The temperature and chronology of heavy-element nucleosynthesis in low-mass stars

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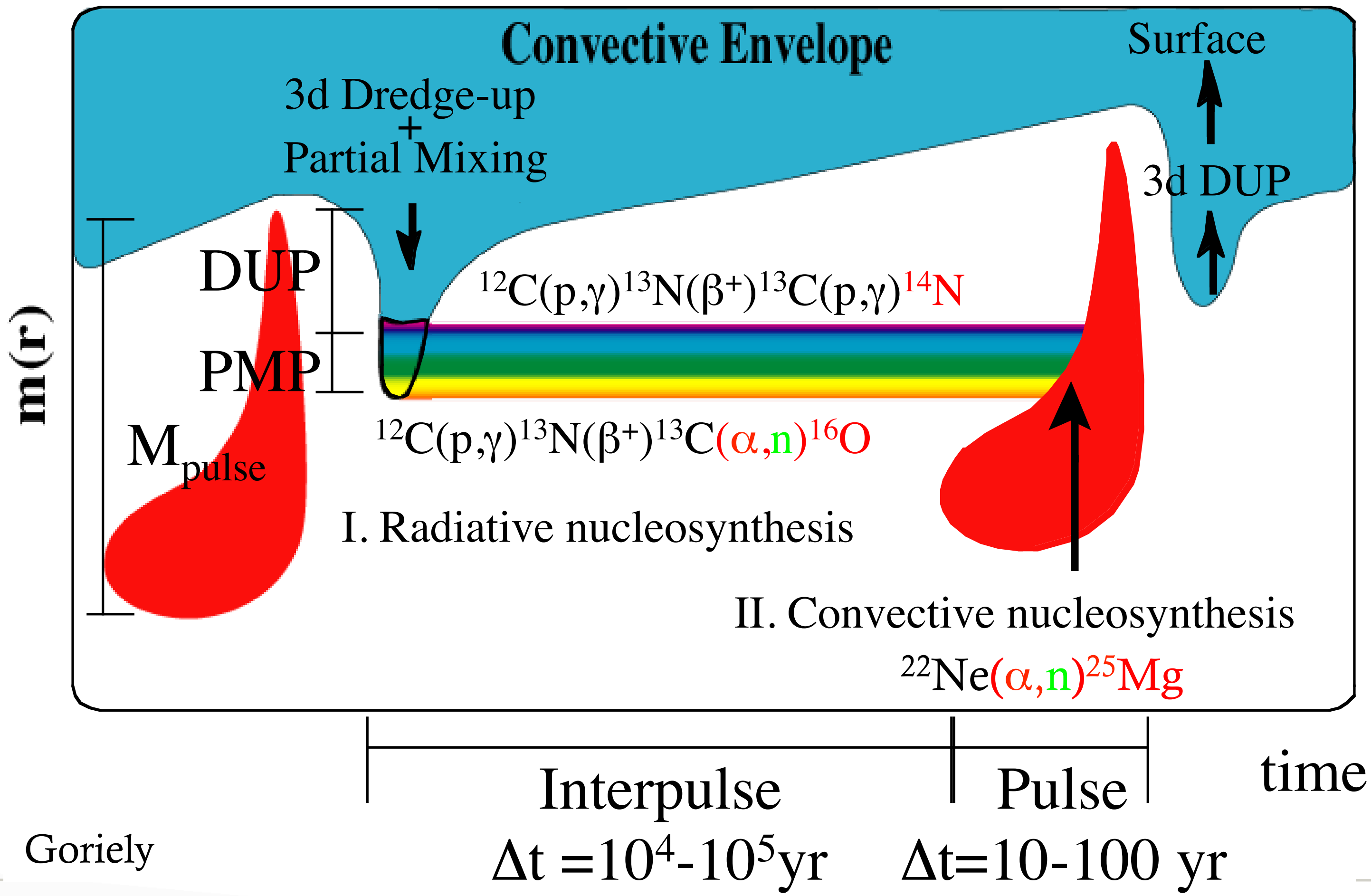
ULB

Physics of Evolved Stars 2015
To the memory of Olivier Chesneau

Nice June 8-12

s-process neutron source



Goriely

s-process neutron source

- if $T \geq 100\ 10^6$K

  $^{13}C(\alpha,n)^{16}O$

- Pro:
  - Stellar evolution models $1\text{-}3M_\odot$: $T_{interpulse} \approx 100\ 10^6$ K

- if $T > 350\ 10^6$K

  $^{14}N(\alpha,\gamma)^{18}F(\beta^+)^{18}O(\alpha,\gamma)^{22}Ne(\alpha,n)^{25}Mg$

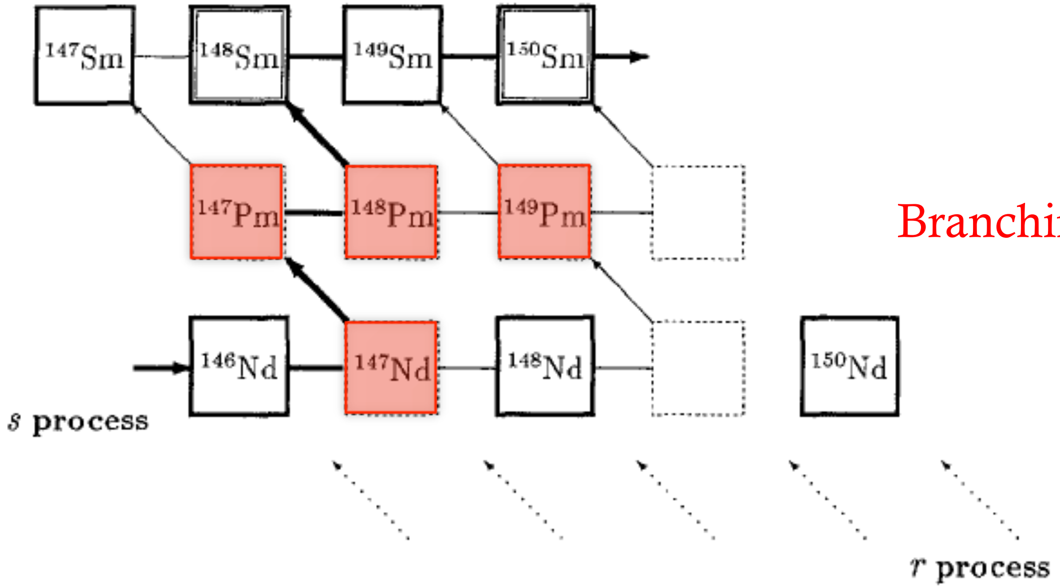
- Pro:
  - Meteoritic isotopic ratio points at $T \approx 300\ 10^6$K

  → require at least a late activation of $^{22}Ne(\alpha,n)^{25}Mg$

- Con:
  - No overabundance of ^{25}Mg in Ba stars based on MgH (Malaney & Lambert 1988)

s-process neutron source

Isotopic abundance patterns in the solar system derived from primitive carbonaceous chondrite meteorites of type CI



Branching points

Fig. 17. The *s*-process reaction path in the Nd/Pm/Sm region with the branchings at A=147, 148, and 149. Note that ^{148}Sm and ^{150}Sm are shielded against the *r* process. These two isotopes define the strength of the branching.

