i-Process Nucleosynthesis in AM CVn Systems (?)

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Universitad de Granada

s,i, & r Element Nucleosinthesis Conference, 8-13 June, 2025, Giulianova (Italy)

CO WD+sdB Binaries

SYSTEM	P (min)	M_{WD} ($M_\odot$)	M_{sdB} ($M_\odot$)
ZTF J2055+4651	56.35	0.65±0.05	0.41±0.04
ZTF J2130+4420	39.34	0.545±0.020	0.337±0.015
HD 265435	99.10	0.91±0.10	0.62±0.15
OW J0815-3421	73.70	0.707±0.084	0.343±0.071
CD-30°11223	70.00	0.74±0.02	0.47±0.02
PTF1 J2238+7430	76.34	0.725±0.026	0.383±0.028

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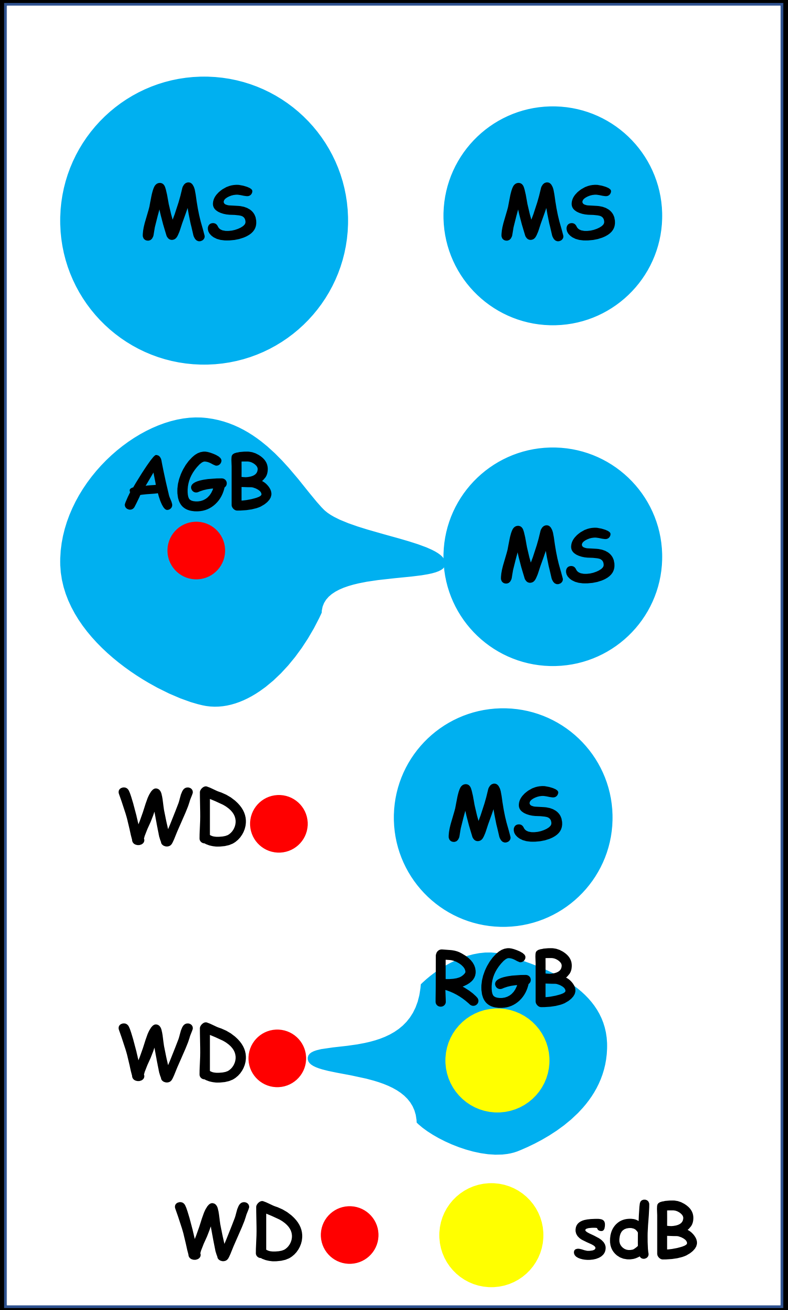

CO WD+sdB Binaries

They are important because…

- Compact objects are not "naked" core

Penultimate progenitors of AM CVn systems

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- Emitters of detectable GWR

Calibration sources for GW antennae

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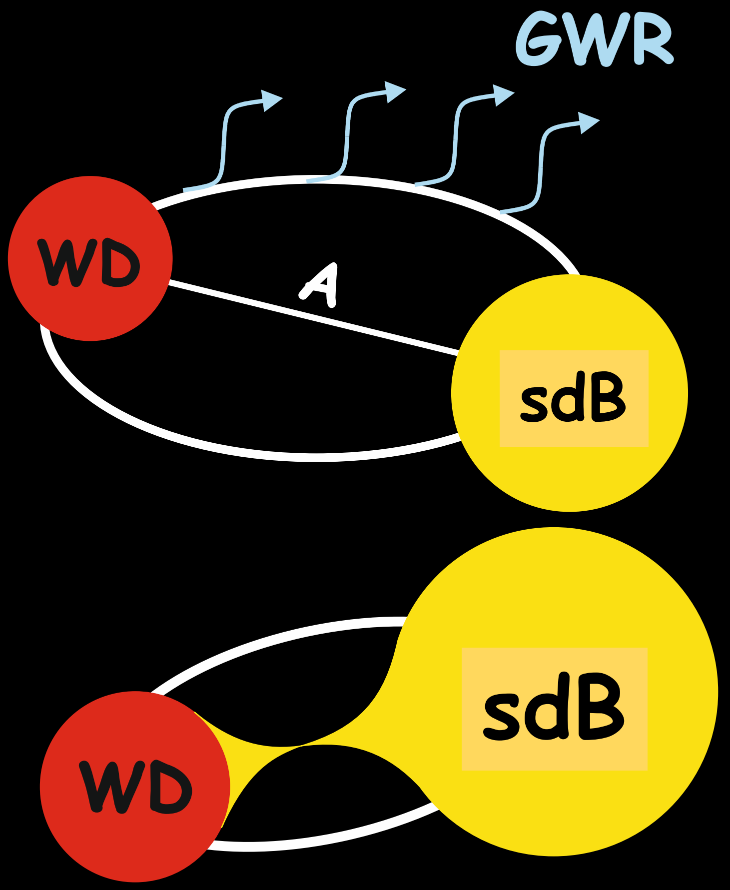
Calibration sources for GW antennae

- The two components will come into contact!!



CO WD+sdB Binaries

They are important because…

- Compact objects are not "naked" core

Penultimate progenitors of AM CVn systems

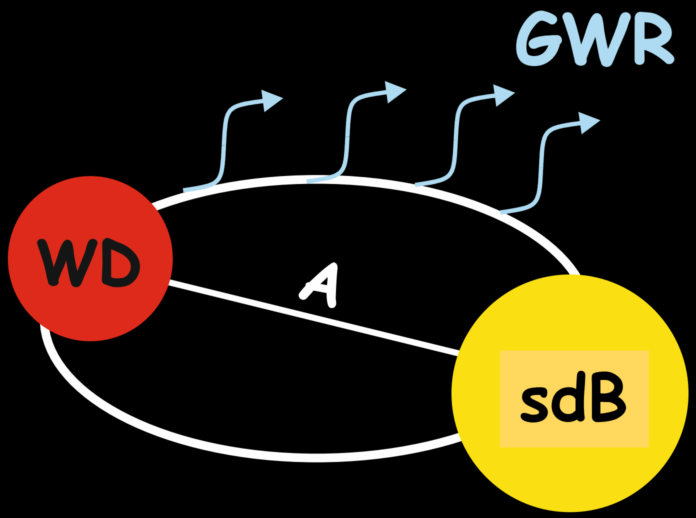
- Emitters of detectable GWR

Calibration sources for GW antennae

- The two components will come into contact!!

Eruptive phenomena!!

Novae, He-novae
Thermonuclear explosion



Realistic WD+sdB systems

The Astrophysical Journal Letters, 925:L12 (10pp), 2022 February 1 https://doi.org/10.3847/2041-8213/ac48f1

OPEN ACCESS

PTF1 J2238+7430

CrossMark

Discovery of a Double-detonation Thermonuclear Supernova Progenitor

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Modelling the AM CVn and double detonation supernova progenitor binary system CD-30°11223

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NOVAE

Mass ejection

Realistic WD+sdB systems

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NOVAE Mass ejection

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PTF1 J2238+7430

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NO ROTATION !!!

During H-accretion…

NOVAE Mass ejection

During He-accretion…

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Faint, low energy, peculiar nucleosynthesis SN Ia

Hypervelocity stars

The PTF1 J2238+7430

A&A, 689, A287 (2024)
https://doi.org/10.1051/0004-6361/202450008

Astronomy & Astrophysics

Expected evolution of the binary system PTF J2238+743015.1

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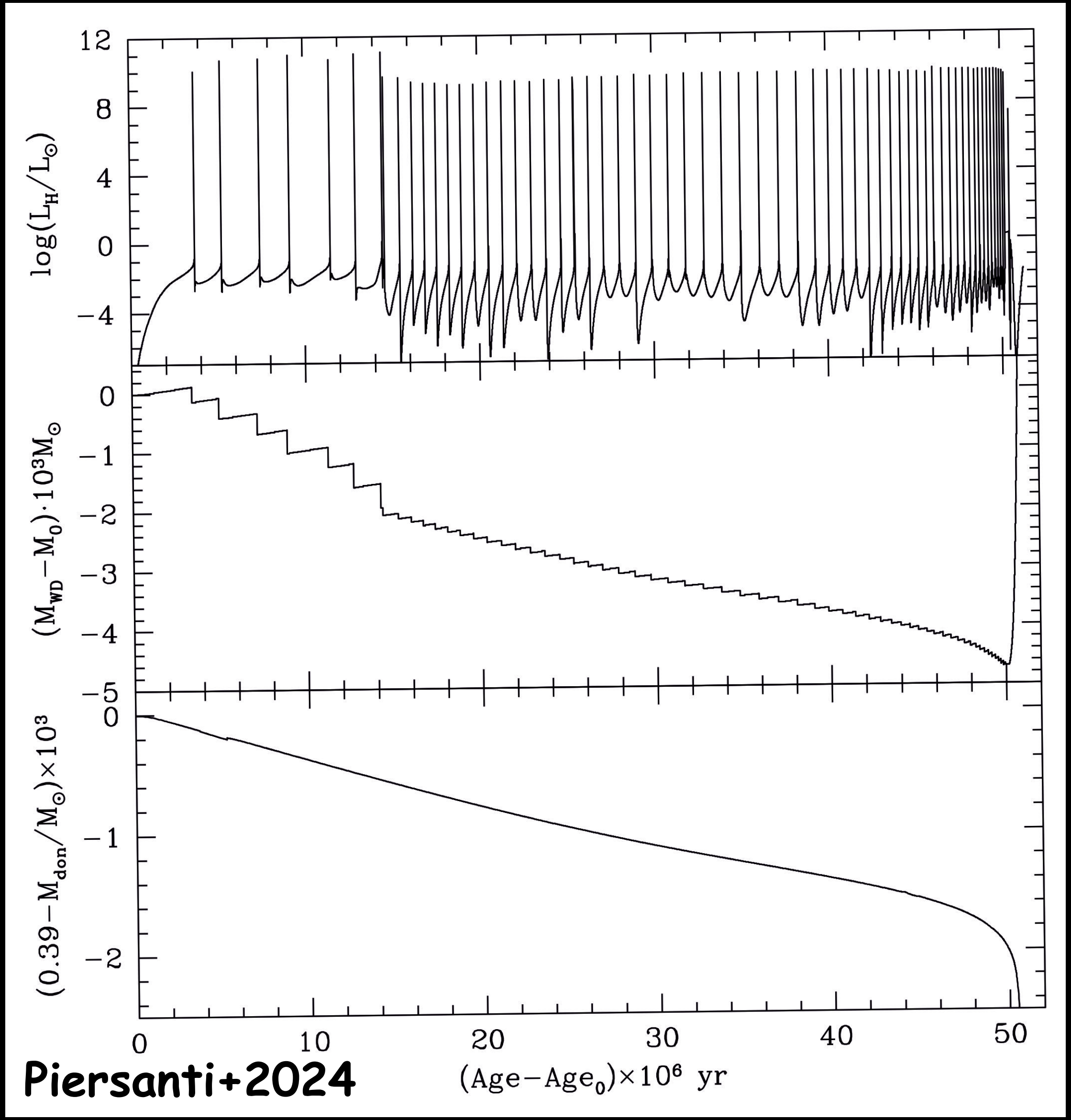
ABSTRACT

Context. Binary systems harboring a low-mass CO WD and a He-rich donor are considered to be the possible progenitors of explosive events via He detonation, producing low-luminosity thermonuclear supernovae with a peculiar nucleosynthetic pattern. Recently, the binary system PTF J223857.11+743015.1 was proposed as a candidate for this kind of stars.
Aims. We investigate the evolution of the PTF J223857.11+743015.1 system, which is composed of a 0.75 $M_\odot$ CO WD and a 0.390 $M_\odot$ subdwarf. We consider the rotation of the WD component.
Methods. Using the FuNS code, we computed the evolution of the two stars simultaneously, taking into account the possible evolution of the orbital parameters, as determined by mass transfer between the components and by mass ejection from the system during episodes of Roche lobe overflow. We consider that the WD gains angular momentum due to accretion and we followed the evolution of the angular velocity profile as determined by angular momentum transport via convection and rotation-induced instabilities.
Results. As the donor H-rich envelope is transferred, the WD experiences recurrent very strong H-flashes triggering Roche lobe overflow episodes during which the entirety of the accreted matter is lost from the system. Due to mixing of chemicals by rotation-induced instabilities during the accretion phase, H-flashes occur inside the original WD. Hence, pulse by pulse, the mass of the accretor is reduced down to 0.7453 $M_\odot$. Afterwards, when He-rich matter is transferred, He detonation does not occur in the rotating WD, which undergoes six very strong He-flashes and subsequent mass-loss episodes. Also in this case, due to rotation-induced mixing of the accreted layers with the underlying core, the WD is eroded. Later, as the mass-transfer rate from the donor decreases, a massive He buffer is piled up onto the accretor, which ends its life as a cooling WD.
Conclusions. The binary system PTF J2238+743015.1 and all other binary systems with components of similar masses and similar orbital parameters are not good candidates as thermonuclear explosion progenitors.

Key words. accretion, accretion disks – nuclear reactions, nucleosynthesis, abundances – binaries: general – stars: individual: PTF J2238+743015.1 – stars: rotation – supernovae: general

The PTF1 J2238+7430

H-accretion



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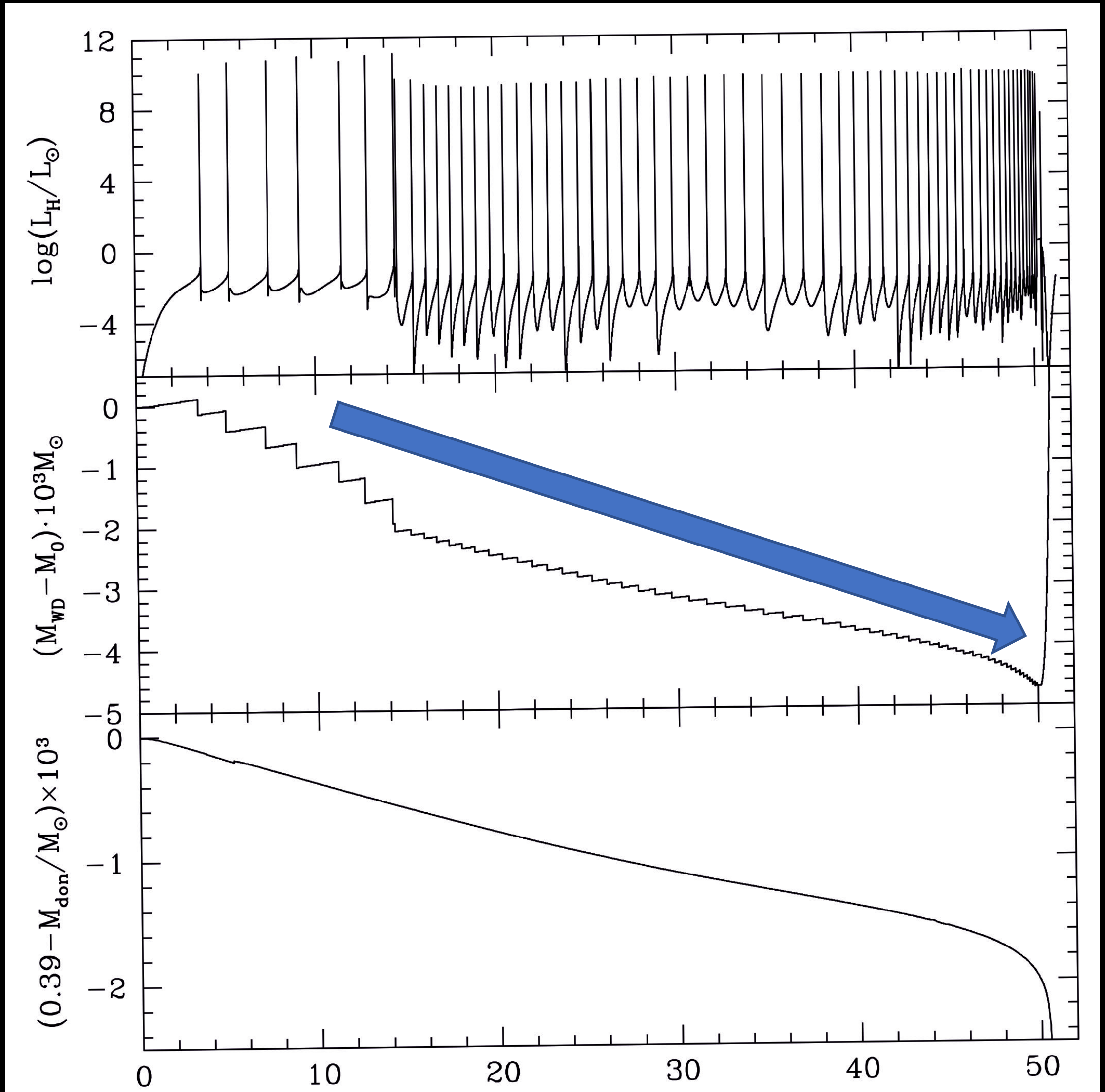

Piersanti+2024

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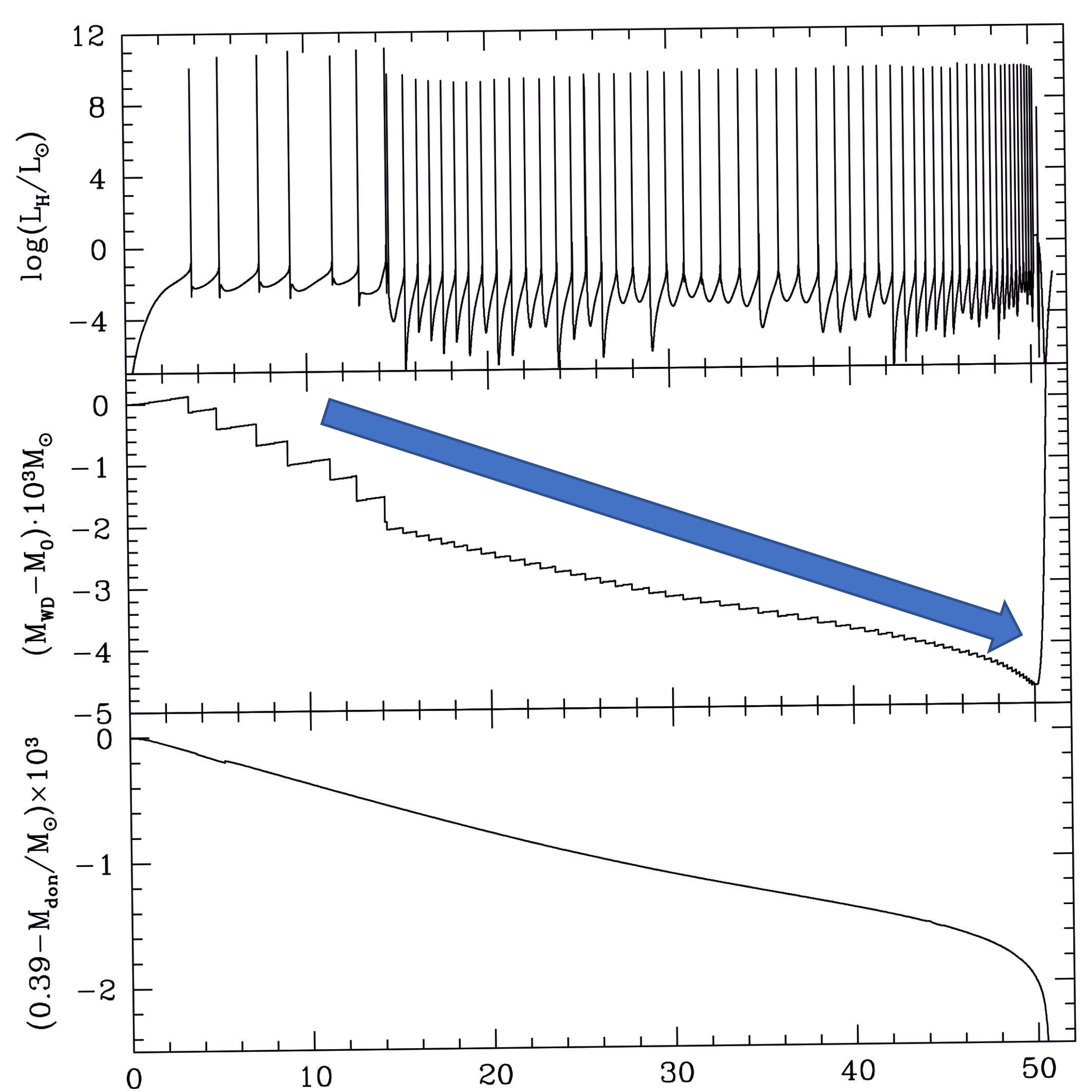

