Crustal cooling of neutron stars

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THERMAL AFTERGLOW FROM TRANSIENT ENERGY RELEASE IN NEUTRON STARS

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ABSTRACT

We consider thermal afterglow from transient energy releases in neutron stars, such as may result from glitches or gamma-ray bursts. If observable, thermal afterglow may provide important information on the nature of these events and on neutron star structure. For standard neutron star models, the energy released is either reradiated within a short time of at most hours for energy release near the surface, or most of the energy is stored in the deep interior and then reradiated over thousands of years. Intermediate time scales of order months are possible for afterglow, but only when the prompt afterglow accounts for a very small fraction of the total energy release, and enormous energy releases $\sim 10^{42}$ ergs are required to make the afterglow last much longer than a few hours. An observational program to detect afterglow will need to accommodate short time scales.

Subject headings: radiation mechanisms — stars: interiors — stars: neutron

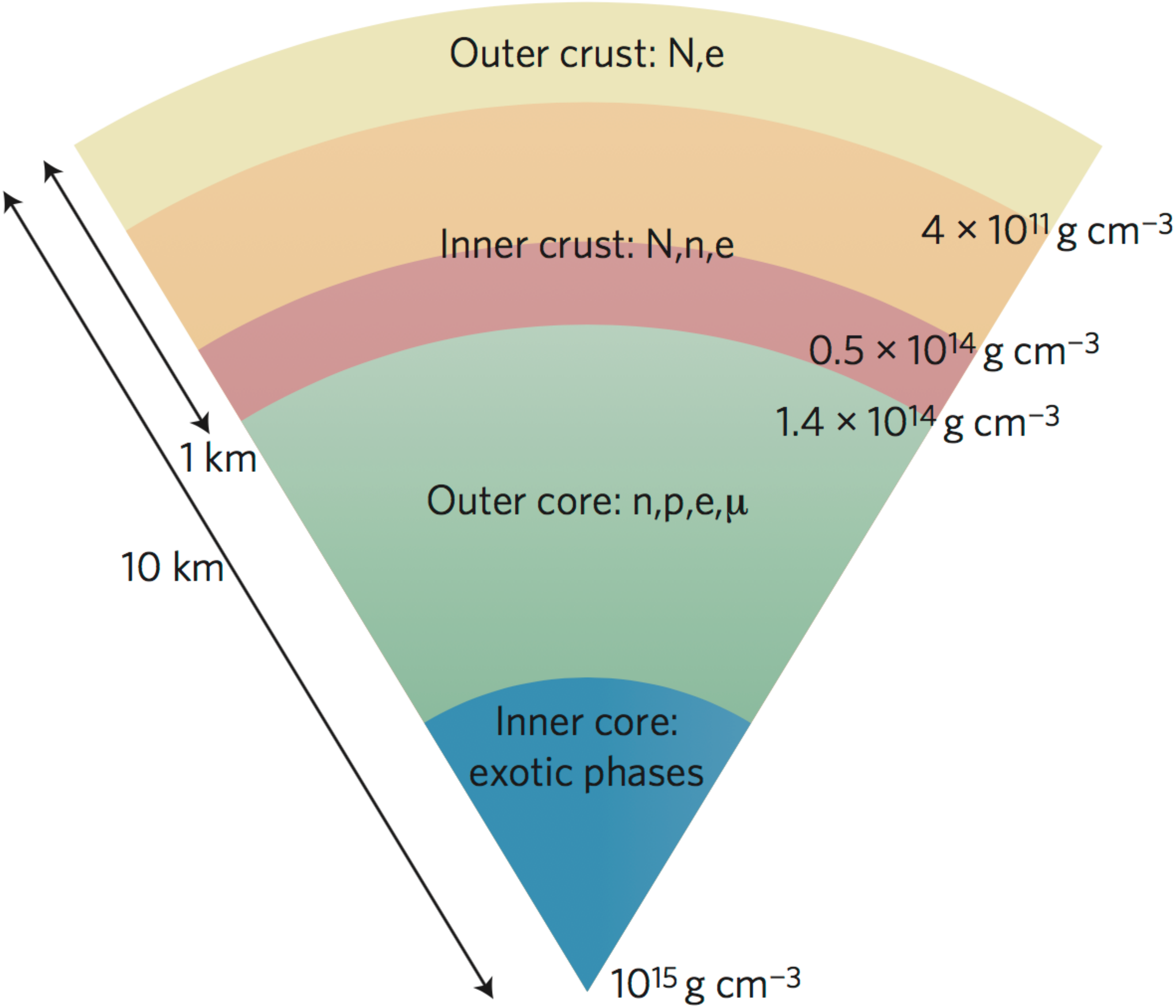
I. INTRODUCTION

The cooling of neutron stars represents one of the few available probes of the physics of their interiors. Much work has gone into calculating the expected cooling rates for young neutron stars following the supernova that creates them (Tsuruta 1980; Richardson 1980; Nomoto and Tsuruta 1981; Van Riper and Lamb 1981; Glen and Sutherland 1981). In virtually all of this work, the initial conditions correspond to a very hot interior, $T \gtrsim 10^9$ K as would be expected for a recently formed neutron star.

Apart from the original supernova, neutron stars may be subject to episodic energy release on a smaller scale, e.g., glitches, gamma-ray and X-ray bursts, starquakes from the shifting of the crust, and thermonuclear flashes. Because of their episodic and spatially local nature, aftergow from such

great, the energy is predominantly conducted into the deep interior of the neutron star and reradiated on a much longer time scale, that for global neutron star cooling. Equivalently, for a sufficiently large depth, neutrino cooling and/or uplifting becomes important if the energy release is too great, while downward conduction dominates if the energy release is too small.

We present the conditions for which the prompt electromagnetic afterglow represents a substantial fraction of the total energy release. Under these conditions, the time scale for the afterglow is generally very short (up to $\sim 10^4$ s, depending on the surface gravity and the amount of energy released), or very long ($> 10^3$ yr) for standard neutron star physics. The implications are that an observational program for observing this afterglow, if it is to have any chance of success, would require a



Newton (2013) Nat Phys

Outline

- Overview of cooling and what can learn
- Composition of the crust
- Shallow heating
- superfluid gaps and pasta
- magnetar cooling

Two types of sources we can use to study cooling:

Accreting neutron stars

$$E_{\rm dep} = \dot{M}\,\Delta t\,Q_{\rm nuc} \sim 10^{43}\ {\rm erg}$$

for a one year outburst

Magnetars

Typical outburst energies are $> 10^{42}\ {\rm erg}$

Energy source probably magnetic field decay, mechanism not understood

(Crust cooling also occurs just after neutron star birth, and would also be a probe of crust structure if it were to be observed, e.g. Lattimer et al. 1994)

What can we learn from cooling curves?

Cooling timescale

crust thickness

heat capacity

$$t_{\mathrm{cool}} = \frac{H^2}{\kappa} \propto \frac{C_P}{g^2 K}$$

thermal
conductivity

gravity

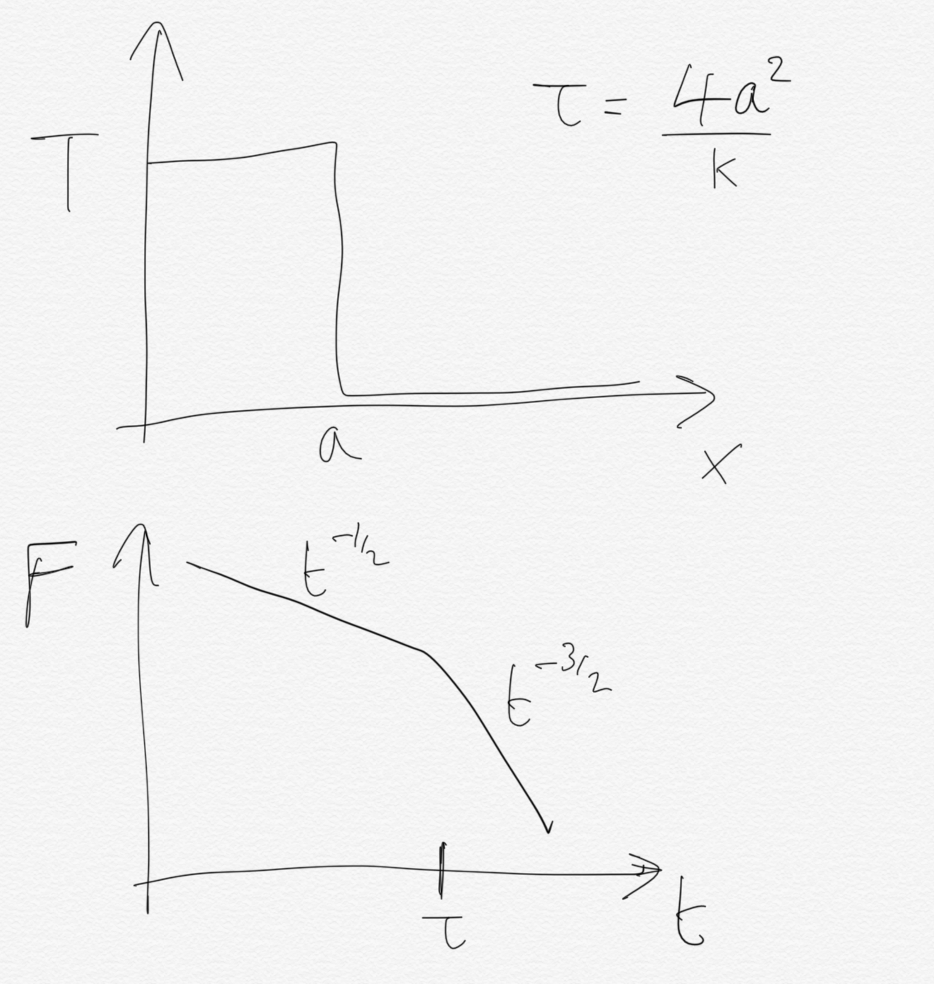
neutrino cooling could
also be important

$$t_\nu \sim \frac{C_P T}{\epsilon_\nu}$$

neutrino
emissivity

What can we learn from cooling curves?

Toy problem:



=> features in the light curve can tell you about particular locations, e.g. heat sources, changing heat capacity or thermal conductivity

Neutron star crust

H/He

$10^5\ \mathrm{g\ cm^{-3}}$

heavy element ocean
(rp ashes)

C burning

solid forms

$10^9\ \mathrm{g\ cm^{-3}}$

outer crust
(nuclei + electrons)

neutron drip

$3 \times 10^{11}\ \mathrm{g\ cm^{-3}}$

inner crust
(nuclei + electrons +
superfluid neutrons)

$\sim 5 \times 10^{13}\ \mathrm{g\ cm^{-3}}$

pasta (non-spherical nuclei)

$10^{14}\ \mathrm{g\ cm^{-3}}$

core

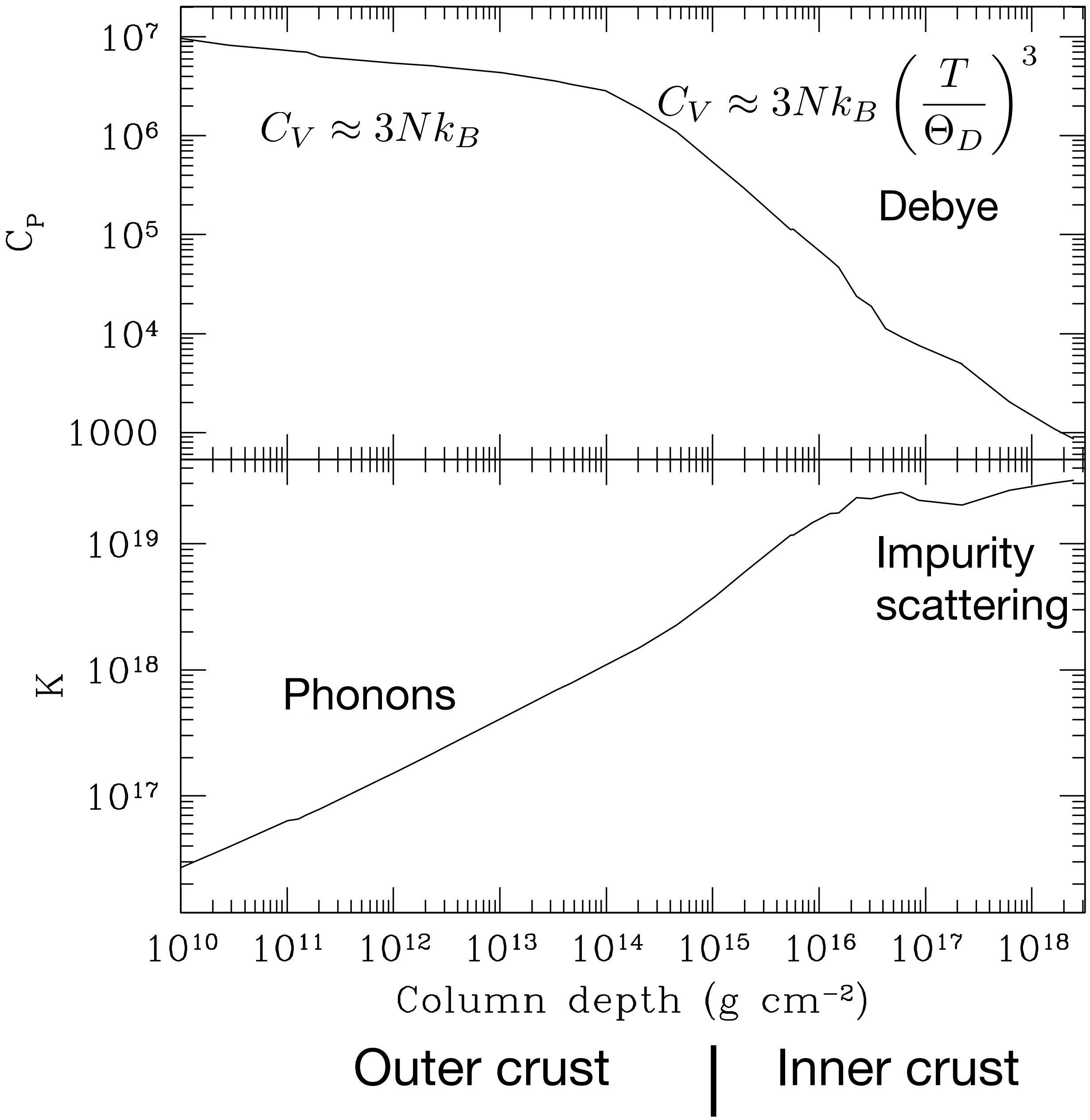
Heat capacity and thermal conductivity in the crust

