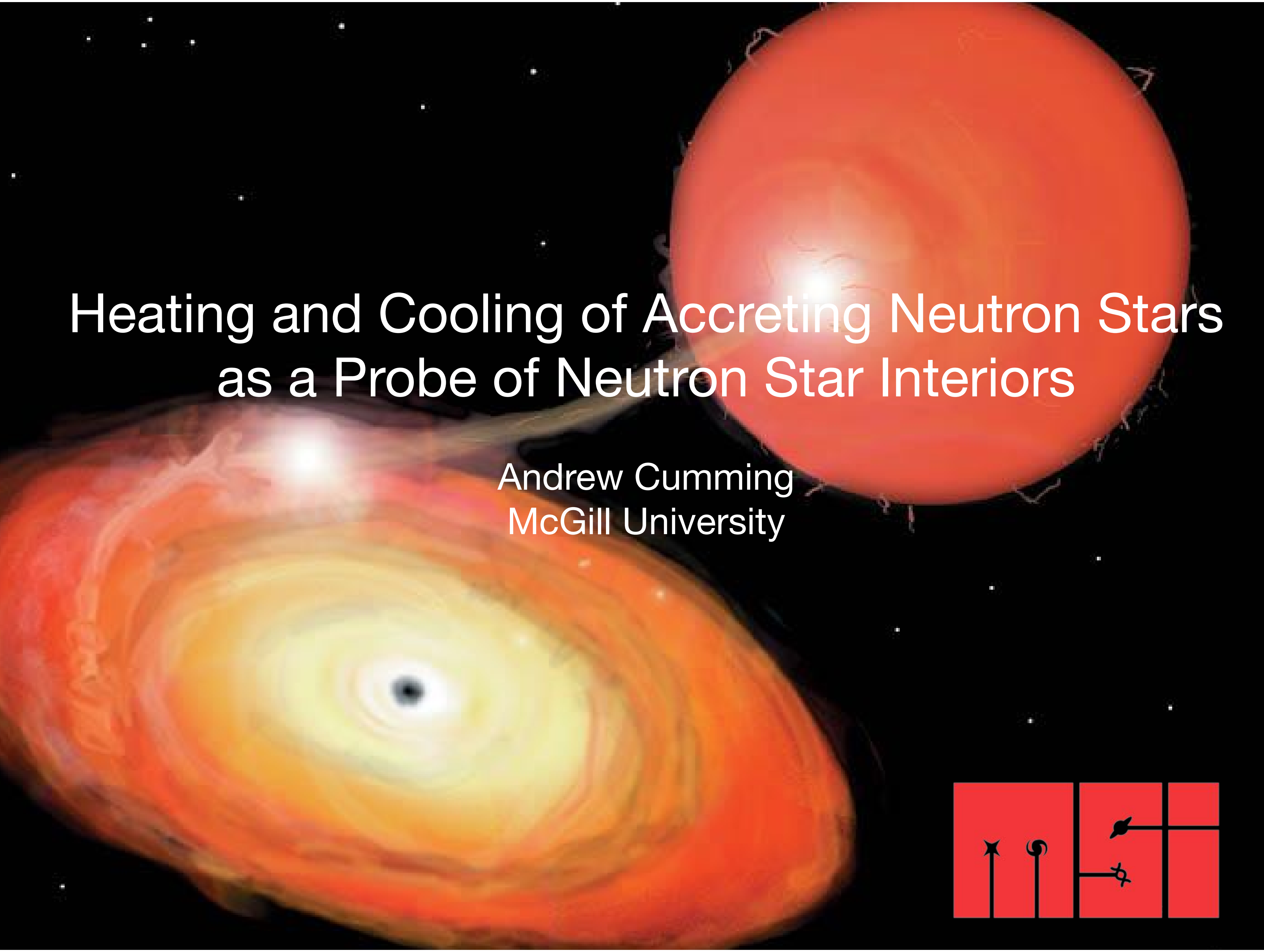
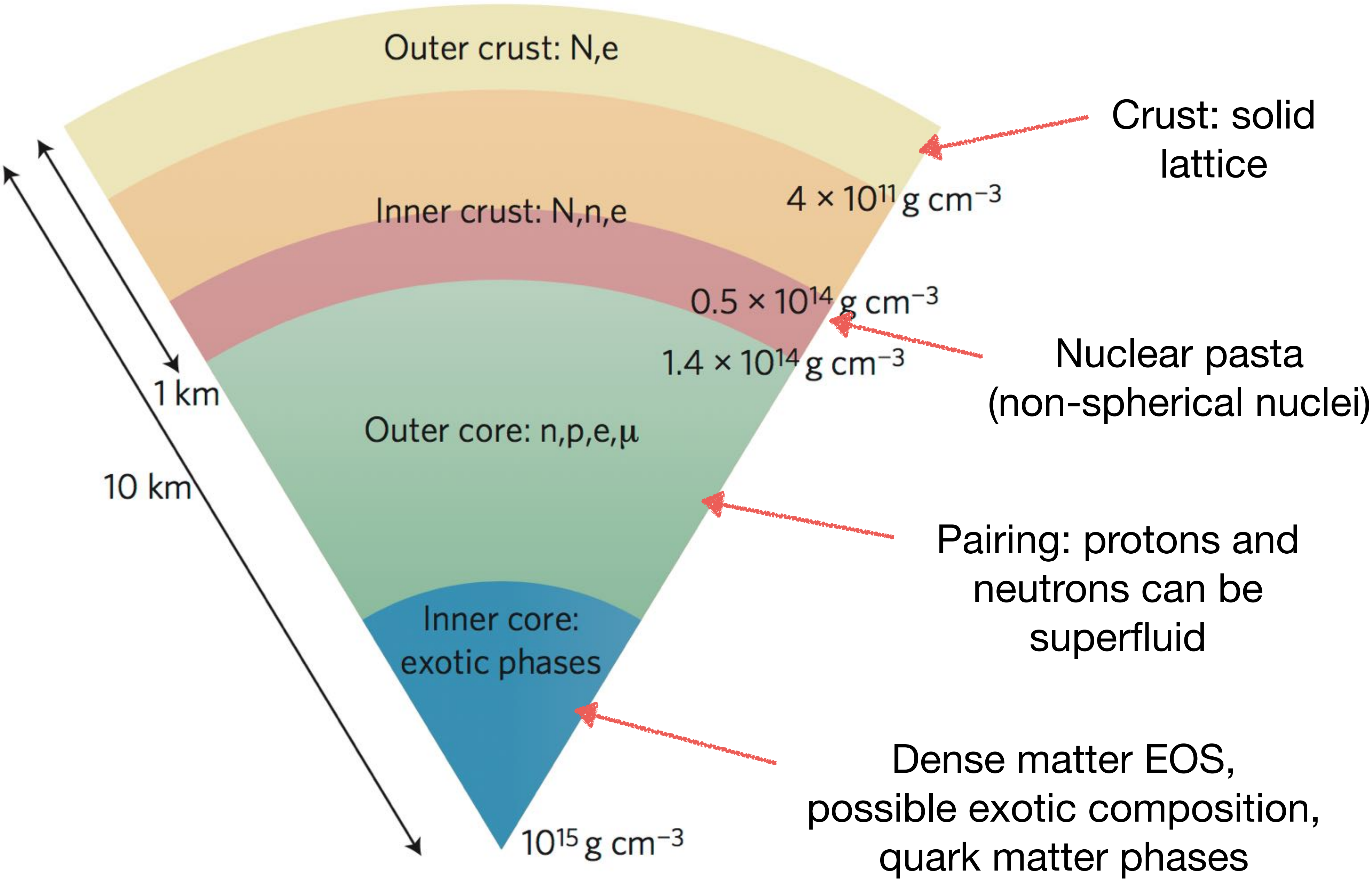


Heating and Cooling of Accreting Neutron Stars as a Probe of Neutron Star Interiors

Andrew Cumming
McGill University



Newton (2013) Nat Phys

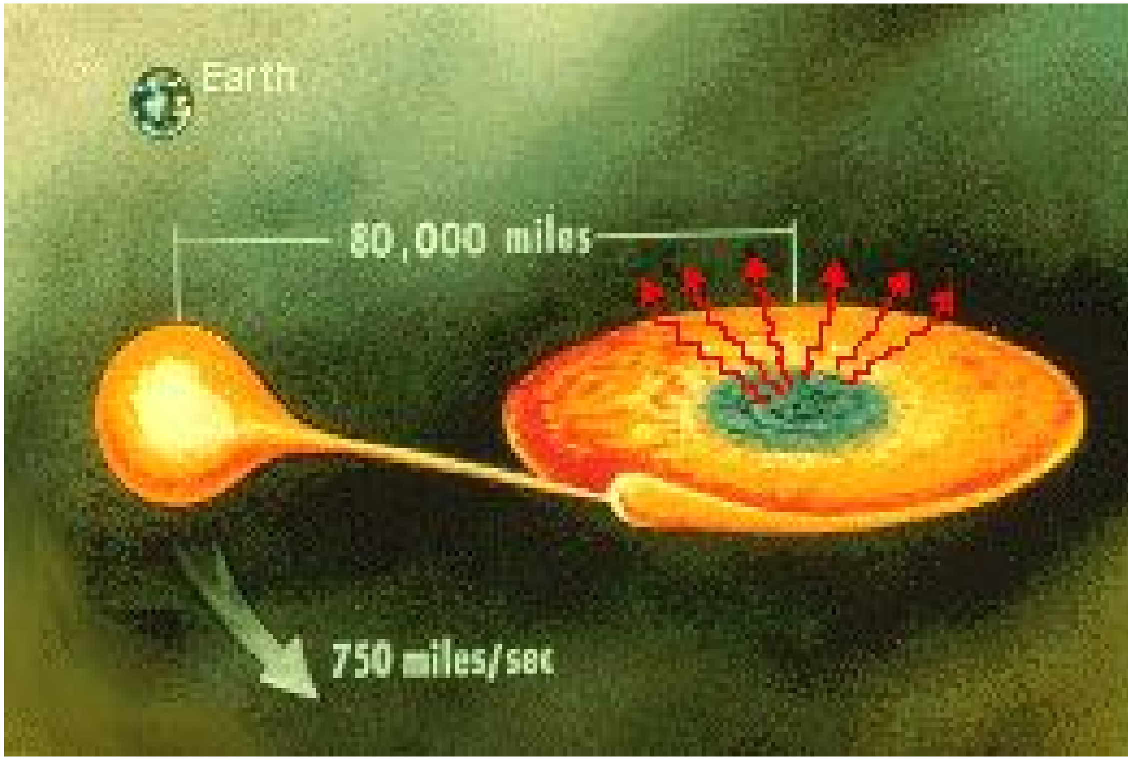
Neutron stars in low mass X-ray binaries

companion mass $\lesssim M_\odot$

orbital periods 10 mins -1 day

- long lived stable accretion
- entire crust can be replaced => matter fully explores the transition from surface to core
- bright X-ray sources while accreting
- or during thermonuclear flashes (X-ray bursts)

$$F_X \sim 10^{-10} - 10^{-8}\ \mathrm{erg\ cm^{-2}\ s^{-1}}$$

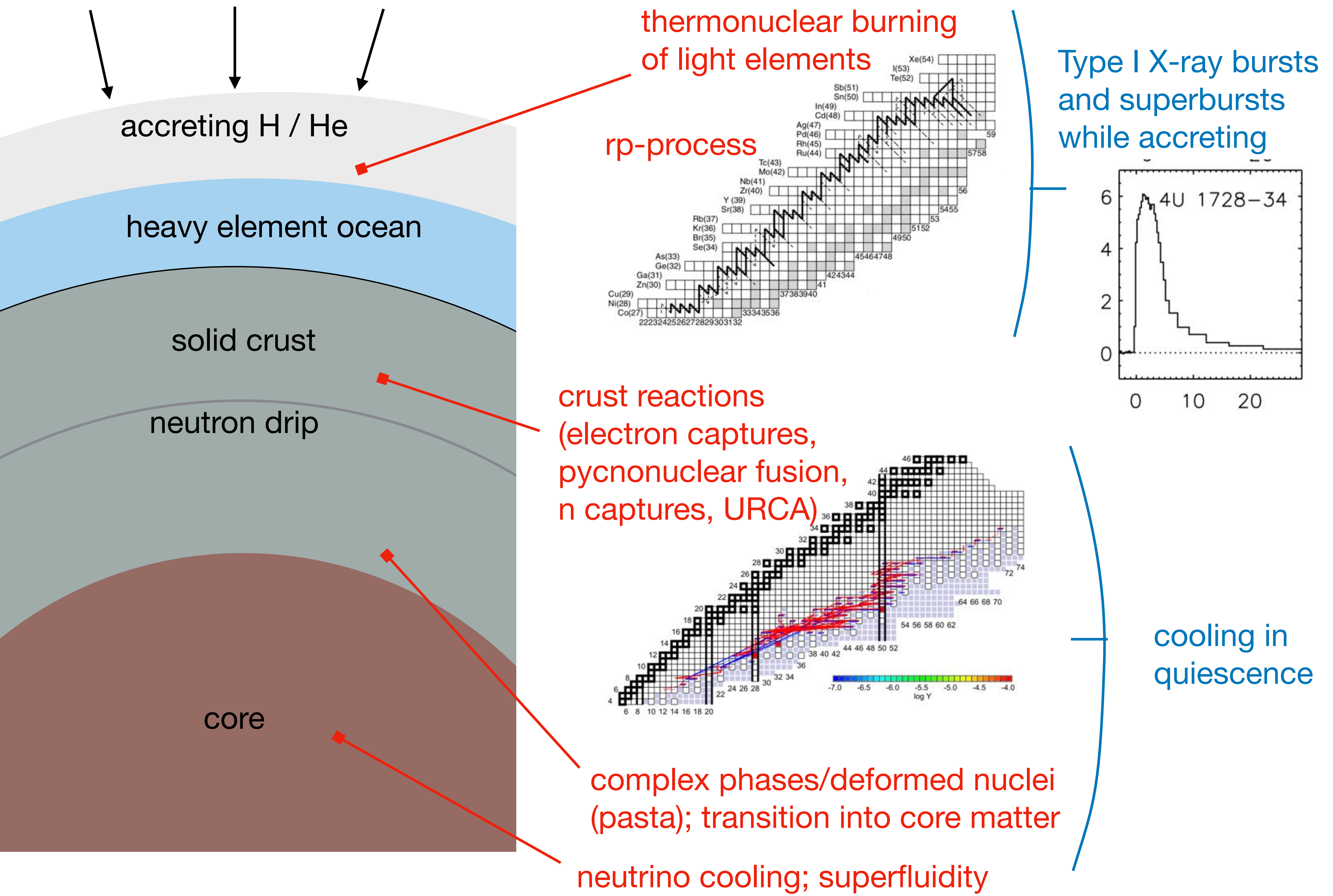


Cartoon of 4U 1820-30 (NASA)

