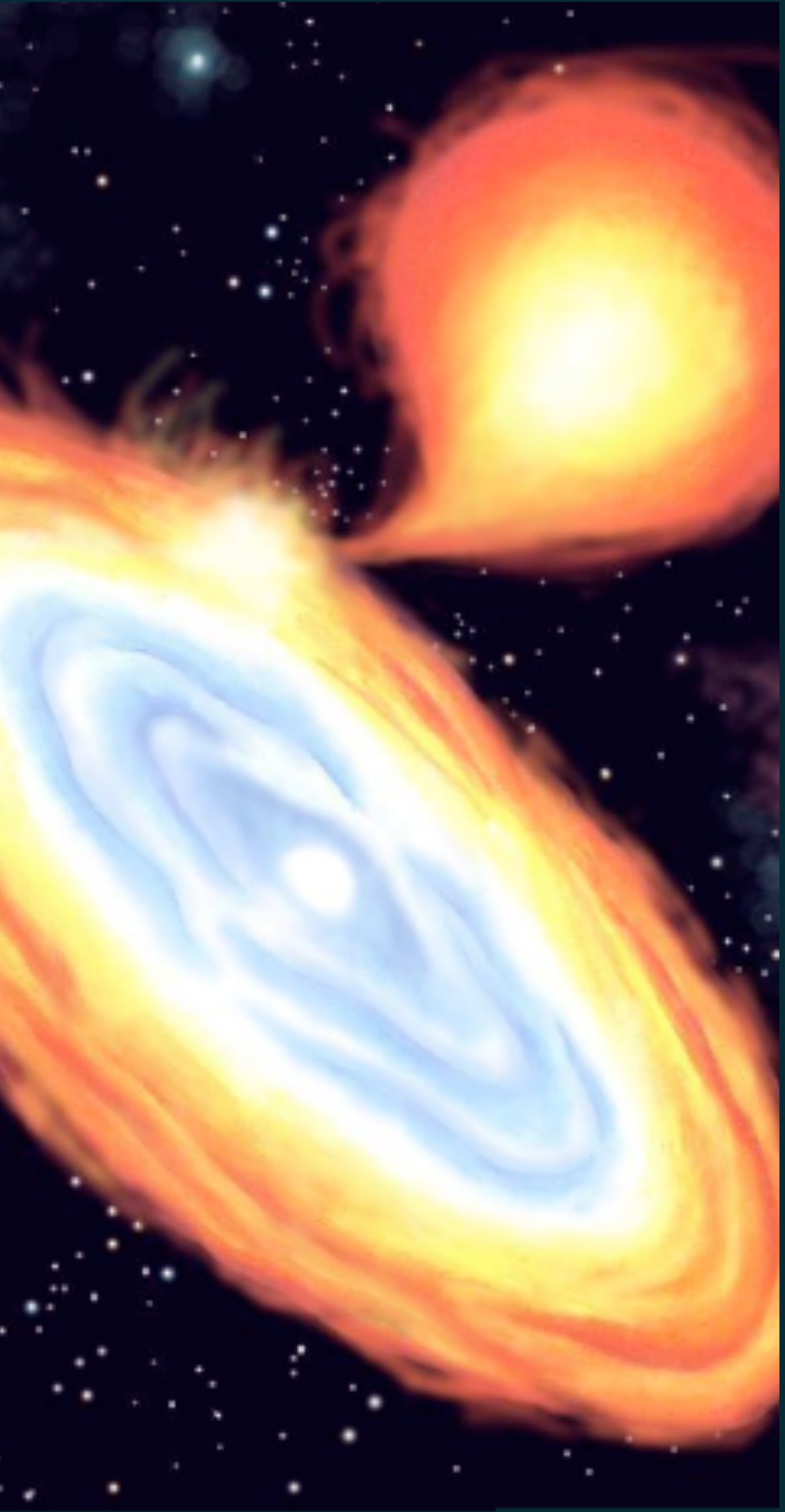
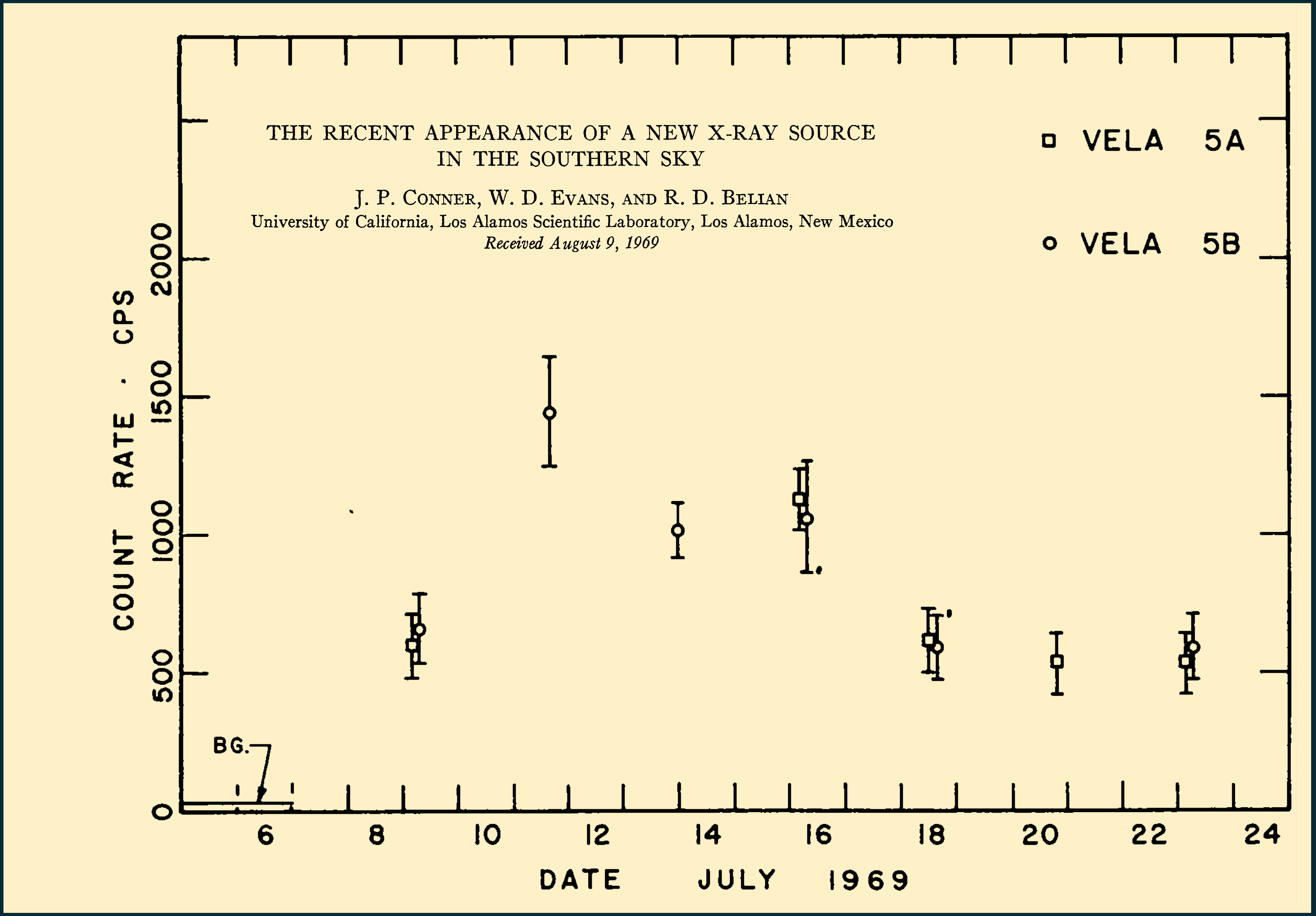


Soft X-ray Transients

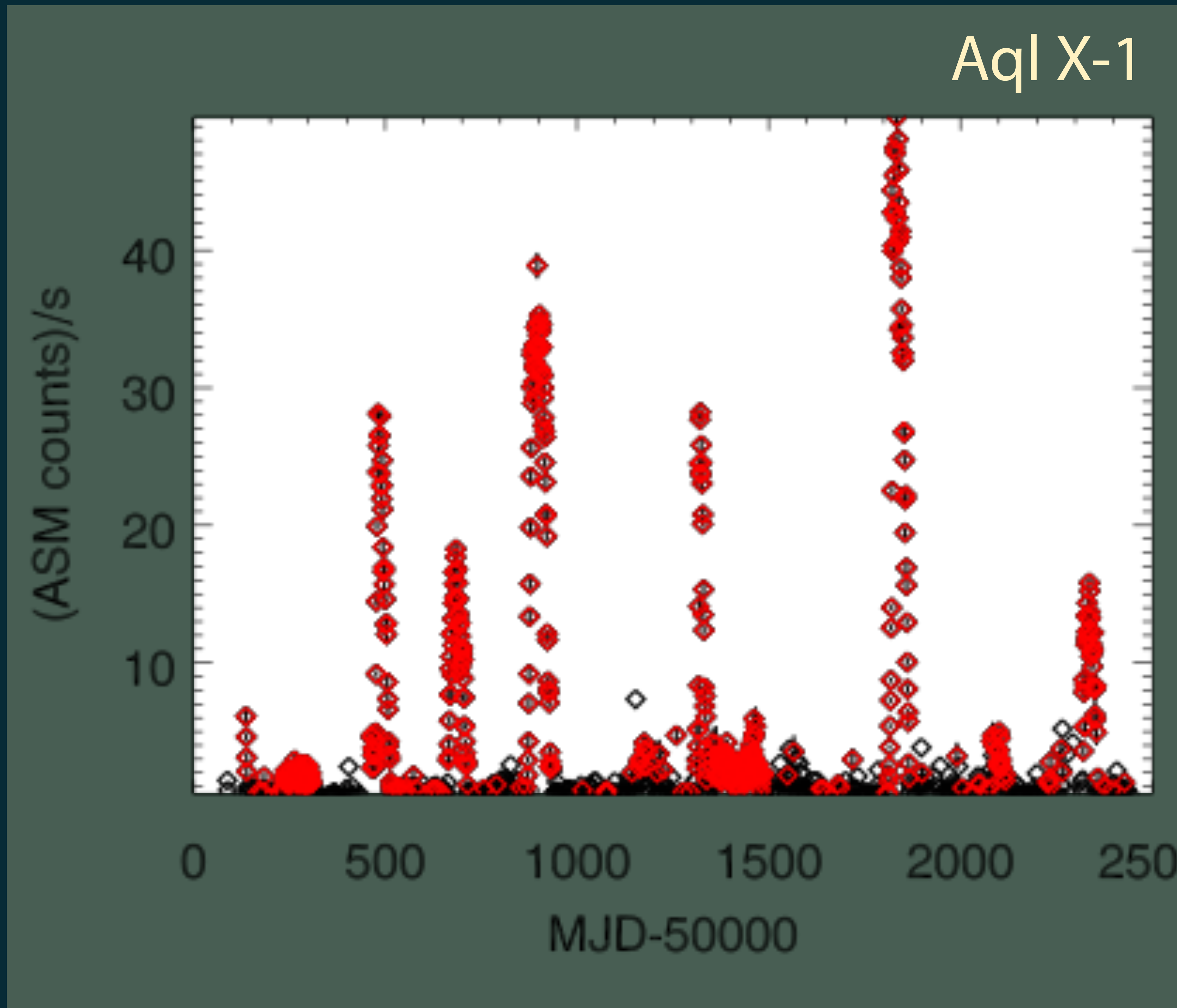
Edward Brown
Michigan State University

artwork courtesy T. Piro

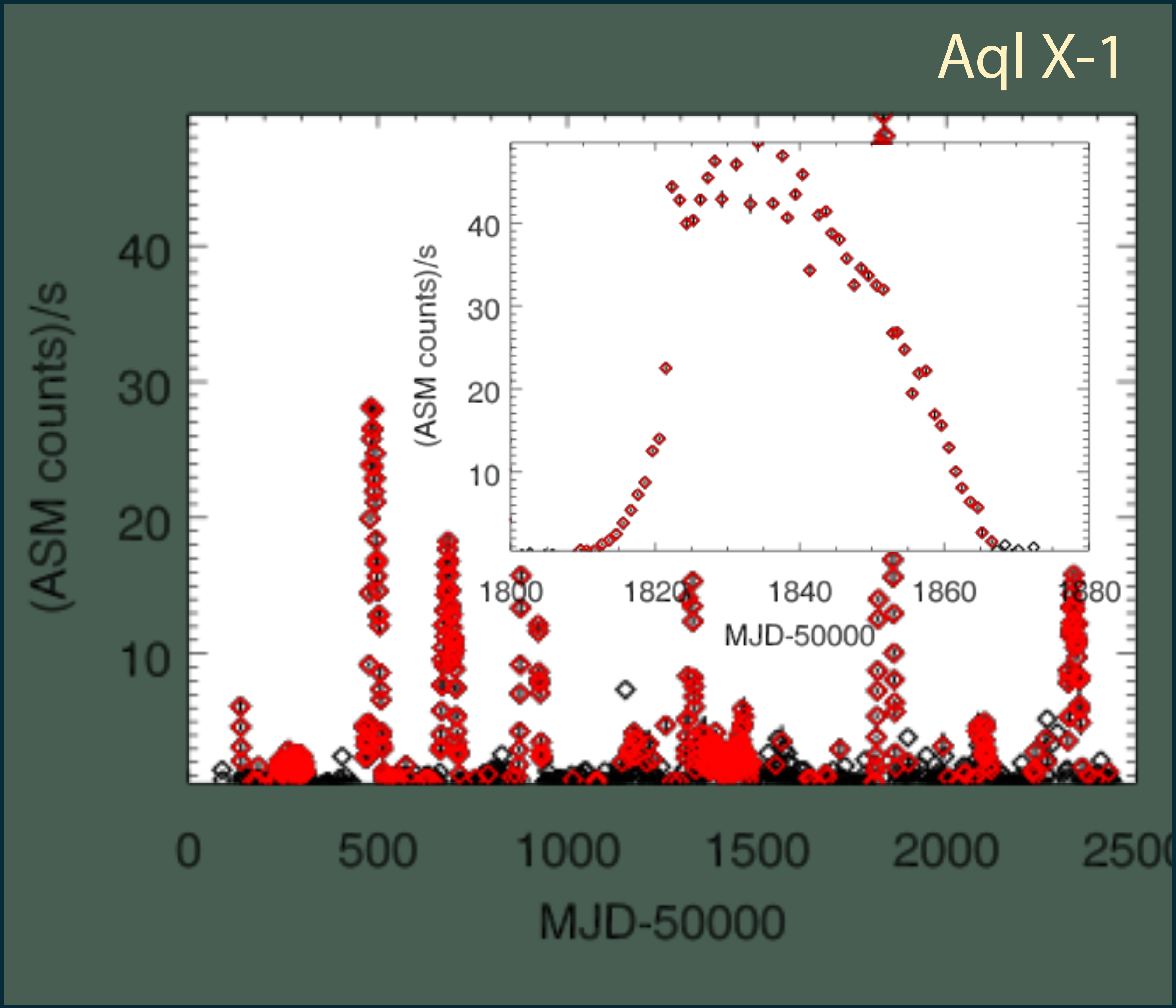
Discovery, Cen X-4



transients



transients

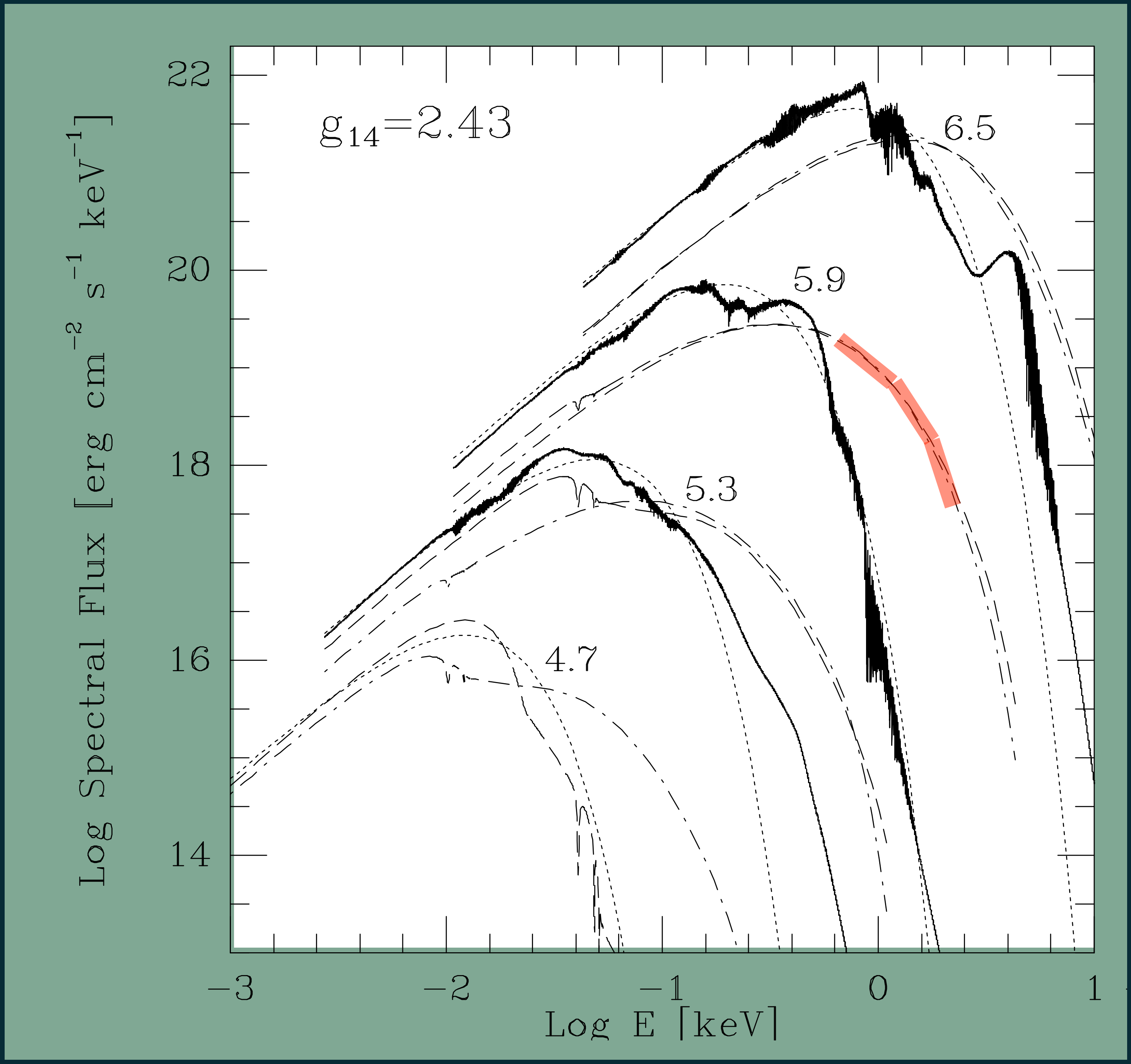


Aql X-1
(ASM counts)/s
40
30
20
10
0
500
1000
1500
2000
MJD-50000
1800
1820
1840
1860
1880

