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

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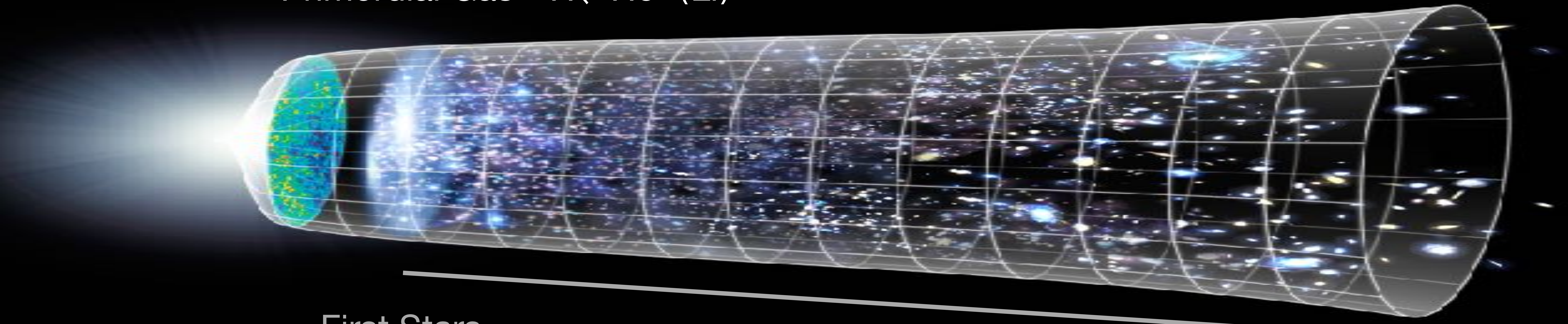
I. INTRODUCTION