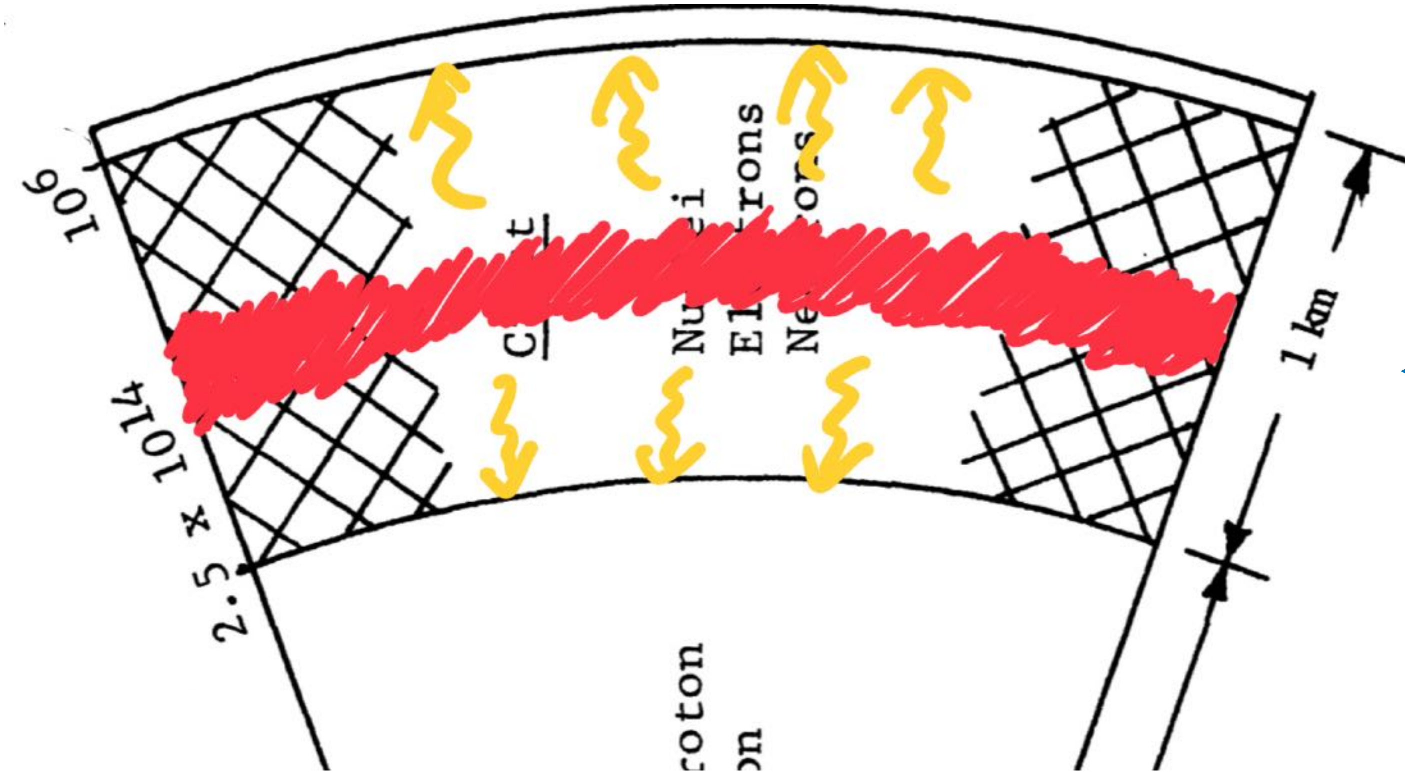
Many are transient

- we can study the neutron star in quiescence
- faint sources in quiescence: requires sensitive X-ray telescope (Chandra/XMM/Swift) $F_q \sim 10^{-14} - 10^{-13}\ \mathrm{erg\ cm^{-2}\ s^{-1}}$

Accreting neutron stars as nuclear physics laboratories



The neutron star crust is heated while it accretes



accretion-driven reactions deposit ~1-2 MeV per nucleon

“Deep crustal heating”

(Sato 1979; Haensel & Zdunik 1990; Brown et al. 1998)

$$E_{\rm dep} = \dot{M}\,\Delta t\; Q_{\rm nuc} \sim 10^{43}\ {\rm erg}\ \ \text{in a 1 year outburst}$$

Two things we can do with this:

1. Core temperature reflects the balance between heating and core neutrino cooling
2. Thermal relaxation of the hot crust after the outburst probes the low density regions

An interesting time to study neutron star interiors

Closing in on the equation of state:

- Improved understanding of the EOS and its uncertainties near nuclear density
- >2 solar mass neutron stars
- tidal deformability constraints from LIGO
- NICER radius measurements
- future moment of inertia measurement in the double pulsar

A new set of observables: many different types of *transient events*:

- cooling from birth
- mergers
- glitches
- magnetar outbursts (including seismology)
- cooling after accretion outbursts

An opportunity to go "beyond the EOS", break degeneracies

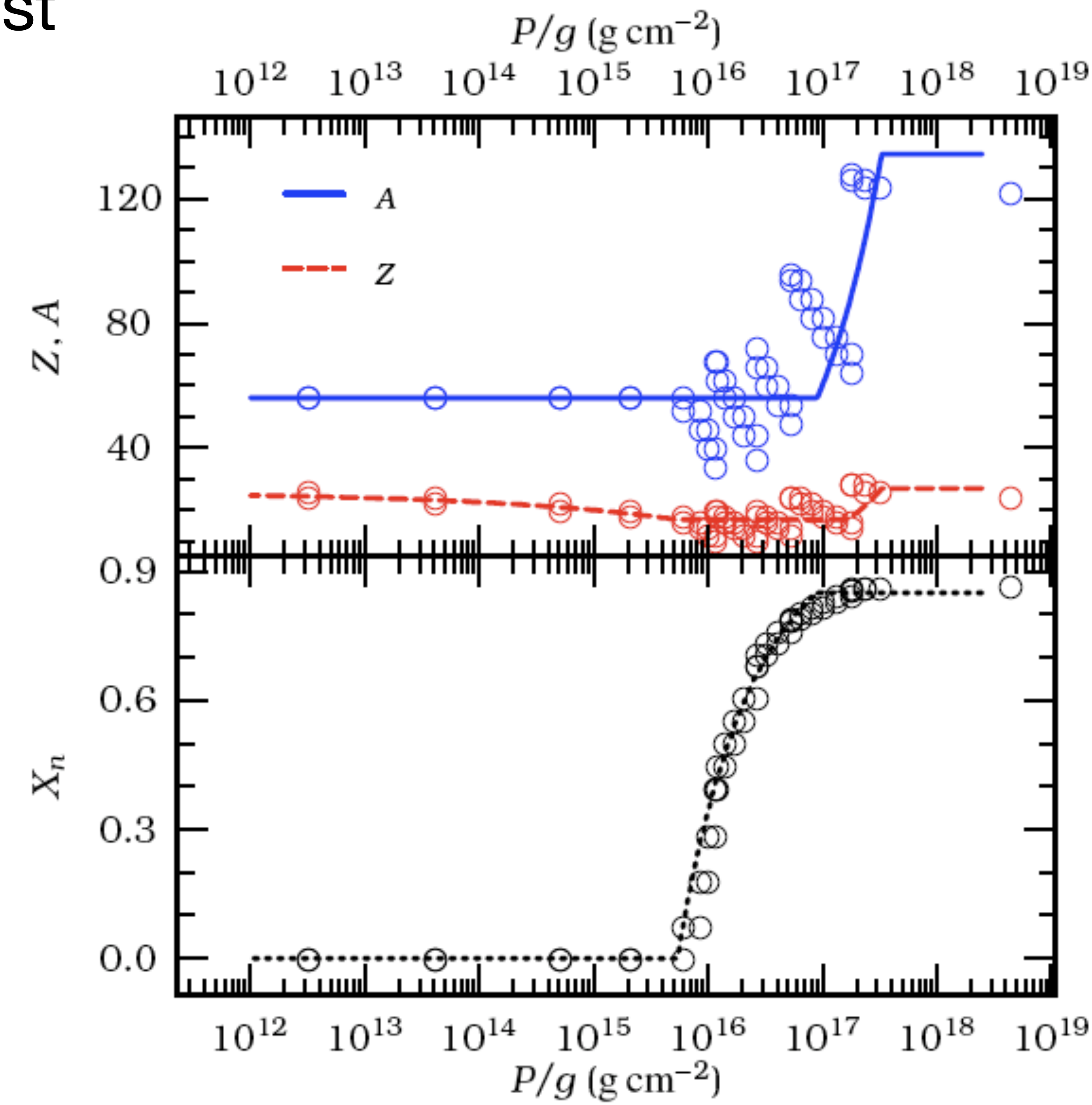
- the state of matter (superfluidity)
- particle content
- transport properties

Reactions in the crust

Example reaction sequences

Outer crust
$^{56}\mathrm{Fe} + e^- \rightarrow {}^{56}\mathrm{Mn} + \nu_e$
$^{56}\mathrm{Mn} + e^- \rightarrow {}^{56}\mathrm{Cr} + \nu_e$

Inner crust
$^{56}\mathrm{Ar} + e^- \rightarrow {}^{56}\mathrm{Cl} + \nu_e$
$^{56}\mathrm{Cl} \rightarrow {}^{55}\mathrm{Cl} + n$
$^{55}\mathrm{Cl} + e^- \rightarrow {}^{55}\mathrm{S} + \nu_e$
$^{55}\mathrm{S} \rightarrow {}^{54}\mathrm{S} + n$
$^{54}\mathrm{S} \rightarrow {}^{52}\mathrm{S} + 2n$

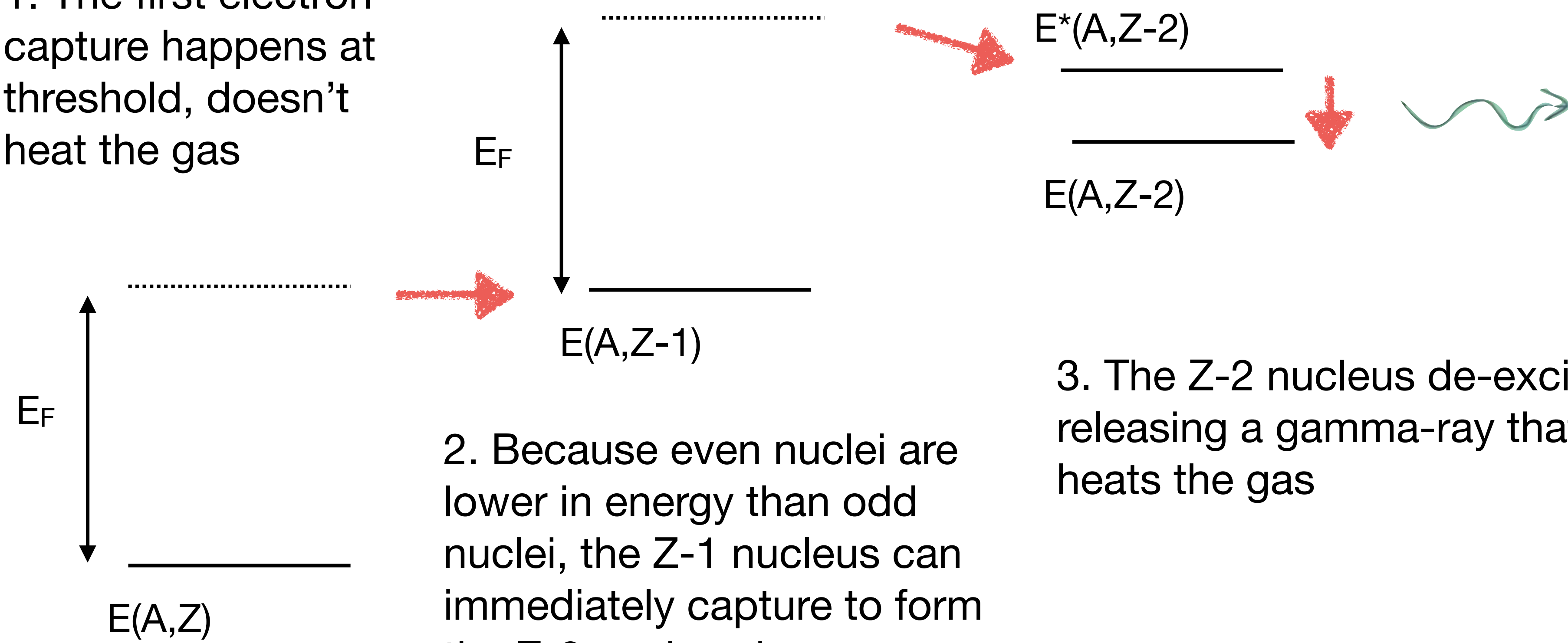


Haensel & Zdunik (1990, 2008); Fantina et al. (2018)

Brown & Cumming 2009

Heating is a non-equilibrium process, determined by nuclear structure

1. The first electron capture happens at threshold, doesn't heat the gas



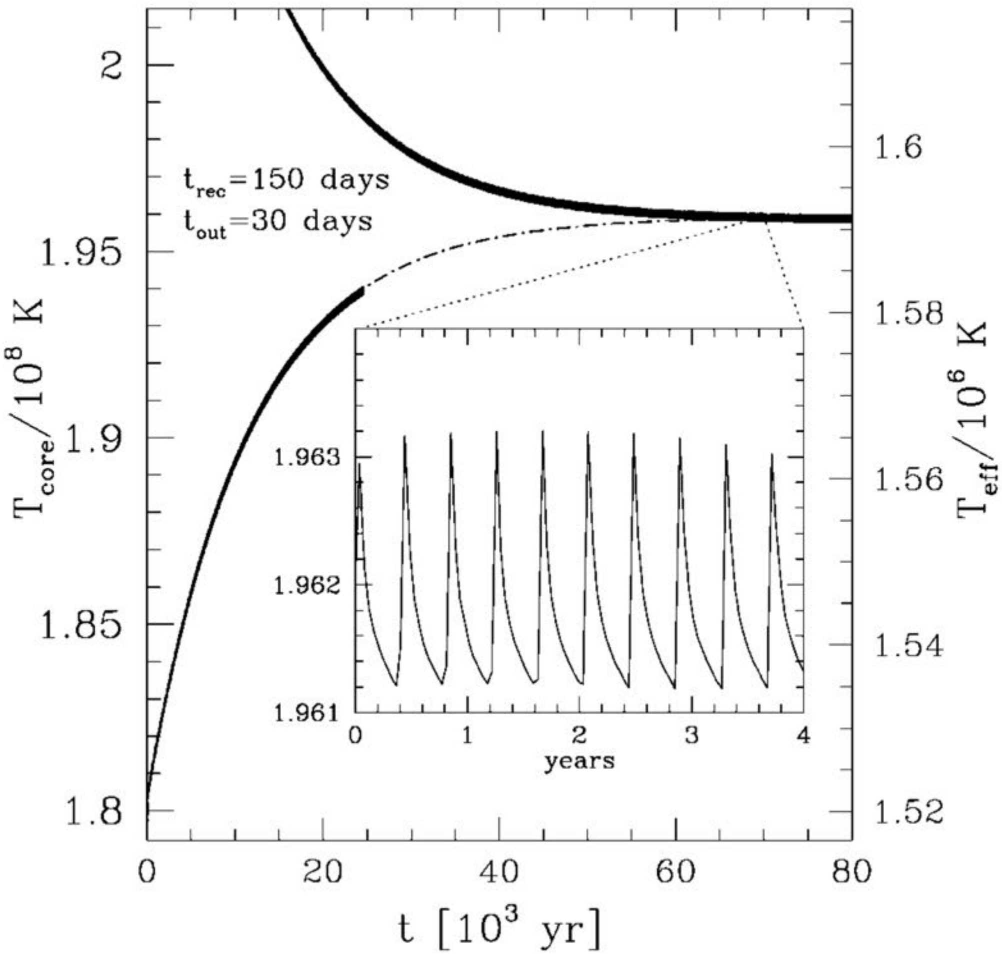
2. Because even nuclei are lower in energy than odd nuclei, the Z-1 nucleus can immediately capture to form the Z-2 nucleus in an excited state.

