Neutron star envelopes in the presence and absence of accretion

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DTP/Talent Nuclear Physics 2024

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Envelope...?


TURIN
3
SELLOS
SECRETARÍA DE SALUD


Christ
Christm
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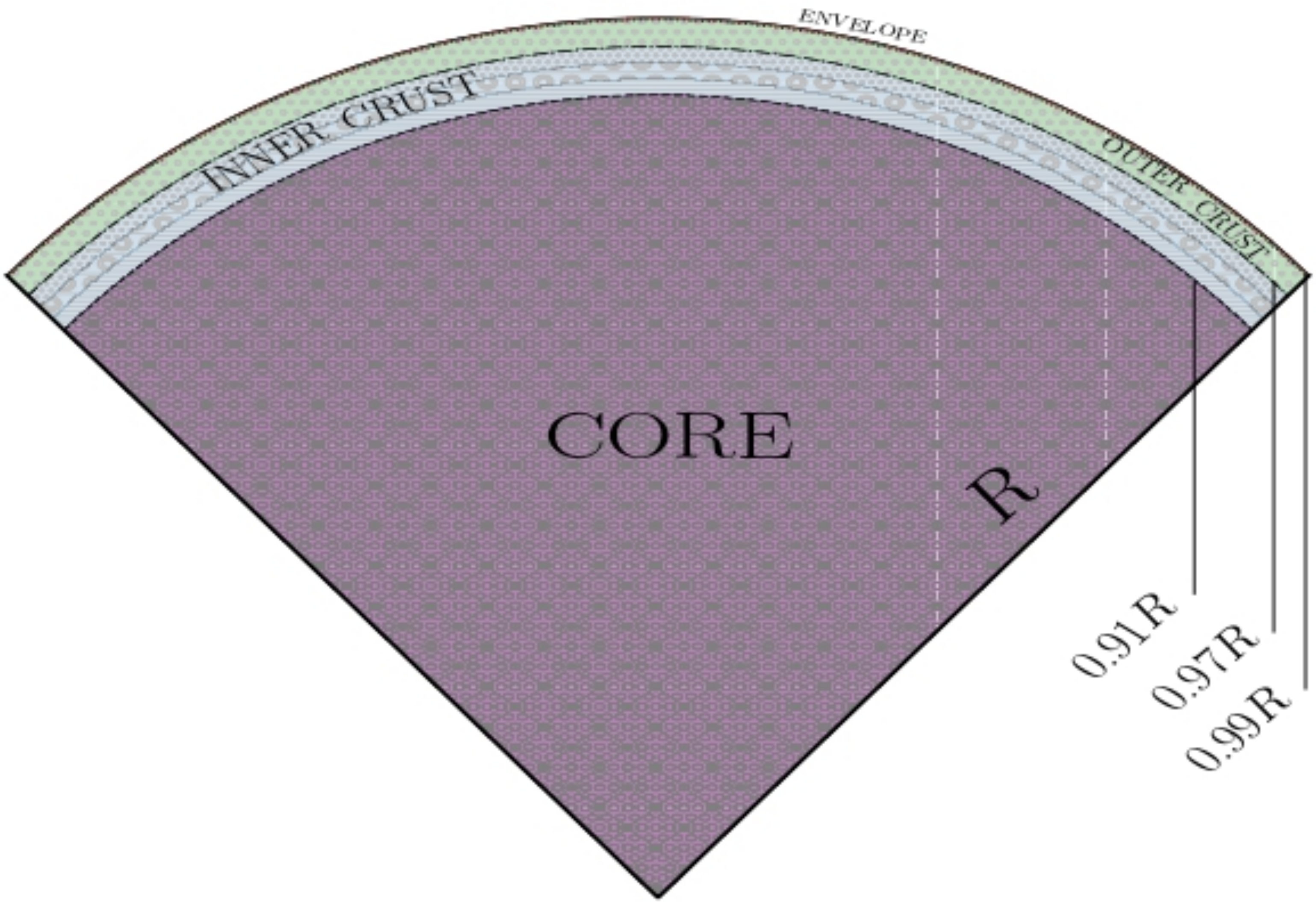
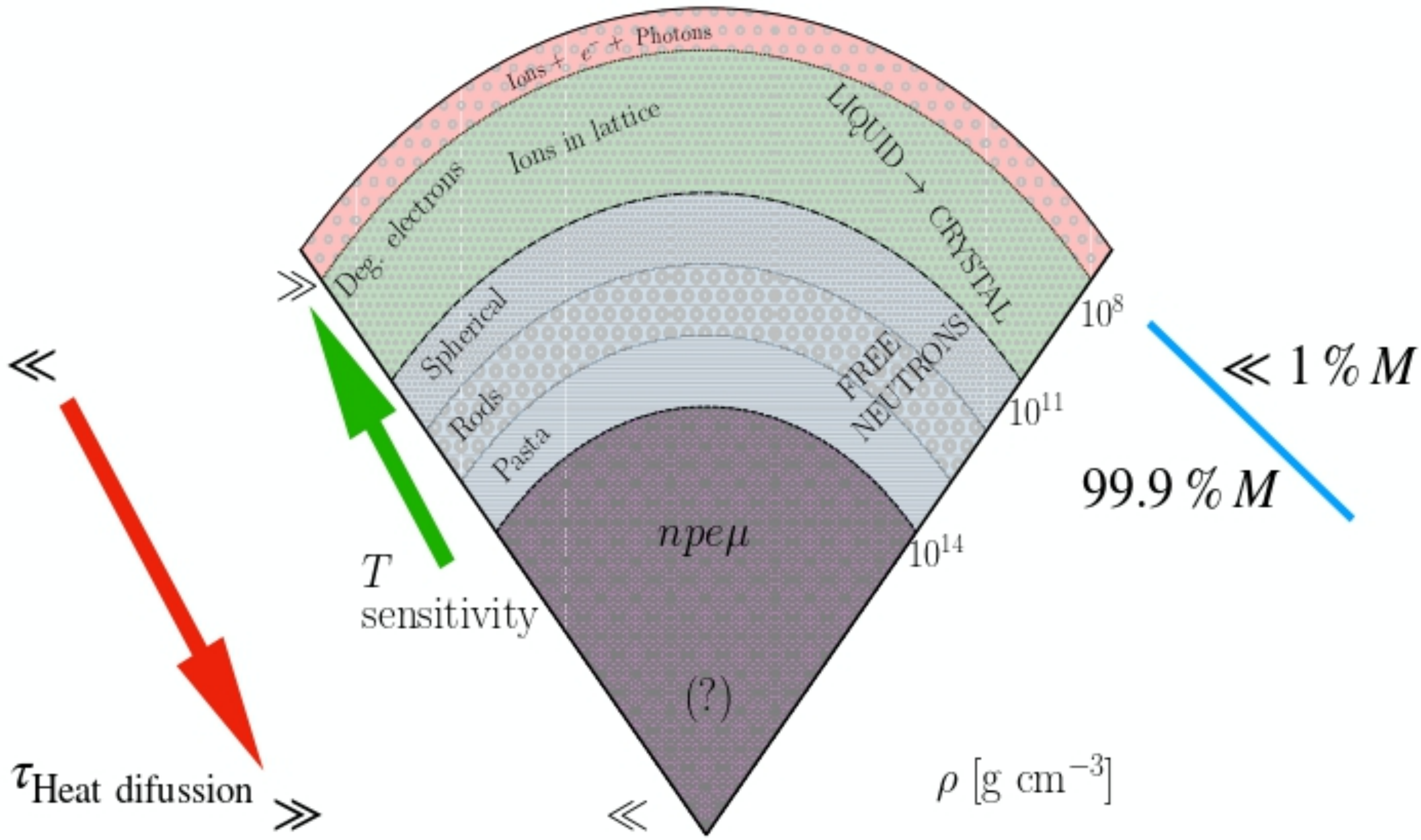
ristmas

