Crust cooling and the neutron star interior: open issues

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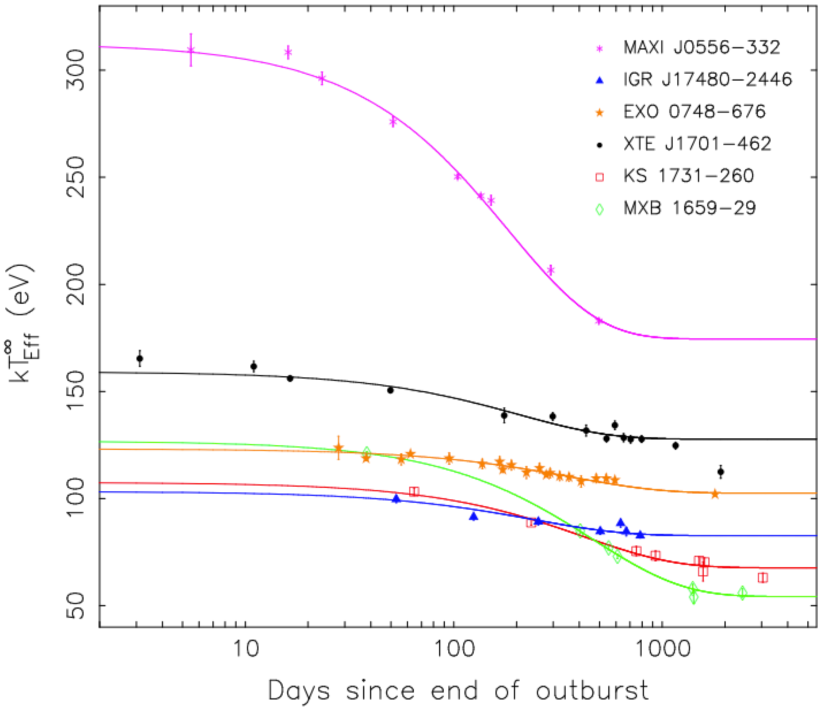
We now have several accreting neutron stars that have been observed to cool over months to years after accretion turns off

This talk:

What have we learned? What are the open questions?



Homan et al. (2014)

Outline

- overview of crust cooling
- thermal conductivity / impurity level of the crust
- fitting multiple outbursts
- physics of the inner crust
- core heat capacity and neutrino emissivity
- magnetar outbursts

Using transient events to constrain neutron star interiors

Lots of progress on neutron star masses and radius:

- >2 solar mass neutron stars
- tidal deformability in mergers
- NICER radius measurement
- moment of inertia

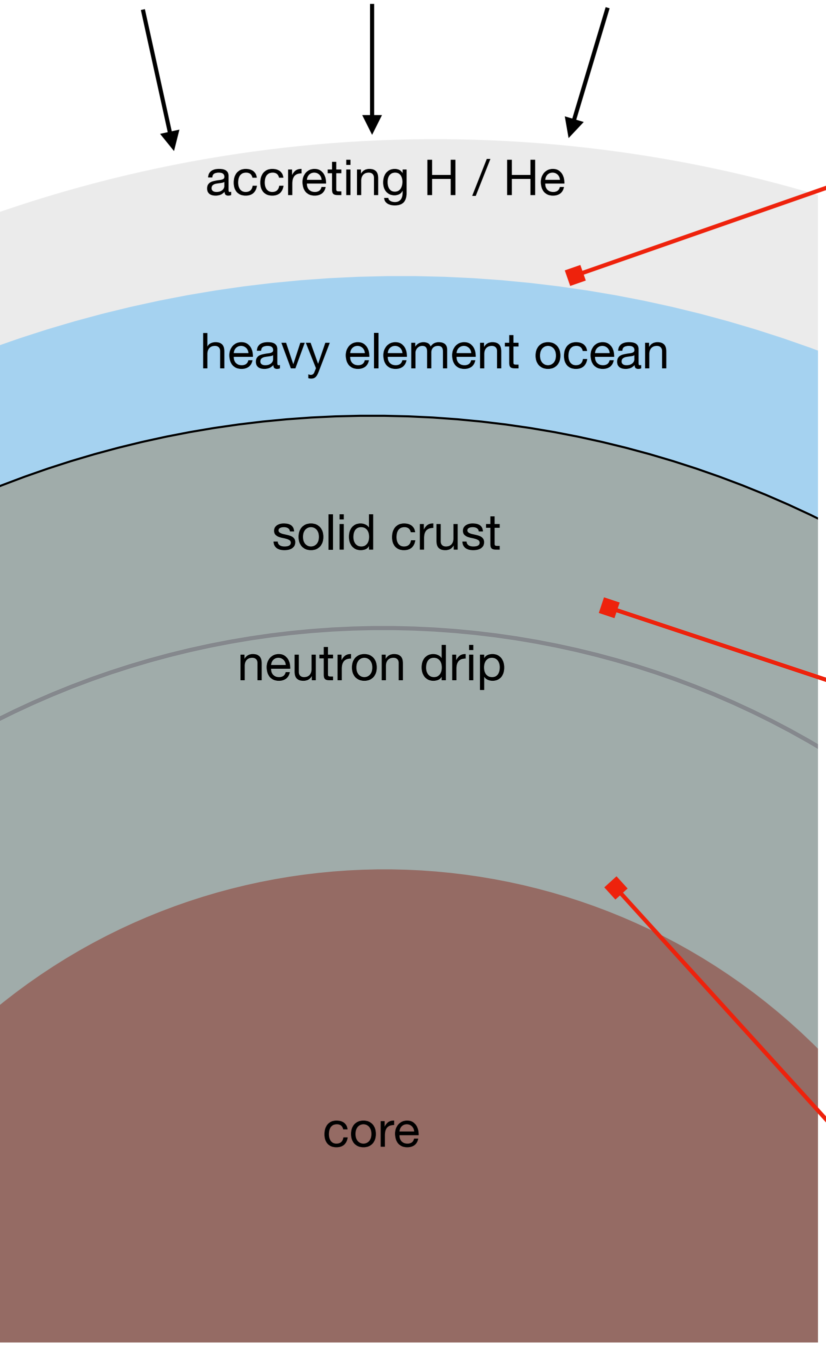
Studying the response of the star to a transient event provides a way to go “beyond the EOS” to constrain things like:

- the state of matter (superfluidity)
- particle content
- transport properties

Many different types of transient events:

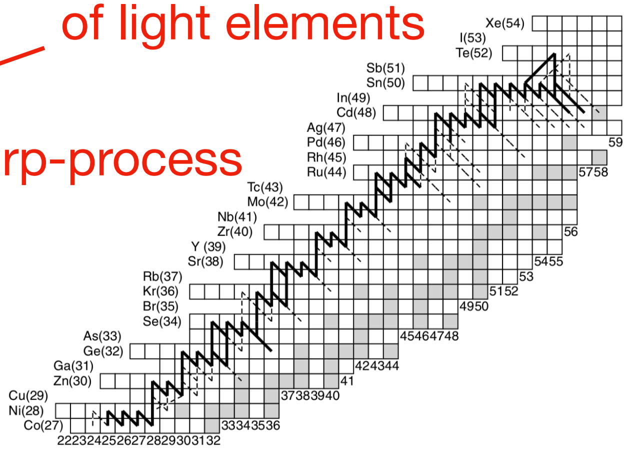
- cooling from birth
- mergers
- glitches
- magnetar outbursts
- cooling after accretion outbursts

