Crustal cooling in accretion heated neutron stars

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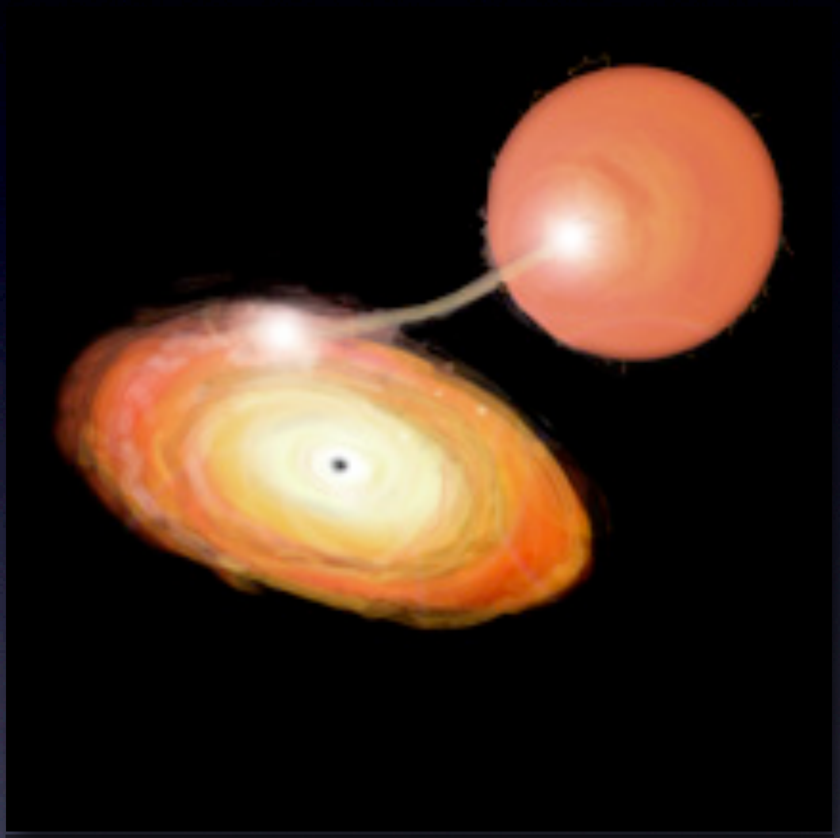
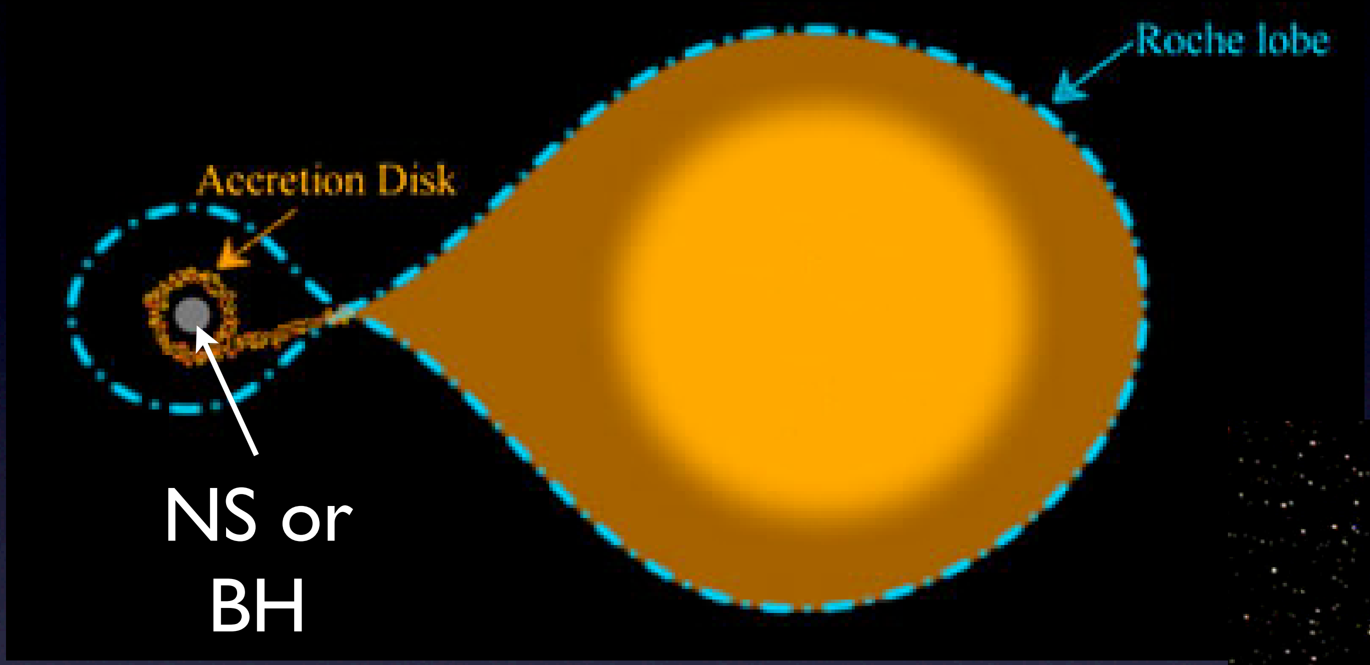
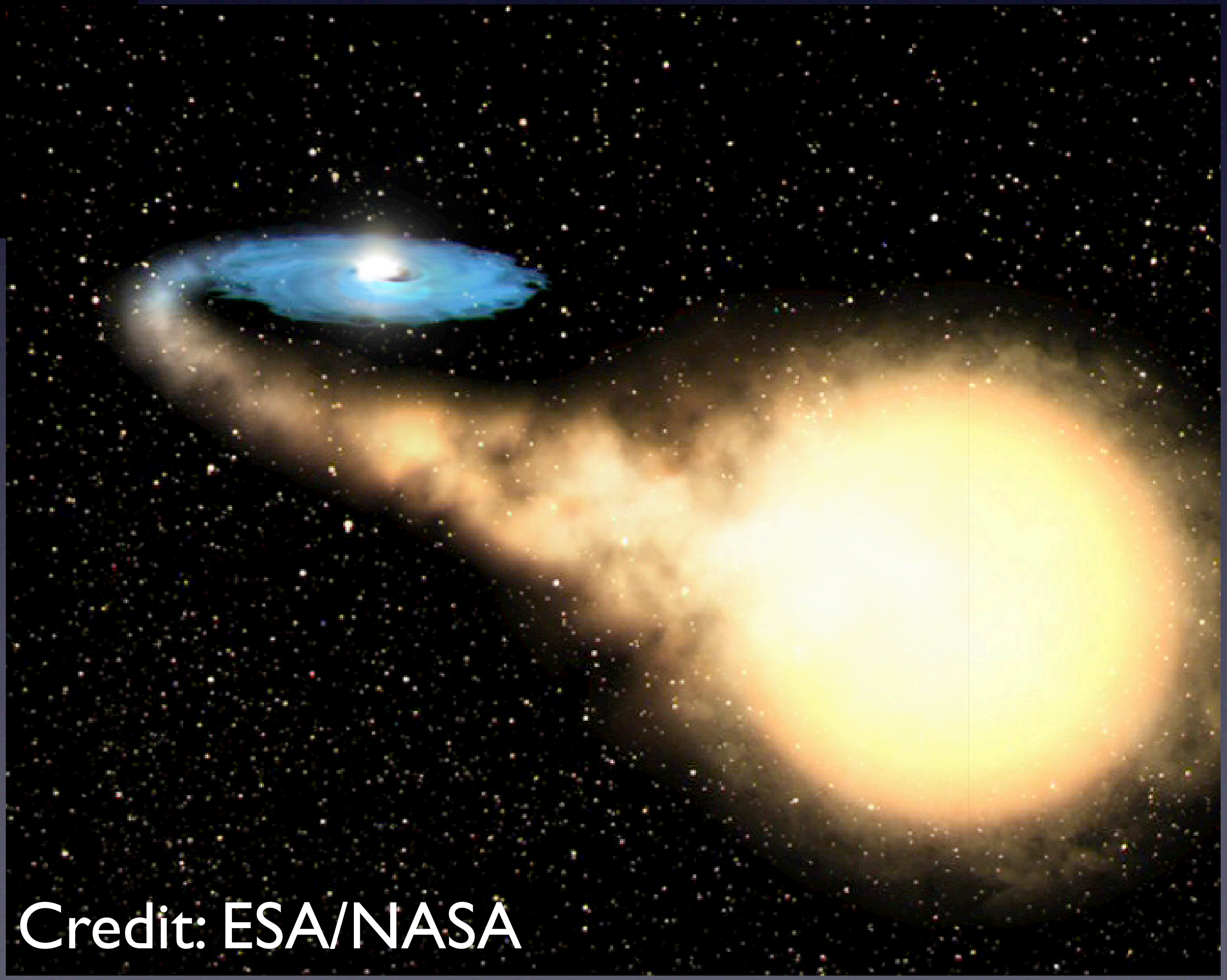
Outline

- X-ray transients
- Accretion heated neutron stars
- Observing NS crusts cooling
- What next?
- *To answer Bob:* we can measure the thermal relaxation time of the crust (we think!)



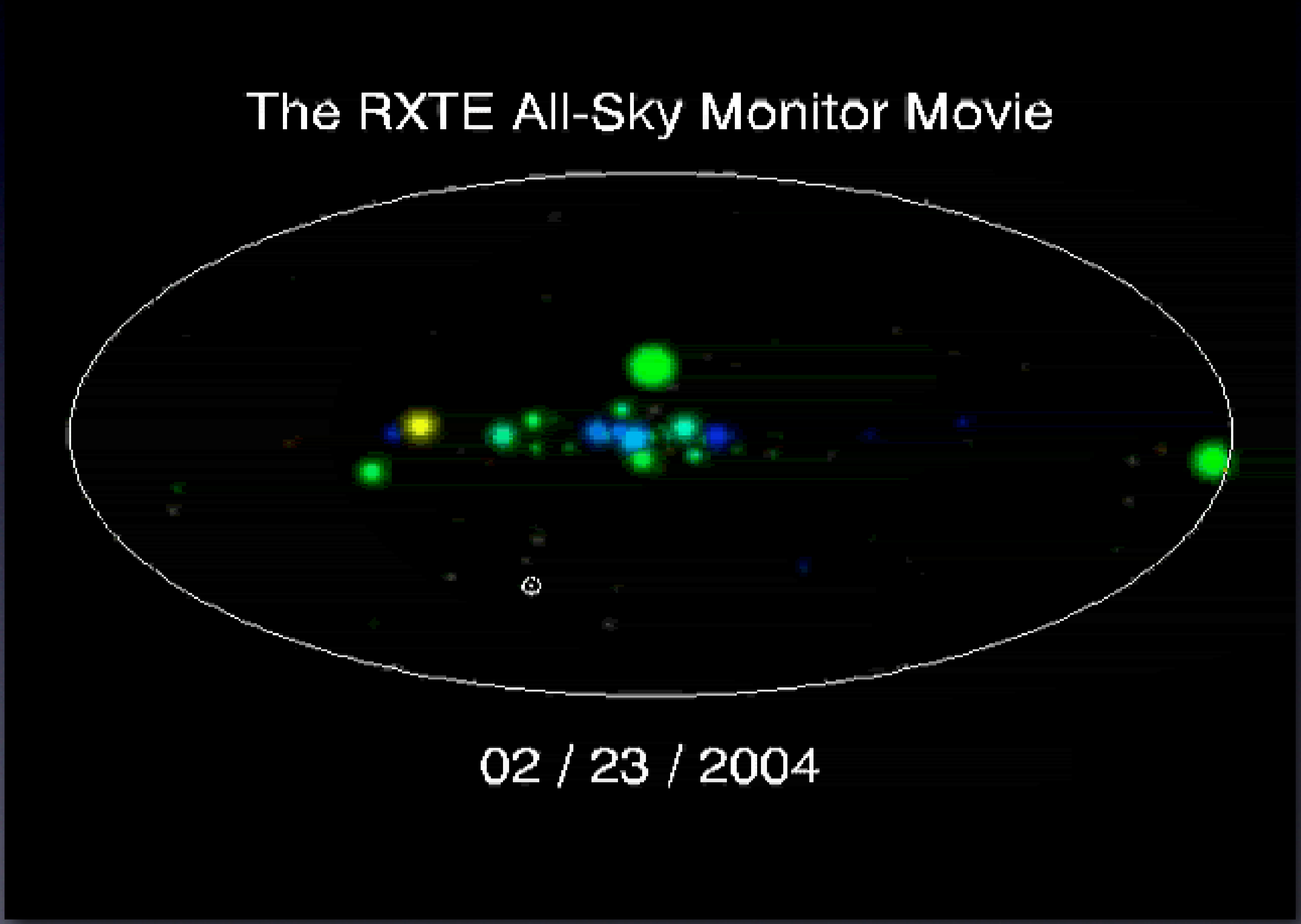
X-ray Binaries





Low-mass X-ray binary (LMXB):
donor ~ 1 $M_{\odot}$

The variable X-ray sky



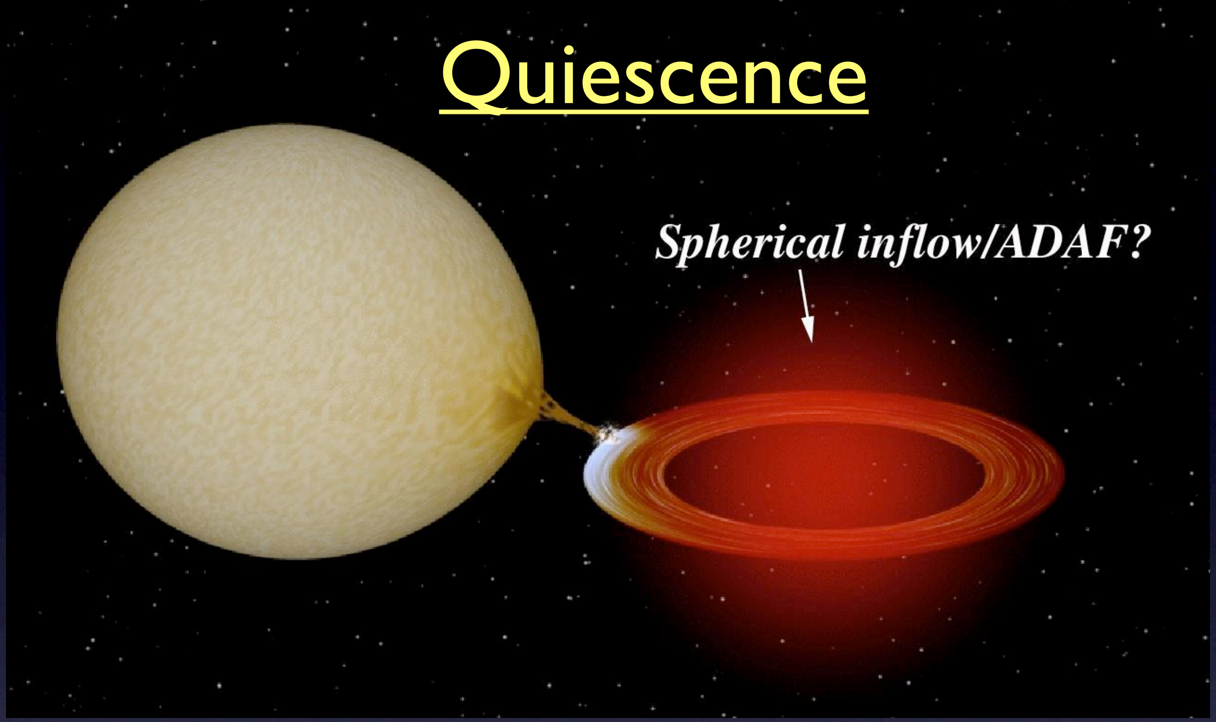
Credit: The RXTE ASM Team

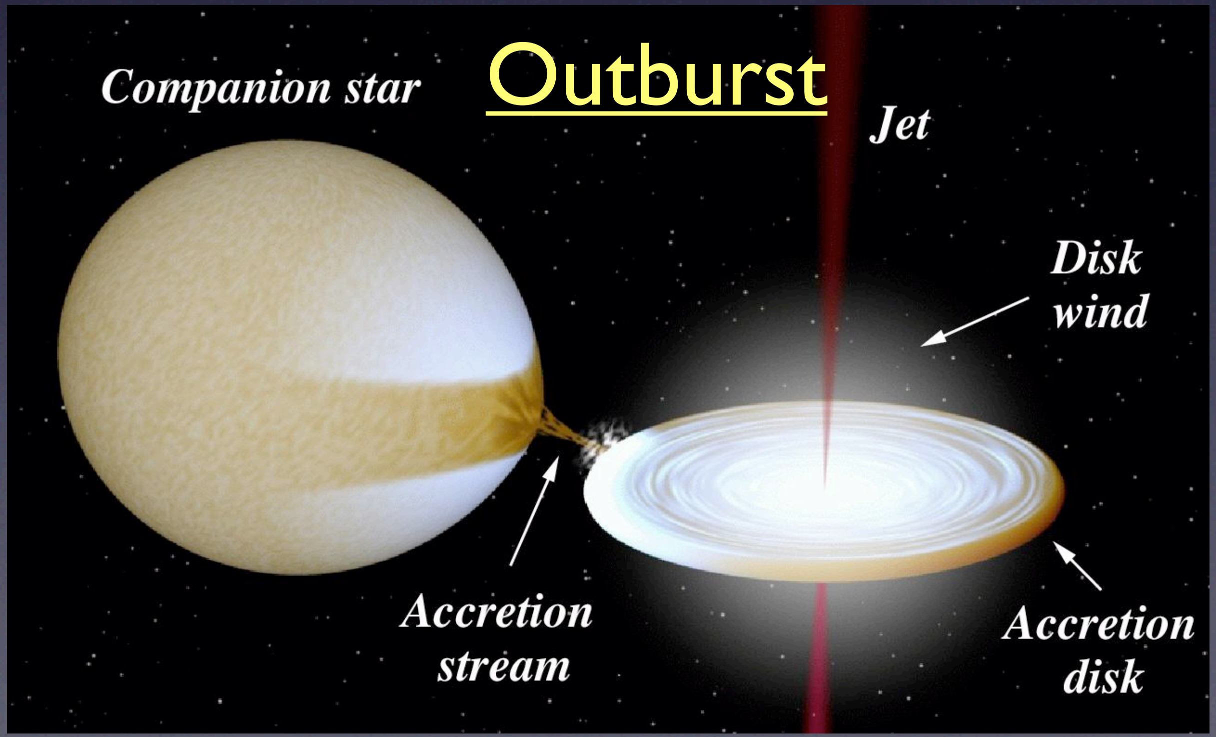
Why are X-ray binaries transient?

