X-ray Bursts, Long Bursts, and Superbursts

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Artwork courtesy T. Piro, Caltech

DISCOVERY OF INTENSE X-RAY BURSTS FROM THE GLOBULAR CLUSTER NGC 6624

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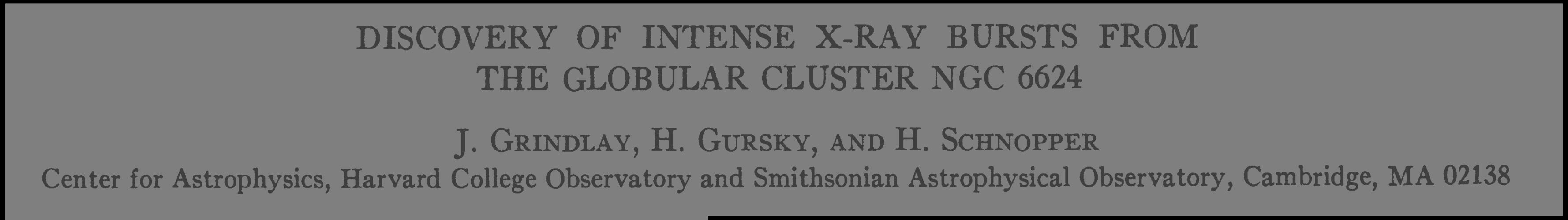
Received 1976 January 14; revised 1976 February 3



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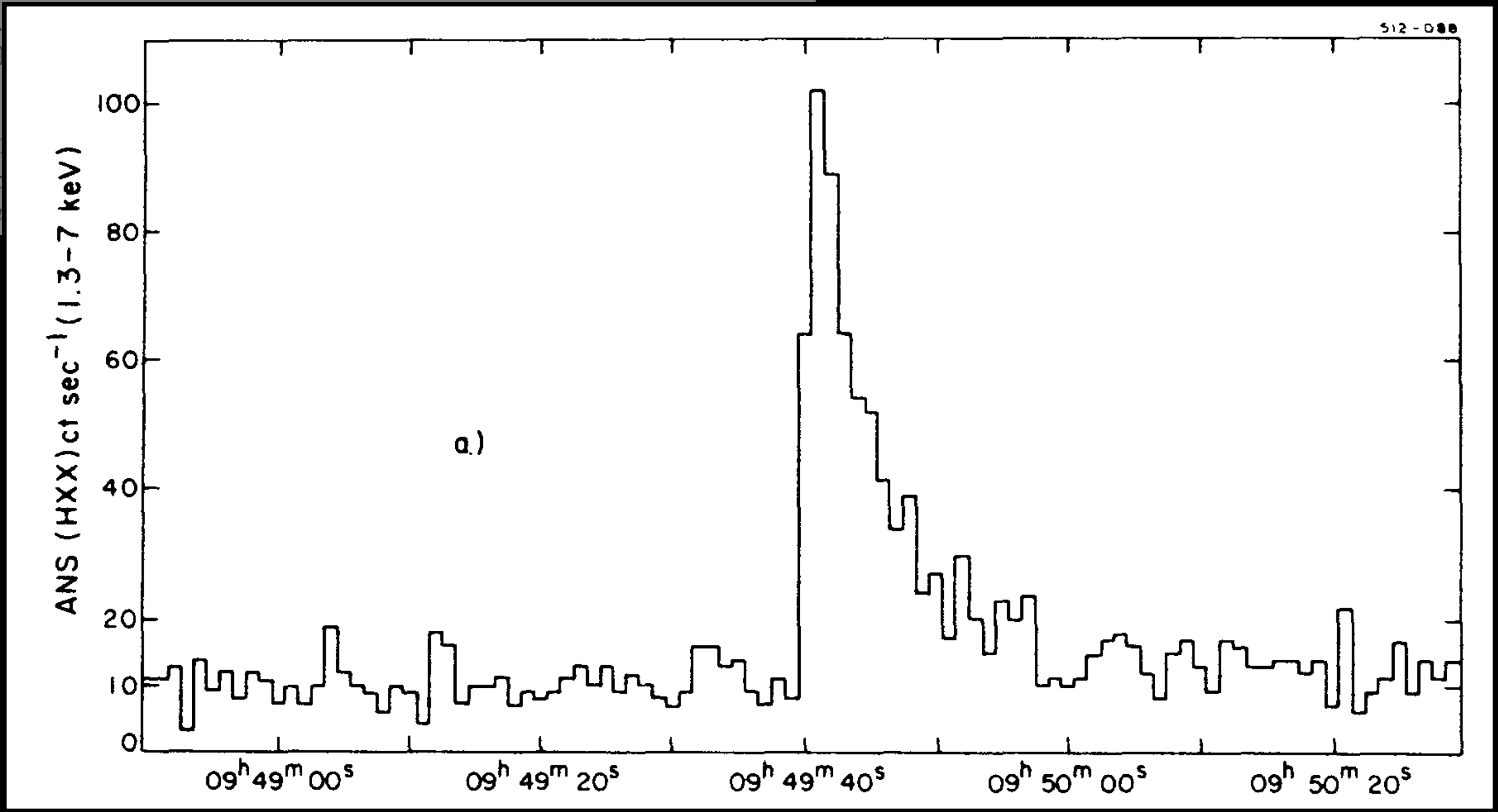
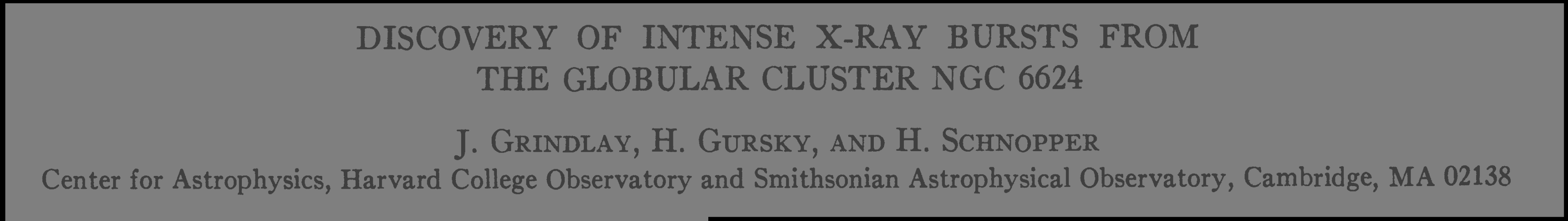


fast rise ~ 1 second

slow, roughly exponential decay ~ 10–100 s

spectral cooling in tail (but see talk by M. Linares)



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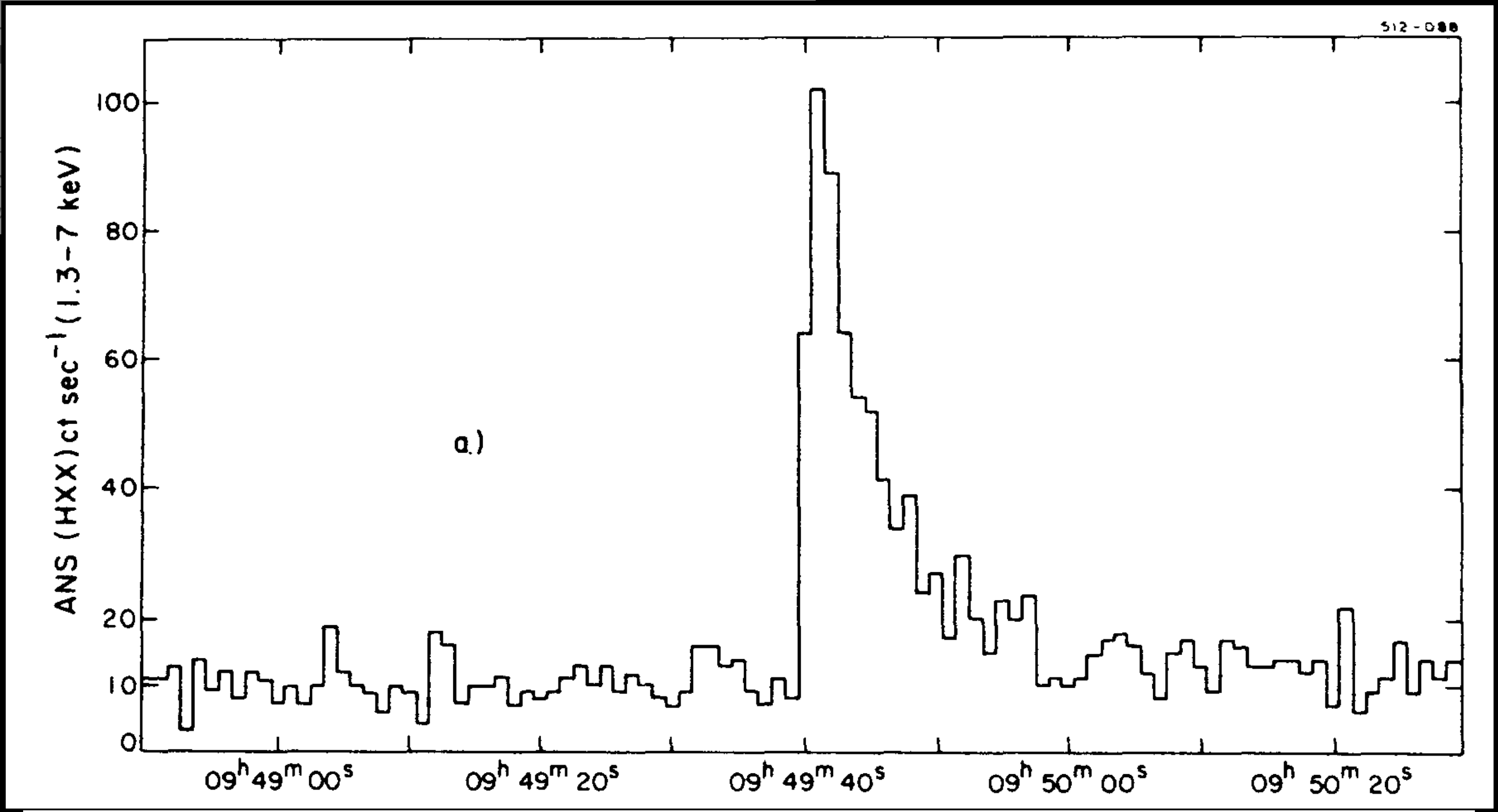
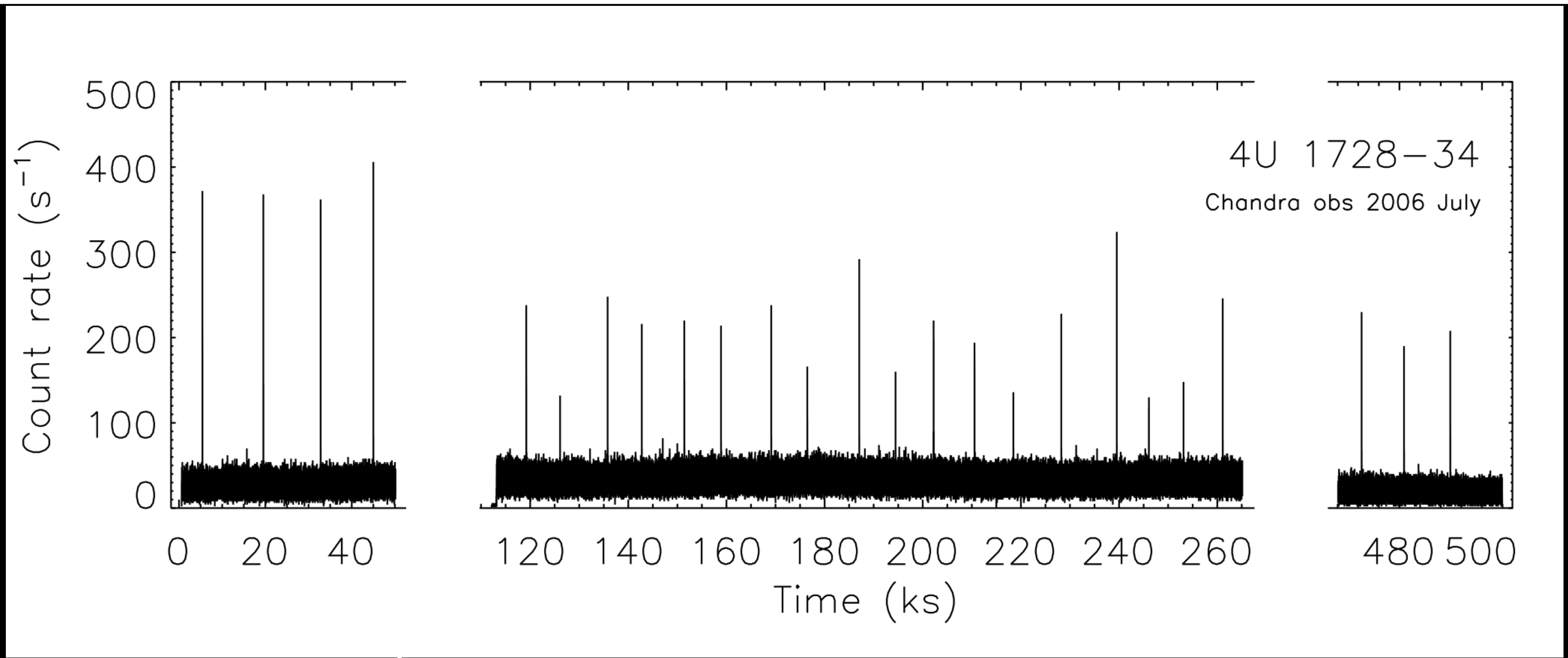
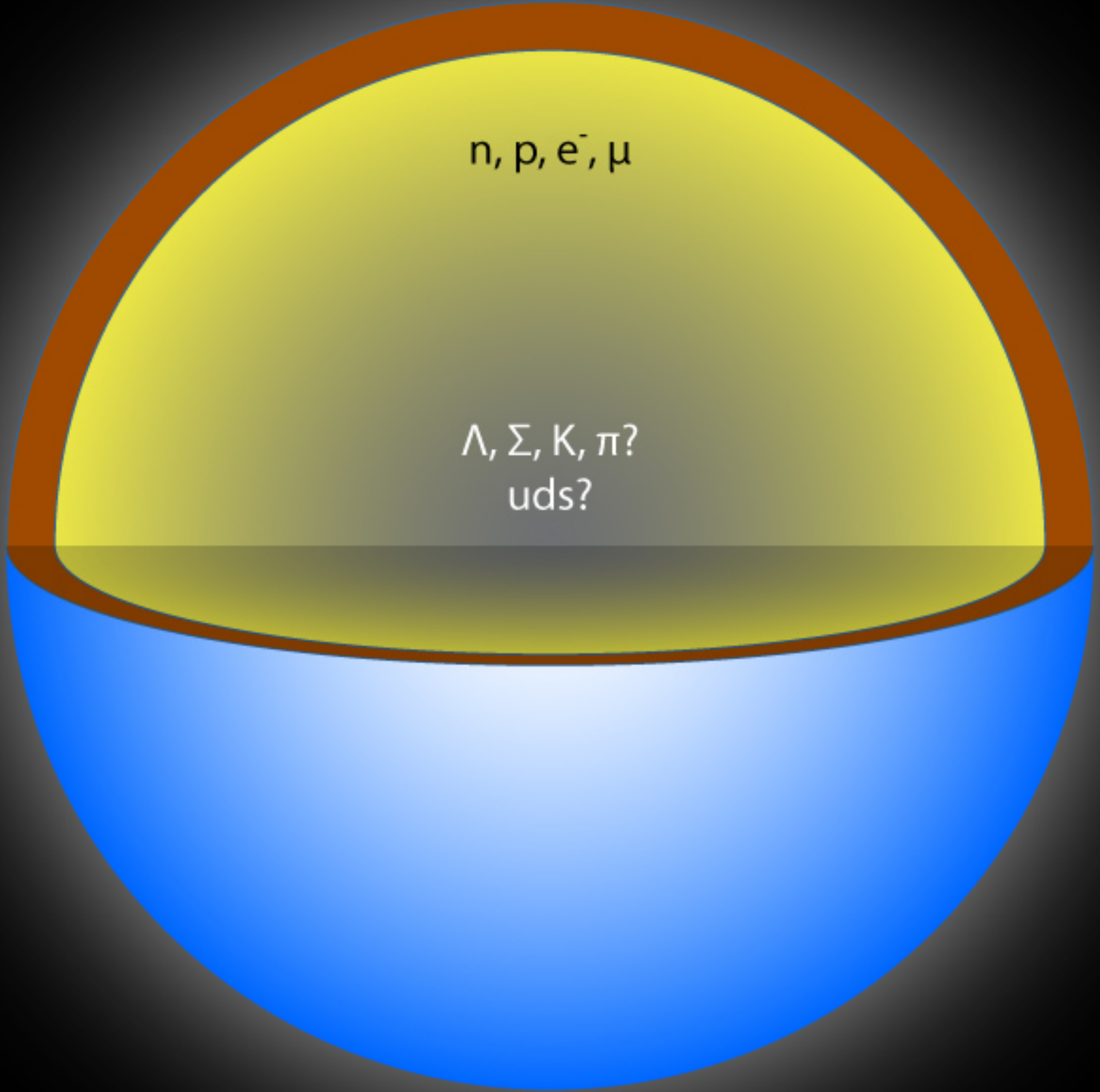
slow, roughly exponential decay ~ 10–100 s

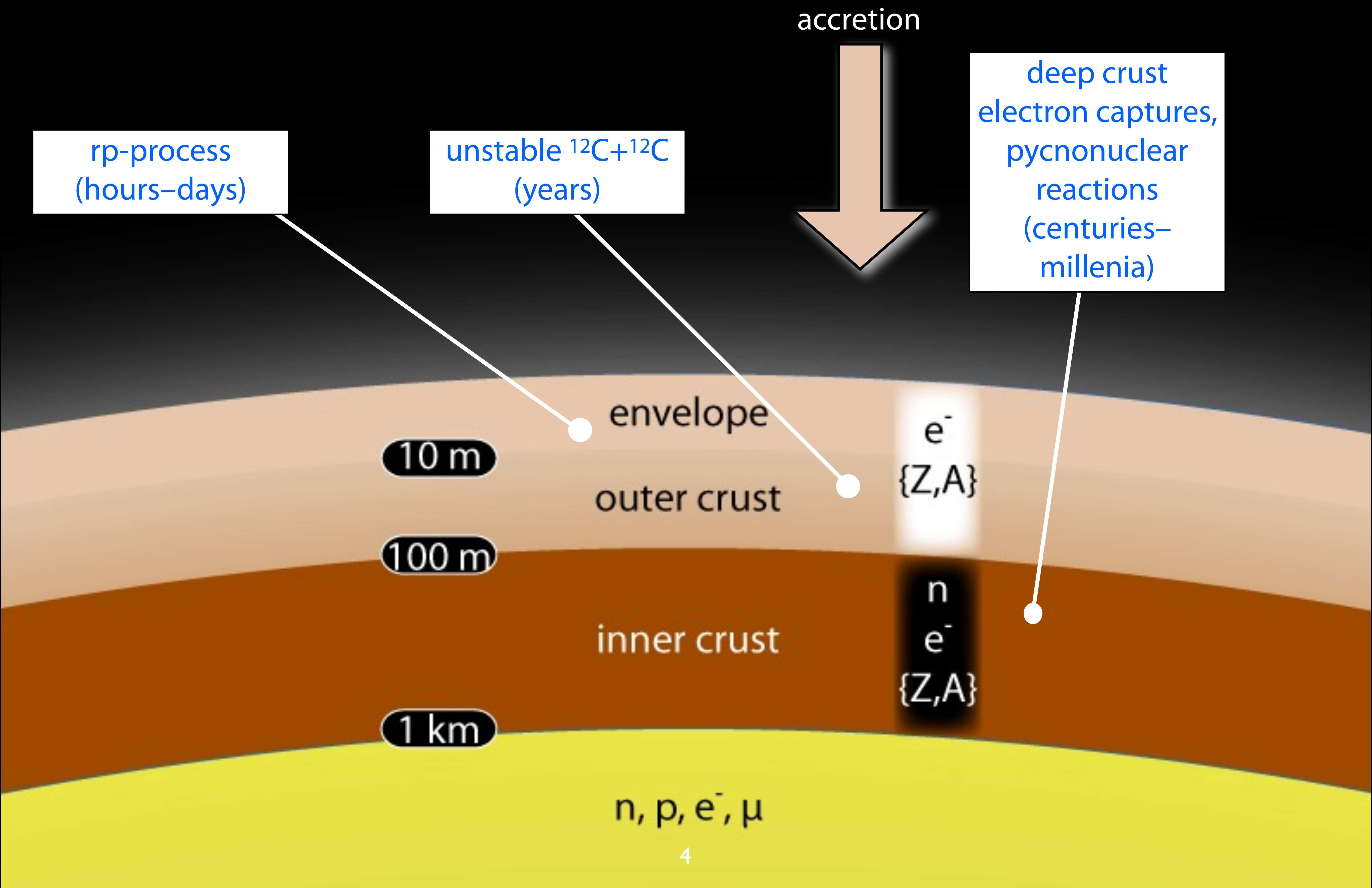
spectral cooling in tail (but see talk by M. Linares)

$$\alpha \equiv \frac{\int dt\ (\text{persistent flux})}{\int dt\ (\text{burst flux})} \sim 30\text{–}100$$






n, p, e^-, μ
Λ, Σ, K, π?
uds?



accretion

rp-process
(hours–days)

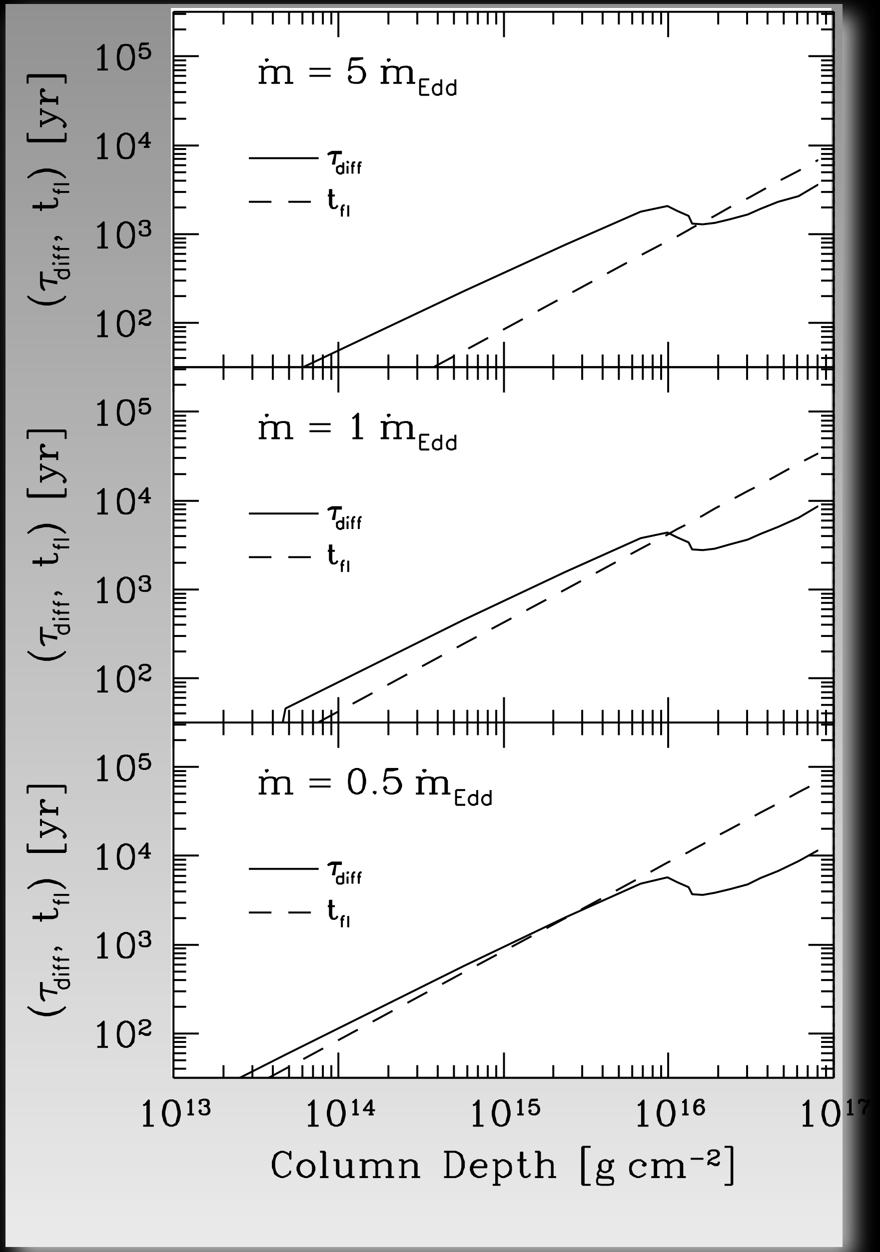
unstable $^{12}C+^{12}C$
(years)

deep crust
electron captures,
pycnonuclear
reactions
(centuries–
millenia)

crust reactions important for...

