Early rotating massive stars

and abundances of extremely metal-poor stars

Arthur Choplin (Konan University)

Origin of Matter and Evolution of Galaxies

July 2-5, 2019

KONAN UNIVERSITY

FNSNF SWISS NATIONAL SCIENCE FOUNDATION

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—> Part 1

and abundances of extremely metal-poor stars

—> Part 2

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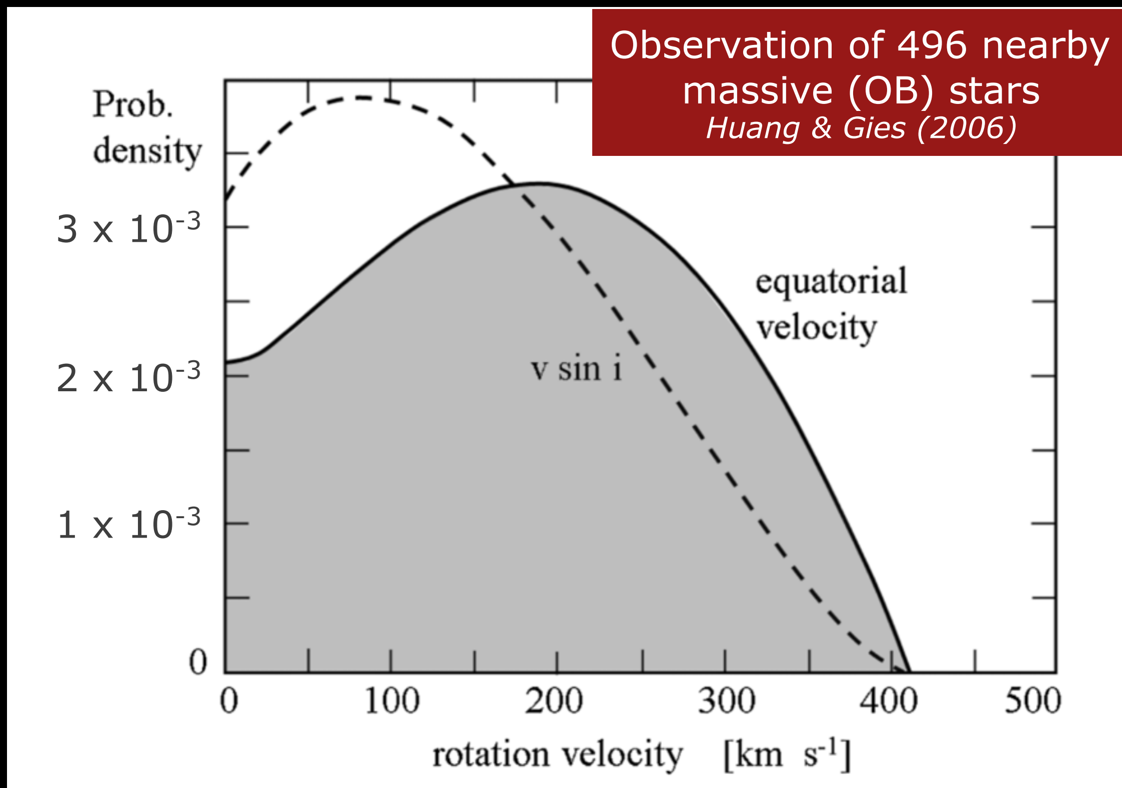
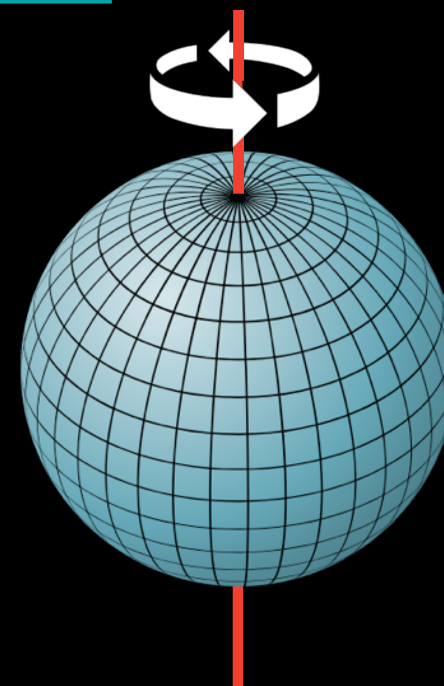
Rotating massive stars

$M_{ini} > 8\ M_{\odot}$

Observation of 496 nearby massive (OB) stars
Huang & Gies (2006)





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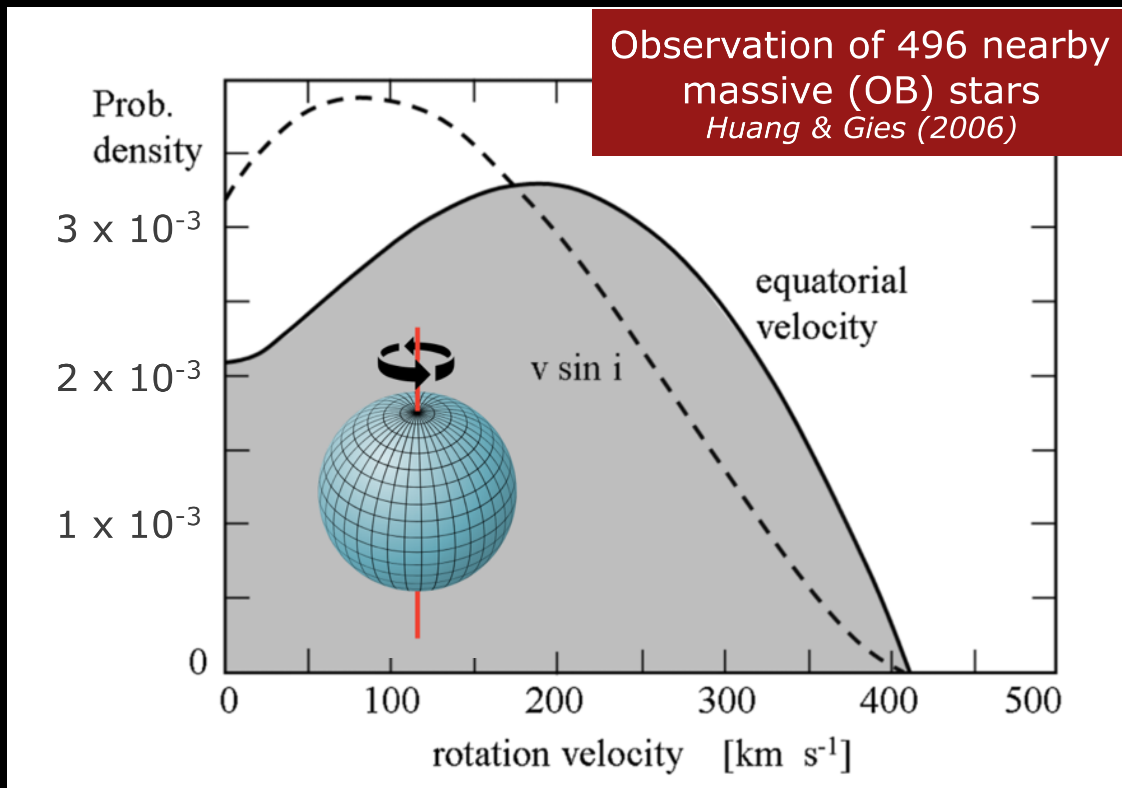
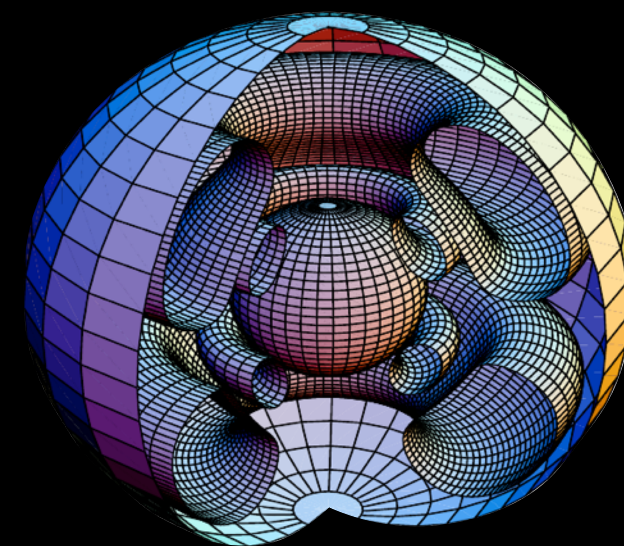


Mixing in the interior

- Meridional currents
- Shear mixing



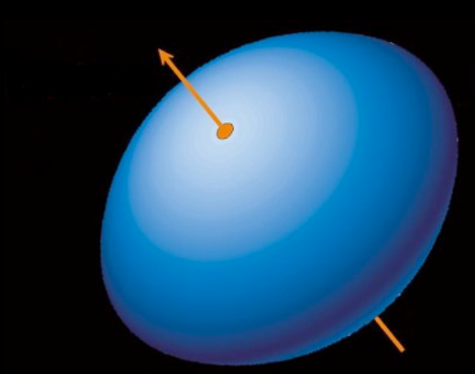
Transport of :

- Angular momentum
- Chemical elements

e.g. Maeder 1997, Heger et al. 2000,…

Mass loss

Meynet & Maeder 2000, …



Oblateness

Achernar, 10 $M_{\odot}$
Carfiofi et al. 2008

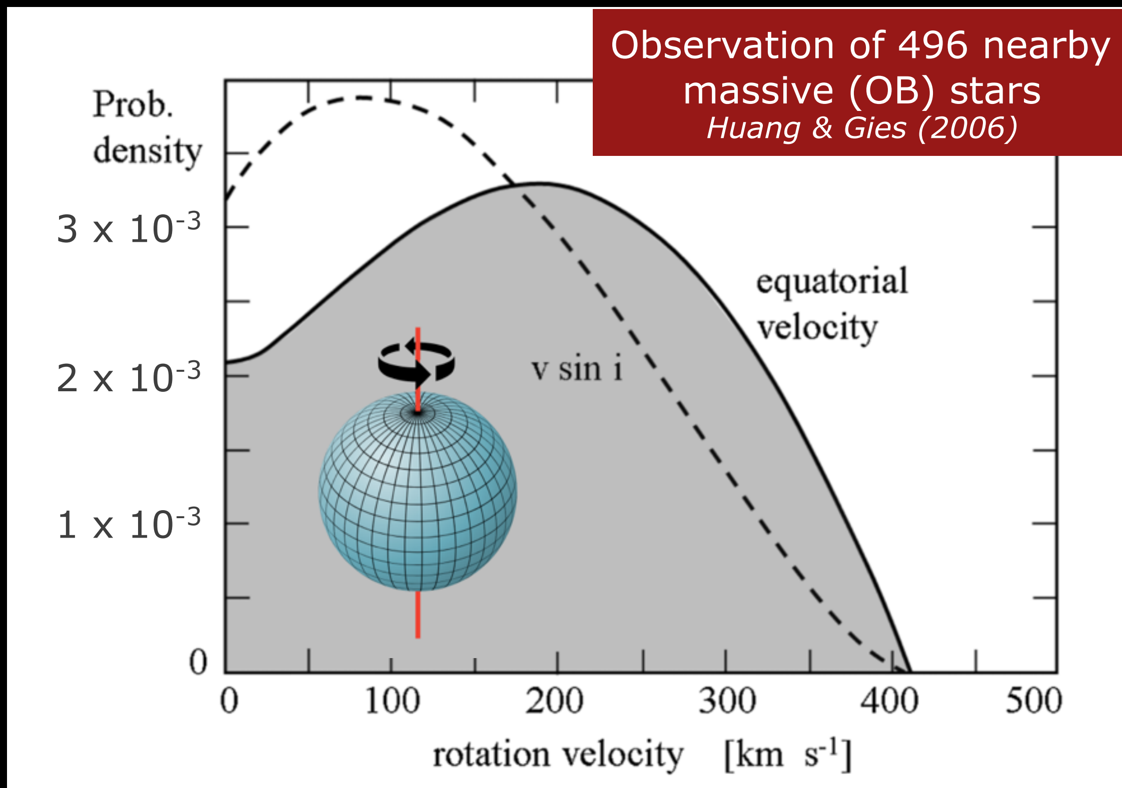
Final fate

Woosley 1993
Yoon & Langer 2005
…

Some effects of rotation

Rotating massive stars

$M_{ini} > 8 M_\odot$



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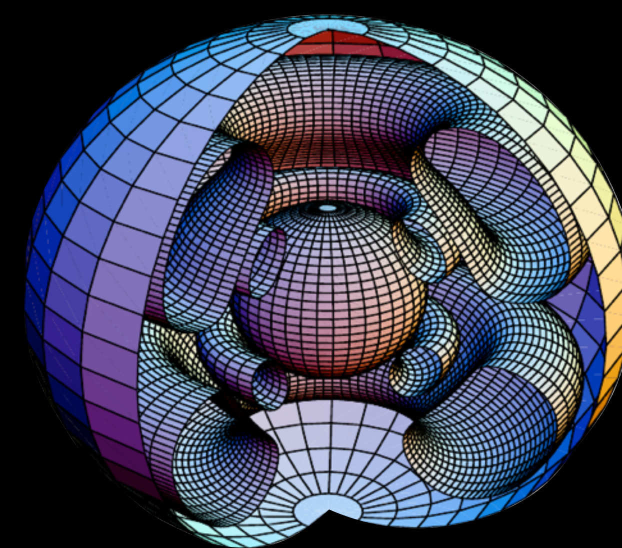

