Transiently accreting neutron stars:

Peeking into their crusts

Nathalie Degenaar

Physics of Neutron Stars 2011

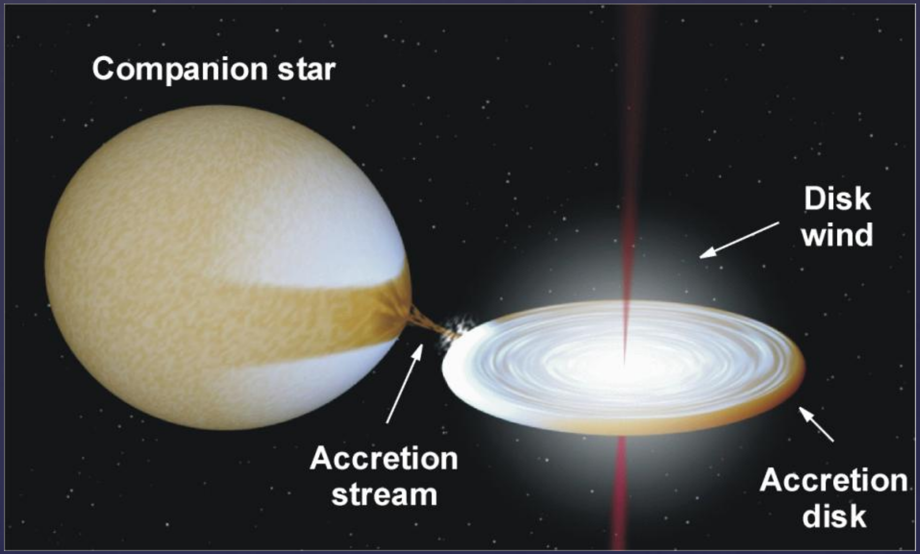
St. Petersburg

Brief summary

Transient x-ray binaries

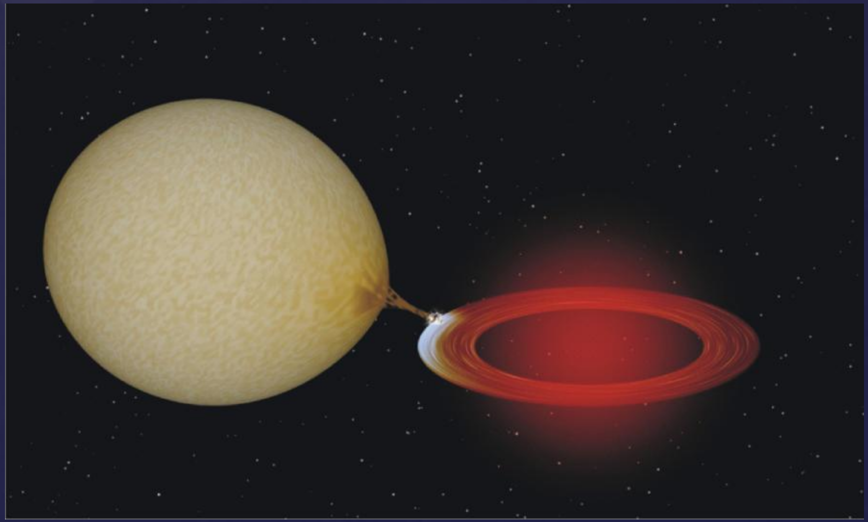
- Accretion heats the neutron star crust, in quiescence it cools down
- Cooling is observable and probes the structure of the crust and several nuclear reactions processes

Neutron stars in transient X-ray binaries

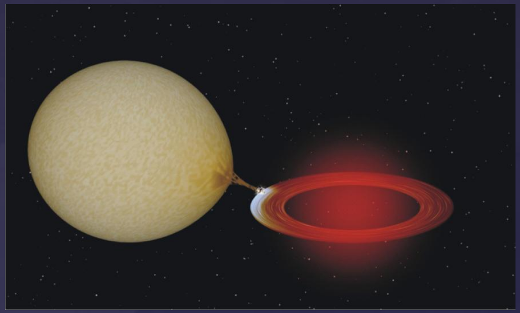


Accretion outburst:
X-ray emission dominated by the accretion disk

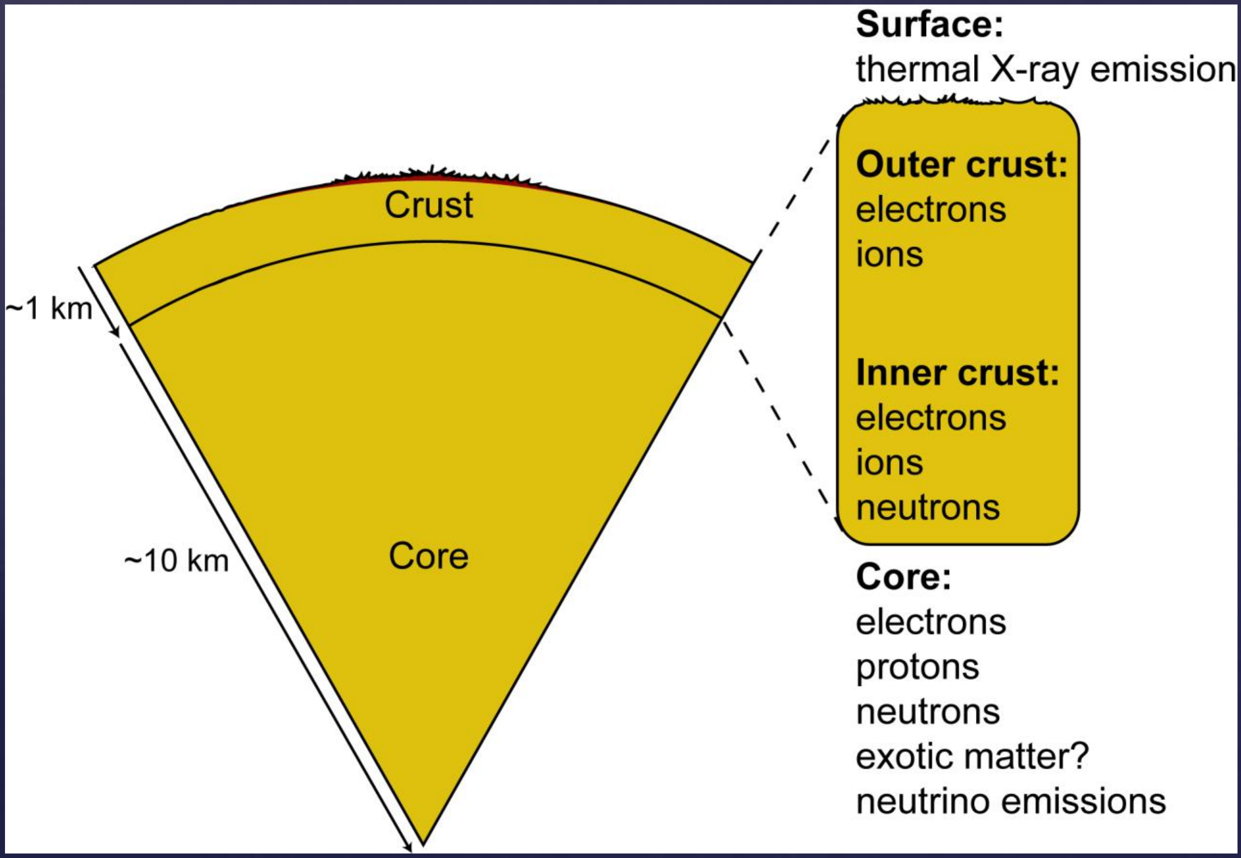
Quiescence:
X-ray emission from the neutron star surface



Neutron star structure



Prior to an accretion outburst

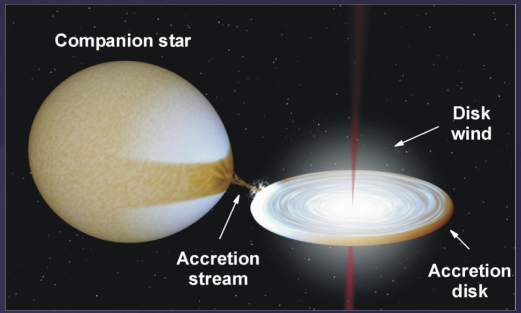


Neutron star cools via:

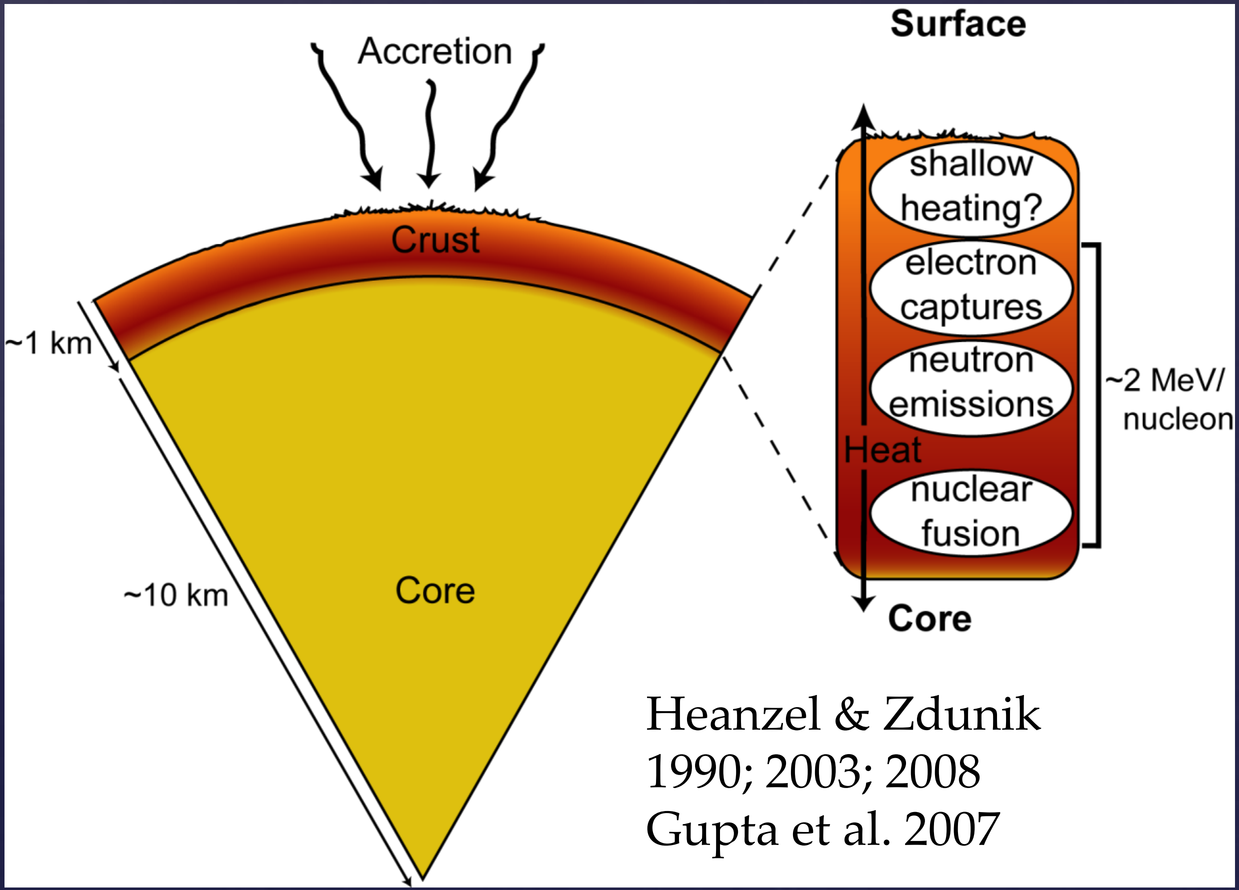
1) Neutrino emission (not observable) core
2) Photon emissions (X-rays) surface

Neutron star interior nearly isothermal → surface temperature tracks core

Neutron star structure



During an accretion outburst



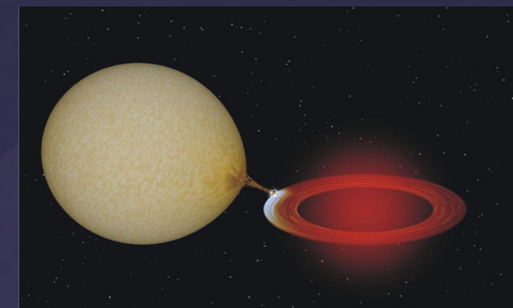
Heanzel & Zdunik 1990; 2003; 2008
Gupta et al. 2007

Crust compressed: nuclear reactions induced

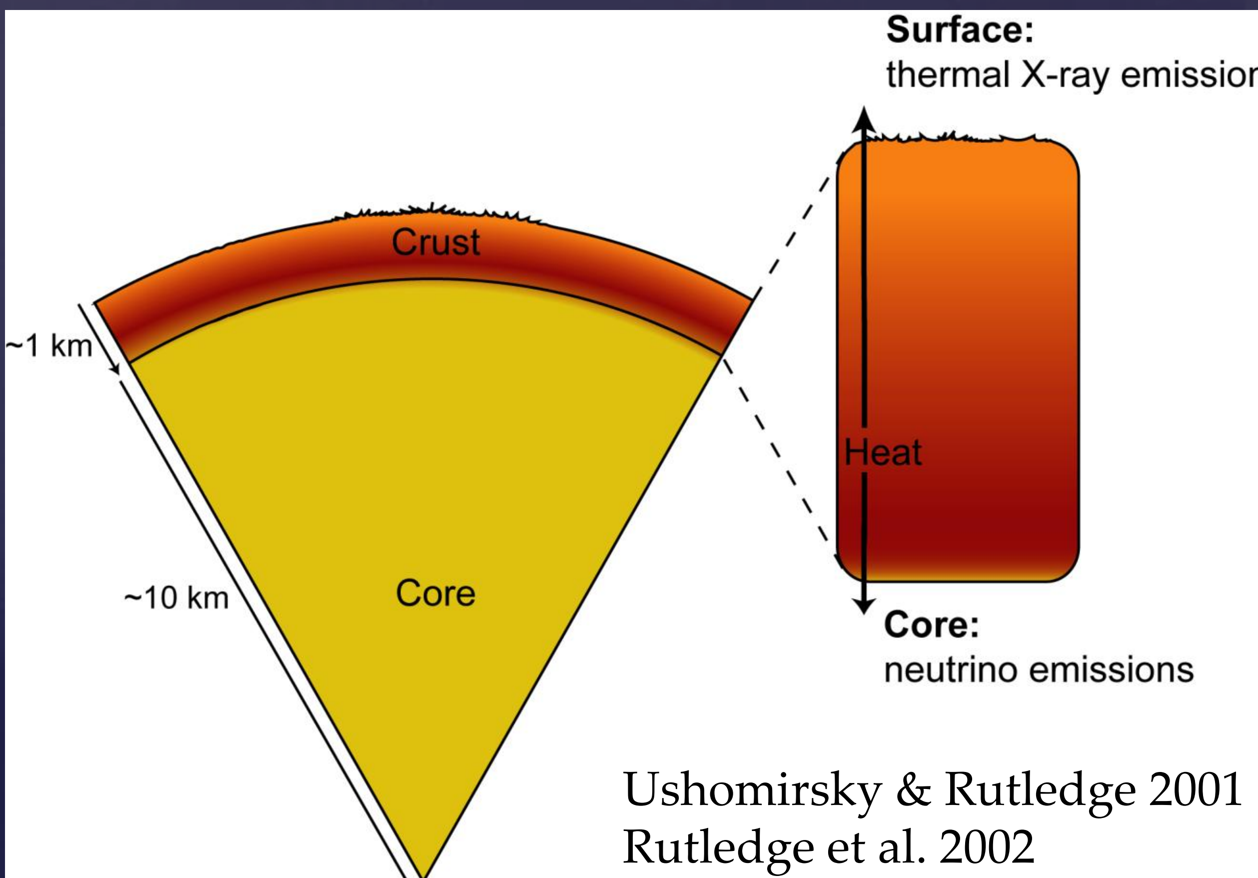
Crust locally heated: heat conducted to core + surface