Piersanti+2024

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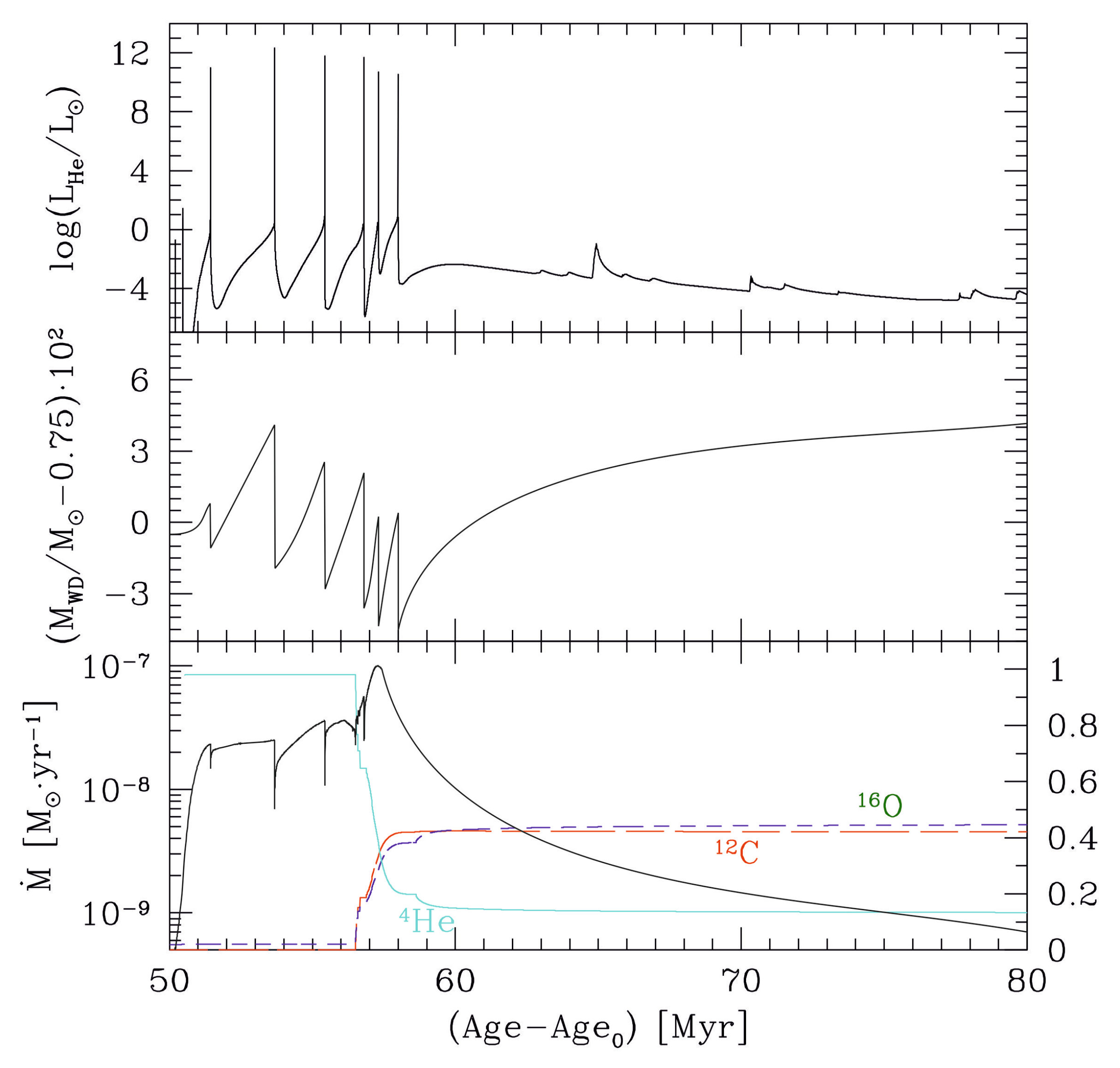

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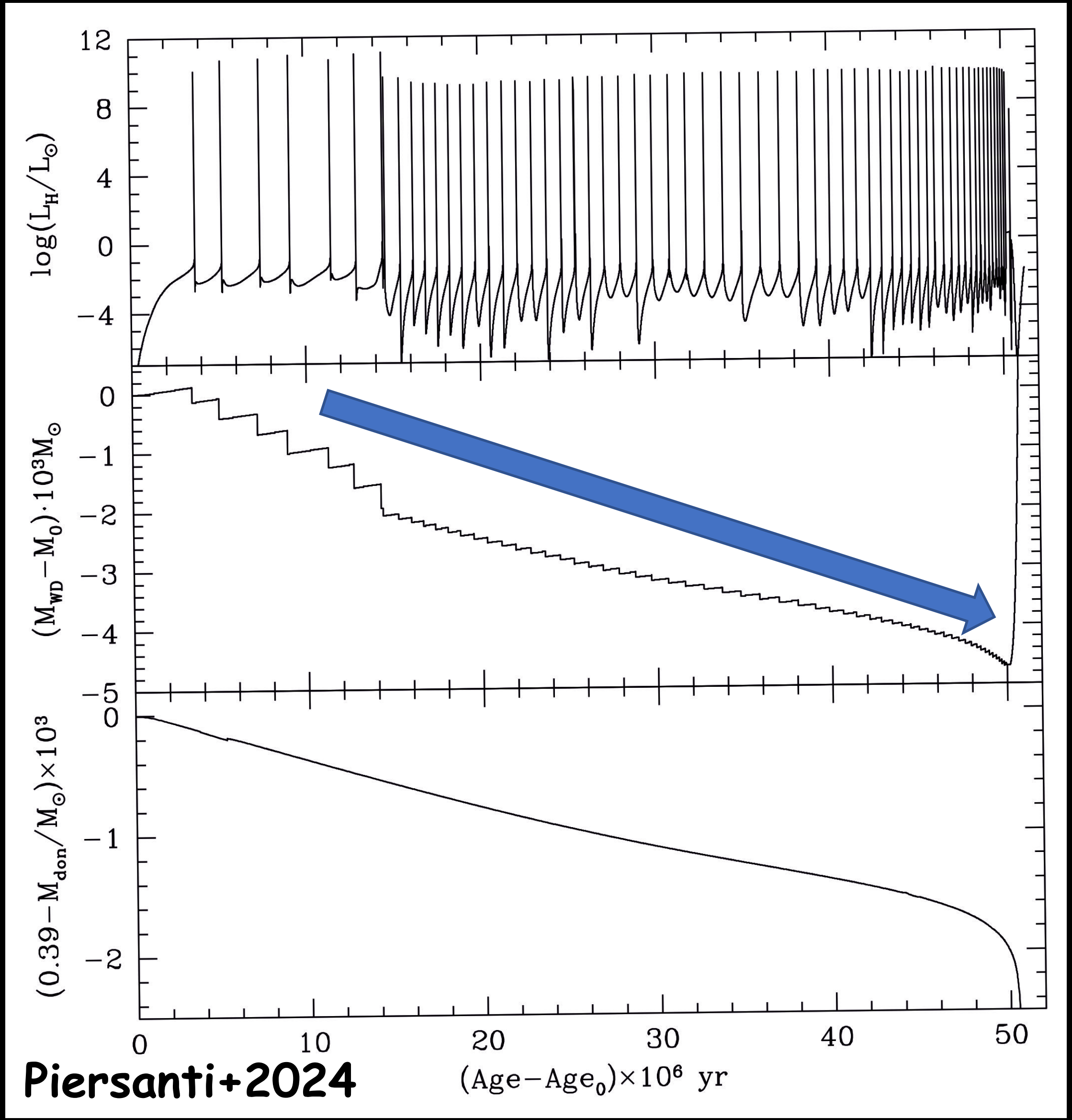

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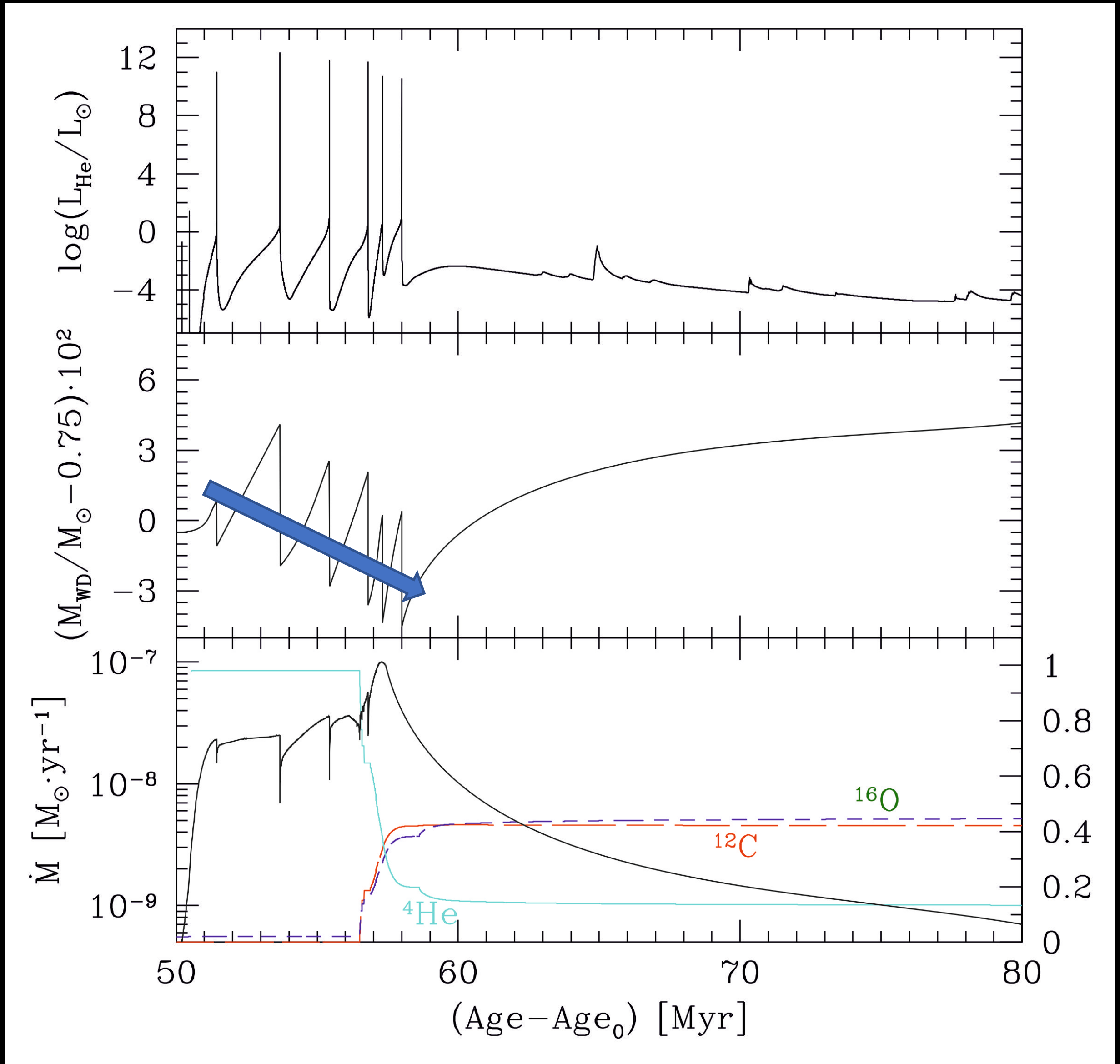

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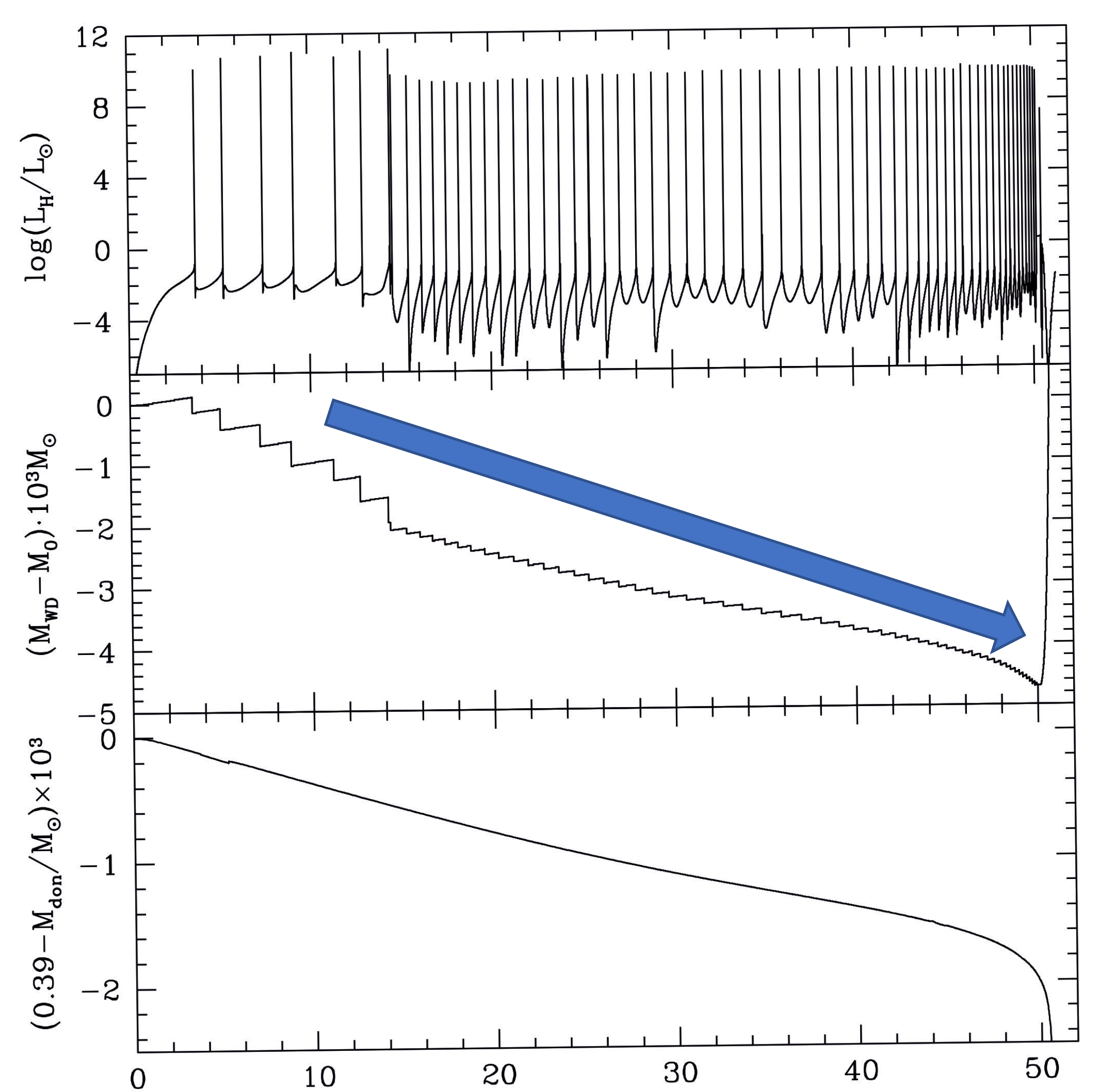

Piersanti+2024

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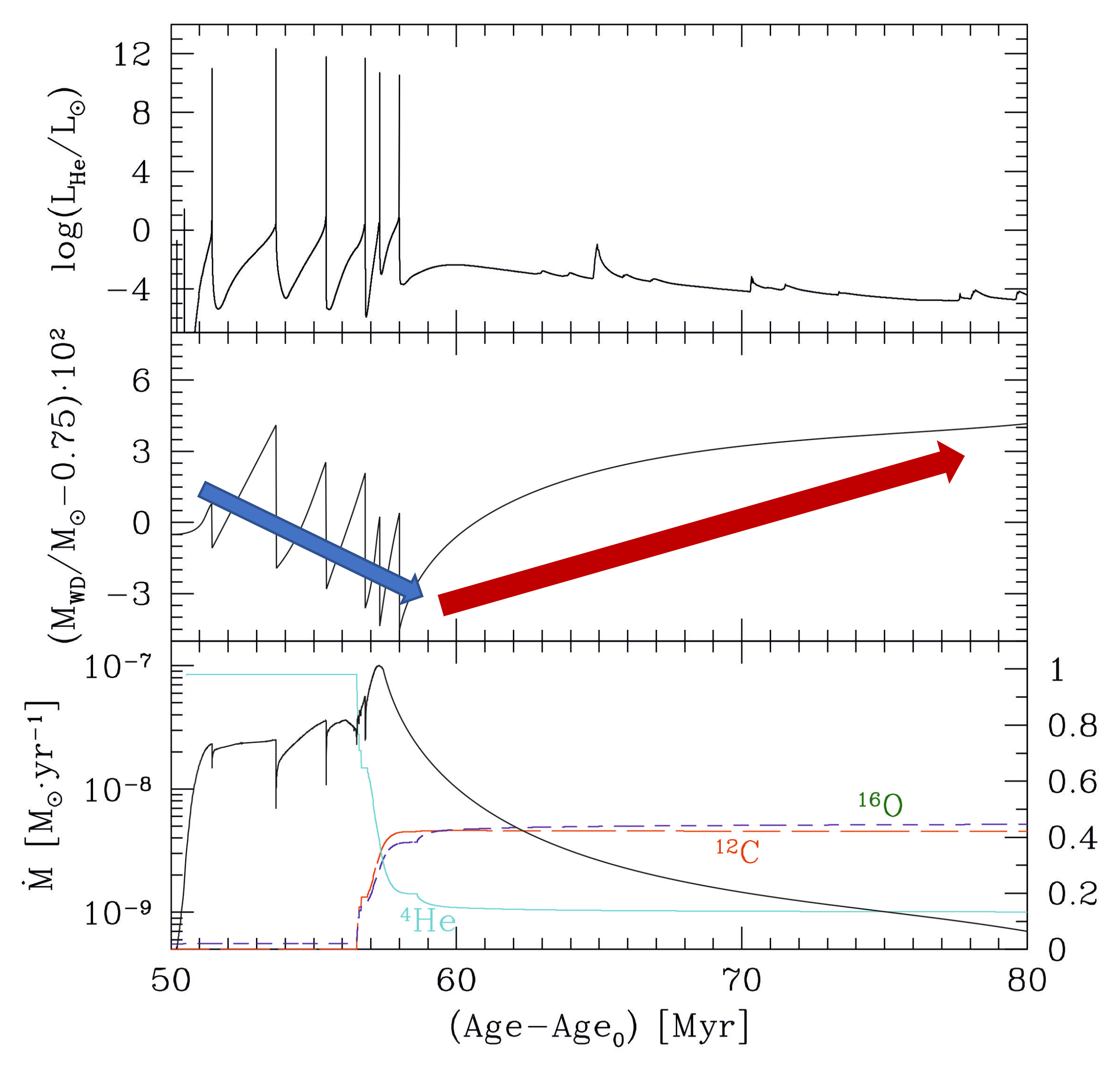
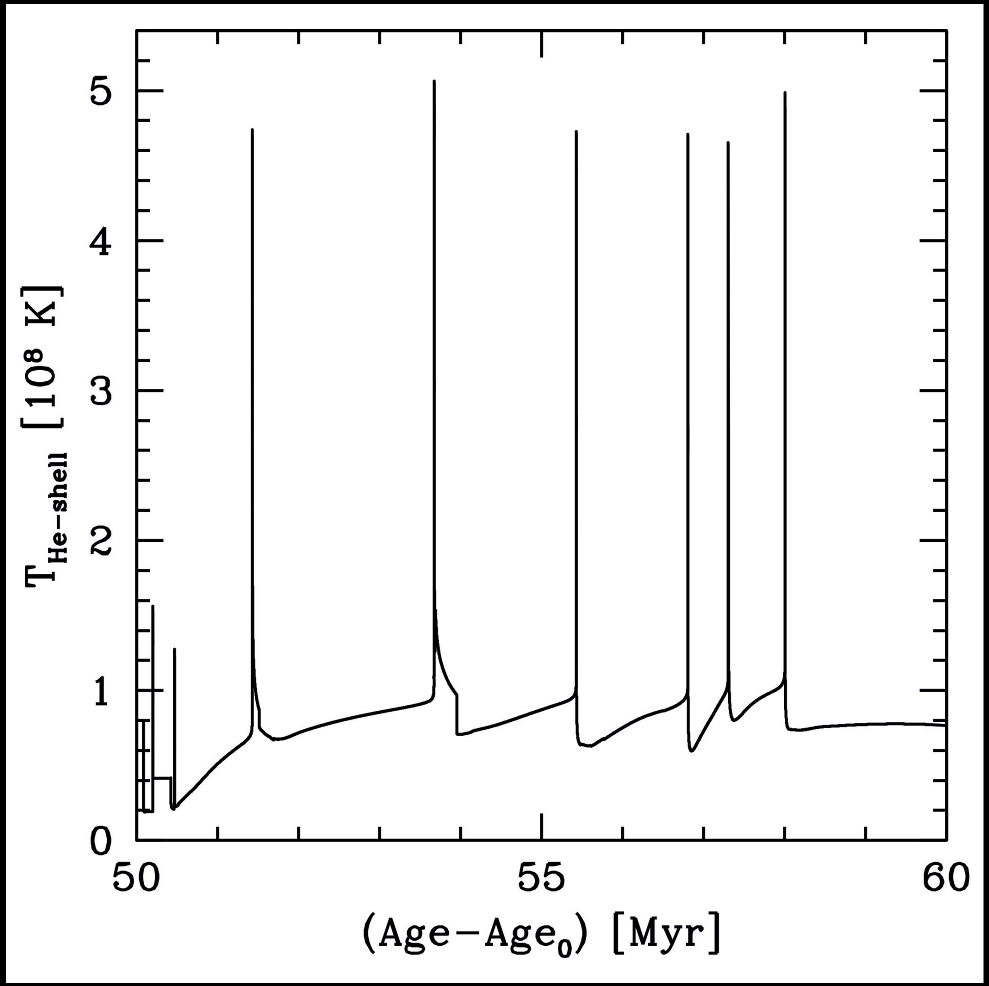


