Crustal reactions, superbursts and soft X-ray transients

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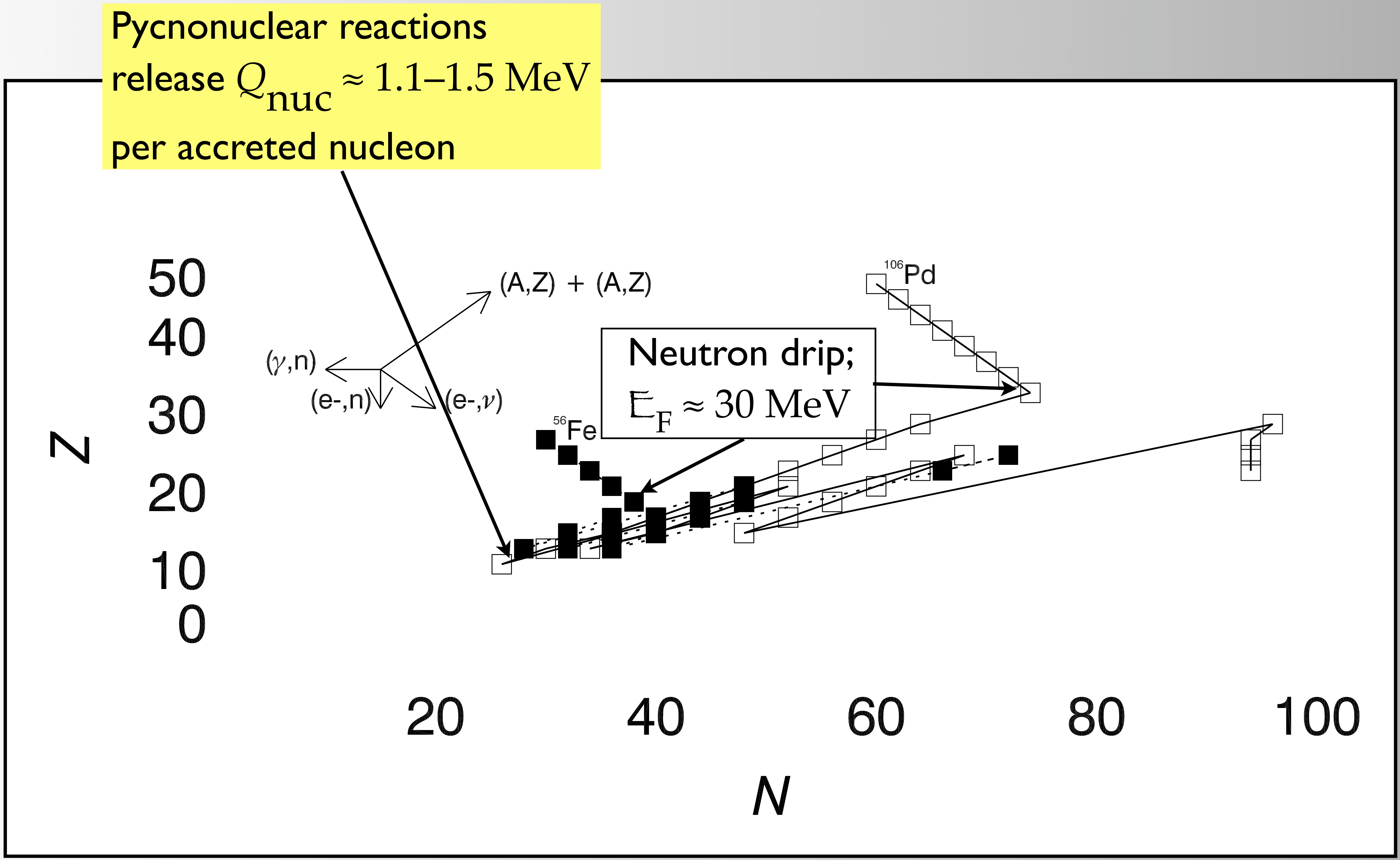
In this talk...

- The quiescent luminosity of transients with long outbursts constrain the temperature in the crust (Rutledge et al 2002)
- The inferred temperature is not consistent with superburst recurrence times
- Towards more realistic models of crust reactions
    - Inclusion of excited states
    - Allowance for (γ,n),(n,γ) reactions
    - Time and temperature dependence

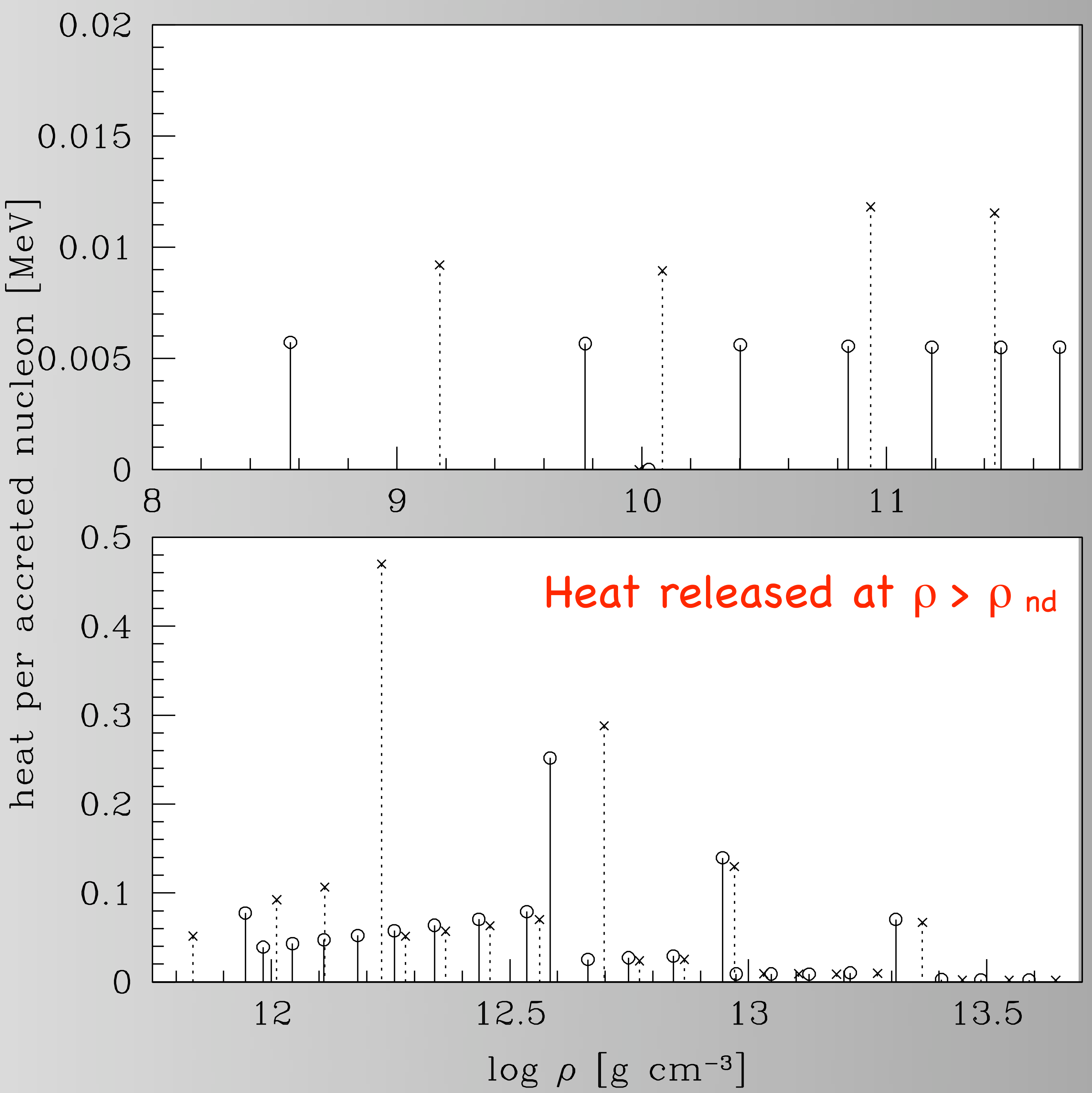
Deep Nuclear Heating
following Haensel & Zdunik 1990, 2003