Neutron star not observable: emission accretion disk

Neutron star structure

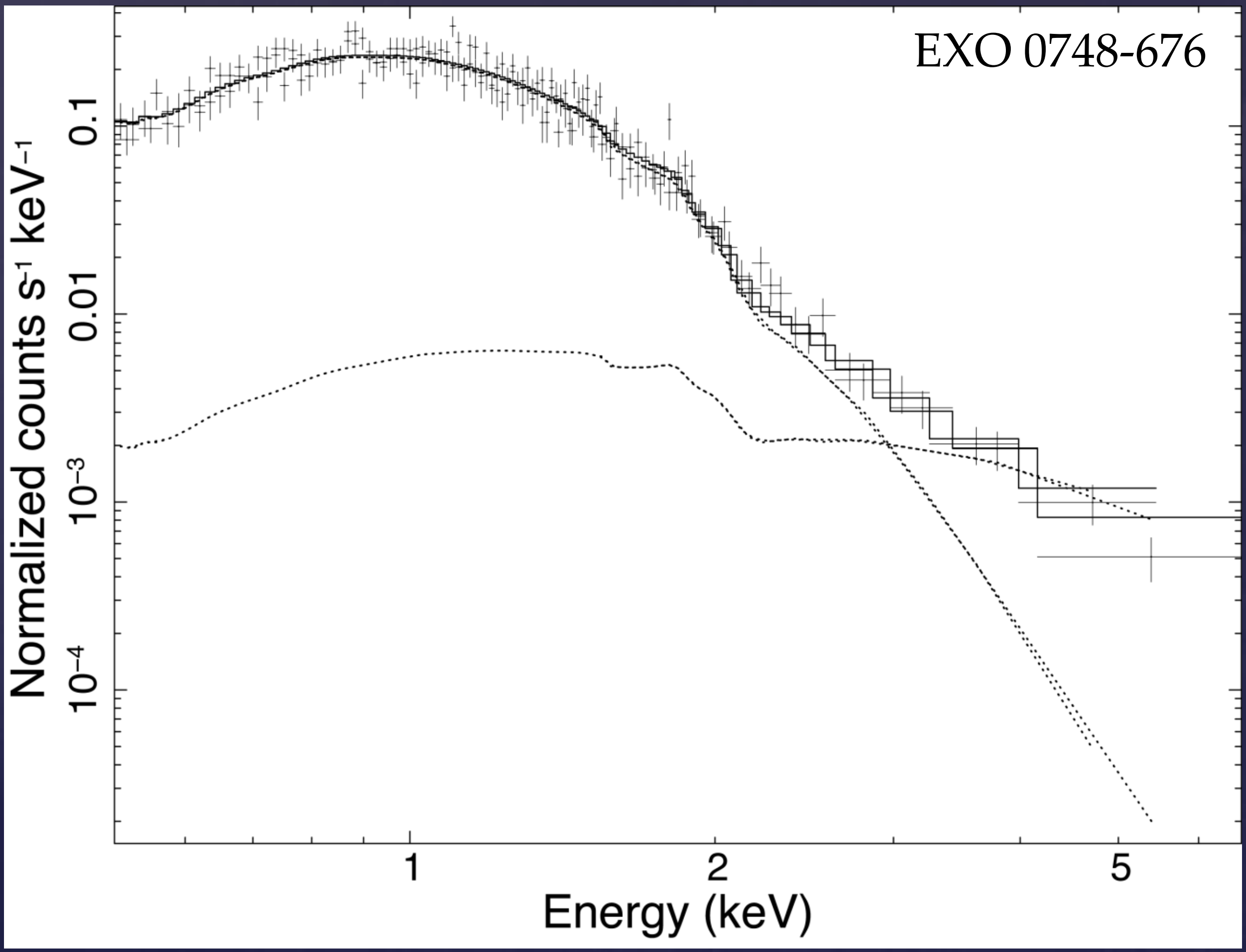


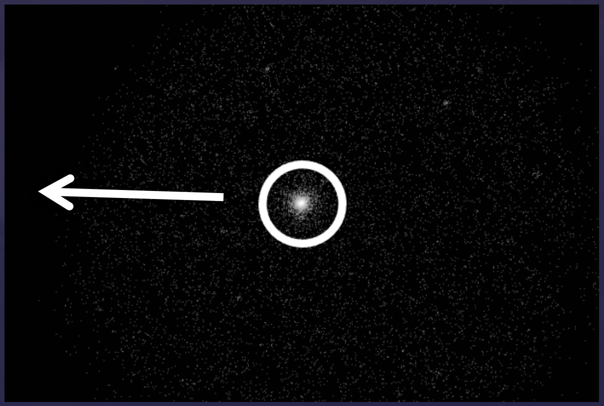
<u>After an accretion outburst</u>



Neutron star crust hotter than core → surface temperature tracks crust!

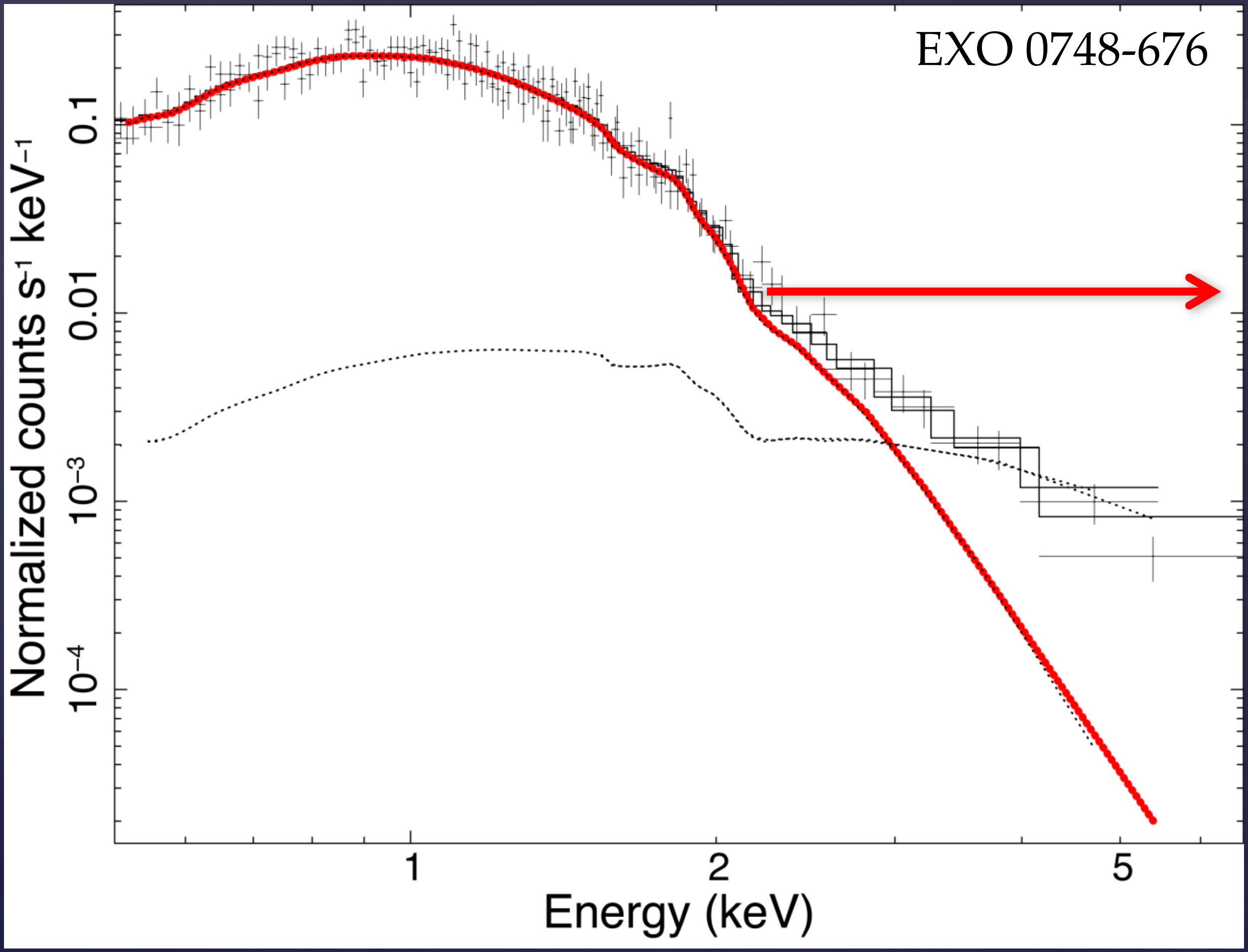
How to detect thermal emission
Quiescent X-ray spectra





Degenaar et al. 2009

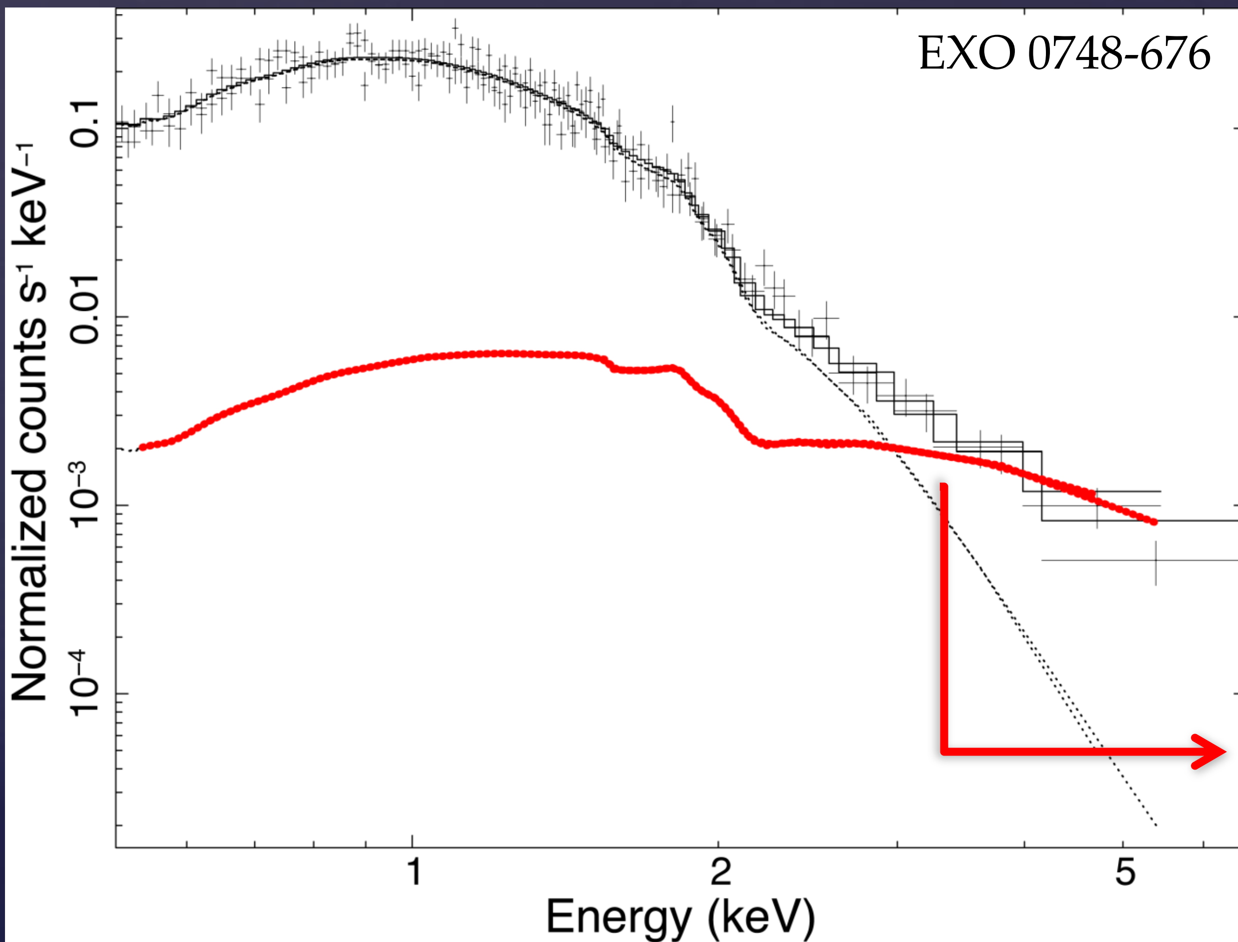
How to detect thermal emission
Quiescent X-ray spectra



Possible components:

1) Soft, thermal
- Peaks below 2 keV
- Thermal emission neutron star surface
- Atmosphere model → temperature

How to detect thermal emission
Quiescent X-ray spectra

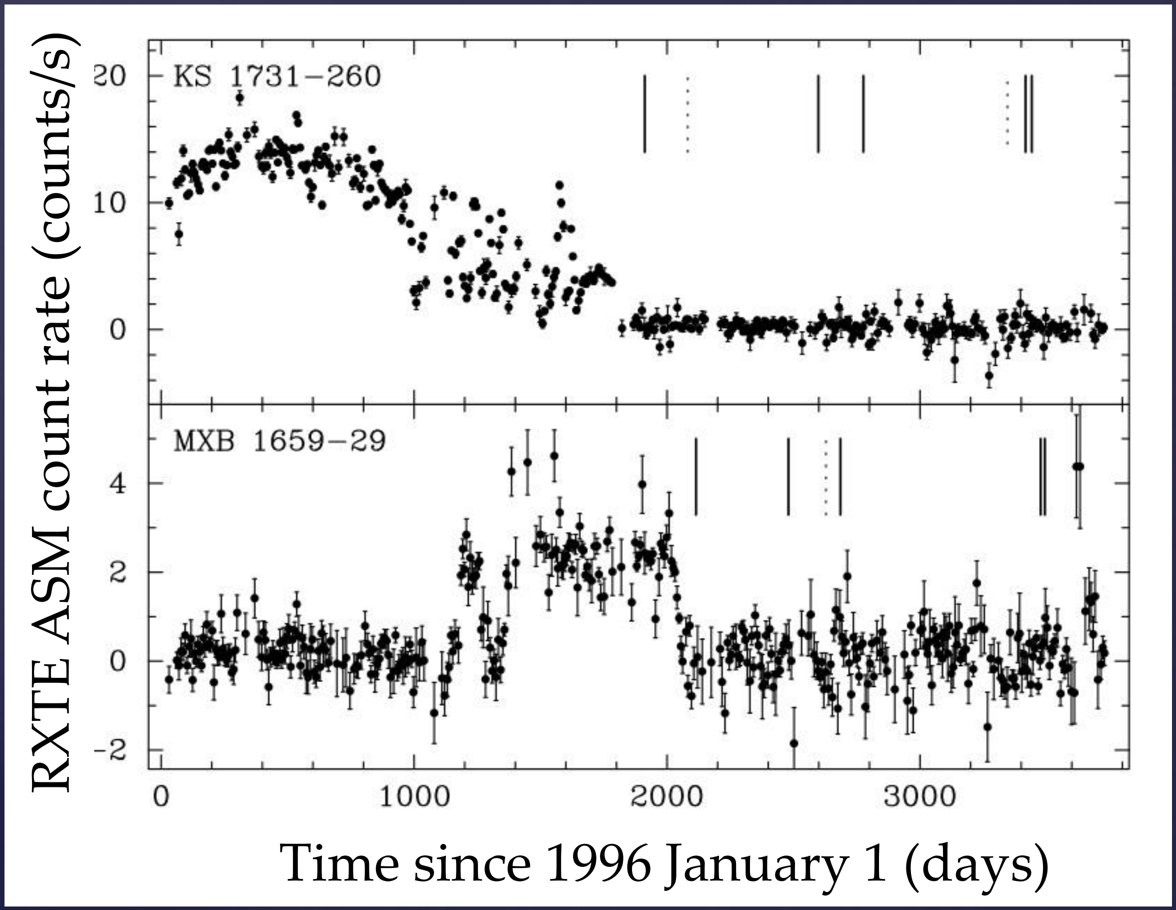


<u>Possible components</u>:

1) Soft, thermal
- Peaks below 2 keV
- Thermal emission neutron star surface
- Atmosphere model → temperature

2) Hard, non-thermal
- Dominates > 2-3 keV
- Contributes 0-100%
- Origin unknown

Quiescent thermal emission: Can we detect a heated crust?