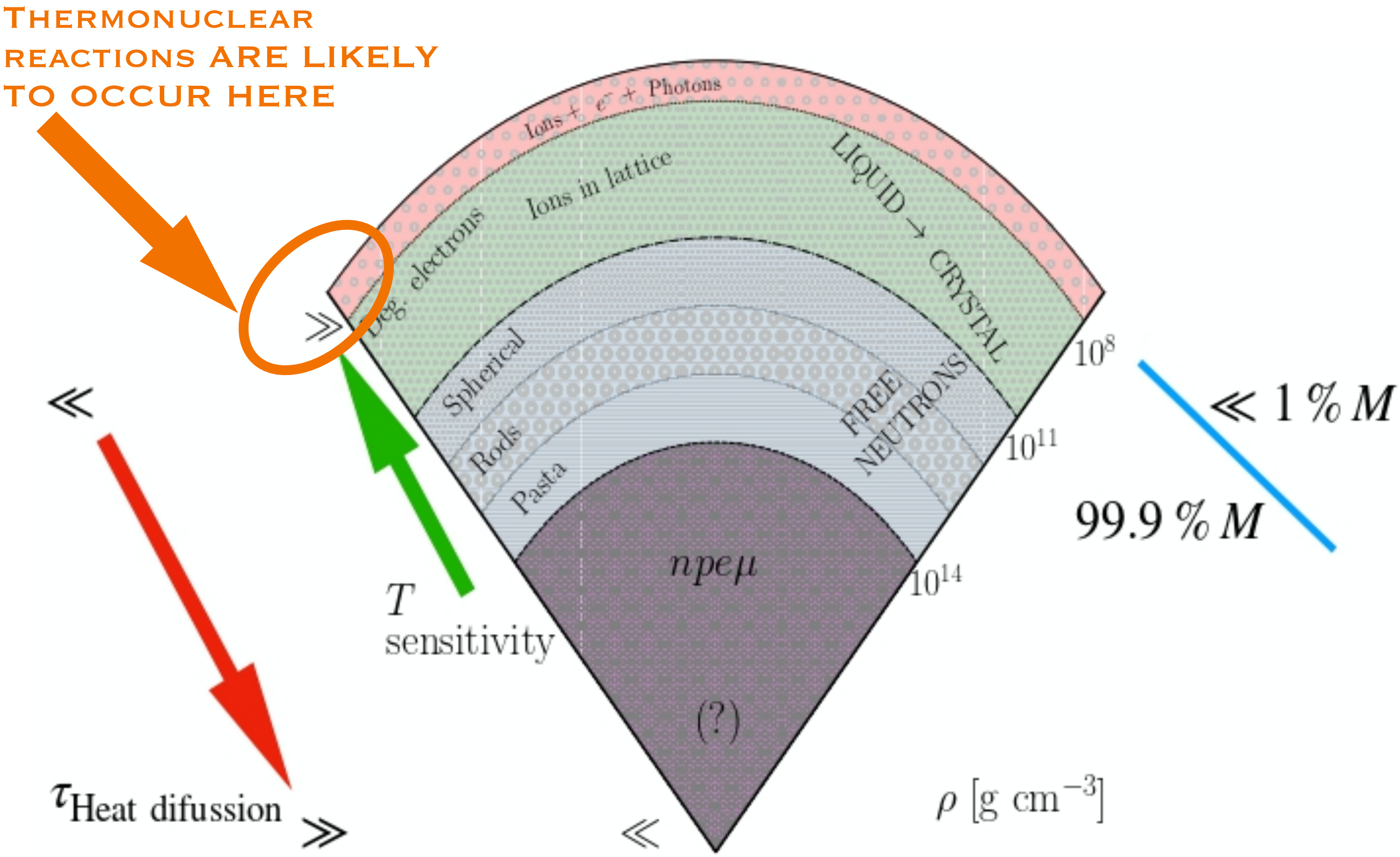
Neutron star envelope



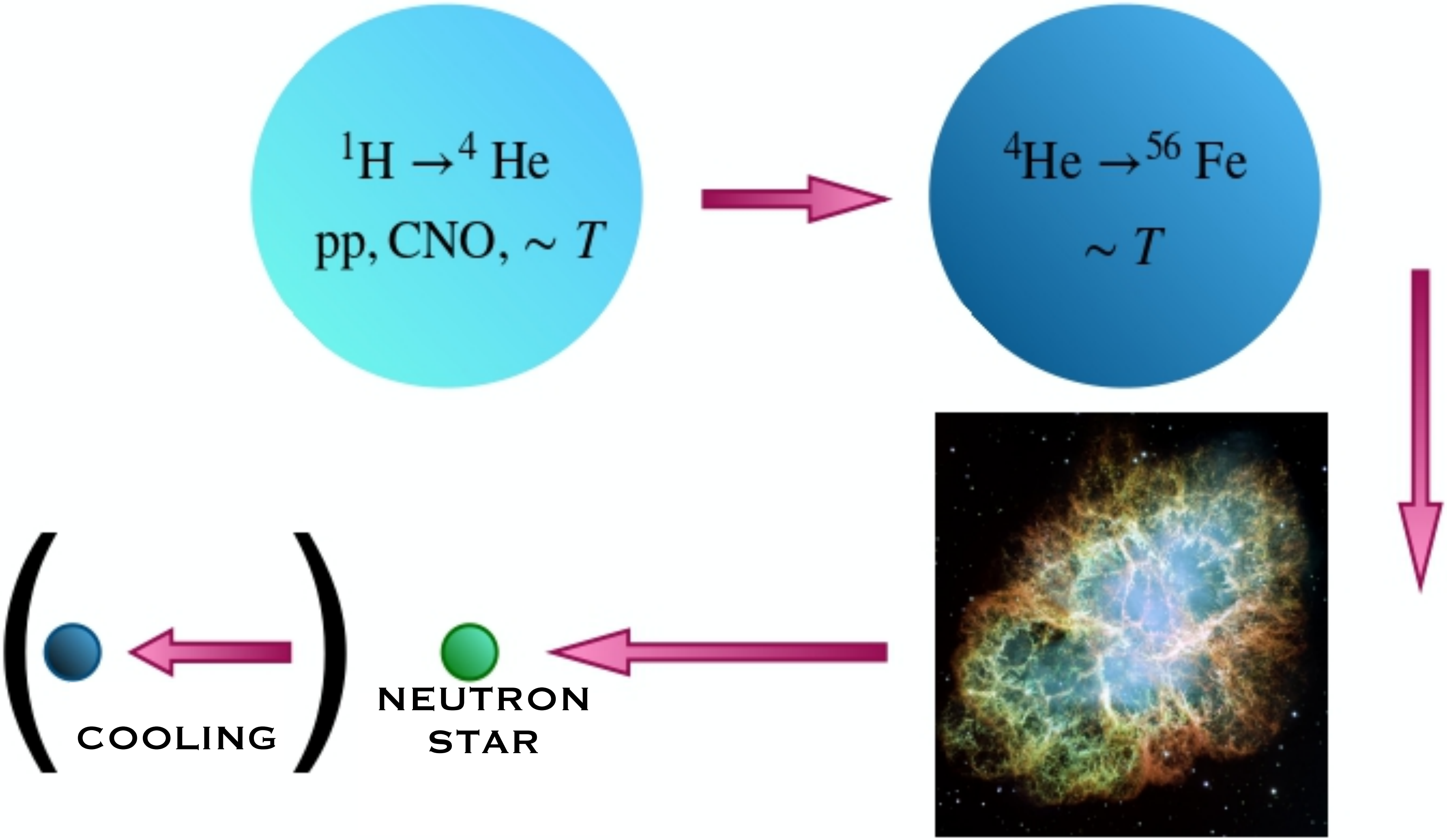
Neutron star envelope



Neutron star envelope

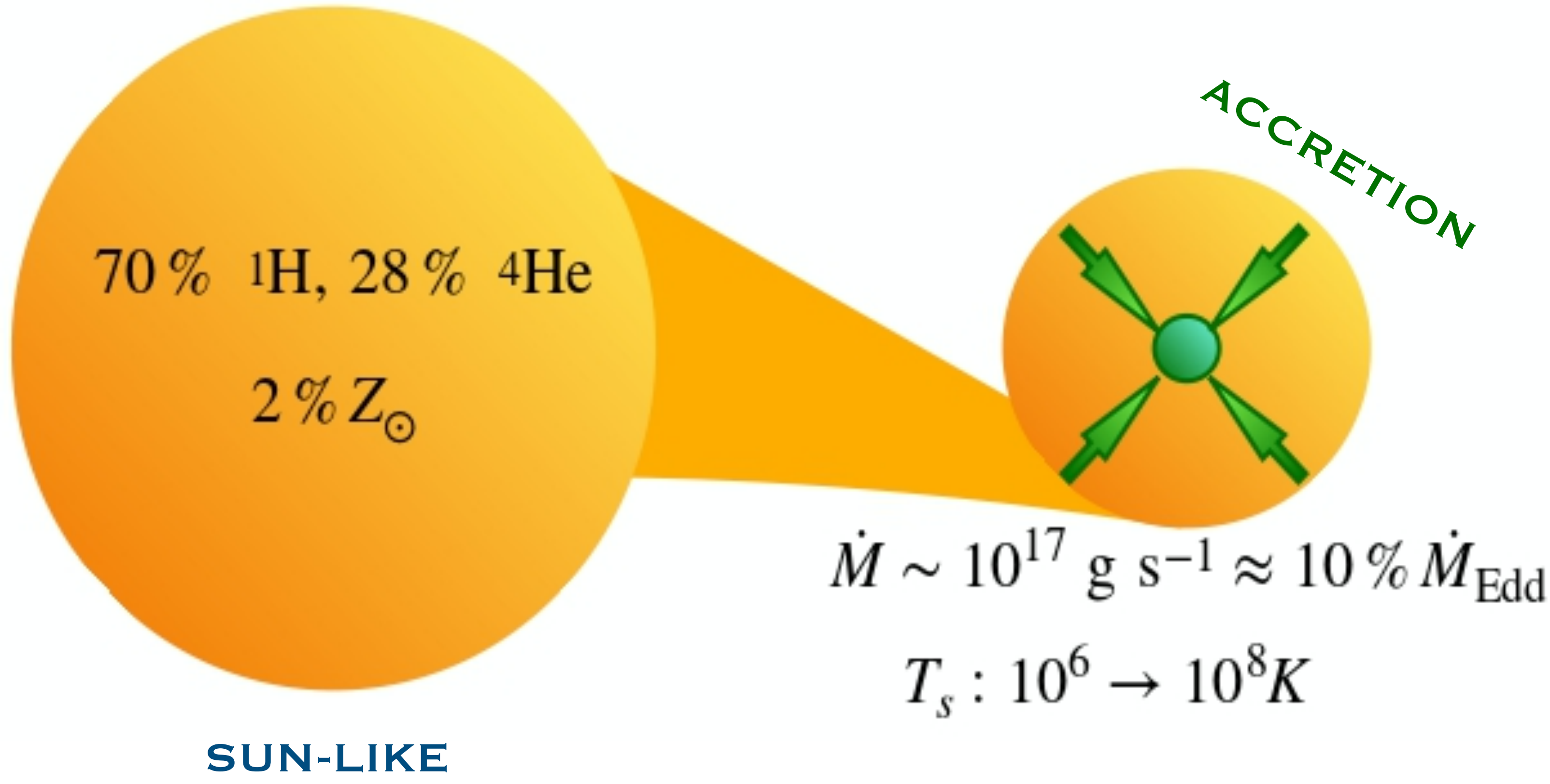


Thermo-nuclear? (But weren't neutron stars...)

