Nuclear burning on accreting neutron stars

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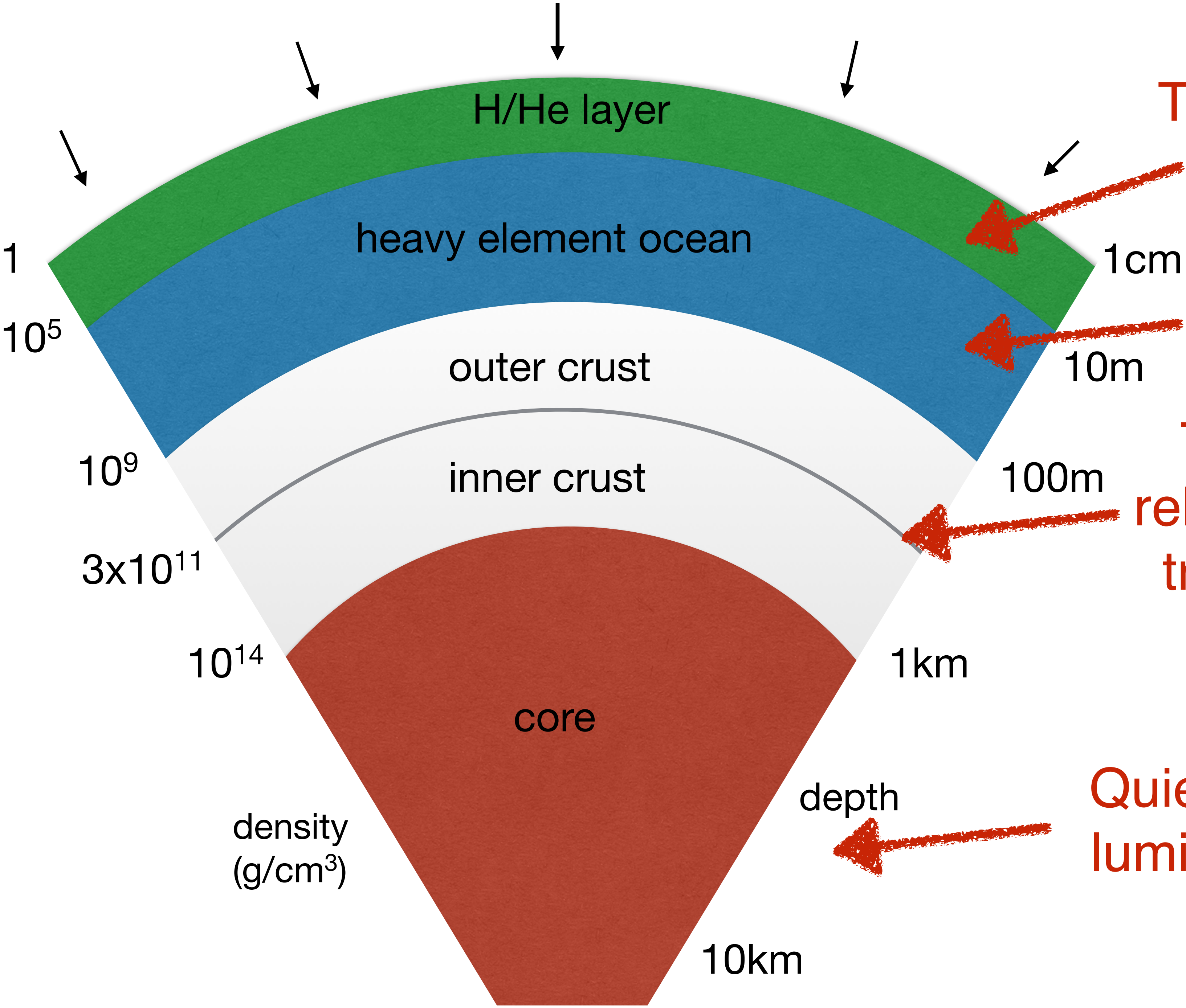
An exciting time to study accreting neutron stars



Type I X-ray bursts

Superbursts

Thermal relaxation in transients

Quiescent luminosity

Open questions

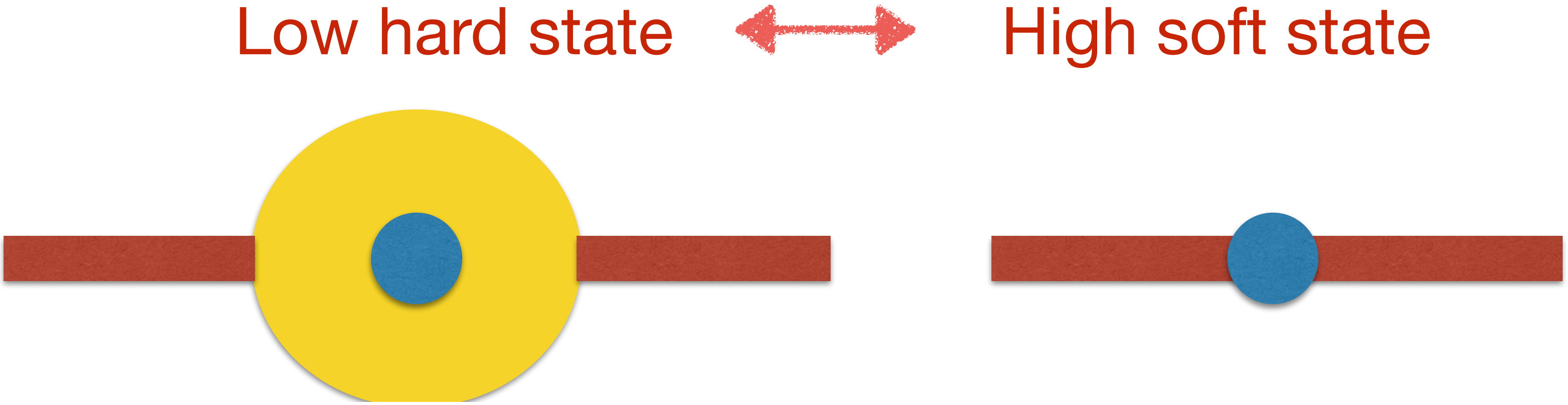
How to ignite superbursts?

Why is the outer crust hot in cooling transients?

Why does the X-ray burst rate drop off at accretion rates > 0.1 Eddington?

What causes burst oscillations?

Why does the colour correction dependence on flux change with accretion state?



Low hard state ↔ High soft state

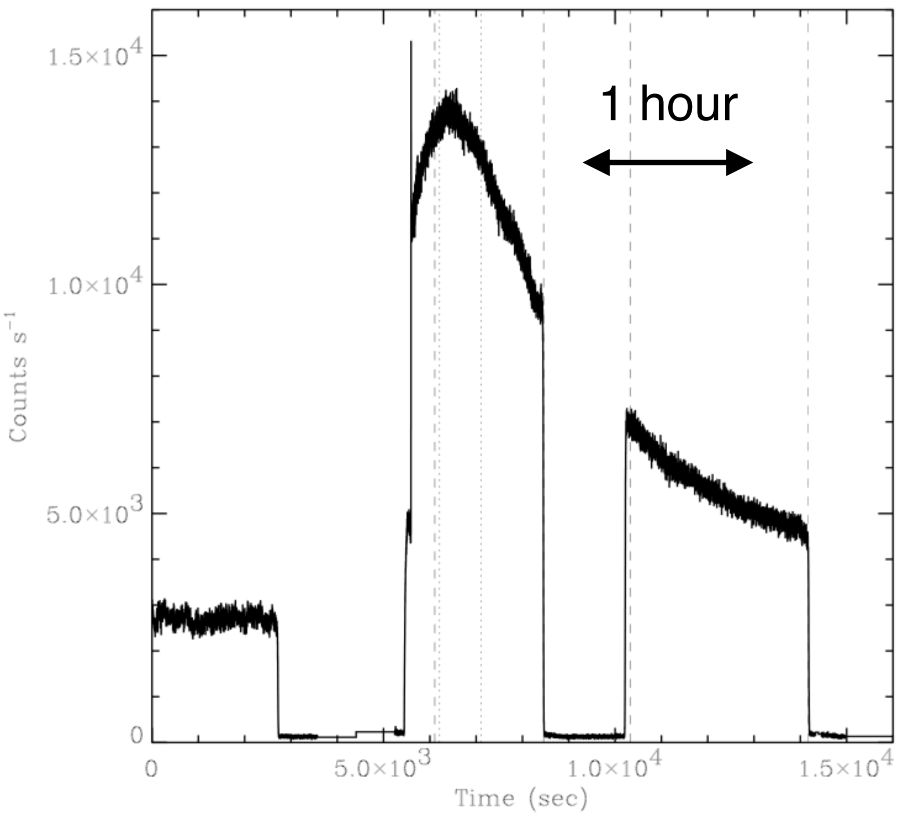
Outline

1. Superbursts
- how to achieve ignition temperature
- how to make the carbon

2. mHz QPOs
- marginally stable burning
- interaction with Type I X-ray bursts

3. A global view of nuclear burning on accreting neutron stars

Observed properties of superbursts



4U 1636-53 Strohmayer & Markwardt (2002)

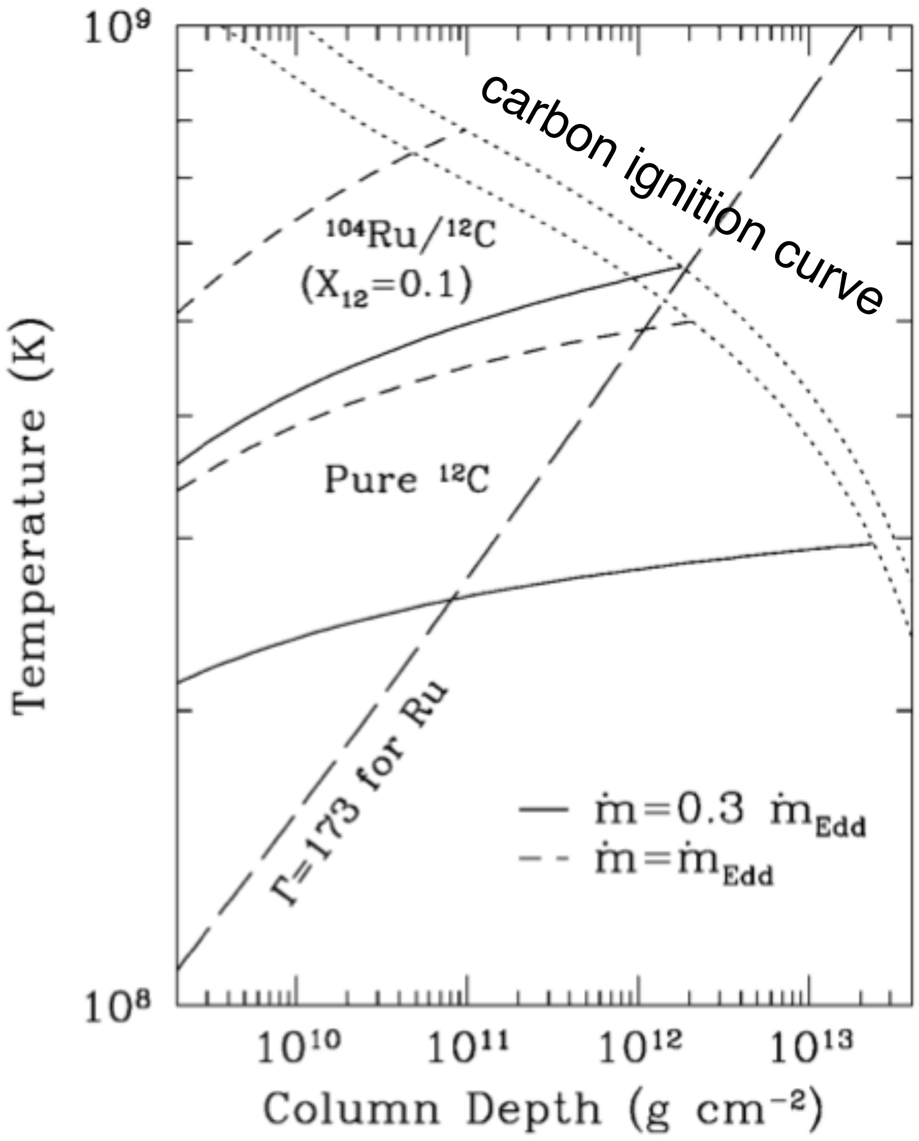
energy ~ 10^{42} erg
durations ~ hours
recurrence times ~ years
accretion rates >~ 0.1 Eddington

for a 1 MeV/nucleon energy release, need a mass of 10^{24}g, or column depth 10^{11} g/cm^2

1000x typical X-ray burst

see Keek & in ’t Zand (2008) for a summary of properties

Carbon ignition in a heavy-element ocean



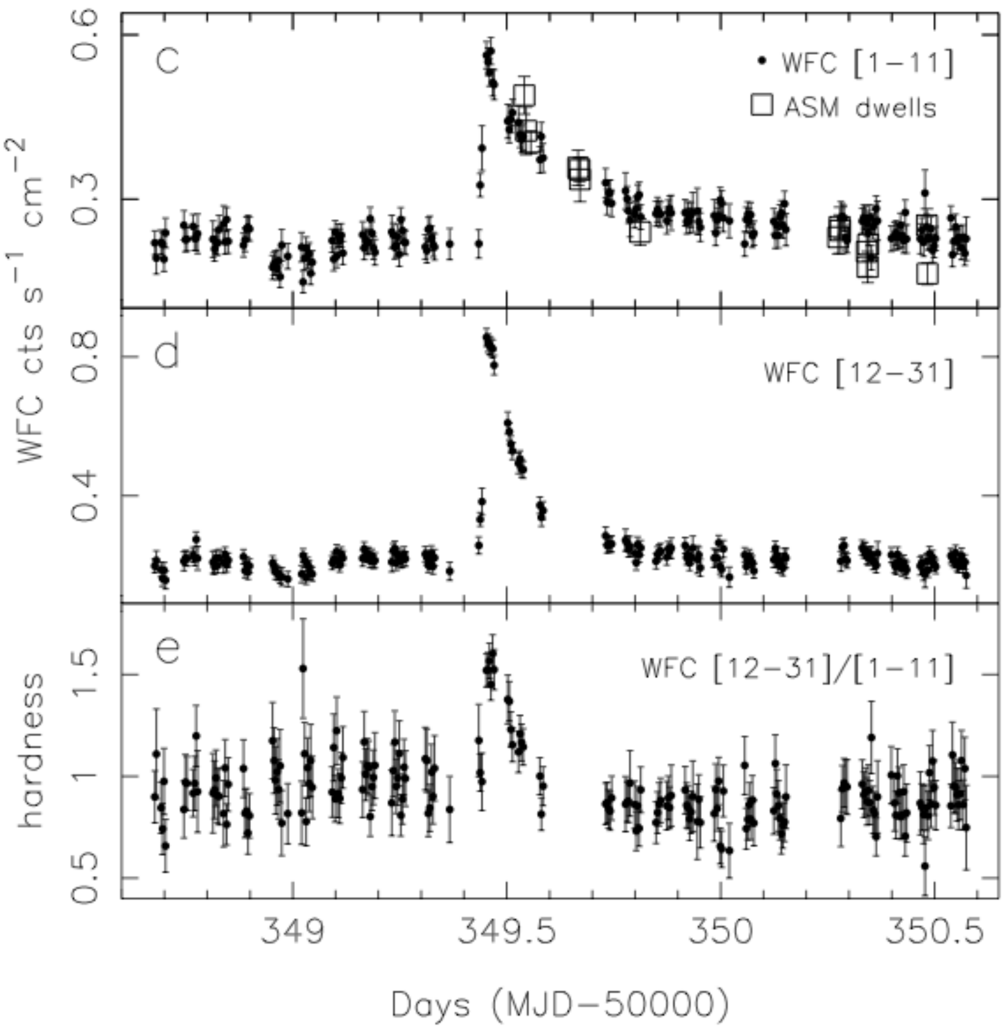
General picture: ignition of the ashes of H/He burning. Approximately 10-20% carbon by mass in a heavy element ocean