Transient neutron stars accreting for years:

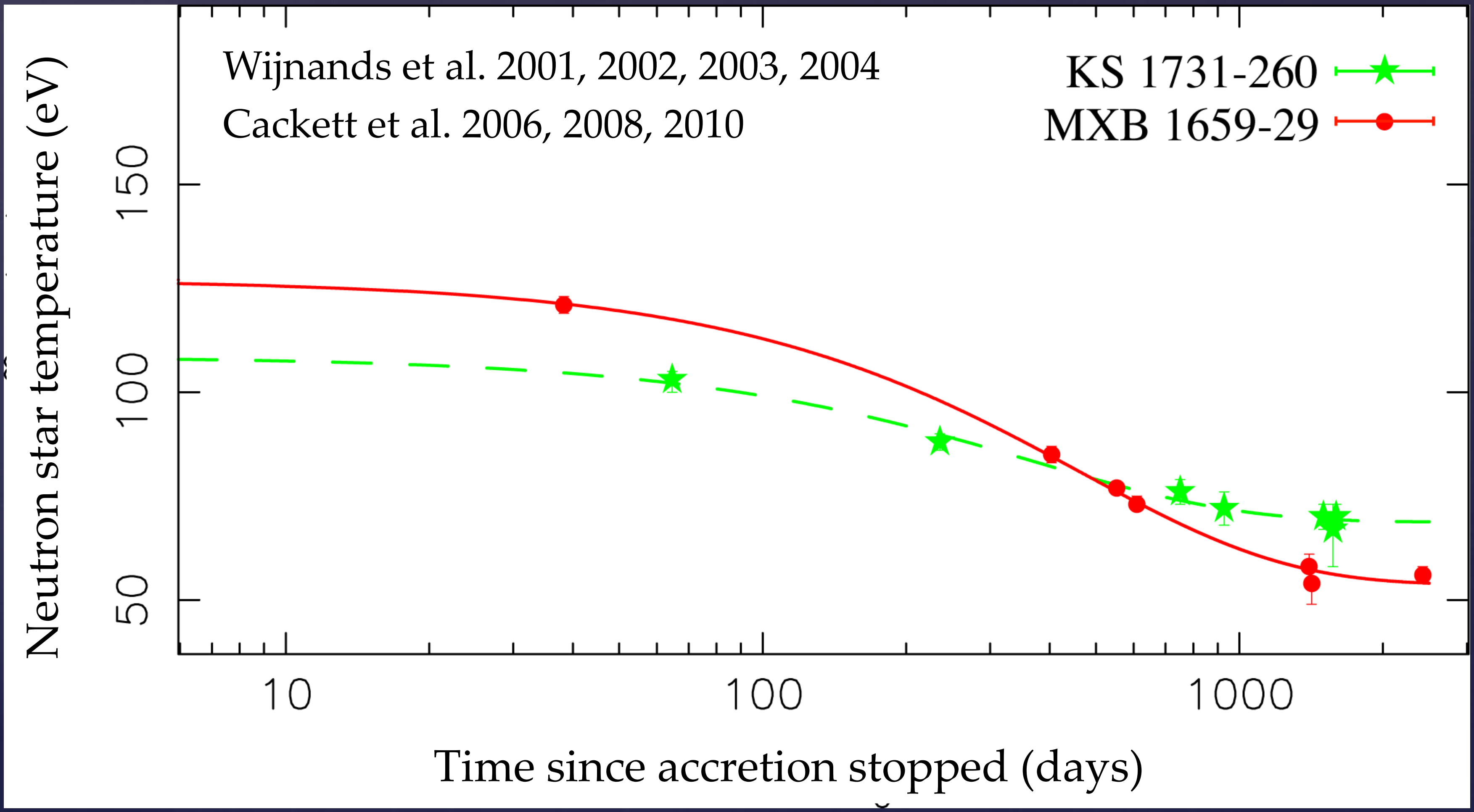
- Outburst: crust severely heated
- Quiescence: crust cools (Rutledge et al. 2001)

Two studied sources:

- KS 1731: active 12.5 yr
- MXB 1659: active 2.5 yr

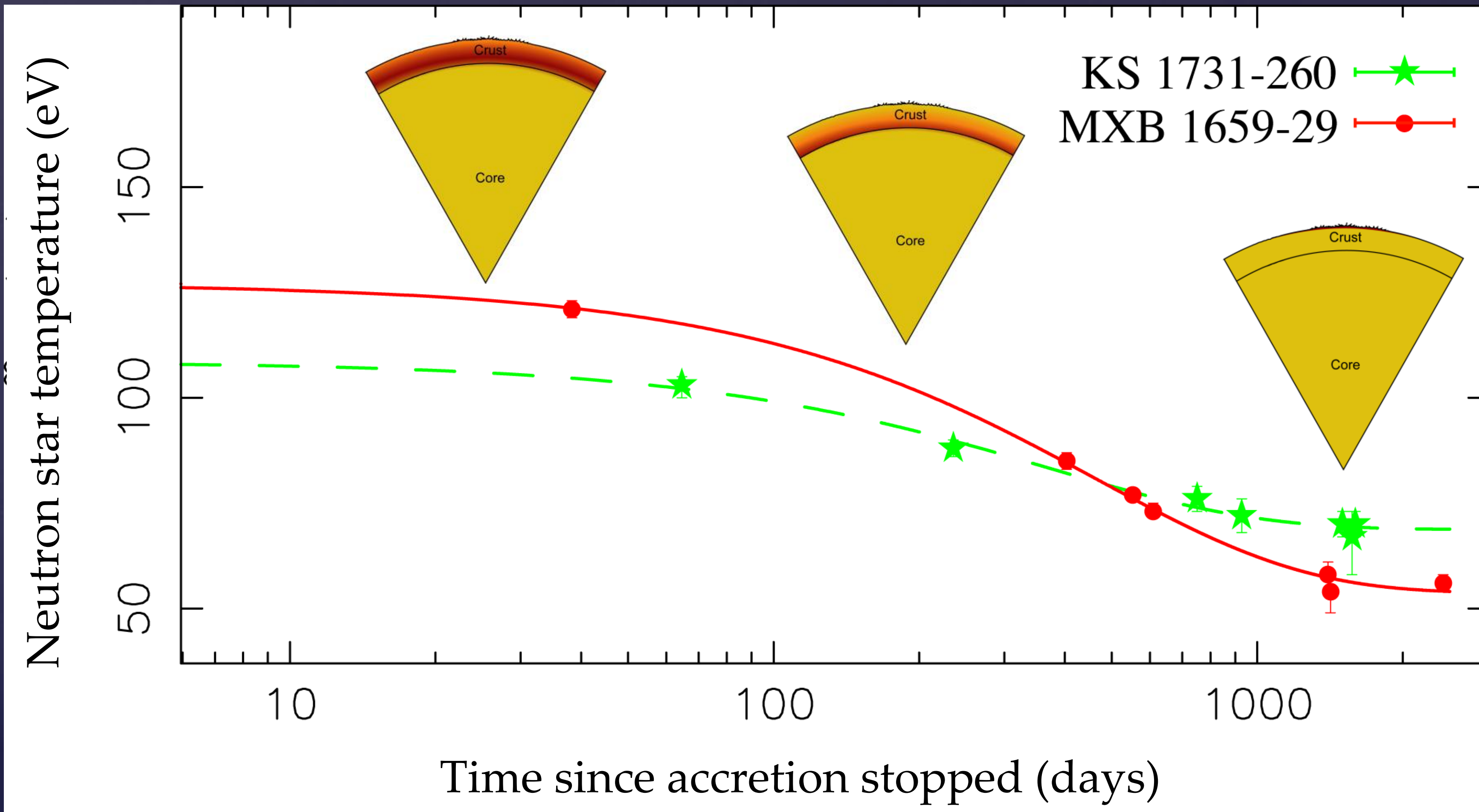
Both quiescent since 2001
→ Monitoring observations

