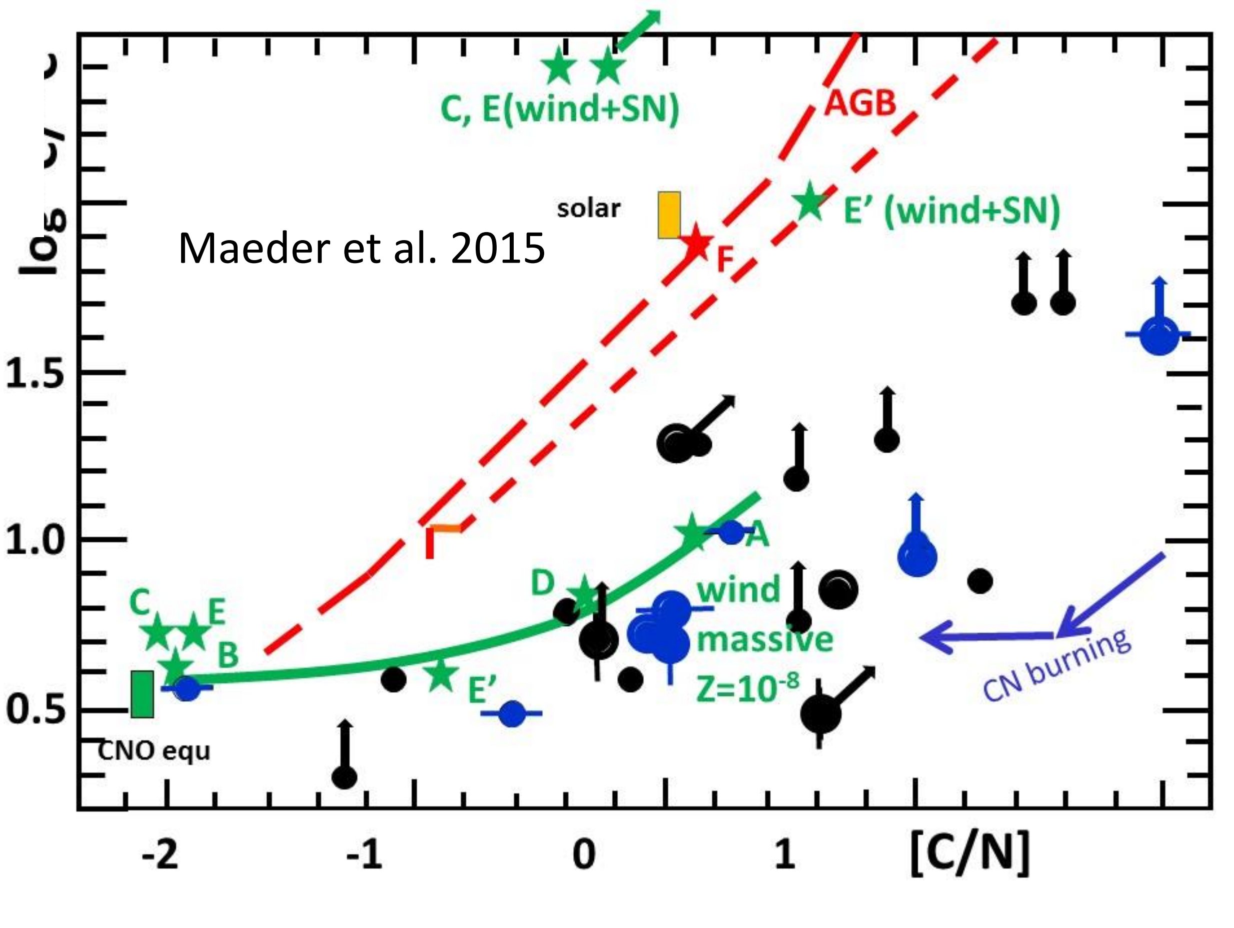
Aim of the talk:

Observational facts in CEMP-no abundances ⟷ The role of massive rotating stars (spinstars)

$^{12}C/^{13}C$ in CEMP-no: very constraining

Low $^{12}C/^{13}C$
→ H-burning
(otherwise ^{13}C would be destroyed !)



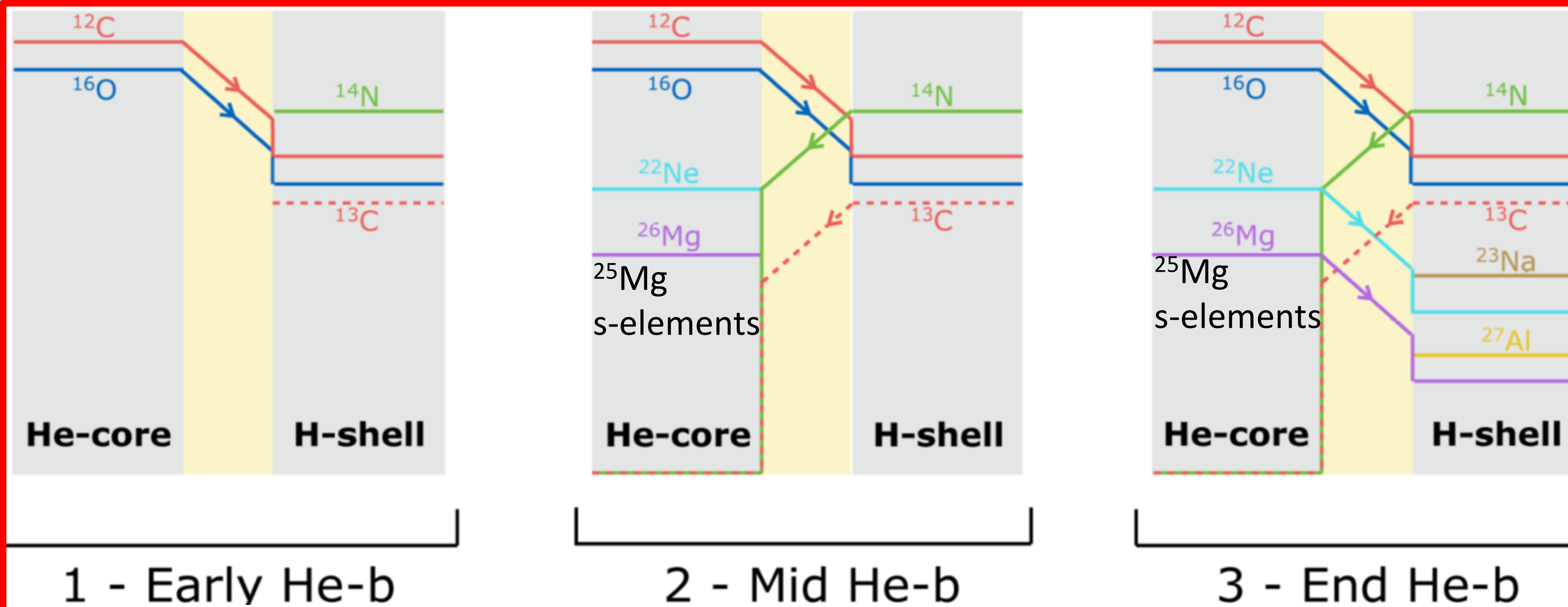
Products of He-burning (C, O) further processed by H-burning
→
Mixing + partial CNO processing

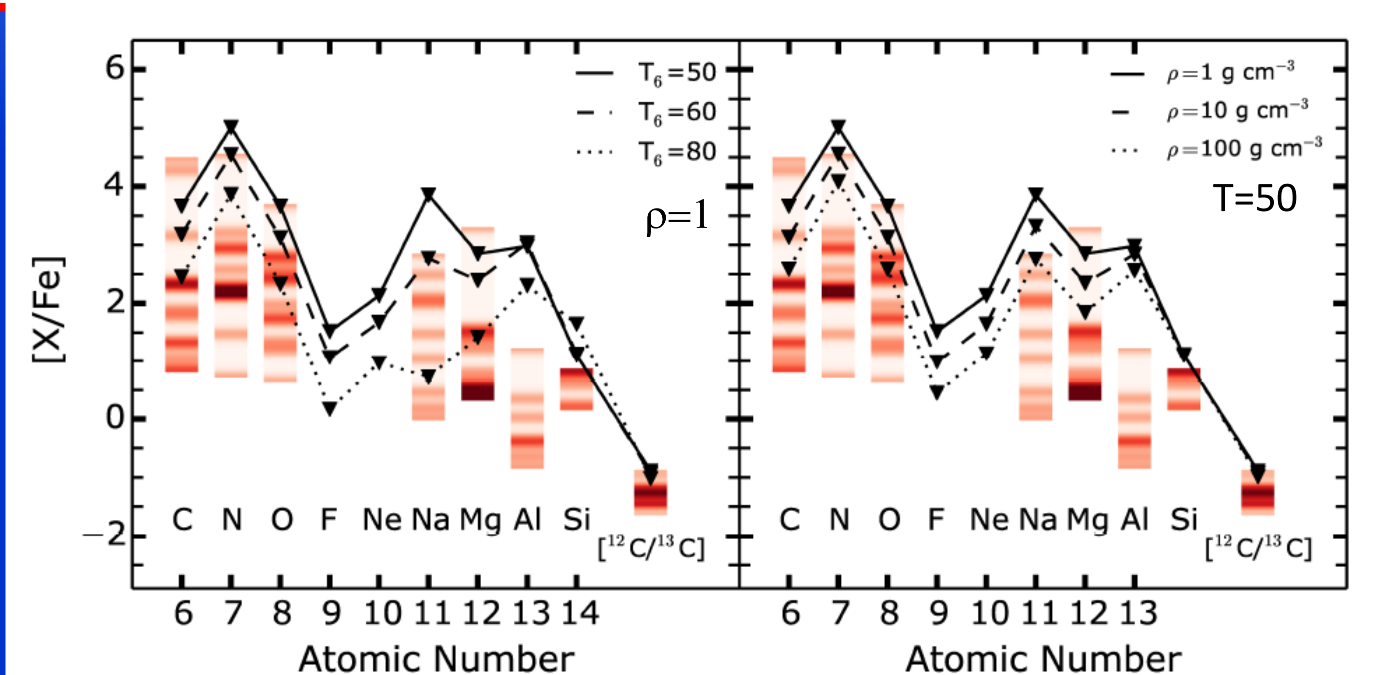
Data by Norris et al. 2013; Masseron et al. 2010

SN contributions seem absent
WIND EJECTA ?
(OB and/or late wind ejecta ?)

NUCLEOSYNTHETIC SEQUENCE

Class 1: products of He-burning:	**WC -stars** C, O, (^{20}Ne) $^{12}C/^{13}C$ → infinite	
Class 2: mixing of C,O + H - processing :	C,O→N (^{20}Ne→^{23}Na) (^{12}C → ^{13}C)	~30 % [Fe/H]=-3.38
Class 3: further mixing in He- burning zone (α-captures on ^{14}N):	^{14}N → $^{22}Ne(\alpha,\gamma)^{26}Mg$ **$^{22}Ne(\alpha,n)^{25}Mg$** **n→ s-elements (1st peak)**	~40 % [Fe/H]=-3.82
Class 4: further mixing in H-burning zone: Ne - Na cycle Mg - Al cycle	C, O → N goes on $^{20,22}Ne$ → ^{23}Na $^{25,26}Mg$ → ^{27}Al, (^{28}Si) s-elements still there	~30% [Fe/H]=-4.11

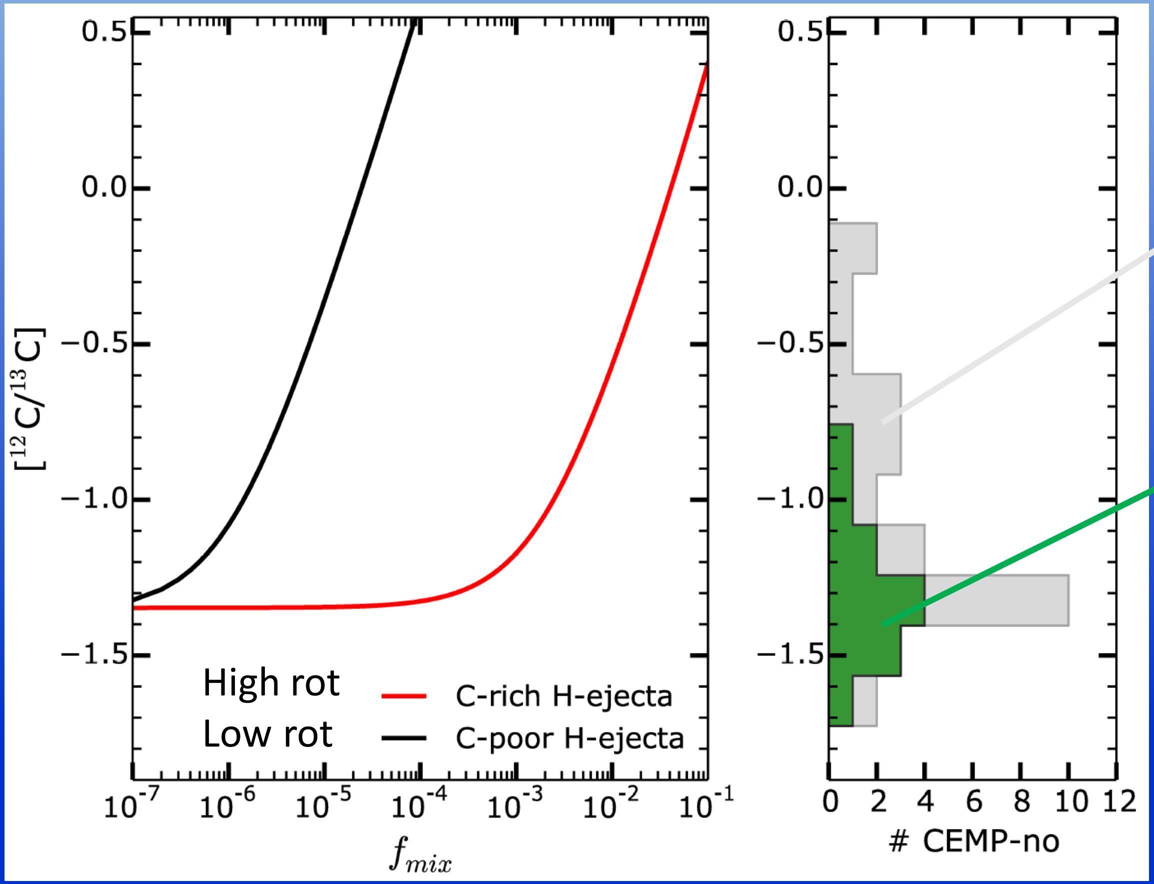




[The back-and-forth mixing]

(Choplin et al. 2016)

Where does the matter of CEMP-no stars come from ?



All CEMP-no

Class 2 and 4

$^{12}C/^{13}C$ extremely constraining !

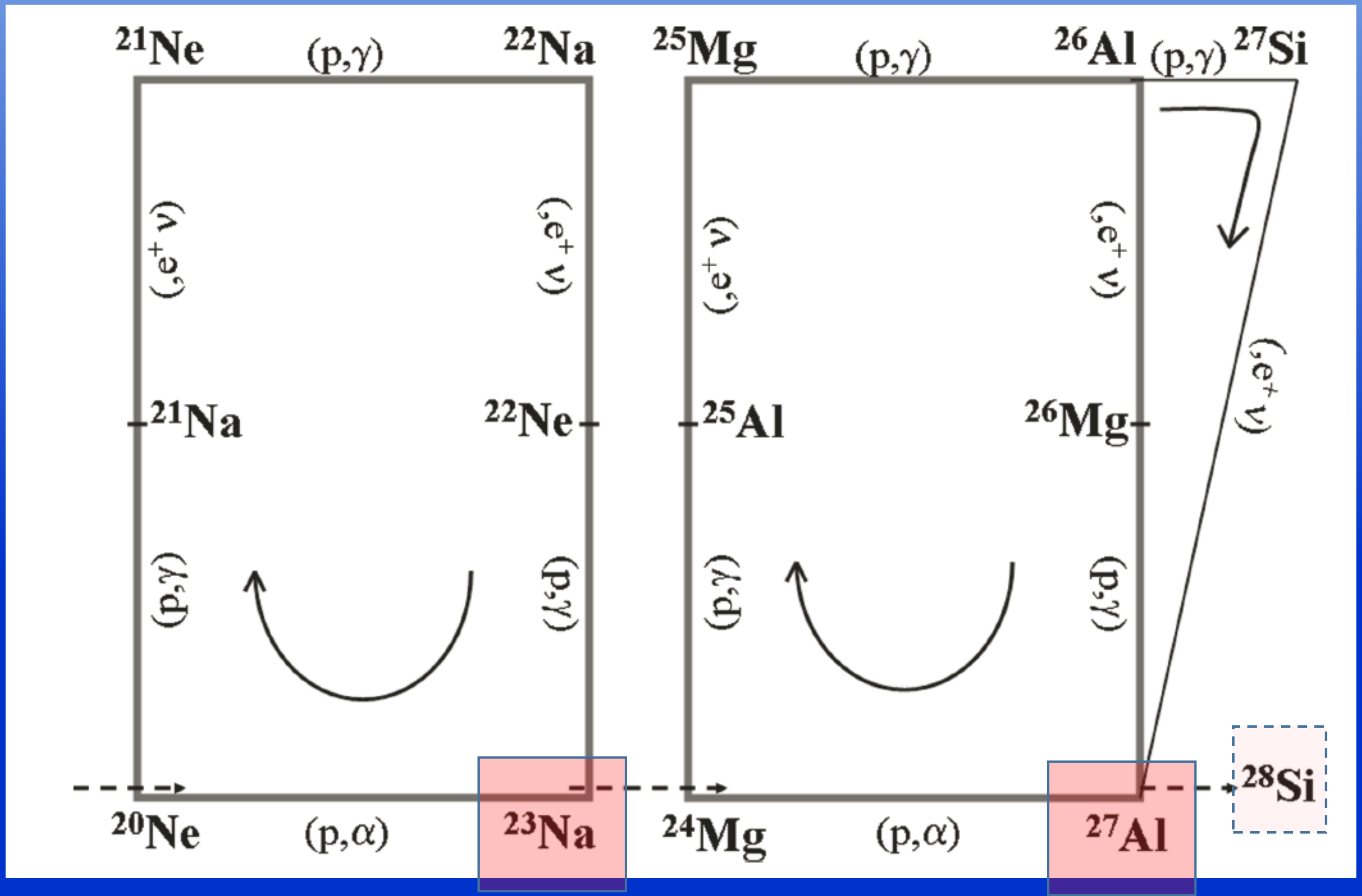
Fraction of matter from He-rich zone mixed H-burning

Choplin et al. 2016

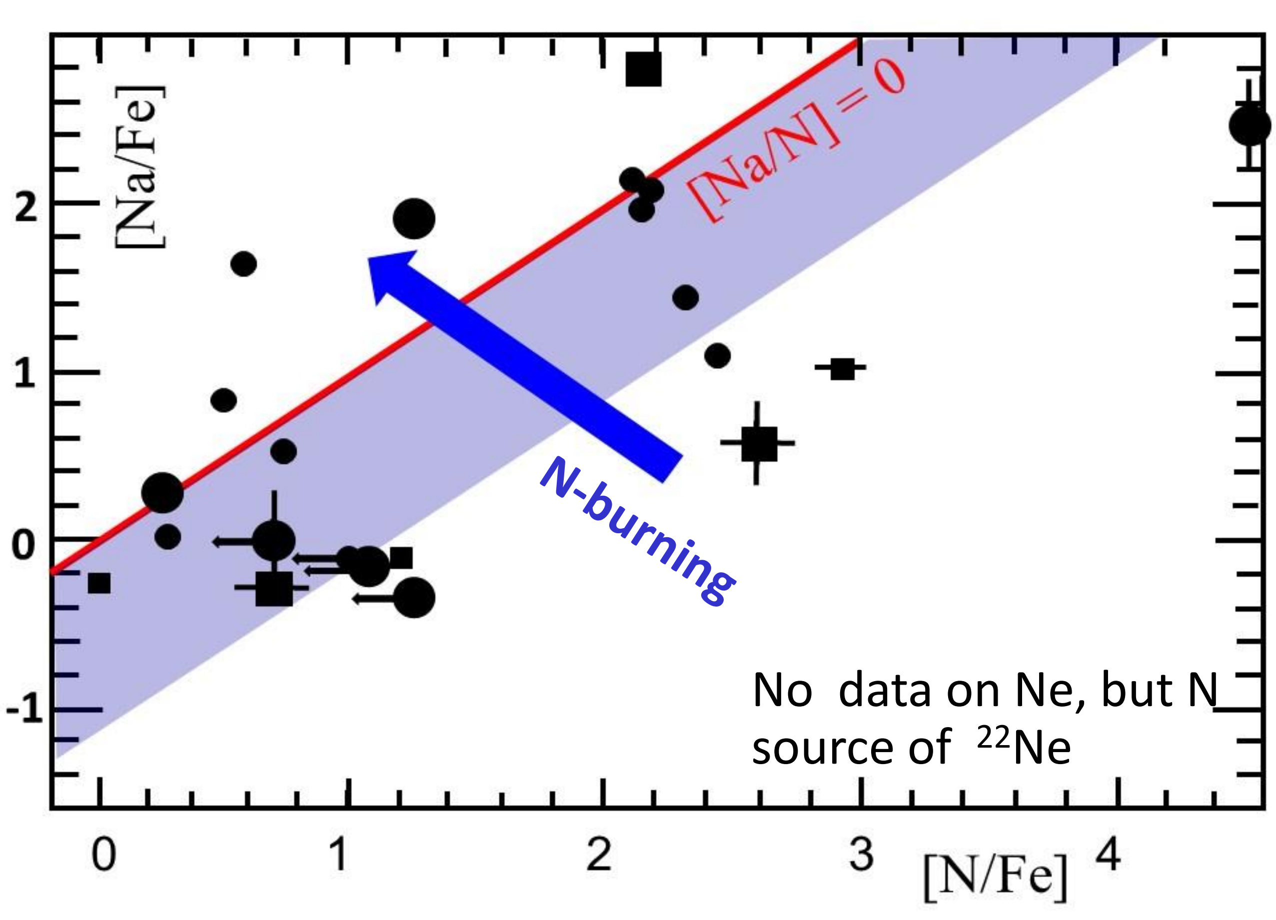
The matter forming CEMP-no stars comes mostly from the H- rich regions of the source stars !

Signatures of H – burning: N from CNO cycle (in various abund.)

^{13}C present Ne – Na and Mg – Al cycle (high T)



Do Na, Al, Mg behave like α–elements or like CNO ?



Signature Ne-Na cycle

More N → more Na

Large scatter , due to N → ^{22}Ne→ ^{23}Na at a given [Fe/H]

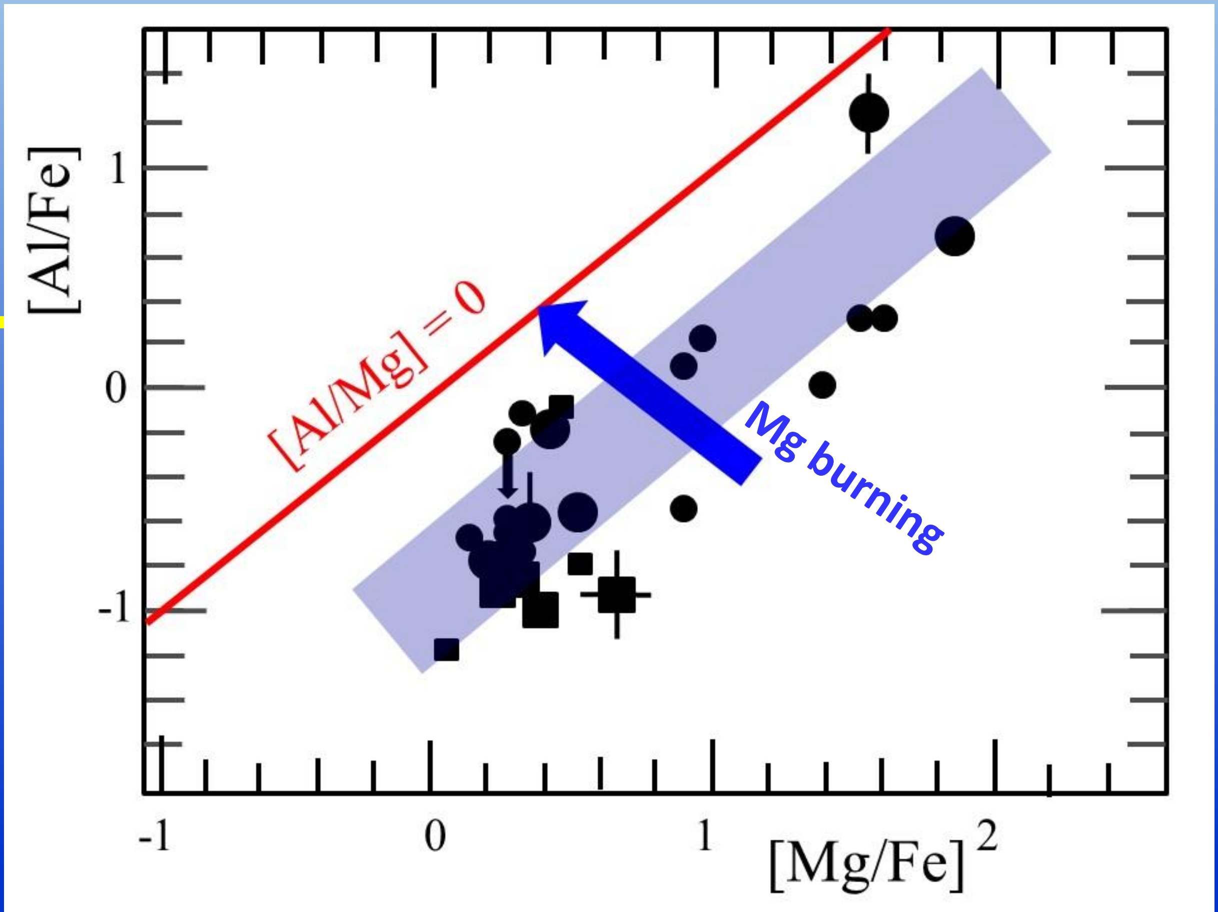
Slope ~ 1 → Na/N keeps ~constant over about 4 dex "daughter-mother"

Consistent with the Ne-Na cycle in CEMP-no stars !

Slope 1 → Al/Mg
about constant,
Rel. mother-daughter:
signatures of
Mg-Al cycles!

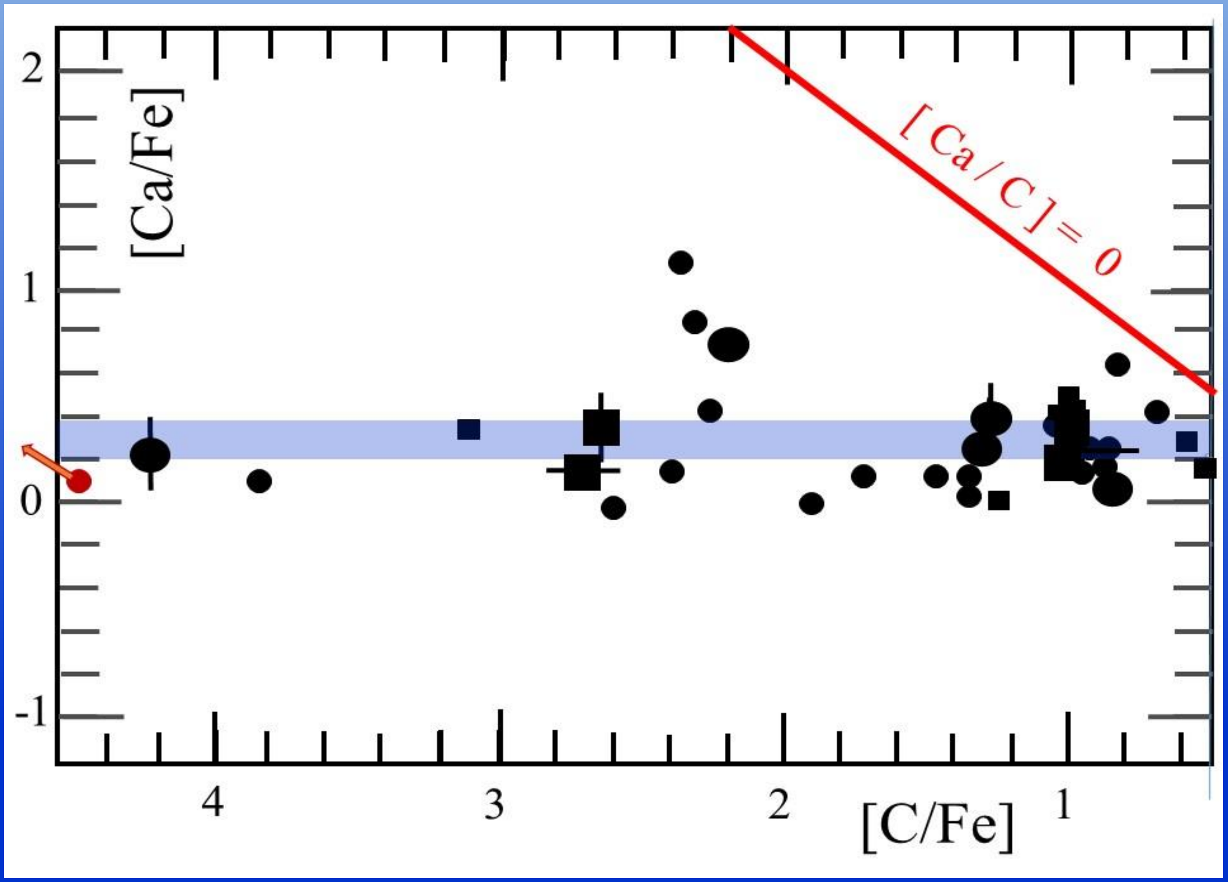
Ne, Na, Mg and Al
behave like CNO.
Signatures of hot H-burning

No relation with SN nucleosynthesis.
Wind ejection, late ejection



What about the anticorrelation in Globular Clusters ?

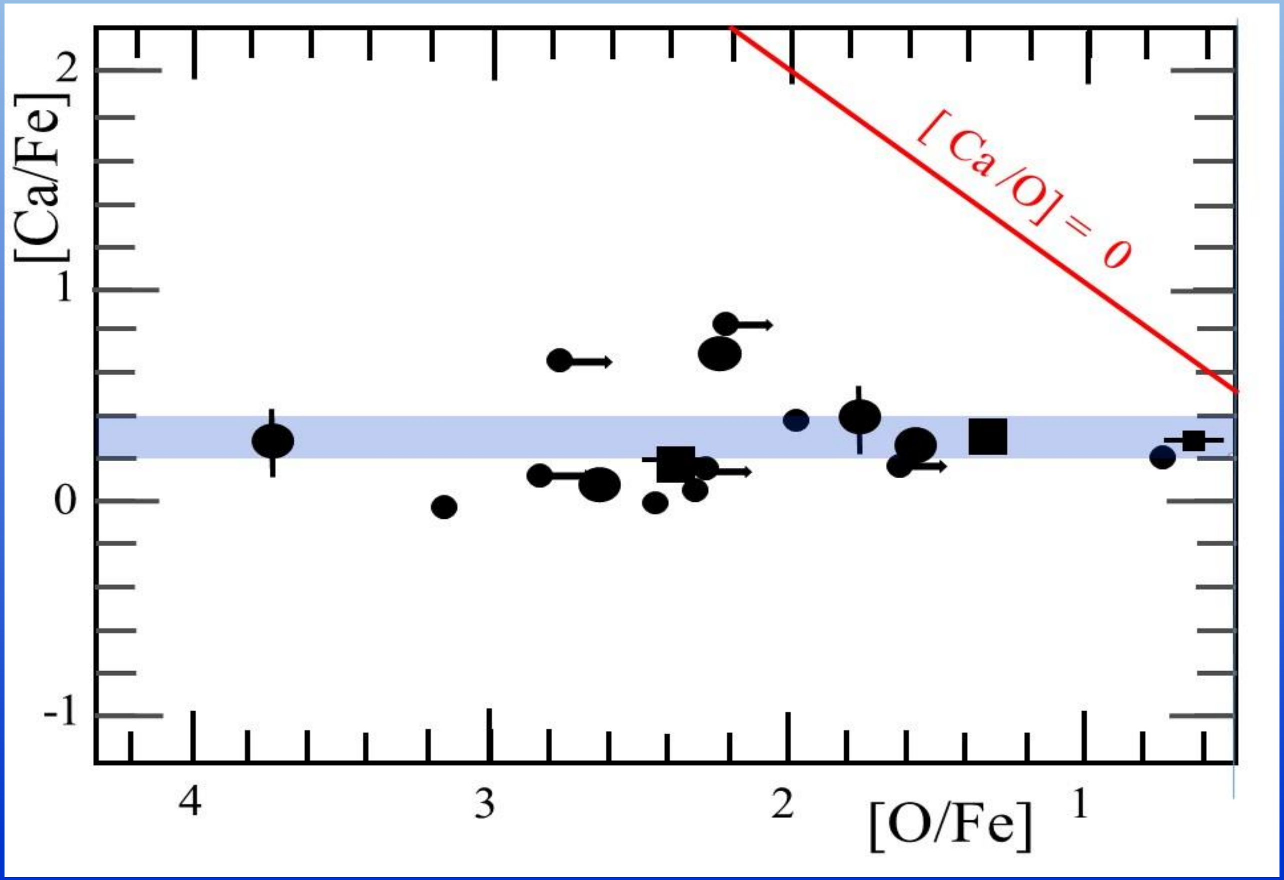
Relation between CNO and α– elements



Range of [Ca/Fe] : small, range of [C/Fe] about 4 dex.

CNO, Na, Mg, Al in CEMP-no stars

behave very differently from α– elements.



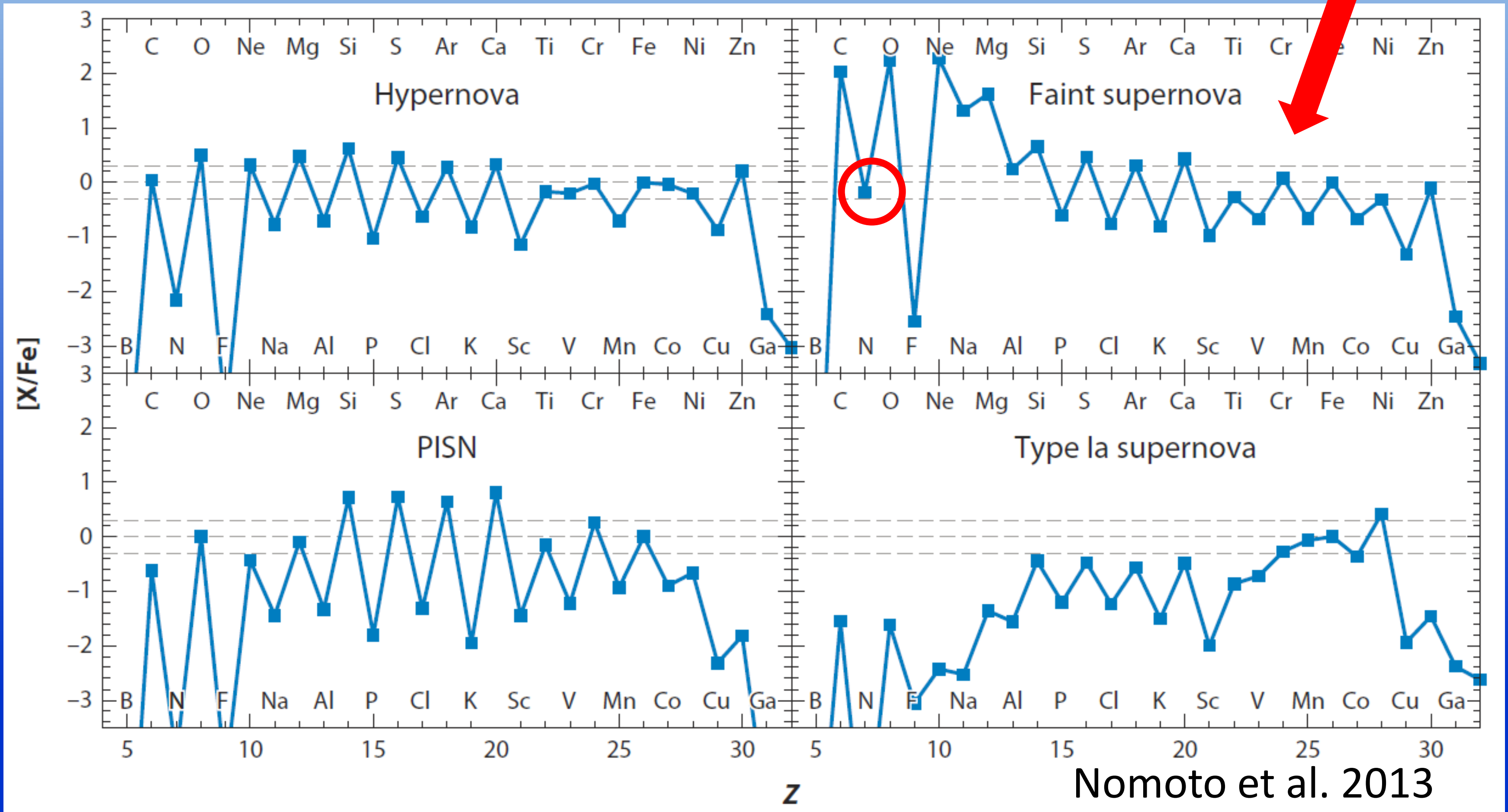
The same although the O layer lies less deep in pre-SN.

<u>**No relation between α– and CNO elements:**</u>

(α– elements necessarily produced in pre-SN)

Consistent with C, N, O from winds of massive stars, while minute amounts of α-elements from SN ejecta.

SUPERNOVA MODELS

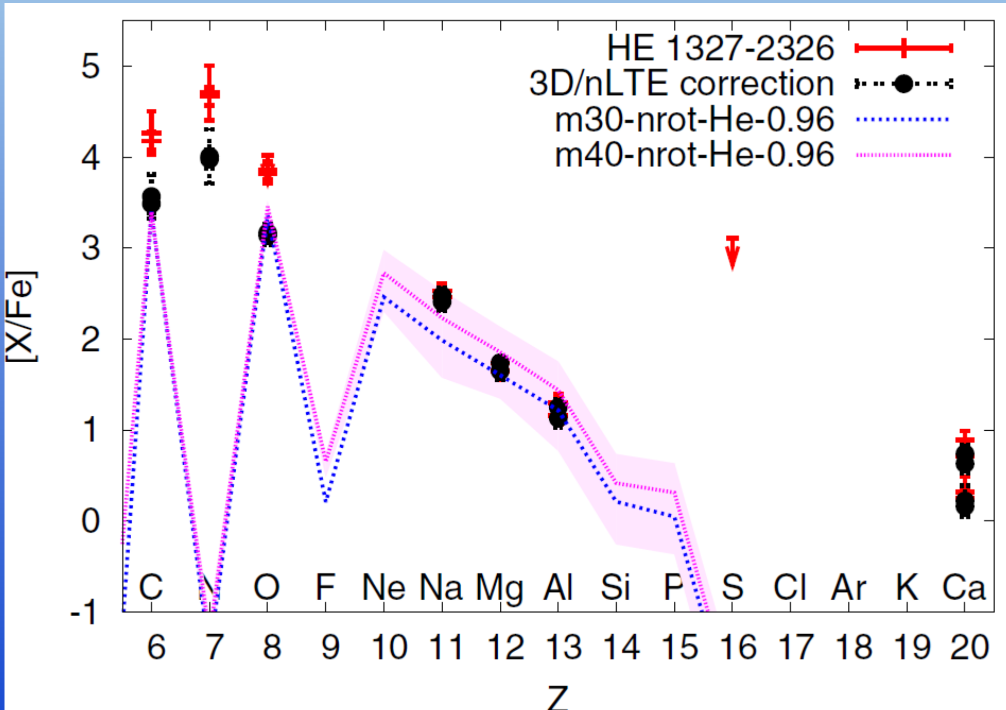


MIXING AND FALLBACK MODELS

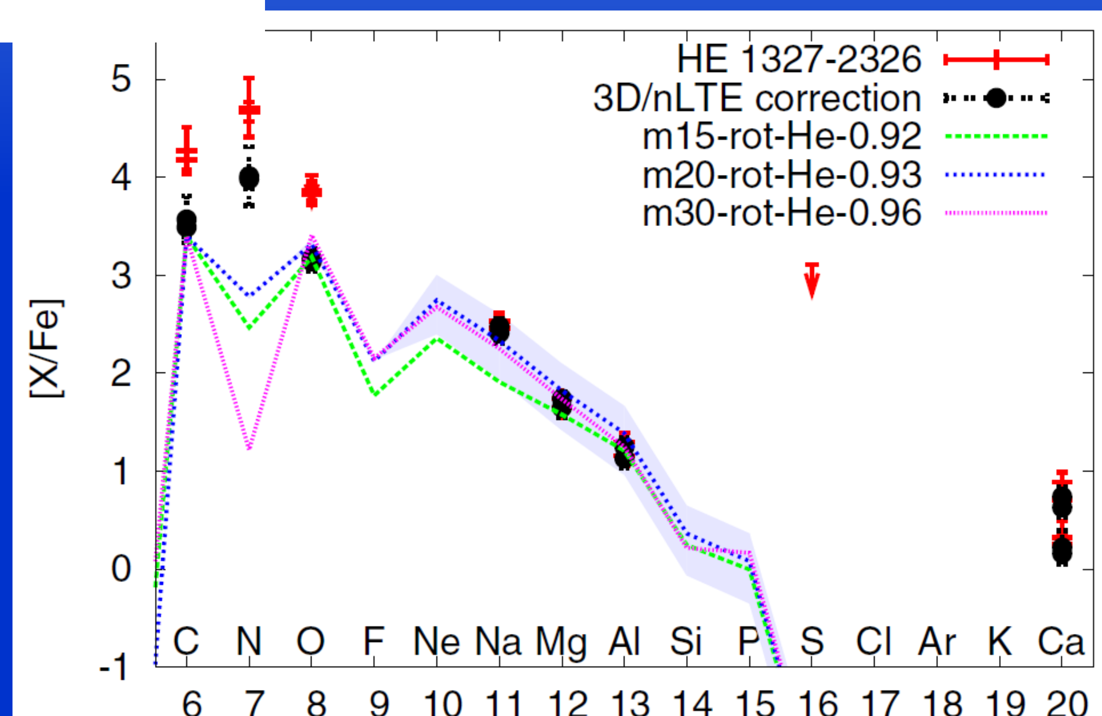
→ Layers between 2 limiting shells are fully mixed

→ All layers below some cutoff mass collapse into the remnant

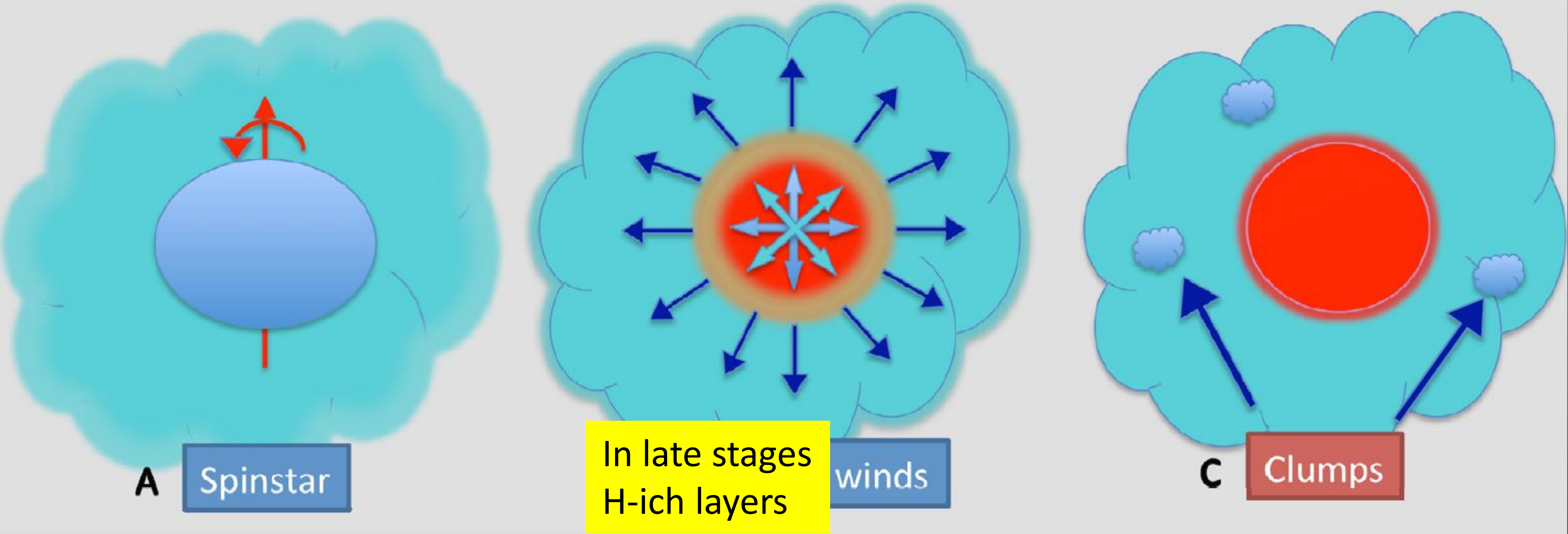
Differently for each star observed



Supernova yields from models without and with rotation
Takahashi et al. 2014



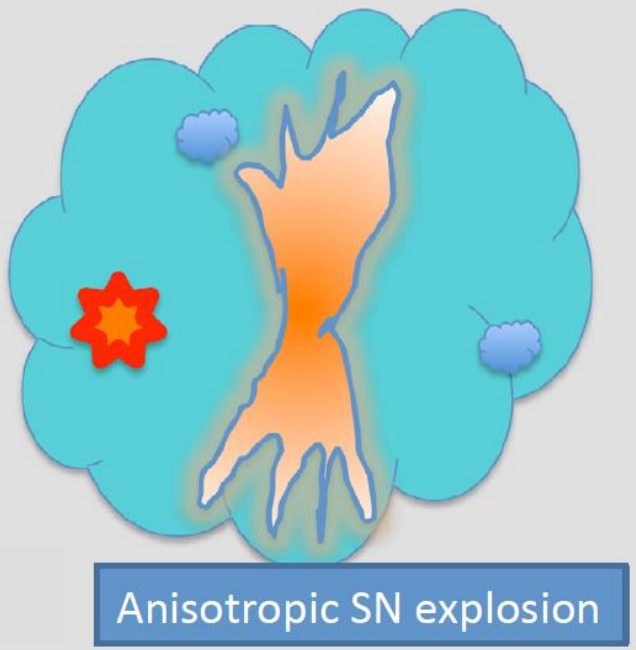
Difficulty for N



WIND + SN ASYMMETRIC EXPLOSION

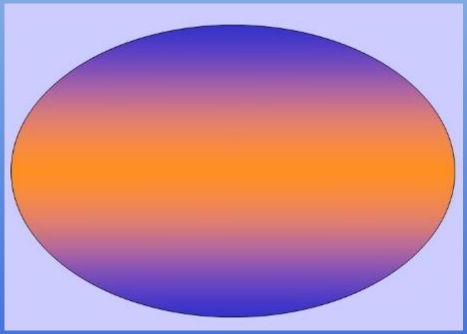
WIND >> SN: CEMP-no
Rich in C, N, O, ^{22}Ne, Mg, Al

WIND << SN: C-normal
metal-poor

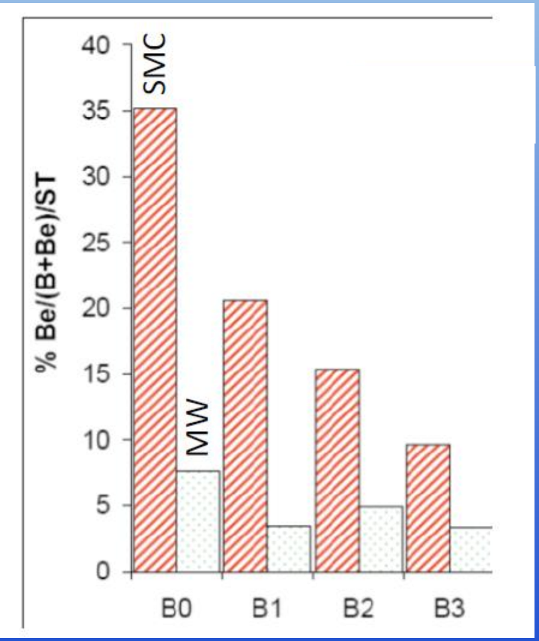


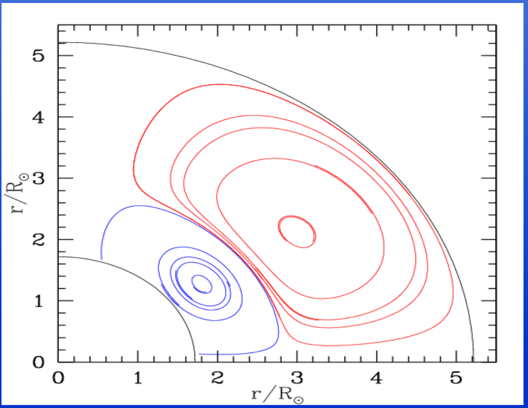
Spinstar model (Meynet et al. 2010)

SPINSTARS



Massive stars rotate faster at lower Z, near break-up → mixing + mass loss
(Maeder et al. 1999;
Martayan et al. 2007;
Stacy et al. 2011)





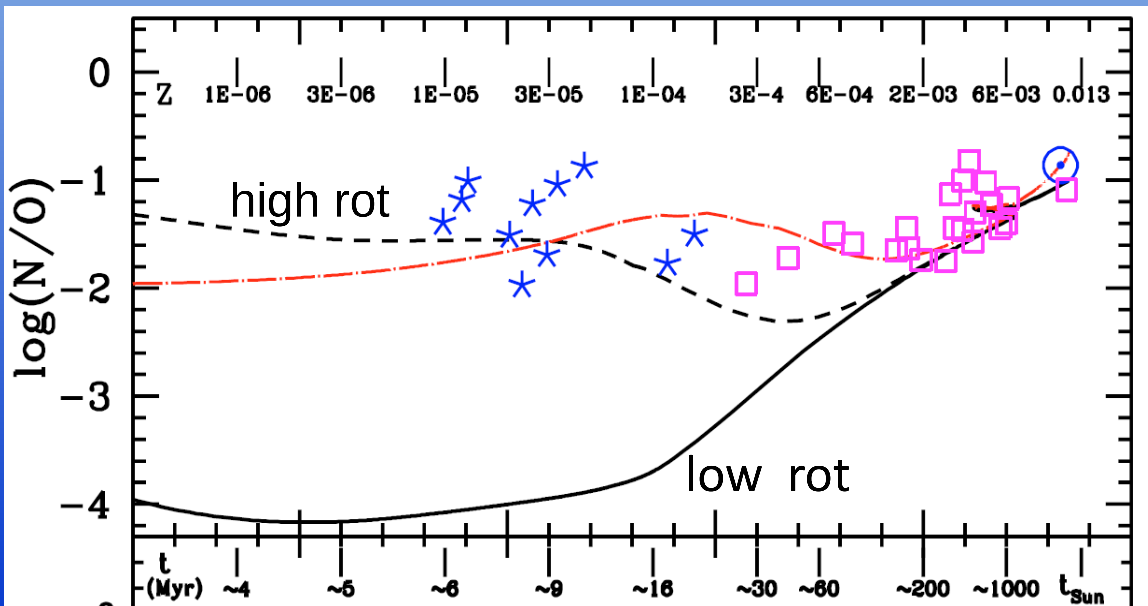
More mixing at low Z
Shears, merid. circulation)
→ primary N, ^{22}Ne, (Maeder & Meynet 2002

MASS LOSS IN RSG, PRE- SN EJECTION

High $\dot{M}$ in RSG: C-rich, dust
(Ekström et al. 2008; Meynet et al. 2010)

Pre- SN ejection: ~ M_o ejected a few 10^2 d. before explosion (Moriya & Langer 2014; Choplin et al. 2018; Arcavi et al. 2018; Taddia et al. 2018; Kuncarayakti et al. 2018; Bostroem et al. 2019)

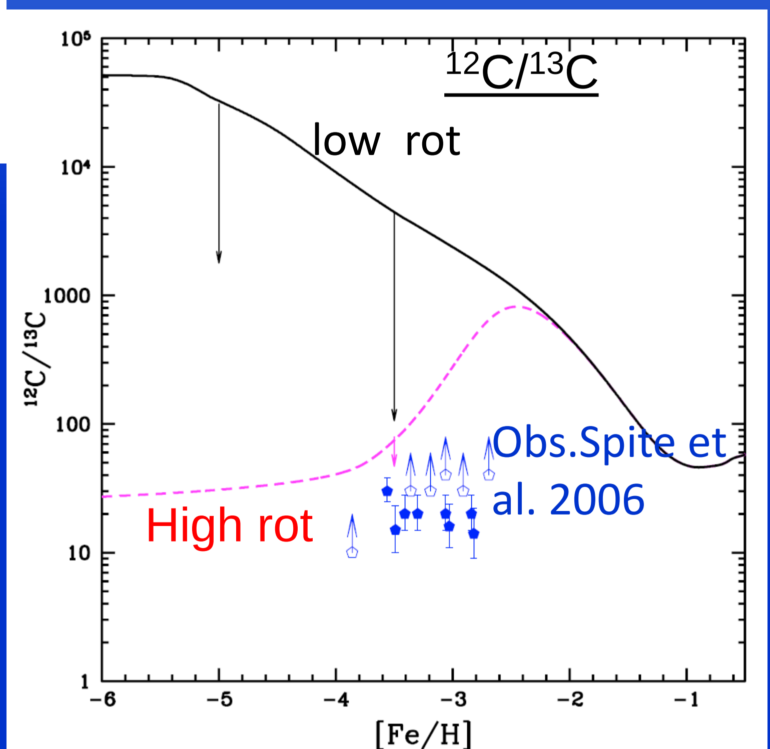
SUPPORTING EVIDENCES OF SPINSTARS ARE NUMEROUS



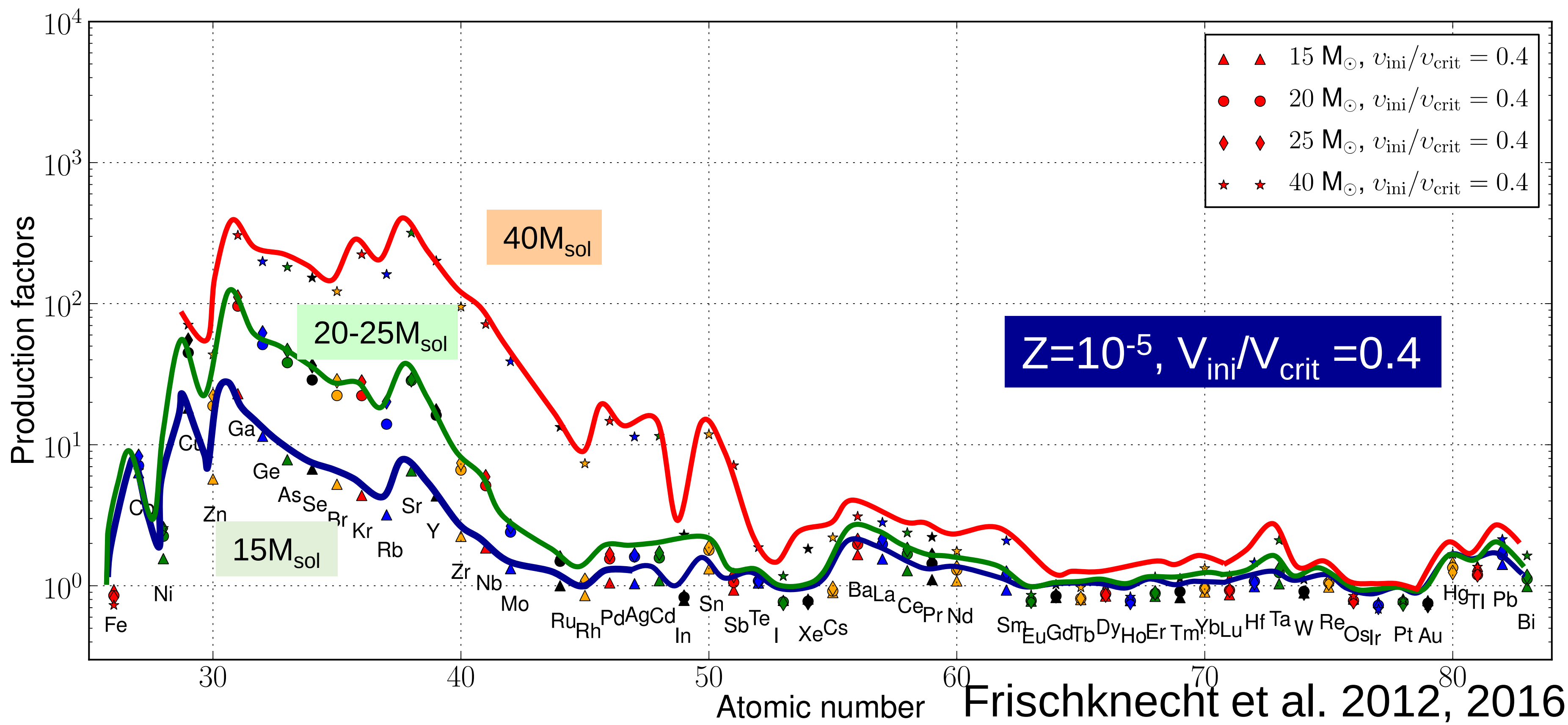
1. N/O at low Z
2. C/O
3. $^{12}C/^{13}C$
4. Primary Be and B
5. s-elements

Comparisons with Geneva models
Chiappini et al. 2008, 2016

□ Israelian et al. 2004
★ Spite et al. 2005



Formation of s-elements of the 1st peak

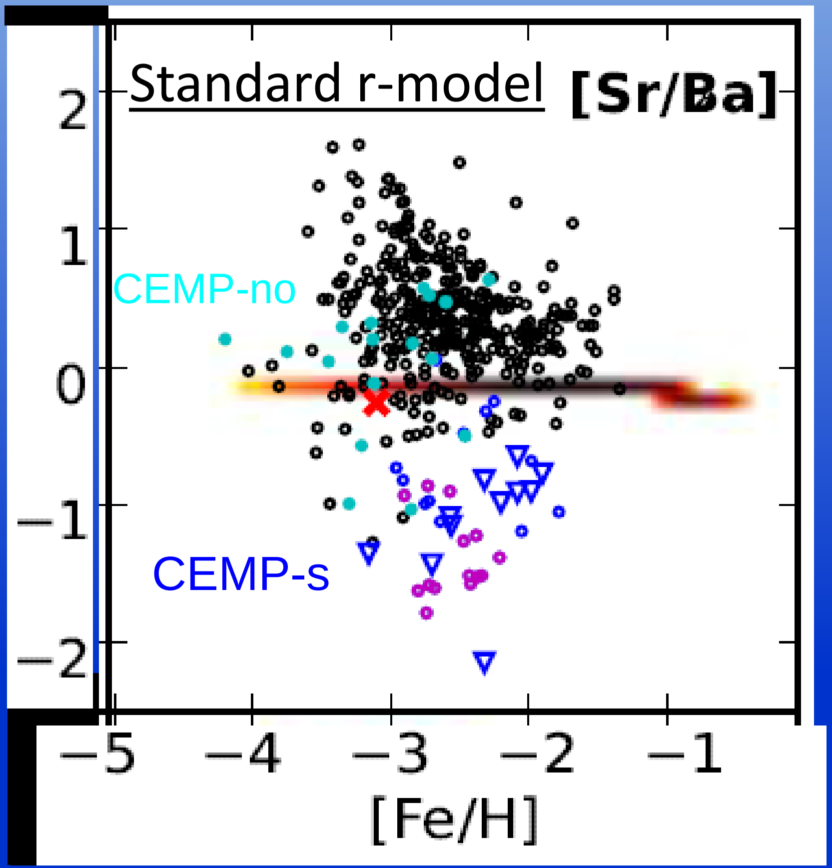


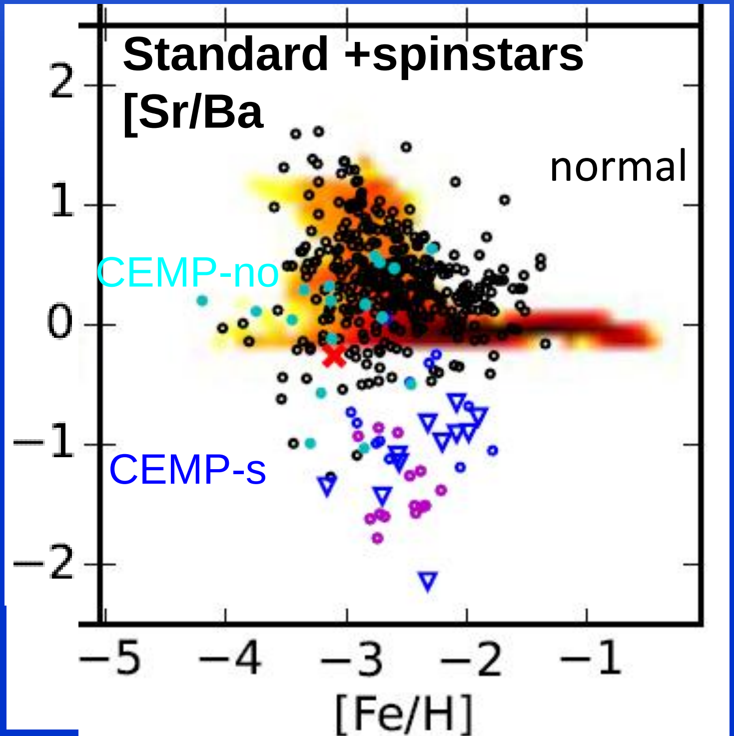
Frischknecht et al. 2012, 2016

α-captures on ^{22}Ne: ^{22}Ne(α,n)^{25}Mg

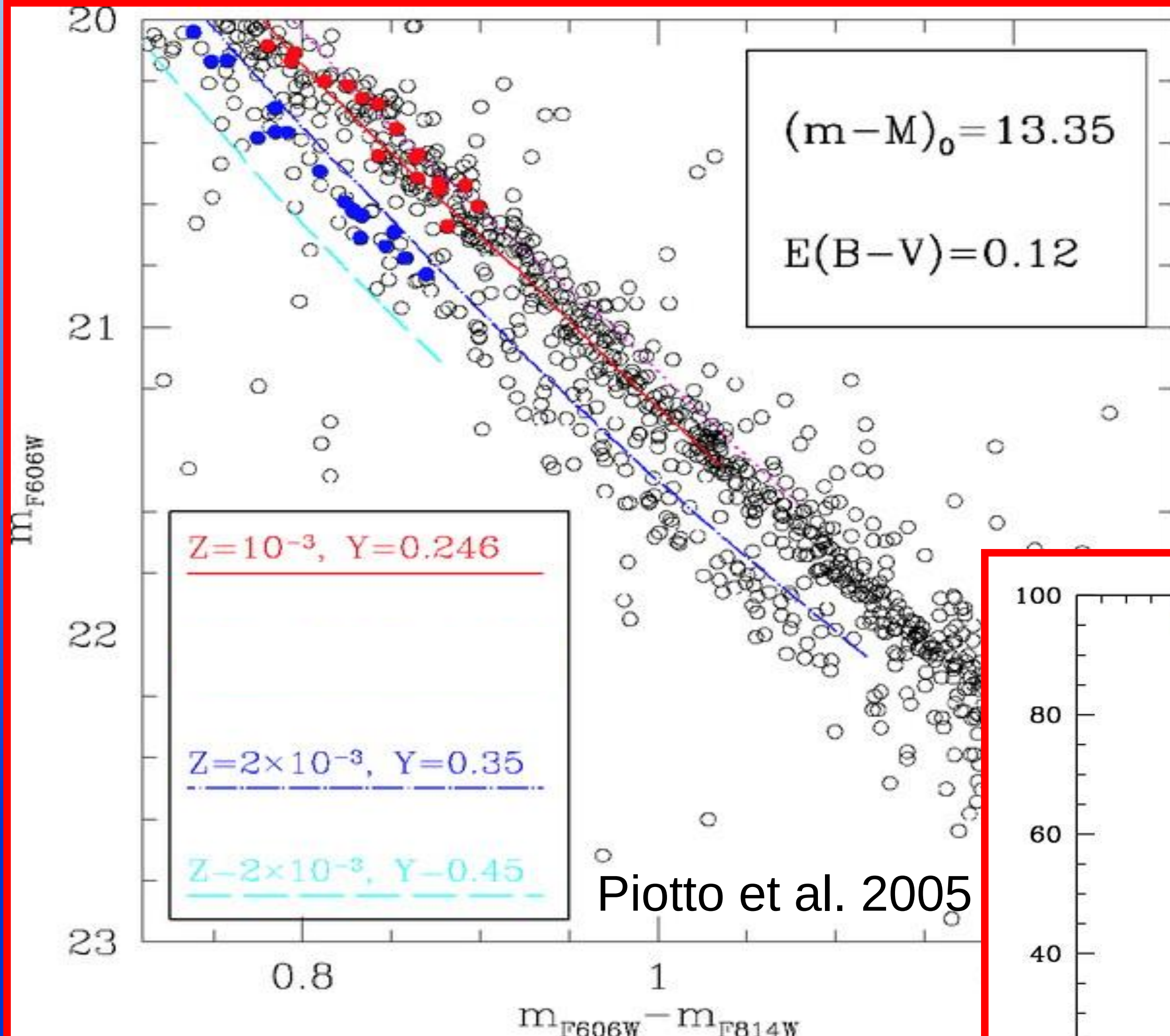
Large scatter of s-elements only explained if contribution from spinstars (Cescutti et al. 2013)

Standard r-process
from SN explosions
AGB make CEMP-s
with low Sr/Ba !





←
With contribution of s-elements from massive rotating stars.



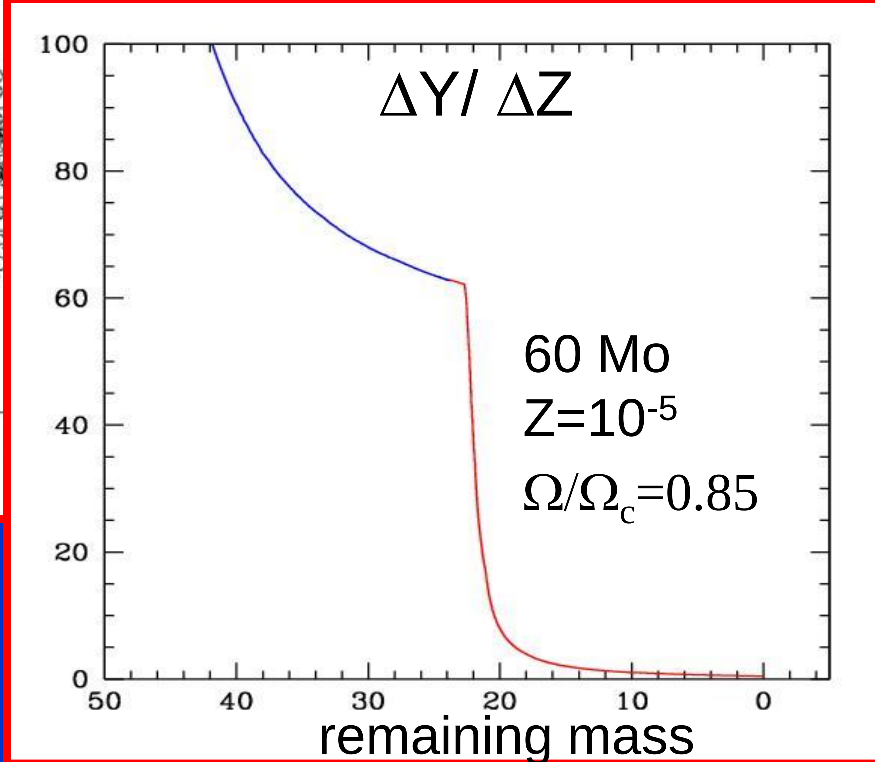
ω Cen

$\Delta Y/\Delta Z$= 70-130

Enrichments possible by stellar winds of massive stars

Maeder & Meynet 2006

Decressin et al. 2010



Multiple sequences observed.

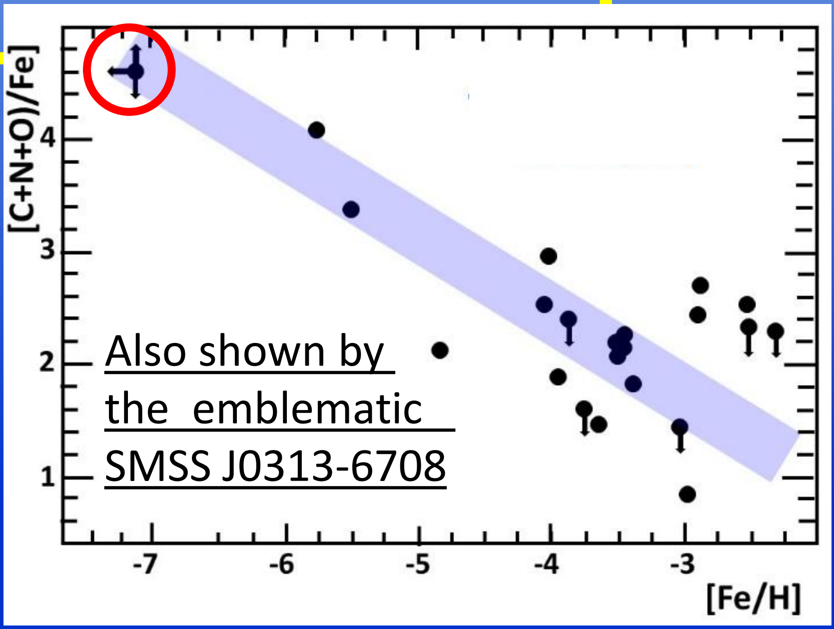
NGC 2008: 3 sequ. RHB (lower Y) BHB (higher Y) Piotto et al. 2007

SPINSTARS OK for CEMP-no stars

①
They are not a marginal scenario for the first stars, but more likely the dominant one at [Fe/H] < - 4.0 !

②
The effects are larger at lower [Fe/H].

- Mixing may also produce a Li-depletion (cf. talk by Aguado)

- 

- **ROTATION + MASS LOSS**
Also at work for LGRBs

Some evidences:

LGRBs ← Hypernovae ← SNIc ← WO

The End