Brown (2004) pointed out that superbursts probe the temperature of the crust
(also Cooper & Narayan 2005)

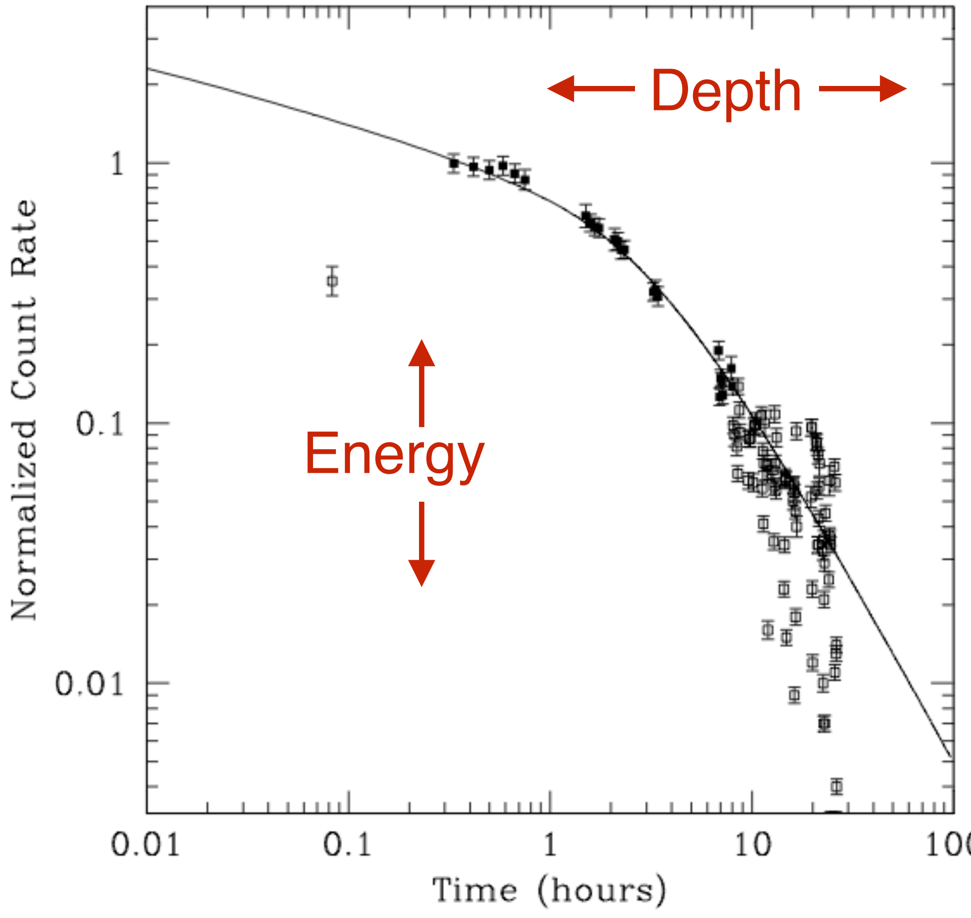
Cumming & Bildsten (2001), Strohmayer & Brown (2002)

Successes: lightcurves and quenching

Lightcurve is a broken power law (Cumming & Macbeth 2004); explains long tails noticed by Kuulkers



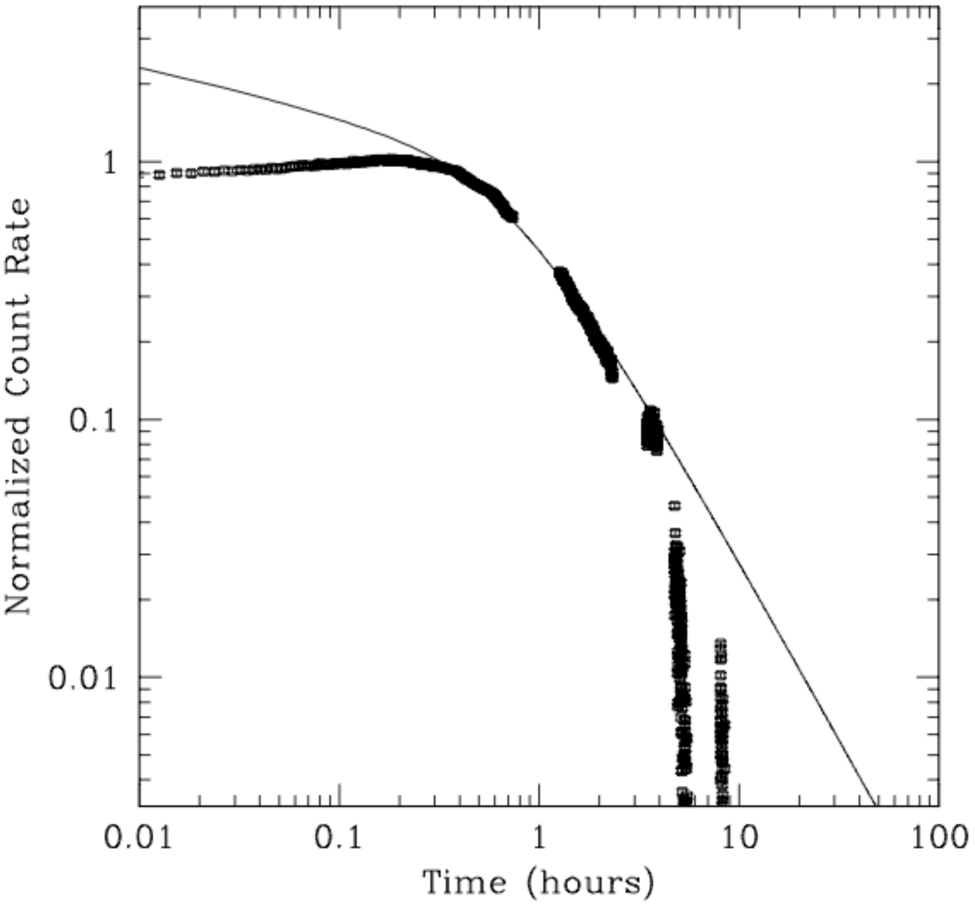
Kuulkers et al. (2002)

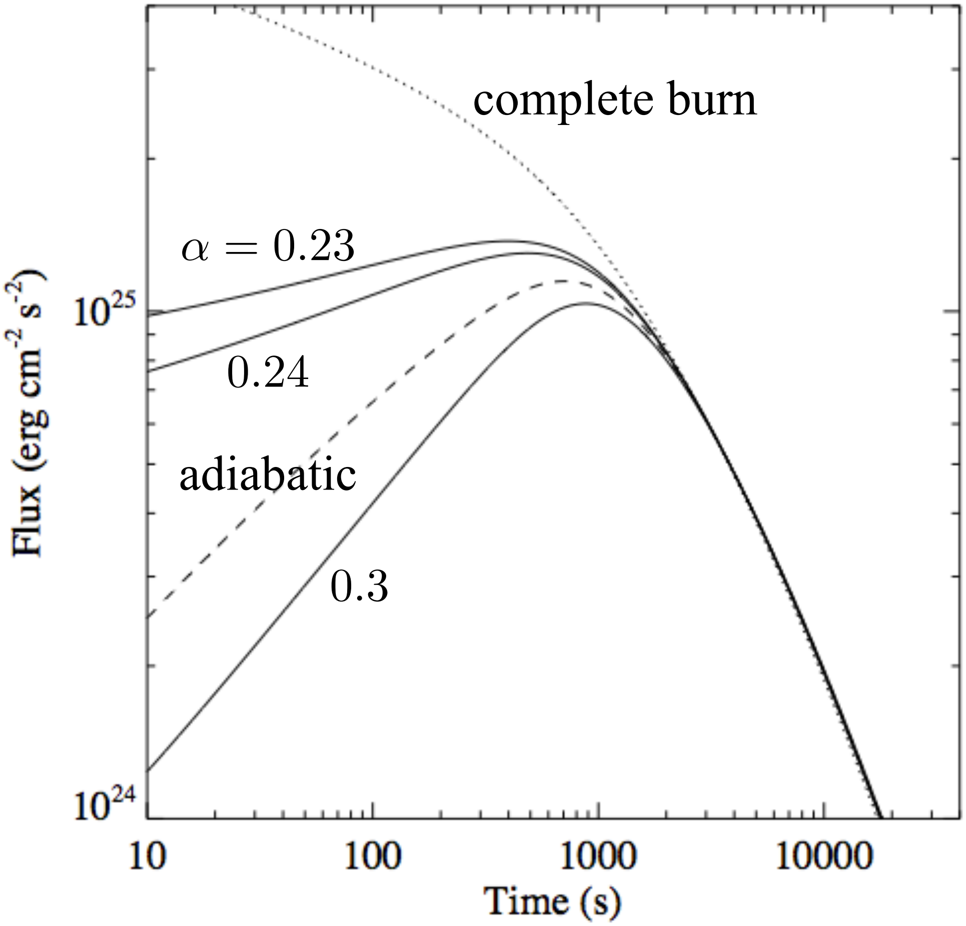


Cumming et al. (2006)

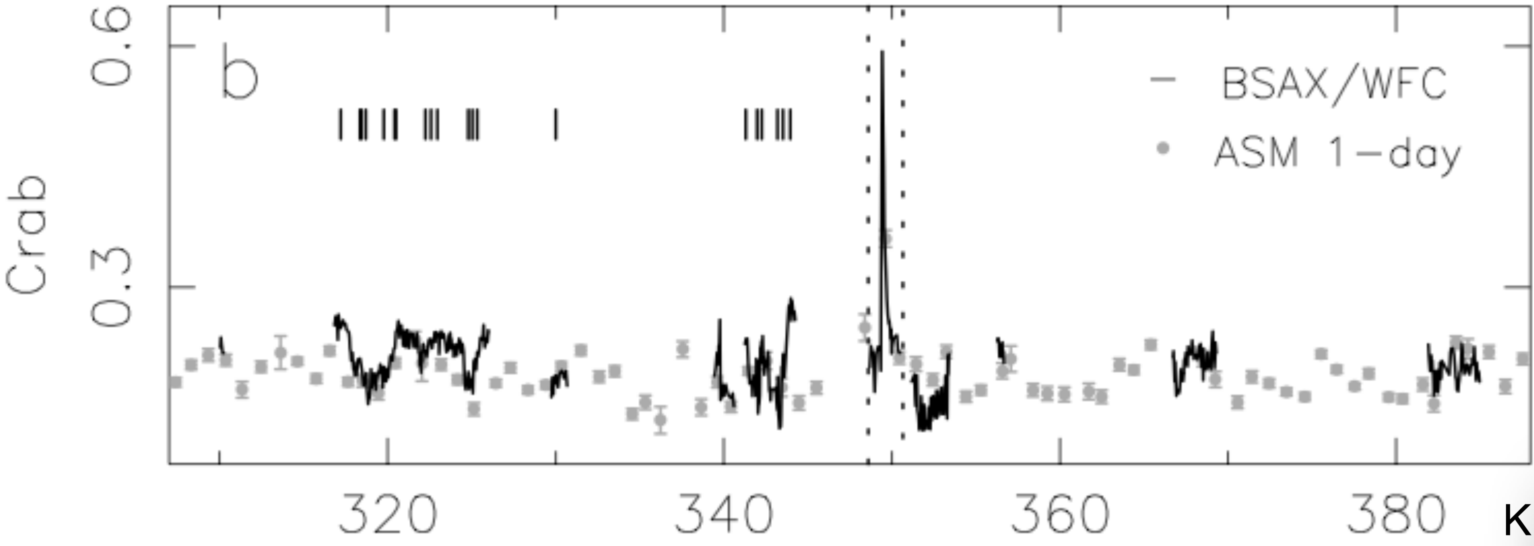
The shape of the light curve encodes the temperature profile after the carbon flame passes through the fuel layer

$$T \propto P^{\alpha}$$

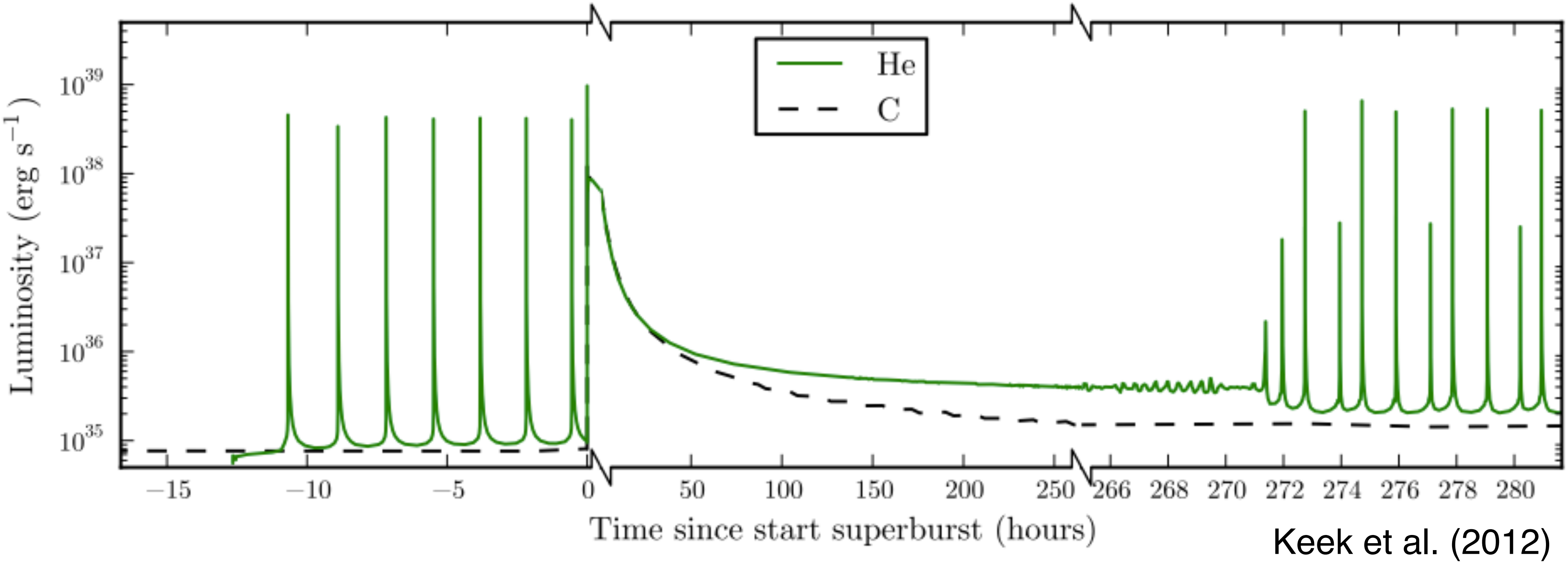




Heat flux from the deep carbon burning layer quenches Type I X-ray bursts for ~weeks