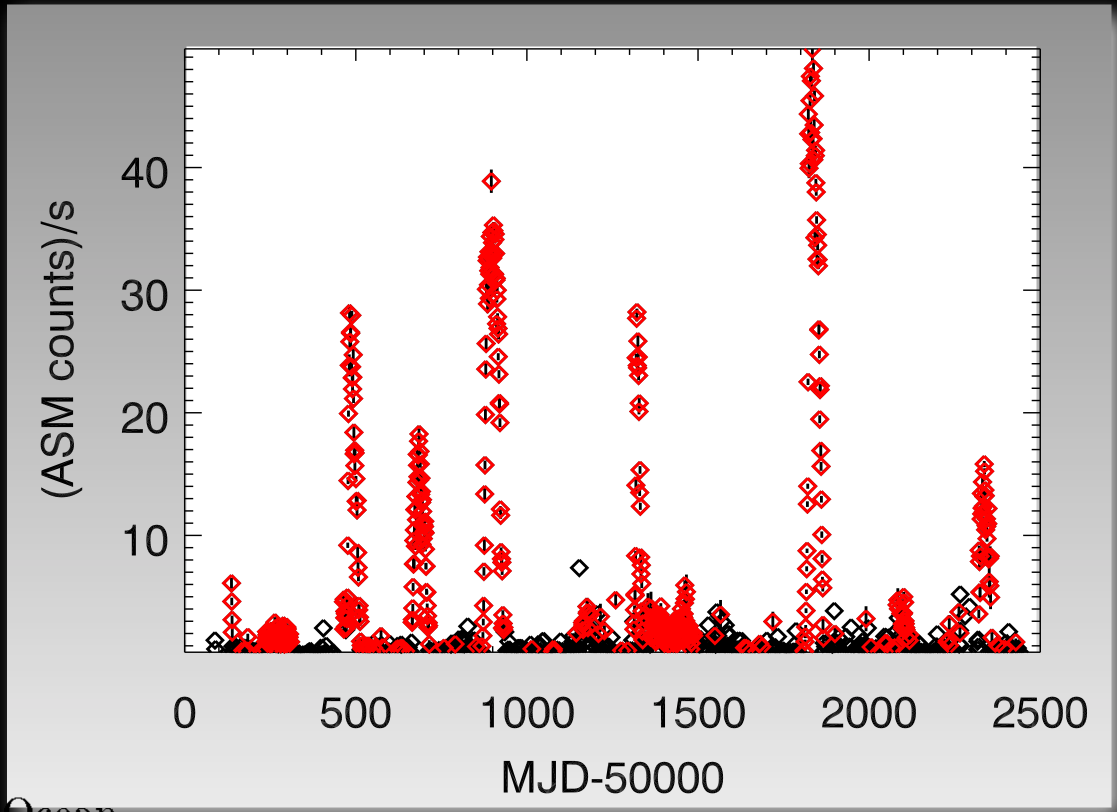
magnetic field evolution

(from Brown & Bildsten 98)



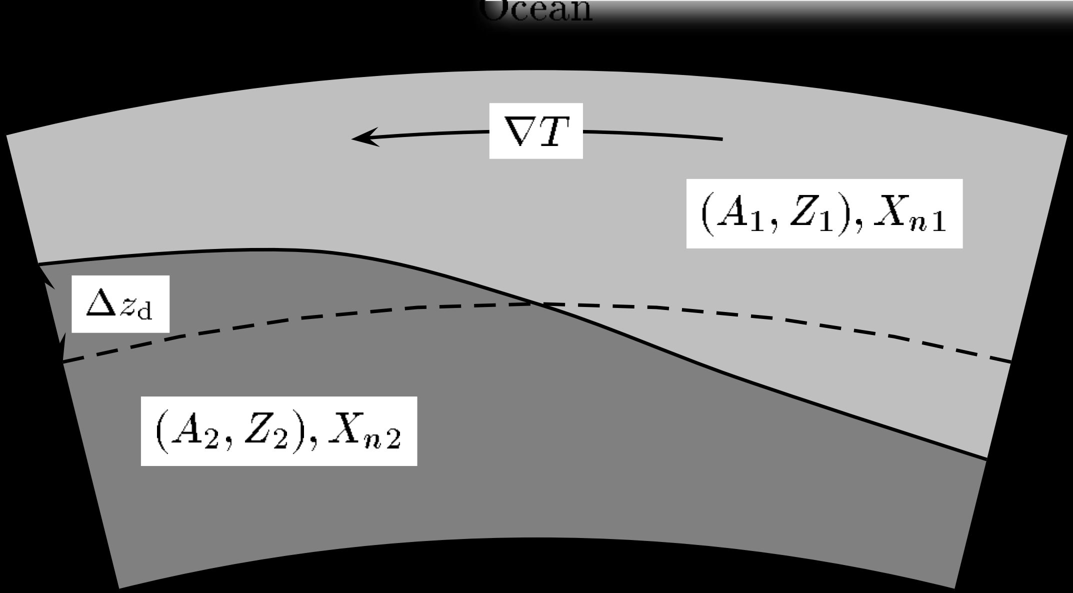
quiescent thermal emission from transients

(RXTE/ASM lightcurve of Aql X-1)



crust mountains

(plot from Ushomirsky et al. '00)



X-ray bursts, long bursts, and superbursts

Context

Basic scenario

- Thin-shell instability in accreted envelope
- Successes and failures of this scenario

Long bursts and superbursts: ignition in the deep

- Implications for crust temperatures
- The challenge of superburst ignition

Concluding remarks

Thin-shell instability

Hansen & van Horn; Fujimoto et al.; see also Narayan & Heyl; Cooper & Narayan

For a thin shell, thermal instability develops where

$$\left.\frac{\partial \ln \varepsilon_{\mathrm{nuc}}}{\partial T}\right|_P > \left.\frac{\partial \ln \varepsilon_{\mathrm{cool}}}{\partial T}\right|_P,$$

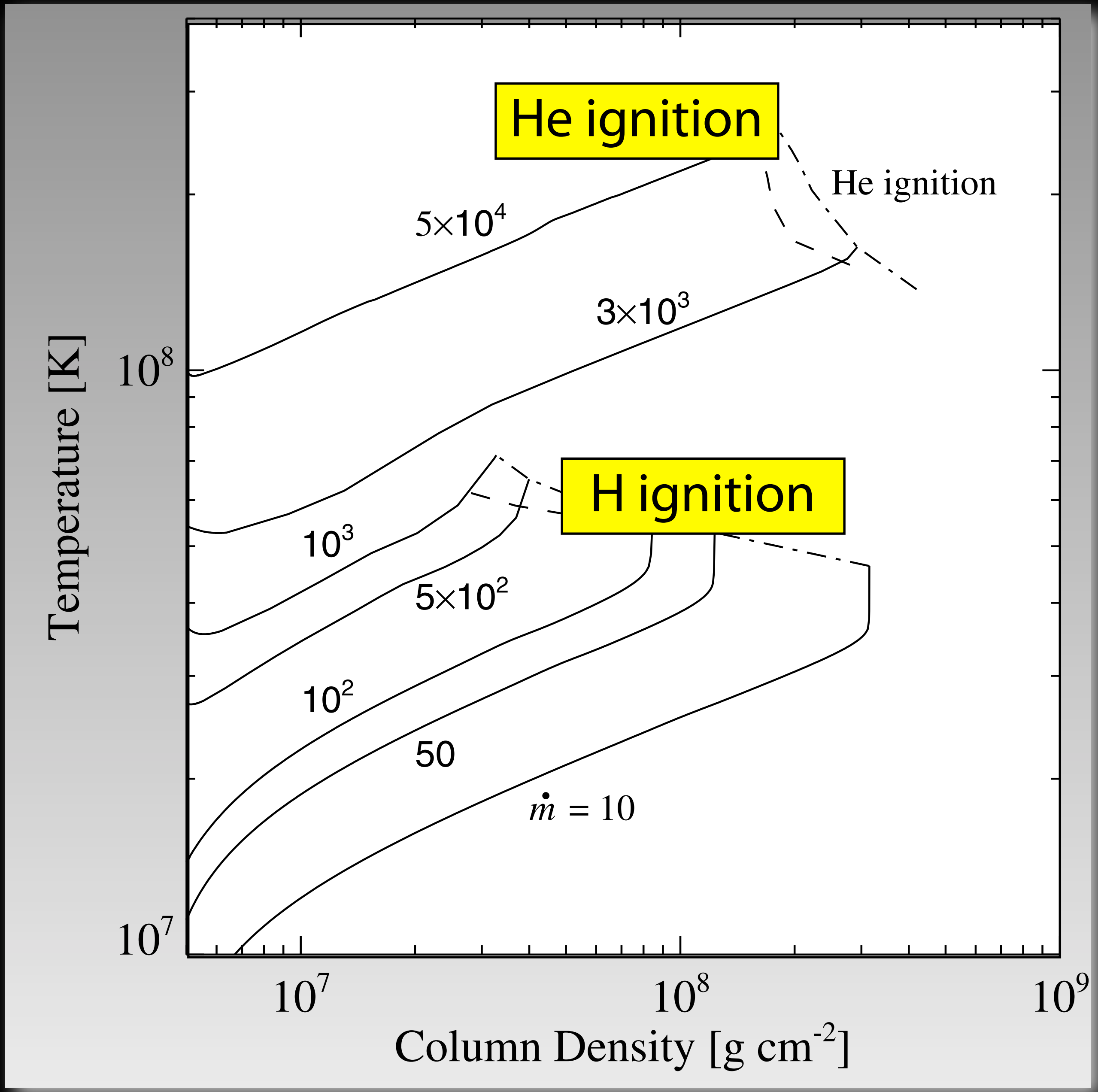
with

$$\varepsilon_{\mathrm{cool}} \sim -\chi\nabla^2 T.$$

A thermal runaway occurs and rapidly consumes fuel; if

$$t_{\mathrm{cool}} \ll t_{\mathrm{accrete}}$$

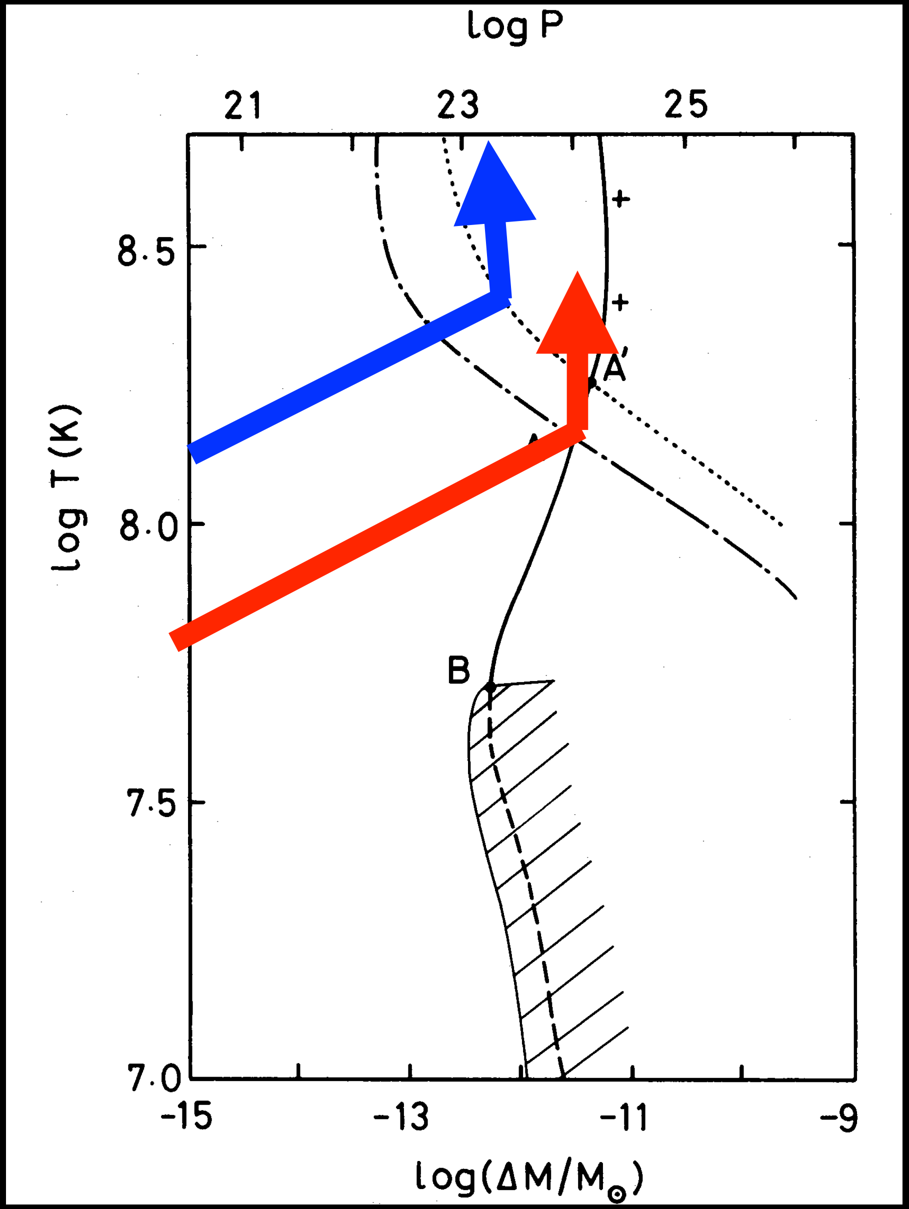
a limit cycle develops.



Peng et al. 2007

Consumption of Hydrogen

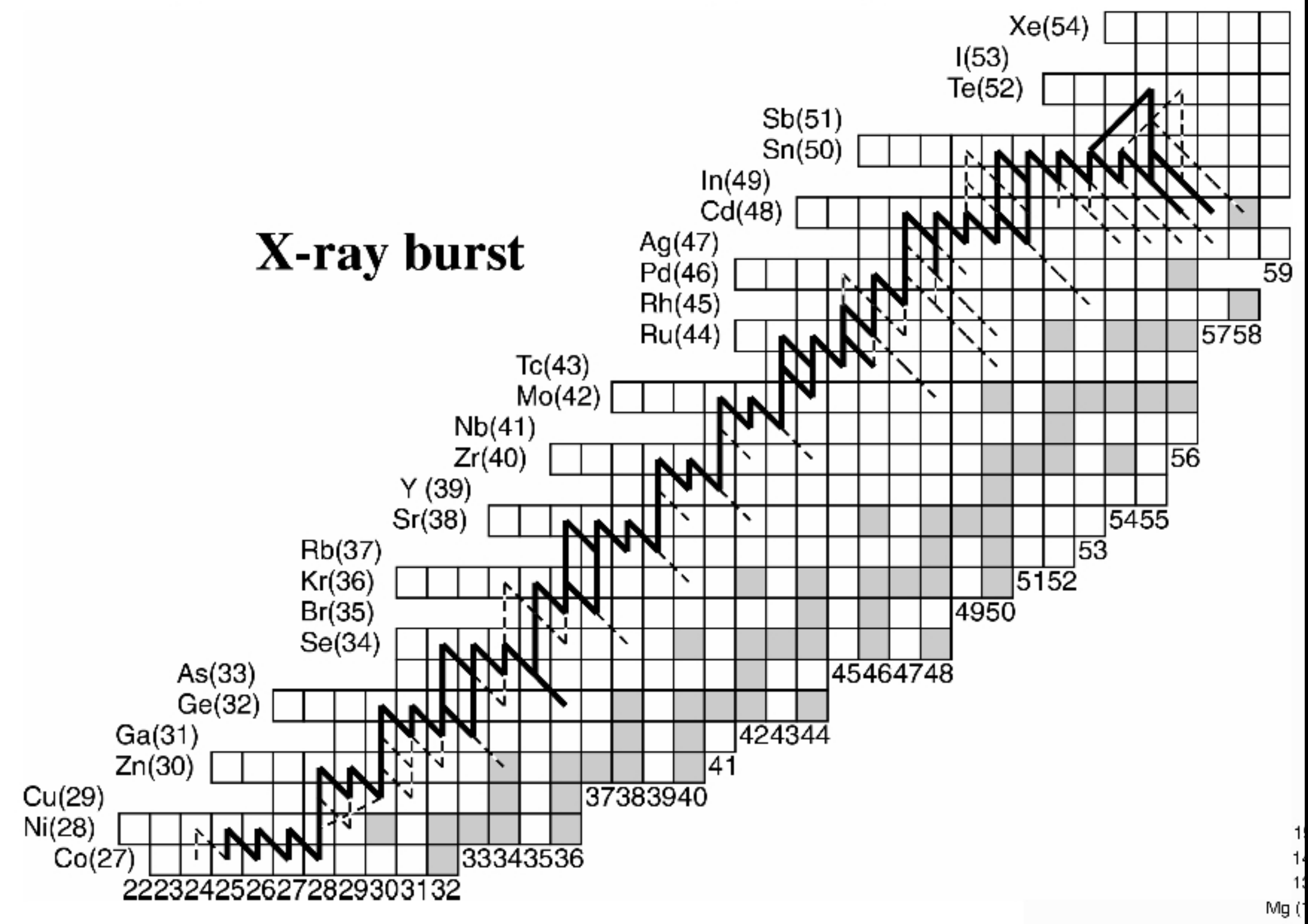
Fujimoto et al.



Assume all H consumed stably via HCNO cycle. Time to consume H set by β-decay of ^{14}O ($t_{1/2} = 71$ s) and ^{15}O ($t_{1/2} = 122$ s).

$$
\begin{aligned}
t_H &= \frac{1}{4}\frac{Y_H}{Y_{CNO}}\frac{193\ \text{s}}{\ln 2} \\
&\approx 18\ \text{hr}\left(\frac{X_H}{0.7}\right)\left(\frac{0.01}{X_{CNO}}\right).
\end{aligned}
$$

$$\boxed{^{12}\text{C}(p,\gamma)^{13}\text{N}(p,\gamma)^{14}\text{O}(\beta^+)^{14}\text{N}(p,\gamma)^{15}\text{O}(\beta^+)^{15}\text{N}(p,{}^4\text{He})^{12}\text{C}}$$



consumption of H via rp-process

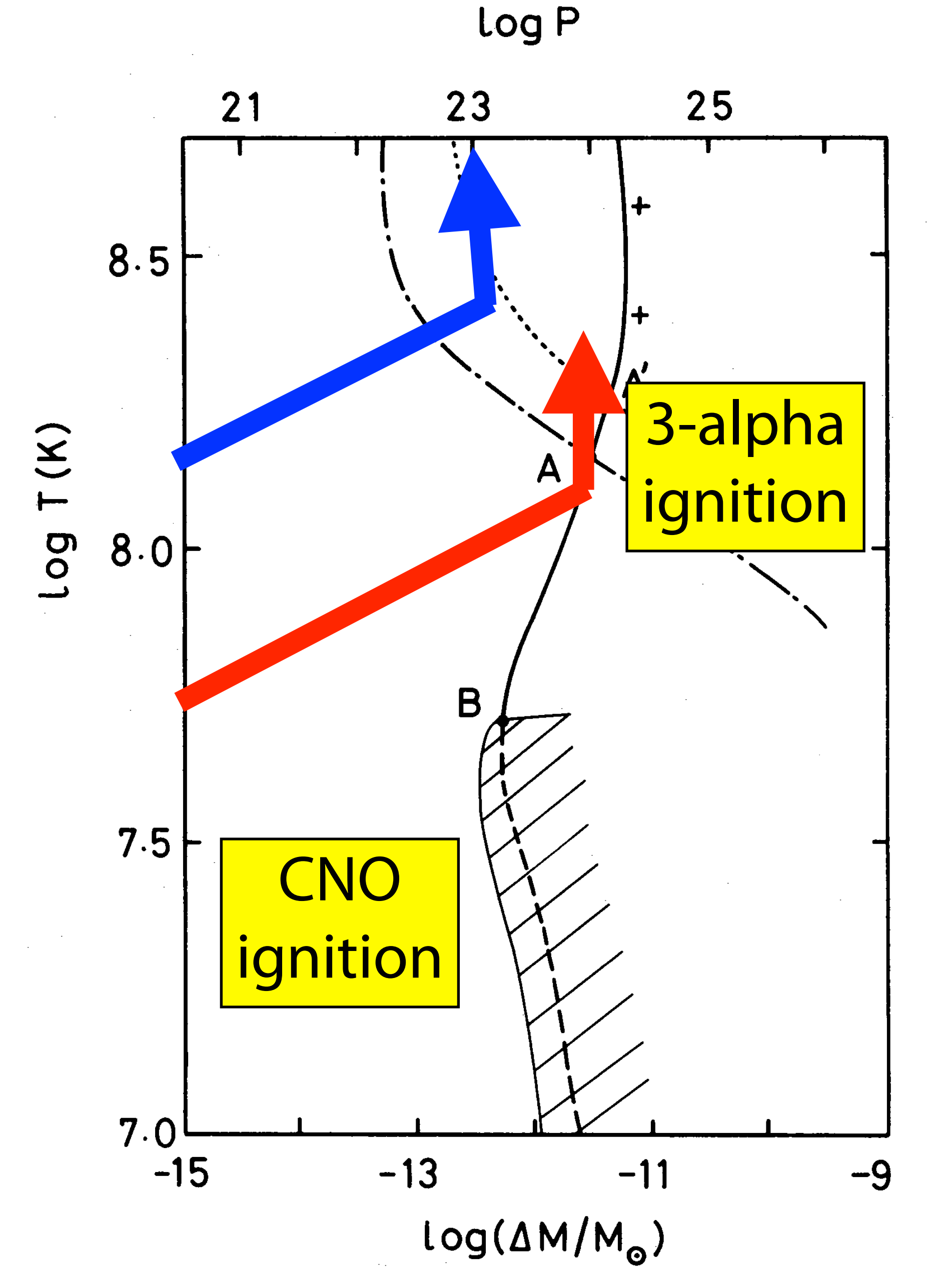
Schatz et al. 2001, *PRL*

Consumption of Hydrogen

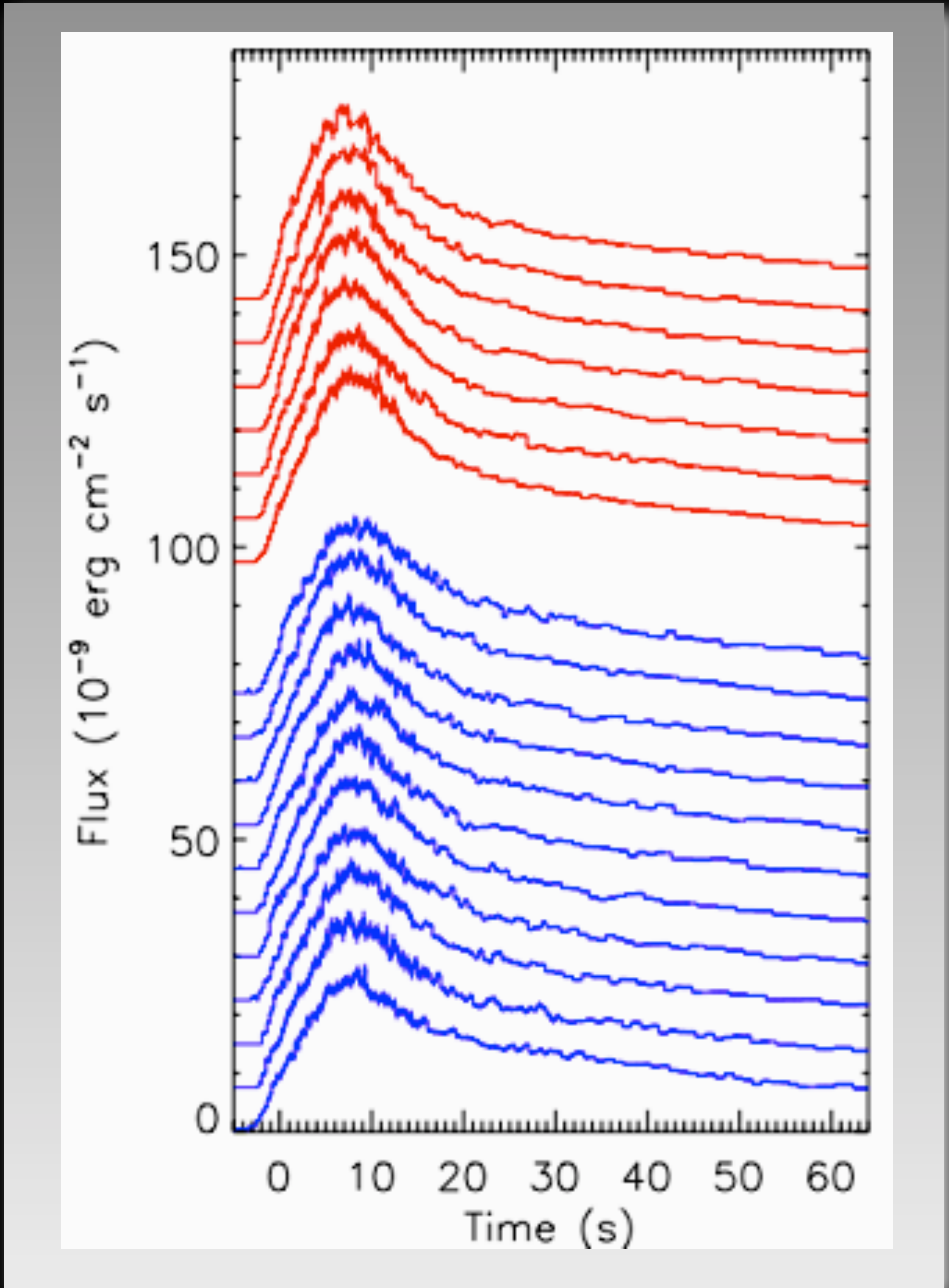
Temperature structure found by integrating

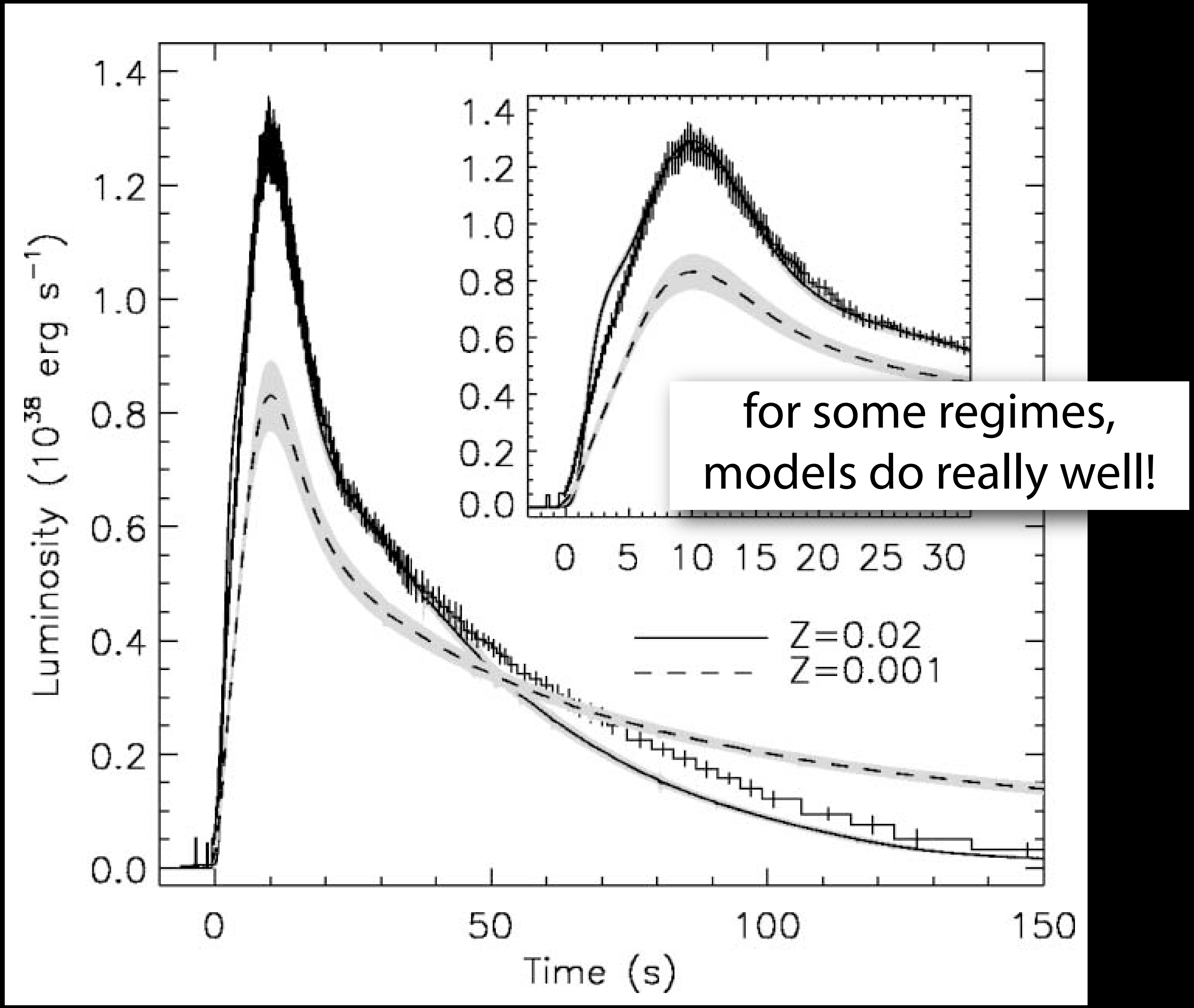
$$\begin{aligned} \dot{m} E_H &= F \\ &= \frac{1}{3} \frac{c}{n_e \sigma} \frac{d a T^4}{dr} \end{aligned}$$

to a column depth $\dot{m} \times t_H$.
For complete consumption of H, this gives $T \approx 3 \times 10^8$ K.



