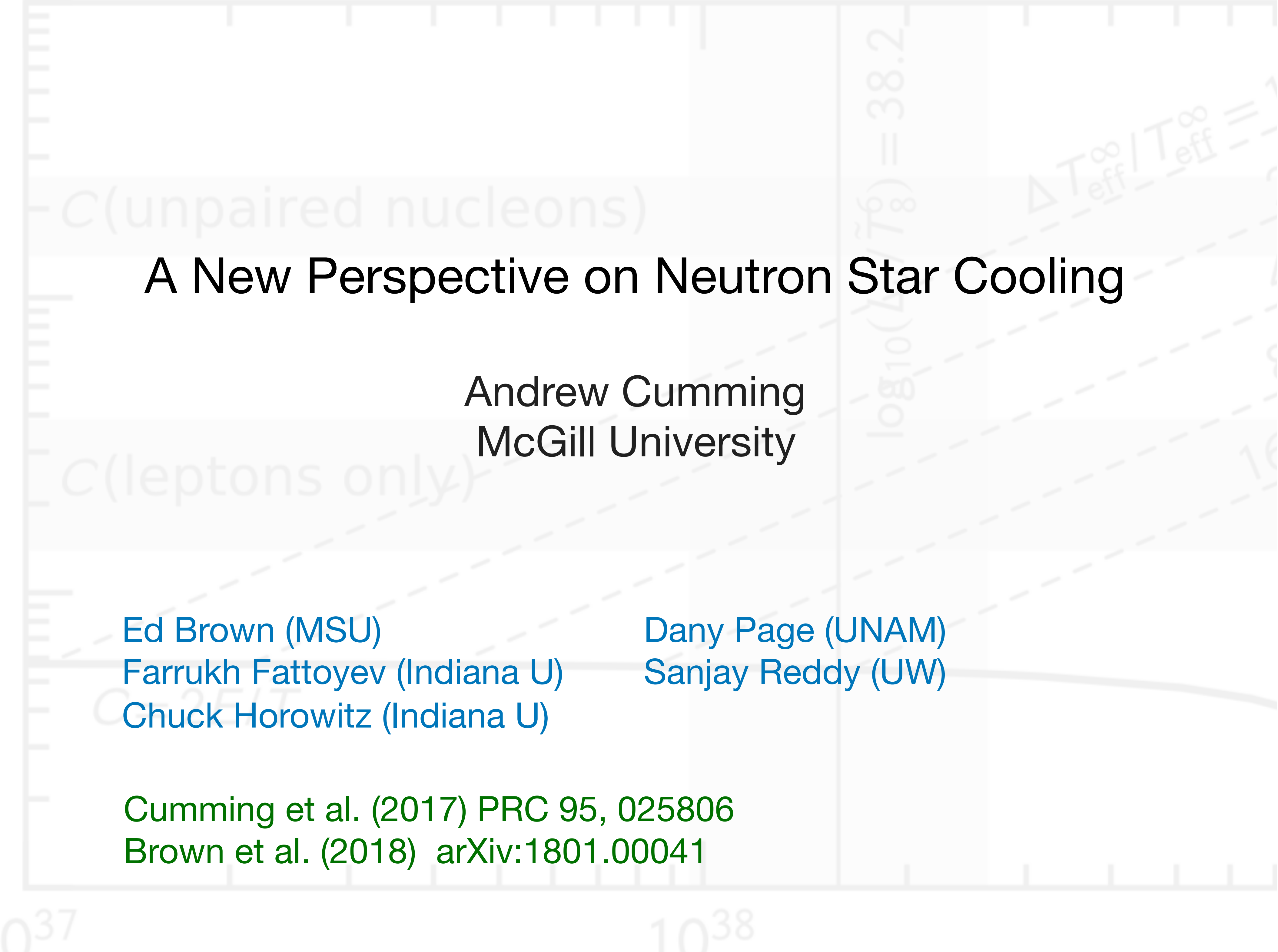

A New Perspective on Neutron Star Cooling

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Cumming et al. (2017) PRC 95, 025806
Brown et al. (2018) arXiv:1801.00041

An interesting time to study neutron stars

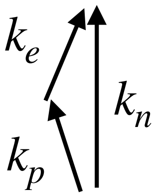
Several recent/upcoming observations to inform us about the equation of state $P(\rho)$ of neutron stars:

- discovery of neutron stars with M>2 solar masses
- mass and radius measurements with NICER
- neutron star mergers from LIGO
- possibility of measuring the moment of inertia in the double pulsar system

"Beyond the EOS": what particles are present? what is the state of matter?

Neutron star cooling probes the **particle content** and **state of matter** in neutron star cores

Neutrino emissivity depends on the available reactions



Divide into fast $\propto T^6$ and slow $\propto T^8$ processes
e.g. direct URCA $n \rightarrow p + e^- + \bar{\nu}_e$ requires $Y_p \gtrsim 0.1$

Threshold mass where fast cooling turns on

Other particles open up new channels: different possible prefactors, ie. L_ν / T^6 etc

Pairing suppresses URCA reactions but gives a new process PBF near T_c. Also takes particles out of the thermal bath, changes the heat capacity.

General picture: $^1S_0$ crust neutrons, core protons
$^3P_2$ core neutrons
but shape of $T_c(\rho)$ highly uncertain

$$Q_{\rm fast} = Q_{\rm f} T_9^6$$

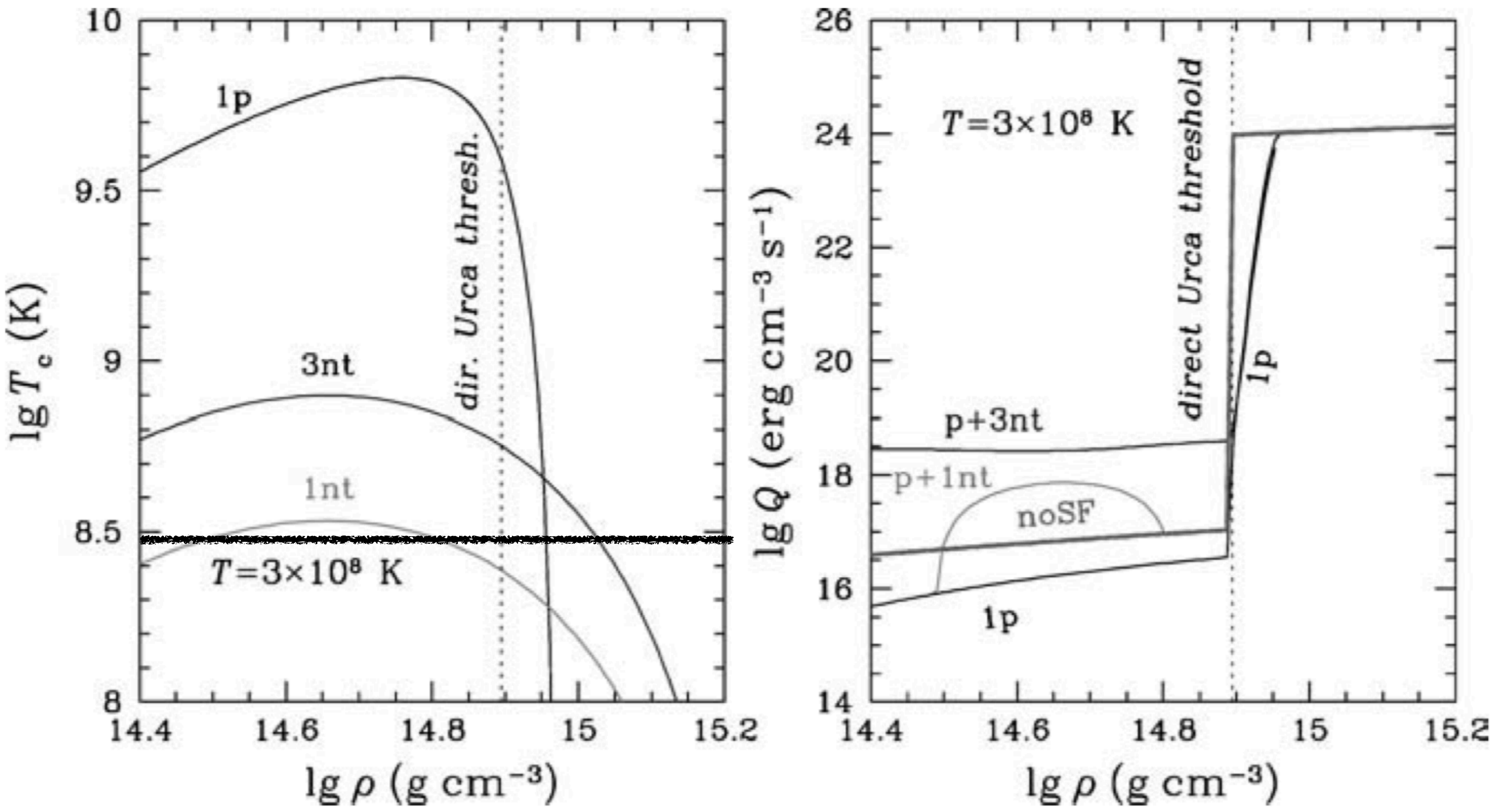
Model	**Process**	$Q_{\rm f}$**[erg cm^{-3} s^{-1}]**
Nucleon matter	$n \to pe\bar{\nu} \quad pe \to n\nu$	10^{26}–3×10^{27}
Pion condensate	$\widetilde{N} \to \widetilde{N}e\bar{\nu} \quad \widetilde{N}e \to \widetilde{N}\nu$	10^{23}–10^{26}
Kaon condensate	$\widetilde{B} \to \widetilde{B}e\bar{\nu} \quad \widetilde{B}e \to \widetilde{B}\nu$	10^{23}–10^{24}
Quark matter	$d \to ue\bar{\nu} \quad ue \to d\nu$	10^{23}–10^{24}

$$Q_{\rm slow} = Q_{\rm s} T_9^8$$

Process		$Q_{\rm s}$ **[erg cm^{-3} s^{-1}]**
Modified Urca	$nN \to pNe\bar{\nu} \quad pNe \to nN\nu$	10^{20}–3×10^{21}
Bremsstrahlung	$NN \to NN\nu\bar{\nu}$	10^{19}–10^{20}

