New Site for Synthesis of Heavy Elements in Massive Pop III and Pop II Stars

Projjwal Banerjee (Shanghai Jiao Tong U.)
Collaborators
Y.-Z. Qian (U. Minnesota) and Alexander Heger (Monash U.)

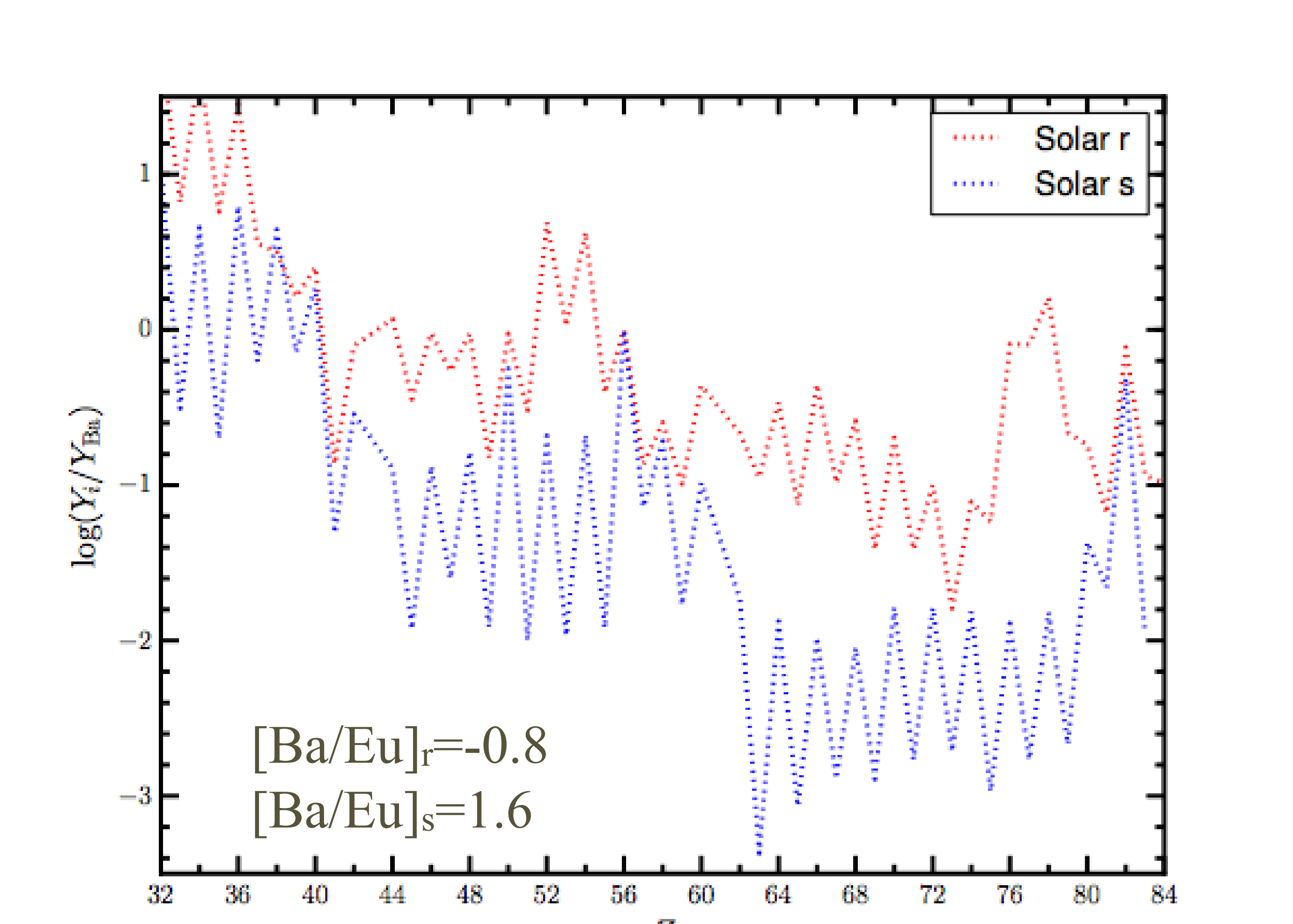
Neutron Capture Processes

r-process

NS-NS and NS-BH mergers (GW170817!)
CCSN: neutrino-wind Z≲50
Jets/MR CSSN? (Mösta et al 2014)

s-process

AGB stars of 1-3 solar masses
Does not operate in the early galaxy
Rotating massive stars: Mostly Sr,Y,Zr
(Frischknecht et al 2016)



Sneden et al 2008

EMP Stars [Fe/H]≲-2

Neutron-capture-rich stars	
r-I	$0.3 \leq [Eu/Fe] \leq +1.0$ and $[Ba/Eu] < 0$
r-II	$[Eu/Fe] > +1.0$ and $[Ba/Eu] < 0$
s	$[Ba/Fe] > +1.0$ and $[Ba/Eu] > +0.5$
r/s	$0.0 < [Ba/Eu] < +0.5$
Carbon-enhanced metal-poor stars	
CEMP	$[C/Fe] > +1.0$
CEMP-r	$[C/Fe] > +1.0$ and $[Eu/Fe] > +1.0$
CEMP-s	$[C/Fe] > +1.0$, $[Ba/Fe] > +1.0$, and $[Ba/Eu] > +0.5$
CEMP-r/s	$[C/Fe] > +1.0$ and $0.0 < [Ba/Eu] < +0.5$
CEMP-no	$[C/Fe] > +1.0$ and $[Ba/Fe] < 0$

Beers & Christlieb 2005

surface pollution

CEMP-s Stars

Mass transfer from AGB companion.
Must be in a binary configuration but
~ 10%-30% are single (Hansen et al 2016)
Low-s CEMP/EMP stars are likely single
(Spite et al 2014)

CEMP-r/s Stars

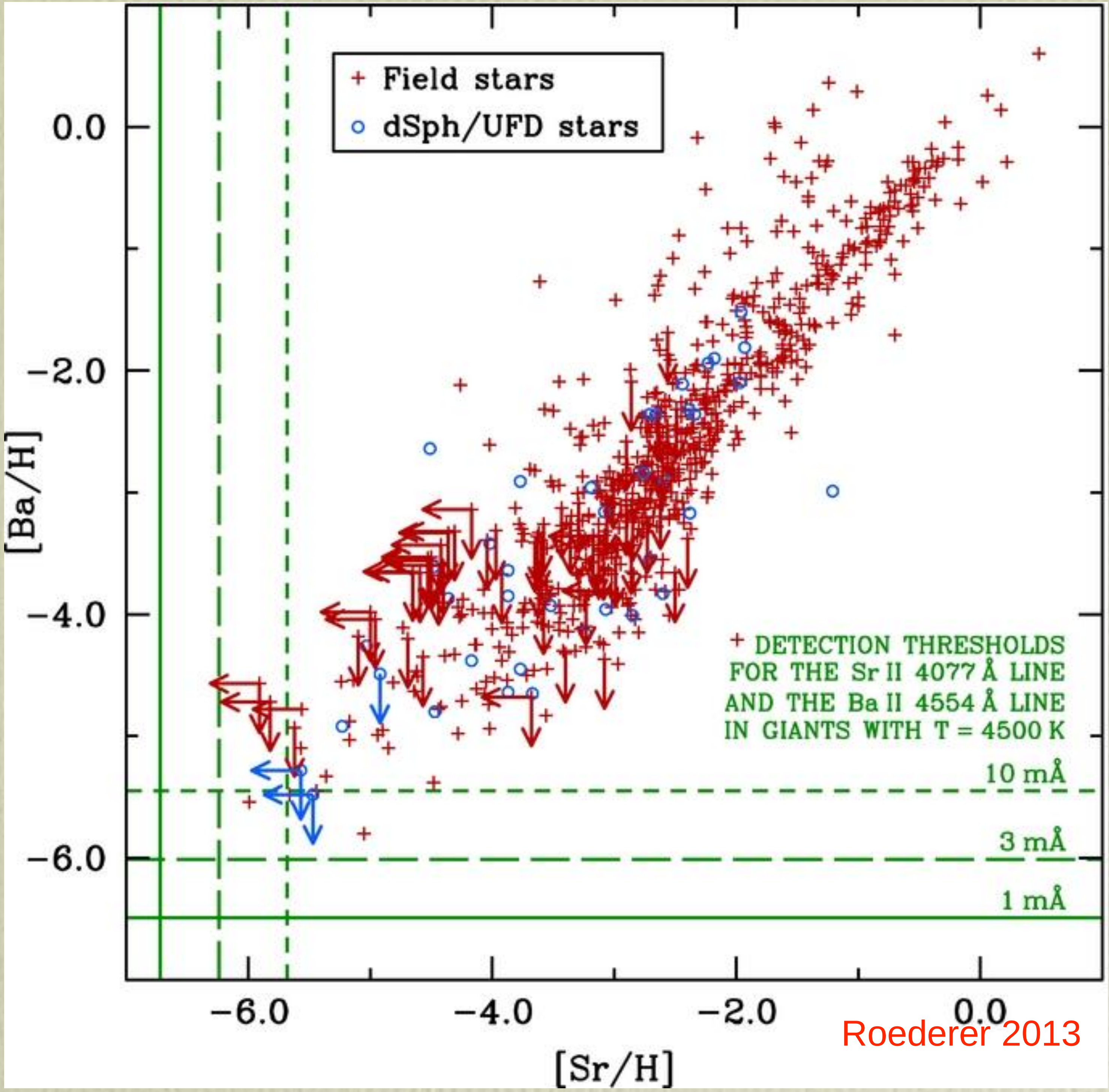
Mass transfer from AGB companion.
Initial gas cloud with high r enrichment
similar to rII stars.
i-process in SAGB? (Jones et al 2015)

ISM

CEMP-no Stars

From Pop III stars?
Origin of heavy elements?

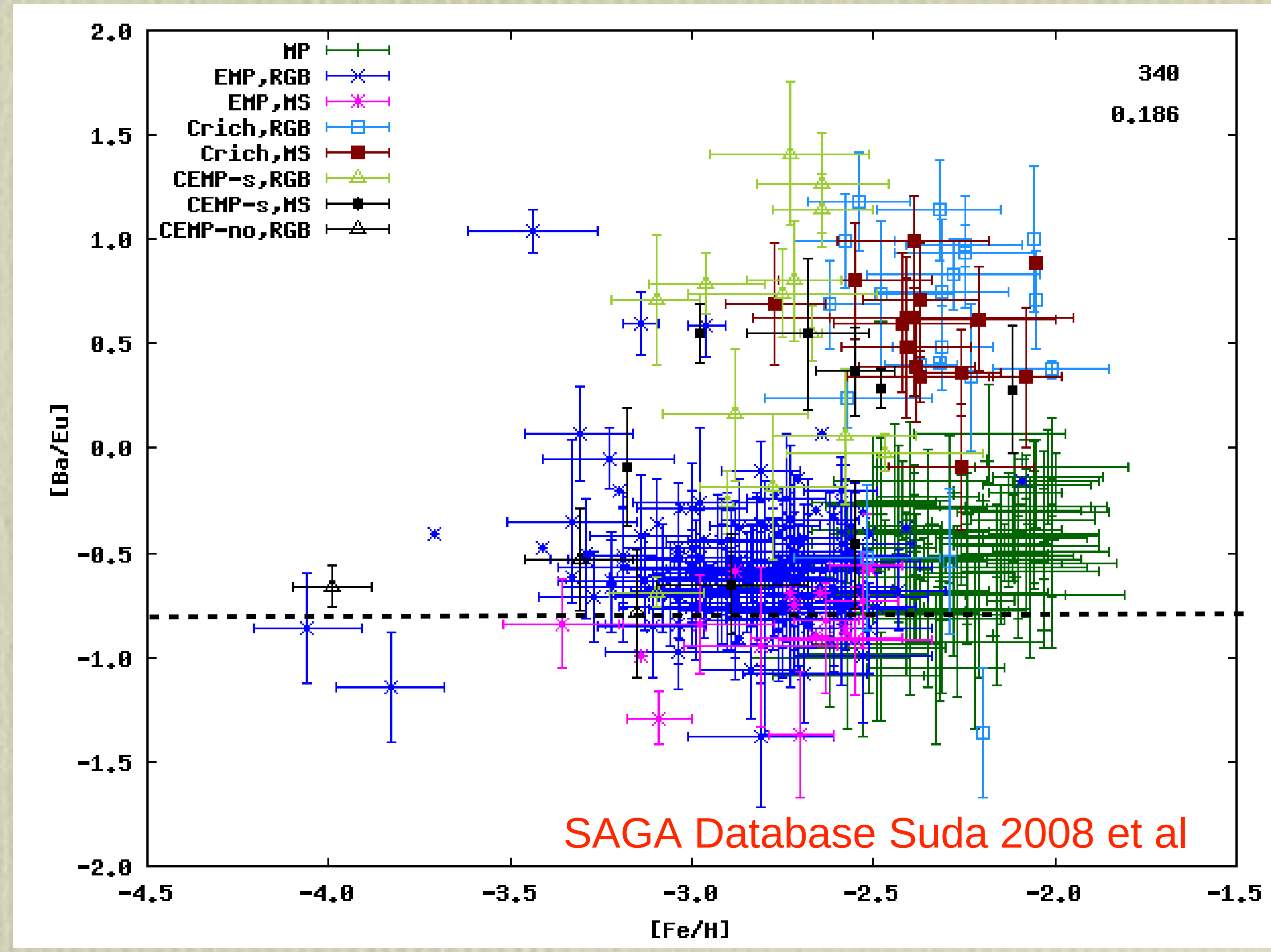
Heavy Elements in EMP Stars



Roederer 2013

Both Ba and Sr are common in early Galaxy

Heavy Elements in EMP Stars



Early deviation from r-process value

Cannot be explained by surface pollution from AGB stars

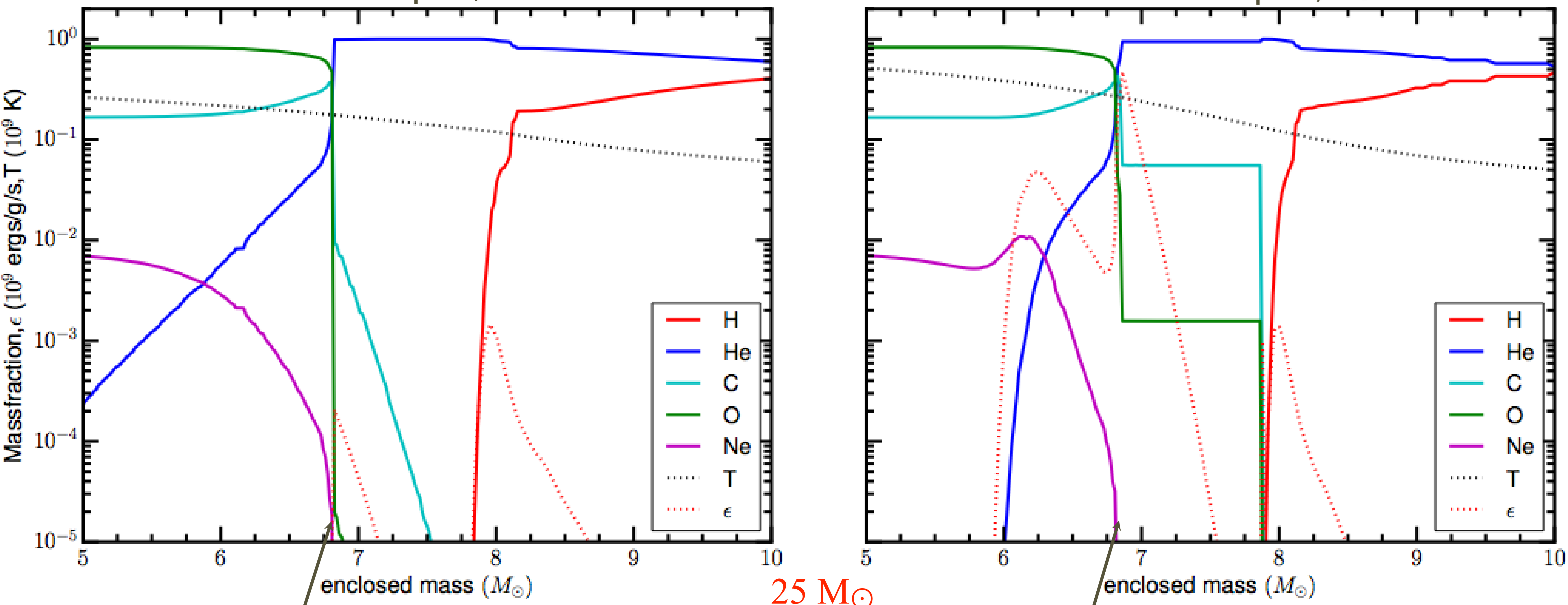
Additional sites for neutron capture associated with massive stars?

C Ignition

10^{11} s before collapse, T_c=5x10^8 K

C Depletion

2x10^7 s before collapse, T_c=1.2x10^9 K



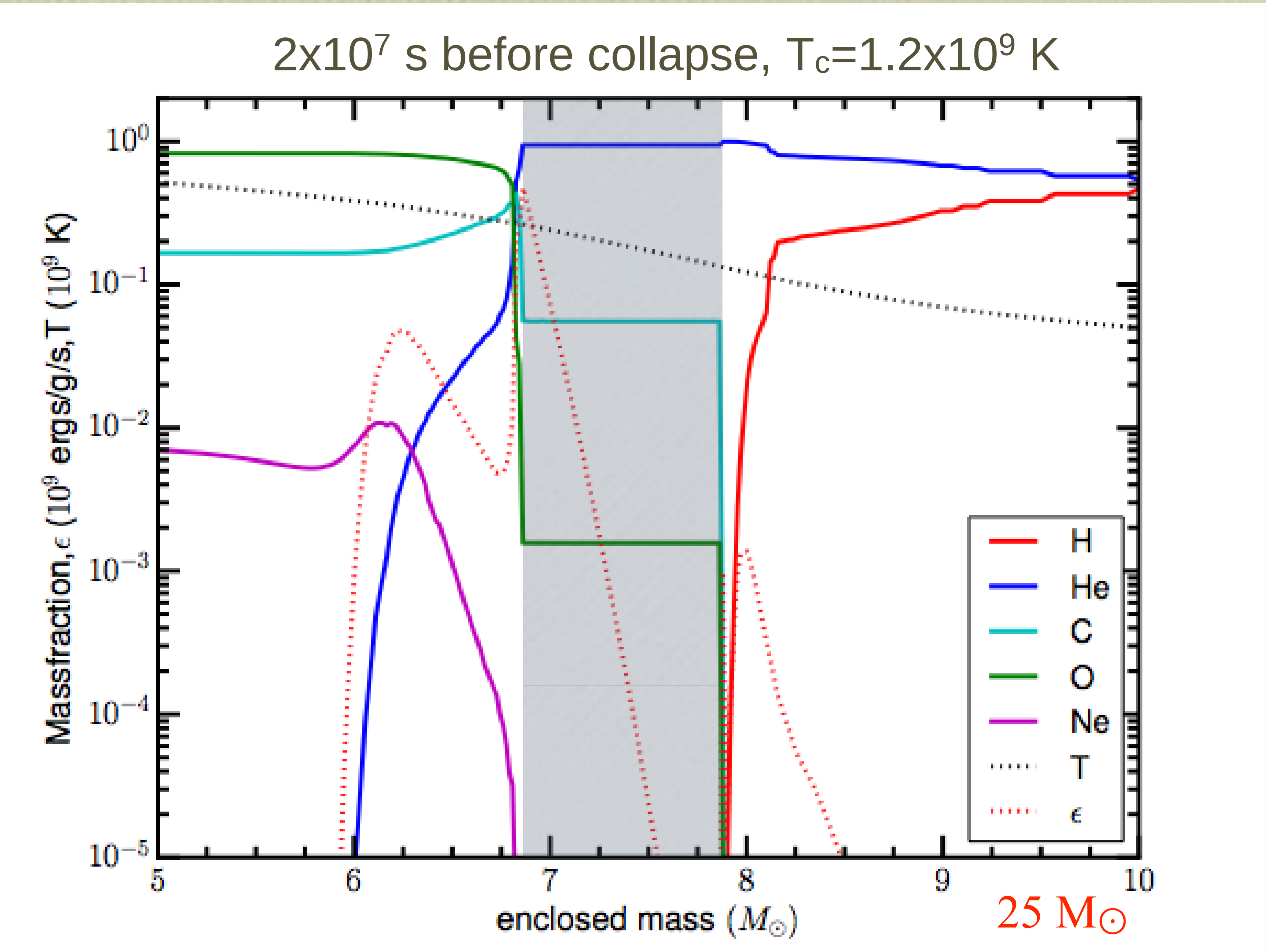
T=1.75x10^8 K
r=11.2x10^9 cm

T=2.7x10^8 K
r=6.95x10^9 cm

$$\epsilon_{3\alpha} \approx 23.1\rho^2 X_\alpha^3 (T_8/2)^{18.5} \text{ ergs/g/s}$$

Primary ^{12}C and ^{16}O production

Proton Ingestion



Growth of convective He shell.
Mixing can occur at the convective boundary.
Including overshoot leads to 10^{-3}-10^{-5} $M_\odot$ of proton ingestion.
Occurs for 20 $M_\odot \lesssim M \lesssim 30\ M_\odot$.
$M \lesssim 20\ M_\odot$: Convection does not reach outer He shell
$M \gtrsim 30\ M_\odot$: Protons are depleted by the time He shell is convective

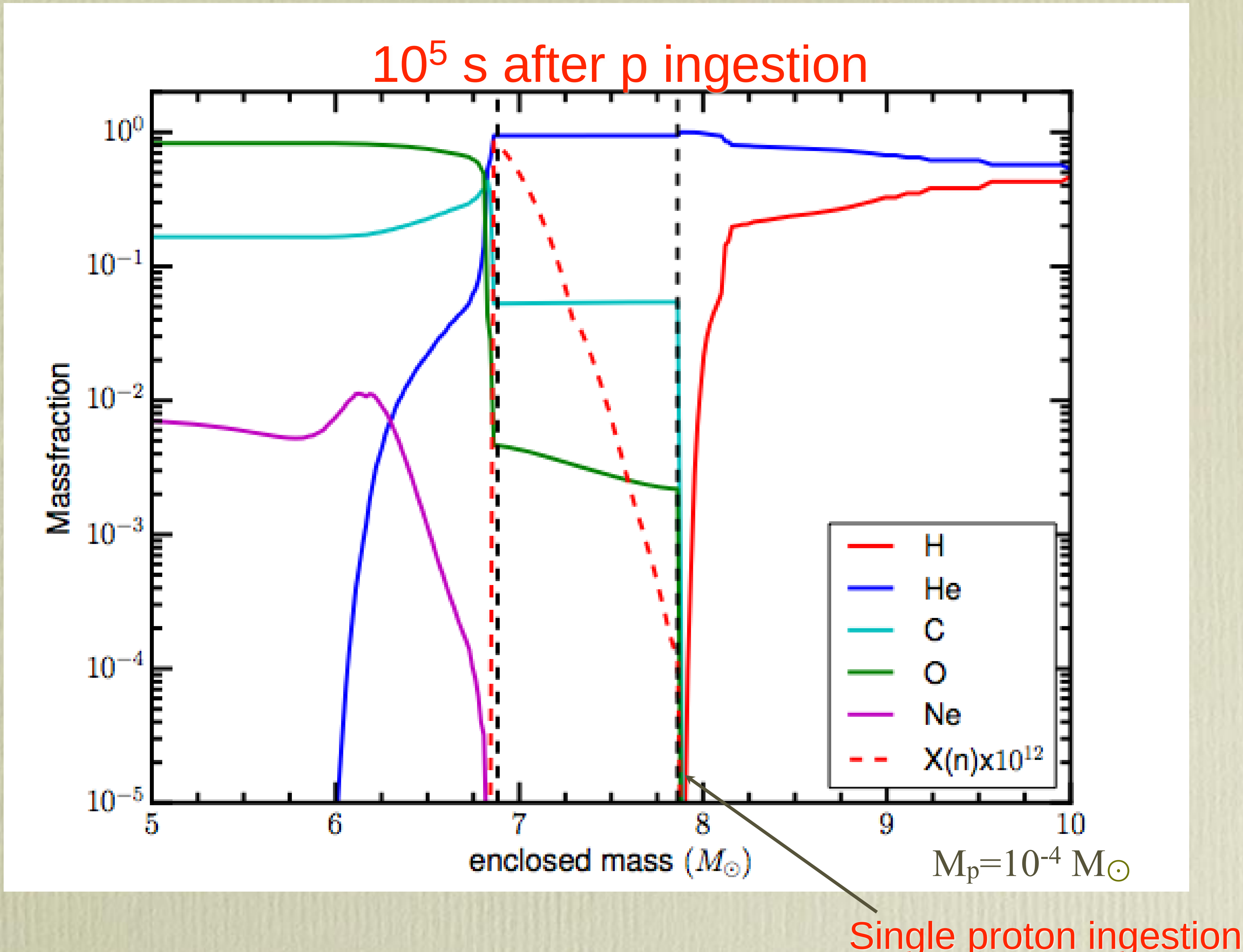
Nucleosynthesis from Proton Ingestion

- 25 $M_\odot$ progenitor, [Z]=-2 to -5 and [Z]=-∞. Scaled Solar abundance up to ^{70}Zn.

- Single proton ingestion at the edge of convective He shell at Cdep (~ 10^7 s before collapse) and/or Odep (~ 10^6 s before collapse).

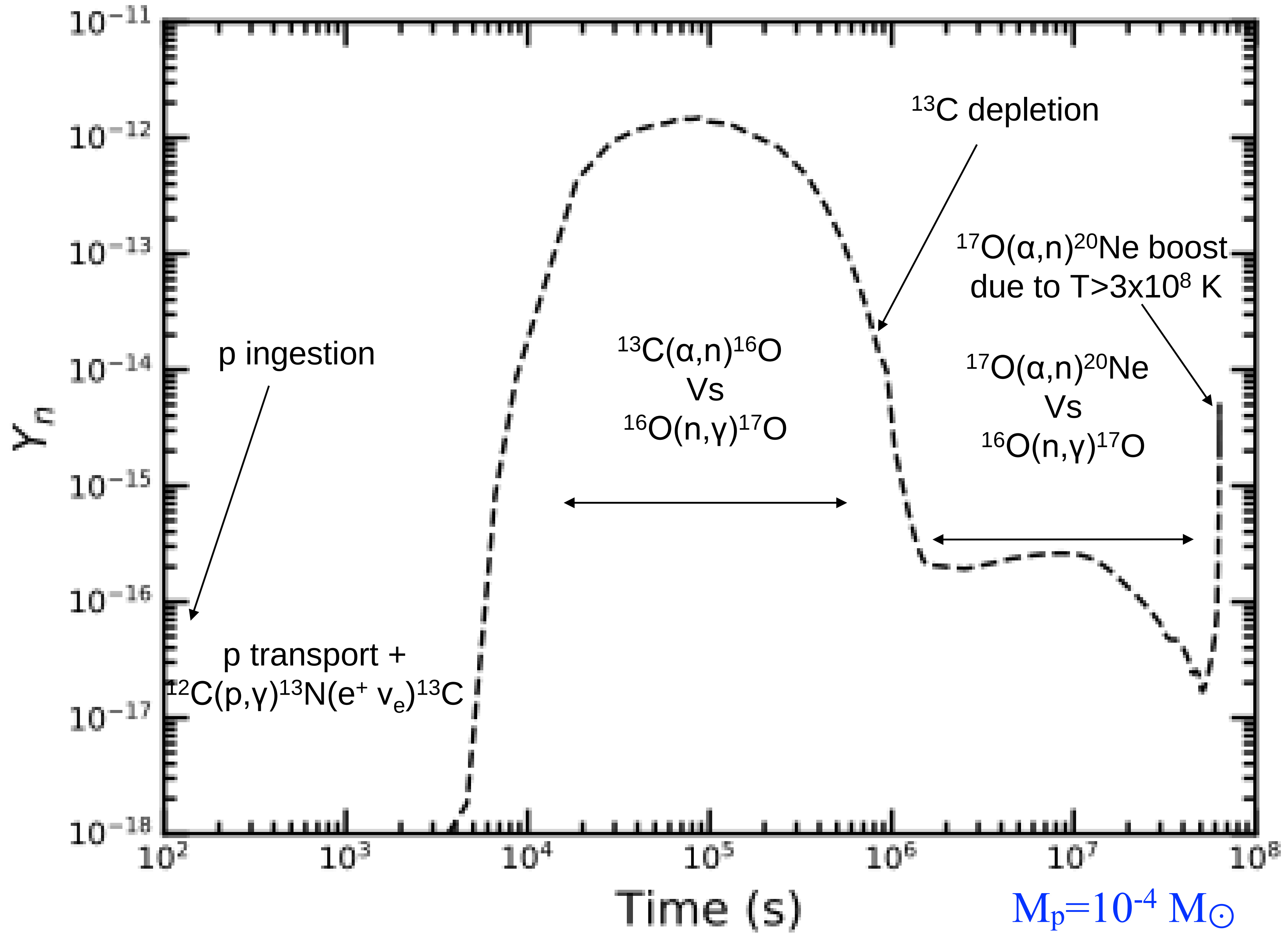
- Small time steps to follow transport of protons and resulting nucleosynthesis self-consistently.

Free Neutrons from Protons

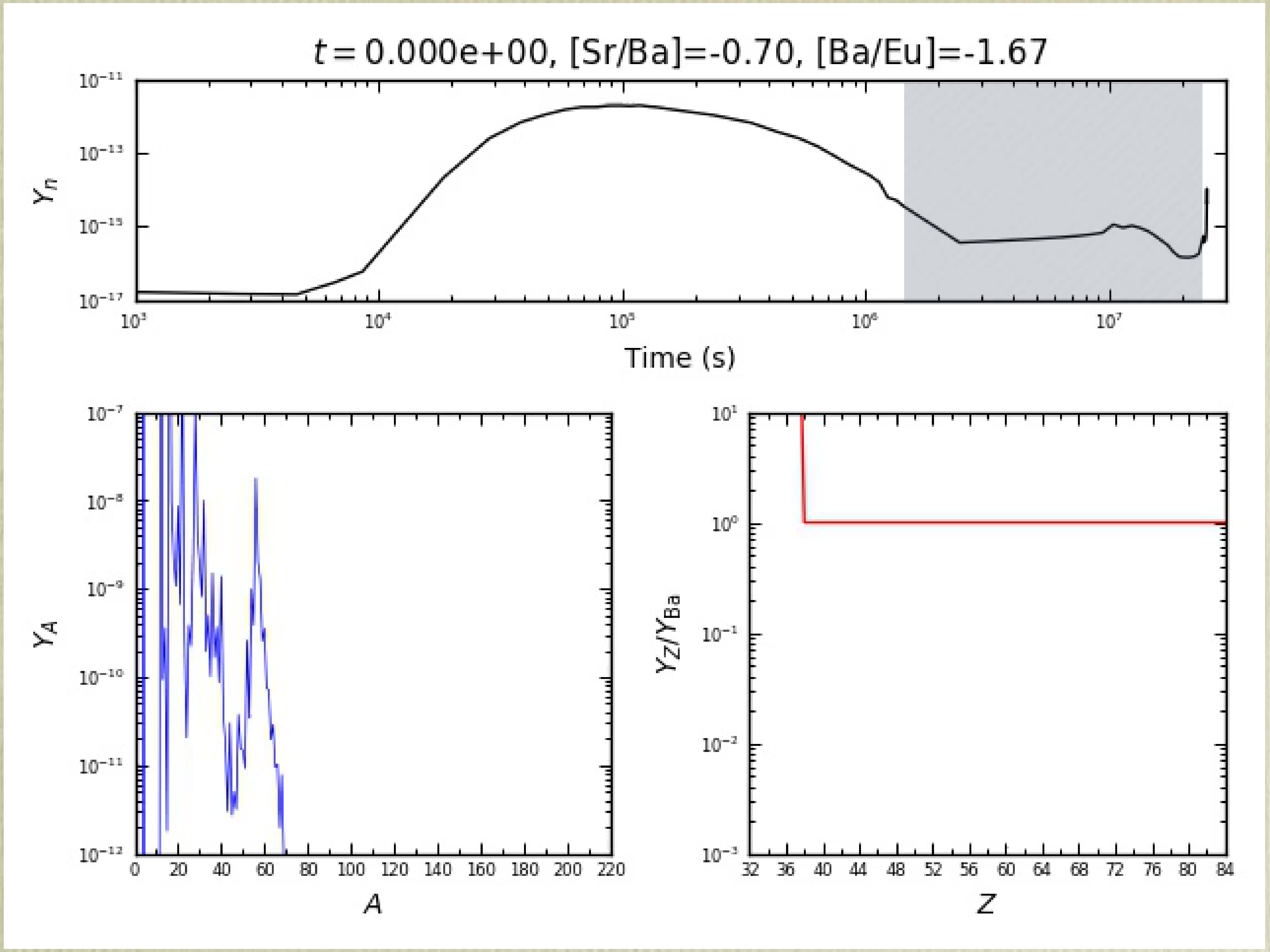


neutron via $^{12}\mathrm{C}(p,\gamma)^{13}\mathrm{N}(e^+\nu_e)^{13}\mathrm{C}(\alpha,n)^{16}\mathrm{O}$

Free Neutrons from Protons



- Mixing timescale ~ $5x10^3$ s.
- Initially Y_n increases on a timescale of ~ 10^4 s.
- Then Y_n decreases on a timescale of ~10^5 s.
- Most of the neutrons captured by ^{16}O.
- Primary neutron production

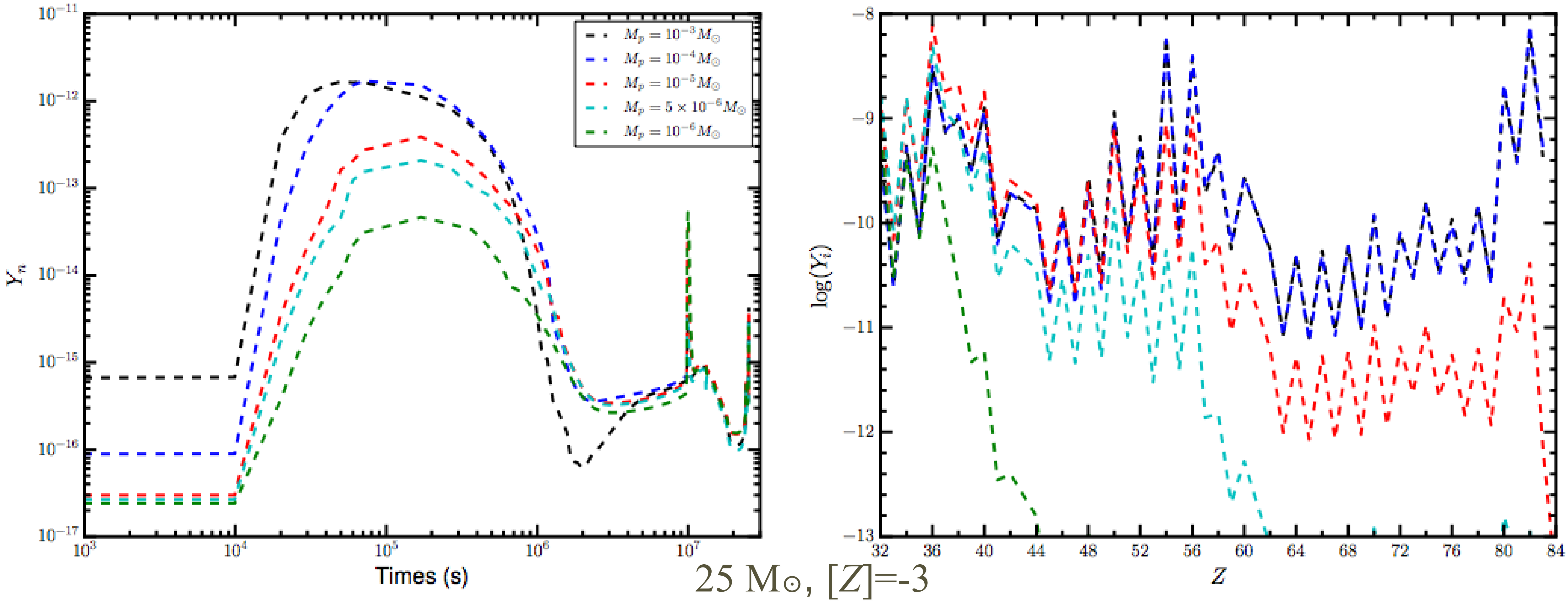


$M_p = 10^{-4}\ M_\odot$

$25\ M_\odot$, $[Z] = -3$

- Most of the neutron capture occurs in the first ~ 10^6 s.
- Can result in both i-process and s-process.
- Final [Ba/Eu] depends on time available Δ for neutron capture.
- [Ba/Eu] can vary from ~ 0.25 to 1 with [Ba/Eu]<0.6 (>0.6) for $\Delta < 10^6$ s ($> 10^6$ s)

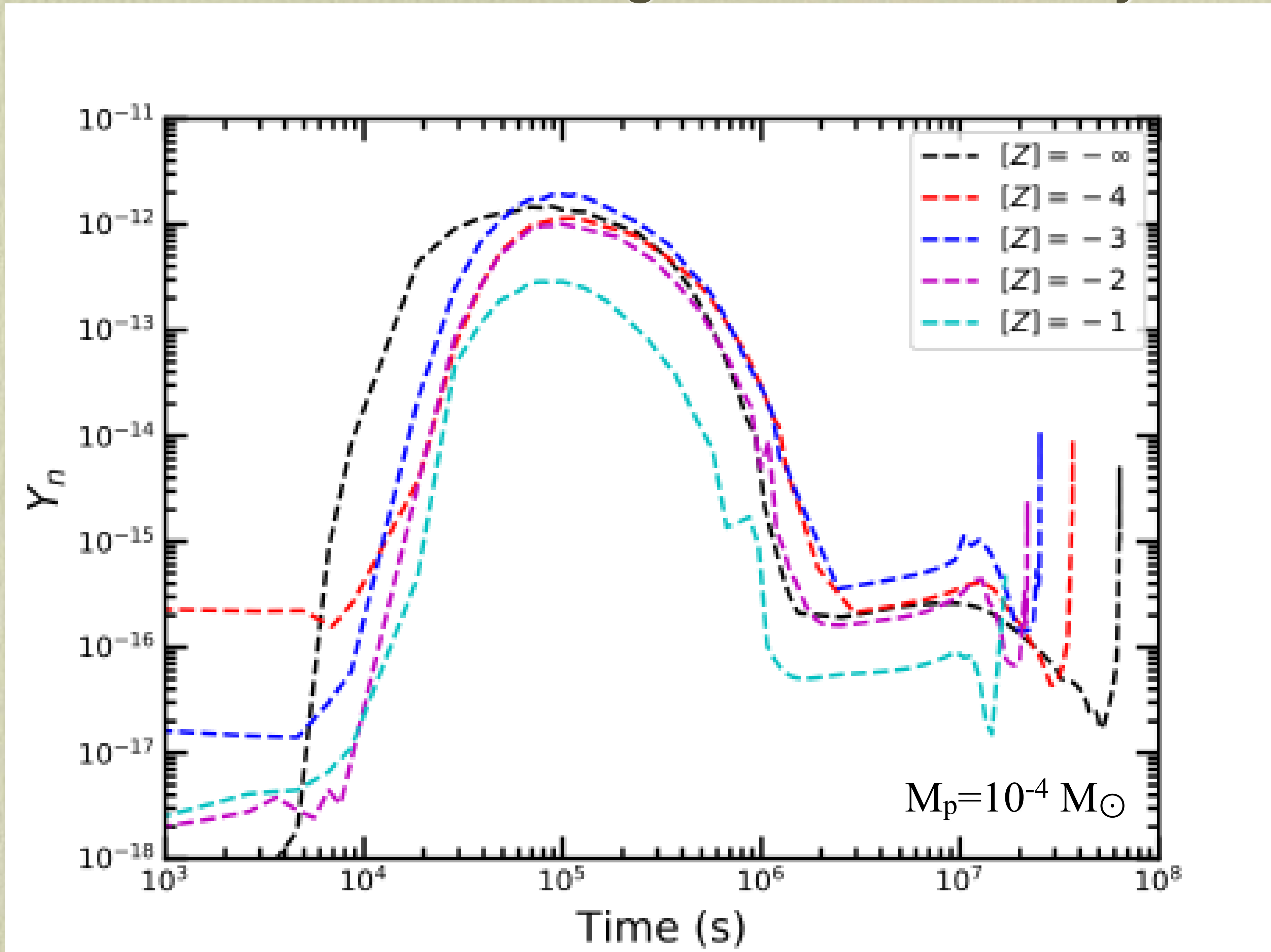
Effect of Amount of Proton Ingestion



25 M⊙, [Z]=-3

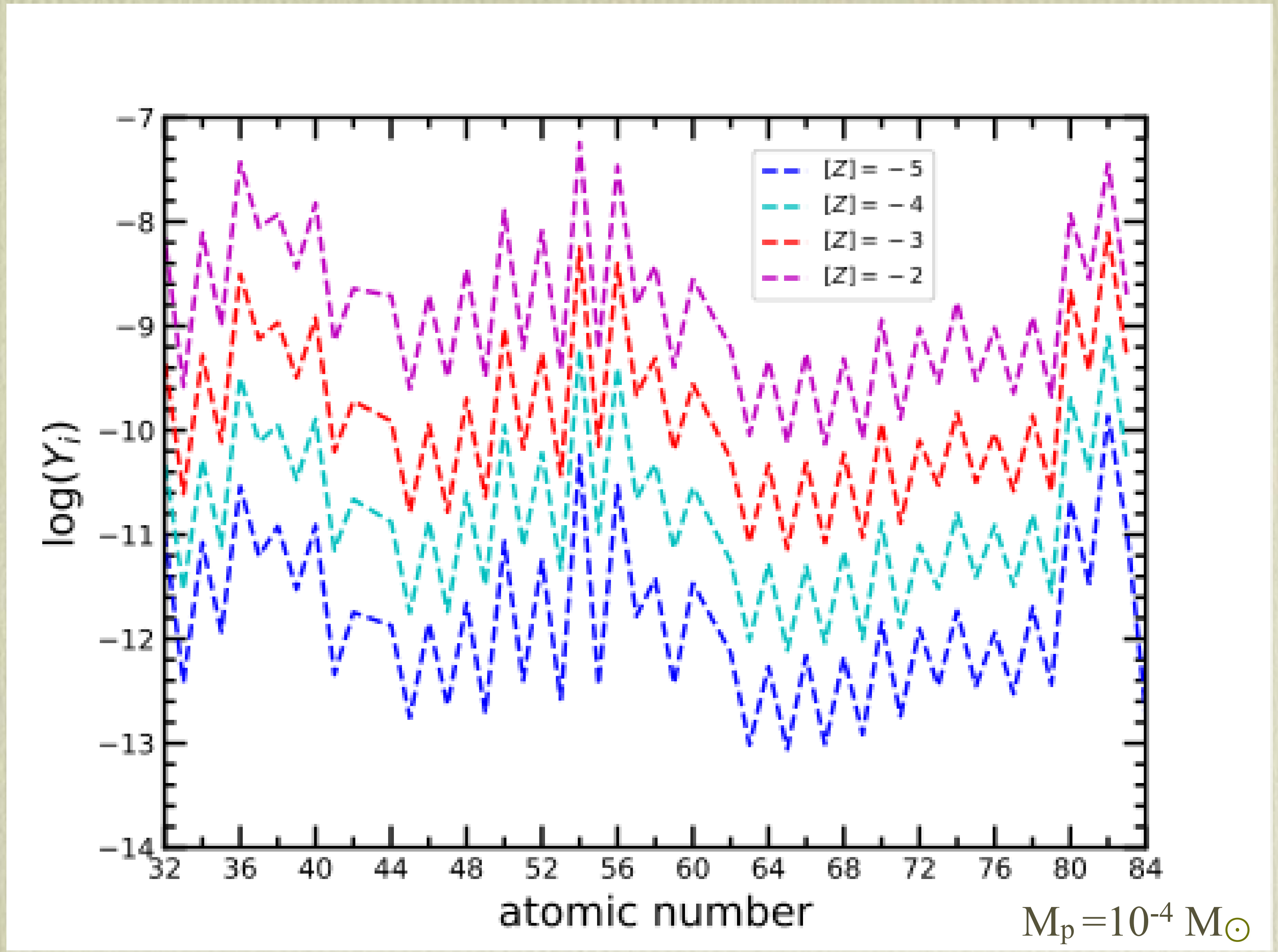
- Neutron abundance depends on the amount of p ingestion.
- Production up to Bi for $10^{-3} \gtrsim M_p \gtrsim 10^{-5}$ M⊙ -1.30≲ [Sr/Ba] ≲ -0.5.
- For 10^{-6} M⊙≲ M_p≲ 10^{-5} M⊙ production up to Ba, high [Sr/Ba] > 0.
- Negligible neutron capture for $M_p < 10^{-6}$ M⊙.

Effect of Progenitor Metallicity



Neutron abundance similar for [Z]≲-2 (^{16}O main poison)
[Z]≳-2 other poisons important.

Effect of Progenitor Metallicity

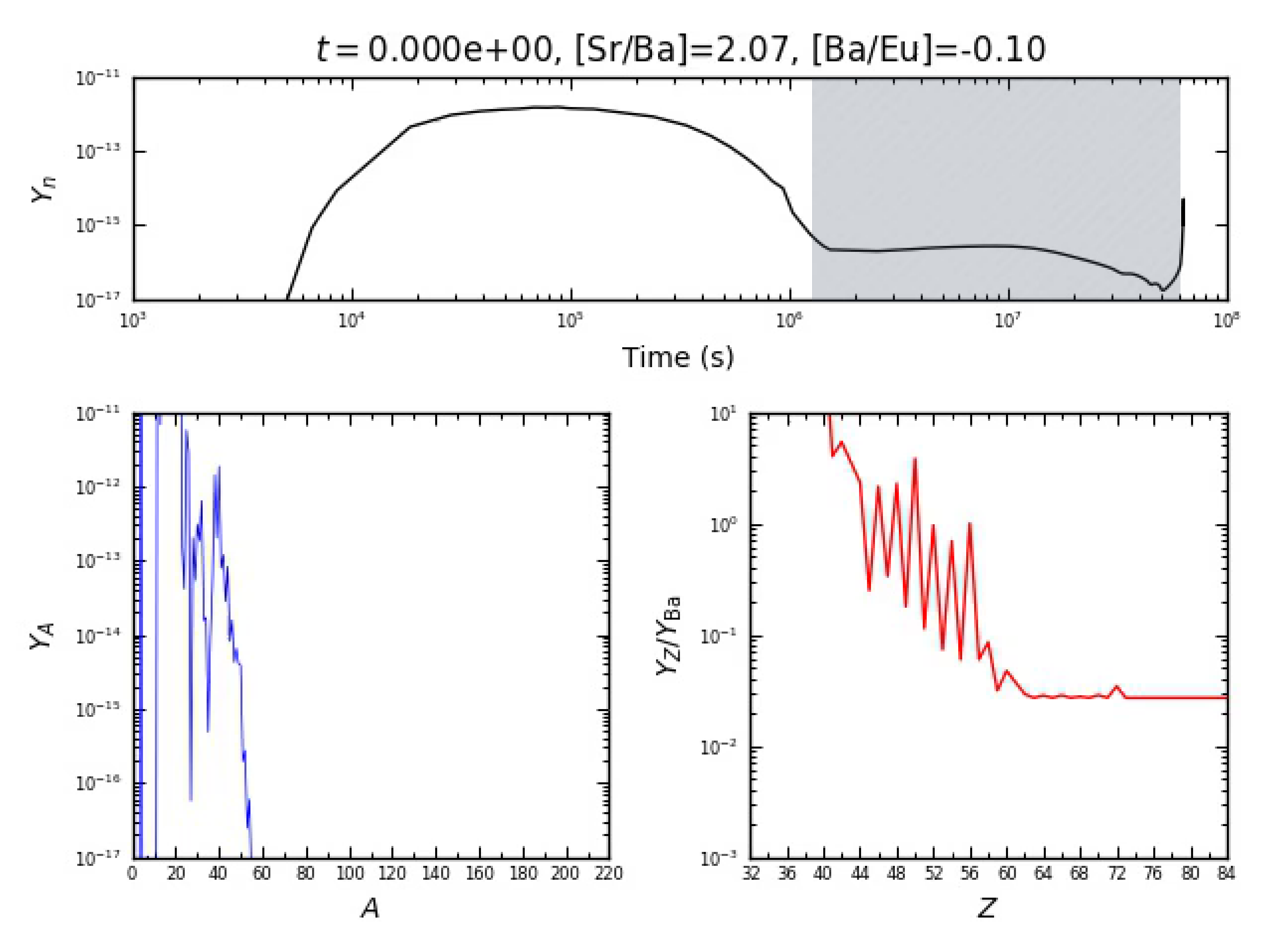


Yield scales linearly with the amount of seeds available.

Increases rapidly for $[Z] \gtrsim -4$

What about Pop III stars? Seeds??

Metal-Free Progenitors

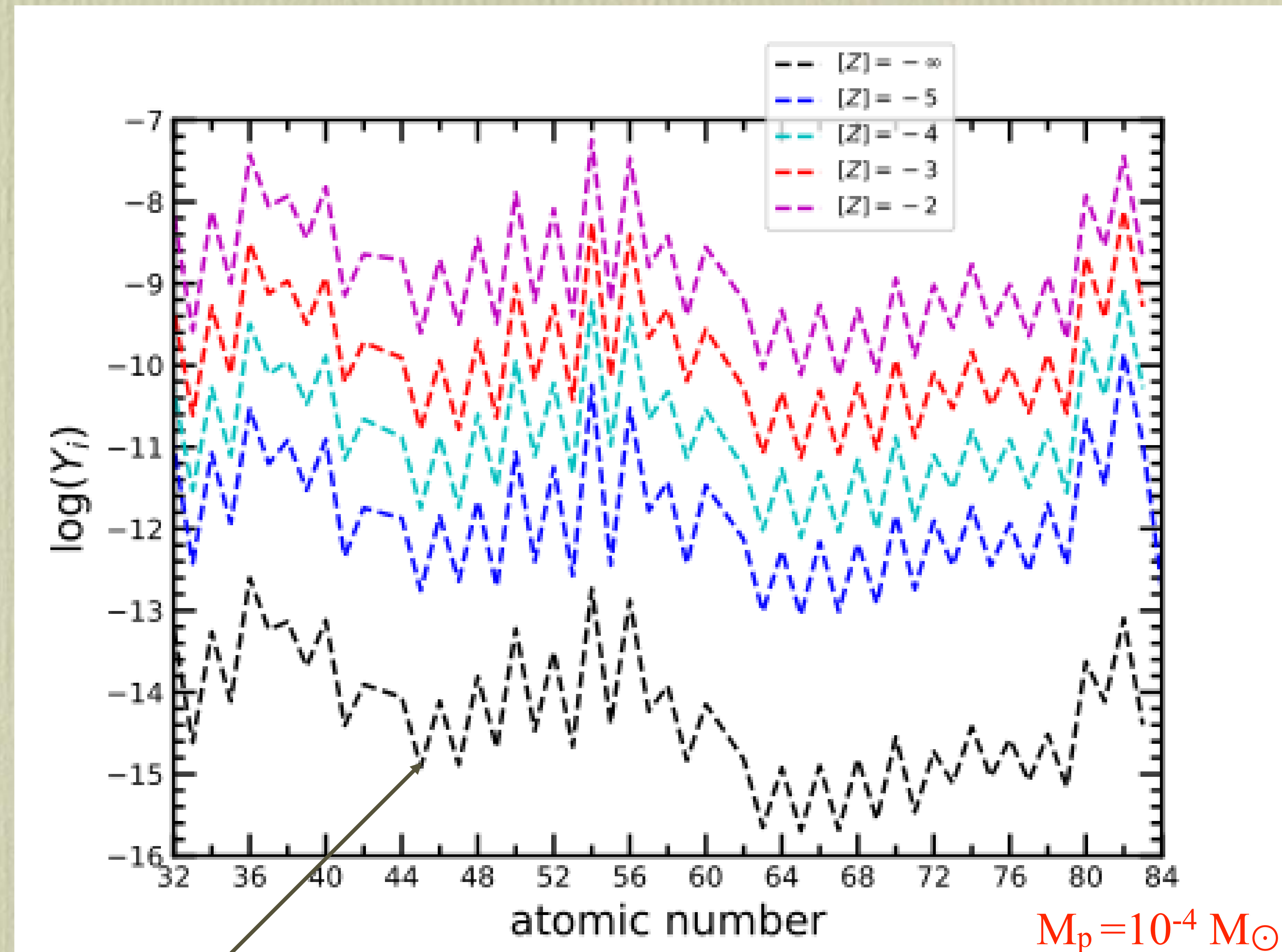


$M_p = 10^{-4}\ M_\odot$

$25\ M_\odot$, $[Z] = -\infty$

- Neutron capture from primary $^{40\text{-}48}$Ca and $^{46\text{-}50}$Ti.
- Hampered by additional N= 20, 28 neutron magic numbers.
- Overall yield limited by very low initial $^{40\text{-}48}$Ca, Ti.
- Much of the seeds remain unused while new seeds are made.
- Can be used in subsequent ingestions.

Effect of Progenitor Metallicity

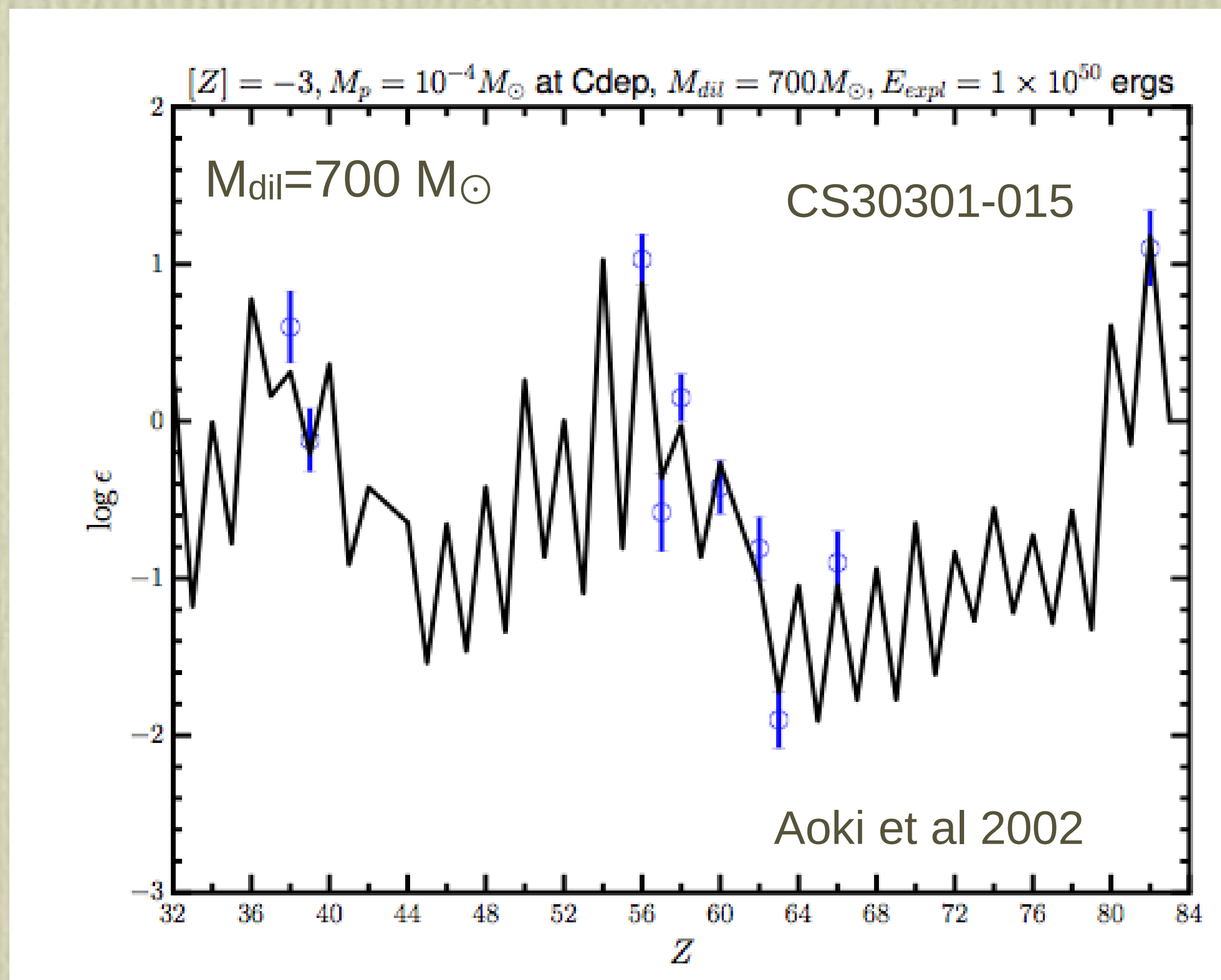


Yield similar to [Z] ~ -7.5

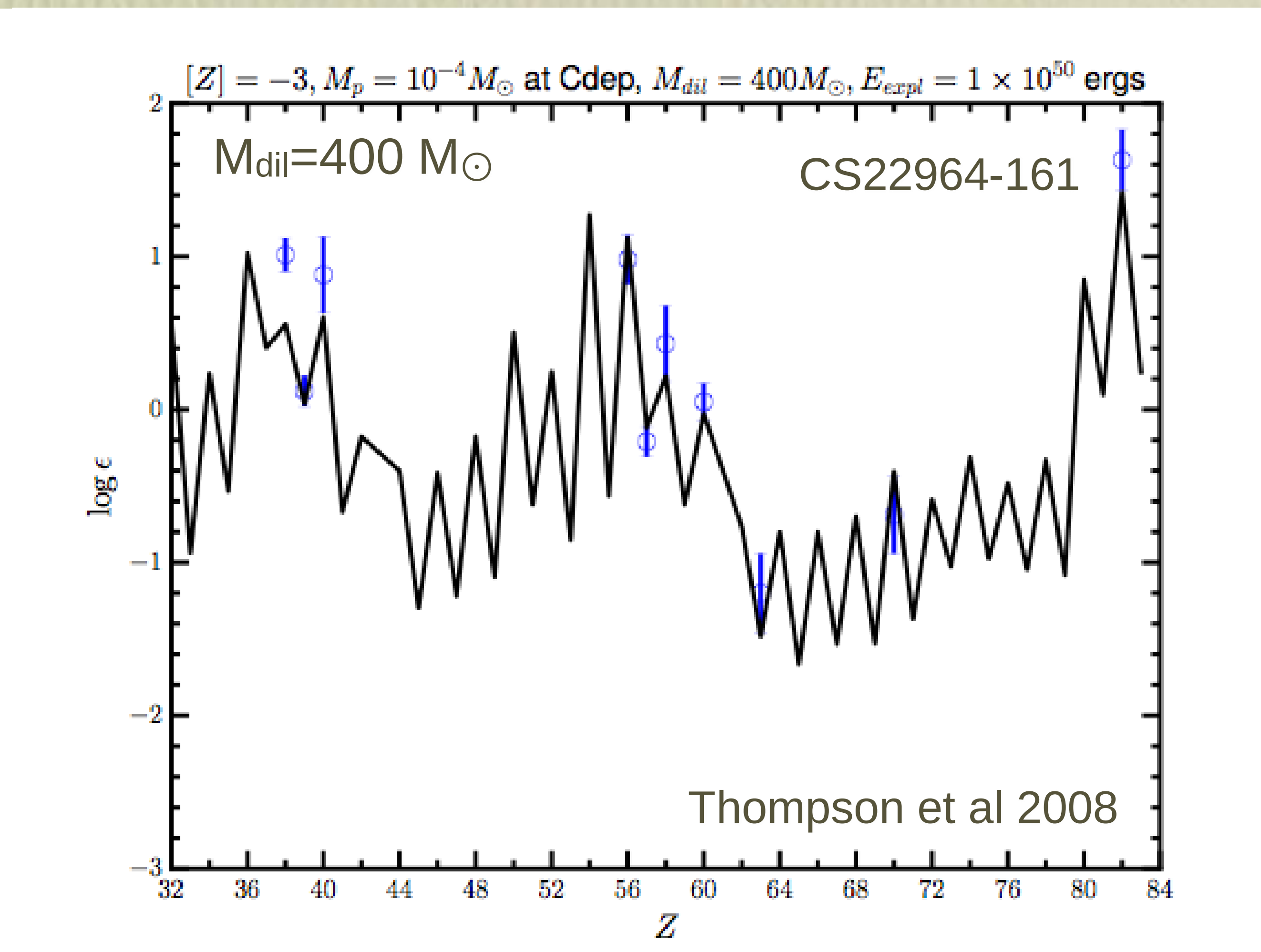
Metal-free progenitors: logϵ(Ba) ~ -5 to -3 for M_{dil} ~ 10^2-10^4 M.

[Z]≲ -2: logϵ(Ba) of up to ~ 2.5 for M_{dil} ≳ 10^2 M⊙.

Diversity: Comparison with Observations



Single CEMP-s star

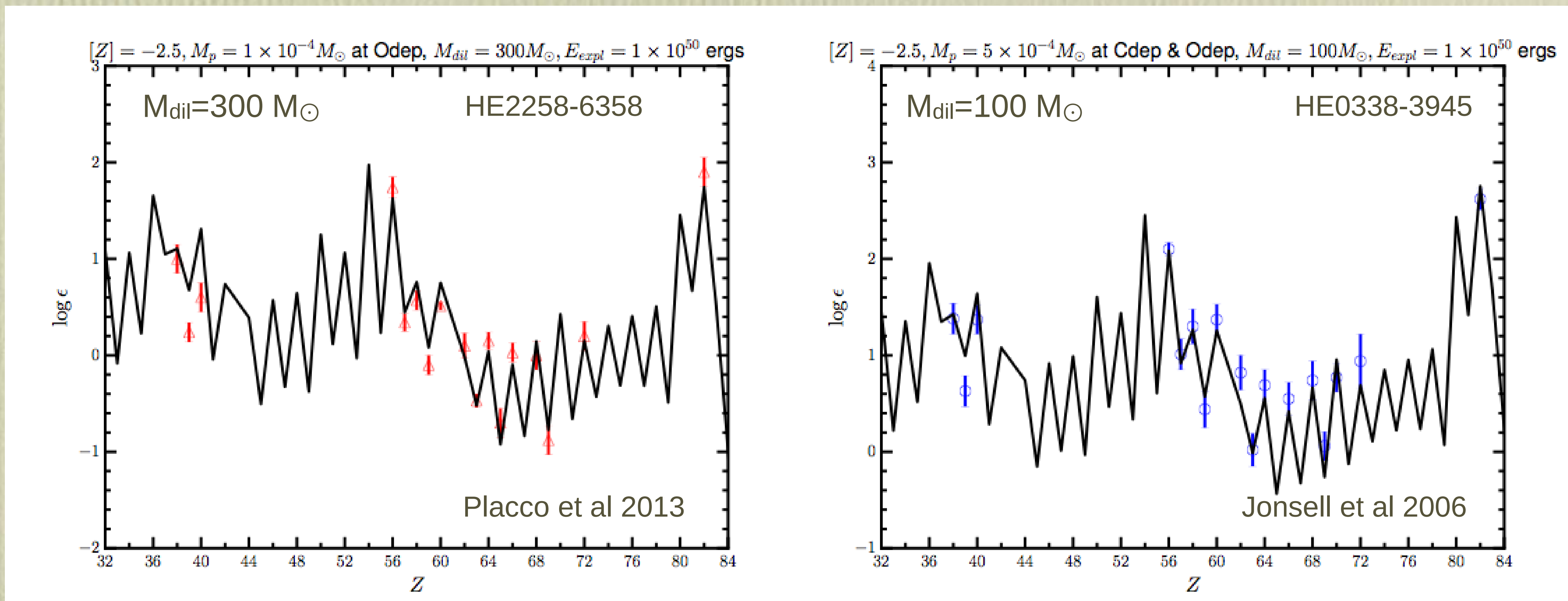


Binary system of CEMP-s star
No sign of third component

Proton ingestion $\gtrsim 10^6$ s before collapse

Low Dilution of $\lesssim 1000\ M_\odot$

Diversity: Comparison with Observations

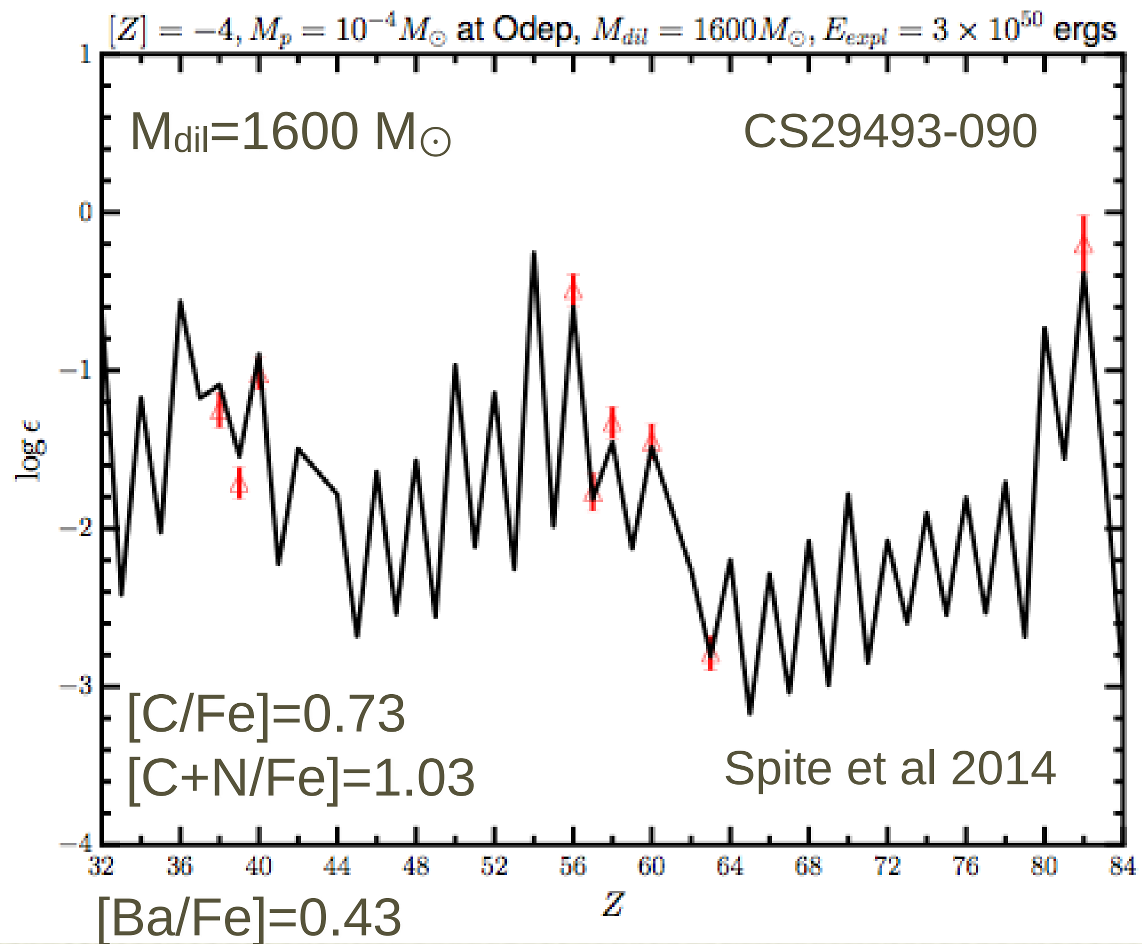


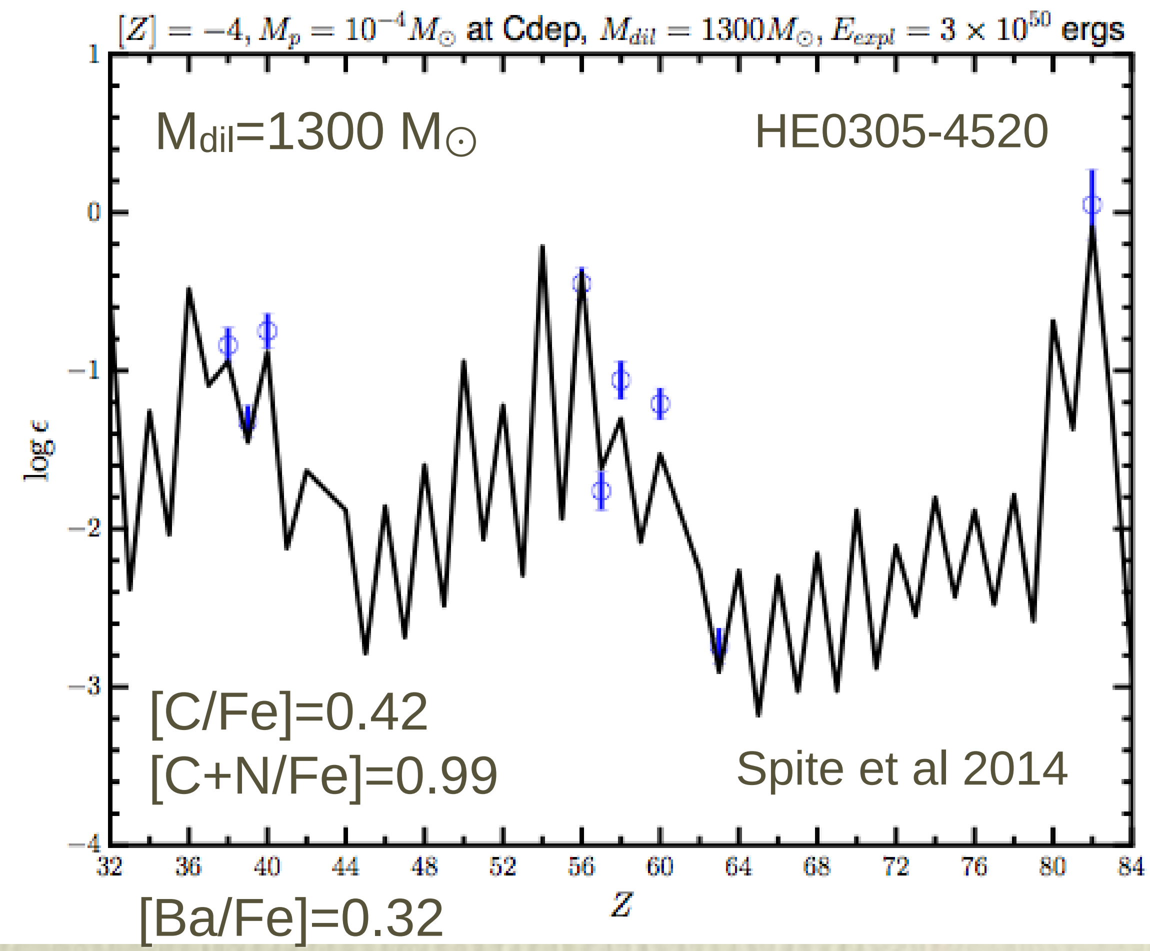
CEMP-r/s star

Proton ingestion $\lesssim 10^6$ s before collapse

Low Dilution of $\lesssim$ 1000 $M_\odot$

Diversity: Comparison with Observations





Low-s CEMP star, 0<[Ba/Fe]<1

No clear variation of radial velocity

Higher Dilution of $\gtrsim$ 1000 $M_\odot$

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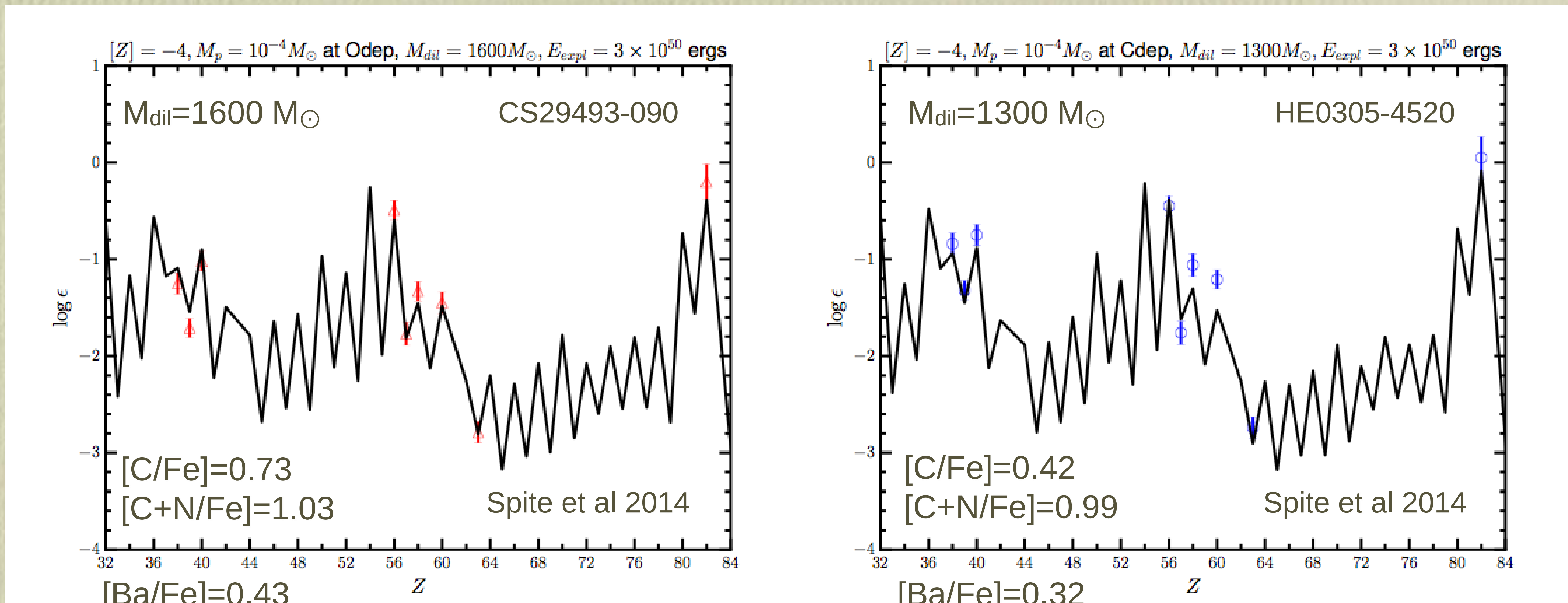

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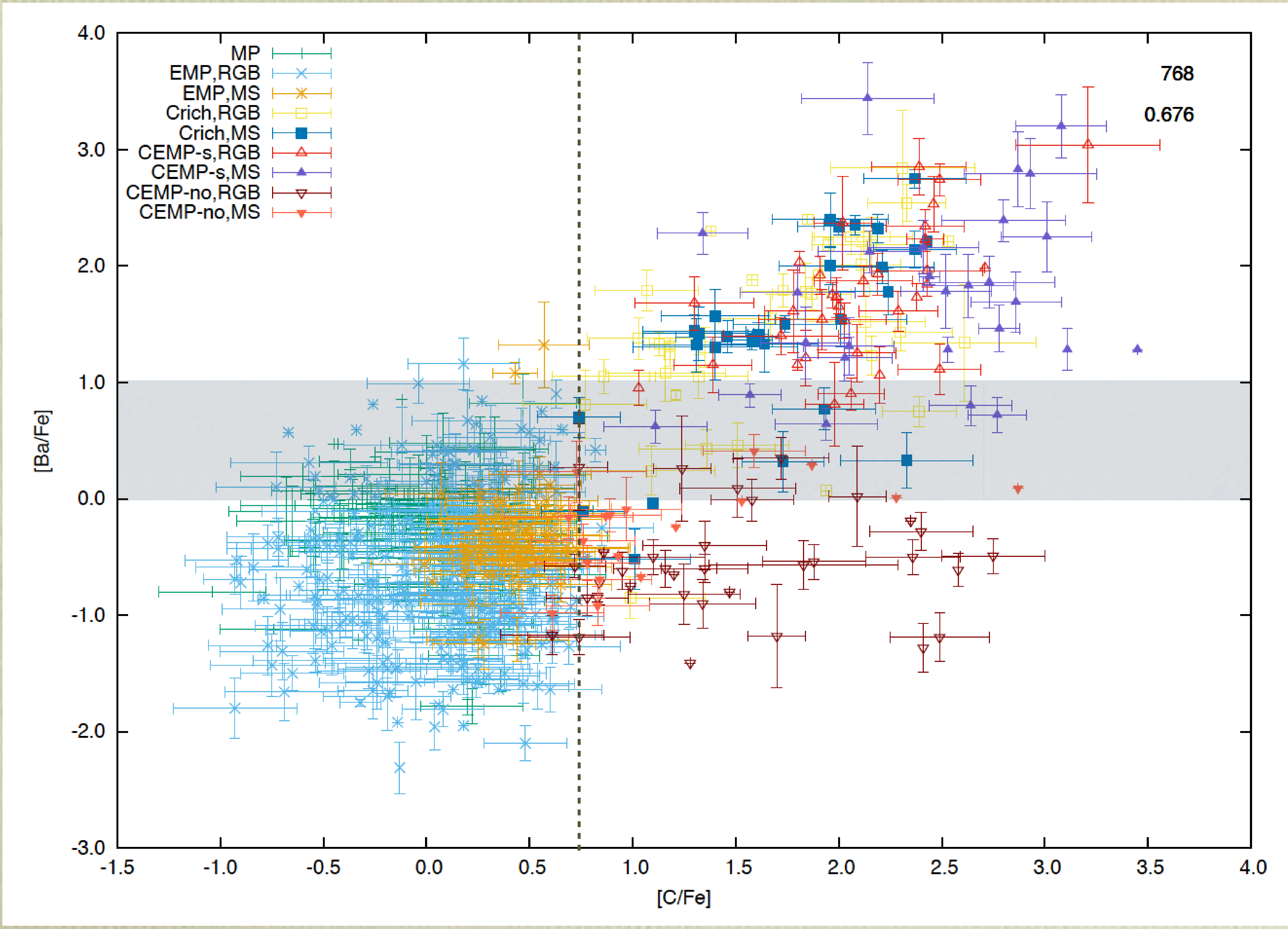
Higher Dilution of $\gtrsim$ 1000 $M_\odot$

For a fixed [Z], dilution controls the overall enhancement



MP
EMP,RGB
EMP,MS
Crich,RGB
Crich,MS
CEMP-s,RGB
CEMP-s,MS
CEMP-no,RGB
CEMP-no,MS
768
0.676
4.0
3.0
2.0
1.0
0.0
-1.0
-2.0
-3.0
[Ba/Fe]
-1.5
-1.0
-0.5
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
[C/Fe]

Discussion: Diverse Abundance Patterns

- $M_p \gtrsim 10^{-5}$ $M_\odot$ → s and r/s pattern with [Sr/Ba] <-0.5 and [Ba/Eu]= 0.25-1.00, Pb comparable to Ba
- $M_p \lesssim 10^{-5}$ $M_\odot$ → high [Sr/Ba]> 0, very little Pb.
- Neutrino-wind contribution for Sr important for [Z]≲-3.

-4 ≲ [Z] ≲ -2 Progenitors

- Low energy explosions → Low dilution → High enhancement → CEMP-s and CEMP-r/s stars
