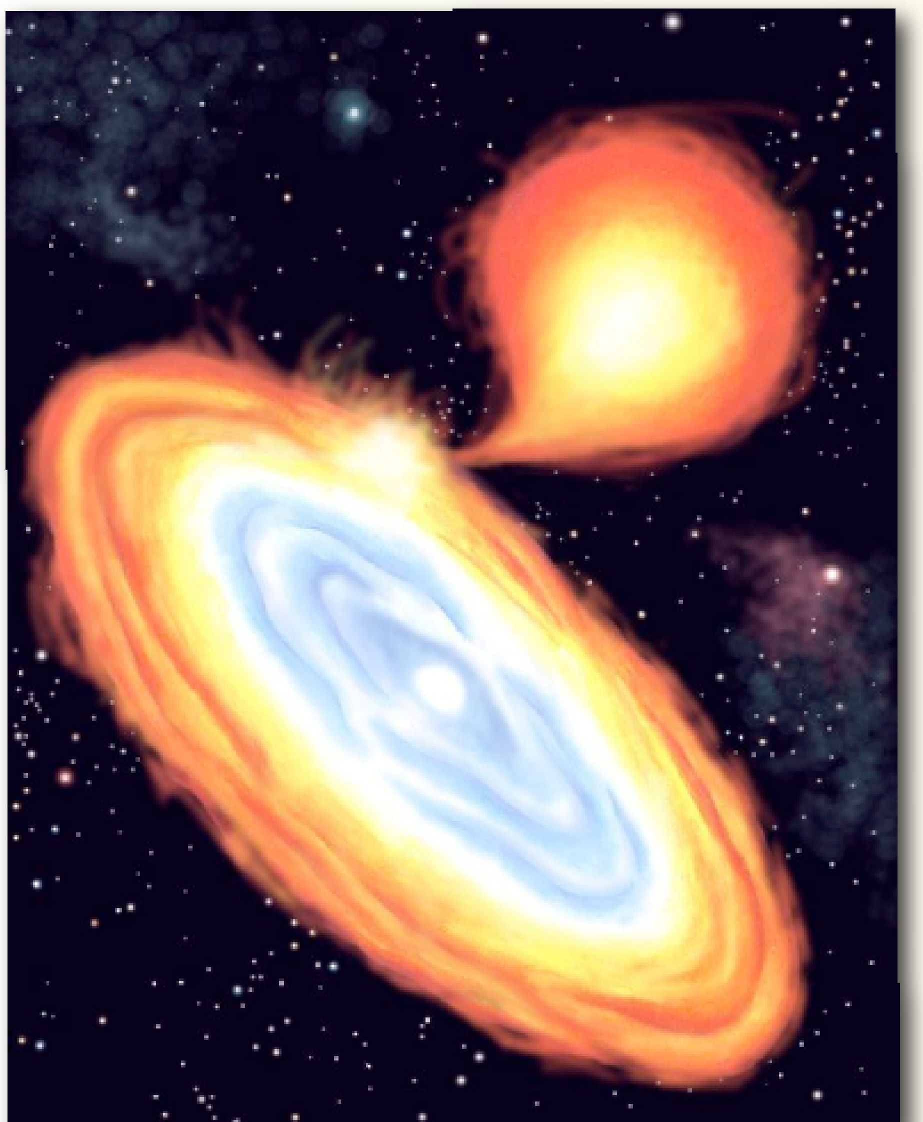
The connection between bursts & crust

Edward Brown

In this talk



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- Overview of accreting neutron stars
- Building the crust from the ashes of X-ray bursts
- The effect on "surface" phenomena

Low-mass X-ray binaries (LMXBs)

- Neutron star primary with ≈solar mass companion in short (< 1 day orbit)
- Mass transfer through Lagrange point
- Drop 1 H atom onto neutron star, receive

$$E \approx \frac{GMm_{\mathrm{H}}}{R} \approx 200\,\mathrm{MeV}$$

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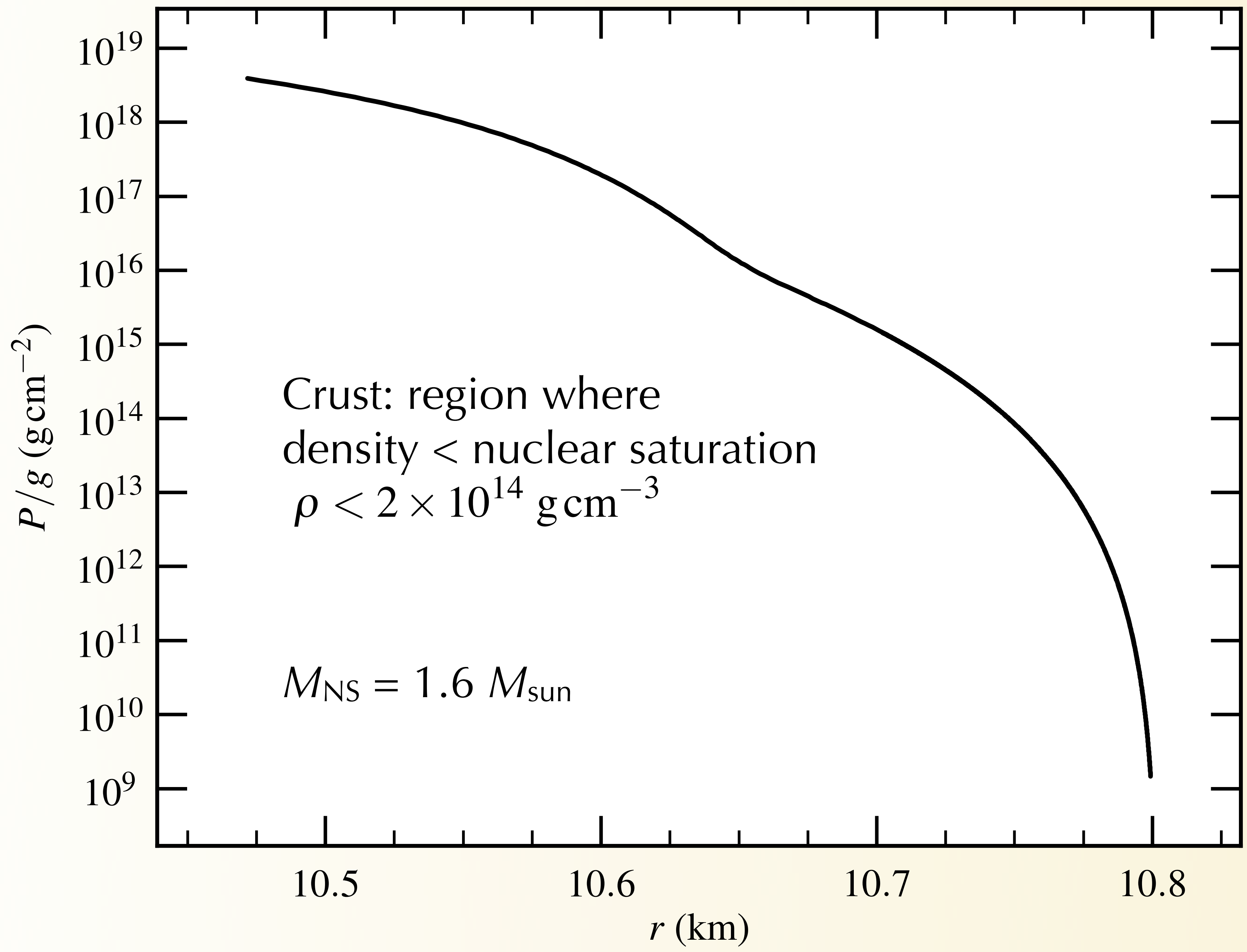
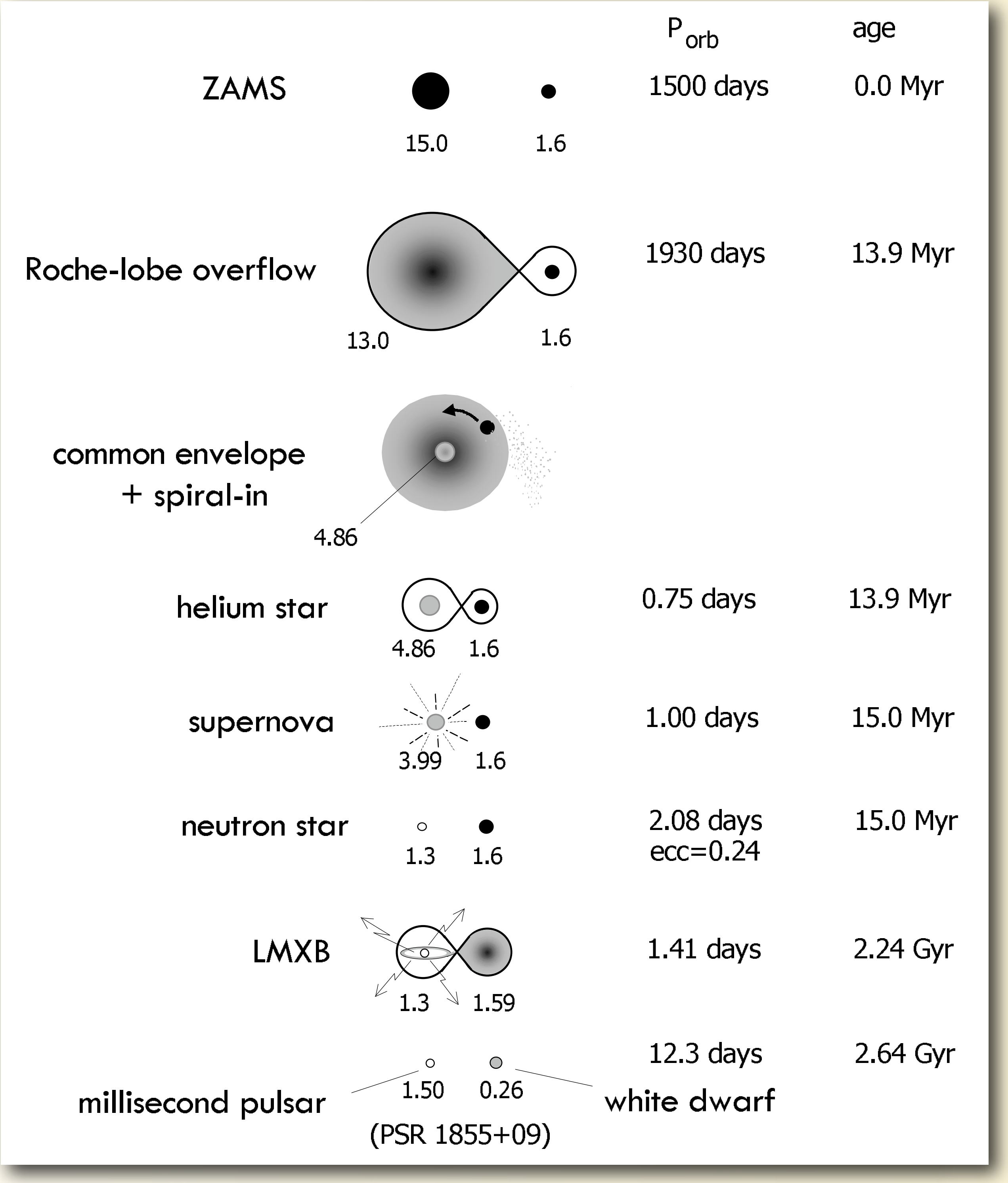
Crust structure



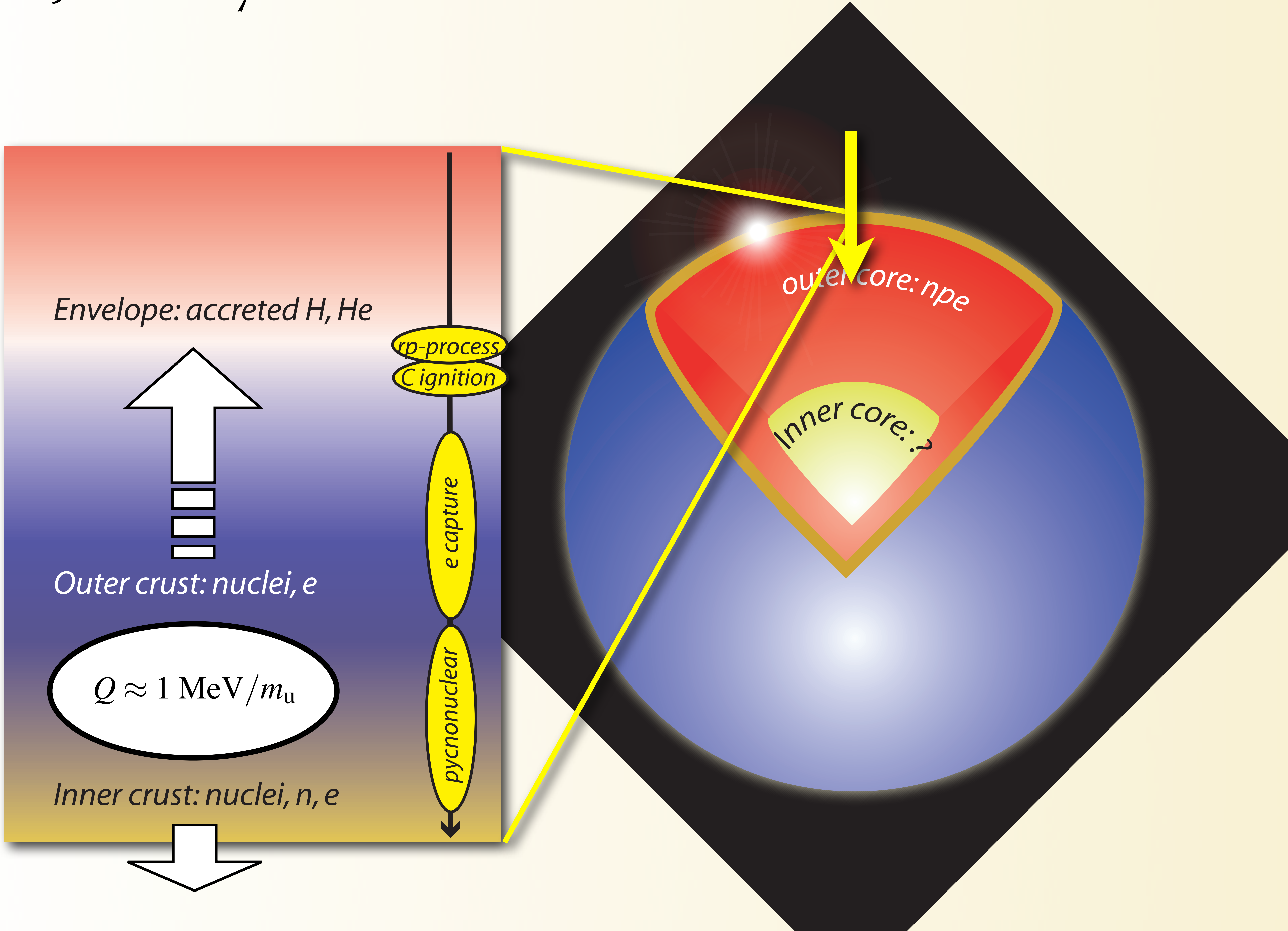
Mass transfer cycle of a LMXB

- Parameters giving a final configuration matching PSR1855+09
  - $\langle \dot{M} \rangle = 5 \times 10^{-10}\, M_{\odot}\, \mathrm{yr}^{-1}$
  - The mass-transfer (LMXB) phase lasts for 0.4 Gyr
  - The neutron star accumulates ≈ 0.2 solar masses
- Most LMXBs should have replaced the original crust