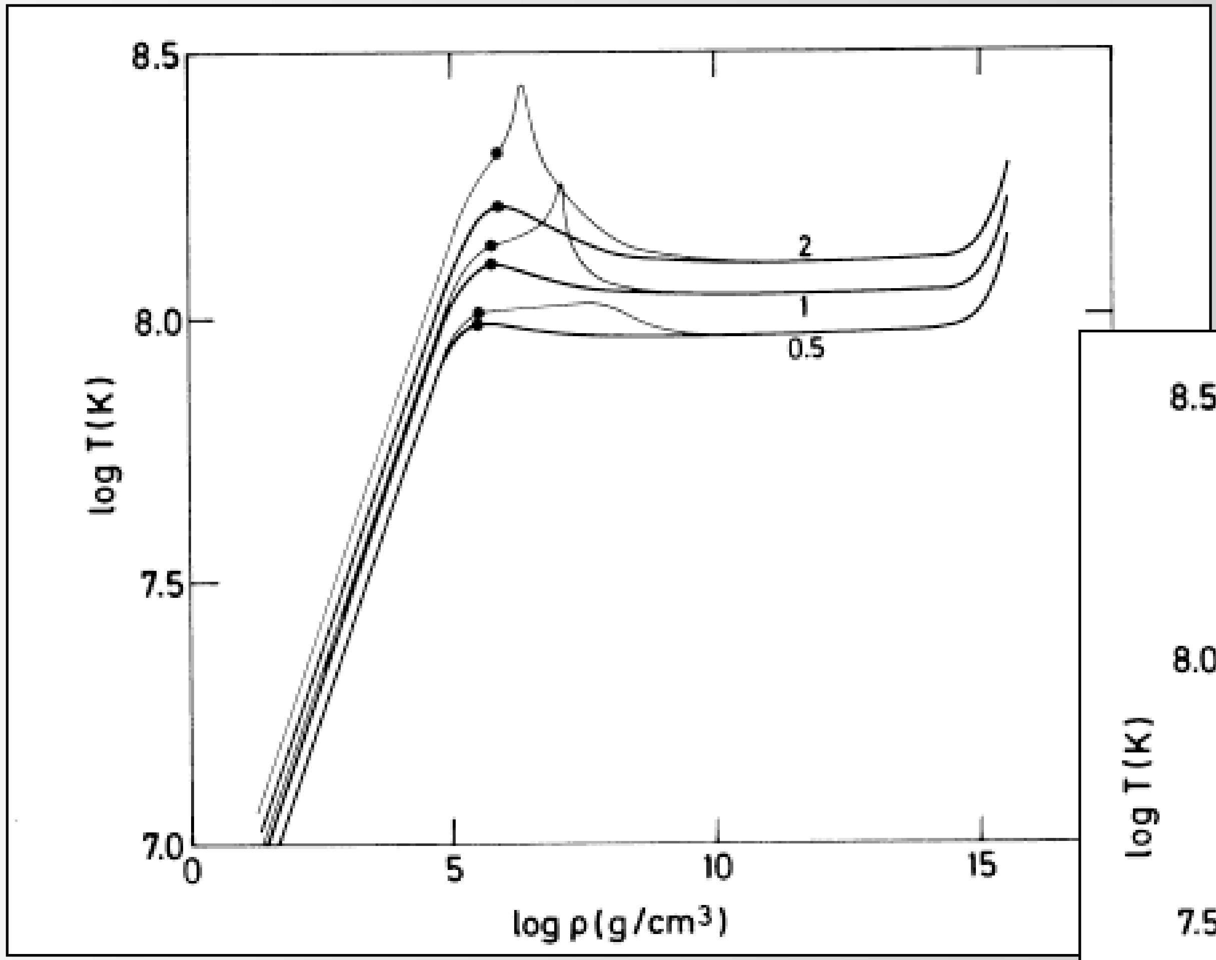
Distribution of ε_{nuc}

(Haensel & Zdunik 1990, 2003)

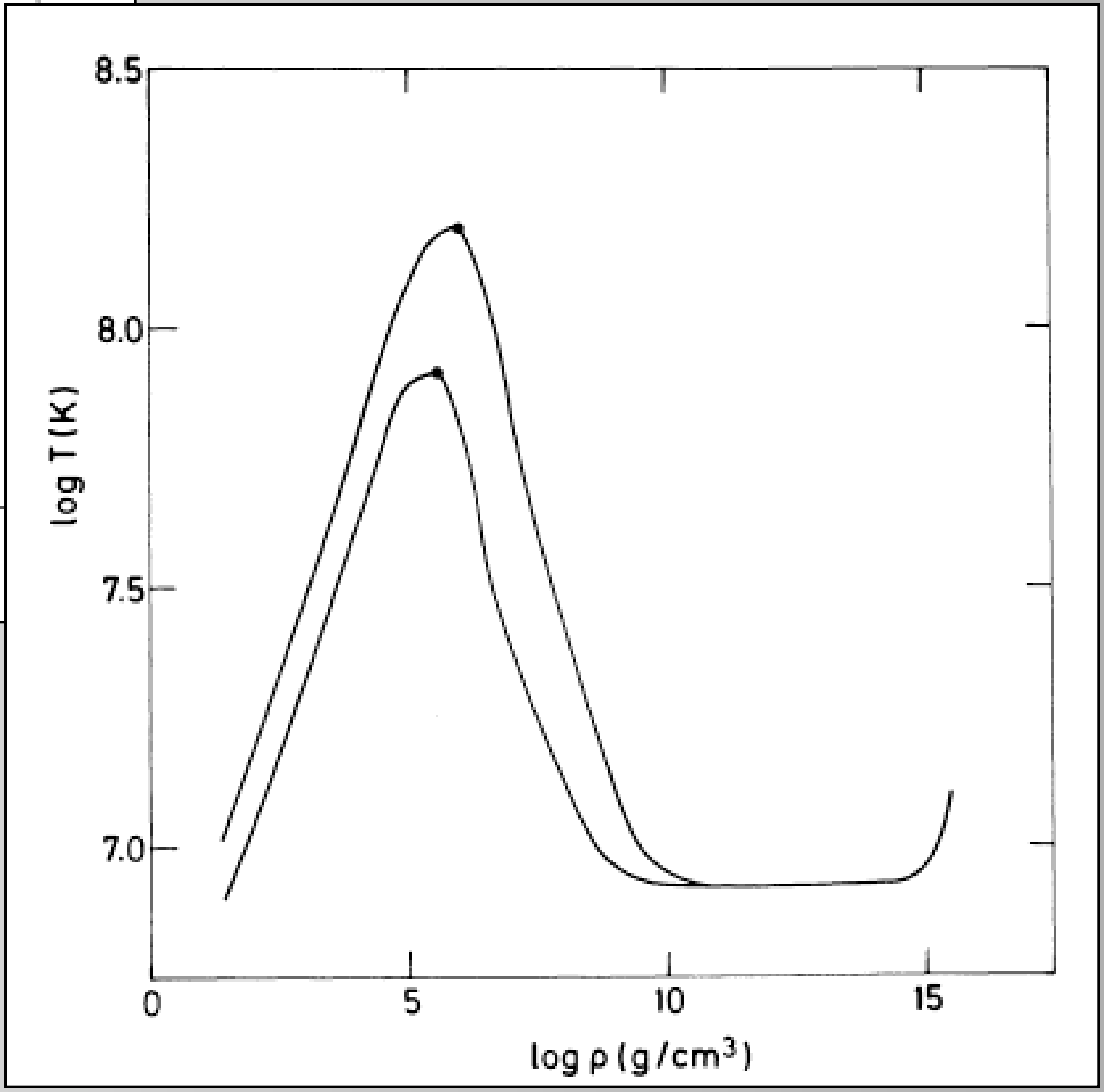
- No consideration of excited states
- Only one nucleus present at a given depth
- Zero-temperature