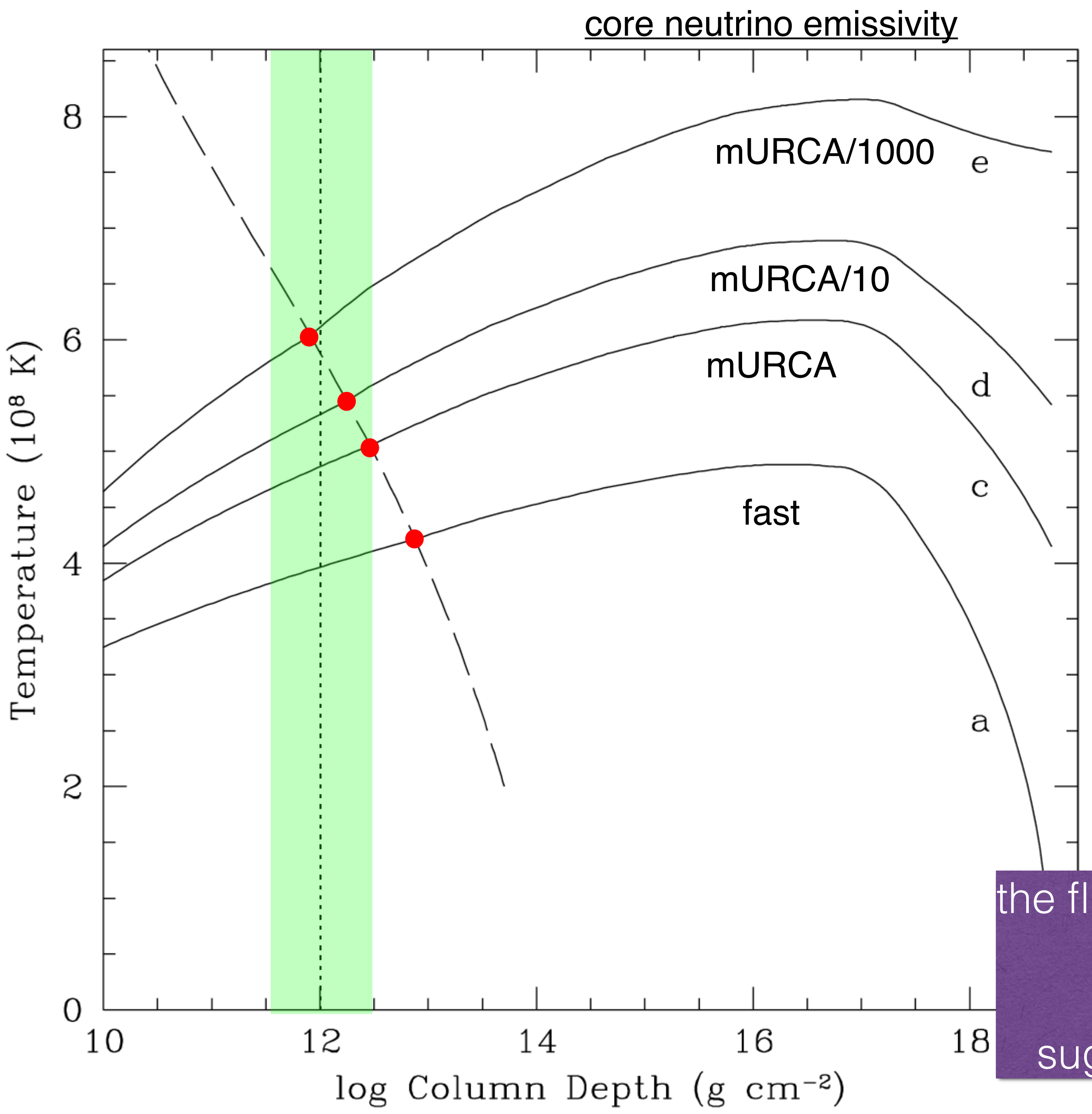


Kuulkers et al. (2002)



Keek et al. (2012)

Achieving the right ignition depth requires a hot neutron star



need *inefficient* core neutrino emission to match observations

Ignition at $y=10^{12}$ g/cm^2 requires:

Q_b=0.2-0.3 MeV/nucleon at 0.3 Edd

L_{crust}=(6-9) x 10^{34} erg/s

T~(5-6) x 10^8K

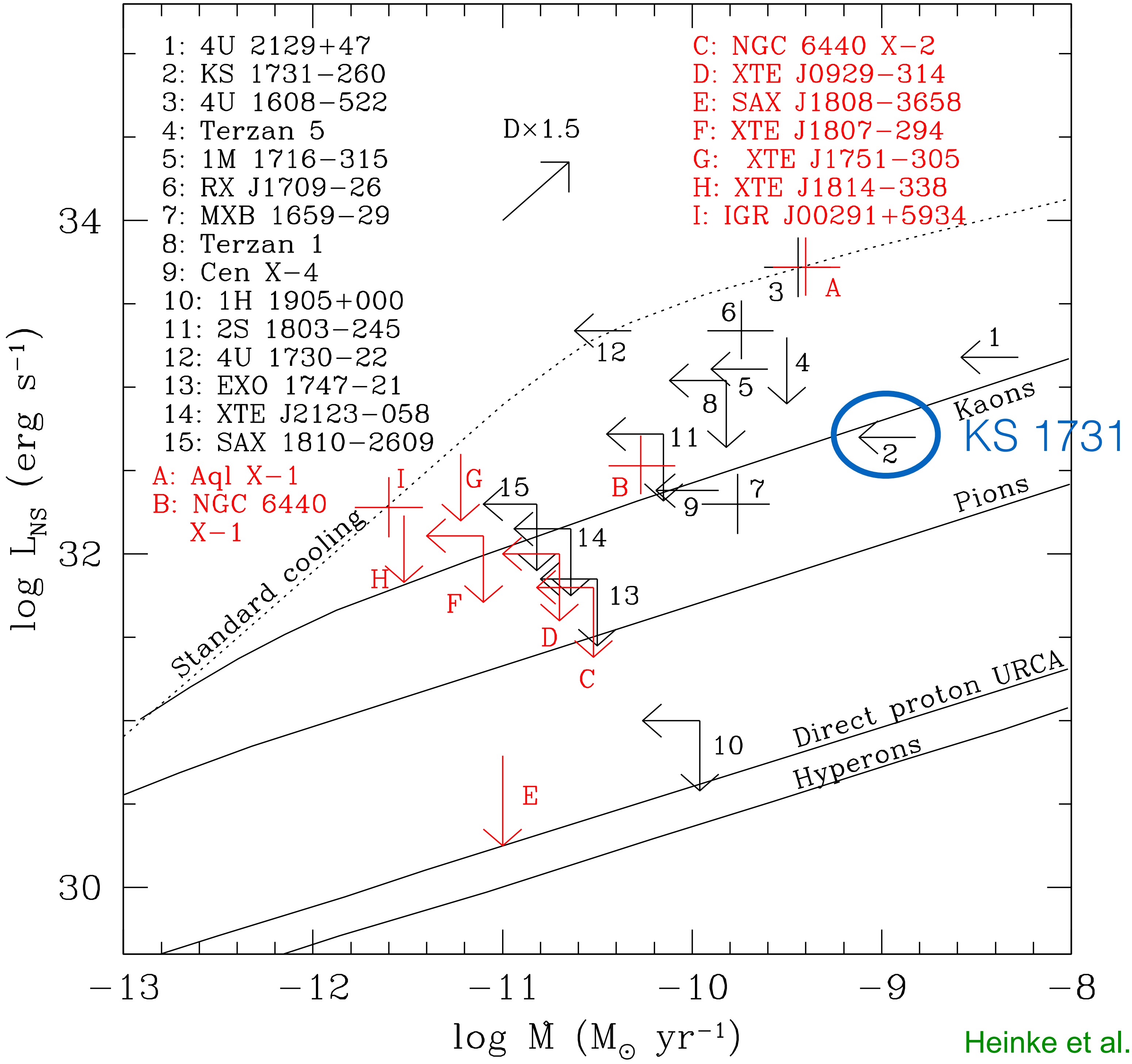
the flux needed is >> the quiescent flux for KS 1731-260!

suggests the heating is shallow

Cumming, Macbeth, in ’t Zand, Page (2006)

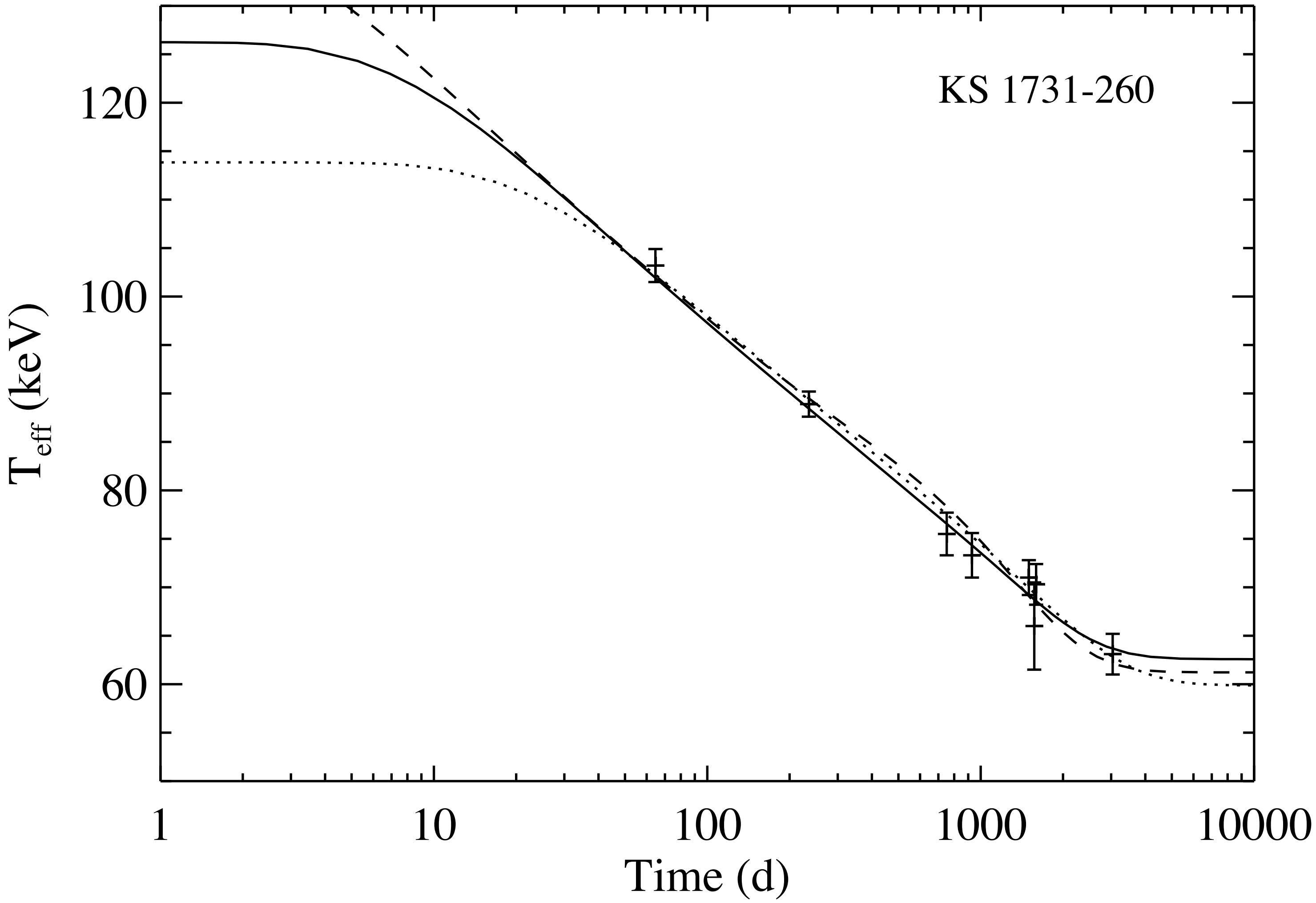
agrees with Brown (2004), Cooper & Narayan (2005)

Quiescent luminosity of transiently accreting neutron stars



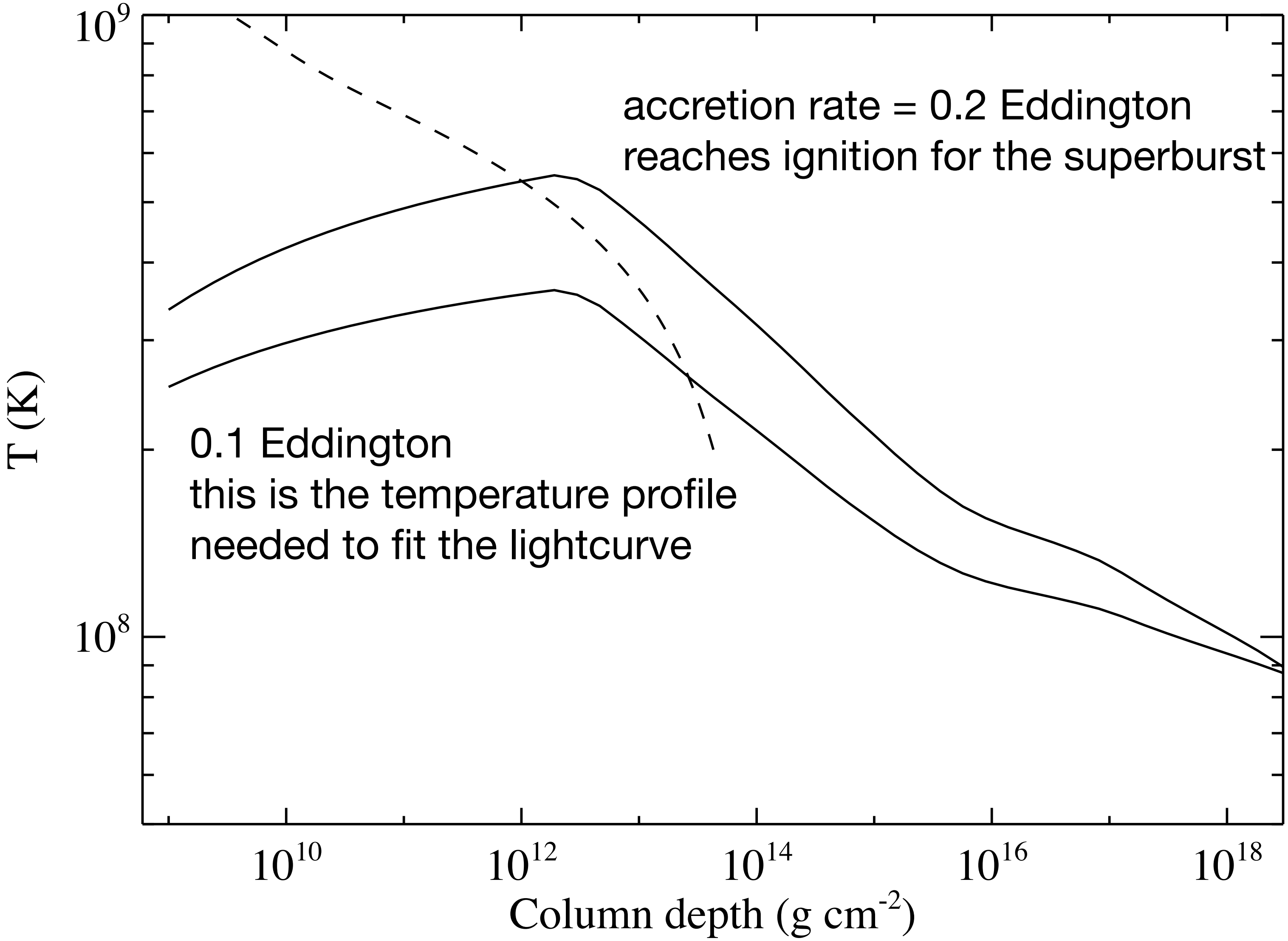
Heinke et al. (2010)

Crust cooling in KS 1731-260 also needs shallow heating



The early temperature measurement of T_{eff} ~105eV implies the outer crust is hot. Does the heating match what we need for the superburst?

