Synthesis of Sc, Ti, and V in Core-Collapse Supernovae toward Constraining the Explosion Mechanism

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Abstract

A core-collapse supernova is an end-of-life product of a massive star. However, the explosion mechanism has not yet been clarified. As a clue to investigate the mechanism, we focused on nucleosynthesis. Metal-poor stars reflect the result of supernova nucleosynthesis in the early universe. Recently, observations show that there are correlations among [Sc/Fe], [Ti/Fe], and [V/Fe] in MP stars. However, the abundances ratios have not been explained by simulations. In this study, we firstly investigate the local physical conditions of nucleosynthesis which reproduce those abundances in MP stars with temperature, density, and neutrino exposure as arbitrary parameters, using the Si layers of Pop III stars as initial compositions. We find that the most important factor to reproduce [Sc/Ti] and [V/Ti] in MP stars is the neutrino exposure. The [Sc/Ti] and [V/Ti] are reproduced especially at low temperatures ($\lesssim 4\,\mathrm{GK}$). Secondly, the feasibility of the requirement on temperature and neutrino exposure obtained from nulceosynthesis calculations is investigated in 2D explosion simulations. The trajectories of maker particles are traced in the post-process and we investigate those physical quantities. As a result, the requirements on temperature and neutrino exposure are not realized in any of the models. However, the rotating models have large scatter in the neutrino exposures at the temperature range, and the neutrino exposure and maximum temperature of some tracer particles could be consistent with the requirement on temperature and neutrino exposure.

1.Introduction

<Core-Collapse Supernova:CCSN>

Explosive end-of-life product of massive star ($M > 8M_{\odot}$)

→ The explosion mechanism is not fully understood (Neutrino heating?)

<Explosion Simulation>

Multi-D : Successful explosion **have not reproduced the explosion energy**[1]

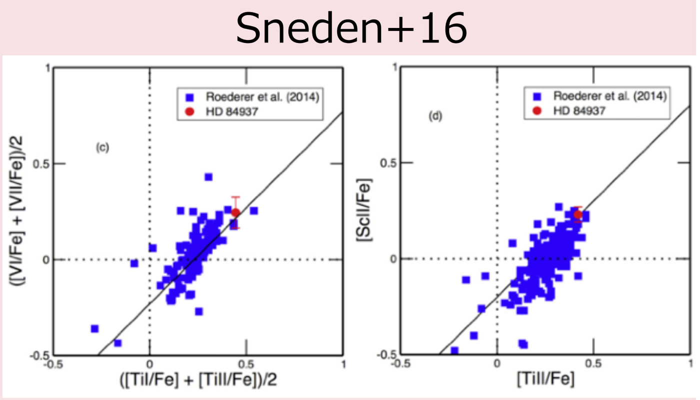
Observation : $0.6 \times 10^{50}\,\mathrm{erg}$[2] <=> Simulation : $\sim 0.1 \times 10^{50}\,\mathrm{erg}$

→ **something is missing in simulations**

<Observation of Metal-Poor Stars>

- Reflect the nucleosynthesis in early universe
- **Positive correlations among** [Sc/Fe], [Ti/Fe], [V/Fe][3]

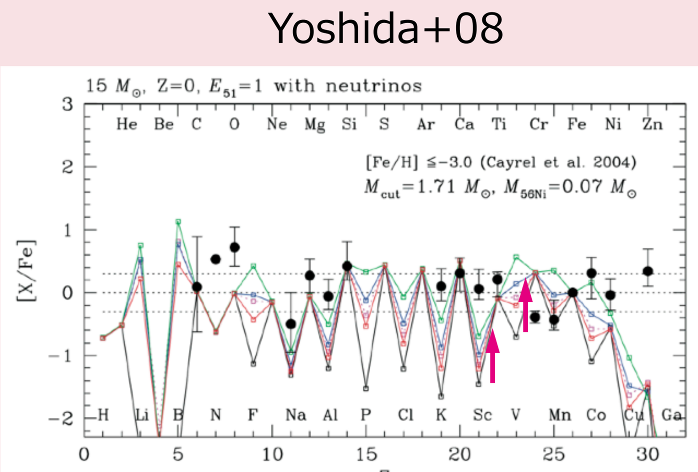
Sneden+16



<Nucleosynthesis Simulation>

- **Could not reproduce these abundances**
- **Sc is deficient**
  - Neutrinos enhance Sc[4]
  - **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**

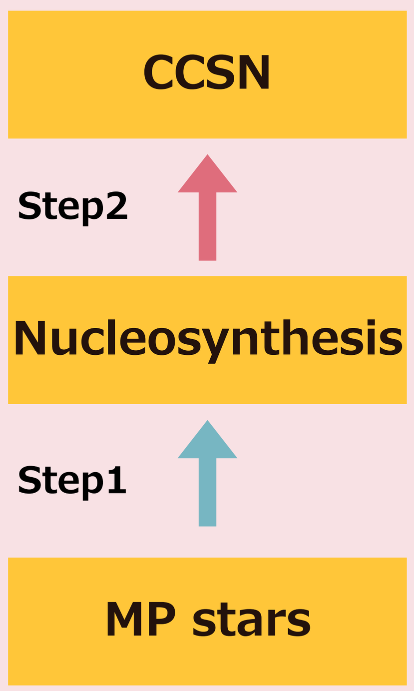
<Aims>

Goal:Confirm/Constrain the explosion mechanism

Step1. Calculating the nucleosynthesis with parameters $(T, \rho, t_{\mathrm{cal}}, F_{\nu})$ **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

<Nucleosynthesis>

Neutrino Energy

$\varepsilon_{\nu} = 3 \times 10^{53}\,\mathrm{erg}$

Neutrino Luminosity

$L_{\nu} = \dfrac{\varepsilon_{\nu}}{3\tau} e^{-t/\tau}$, $\tau = 3\,\mathrm{s}$

Initial Composition

$13M_{\odot}, Z = 0$[5]

