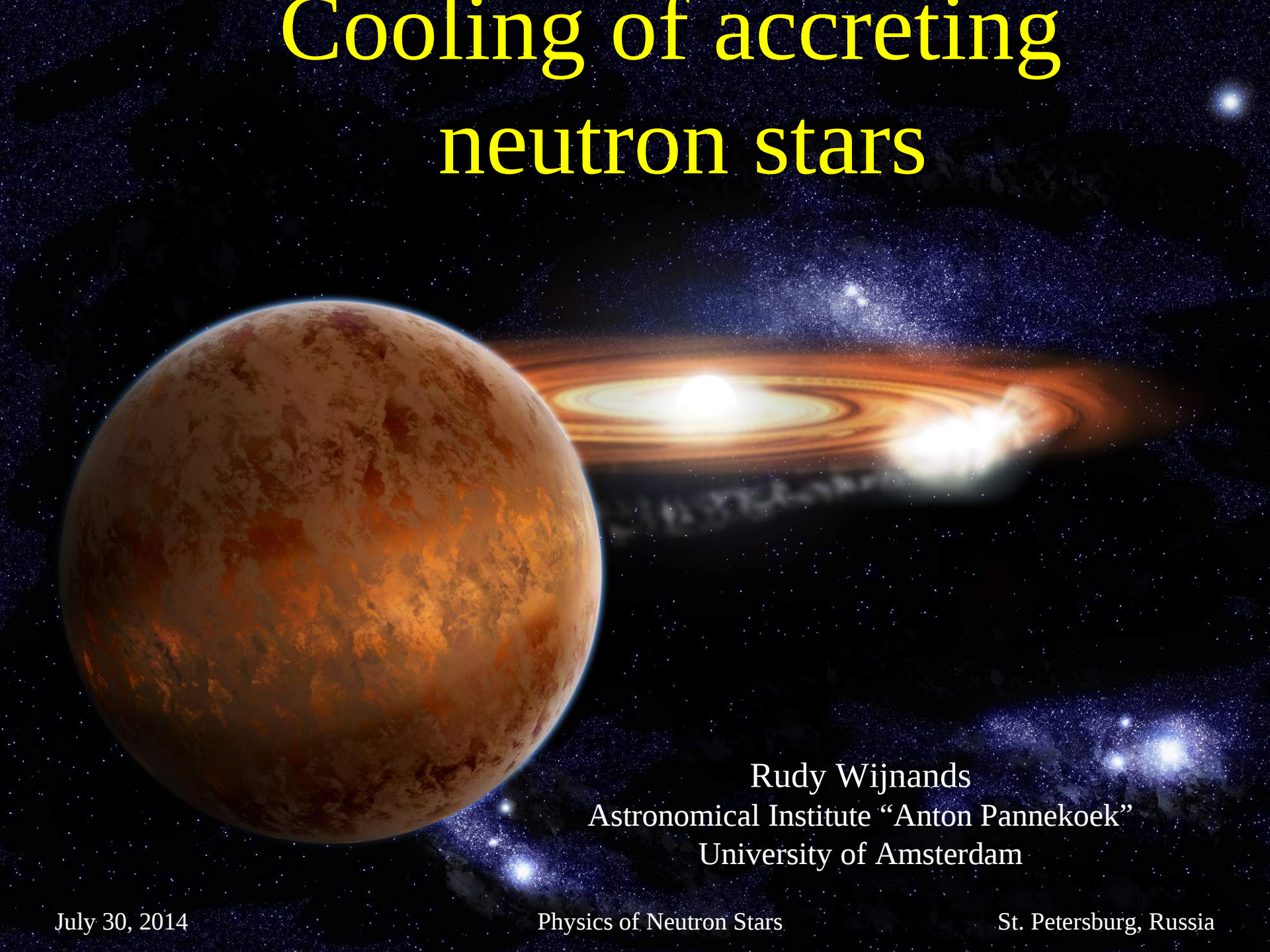
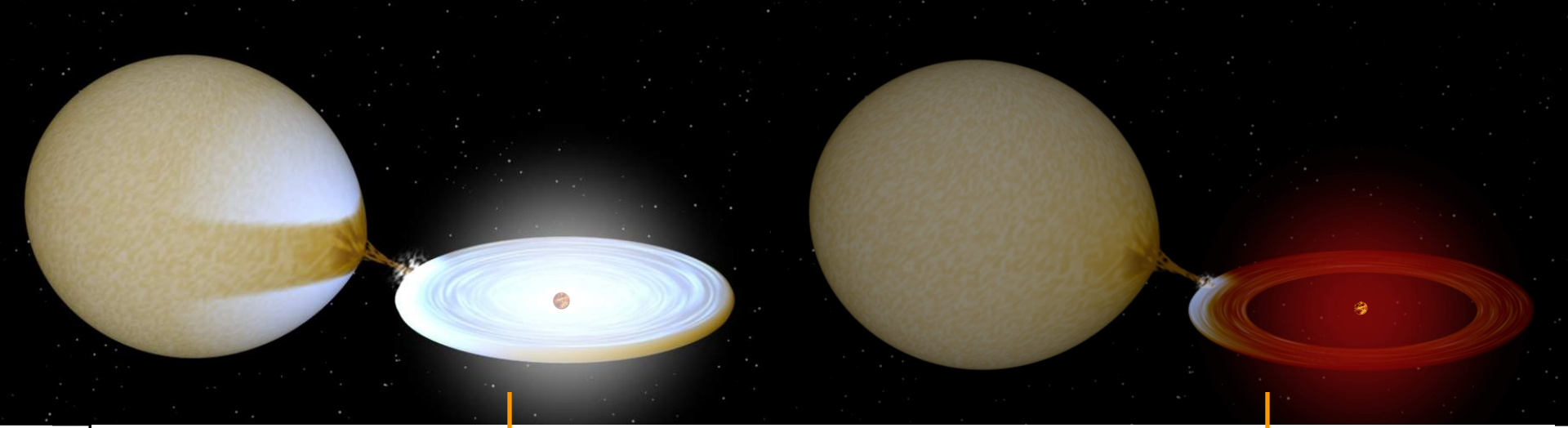
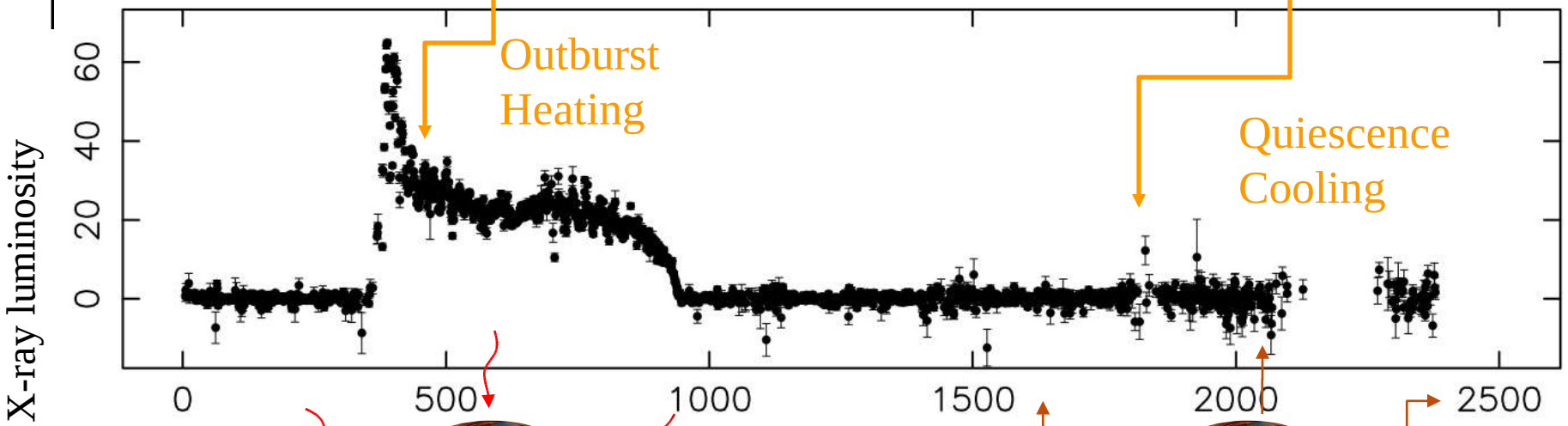
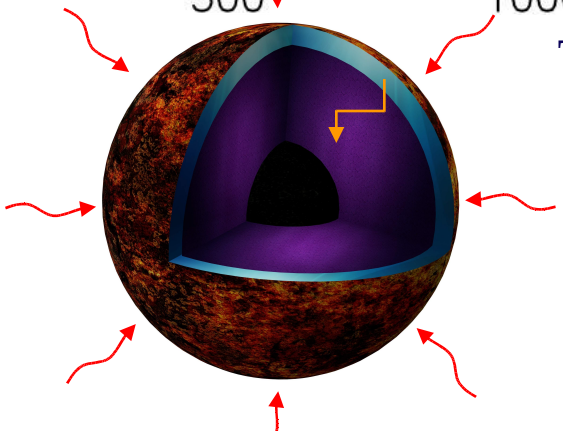
Cooling of accreting neutron stars

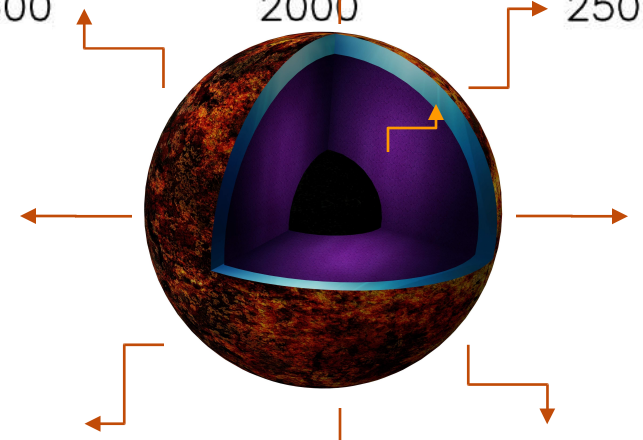


Rudy Wijnands
Astronomical Institute “Anton Pannekoek”
University of Amsterdam




X-ray luminosity
0
20
40
60
0
500
1000
1500
2000
2500
Time in days
Outburst
Heating
Quiescence
Cooling



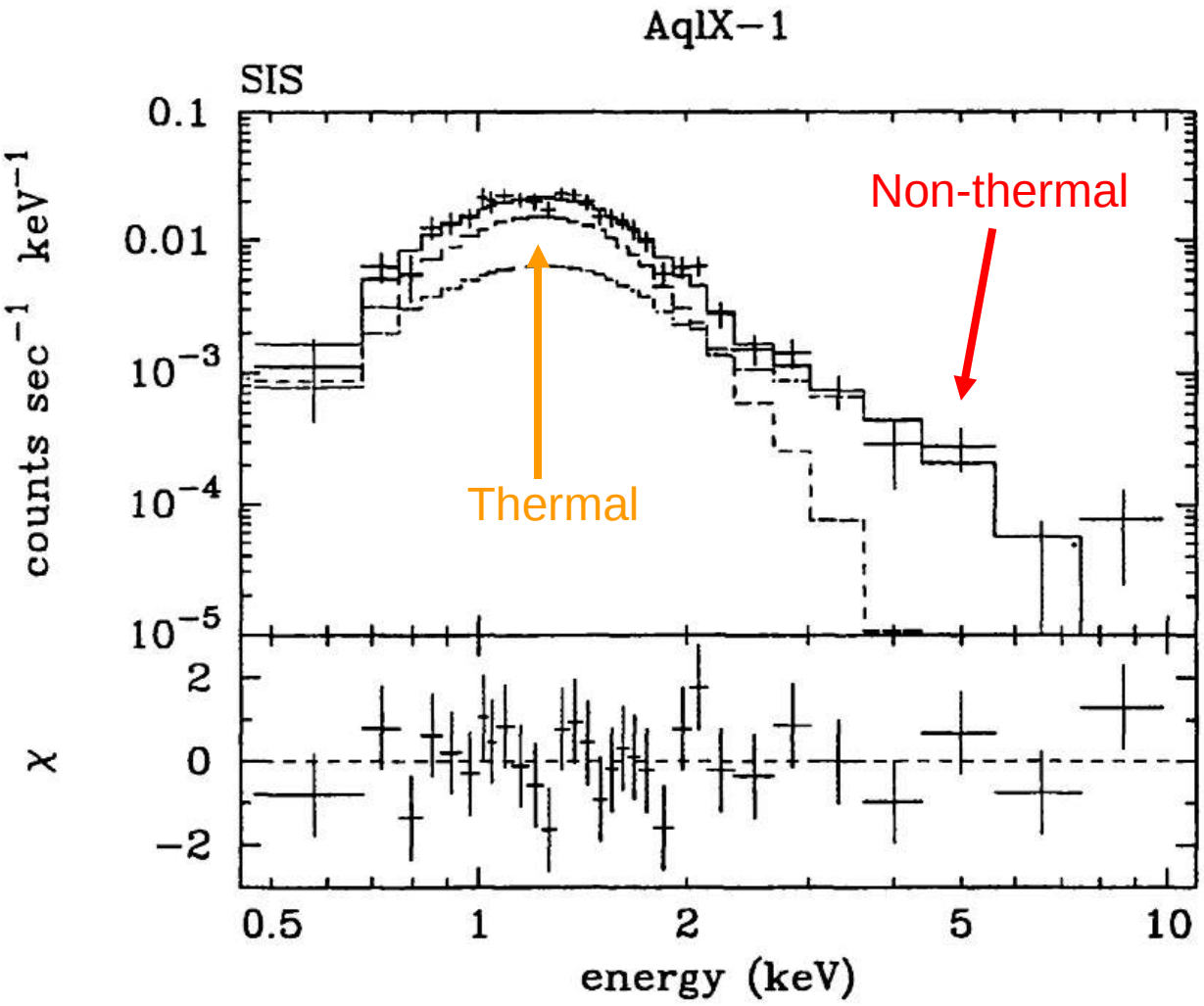


Heating and cooling of accreting neutron stars

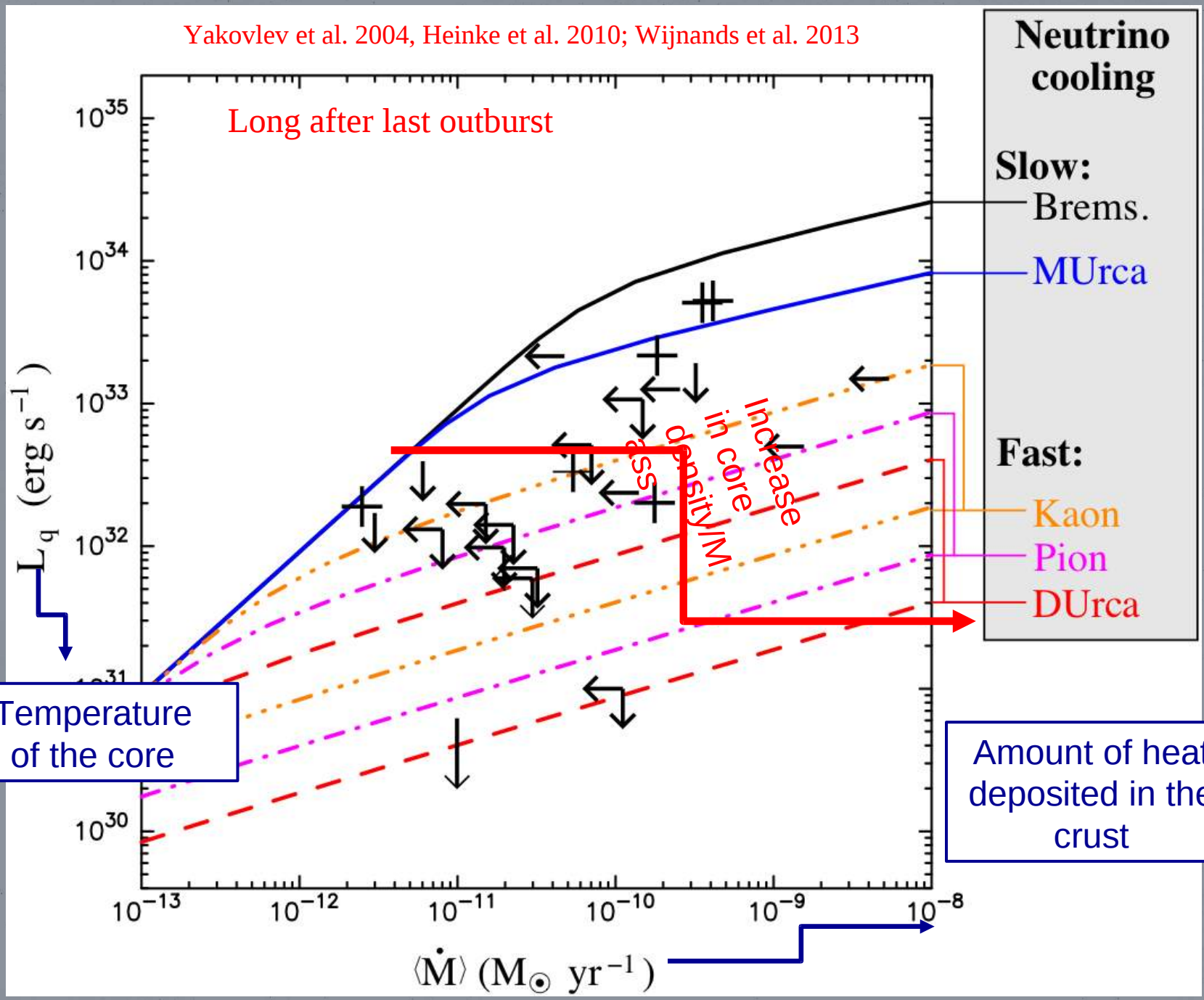
- A lot of energy is dumped on the neutron star
  - Release of gravitational energy (200 MeV/nucleon)
  - Thermonuclear reactions (1-5 MeV/nucleon)
  - Pycnonuclear reactions (1-2 MeV/nucleon)
- Will that heat up the neutron star?
- Can we observe that?
  - Cooling neutron stars in X-ray transients

Do we detect cooling neutron star?