The PTF1 J2238+7430

During He-accretion…

T_{He} increases above 3×10^8 K



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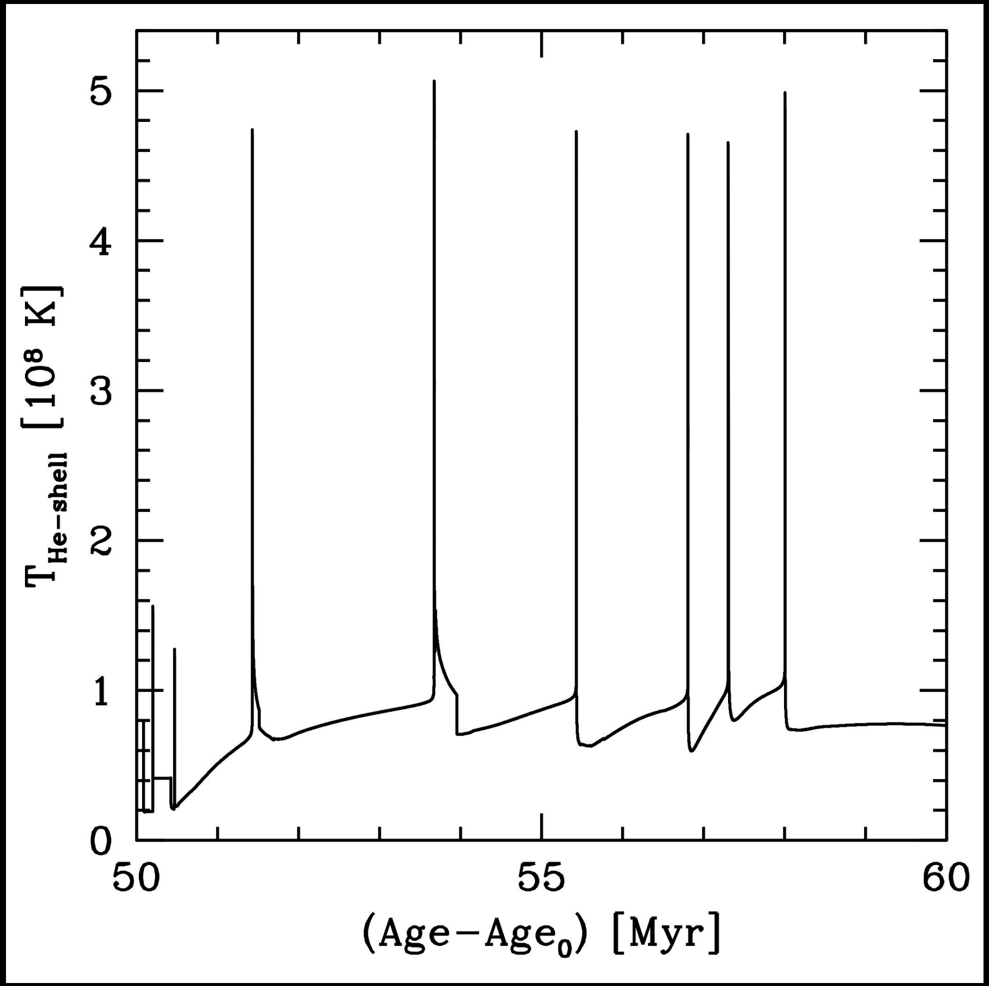
During He-accretion…

T_{He} increases above 3×10^8 K

α-captures on ^{22}Ne become active



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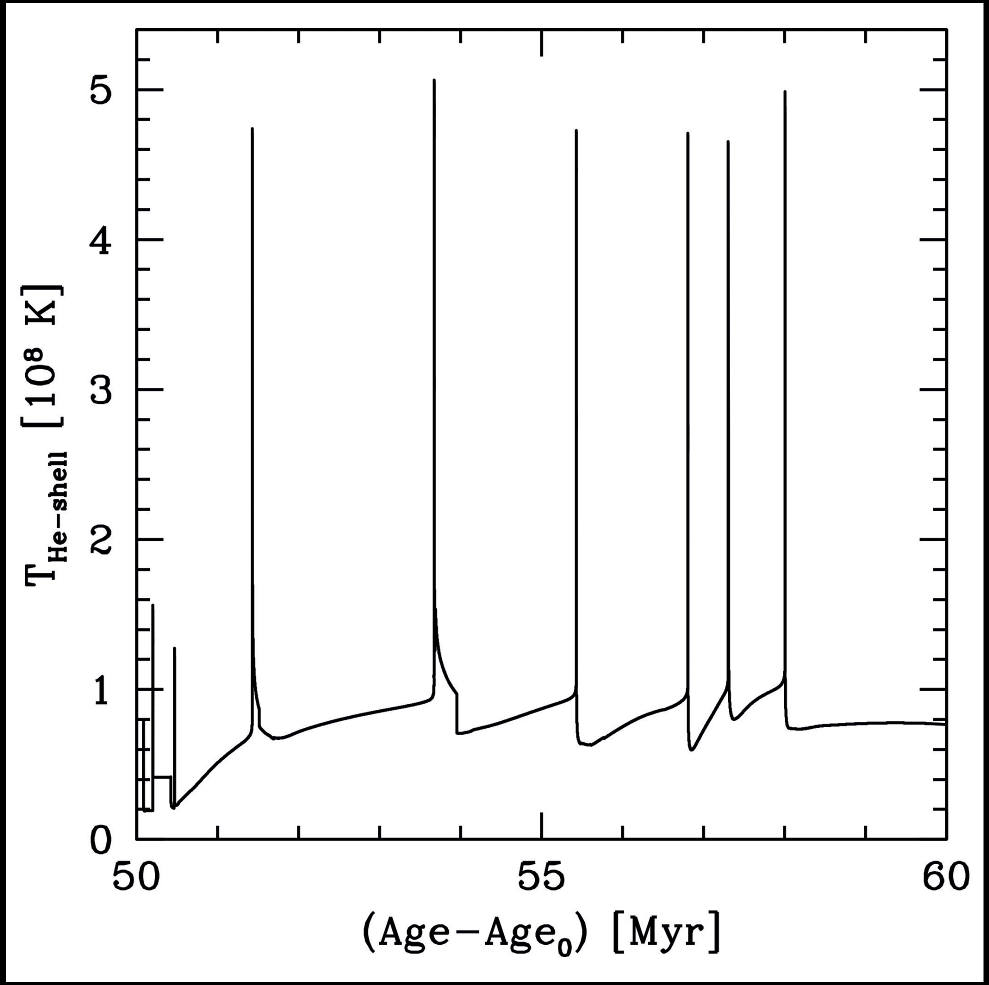
$$^{14}N(\alpha,\gamma)^{18}F \xrightarrow{\beta^+} {}^{18}O(\alpha,\gamma)^{22}Ne$$



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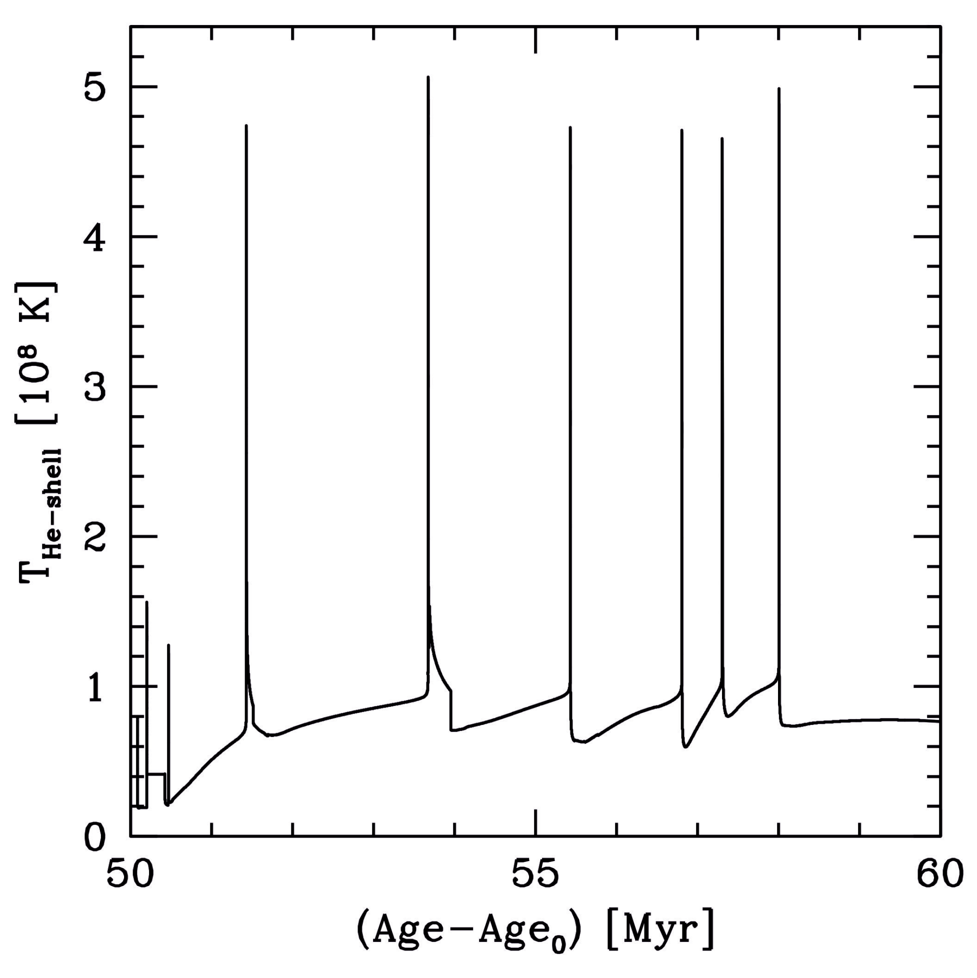

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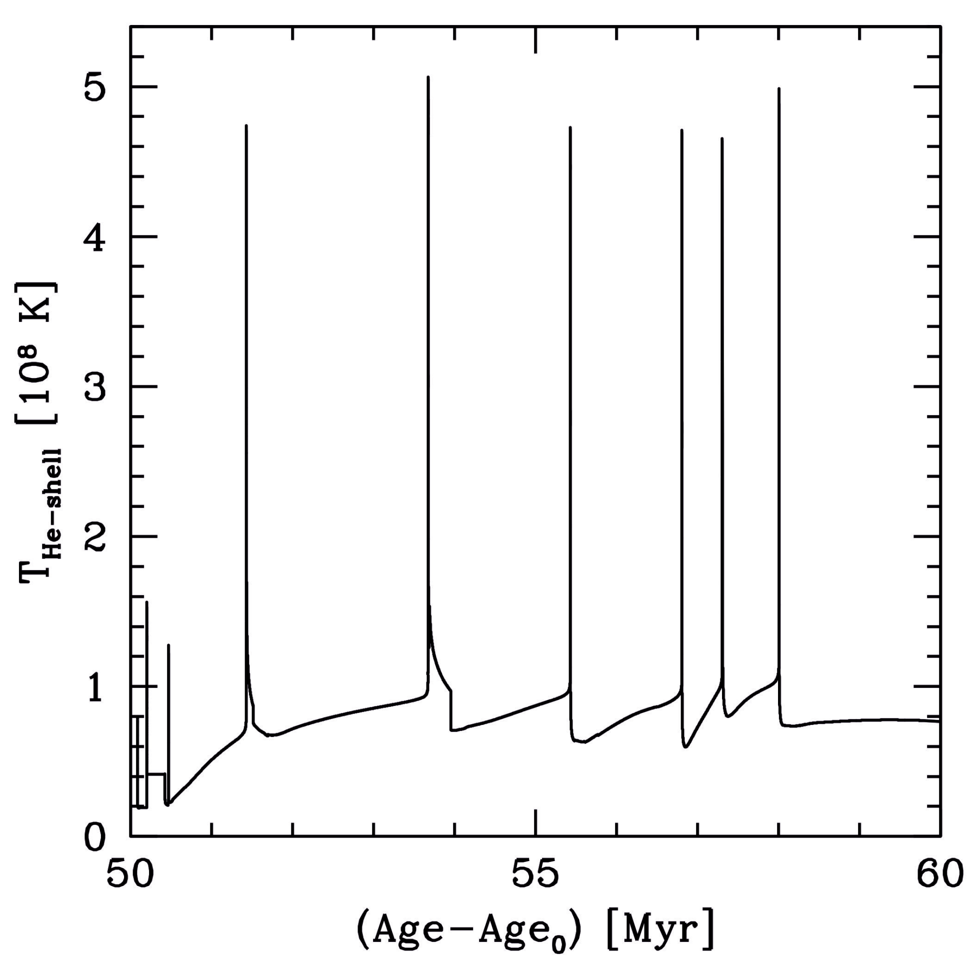
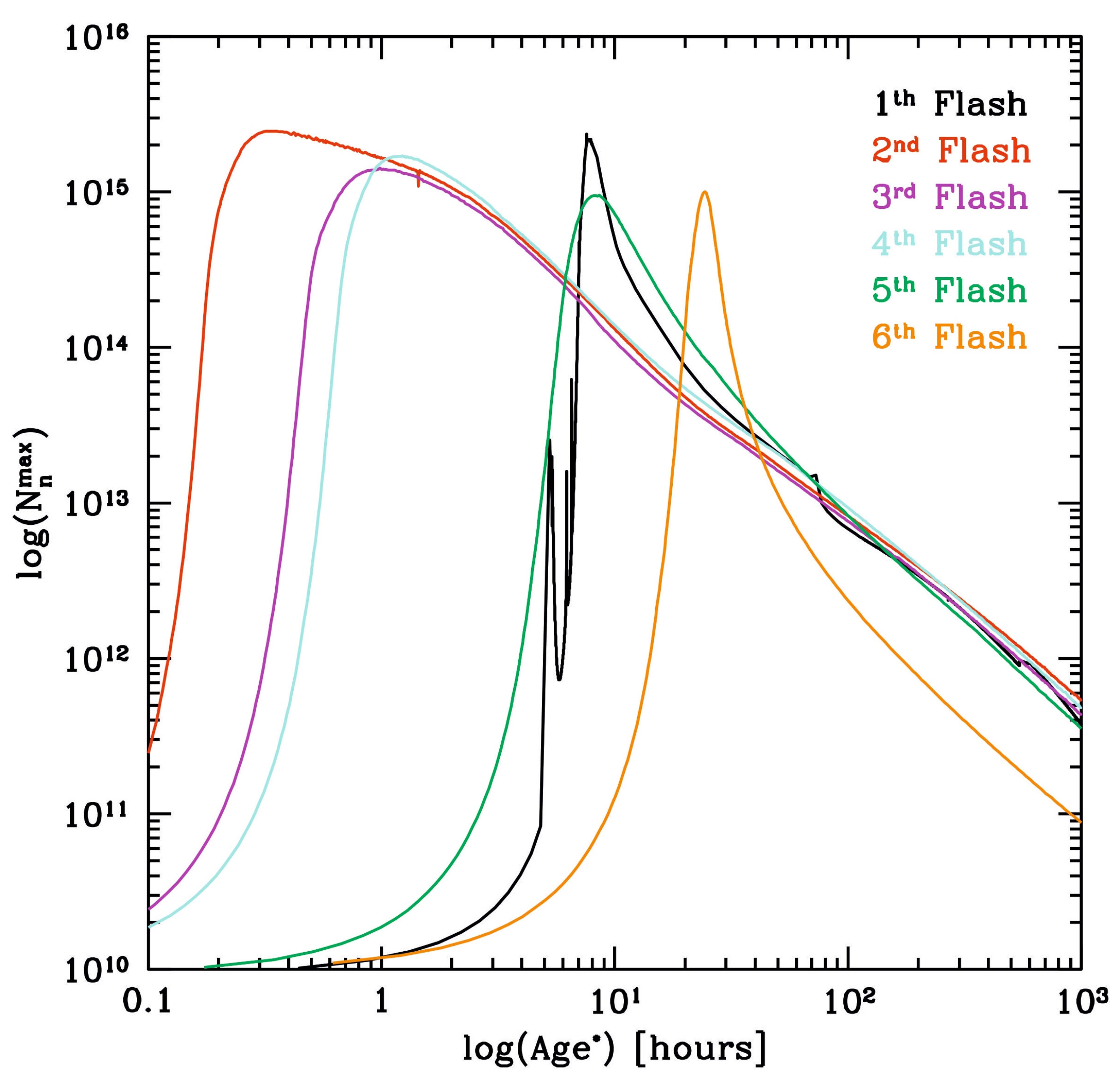
$$^{14}N(\alpha,\gamma)^{18}F \xrightarrow{\beta^+} {}^{18}O(\alpha,\gamma)^{22}Ne$$

$$X(^{22}Ne) \sim Z_{ini}$$



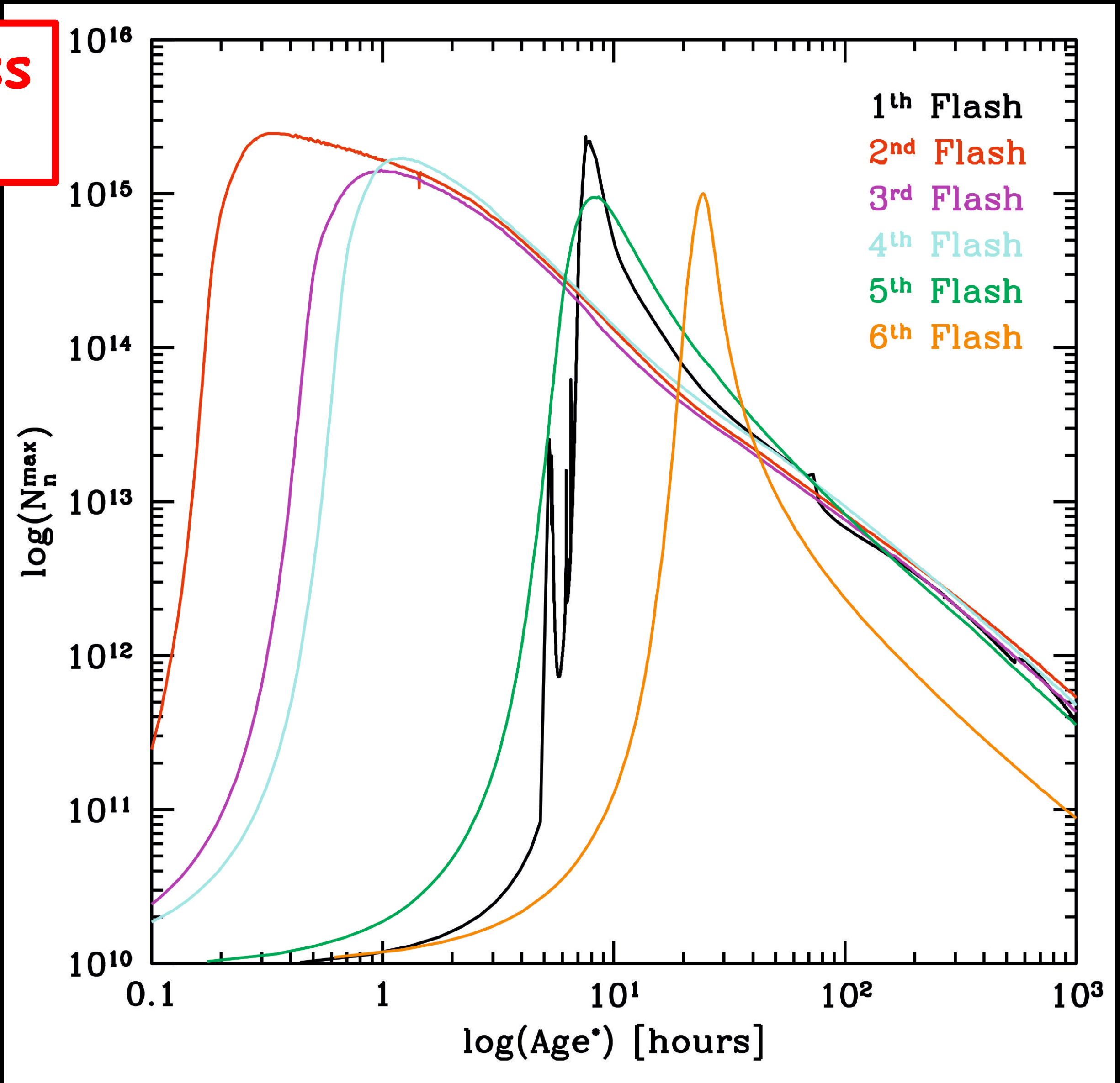
Huge neutron flux is expected!!!

The PTF1 J2238+7430



The PTF1 J2238+7430

Typical of i-process nucleosynthesis!