Without deep heating, no superbursts

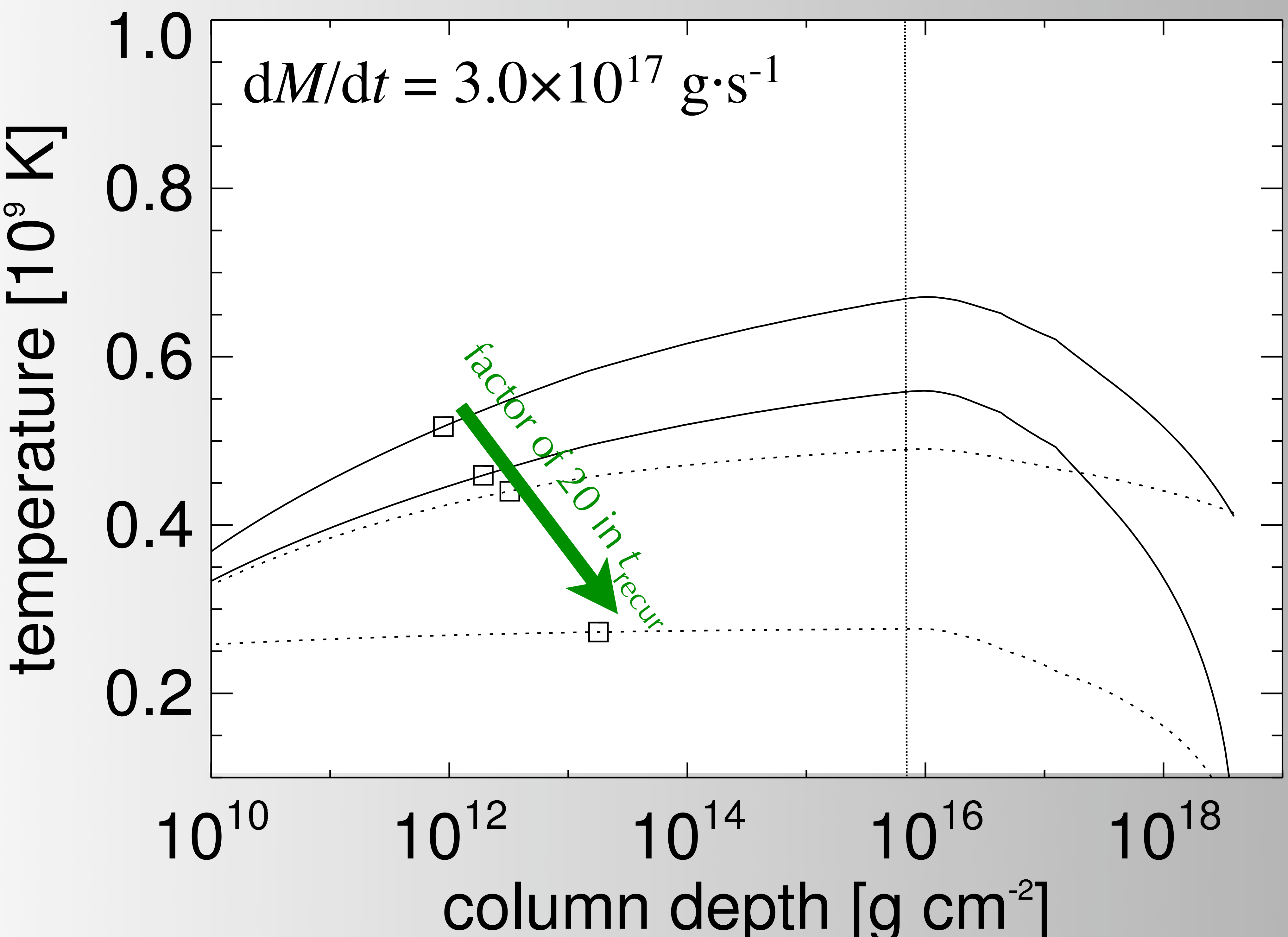


eg, Fujimoto et al. 1987



Ignition columns and recurrence times

Brown 2004
Cooper & Narayan 2005



Two extreme assumptions

i. Thermal conductivity is a lower limit: ignores phonon transport, assumes no long-range order in crust

Cf. estimate of Jones (2004, *PRL*)

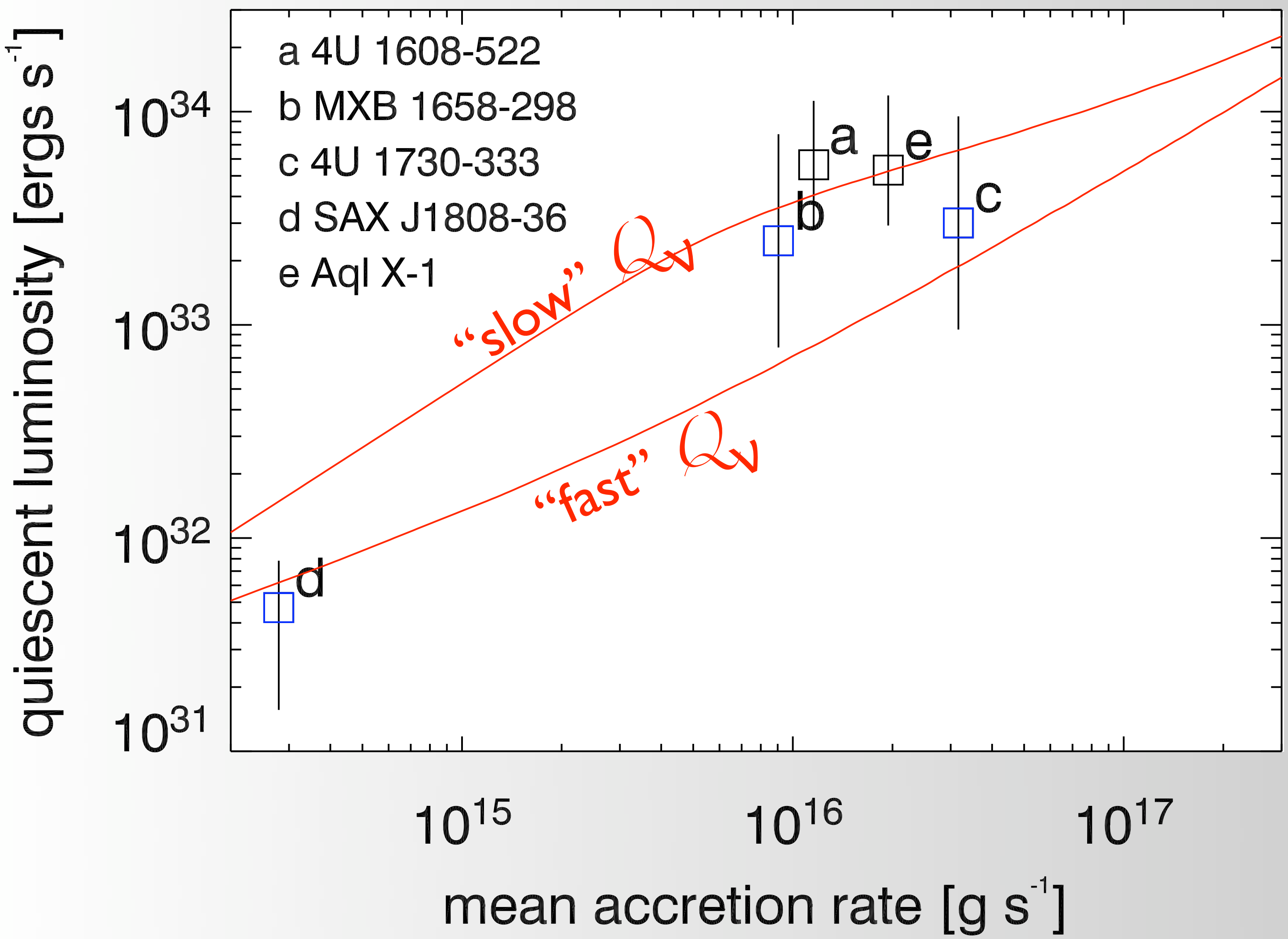
Neglects phonon transport: may be important in the inner crust

$$K \sim \frac{1}{3} C s \lambda$$

v. No substantial crust neutrino emission ($T_{\mathrm{c,n}}(^1S_0) \gg T$).

