Physical Conditions for Synthesis of Sc, Ti, and V in Neutrino-driven Supernovae

Link to Paper

based on *Hatami et al. 2026, ApJ, 997, 200*

Ryota Hatami (SOKENDAI/NAOJ), Nozomu Tominaga (NAOJ),
Tomoya Takiwaki (NAOJ), Takashi Yoshida (Kyoto U.), Hideyuki Umeda (U. Tokyo)

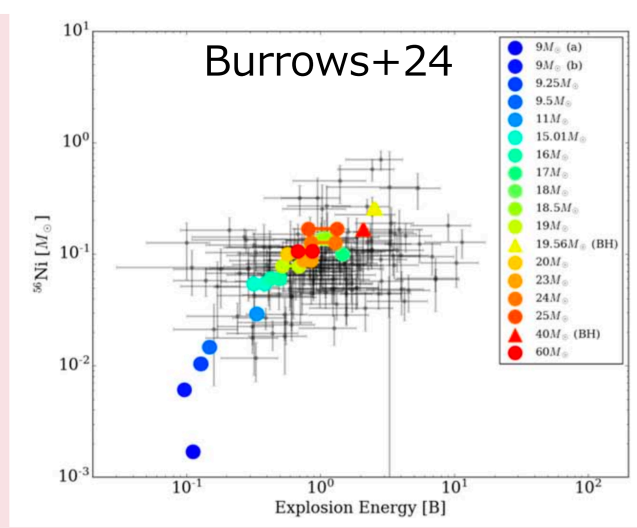
Abstract

We present the results of simulations of nucleosynthesis in a core-collapse supernova (CCSN) including the neutrino process. Using the Si layer of $13 M_\odot$ zero-metal progenitor as the initial composition, we calculate the nucleosynthesis by adopting the temperature, density, neutrino flux, and duration of nucleosynthesis as arbitrary parameters and compare the results with the observed abundances ratio of Sc, Ti, and V in very metal-poor (VMP) stars taken from the Stellar Abundances for Galactic Archaeology (SAGA) database. As a result, for the first time, we identify the quantitative requirements on local physical conditions. To reproduce the abundances ratios in the VMP stars, the explosive nucleosynthesis should take place under the neutrino exposure, which is time integration of neutrino flux, of $\sigma_\nu \sim 10^{35}\,\mathrm{erg\ cm^{-2}}$ and temperature of $2.0\,\mathrm{GK} \le T \le 3.2\,\mathrm{GK}$. The dependence on the density and each value of the neutrino flux and the duration of nucleosynthesis is weak. We also discuss whether the quantitative requirements are realized during the explosion. Although the requirements are difficult to be realized in the one-dimensional simulations, the non-monotonic thermal evolution shown in recent three-dimensional simulations may satisfy them. Because the evolution is likely caused by turbulent motion stemming from the initial asphericity of the progenitor, it is important to calculate the long-term three-dimensional supernova explosion of multi-dimensional metal-free progenitor models and follow the nucleosynthesis self-consistently.

1.Introduction

<CCSNe Observation vs Simulations>

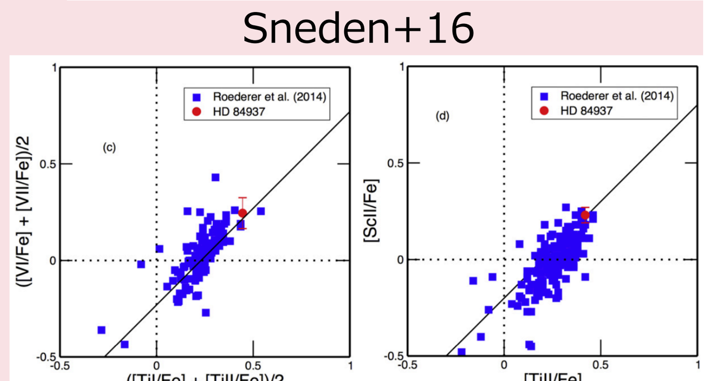
- Long-term multi-D simulations reproduce explosion energy and ^{56}Ni mass (Burrows+24)
- Those are sensitive to Numerical methodology and Microphysics (e.g., Just+18, Nagakura+19)
- Still too limited to draw definitive conclusions
  => Our understanding of explosion mechanism remains under development



<Observation of Metal-Poor Stars>

- Reflect the nucleosynthesis in early universe
- **Positive correlations among** [Sc/Fe], [Ti/Fe], [V/Fe] (Sneden+16)

