Long Type I X-Ray Bursts and Neutron Star Interior Physics

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Superbursts (SBs)

- A new regime of nuclear burning on accreting NSs
- 1000 x more energetic and duration of normal Type I X-ray bursts
- Otherwise look very similar, spectral softening during decay
- They directly affect the Type I bursting behavior

Initial interest – nuclear physics

carbon production in rp-process $\Rightarrow$ $\approx 10\%$ ^{12}C
$\approx 90\%$ heavy

Cumming & Bildsten (2001) Strohmayer & Brown (2002) showed that such a mixture would ignite unstably to give a burst with roughly the right properties

But in fact, Brown (2004) Cooper & Narayan (2005) showed that ignition is much more sensitive to the interior thermal properties

a new way to study NS interiors
complementary to isolated cooling NSs and accreting NSs in quiescence

This talk

What are the ignition conditions for SBs?

What does that tell us about interior properties?

We find that to get ignition at the shallow depths inferred from SB properties, need to adjust parameters so that as much heat flux as possible comes out.

Any kind of efficient neutrino emission (eg. from neutron Cooper pairing in the crust) makes it difficult to reproduce observed ignition conditions.

Superburst Energetics

Observed energy is $\approx 10^{42}$ erg

$/ \; 10^{18}$ erg/g $\Rightarrow$ $\boxed{10^{24} \text{ g of fuel}}$

Recurrence time estimates 0.5 – 4 years

(Wijnands 2001; in't Zand 2003)

Accretion rates $\dfrac{L_X}{GM/R} \approx (1\text{-}3) \times 10^{17}$ g/s

$\approx (0.1\text{-}0.3)\, \dot{M}_{Edd}$

$\Rightarrow \Delta M = \dot{M} \Delta t \approx \boxed{(0.2 - 3.6) \times 10^{25} \text{ g}}$

column depth $y = \dfrac{\Delta M}{4\pi R^2} \approx (0.2 - 3.6) \times 10^{12}$ g/cm^2

energy release $\dfrac{10^{42} \text{ ergs}}{\Delta M} \approx (0.3 - 5.0) \times 10^{17}$ erg/g

Cooling models for SB lightcurves

Cumming & Macbeth (2004)

assume the fuel burns very rapidly $\int c_p \, dT = E_{nuc}$

$T_i \simeq (3-8) \times 10^8 \, K \qquad T_f \simeq 4 \times 10^9 K \sqrt{E_{17}}$

then follow the cooling

$$\boxed{c_p \frac{\partial T}{\partial t} = -\frac{1}{\rho} \underline{\nabla} \cdot \underline{F} - \varepsilon_\nu} \qquad \boxed{\underline{F} = -K \underline{\nabla} T}$$

electrons + ions

$E_F \simeq 3 MeV \qquad \rho \simeq 10^8 - 10^9 \, g/cm^3$

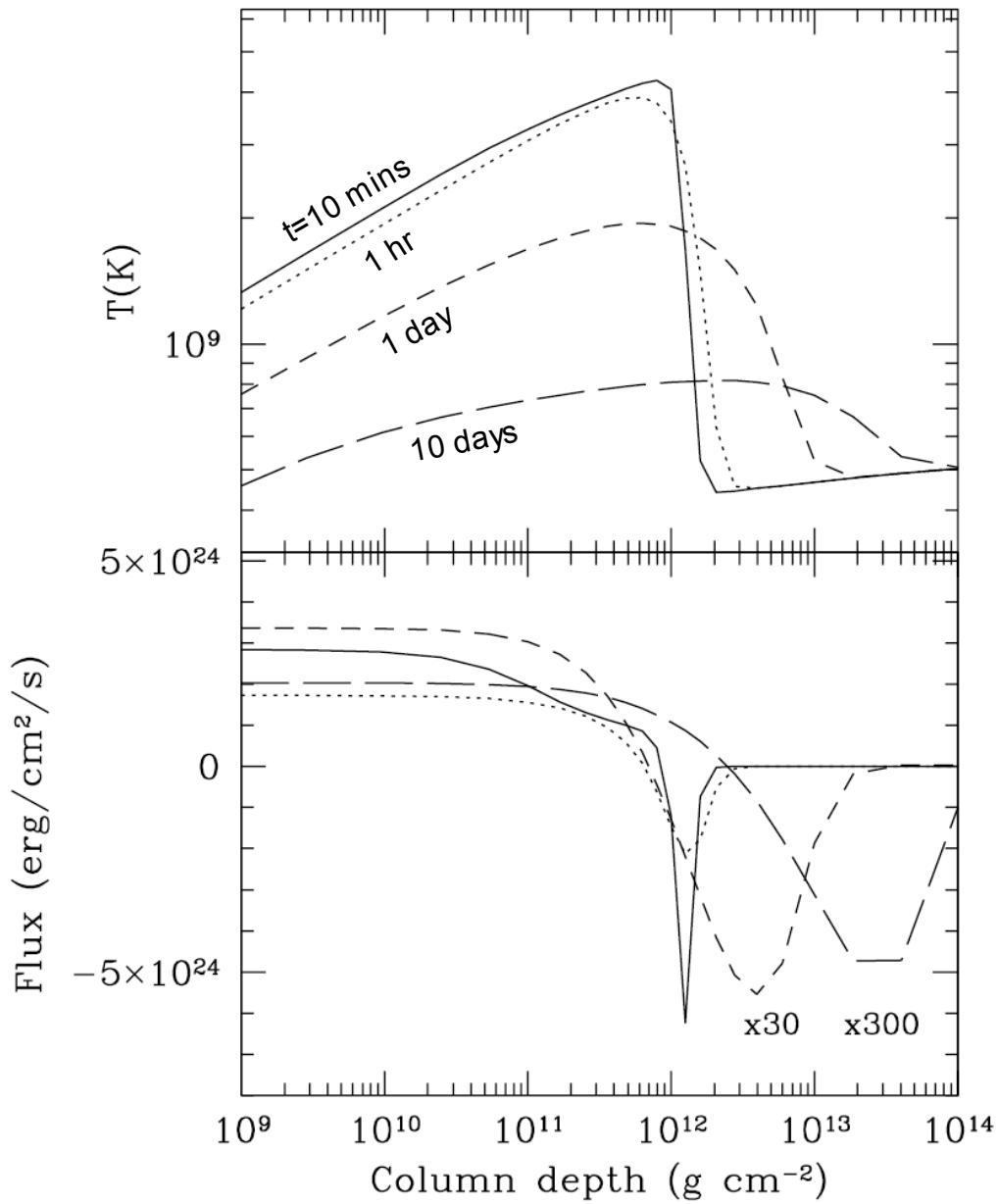
$\Gamma = \frac{Z^2 e^2}{a k_B T} \simeq 70 \left(\frac{T_8}{5}\right)^{-1}$