D. Page; see talk by A. Cumming, next session

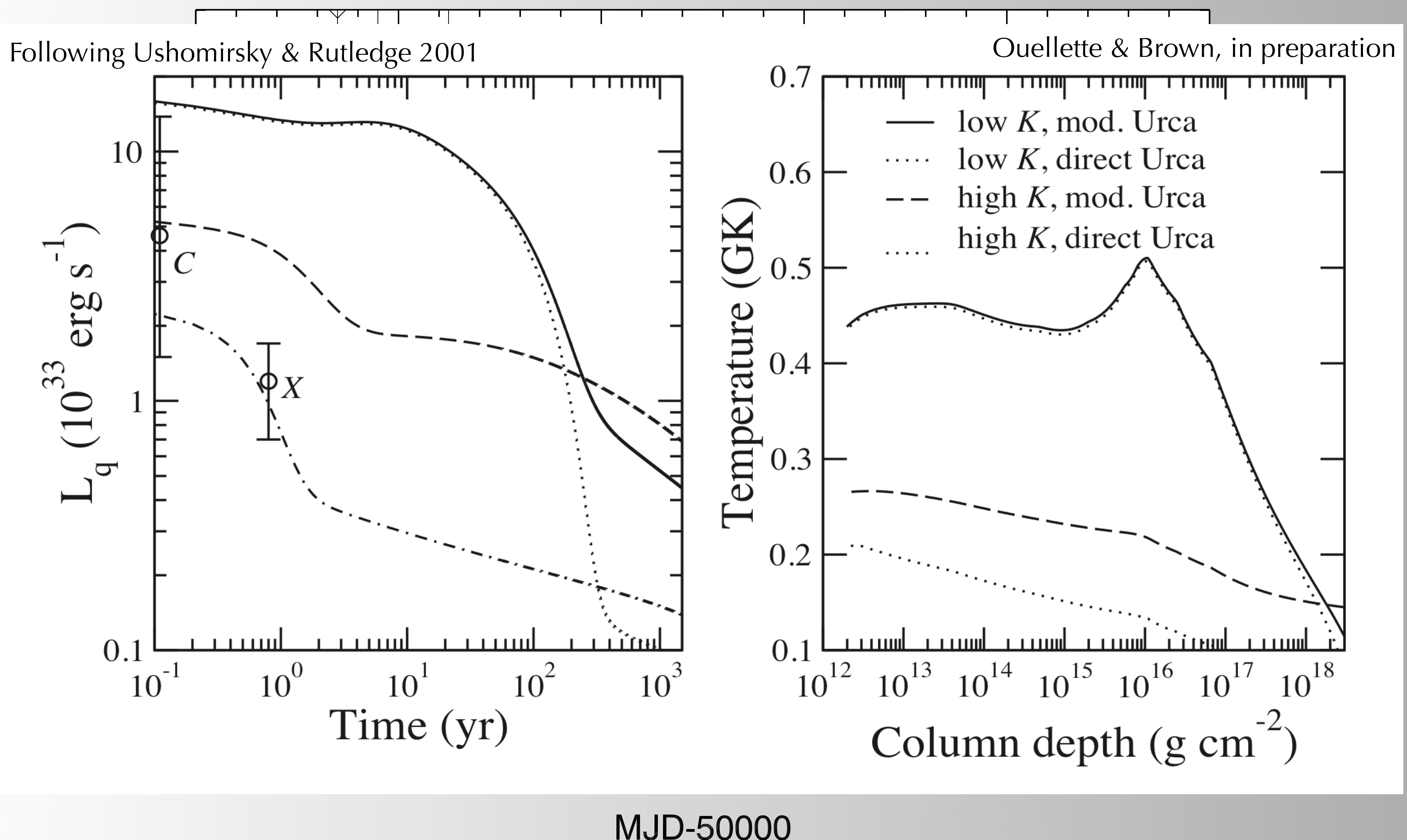
Measuring ν-cooling with neutron star transients



- Heat deposited during outburst is ≪ heat content
  - T_{crust} changes little over an outburst/quiescent cycle (if not a strange star!)
  - Colpi et al. 2001; Ushomirsky & Rutledge 2001; Yakovlev et al. 2003
- Two core models
  - *slow*: mod. urca
  - *fast*: direct Urca for *r* < 5 km

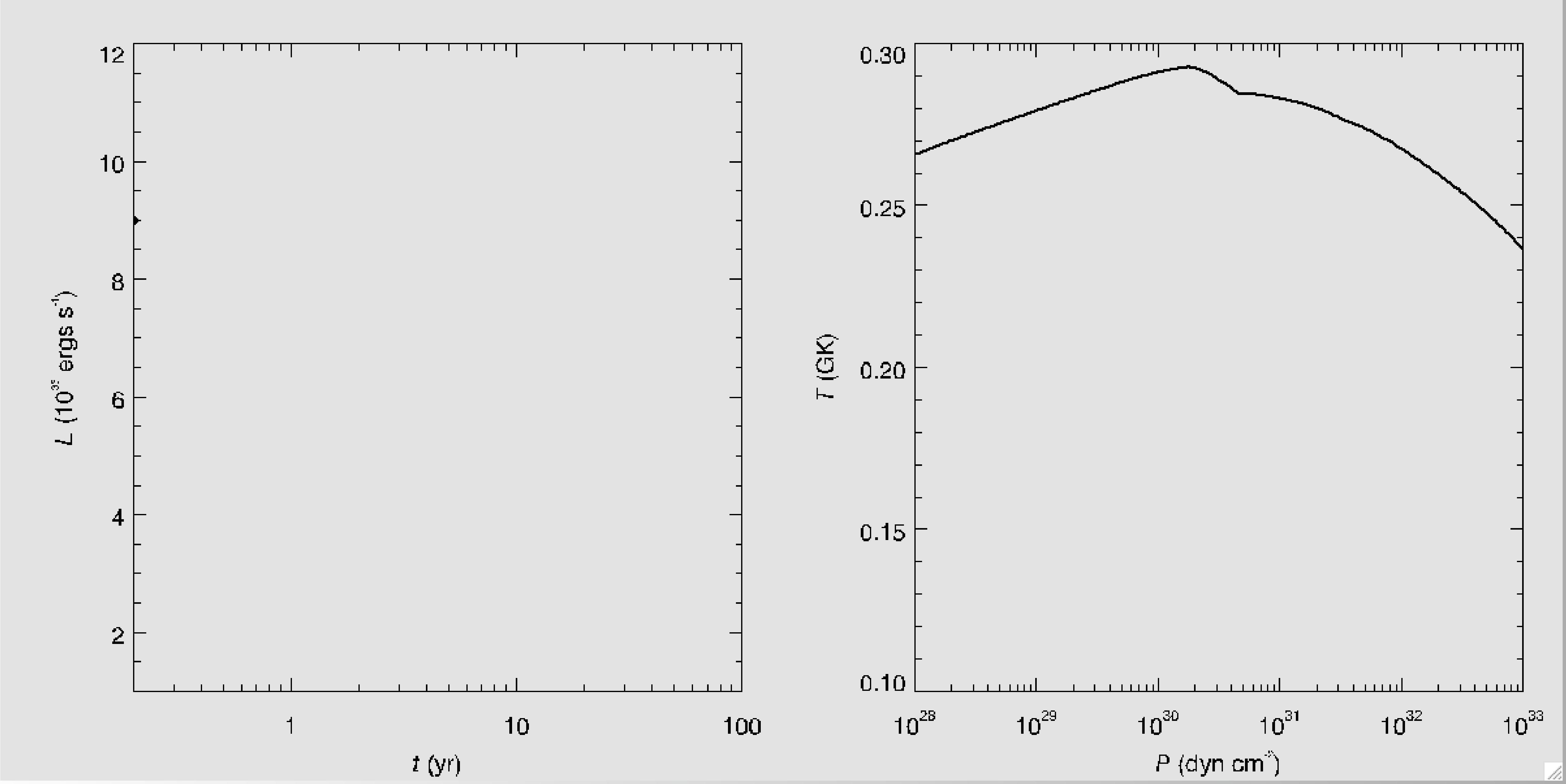
KS1731–260 cooling after a long outburst

