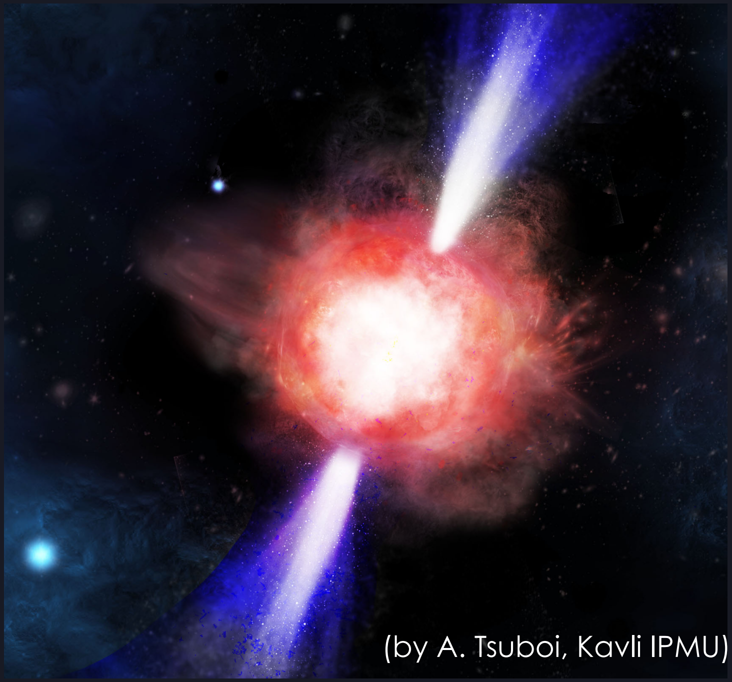
# Implications of the extremely metal-poor stars on the masses of the first stars

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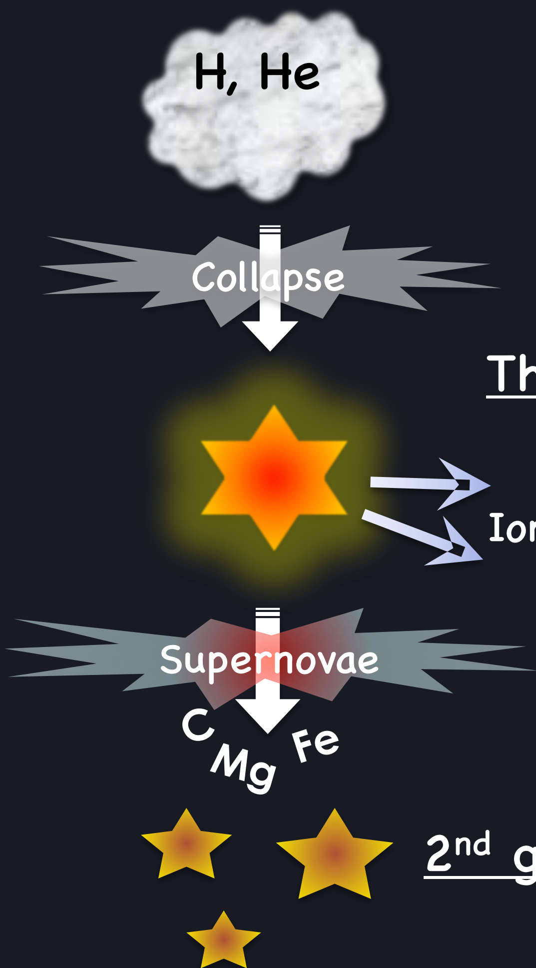
*Ishigaki et al. submitted*

