



NEUTRON STAR ENVELOPES IN THE PRESENCE AND ABSENCE OF ACCRETION

MARTIN JAVIER NAVA CALLEJAS

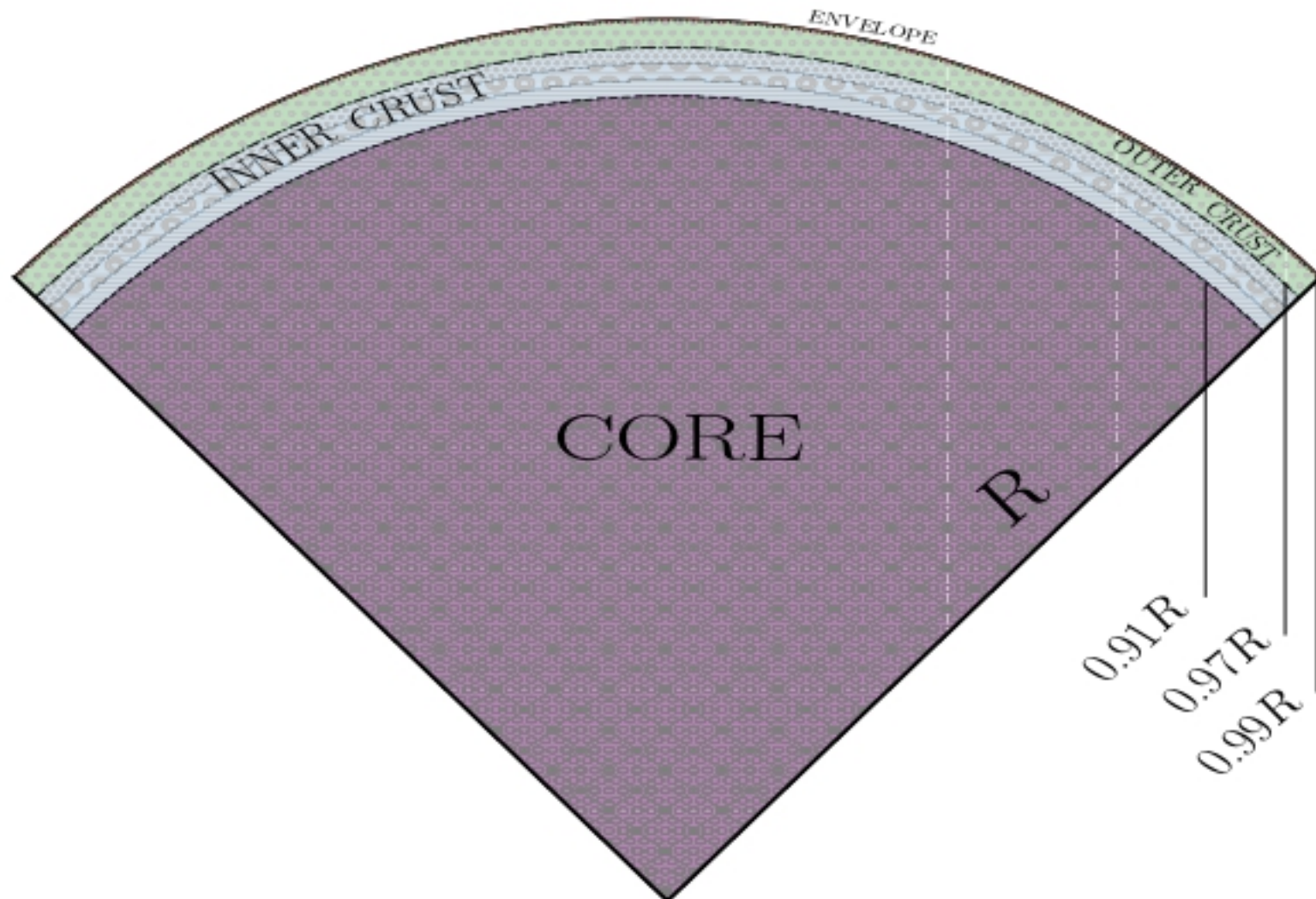
DTP/TALENT NUCLEAR PHYSICS 2024

JULY 18TH, 2024

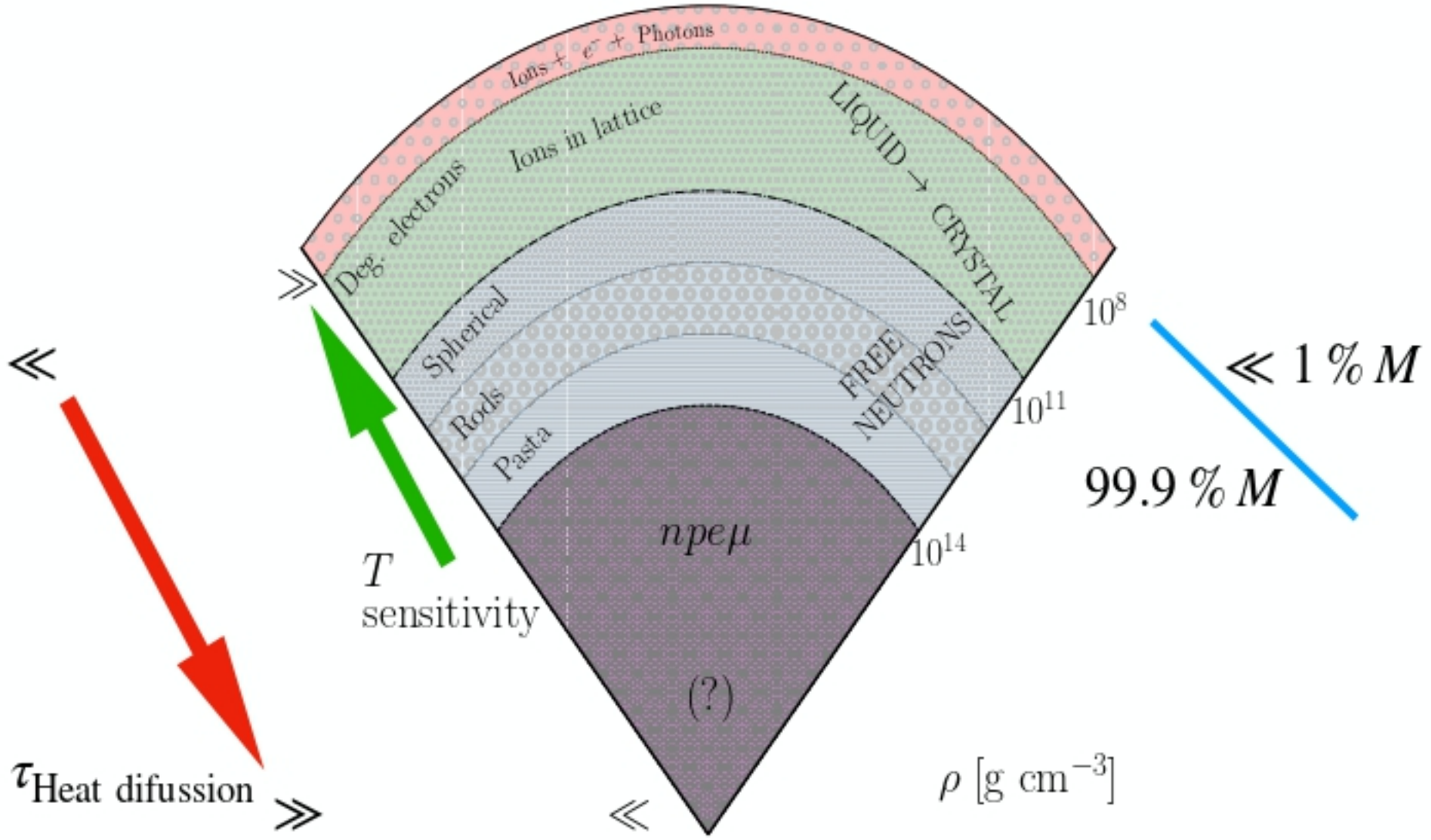
ENVELOPE...?