A consistent model for KS 1731: The same heating with a factor of 2 higher accretion rate crosses the ignition depth at y~10^{12} g/cm^2, which is the inferred depth of the 1731 superburst

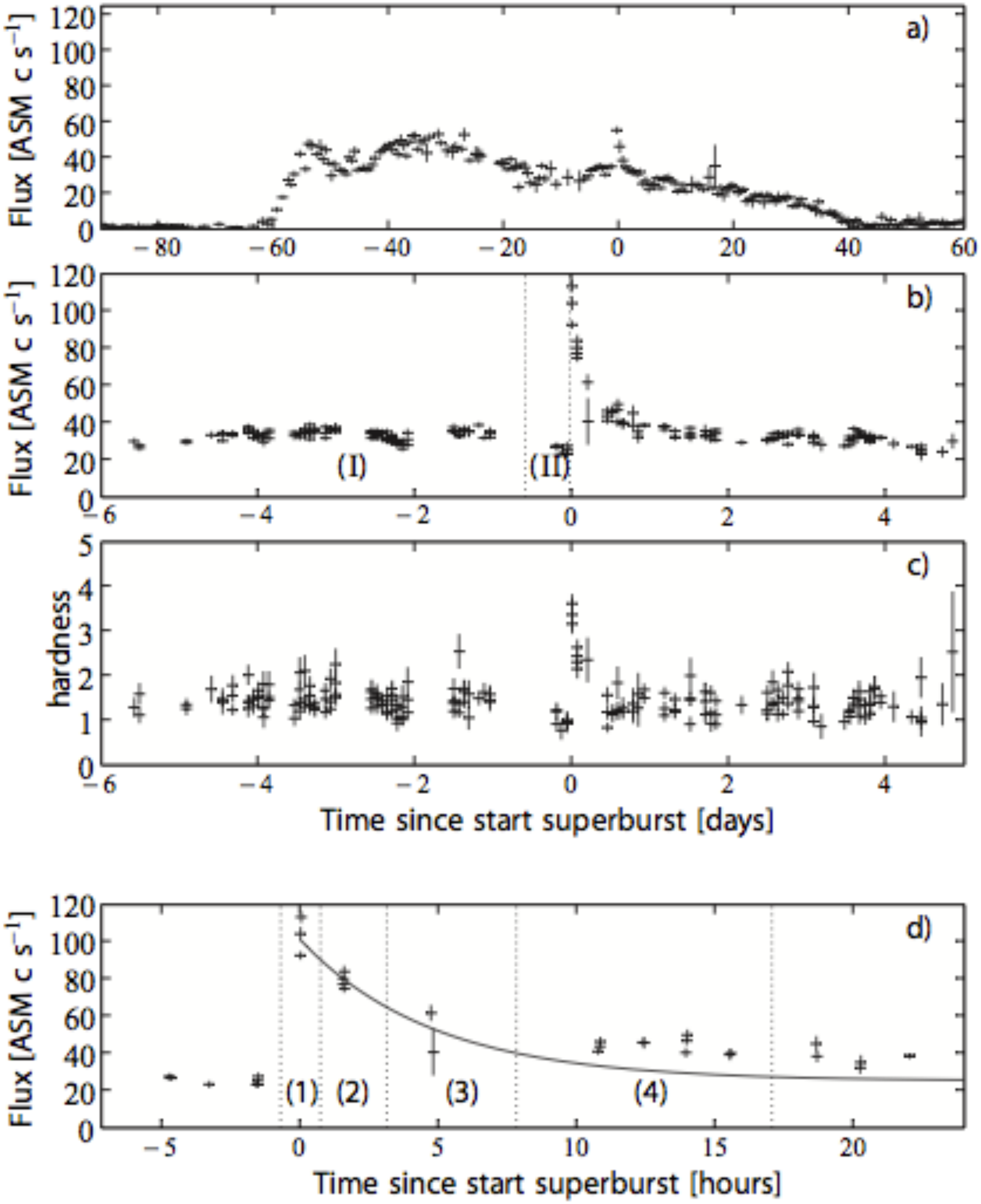


accretion rate = 0.2 Eddington
reaches ignition for the superburst

0.1 Eddington
this is the temperature profile
needed to fit the lightcurve

shallow heating of 1.3 MeV/nucleon at y=3e12 g/cm^2

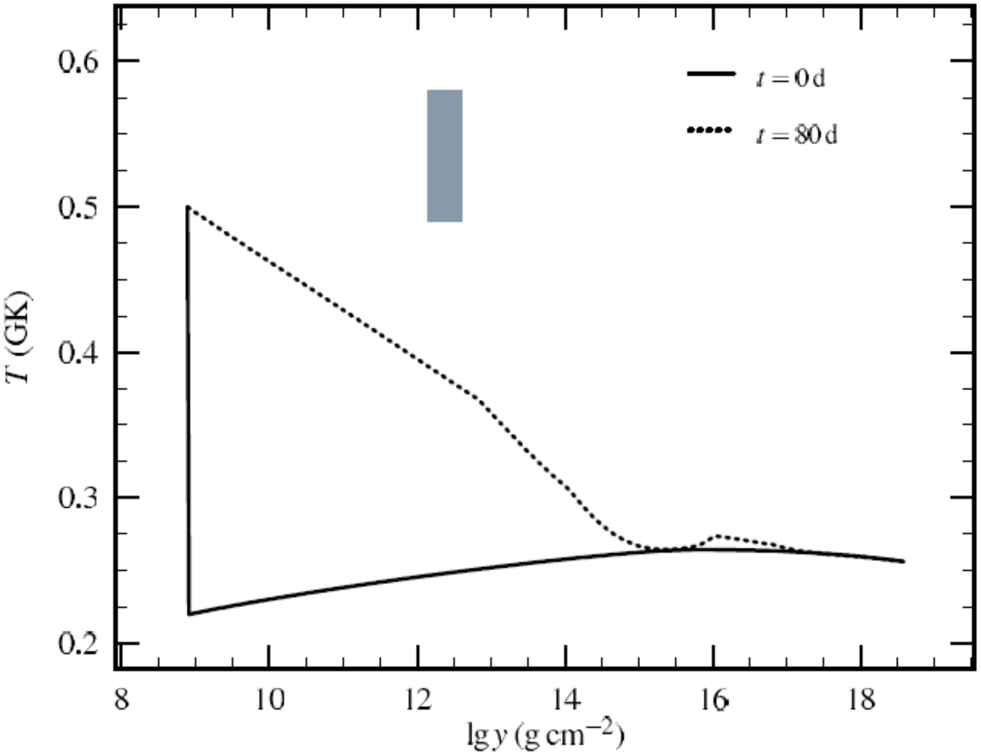
A superburst from the classical transient 4U 1608-52



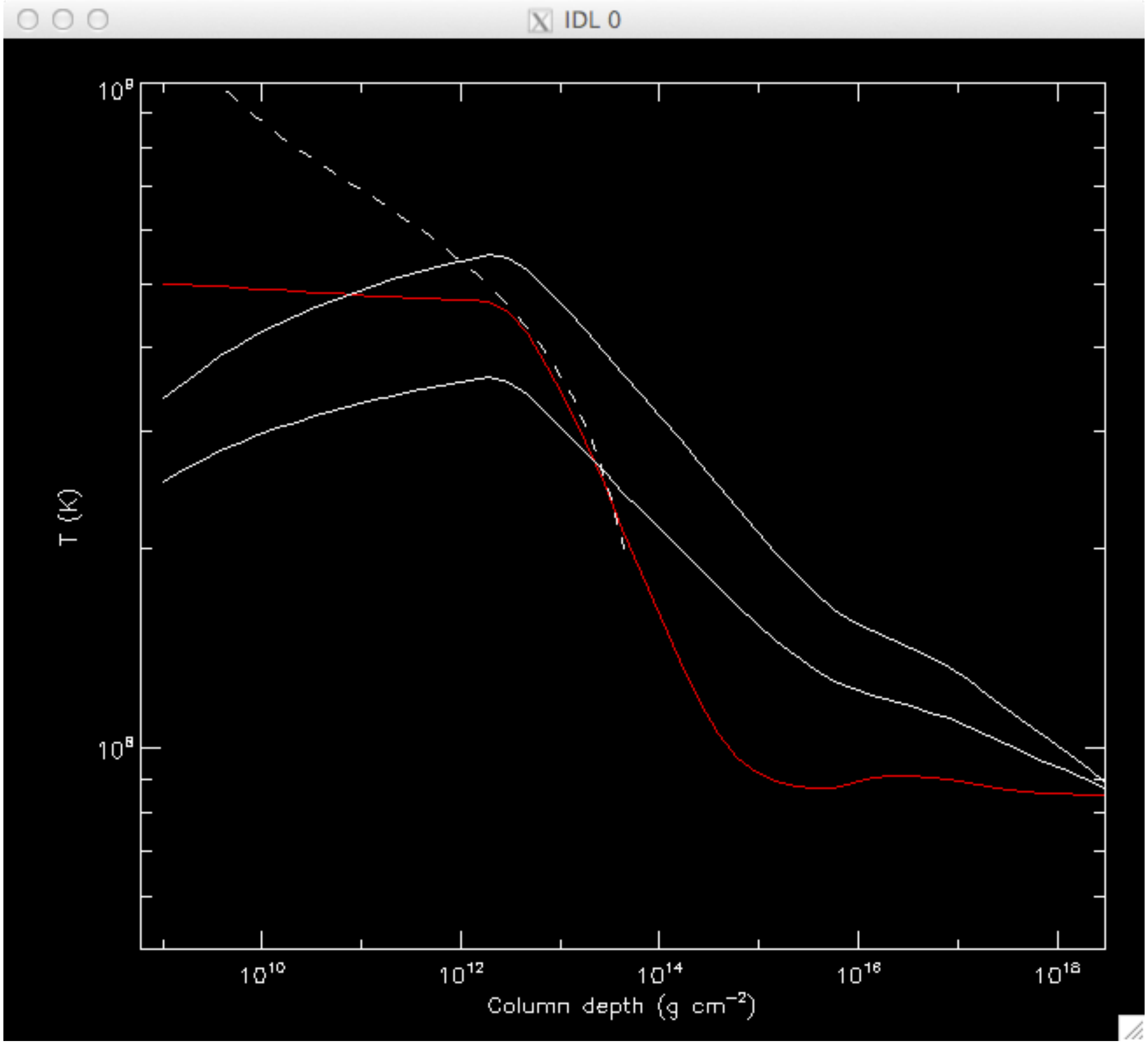
Keek et al. (2008)

A superburst was observed ~60 days into outburst

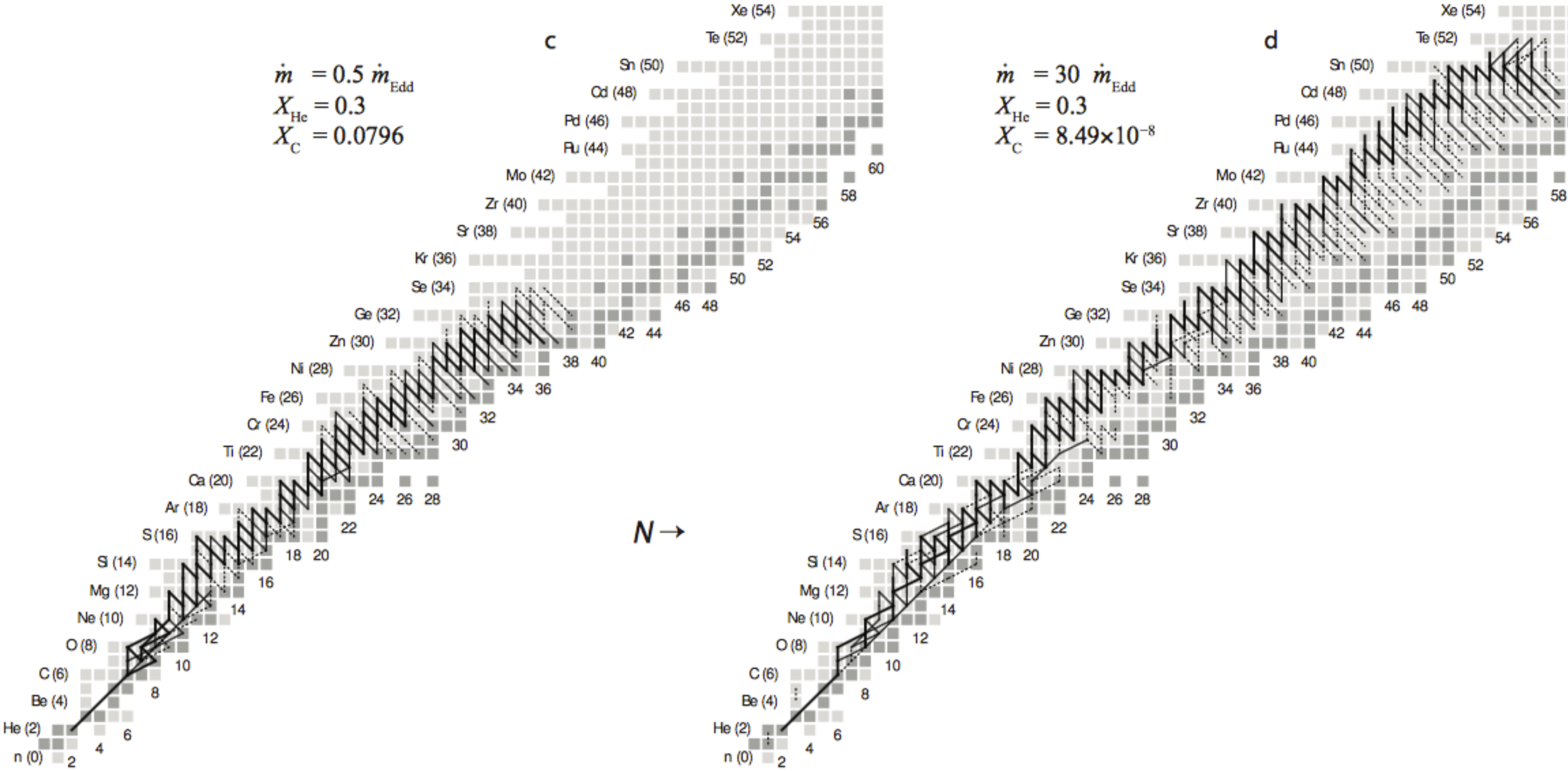
No way to heat the ocean to ignition temperature in such a short time



Same heating as for 1731, but now accrete for 80 days, and hold top at 5x10^8K: reaches superburst conditions!   This is a general question: can the same shallow heating explain all the sources we see?