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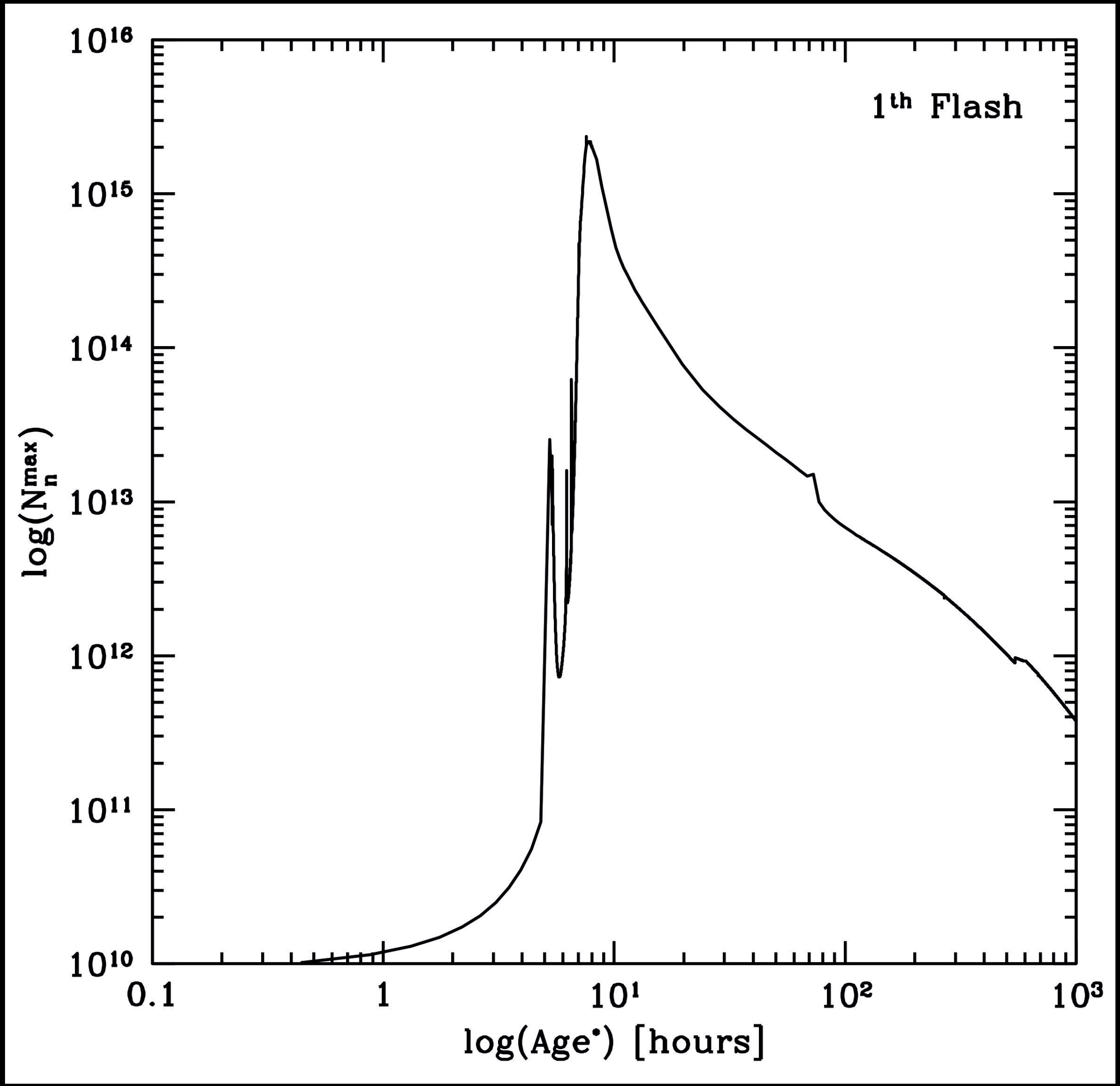

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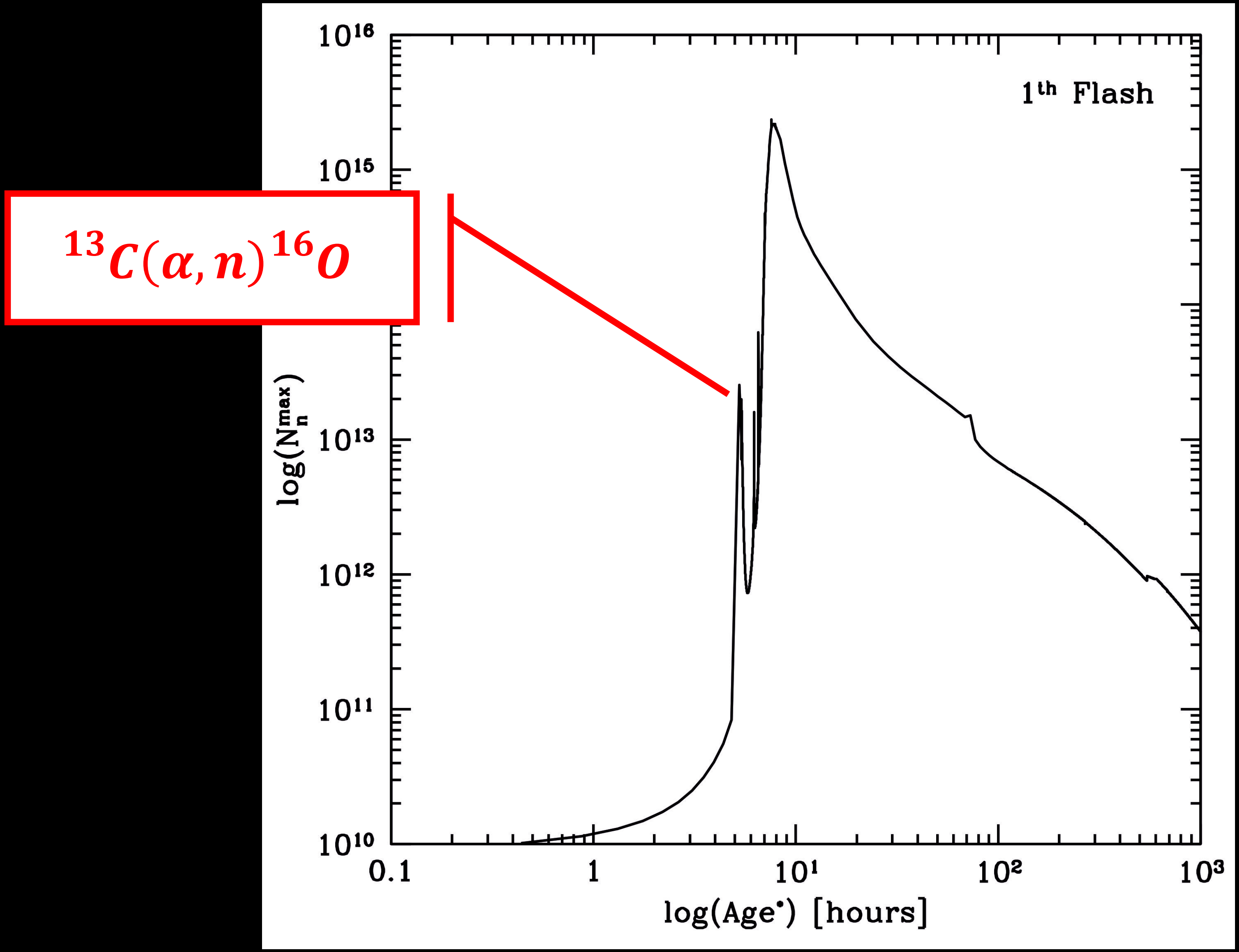

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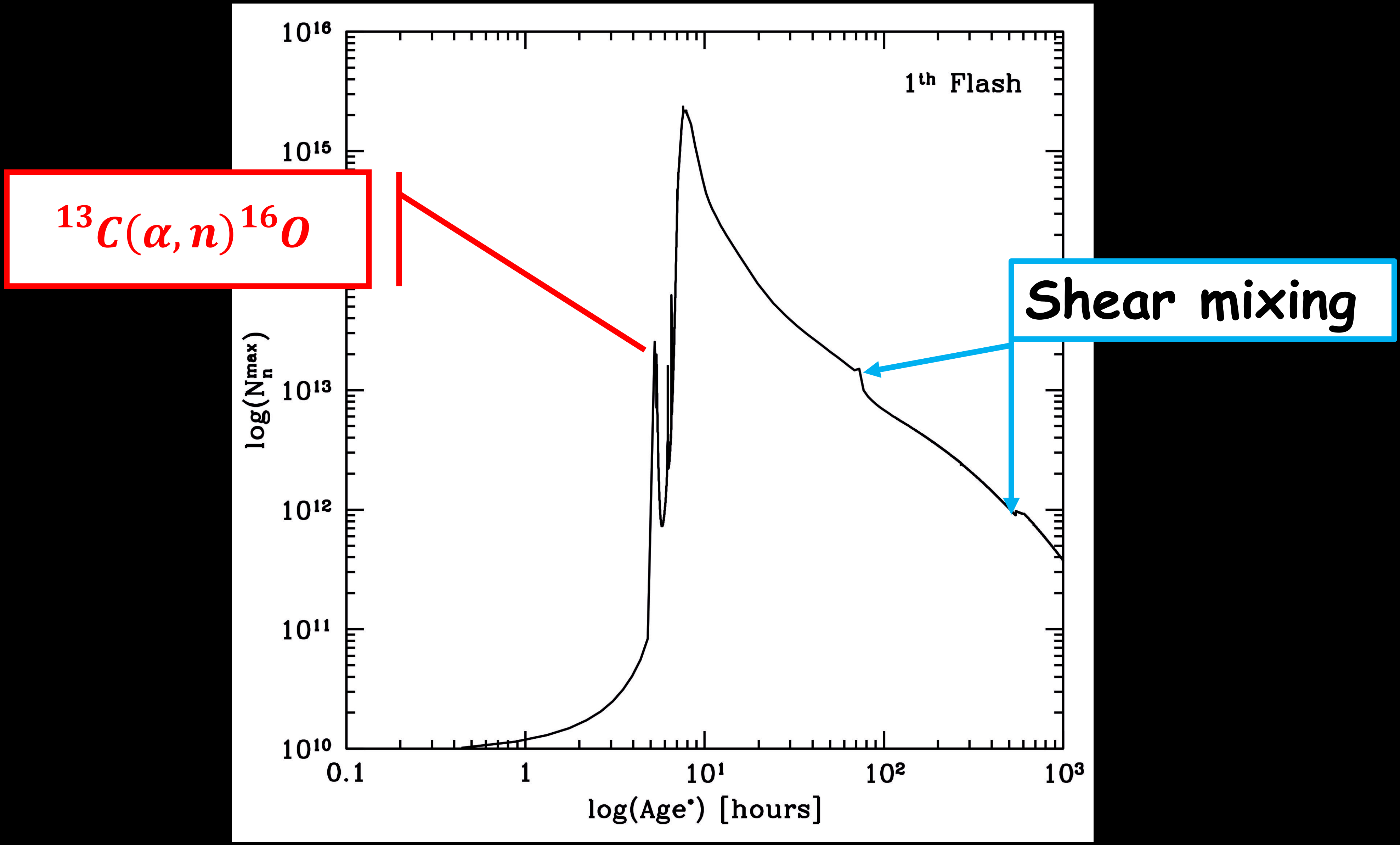

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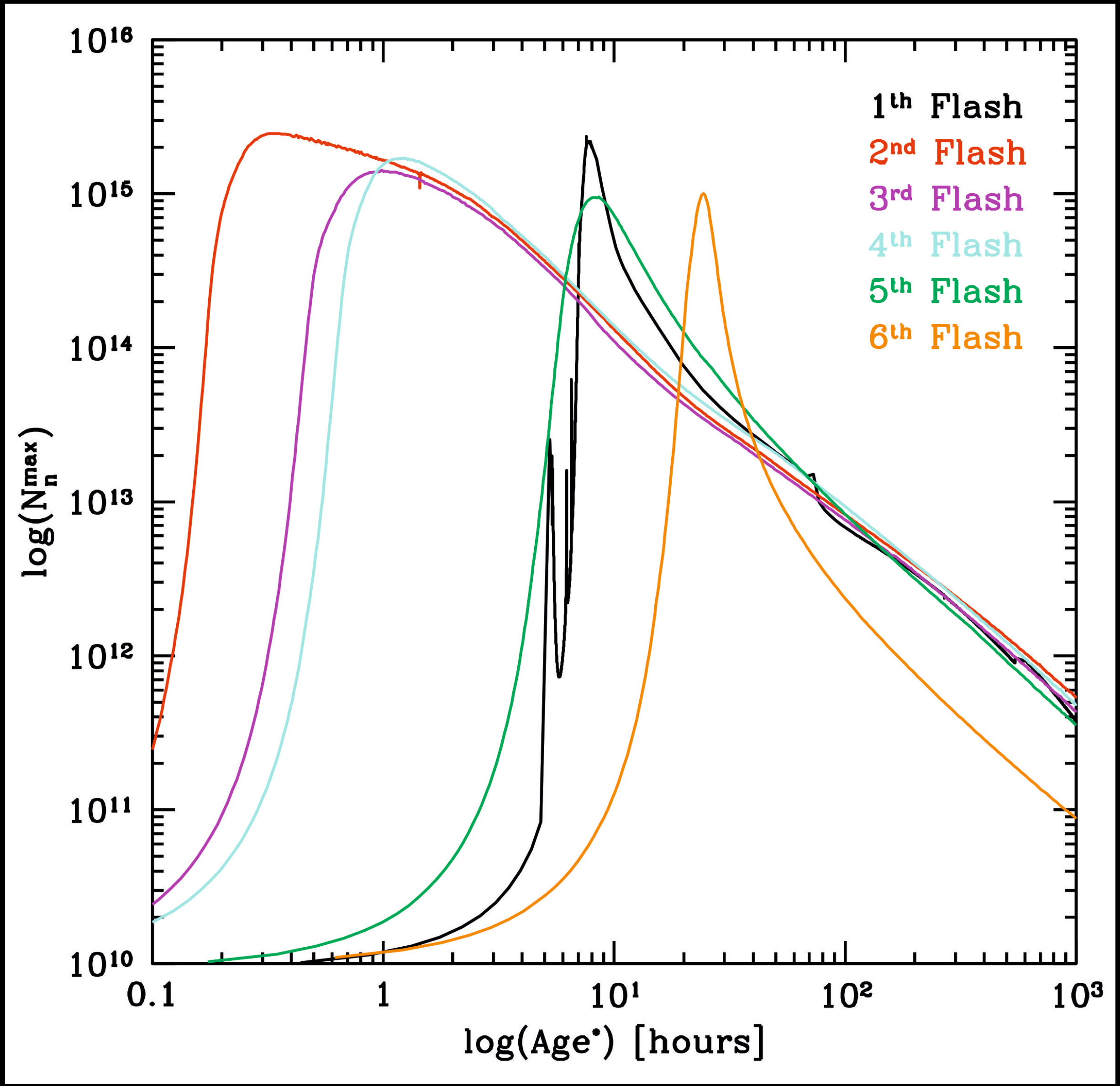

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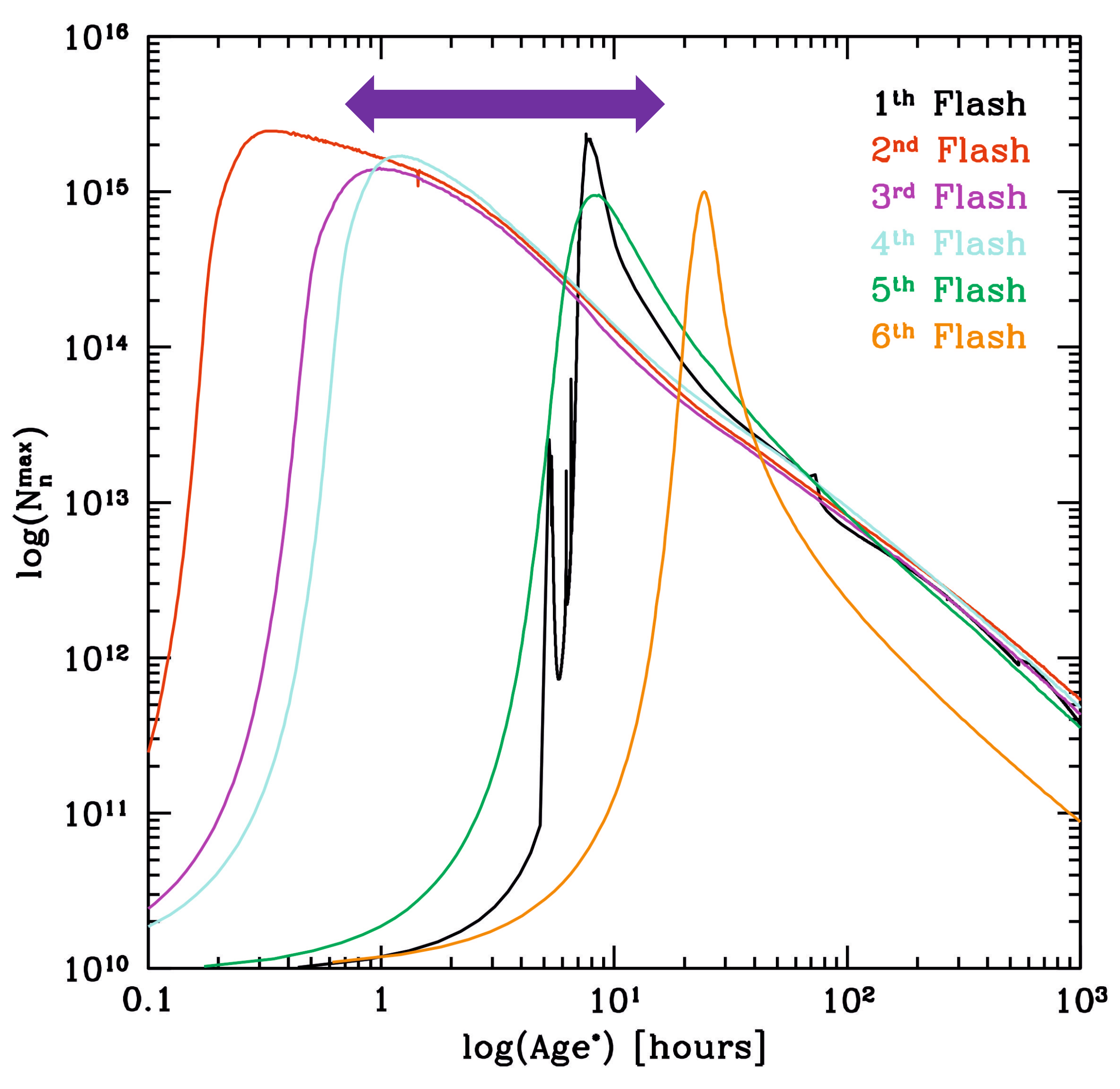

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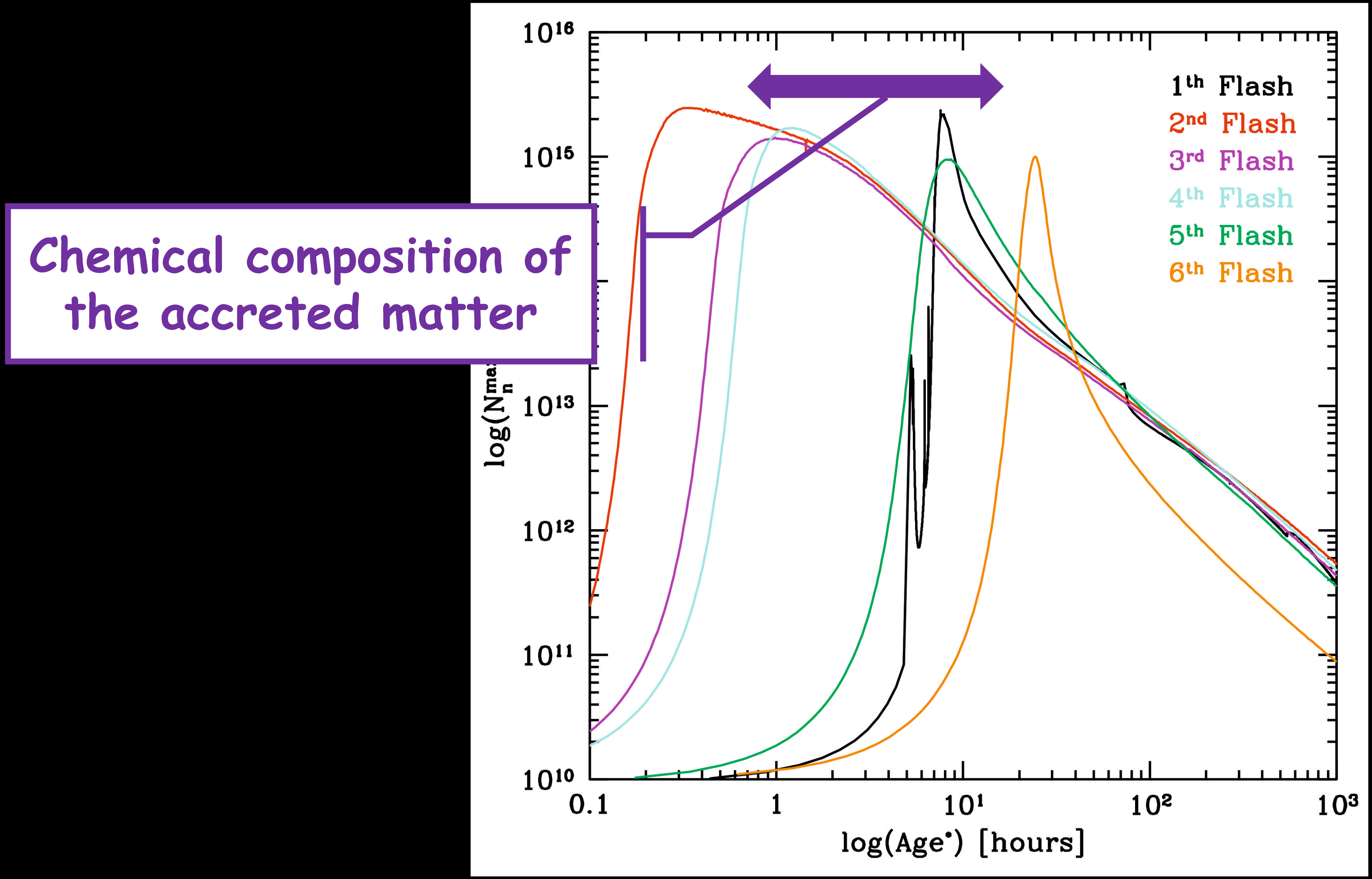

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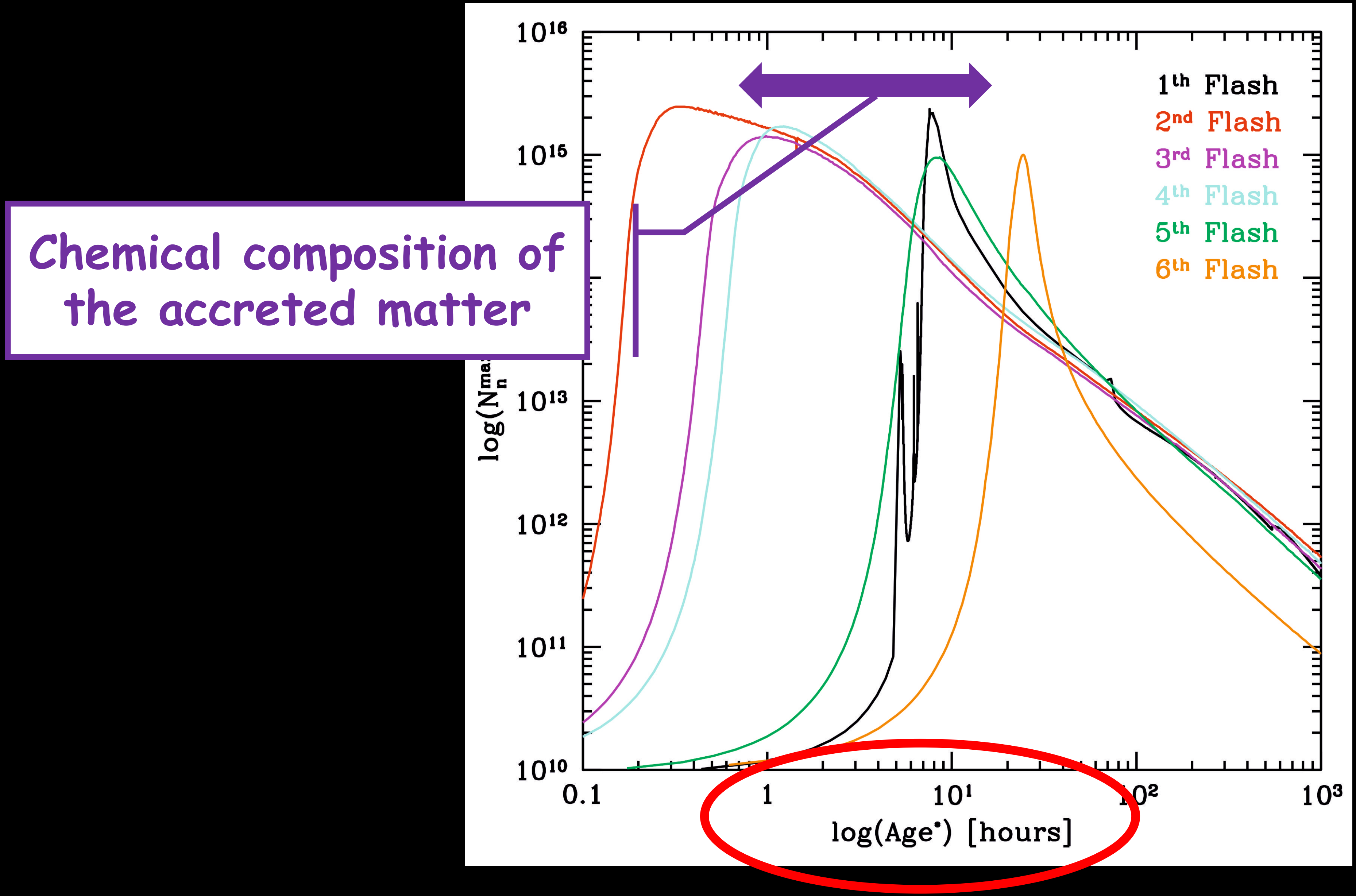