thermal time

$$\tau = \left[\int_0^z \left(\frac{\rho C_P}{4K}\right)^{1/2} dz\right]^2$$

thermal conductivity

$$K = \frac{\pi^2}{3}\frac{n_e k_B^2 T \tau}{m_\star}$$



Models of crust cooling

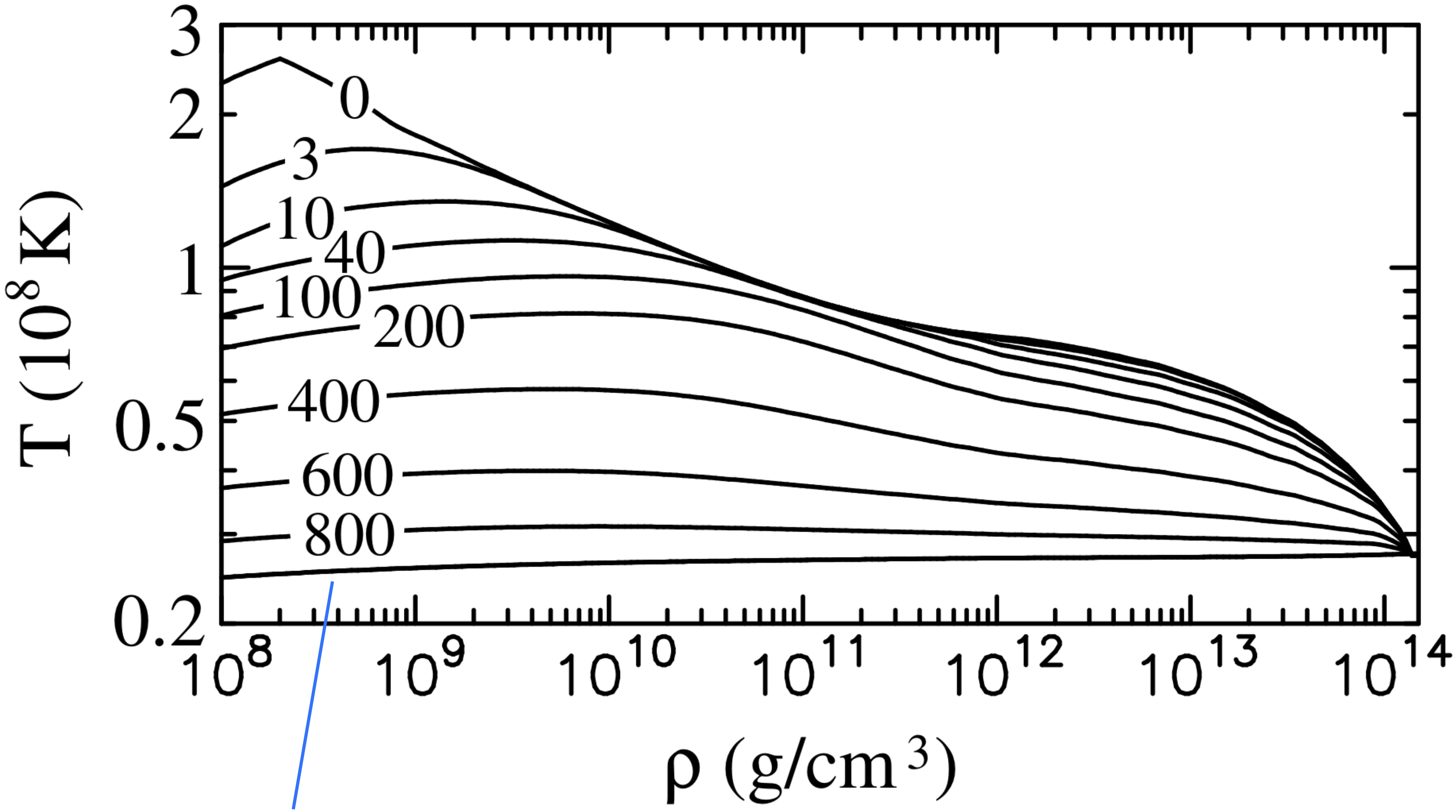
$$C_V \frac{\partial T}{\partial t} = Q_h - Q_\nu - \frac{1}{4\pi r^2}\frac{\partial L}{\partial r}$$

$$F = -\kappa \frac{\partial T}{\partial r} \quad \text{with} \quad L = 4\pi r^2 F$$

Shternin et al. 2007; Brown & Cumming 2009; Page & Reddy 2012, 2013; Pons & Rea (2012); Turlione et al. 2015

Codes available, e.g. `dStar` on github (based on MESA)
`crustcool` (includes B field for magnetars)
`NScool` (see Dany Page's website, does whole star)

Time evolution of the crust temperature profile



days after outburst

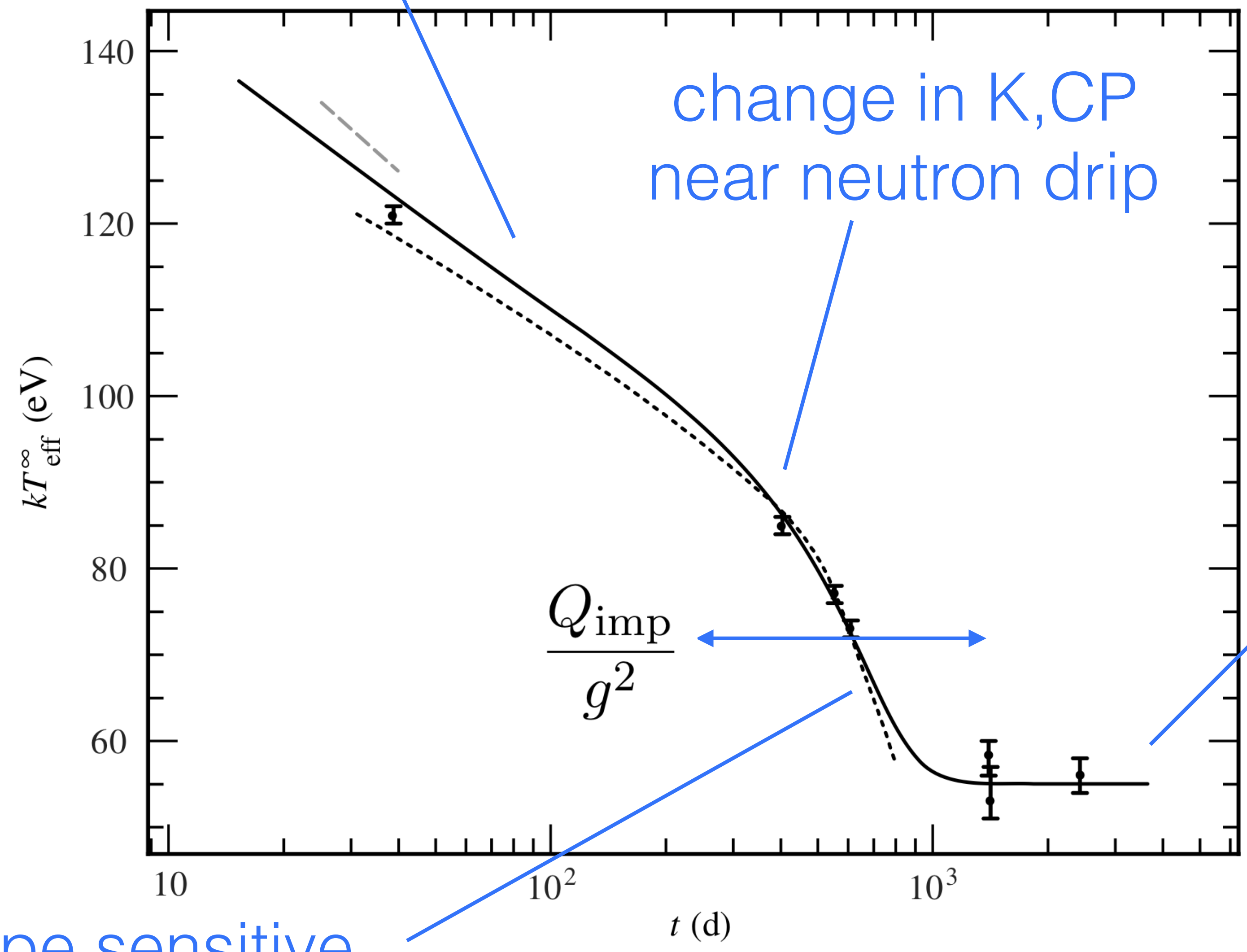
Page & Reddy (2012)

General shape of the cooling curve

outer crust

change in K,CP
near neutron drip

Tc, pasta



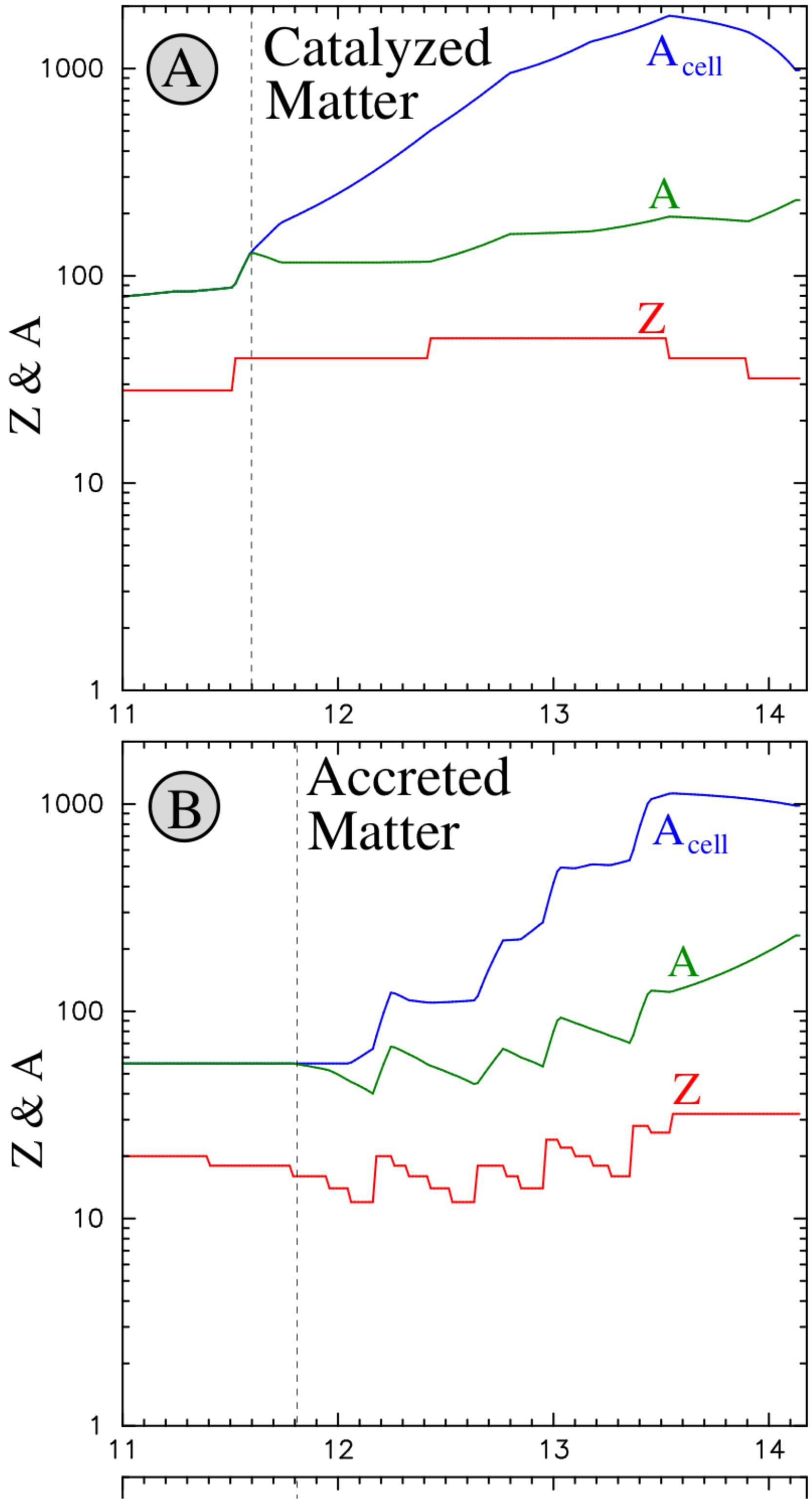
shape sensitive
to $T_c(\rho)$

Brown & Cumming (2009)

Outline

- Composition of the crust
- Shallow heating
- superfluid gaps and pasta
- magnetar cooling

Equilibrium and accreted crusts have quite different compositions



Page & Reddy 2012

Impurity parameter

$$Q_{\rm imp} = \frac{1}{n}\sum n_i (Z_i - \bar{Z})^2$$

$$= \bar{Z^2} - \bar{Z}^2$$

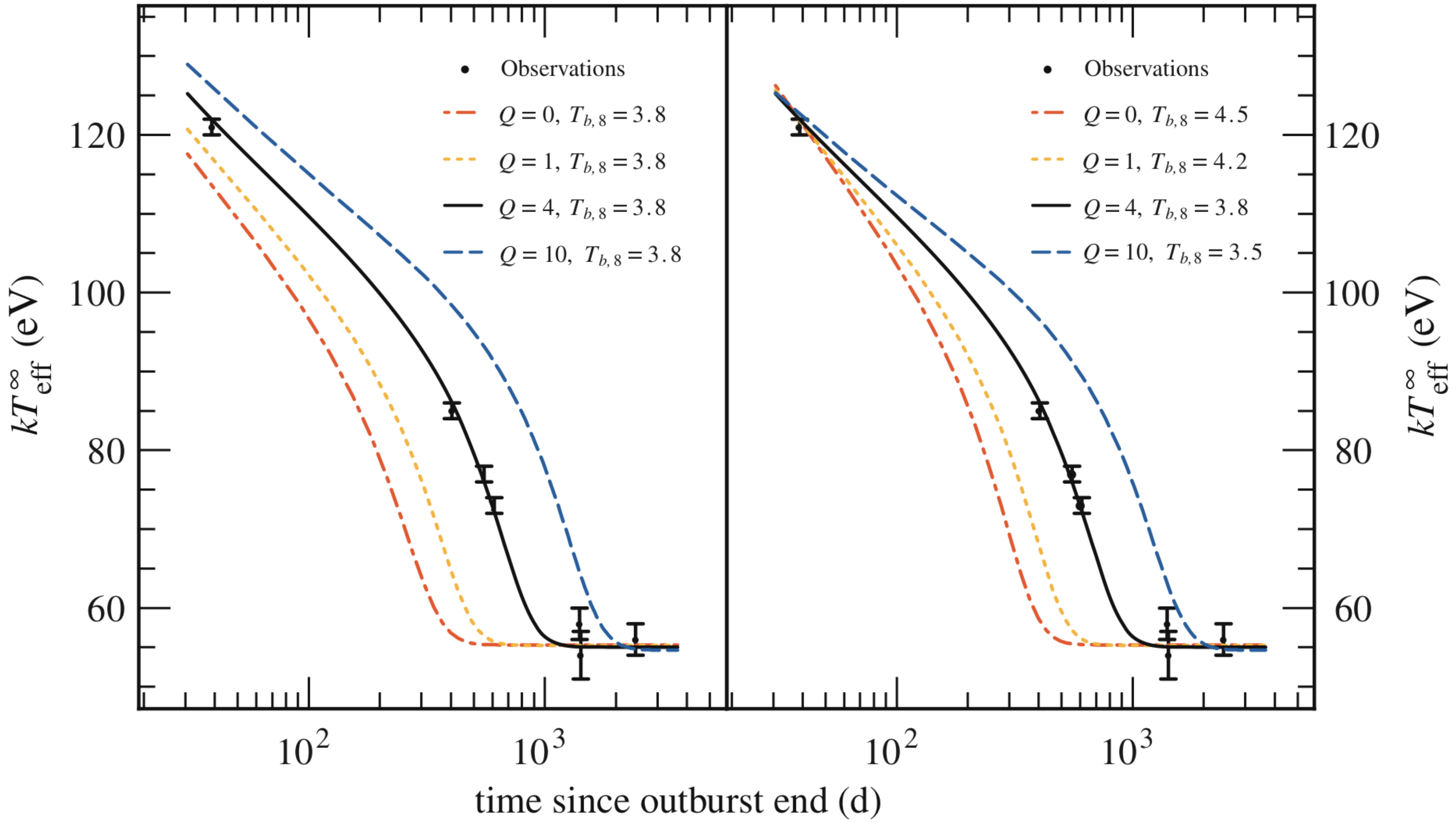
determines electron scattering rate
for cold crust (typically in inner crust)

Estimates/calculations of the impurity parameter:

- equilibrium crust
  - ~1e-3 (Flowers & Ruderman 1977)
  - ~1 (Jones 2004)
- accreted crust
  - ~100 rp-process ashes (Schatz et al. 1999)
  - ~Z^2 ~ 1000 amorphous solid (Brown 2000)

Cooling curves immediately ruled out amorphous crust!
(Wijnands et al. 2002 based on the first cooling curve
predictions from Rutledge et al 2002)

Constraint on the impurity parameter for MXB 1659-29



Brown & Cumming (2009)