3. The Z-2 nucleus de-excites, releasing a gamma-ray that heats the gas

Nuclear levels matter — e.g. capture into excited states gives much more heating (Gupta et al. 2007) (and can lead to URCA cooling - Schatz et al. 2014)

Basic idea:

Core quickly (~1-100ky) reaches an equilibrium temperature

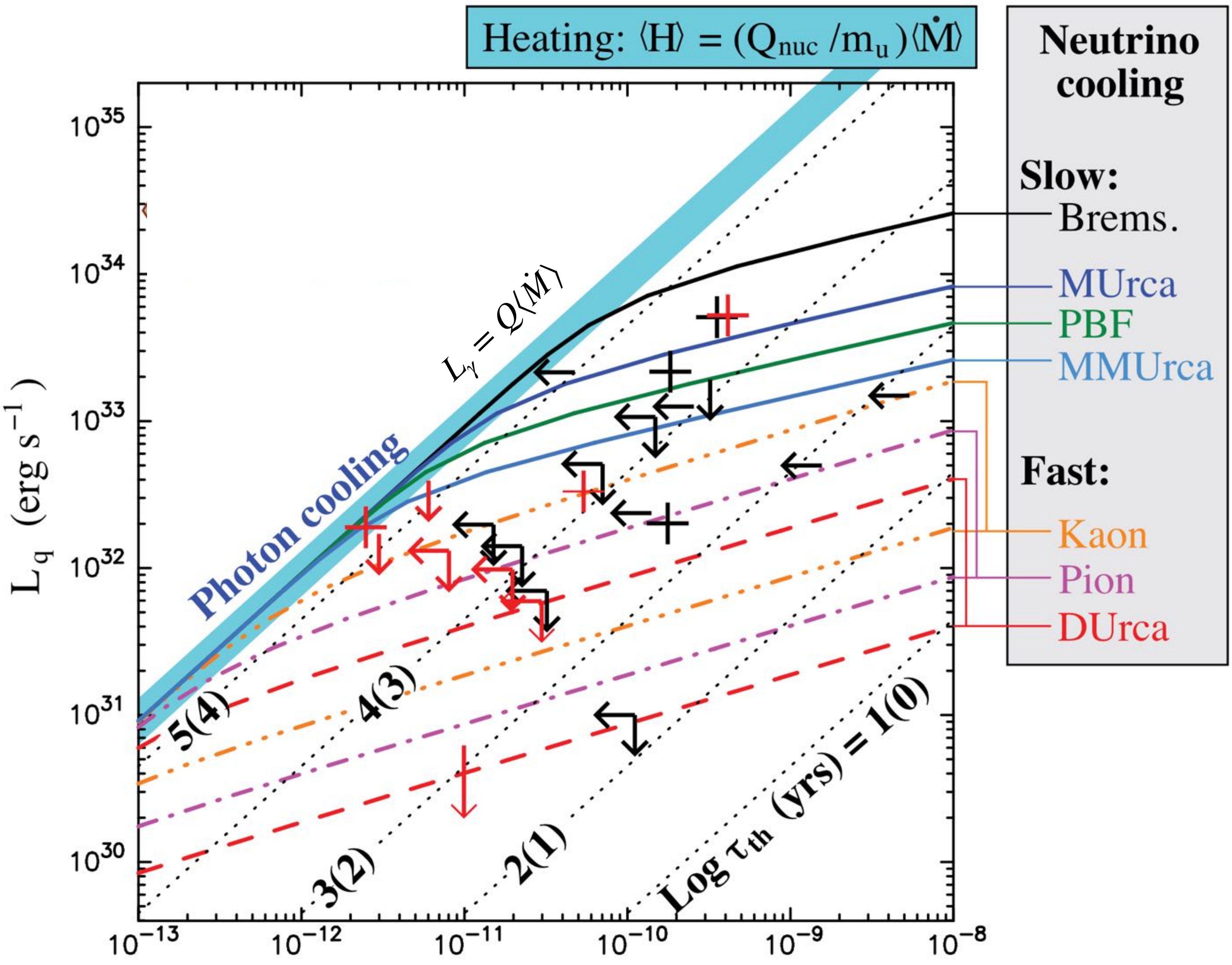


Observable

$$Q\langle\dot{M}\rangle = L_\nu + L_\gamma$$

=> can infer the neutrino luminosity

Colpi et al. (2001) (see also Miralde-Escudé et al. 1990; Brown et al. 1998)



Wijnands et al. (2013)

Model ingredient 1: Neutrino emission processes

- "Fast" e.g. direct URCA

$$n \rightarrow p + e^- + \bar{\nu}_e$$

$$p + e^- \rightarrow n + \nu_e$$

$$L_\nu \propto T^6$$

momentum conservation requires critical proton fraction $Y_p = 0.11\text{–}0.15$

- "Slow" e.g. modified URCA

$$n + n \rightarrow n + p + e^- + \bar{\nu}_e$$

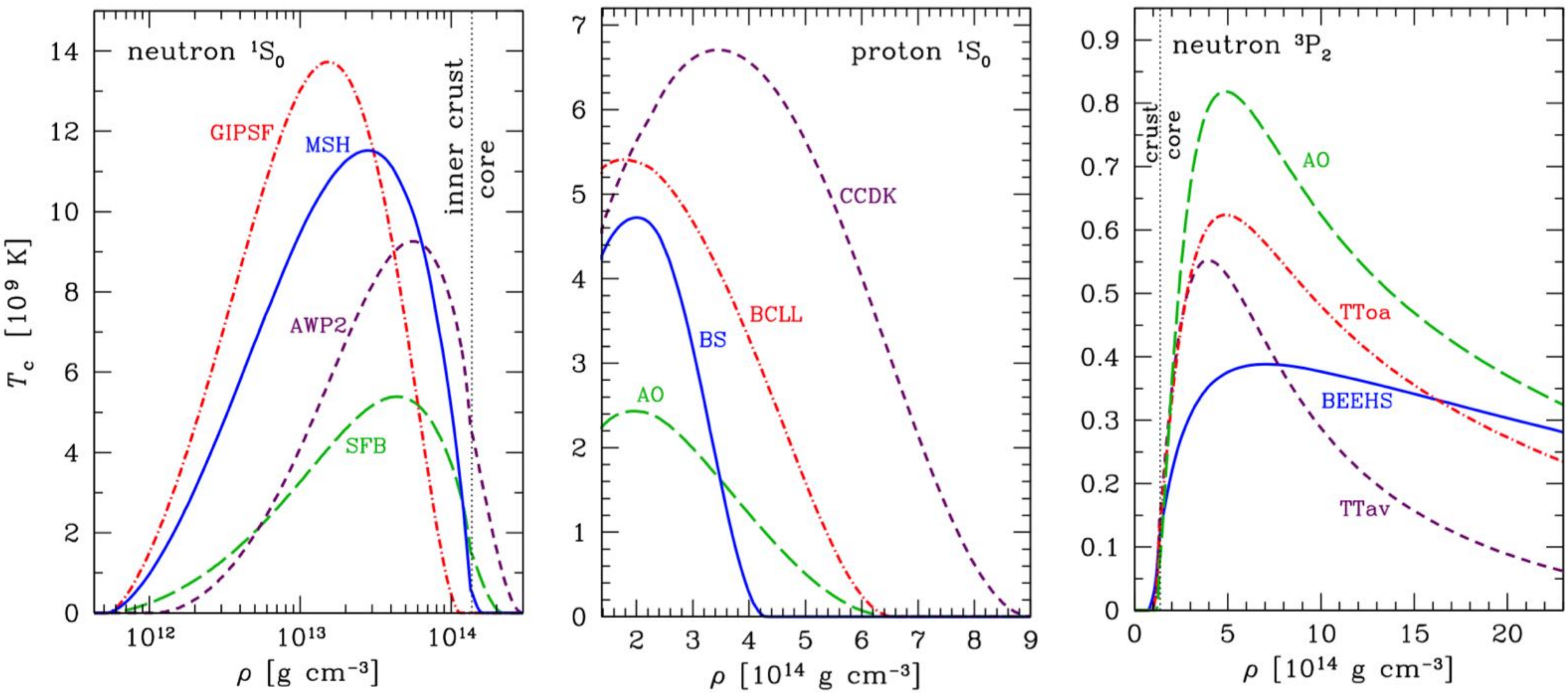
$$L_\nu \propto T^8$$

suppression factor $\approx (k_B T/\mu)^2 \simeq 10^{-7}$ at 10^8 K

=> dramatic increase in neutrino luminosity at a particular density/neutron star mass!

Model ingredient 2: Superfluidity

- Pairing suppresses neutrino-emitting reactions for $T<T_c$

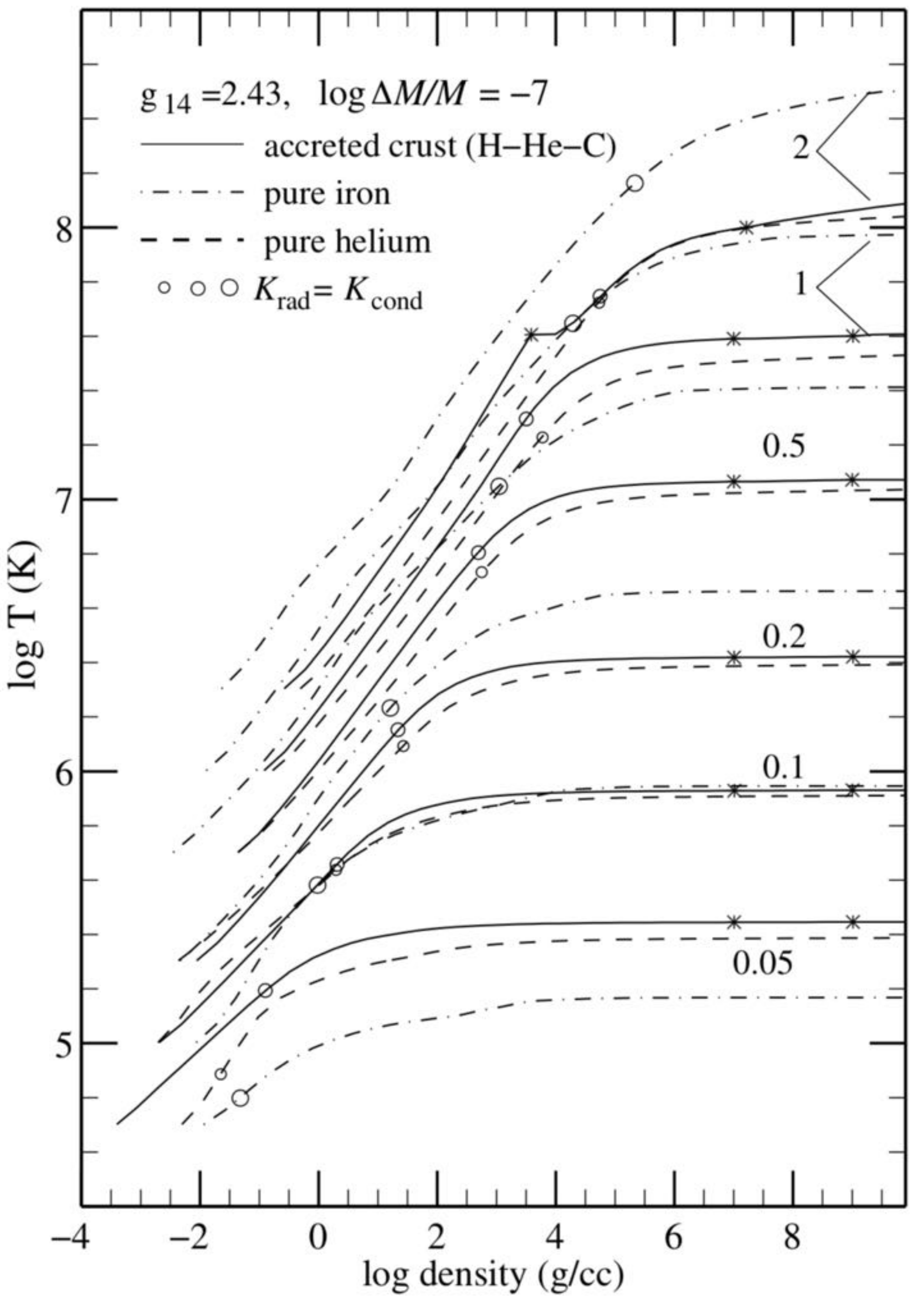


Potekhin, Pons, Page (2015)

- New neutrino emission process near $T \sim T_c$

$$L_\nu \propto T^7 f(T/T_c)$$

Model ingredient 3: Envelope composition



For a given observed effective temperature, the envelope composition makes a ~ factor of 2 difference in the inferred core temperature

Fe envelope

$$\tilde{T} = 7.0 \times 10^7\ \mathrm{K} \left(\frac{T_{\mathrm{eff}}^{\infty}}{63.1\ \mathrm{eV}} \right)^{1.82}$$