For GS1826–24, models do remarkably well





for some regimes, models do really well!

Heger et al. 07

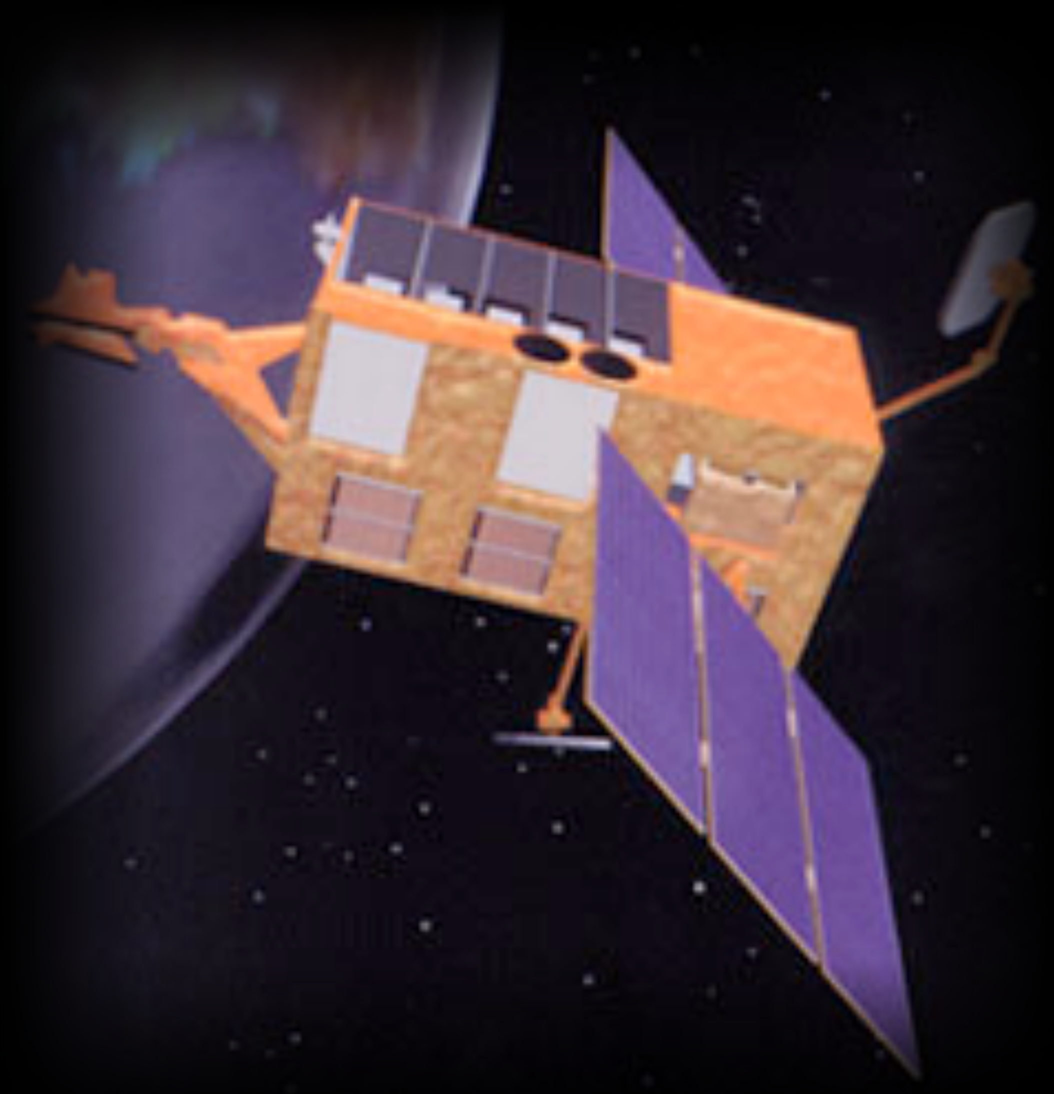
Challenges

Most systems are not like GS1826–24!

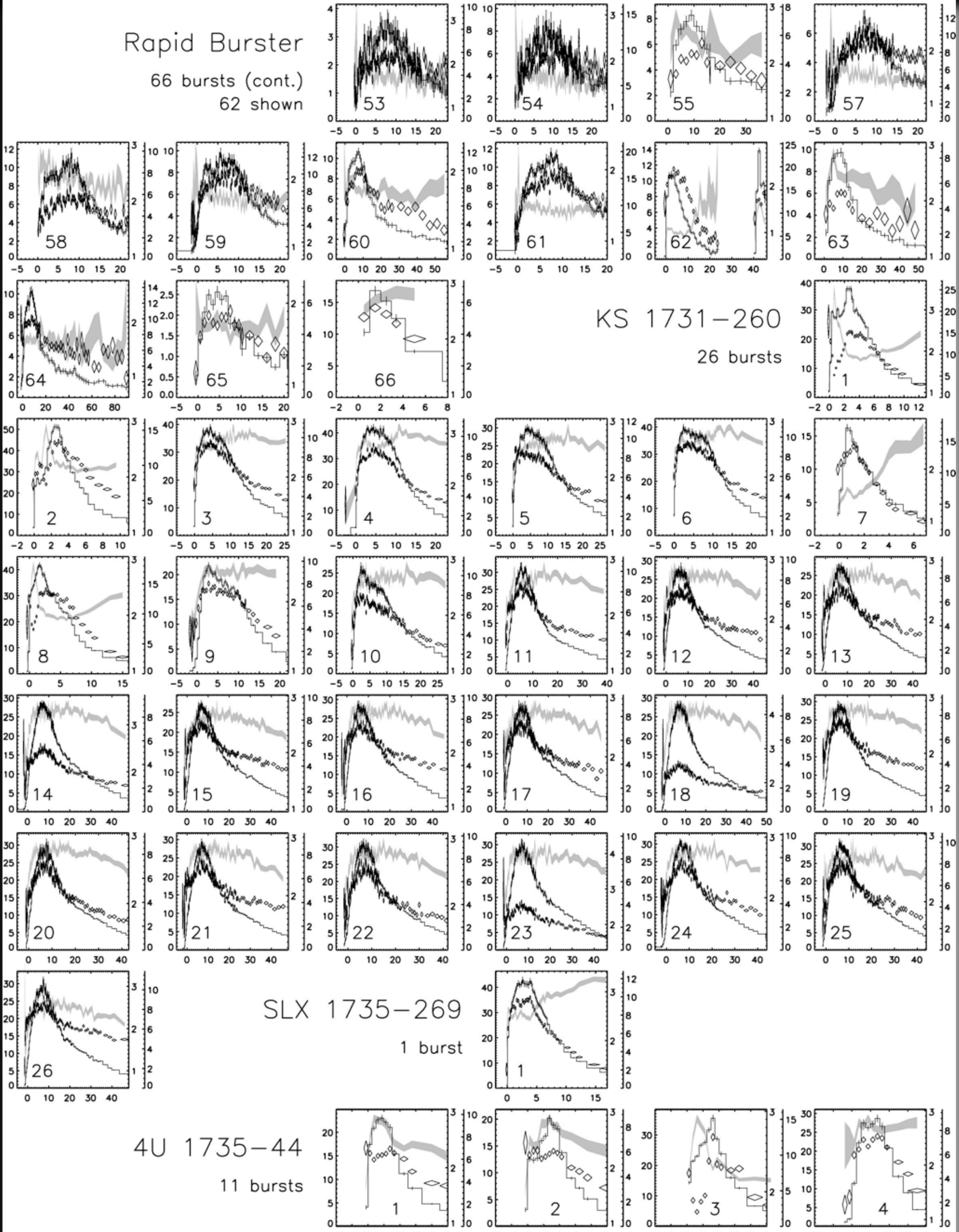
Above 0.1 Eddington accretion, evidence for some stable burning

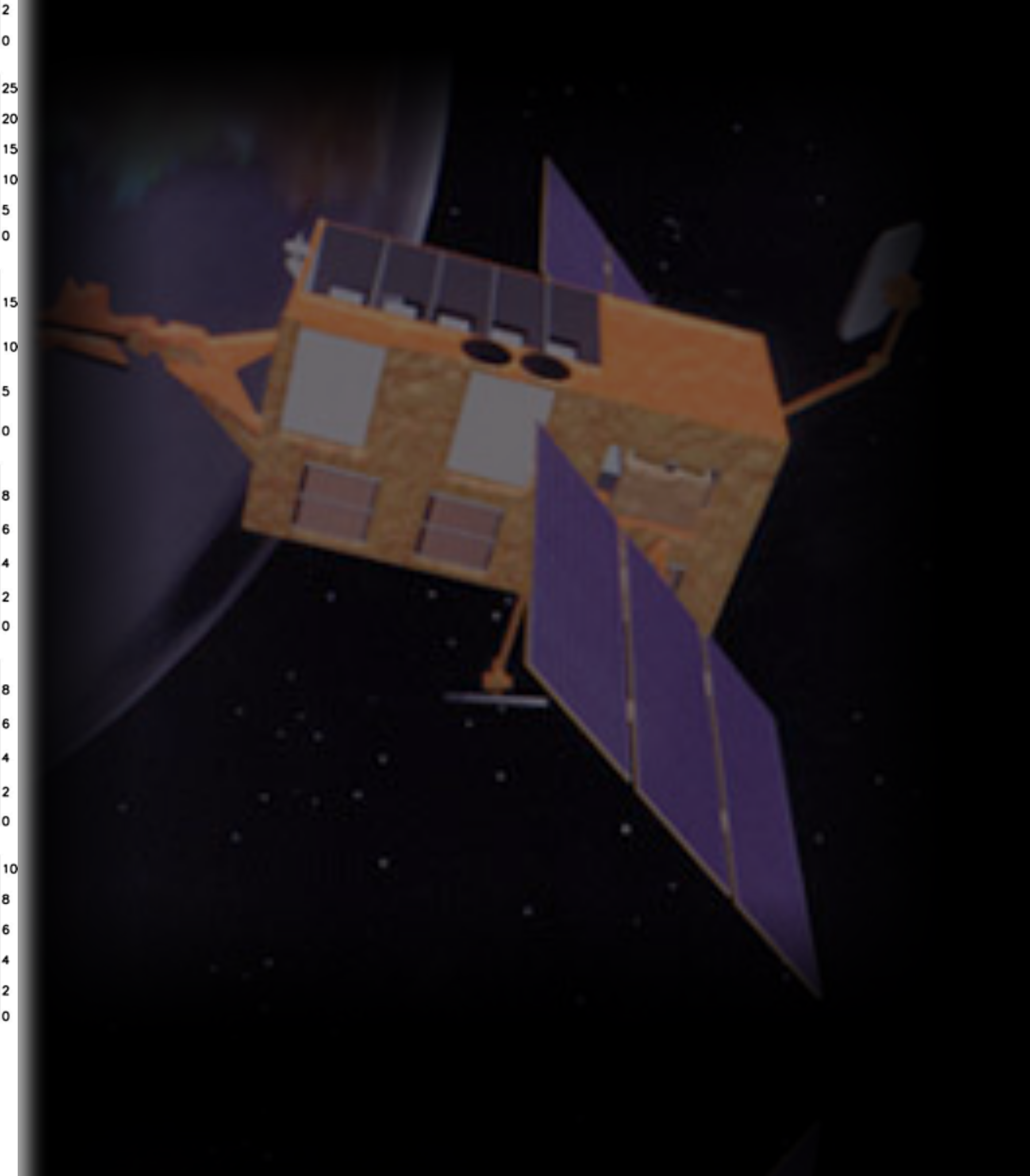
- Burst frequency increases (model predicts a decrease)
- Bursts become shorter, indicating less H

Some groups come in “clusters”: a group of up to 4 bursts, separated by waits of a few minutes (see Keek et al. 2010)



Galloway et al. 2008
A sample of 1187 X-ray bursts from 48 sources





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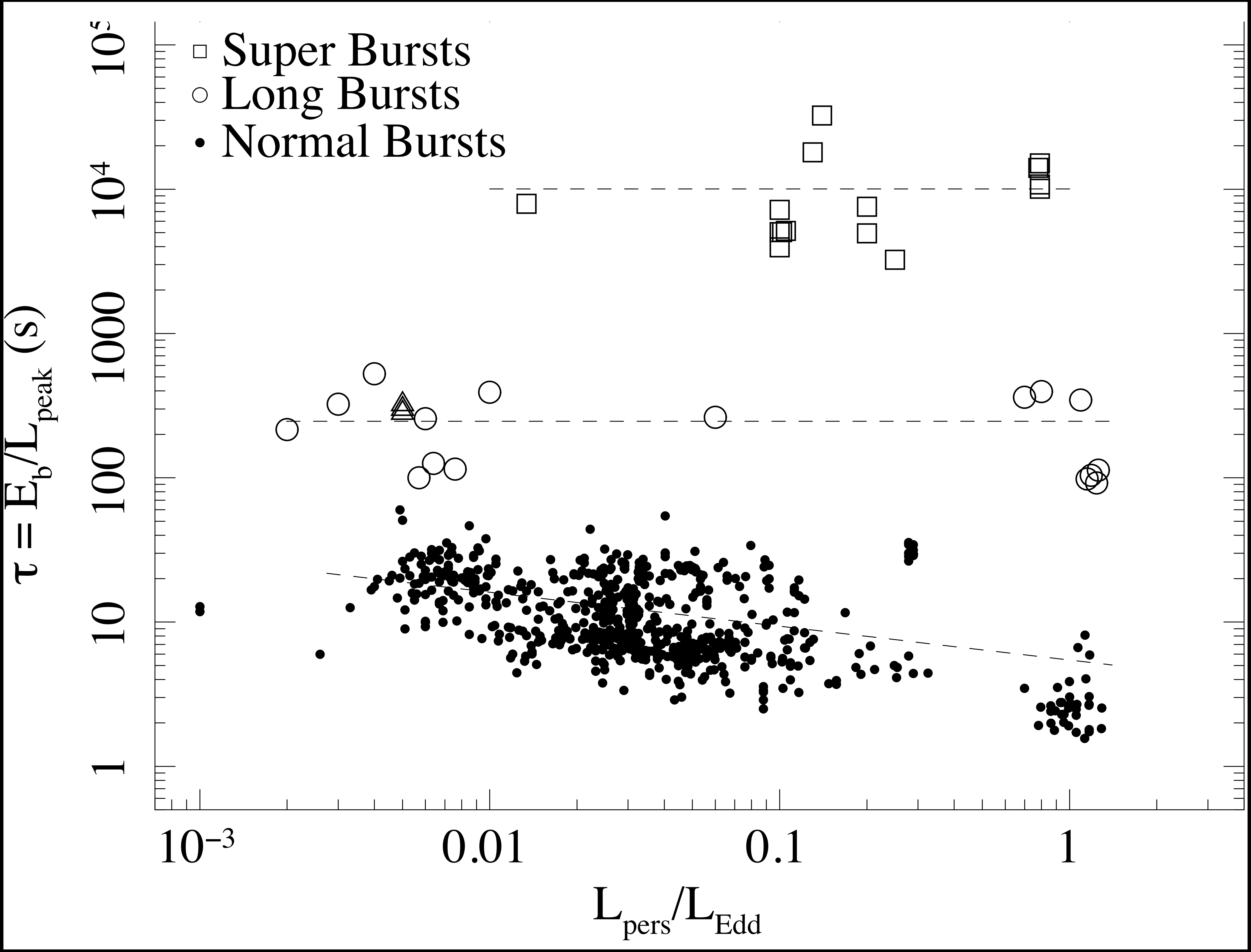
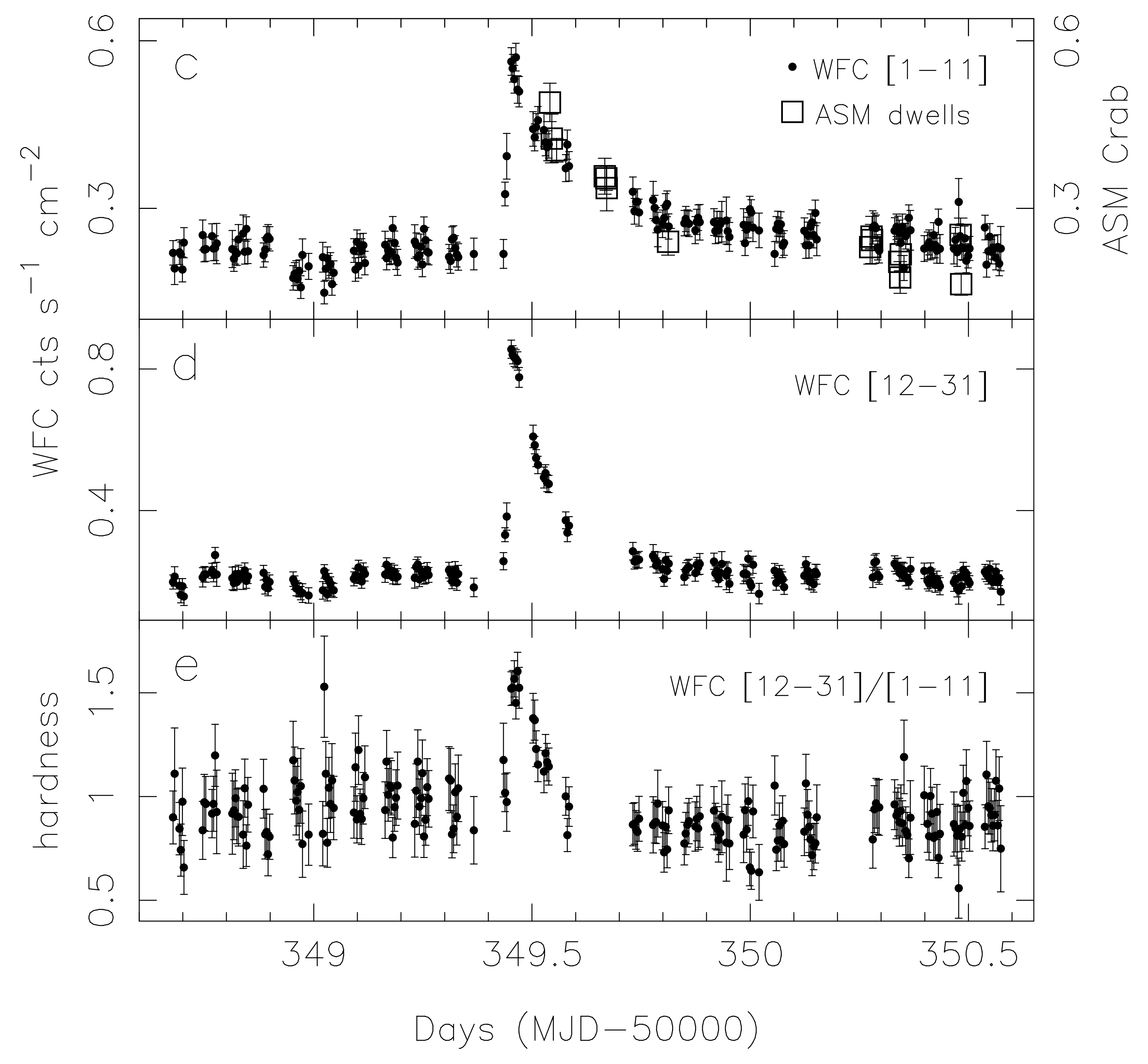


Falanga et al. 2008; see talk by Chenevez

KS 1731–260 superburst
Kuulkers 2002



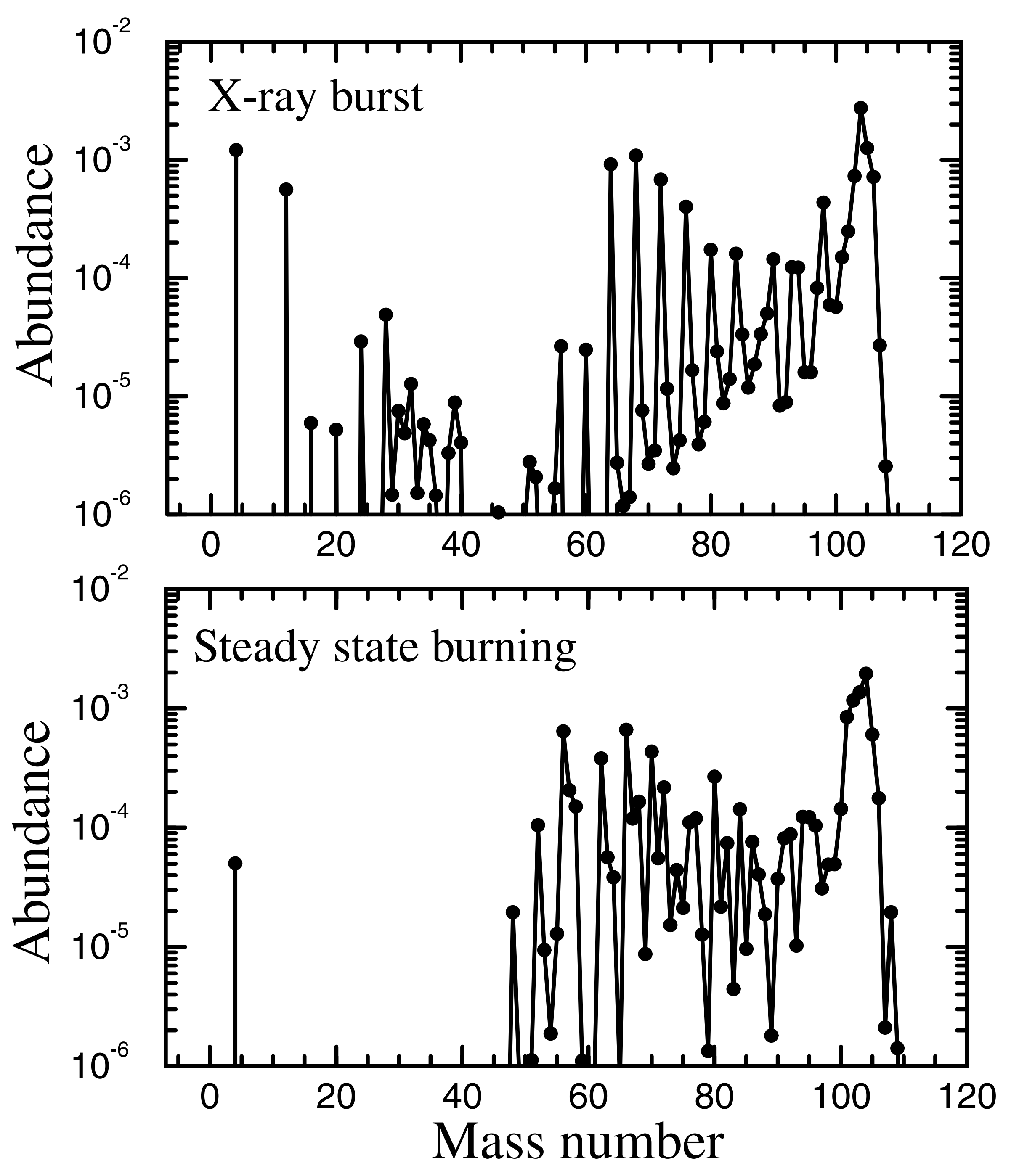
Why weren’t these predicted?