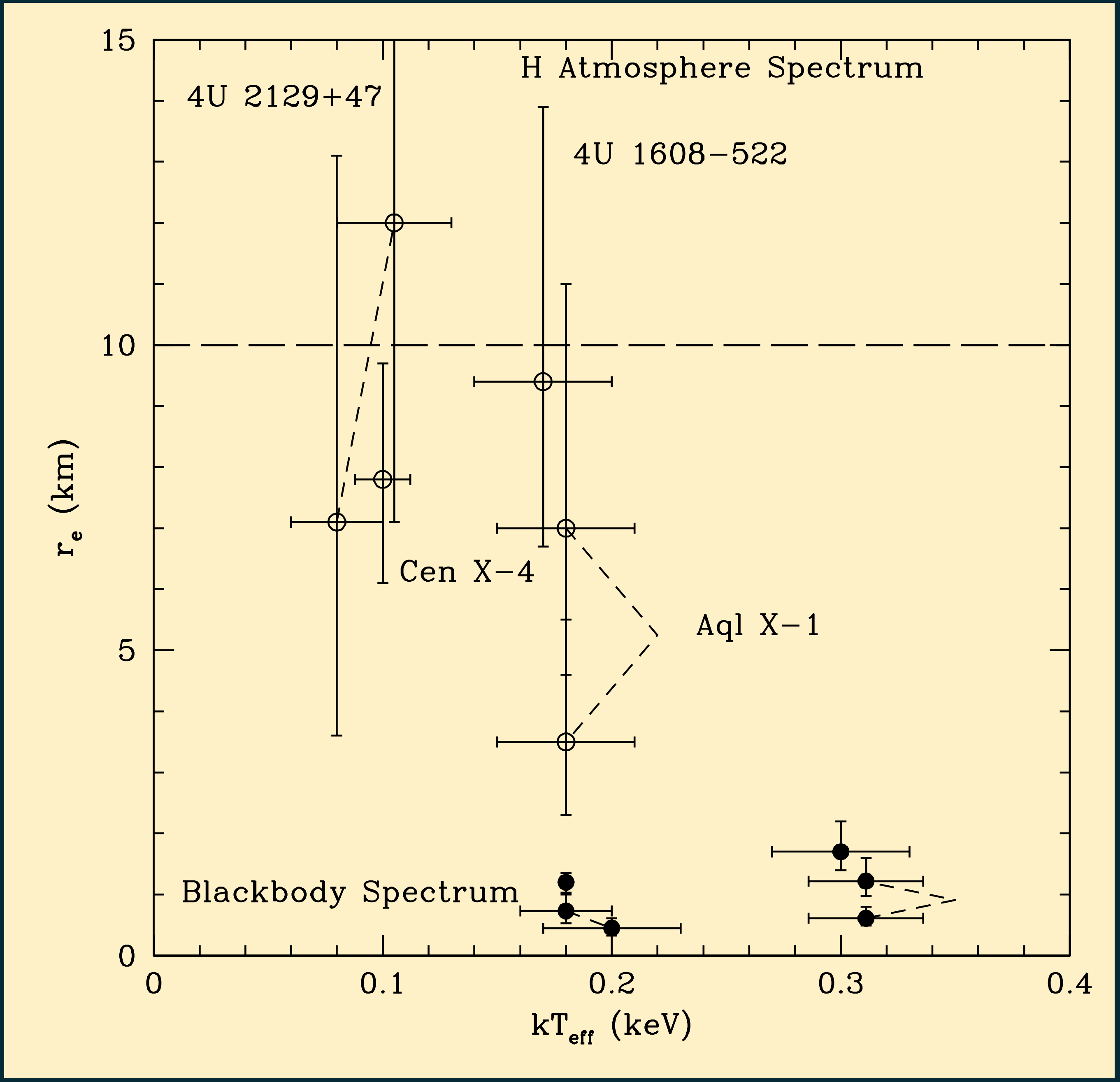
H-atmosphere; Zavlin et al. ‘96

heavier species rapidly sink from photosphere; Bildsten et al. ’92

gives radii consistent with NS star surface



Quiescent emission consistent with emission from NS surface



Rutledge et al. '00

NUCLEOSYNTHESIS IN SUPERNOVA OUTBURSTS AND THE CHEMICAL COMPOSITION OF THE ENVELOPES OF NEUTRON STARS

G. S. BISNOVATYI-KOGAN and V. M. CHECHETKIN

Institute of Applied Mathematics, U.S.S.R. Academy of Sciences, Moscow, U.S.S.R.

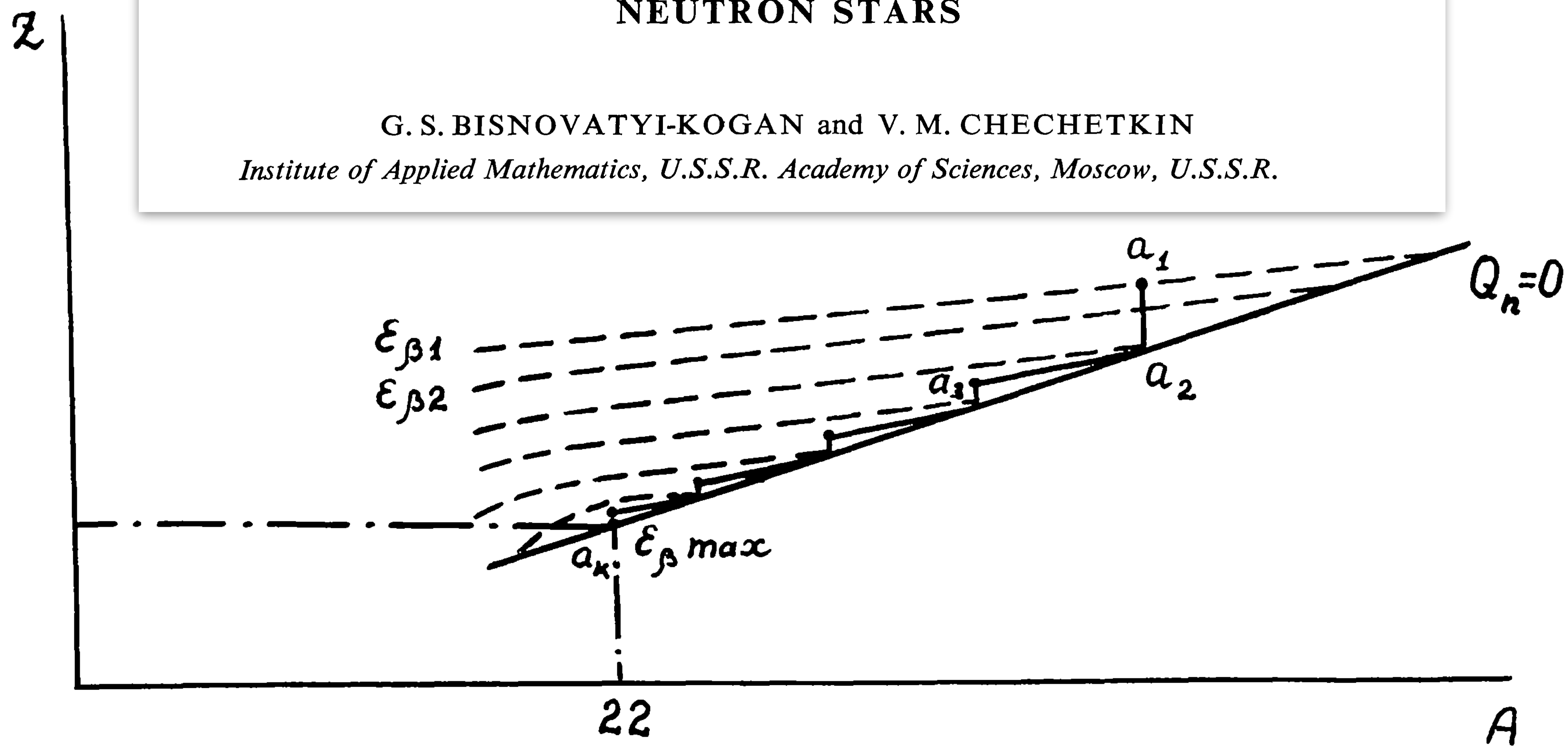
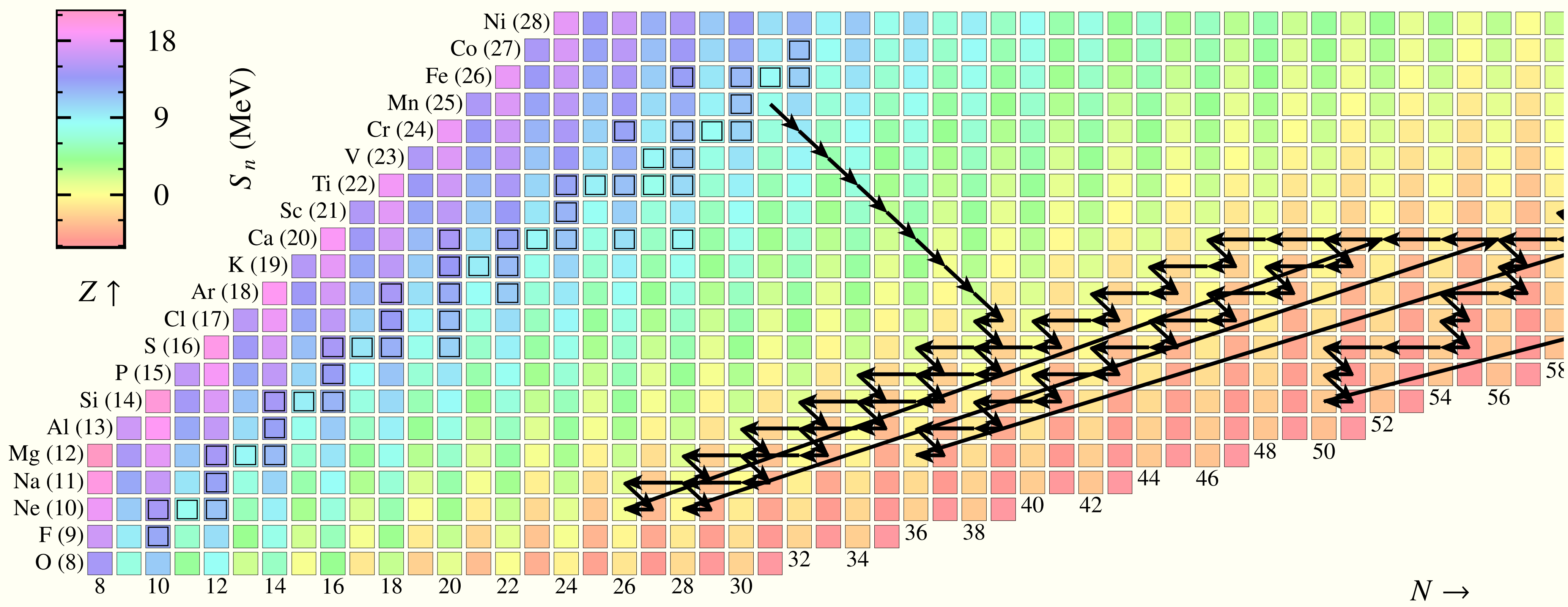


Fig. 2. Schematic representation of (A, Z). The curves of constant $\varepsilon_\beta = Q_p - Q_n$ have been indicated by dashed lines. The thick black line indicates the boundary of existence of a nucleus for which $Q_n = 0$. The step line $a_1 a_2 a_3 \ldots a_k$ correspond to variations of (A, Z) with increasing density of the cold material. At the point a_k, ε_β attains the maximum $\varepsilon_{\beta \max}$.

crust reactions | deep heating

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



see poster by A. Deibel

crust reactions | deep heating

Bisnovatyi-Kogan and Chechetkin '74; Sato '79; Haensel & Zdunk '90; Gupta et al. '07; Steiner '12; Schatz et al. '13; Deibel et al. (in prep)

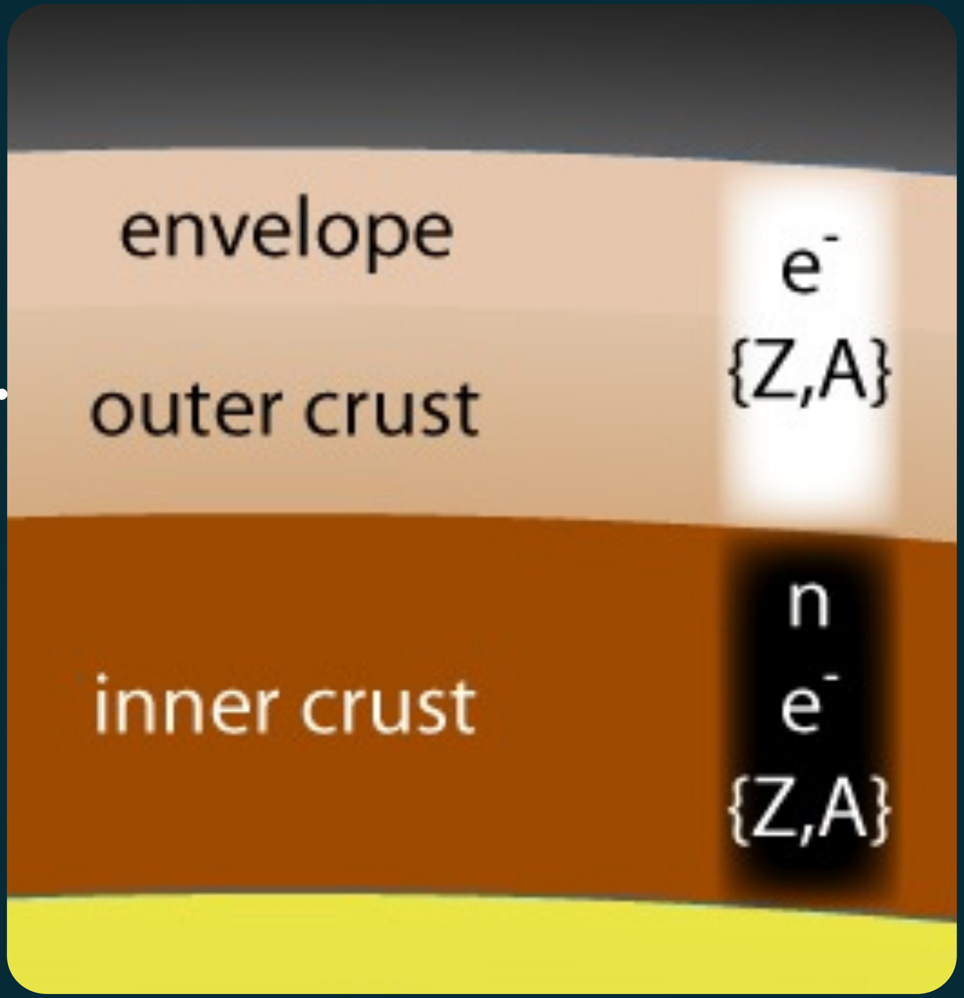
neutronization

$$E \approx -a_V(N+Z) + a_A \frac{(N-Z)^2}{N+Z}$$

In β-equilibrium, $\mu_e = \mu_n - \mu_p$, with

$$\mu_n = \left(\frac{\partial E}{\partial N}\right)_Z, \quad \mu_p = \left(\frac{\partial E}{\partial Z}\right)_N.$$

$$\frac{Z}{A} \approx \frac{1}{2} - \frac{\mu_e}{8a_A}$$



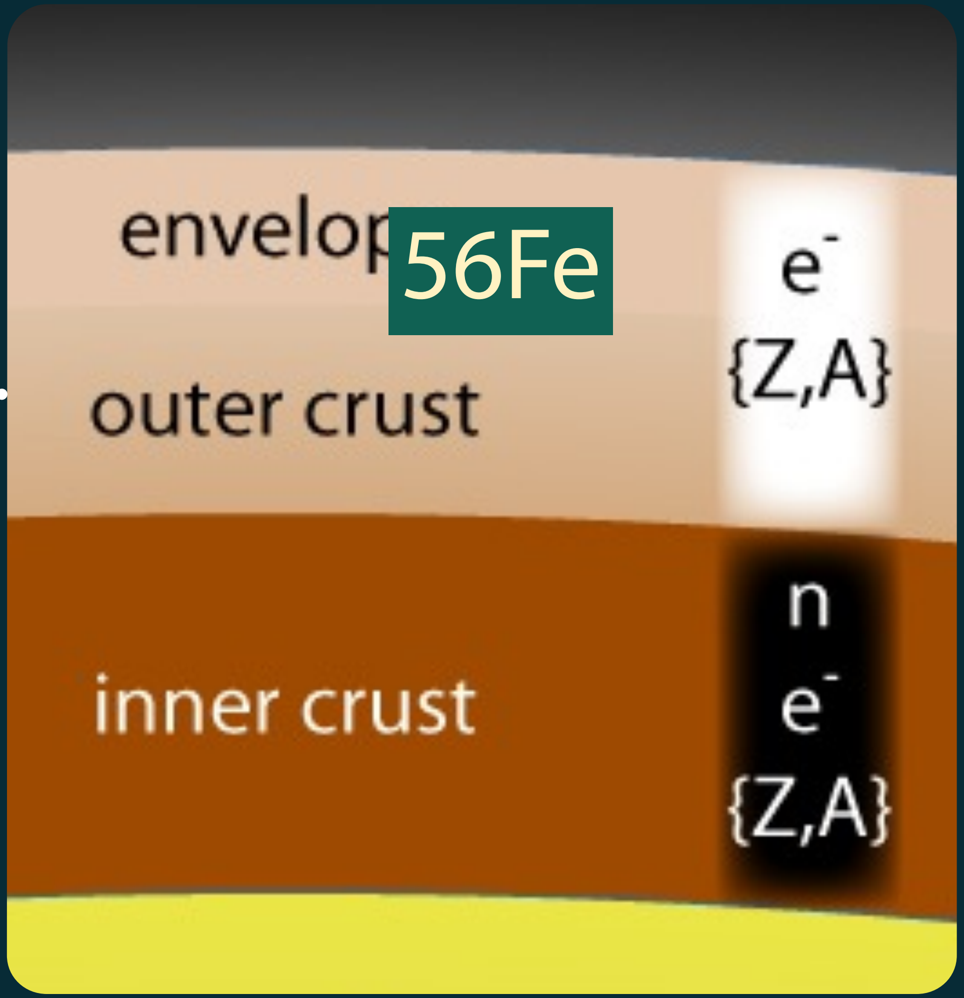
neutronization

$$E \approx -a_V(N+Z) + a_A \frac{(N-Z)^2}{N+Z}$$

In β-equilibrium, $\mu_e = \mu_n - \mu_p$, with

$$\mu_n = \left(\frac{\partial E}{\partial N}\right)_Z, \quad \mu_p = \left(\frac{\partial E}{\partial Z}\right)_N.$$

