Super high-speed 3-D hydro simulations of supernova remnants in the era of micro-calorimetric X-ray spectroscopy

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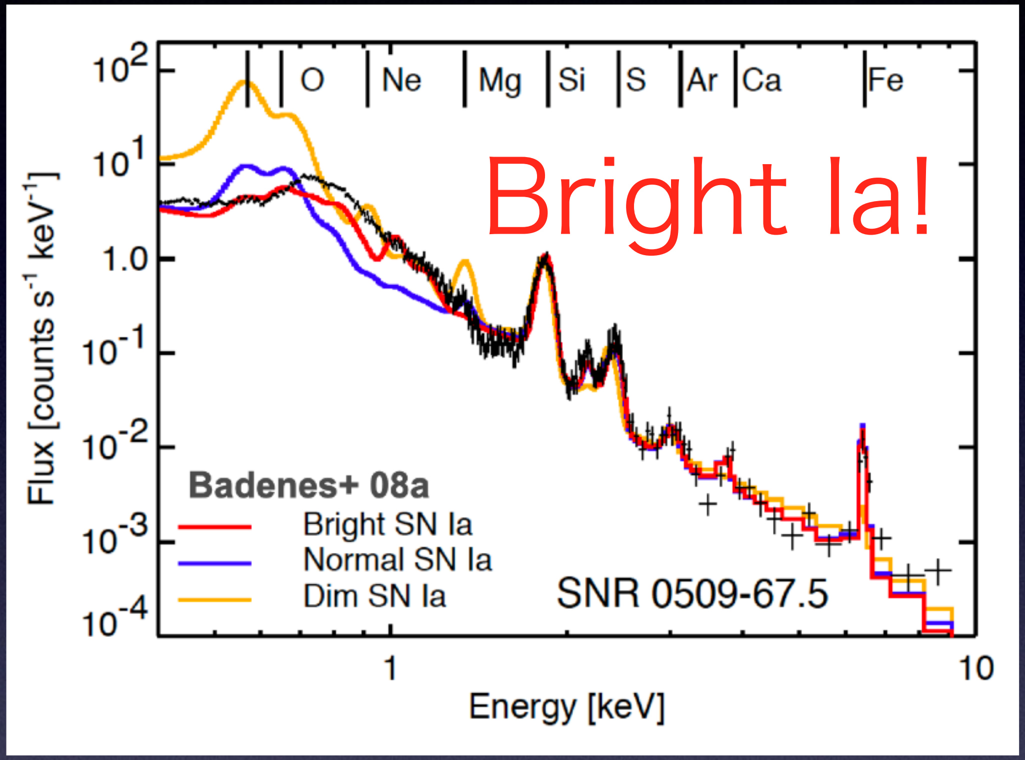
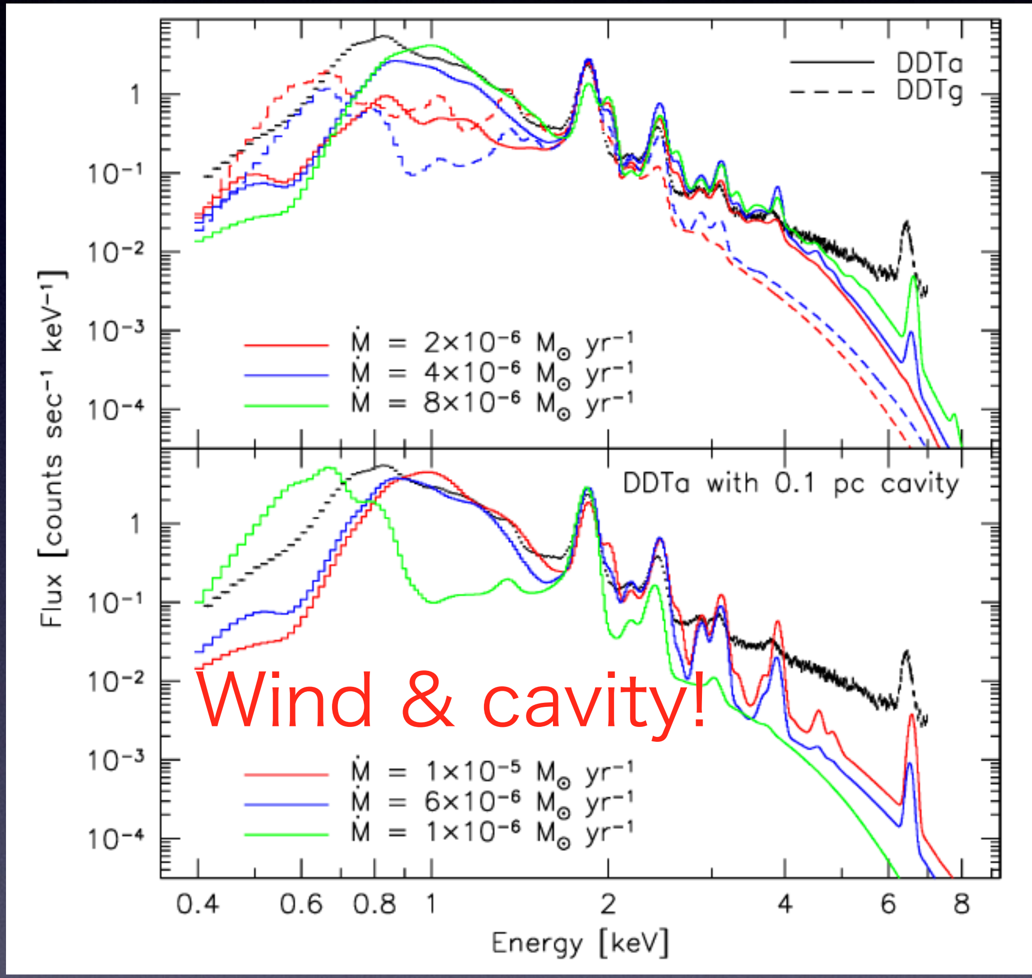
Contents

- **Triumph and limits of 1-D hydro models** of SNR evolution and broadband emission
- The **why's and when's for 3-D** and the challenges
- **Super high-speed 3-D hydro simulations** of long-term evolution of SNRs with microphysics
- Some examples
- Future add-ons

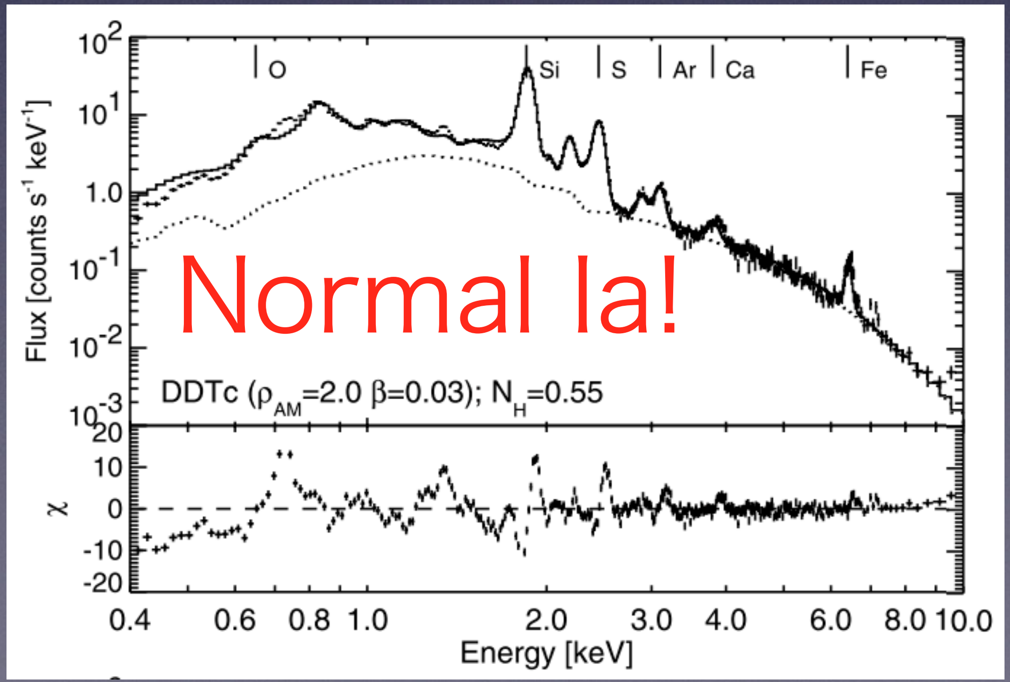
1-D hydro modeling has been fruitful for interpreting SNR emission



Badenes+ (2008) on **0509-67.5**



Patnaude+ (2012) on **Kepler**

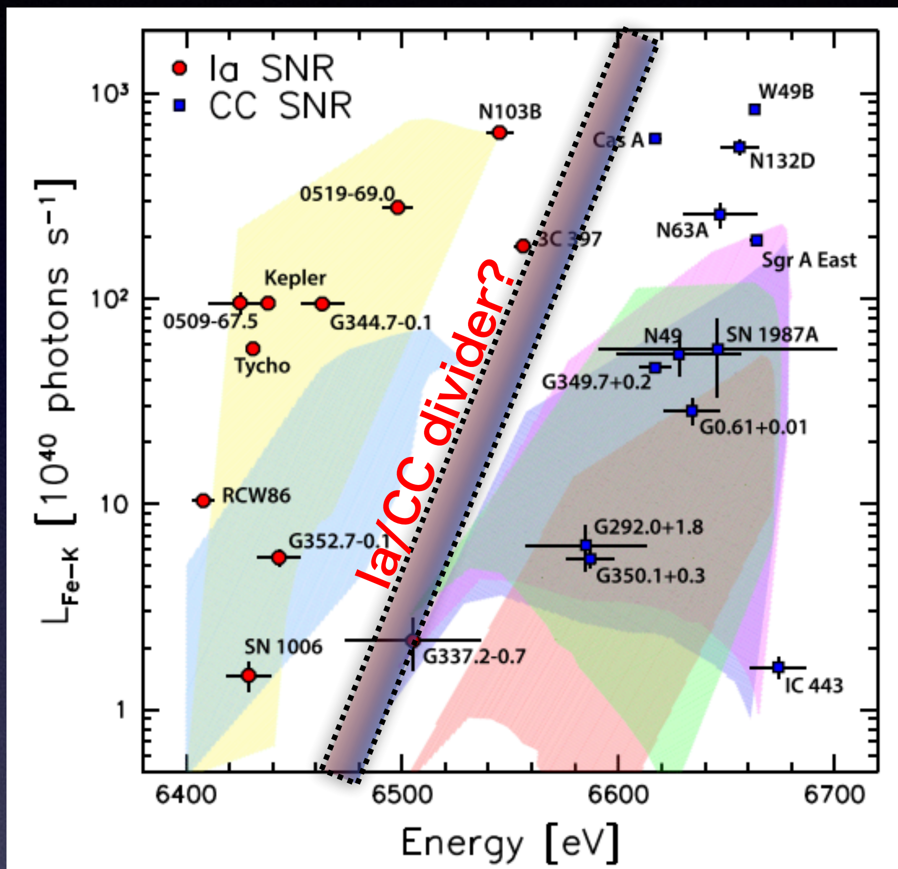


Badenes+ (2006) on **Tycho**

1-D explosive nucleosynthesis + hydro models work especially well for Type Ia's with relatively less spatial asymmetries (Lopez+ 2009 etc)

End-to-end 1-D model grids

Uncover general trends in bulk properties



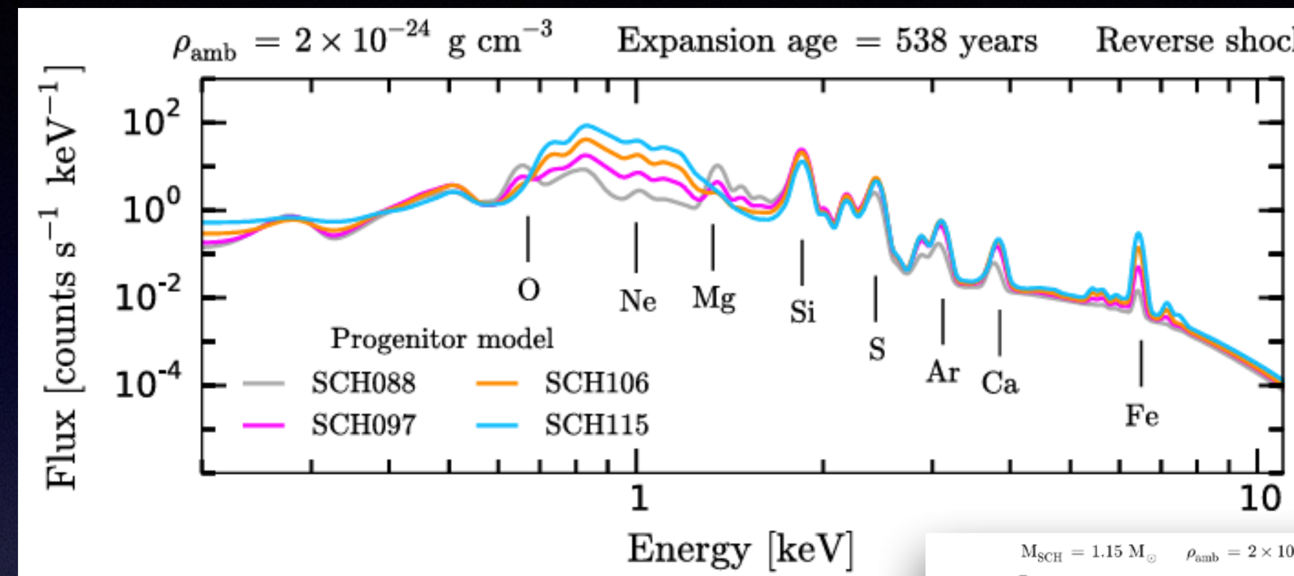
Models: Patnaude, HL+ ('15, '17)

Obs.: Yamaguchi+ (2014)

Fe-K line centroid divides Ia and core-collapse SNRs!? Explained by hydro models

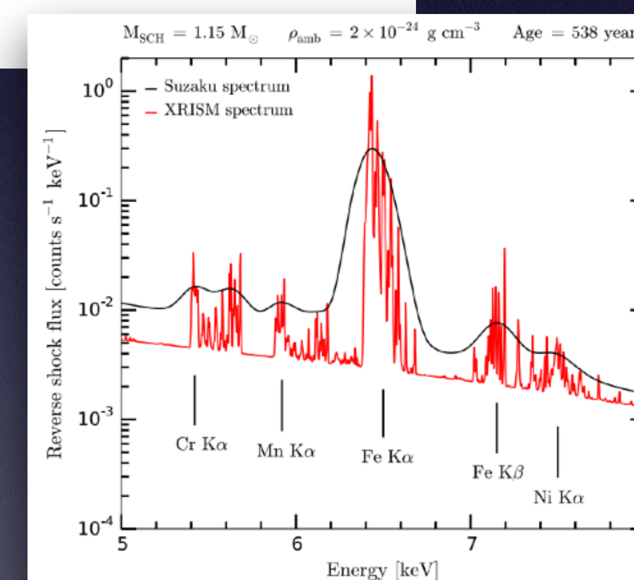
What "end-to-end"?