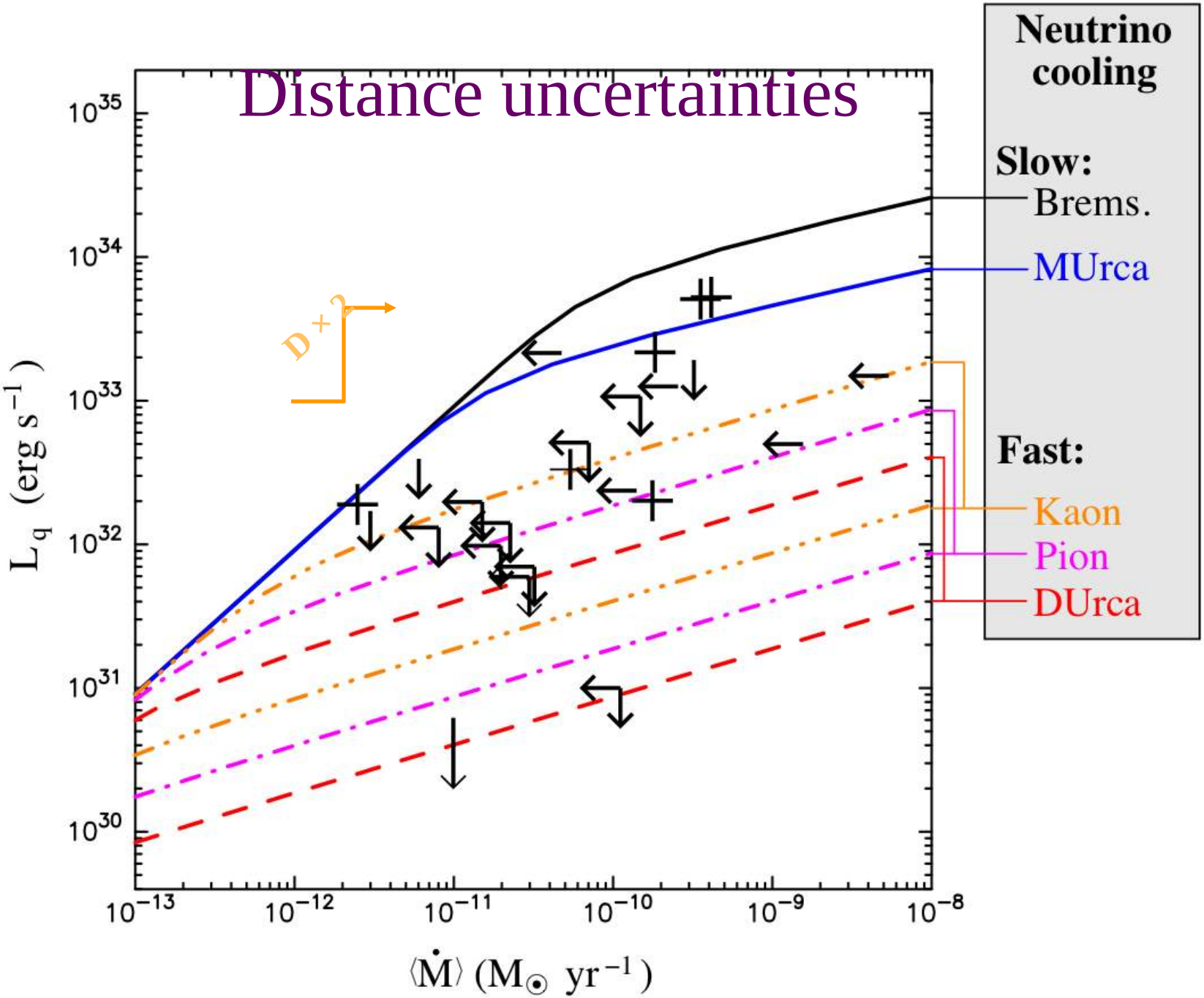
Asai et al. 1998



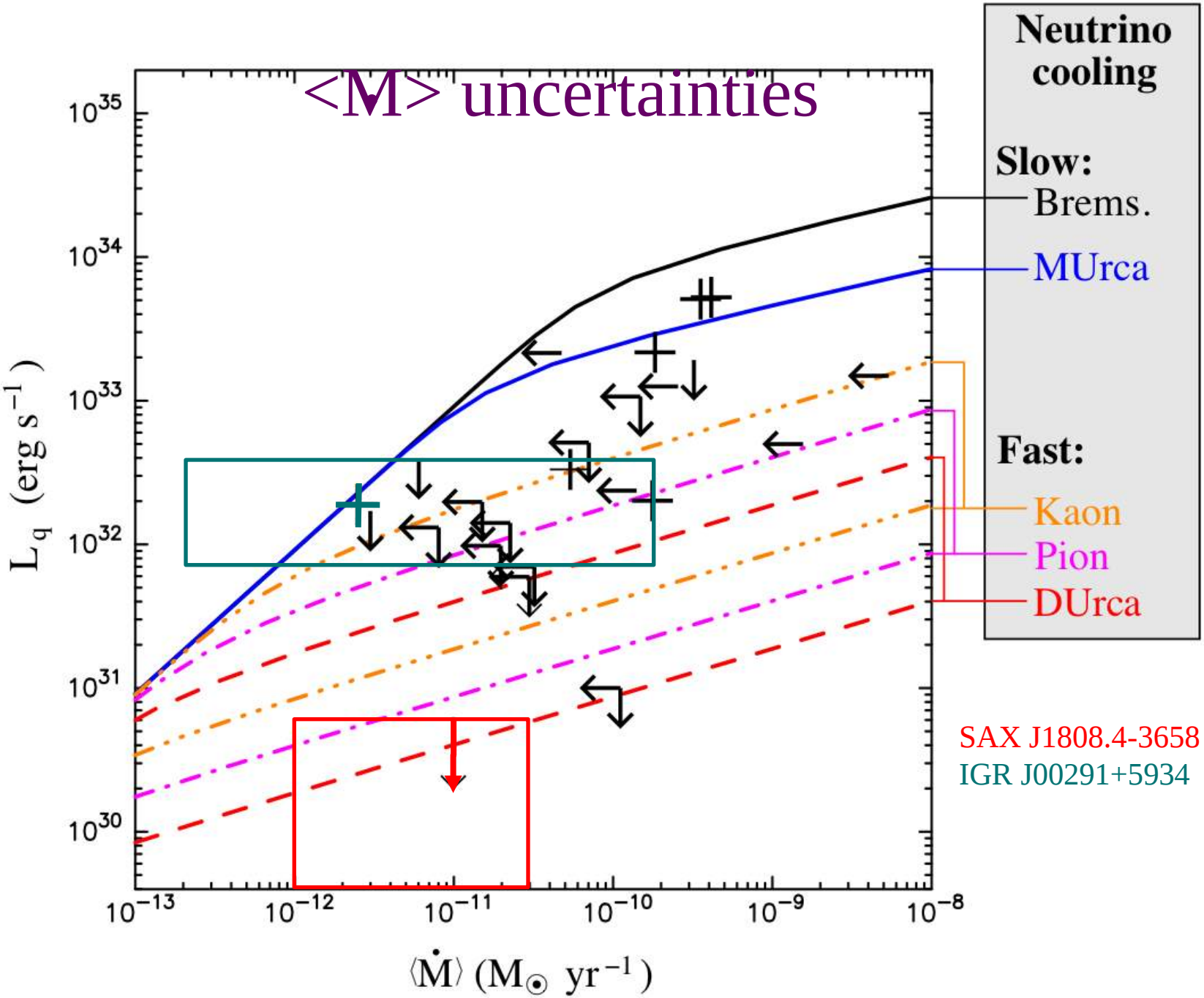
For low statistic data, the thermal component, the power-law component *and* the column density are interfering with each other!

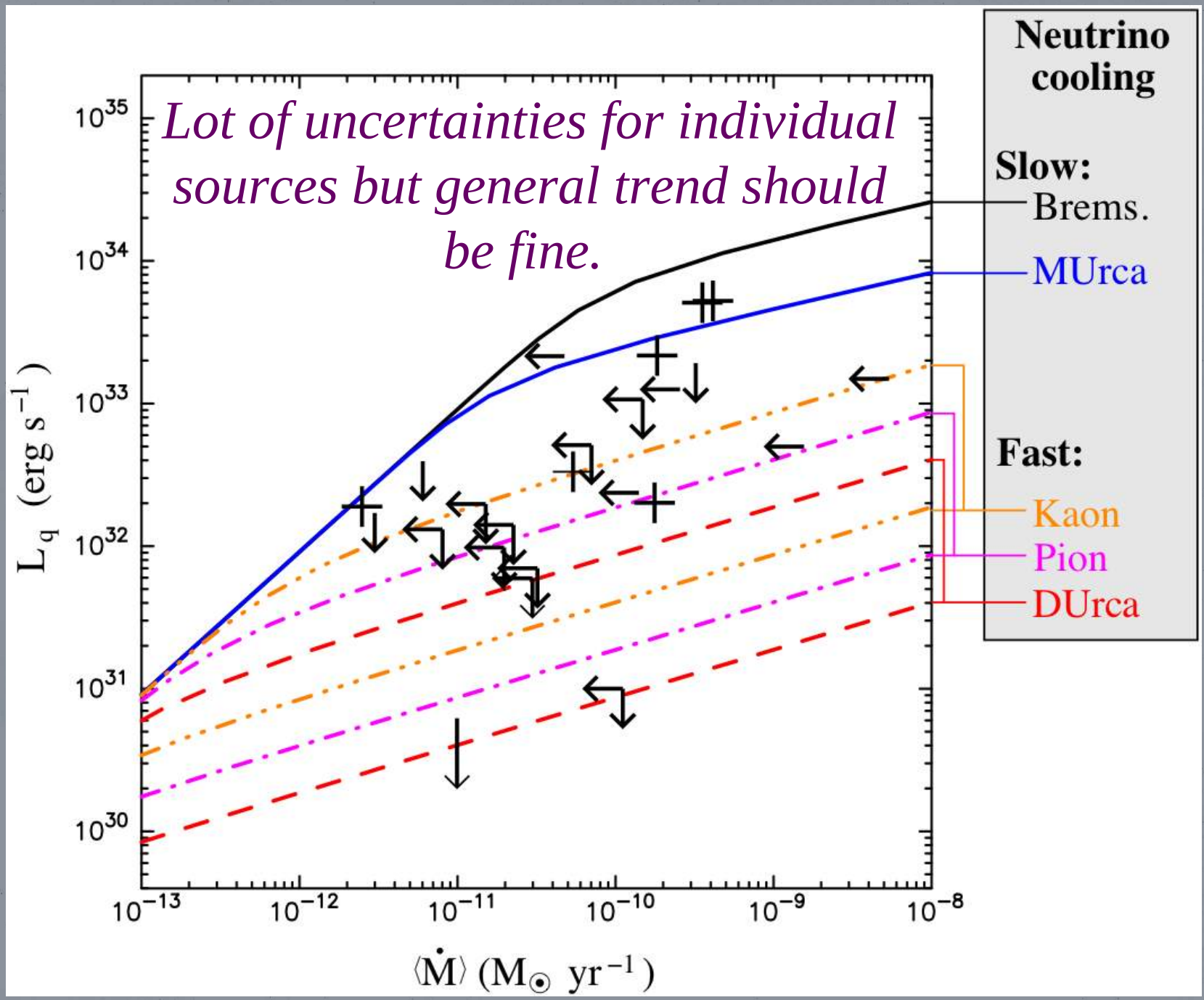

Yakovlev et al. 2004, Heinke et al. 2010; Wijnands et al. 2013
Long after last outburst
Neutrino cooling
Slow:
Brems.
MUrca
Fast:
Kaon
Pion
DUrca
Increase in core density/Mass
L_q (erg s^{-1})
10^{35}
10^{34}
10^{33}
10^{32}
10^{30}
10^{-13}
10^{-12}
10^{-11}
10^{-10}
10^{-9}
10^{-8}
$\langle \dot{M} \rangle$ ($M_\odot$ yr^{-1})
Temperature of the core
Amount of heat deposited in the crust