- Majority of the time spent in quiescence - little or no accretion
- Matter builds up in outer disk
- Thermal instability triggers rapid accretion

➡ outburst

see e.g., Lasota (2001)

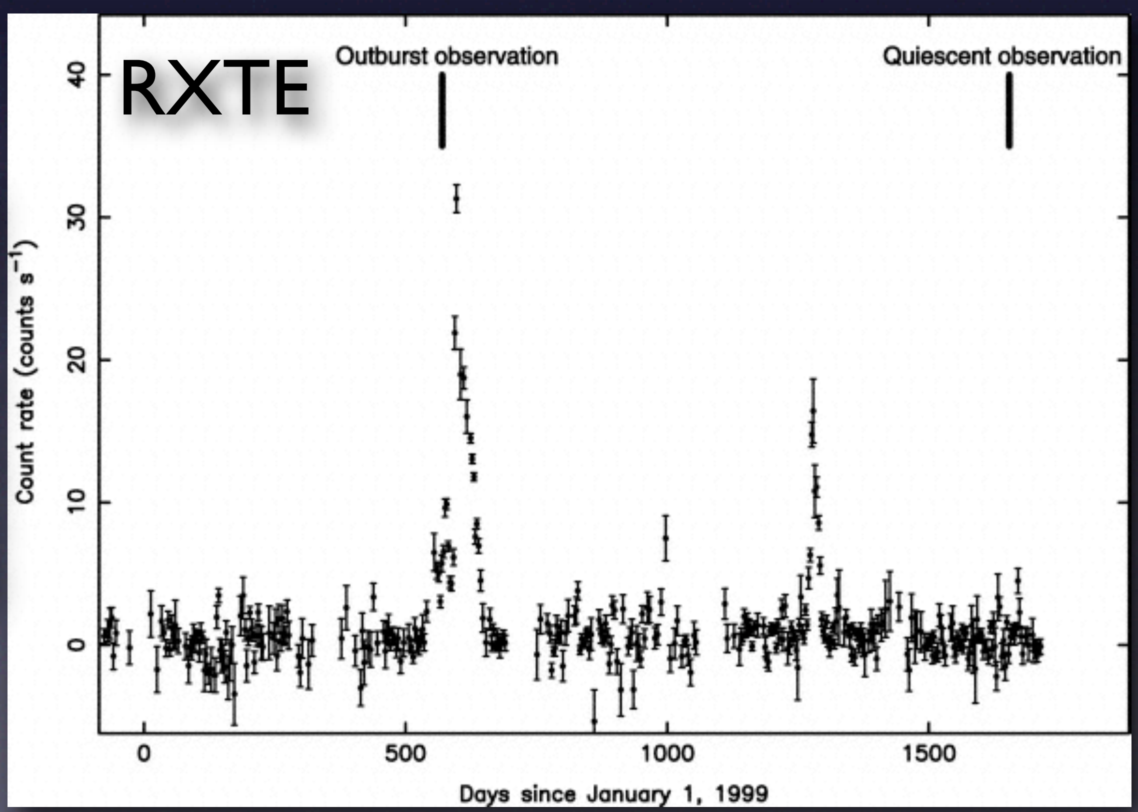




Transients

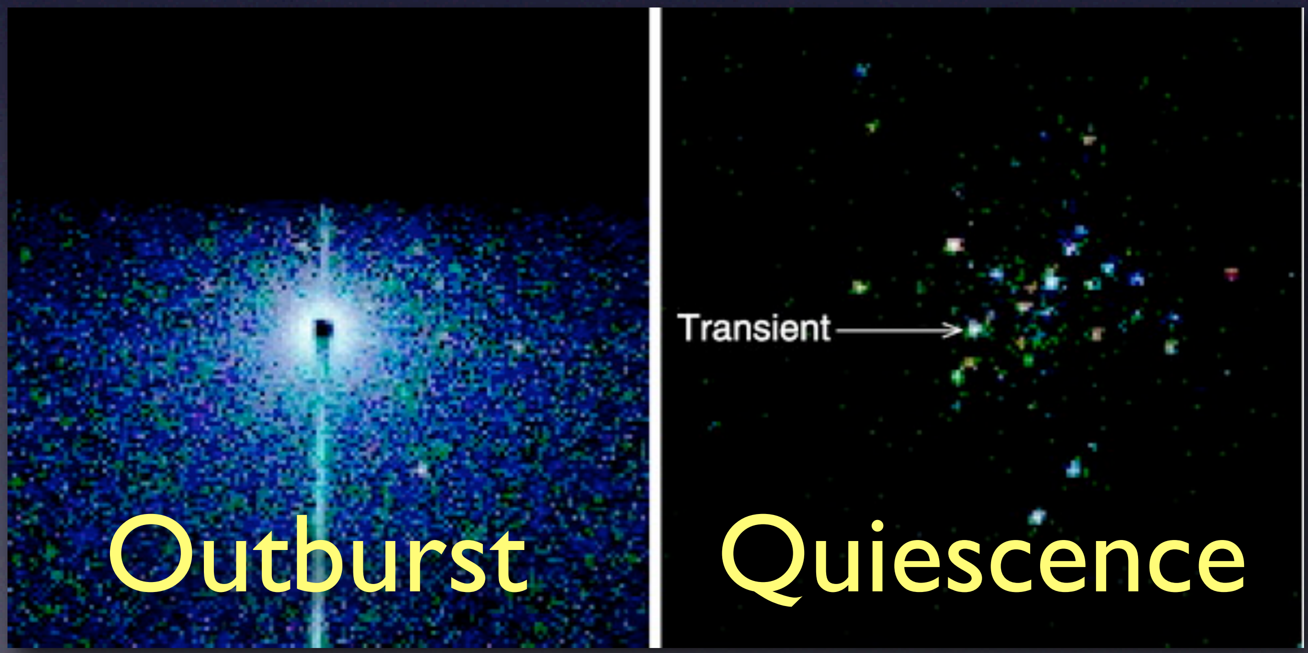
- Increase by 10^3 - 10^4 in luminosity
- Outbursts last typically *weeks - months*
- Recurrence timescale typically *years - decades*

Count rate



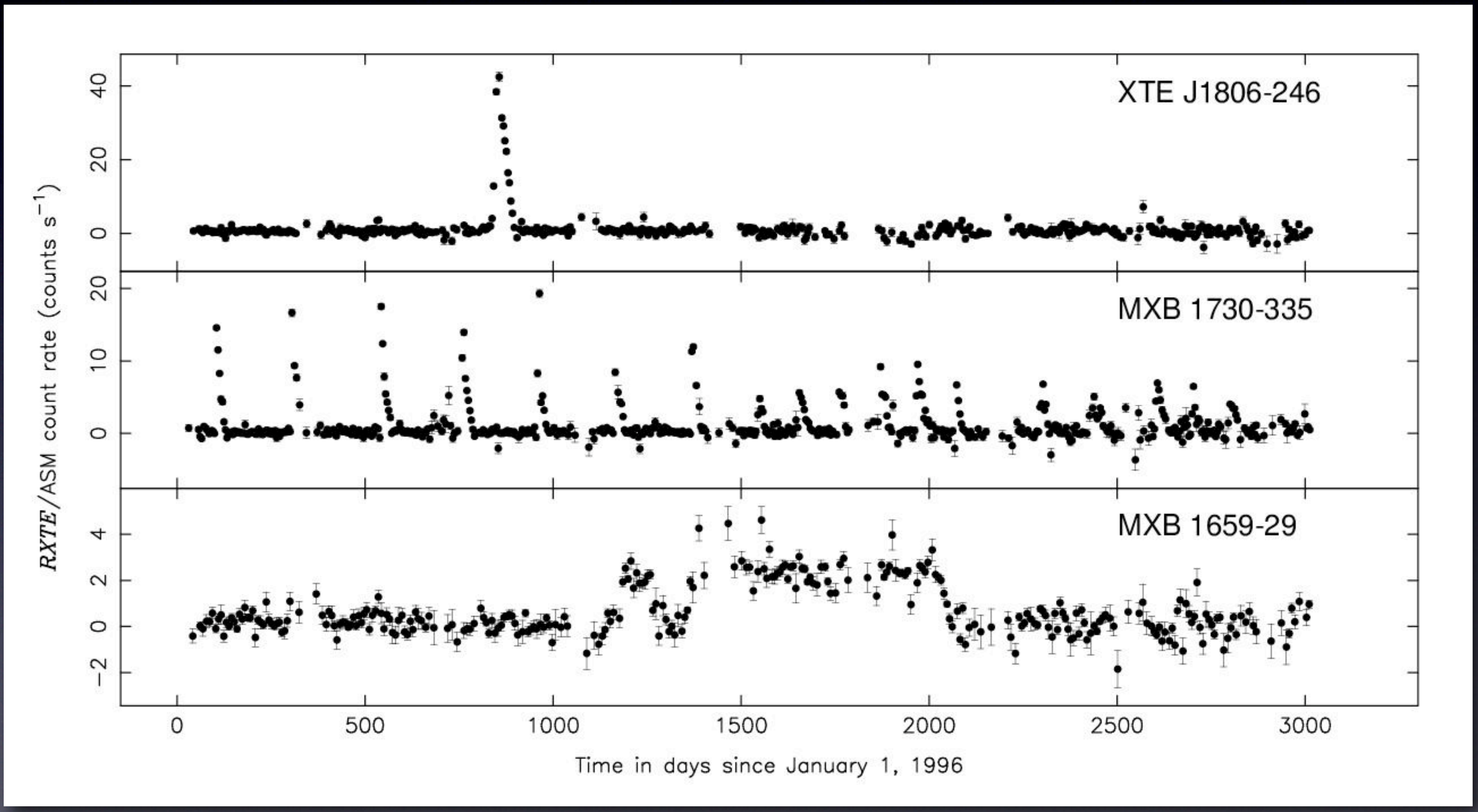
Time

EXO 1745-248 in Terzan 5



Wijnands et al. 2005

Some transient lightcurves...



Count rate

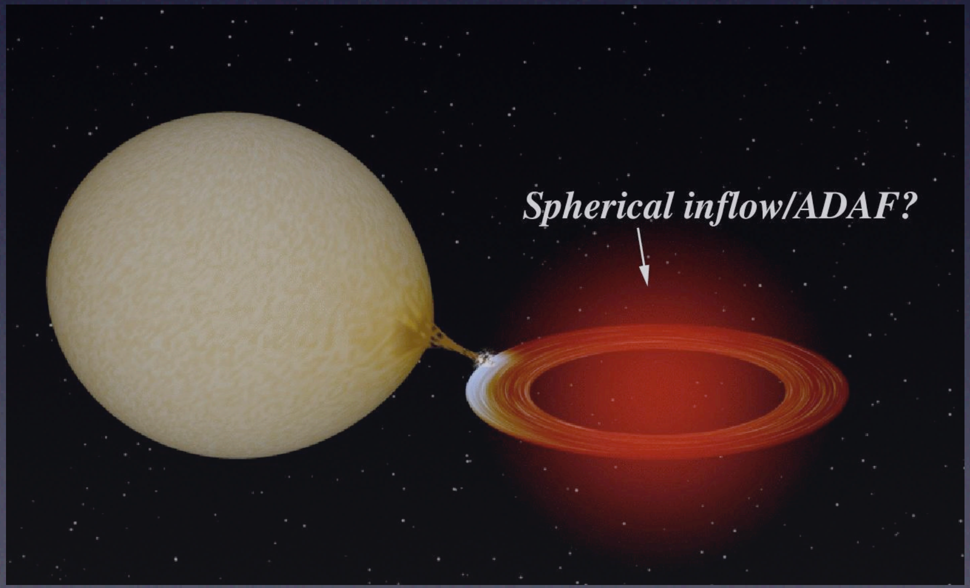
Time (days)

Data from RXTE ASM Team

Why look at quiescent neutron stars?

- Outburst luminosity 10^{36} - 10^{38} erg s^{-1}
  - dominated by X-rays from accretion disk
- Quiescent luminosity $<10^{34}$ erg s^{-1}
  - mostly thermal X-rays NS
- But, NS in LMXBs are old

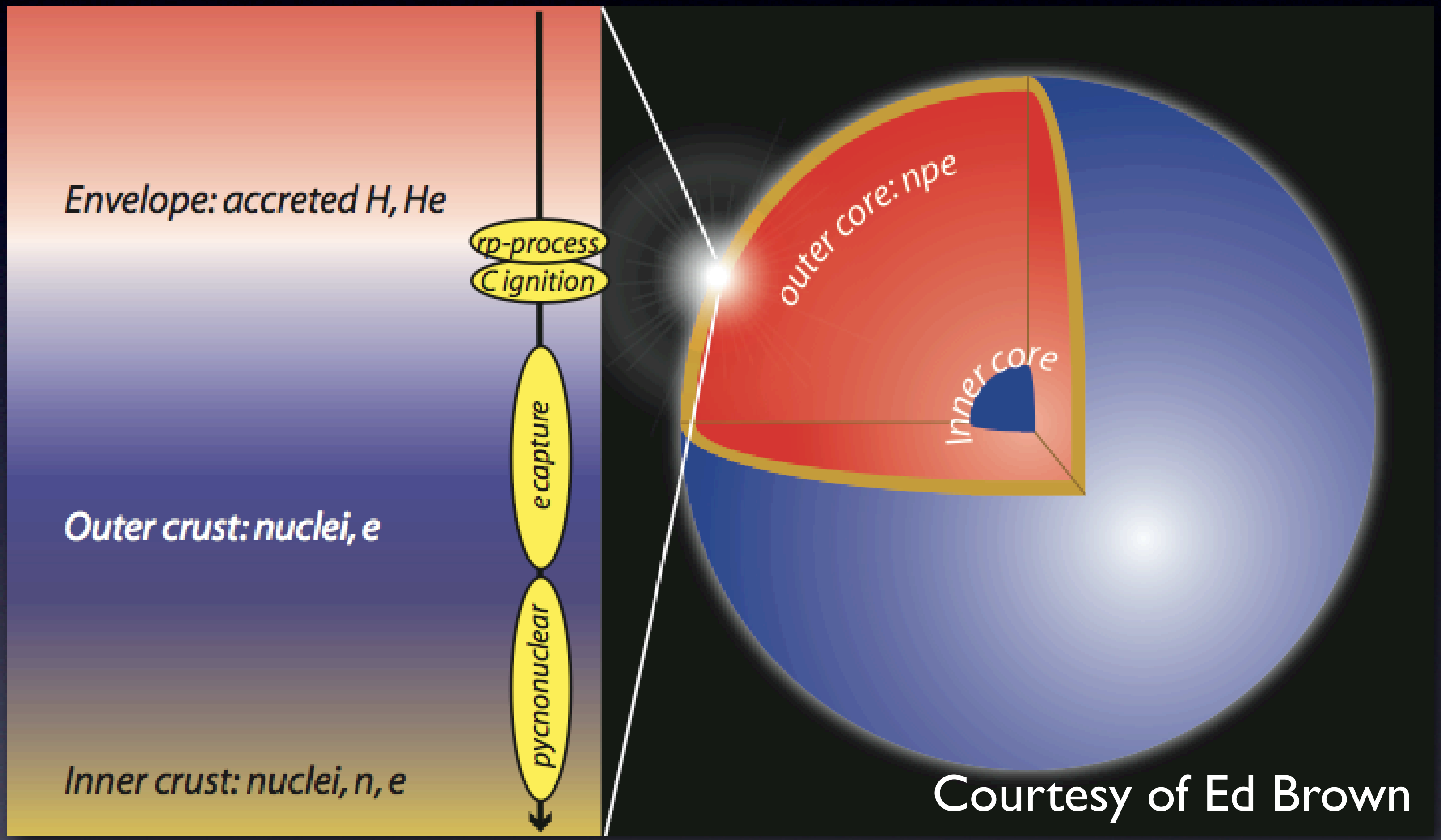
➡ why is it still hot?