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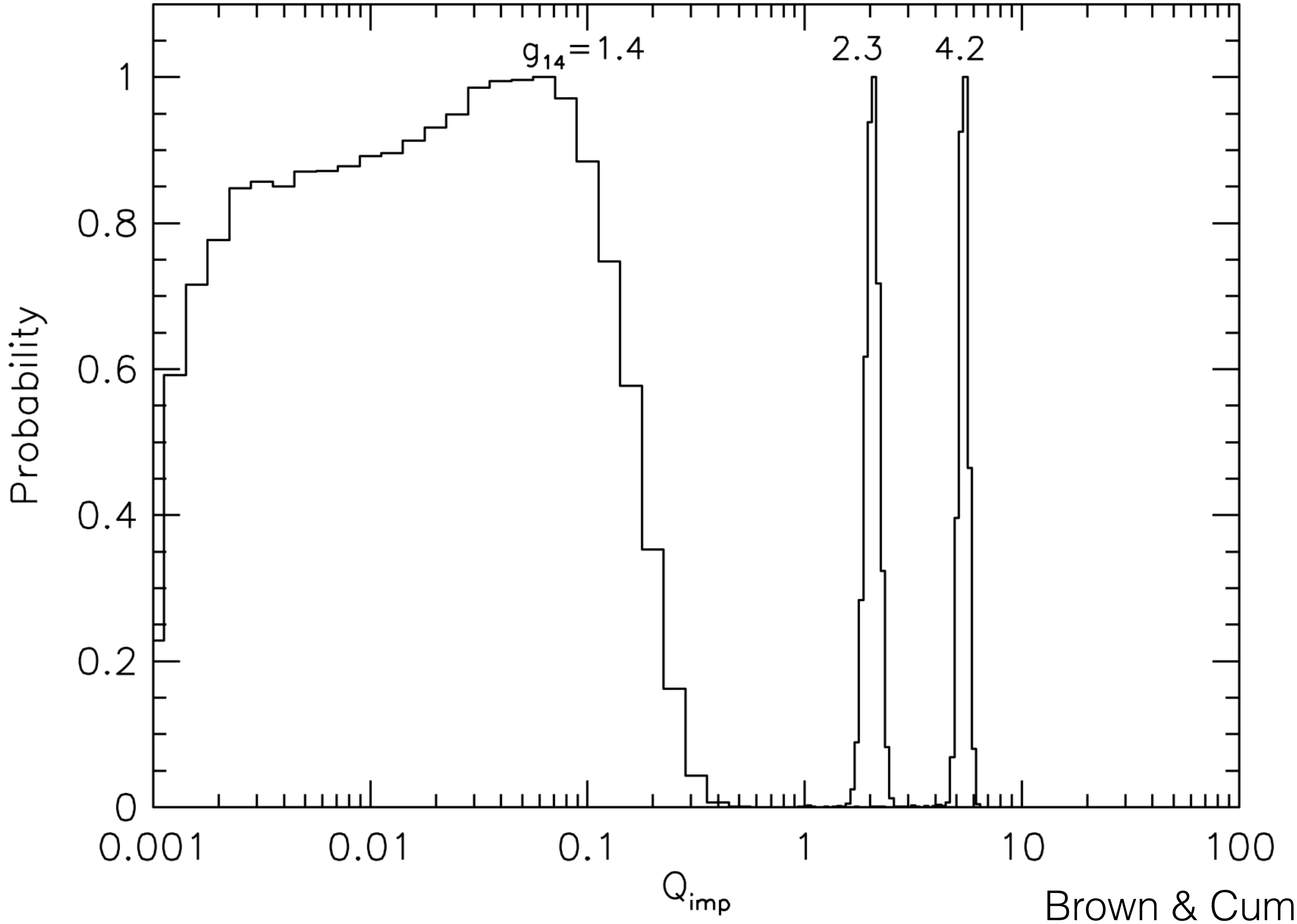


Brown & Cumming (2009)

Marginalizing over M,R gives $Q_{\rm imp} < 10$

How does the composition evolve through the crust?

- **change in composition on freezing**

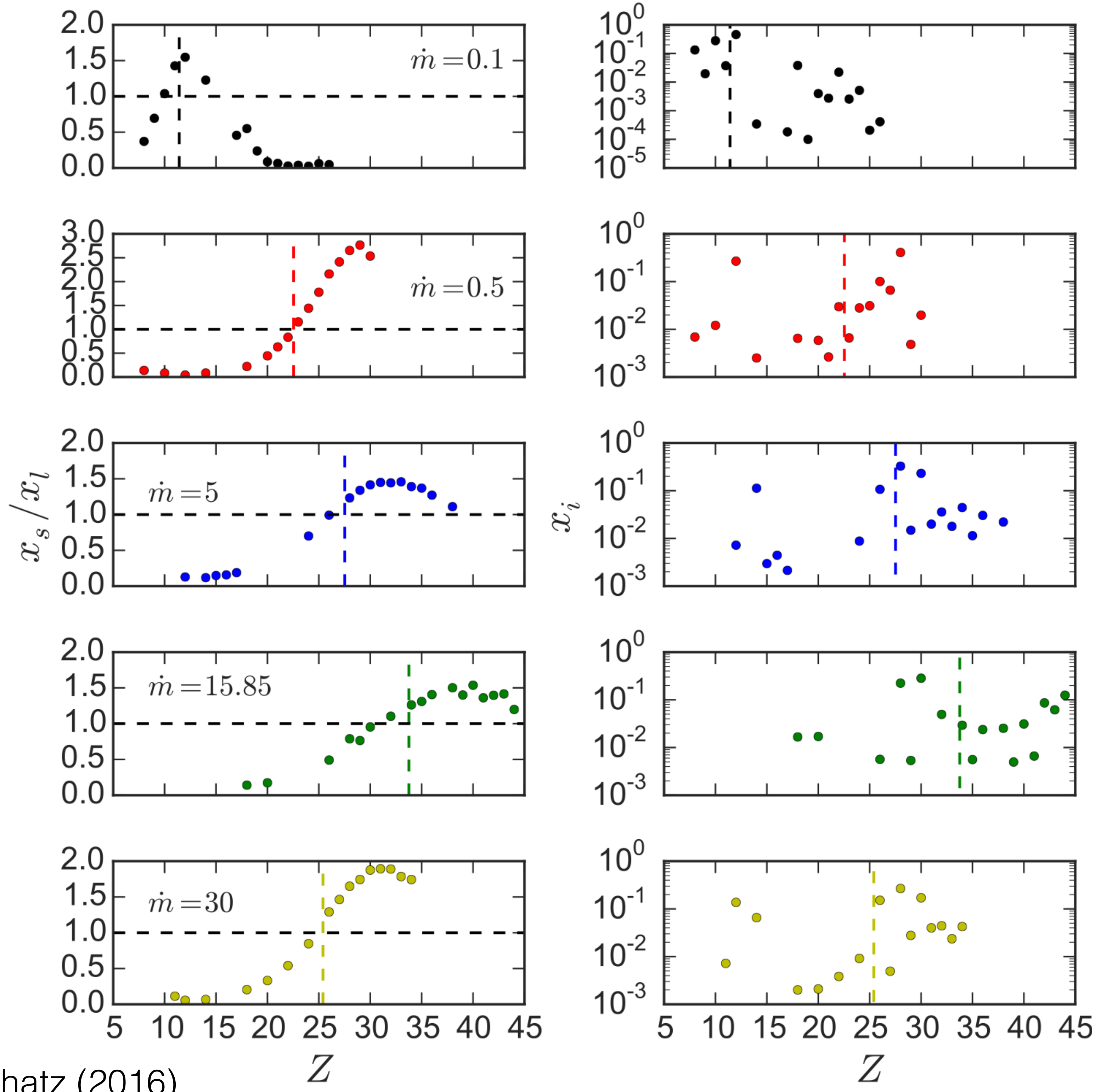
molecular dynamics calculations show that a lattice still forms even for rp-process ashes (Horowitz et al. 2007,2009)
-> simulations show chemical and phase separation

- **nuclear evolution** near neutron drip simplifies the mixture

Gupta et al. (2008), Horowitz et al. (2009), Jones (2005), Steiner (2012)

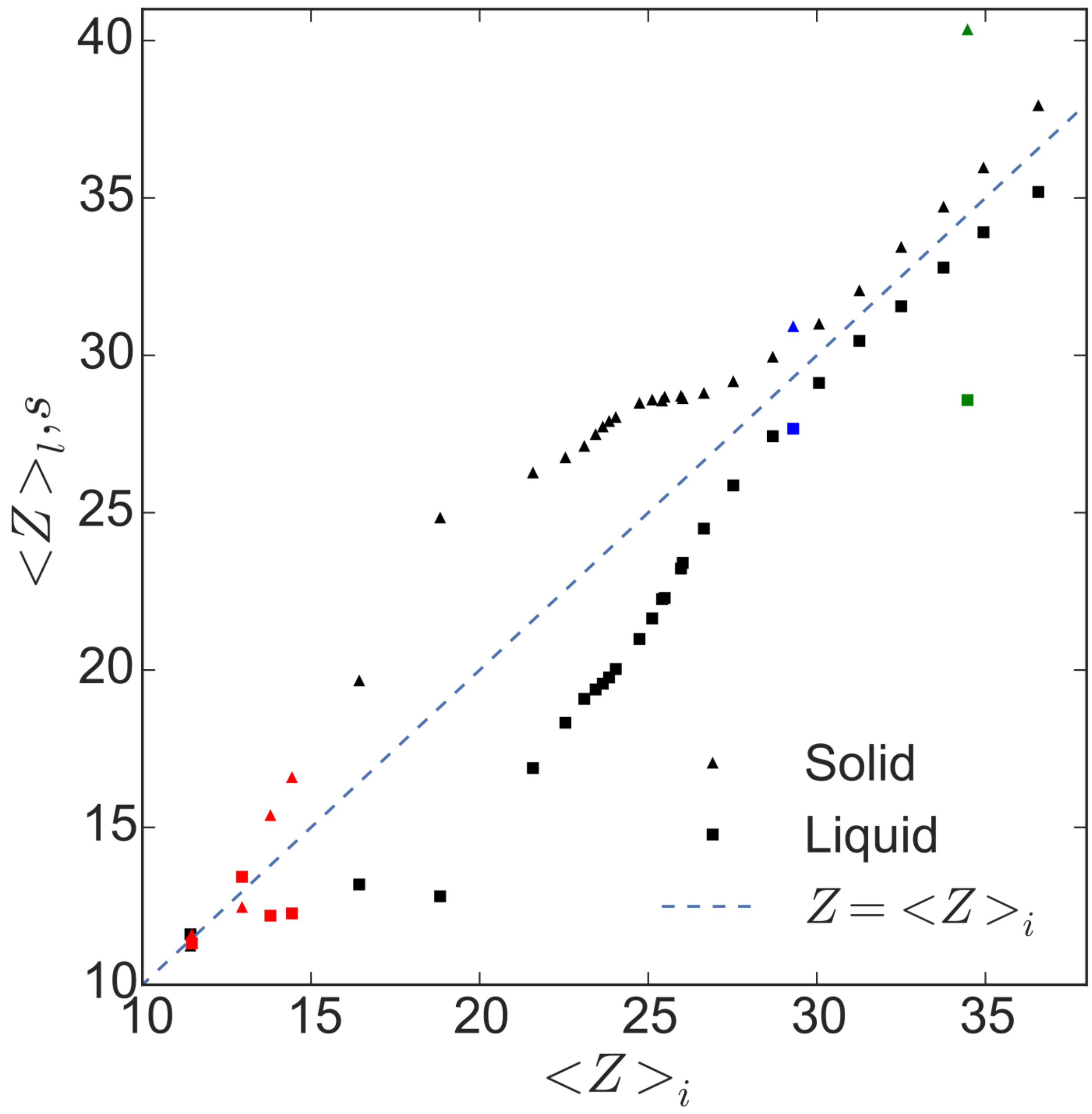
- **Can we constrain Q as a function of depth?**
- Cooling curves mostly sensitive to Qimp in the inner crust (phonon scattering dominates in outer crust),
- but Page & Reddy (2013) found best fitting models for XTEJ had Q~15-30 for rho<1e12 and 3-4 for rho>1e13

Chemical separation on freezing



Mckinven, AC, Medin, Schatz (2016)

Chemical separation on freezing



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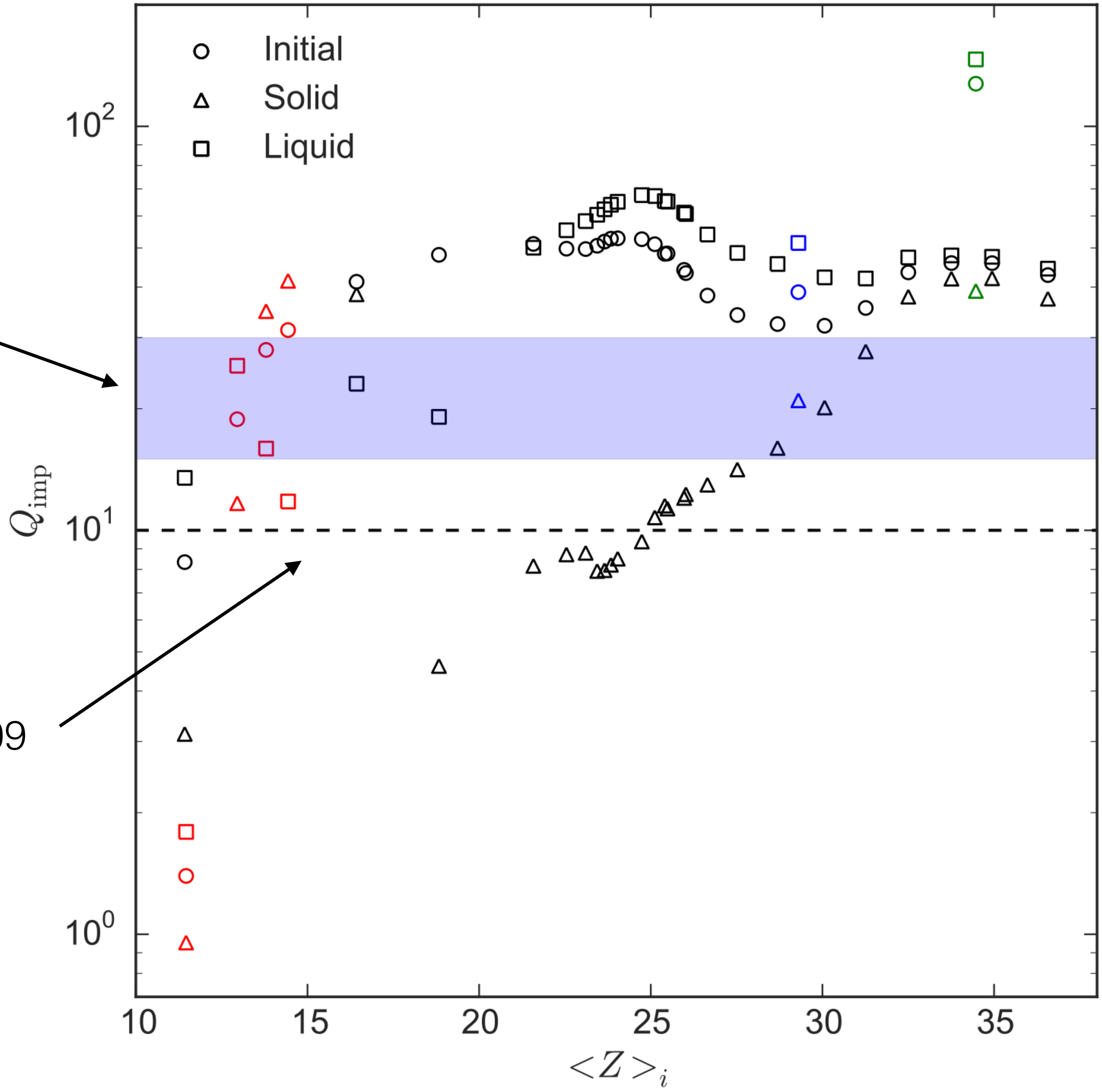
Chemical separation on freezing