Yakovlev & Haensel (2004) ARAA

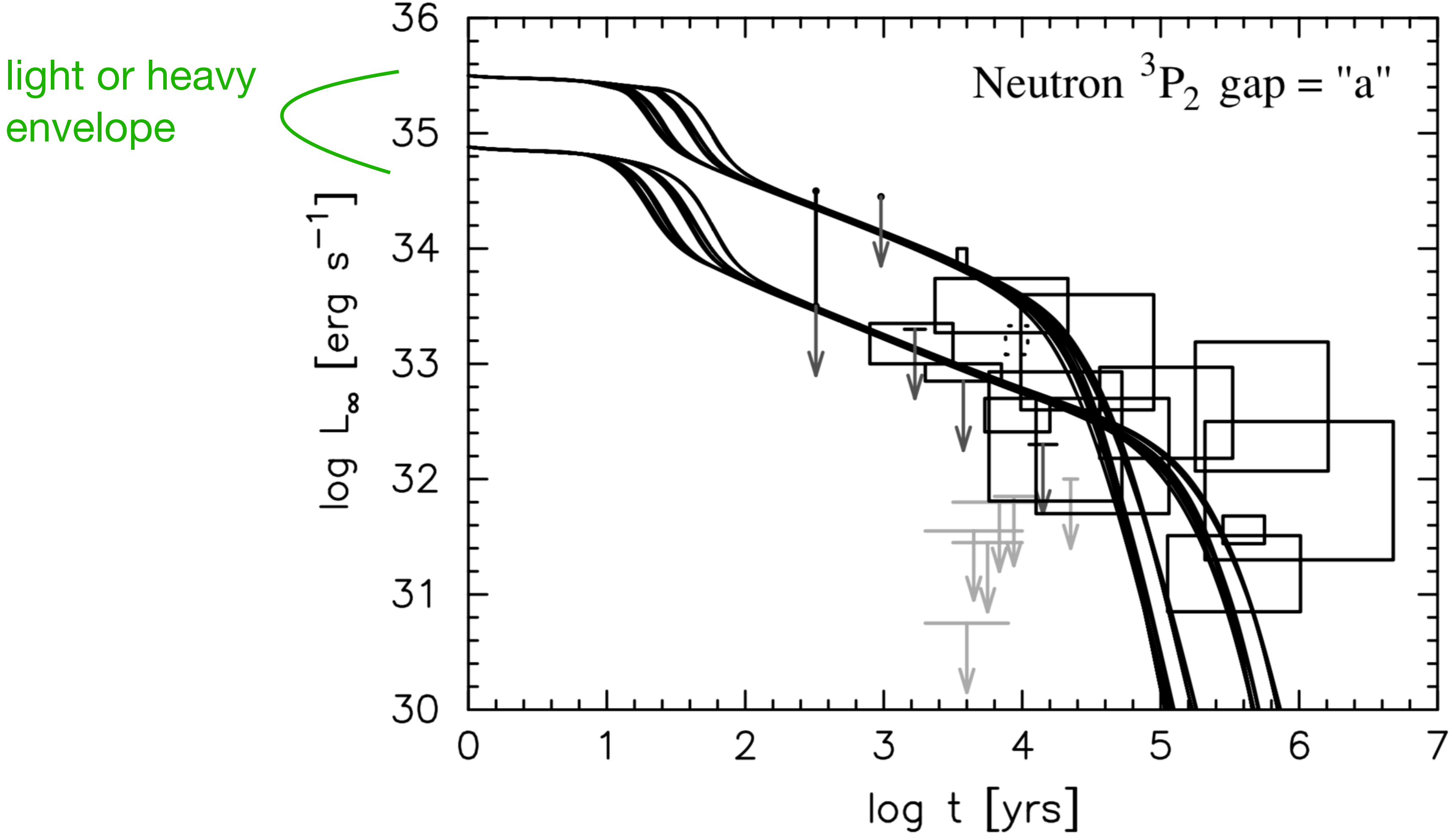
superfluid critical temperatures → neutrino emissivity



Yakovlev & Haensel (2004) ARAA

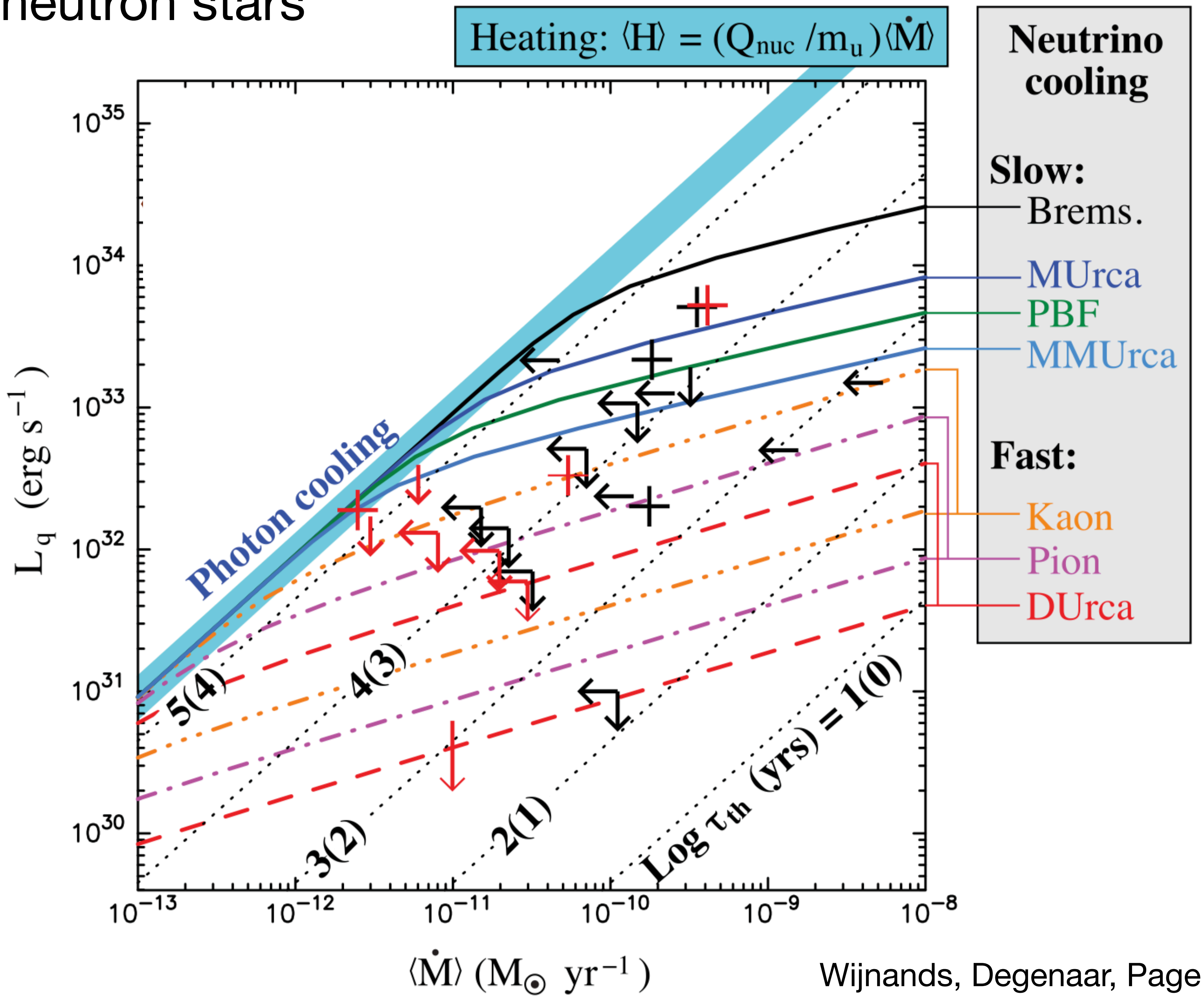
Cooling of isolated neutron stars

$$C_V \frac{dT}{dt} = -L_\nu - L_\gamma$$



Page et al. (2004, 2009) “Minimal cooling”:
assume mURCA for neutrinos => certain shape for the $^3P_2$ neutron gap

Accreting neutron stars



Wijnands, Degenaar, Page (2013)

Fortin et al. (2017), Han & Steiner (2017) :
Small n gap needed to allow dURCA for the coldest sources

Main points of the talk

- We can use transiently-accreting neutron stars to obtain independent constraints on the core neutrino luminosity and heat capacity

- we'll constrain the prefactors $L_\nu/T^6, \; C/T$

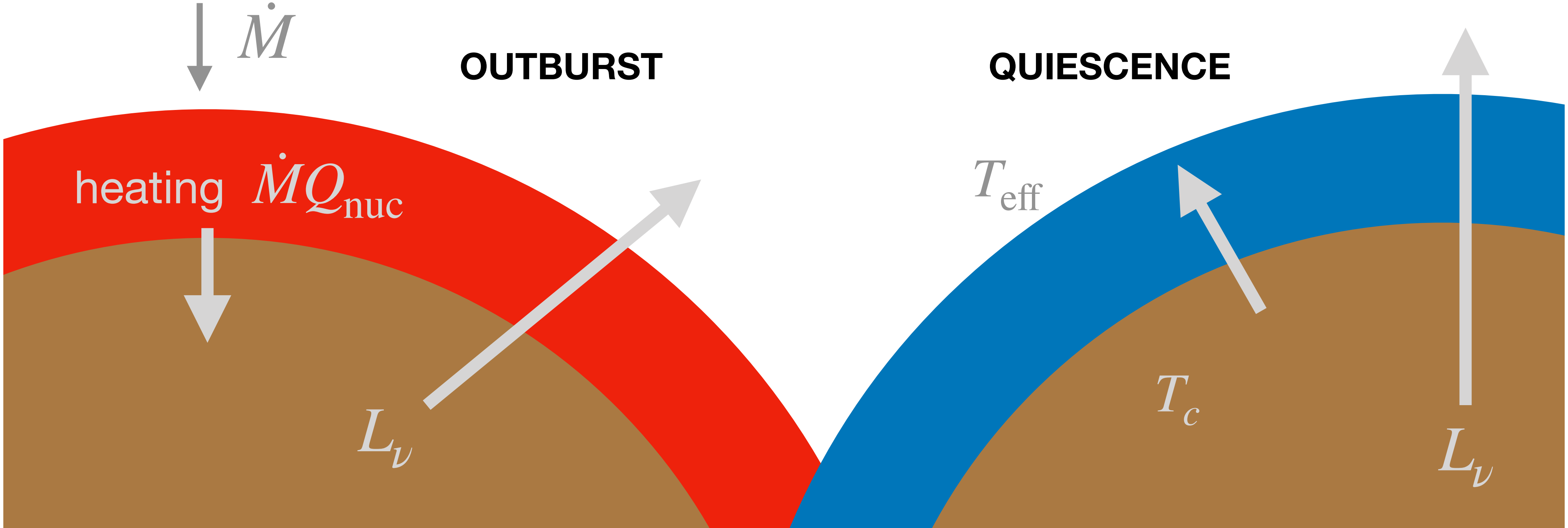
- gives a way to untangle the different contributions to the core microphysics

