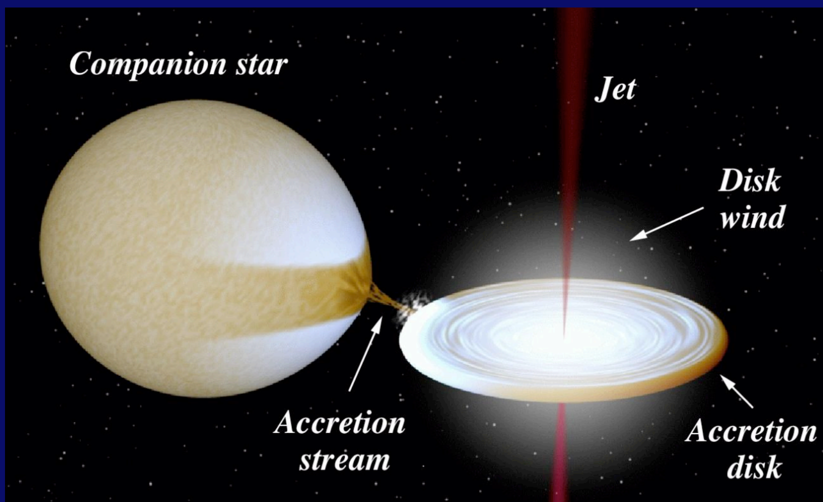
X-ray emission from neutron stars in low-mass X-ray binaries

Cooling of accretion-heated neutron stars

Rudy Wijnands
Astronomical Institute "Anton Pannekoek"
University of Amsterdam

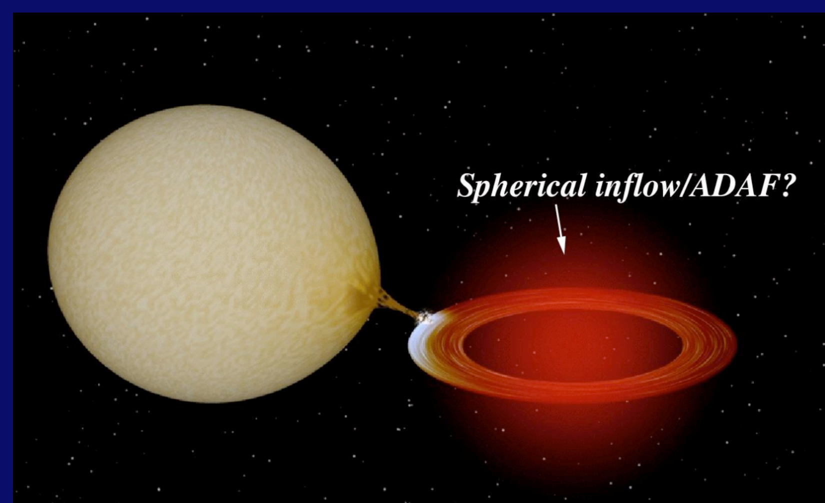
Persistent and transient LMXBs

Outburst



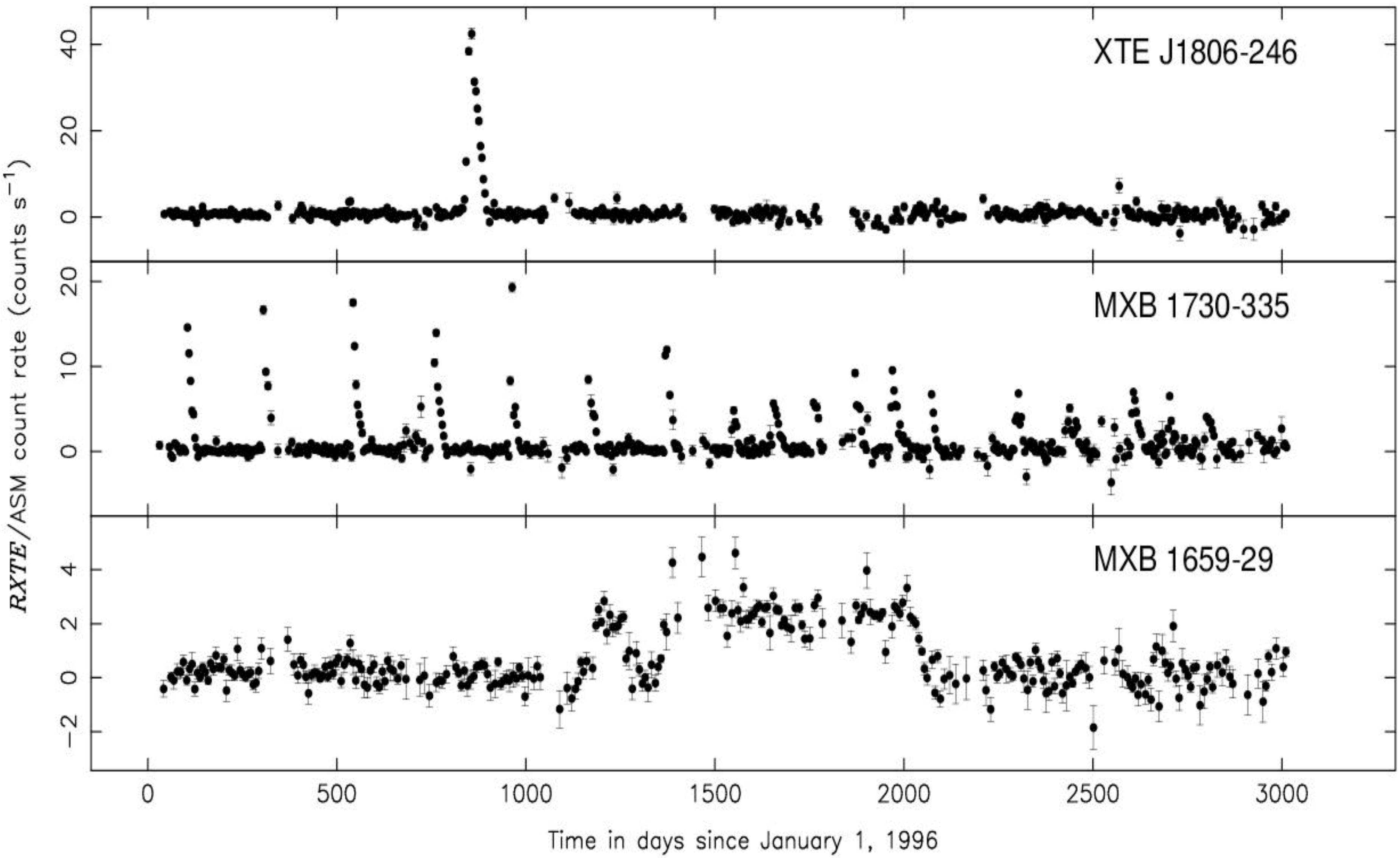
NS heating

Quiescence



NS cooling

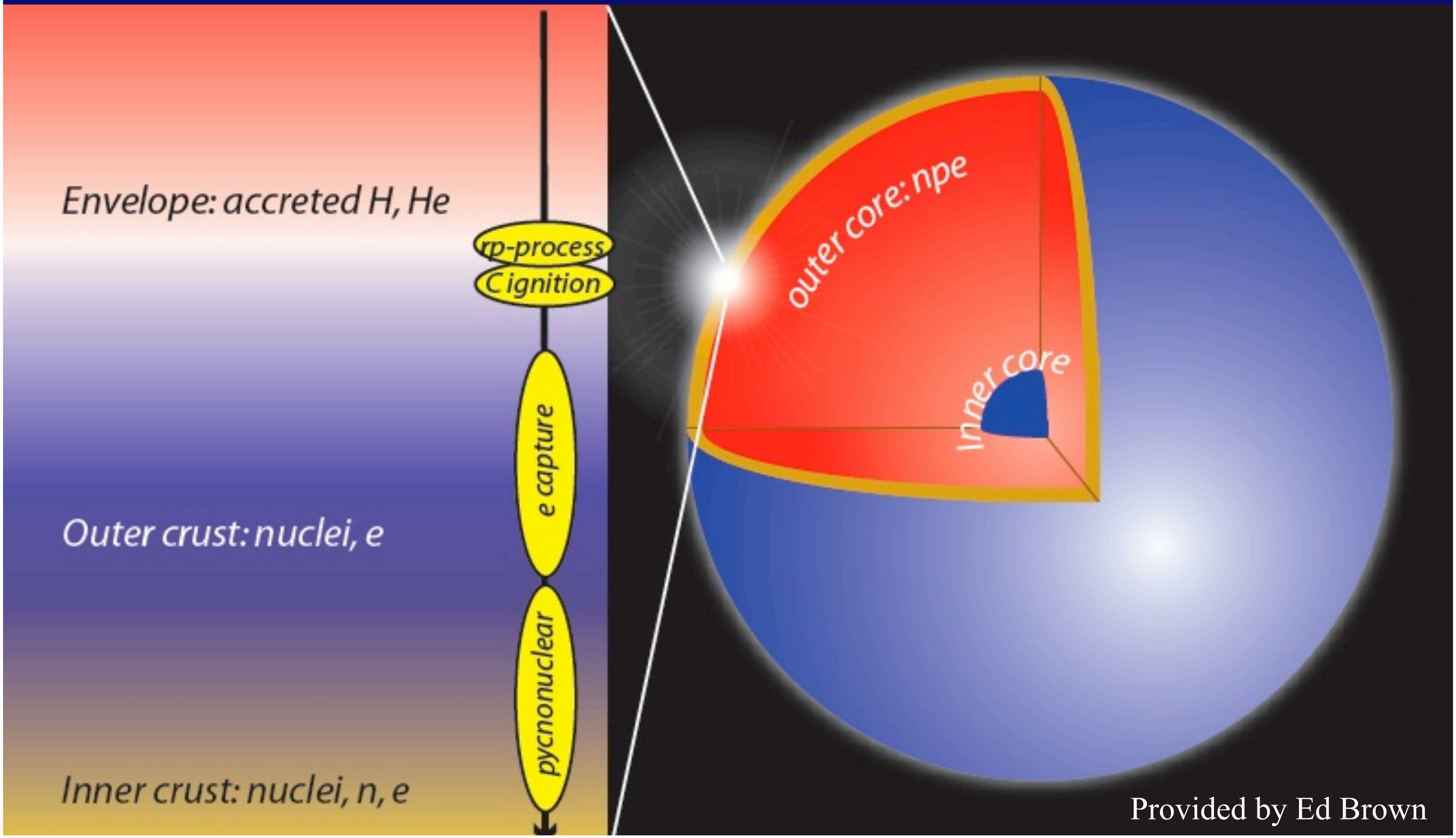
Transient LMXBs



Study neutron stars in LMXBs

- Actively accreting
  - Difficult to observe the neutron star
    - Accretion luminosity usually outshines neutron star
    - Thermonuclear flashes
    - Quasi-stable burning
    - X-ray pulsars
  - Indirect studies
    - Spectral and variability studies (e.g., quasi-periodic oscillations, iron line studies)
- Transiently accreting neutron stars in LMXBs
  - Heating in outburst, cooling in quiescence
  - Study them in quiescence