Deep crustal heating

Brown, Bildsten & Rutledge (1998)

- Energy deposited during outburst
- Freshly accreted material compresses inner crust (~300 m deep)
- Trigger nuclear reactions
- Repeated outbursts heat core (over 10^4 yr)
- Get to a steady-state



→ Quiescent luminosity set by time-averaged accretion rate

Deep crustal heating continued......

Quiescent Luminosity

Time-averaged mass accretion rate

$$L_q = 8.7 \times 10^{33} \left(\frac{\langle \dot{M} \rangle}{10^{-10}\ M_\odot\ \mathrm{yr}^{-1}} \right) \frac{Q}{1.45\ \mathrm{MeV}}\ \mathrm{ergs\ s}^{-1}$$

Heat deposited in crust per accreted nucleon

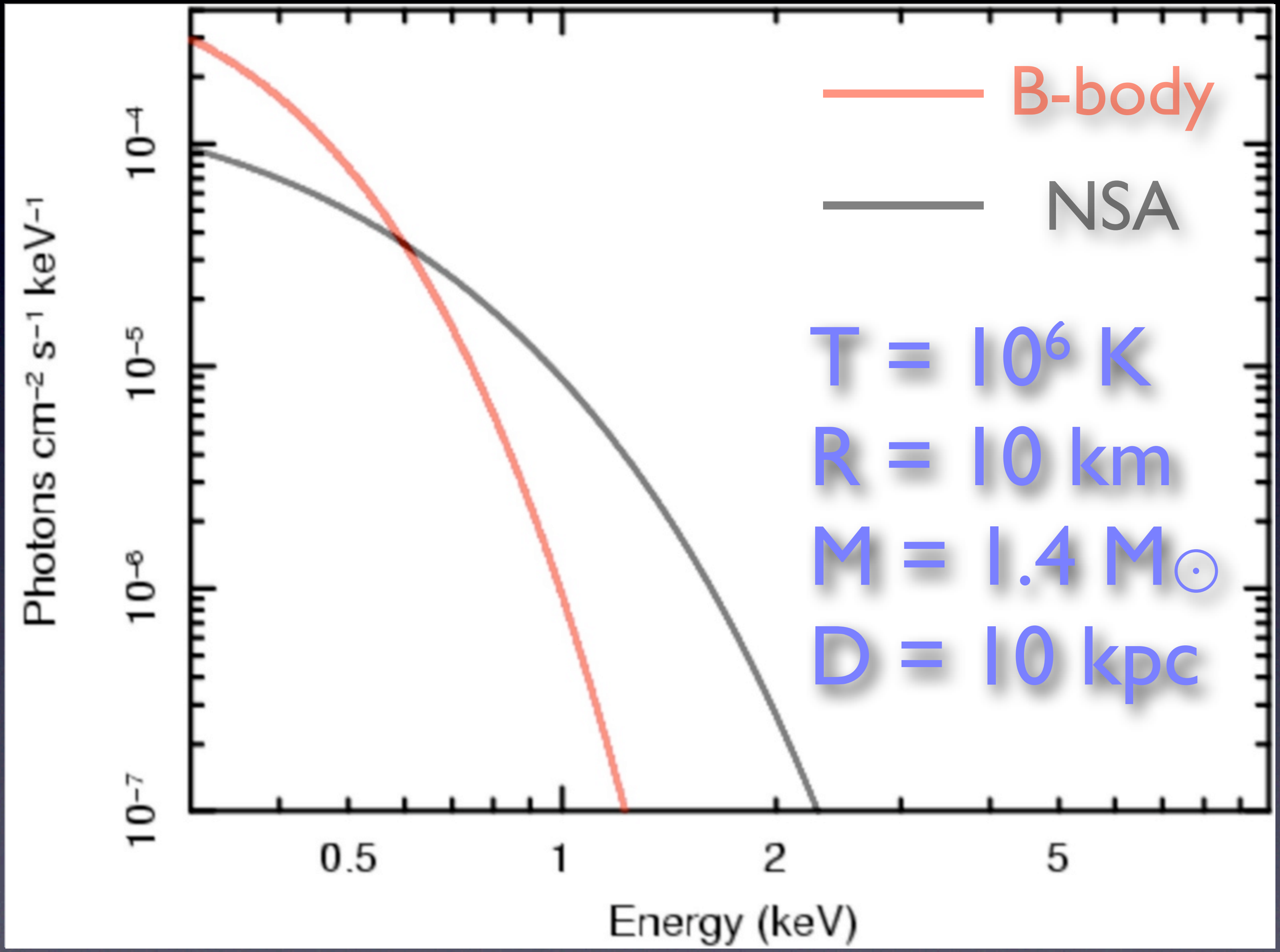
Learning about NS interior

- Quiescent luminosity depends on level of neutrino emission
- Measure the quiescent fluxes (luminosities) of as many NS as possible
- Put them all together - can learn something about NS cooling.......leave for Craig Heinke

Observing neutron stars in quiescence

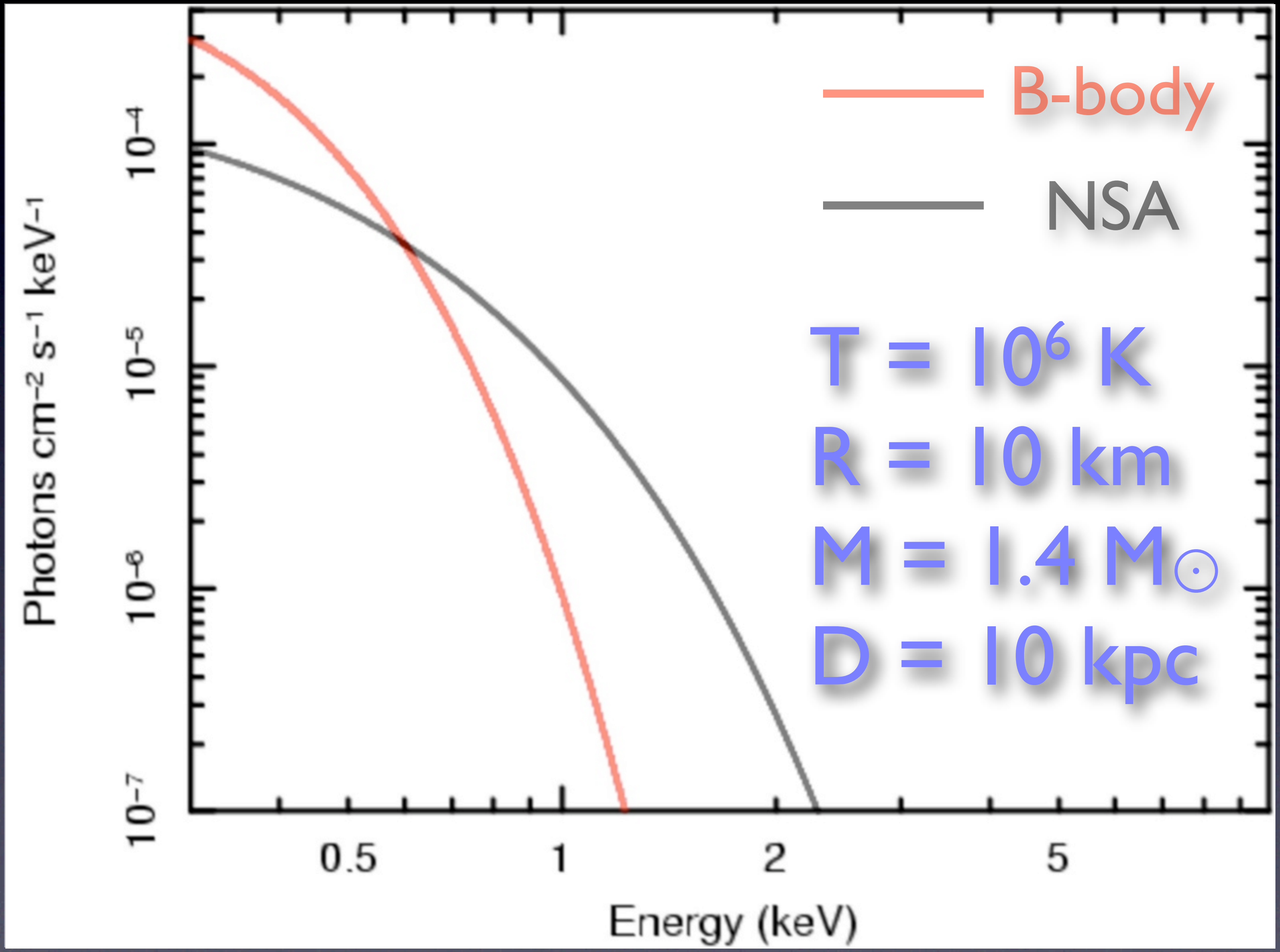
- Dominated by thermal emission (generally!)
- Blackbody: Flux $\propto$ (Radius/Distance)^2
- But blackbody fits give too small a radius (e.g. Rutledge et al. 1999)
- Need to use atmosphere spectra (e.g. Zavlin et al. 1996)
- Simpler than in isolated neutron stars:
- H dominant, and low B

Neutron star atmosphere spectrum



NSA model: Zavlin et al. (1996)

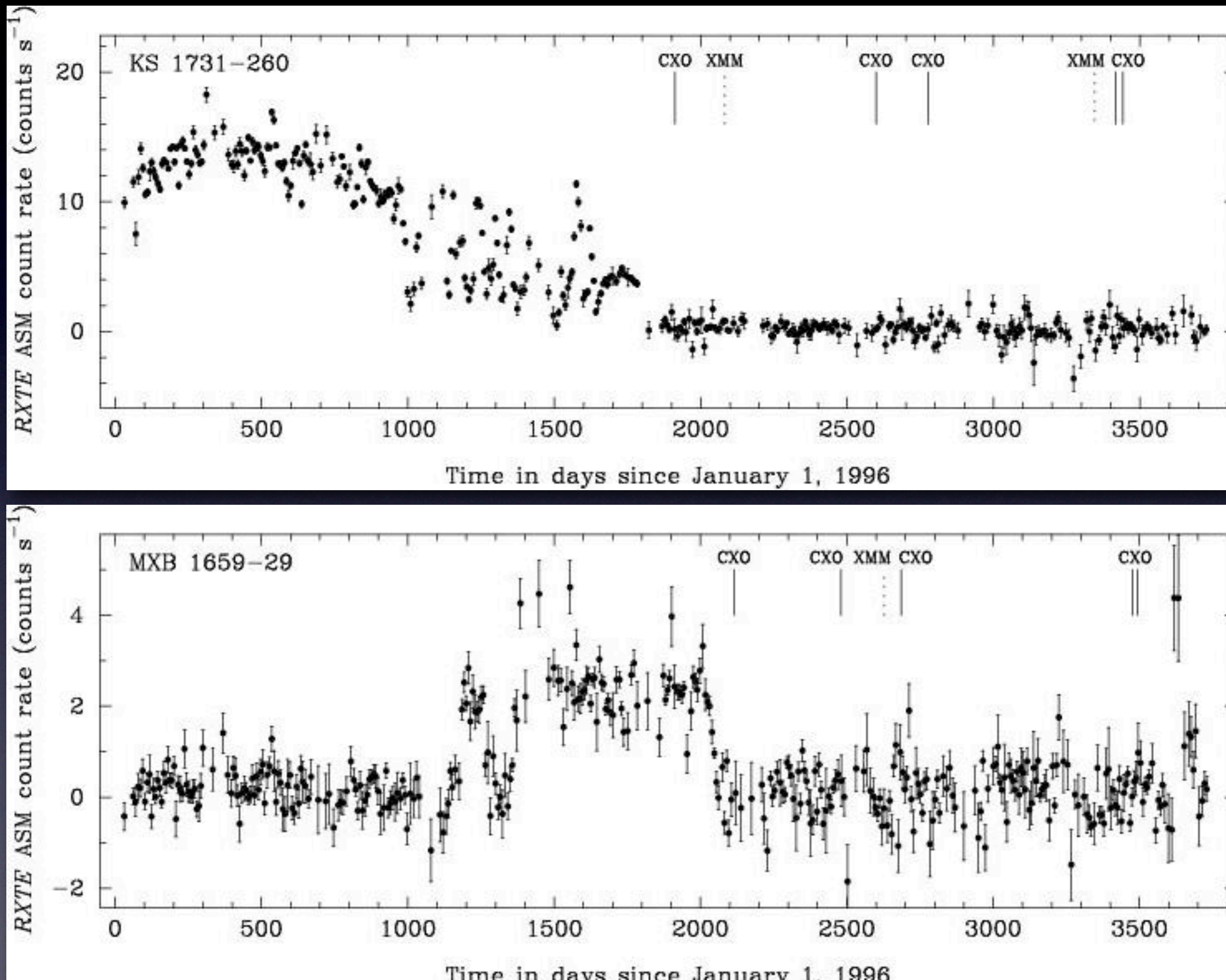
Neutron star atmosphere spectrum



NSA model: Zavlin et al. (1996)

- Example: fitting B-body to NSA
  R = 1.7 km
  T = 2×10^6 K
- Temperature: *too high*
- Radius: *too small*