NEUTRON STAR ENVELOPE

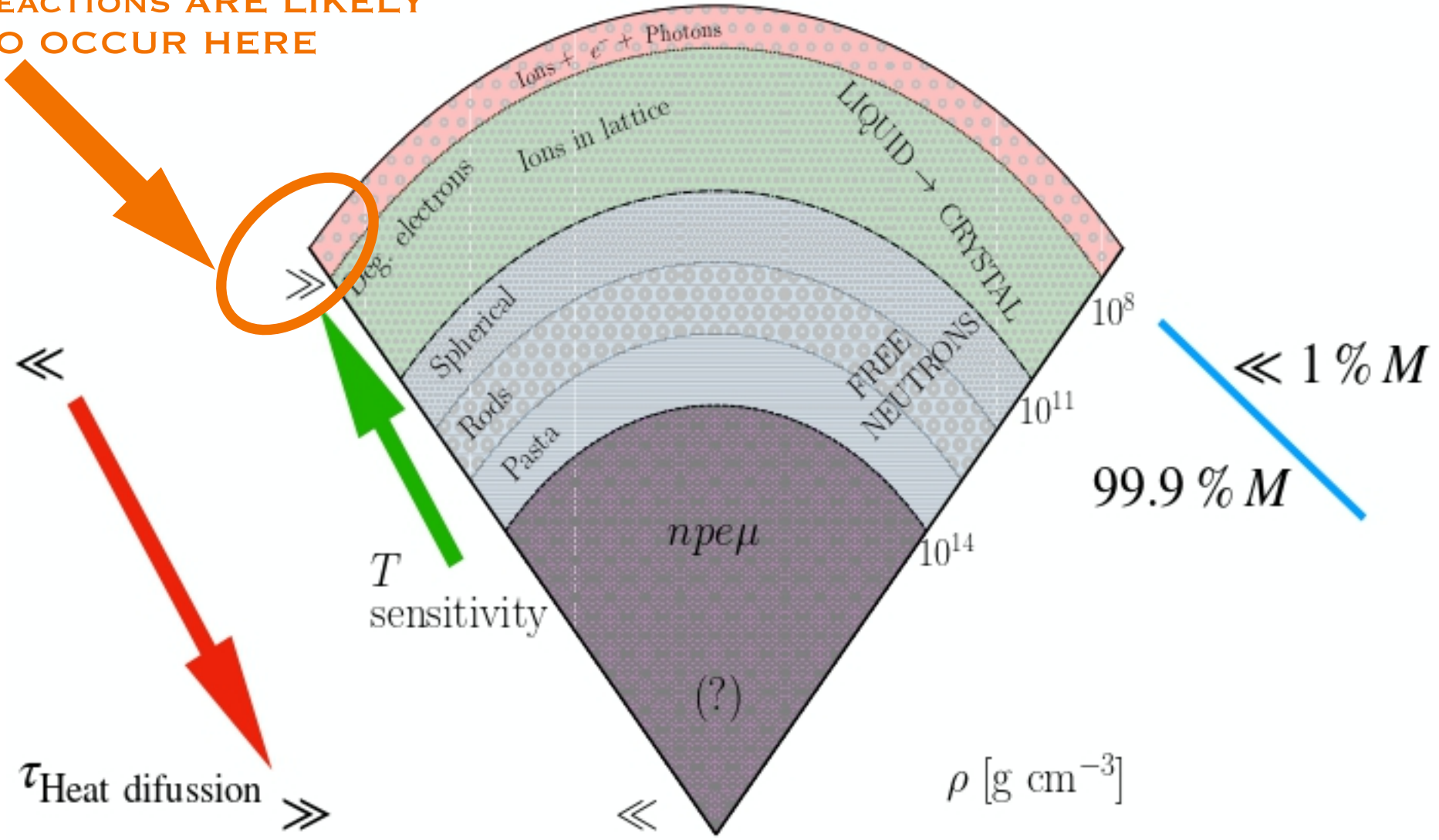


NEUTRON STAR ENVELOPE

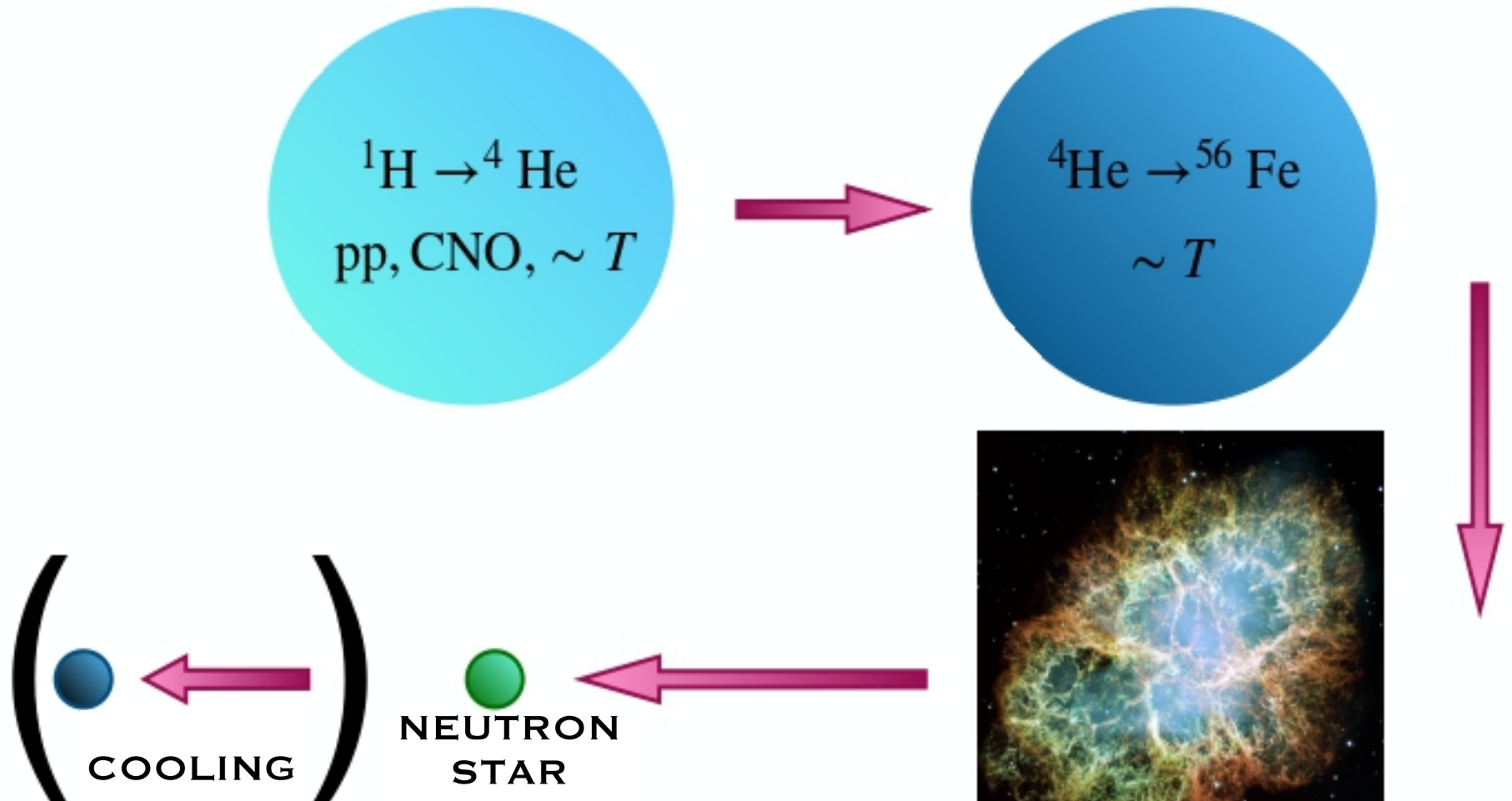


NEUTRON STAR ENVELOPE

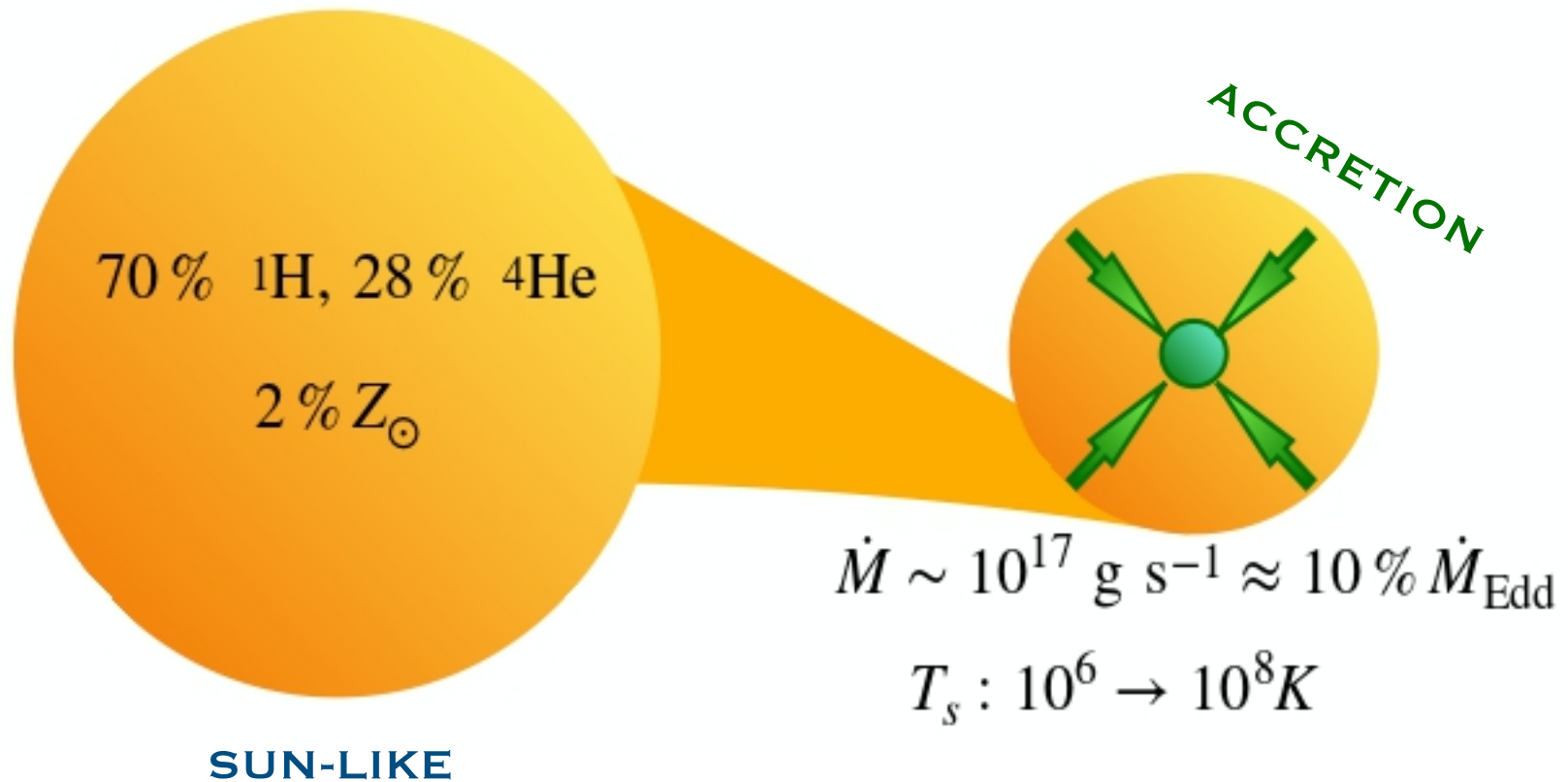
THERMONUCLEAR REACTIONS ARE LIKELY TO OCCUR HERE