Käppeler F., Prog. Part. Nucl. Phys. 43, 419 – 483 (1999).

s-process neutron source

Table 2
Results from various branching analyses of relevance for the main *s*-process component

Branch point isotope	Deduced *s*-process parameter	Reference
$^{147}Nd/^{147}Pm/^{148}Pm$	$n_n = (4.1 \pm 0.6) \cdot 10^8$ cm^{-3}	[123]
$^{151}Sm/^{154}Eu$	$T_8 = 3.5 \pm 0.4$	[58]
$^{163}Dy/^{163}Ho$	$\rho_s = (6.5 \pm 3.5) \cdot 10^3$ g cm^{-3}	[151]
^{176}Lu	$T_8 = 3.1 \pm 0.6$	[137,152]
$^{121}Sn/^{122}Sb$	$T_8 > 2.4$	[153]
^{134}Cs	$T_8 = 1.9 \pm 0.3$	[154]
	$T_8 = 1.7 \pm 0.5$	[51]
$^{185}W/^{186}Re$	$n_n = (3.5^{+1.7}_{-1.1}) \cdot 10^8$ cm^{-3}	[155]

$kT = 8.62 \times T_8$ keV

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Consistent

Discrepant with the above ones but uncertainty in the T-dependent β-decay rate of ^{134}Cs (Käppeler 1999, from Takahashi and Yokoi 1987).

Käppeler F., Prog. Part. Nucl. Phys. 43, 419 – 483 (1999).

A new s-process thermometer

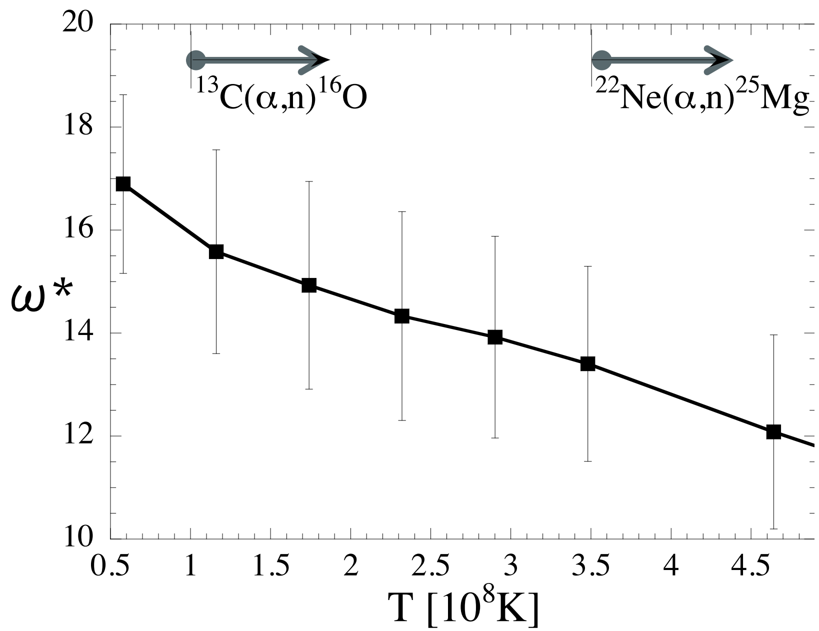
- The s-process is in local equilibrium within a given isotopic chain
  → $N_s(^{A}Zr) <\sigma_A> = cst$ within the Zr chain

$\omega^* = Zr/^{93}Zr$

$$\omega^* = \langle\sigma_{93}\rangle \times \left[\frac{1}{\langle\sigma_{90}\rangle} + \frac{1}{\langle\sigma_{91}\rangle} + \frac{1}{\langle\sigma_{92}\rangle} + \frac{1}{\langle\sigma_{94}\rangle}\right]$$

- n-capture cross-sections are temperature-sensitive

→ ω^* is a sensitive function of temperature



A new s-process thermometer

- Problems:
  - Atomic lines of Zr: no detected isotopic shift
  - Molecular lines: ZrO: only targets are S-type stars

(giants, temperatures 2700-4000, s-process-enriched, $0.5<C/O<1$)

  - Contrarily to previous claim (Lambert et al. 1995), ^{93}ZrO band heads at 692.5 nm, 674.2 nm, 681.15 nm, and 639.05 nm could not be detected
  - Fraction of Zr isotopes for a 2 $M_\odot$ solar-metallicity model after 10 thermal pulses (STAREVOL):

Isotope	^{90}Zr	^{91}Zr	^{92}Zr	^{93}Zr	^{94}Zr	^{96}Zr
Fraction	0.466	0.099	0.164	0.045	0.222	0.004