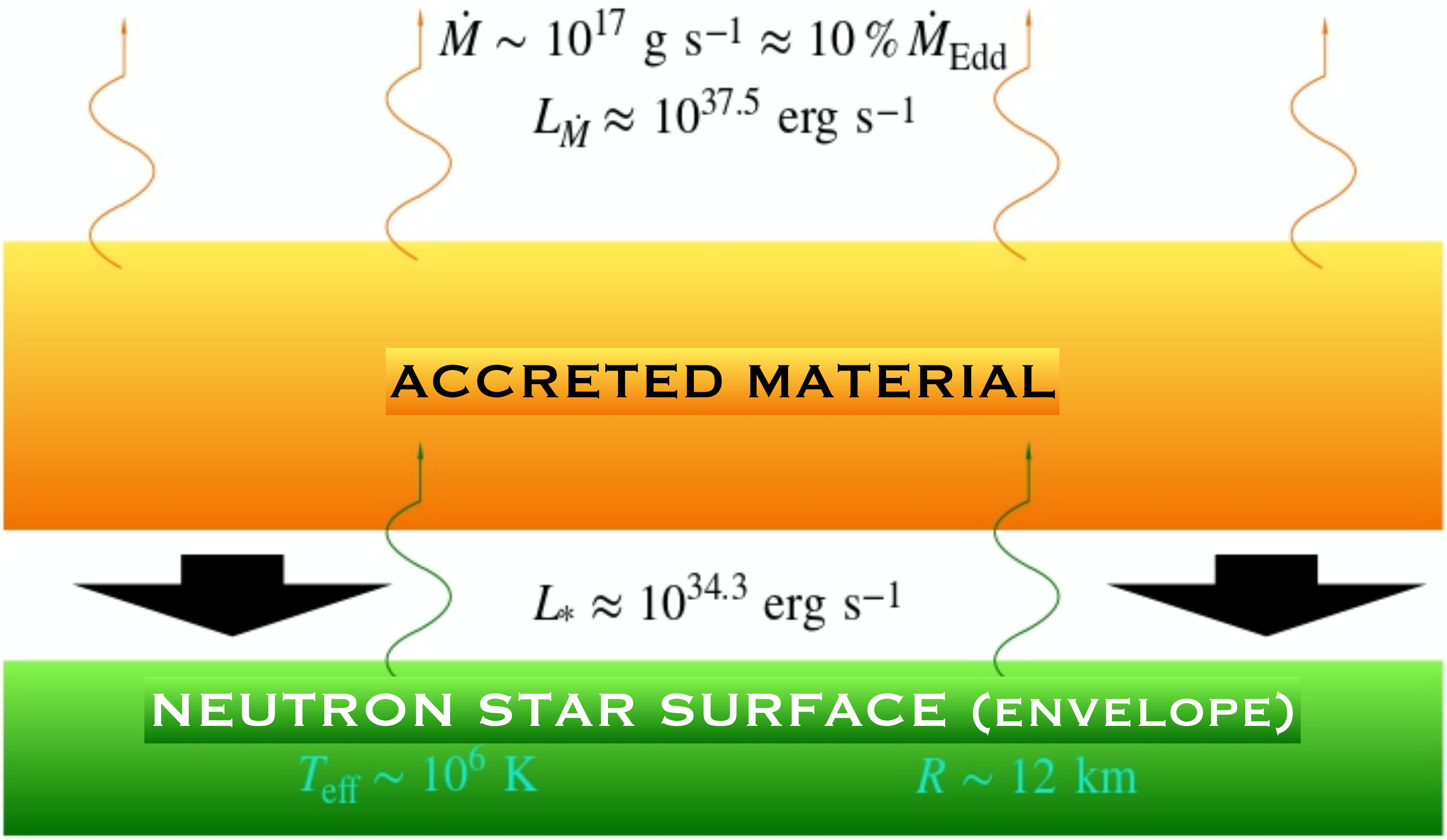


Crab Nebula. Credits: NASA, ESA, J. Hester and A. Loll (Arizona State University)

Enter: low-mass x-ray binary systems

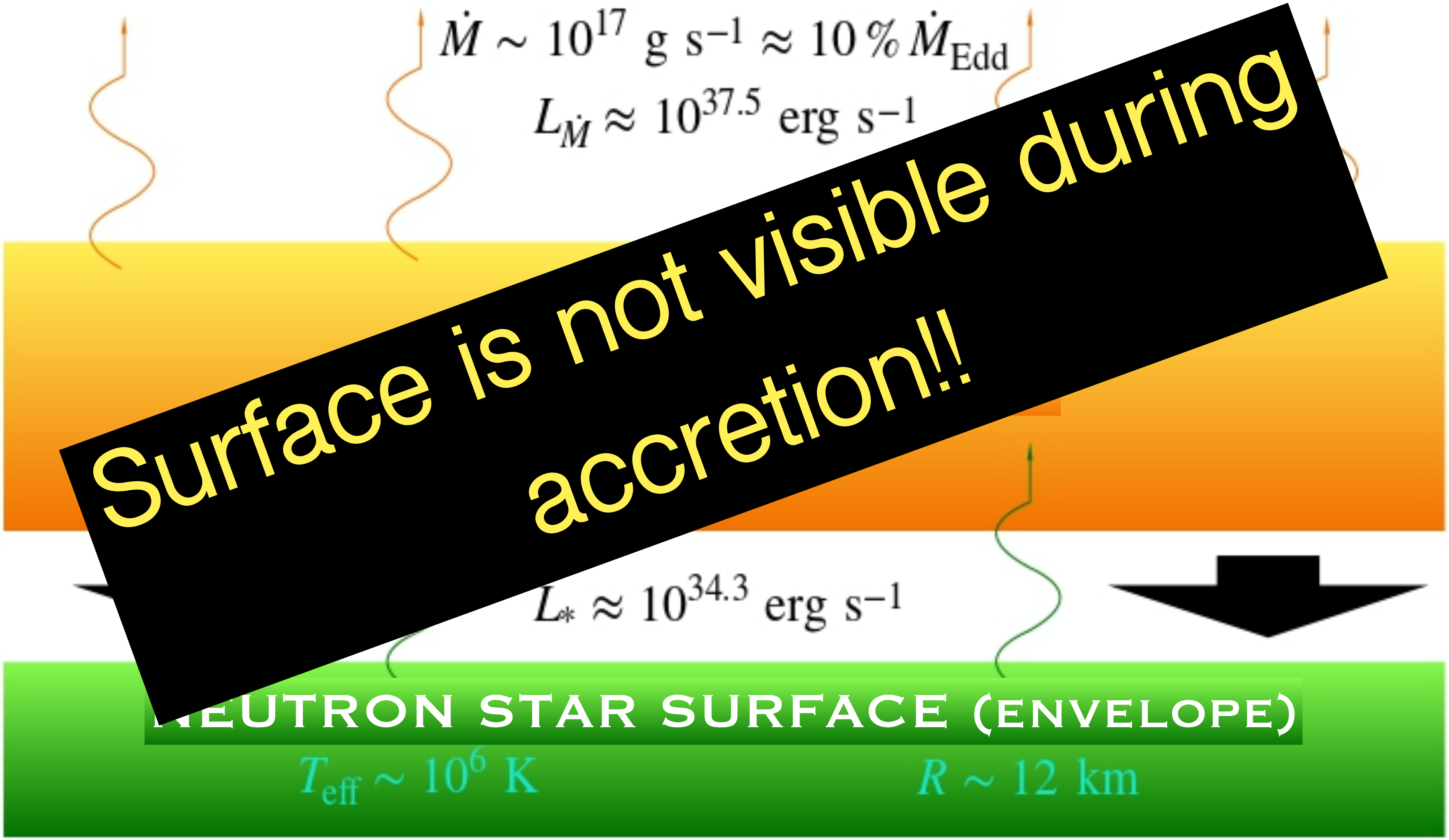


But, then...?



$\dot{M} \sim 10^{17}$ g s^{-1} $\approx 10\,\%\,\dot{M}_{Edd}$
$L_{\dot{M}} \approx 10^{37.5}$ erg s^{-1}
ACCRETED MATERIAL
$L_{*} \approx 10^{34.3}$ erg s^{-1}
NEUTRON STAR SURFACE (ENVELOPE)
$T_{eff} \sim 10^{6}$ K
$R \sim 12$ km

But, then...?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$L_{\dot{M}} \approx 10^{37.5}$ erg s^{-1}
Surface is not visible during accretion!!
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EUTRON STAR SURFACE (ENVELOPE)
$T_{\rm eff} \sim 10^6$ K
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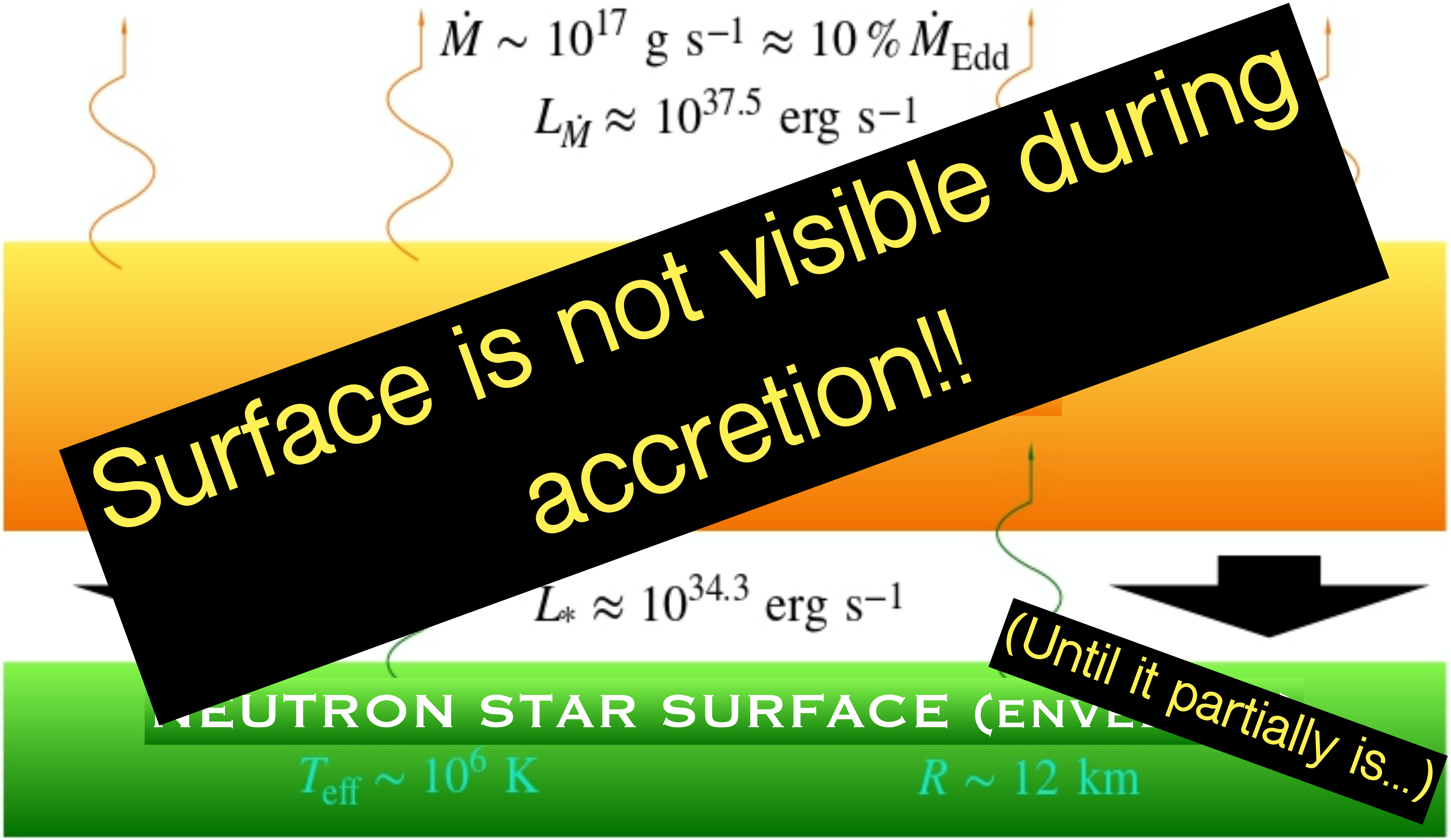
But, then...?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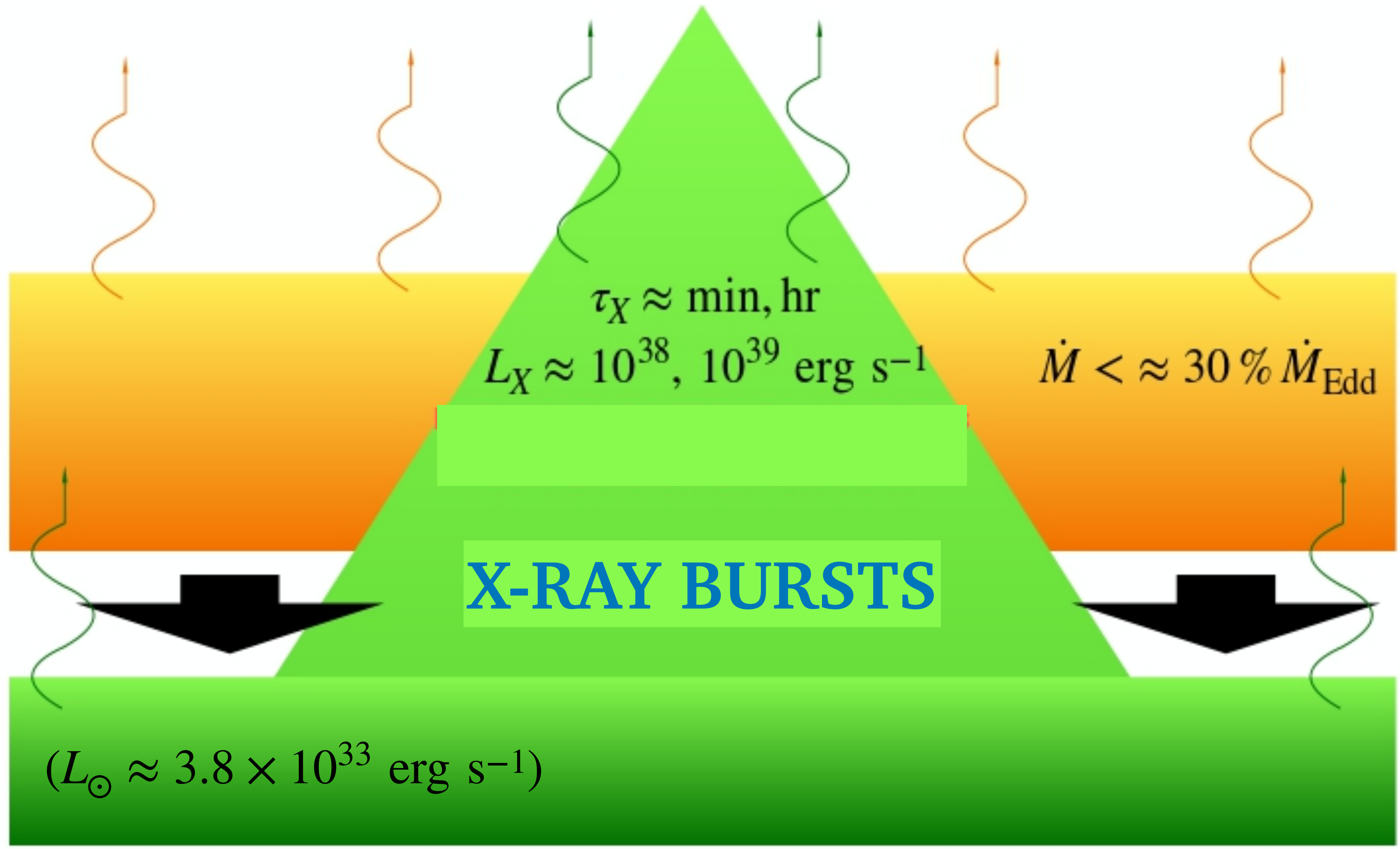
$L_{\dot{M}} \approx 10^{37.5}$ erg s^{-1}
$L_{*} \approx 10^{34.3}$ erg s^{-1}
$T_{\mathrm{eff}} \sim 10^{6}$ K
$R \sim 12$ km
Surface is not visible during accretion!!
(Until it partially is...)