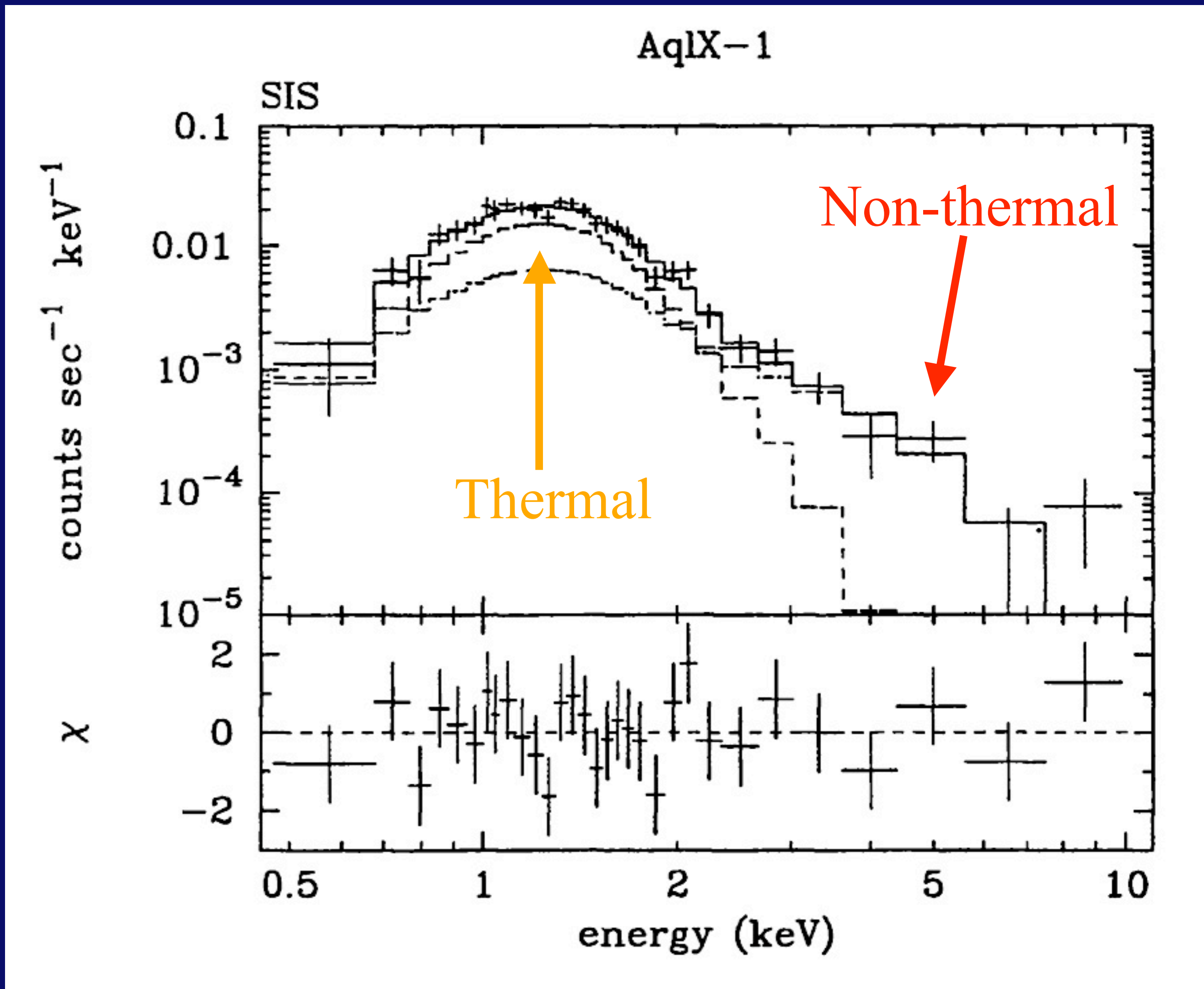
Heating of accreting neutron stars



Provided by Ed Brown

Do we detect cooling neutron star?

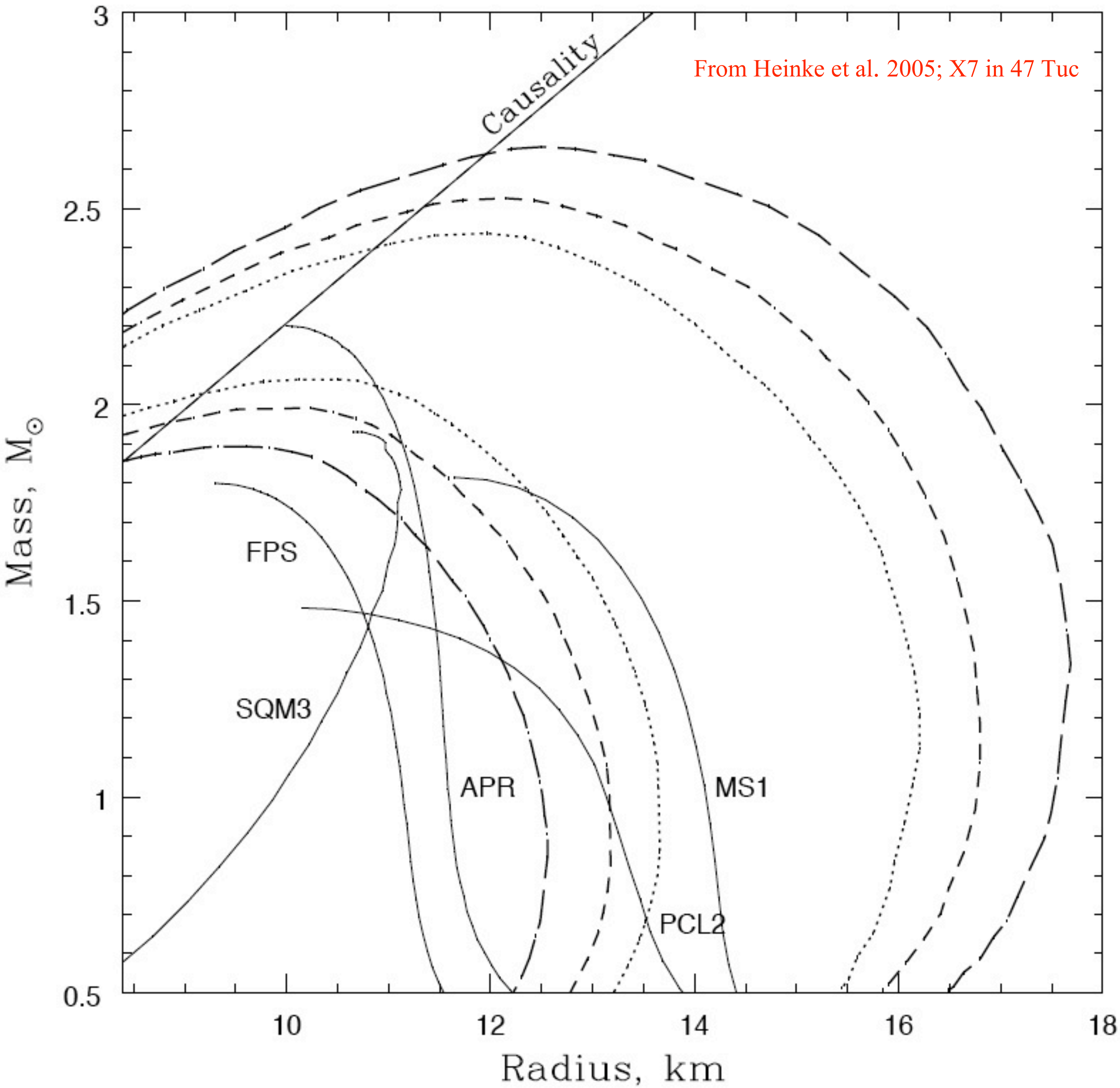
Asai et al. 1998



Lets assume: we detect cooling from reheated neutron star

Several ways to constrain properties of ultra dense matter in neutron stars

- Measure mass/radius from the thermal spectrum
  - Need distance ⇒ globular clusters
  - NSA model dependent + nasty power-law component
- Gravitational red-shifted lines
  - Only if residual accretion on NS surfaces occurs
- Inferred core temperature versus predicted one
- Crust cooling after prolonged (>years) outburst


From Heinke et al. 2005; X7 in 47 Tuc
Causality
FPS
SQM3
APR
MS1
PCL2
Mass, M☉
Radius, km
3
2.5
2
1.5
1
0.5
10
12
14
16
18