$$\frac{Z}{A} \approx \frac{1}{2} - \frac{\mu_e}{8a_A}$$



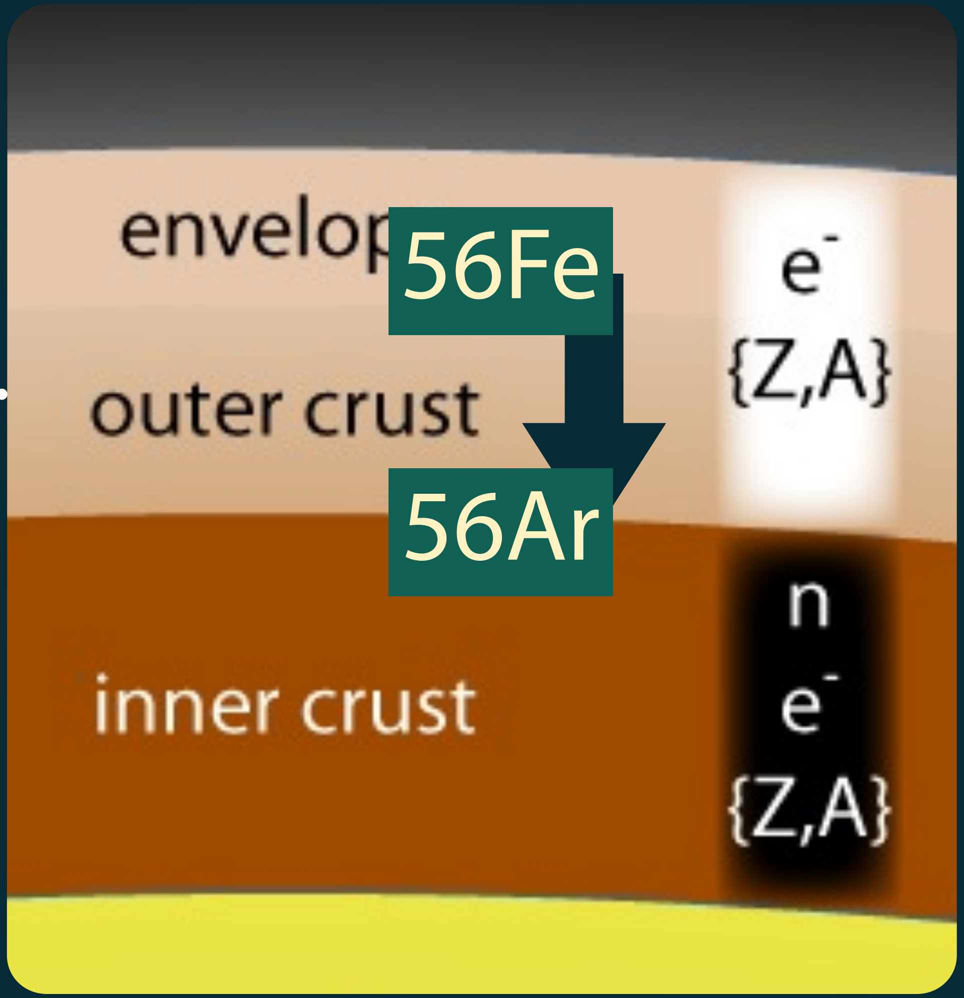
neutronization

$$E \approx -a_V(N+Z) + a_A \frac{(N-Z)^2}{N+Z}$$

In β-equilibrium, $\mu_e = \mu_n - \mu_p$, with

$$\mu_n = \left(\frac{\partial E}{\partial N}\right)_Z, \quad \mu_p = \left(\frac{\partial E}{\partial Z}\right)_N.$$

$$\frac{Z}{A} \approx \frac{1}{2} - \frac{\mu_e}{8a_A}$$



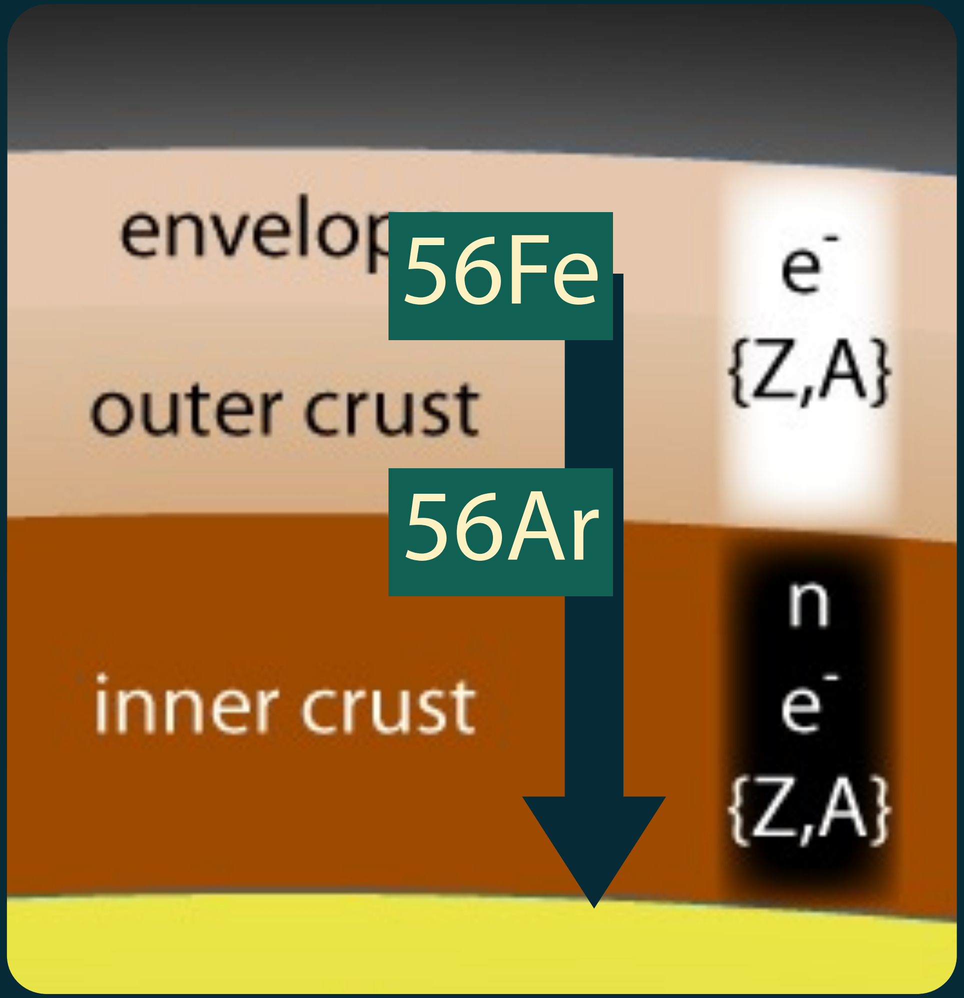
neutron drip

$$E \approx -a_V(N+Z) + a_A \frac{(N-Z)^2}{N+Z}$$

At neutron drip,

$$\mu_n = \left(\frac{\partial E}{\partial N}\right)_Z \to 0$$

$$\mu_e \approx 2a_V \approx 30 \text{ MeV}$$



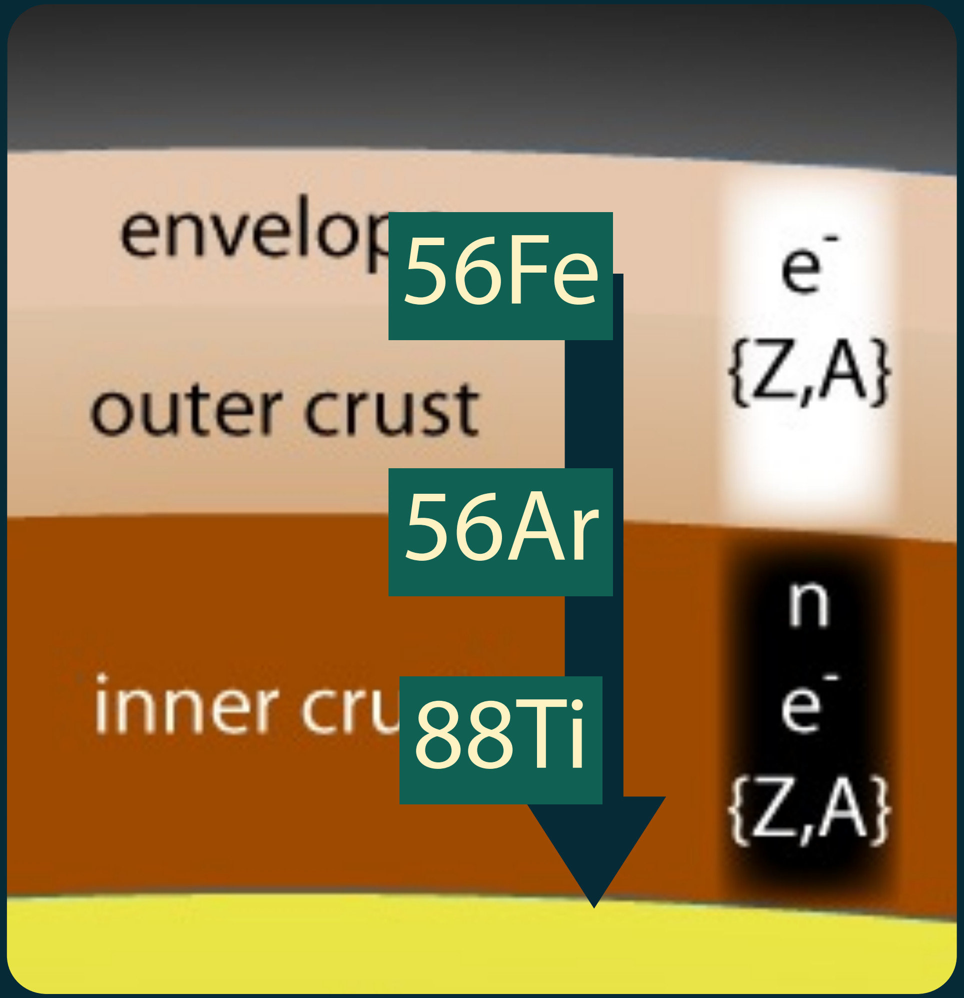
neutron drip

$$E \approx -a_V(N+Z) + a_A \frac{(N-Z)^2}{N+Z}$$

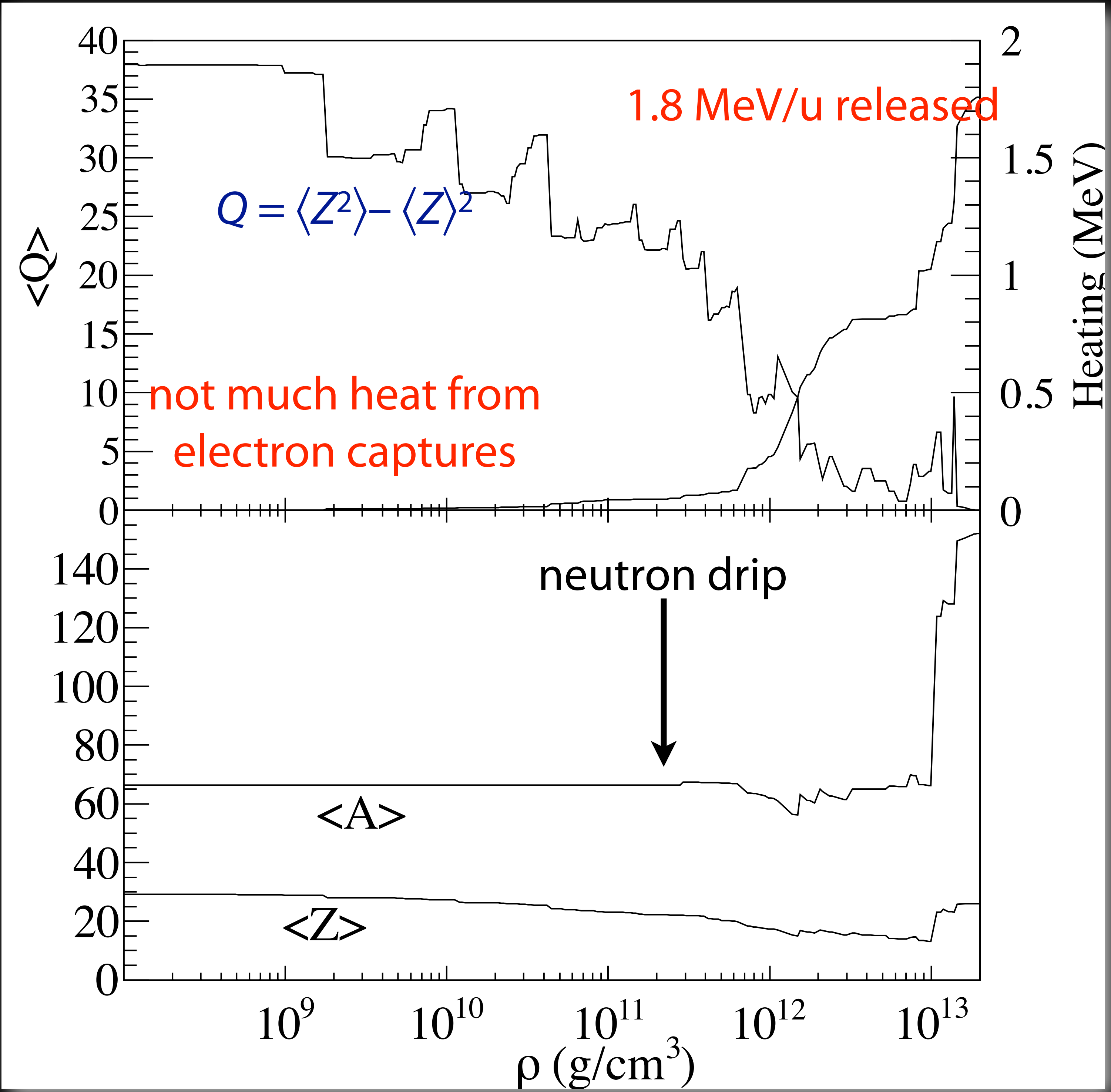
At neutron drip,

$$\mu_n = \left(\frac{\partial E}{\partial N}\right)_Z \to 0$$

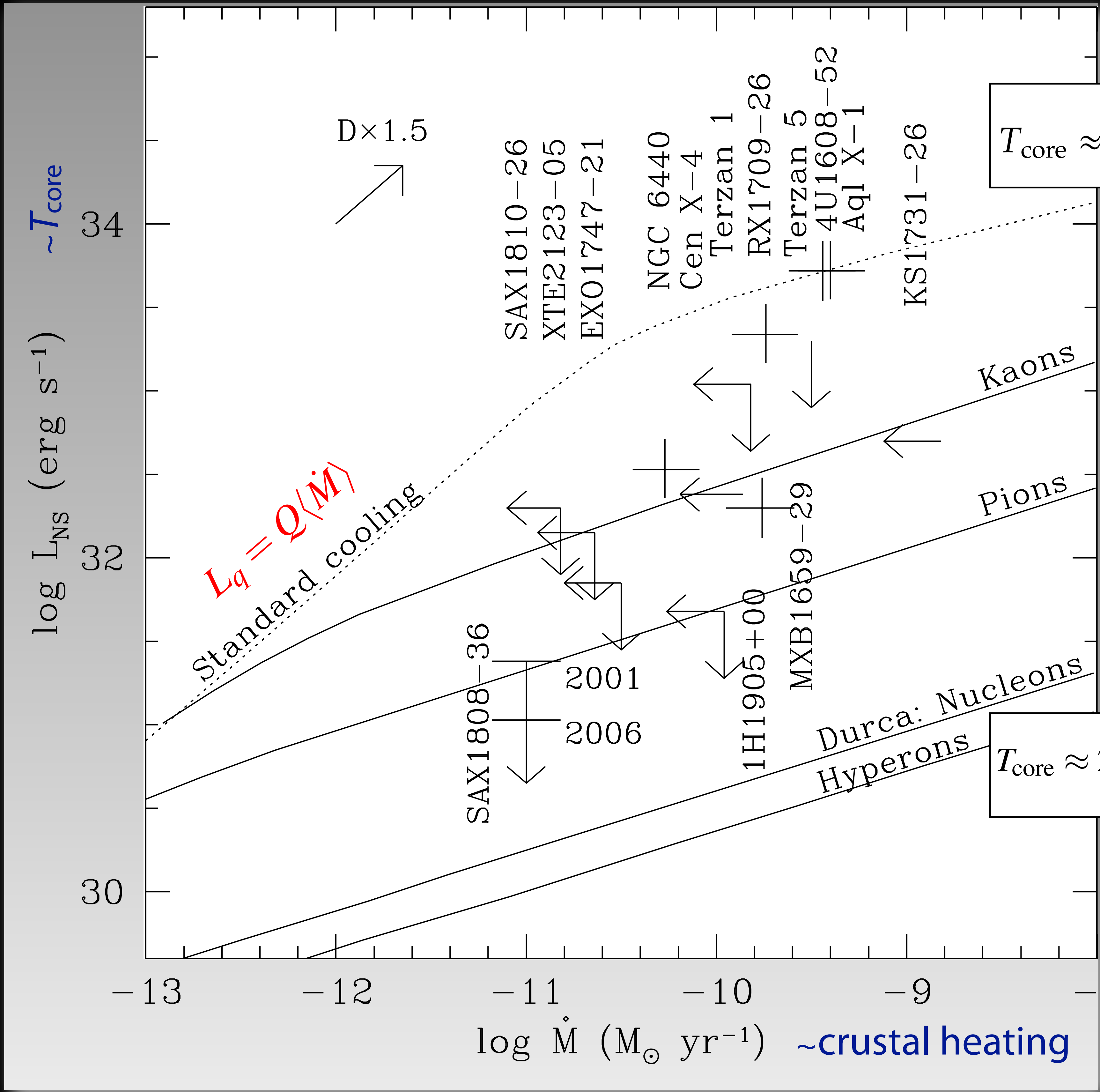
$$\mu_e \approx 2a_V \approx 30 \text{ MeV}$$



plot courtesy A. Steiner



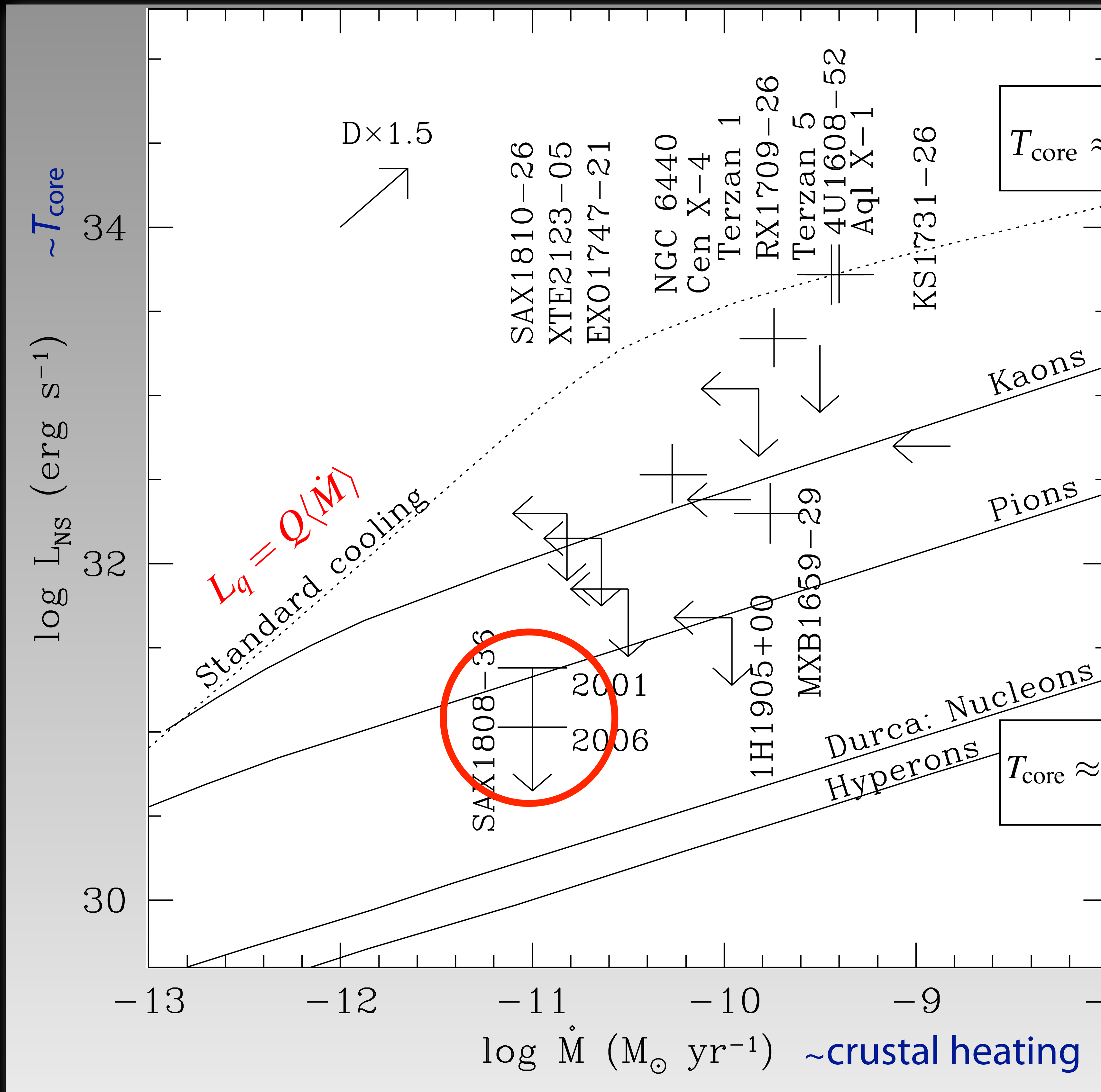
Heinke et al. 2007, following Yakovlev et al. 2004



$$T_{\rm core} \approx 2\times10^{8}\,{\rm K}\left(\frac{\langle\dot{M}\rangle}{10^{-10}\,M_\odot\,{\rm yr}^{-1}}\right)^{1/8}$$

$$T_{\rm core} \approx 2\times10^{7}\,{\rm K}\left(\frac{\langle\dot{M}\rangle}{10^{-10}\,M_\odot\,{\rm yr}^{-1}}\right)^{1/6}$$