neutrino cooling (pairs) important for $E_{17} \gtrsim 2$

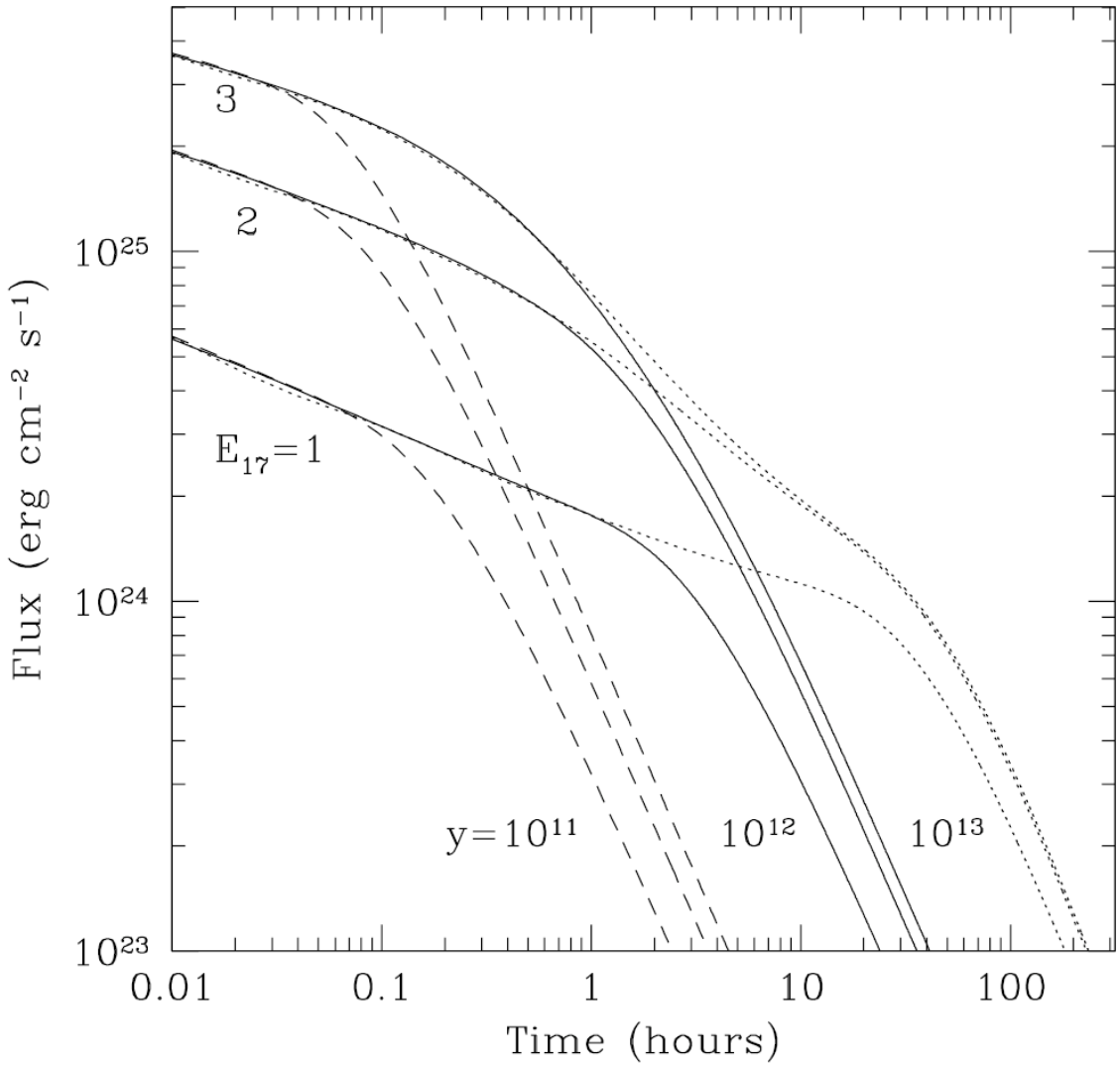
electron conduction with e-ion scattering (radiative at peak T's)

Two parameters: energy release E_{17} (10^{17} erg/g)
ignition depth y_{12} (10^{12} g/cm^2)

SEE ALSO Eichler & Cheng (1989)



Cumming & Macbeth (2004)



at late times

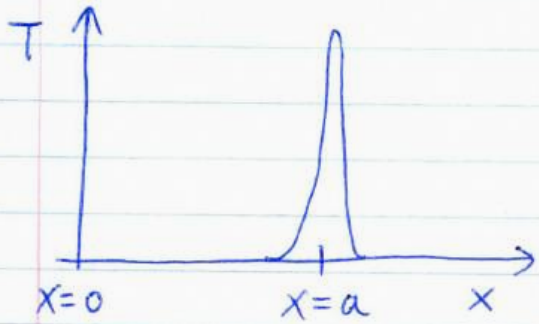
$$F \propto t^{-4/3}$$

Cumming & Macbeth (2004)

A simple model

Constant thermal conductivity
eg. a metal

① DELTA FUNCTION



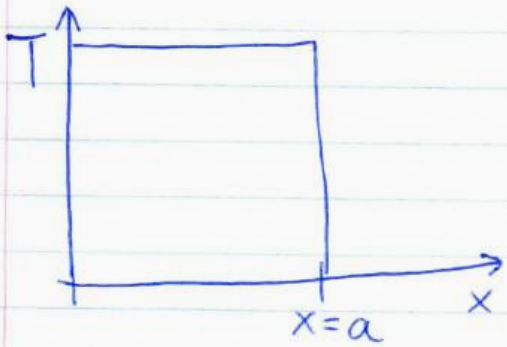
$$T(x,t) = \frac{\sinh\left(\frac{ax}{2Dt}\right)}{\sqrt{\pi D t}} \, e^{-\left(\frac{x^2+a^2}{4Dt}\right)}$$

flux at the surface $(x=0)$ is

$$\boxed{F \propto t^{-3/2} e^{\tau/t}}$$

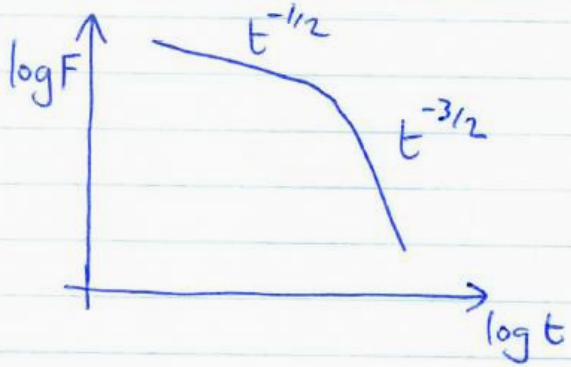
where $\tau = \frac{4a^2}{D}$ thermal time