# The first (Population III/Pop III) stars

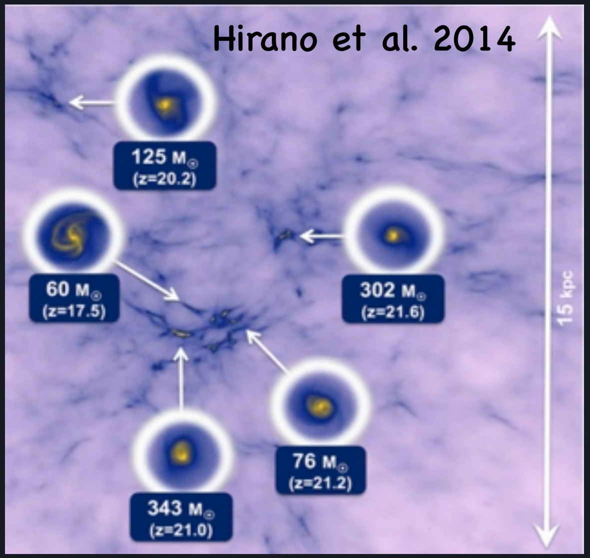



The first stars

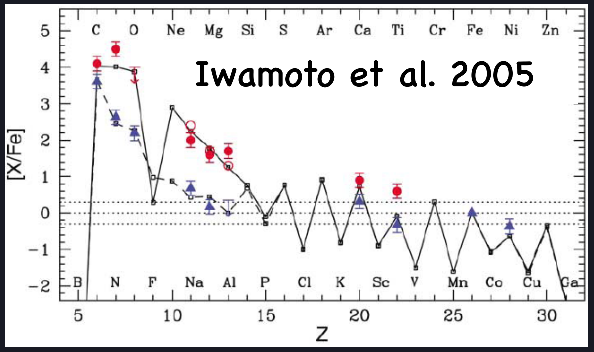
Ionizing radiation

$2^{nd}$ generation stars

Cosmological simulations

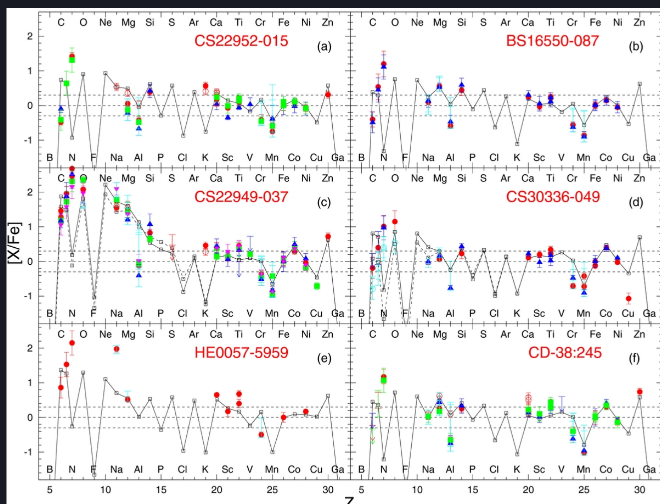



Elemental abundances of EMP

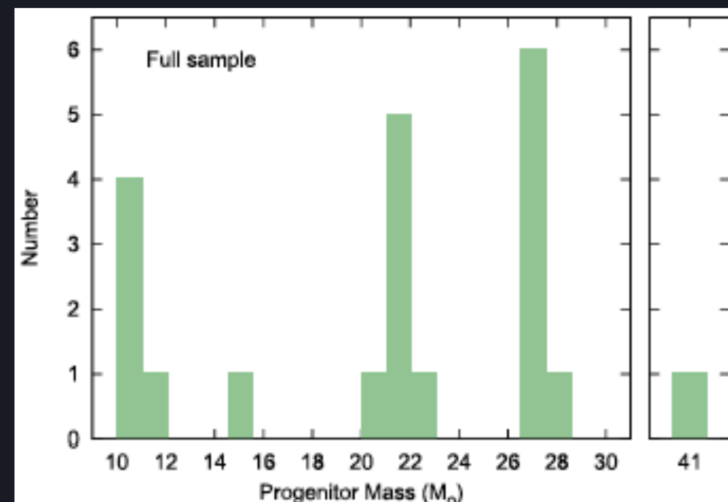


# EMP vs Pop III supernova yields

Abundance profiling
(Tominaga et al. 2014)




20 UMP stars with the STARFIT algorithm
(Heger & Woosley 2010; Placco et al. 2015)



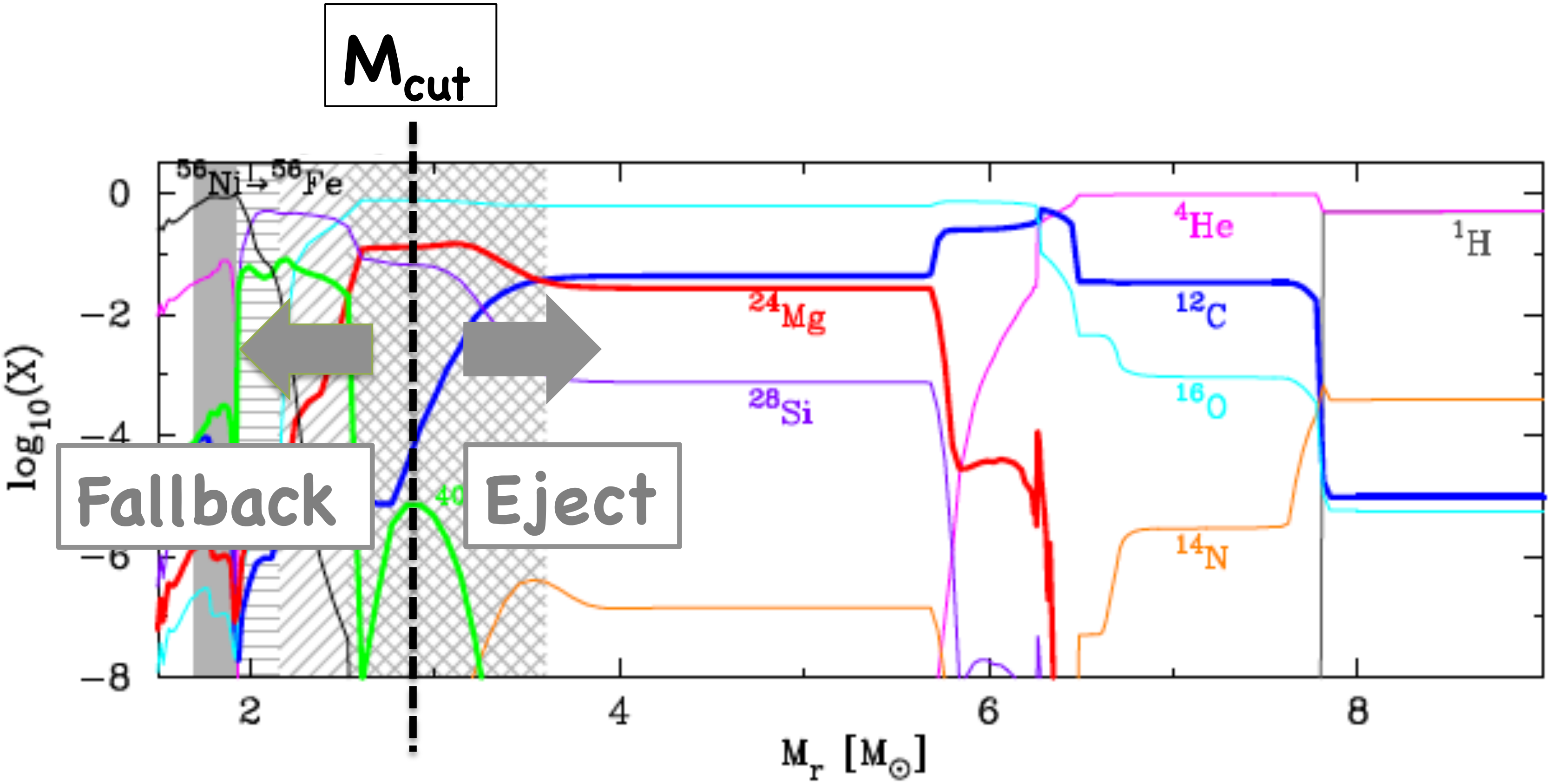

This study: Compile the largest sample of EMP stars

➡ combined insights into the masses of the Pop III stars

The key questions:

- ❑ The impact of the theoretical uncertainties arising from *the mixing and fallback process* in the primordial supernovae?
- ❑ What are the most important diagnostic elements?

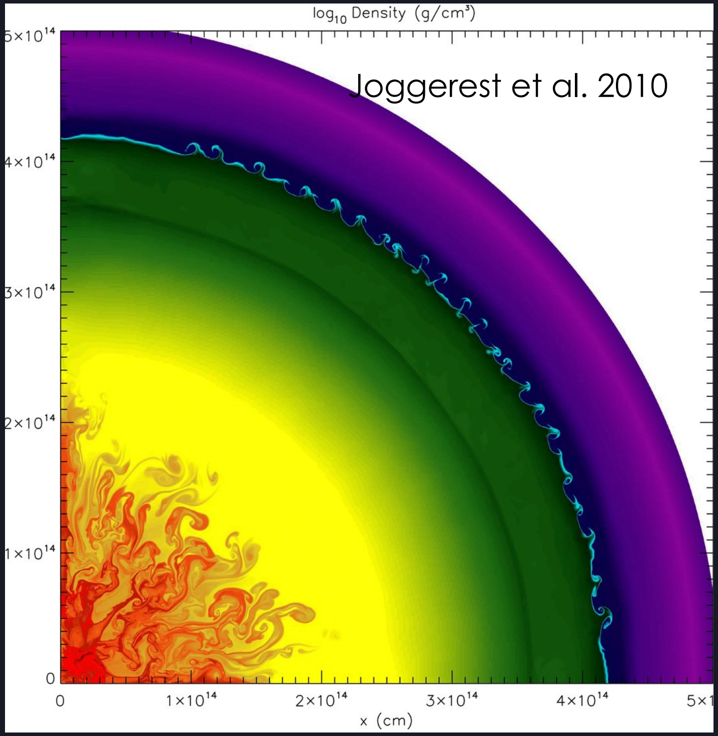
# Calculation of supernova yields



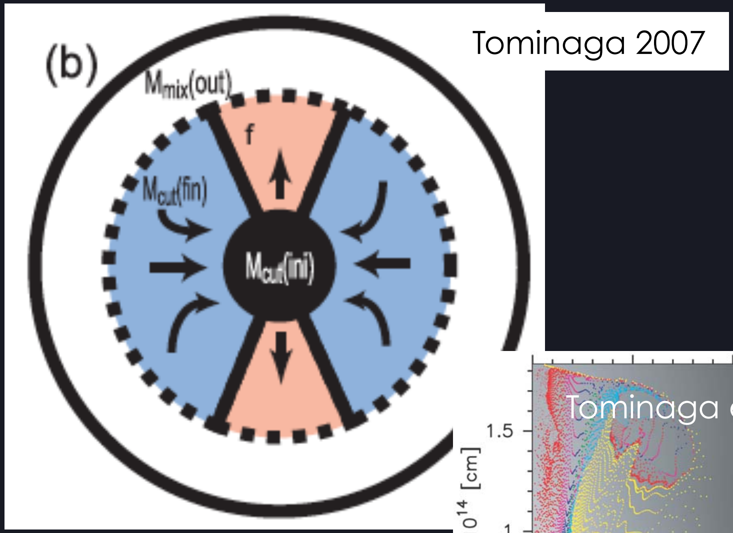

Calculated abundance distribution vs. enclosed mass ($M_r$) after the supernova of a metal-free star (Iwamoto et al. 2005; Tominaga et al. 2007)