Accreting neutron stars as calorimeters

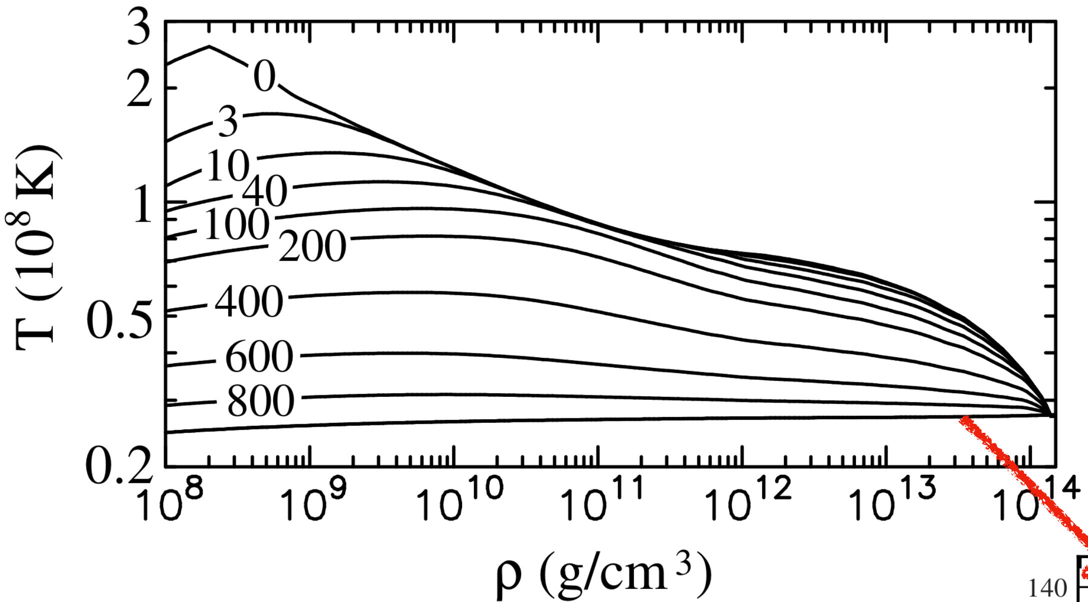
- During outburst deposit an energy ~ (1—2) MeV per nucleon into the core, or a total

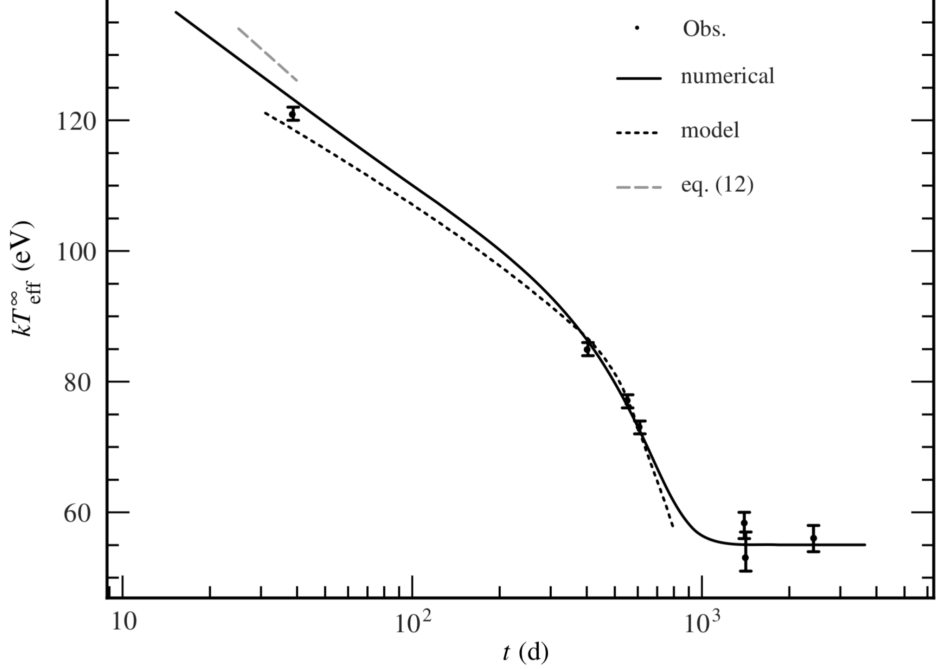
$$E \approx 6.0 \times 10^{43}\ \mathrm{erg} \left(\frac{\dot{M}}{10^{17}\ \mathrm{g\,s^{-1}}}\right)\left(\frac{t_\mathrm{o}}{10\ \mathrm{yr}}\right)\left(\frac{Q_\mathrm{nuc}}{2\ \mathrm{MeV}/m_\mathrm{u}}\right)$$

- In quiescence, measure the temperature of the neutron star
- Calorimeter has a “leak” — core can emit neutrinos



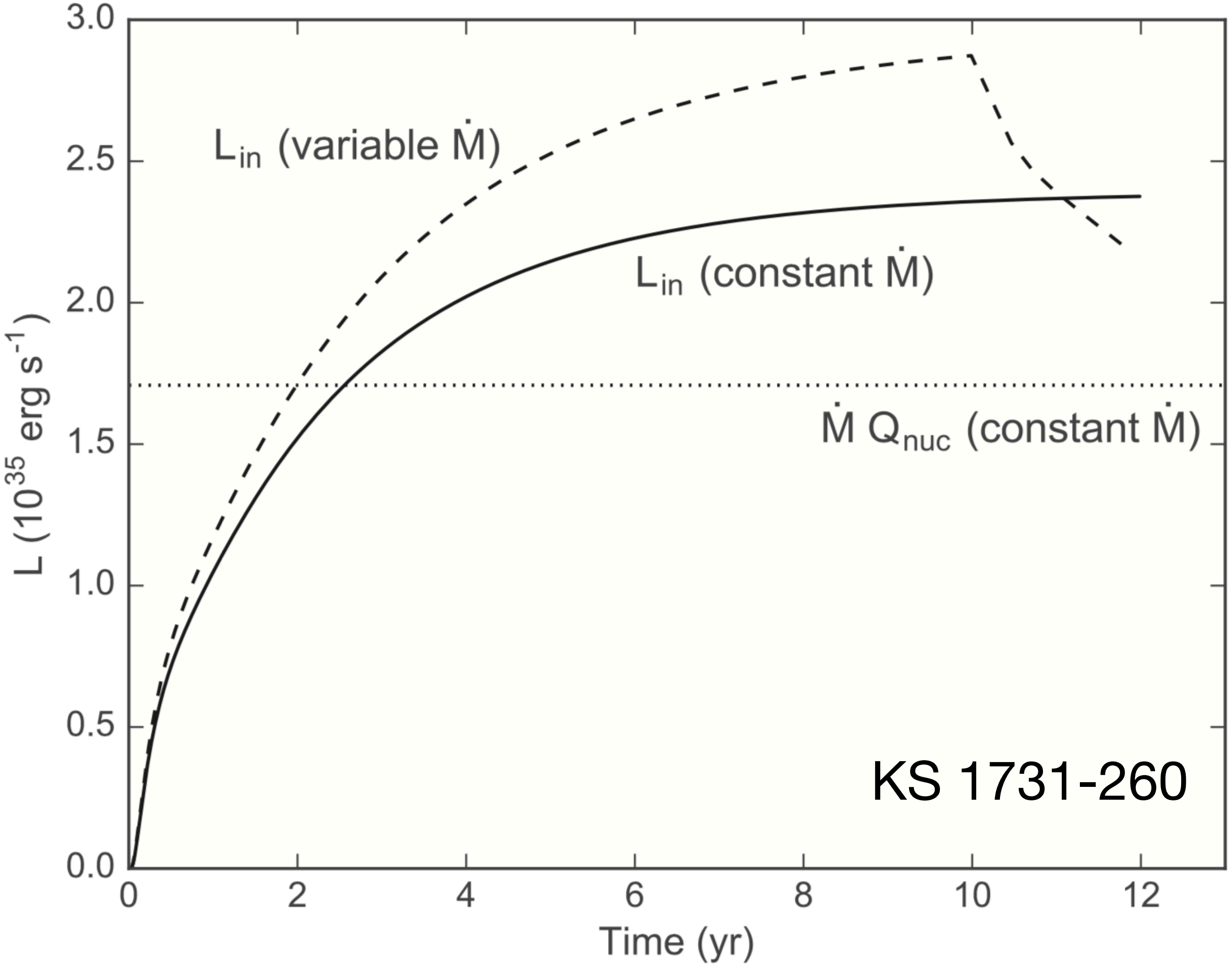
By modelling the crust relaxation after outburst we can determine the temperature profile in the crust