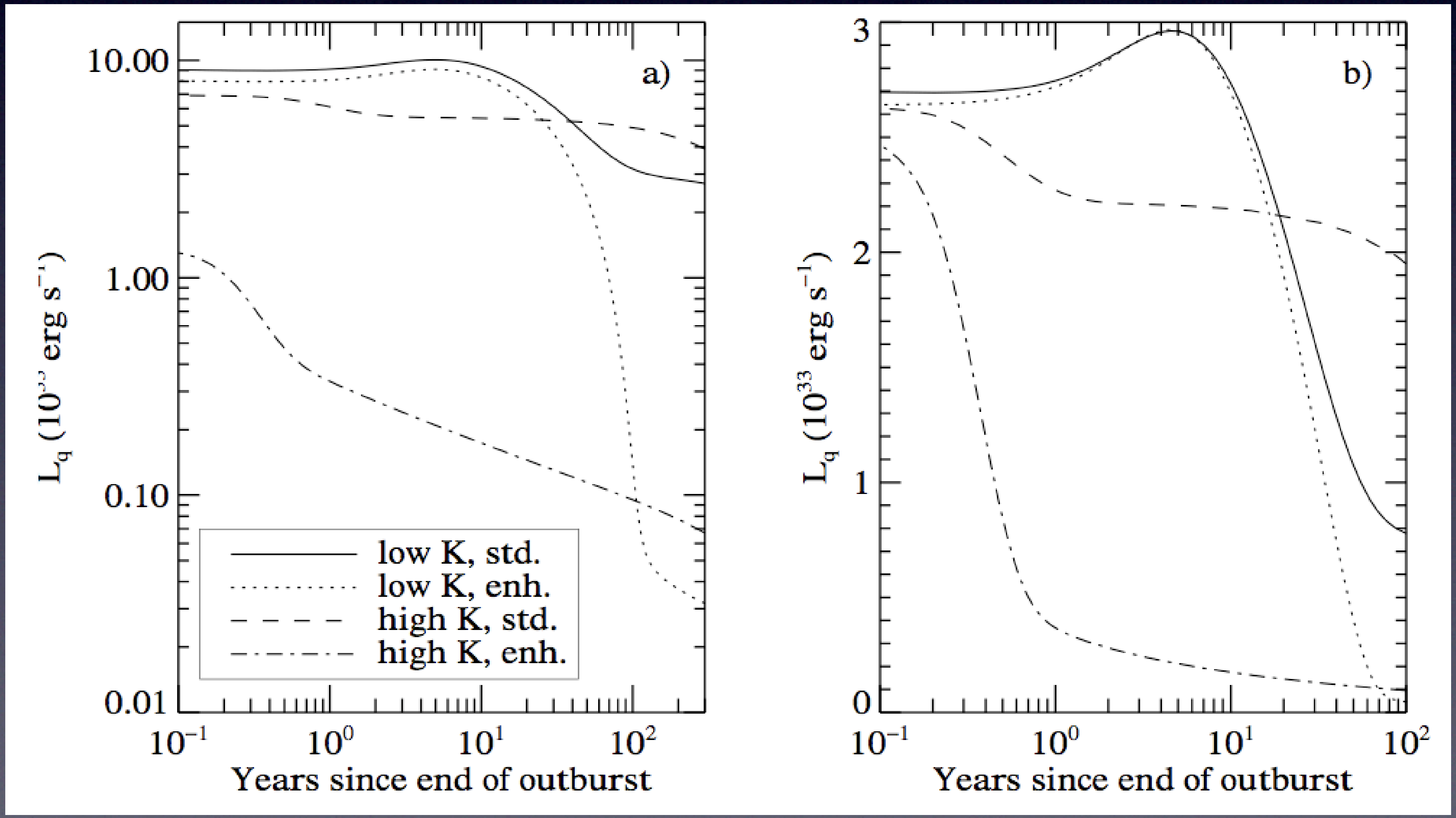
Transients with extra-long outbursts



Data from RXTE ASM Team

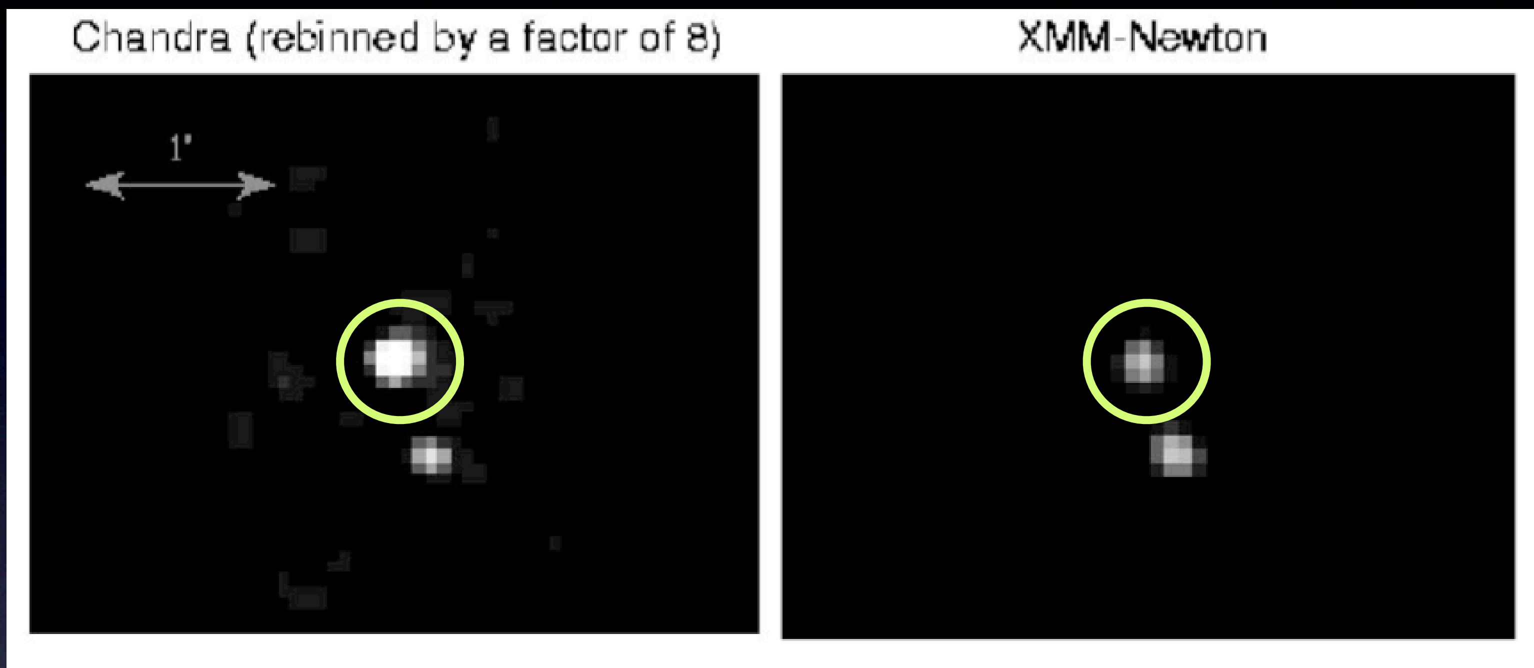
KS 1731-260

- 12.5 year outburst, no other outbursts seen
- Source goes into quiescence in Jan 2001 (Wijnands et al. 2001)
- Rutledge et al. (2002) predict crust will be heated significantly out of thermal equilibrium with interior, and should cool



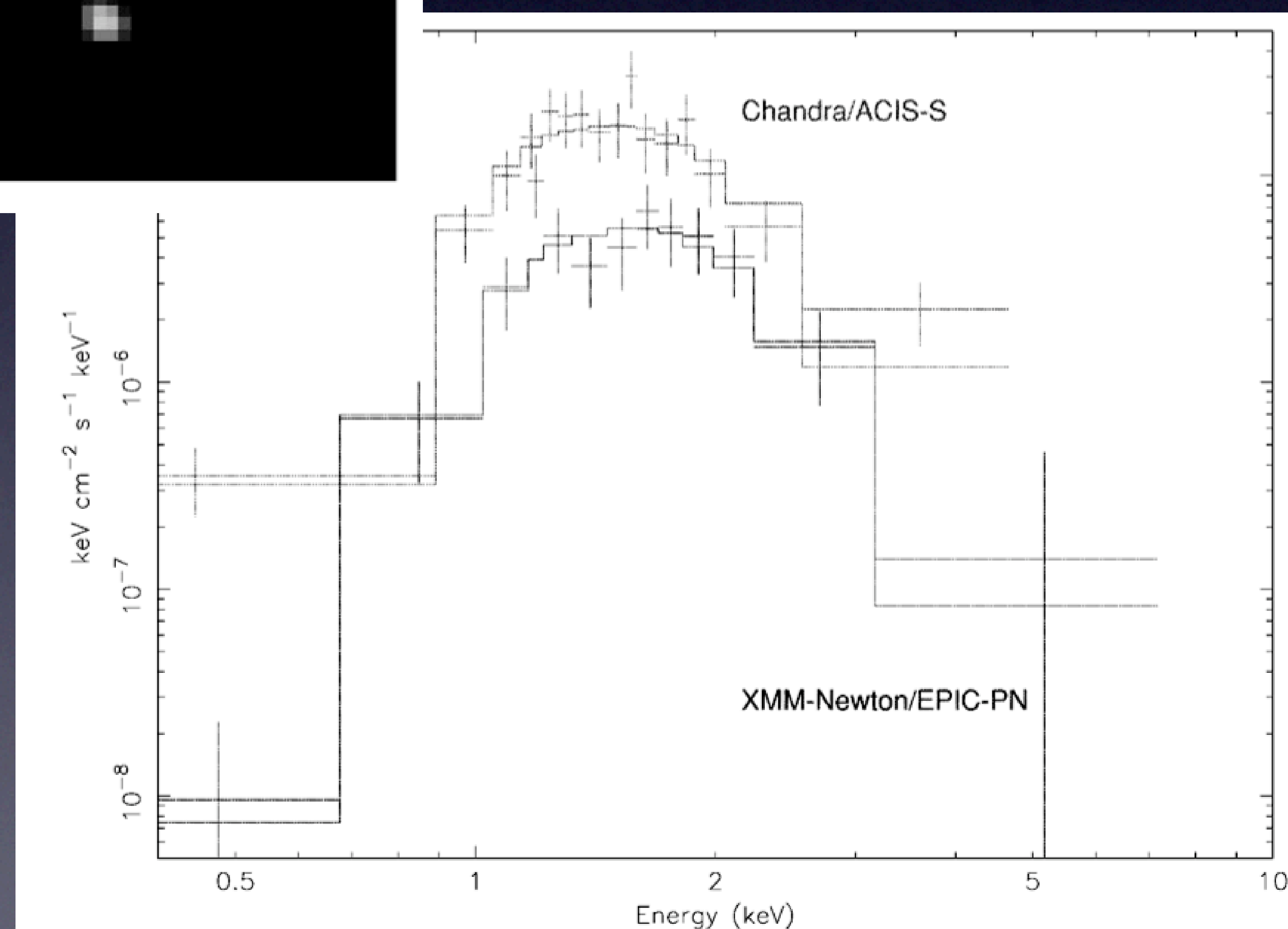
Rutledge et al. 2002

KS 1731-260: did it cool?



YES!

