

Investigation of Type Ia Supernova Remnants in Fast Hydrodynamic Simulations with X-ray Spectral Synthesis

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Supervisor: Shiu-Hang Lee

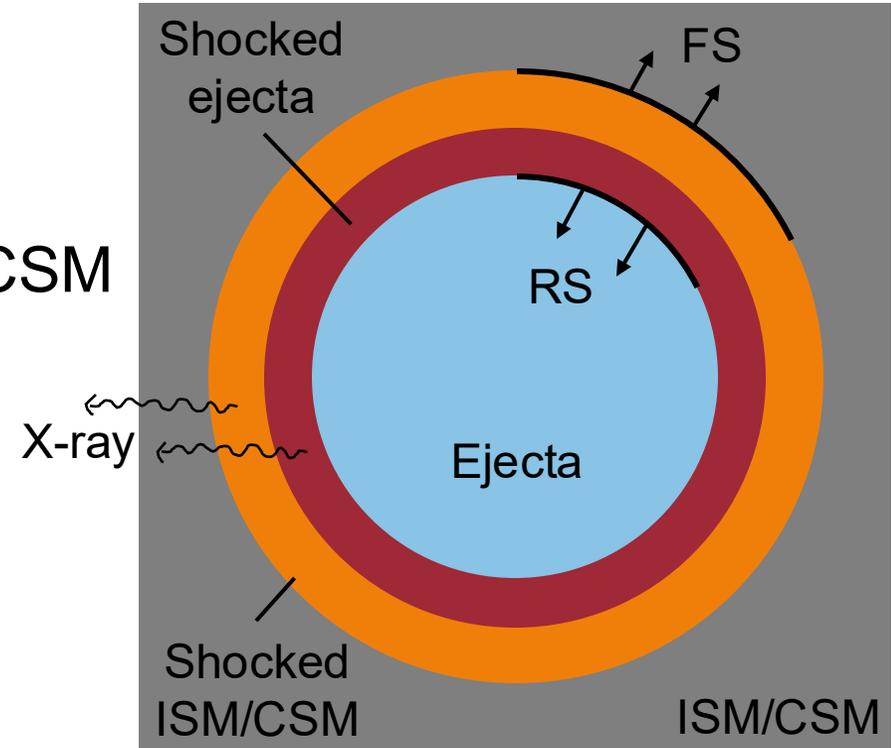
Gilles Ferrand (U. of Manitoba), Daniel Patnaude (SAO), Shigehiro Nagataki (RIKEN),
Rüdiger Pakmor (MPIA), Samar Safi-Harb (U. of Manitoba), Friedrich K. Röpke (HITS),
Anne Decourchelle (CEA Saclay), Ivo Seitenzahl (ANU)

Outline

- Introduction
- Methods
- Uniform environment case
- (3-D CSM case)

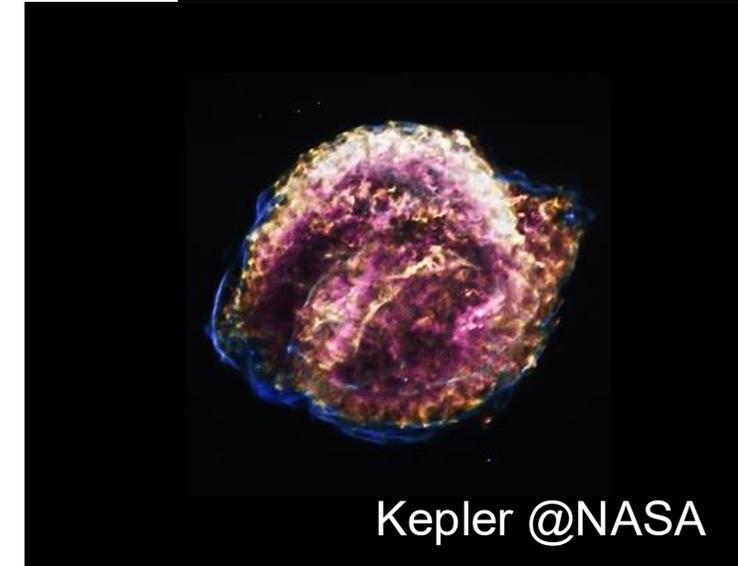
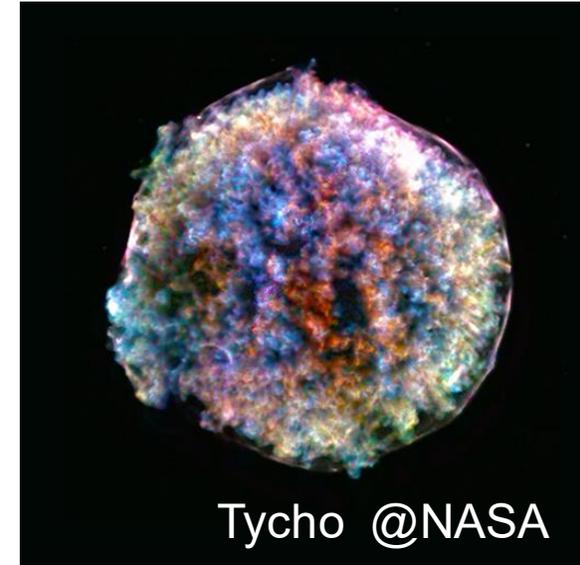
Supernova Remnants (SNRs)

- SNe eject material → Interact with ISM/CSM
- This interaction produce **two shocks**
 - Forward shock: propagate outward and heat ISM/CSM
 - Reverse shock: propagate inward and heat ejecta
- Shock heated plasma emit thermal X-ray
 - Thermal bremsstrahlung
 - Emission line from ions→ **Plasma state**



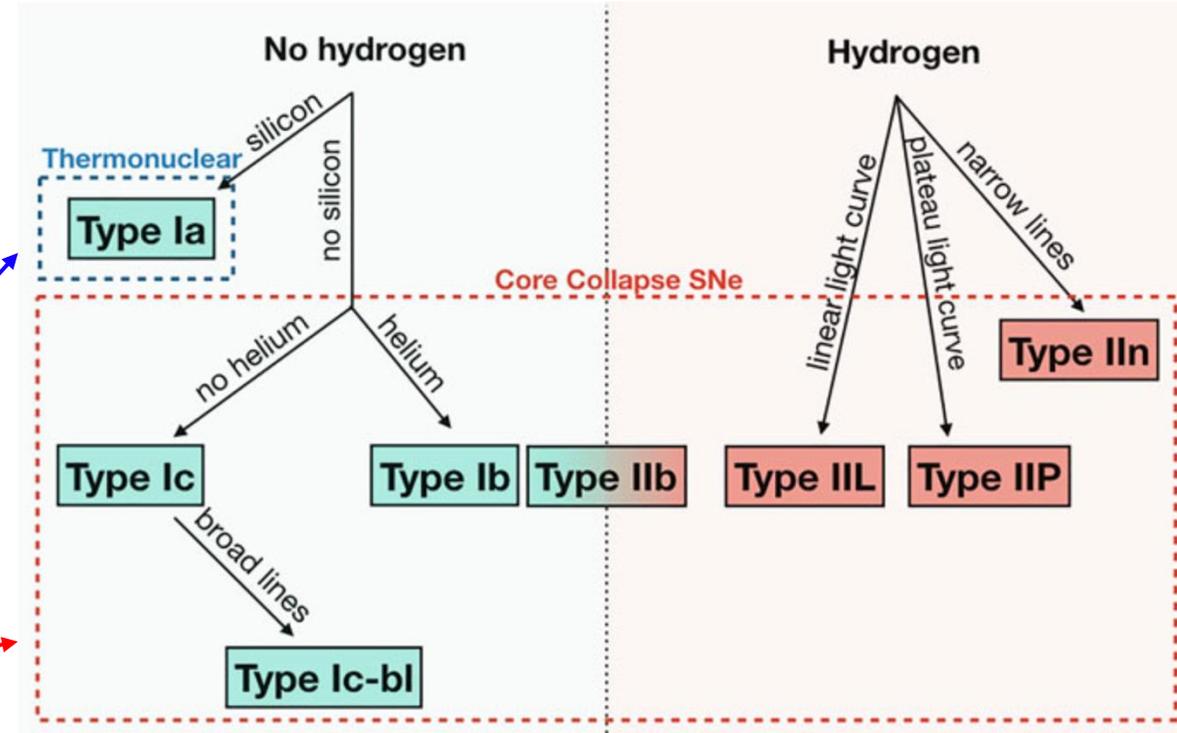
Supernova Remnants (SNRs)

- SNRs are **spatially extended sources**, not point sources
 - We can observe their spatial distribution
 - Clumpy structure
 - Symmetric or asymmetric structure
- Where do they come from?
 - Explosion properties, environments, ...
- **SNRs can play crucial roles in constraining their progenitor systems**



Supernovae (SNe)

- One of the most extreme phenomena in the universe
- Typical energy $\sim 10^{51}$ erg
- Historically, SNe have been classified based on optical observations
- Supernovae are divided into two classes by their mechanism
 - Only Type Ia: Thermonuclear
 - All others: Core Collapse



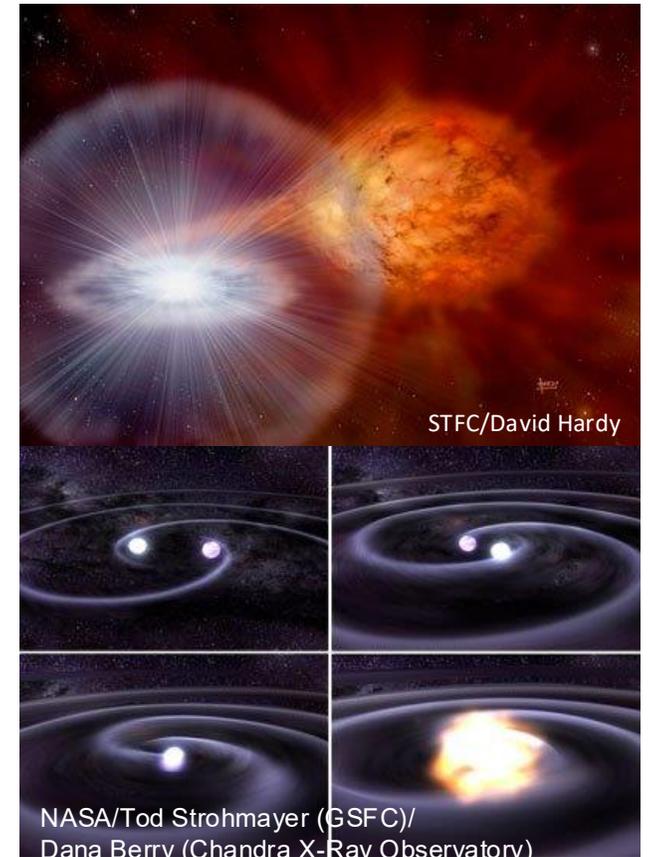
From Vink (2020), *Physics and Evolution of Supernova Remnants*

Type Ia Supernovae

- Major sources of iron group elements
- Used as standard candles (Riess et al. (1998), Perlmutter et al.(1999))
expect they are homogeneous...