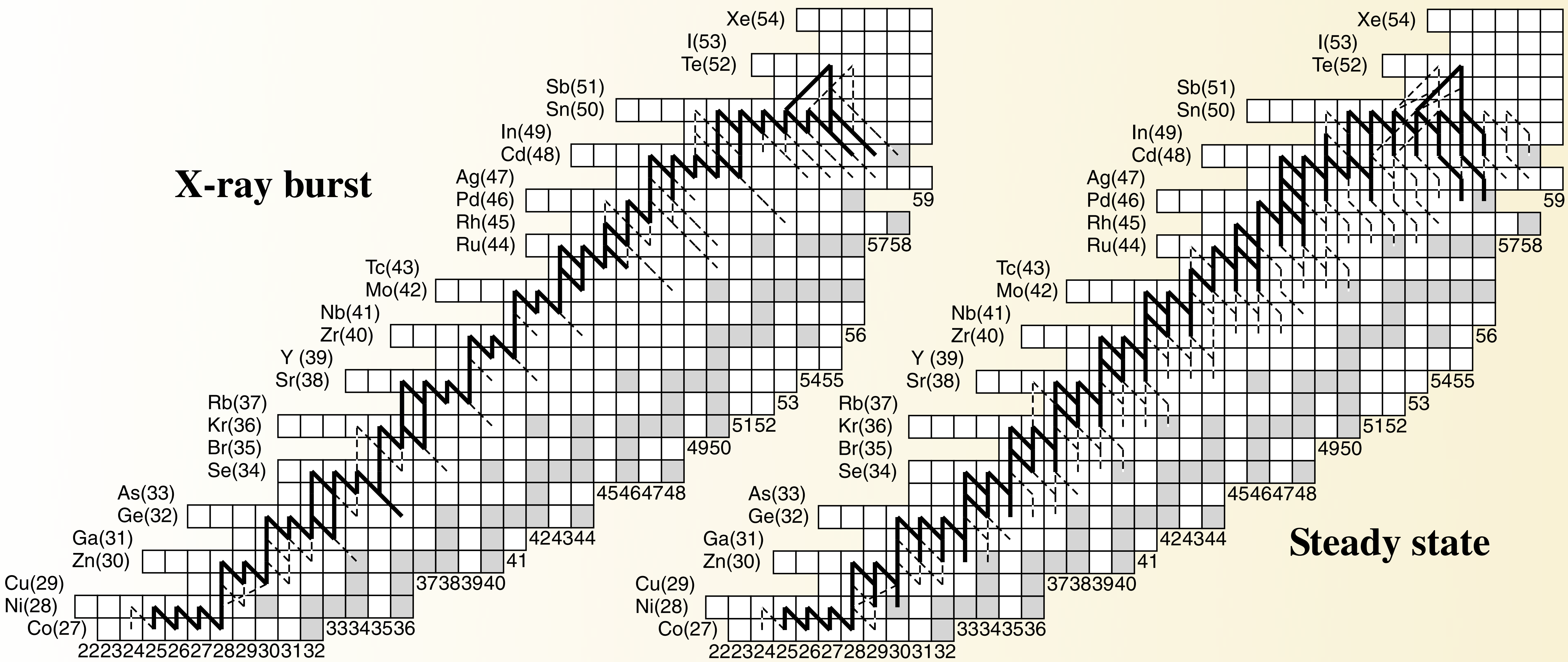
Tauris & van den Heuvel



Journey of an accreted fluid element

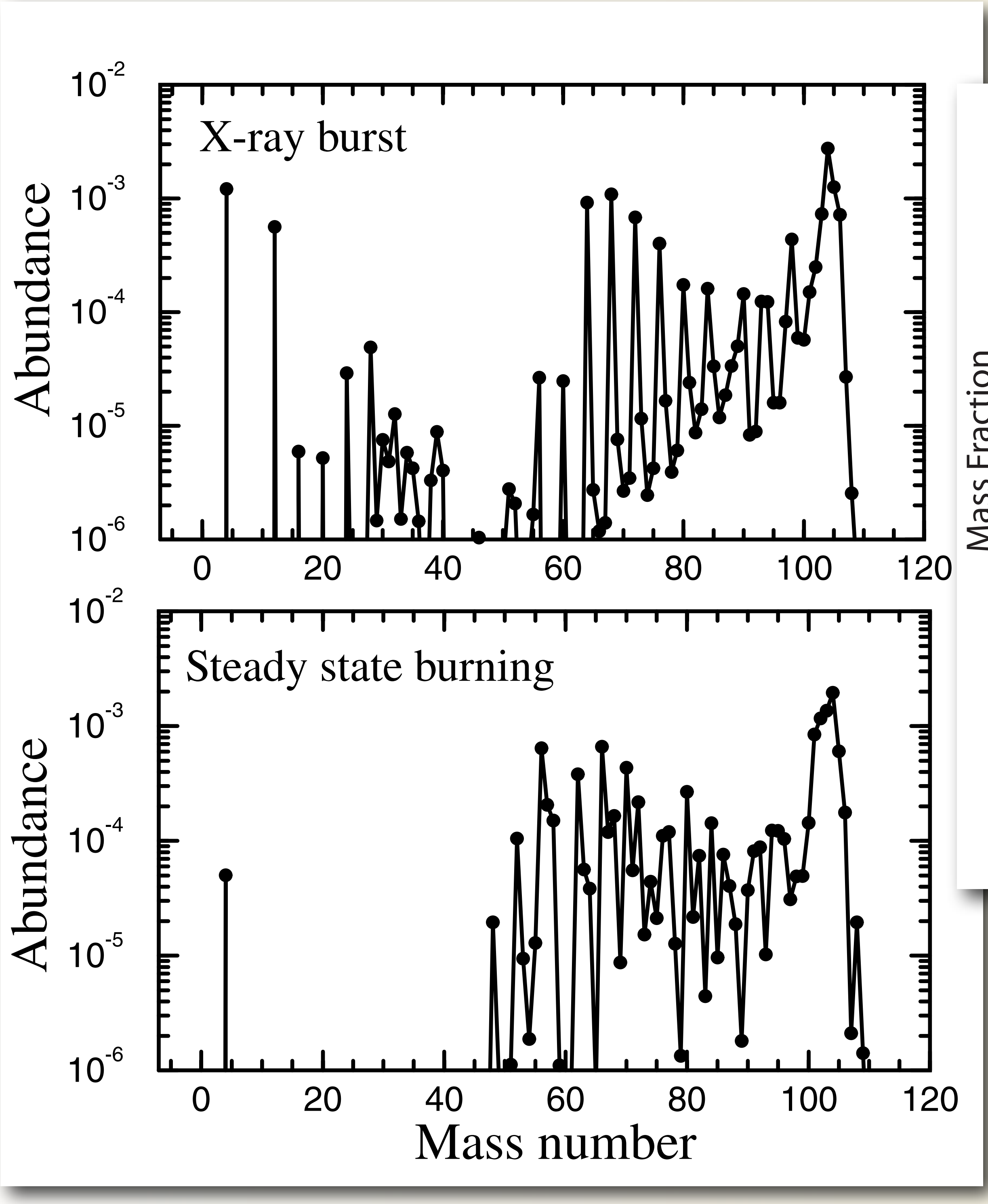


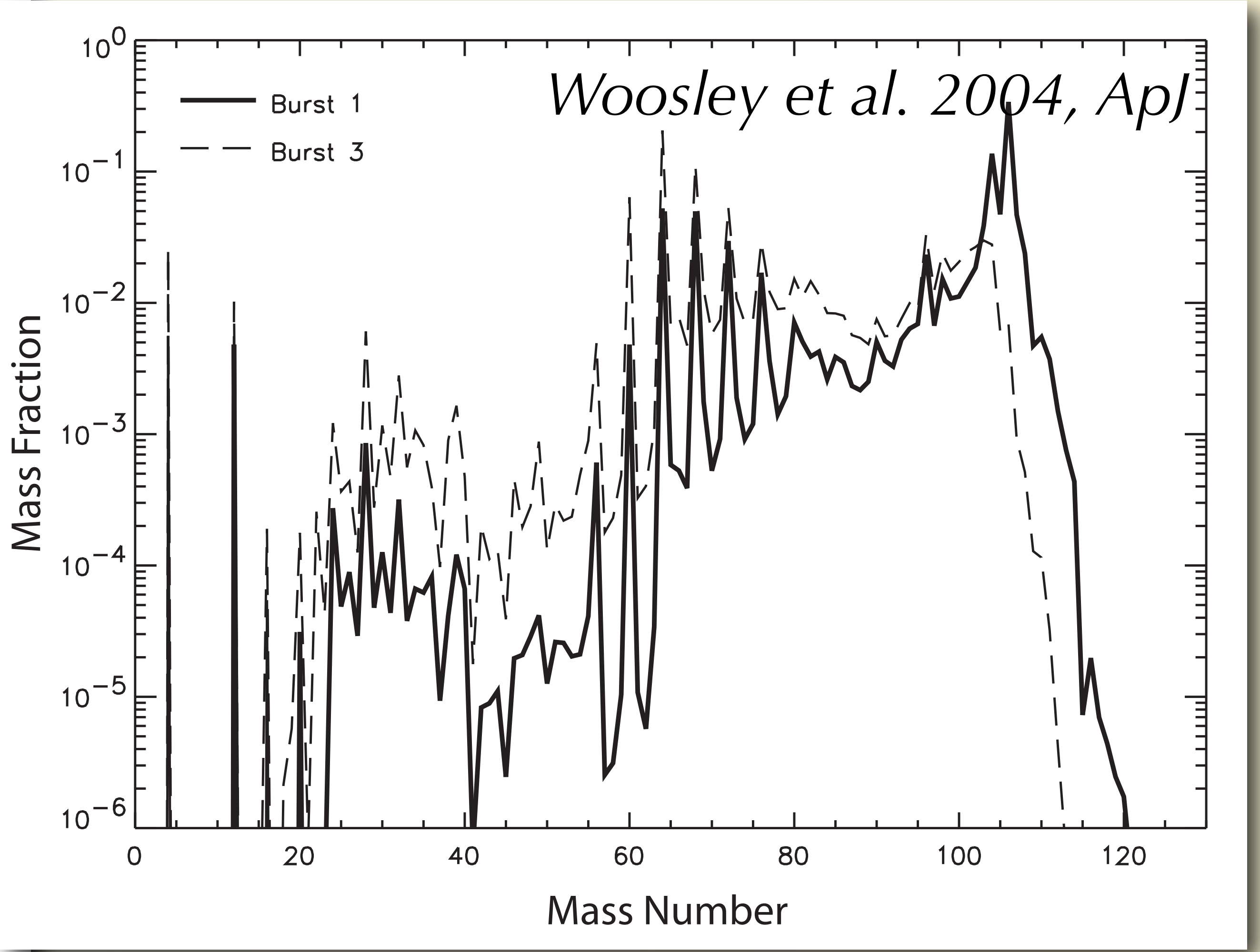
Rp-process



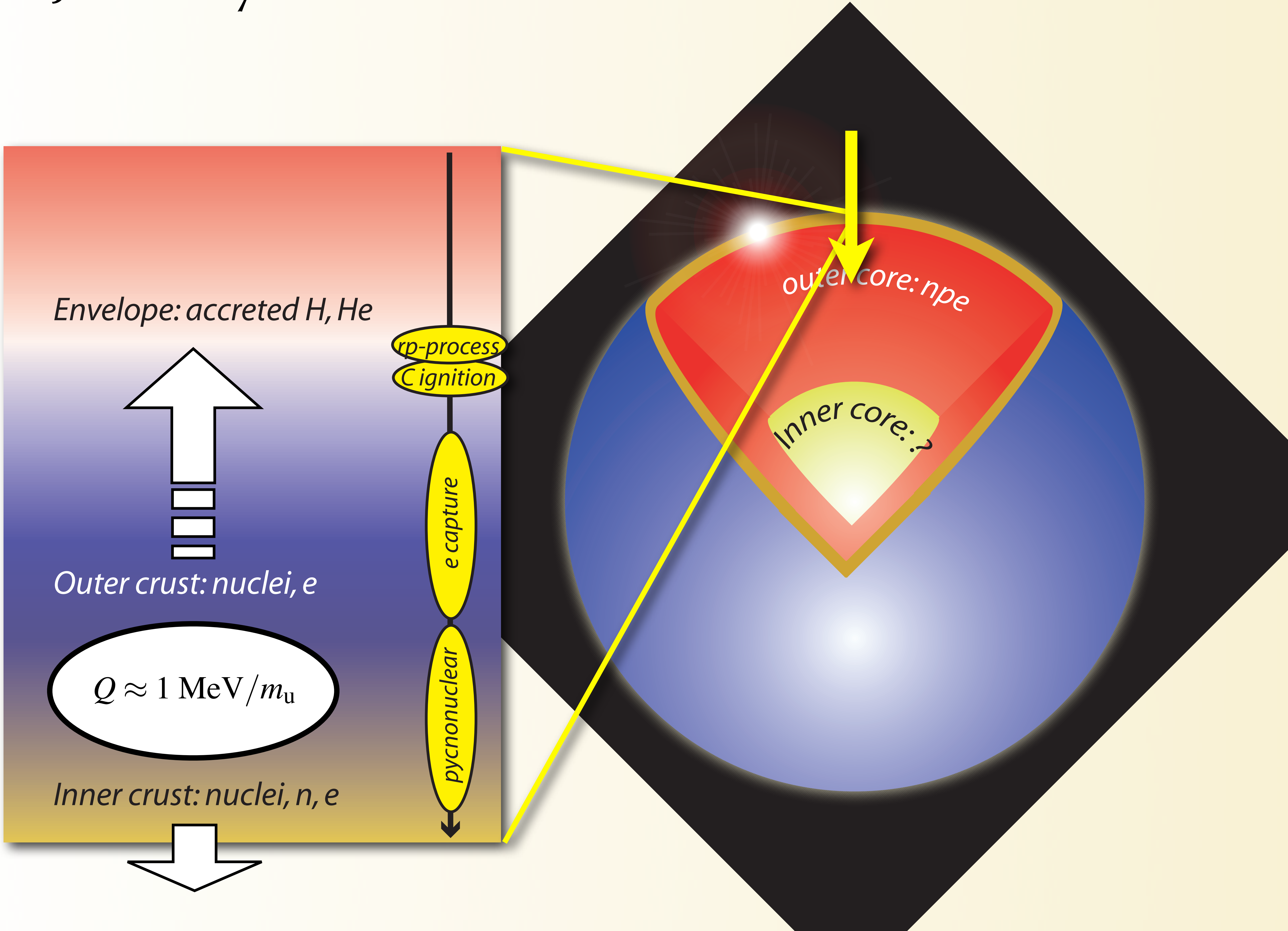
Schatz et al. 2001