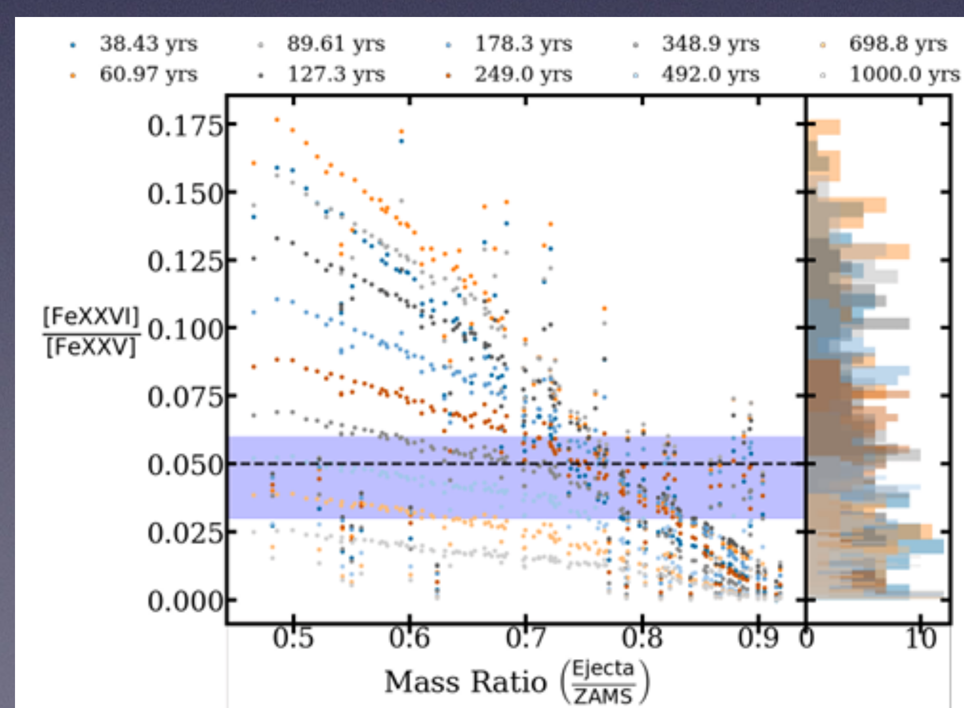
e.g., MESA→SNEC→ChN



Martinez-Rodriguez…HL+ (2018)

Broadband spectral prediction for **various type Ia progenitors**



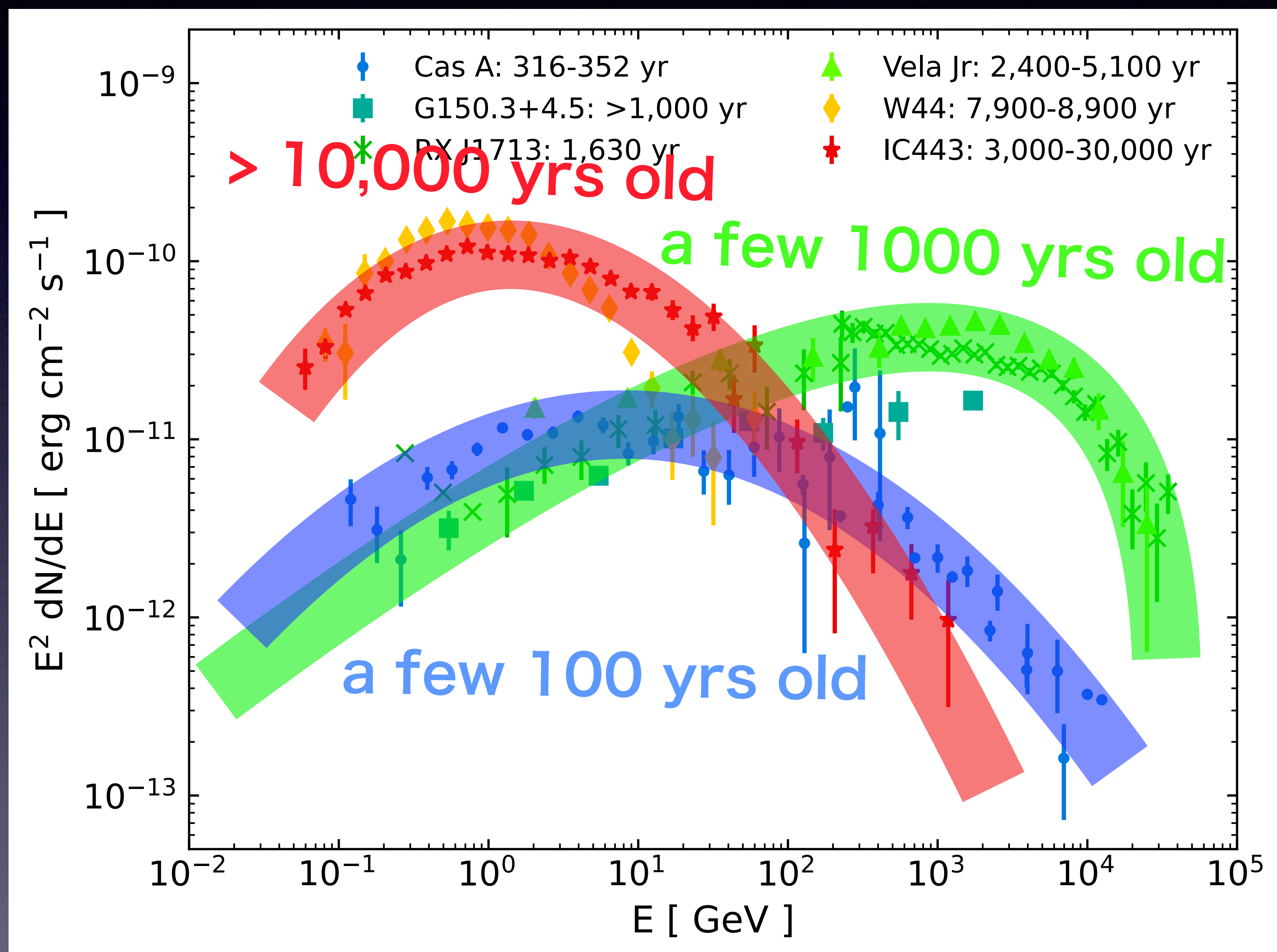


Jacovich…HL+ (2021)

H-like to He-like Fe ratio vs ejecta/ZAMS mass ratio from **core-collapse SNR models**

Case of non-thermal? an example

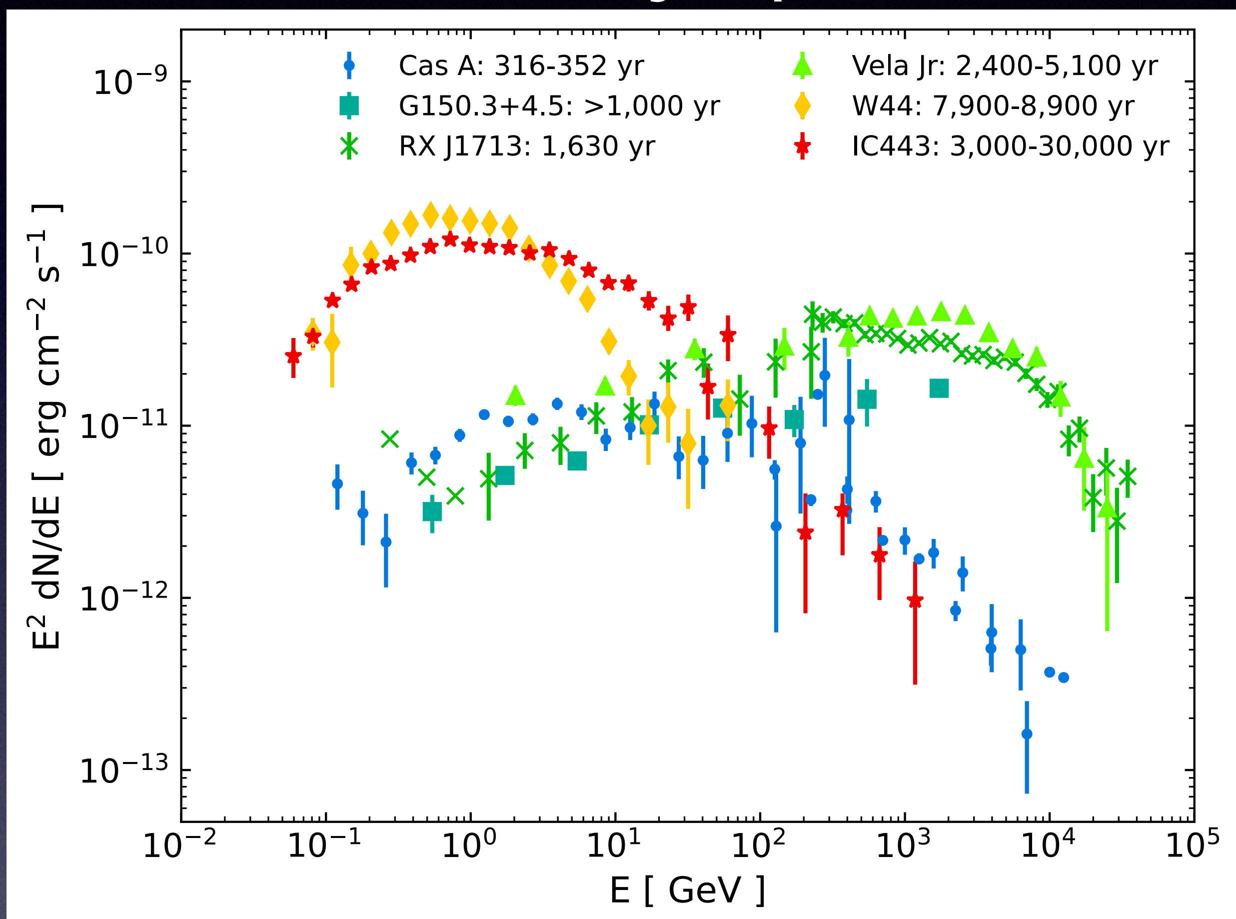
Diversity of gamma-ray spectra in core-collapse SNRs



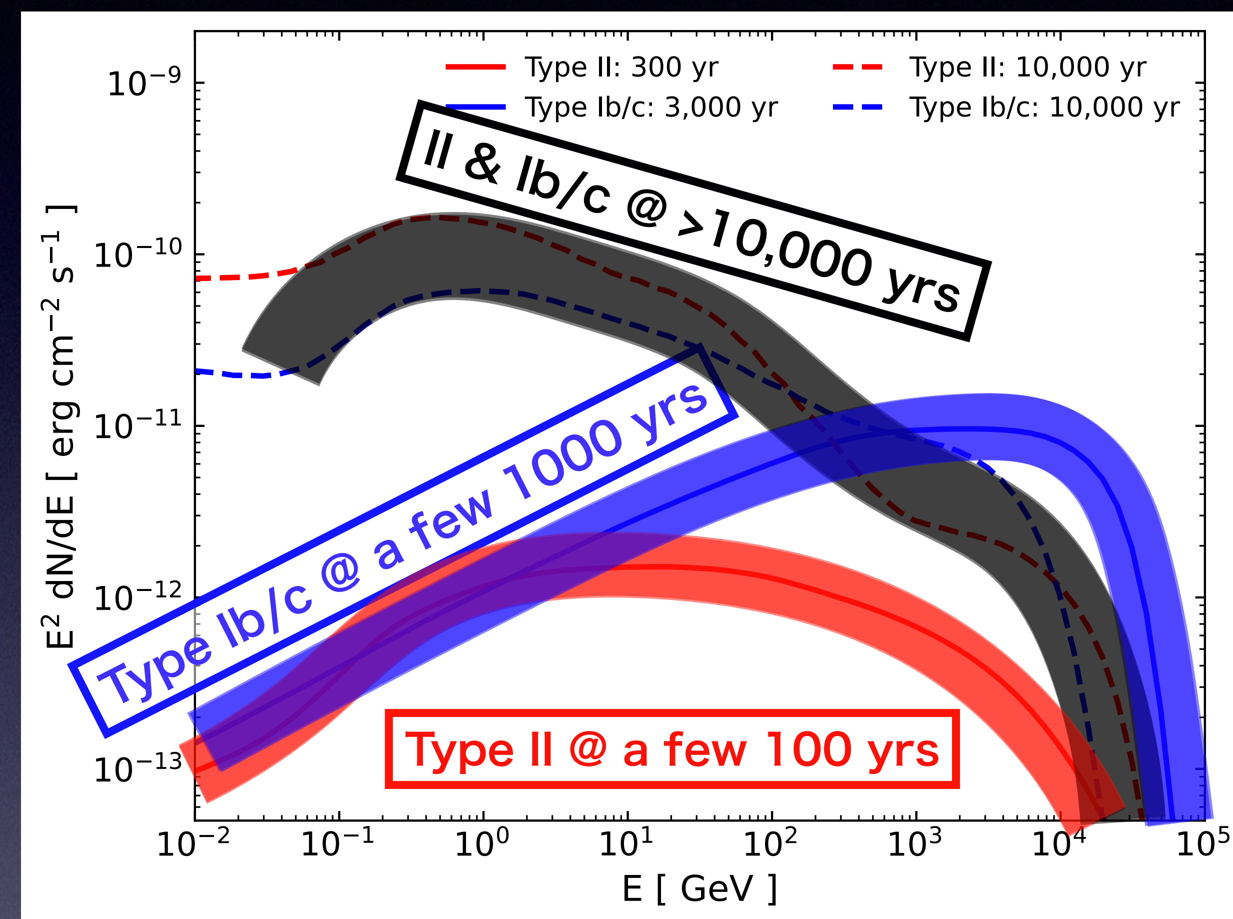
Tempting to link with an age-sequence (spectral evolution) of CC SNRs

Gamma-ray diversity not an age-sequence!