Accreting neutron stars as nuclear physics laboratories

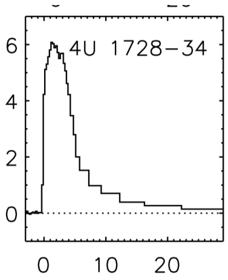


thermonuclear burning of light elements

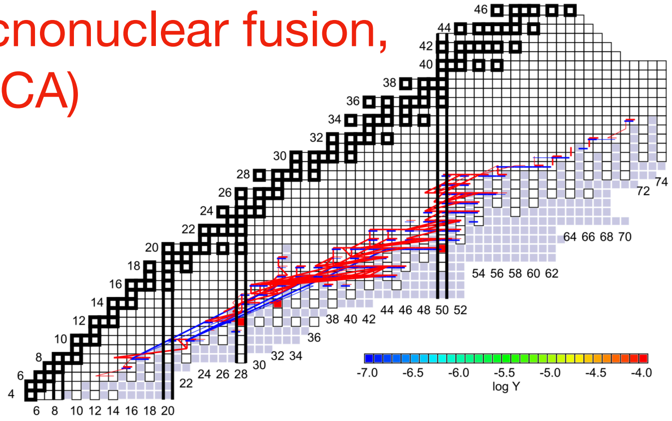
rp-process



Type I X-ray bursts and superbursts while accreting



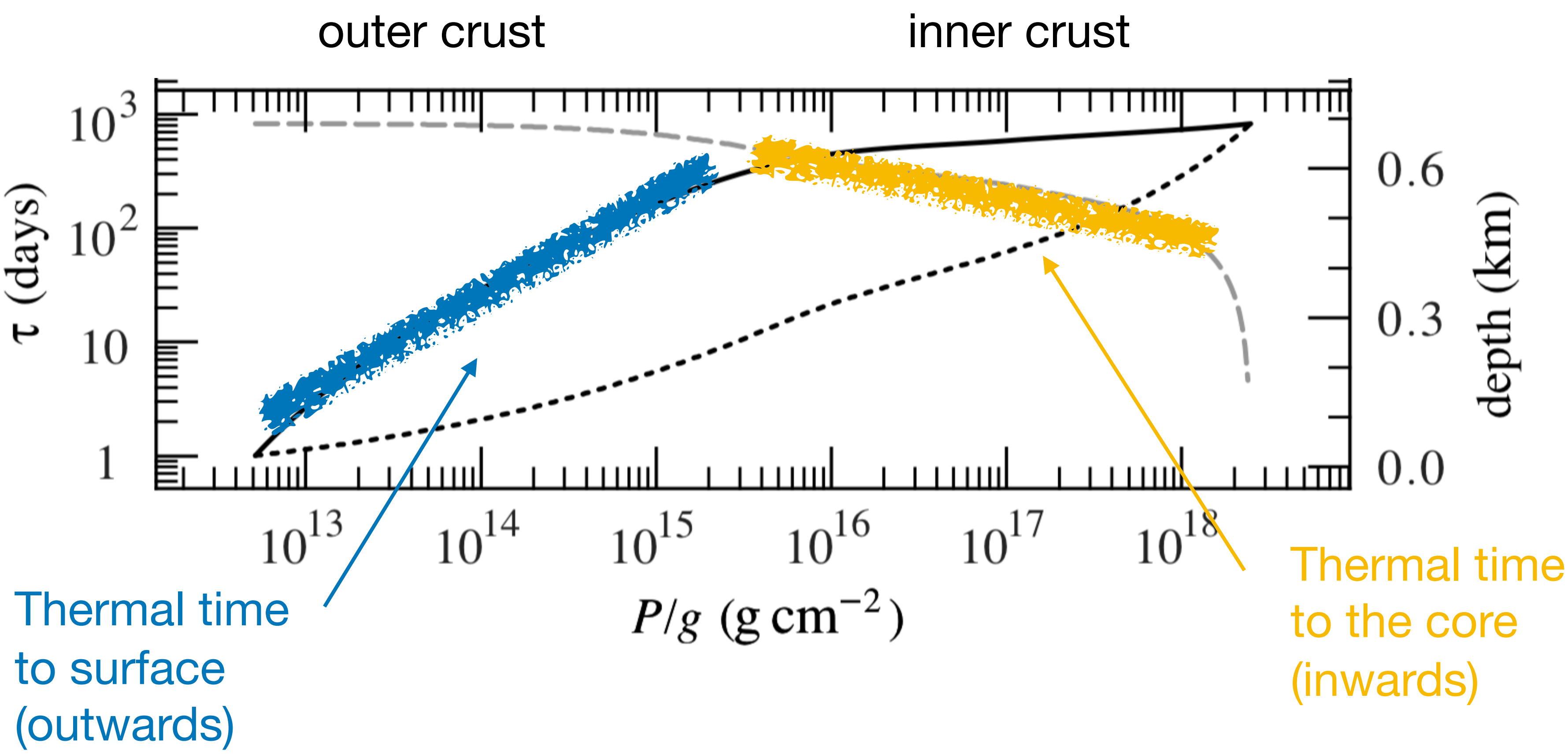
crust reactions (electron captures, pycnonuclear fusion, URCA)



cooling in quiescence

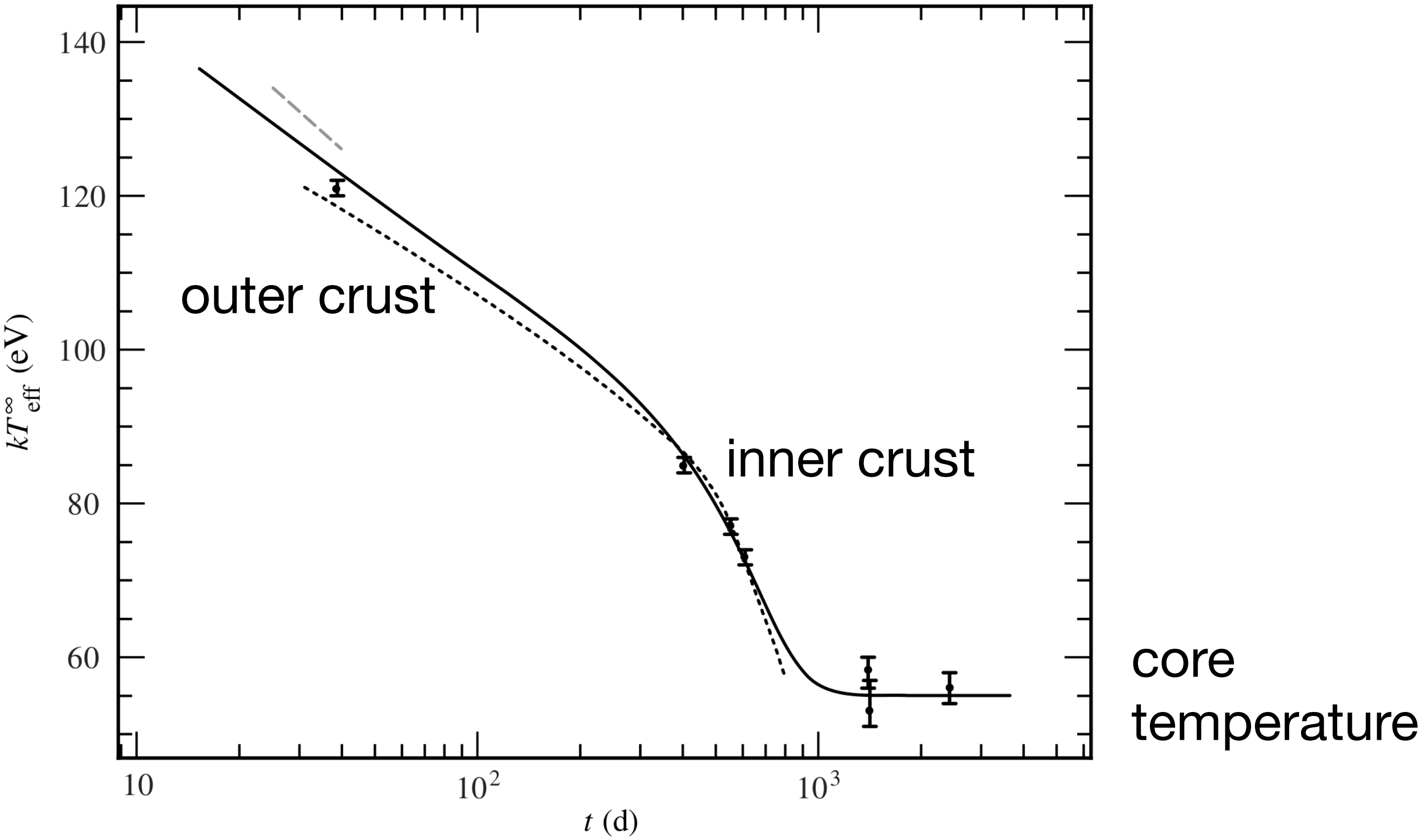
complex phases/deformed nuclei (pasta); transition into core matter

Crust cooling: different timescales probe different depths



Brown & Cumming (2009)