Can we detect a heated crust? Yes! Cooling down in quiescence



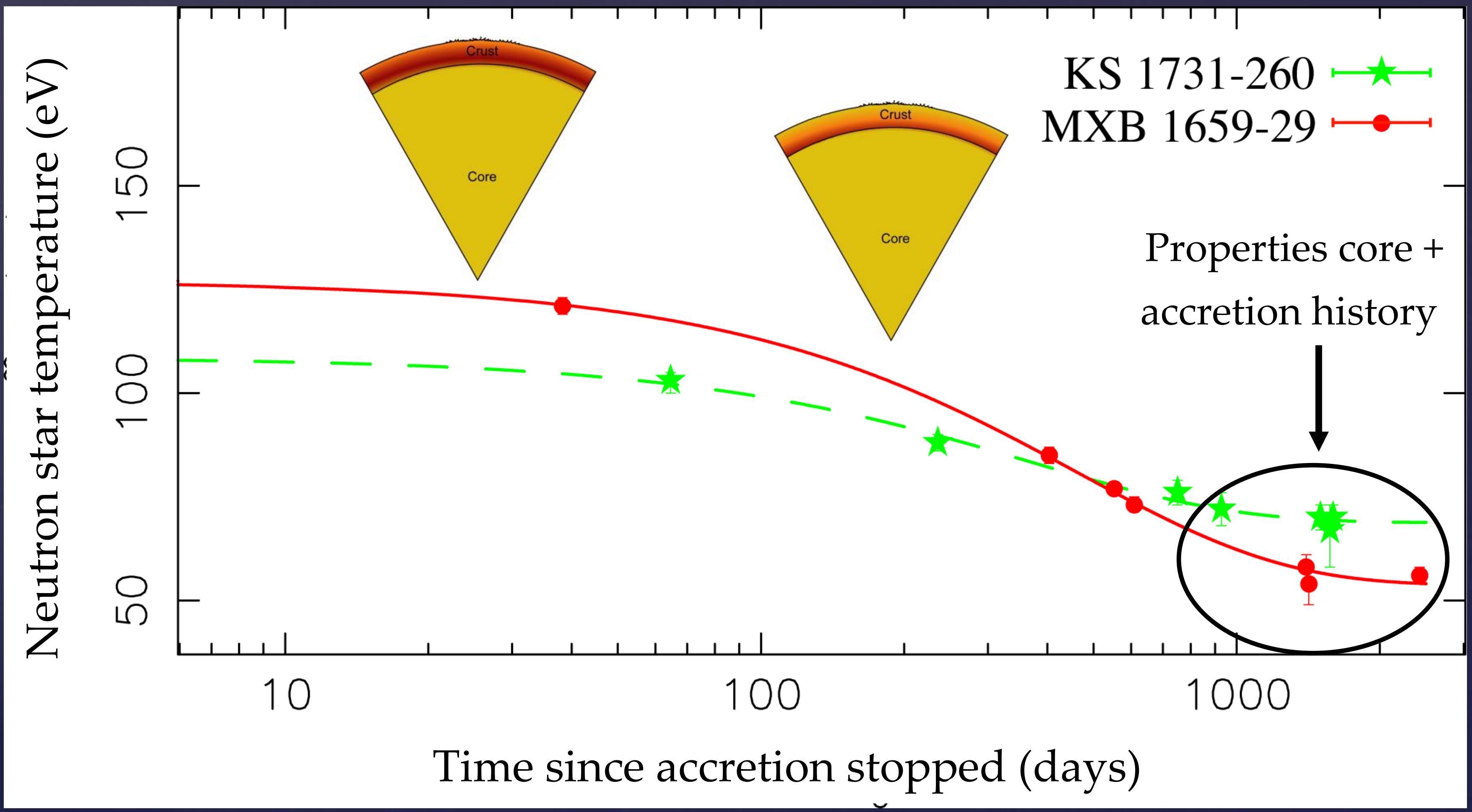
t ~ 4 yr

Can we detect a heated crust?
Yes! Cooling down in quiescence



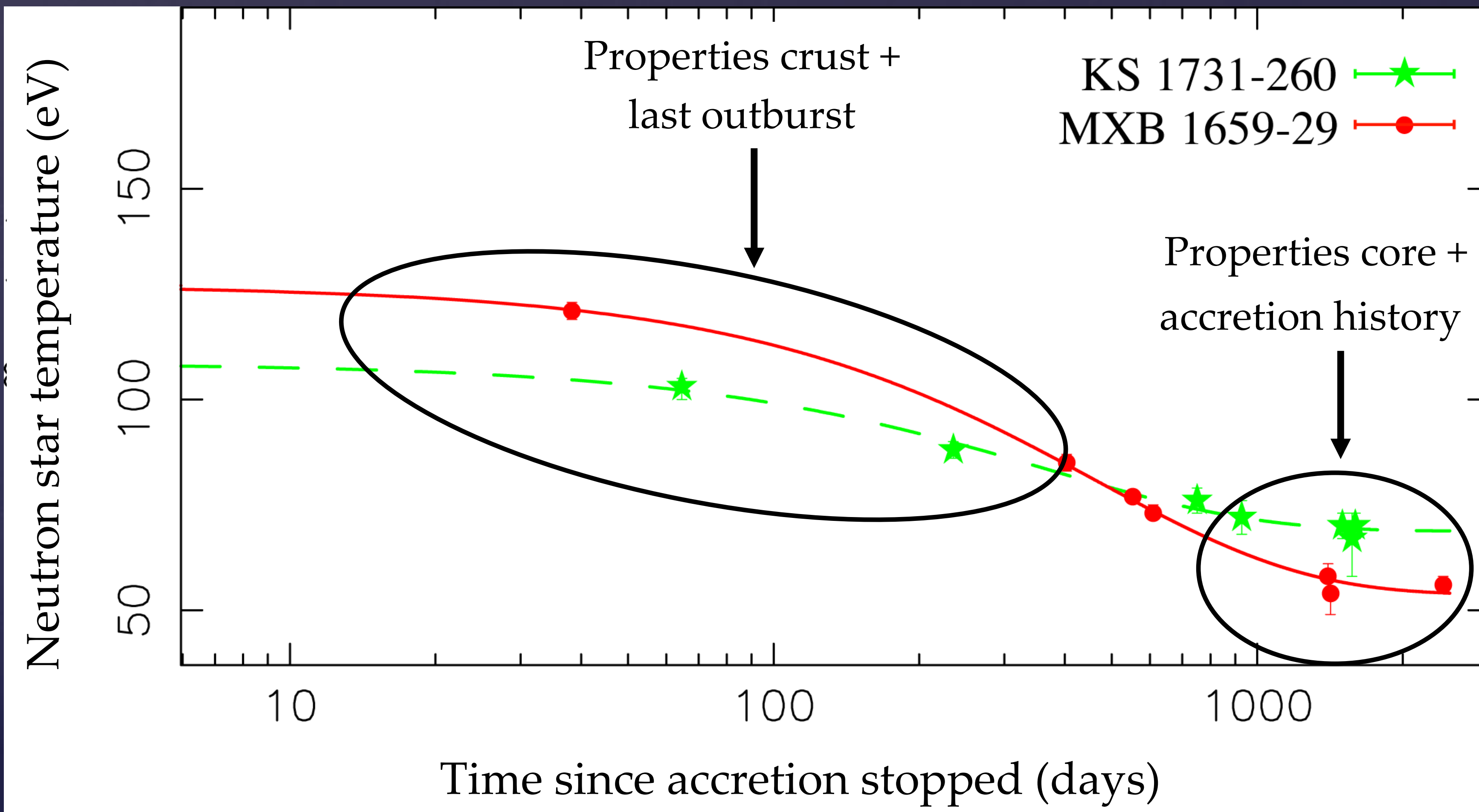
t ~ 4 yr

Can we detect a heated crust? Yes! Cooling down in quiescence



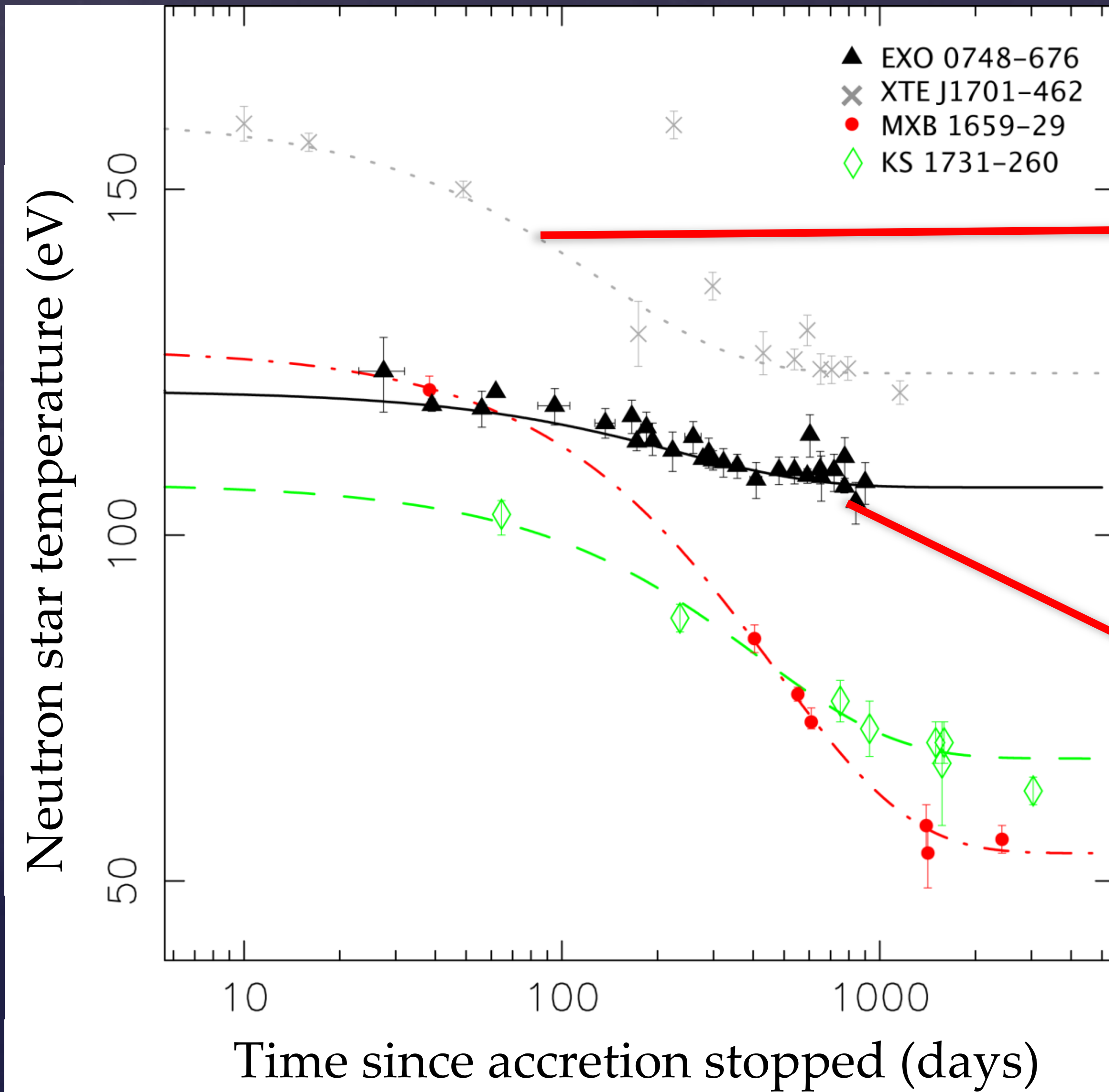
t ~ 4 yr

Can we detect a heated crust?
Yes! Cooling down in quiescence



t ~ 4 yr

Crust cooling: 2 more sources



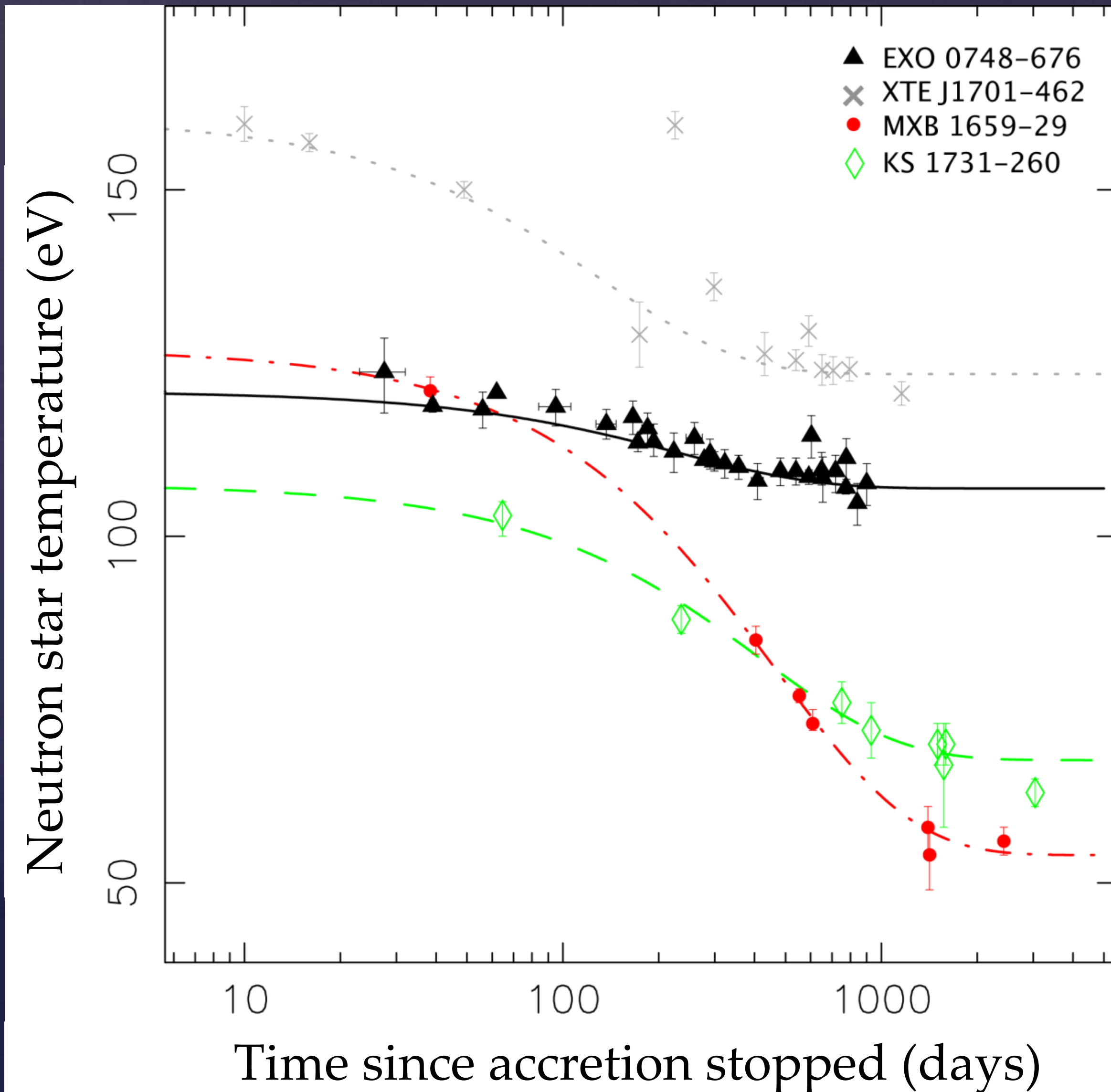
1) XTE J1701-462:
Active 1.5 yr
Quiescent since 2007

Fridriksson et al. 2010, 2011

2) EXO 0748-676:
Active 24-28 years
Quiescent since 2008

Degenaar et al. 2010, 2011
Diaz Trigo et al. 2011

Crust cooling: 4 sources



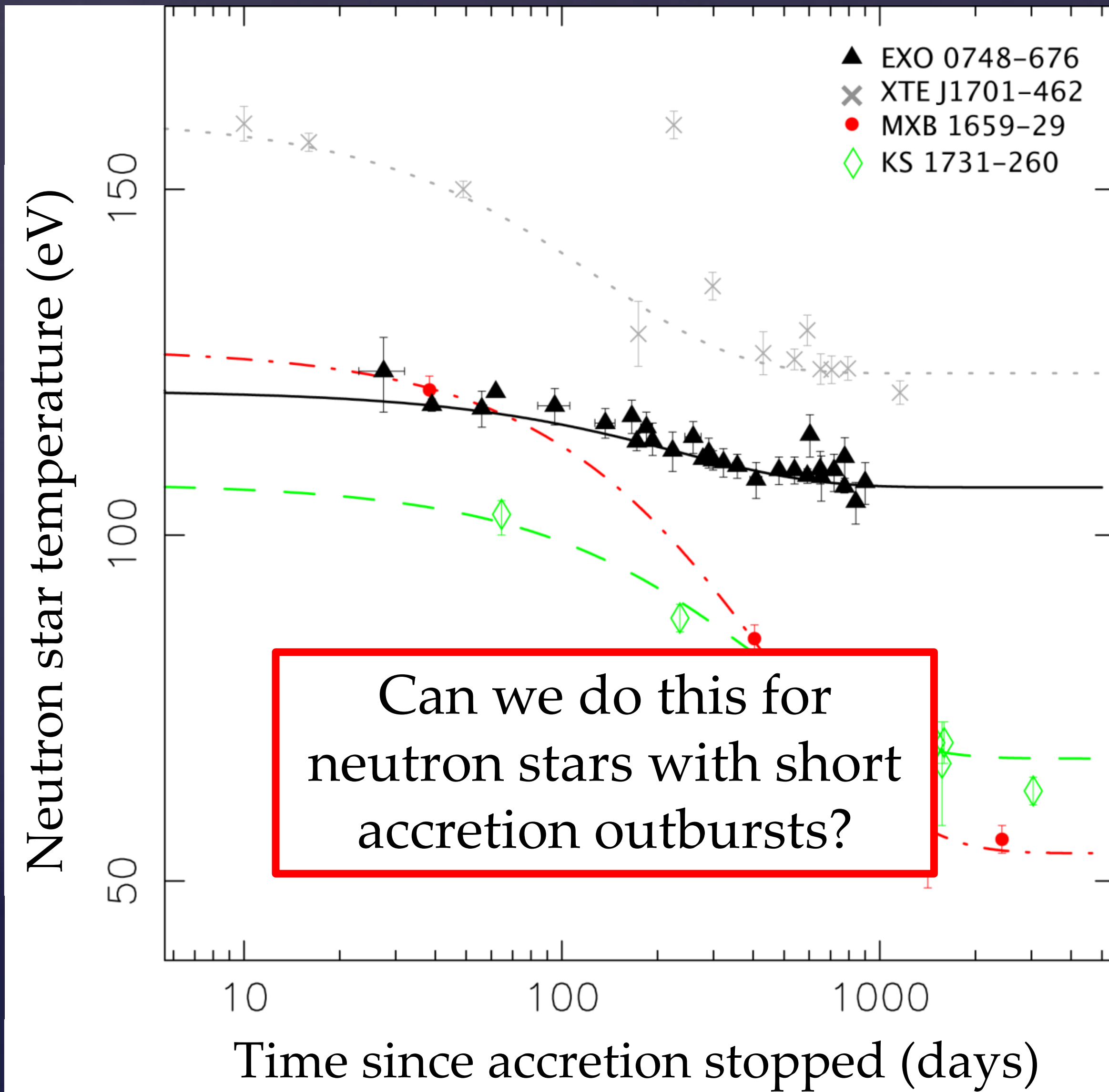
What have we learned:

1) Crust cooling is observable!
2) Neutron star crust is highly conductive
3) Additional heat sources in crust?

Shternin et al. 2007
Brown & Cumming 2009
<u>See poster by M. Fortin</u>

Disadvantage:
Long outbursts are rare!
Few sources available for future study

Crust cooling: 4 sources



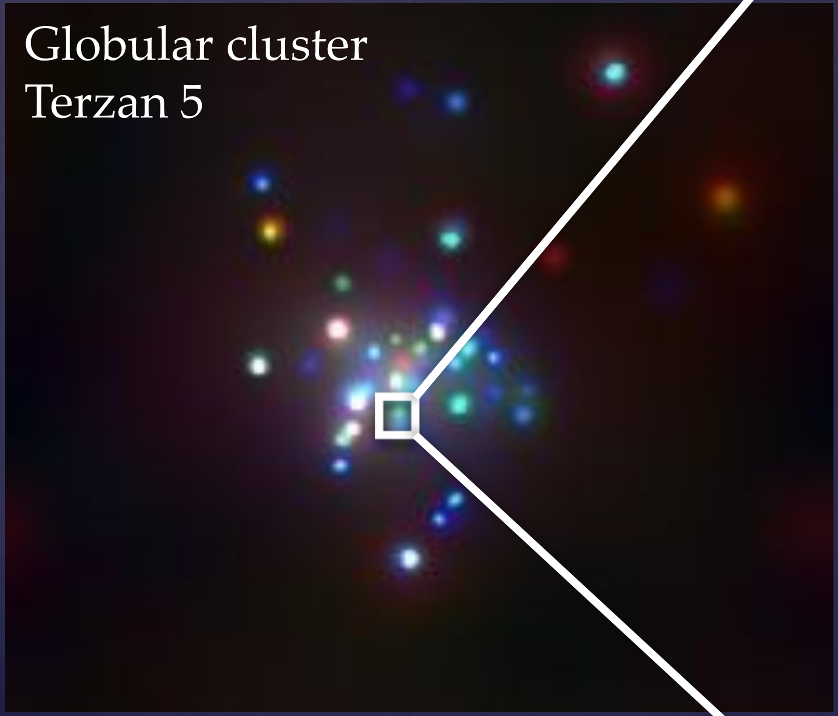
What have we learned:

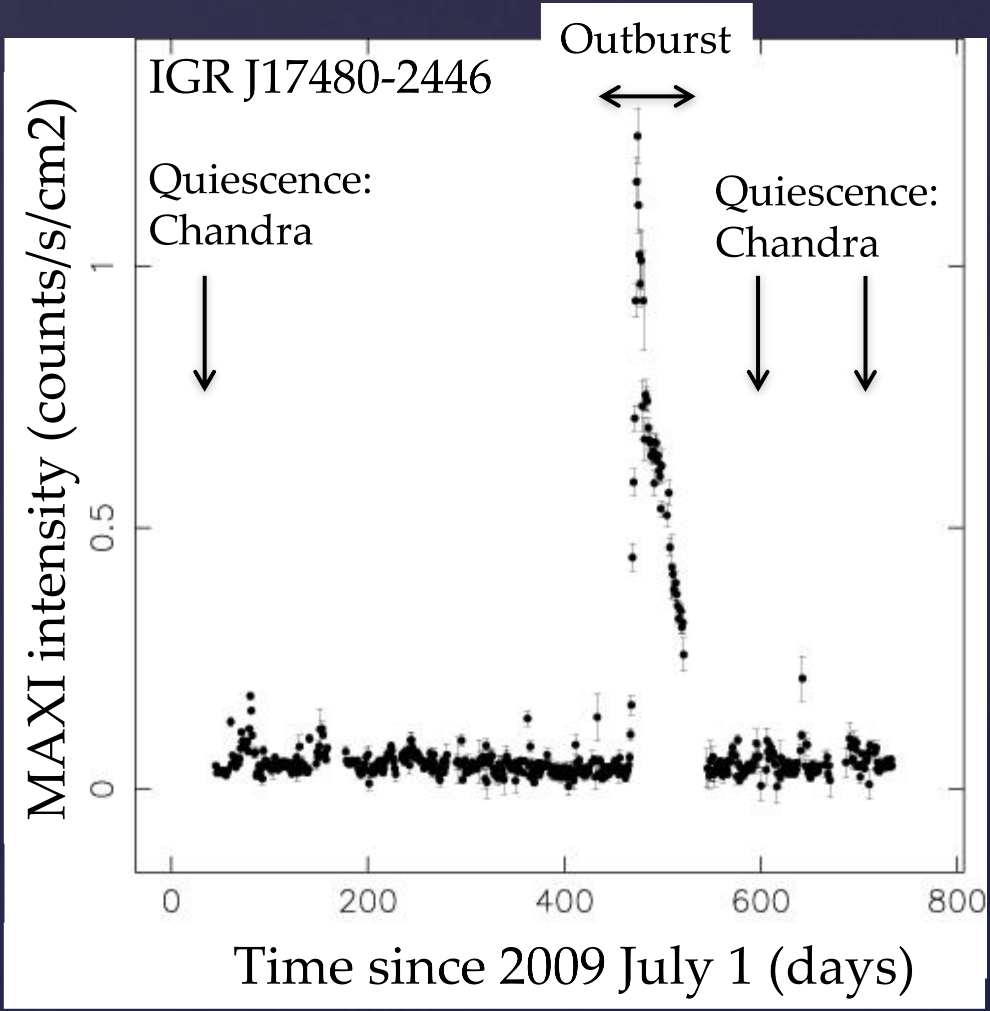
1) Crust cooling is observable!
2) Neutron star crust is highly conductive
3) Additional heat sources in crust?

Shternin et al. 2007
Brown & Cumming 2009
See poster by M. Fortin

Disadvantage:
Long outbursts are rare!
Few sources available for future study

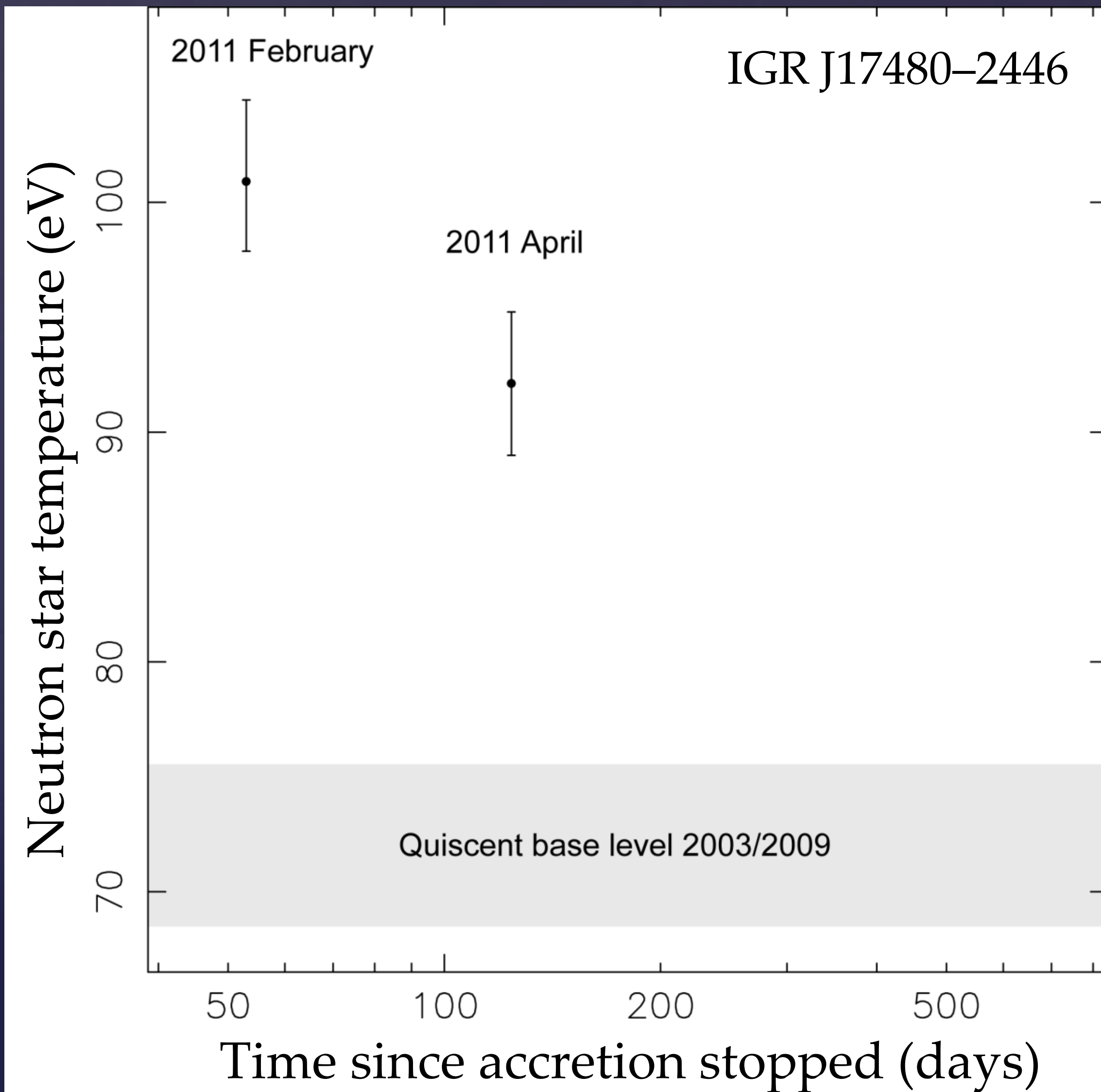
Can we detect crust cooling if the outburst is short? – Test case!





10-week accretion outburst
2010 October-December

Thermal evolution: crust cooling?

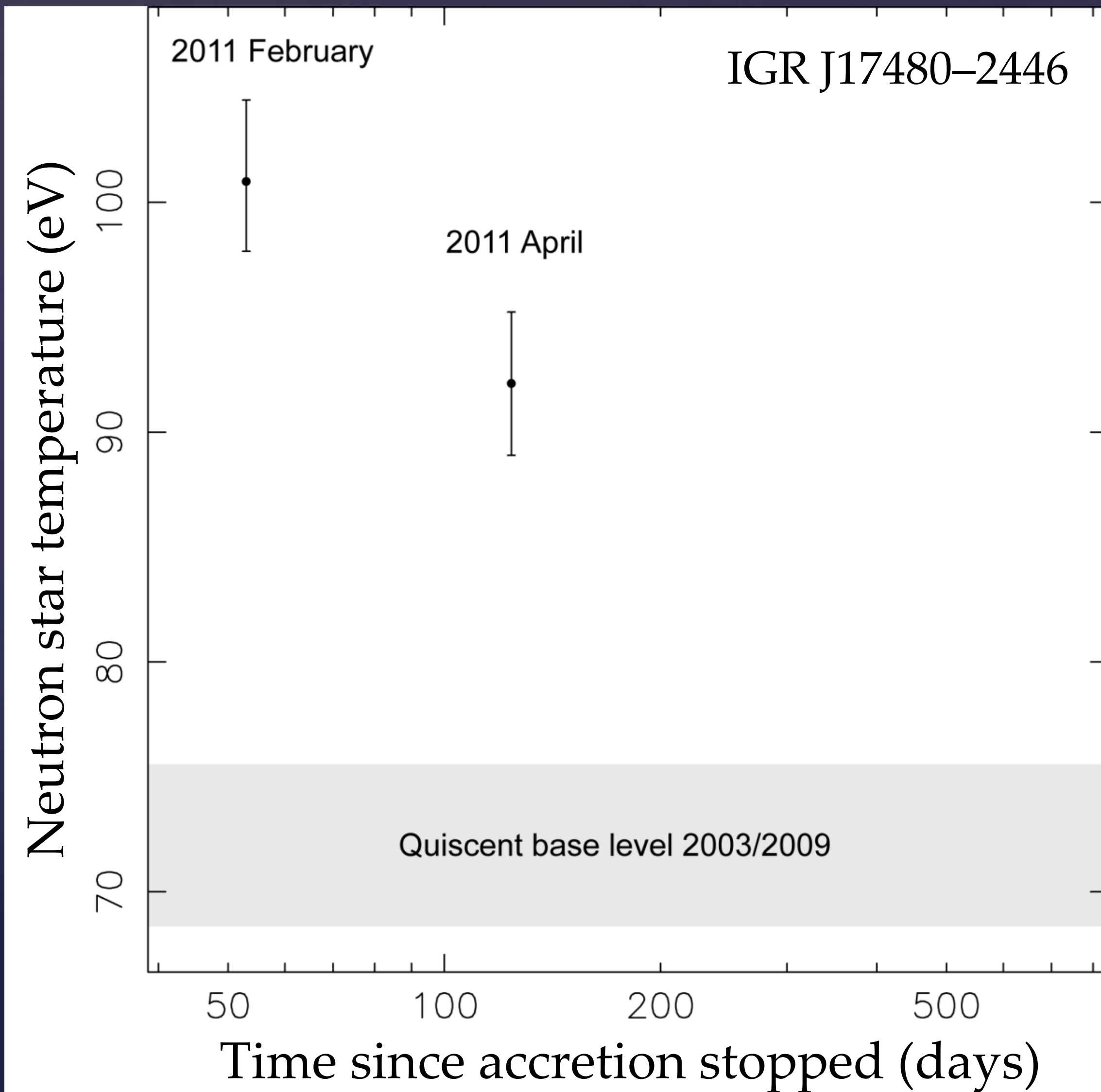


(Outburst: 2010 Oct-Dec)

- Thermal emission initially enhanced, but decreasing

Degenaar & Wijnands 2011a,b
Degenaar, Brown & Wijnands submitted

Thermal evolution: crust cooling?



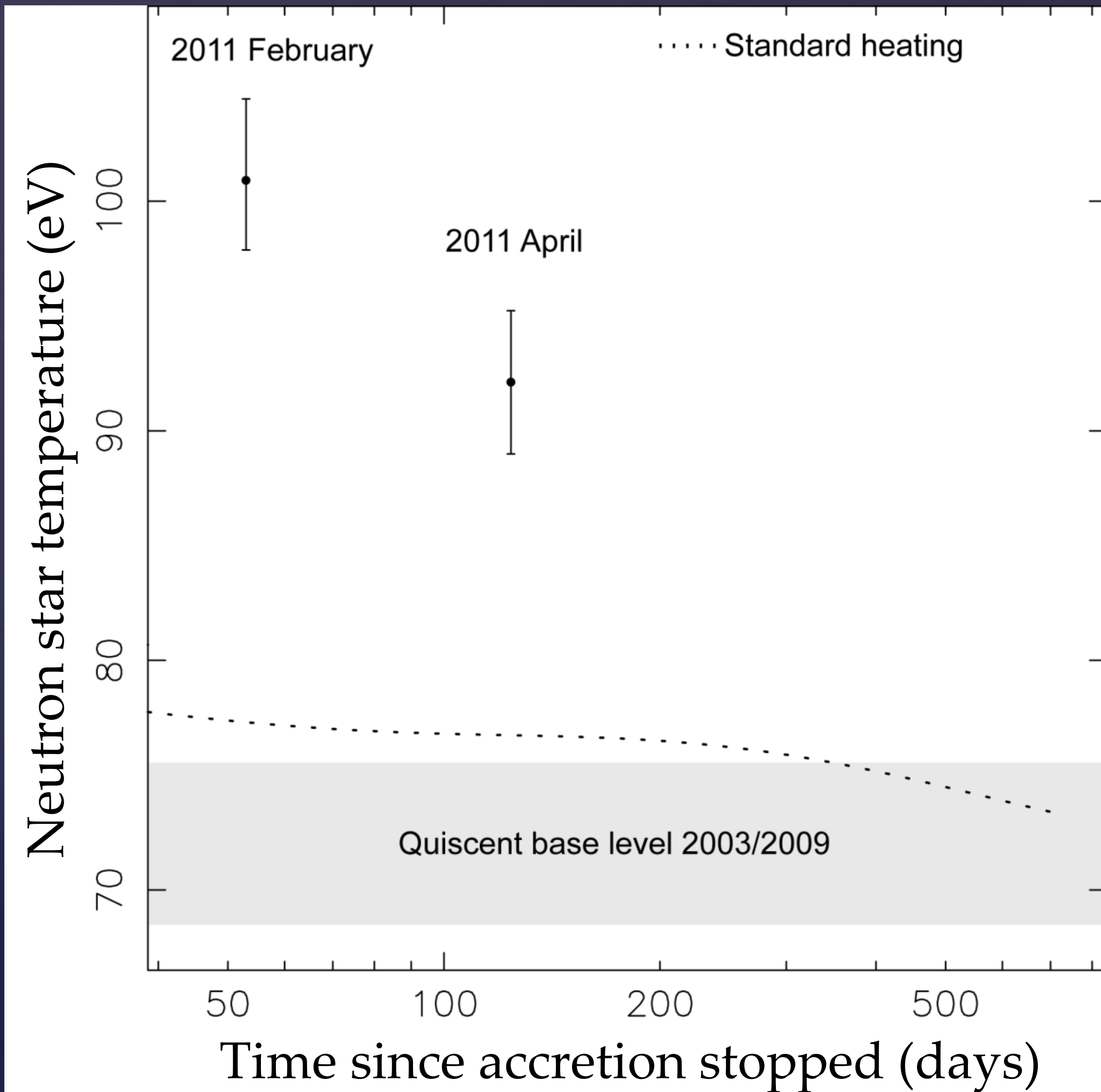
(Outburst: 2010 Oct-Dec)

- Thermal emission initially enhanced, but decreasing

Crust cooling?

Degenaar & Wijnands 2011a,b
Degenaar, Brown & Wijnands submitted

Thermal evolution: crust cooling?



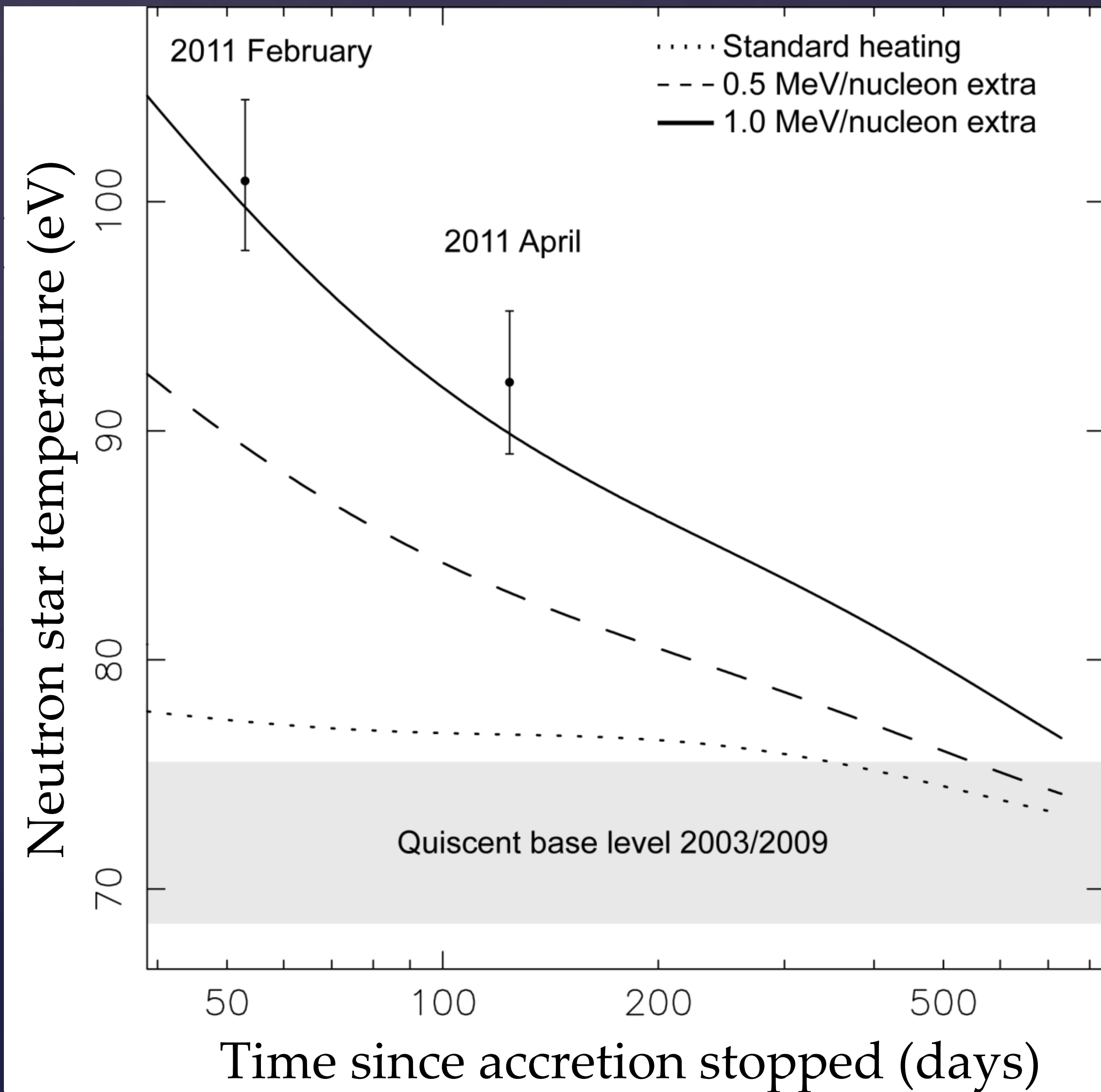
(Outburst: 2010 Oct-Dec)

- Thermal emission initially enhanced, but decreasing
- Cooling curve standard heating → no match!

Thermal evolution code Brown & Cumming 2009

Degenaar & Wijnands 2011a,b
Degenaar, Brown & Wijnands submitted

Thermal evolution: crust cooling!



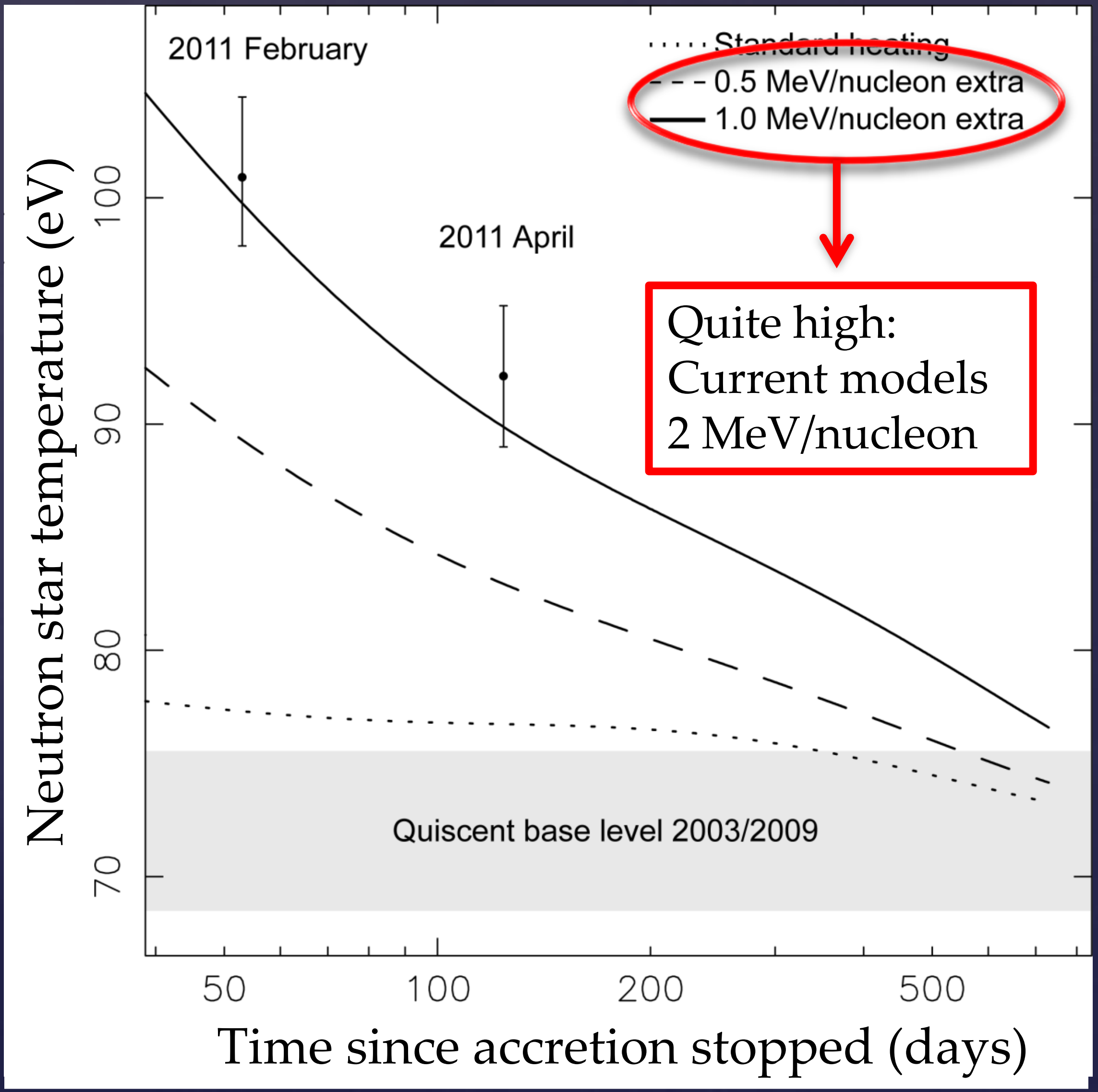
(Outburst: 2010 Oct-Dec)

- Thermal emission initially enhanced, but decreasing
- Cooling curve standard heating → no match!
- Extra shallow heating → match!

Thermal evolution code Brown & Cumming 2009

Degenaar & Wijnands 2011a,b
Degenaar, Brown & Wijnands submitted

Thermal evolution: crust cooling!



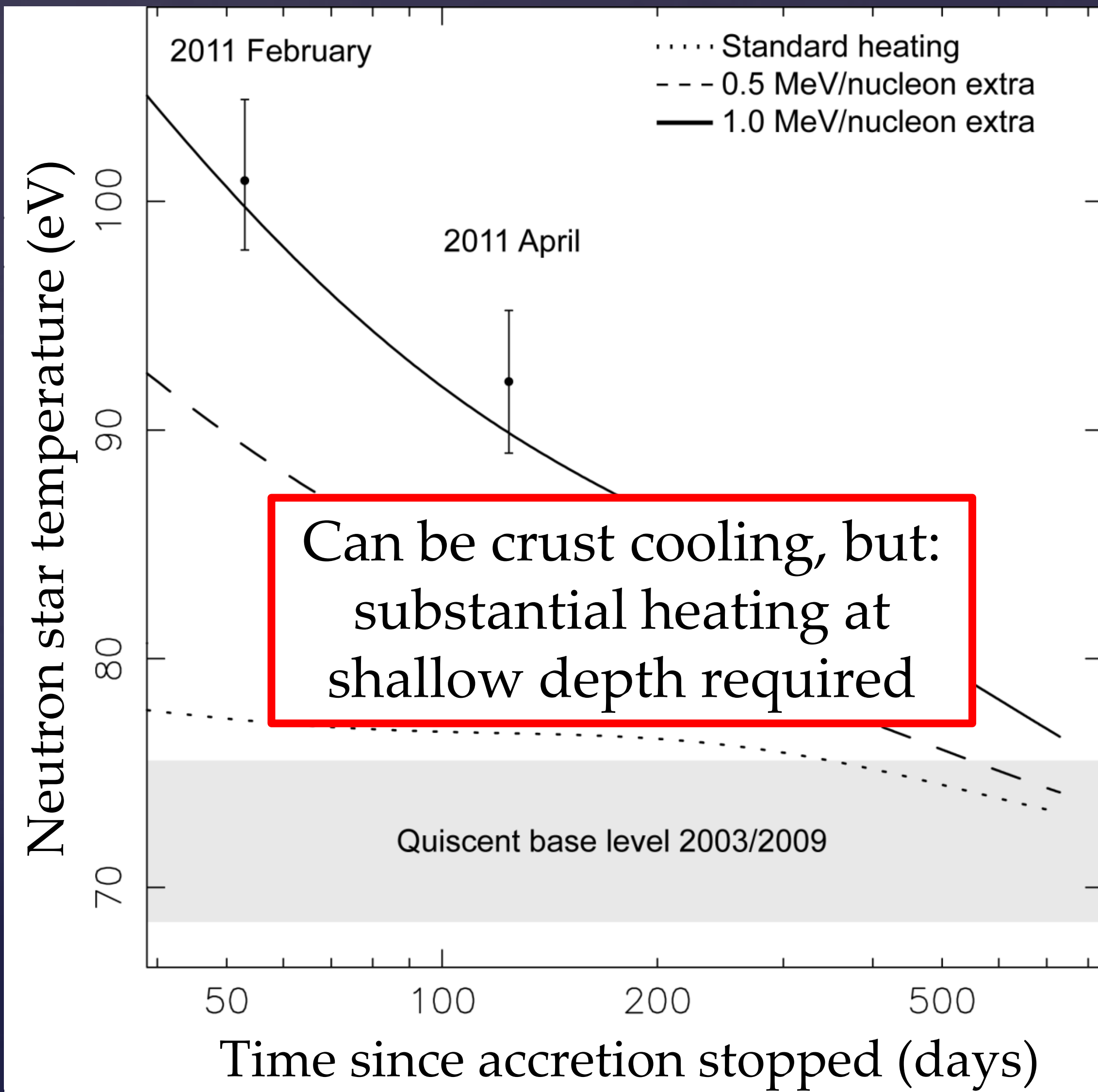
(Outburst: 2010 Oct-Dec)

- Thermal emission initially enhanced, but decreasing
- Cooling curve standard heating → no match!
- Extra shallow heating → match!

Thermal evolution code Brown & Cumming 2009

Degenaar & Wijnands 2011a,b
Degenaar, Brown & Wijnands submitted

Thermal evolution: crust cooling!