A new s-process thermometer

Olivier:
Close circumstellar environment of π^1 Gru

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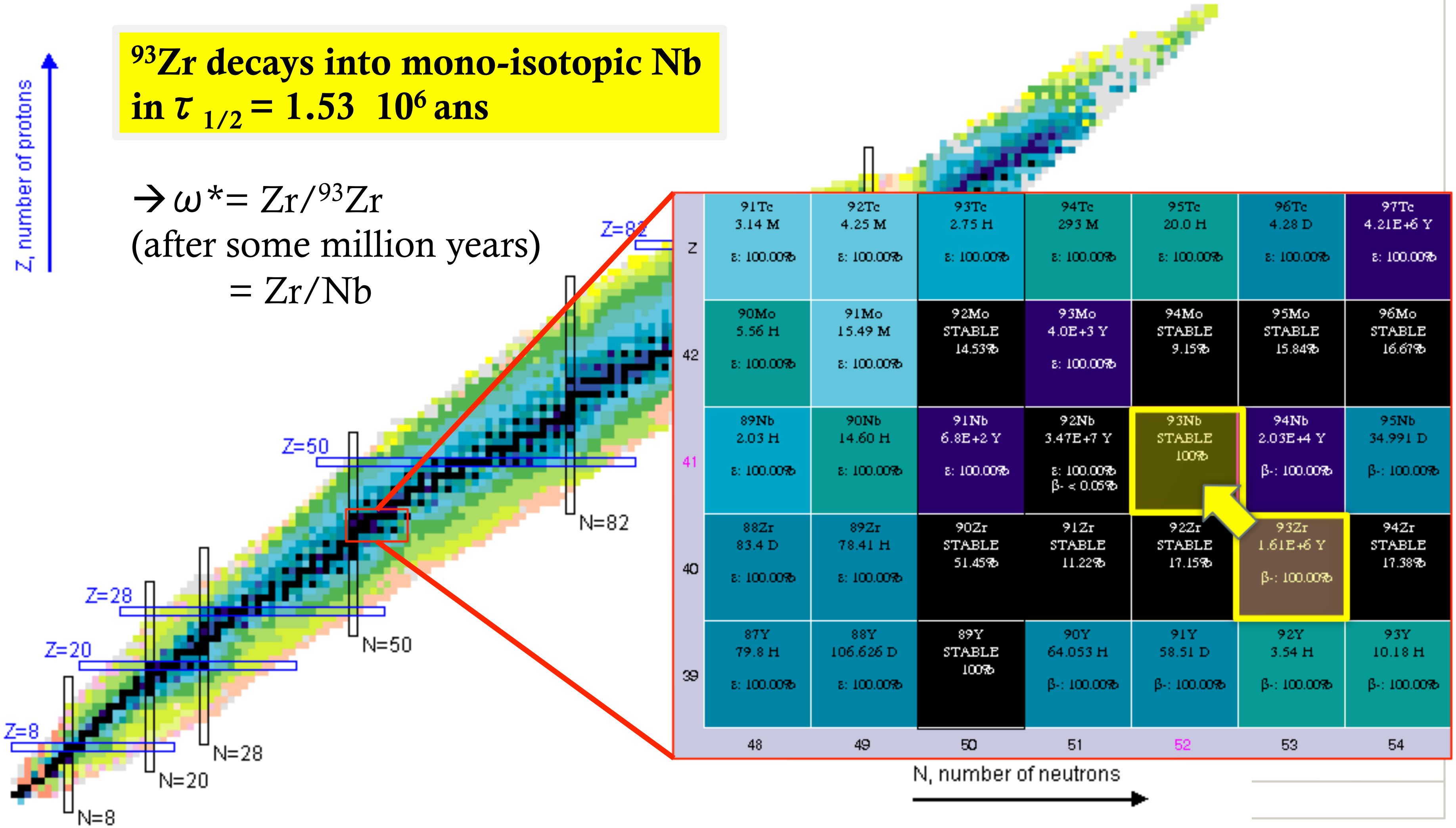
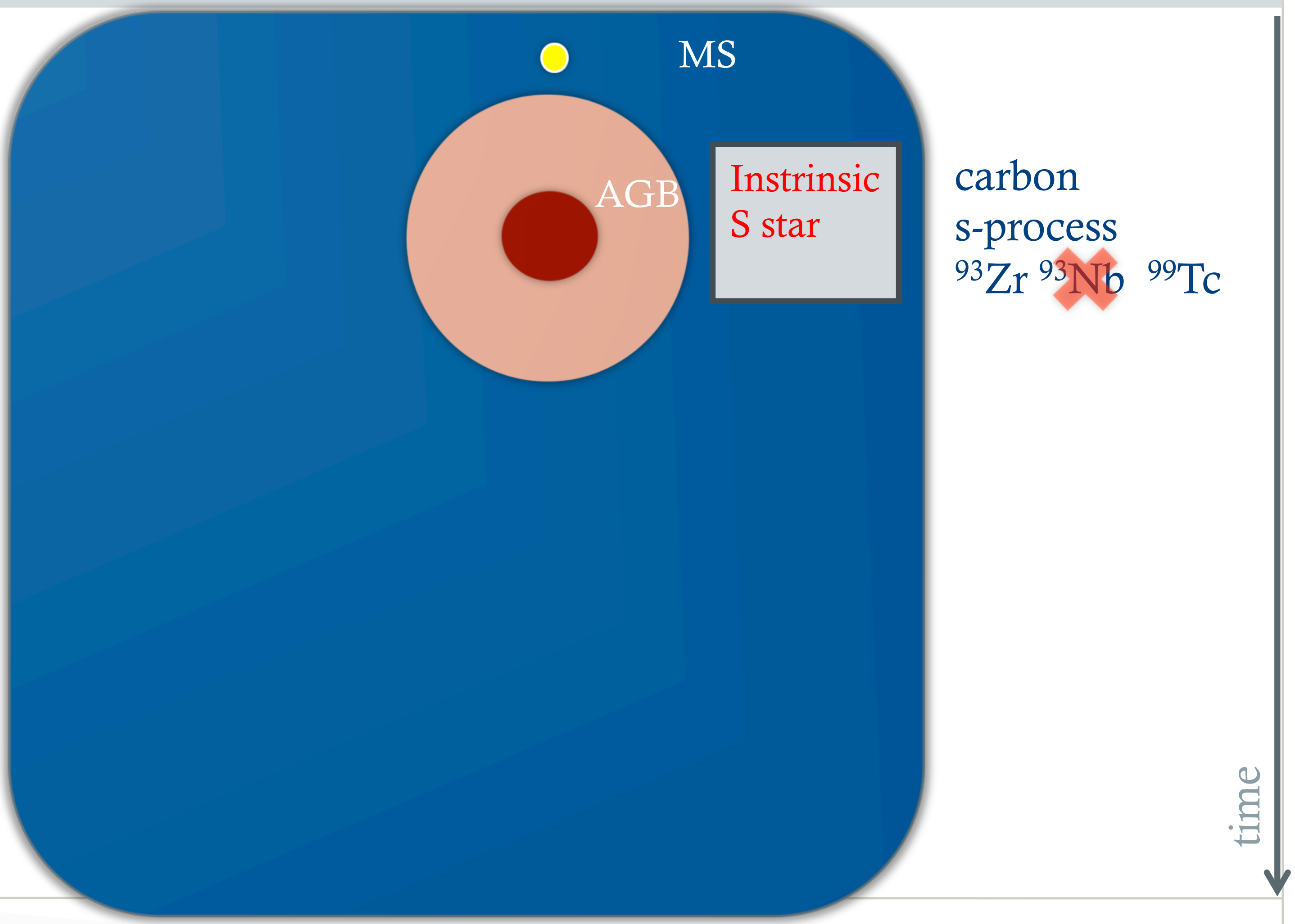
A new s-process thermometer