Wijnands 2001; Rutledge et al. 2002; Wijnands et al. 2002



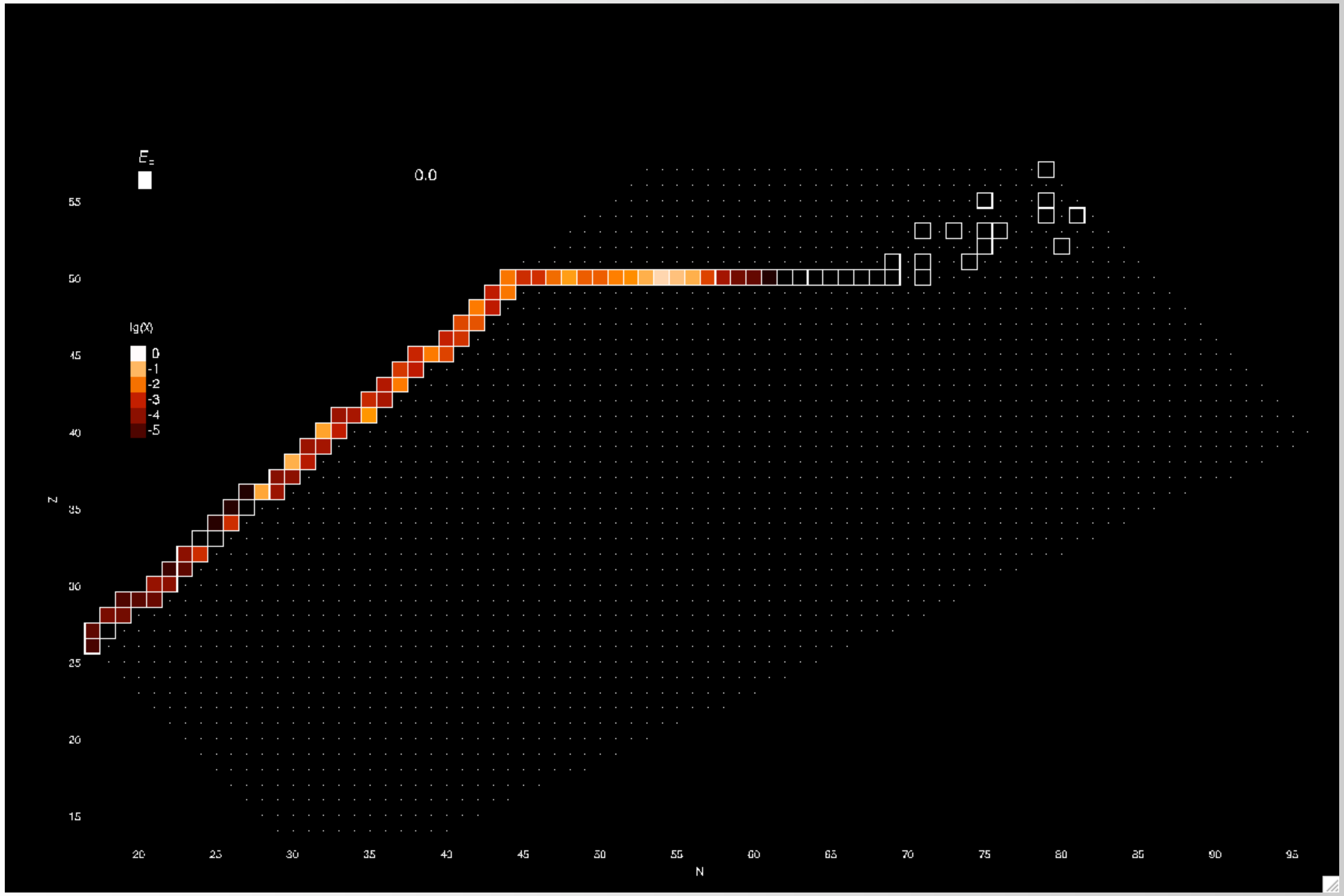
Quiescent evolution, KS 1731-260

Includes L_ν^{Cooper}



Ouellette & Brown, in preparation

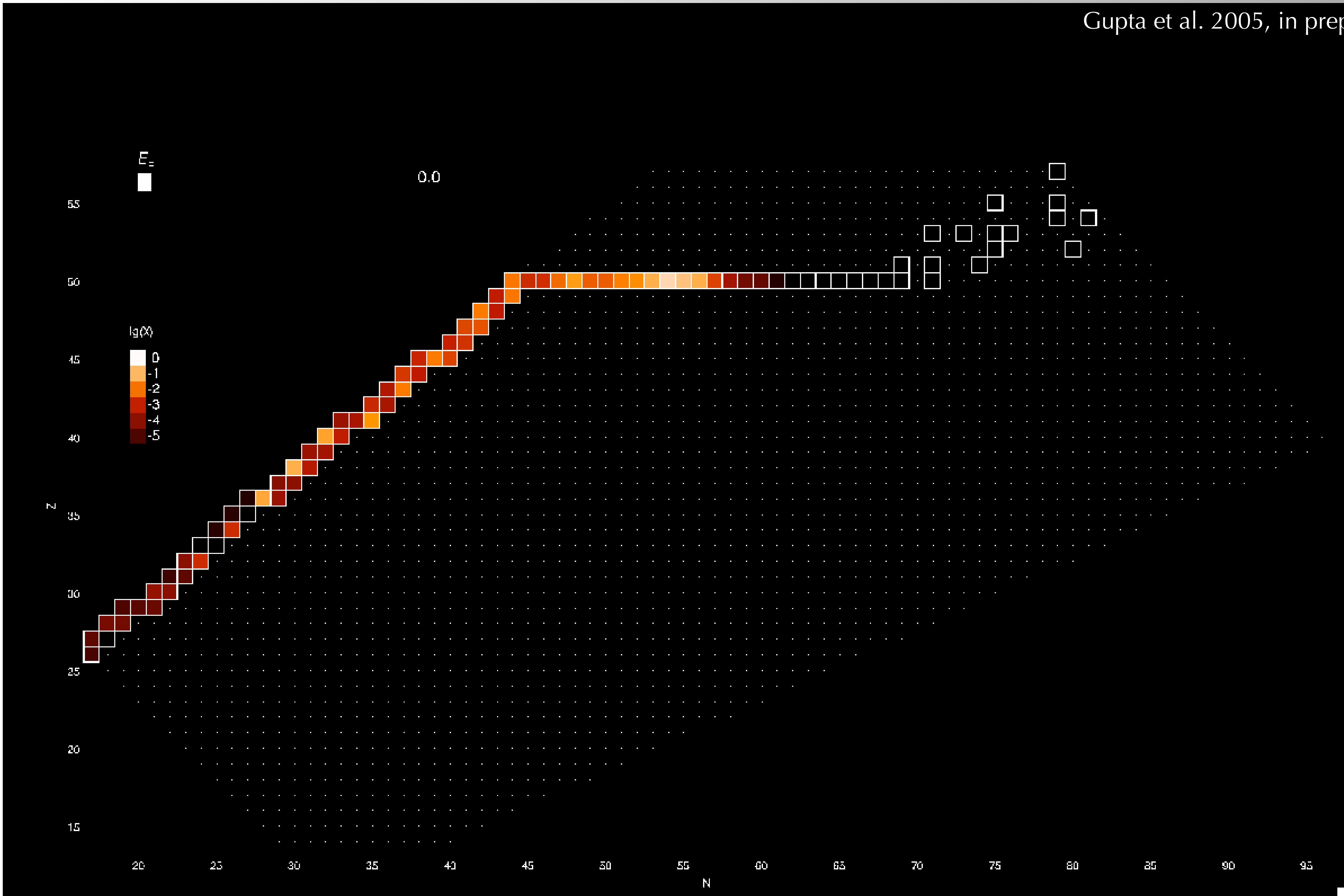
Electron captures in crust



Gupta, et al. 2005, in prep.

- Start with rp-process ashes (Schatz et al. 2004, PRL)
- log(*ft*) for excited states computed from QRPA model (P. Möller), with analytical computation of phase space (Gupta)
- E_F is incremented in steps of 0.1 MeV to 25.0 MeV
- Electron captures are evolved at constant E_F and $T(E_F)$ (Brown 2004)

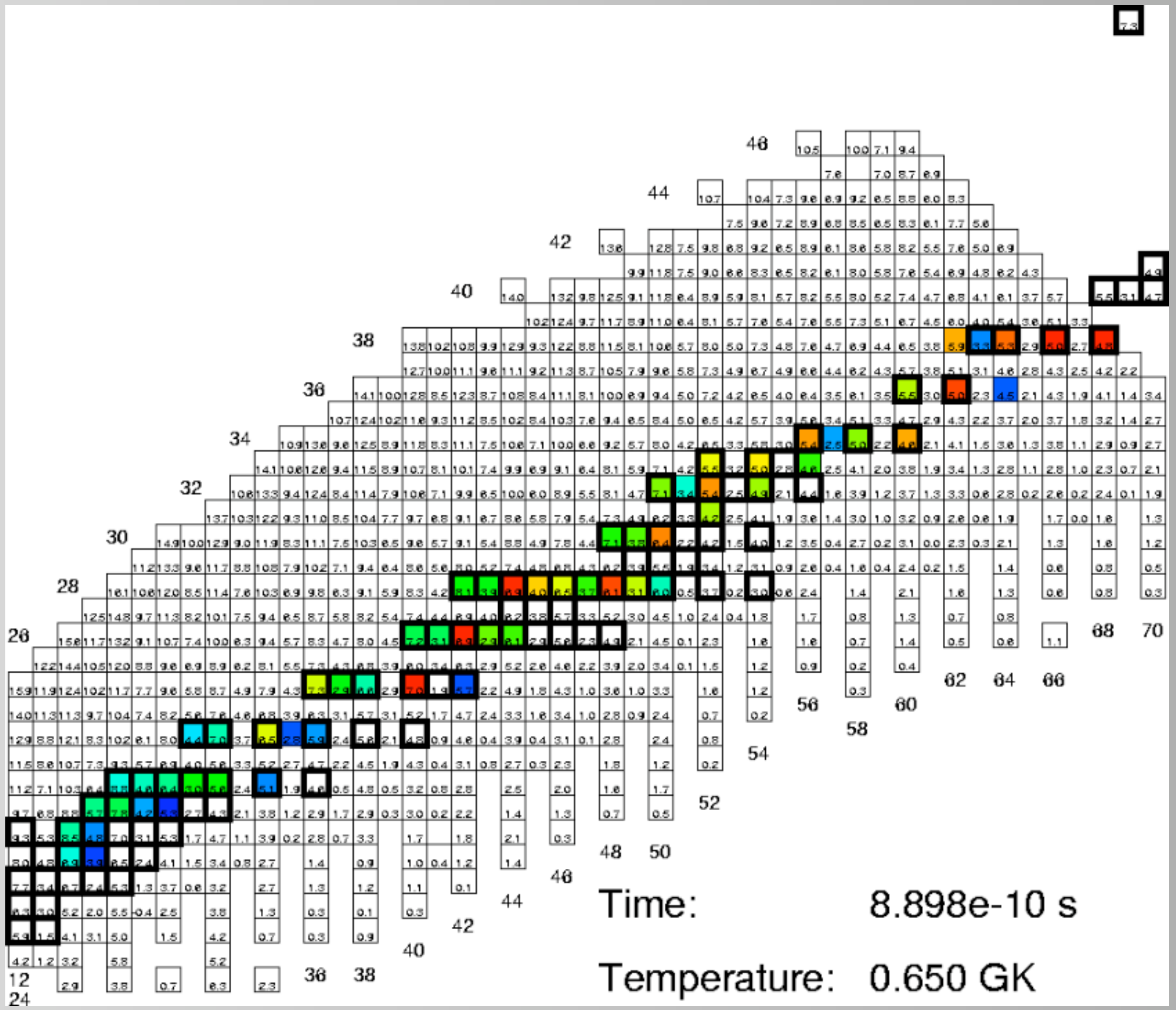
JINA project!