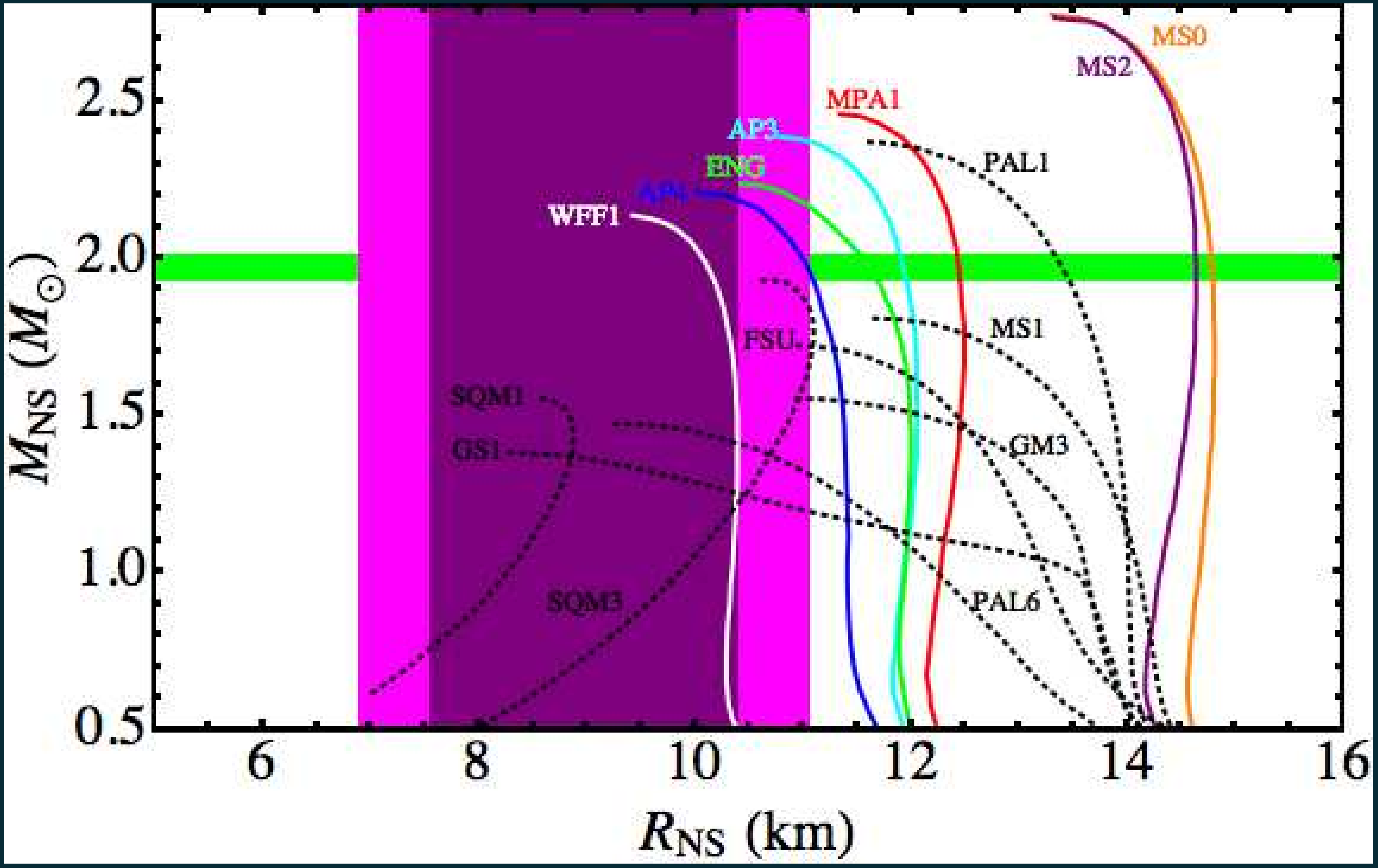
Heinke et al. 2007, following Yakovlev et al. 2004



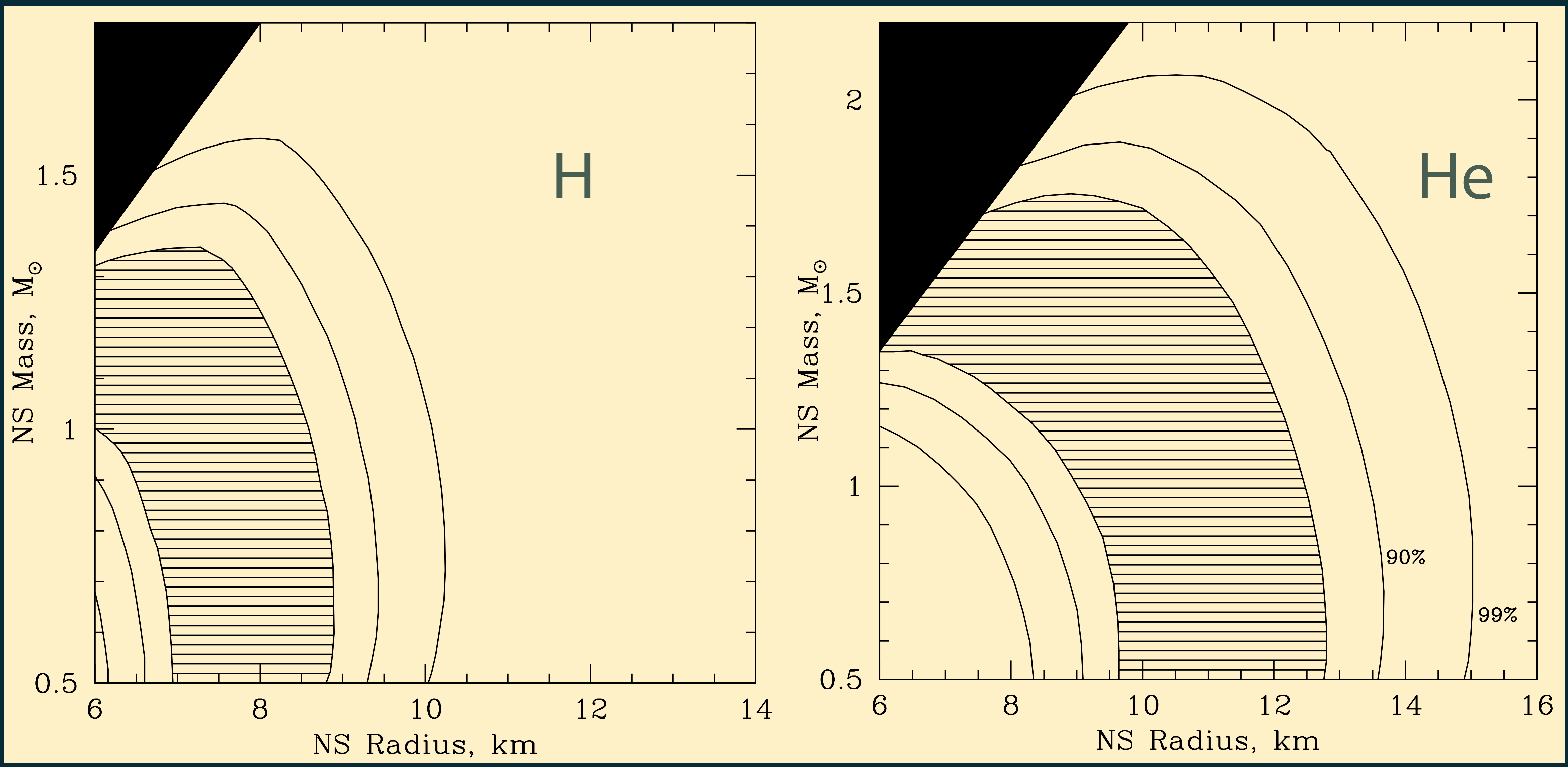
$$T_{\rm core} \approx 2\times10^8\,{\rm K}\left(\frac{\langle\dot{M}\rangle}{10^{-10}\,M_\odot\,{\rm yr}^{-1}}\right)^{1/8}$$

$$T_{\rm core} \approx 2\times10^7\,{\rm K}\left(\frac{\langle\dot{M}\rangle}{10^{-10}\,M_\odot\,{\rm yr}^{-1}}\right)^{1/6}$$

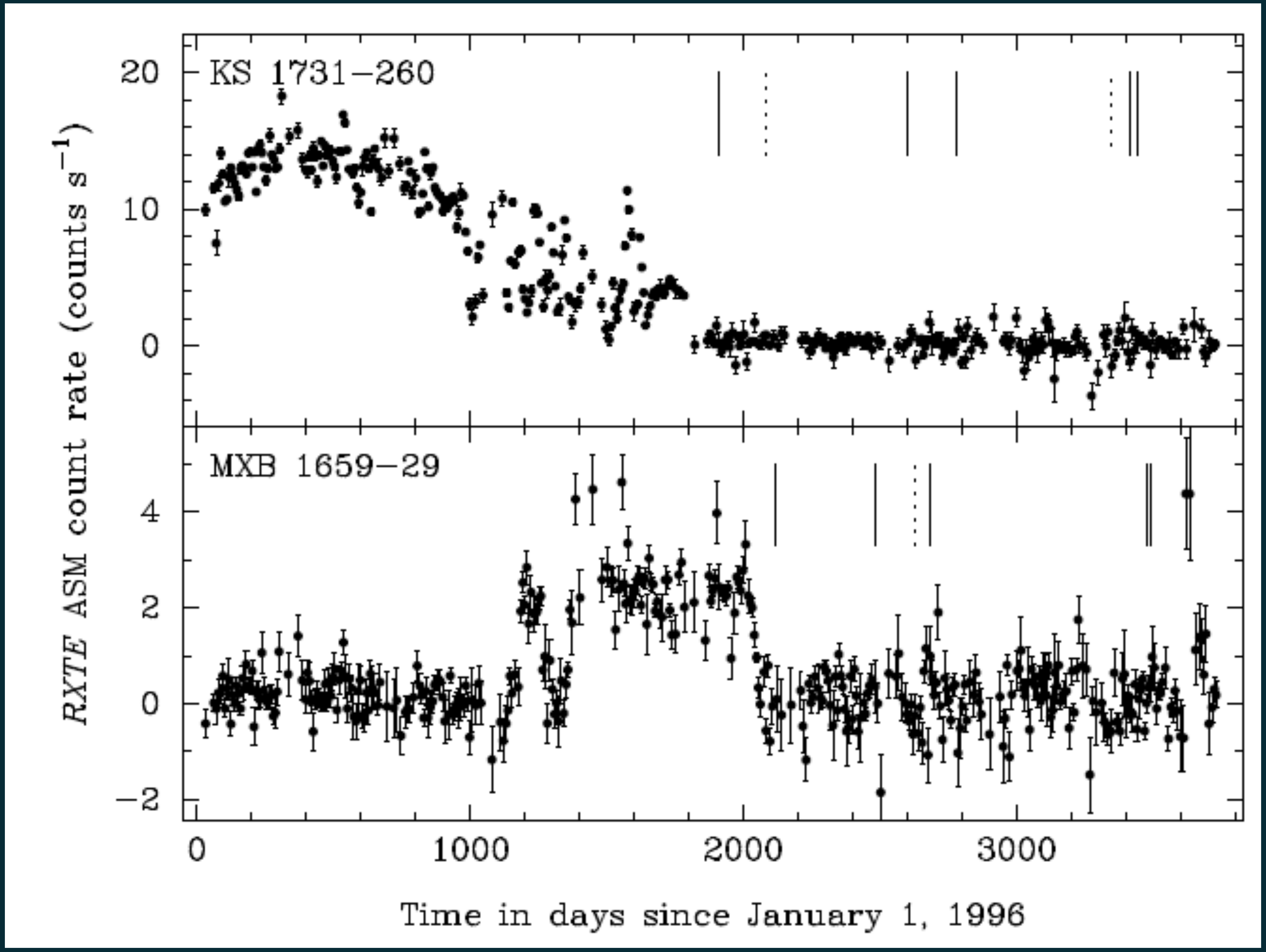
determination of NS radius
Guillot et al. 2013