② TOP HAT

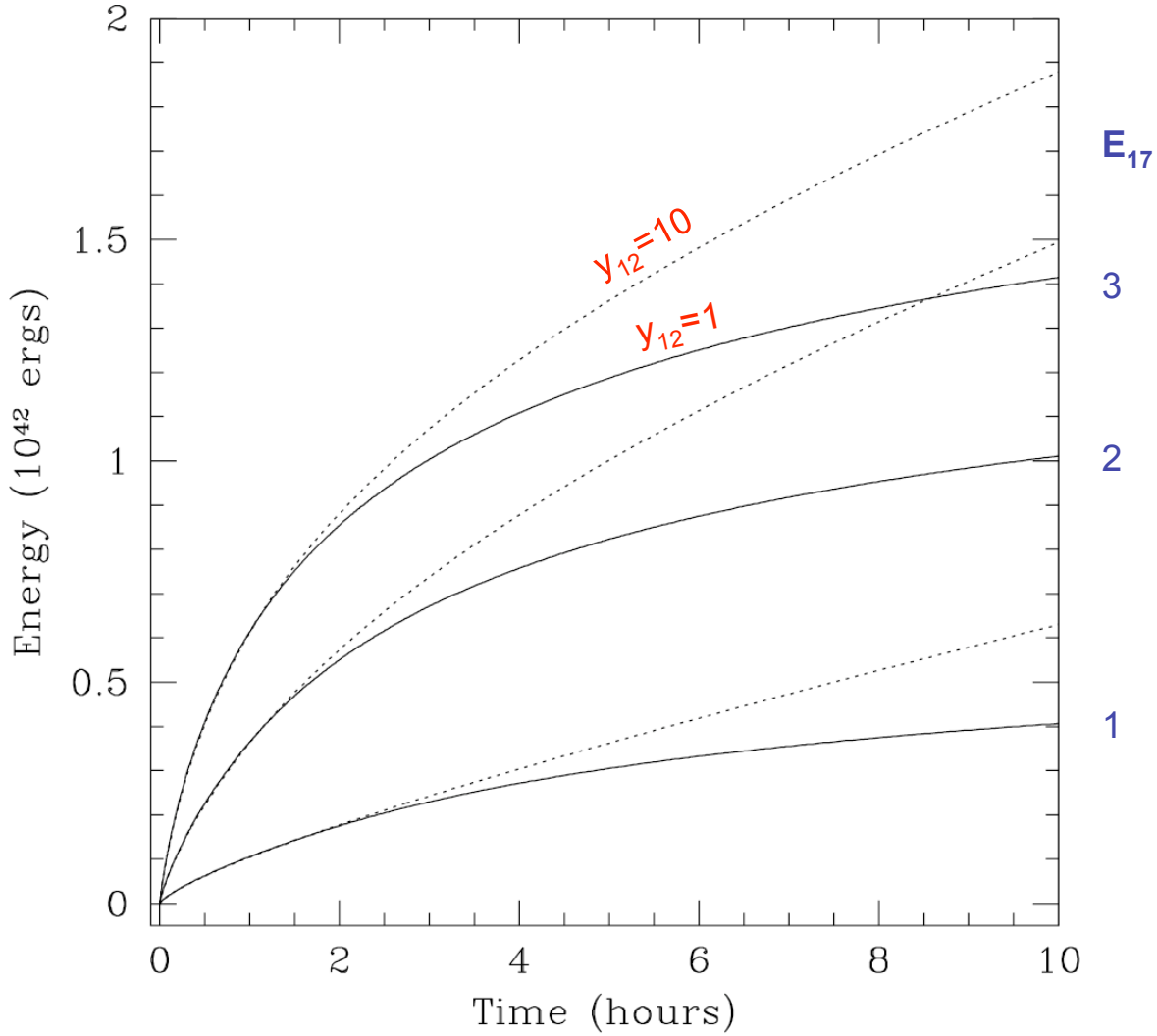


this time

$$\boxed{F \propto \left(\frac{\tau}{t}\right)^{1/2} \left[1 - e^{\tau/t}\right]}$$



Neutrino "thermostat" sets characteristic energy of 10^{42} ergs

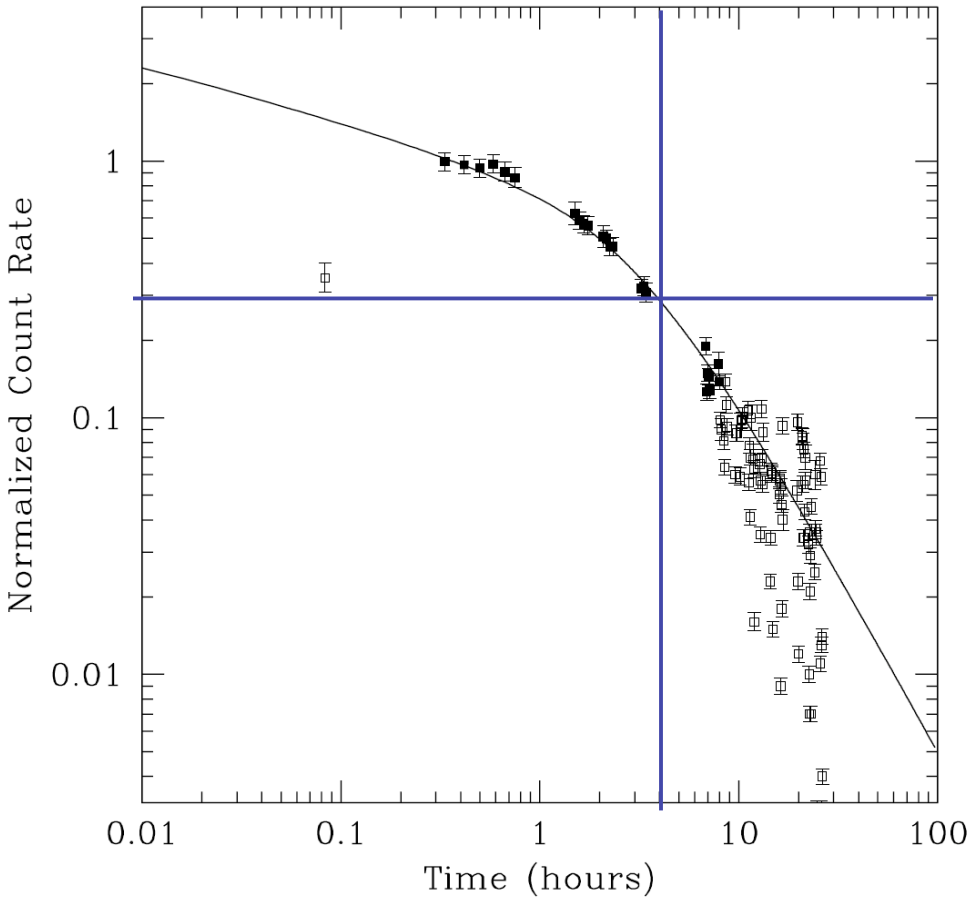


Cumming & Macbeth (2004)

Fits to SB lightcurves...