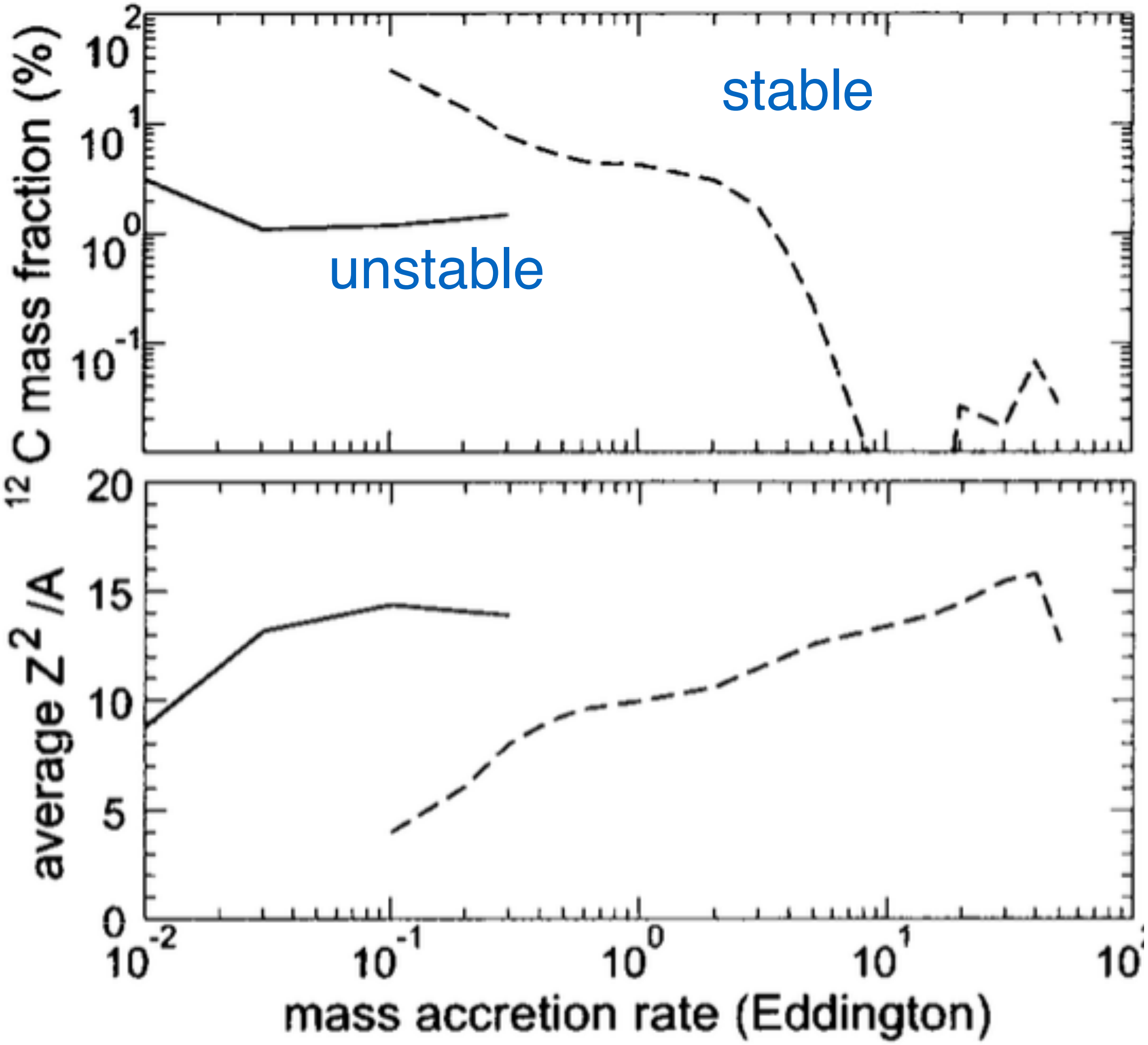
Carbon production requires a short rp-process



Carbon produced by triple alpha, but only survives if the hydrogen has burned away (Schatz et al. 2003)

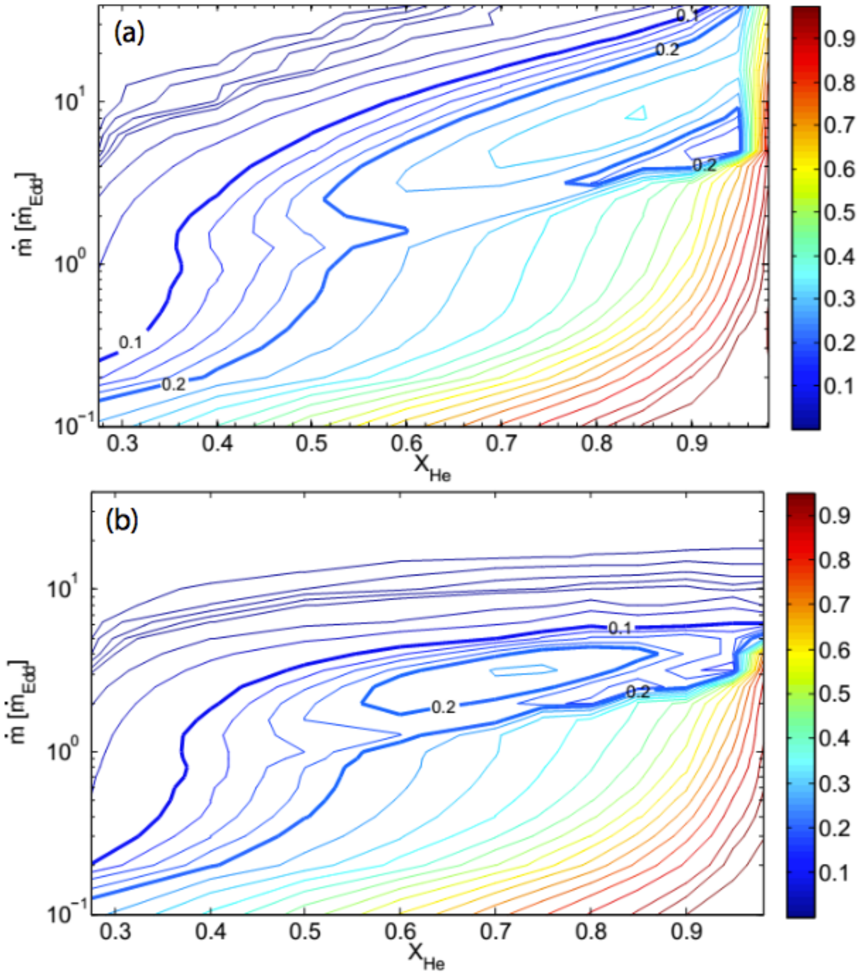
Stevens et al. (2014)

Carbon production in unstable vs stable burning



Schatz et al. 2003

Q_b = 0.001 MeV/nuc



Q_b = 1 MeV/nuc

Stevens et al. (2014)

Superbursters have large alpha values

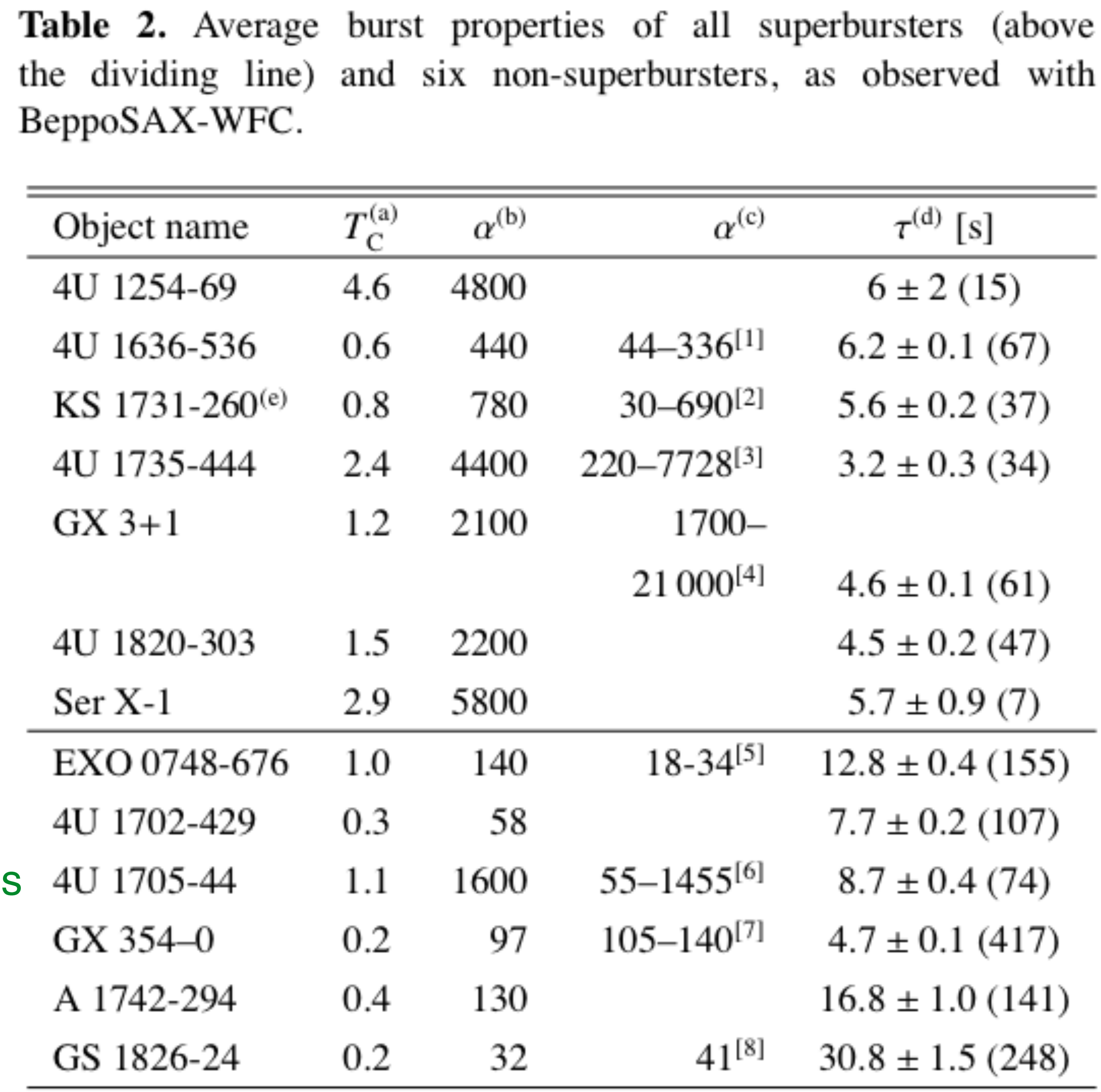


Table 2. Average burst properties of all superbursters (above the dividing line) and six non-superbursters, as observed with BeppoSAX-WFC.

Object name	$T_{\rm C}^{\rm (a)}$	$\alpha^{\rm (b)}$	$\alpha^{\rm (c)}$	$\tau^{\rm (d)}$ [s]
4U 1254-69	4.6	4800		6 ± 2 (15)
4U 1636-536	0.6	440	44–336[1]	6.2 ± 0.1 (67)
KS 1731-260(e)	0.8	780	30–690[2]	5.6 ± 0.2 (37)
4U 1735-444	2.4	4400	220–7728[3]	3.2 ± 0.3 (34)
GX 3+1	1.2	2100	1700–21 000[4]	4.6 ± 0.1 (61)
4U 1820-303	1.5	2200		4.5 ± 0.2 (47)
Ser X-1	2.9	5800		5.7 ± 0.9 (7)
EXO 0748-676	1.0	140	18-34[5]	12.8 ± 0.4 (155)
4U 1702-429	0.3	58		7.7 ± 0.2 (107)
4U 1705-44	1.1	1600	55–1455[6]	8.7 ± 0.4 (74)
GX 354–0	0.2	97	105–140[7]	4.7 ± 0.1 (417)
A 1742-294	0.4	130		16.8 ± 1.0 (141)
GS 1826-24	0.2	32	41[8]	30.8 ± 1.5 (248)

superbursts

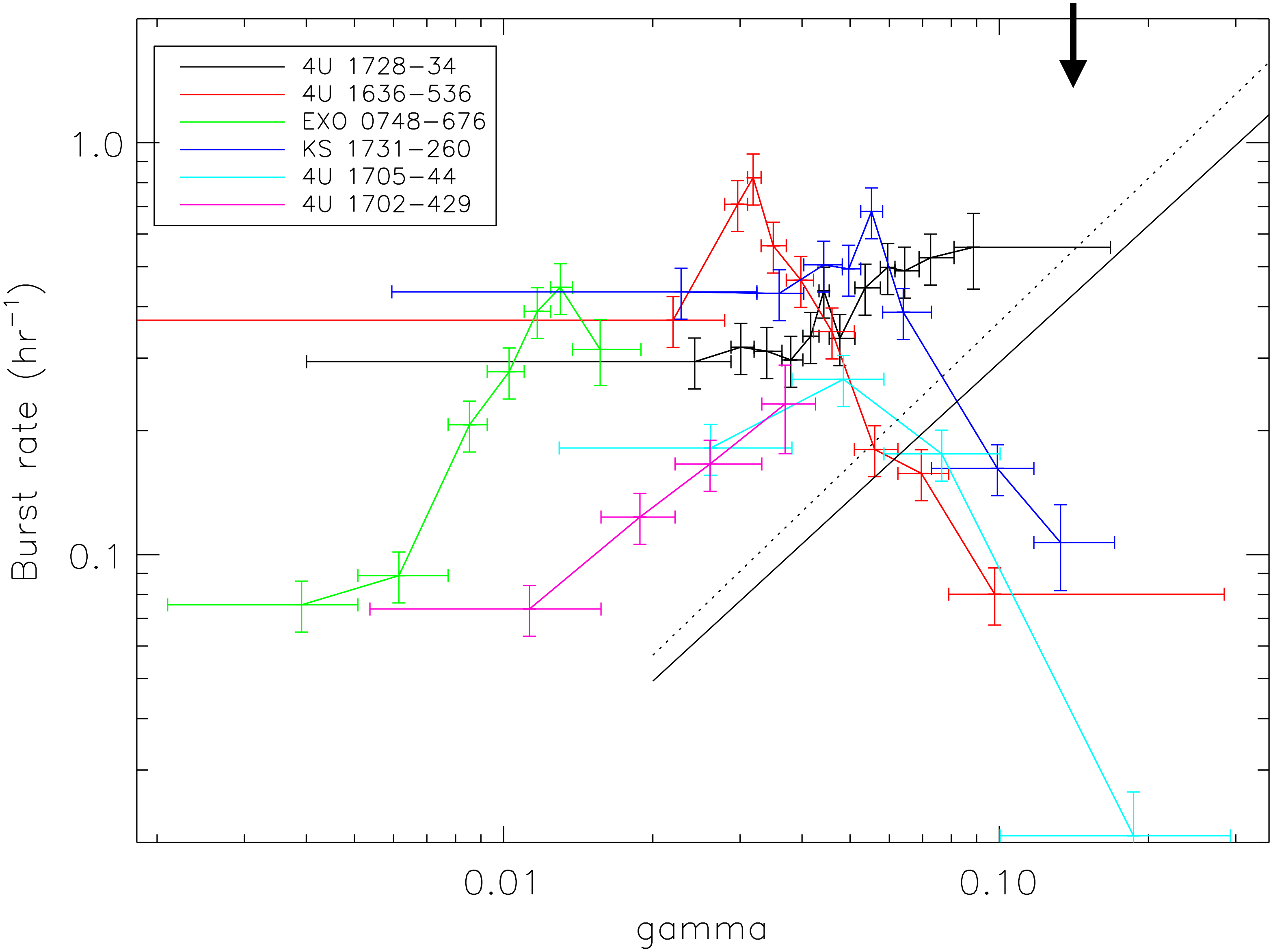
no superbursts

est. from counts

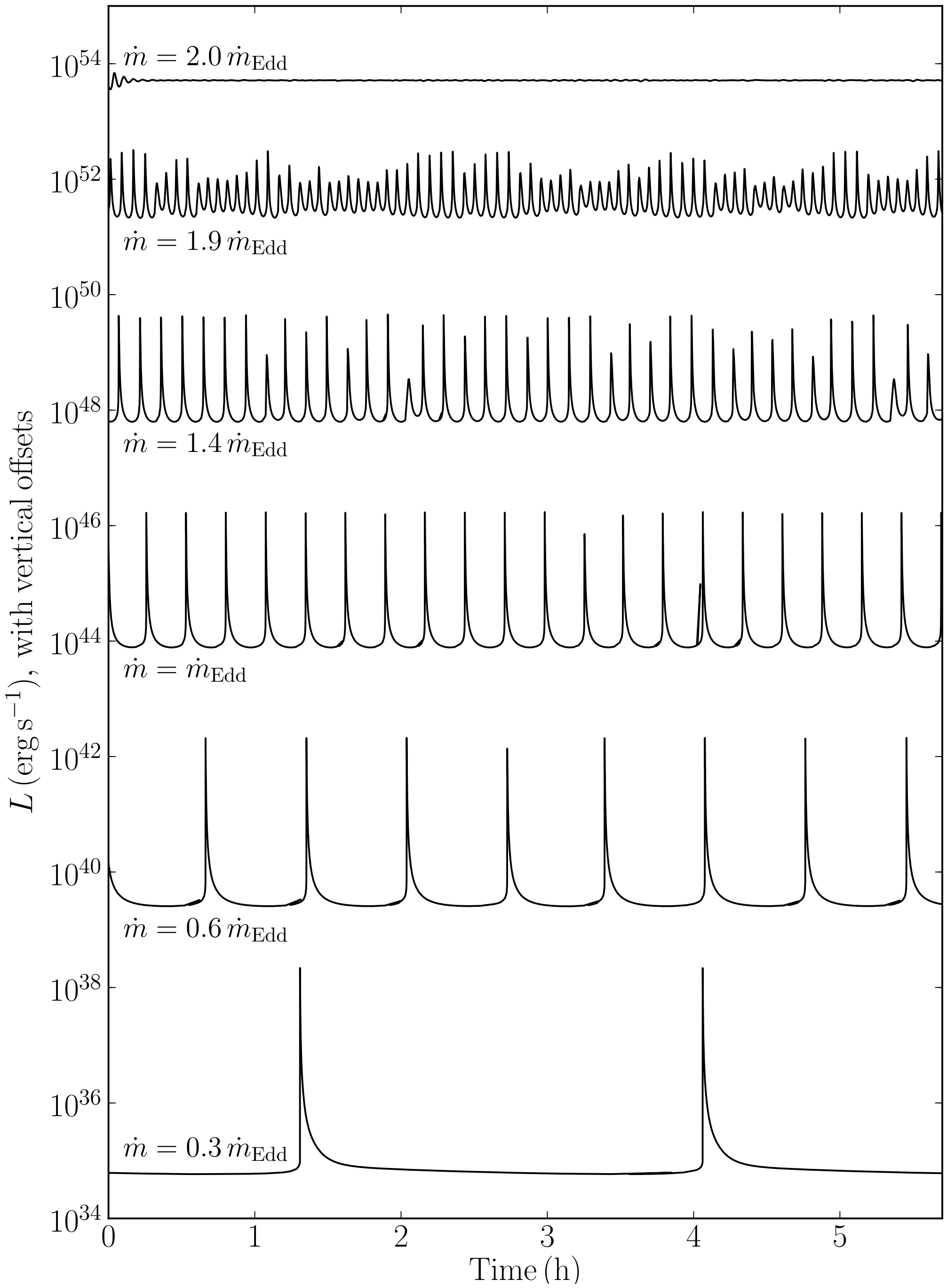
literature

in ’t Zand et al. 2003

superbursts



Lampe, Galloway et al. (2014)