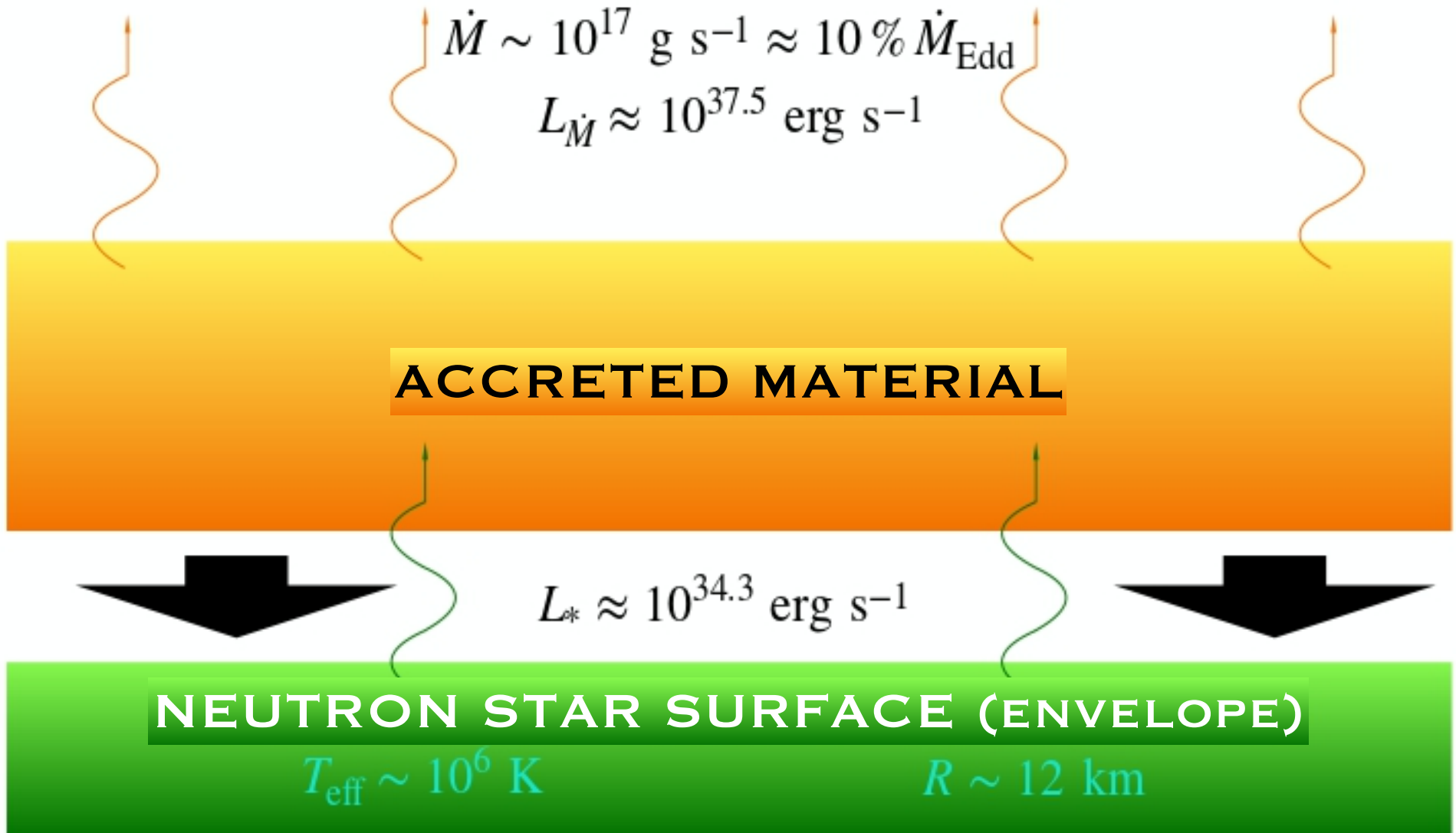
THERMO-NUCLEAR? (BUT WEREN'T NEUTRON STARS...)



ENTER: LOW-MASS X-RAY BINARY SYSTEMS



BUT, THEN...?



BUT, THEN...?

$$\dot{M} \sim 10^{17} \text{ g s}^{-1} \approx 10\% \dot{M}_{\text{Edd}}$$
$$L_{\dot{M}} \approx 10^{37.5} \text{ erg s}^{-1}$$

Surface is not visible during accretion!!

$$L_* \approx 10^{34.3} \text{ erg s}^{-1}$$

NEUTRON STAR SURFACE (ENVELOPE)

$$T_{\text{eff}} \sim 10^6 \text{ K}$$

$$R \sim 12 \text{ km}$$

BUT, THEN...?

$$\dot{M} \sim 10^{17} \text{ g s}^{-1} \approx 10\% \dot{M}_{\text{Edd}}$$
$$L_{\dot{M}} \approx 10^{37.5} \text{ erg s}^{-1}$$

Surface is not visible during accretion!!

$$L_* \approx 10^{34.3} \text{ erg s}^{-1}$$

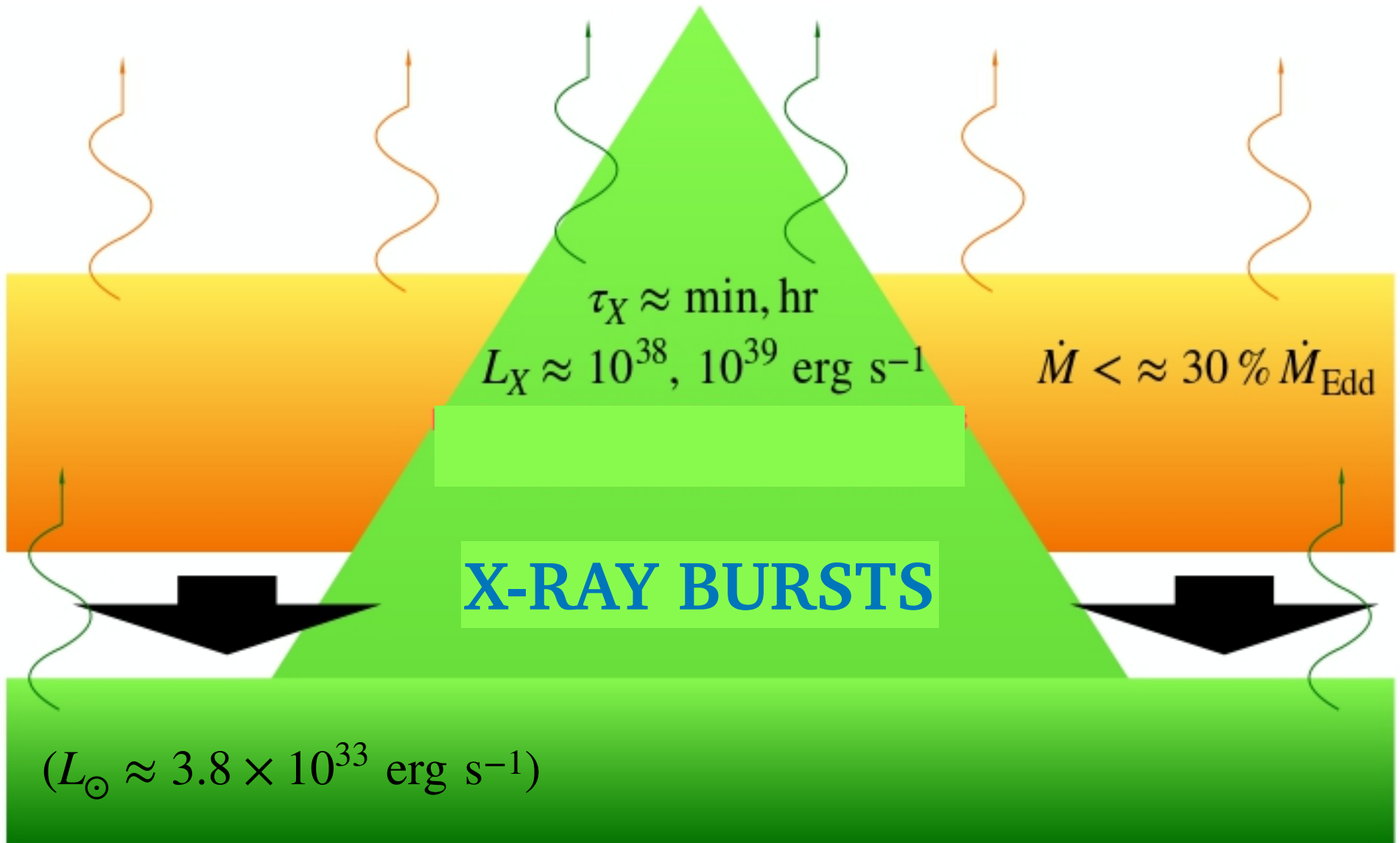
NEUTRON STAR SURFACE (ENVELOPE)

$$T_{\text{eff}} \sim 10^6 \text{ K}$$

$$R \sim 12 \text{ km}$$

(Until it partially is...)

...VIA THERMONUCLEAR EXPLOSIONS!



THEORY VS OBSERVATION

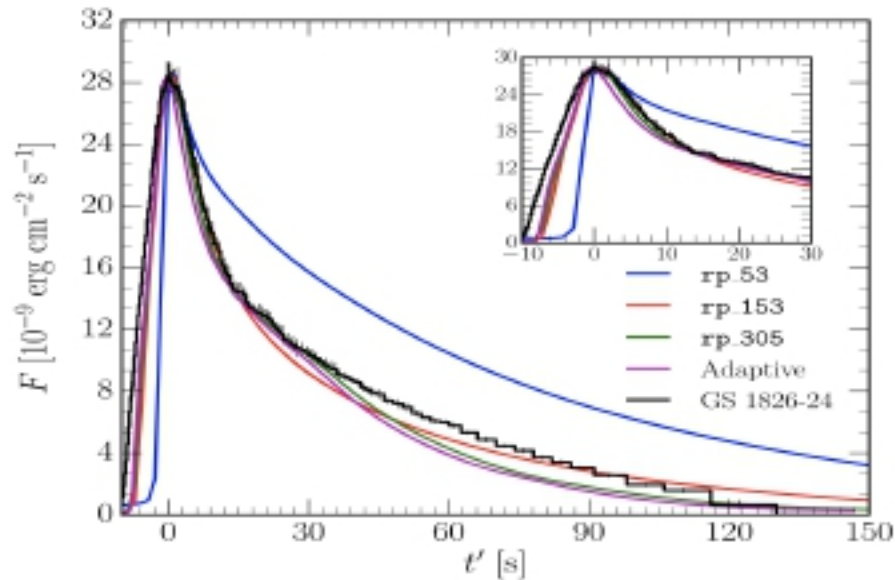


Figure: A typical X-ray burst over GS 1826–24 (black) against theoretical models employing **MESA**

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

Time-dependent codes such as **MESA*** are required!

