Thermal evolution of accreting neutron stars at high accretion rates: energy leakage towards the interior of the star?

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IReNA-INT Joint Workshop on Thermal and Magnetic Evolution of Neutron Stars

December 9th, 2024

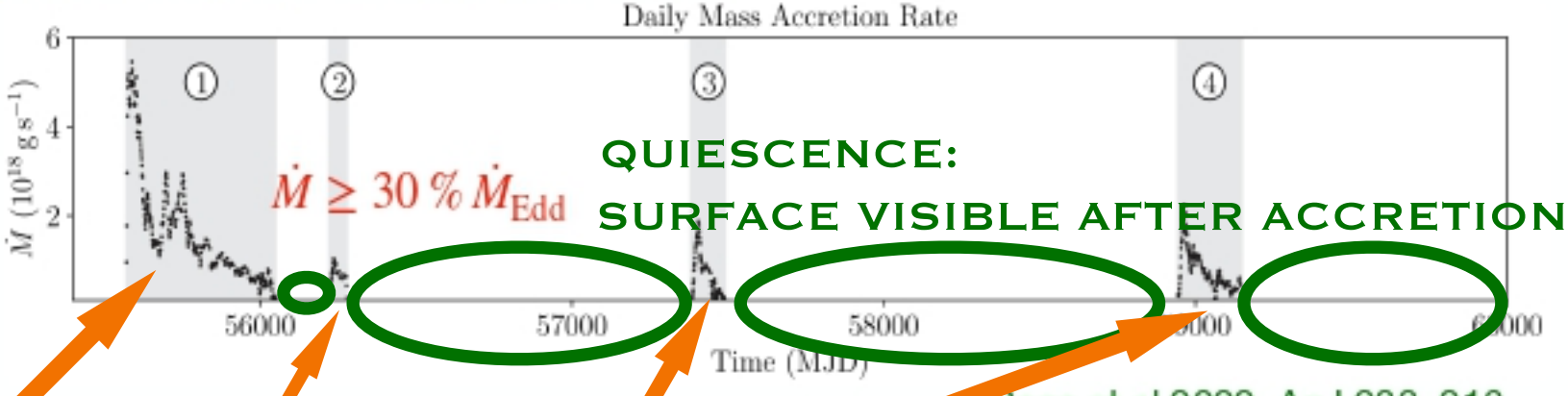
OVERVIEW

PREFACE

(A SORT OF HOMECOMING)

LMXBs: BURN AND RELAX

MAXI J0556-332: Transient accretion of months

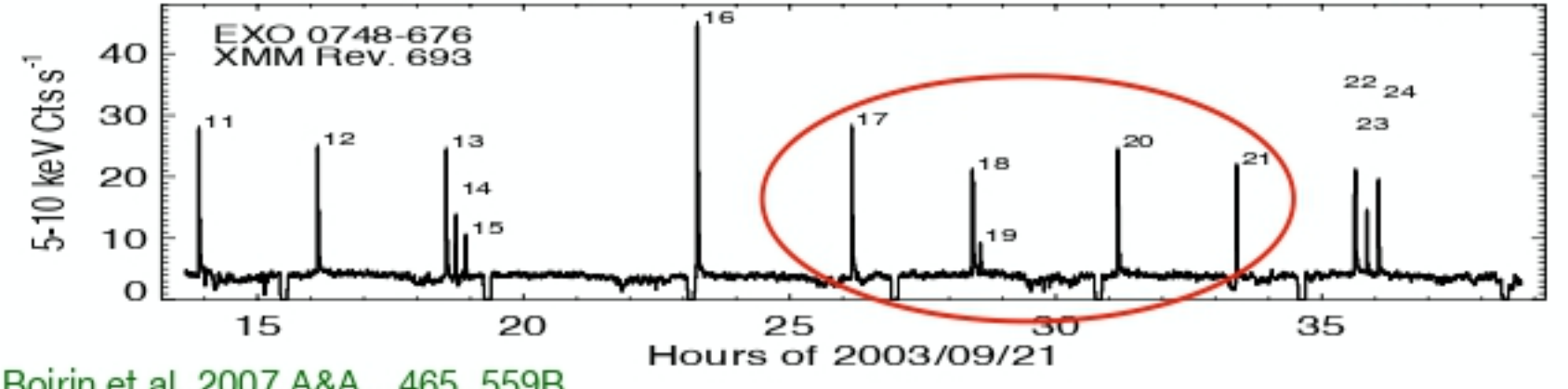


QUIESCENCE:
SURFACE VISIBLE AFTER ACCRETION!

Page et al 2022, ApJ 933, 216

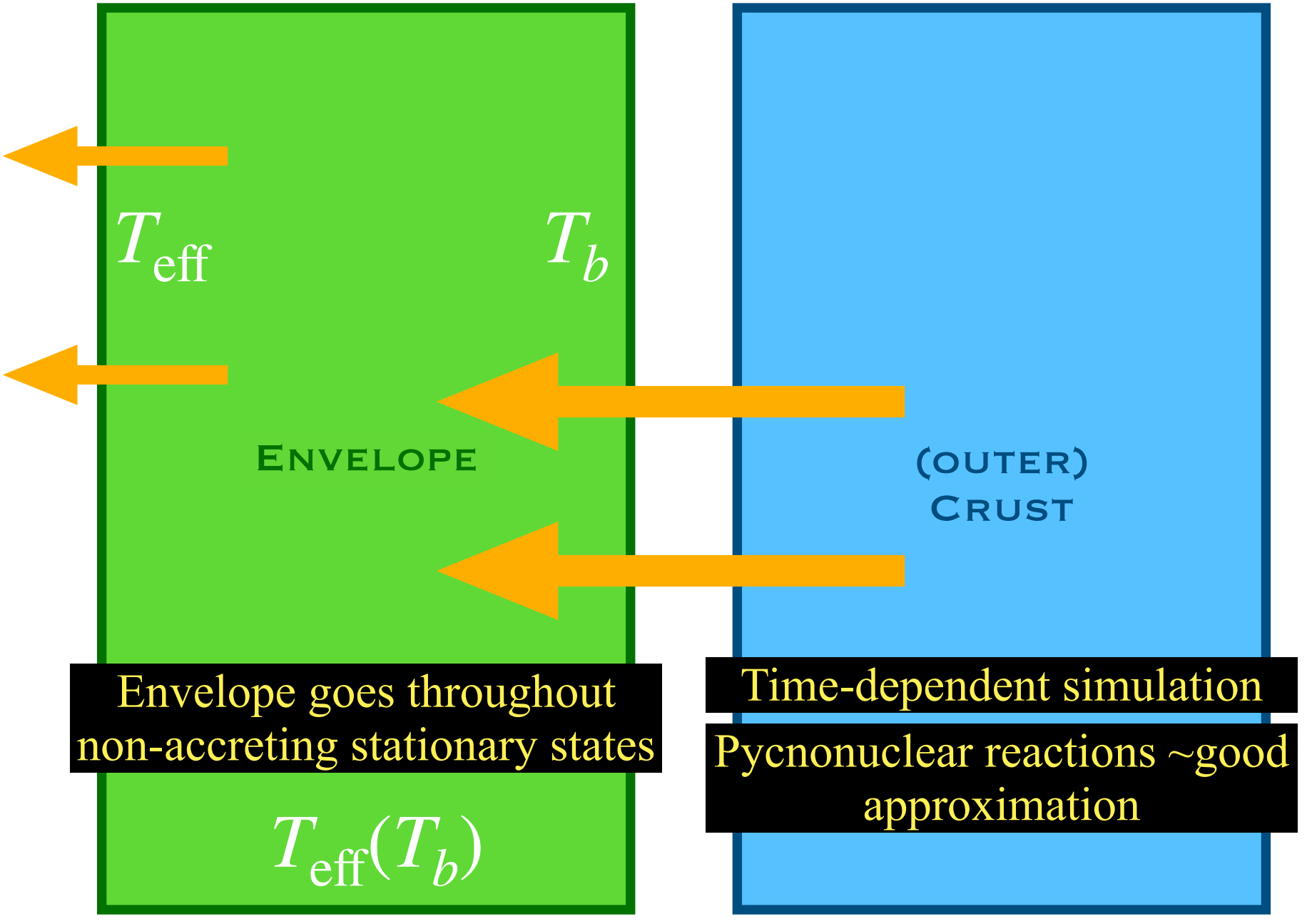
STABLE/UNSTABLE NUCLEAR BURNING

EXO 0748-676: Accretion and X-ray bursts



Boirin et al, 2007 A&A...465..559B

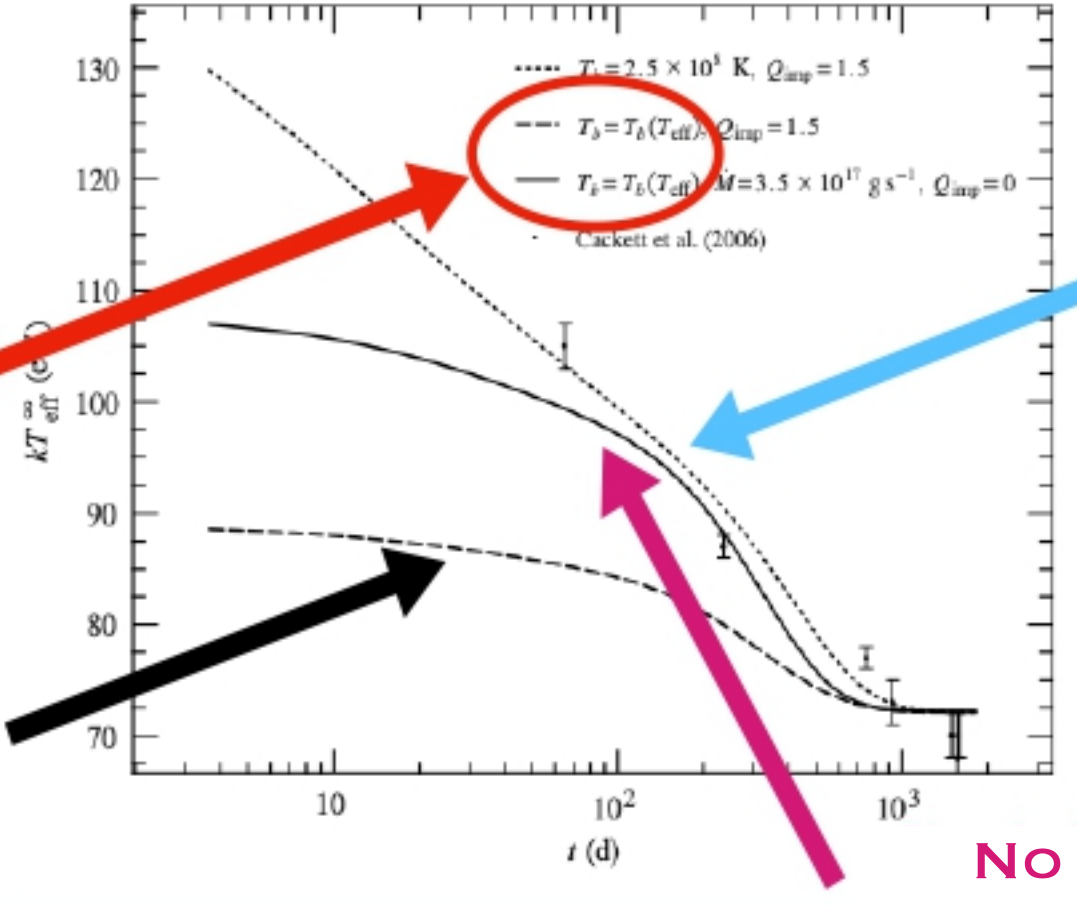
Current paradigm



The *shallow heating* open question

Stationary approximation for the envelope:

$T_b(T_{\rm eff})$



With shallow heating

Without shallow heating

No shallow heating but different accretion rate

Edward F. Brown and Andrew Cumming 2009 *ApJ* **698** 1020

Do we need to check the envelope?