Carbon flashes were investigated Taam & Picklum 1978, Brown & Bildsten 1998

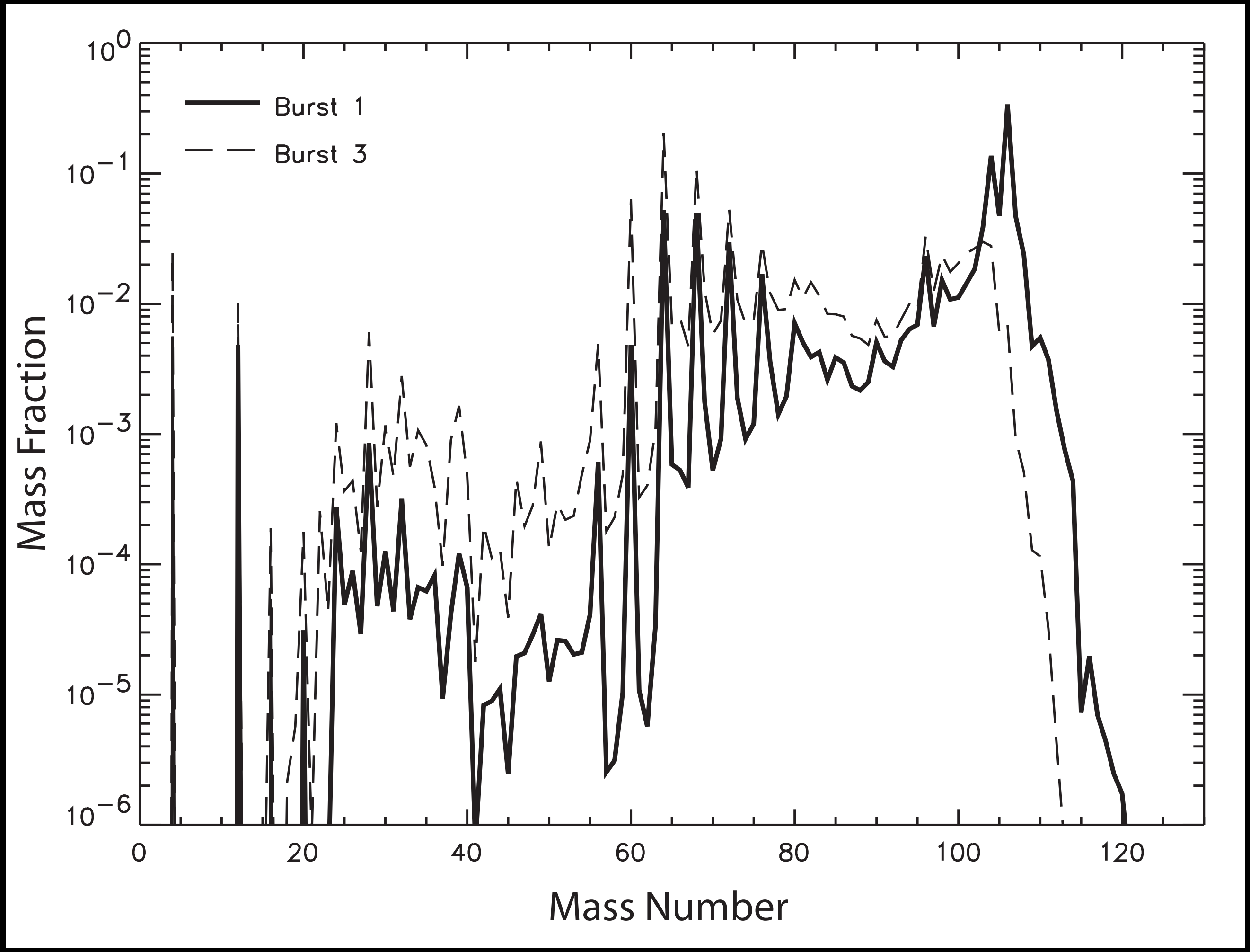
Two missing ingredients in these studies

1. production of carbon in H, He bursts
2. igniting carbon with a small ignition mass

ashes of H-He burning



Woosley et al. 2004, ApJ



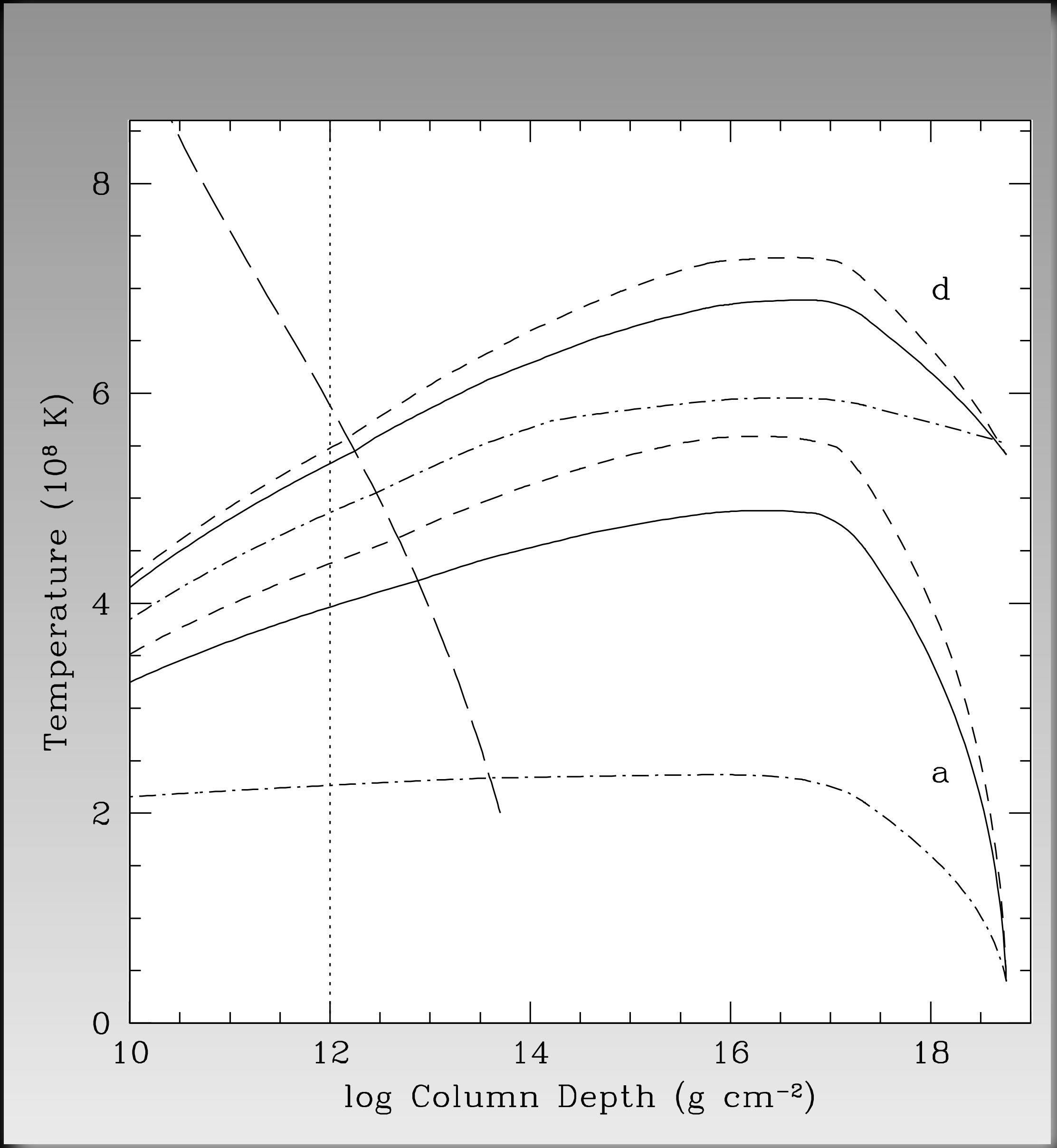
Schatz et al. 2001, PRL

superburst ignition

Thermally unstable ^{12}C + ^{12}C is the likely cause of superbursts (Cumming & Bildsten '01, Strohmayer & Brown '02, Cooper et al. '10)

A hot crust is required to match inferred ignition depth (Brown '04; Cooper & Narayan '05; Cumming et al. '06)

But the cooling of quasi-persistent transients suggests that the crust is cold! (Shternin & Yakovlev '07; Brown & Cumming '09; see poster by Fortin)



Plot from Cumming et al. '06

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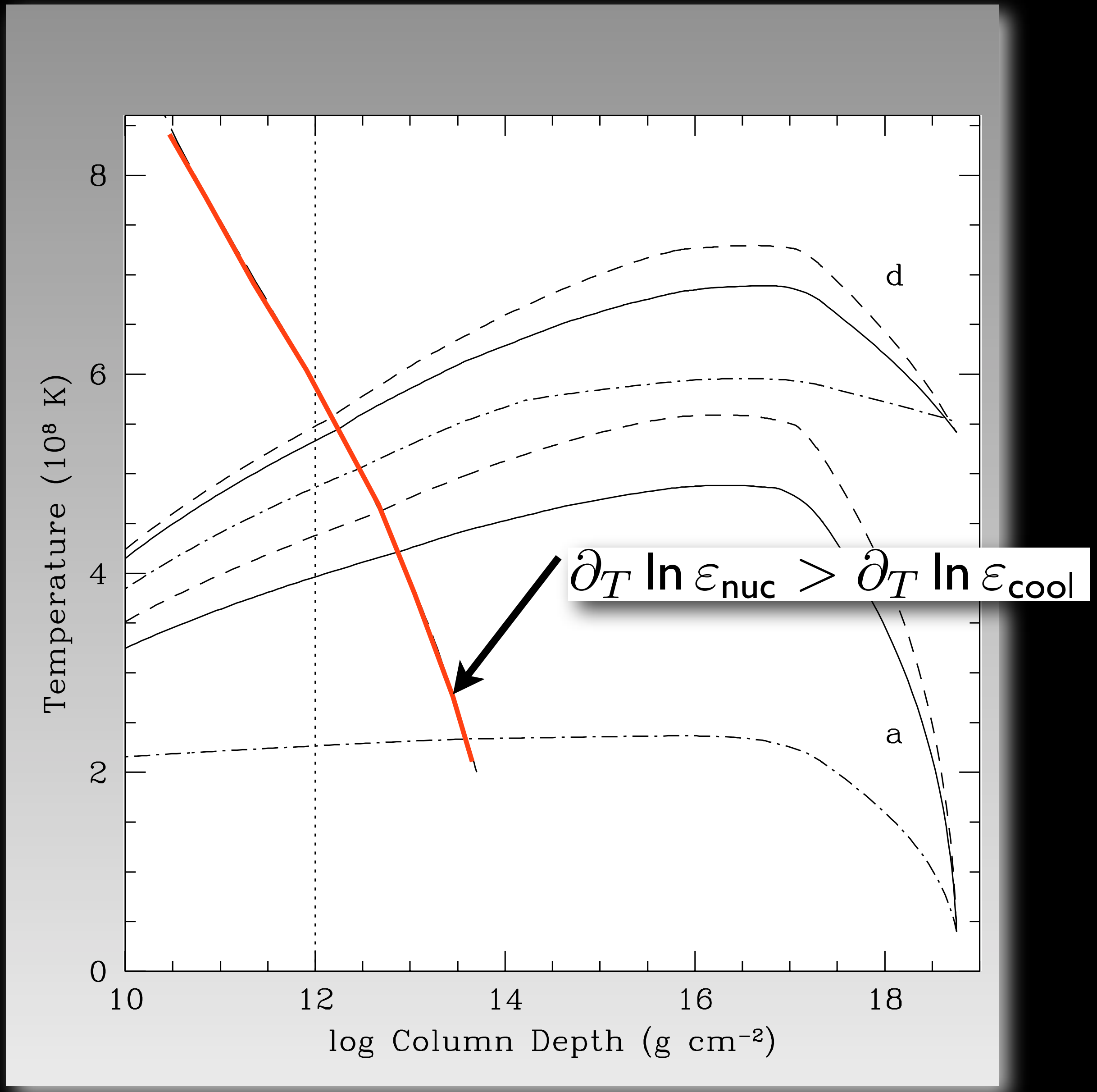

$\partial_T \ln \varepsilon_{\rm nuc} > \partial_T \ln \varepsilon_{\rm cool}$

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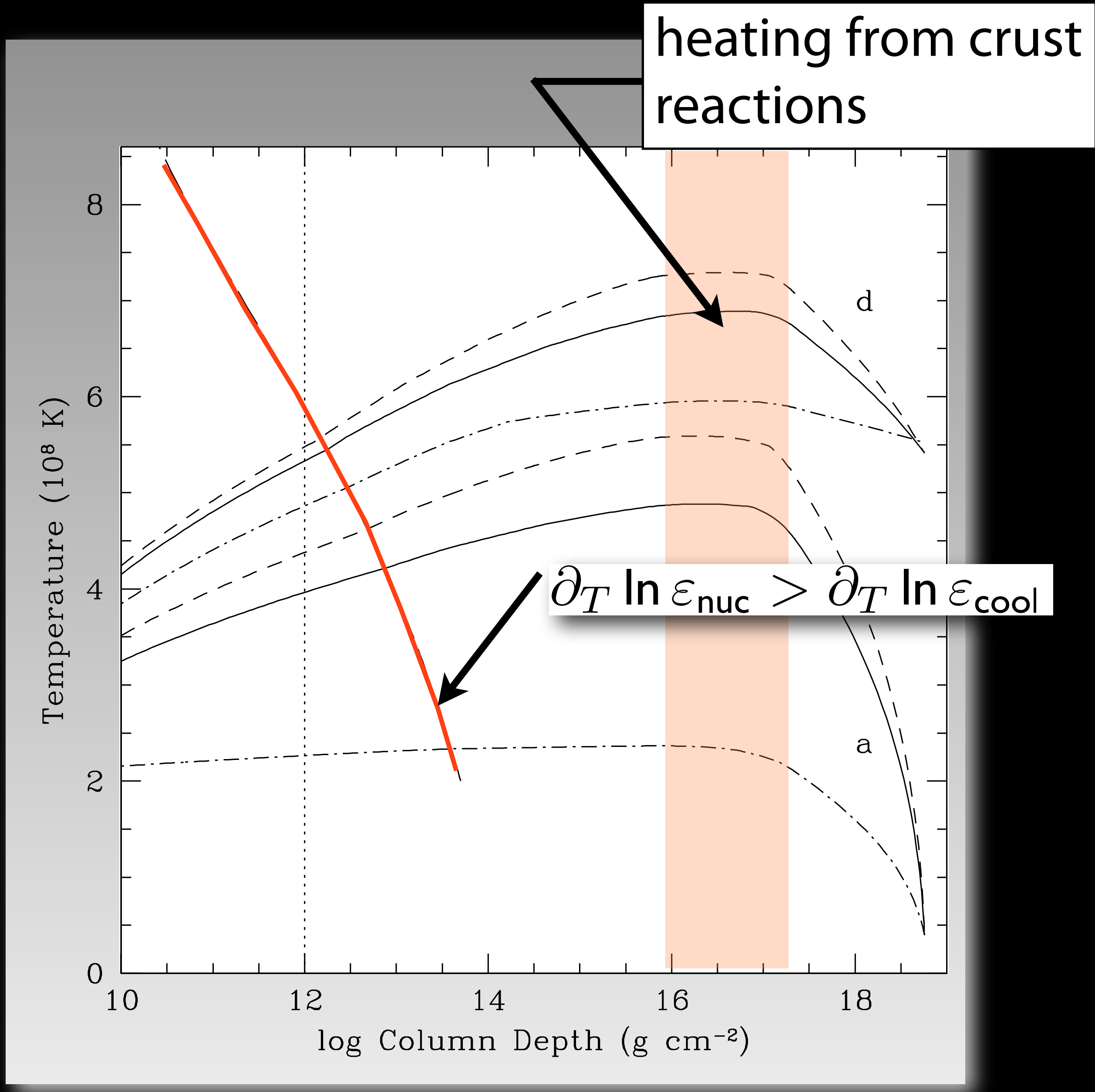

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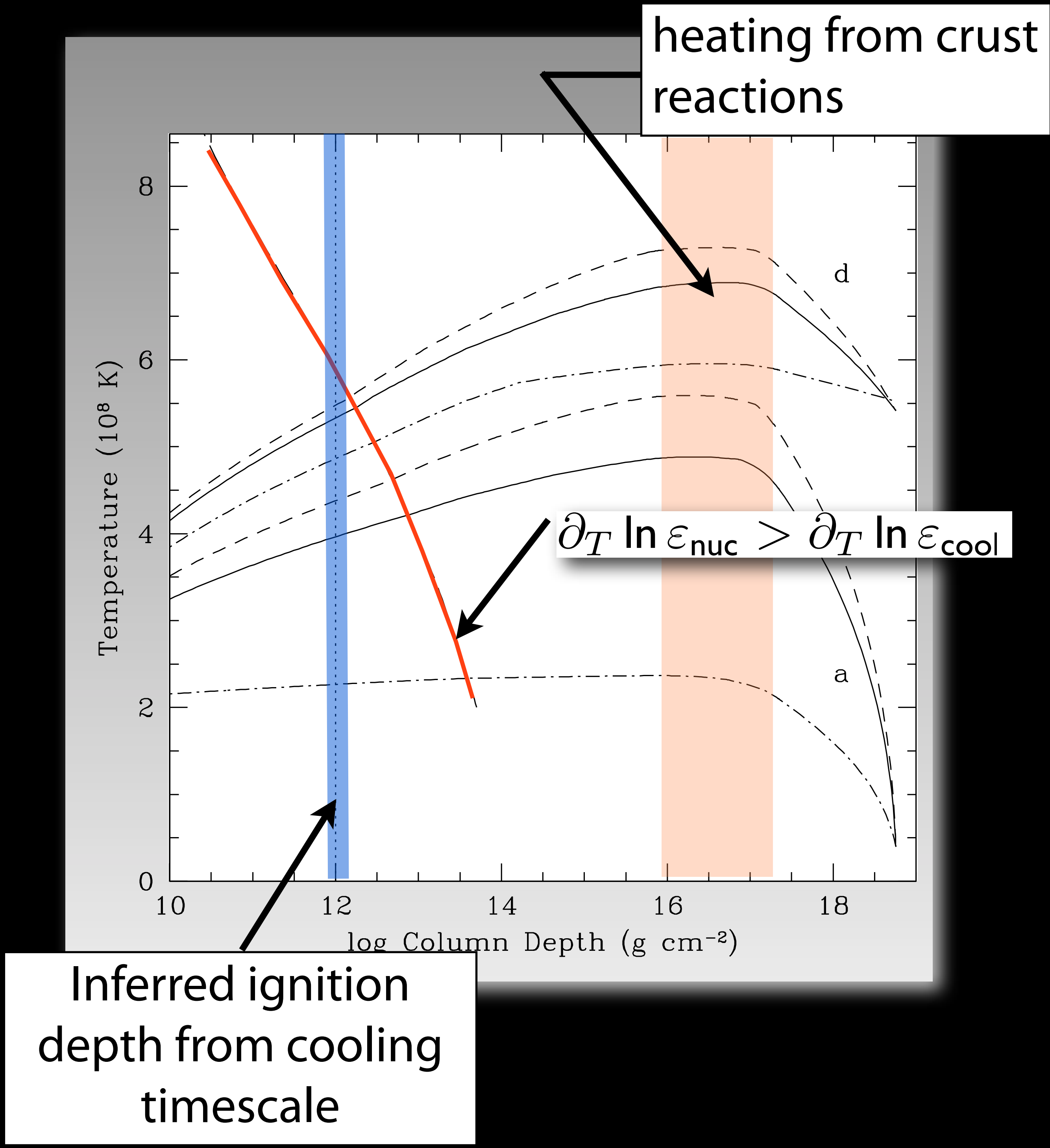


heating from crust reactions

$\partial_T \ln \varepsilon_{\rm nuc} > \partial_T \ln \varepsilon_{\rm cool}$

Inferred ignition depth from cooling timescale

Plot from Cumming et al. '06

a cooling slab

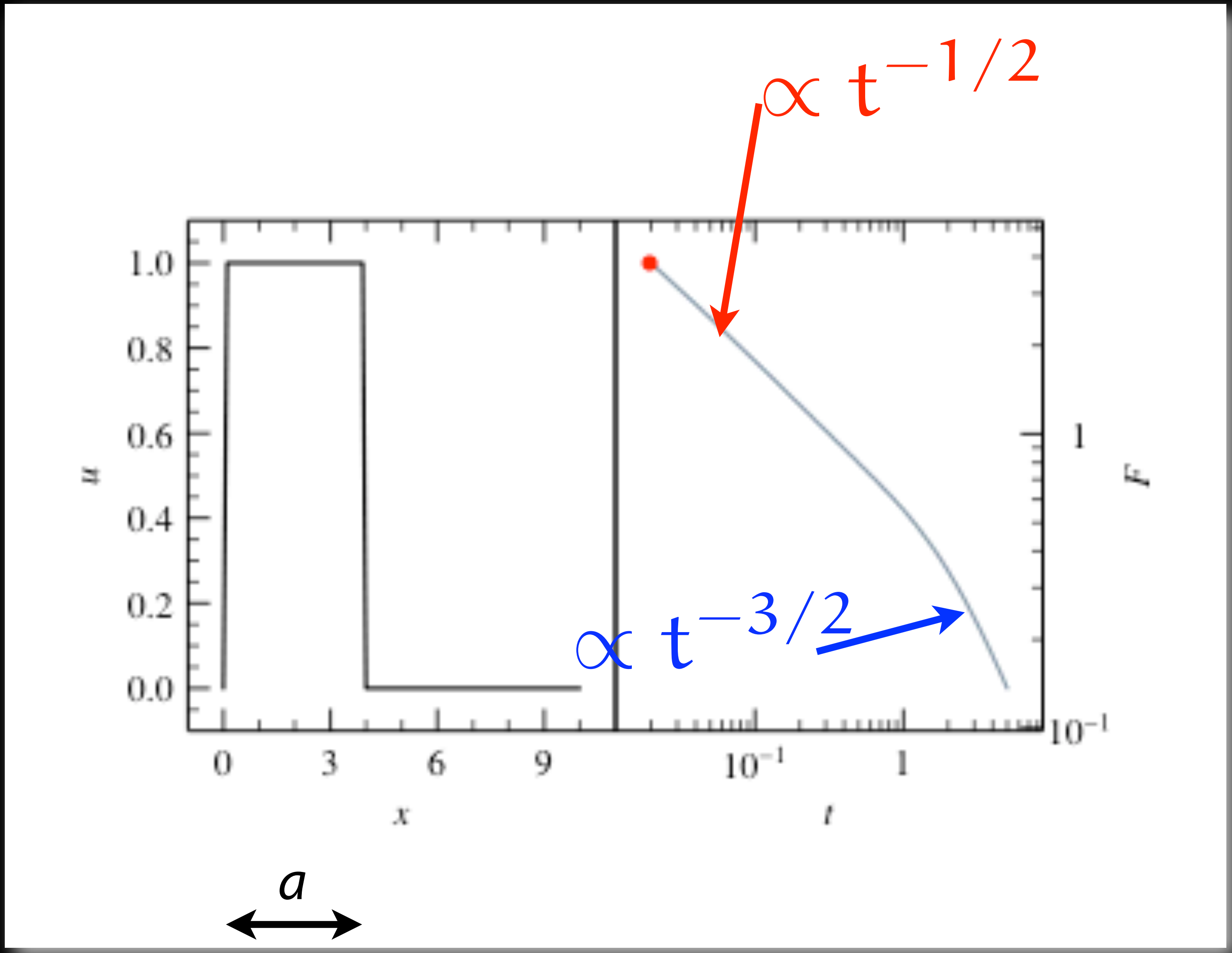
For

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

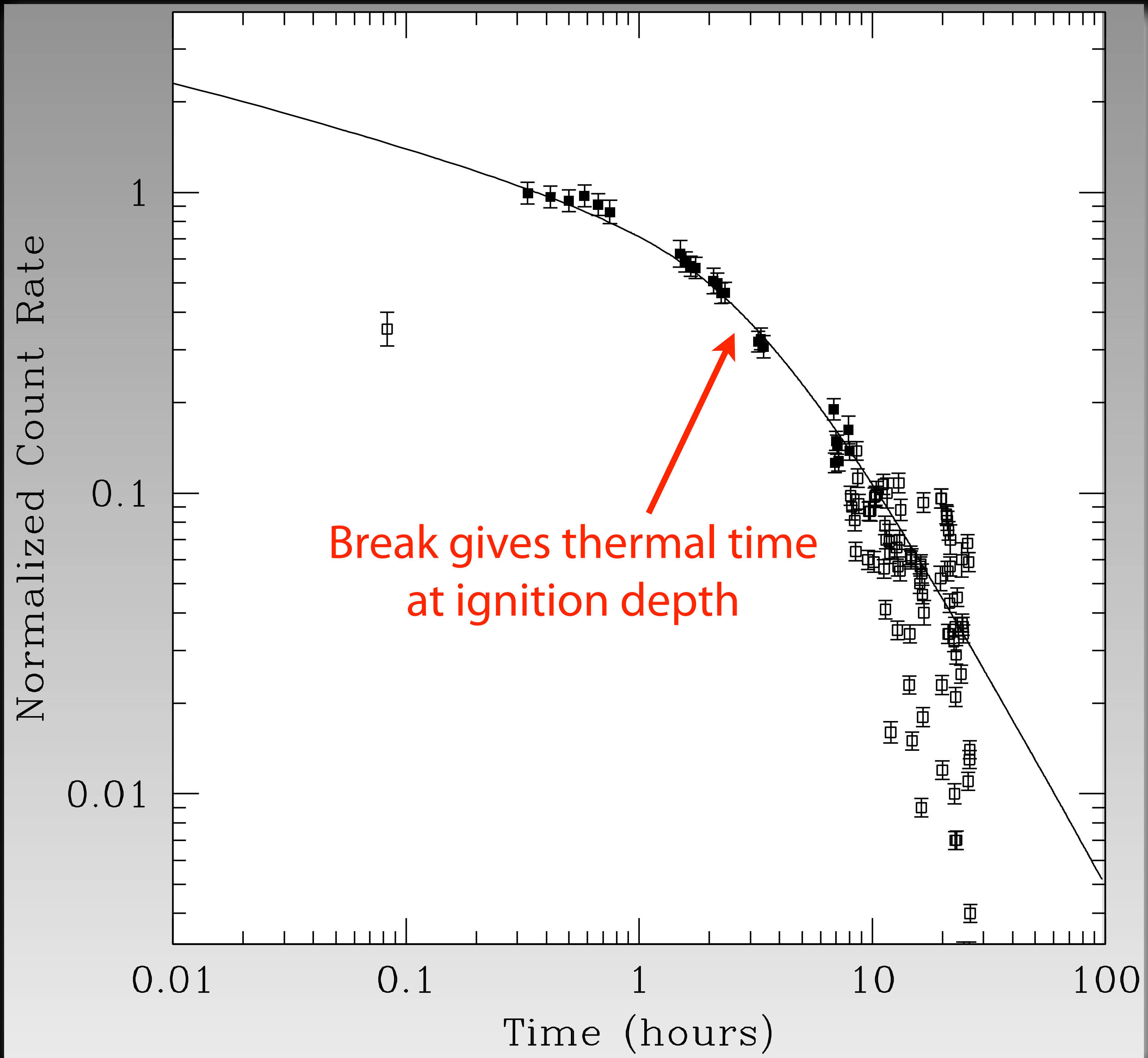
the flux at $x = 0$ is

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

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



ignition masses



Break gives thermal time
at ignition depth

From Cumming et al. 2006

superburst ignition

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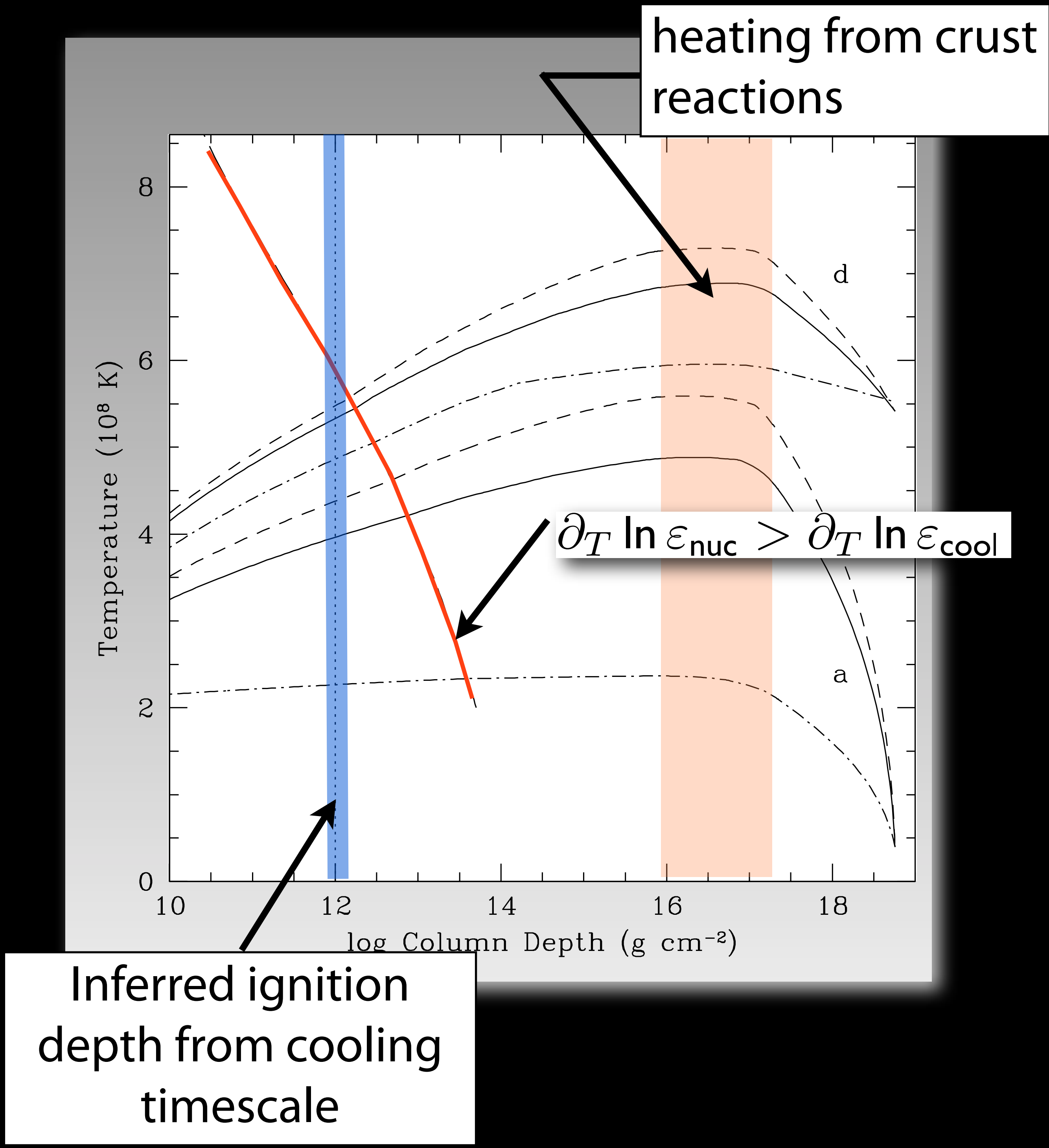