Products of X-ray bursts

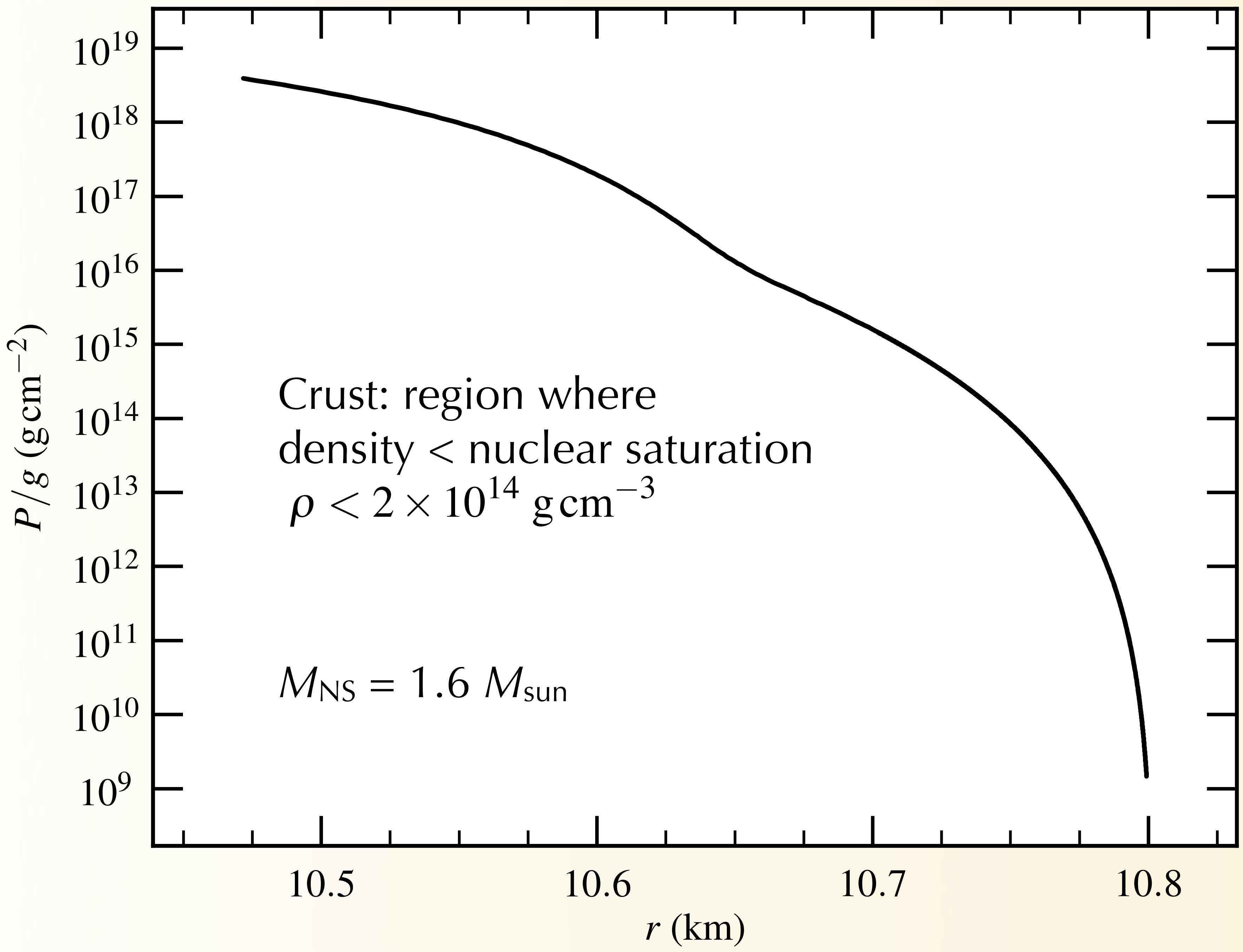




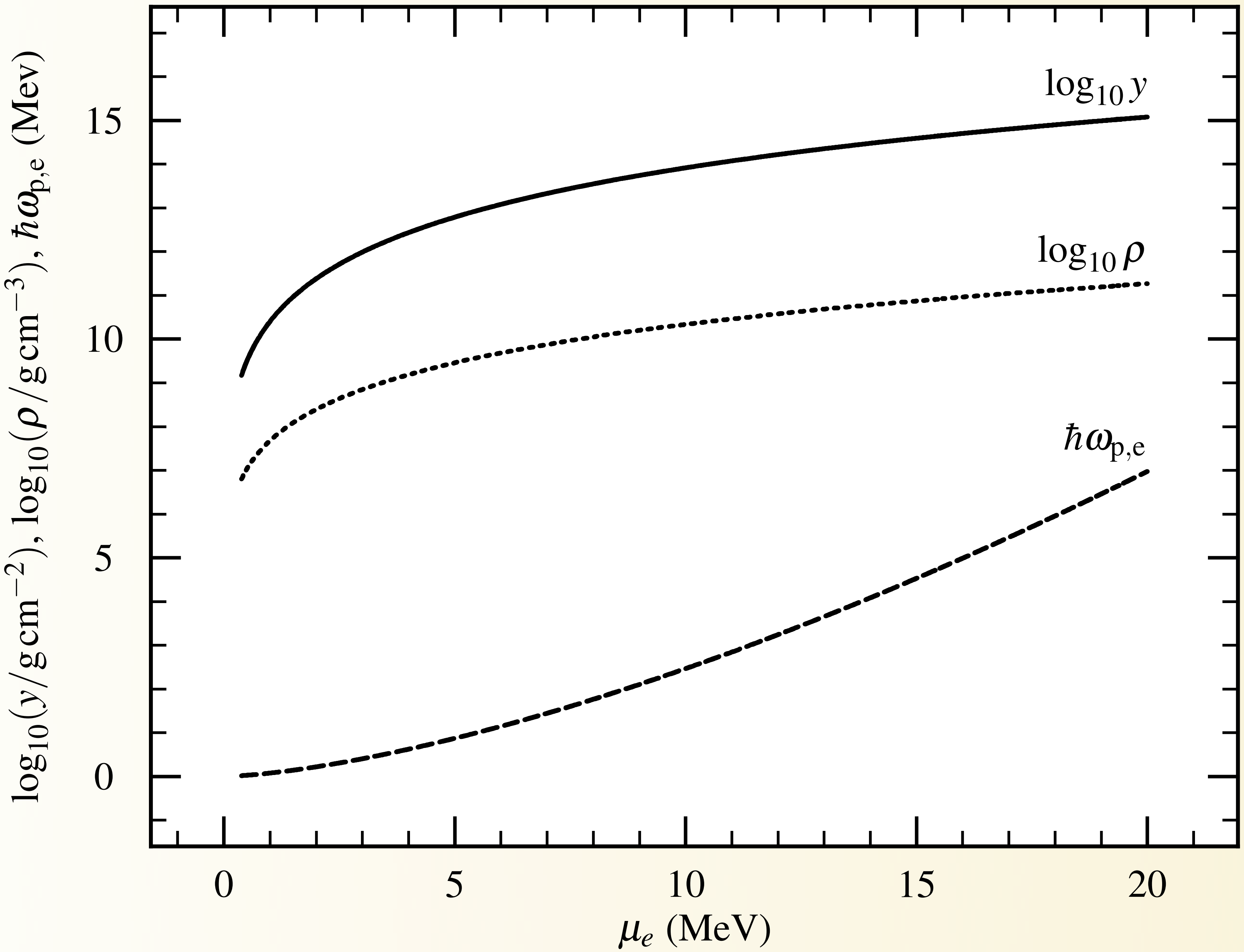
Journey of an accreted fluid element



Crust structure



Path to neutron drip



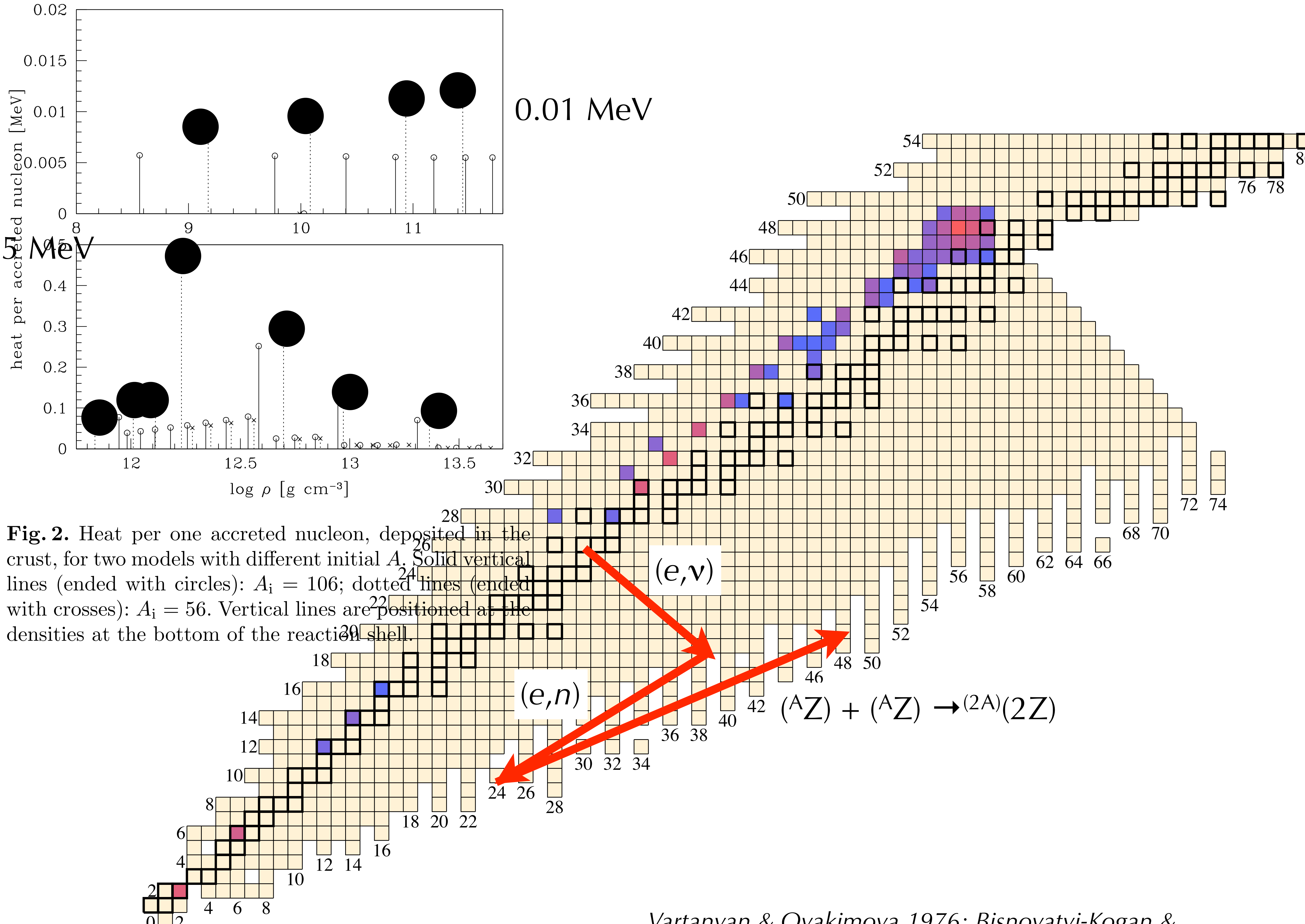
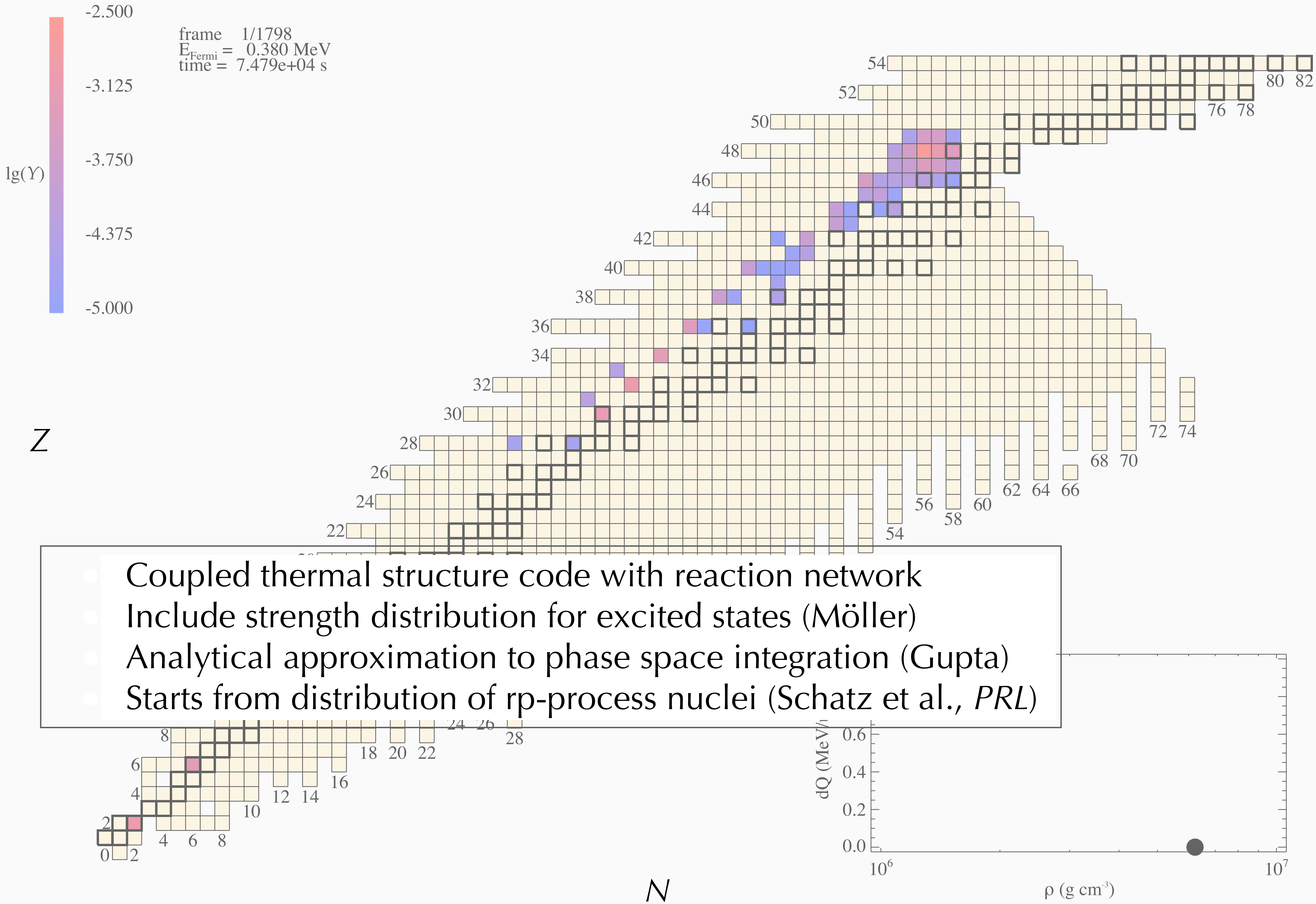