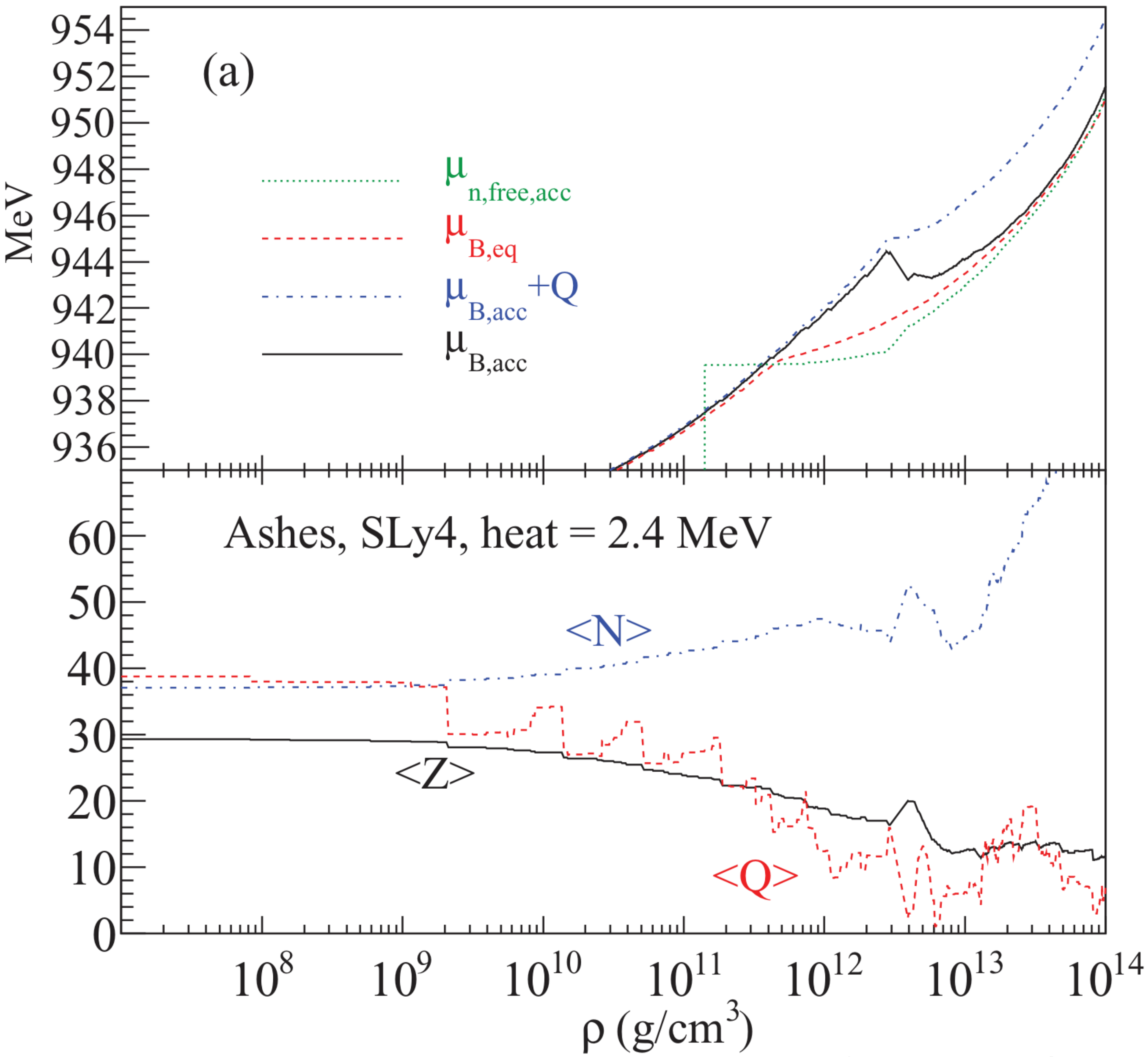


Q_outer from Page & Reddy (2013)

limit on Q_imp from BC09

Mckinven, AC, Medin, Schatz (2016)

Nuclear reactions simplify the mixture



Gupta et al. (2008),
Horowitz et al. (2009),
Jones (2005)
Steiner (2012)

consistent with Q<10 in the inner crust

more work needed on this!

Steiner (2012)

Summary of composition

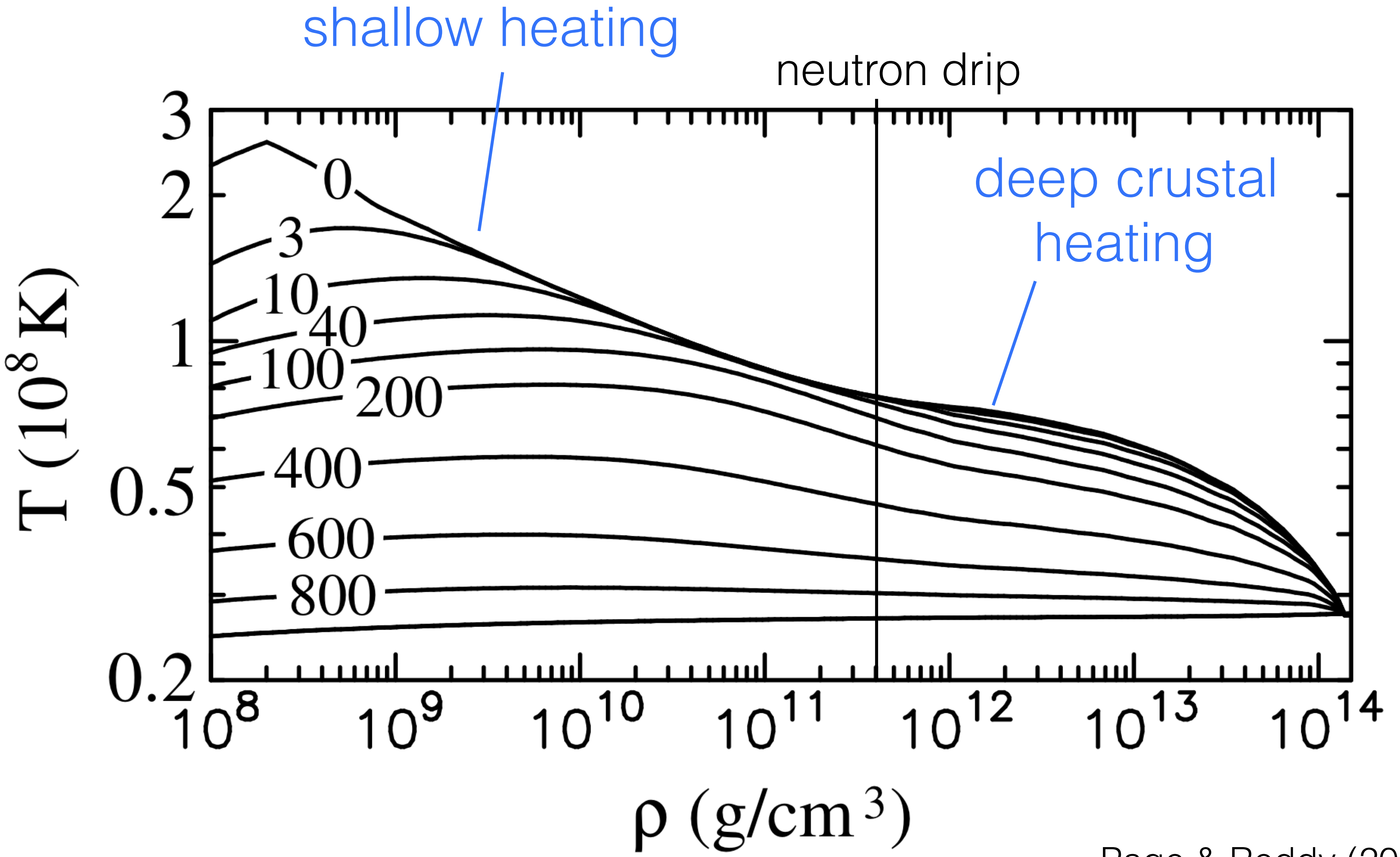
Cooling timescales => Q~1 consistent with evolution due to freezing/nuclear deeper in the crust

More work needed on nuclear evolution. Do we understand the properties of these neutron rich nuclei (well beyond the neutron drip line) well enough to model this?

Can we get constraints on Qouter and Qinner separately from cooling curves?

Does the inferred Q mean what we think it does? Roggero & Reddy (2016) find that the actual impurity parameter is about 2-4 times smaller than the standard thermal conductivity formula would suggest

MXB 1659 and KS 1731 require a ~ 1 MeV/nucleon heat source be added to the model near the top of the outer crust.


shallow heating

neutron drip

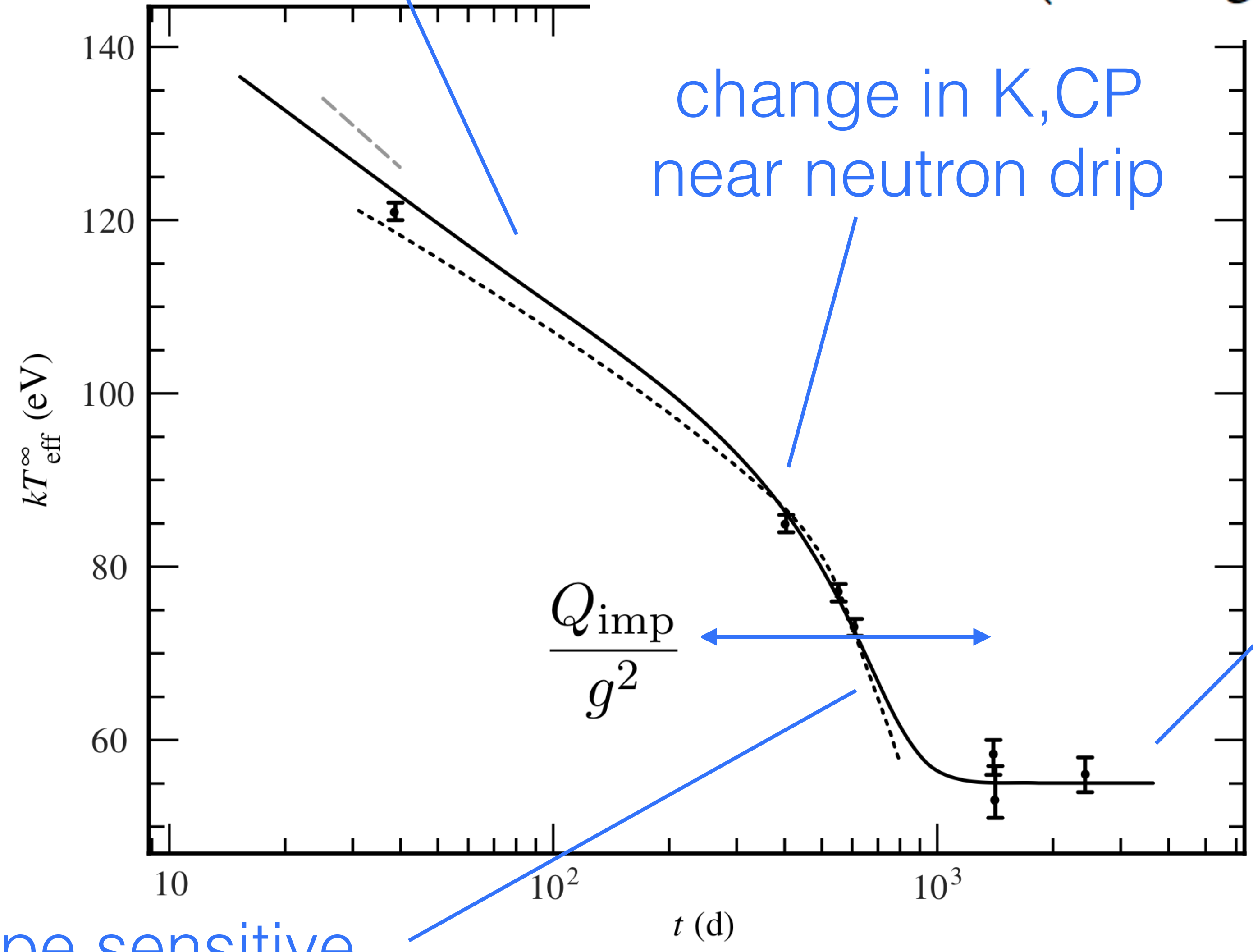
deep crustal heating

Page & Reddy (2012)

General shape of the cooling curve

outer crust

$$\frac{d\ln T_{\mathrm{eff}}^{\infty}}{d\ln t} = 0.03\left(\frac{F}{10^{21}\ \mathrm{erg\ s^{-1}\ cm^{-2}}}\right)$$



change in K,CP near neutron drip

Tc, pasta

$$\frac{Q_{\mathrm{imp}}}{g^2}$$

shape sensitive to $T_c(\rho)$

Brown & Cumming (2009)

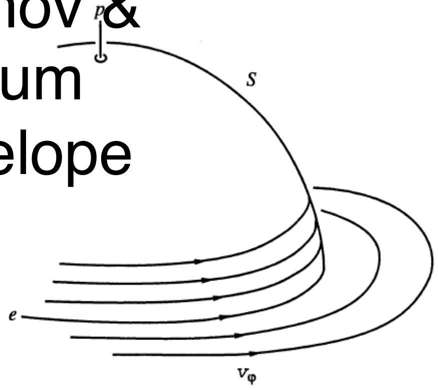
What powers the shallow heat source?

- Gravitational energy released by light elements that rise upwards from the ocean floor following **chemical separation** at the ocean/ crust interface (Medin & Cumming 2011) ~0.1 MeV/nucleon, probably not enough

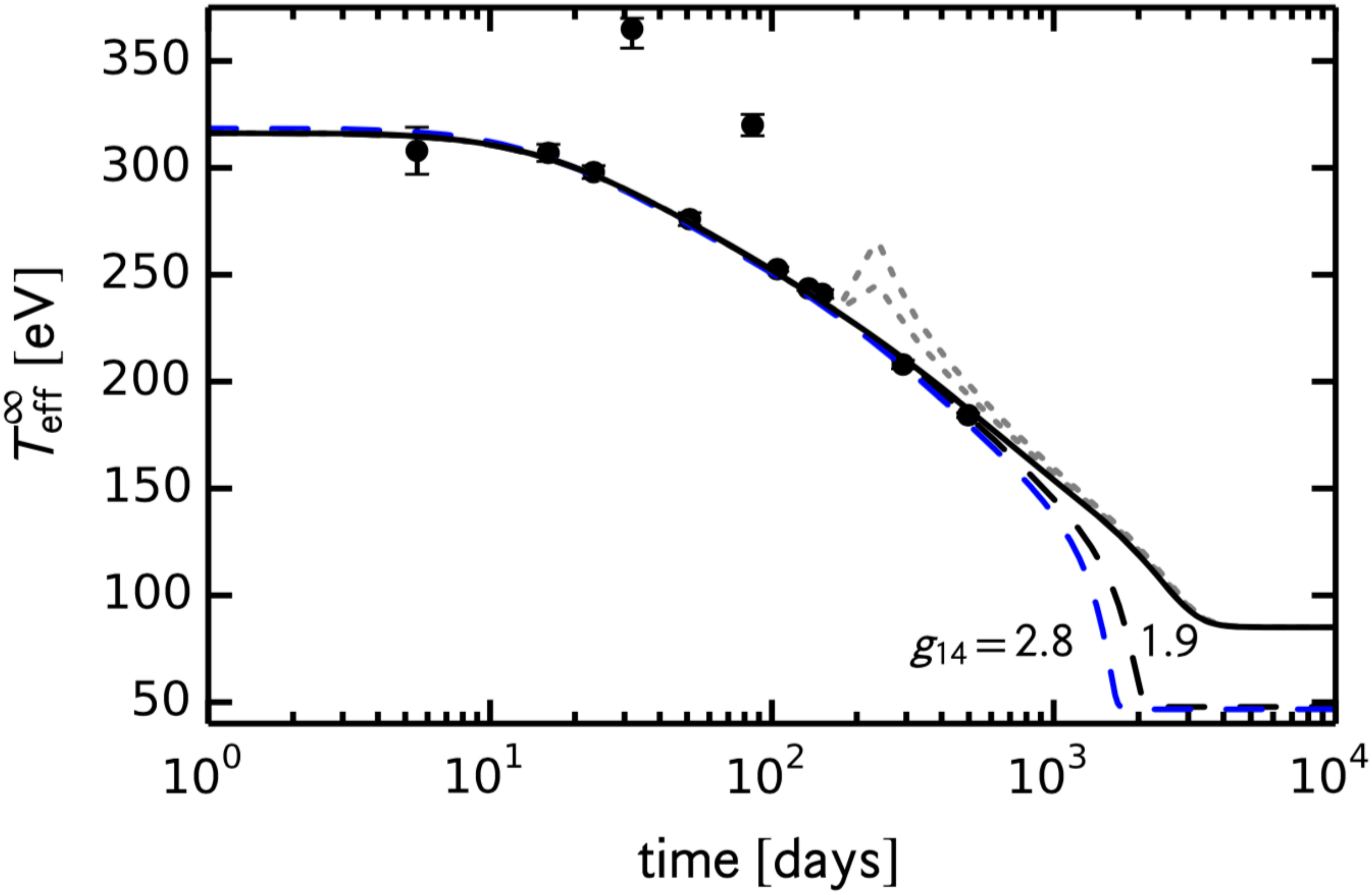
- **Electron captures** in the outer crust release more energy than previously thought (Gupta et al. 2007)