A "Hyperburst" in the MAXI J0556–332 Neutron Star: Evidence for a New Type of Thermonuclear Explosion

Dany Page[1], Jeroen Homan[2], Martin Nava-Callejas[1], Yuri Cavecchi[1], Mikhail V. Beznogov[1,3], Nathalie Degenaar[4], Rudy Wijnands[4], and Aastha S. Parikh[4]

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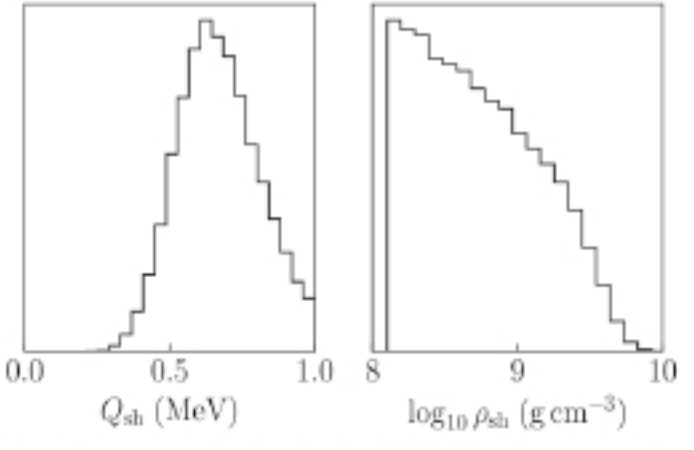


Figure 9. Histograms of the distribution of the shallow heating strength, $Q_{\rm sh}$, and lower density, $\rho_{\rm sh}$, in scenario "C."

Monte-Carlo Markov Chain simulations (MCMC): find the "best" parameters to adjust observations

Apparently, shallow heating might come from the envelope

Theory vs observation of X-ray bursts

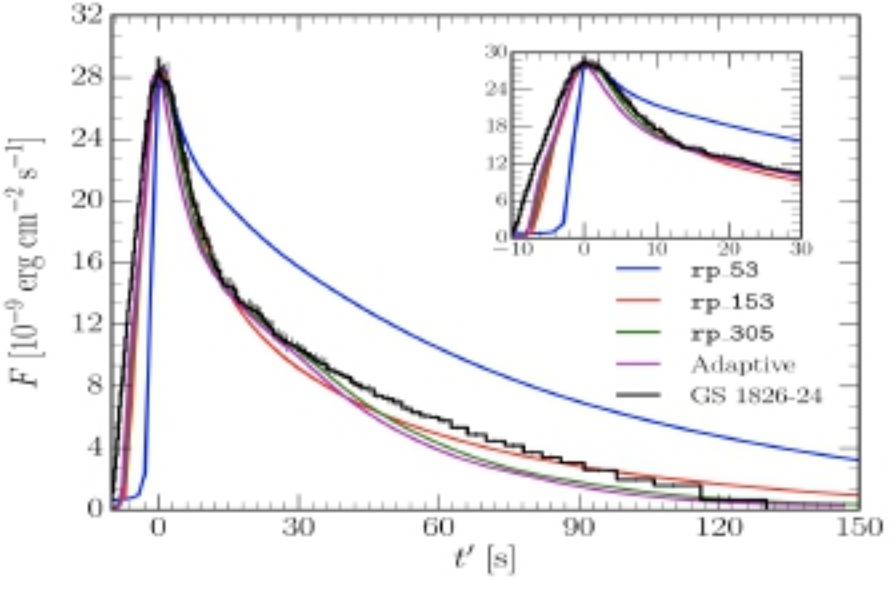


Figure: A typical X-ray burst over GS 1826-24 (black) against theoretical models employing **MESA**

- Observationally they occur at $\dot{M} < 0.3\dot{M}_{\mathrm{Edd}}$ ($\approx 10^{-9} M_{\odot}\ \mathrm{yr}^{-1}$)
- Explosions start at $\sim 10^{5.75}$ g cm^{-3} $\equiv$ **ENVELOPE**
- From H into Fe and beyond: ***rp-process***

Time-dependent codes such as MESA* are required!

*Modules for Experiments in Stellar Astrophysics

Theory vs observation of X-ray bursts

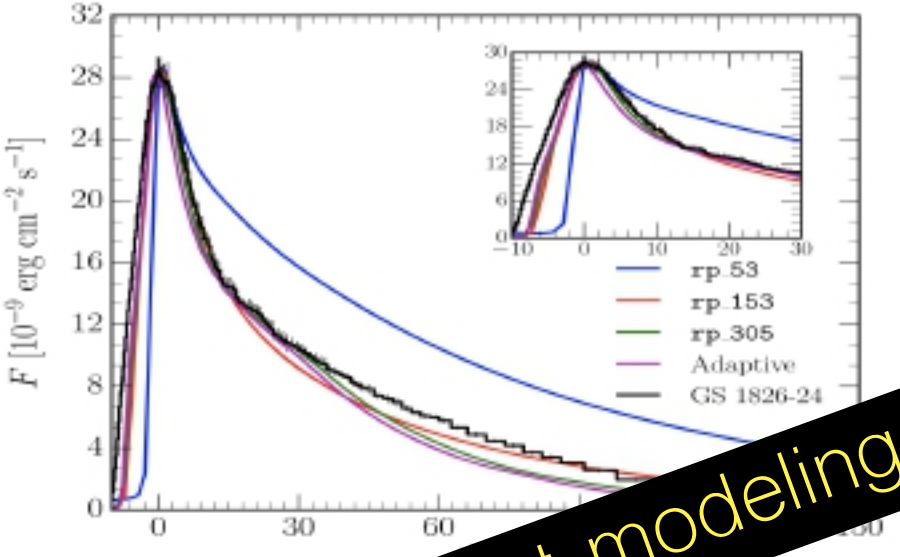


Figure: A[illegible] ray burst ove[illegible]24 (black) against the[illegible]tical models employing **MESA**

- Observationally the[illegible]t $\dot{M} < 0.3\dot{M}_{\mathrm{Edd}}$ ($\sim 10^{-8}\ M_\odot\ \mathrm{yr}^{-1}$)
- [illegible]ions start at $\sim 10^{5.75}$ g cm^{-3} ≡ **ENVELOPE**
- From H into Fe and beyond: ***rp-process***

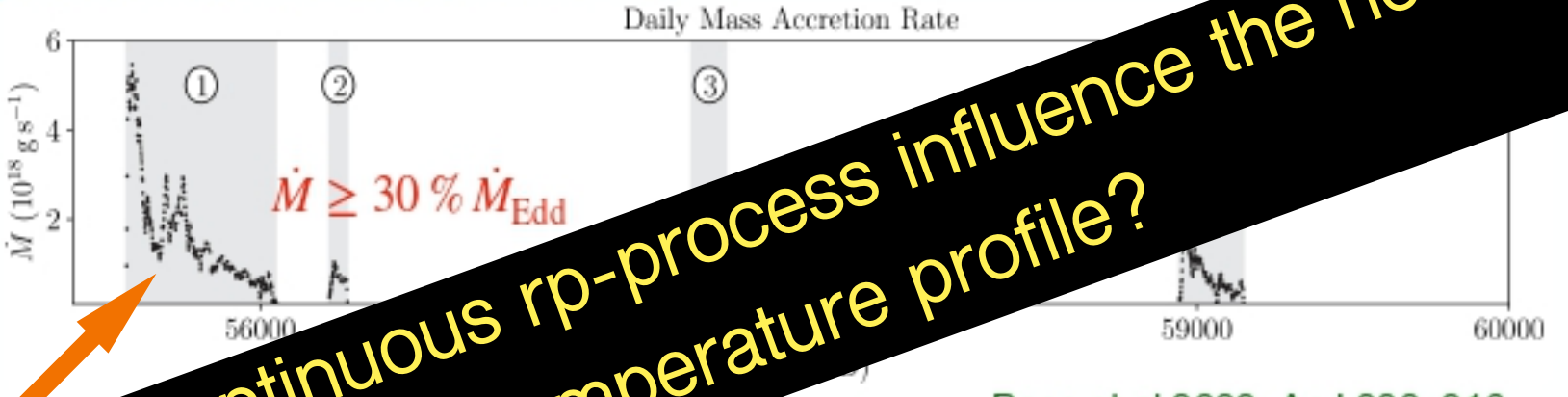
Self-consistent modeling of all star takes too long!

Time-dependent codes such as MESA* are required!

*Modules for Experiments in Stellar Astrophysics

Transient systems: burn and relax

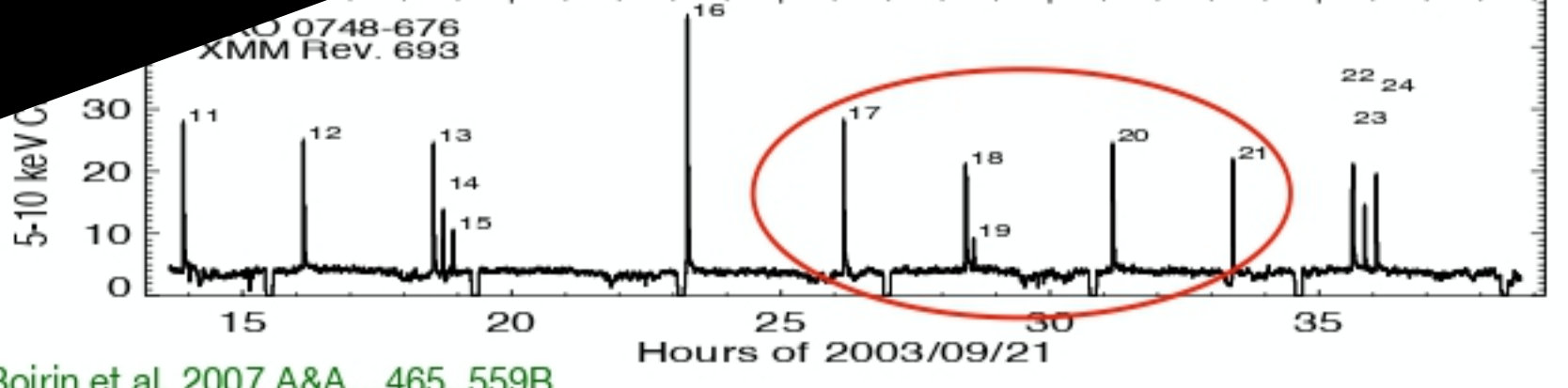
MAXI J0556-332: Acreción transitoria



Page et al 2022, ApJ 933, 216

How does continuous rp-process influence the neutron star's temperature profile?