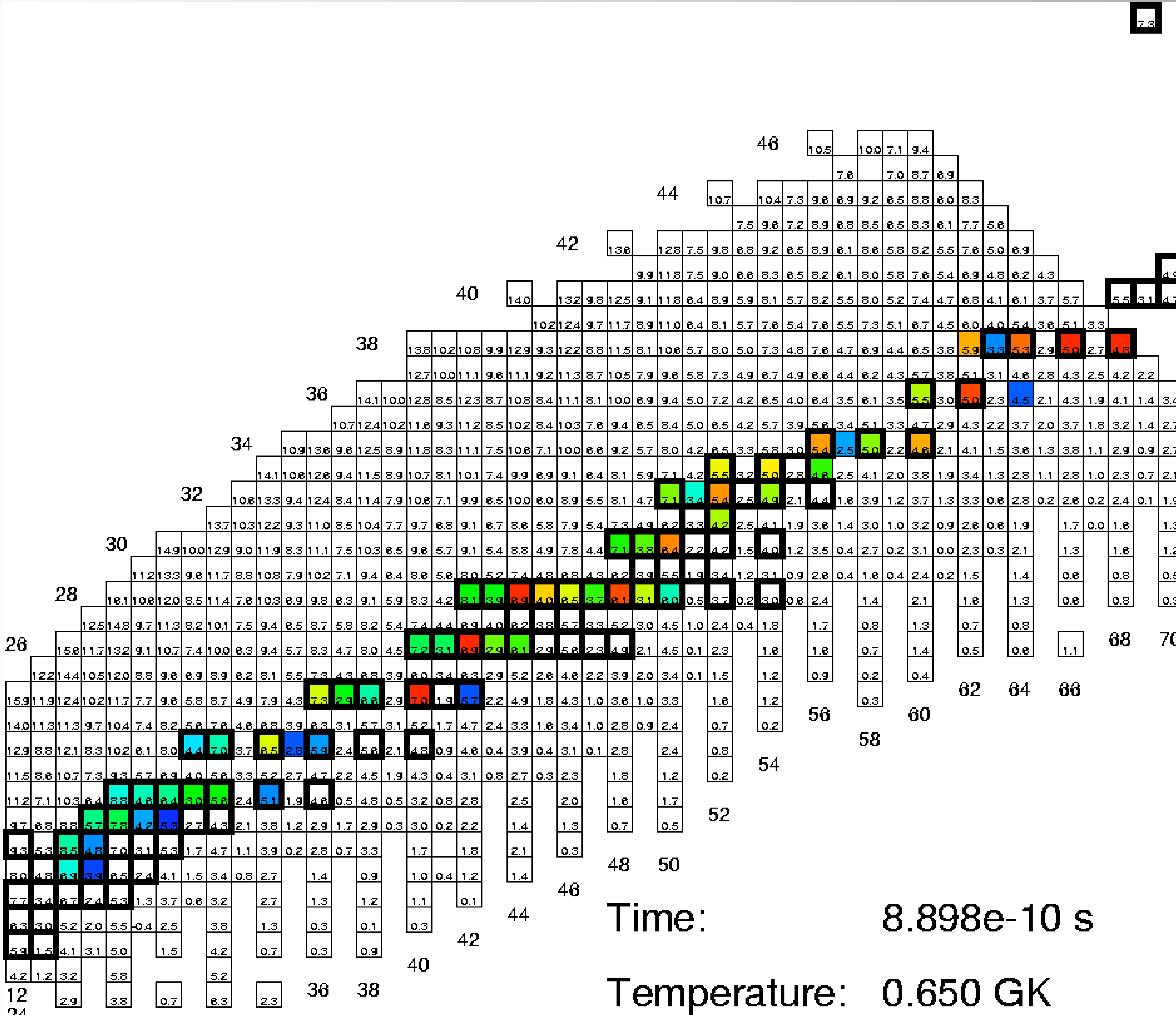

Gupta et al. 2005, in prep.
E_x
0.0
lg(X)
0
-1
-2
-3
-4
-5
Z
55
50
45
40
35
30
25
20
15
N
20
25
30
35
40
45
50
55
60
65
70
75
80
85
90
95

A new effect

Gupta et al. 2005, in preparation

- Contours of constant Q_{ec} are misaligned from those of constant S_n
  - A composition that is β-stable is not in equilibrium with respect to (γ,n)–(n, γ) reactions
- At a given E_F, a sufficient $k_B T$ will trigger (γ,n),(n,γ) reactions
- $Y_n \approx 10^{-5}$: neutrons are non-degenerate
- Look for the following
  - T rapidly increases to ~GK within 10^{-2} s and (γ,n)–(n, γ) equilibrium is attained
  - Further heating from pre-threshold electron captures



