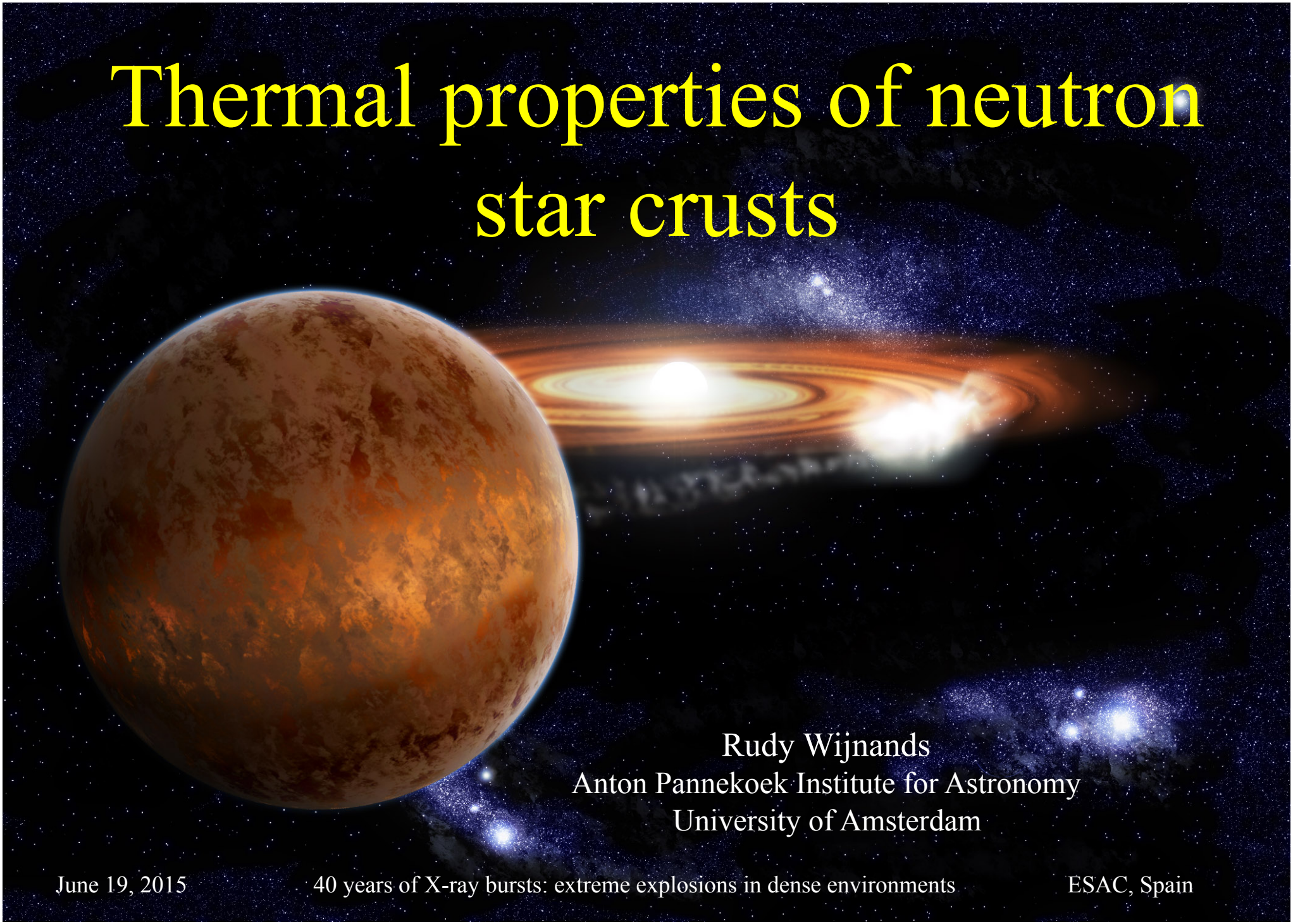
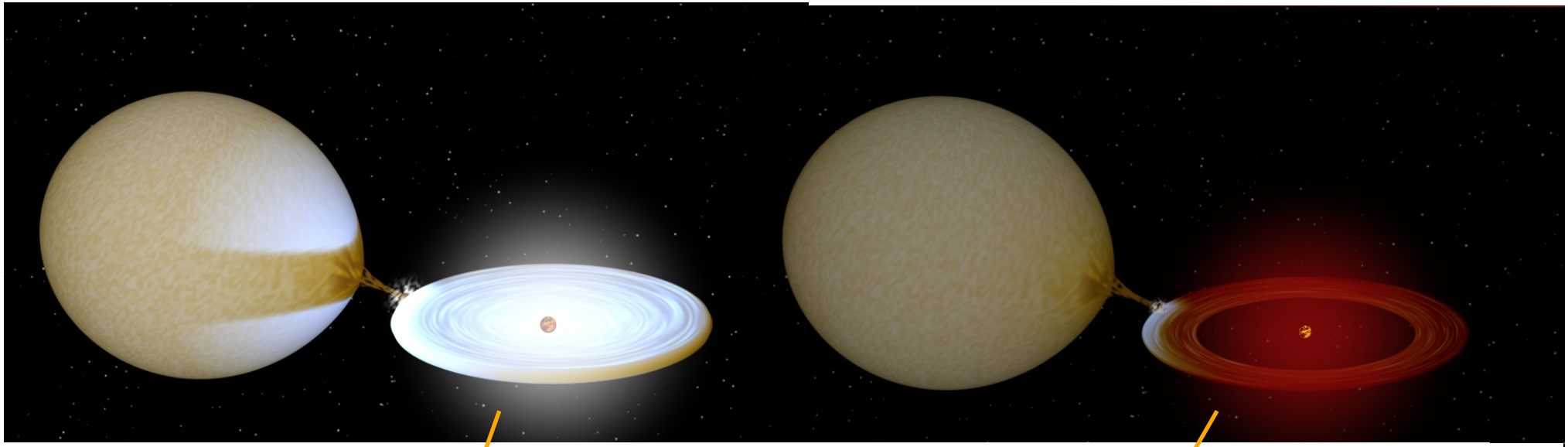
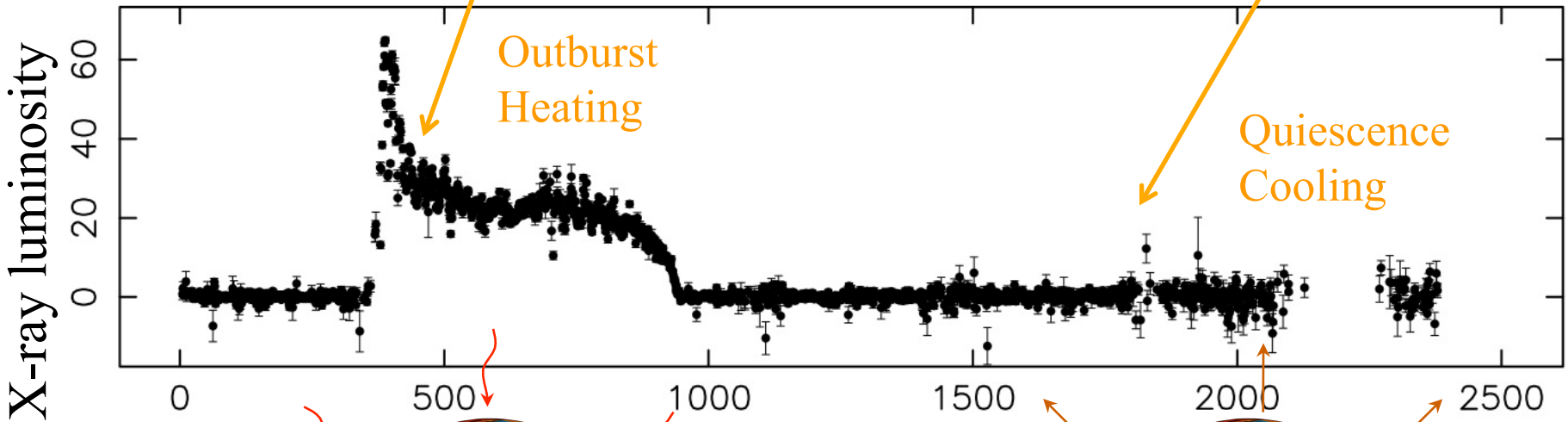
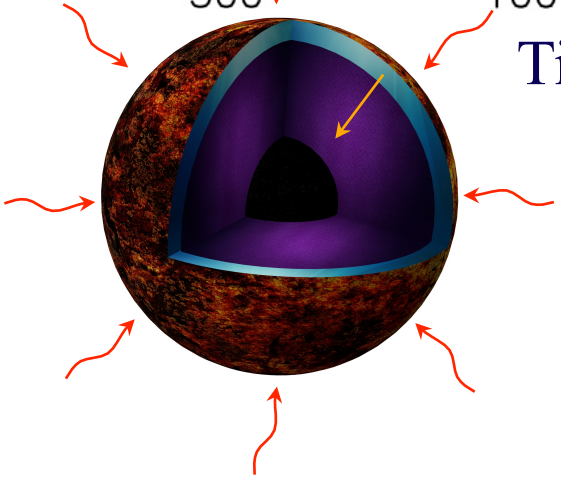
Thermal properties of neutron star crusts