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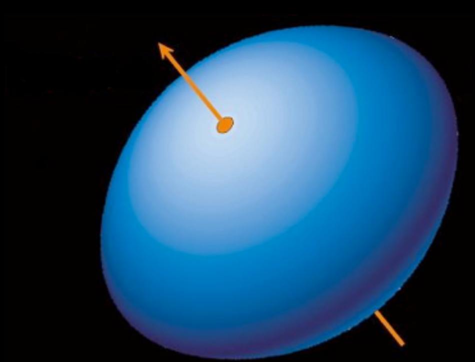

Oblateness

Achernar, 10 $M_\odot$
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Final fate

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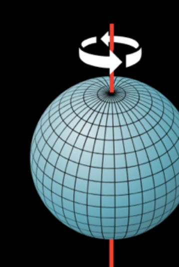
Low metallicity

More compact
=> faster rot.
=> smaller τ_{mix}

e.g. Maeder et al. 2001, …



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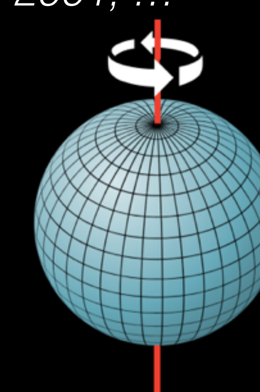


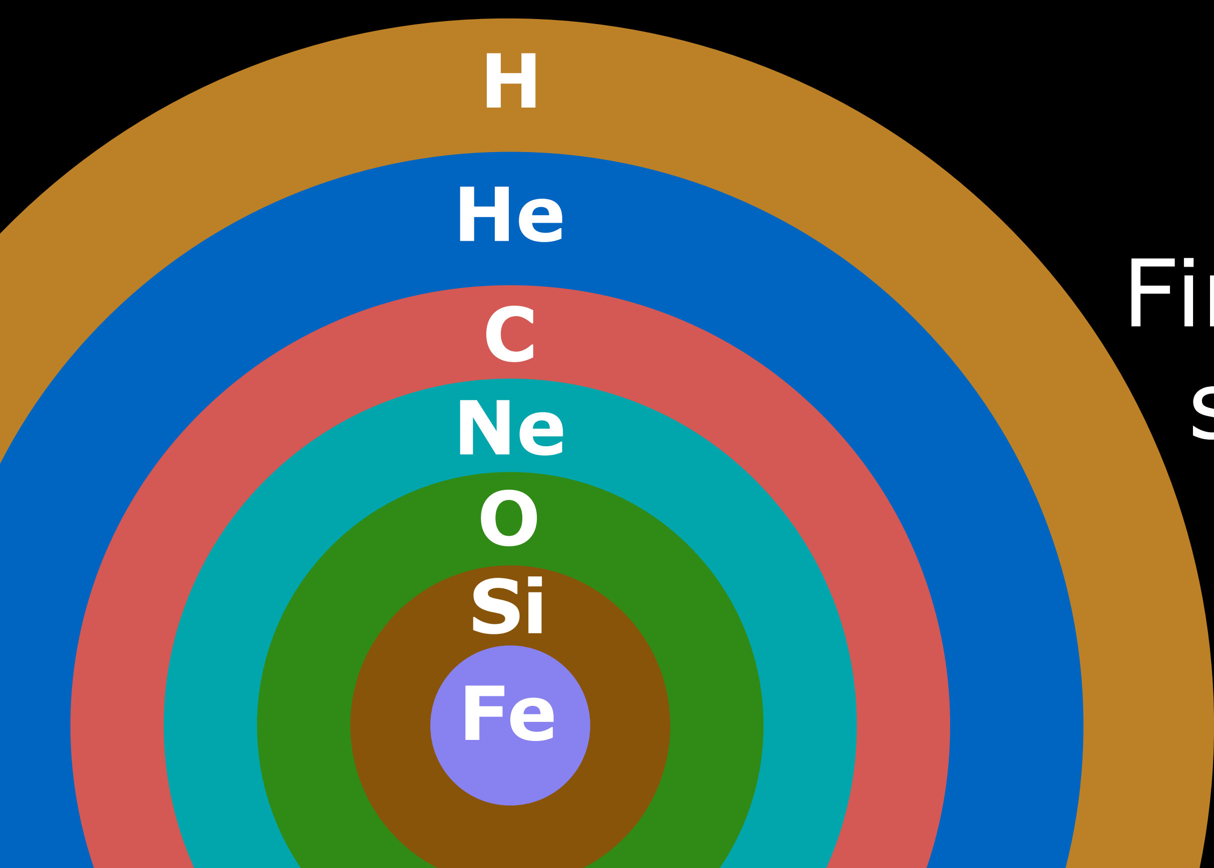
high metallicity

Nucleosynthesis in massive stars

No rotation

e.g. Woosley & Heger (2002), Rauscher et al. (2002)…

Core **Hydrogen** burning →	Core **Helium** burning →	Core **Carbon** burning →	Core **Neon** photo. →	Core **Oxygen** burning →	Core **Silicon** burning
~10 Myr	~0.5 Myr	~100 yr	~1 yr	~1 yr	~1 day
He	C, O	Ne, Na, Mg, Al	O, Mg, Si	Si, S, Ar, Ca	Ni, Cr, Ti…



Final structure

(Not at scale)

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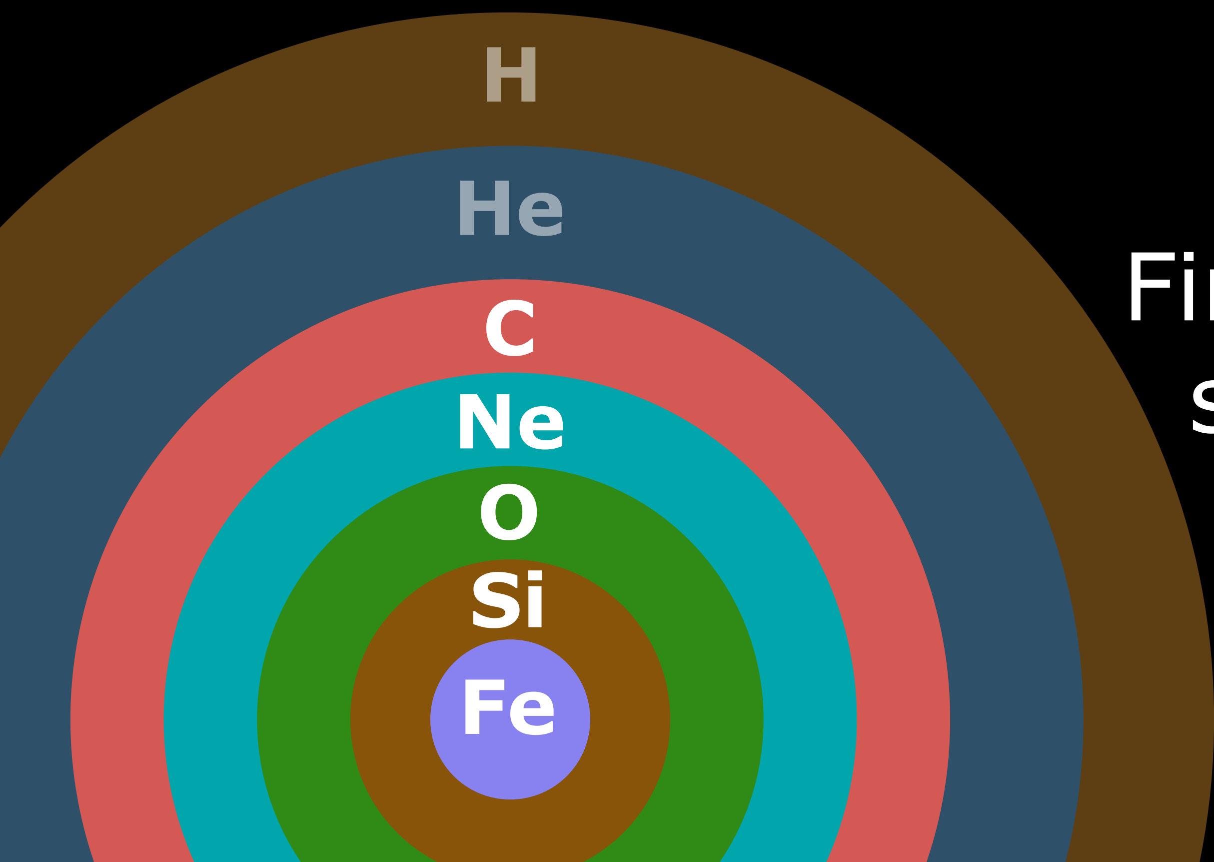
↓

Supernova
explosive C-, Ne-, O-, Si-burning

e.g. Thielemann et al. (1996), Nomoto et al. (2013) …

+ r-process?