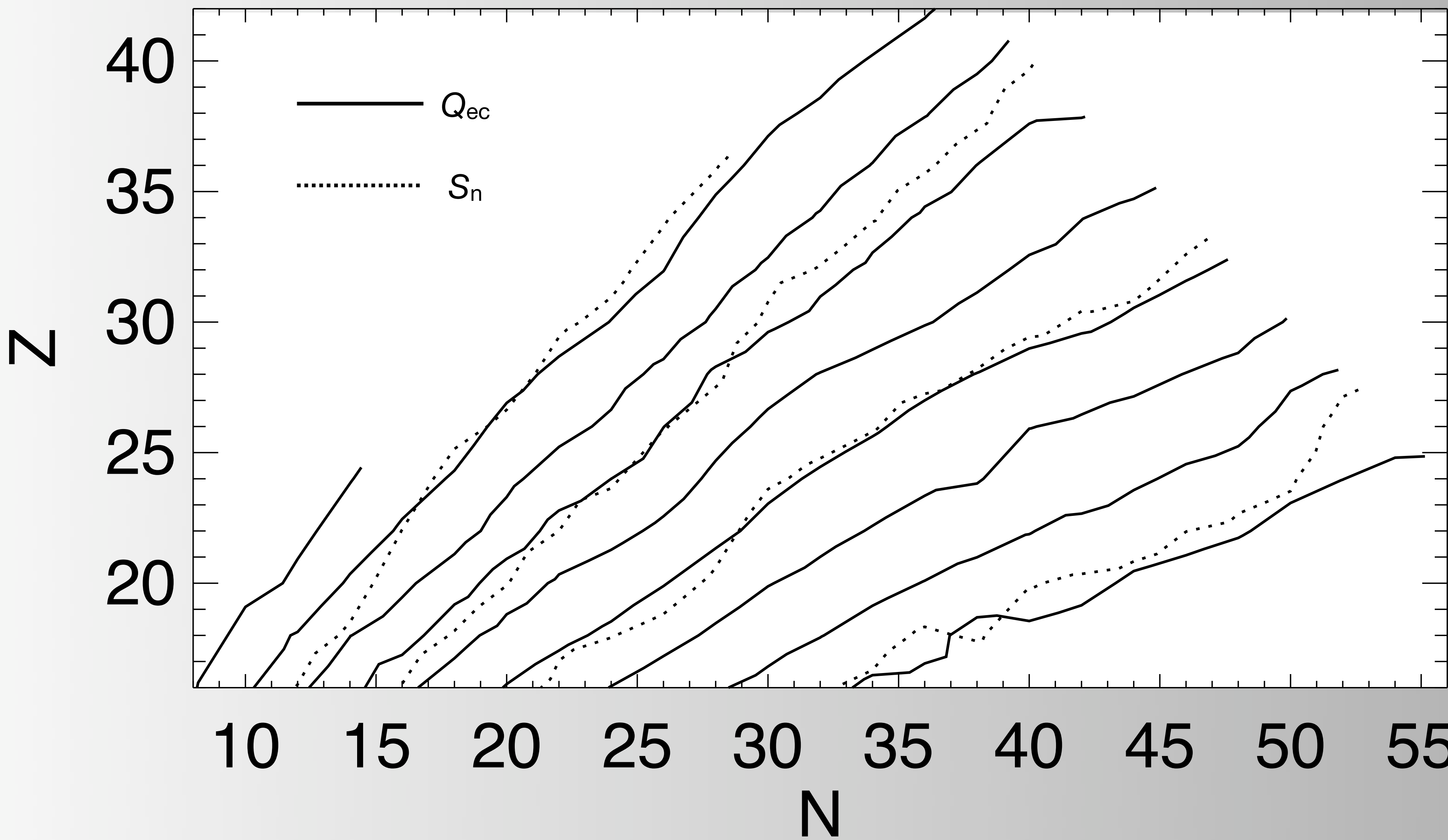

Time: 8.898e-10 s
Temperature: 0.650 GK

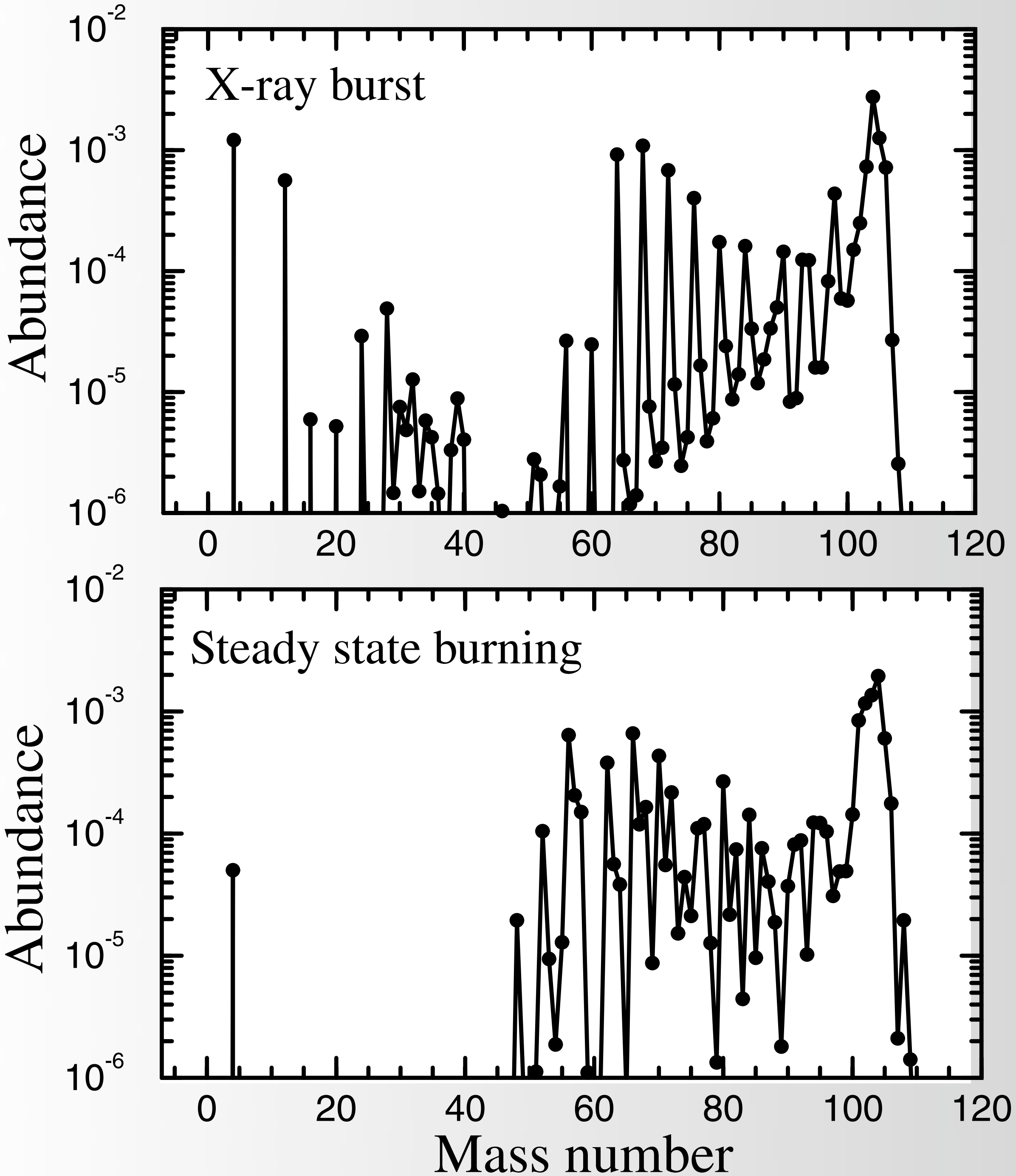
Summary

- Ignition of superburst in KS 1731–260 is incompatible with observed L_q
- Misalignment of electron capture thresholds, neutron separation energies opens channels for shuffling of nuclei
- A realistic distribution of isotopes is susceptible to heating from (n,γ)–(γ,n). Unsafe at any temperature

Stay tuned...

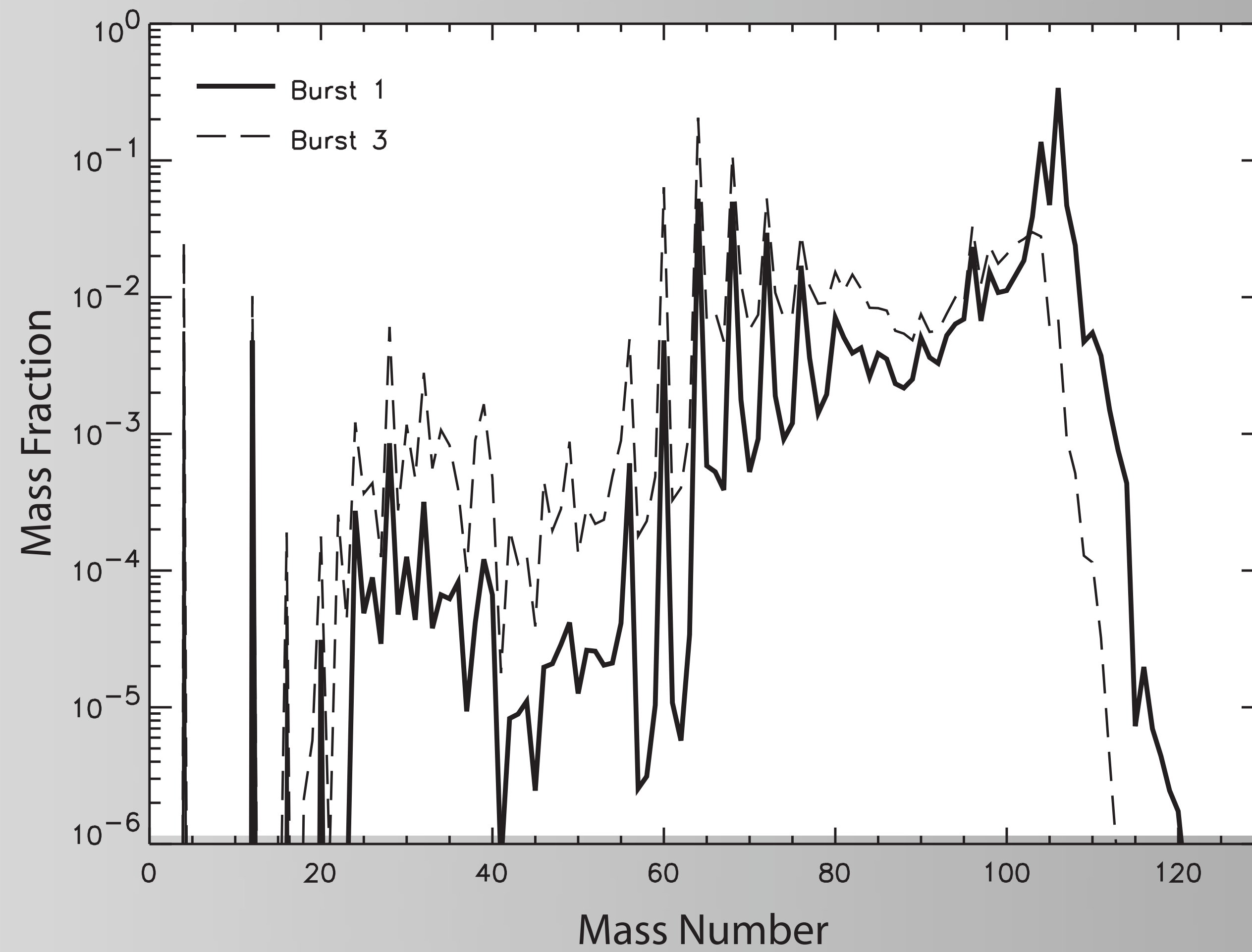
EC and (γ,n) Q-values





Schatz et al. 2001, *PRL*

Woosley et al. 2004, *ApJ*



An Amorphous Crust

- Crust unlikely to be a pure lattice
  - Different phases of nuclear matter may coexist in inner crust (Magierski & Heenan 2002)
  - Fluctuations in composition during cooling from birth (Jones 2004)
  - Distribution of isotopes from burning of H, He
- Estimate relaxation time by setting structure factor to unity (as for a liquid)

$$\tau_{\mathrm{amp}}^{-1} \approx \frac{4\pi e^4}{p_{\mathrm{F}}^2 v_{\mathrm{F}}} \rho N_{\mathrm{A}} \Lambda \langle Z^2 \rangle$$

- Cf. estimate of Jones (2004, *PRL*)
- Neglects phonon transport: $K \sim \frac{1}{3} C s \lambda$
  - May be important in the inner crust