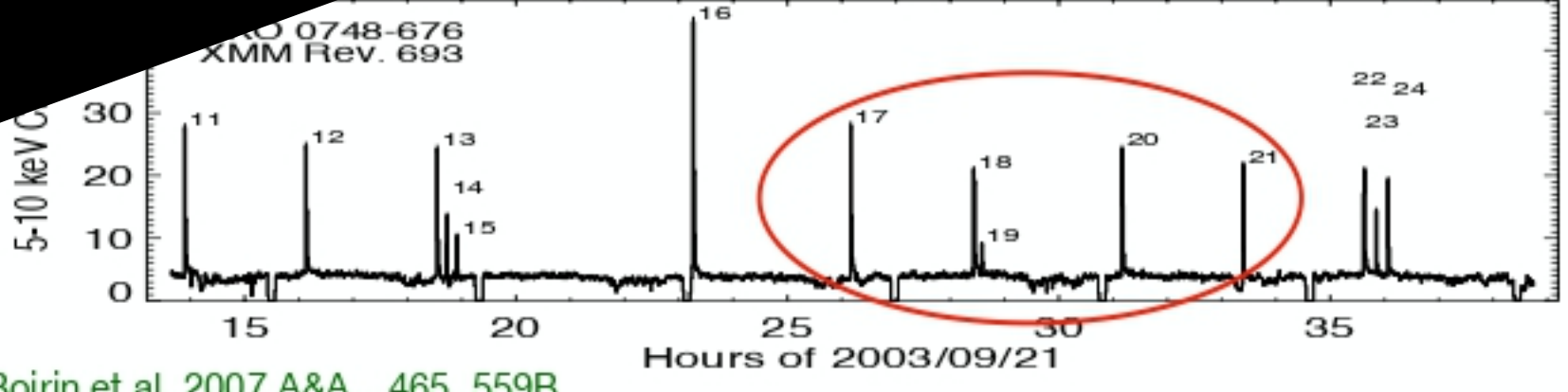
EXO 0748-676: Acreción y X-ray bursts



Boirin et al, 2007 A&A...465..559B

Transient systems: burn and relax

MAIN GOAL: To develop an approximating scheme to model transient (& possibly continuous) accreting sources



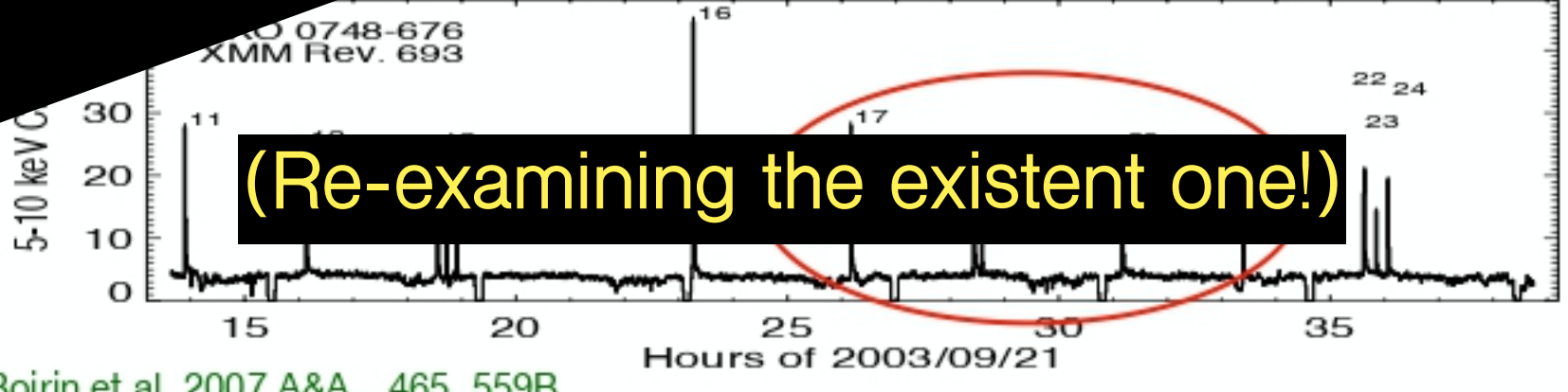
Boirin et al, 2007 A&A...465..559B

Transient systems: burn and relax

MAIN GOAL: To develop an approximating scheme to model transient (& possibly continuous) accreting sources

Hov

(Re-examining the existent one!)



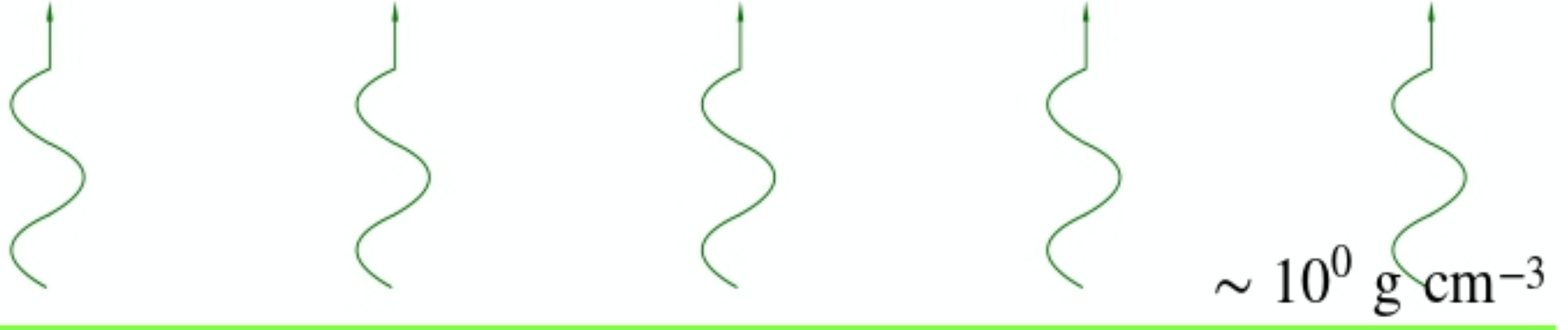
Boirin et al, 2007 A&A...465..559B

CHAPTER 1

ENVELOPES WITH ACCRETION: STATIONARY STATES

(Moving pictures)

Current: The $T_b(T_{\rm eff})$ scheme



$\sim 10^0$ g cm^{-3}

$T_{\rm eff}$

ENVELOPE:

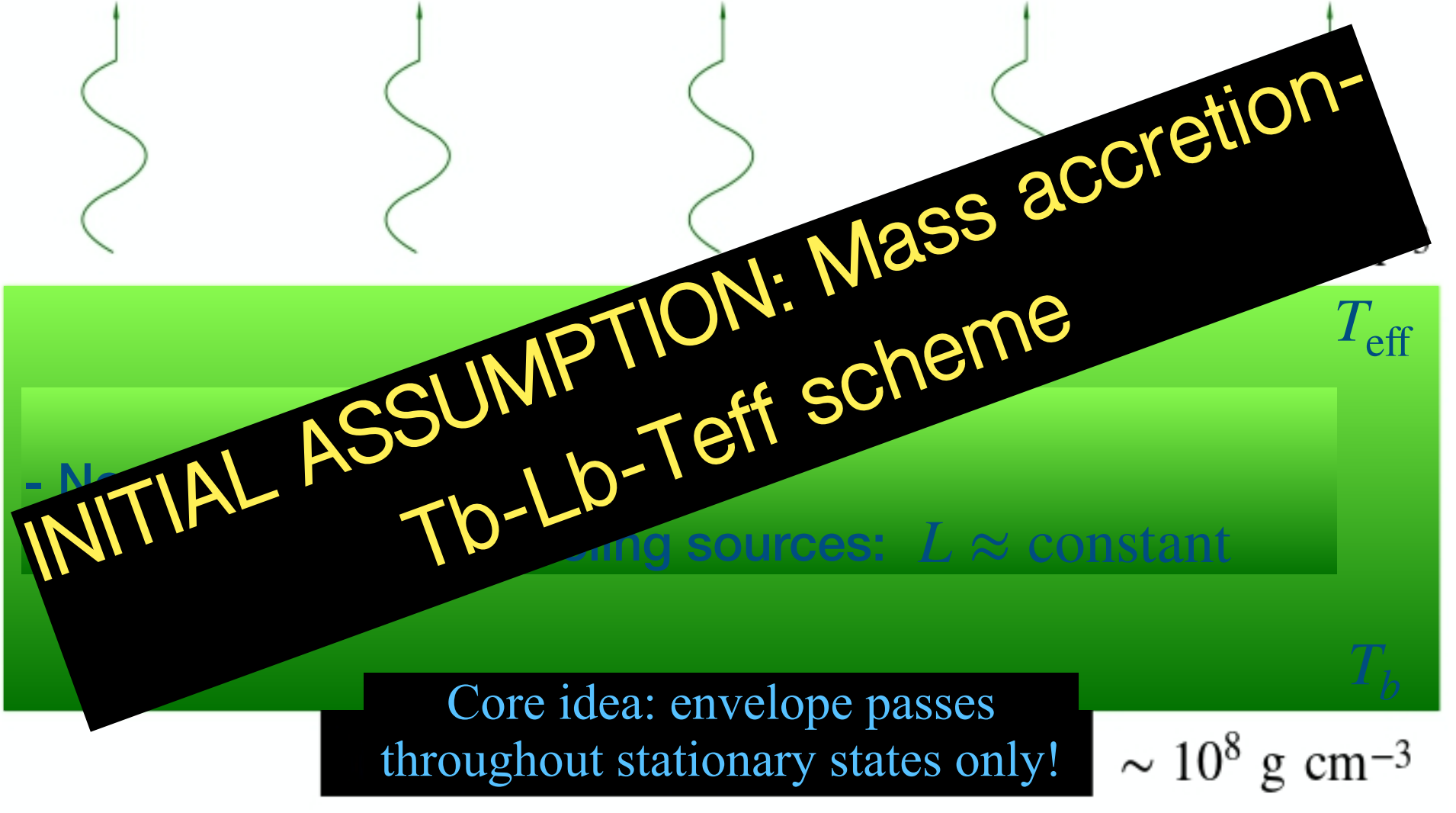
- No accretion
- No further heating/cooling sources: $L \approx$ constant

T_b

Core idea: envelope passes throughout stationary states only!

$\sim 10^8$ g cm^{-3}

Current: The $T_b(T_{\rm eff})$ scheme



INITIAL ASSUMPTION: Mass accretion-Tb-Lb-Teff scheme

- No

ing sources: $L \approx$ constant

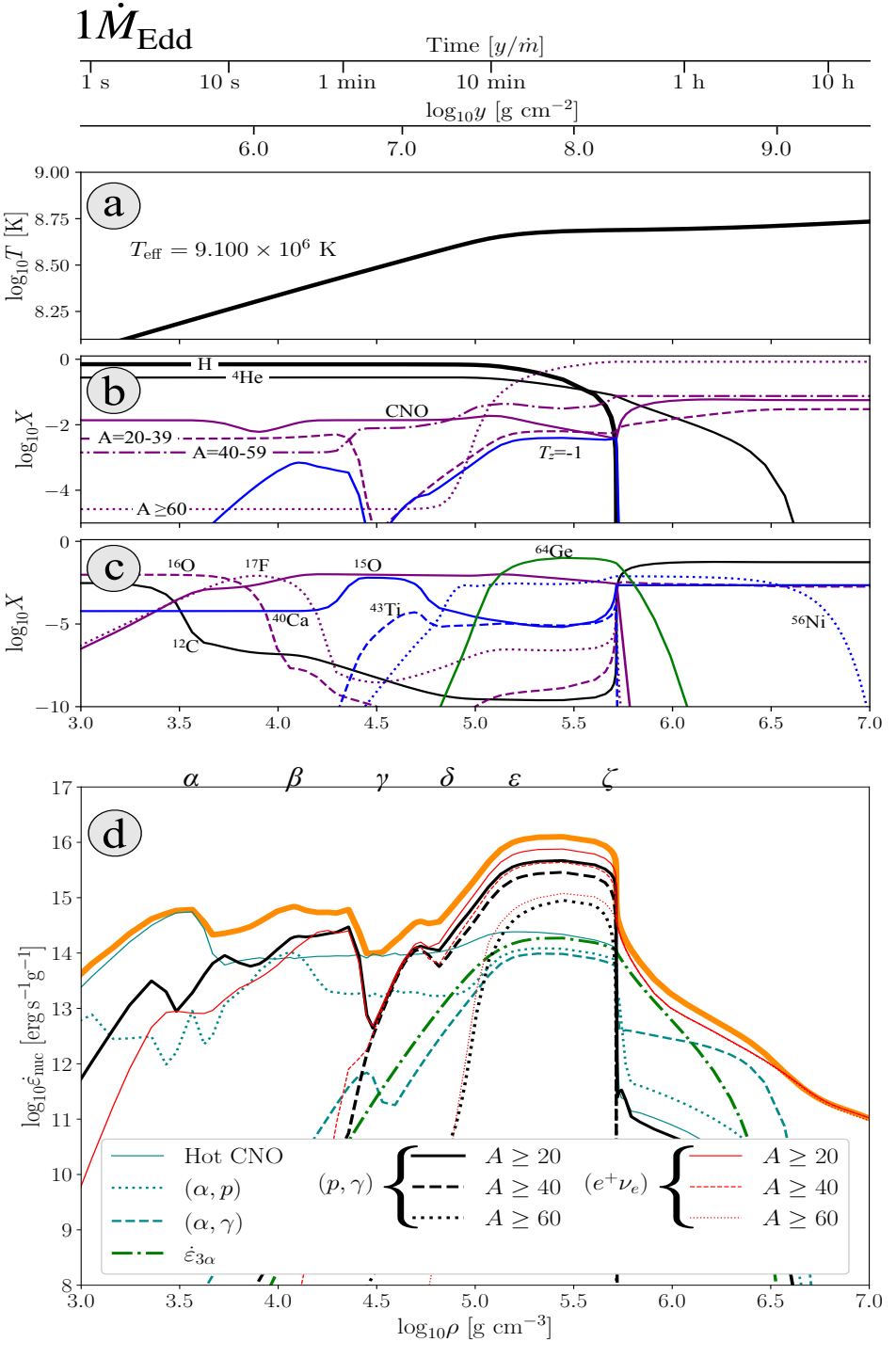
Core idea: envelope passes throughout stationary states only!