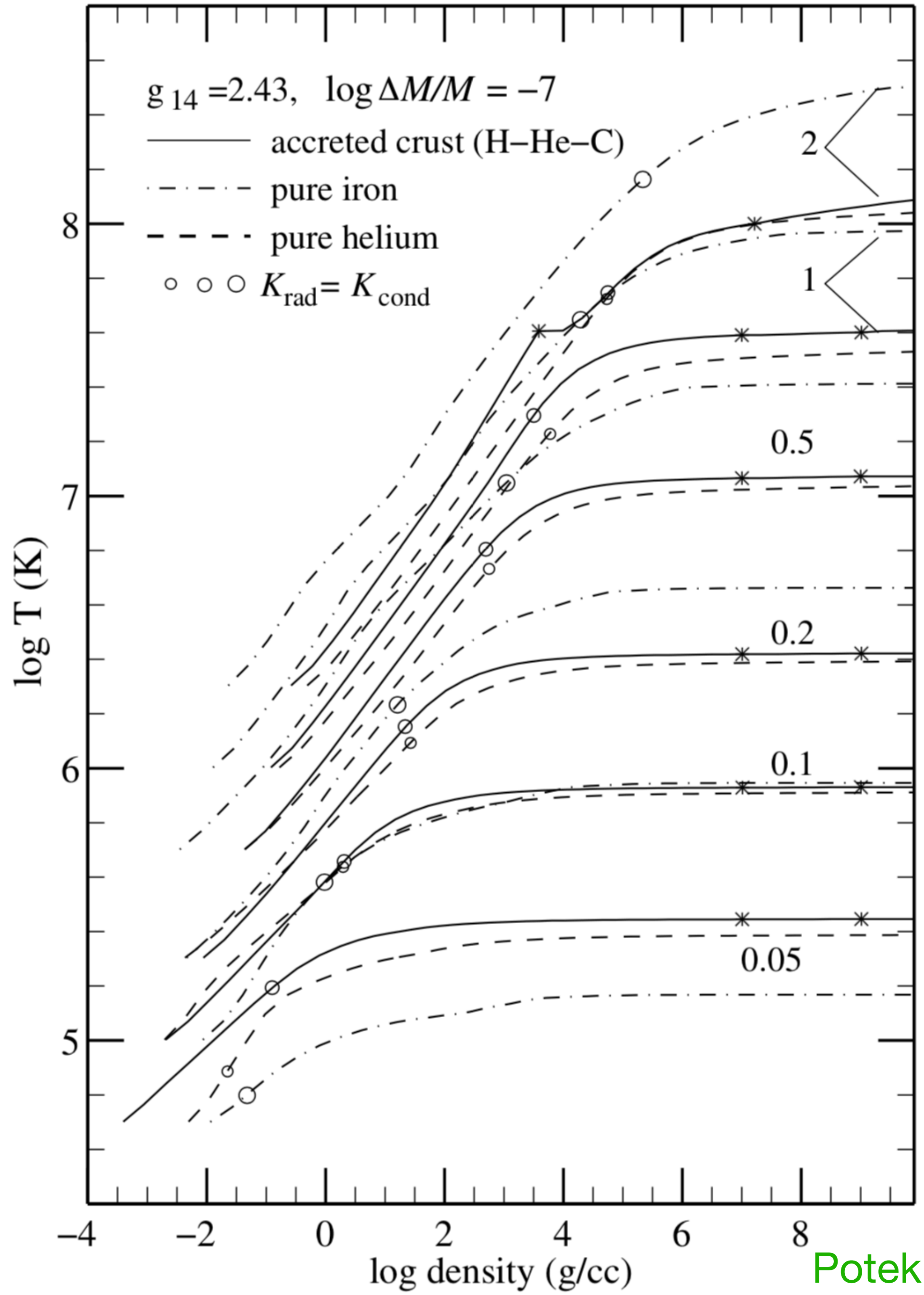


Brown & Cumming (2009), see also Shternin et al. (2007), Page & Reddy (2012), Turlione et al. (2015)

The curst cooling model gives us the luminosity going into the core during outburst



Cumming et al. (2017)



For a given $T_{\rm eff}$, envelope composition => factor of 2 difference in the core temperature

Fe envelope

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

Gudmundsson, Pethick & Epstein (1983)

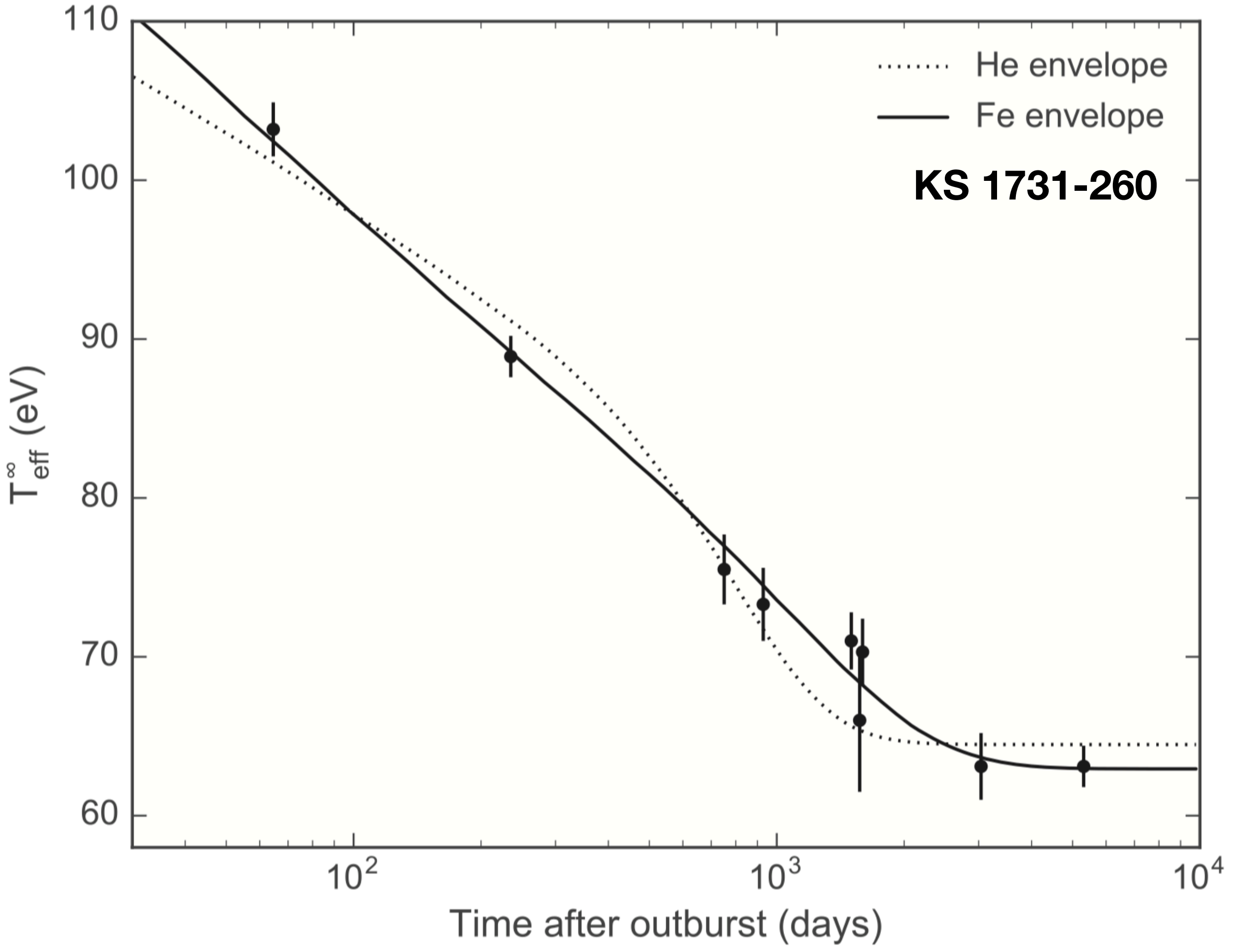
light element envelope

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

Potekhin, Chabrier & Yakovlev (1997)

Potekhin, Chabrier & Yakovlev (1997)

The shape of the crust relaxation depends on the envelope composition



Heavy element envelope => hotter crust => lower thermal conductivity and higher heat capacity

A lower limit on the core heat capacity

Basic idea is to use the core as a **calorimeter**:
the change in core temperature caused by an outburst is

$$\int_{T_1}^{T_2} C(T)dT = E_{\rm dep}$$

If we've only seen one outburst, we don't know T_1, but it must be >0 … setting $T_1=0$ gives a lower limit

$$C \geq \frac{2E_{\rm dep}}{T_c}$$

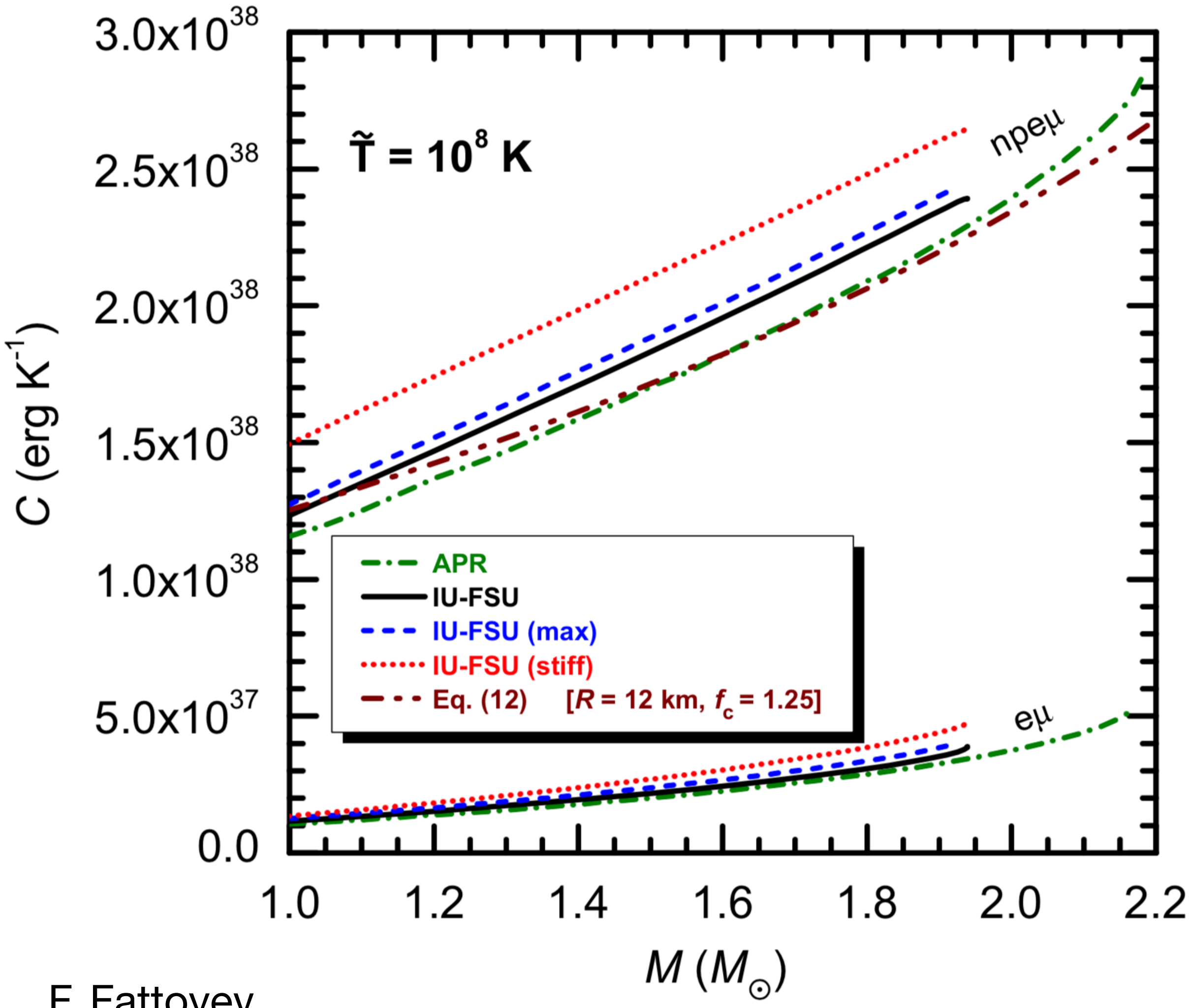
energy deposited inferred from modelling the outburst