Lets assume: we detect cooling from reheated neutron star

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Need better data

Lets assume: we detect cooling from reheated neutron star

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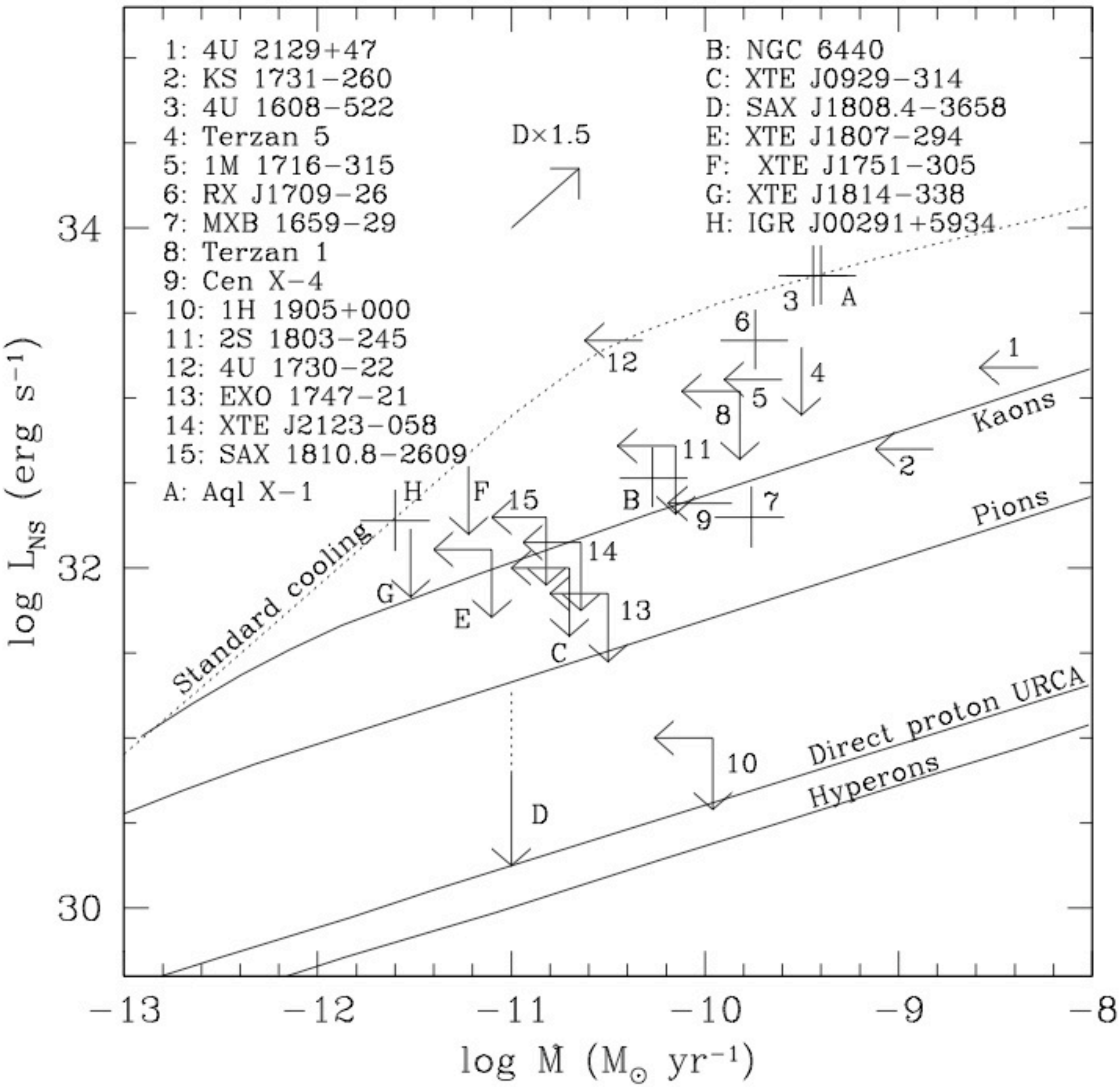
Brown et al. 1998
Heinke et al. 2008
Yakovlev et al. 2004



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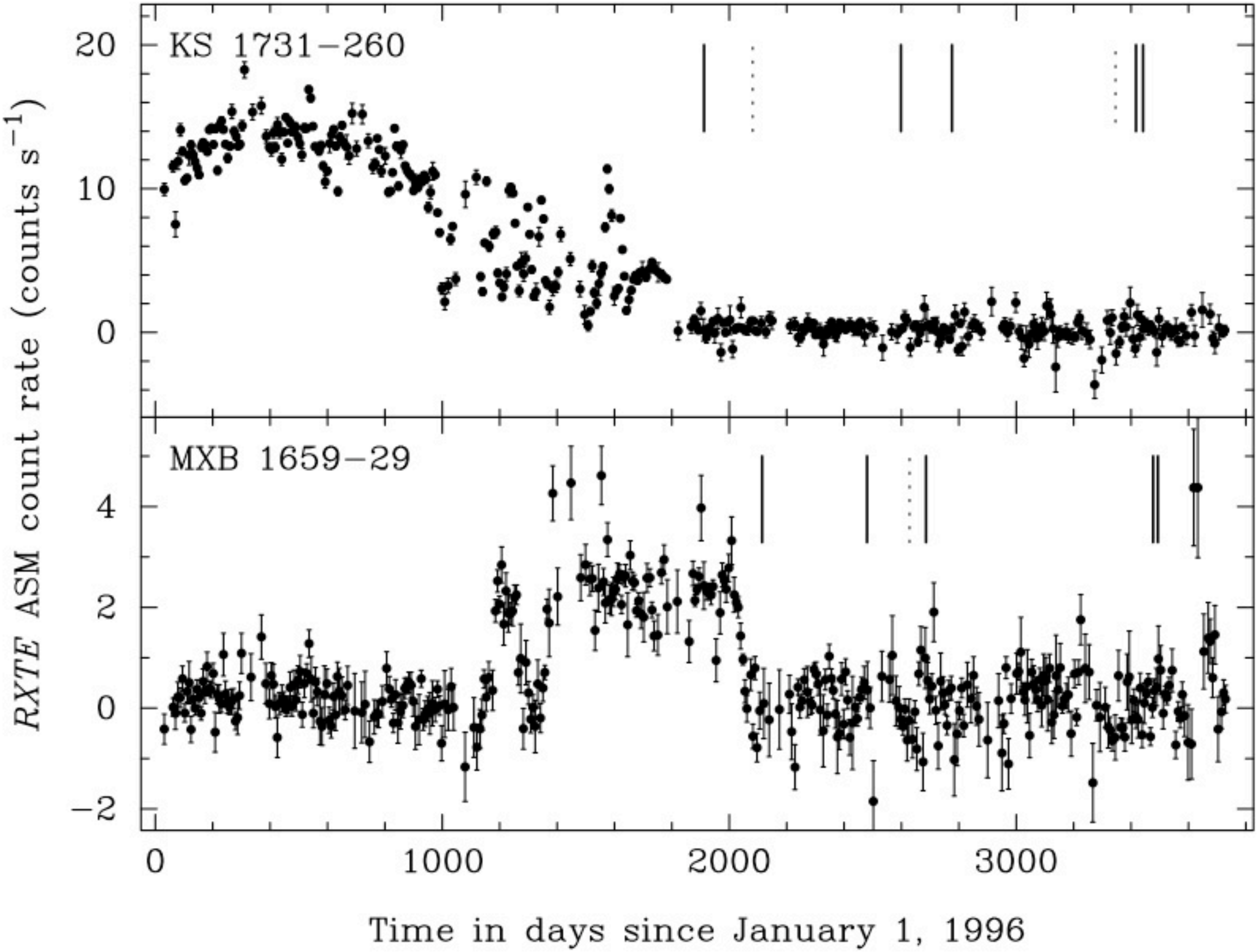
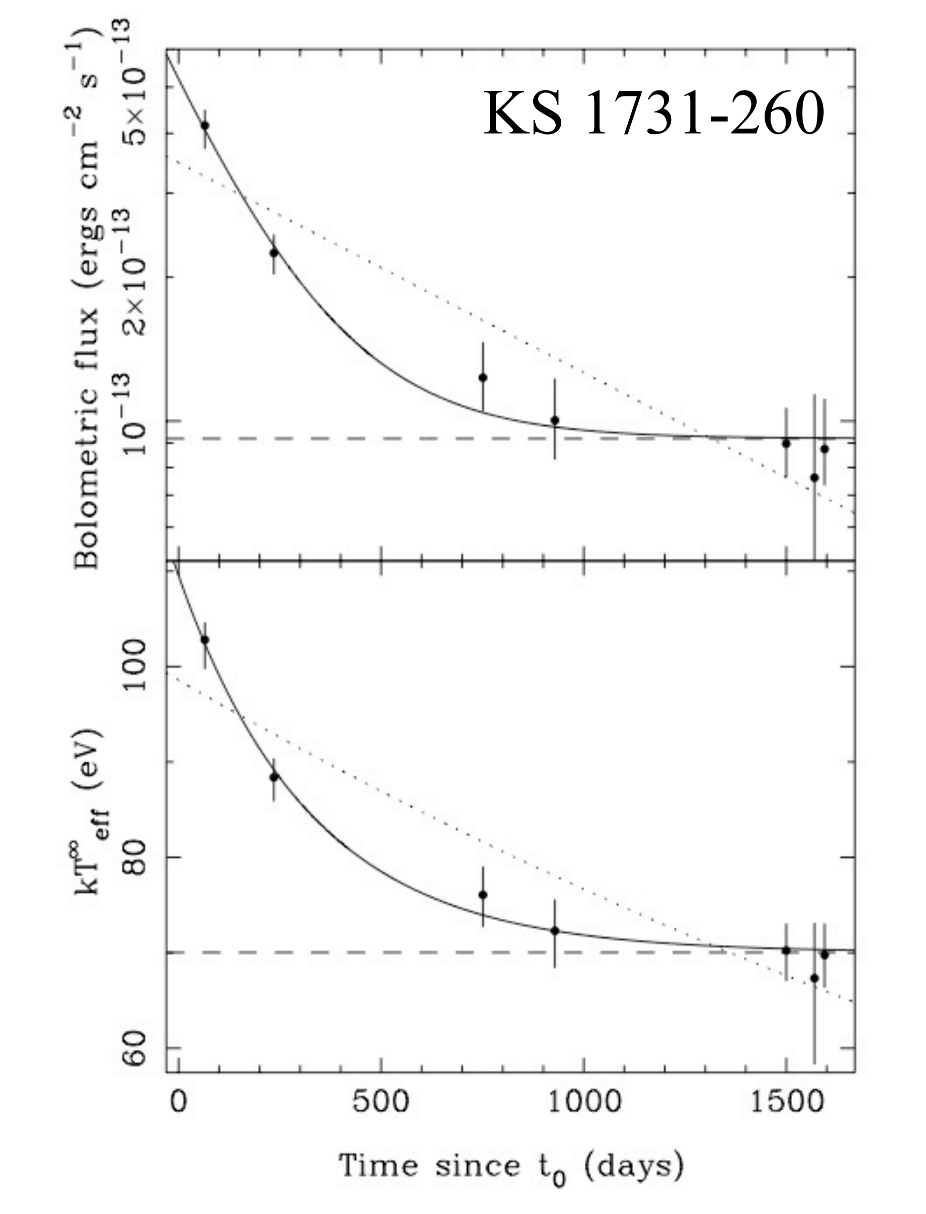
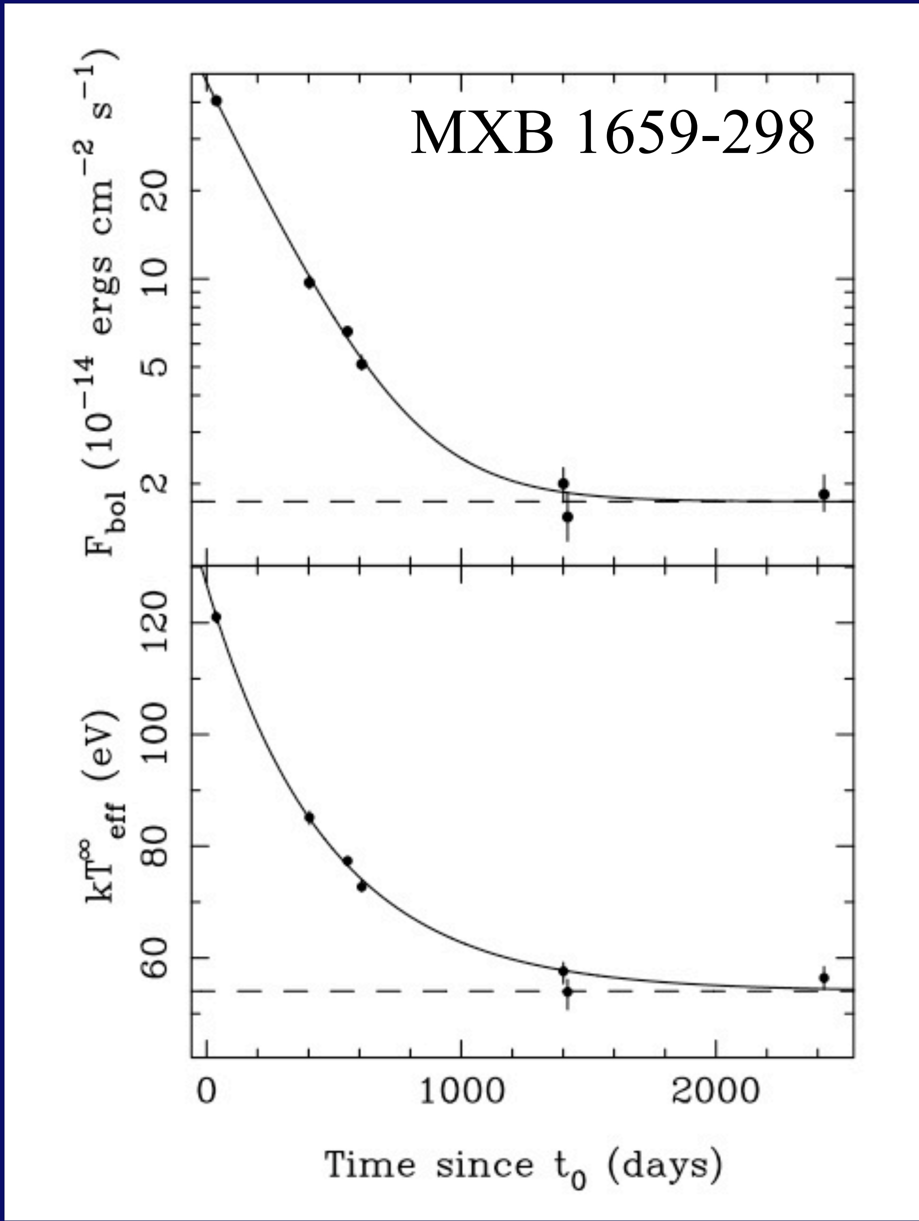