WD explode in binary system

- Progenitor system scenario
 - Single degenerate (WD + MS)
 - Double Degenerate (WD + WD)
- Explosion mechanism
 - near M_{ch} (e.g., delayed detonation, pure deflagration)
 - sub M_{ch} (e.g., double detonation, violent merger)

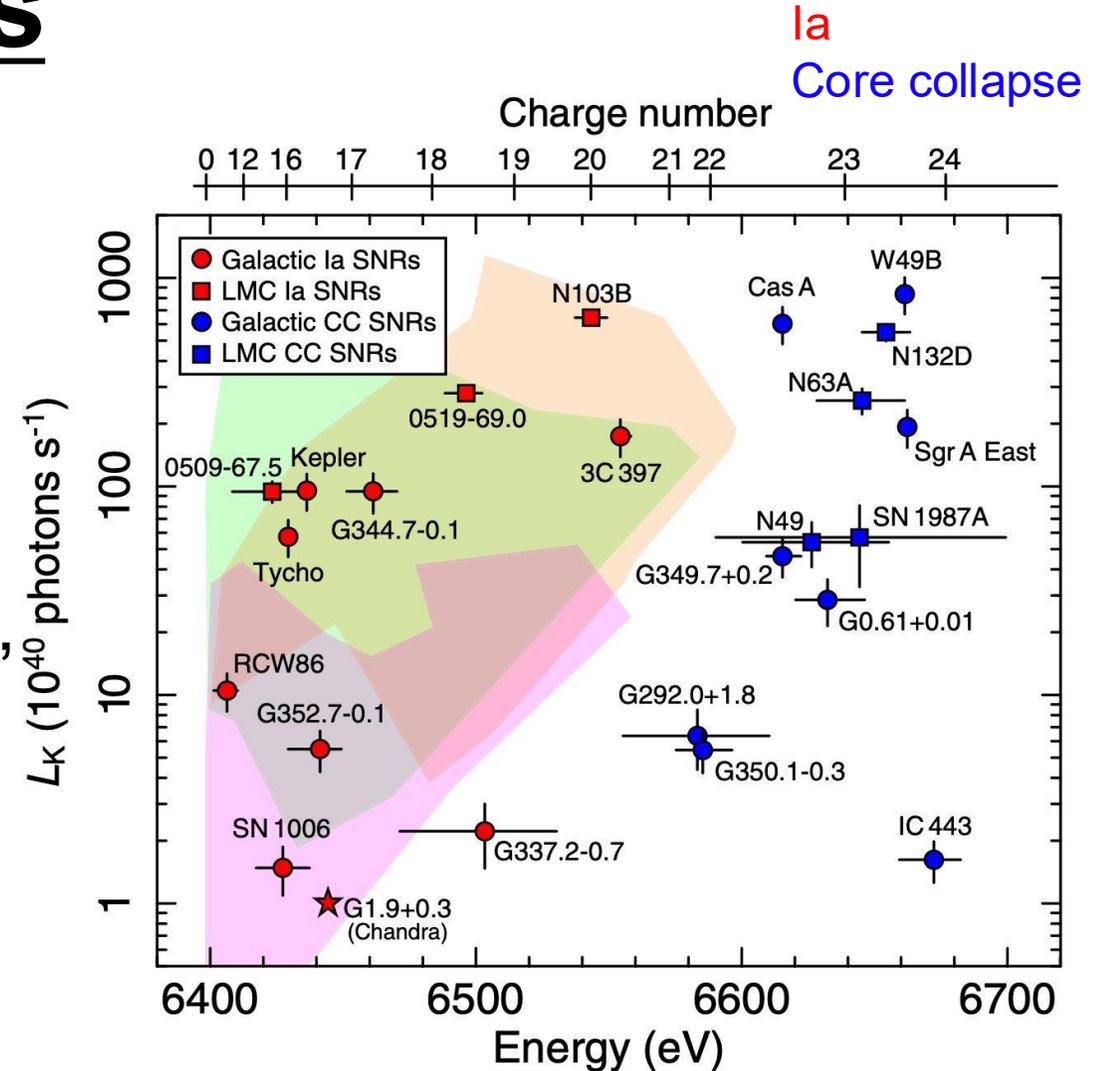


Diversity of Type Ia SNRs

- It is suggested that Fe-K α line is useful to discriminate origin of SNRs
For Type Ia, density of iron is lower than CC
→ Low ionized, low centroid energy

- Even for only Type Ia SNRs (red points), spread over wide range in both E and L

→ Diversity of Type Ia SNRs



Centroid energy and line luminosity of Fe K α
(Yamaguchi et al. (2014))

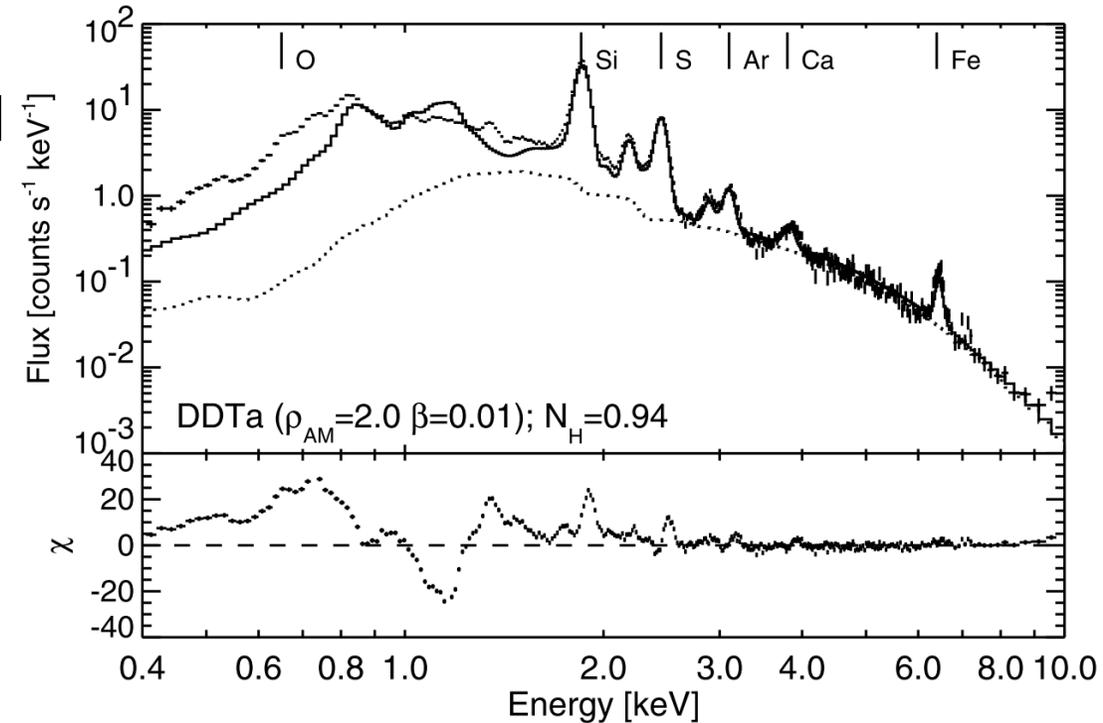
Previous Simulations of Ia SNRs – 1-D

1D hydro with X-ray spectral synthesis

- Badenes et al. (2003, 2005, 2006)

Badenes et al. (2006) suggest that DDT model reproduces Tycho's spectrum well

- Court et al. (2024, 2025)

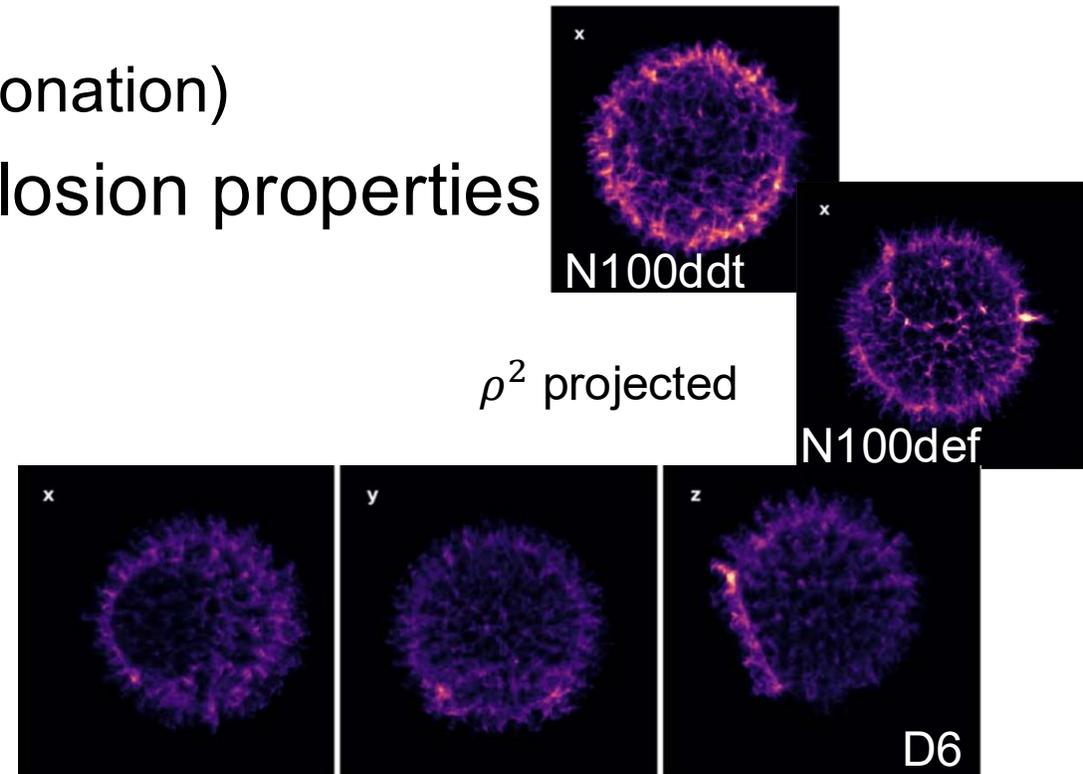


Badenes et al. (2006)

Previous Simulations of Ia SNRs – 3-D

- Morphological study of 3-D hydrodynamic simulation of Type Ia SNRs in uniform density environment
 - Ferrand et al. (2021): SD models (delayed detonation, pure deflagration)
 - Ferrand et al. (2022): D6 model
 - Ferrand et al. (2025): DD models (double detonation)
- Various morphologies correspond to explosion properties
 - Explosion asymmetry
 - Existence of companion
 - Whether if secondary explode

• No spectral synthesis



Main Goal

To qualitatively understand the 3-D evolution of Type Ia SNe and their X-ray spectral properties

(To connect 3-D simulations to XRISM observations and constrain progenitor models)

Methods

- ① Hydrodynamic simulation
- ② Spectral synthesis

Methods – Hydrodynamic Simulation

- 3-D Eulerian hydrodynamic NEI code
 - VH-1 code (e.g., Blondin & Ellison (2001))
 - PPMLR scheme
 - Co-moving Cartesian mesh that expands with SNR
 - long-term evolution with sufficient resolution
 - Solve local physics such as NEI in Lagrangian tracer particles
- Low computational costs (1/2 days with 32 cores for 1000 year)
- allows us to perform **parameter surveys in 3-D**

Non-equilibrium Ionization (NEI)

- Collisionless shocks heat quickly, but ionization is slow
→ high T_e , low ionization state

$$\frac{dn_{i,z}}{dt} = n_e \left\{ \underbrace{\alpha_{i,z+1}(T_e)n_{i,z+1} + S_{i,z-1}(T_e)n_{i,z-1}}_{\text{change to } z} - \underbrace{[\alpha_{i,z}(T_e) + S_{i,z}(T_e)]n_{i,z}}_{\text{change from } z} \right\},$$

where α is recombination rate and S is ionization rate

Methods – Spectral Calculation

- SOXS (John ZuHone et al. (2023))
- Thermal bremsstrahlung
- Emission line from ions
- Input: particle file of hydrodynamic simulation
- Output: Flux from each tracer particle
- Volume-integrated X-ray spectra, specific region spectra
- Run time: about 1 day per model per epoch

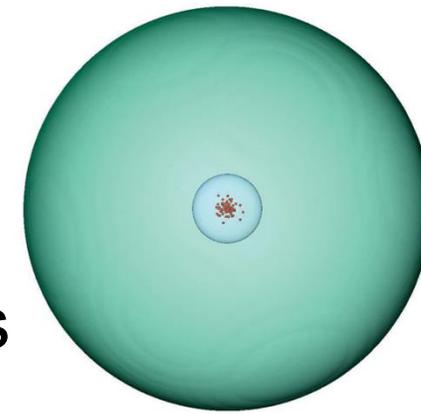
Initial Conditions

- 3-D Type Ia supernova explosion models
 - Two delayed detonation models
 - Two pure deflagration models
 - Two double detonation models
) 6 models → assume free expansion to 3 years
- Uniform ambient density
 - $0.3 m_p \text{ cm}^{-3} \sim 0.5 \times 10^{-25} \text{ g cm}^{-3}$ → consistent with Tycho's environment