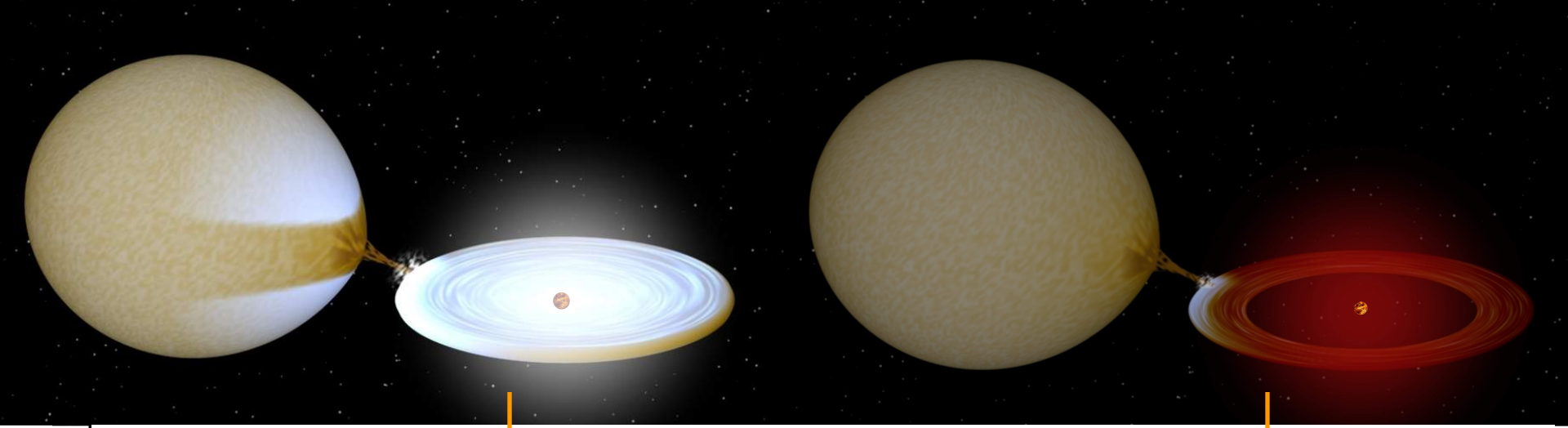
Distance uncertainties

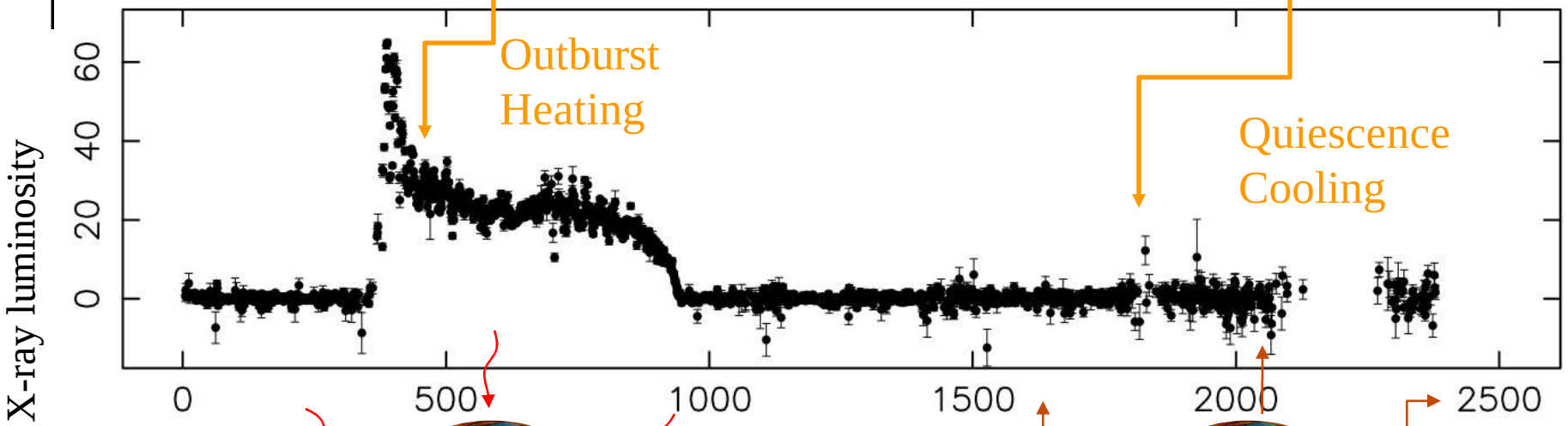


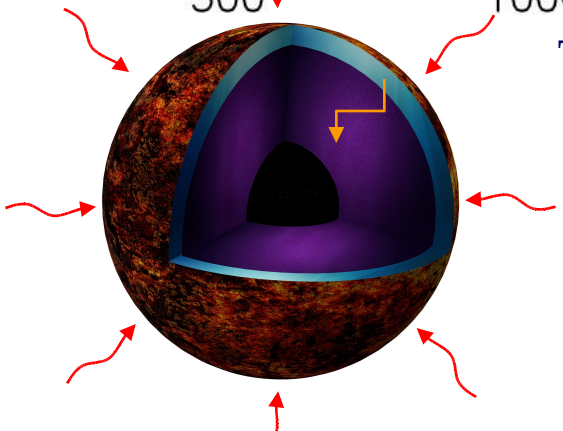
<M> uncertainties

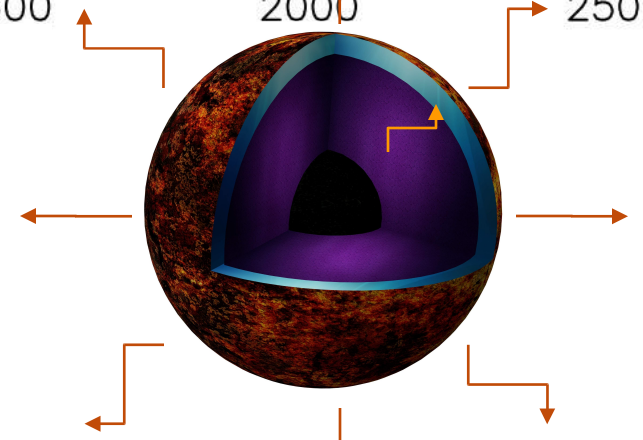


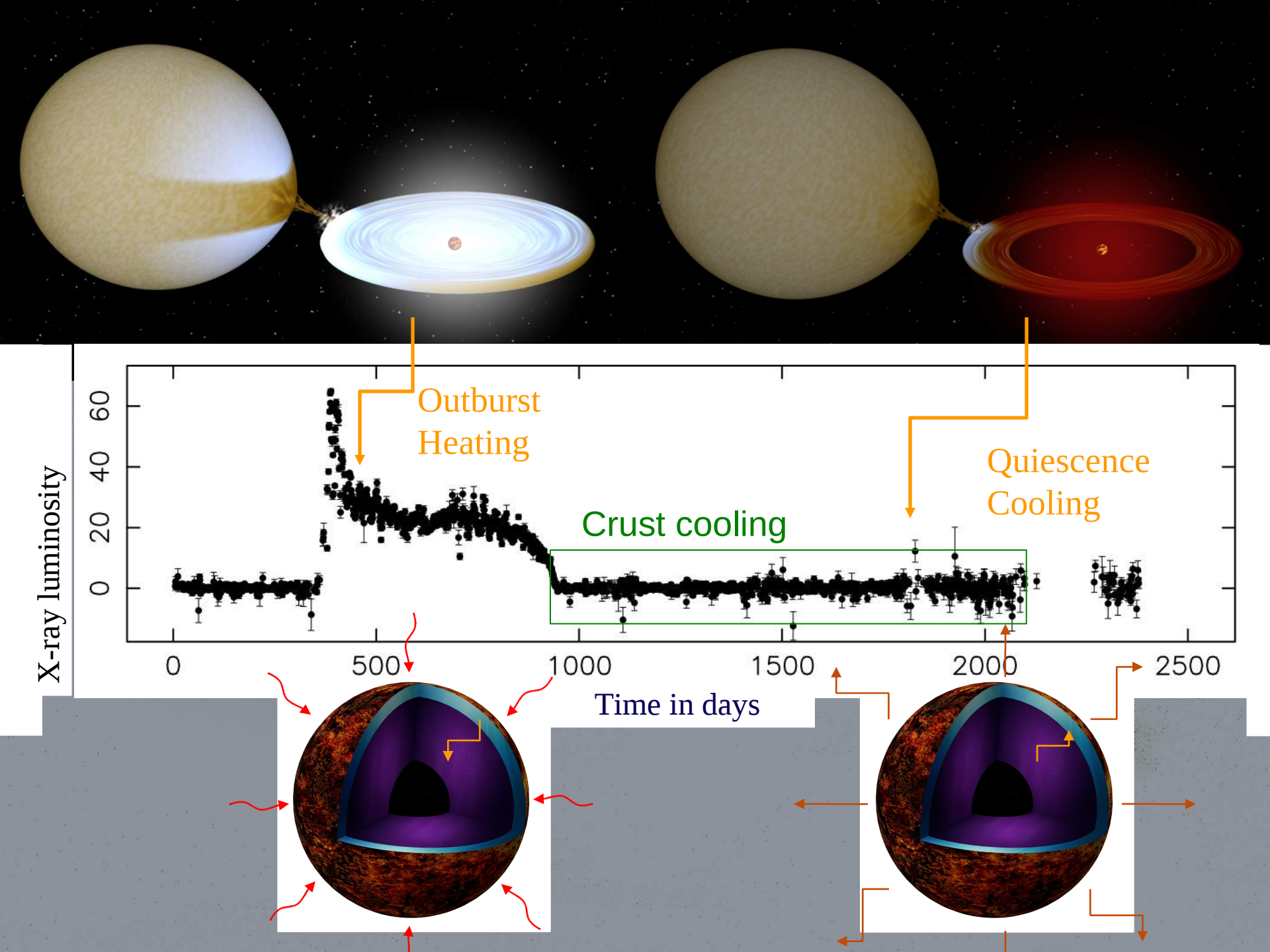

Lot of uncertainties for individual sources but general trend should be fine.
Neutrino cooling
Slow:
Brems.
MUrca
Fast:
Kaon
Pion
DUrca
L_q (erg s^{-1})
10^{35}
10^{34}
10^{33}
10^{32}
10^{31}
10^{30}
10^{-13}
10^{-12}
10^{-11}
10^{-10}
10^{-9}
10^{-8}
$\langle \dot{M} \rangle$ ($M_\odot$ yr^{-1})




X-ray luminosity
0
20
40
60
0
500
1000
1500
2000
2500
Time in days
Outburst
Heating
Quiescence
Cooling

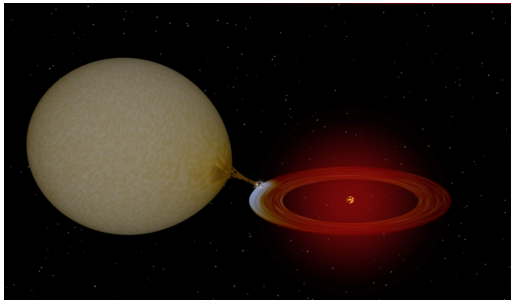


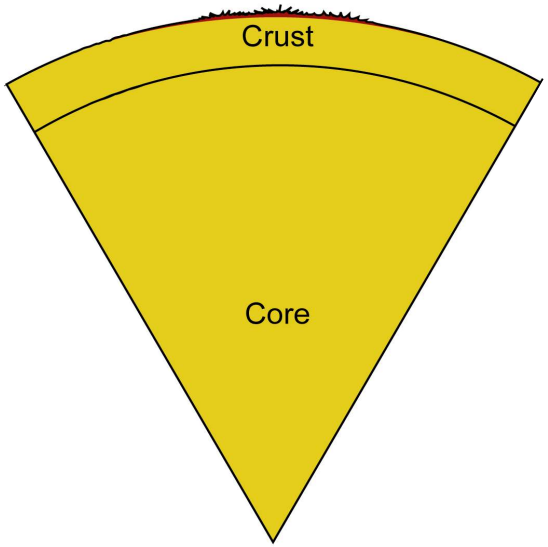



Outburst
Heating
Crust cooling
Quiescence
Cooling
X-ray luminosity
0
20
40
60
0
500
1000
1500
2000
2500
Time in days