Gamma-ray spectra



Yasuda, HL & Maeda (2021, 2022)



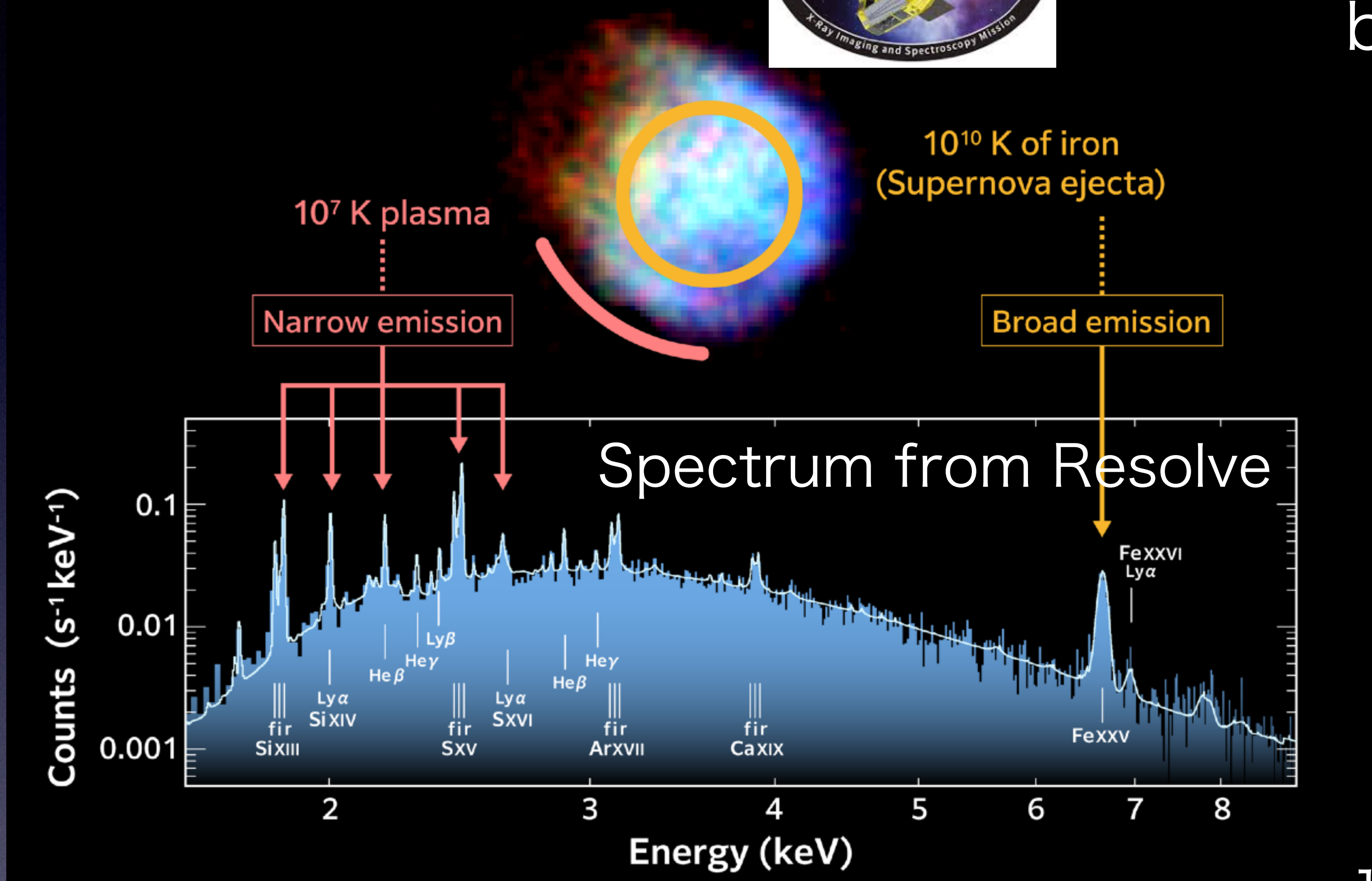
Self-consistent modeling w/ hydro + non-linear DSA + multi-phase CSM

1) Type II's are bright at a few 100 yrs but darken after ~ 1,000 yrs
2) Type Ib/c's are faint at a few 100 yrs but re-brighten after ~ 1,000 yrs
3) Both types are bright at GeV after ~10,000 yrs

But now that we can see almost **too** well···

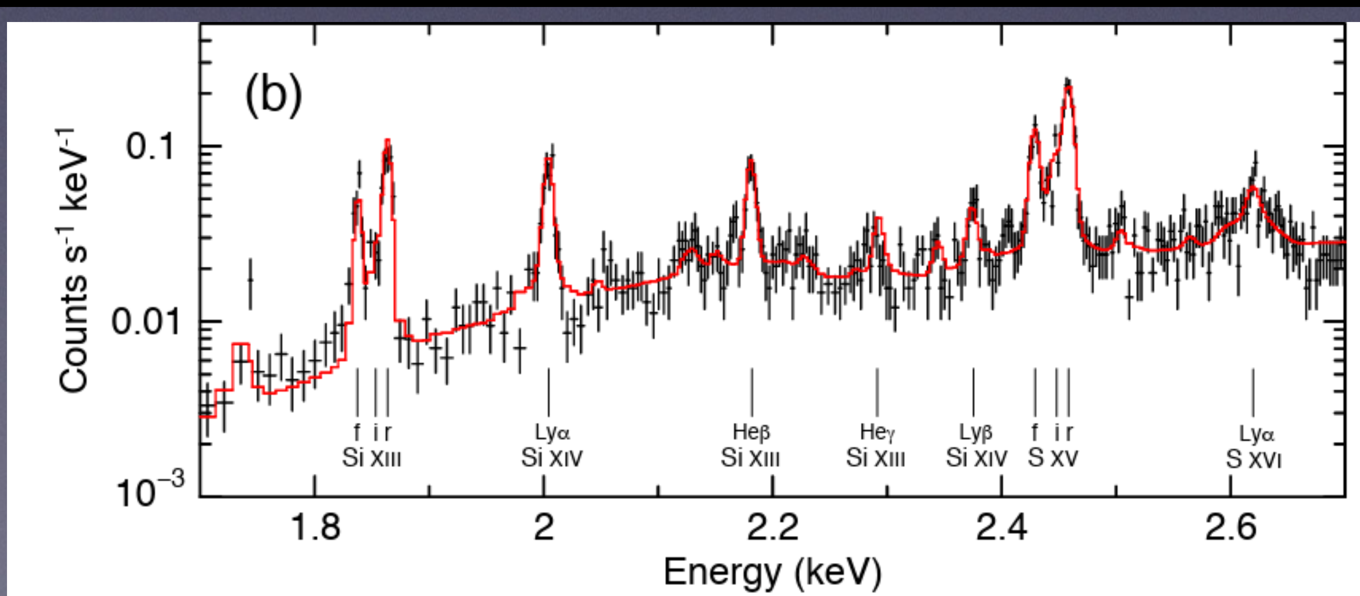
(see Hiroya's talk)

First-light observation of N132D by XRISM (2024)



At a few eV resolution, many things not captured by CCD detectors start to be unveiled!

Most cannot be modeled accurately in 1-D,
e.g., detailed line ratios, complex line profiles, sub-structures, etc···

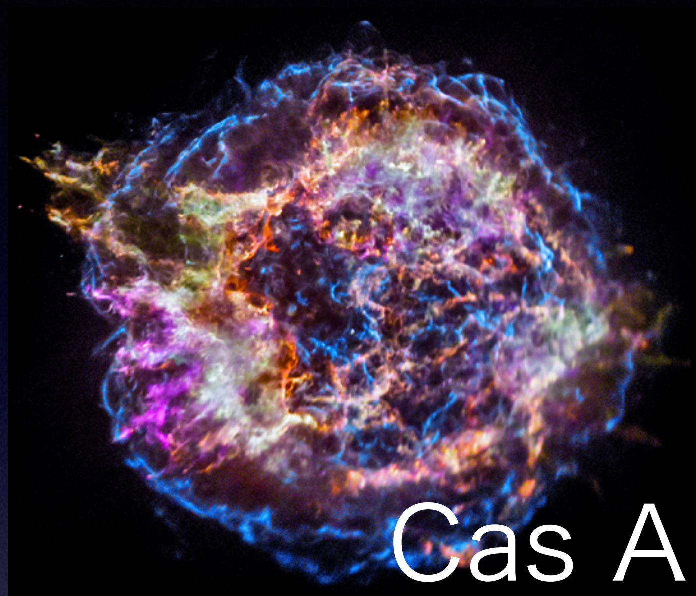


1-D model surveys stay meaningful for gaining general insights

But SNR observations have begun to demand fully 3-D models

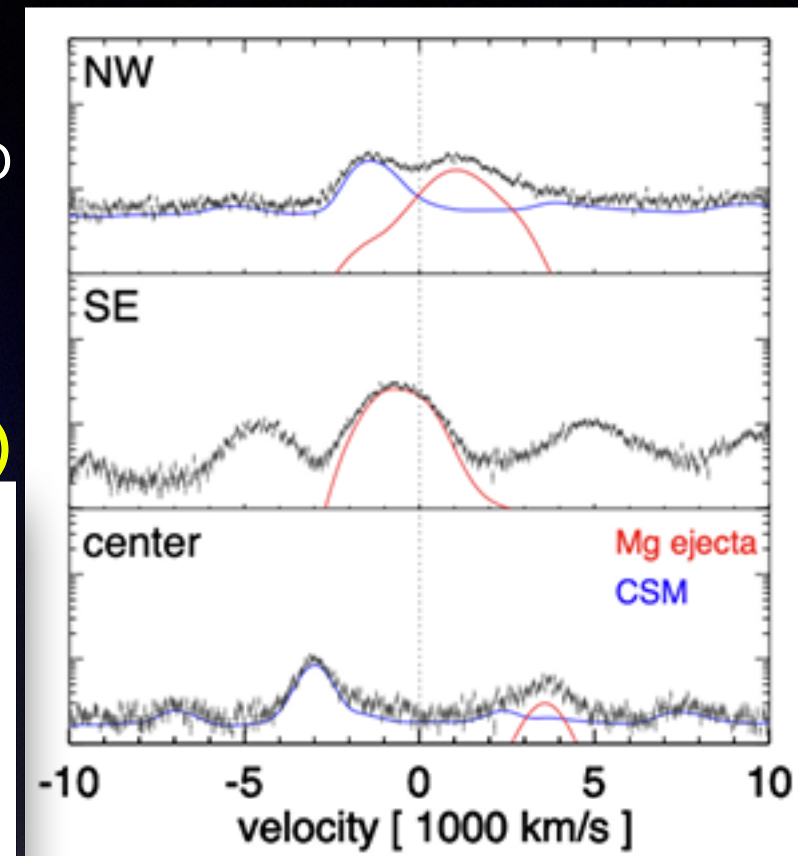
Linking 3-D simulations to observations

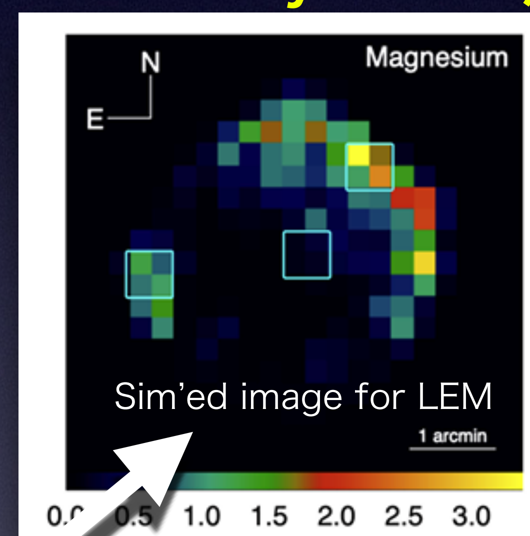
From pre-SN stages to SNR phase



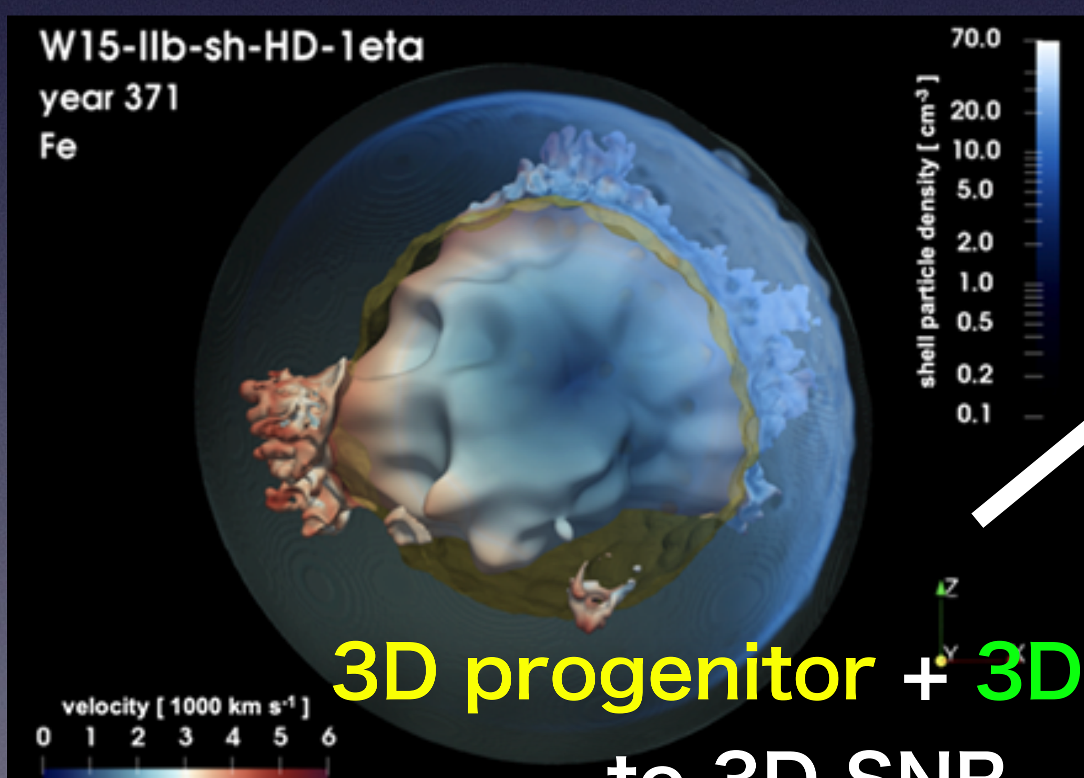
Complex line profiles in synthetic spectrum due to asymmetric CSM shell AND ejecta