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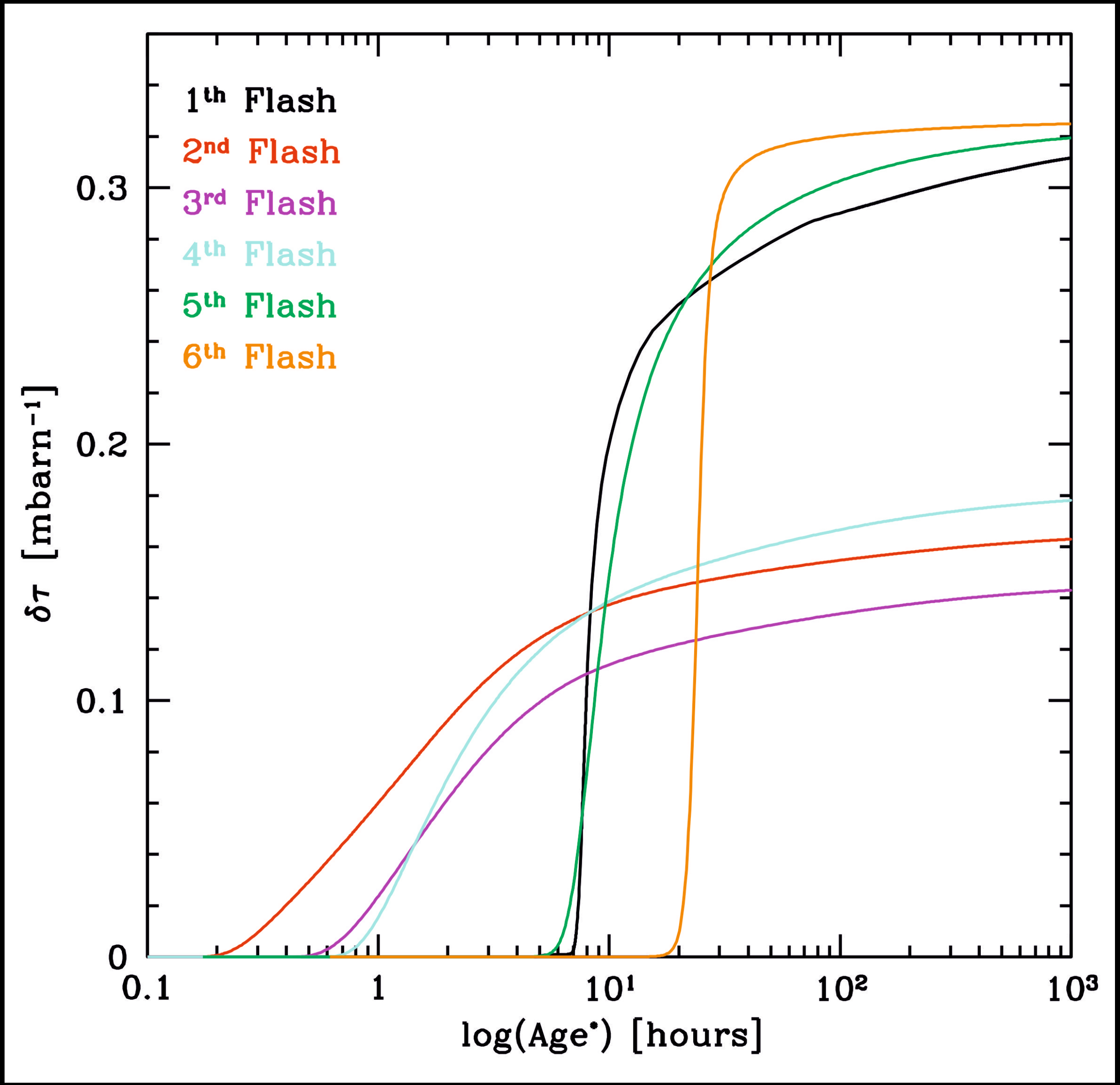

$$\delta\tau = \int_{\Delta t} \frac{\int_{M_{conv}} N_N v_{th} dm}{\int_{M_{conv}} dm} dt$$

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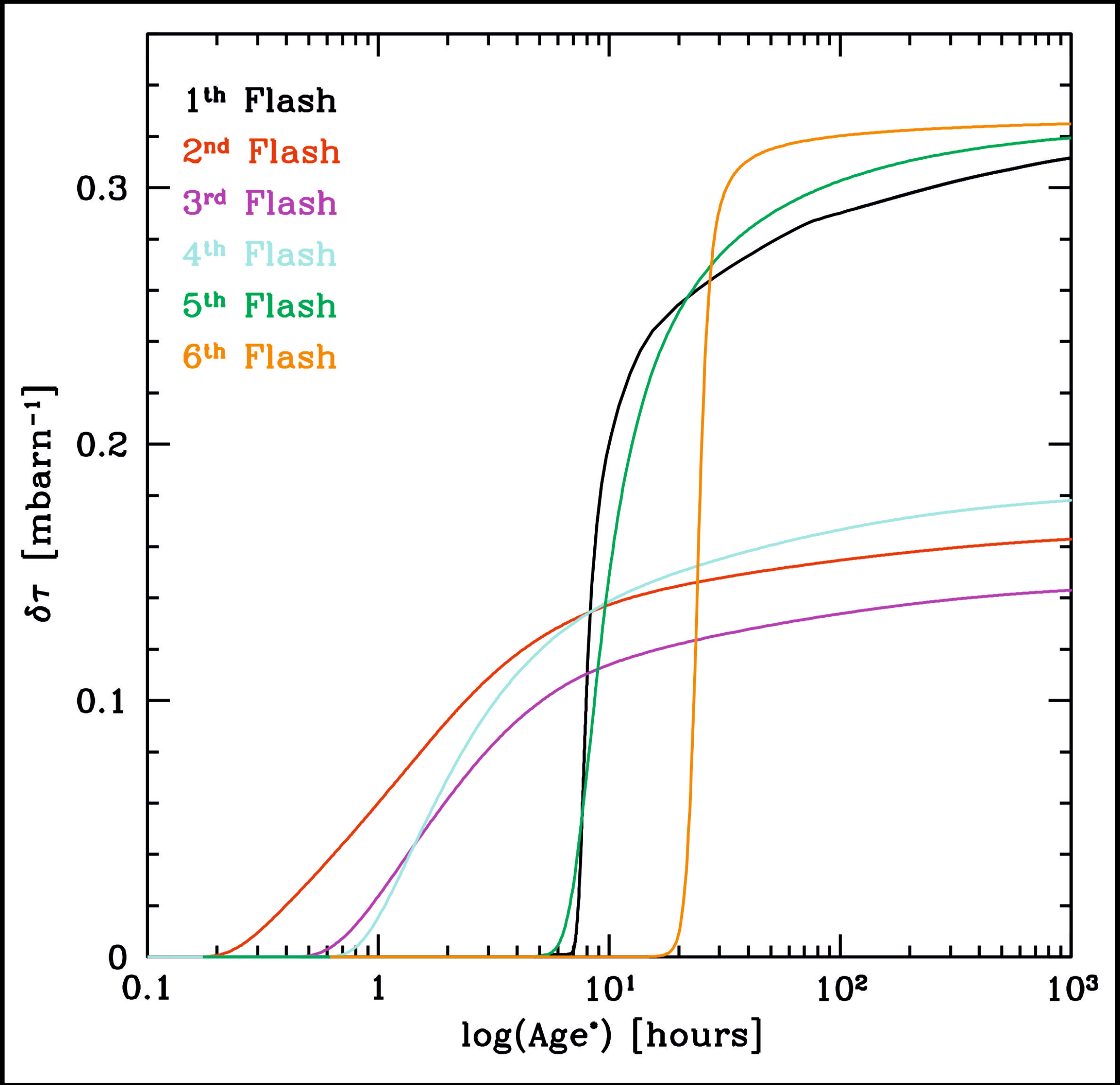

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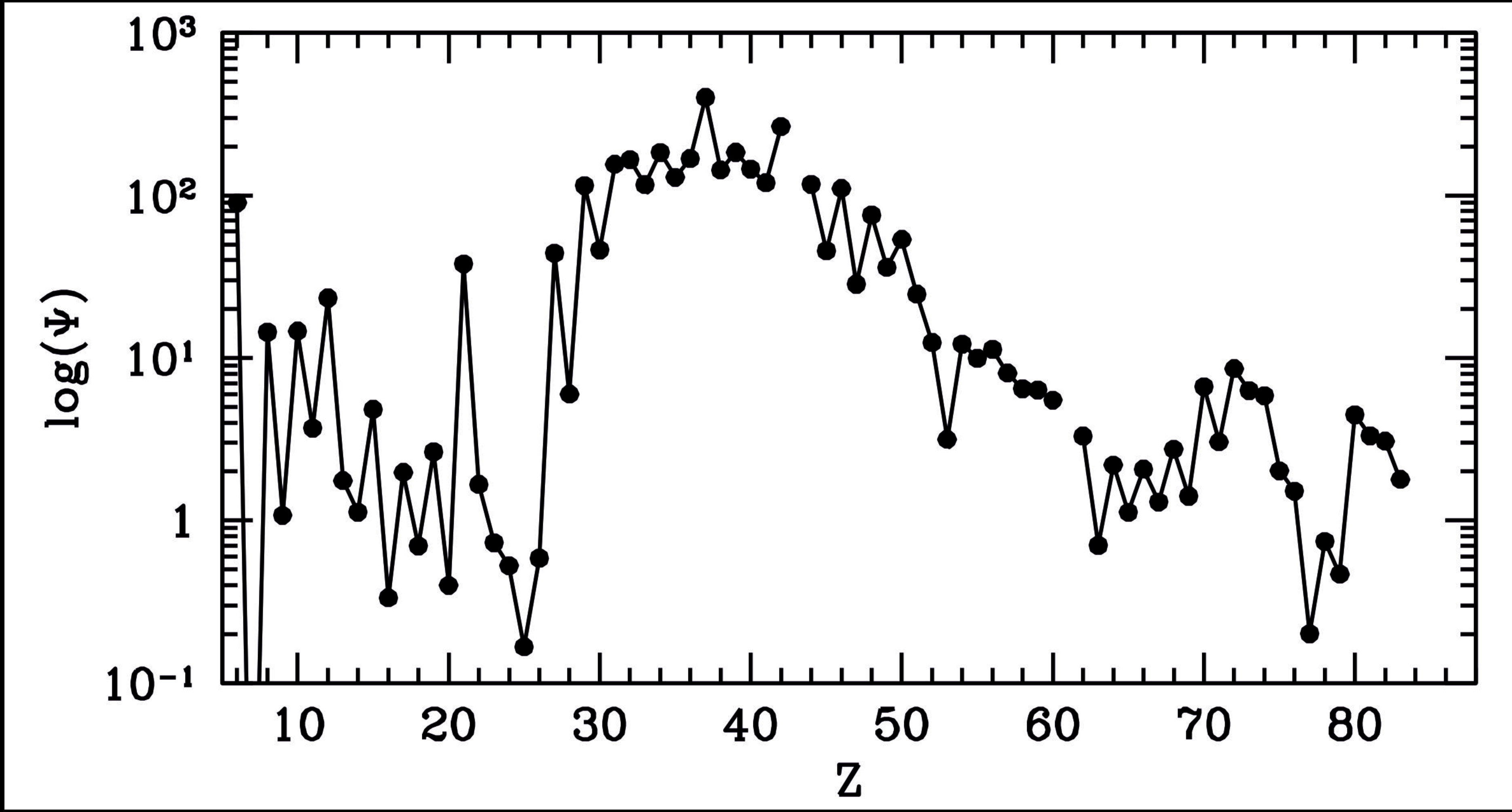
Weak-s nucleosynthesis

The PTF1 J2238+7430



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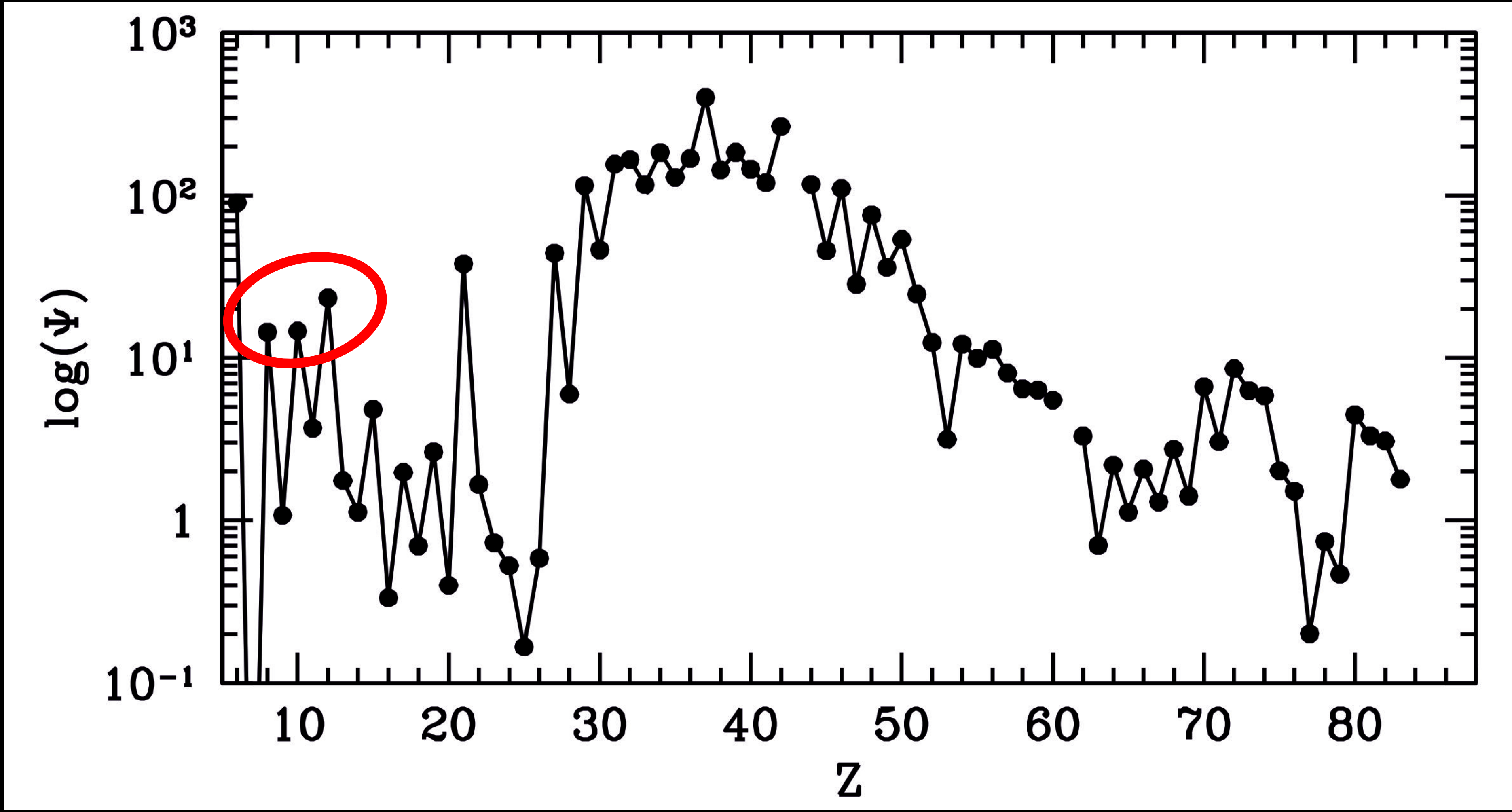

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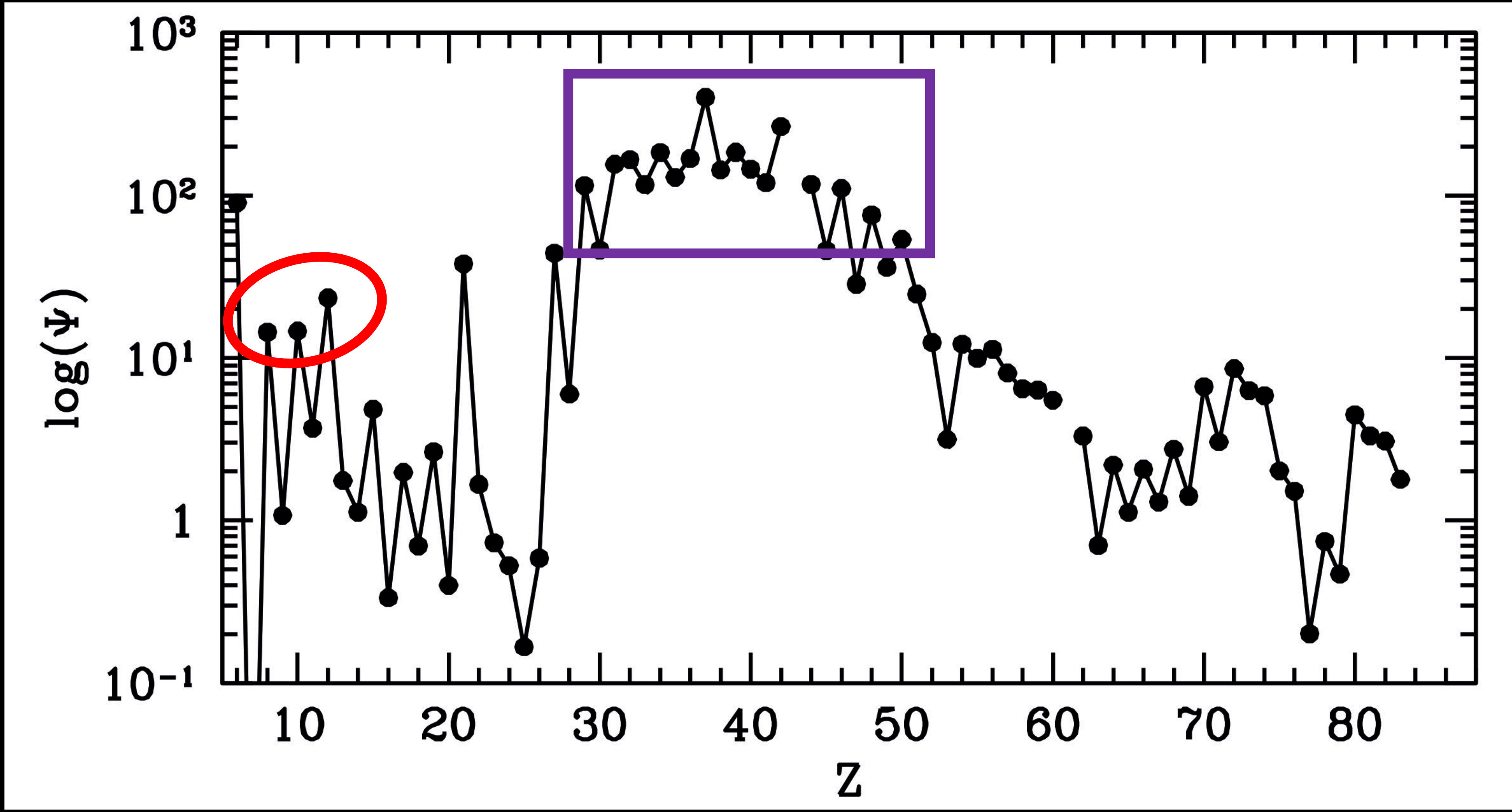

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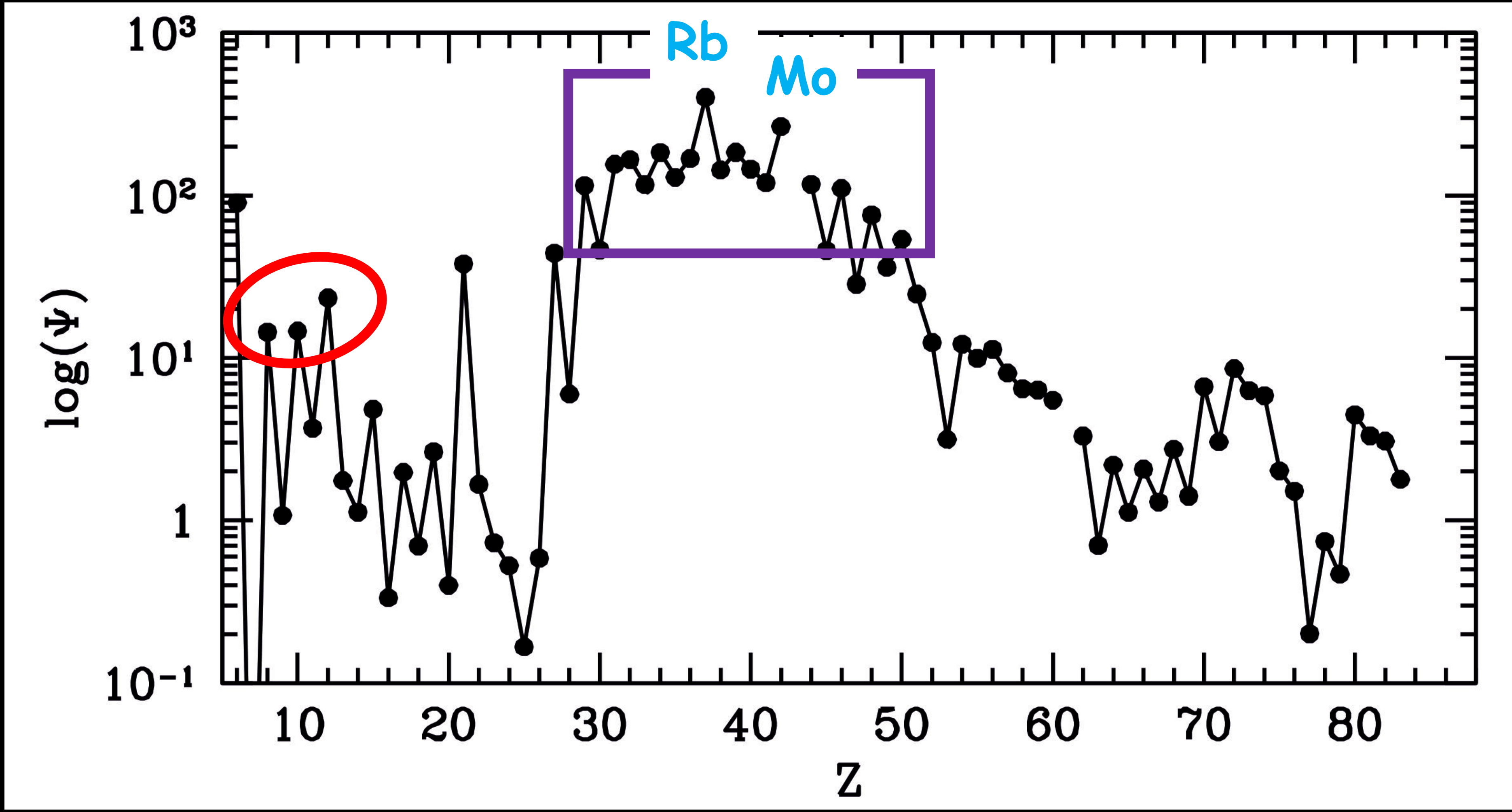