Zamfir, Cumming, & Niquette (2014)

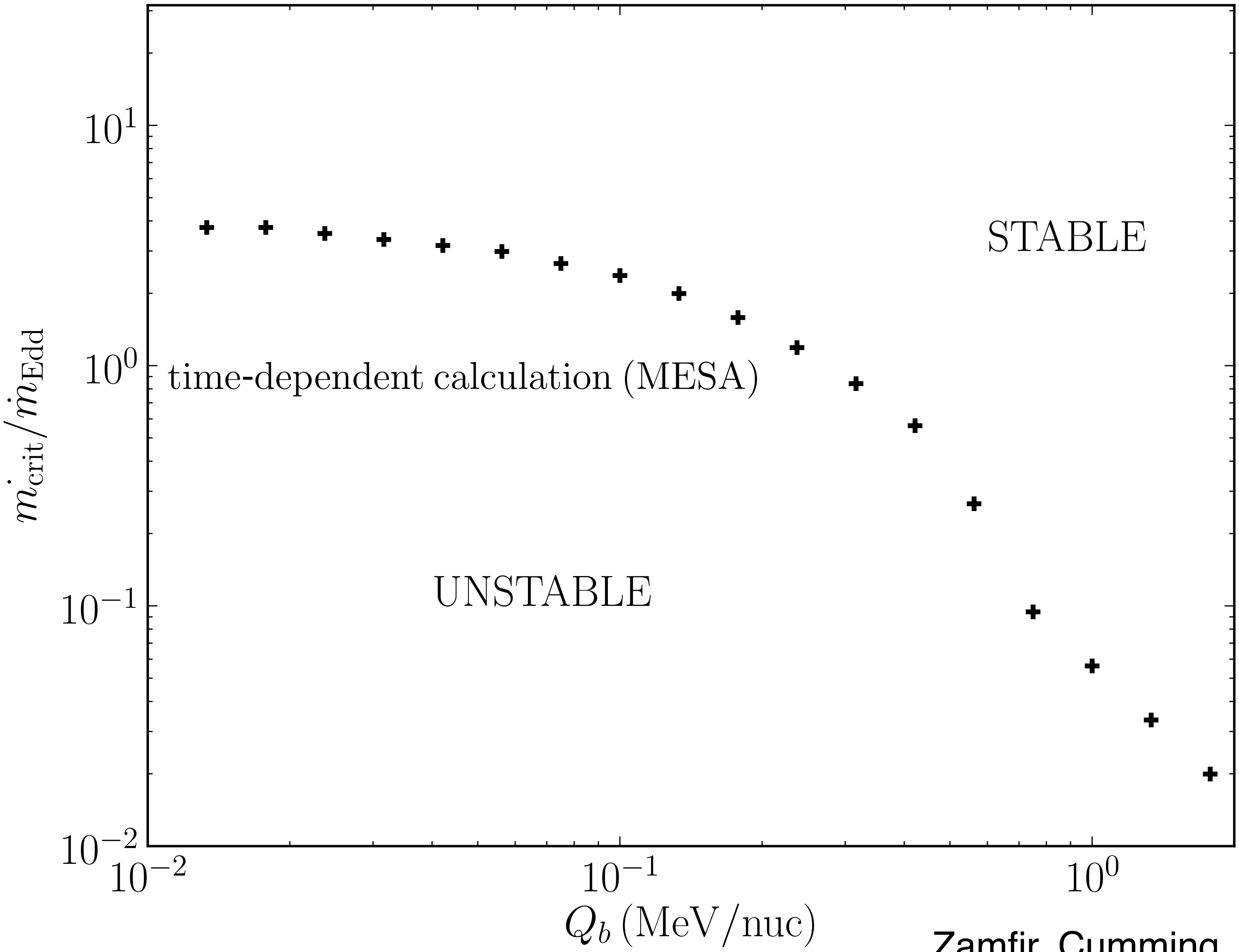
In 1D models, burning stabilizes at high accretion rates
—> hot layer has less sensitive reactions and cannot drive instability

But 1D models predict burning stabilizes at ~ Eddington rate **~10 times larger than observed!**

Explanations:
- burning mode changes (Bildsten 1995)
- partial covering of fuel (Bildsten 1998)
- rotational instabilities drive mixing (Fujimoto et al. 1987)
- heating of layer associated with fuel spreading (Inogamov & Sunyaev 1999,2010)

A heat flux from below stabilizes H/He burning

A hotter layer has less-temperature-sensitive nuclear reactions and is more likely to be thermally stable (Bildsten 1995; Fushiki & Lamb 1987; Keek et al. 2009)



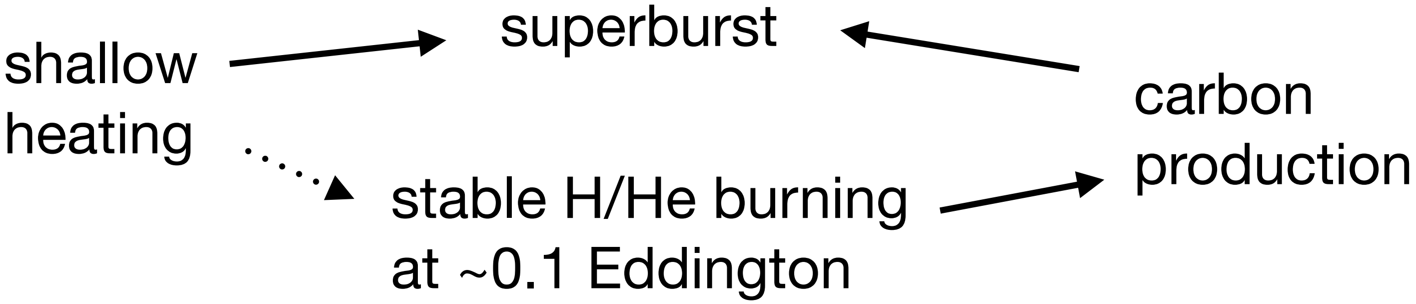
Zamfir, Cumming, & Niquette (2014)

Summary so far

1. Superburst ignition requires temperatures 6x10^{8}K at column depths 10^{12} g/cm^{2}. Needs a heat source ~1 MeV per nucleon
Consistent with the heat source required for early time crust cooling in quiescent transients

2. Carbon production requires stable burning. Stable burning is observed!
But theory predicts H/He burning should be unstable at superburst accretion rates.

3. Shallow heating can stabilize the burning at accretion rates ~0.1 Eddington typical of superburst sources
BUT: too much heating leads to stable carbon burning (CB2001), so we need to stabilize the H/He but not the carbon. Needs further investigation!



shallow heating

superburst

stable H/He burning at ~0.1 Eddington

carbon production

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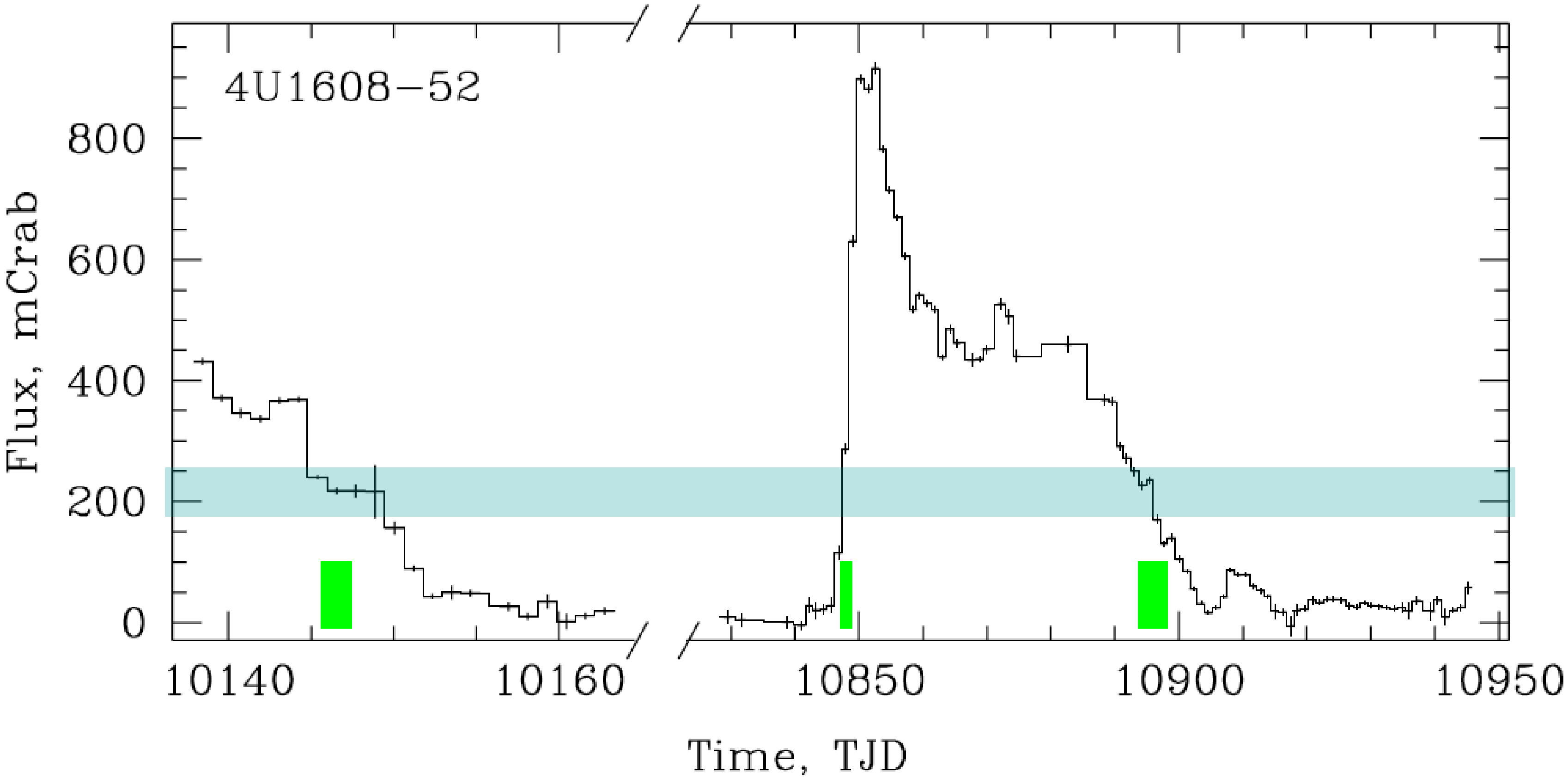
Observations of mHz QPOs

- discovered from Atoll sources 4U 1608-52, 4U 1636-53, Aql X-1 by Revnitsev et al. (2001) with frequencies (7-9) mHz
- flux variations at ~few percent level
- unusually for a QPO, they are *soft* (<5 keV)
- they occur in a narrow range of luminosity (0.5-1.5) x 10^{37} erg/s



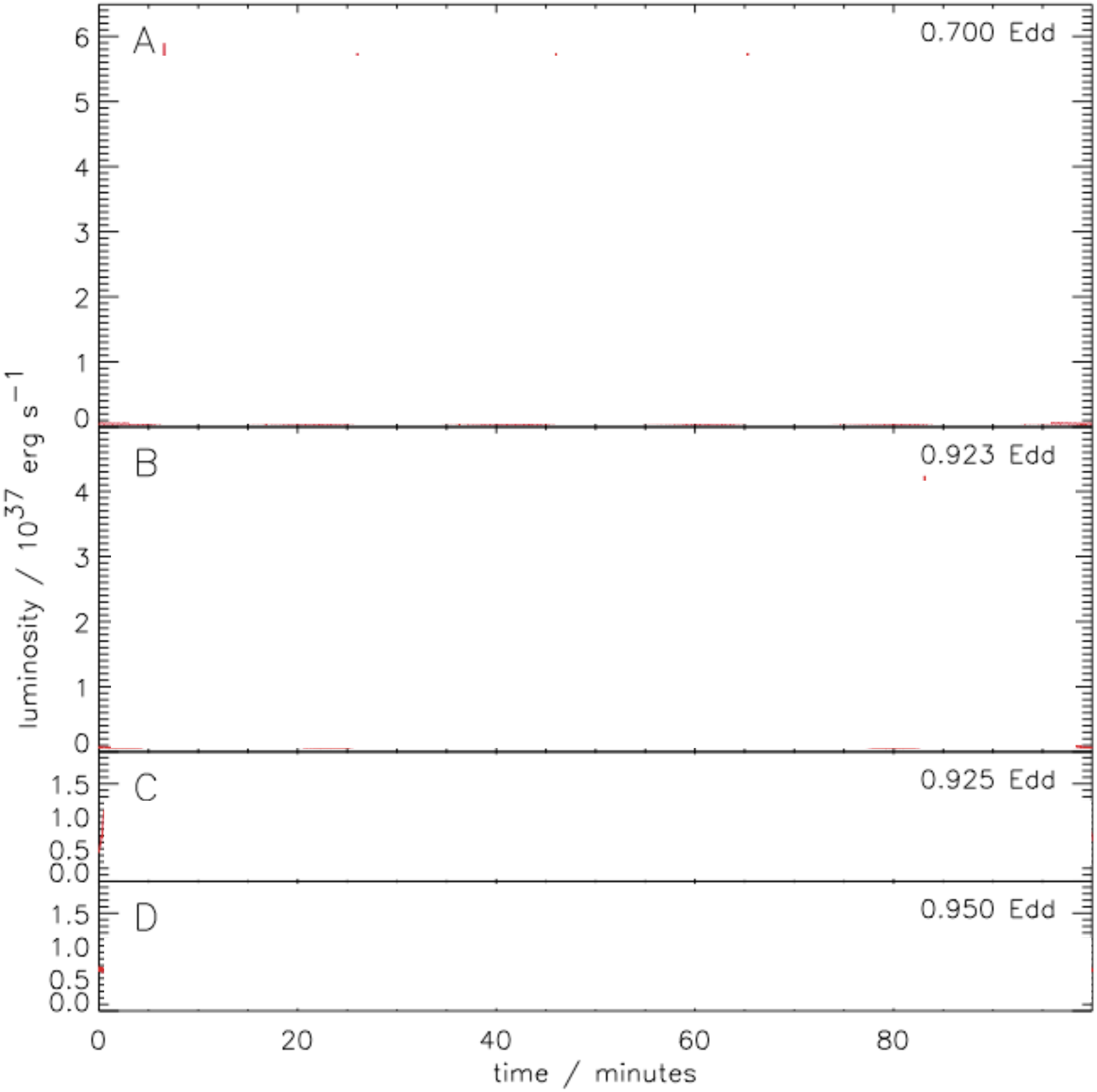
Revnitsev et al. (2001) suggested that we are seeing a new mode of nuclear burning

Calculations of the transition to stable burning

- Extensions of the Woosley et al. 2003 ApJS calculations to higher accretion rates

- Kepler code, follow >1000 nuclei at each depth

- At the boundary between unstable and stable burning see oscillations with periods of 3 minutes



Heger, Cumming, & Woosley (2007)

The physics of the oscillation

- Simple one-zone model

$$c_P \frac{dT}{dt} = \epsilon - \frac{F}{y}$$

$t_{\mathrm{therm}} \sim 10$s

$$\frac{dy}{dt} = \dot{m} - \frac{\epsilon}{E_\star} y.$$

$t_{\mathrm{accr}} \sim 1000$s

- Linear perturbations

$$\frac{\partial^2 f}{\partial t^2} + \left(\frac{4-\alpha}{t_{\mathrm{therm}}} - \frac{1}{t_{\mathrm{accr}}} \right) \frac{\partial f}{\partial t} + \frac{2\alpha}{t_{\mathrm{accr}} t_{\mathrm{therm}}} f = 0.$$

Usually thermal time dominates
with strong driving or damping

Oscillation period $\approx \left(t_{\mathrm{therm}} t_{\mathrm{accr}} \right)^{1/2}$

- A clock on the NS surface that depends on g, X … no mdot uncertainty!