H vs He atmosphere
NGC 6397, Heinke et al. '14



quasi-persistent transients



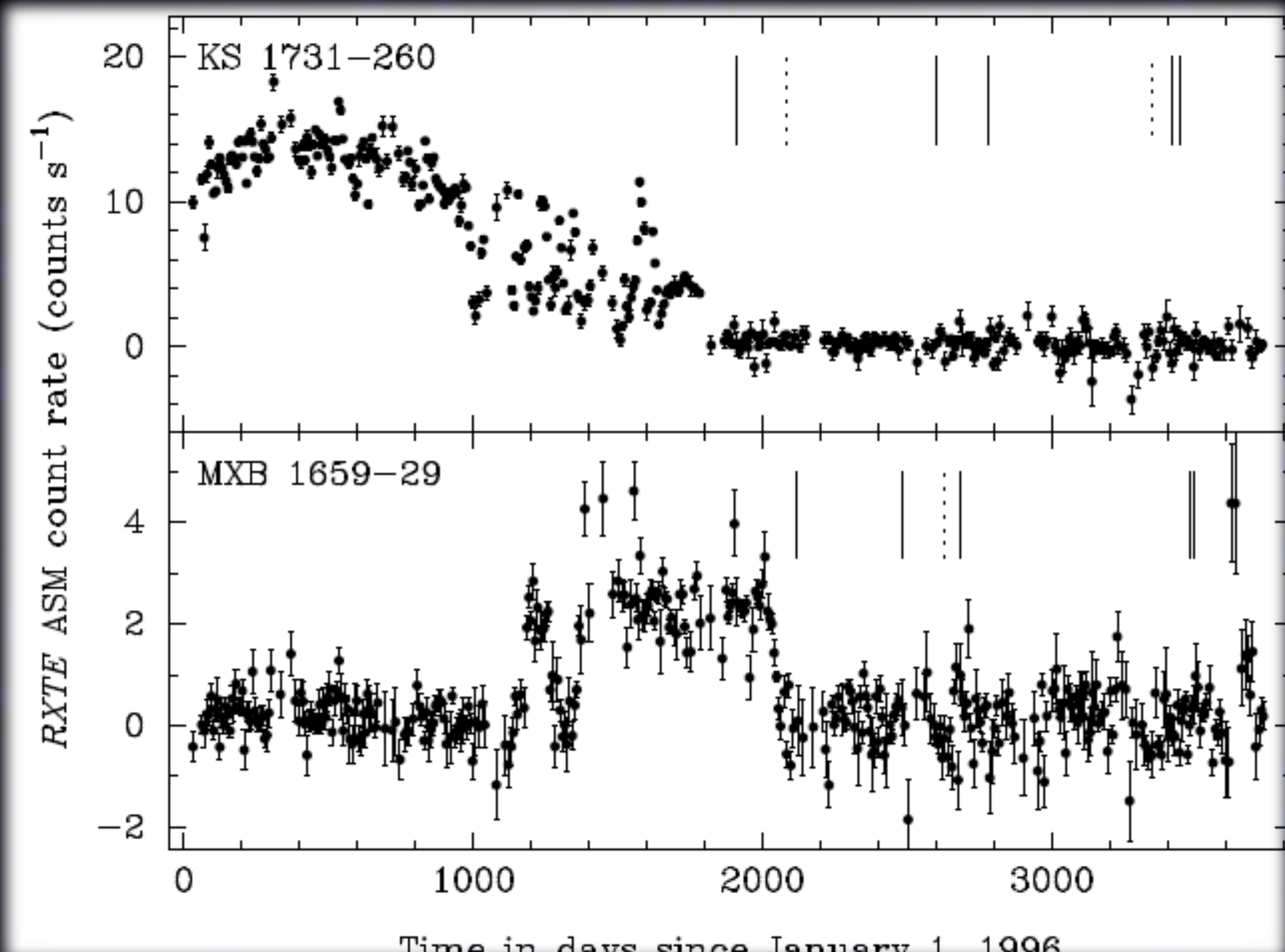
Cackett et al. '06

quasi-peristent transients

Rutledge et al., Shternin et al., Brown & Cumming; Page & Reddy

quasi-peristent transients

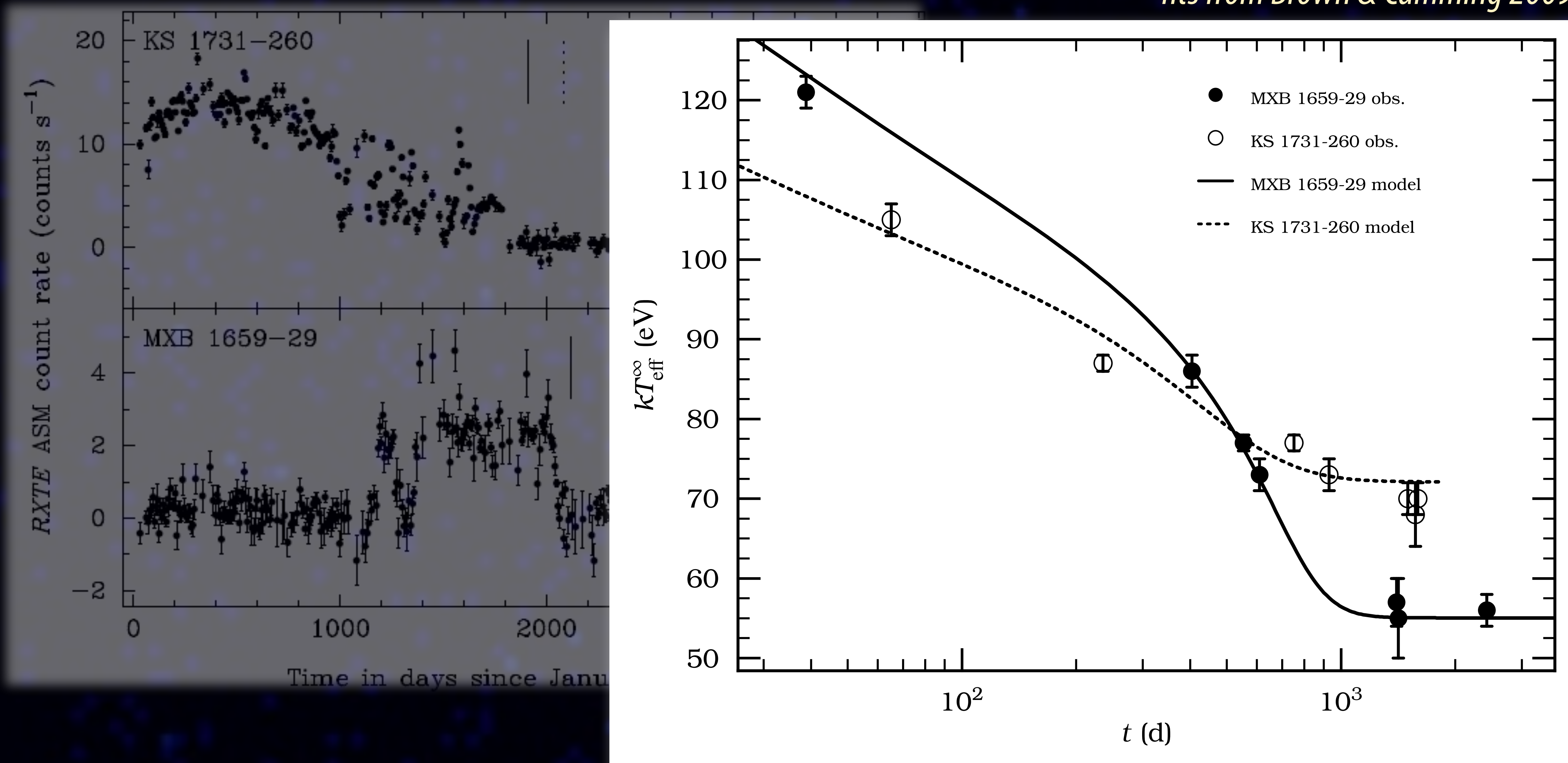
Rutledge et al., Shternin et al., Brown & Cumming; Page & Reddy