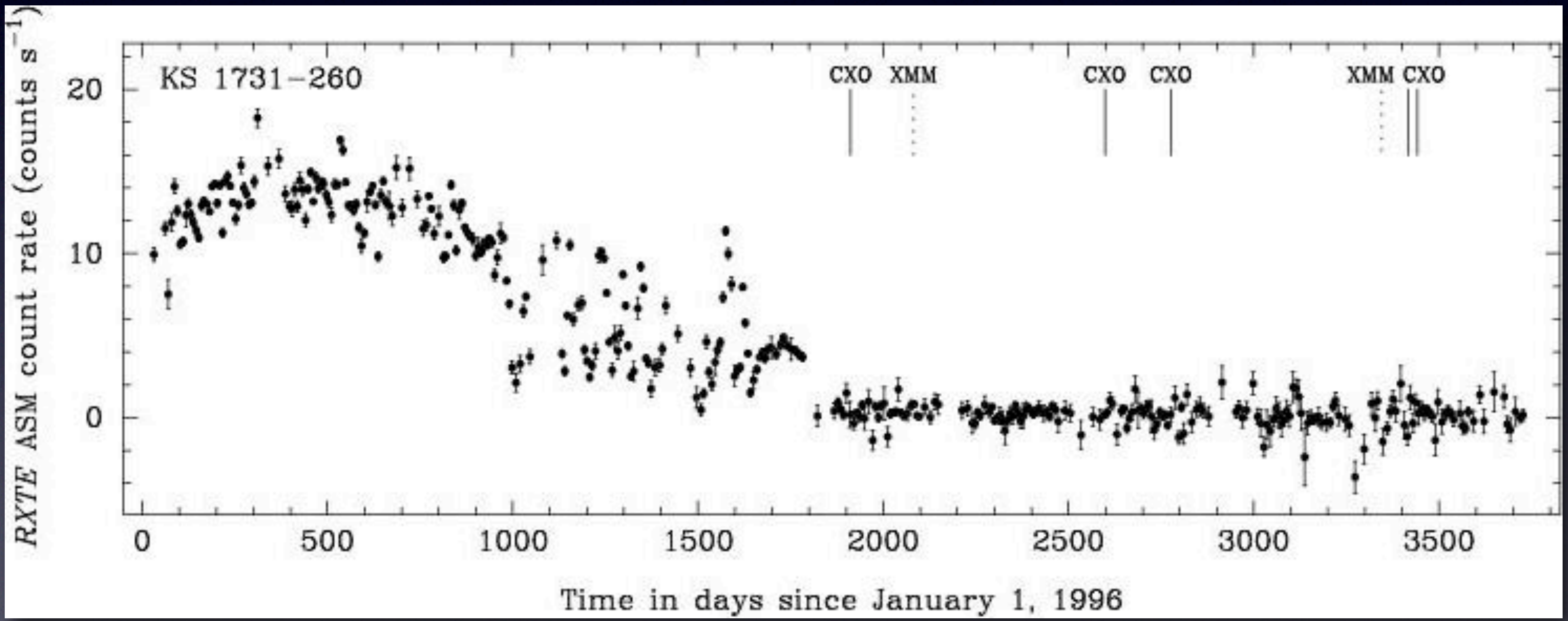
Wijnands et al. 2002



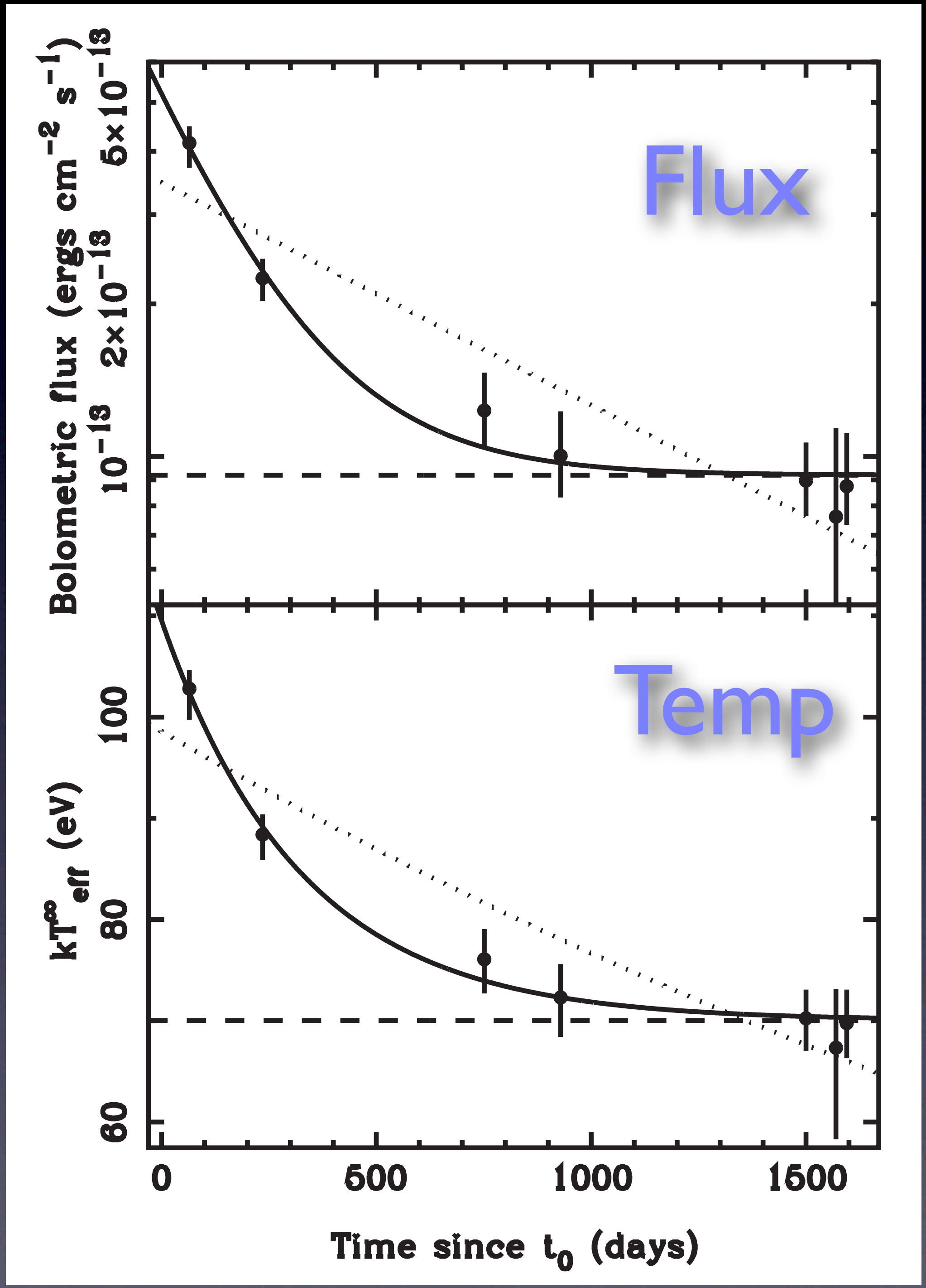
KS 1731-260: observations

5 Chandra

2 XMM-Newton



Cooling crust of KS 1731-260



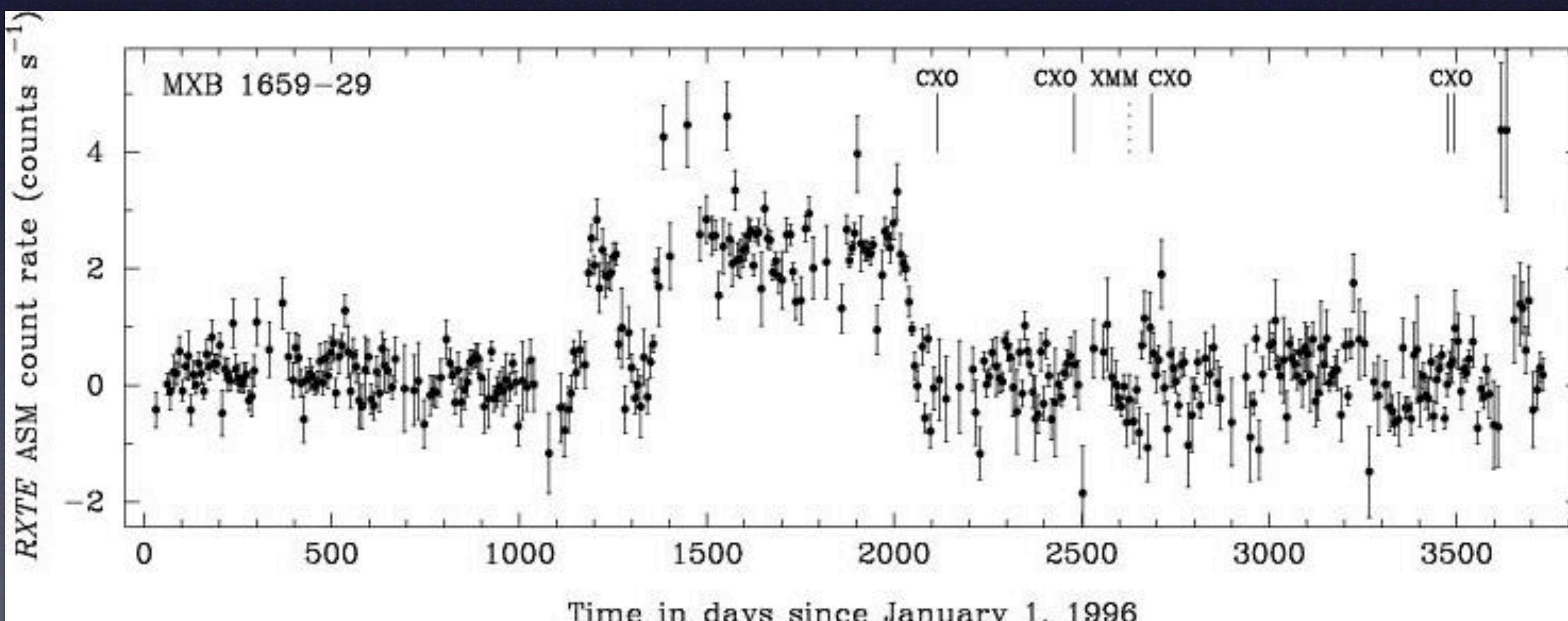
← ~ 4 yr →

- Require exponential that levels off to a non-zero value
  - ➡ returning to thermal equilibrium with core
- e-folding time:
  - 325 ± 101 d for temperature

Cackett et al. 2006

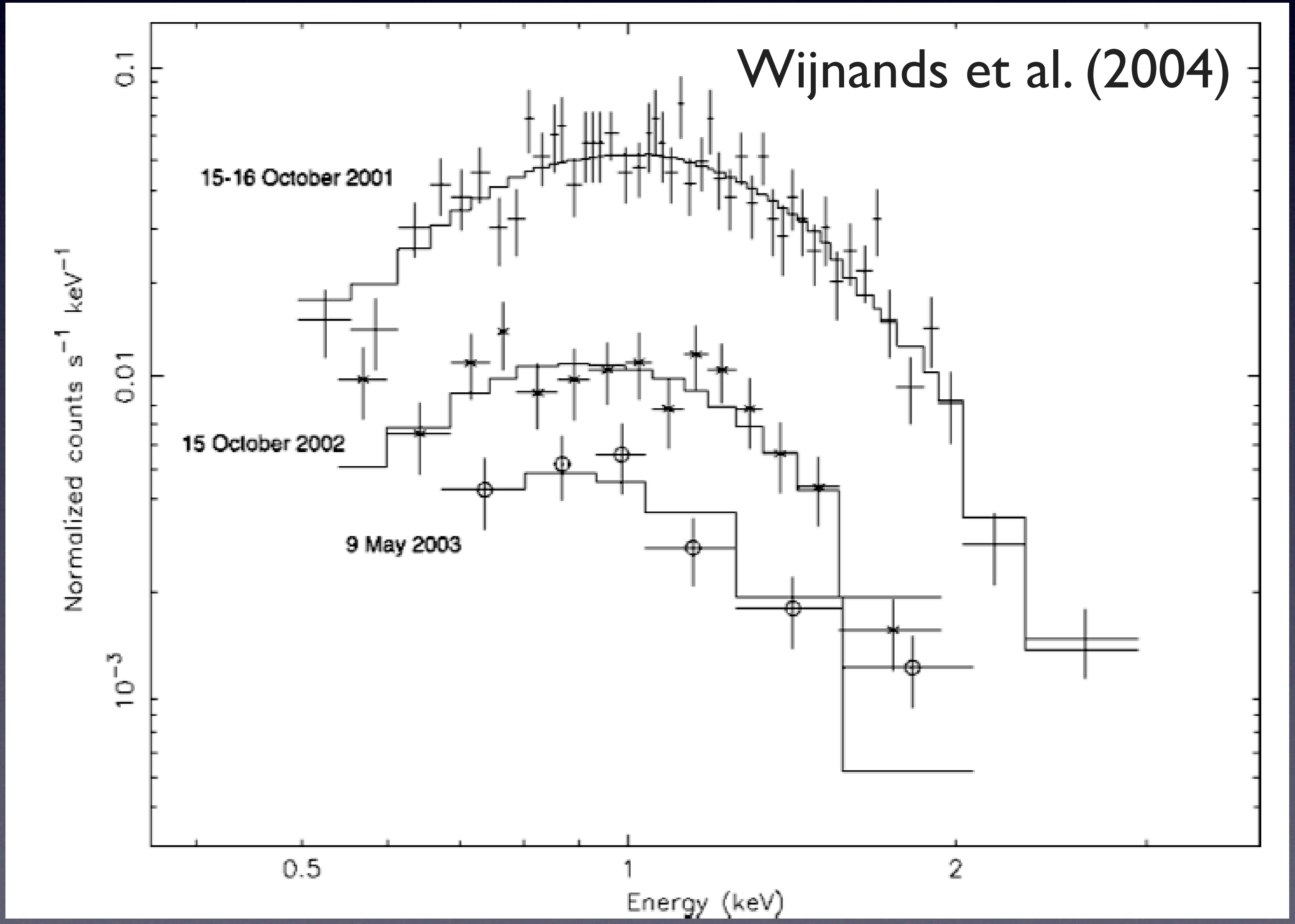
MXB 1659-29

- First detected in 1976
- Turned off in 1979, and remained in quiescence for 21 year
- Then, 2.5 year outburst
- Returned to quiescence in Sept. 2001

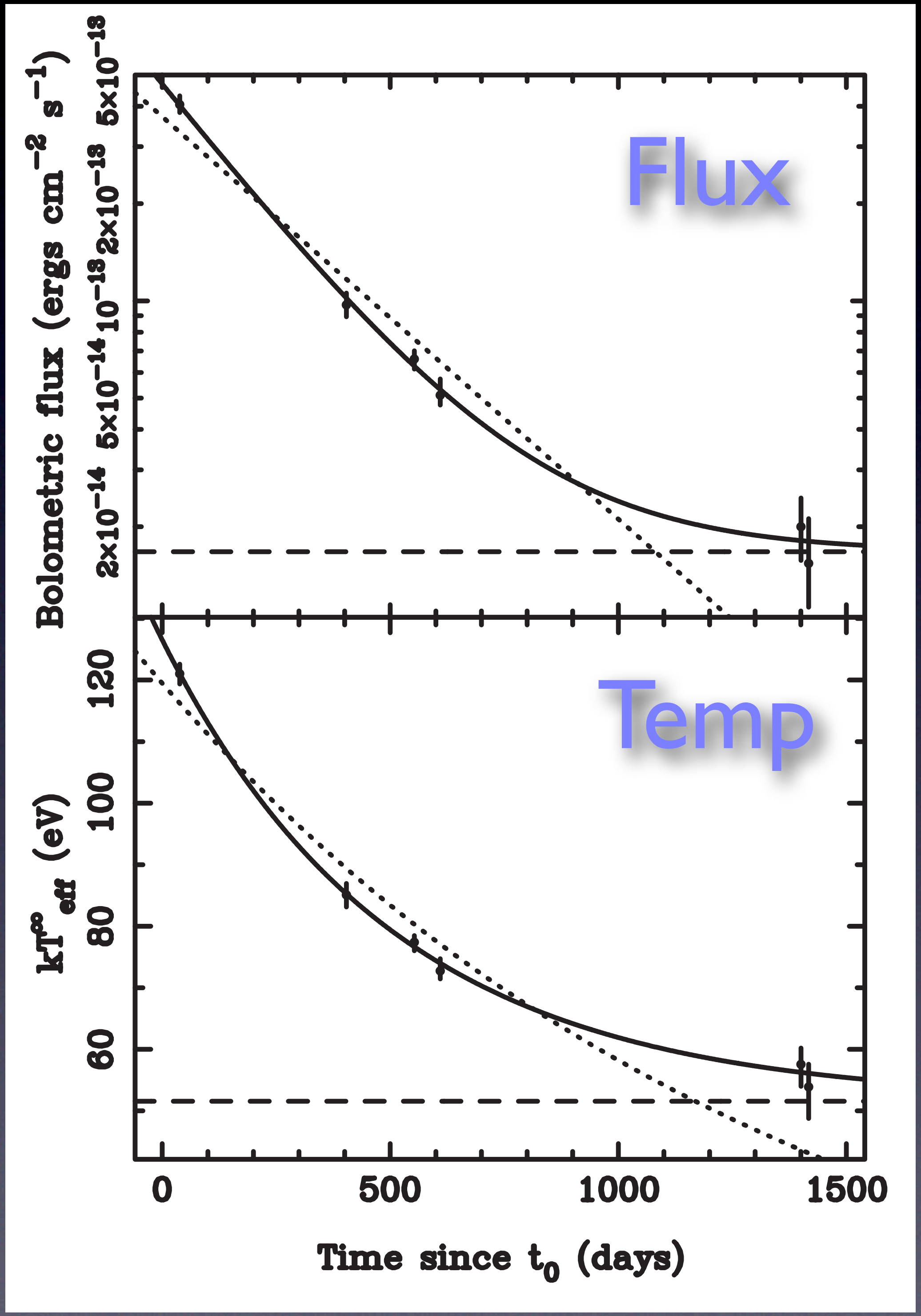


MXB 1659-29 in quiescence

- As in KS 1731: crust heated out of thermal equilbirium with core, and cools once in quiescence



Cooling crust of MXB 1659-29



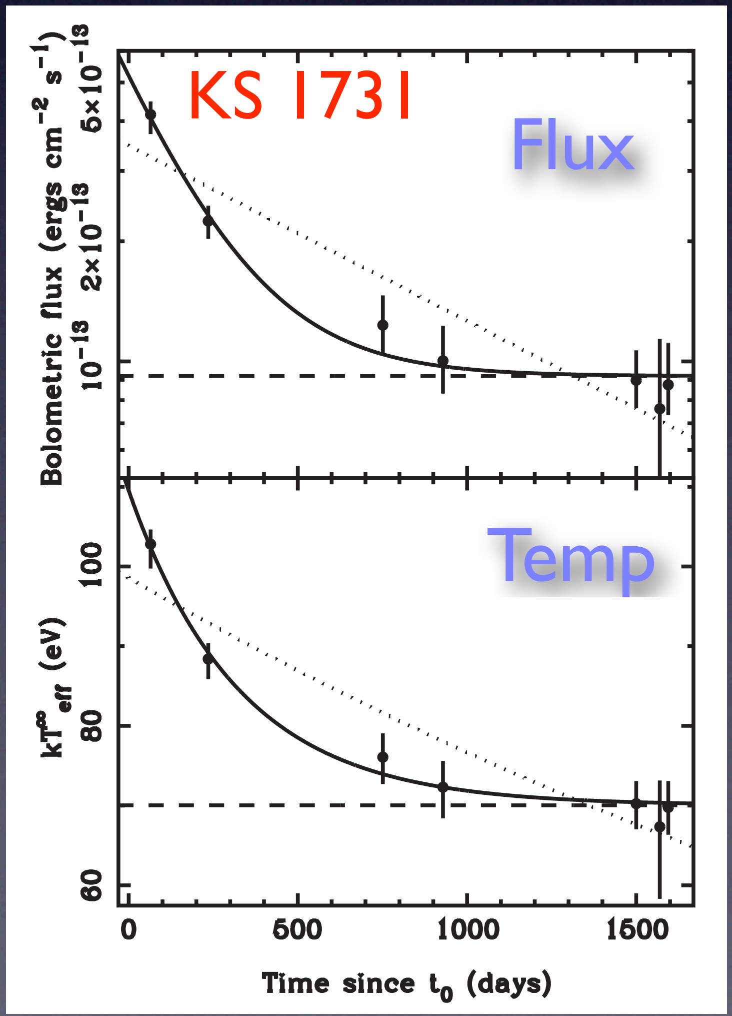
← ~ 4 yr →

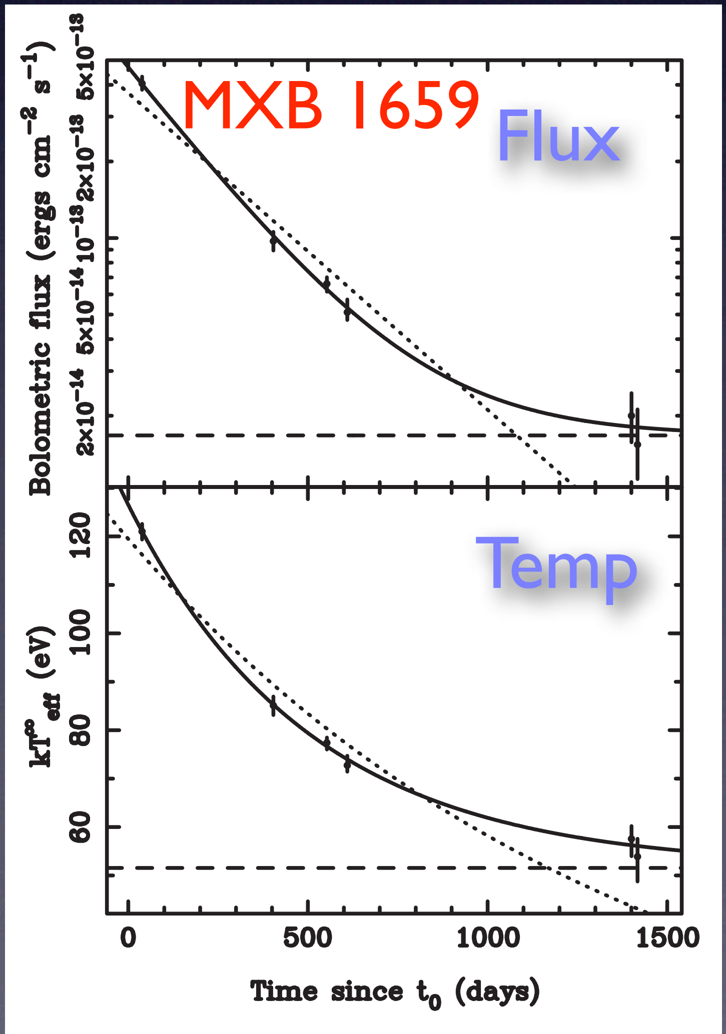
- Again, require exponential to level off
- e-folding time:
  - 505 ± 59 d for Temp
- e-folding times different:
  - KS 1731-260 cools faster by a factor ~1.6