Marginally stable burning can explain some but not all observed properties of mHz QPOs

- frequency is correct: geometric mean of thermal and accretion times gives few minute periods

- explains narrow luminosity range where mHz QPOs are observed in 4U 1608-52. BUT: in general, observed range of luminosity where mHz QPOs are seen is larger than predicted by theory.

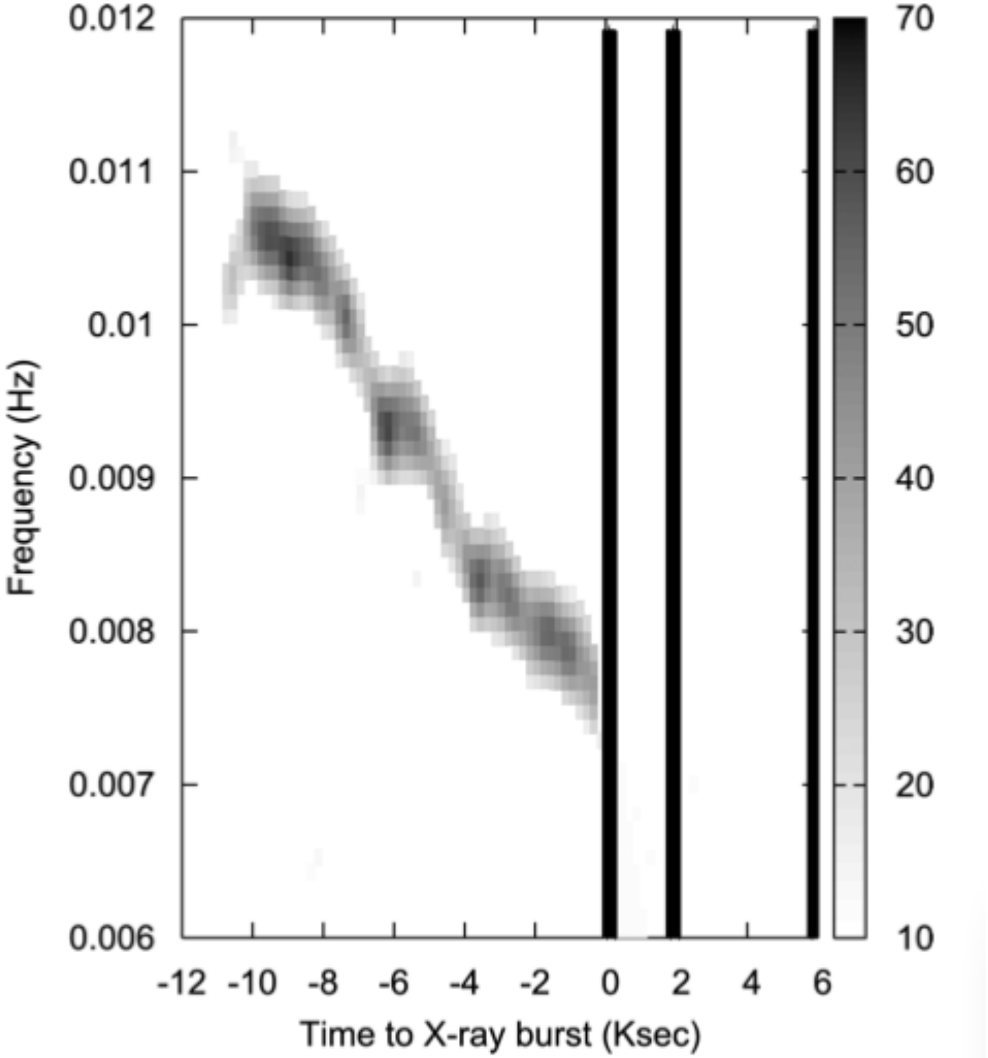
- amplitude: few percent amplitudes (roughly nuclear to gravitational energy)

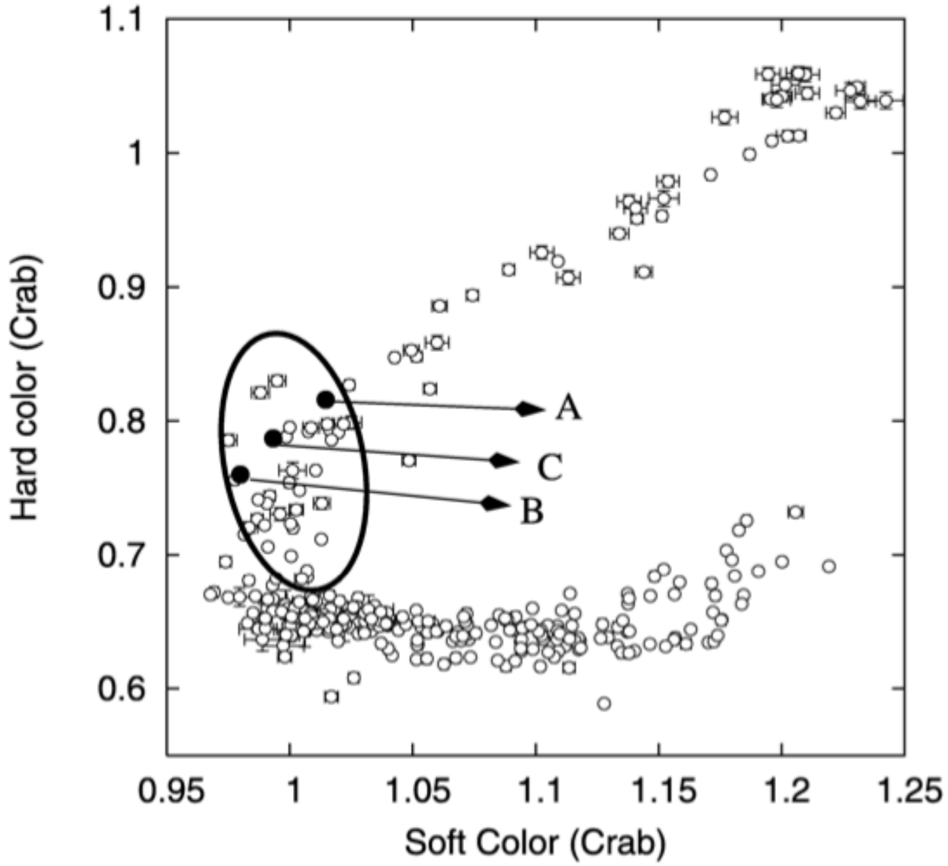
- accretion rate does not agree: theoretically, the transition to unstable burning occurs close to Eddington => 10^{38} erg/s
  whereas the observed luminosity is ~ 10^{37} erg/s

- **Possible solution**: what matters is the local accretion rate - one way out is that the accreted material covers only 10% of the area ?

mHz QPOs can be used to predict when a Type I burst will happen

Altamirano et al. (2008) 4U 1636-53





mHz QPO summary

1. mHz QPO frequencies match marginally stable burning

2. stable burning in the models happens at 1 Eddington, but at 0.1 Eddington in the observed systems

3. the interaction between mHz QPOs and Type I burst suggests a two-component system

4. we don't have a good model for this, but Heger et al. (2007) suggested the mHz QPOs are from a belt near the equator covering ~10% of the surface of the star

5. If shallow heating is responsible for stabilizing H/He burning at 0.1 Eddington, what would be the mHz QPO frequency? Need to calculate it!

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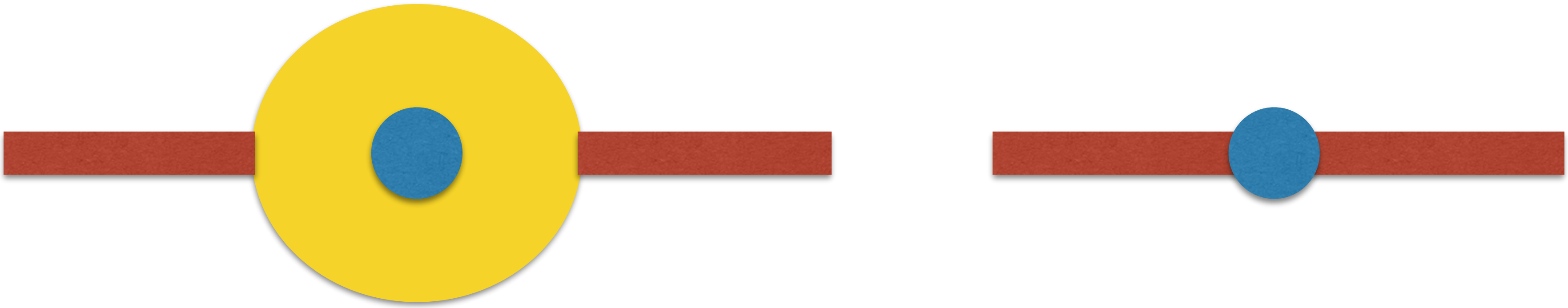
3. **A global view of nuclear burning on accreting neutron stars**

Low hard state ↔ High soft state



regular bursting

significant color correction evolution during bursts

stable burning; irregular bursting

superbursts

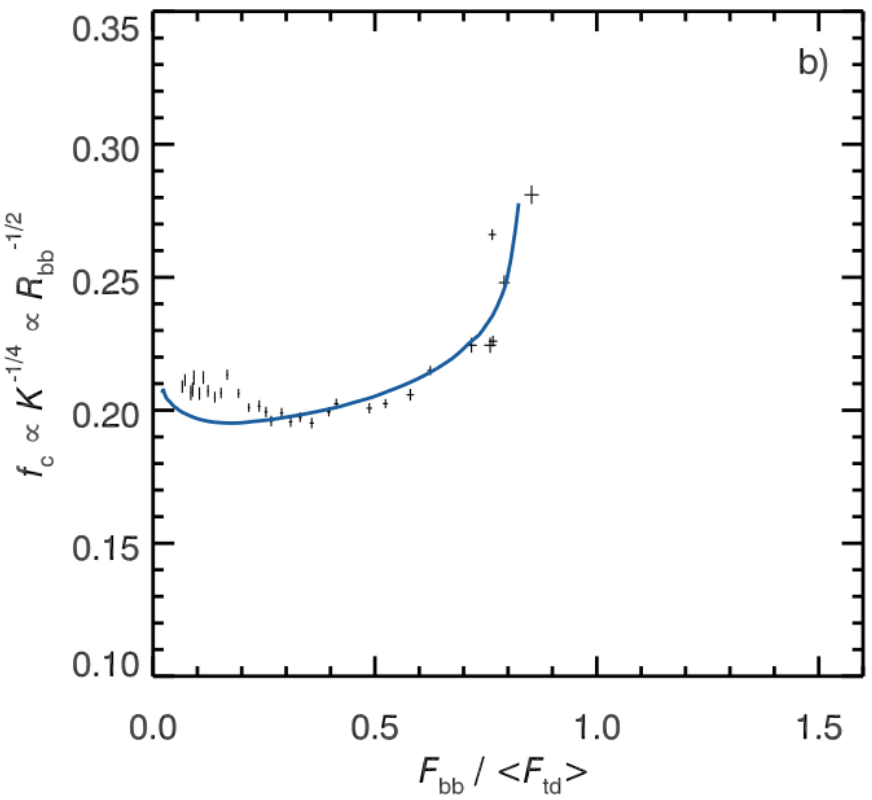
mHz QPOs

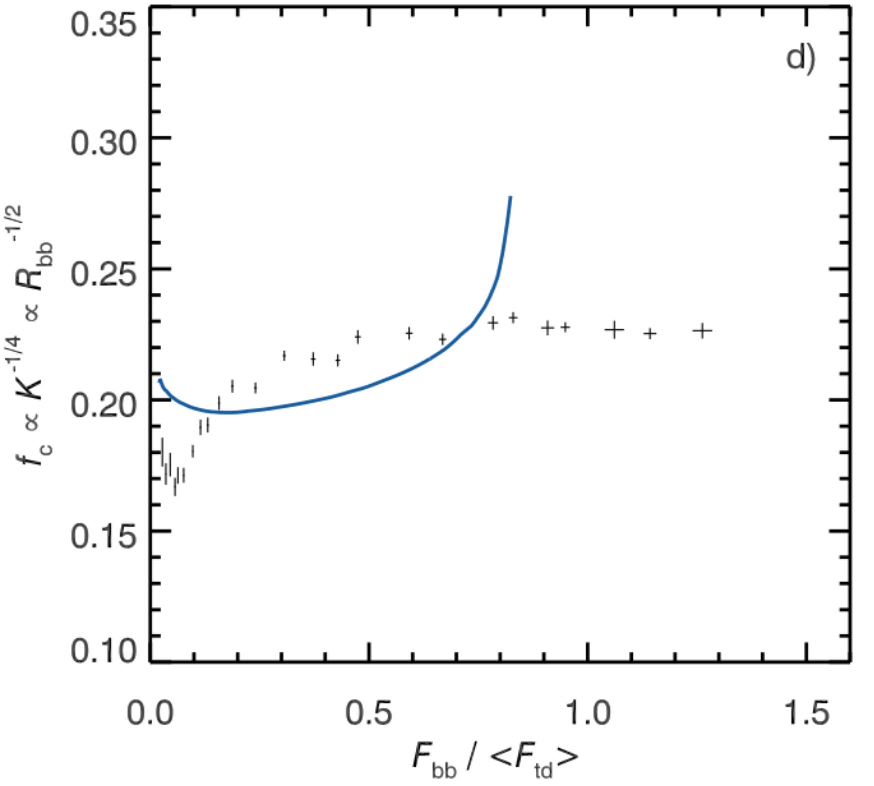
burst oscillations

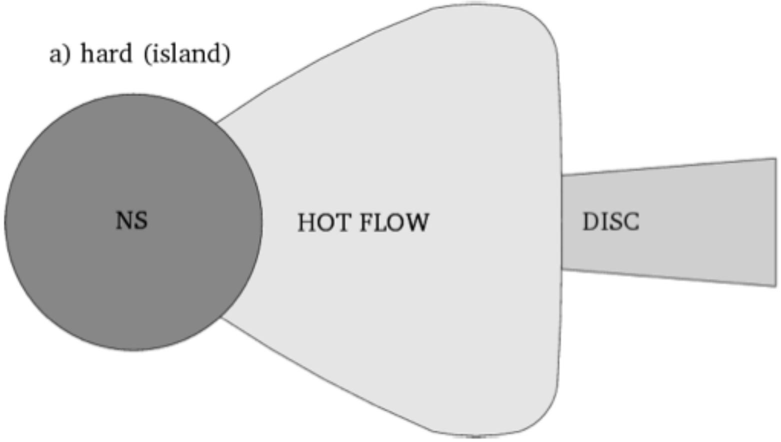
color correction almost constant during burst