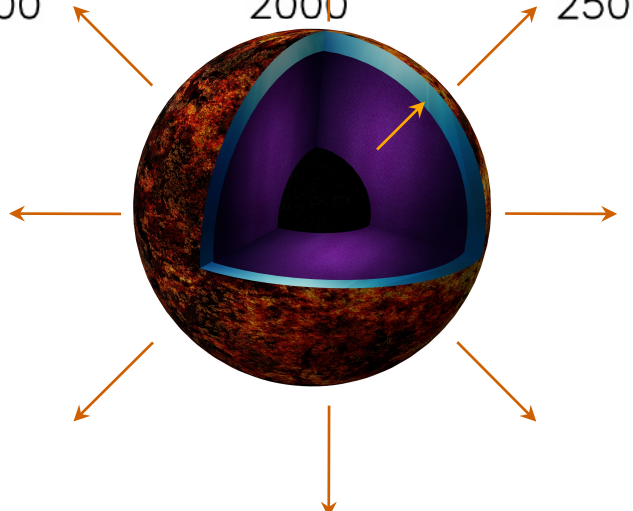


Rudy Wijnands
Anton Pannekoek Institute for Astronomy
University of Amsterdam




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

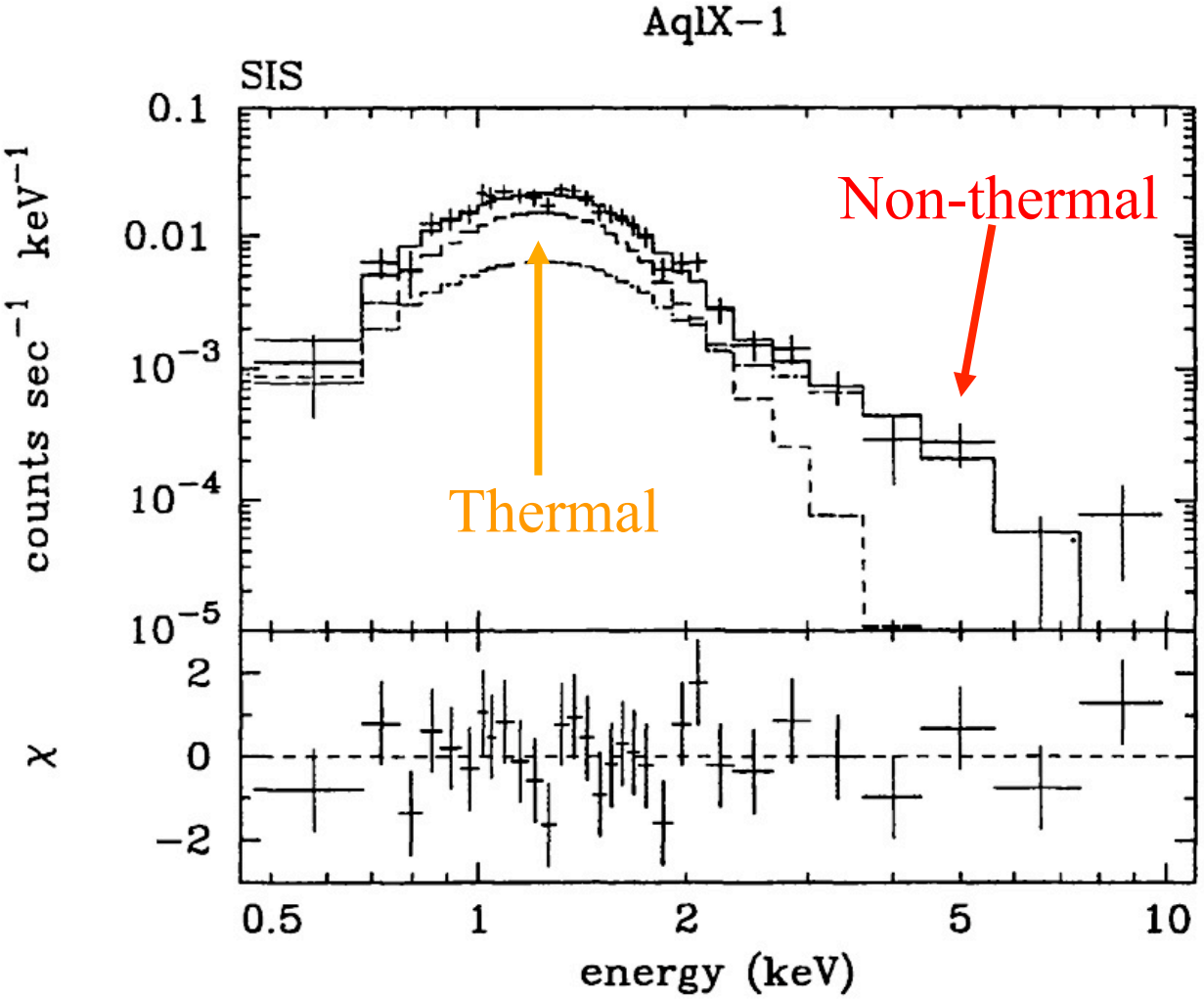




Heating and cooling of accreting neutron stars

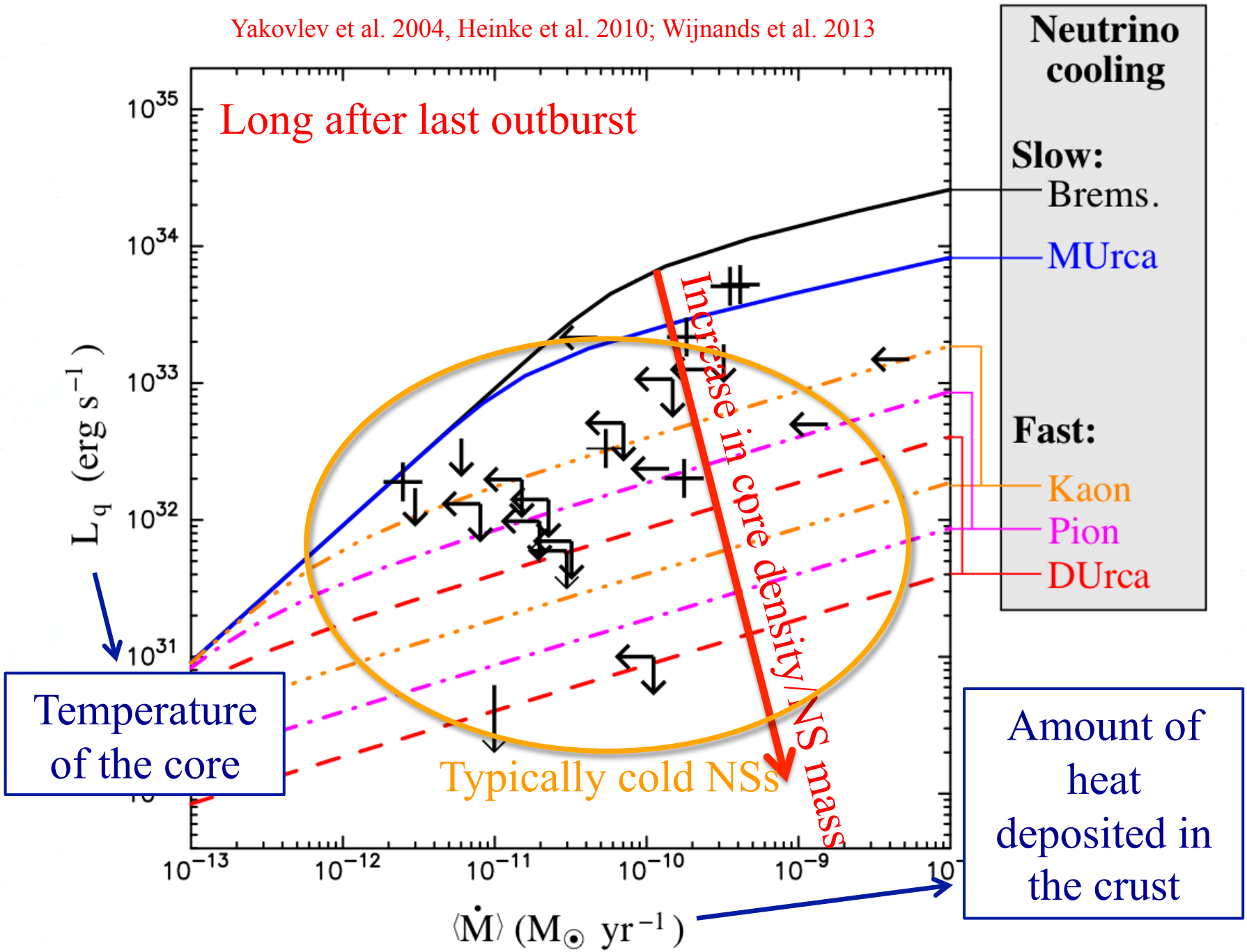
- A lot of energy is dumped on the neutron star
  - Release of gravitational energy (100-200 MeV/nucleon)
  - Thermonuclear reactions (1-5 MeV/nucleon)
  - Pycnonuclear reactions (1-2 MeV/nucleon)
- Will that heat up the neutron star?
- Can we observe that?
  - Cooling neutron stars in X-ray transients
  - Comparing the results with those obtained using type-I X-ray bursts

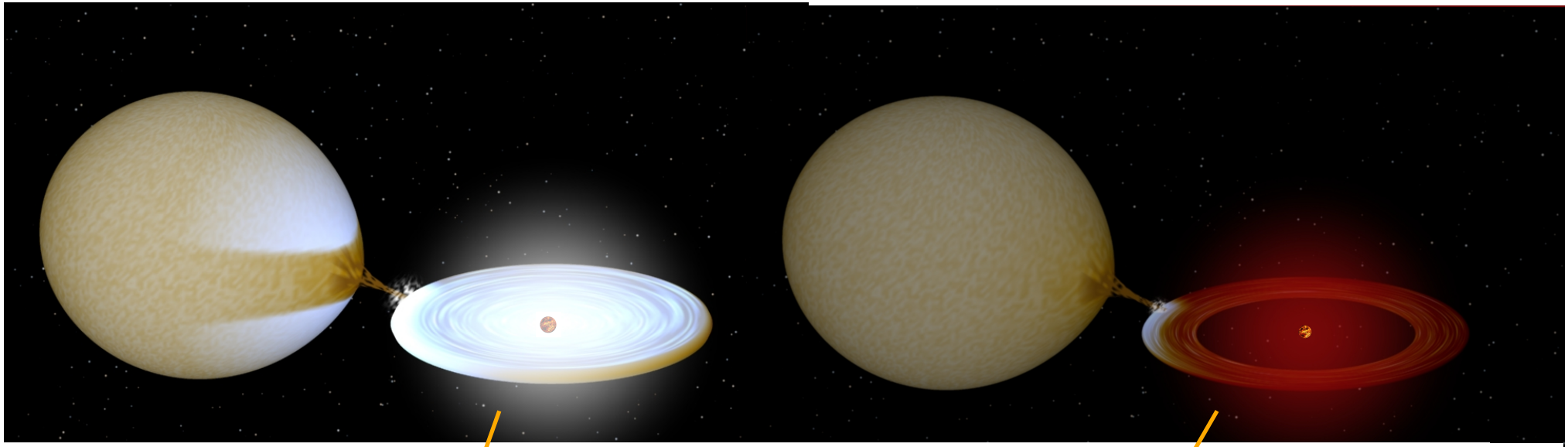
Do we detect cooling neutron star?

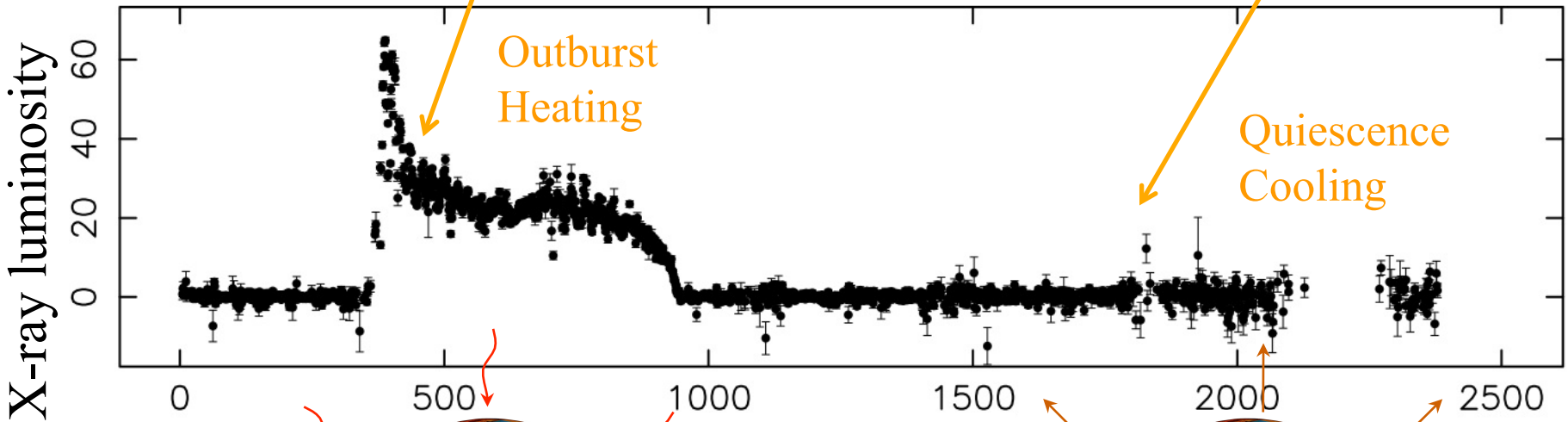


Asai et al. 1998

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/NS mass
Typically cold NSs
Temperature of the core
Amount of heat deposited in the crust
L_q (erg s^{-1})
$\langle \dot{M} \rangle$ ($M_\odot$ yr^{-1})
10^{35}
10^{34}
10^{33}
10^{32}
10^{31}
10^{-13}
10^{-12}
10^{-11}
10^{-10}
10^{-9}




X-ray luminosity
0
20
40
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Outburst
Heating
Quiescence
Cooling
0
500
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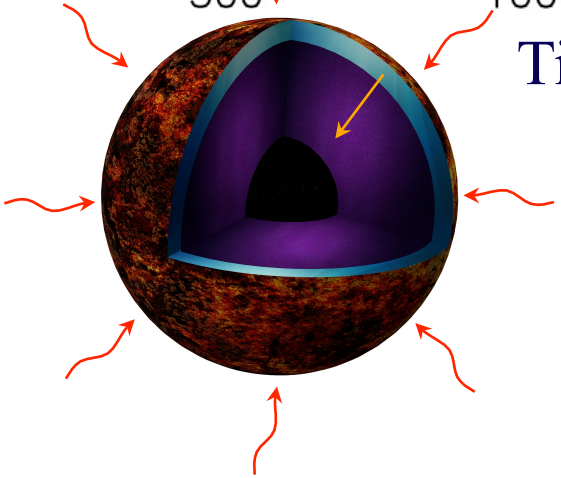
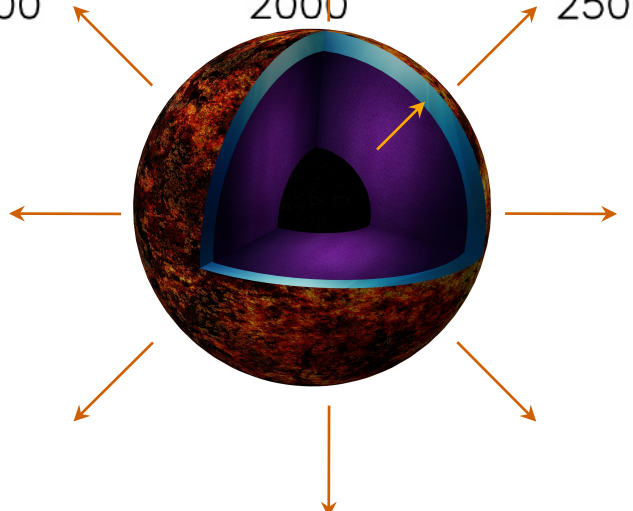
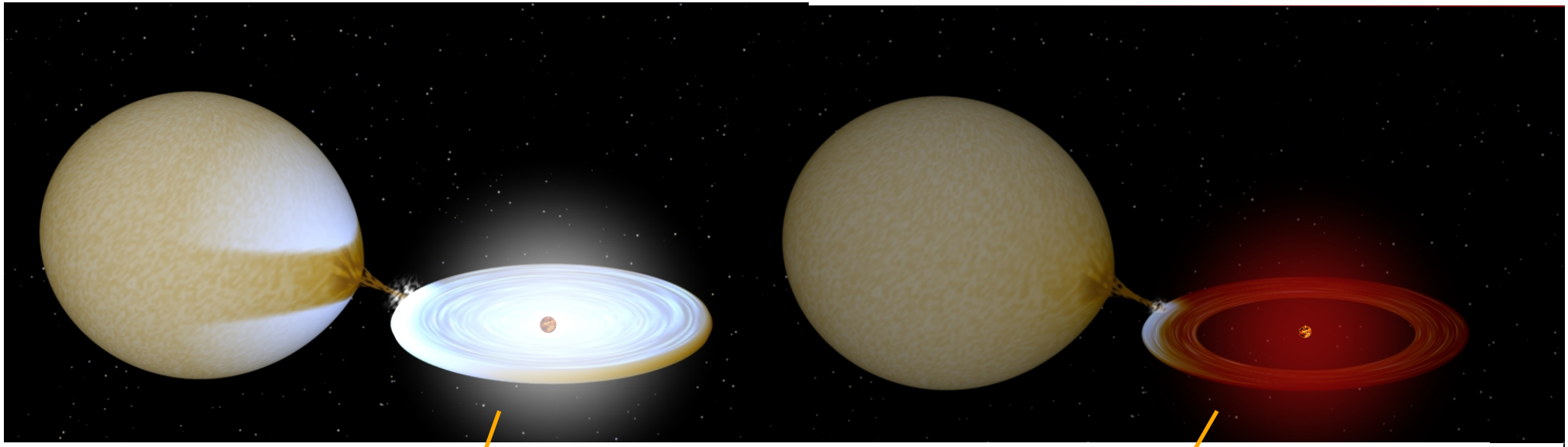
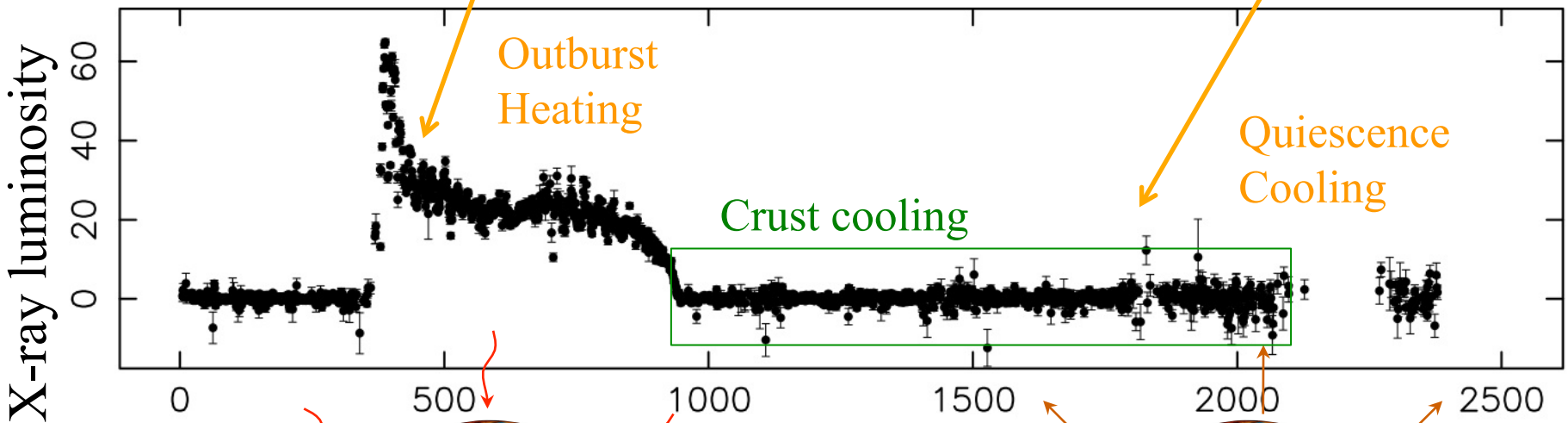
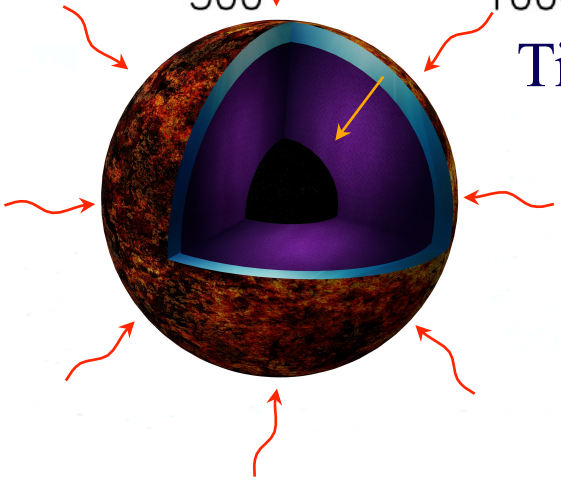
Time in days

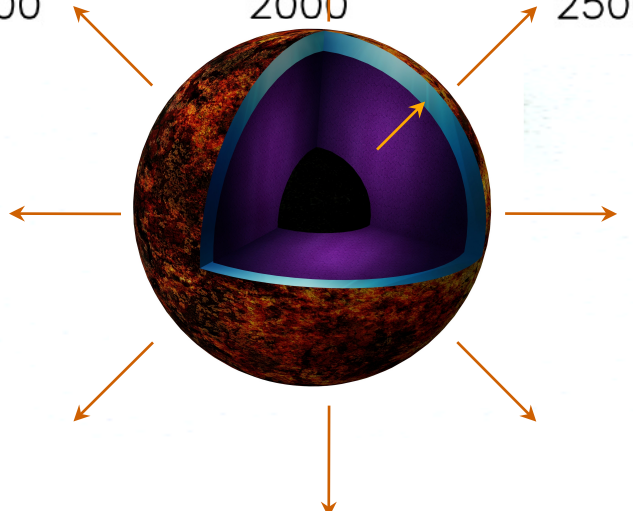






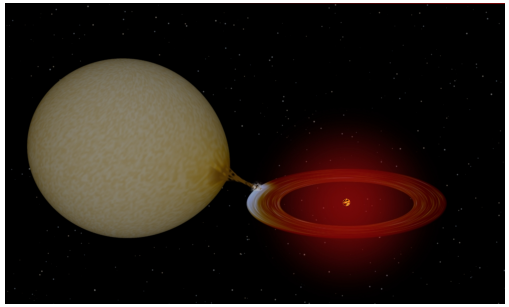

X-ray luminosity
0
20
40
60
Outburst
Heating
Crust cooling
Quiescence
Cooling
0
500
1000
1500
2000
2500
Time in days

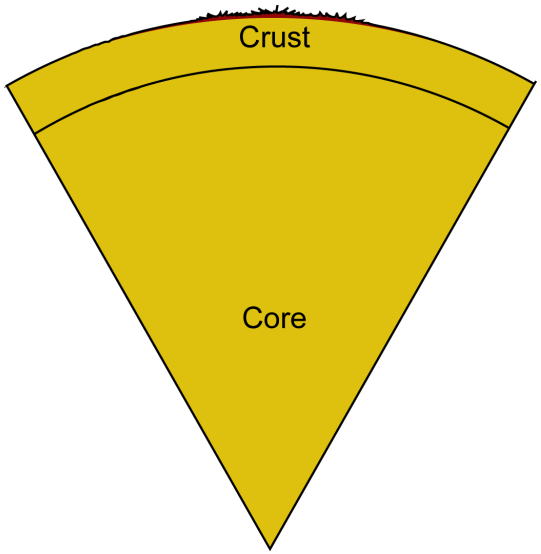




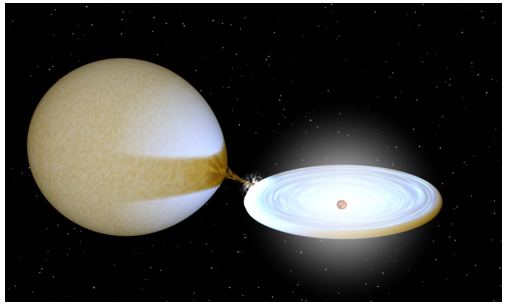
Heating of the crust

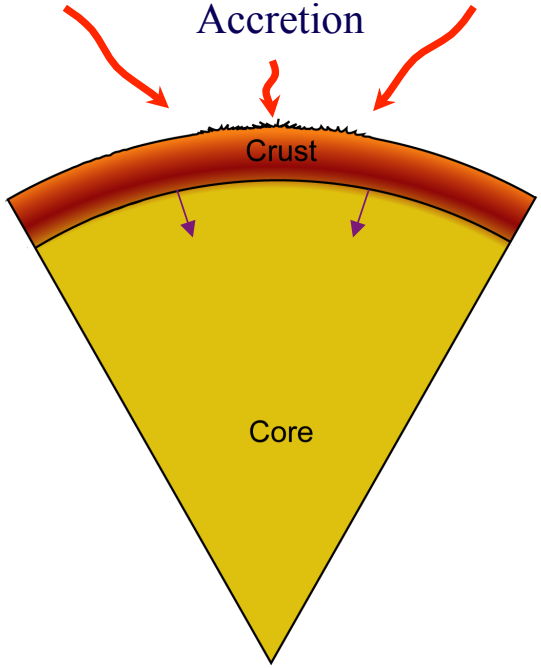
Before



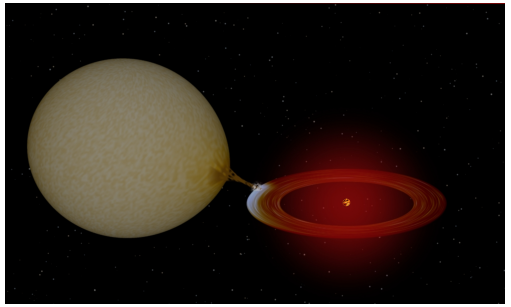


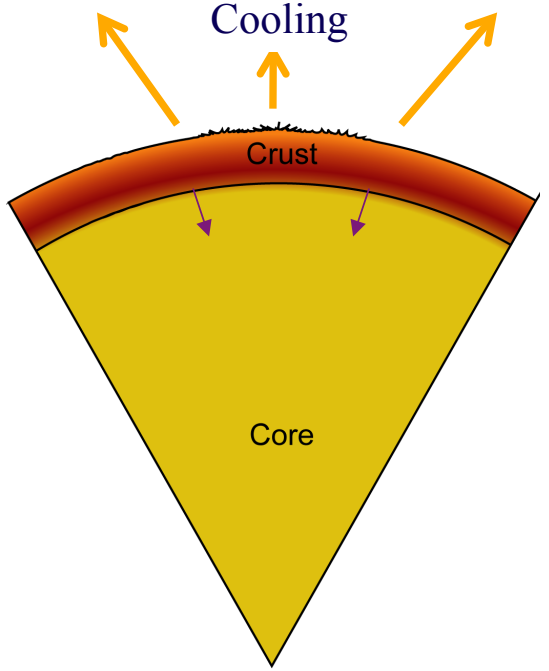
During



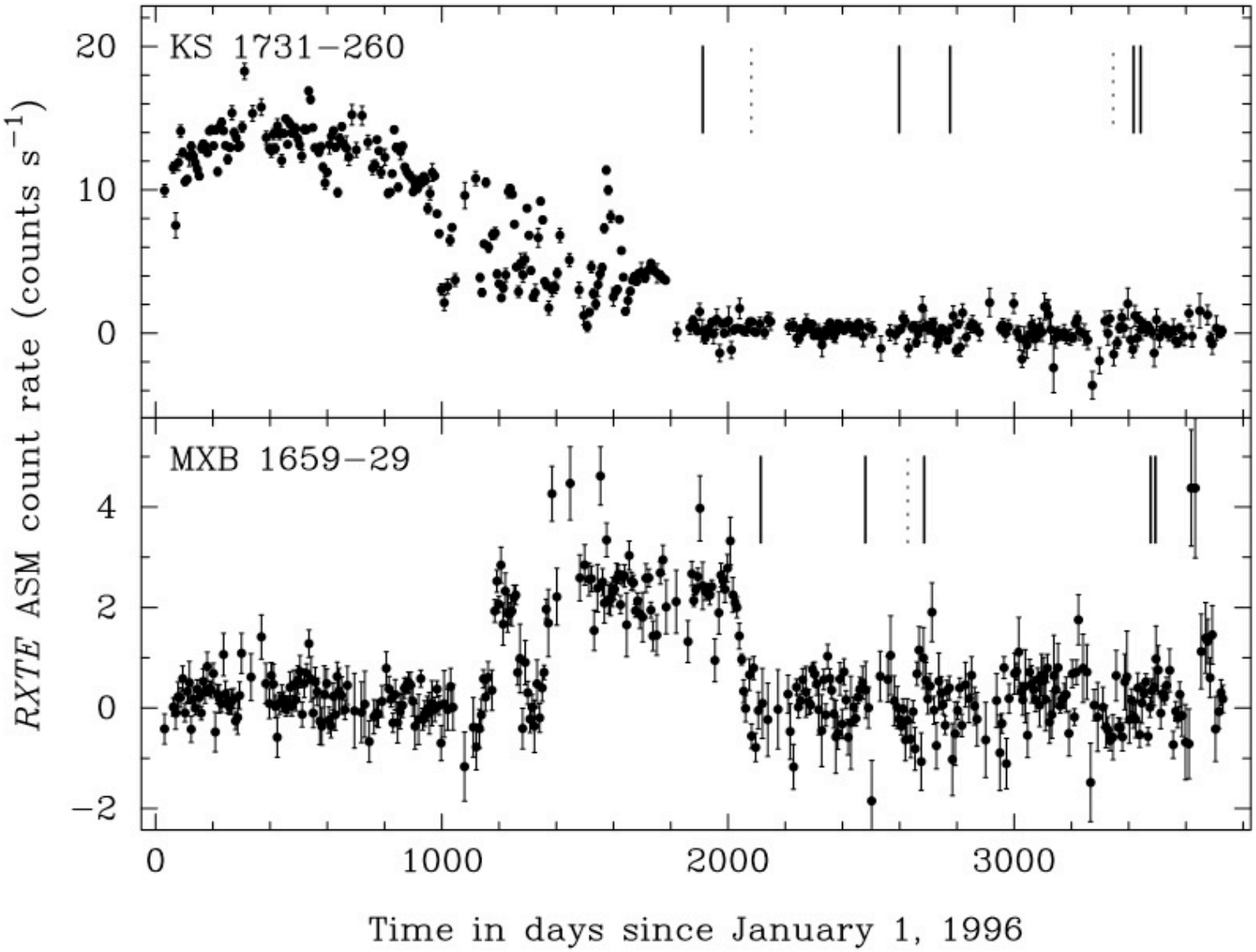


After



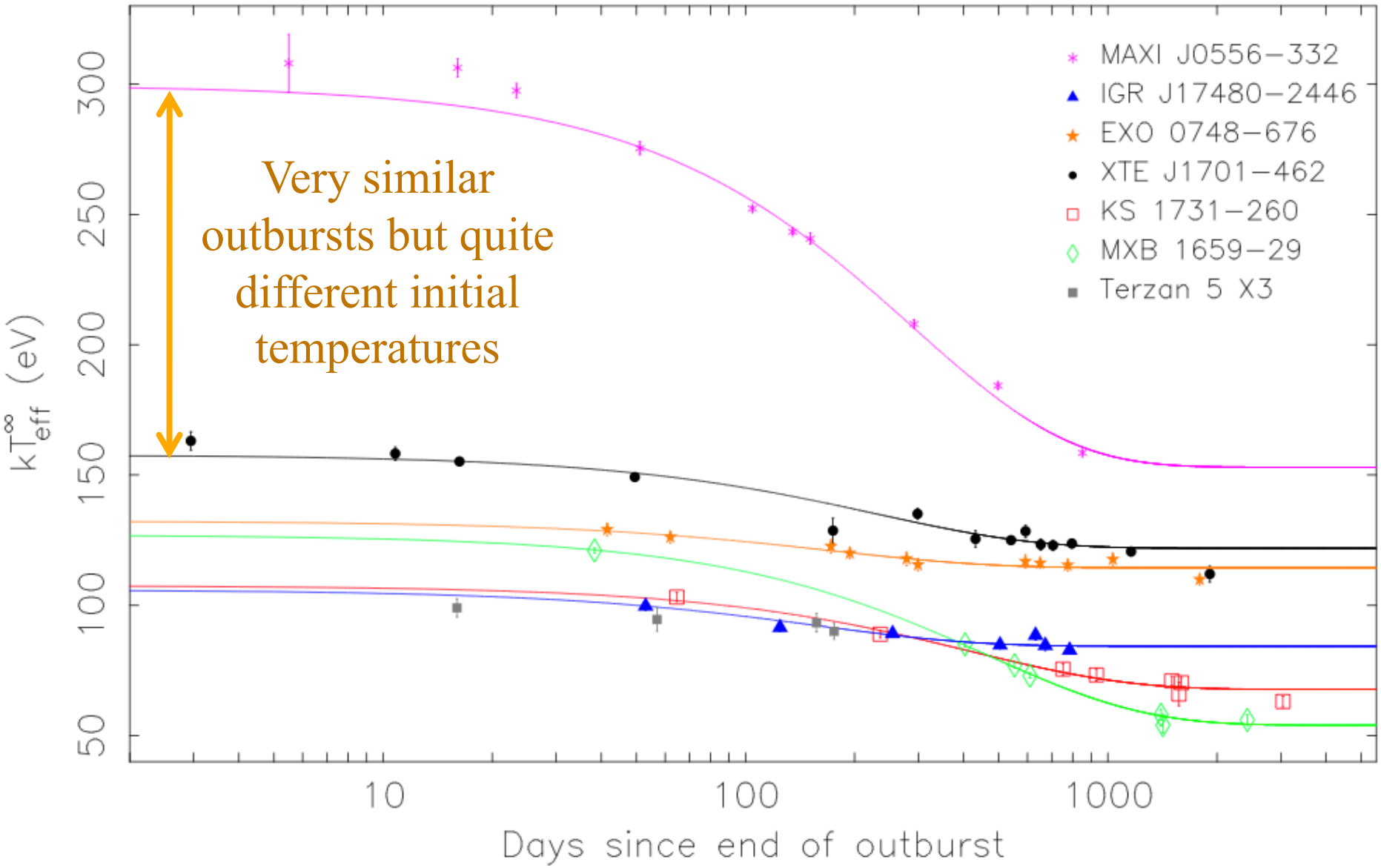


Study the cooling



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