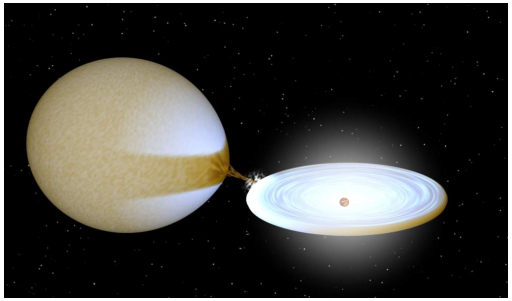
Heating of the crust

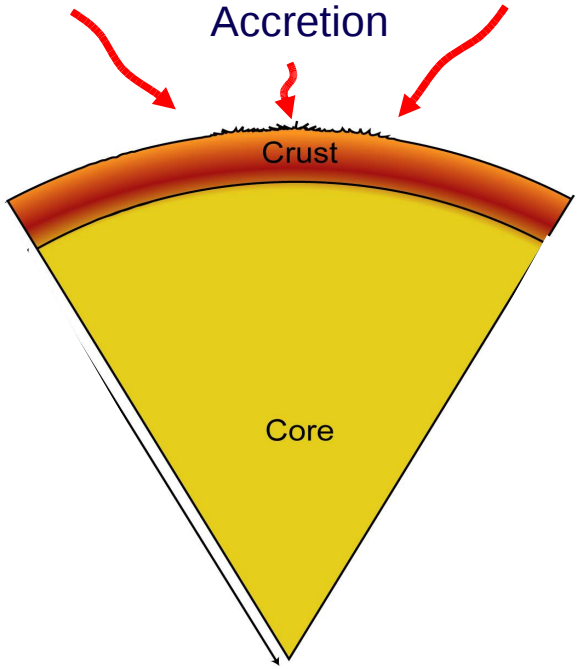
Before



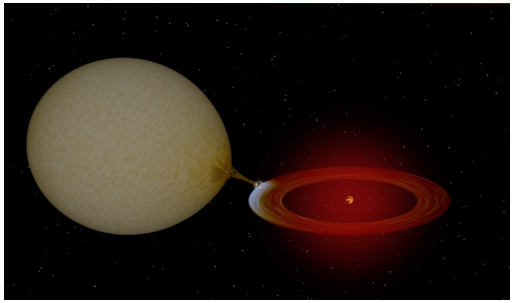


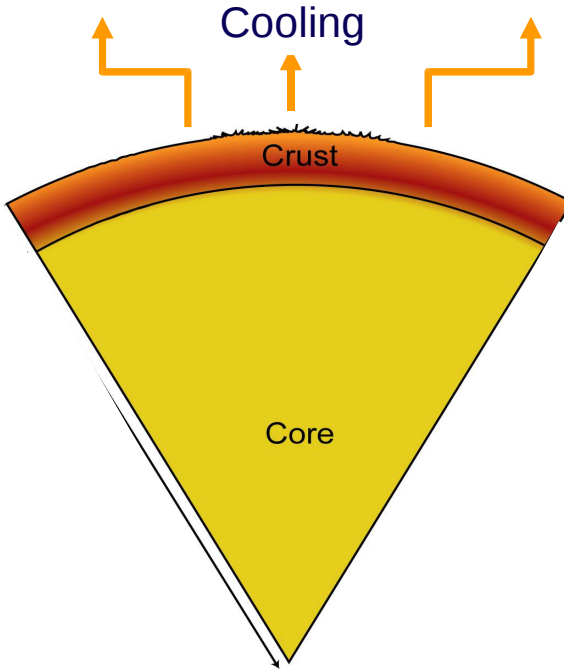
During



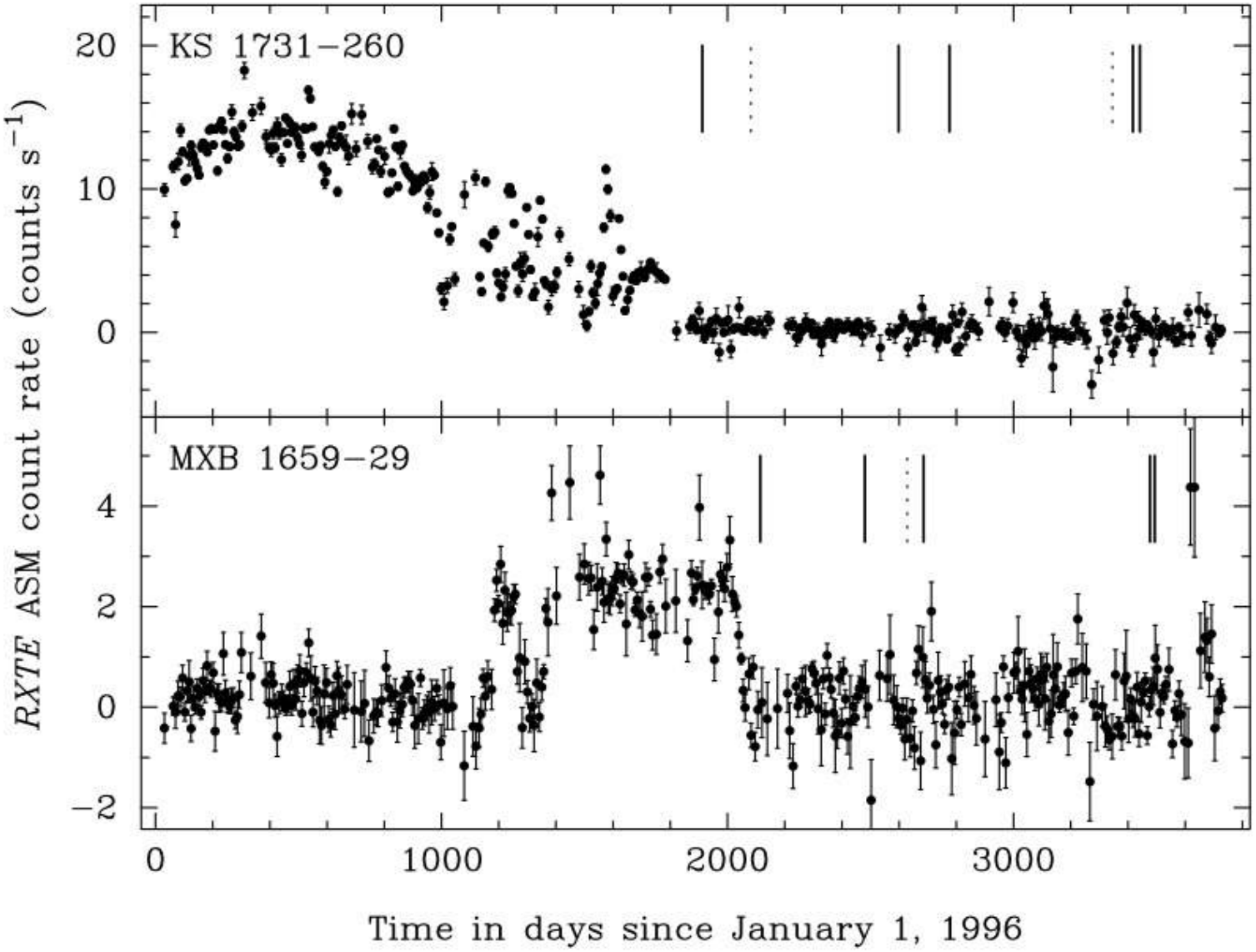


After



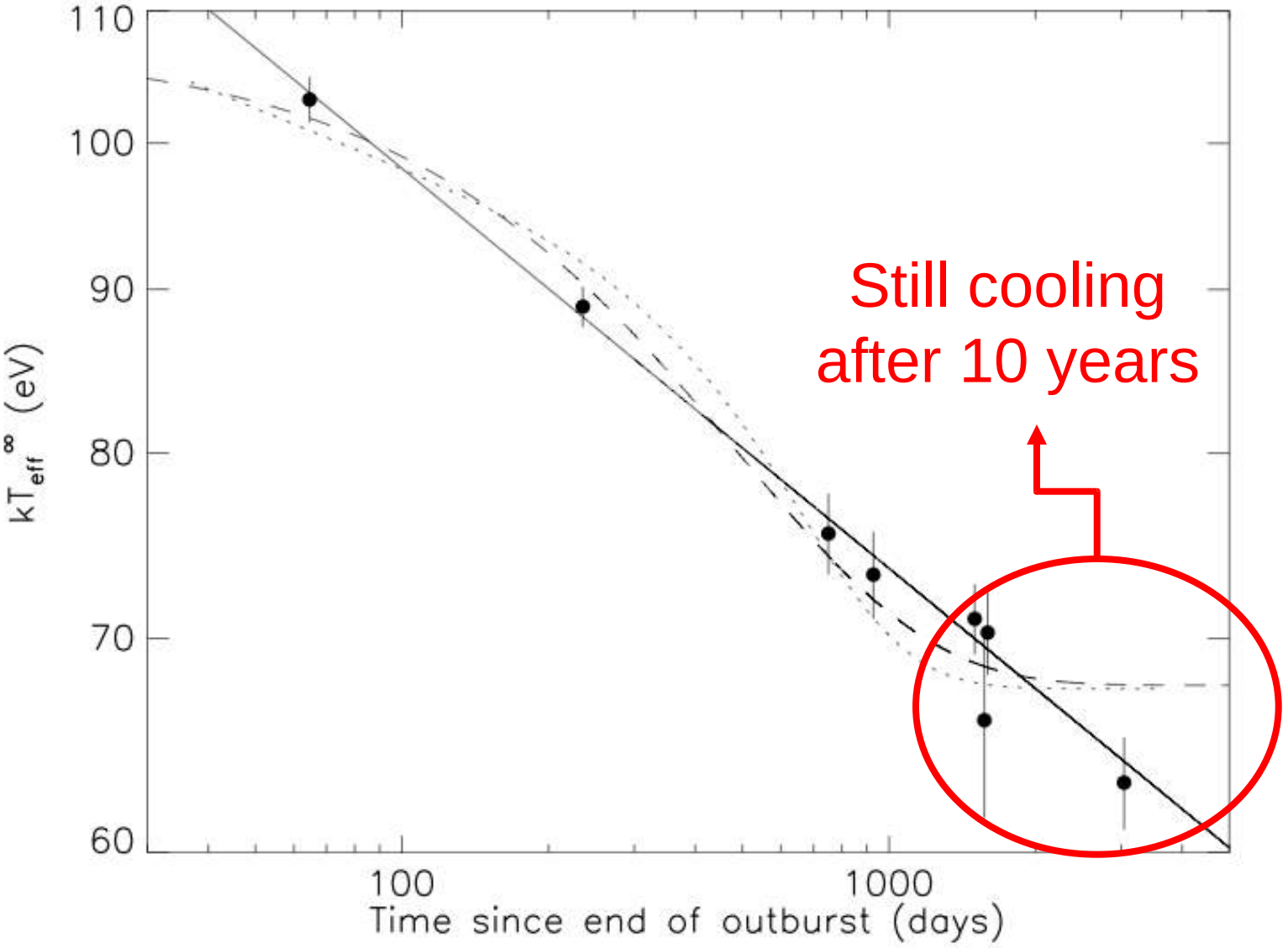


Quasi-persistent sources



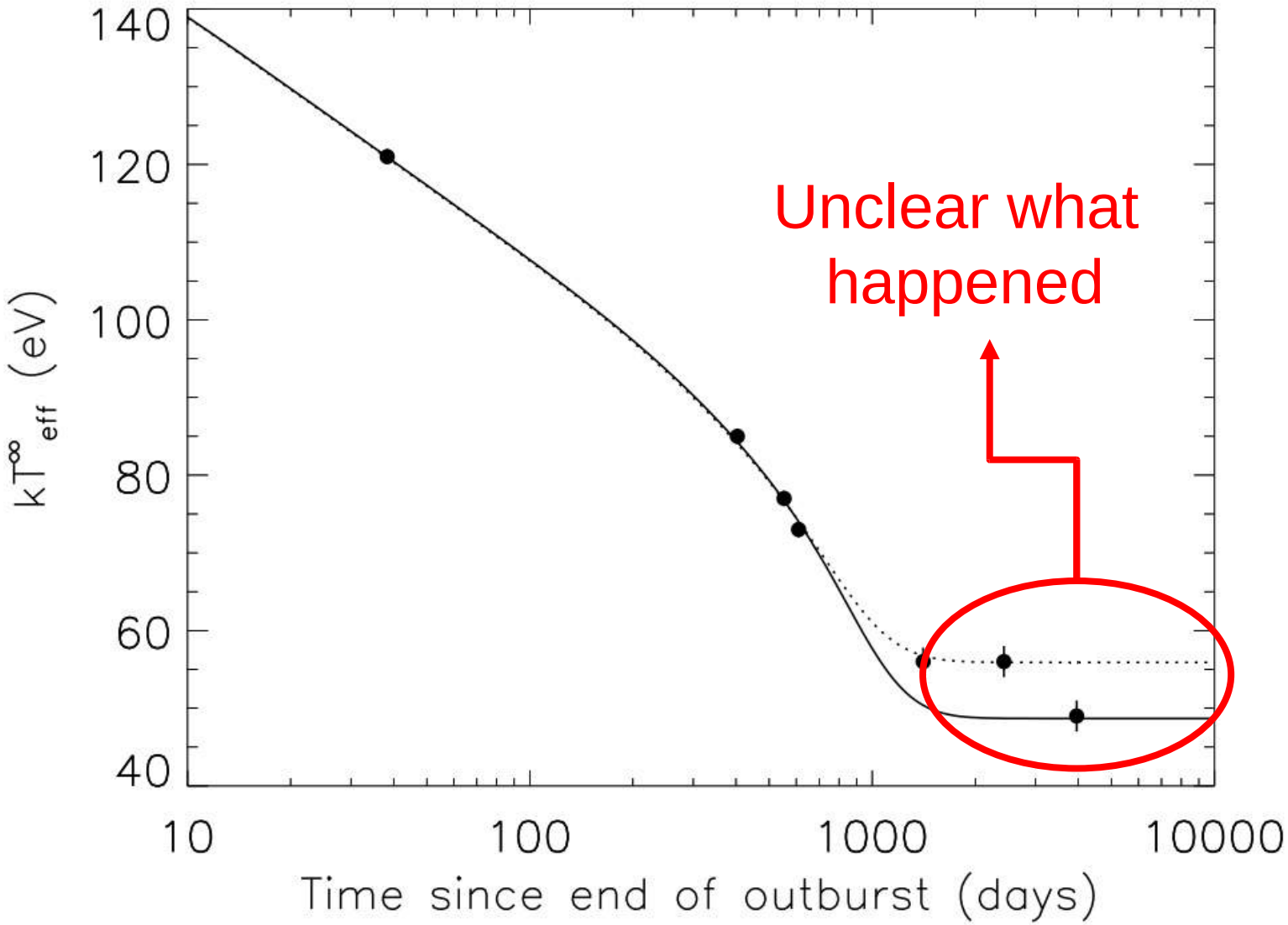
Wijnands et al. 2001, 2004; Cackett et al. 2006

KS 1731-260



Cackett et al. 2010

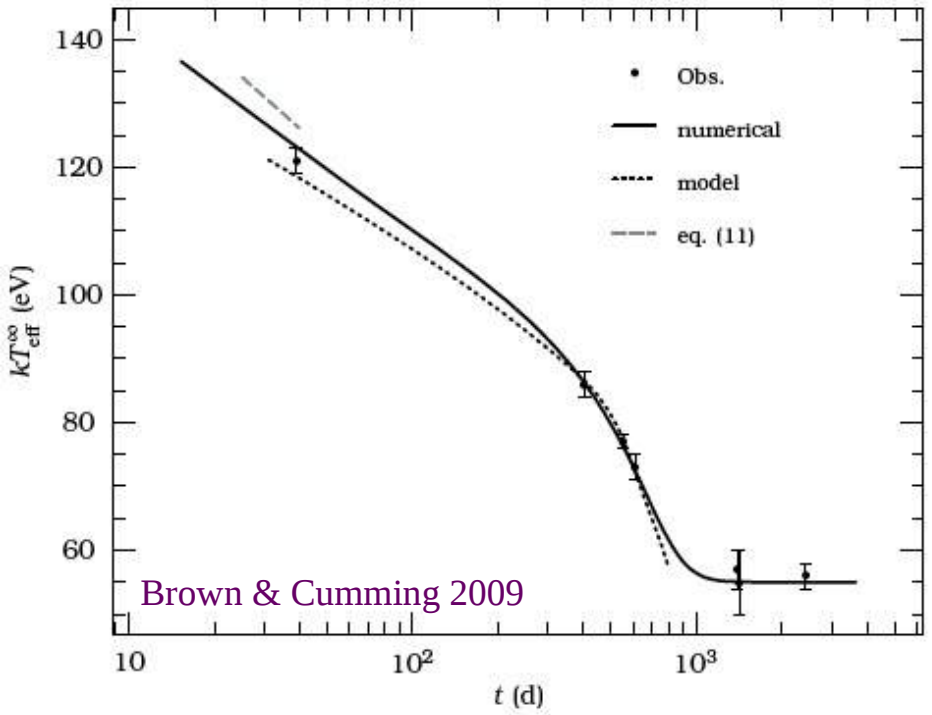
MXB 1659-298



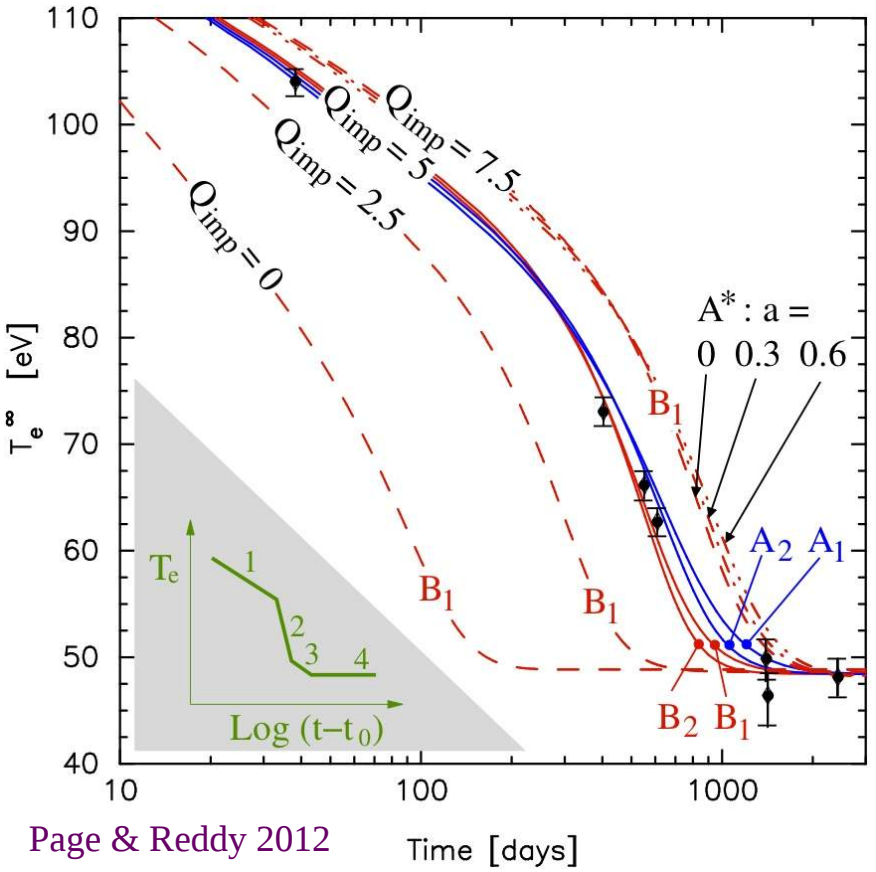
Cackett et al. 2013

Calculations of cooling curves

- Larger heat conductivity in the crust than anticipated
- Need of additional shallow heating source
- Rutledge et al. 2001; Shternin et al. 2008; Brown & Cumming 2009; Page & Reddy 2012, 2013; Turlione et al. 2014; Medin & Cumming 2014