...via Thermonuclear explosions!



Theory vs observation

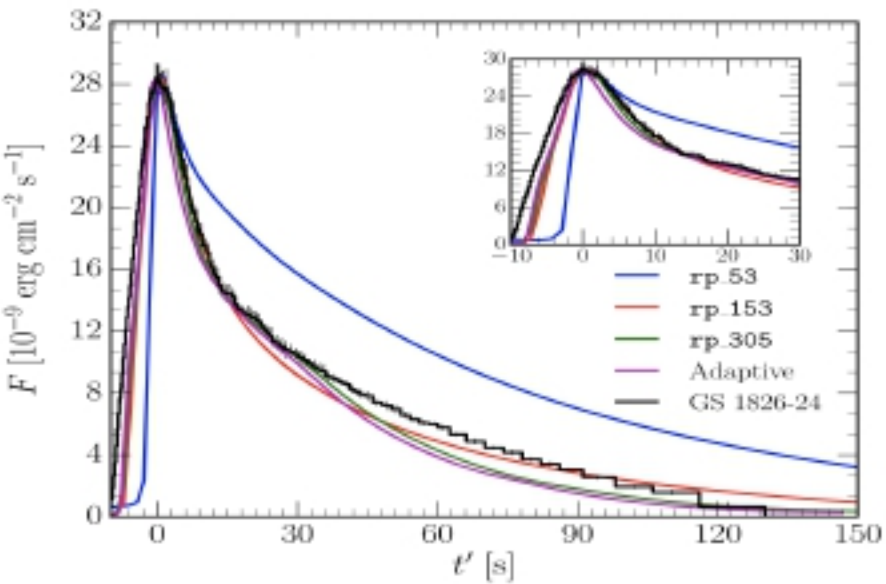


Figure: A typical X-ray burst over GS 1826-24 (black) against theoretical models employing **MESA**

- Observationally they occur at $\dot{M} < 0.3\dot{M}_{\rm Edd}$ ($\approx 10^{-9} M_\odot$ 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

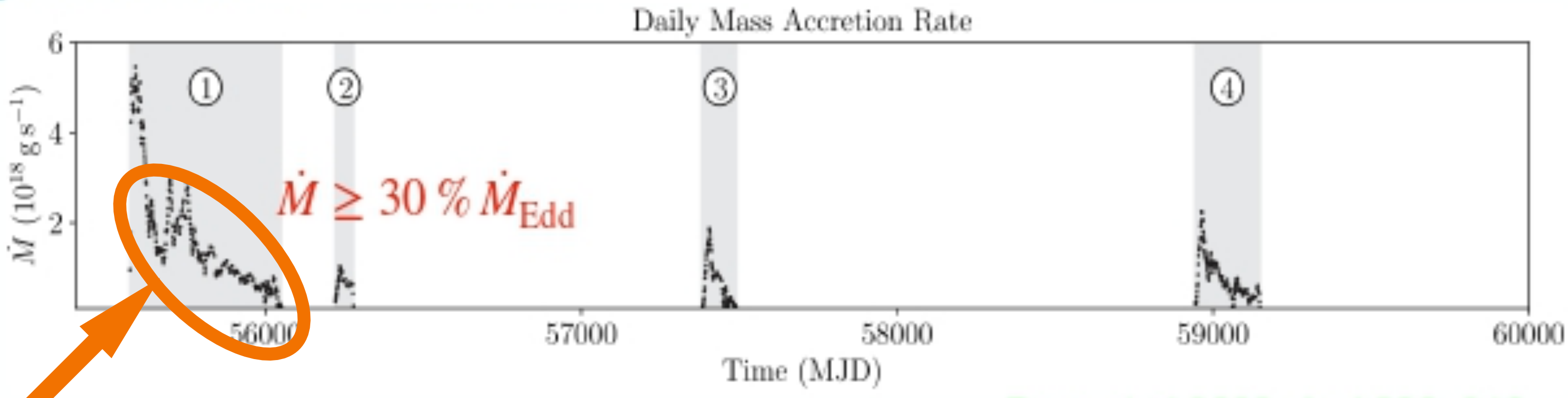
RP IN A NUTCRACKER

Figura: Créditos: Nutcracker Museum.

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

Rp, rp everywhere

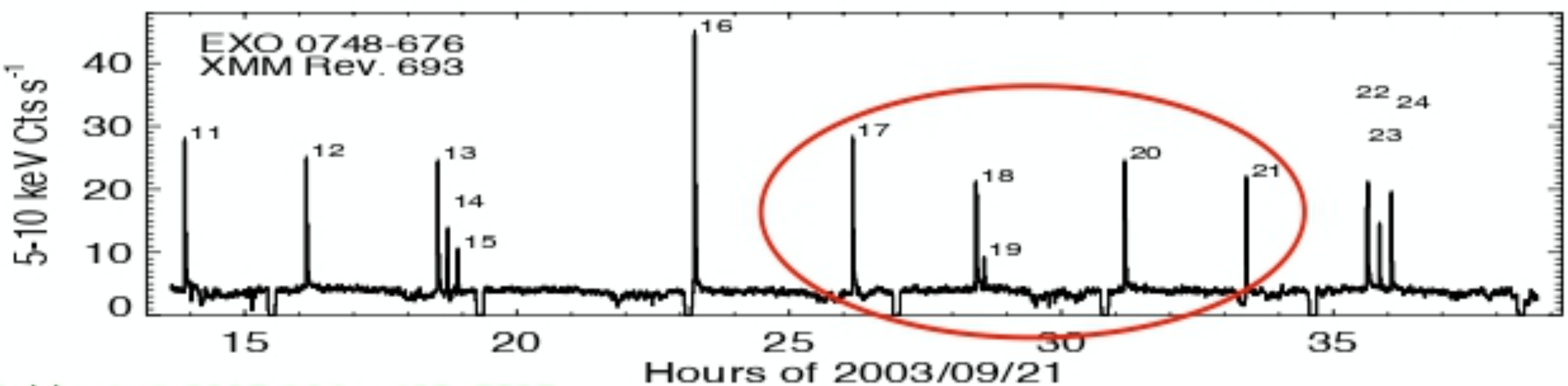
MAXI J0556-332: **Transient accretion of months**