quasi-peristent transients

Rutledge et al., Shternin et al., Brown & Cumming; Page & Reddy

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



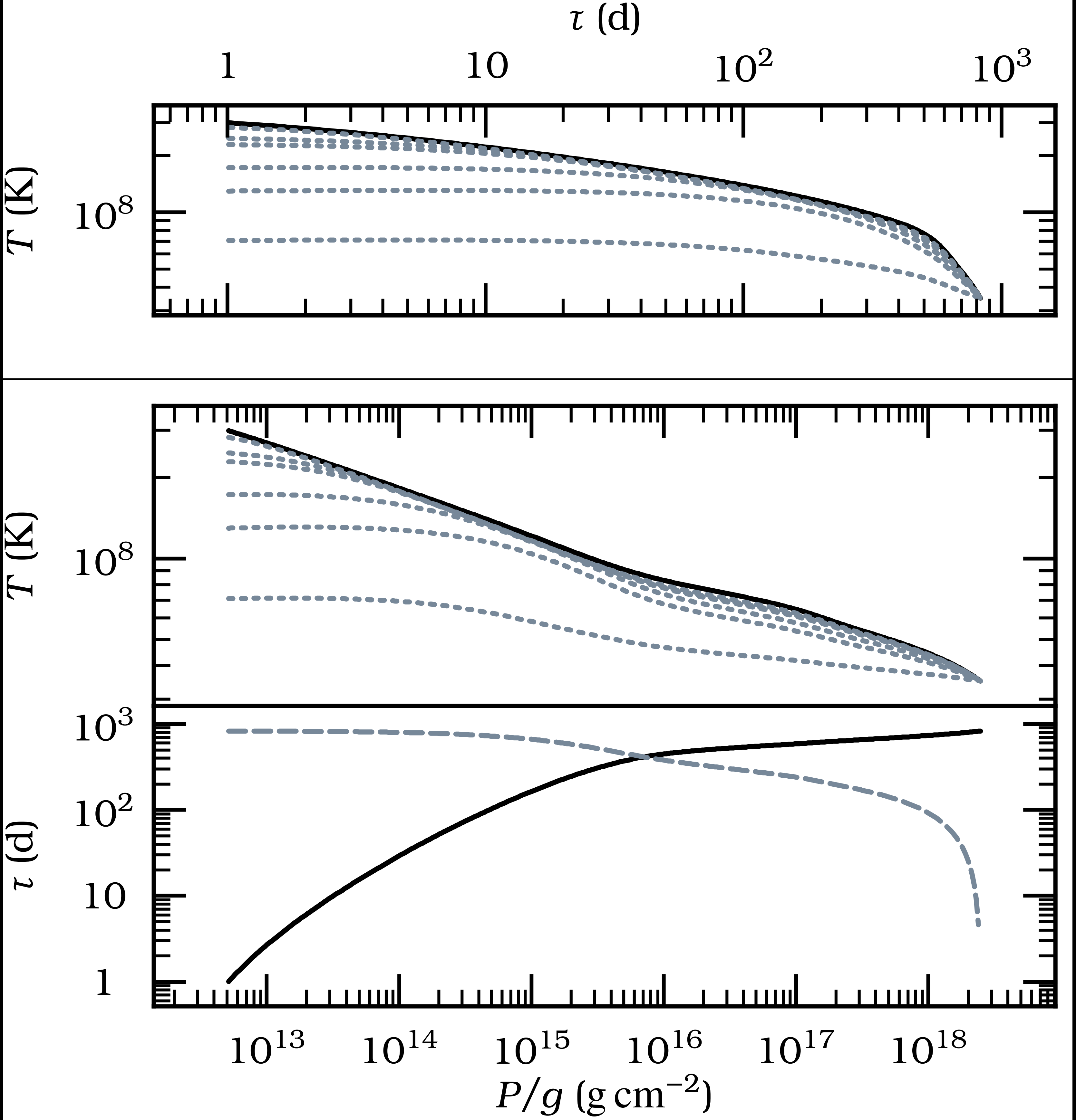
basic physics of the lightcurve

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

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



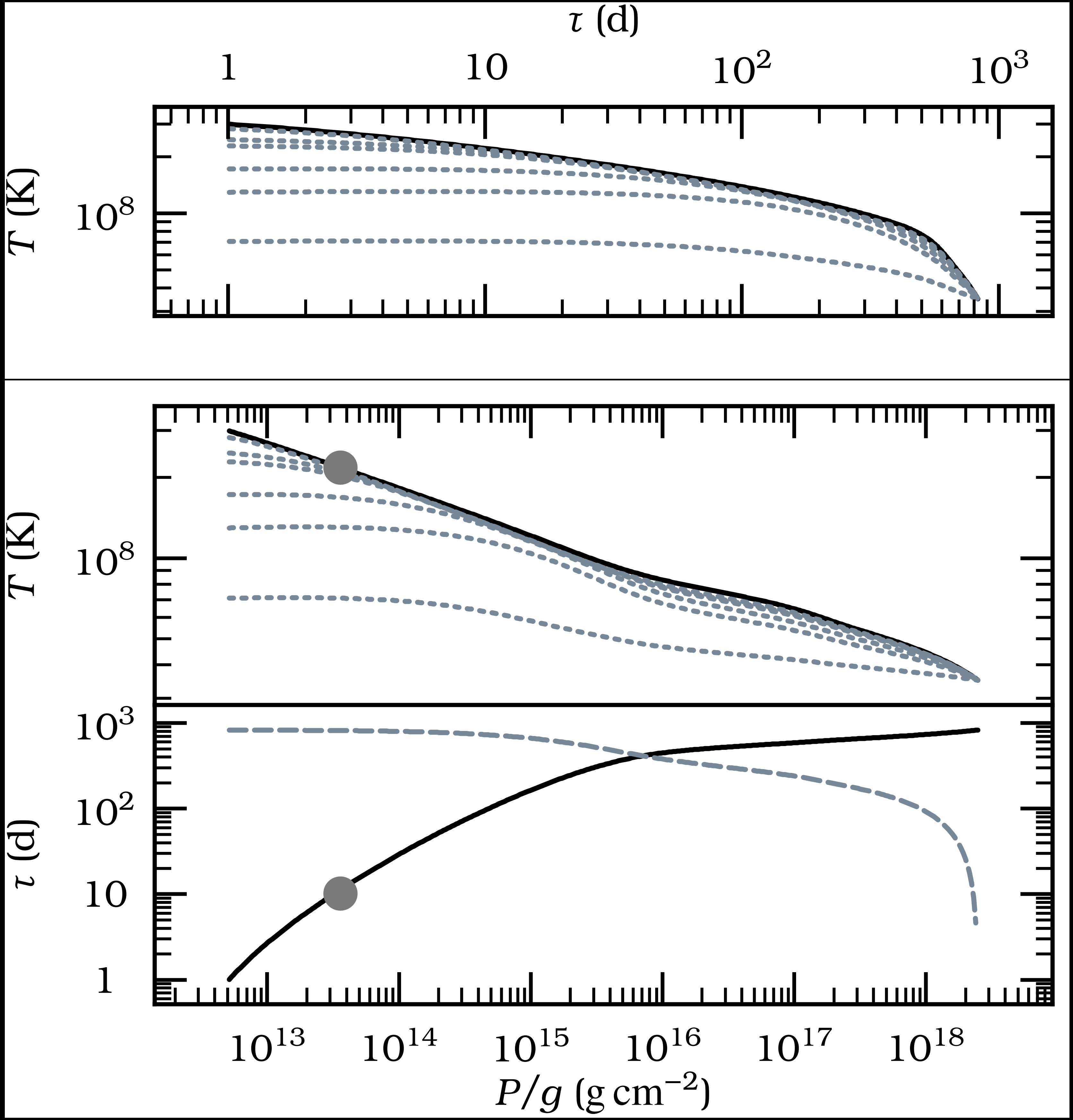
basic physics of the lightcurve

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

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



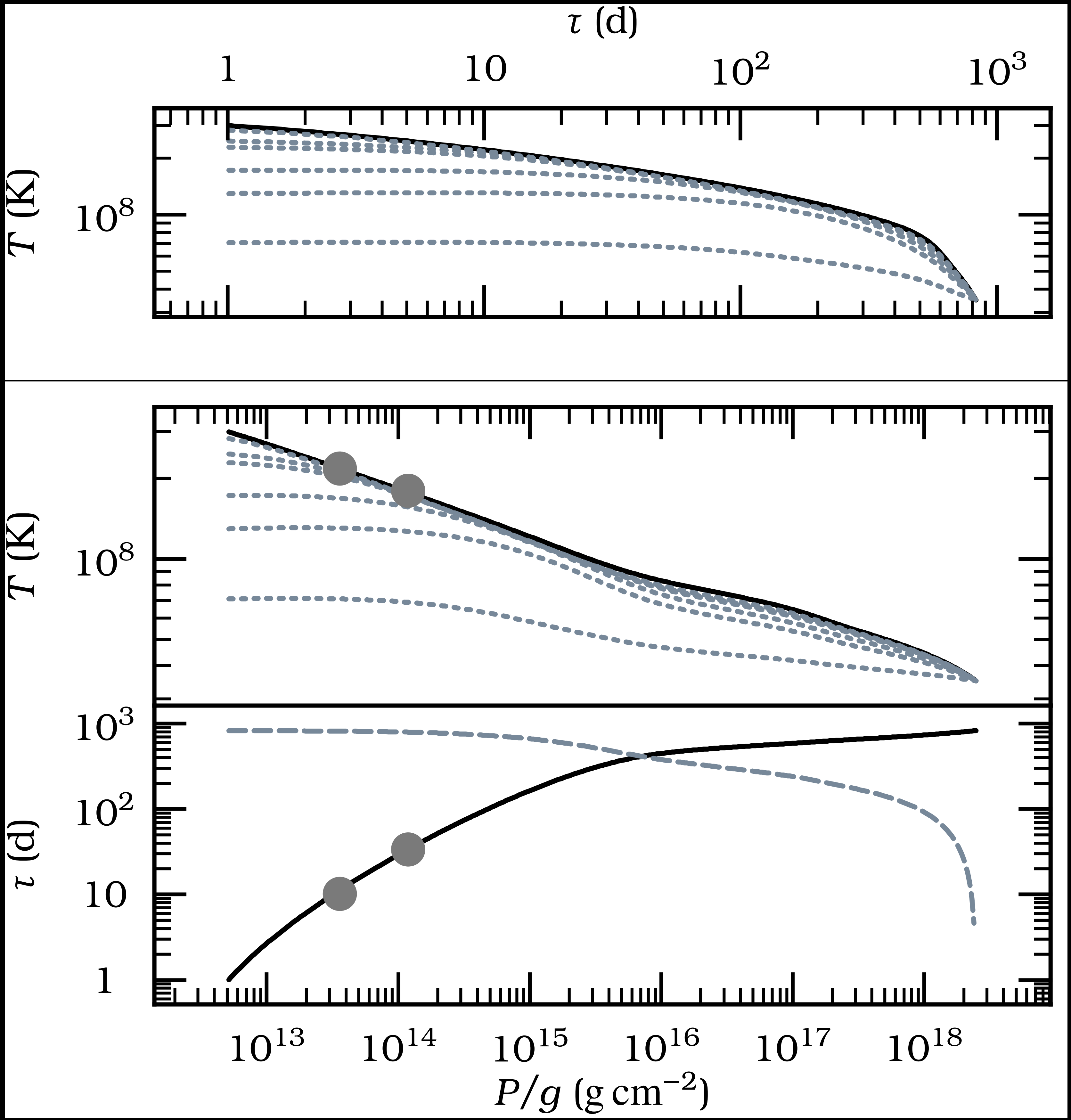
basic physics of the lightcurve

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

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



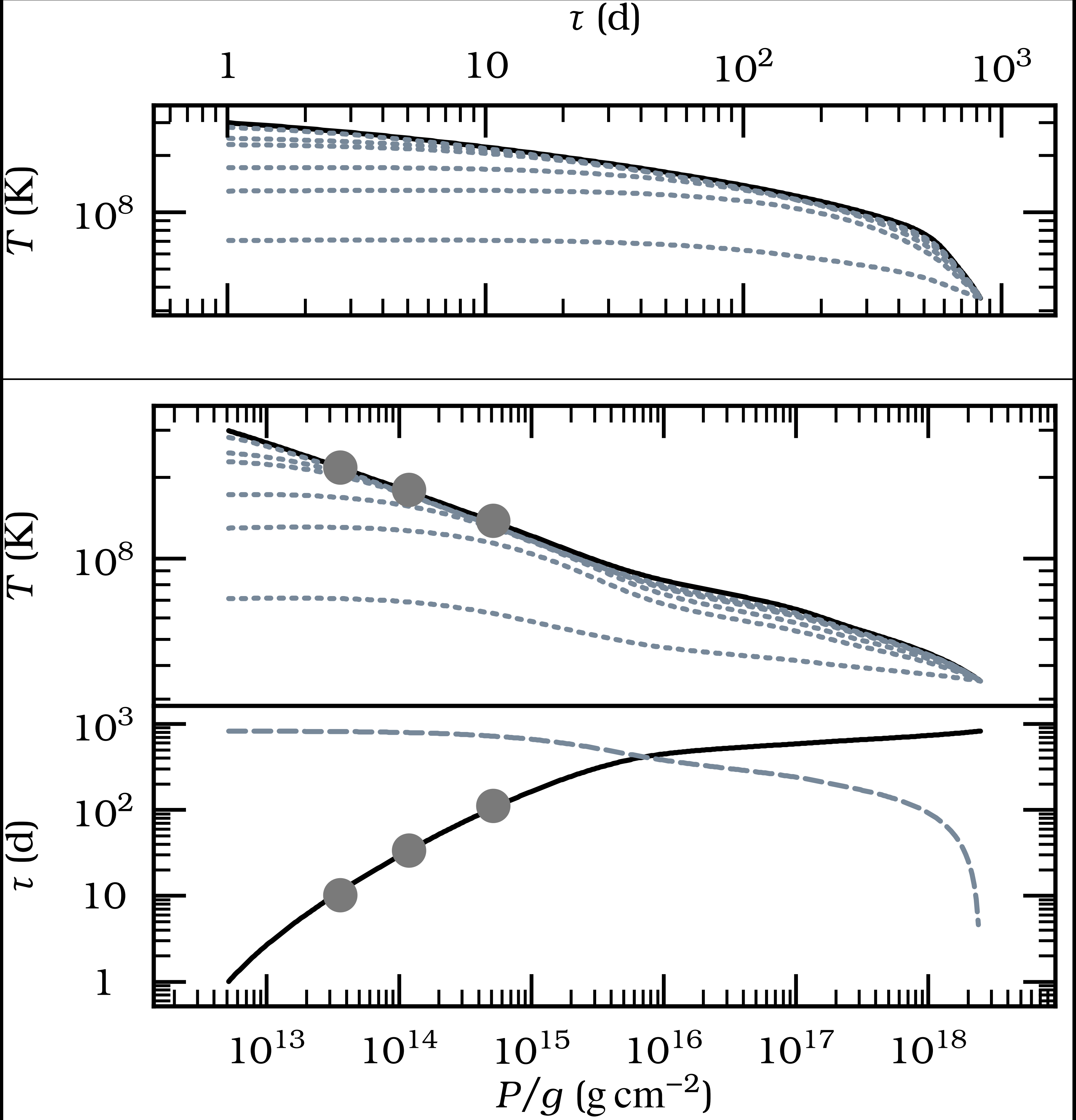
basic physics of the lightcurve

For a cooling crust,

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

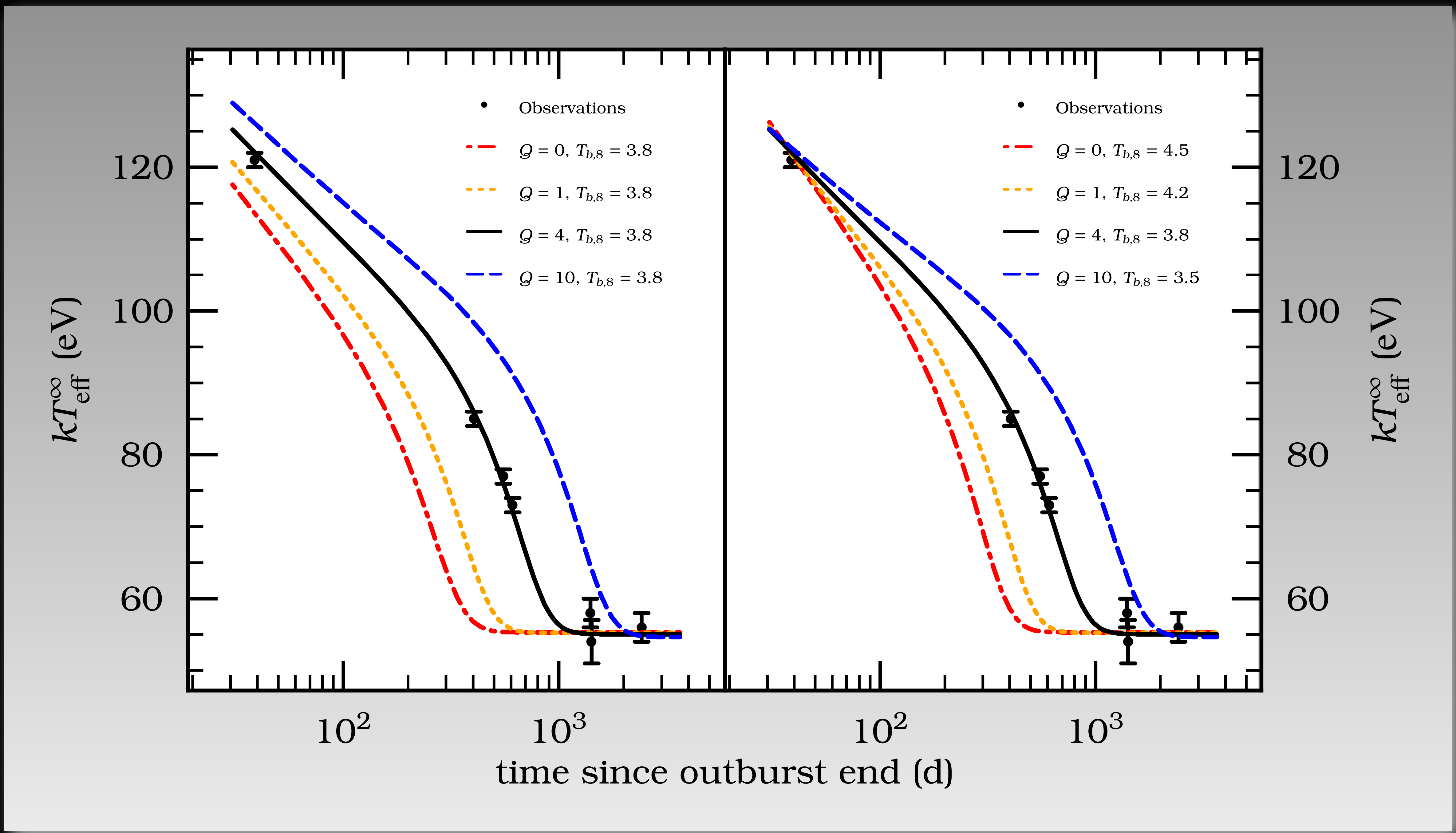
and a cooling front propagates into crust on a timescale

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



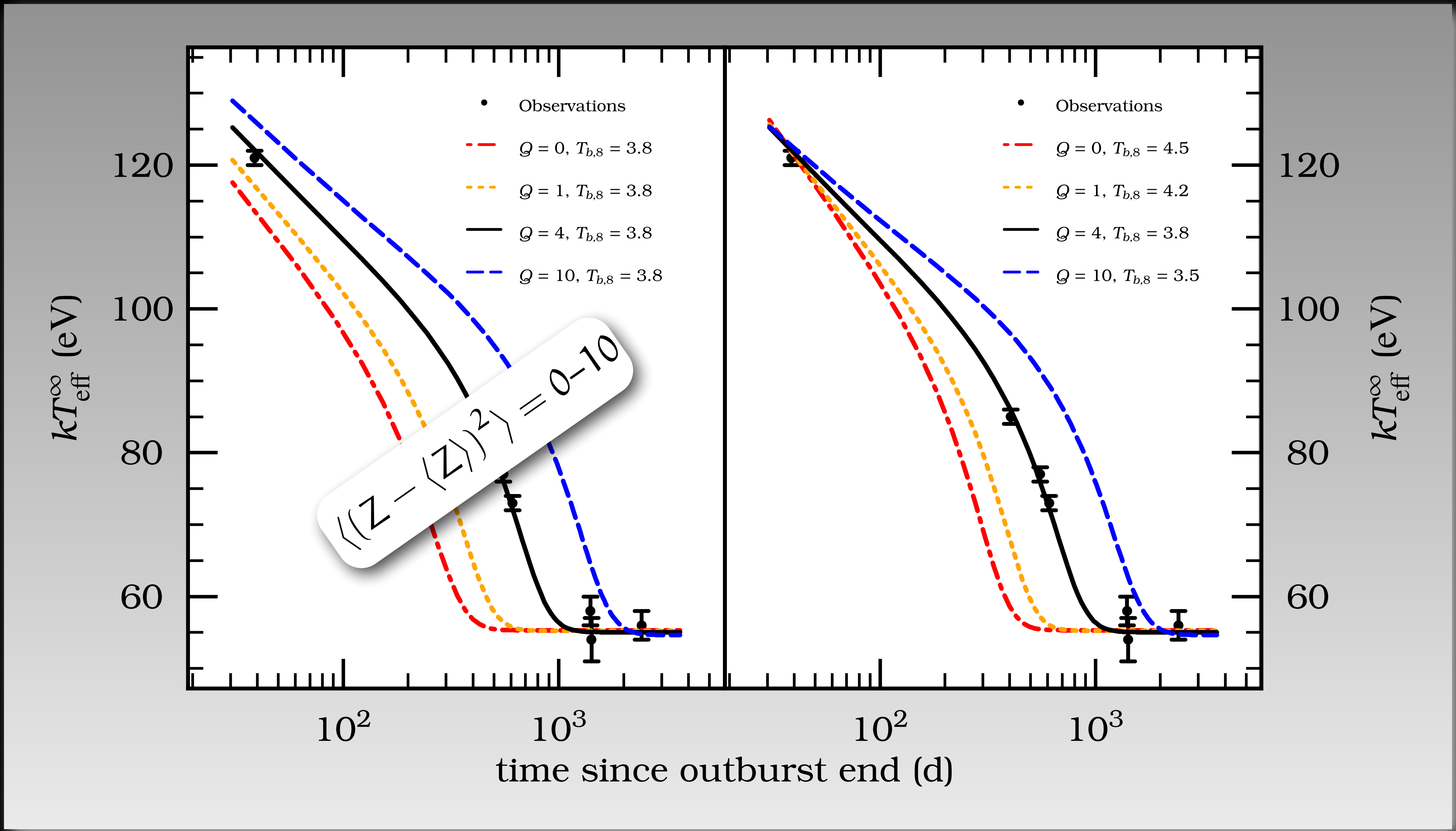
How impure is the crust? $Q < 10$

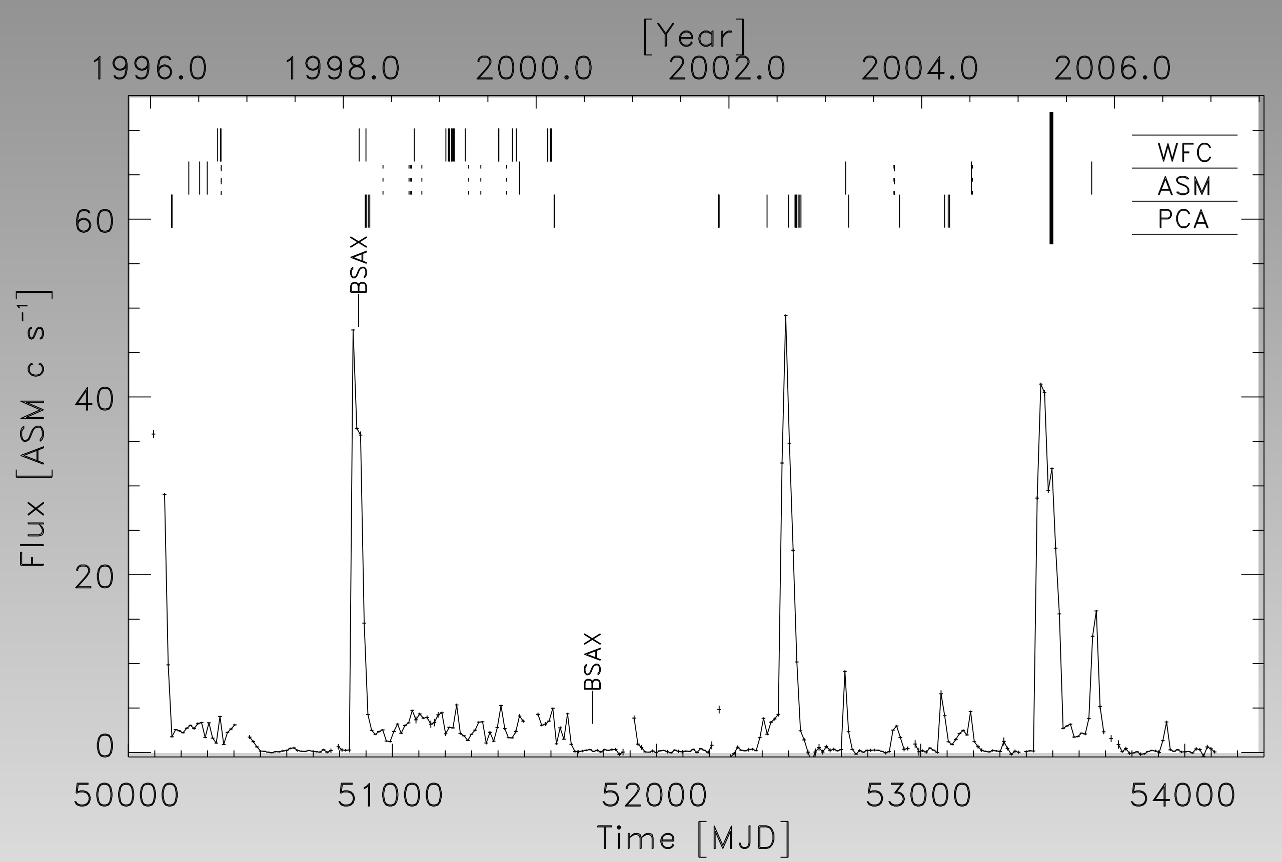
Shternin et al. 2007; Brown & Cumming 2009; see talk by D. Page

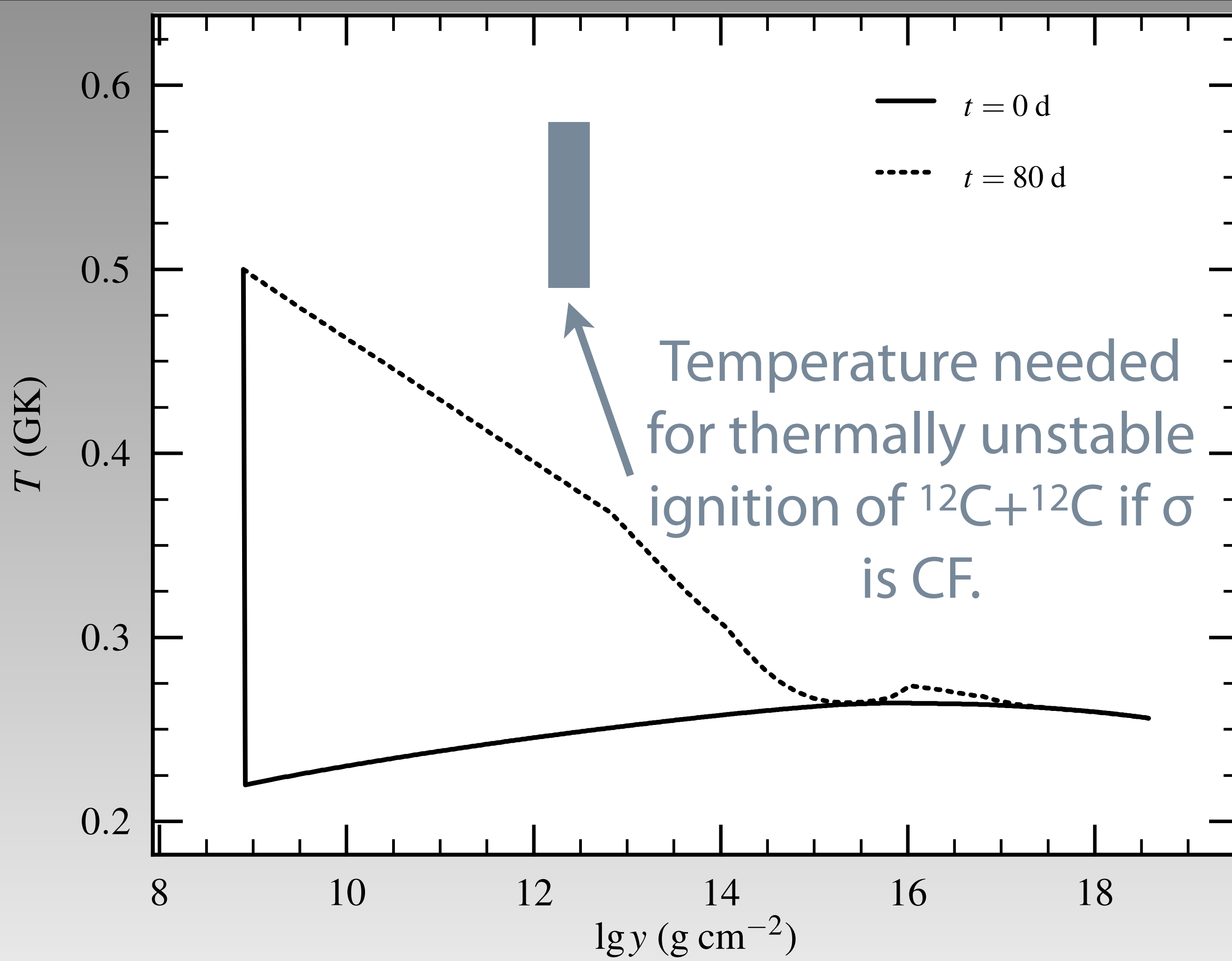


How impure is the crust? $Q < 10$

Shternin et al. 2007; Brown & Cumming 2009; see talk by D. Page







Superburst in 4U 1608–522
Keek et al. ’07

LETTER

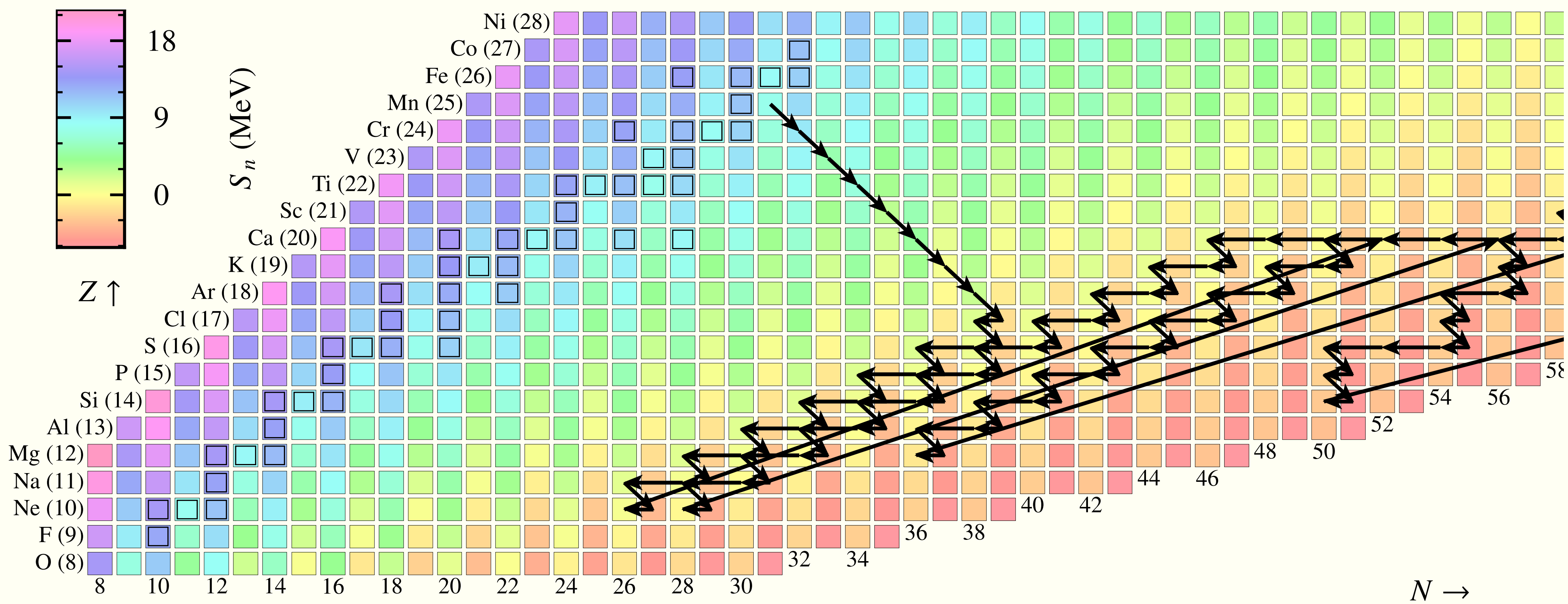
doi:10.1038/nature12757

Strong neutrino cooling by cycles of electron capture and β^- decay in neutron star crusts

H. Schatz[1,2,3], S. Gupta[4], P. Möller[2,5], M. Beard[2,6], E. F. Brown[1,2,3], A. T. Deibel[2,3], L. R. Gasques[7], W. R. Hix[8,9], L. Keek[1,2,3], R. Lau[1,2,3], A. W. Steiner[2,10] & M. Wiescher[2,6]

- How it works
- Why it wasn’t noticed before
- What it means for X-ray bursts and superbursts