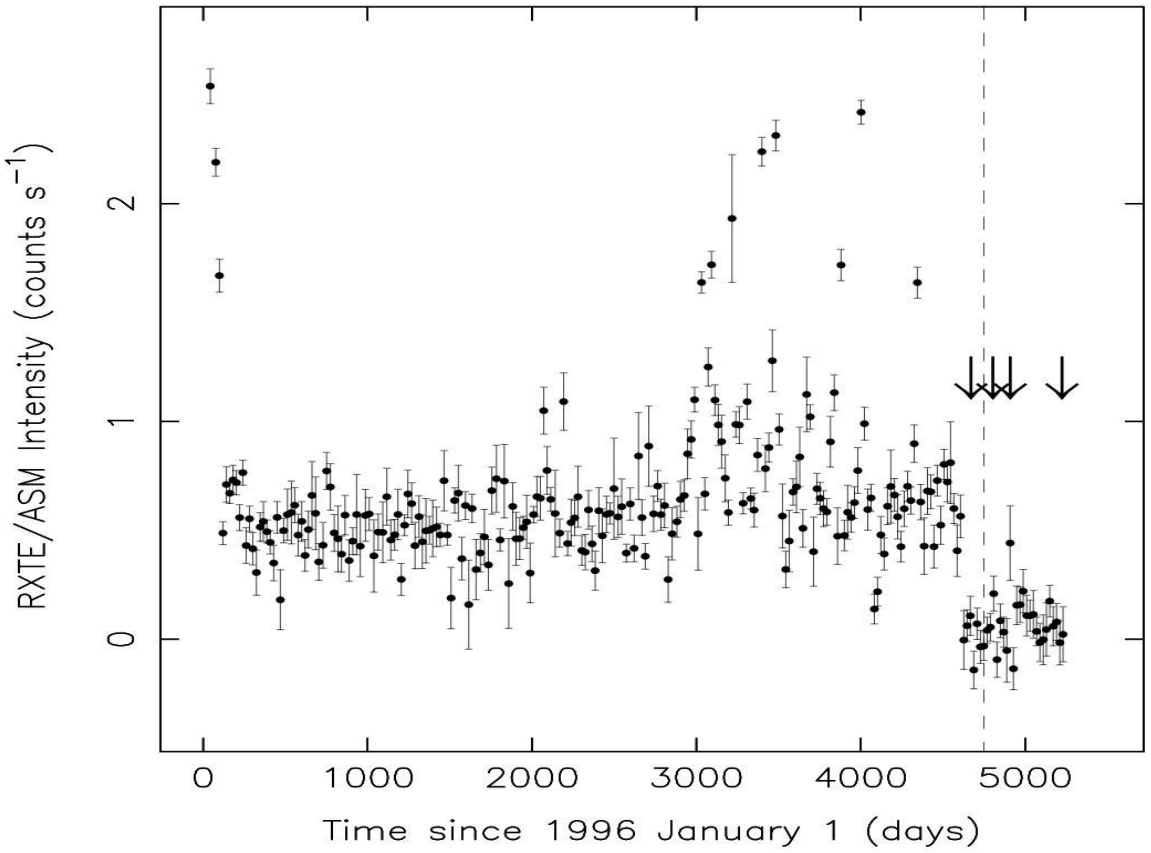


MXB 1659-29



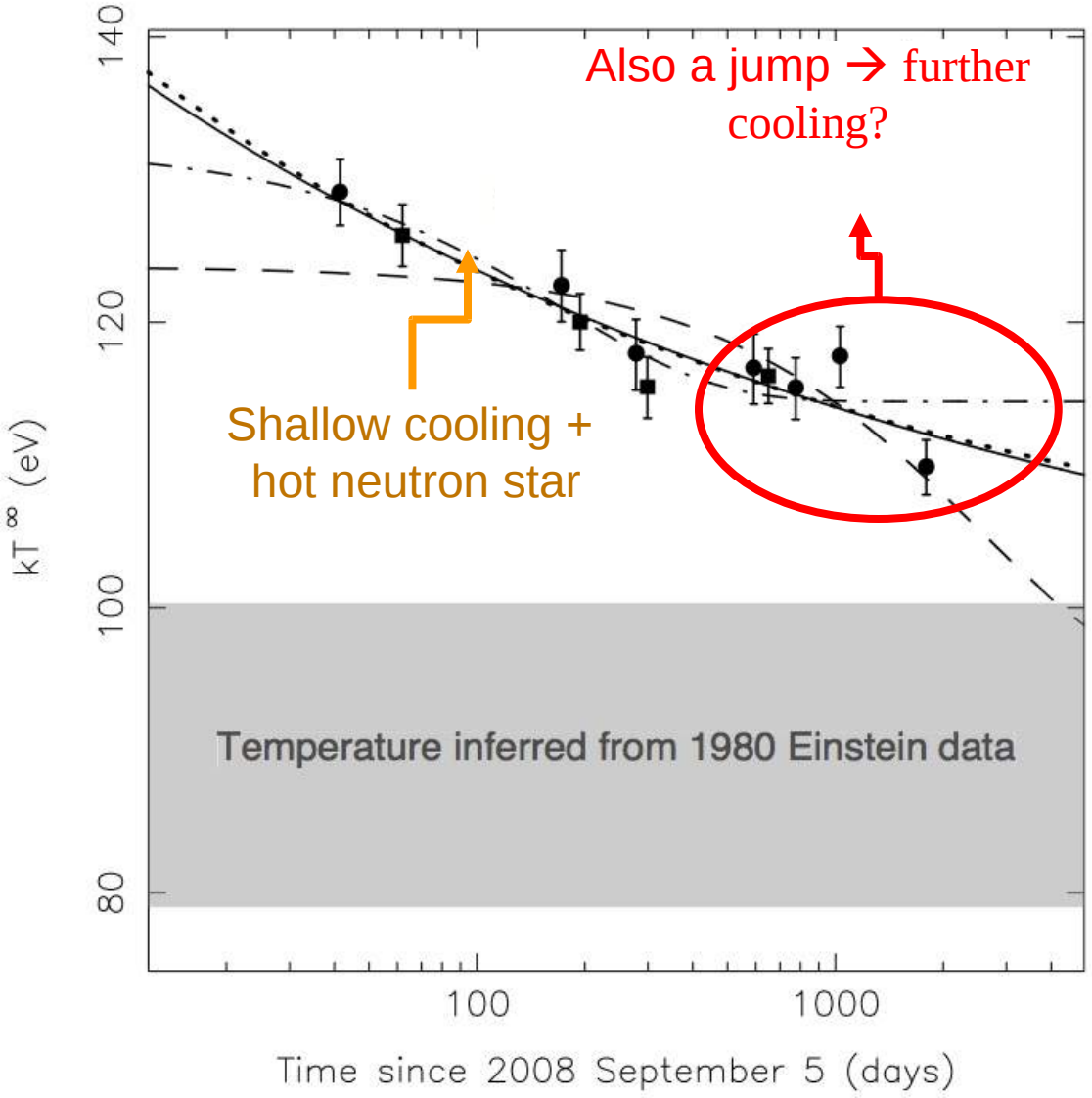
Three additional sources

- EXO 0748-676
  - In outburst from July 1984 to September 2008
  - Low outburst luminosity → ~ 1% LEddington



Degenaar et al. 2009, 2011

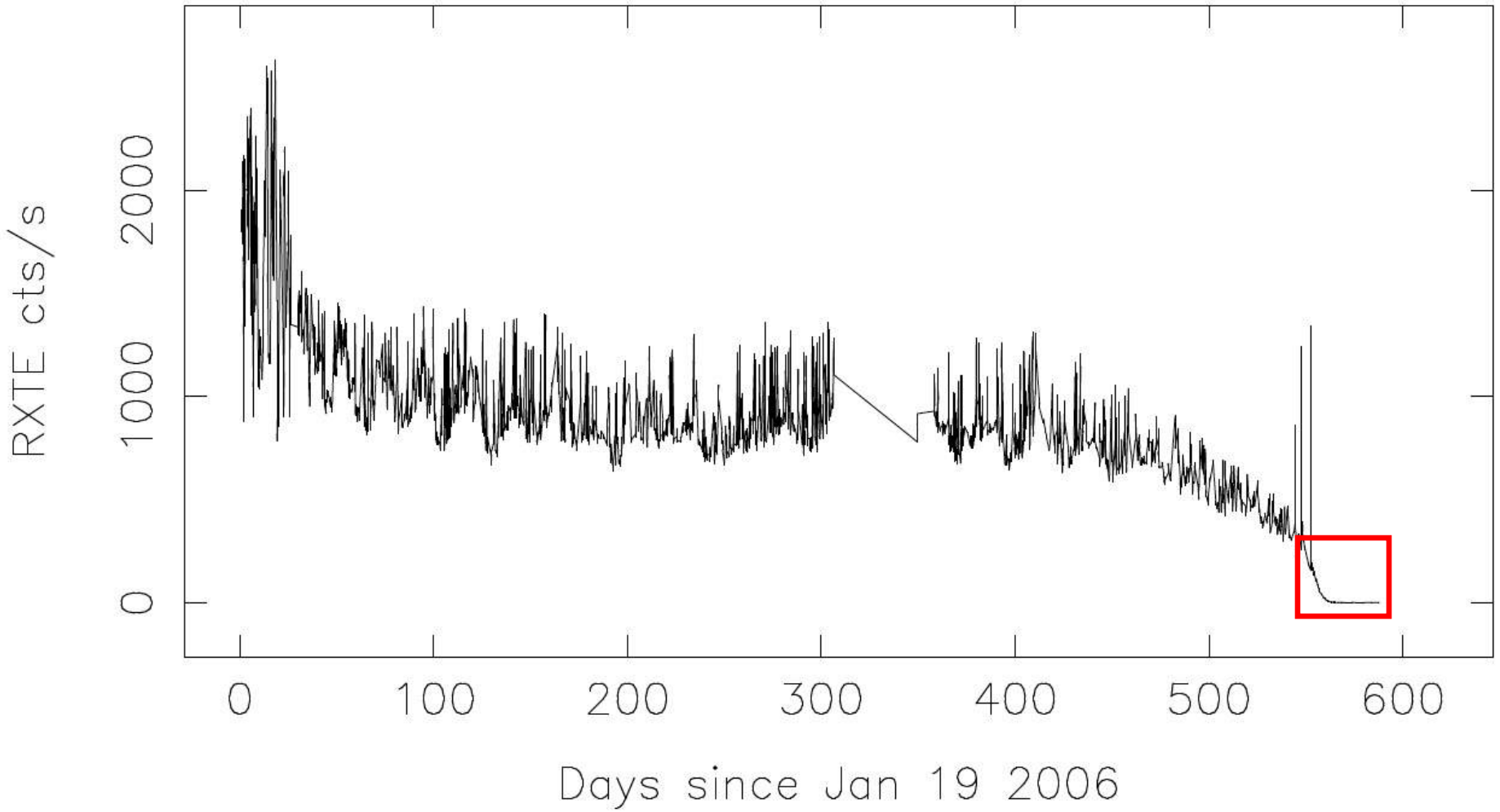
EXO 0748-676



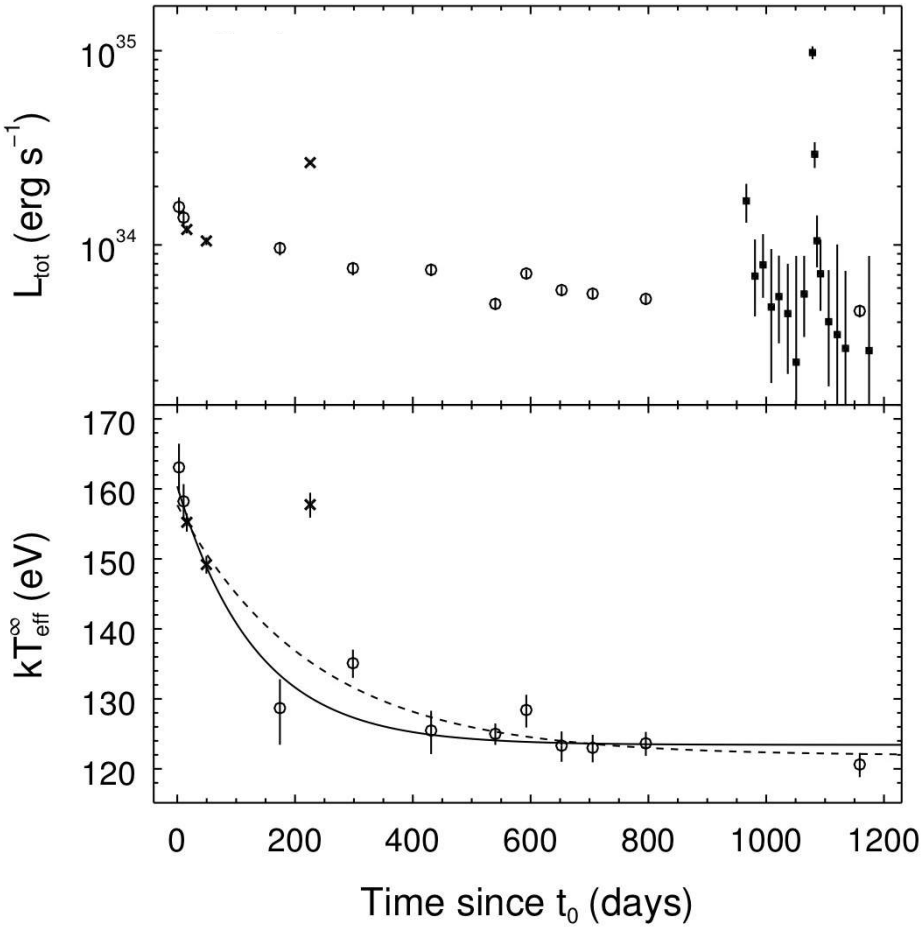
Degenaar et al. 2011, 2014

Pre-outburst level: kT~90 eV → further cooling or sign of variable atmosphere composition?

XTE J1701-462



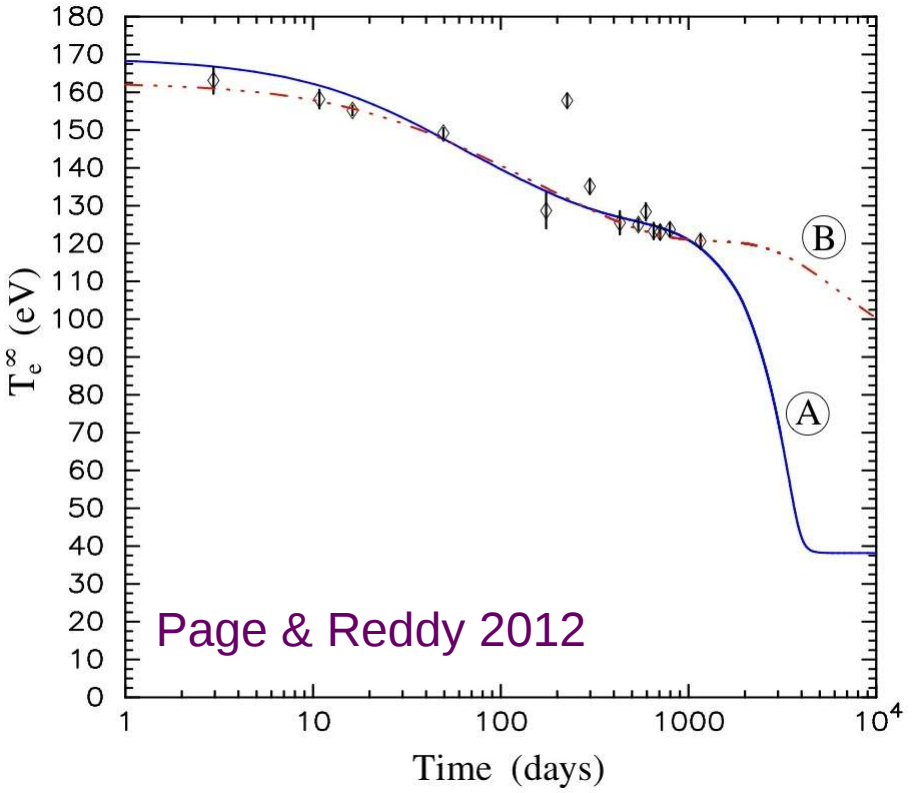
For 1.5 years active in 2006-2007 at near Eddington luminosities



- Accretion flares
- Initial cooling faster than for the other sources

XTE J1701-462

Fridriksson et al. 2010, 2011



Page & Reddy 2012, 2013

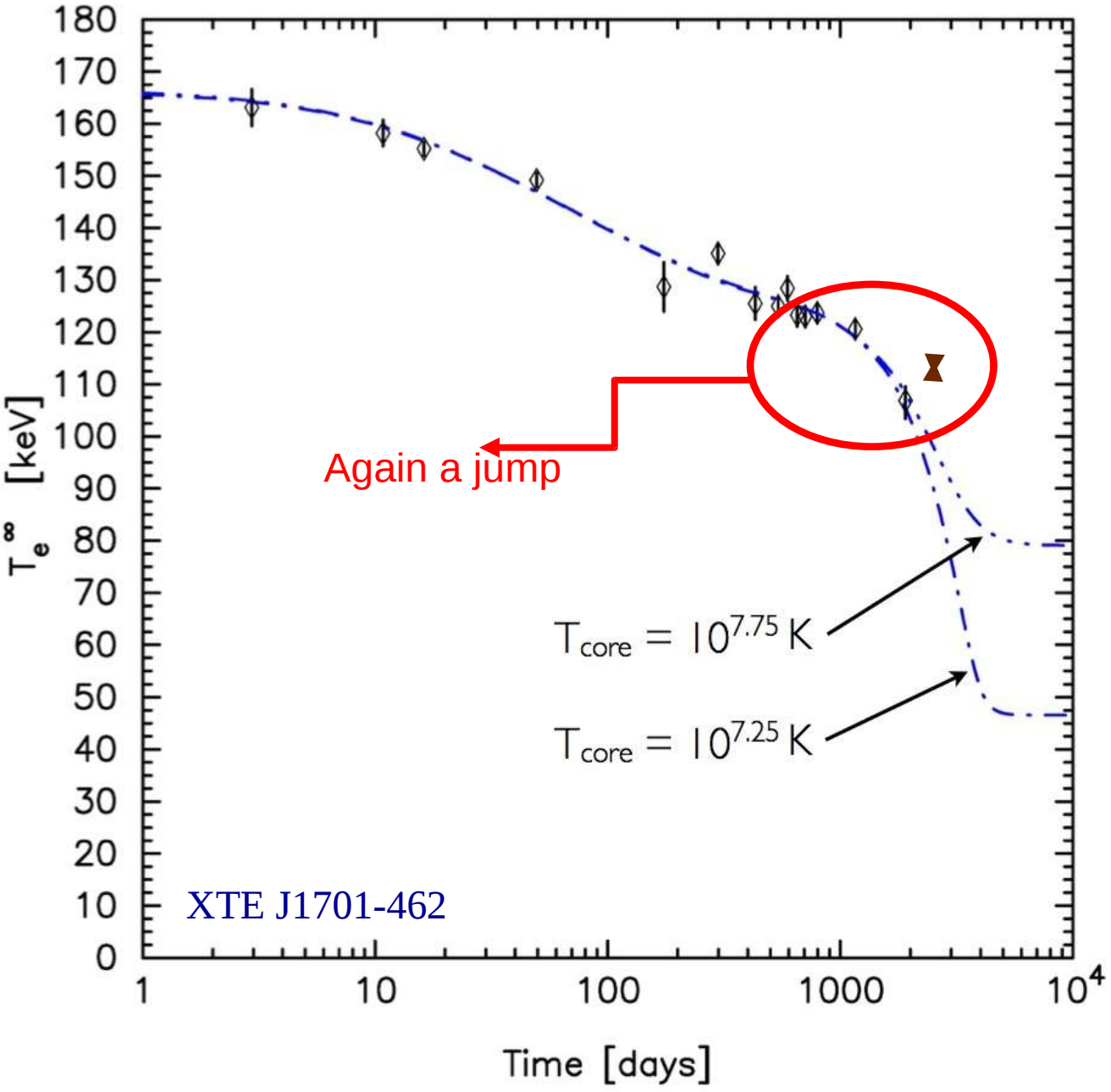
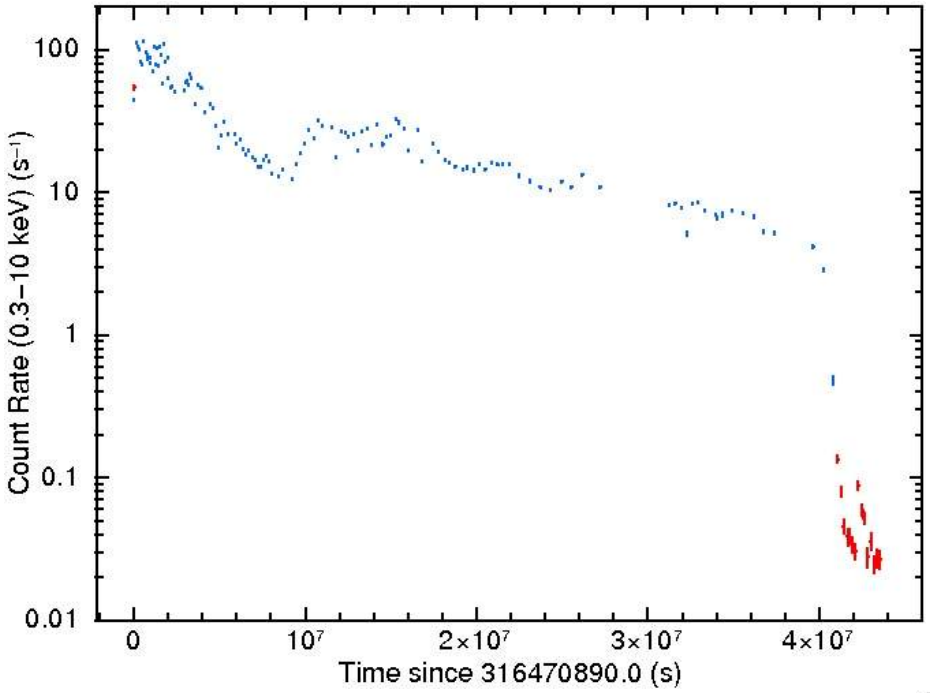