- **Fusion** of light elements in the outer crust, e.g. ^{24}O will fuse at a density ~10^{11} g/cm^3 (Horowitz, Dussan, & Berry 2008)

- **Differential rotation** between the fluid envelope and solid crust leads to strong heating ~tens of MeV/nucleon (Inogamov & Sunyaev 2010). This requires inwards angular momentum transport from the accreted material to spin up the envelope



MAXI J0556-332: The hottest cooling source so far



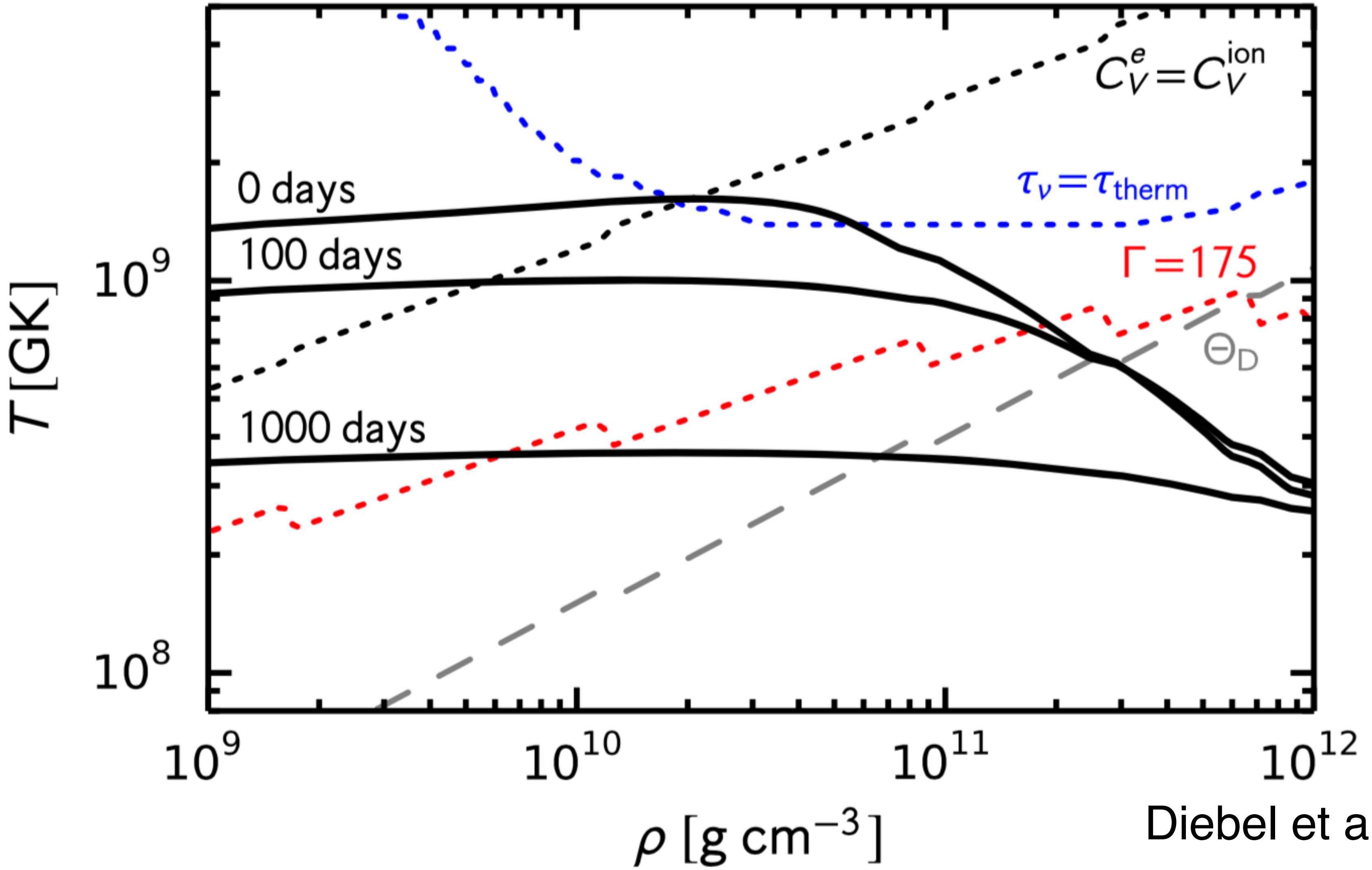
~ 1 year outburst at ~ Eddington accretion rate (10x greater than KS 1731 or MXB 1659)

Need a 4-10 MeV heat source at ~ 3×10^{10} g/cm^3

$$Q_{\mathrm{in}} = 3.4\ \mathrm{MeV\ u}^{-1}\ P_{28}^{1/4} \left(\frac{T_{\mathrm{eff},\infty}}{300\ \mathrm{eV}} \right)^{1.82} \left(\frac{\dot{m}}{\dot{m}_{\mathrm{Edd}}} \right)^{-1} \left(\frac{g_{14}}{2} \right)^{11/20},$$

Diebel et al. (2015)

MAXI J0556-332: The hottest cooling source so far



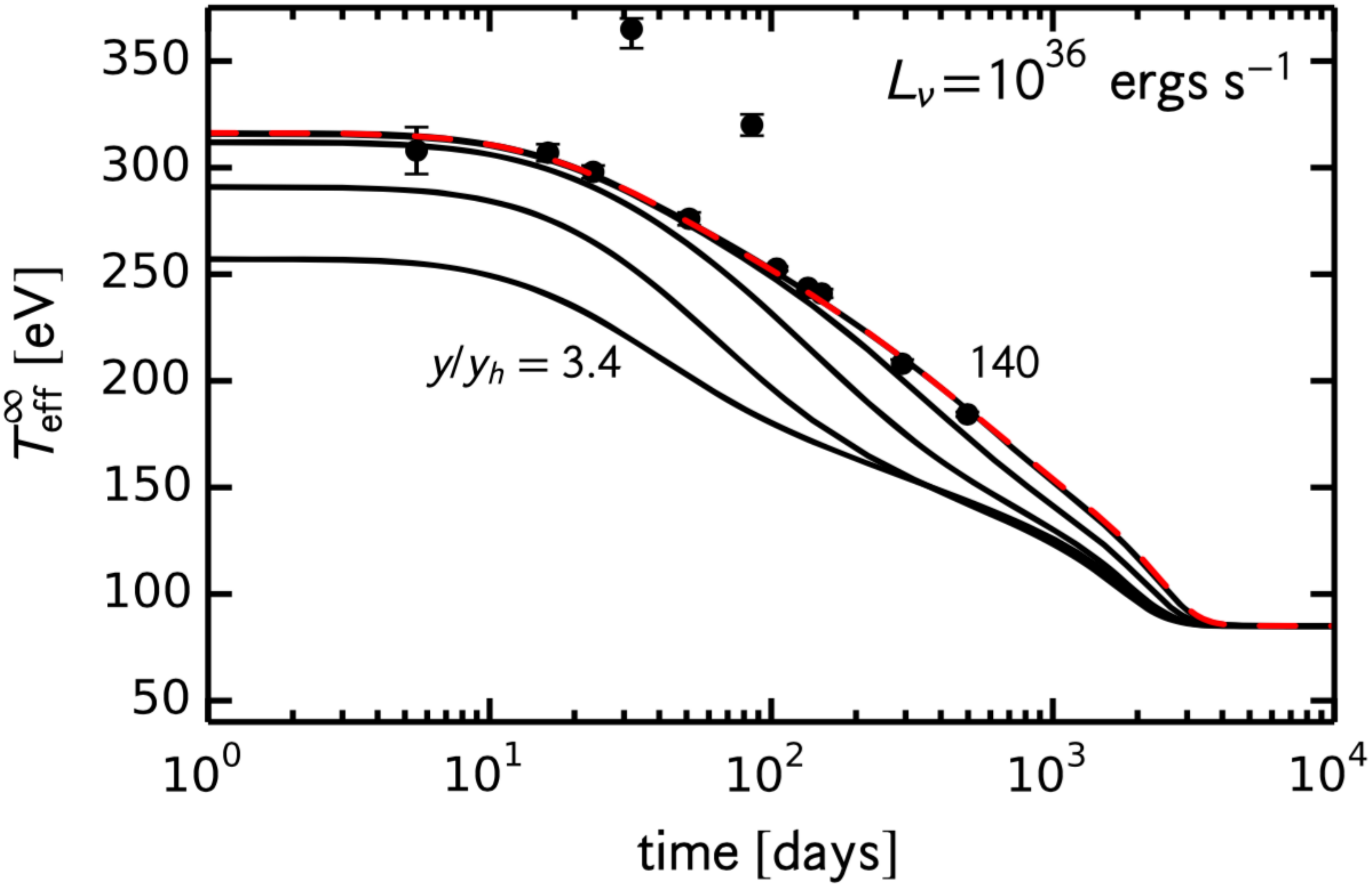
Diebel et al. (2015)

Close to the maximum temperature allowed by neutrino cooling

The break in the lightcurve at ~10 days gives the heating depth

Most of the outer crust melts; phonons dominate scattering in the solid

An URCA cooling source near the heating depth would change the lightcurve shape



Diebel et al. (2015)

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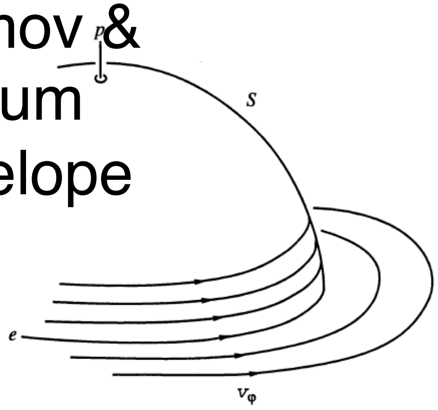
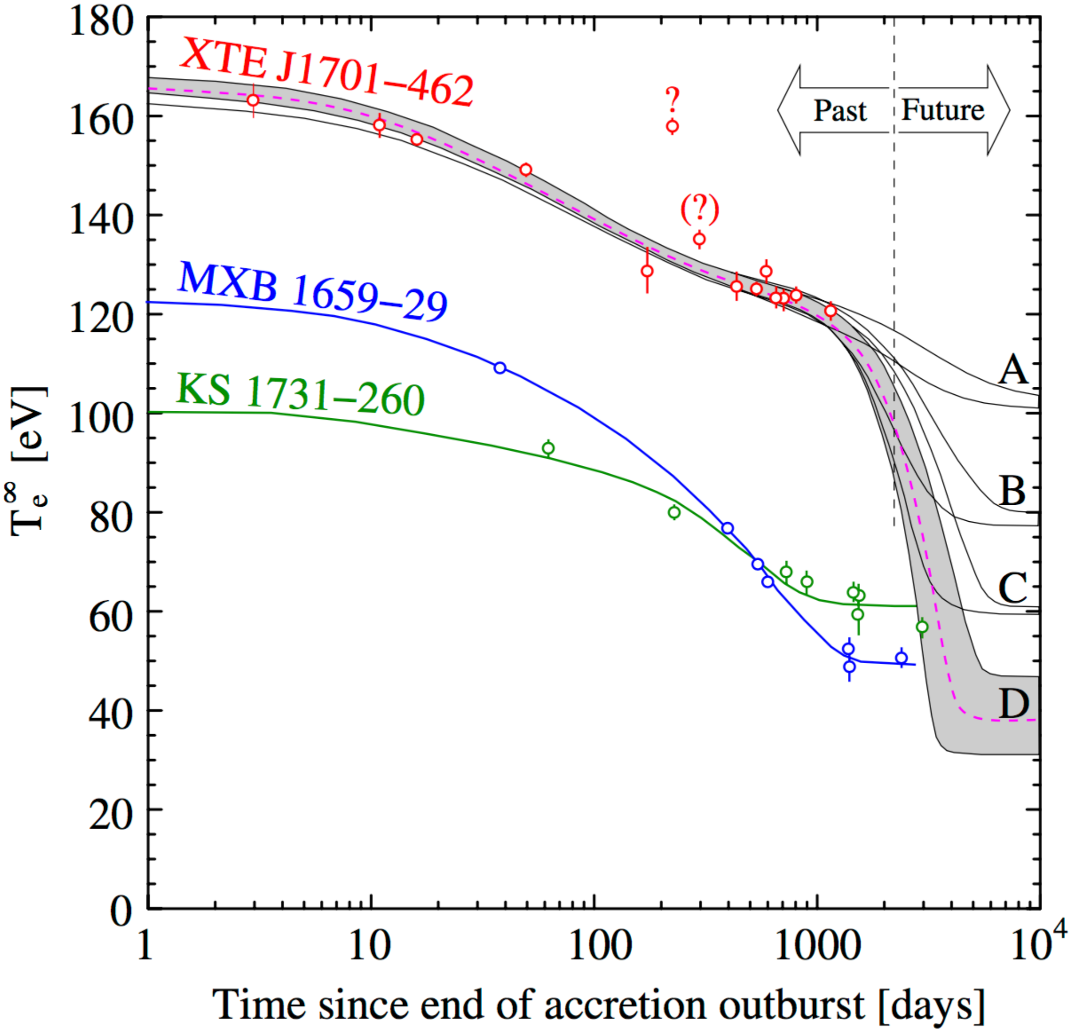
How to get the energy in deep enough?



MAXI 0556 contrasts with XTE J1701

* similar outburst properties (~Eddington accretion rate for a year)

* XTEJ lightcurve can be modelled with no shallow heating (Page & Reddy 2013)



Observations of short duration transients

Shallow heating depth => significant temperature changes with even a short accretion outburst

Three sources have been followed so far:

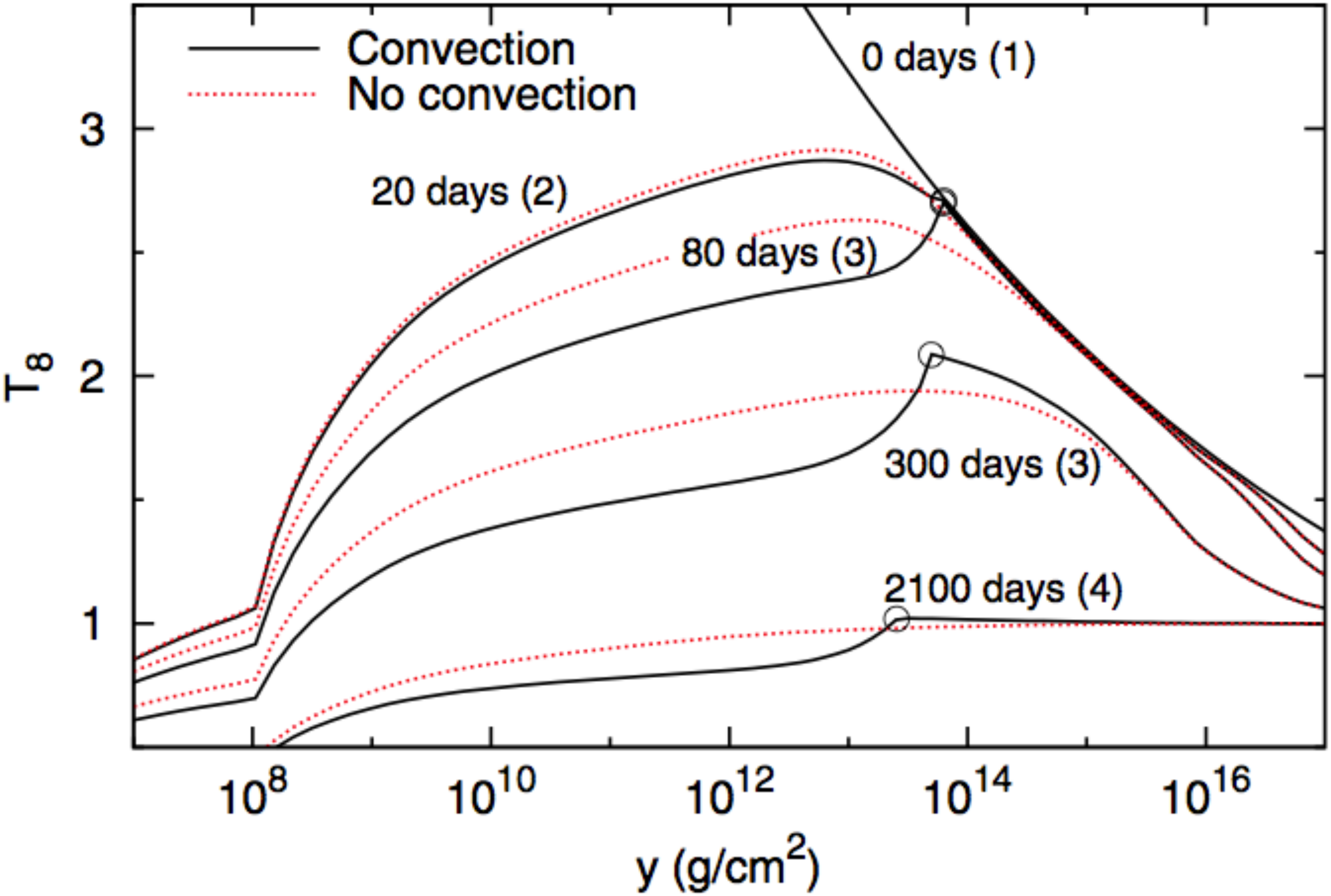
* IGR J17480-2446 Degenaar et al. (2013)
* Swift J174805.3-244637 Degenaar et al. (2015)
* Aql X-1 Waterhouse et al. (2016)

