大質量星におけるリン合成とリン過剰星の起源

2025/12/1-3:初代星・初代銀河研究会 2025 @福井🦖

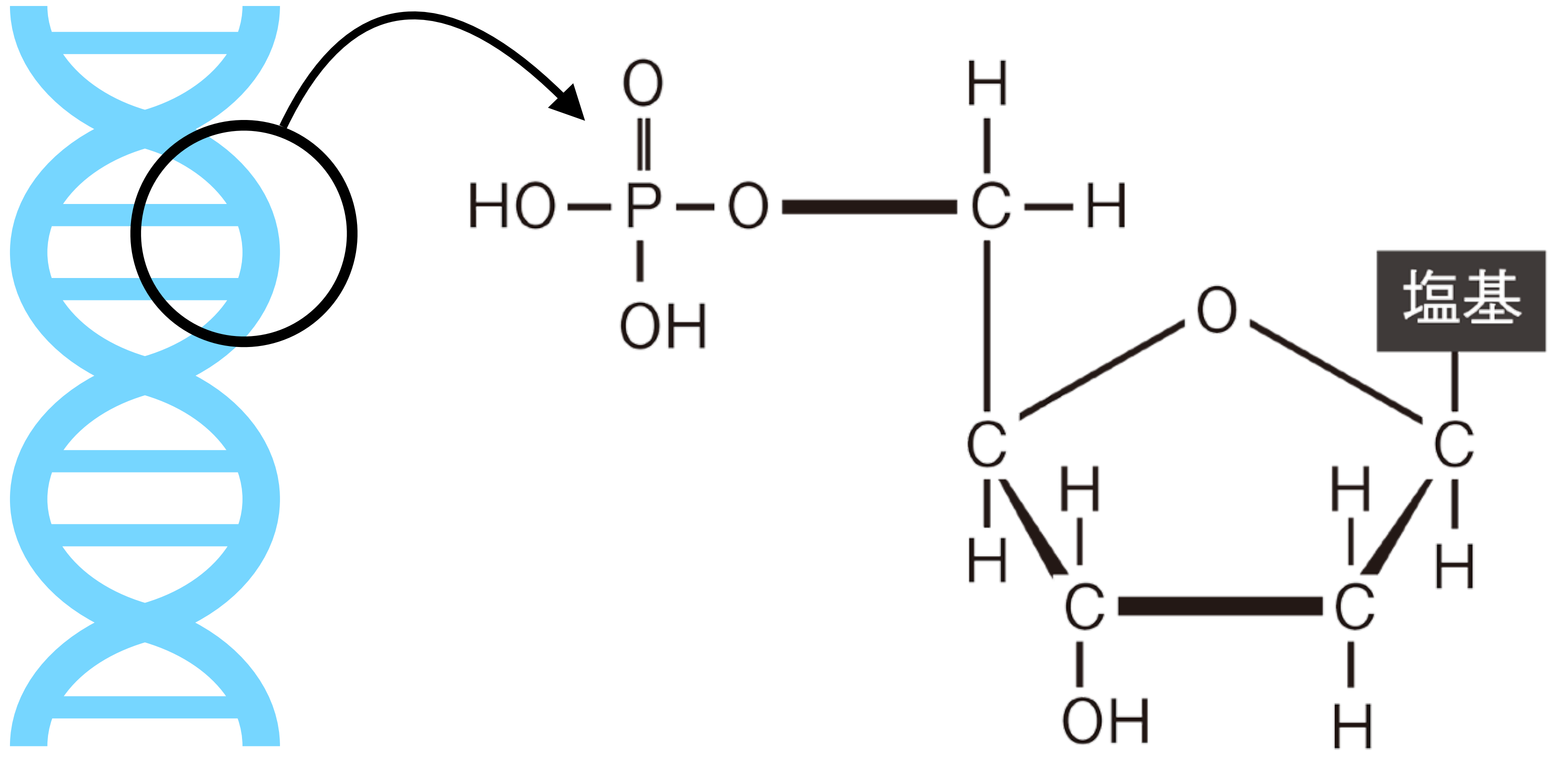
播田實 りょう太 (D1 総研大/国立天文台)
共同研究者: 冨永望, 高橋亘, 青木和光, 辻元拓司 (国立天文台),
松永典之(東大), 谷口大輔(都立大), IRD team

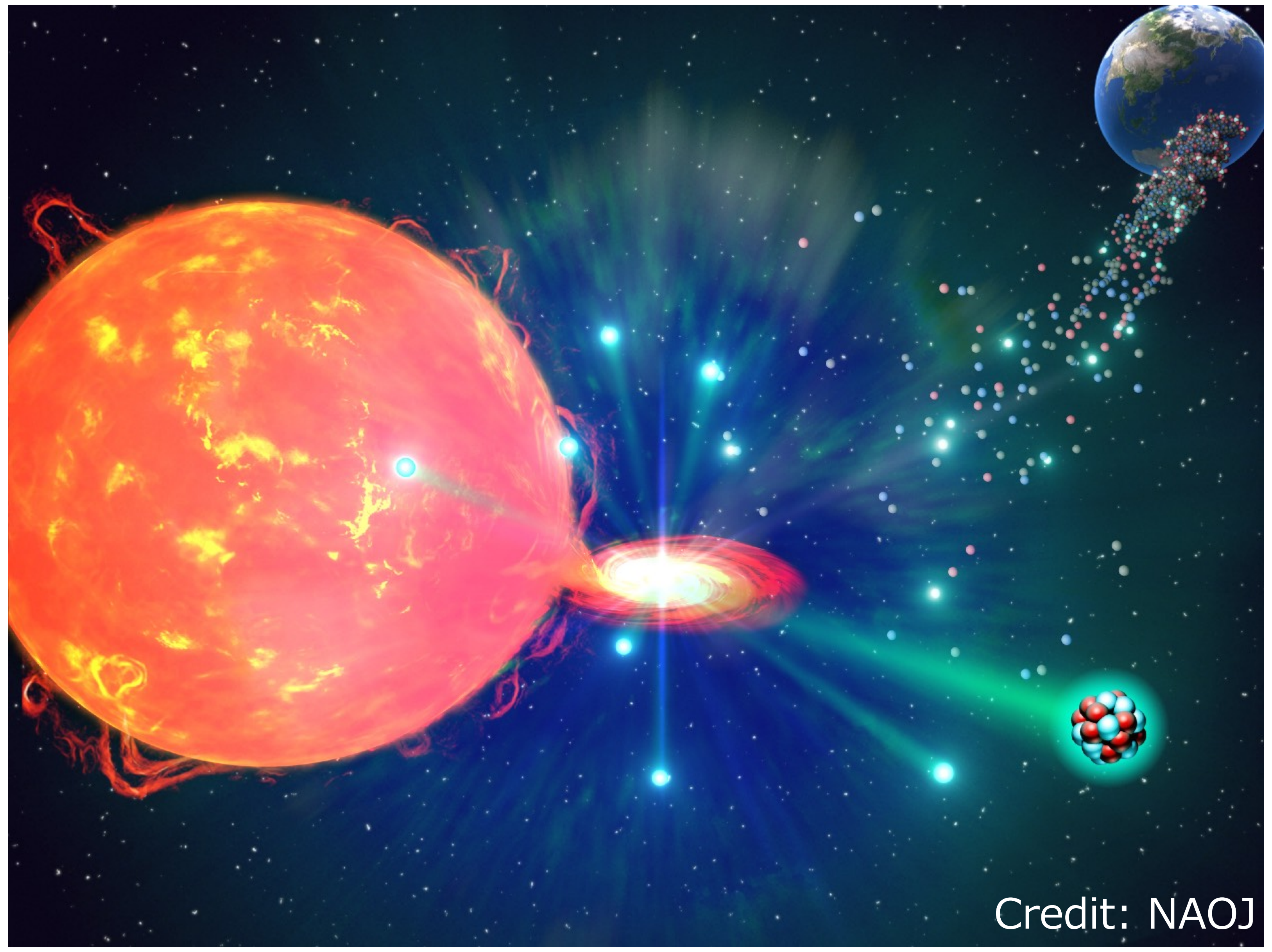
Phosphorus in the Universe

- Components of DNA/RNA, ATP, and Phospholipid
  → Essential elements for earthly life
- P synthesis sites are not fully understood

=＞Investigation of the origin of P leads not only the **understanding of P synthesis sites** but also **implications for the origin of earthly life**

DNA





Credit: NAOJ

Phosphorus Synthesis Sites and Evolution

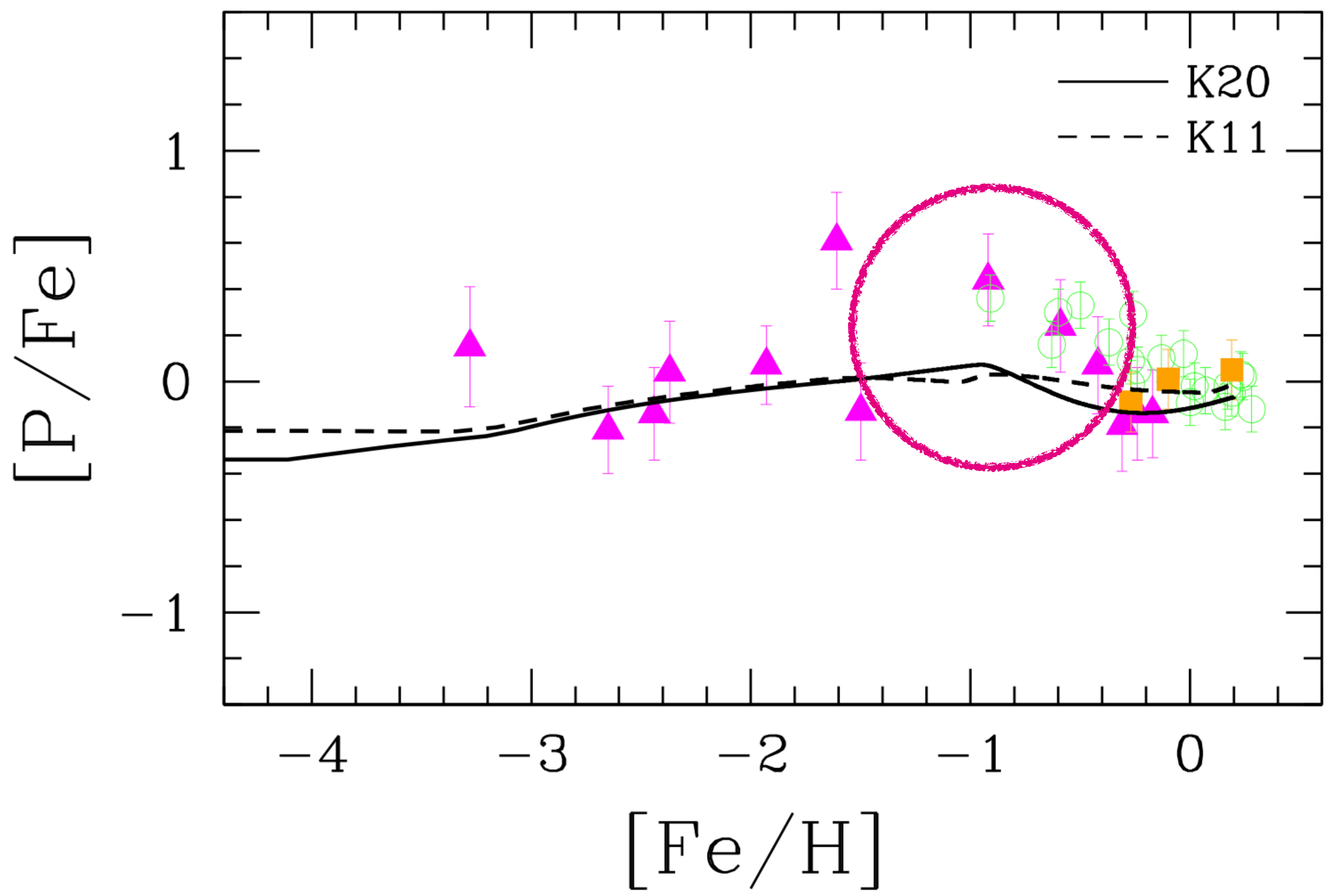
Phosphorus abundance and its time evolution haven't been reproduced by simulations around [Fe/H] ~ -1

$$[\mathrm{A/B}] := \log(N_\mathrm{A}/N_\mathrm{B}) - \log(N_\mathrm{A}/N_\mathrm{B})_\odot$$

Important sites around [Fe/H] ~ -1⋯ ?

- Classical nova (ONeMg WD $\sim 1.35 M_\odot$)
- C-O shell merger (Massive stars $10\text{-}25 M_\odot$?)

Kobayashi+20



P-rich Stars

- Even though P-normal stars abundance haven't been reproduced…

  → Recent observations revealed

  P-rich stars w/ [P/Fe]>+1.0

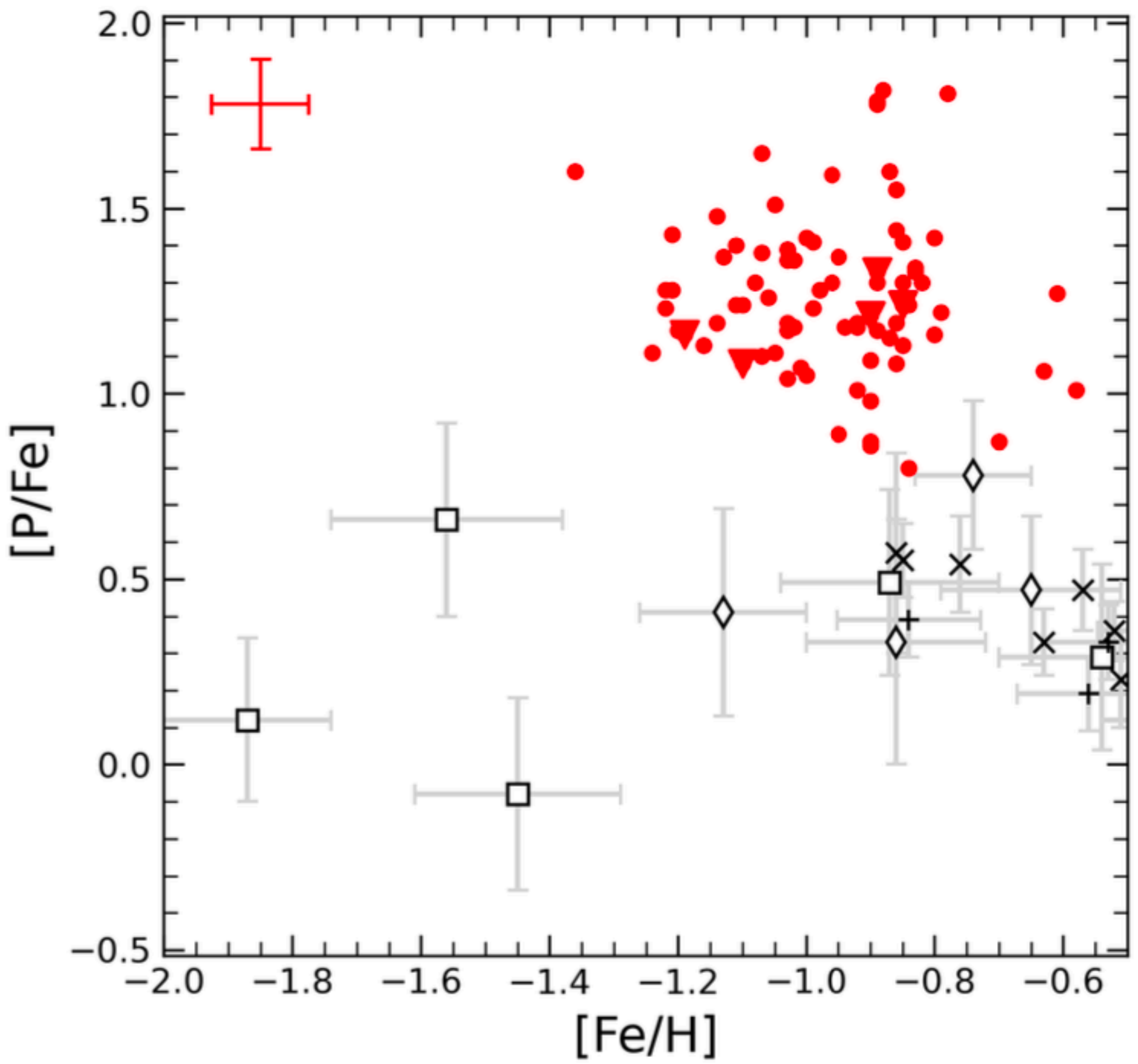
  (Masseron+20, Brauner+23)

=＞Synthesis of P and other elements around P should be investigated!!

Classical novae can synthesize up to [P/Fe]~+0.7 (Bekki & Tsujimoto 24)

→ How about massive stars?

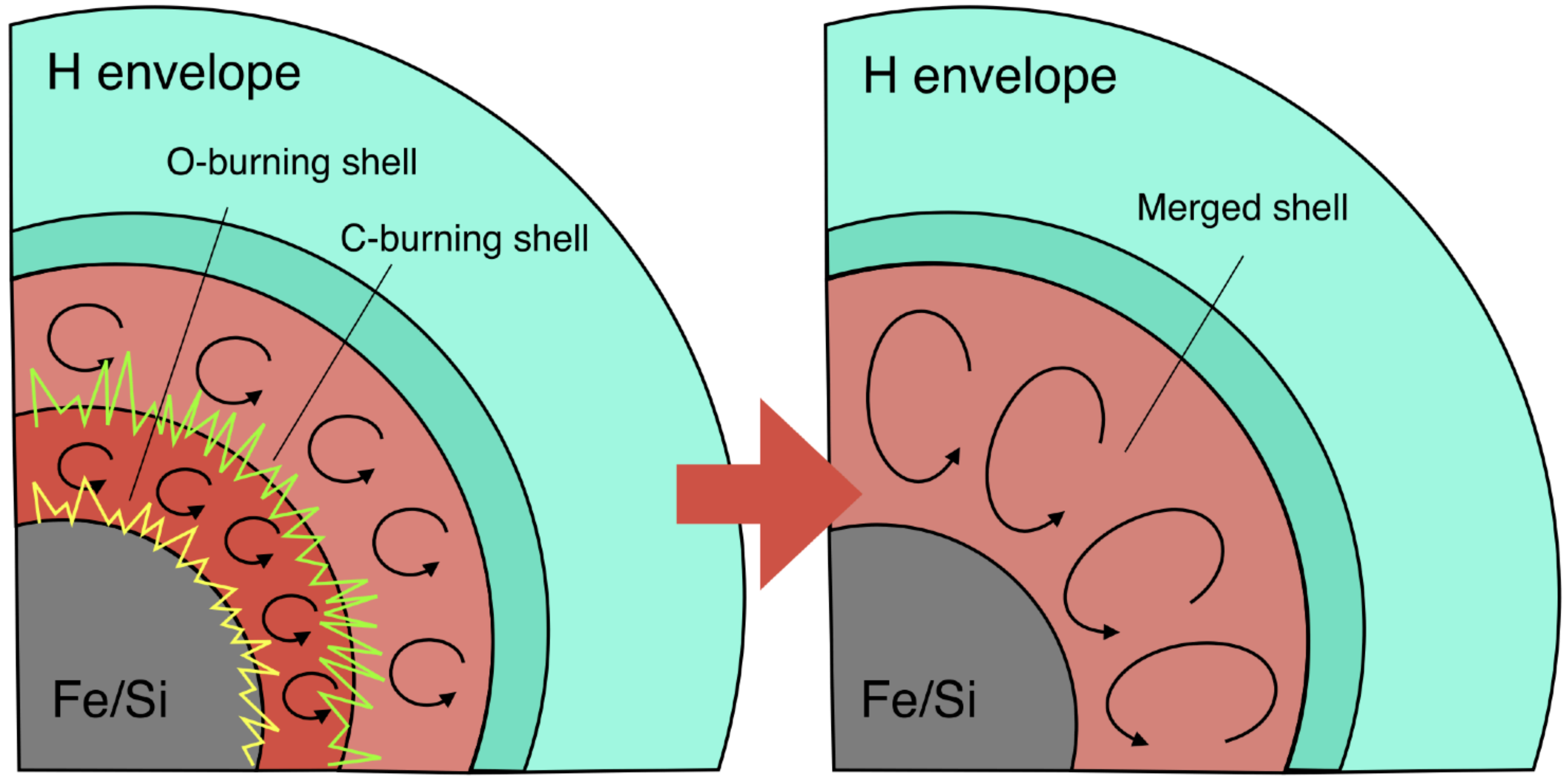
Brauner+25



What is C-O Shell Merger

- Convective merging between **O burning shell** and **C burning shell (C-O shell merger)**
- Occurring a few days~hours before collapse

Sato+25a



1. Density jump at Si/O interface (Bruenn+23)
   → It supports shock propagation
2. Enhancement of odd-Z elements (P, Cl, K, Sc) and O burning products (Si, S) (Ritter+18, Roberti+25)
   → It helps **explain stellar abundance** (and SNRs?)

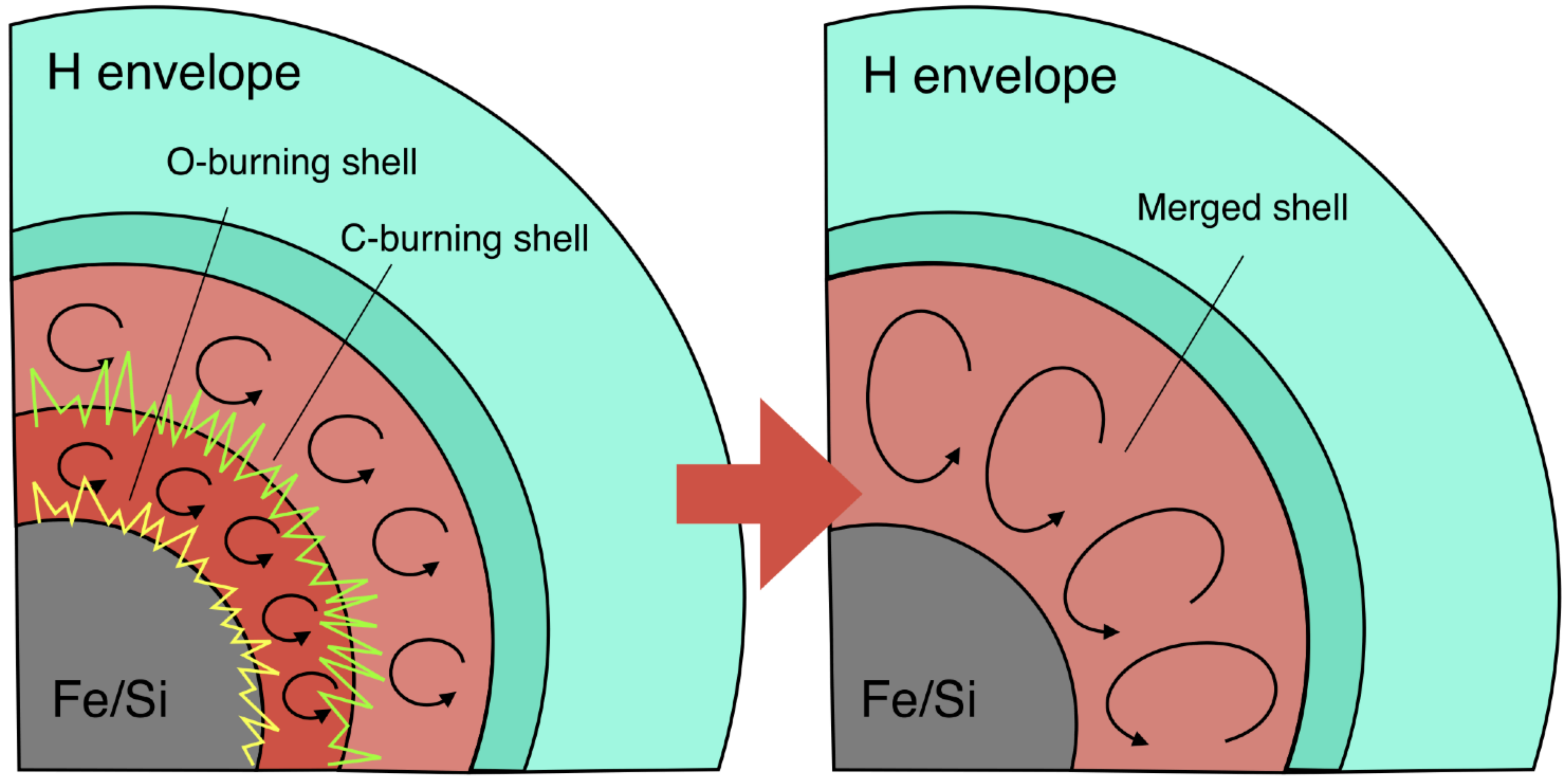
Nucleosynthesis during Shell Merger

Nucleosynthesis is different from the case with no merger

C, O, C burning products (Na, Mg, Al) and Ne injected into O shell burning region
→ C+C, C+O, O+O, Ne+γ,
p, α capture etc. are activated
=> Odd-Z elements (**P, Cl, K, Sc**) and
O burning products (**Si, S**) are enhanced
(Ritter+18, Roberti+25)

C-O shell merger could reproduce P-rich stars?

Sato+25a



Purpose

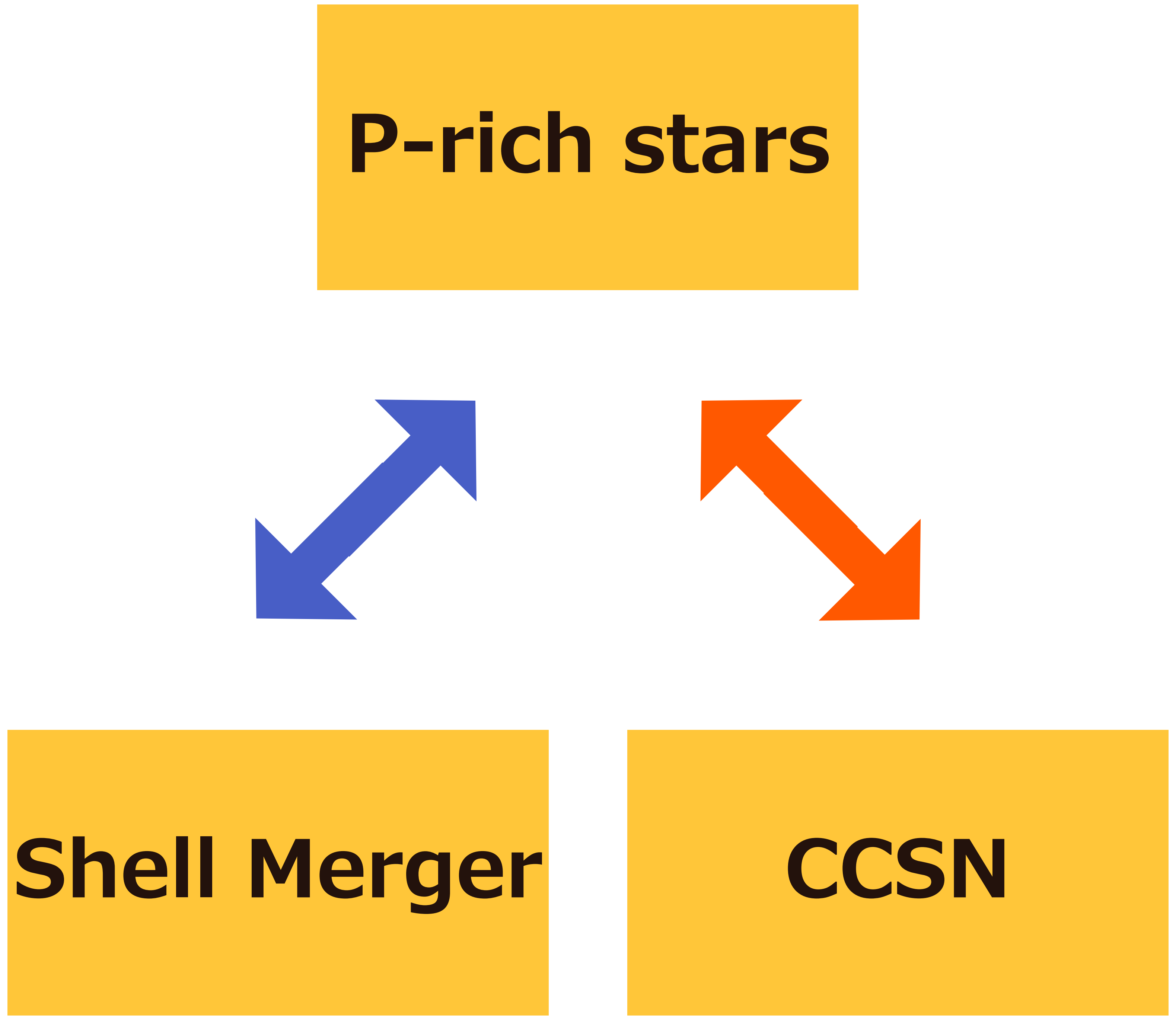
Aim:Investigate the influence of C-O shell merger and supernova nucleosynthesis on P-rich stars

Stellar Nucleosynthesis

Calculate stellar evolution with different parameters such as stellar mass, initial rotation, etc. and examine whether shell merger occurs or not

Supernova Nucleosynthesis

Based on ρ - T history taken from explosion simulation, calculate nucleosynthesis and compare with abundances of P-rich stars



Method: Stellar Evolution

Code: HOSHI (**HO**ngo **S**tellar **H**ydrodynamics s**I**mulator; Takahashi+18, Takahashi & Langer 21)

Nuclear Network: 300 species (p-^{79}Br)

Parameters: Mass, Rotation

Metallicity: $Z = 0.1 Z_\odot$
(to compare with the abundances of P-rich stars)

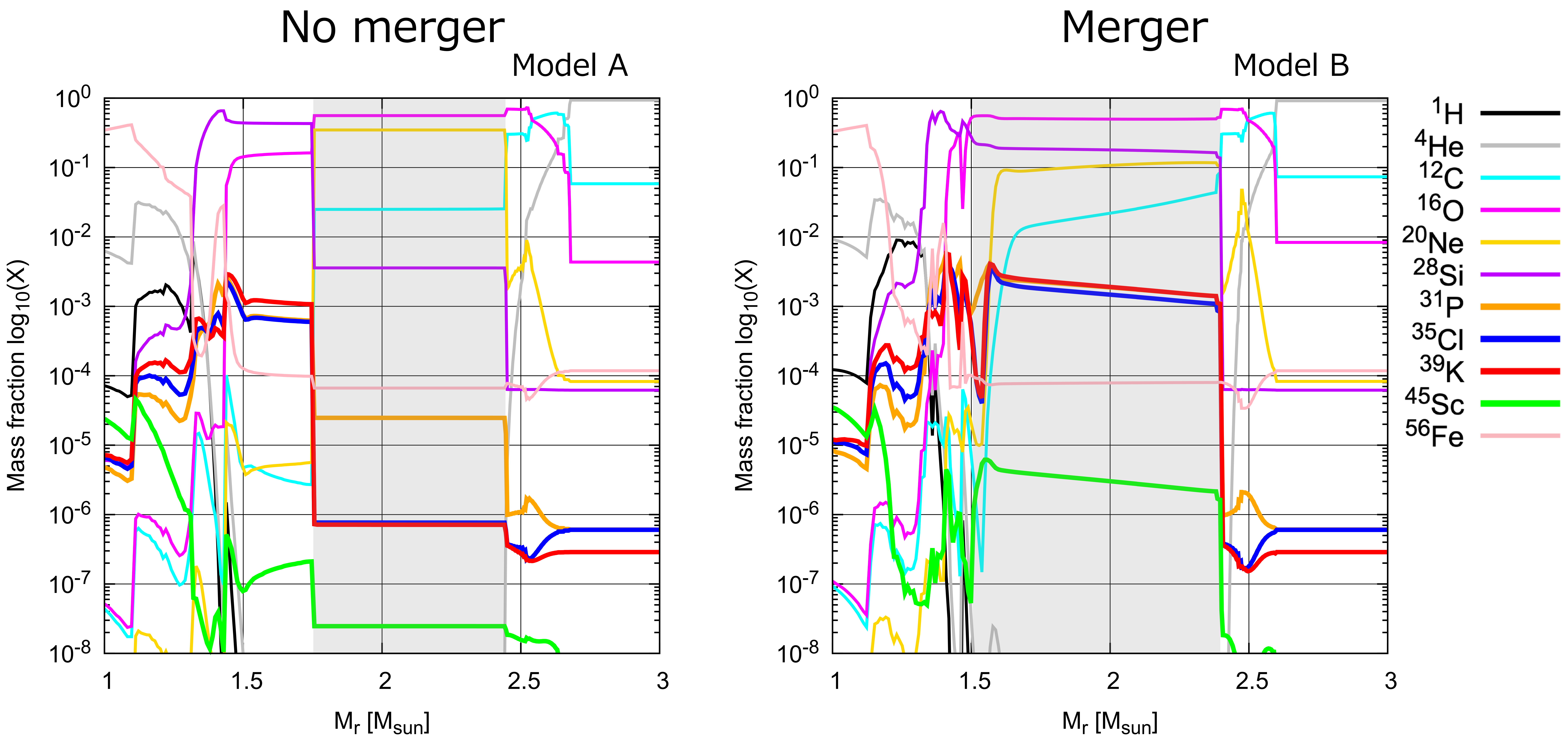
Models and Parameters

	A	B
Mass ($M_\odot$)	15	15
Metallicity ($Z_\odot$)	10^{-1}	10^{-1}
Rotation (Ω/Ω_{Kepler})	0	**0.2**

Merger or No Merger: Kippenhahn Diagram

No merger | Merger

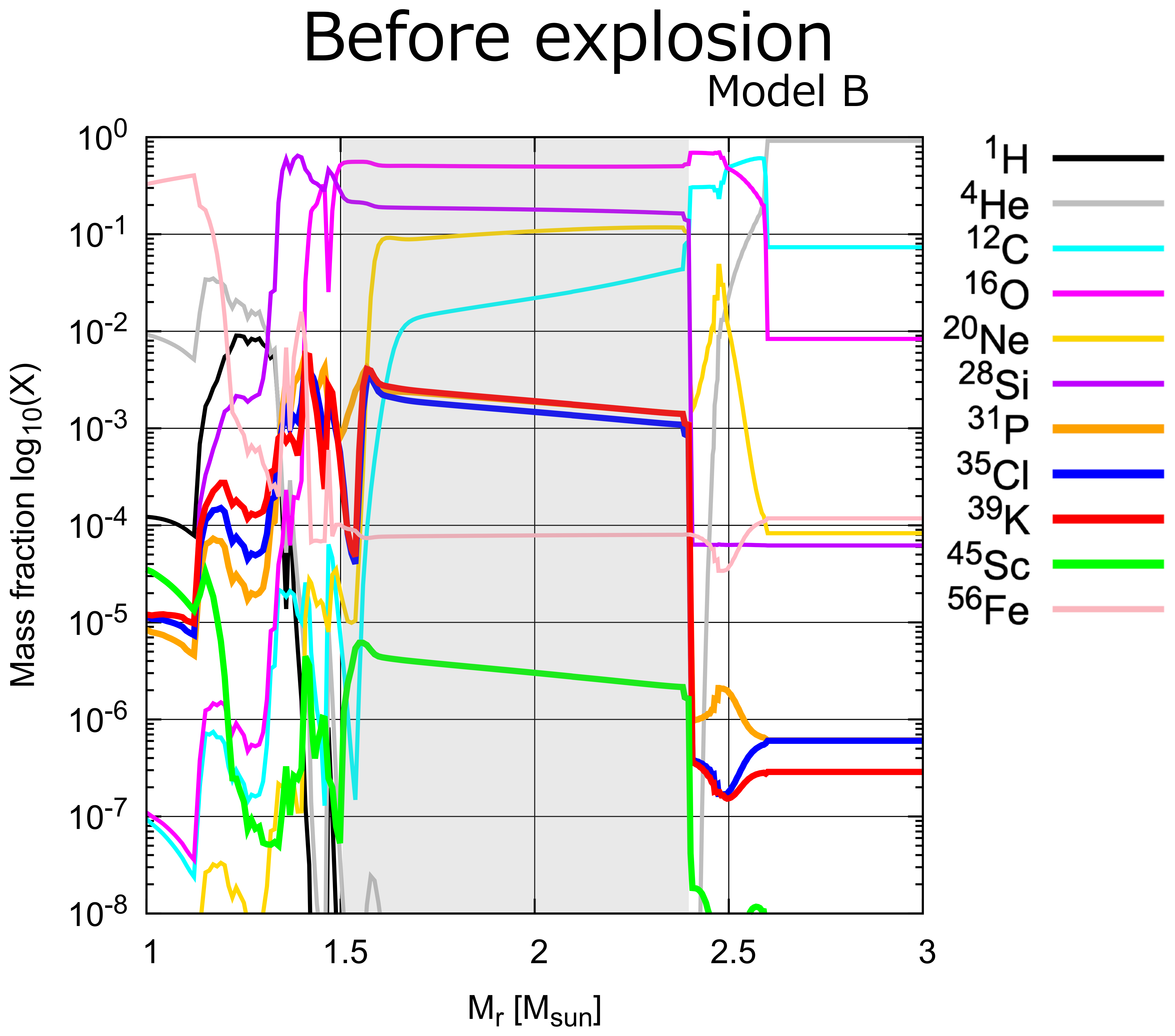
Final Abundance Distribution



Explosion: Thermal Bomb

Thermal bomb

- Injected energy: $3\,\mathrm{B}$ $(= 3 \times 10^{51}\,\mathrm{erg})$
  - Injected at $M_r \simeq 0.8 M_\odot$
  - Time scale of injection: $10^{-3}\,\mathrm{s}$
- Final explosion energy: $\sim 1.2\,\mathrm{B}$
- Network: 300 species (p-^{79}Br)



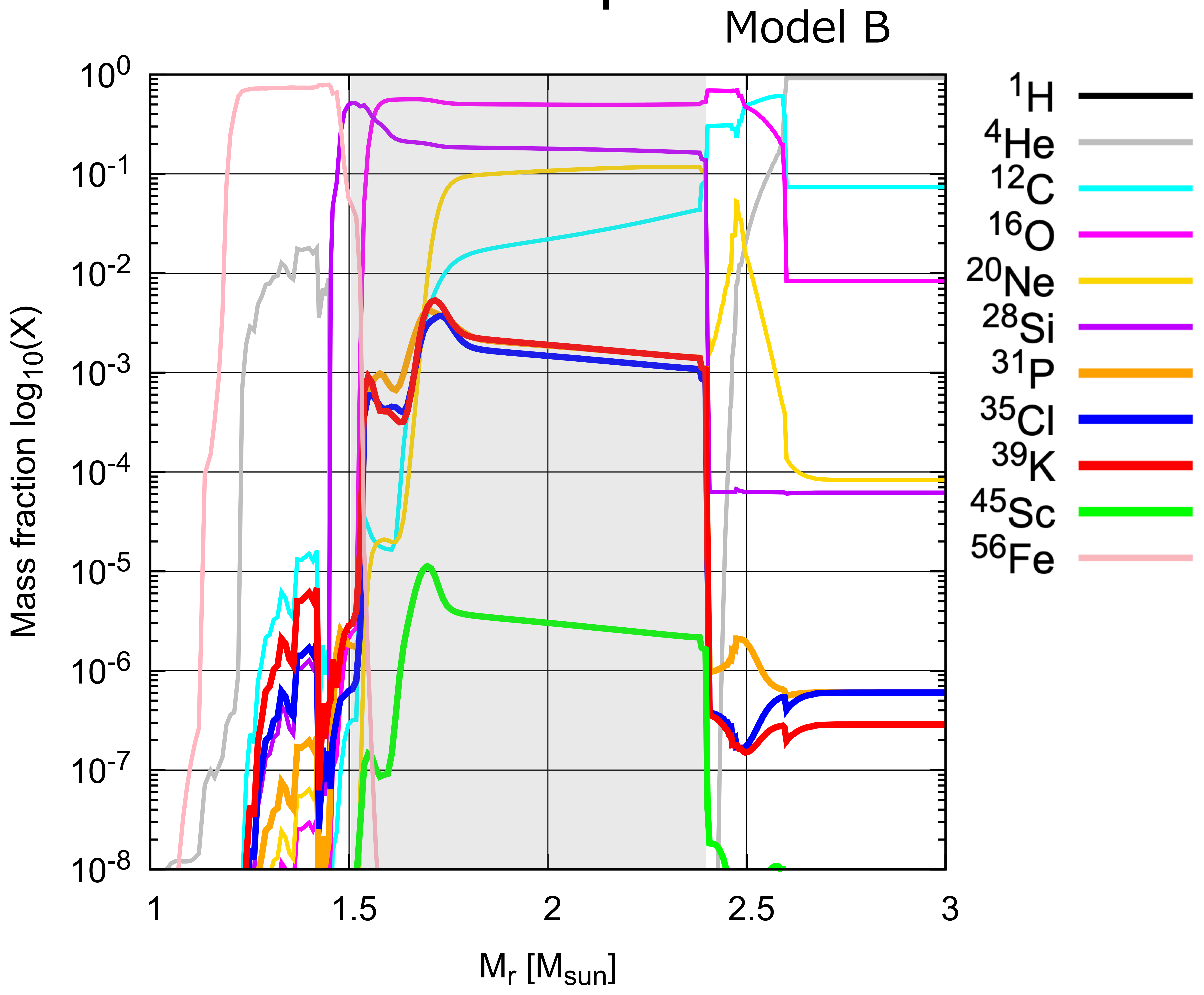
Abundance Distribution

Only the bottom region of O layer experienced explosive burning

→ Outer region **remain pre-supernova composition**

Integrate from outer region to the radius where $M(^{56}\mathrm{Ni}) = 0.07 M_\odot$

After explosion



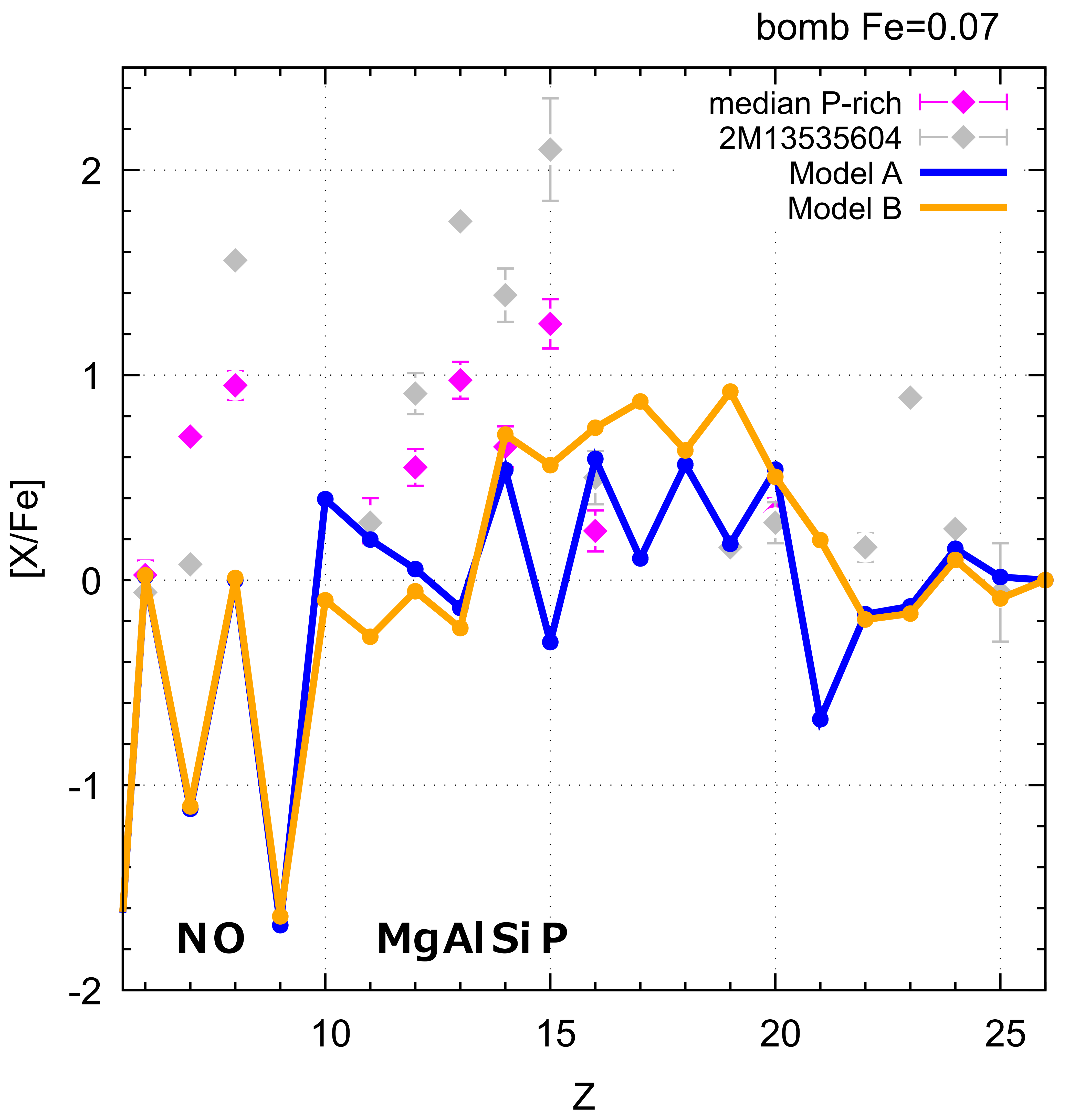
Abundance Pattern

If shell merger occur,
[P/Fe] can be enhanced to ~+0.6
(still lower than P-rich stars)

👍: P can be enhanced as much as nova

👎: Not only P but also N, O, Mg, and Al are deficient

=> Need to combine with other nucleosynthesis sites?



Summary/Future work

Aim

Investigate P synthesis in massive stars (especially C-O shell merger) and the effects on the origin of P-rich stars

Results

- C-O shell merger occurred in some models and **P can be enhanced as much as massive novae**
- Even though C-O shell merging models, **[P/Fe] is lower than +1.0**

Future work

- Investigate the cause of C-O shell merger (Neutrino Cooling?)
- Confirm P and other elements abundance in P-rich stars (in progress)
- Calculate nucleosynthesis based on neutrino-hydrodynamical simulations