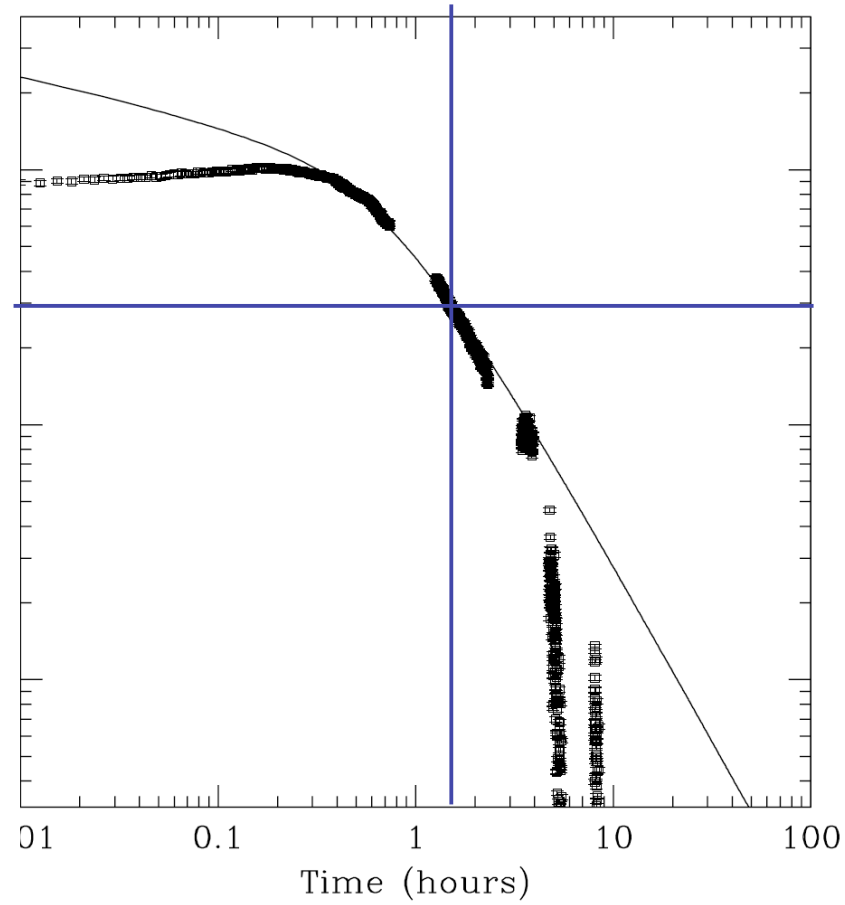
AC, Macbeth, in 't Zand, Page (2005)

KS 1731-254 (BeppoSAX/WFC)



y_{12}=1.3

4U 1636-54 (RXTE/PCA)



y_{12}=0.48

Fits to SB lightcurves

E_{17}=2 y_{12}=0.5-3

Source	f_{peak}[a]	d/R[b]	E_{17}[c]	y_{12}[c]
4U 1254-690	0.22	13	1.5	2.7
4U 1735-444	1.5	8	2.6	1.3
KS 1731-260	2.4	4.5	1.9	1.0
GX 17+2 burst 2	0.8	8	1.8	0.64
Ser X-1	1.9	6	2.3	0.55
4U 1636-54	2.4	5.9	2.6	0.48

Ignition Models

- steady state $\quad \frac{dF}{dy} = -\varepsilon \qquad \frac{dT}{dy} = \frac{F}{\frac{4acT^3}{3K}}$

- criterion for ignition

$$\frac{d\varepsilon_{heat}}{dT} > \frac{d\varepsilon_{cool}}{dT}$$

Fushiki & Lamb (1987)

sets thickness of the fuel layer

- physics input

  neutrino cooling in crust and core

  crust composition $\quad {}^{56}Fe$ or ${}^{104}Pd$

  $Q = 100$ or amorphous

- fixed core EOS $\quad \rho(r) = \rho_c \left(1 - \left(\frac{r}{R}\right)^2\right)$

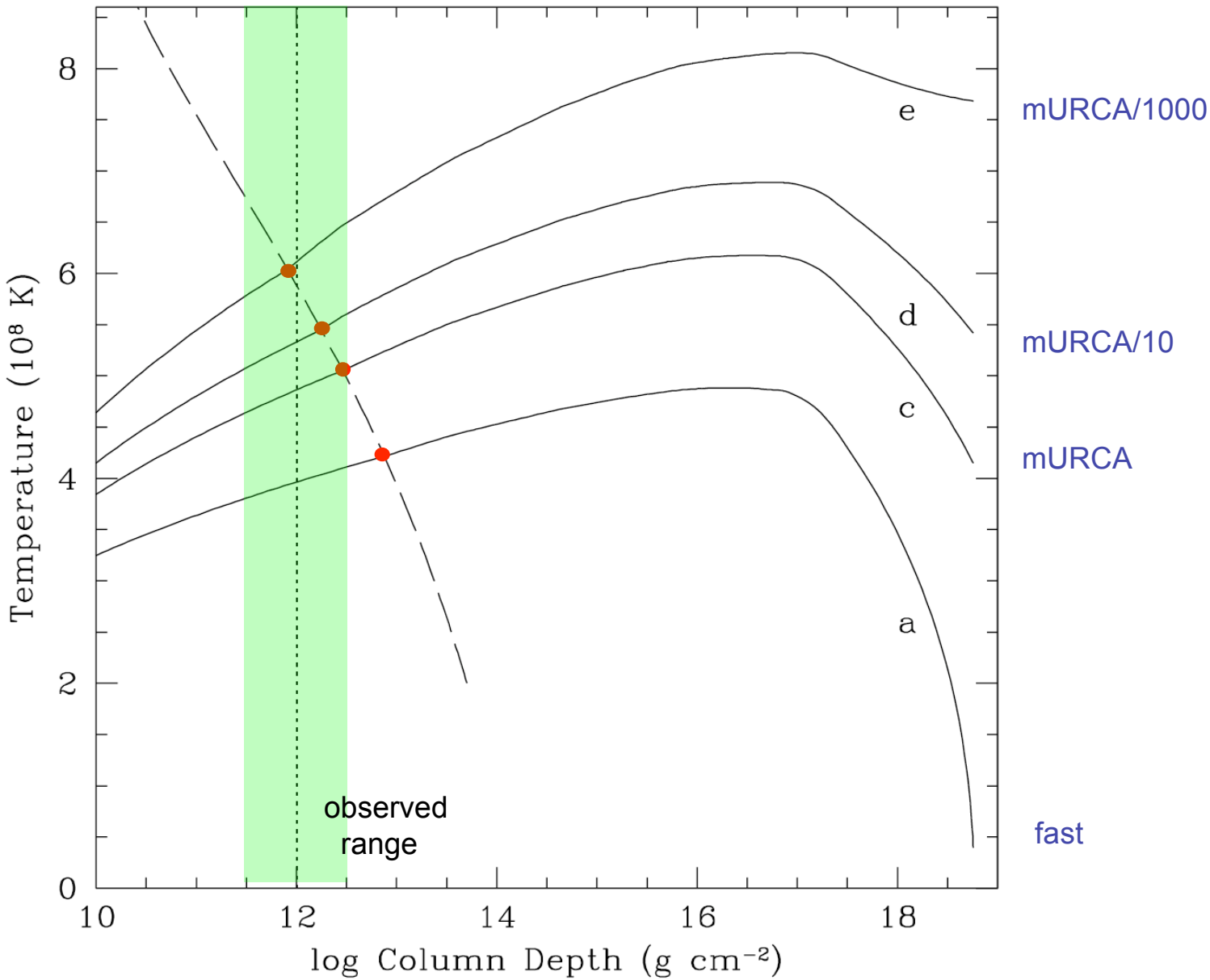
  energy deposition $\quad Q_{nuc} = 1.4$ MeV/nucleon

Label	Type[a]	Prefactor[b] (erg cm^{-3} s^{-1})	Comment
a	fast	10^{26}	fast cooling
b	slow	3×10^{21}	enhanced
c	slow	10^{20}	mURCA
d	slow	10^{19}	nn Bremsstrahlung
e	slow	10^{17}	suppressed

[a]Fast and slow cooling laws are of the form $Q_\nu = Q_f(T_c/10^9\ \mathrm{K})^6$ and $Q_\nu = Q_s(T_c/10^9\ \mathrm{K})^8$ respectively.