Analysis of stationary states

Examine time-independent envelopes at high accretion rates

Construction of a numerical code with 380 species (With room for more/ less nuclides)

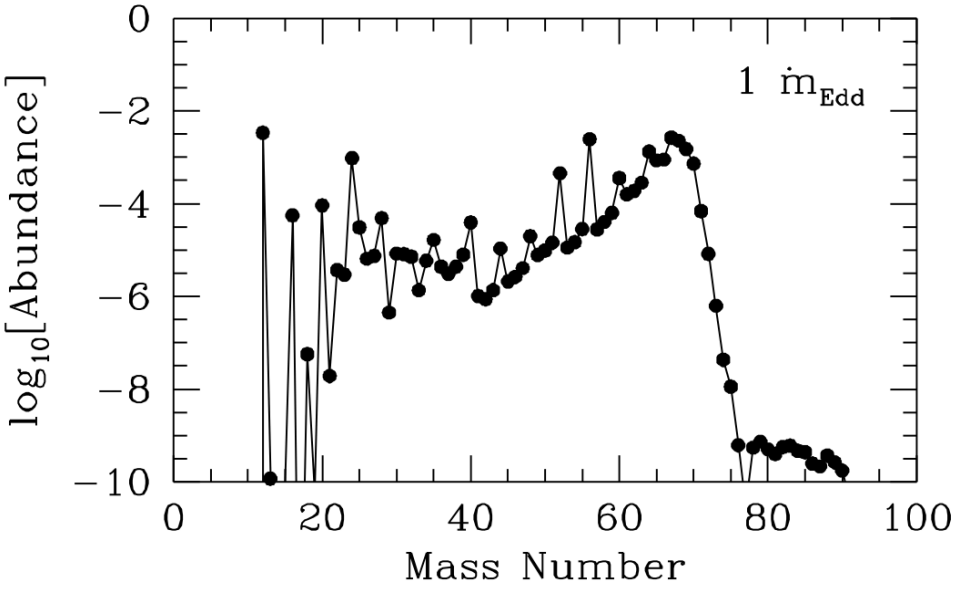
Own's code output as initial condition for MESA

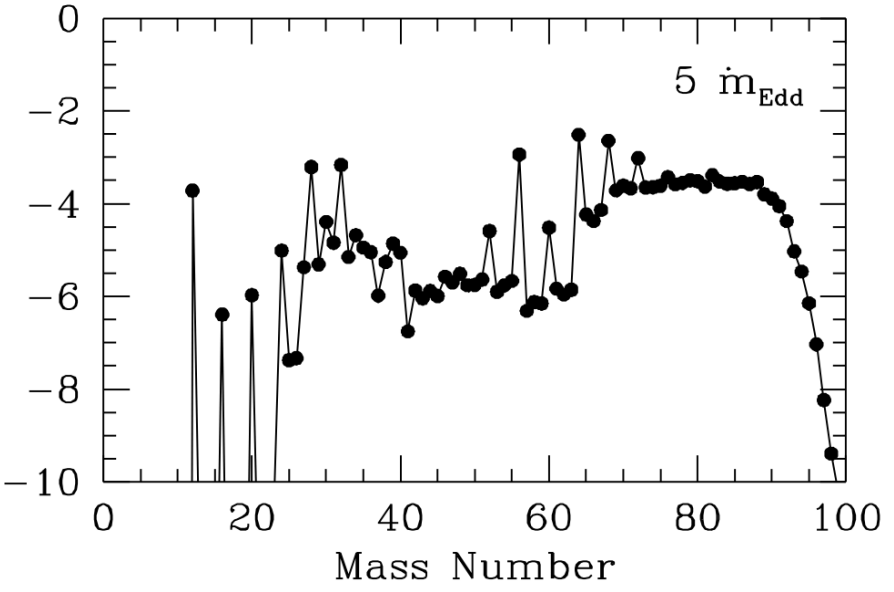


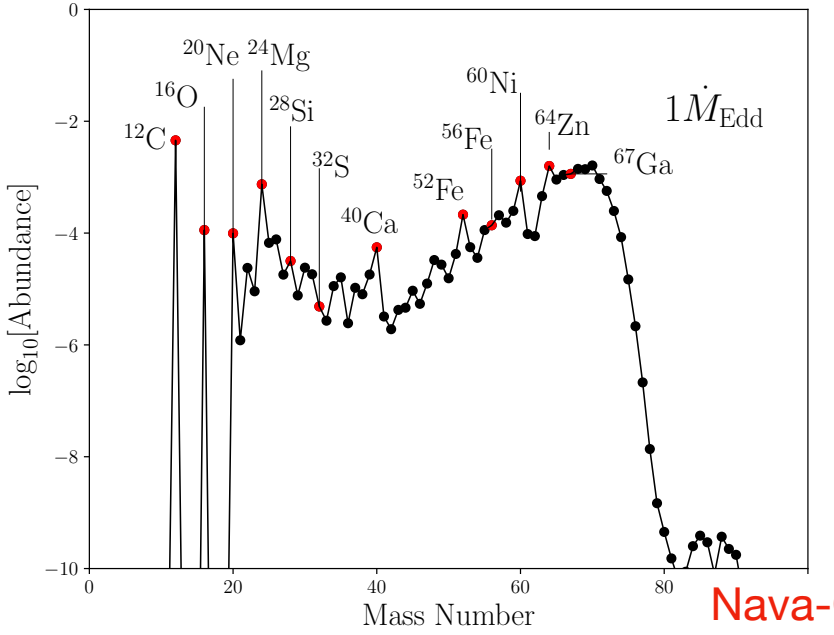
Nava-Callejas et al, 2024, arXiv:2403.13994 (RASTI, in press, https://doi.org/10.1093/rasti/rzae055)