Cooling is observed; ~1MeV heating is consistent with the observations (not always needed)

surface of
the star

ocean

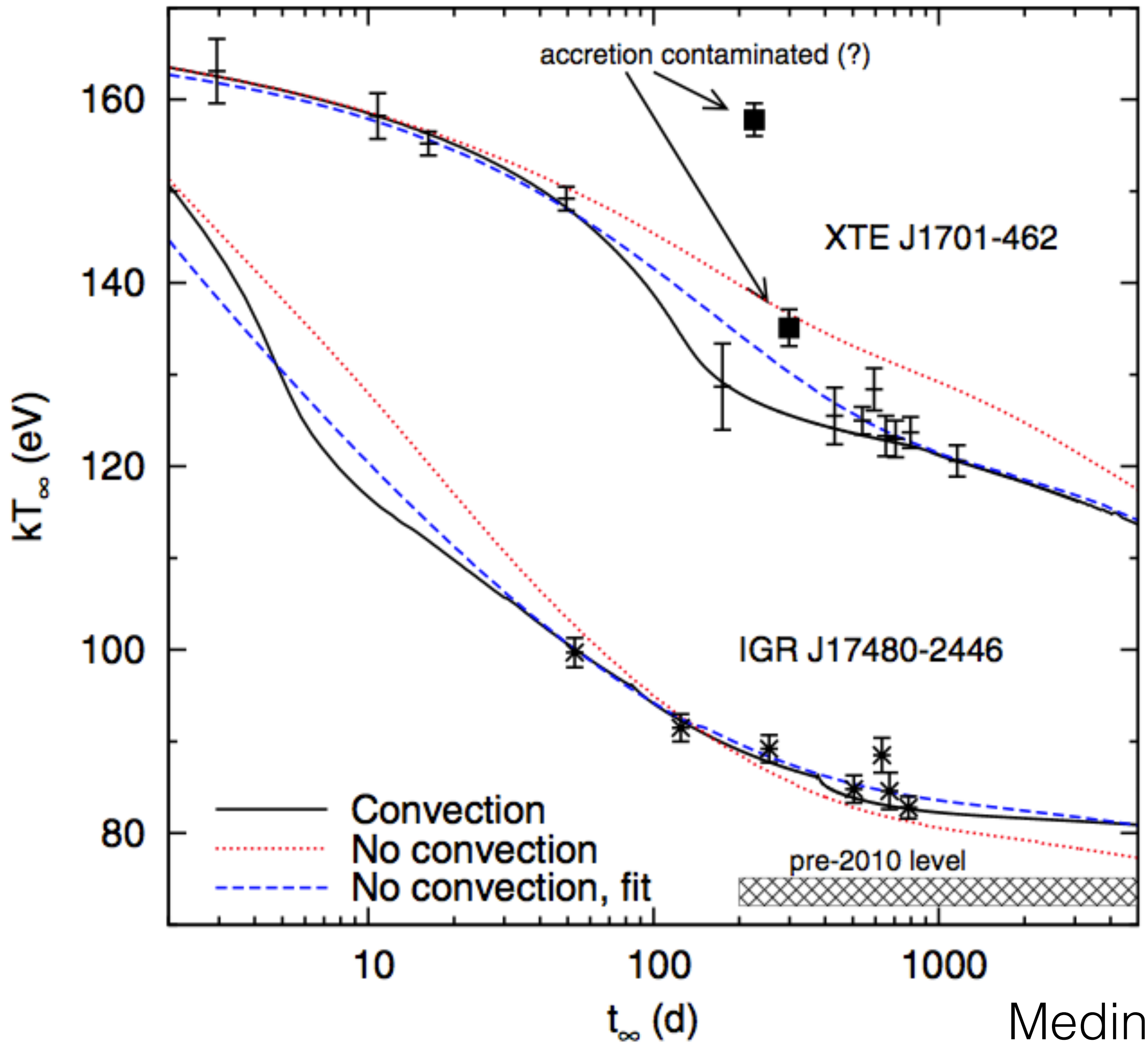
crust



compositionally-driven convection
transports heat inwards

Medin & Cumming (2014)

compositionally-driven convection can change the early part of the lightcurve



Medin & Cumming (2014)

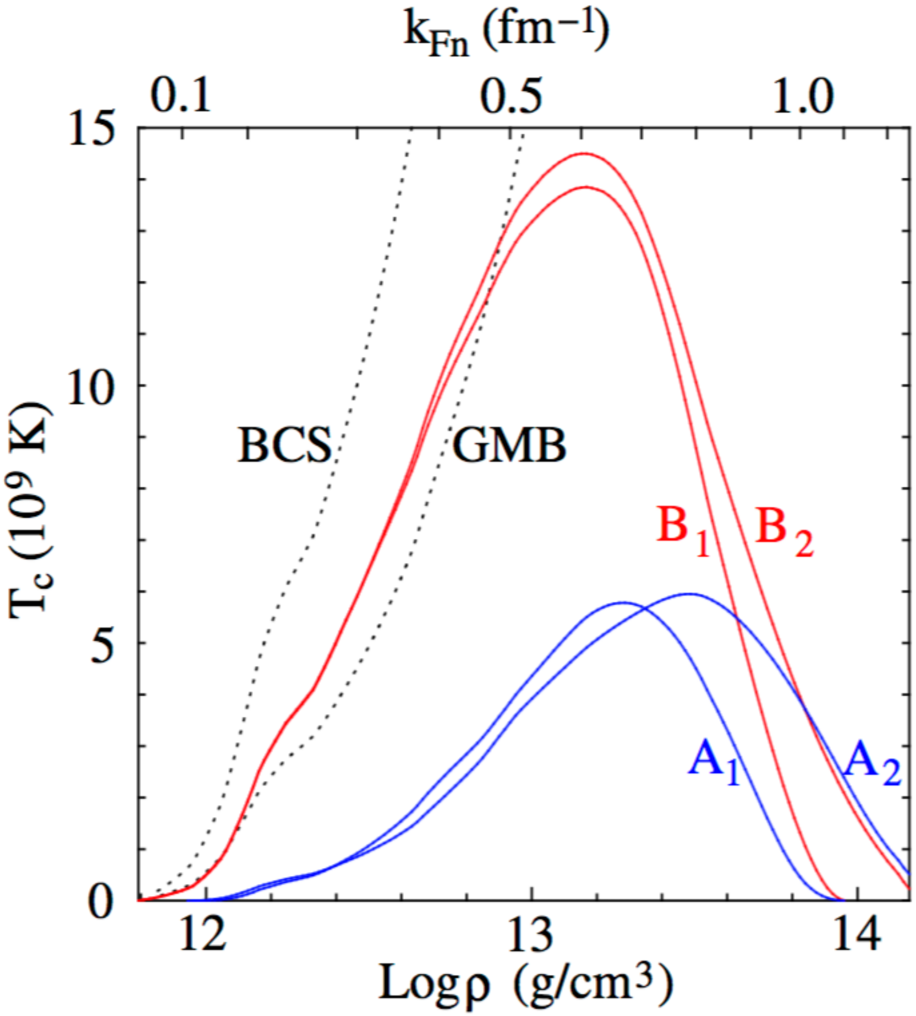
Summary of shallow heating

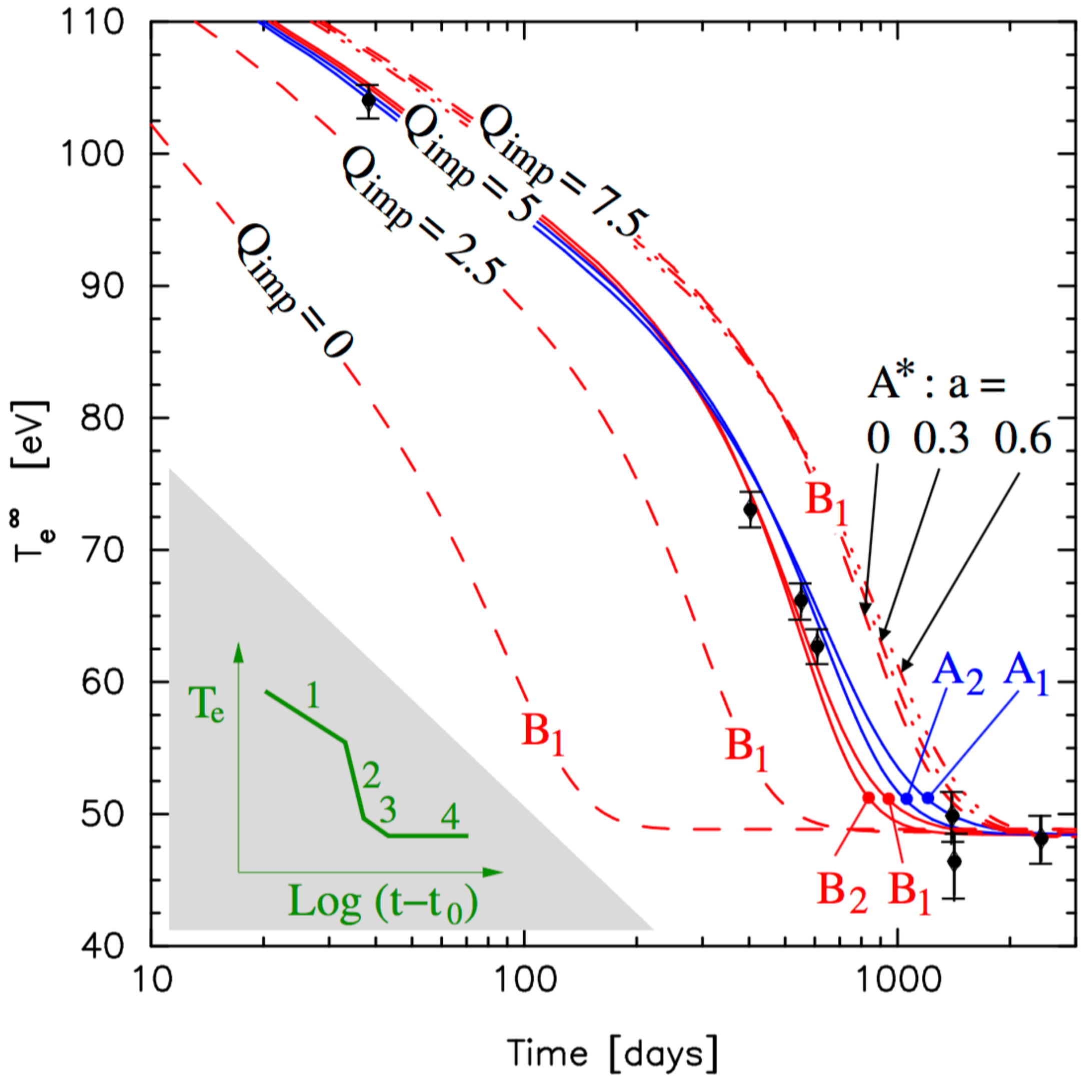
What is the shallow heating? If differential rotation, how is it transported to depth? (Inogamov and Sunyaev don't put it deep enough)

How does shallow heating depend on outburst duration, strength, other properties of the source?

Can shallow heating explain unexplained X-ray burst behaviour ?

Other physics near neutron drip: Tc and entrainment





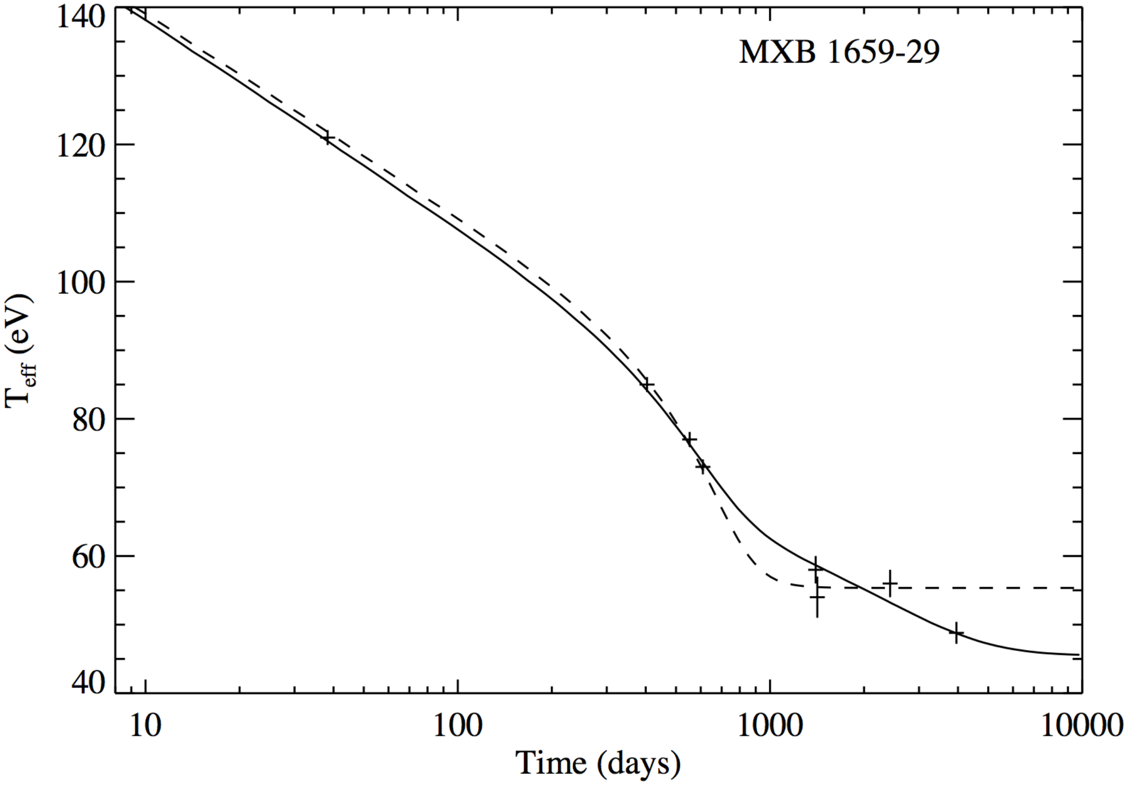
Page & Reddy 2012

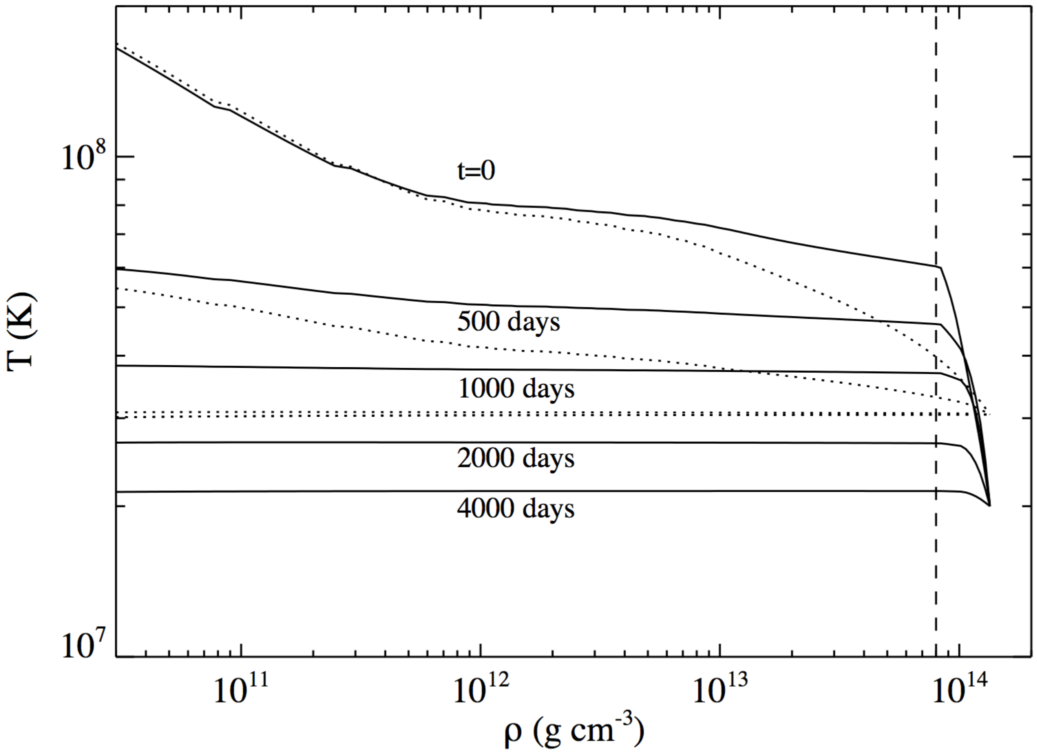
Late time cooling is a probe of the pasta region