e.g. Winteler et al. (2012), Nishimura et al. (2015) …



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Rotational mixing

=> exchanges of material between **He-core** and **H-shell**

=> Rich & varied nucleosynthesis

e.g. Takahashi et al. (2014), Maeder et al. (2015), Choplin et al. (2018) Limongi & Chieffi (2018)
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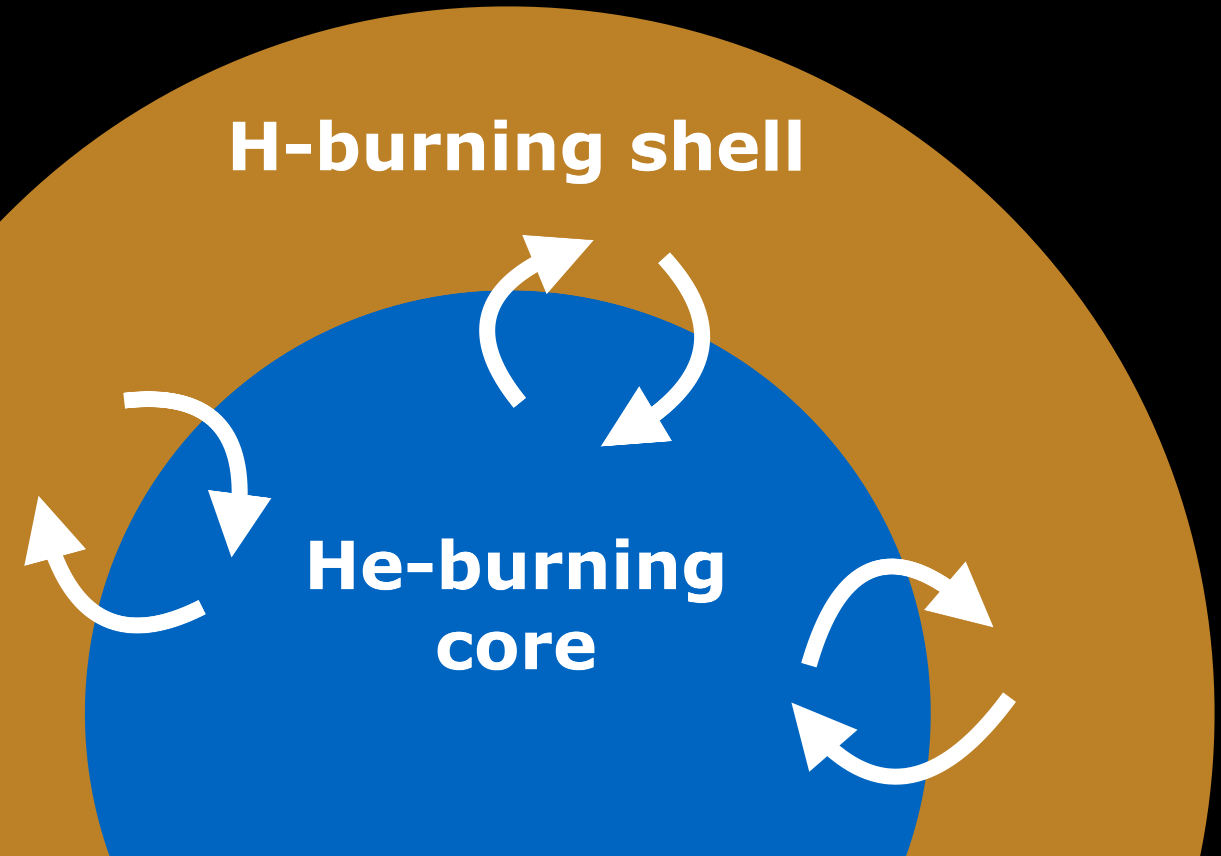

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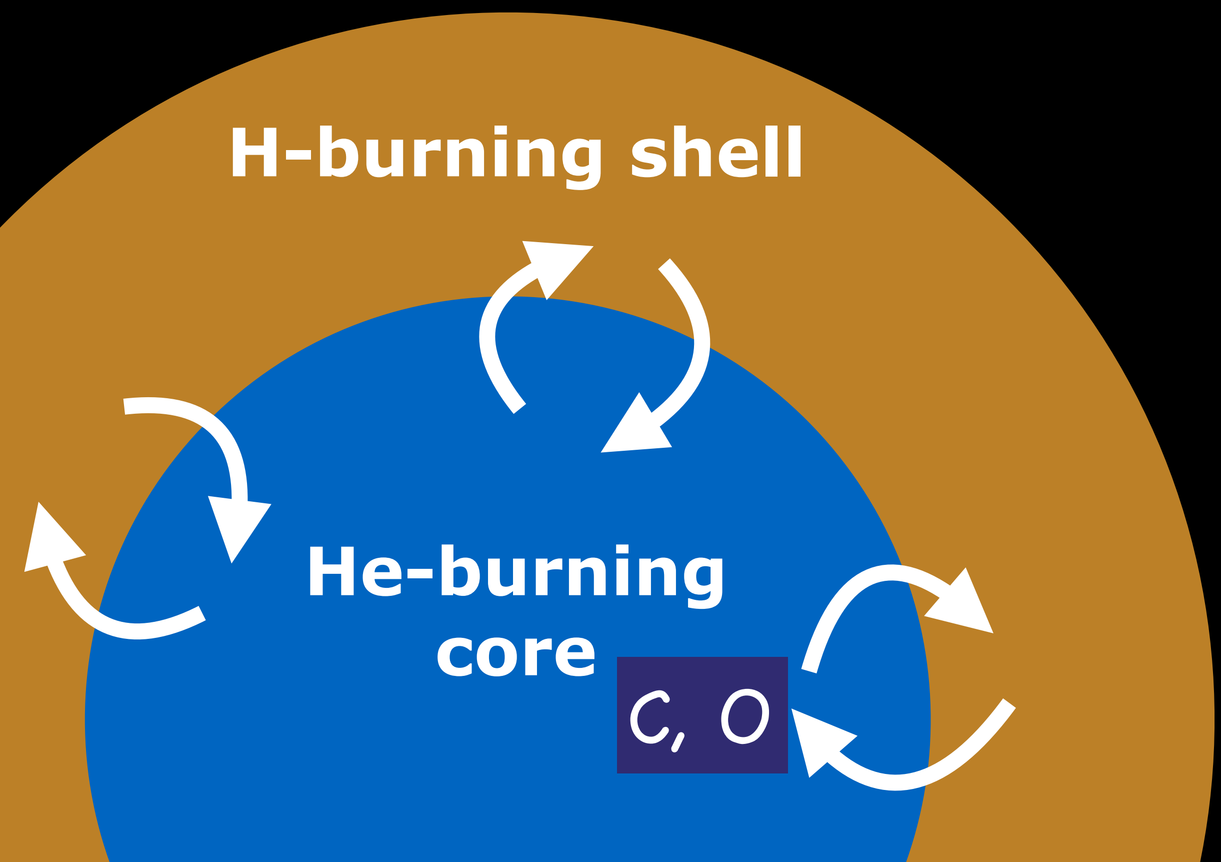

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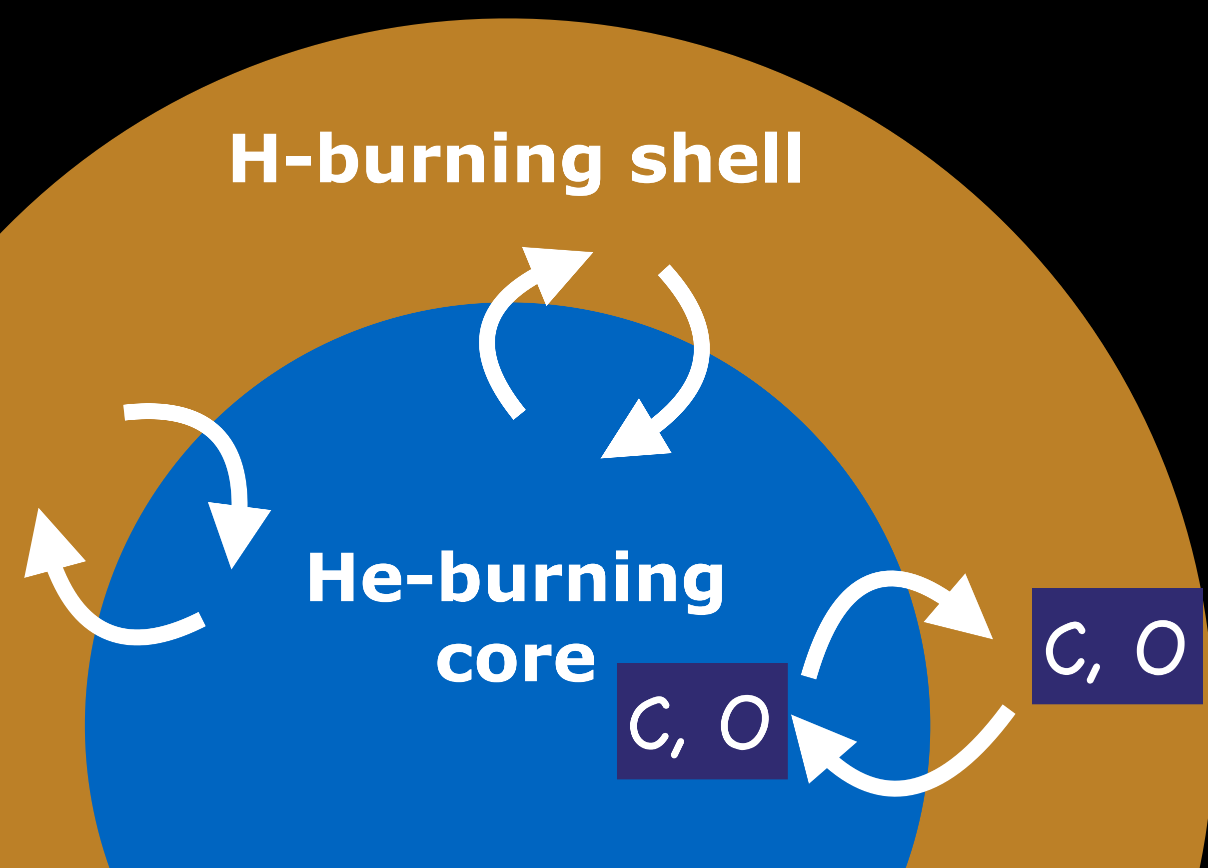

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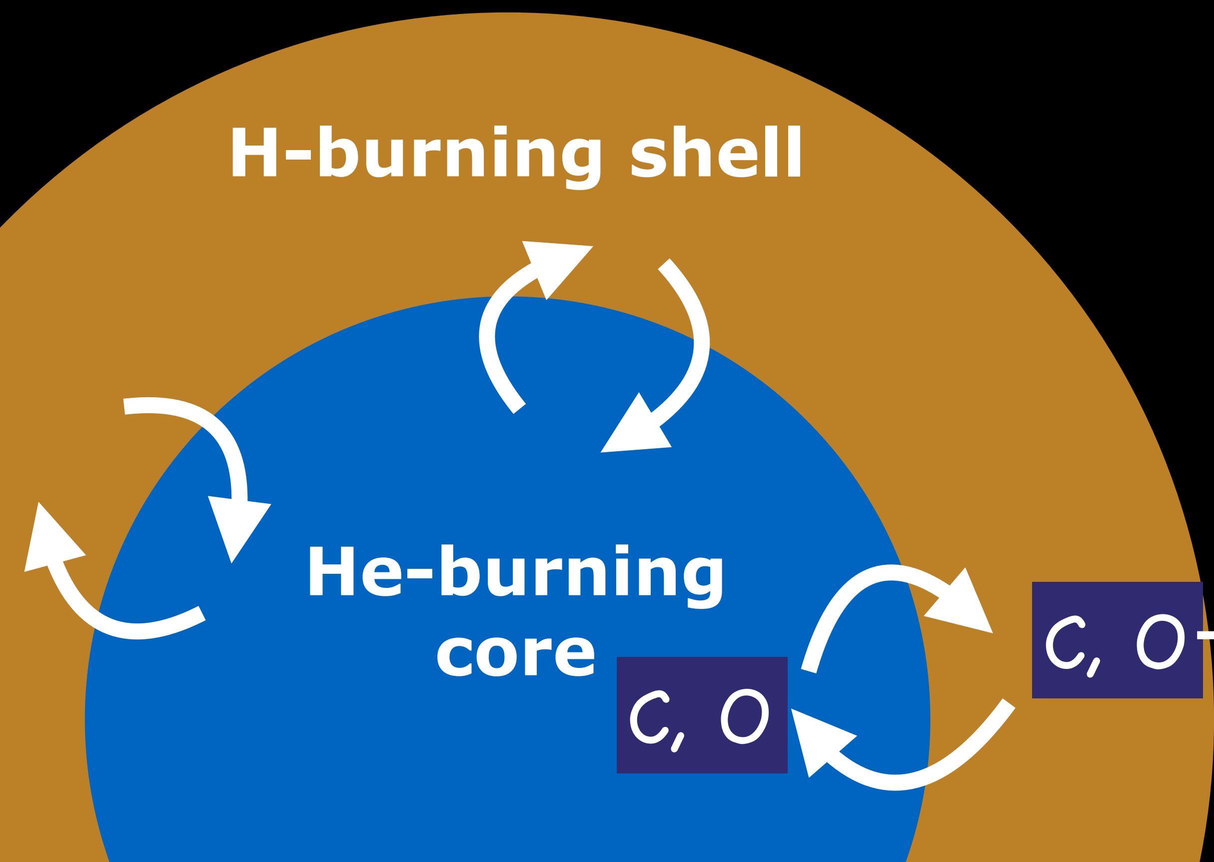

C, O → N, ^{13}C (CNO cycle)

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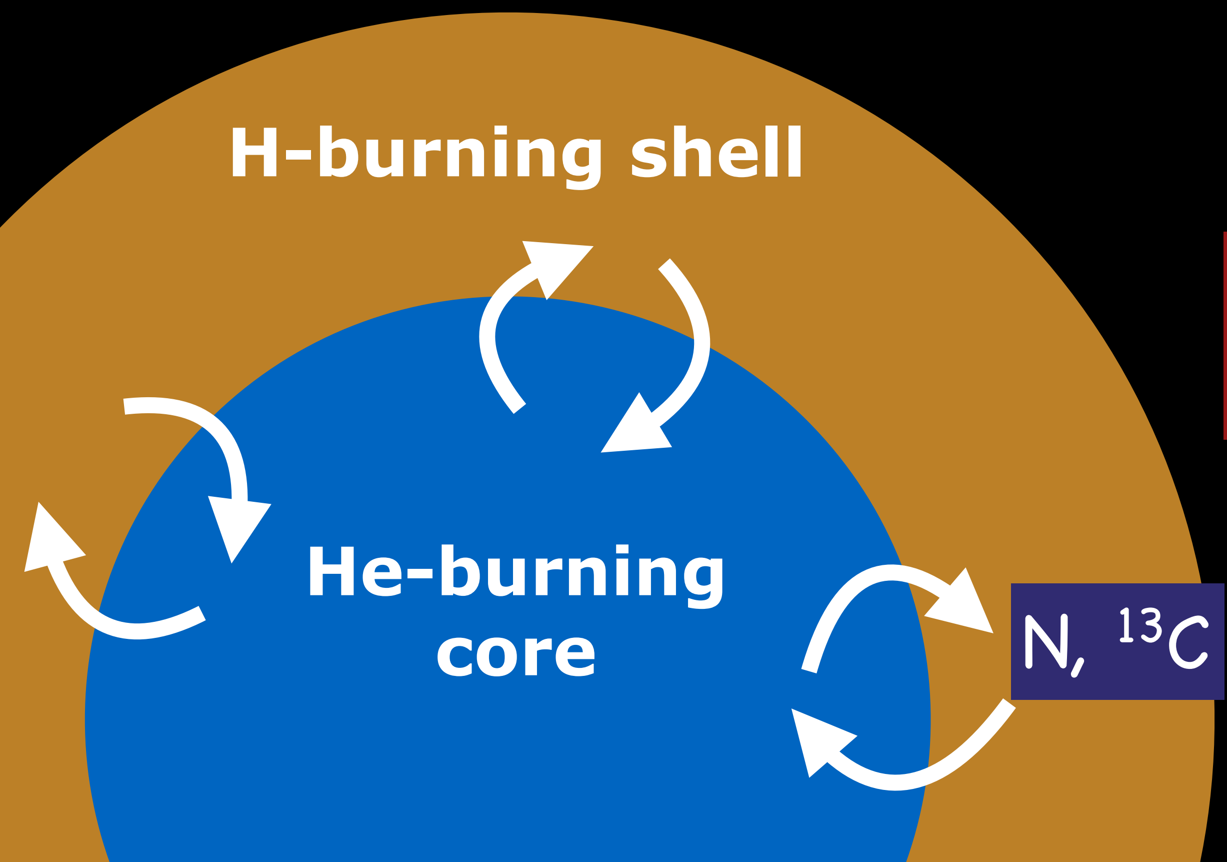

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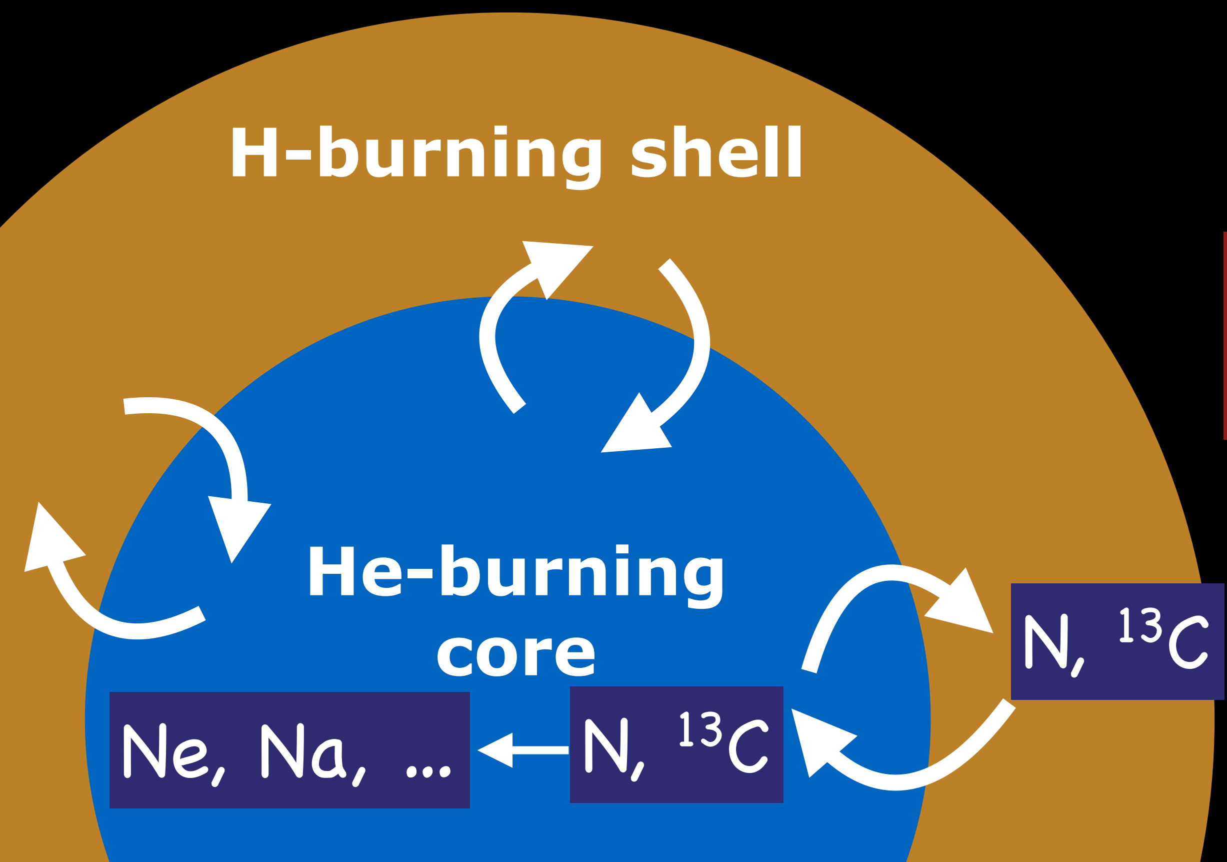

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Nucleosynthesis in massive stars

With rotation

only one burning zone

$\tau_{MIX} \gg \tau_{C}, \tau_{Ne}, \tau_{O}, \tau_{Si}$

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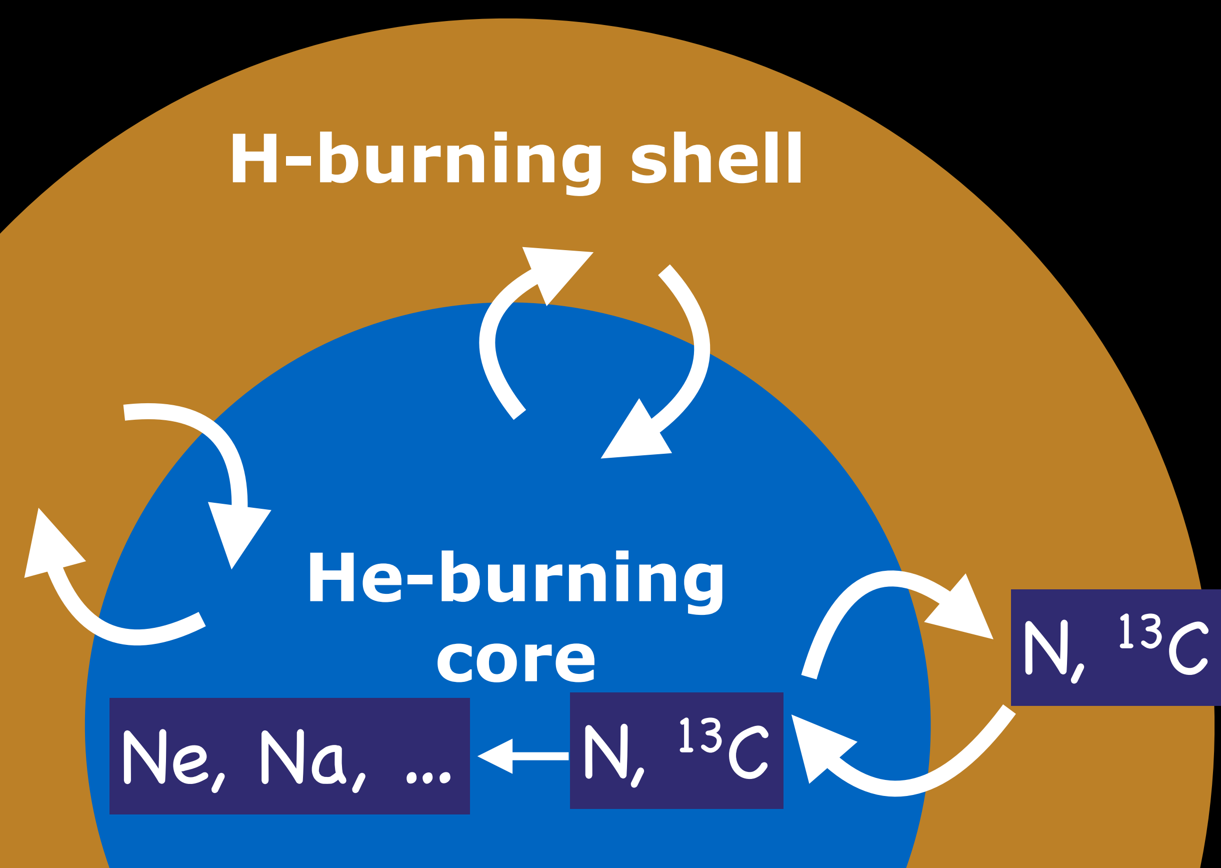

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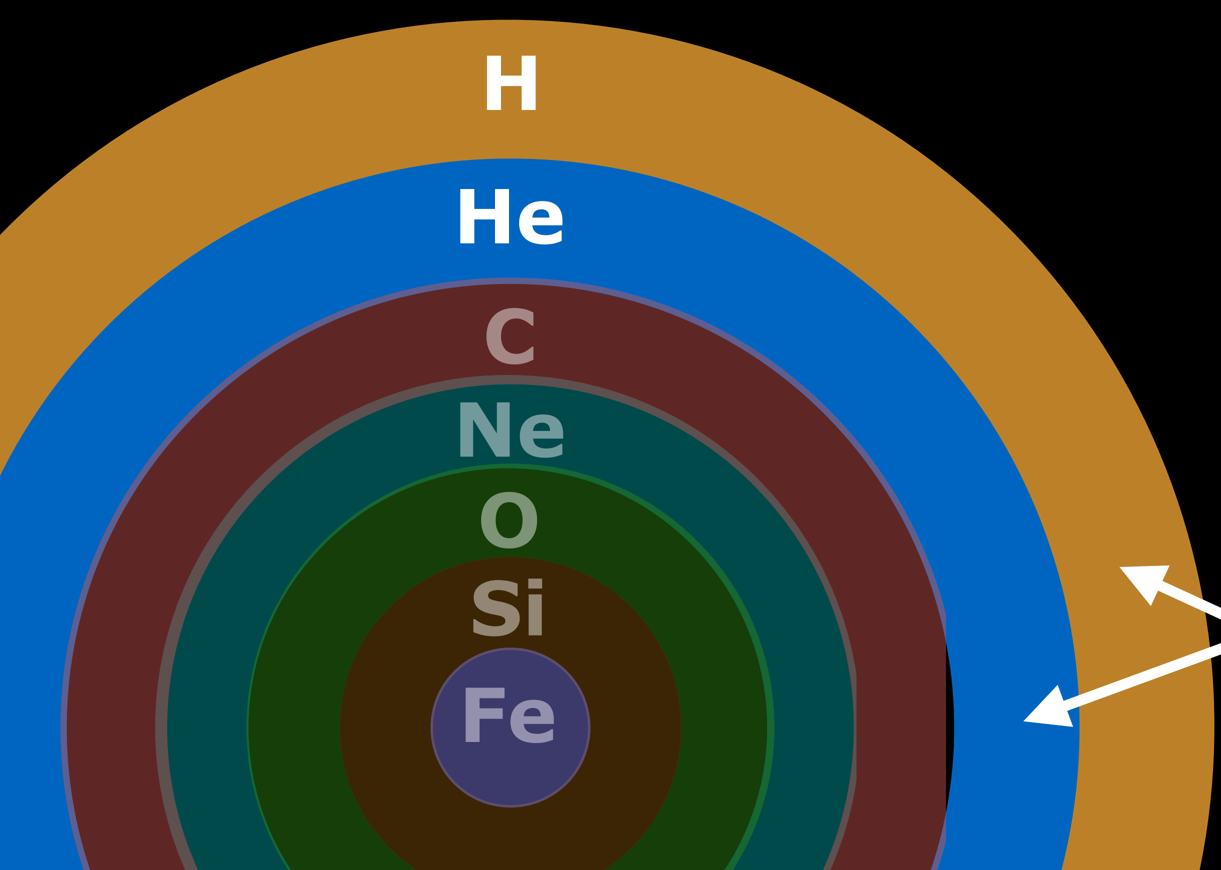
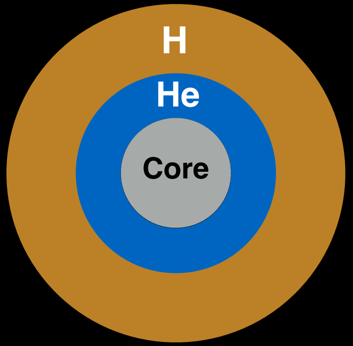


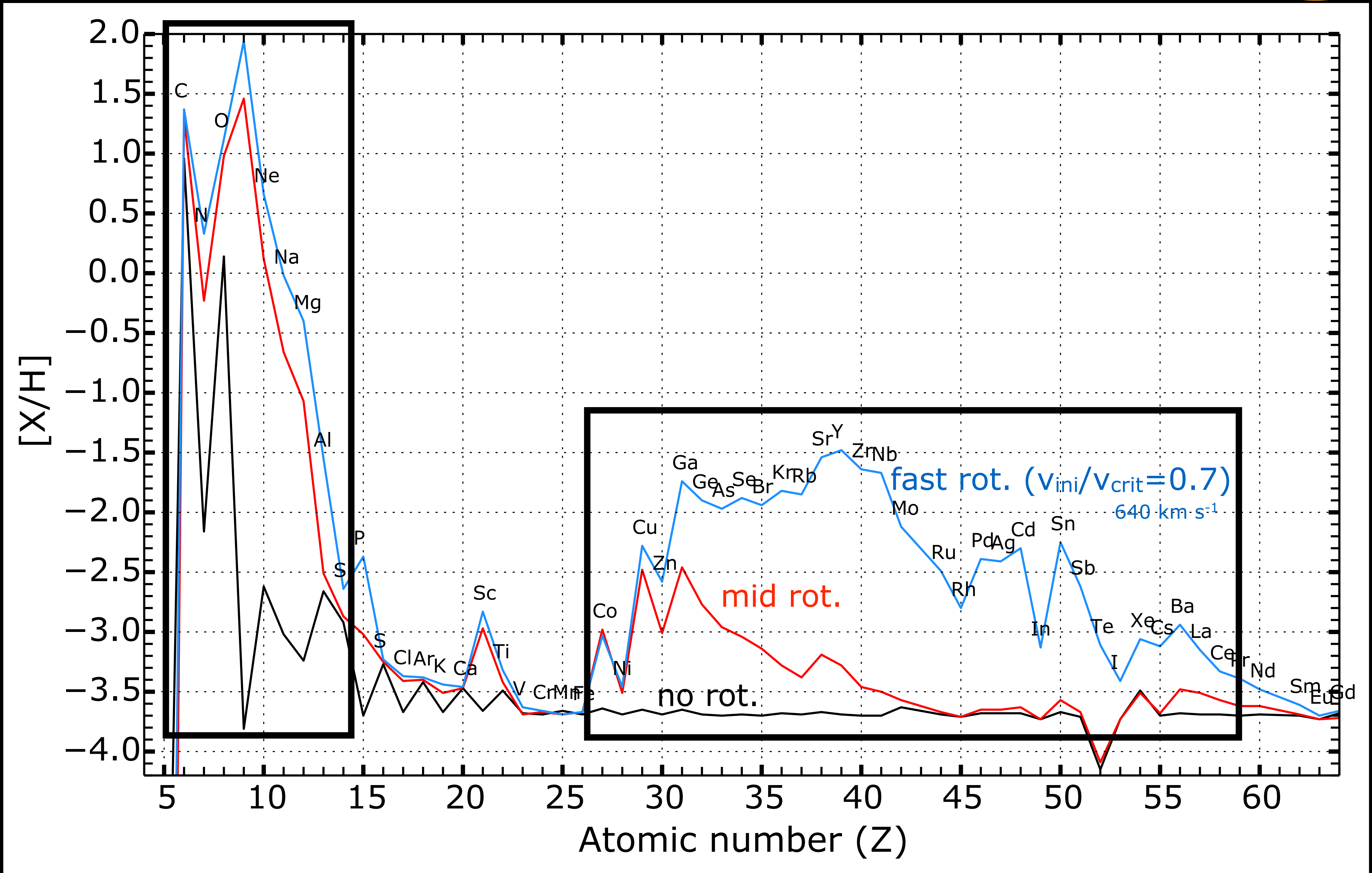
layers mostly impacted by rot. mixing
~70% of total mass in a 20 Mo

Rotating massive stars

Integrated [X/H] ratios in the H+He layers

- 20 $M_\odot$
- $Z=10^{-5}$ ([Fe/H] ~ -3.8)
- 3 initial rotations





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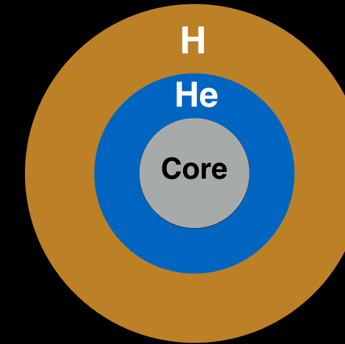

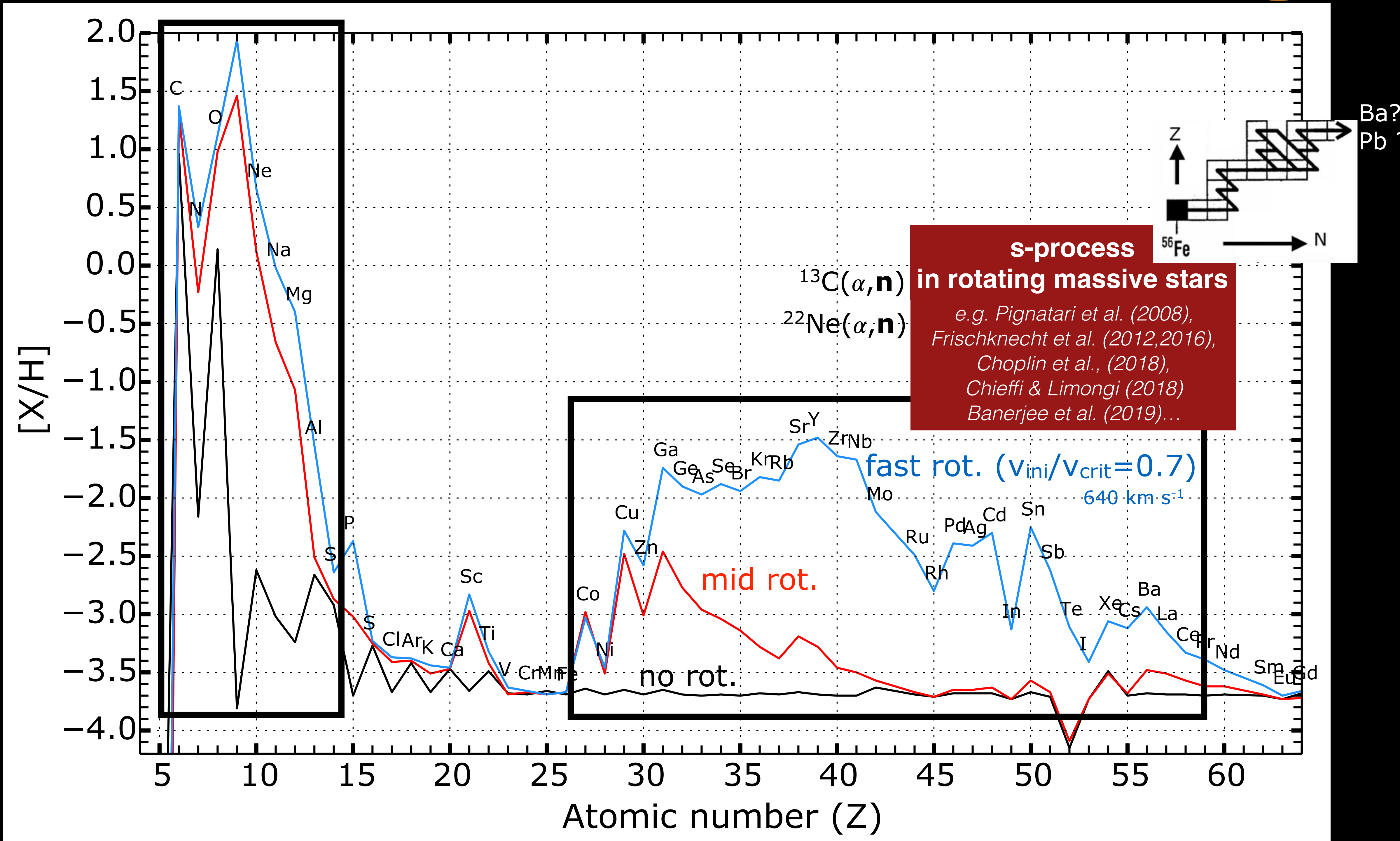

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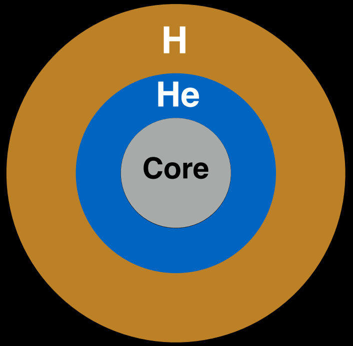

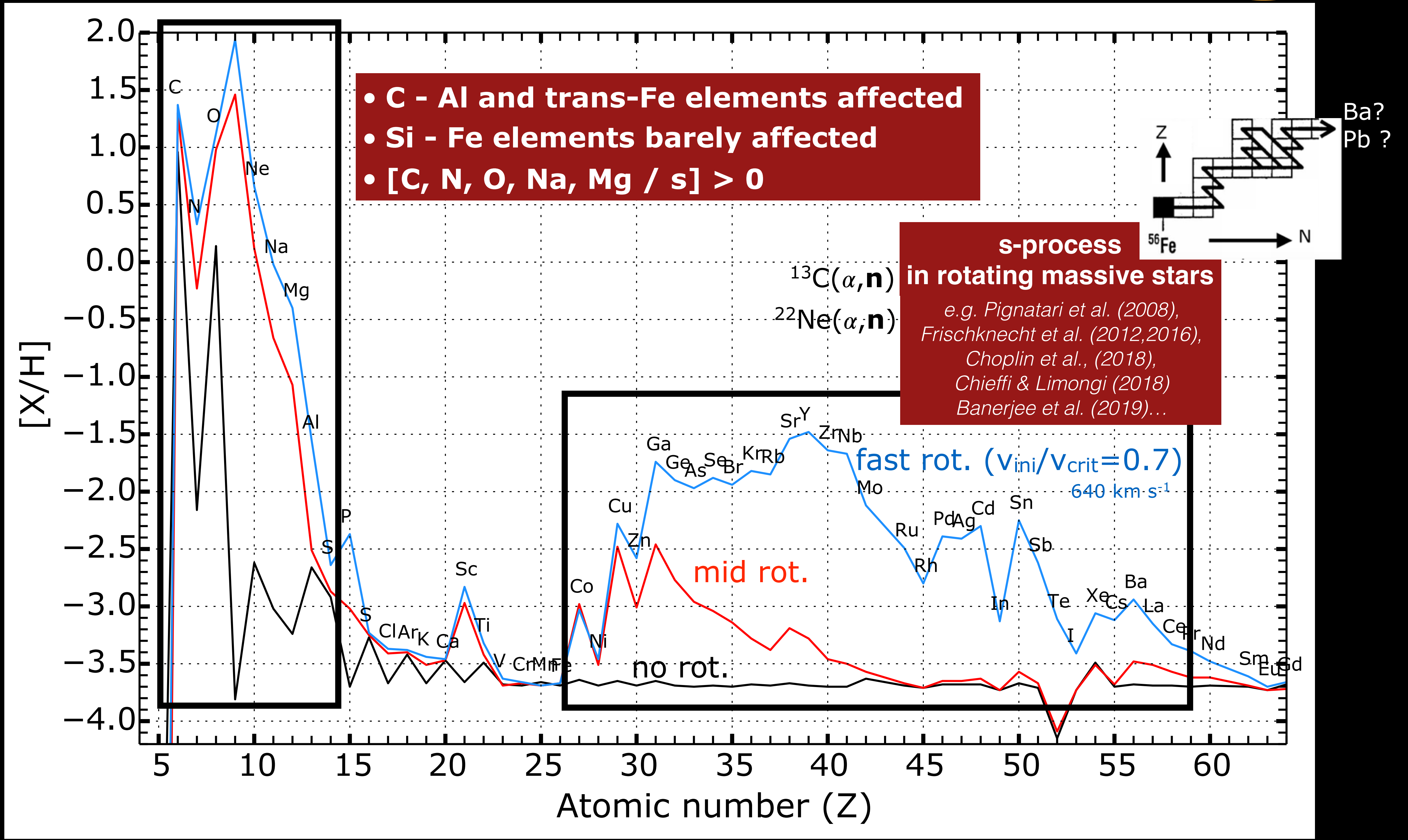

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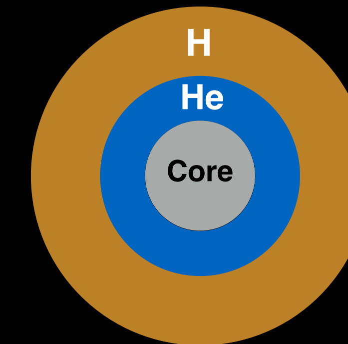

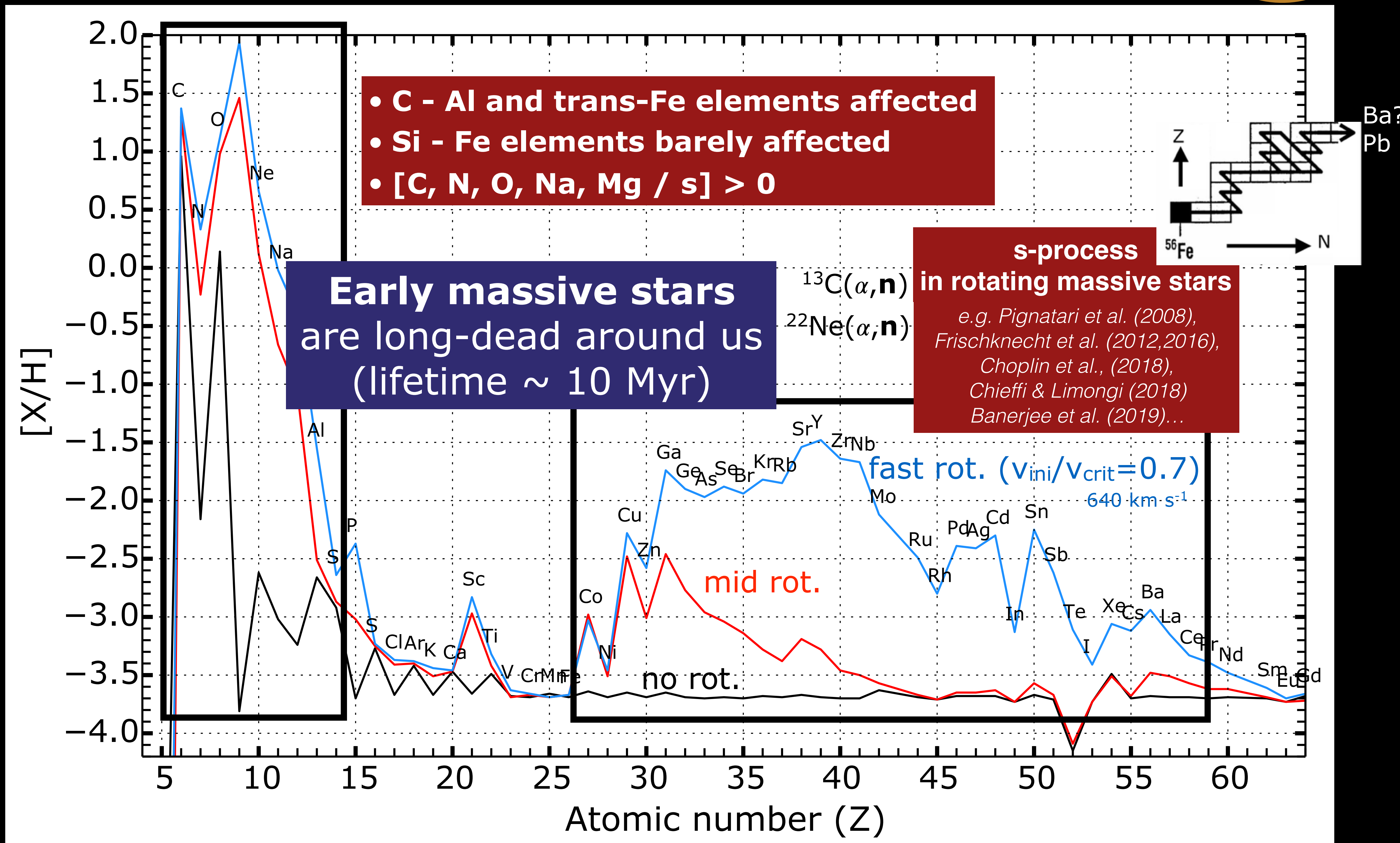

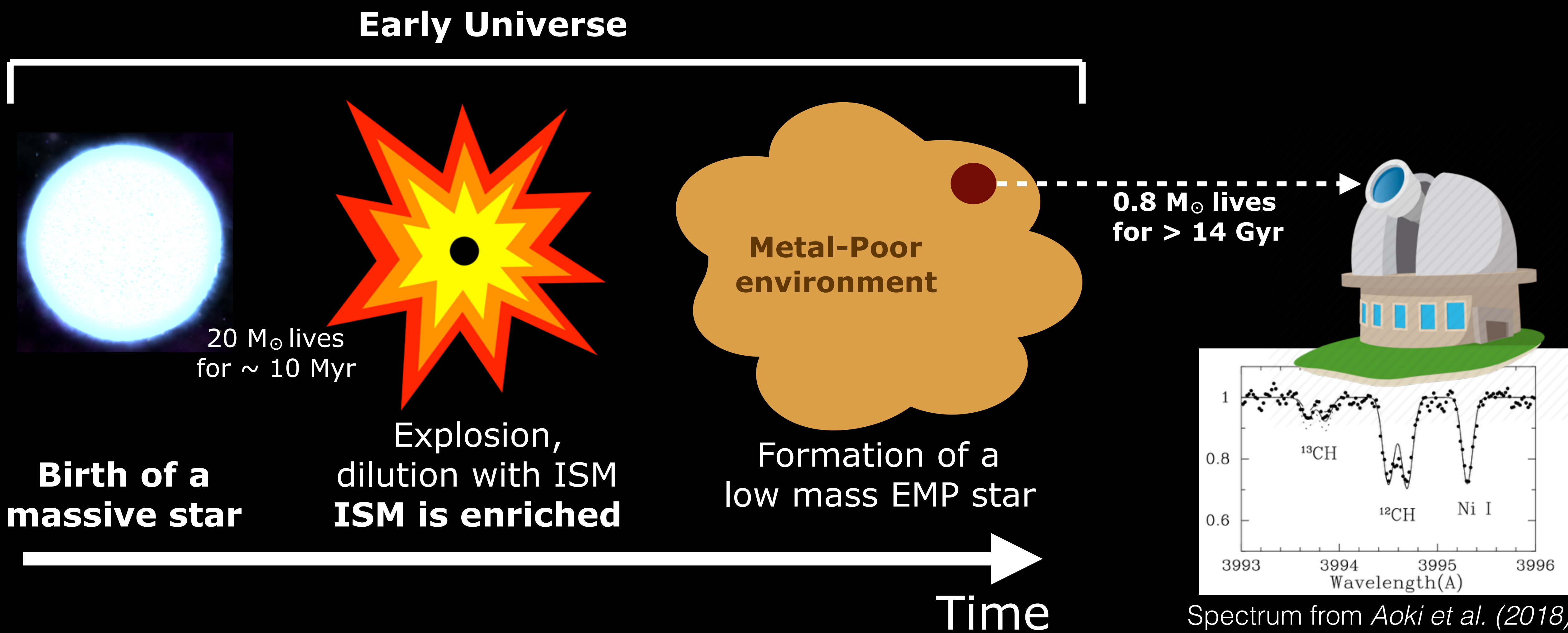

Spectrum from *Aoki et al. (2018)*

stellar archaeology

e.g. Beers et al. (2005), Aoki et al. (2007),
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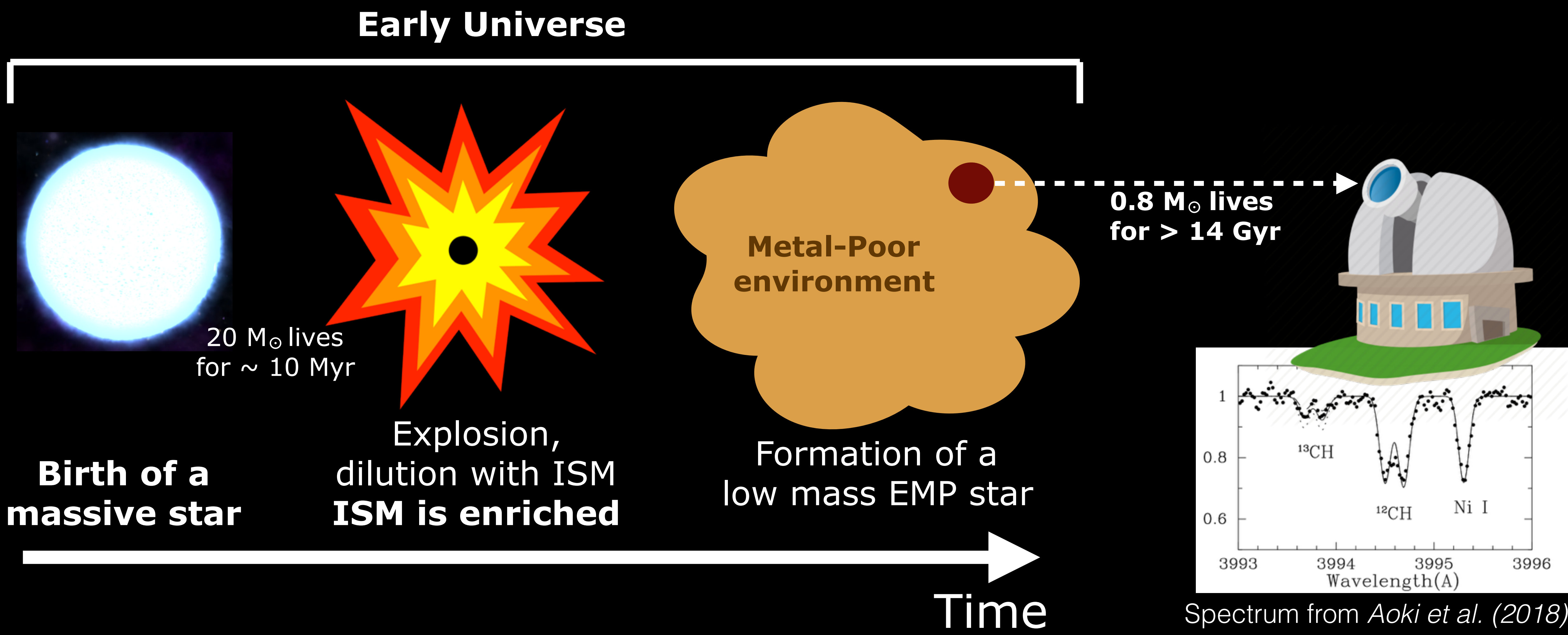

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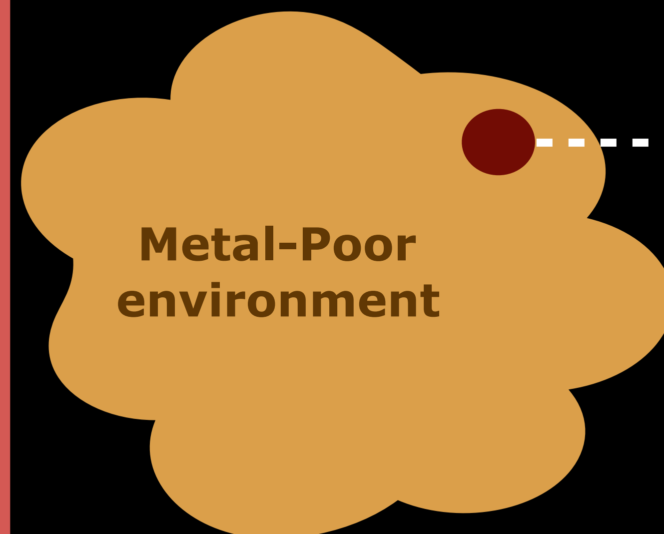
Hundreds of extremely (CE)MP stars
[Fe/H] < -3

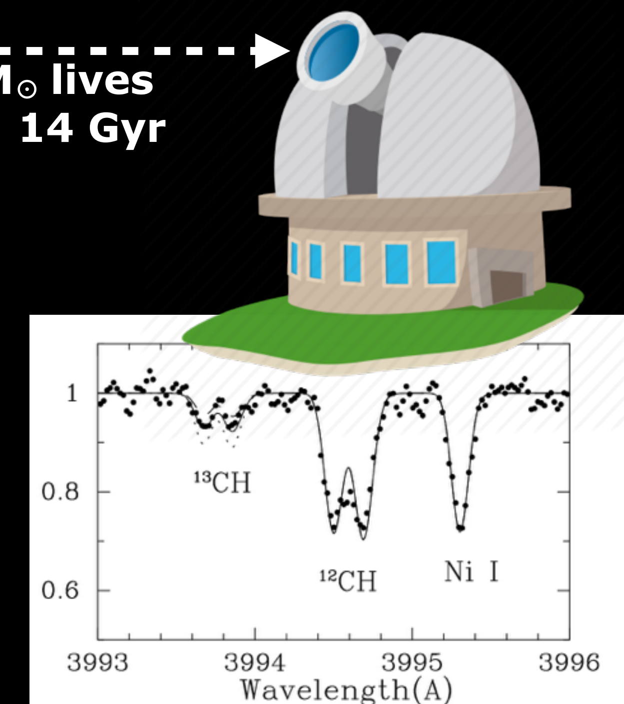
e.g. SAGA database *(Suda+2007)*, JINAbase *(Abohalima+2018)*

Early Universe

20 $M_\odot$ lives for ~ 10 Myr



0.8 $M_\odot$ lives for > 14 Gyr



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Birth of a massive star

Explosion, dilution with ISM
ISM is enriched

Formation of a low mass EMP star

Time

—> Mixing & fallback
Umeda & Nomoto (2002), Iwamoto et al. (2005)…

—> Fast rotation
Meynet et al. (2006), Hirschi (2007), Maeder et al. (2015) …

—> Jet-induced SN
Maeda & Nomoto 2003, Tominaga 2009

—> Shell merging, proton ingestion
e.g. Clarkson et al. (2018), Banerjee et al (2018)

—> AGB stars *e.g. Suda & Fujimoto (2010)*

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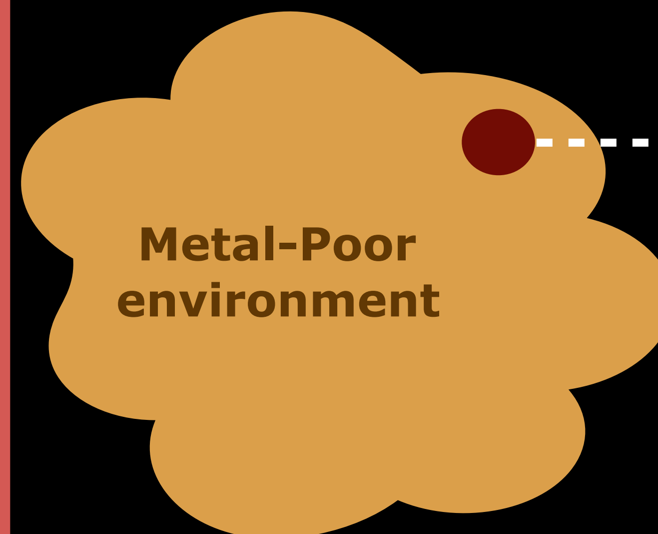

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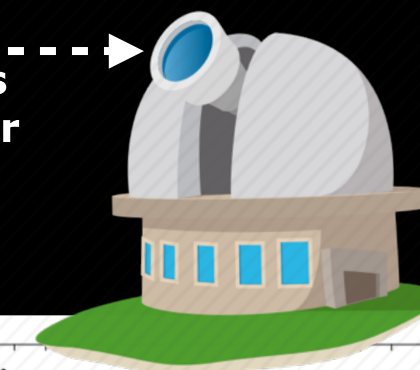

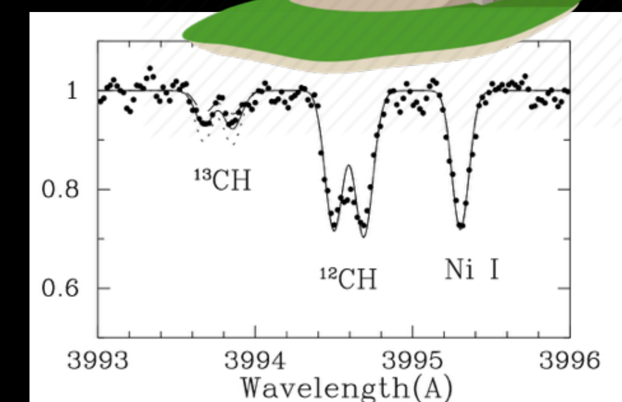

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EMP stars => window on
early massive (AGB) stars

stellar archaeology

e.g. Beers et al. (2005), Aoki et al. (2007),
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Hundreds of extremely (CE)MP stars
[Fe/H] < -3

e.g. SAGA database *(Suda+2007)*, JINAbase *(Abohalima+2018)*

=> allows to guess
the average characteristics
of first massive stars

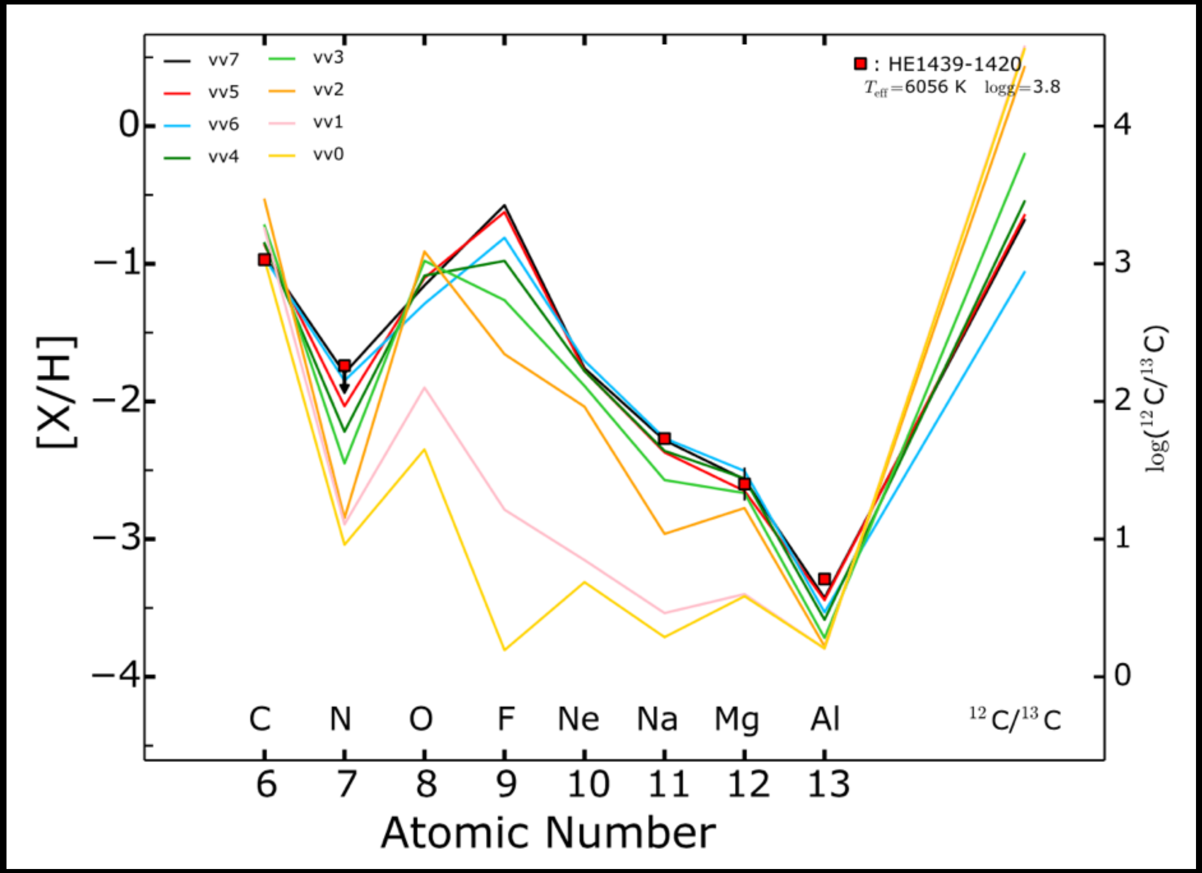
e.g. Ishigaki et al. (2018)

Guessing the velocity of early massive sars from EMP stars

Choplin et al. (submitted)

- 20 $M_\odot$, [Fe/H] = -3.8
- v_{ini} / v_{crit} = 0, 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7
- M_{cut} , dilution factor : free param.
- Explo. with strong fallback assumed

- Sample : 272 EMP with -3 < [Fe/H] < -4
- Analysis of light elements (C - Al)
- Evolutionnary effects in EMP => correction / limits
  (Dredge up, thermohaline mixing) *Placco et al. (2014)*



HE1439-1420 : abundance data from Cohen et al. (2013)