^{93}Zr decays into mono-isotopic Nb in $\tau_{1/2}$ = 1.53 10^6 ans

→ $\omega^* = Zr/^{93}Zr$
(after some million years)
= Zr/Nb



Intrinsic and extrinsic S stars



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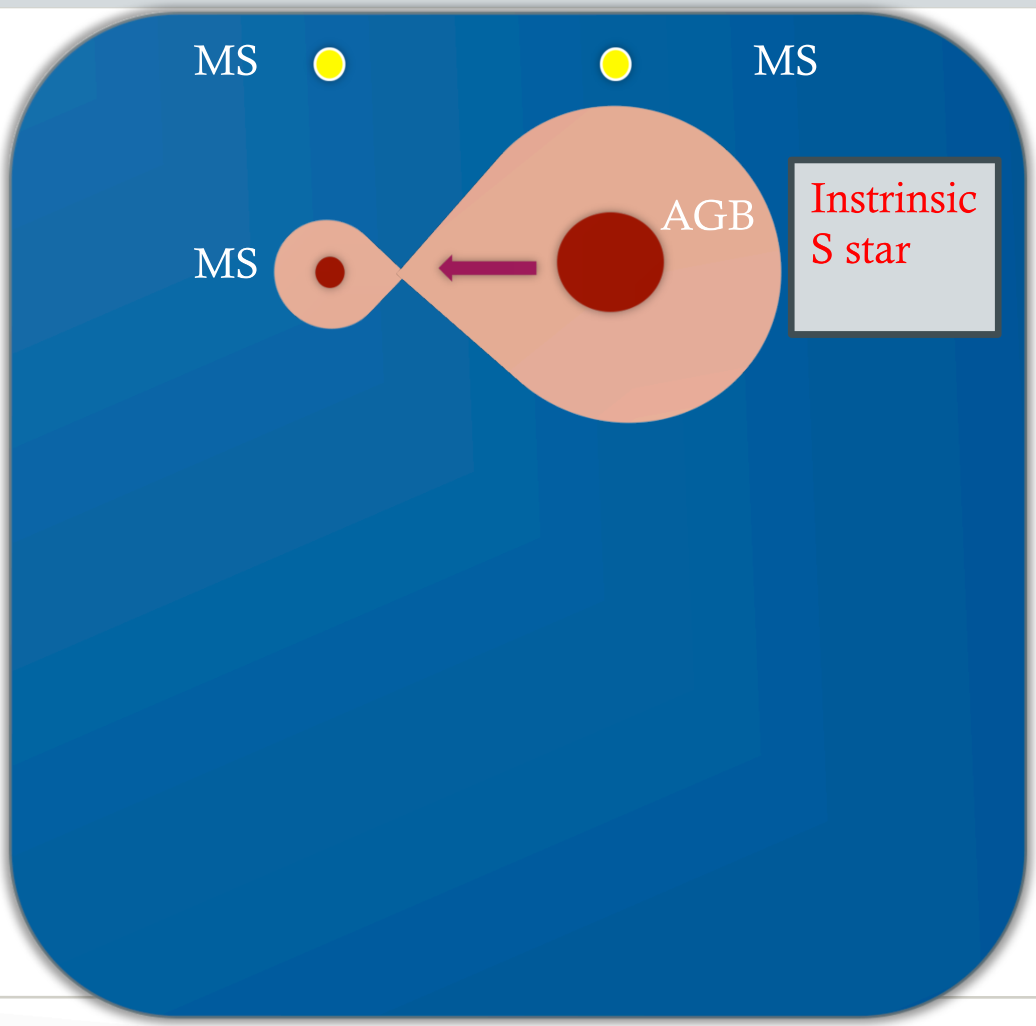
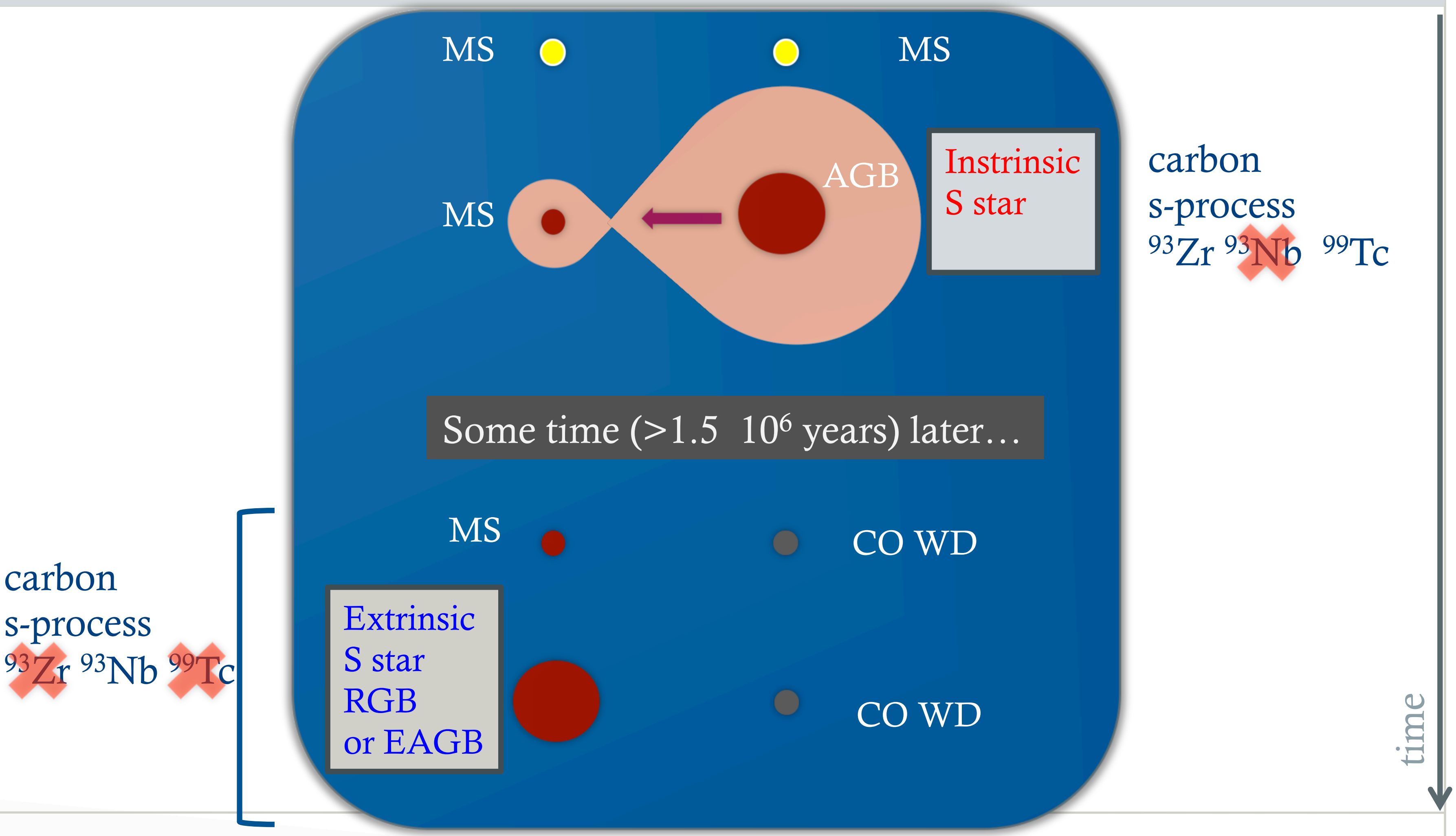


carbon
s-process
^{93}Zr ^{93}Nb ^{99}Tc

Intrinsic and extrinsic S stars



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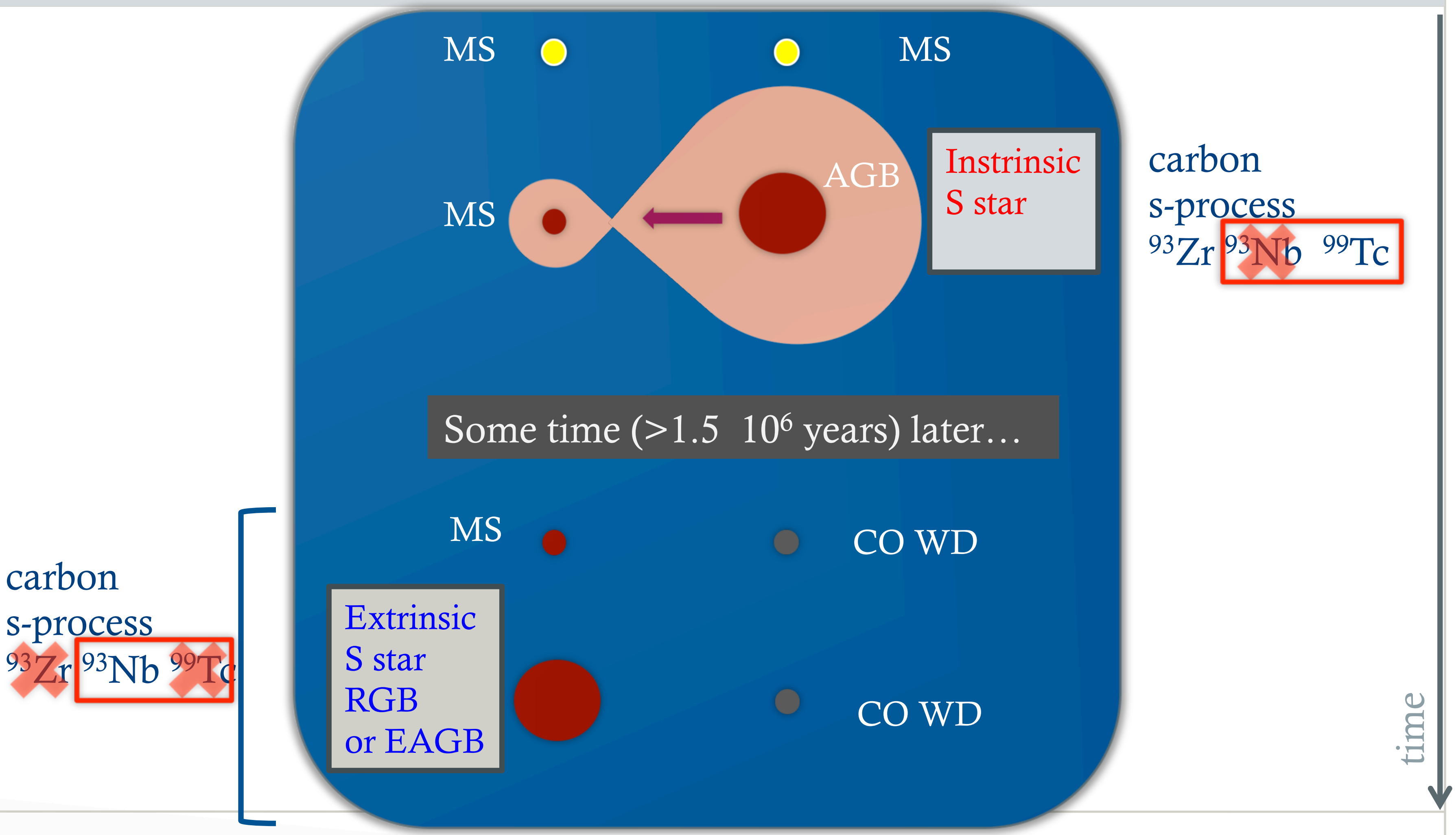