Gudmundsson, Pethick & Epstein (1983)

light element envelope

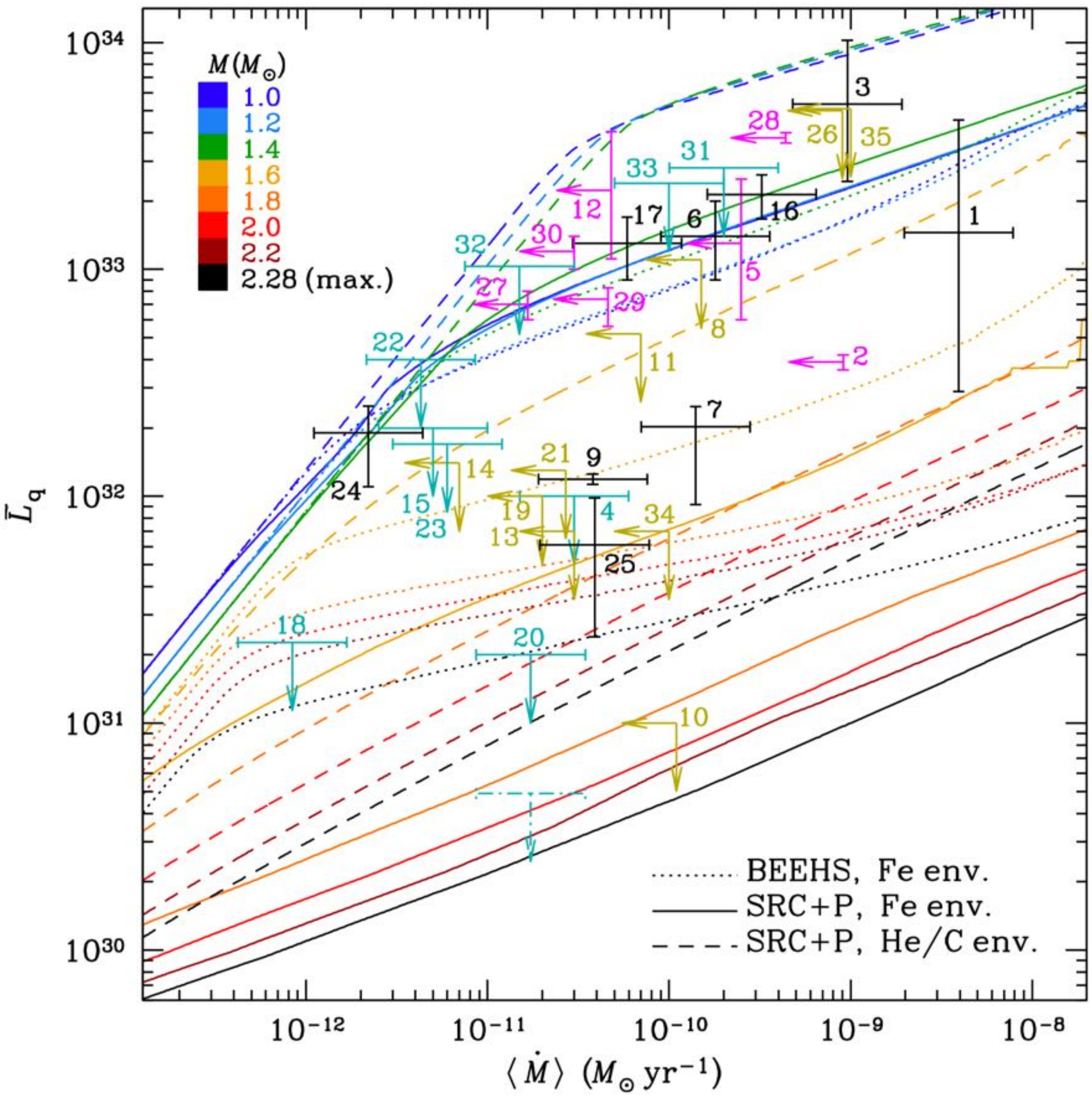
$$\tilde{T} = 3.1 \times 10^7\ \mathrm{K} \left(\frac{T_{\mathrm{eff}}^{\infty}}{63.1\ \mathrm{eV}} \right)^{1.65}$$

Potekhin, Chabrier & Yakovlev (1997)

Potekhin, Chabrier & Yakovlev (1997)

Example of modelling results:

Potekhin, Chugunov, Chabrier (2019)

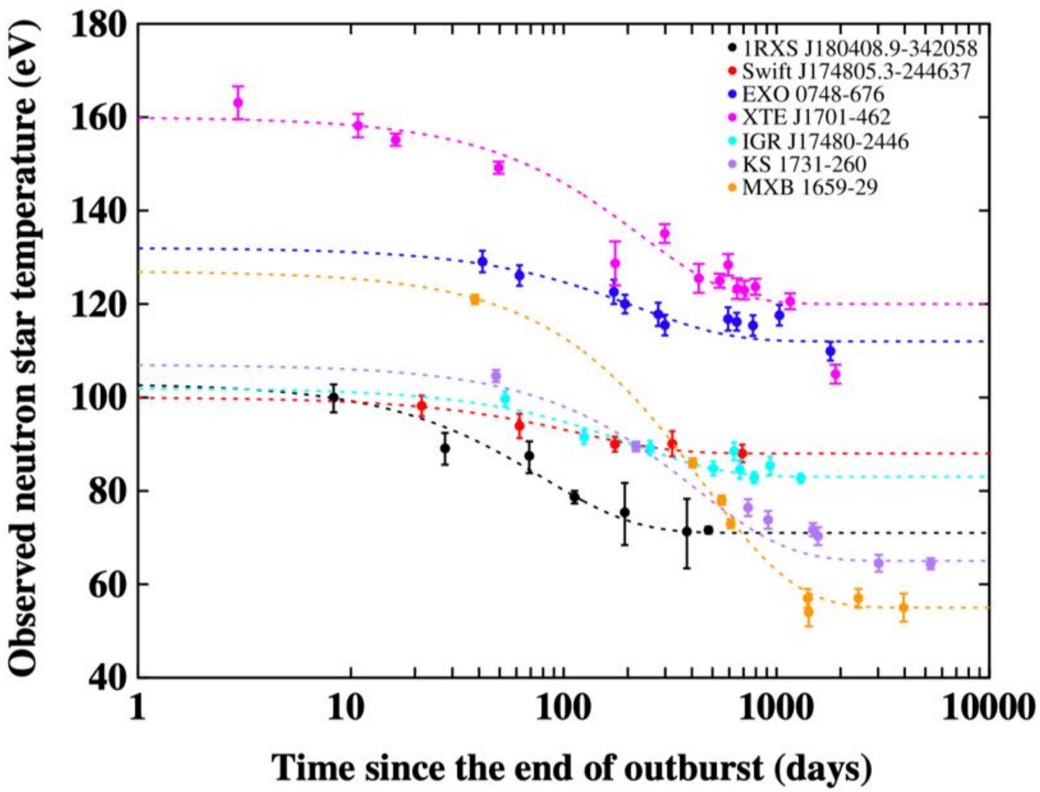


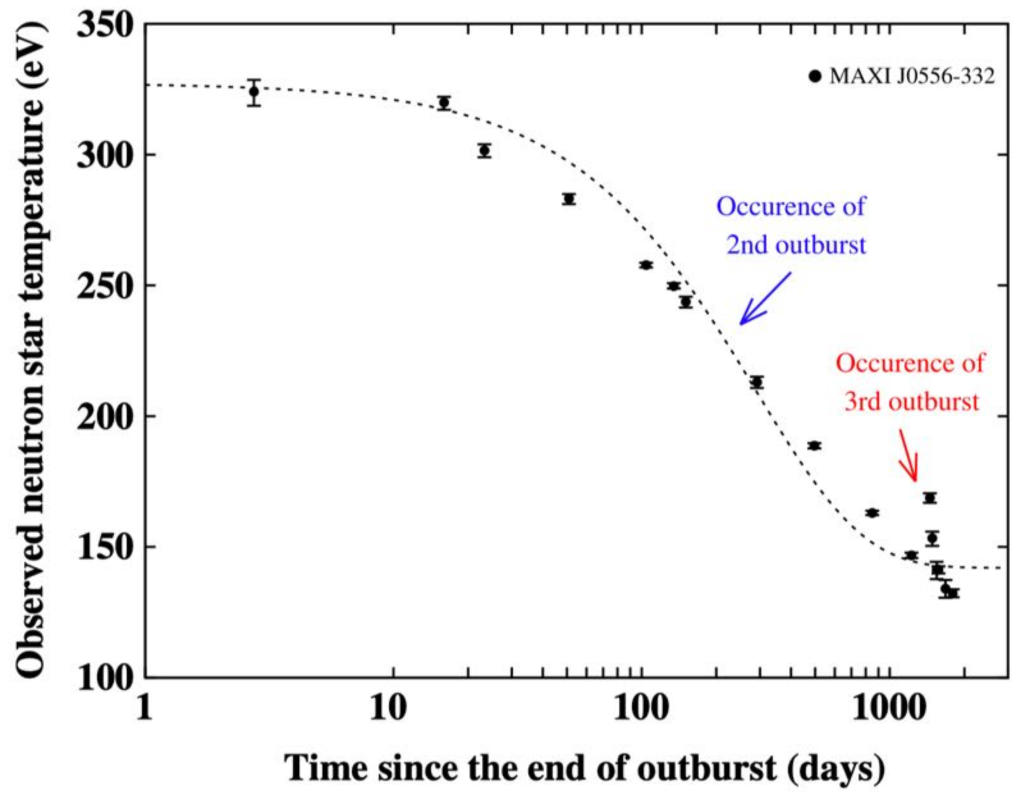
See also Liu et al. (2021), Han & Steiner (2017), Beznogov & Yakovlev (2015)

- Use neutron star mass to move from slow neutrino cooling to fast cooling
- Hottest sources need light element envelopes
- Coldest sources need fast cooling (and iron envelope?)
- Inefficient neutron pairing at high densities so that dURCA is allowed
- Intermediate luminosity sources => Transition between slow and fast needs to be “smoothed” (Beznogov) (by superfluidity)

Crust cooling

- A long accretion outburst heats the crust significantly; afterwards it cools back down to the core temperature
- Rutledge et al. (2002) made predictions for the cooling curves
- This has now been observed in several sources





Wijnands, Degenaar, Page (2017)

(+ HETE J1900.1-2455 with T_{eff}=35 eV, Degenaar et al. 2021, more on that later)

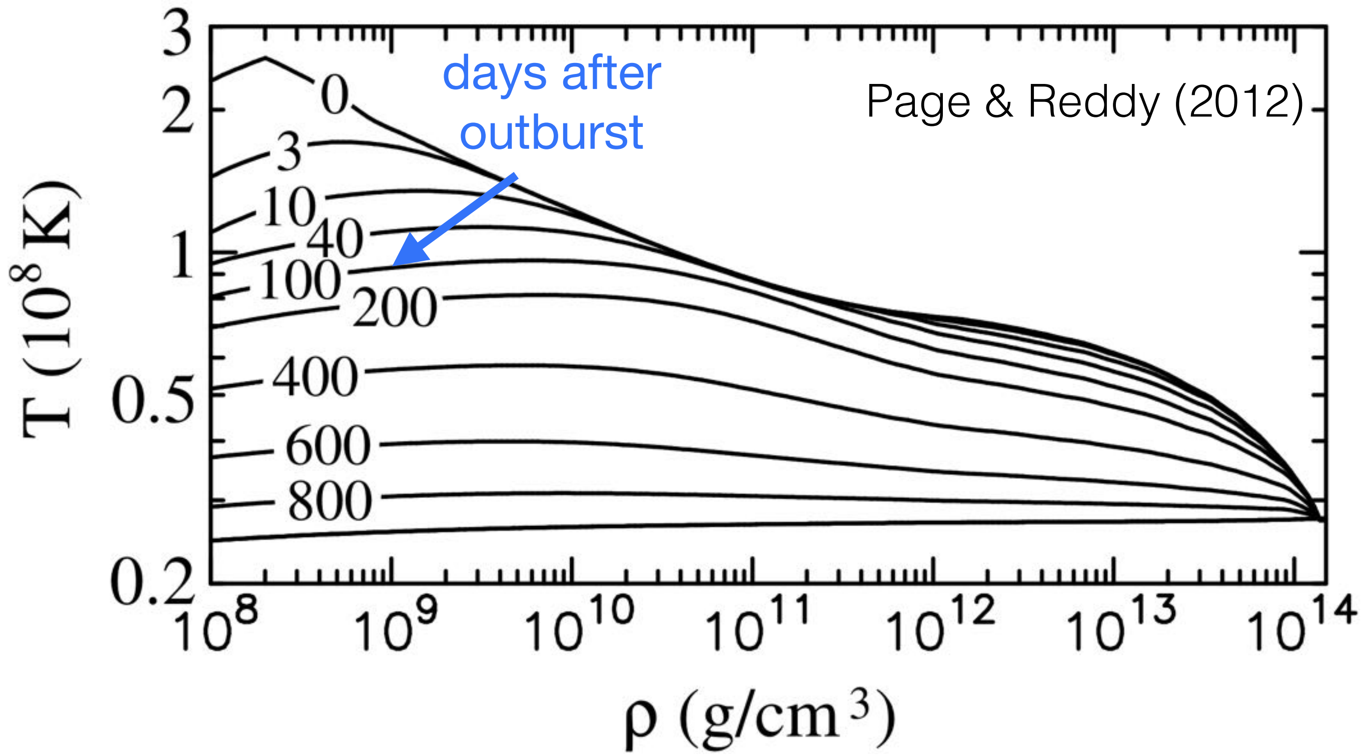
Time evolution of the crust temperature profile

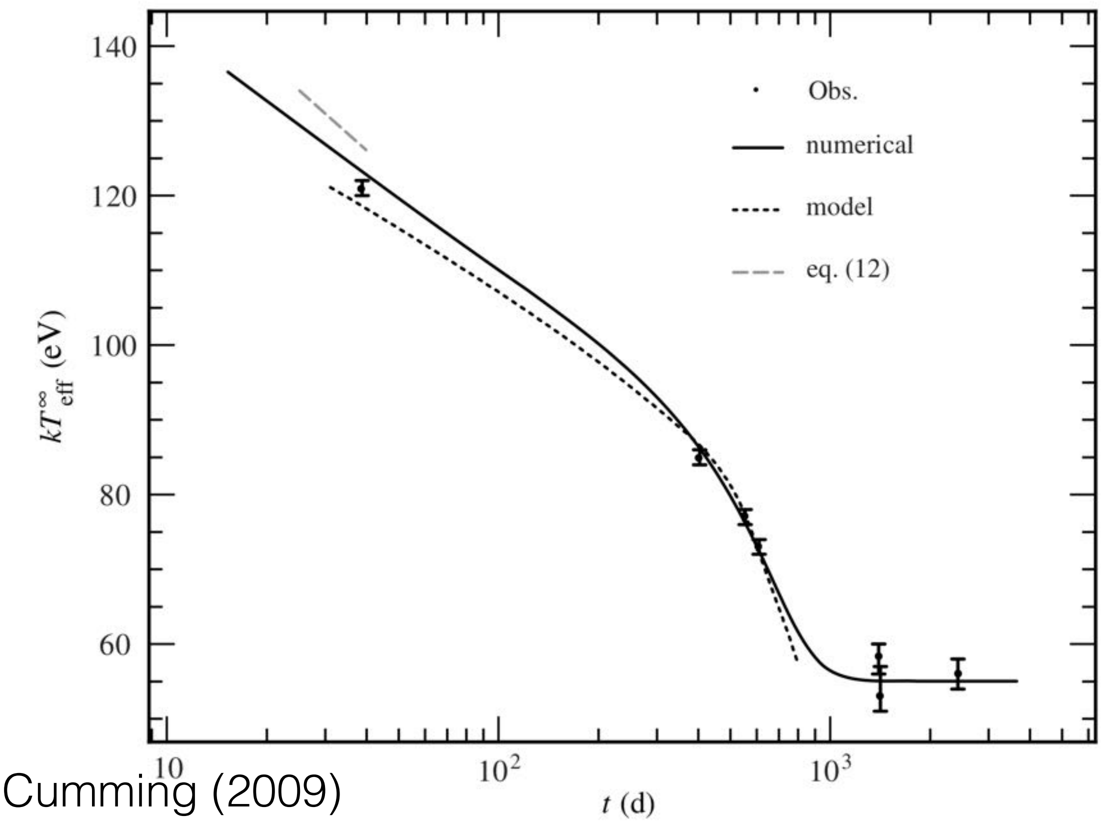
- Solve the thermal diffusion equation in the crust

- Low density regions near the surface relax first
- Cooling wave reaches neutron drip at ~ 100-300 days, which is also the time for the inner crust to cool inwards to the core
- Then see a rapid drop in temperature to the core temperature

- The cooling curve tell us the crust temperature profile at the end of the outburst

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





Brown & Cumming (2009)