RP IN A NUTCRACKER

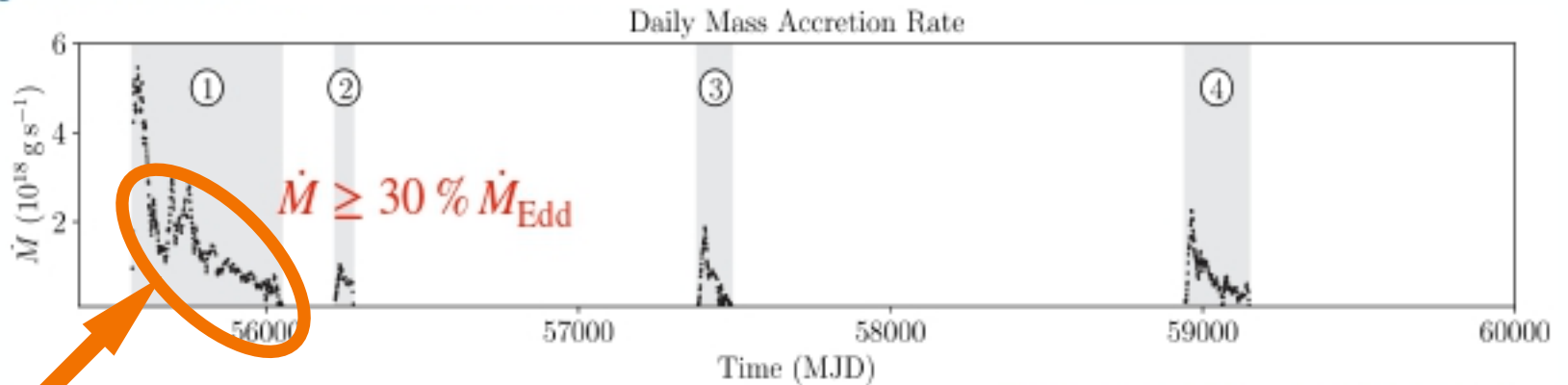


Figura: Créditos: Nutcracker Museum.

- Synthesis of ^{56}Fe , ^{60}Ni , ^{64}Zn , ^{70}Ge via **burning** of ^1H .
- $t_{\text{burning}}(^1\text{H}) \sim 10^3 \text{ s} \approx \mathbf{16 \text{ min.}}$
- **Extreme** conditions: $\rho \geq 10^5 \text{ g cm}^{-3}$, $T \geq 3 \times 10^8 \text{ K}$.
Sun's core: $\sim 10^2 \text{ g cm}^{-3}$ y
 $T \sim 10^7 \text{ K}$.

RP, RP EVERYWHERE

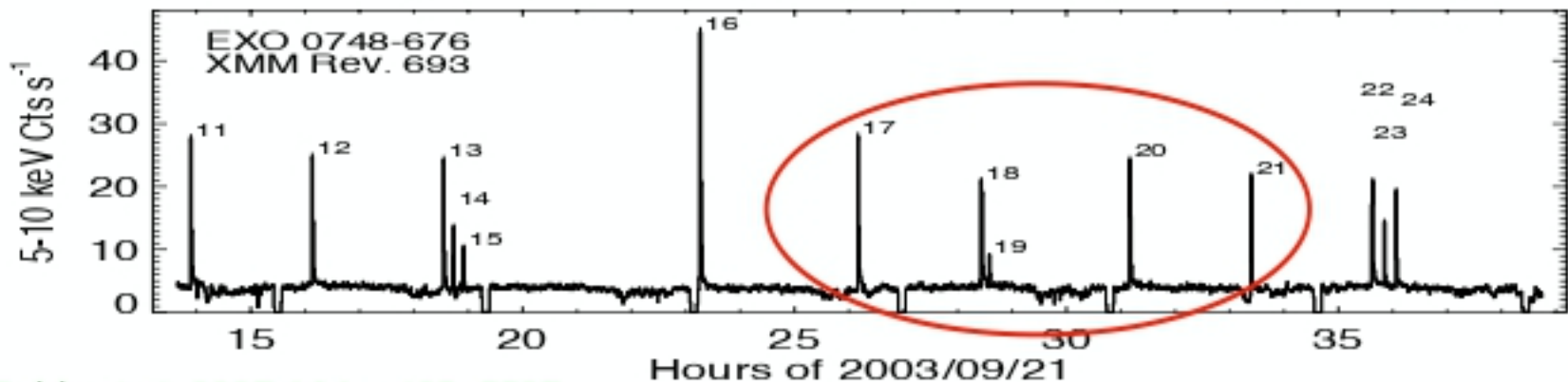
MAXI J0556-332: Transient accretion of months



Page et al 2022, ApJ 933, 216

(YES, EVEN HERE!)

EXO 0748-676: Accretion and X-ray bursts



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

ORIGINAL COMPOSITION

\dot{M}



70% ${}^1\text{H}$, 28% ${}^4\text{He}$, 2% Z_{\odot}

$\rho \sim 10^6 \text{ g cm}^{-3}$

${}^{12}\text{C}$, ${}^{24}\text{Mg}$, ${}^{40}\text{Ca}$
 ${}^{56}\text{Fe}$, ${}^{64}\text{Zn}$, ..., ${}^{104}\text{Cd}$?

rp-process

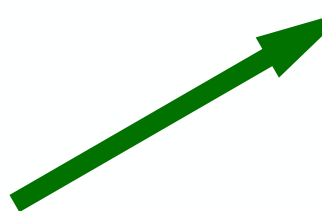


$\rho \sim 10^8 \text{ g cm}^{-3}$

${}^{20}\text{Ne} \rightarrow {}^{20}\text{O}$

${}^{56}\text{Fe} \rightarrow {}^{56}\text{Co} \rightarrow {}^{56}\text{Ti}$

Pycno-nuclear sector



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

MAIN CHALLENGE: NUCLEAR NETWORK OF REACTIONS

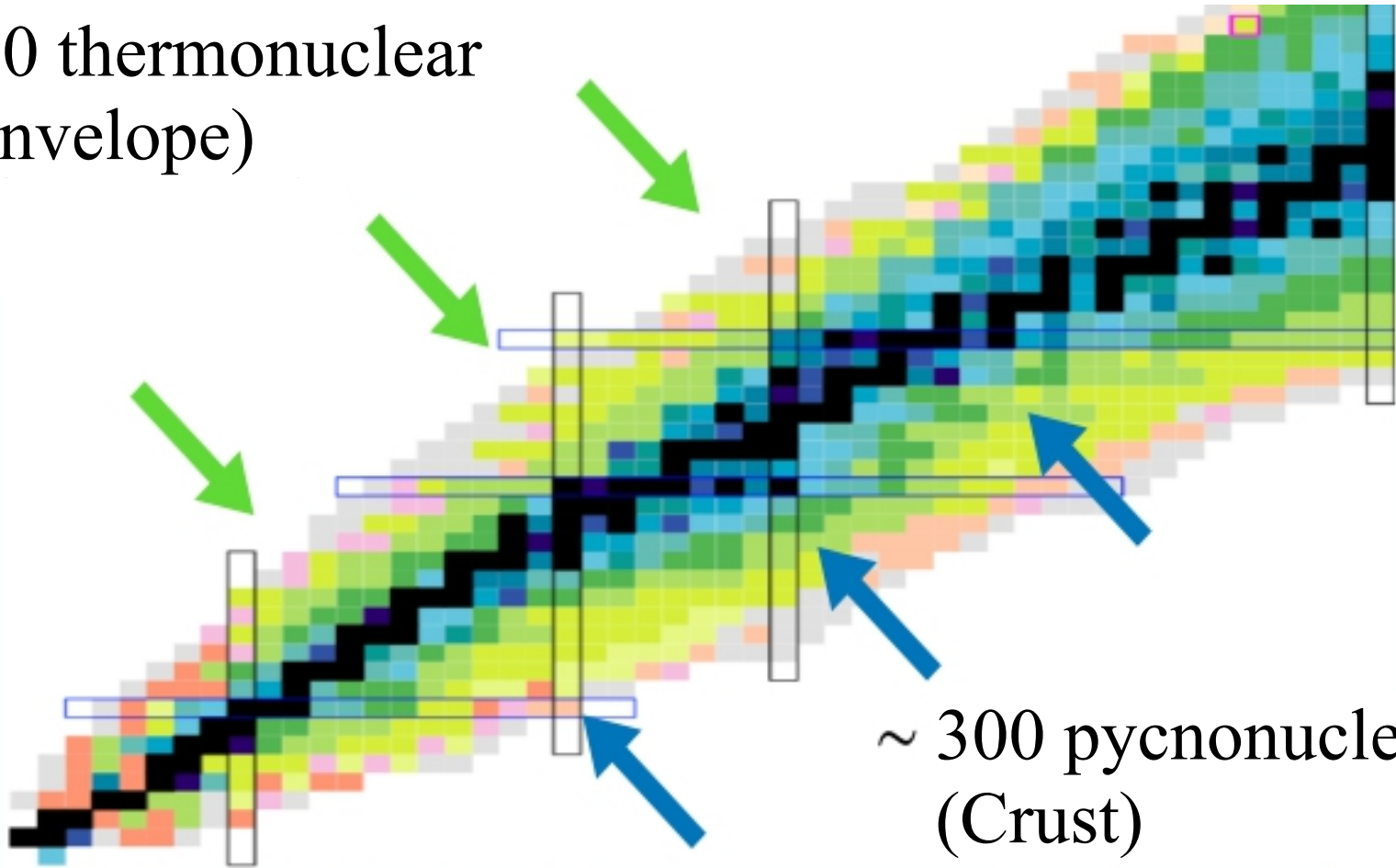


Figura: Cables conectados como analogía.

- Interacting arrays of bounded protons and neutrons
 $^{12}\text{C} + p \rightarrow ^{13}\text{N} + \gamma$, $3\alpha \rightarrow ^{12}\text{C}$.
- 1 array = 1 species
 ^{48}Fe , ^{49}Fe , ^{50}Fe , ..., ^{58}Fe .
- **1 species = 1 partial differential equation for its mass fraction**

How many species do we actually need?