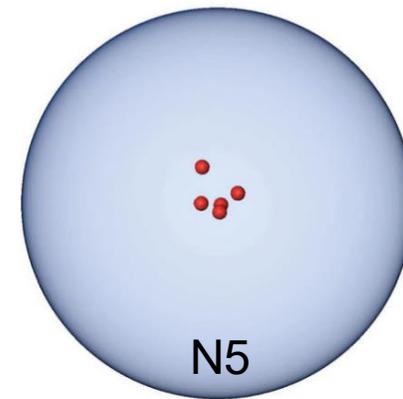
| Model | System | Mechanism | $M_{\text{ej}} (M_{\odot})$ | $E_{\text{kin}} (\text{erg})$ | ^{56}Ni | IGE | IME | Reference |
|---------|--------|--------------------|-----------------------------|-------------------------------|------------------|-----|-----|--------------------------|
| N100ddt | SD | Delayed Detonation | 1.40 | 1.43×10^{51} | 43% | 60% | 32% | Seitenzahl et al. (2013) |
| N5ddt | | | 1.40 | 1.55×10^{51} | 70% | 81% | 14% | |
| N100def | | Deflagration | 1.31 | 6.15×10^{50} | 27% | 42% | 11% | Fink et al. (2014) |
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| OneExp | DD | Double Detonation | 1.09 | 1.4×10^{51} | 41% | 46% | 39% | Pakmor et al. (2022) |
| TwoExp | | | 1.75 | 1.9×10^{51} | 26% | 29% | 42% | |

Initial Conditions

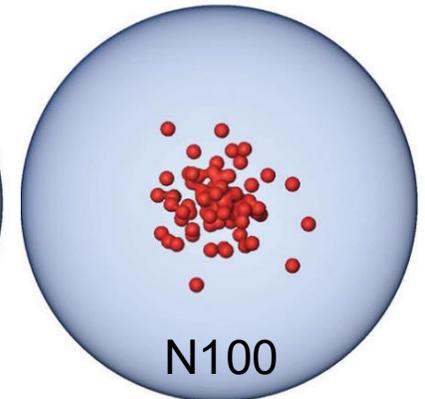
- “100” and “5” refer to the number of ignition points
 → a smaller number corresponds to a more asymmetric model
- Secondary also explodes



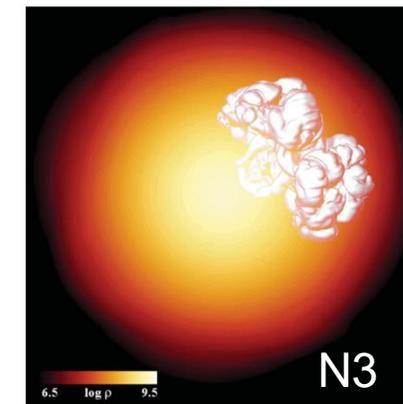
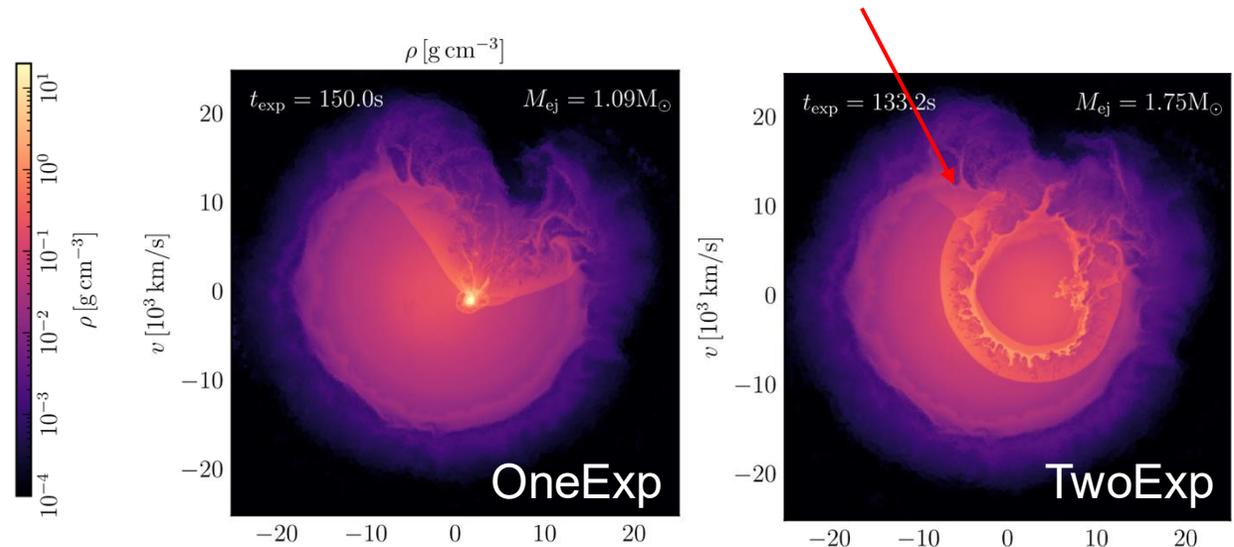
(a) Central ignition region deep inside the WD (for model N100)



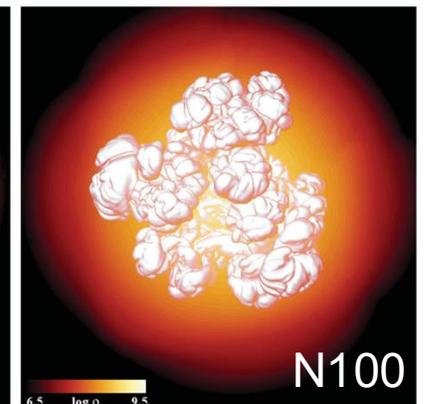
(d) N5



(h) N100(L,H)



(a) N3; t = 0.80 s



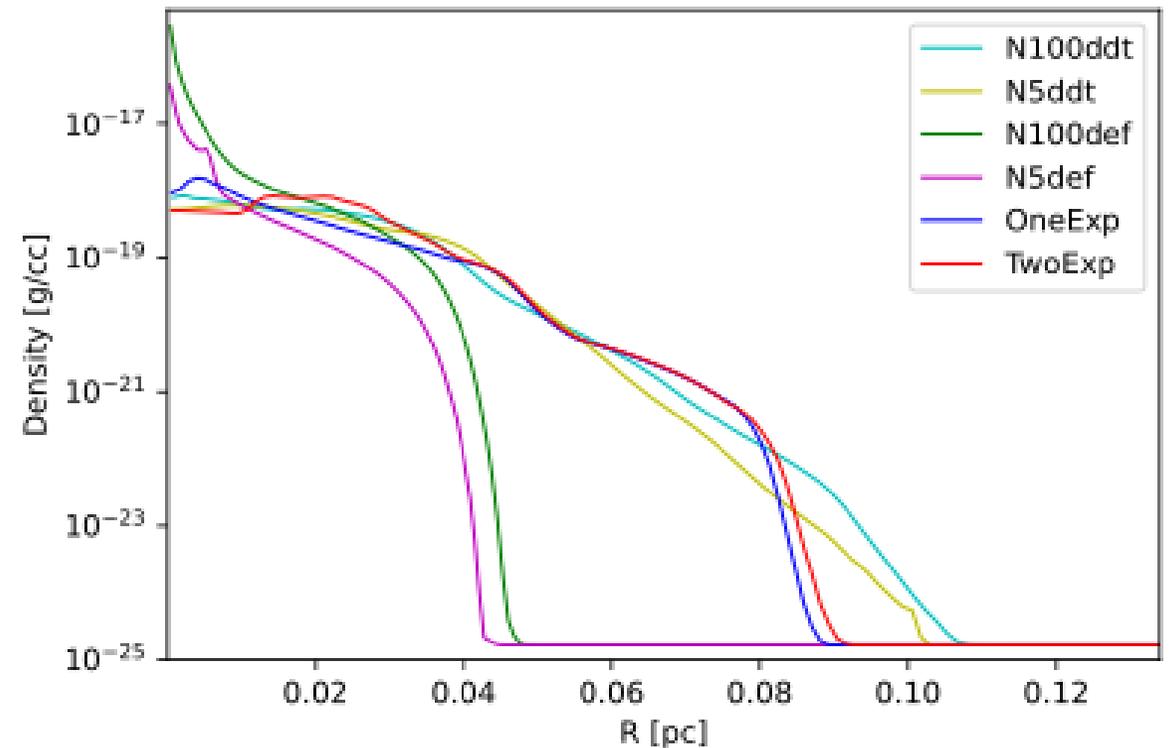
(b) N100; t = 0.70 s

Initial Conditions – density distribution

Difference distribution correspond to explosion mechanisms

- DDT:
- DEF: weaker explosion
→ higher density in center
- DD: existence of companion
→ Double peak like structure
(DDT, DEF: no companion)

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1-D radial profile of the initial density at 3 years

Initial Conditions – elemental distribution

DDT (Top)

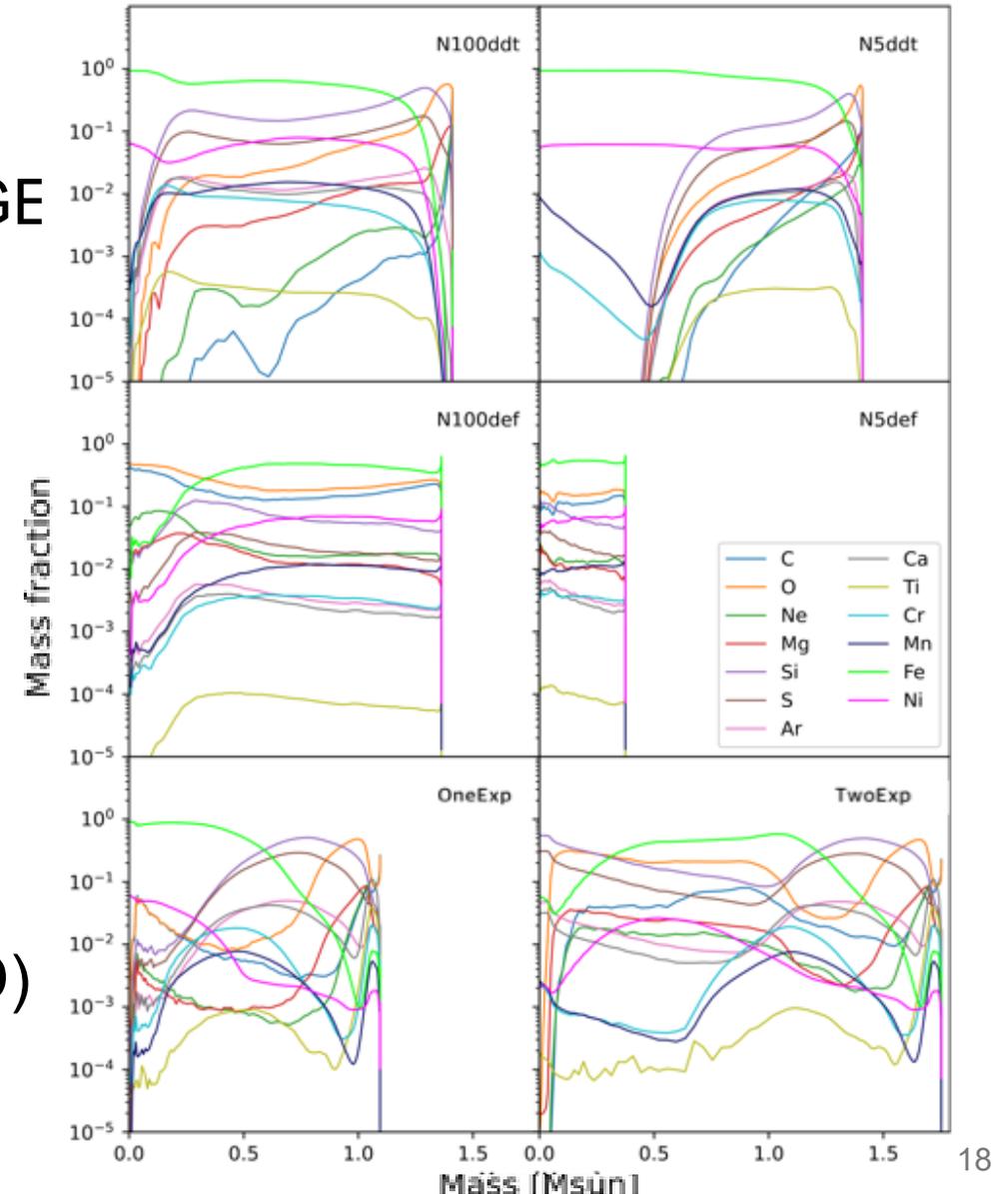
- The central region of N5ddt is dominated by IGE
→ **density is higher** (weak deflagration)

DEF (middle)

- Both show relatively **uniform** distributions
- N5def is more uniform

DD (bottom)

- Complex distribution due to companion
- In TwoExp, IMEs dominate the central region
→ effect of secondary explosion (low mass WD)



Other Setup

Hydrodynamic simulation

- Cartesian mesh 256^3
- Lagrangian tracer particle number 100,000 (ejecta: 70,000 ISM:30,000)
- Electron heating at collisionless shocks is parameterized as

$$\beta = T_e/T_p = 0.02 \quad (\text{Raymond et al. (2023)})$$

Spectral synthesis

- 9,000 energy bins in 0.3-10.0 keV \rightarrow energy resolution ~ 1 eV

We follow the SN-to-SNR evolution self-consistently

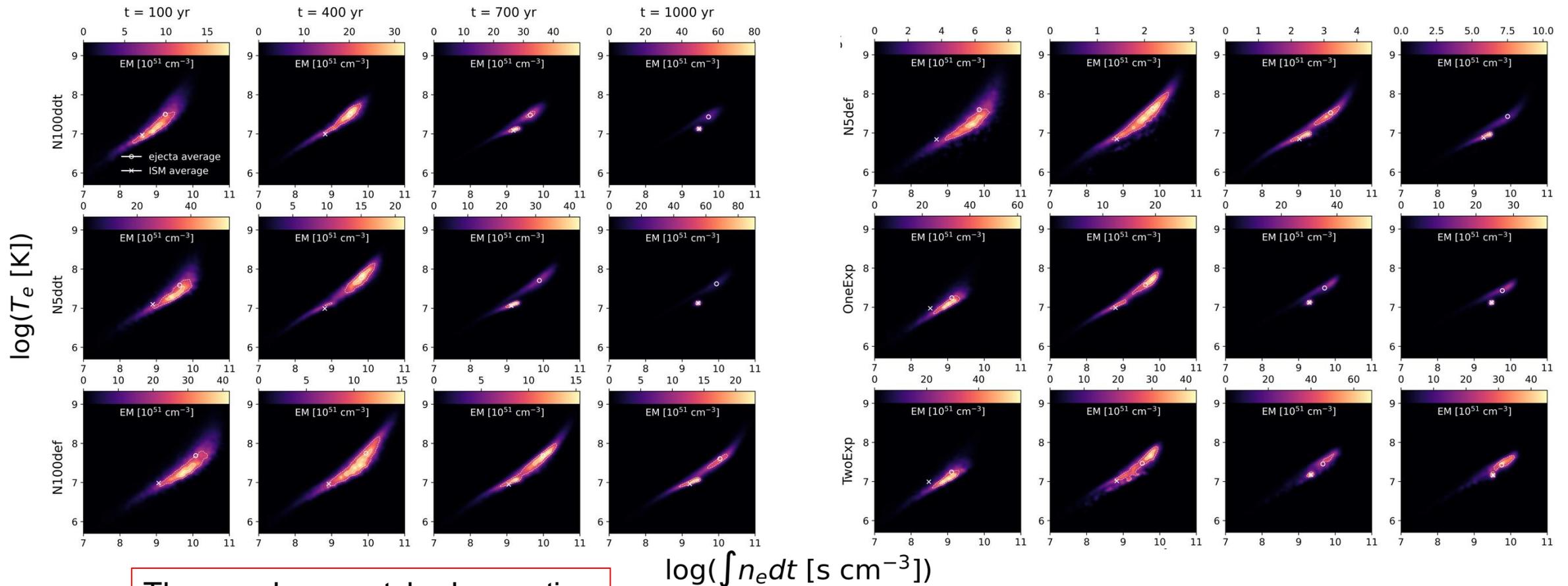
Note that equation of shock heating is given by

$$kT = \frac{3}{16} mV_{sh}^2,$$

from this, $\beta = m_e/m_p$

Plasma Evolution – EM distribution in $\int n_e dt - T_e$ space

- $EM \equiv \int n_e n_{ion} dV$, indicator of the intensity of X-ray emission
- $\int n_e dt$ is ionization time – the plasma’s progress toward ionization equilibrium



These values match observation

$\log(\int n_e dt [s \text{ cm}^{-3}])$
Tuesday seminar 2025

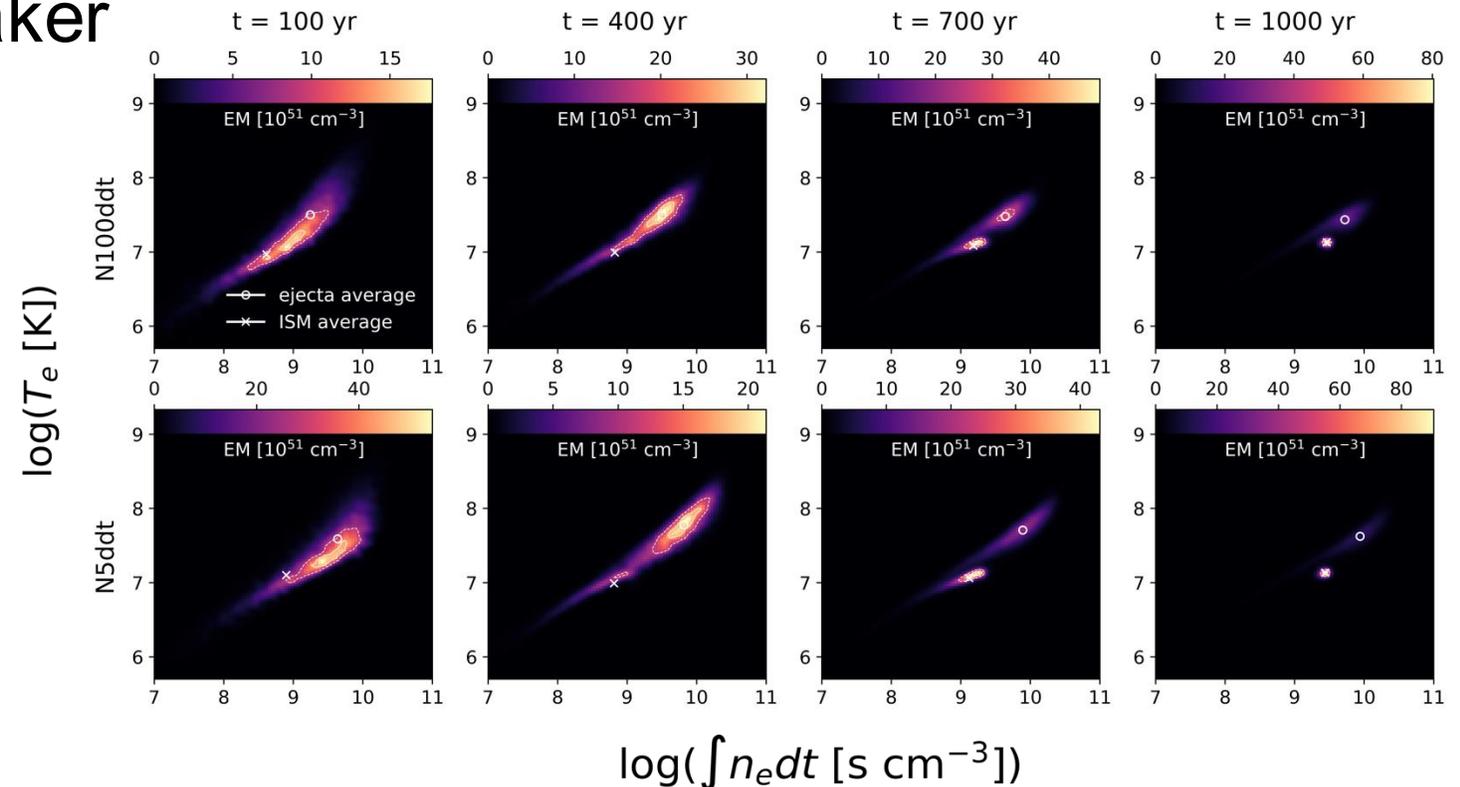
N100ddt vs N5ddt

- N5ddt is shifted toward the right side compared to N100ddt

→ Deflagration of N5ddt is weaker than that of N100ddt

→ High density of inner ejecta

→ Ionization proceeds more efficiently



N100ddt vs N100def

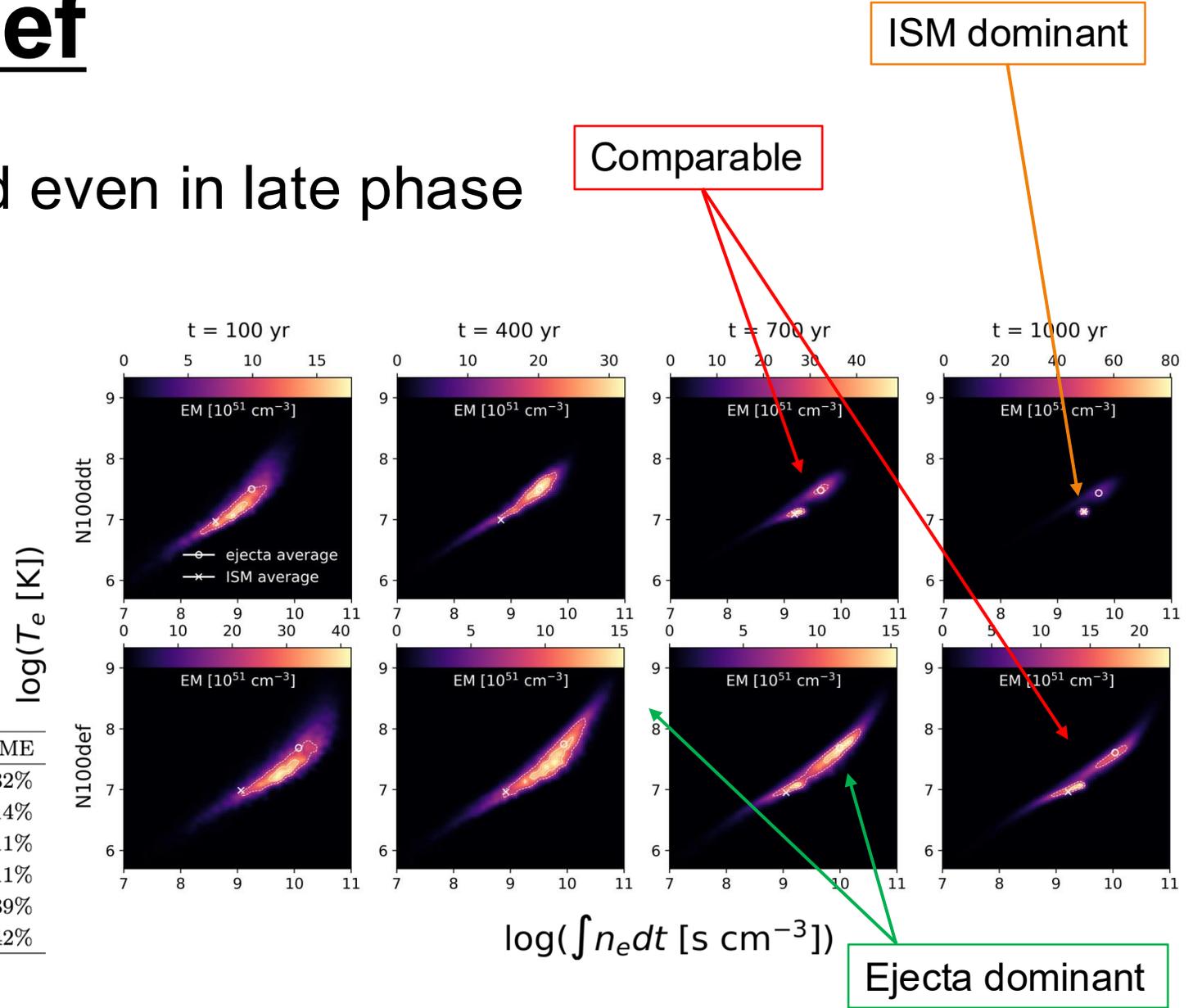
- In N100def, ejecta dominated even in late phase