core temperature measured in quiescence

(we assume $C \propto T$,
as expected for fermions)

Cumming et al. (2017) PRC

Heat capacity with and without nucleon pairing



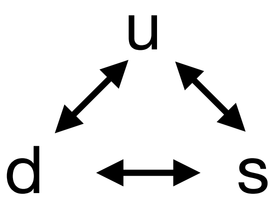
F. Fattoyev

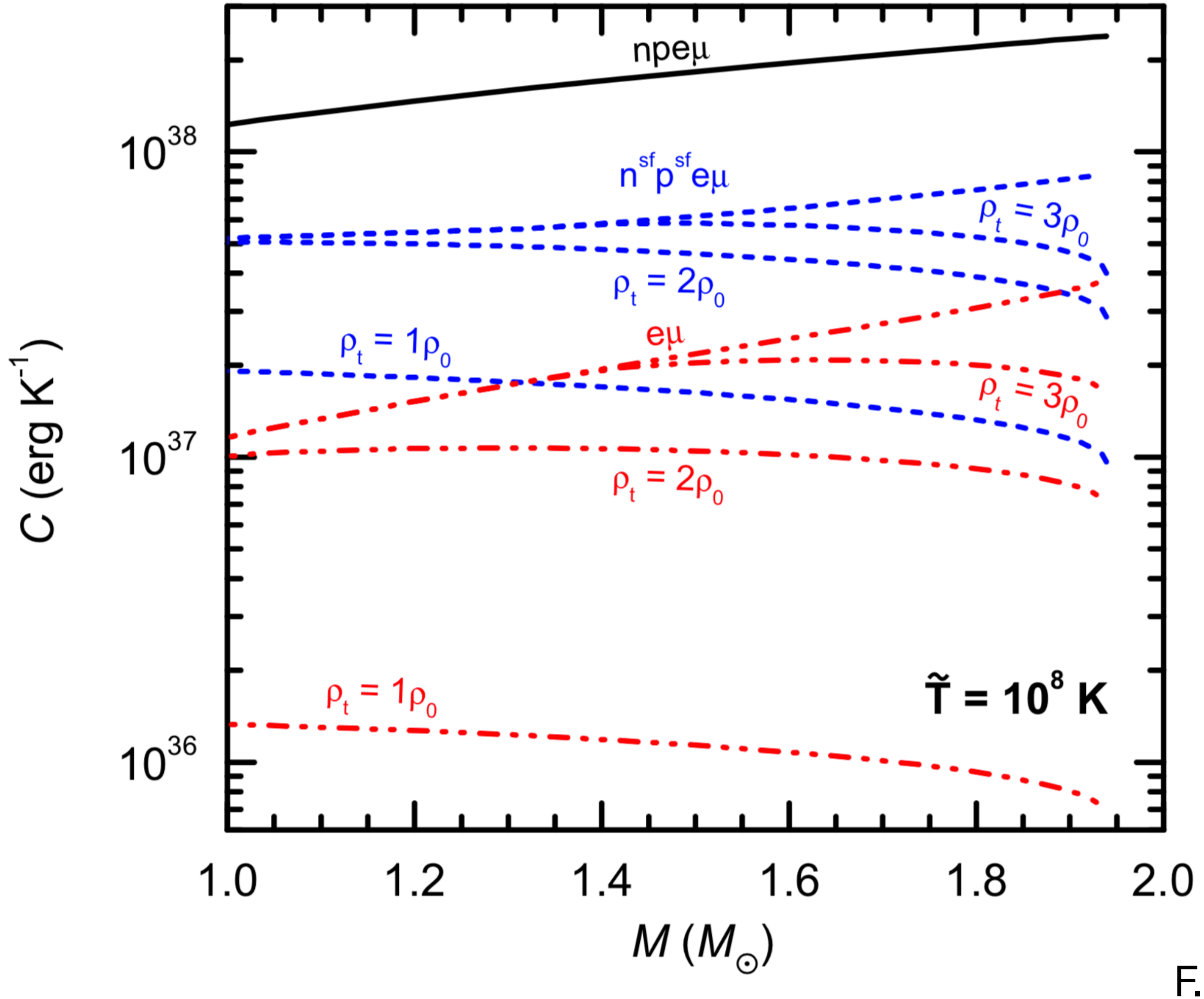
$$C_V \sim k_B \left(\frac{k_B T}{E_F} \right)$$

per particle (degenerate fermions)

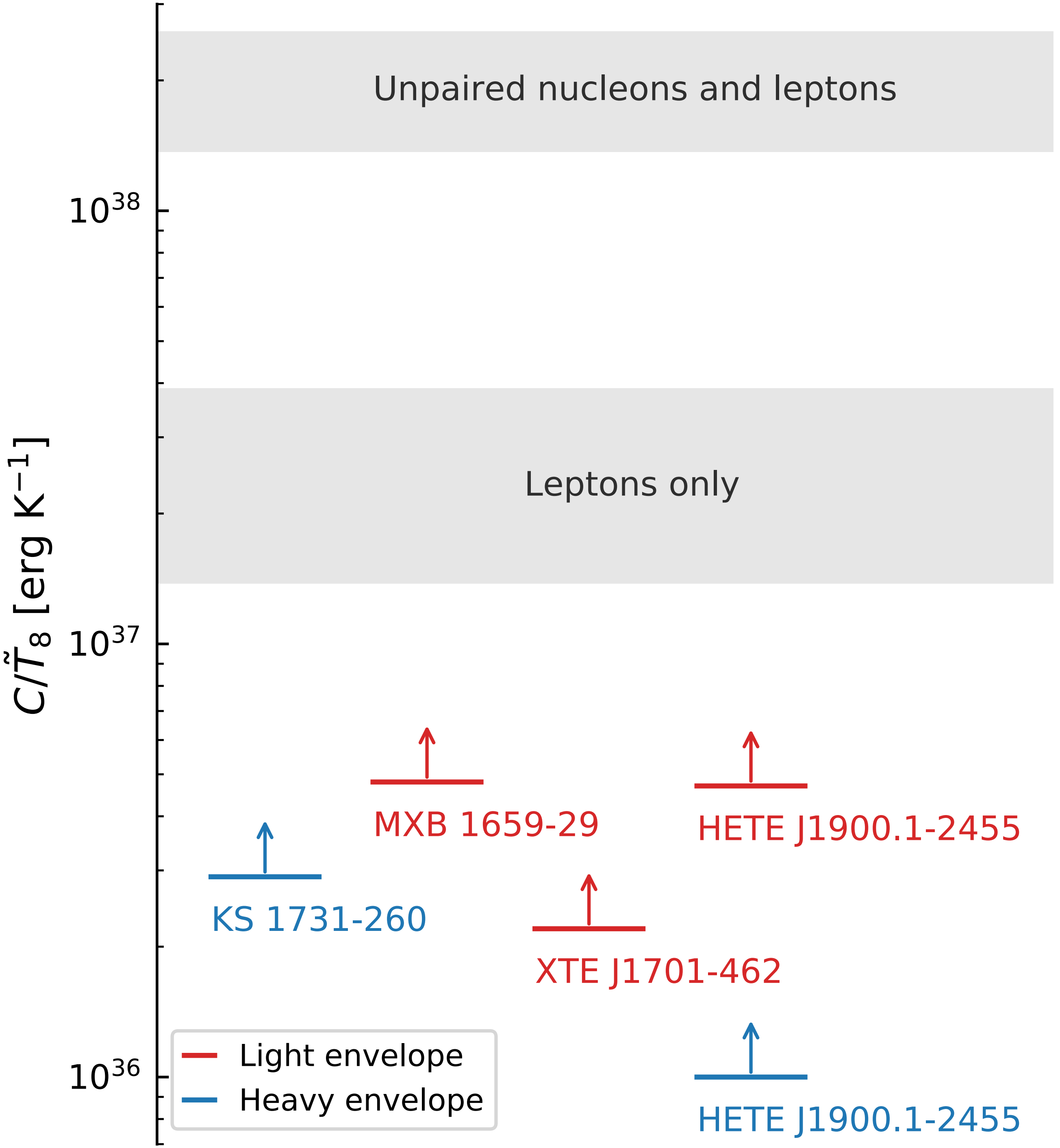
- paired particles don’t contribute: the heat capacity “counts” the unpaired degrees of freedom
- electrons provide a baseline heat capacity

A color flavor locked (CFL) quark matter phase has a very small heat capacity —u,d,s quarks satisfy charge neutrality => no electrons