Crust cooling: different timescales probe different depths



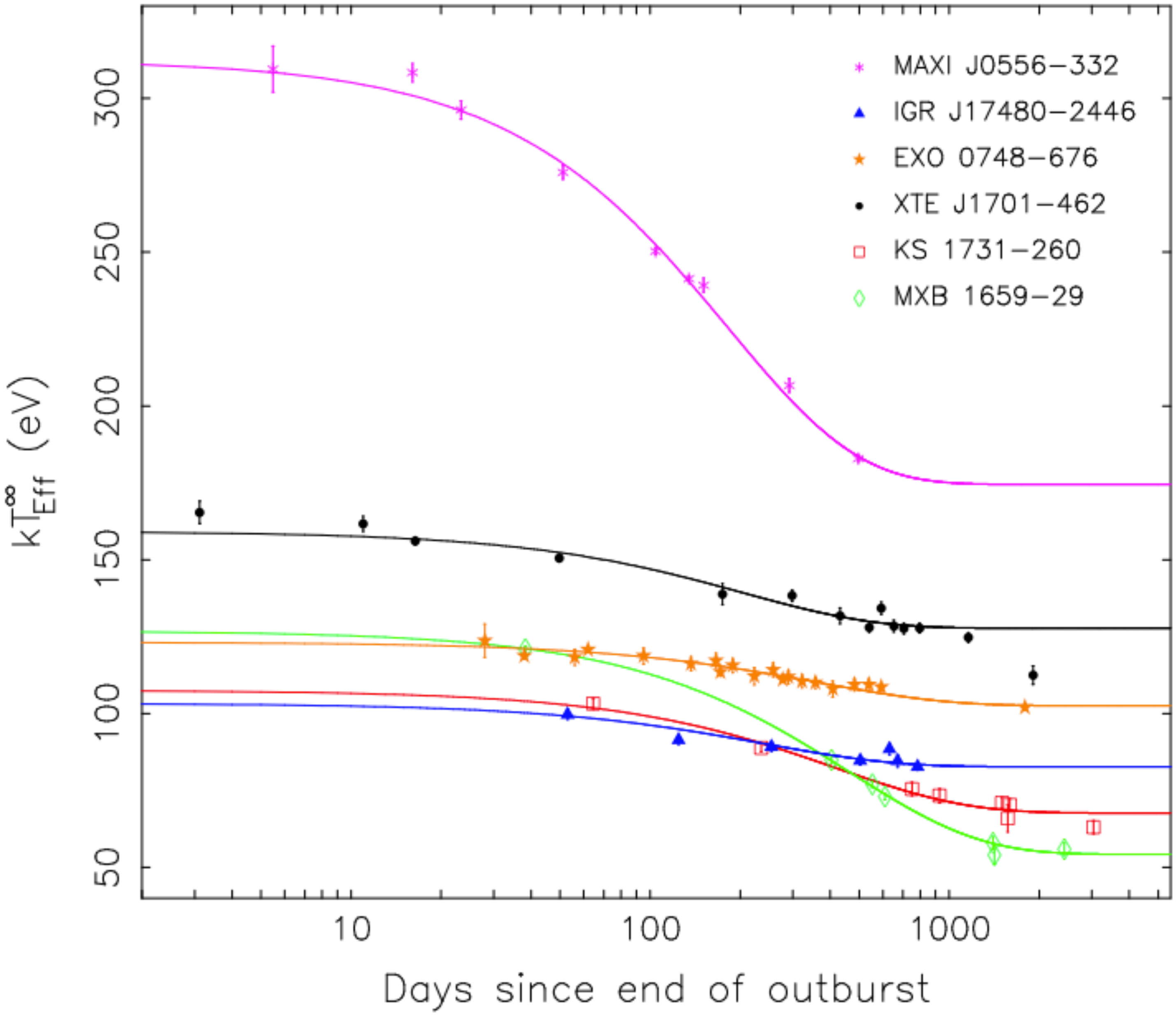
cooling curve tells us the temperature profile
at the end of the accretion outburst

$$L(t) \leftrightarrow T(\rho)$$

Brown & Cumming (2009)

Observed cooling curves

Homan et al. (2014)



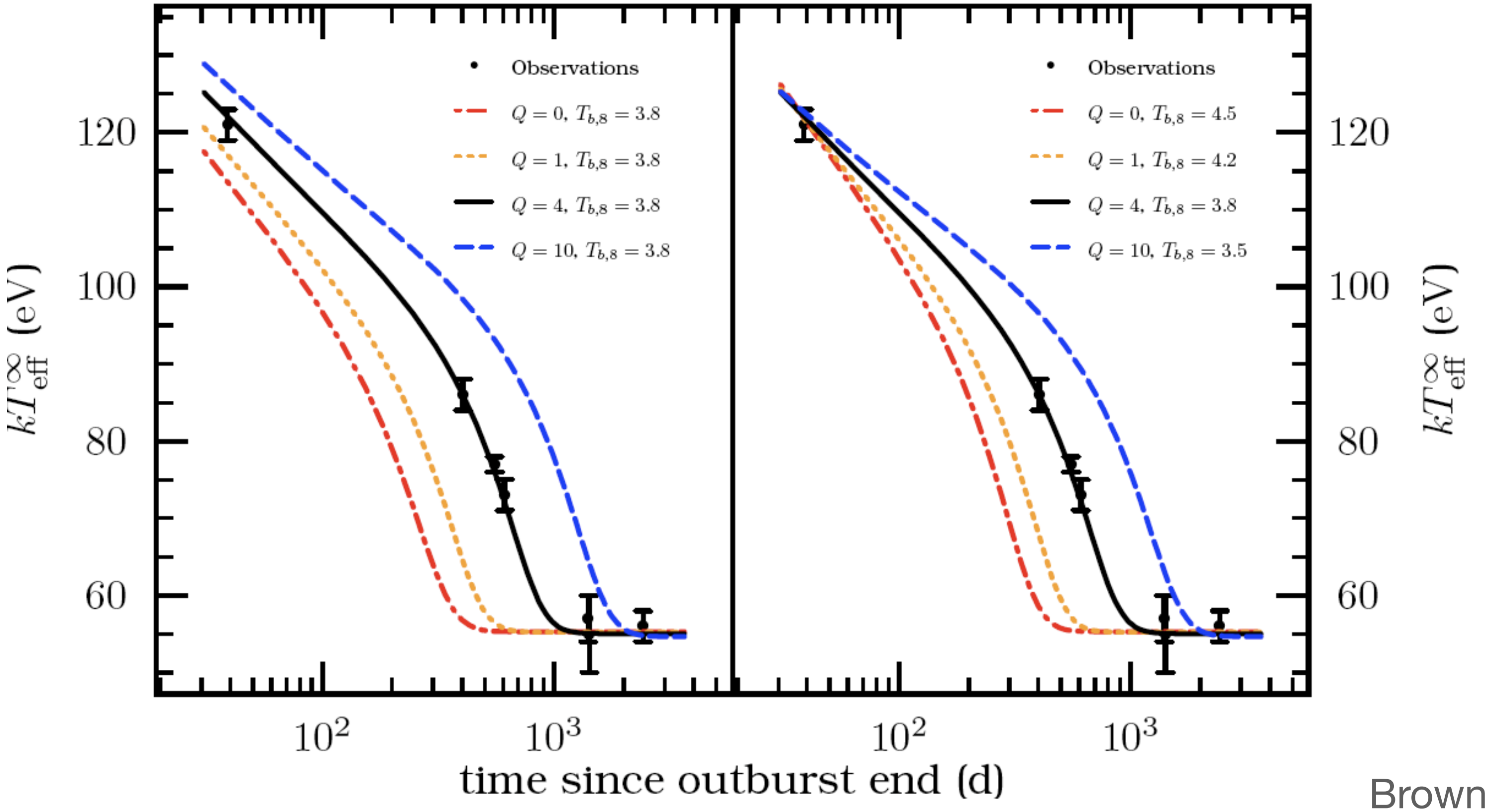
1. Thermal conductivity of the crust

The cooling timescale => crust has to be relatively pure: not amorphous

Impurity parameter $Q_{\rm imp} \equiv n_{\rm ion}^{-1} \sum_i n_i (Z_i - \langle Z \rangle)^2$ is <10

Smaller than expected: $Q_{\rm imp}$ ~ 100 in rp-process ashes

$Q_{\rm imp}$ ~ Z^2 ~ 1000 for amorphous solid



Brown & Cumming (2009)