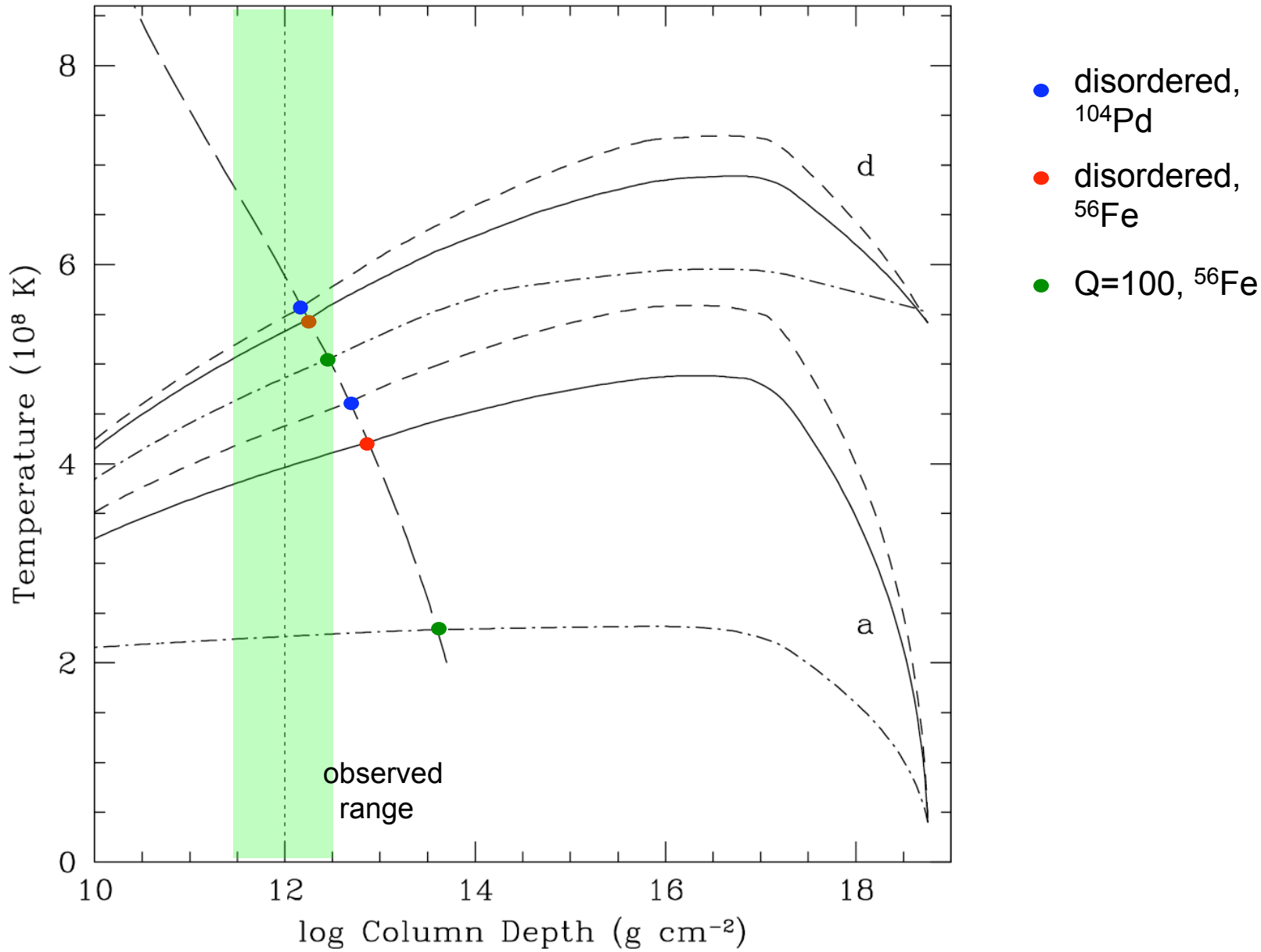
[b]Either Q_s or Q_f for slow or fast cooling, respectively.