Big Bang Nucleosynthesis
Primordial Gas：H、He（Li）

Credit: NASA / WMAP Science Team



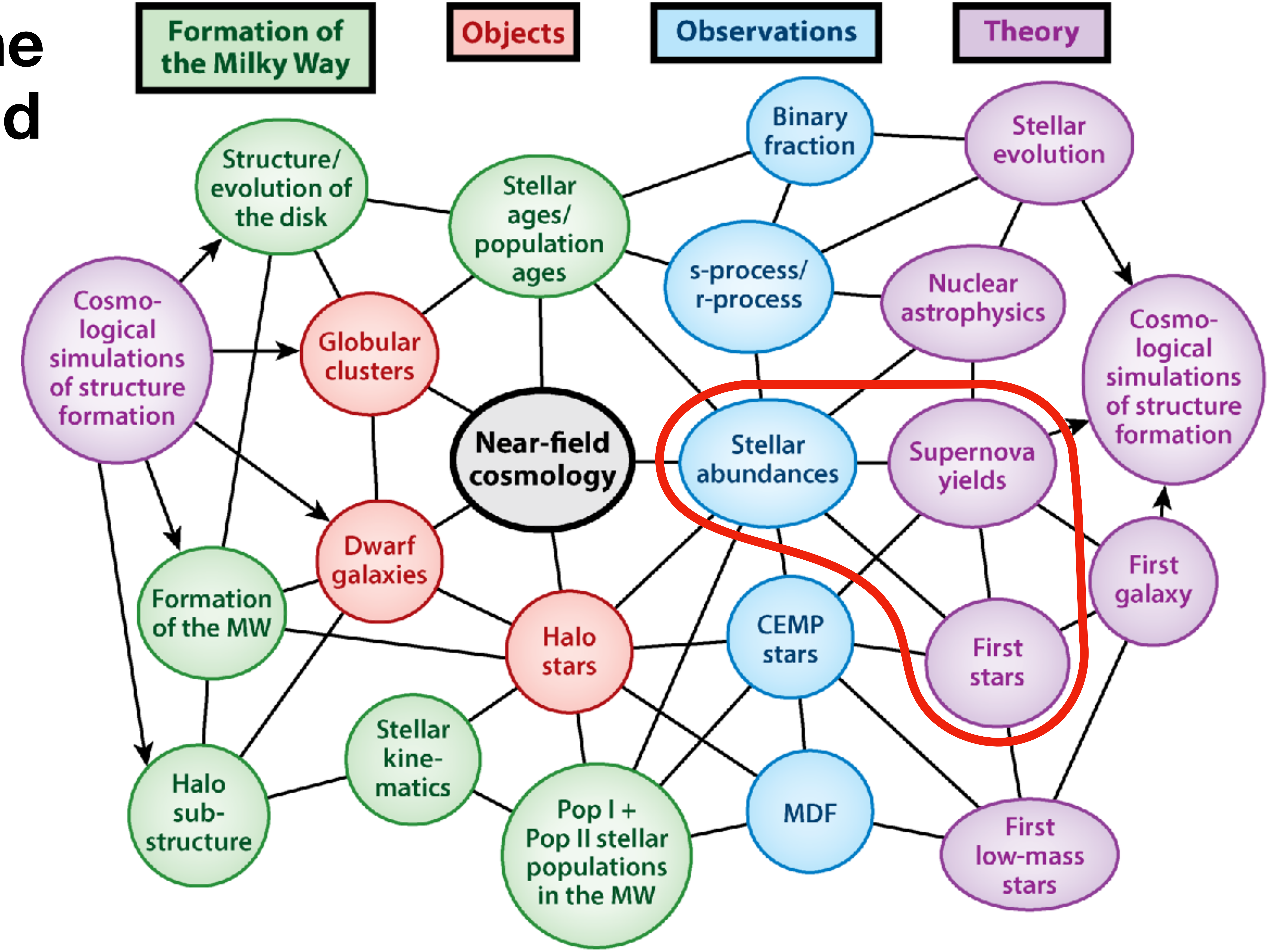
First Stars → Now

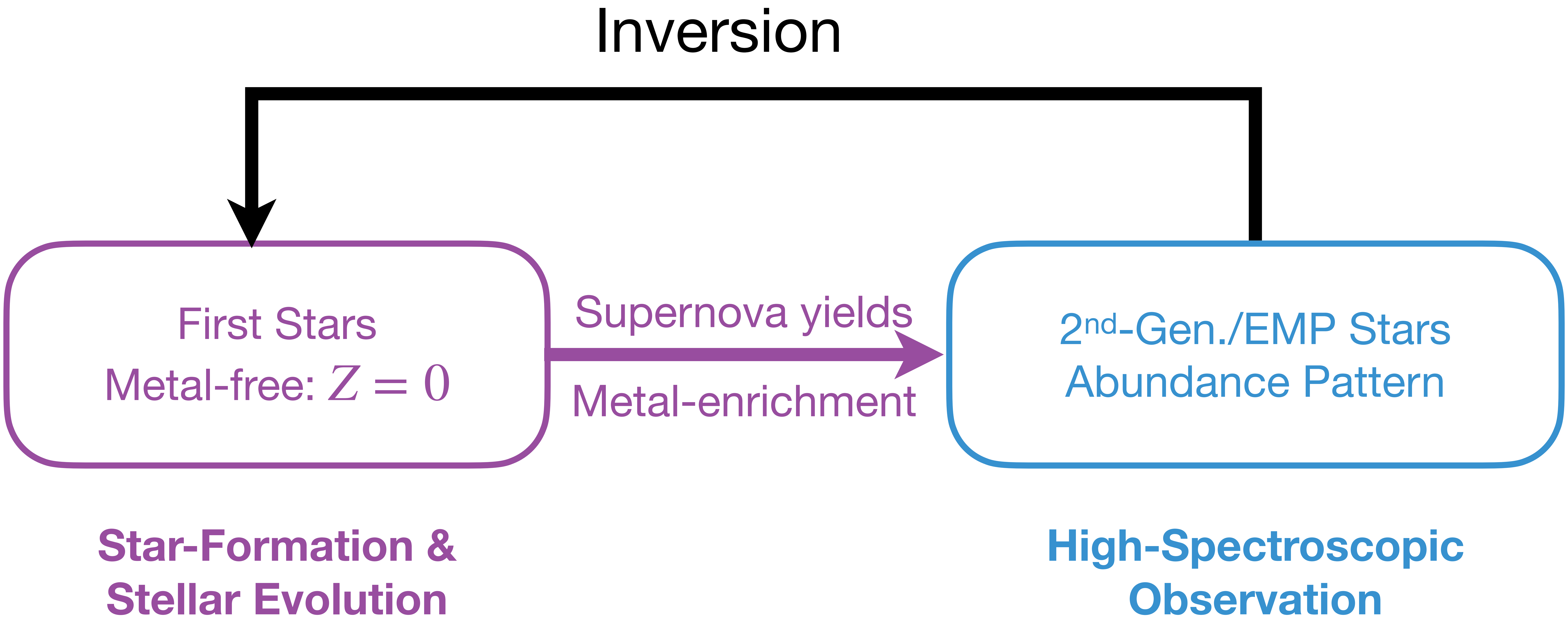
Stars Form & Evolve → Supernovae Expl. → Ejecta Mix & Cool → Stars Form & Evolve

Schematic overview of the topics related to near-field cosmology

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

- Stars are also the easily accessible local equivalent of the high-redshift Universe
- The chemical environment at stellar formation are reserved in their atmospheric elemental abundances.




Inversion
First Stars
Metal-free: $Z = 0$
Supernova yields
Metal-enrichment
2^{nd}-Gen./EMP Stars
Abundance Pattern
Star-Formation &
Stellar Evolution
High-Spectroscopic
Observation

II. MODEL & DATA

Physical Structure

Nuclear Burning

Chemical Mixing

Rotation

$$\frac{\partial P}{\partial M} = -\frac{GM}{4\pi R^4} f_P$$

$$\frac{\partial R}{\partial M} = \frac{1}{4\pi \rho R^2}$$

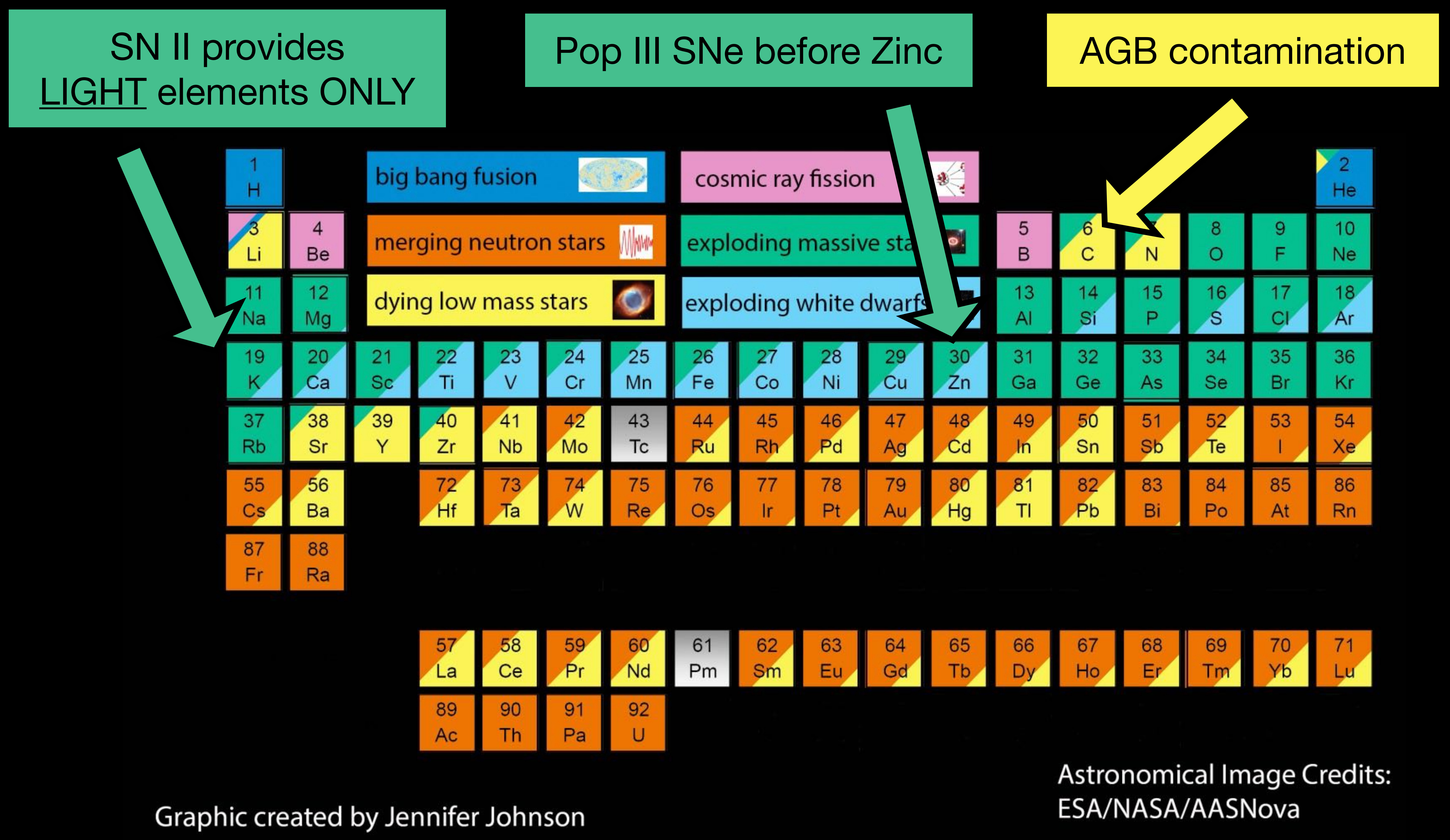
$$\frac{\partial T}{\partial M} = -\frac{GMT}{4\pi R^2 P} \nabla \frac{f_T}{f_P}$$

$$\frac{\partial L}{\partial M} = \varepsilon$$

$$\frac{\partial Y_i}{\partial t} = \left(\frac{\partial Y_i}{\partial t}\right)_{\mathrm{nuc}} + \frac{\partial}{\partial m}\left[\left(4\pi \rho r^2\right)^2 \left(D_{\mathrm{mix}} + D_{\mathrm{semi}} + D_{\mathrm{rot}}\right)\left(\frac{\partial X_i}{\partial m}\right)\right]$$

$$\rho \frac{d}{dt}\left(r^2 \omega\right) = \frac{1}{5r^2}\frac{\partial}{\partial r}\left(\rho r^4 \omega U\right) + \frac{1}{r^2}\frac{\partial}{\partial r}\left(\rho D_{\mathrm{shear}} r^4 \frac{\partial \omega}{\partial r}\right)$$

$$\rho \frac{d}{dt}\left(r^2 \omega\right) = \frac{1}{r^2}\frac{\partial}{\partial r}\left(\rho D r^4 \frac{\partial \omega}{\partial r}\right)$$