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actually measure

$$t_{\rm cool} \propto H^2 Q_{\rm imp}$$

$$\propto \frac{Q_{\rm imp}}{g^2}$$

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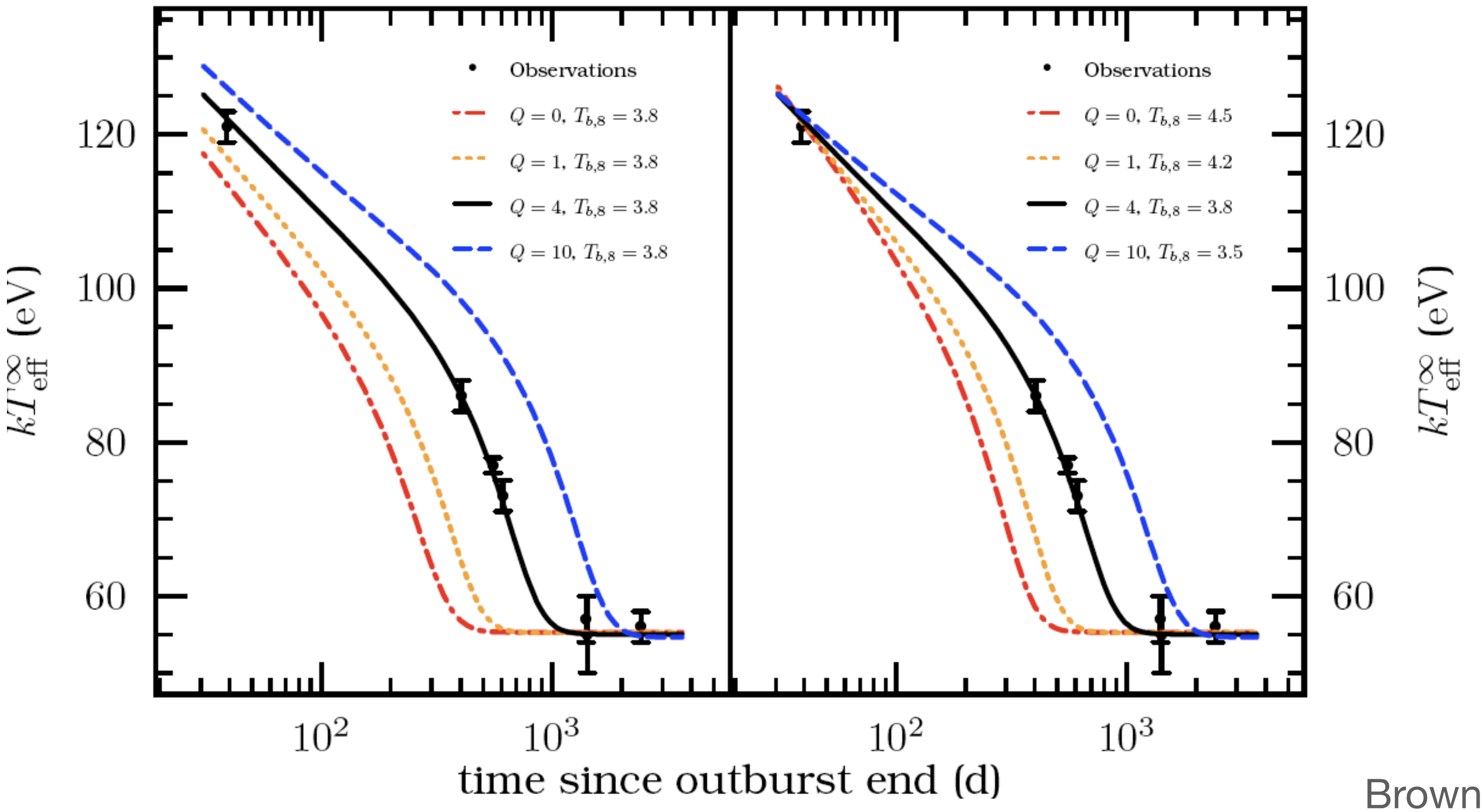
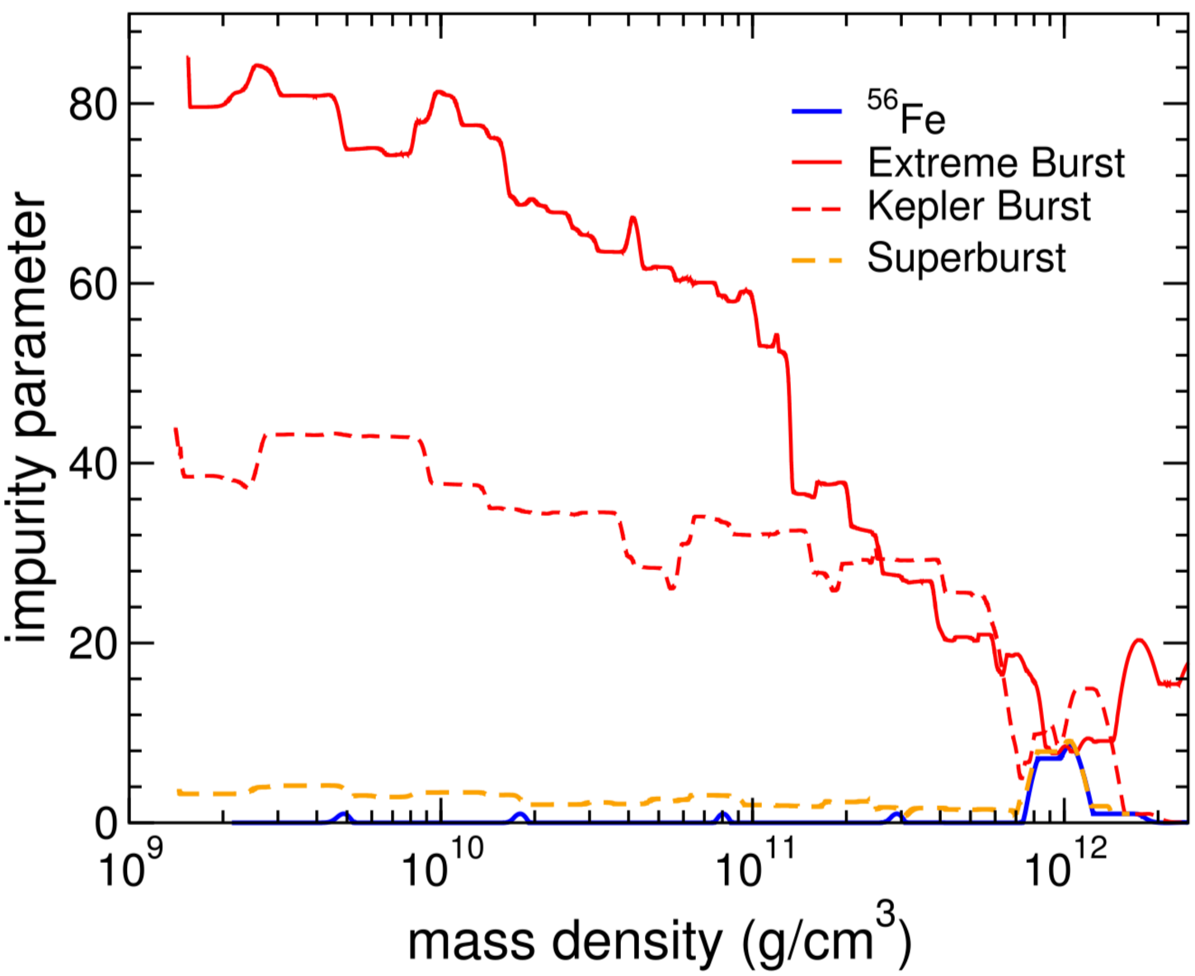


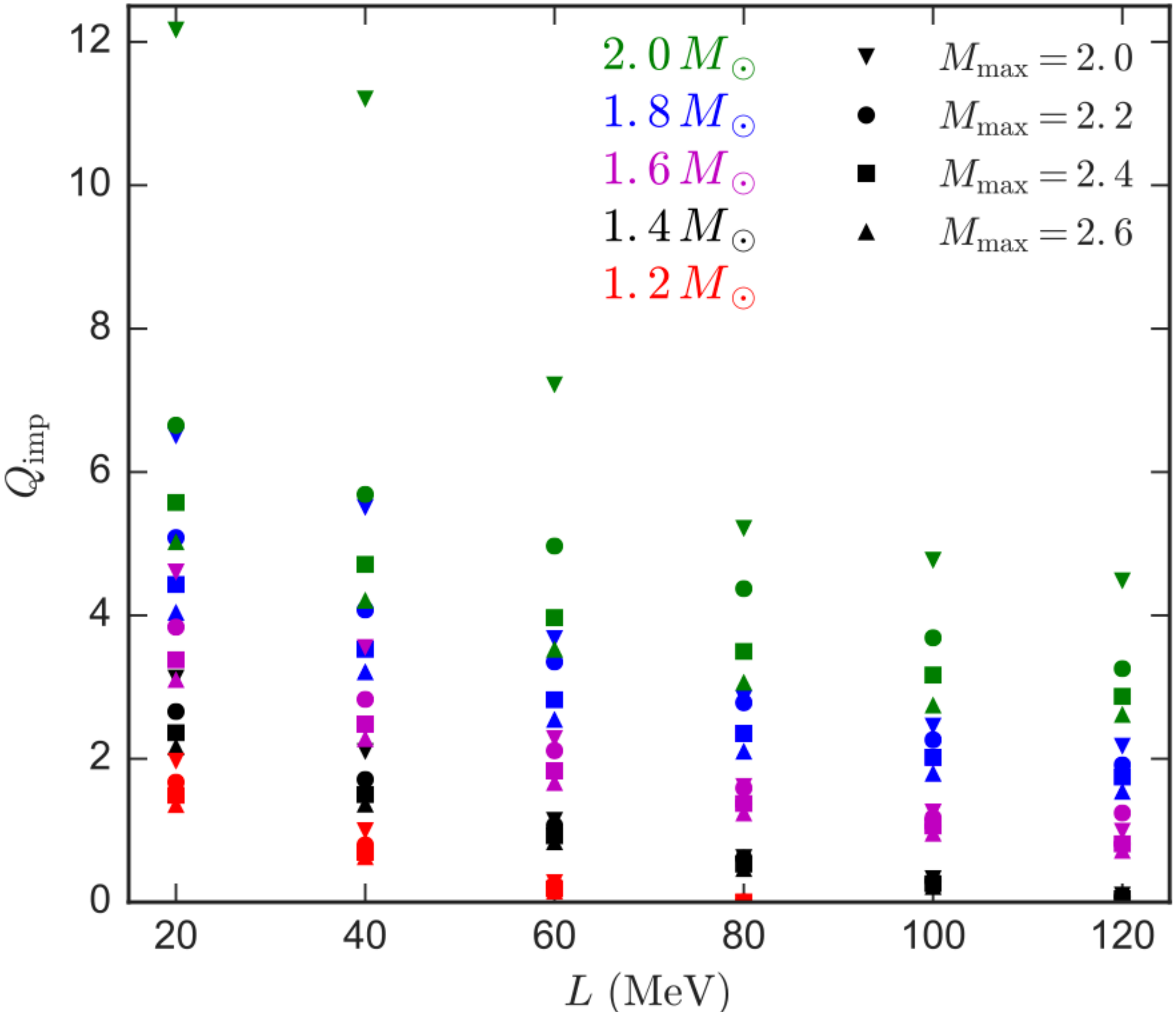
Brown & Cumming (2009)