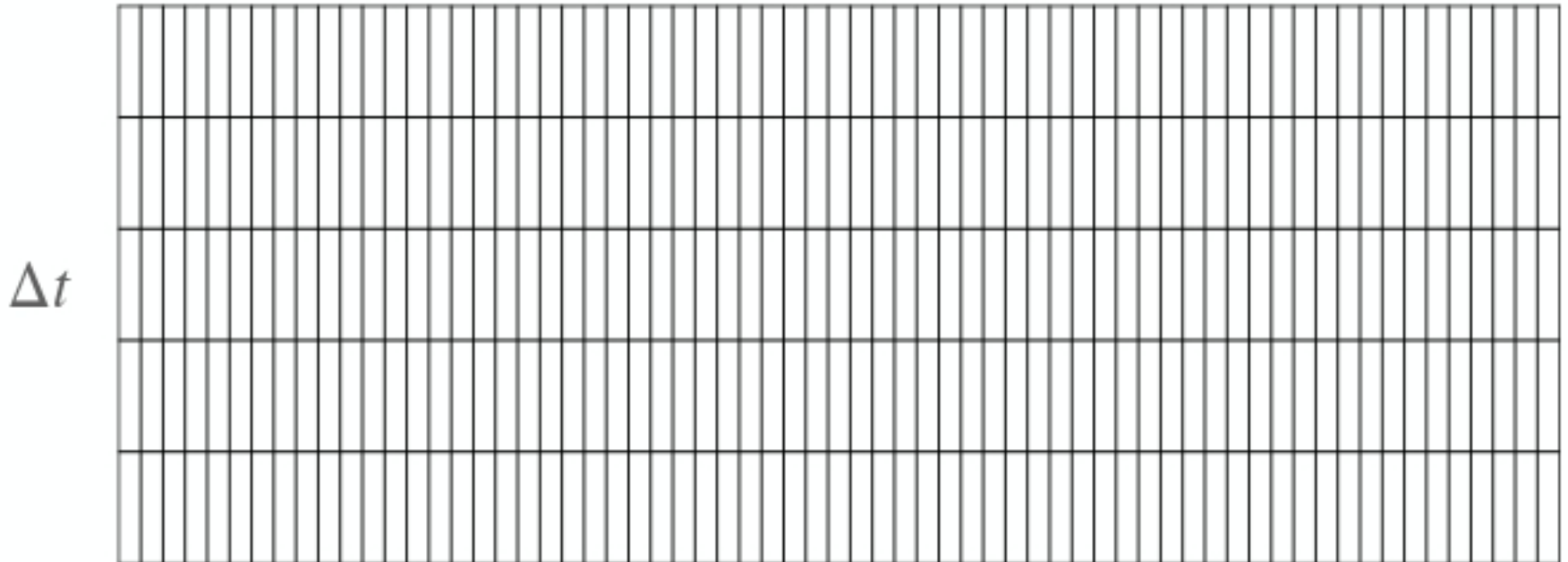
~ 300 thermonuclear
(Envelope)



~ 300 pycnonuclear
(Crust)

Only the envelope!

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



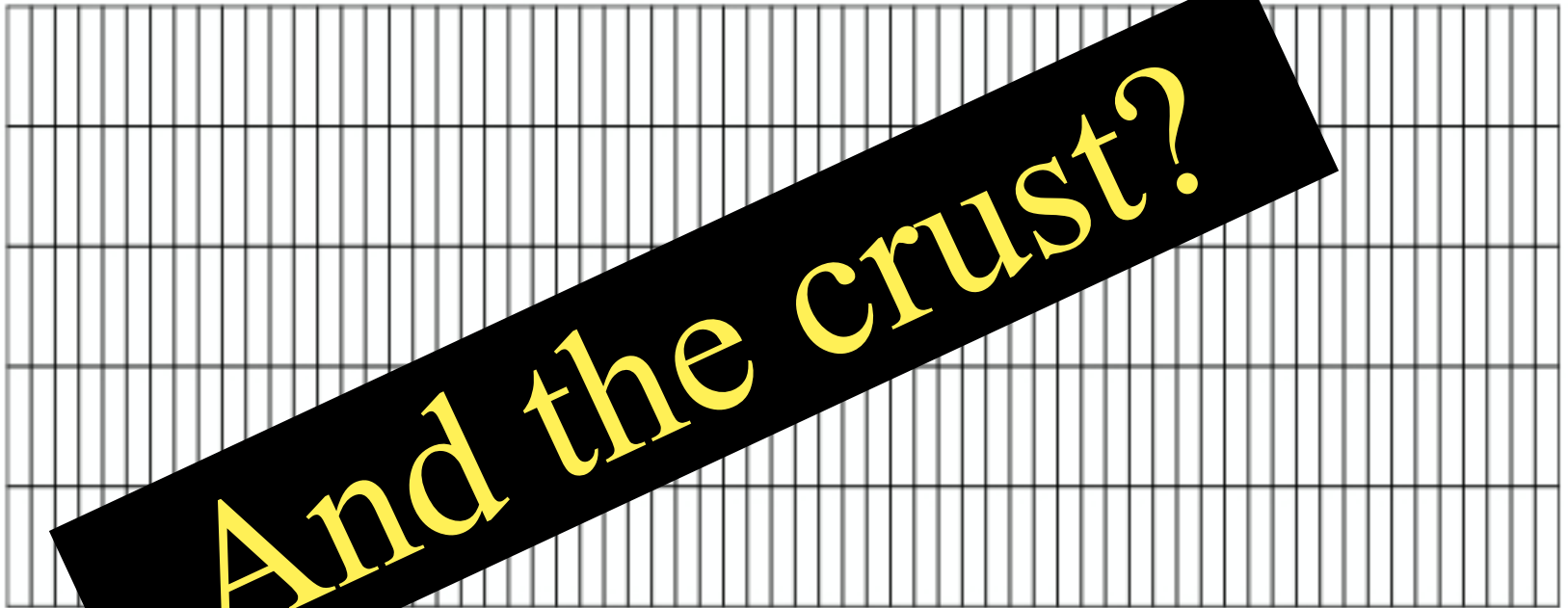
$$\Delta r, \Delta m : N_{\text{celdas}} \geq 300$$

$$N_{\text{celdas}} \times N_{\text{eqs}} \approx 300 \times 400 = 1.2 \times 10^5 \text{ eqs}$$

Only the envelope!

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

Δt



And the crust?

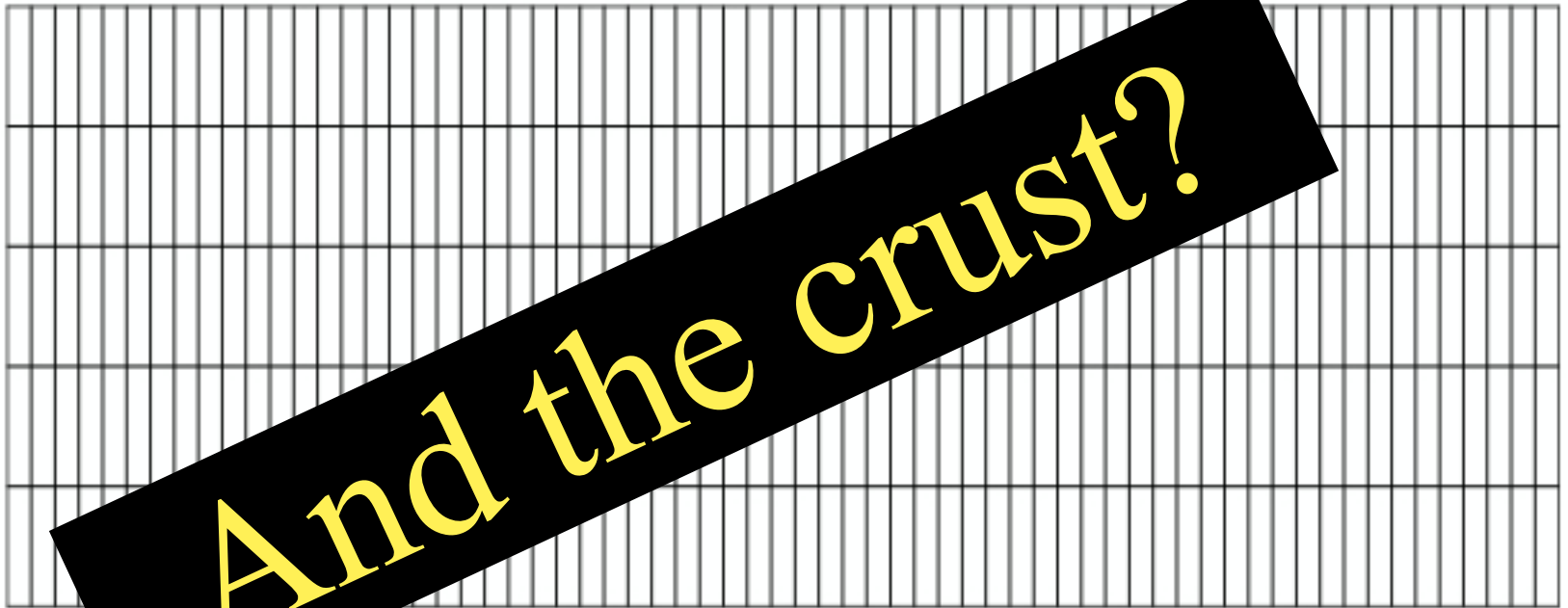
$$\Delta r, \Delta m : N_{\text{celdas}} \geq 300$$

$$N_{\text{celdas}} \times N_{\text{eqs}} \approx 300 \times 400 = 1.2 \times 10^5 \text{ eqs}$$

Only the envelope!

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

Δt



And the crust?