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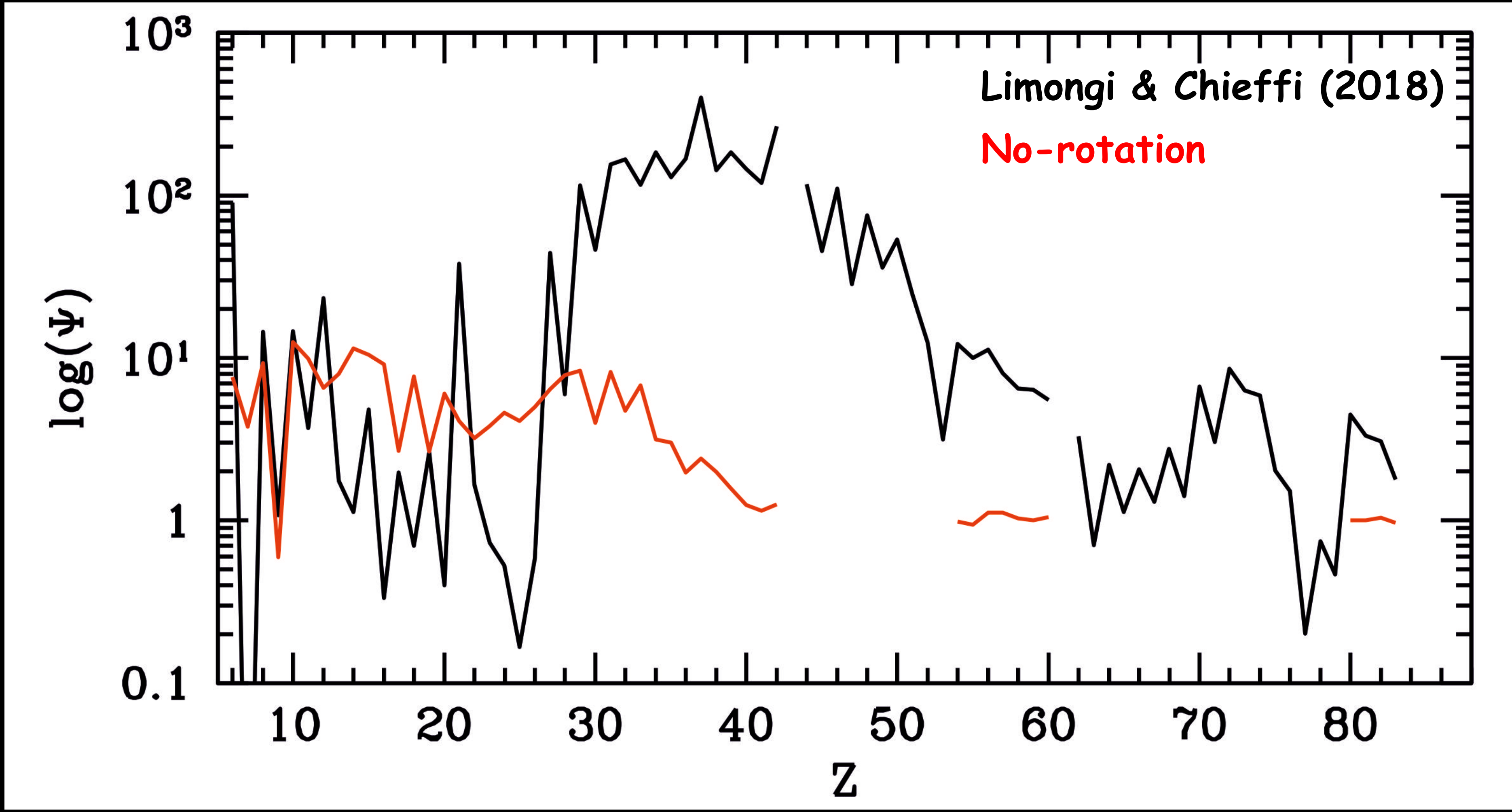

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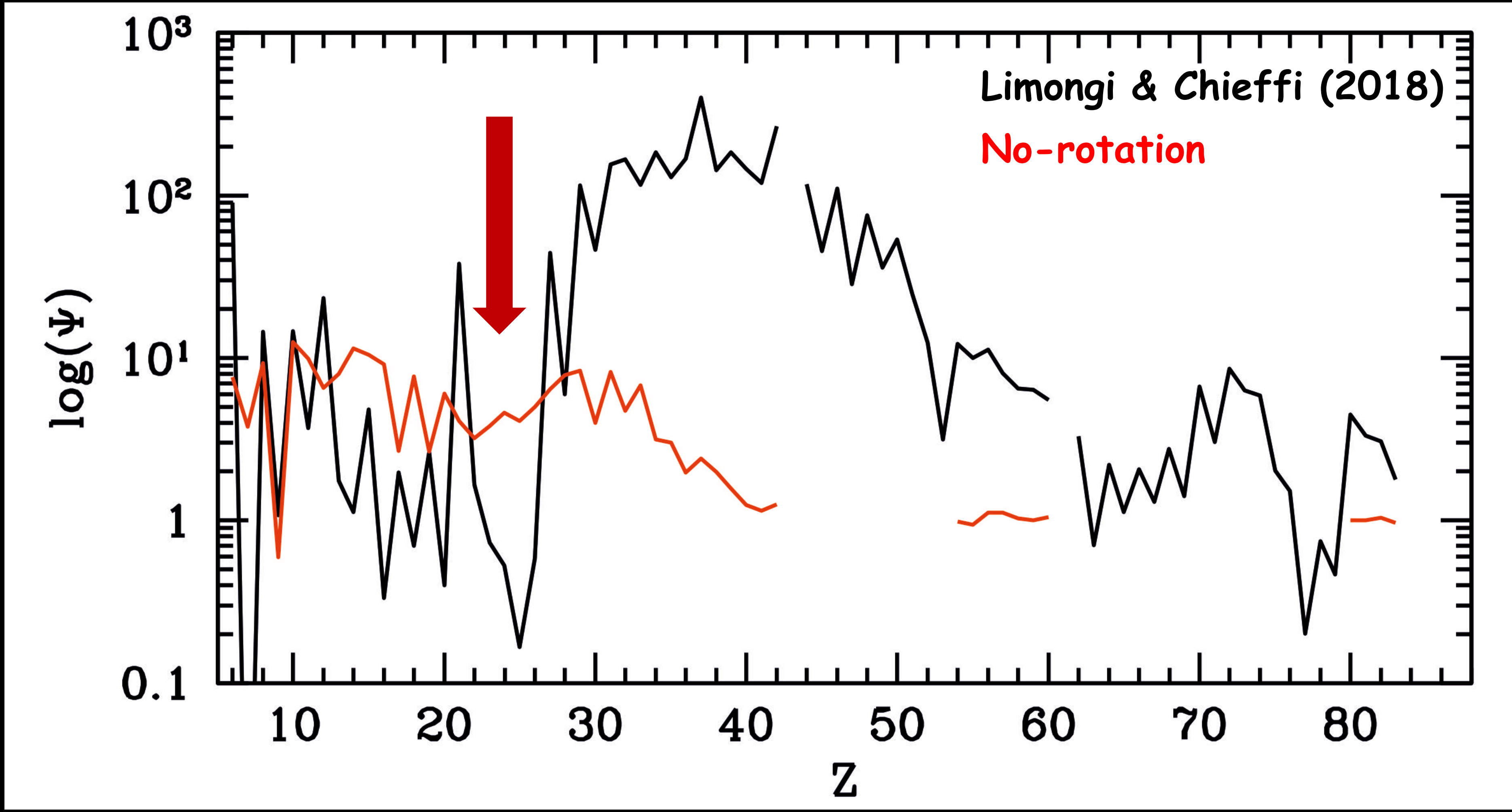

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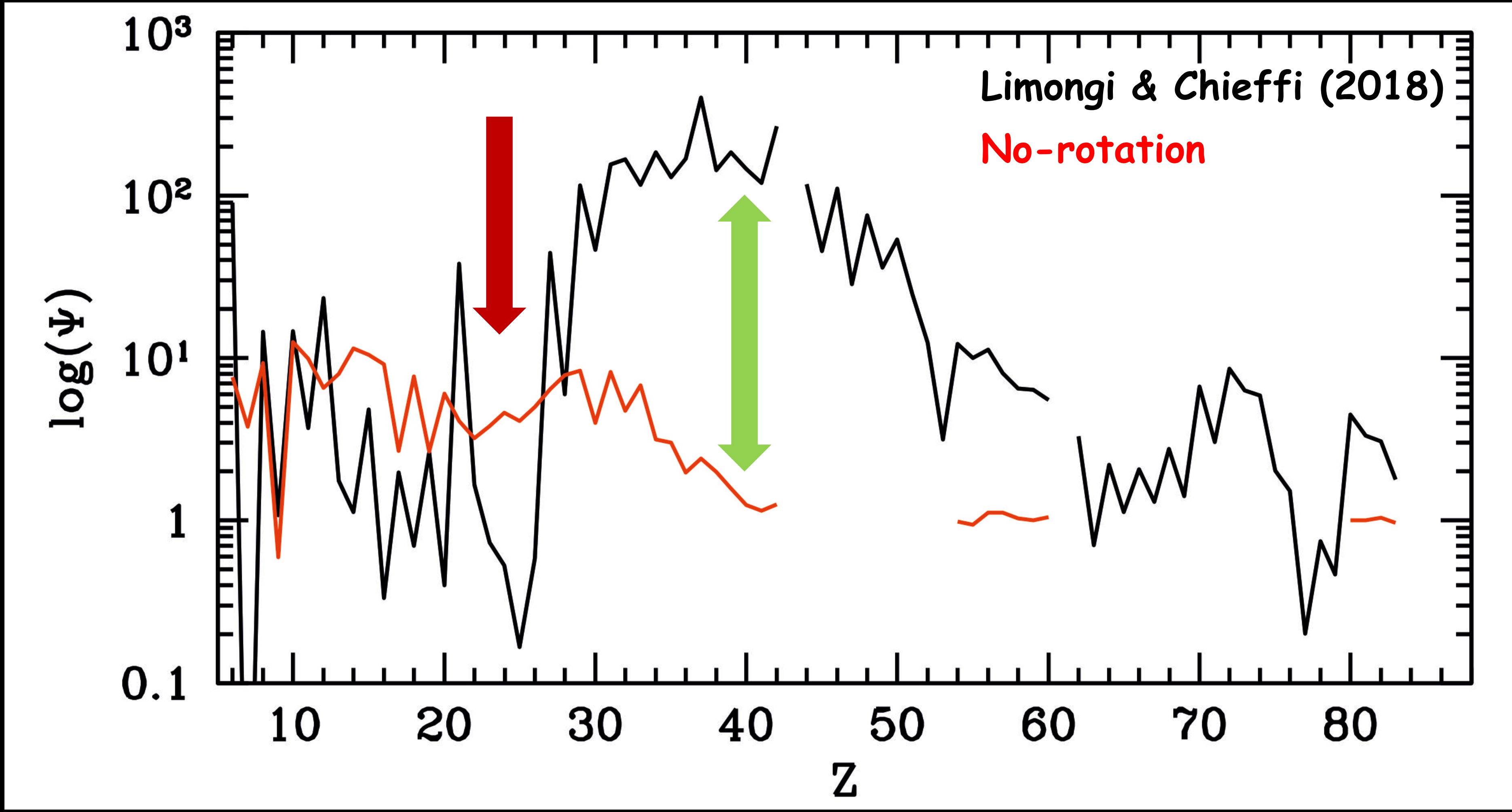

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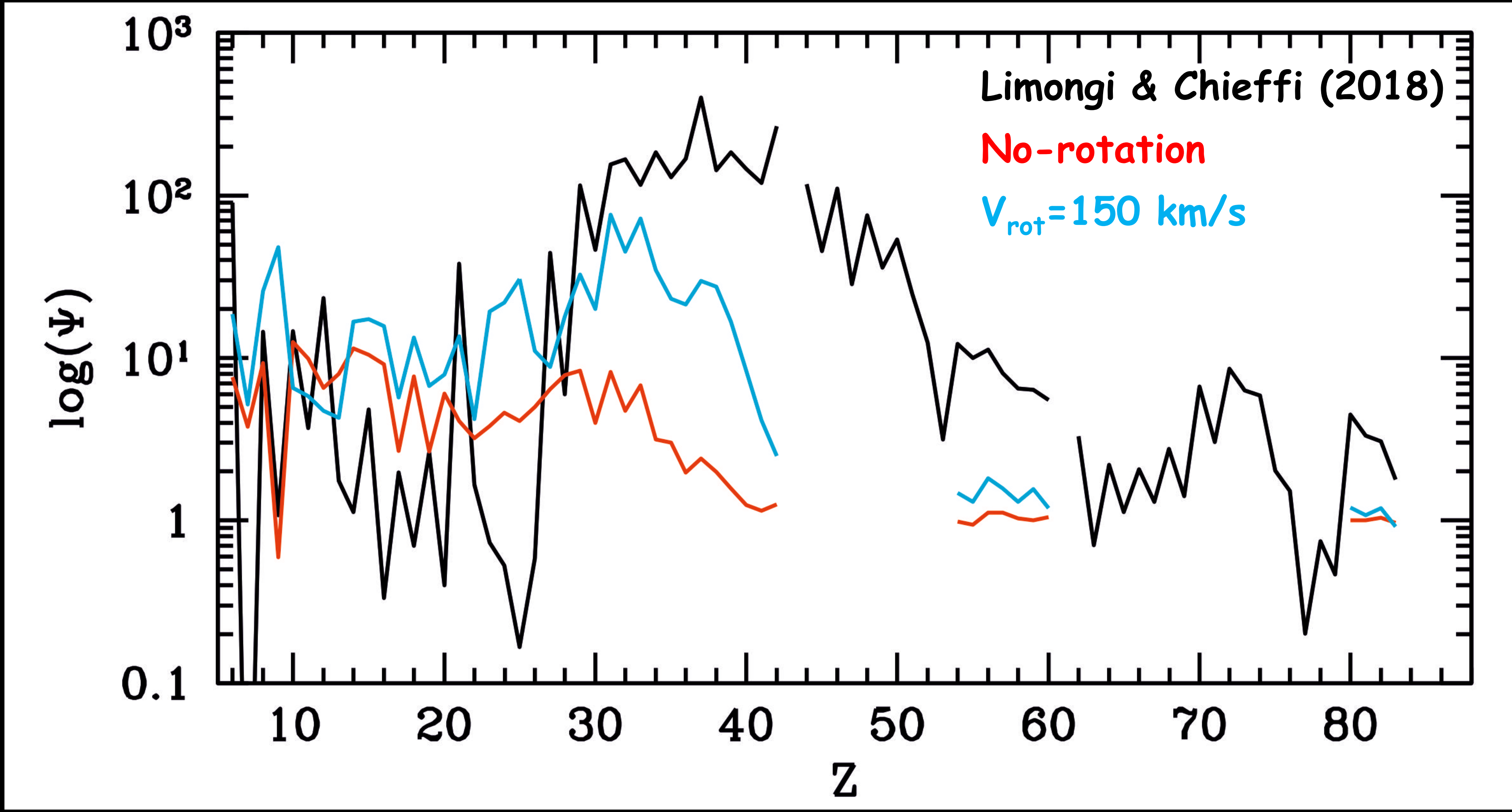

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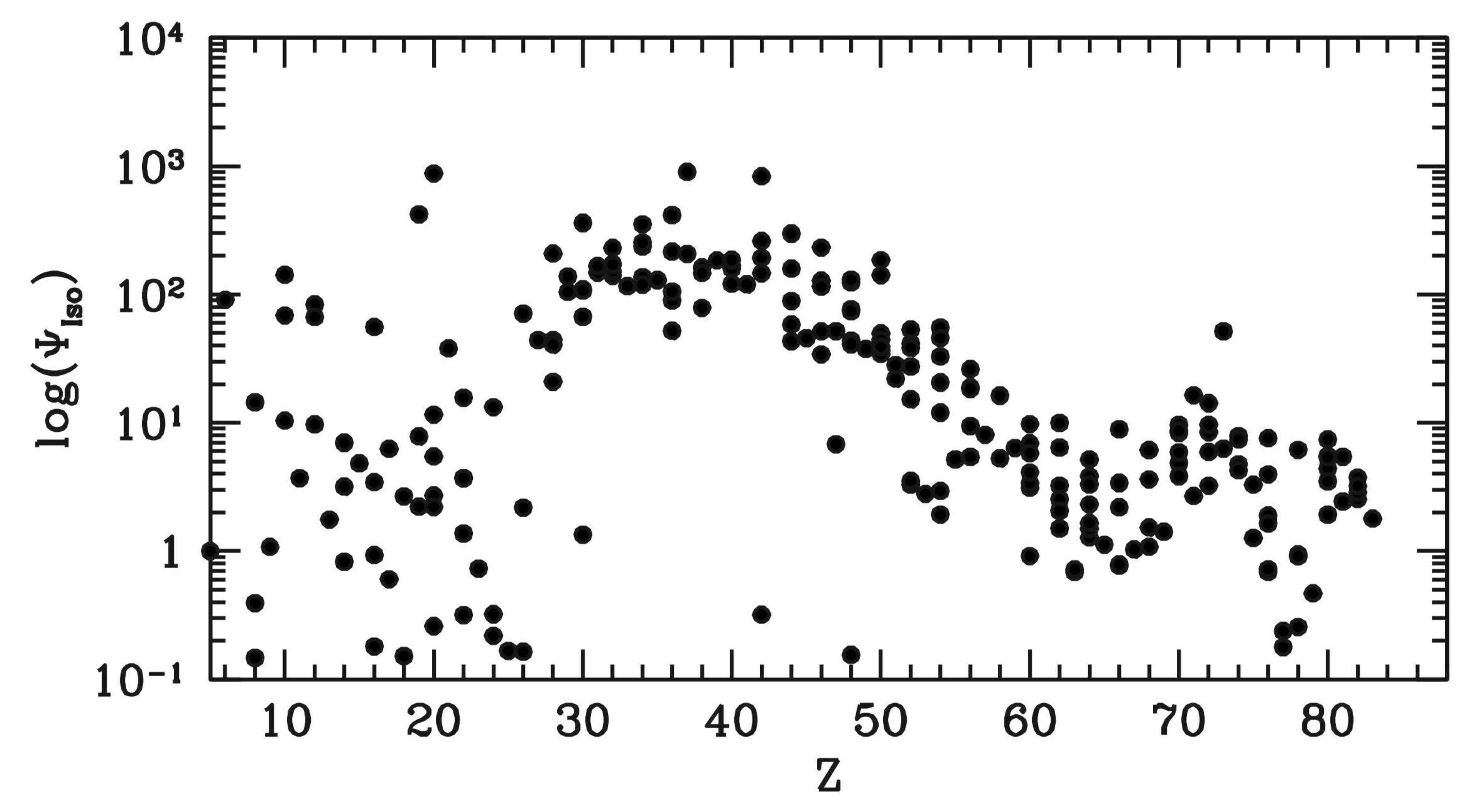