(see also Hiroya's talk)



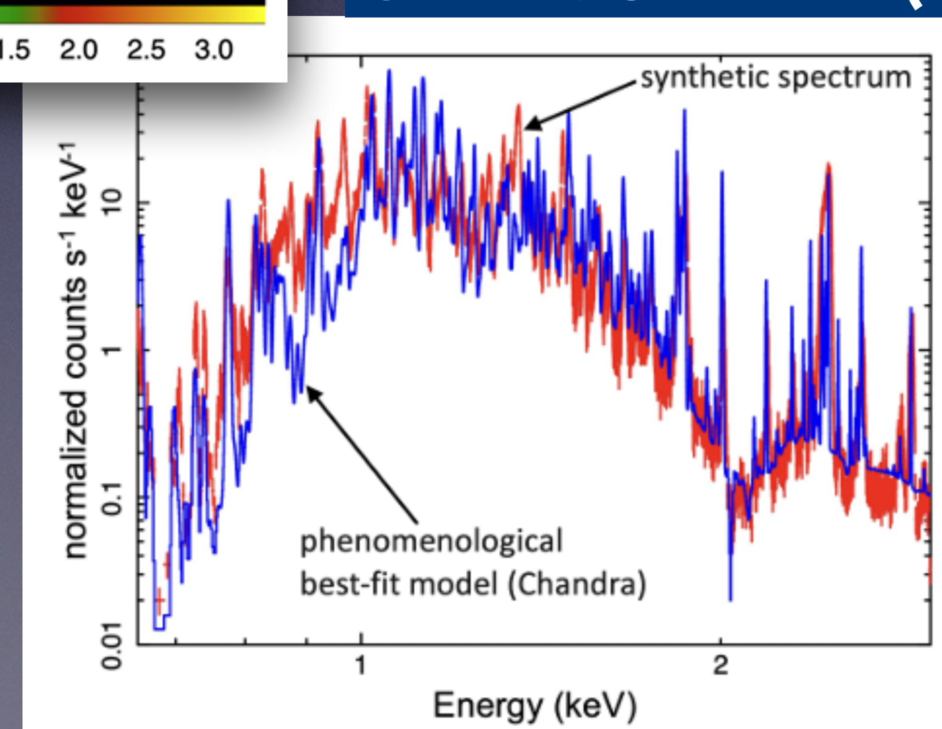


Orlando…HL+ (2024)



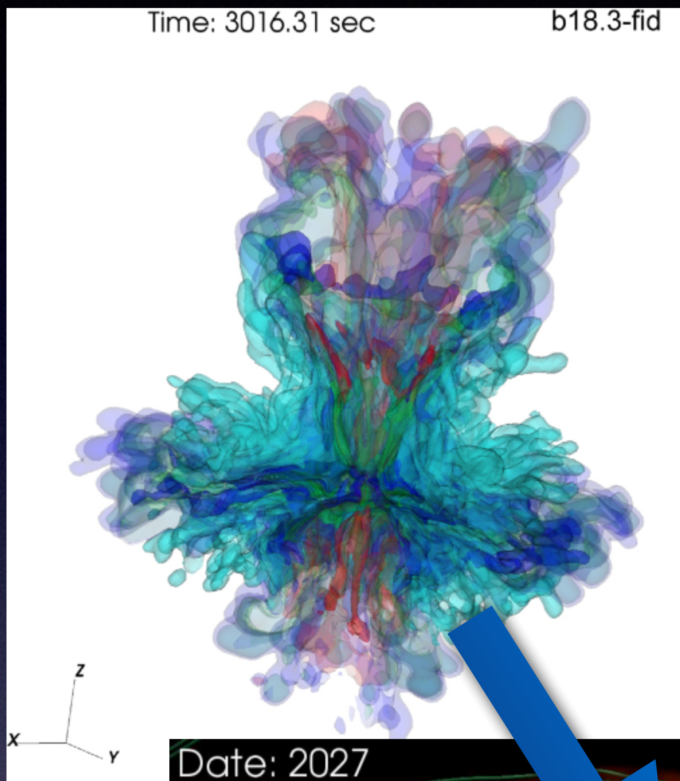
3D progenitor + 3D CSM to 3D SNR

Orlando+ (2022)

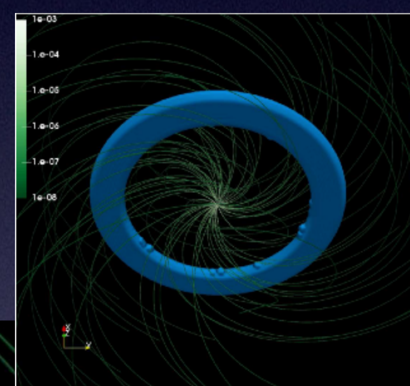


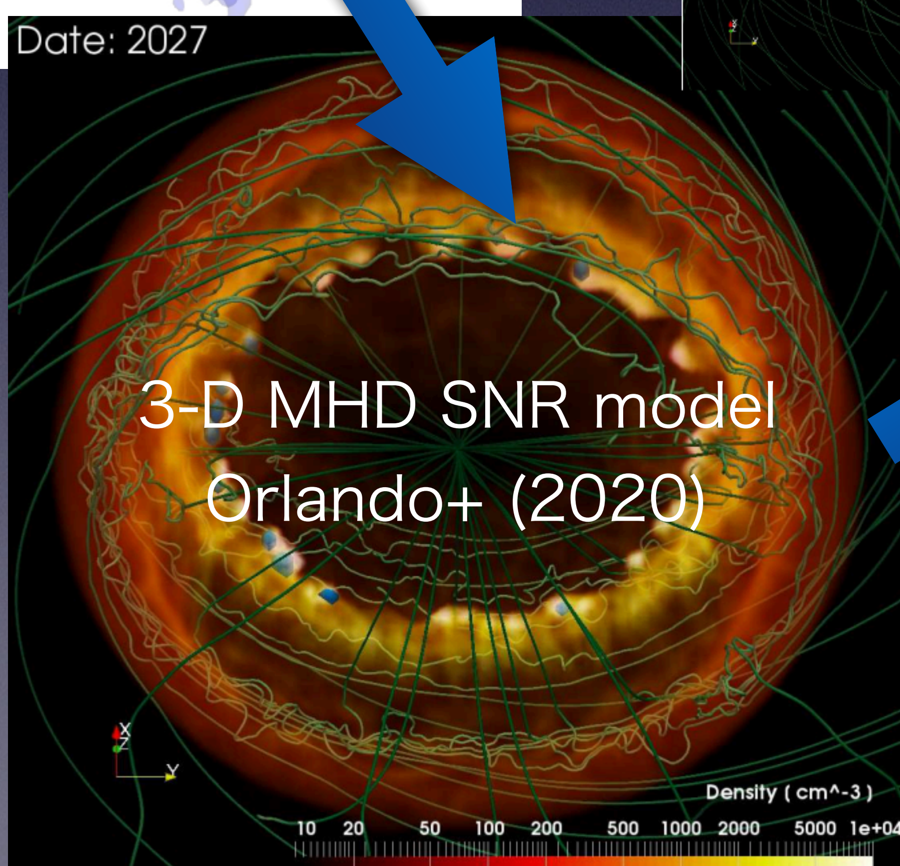
Application for XRISM

Case of SN1987A (see Ono-san's talk)

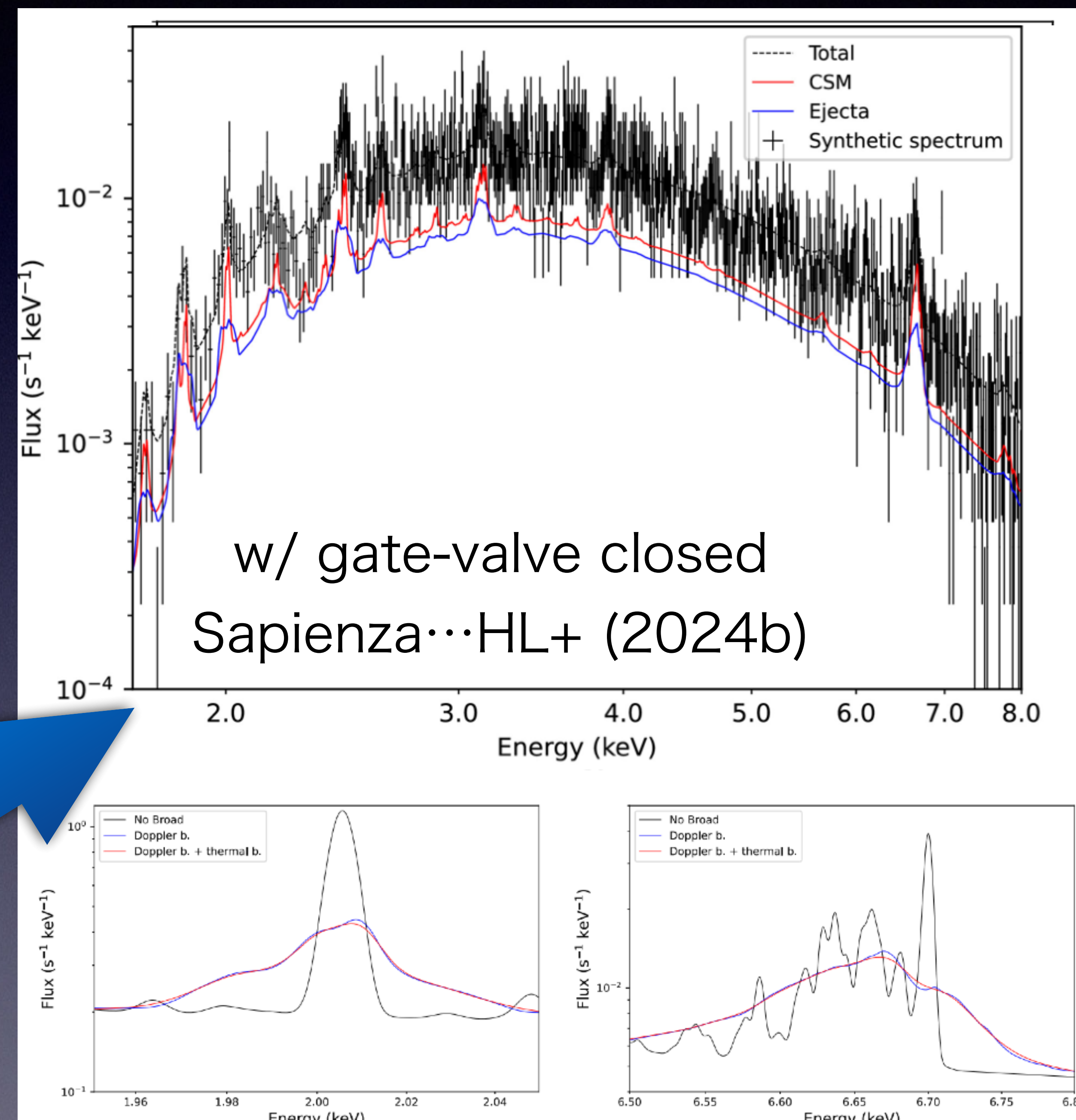


SN ejecta from a binary merger model
Ono+ (2020)