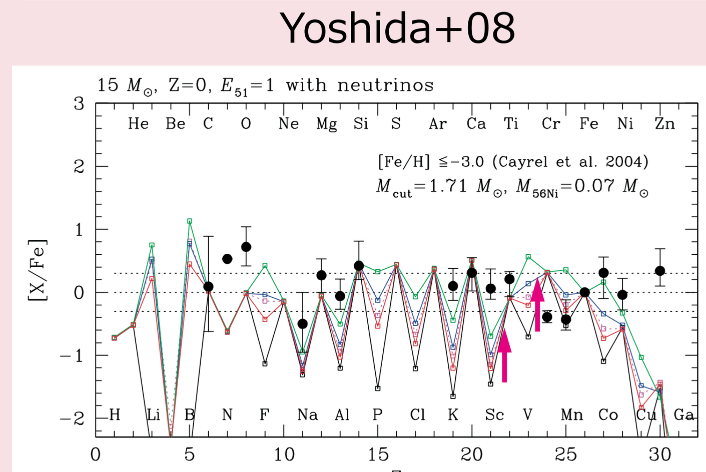
Sneden+16



<Nucleosynthesis Simulation>

- **Could not reproduce these abundances**
- **Sc is deficient**
  - Neutrinos enhance odd-Z elements **such as Sc** (Yoshida+08)
  - **Important roles in explosion**
    → evidence of interaction between matter and neutrinos

Yoshida+08



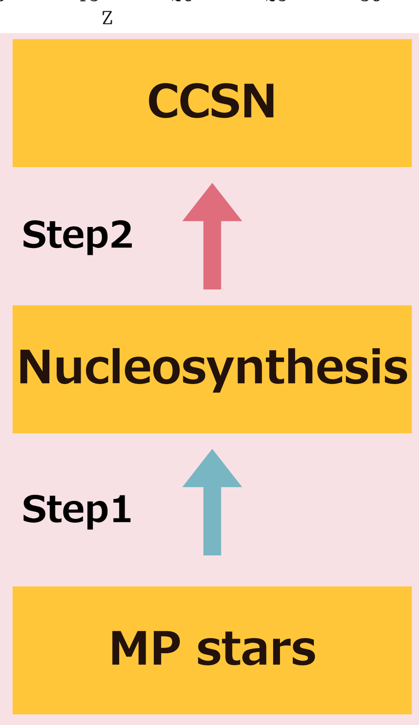
=> Investigating Sc, Ti, and V synthesis lead to **confirm/constrain the explosion mechanism**

<Aims>

Goal: **Confirm/Constrain the explosion mechanism**

Step1. Calculating the nucleosynthesis with parameters $(T, \rho, t_{\rm nuc}, F_\nu)$ **to identify the physical composition which reproduce the Sc, Ti, V abundance in MP stars**

Step2. Comparing multi-D simulation with the physical conditions to consider the feasibility of the conditions
→ **constrain the dynamics of explosion**



2.Models

<Setting for Nucleosynthesis>

Progenitor Model
$13 M_\odot, Z = 0$ (Umeda+00)

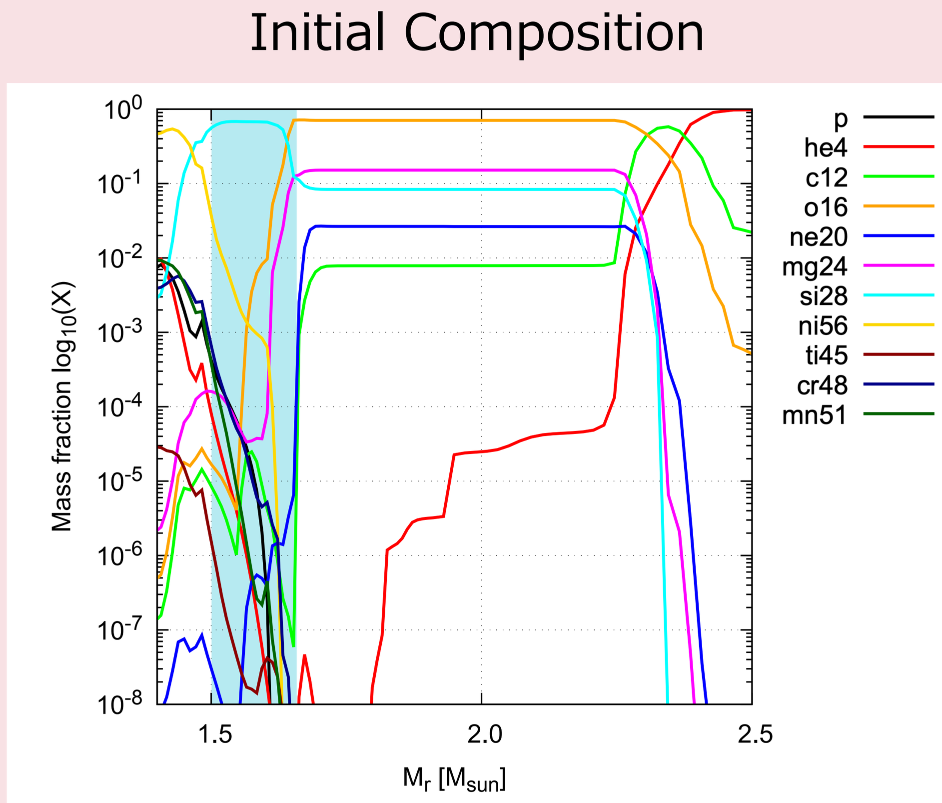
Temperature [GK]
$1 \le T \le 7$

Density [g/cm^3]
$10^5 - 10^8$

Neutrino Flux [erg/(cm^{2}s)]
$2.65 \times 10^{31} - 2.65 \times 10^{37}$

Duration of Nucleosynthesis [s]
$10^{-3} - 1$

Initial Composition



Neutrino Temperature [MeV/k_B]
$\bar{T}_\nu = \bar{T}_{\bar{\nu}_e} = 4.0, \bar{T}_{\nu_x} = 6.0$

Neutrino Spectra
Fermi-Dirac Distribution with zero chemical potential

<Observational Data>

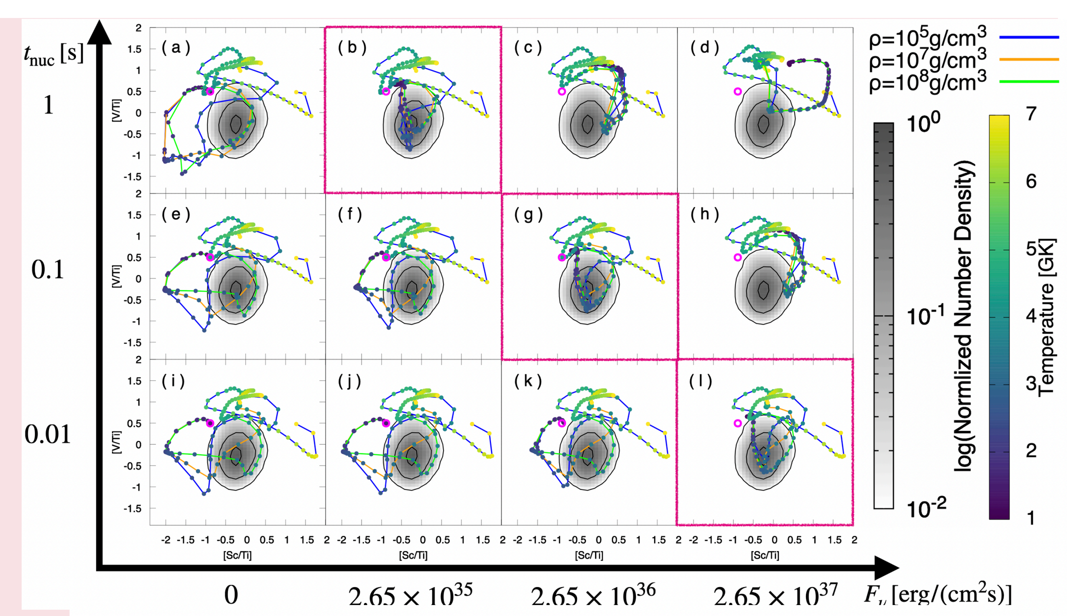
Observational data are taken from SAGA database (Suda+17)
441 VMPs are used for comparison, other VMPs with suspiciously high abundance ratios or with only upper limits are excluded

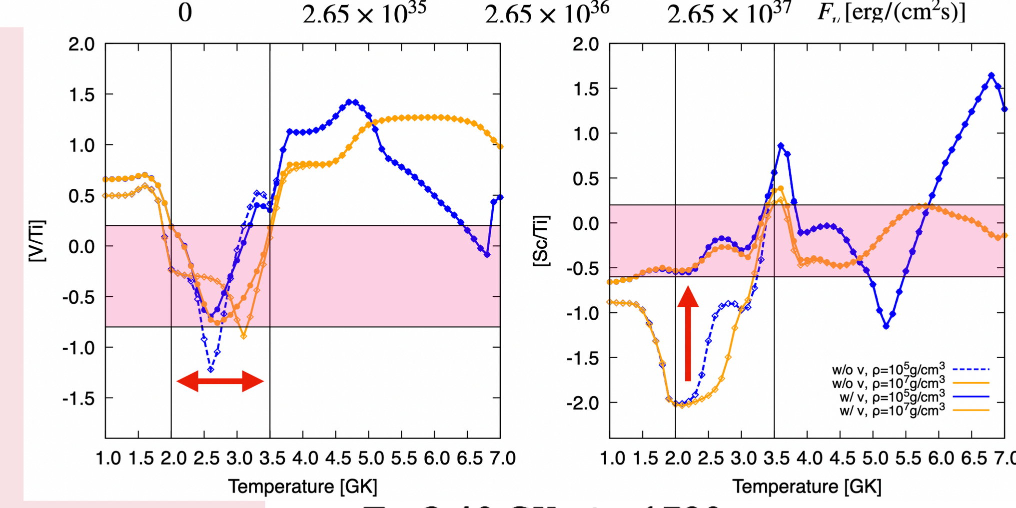
3.Results/Discussion

<Step 1>

- **Neutrinos enhance Sc**
  $(Z, A) + \nu \rightarrow (Z, A-1) + \nu'$
- Physical conditions
  Temperature : $2.0 \le T_9 \le 3.2$
  Neutrino exposure :
  $\sigma_\nu = F_\nu t_{\rm nuc} \sim 10^{35}\,\mathrm{erg/cm^2}$
- Sc constrains σ_ν
- V constrains T
- 1D spherical model…
  Neutrino flux: too low
  Temperature: too high

→ Previous studies cannot reproduce Sc-Ti-V





<Step 2>

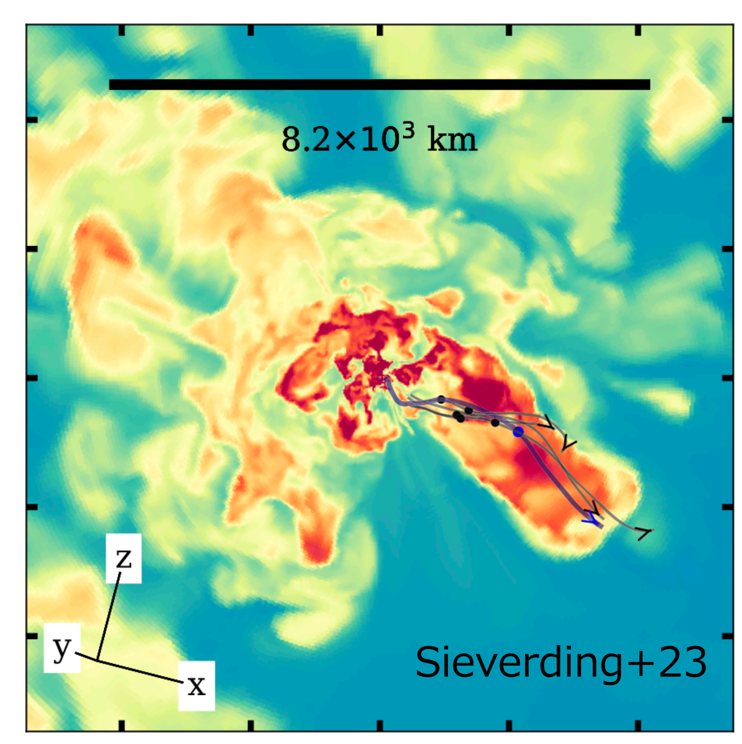
Are those conditions realized in long-term 3D explosion?

In Sieverding+23……

- Seconds scale turbulent motion
- Oscillate around 2GK
  (T condition ▲)
- Drift around ~10^{3}km
  (Neutrino conditions ◎)

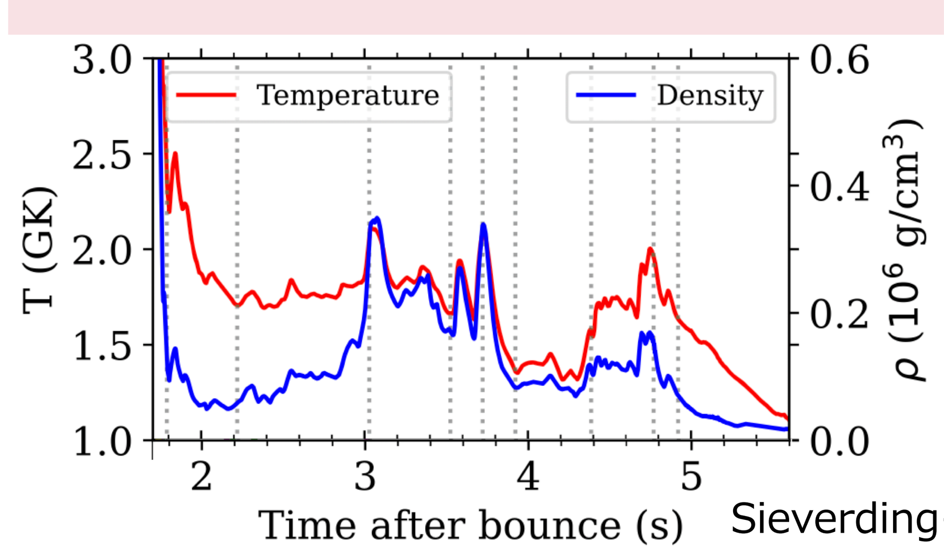
$L_\nu \sim 10^{52}$ erg/s
$r \sim 10^3$ km
$=> F_\nu \sim 10^{35}$ erg/cm^2/s

T = 2.40 GK, t = 1790 ms



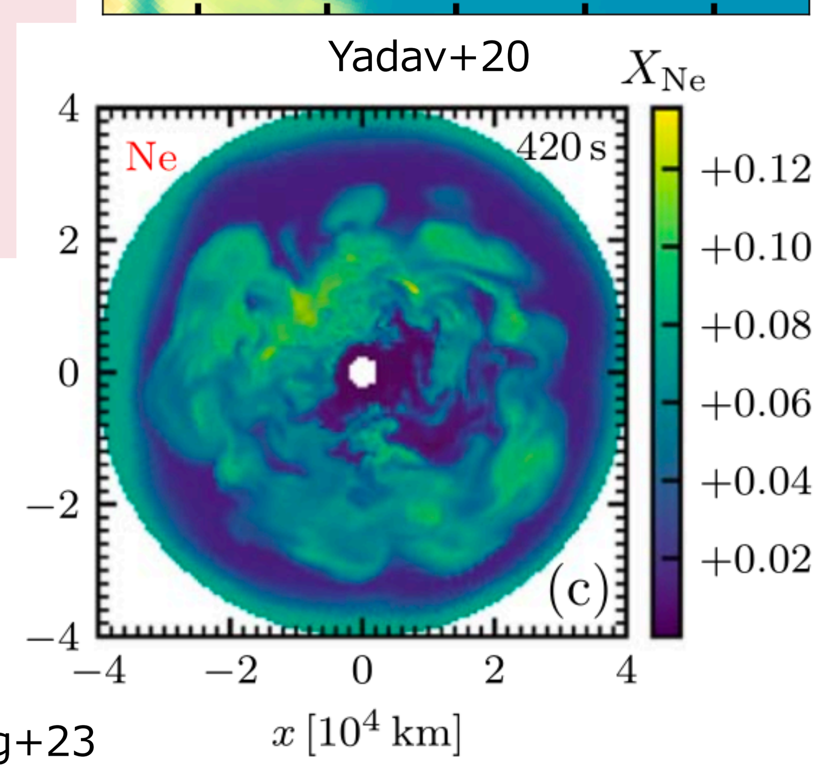
Their progenitor model experienced shell merger (Yadav+20)

- Shell merger also enhances Sc
  → Should be considered?



Sieverding+23

Yadav+20



4.Summary/Future work

Aim

To verify/constrain the explosion mechanism of CCSN by investigating the physical conditions for reproducing MP stars' [Sc/Ti] and [V/Ti]

Results

- We identified **Temperature condition: $2.0\,\mathrm{GK} \le T \le 3.2\,\mathrm{GK}$** and **Neutrino exposure condition: $\sigma_\nu \sim 10^{35}\,\mathrm{erg/cm^2}$**
- Those conditions **might be realized in long-term 3D simulation**

Future work

- Calculate nucleosynthesis based on long-term 3D simulations using metal-free progenitor to confirm our conditions
- Need to consider not only neutrino-interaction but also shell merger

Reference

Burrows, A., et al. 2024, ApJL, 964, L16. Just, O., et al., 2018, MNRAS, 481, 4786. Nagakura, H., et al., 2019, MNRAS, 536, 280.
Sneden, C., et al. 2016, ApJ, 817, 53. Yoshida, T., et al. 2008, ApJ, 672,1043. Umeda, H., et al. 2000, In Proceedings of The First Stars.
Suda T., et al. 2017, PASJ 69 76. Sieverding, A., et al., 2023, ApJL, 957, L25. Yadav, N., et al., 2020, ApJ, 890, 94.