$\Delta r, \Delta m : N_{\text{celdas}} \geq 300$

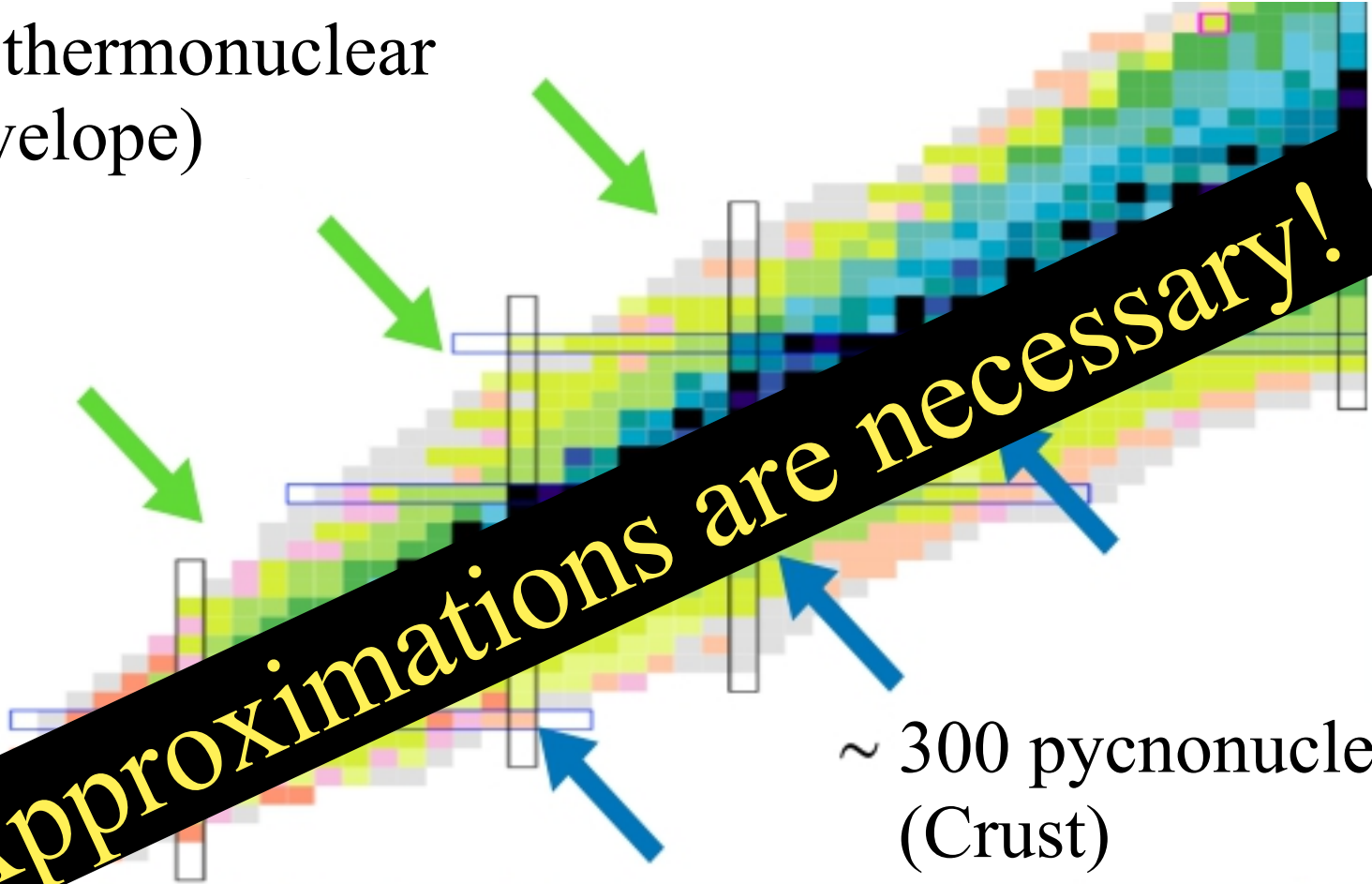
$N_{\text{celdas}} \times N_{\text{eqs}} \approx 300 \times 400 = 1.2 \times 10^5 \text{ eqs}$

And the core?

~ 300 thermonuclear
(Envelope)

Approximations are necessary!

~ 300 pycnonuclear
(Crust)



SURFACE VISIBLE AFTER ACCRETION!

XTE J1701-462: Transient accretion of months

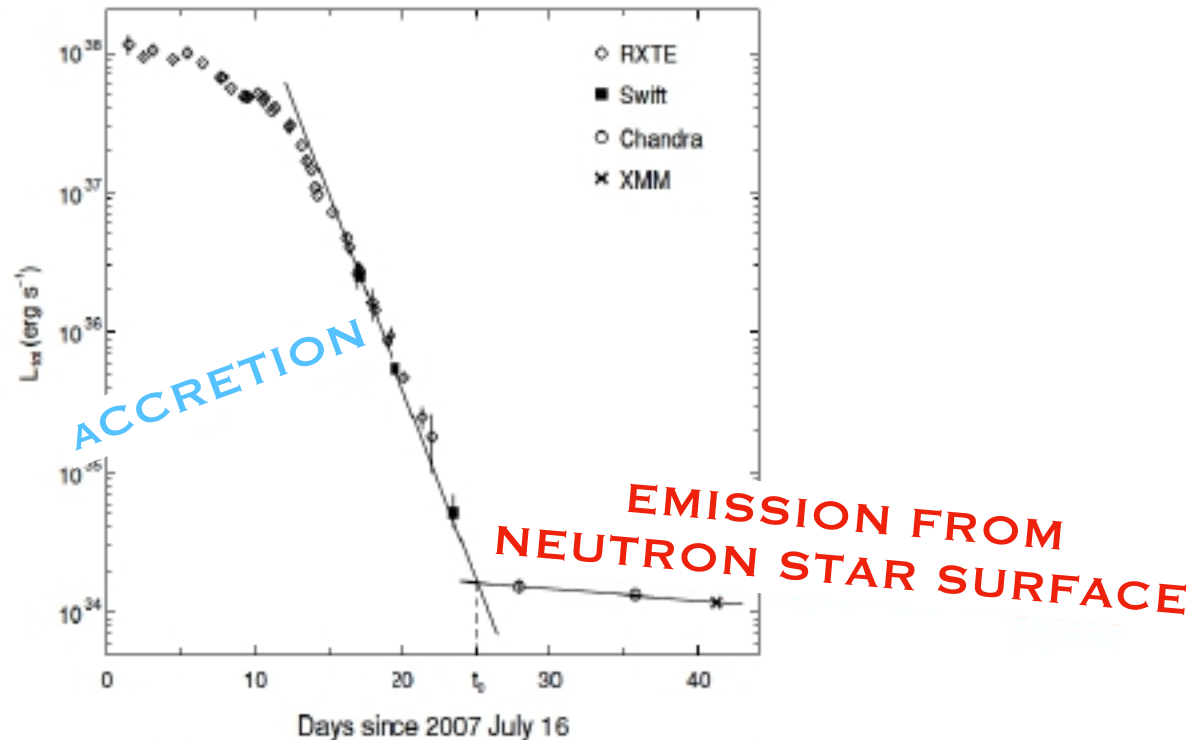


Figure 2. Total unabsorbed luminosity in the 0.5–10 keV band around the end of the outburst. The two lines are best-fit exponential decay curves for the three *Swift* observations, and the first three *Chandra* and *XMM-Newton* observations. The intersection of these curves defines the end time of the outburst, t_0 .

SURFACE VISIBLE AFTER ACCRETION!

XTE J1701-462: **Transient accretion of months**

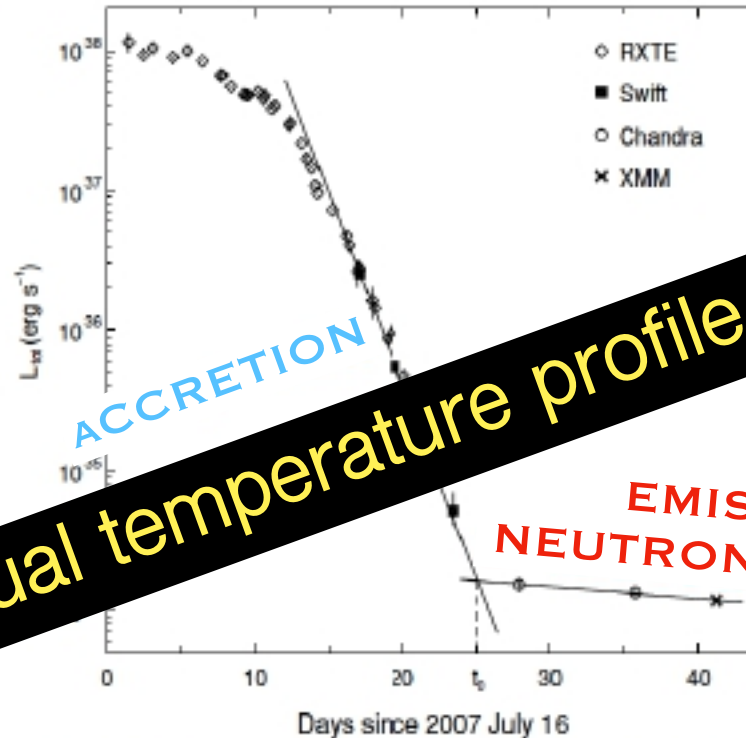


Figure 2. Total unabsorbed luminosity in the 0.5–10 keV band around the end of the outburst. The two lines are best-fit exponential decay curves for the three *Swift* observations, and the first three *Chandra* and *XMM-Newton* observations. The intersection of these curves defines the end time of the outburst, t_0 .

