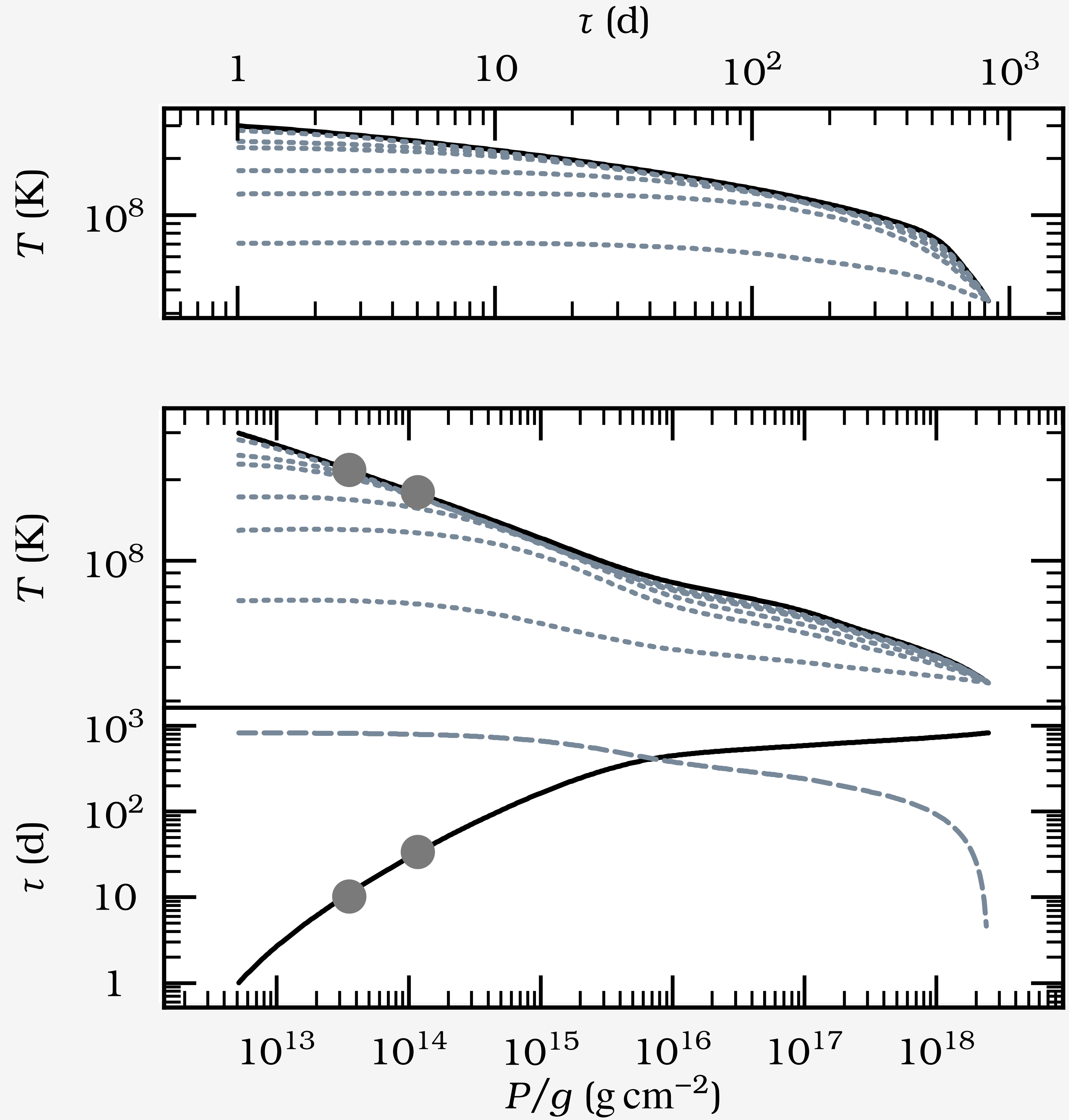

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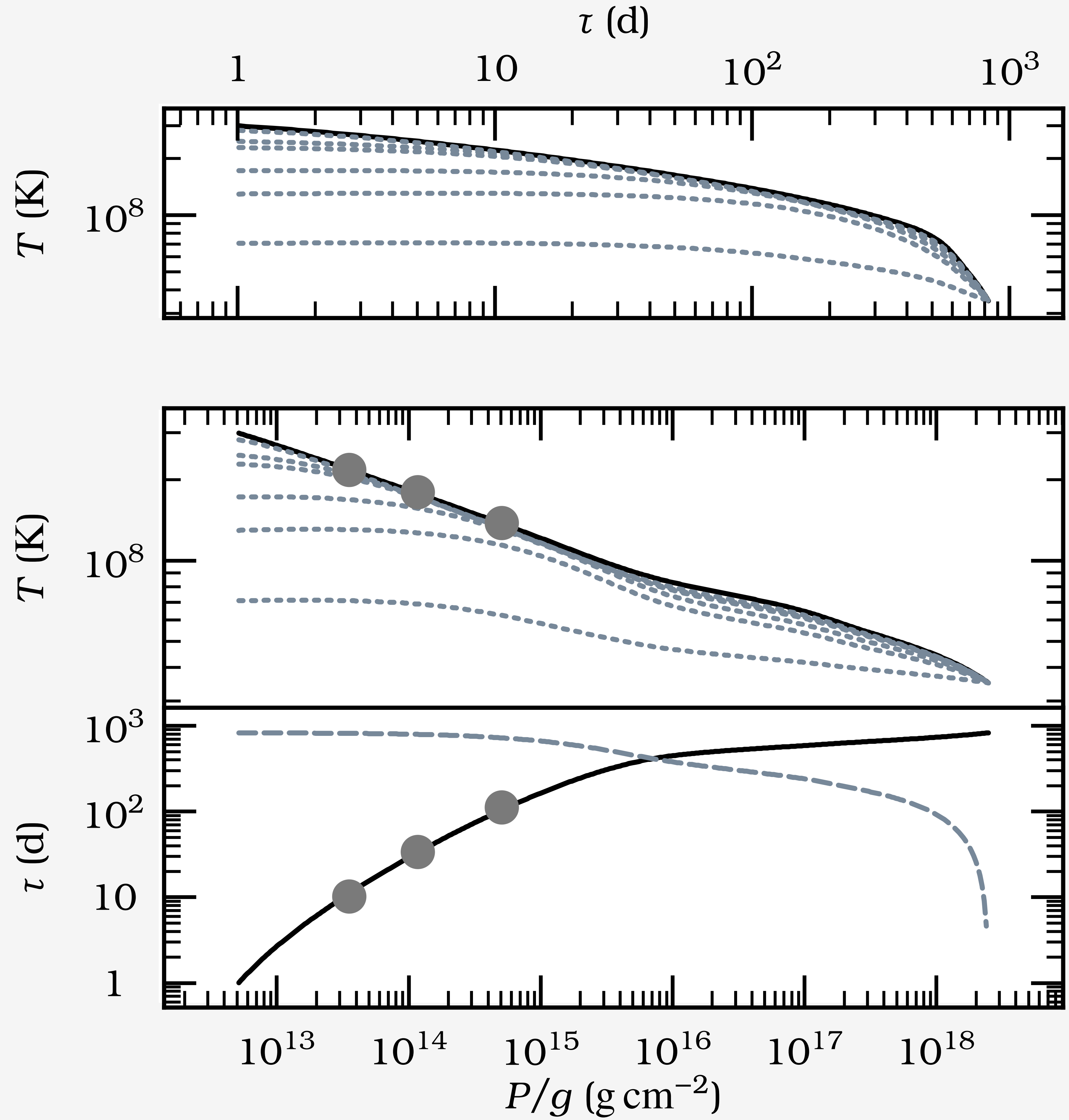
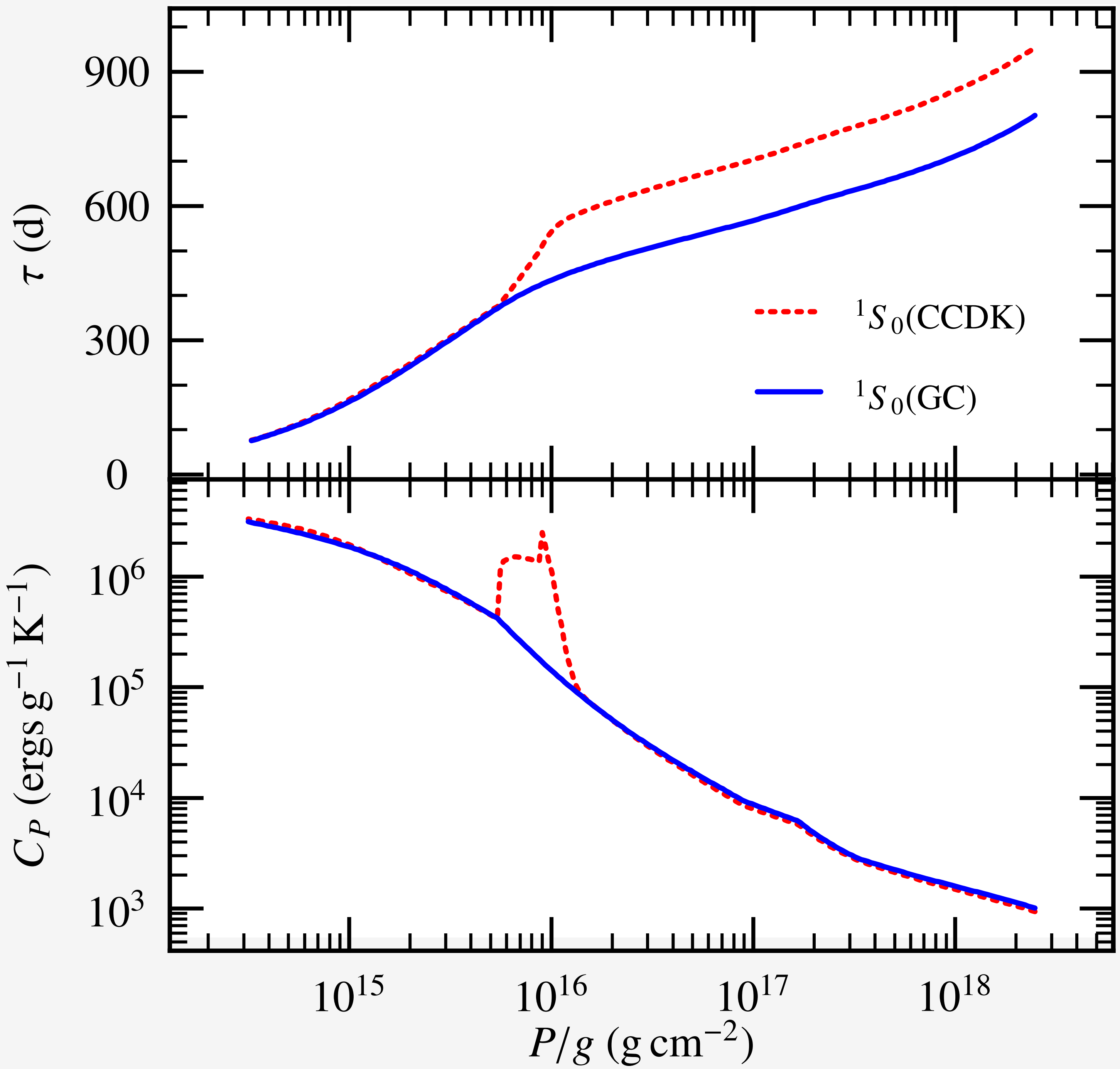