heating from crust reactions

$\partial_T \ln \varepsilon_{\rm nuc} > \partial_T \ln \varepsilon_{\rm cool}$

Inferred ignition depth from cooling timescale

Plot from Cumming et al. '06

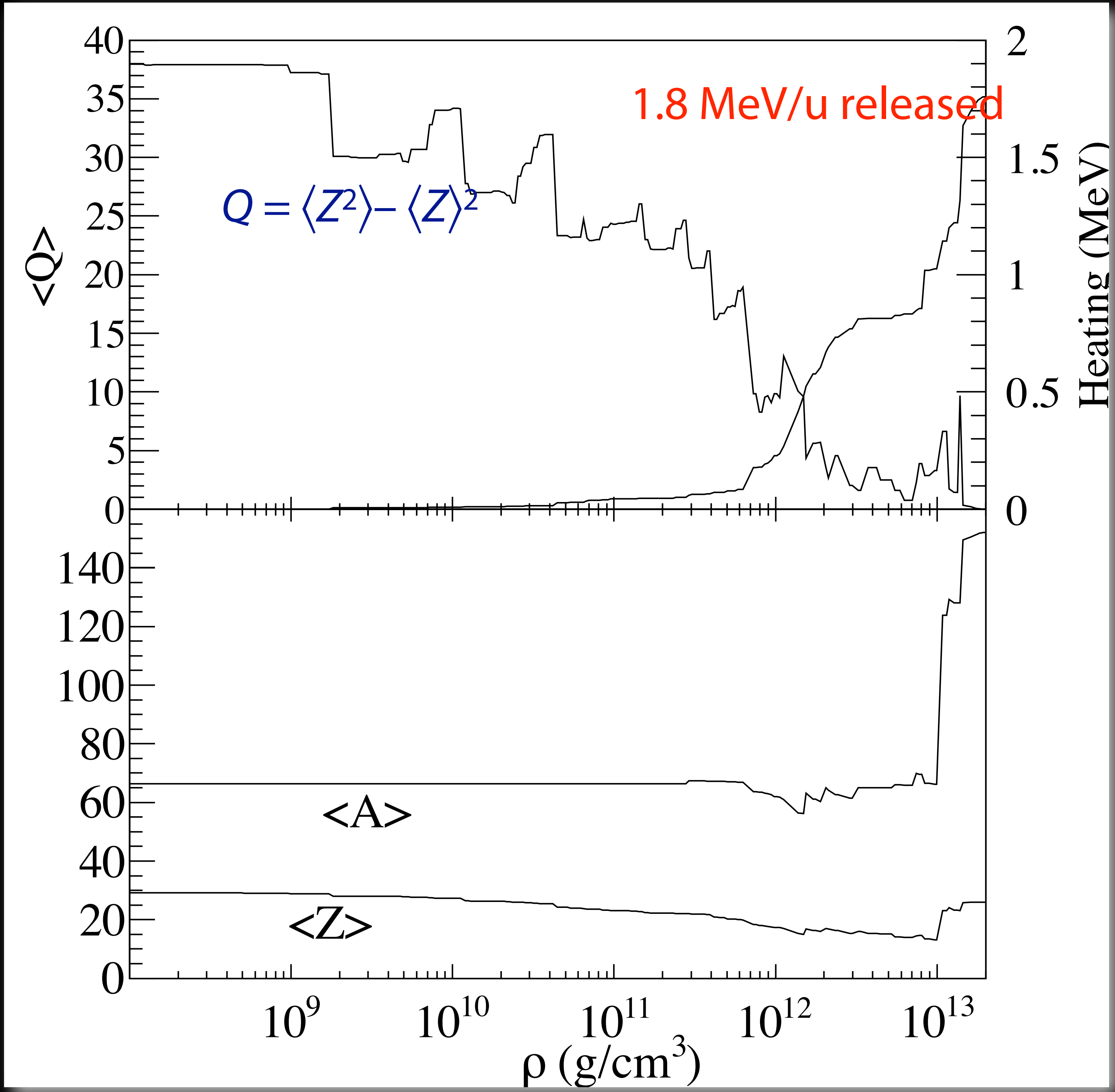
deep crustal heating

Sato; Haensel & Zdunik; Gupta et al.

crust reactions deposit ~1.8 MeV/u in the inner crust

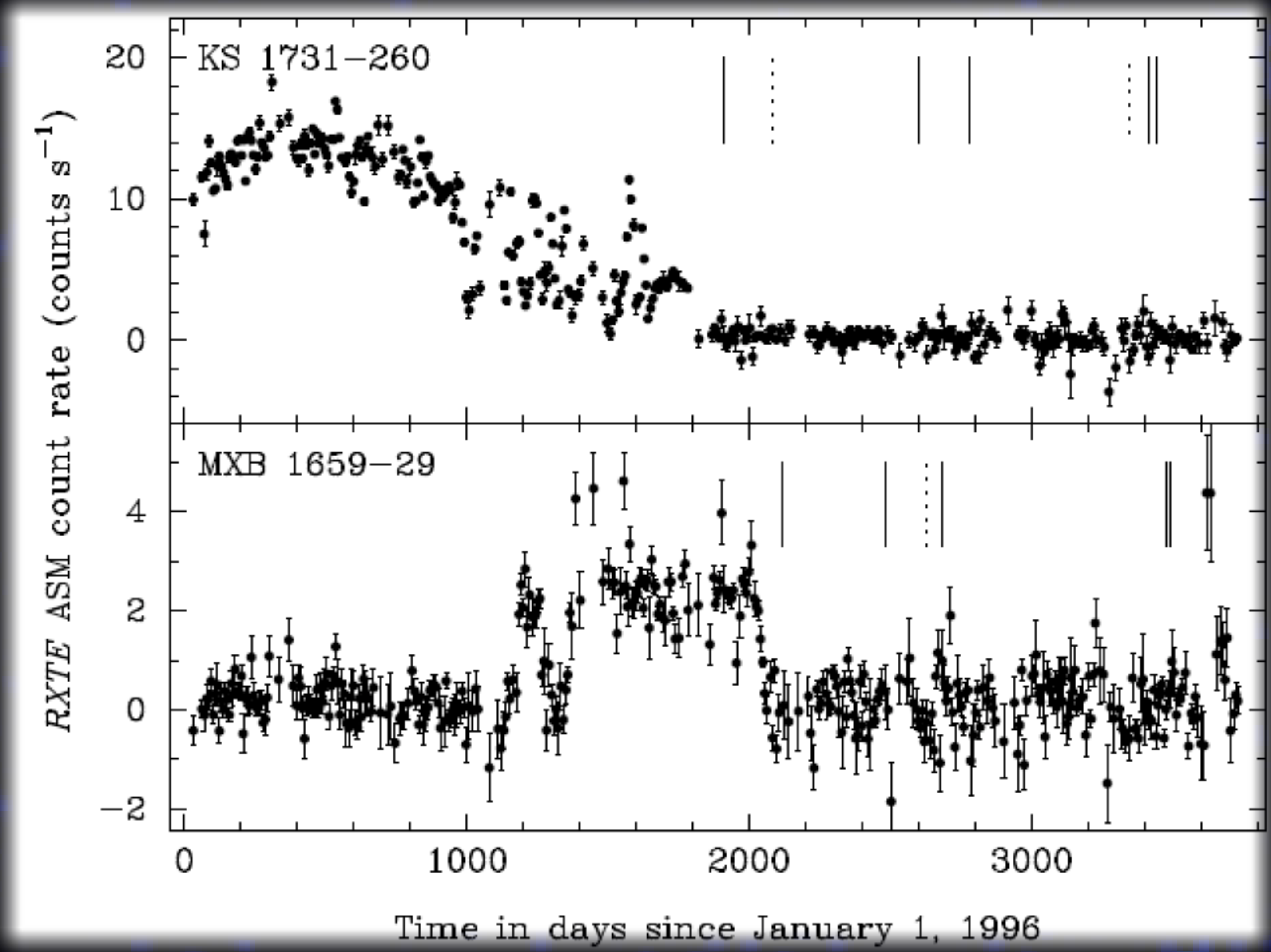
1. core temperature set by balance of heating, neutrino cooling
2. crust is not in thermal equilibrium with core

plot courtesy A. Steiner



quasi-persistent transients

Rutledge et al. 2002, Shternin et al.2007, Brown & Cumming 2009; talk by Degenaar



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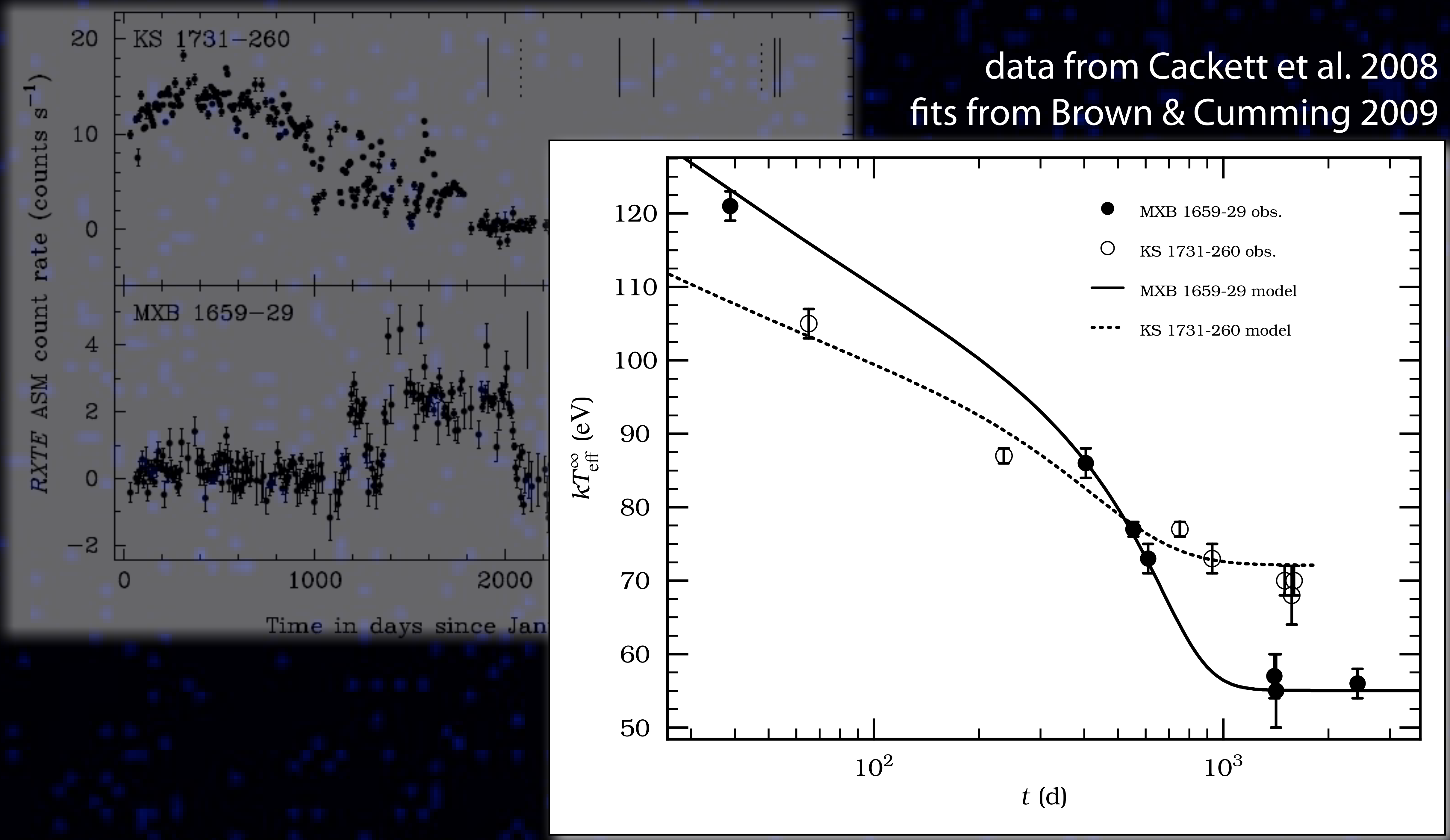


data from Cackett et al. 2008
fits from Brown & Cumming 2009

basic physics of the lightcurve

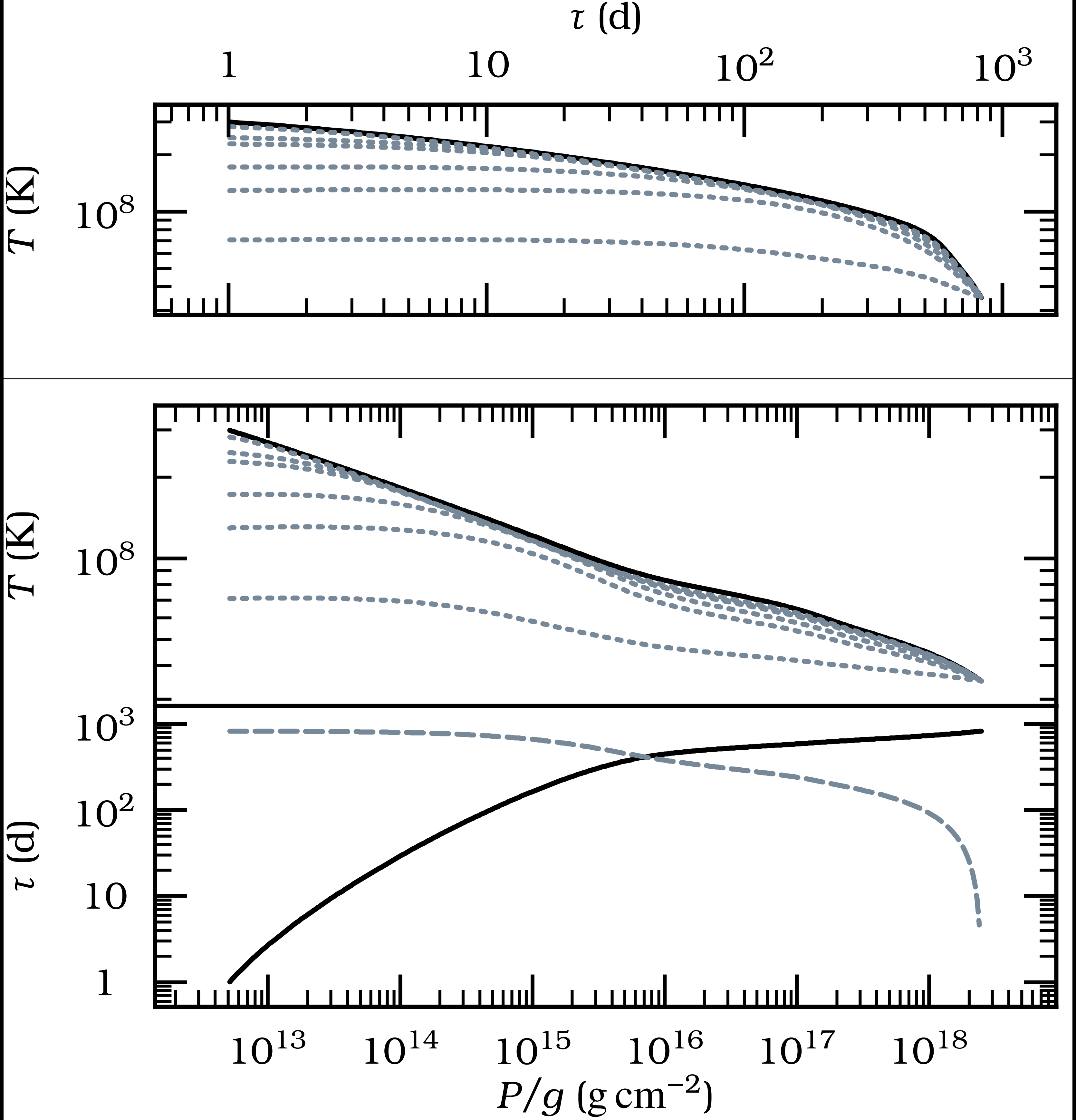
For a cooling crust,

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

and a cooling front propagates into the crust on a timescale (Henyey & L'Ecuyer 1969)

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

power-law cooling behavior in other contexts:
white dwarfs in DN (Piro et al.)
superbursts (Cumming et al.),
magnetars (Eichler & Cheng, Kaminker et al.)



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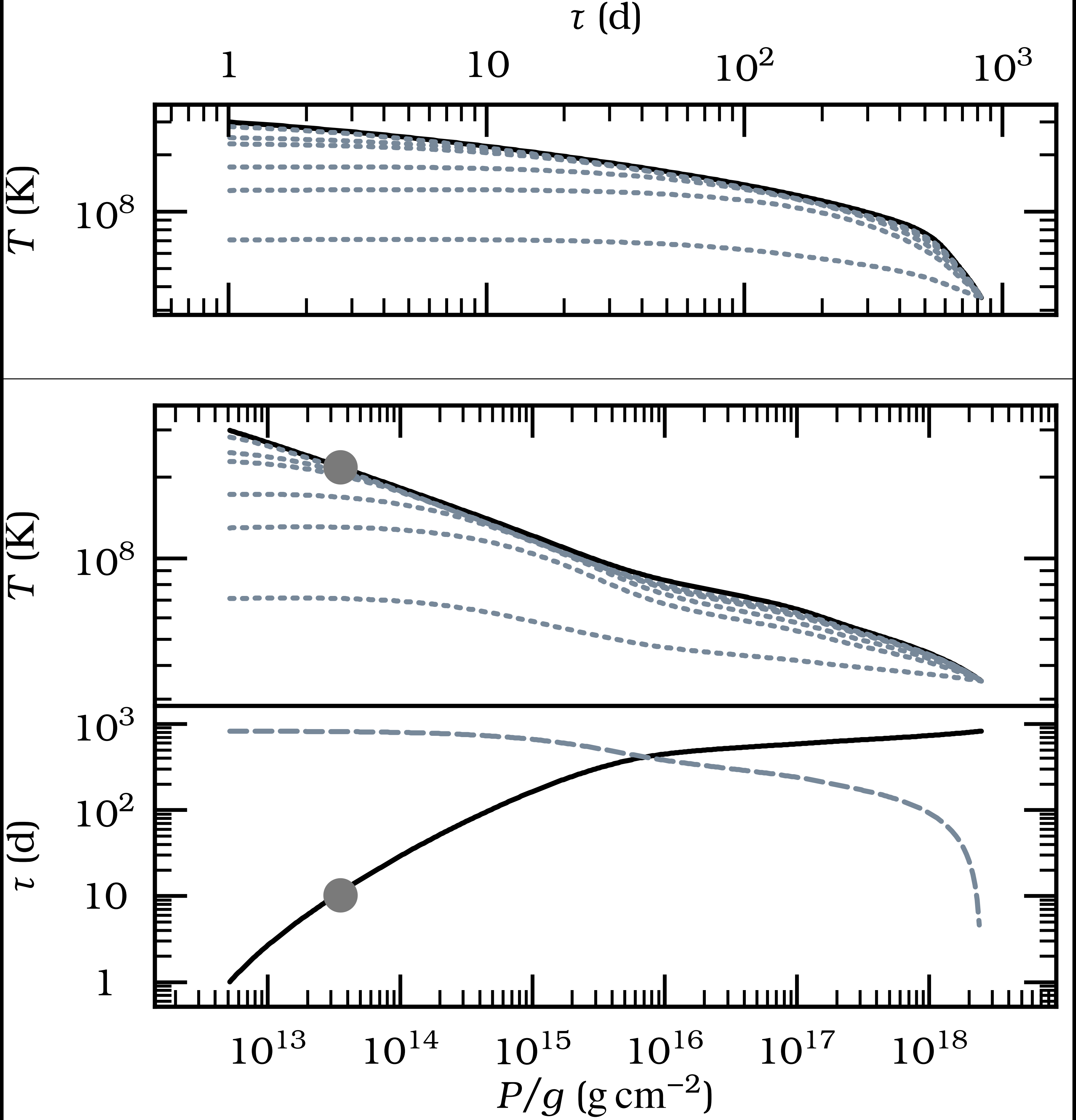

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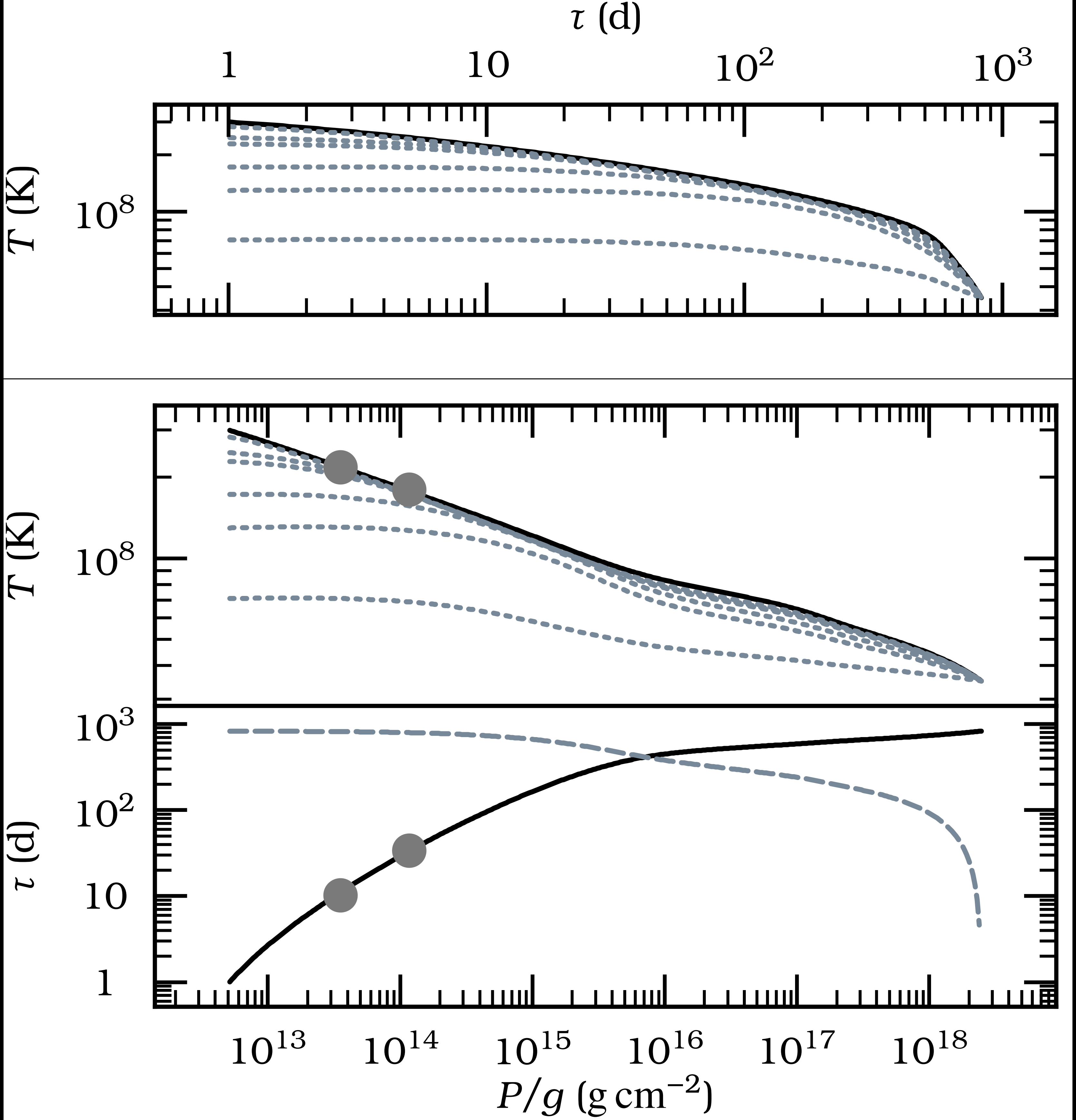