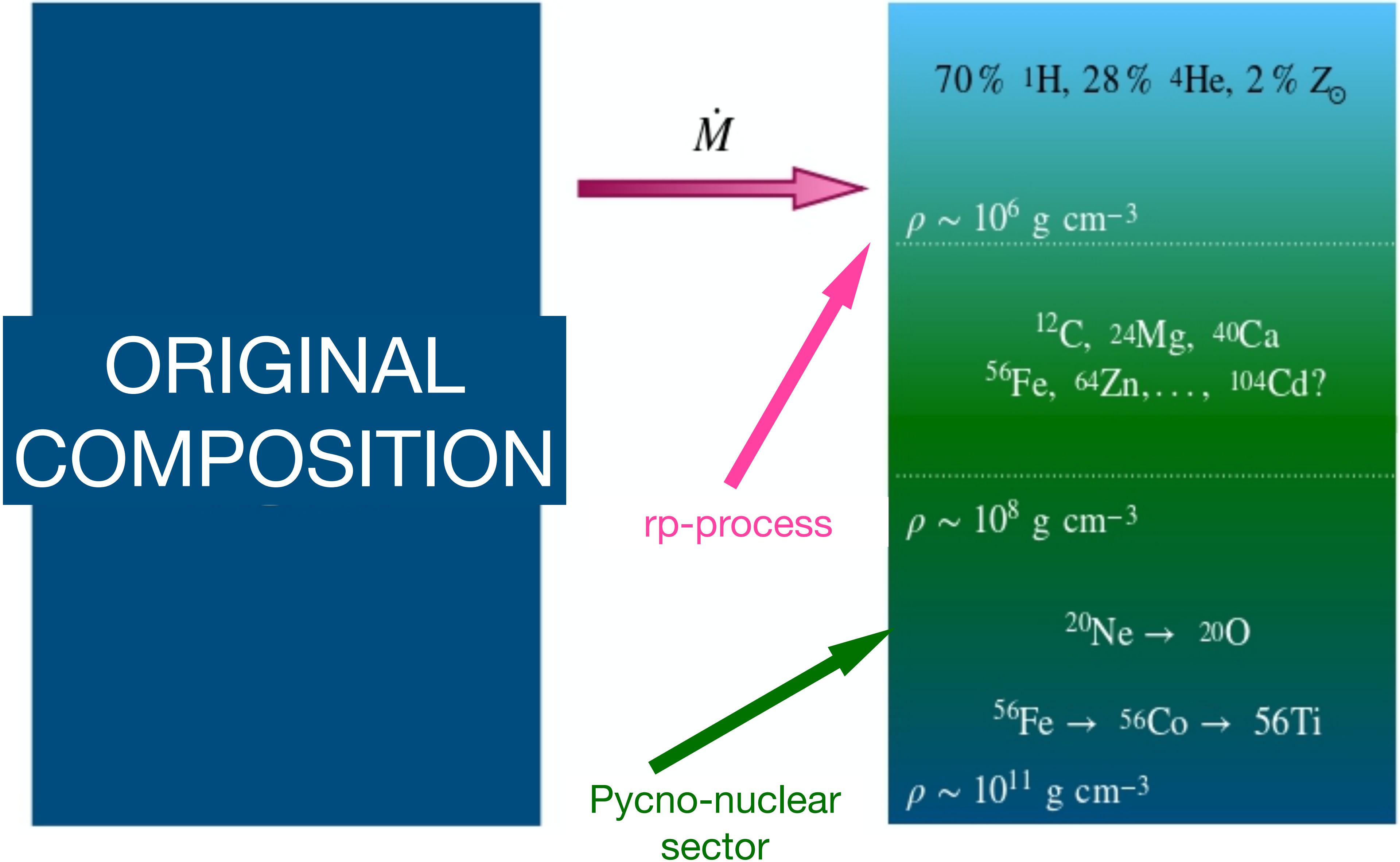
Page et al 2022, ApJ 933, 216

(Yes, even here!)

EXO 0748-676: Accretion and X-ray bursts



Boirin et al, 2007 A&A…465..559B

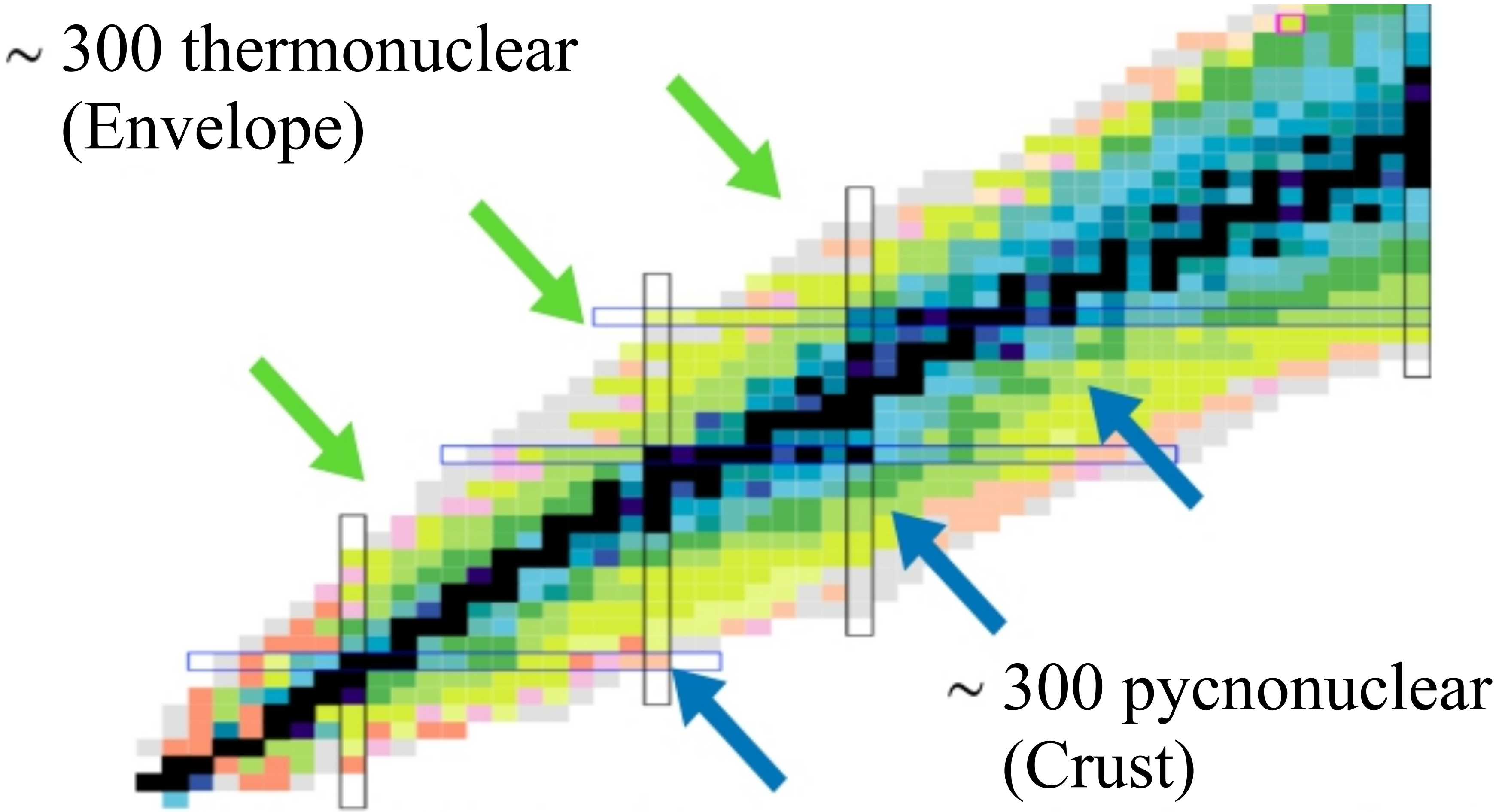

ORIGINAL COMPOSITION
$\dot{M}$
70 % ^{1}H, 28 % ^{4}He, 2 % $Z_\odot$
$\rho \sim 10^{6}$ g cm^{-3}
^{12}C, ^{24}Mg, ^{40}Ca
^{56}Fe, ^{64}Zn, . . . , ^{104}Cd?
$\rho \sim 10^{8}$ g cm^{-3}
rp-process
^{20}Ne → ^{20}O
^{56}Fe → ^{56}Co → 56Ti
$\rho \sim 10^{11}$ g cm^{-3}
Pycno-nuclear sector

Main challenge: nuclear network of reactions

Figura: Cables conectados como analogía.

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

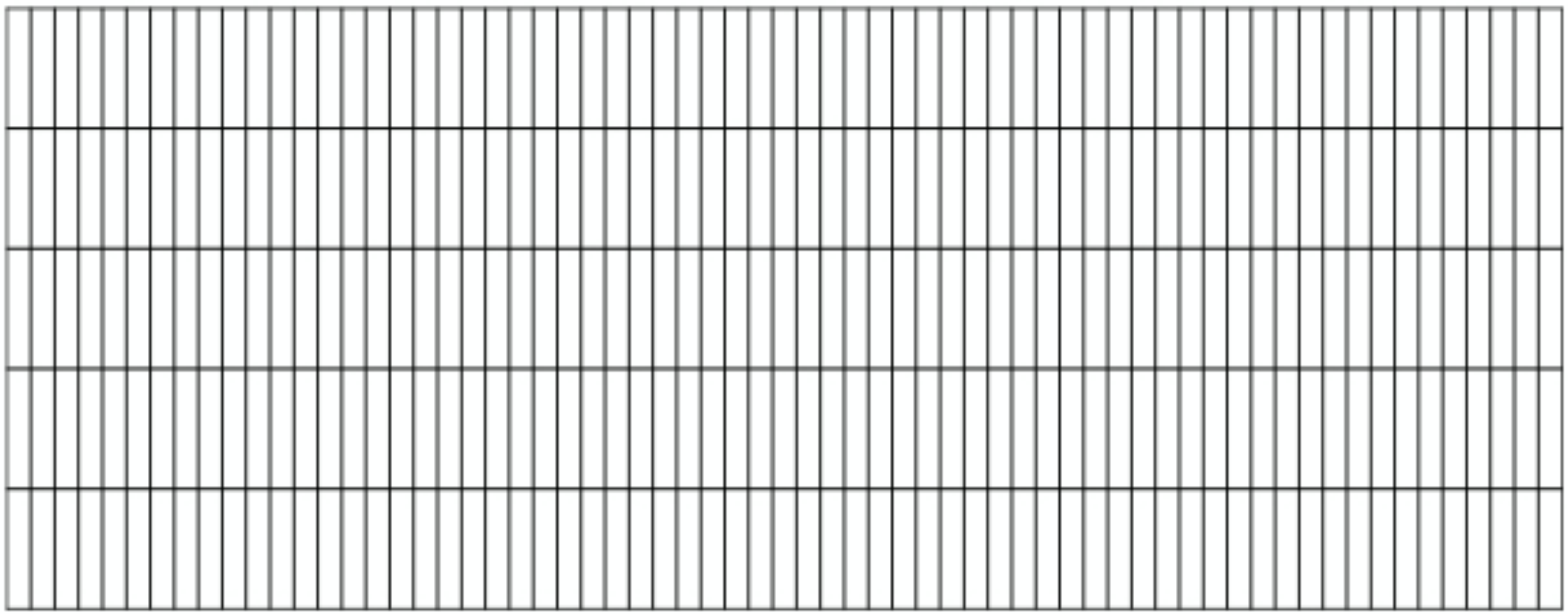
How many species do we actually need?


~ 300 thermonuclear
(Envelope)
~ 300 pycnonuclear
(Crust)

Only the envelope!