Figure and data provided by Joel Fridriksson

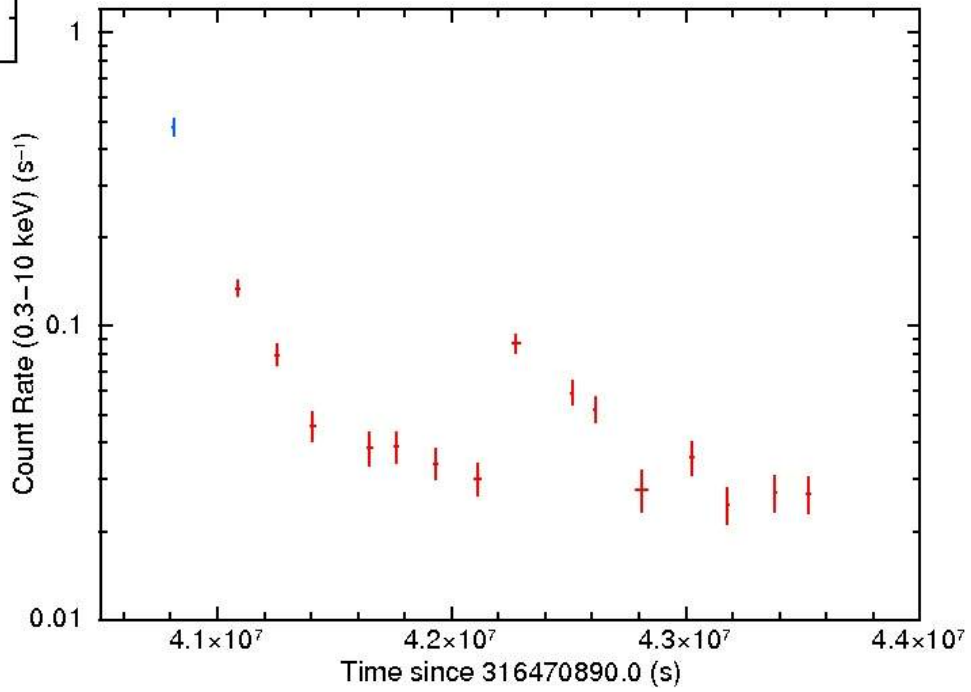
MAXI J0556-332



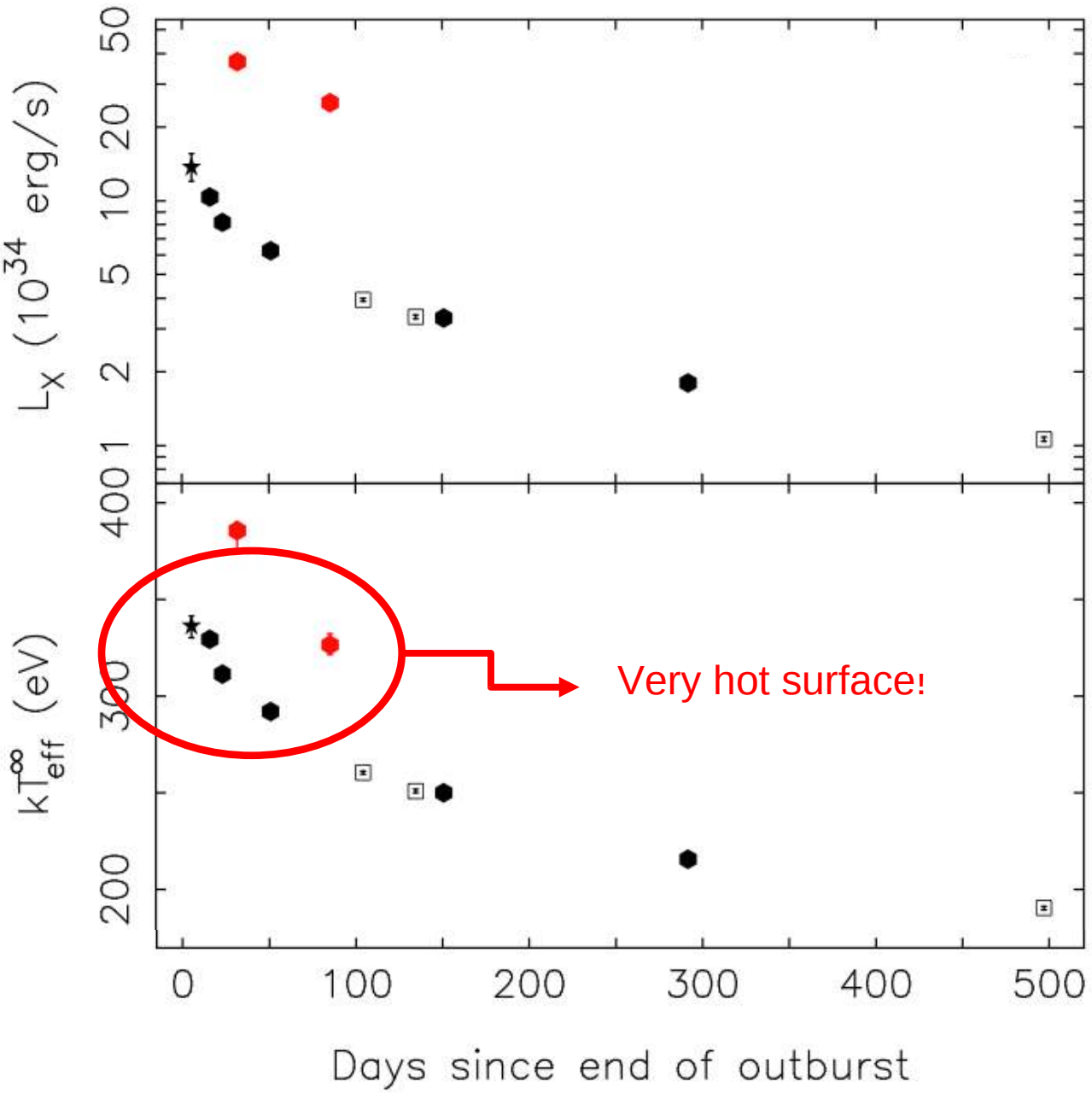
Active since Jan 2011
- Near Eddington rate?
- Large distance (>30-40 kpc)

Turned off in the summer of 2012 after 1.5 yrs of accreting

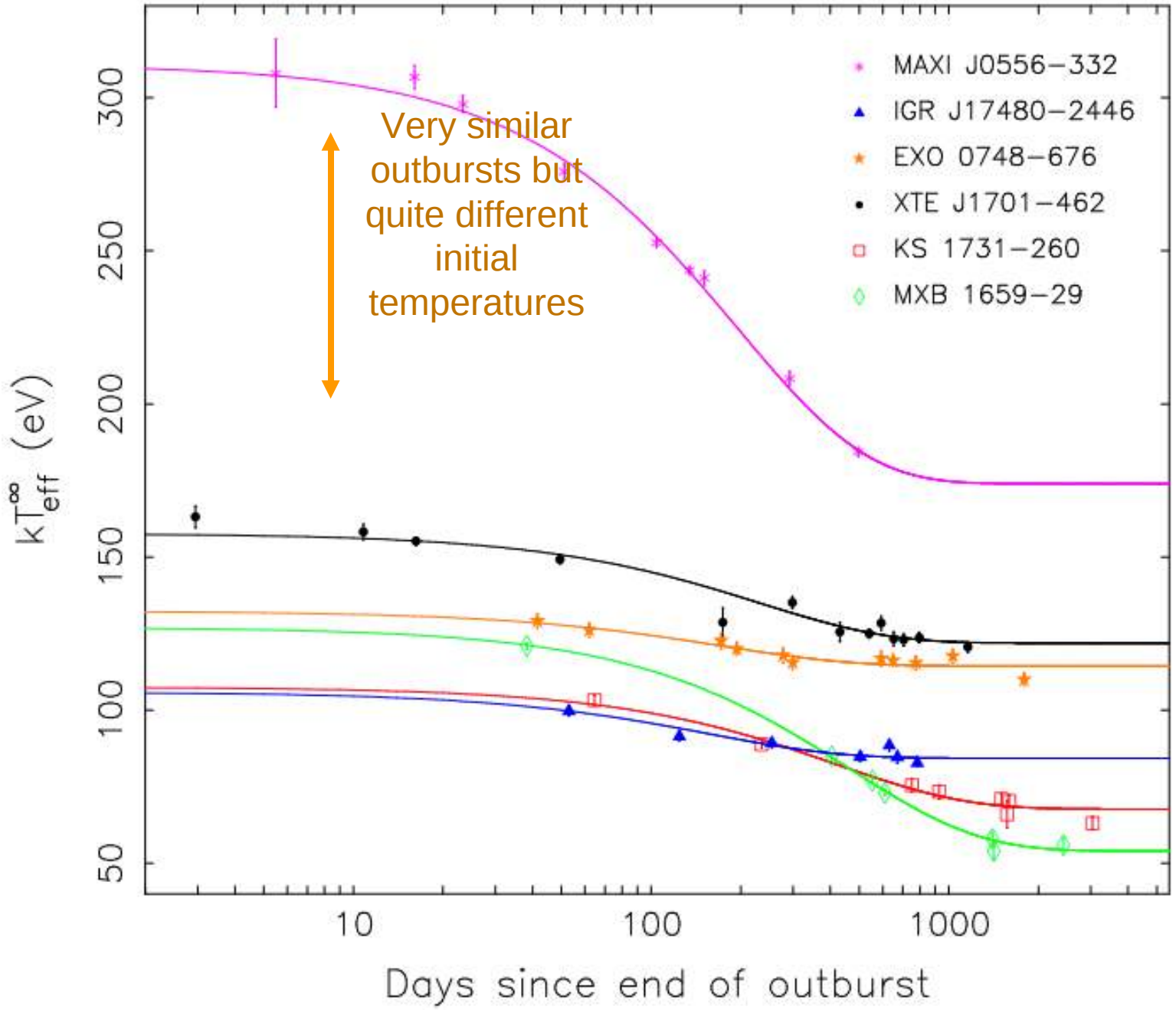
Swift, Chandra, XMM monitoring
- Accretion flares