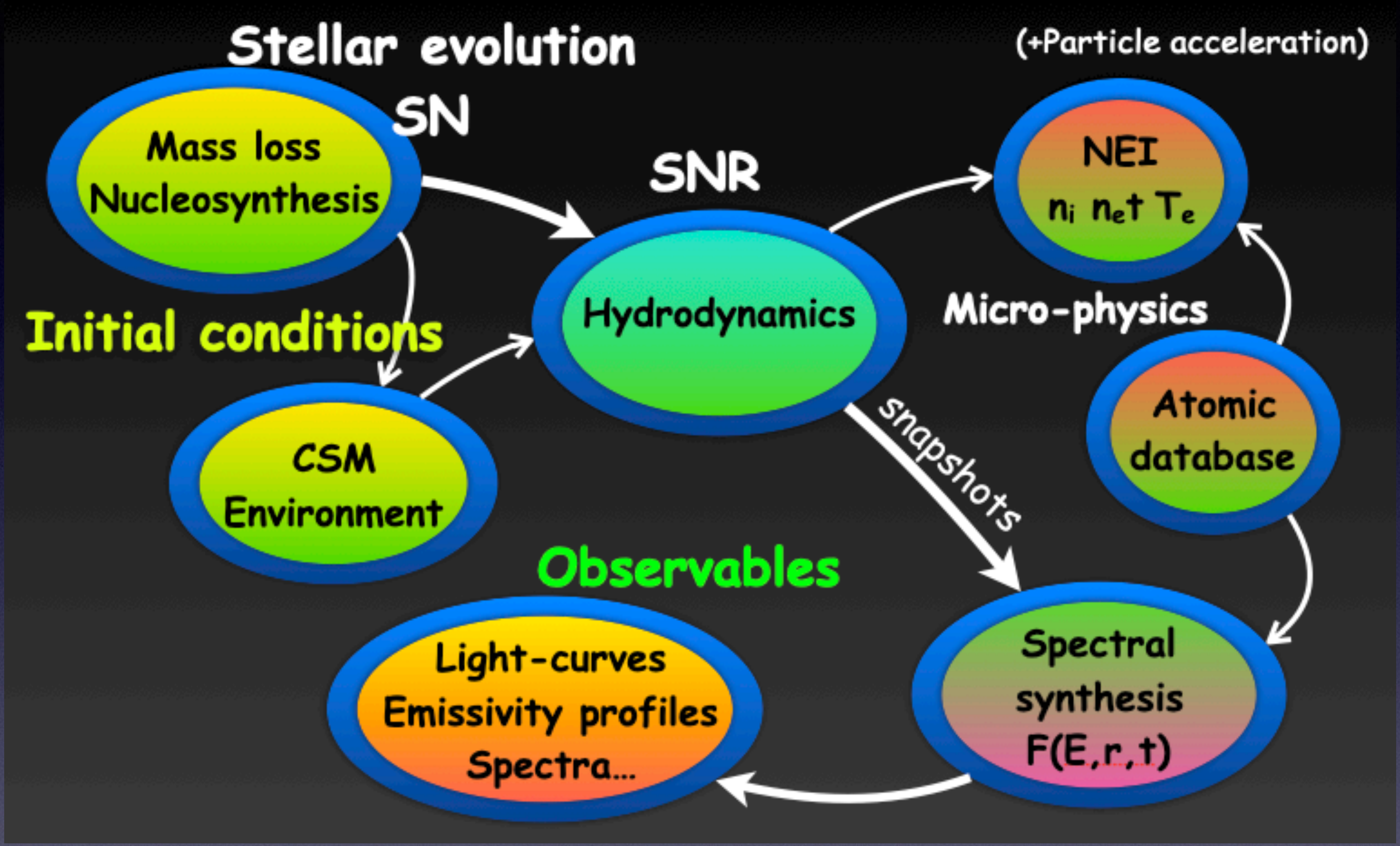
3-D MHD SNR model
Orlando+ (2020)



w/ gate-valve closed
Sapienza…HL+ (2024b)

Predicted synthetic spectrum @ 2024
Sapienza…HL+ (2024a)

Computation flow



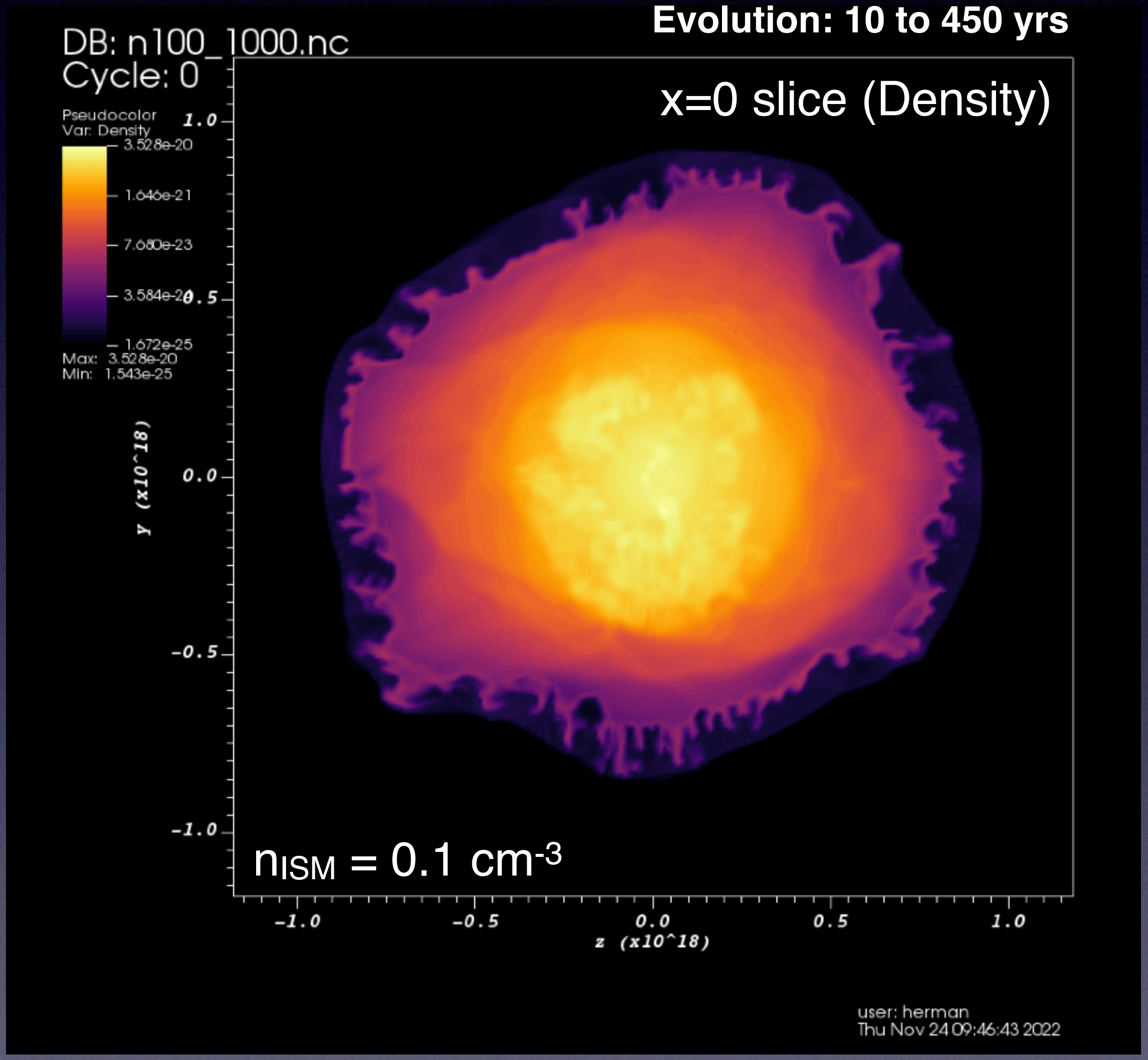
Typical work flow of a self-consistent progenitor-to-SNR simulation

- Problem is, fitting data is a complicated back-and-forth **iterative process**
- 3-D simulations are **typically way too heavy** to serve this purpose efficiently
- Need some **turbo boost in the pipeline** to be practical

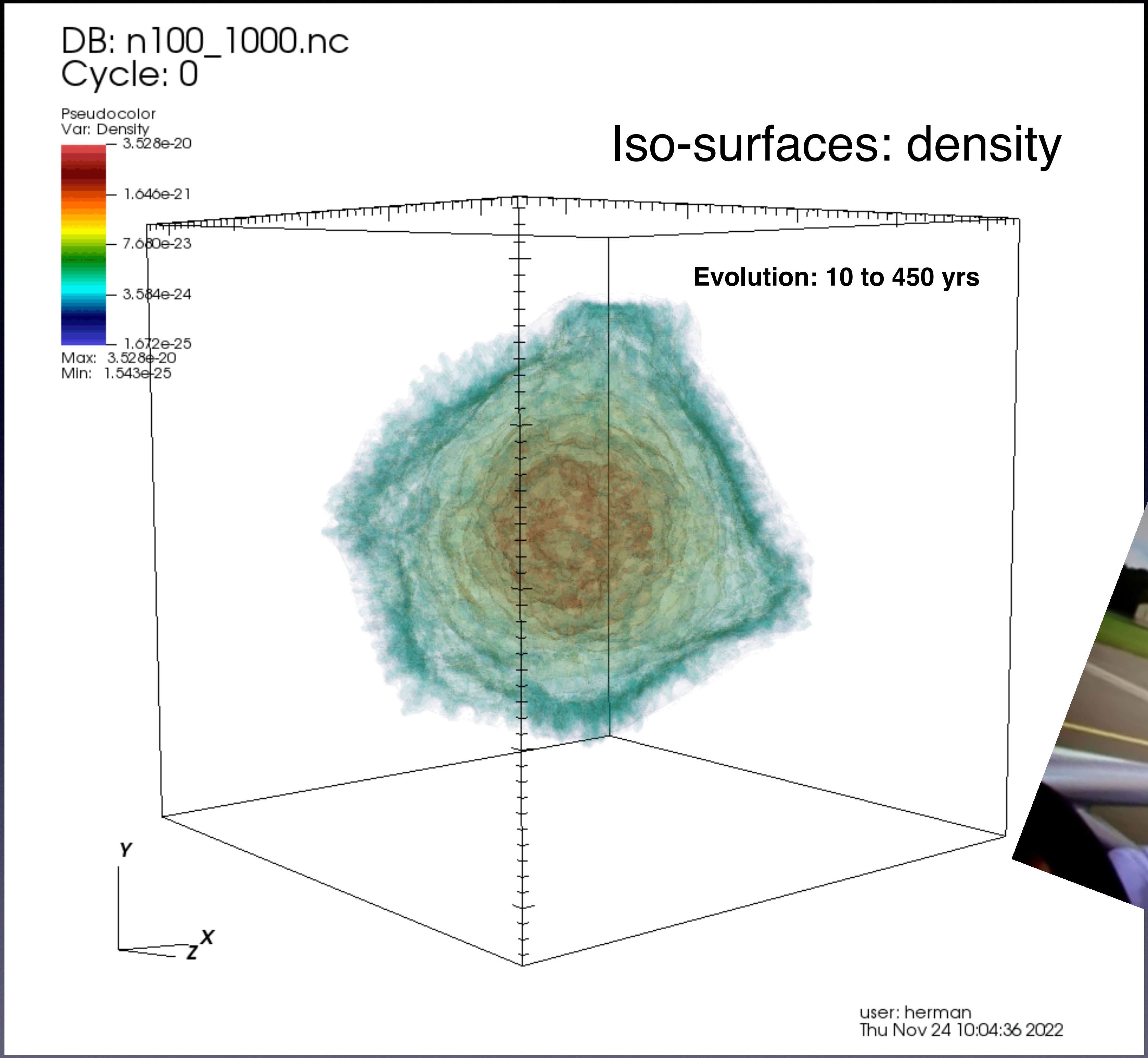
Super high-speed 3-D hydro simulations for long-term evolution of SNRs

Main features

- **From SN to SNR:** fully 3-D SN ejecta from various explosion models
- **Accelerating frame:** co-moving mesh with customizable scale factor a(t) (see e.g., Ferrand+ 2019)
  —> **long-term evolution** possible with low computational cost
- **Lagrangian particles:** populated in ejecta and ambient environment to trace plasma evolution
- **Observation simulations:** sky-projected images and spectra with mocked photon statistics & background estimation



SNR model from a 3-D DDT Type Ia explosion

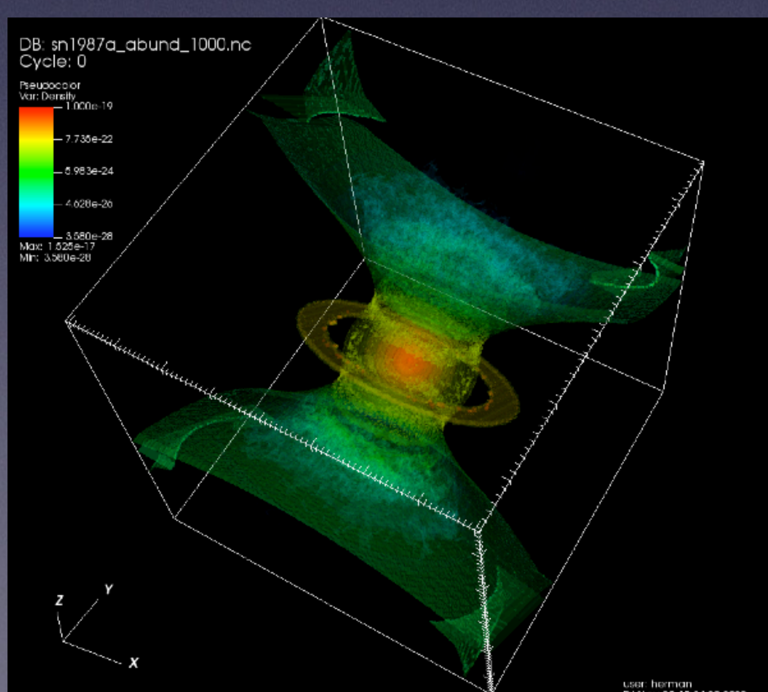


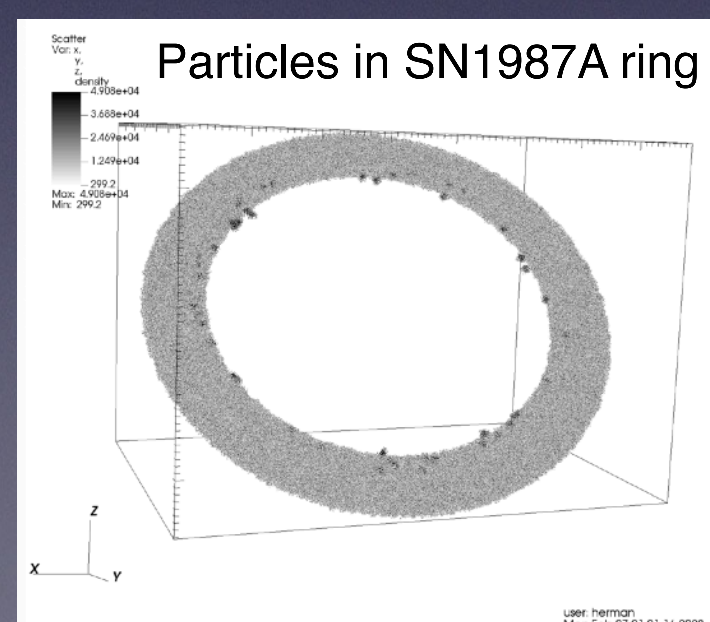
Simulation for a ~1,000 yr old SNR typically takes

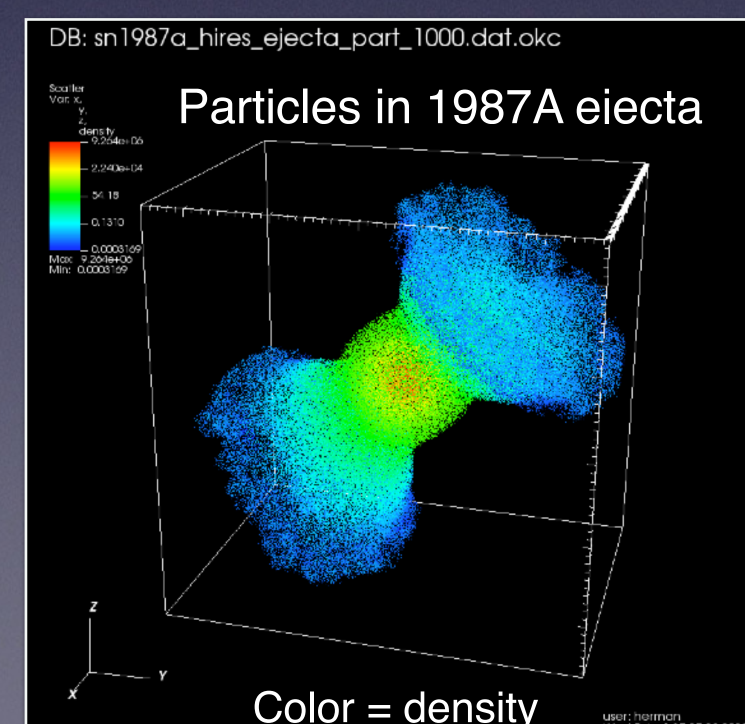
less than 1 day on a reasonably powerful PC

What's inside the box

- Initialization from age ~ 1 yr by homologous expansion from SN model
- Typical resolution ~ 256^3 cells
- Spatial-dependent chemical abundances from Z = 1 to 30 (Zn)
- Space-time-resolved non-equilibrium ionization (NEI) for all ion species
- Temperatures for all elements allowed to evolve and equilibrate
- **Tracer particles** keep track of these good stuff anywhere, anytime
- Others processes e.g., radiative cooling, ionization cooling
- Seamlessly linked to an observation simulation package (such as SOXS)

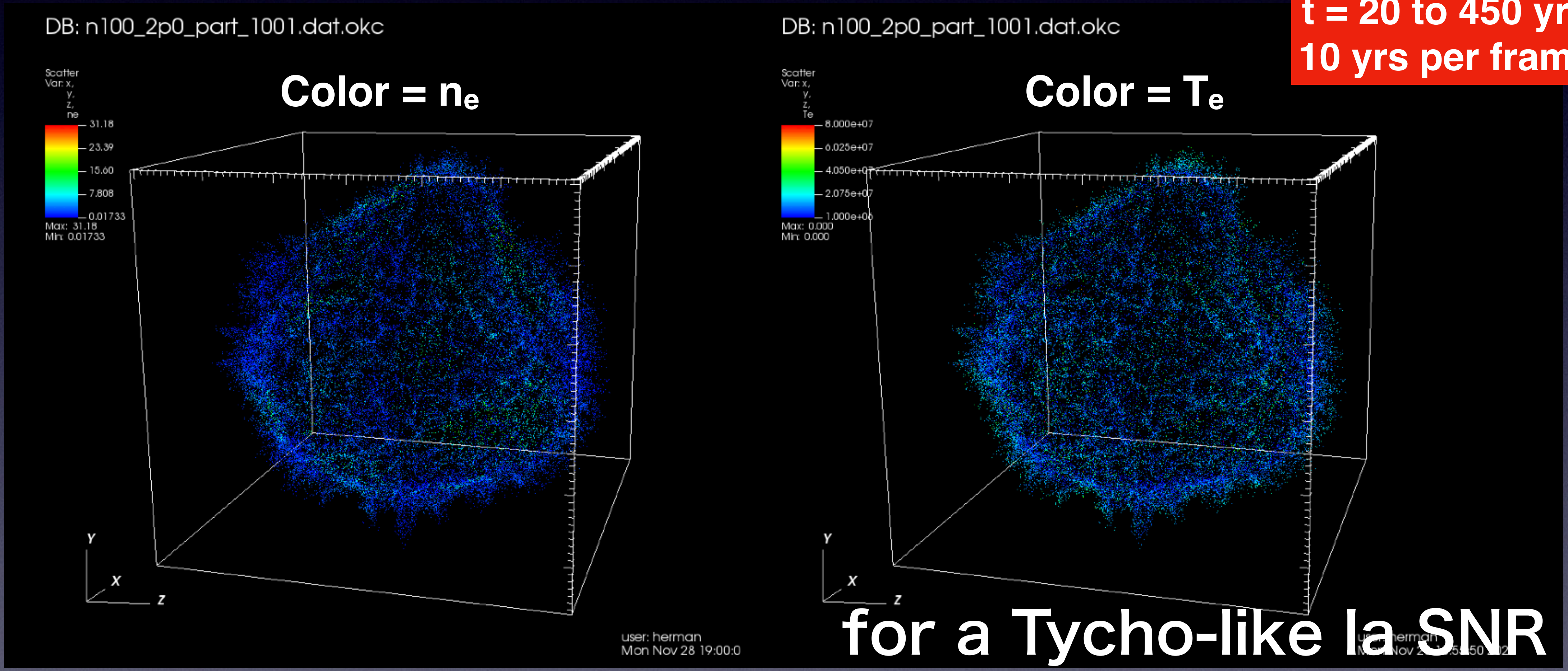






Lagrangian particle propagation

<u>Shocked particles in ejecta</u>
($N_{particle}$ = 100,000 in shown example)



Each particle records ionization history and thermodynamic evolution

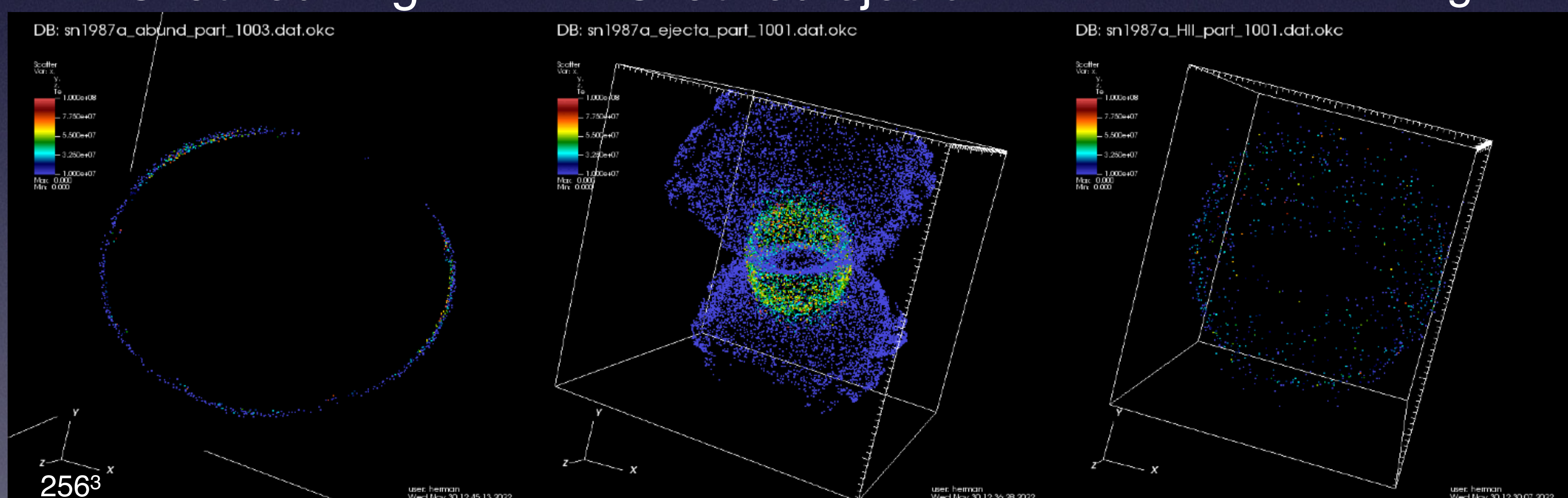
Convergence against $N_{particle}$ can be confirmed easily through plasma properties

Divide and conquer

- We can put particles in different regions in <u>separate simulations</u> and then merge them later —> save memory

Example: 1987A

shocked ring | shocked ejecta | shocked HII region

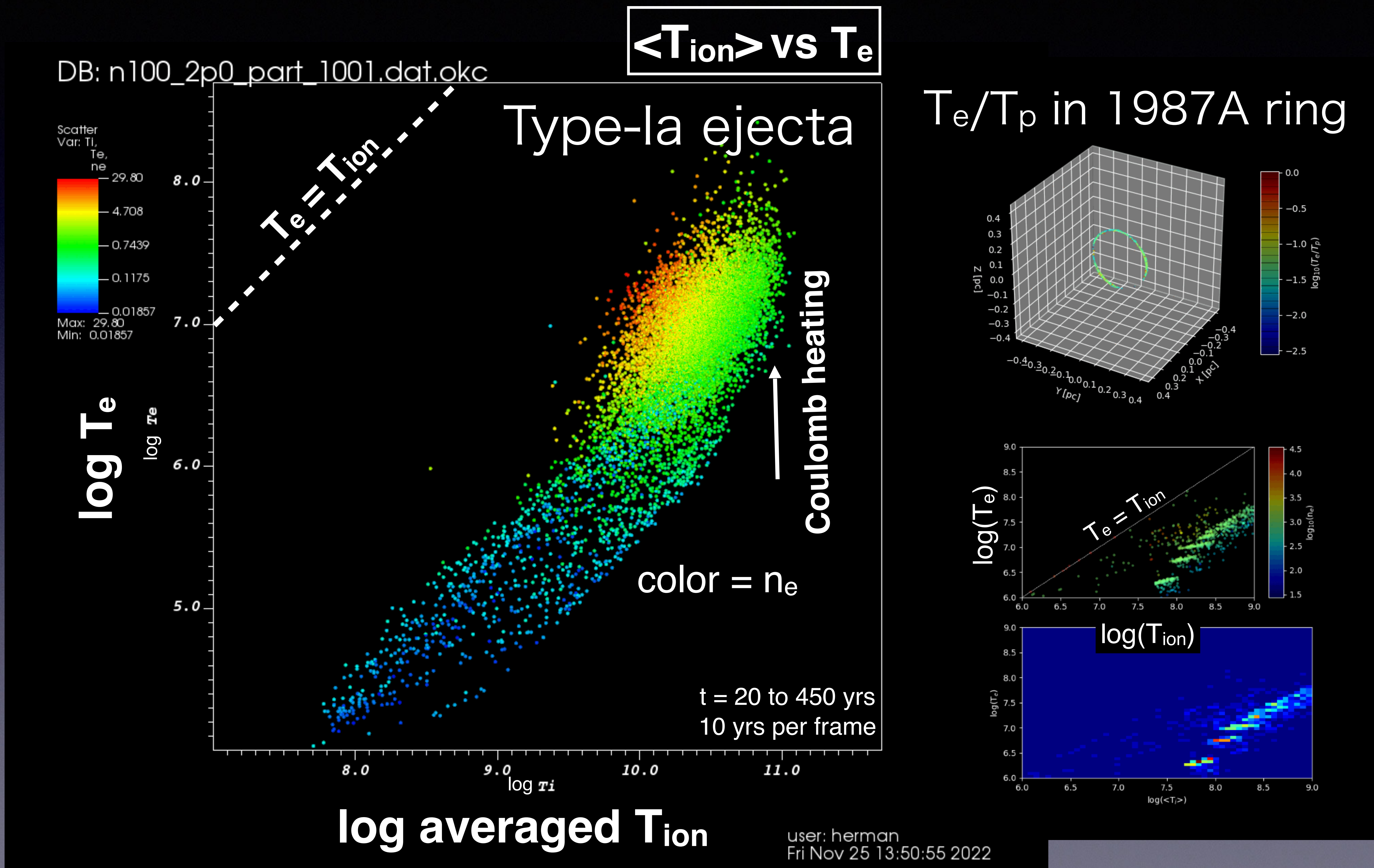


Note: shown box sizes adapted to respective features

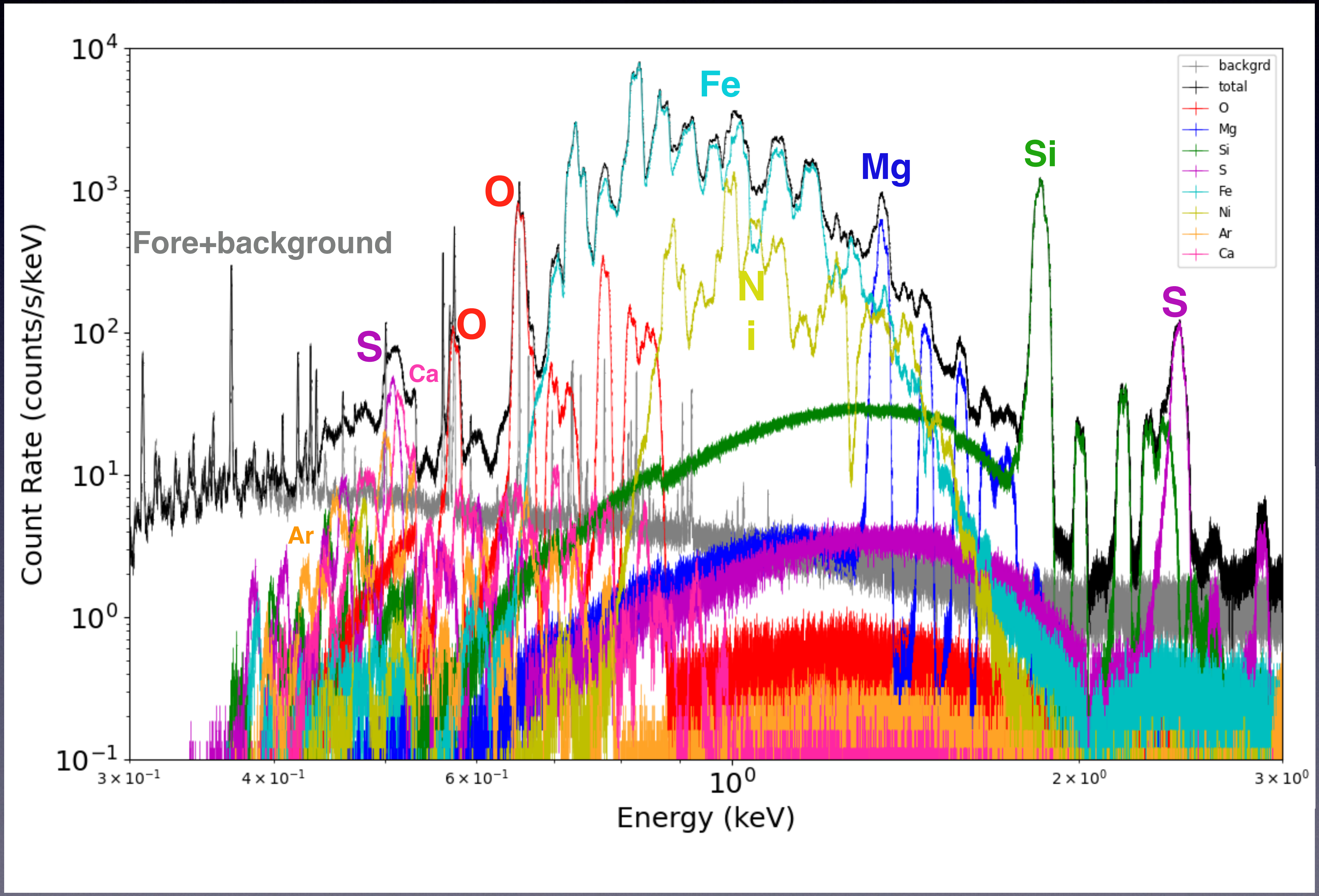
1997 to 2097

Color = T_e

Temperature per element followed in real-time
Realistic prediction for thermal broadening of lines