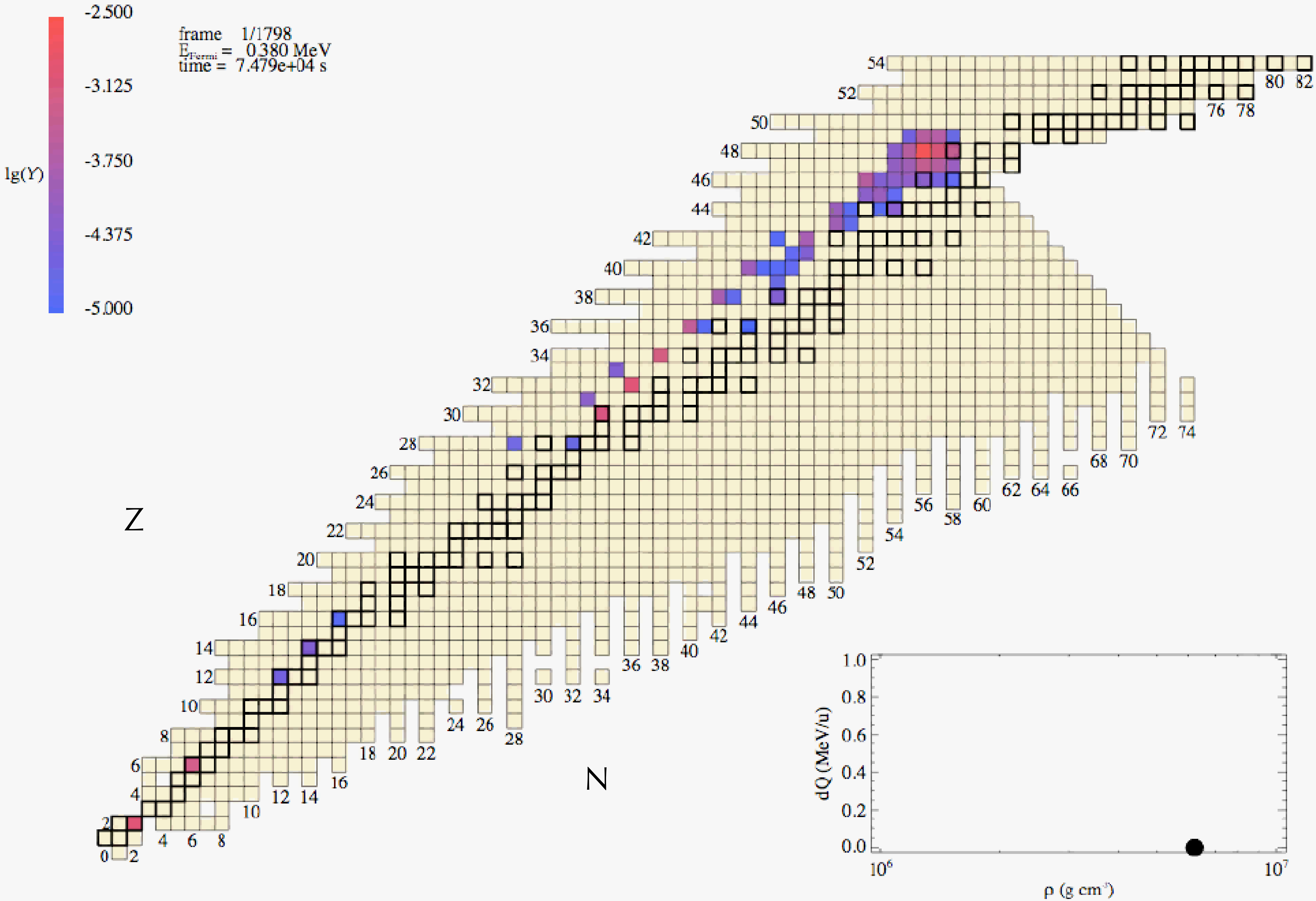
Fig. 2. Heat per one accreted nucleon, deposited in the crust, for two models with different initial A. Solid vertical lines (ended with circles): $A_{\rm i} = 106$; dotted lines (ended with crosses): $A_{\rm i} = 56$. Vertical lines are positioned at the densities at the bottom of the reaction shell.

Vartanyan & Ovakimova 1976; Bisnovatyi-Kogan & Chechetkin 1978; Sato 1979; Haensel & Zdunik 1990, 2003

Gupta, Brown, Schatz, Möller, & Kratz (2007)



- Coupled thermal structure code with reaction network
- Include strength distribution for excited states (Möller)
- Analytical approximation to phase space integration (Gupta)
- Starts from distribution of rp-process nuclei (Schatz et al., *PRL*)



-2.500
-3.125
-3.750
-4.375
-5.000
lg(Y)
frame 1/1798
E_Fermi = 0.380 MeV
time = 7.479e+04 s
Z
N
0 2 4 6 8 10 12 14 16 18 20 22 24 26 28 30 32 34 36 38 40 42 44 46 48 50 52 54
0 2 4 6 8 10 12 14 16 18 20 22 24 26 28 30 32 34 36 38 40 42 44 46 48 50 52 54 56 58 60 62 64 66 68 70 72 74 76 78 80 82
dQ (MeV/u)
1.0
0.8
0.6
0.4
0.2
0.0
10^6
10^7
ρ (g cm^-3)

Composition set by rising Fermi energy

Consider the symmetry term in the mass fmla.,

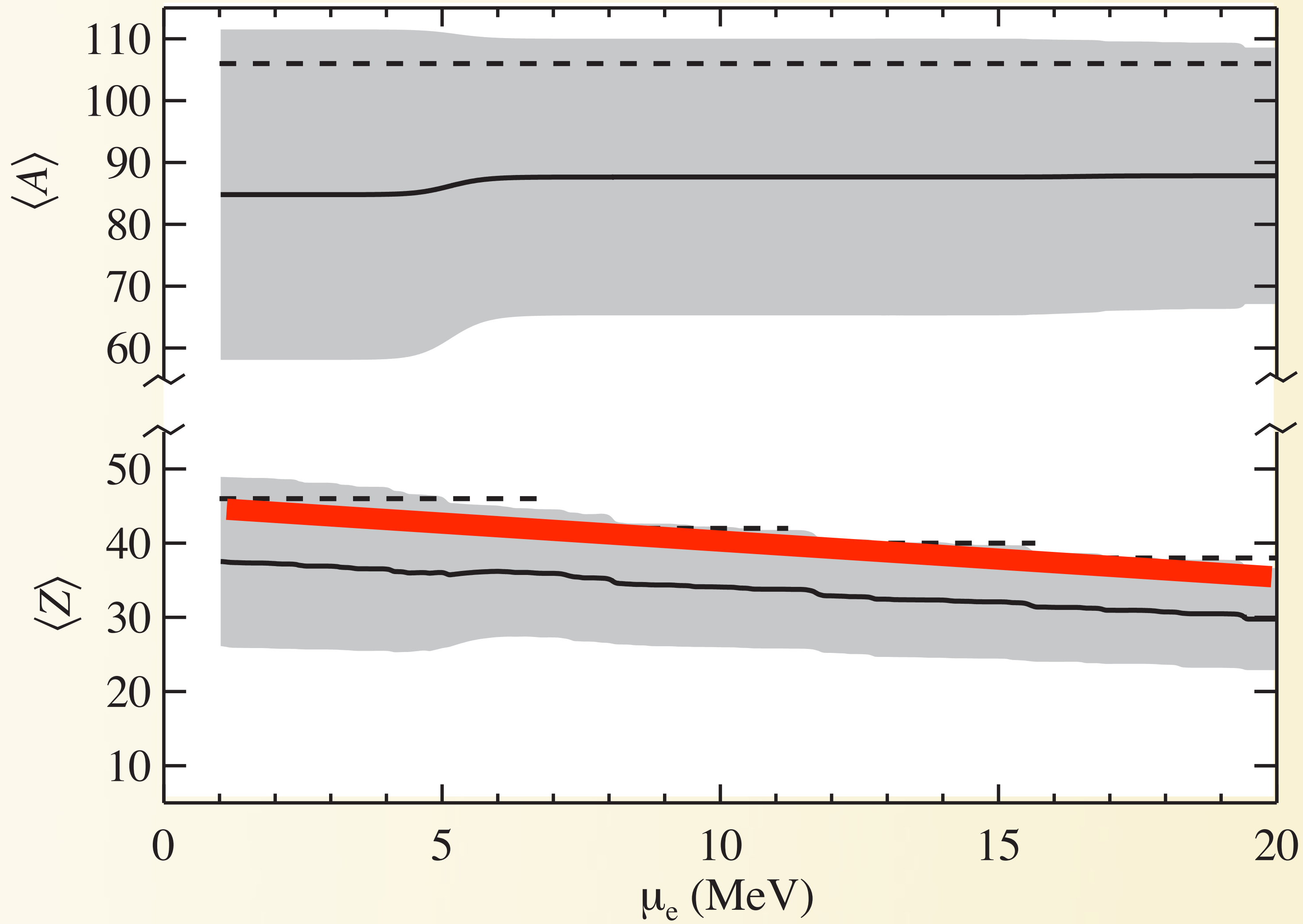
$$\frac{E}{A} = \ldots + E_s\left(\frac{N-Z}{N+Z}\right)^2 = \ldots + E_s(1-2Y_e)^2.$$

The electron Gibbs energy, per nucleon is

$$\frac{1}{n_b}(E+PV) = Y_e\mu_e$$

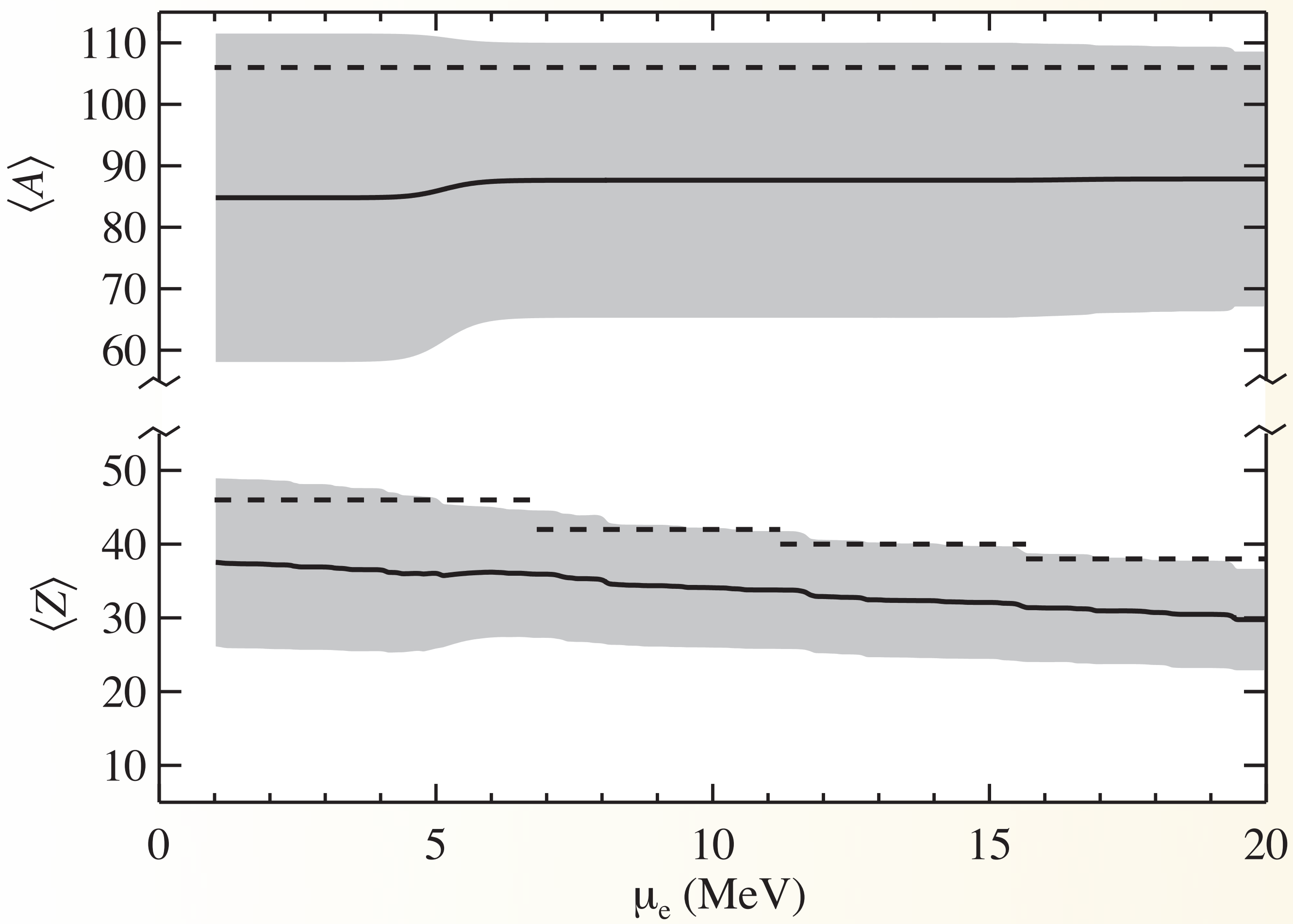
and minimizing the total energy with respect to Y_e gives

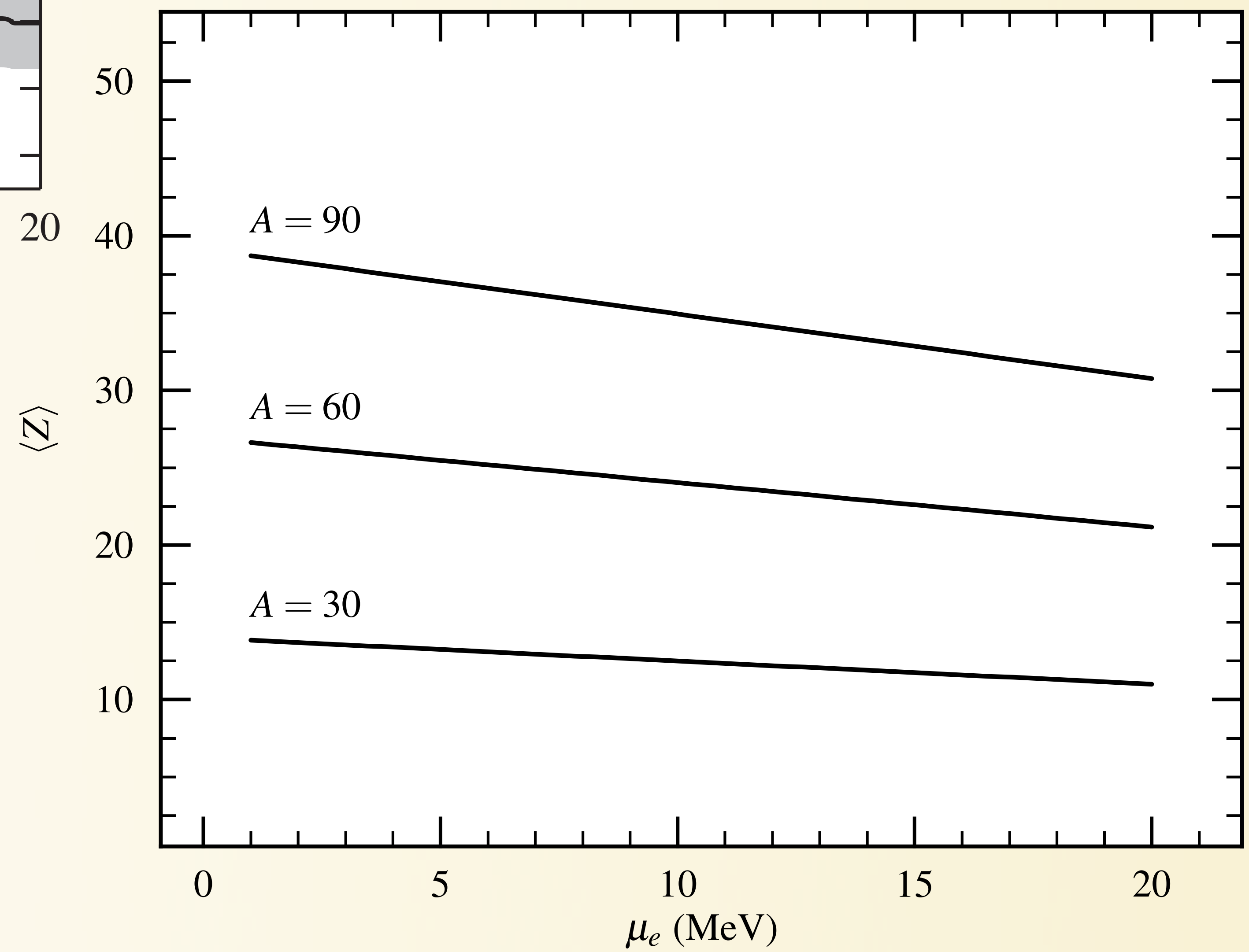
$$Y_e \approx \frac{1}{2} - \frac{\mu_e}{8E_s}.$$