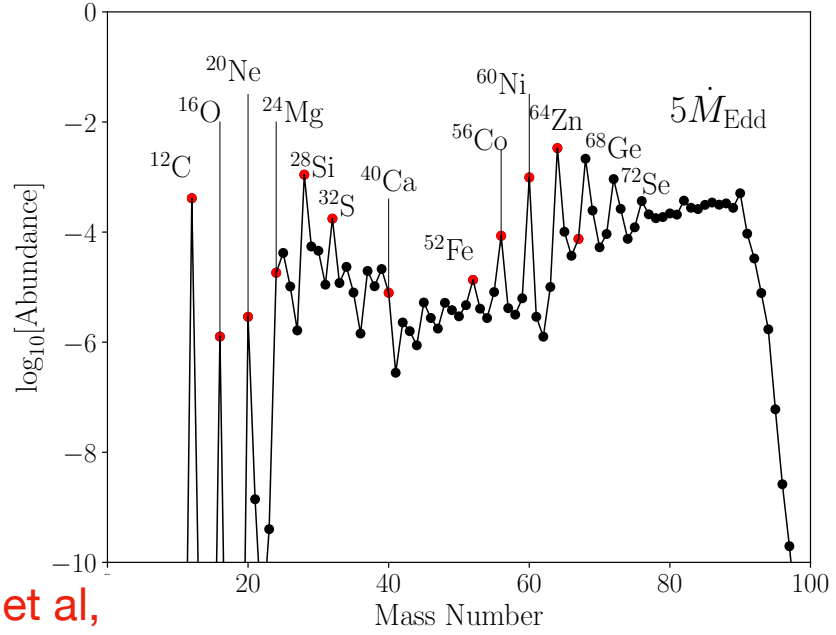
Comparison with former works

Schatz et al, 1999



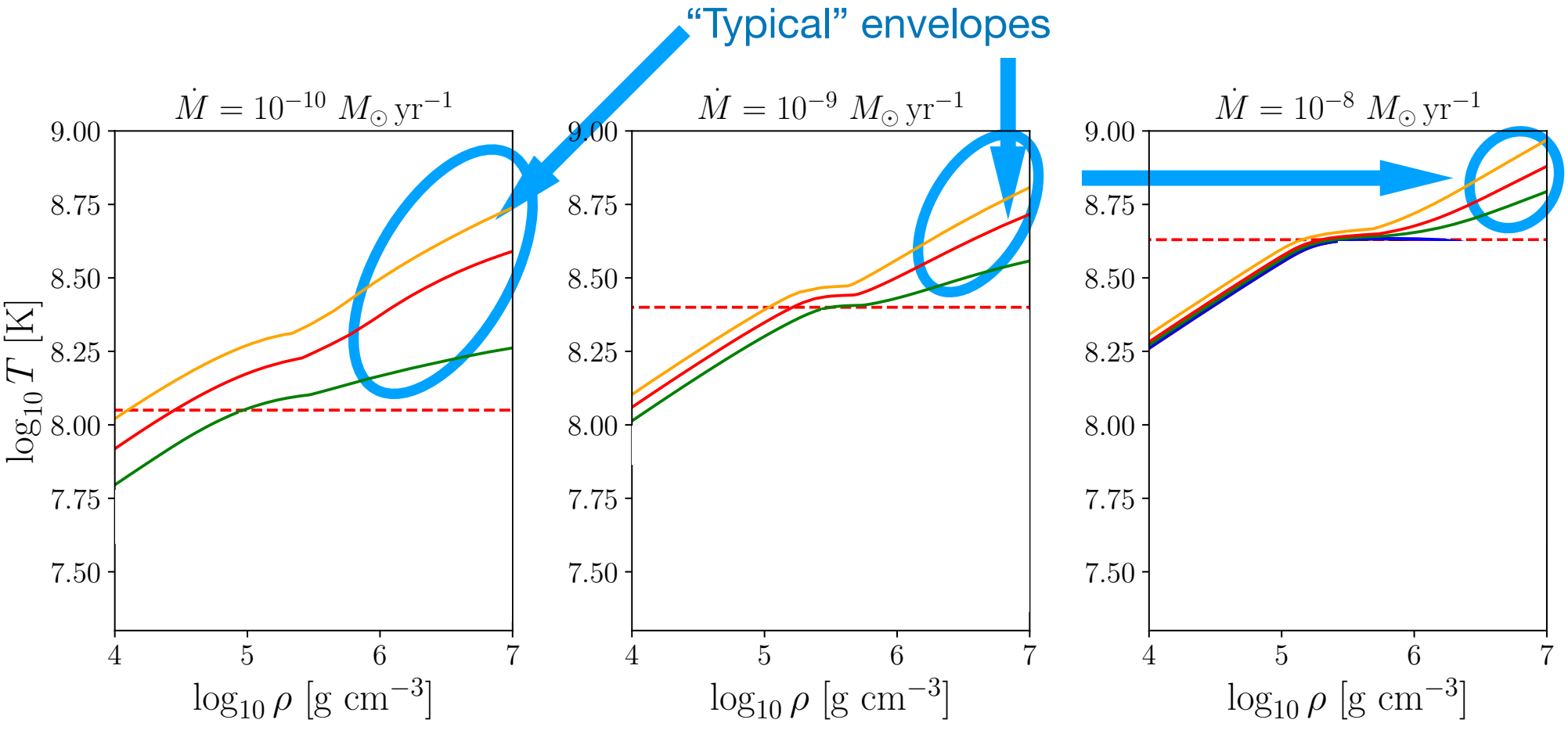




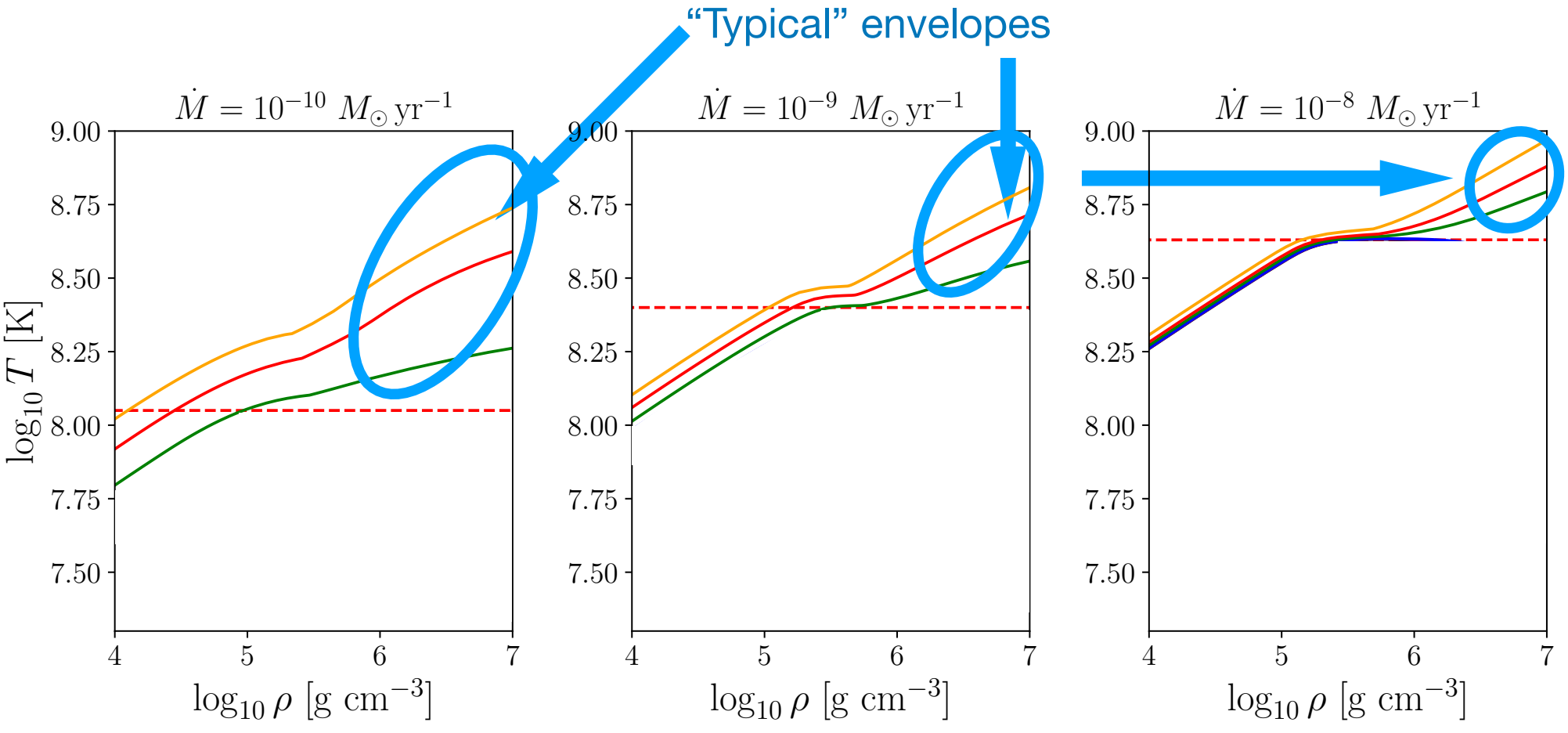


Nava-Callejas et al, 2024

Stationary states "families"



Stationary states "families"

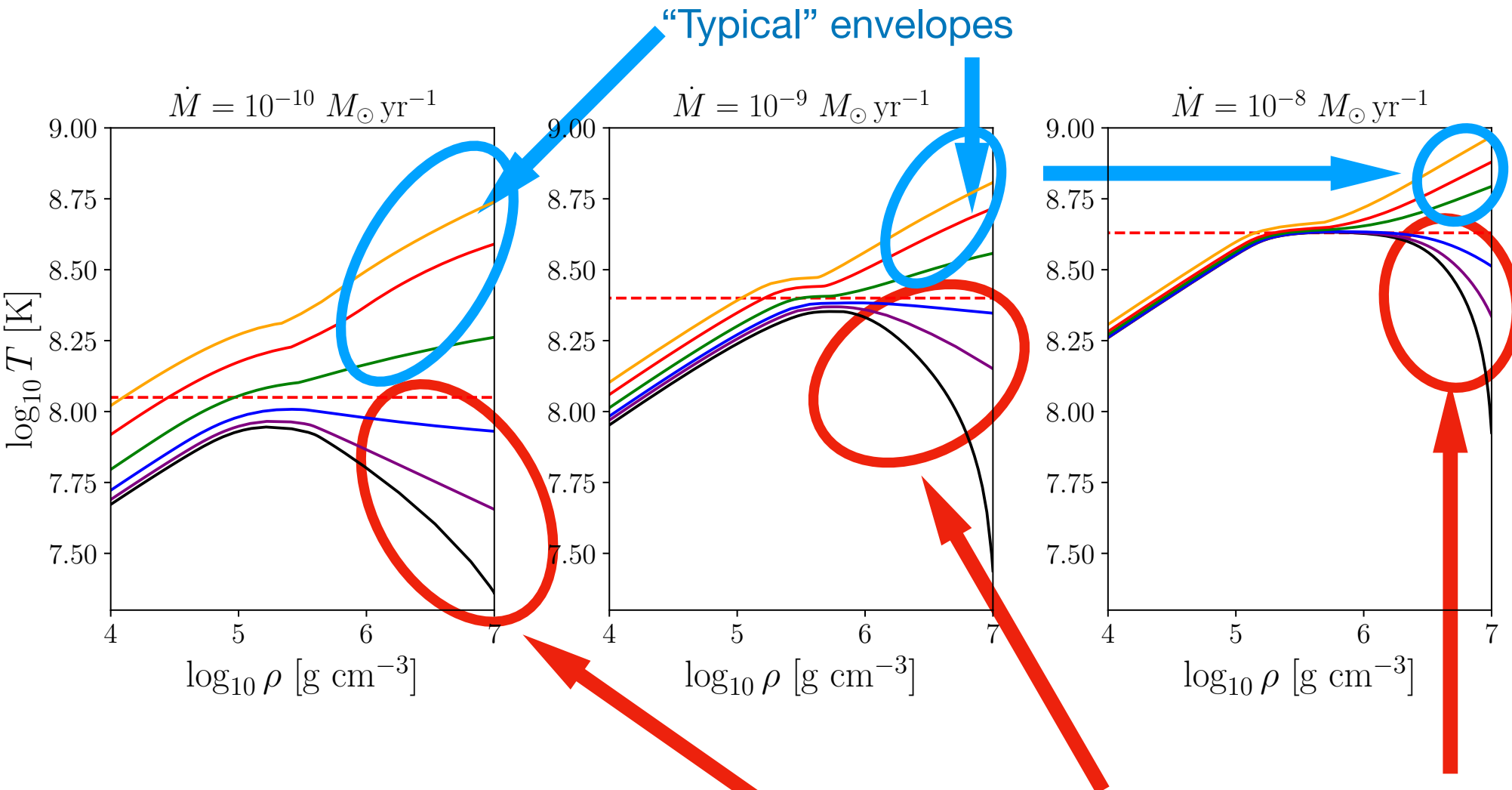


$T_{\rm eff} \approx$ same as $\dot{M} \to \dot{M}_{\rm Edd}$.

Drastic variation of L_b & T_b

$\dot{M} - T_{\rm eff} - L_b - T_b$ not very viable.

Stationary states "families"



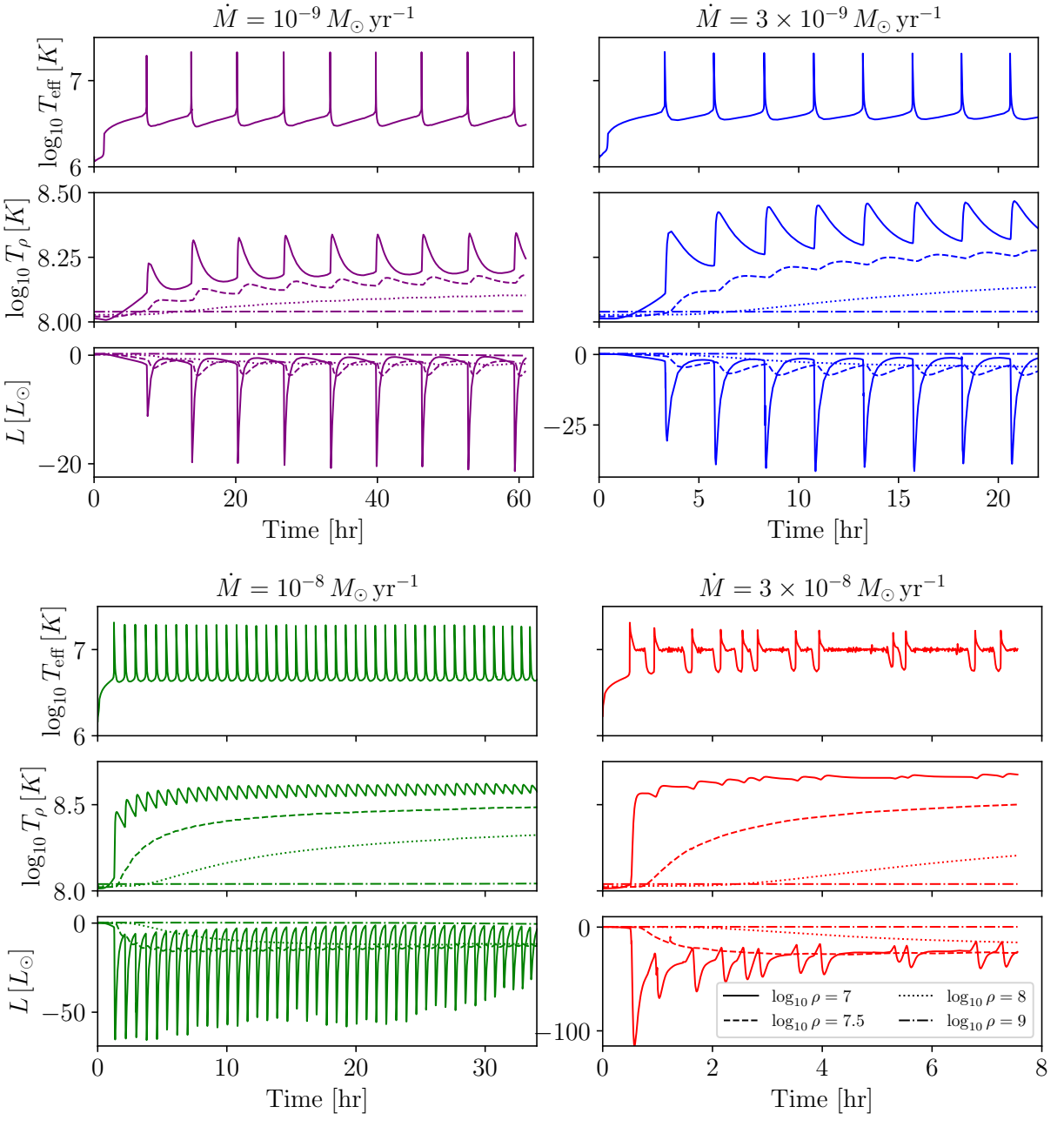
CHAPTER 2

THERMAL EVOLUTION: A FIRST LOOK

(Under the iron sea)

Energy towards the interior?