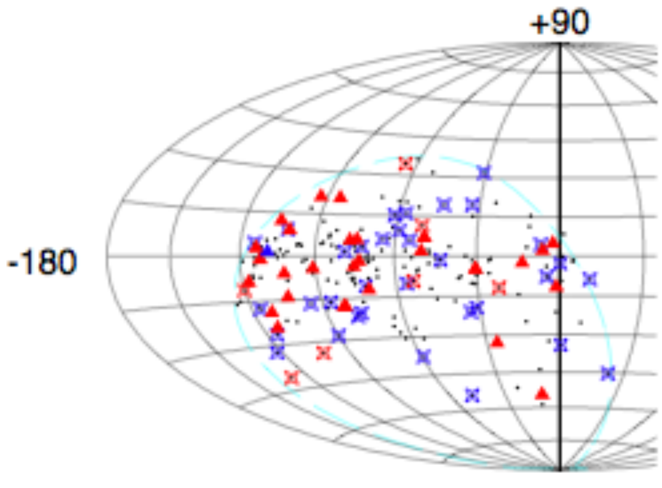
The Henize sample of S stars

- The Henize sample of 205 S stars:
- R < 10.5, declin. < -25°

~ 50% of intrinsic S stars (genuine TPAGB)

~ 50% of extrinsic S stars (binary masqueraders)

(Van Eck et al. 1999, 2000, 2000, 2015)



- Available data:
  - Geneva UBV B1 B2 V1 G photometry
  - SAAO JHKL photometry
  - Colours dereddened according to Drimmel et al. (2003)
  - 160 low resolution spectra: $\Delta\lambda$= 3 Å , 4400-8400 Å , **ESO Boller & Chivens**
  - 70 high-resolution spectra (**ESO CAT**, R=30 000 -60 000) centered on the Tc lines around 4250 Å
  - 23 **HERMES** spectra (Raskin et al. 2011,

talk of H. Van Winckel),

R=85 000, 380-900nm

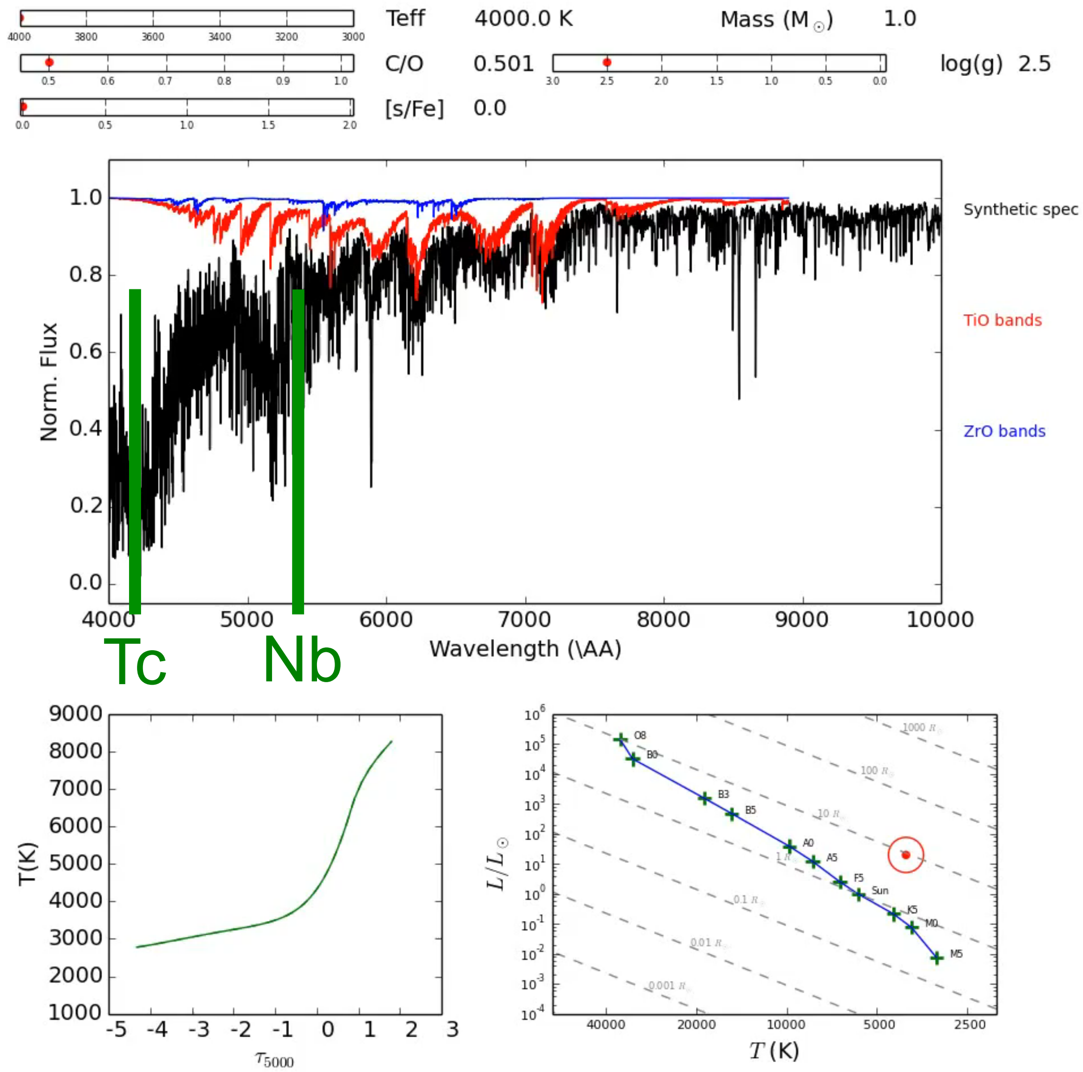
S stars parameters

- MARCS model atmospheres for late-type stars:

(Gustafsson, Edvardsson, Eriksson, Jorgensen, Nordlund & Plez, 2008, A&A 486, 951)