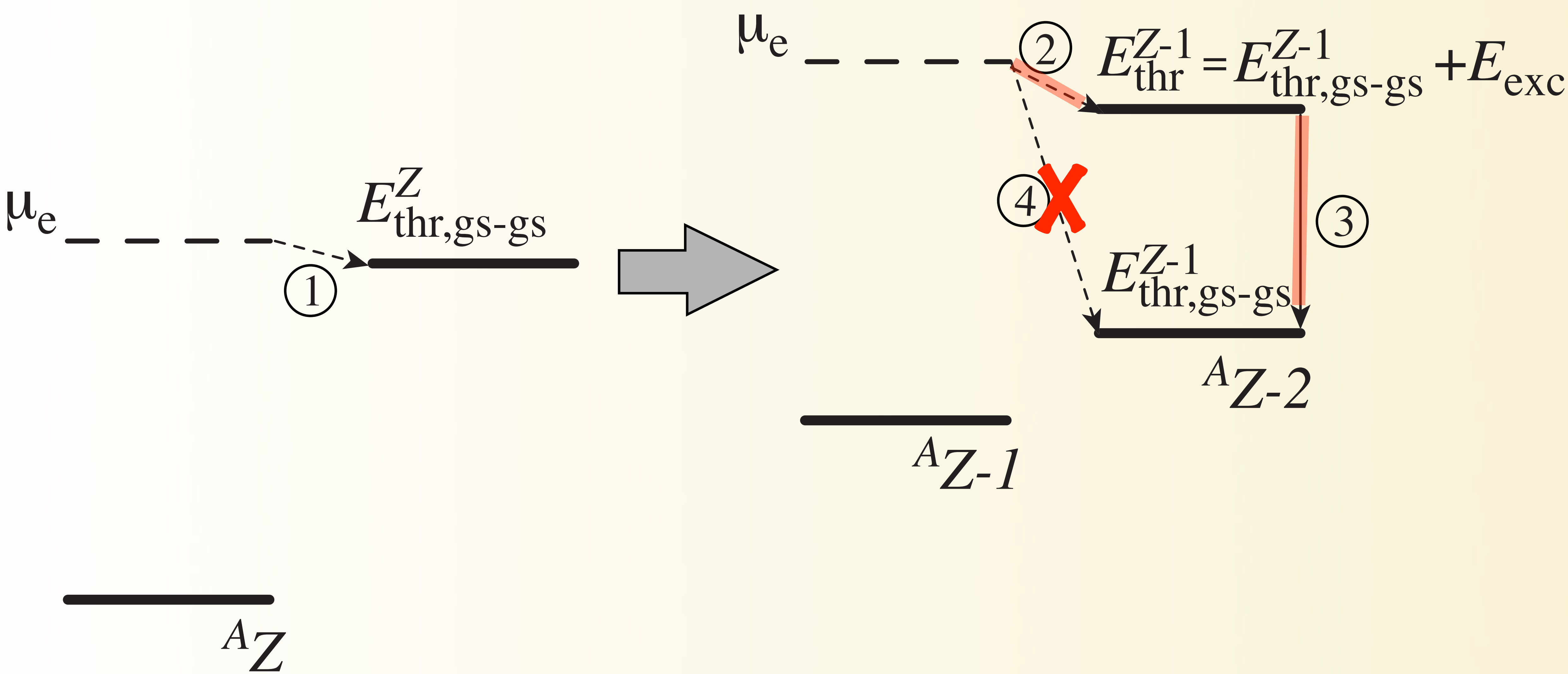


NB. This fmla. also follows from $\mu_e = \mu_n - \mu_p$

With Coulomb term included

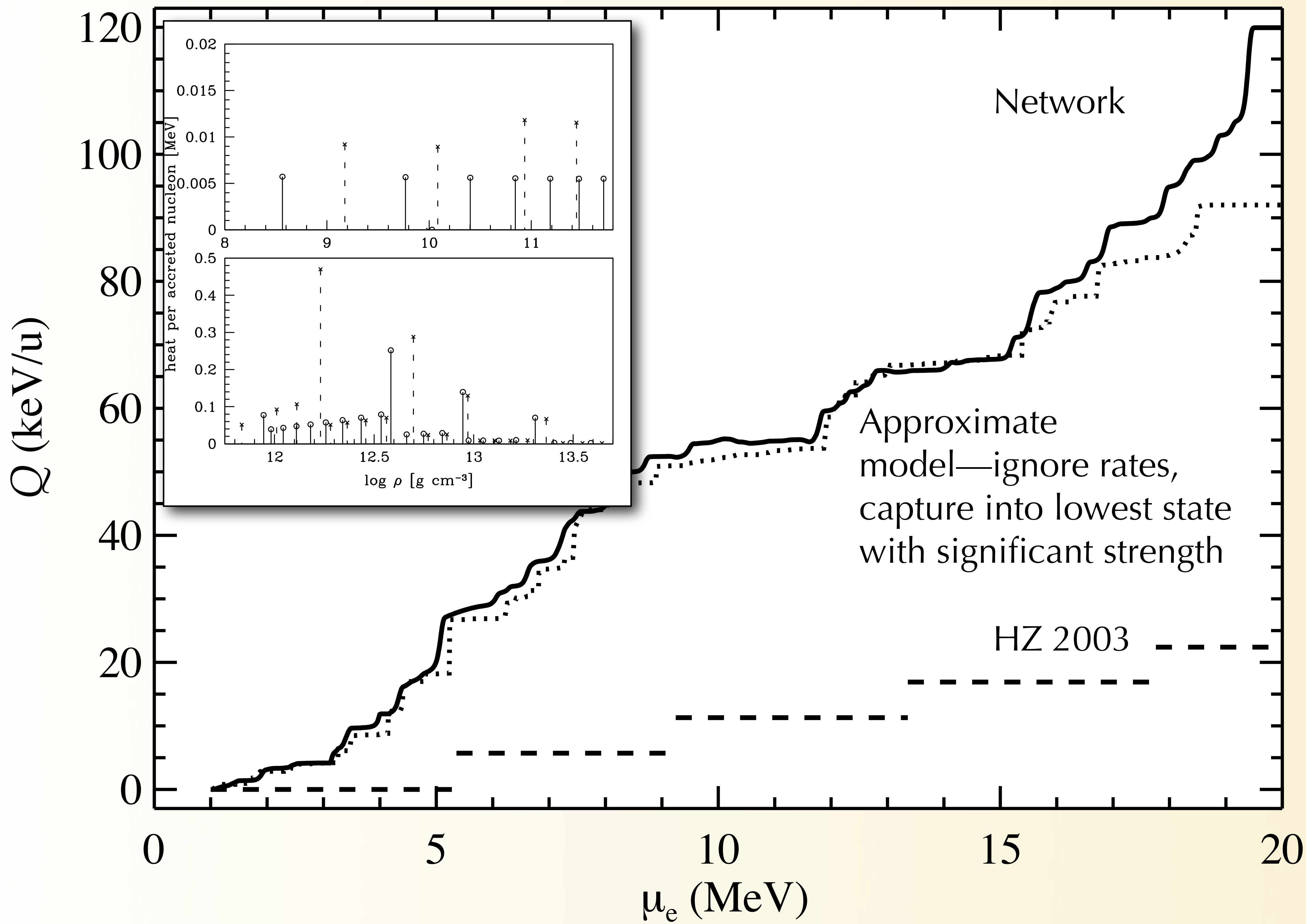




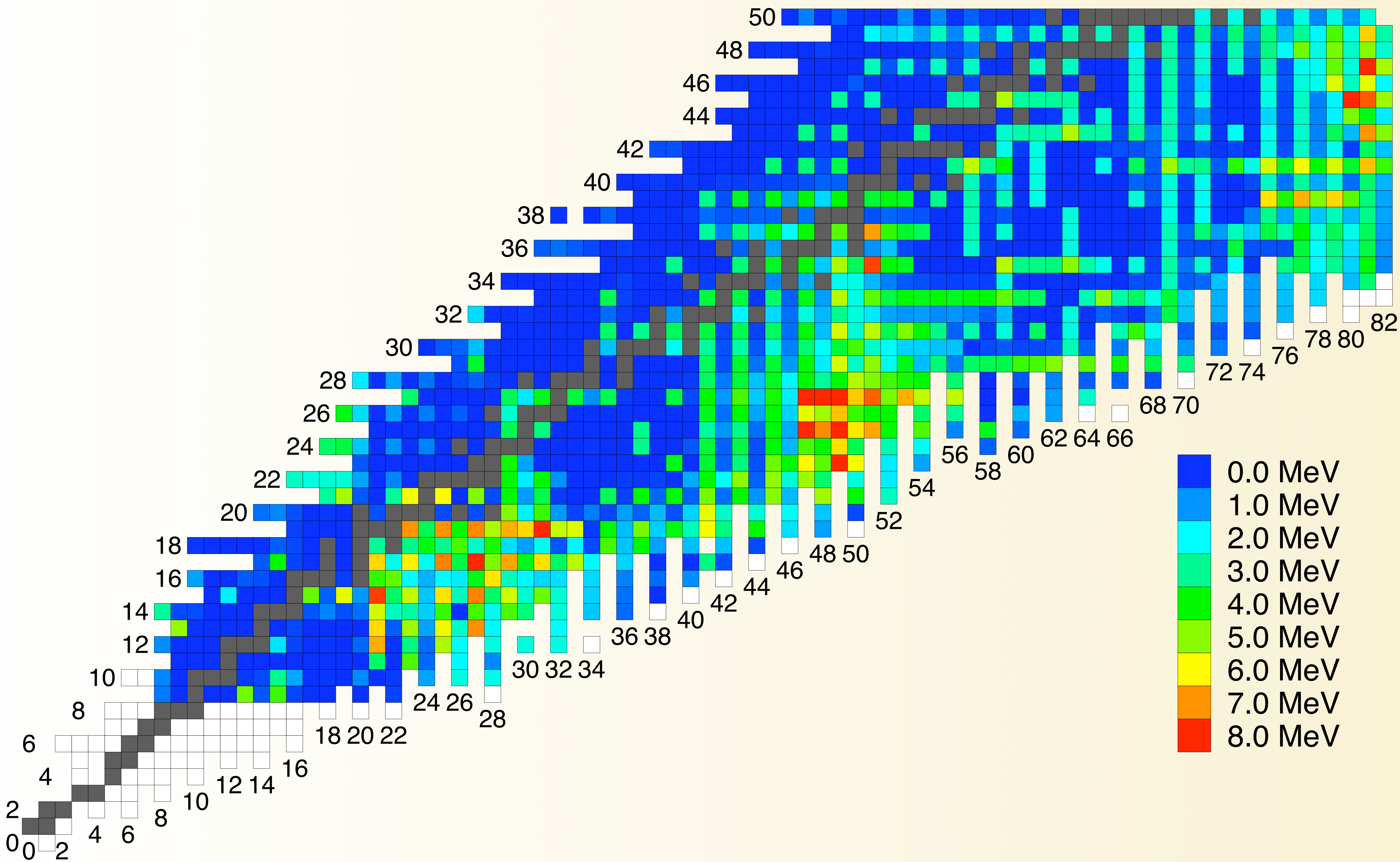


μe
$E^{Z}_{\text{thr,gs-gs}}$
1
^{A}Z
μe
2
$E^{Z\text{-}1}_{\text{thr}} = E^{Z\text{-}1}_{\text{thr,gs-gs}} + E_{\text{exc}}$
4
3
$E^{Z\text{-}1}_{\text{thr,gs-gs}}$
$^{A}Z\text{-}2$
$^{A}Z\text{-}1$

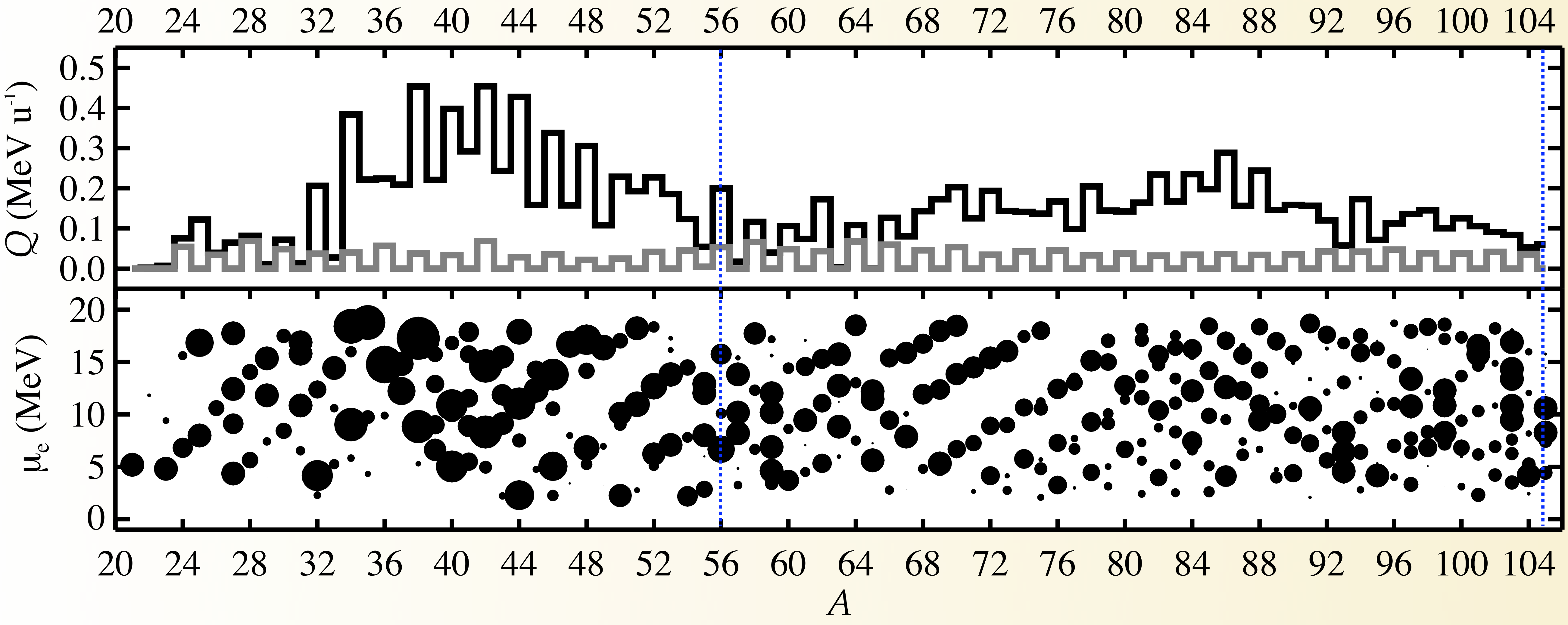
With captures into excited states



Nuclear Structure Effects



Electron capture reactions, outer crust



Composition matters!