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

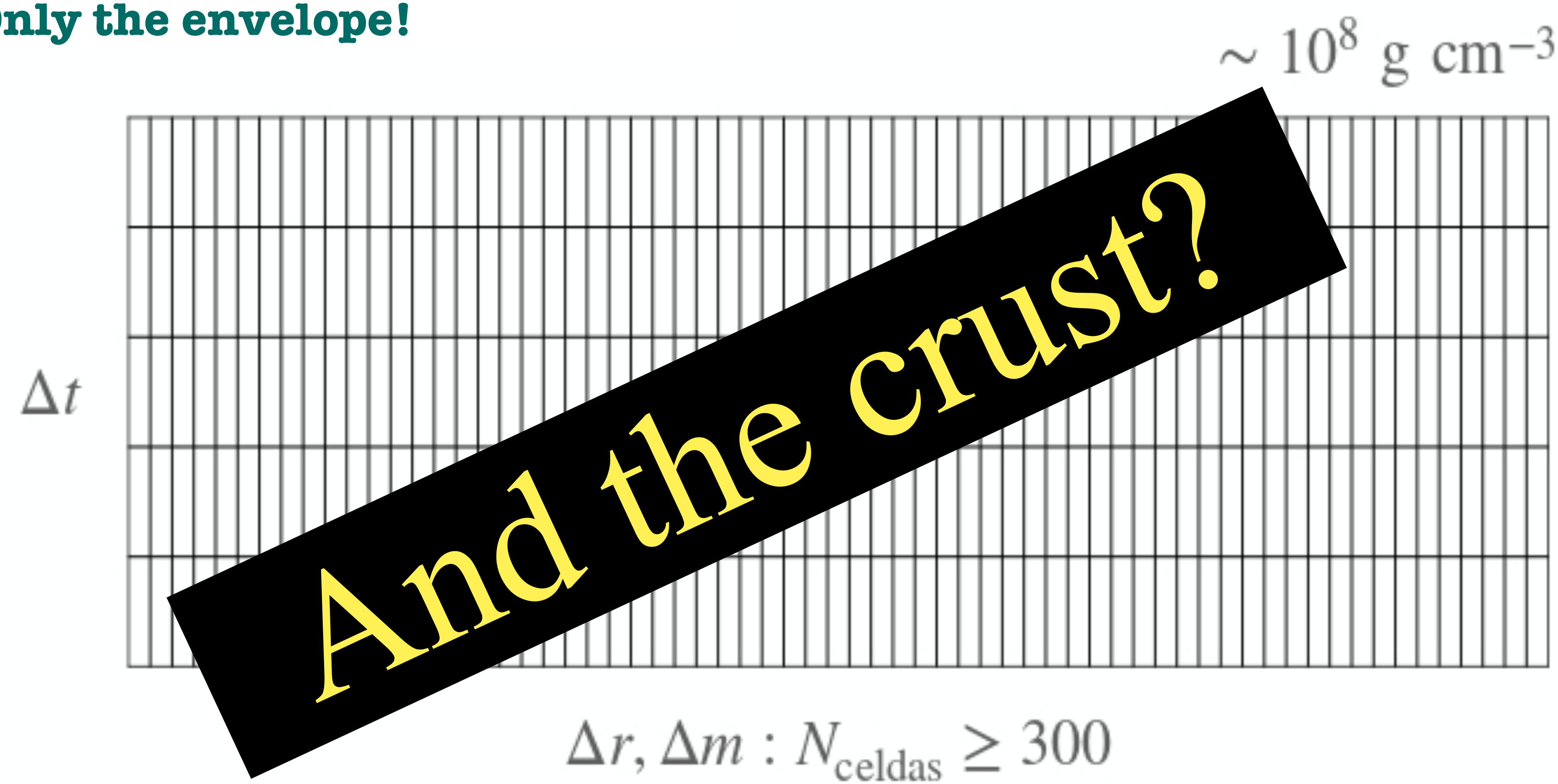
Δt



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

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

Only the envelope!



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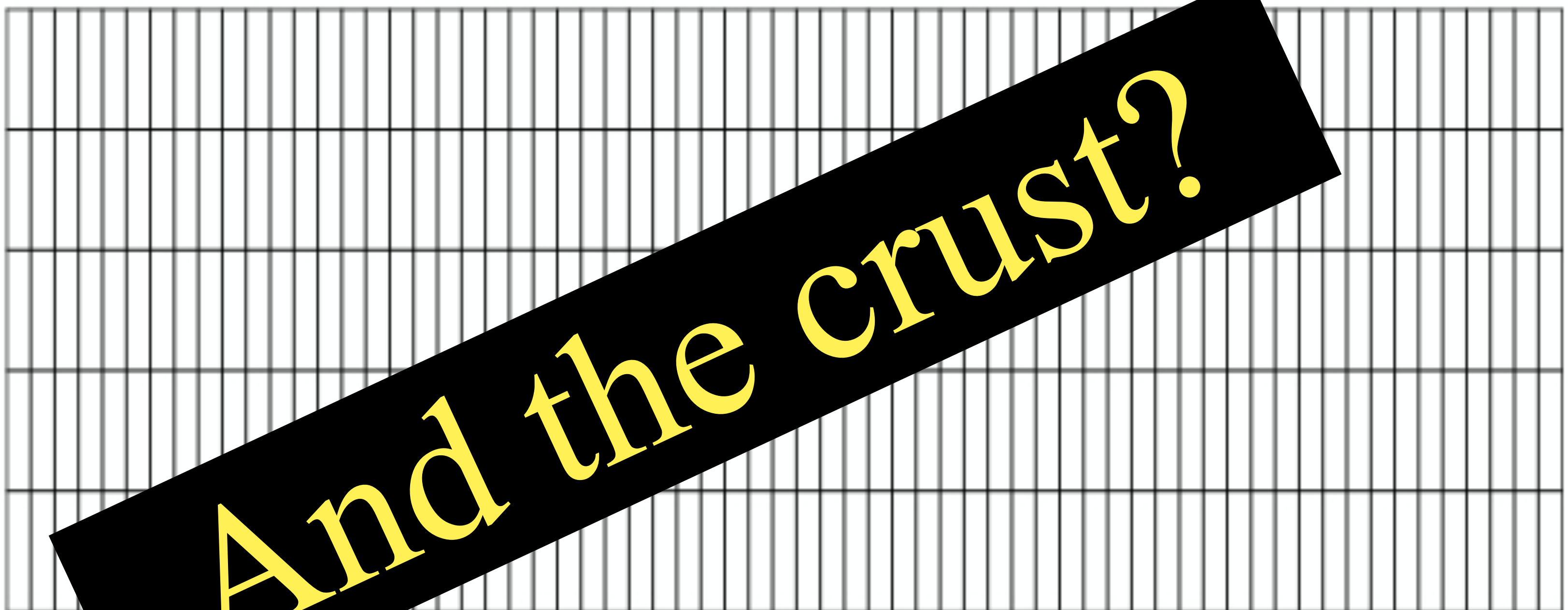
Only the envelope!

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

Δt

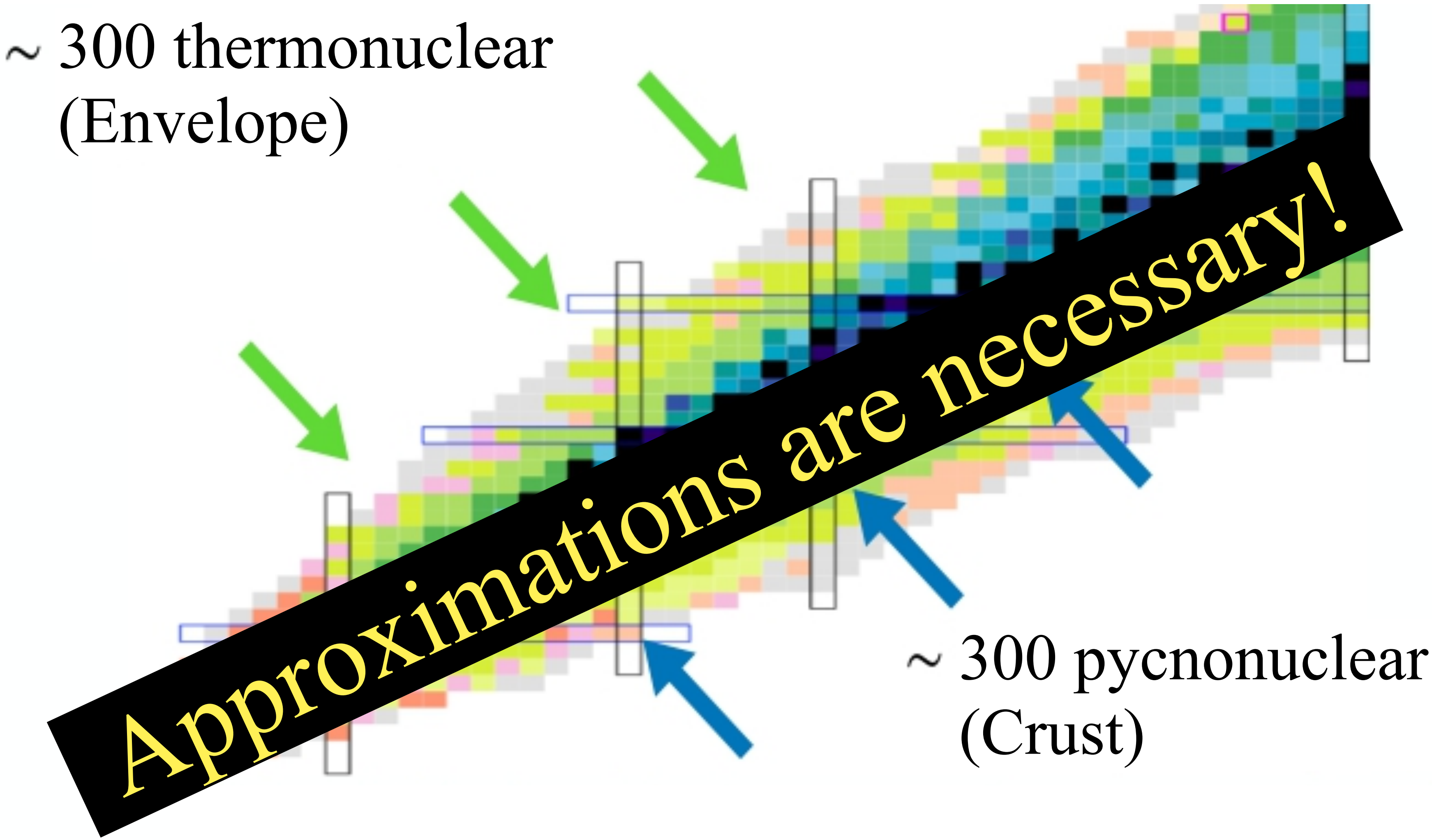


And the crust?

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

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

And the core?


~ 300 thermonuclear
(Envelope)
~ 300 pycnonuclear
(Crust)
Approximations are necessary!

Surface visible after accretion!