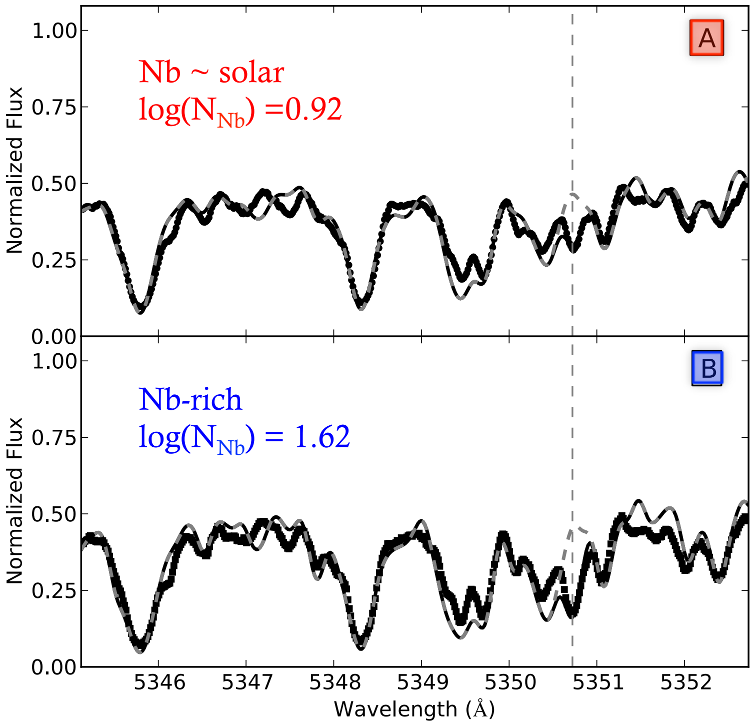
- MARCS model atmospheres for S and SC stars:
  - hydrostatic equilibrium, LTE, convection: MLT
  - Spherical symmetry for log g < 2, plane-parallel otherwise
  - New ZrO linelist
  - Opacity sampling > 105 wavelength points
  - 2700K < Teff < 4000K (step 100K)
  - C/O = 0.5, 0.750, 0.899, 0.925, 0.951, 0.971, 0.991
  - [s/Fe] = 0.,+1.,+2.
  - [Fe/H] = 0., -0.5 ; [alpha/Fe] = -0.4 x [Fe/H]
  - Log(g) = 0, 1 , 2 , 3 , 4 , 5
  - M = 1M0
- More than 3500 converged model atmospheres
- Parameters derived from comparison between synthetic and observed spectra and photometric colors

S stars abundances



S stars abundances

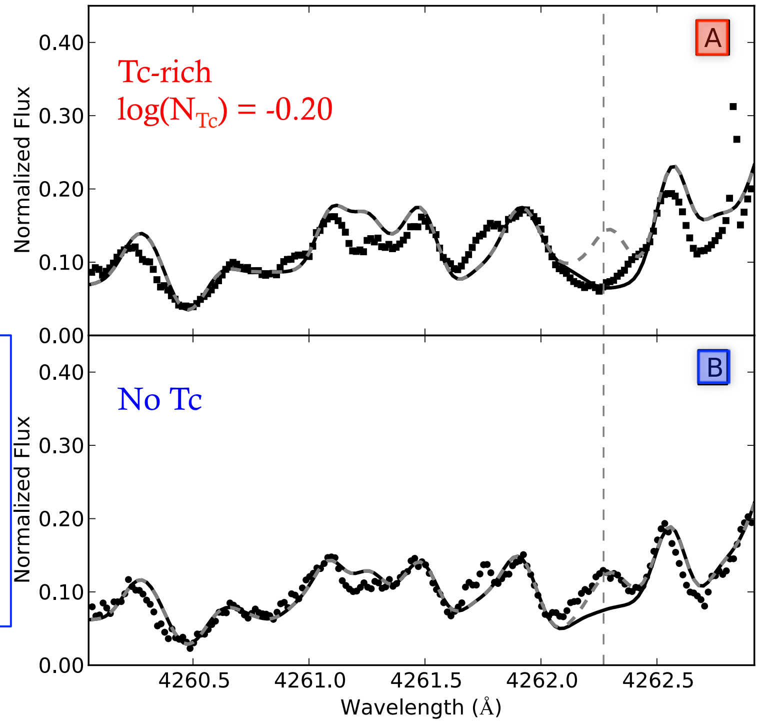
Nb I



A= NQ Pup
Intrinsic
^{93}Nb Tc

B = V613 Mon
Extrinsic
^{93}Nb Tc

Tc I



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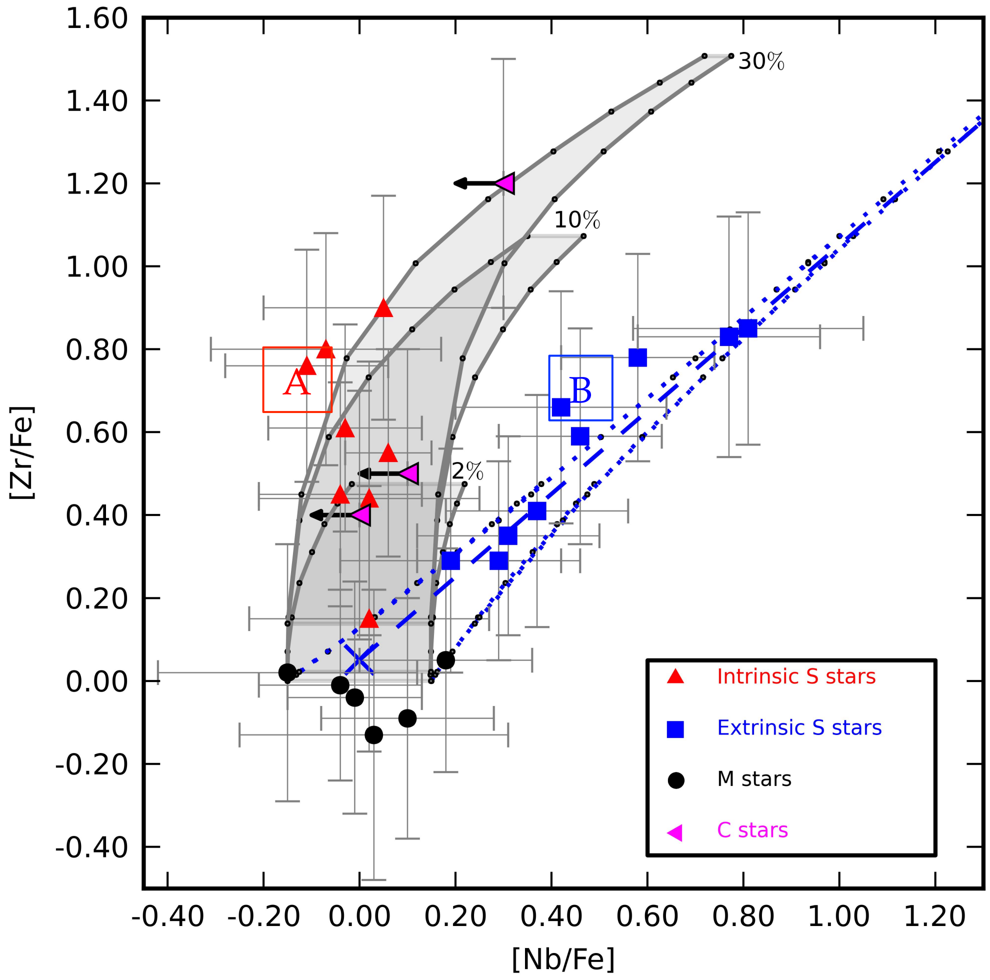