SN II provides LIGHT elements ONLY
Pop III SNe before Zinc
AGB contamination
big bang fusion
cosmic ray fission
merging neutron stars
exploding massive stars
dying low mass stars
exploding white dwarfs
Graphic created by Jennifer Johnson
Astronomical Image Credits: ESA/NASA/AASNova

Data Source

SAGA database

5455 VMP

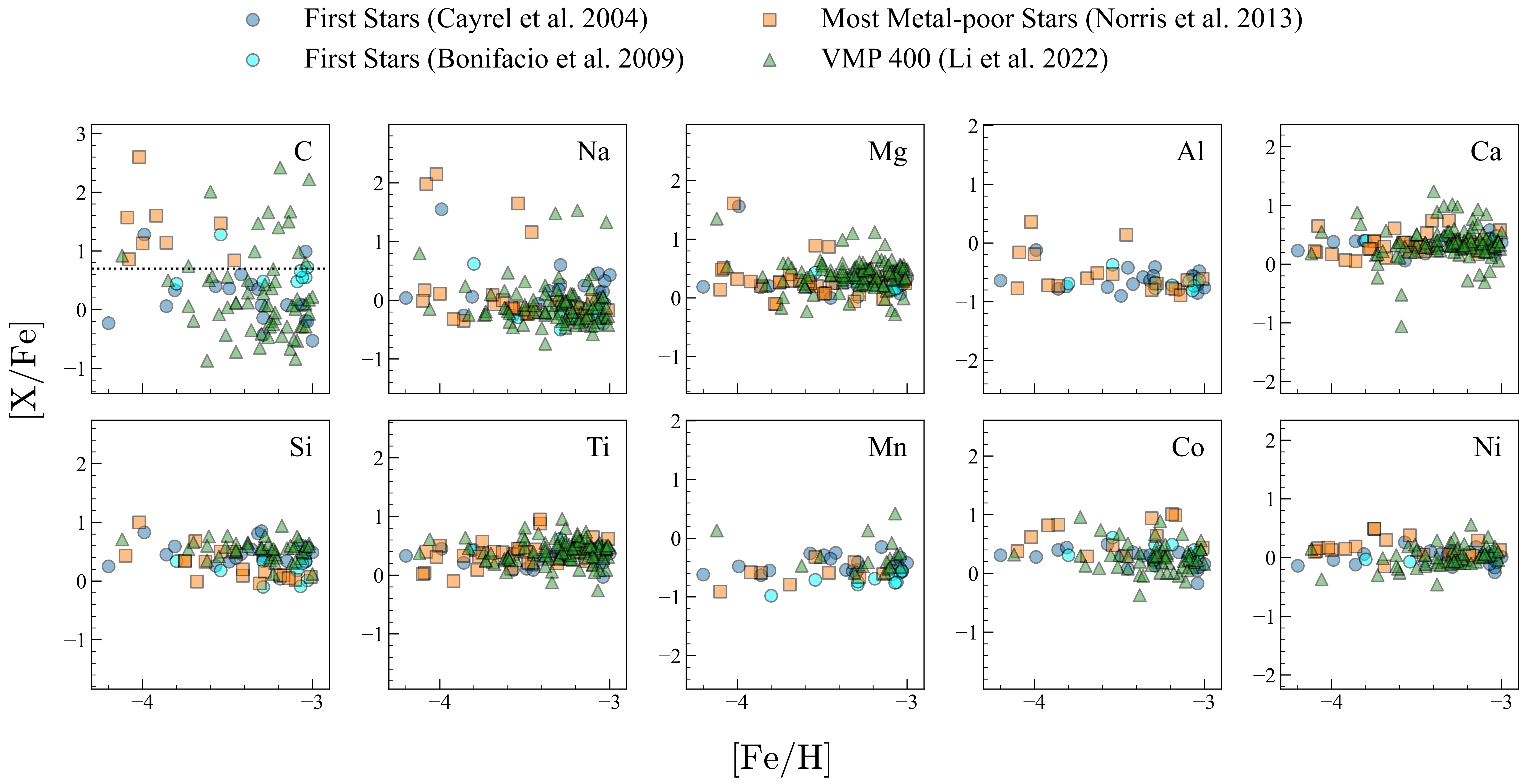
LAMOST/Subaru

385 VMP

Selection

$[Fe/H]$ Ceiling

CCSN: -3.0



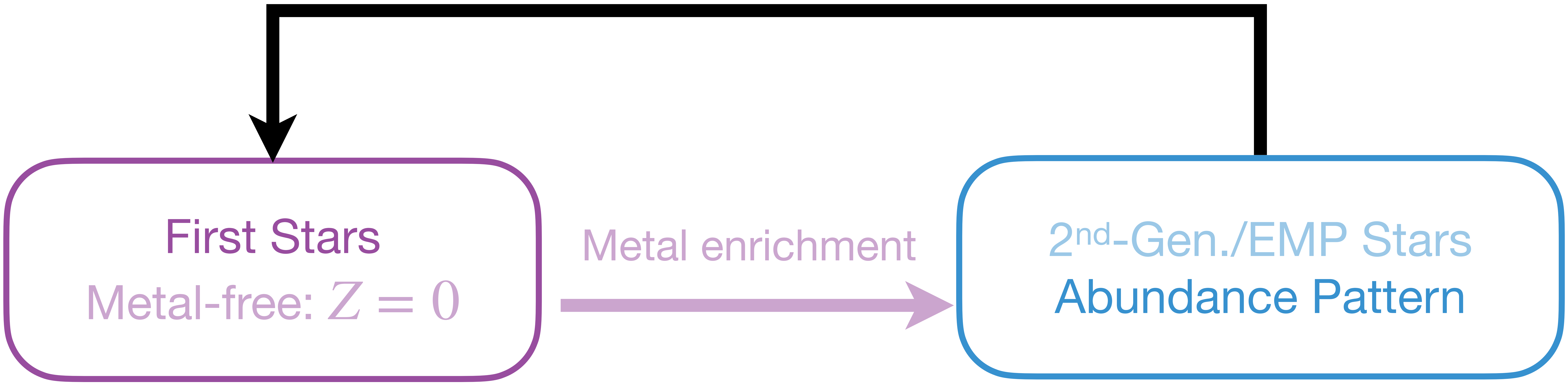
Abundance Distribution of Homogeneous Subsamples

III. METHOD

Traditional Inversion:

Point Estimation based on χ^2 **minimum**

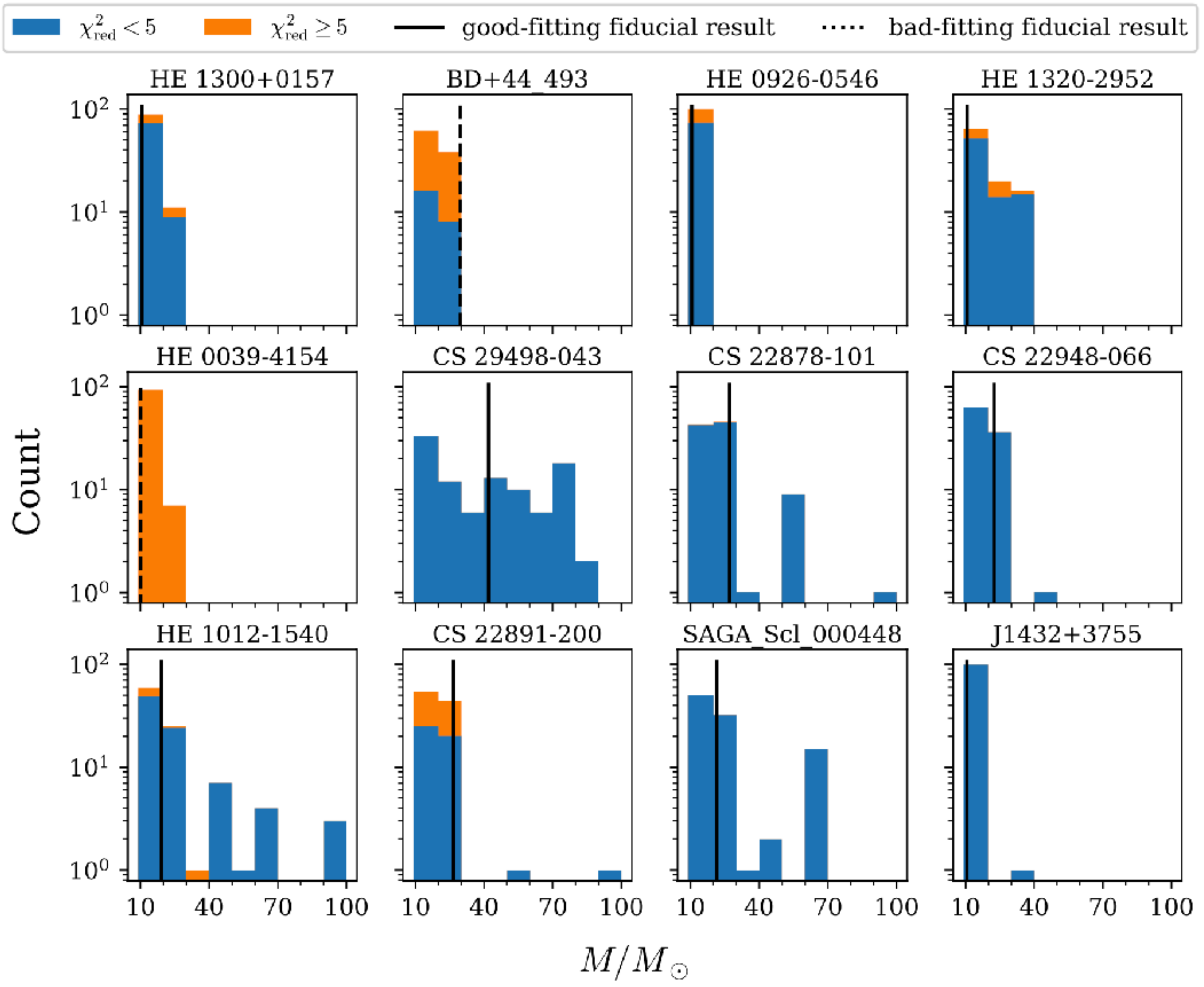
$$\chi^2 = \sum_{i=1}^{N} \frac{(A_i - O_i)^2}{\sigma_i^2}$$



Robust Inversion

- Traditional inversion is seriously affected by uncertainty from both model and observation.
- We develop a Bayesian-Inference progenitor θ derivation according to abundance pattern $\mathbf{y}$:

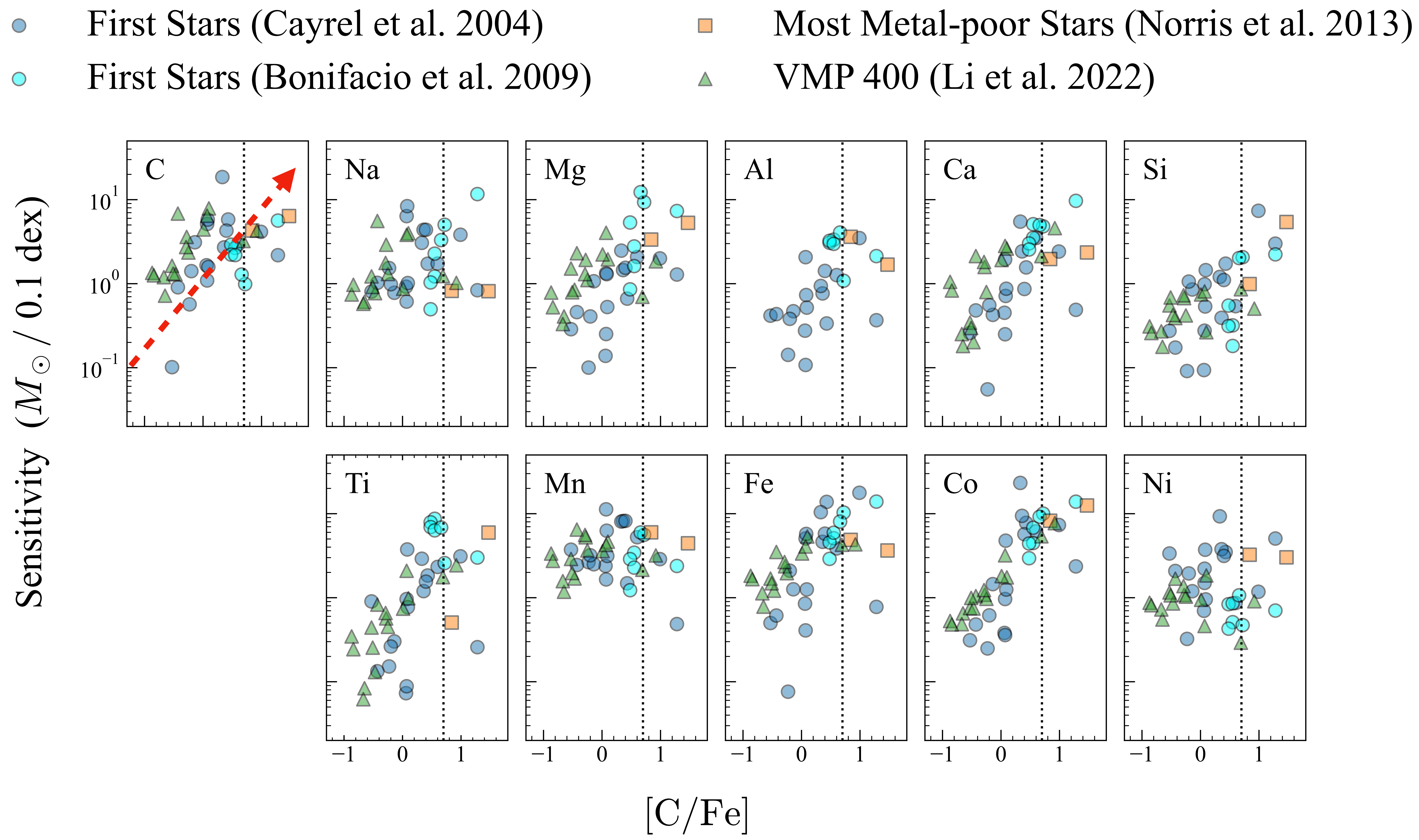
$$p(\boldsymbol{\theta}|\mathbf{y}) \propto \pi(\mathbf{y}|\boldsymbol{\theta})p(\boldsymbol{\theta})$$



Traditional inversion based on a Monte-Carlo sampling of observations.

IV. RESULT & DISCUSSION

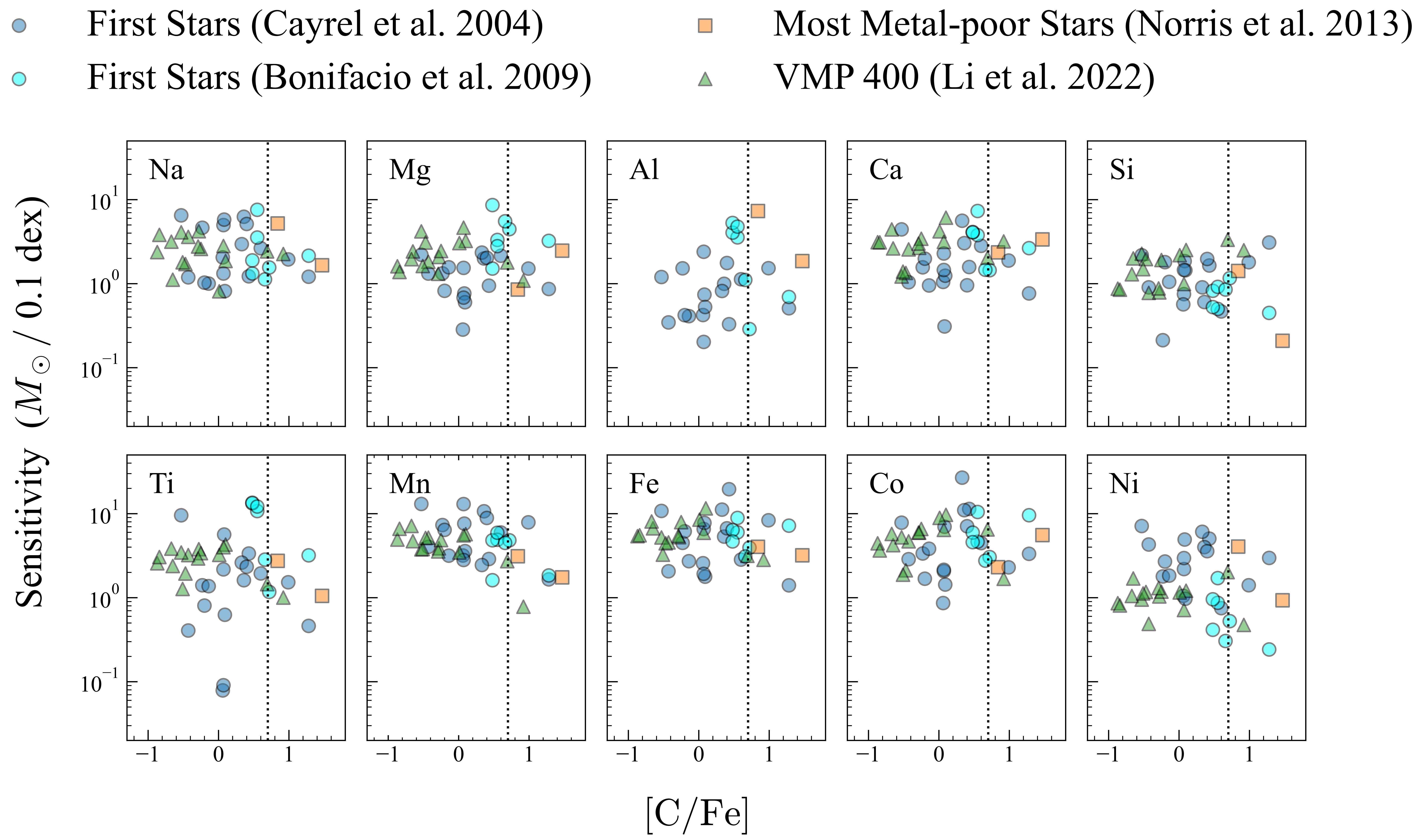
Influence of individual elements



Sensitivity of each element based on Bayesian framework

- Y-axis value, "sensitivity", could be viewed as the **DEVIATION** of the progenitor mass under a typical observational uncertainty (0.1 dex).
- The higher sensitivity, the less robustness.
- Robustness rises with increasing [C/Fe].

Influence of individual elements



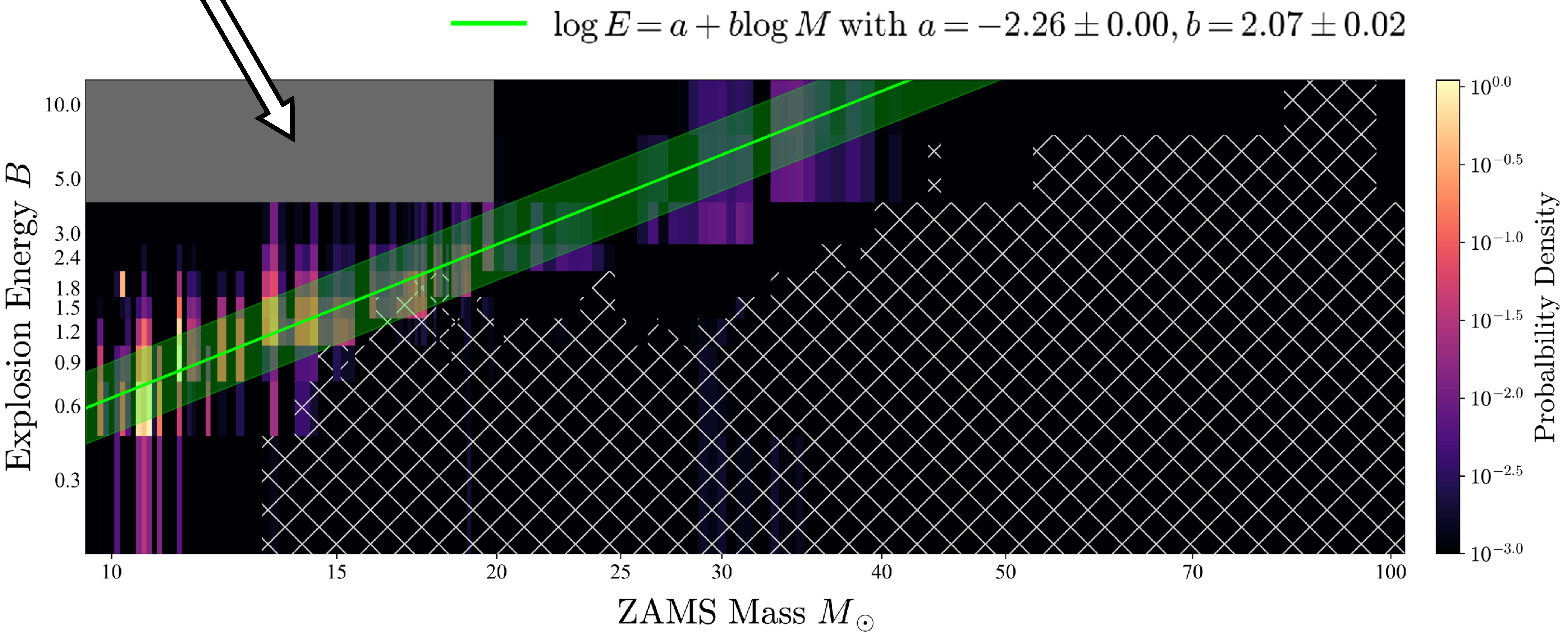
Sensitivity of each element, but *carbon is excluded* during abundance fitting

- Y-axis value, "sensitivity", could be viewed as the **DEVIATION** of the progenitor mass under a typical observational uncertainty ($0.1\ \mathrm{dex}$).
- The higher sensitivity, the less robustness.
- Robustness rises with increasing $[\mathrm{C/Fe}]$. However, this trend is broken when carbon is excluded.

Pop III SNe Mass-Energy Distribution (MER):

$$M \propto E^2$$

Low-mass HNe excluded



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)

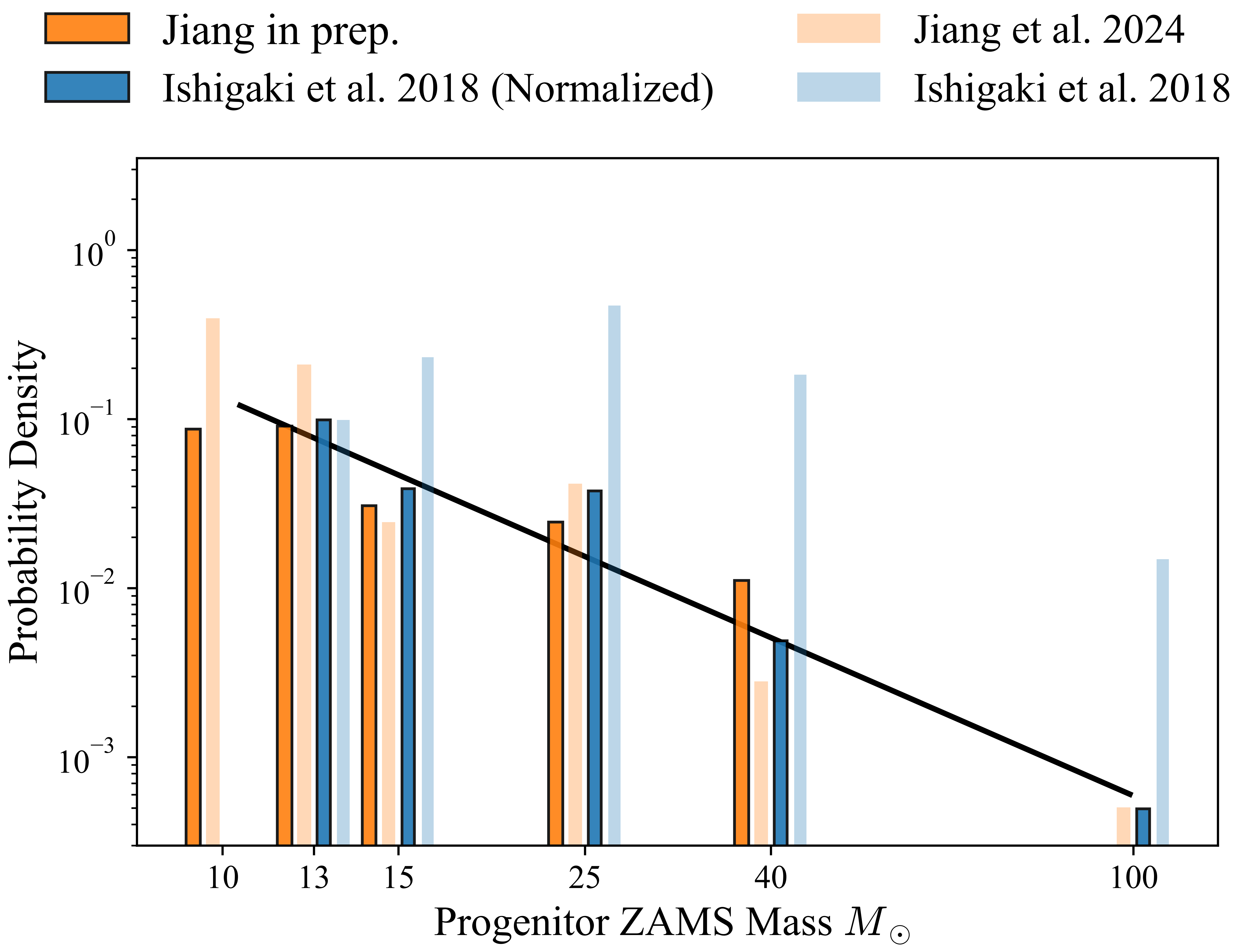