Nuclear processing of the mixture leads to reduced Q_{imp} in the inner crust



Lau et al. (2018) (see also Jones 2005, Gupta et al. 2008, Horowitz et al. 2009, Steiner 2012)

Fits to MXB 1659-29 with self-consistent nuclear EOS for core and crust



Cumming & Newton, in prep

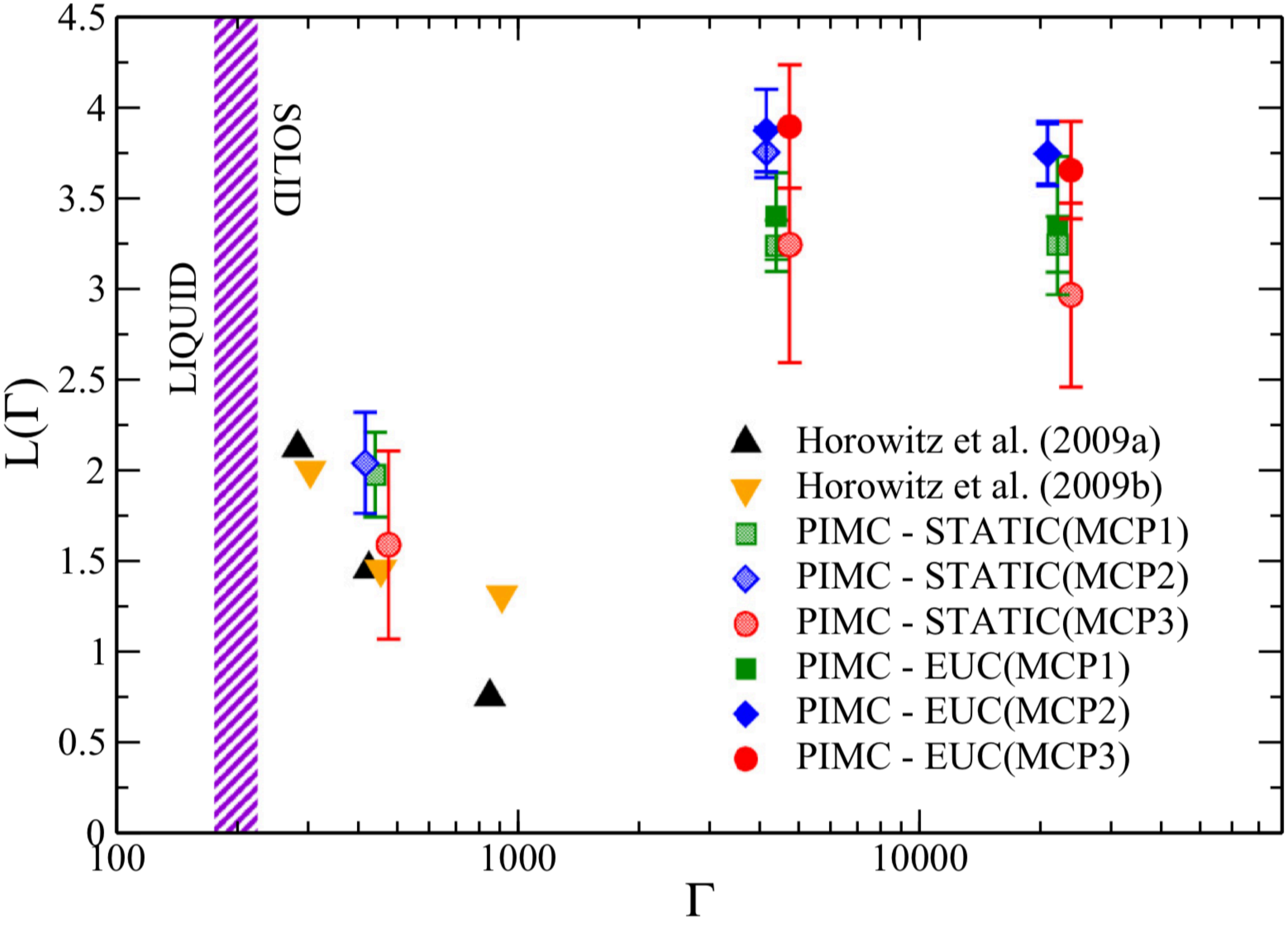
(for EOS parameterized by L, $M_{\rm max}$, see Newton, Steiner, Yagi 2018)

in principle both axes can be calculated from nuclear physics !

The impurity parameter formalism for thermal conductivity assumes a low level of uncorrelated impurities in a majority lattice. Taking into account correlations between difference species gives a modified “effective impurity parameter”

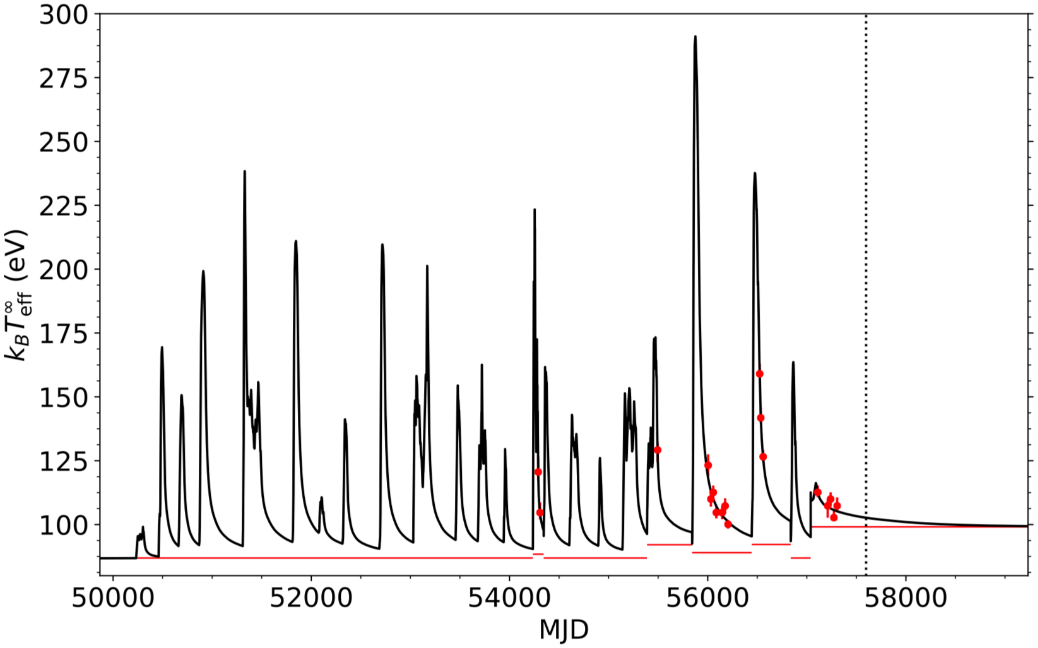
$$\widetilde{Q}_{\rm imp} = L\,Q_{\rm imp}$$

Roggero & Reddy (2016)



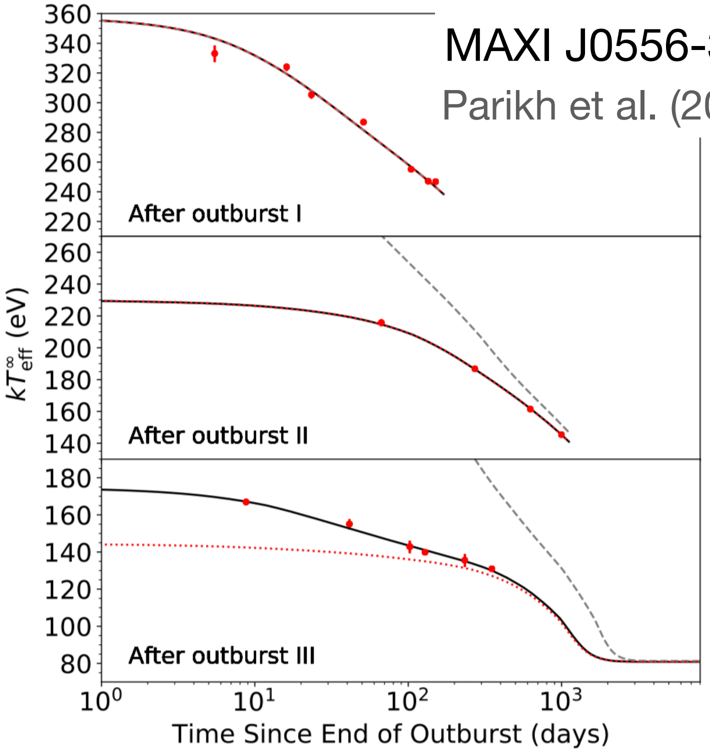
2. Fitting multiple sources and outbursts: shallow heating