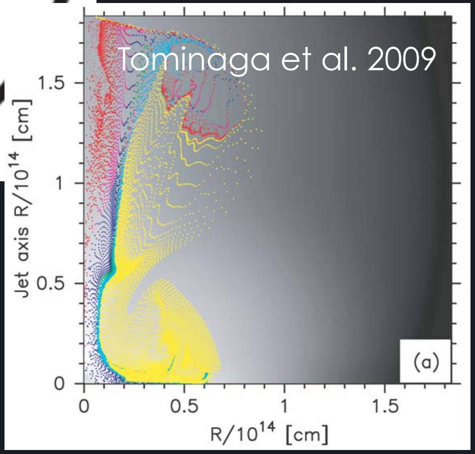
# Mixing

Rayleigh-Taylor instability

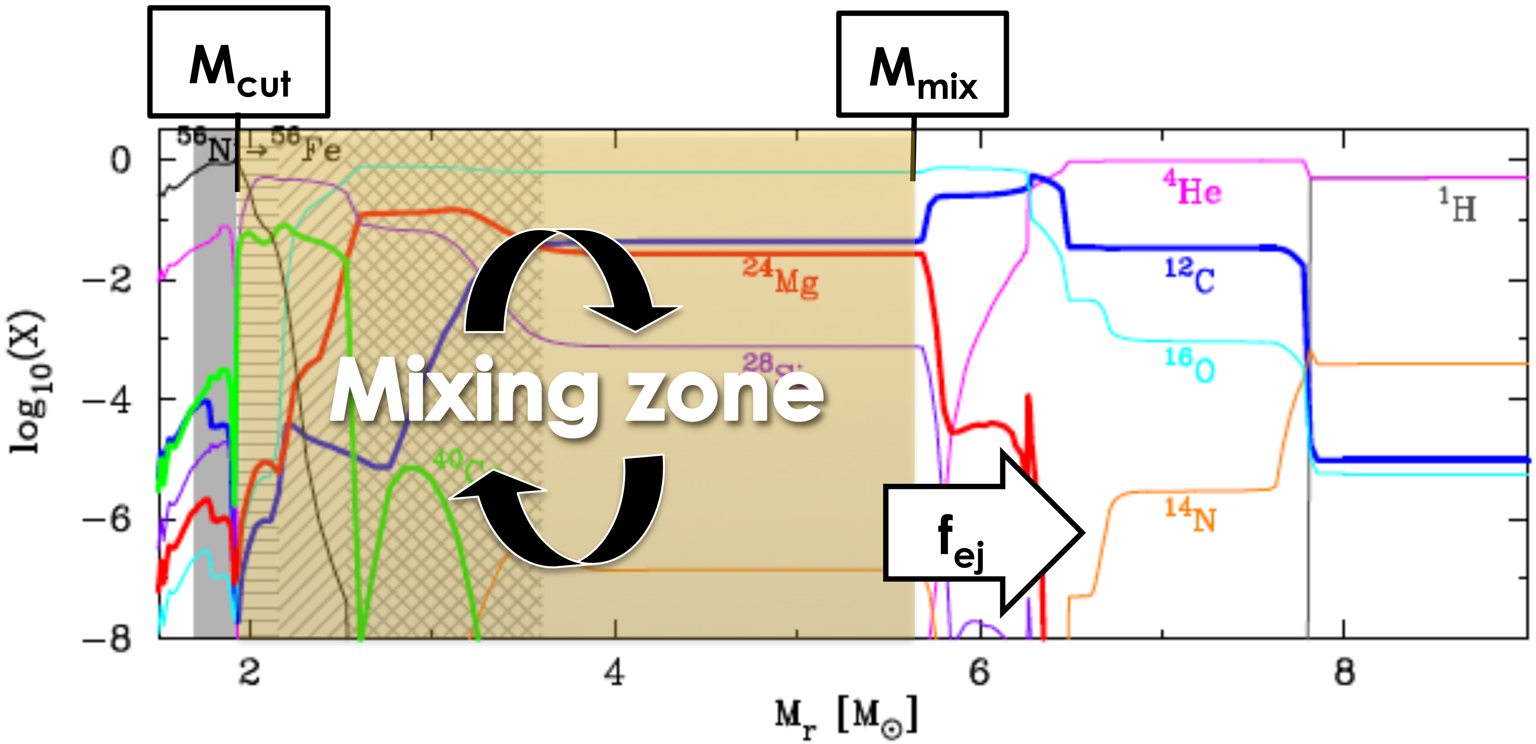



Non-spherical supernova



# The mixing-fallback model



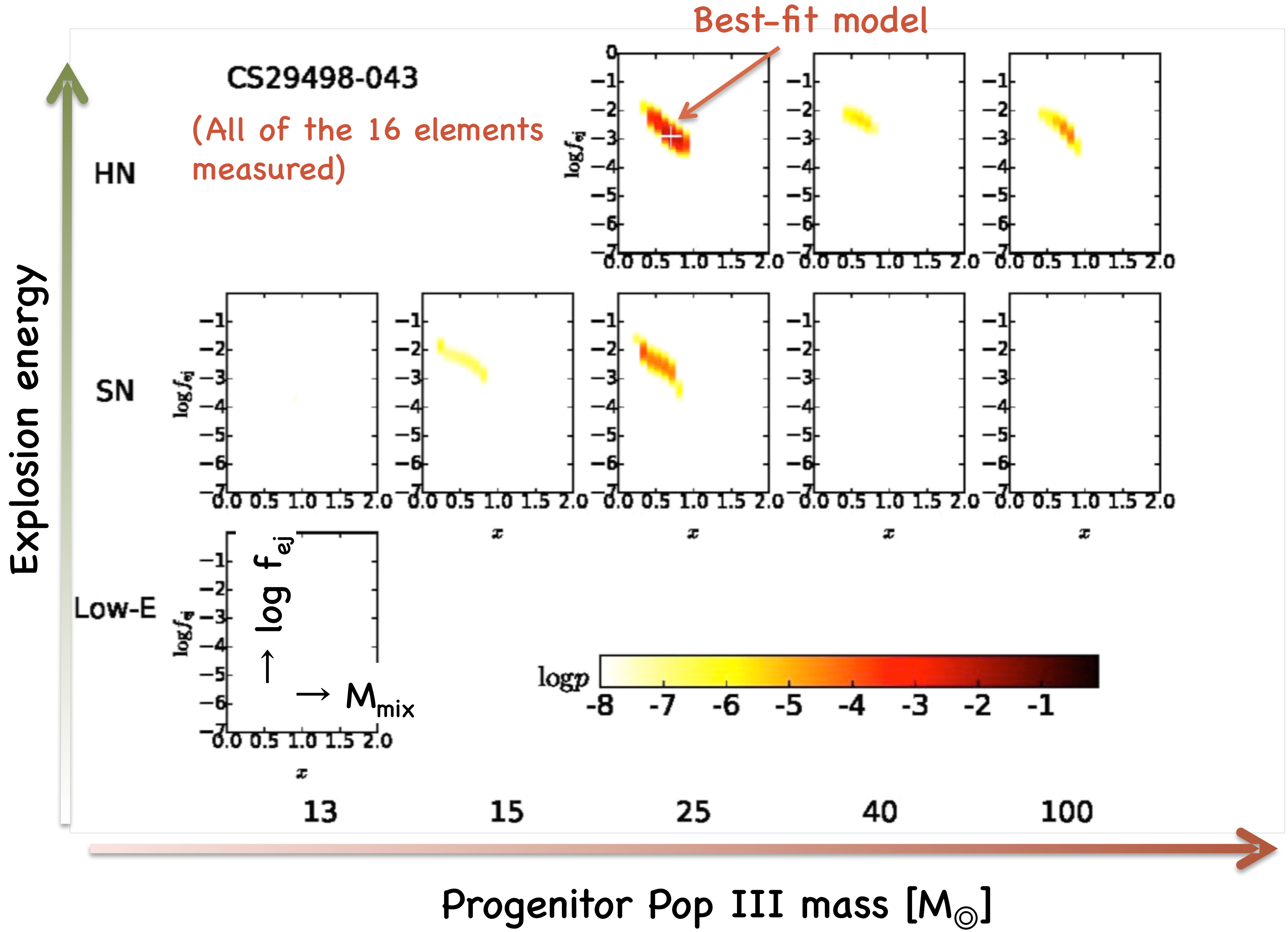

e.g. Umeda & Nomoto 2002, 2003, Tominaga et al. 2007

- $M_{cut}$: Inner boundary of the mixing zone
- $M_{mix}$: Outer boundary of the mixing zone
- $f_{ej}$: ejected fraction (fraction of mass ejected in the mixing zone)

# Fitting abundance patterns of ~200 EMP stars

- Observation
  - Elemental abundance measurements for *~200 EMP stars* ([Fe/H]<-3) based on high-resolution spectroscopy available from recent literature (Yong et al. 2013; Cohen et al. 2013; Roederer et al. 2014; Jacobson et al. 2015; Hansen et al. 2014; Placco et al. 2015, 2016; Frebel et al. 2015; Melendez et al. 2016)
  - Multiple abundance measurements (at least 7) of C, N, O, Na, Mg, Al, Si, Ca, Sc, Ti, Cr, Mn, Fe, Co, Ni, and Zn
- Model
  - One-dimensional stellar evolution and nucleosynthesis calculations for Pop III supernovae (Umeda & Nomoto 2005; Tominaga et al. 2007)
  - The mixing-fallback model to calculate supernova yields of various Pop III progenitor masses and explosion energies
- Fitting the abundances with the supernova yields
  - $\chi^2$ calculation *with uncertainties in both observation and theory*

# The mass, energy, M-F parameter spaces

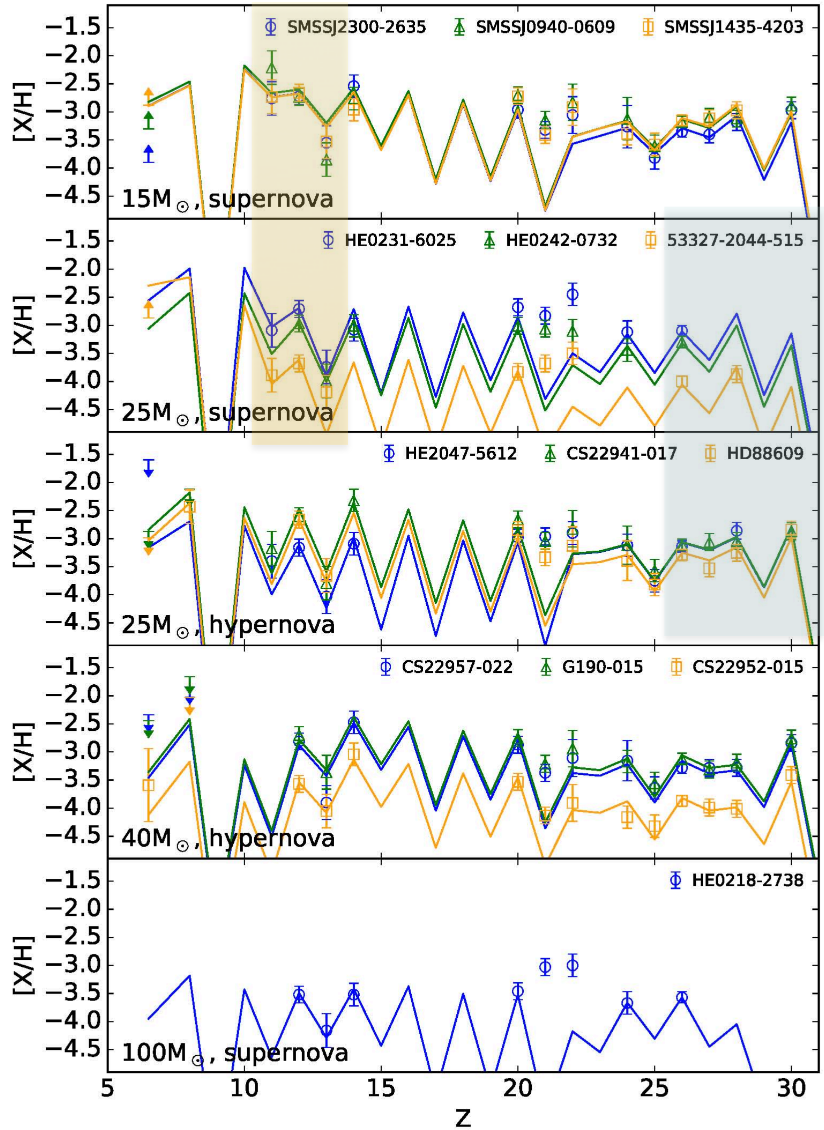


# Abundance fitting results

*5 out of 9 mass-energy models best-fit at least one EMP with $\chi^2_\nu$<3*

Na-Mg-Al-Si

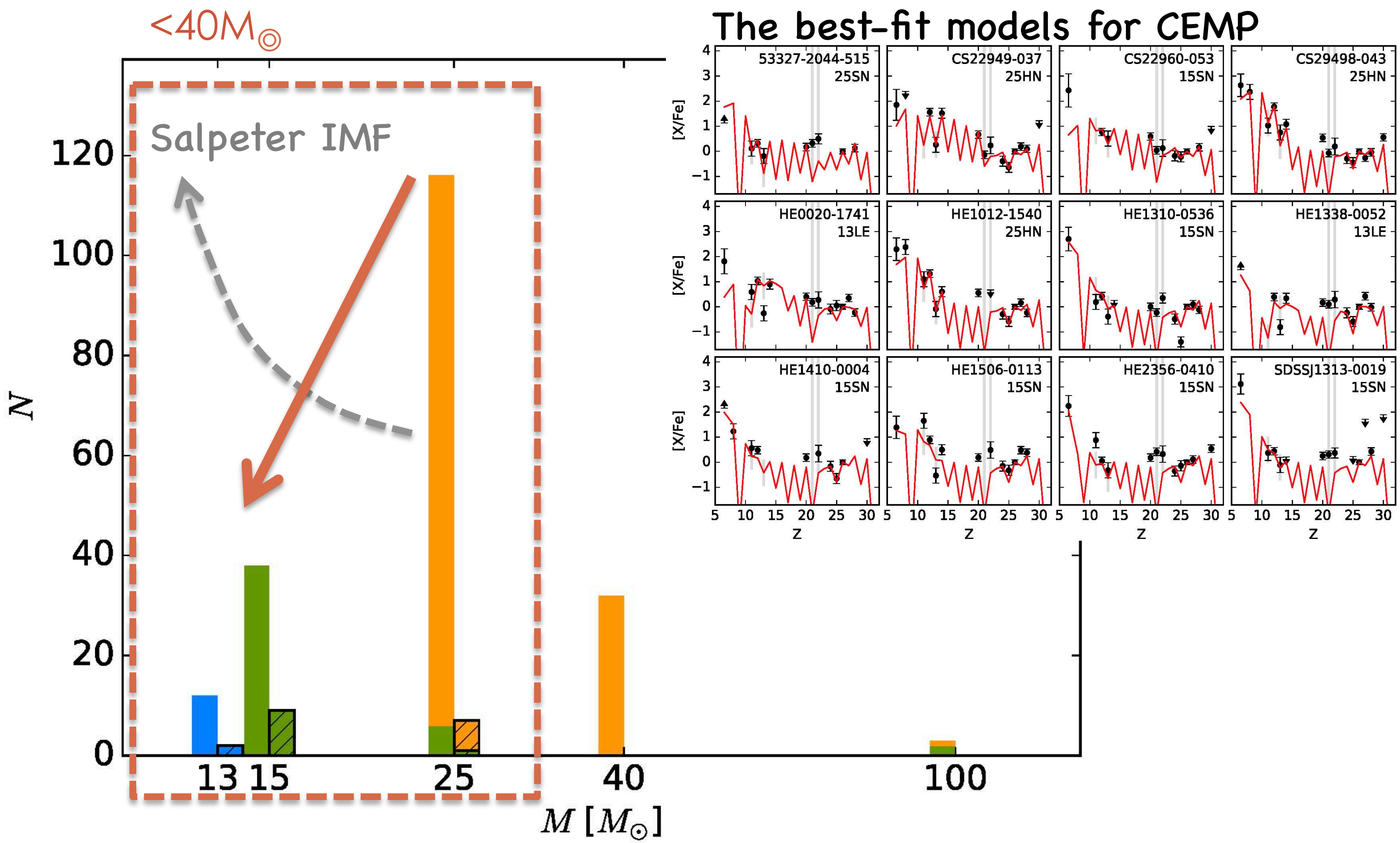
Pop III mass
15 vs 25 M$_\odot$




Fe-group: Co-Ni-Zn

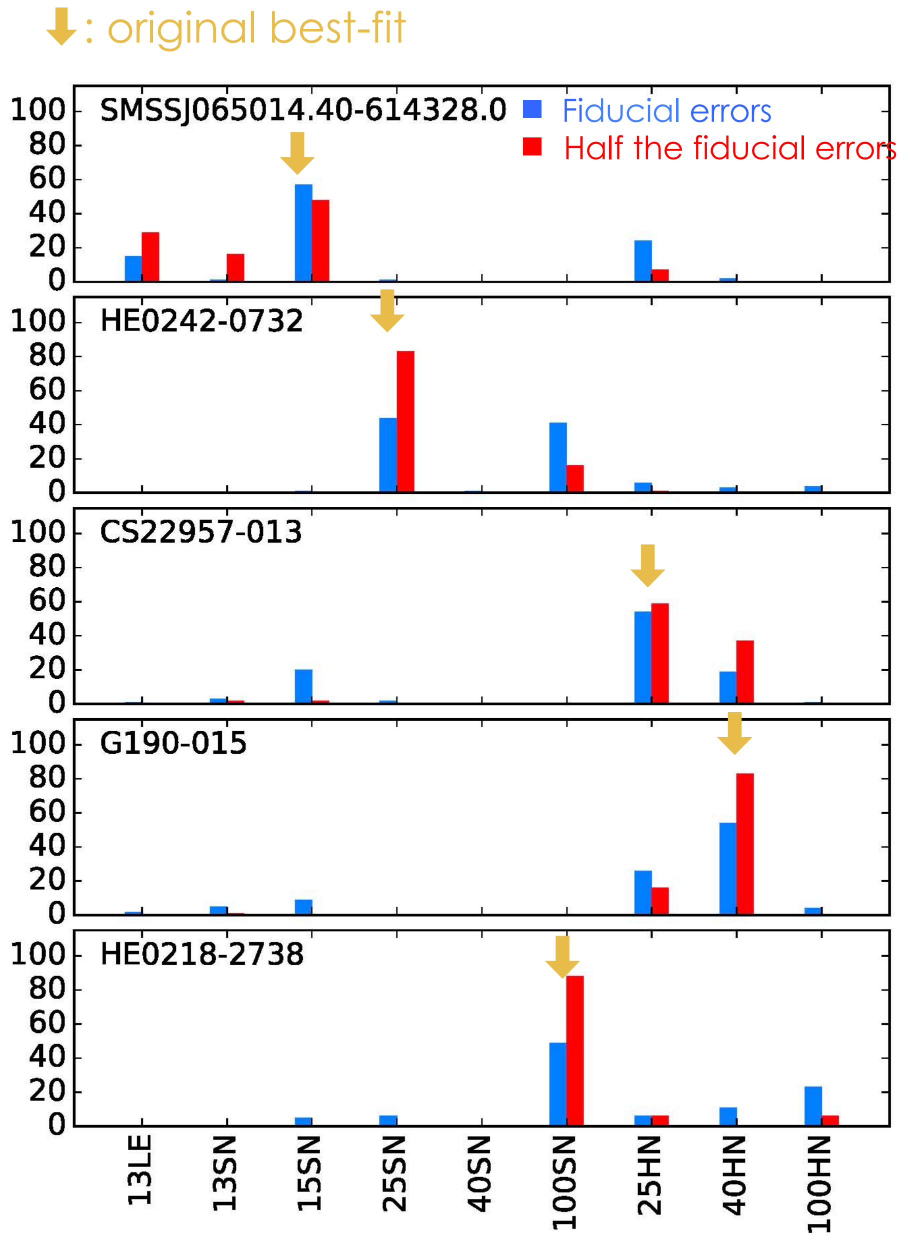
Explosion energy
Supernova vs. Hypernova

# Masses of the Pop III progenitors



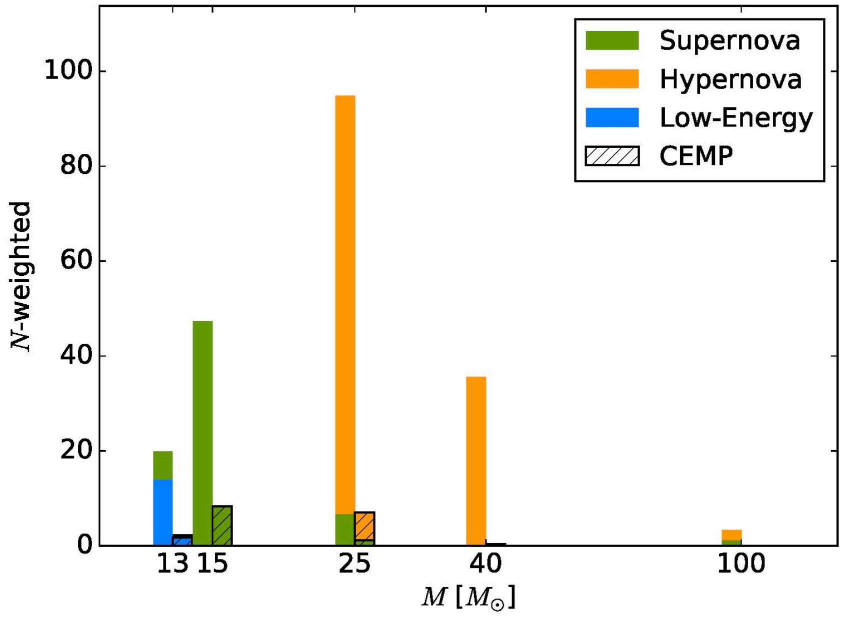

- ❑ The largest contribution from M=25M◎ model which decreases at lower masses
- ❑ ~ 80% best witted with the models with M<40M◎
- ❑ For CEMP, contribution from M=15M◎ models are larger than the 25M◎ models

# Effects of observational uncertainties

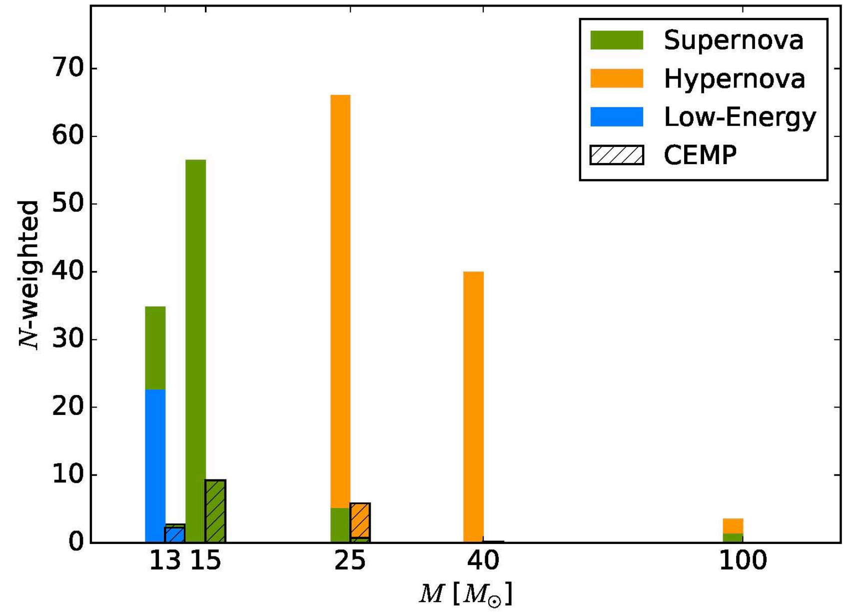


# The effect of NLTE on Al abundances

The original histogram

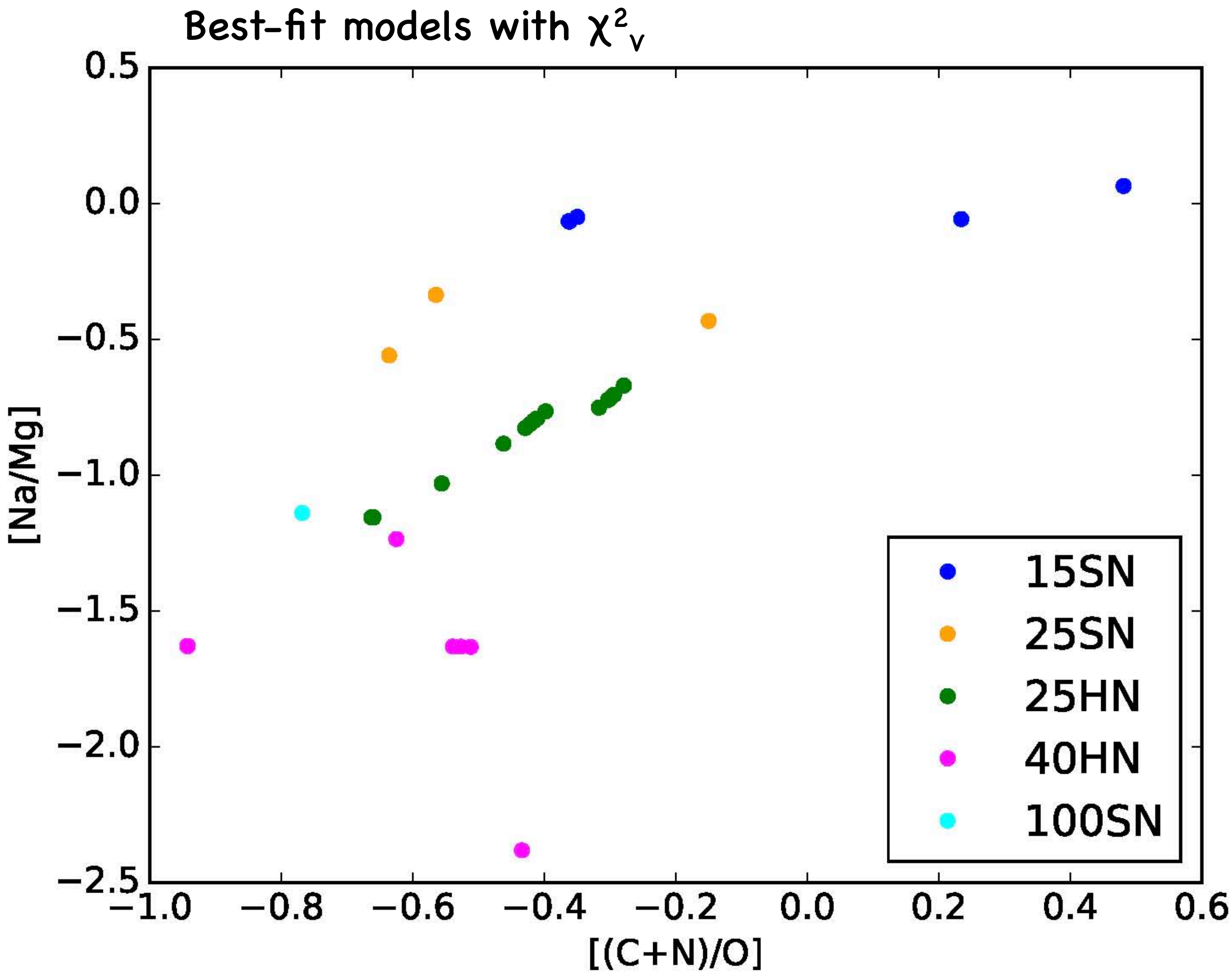



[Al/H] increased by 0.6 dex




Taking into account NLTE effects are important in discrimination the Pop III models with different Pop III masses at ≲25$M_{\odot}$.

# [(C+N)/O] – [Na/Mg] diagram



# Summary & Discussion

- The abundance fitting to observed abundances of ~200 EMP stars with Pop III supernova yields using the mixing-fallback model:
  - The distribution for the masses of the Pop III yield models is peaked at $25M_{\odot}$ with a decreasing contribution toward lower masses
  - The majority of the EMP stars are better explained by the Pop III star models with < $40M_{\odot}$. This implies that the higher-mass Pop III stars are either
    - ① *less abundant*
    - ② *directly collapse in to a black hole,*
    - ③ *their supernovae inhibit the formation of the next-generation stars*
  - The CEMP stars are explained by the models with the similar progenitor mass range
- What are possible diagnostic elements?
  - [(C+N)/O] and [Na/Mg] + other elemental abundance ratios to empirically constrain the mixing-fallback parameters
- Limitation:
  - Stellar evolution without rotation
  - The sample size, the number of elements measured