- Expansion velocity is low because of low E_{kin}

- Swept mass is small

- ISM become dominant in later phase

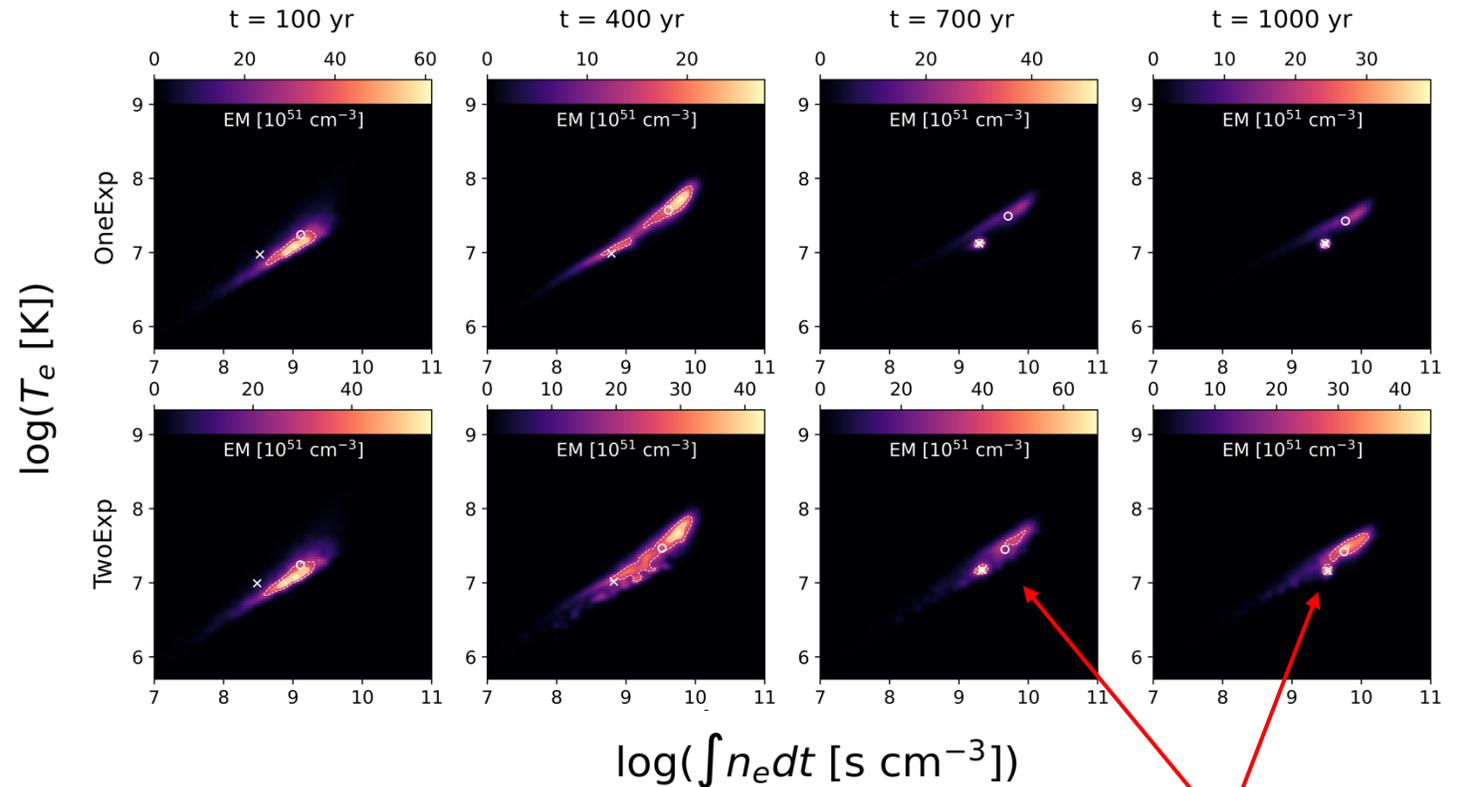
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N100ddt vs N100def

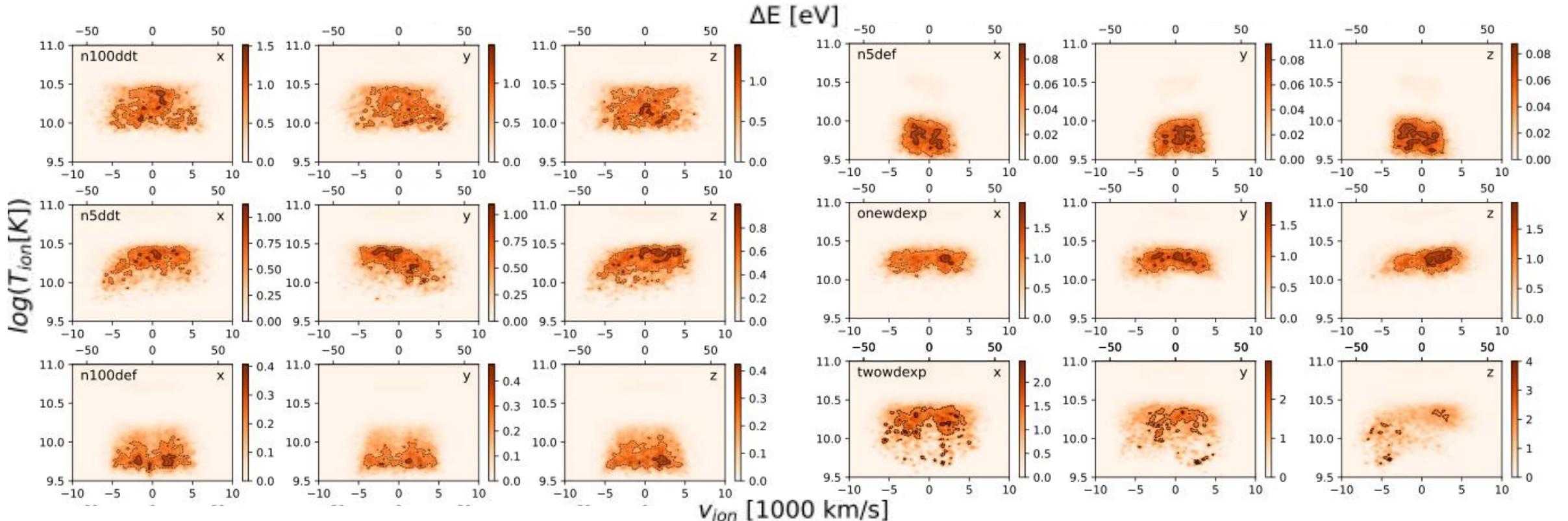
- At 100 years, they are similar but ...
- At 400 years and later, they are clearly different

→ Secondary explosion effect



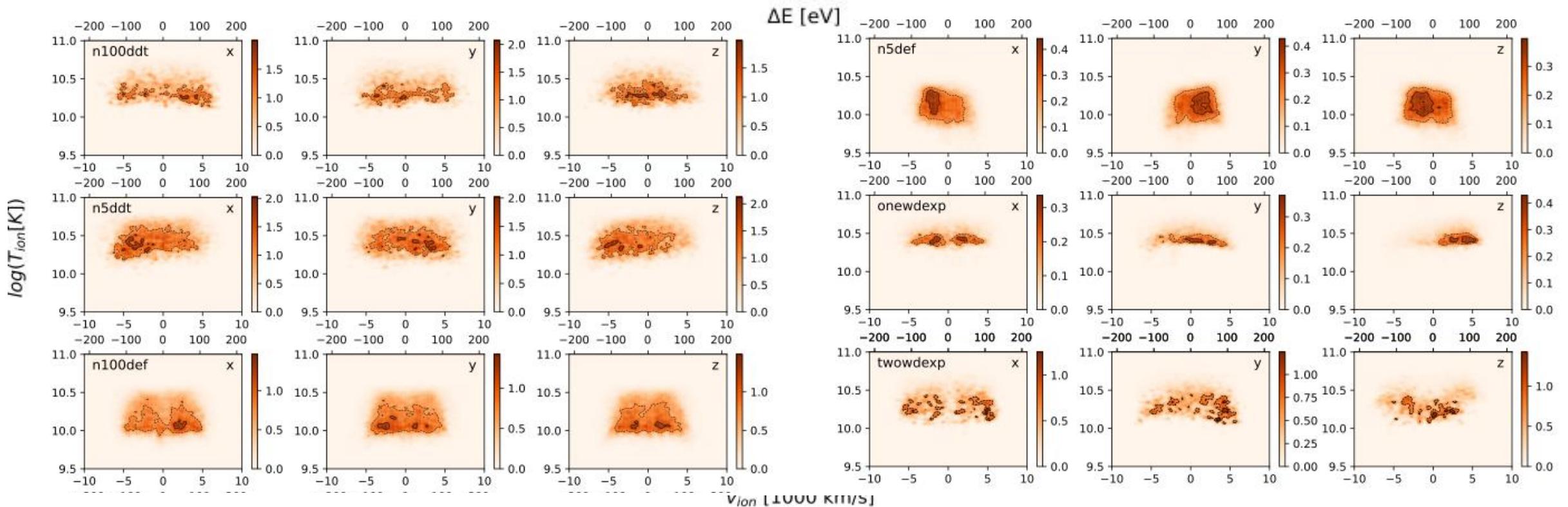
Plasma Evolution – EM distribution in $v_{\text{ion}}-T_{\text{ion}}$ space (Si)

- Standard deviation of thermal broadening is given by $\sigma = \sqrt{\frac{k_B T}{m c^2}} E_0$
- $\sigma \sim 10 \text{ eV}$ at $T_{\text{Si}} = 10^{10} \text{ K} \rightarrow$ comparable to Doppler shift



Plasma Evolution – EM distribution in $v_{\text{ion}}-T_{\text{ion}}$ space (Fe)

- $\sigma \sim 10 \text{ eV}$ at $T_{\text{Fe}} = 10^{10} \text{ K}$
- For iron, $v_{\text{los}} = 5000 \text{ km/s}$ correspond to $\Delta E_{\text{Doppler}} \sim 110 \text{ eV}$

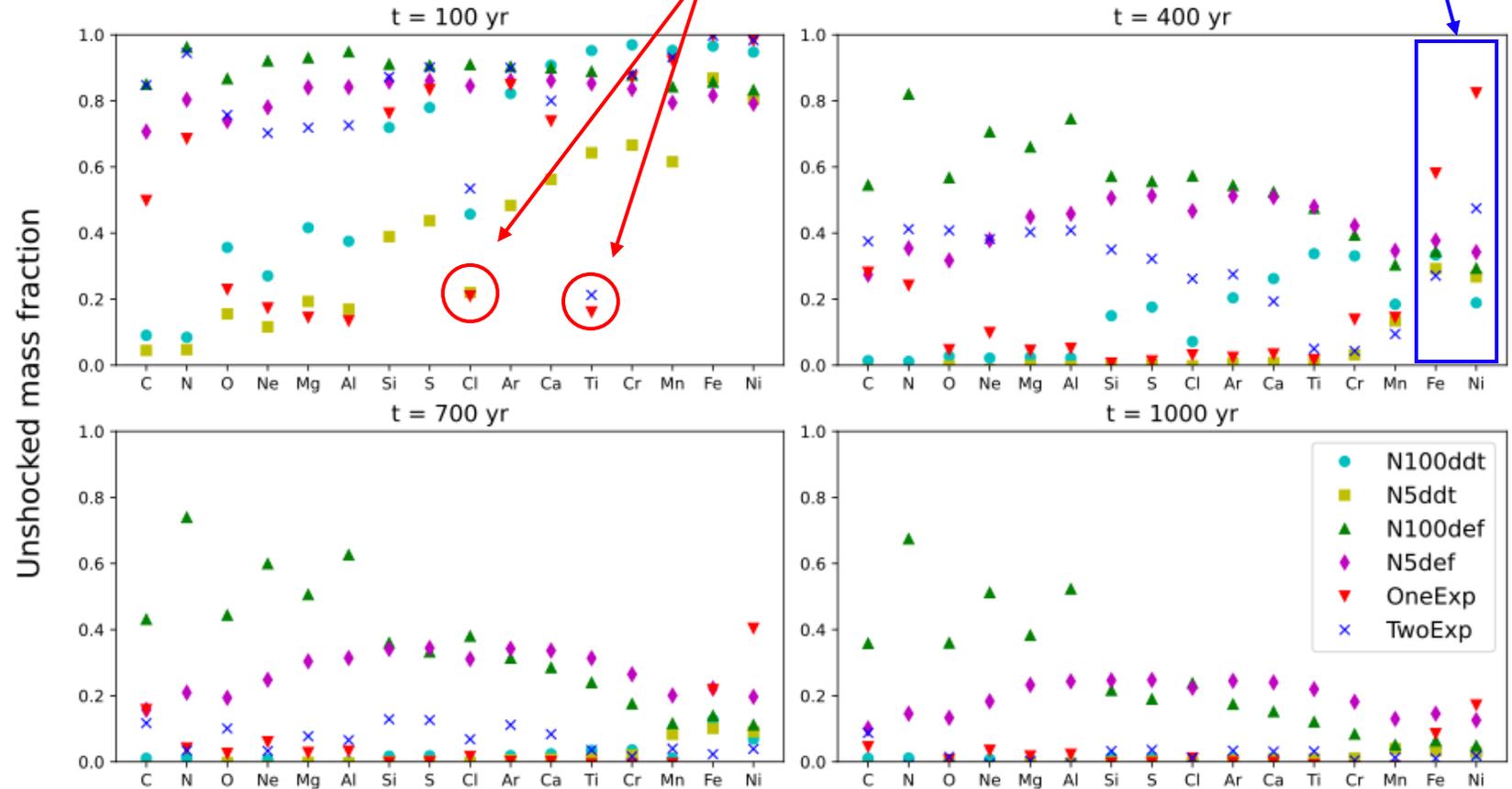


Unshocked Mass Fractions

- Different evolution between elements
- Can't use abundances of SNe for spectral fitting
- Roughly correspond to 1-D radial density

Remain largely unshocked

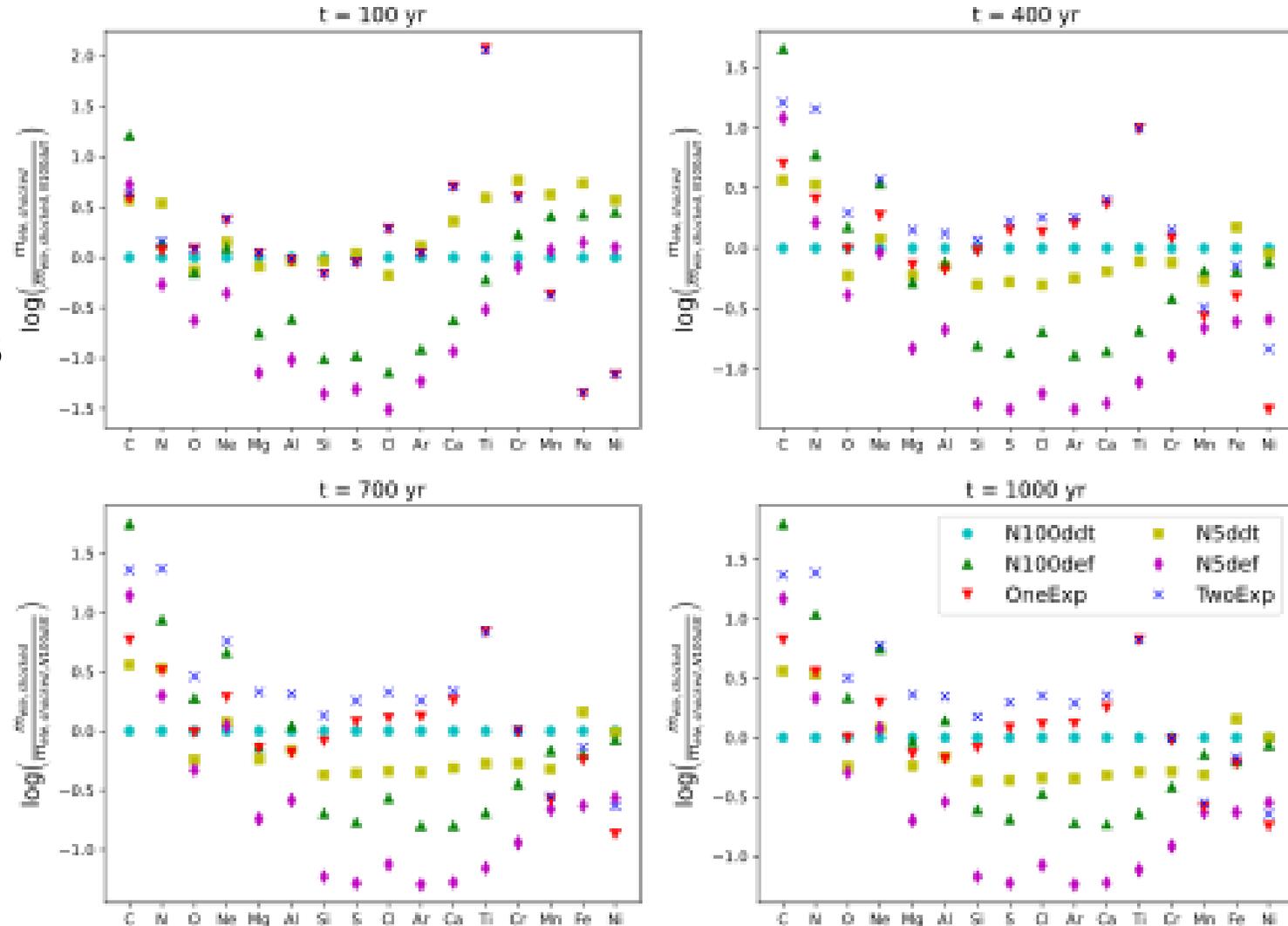
Large fraction is shocked in the early phase



Shocked Ejecta Masses

Normalized by N100ddt

- The same trend at any given time
- Reflecting element synthesis in the explosion model



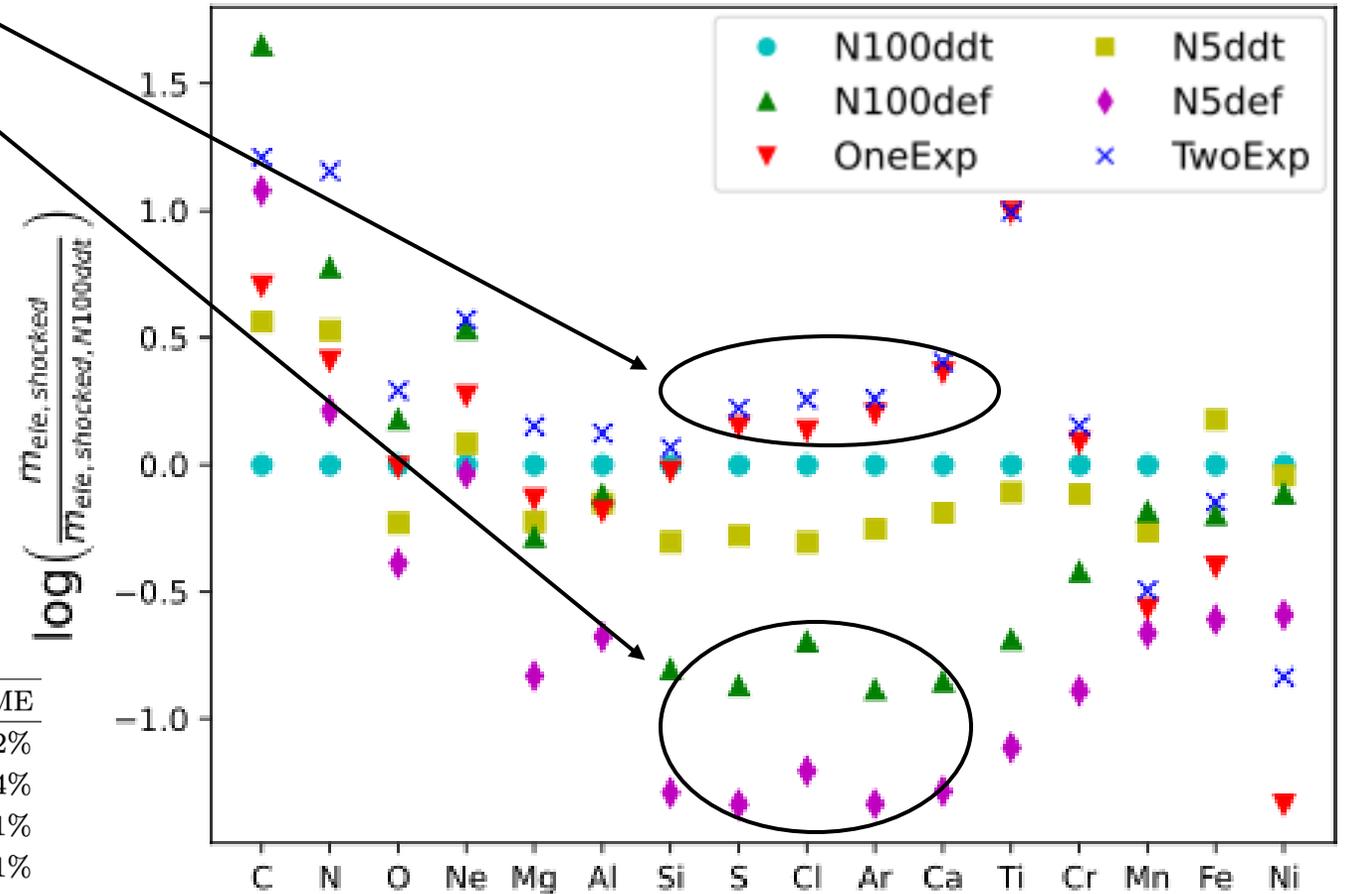
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Shocked Ejecta Masses

- High IME yields of DD models
 - Low IME yields of def models
 - Elements exhibiting **characteristic differences**
- How does it appear in the spectra?