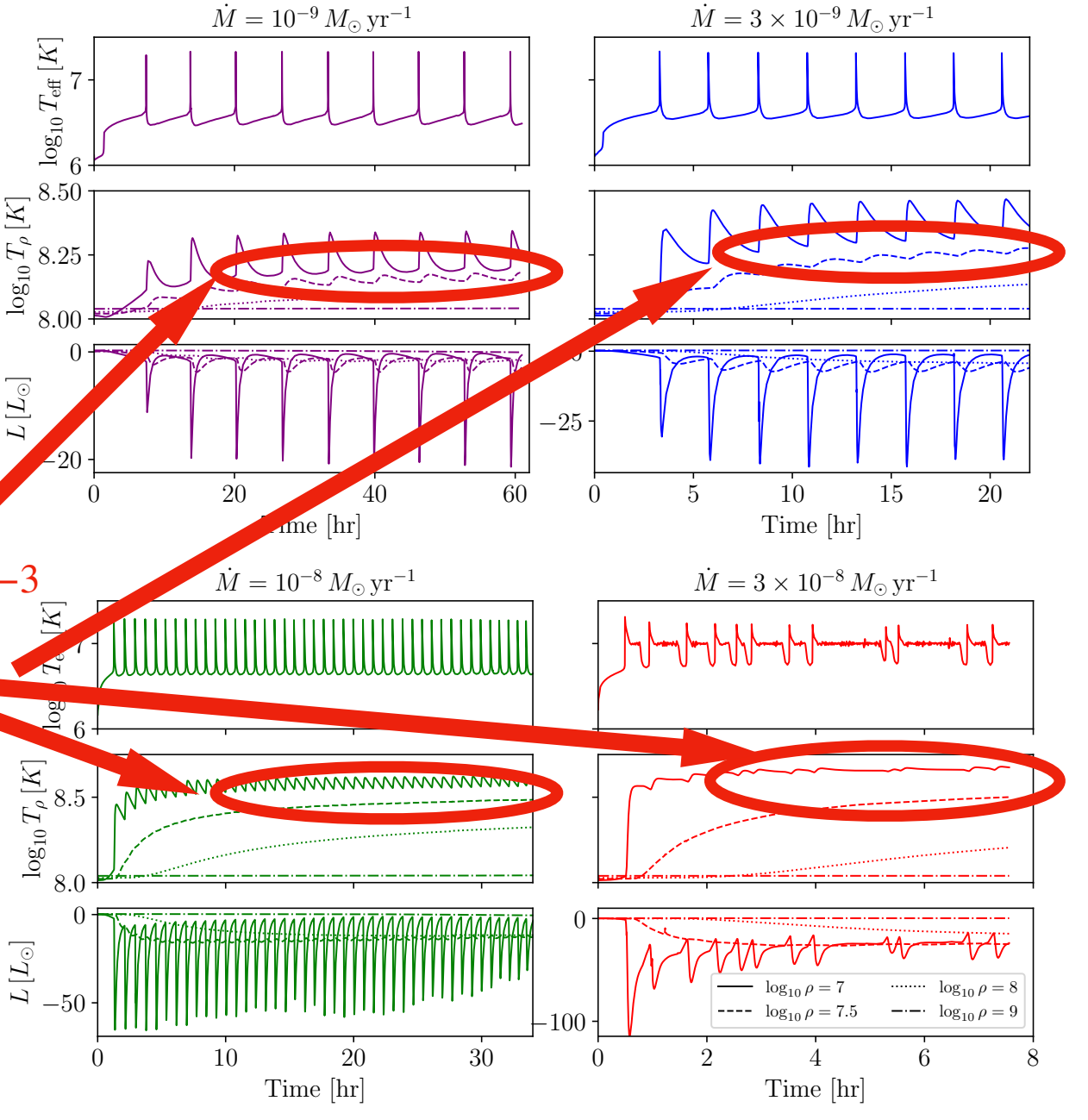
MESA: Energy flowing towards the interior **is viable**



Energy towards the interior?

MESA: Energy flowing towards the interior **is viable**

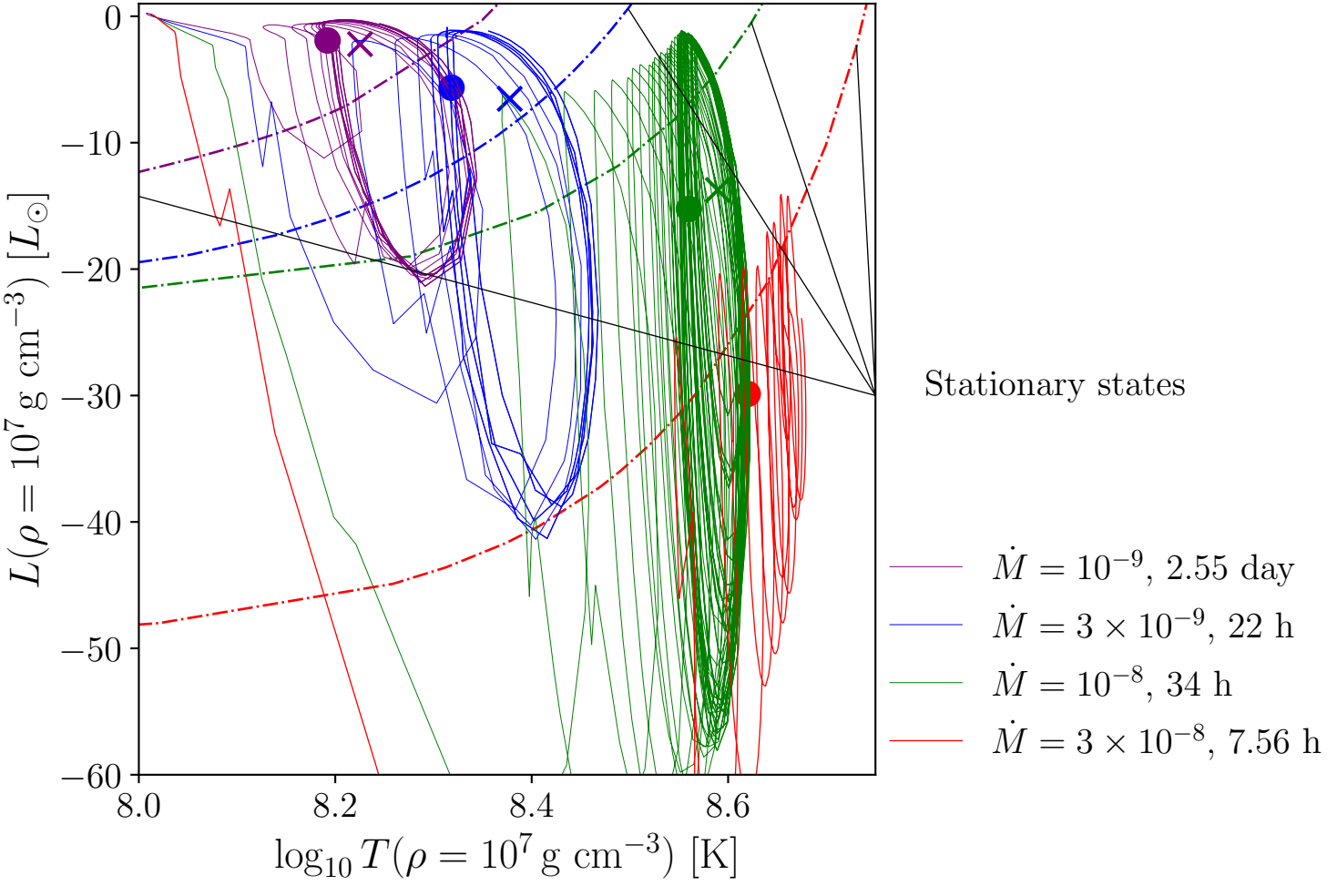
Are these $\rho \sim 10^7$ g cm^{-3} regions reaching a ~stationary state?



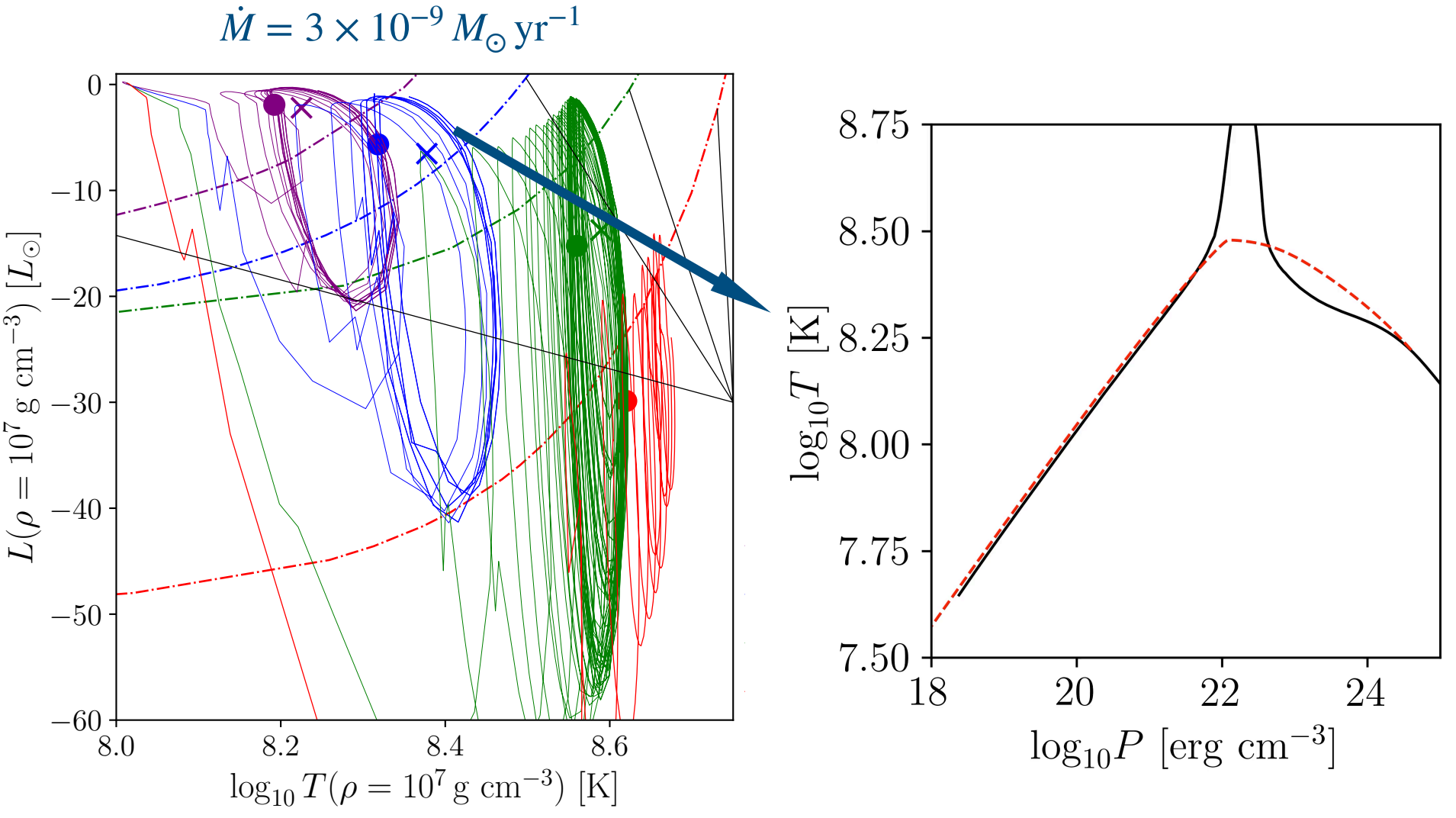
Energy towards the interior?