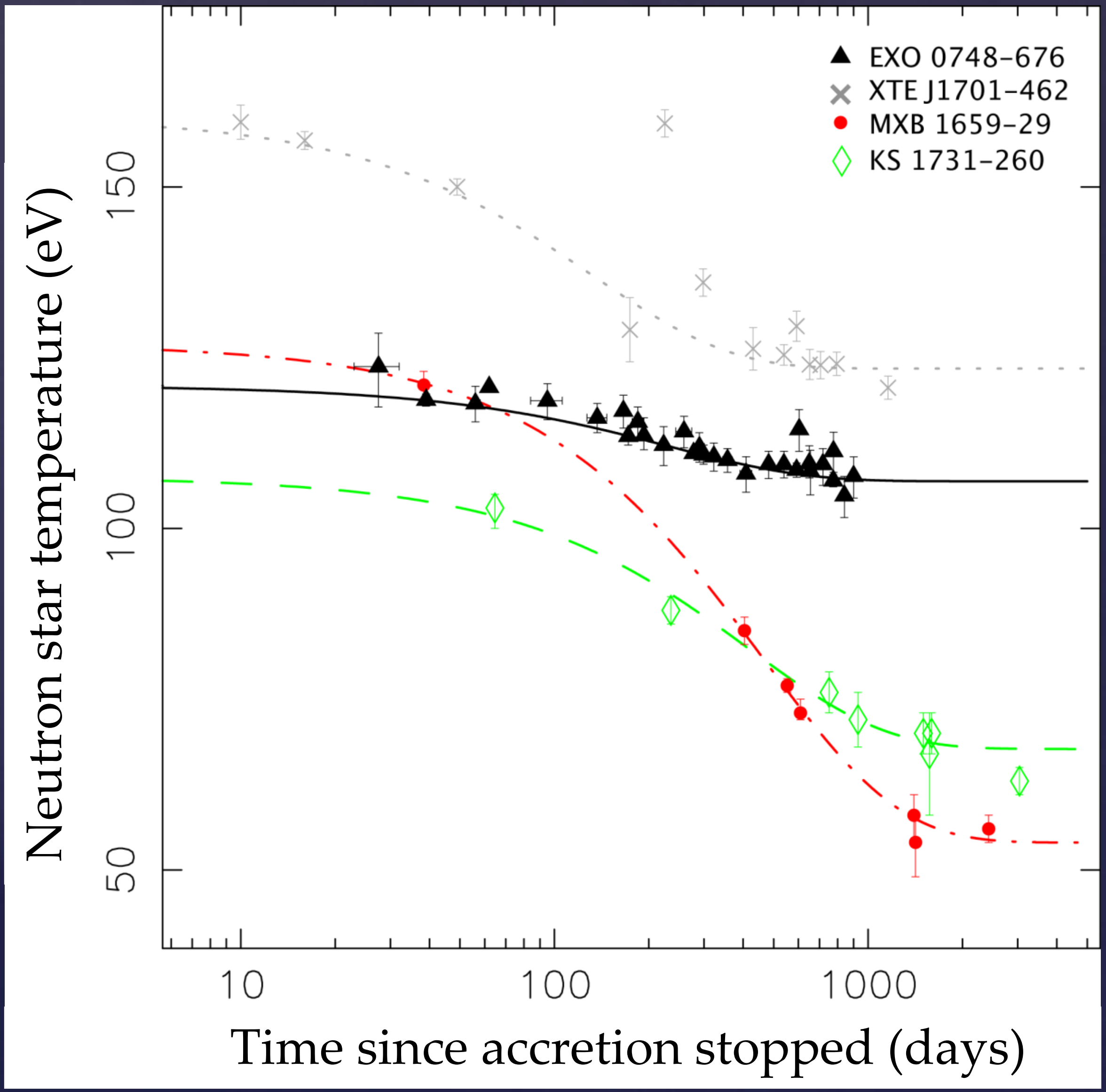
(Outburst: 2010 Oct-Dec)

- Thermal emission initially enhanced, but decreasing
- Cooling curve standard heating → no match!
- Extra shallow heating → match!

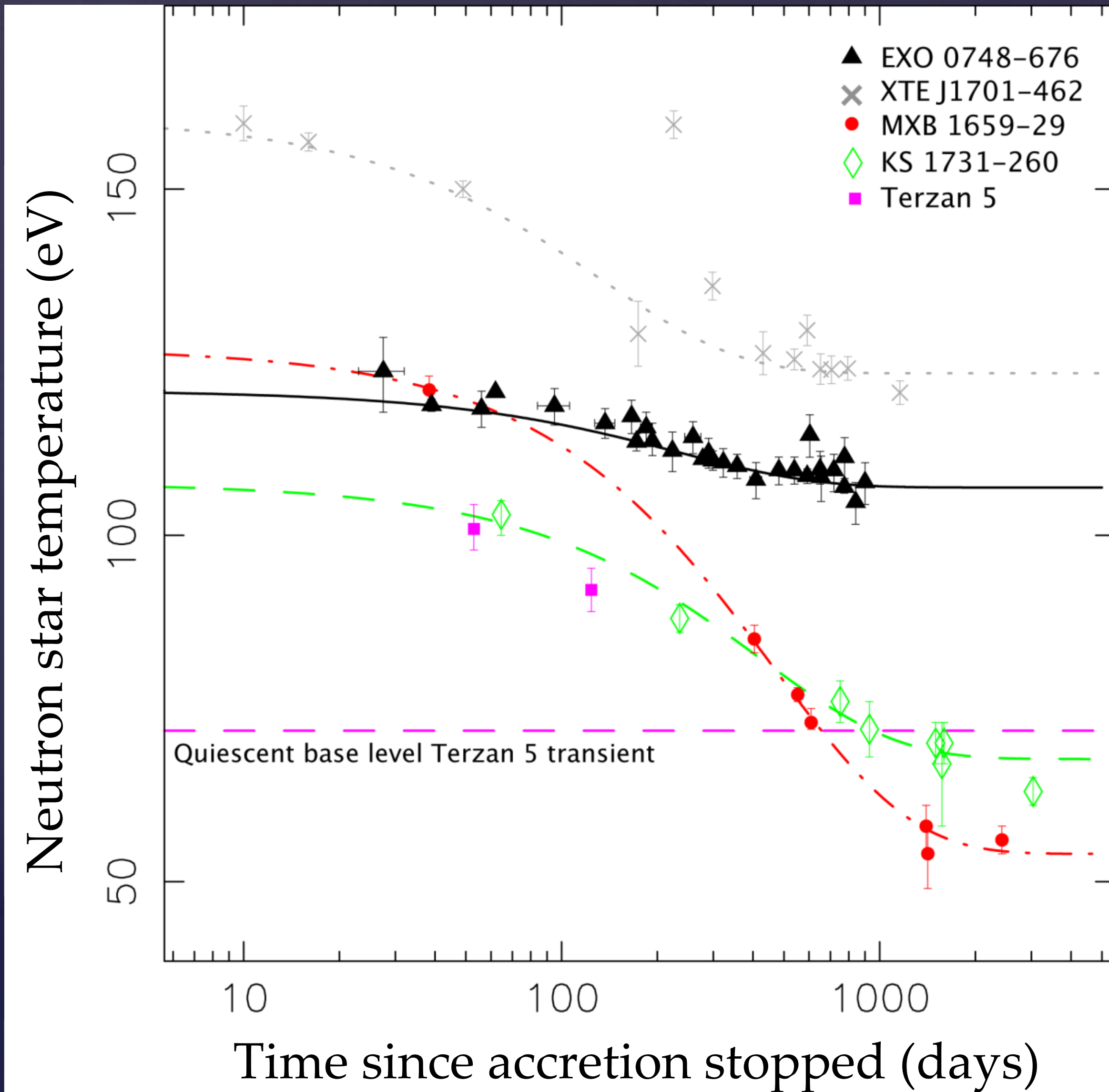
Thermal evolution code Brown & Cumming 2009

Degenaar & Wijnands 2011a,b
Degenaar, Brown & Wijnands submitted

Crust cooling: 4 sources



Crust cooling: 5 sources!



Crust cooling observable also for short outbursts

- Heating at shallow depth required: has been hypothesized

Horowitz et al. 2007
Gupta et al. 2007
Brown & Cumming 2009
See also poster by M. Fortin

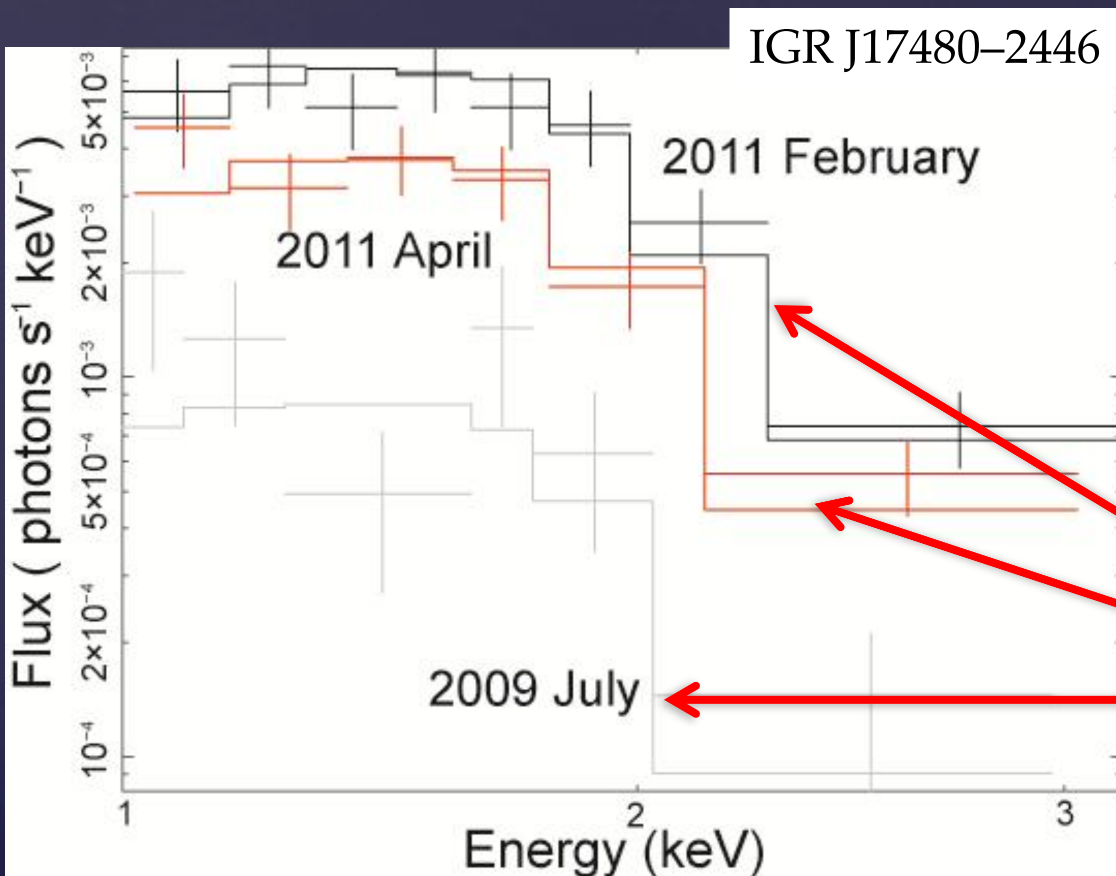
- More source available for study!

To take away

<u>Transient neutron star X-ray binaries in quiescence</u>

- Thermal emission from neutron star surface observable:
  Probe properties neutron star crust + core
- Cooling of the heated crust observed after long outbursts:
  Probe neutron star crust properties + nuclear physics
- Crust cooling now observed after a short outburst:
  More common, so more sources available for study
  Indications of extra heating sources at shallow depth

Quiescent X-ray spectra before and after 2010 accretion outburst



Degenaar & Wijnands 2011a,b
Degenaar, Brown & Wijnands submitted

(Outburst: 2010 Oct-Dec)

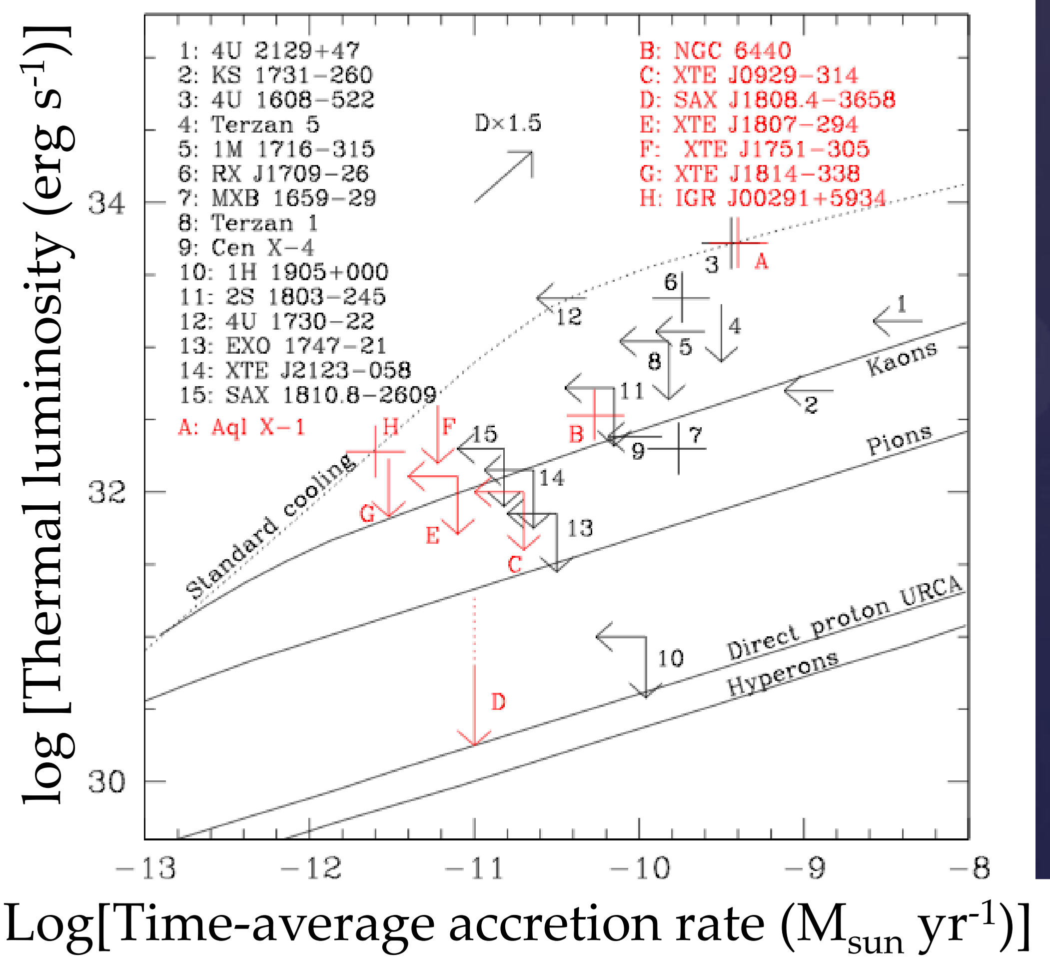
- Thermal emission detectable!
- Clear difference before and after

2 months after outburst
4 months after outburst
1 year before outburst

Crust cooling?