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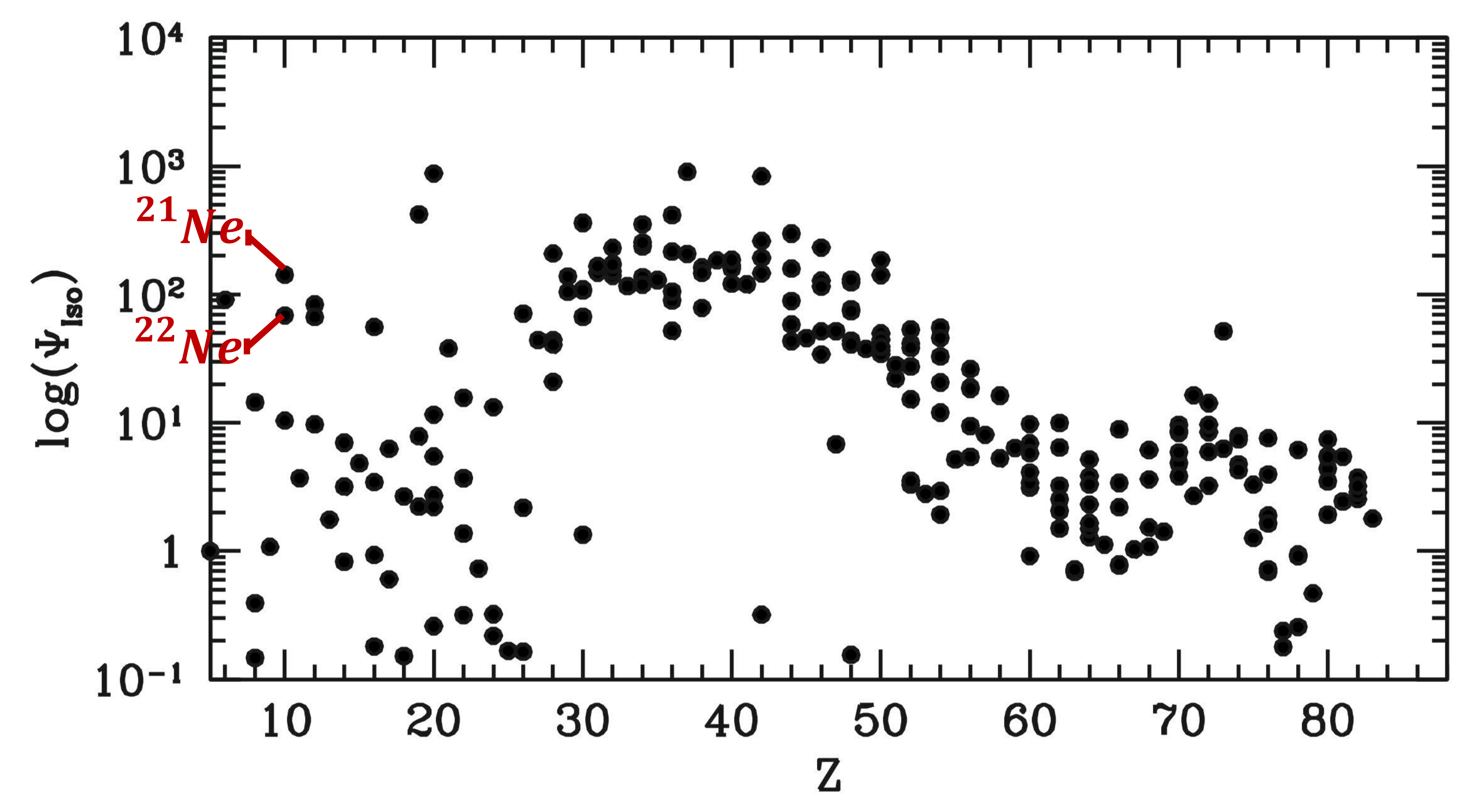

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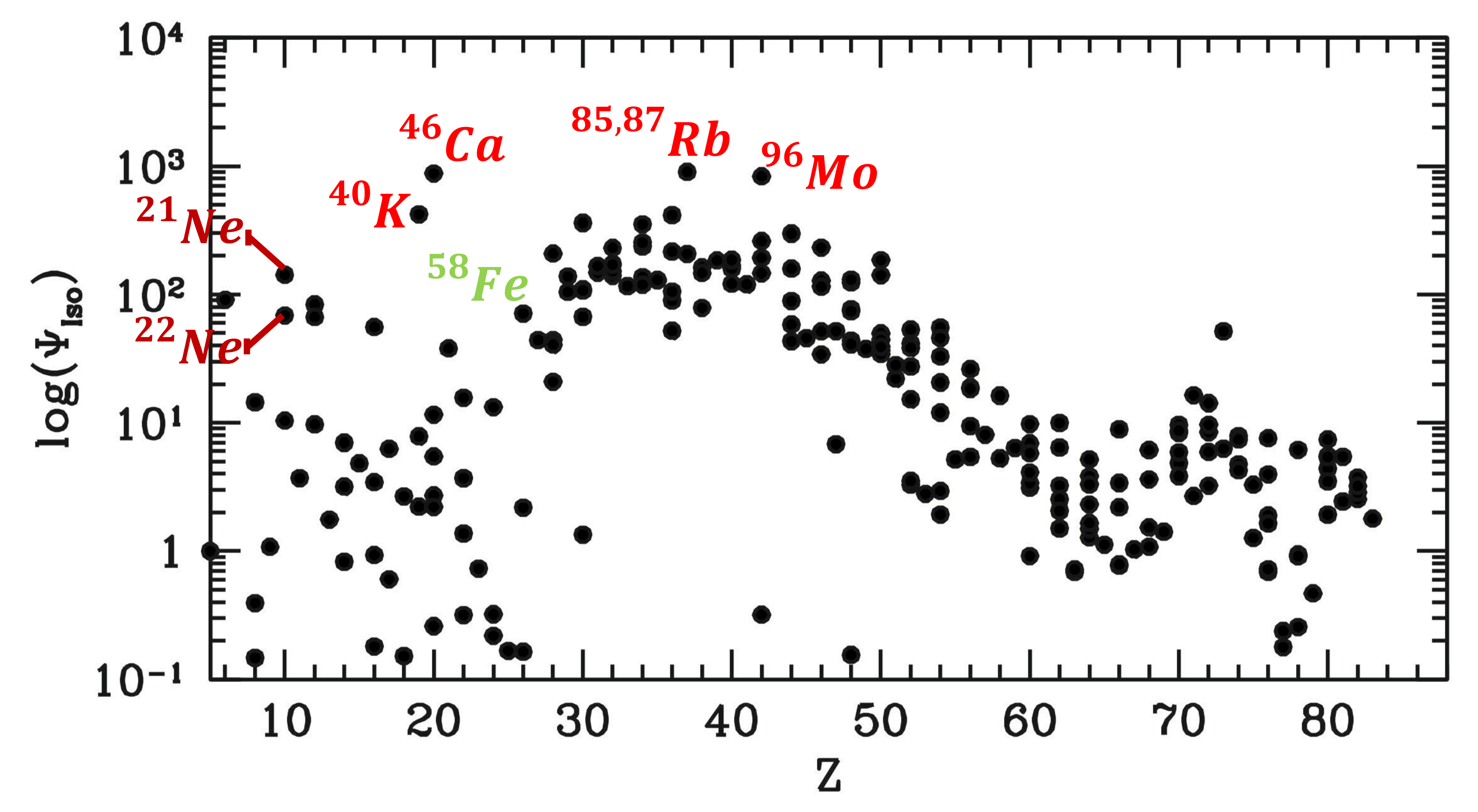

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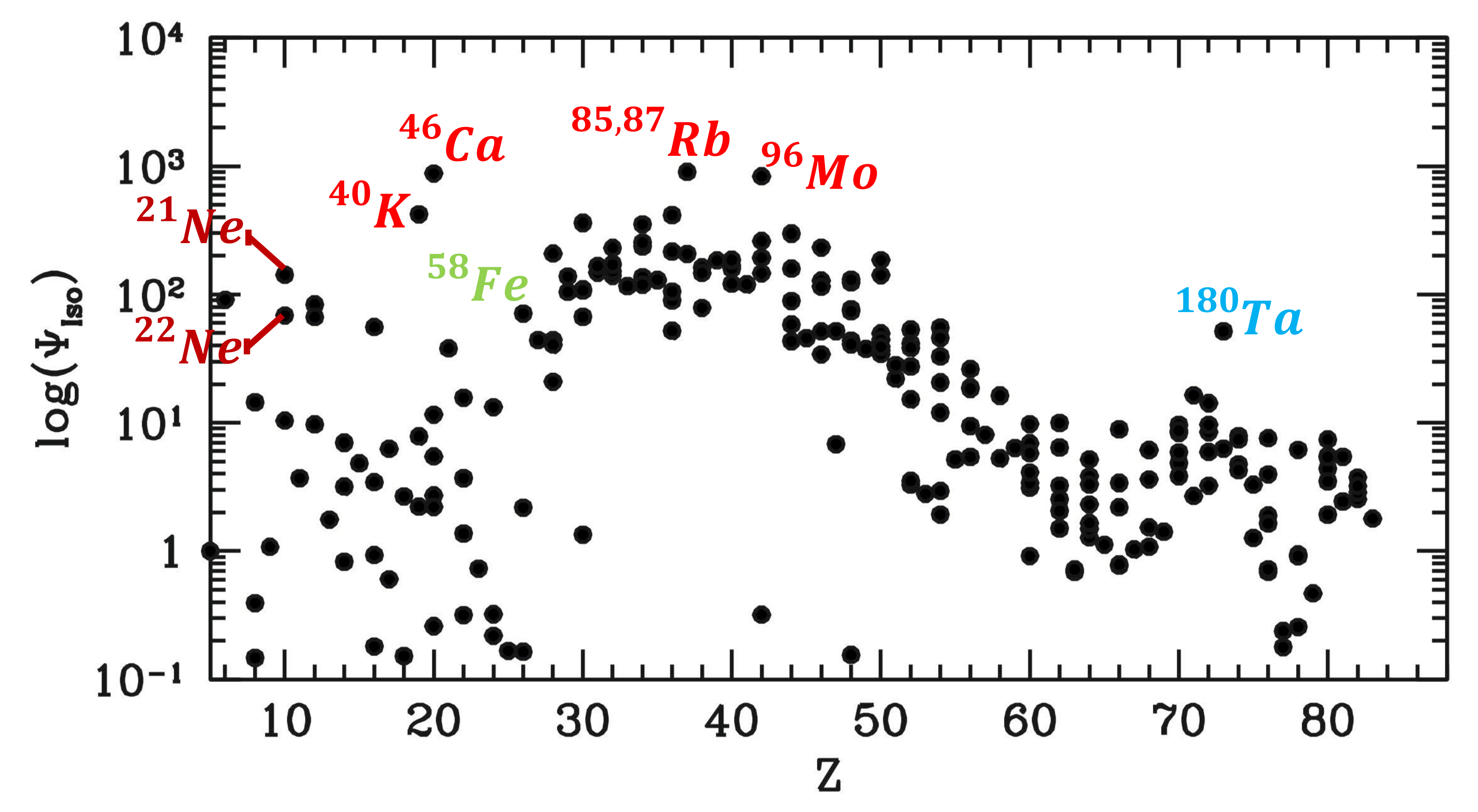

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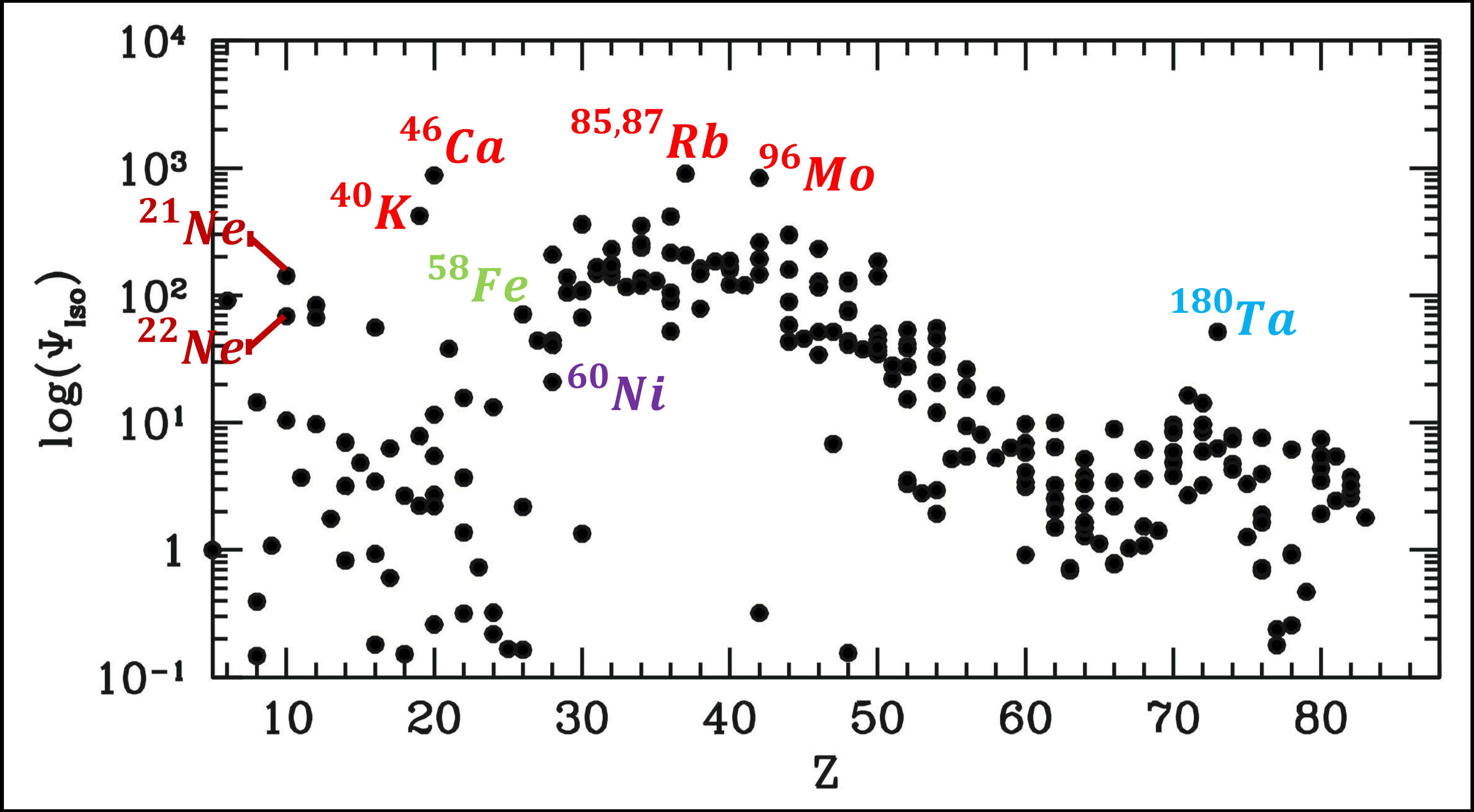

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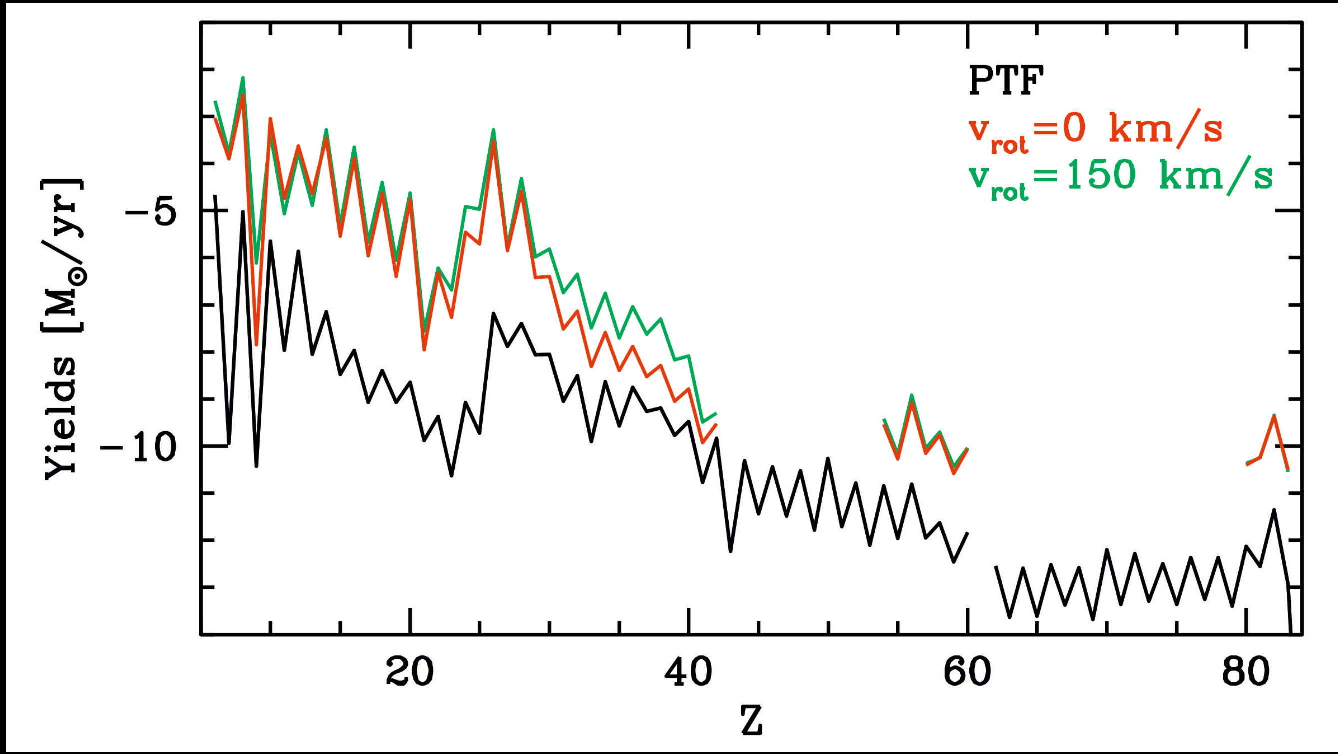

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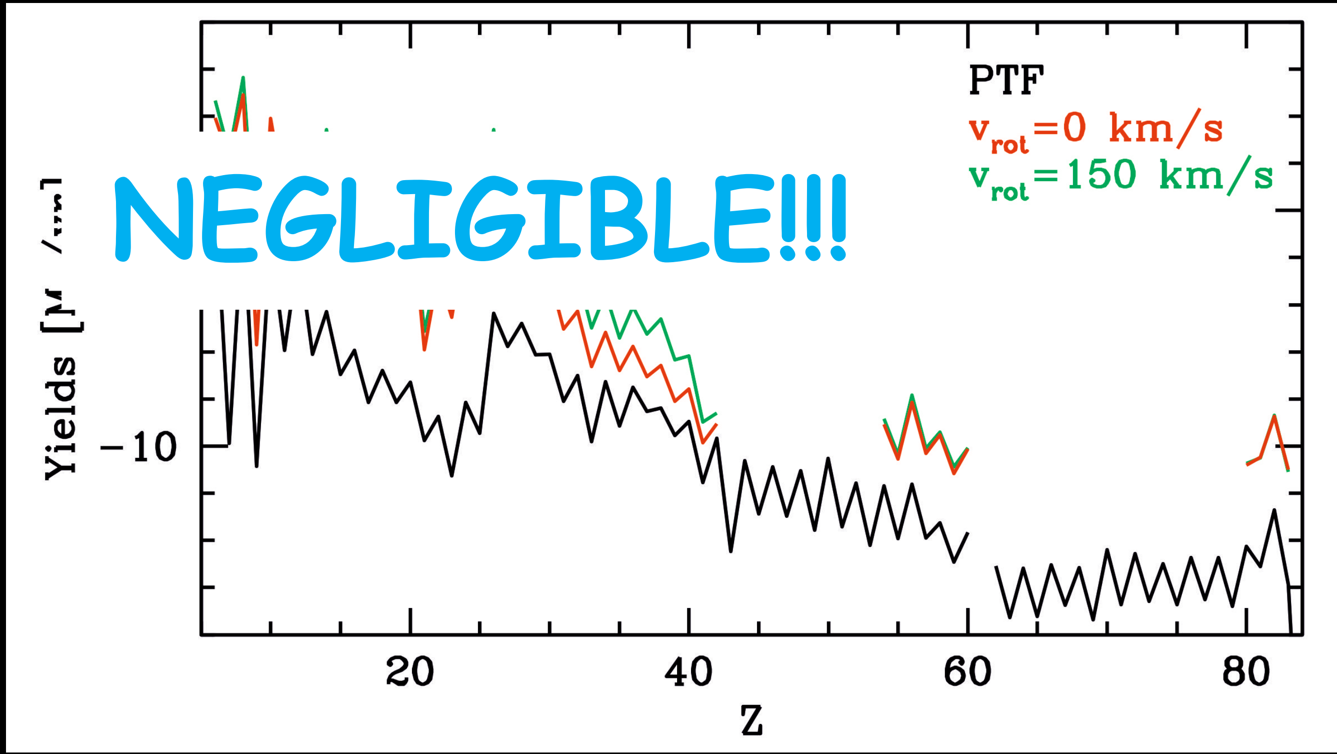

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NEGLIGIBLE!!!

$\Psi(^{60}Ni) = 21$

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$\Psi(^{60}Ni) = 21$

$M_{PTF}(^{60}Fe) \sim 3.2 \cdot 10^{-8} M_\odot$

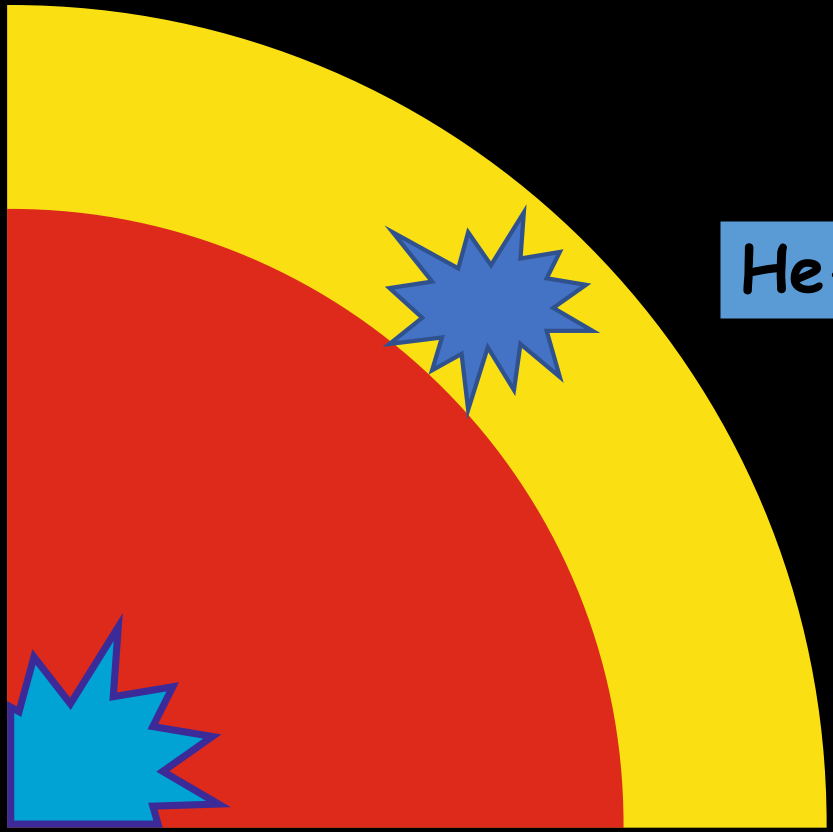
$M_{M,0}(^{60}Fe) \sim 2.9 \cdot 10^{-8} M_\odot$

$M_{M,150}(^{60}Fe) \sim 4.6 \cdot 10^{-7} M_\odot$

THANKS FOR YOUR ATTENTION!!