Microphysics changes from the outer to inner crust

thermal time

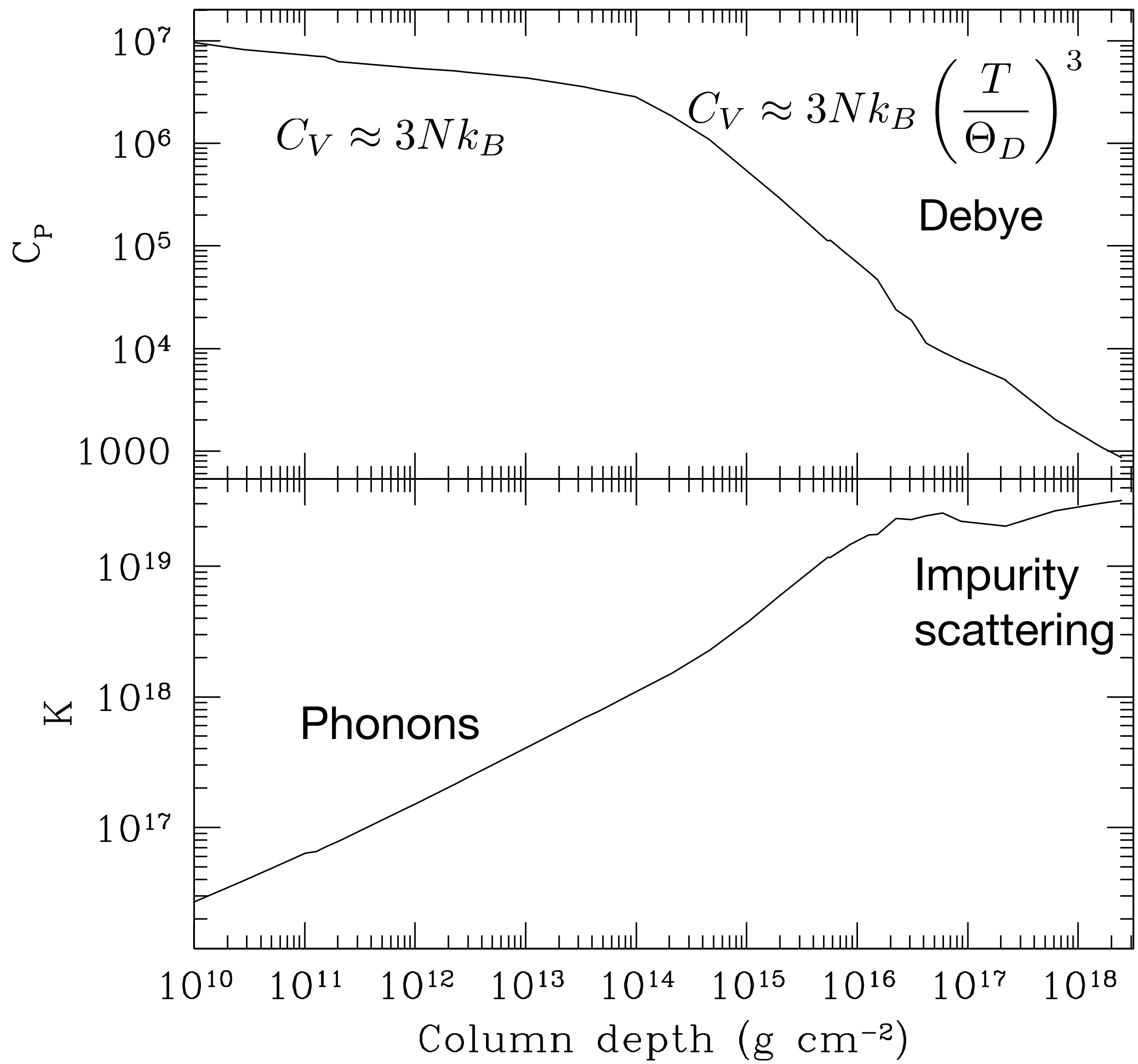
$$\tau = \left[\int_0^z \left(\frac{\rho C_P}{4K}\right)^{1/2} dz\right]^2$$

thermal conductivity

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

impurity parameter

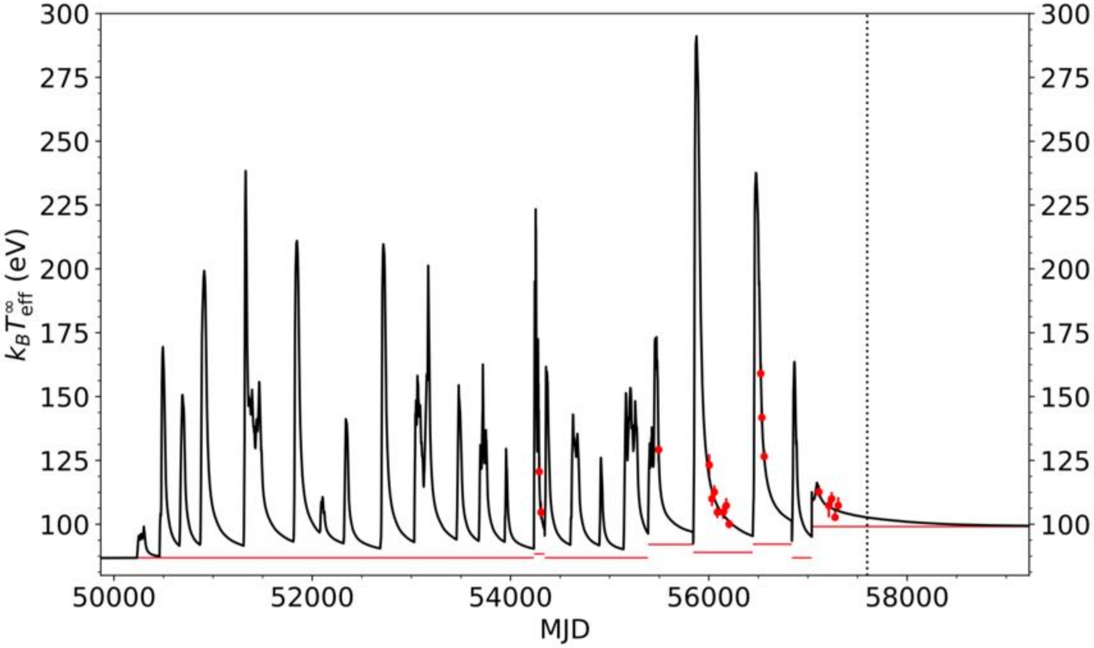
$$Q_{\rm imp} \equiv n_{\rm ion}^{-1} \sum_i n_i (Z_i - \langle Z \rangle)^2$$



Outer crust | Inner crust

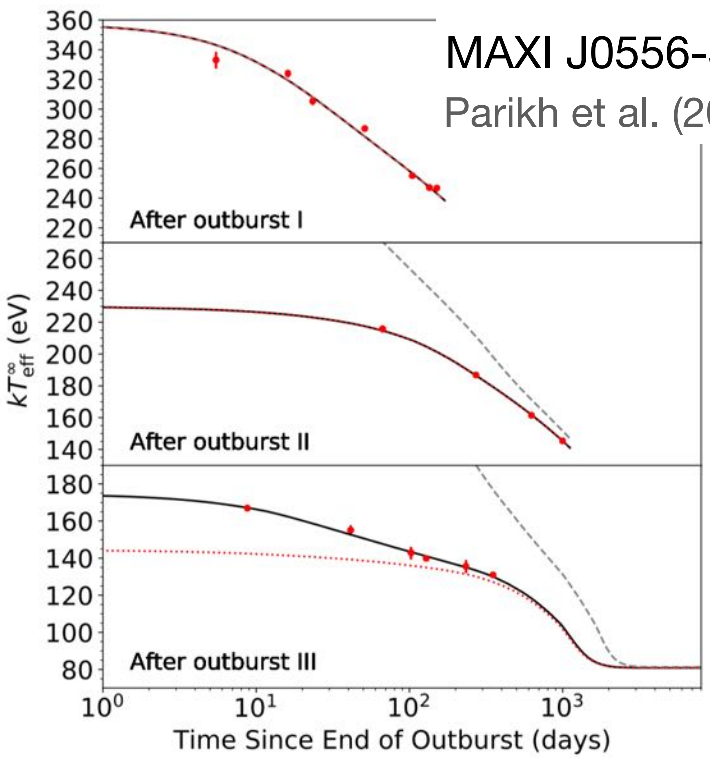
Aql X-1

Ootes et al. (2018)



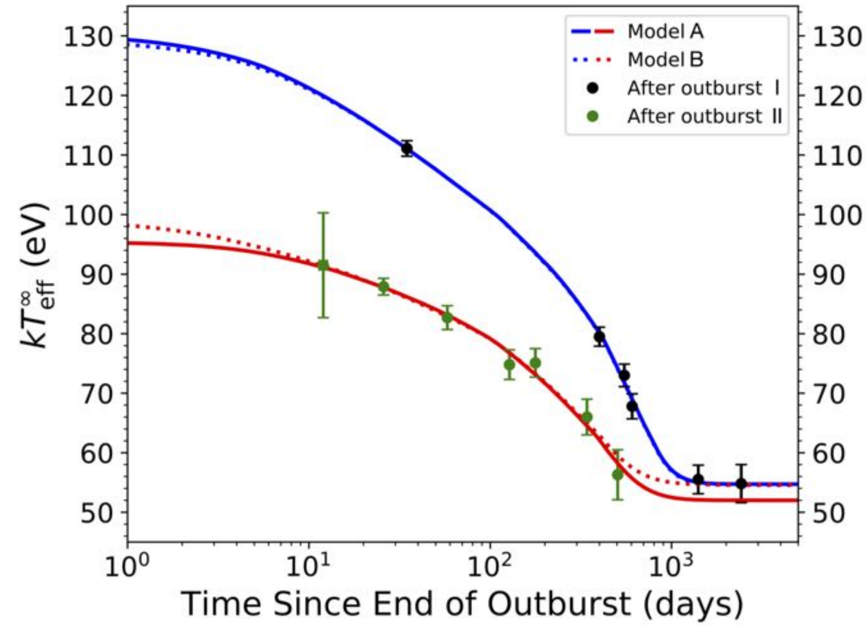
MAXI J0556-332

Parikh et al. (2017)



MXB 1659-29

Parikh et al. (2018)

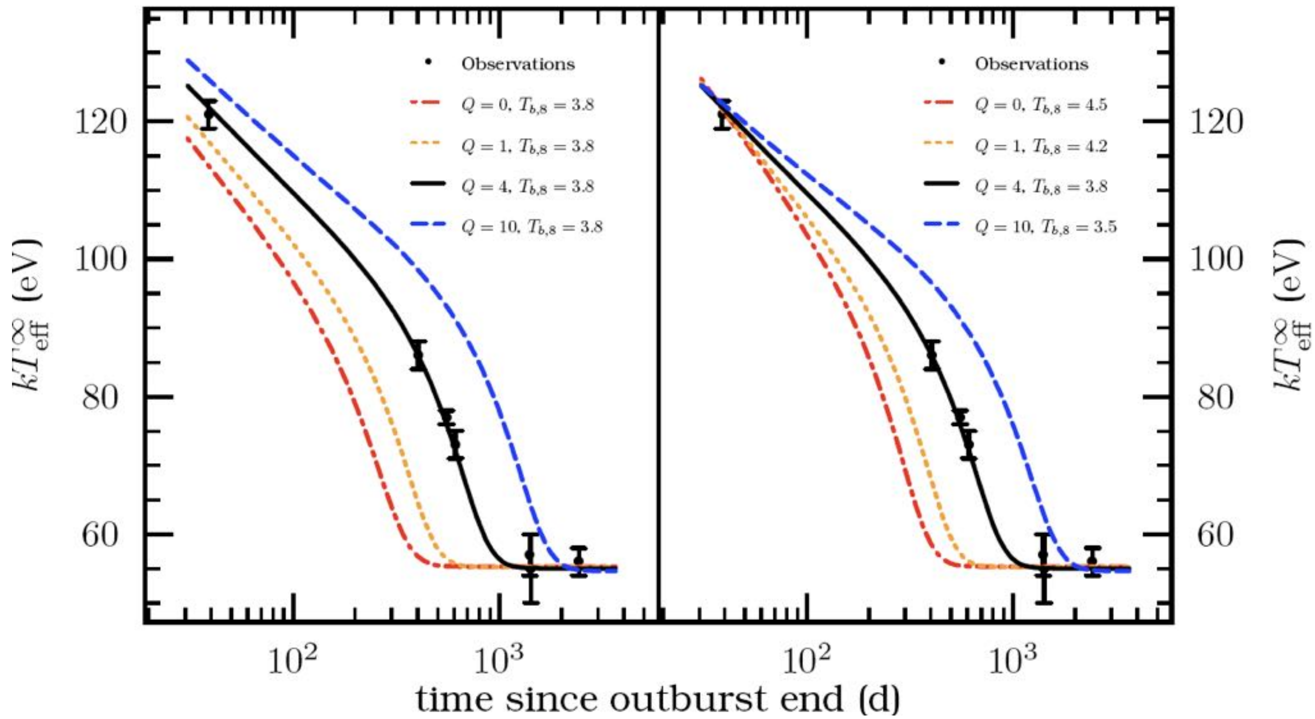


(and Turlione et al. 2015 for fits to multiple sources)

Constraint on impurity parameter

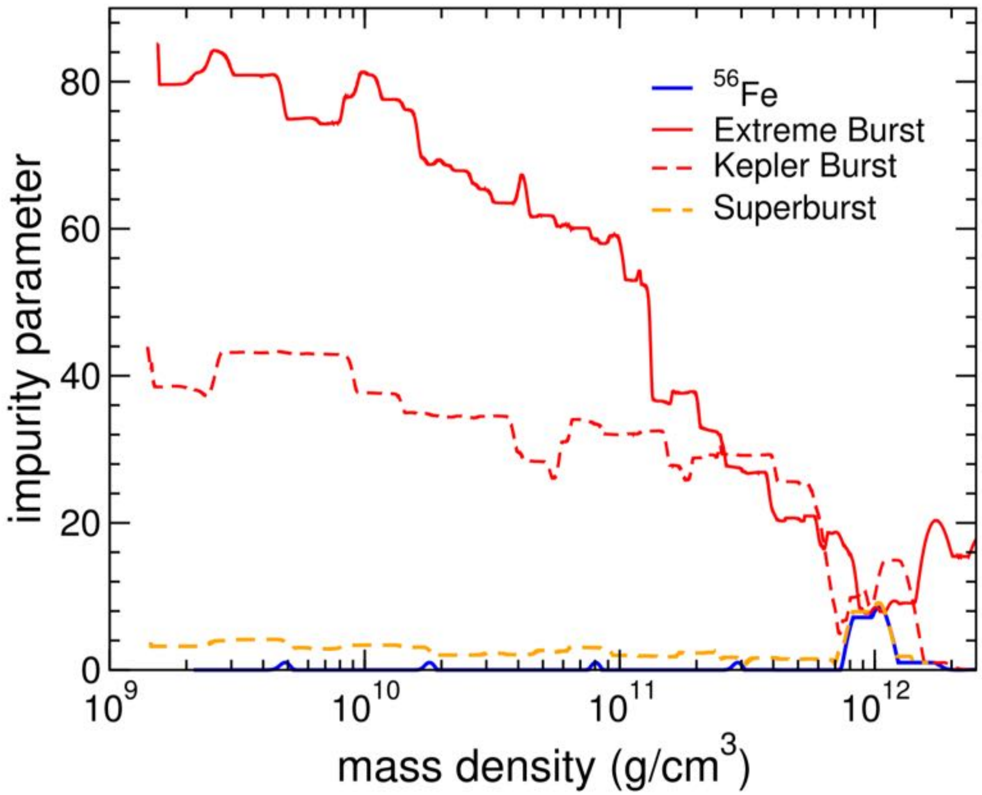
- H/He burning at the neutron surface generates a complex mixture of elements (Q_{imp}~100)
- There had been suggestions that the solid formed from such a mixture would be amorphous (Q_{imp}~Z^2~1000)