Cackett et al. 2006

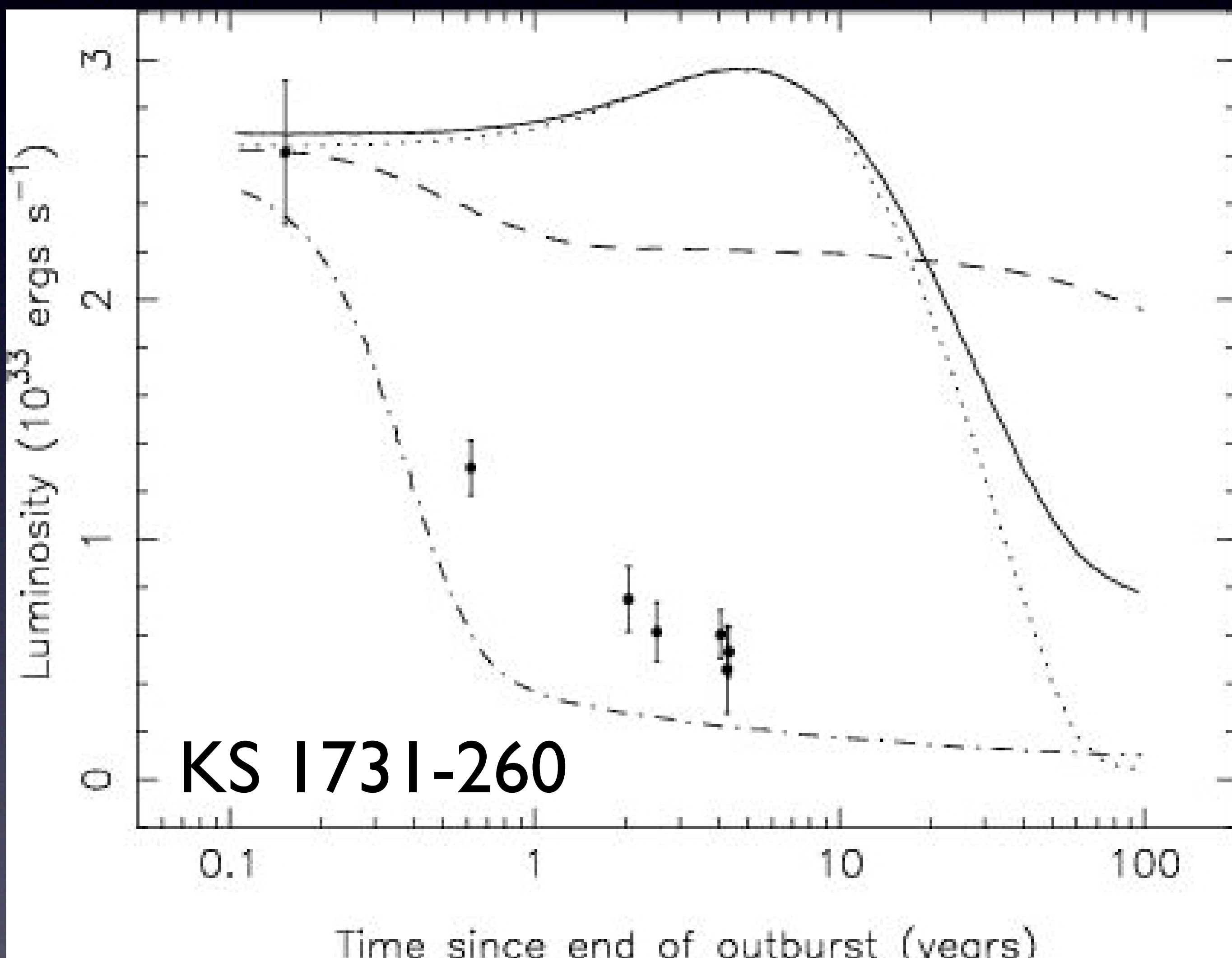
Crustal cooling

- So, in both objects we've seen the crust cool (apparently to thermal equilibrium with core)
- *We can measure the thermal relaxation time*
- But what does it tell us about the crust?





What's this tell us about the crust?

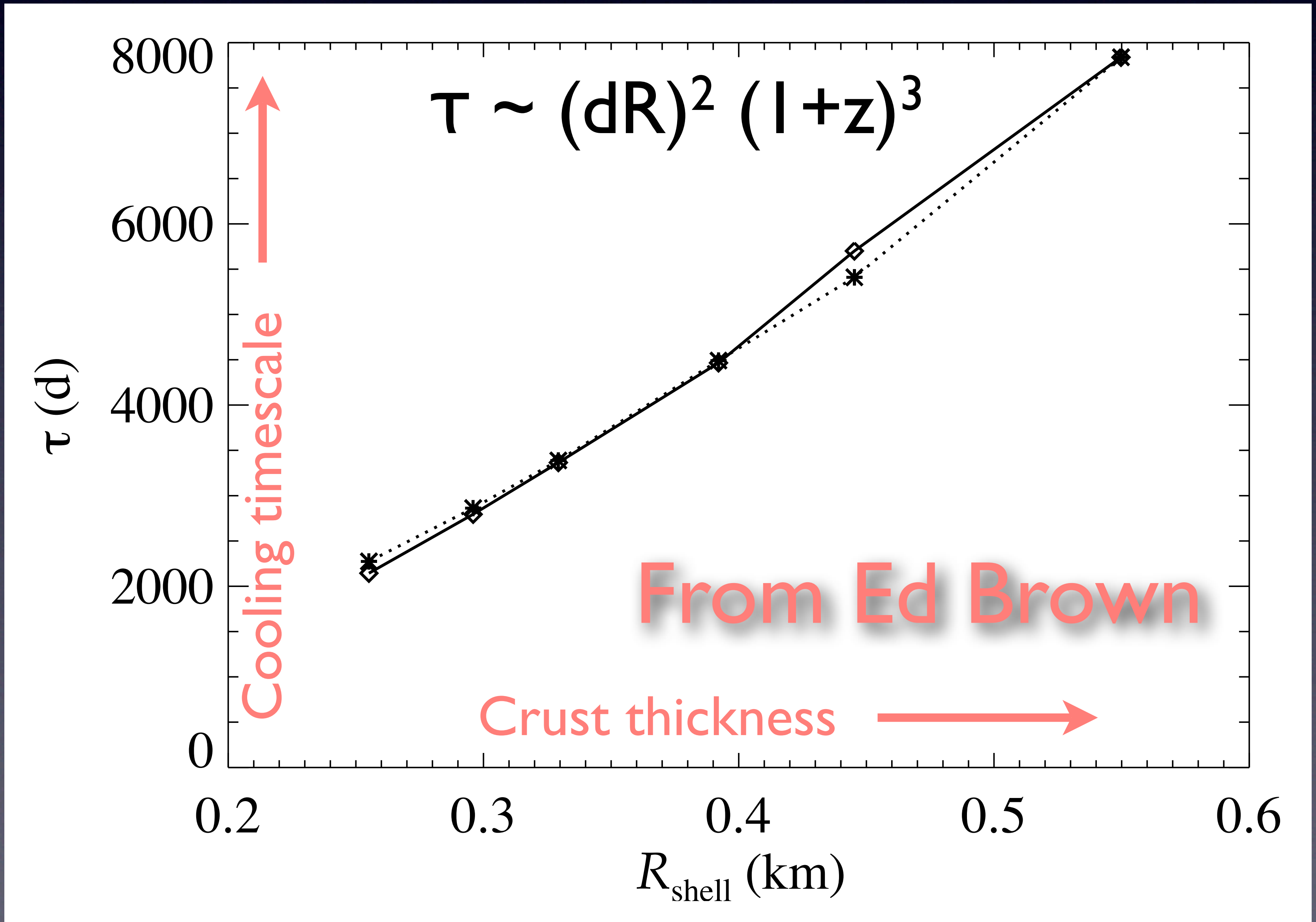


Curves from Rutledge et al. (2002)

- In the Rutledge et al. models, implies crusts have high thermal conductivity
- KS 1731 cools quicker by a factor of 1.6 - *why?*
  - Different compositions?
  - Different crust thickness?

Timescale vs. crust thickness

- Higher mass (surface gravity), thinner crust, faster cooling
- KS 1731 would need to be ~25% more massive

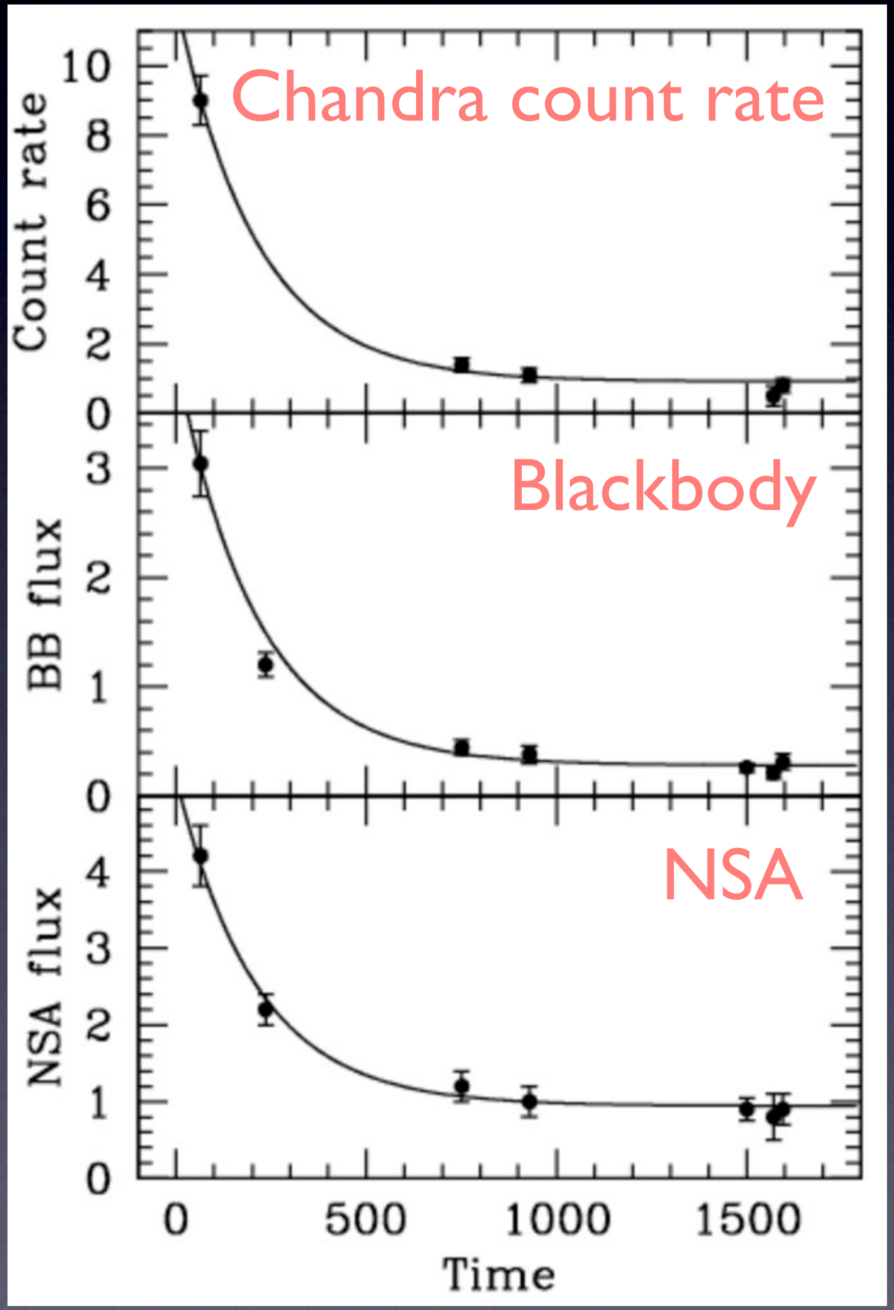


Points: numerical results assuming Haensel & Zdunik (1990) composition

Dotted line: Lattimer et al. 1994 scaling

Is the thermal relaxation time model independent?

- We recover the same timescales if using a blackbody model
- Or, just using raw Chandra count rates
- Timescale, and observed trend is robust



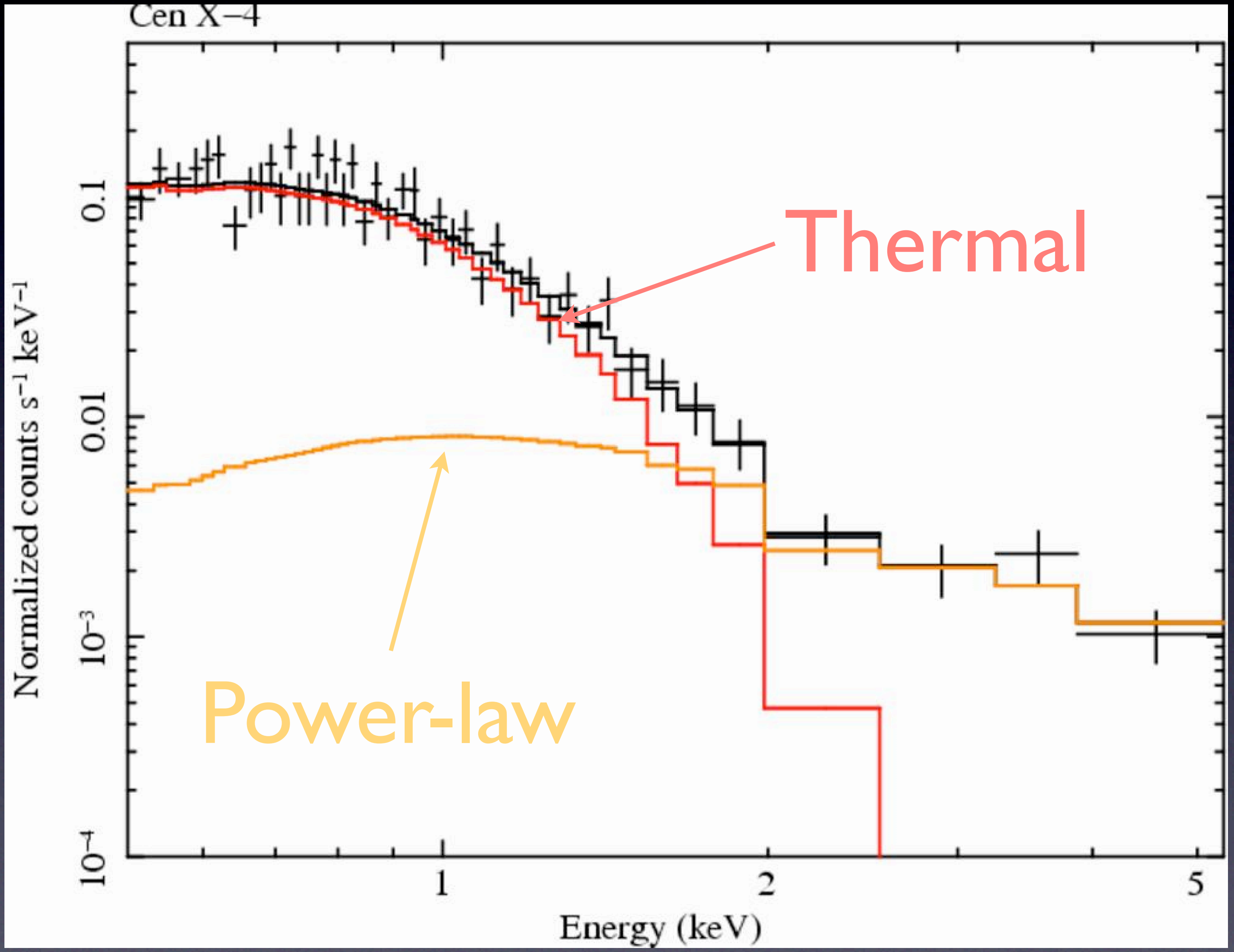
KS 1731-260

Further observational issues

- Is the spectrum purely thermal?
- Has it really stopped cooling - what will happen next?

Is the spectrum *just* thermal?