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



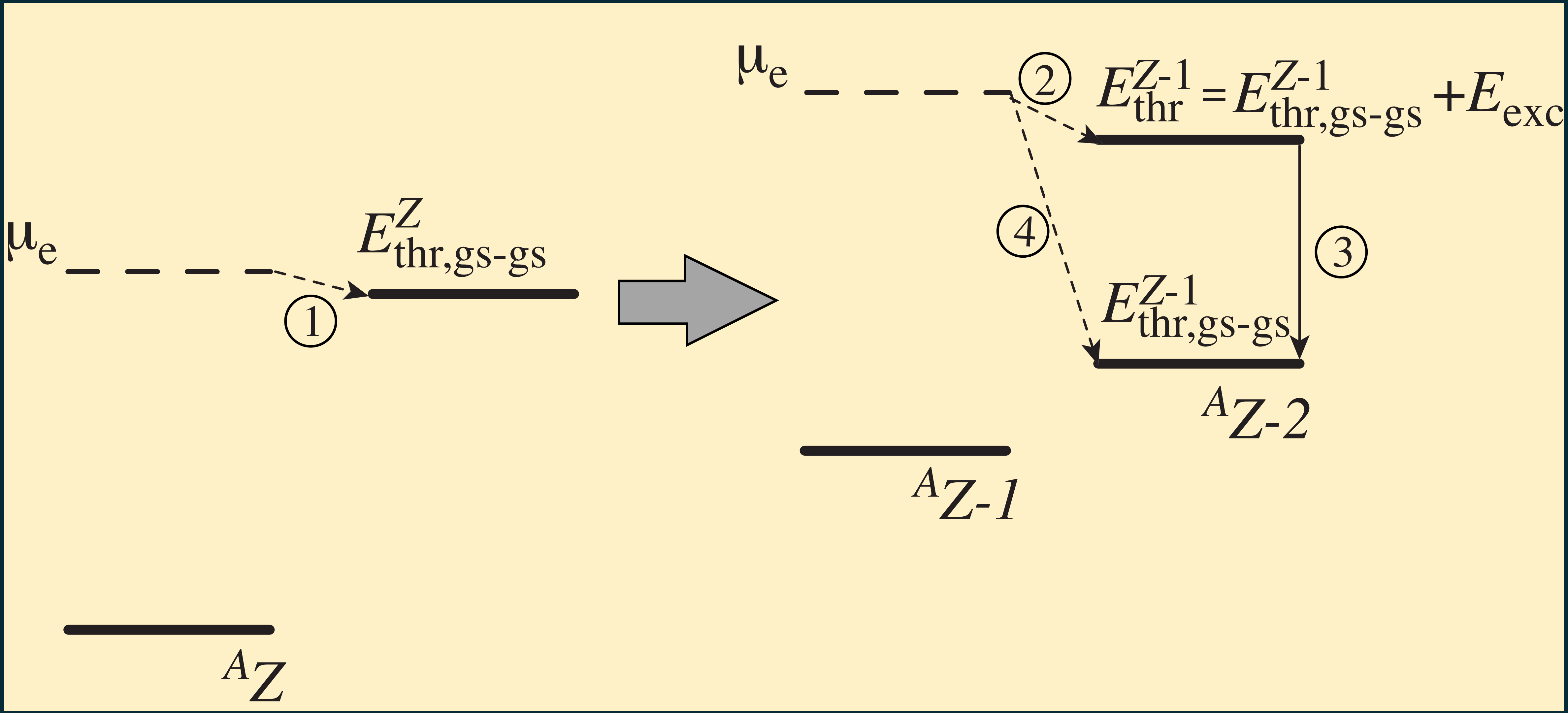
see poster by A. Deibel

crust reactions | deep heating

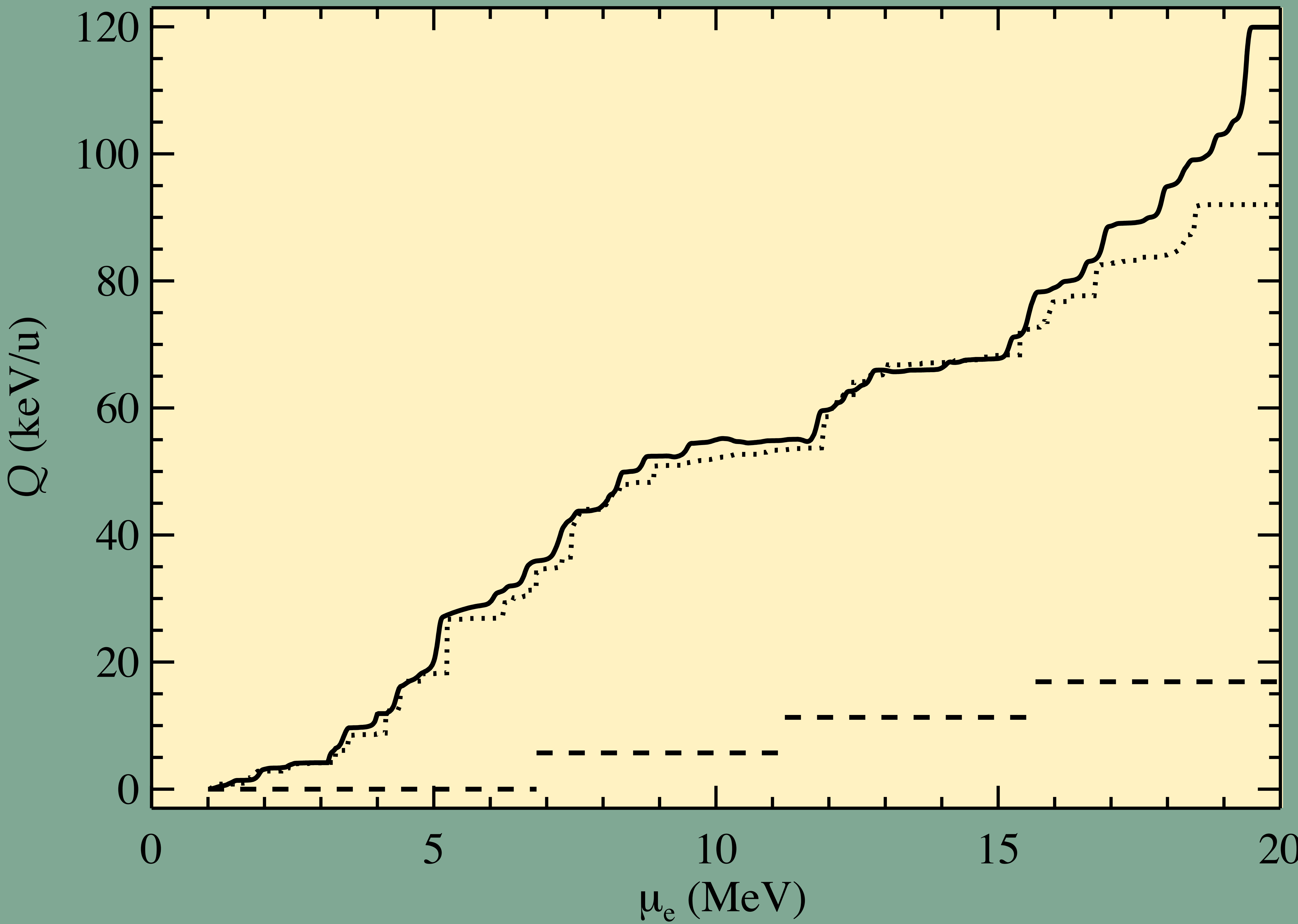
Bisnovatyi-Kogan and Chechetkin '74; Sato '79; Haensel & Zdunk '90; Gupta et al. '07; Steiner '12; Schatz et al. '13; Deibel et al. (in prep)

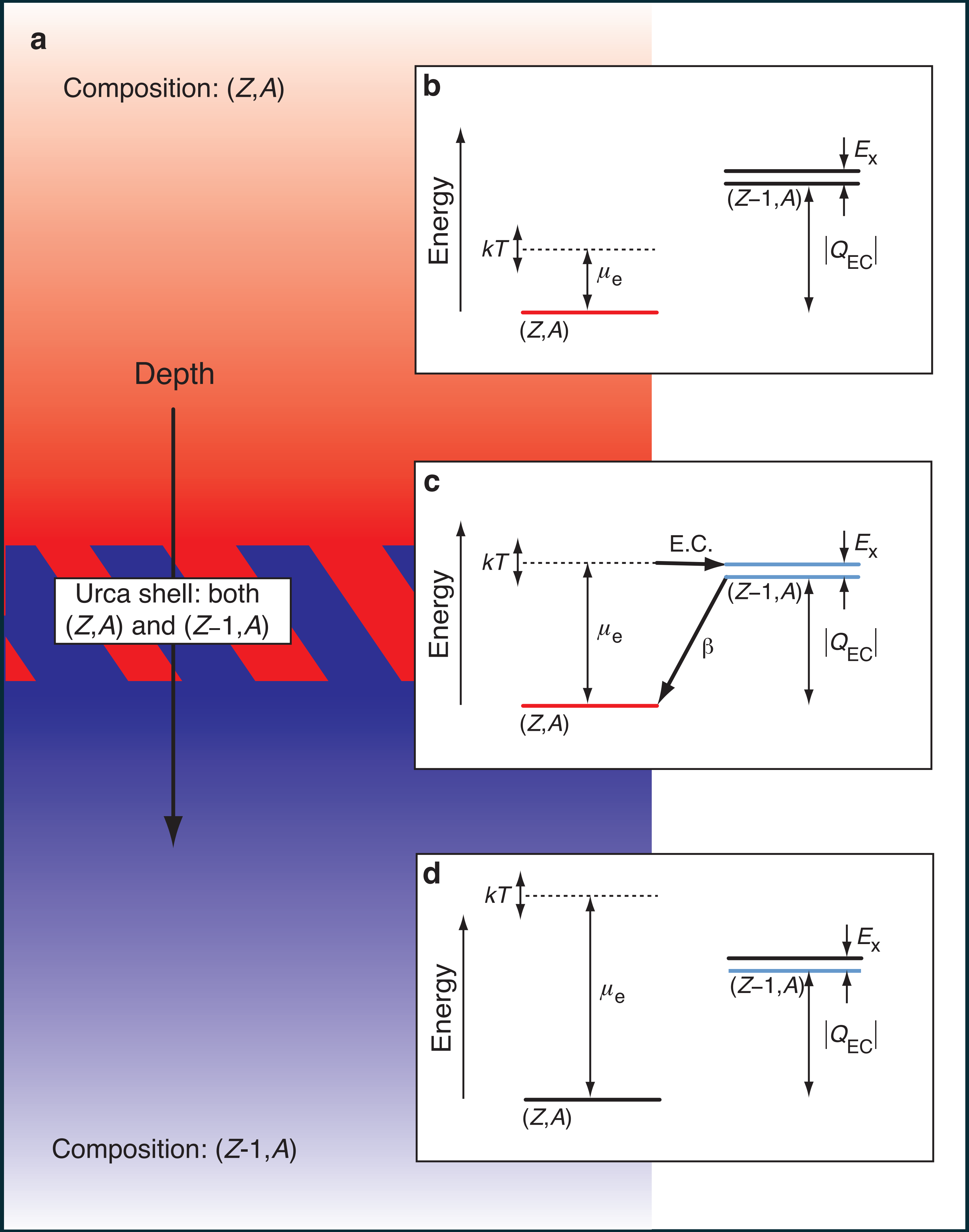
Review | electron captures

(Bisnovatyi-Kogan & Chechetkin; Sato; Haensel & Zdunik; Gupta et al.)



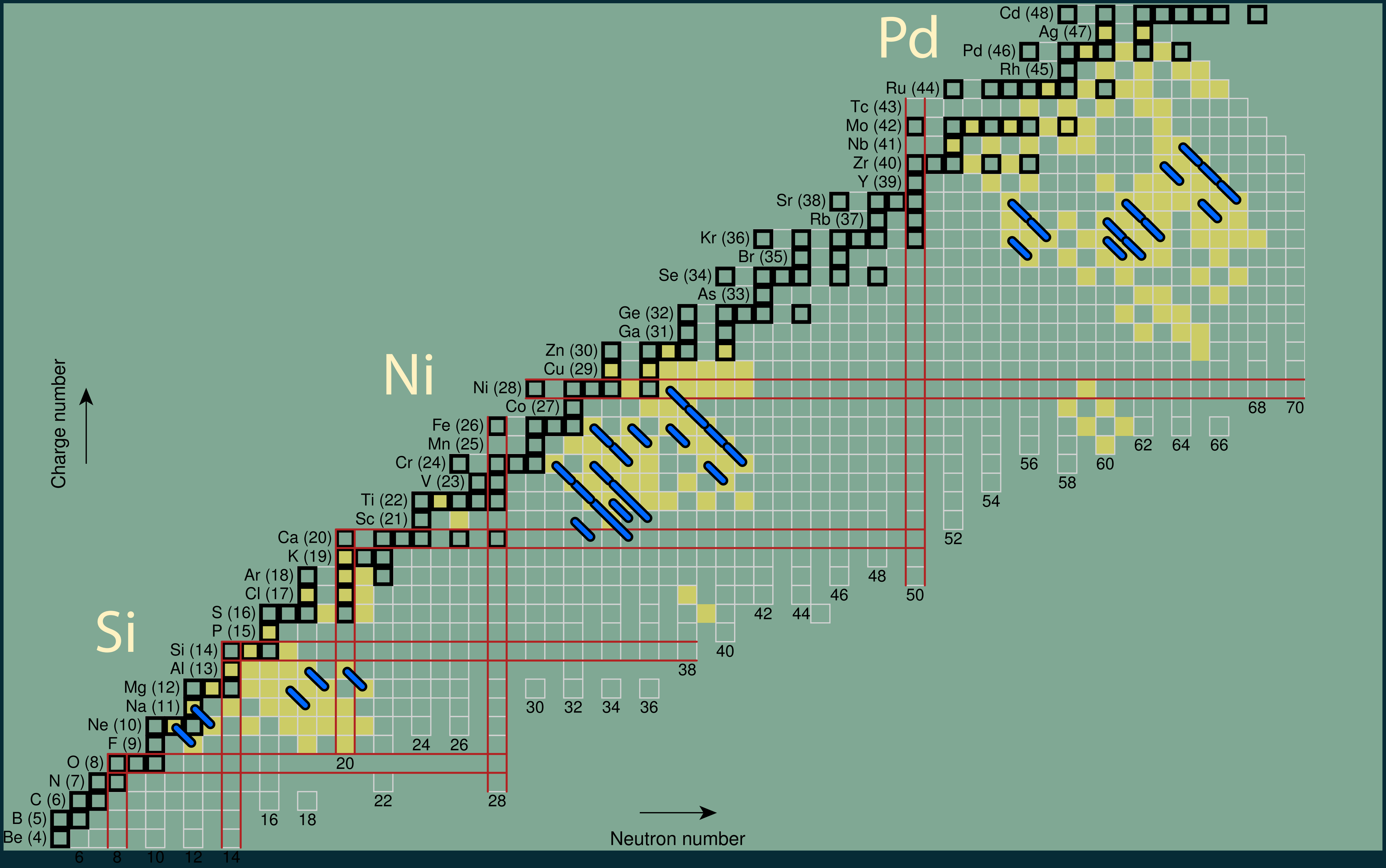
Gupta et al. 2007; cf. Sato 1979, Haensel & Zdunik 1990, 2003





a
Composition: (Z,A)
Depth
Urca shell: both (Z,A) and (Z–1,A)
Composition: (Z-1,A)
b
Energy
kT
μe
(Z,A)
(Z–1,A)
Ex
|QEC|
c
Energy
kT
μe
(Z,A)
E.C.
β
(Z–1,A)
Ex
|QEC|
d
Energy
kT
μe
(Z,A)
(Z–1,A)
Ex
|QEC|

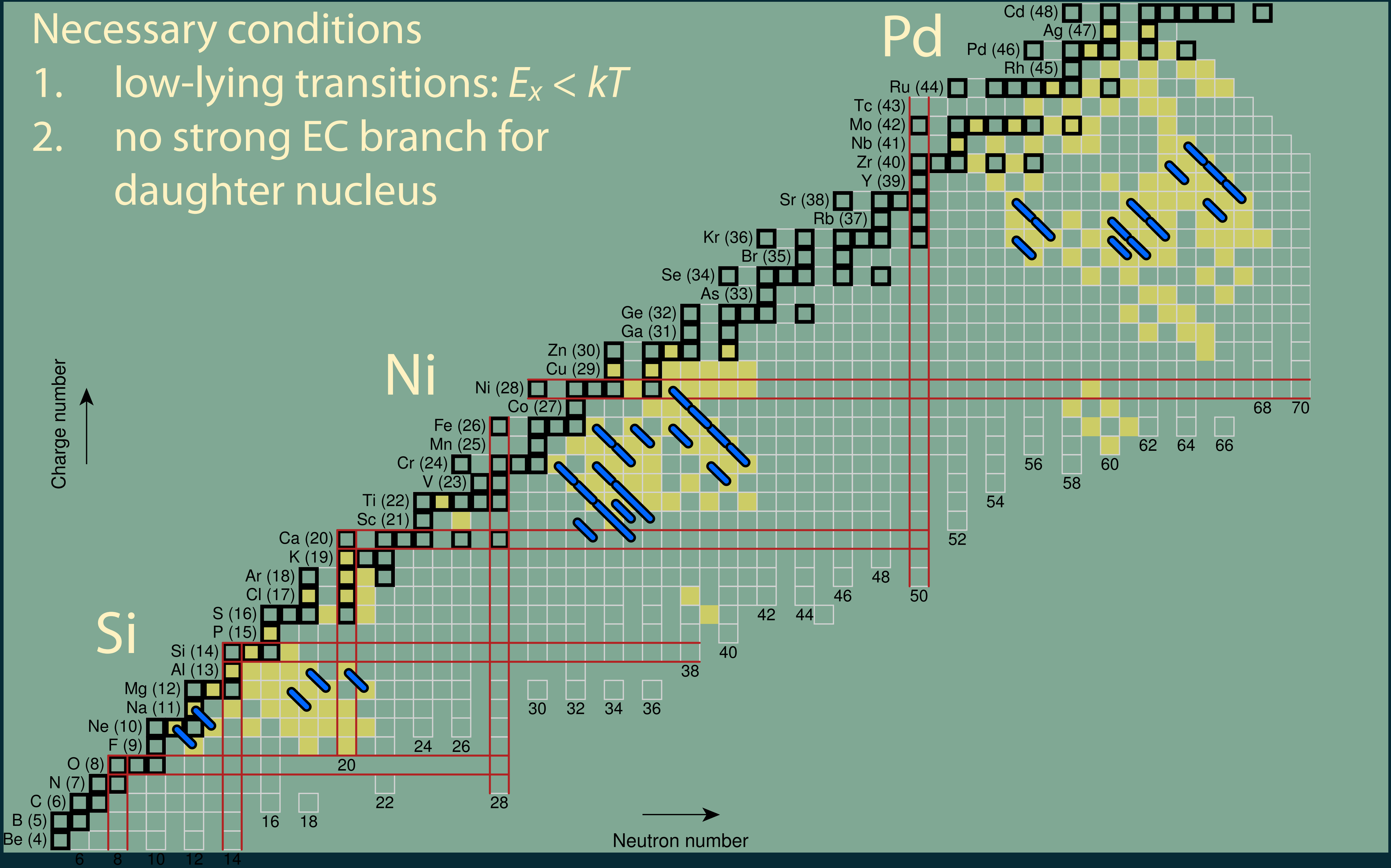
Urca pairs | which nuclei?