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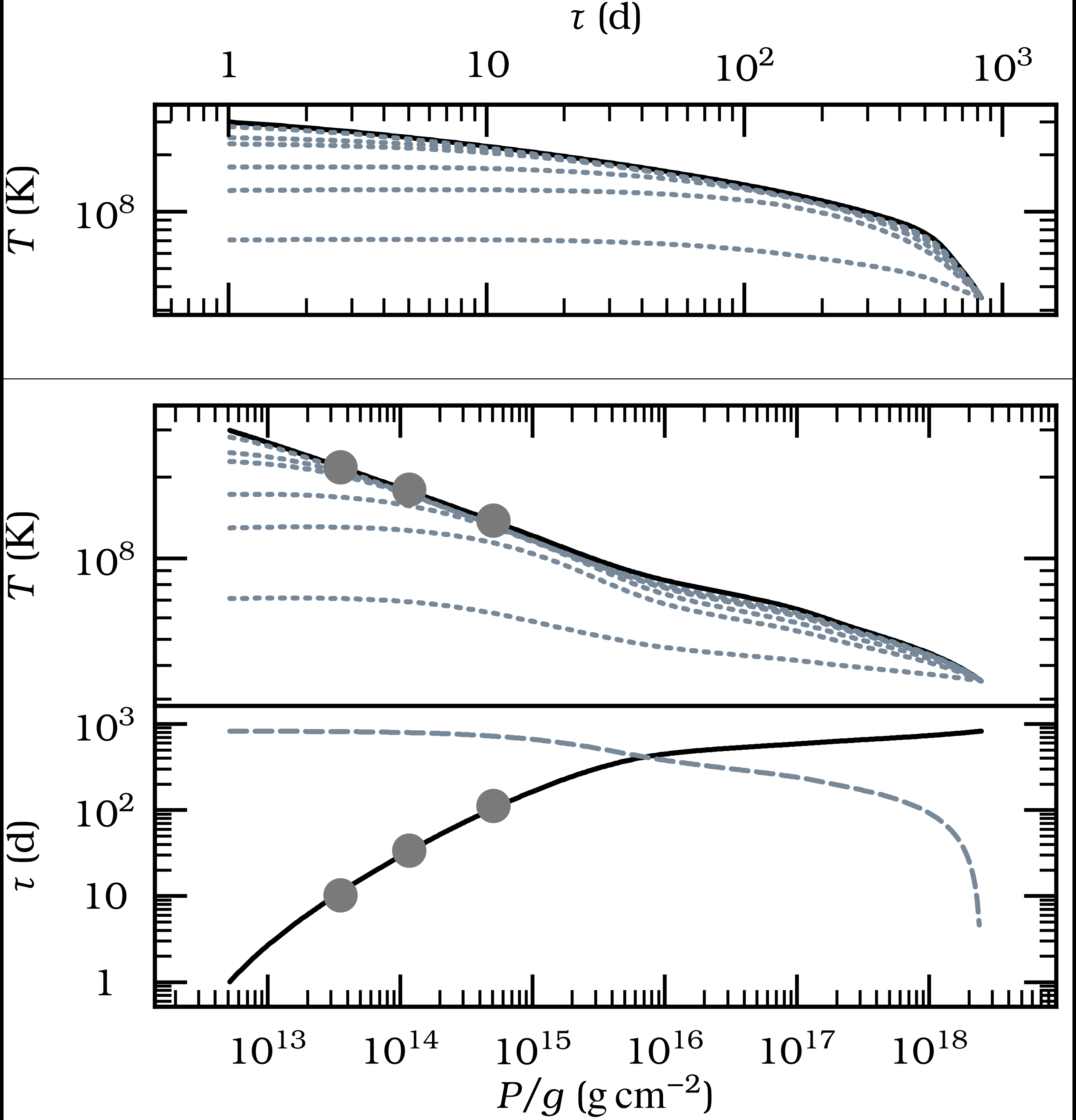
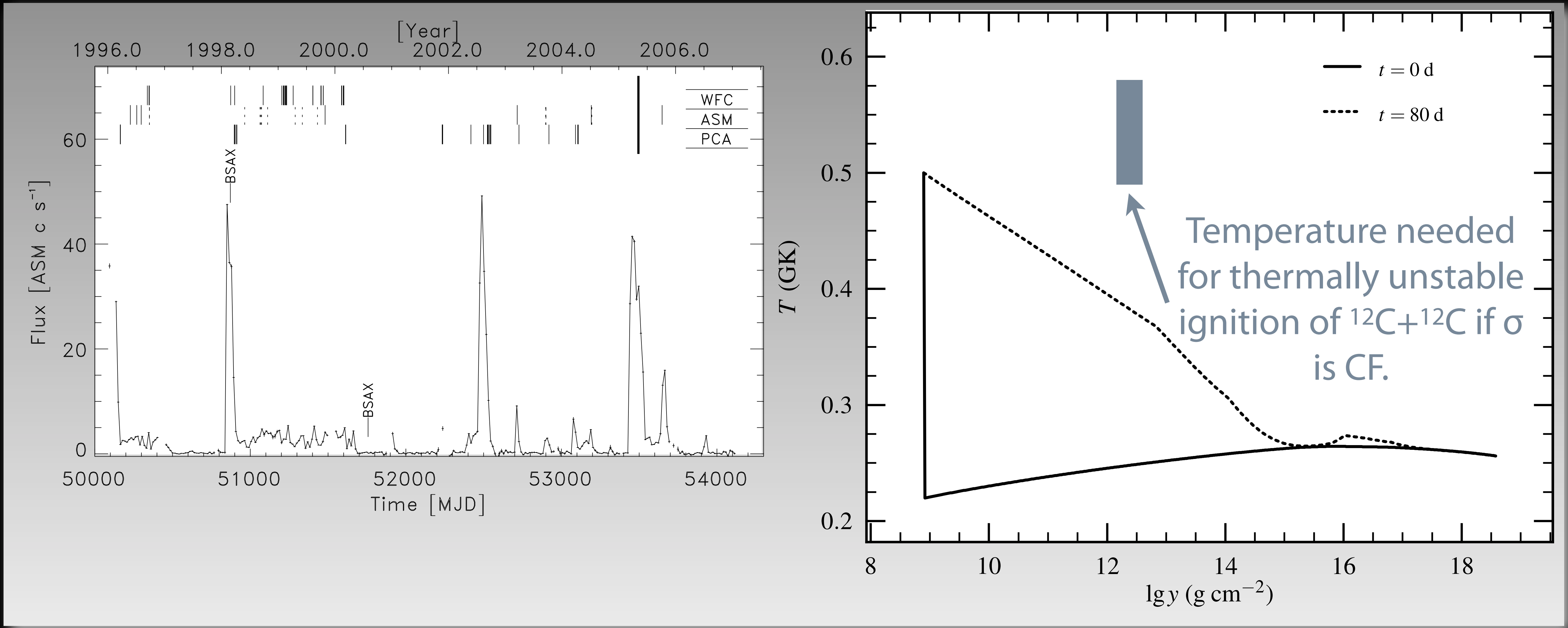




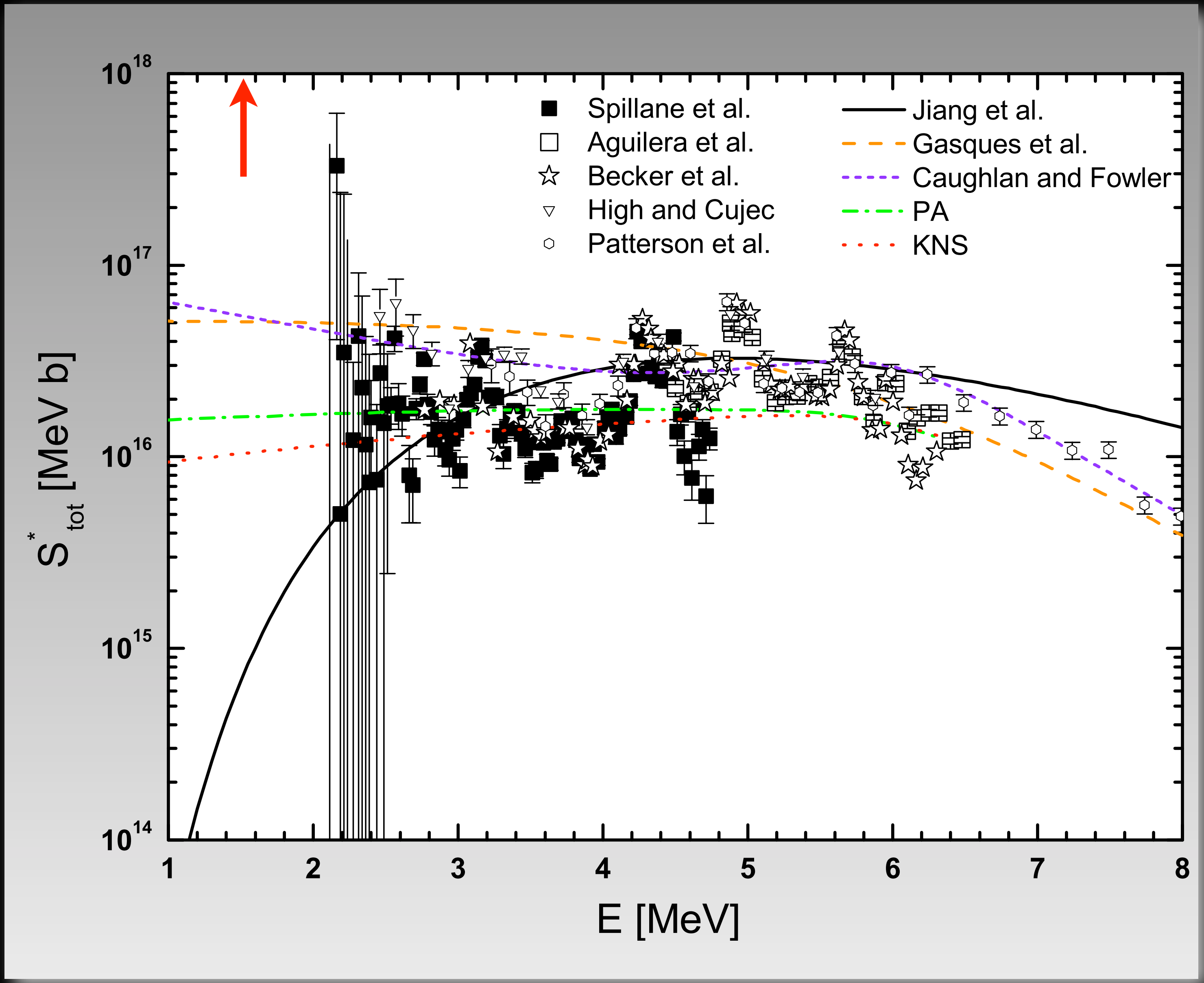
Temperature needed for thermally unstable ignition of $^{12}C+^{12}C$ if σ is CF.

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

A resonance in the ^{12}C + ^{12}C cross-section?

Cooper, Steiner, & Brown 2009

From Costantini et al. 2009, Rep. Prog. Phys.

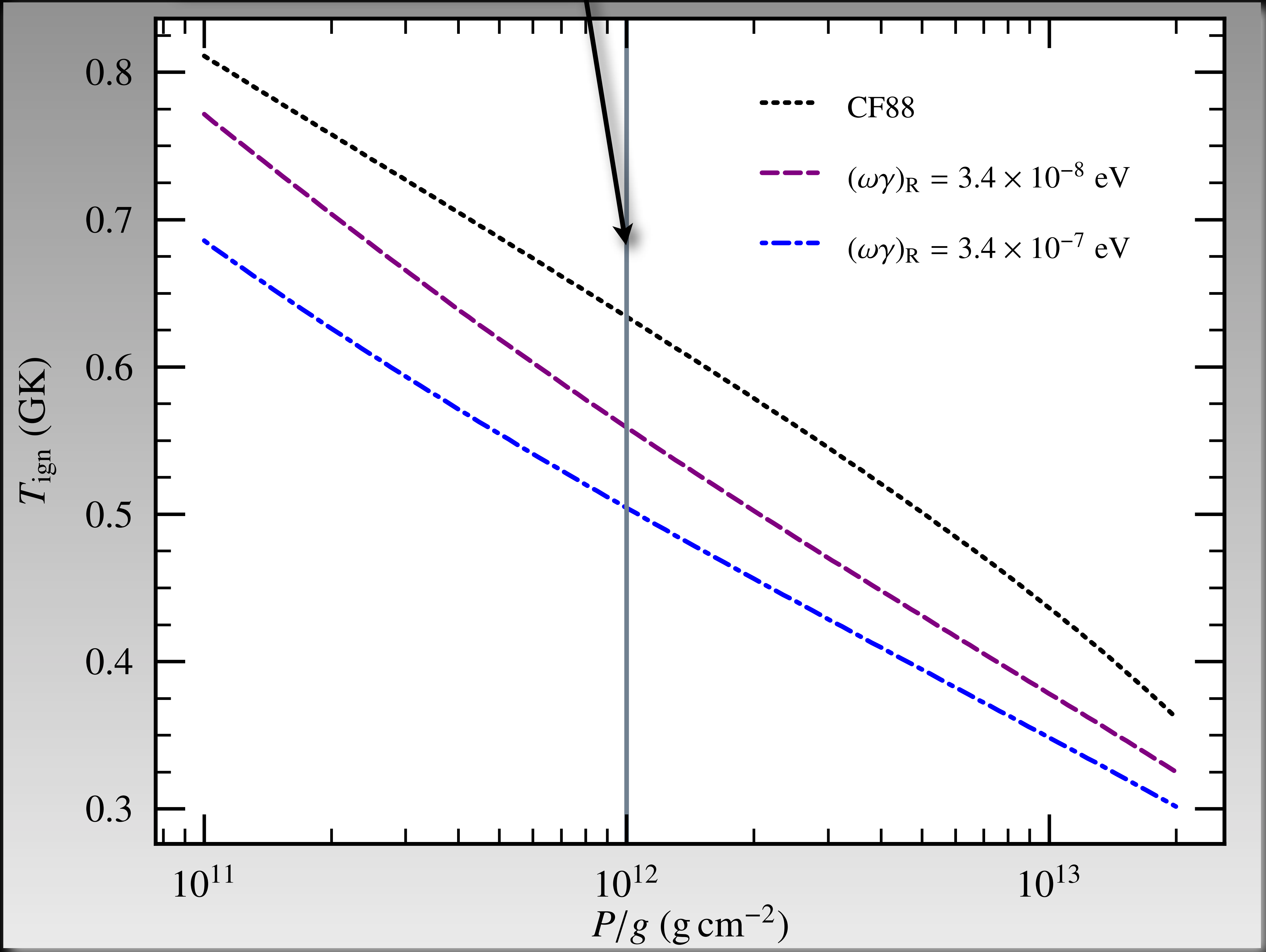


Resonances predicted at < 2 MeV

Perez-Torres et al. 2006

typical superburst
ignition depth

Cooper, Steiner, & Brown 2009



depth →

typical superburst
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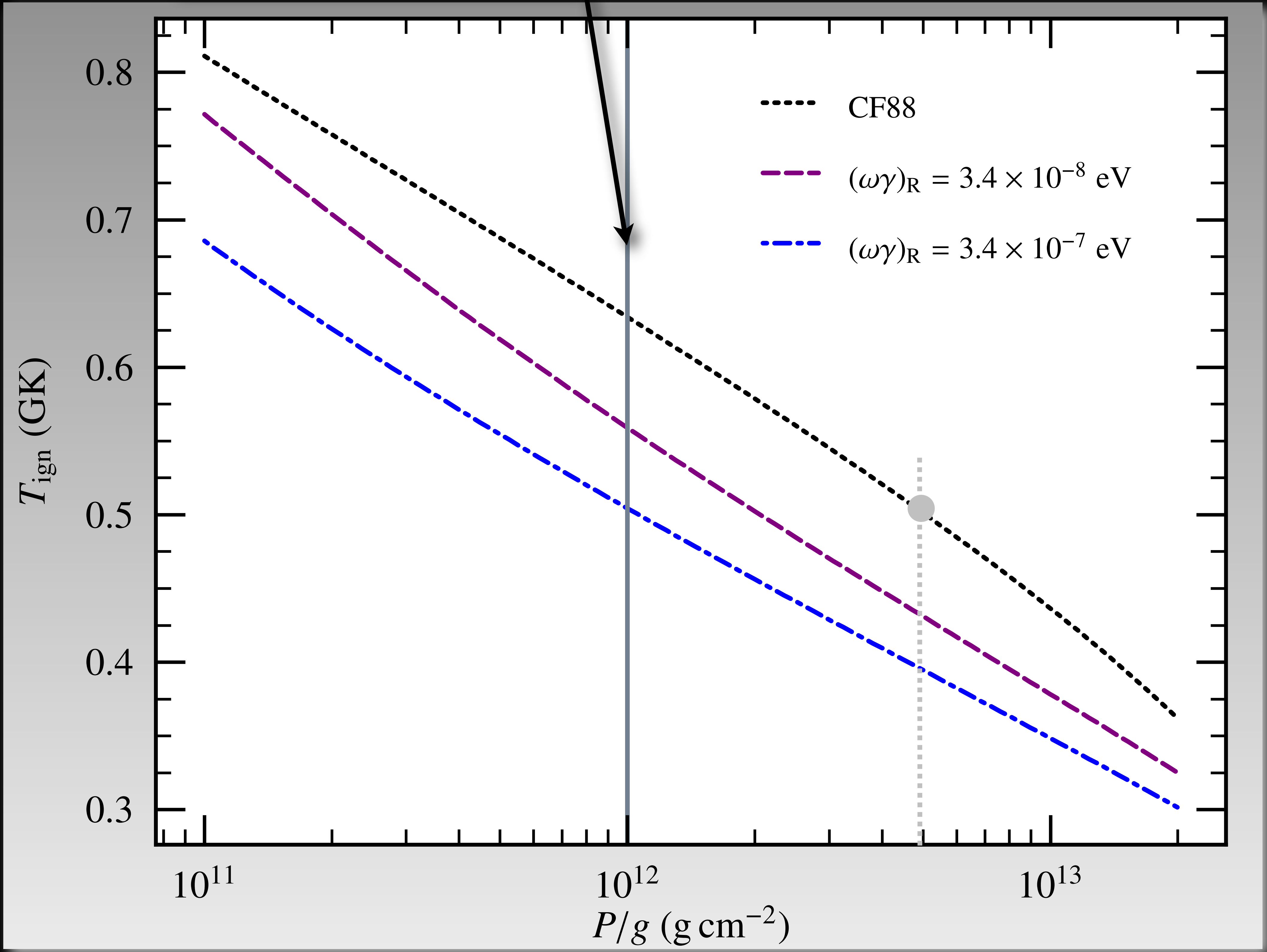
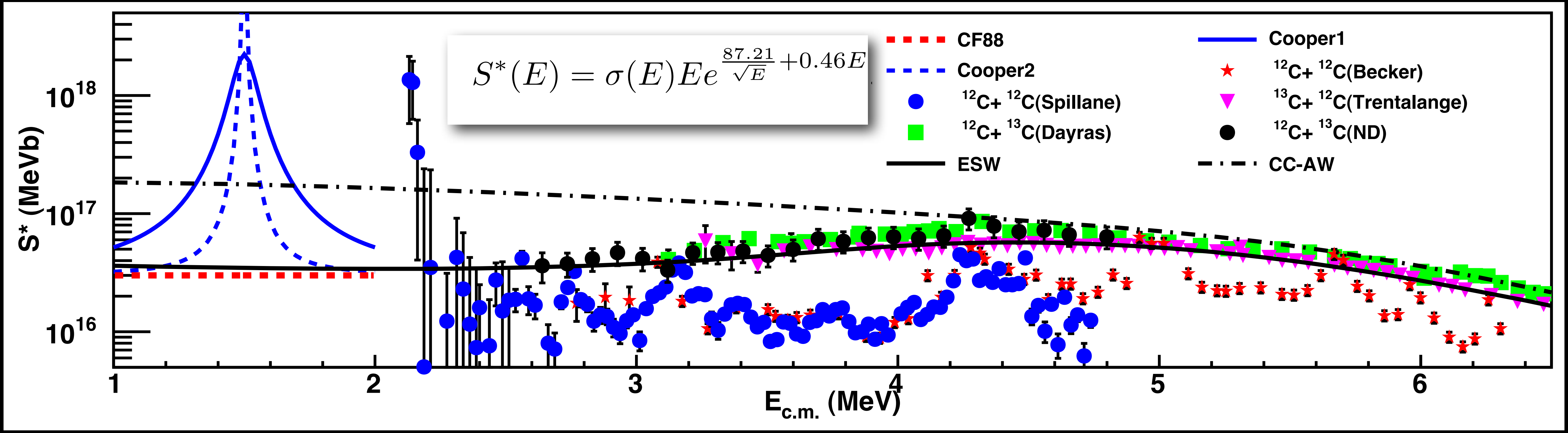
Cooper, Steiner, & Brown 2009

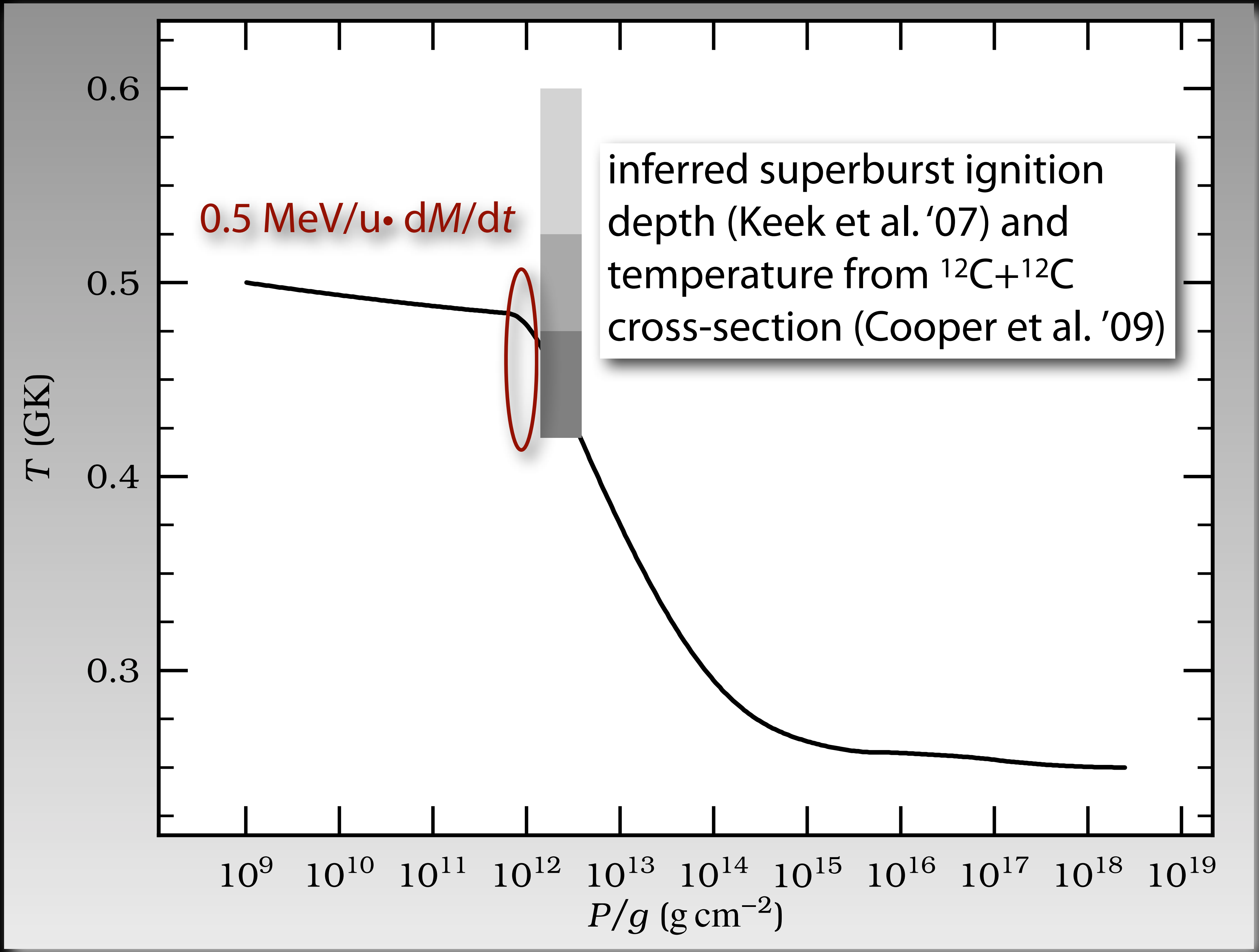


depth →



$$S^*(E) = \sigma(E) E e^{\frac{87.21}{\sqrt{E}} + 0.46E}$$

X-D Tang et al.: $^{12}C+^{12}C$ cross-section at most 6 times larger than CF88 value



inferred superburst ignition depth (Keek et al. '07) and temperature from $^{12}C+^{12}C$ cross-section (Cooper et al. '09)

4U 1608–522

Summary

Well-developed analytical and numerical theory of nuclear burning in neutron star envelopes

- Successfully reproduces bursting behavior in some sources
- For many sources, observed trends are not reproduced

Long bursts are useful probes of neutron star crust

- Complementary to observations of cooling in quasi-persistent transients (talk by Degenaar)
- Difficulty in explaining ignition of superbursts

one more thing…

XII International Symposium on Nuclei in the Cosmos

Cairns Convention Centre
Queensland, Australia
5th - 10th August 2012
WWW.NIC2012.ORG