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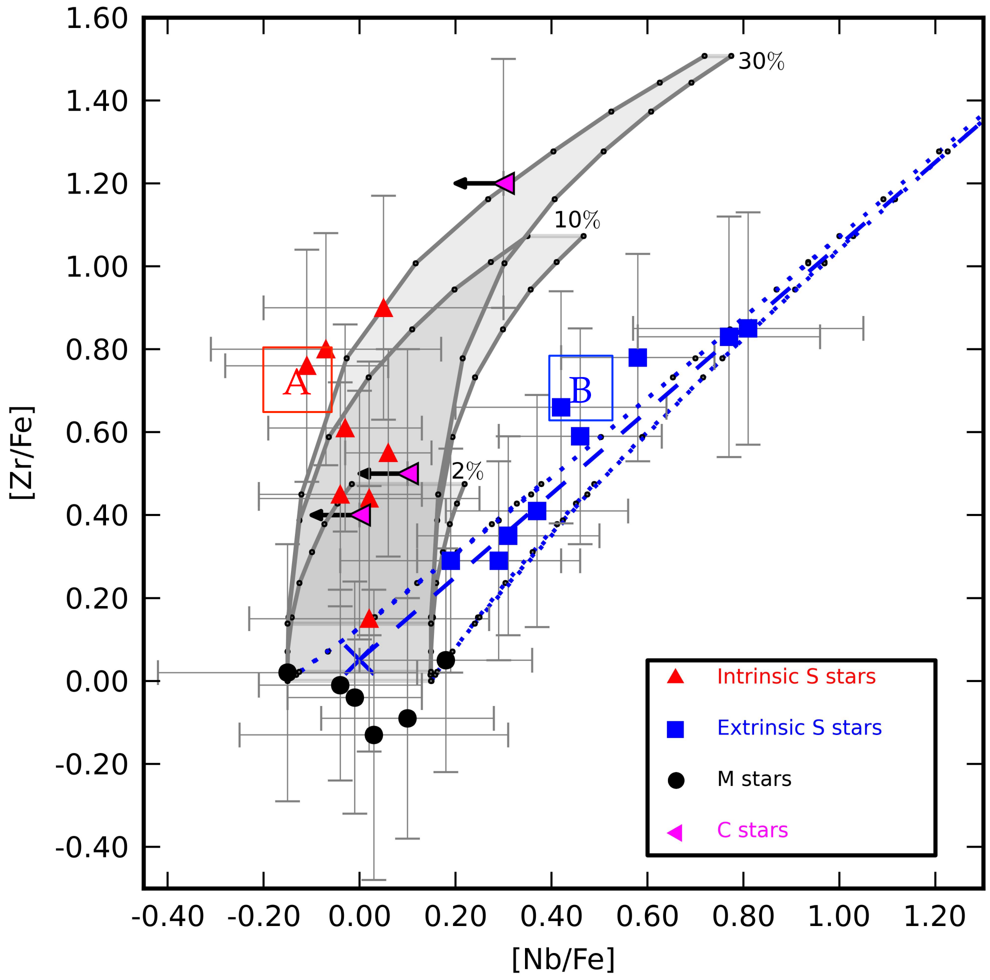


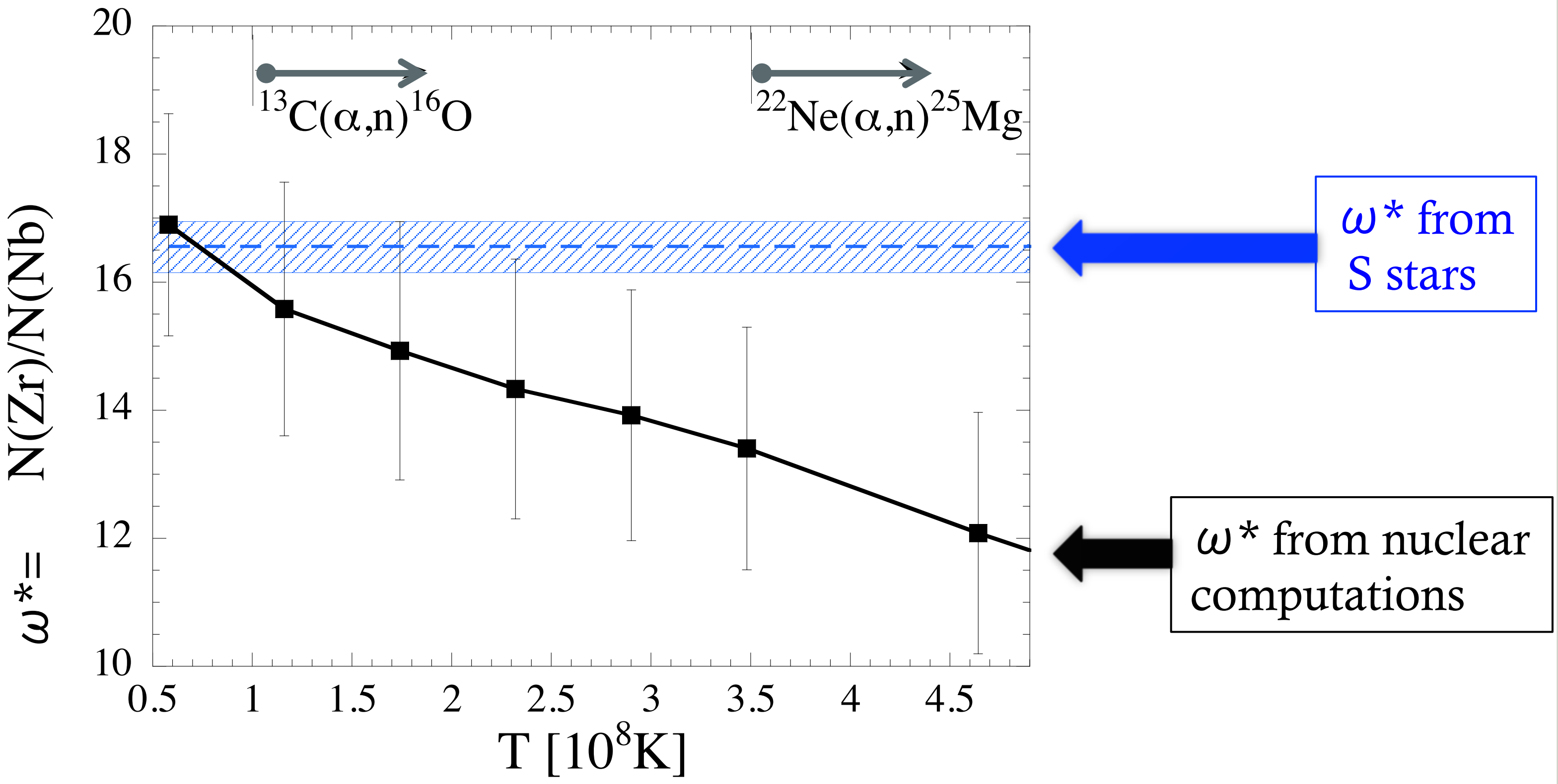
$$\omega^* = \frac{N_S(\mathrm{Zr})}{N_S(^{93}\mathrm{Zr})}$$

$$\left[\frac{\mathrm{Zr}}{\mathrm{Fe}}\right] = \left[\frac{\mathrm{Nb}}{\mathrm{Fe}}\right] + \underbrace{\log \omega^* - \log \frac{N_\odot(\mathrm{Zr})}{N_\odot(\mathrm{Nb})}}_{\text{y-intercept} \rightarrow \omega^*}$$

NB:

- The derived temperature is an upper estimate

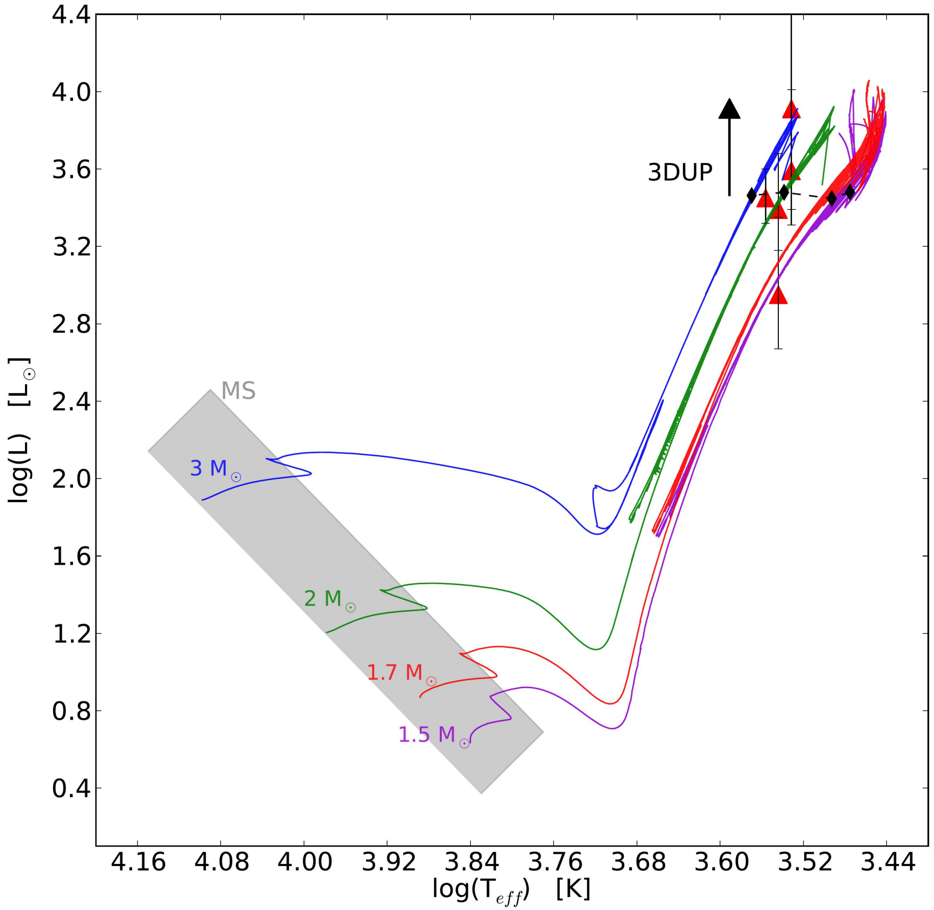
A new s-process thermometer



→ Neutron source in S stars identified: $^{13}C(\alpha,n)^{16}O$

s-process cosmo-chronology

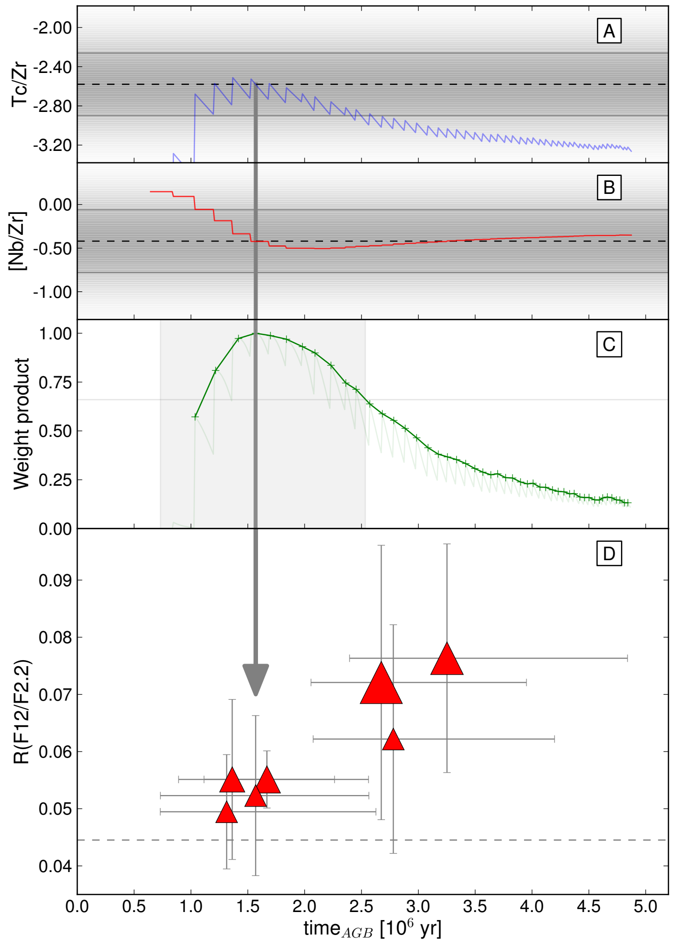
Intrinsic S stars



s-process cosmo-chronology

^{99}Tc→^{99}Ru ($\tau_{1/2}$ = 0.21 10^6 yrs)

^{93}Zr→^{93}Nb ($\tau_{1/2}$ = 1.53 10^6 yrs)



The derived ages correlate with the infrared excess:
R = F(12 μm)/F(2.2 μm)

s-process cosmo-chronology

Table 1: Derived ages and masses for our sample of intrinsic S stars.

Star Name	Mass loss	t_{TP} (Myr)	$t_{TP,min}$ (Myr)	$t_{TP,max}$ (Myr)	t_S (Myr)	M_{mod} ($M_\odot$)	$\log(L/L_\odot)$	C/O	[Fe/H]
o^1 Ori	VW	1.3	0.7	2.6	0.6	2	3.45	0.50	-0.45
	S	1.8	0.7	3.9	0.6	3			
AA Cam	VW	1.4	0.9	2.3	0.6	3	3.91	0.50	-0.40
	S	1.6	0.7	2.7	0.4	3			
KR CMa	VW	1.6	0.7	2.6	0.8	3	-	0.50	-0.34
	S	1.8	0.7	3.9	0.6	3			
CSS 454	VW	1.7	1.1	2.6	1.0	2	-	0.50	-0.40
	S	1.7	1.0	3.9	1.0	2			
HIP 103476	VW	2.2	1.2	3.2	1.4	3	3.59	0.50	-0.01
	S	2.5	1.5	4.0	1.3	3			
AD Cyg	VW	2.7	2.1	3.9	1.9	3	-	0.97	-0.05
	S	3.0	2.2	4.0	1.8	3			
NQ Pup	VW	2.8	2.1	4.2	2.0	3	2.95	0.50	-0.31
	S	3.1	2.3	4.0	1.9	3			
HR Peg	VW	3.2	2.4	4.8	2.4	3	3.39	0.75	0.00
	S	3.0	2.4	3.7	1.8	3			

Summary

- **s-process neutron source** identified in low-mass AGB stars: **$^{13}C(\alpha,n)^{16}O$**
  - Not derived from meteoritic abundances resulting from a mix of nucleosynthetic events, but **from individual stellar sites**
  - The s-process temperature in low-mass stars is lower than 250 10^6 K
  - This estimate is independent from stellar evolution models

- **Quantitative constrains on AGB evolution:** intrinsic S stars have spent :
  - between 1.3 and 3.2 10^6 years on the TP-AGB (since the occurrence of the first thermal pulse)
  - between 0.4 and 2.4 10^6 years as S stars (since the occurrence of the first 3rd dredge-up)

P. Neyskens, S. Van Eck, A. Jorissen, S. Goriely, L. Siess & B. Plez,
Nature 517, 174–176 (08 January 2015)

Jobs announcement

- **3 PhD positions, ULB + KULeuven + ROB (Belgium)**

STARLAB project:

“Physical and chemical processes at work in single and binary low- and intermediate-mass stars “

- **1 Post-doc position, ULB (Belgium)**

“Binary and extrinsic stars in the Gaia-ESO and GAIA era”

- Deadline for application is June 28
- See http://www.astro.ulb.ac.be **(Jobs announcement)**