Wijnands et al. 2001, 2004; Cackett et al. 2006

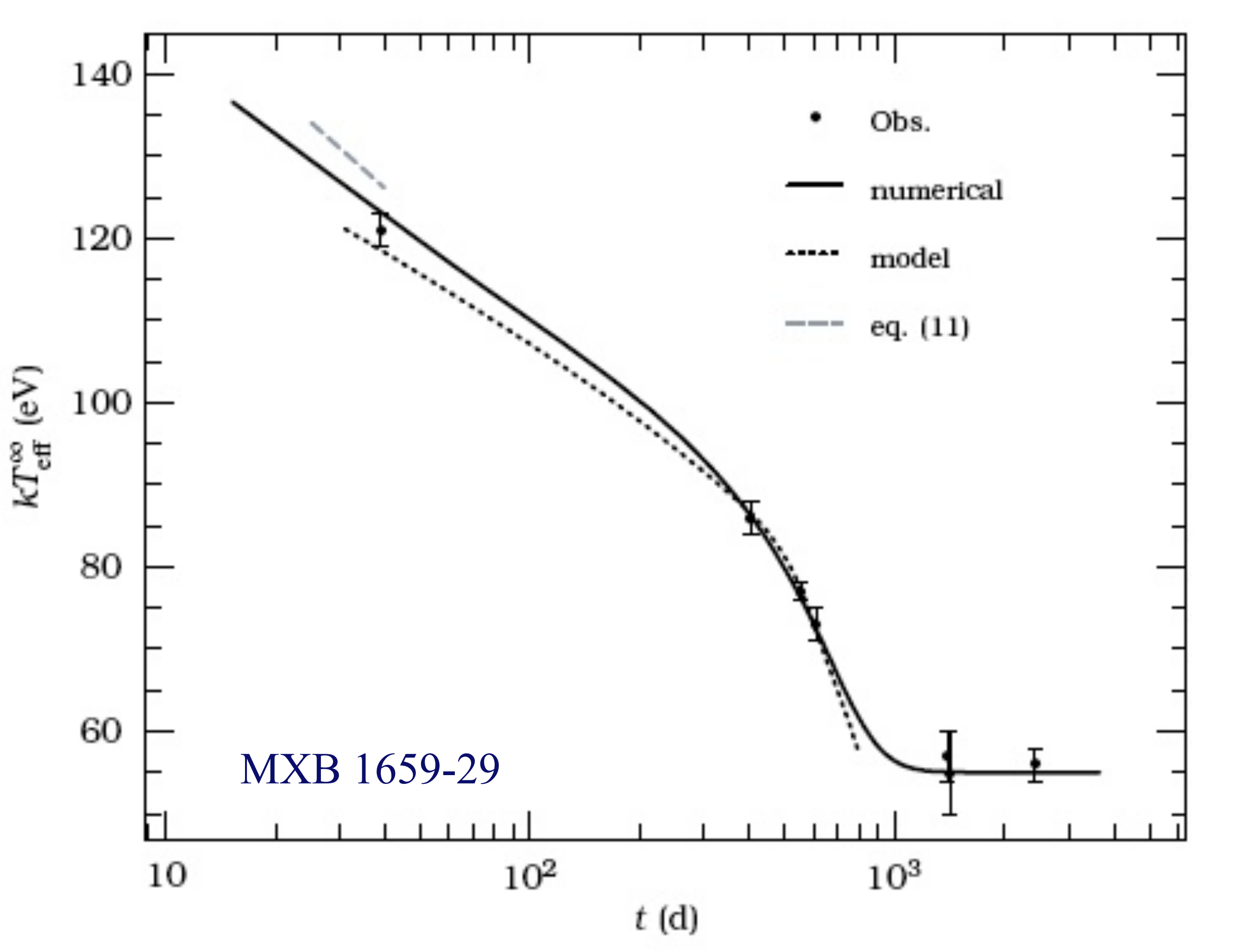




Wijnands et al. 2001, 2002, 2003, 2004; Cackett et al. 2006, 2008

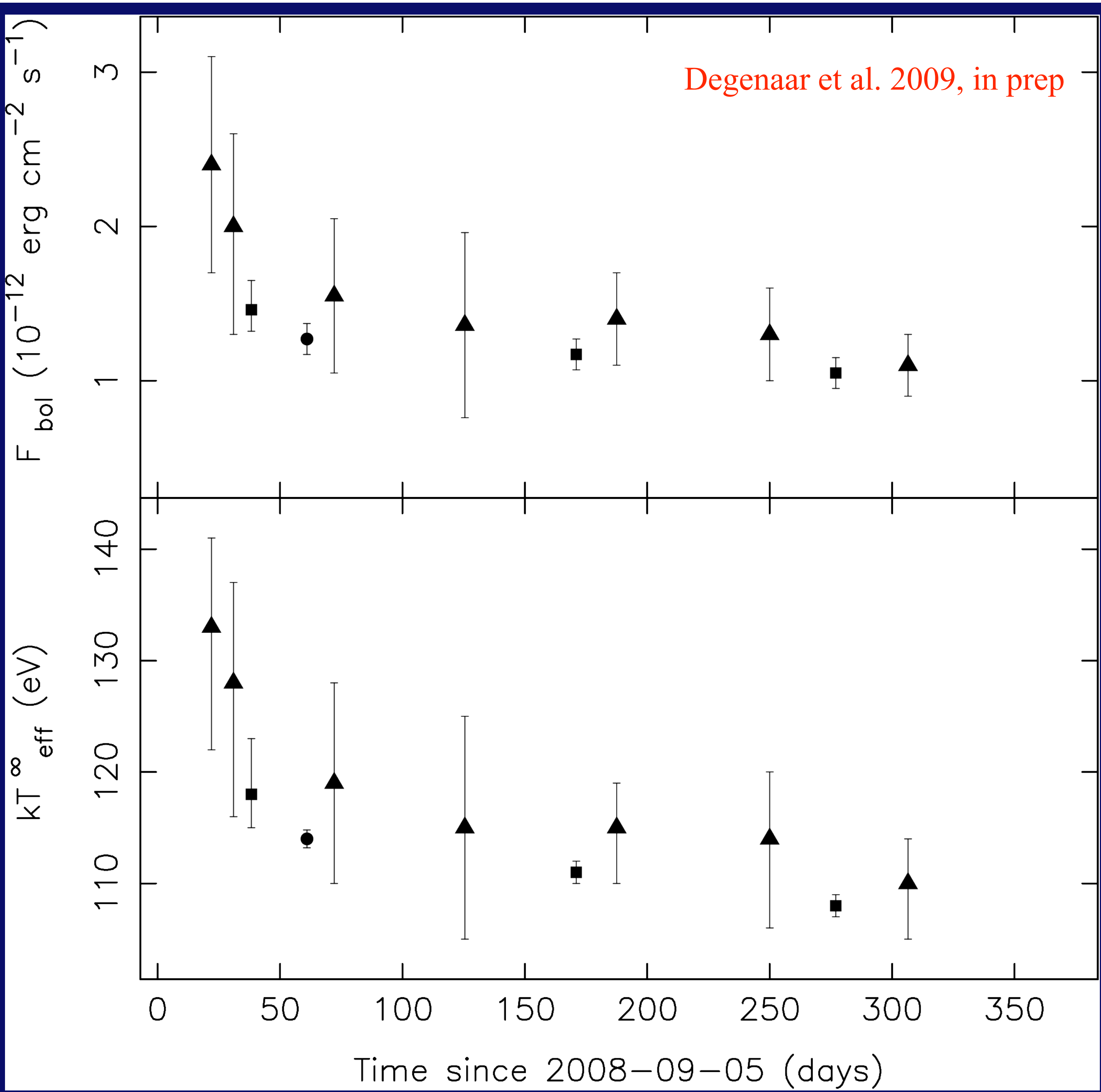
Calculations of cooling curves

- High heat conductivity in the crust
  - Rutledge et al. 2001; Shternin et al. 2008; Brown & Cumming 2009