- Medium/high energy explosions → Higher dilution → Lower/No enhancement → CEMP-no/EMP-no/low-s stars.

Metal-free and [Z] ≲-4 Progenitors

Lower yields →CEMP-no/EMP-no stars.

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- $M_p \lesssim 10^{-5}$ $M_\odot$ → high [Sr/Ba]> 0, very little Pb.
- Neutrino-wind contribution for Sr important for [Z]$\lesssim$-3 to -4.

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Common origin of some the CEMP-s/CEMP-r/s and CEMP-no stars

Summary

- We identified a new site for synthesis of neutron-capture elements in metal-poor stars with $20\ M_\odot \lesssim M \lesssim 30\ M_\odot$ including primordial stars.
- Neutron capture occurs during the last phases of massive stars when protons are ingested at the boundary of a fully convective He shell.
- Neutron production is primary whereas neutron capture is secondary in progenitors with initial metals.
- Neutron production and capture is primary in primordial metal-free stars.
- Can explain the ubiquity of neutron capture elements Sr and Ba observed in EMP stars.
- Can explain the early deviation of [Ba/Eu] from pure r-process value.
- Can be the source s-process elements in the early Galaxy.
- Excellent fit to individual abundance patterns of several CEMP-s, CEMP-r/s, low-s stars.
- Points to a common source for some of the CEMP-s, CEMp-r/s and CEMP-no stars.
- Can be useful in constraining the IMF of Pop II and Pop III stars.
- Neutron capture is efficient up to [Z]~-1, can produce more Sr than weak-s process.
- Mixing with initial r-process enriched ISM could explain other EMP stars.
- Could be processed further by AGB stars initially enriched by this mechanism.