XTE J1701-462: Transient accretion of months

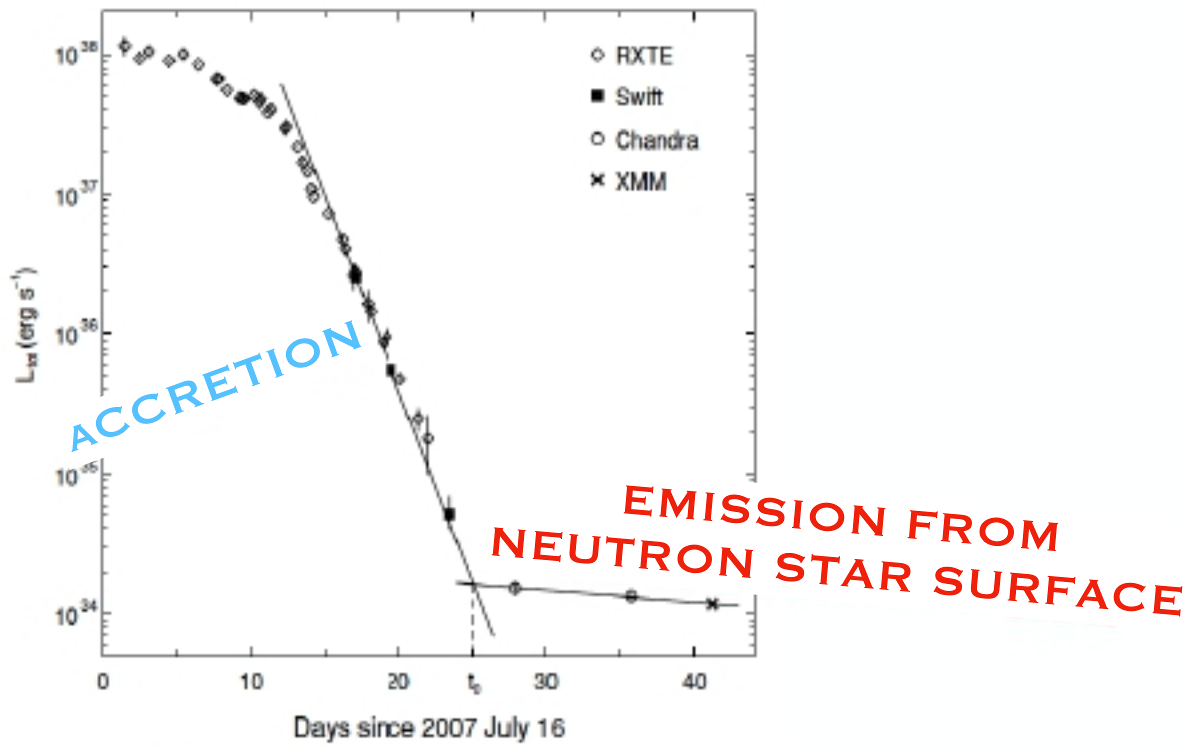


Figure 2. Total unabsorbed luminosity in the 0.5–10 keV band around the end of the outburst. The two lines are best-fit exponential decay curves for the three *Swift* observations, and the first three *Chandra* and *XMM-Newton* observations. The intersection of these curves defines the end time of the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

Fridriksson et al, 2010ApJ...714..270F

Surface visible after accretion!

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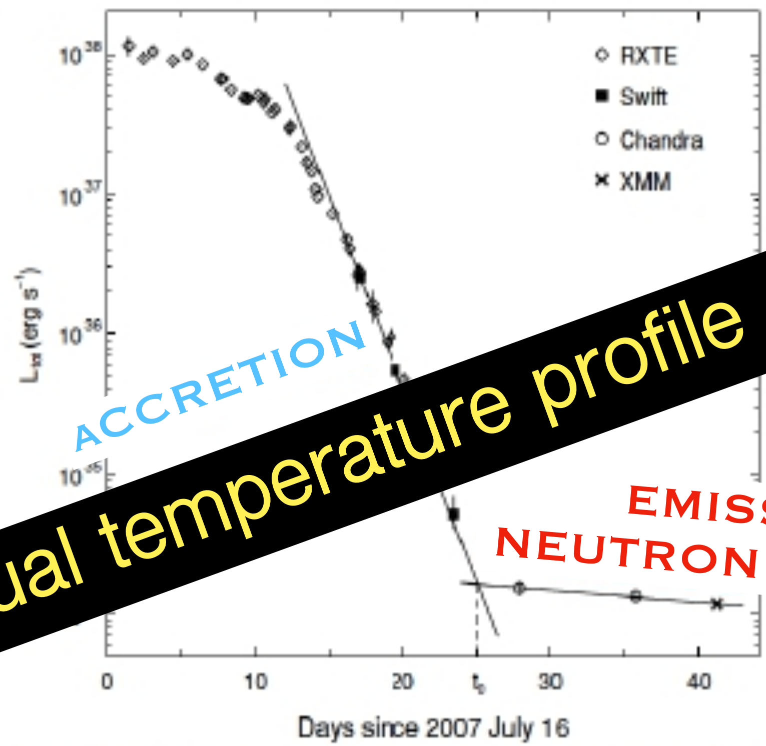

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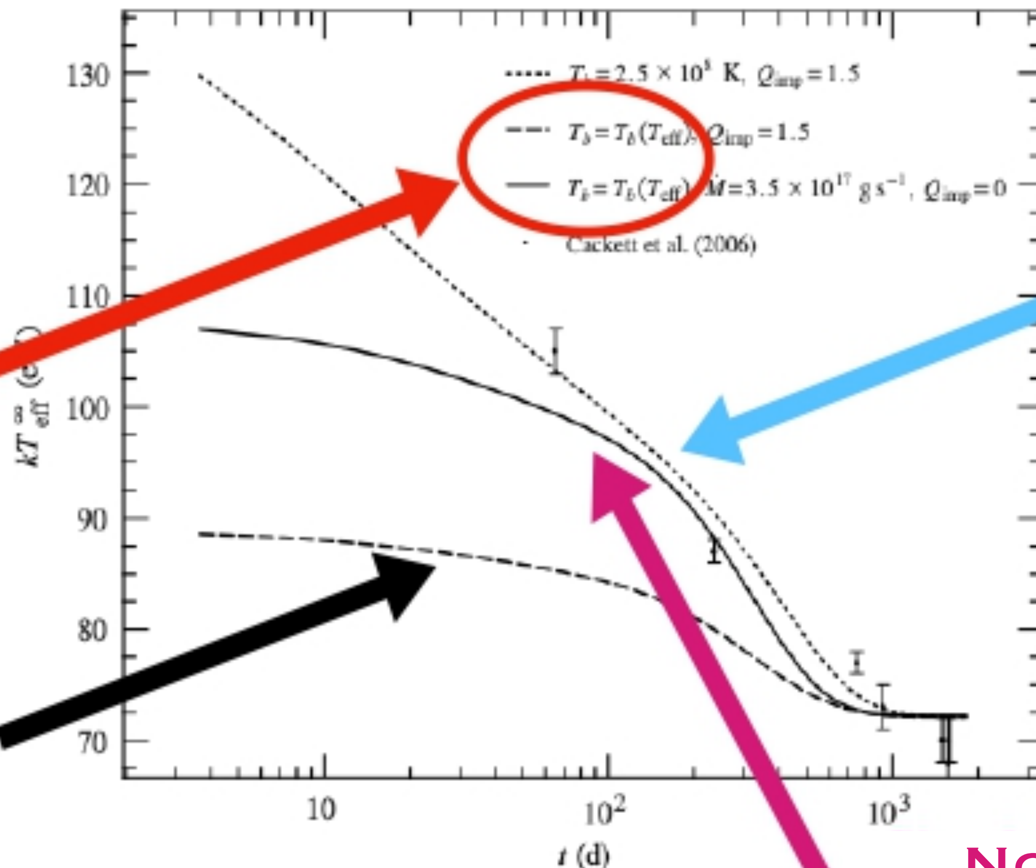
Fridriksson et al, 2010ApJ...714..270F

The *shallow heating* paradigm

Stationary approximation for the envelope:

$T_b(T_{eff})$



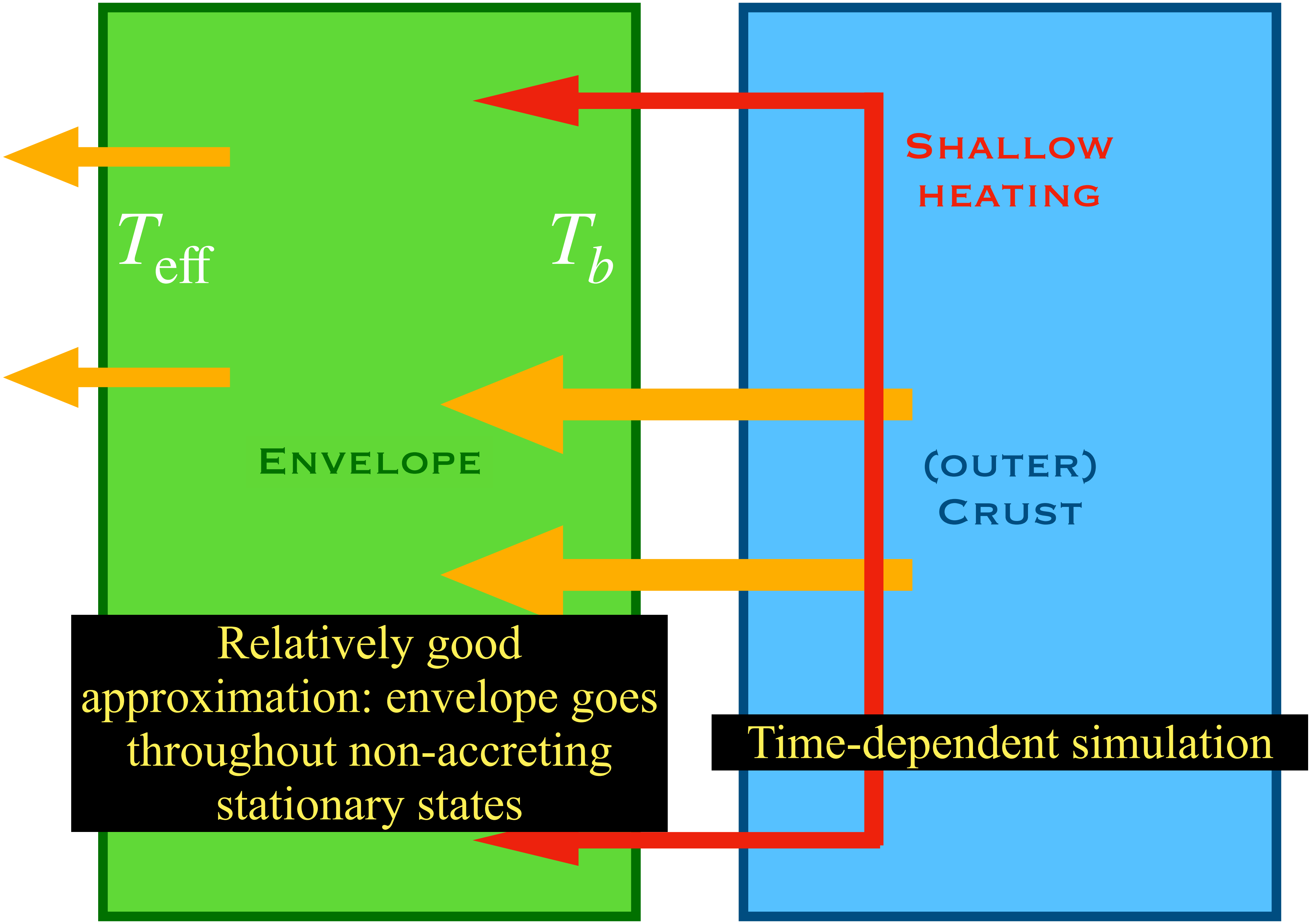
Edward F. Brown and Andrew Cumming 2009 *ApJ* **698** 1020