- Instead, typically see Q_{imp}~10 or smaller, ie. thermal conductivity is consistent with expectations for solid lattice

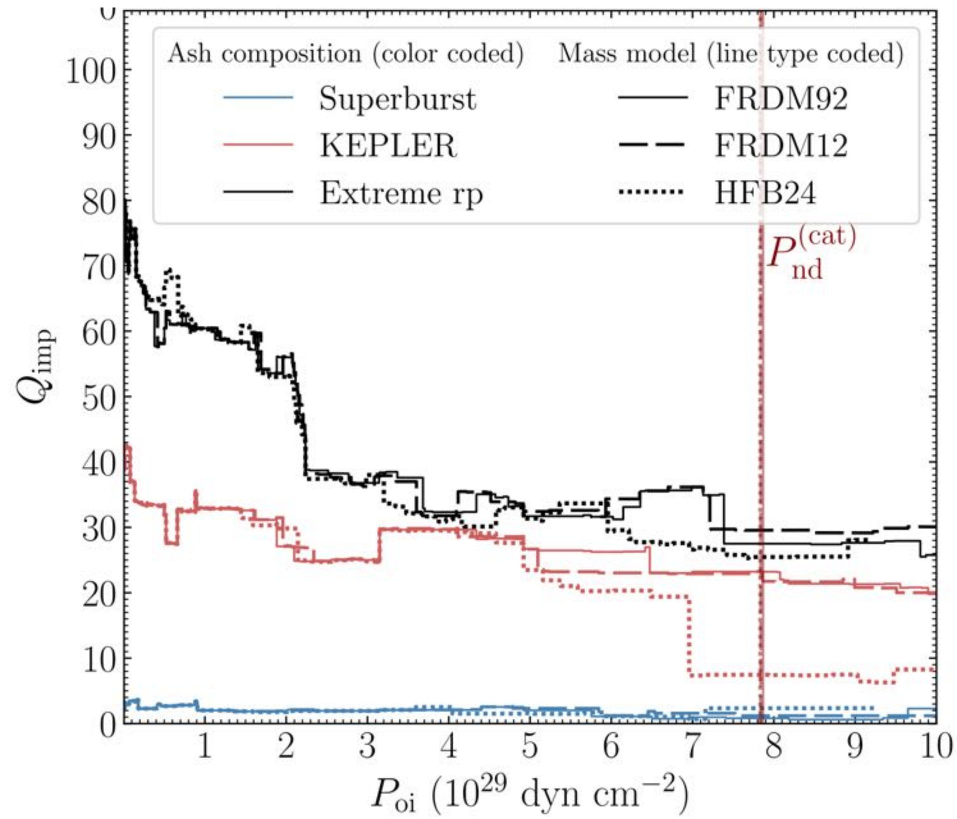


Brown & Cumming (2009)

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



Lau et al. (2018)



Shchechilin, Gusakov, Chugunov 2021

- Some heavy initial compositions get stuck in a large Q_{imp} state

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

Shallow heating

- The temperature profiles needed to match the observed cooling curves peak at much lower densities than the location of the deep crustal heating reactions
- ie. the outer crust is hot and has an inwards-directed heat flux => need a source of "shallow heating"
- previously had been suggested to explain properties of Type I X-ray bursts
- physical origin is unknown!

What do we know about it?

- strength of the heating is typically ~ 1MeV per accreted nucleon at a depth ~ 10^9-10^{10} g/cm^3 (but ~10 times larger in one case)

- it has to turn on and off "quickly" (~weeks?)

- strength is consistent between outbursts from the same source in some cases, but not in others. Sources with similar looking outbursts seem to have very different shallow heating


WHAT WAS ONCE IN THE DEEP
IS NOW IN THE SHALLOWS
THE
SHALLOWS
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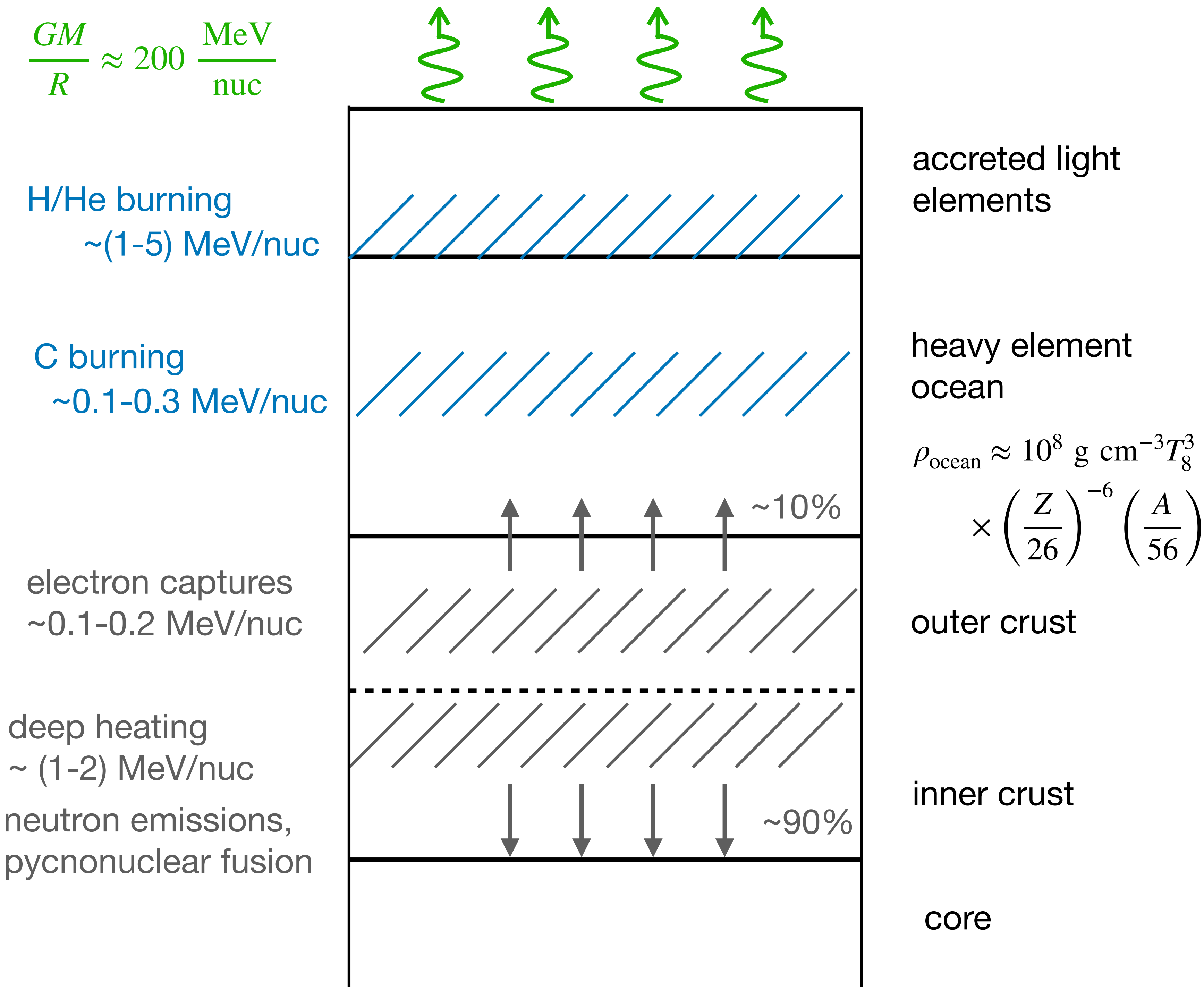
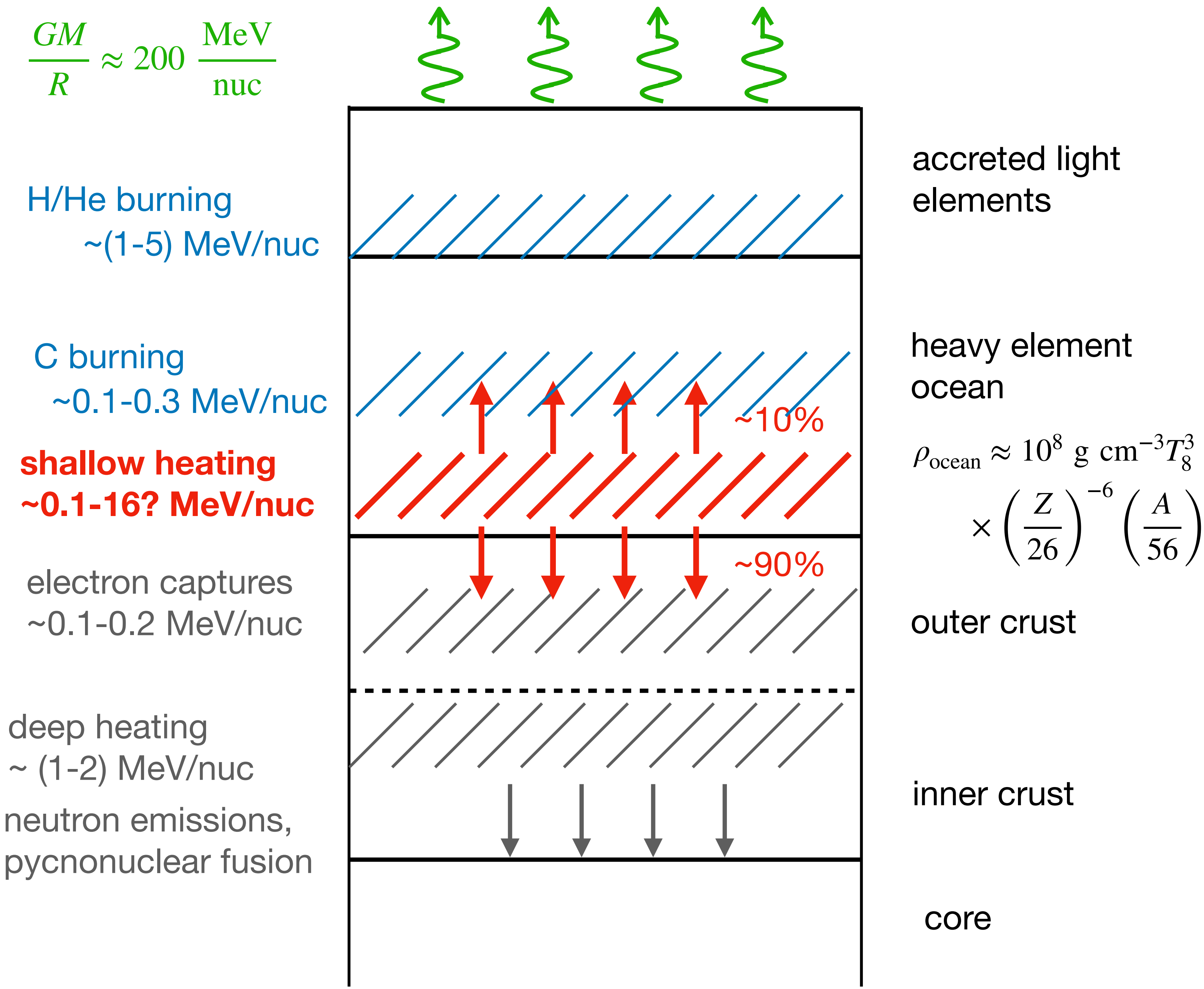
Energy sources in an accreting neutron star



Energy sources in an accreting neutron star



Low density nuclear reactions

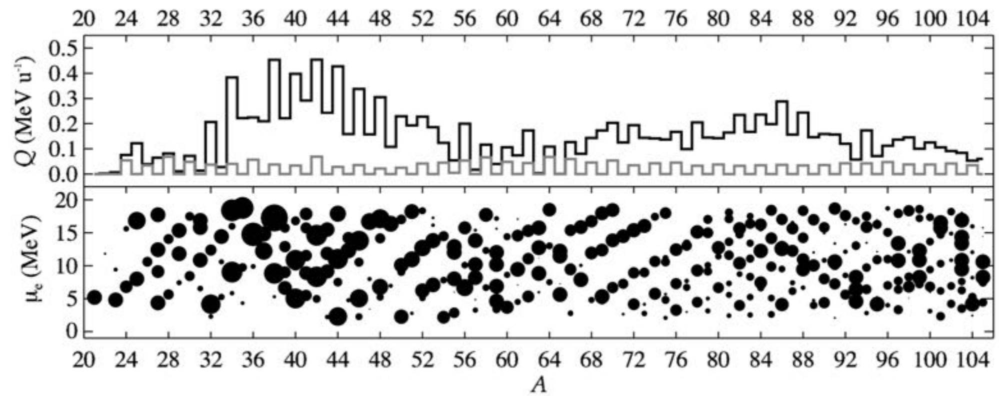
See Meisel et al. (2018) for a review

- **Electron captures** in the outer crust

$$Q \lesssim 0.3 - 0.5 \text{ MeV}$$

captures into excited states
=> less energy loss to neutrinos

Gupta et al. (2007)

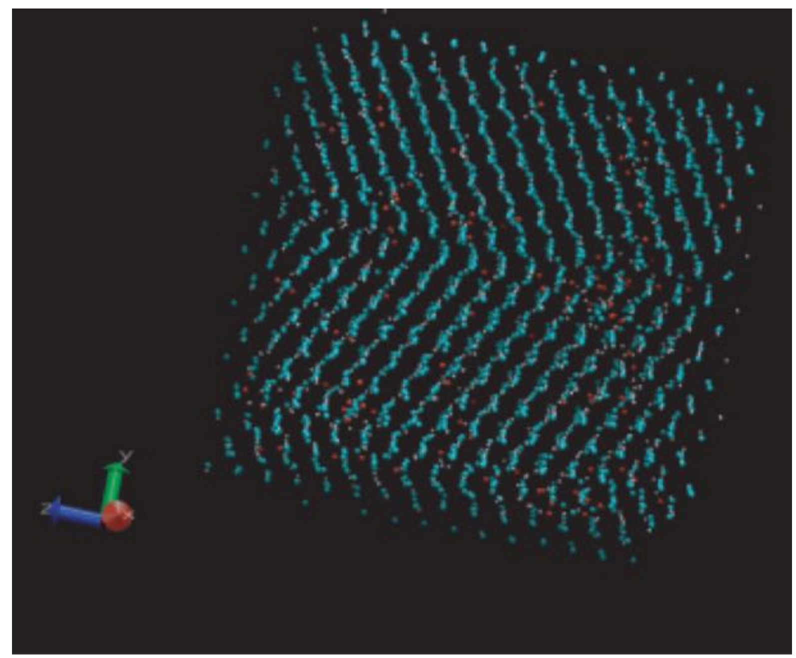


- Low density **fusion** reaction Horowitz et al. (2008)