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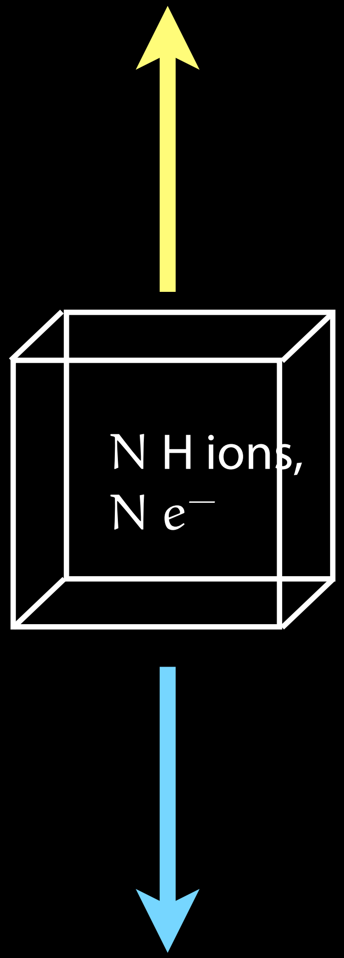
Eddington Limit

$$\frac{L}{c}\frac{N\sigma_{Th}}{4\pi r^2}$$

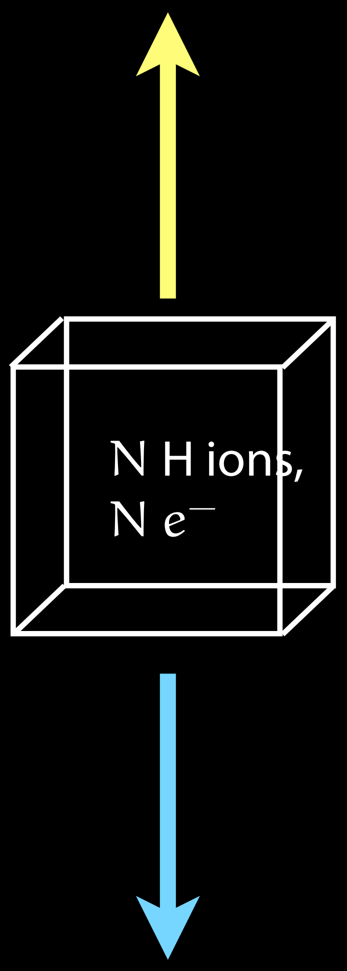


N H ions,
N e^-

$$N\frac{GMm_H}{r^2}$$

Eddington Limit

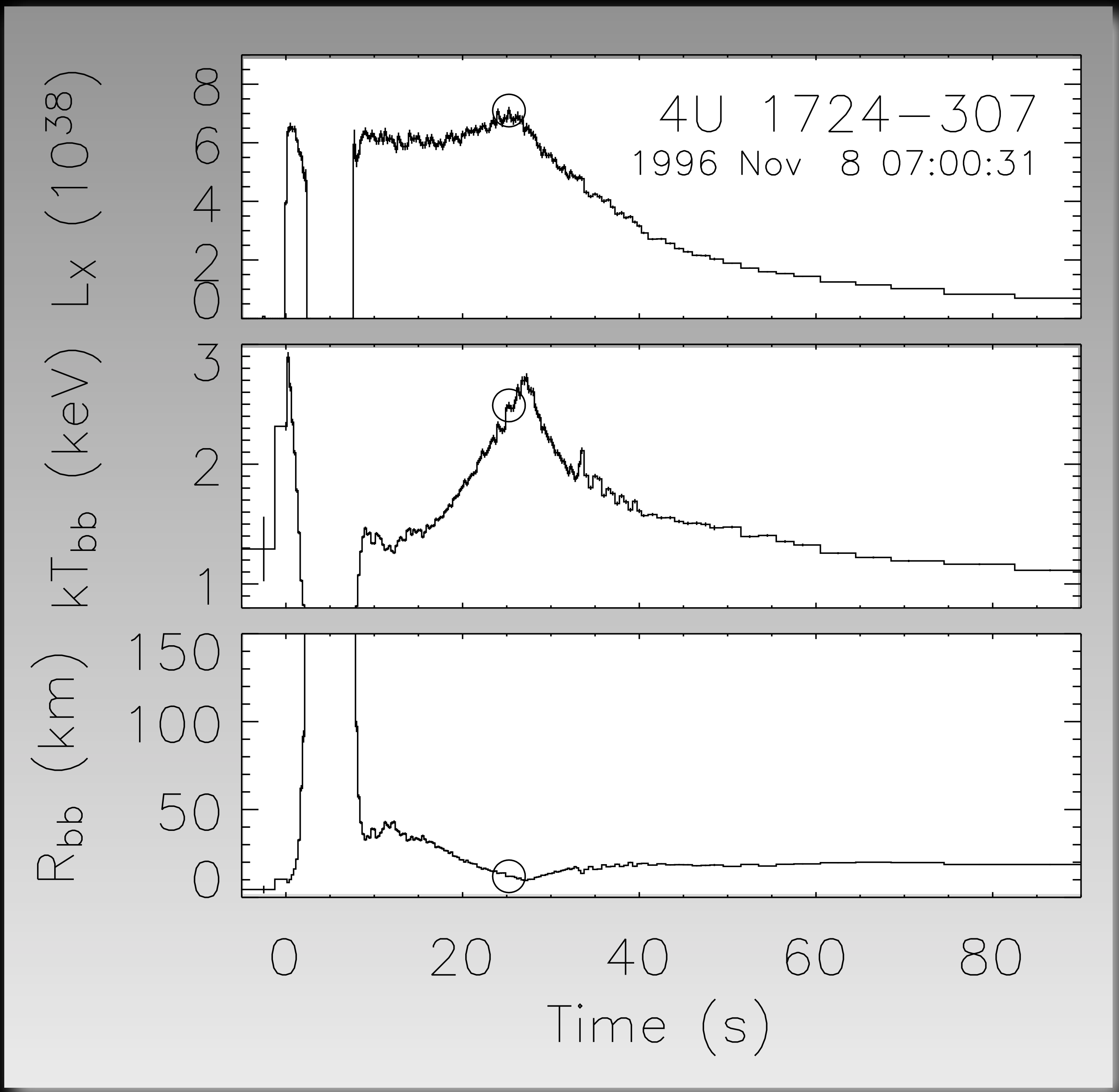
$$\frac{L}{c}\,\frac{N\sigma_{Th}}{4\pi r^2}$$



N H ions,
N e^-

$$N\,\frac{GMm_H}{r^2}$$

RXTE observations; Galloway et al. '08



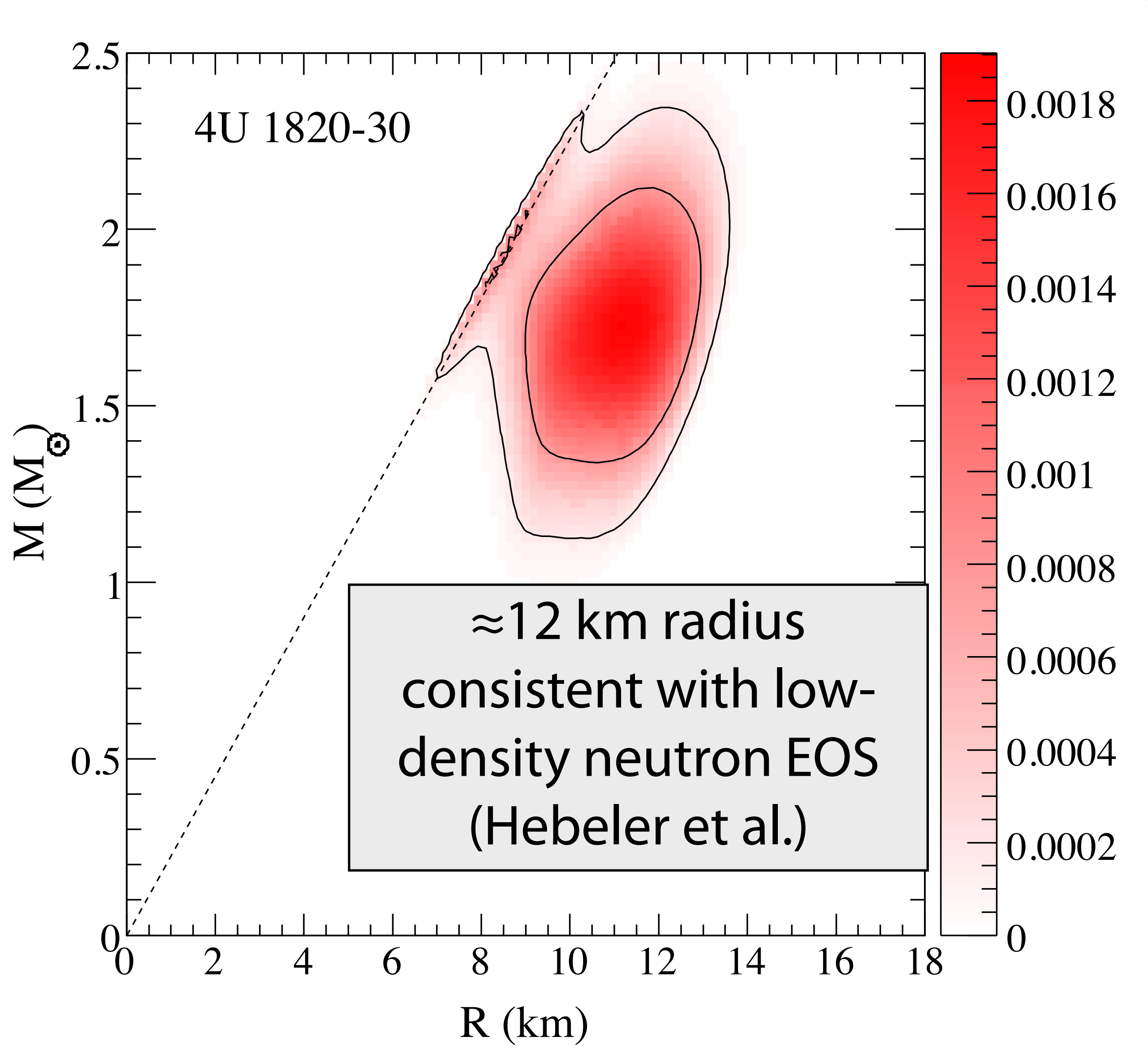
Bursts used to constrain neutron star mass, radius

see talks by Postnikov, Poutanen, Boutlakis, Majczyna

From X-ray bursts with *photospheric radius expansion* (van Paradijs, Özel et al., Steiner et al., Suleimanov et al.)

$$F_{\mathrm{Edd}} = \frac{GMc}{\kappa D^2}\left(1 - 2\frac{GM}{r_{\mathrm{ph}}c^2}\right)^{1/2}$$

$$\frac{F}{\sigma T_{\mathrm{eff}}^4} = \left(\frac{R}{D}\right)^2\left(1 - 2\frac{GM}{Rc^2}\right)^{-1}$$

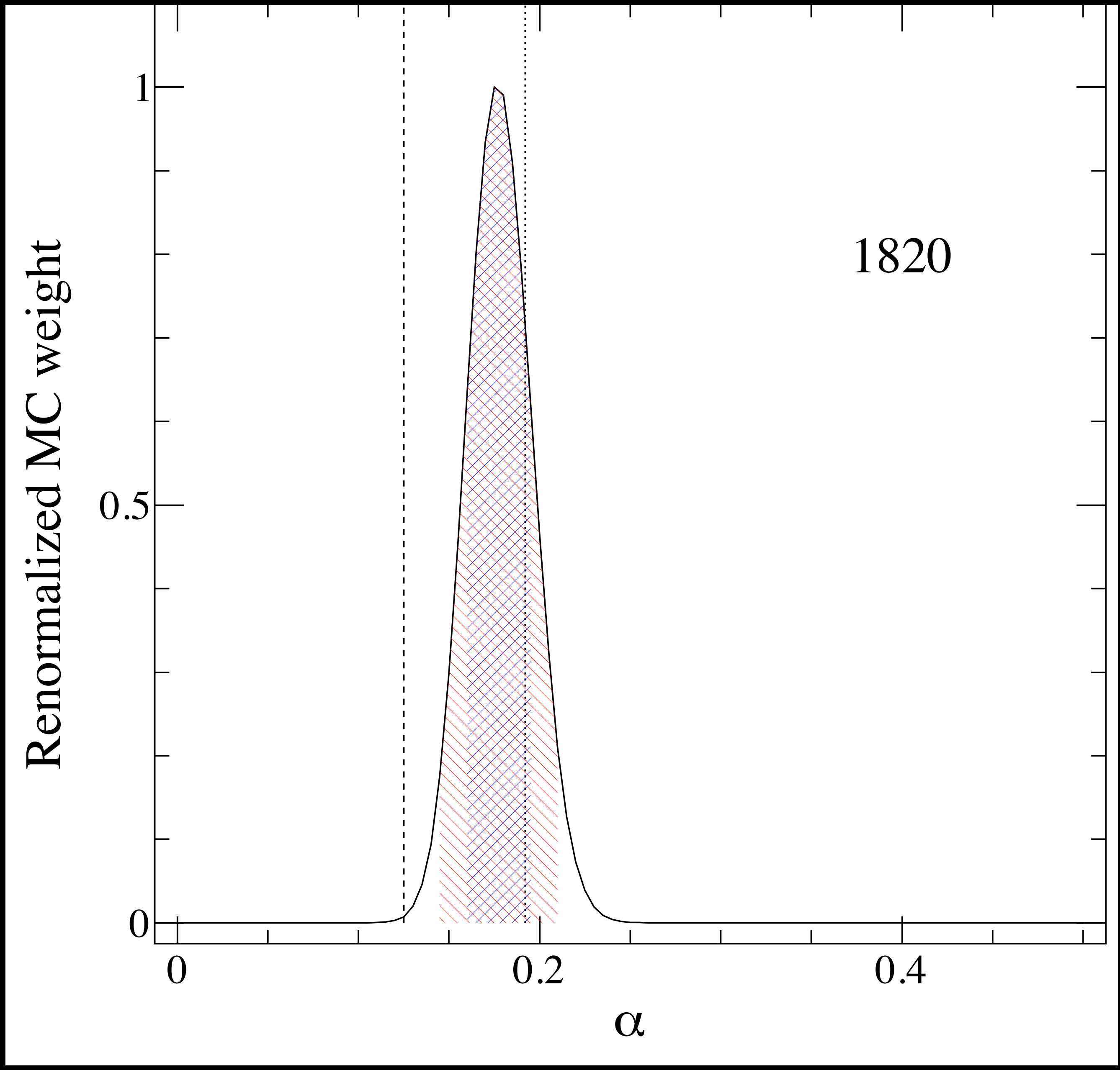


≈12 km radius consistent with low-density neutron EOS (Hebeler et al.)

Steiner et al.; data from Guver et al. '10

Is the model correct?

Central values of f_c, D, X_H do not produce solutions for M, R



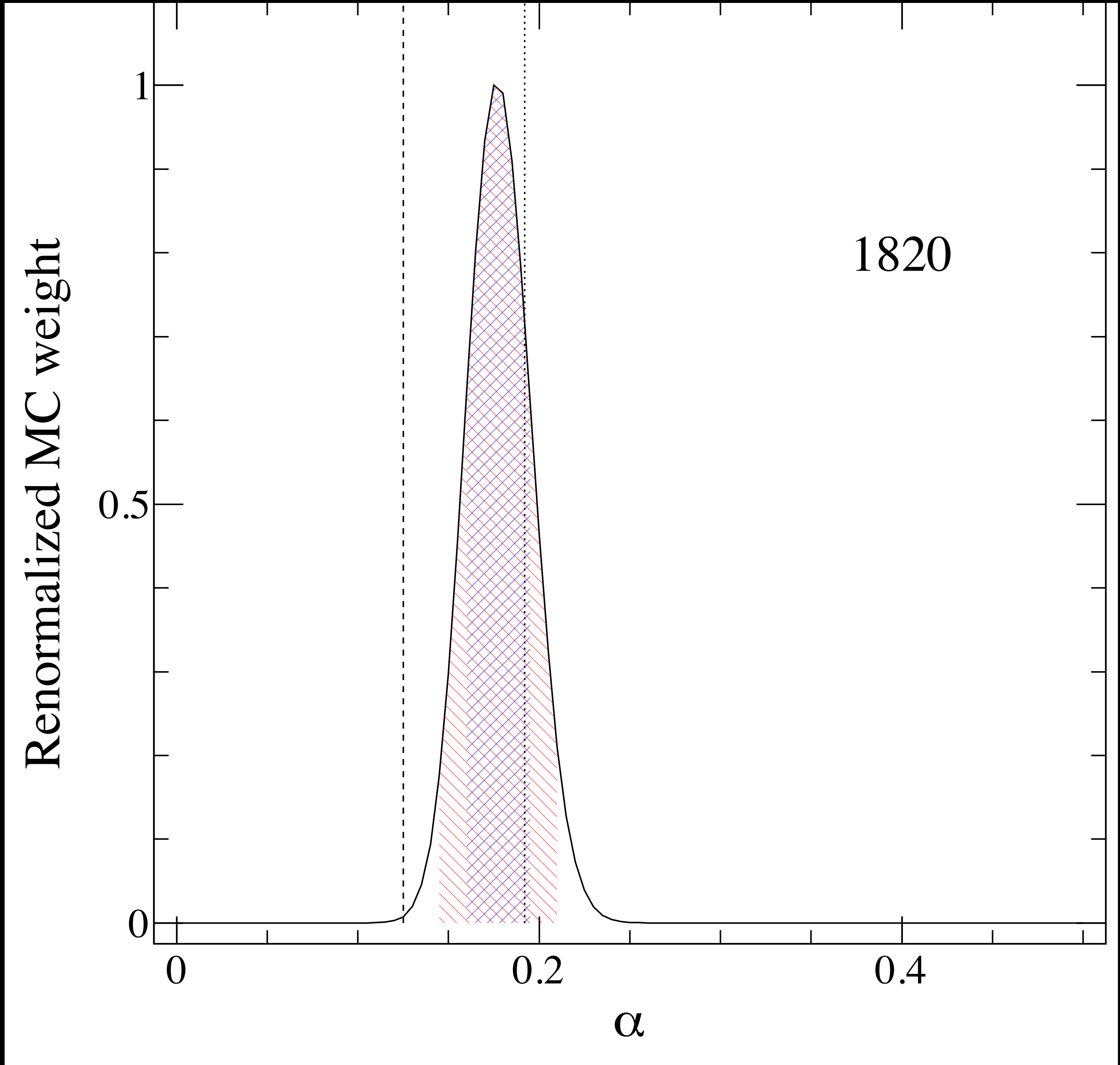
Is the model correct?

Central values of f_c, D, X_H do not produce solutions for M, R

$$\frac{GM}{Rc^2} = \frac{1}{4} \pm \frac{1}{4}\sqrt{1-8\alpha}$$

$$\alpha = \frac{F_{TD,\infty}}{\kappa D} c^3 f_c^2 \sqrt{\frac{\sigma T^4_{bb,}}{F_{tail,}}}$$

For a real-valued solution, $\alpha < 1/8$.



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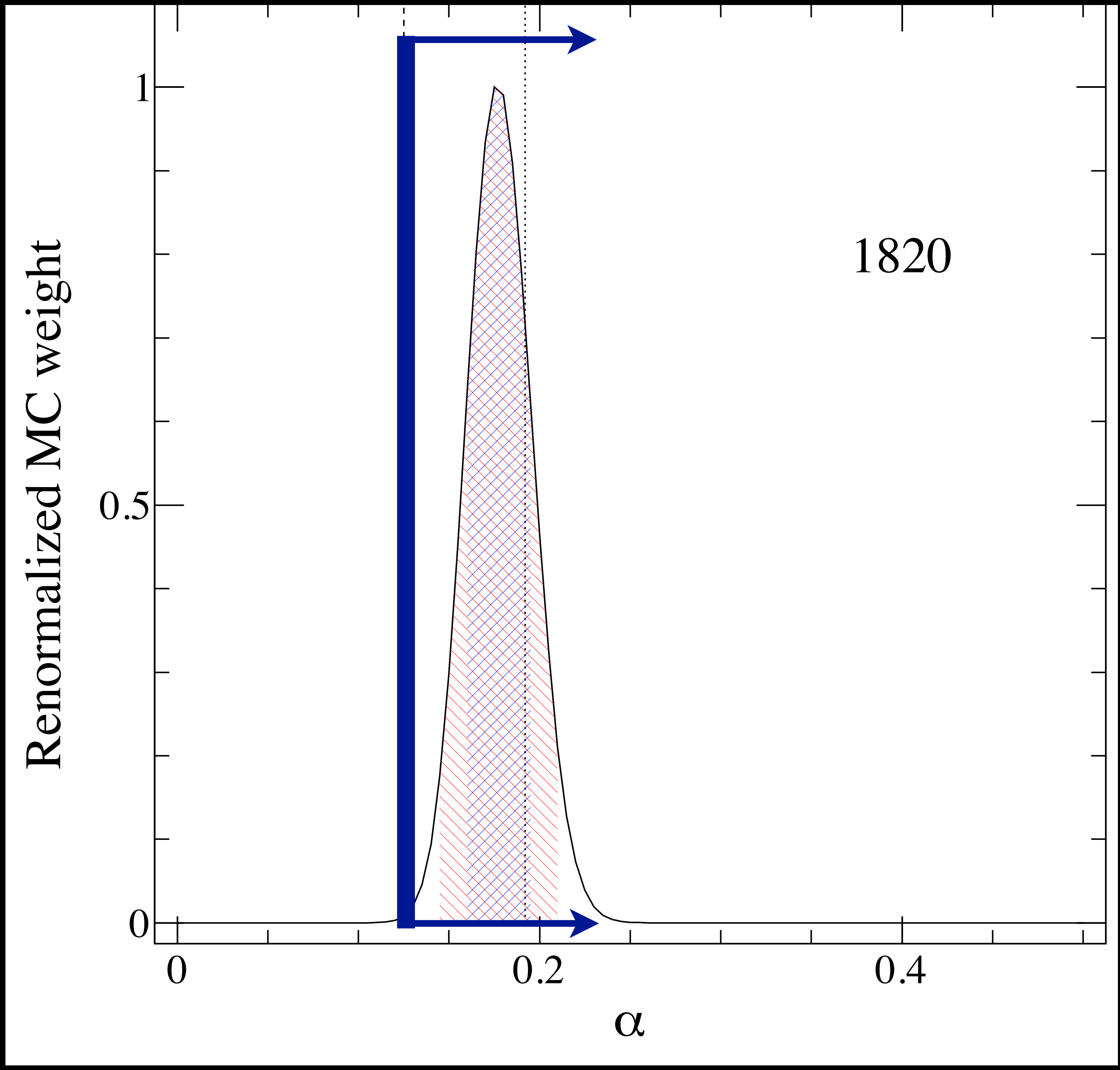


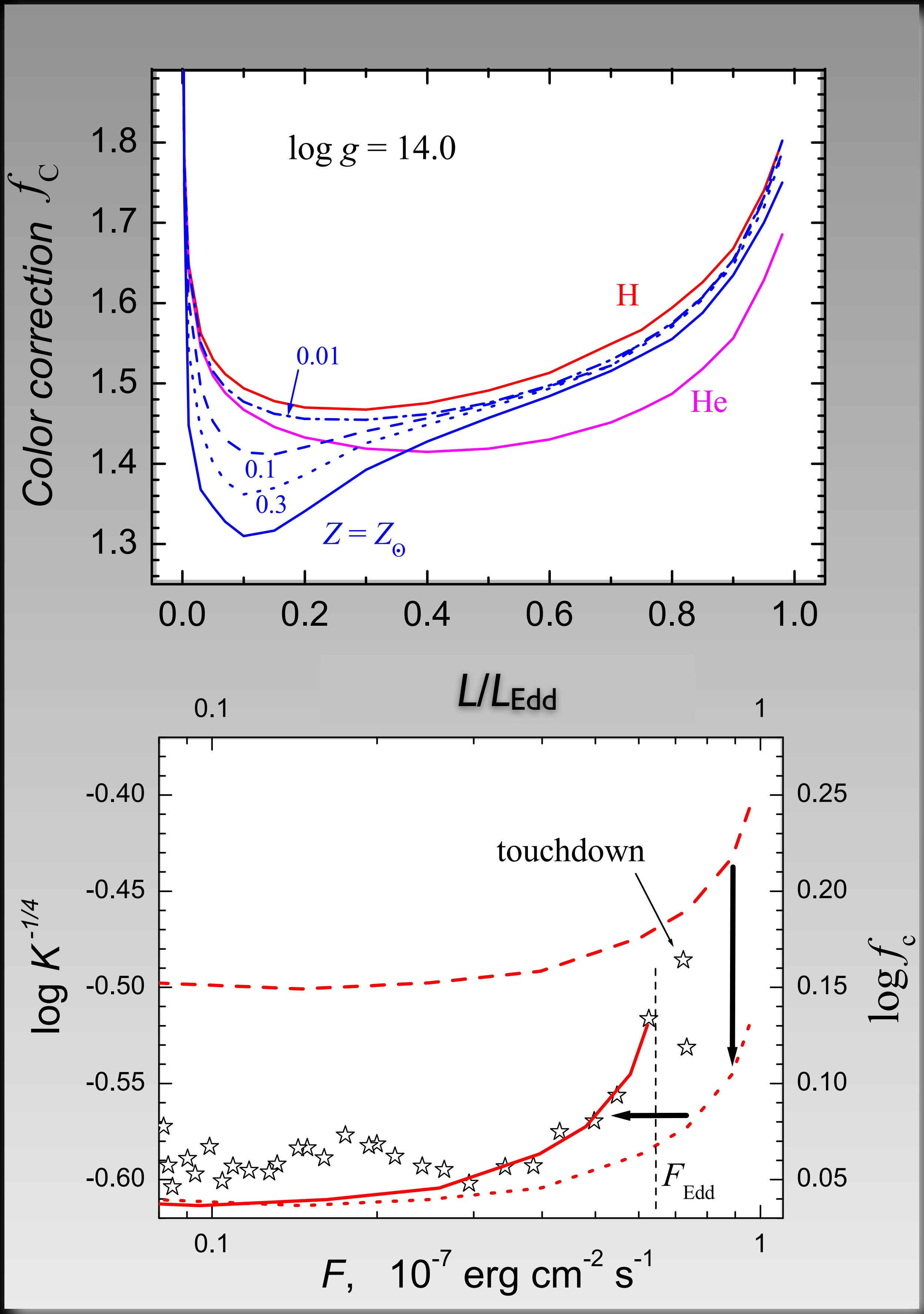
Systematic uncertainties (Suleimanov et al.)

