Nucleosynthesis in Pop III / II (rotating) massive stars and the chemical composition of observed metal-poor stars

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Konan University, Japan

Collaborators:
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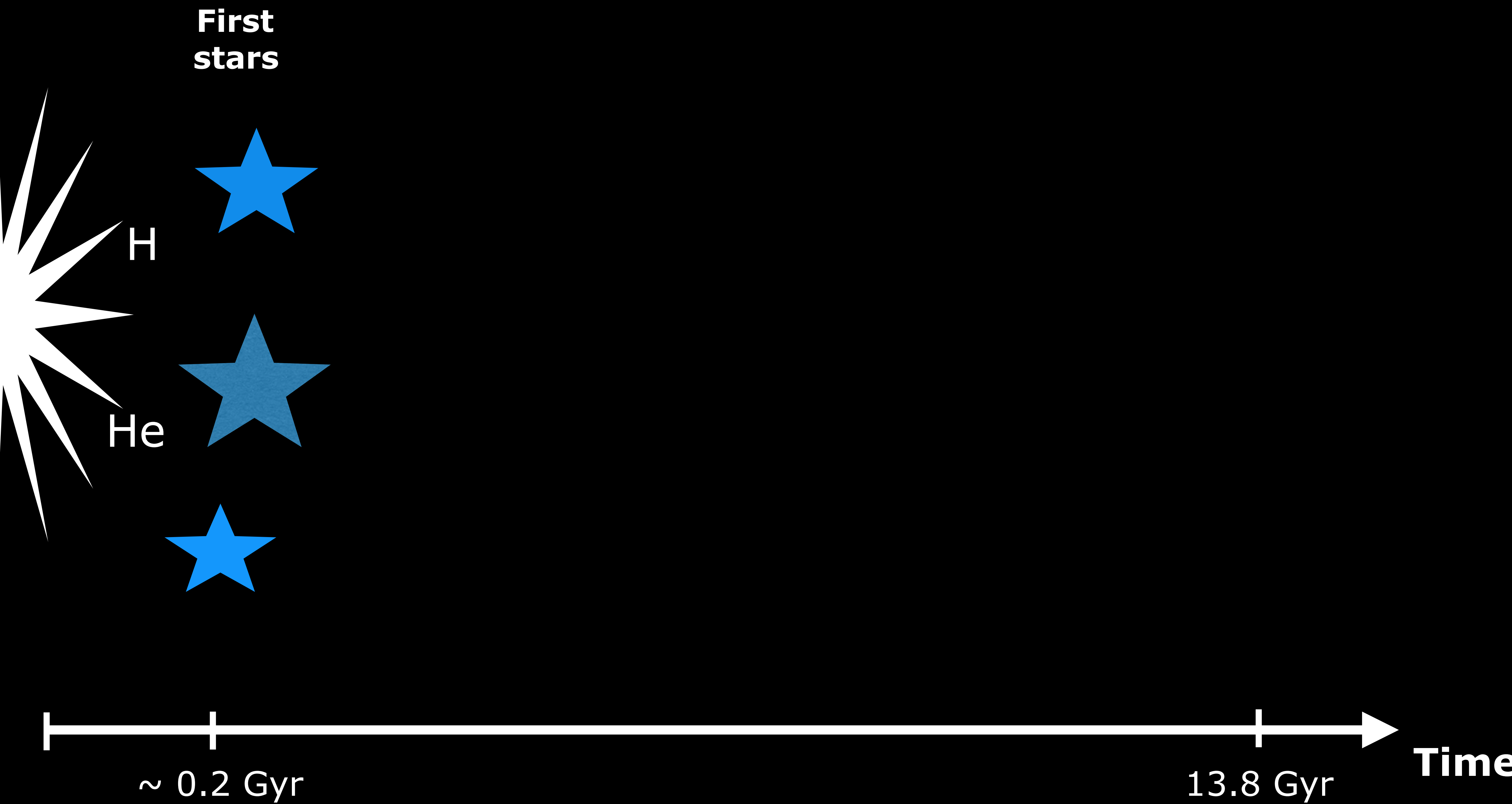
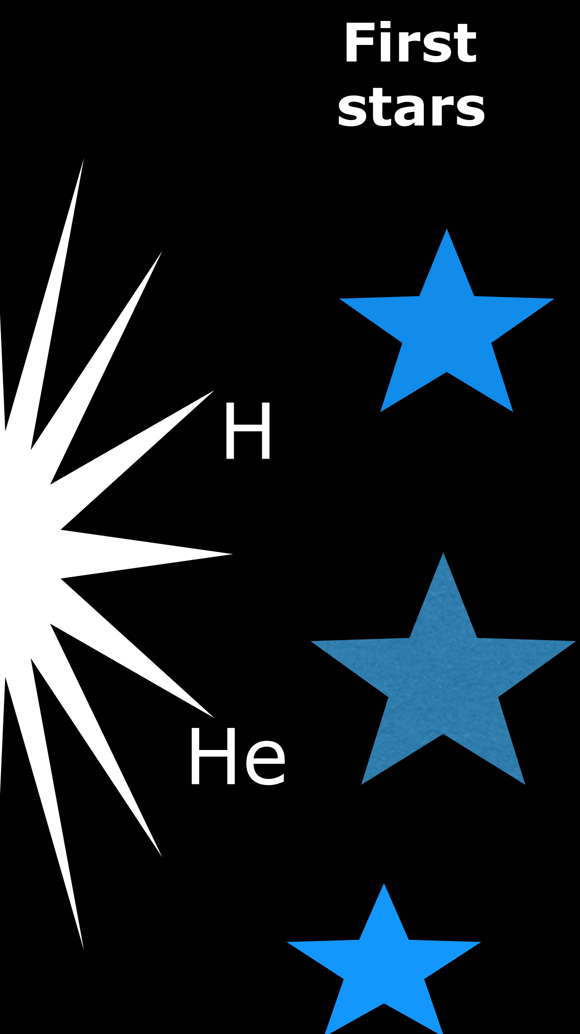
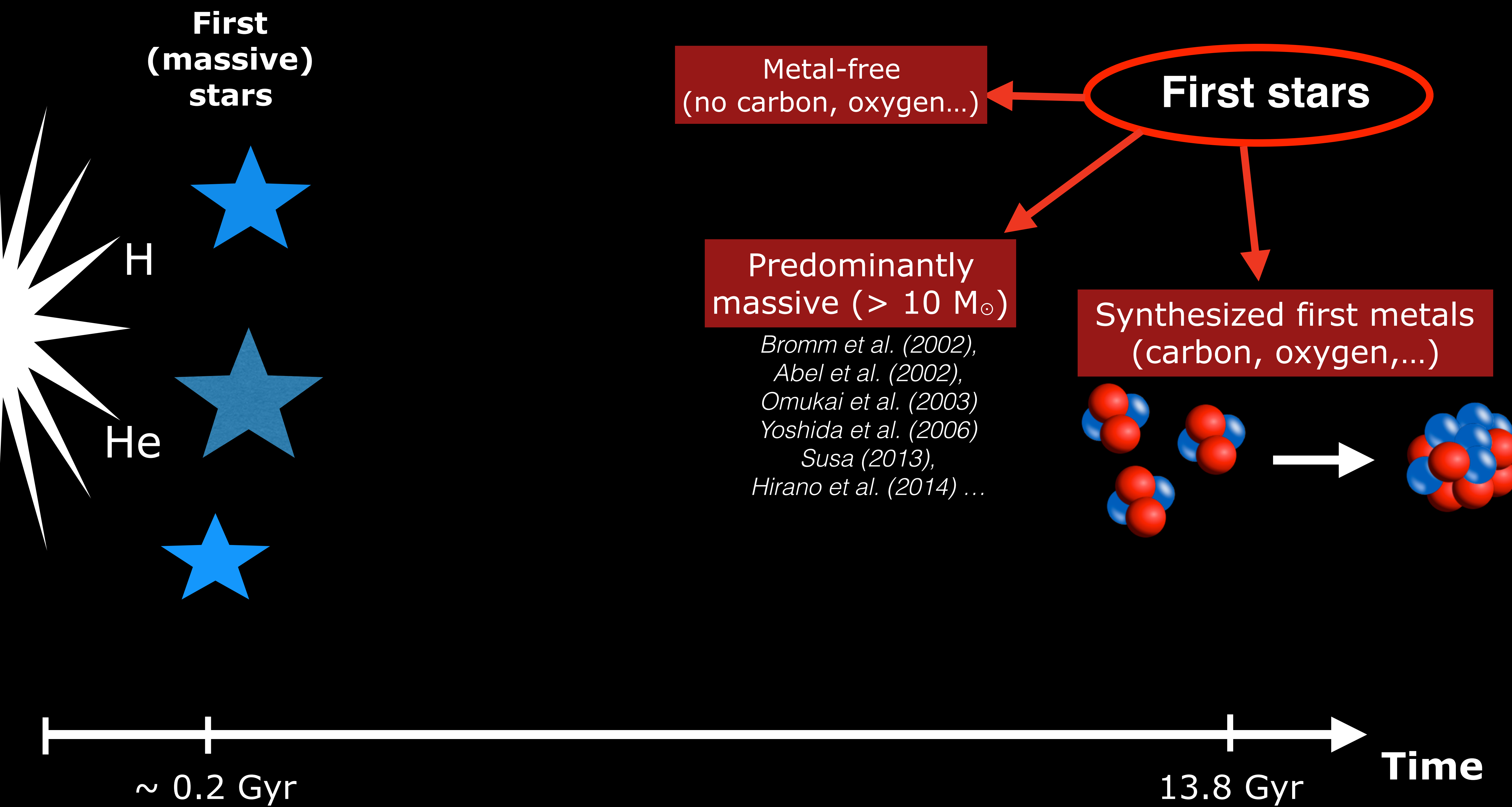
November 11th
Nagoya


First stars
H
He
~ 0.2 Gyr
13.8 Gyr
Time



What are their properties ?

—> Origin of the elements
—> First supernovae
—> Reionization
—> …


First
(massive)
stars
H
He
Metal-free
(no carbon, oxygen…)
First stars
Predominantly
massive (> 10 M☉)
Bromm et al. (2002),
Abel et al. (2002),
Omukai et al. (2003)
Yoshida et al. (2006)
Susa (2013),
Hirano et al. (2014) …
Synthesized first metals
(carbon, oxygen,…)
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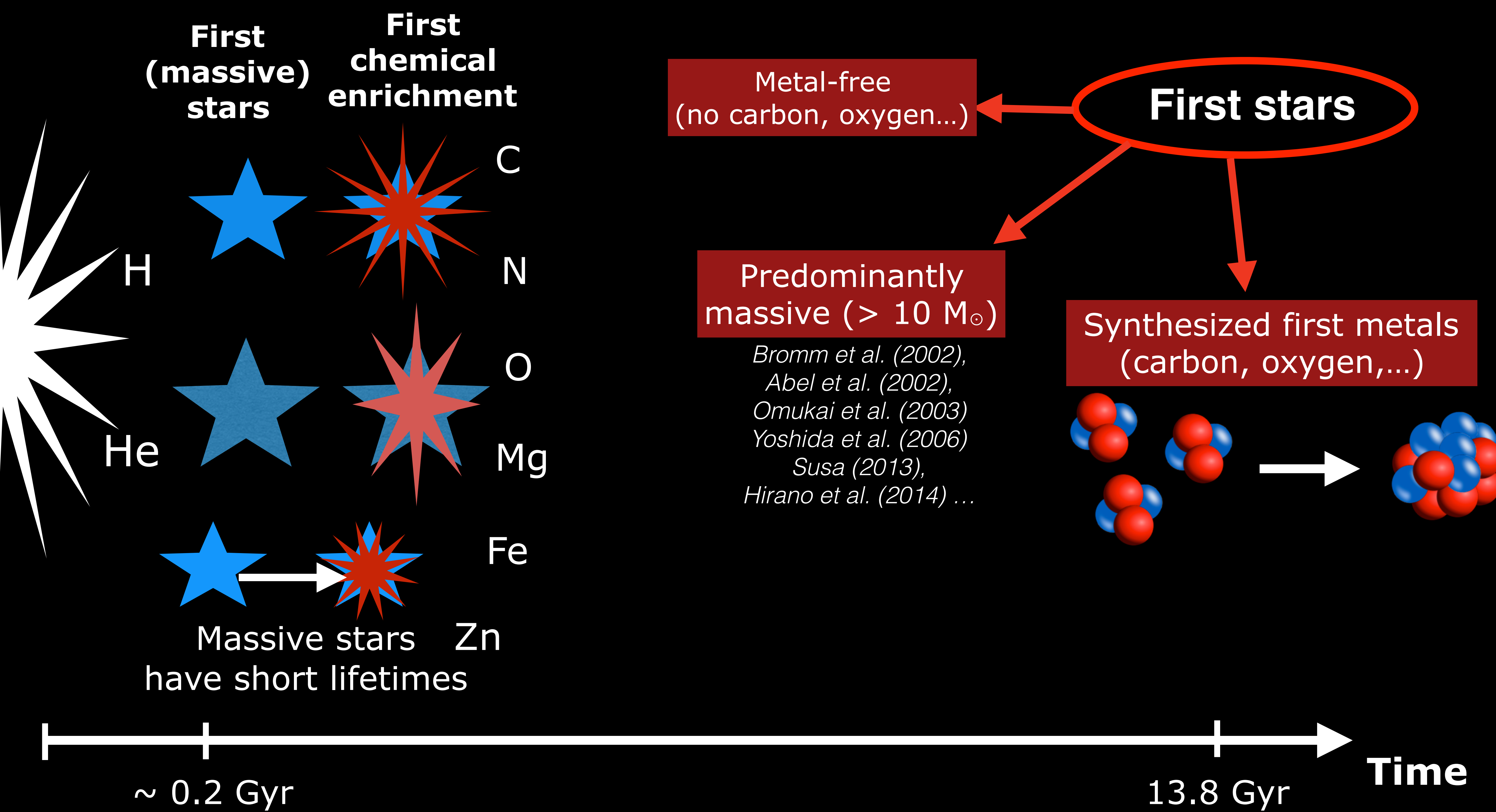
First (massive) stars
First chemical enrichment
H
He
C
N
O
Mg
Fe
Zn
Massive stars have short lifetimes
Metal-free (no carbon, oxygen...)
First stars
Predominantly massive (> 10 M☉)
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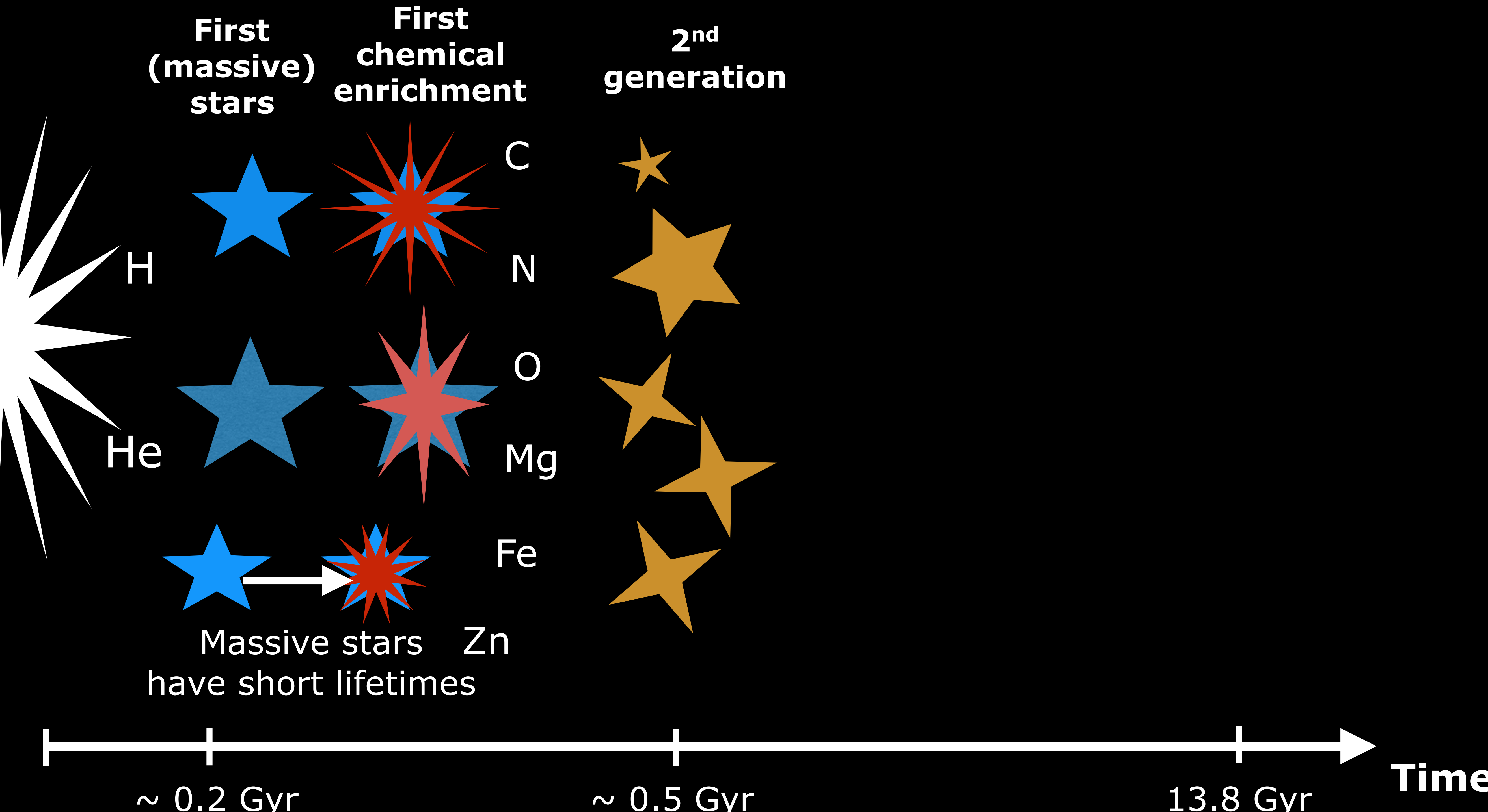
First (massive) stars
First chemical enrichment
2nd generation
H
He
C
N
O
Mg
Fe
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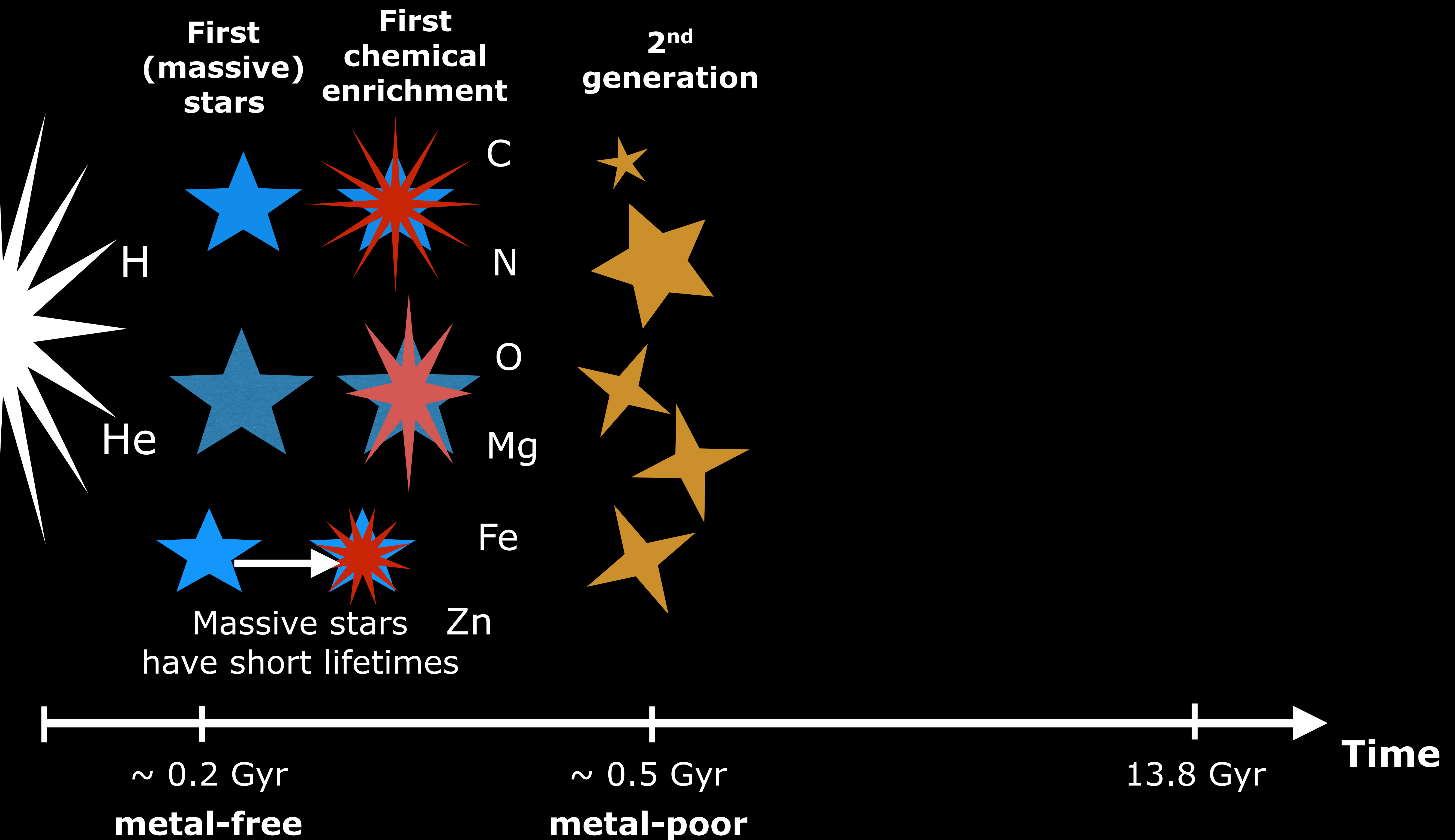
Massive stars have short lifetimes
~ 0.2 Gyr
~ 0.5 Gyr
13.8 Gyr
Time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Massive stars
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metal-free
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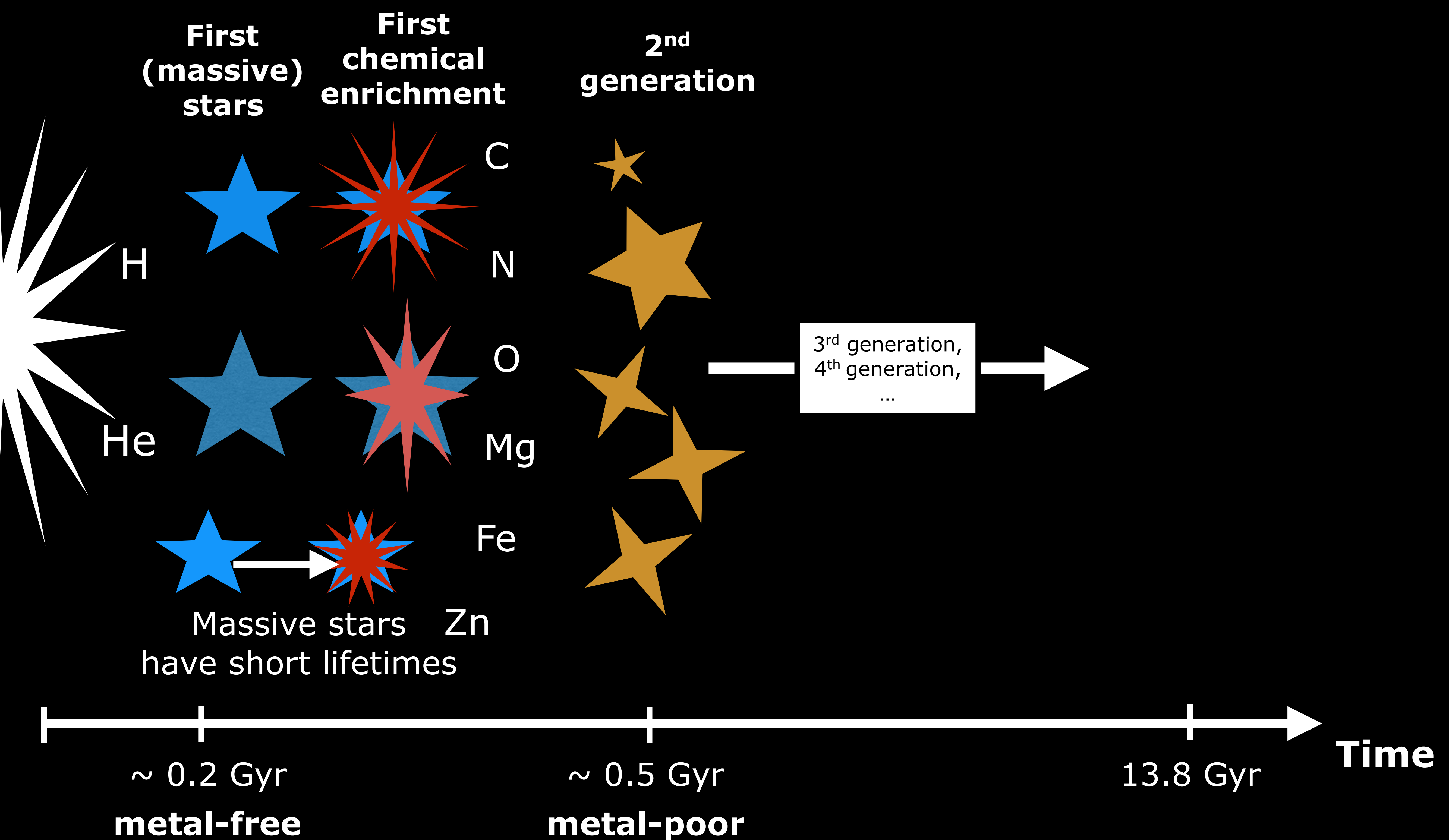
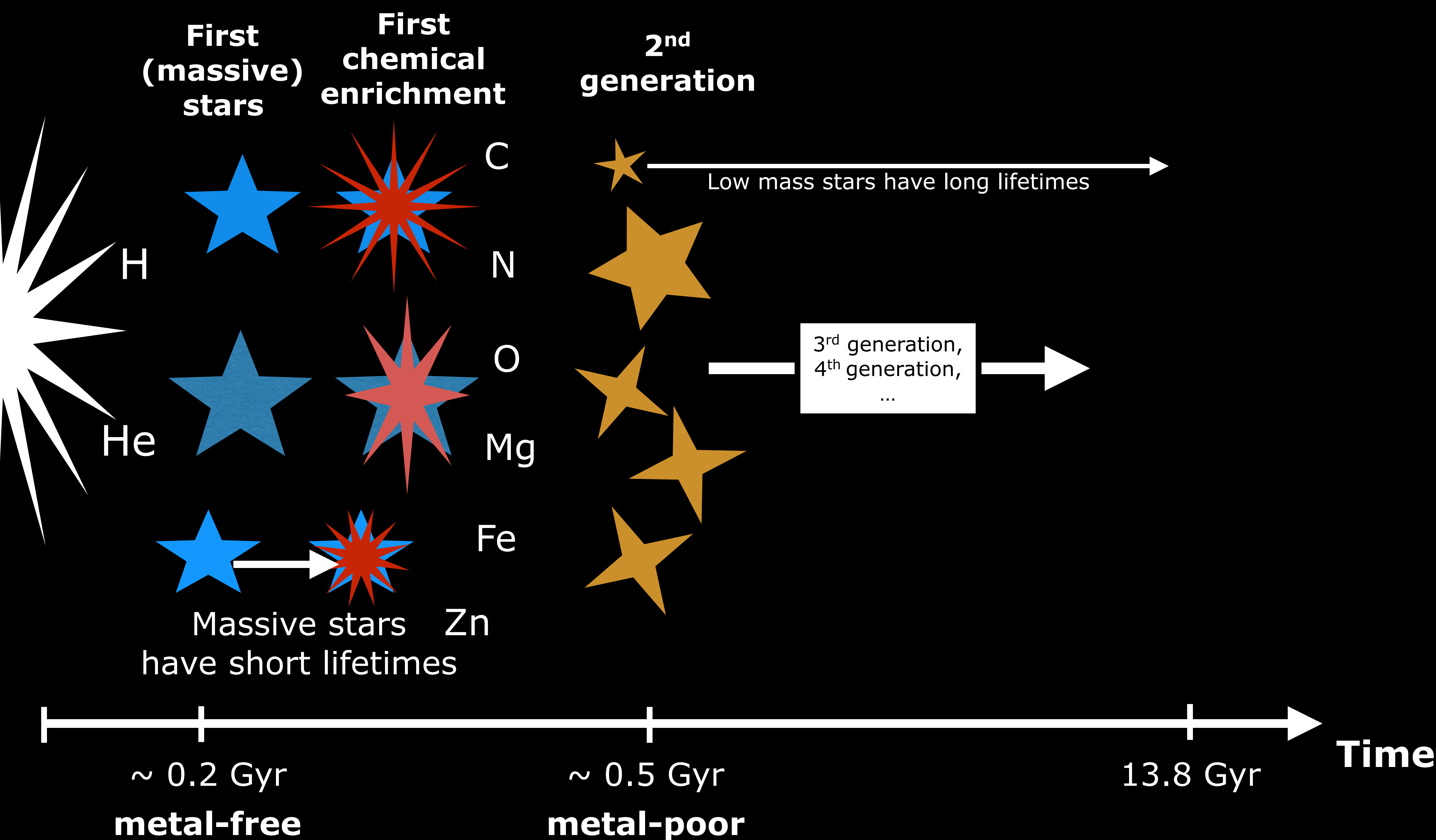
metal-poor
13.8 Gyr
Time


First (massive) stars
First chemical enrichment
2nd generation
H
He
C
N
O
Mg
Fe
Zn
3rd generation, 4th generation, ...
Massive stars have short lifetimes
~ 0.2 Gyr
metal-free
~ 0.5 Gyr
metal-poor
13.8 Gyr
Time


First (massive) stars
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2nd generation
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Low mass stars have long lifetimes
3rd generation, 4th generation, ...
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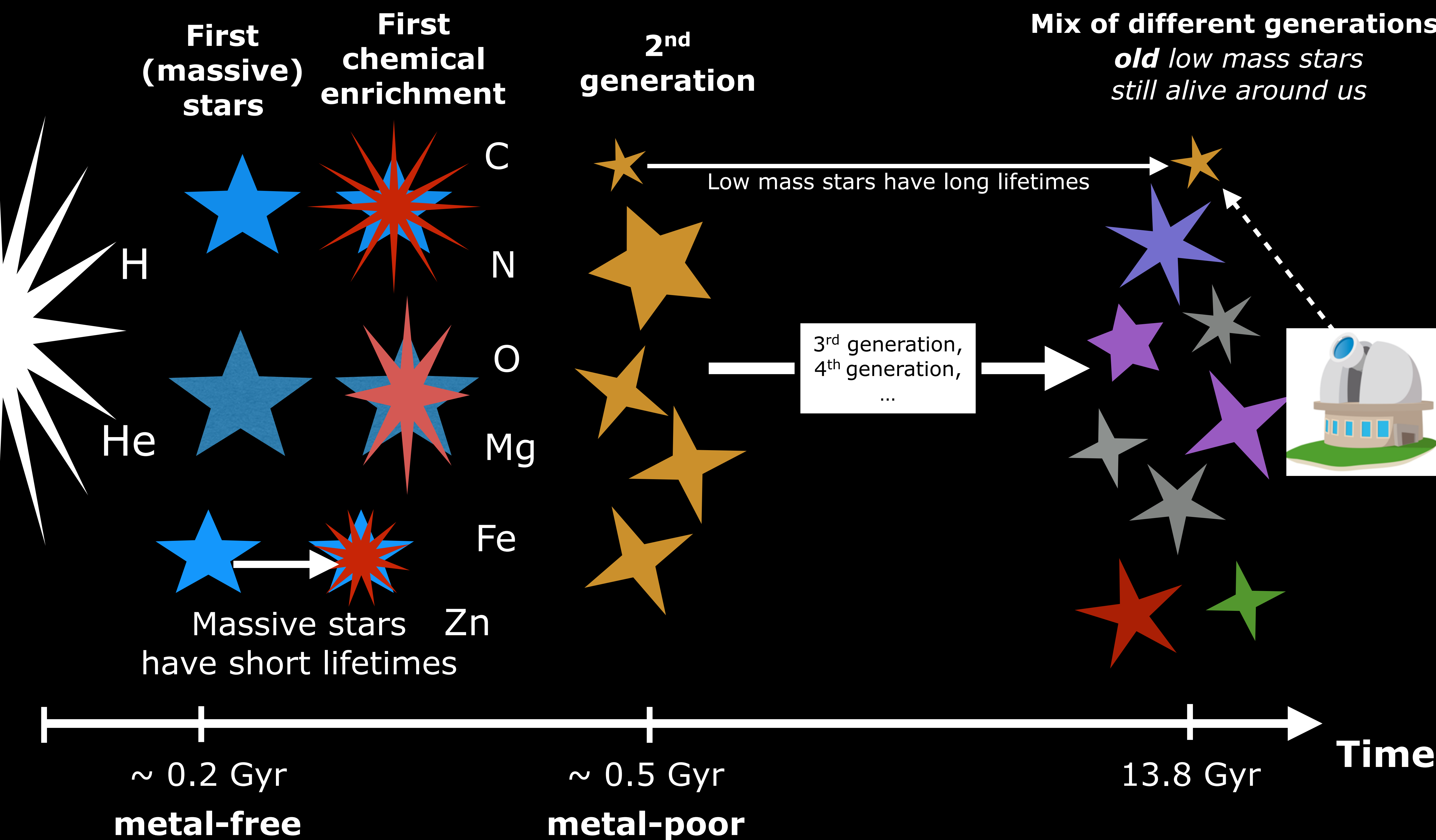
13.8 Gyr
Time


First (massive) stars
First chemical enrichment
2nd generation
Mix of different generations
old low mass stars still alive around us
H
He
C
N
O
Mg
Fe
Zn
Low mass stars have long lifetimes
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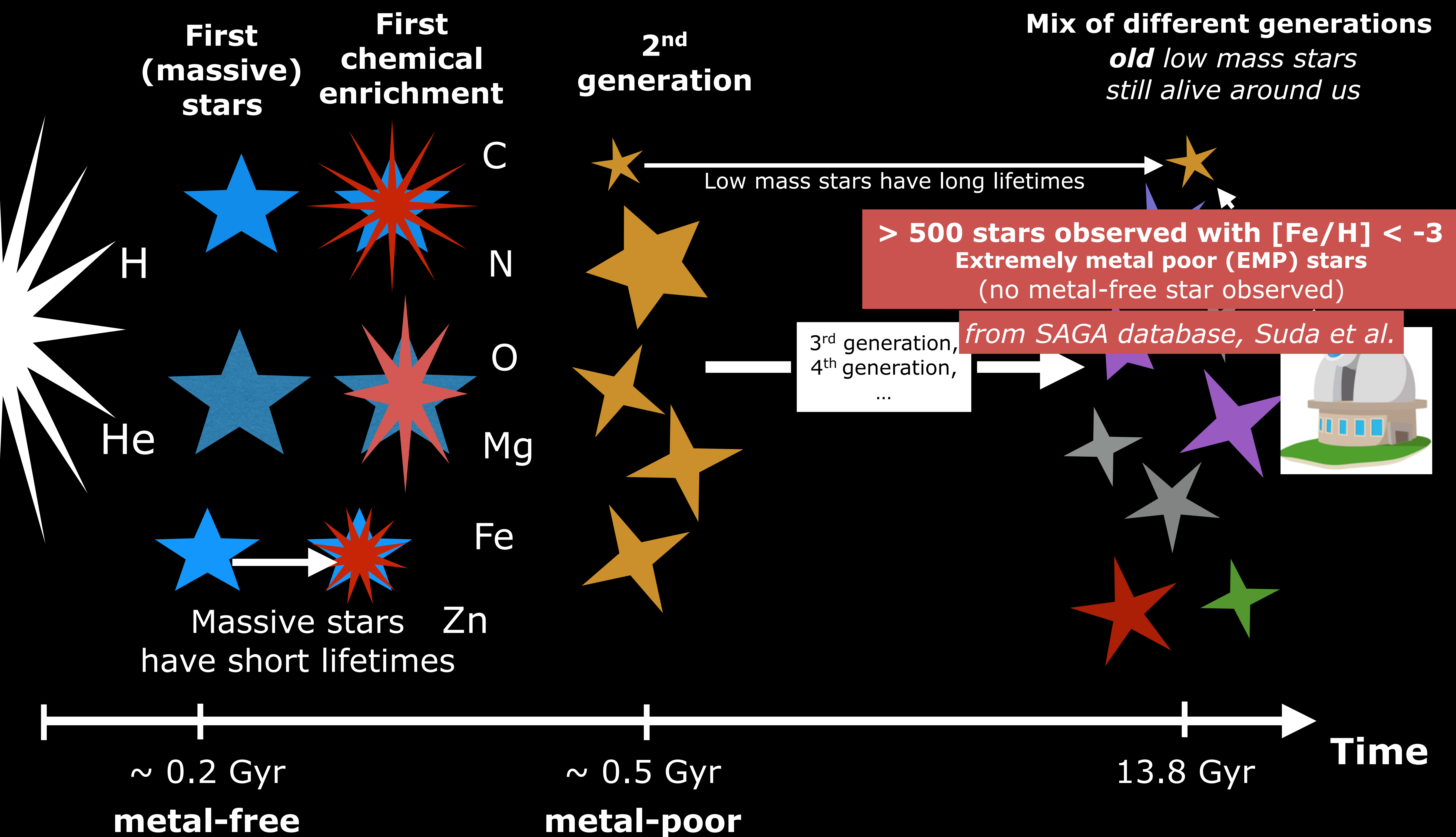
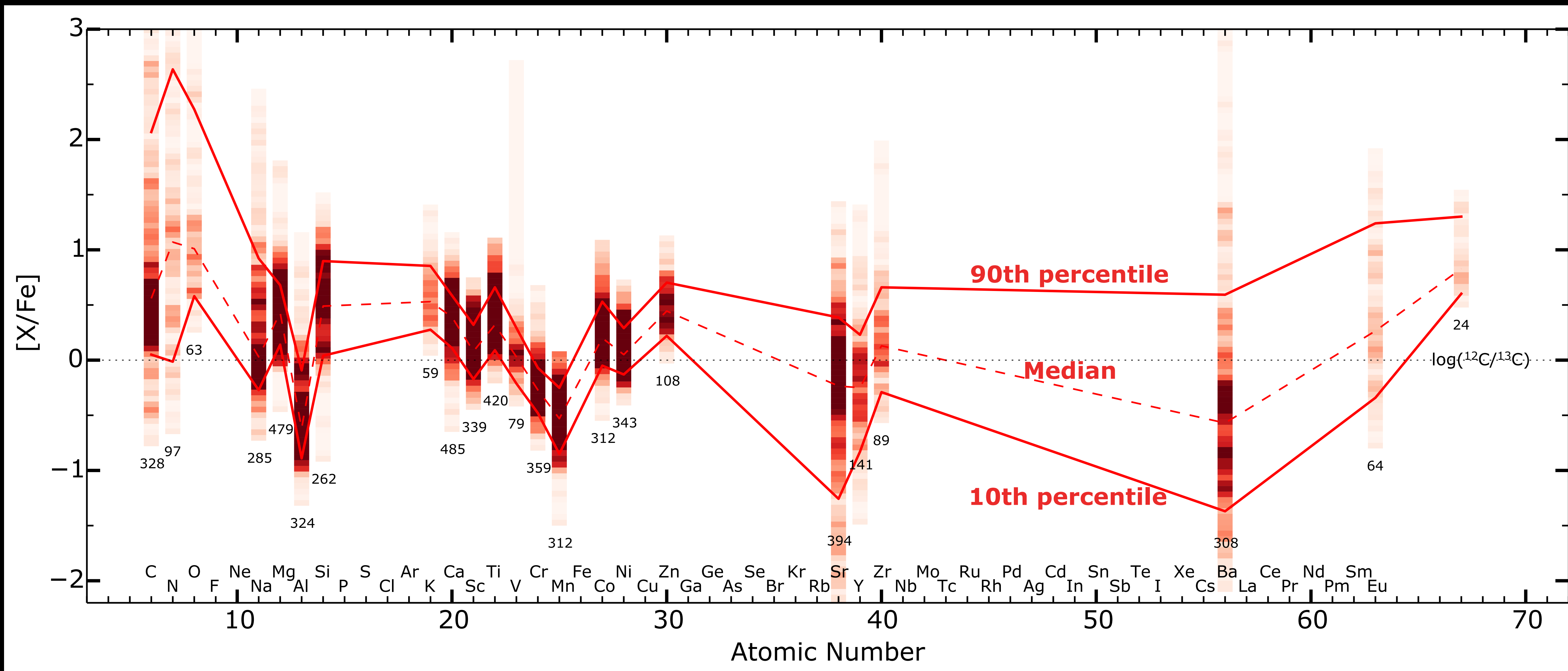


[ ] : in log scale, relatively to the Sun

Observations of extremely metal-poor (EMP) stars

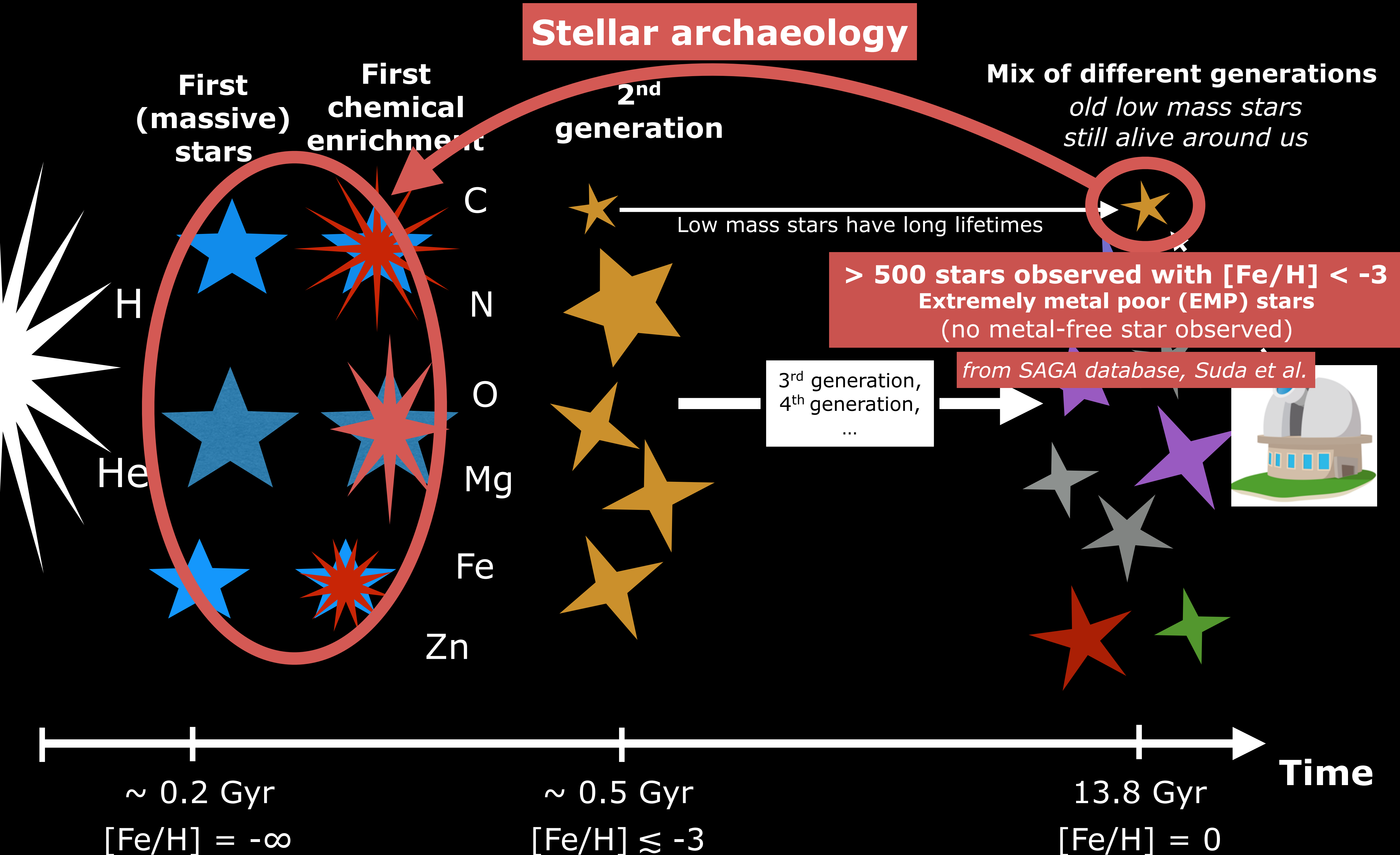
Chemical composition (abundances) of stars with [Fe/H] < -3



data from SAGA database
Suda et al 2008, 2017

Diverse chemical compositions

[ ] : in log scale, relatively to the Sun


Stellar archaeology
First (massive) stars
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Mix of different generations
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H
He
C
N
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Mg
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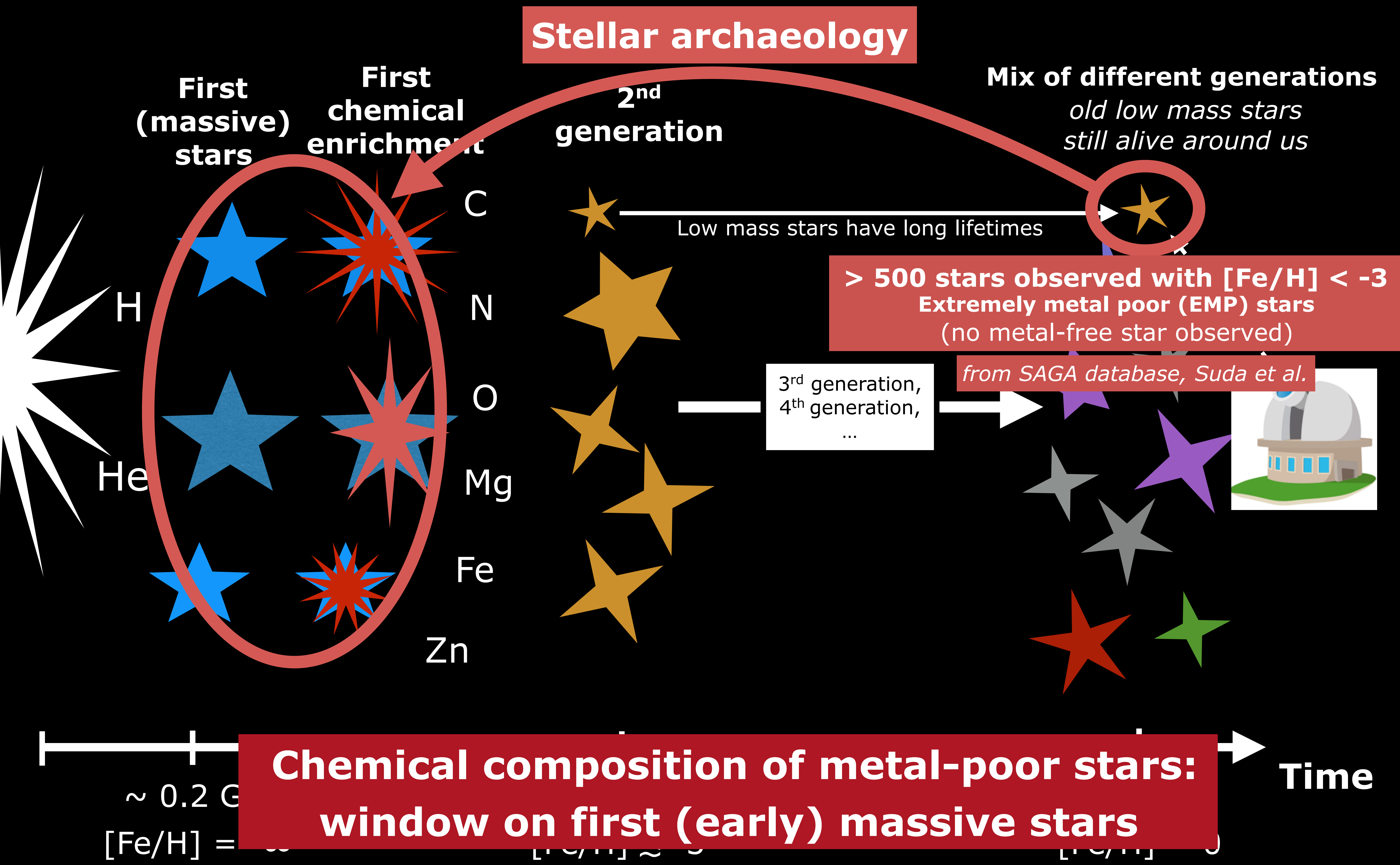
Zn
Low mass stars have long lifetimes
> 500 stars observed with [Fe/H] < -3
Extremely metal poor (EMP) stars
(no metal-free star observed)
from SAGA database, Suda et al.
3rd generation, 4th generation, …
~ 0.2 Gyr
[Fe/H] = -∞
~ 0.5 Gyr
[Fe/H] ≲ -3
13.8 Gyr
[Fe/H] = 0
Time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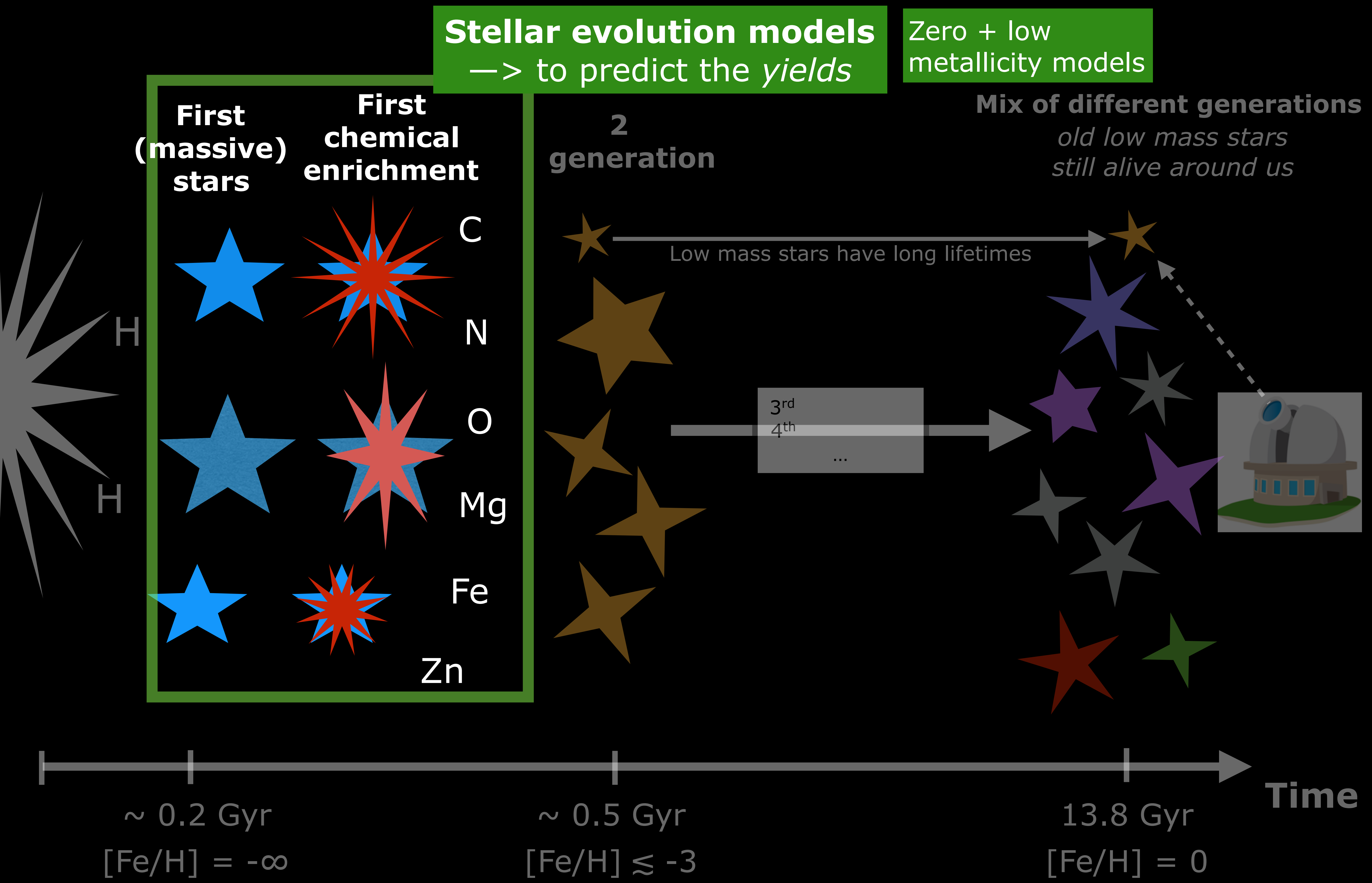
3rd generation, 4th generation, …
Time
Chemical composition of metal-poor stars: window on first (early) massive stars



Stellar evolution models
—> to predict the *yields*
Zero + low metallicity models
First (massive) stars
First chemical enrichment
C
N
O
Mg
Fe
Zn
H
H
2 generation
Mix of different generations
old low mass stars still alive around us
Low mass stars have long lifetimes
3rd
4th
...
Time
~ 0.2 Gyr
[Fe/H] = -∞
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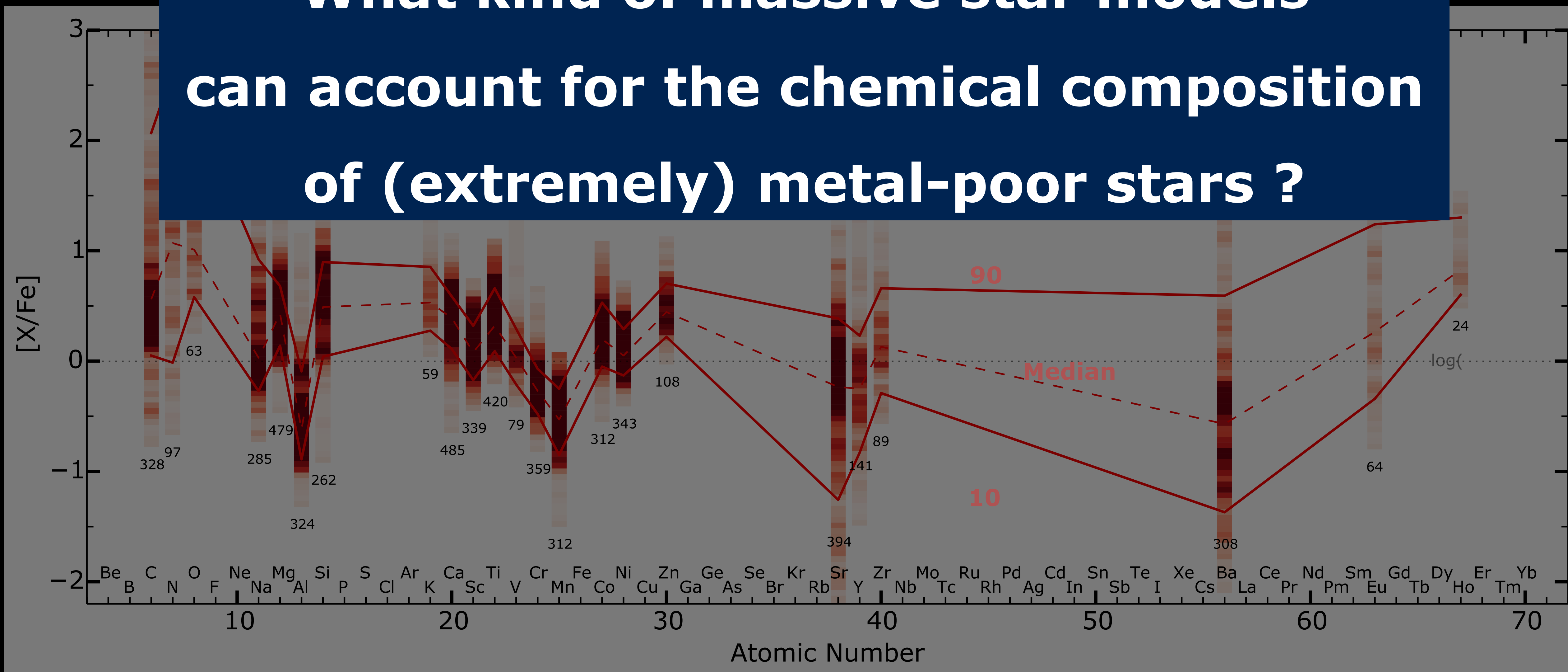
13.8 Gyr
[Fe/H] = 0

What kind of massive star models can account for the chemical composition of (extremely) metal-poor stars ?



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What is the nature of the first massive stars ?

—> Deduced from (some) EMP stars

(list is not complete)

- **Mixing & Fallback + faint SN** — *Umeda & Nomoto 2003, 2005, Iwamoto+2005, Ito+2013, Tominaga+2007, 2014, Kobayashi+2014, Ishigaki+2014*
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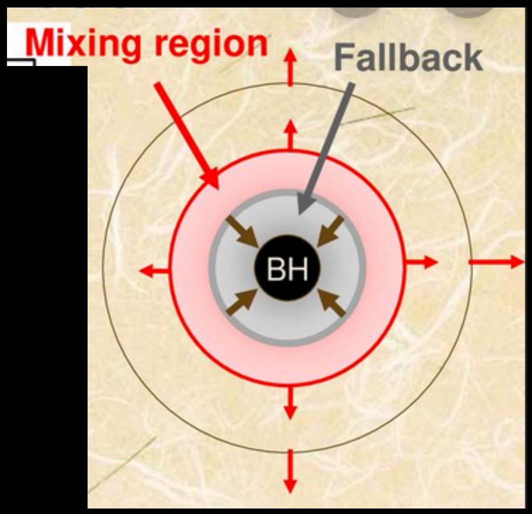
Mixing & Fallback



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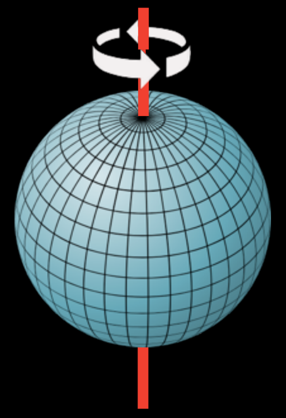
Rotation



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Event during the EMP star life

Other scenarios

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Still debated
—> importance of **mixing**

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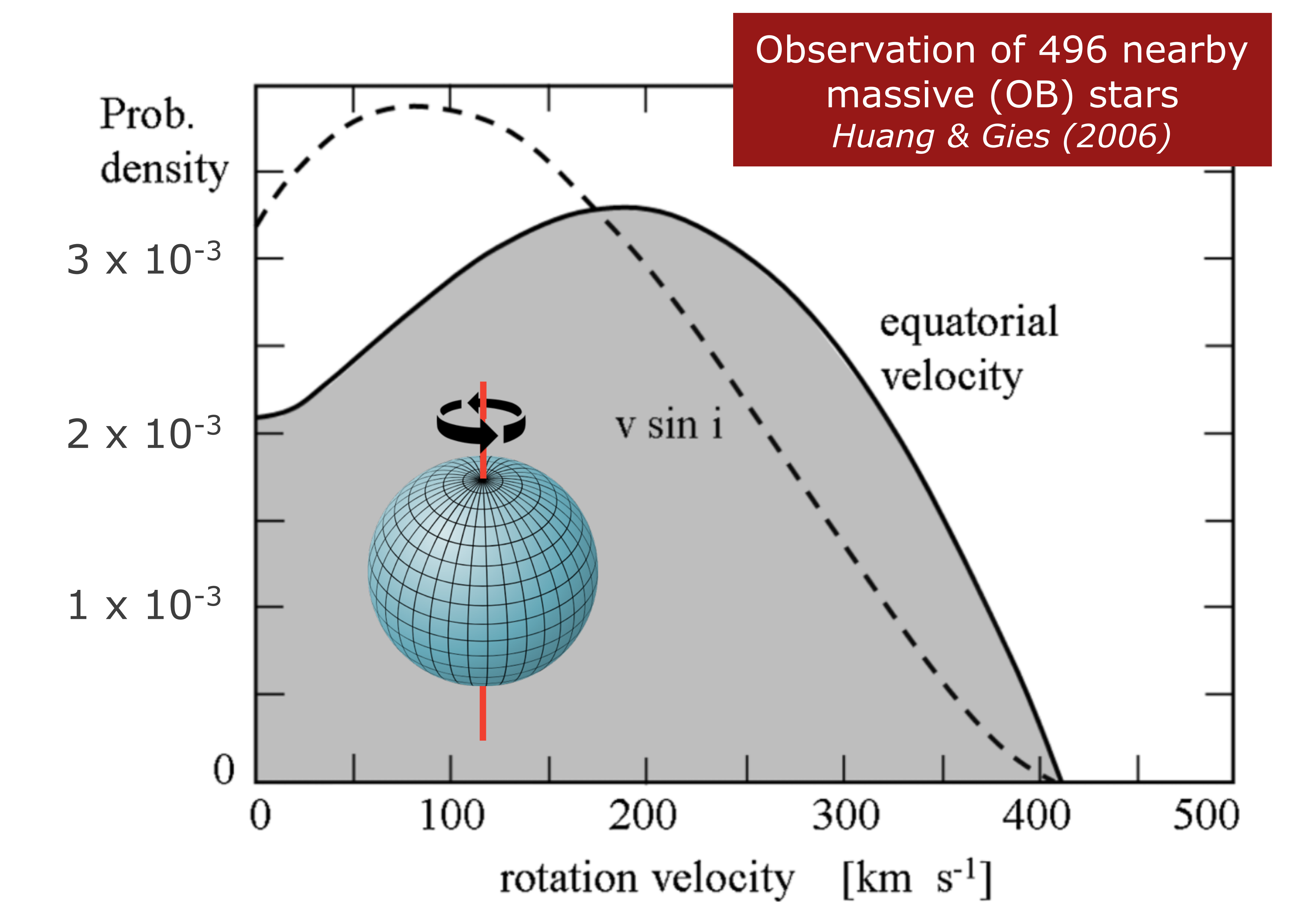

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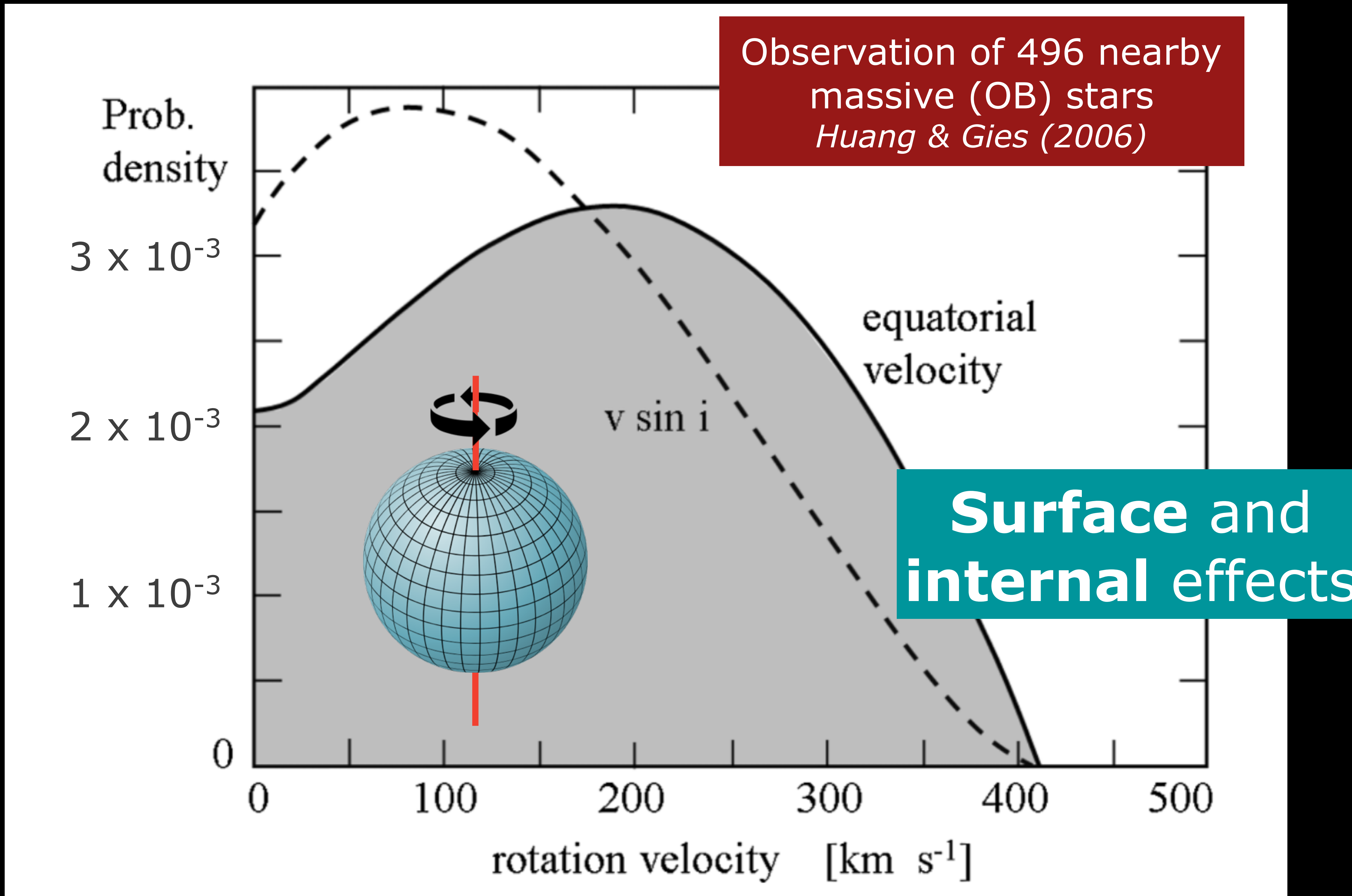
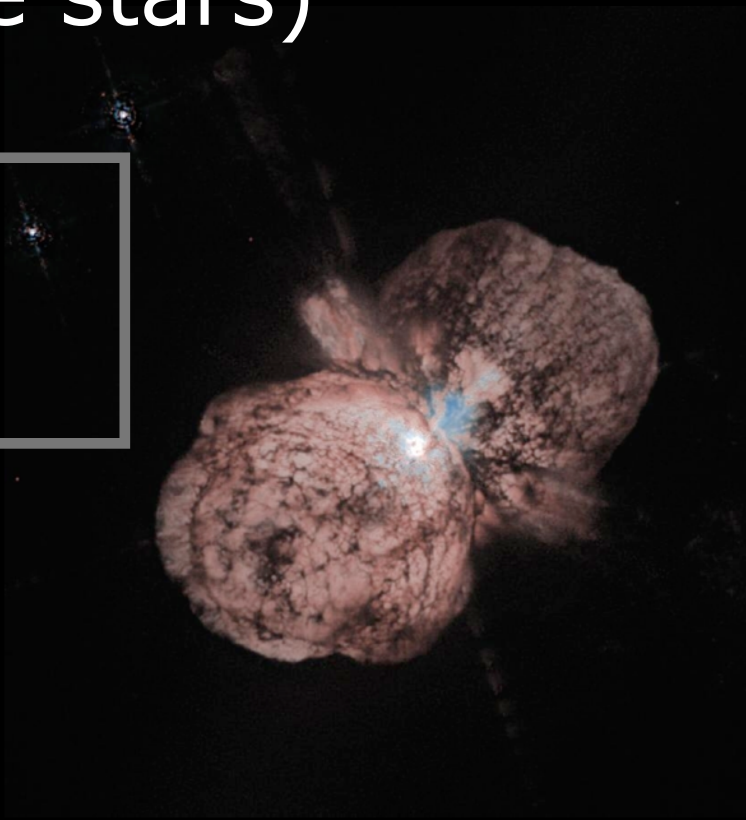


Surface effects of rotation (massive stars)



Mass loss

- **Mechanical mass loss**

  —> when gravity = centrifugal effect

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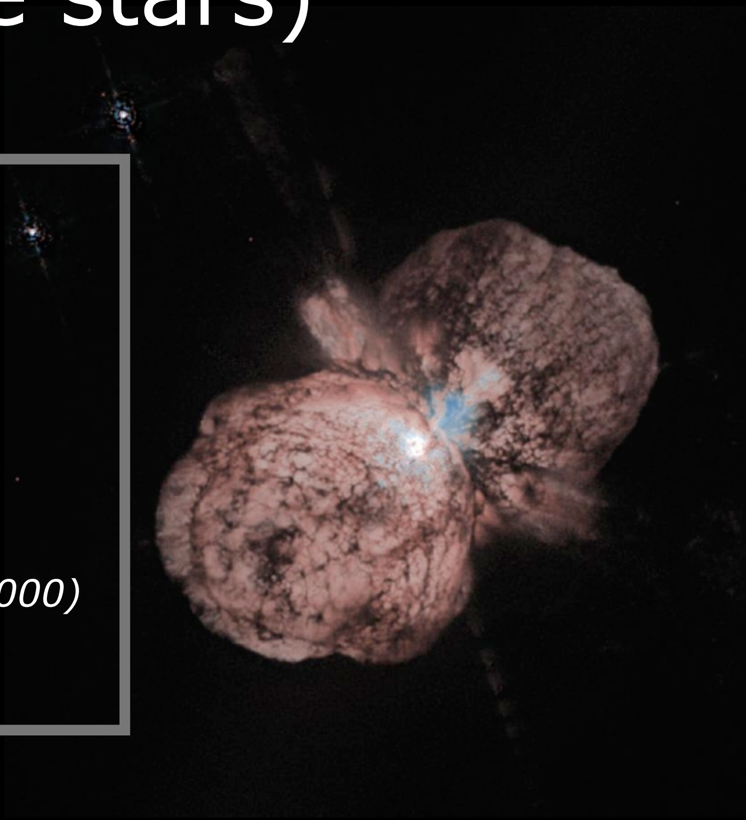

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- **Radiatively driven stellar winds**

  —> anisotropies => polar + equatorial ejections *(Owocki 1996, Maeder+1999, 2000)*

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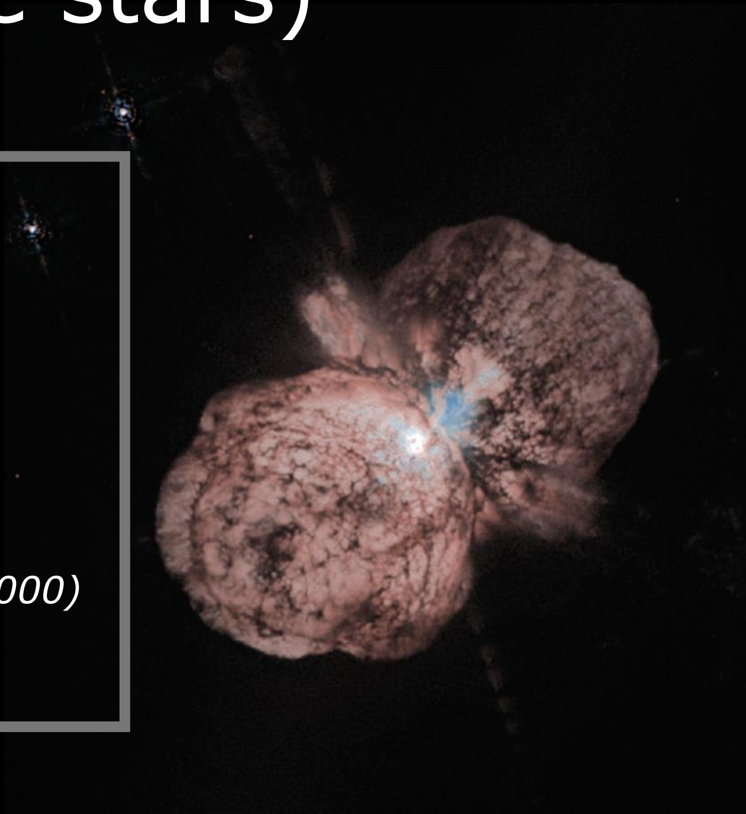

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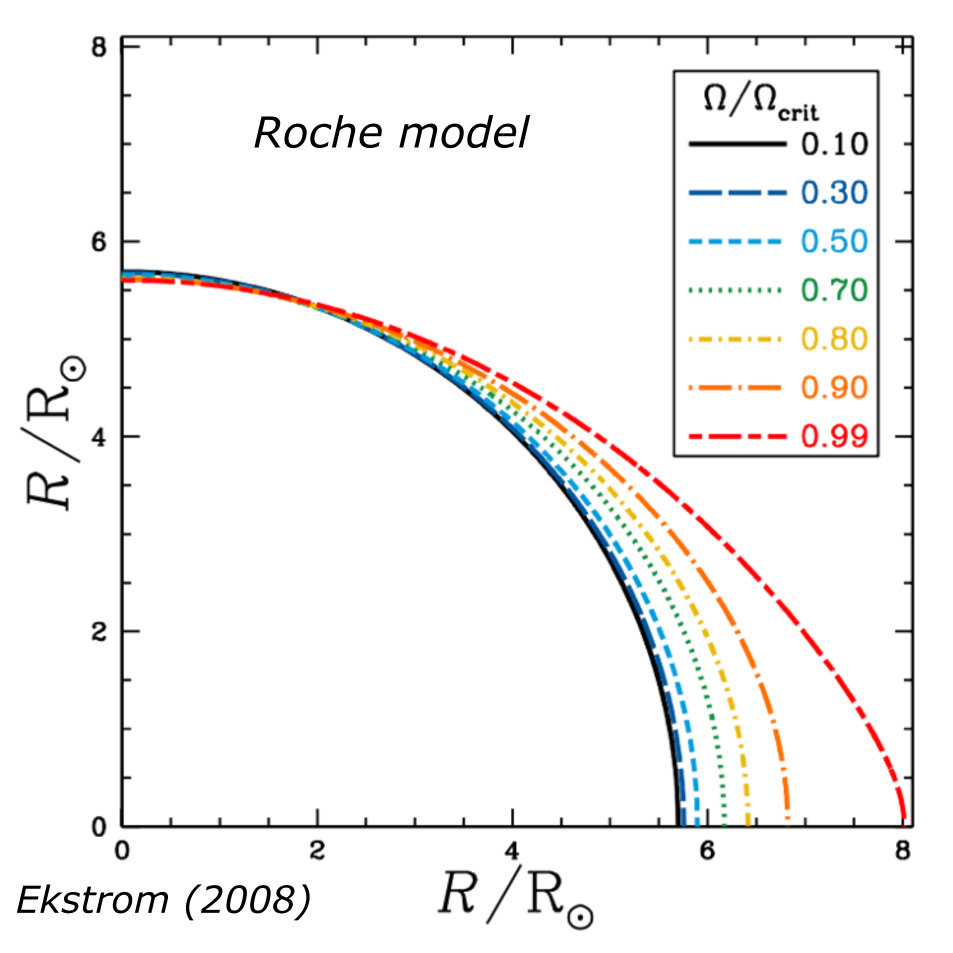
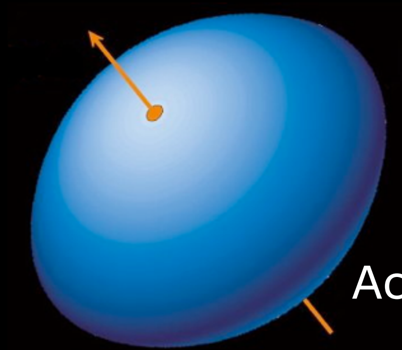
- **Surface deformation**





Achernar, ~10 $M_\odot$

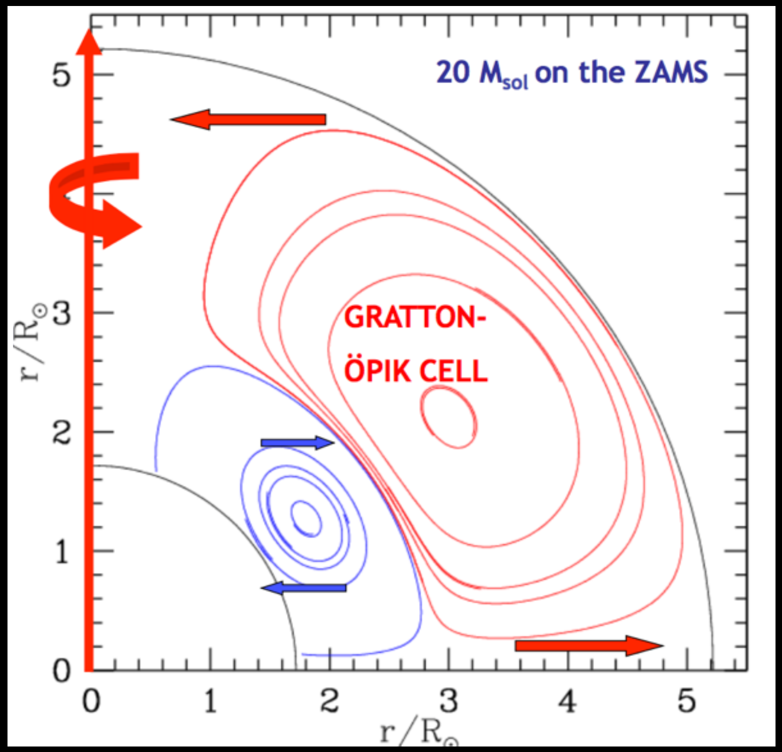
from interferometry :

—> Req / Rp ~ 1.5
—> at critical velocity

De Souza et al. (2003)
Carfiofi et al. (2008)

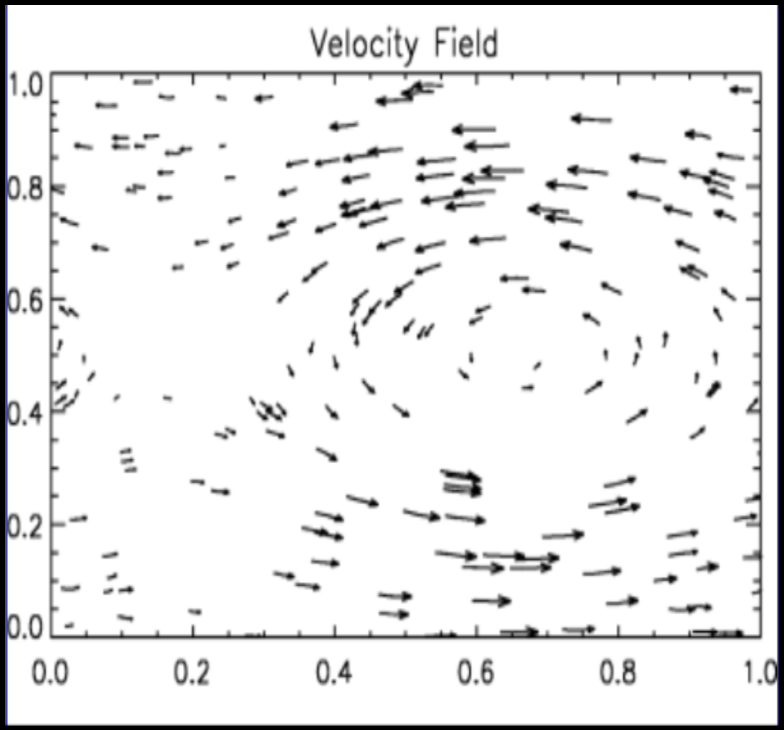
Internal effects of rotation (massive stars)

- **Meridional circulation** *(or Eddington–Sweet circulation)*



Maeder+2000

- **Shear mixing**



Brueggen+2001

- Transport of **angular momentum**
- Transport of **chemical elements**

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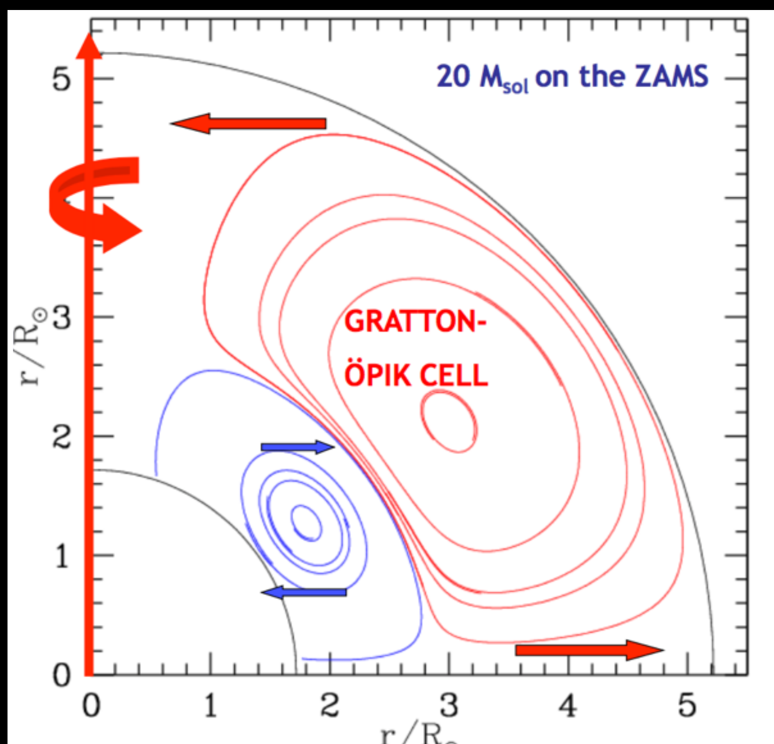

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τ ~ 10^5 years

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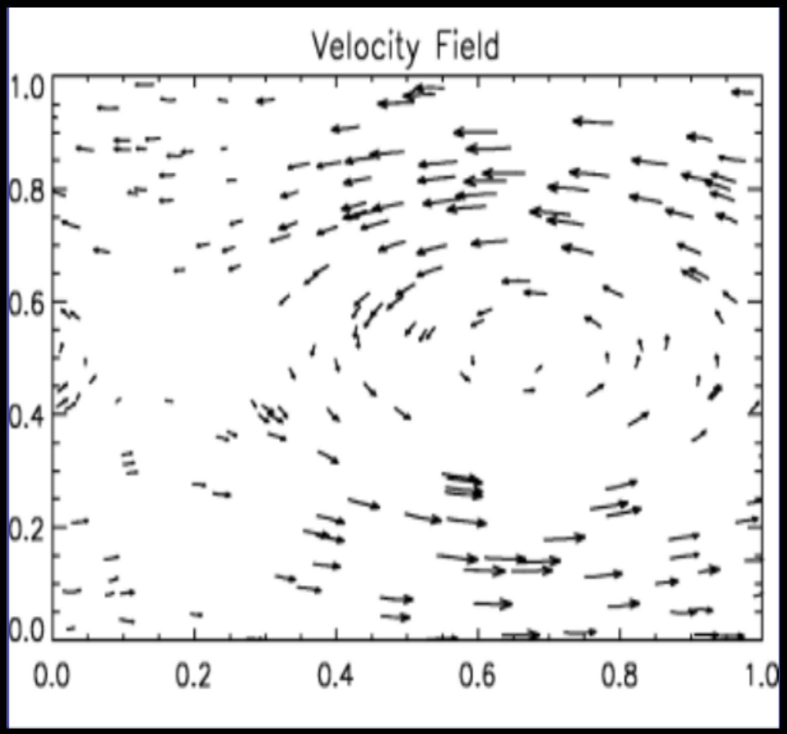

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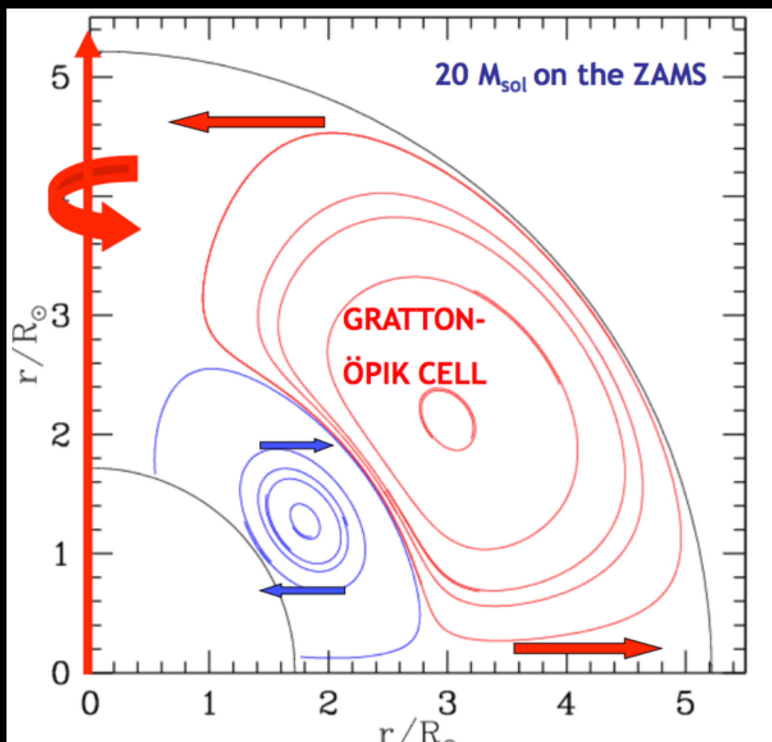

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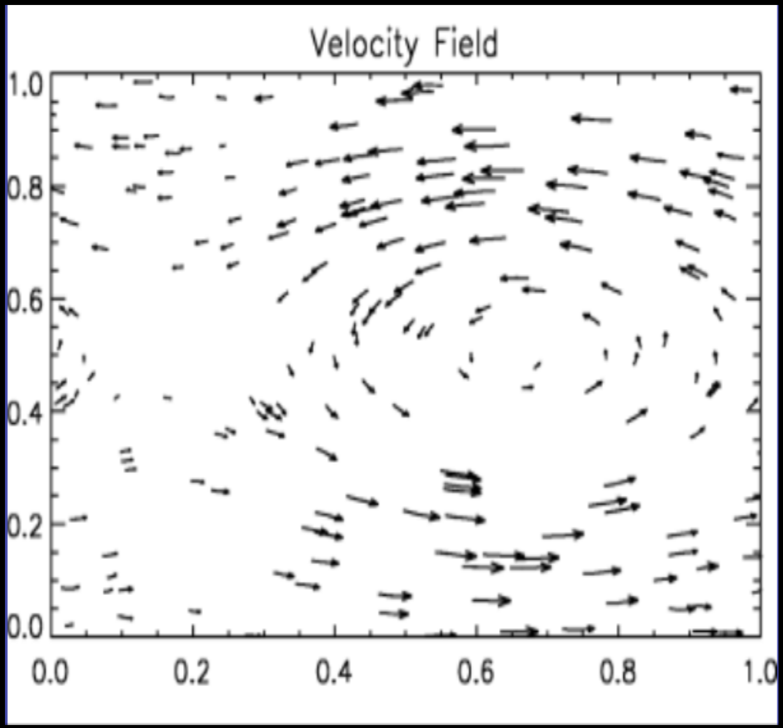

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Full life/scale of stars —> only in 1D…

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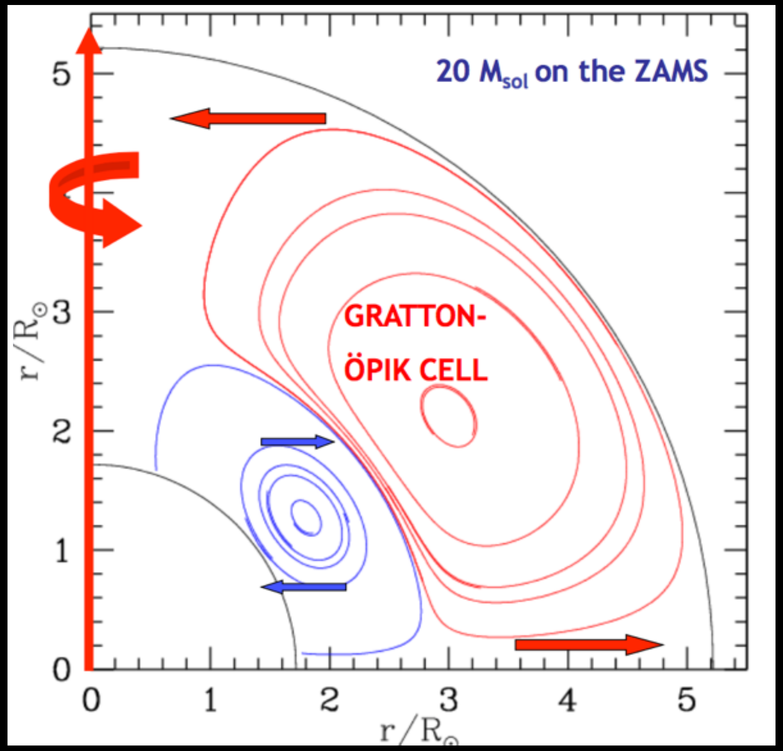

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$\tau \sim 10^5$ **years**

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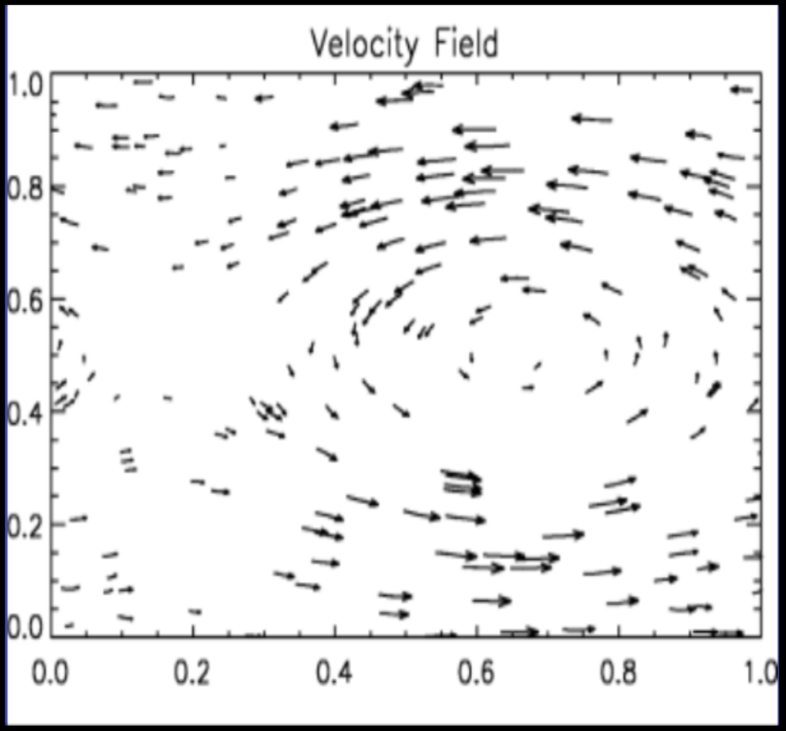


Brueggen+2001

$\tau \sim 10^5$ **years**

Full life/scale of stars —> only in 1D…

- Transport of **angular momentum**
- Transport of **chemical elements**

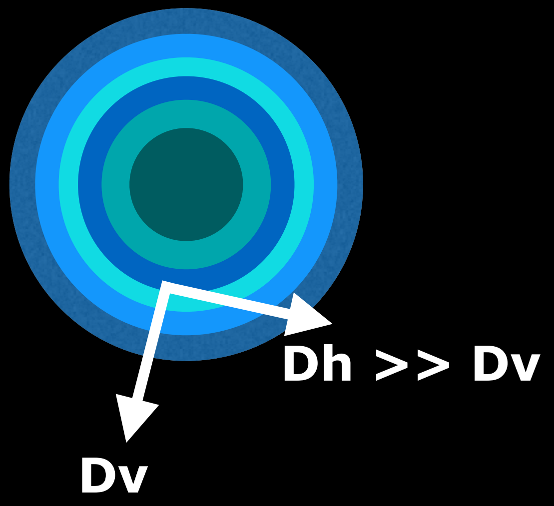
strong horizontal turbulence

=> Ω constant on isobars

=> ~ Ω(r)

=> **shellular rotation** (1D approx.)

Zahn (1992), Maeder book (2008), …



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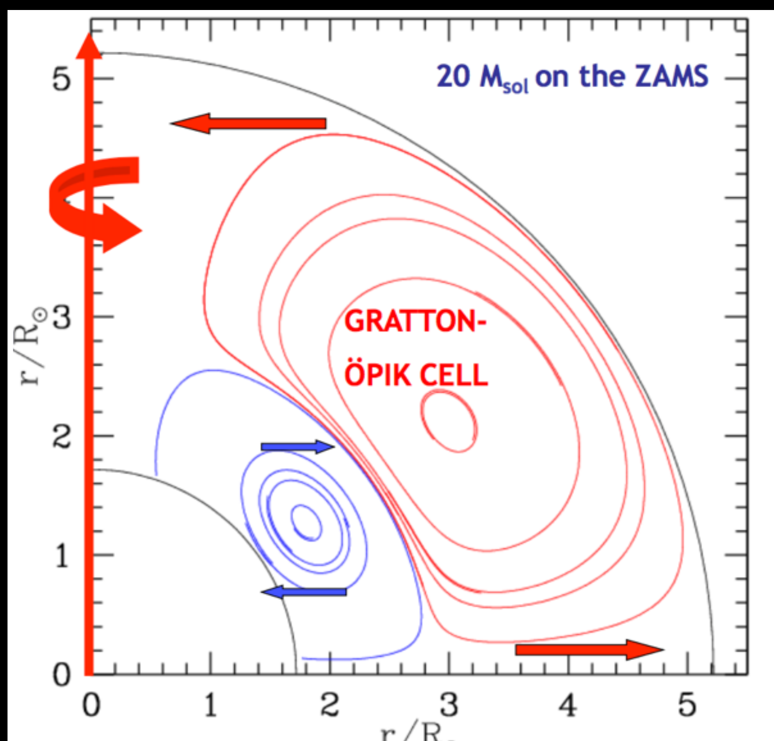
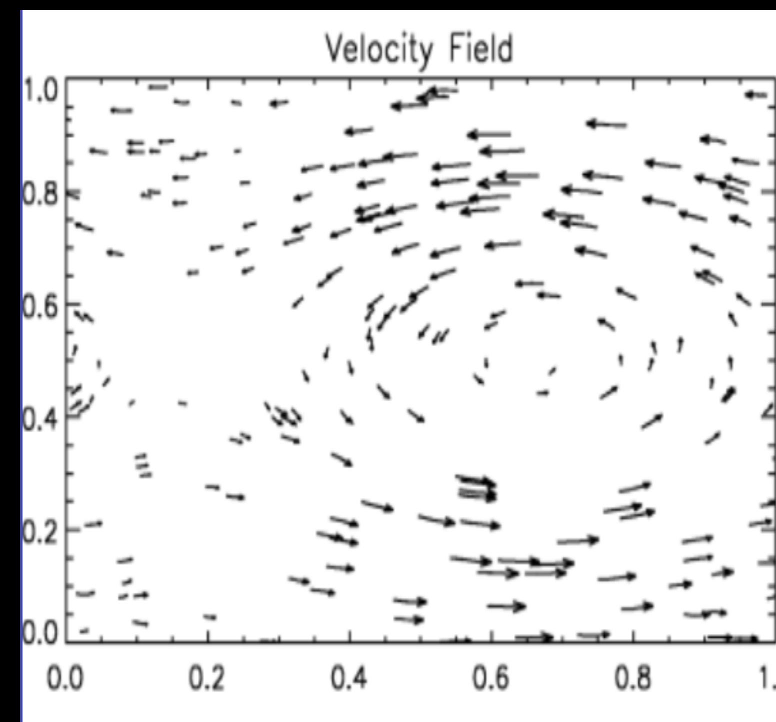


Maeder+2000

$\tau \sim 10^5$ **years**

- **Shear mixing**



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Full life/scale of stars —> only in 1D...

- Transport of **angular momentum**
- Transport of **chemical elements**

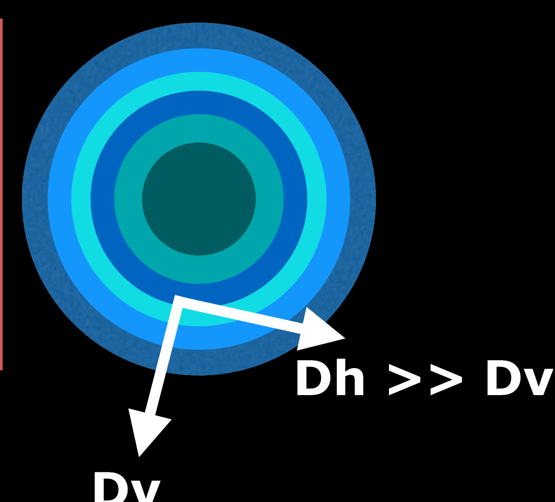
strong horizontal turbulence

=> Ω constant on isobars

=> ~ Ω(r)

=> **shellular rotation** (1D approx.)

Zahn (1992), Maeder book (2008), …



$$\rho \frac{dX_i}{dt} = \frac{1}{r^2}\frac{\partial}{\partial r}\left[\rho r^2 (D + D_{\rm eff})\frac{\partial X_i}{\partial r}\right]$$

diffusive equation

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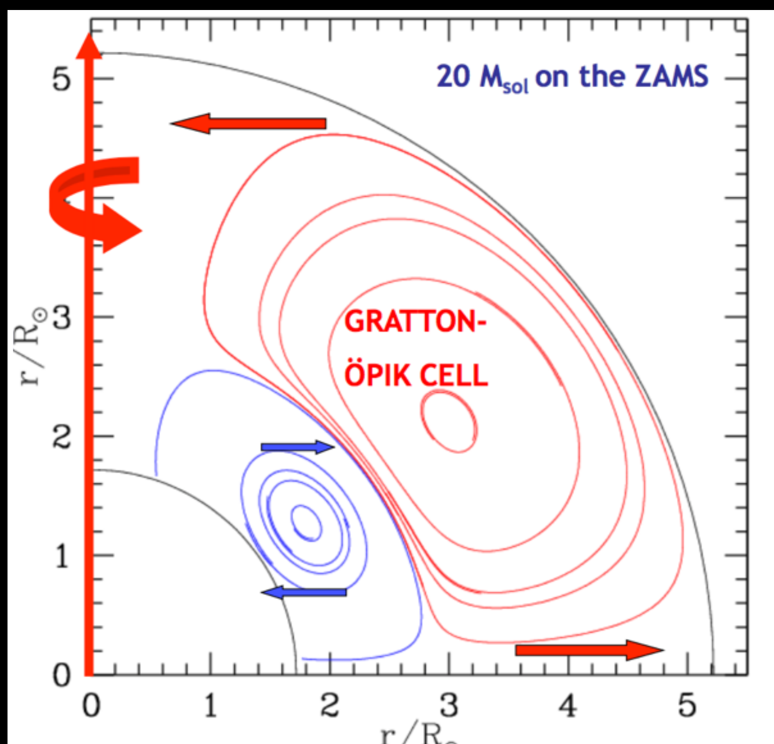

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τ ~ 10^5 years

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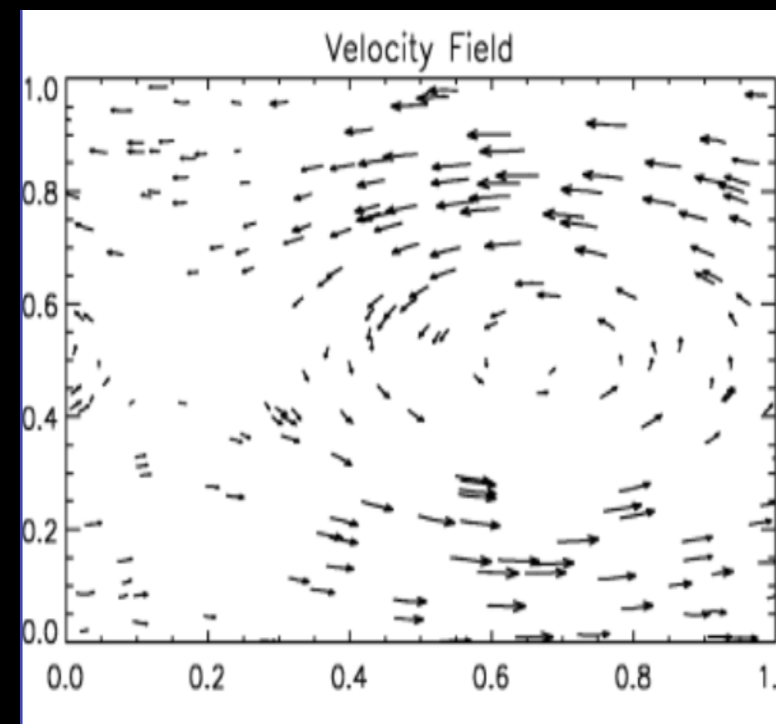

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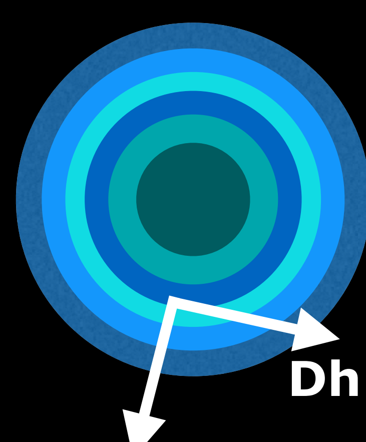

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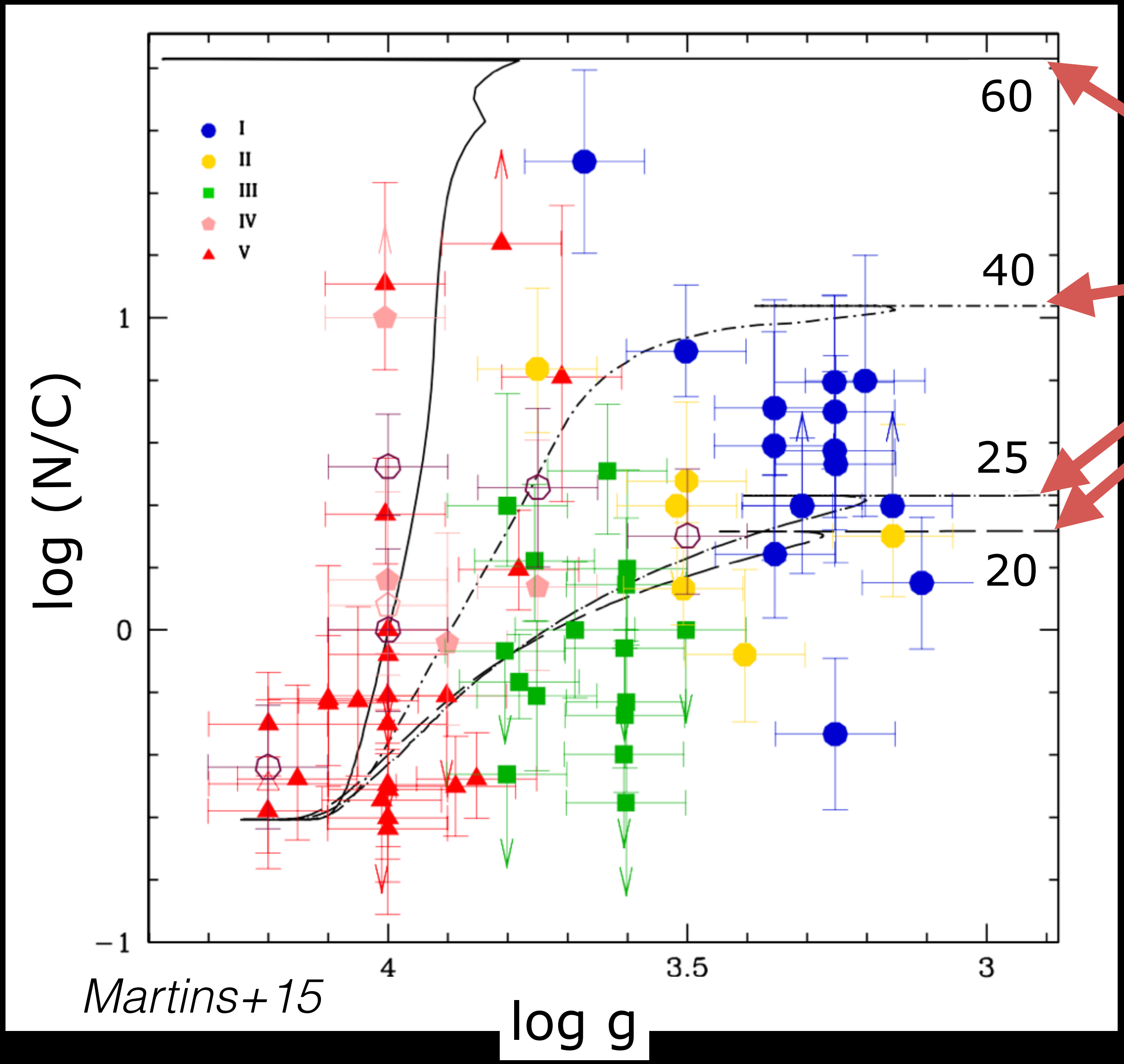
Stellar evolution with rotation

$Z = Z_\odot$
(solar metallicity)



Observed OB (massive) stars

vs.

20 - 60 $M_\odot$ rotating models

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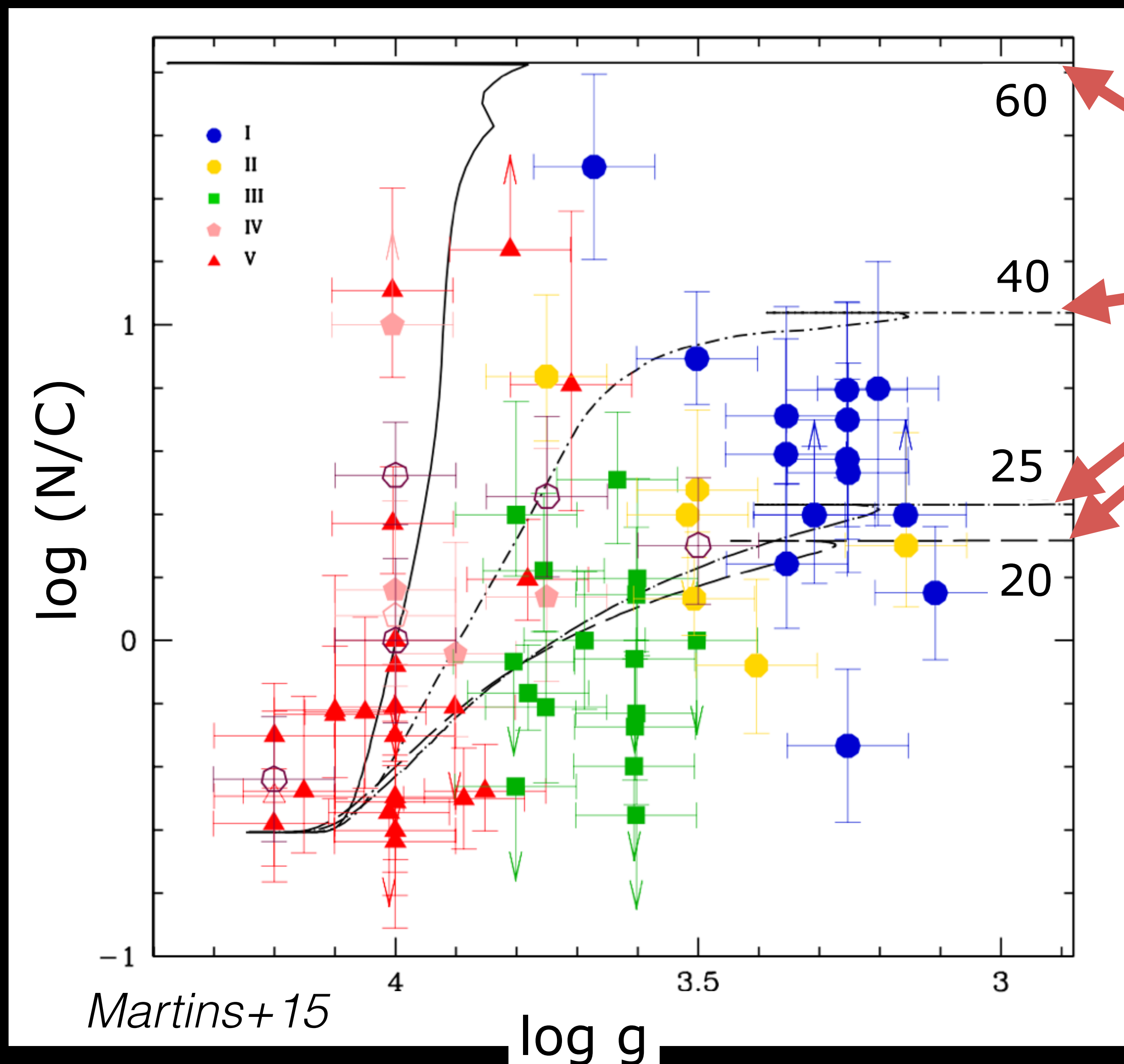

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—> CNO cycle in the **core**

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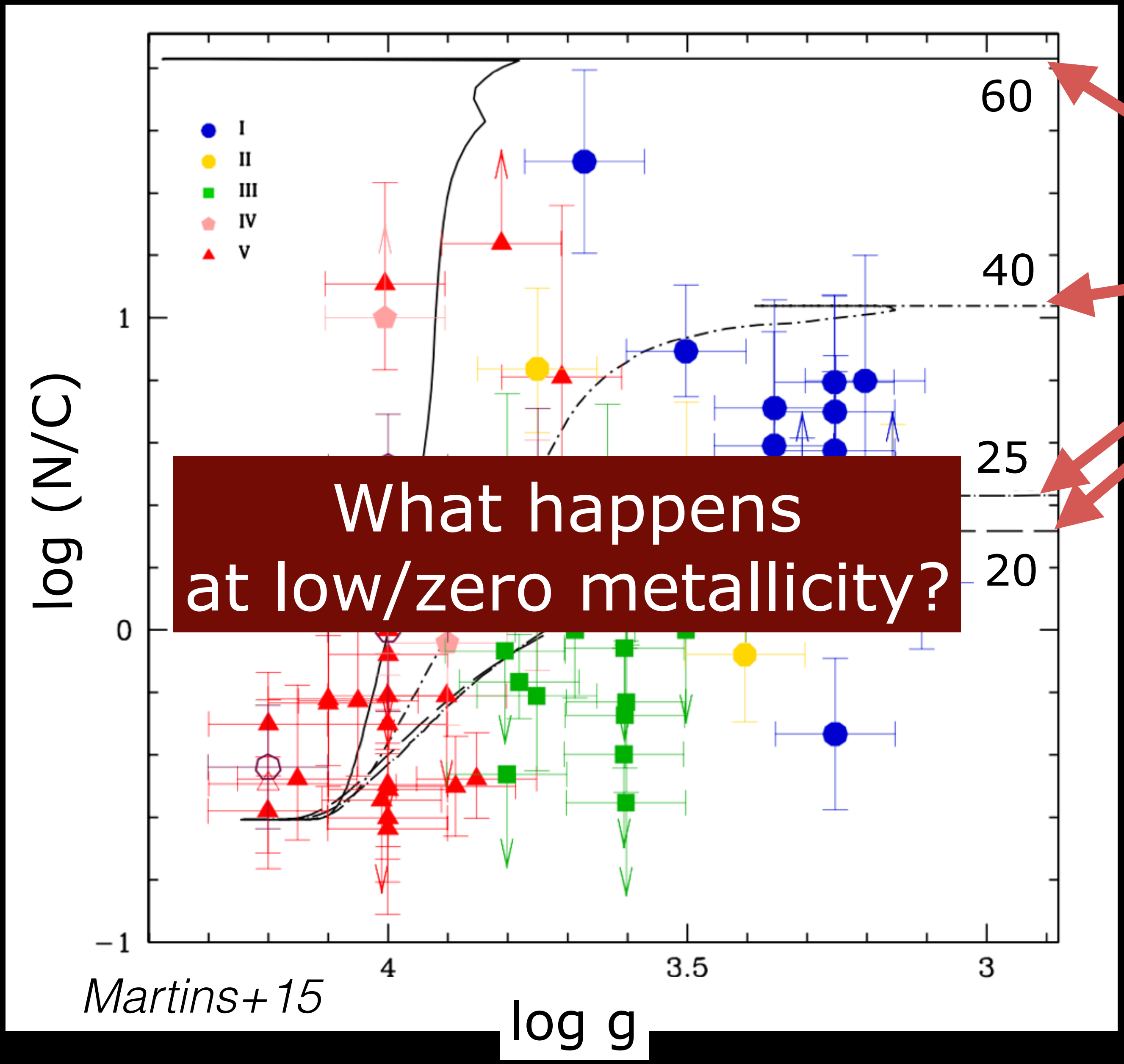

What happens
at low/zero metallicity?

Observed OB (massive) stars

vs.

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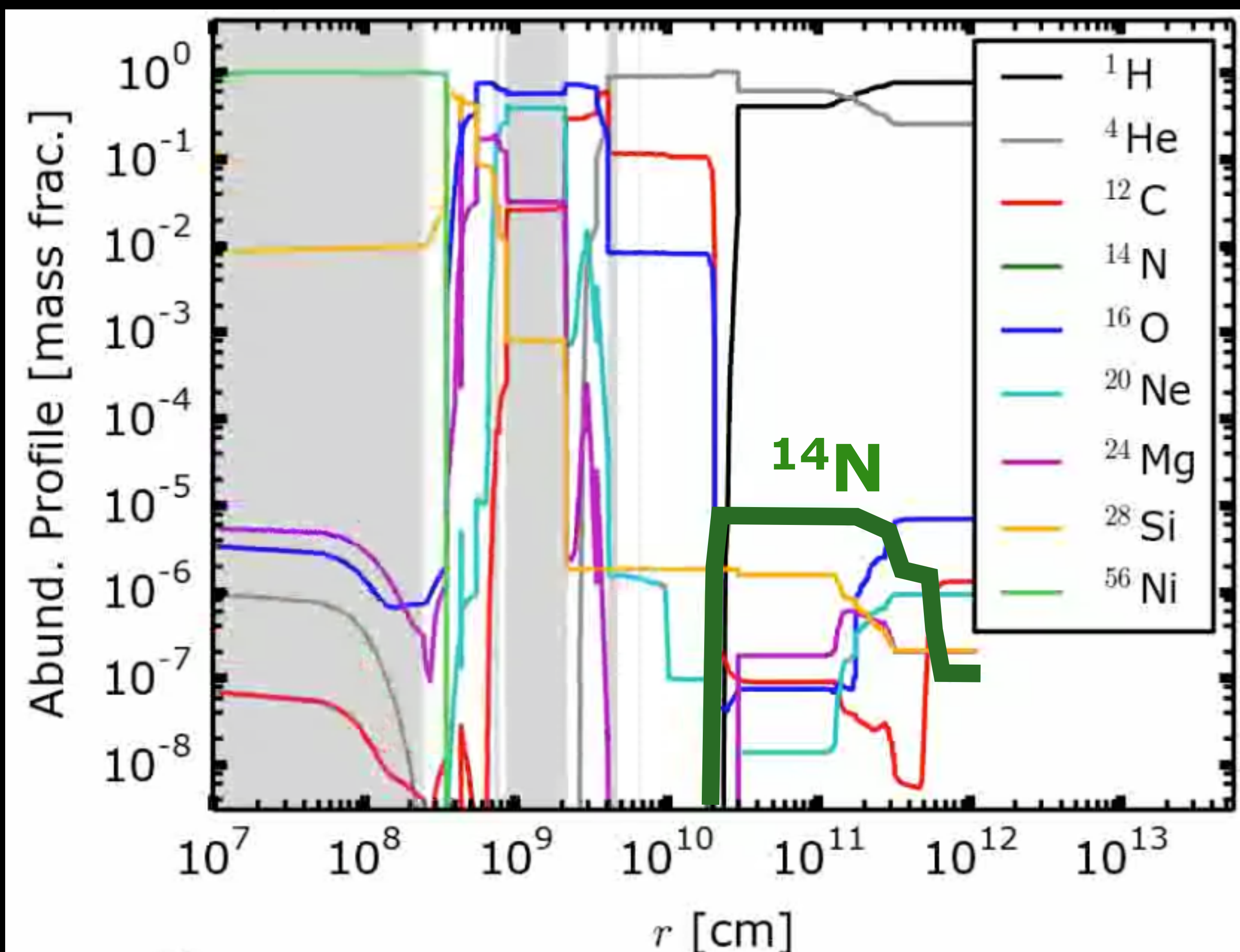
Nucleosynthesis in rotating massive stars

$Z = 10^{-5}$

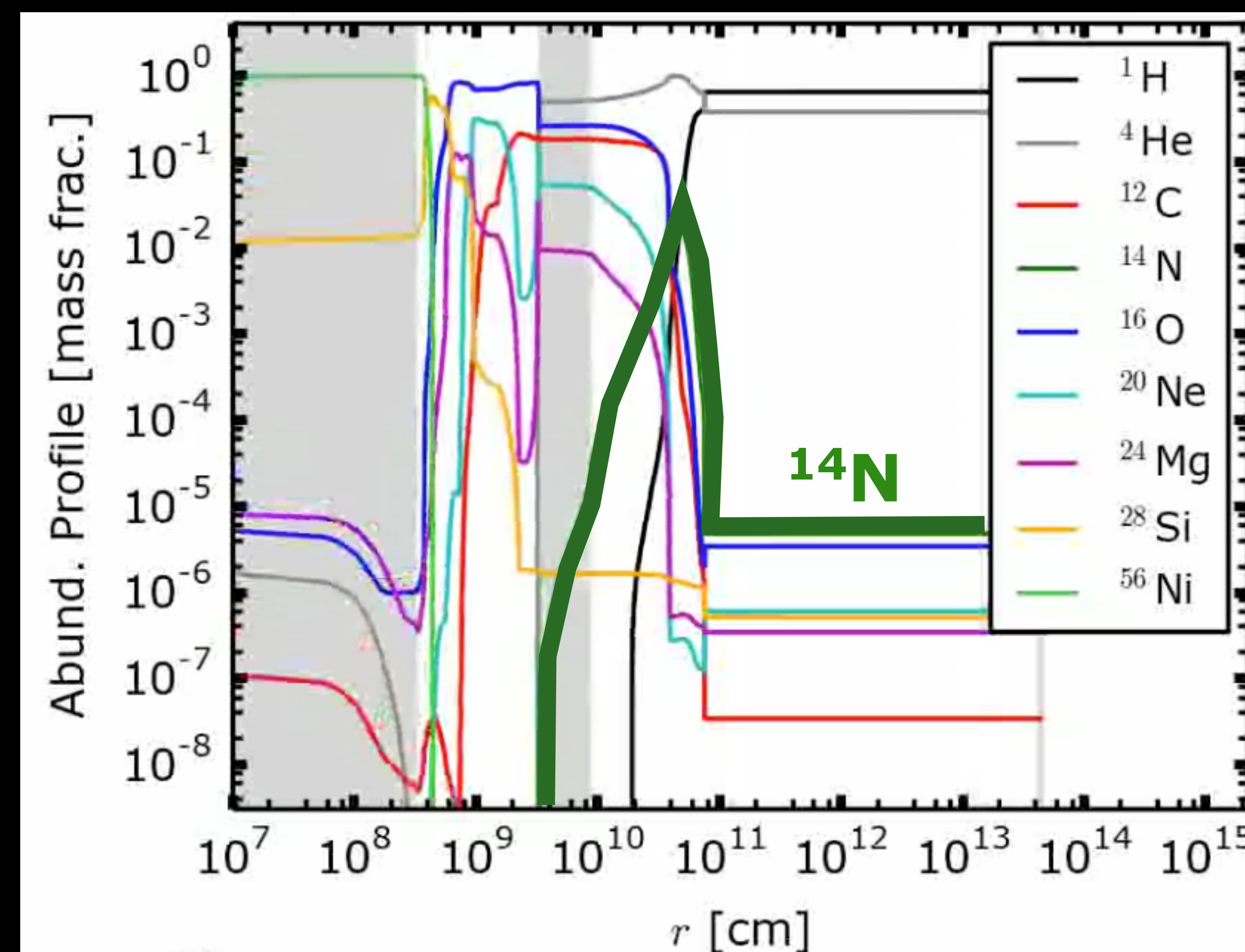
[Fe/H] ~ -4

20 $M_\odot$ at the end of evolution (pre-SN)

No rotation



Rotation (v_{ini} ~ 600 km/s)



Rotation => Nitrogen (mixing between H- and He-burning regions)

: convective zones

Effect of rotation on nucleosynthesis:
e.g. *Meynet+2002, Ekstrom+ 2008, Pignatari+2008, Takahashi+2014, Frischknecht+2016, Choplin+2018, Chieffi+2018, Banerjee+2019…*

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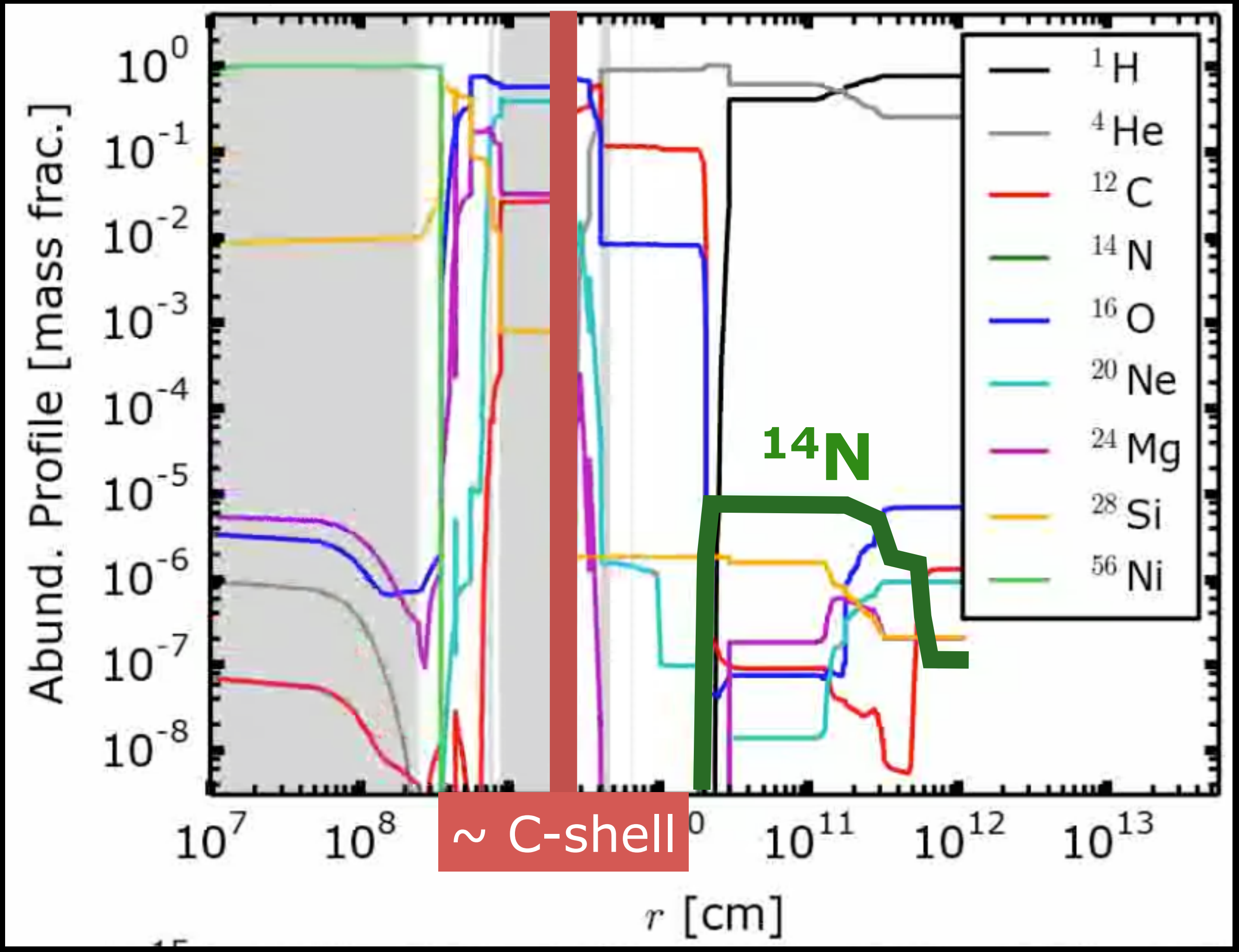

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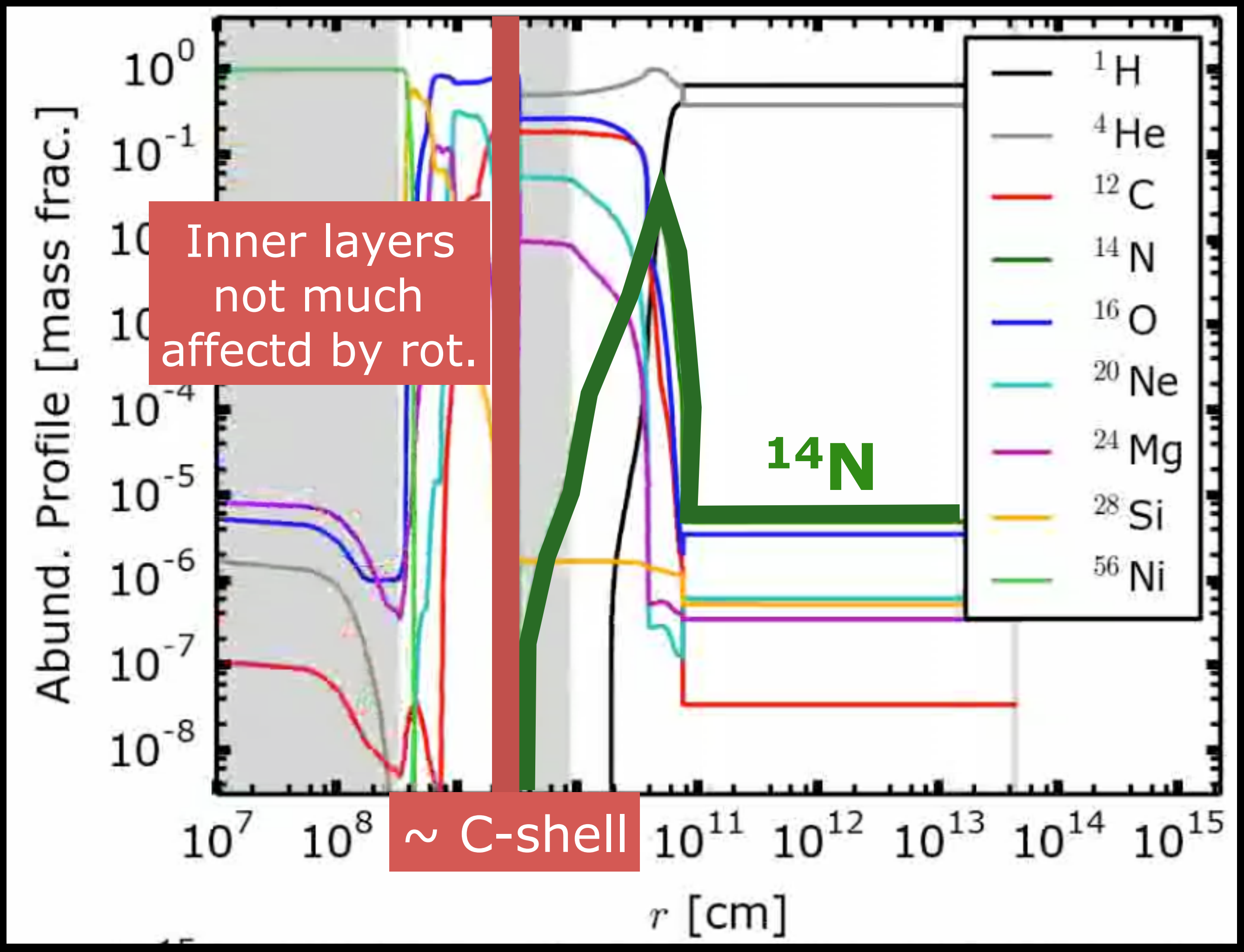

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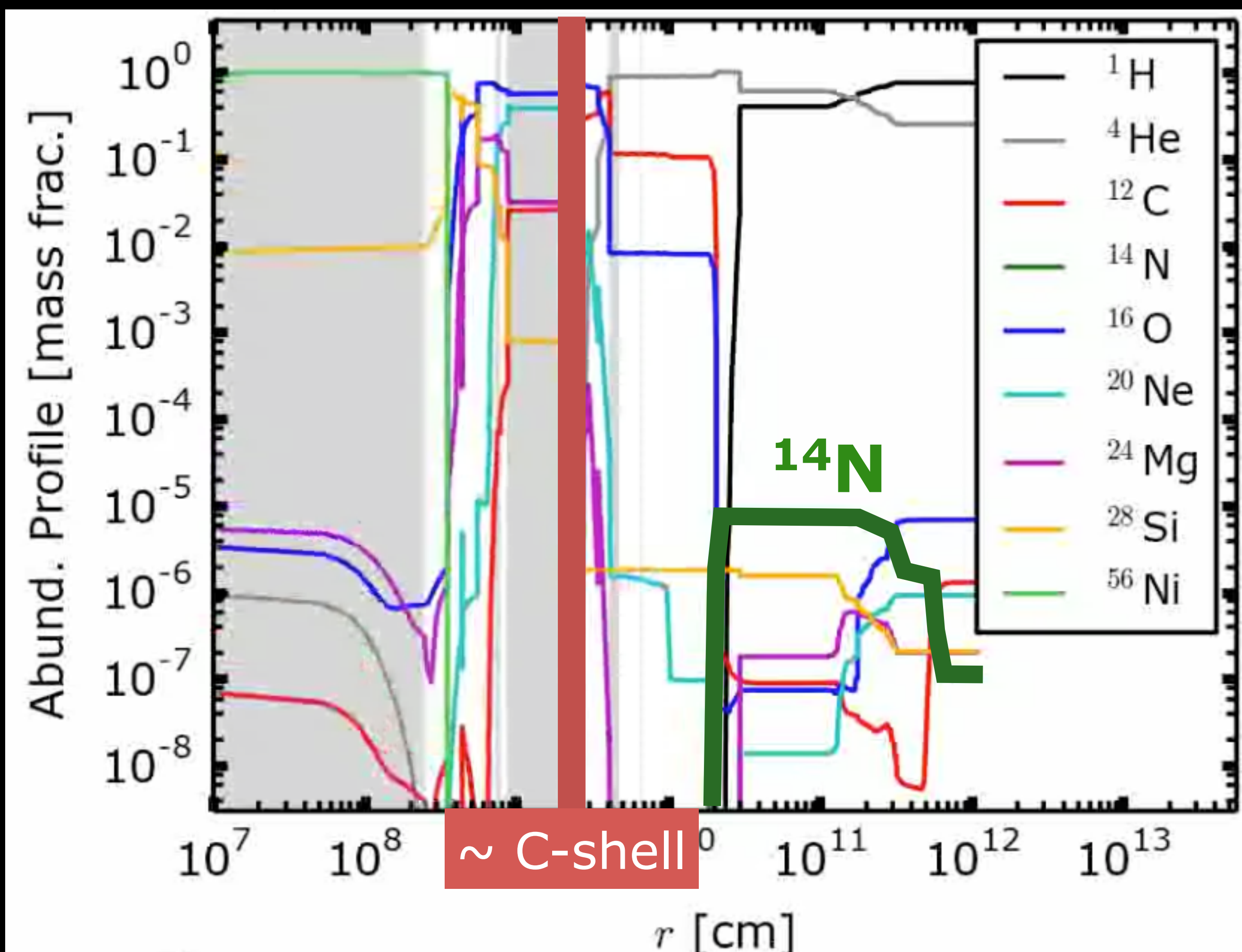

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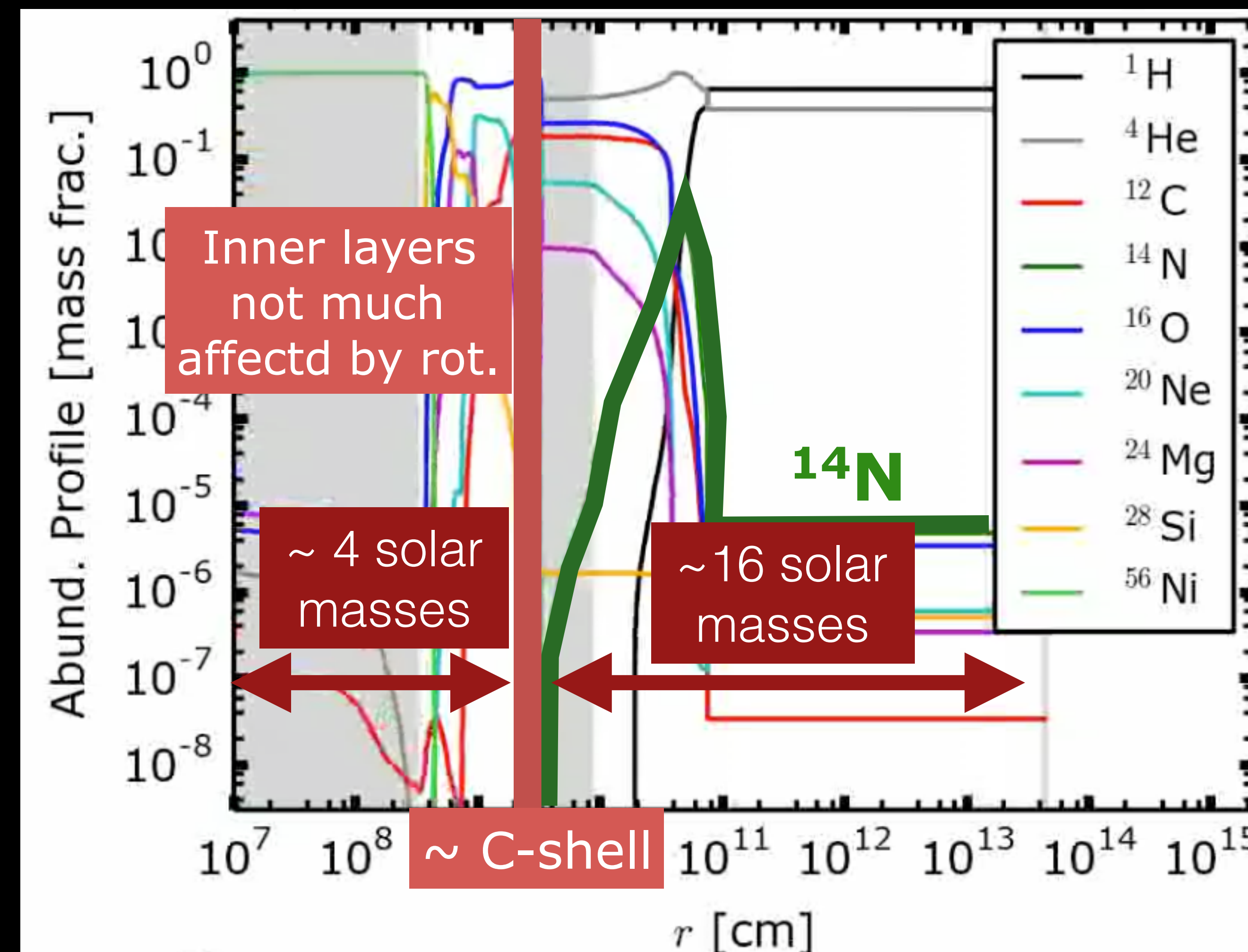

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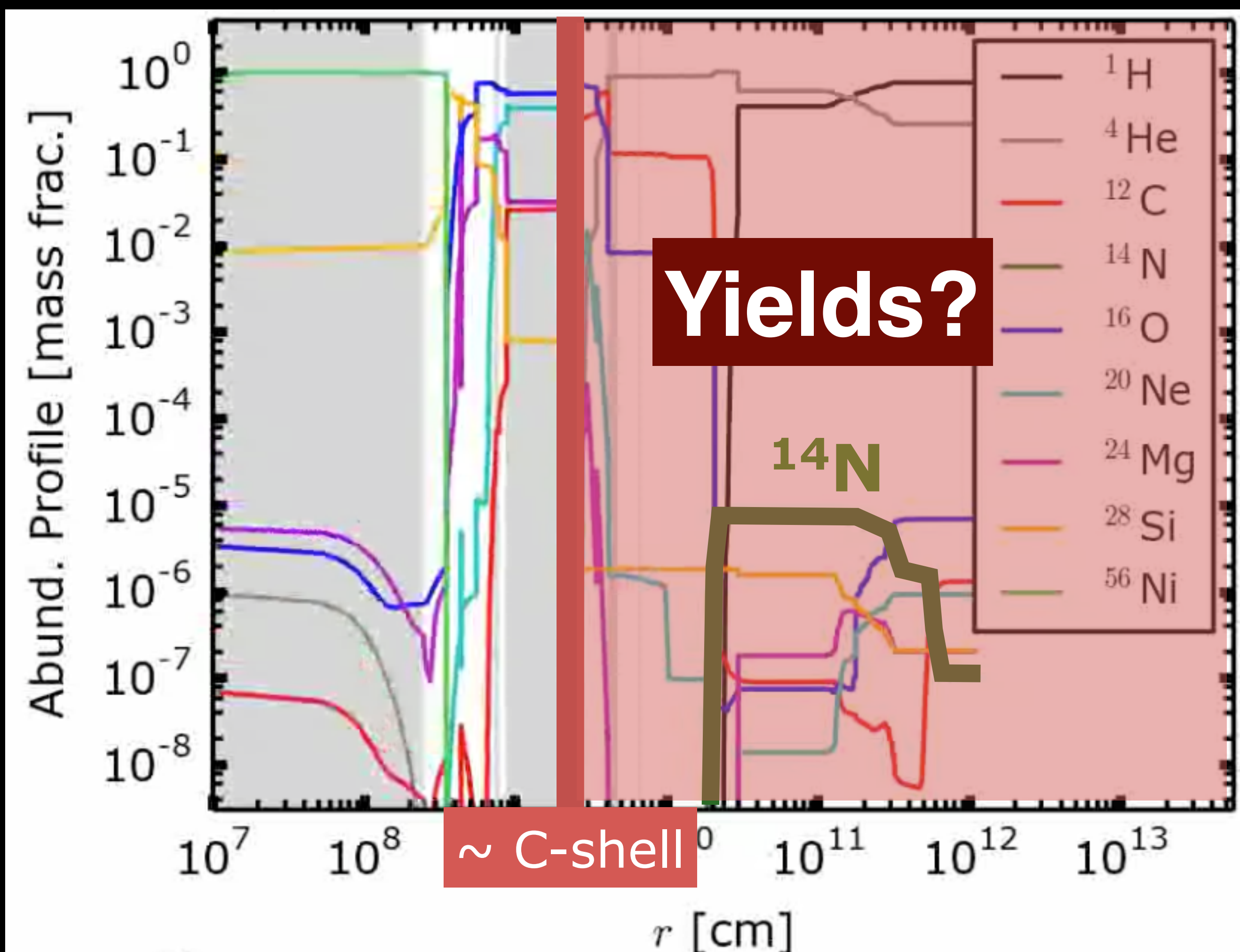

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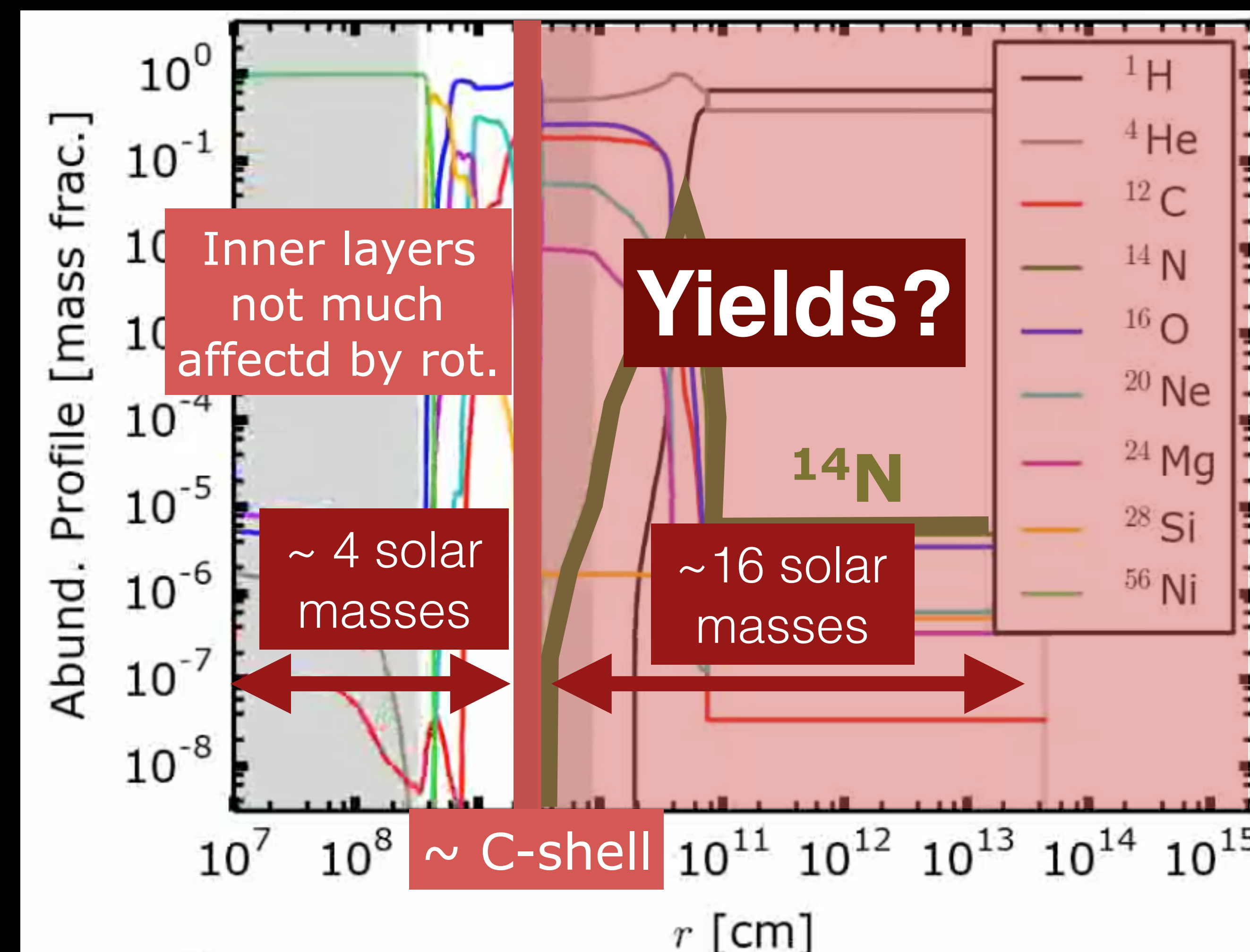

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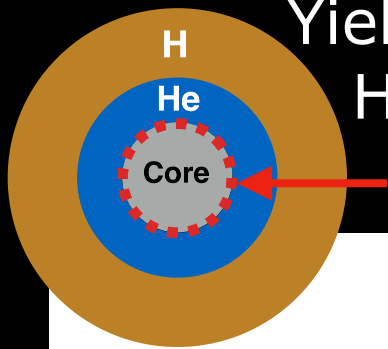
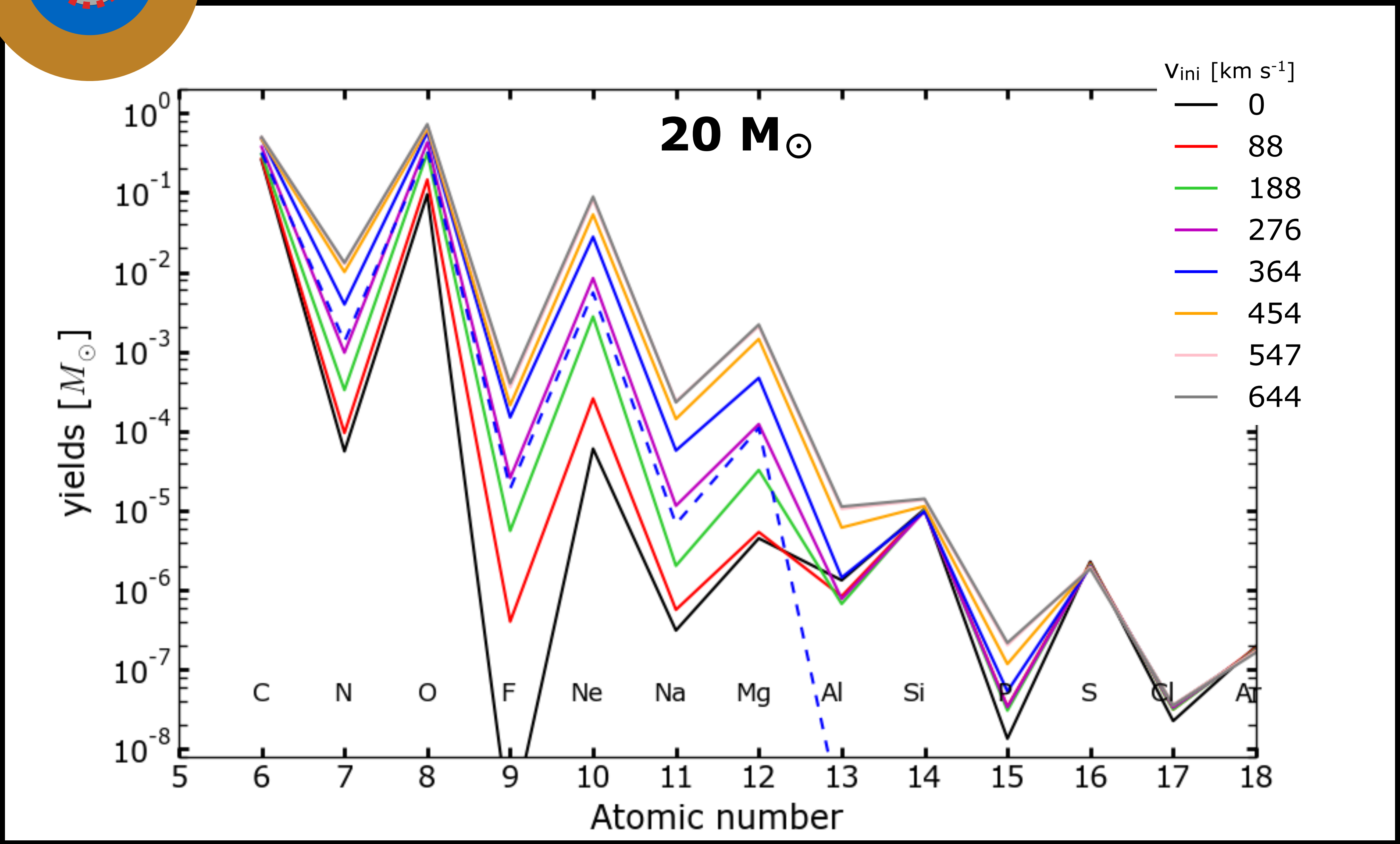


Yields of H+He layers

$M_{cut} \sim 4 - 5\ M_\odot$

• ~ C - Mg yields boosted by rotation



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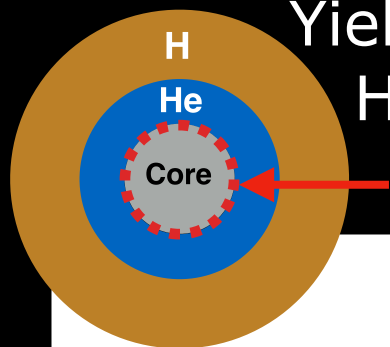

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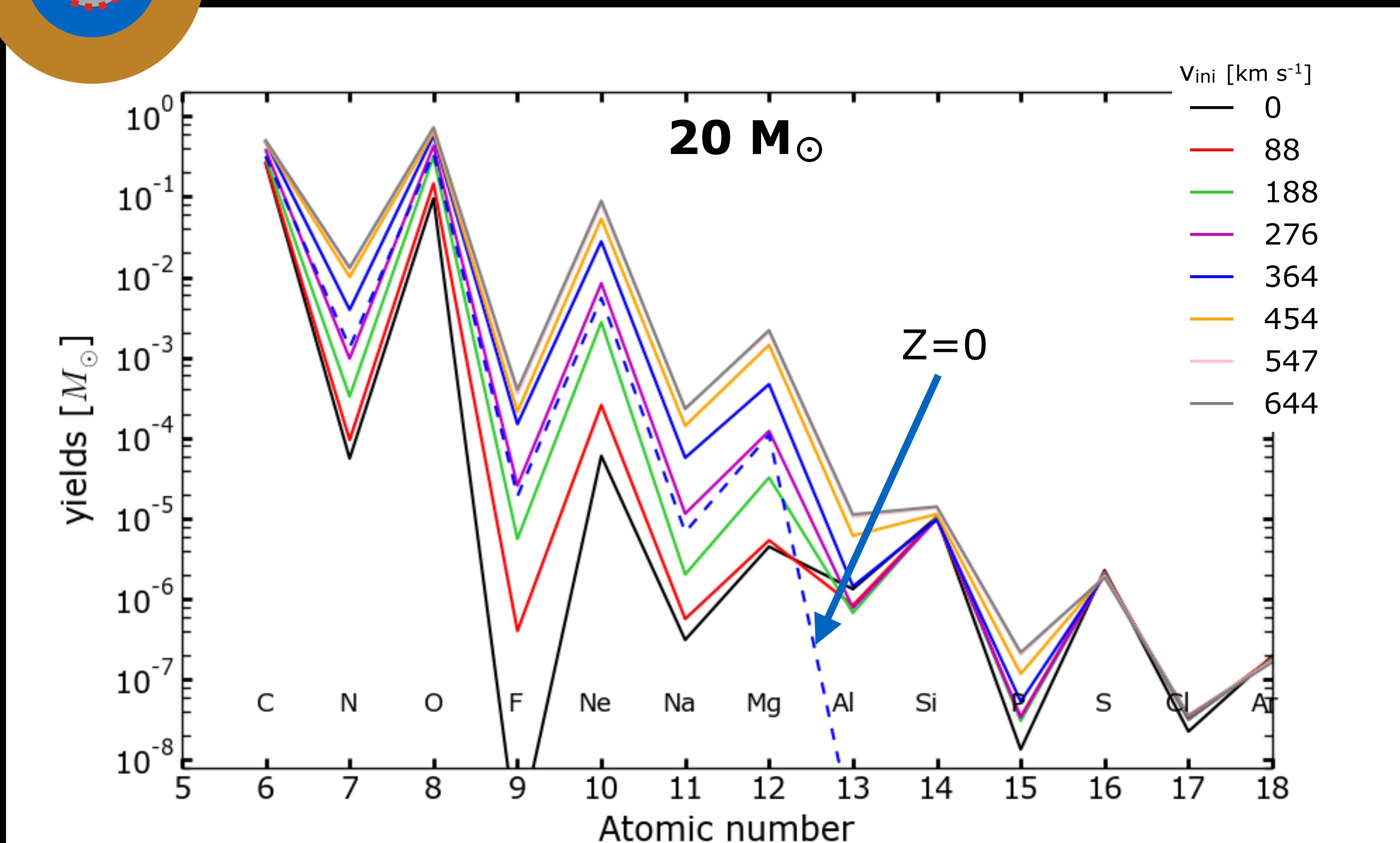

Rotating massive stars yields *(assuming explosion with strong fallback)*

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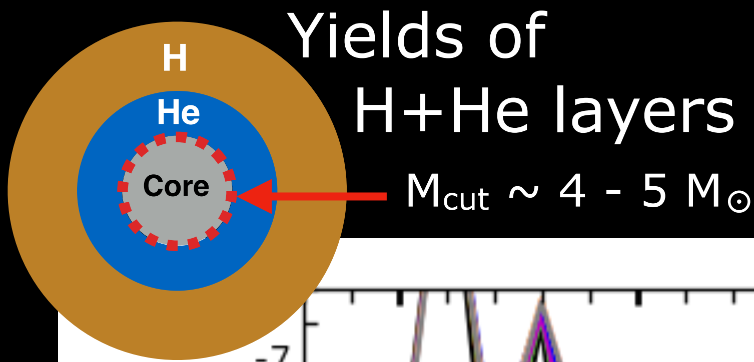
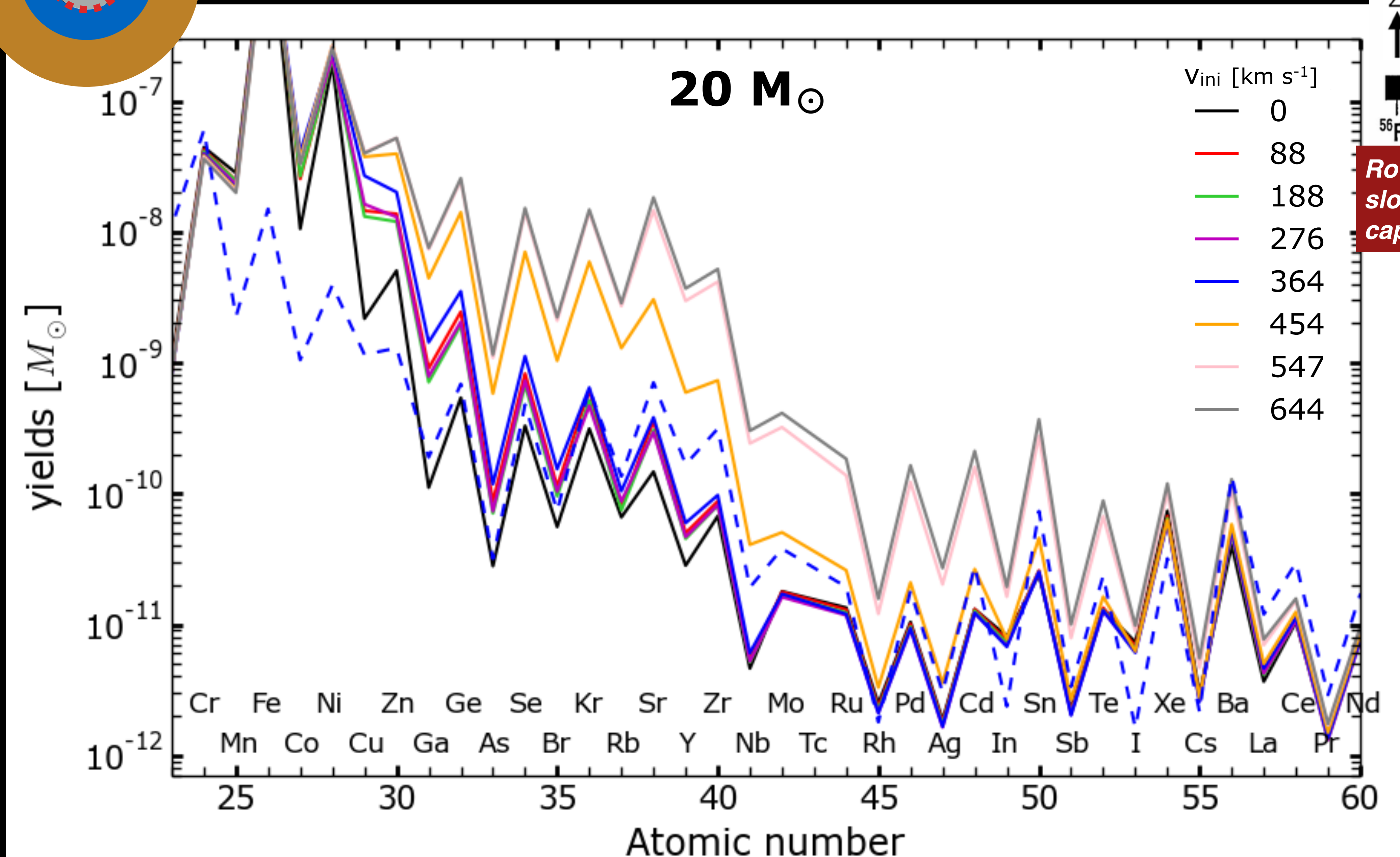
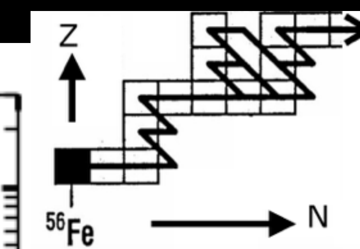
• Trans-Fe yields boosted by rotation







Rotation boosts the slow neutron capture-process

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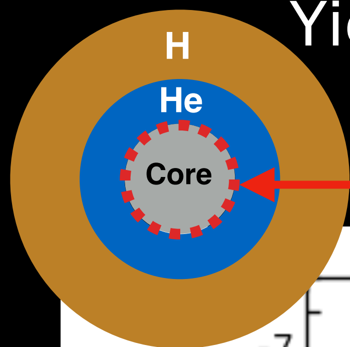

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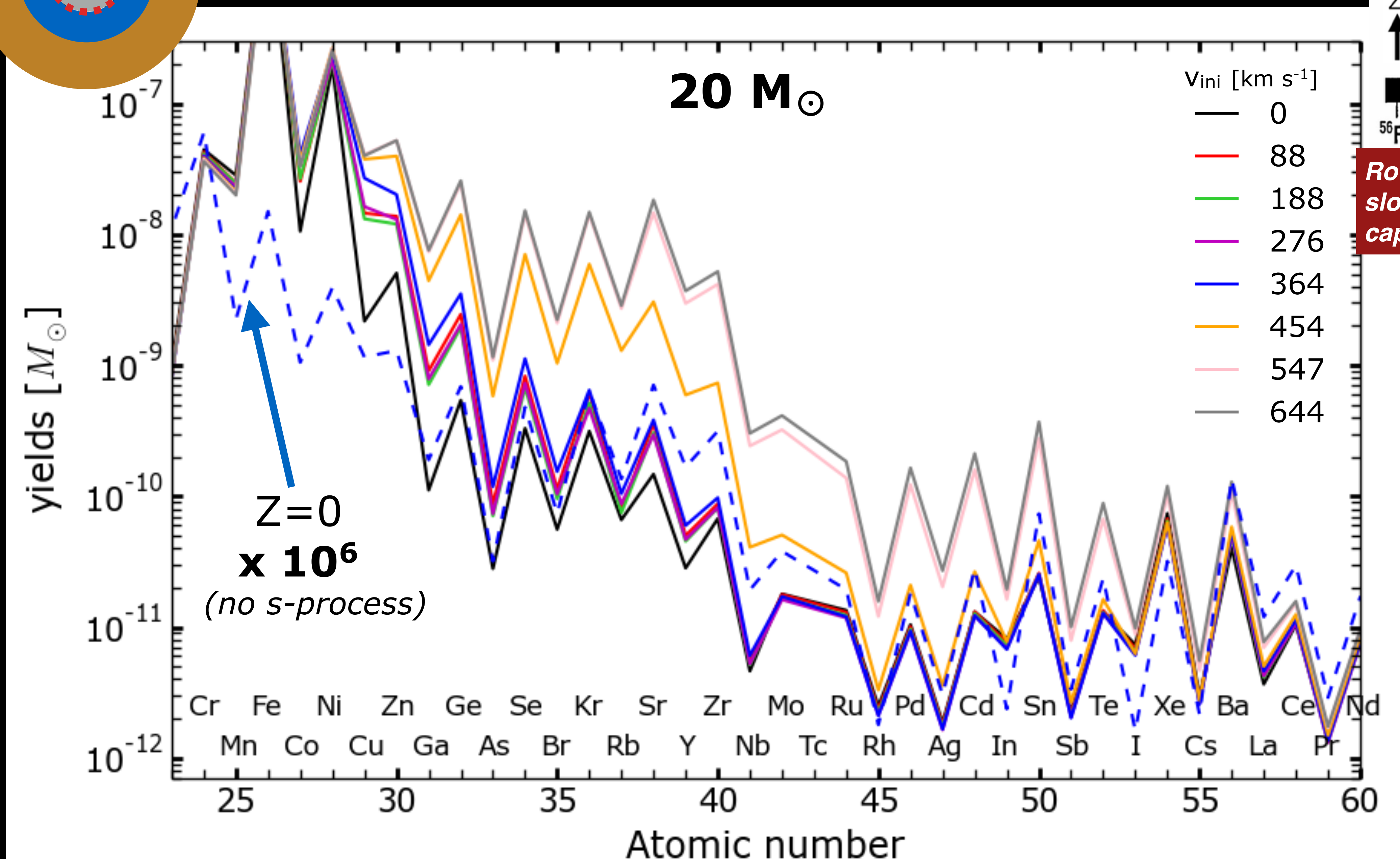

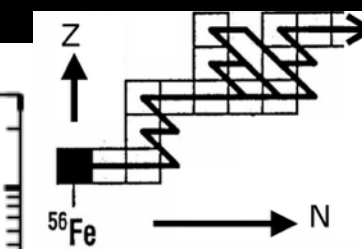

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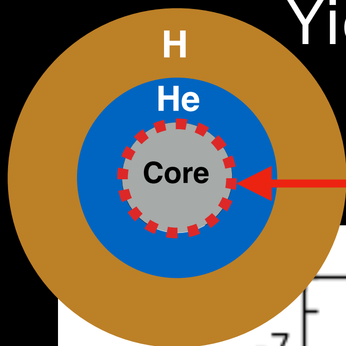

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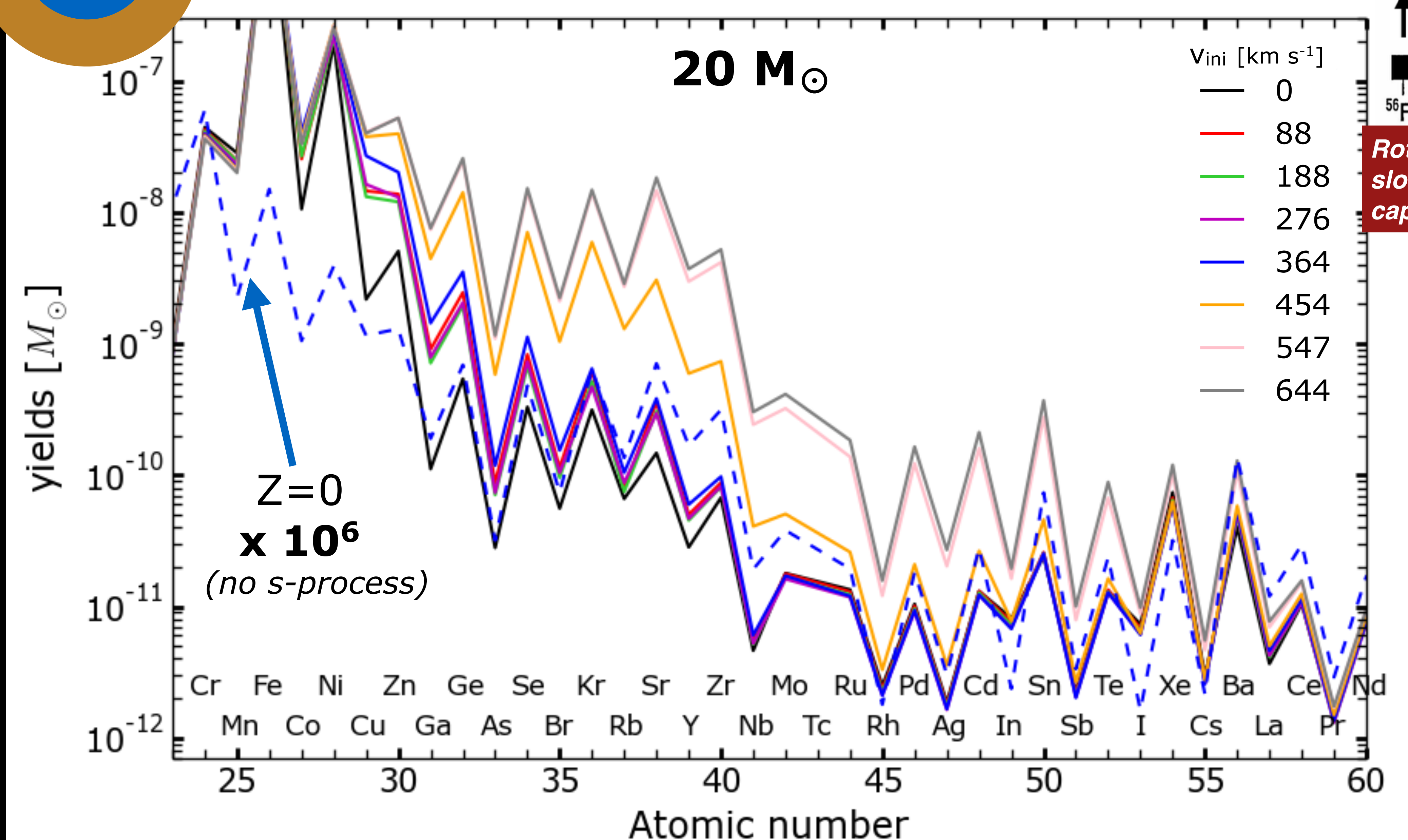
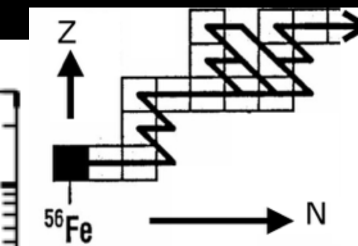
• Trans-Fe yields boosted by rotation but strongly depend on metallicity





Rotation boosts the slow neutron capture-process

Rotating massive stars yields

Effect of initial mass + rotation on trans-Fe elements yields

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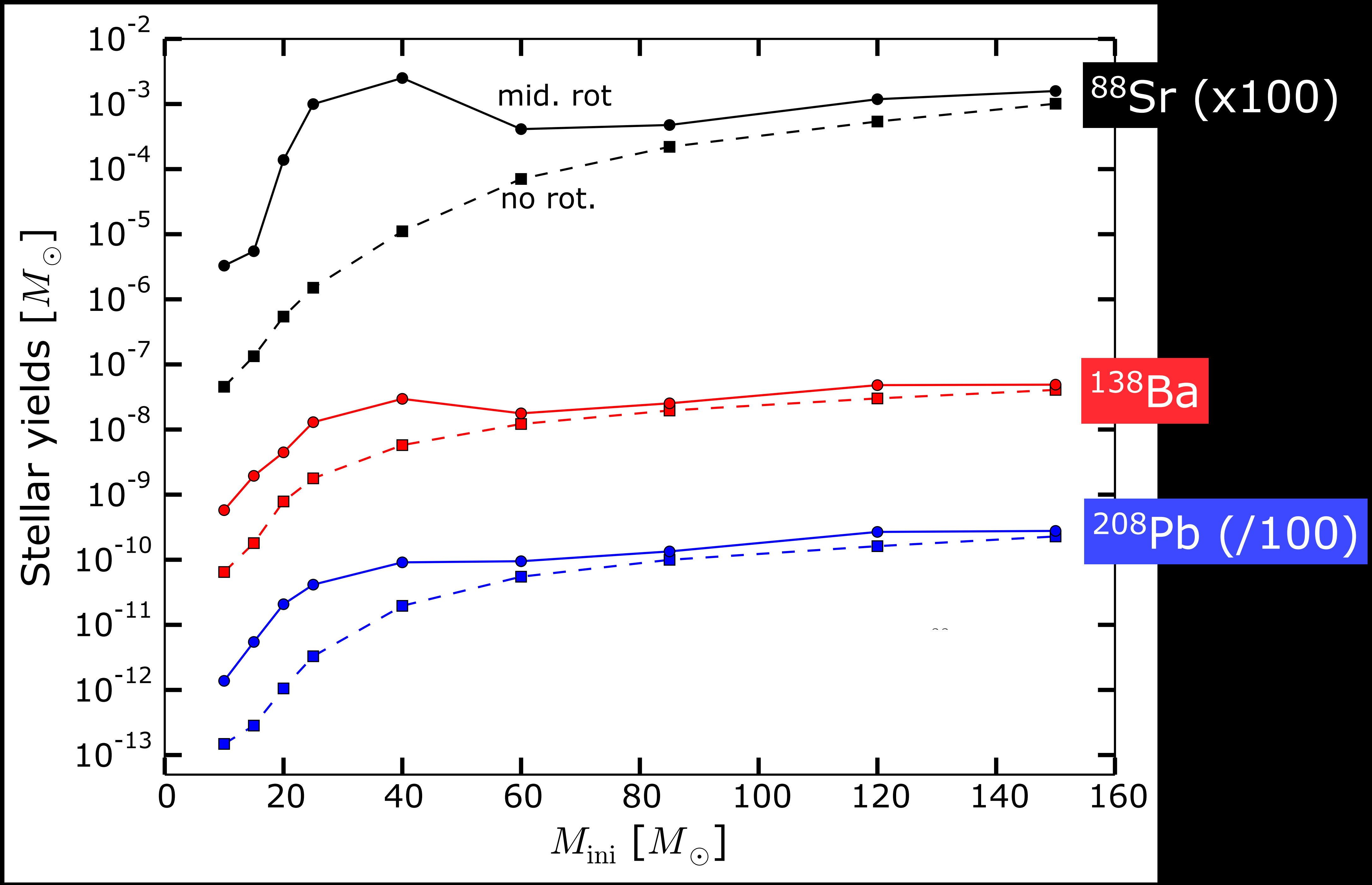

Choplin et al. (2018)

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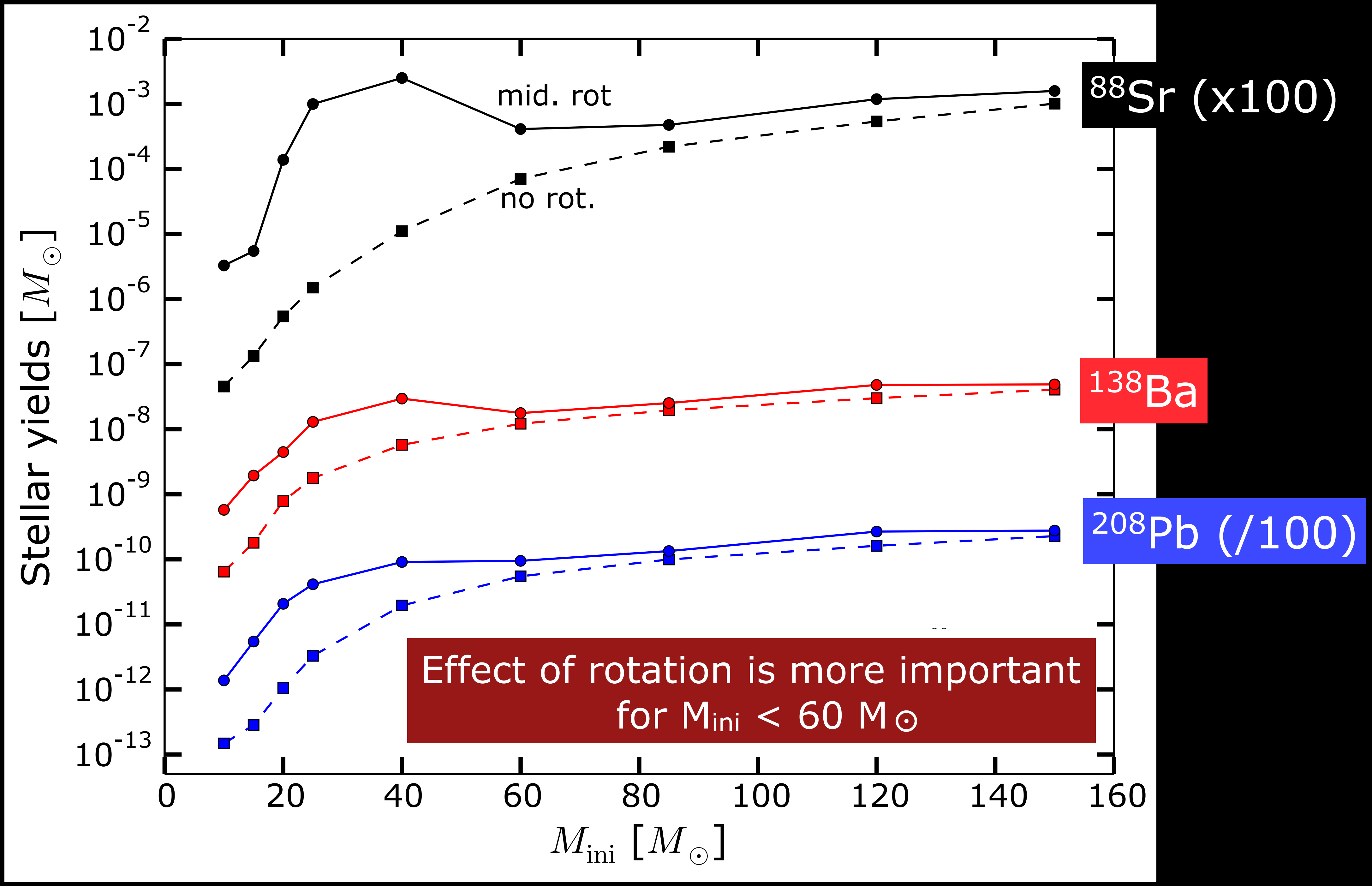

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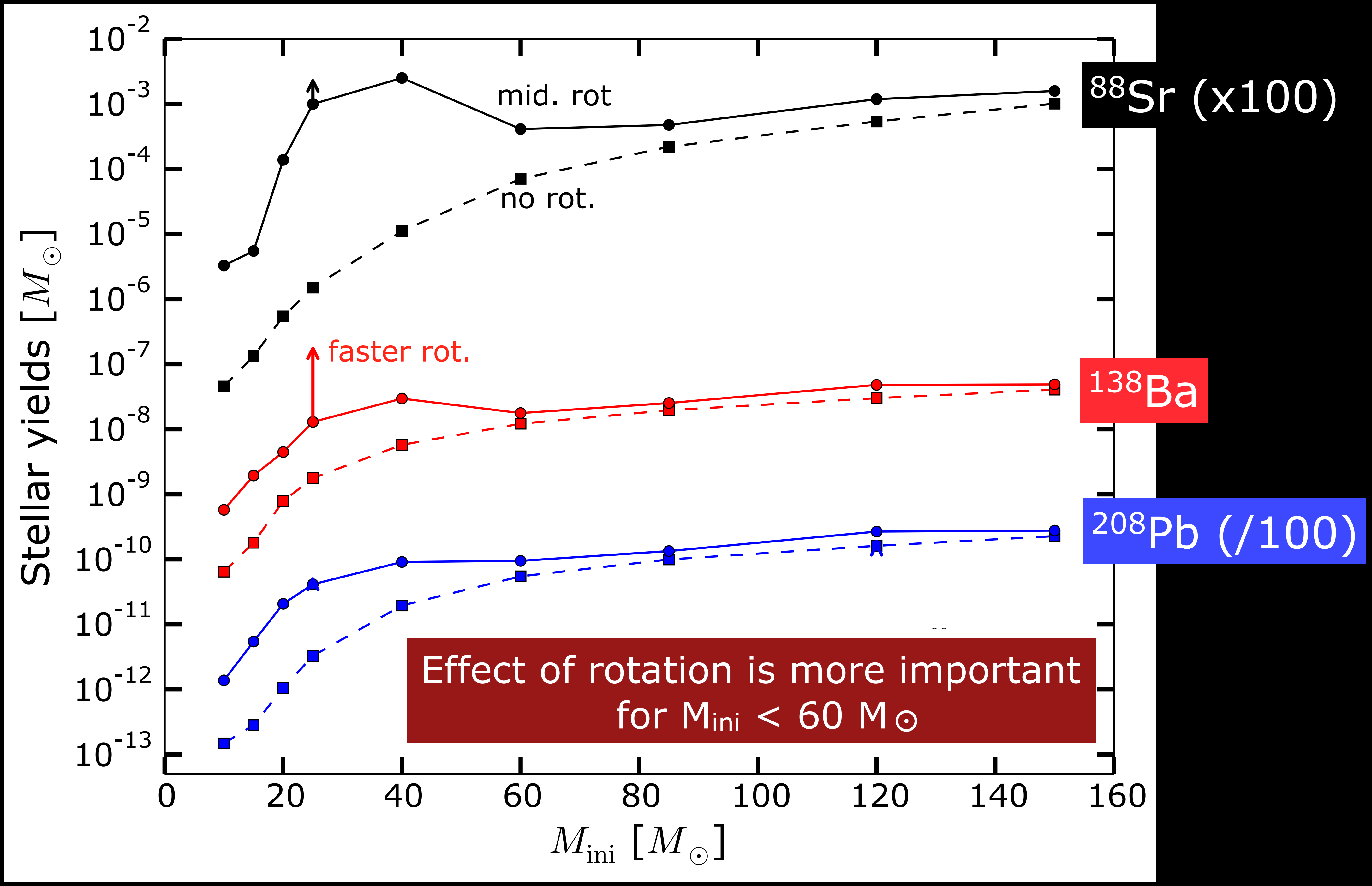

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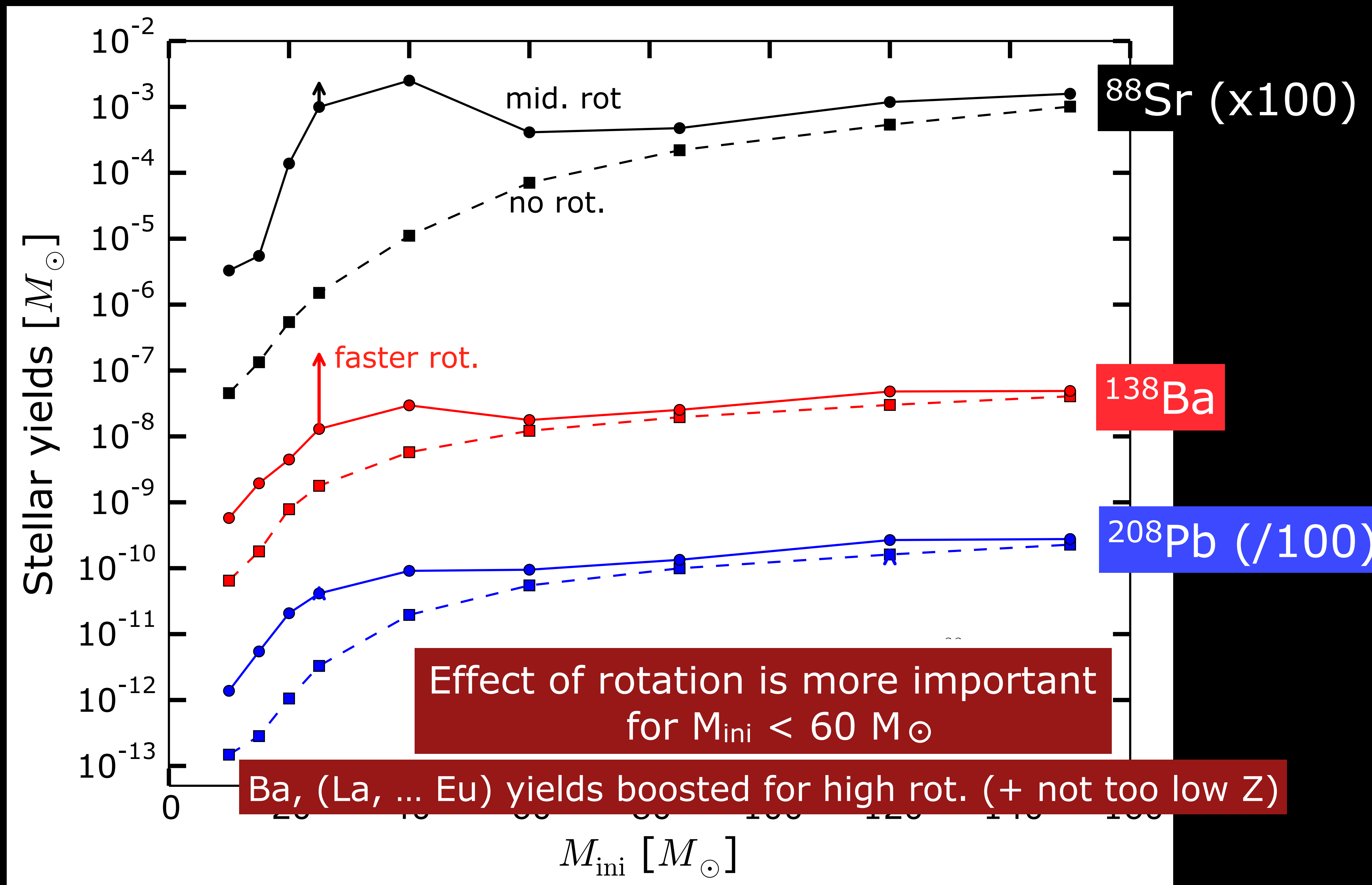

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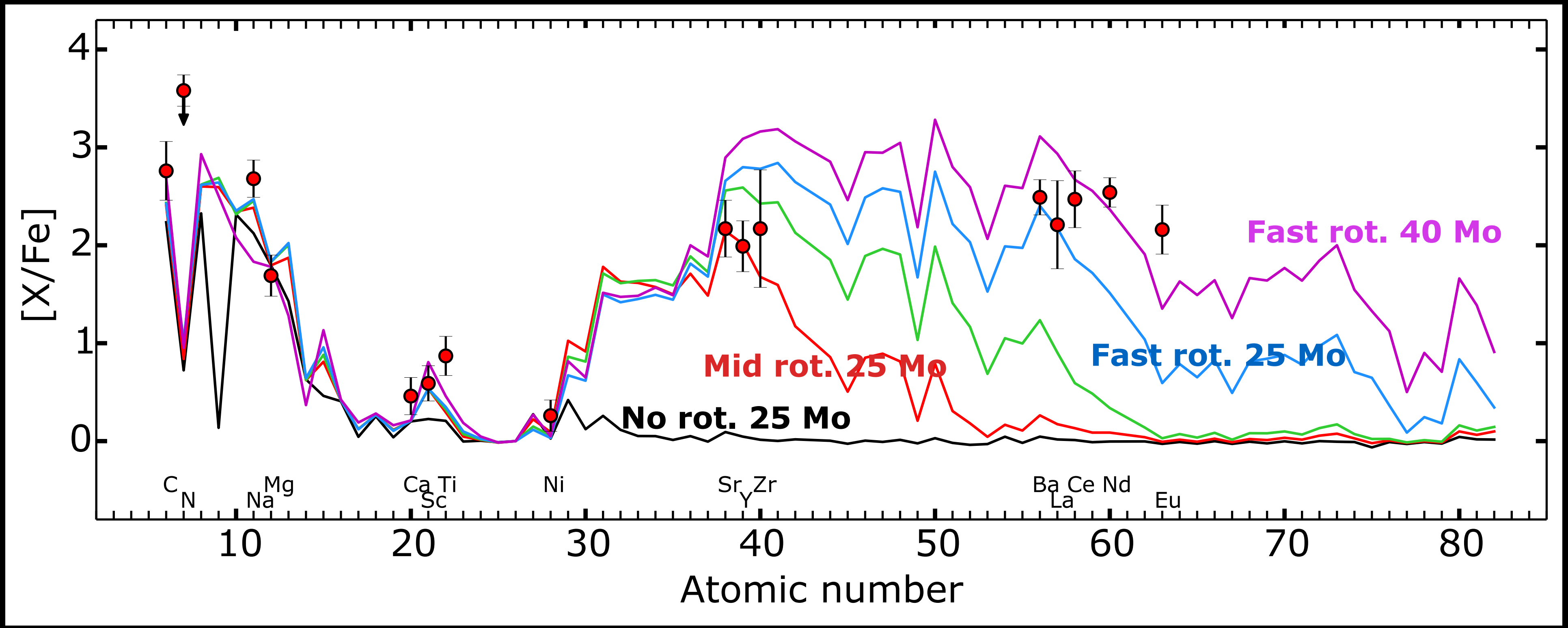
Chemical signatures of (fast) rotating massive stars in metal-poor stars

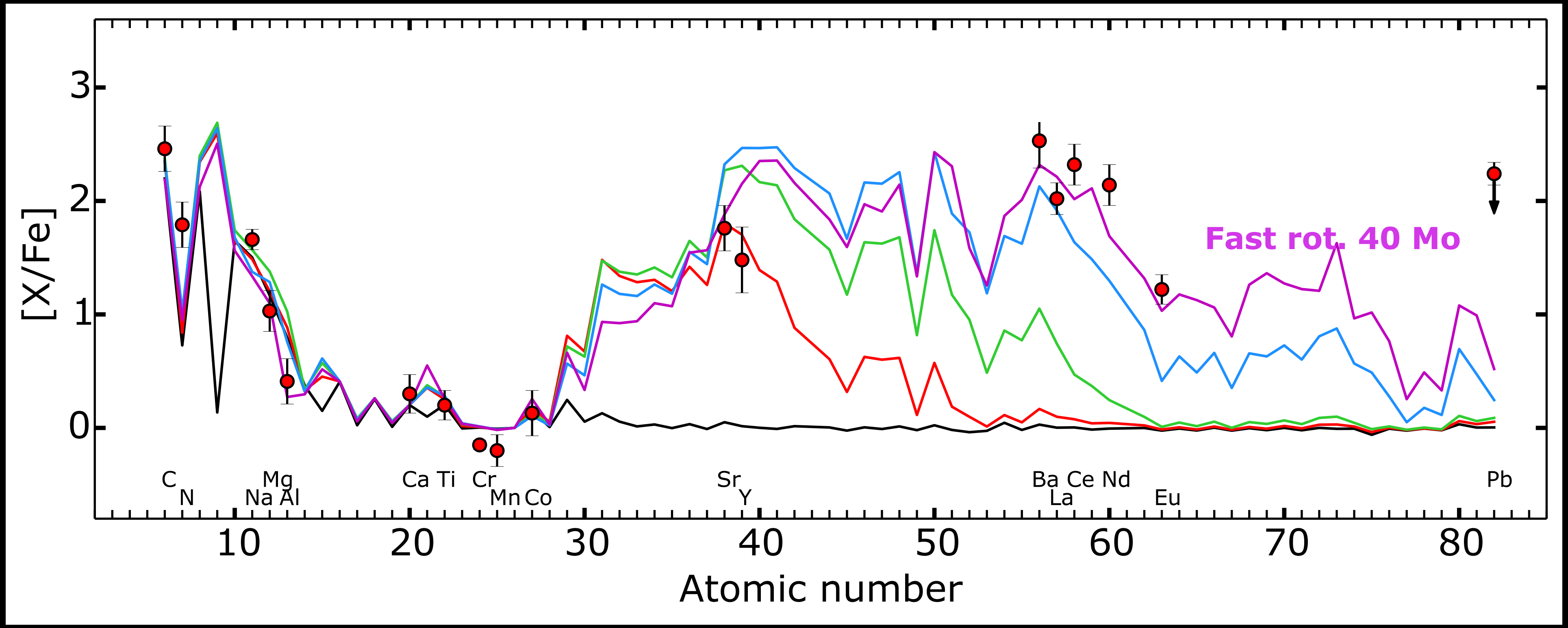
Signature of fast rotating massive stars in metal-poor stars?

e.g. Choplin+2017, Banerjee+2019



CS29528-028

Abundances from Aoki et al. 2007, Allen et al. 2012



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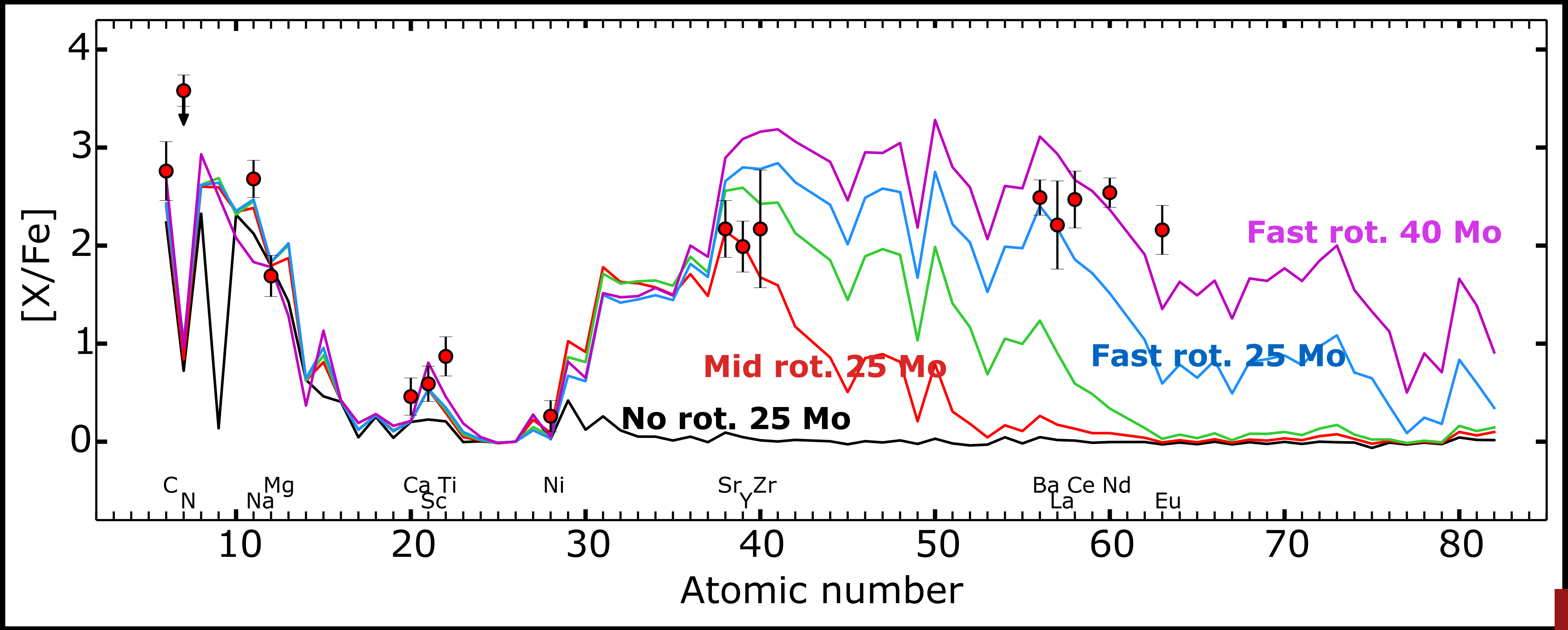

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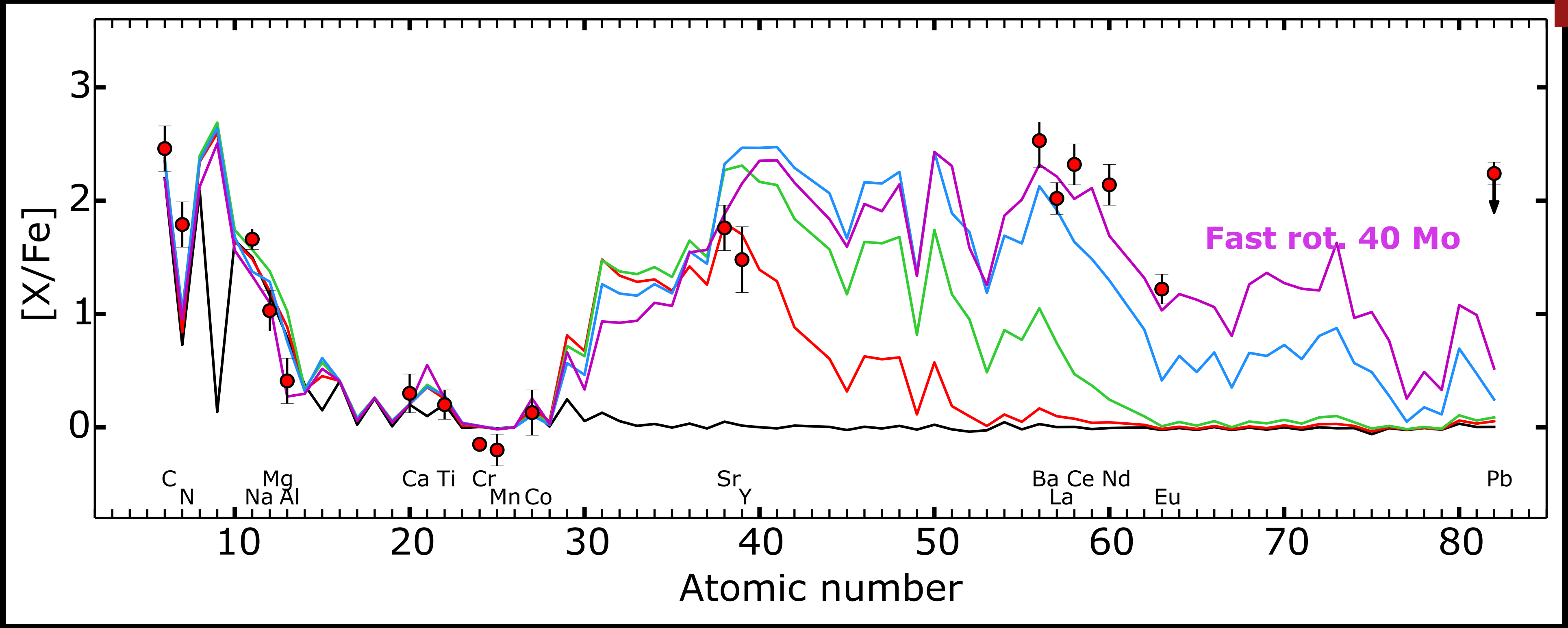
Smallest chi2 given by a fast rot. 40 M⊙



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Systematic comparison : rotating massive stars *vs.* EMP stars

Choplin, Tominaga & Ishigaki (2019)

- 272 EMP with -4 < [Fe/H] < -3
- Analysis of light elements (C - Al)
- Evolutionnary effects in EMP => corrections
  (e.g. dredge up) *Placco et al. (2014)*