MAXI J0556-332

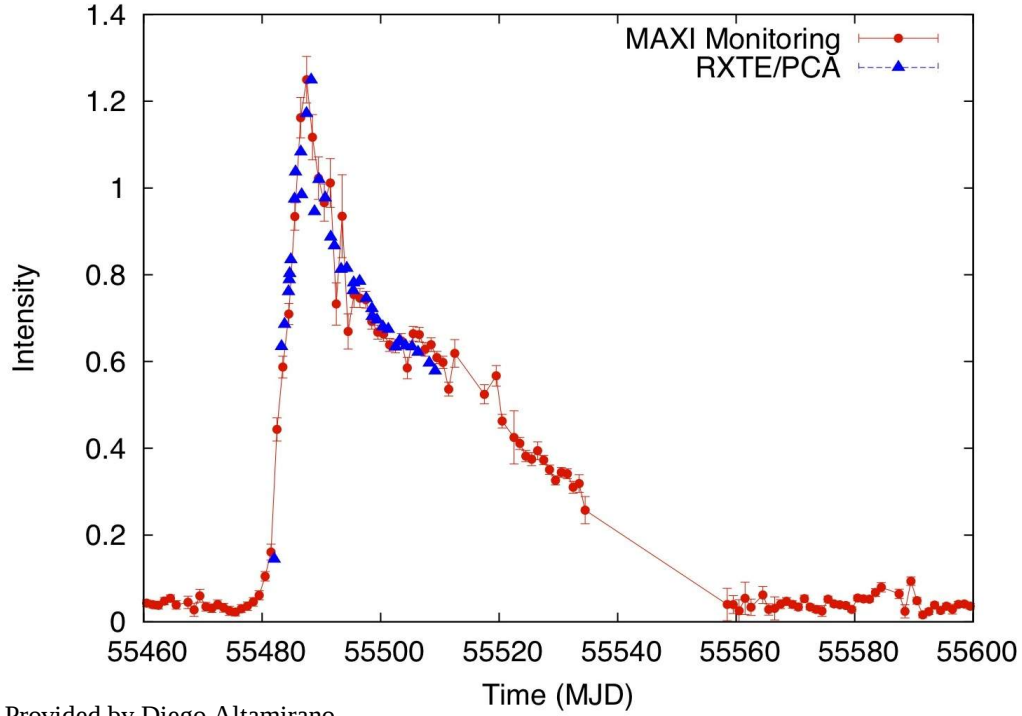


Homan et al. 2014



Homan et al. 2014

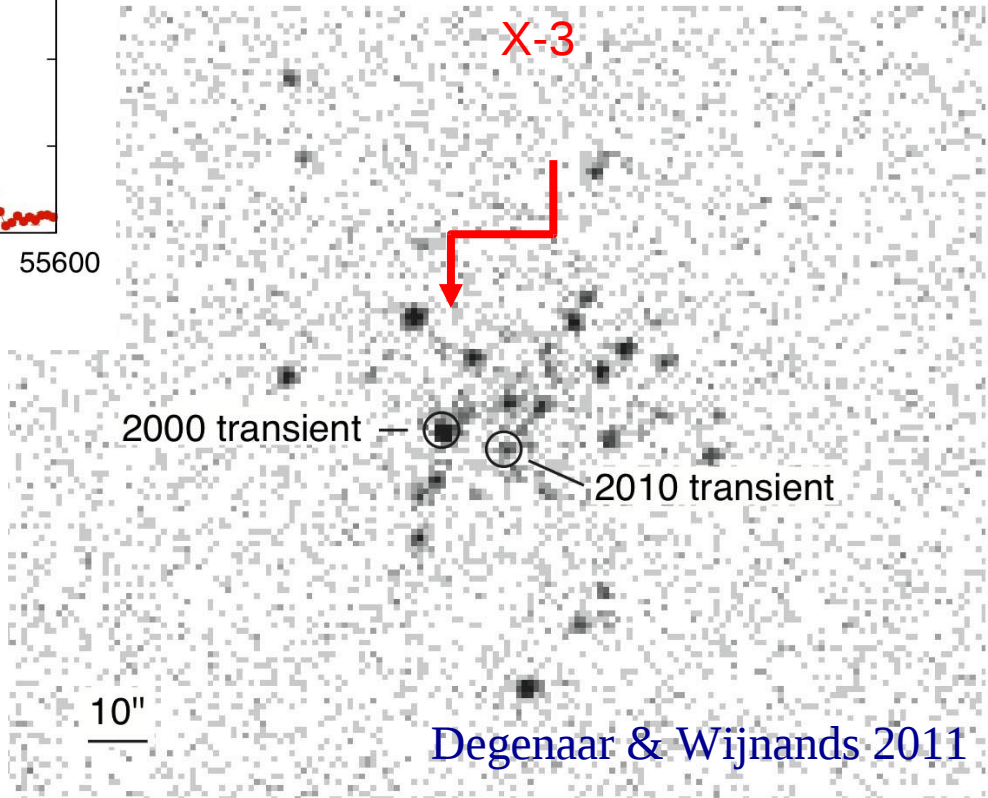
11 Hz pulsar in Terzan 5



Provided by Diego Altamirano

Ordinary transient
- Discovered in 2010
- Outburst lasted ~2 months

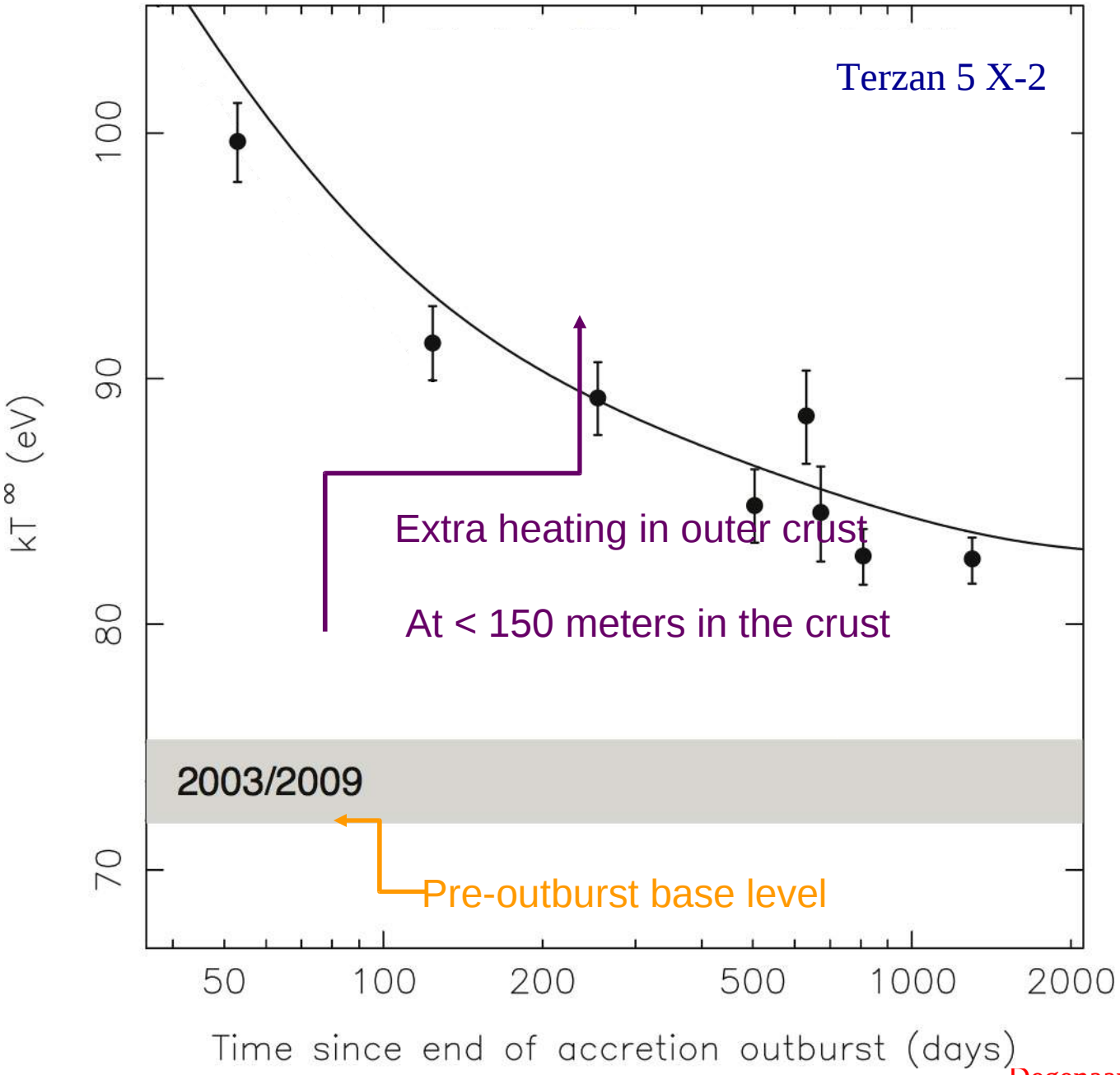
Near Eddington accretion rate



Degenaar & Wijnands 2011

Terzan 5 X-2

Figure provided by Nathalie Degenaar



Decay time scale 100-200 days

Degenaar & Wijnands 2011
Degenaar, et al. 2011, 2013

Terzan 5 X-3

- Active in summer 2012 for 2 months
  - Bahramian et al. 2014

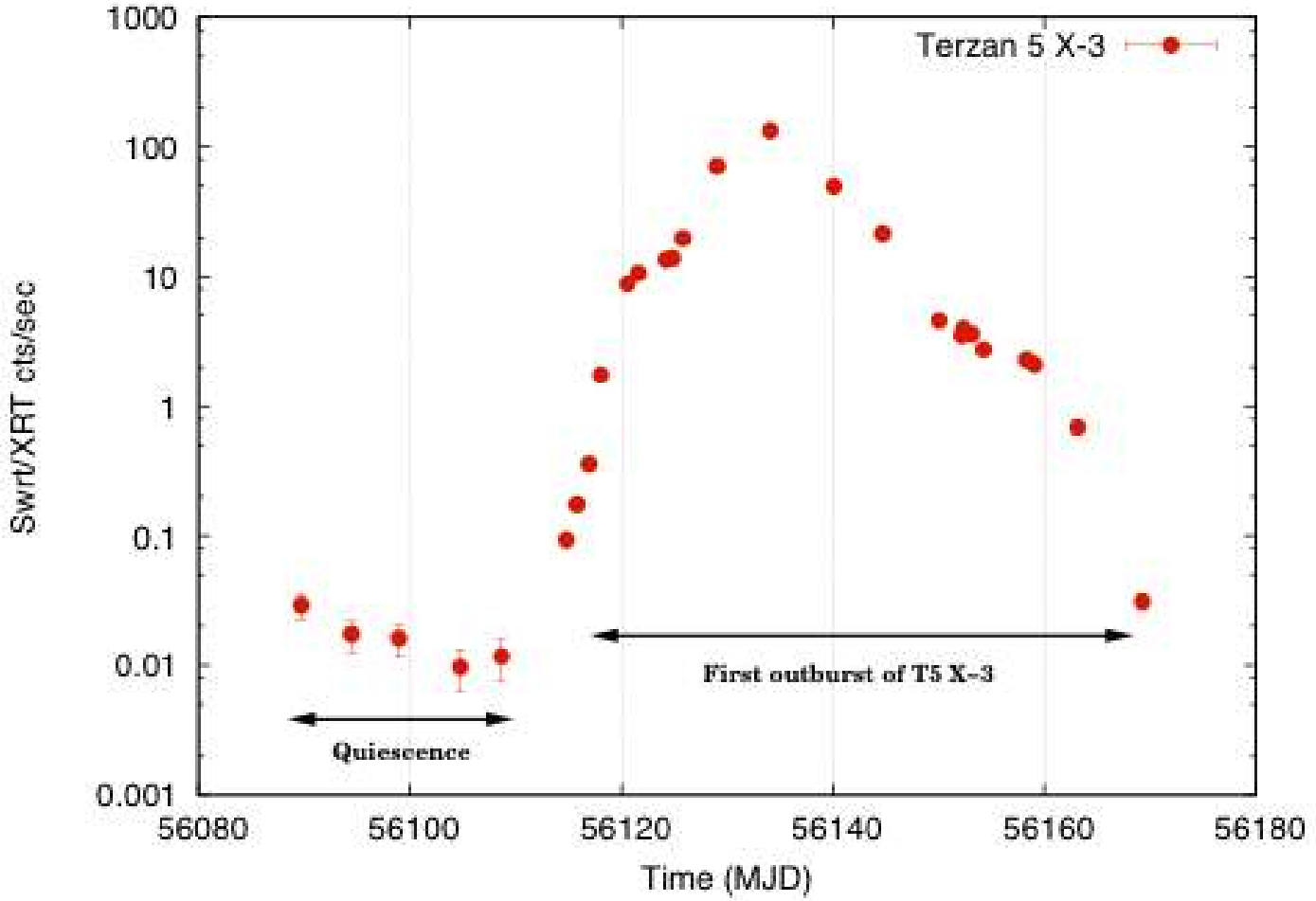
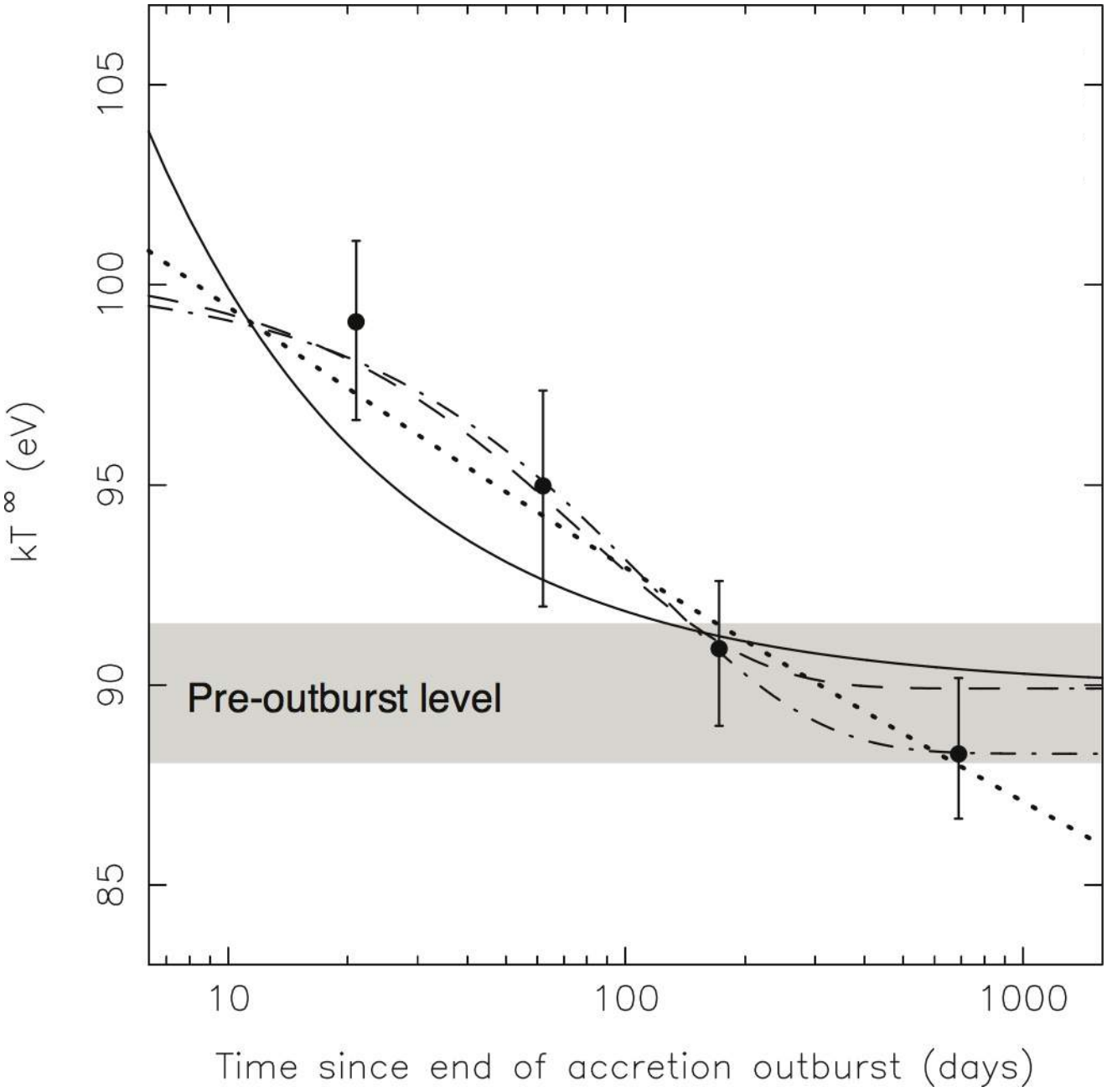


Figure provided by Diego Altamirano

Figure provide by Nathalie Degenaar



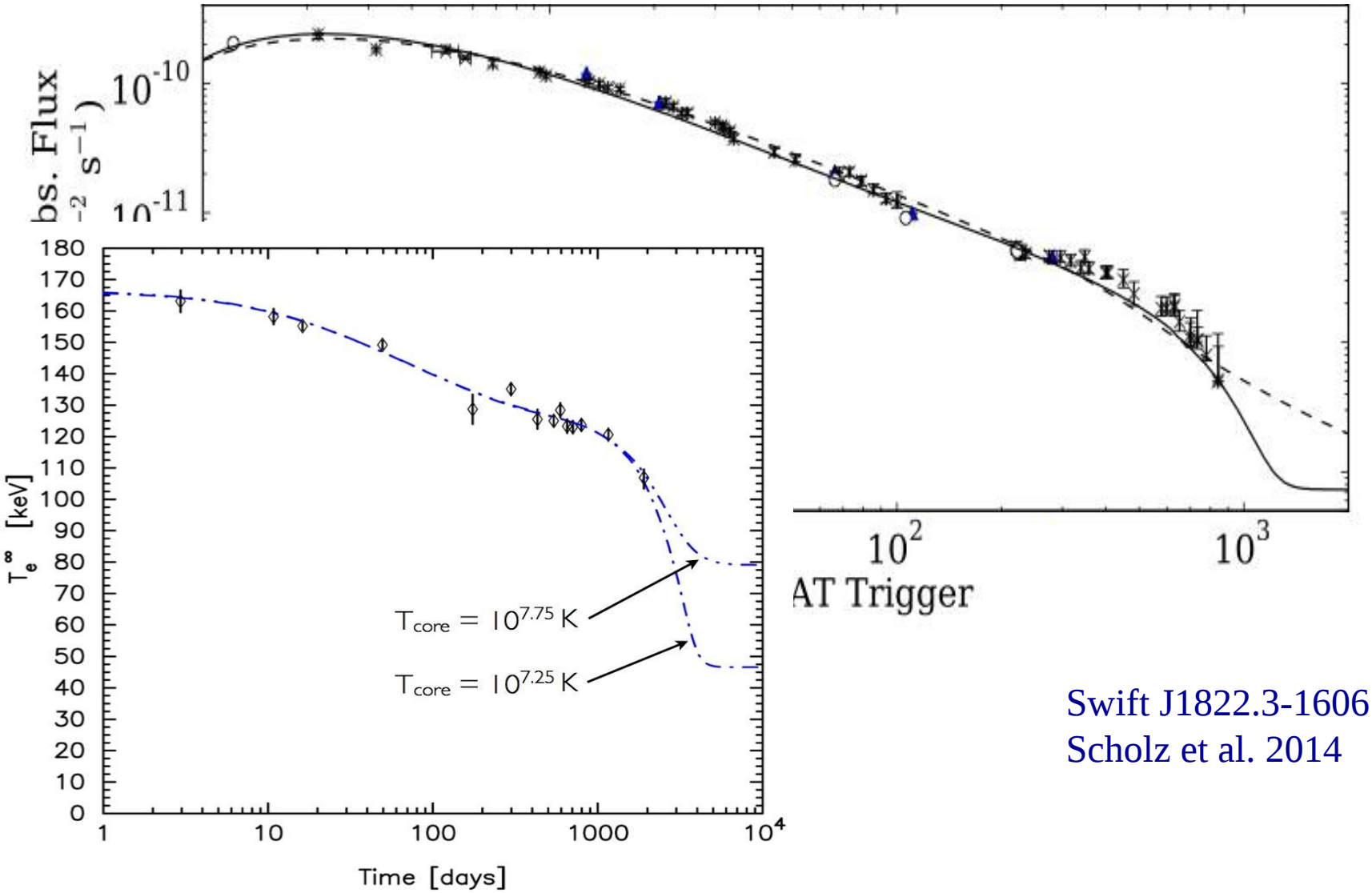
Wijnands et al. in preparation

Terzan 5

Conclusions

- Crust cooling seems particular promising to probe ultra-dense matter
  - High crustal heat conductivity/shallow heat production
- Unknowns
  - What causes the differences in decay times and base levels?
  - Is the “jump” a common feature?
  - What causes the shallow heating?
  - Schatz et al. 2014 → Strong neutrino cooling in the crust? → Shallow layers decoupled from deeper layers and the core?
- We need more sources!
  - Also high magnetic field neutron star systems
    - Also compare with magnetar outburst physics