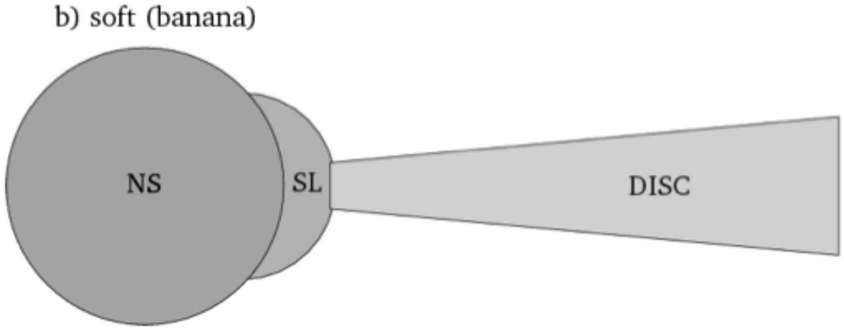
Color correction variations during bursts

Kajava et al. (2014)



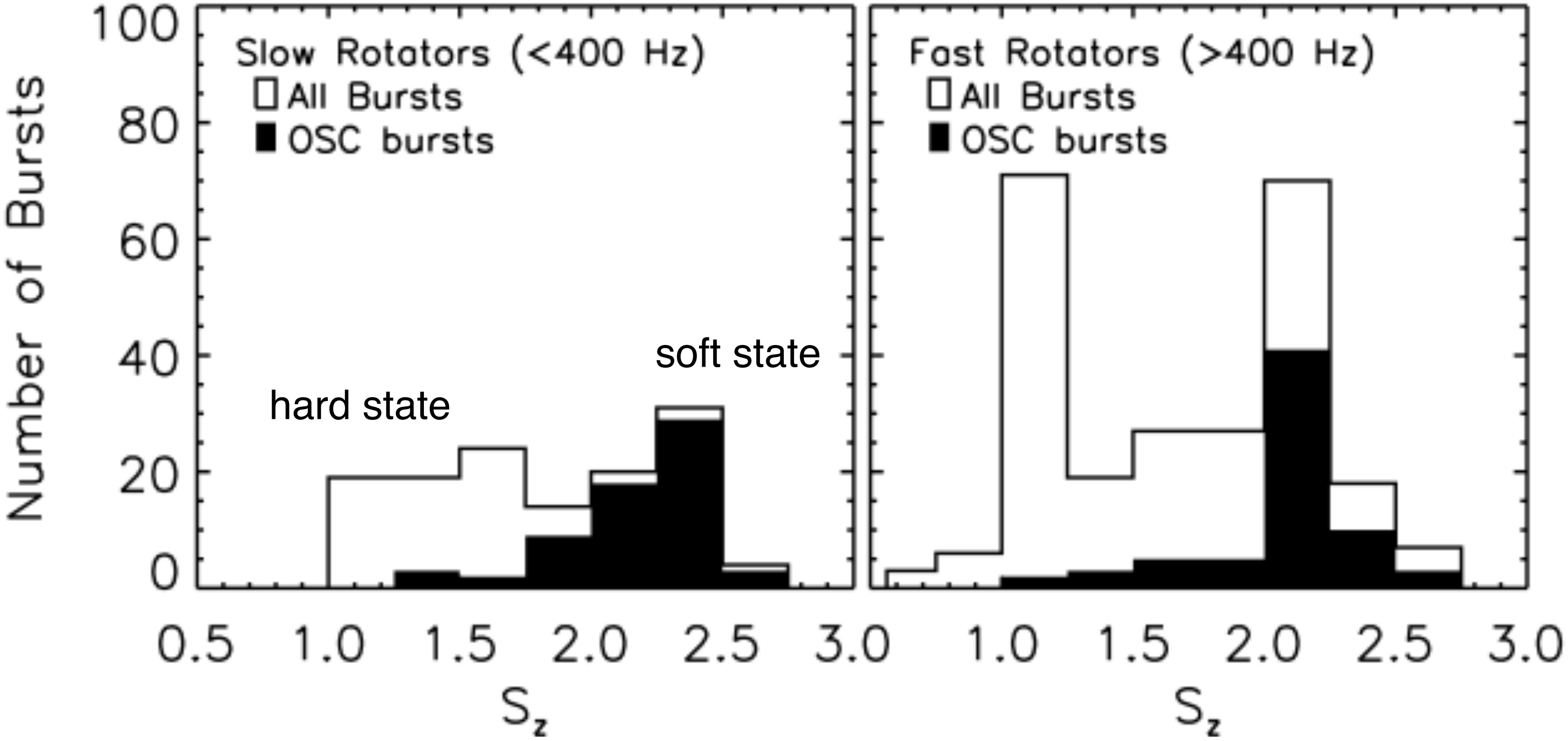






Burst oscillations preferentially happen in the soft accretion state

Galloway et al. (2008), see also Muno et al. (2004)



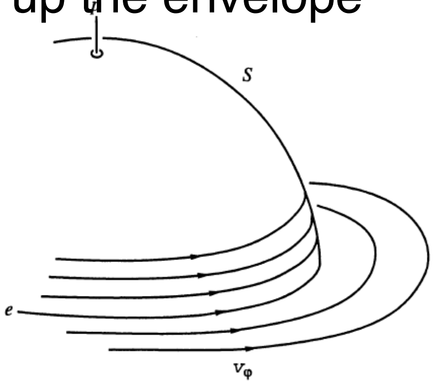
hard state

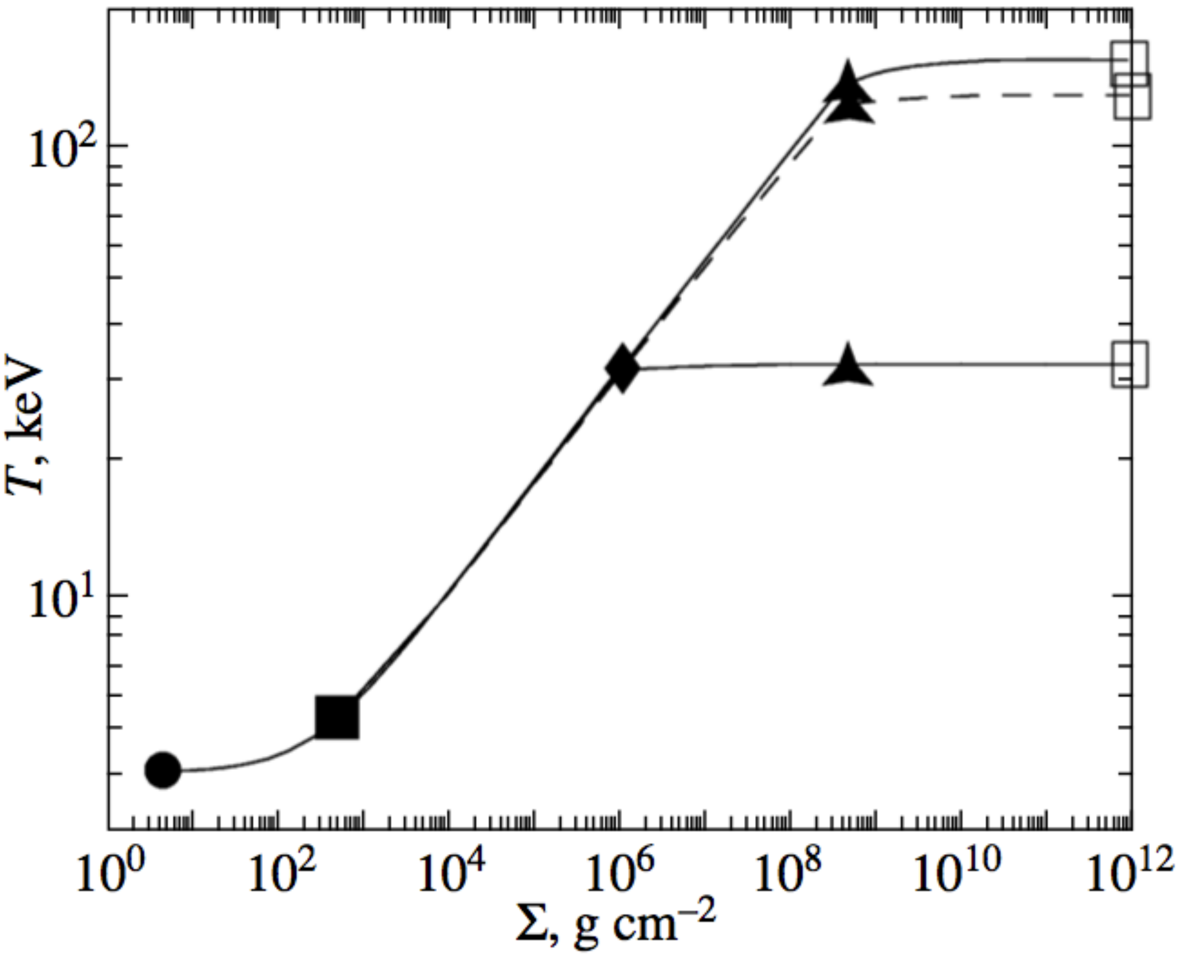
soft state

The nature of the shallow heat source is a puzzle

Evidence suggests a ~ 1 MeV/nucleon heat source at column depths ~10^{13}-10^{14} g/cm^2. Possible sources of energy are:

- Gravitational energy released by light elements that rise upwards from the ocean floor following **chemical separation** at the ocean/crust interface (Medin & Cumming 2011) ~0.1 MeV/nucleon, probably not enough
- **Electron captures** in the outer crust release more energy than previously thought (Gupta et al. 2007)
- **Fusion** of light elements in the outer crust, e.g. ^{24}O will fuse at a density ~10^{11} g/cm^3 (Horowitz, Dussan, & Berry 2008)
- **Differential rotation** between the fluid envelope and solid crust leads to strong heating ~tens of MeV/nucleon (Inogamov & Sunyaev 2010). This requires inwards angular momentum transport from the accreted material to spin up the envelope

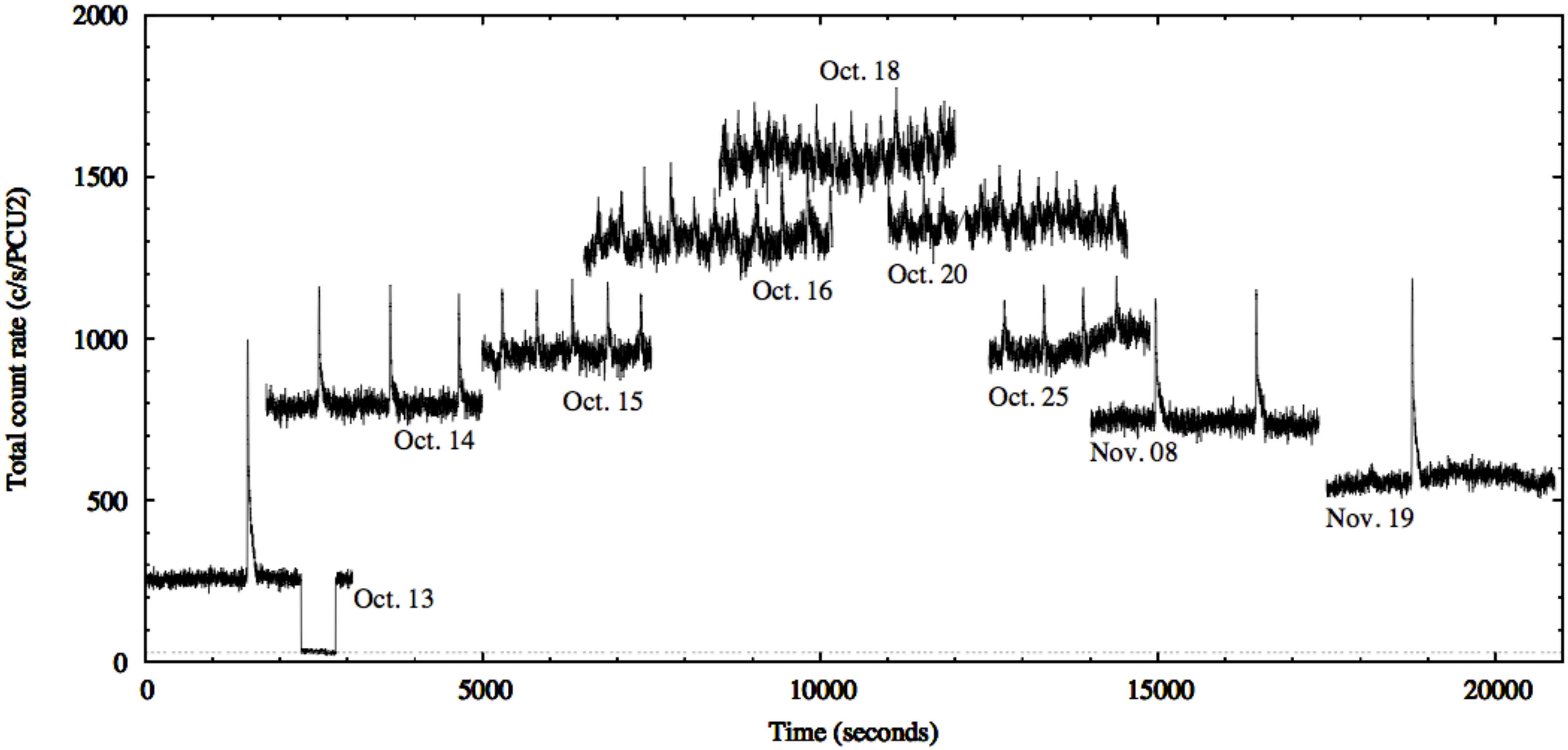




Inogamov & Sunyaev (2010)

A smooth transition from bursts to mHz QPOs in the 11 Hz pulsar IGR J17480-2446 in Terzan 5

Linares et al. (2011)

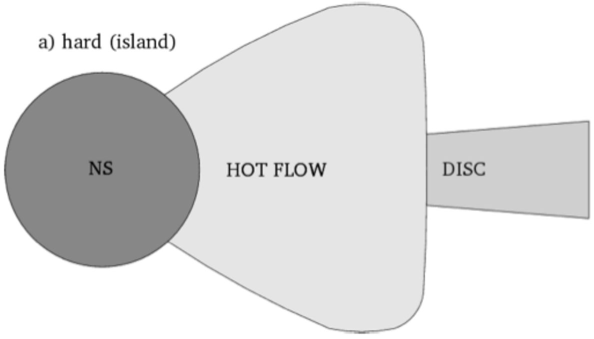


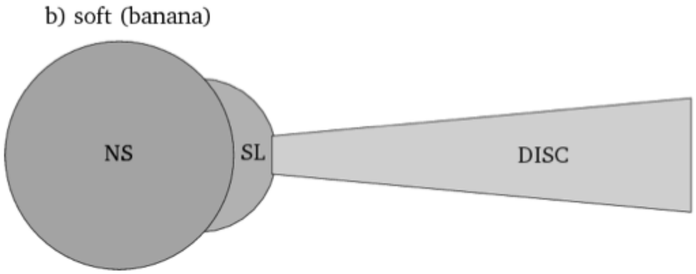
perhaps the difference is not coming from the low neutron star spin, but from whether or not there is disk accretion onto the star?

Conclusions

Shallow heating helps to explain superburst ignition, crust cooling, and potentially other thermonuclear bursts properties such as recurrence times and the transition to stable burning.

Several aspects of burst phenomenology change on going from low state to high state





Accretion state appears to affect burning: is it due to heating from spreading layer?