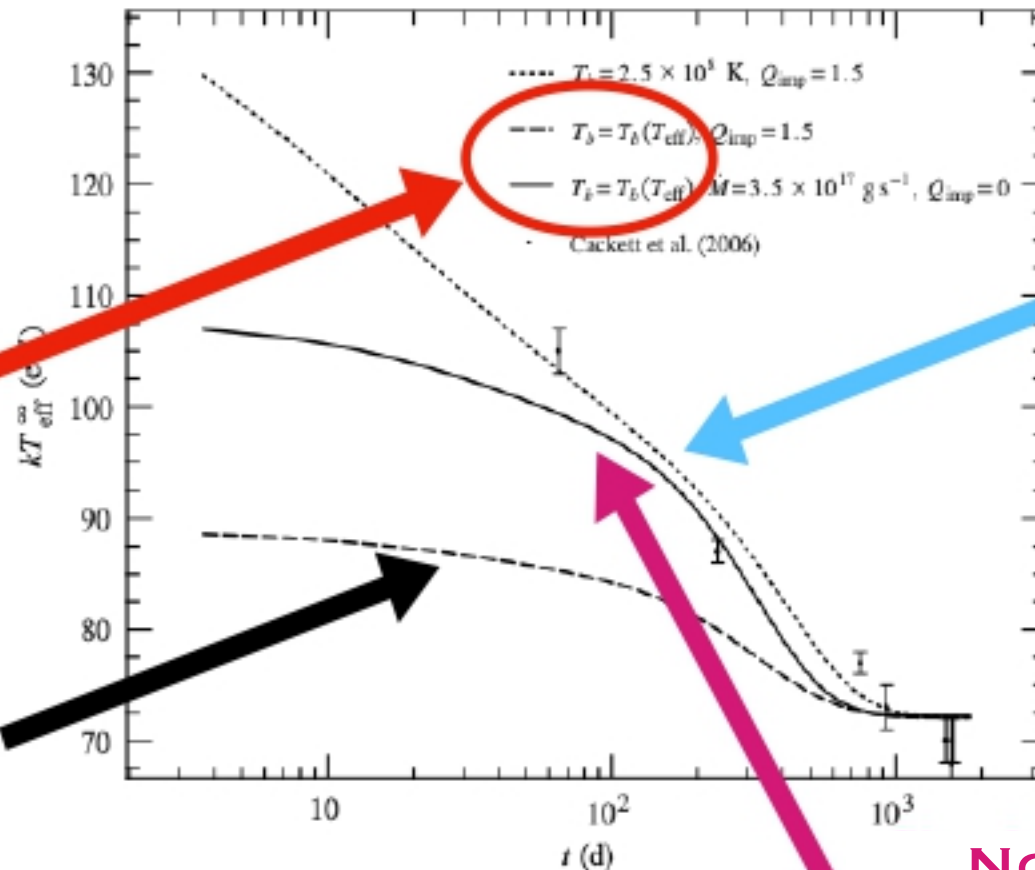
What is the actual temperature profile after accretion?

The *shallow heating* paradigm

STATIONARY
APPROXIMATION
FOR THE
ENVELOPE:

$$T_b(T_{\text{eff}})$$

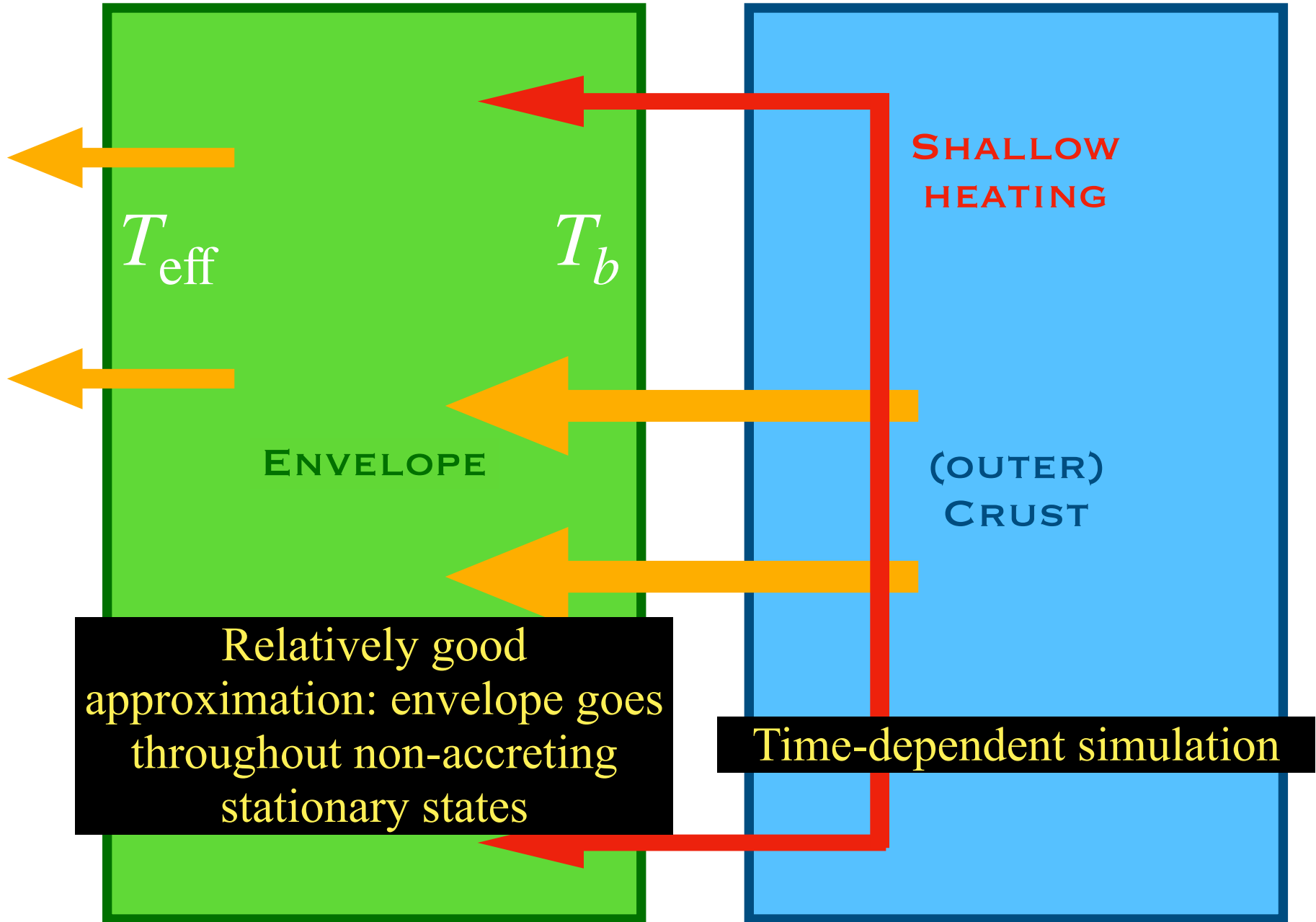
WITHOUT
SHALLOW
HEATING



WITH
SHALLOW
HEATING

NO SHALLOW
HEATING BUT
DIFFERENT
ACCRETION RATE

Is there something missing?



Do we need to check the envelope again?

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

Dany Page¹, Jeroen Homan², Martín Nava-Callejas¹, Yuri Cavecchi¹, Mikhail V. Beznogov^{1,3}, Nathalie Degenaar⁴, Rudy Wijnands⁴, and Aastha S. Parikh⁴

¹Instituto de Astronomía, Universidad Nacional Autónoma de México, Ciudad de México, CDMX 04510, Mexico; page@astro.unam.mx, ycavecchi@astro.unam.mx, mnava@astro.unam.mx

²Eureka Scientific, Inc., 2452 Delmer Street, Oakland, CA 94602, USA; jeroenhoman@icloud.com

³National Institute for Physics and Nuclear Engineering (IFIN-HH), RO-077125 Bucharest, Romania; mikhail.beznogov@nipne.ro

⁴Anton Pannekoek Institute for Astronomy, University of Amsterdam, Postbus 94249, 1090 GE Amsterdam, The Netherlands; degenaar@uva.nl, r.a.d.wijnands@uva.nl

Received 2022 February 8; revised 2022 May 4; accepted 2022 May 20; published 2022 July 15

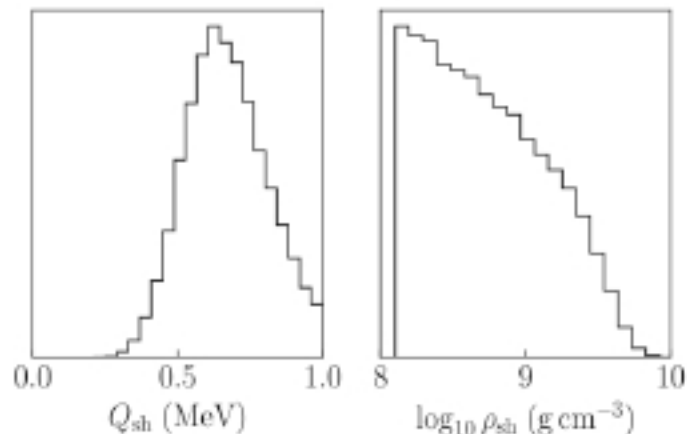


Figure 9. Histograms of the distribution of the shallow heating strength, Q_{sh} , and lower density, ρ_{sh} , in scenario “C.”

MONTE-CARLO MARKOV CHAIN SIMULATIONS (MCMC): FIND THE “BEST” PARAMETERS TO ADJUST OBSERVATIONS

APPARENTLY, SHALLOW HEATING MIGHT COME FROM THE ENVELOPE

Do we need to check the envelope again?