Can fit all sources with common crust model, but with a caveat: introduce an unknown source of shallow heating to heat the outer layers of the crust



Aql X-1

Ootes et al. (2018)

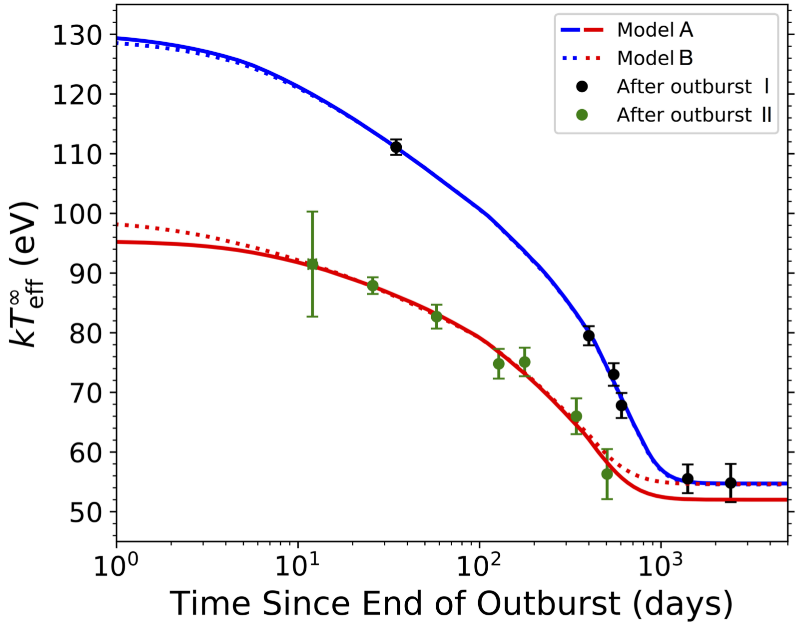


MAXI J0556-332

Parikh et al. (2017)

MXB 1659-29

Parikh et al. (2018)



(and Turlione et al. 2015 for fits to multiple sources)

2. Fitting multiple sources and outbursts: shallow heating

Can fit all sources with common crust model, but with a caveat: introduce an unknown source of shallow heating to heat the outer layers of the crust

The shallow heat source is needed to explain the early time temperatures
Typical values are ~1 MeV per accreted nucleon
One source MAXI J0556-332 needs ~ 10 MeV per accreted nucleon for one outburst

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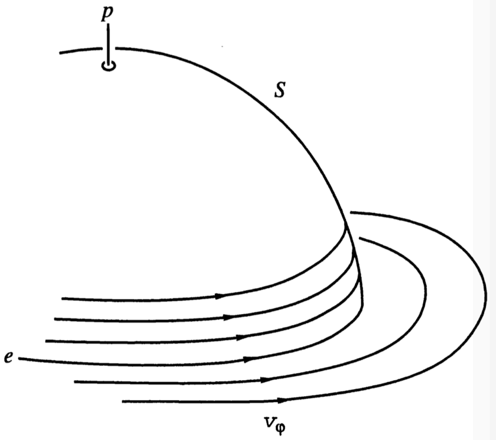
Physical mechanism: UNKNOWN!
Energy of 10 MeV rules out nuclear

Plenty of energy in incoming gas (GM/R~100 MeV per nucleon), could be related shear between the star and the accretion disk (Inogamov & Sunyaev 2008)
Challenge is to deposit this energy so deep in the envelope (at densities ~ 10^9 g/cm^3)

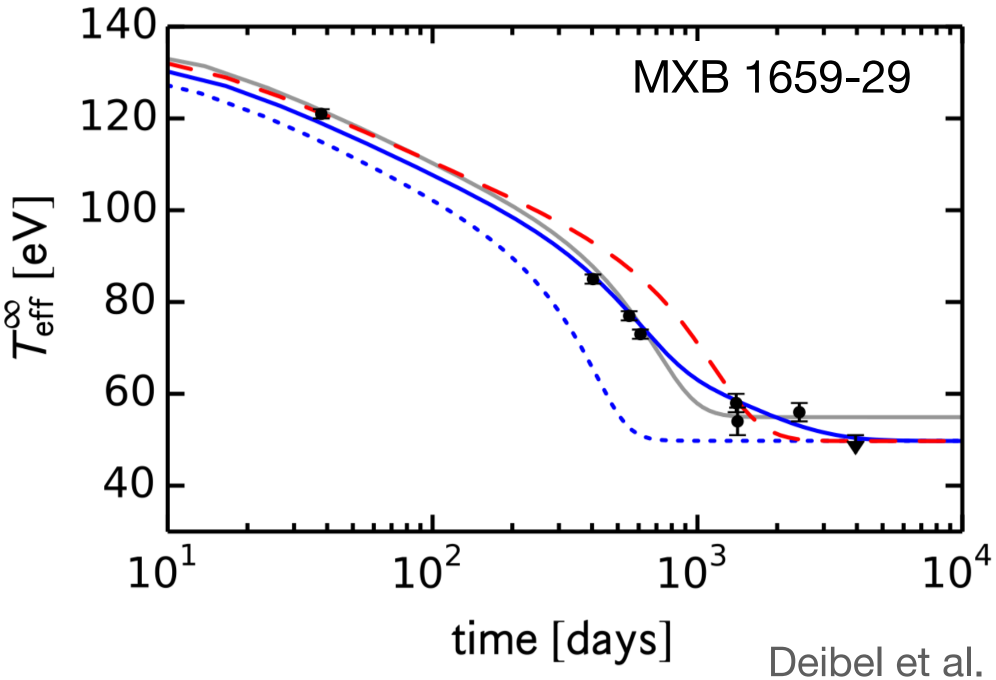


3. Late time cooling: inner crust properties

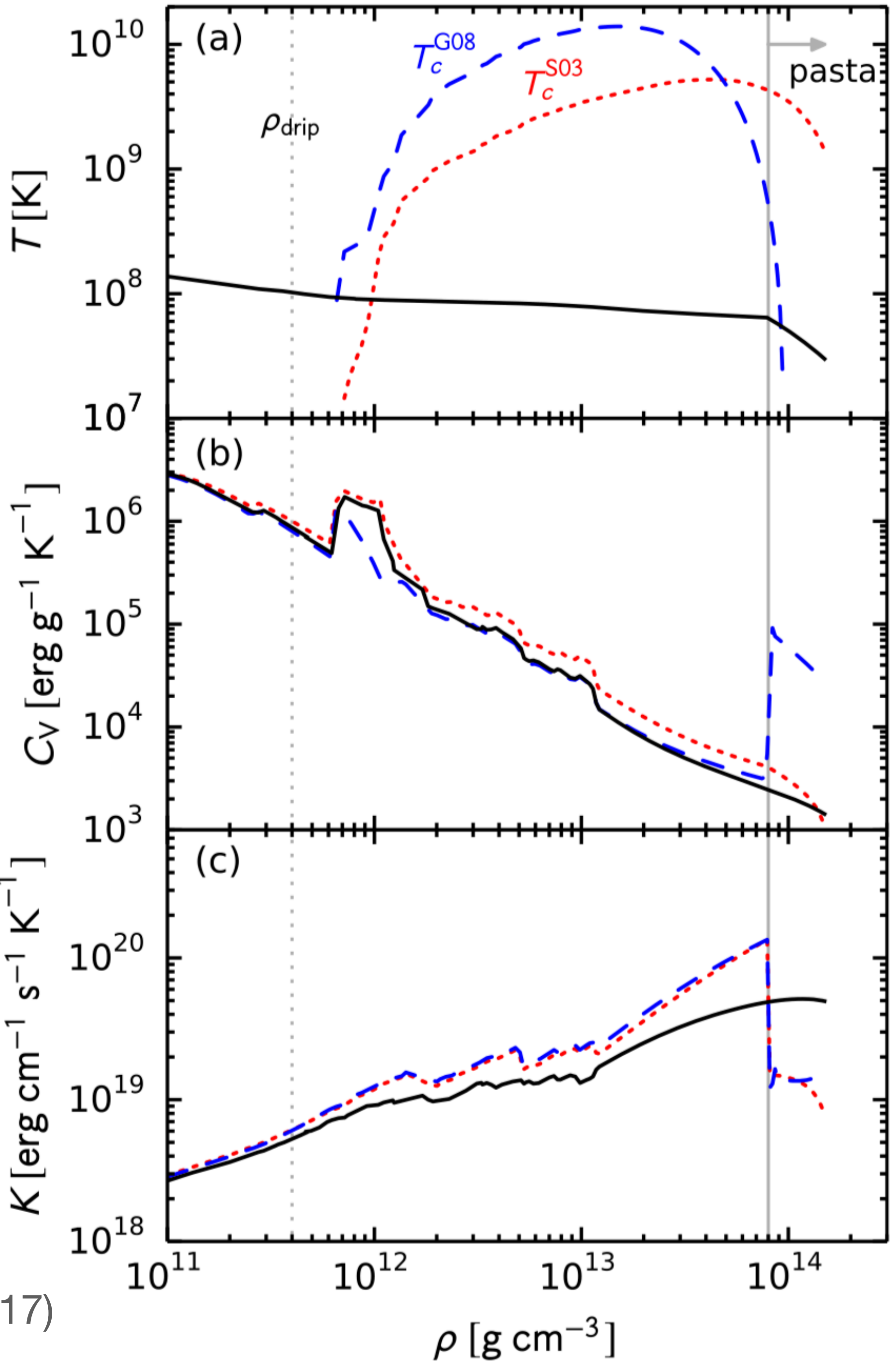
The cooling timescale of the inner crust can be much longer if:

- there are normal neutrons at the base of the crust (gap closes before the crust/core transition)
- the thermal conductivity is low at the base of the crust (pasta?)

Pons et al. 2013; Horowitz et al. 2015



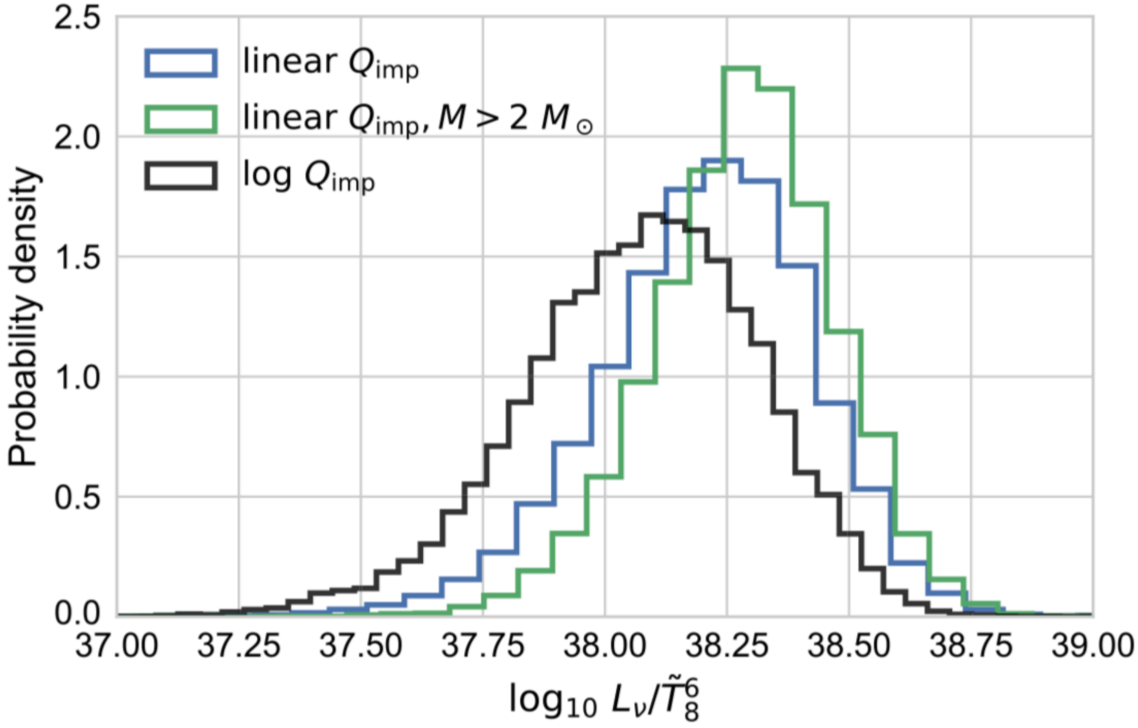
Deibel et al. (2017)



4. Core physics: heat capacity and neutrino emissivity

See talk by E. Brown

Modeling the outburst decay gives us confidence we understand the temperature profile in the crust and energy flowing into the core during outburst.



Brown et al. (2018)

5. Another class of cooling transients: magnetars

Magnetar outbursts are often well-fit with crust cooling models; shape of the light curve is naturally reproduced

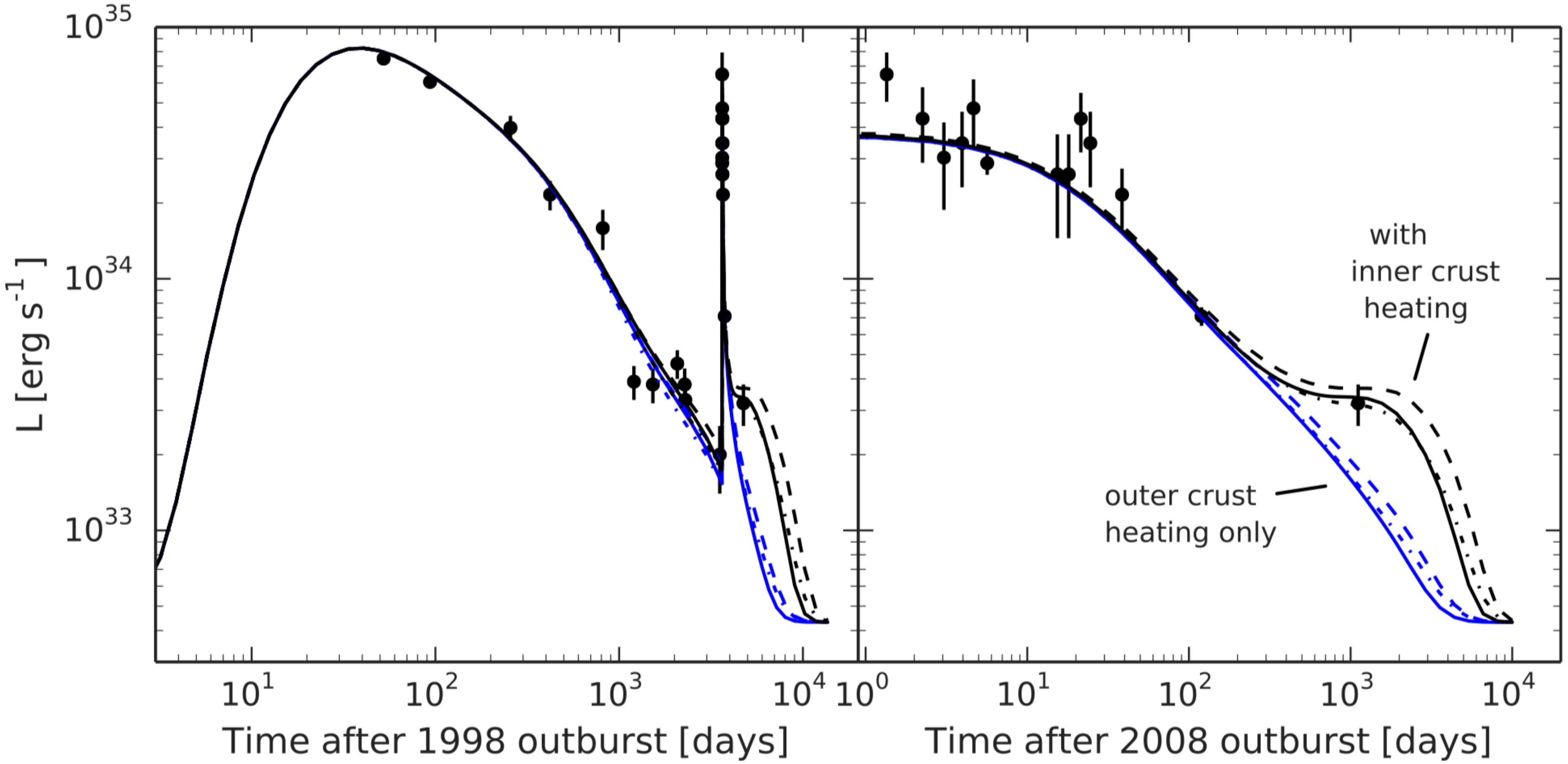
Many more sources (>20), outbursts can recur frequently, high cadence of observations

Open questions:

- Heating profile is not known (something we would like to learn about)
- Spectral behaviour doesn't always look like cooling, e.g. fairly constant T_{eff} but shrinking emitting area
- Contribution from magnetospheric emission can be significant and difficult to model