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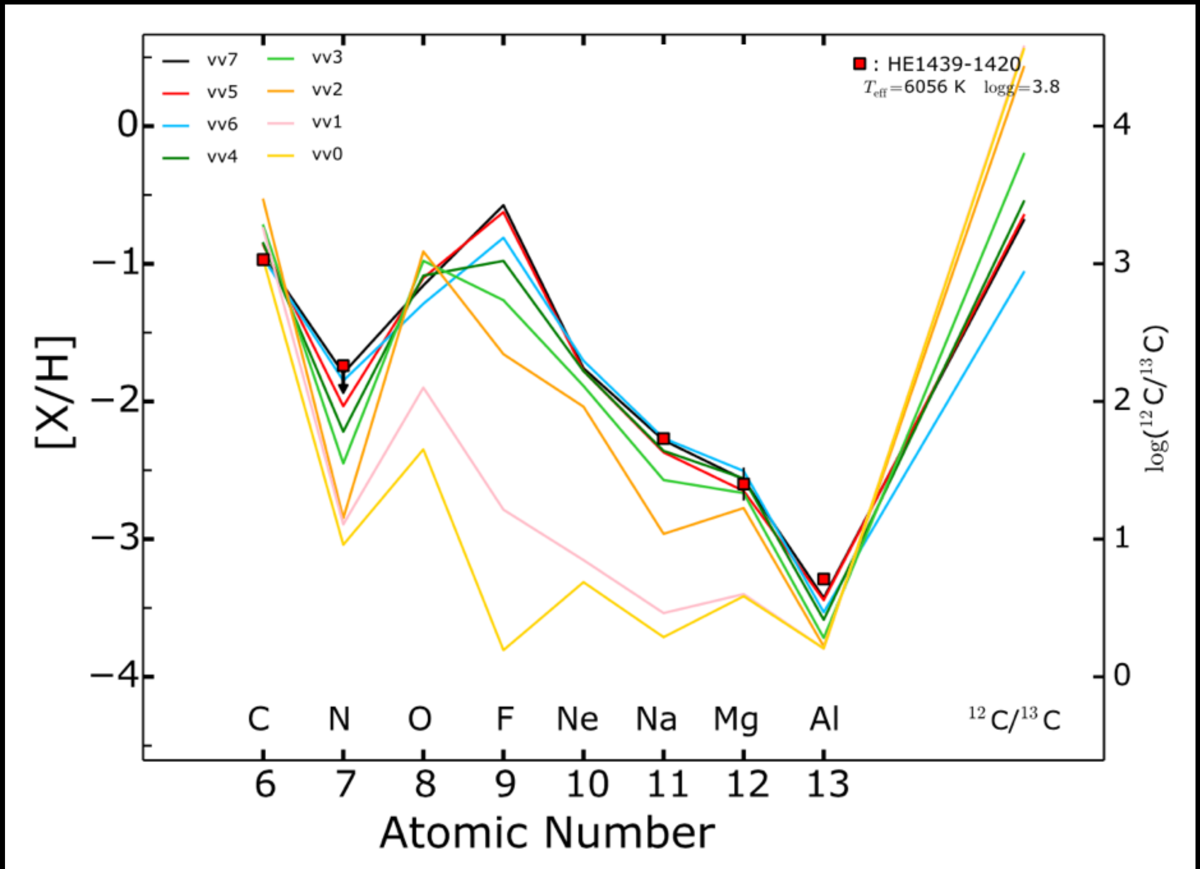
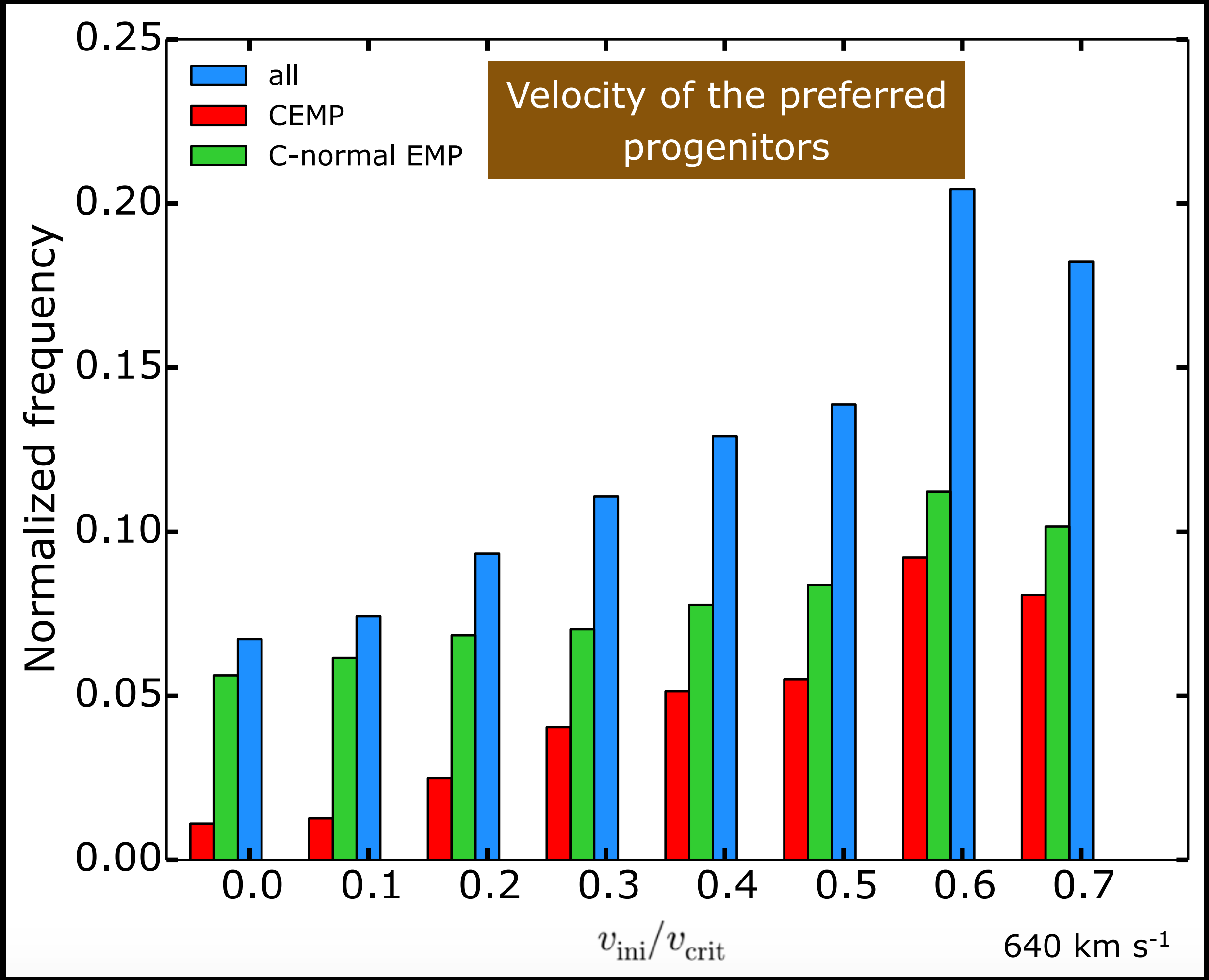
- ~ 40% of fits with $X_\nu{}^2 < 2$
- ~ 60% of fits with $X_\nu{}^2 < 3$
- Sometime: several good candidates => weigths

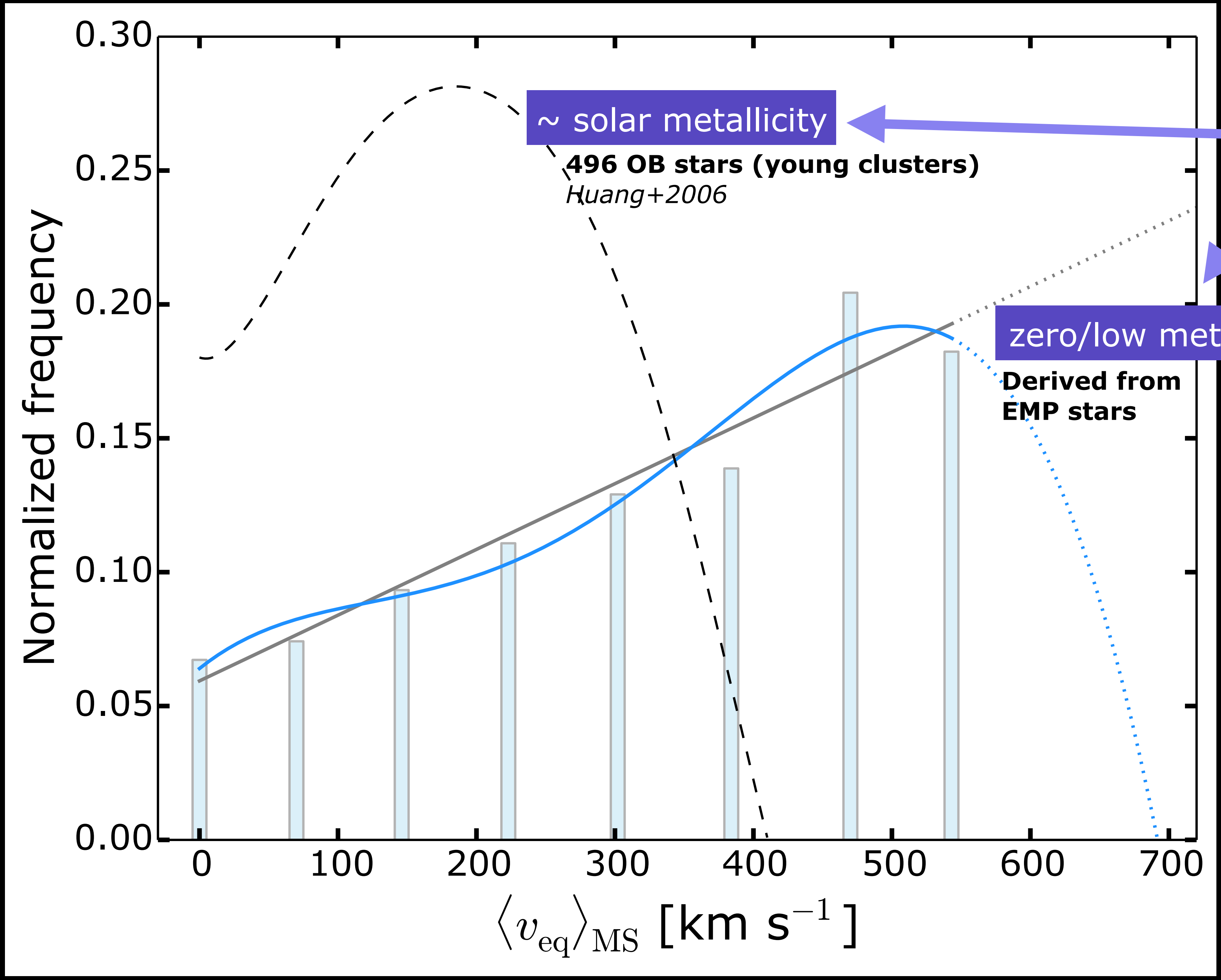


HE1439-1420 : abundance data from Cohen et al. (2013)



Guessing the velocity of early massive sars from EMP stars

Choplin et al. (submitted)



Different metallicity environments

Low Z

- stars more compact
- mass loss ~ $Z^{0.5 - 0.85}$

=> faster rotation (?)

and/or more angular momentum at birth?

Summary

- In low metallicity rotating massive stars
  - C - Al and trans-Fe elements overproduced (to Ba? Pb?)
  - Si-Fe elements barely affected

- Extremely Metal-Poor stars: window on early massive stars

  Large sample of EMP stars => average characteristics of early massive stars.

- Abundances of EMP stars may suggest a velocity distrib. of early massive stars peaking at $\gtrsim$ 400-500 km s^{-1} (vs. ~ 200 km s^{-1} in the local Universe)

  —> If fast rot., impact on reionization, light from high redshift galaxies…

One of the limit :

- Uncertainties. Affect both models and abundances of EMP stars

models ↙ convection, rotation, …
—> talk by K. Takahashi

abundances of EMP stars ↘ NLTE, 3D effects
e.g. Norris & Yong (2019)