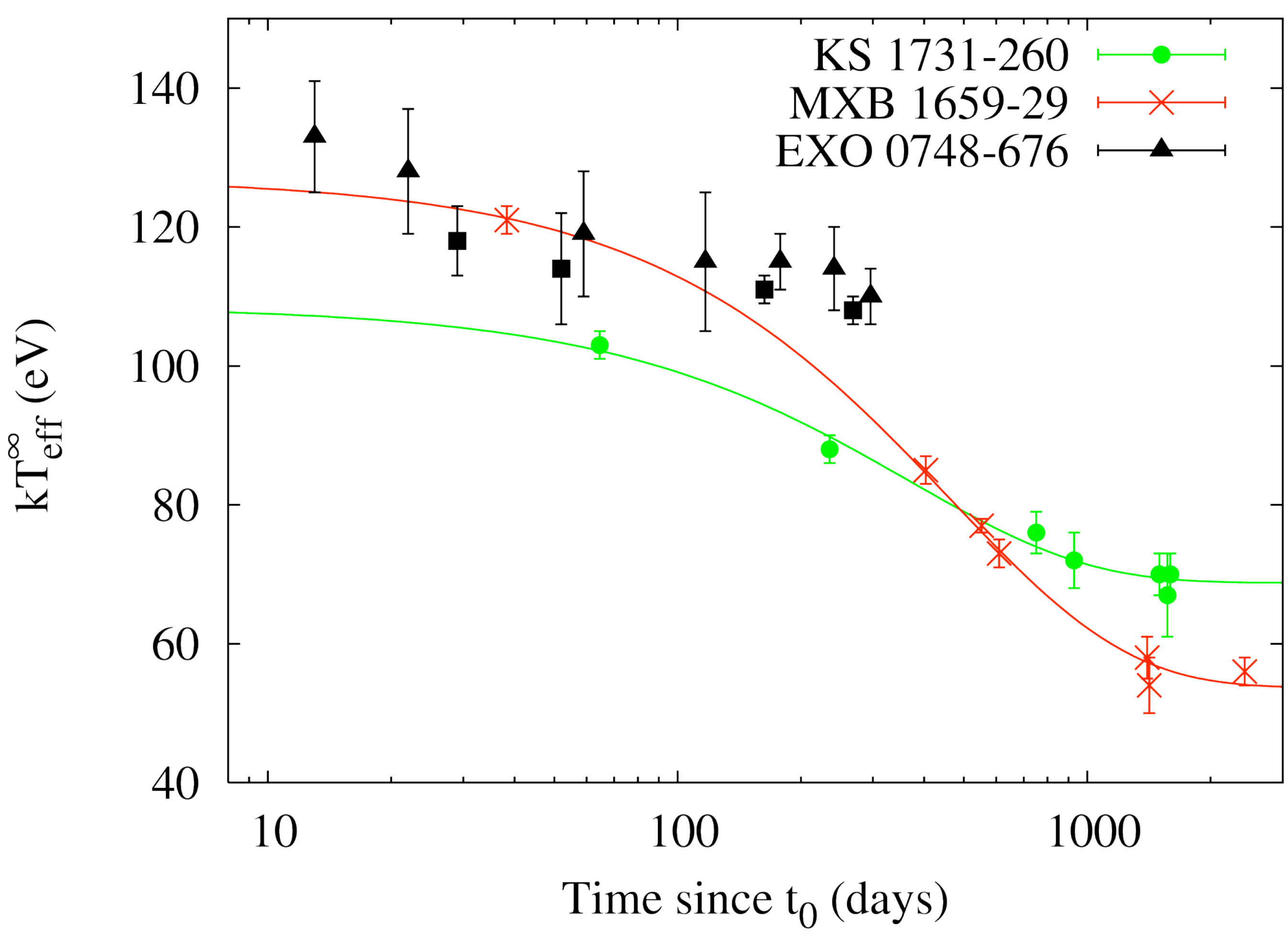


New results

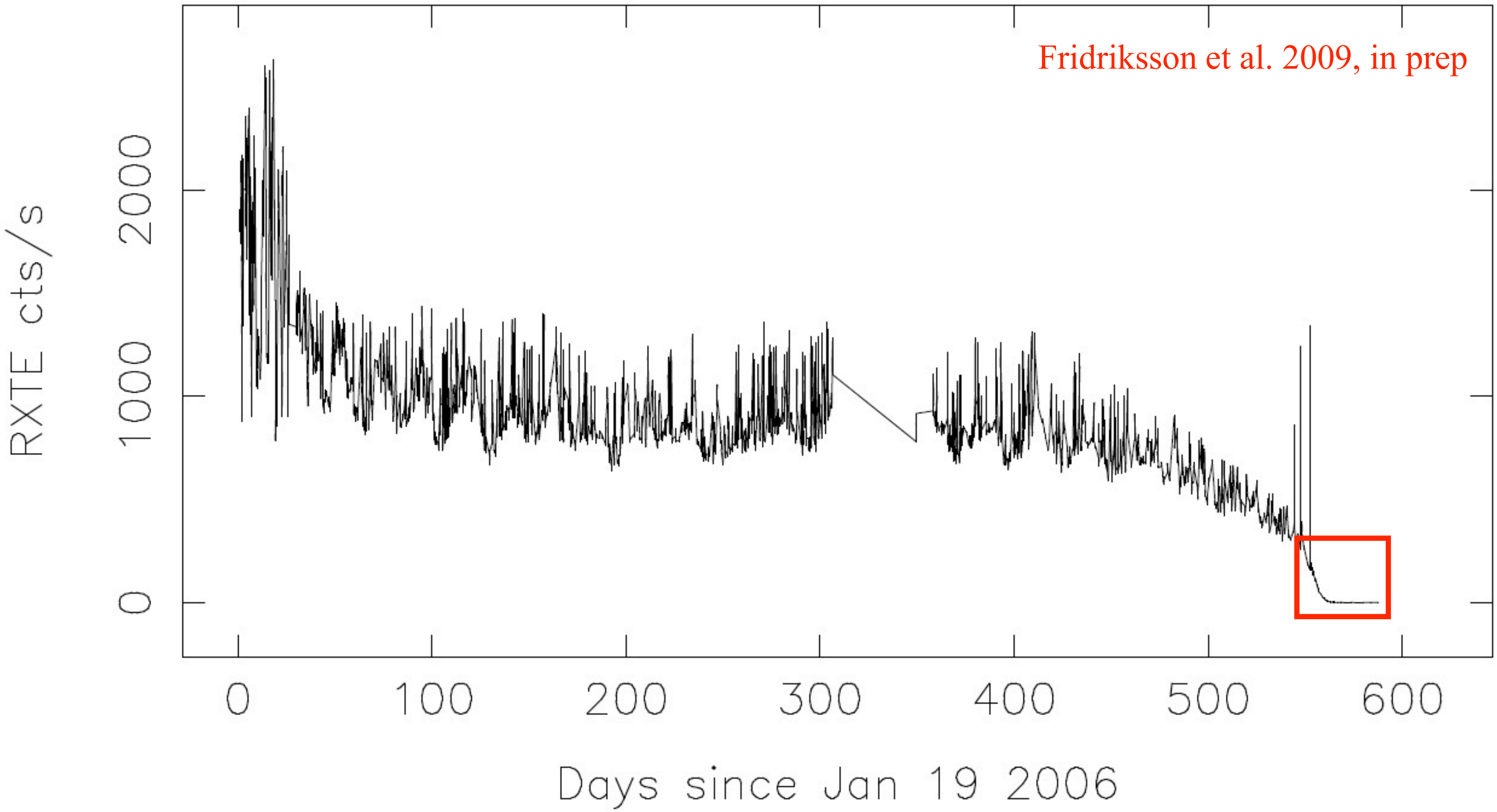
- EXO 0748-676 and XTE J1701-462
- First EXO 0748-676
  - In outburst since approximately July 1984
  - Outburst stopped in August/September 2008
  - Many Swift, one XMM-Newton and 3 Chandra observations
  - Degenaar et al. 2009