SGR 1627-41

An et al. 2012, Deibel et al. 2016, An et al. 2017

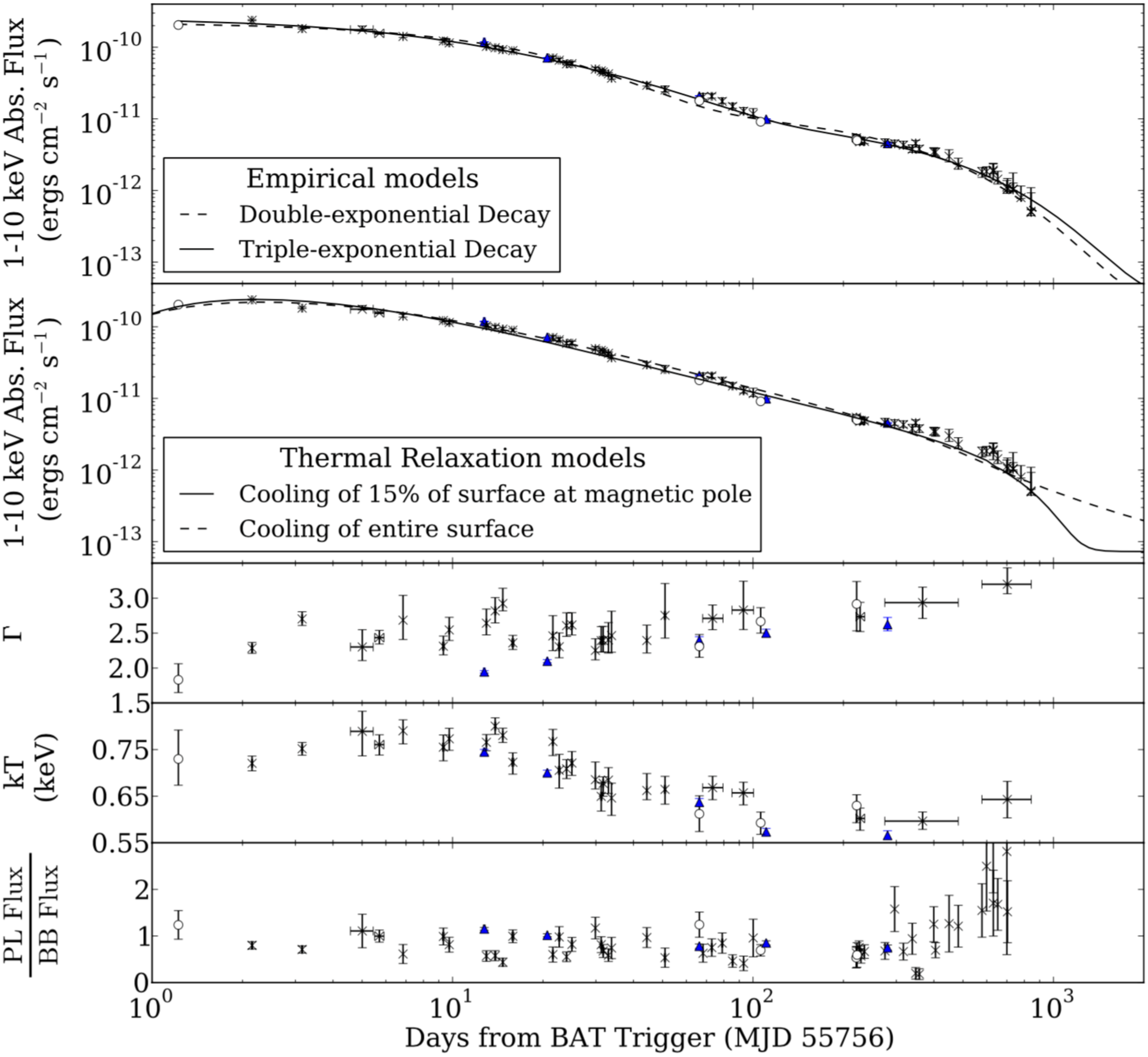


Deibel et al. (2017)

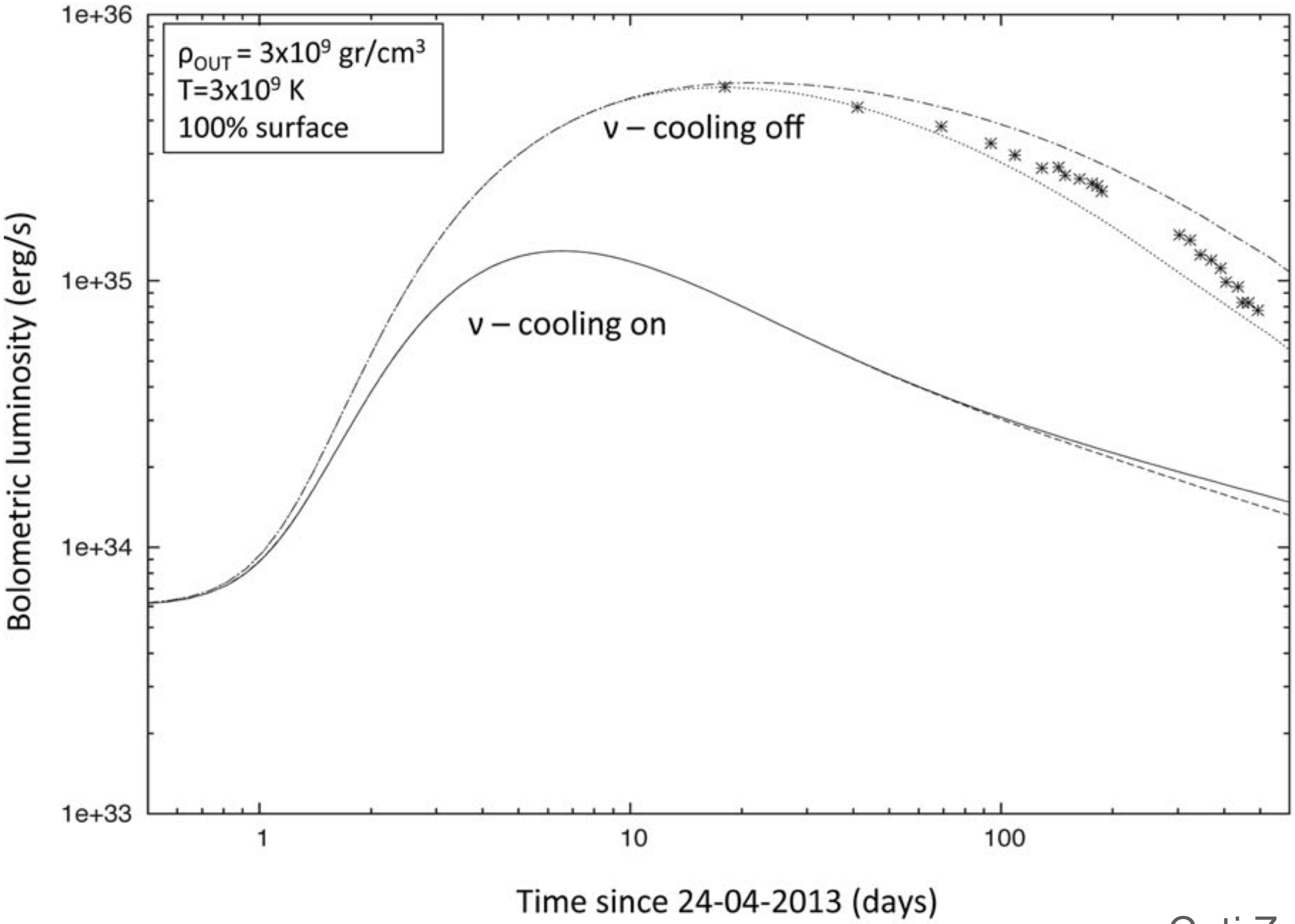
- energy in outer crust differs by an order of magnitude between outbursts, but is similar for the inner crust

Swift J1822.3-1606

Scholz et al. (2014)



The Galactic centre magnetar SGR J1745-2900 can be fit only if neutrino emission is turned off!



Coti Zelati et al. (2016)

Do we understand plasmon neutrino emission in strong B?

Kennett and Melrose (1998); Yakovlev et al (2001)

Summary

- We now have several sources that have been observed to cool into quiescence, some with multiple outbursts
- Thermal conductivity is generally consistent with Q_{imp} ~ O(1), limited by the fact that we don't know M and R.
- The inferred values of Q_{imp} are consistent with calculations of nuclear processing through neutron drip
- Major unsolved question is **origin of shallow heating**
- Deep crust: does the neutron gap close before the crust/core boundary; does the pasta layer have a low thermal conductivity? If so, the cooling of the inner crust can be slow enough to see it!
- Magnetars: a promising new sample of sources to study. Lightcurve shapes are naturally matched by crust cooling models but need to understand what's going on with the spectra
- May be worth revisiting neutrino emissivities (plasmon) with strong magnetic fields