Double-detonation Thermonuclear Supernova

When the He-buffer exceeds a critical value …



He-detonation occurs

The CO core detonates

A"normal" SNe Ia requires that the CO core is massive ($M_{CO} > 1.0\ M_{\odot}$)

… otherwise a "faint" SNe Ia

The PTF1 J2238+7430

FUNS model WITHOUT ROTATION

M_{WD}=0.75 $M_\odot$ | M_{sdB}=0.39 $M_\odot$ | ΔM_H=2x10^{-3} $M_\odot$

At the epoch of He-ignition…

$\Delta M_{He} \sim 0.14\ M_\odot$ $\rho_{He} = 6.81 \times 10^5 g \cdot cm^{-3}$

HE-DETONATION

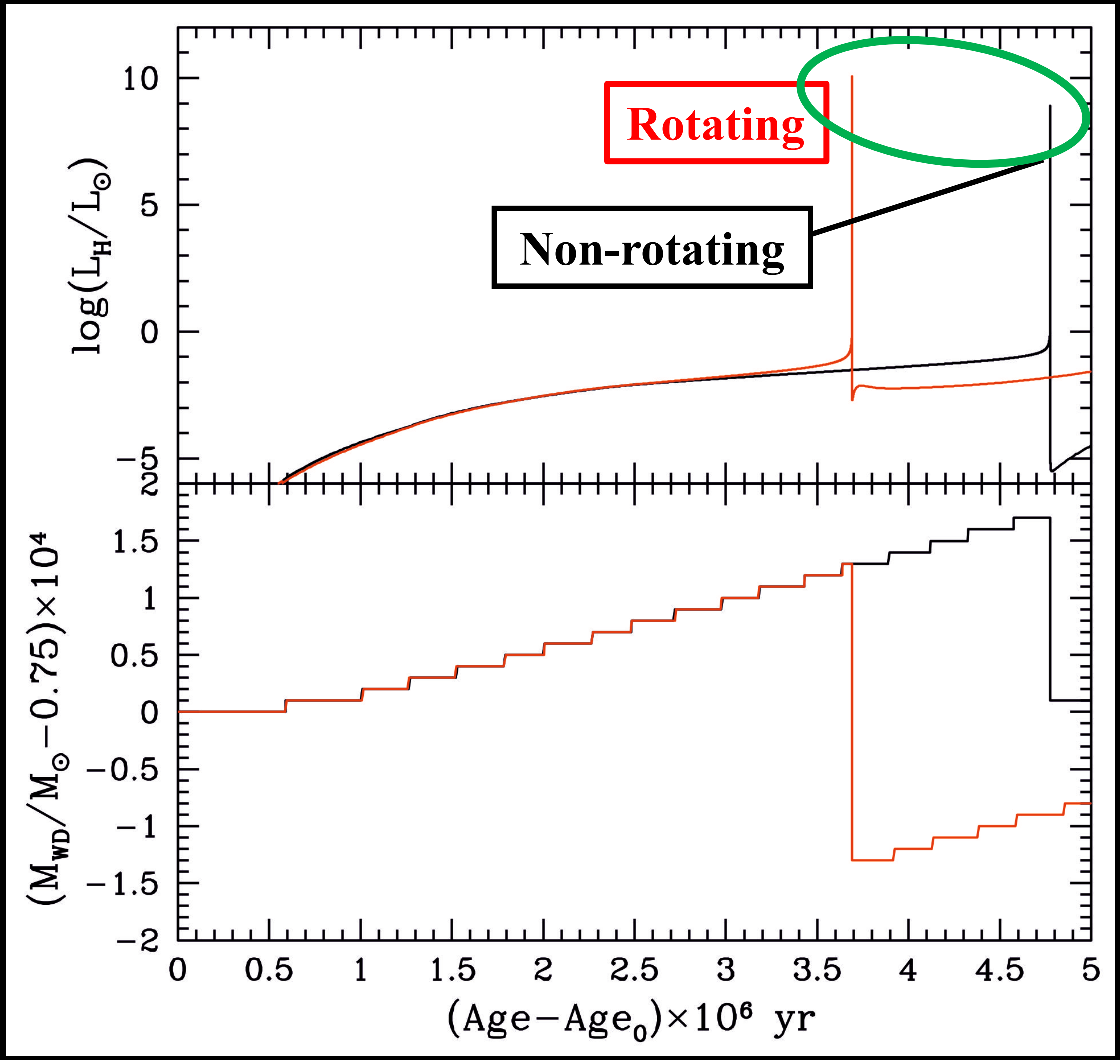
$E_{kin} = 0.743\ foe$

$M(^{56}Ni) = 0.104 M_\odot$
$M(C+O) = 0.273 M_\odot$
$M(Si+S) = 0.374 M_\odot$

$v_{orb}^{sdB} = 865\ km/s$

The PTF1 J2238+7430

FUNS model WITH ROTATION



$$\rho_H = 2.82 \times 10^3 g \cdot cm^{-3}$$

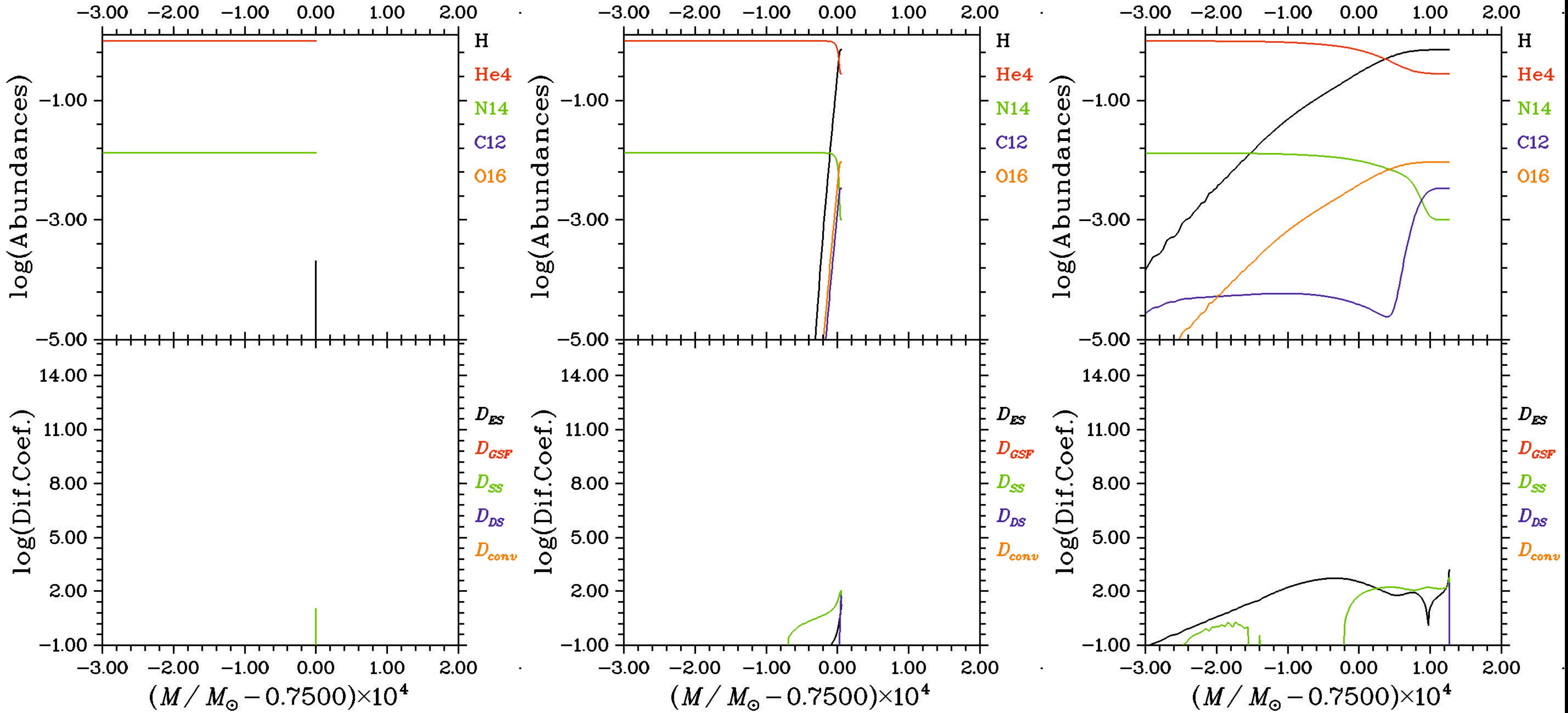
$$\rho_H = 4.89 \times 10^3 g \cdot cm^{-3}$$

$$\eta = 0$$

$$\eta = -105\%$$

The PTF1 J2238+7430

FUNS model WITH ROTATION



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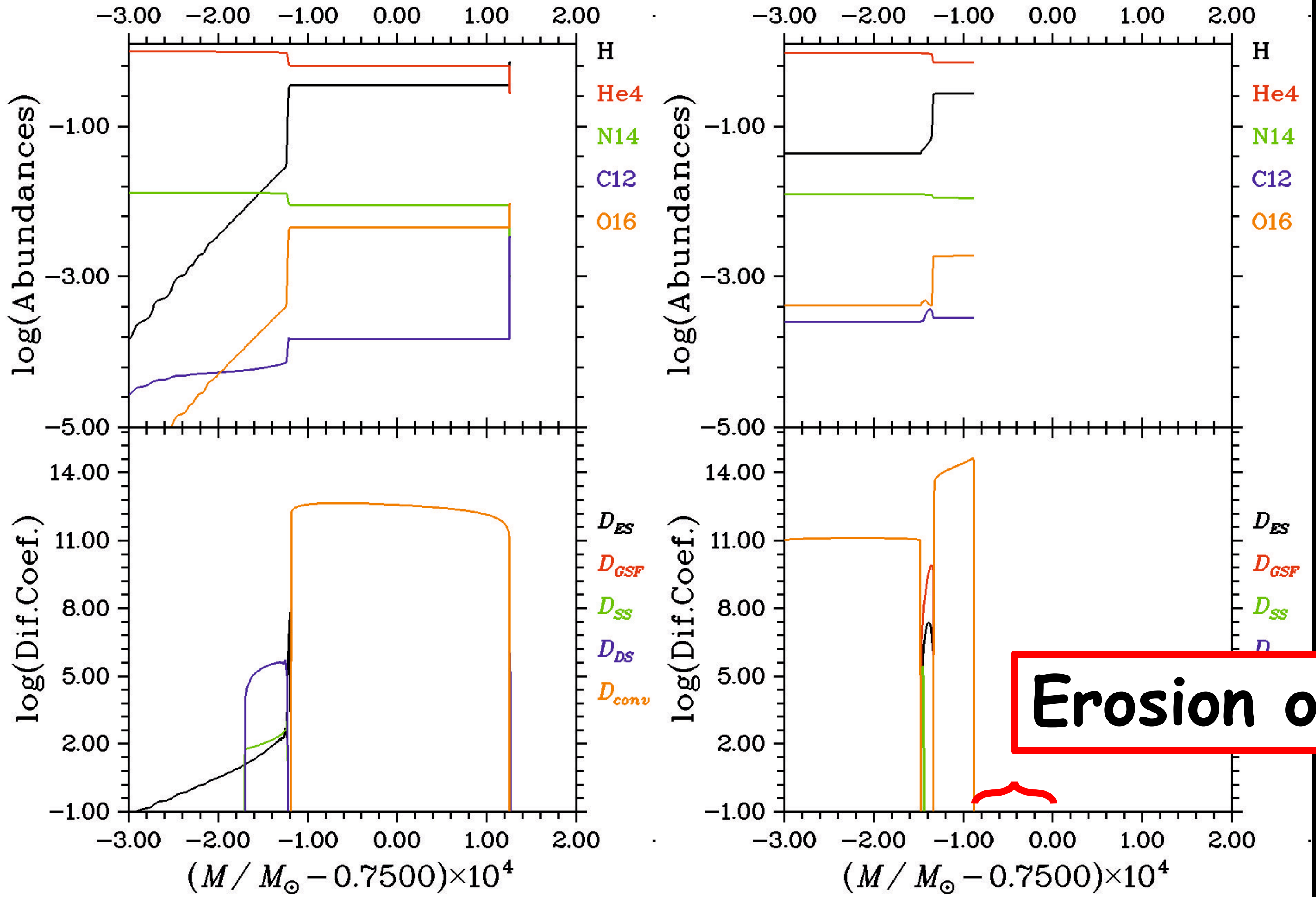
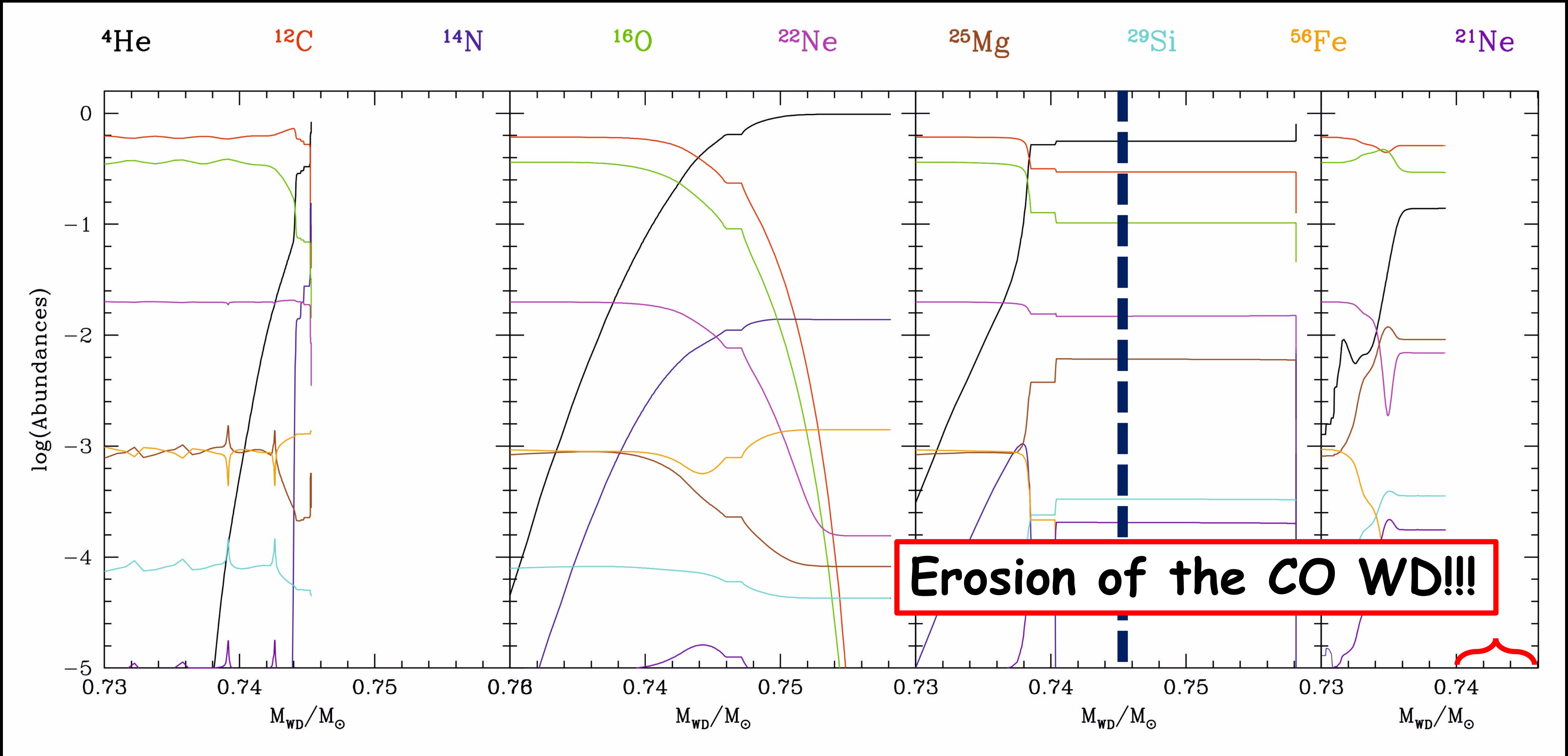


Erosion of the CO WD!!!

The PTF1 J2238+7430



The PTF1 J2238+7430

BRAKING WDs

Rotating WDs emit GWR!!!

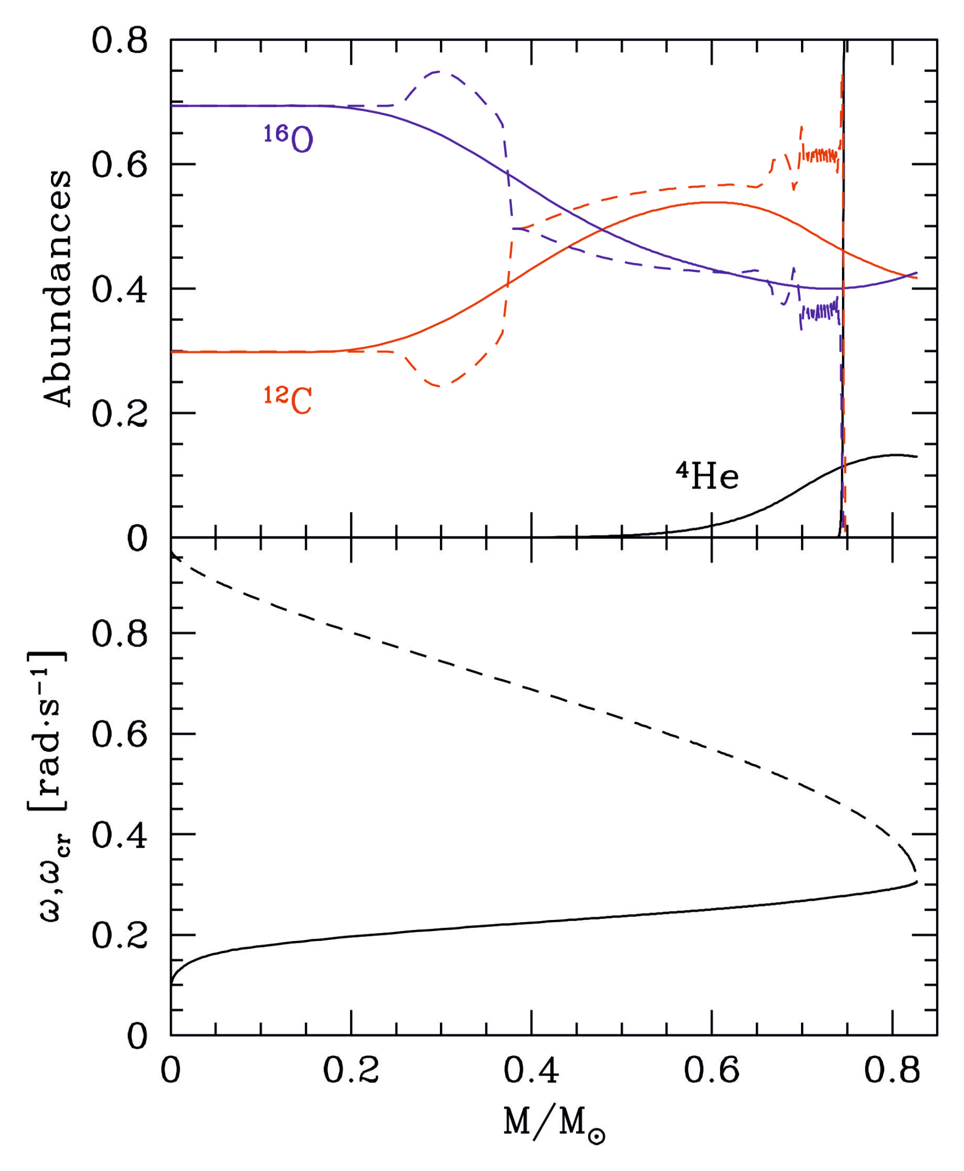
No GWR for *f*-mode instability

GWR for *r*-mode instability

$$\tau_r = \left[\frac{2\pi}{25} \left(\frac{4}{3} \right)^8 \frac{G}{c} \int_0^R \rho(r) \left(\frac{r\omega(r)}{c} \right)^6 dr \right]^{-1} \geq 10^9\ yr$$

Cooling

If there exists a physical process working on shorter τ ...



The PTF1 J2238+7430

$$\frac{d\omega}{dt} = \frac{1}{i}\frac{d}{dm}\left[(4\pi r^2\rho)^2 i\nu\left(\frac{d\omega}{dm}\right)\right]$$

$$\begin{aligned}\nu &= D_{conv} + \nu_{rot} \\ &= D_{conv} + \nu_{ES} + \nu_{GSF} + \nu_{DS} + \nu_{SS}\end{aligned}$$

Circulation velocity

$$v_{ES} = \frac{\nabla_a}{\delta(\nabla_{ad} - \nabla)}\frac{l_r}{Gm_r}\left[\frac{2\varepsilon r^2}{l_r} - \frac{2r^2}{m} - \frac{3}{4\pi\rho r}\right]\left(\frac{\omega}{\omega_{cr}}\right)^2$$

(Heger+2000)

$$v_{GSF} = \frac{2H_T r}{H_j}\frac{\mathrm{dlnr}}{\mathrm{dln}\omega} v_{ES}$$

(Heger+2000)

$$v_{DS} = \frac{H_P}{\tau_{dyn}}\left(1 - \max\left[\frac{R_i}{R_{i,C}}, 0\right]\right)^2$$

(Yoon+2004)

$$v_{SS} = \frac{1}{3}\frac{KR_{i,c}}{N^2}\left(\frac{d\omega}{dlnr}\right)^2\left(1 - \frac{\max[R_{i,1}, R_{i,2}]}{R_{i,C}}\right)$$

(Yoon+2004)

The PTF1 J2238+7430

Stabilizing effect of μ-current:

$$v_\mu = f_\mu \frac{H_P}{\tau_{KH}^*} \frac{\varphi \nabla_\mu}{\delta(\nabla_{ad} - \nabla)}$$

$$v_{ES}^{eff} = \max\left(|v_{ES}| - |v_\mu|, 0\right)$$

$$v_{GSF}^{eff} = \max\left(|v_{GSF}| - |v_\mu|, 0\right)$$

Mixing of chemicals:

$$\frac{dX_i}{dt} = \frac{d}{dm}\left[(4\pi r^2\rho)^2 D \left(\frac{d\omega}{dm}\right)\right]$$

$$D = D_{conv} + D_{rot}$$
$$= D_{conv} + f_C(\nu_{ES} + \nu_{GSF} + \nu_{DS} + \nu_{SS})$$

Rotational energy dissipation:

$$\frac{dL}{dm_\Psi} = \varepsilon + \varepsilon_{diss}$$

$$\varepsilon_{diss} = \frac{1}{2}\nu_{rot}\left(\frac{\partial\omega}{\partial \ln r}\right)^2$$

$$[f_\mu, f_C] = [0.05, 0.04]$$

Yoon & Langer2004: