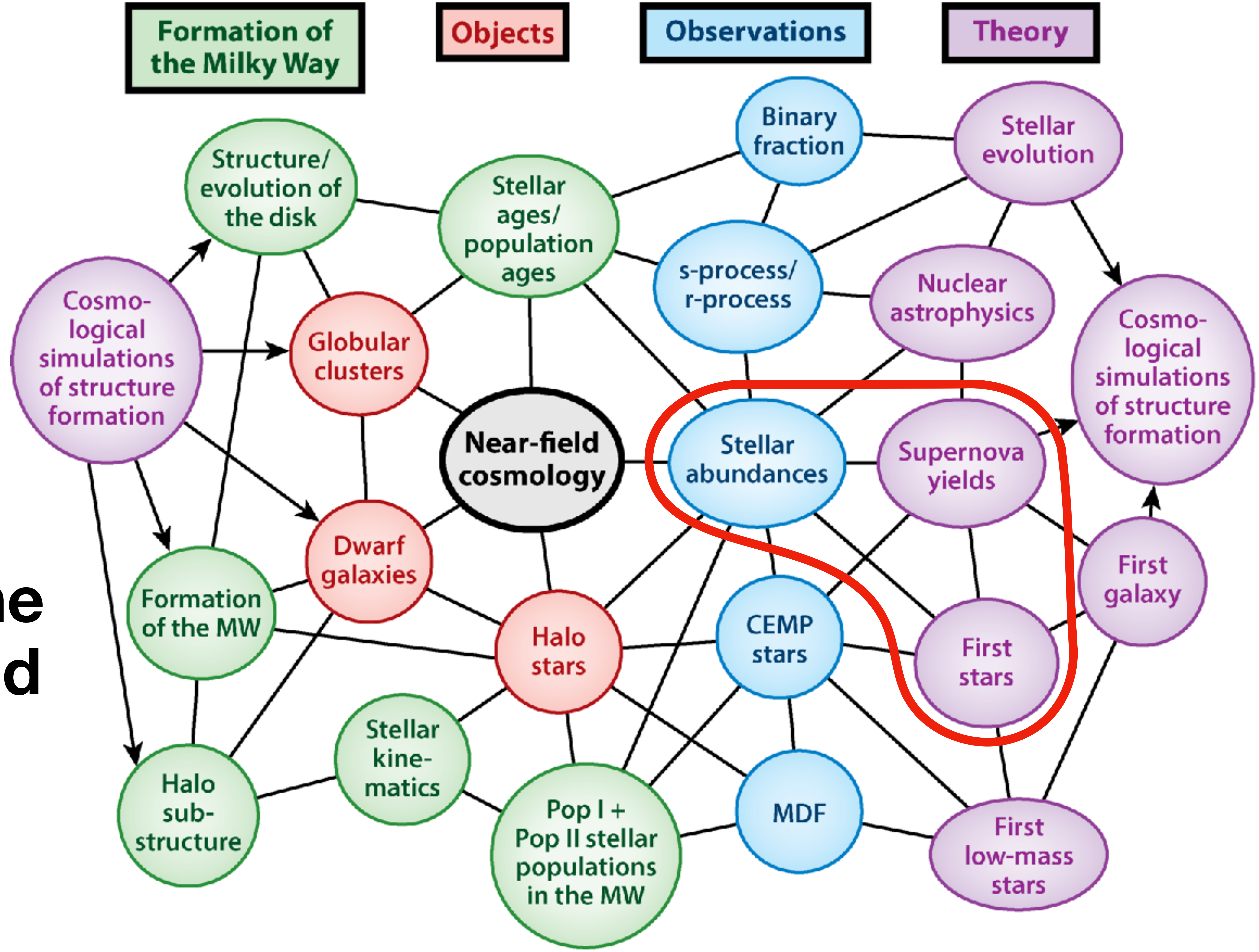
中国科学院国家天文台
NATIONAL ASTRONOMICAL OBSERVATORIES, CAS

Deriving Progenitors of Extremely Metal-poor Stars with Nucleosynthesis Yields of Massive Stars

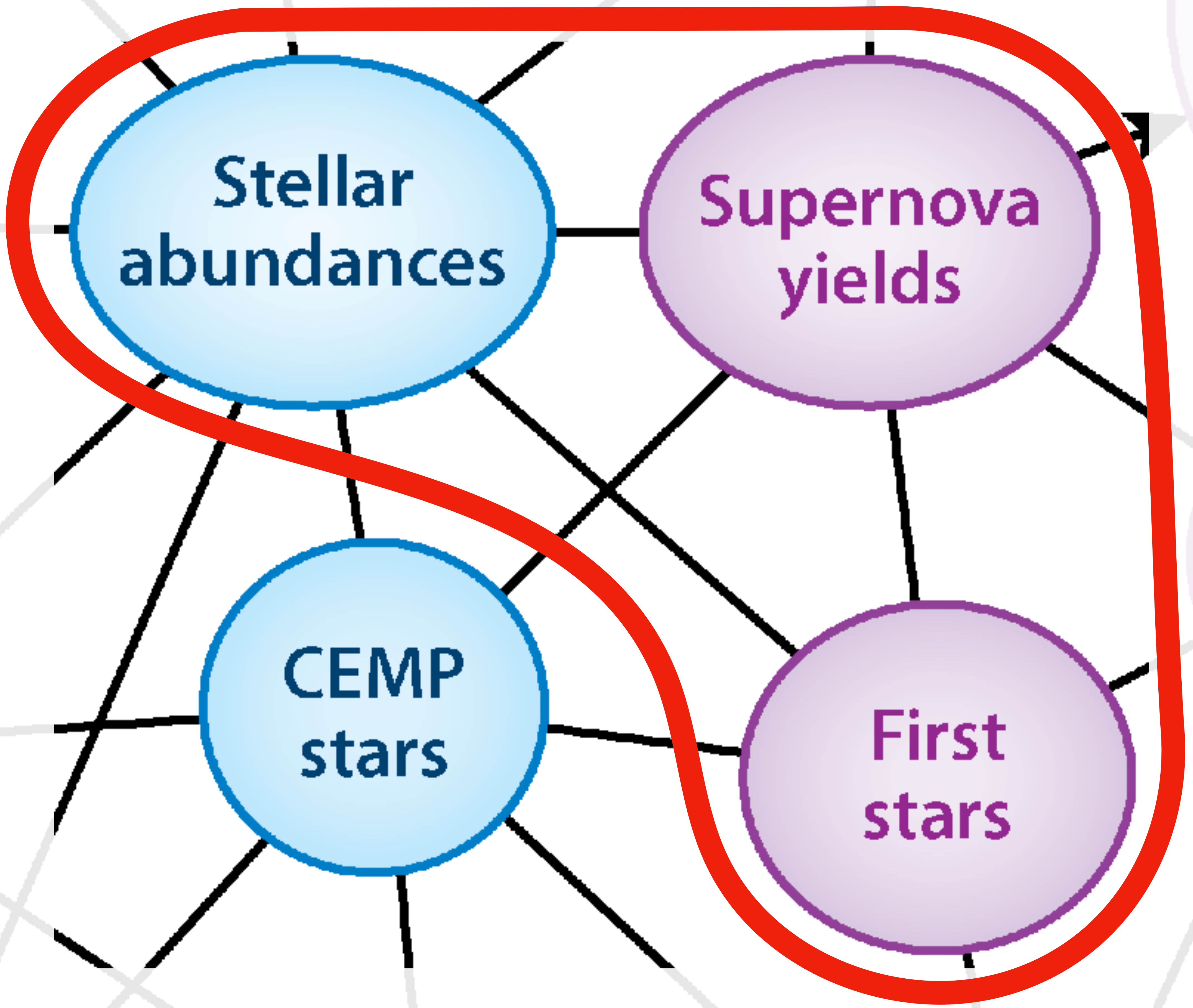
Ruizheng Jiang, Gang Zhao, Haining Li, Qianfan Xing and Wenyu Xin
2025/06/16@Girona

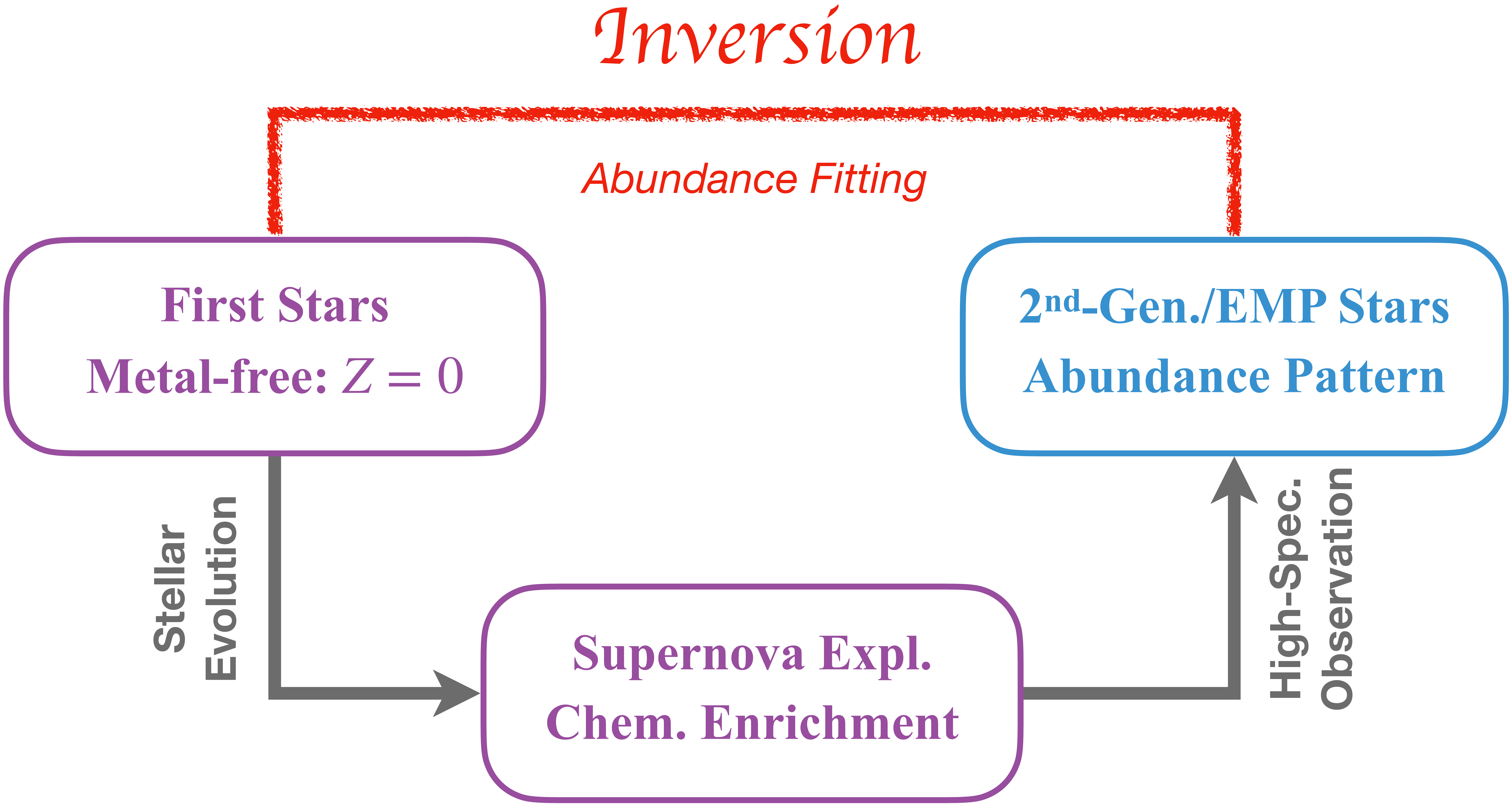
Schematic overview of the topics related to near-field cosmology



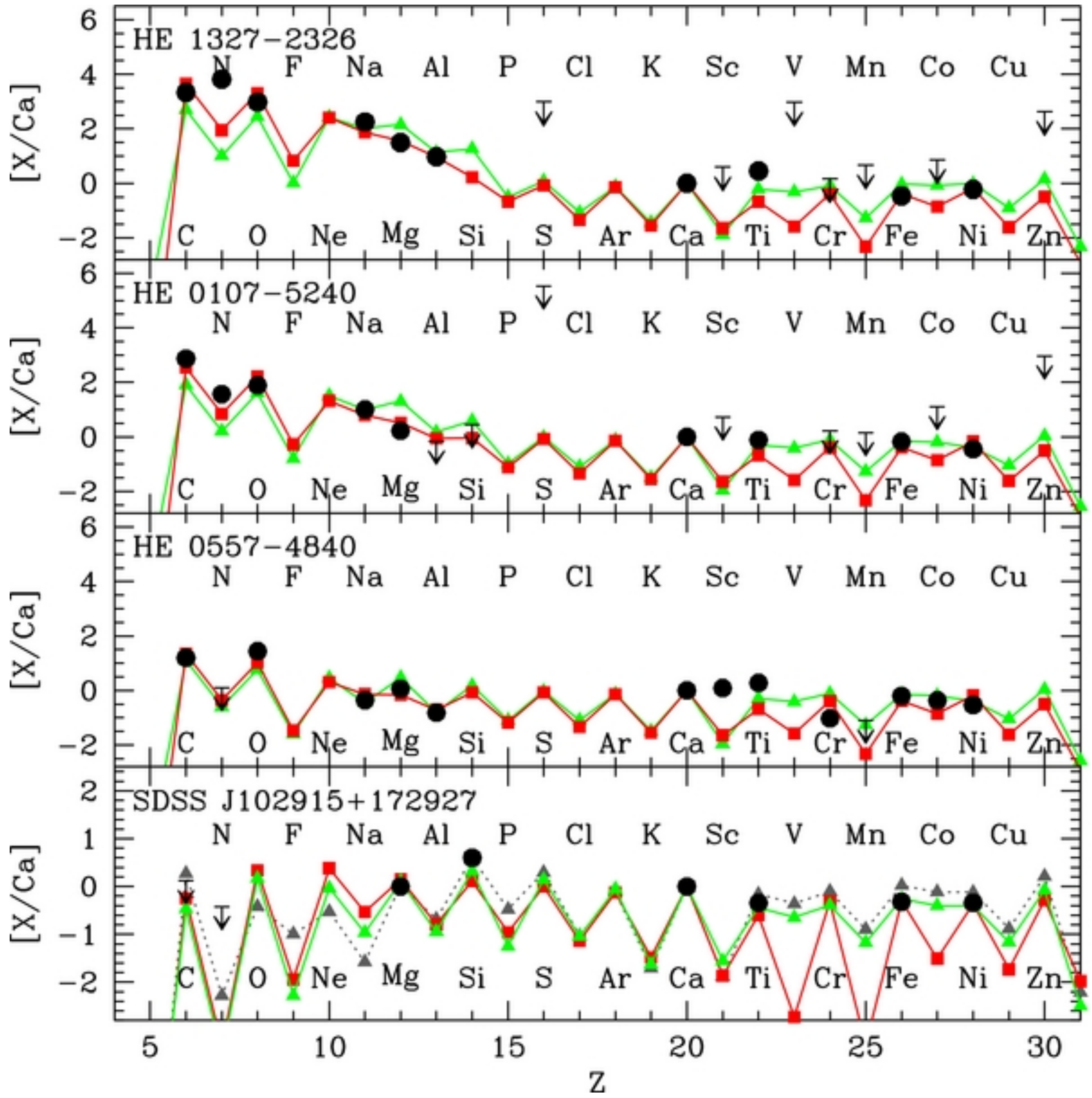
Frebel A, Norris JE. 2015.
Annu. Rev. Astron. Astrophys. 53:631–88

- Atmospheric abundances preserve the chemical environment **at birth**
- **Metal-poor** stars are local equivalent to the **high-redshift** Universe




Inversion
Abundance Fitting
First Stars
Metal-free: $Z = 0$
2nd-Gen./EMP Stars
Abundance Pattern
Stellar Evolution
Supernova Expl.
Chem. Enrichment
High-Spec. Observation

Examples

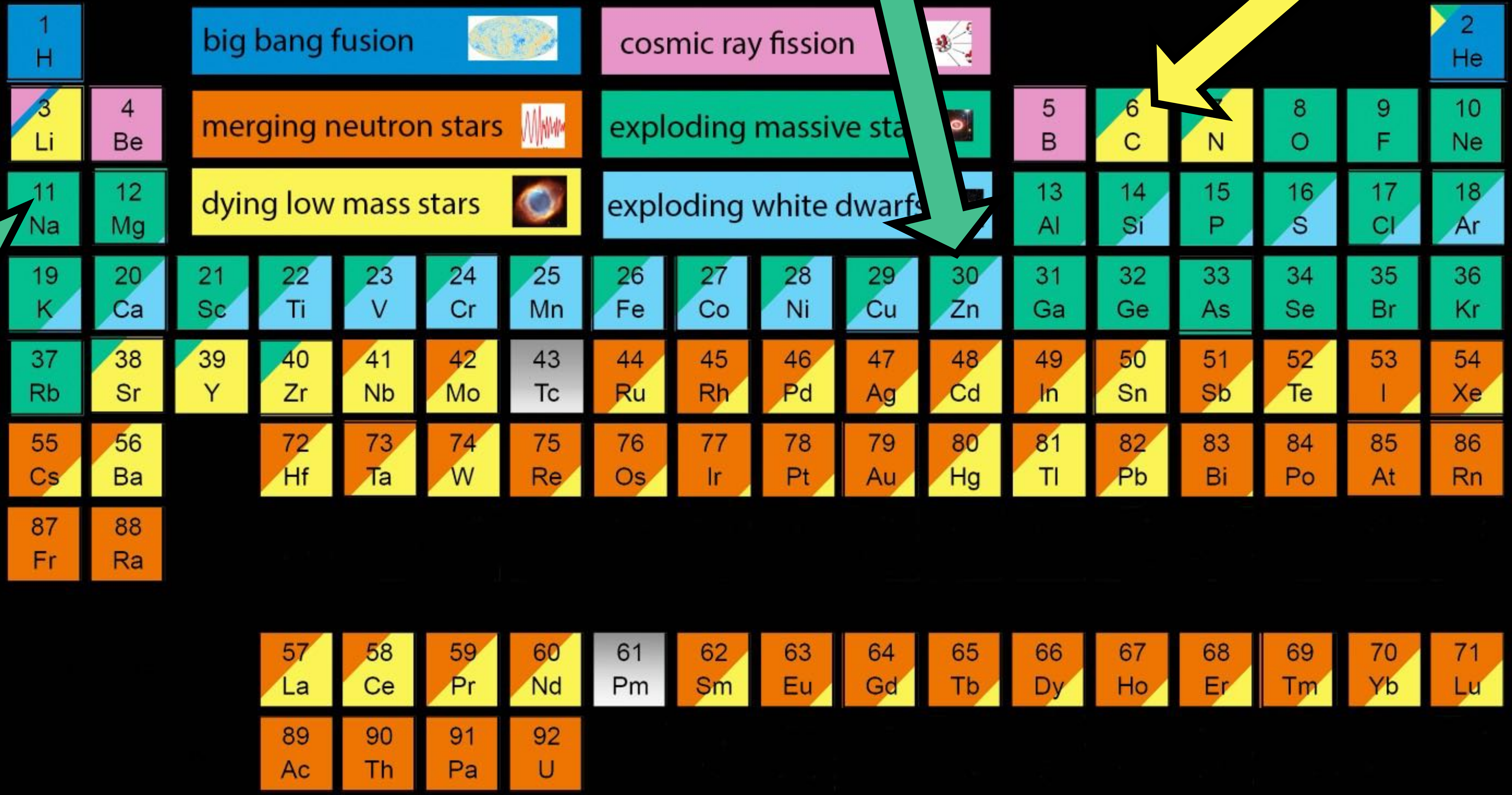


Ishigaki et al. 2014

SN II produces **LIGHT** elements

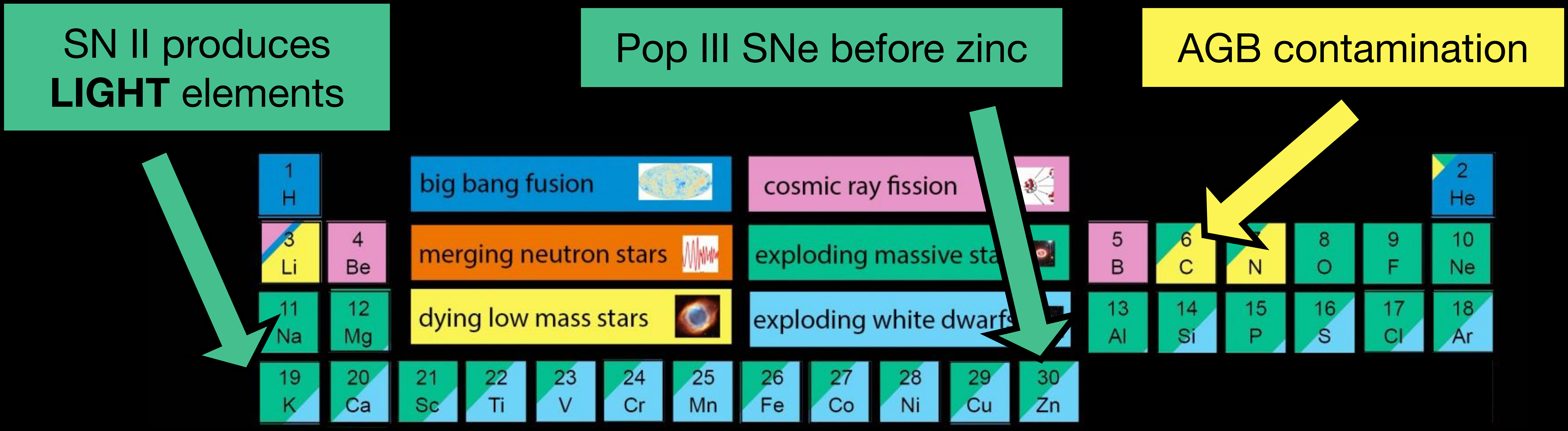
Pop III SNe before zinc

AGB contamination



Graphic created by Jennifer Johnson

Astronomical Image Credits:
ESA/NASA/AASNova



Other filters

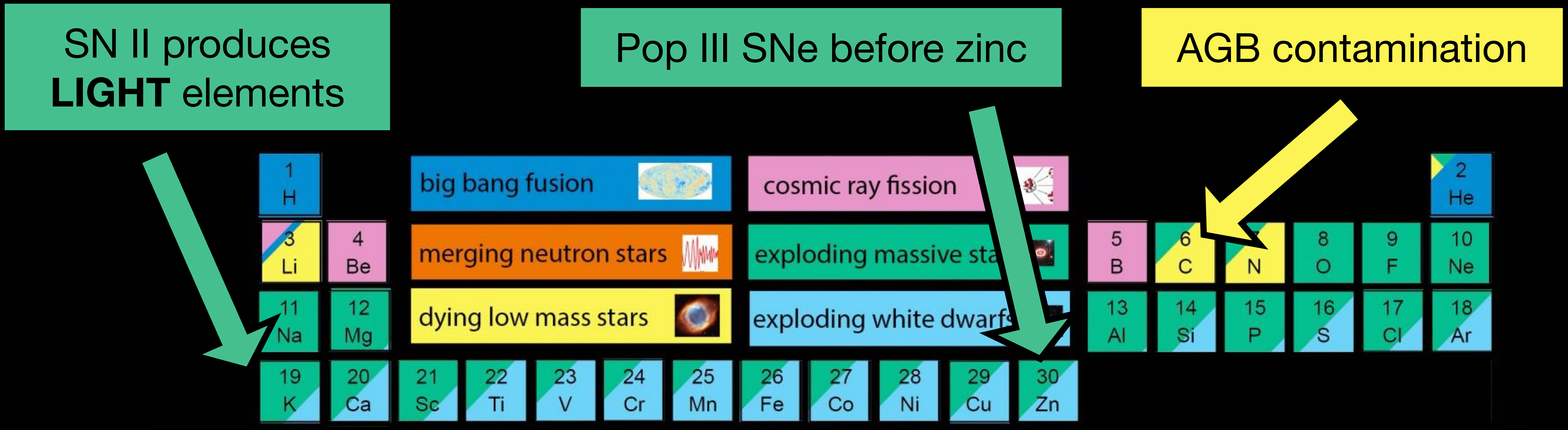
1. Hard to measure (e.g. potassium)
2. Large discrepancies between obs. and theory (scandium & chromium)

Element considered

α-element: carbon, magnesium, silicon, calcium and titanium

Odd element: sodium, aluminum

Iron group: manganese, iron, cobalt and nickel



Other filters

1. Hard to measure (e.g. potassium)
2. Large discrepancies between obs. and theory (scandium & chromium)

Element considered

α-element: carbon, magnesium, silicon, calcium and titanium

Odd element: sodium, aluminum

Iron group: manganese, iron, cobalt and nickel

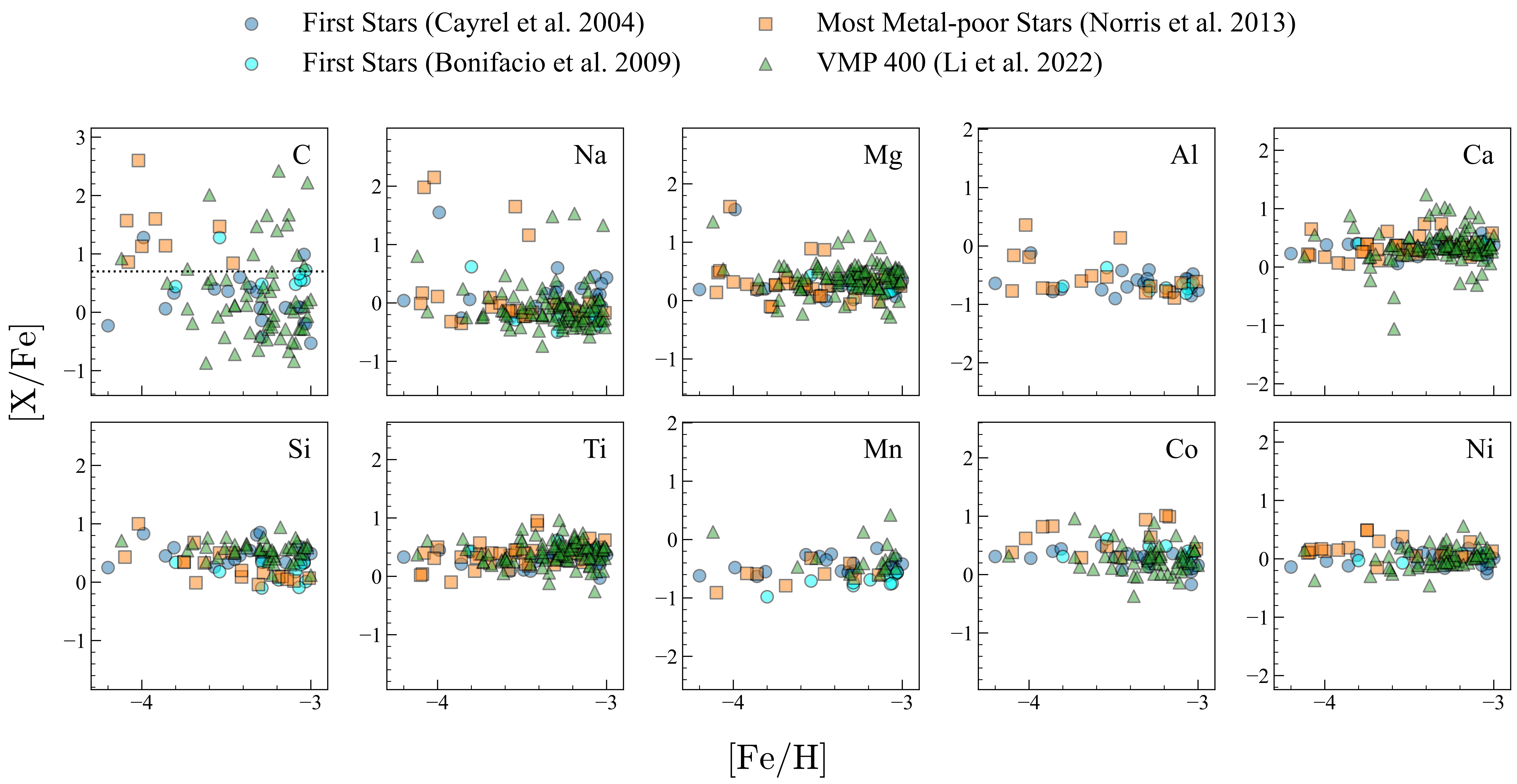
Data Source

SAGA database
5455 VMP

LAMOST/Subaru
385 VMP

Selection

[Fe/H] Ceiling
CCSN: -3.0

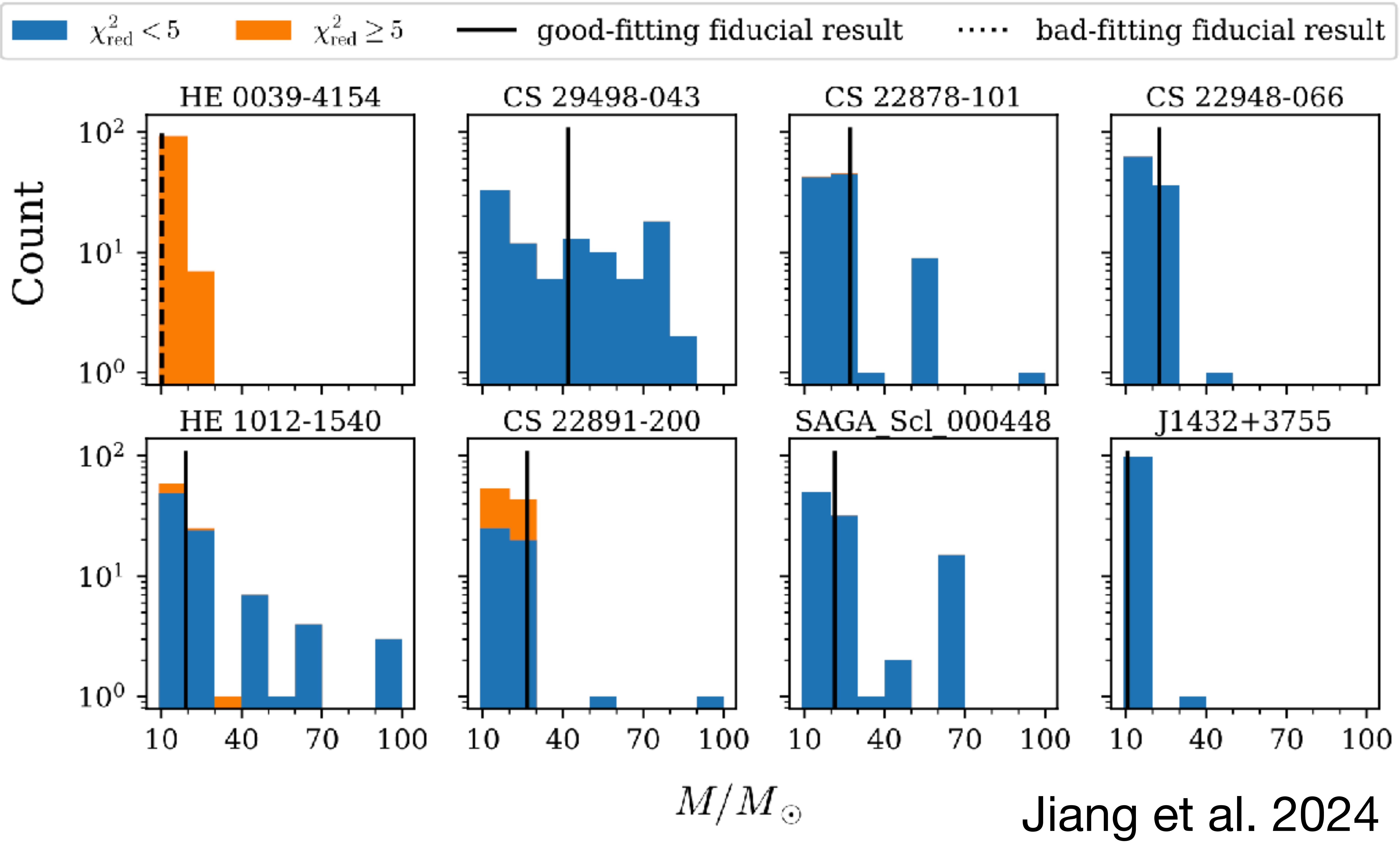


Abundance Distribution of Homogeneous Subsamples

Traditional Inversion: Point Estimation

Easy & fast by χ^2 minimum

Seriously affected by uncertainties (model & obs)



Jiang et al. 2024

Bayesian statistics:

$$p(\boldsymbol{\theta}|\mathbf{y}) \propto \pi(\mathbf{y}|\boldsymbol{\theta})p(\boldsymbol{\theta})$$

θ progenitor property; $\mathbf{y}$ abundance pattern

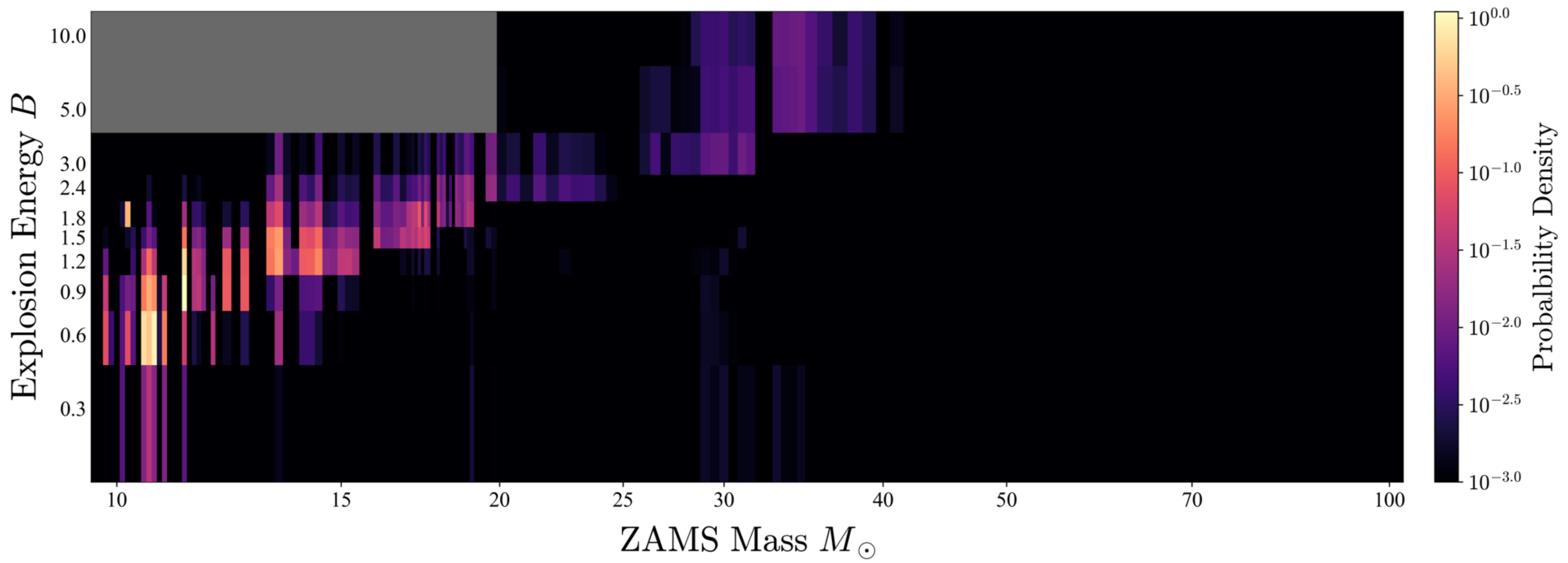
Two-dimensional distribution of EMP progenitor properties

Bayesian statistics:

$$p(\boldsymbol{\theta}|\mathbf{y}) \propto \pi(\mathbf{y}|\boldsymbol{\theta})p(\boldsymbol{\theta})$$

θ progenitor property; $\mathbf{y}$ abundance pattern

Two-dimensional distribution of EMP progenitor properties

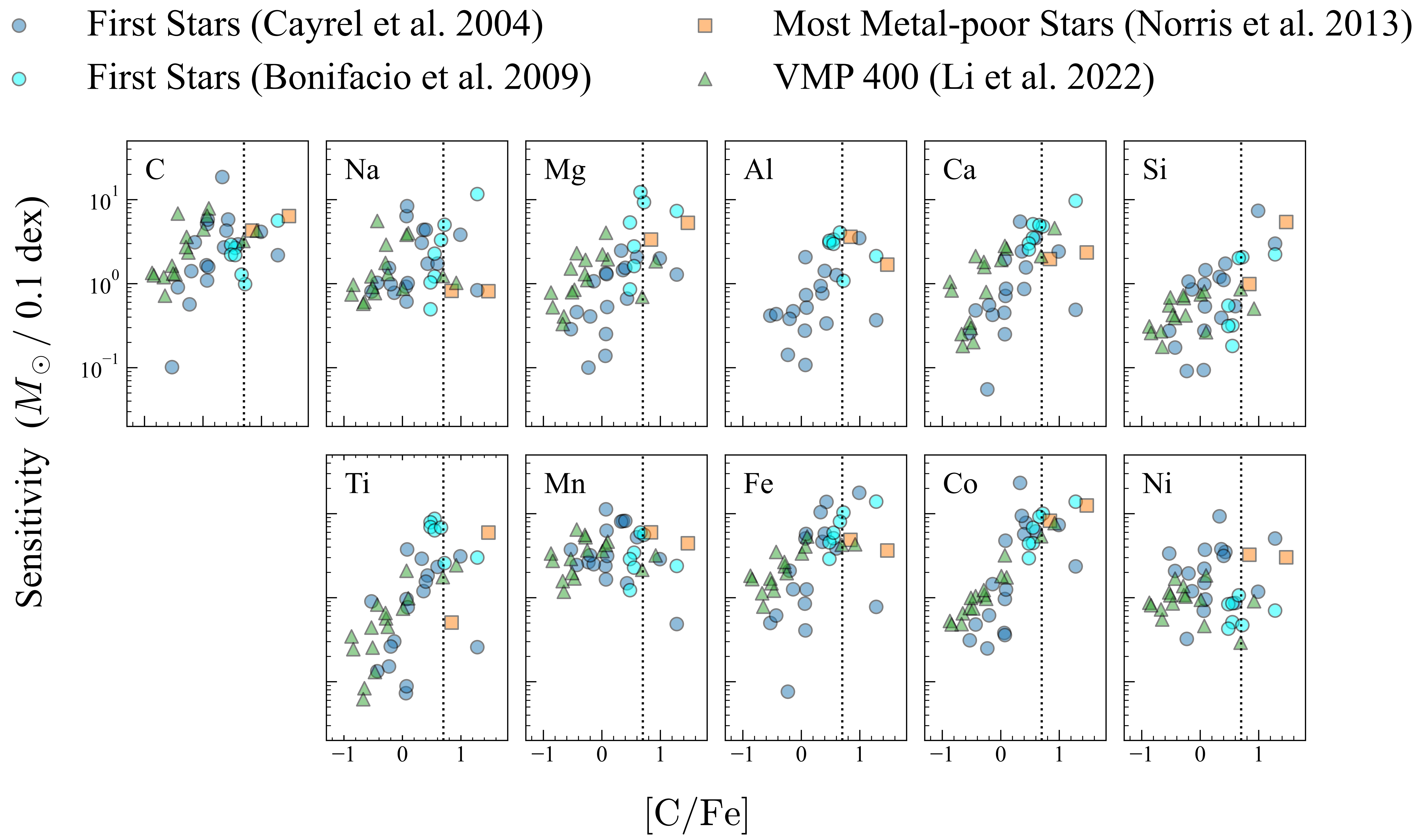


How about using Monte Carlo method?

✅Bayesian and uncertainties considered

❌Slow, hard to converge in an acceptance iterations

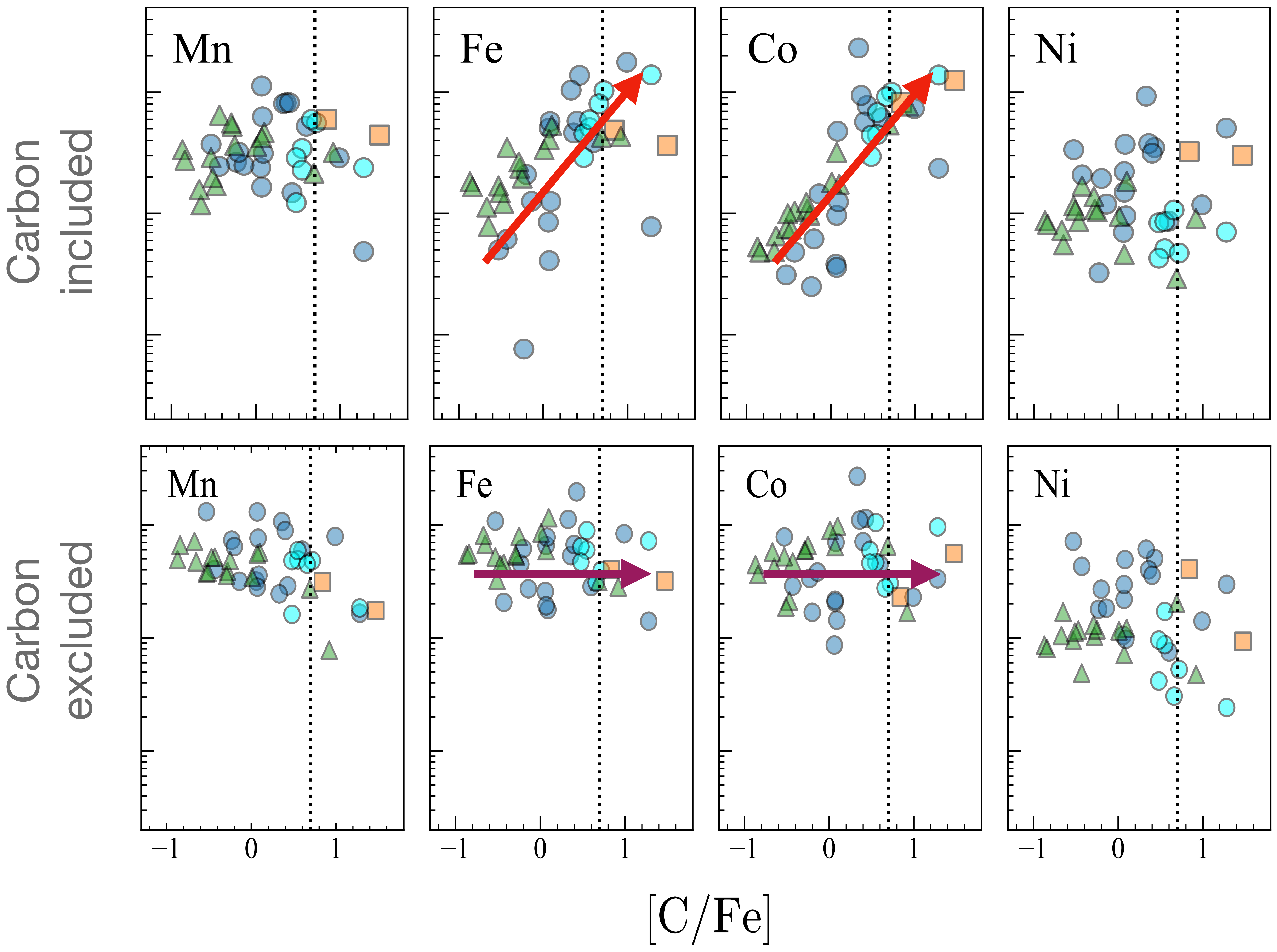
Influence of individual elements



Sensitivity of each element based on Bayesian framework

- Sensitivy: **<u>DEVIATION</u>** of the progenitor mass under a typical observational uncertainty (0.1 dex).

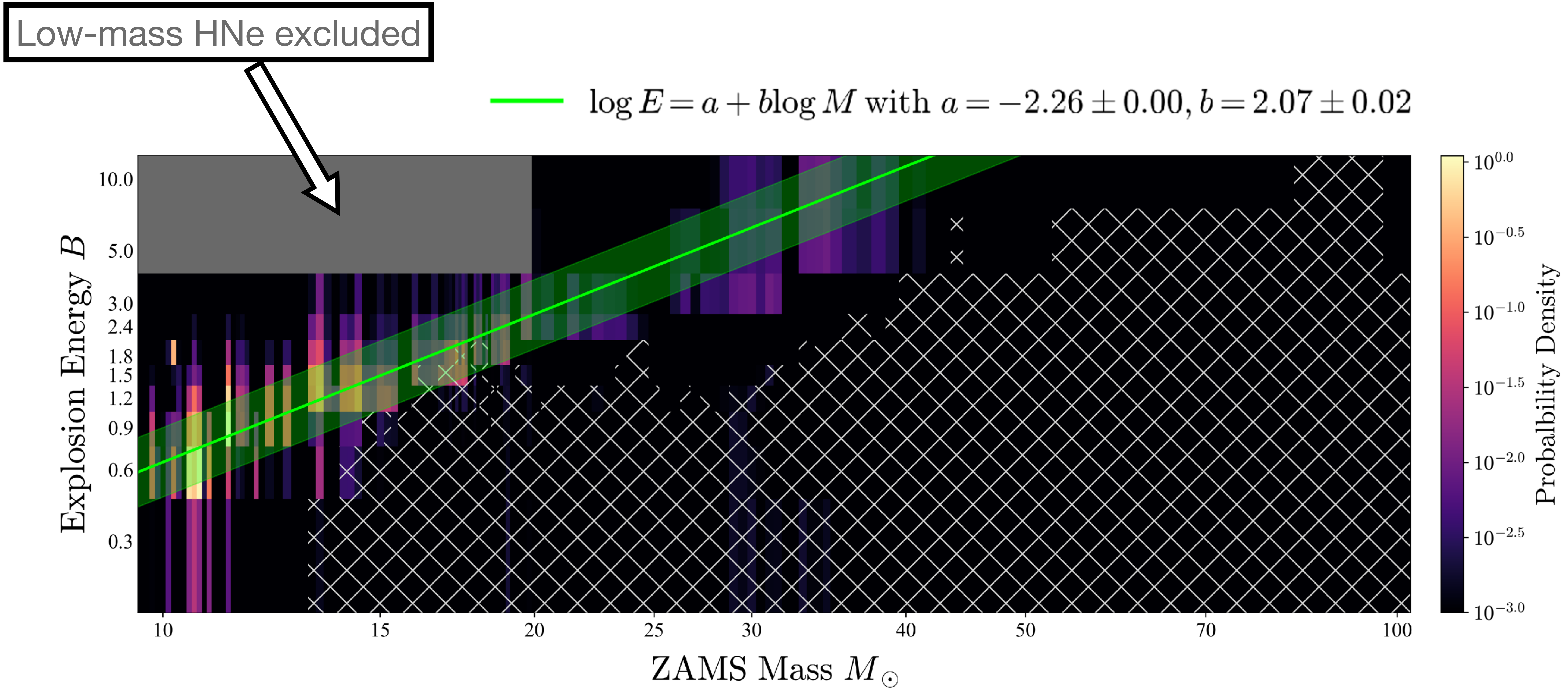
Influence of individual elements



- Sensitivity behaves differently when carbon is included/excluded.
- Possibly due to lack of explain. for large dispers. of carbon abundances.
- Carbon is not included in further analysis.

Pop III SNe Mass-Energy Distribution (MER):

$$M \propto E^2$$



Population III Initial Mass Function

Comparison against diff. SN models

- **KEPLER:** Power-law distribution

  Jiang et al. 2024 (transparent orange)

  Jiang in prep. (solid orange)

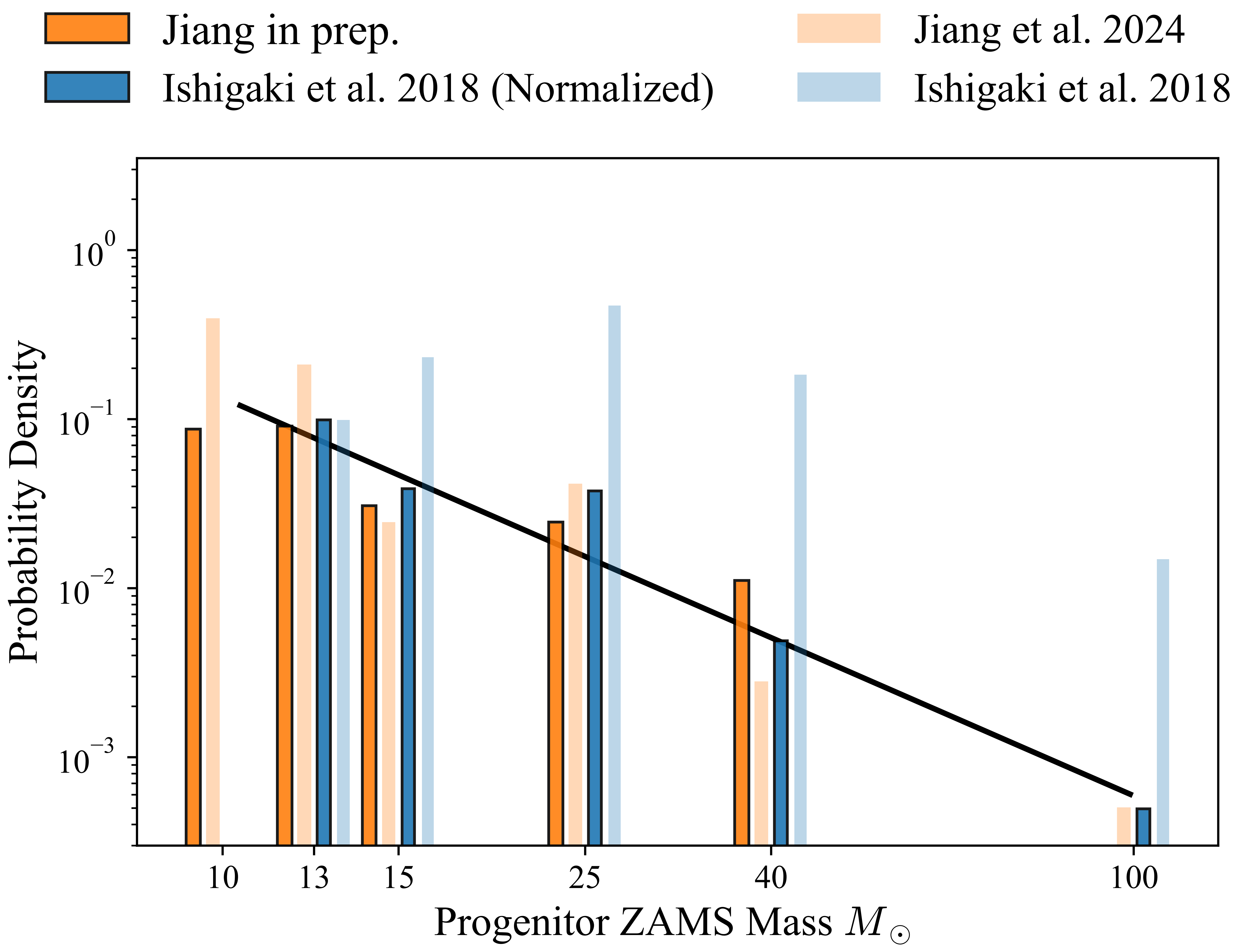
- **HOSHI:** Log-normal distribution

  Ishigaki et al. 2018 (transparent blue)

Normalizing model resolution with Bayesian Inference

A general ***POWER-LAW*** distribution is consistent

Large discrepancy at $\sim 25\,M_\odot$



First Stars → Supernovae / Chemical Enrichment → EMP Stars

Fitting IMF & EDF with explodability

1. *Modified IMF & EDF*

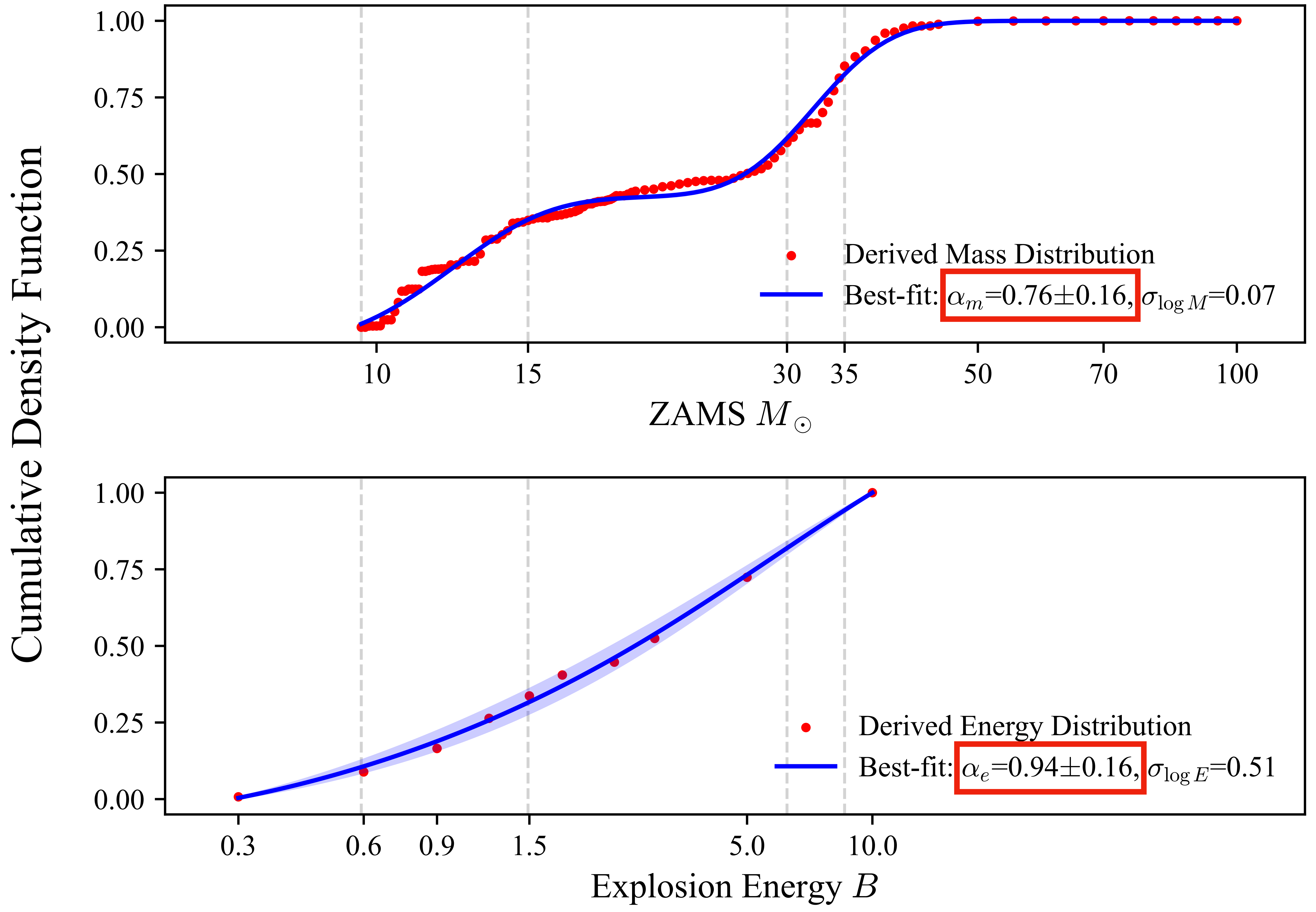
$$p(M) \propto \zeta(M) M^{-\alpha_m}$$

2. Explodability $\zeta(M)$, *two concentrated intervals*

$$\begin{cases} 1, & (9.6, 15) \cup (30, 35) \\ 0, & (15, 30) \cup (35, 100) \end{cases}$$

3. *Uncertainty broadening* with Gaussian kernel in log space

$$p(\log M) * G(\log M; \sigma_{\log M})$$



Further test for α_m & α_e with MER $M \propto E^2$

Transformation of probability:

$$p(M)\,\mathrm{d}M = p(E)\,\mathrm{d}E$$

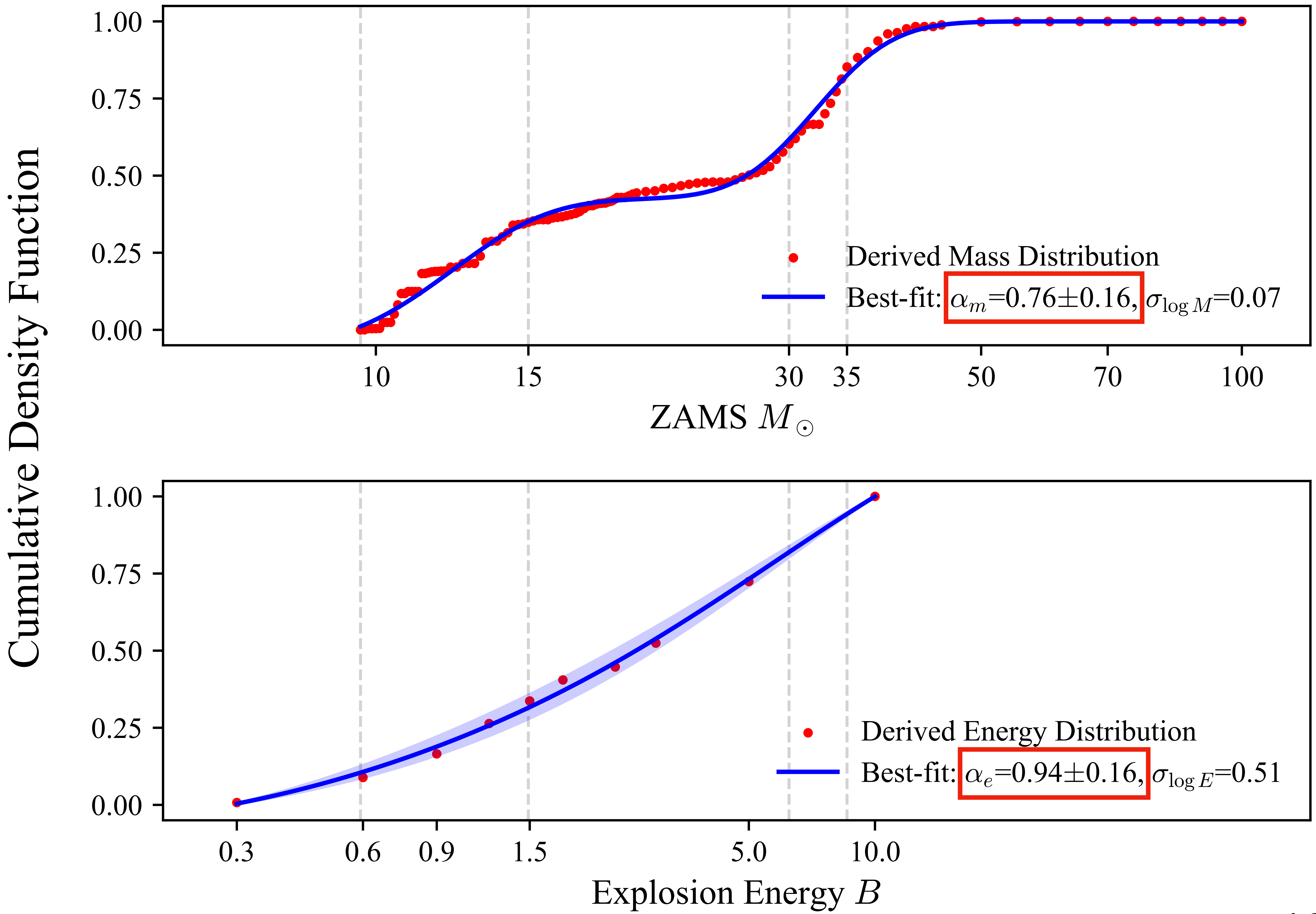
$$M^{-\alpha_m}\,\mathrm{d}M \propto M^{-2\alpha_e+1}\,\mathrm{d}M$$

$$\Rightarrow \quad \alpha_m + 1 = 2\alpha_e$$

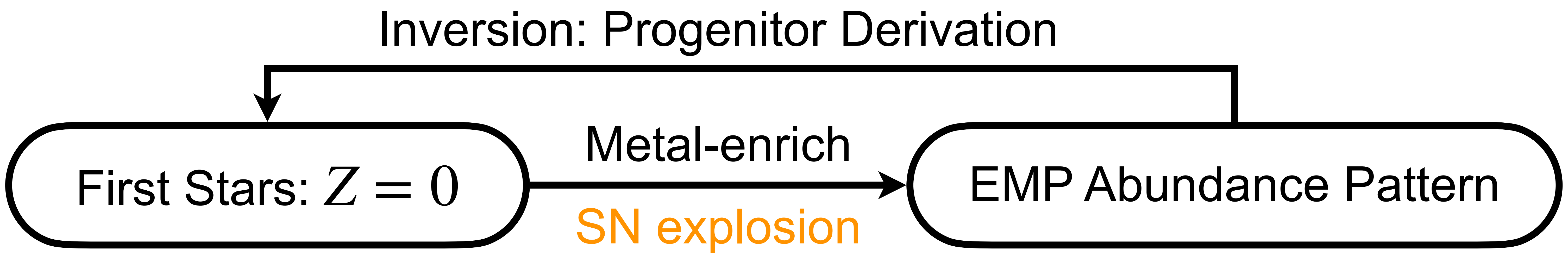
Using best-fit parameters:

$$\alpha_m + 1 = 1.76 \pm 0.16$$

$$2\alpha_e = 1.88 \pm 0.32$$

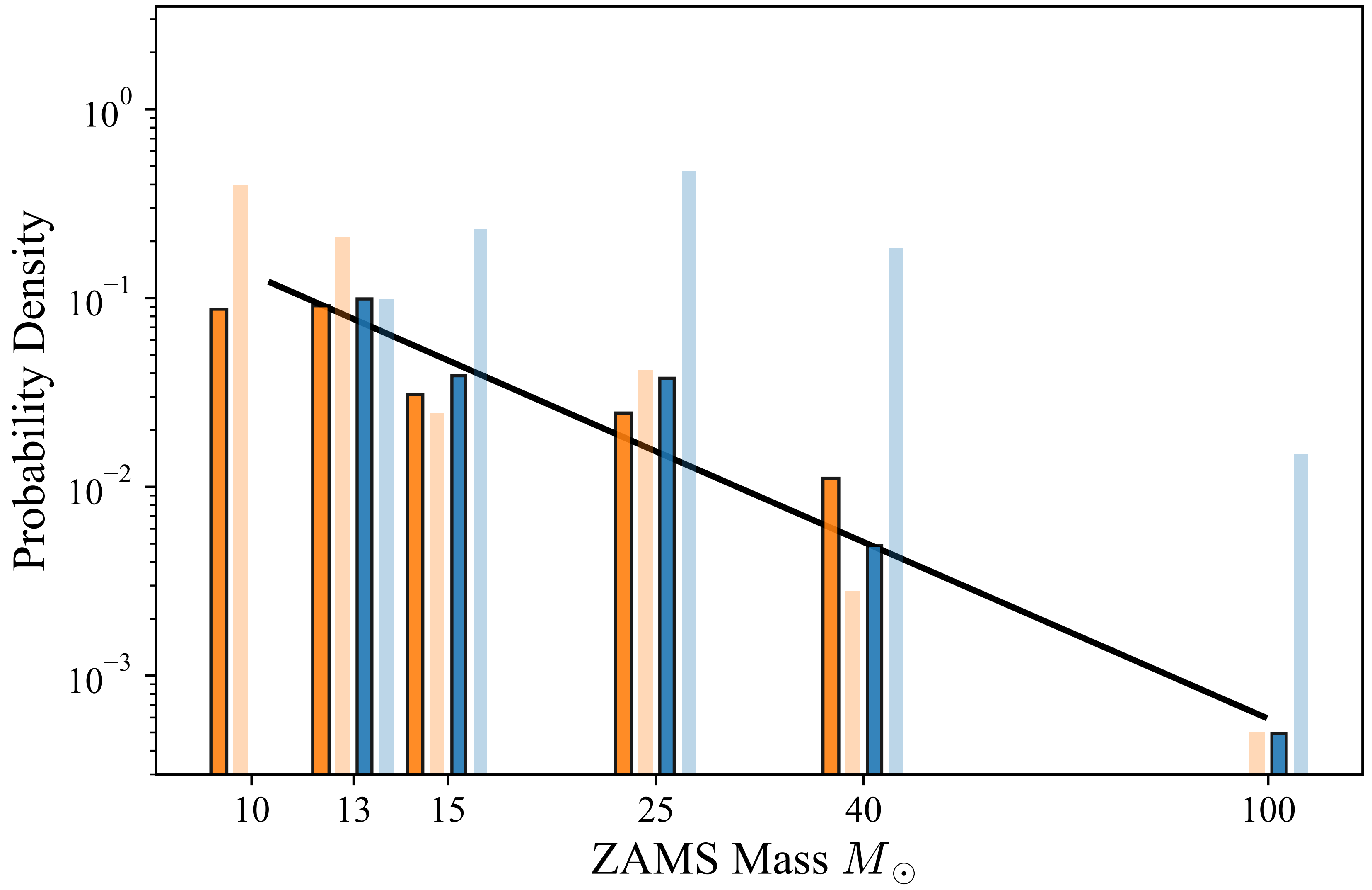


SUMMARY

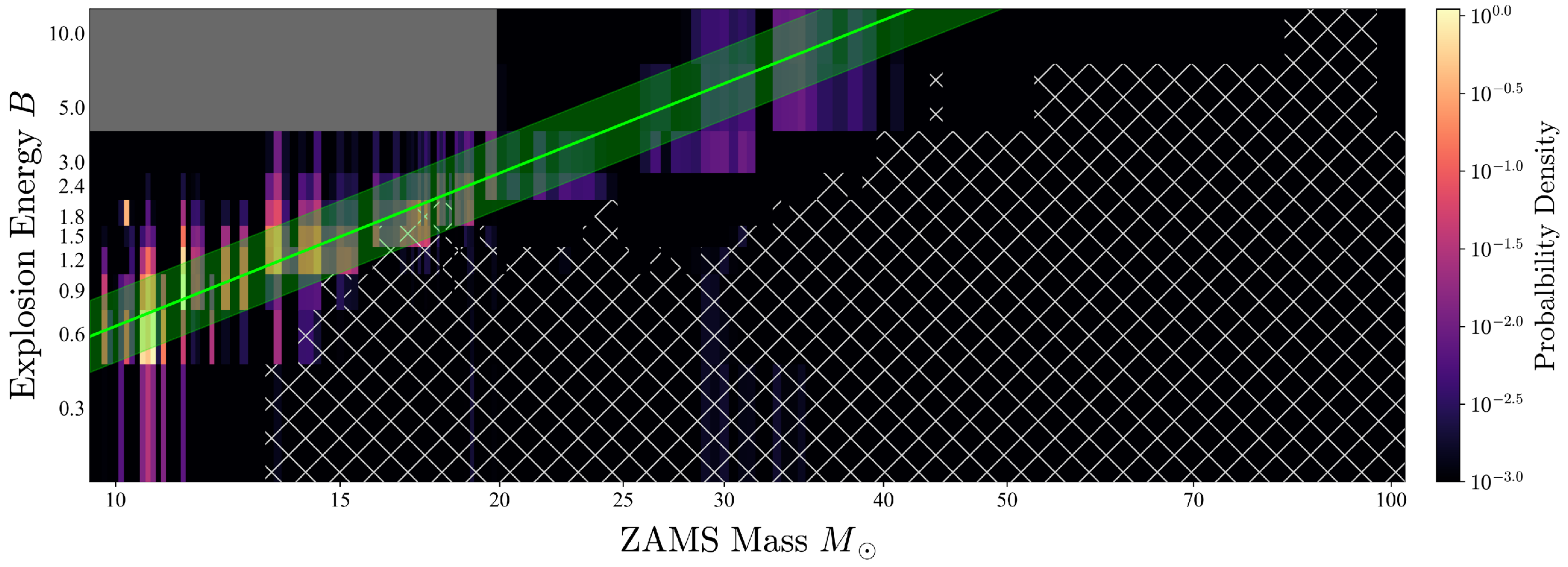


(a) Pop III IMF: explodability-modifying ***POWER-LAW*** ($\alpha = 0.76$)

(b) First SNe Mass-Energy Relation: $M \propto E^2$



(a) Pop III IMF with different SN models



(b) Mass-Energy distribution of first supernova