Normalized by N100ddt

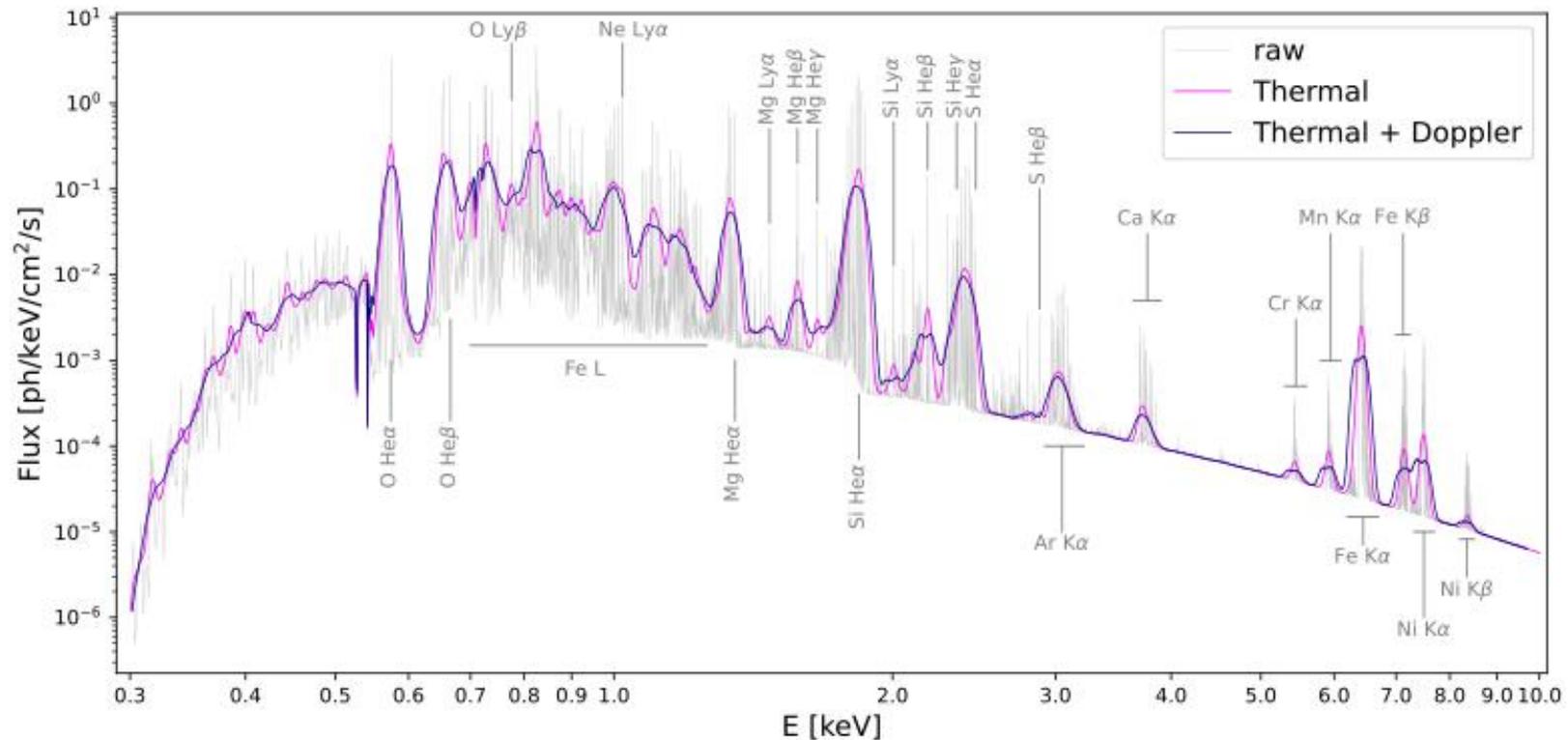
t = 400 yr



| Model | System | Mechanism | $M_{ej} (M_{\odot})$ | $E_{kin} (erg)$ | ^{56}Ni | IGE | IME |
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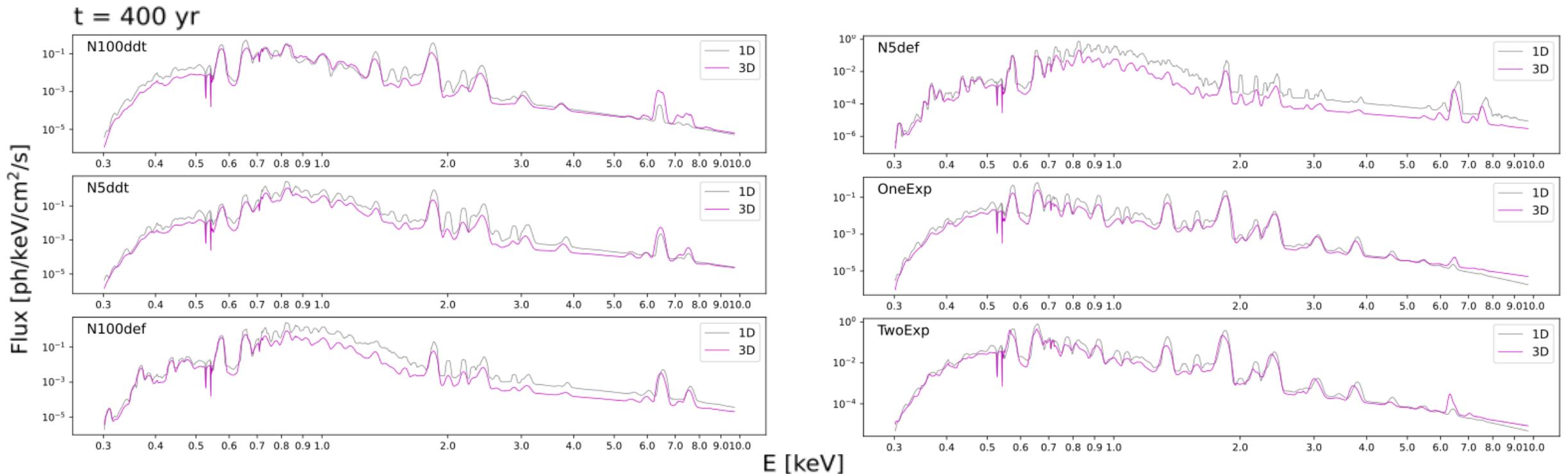
What Composes the Spectrum?

- Silver line shows raw spectra without thermal and Doppler effects
→ **individual transitions** are clearly visible
- Thermal motion make line broader
→ reflect T_{ion}
- Doppler effects make the lines asymmetric
→ **Velocity distribution**



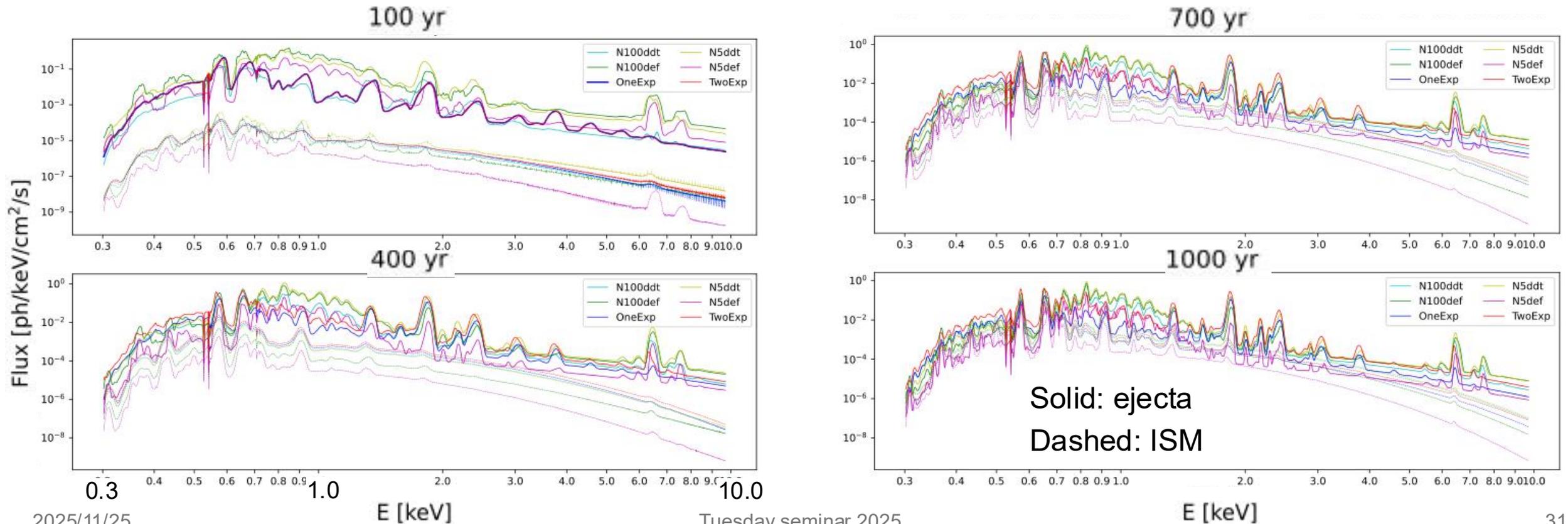
1-D spectra vs 3-D spectra

- Emission line of 3-D spectra are more asymmetric
- Continuum slope indicate electron temperature
→ 3-D spectra indicate higher T_e than 1-D → **effect of clumpy structures**



X-ray Spectra – time evolution

- Thermal broadening decreases over time → narrower lines
- Ejecta fraction decreases as shocked ISM becomes dominant

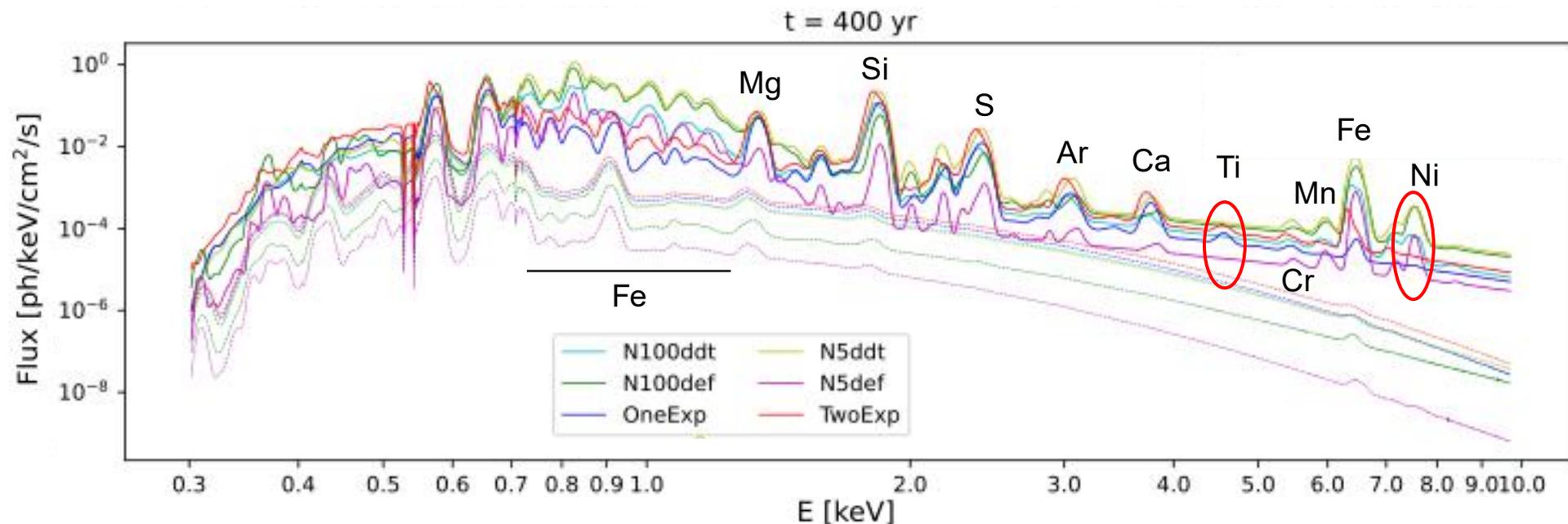


X-ray Spectra – Comparison

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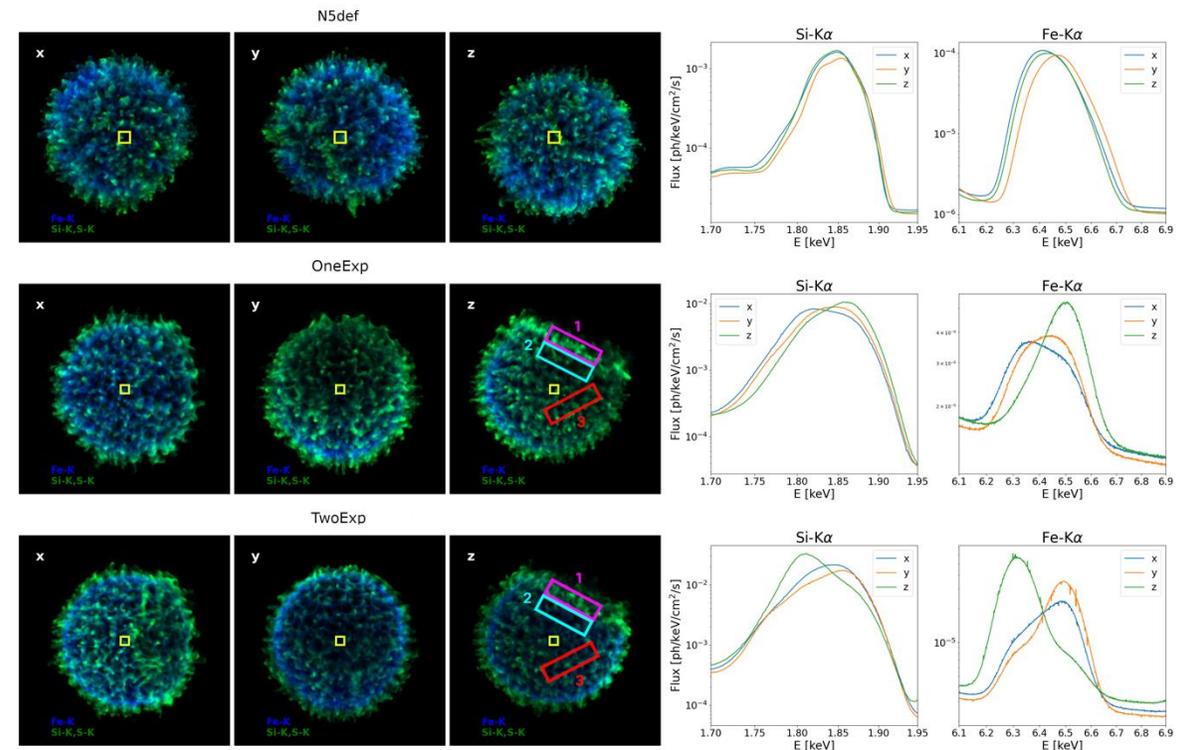
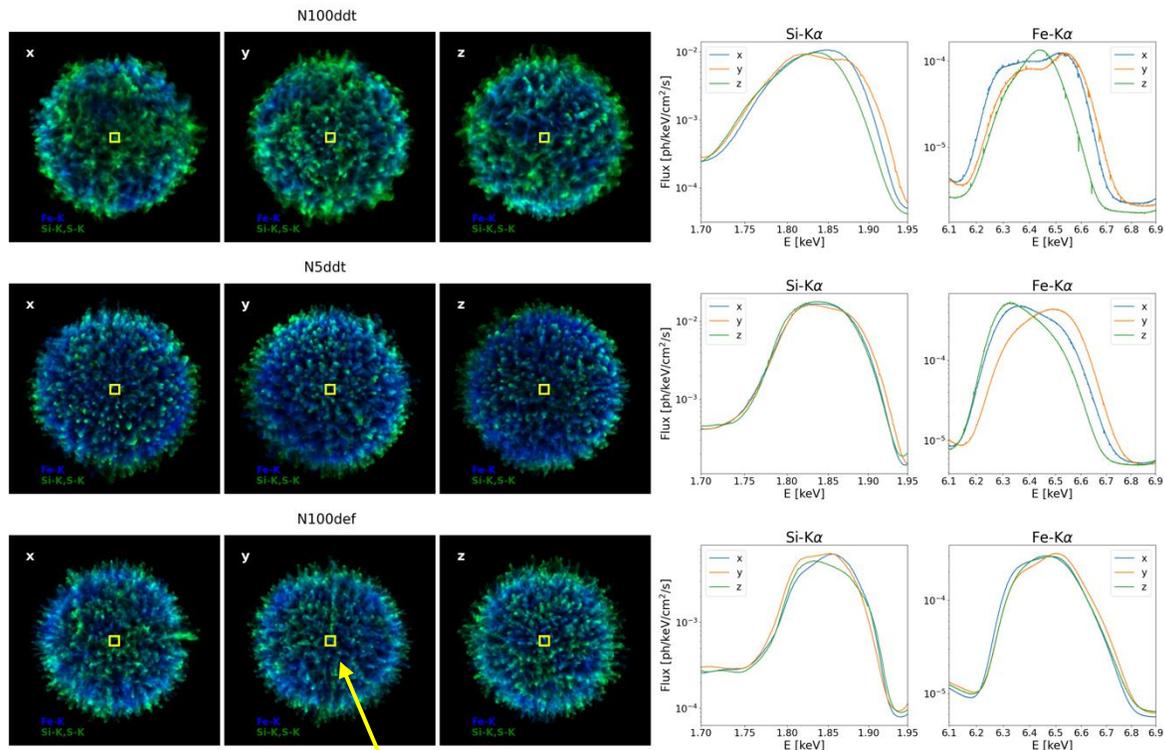
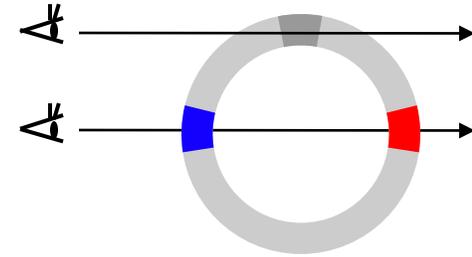
- Presence or absence of emission lines \rightarrow explosion properties
- Line structure, position \rightarrow line-of-sight velocity, ionization state