$^{24}O + {}^{24}O \qquad Q = 0.52$ MeV

$$\rho \sim 10^{11} \text{ g cm}^{-3}$$

oxygen ions in interstitial sites



Horowitz et al. (2008)

- **URCA cooling** reactions associated with odd-A nuclei => neutrino *cooling*

Schatz et al. (2014), Deibel et al. (2015, 2016)

- **neutron transfer** reactions involving odd-A nuclei in outer crust

Chugunov (2019) Schatz et al. (2022)

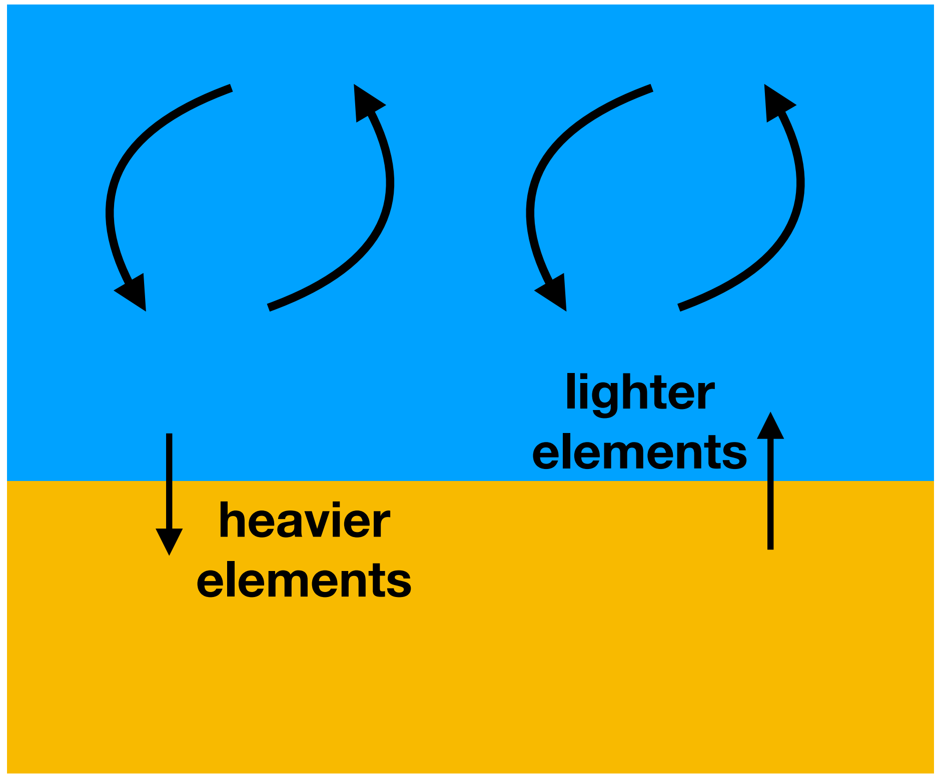
- sudden release of energy rather than continuous heating? — hyperburst Page et al. (2022)

Chemical separation changes heat transport in the ocean

composition flux $F_X \uparrow$

heat flux $F \downarrow$

$$\frac{F}{c_P T} = -\left(\frac{\chi_X}{\chi_T}\right)\frac{F_X}{X}$$



ocean floor

$$\rho_{\rm ocean} \approx 10^8\ {\rm g\ cm^{-3}} T_8^3 \times \left(\frac{Z}{26}\right)^{-6}\left(\frac{A}{56}\right)$$

for steady accretion, the effective heating is

$$\frac{F}{\dot{m}} \approx 0.01 \frac{E_F}{m_p}\frac{\Delta X}{X} \qquad \Rightarrow Q \lesssim 0.2\ {\rm MeV}$$

$$E_F = 5.1\ {\rm MeV}\ \rho_9^{1/3} Y_e^{1/3}$$

Medin & Cumming (2011)

Horowitz et al. (2009), Medin & Cumming (2011, 2014, 2015), Mckinven et al. (2016), Caplan et al. (2018)

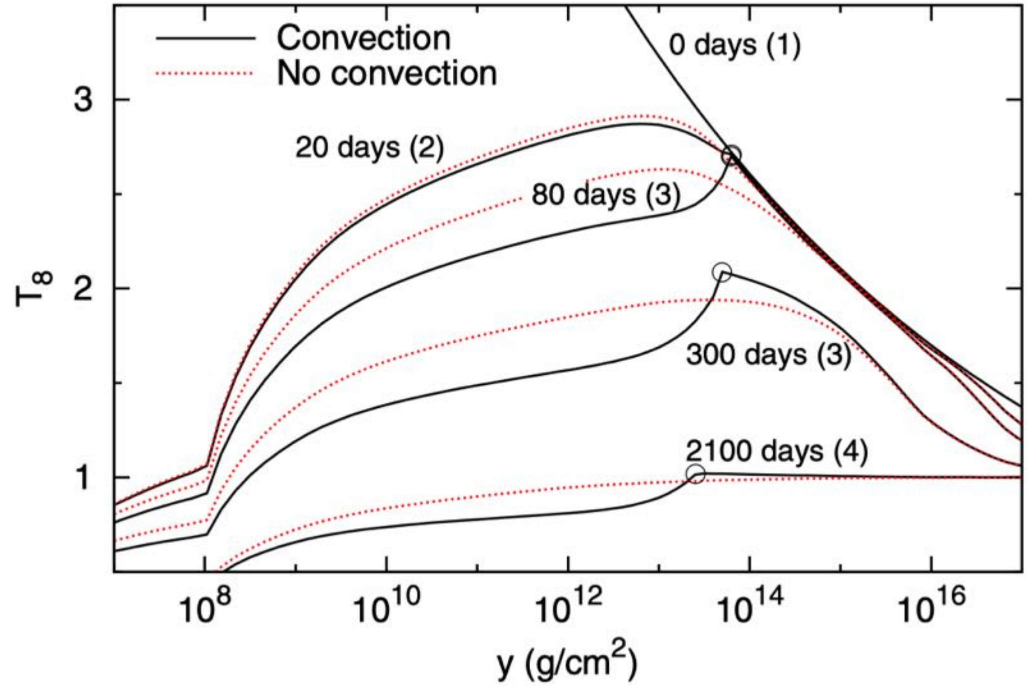
Signature of chemical separation at early times during cooling

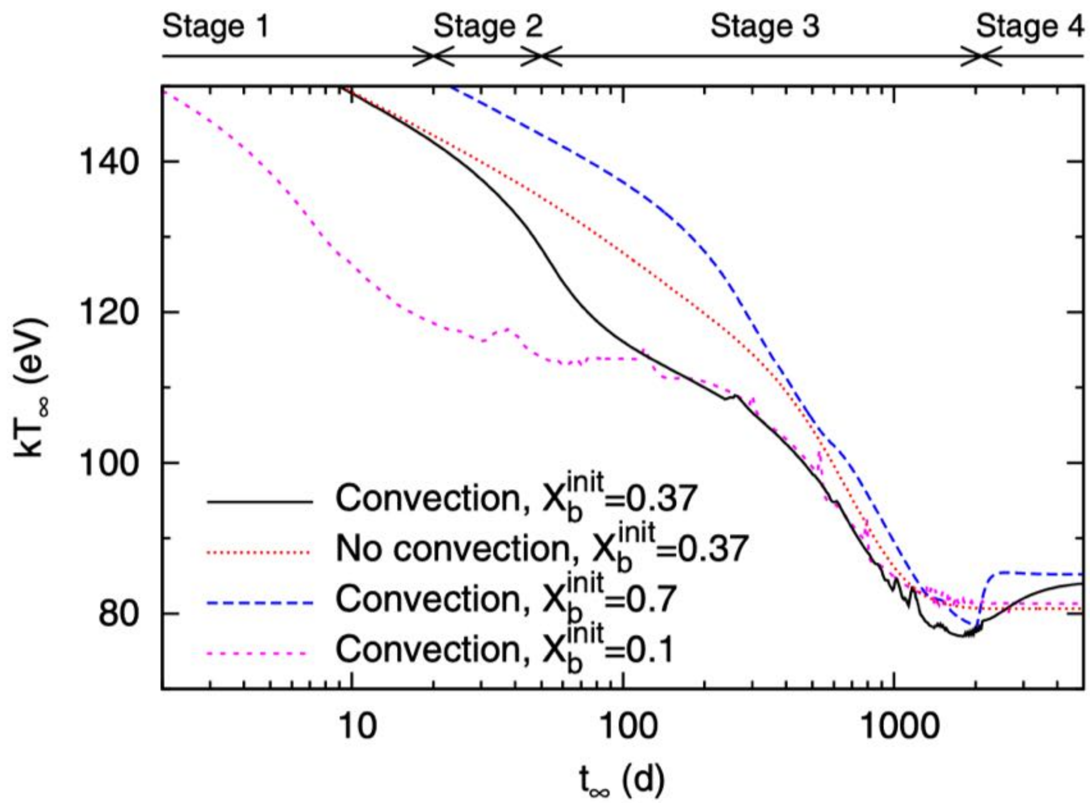
- After an outburst, the ocean refreezes as the star cools down

$$F_{\rm conv} \approx -10^{25}\,{\rm erg\,cm^{-2}s^{-1}}\,y_{14}^{5/4}\left(\frac{\partial t/\partial \ln X}{10\,{\rm days}}\right)^{-1}$$

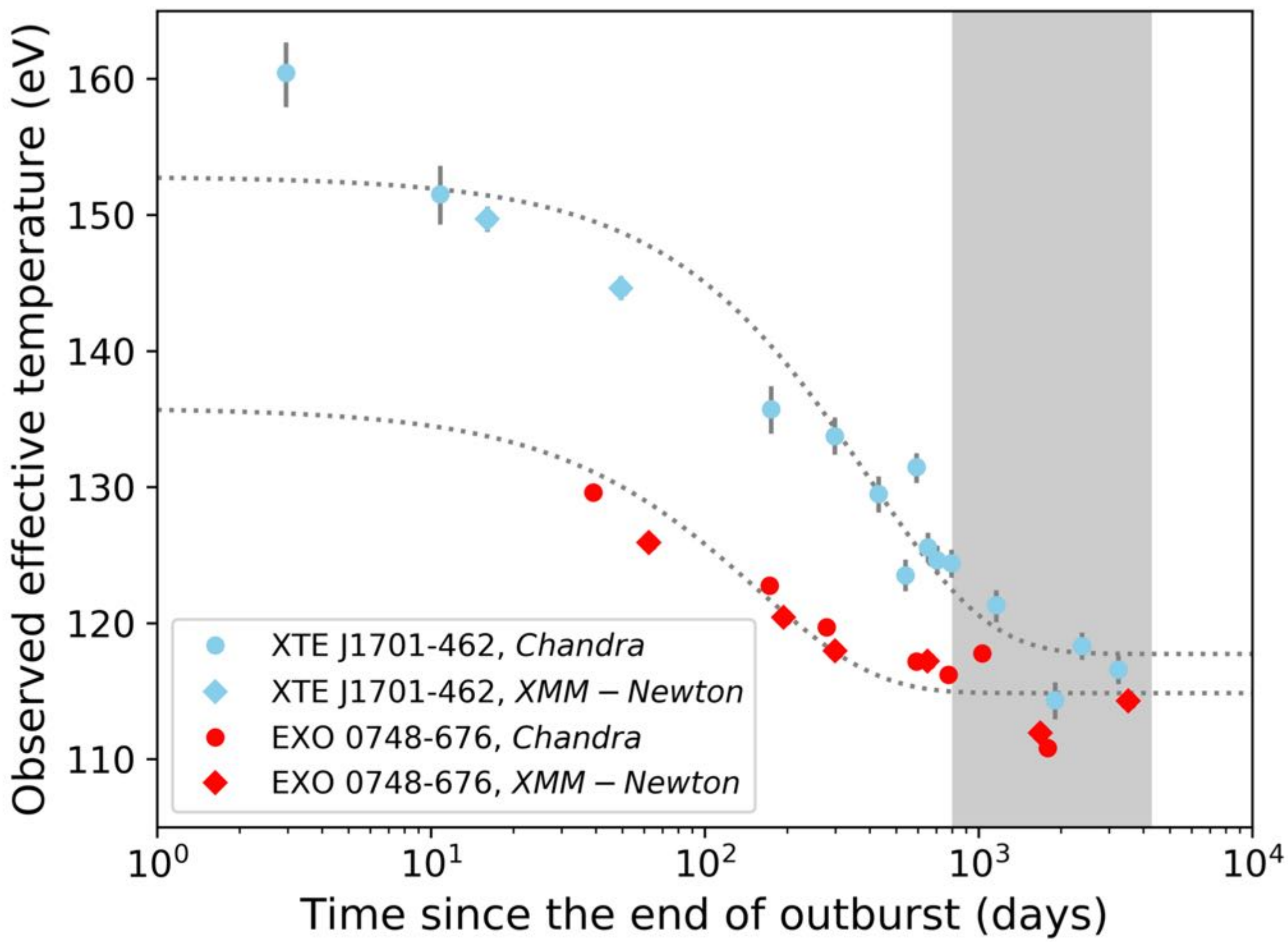
Medin & Cumming (2014)

- Inwards heat flux acts as “latent heat”; ocean cools rapidly; large portions of the ocean can freeze and unfreeze; eventually returns to the “standard” cooling curve
- Rapid redistribution of light elements during ocean freezing: could affect the T_{eff}-T_b relation
- Potentially complicates interpretation of early time data (e.g. to measure shallow heating)





Unexpected late time temperature increases



Parikh et al. (2020)

Shear heating

- How does matter accreting through a disk join the star and spread over the stellar surface?