The heating sets

- the quiescent luminosity of transients (previous talks)
- ignition depth of superbursts (Brown, Cooper & Narayan, Cumming et al.)
- X-ray bursts at low accretion rates (Cumming et al., Peng et al.)

The composition sets

- transport properties
- mass quadrupole (Bildsten 1998, Ushomirsky et al. 2000, Haskell et al. 2006)

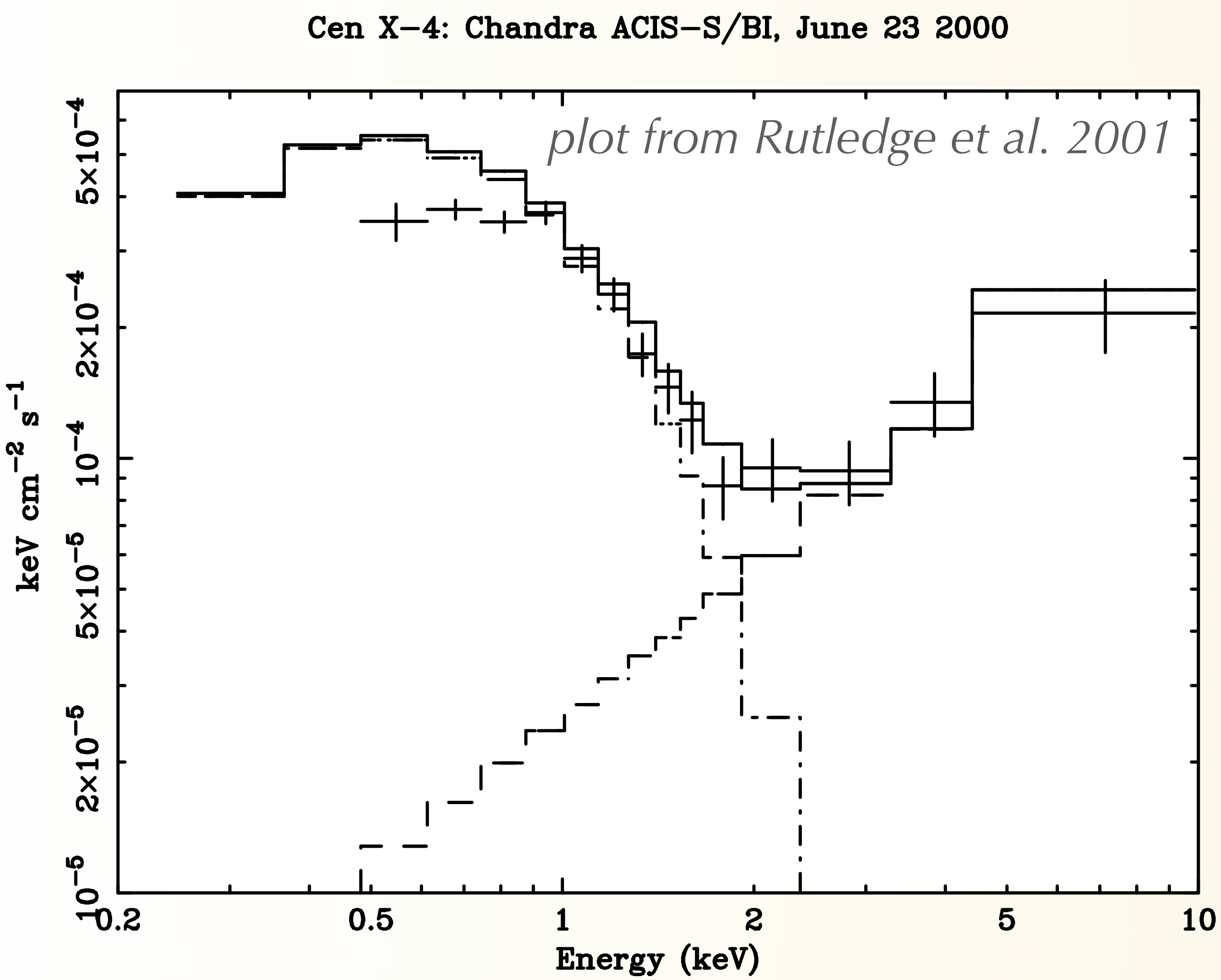
Can this heating be observed?

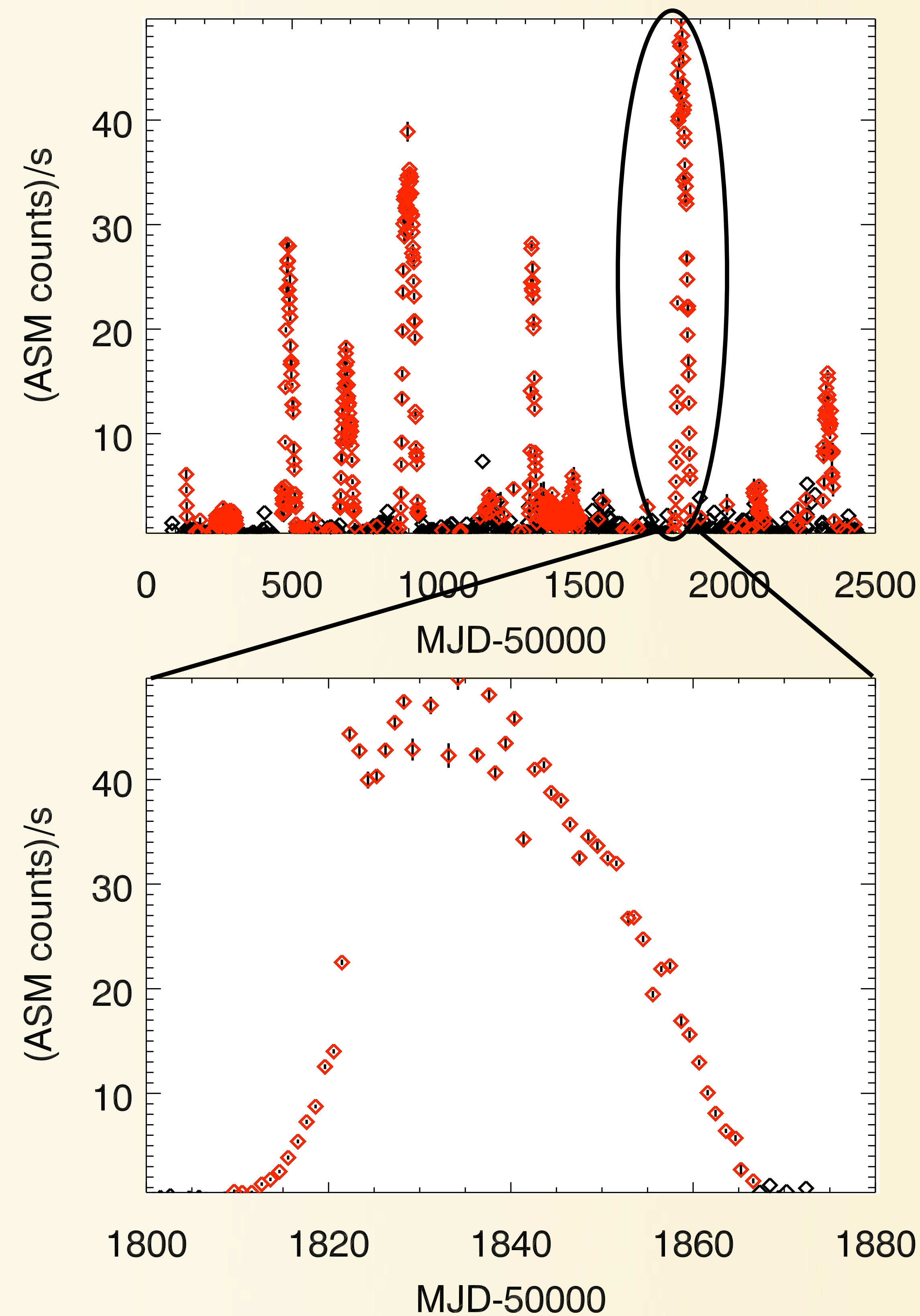
For steady accretors, ***no***

E_{grav} ~ 200 MeV/nucleon

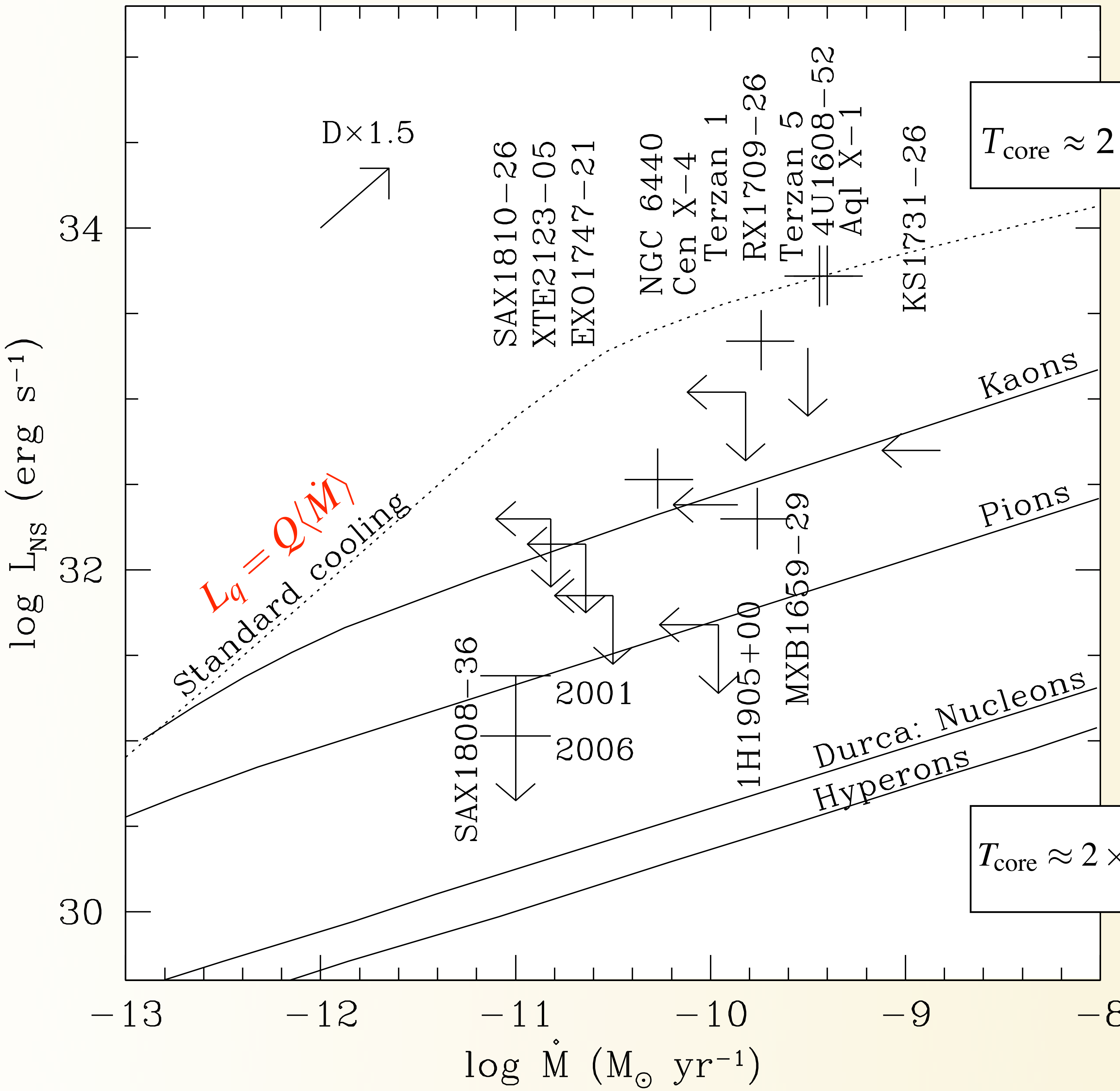
Q_{nuc} ~ 1 MeV/nucleon

But many sources accrete *transiently—observe heated crust in quiescence (Brown, Bildsten & Rutledge 1998)*





Lightcurves courtesy of ASM team, http://xte.mit.edu/ASM_lc.html *from Heinke et al. 2007, following Yakovlev et al. 2004*



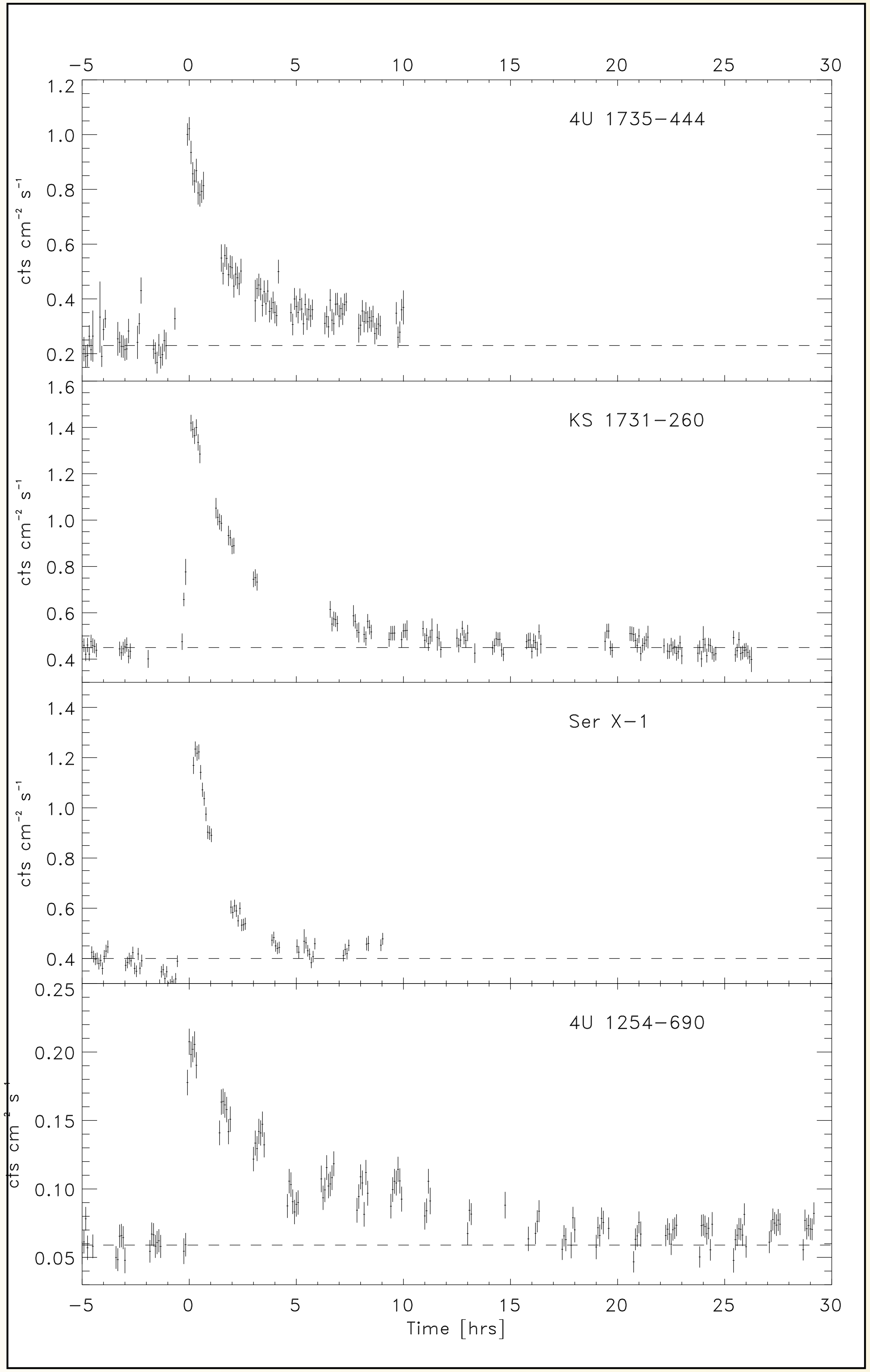
$$T_{\rm core} \approx 2\times10^{8}\,{\rm K}\left(\frac{\langle\dot{M}\rangle}{10^{-10}\,M_\odot\,{\rm yr}^{-1}}\right)^{1/8}$$