Quiescent thermal emission: Probe neutron star interior

Heinke et al. 2009; Yakovlev&Pethick 2004

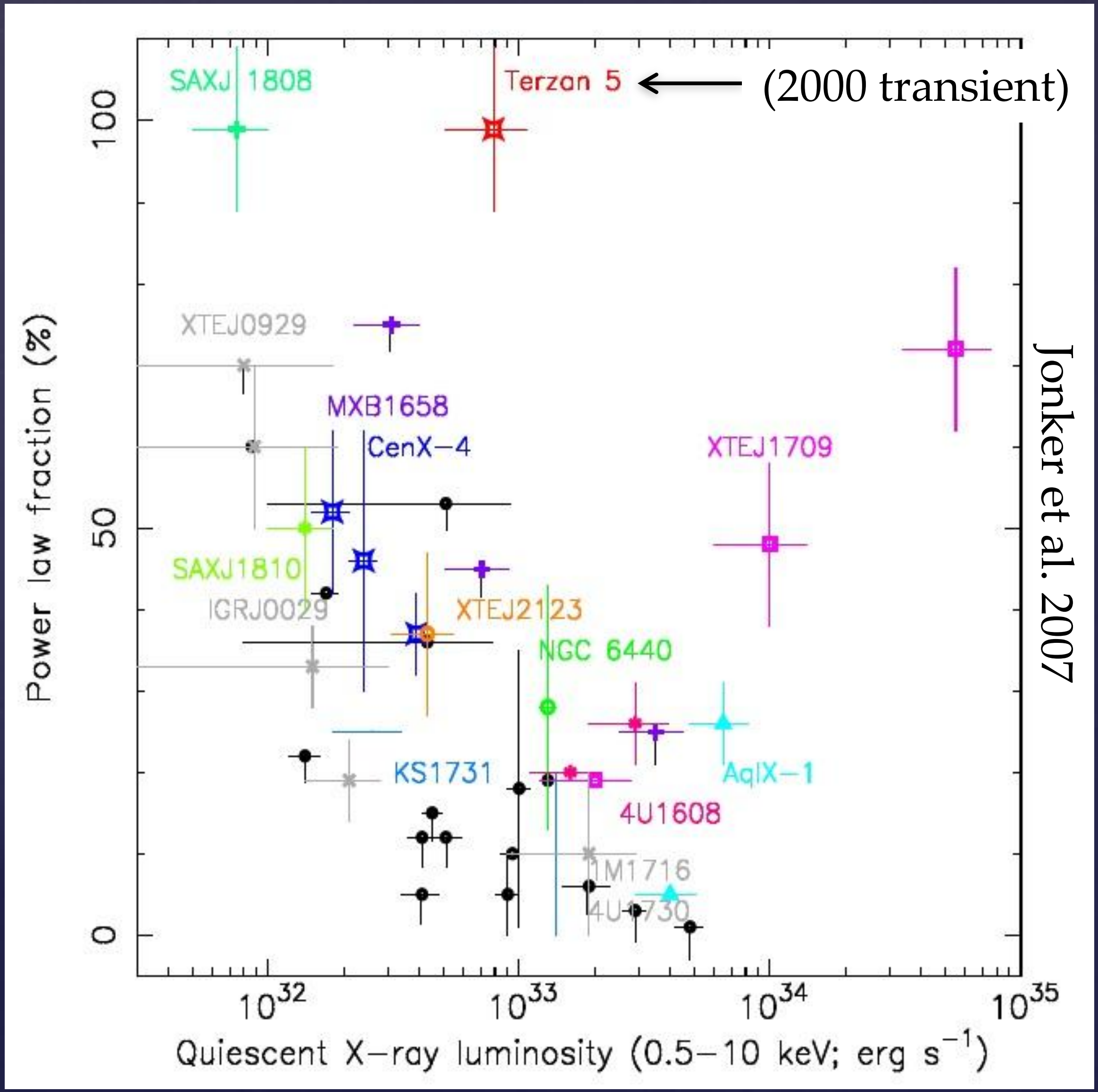


Isothermal interior: Thermal emission measures core temperature

Core temperature set by:

1) Time-averaged mass-accretion rate =heating
2) Rate of neutrino emission from core =cooling

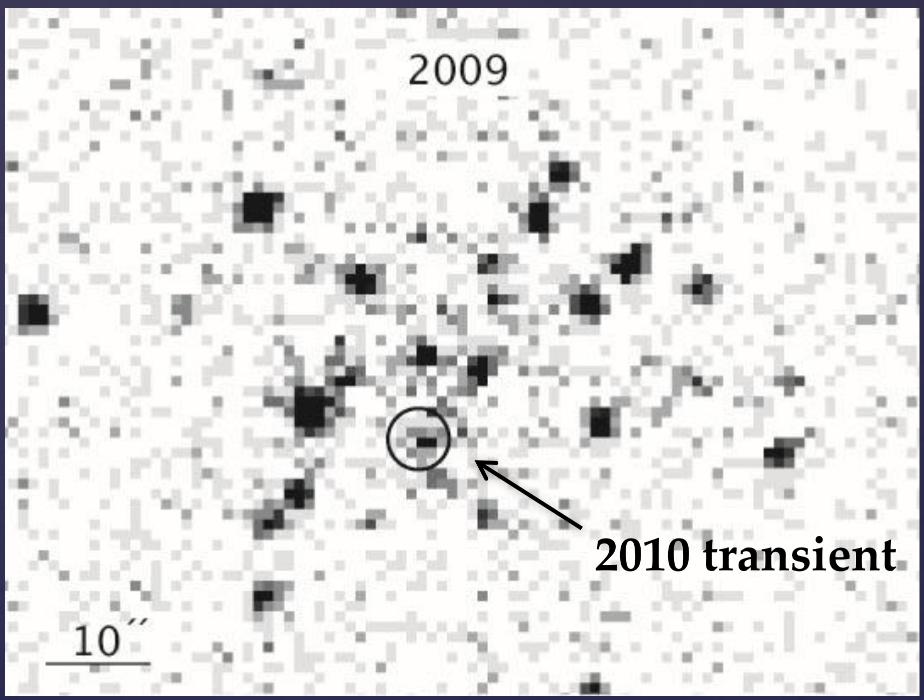
Contribution powerlaw



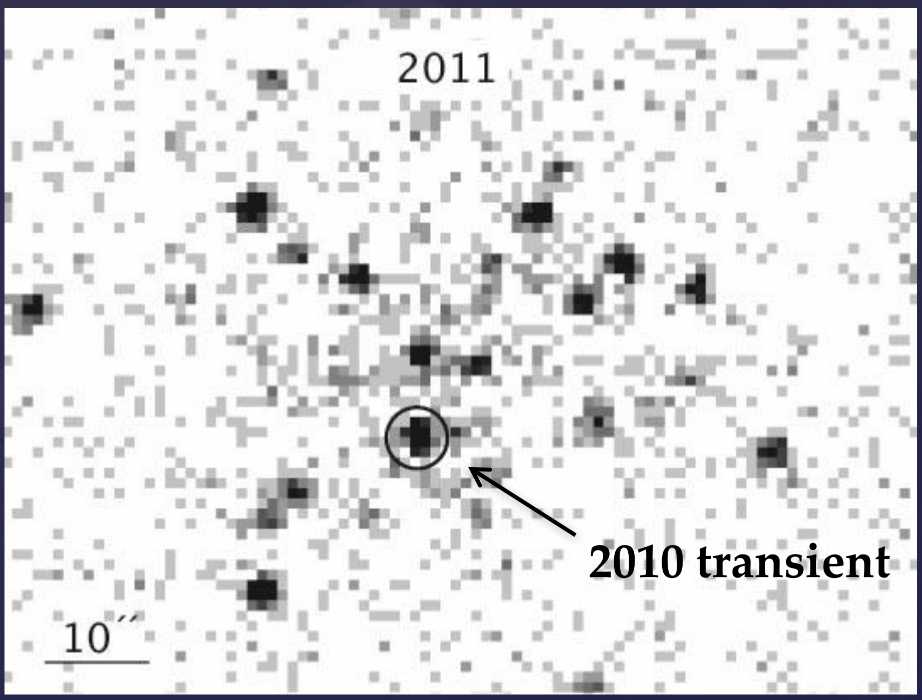
Hard powerlaw:
- Contributes 0-100%
- Varies widely between sources
- Correlated with luminosity?

AMXPs:
>50% powerlaw
- Pulsar wind mechanism
- Accretion onto the magnetosphere?

Pre- and post-outburst images

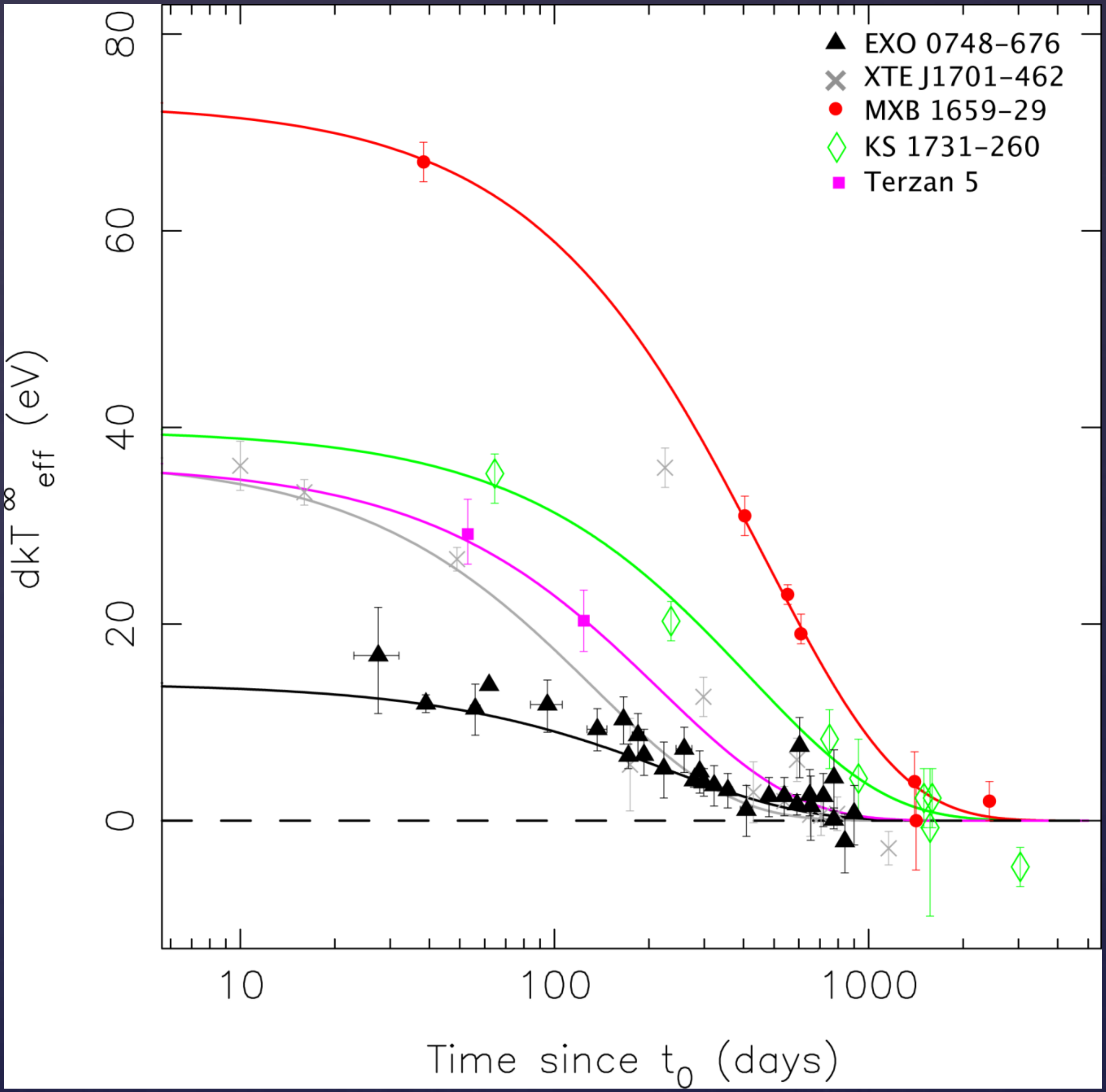


~64 weeks prior to the 2010 outburst

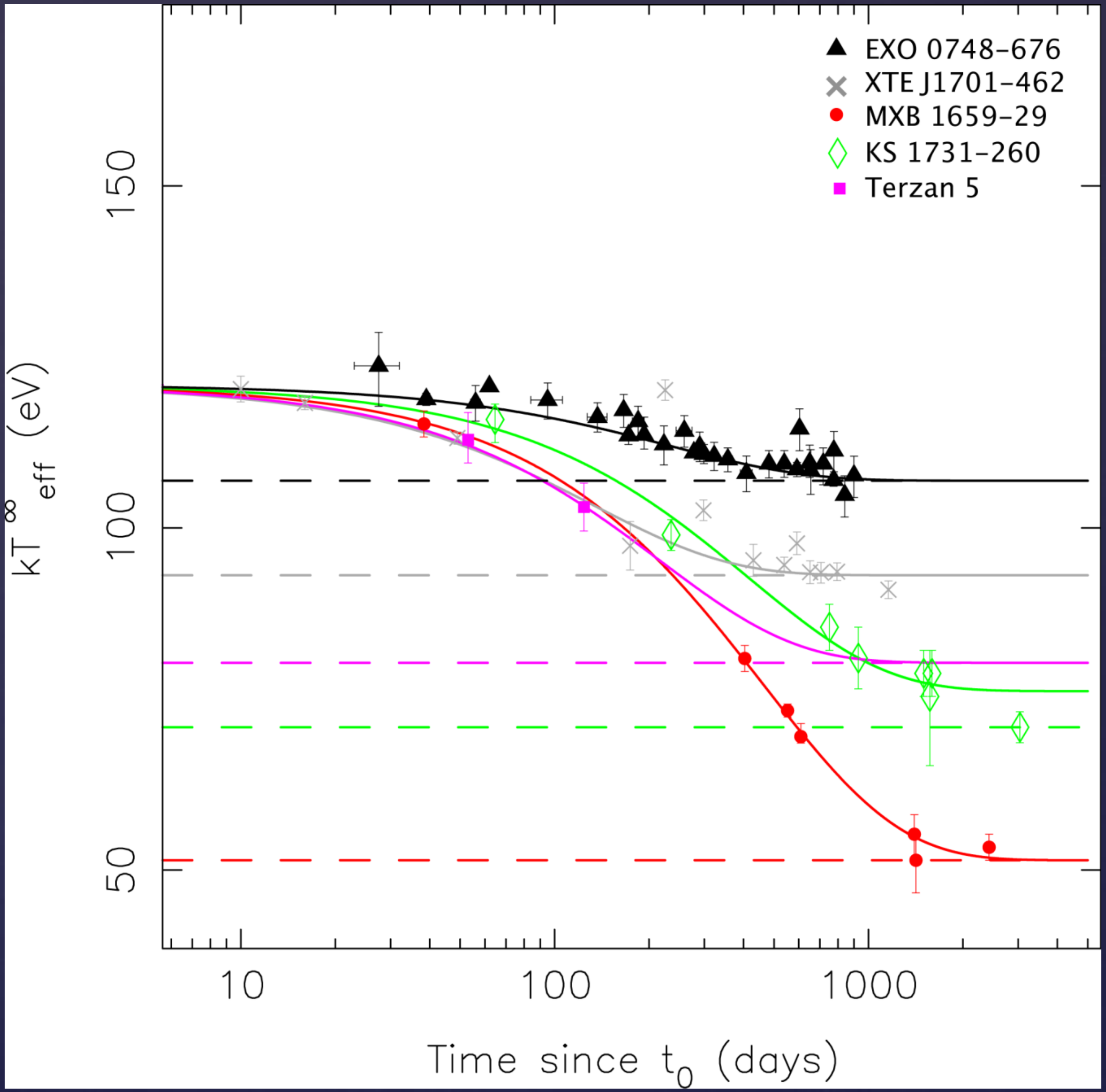


~8 weeks after the 2010 outburst

(exposure times are similar)



EXO 0748-676
XTE J1701-462
MXB 1659-29
KS 1731-260
Terzan 5
80
60
40
20
0
dkT∞eff (eV)
10
100
1000
Time since t0 (days)


EXO 0748-676
XTE J1701-462
MXB 1659-29
KS 1731-260
Terzan 5
150
100
50
$kT^{\infty}_{\rm eff}$ (eV)
10
100
1000
Time since t_0 (days)