Comparing with a magnetar outburst



Swift J1822.3-1606
Scholz et al. 2014

Conclusions

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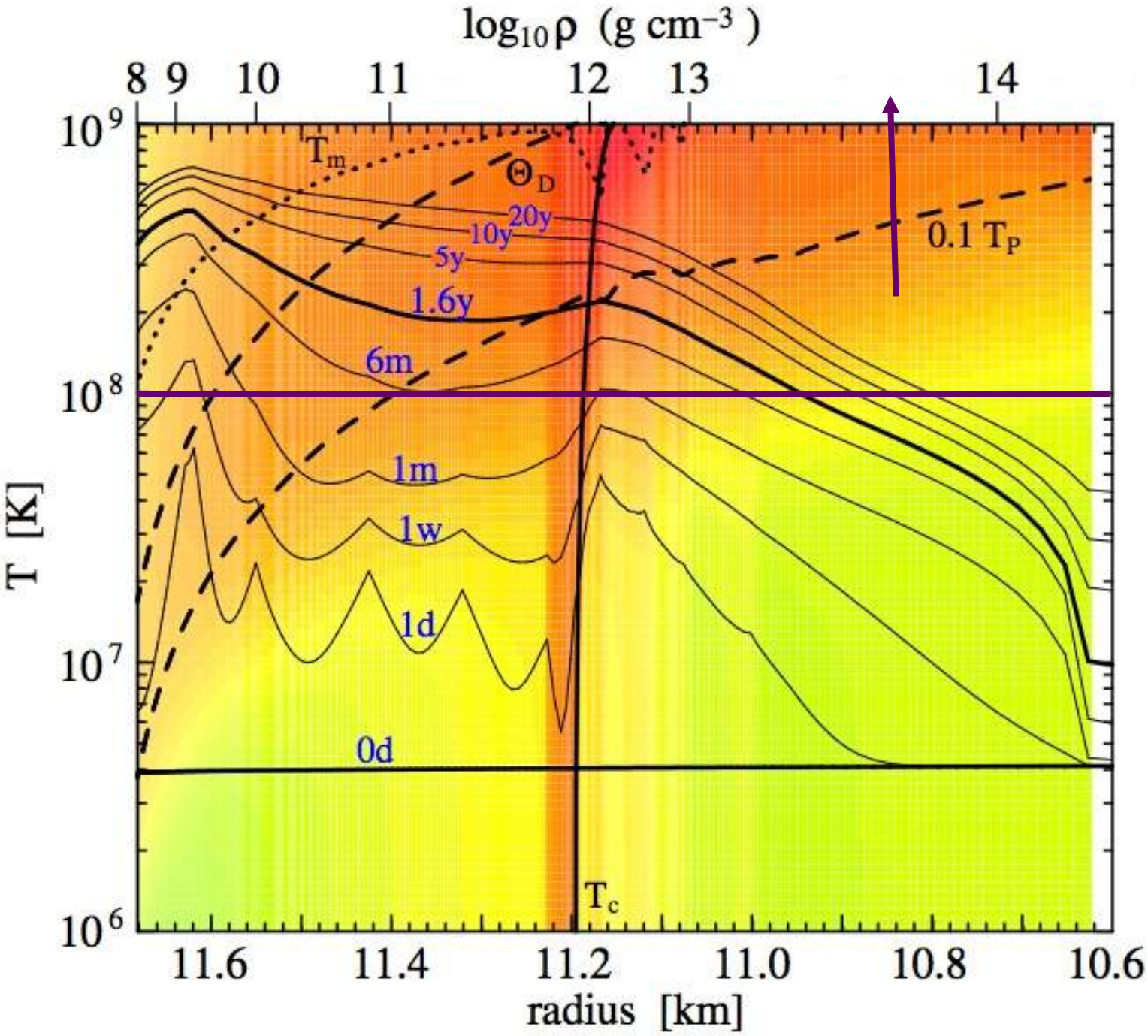
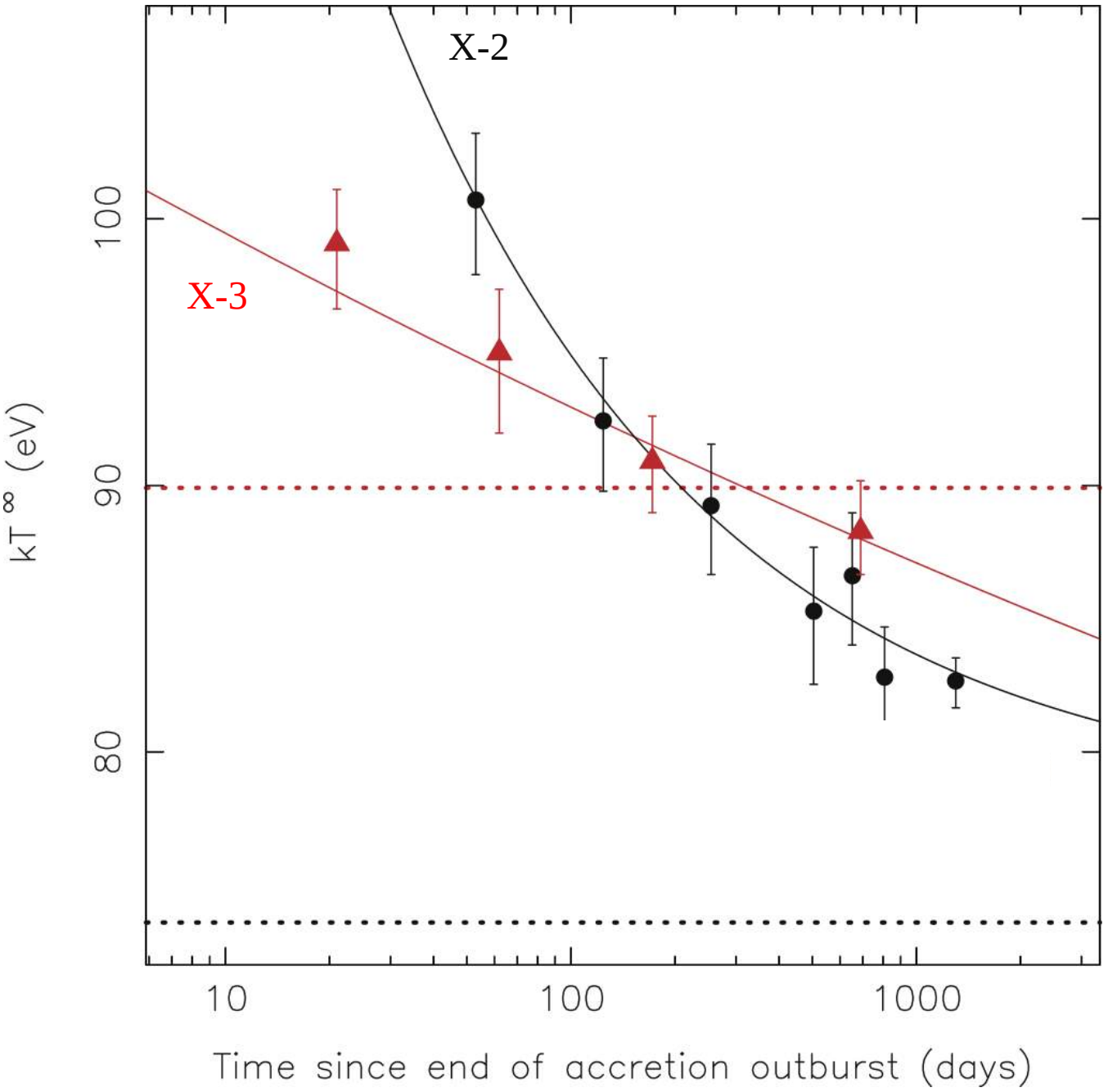


Page & Reddy 2013


X-2
X-3
100
90
80
kT ∞ (eV)
10
100
1000
Time since end of accretion outburst (days)

Reheating of accreting neutron stars

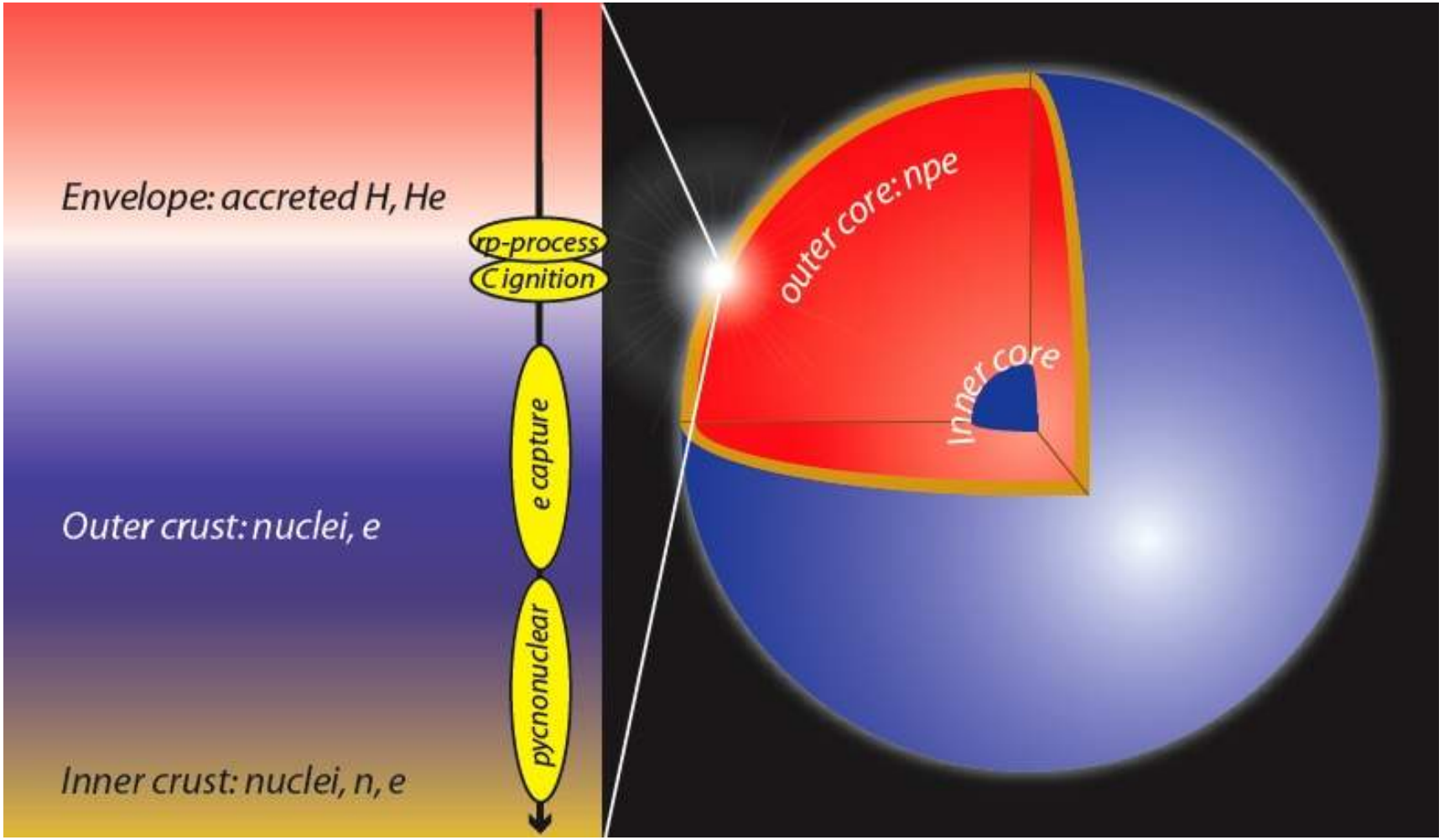
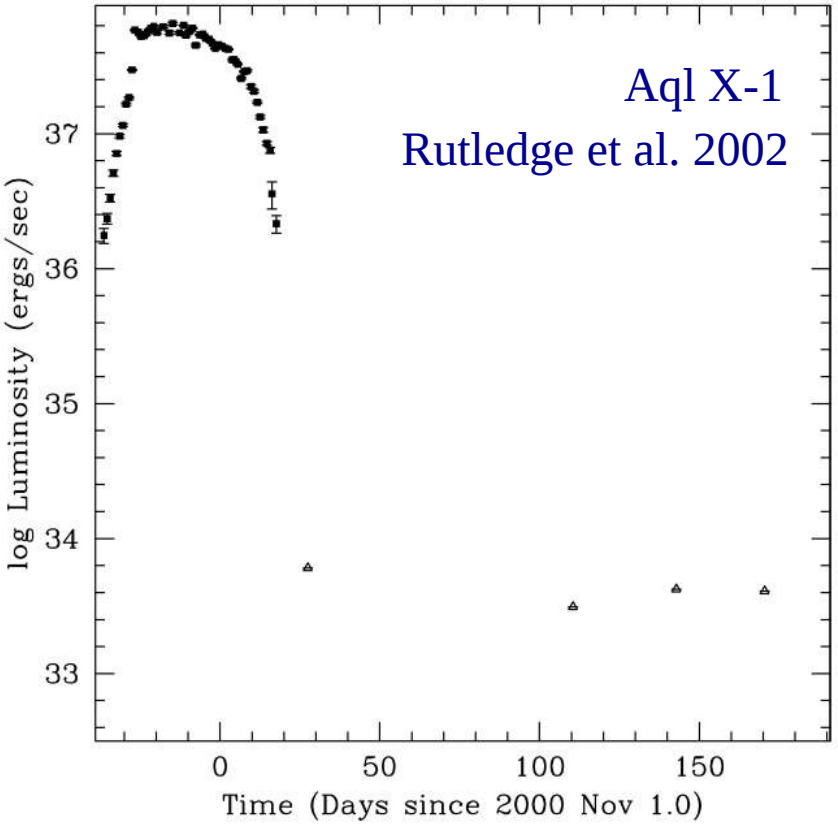


Figure by Ed Brown

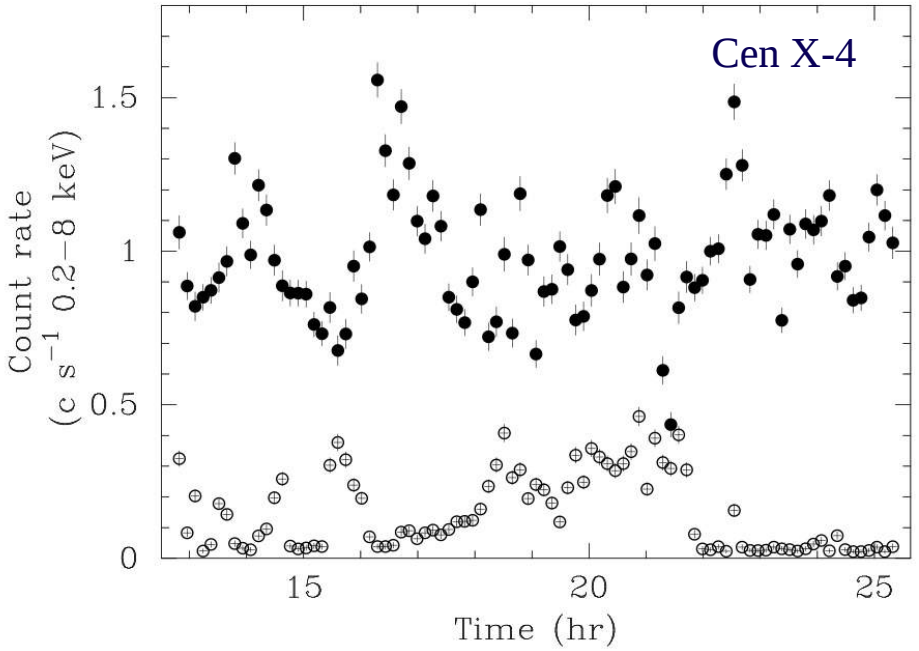
Heating mostly due to pycnonuclear reactions

Variability



Always use lowest kT or Lq value!

Campana et al. 2004



Also in thermal component
- Accretion on NS surface