Constrain explosion models by comparing with XRISM observations



Specific Region Spectra – Center Region

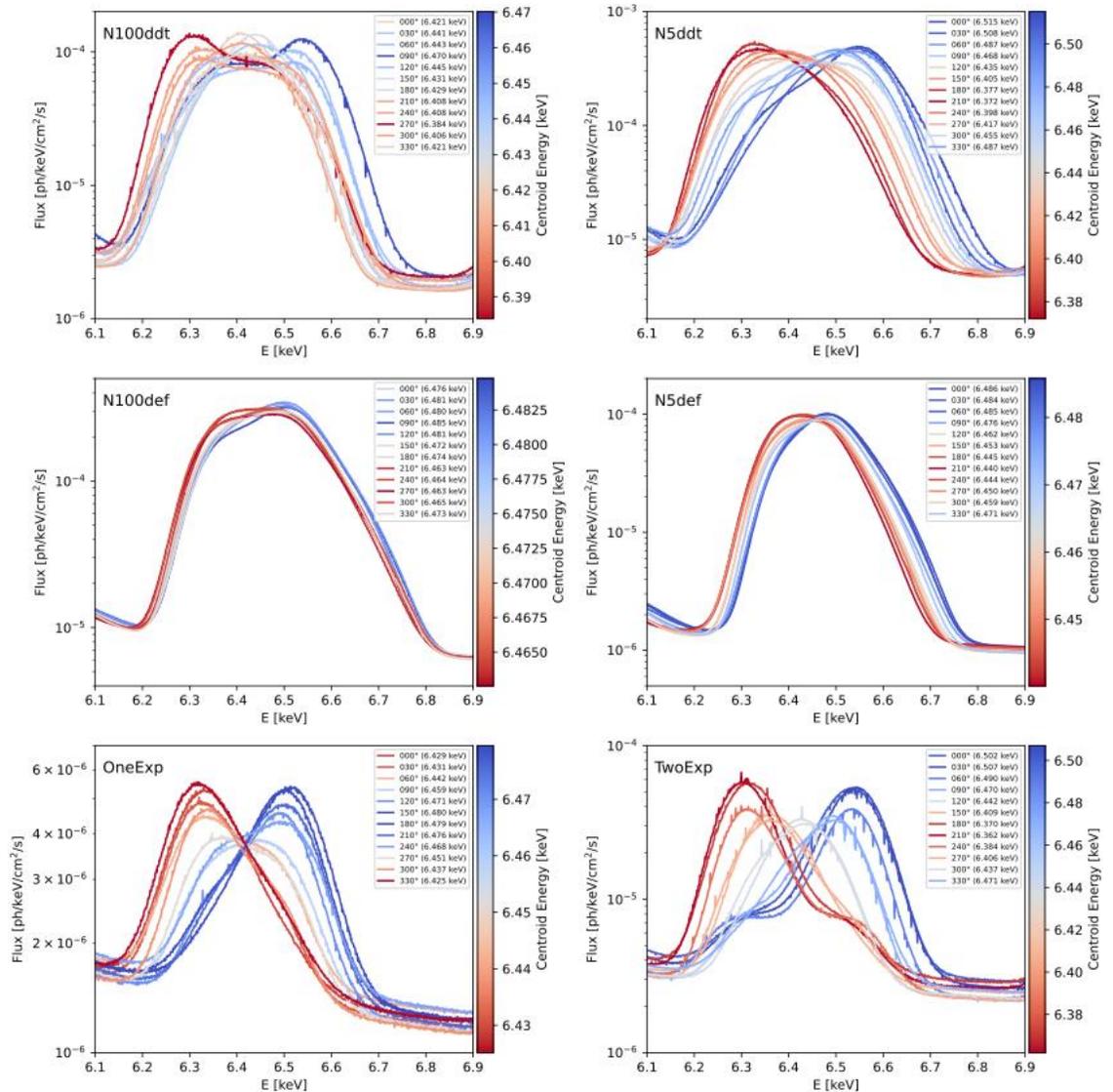
- The central region enhances Doppler shifts
- Asymmetric model: asymmetric lines (shift to one side)
- Symmetric model: double-peaked structures



Specific Region Spectra – Center Region

- Rotated around the z-axis
- Broad line profiles
→ redshifted and blueshifted components are comparable
- Lines shifted toward one side

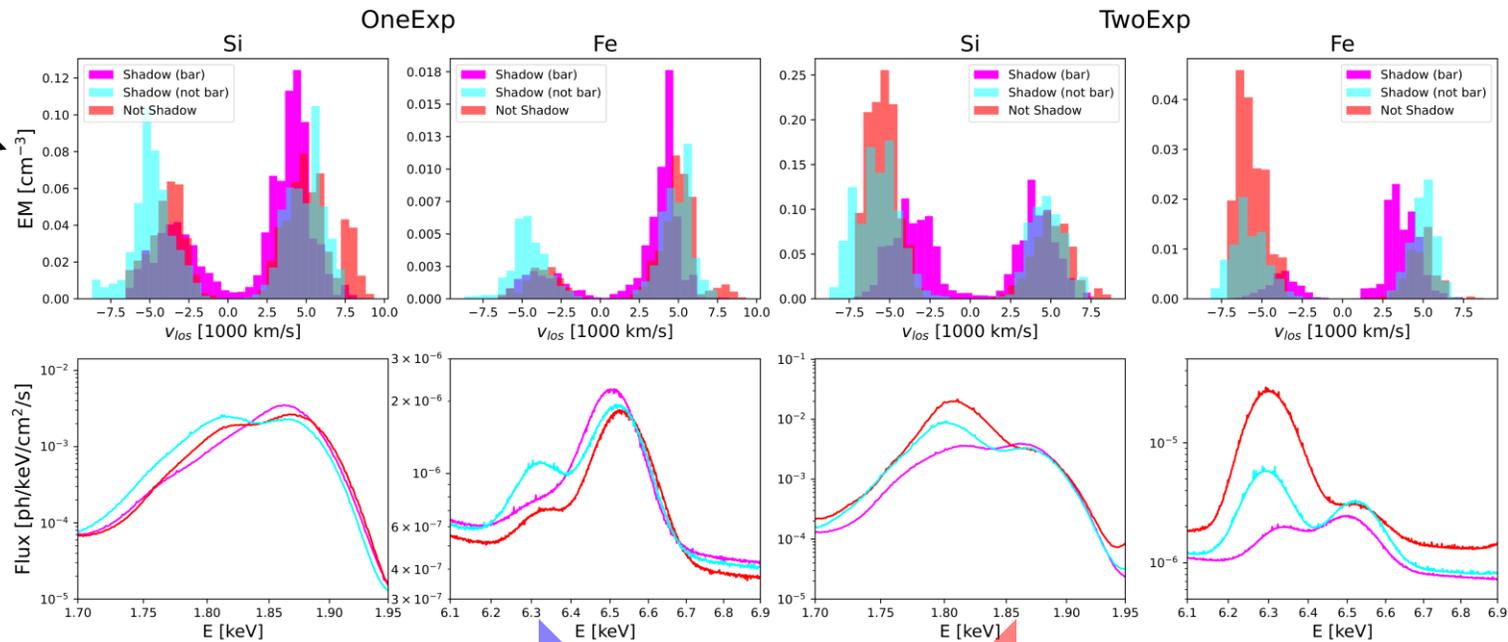
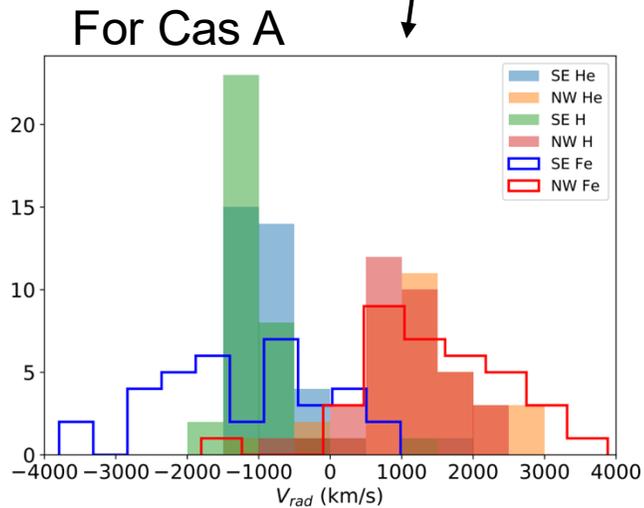
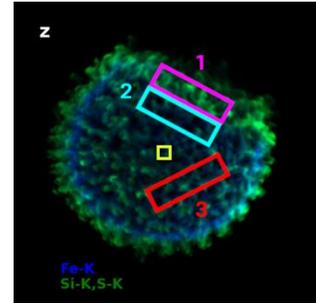
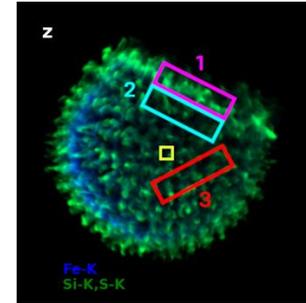
It is difficult to determine the line-of-sight direction that matches the observations



Specific Region Spectra – arbitrary Regions

- Different regions have different Doppler shift characteristics

- Direct comparison with XRISM observation



Summary

- We perform **3-D hydrodynamic simulations** and **spectral synthesis**
- Our results in a **uniform** ambient medium generally **match observations**
- There are **differences** that come from the explosion properties
- **possibility to constrain progenitor by comparing with XRISM observations**

Future work

- Application to XRISM observations
- We need another 3-D CSM setup