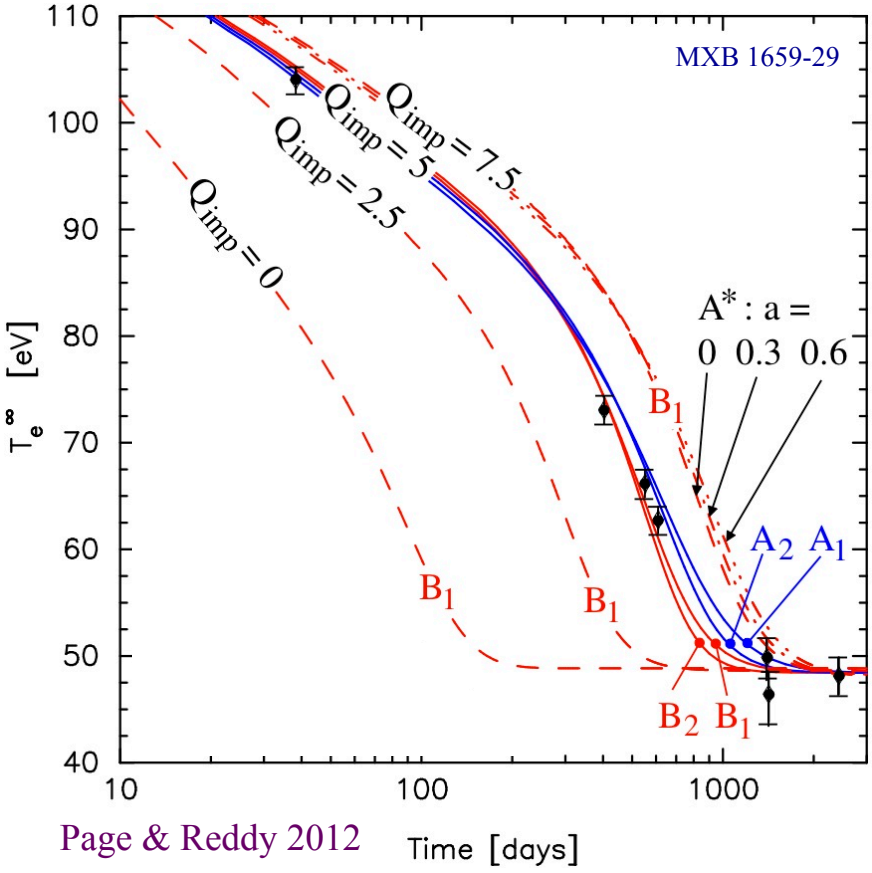
Seven sources studied so far



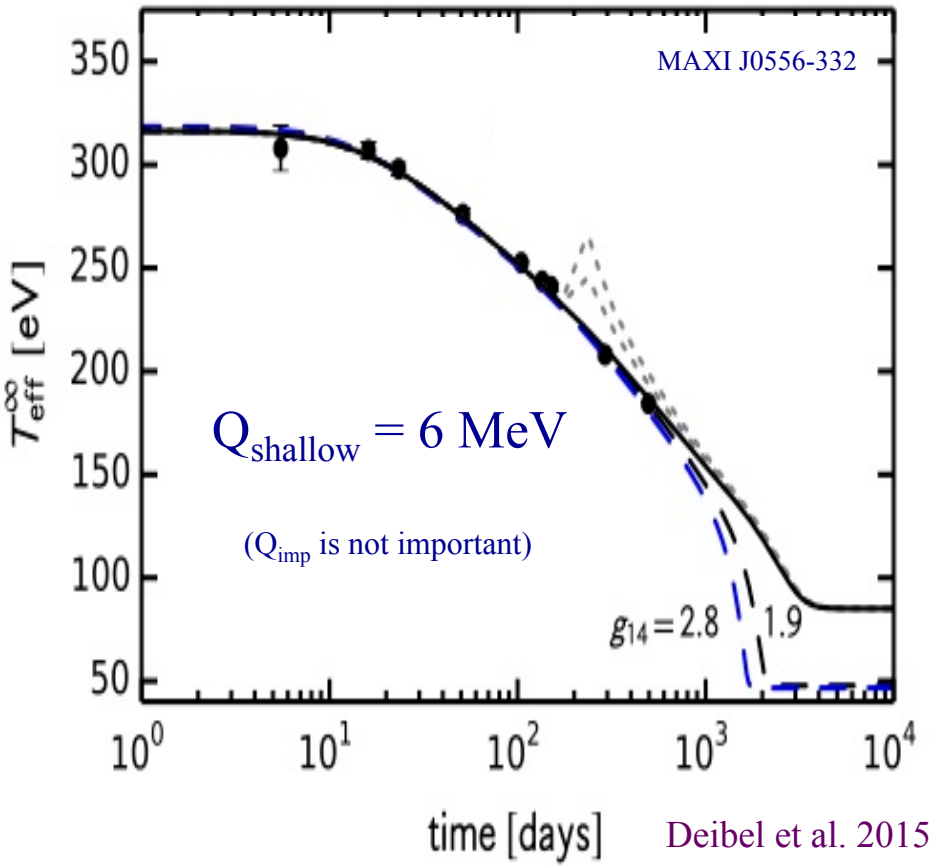
After Homan et al. 2014

Calculations of cooling curves

- Larger heat conductivity in the crust than anticipated
- Need of additional shallow heating source
- Rutledge et al. 2002; Shternin et al. 2008; Brown & Cumming 2009; Page & Reddy 2012, 2013; Medin & Cumming 2015; Horowitz et al. 2015; Turlione et al. 2015; Deibel et al. 2015