1. CORE NEUTRINO EMISSIVITY

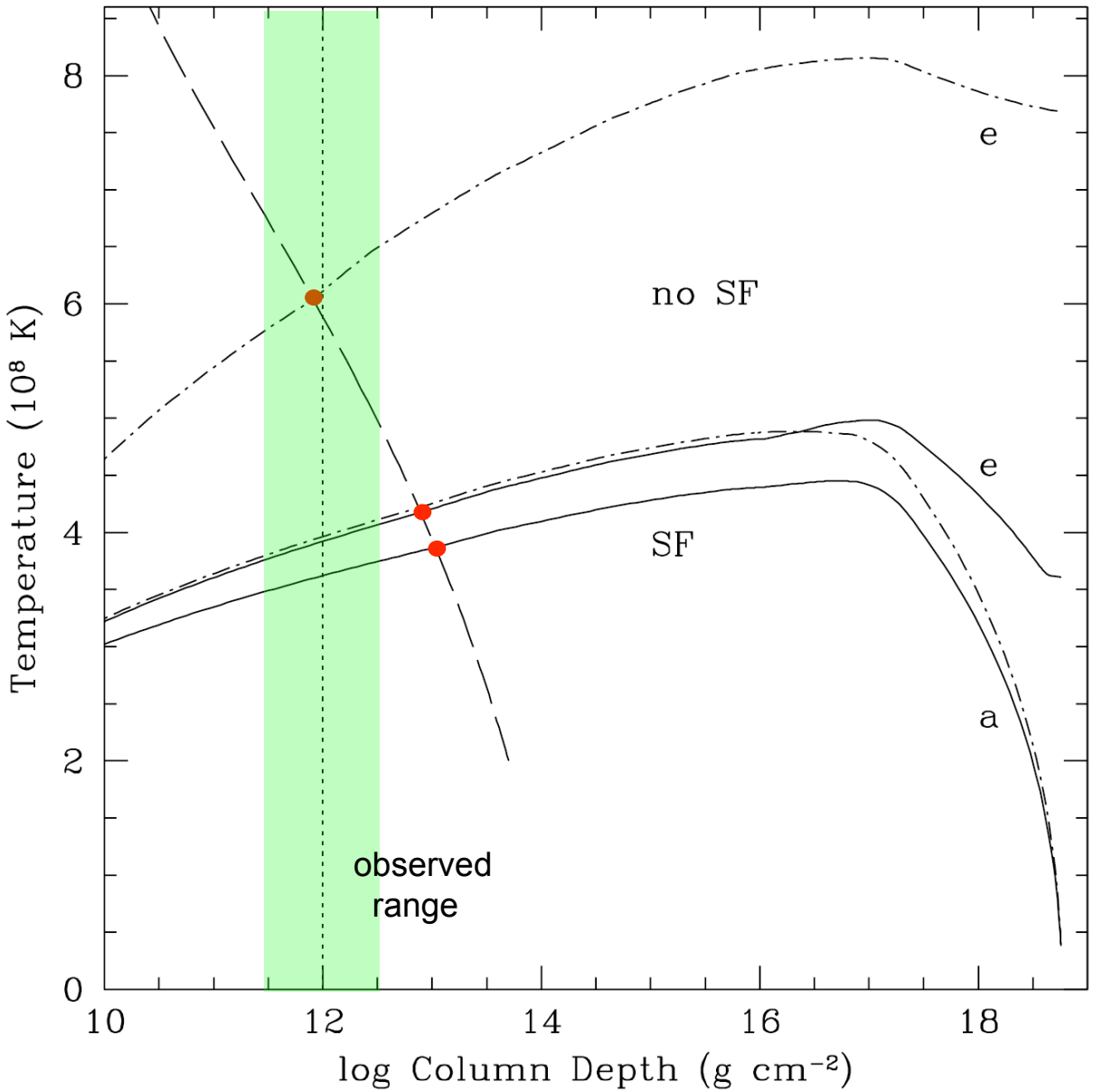


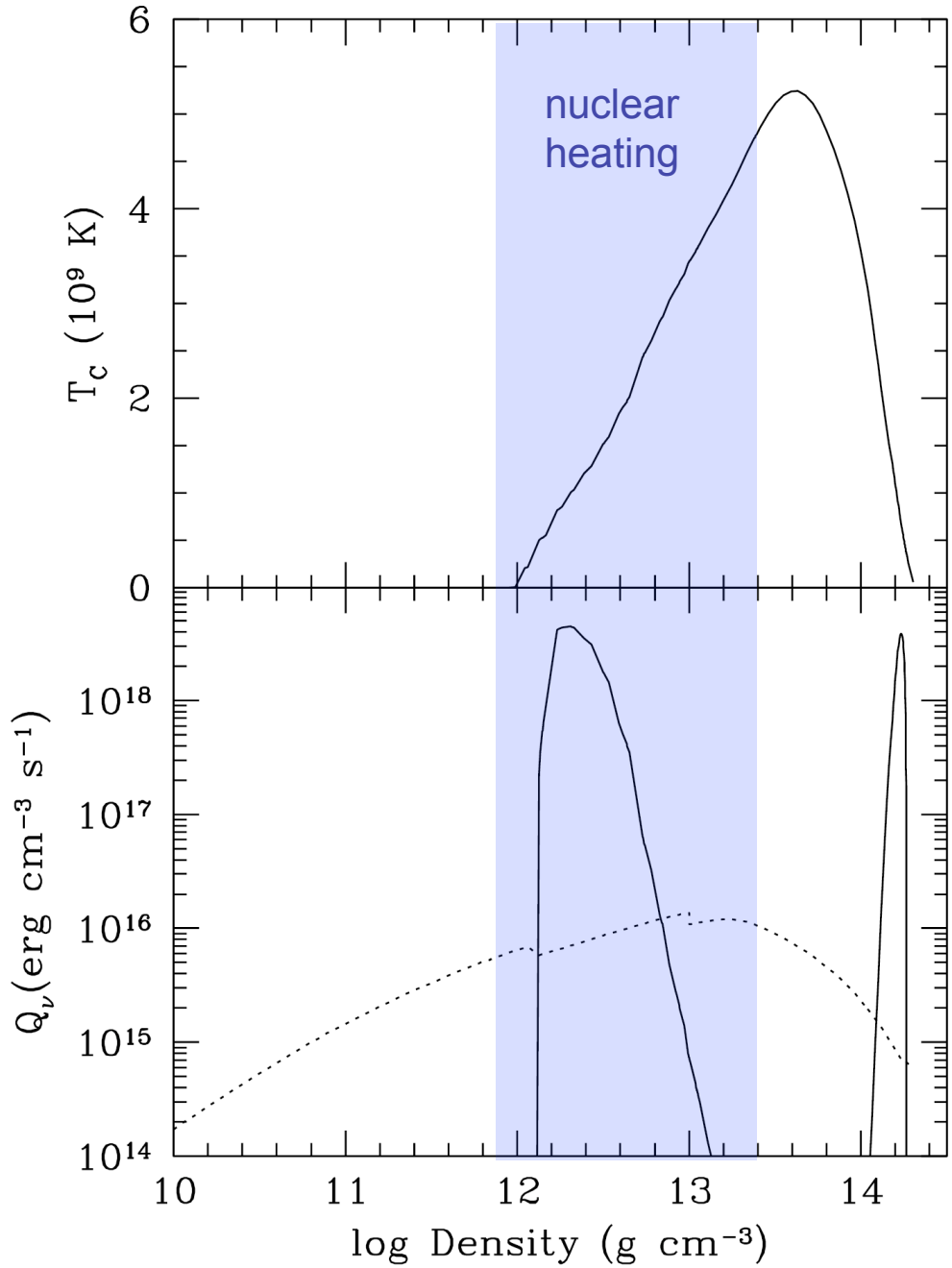
Cumming et al. (2005)

2. CRUST COMPOSITION



3. COOPER PAIR NEUTRINOS IN CRUST




nuclear
heating
T_c (10^9 K)
0
2
4
6
Q_ν(erg cm^{-3} s^{-1})
10^{14}
10^{15}
10^{16}
10^{17}
10^{18}
10
11
12
13
14
log Density (g cm^{-3})

Limiting temperature of the crust from neutrino cooling

① Bremsstrahlung

$$Q_\nu \simeq 0.3 \text{ erg/g/s } T_8^6 \, L \, (1-Y_n) \frac{Z^2}{A}$$

$$\Rightarrow L_\nu \approx 3 \times 10^{30} \text{ erg/s } T_8^6$$

set equal to the heating rate $L_{crust} \simeq 10^{36} \text{ erg/s} \left(\frac{\dot{m}}{\dot{m}_{Edd}}\right)$