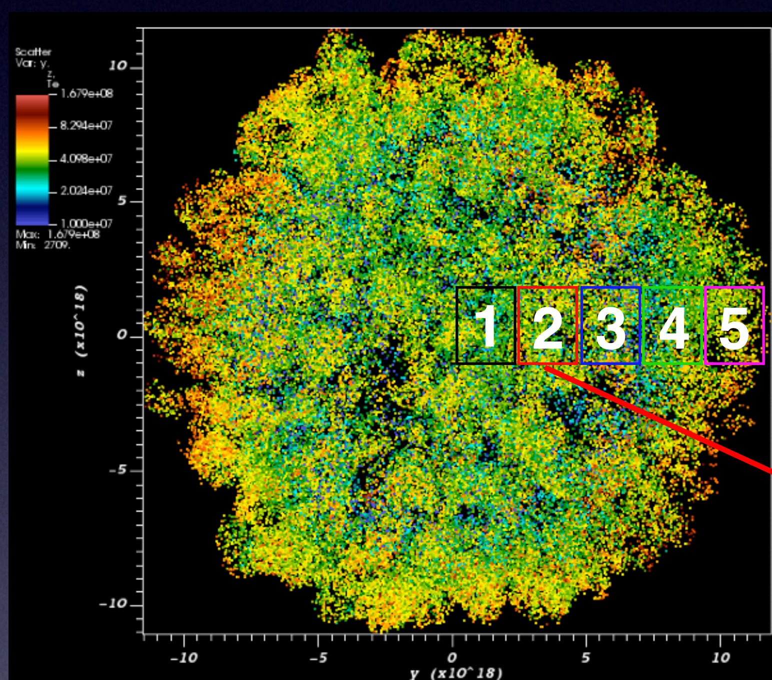


Now simulate spectrum to your heart’s content

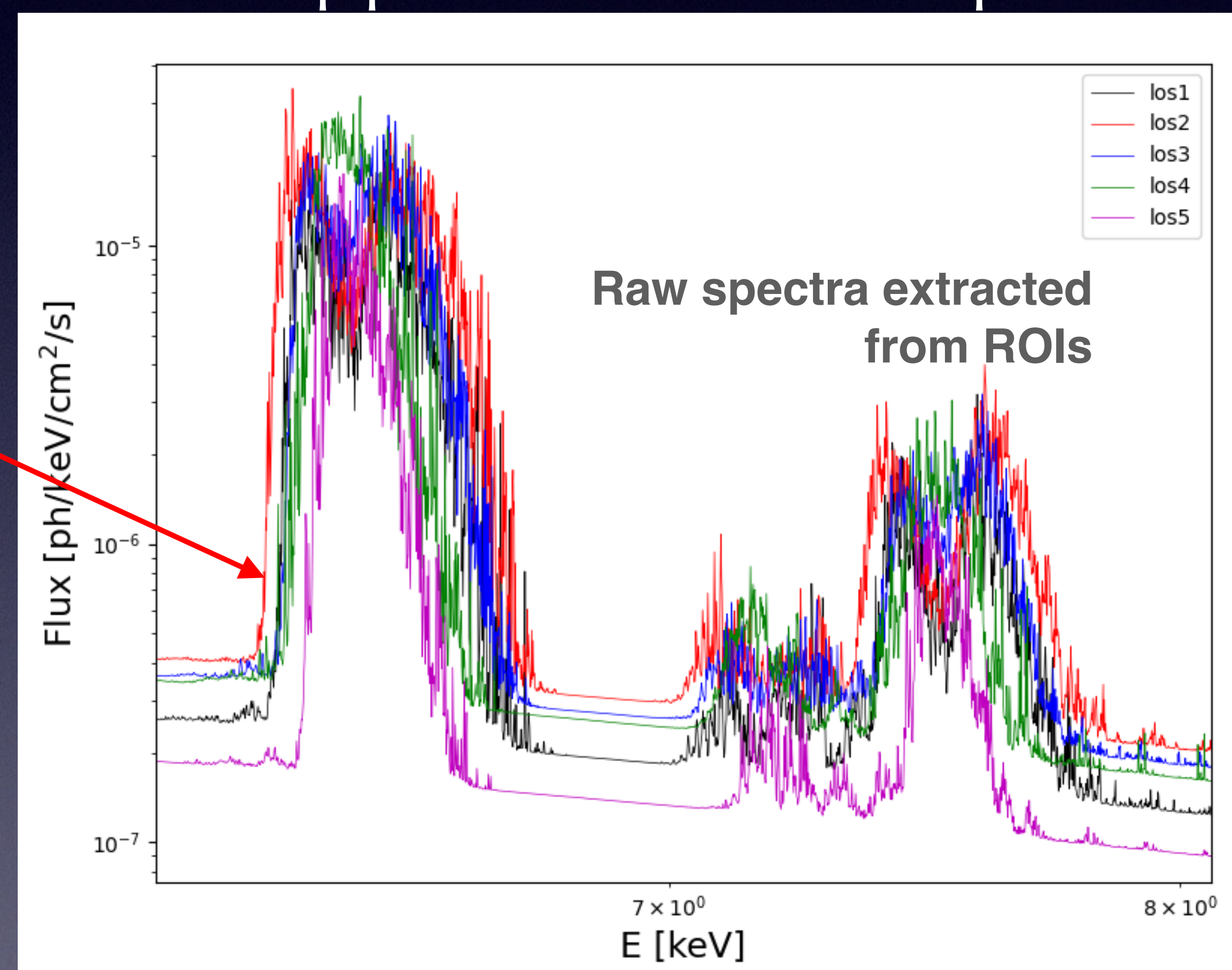


Be (line-of-sight) specific

Probing dynamic structures in SNRs



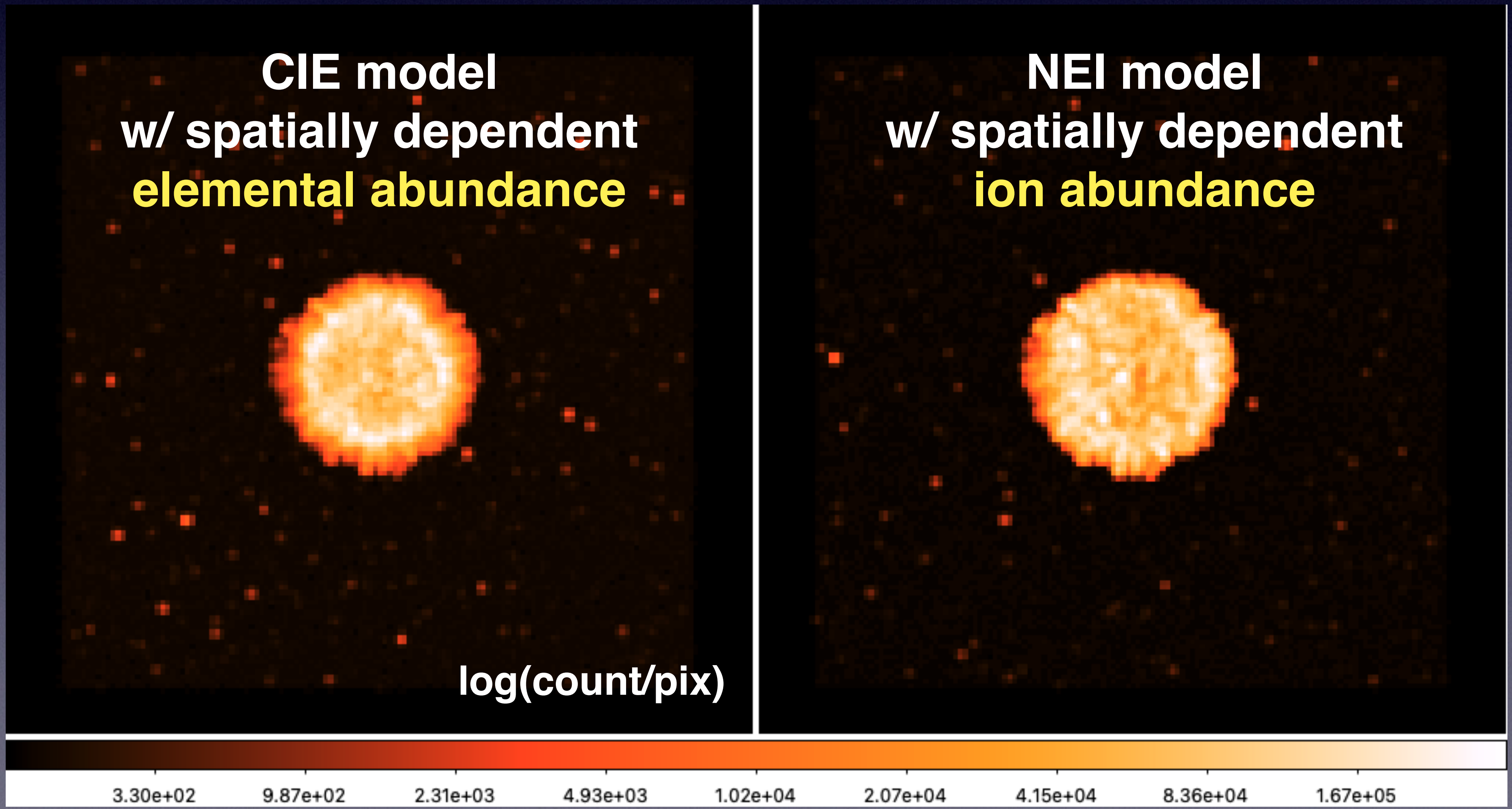
Doppler-shifted line profiles



Importance of solving NEI in 3-D hydro

Not just spectral, effect on predicted SNR morphology can be profound

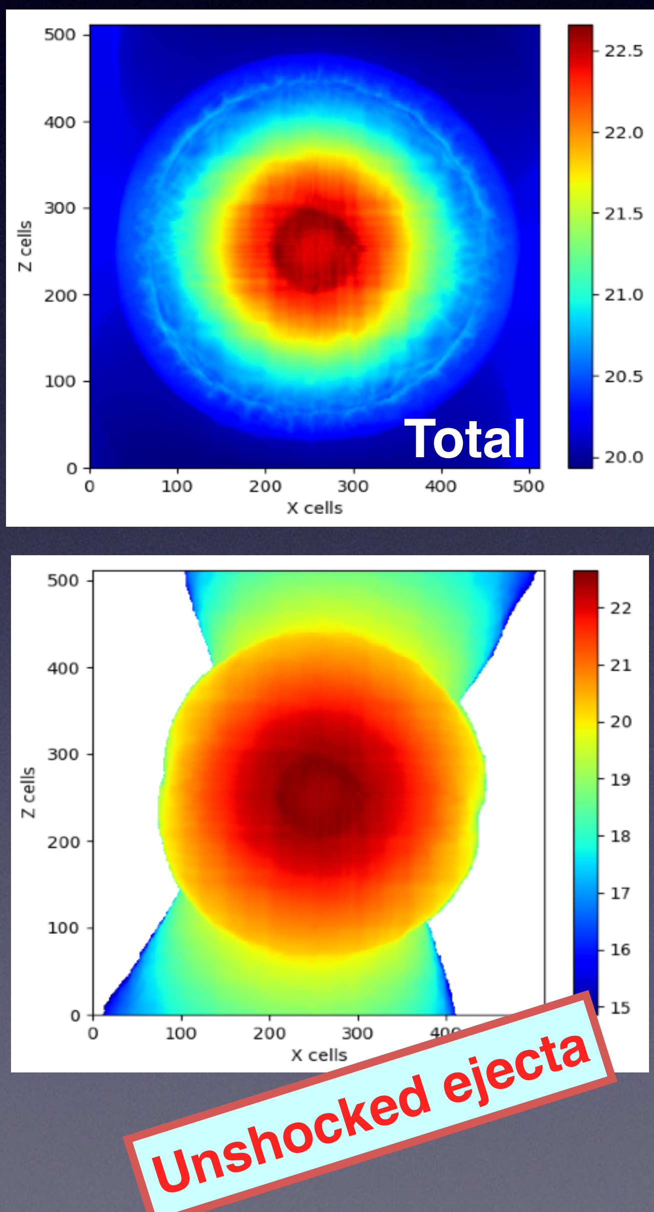
Simulated X-ray images of a young type Ia SNR model