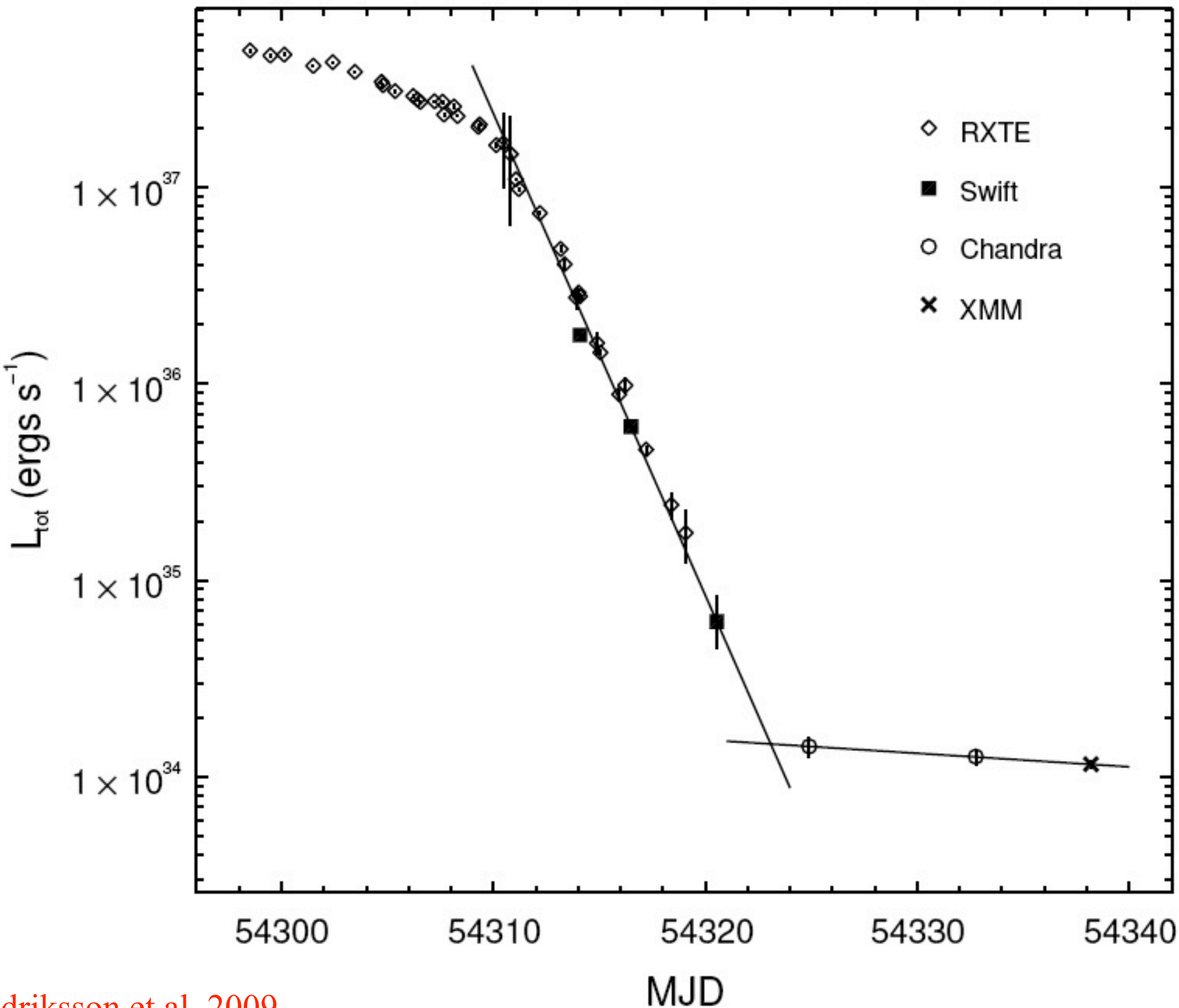

Degenaar et al. 2009, in prep
F bol (10^-12 erg cm^-2 s^-1)
3
2
1
kT∞eff (eV)
140
130
120
110
0
50
100
150
200
250
300
350
Time since 2008-09-05 (days)

Comparison with other two sources



XTE J1701-462

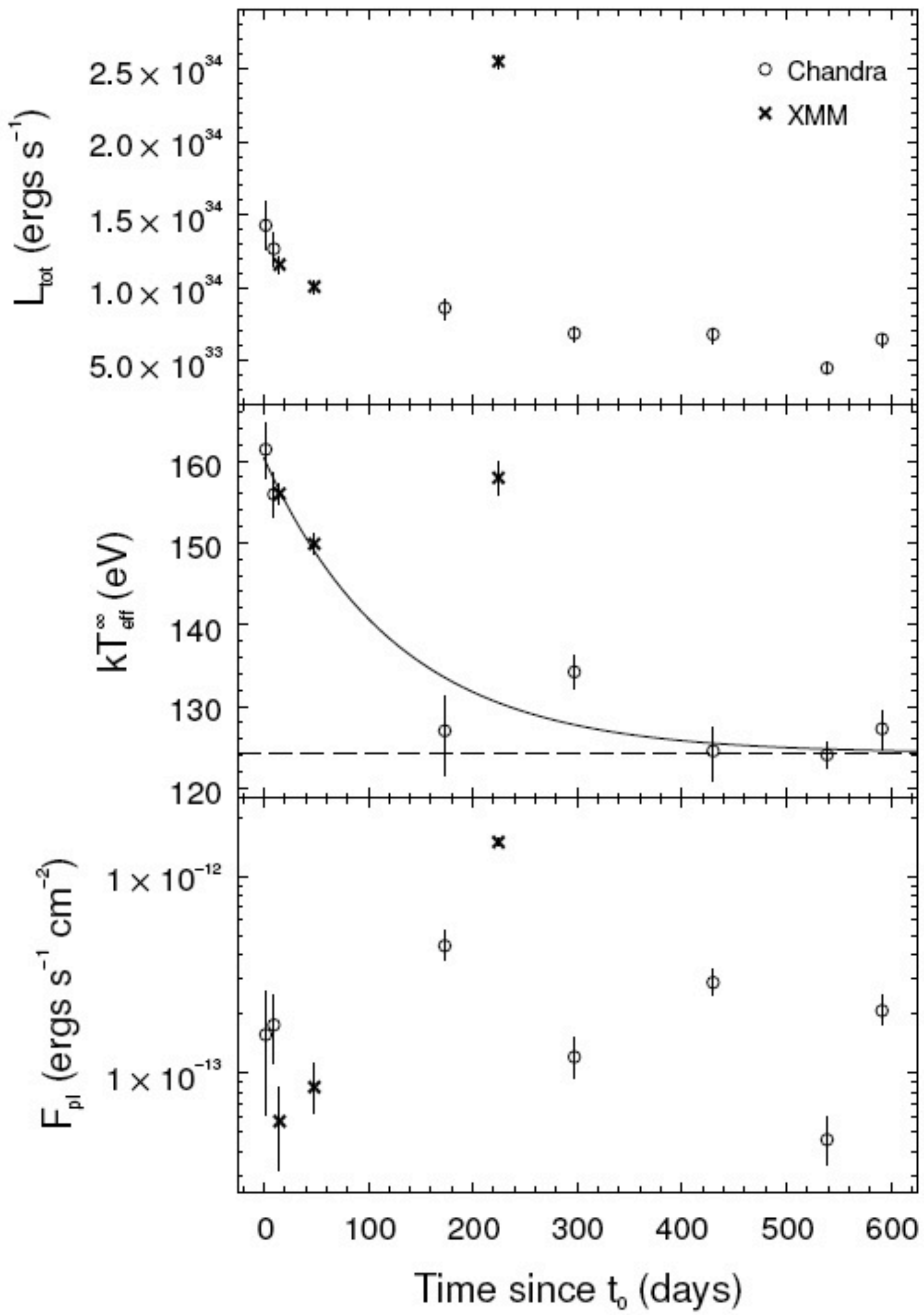




Fridriksson et al. 2009

Most recent result

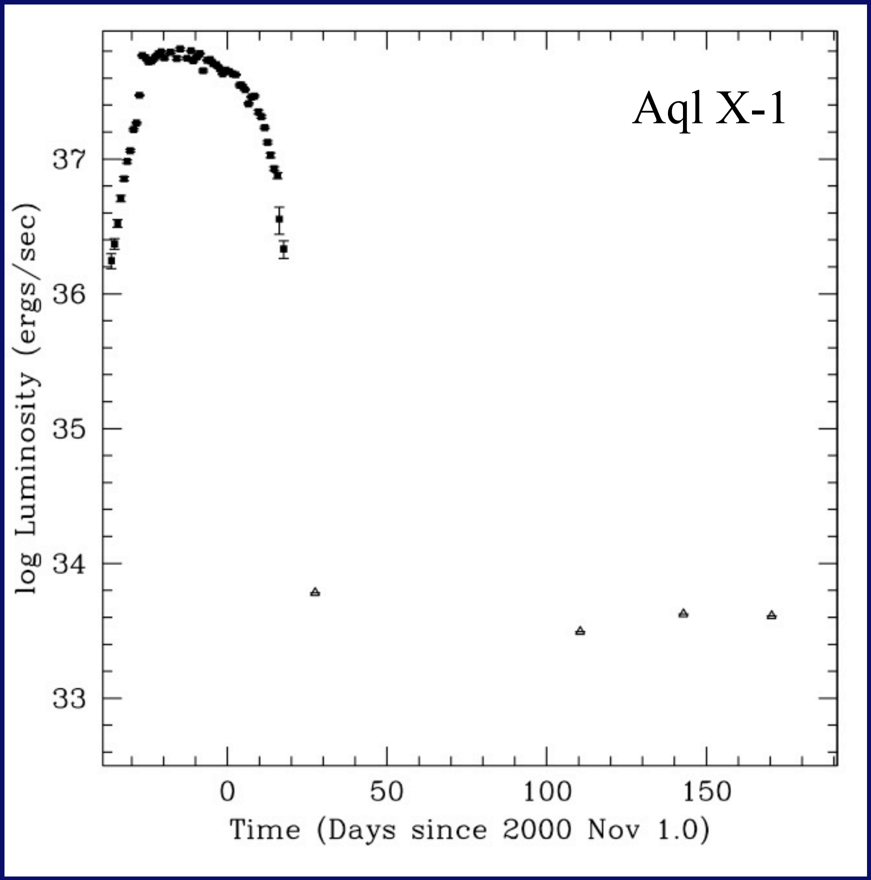
- More complicated than hoped
  - Likely some residual accretion during some observations
  - But still very promising
  - Cooling significantly faster than for the other sources
  - Fridriksson et al. 2009