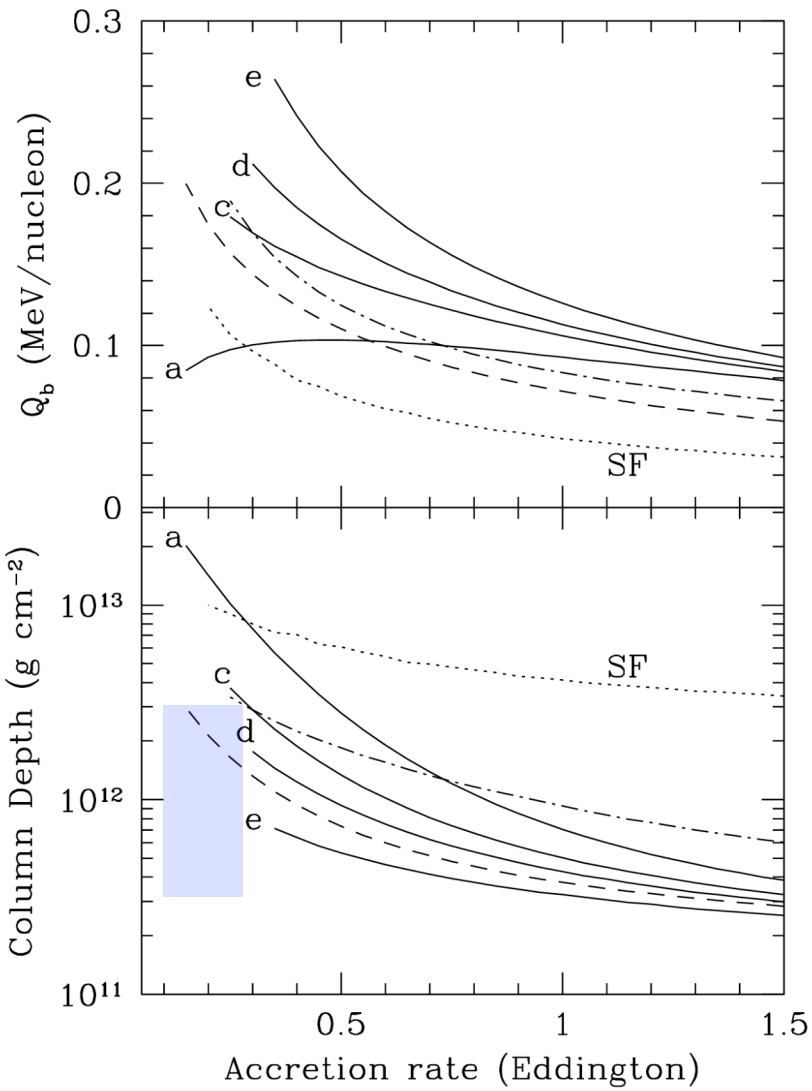
$$\Rightarrow \boxed{T_8 \approx 8 \left(\frac{\dot{m}}{\dot{m}_{Edd}}\right)^{1/6}}$$

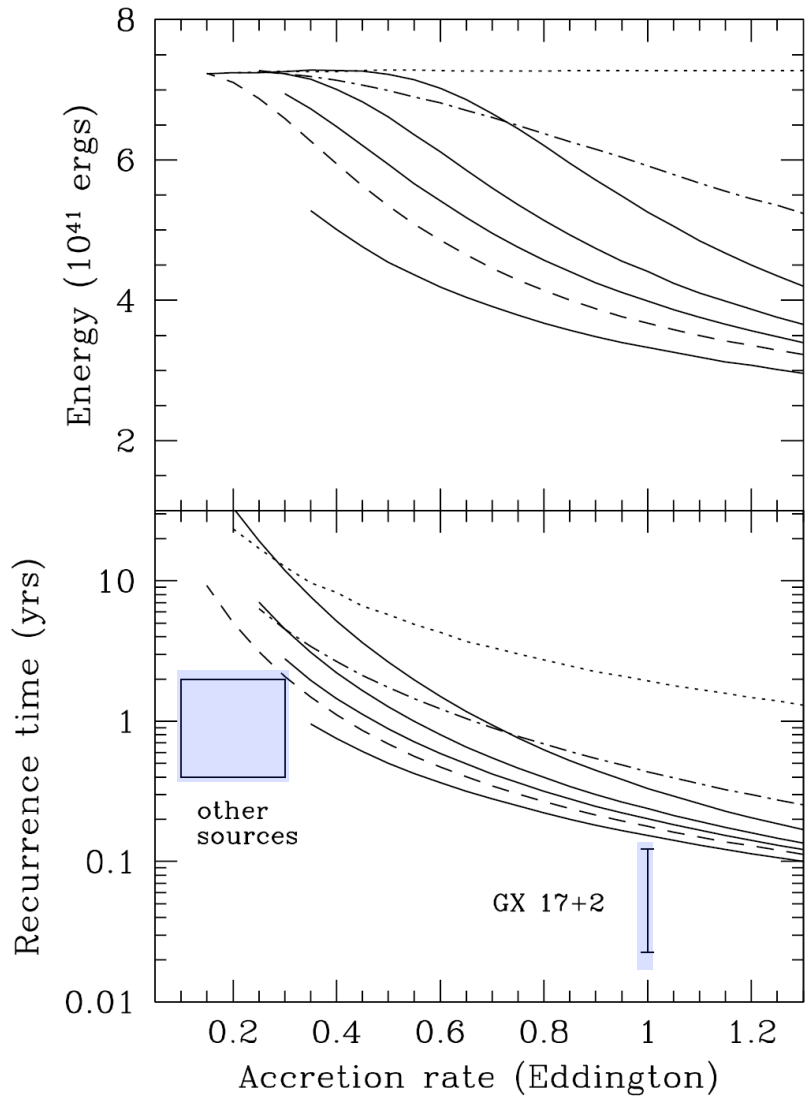
② COOPER PAIRS

$$Q_\nu \simeq 7 \times 10^{20} \text{ erg/cm}^3\text{/s } T_8^7 \left(\frac{k_F}{\text{fm}^{-1}}\right)$$

$$\Rightarrow L_\nu \approx 3 \times 10^{31} \text{ erg/s } T_8^7$$

$$\Rightarrow \boxed{T_8 \approx 4.4 \left(\frac{\dot{m}}{\dot{m}_{Edd}}\right)^{1/7}}$$


0.3
0.2
0.1
0
Q_b (MeV/nucleon)
e
d
c
a
SF
a
c
d
e
SF
10^{13}
10^{12}
10^{11}
Column Depth (g cm^{-2})
0.5
1
1.5
Accretion rate (Eddington)


8
6
4
2
Energy (10^{41} ergs)
10
1
0.1
0.01
Recurrence time (yrs)
other
sources
GX 17+2
0.2
0.4
0.6
0.8
1
1.2
Accretion rate (Eddington)

Pure Helium Accretion

Ultracompact binaries (orbital periods < 80 mins)

	4U 1820-30	2S 0918-549
ignition depth	$\simeq 10^8$ g/cm^2	$\simeq 10^{10}$ g/cm^2
$\dot{M}$	$\simeq 0.3\ \dot{M}_{Edd}$	$\simeq 0.01\ \dot{M}_{Edd}$