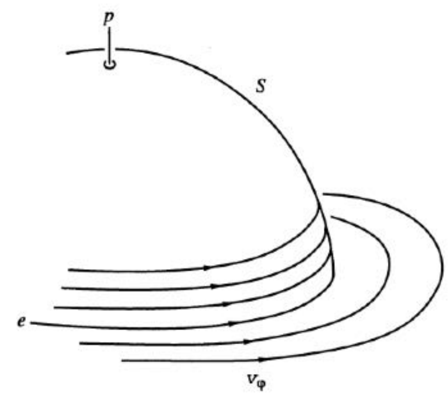
- Kinetic energy of incoming matter

$$\frac{1}{2}v_K^2 = \frac{GM}{2R} \approx 100\ \frac{\text{MeV}}{\text{nuc}}$$

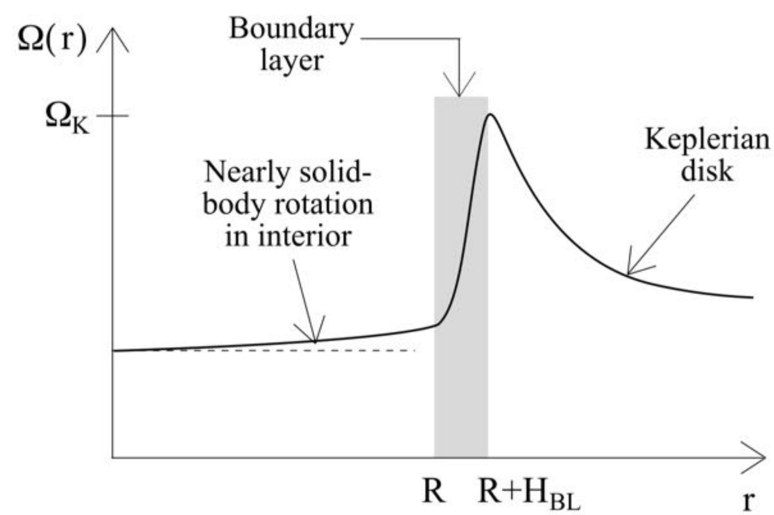
1-10% of this would be enough to explain the shallow heating we see

- Studies of how matter spreads suggest it happens at low density
- Wave transport could perhaps deposit energy deep

Inogamov & Sunyaev (2010) — gravity wave transport in the envelope
Phillipov & Rafikov (2016) — acoustic waves from the boundary layer



Inogamov & Sunyaev (1999)



Piro & Bildsten (2007)

Other physics issues relevant for crust heating/cooling

- lattice distortions by impurities change the thermal conductivity, interpretation of Q_{imp} (Roggero & Reddy 2016)
- URCA cooling reactions (Deibel et al. 2015, Meisel et al. 2021)
- Thermal signature of the pasta layer: need a low thermal conductivity and non-superfluid neutrons (gap closes inside crust), then you can get a late time drop in temperature (1000's of days) (Horowitz et al. 2015)
- The lightcurve shape at ~100 days-1 year is sensitive to physics near neutron drip (gap model and entrainment) (Page & Reddy 2012)
- Neutron diffusion redistributes neutrons vertically in the crust (Chugunov & Shchechilin 2020; Shchechilin, Gusakov, Chugunov 2021)

Go back to the core…

Previously we set $Q\langle\dot{M}\rangle = L_\nu + L_\gamma$ to constrain the core neutrino luminosity

We can also use the fact that each outburst we are depositing an energy into the core $E_{\rm dep} = \dot{M}\,\Delta t\; Q_{\rm nuc} \sim 10^{43}\ {\rm erg}$

(determined by modelling the cooling curve)

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(determined by modelling the cooling curve)

- Look at the response of the core to the deposited energy (calorimeter) => constrains the core heat capacity

$$\Delta T_c = E_{\rm dep}/C$$

Cumming et al. (2017), Degenaar et al. (2021)

- Put a limit on the neutrino emissivity in the core: it has to be smaller than the inwards luminosity during the accretion outburst

e.g. KS 1731 $\epsilon_\nu < 10^{23}\ {\rm erg\ cm^{-3}\ s^{-1}}\ T_9^6$ Cumming et al. (2017)

i.e. < ~10^{-4} of the dURCA rate

- If we have multiple outbursts, can determine the neutrino luminosity:

$$L_\nu = \frac{E_{\rm dep}}{t_{\rm recur}}$$

e.g. MXB 1659-29 $\frac{2\times 10^{43}\ {\rm erg}}{20\ {\rm yr}} \approx 3\times 10^{34}\ {\rm erg\ s^{-1}}$

Brown et al. (2018)

Core heat capacity constraints

- Even with just one outburst, we can put a lower limit on the neutron star heat capacity

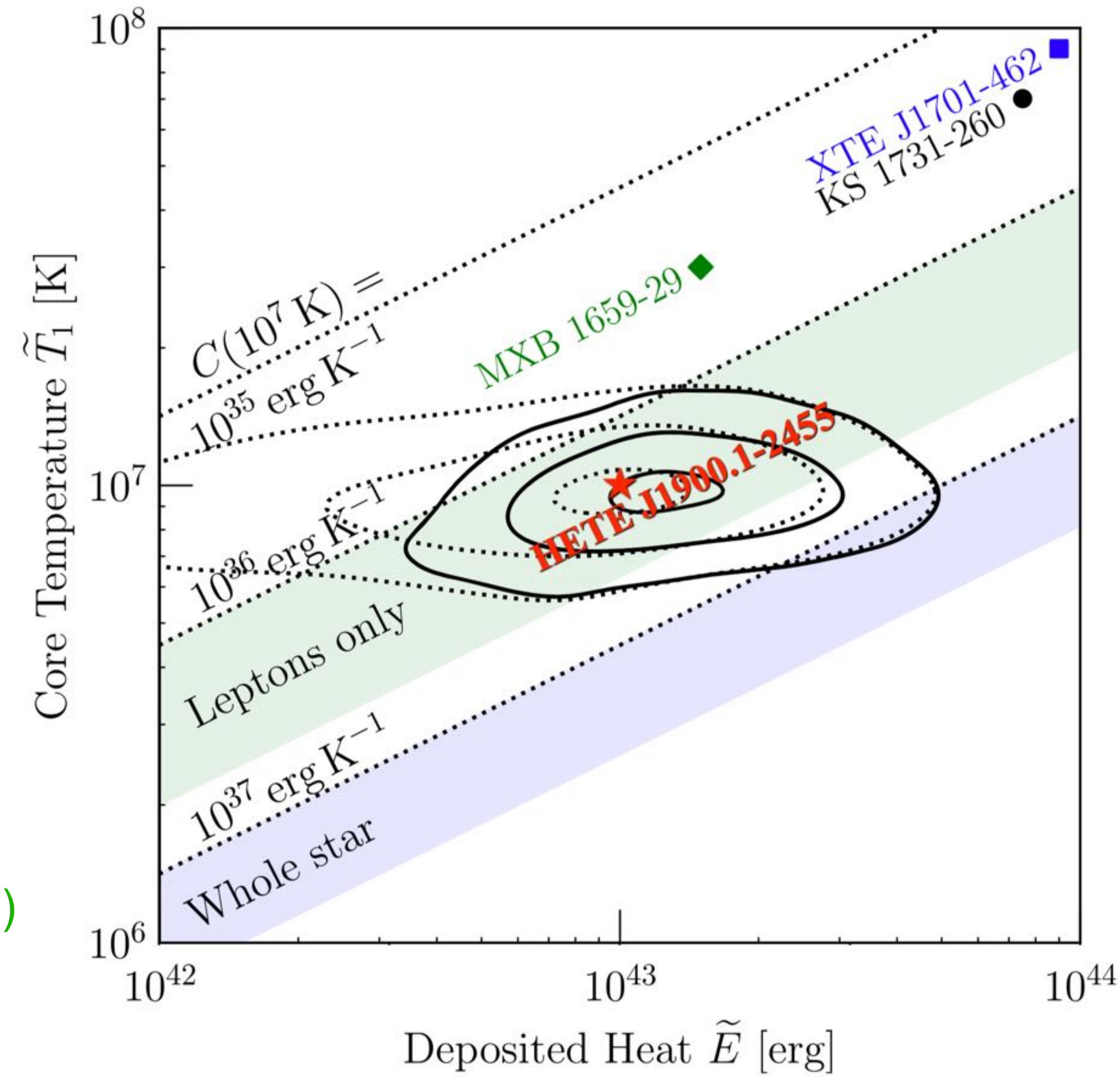
$$C > \frac{E_{\mathrm{dep}}}{T_c}$$

Cumming et al. (2017)

- New measurement of HETE J1900 has T_{eff} ~ 35 eV

Most constraining yet, this source may cool further

Degenaar et al. (2021)



The cooling curve shape is sensitive to the envelope composition

$$\tilde{T} = 7.0 \times 10^7\ \mathrm{K} \left(\frac{T_{\rm eff}^{\infty}}{63.1\ \mathrm{eV}} \right)^{1.82}$$ (Fe envelope)

Gudmundsson, Pethick, Epstein (1983)

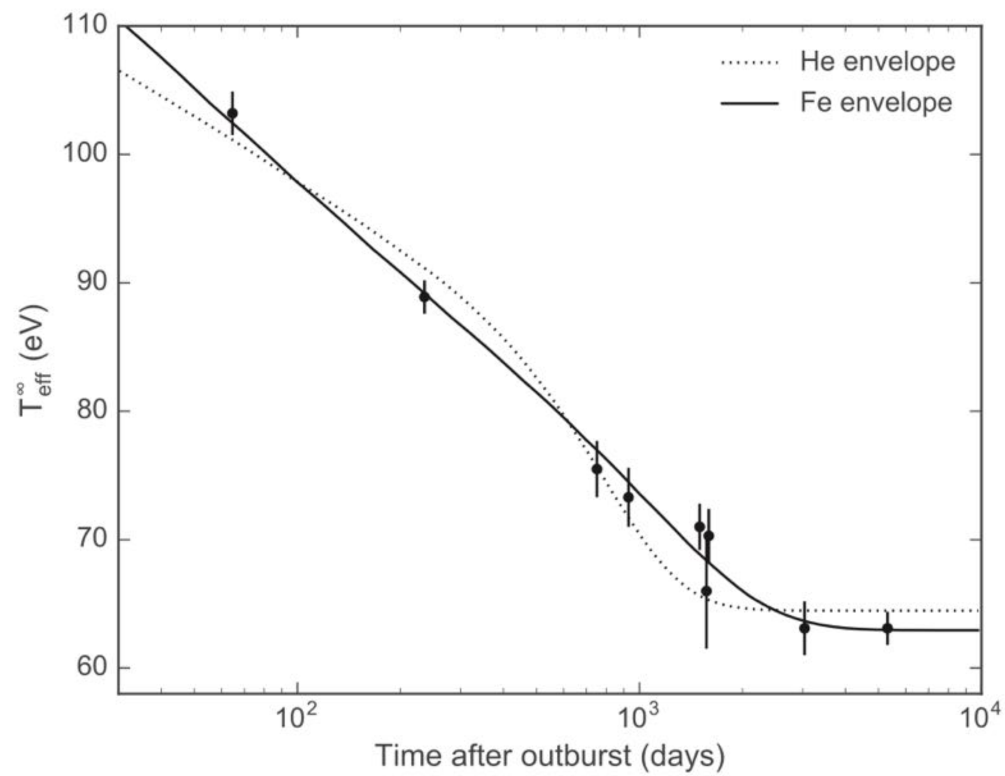
$$\tilde{T} = 3.1 \times 10^7\ \mathrm{K} \left(\frac{T_{\rm eff}^{\infty}}{63.1\ \mathrm{eV}} \right)^{1.65}$$ (He envelope)

Potekhin, Chabrier, Yakovlev (1997)

inferred core temperature

observed effective temperature

e.g. KS 1731 prefers heavy envelope (unexpected in an accreting star??)



Joint constraints on the heat capacity and neutrino luminosity in MXB 1659-29

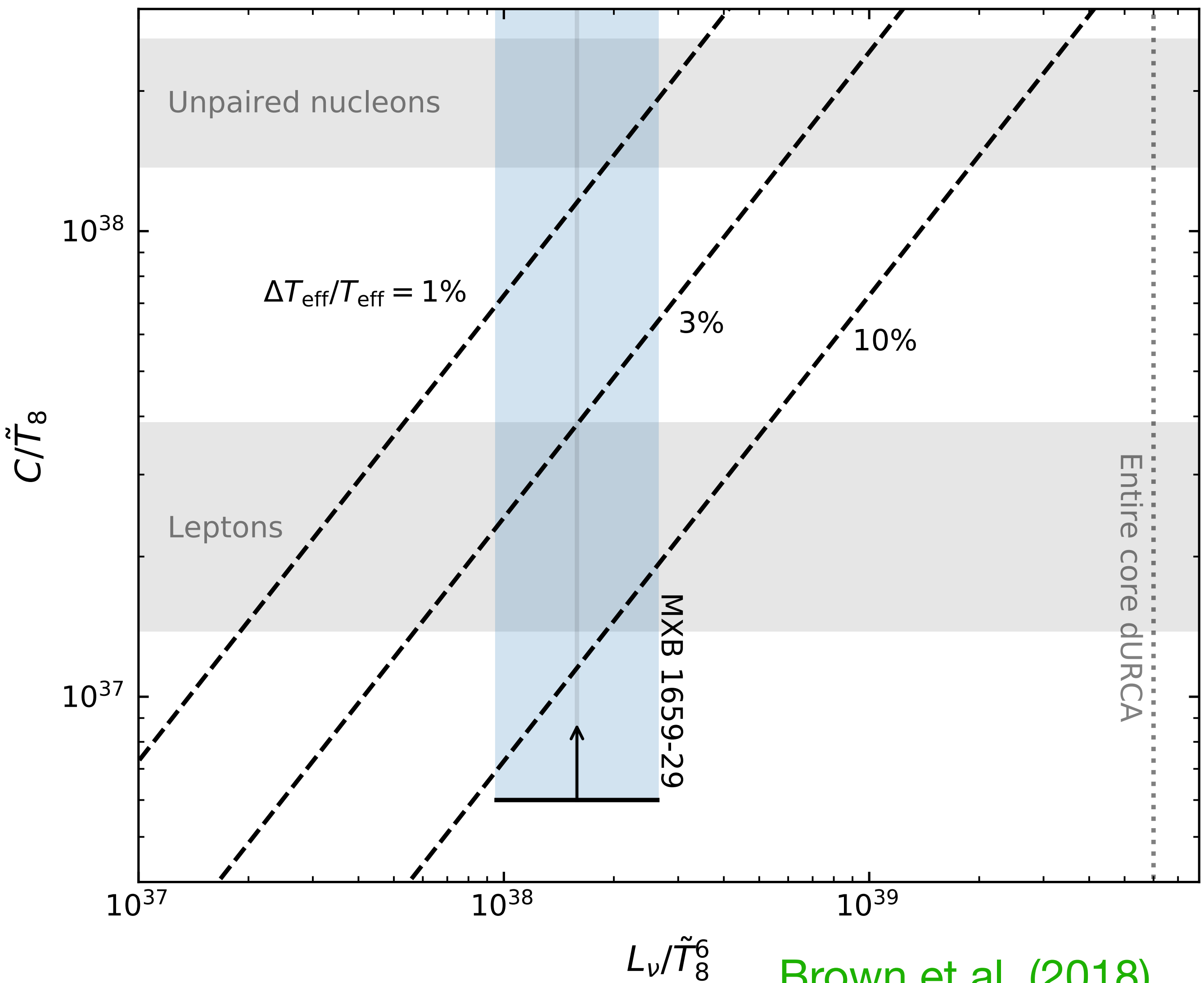
- Inferred neutrino luminosity is too large for a slow cooling process

- The neutrino luminosity is ~ 1% of the entire core doing direct URCA

- Is this a result of suppression by superfluidity? or the star is just over the dURCA threshold mass? Another less efficient process?

- Currently looking at detailed models of nucleon dURCA + SF: appear to need fine-tuning of either the mass or the gap

(Melissa Mendes et al., in prep)



Brown et al. (2018)

Summary

- observations of accreting neutron stars address (and have stimulated a lot of work on..) a wide range of physics issues in neutron star interiors

For **core cooling**

- remarkable overall agreement between the observed luminosities and predictions from models that use deep crustal heating and slow and fast neutrino cooling
- coldest sources consistent with direct URCA neutrino cooling; hottest sources have slow neutrino cooling and accreted envelopes
- crust cooling curves can help to determine the envelope composition, and open up new constraints (calorimeter)
- not clear observationally whether the colder sources are more massive
- the intermediate sources (between cold and hot) are perhaps the most puzzling — how to "smooth" the transition between slow and fast cooling?

For **crust cooling**

- cooling models prefer a low impurity parameter, consistent with nuclear processing of the mixture through neutron drip (at least for some compositions?)
- some indications for heavy envelopes (KS 1731)- does this make sense?
- shallow heating is required and not understood! How to make progress? Is it nuclear or something else?