With shallow heating

Without 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 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]

[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

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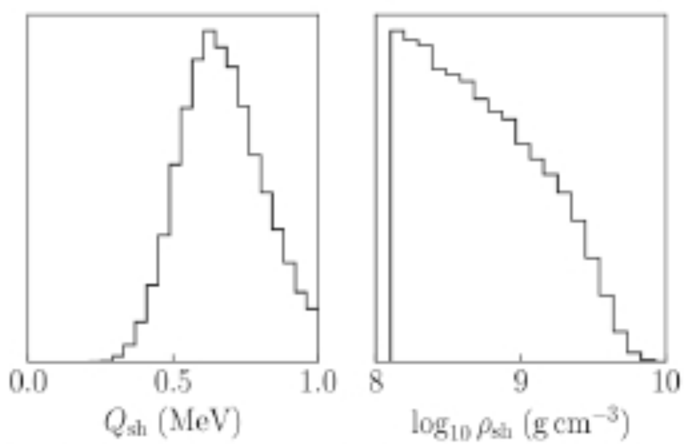

Figure 9. Histograms of the distribution of the shallow heating strength, Q_{sh}, and lower density, ρ_{sh} in scenario "C."

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?

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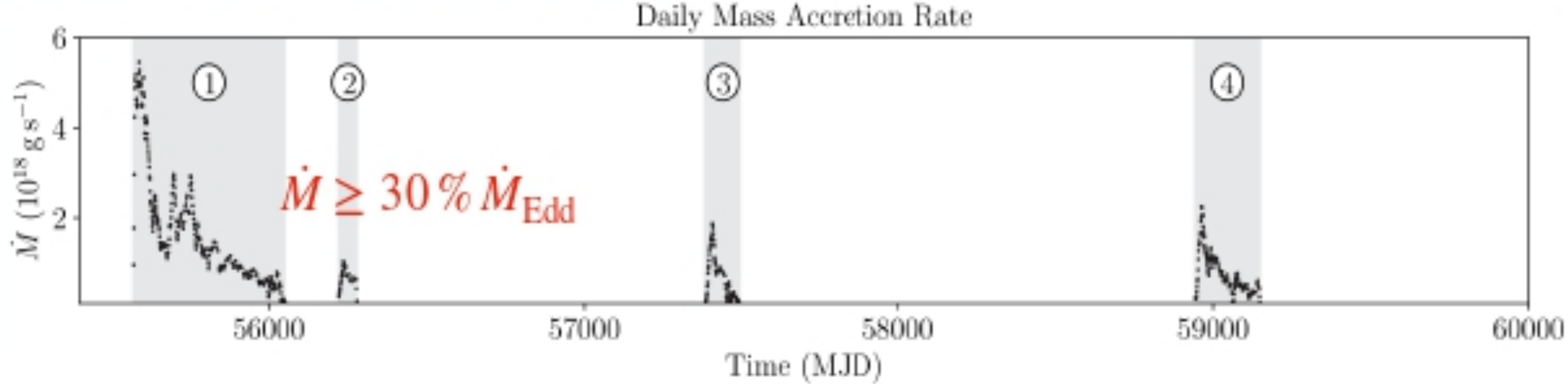
MAXI J0556-332: Transient accretion of months

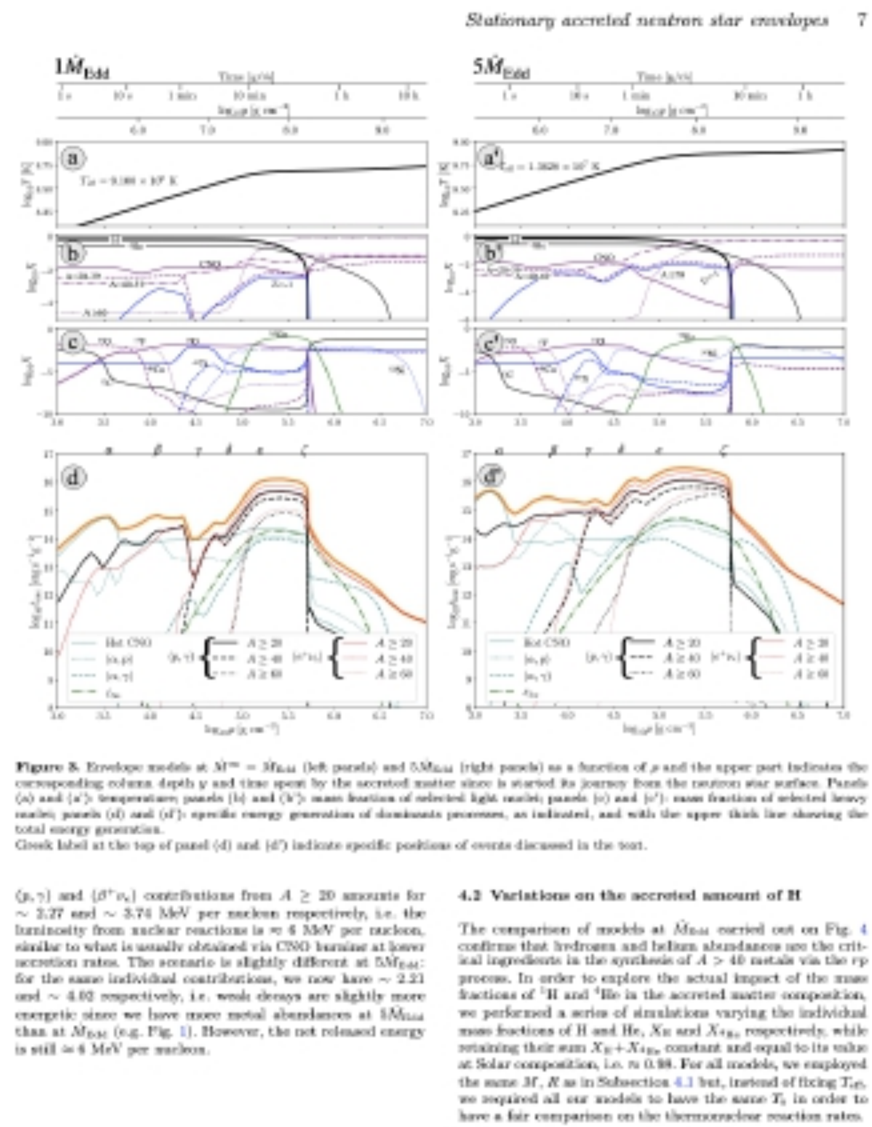


No bursts: $T_b(T_{\rm eff})$ & $L_b(T_{\rm eff})$?

Work in progress

1. **Examine time-independent envelopes at high accretion rates**
   - Construction of a numerical code with 380 species
   - arXiv:2403.13994

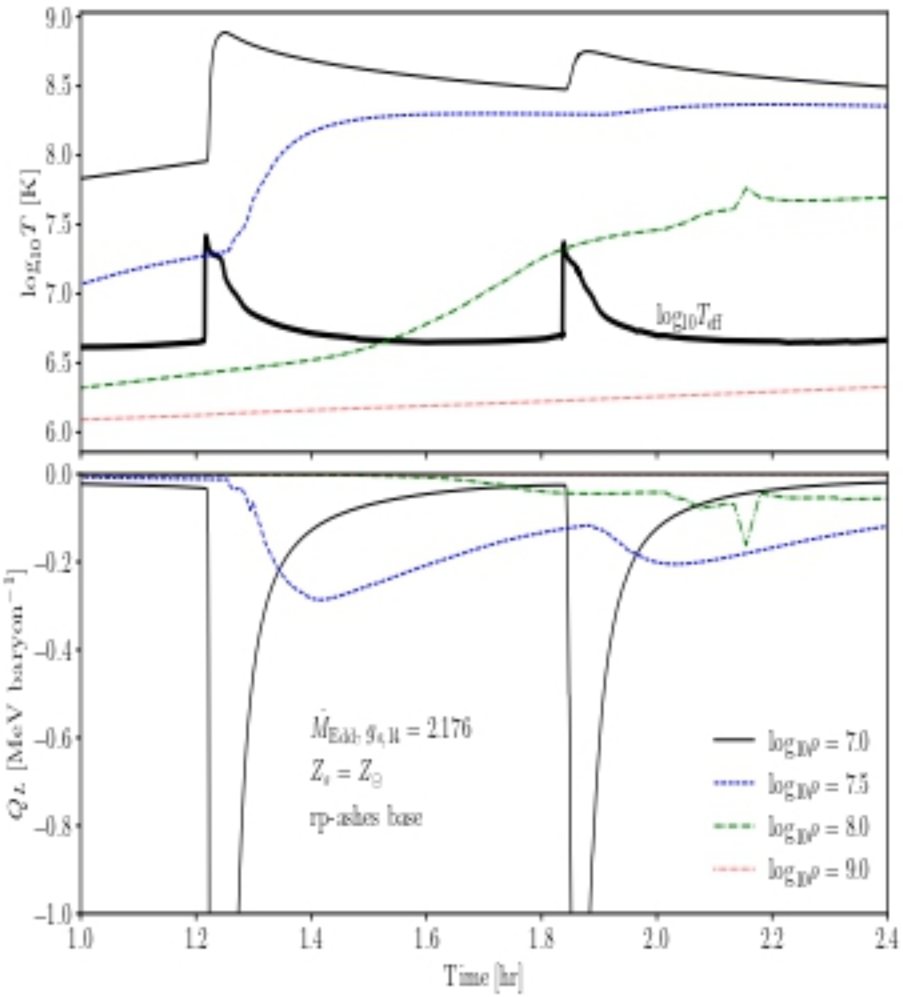
2. **Understand and model thermonuclear explosions**
   - MESA - Stellar evolution code
   - Own's code output as initial conditions
   - Do envelopes with negative luminosity at base make sense?



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"*