F. Fattoyev



Cumming et al. (2017) PRC

Upper limit on the neutrino luminosity

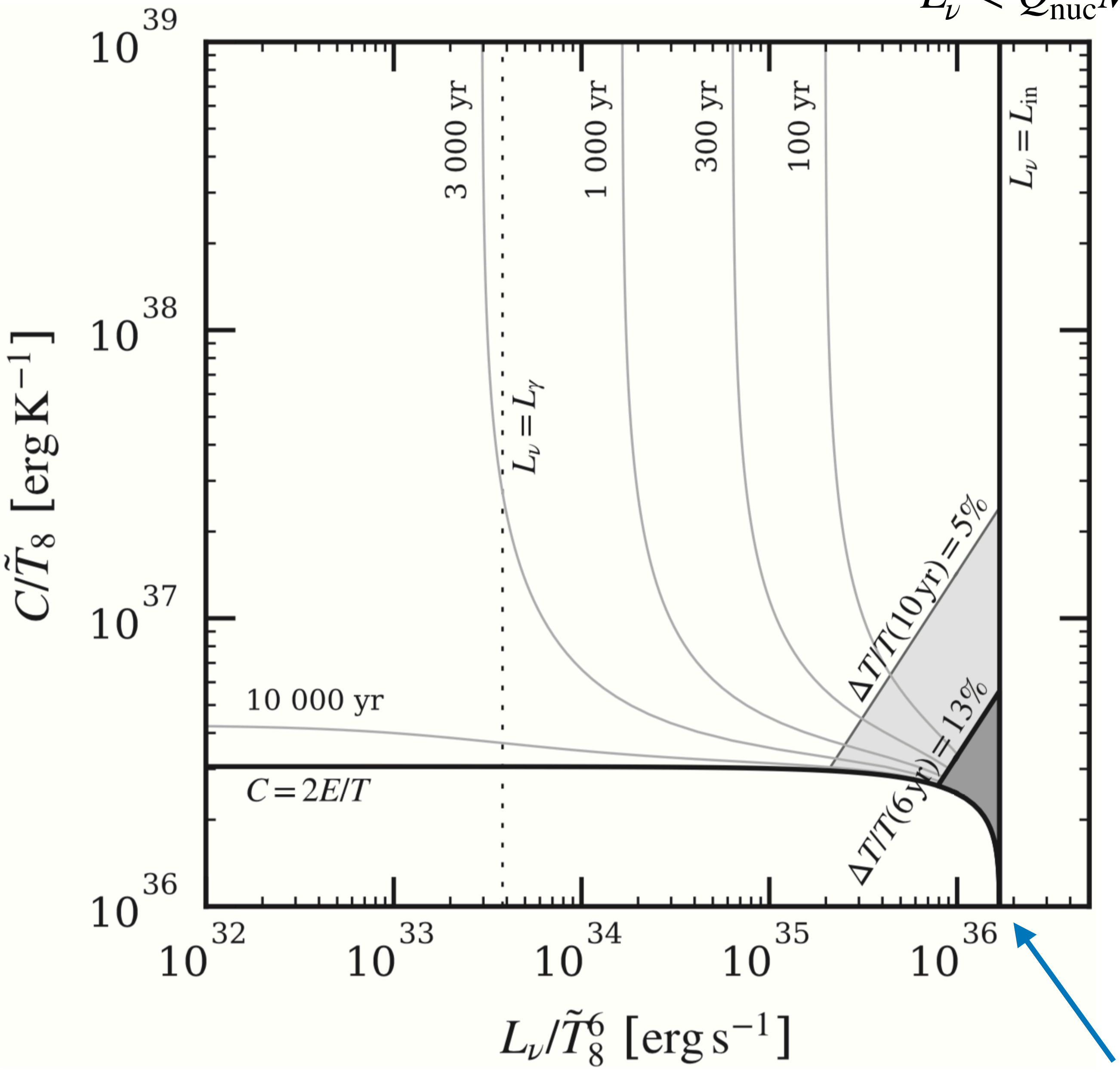
The neutrino luminosity must be smaller than the luminosity going into the core during outburst

$$L_\nu < Q_{\rm nuc}\dot{M} \sim 10^{35}\ {\rm erg\ s^{-1}}$$

Once we've measured the core temperature, we can turn this into a limit on the neutrino cooling prefactor

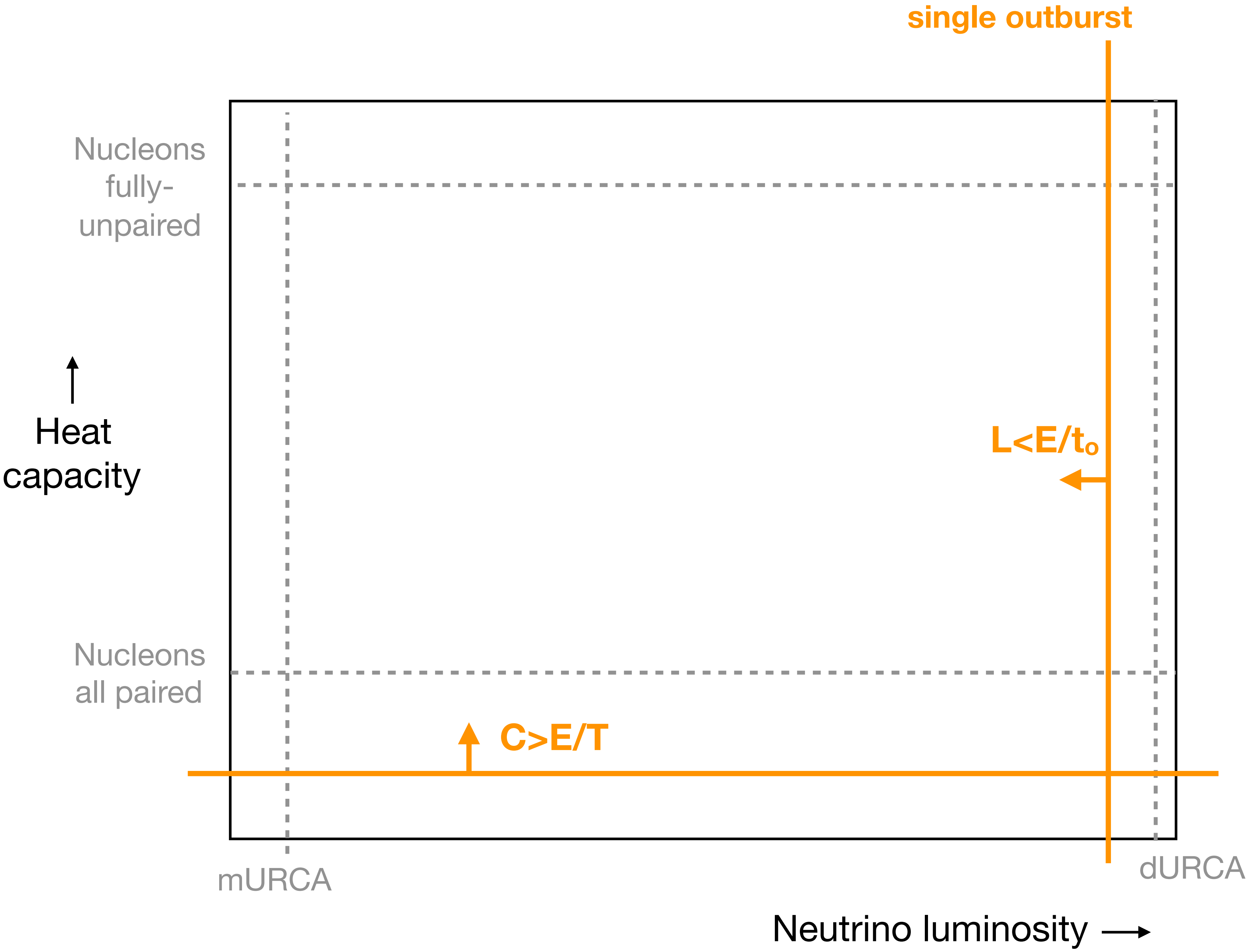
For neutrino luminosities close to this limit, the heat capacity limit no longer applies (the calorimeter leaks)