- No convection/ thermohaline

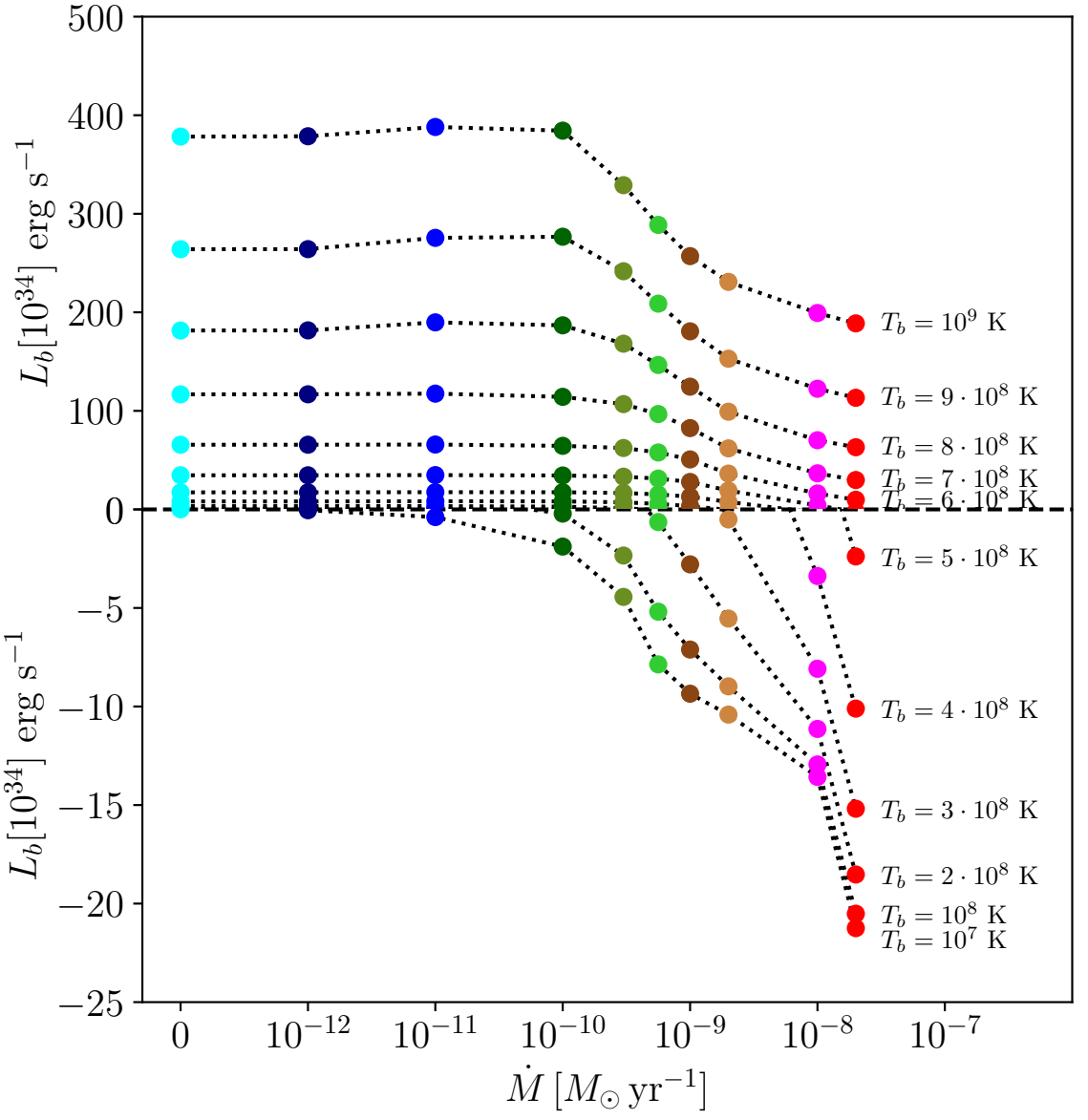
- No GR corrections (for fair comparison)



$\dot{M} - L_b - T_b$ seems viable .


$\dot{M} = 3 \times 10^{-9}\, M_\odot\, \mathrm{yr}^{-1}$
0
−10
−20
−30
−40
−50
−60
$L(\rho = 10^7\ \mathrm{g\ cm^{-3}})\ [L_\odot]$
8.0
8.2
8.4
8.6
$\log_{10} T(\rho = 10^7\ \mathrm{g\ cm^{-3}})\ [\mathrm{K}]$
8.75
8.50
8.25
8.00
7.75
7.50
$\log_{10} T$ [K]
18
20
22
24
$\log_{10} P$ [erg cm^{-3}]