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

Dany Page¹, Jeroen Homan², Martín Nava-Callejas¹, Yuri Cavecchi¹, Mikhail V. Beznogov^{1,3}, Nathalie Degenaar⁴, Rudy Wijnands⁴, and Aastha S. Parikh⁴

¹ Instituto de Astronomía, Universidad Nacional Autónoma de México, Ciudad de México, CDMX 04510, Mexico; page@astro.unam.mx, ycavecchi@astro.unam.mx, mnava@astro.unam.mx

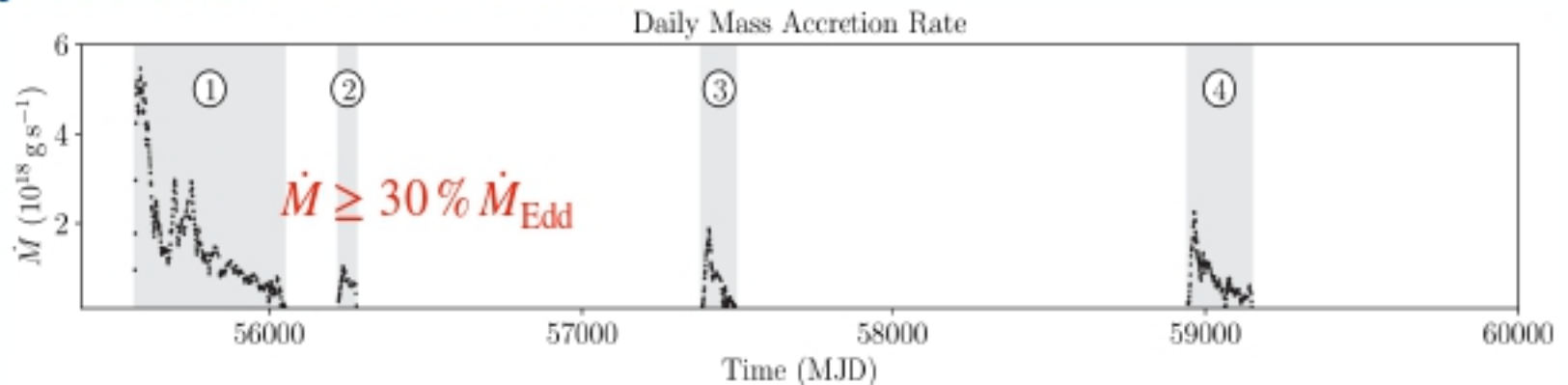
² Eureka Scientific, Inc., 2452 Delmer Street, Oakland, CA 94602, USA; jeroenhoman@icloud.com

³ National Institute for Physics and Nuclear Engineering (IFIN-HH), RO-077125 Bucharest, Romania; mikhail.beznogov@nipne.ro

⁴ Anton Pannekoek Institute for Astronomy, University of Amsterdam, Postbus 94249, 1090 GE Amsterdam, The Netherlands; degenaar@uva.nl, r.a.d.wijnands@uva.nl

Received 2022 February 8; revised 2022 May 4; accepted 2022 May 20; published 2022 July 15

MAXI J0556–332: Transient accretion of months



NO BURSTS:

$T_b(T_{\text{eff}})$ & $L_b(T_{\text{eff}})$?

Work in progress

1 **EXAMINE TIME-INDEPENDENT ENVELOPES AT HIGH ACCRETION RATES**

- ▶ CONSTRUCTION OF A NUMERICAL CODE WITH 380 SPECIES
- ▶ arXiv:2403.13994

2 **UNDERSTAND AND MODEL THERMONUCLEAR EXPLOSIONS**

- ▶ MESA - STELLAR EVOLUTION CODE
- ▶ OWN'S CODE OUTPUT AS INITIAL CONDITIONS
- ▶ DO ENVELOPES WITH NEGATIVE LUMINOSITY AT BASE MAKE SENSE?

Stationary accreted neutron star envelopes 7

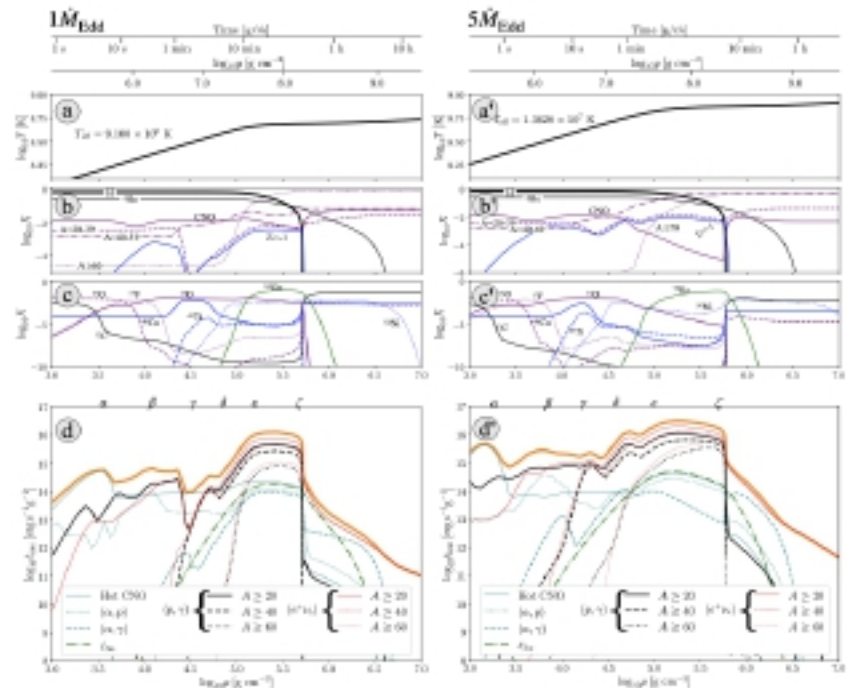


Figure 8. Envelope models at $\dot{M} = 3\dot{M}_{\text{Edd}}$ (left panels) and $5\dot{M}_{\text{Edd}}$ (right panels) as a function of μ and the upper part indicates the corresponding column depth y and time spent by the accreted matter since it started its journey from the neutron star surface. Panels (a) and (a'): temperature; panels (b) and (b'): mass fraction of selected light nuclei; panels (c) and (c'): mass fraction of selected heavy nuclei; panels (d) and (d'): specific energy generation of dominant processes, as indicated, and with the upper thick line showing the total energy generation. Greek label at the top of panel (d) and (d') indicate specific positions of events discussed in the text.

(β, γ) and $(\beta^+ \nu_e)$ contributions from $A \geq 20$ amounts for ~ 3.27 and ~ 3.74 MeV per nucleon respectively, i.e. the luminosity from nuclear reactions is ≈ 6 MeV per nucleon, similar to what is usually obtained via CNO burning at lower accretion rates. The scenario is slightly different at $5\dot{M}_{\text{Edd}}$: for the same individual contributions, we now have ~ 2.21 and ~ 4.02 respectively, i.e. weak decays are slightly more energetic since we have more metal abundances at $5\dot{M}_{\text{Edd}}$ than at $3\dot{M}_{\text{Edd}}$ (e.g. Fig. 1). However, the net released energy is still ≈ 6 MeV per nucleon.

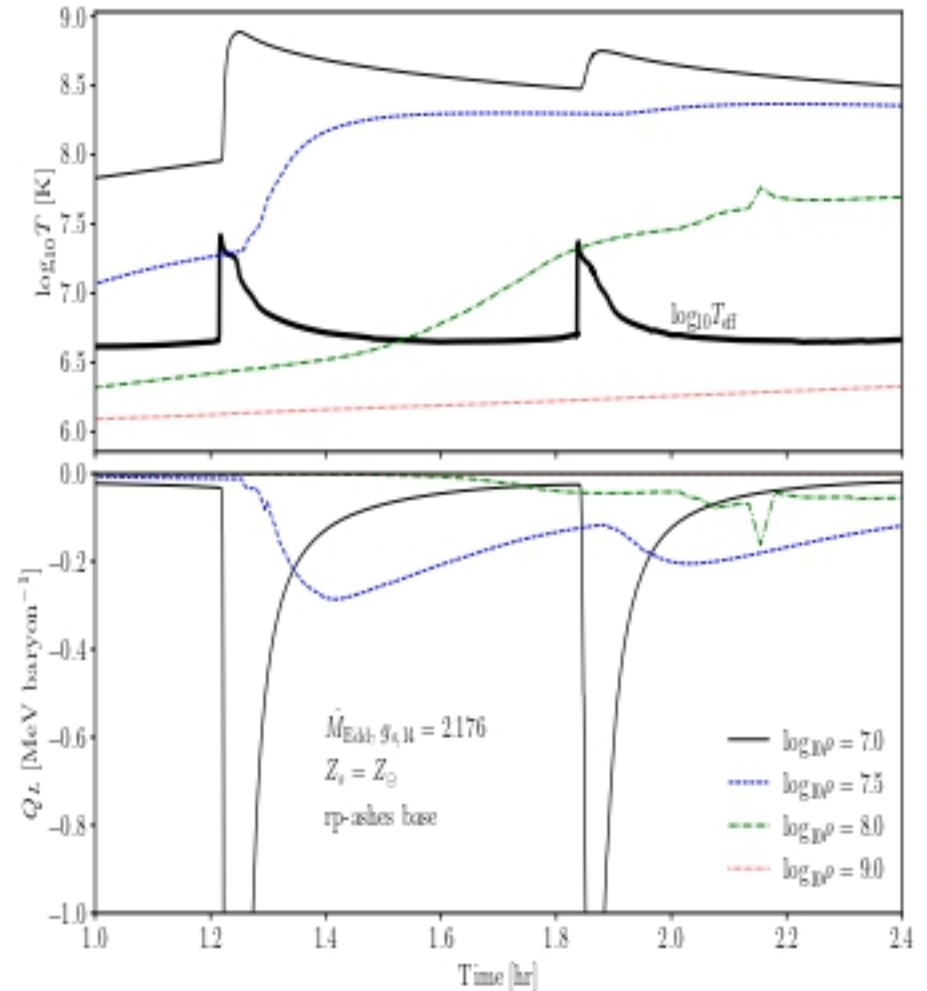
4.2 Variations on the accreted amount of H

The comparison of models at \dot{M}_{Edd} carried out on Fig. 4 confirms that hydrogen and helium abundances set the critical ingredients in the synthesis of $A > 40$ metals via the rp process. In order to explore the actual impact of the mass fractions of ^1H and ^4He in the accreted matter composition, we performed a series of simulations varying the individual mass fractions of H and He, X_{H} and X_{He} , respectively, while retaining their sum $X_{\text{H}} + X_{\text{He}}$ constant and equal to its value at Solar composition, i.e. ≈ 0.99 . For all models, we employed the same Z, N as in Subsection 4.1 but, instead of fixing T_{E5} , we required all our models to have the same T_{E5} in order to have a fair comparison on the thermonuclear reaction rates.

Work in progress

ENERGY TOWARDS THE INTERIOR OF THE STAR?

- THERE ARE STATIONARY STATES WITH THIS CONDITION
- MESA: THEY ARE VIABLE
- COULD THEY BE RELATED TO THE SHALLOW HEATING PARADIGM?



FINAL REFLECTIONS



Figura: *“La libertad, Sancho, es uno de los más preciosos dones [...] con ella no pueden igualarse los tesoros que encierra la tierra[...].”* - Miguel de Cervantes Saavedra

Figura: ardevaaS setnavreC ed leugiM -
“arreit al arreicne euq soroset sol esralaugi nedeup on alle noc [...] senod sosoicerp sàm sol ed onu se, ohcnaS, datrebil aL”