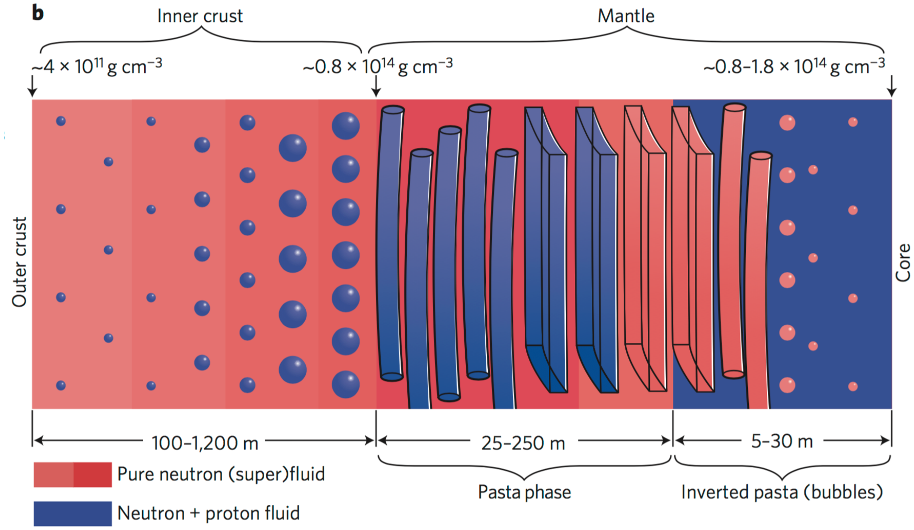
Horowitz et al. (2014)

Topological defects in lasagne-type pasta could act as scattering centers, reducing K

(see also Pons et al. who use pasta to get rapid field decay and explain the 10s pulsars)







Magnetar caveats/Opening remarks

- We don’t know what powers magnetar outbursts. If it is magnetic field decay, what triggers the outburst and sets the energy?

=> crust cooling can help us answer this question

- We don’t know if we’re actually seeing crust cooling

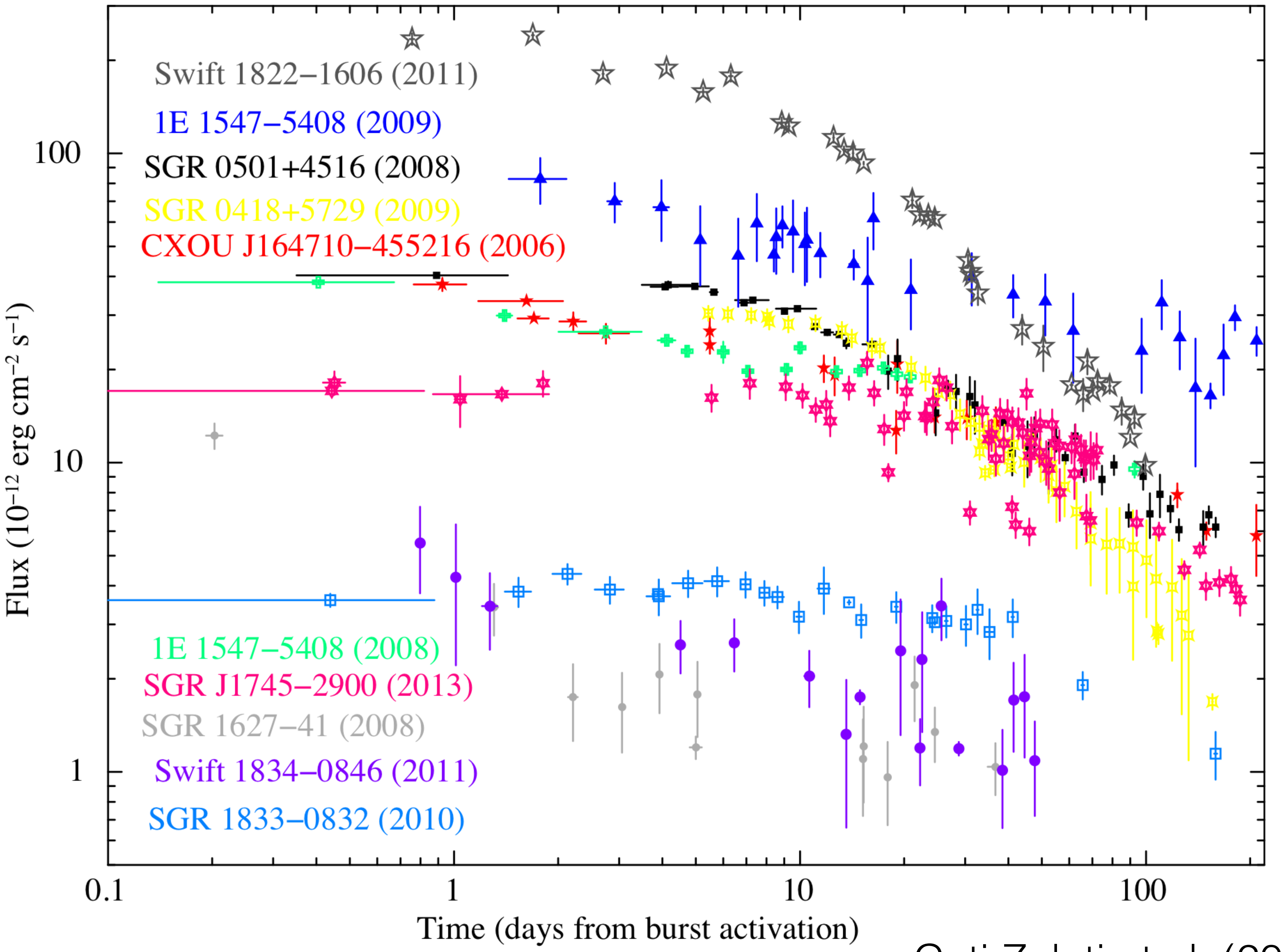
  => could be external heating from twisted magnetosphere (Beloborodov 2009)

  (test this with L-area scaling)

- Spectra are not consistent with cooling T at fixed R (generally the opposite)
- Likely to be a small spot cooling rather than whole stellar surface; sometimes evidence for two thermal components

=> take the approach of fitting the luminosity lightcurve

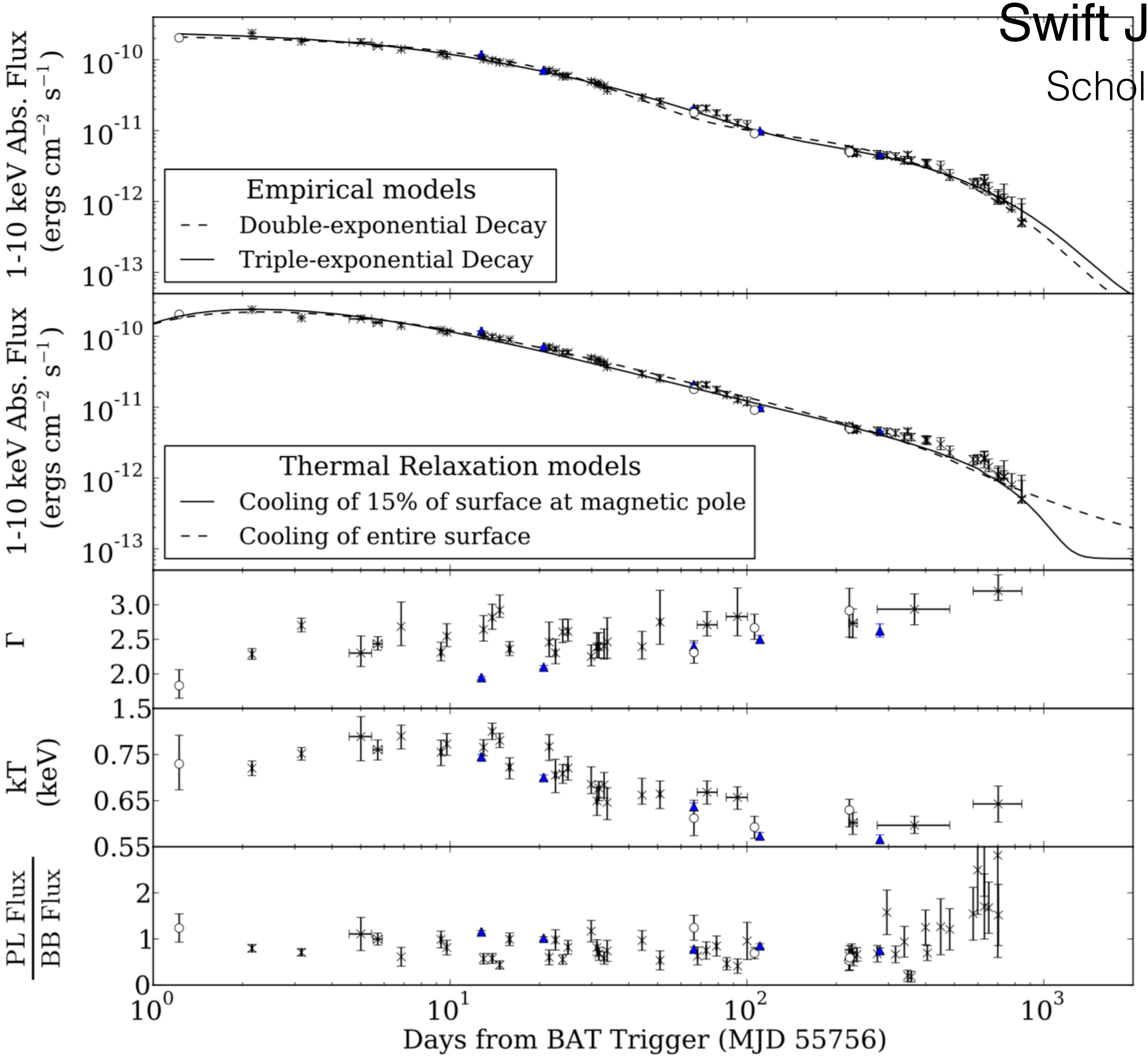
A recent compilation of magnetar outburst lightcurves

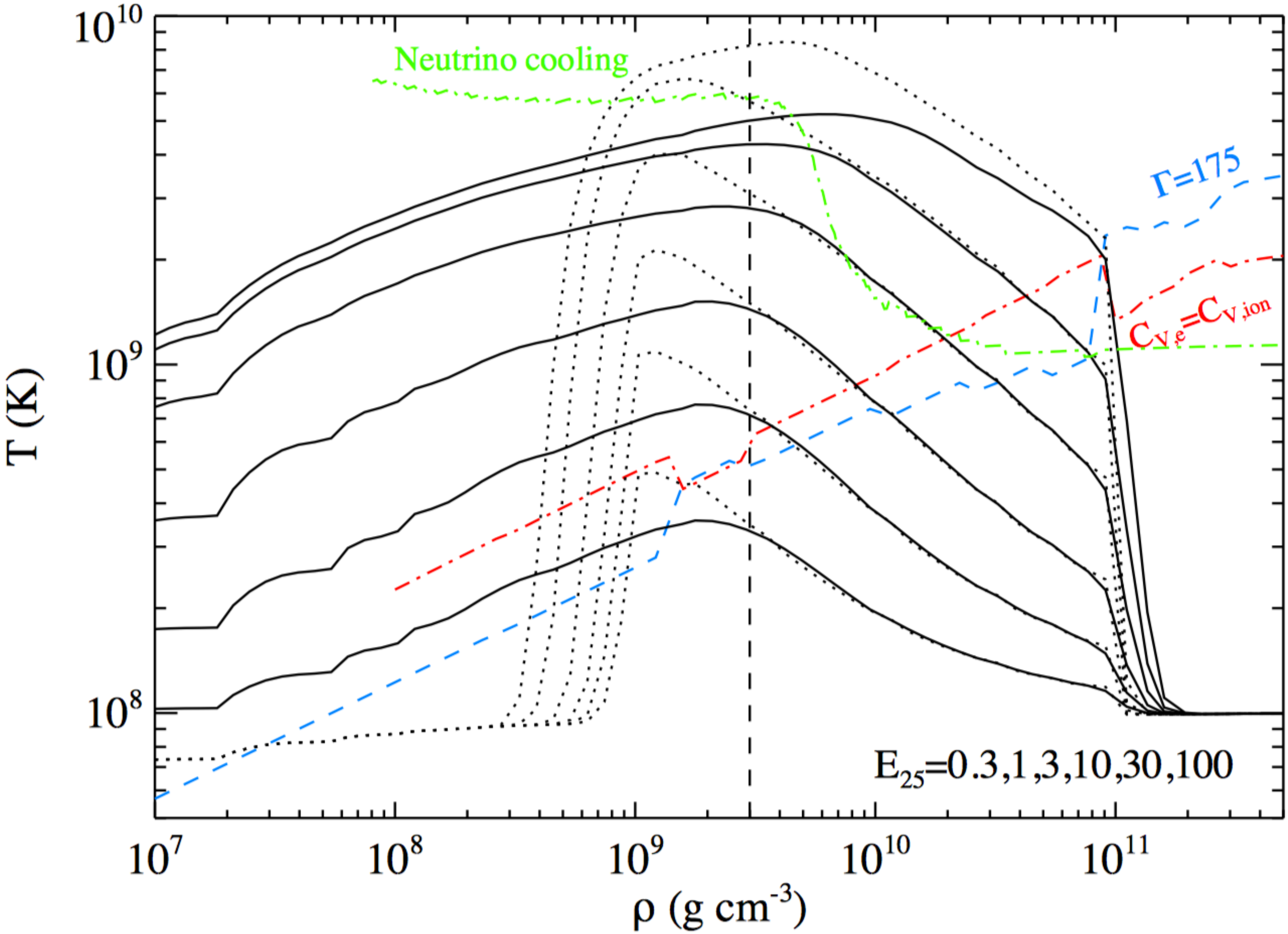


Coti Zelati et al. (2016)

Swift J1822.3-1606

Scholz et al. (2014)