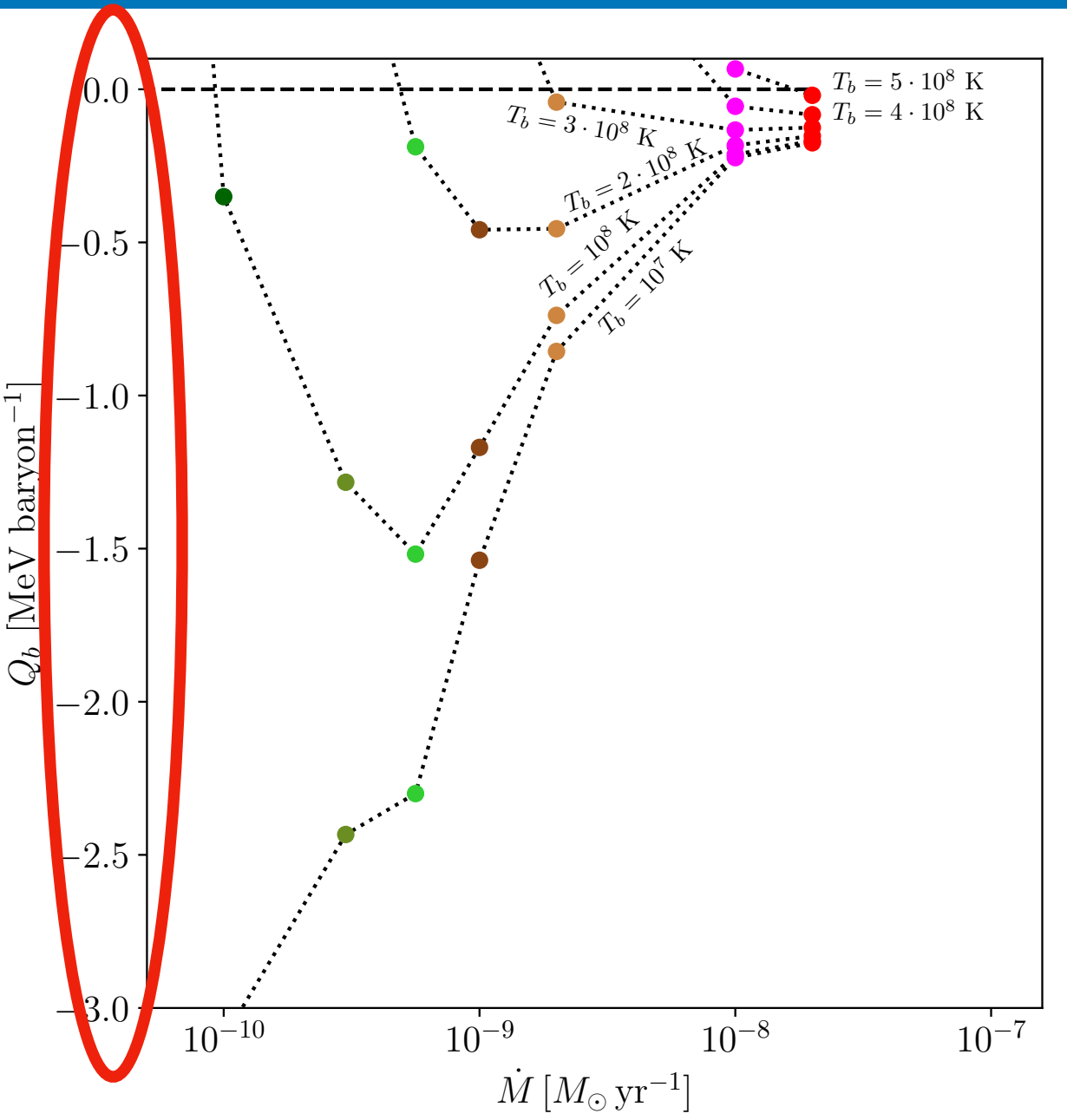
Boundary conditions for NSCool



Boundary conditions for NSCool

$L_b \rightarrow Q_b$

~Typical shallow heating values



Actual runs with NSCool

- Continuous & constant mass accretion for $\sim 10^5$ years

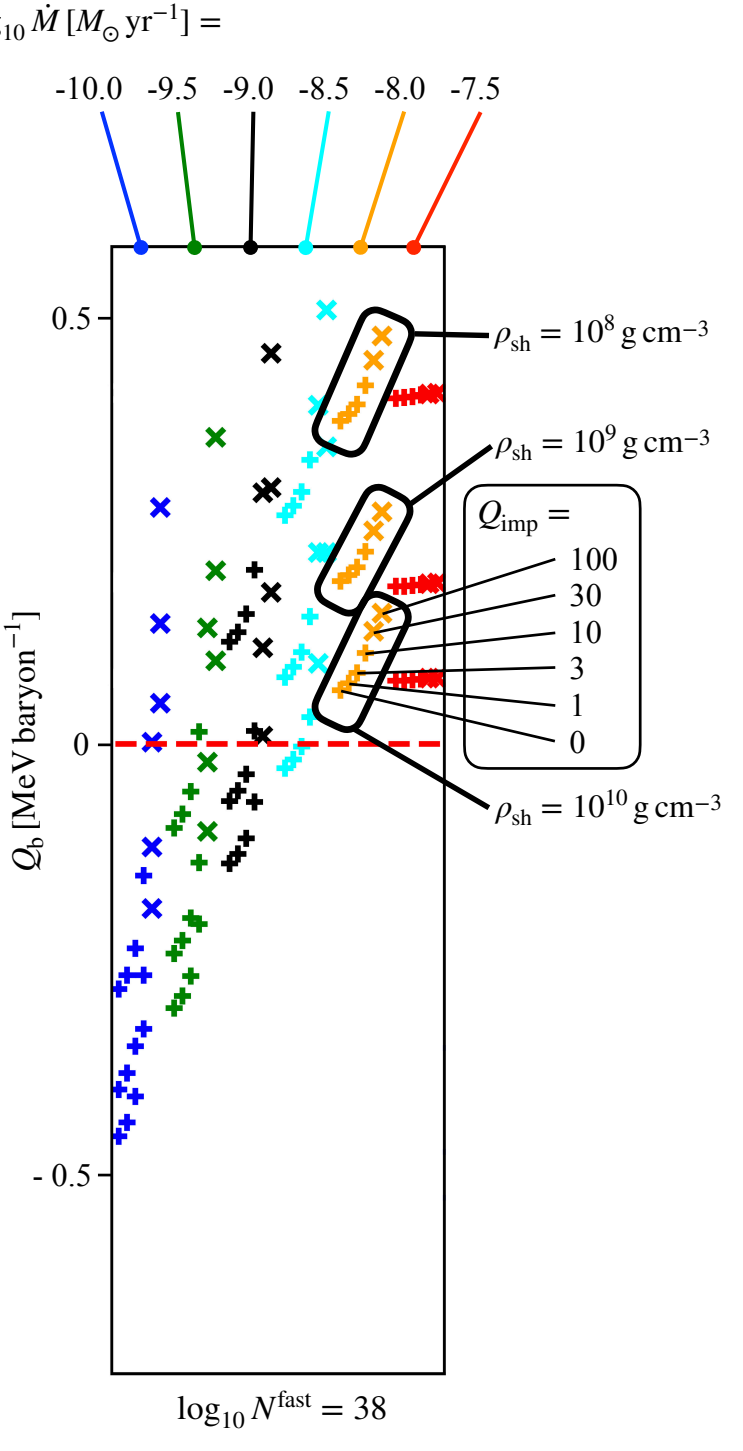
- Different values of impurities in the crust: $Q_{\rm imp}$

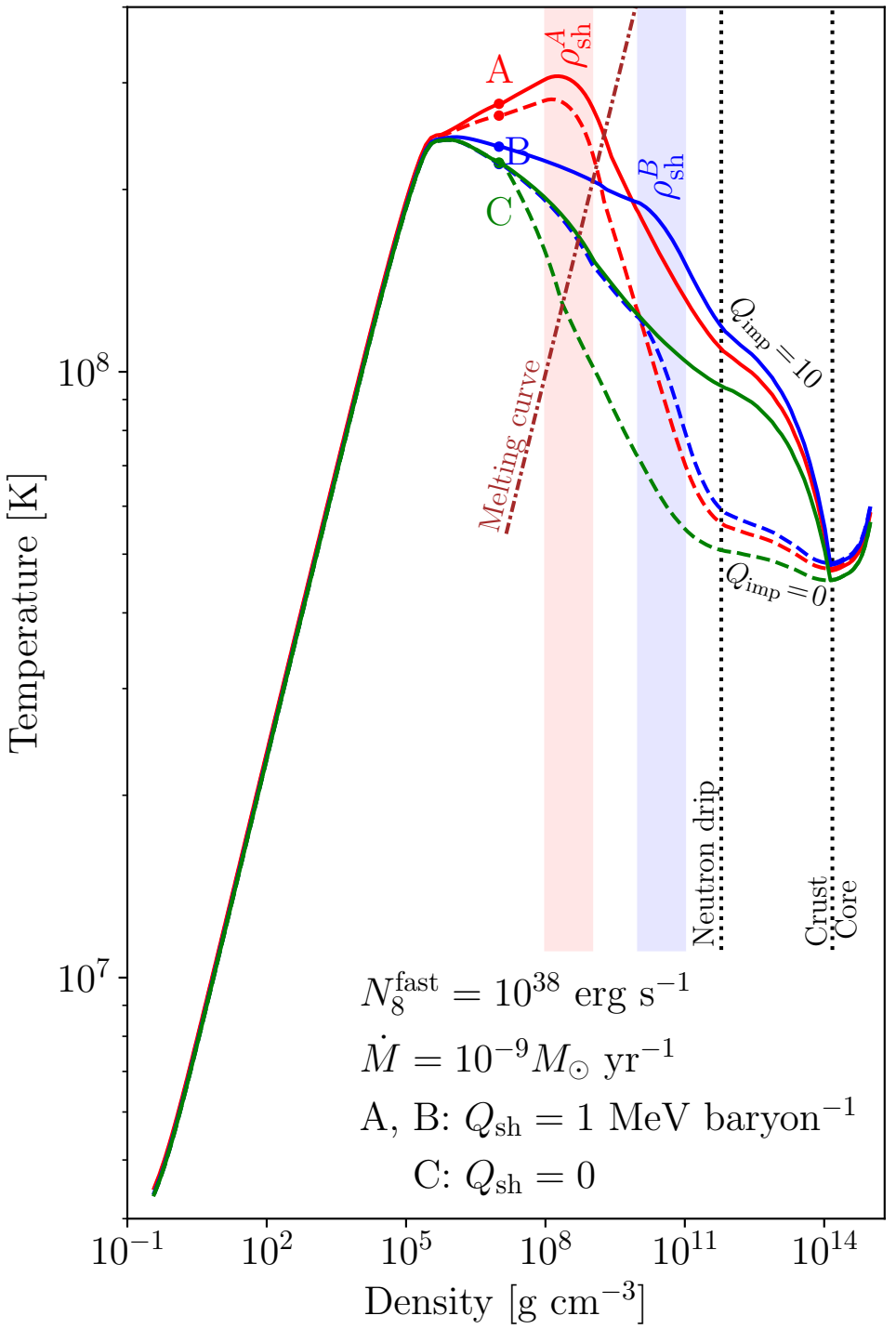
- Additional *shallow heating* amount at different locations: $Q_{\rm sh}$ @ $\rho_{\rm sh}$

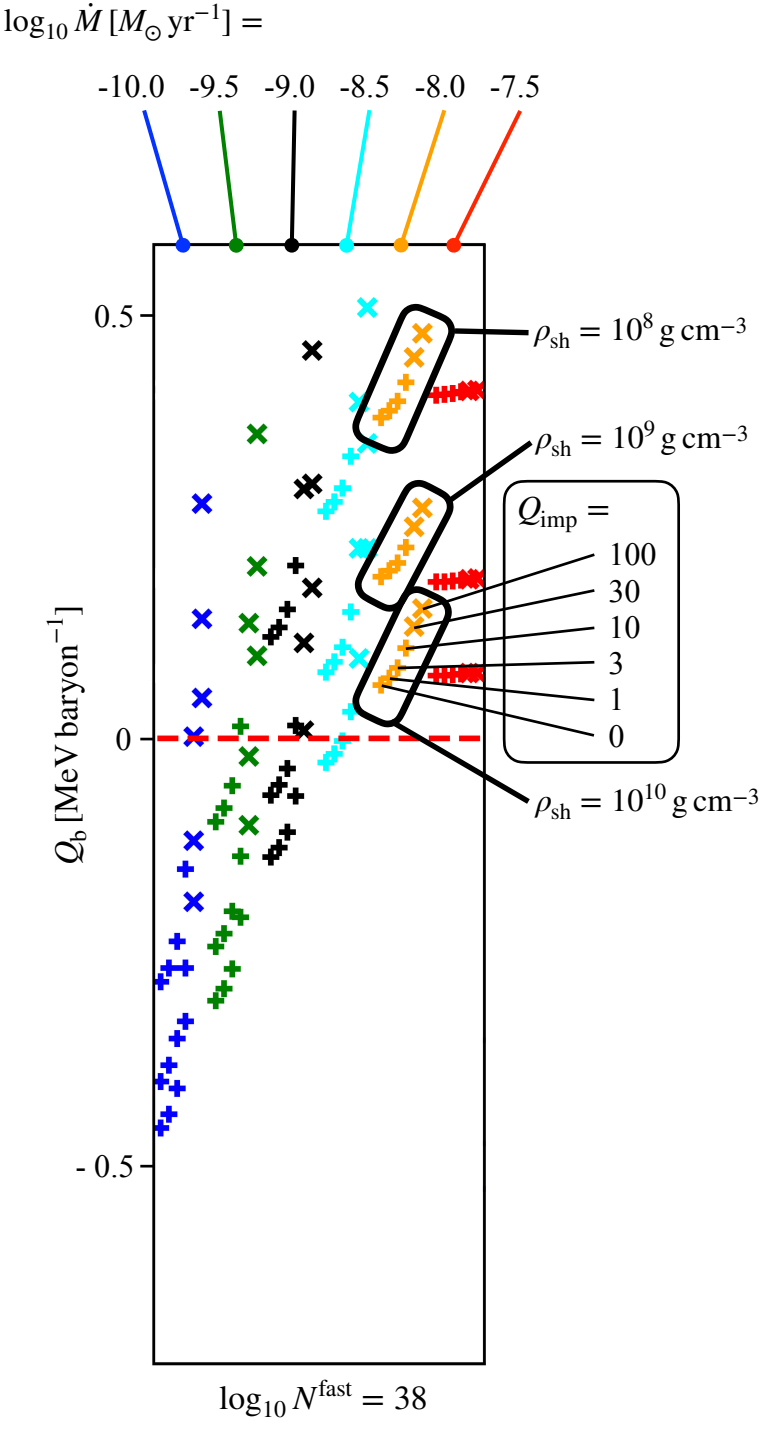
- Fiducial neutrino cooling mechanism at core: $L_\nu = N_{s/f}(T/10^8\,{\rm K})^{p_{s/f}}$

$N_s \in [10^{31},10^{35}]\,{\rm erg\ s^{-1}}$ & $p_s = 8$ (Slow)

$N_f \in (10^{35},10^{43}]\,{\rm erg\ s^{-1}}$ & $p_f = 6$ (Fast)




A
B
C
$\rho_{\rm sh}^A$
$\rho_{\rm sh}^B$
$Q_{\rm imp} = 10$
$Q_{\rm imp} = 0$
Melting curve
Neutron drip
Crust
Core
10^8
10^7
Temperature [K]
$N_8^{\rm fast} = 10^{38}$ erg s^{-1}
$\dot{M} = 10^{-9} M_\odot$ yr^{-1}
A, B: $Q_{\rm sh} = 1$ MeV baryon^{-1}
C: $Q_{\rm sh} = 0$
10^{-1}
10^2
10^5
10^8
10^{11}
10^{14}
Density [g cm^{-3}]


$\log_{10} \dot{M}\,[M_\odot\,{\rm yr}^{-1}]$ =
-10.0
-9.5
-9.0
-8.5
-8.0
-7.5
0.5
0
- 0.5
$Q_{\rm b}$ [MeV baryon^{-1}]
$\rho_{\rm sh} = 10^8$ g cm^{-3}
$\rho_{\rm sh} = 10^9$ g cm^{-3}
$\rho_{\rm sh} = 10^{10}$ g cm^{-3}
$Q_{\rm imp}$ =
100
30
10
3
1
0
$\log_{10} N^{\rm fast} = 38$

EPILOGUE

(Naturally)

Ongoing and future work

- Energy might flow **from the exterior to the interior** of the star

- Stationary states: $\dot{M} - T_b - L_b$ ~good approximation

– **Continuous accretion:** energy keeps flowing **inwards**

- **For tomorrow:** Dany will provide further details on the simulations

- **Work in progress/future:** study transient sources & include additional effects (Core EOS, superfluidity....)