272 observed EMP stars

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- 20 $M_\odot$, [Fe/H] = -3.8
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- Explo. with strong fallback

massive stars models

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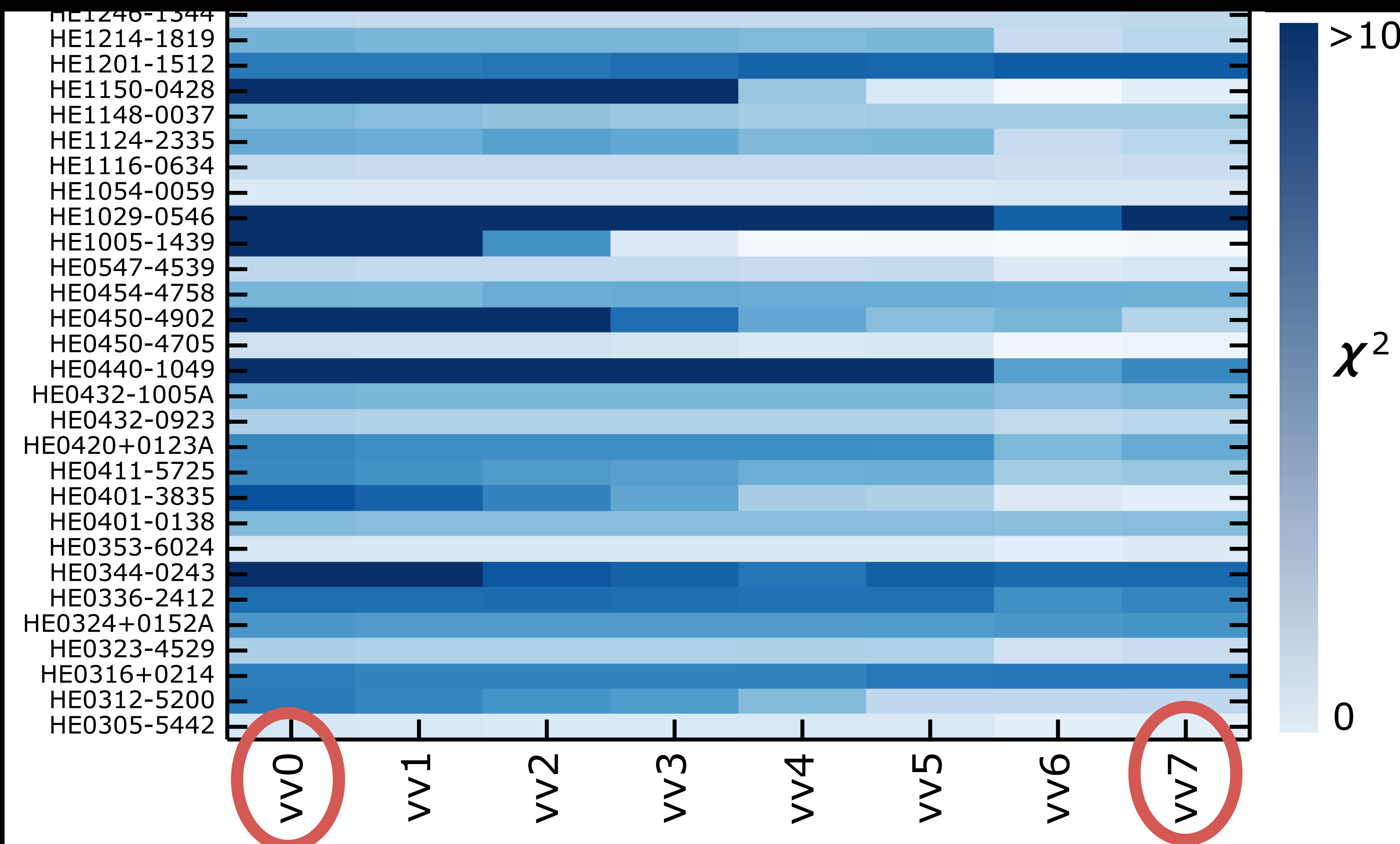

extract of the 8 x 272 table

No rotation

Fast rotation

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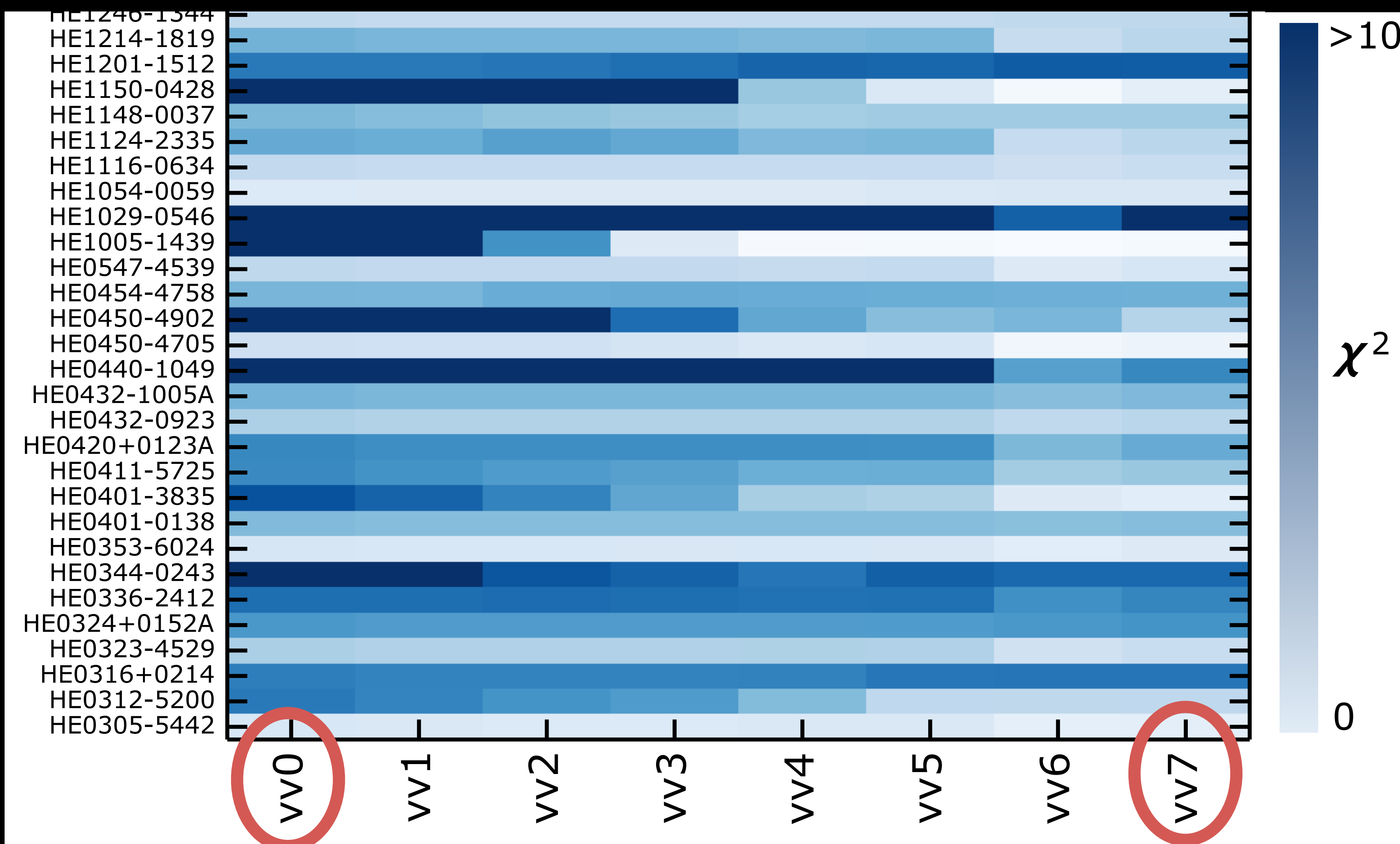

extract of the 8 x 272 table

- ~ 50 % of EMP have at least one good solution ($X_v^2 < 2$)
- ~ 70 % of C-rich EMP have at least one good solution
- ~ 30 % of C-normal EMP have at least one good solution

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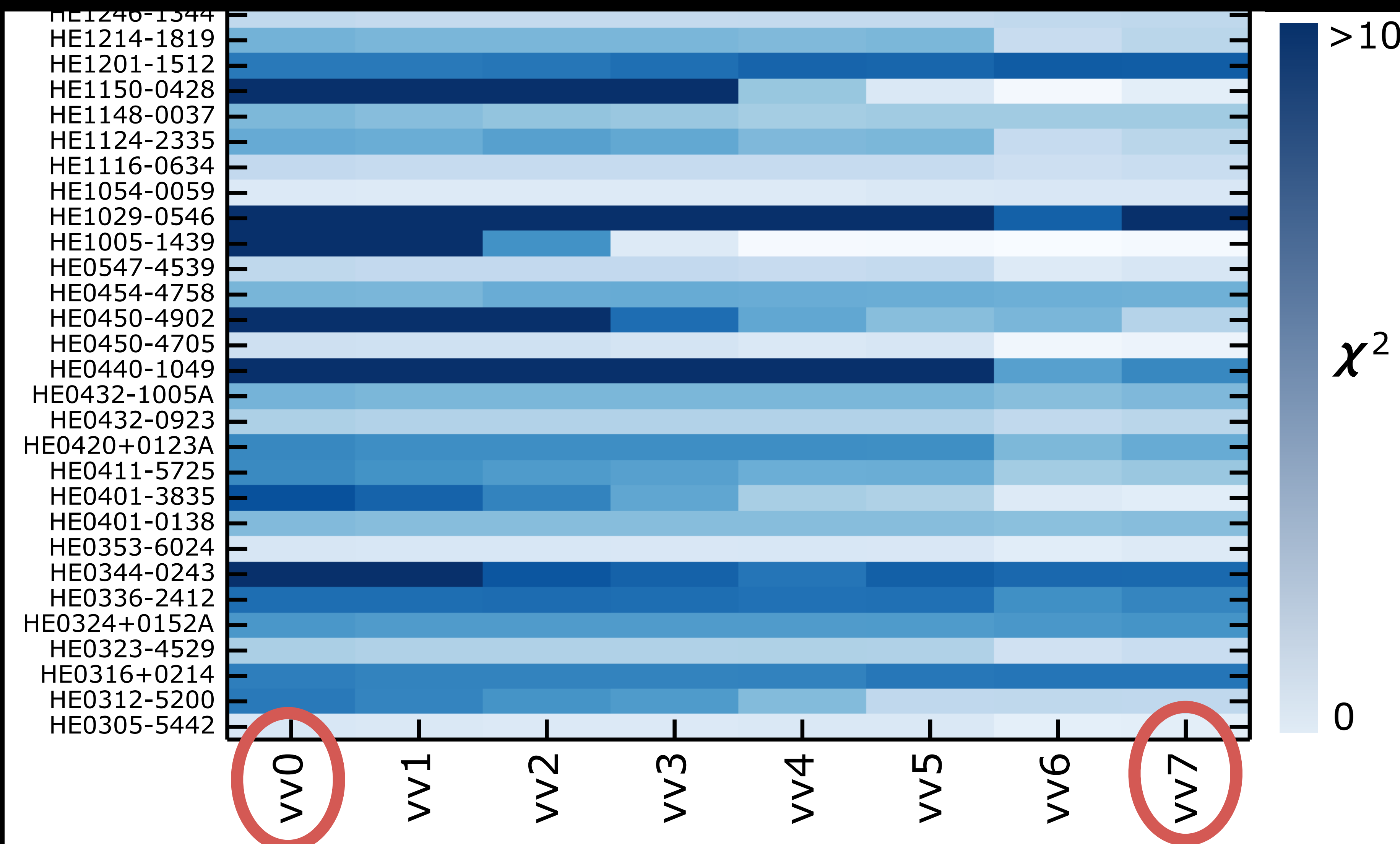

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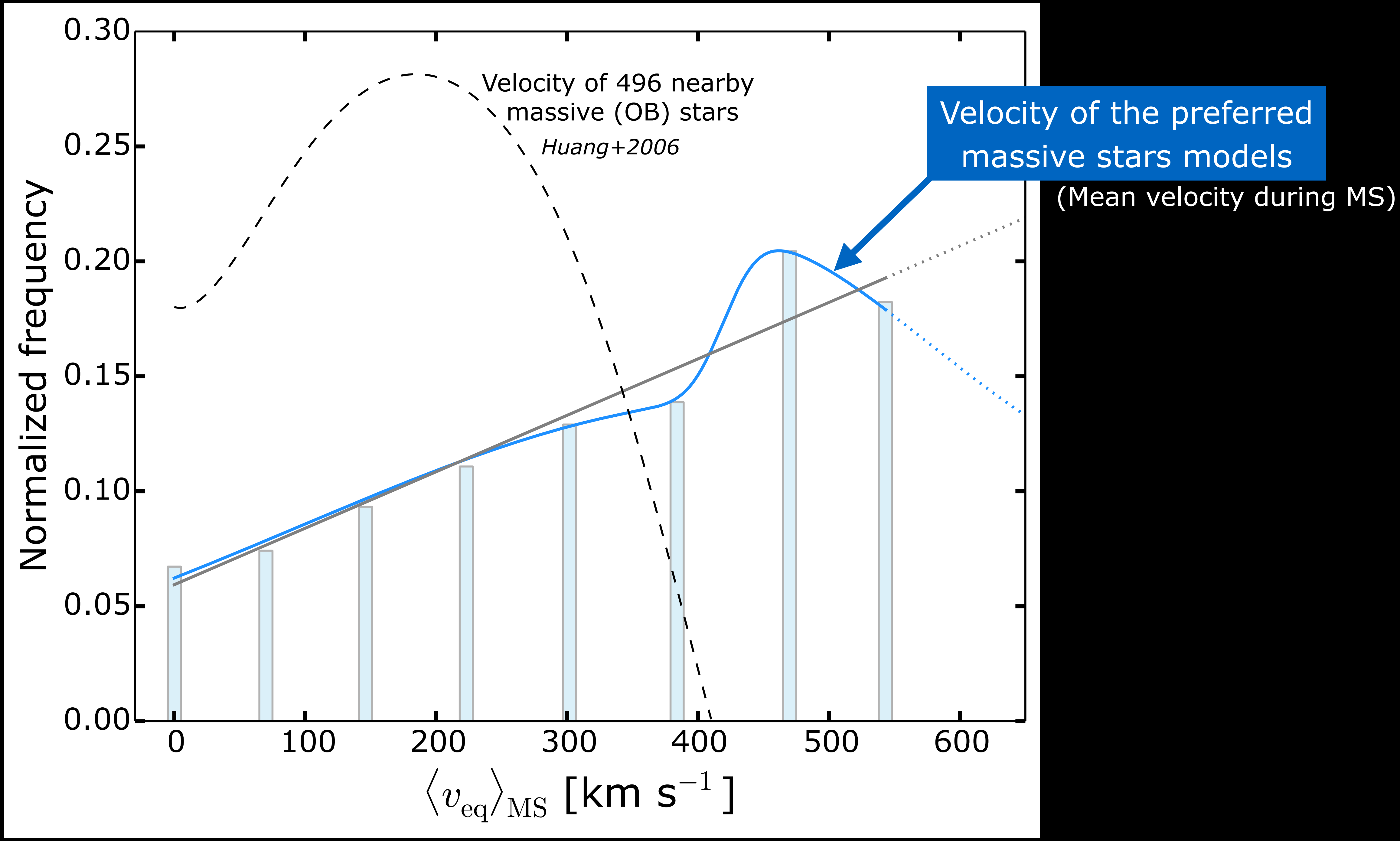
Models are adequate to reproduce most of the C-rich EMP stars

Guessing the velocity of early massive sars from EMP stars

Choplin, Tominaga & Ishigaki (2019)



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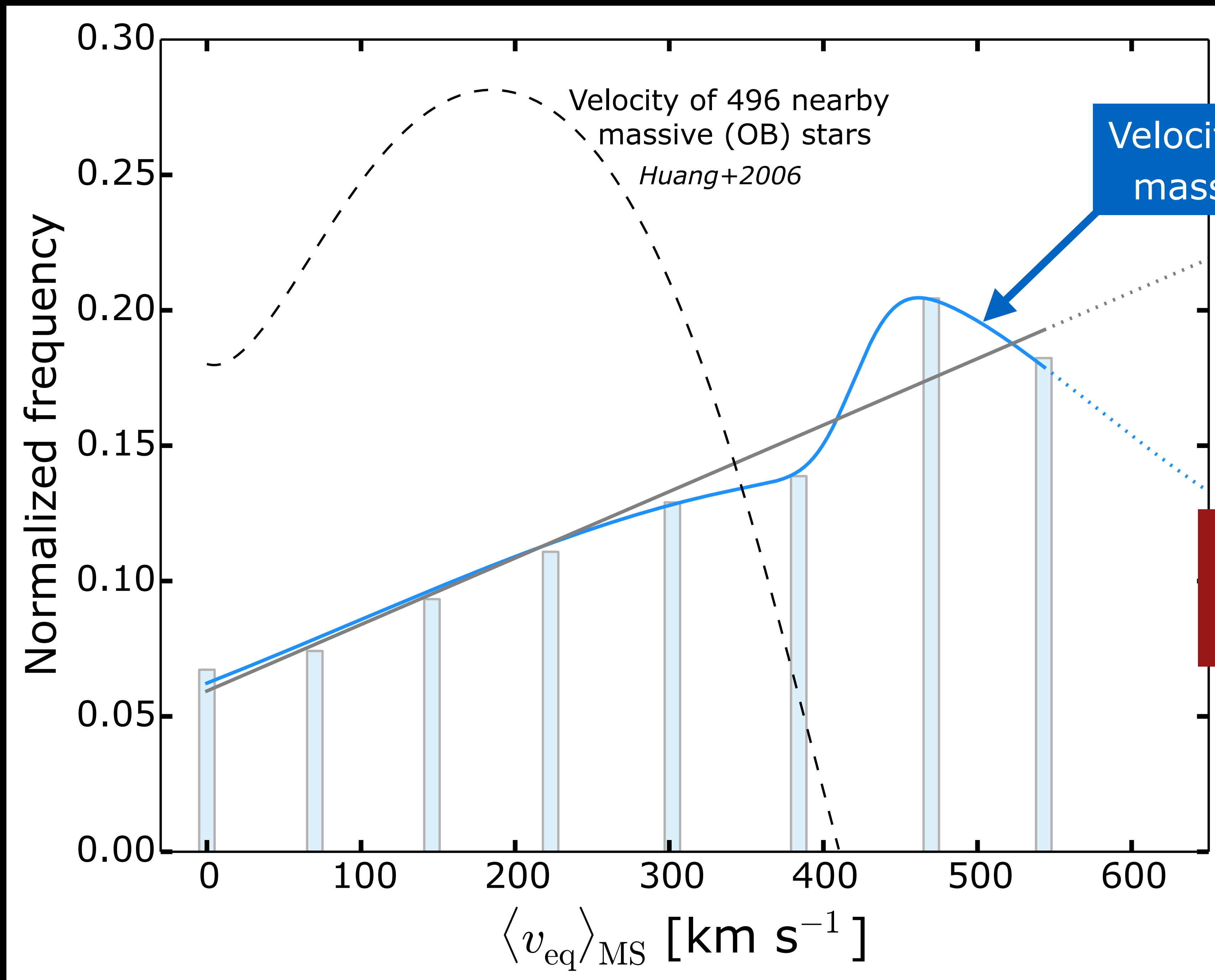

Velocity of the preferred massive stars models

(Mean velocity during MS)

Suggests numerous fast rotating massive stars in the early Universe

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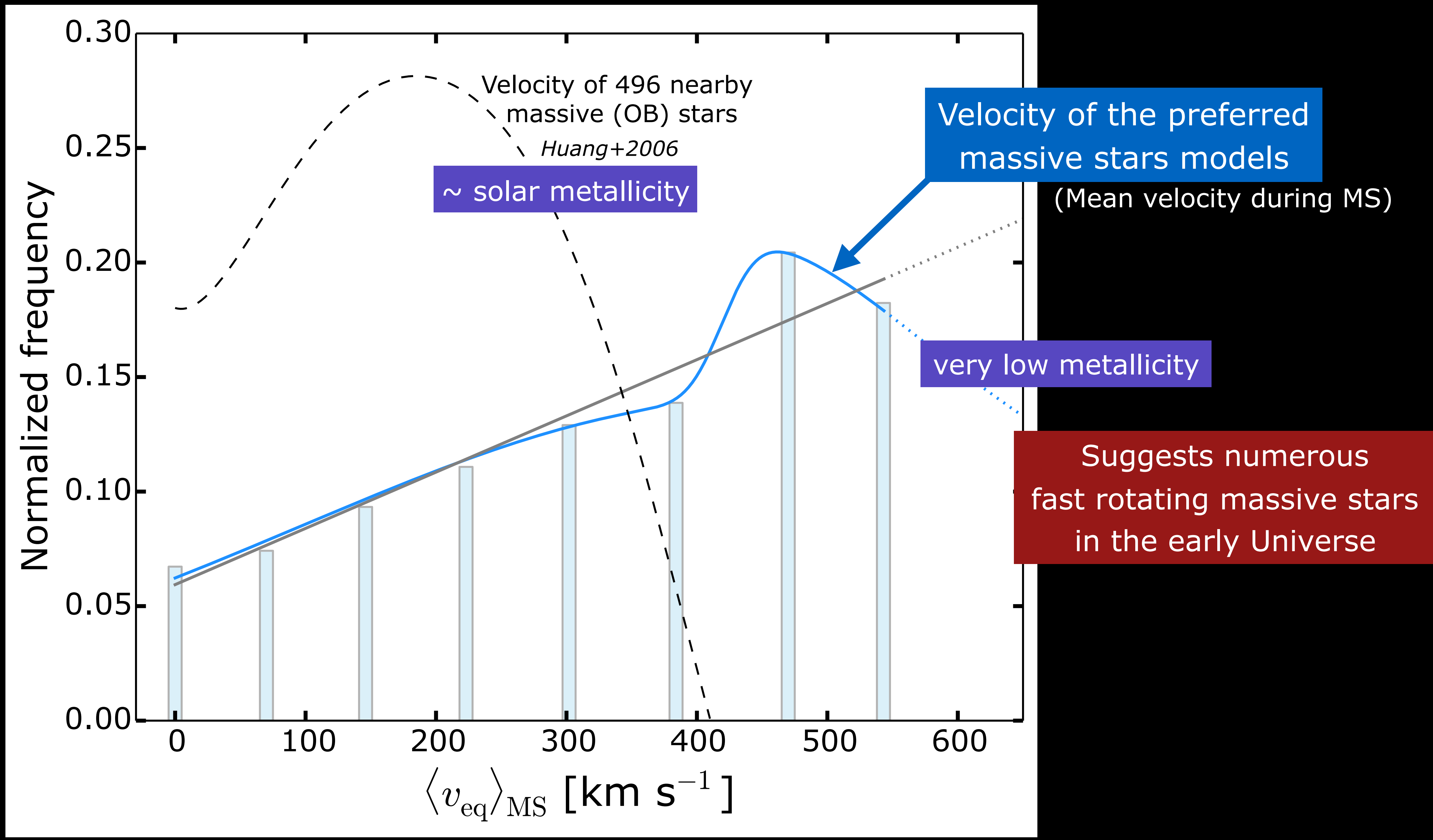

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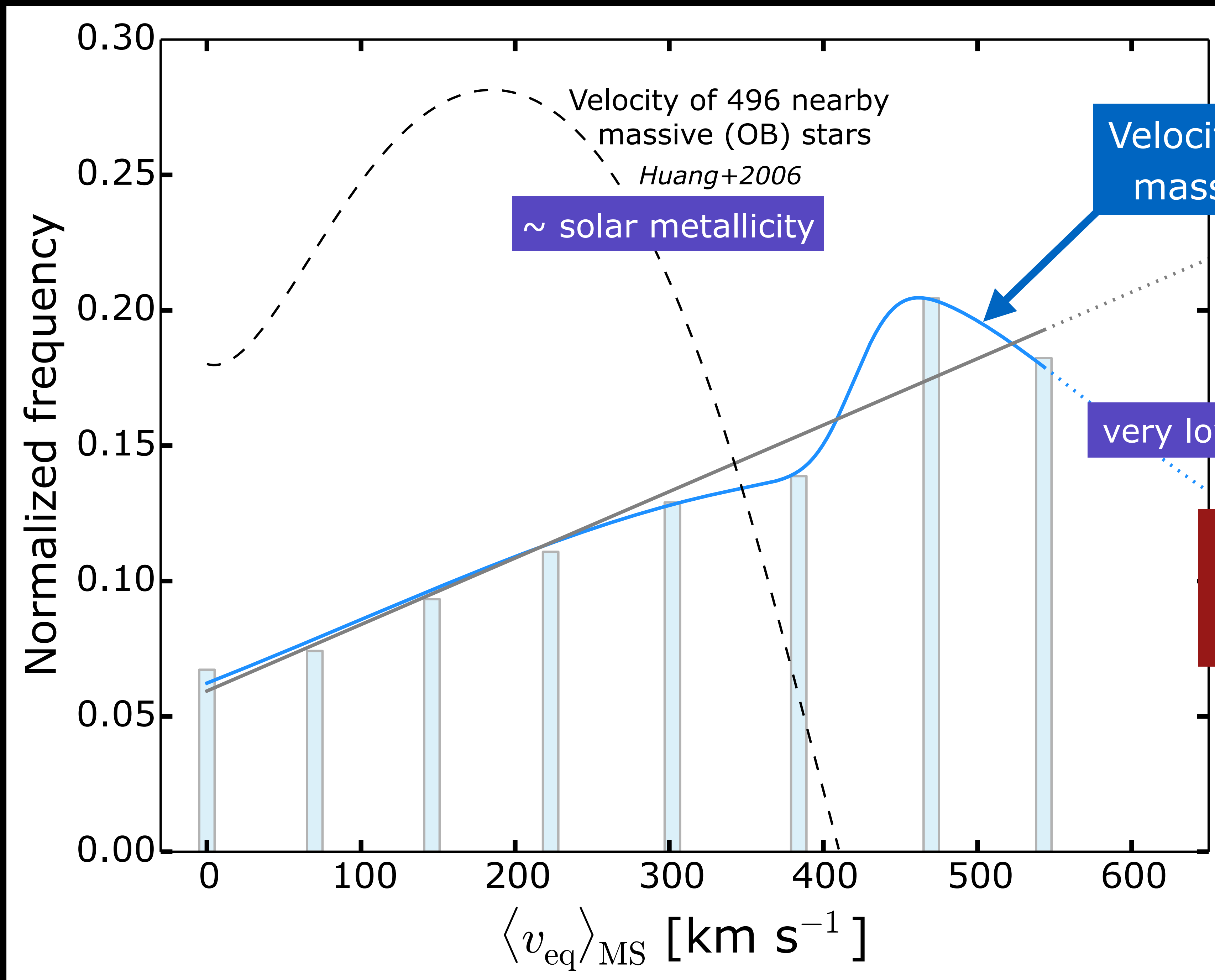

Velocity of the preferred massive stars models

(Mean velocity during MS)

Suggests numerous fast rotating massive stars in the early Universe

more fast rotators than in the present-day Universe

Summary

- Metal-poor stars —> window on first massive stars

  —> **mixing processes** *(mixing & fallback, rotation, shell mixing…)*

- Rotation in low/zero metallicity massive stars => light / trans-Fe elements overproduced

  —> **signature in some EMP(-s) stars**

Summary

- Metal-poor stars —> window on first massive stars

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  —> Impact on reionization, light from high redshift galaxies, GRBs…?

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Caution required because of :

- Limiting assumptions
- Uncertainties. Affect both <u>models</u> and <u>abundances of EMP stars</u>

- Convection,
- Rotation
  - Different prescriptions
  - Additional mixing? *e.g. Eggenberger (2017)…*
  - …
- …

- NLTE,
- 3D effects
  e.g. Norris & Yong (2019)