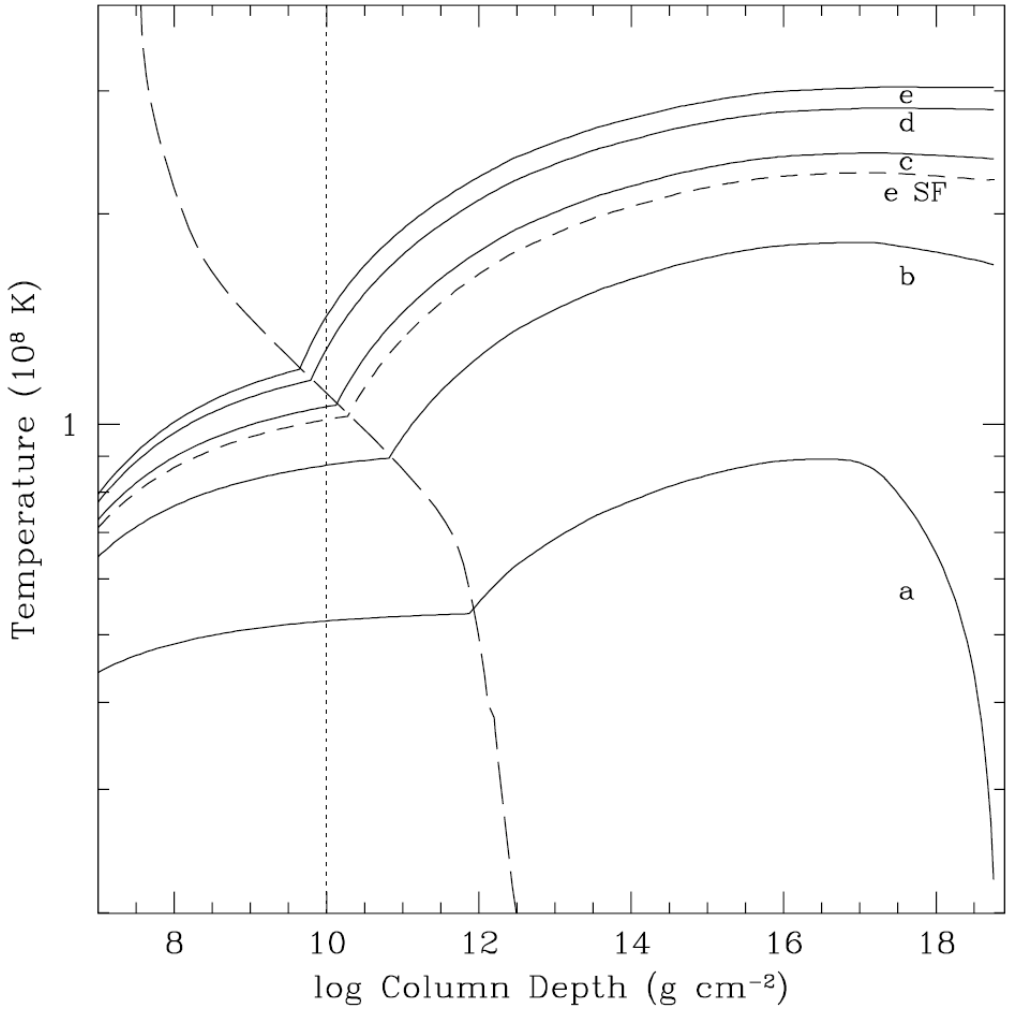
in't Zand, AC, et al. (2005) 2S0918-549

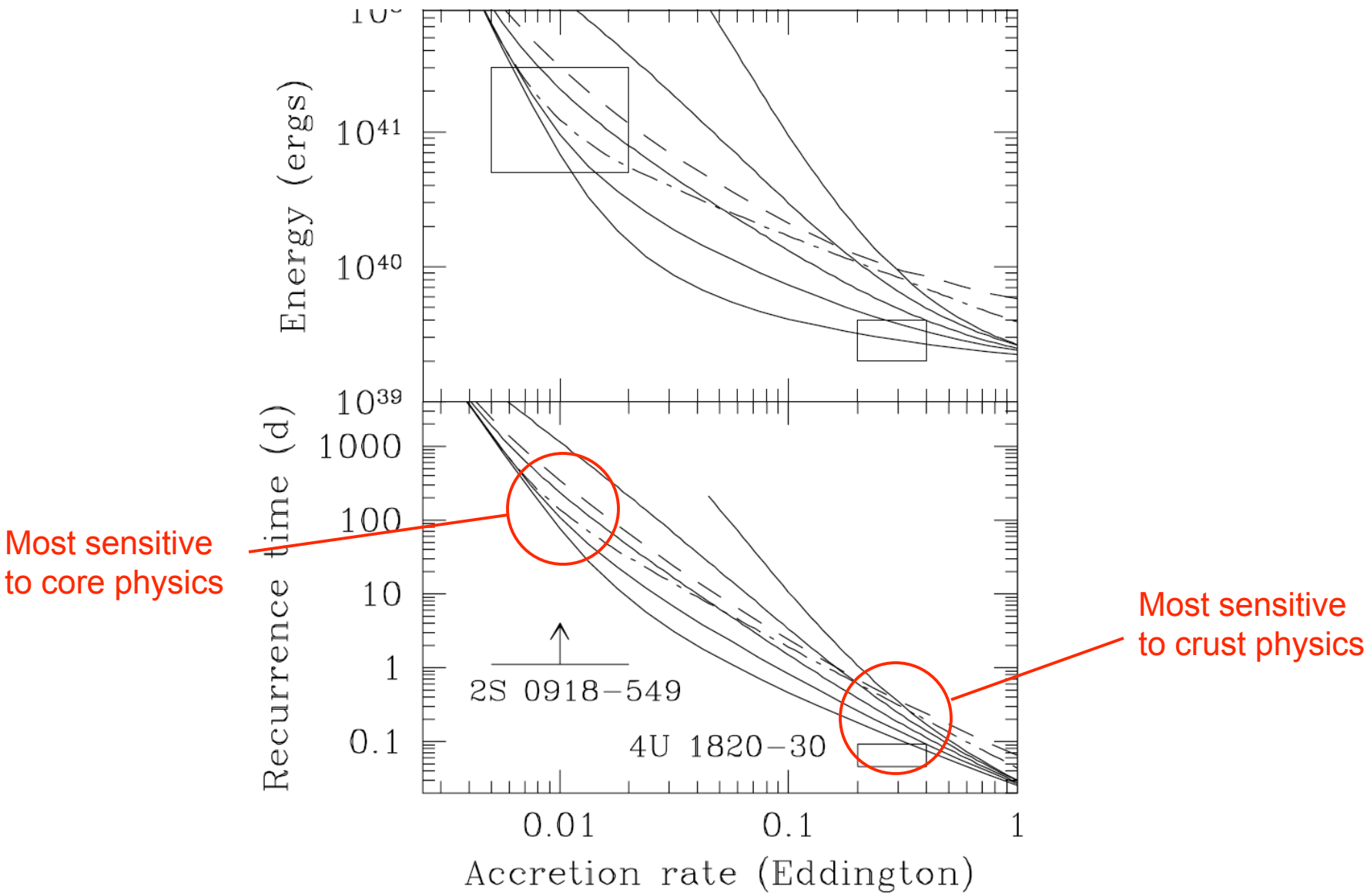
long burst with duration 40 minutes

energy $\simeq 10^{41}$ ergs

Ignition of pure He at a depth $y \simeq 10^{10}$ g/cm^2 matches energetics and lightcurve

— but need most of the energy released in the crust to flow OUT!


e
d
c
e SF
b
a
1
Temperature (10^8 K)
8
10
12
14
16
18
log Column Depth (g cm^{-2})


Energy (ergs)
10^{41}
10^{40}
10^{39}
Recurrence time (d)
1000
100
10
1
0.1
2S 0918−549
4U 1820−30
0.01
0.1
1
Accretion rate (Eddington)
Most sensitive to core physics
Most sensitive to crust physics

Summary

- Ignition conditions for both superbursts (^{12}C) and "intermediate duration" bursts (^{4}He) are sensitive to the thermal state of the NS interior.

- Lightcurves usefully constrain the ignition depth and energetics

- Cooper pairing of neutrons in the crust $\Rightarrow T_{crust} \lesssim 5 \times 10^8$ K
  - gives SB ignition depths ten times larger than observed

- Solution — additional heating ?
  strange star ?

- Problem even worse for transients (we assumed steady state)