Page & Reddy 2012



Deibel et al. 2015

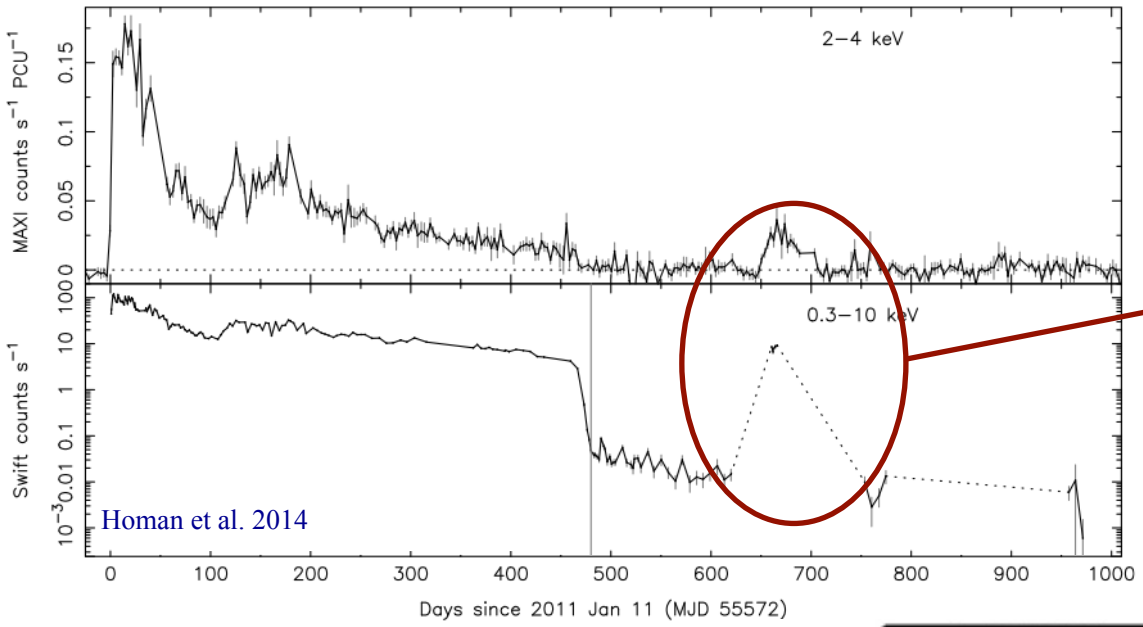
Need for shallow heating

- Very strong shallow heating
  - MAXI J0556-332 (lack of bursts)
- Sources with shallow heating
  - MXB 1659-29
  - EXO 0748-676
  - Terzan 5 X-2: mHz QPO/bursting behavior
  - KS 1731-260: superburst
- Sources with marginal or no shallow heating
  - XTE J1701-462
  - Terzan 5 X-3: not well constrained (up to 1.4 MeV allowed)
- Note: not all theorists agree on the exact values

Conclusions

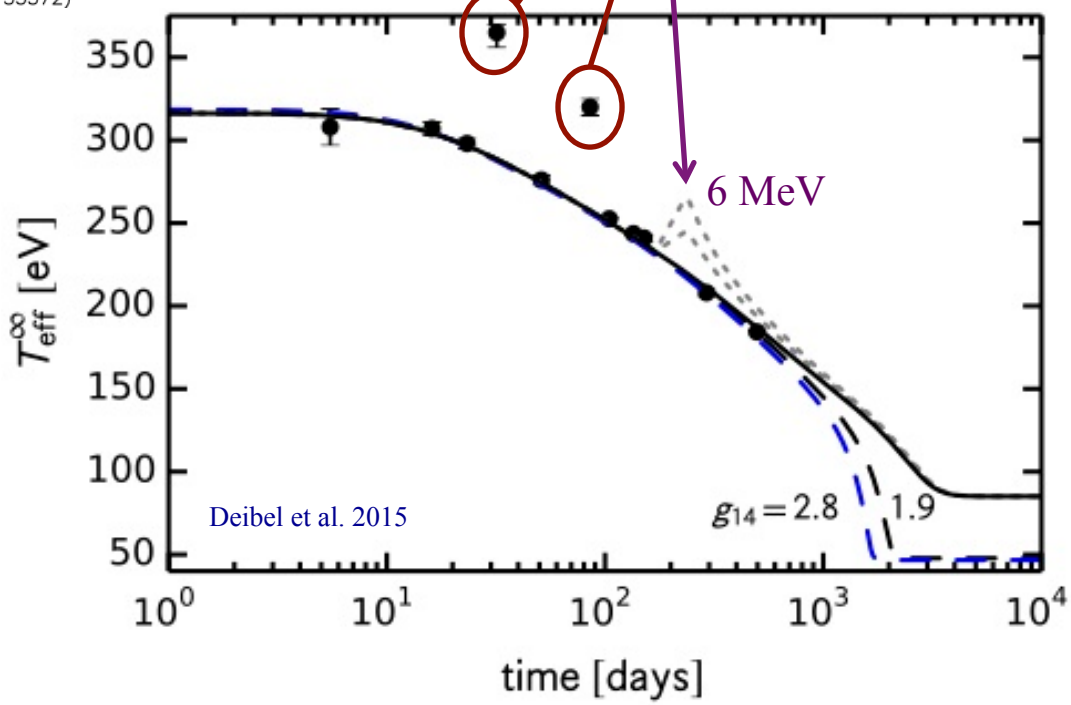
- Neutron stars in X-ray bursters are cold
  - Not much heat flux from the core
  - And thus bottom of the curst at start of accretion
- Crust cooling indicates the need of a shallow heating source or sources
  - *Also needed for explaining some burst phenomena!*
    - Which additional bursters need shallow heating? Any transients?
  - Several toy-models but nothing conclusive
  - Not all sources need the same extra heat
    - Why? Difference in NS properties or environment?
  - Can MAXI J0556-332 give some clues?

MAXI J0556-332



Mini outburst

Accretion flares



Different shallow heating for different ‘outbursts’?

- Strength not simply proportional to Mdot
- Does this eliminate the dependency on NS specific properties?