- **HOSHI:** Log-normal distribution

  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*

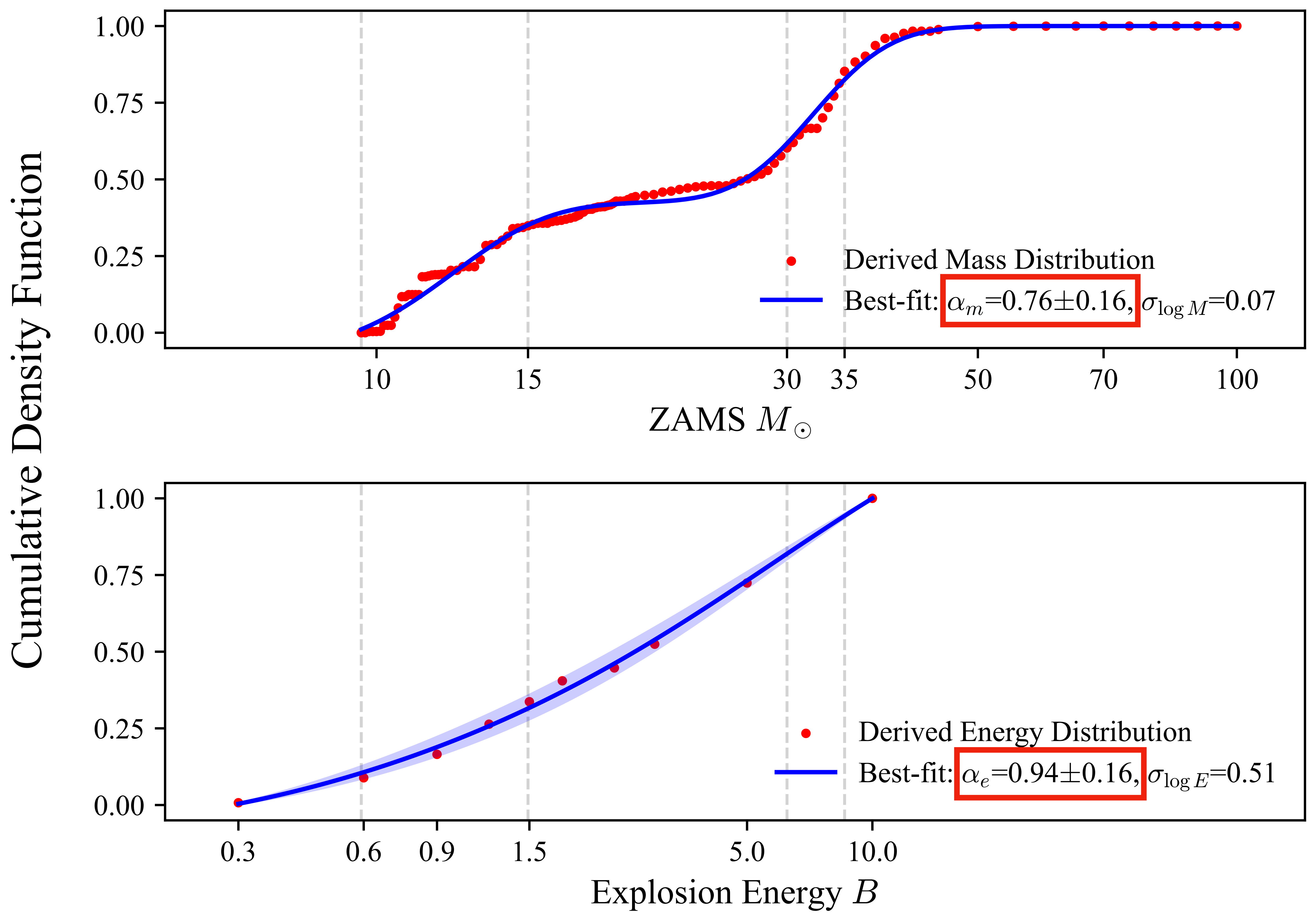
   $$p(M) \propto \zeta(M) M^{-\alpha_m}$$

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:

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

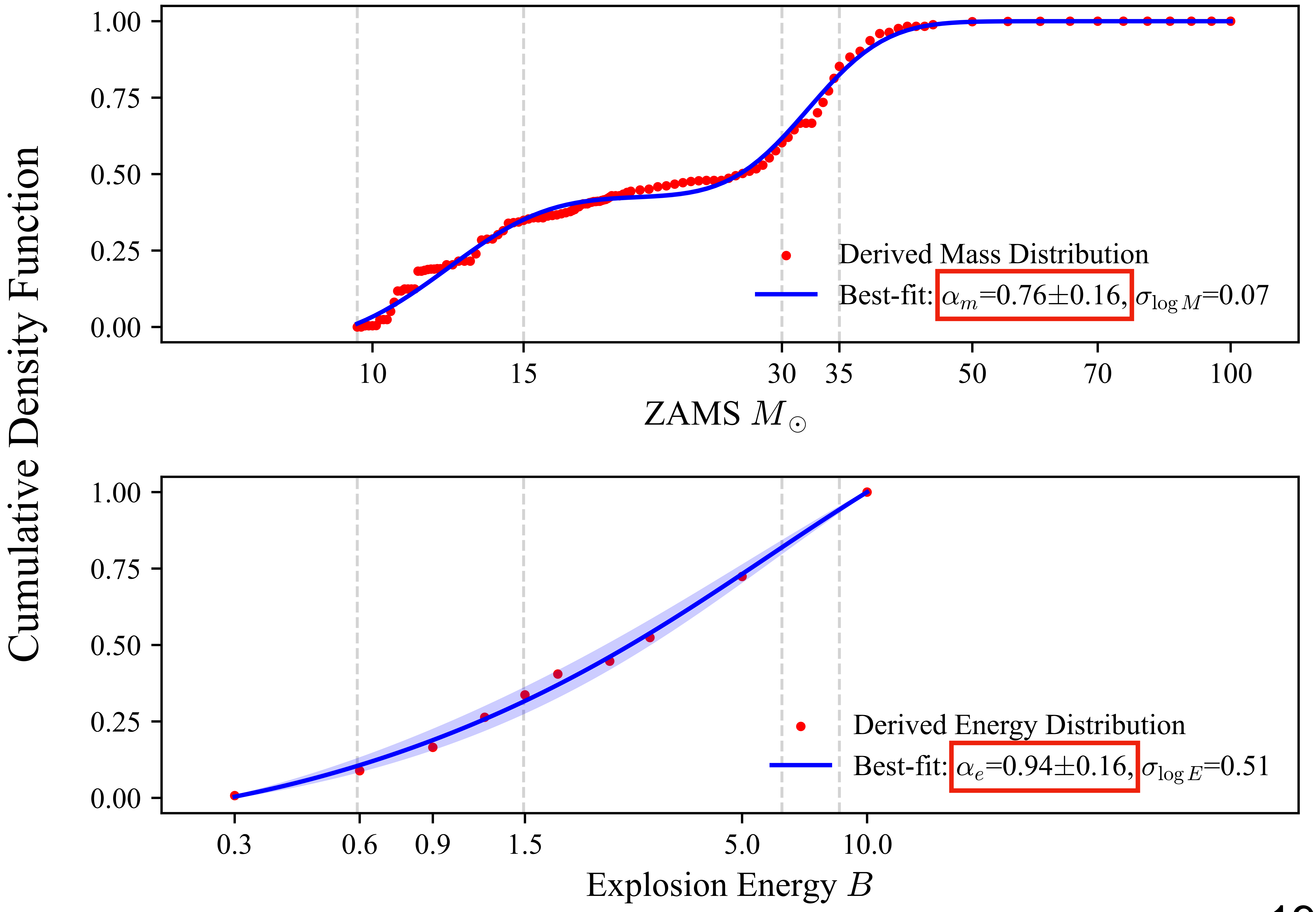
$$M^{-\alpha_m}\,\mathrm{d}M \propto M^{-2\alpha_e+1}\,\mathrm{d}M$$

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

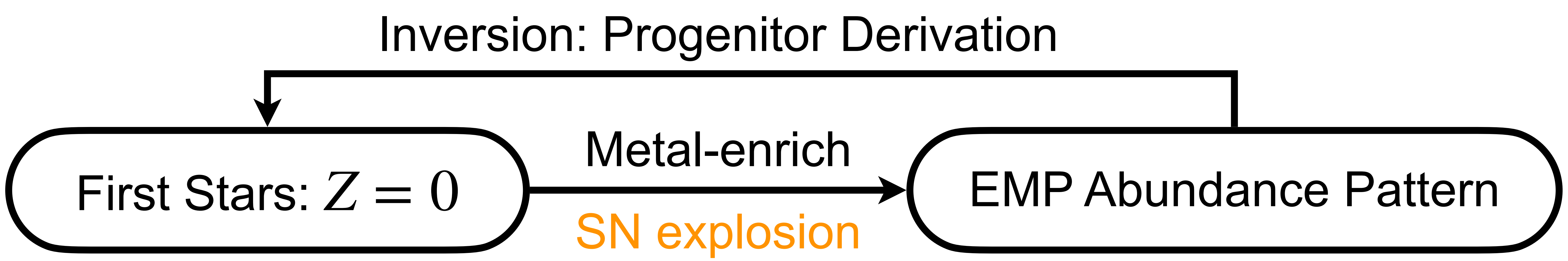
Using best-fit parameters:

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

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

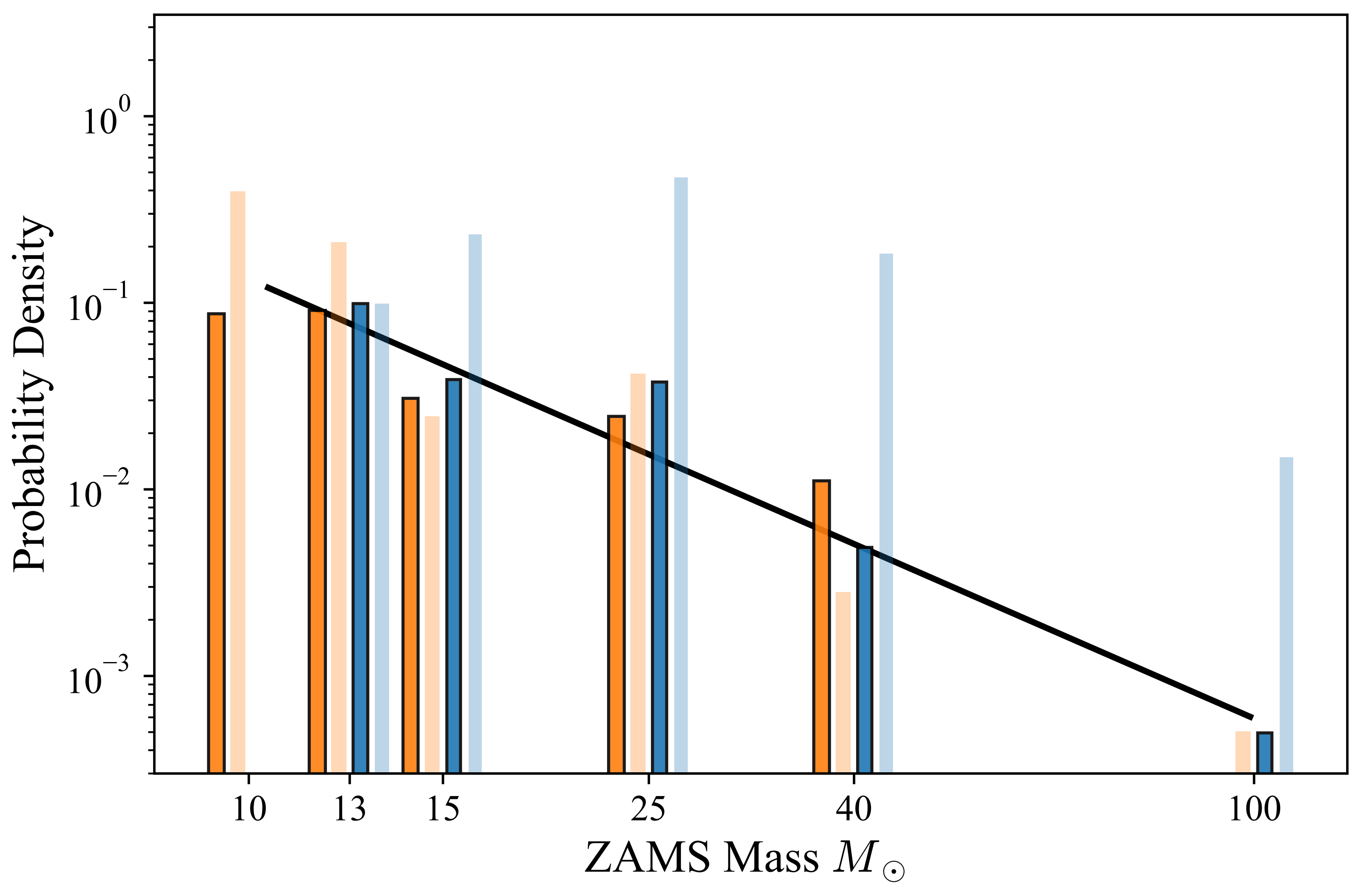


SUMMARY

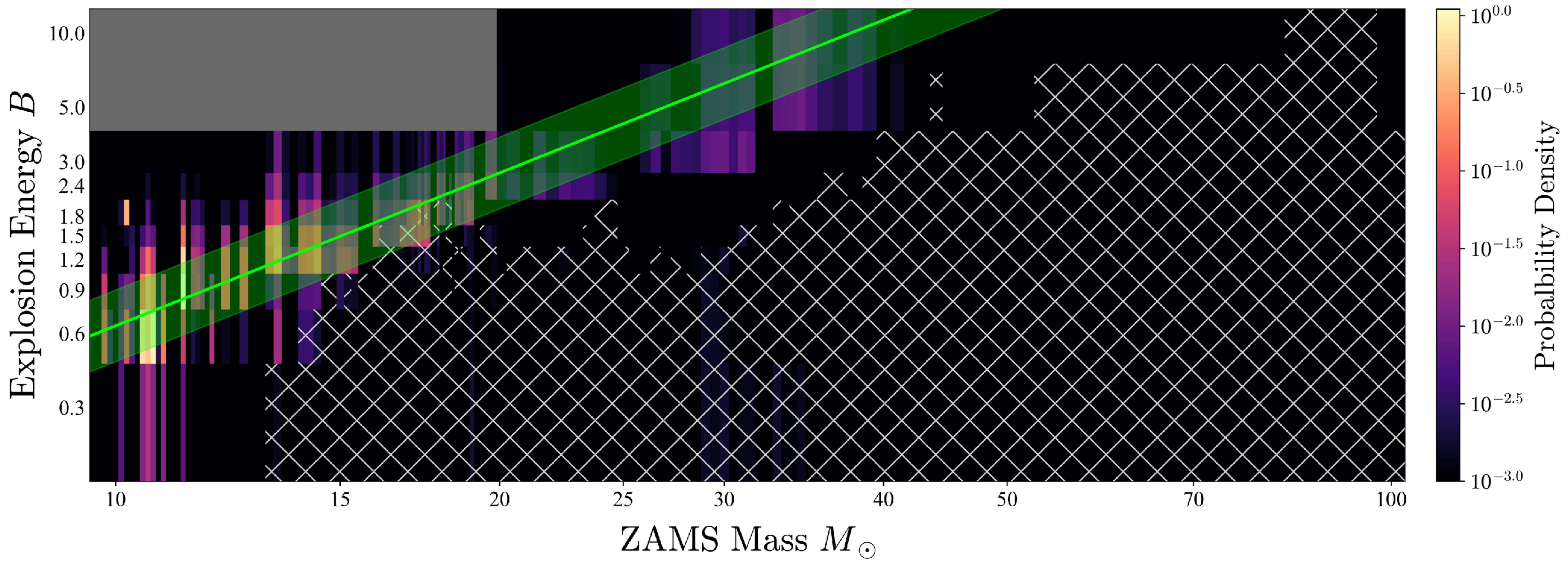


(a) Pop III IMF: explodability-modifying ***POWER-LAW*** ($\alpha = 0.76$)

(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