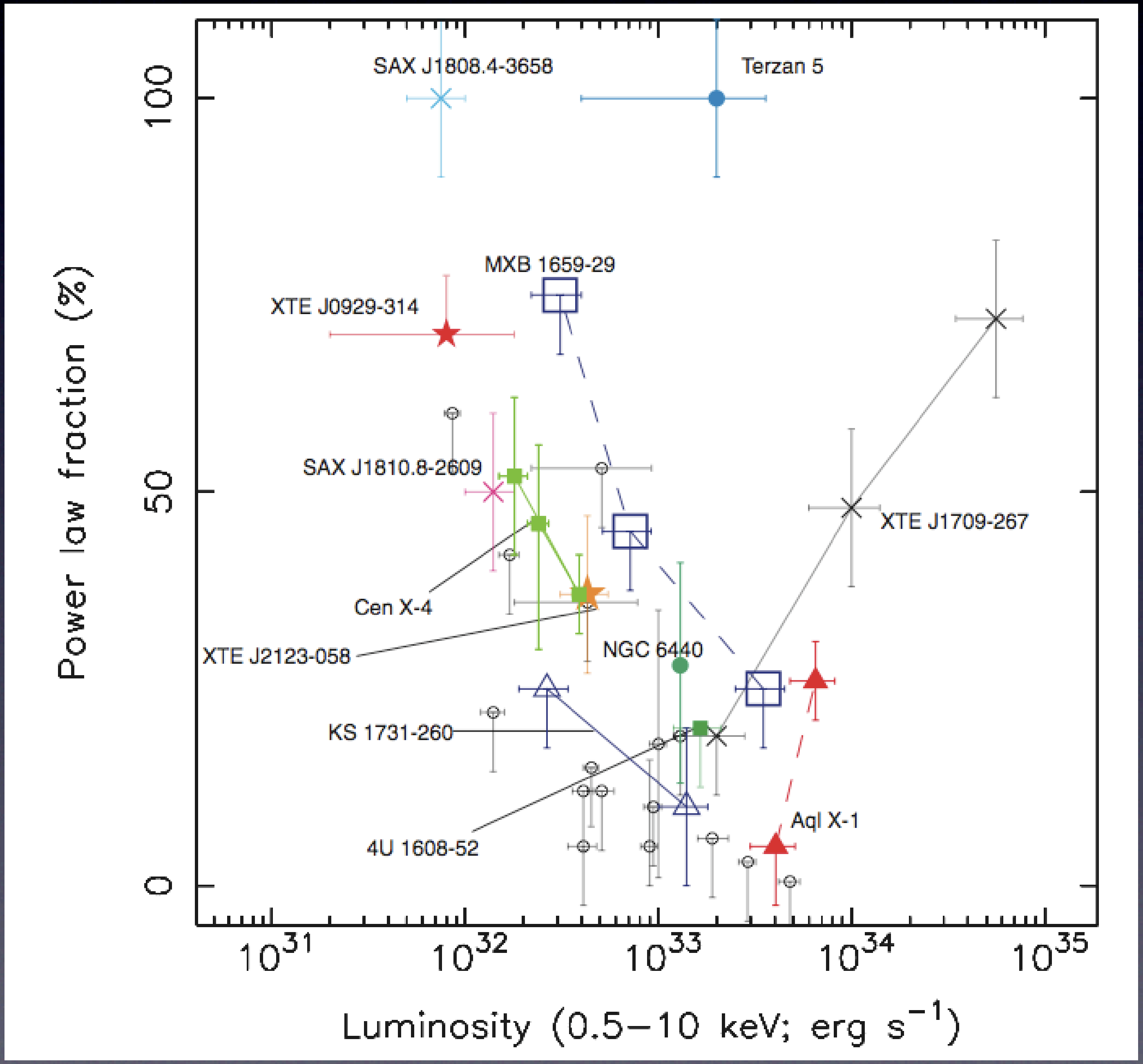
- Some quiescent neutron stars require power-law components (e.g. Cen X-4) in addition to the thermal component
- Not needed in KS 1731-260 and MXB 1659-29, but what about the faintest observations.......can't tell!



Cen X-4: PL about 50% of 0.5-10 keV flux

Is the spectrum really thermal?

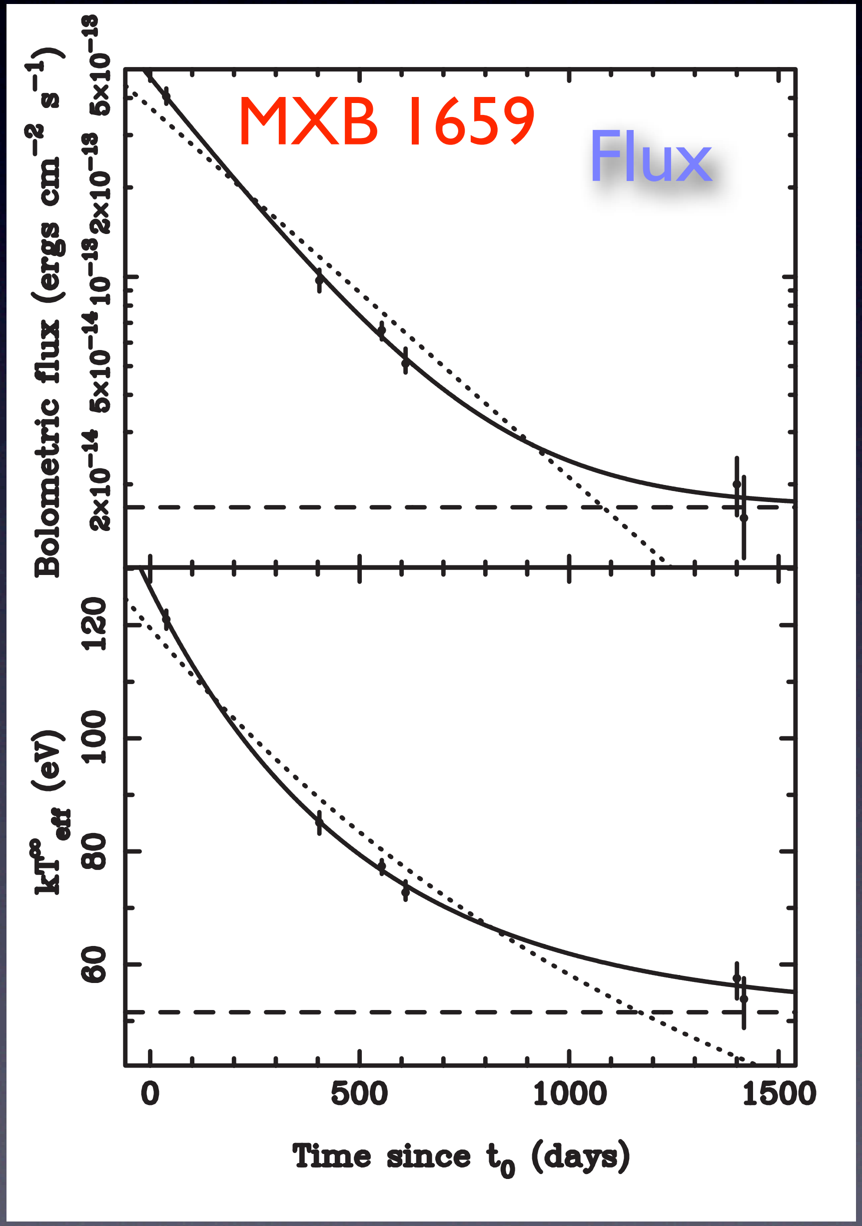
- Power-law component becomes more prominent as sources fade
- Need deeper observations of these sources to tell the significance



Jonker et al. 2004

What will happen next?

- Possibilities:
  - Steady flux - great news, everything ok!
  - Continued cooling - what's going on?
  - Variability around steady flux - residual accretion important



?

What do we need to do?

Observationally:

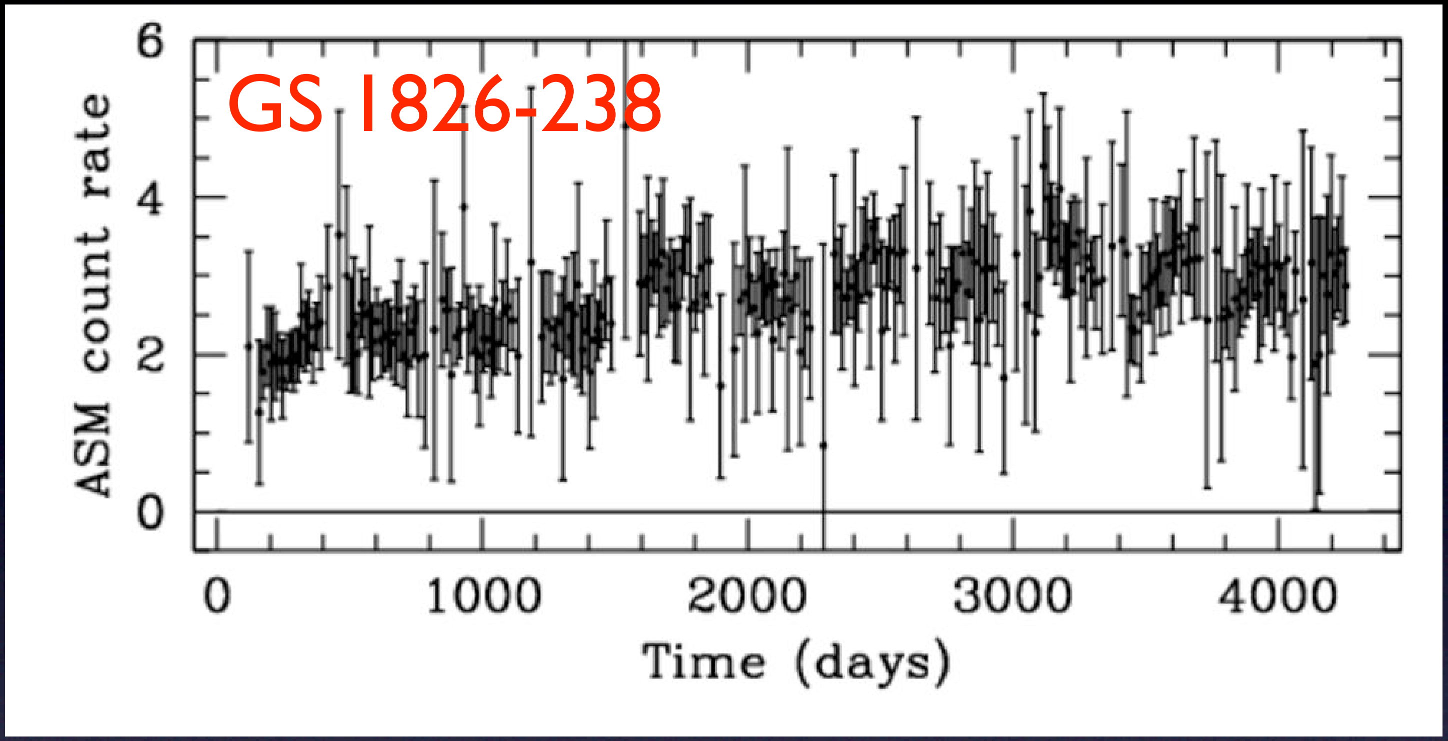
- Continued observations of KS 1731-260 and MXB 1659-29
- Monitoring of the *next* quasi-persistent source to go into quiescence

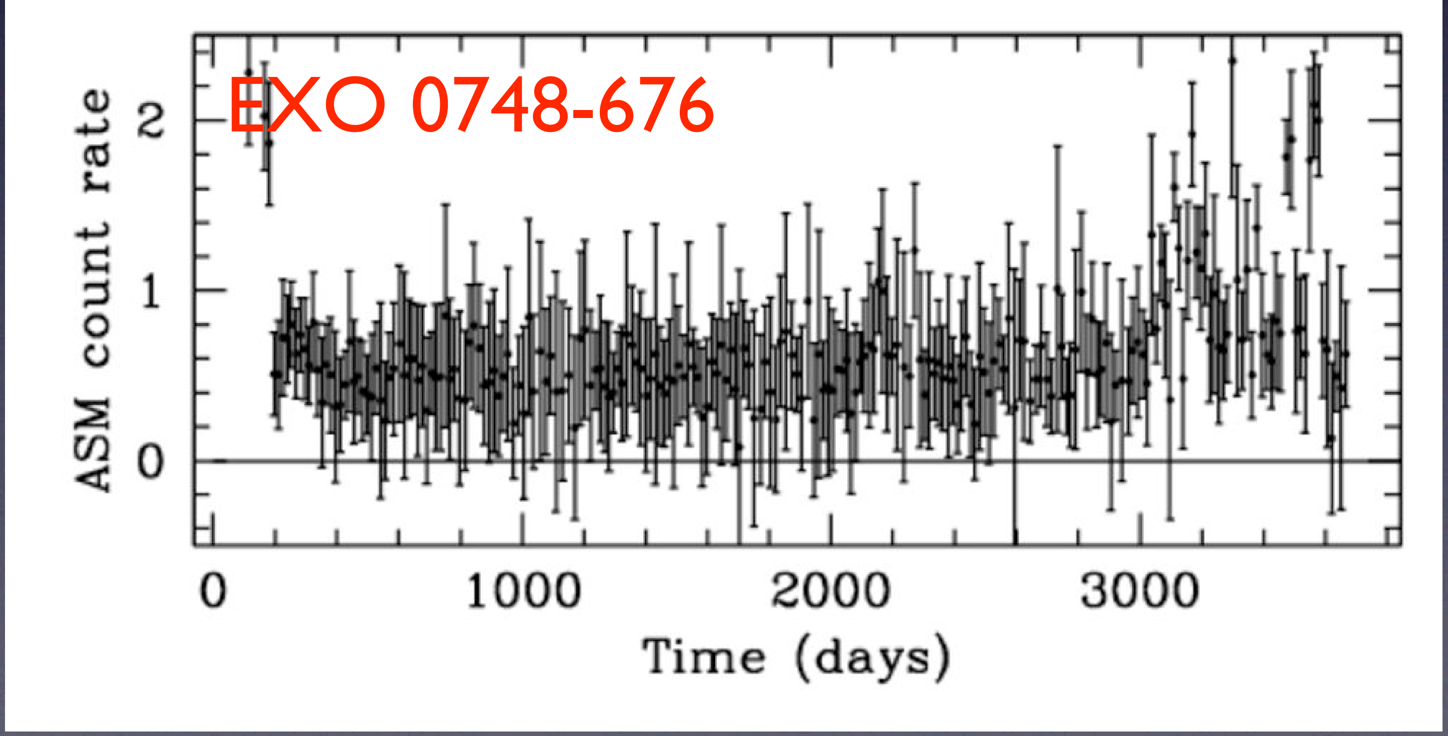
Theoretically:

- Can crust models explain these timescales?
- Why are the timescales different?

Other possible sources

- Want:
  - ➡ Long outburst (> 2ish years)
  - ➡ ideally low hydrogen column density