Final remarks

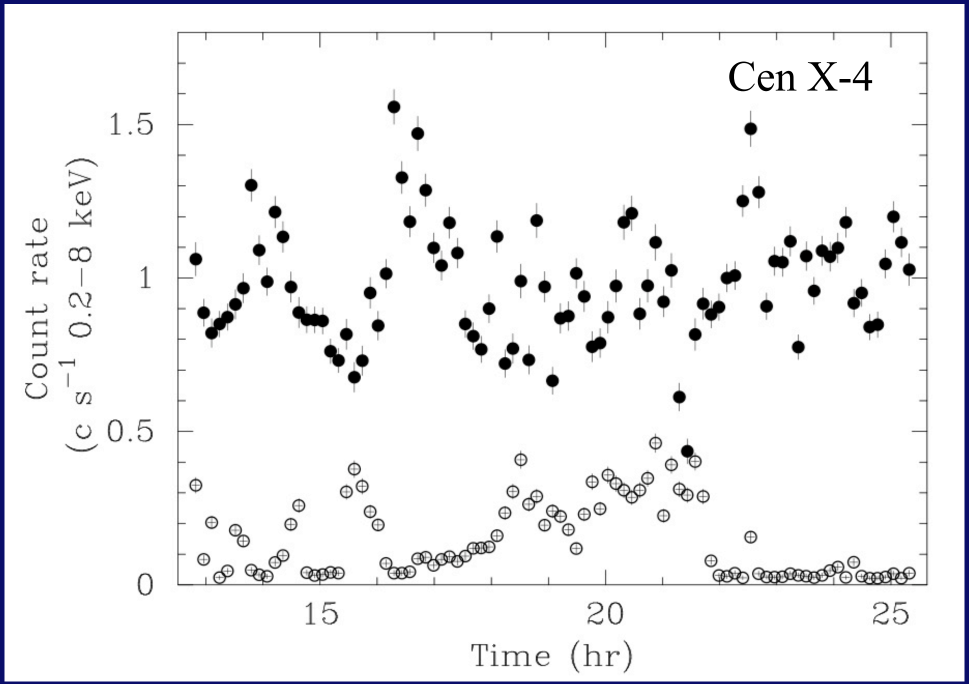
- Potential to probe ultra-dense matter with the cooling of accretion heated neutron stars
- Crust cooling seems particular interesting
  - High crustal heat conductivity
  - Need more sources
- Uncertainties in models
  - Cooling + heating
- Variability and non-thermal component complications

Complication: variability



Rutledge et al. 2002

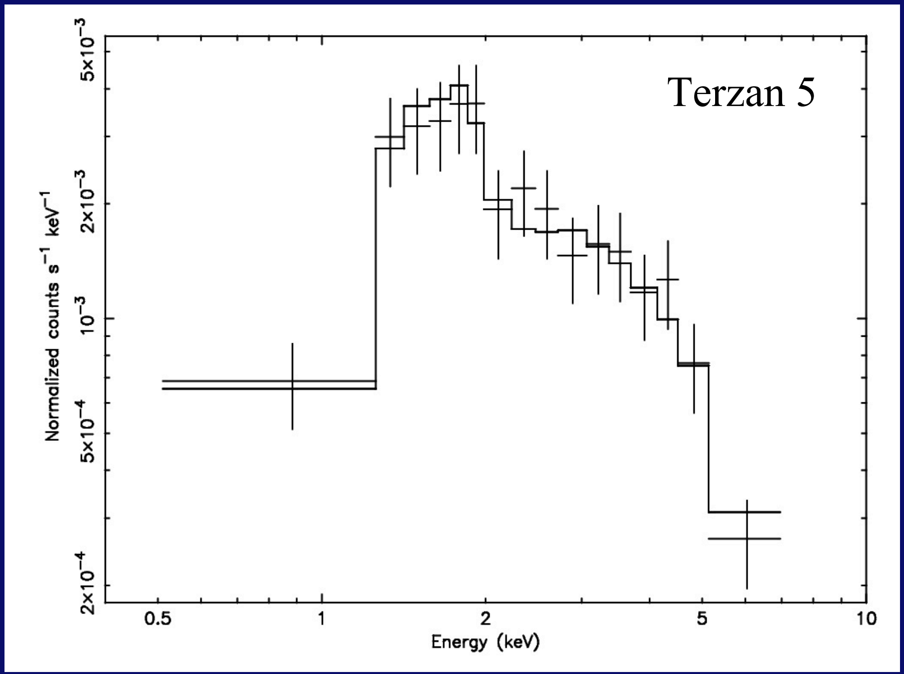
Campana et al. 2004



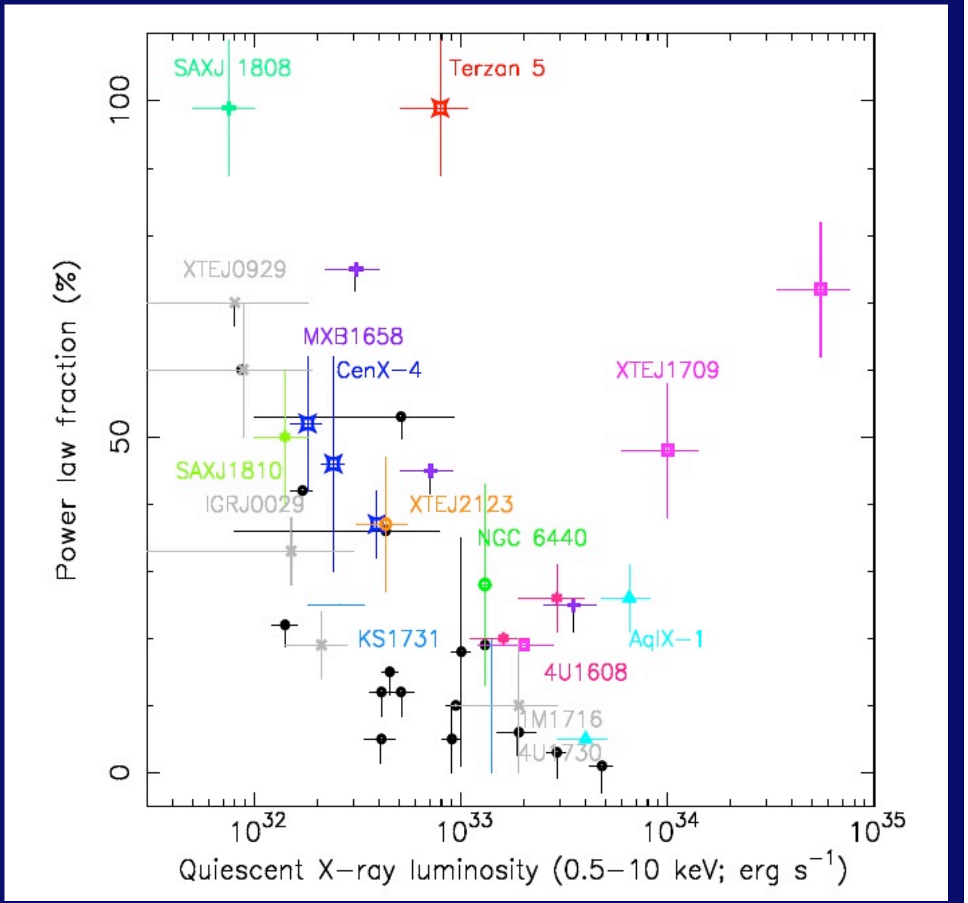
Thermal or non-thermal?

- Accretion on surface?