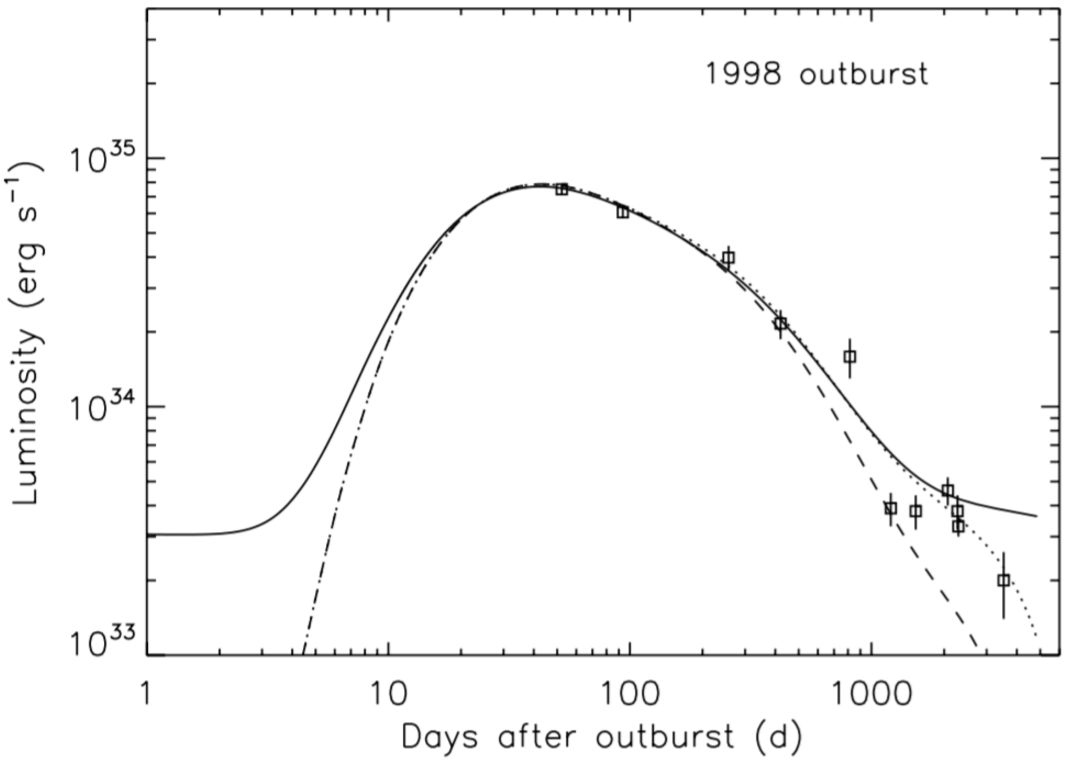
10^{10}
10^9
10^8
T (K)
10^7
10^8
10^9
10^{10}
10^{11}
ρ (g cm^{-3})
Neutrino cooling
Γ=175
$C_{V,e}$=$C_{V,ion}$
E_{25}=0.3,1,3,10,30,100

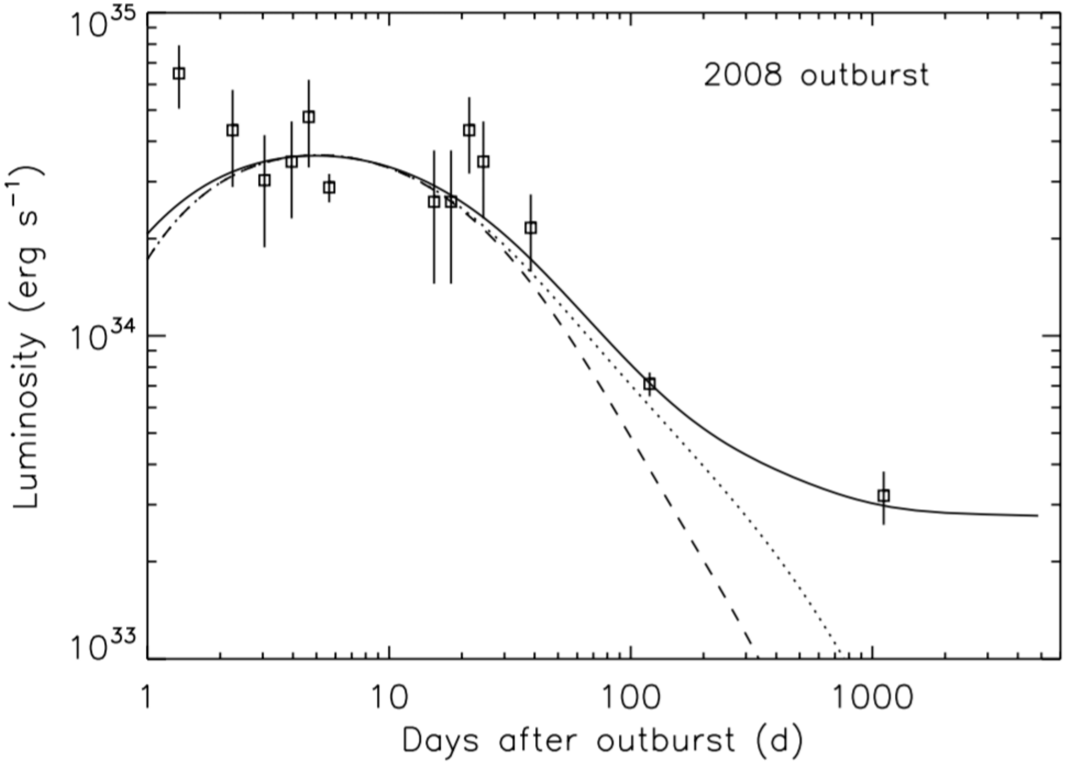
Summary of crust cooling fits to magnetars

- Several sources have been fit with crust cooling models:
  SGR 0418 (Rea et al. 2013)
  Swift J1822 (Rea et al. 2012, Scholz et al. 2012,2014)
  SGR 0501 (Camero et al. 2014)
  SGR 1900+14 (Lyubarsky et al. 2002)
  SGR 1627-41 (Kouveliotou et al. 2003, An et al. 2012)
  CXOU J1647 (An et al. 2013)
  SGR J1745-2900 (Coti-Zelati et al. 2015) (Galactic centre)

- Main result: lightcurves generally well fit by crust cooling models

- need to deposit ~(0.3-3)x10^{42} ergs in the outer crust between 10^{10} - 10^{11} g cm^{-3} over a few % of the surface



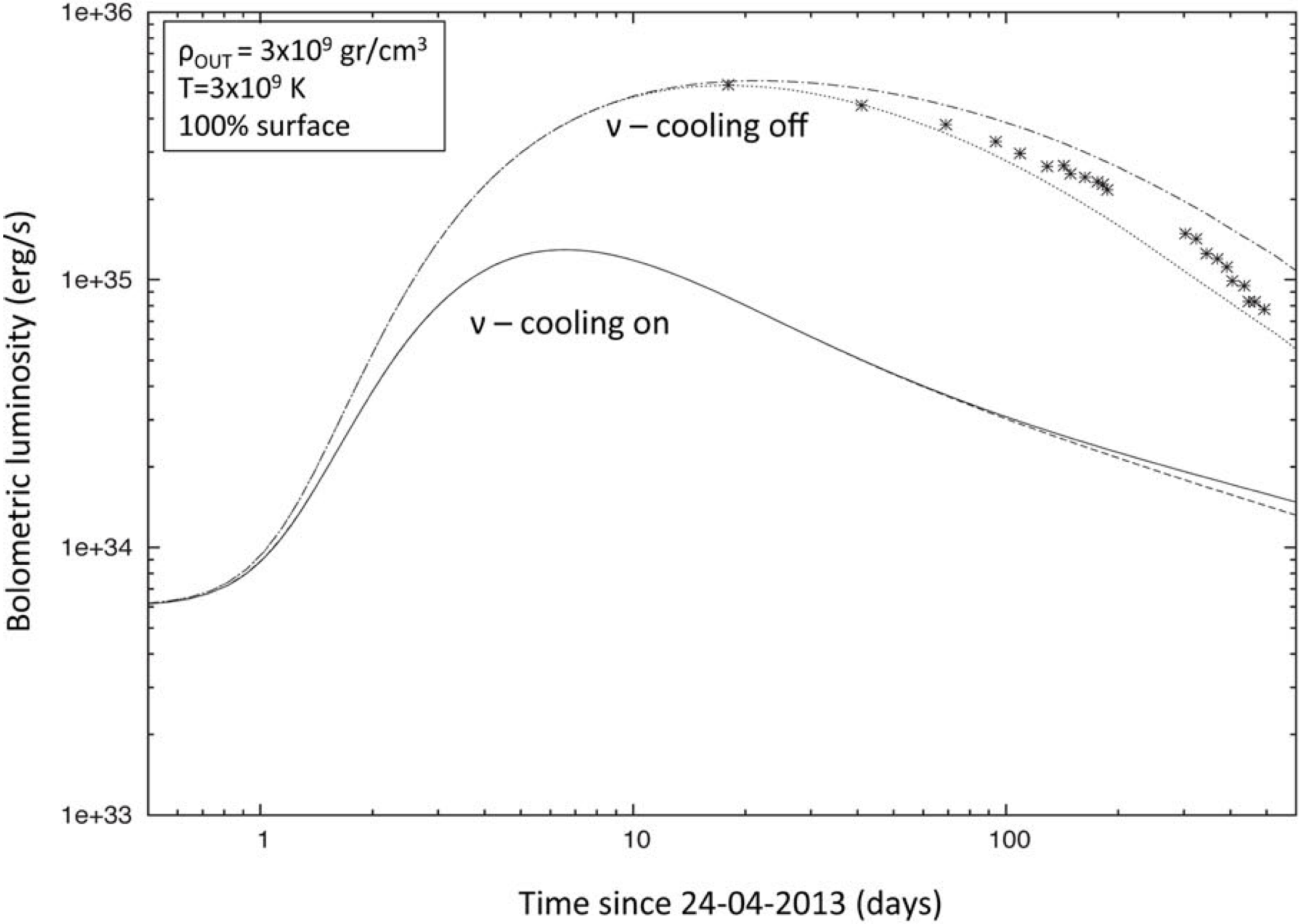


SGR 1627-41
An et al. (2014)

Two outbursts with different total energies and depths

2008 outburst shows late time cooling - pasta ?

SGR J1745-2900 can be fit only if neutrino emission is turned off!



SGR J1745-2900 Galactic center magnetar
Coti Zelati et al. (2016)

Energy deposition profile constrains the energy source

magnetic energy

$$E_B = 4 \times 10^{26} \text{ erg cm}^{-3} \; f \; B_{14}^2$$

$$4\pi R^2 \Delta z E_B = 1.4 \times 10^{44} \; f \; B_{14}^2 \; \rho_{10}^{1/3}$$

elastic energy

$$E_{\rm elastic} \approx \epsilon_b^2 \mu$$

$$E_{\rm elastic} \approx 10^{-4} P \left(\frac{\epsilon_b}{0.1}\right)^2$$

$$= 7.8 \times 10^{23} \text{ erg cm}^{-3} \; \rho_{10}^{4/3} \left(\frac{Y_e}{0.4}\right)^{4/3} \left(\frac{\epsilon_b}{0.1}\right)^2$$

$$4\pi R^2 \int E_{\rm elastic} dz = 2.2 \times 10^{41} \text{ erg } \rho_{b,10}^{5/3} \left(\frac{\epsilon_b}{0.1}\right)^2$$

another possibility is nuclear energy release

(Cooper & Kaplan 2010)

changes in B change the total pressure and drive electron captures

$$\Delta y = \frac{fB^2}{8\pi g} = 2.5 \times 10^{12}\ \mathrm{g\ cm^{-2}}\, fB_{14}^2 \left(\frac{g_{14}}{1.6}\right)^{-1}$$

$$E_{\mathrm{nuc}} = \frac{\rho Q_{\mathrm{nuc},i}}{m_p} = 4 \times 10^{26}\ \rho_{10} \left(\frac{Q_{\mathrm{nuc},i}}{0.04\ \mathrm{MeV}}\right)$$

per electron capture $1.7 \times 10^{42}\ \mathrm{ergs}\ f\ B_{14}^2 \left(\frac{Q_{\mathrm{nuc},i}}{0.04\ \mathrm{MeV}}\right)$

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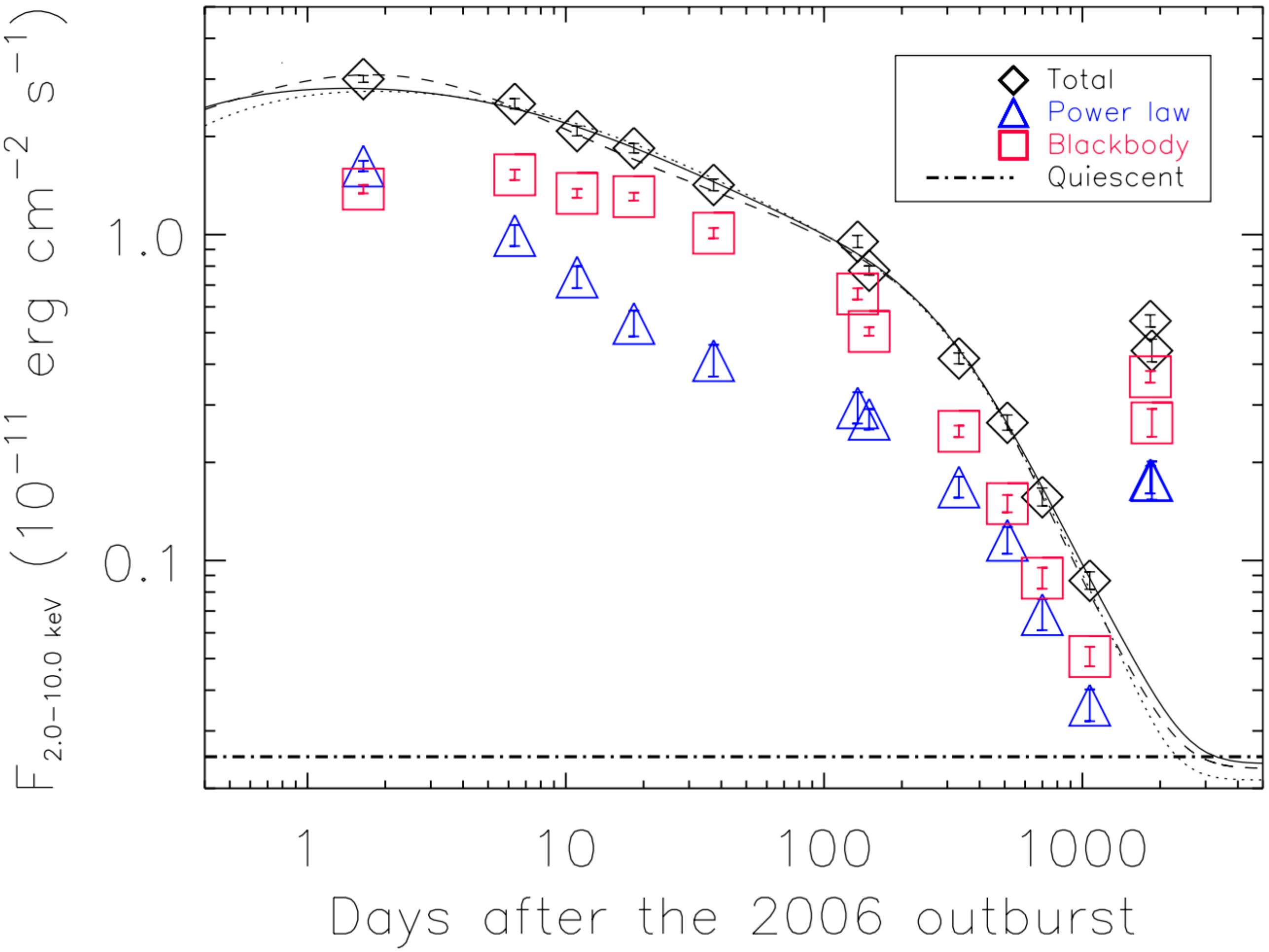
An et al. (2013)



Energy deposition has to be closer to constant energy per gram than constant energy per volume

Questions for discussion

How well can we/do we need to understand the properties of neutron rich nuclei to follow the composition of the crust through neutron drip?

Can we get constraints on Qouter and Qinner separately from cooling curves?

What is shallow heating? Can energy from differential rotation with a disk be deposited deep in the envelope?
How does shallow heating impact X-ray burst models?

If we can constrain superfluid gaps with cooling curves, what do we learn from a microscopic physics point of view?

What is the impact of high B on neutrino emissivity in the crust?