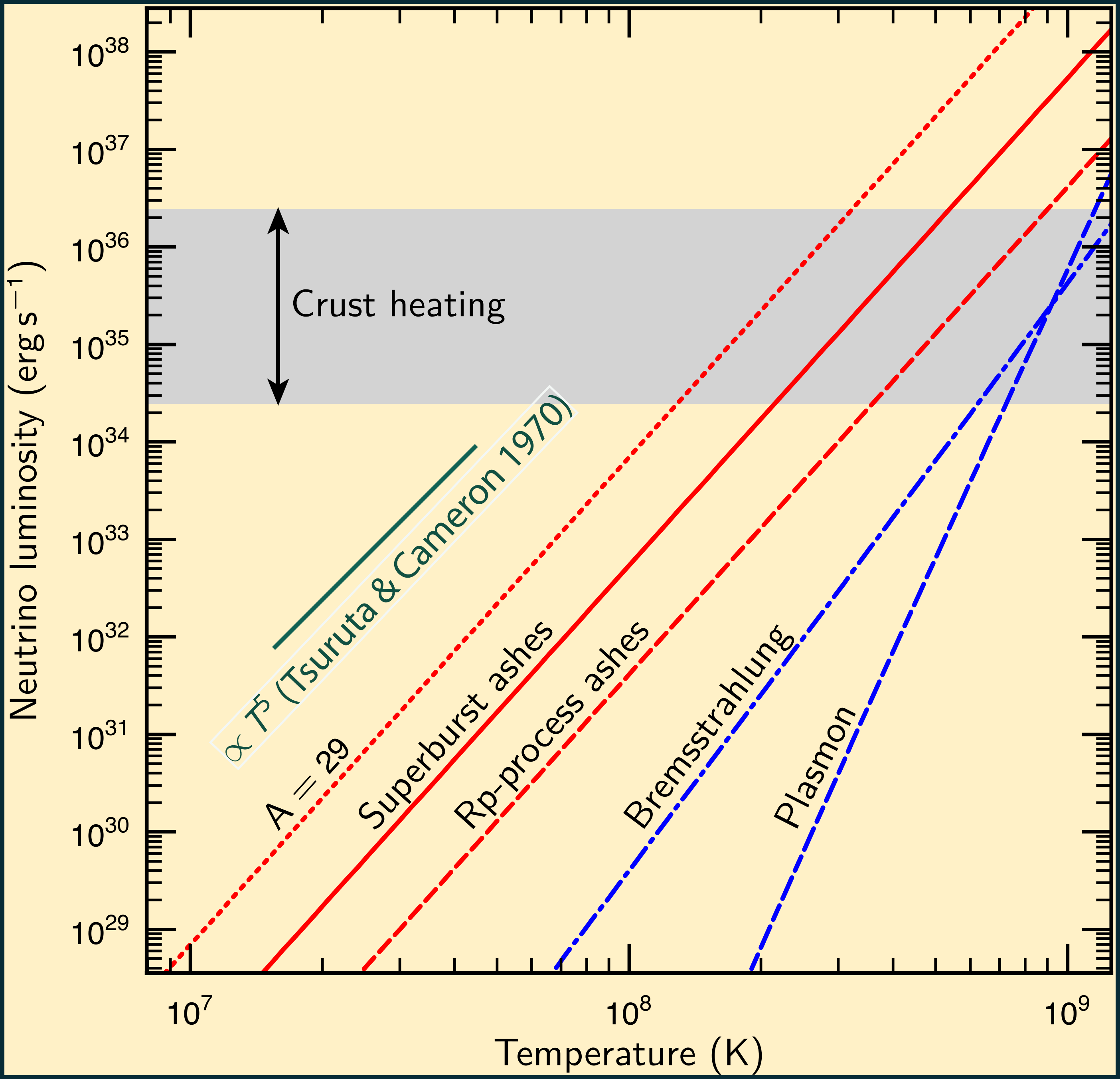
Urca pairs | which nuclei?

Necessary conditions

1. low-lying transitions: $E_x < kT$
2. no strong EC branch for daughter nucleus



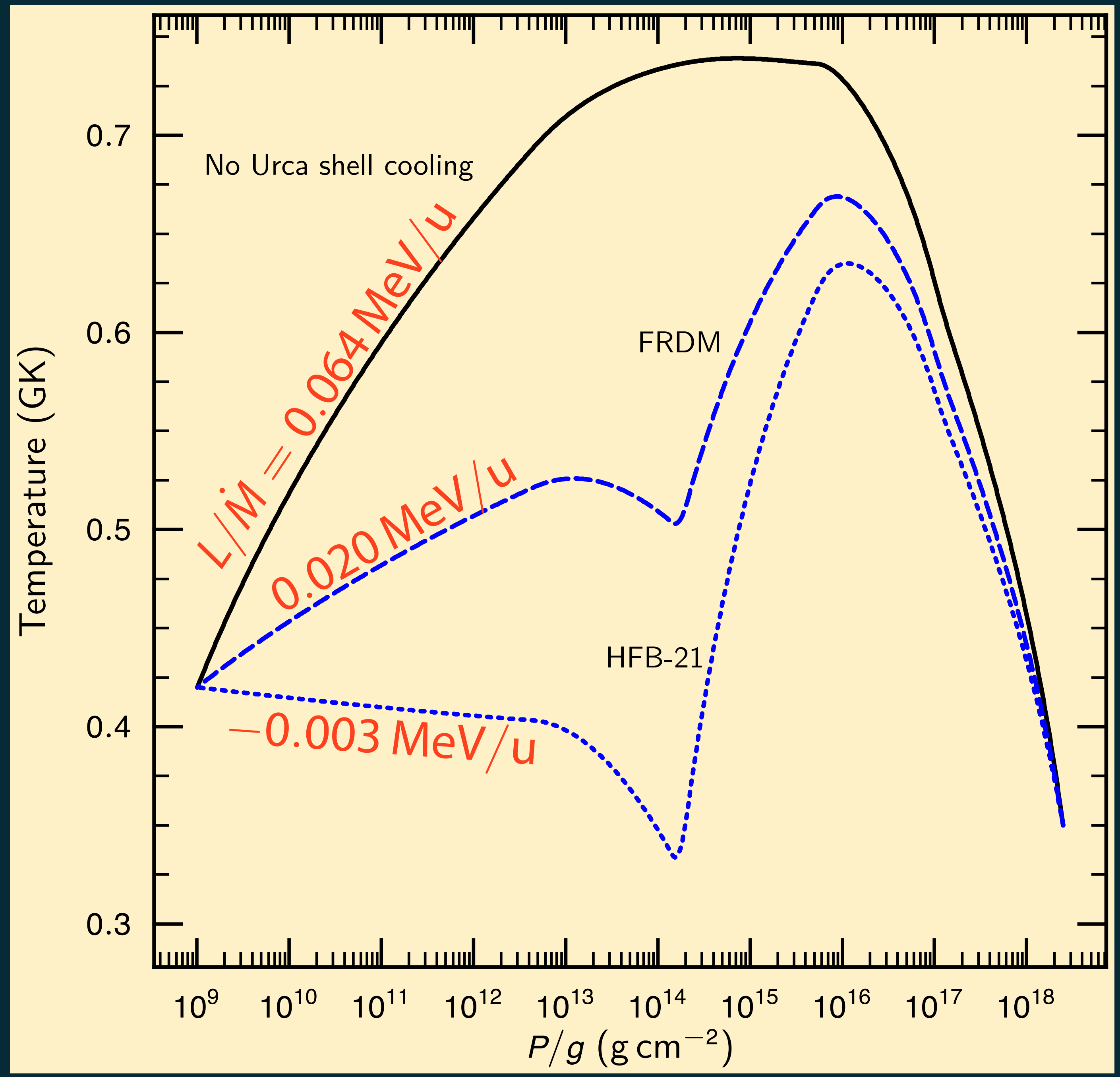
Compare | neutrino luminosities



Urca shell | cold layer

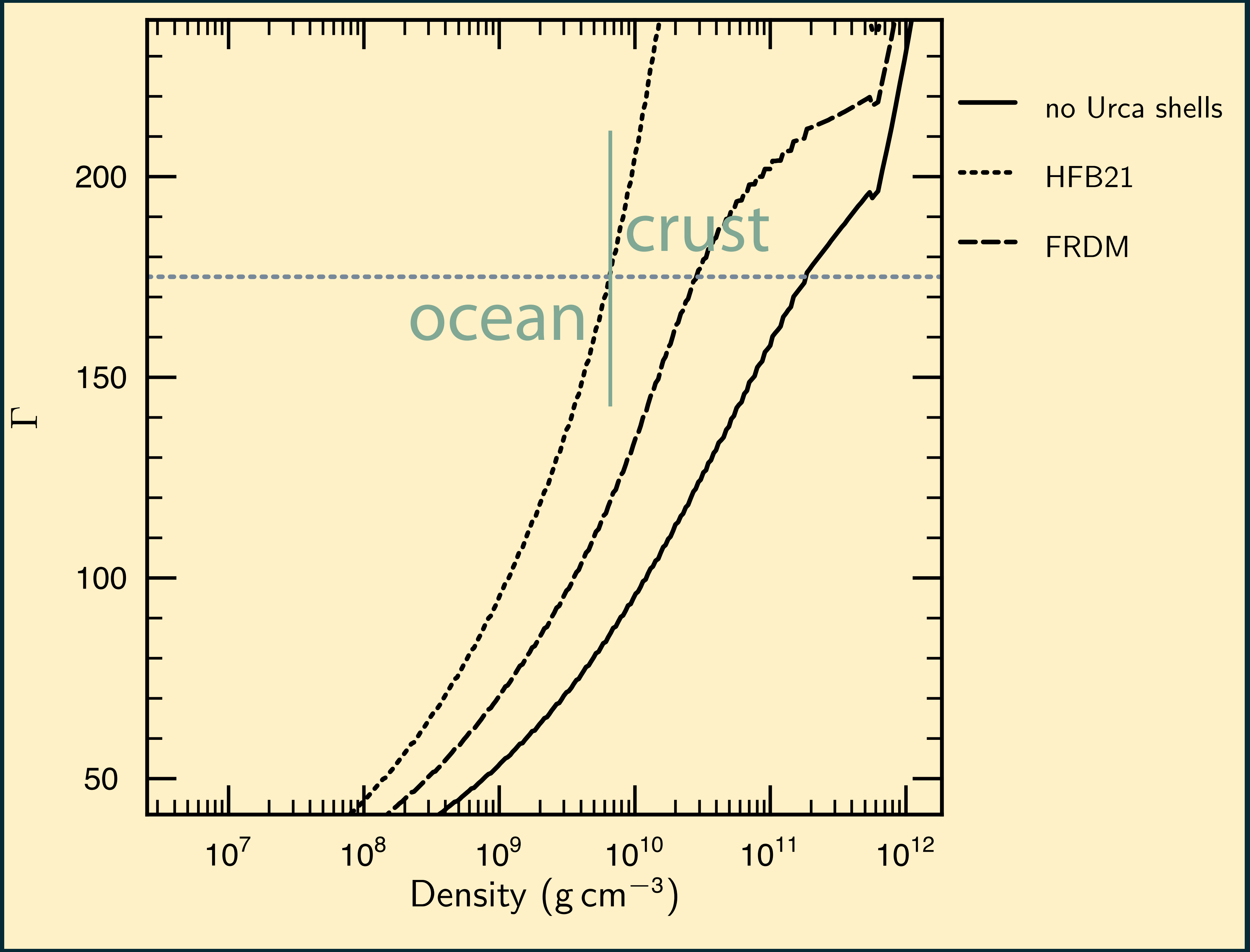
$\dot{M} = 3.0 \times 10^{17}\,\mathrm{g\,s^{-1}}$

cf. Gupta et al. '07

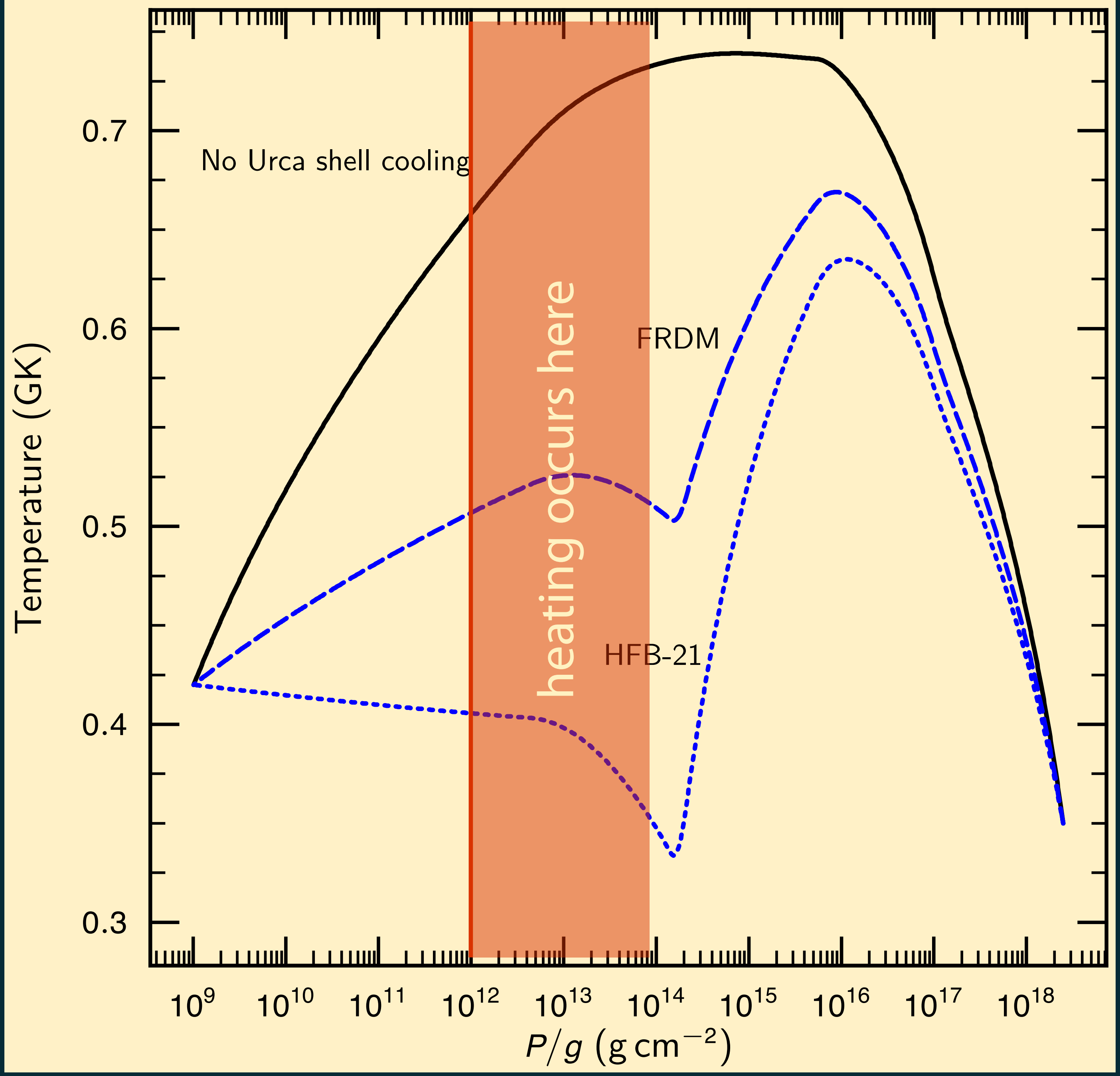


Urca shell | cold layer

$\dot{M} = 3.0 \times 10^{17}\,\mathrm{g\,s^{-1}}$
cf. Gupta et al. '07



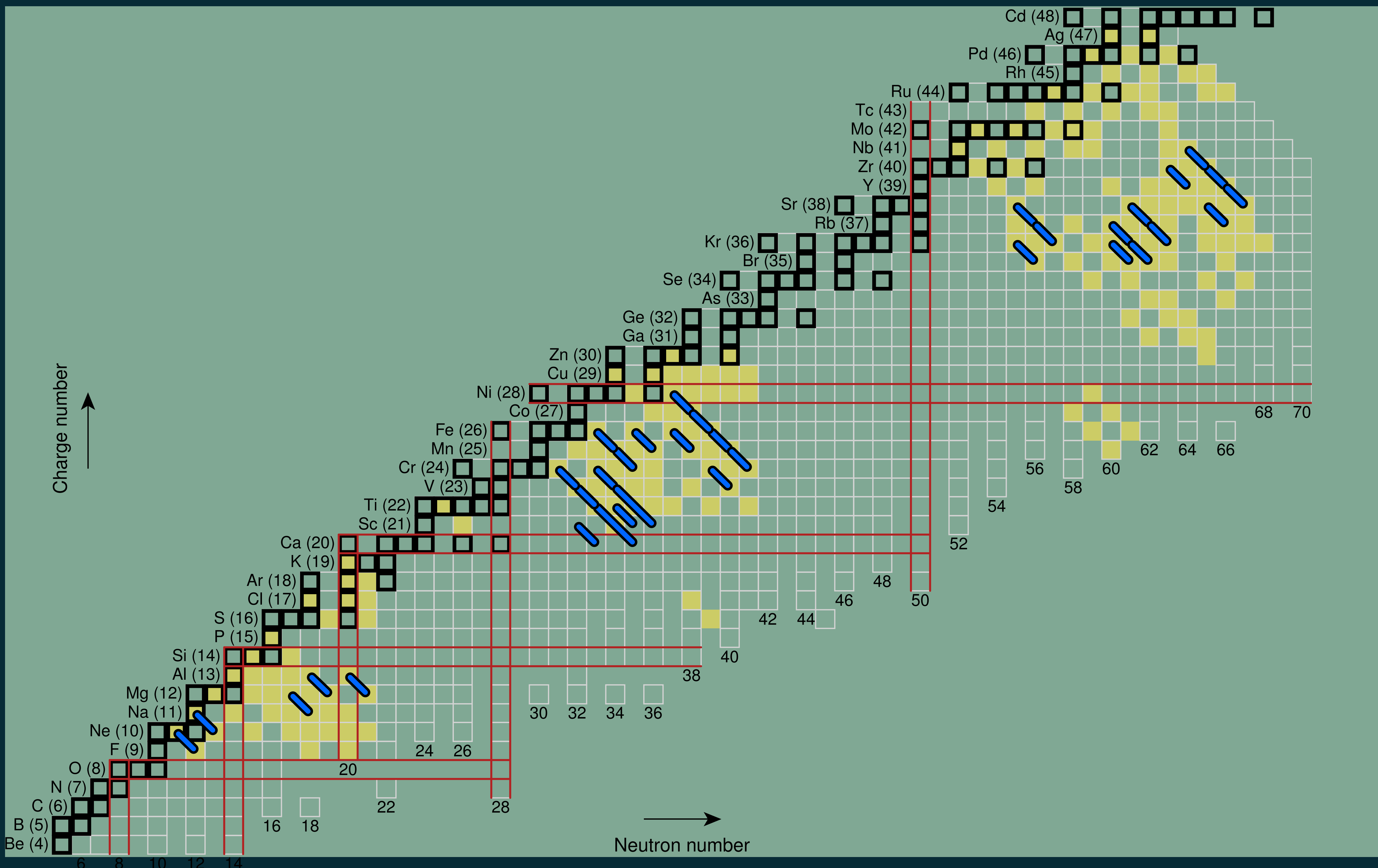
superburst | ignition



Facility for Rare Isotope Beams

Michigan State University

Urca pairs | which nuclei?



conclusions

- Soft X-ray transients provide information on physics of interior
  - radii from surface thermal emission
  - thermal conductivity, specific heat of crust from cooling
- electron captures/beta decays in outer crust set a limit on the crust temperature: need additional heating in outer crust to explain superbursts?