Temperature

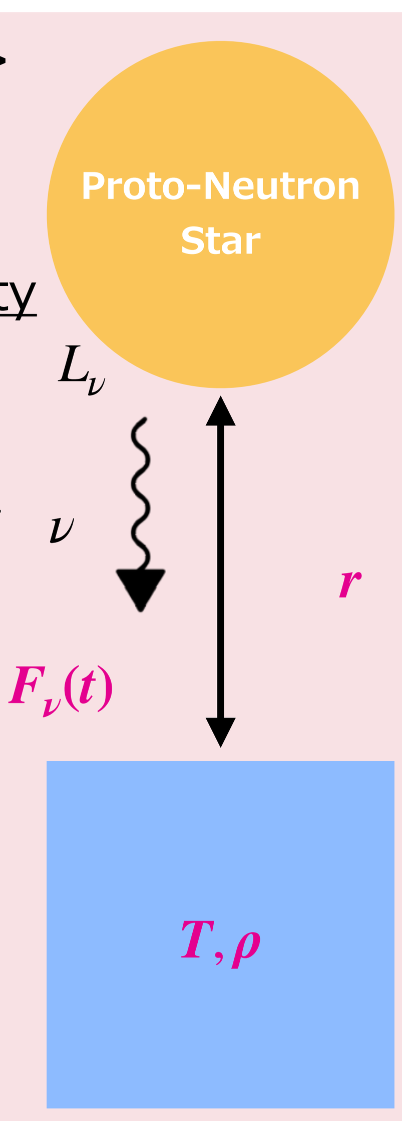
$1 \leq T_9 \leq 7$

Density

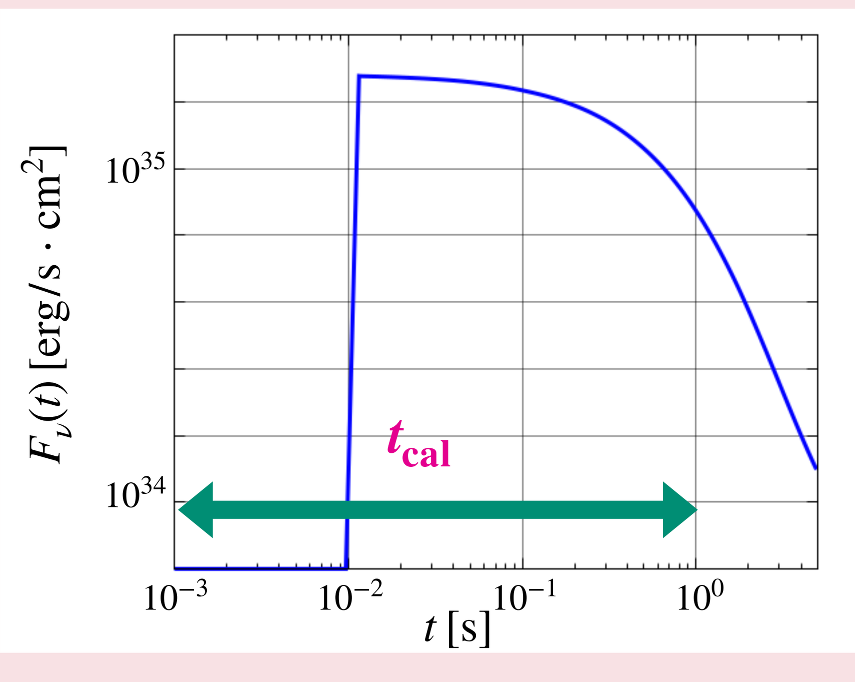
$10^{4-9}\,\mathrm{g/cm^3}$

Distance (km)

$3 \times 10^2 \leq r \leq 3 \times 10^5$



Time evolution of F_{ν}
(at $r = 3000\,\mathrm{km}$)



<2D Neutrino-Hydrodynamical Simulation>

Code:3DnSNe[6]

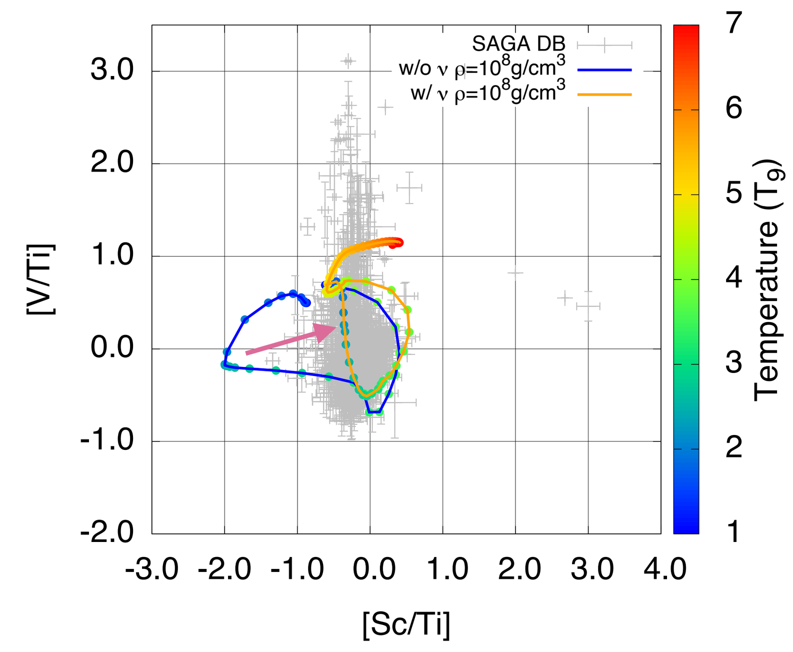
2D : $M = 13, 20, 23, 25, 29, 40M_{\odot}, Z = 0$ [7]

Rotation : $\Omega = \Omega_0 \times \dfrac{1}{1 + (r/R_0)^2}$, $R_0 = 10^3\,\mathrm{km}, \Omega_0 = 0.5\,\mathrm{s}^{-1}$

3.Results/Discussion

<Step 1>

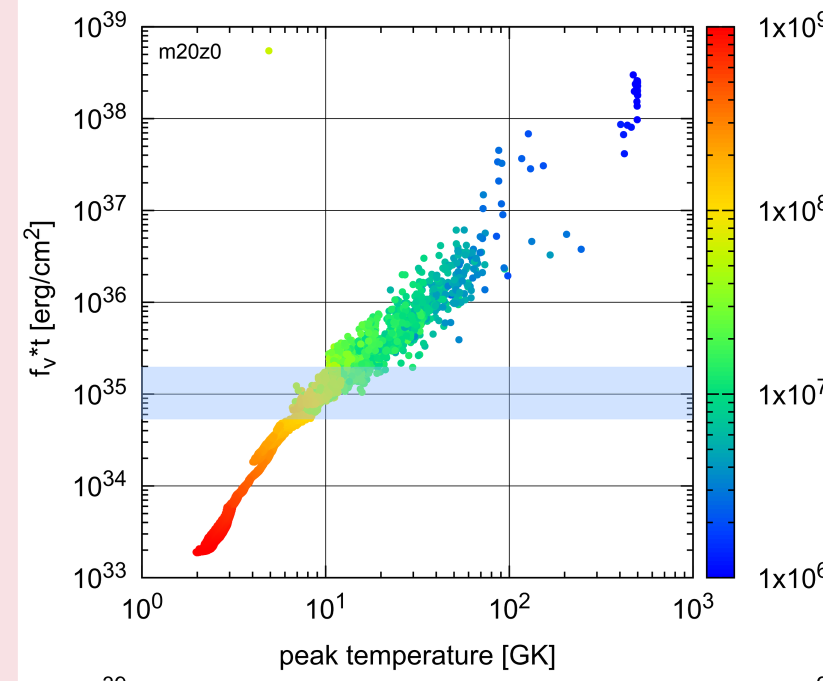
- **Neutrinos enhance Sc,V**
  e.g. $(Z, A) + \nu \rightarrow (Z, A-1) + \nu'$
- Physical conditions
  temperature : $T_9 \leq 4$
  Neutrino exposure :
  $F_{\nu}(t) \cdot t_{\mathrm{cal}} \simeq 10^{35}\,\mathrm{erg/cm^2}$
  Density : $\rho = 10^{4-9}\,\mathrm{g/cm^3}$
- Sc, Ti, V synthesis depend on
  ***T* and $F_{\nu}t$**



<Step 2>

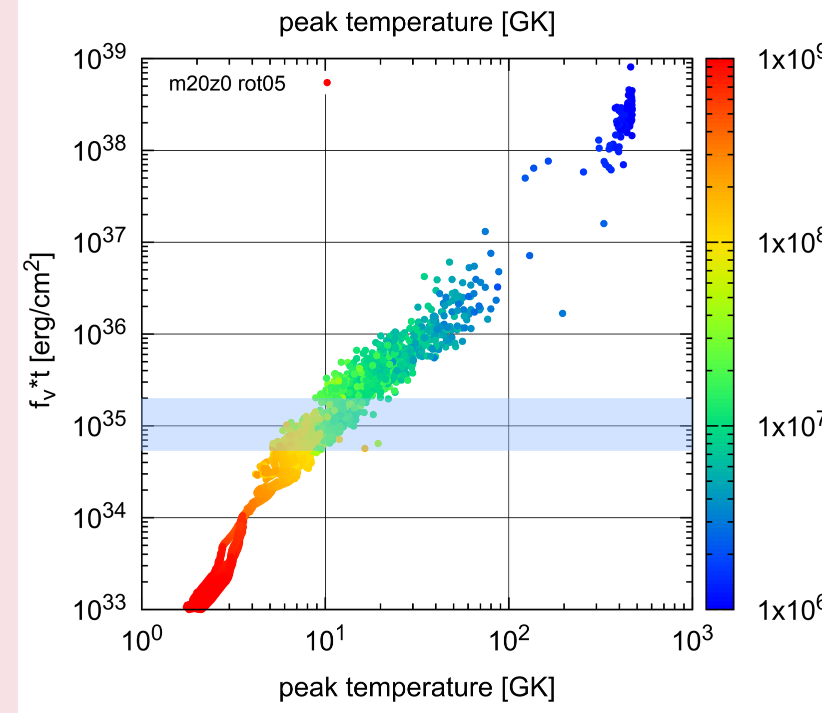
2D model

- Only T or $F_{\nu}t$ condition is satisfied
- **Scatter of neutrino exposure**
  High/low T → large/small



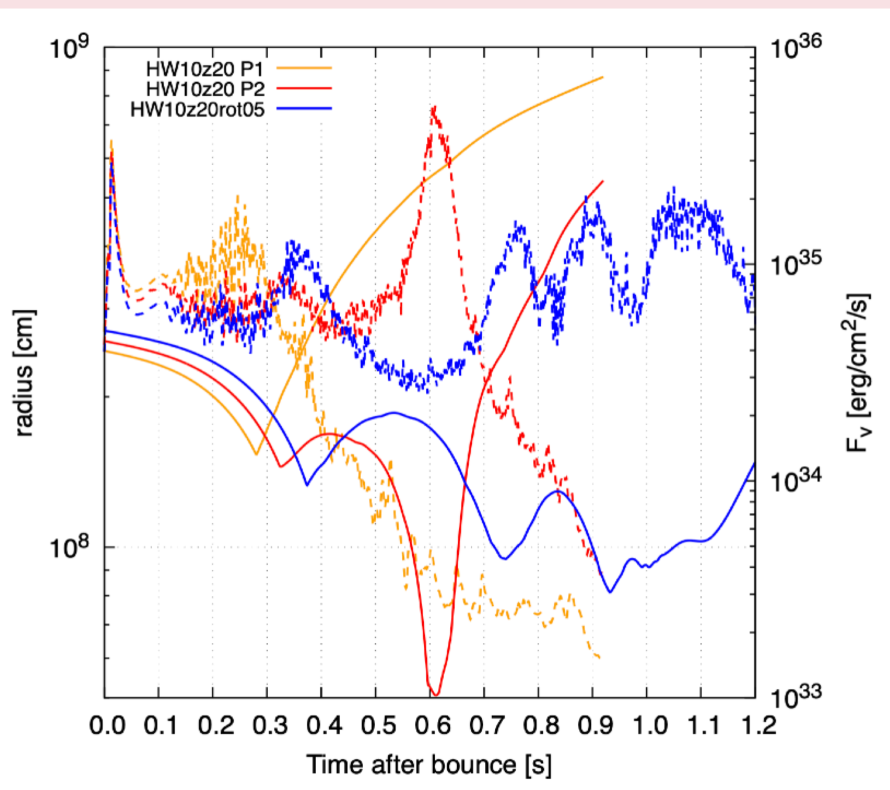
Rotating model

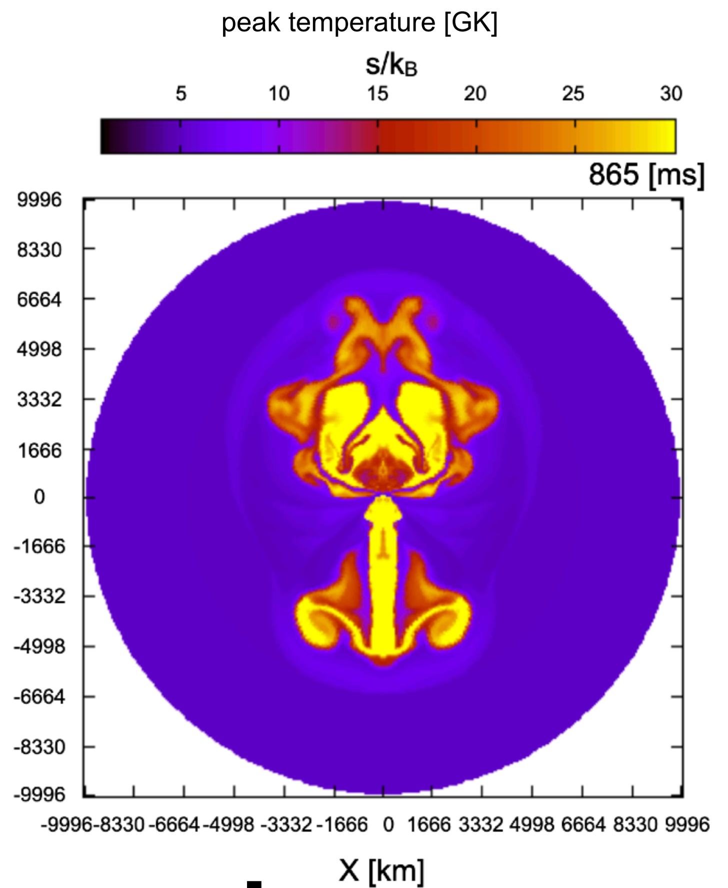
- **The conditions are not satisfied**
- However……
  scatter of $F_{\nu}t$ become large
  → why do such enhancements occur?



Trajectory of marker particle

- Compare non-rotating model with rotating model
- Particles in rotating model
  → non monotonic motion
- Turbulent cause such motion
  → Rotation enhance the convection





4.Summary/Future work

<Summary>

- We identified the physical condition which reproduce Sc, Ti, and V in MP stars
- Such conditions are not satisfied simultaneously in non notating model
- Rotation cause convection and non monotonic trajectories of particles
  → scatter of neutrino exposure become larger than non rot. model

<Future Work>

- Comparing with other model (e.g. 3D or faster rotating model)
- Investigating other elements like Fe

Reference

[1] Burrows, A., et al. 2020, MNRAS, 491, 2715. [2] Martinez, L., et al. 2022, A&A, 660, A41. [3] Sneden, C., et al. 2016, ApJ, 817, 53.
[4] Yoshida, T., et al. 2008, ApJ, 672,1043. [5] Umeda, H., et al. 2000, In Proceedings of The First Stars. [6] Takiwaki, T., et al. 2016, MNRASL, 461, 112.
[7] Woosley, S., et al. 2002, Rev. Mod. Phys., 74, 1015.