Complication: non-thermal component



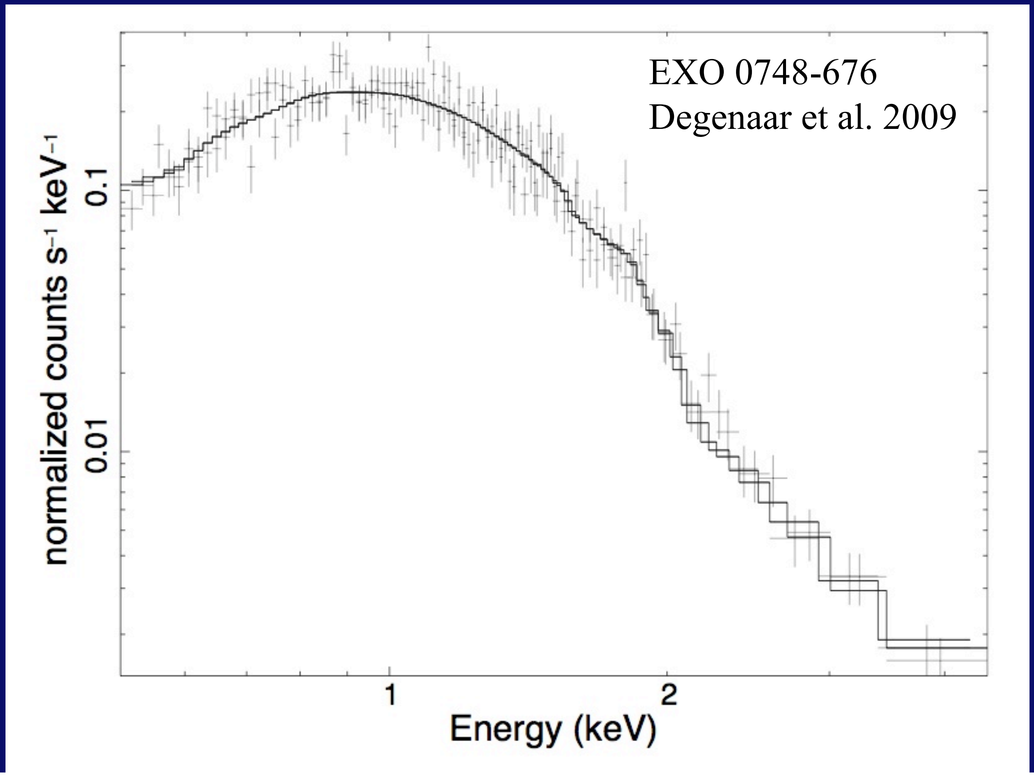
Wijnands et al. 2005



Jonker et al. 2007

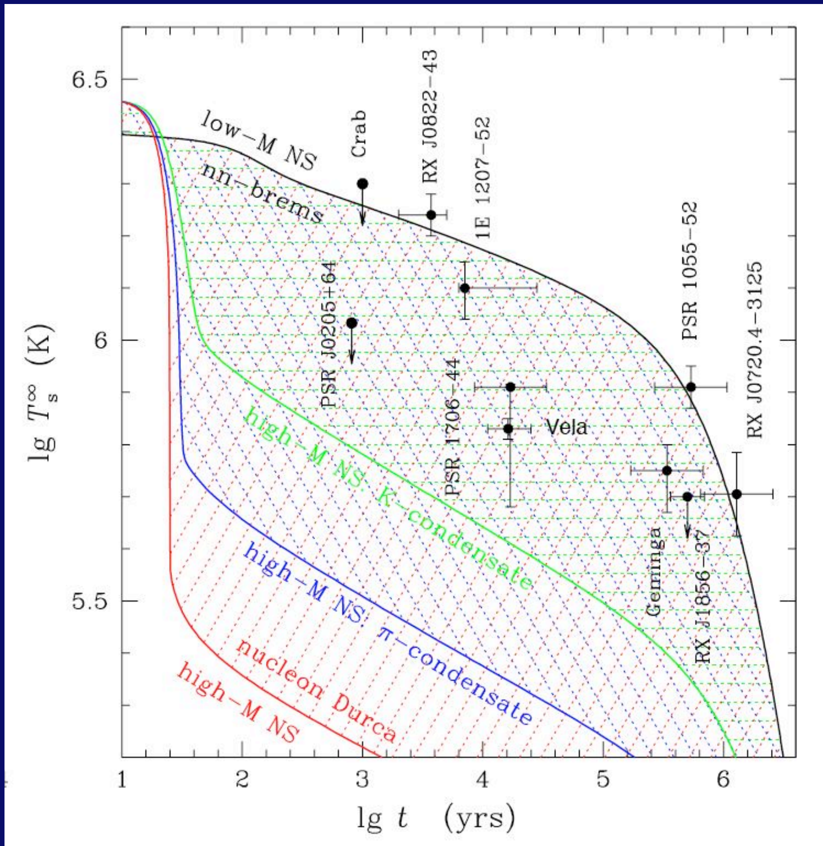
Nasty non-thermal influences

- Seriously complicates our ability to measure the luminosity and temperature of the thermal component
  - And thus constrain M and/or R



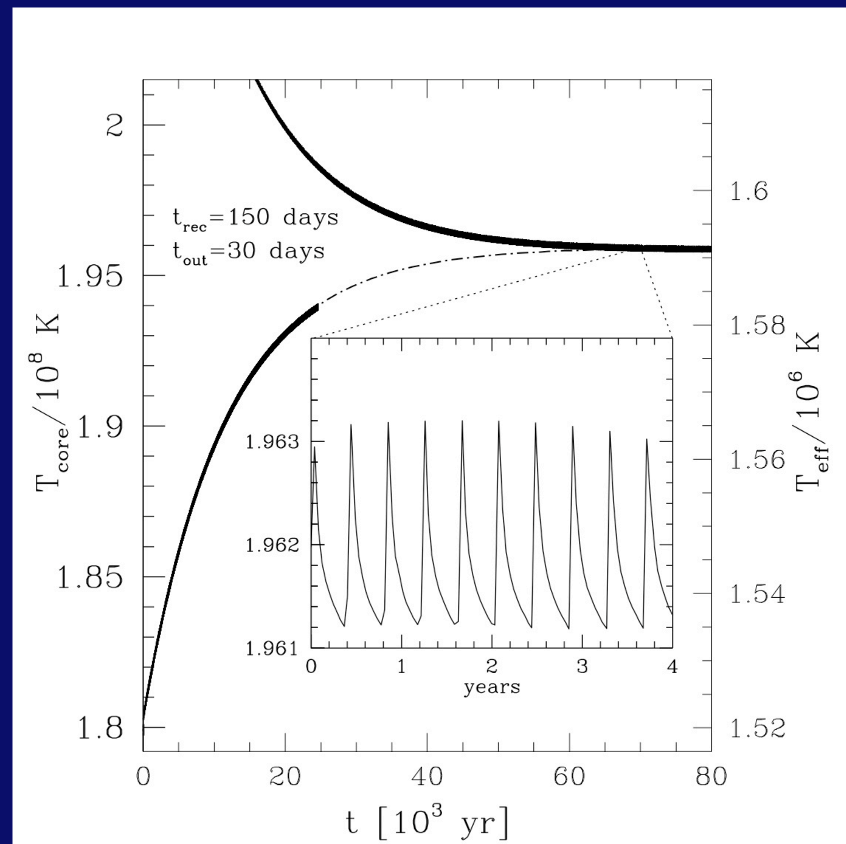
Isolated neutron stars: cooling after formation

- E.g., talk by Dany Page



Yakovlev 2004

Reheating of neutron star in binaries



Colpi et al. 2001

XTE J1701-462

- Very bright transient
  - Near Eddington luminosity
- In outburst in 2006-2007
  - Outburst lasted approximately 1.5 years
  - Was the crust temperature profile that of a steady state?
- Excellent coverage when source decayed to quiescence again
  - RXTE $\Rightarrow$ Swift $\Rightarrow$ Chandra + XMM-Newton

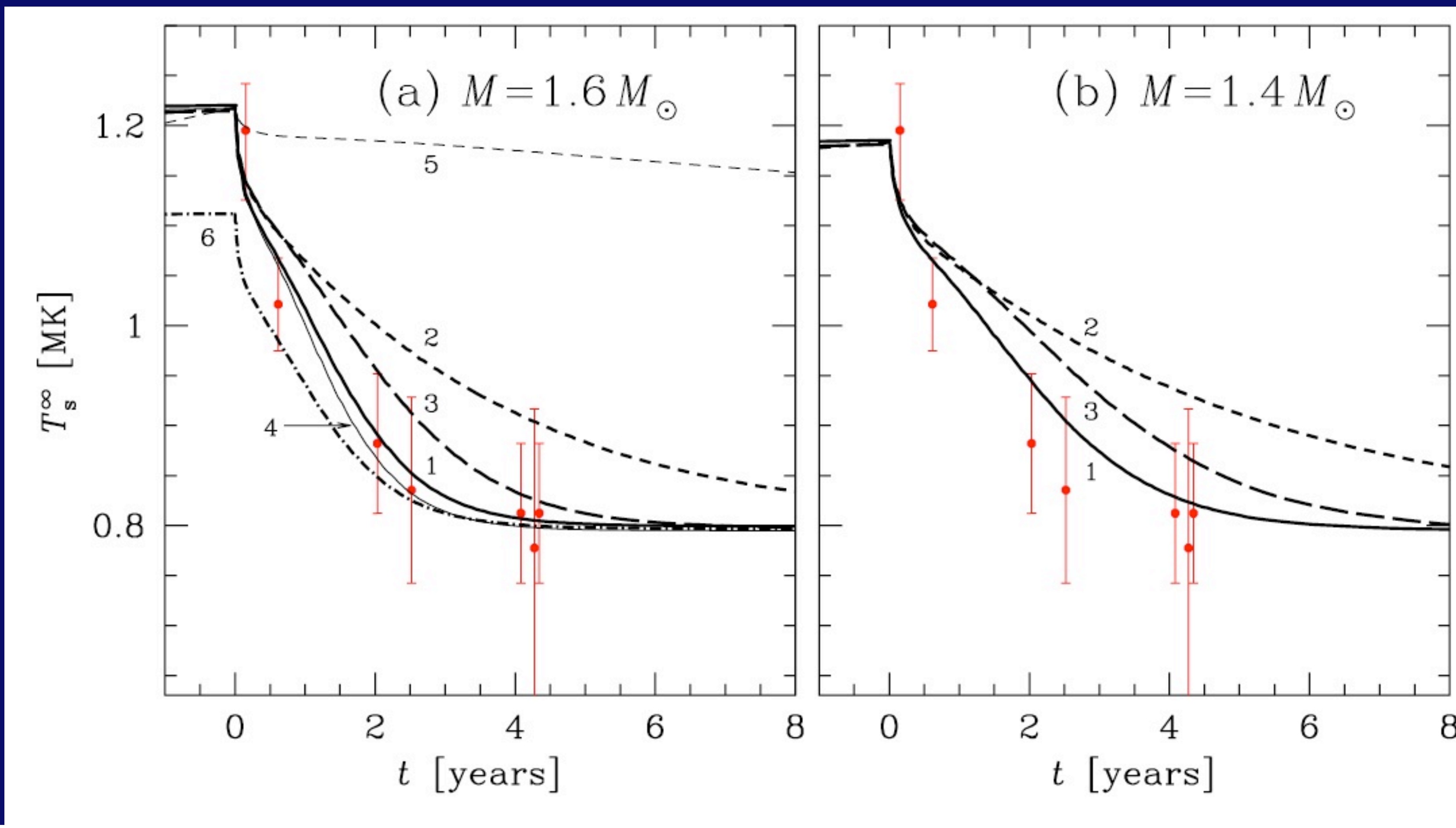
Uncertainties

- Again the distance
  - Affects luminosity and inferred temperature
- Time averaged mass accretion rate
  - Core temperature determined over > 10^{3-4} years
  - But only observe these systems for < 40 years
    - Significant errors in <Mdot> exist in the literature
    - Everybody uses his/her own estimates but unclear which are the best
- Uncertainties in heating and cooling models

Curve	T_{s0}^{∞} MK	Crust model	Conduction in crust	Superfluid in crust
1a	0.8	A	normal	moderate
2a	0.8	GS	normal	none
3a	0.8	GS	normal	moderate
4a	0.8	A	normal	strong
5a	0.8	A	low	moderate
6a	0.8	A	normal	moderate
1b	0.8	A	normal	moderate
2b	0.8	GS	normal	none
3b	0.8	GS	normal	moderate

Cooling curves for KS 1731-260

- Rutledge et al. 2001
- Shternin et al. 2008
- Brown & Cumming 2009
- Need high heat conductivity in crust



Calculating cooling curves

- The modeled curves depend on many parameters
  - Crust properties
    - Heat conductivity
    - Likely fully replaced crust
  - Crustal heating properties
    - Deep crustal heating and maybe also outer crust heating
    - Assume steady state temperature profile
  - Neutron star equation of state
  - Core cooling processes
- Observational uncertainties
  - Distance
  - Heat deposited in the crust during outburst
    - Time averaged accretion rate
  - When did accretion stop?
  - Residual accretion in quiescence