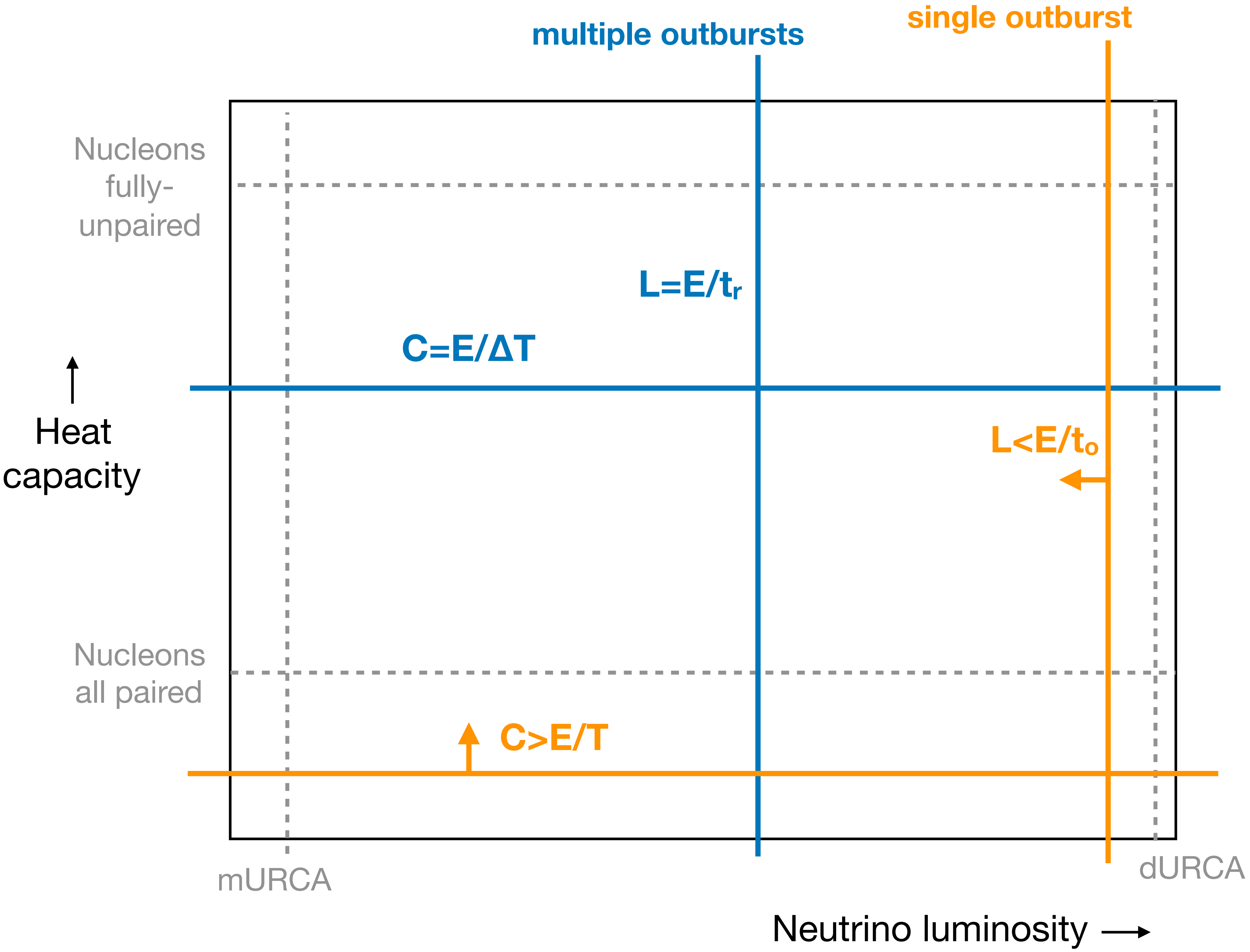
KS 1731-260



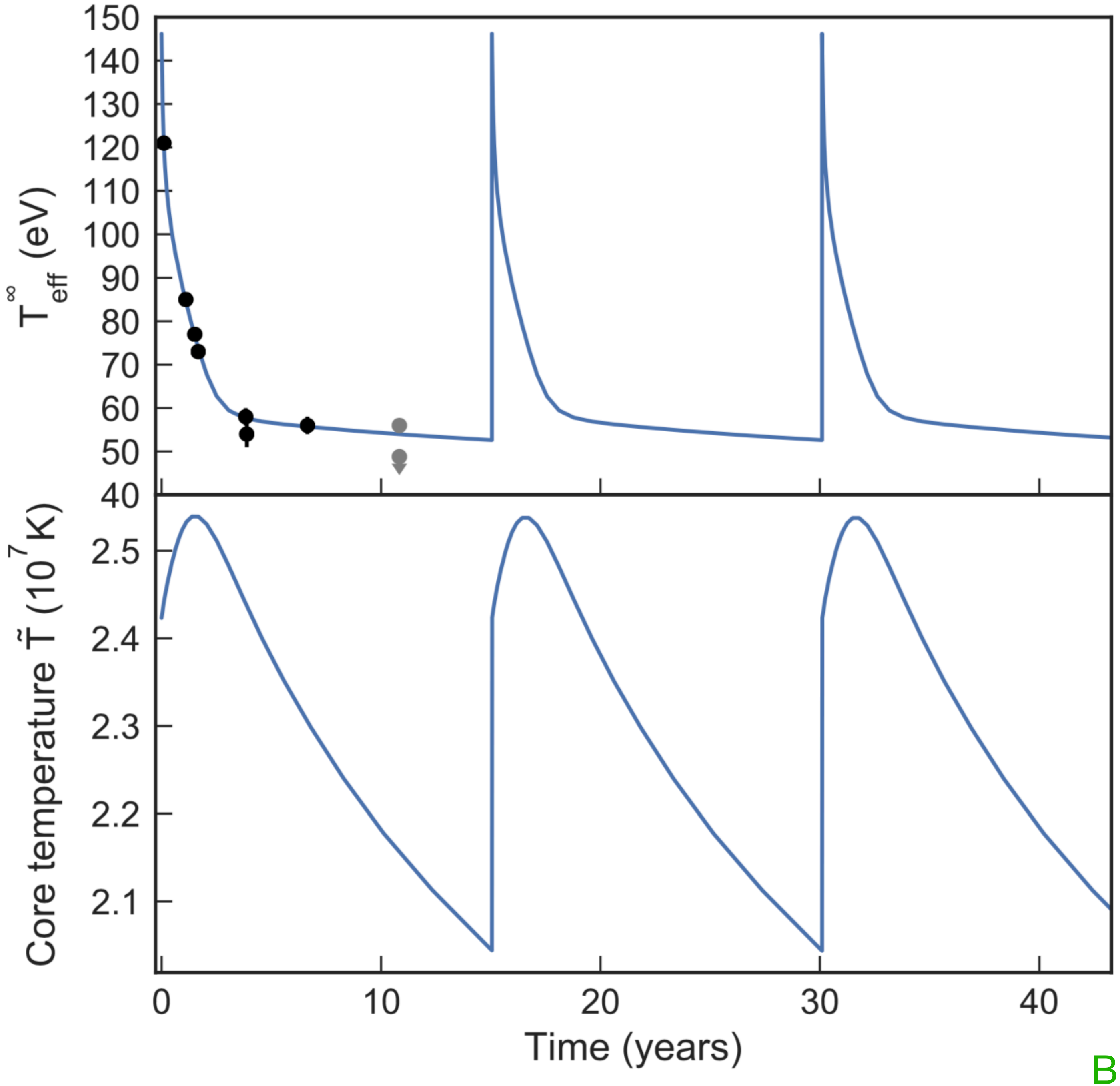
$L_\nu < Q_{\rm nuc}\dot{M}$

$\sim 10^{-4}$ x direct URCA


single outburst
Nucleons fully-unpaired
Heat capacity
L<E/t₀
Nucleons all paired
C>E/T
mURCA
dURCA
Neutrino luminosity


single outburst
multiple outbursts
Nucleons fully-unpaired
$L=E/t_r$
$C=E/\Delta T$
Heat capacity
$L<E/t_o$
Nucleons all paired
$C>E/T$
mURCA
dURCA
Neutrino luminosity

MXB 1659-29 has gone back into outburst…



Brown et al. (2018)

MXB 1659-29 has had three outbursts, separated by 21 and 15 years

If the core is in long term equilibrium, its neutrino luminosity must be

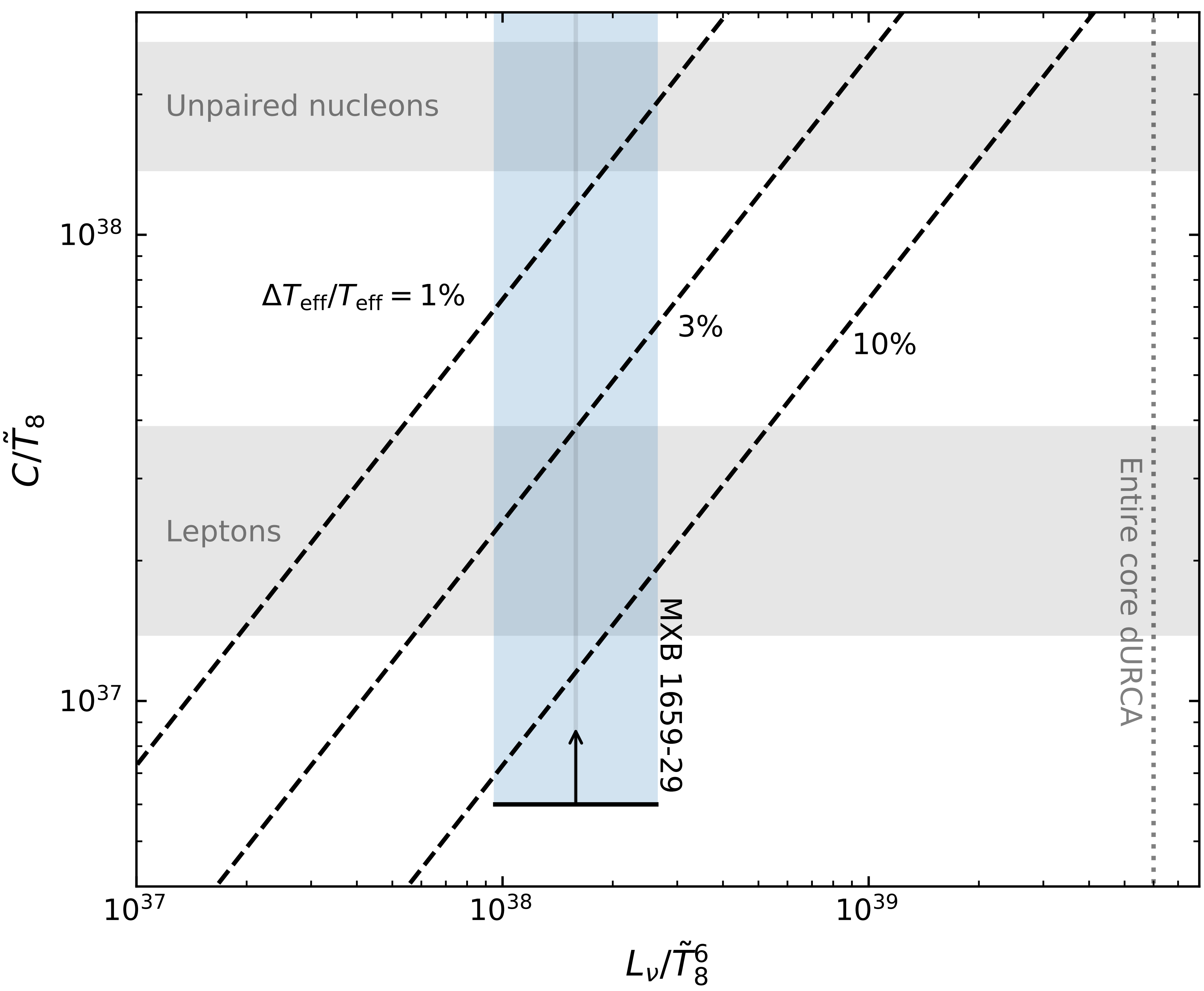
$$L_\nu \sim \frac{2 \times 10^{43}\ \mathrm{ergs}}{5 \times 10^{8}\ \mathrm{s}} \sim 3 \times 10^{34}\ \mathrm{erg\ s^{-1}}$$