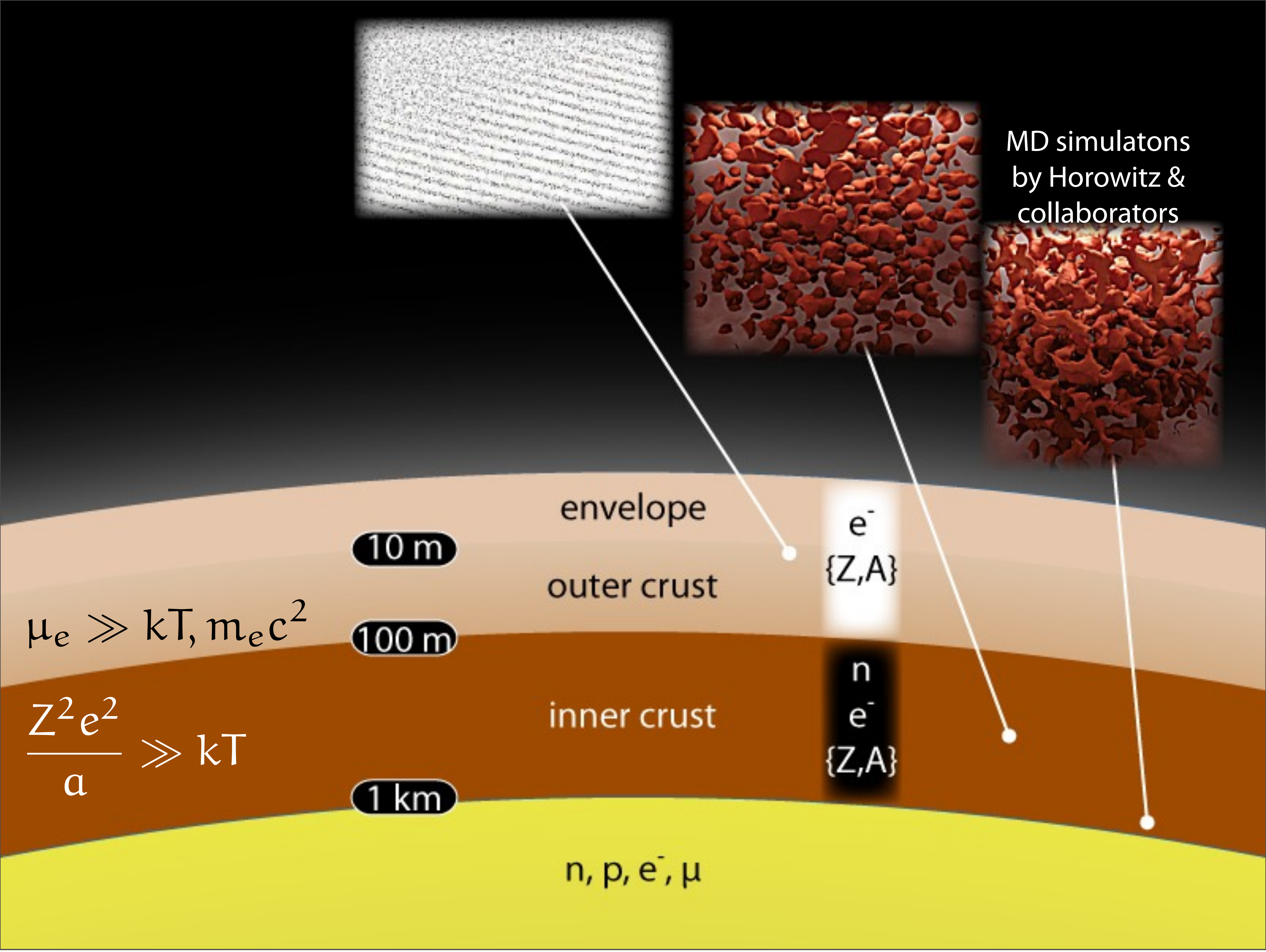


Effects of superfluidity

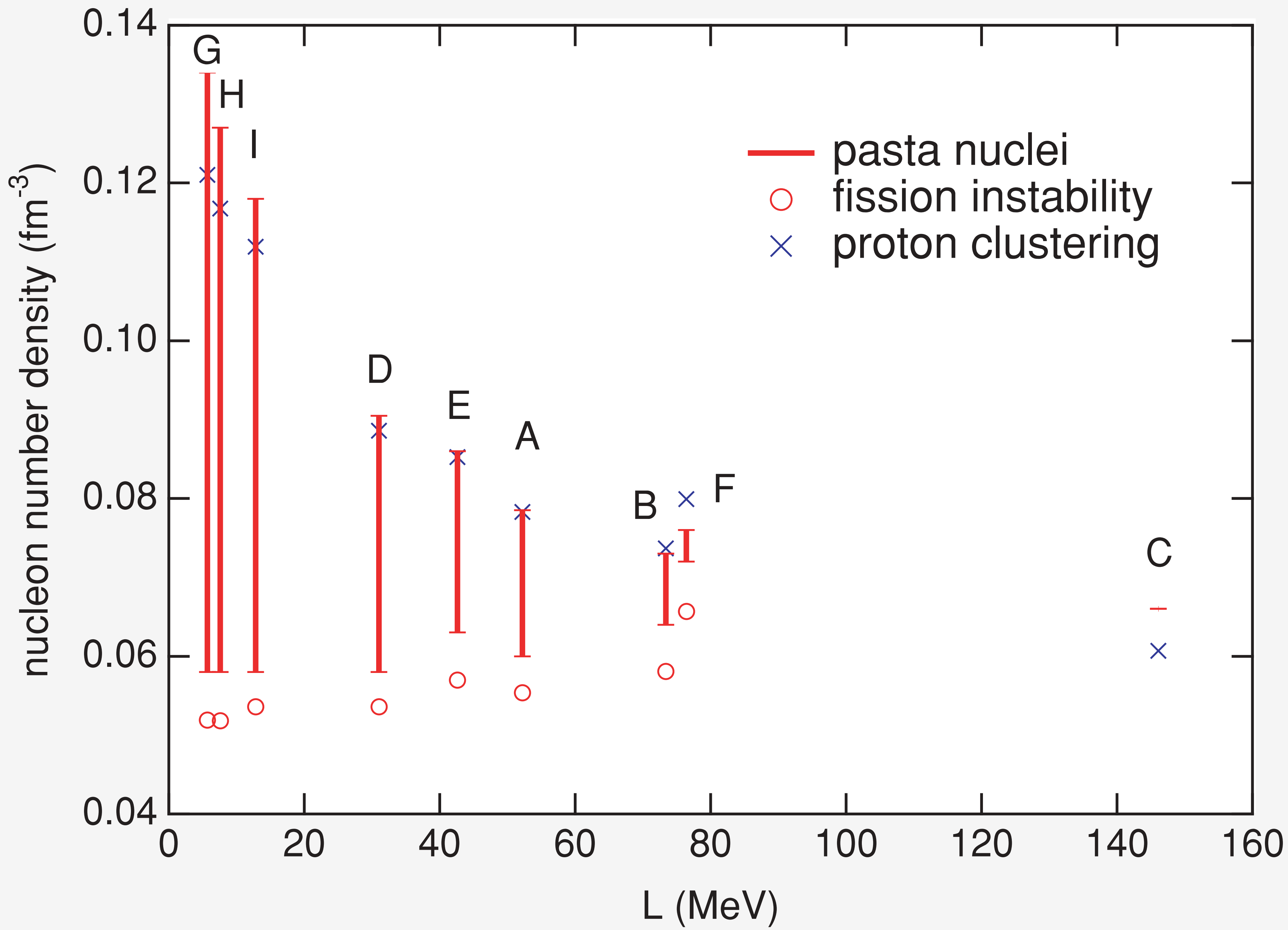
a greater C_P causes a longer diffusion timescale (Shternin et al. 2007; Brown & Cumming 2009; Page & Reddy)



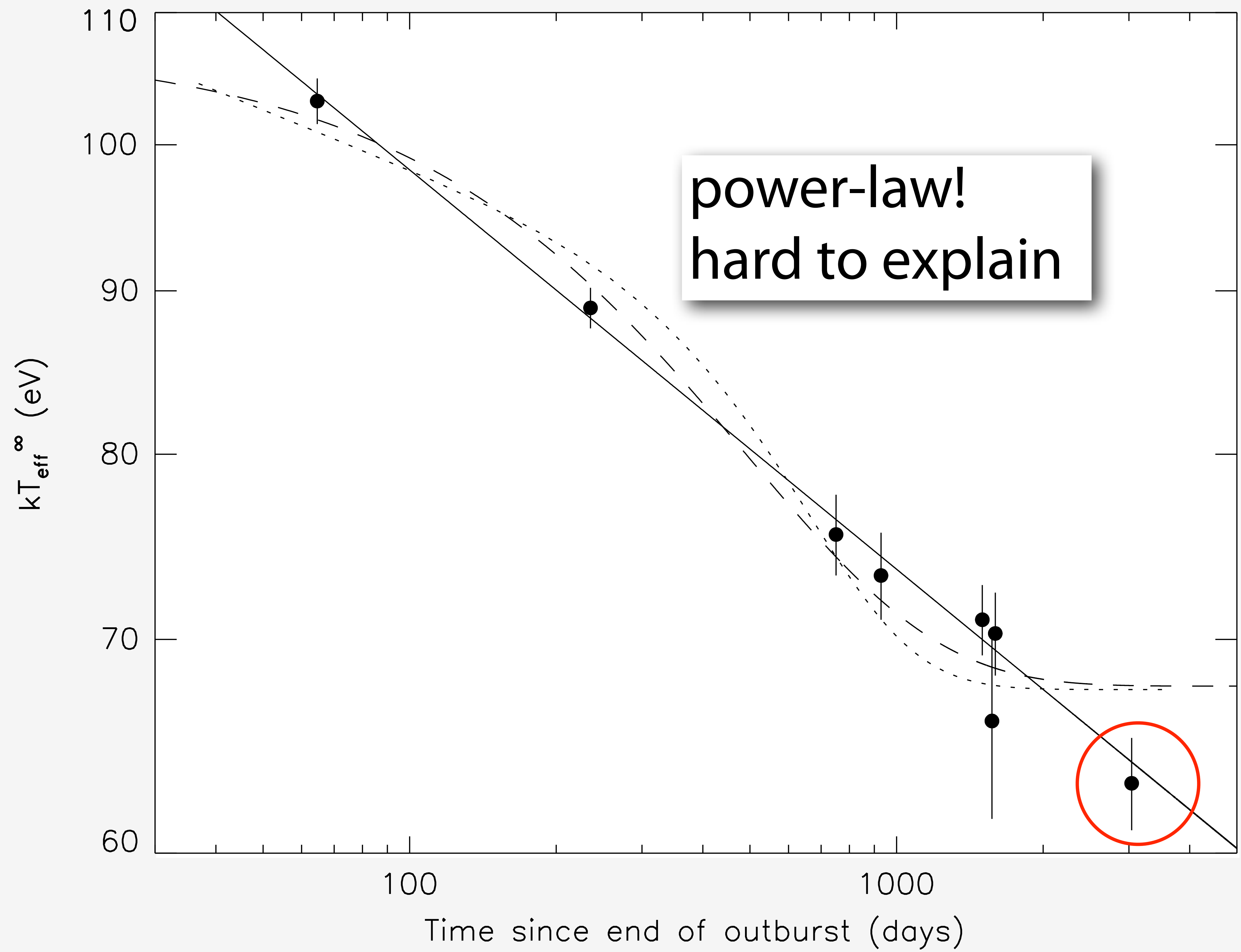

MD simulatons
by Horowitz &
collaborators
envelope
10 m
outer crust
$\mu_e \gg kT, m_e c^2$
100 m
inner crust
$\frac{Z^2 e^2}{a} \gg kT$
1 km
e^-
{Z,A}
n
e^-
{Z,A}
n, p, e^-, μ

Pasta/transition to core as functions of *L*

Oyamatsu & Iida ’07



Continued cooling in KS 1731 (Cackett et al. '10)



Neutron star cooling and the symmetry energy

1. Need to understand how much our prior knowledge of low-density nuclear matter is factored into the high-density EOS
2. A given EOS makes predictions for cooling
3. To what extent can we assign transport properties (e.g., viscosity, specific heat, superfluidity) to a given EOS? Currently these are treated independently.