単一の初代星超新星爆発由来の第二世代星の抽出

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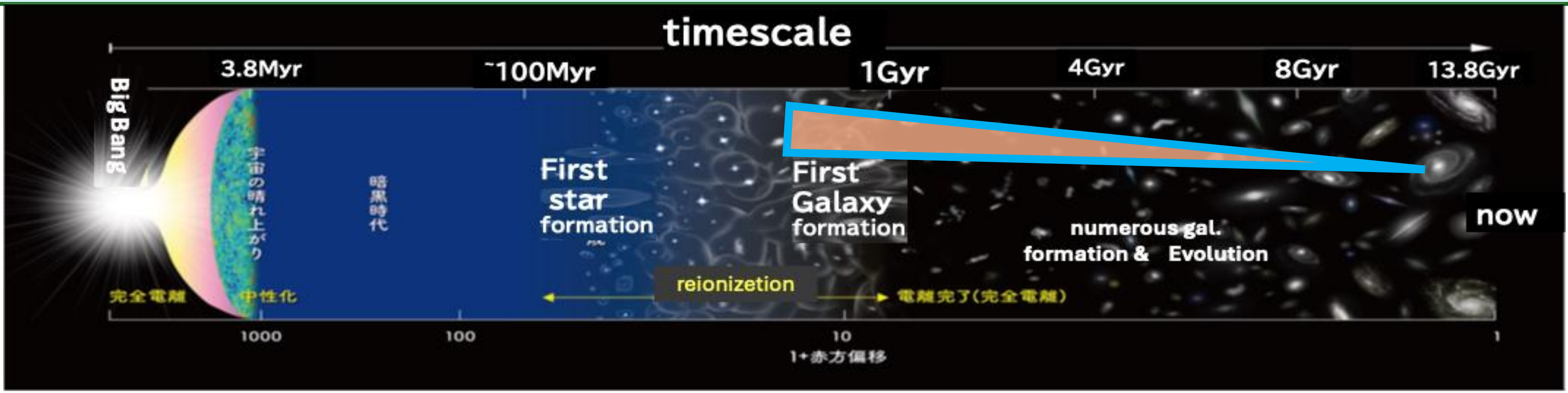
1. Introduction

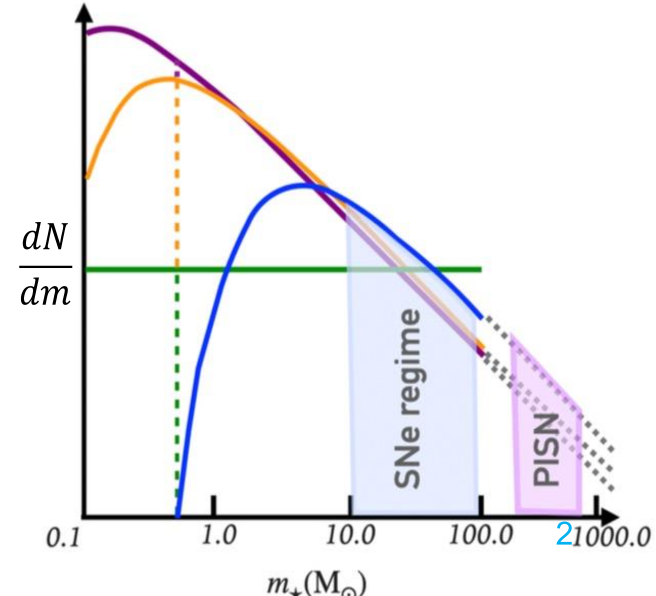


Ultimate goal of this study:

Estimate PopⅢ stars' properties, especially IMF from nearby observation

Theoretical studies suggest top-heavier IMF (Susa+ 14',chon +'21,...)

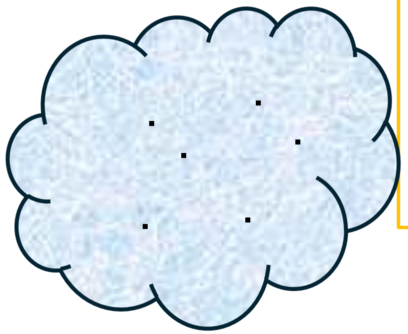
Cannot find PopⅢ stars directly (e.g. ZERO survey)



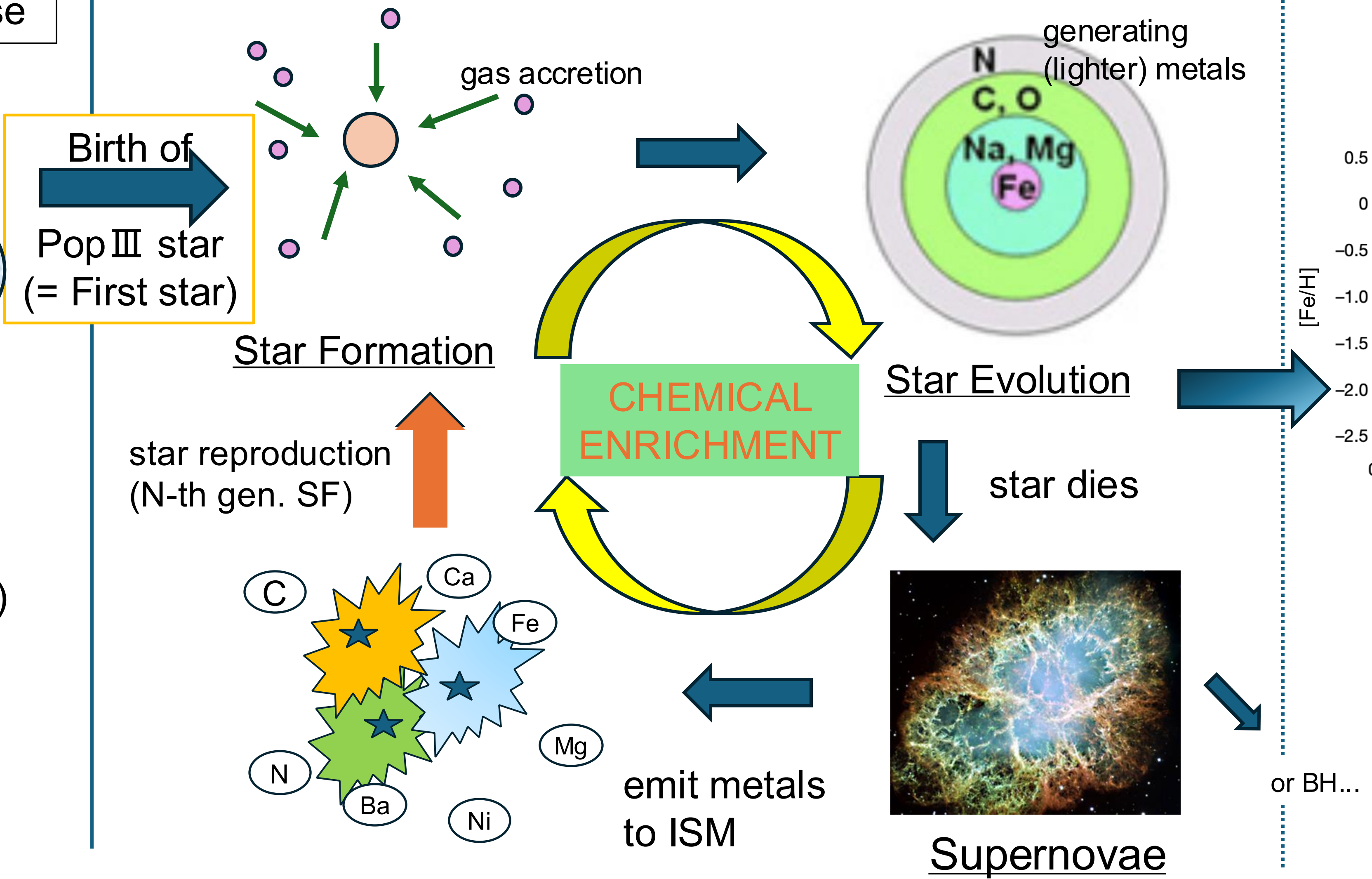
1. Introduction

Chemical evolution

Earliest universe

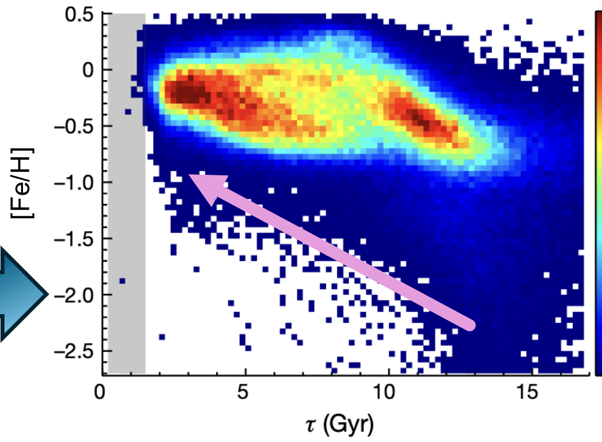


Pristine:
only H, He
(+fraction of Li)
exists



Present-day

Age- Metallicity relation



Xiang+ 22'

1. Introduction

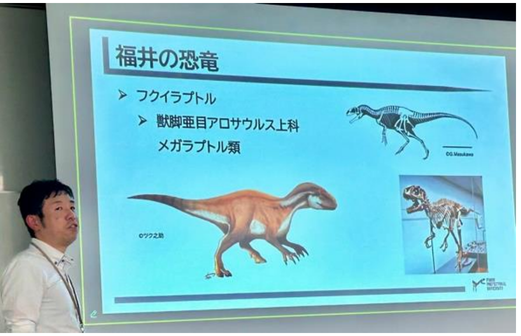
Ultimate goal of this study:

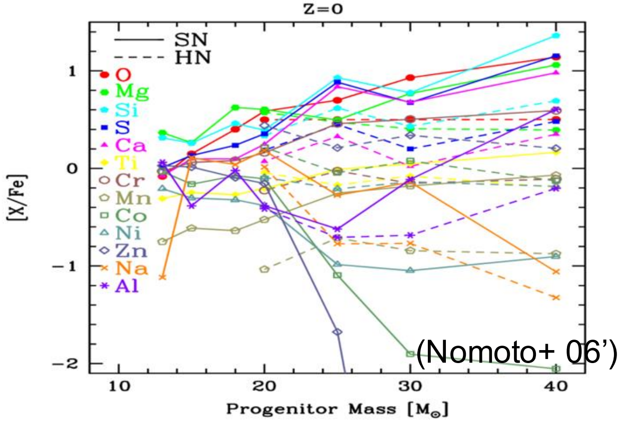
Estimate PopIII stars' properties,
especially IMF from nearby observation

Theory of PopⅢ SNe yields

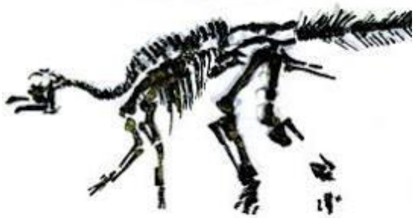
×

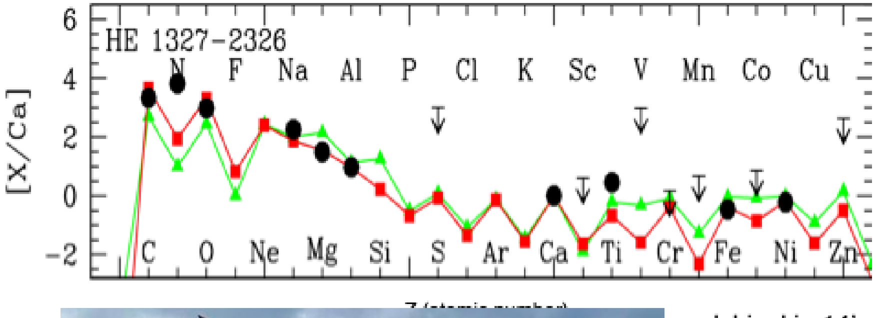
Observational information of 2nd generation stars



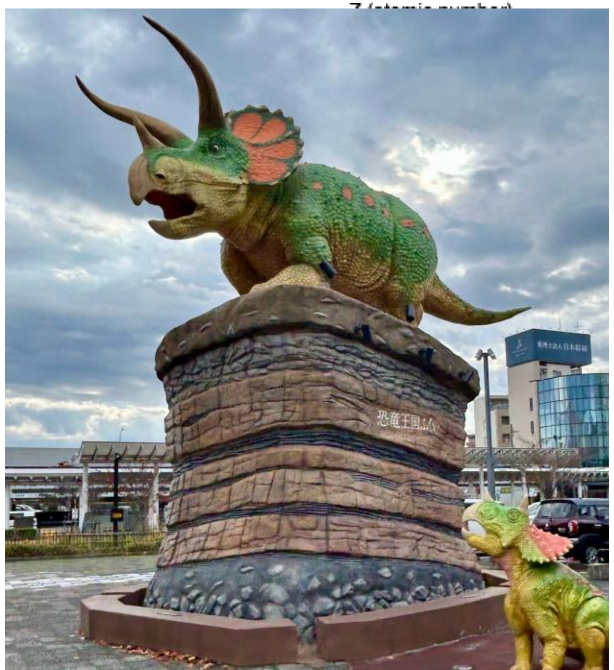


(Nomoto+ 06')





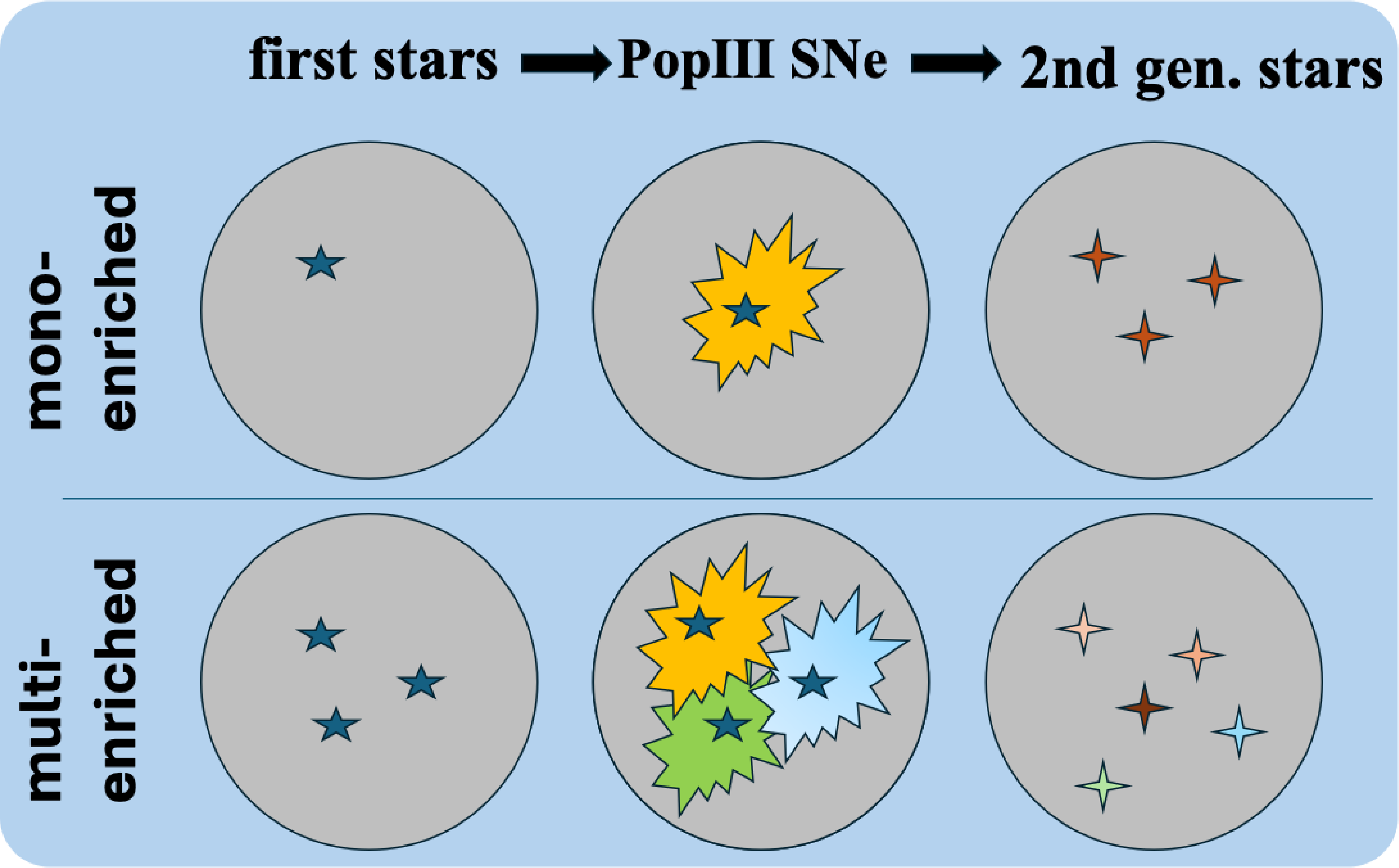
Ishigaki+ 14'



Reveals the statistical properties of the Milky Way at birth,
using observational information from First stars' 'their own children'.

2. mono/multi –enriched stars

Classify 2nd Gen. stars with the history of chemical enrichment



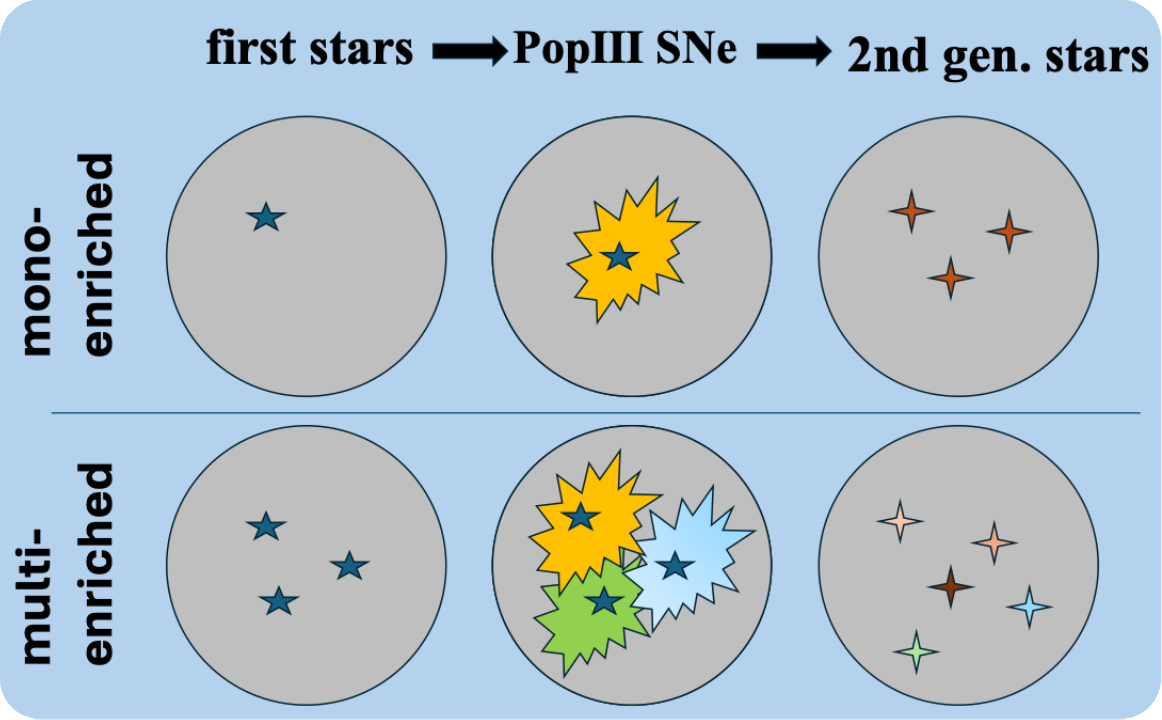
2nd generation stars that enriched only by SINGLE PopⅢ SN

2nd generation stars that enriched by Multiple PopⅢ SNe

2.1 mono/multi –enriched stars

mono/ multi enriched star classification

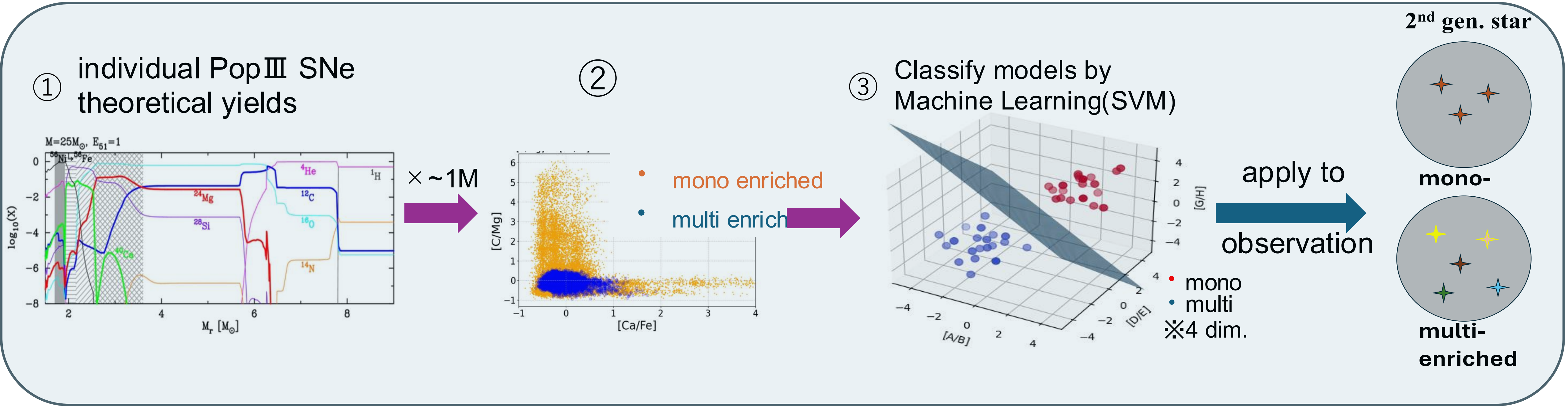
- The enrichment history cannot be distinguished from observation directly
- Only mono-enriched stars from their abundance ratios tell us the properties of PopⅢ stars



Try to classify observed 2nd gen. stars using machine learning to determine which enrichment history they have experienced.

3. Methods & Data

general flow



② : construct each mono/multi-enriched model by superposing PopⅢ yield model

that also considered hypothetical IMF/ explosion function $(p(\alpha, \xi(M)))$

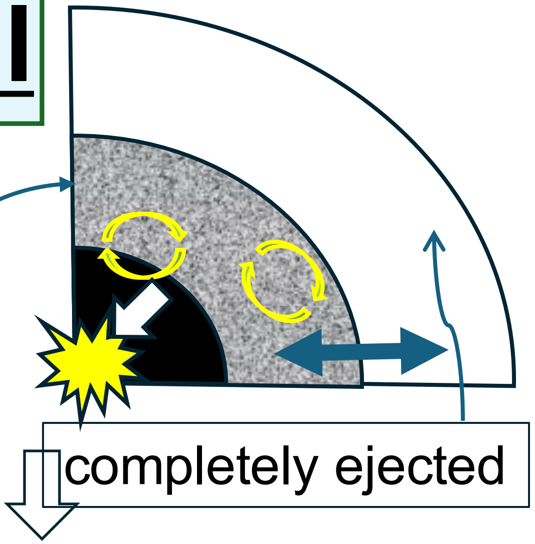
- Hypothetical IMF: $\frac{dN(m)}{dm} \propto m^{(-\alpha)}$

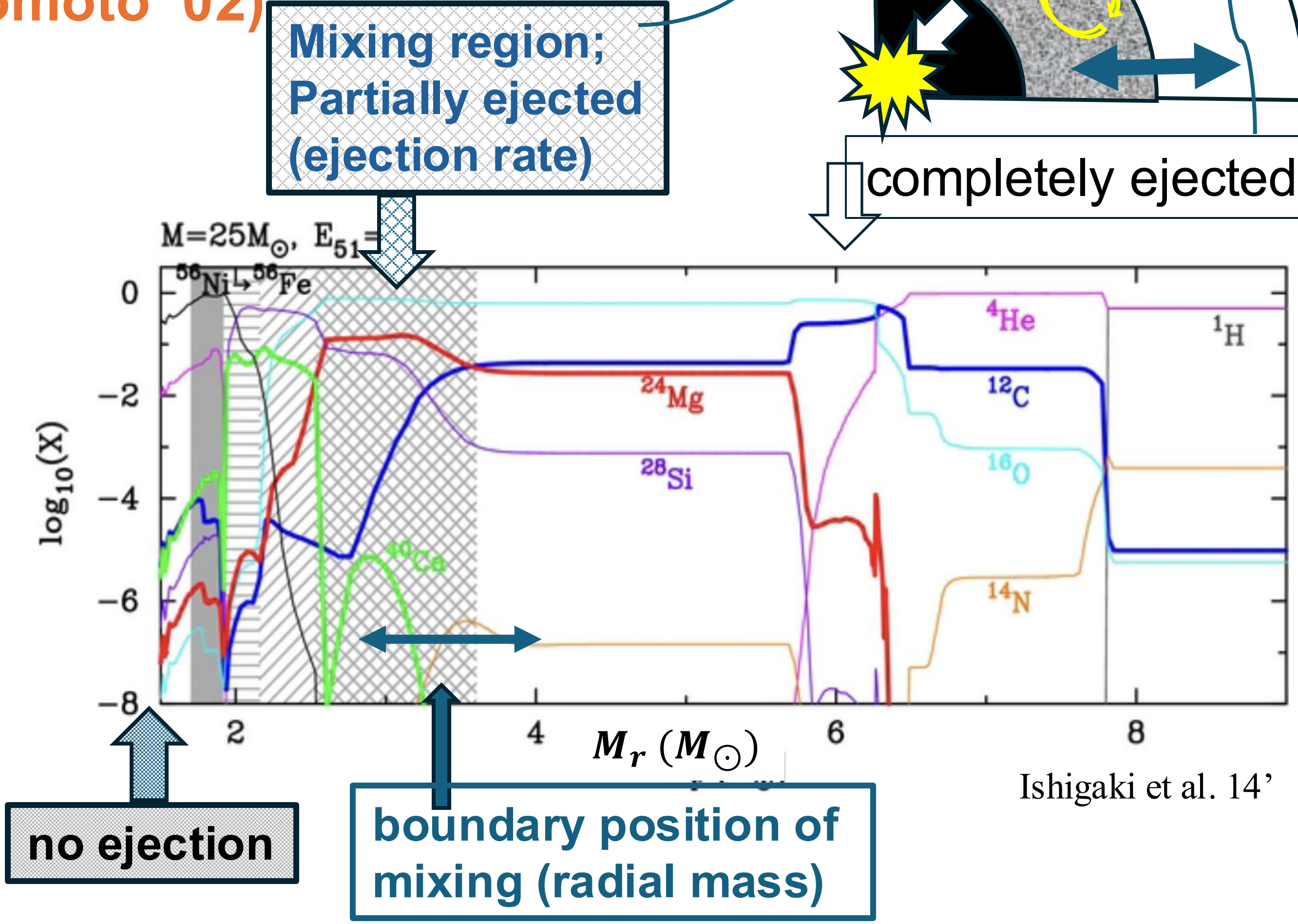
(cf.) Salpeter IMF: α=2.35, Top-heavy -> smaller α)

3.1 Theoretical Pop Ⅲ SNe yield model

Determine individual Pop Ⅲ SNe yield
from **Mixing-fallback model(Umeda &Nomoto '02)**

- **Averaging approximation for non-symmetrical (jet) explosions**
- Observationally motivated model (pattern-fitting)
- **More flexible for observation, especially like faint-SN,CEMP**
  ⇆(canonical model
  (Heger &Woosley 02' ,etc.))





Ishigaki et al. 14'

Variables:

- Initial stellar mass (13 -100$M_\odot$)
- Explosion energy (0.8~60 $\times 10^{51}$erg)
- Mixing parameters
  (**mixing mass & ejection rate**)

Used as source of training data for Machine Learning,
set "coarse" constraints from observation against mixing-fallback model

3. Methods& Data

3.2 construct mono/multi enriched dataset

construct each models by superposing PopⅢ yield model
that also considered hypothetical IMF/ explosion function $(p(\alpha, \xi(M)))$

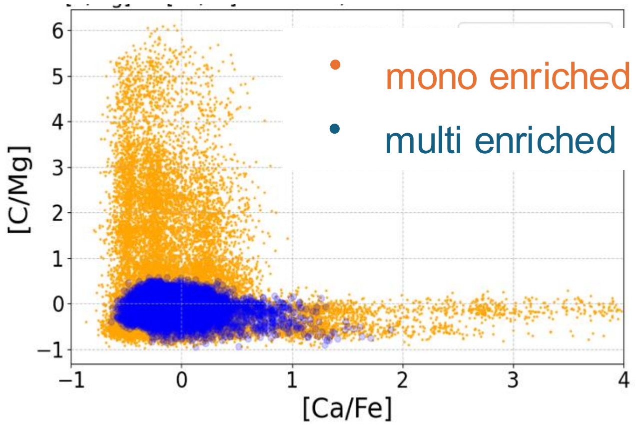
- Hypothetical IMF: $\frac{dN(m)}{dm} \propto m$ ^$(-\alpha)$

(cf.) Salpeter IMF: α=2.35, Top-heavy -> smaller α)

Determine the occurrence fraction of each (M, E)

↓

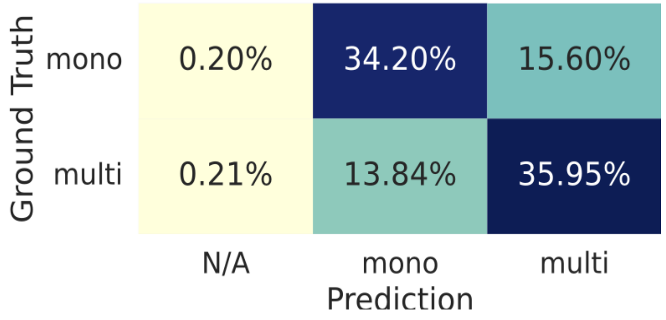
Extract realistic mixing-parameter models within them

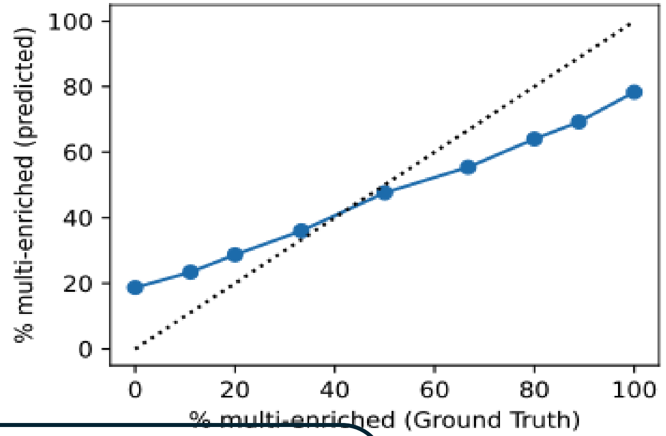


3.3 classification

- previous study for mono/multi –enriched classification

Hartwig et al.23'





Hartwig et al.23

  - Attempt to classify mono/multi enriched by 10 of 4-abundance ratios using SVM

    # of elements used in the analysis: 13
    (C, O, Na, Mg, Al, Si, Ca, Cr, Mn, Fe, Co, Ni, Zn)

    Note: H is not included,
    i.e. the **classification is independent of metallicity**

  - applicable only on classical abundance models

→**Models do not handled with peculiar stars**

  - no prior of constructing dataset

→**could not discuss the property of Pop III stars**

this work:

considering various hypothetical PopⅢ IMFs (/explosion fc.) **as prior & using models also applicable to peculiar stars**

3. Methods& Data

3.4 observational dataset

SAGA database (Suda et al.08')

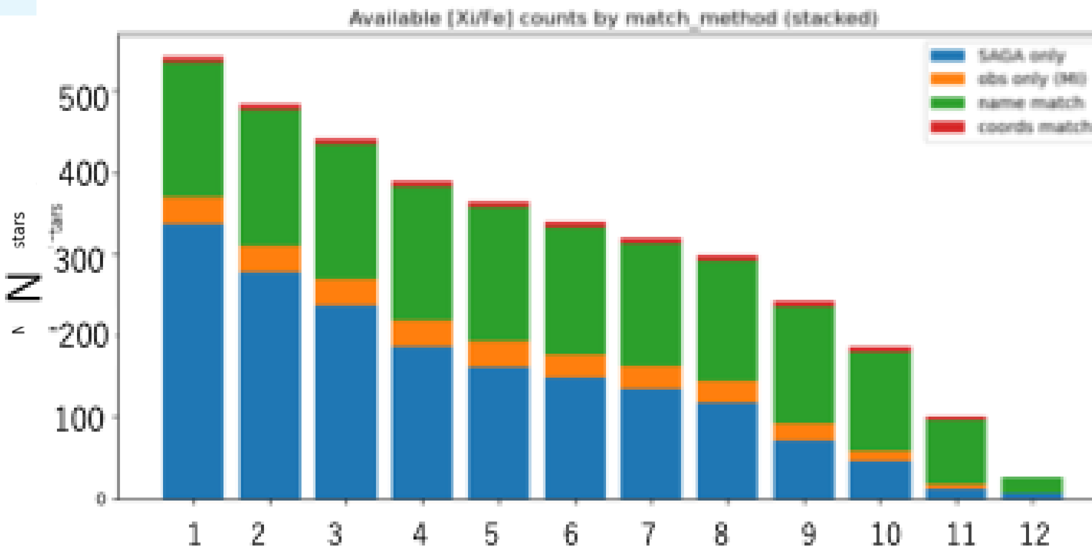
- summary of various local stars' spectroscopic observation

N=510

+

Other EMP data (private conversation with M. Ishigaki) N=206

⇨ 544 objects

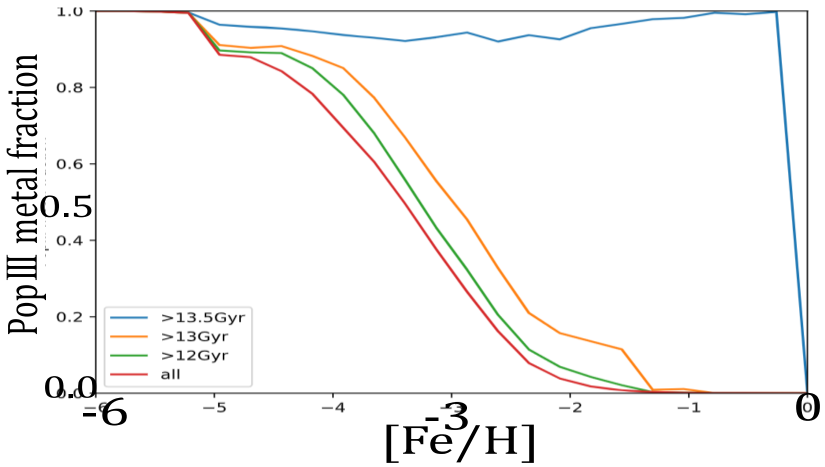


Number of stars with known [X/Fe] abundance ratios

Data selection:

- objects of $[Fe/H] \leq -3.0$(EMP) (MW:486, Dwarf galaxy:57)
  - (2nd gen. stars: mainly observed as EMP)
- measured $\geq$ **6** abundances of 13elements below
  (≧ 6 abundance ratio)
  (C, O, Na, Mg, Al, Si, Ca, Cr, Mn, Fe, Co, Ni, Zn)
  (↑ elements set also used as training dataset for ML)

→ **339 objects**

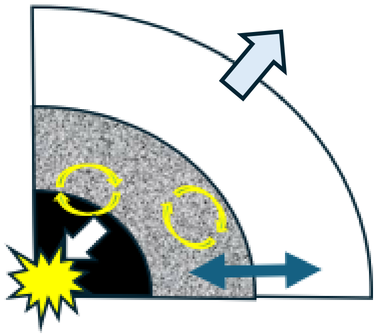


※ $[Fe/H] = X \quad \rightarrow \quad Z \sim 10^X Z_\odot$

4. **Results**: realistic models from abundances

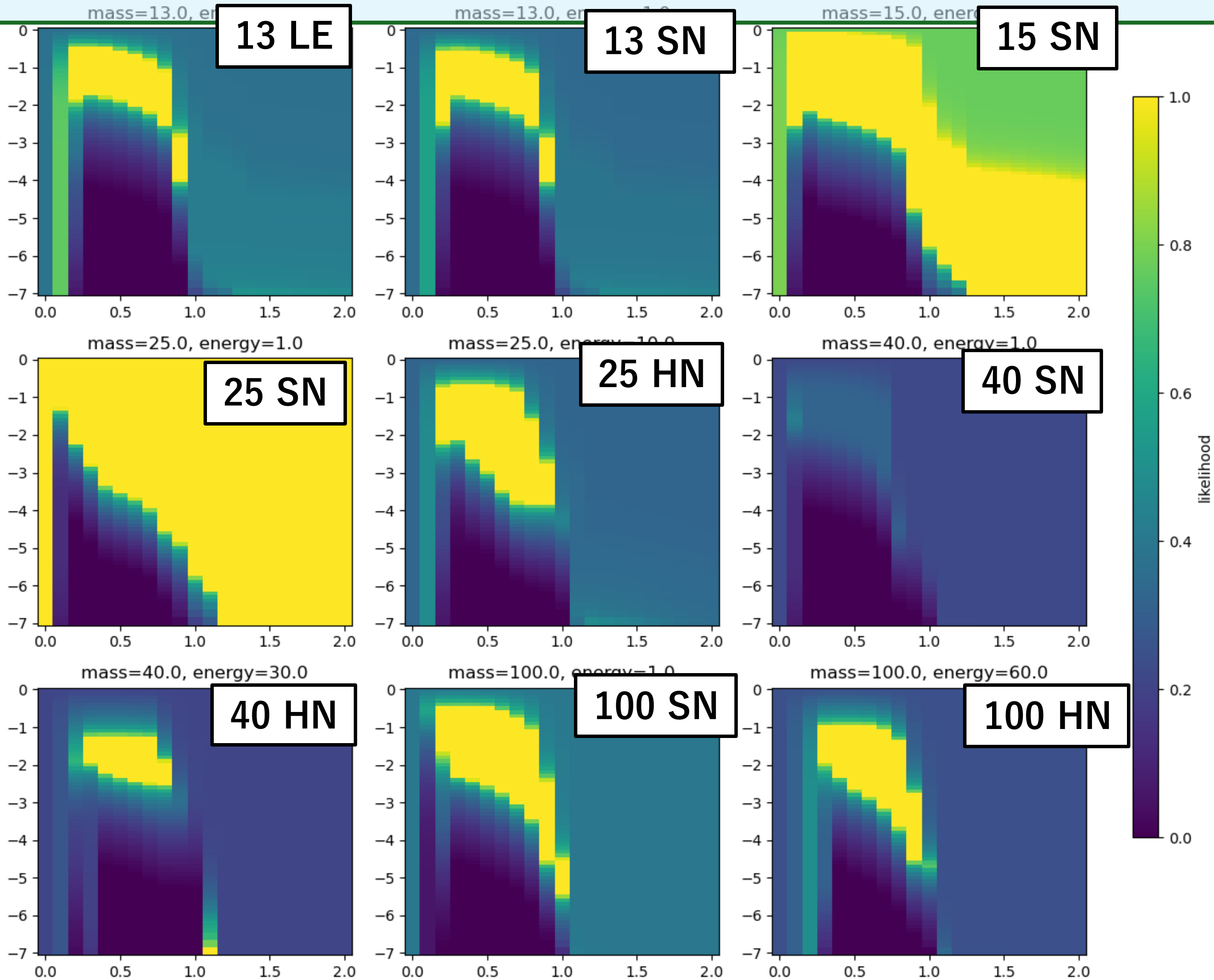
- Realistic mixing-fallback models

LE: low-energy SN
SN: classical SN(10^{51}erg)
HN: Hypernova



likely
possibly
unlikely occur

size of Mixing region



ejected range

- many of 15/25 $M_{\odot}$ SNe model can readily reflect observation (if all mono-enriched)
- HNe are also applicable

4. Results: mono/multi classification

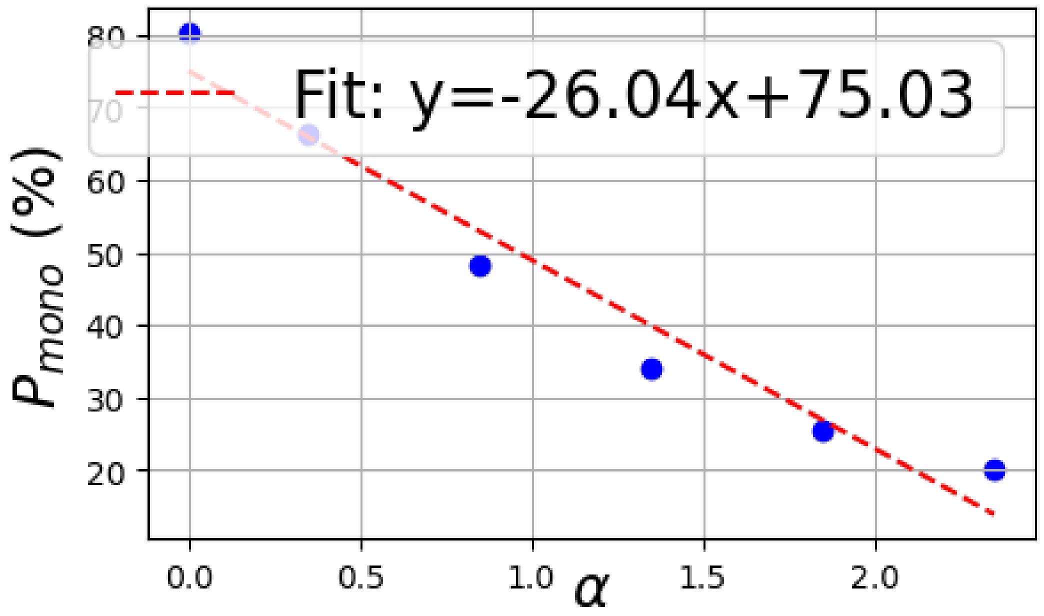
Mono-/ Multi-enriched classification

$\frac{dN(m)}{dm} \propto m^{-\alpha}$

CV1, 1sigma

α	N_{mono}	N_{multi}	P_{mono}(%)		ML classifying accuracy(%)
0.0	163	33	**83.2**		72.4
0.35	123	60	**67.2**		73.1
0.85	89	88	**50.3**		73.2
1.35	66	120	**35.5**		73.4
1.85	46	151	**23.4**		73.3
2.35	37	172	**17.7**		72.9

N_ mono/multi :
# of stars classified as
mono/multi enriched ≥ 1σ
out of 339

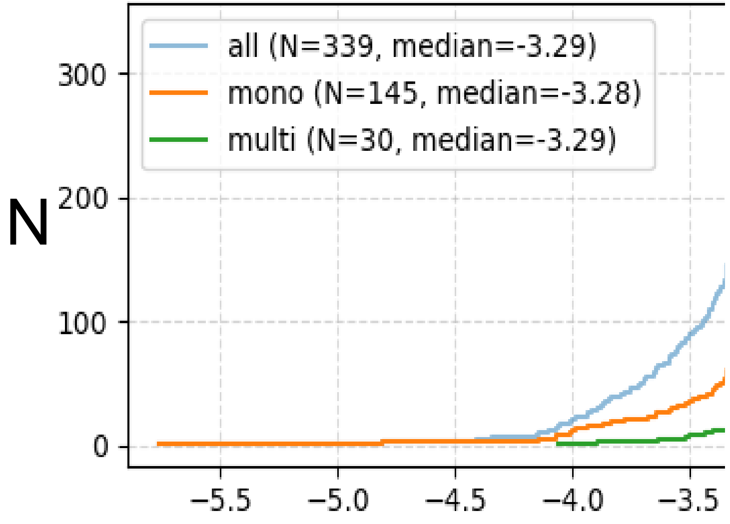


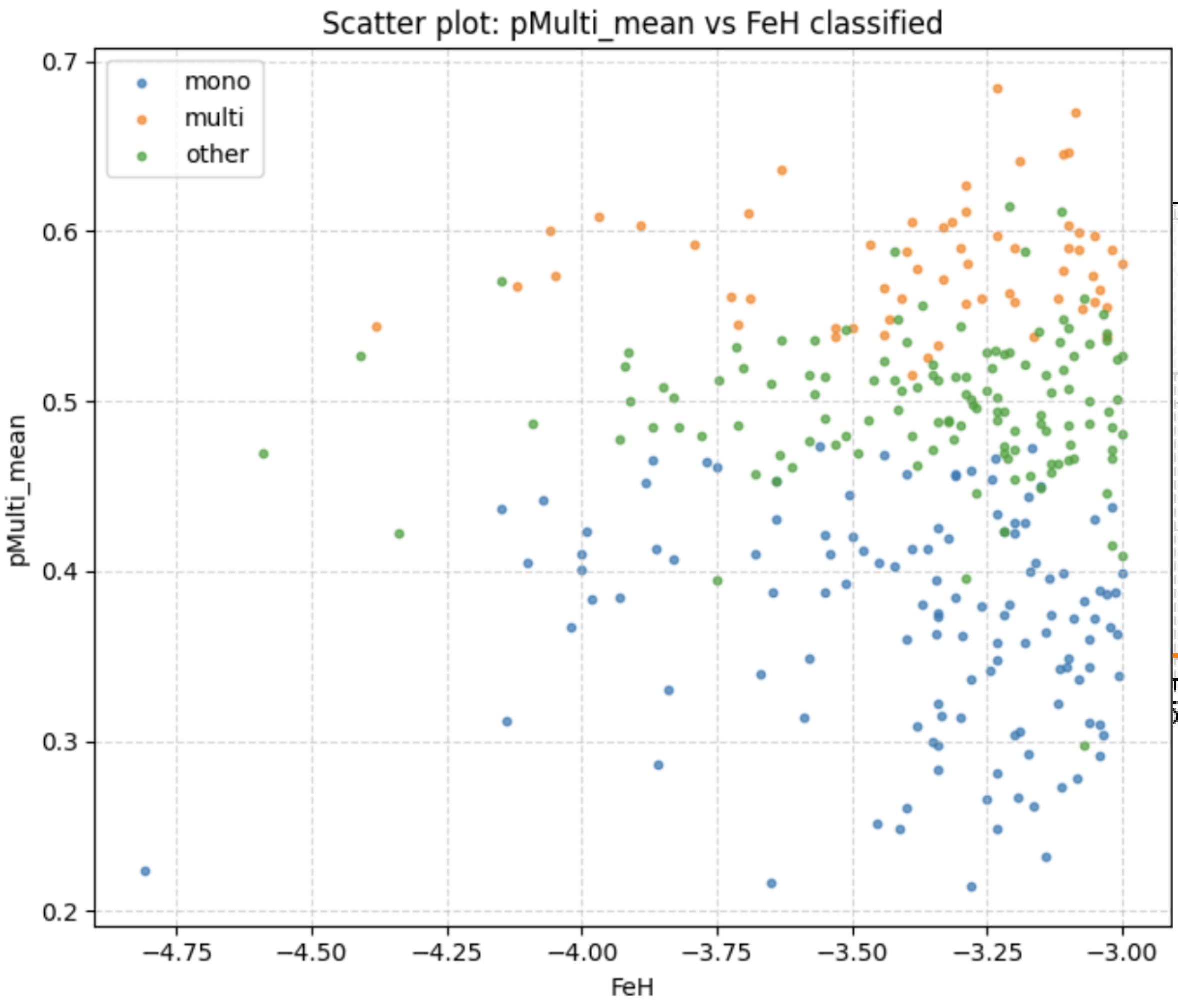
- Certain amount of PopⅢ stars has formed in the (mini)halo.
  (consistent with hydrodynamical simulation (Hirano+. 17';Susa+19'))
- hypothetical α ↘ → proportion of mono-enriched ↗ (cf. Hartwig+23: 31%)
  strong α- P_{mono} relation → degeneracy ?

4. Results: mono/multi classification

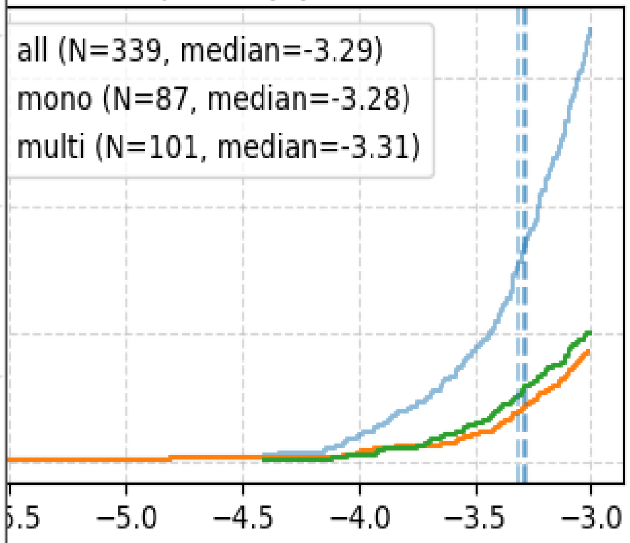
- **metallicity**

α=0.0





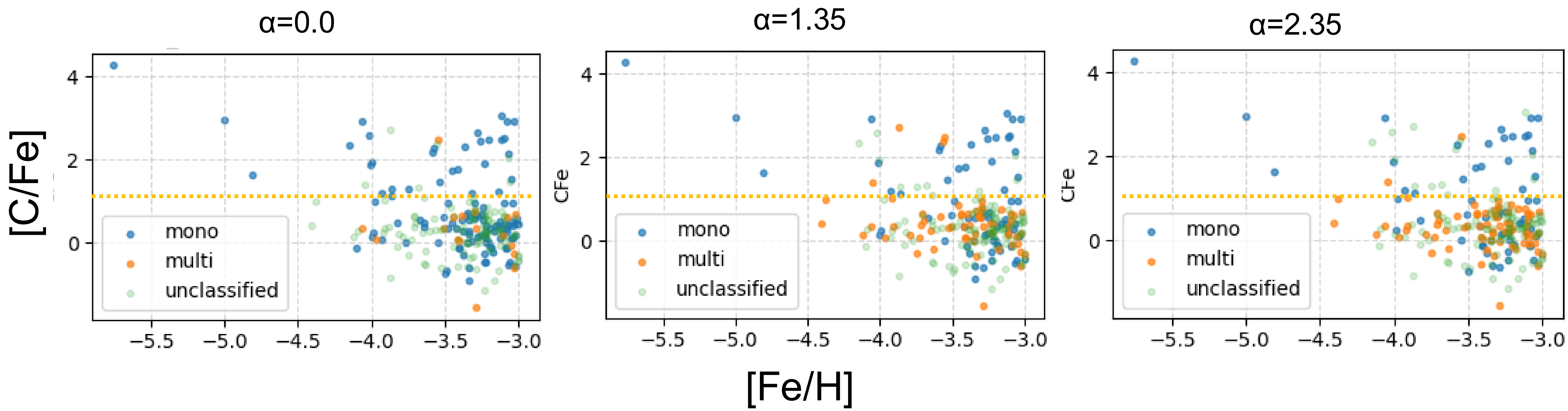
α=2.35



- metallicity does not distinguish between mono/multi enriched classifications.

4. Results: mono/multi classification

- **carbon abundances**



- Regardless of hypothetical IMF (α), at high [C/Fe] ratios, they are likely to be classified as mono-enriched.
- →huge samples of CEMP(carbon-enhanced EMP) stars will help us understand the nature of the first stars in the Milky way.

6. Summary①

- **All hypothesis models suggest...**
  Certain amount of Pop III stars has formed in the (mini-)halo.
  (consistent with hydrodynamical simulation)

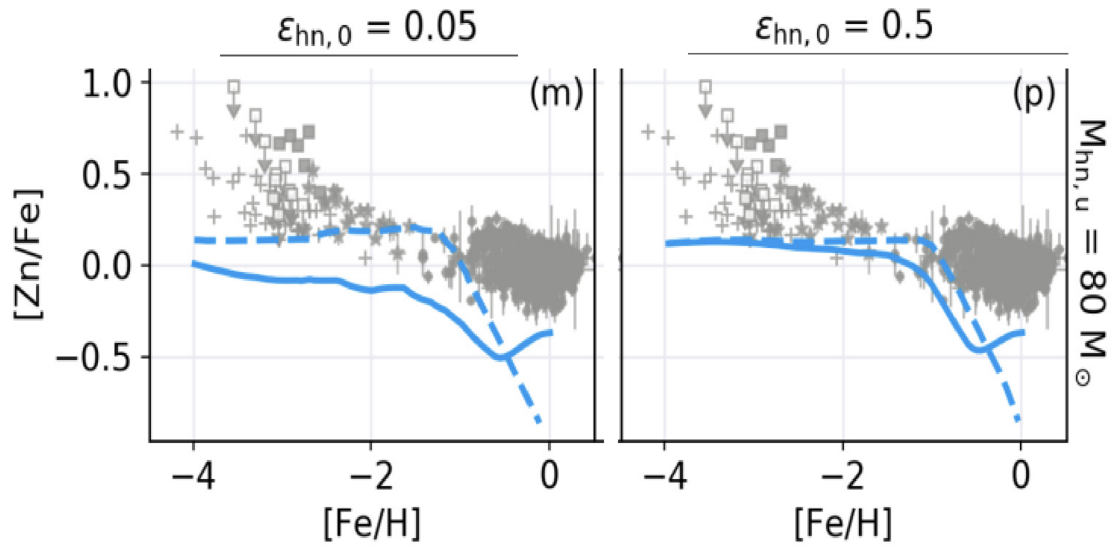
- **Top-heavier IMF hypothesis leads to**
  higher probability of mono enriched stars.
- **Degeneracy** exists between **IMF(α) & mono-enriched probability.**
  Determining the pop III stars' IMF enables us to reveal
  the enrichment history experienced by each star.

- **Carbon** Abundance is strong indicator for finding mono enriched stars.
  → **Large samples of CEMP** stars, with chemical abundance data
  (especially; C, Ca, Zn) .

5. Why consider SN propagation & dilution?

- Observations:
  EMP stars often show high [Zn/Fe],
  indicating strong Hypernovae contributions.

- Theoretically: Pop III Hypernova birth fraction is expected to be low (~1–5%),
  inconsistent with observations.



Grimmett +20'

5. Why consider SN propagation & dilution?

- **Physical vs Observed multi-enriched star**

- **Physically multi:**
  - geometric overlap of multiple SNRs.
  - Larger SNR radius → higher overlap → physical “multi” increases.

- **Observed multi:**
  - later SN signatures must exceed abundance detection limits.
  - Larger diffusion volume → stronger dilution → observed multi decreases (appears like “mono”)

⇒ Physically multi ≠ Observed multi

Diffusion scale of Pop III SNe

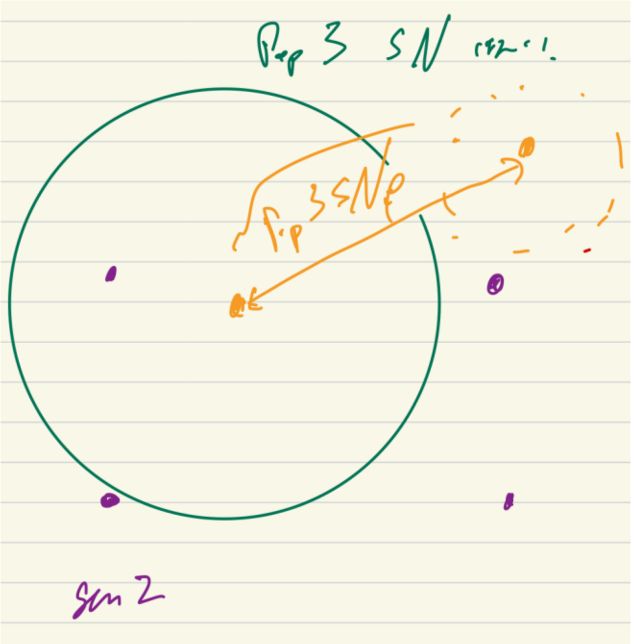
- Effect of SNe yield diffusion that depends on explosion energy
  - timescale vs. 2nd gen. stars formation,
  - scale radius
  - concentration, etc.

  re-constructing multi enriched models by taking these effects into account

- **Diffusion volume: $V \propto R^3$:**

  HN can pollute 10–30× larger regions.

$$\boxed{V_{shell\_pd\_snowplow} \propto 4\pi R^2 \times R_\delta \propto E^{0.58}}$$



→Even a small HN birth fraction can dominate the pollution of 2nd-gen stars.

6. Summary

- Built an ML-based framework to classify mono/ multi-enriched 2nd gen. stars using Pop III CCSN mixing–fallback yields.

- Applied the method to synthetic datasets with explicit assumptions on the Pop III IMF and explosion-energy distribution and quantified the mono fraction p_mono for each model.

- Found a strong IMF–p_mono degeneracy, where top-heavy IMFs yield apparently larger mono fractions, and showed that [Fe/H] is uninformative while carbon abundances (CEMP stars) act as the most effective discriminators.

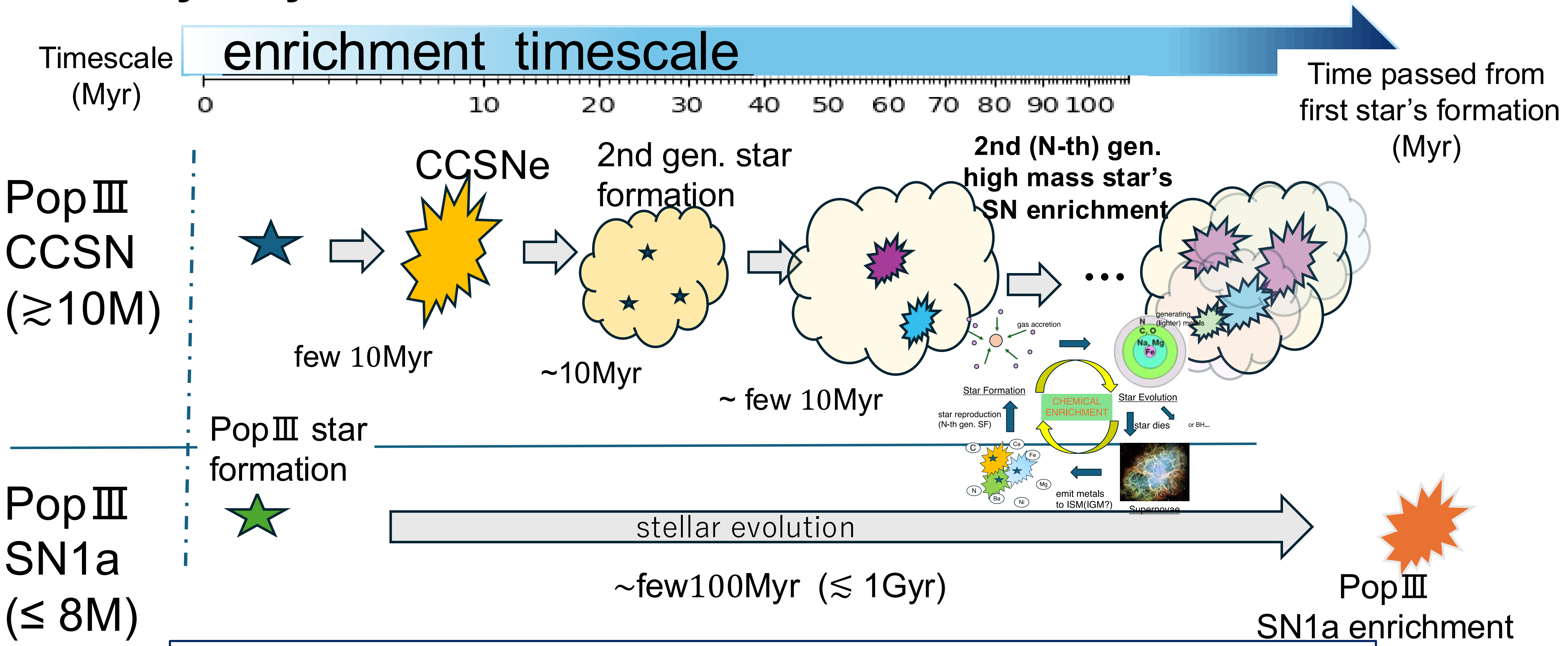
- Physically multi-enriched and observed multi-enriched do not necessarily coincide. SN propagation and metallicity dilution are taken into account.

Next step:
construct a diffusion-based physical model for p_gen2(M, E) that links Pop III SN mass, energy, diffusion scale, and the observed mono fraction to interpret and ultimately break the IMF–p_mono degeneracy.

back-up

2.2 Theoretical PopⅢ SNe yield model

① Why only CCSNe?



No PopⅢ only enrichment stars include PopⅢ SN1a

2.2 Theoretical PopⅢ SNe yield model

① **Why only CCSNe?**

Type 1a SN : $M < 8M_{\odot}$

CCSN : $10M_{\odot} < M < 100M_{\odot}$

matter partly ejected

PPISN : $100M_{\odot} < M < 140M_{\odot}$

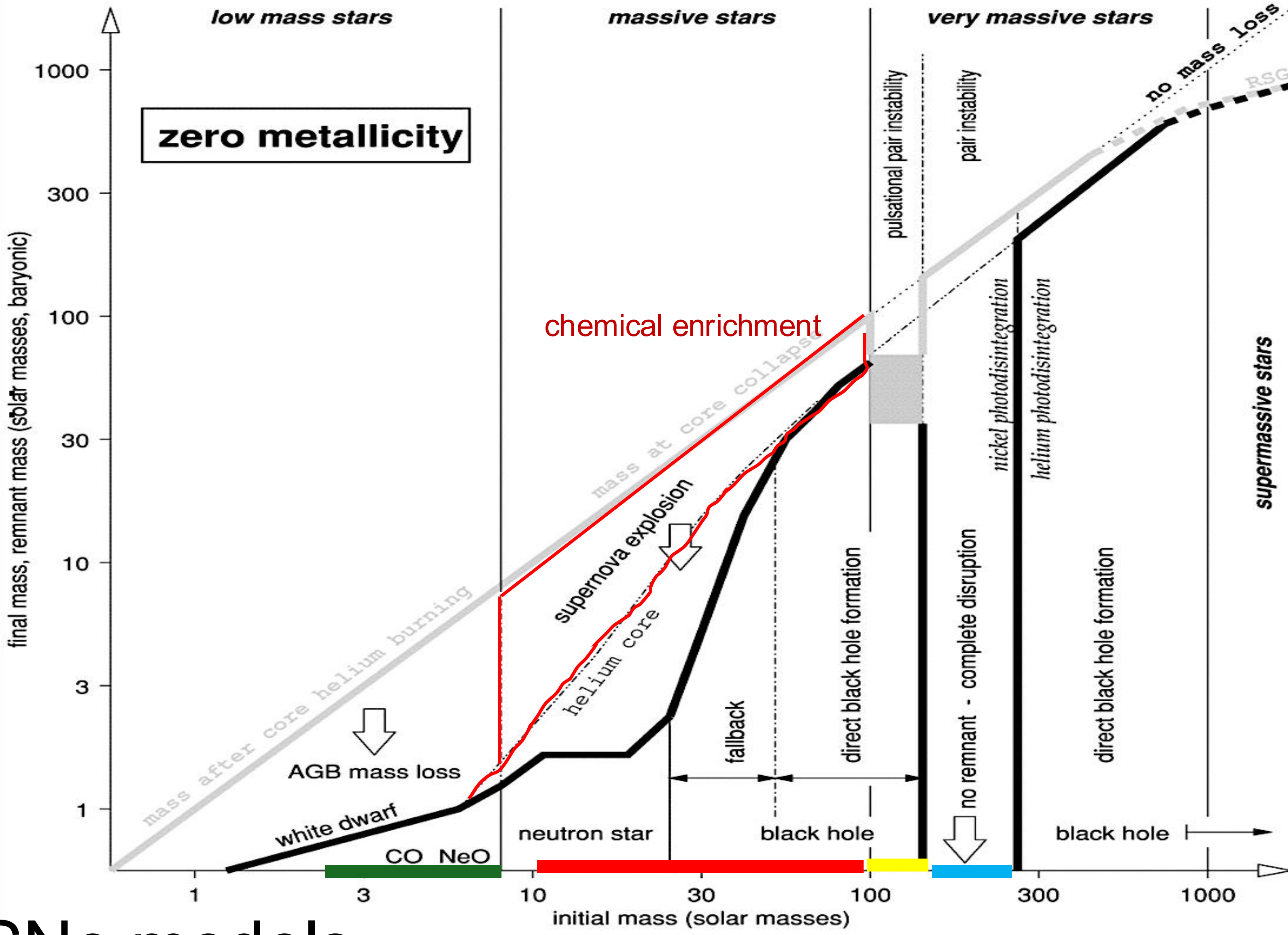
Direct BH formation

PISN : $140M_{\odot} < M < 260M_{\odot}$

completely disrupted
not understand well

(Supermassive) :$260M_{\odot} < M$

Direct BH formation



Heger &Woosley 02'

Used only PopⅢ CCSNe models

2.2 Theoretical PopⅢ SNe yield model

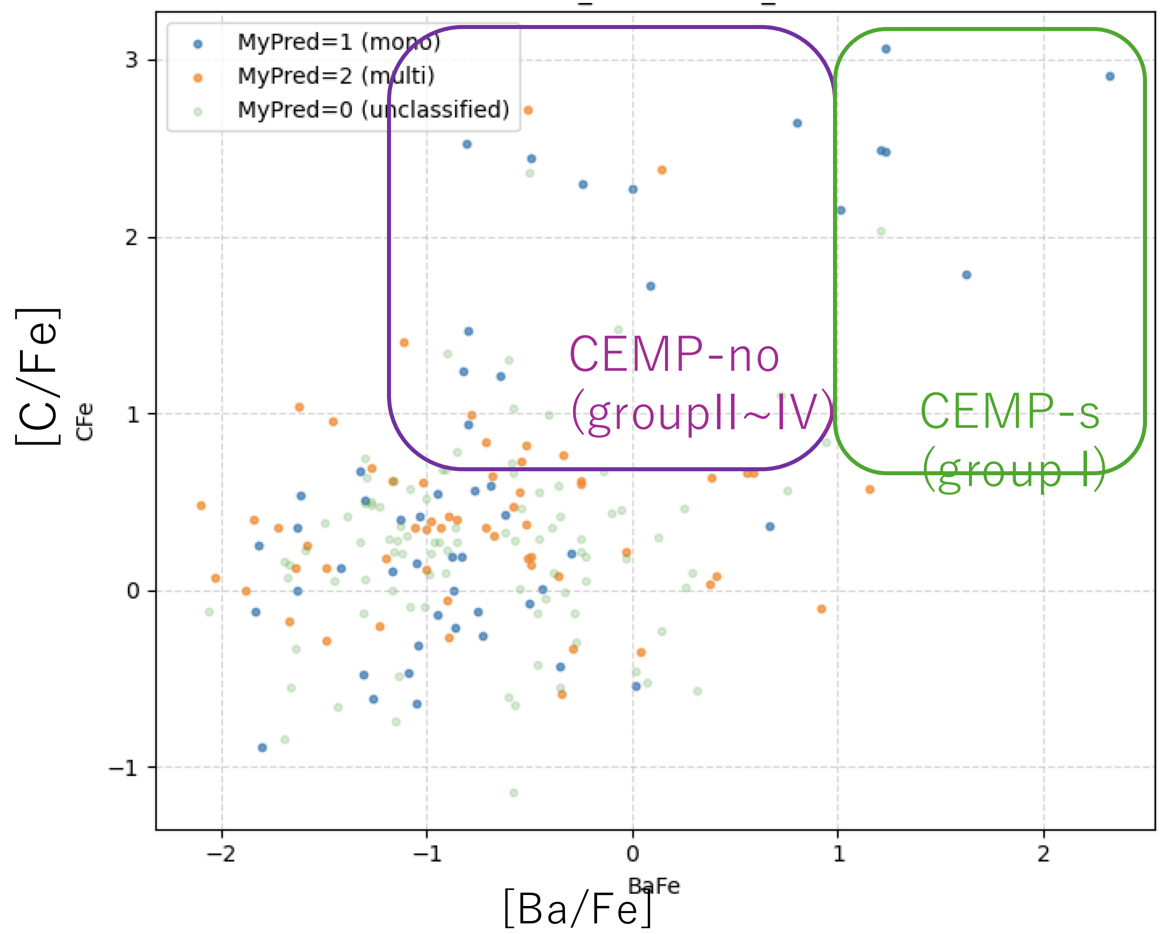
② PopIII SNe yield model type

1. **Widely used reference models:**
   - **Canonical model（Heger& Woosley 02',10'）**
     - 1D piston-driven explosion model of collapsing iron core, tracking 1D shock propagation and nucleosynthesis.
     - Theoretical baseline

2. **Adapted in this work:**
   - **Mixing-fallback model(Umeda &Nomoto et al. '02)**
     - Observationally motivated (pattern-fitting) model

• neutron capture elements

・additional dimension of Ba(s-process)



UMP: [Fe/H] < -4.0

←Ba: did not used as classification

- (Strong) positive correlation between [Ba/Fe] &[C/H]

- s-process rich → CEMP
- CEMP-s are not UMPs, also classified as mono-enriched →implies **AGB mass transfer**? (enriched not only by mono/multi enriched EMP star)

With using Ba abundance, we can exclude some stars "classified as mono-enriched" but that are not in fact so.

JS-divergence

- Identify which elemental ratios are most effective in separating mono-/multi-enriched models

  Evaluate IMF-dependent differences quantitatively (not just visually)

  Apply **Jensen–Shannon divergence (JSD)**
  – a distance-based variant of KL divergence that measures the similarity between probability distributions

$$JS(P||Q) = \frac{1}{2}KL(P||M) + \frac{1}{2}KL(Q||M)$$

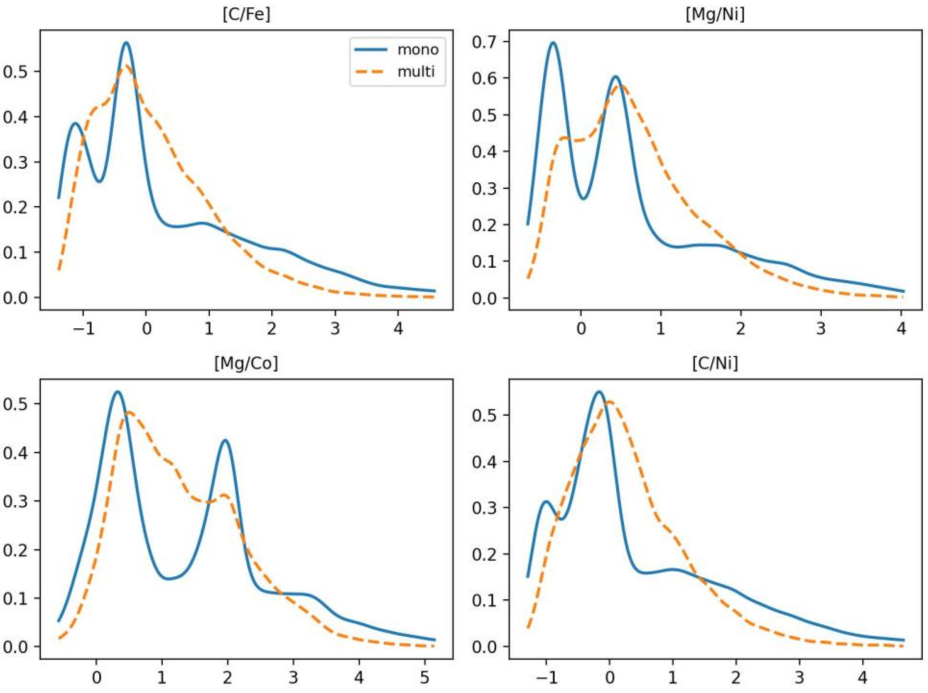
$$D_{KL}(P||Q) = \int P(x)\log\frac{P(x)}{Q(x)}\,dx$$

Kullback–Leibler (KL) divergence:
A measure that quantifies the difference between two probability distributions in an information-theoretic sense.

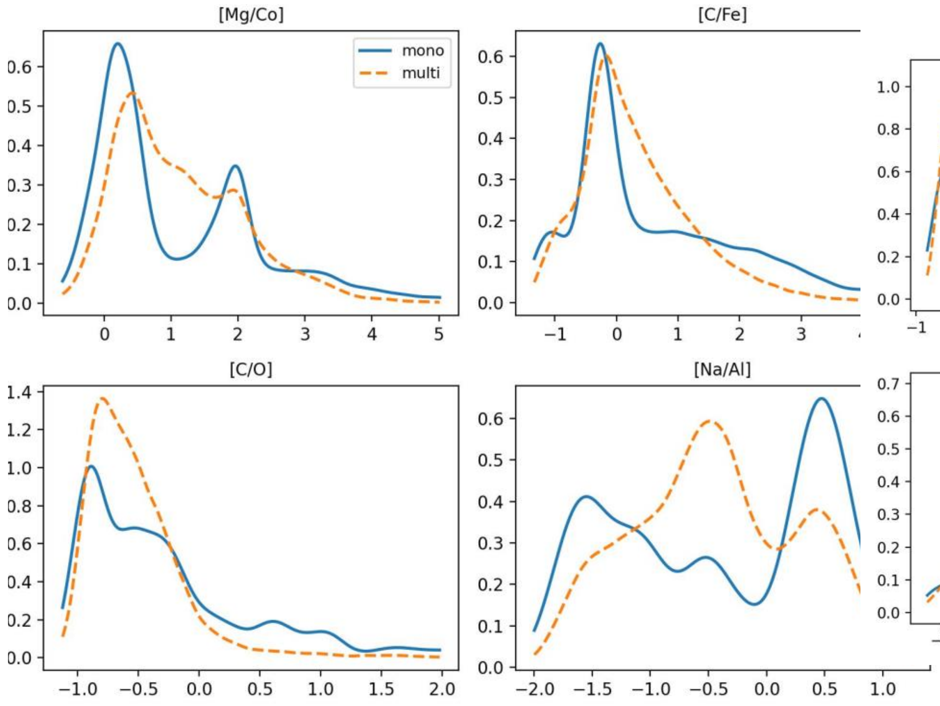
1D/2D distribution

top 4 JS divergence abundance ratio

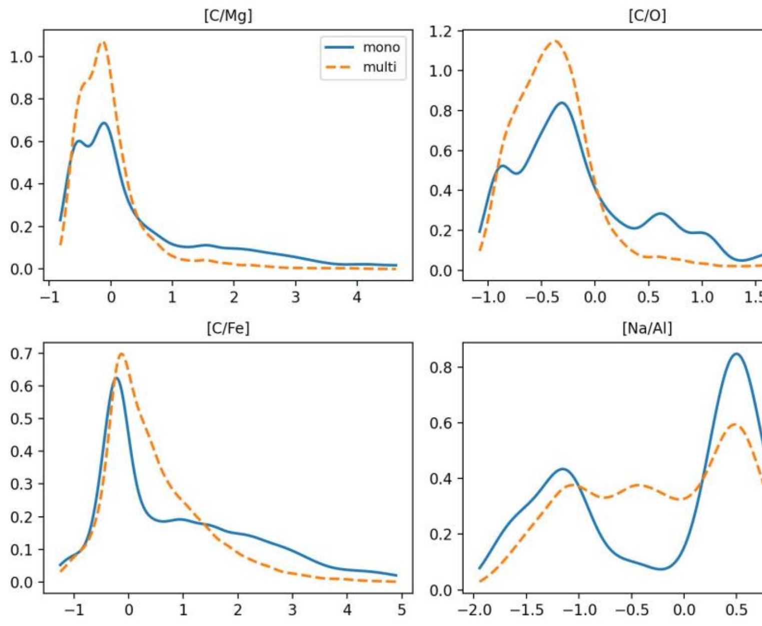
$\alpha = 0.0$



$\alpha = 1.35$



$\alpha = 2.35$



1D/2D distribution

effective ratio &
difference between
hypothetical IMF