The core temperature is inferred to be (He envelope)

$$\tilde{T} \approx 2.5 \times 10^{7}\ \mathrm{K}$$

Assuming fast neutrino emission, this corresponds to

$$L_\nu \approx 10^{38}\ \mathrm{erg\ s^{-1}}\ \tilde{T}_8^6$$


Unpaired nucleons
Leptons
$\Delta T_{\rm eff}/T_{\rm eff} = 1\%$
3%
10%
MXB 1659-29
Entire core dURCA
$C/\tilde{T}_8$
10^{38}
10^{37}
10^{37}
10^{38}
10^{39}
$L_\nu/\tilde{T}_8^6$

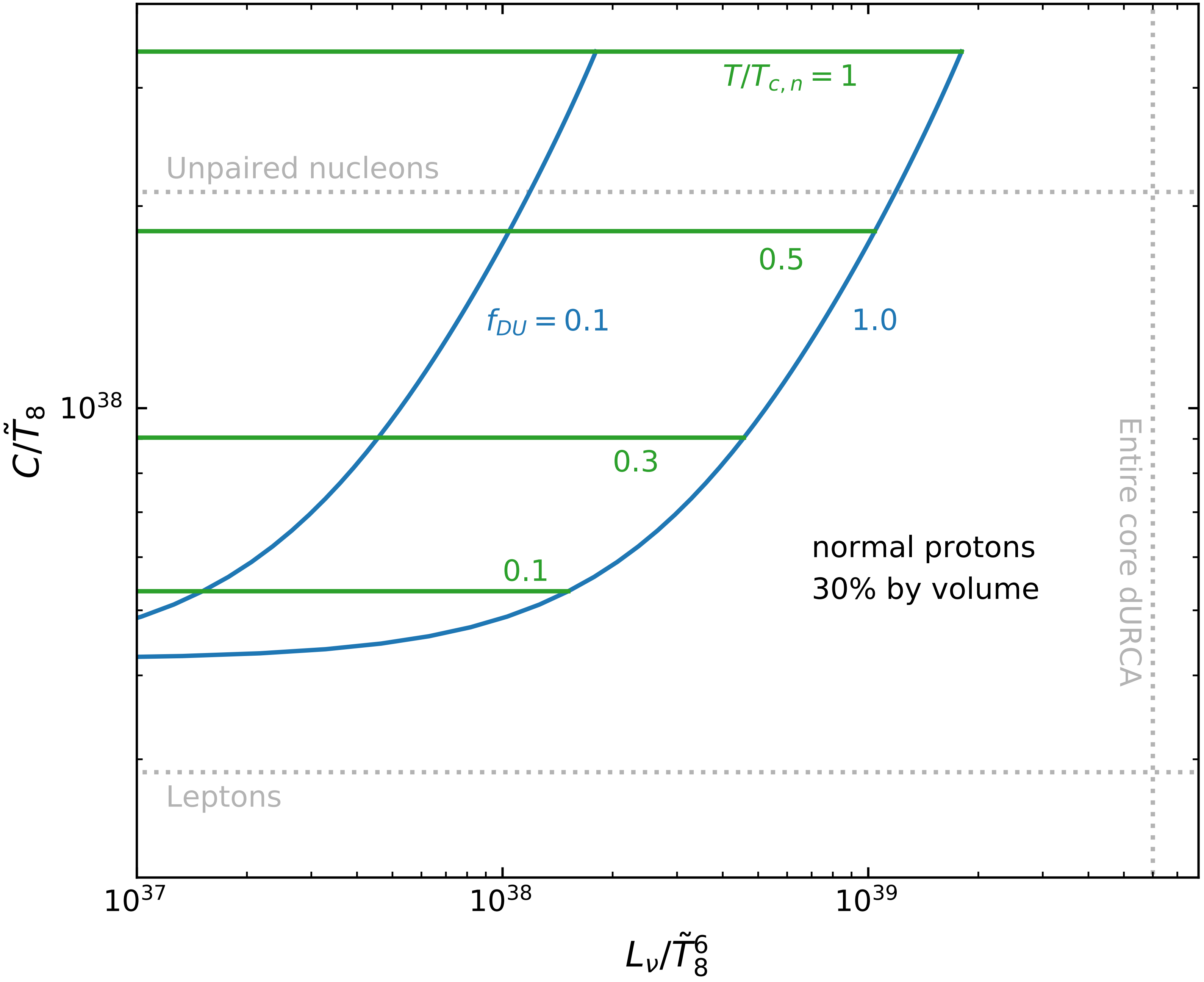
Future measurements will provide a cross-check:

- temperature variation <1% per decade => nucleons are unpaired in most of the core => direct URCA turned on by the proton fraction threshold

- temperature variation of ~10% per decade => nucleons are paired in most of the core => pairing suppresses direct URCA in most of the core

(If a density threshold, there may be a fine tuning issue, need the star to be only ~0.03 solar masses above threshold.)

Simple model with 30% normal protons in the core, with different neutron critical temperatures and direct URCA thresholds



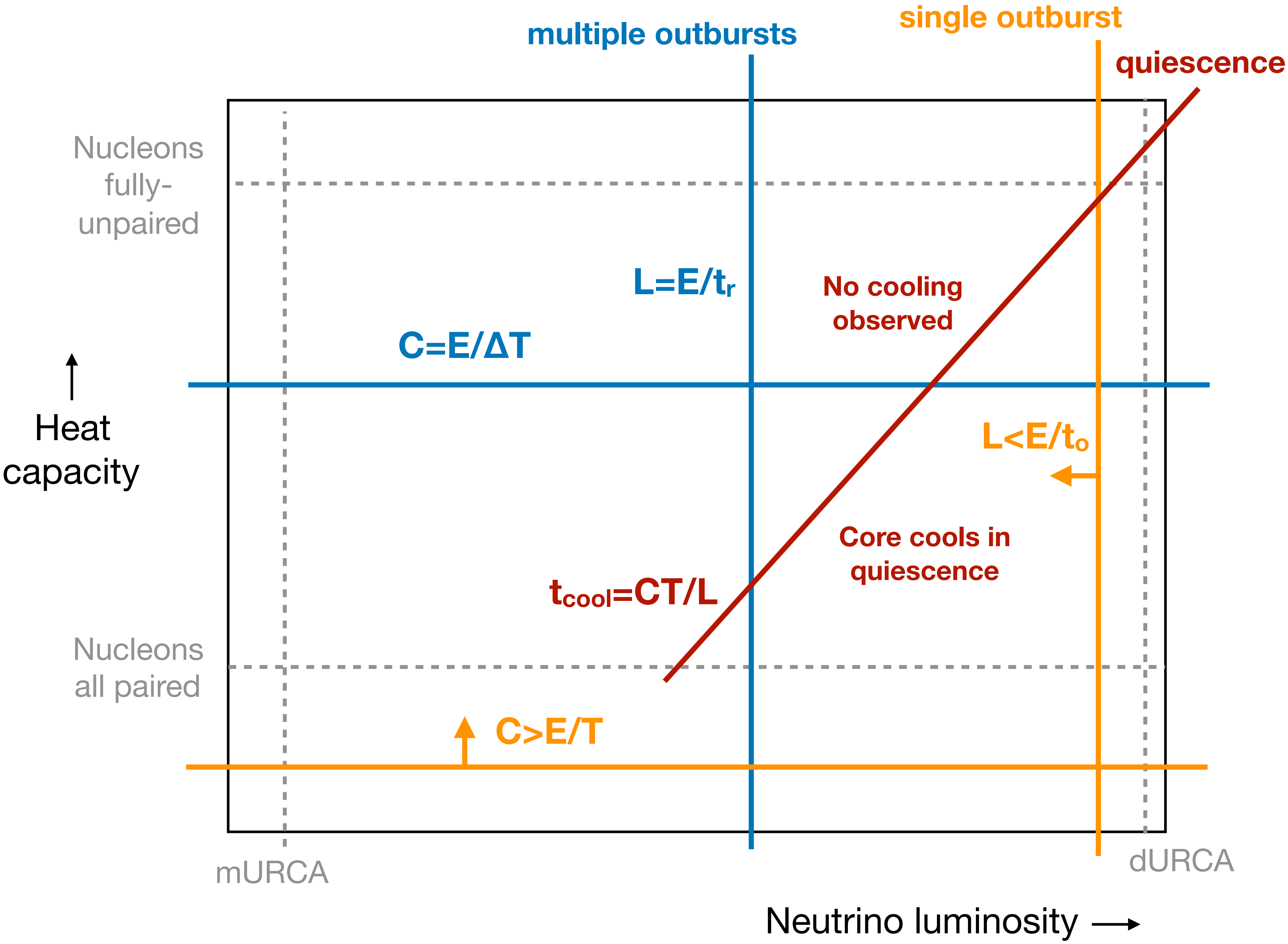
Slow and fast neutrino cooling:

Alternatives to direct URCA are possible, but cannot be less than 1% of the dURCA rate (as they would then have to happen over > the entire core)

On the other hand, a fast neutrino process in KS 1731-260 has to be $<10^{-4}$ of direct URCA … suggests that neutrino emission is “slow” e.g. modified URCA in KS 1731

A slow neutrino process does not work for MXB 1659 (it would have to be orders of magnitude more efficient than modified URCA)

Other sources without detectable thermal emission (SAXJ1808, 1H1905) may be more massive neutron stars well over threshold (e.g. Beznogov & Yakovlev 2015)


single outburst
multiple outbursts
quiescence
Nucleons
fully-
unpaired
$L=E/t_r$
No cooling
observed
$C=E/\Delta T$
Heat
capacity
$L<E/t_o$
Core cools in
quiescence
$t_{cool}=CT/L$
Nucleons
all paired
$C>E/T$
mURCA
dURCA
Neutrino luminosity

Summary

Accreting transients offer a way to independently constrain neutrino luminosity and heat capacity — because they "know" about each other, this can potentially distinguish different possibilities for particle content and pairing gaps

The shape of the cooling curve depends on the crust temperature which can distinguish light and heavy envelopes

Cold neutron stars with long outbursts give the most constraining limits on the core heat capacity

The neutron star in MXB 1659 requires a fast neutrino cooling process; monitoring its return to quiescence will tell us a lot about the core (leaky calorimeter experiment)