model spectral evolution over entire burst: check on whether model matches burst behavior

touchdown flux > Eddington

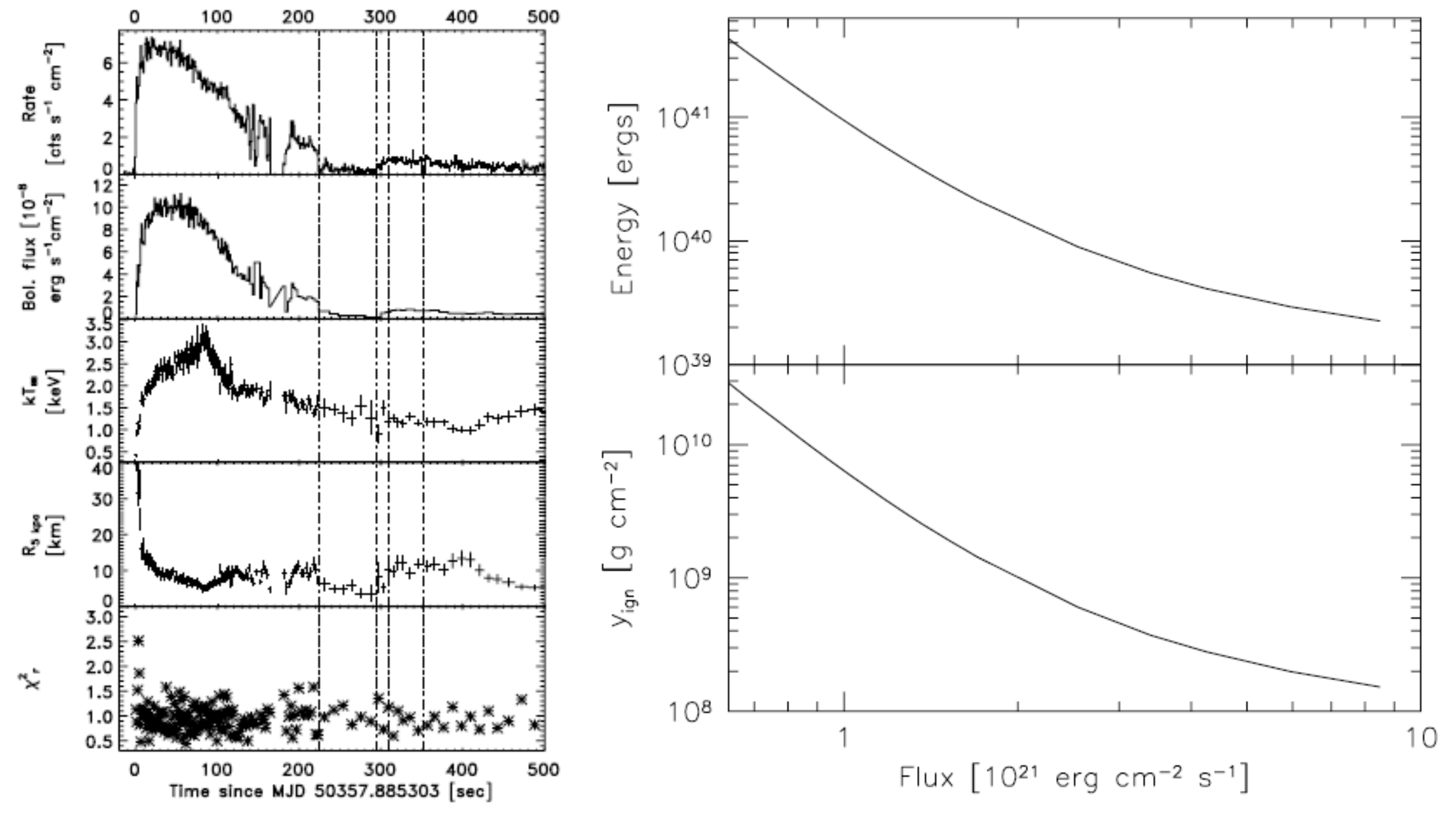
color correction factor f_C is not constant, and it depends on composition

NB. $f_c \equiv \frac{T_{bb}}{T_{eff}}$



Long (He) X-ray bursts in 2S 0918–549

(in ‘t Zand ‘05)



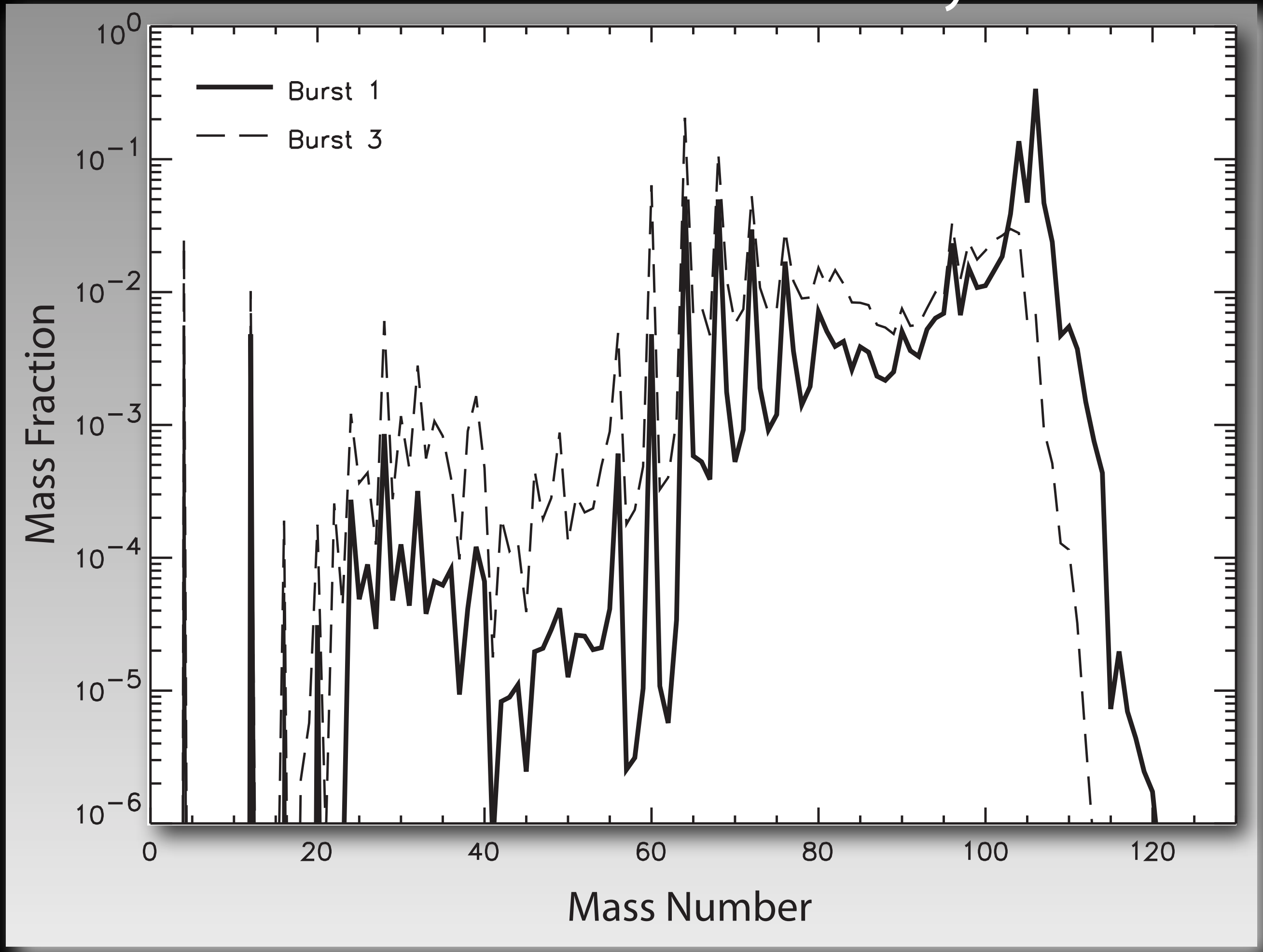
How impure is the crust?

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

$$D \propto \nu\,(n\sigma)^{-1}$$

$$\sigma \propto \left\langle (Z - \langle Z\rangle)^2 \right\rangle$$

X-ray burst calculation from
Woosley et al. 2004



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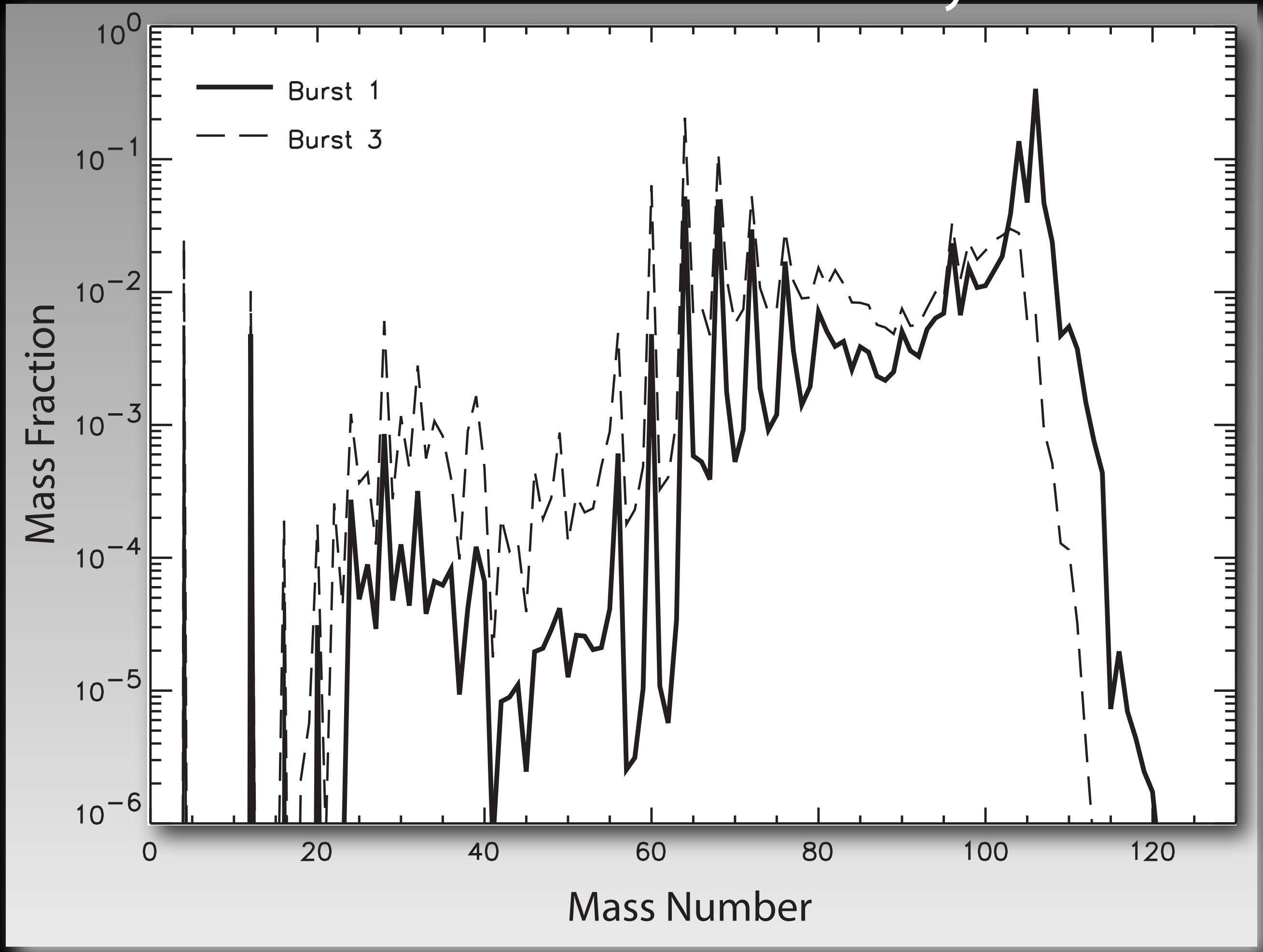
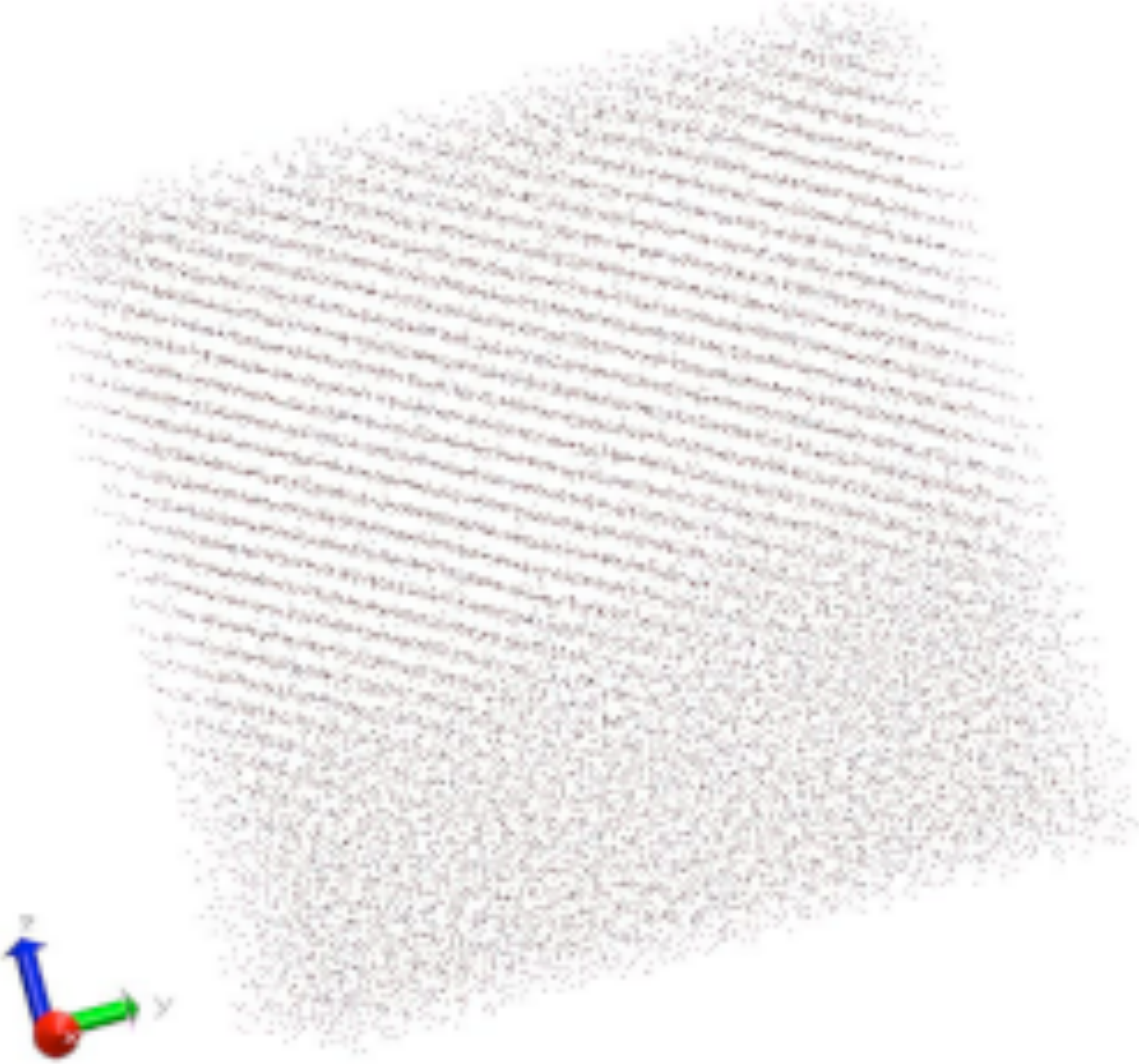
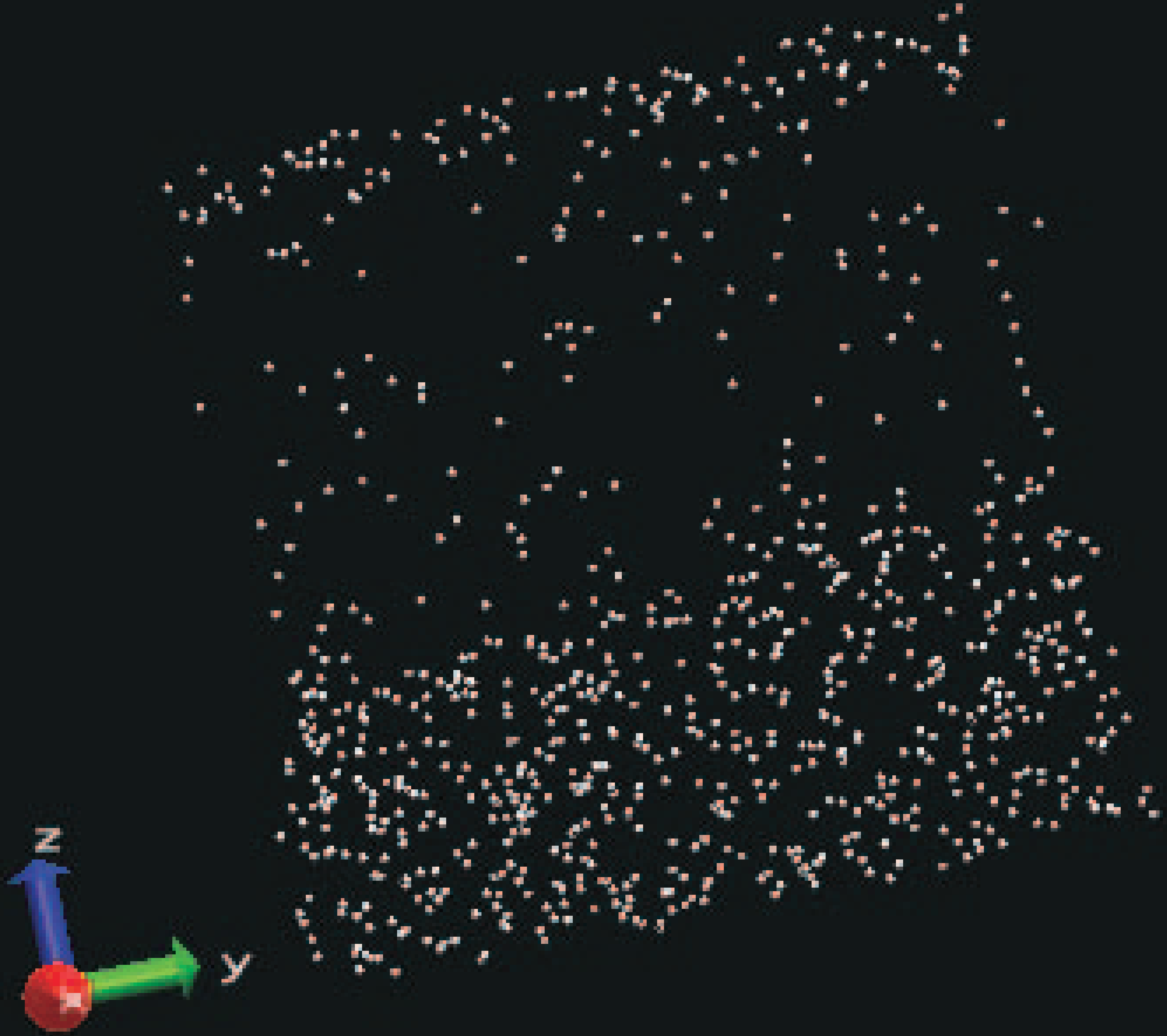


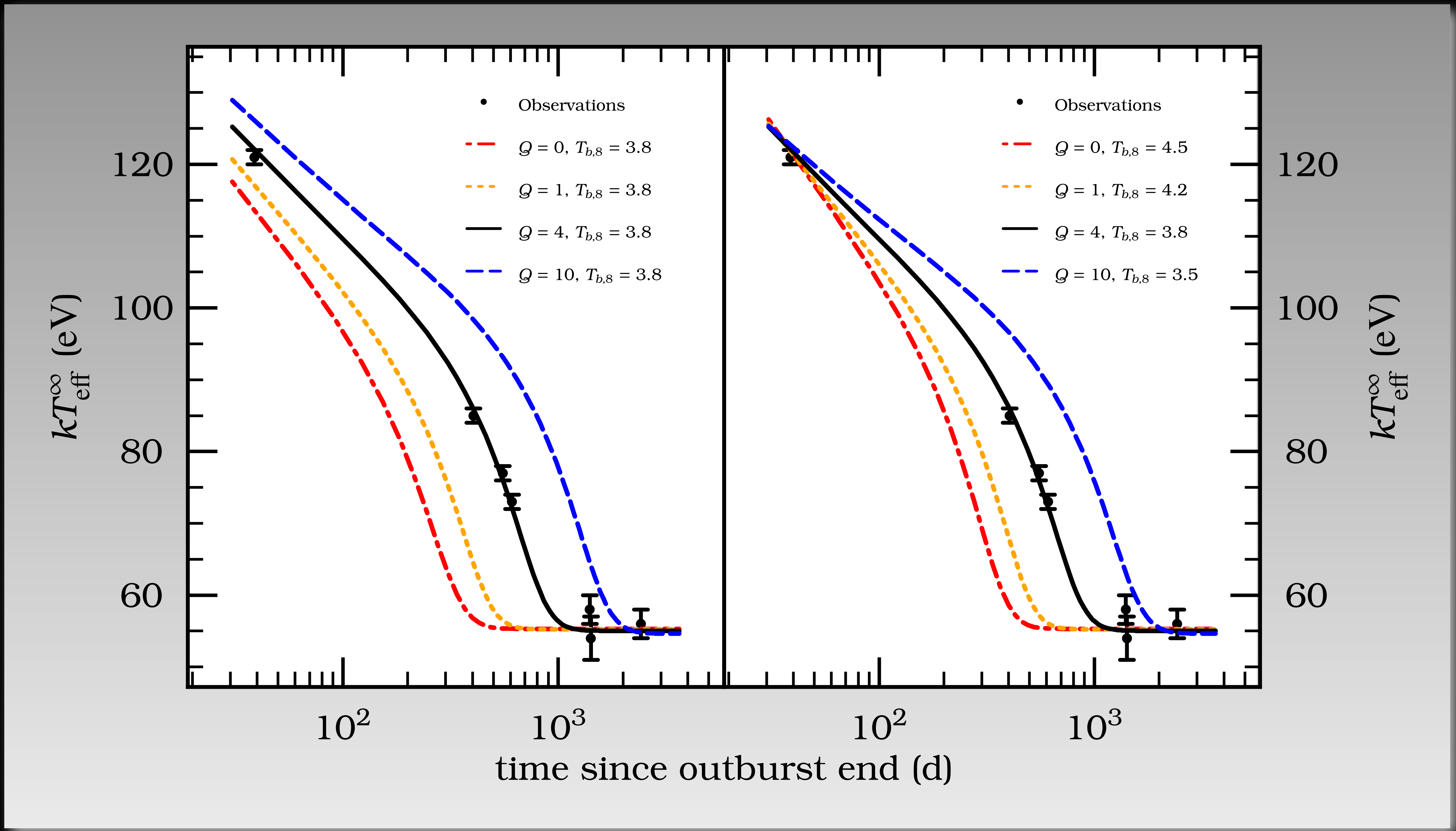
for this mixture, $\left\langle \left(Z - \langle Z\rangle\right)^2 \right\rangle \approx 100$


z
y


z
y

How impure is the crust? $Q < 10$

Shternin et al. 2007; Brown & Cumming 2009



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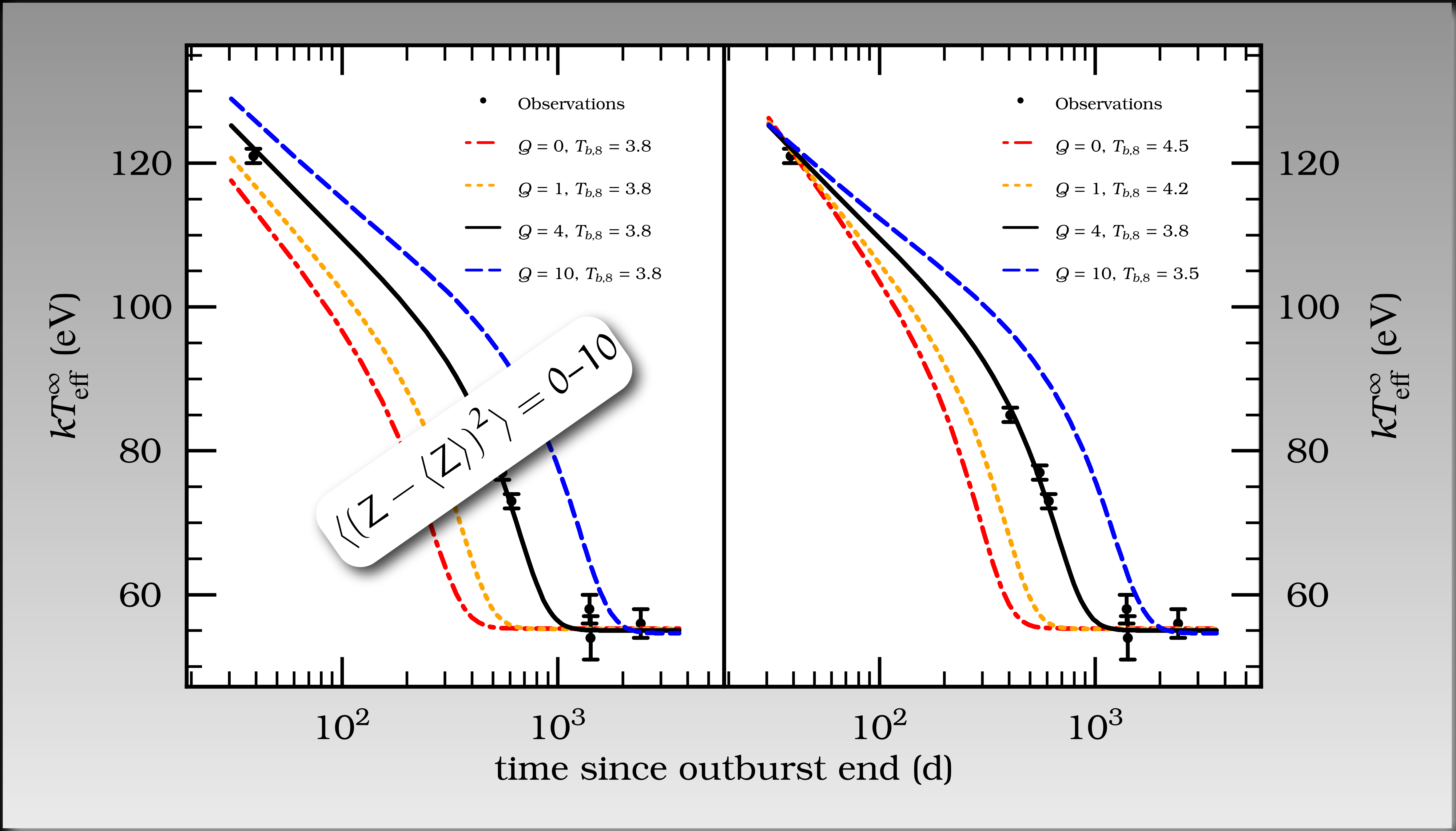

$\langle (Z - \langle Z \rangle)^2 \rangle = 0\text{–}10$