“slow” neutrino emissivity

“fast” neutrino emissivity

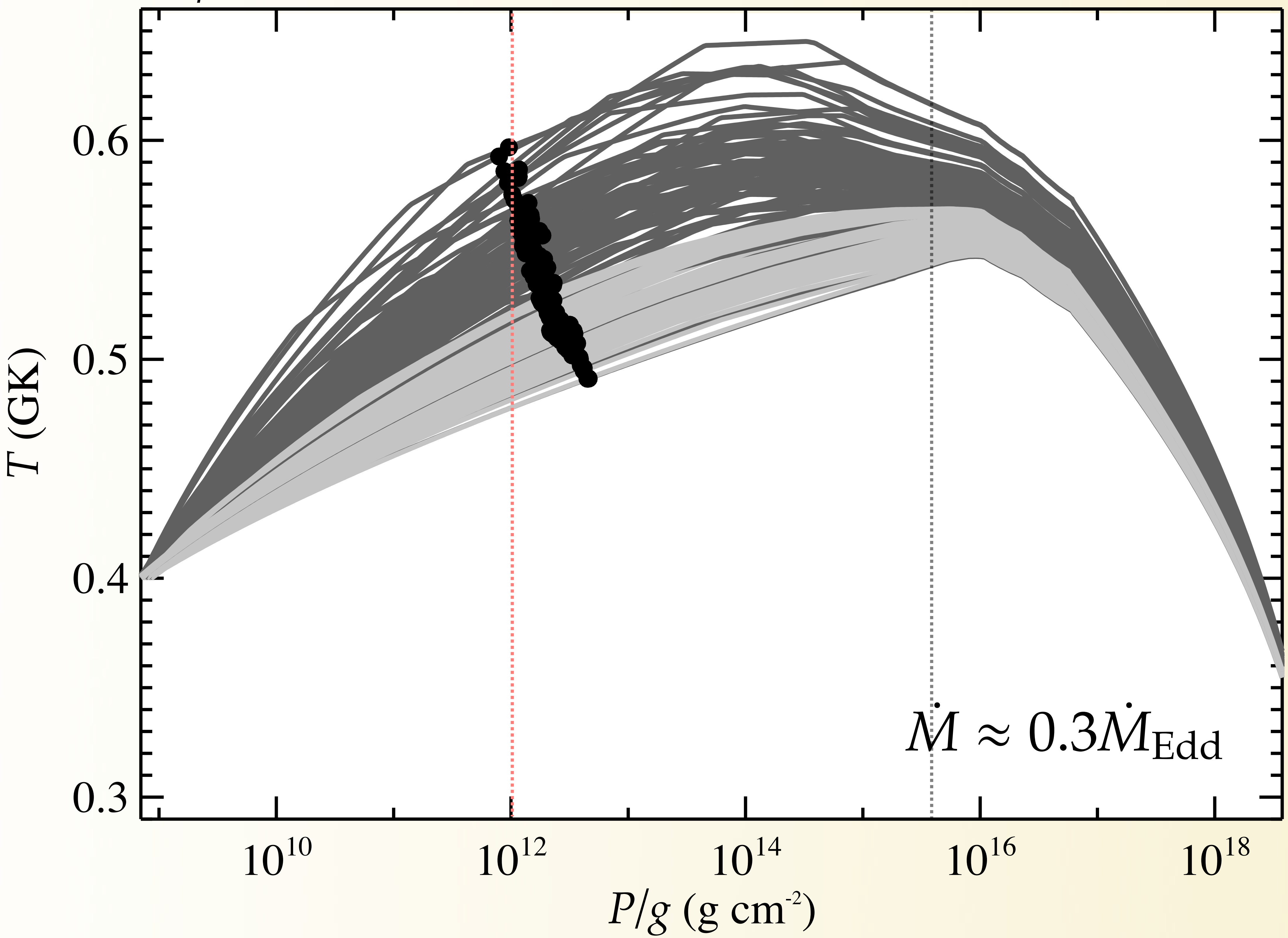
$$T_{\rm core} \approx 2\times10^{7}\,{\rm K}\left(\frac{\langle\dot{M}\rangle}{10^{-10}\,M_\odot\,{\rm yr}^{-1}}\right)^{1/6}$$