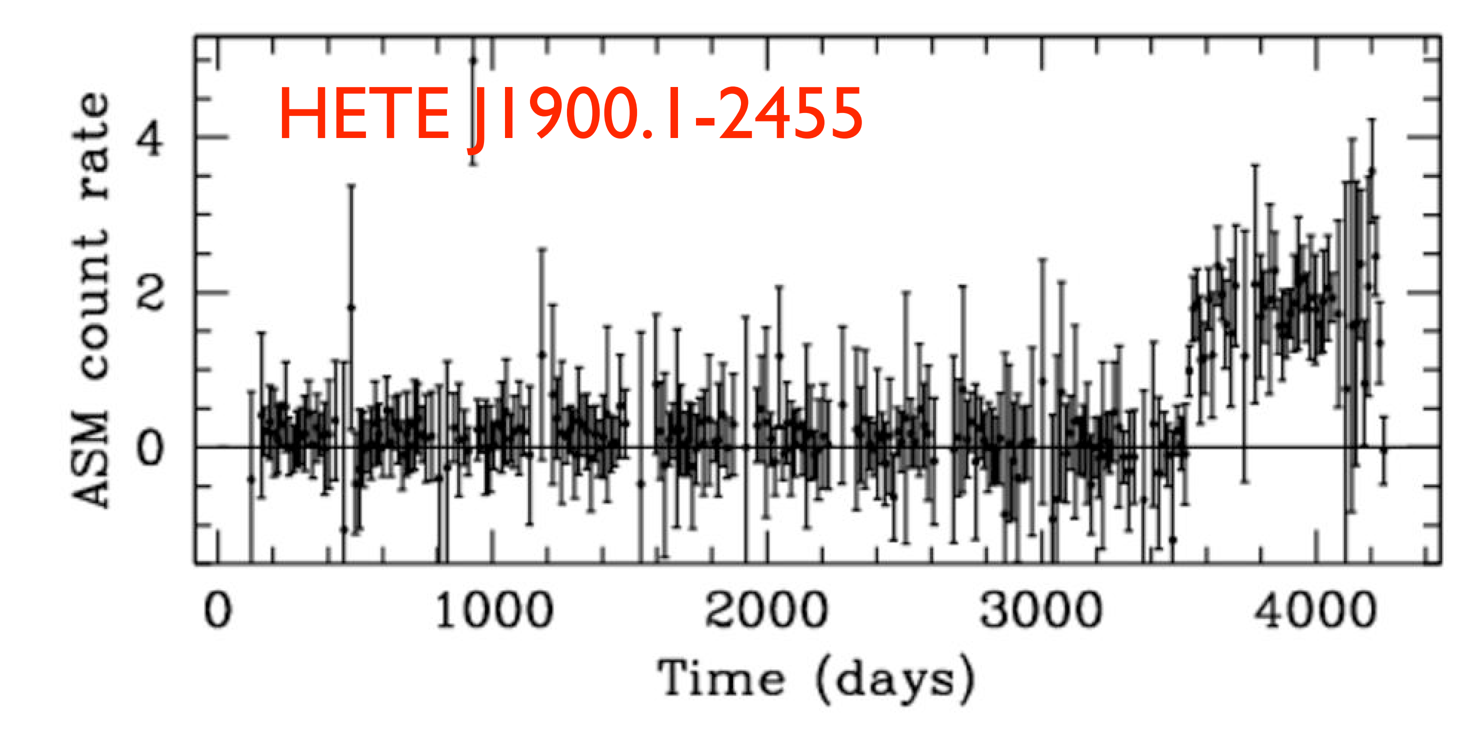




Data from *RXTE*/ASM team

HETE J1900.1-2455

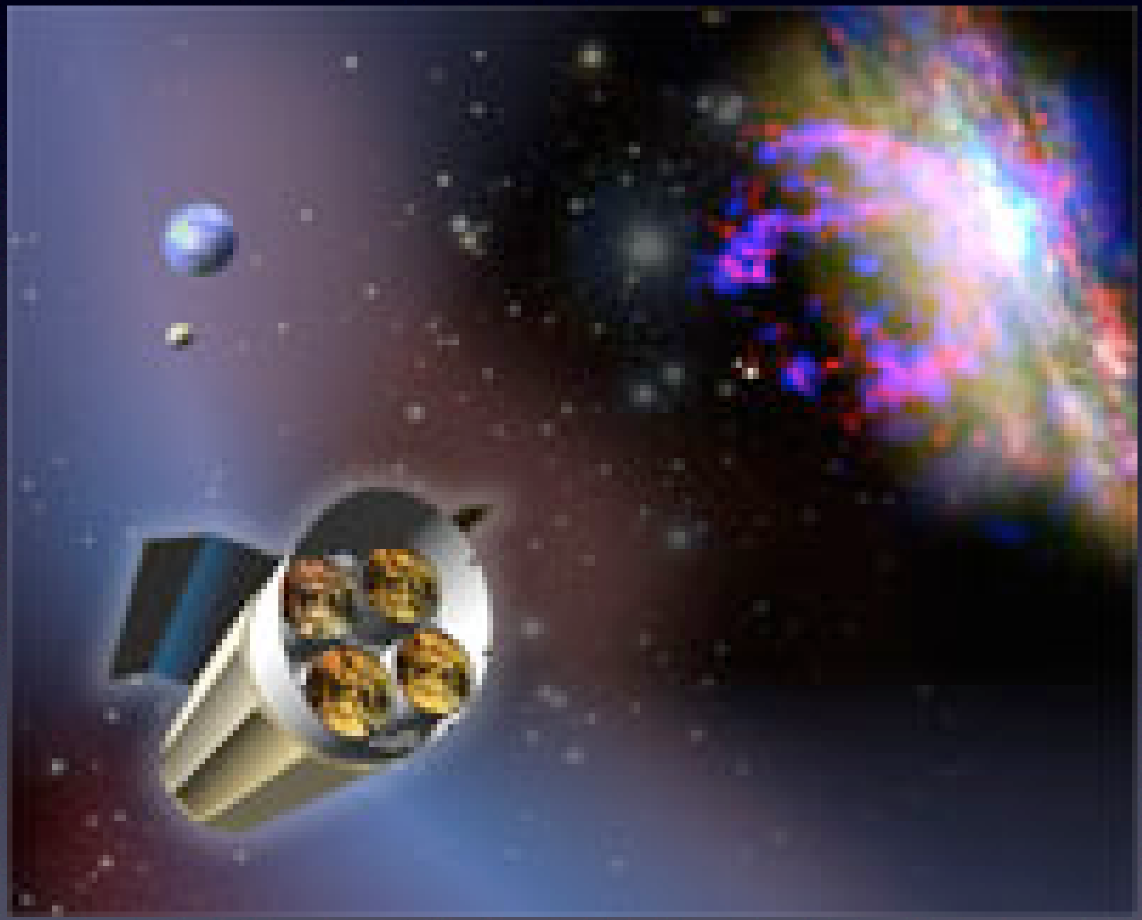
- Recently discovered accretion-powered millisecond X-ray pulsar (Kaaret et al. 2006)
- Accreting for ~2 years
- Looked like it was turning off.........
- ......but bounced back up again



Data from *RXTE*/ ASM team

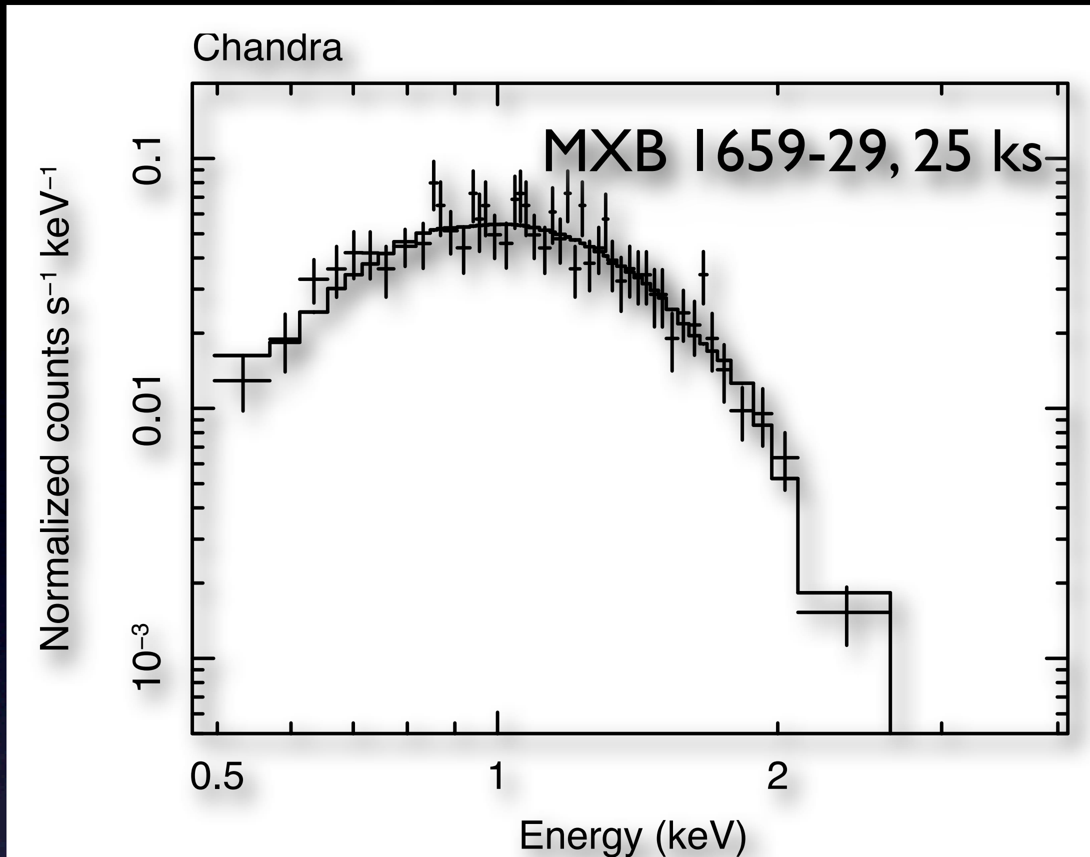
And finally: the next generation: Constellation-X

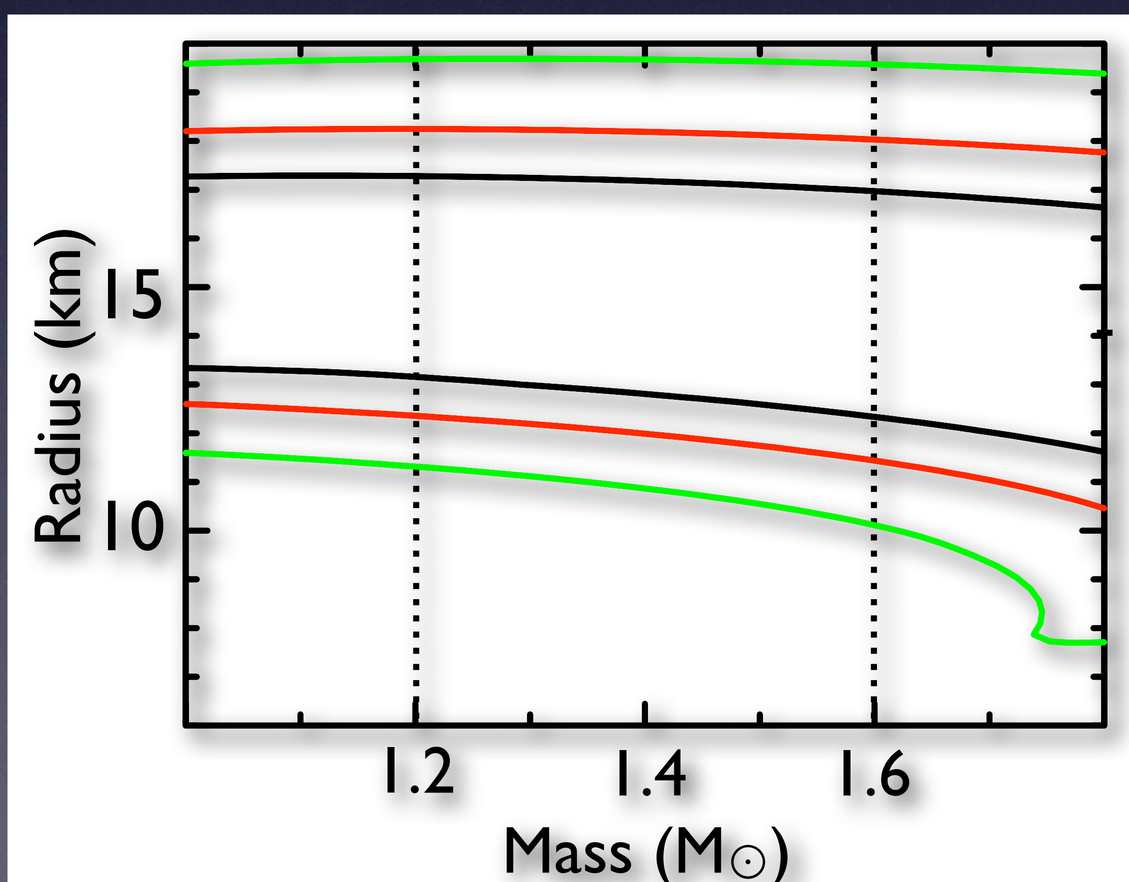
- NS radii: currently accurate to a few km at best
- Hard to get enough photons from most sources!
- With Con-X radius will be limited by accuracy of distance measurement and models



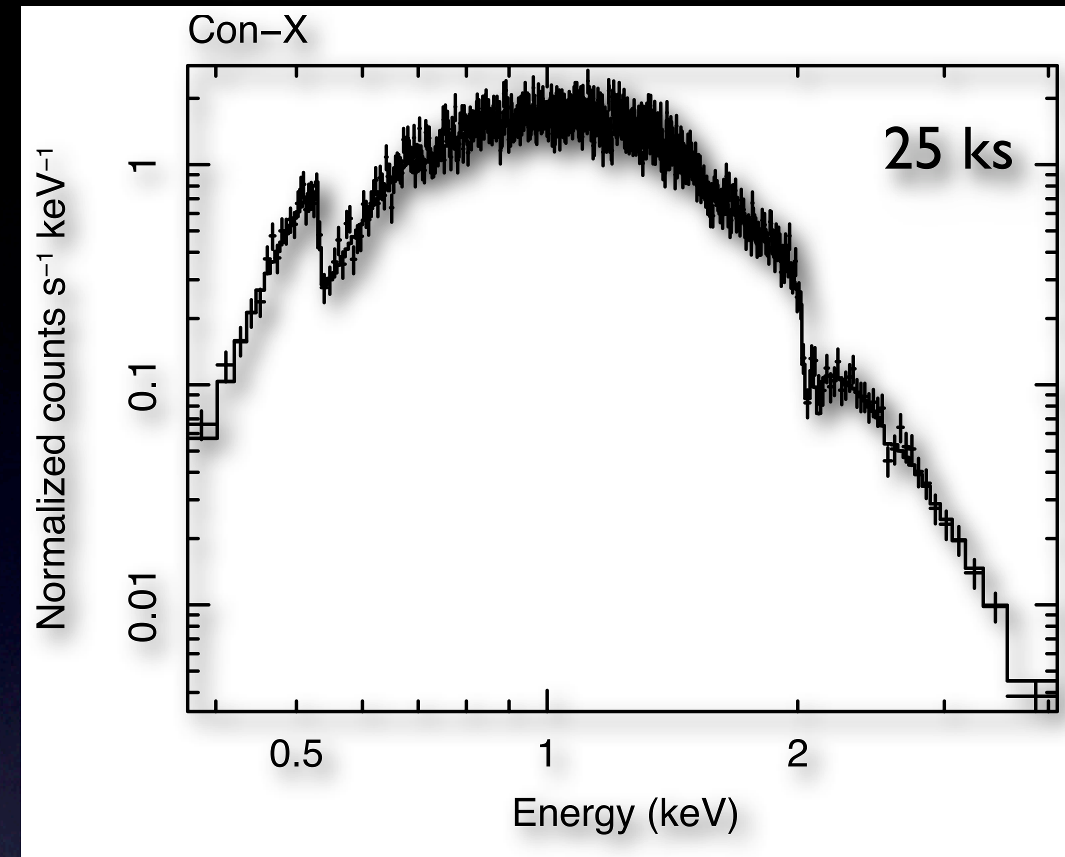
Credit: NASA

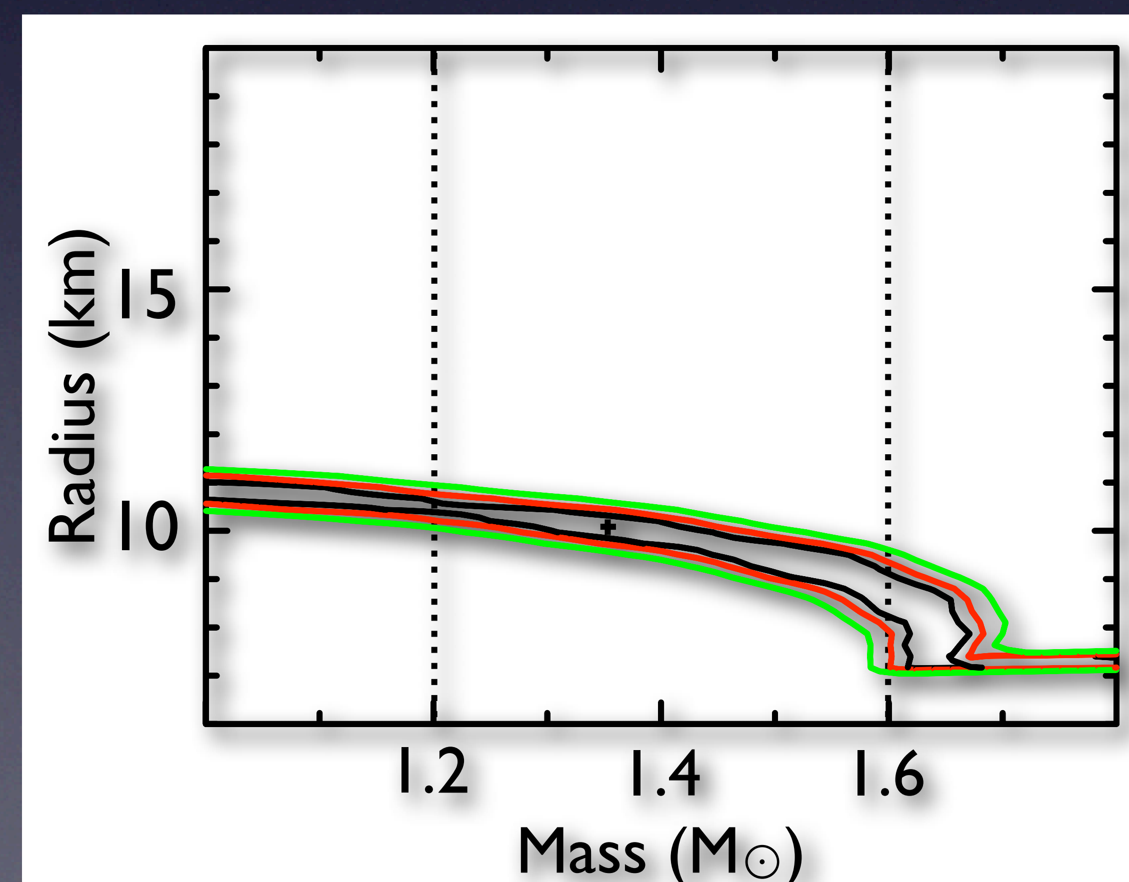
Chandra





Constellation-X





The one thing to take away:

Quasi-persistent sources provide a rare opportunity to observe crustal cooling........and we think we've measured the thermal relaxation time of the crust in 2 sources.