Superburst profiles in ‘t Zand et al. 2003



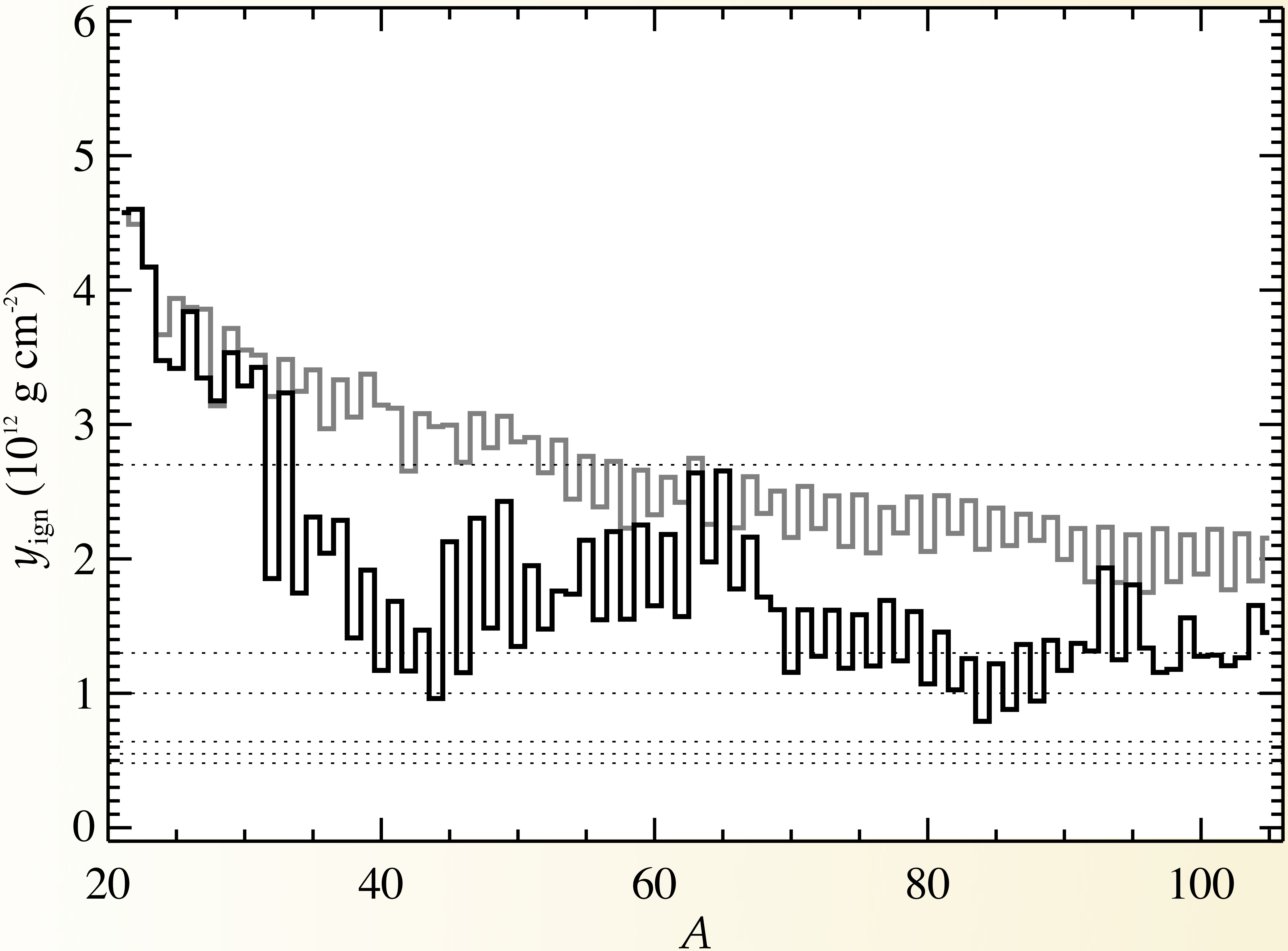
Variation of crust temperature

Gupta, Brown, Schatz, Möller, & Kratz 2007



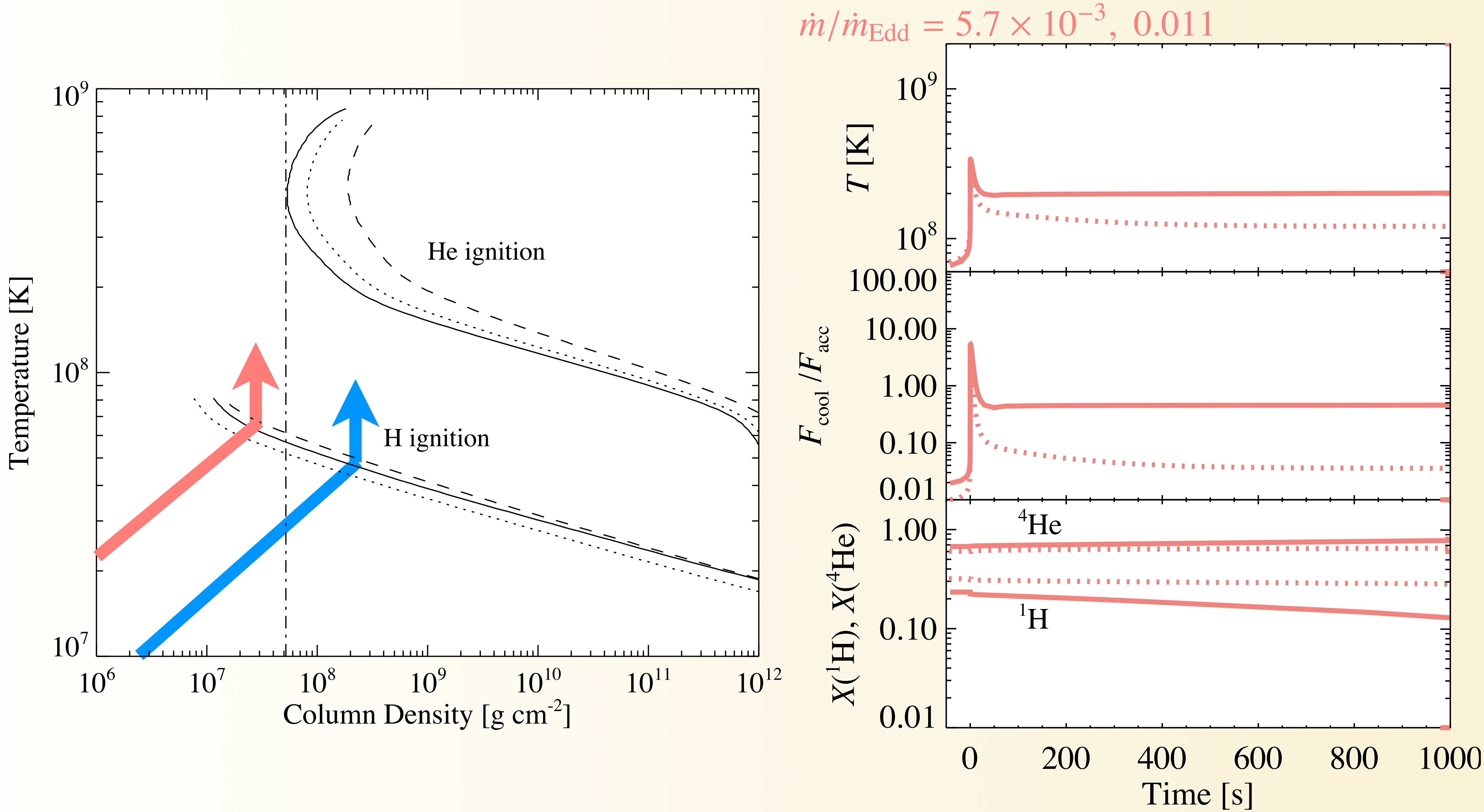
Ignition columns

Gupta, Brown, Schatz, Möller, & Kratz 2007

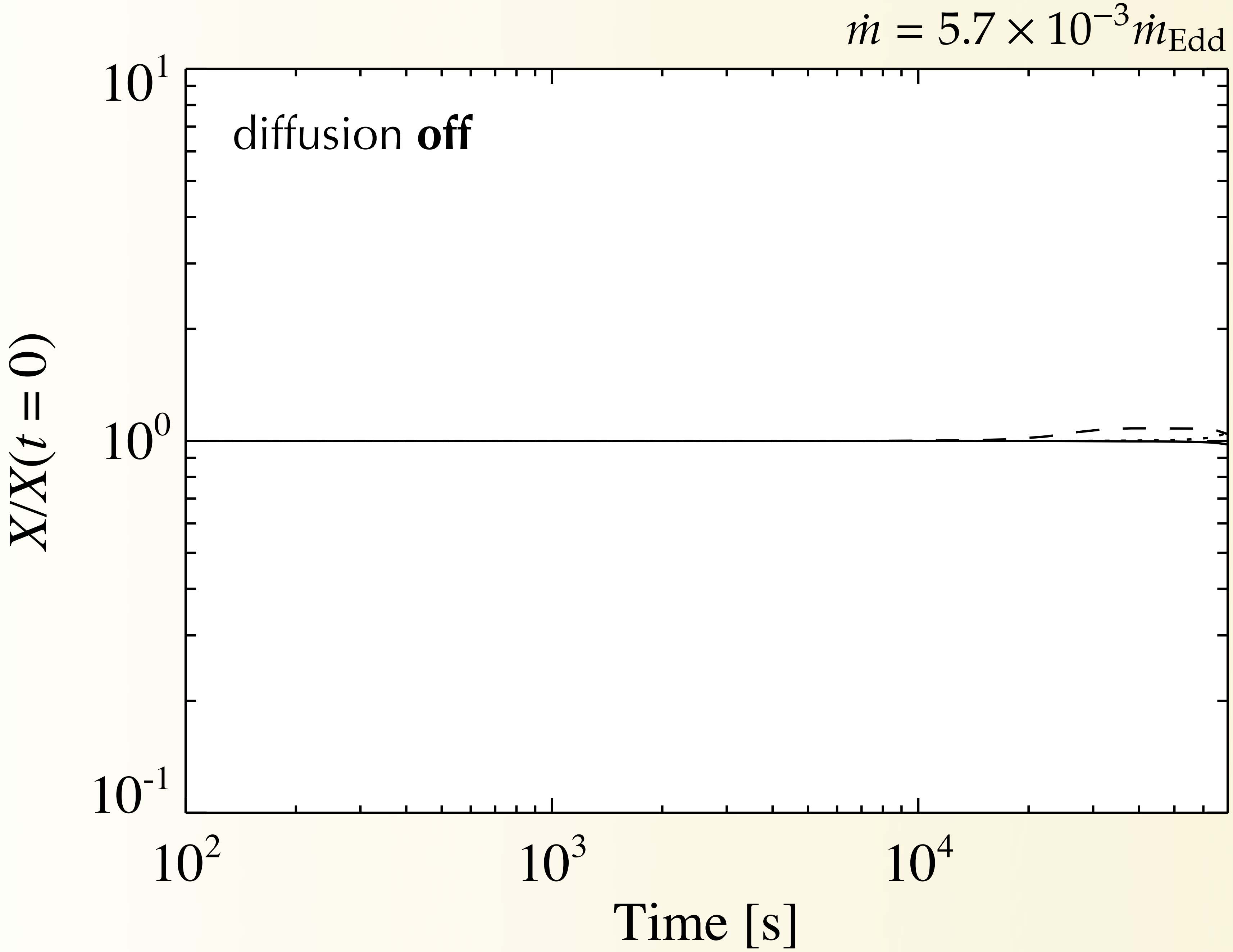


Ignition at very low accretion rates

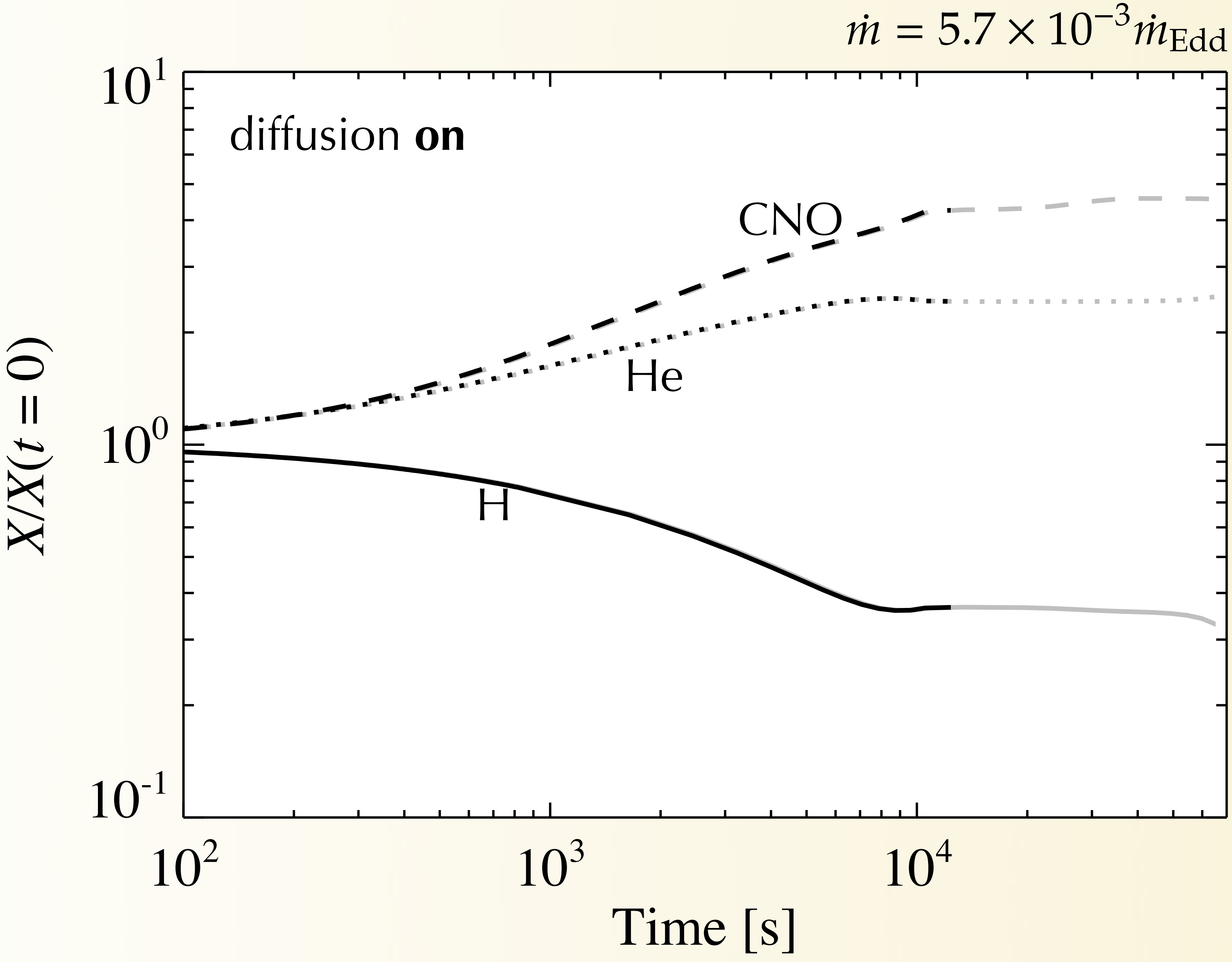
Peng, Brown, & Truran 2007, following Fujimoto et al. 1981



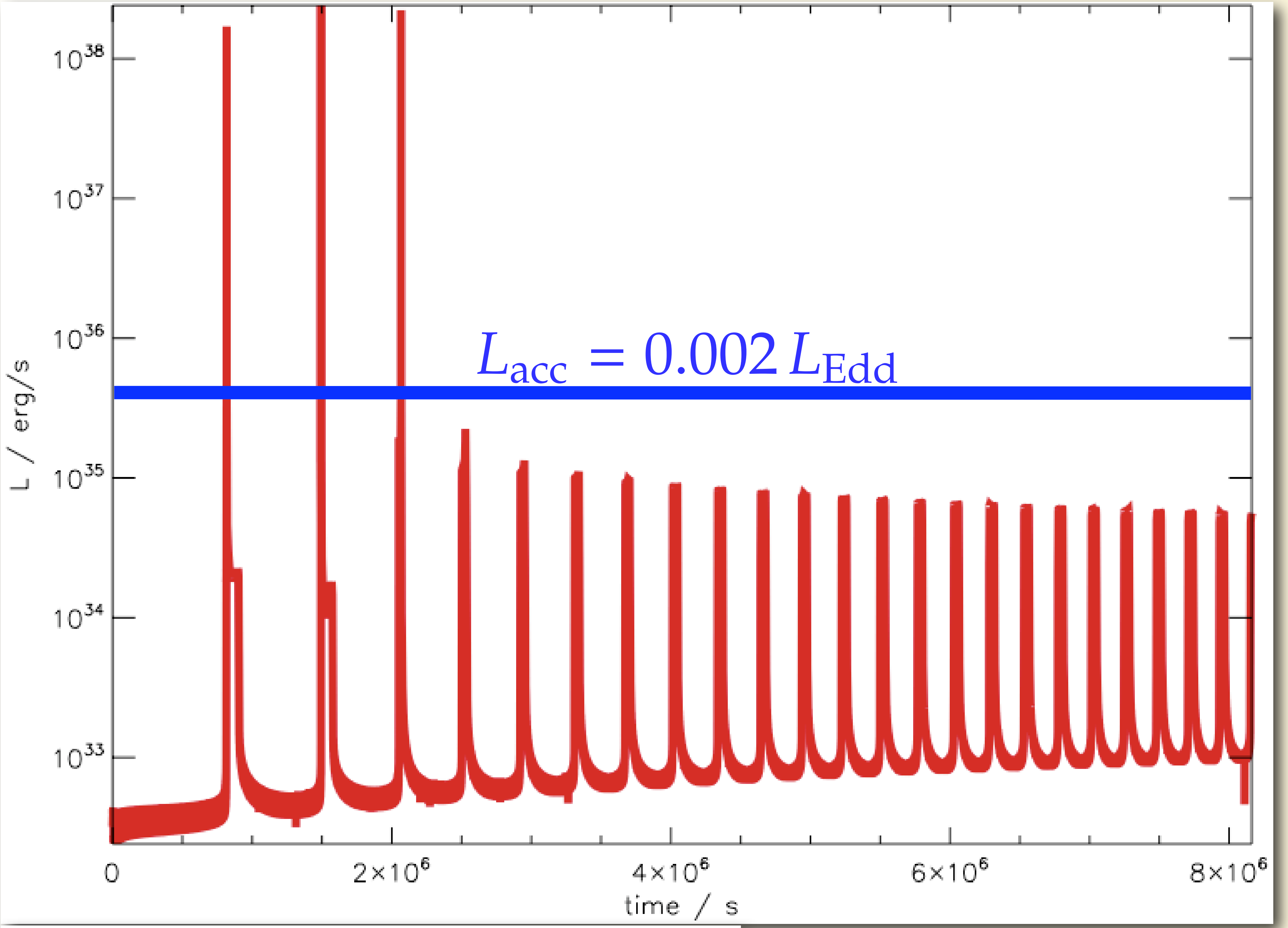
Composition at base of accreted layer



Composition at base of accreted layer



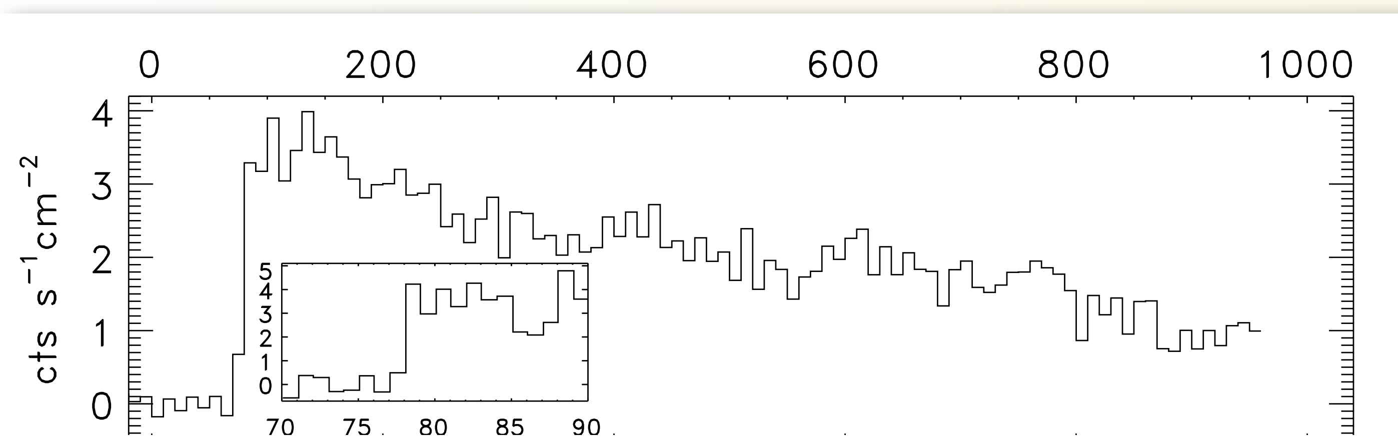
Simulations find weak flashes!



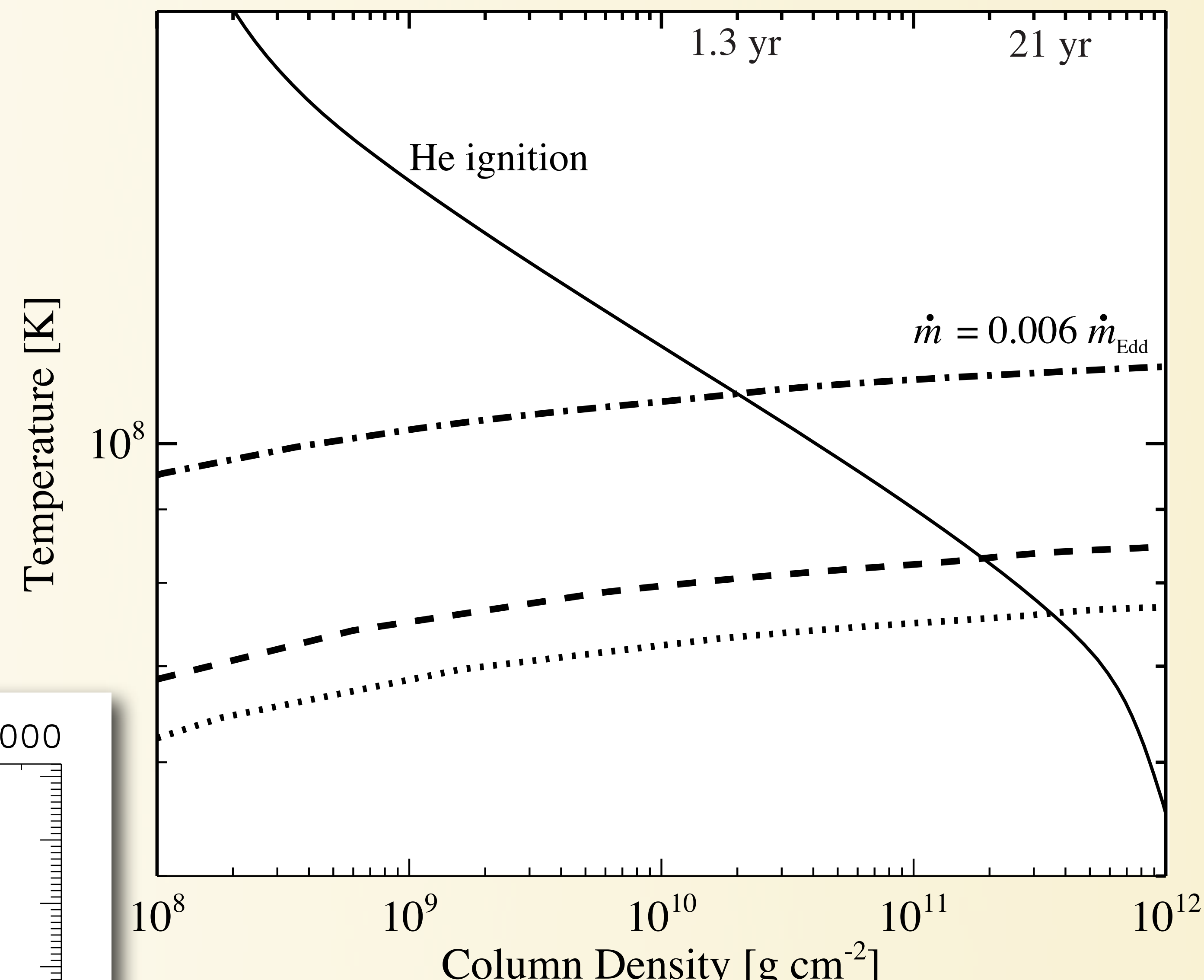
Multi-zone simulation by Alexander Heger

He flashes at large depth

- Repeated flashes build up massive He layer
- Eventually 3α ignites, produces more energetic burst
- Ignition depth sensitive to heat flux from reactions in crust *(Brown 2004, Cooper & Narayan 2005, Cumming et al. 2006)*



SLX 1737-282; in't Zand et al. 2005, A&A ***389*** *L43*



Summary

- Deep crustal heating
  - In the outer crust, nuclear structure & composition matters!
  - Amount of outer crust heating affects ignition of superbursts, long X-ray bursts (Cumming et al. 2006, Peng et al. 2007)
- Pay attention to all phenomena