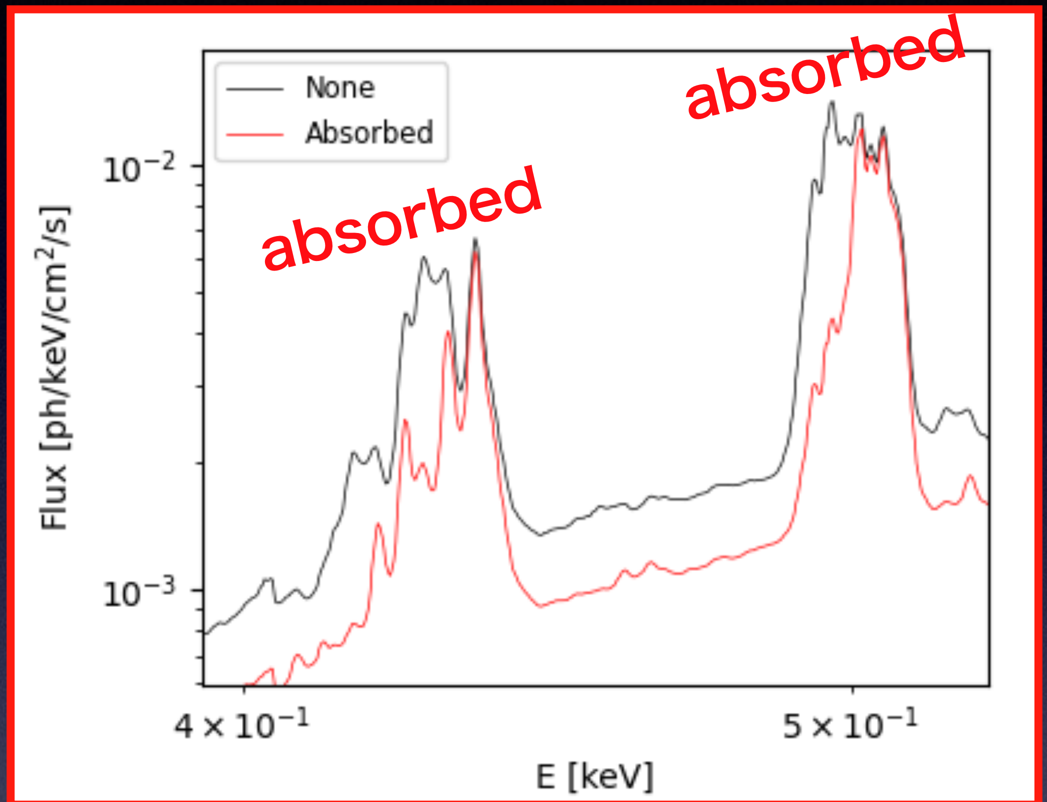


(Simulated for Line Emission Mapper)

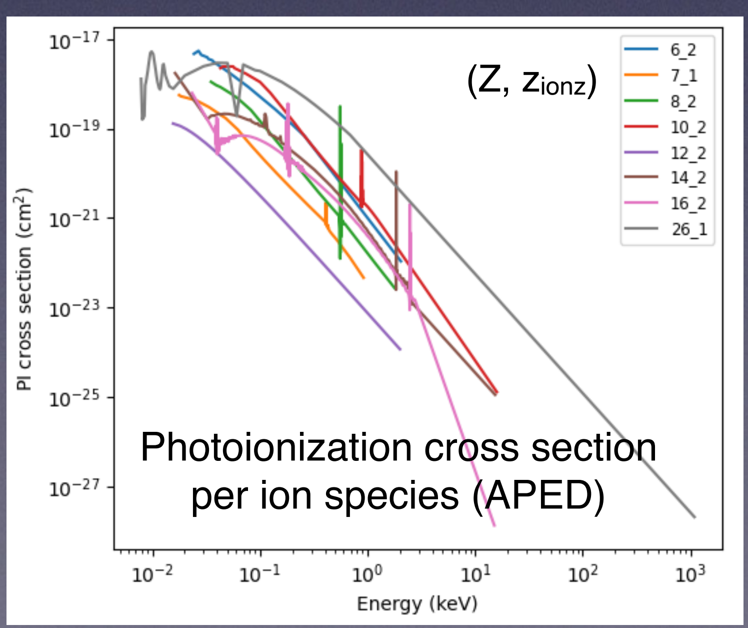
Internal absorption by cold (unshocked) ejecta

Column density $\log_{10}(n_H)$





Sim'ed for SN1987A in the 2030's



X-ray of very young SNRs can be prone to absorption by the cold & dense unshocked ejecta

e.g., much of **red-shifted component can be suppressed** by internal absorption

- Can be additional **probe of mass and distribution of nucleosynthesis products in inner ejecta**

But, is it useful?

- **Generally**: 3-D model surveys tell us **what to look for** in observation data when we try to single out things like
  - Progenitor type
  - Explosion channel
  - CSM environment, pre-SN activities
- **Specifically**: apple-to-apple comparison of a model with real SNR data thru observation simulations

Example

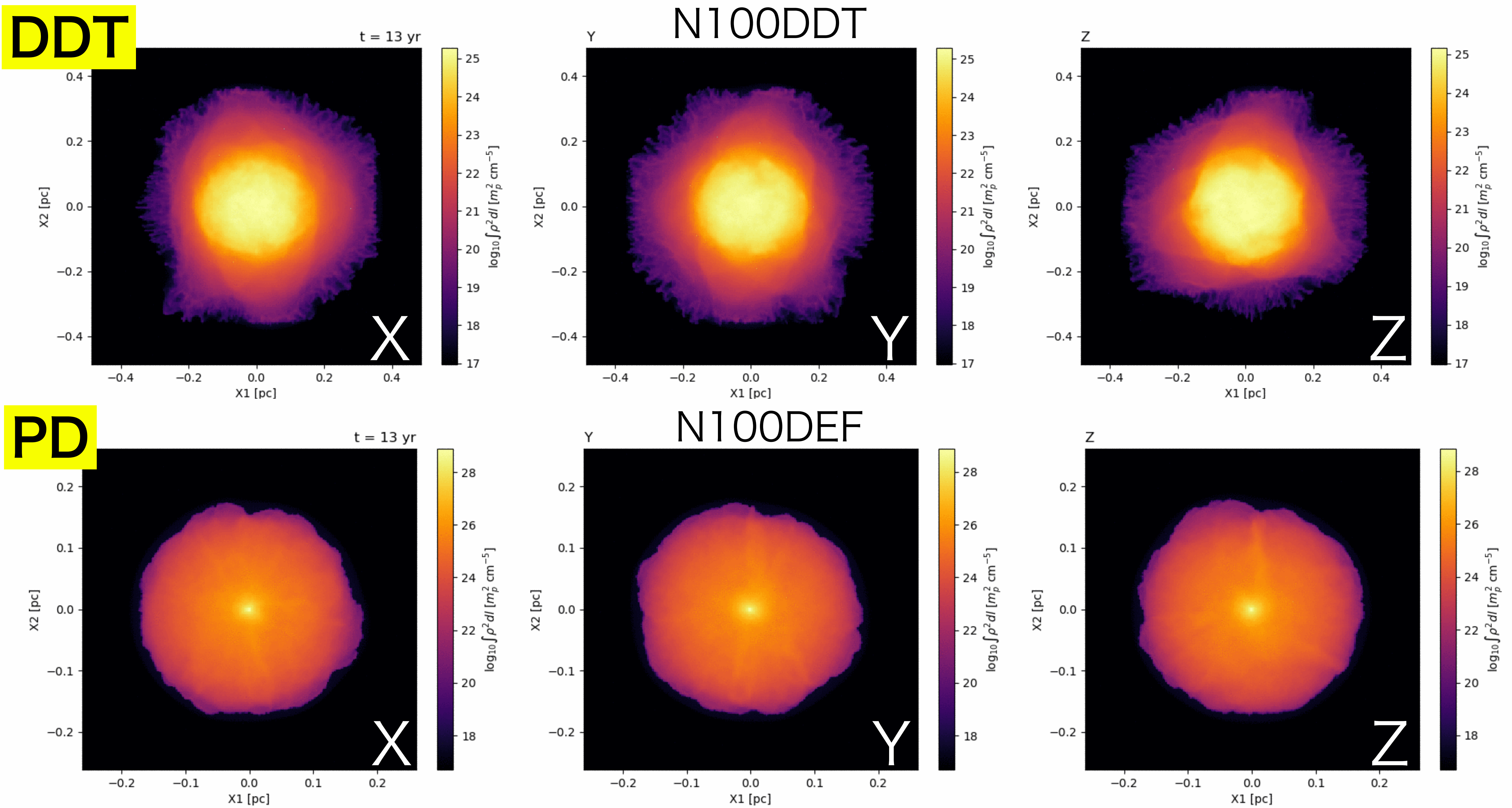
- Q: how do we **discriminate Type Ia explosion models** from SNR X-ray observation? (see also Gilles's talk)
  - Start from gathering a collection of SN ejecta models from different explosion channels
    - e.g., SD vs DD, single vs double detonation, DDT vs pure deflagration, WD ignition pattern, WD type and so on
  - Evolve them to a good age and **look for observable characteristics**
    - Detailed morphology and temporal change
    - Spectroscopic properties: abundance ratios, ion states, resolved line profiles, etc…

Example: diversity of Ia SNRs

(see Yusei's poster for model details & spectral calculations)

I. SD: DDT vs pure deflagration

$\int \rho^2 \, d\ell$

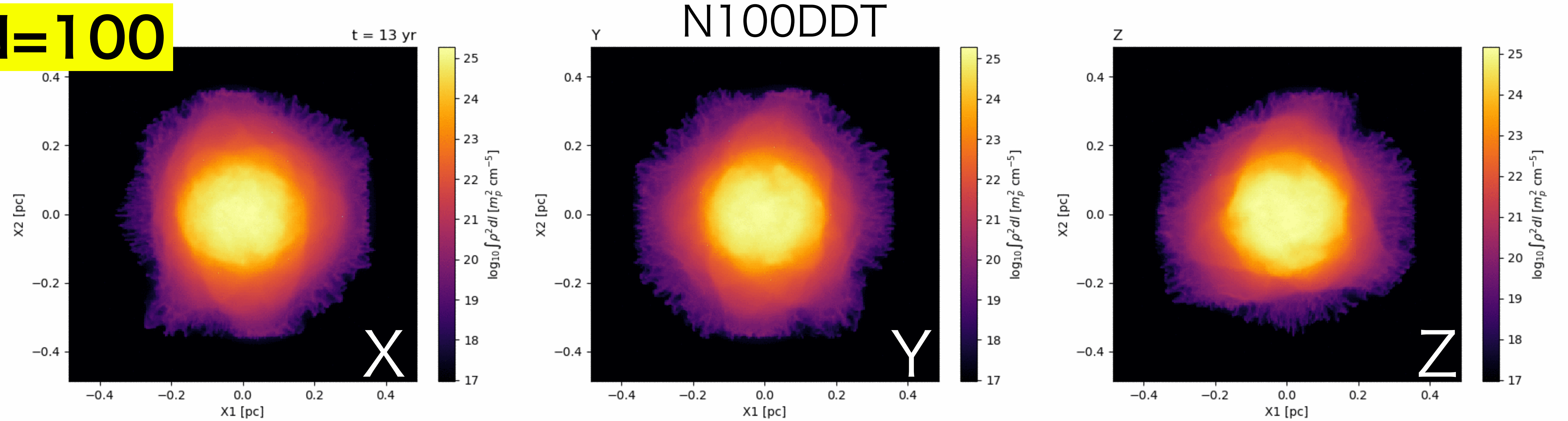


Example: diversity of Ia SNRs

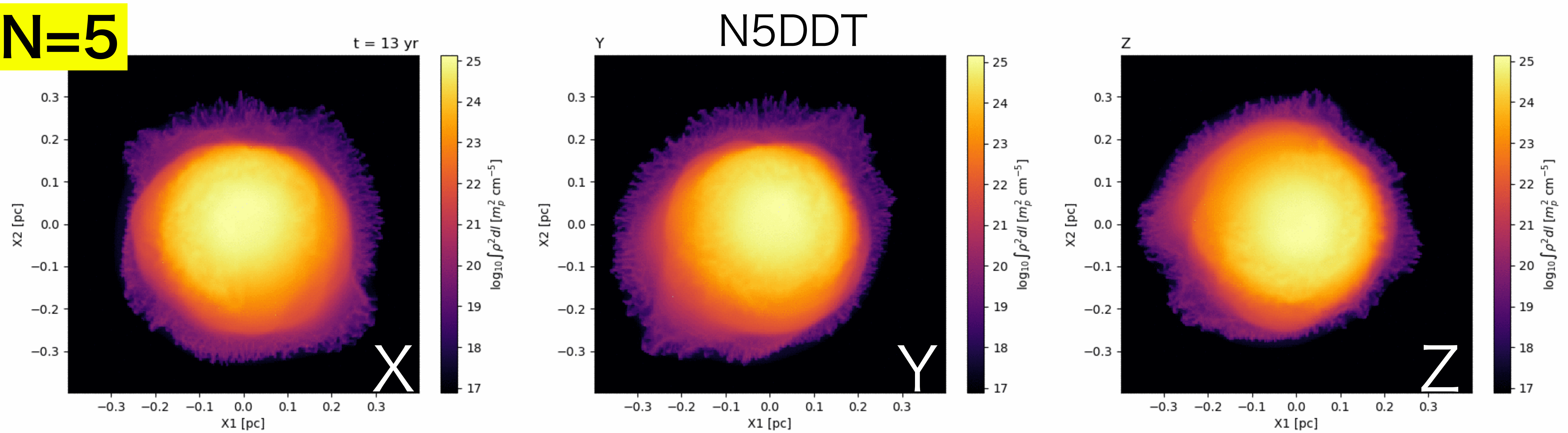
II. SD: # of ignition points

$\int \rho^2 d\ell$

N=100



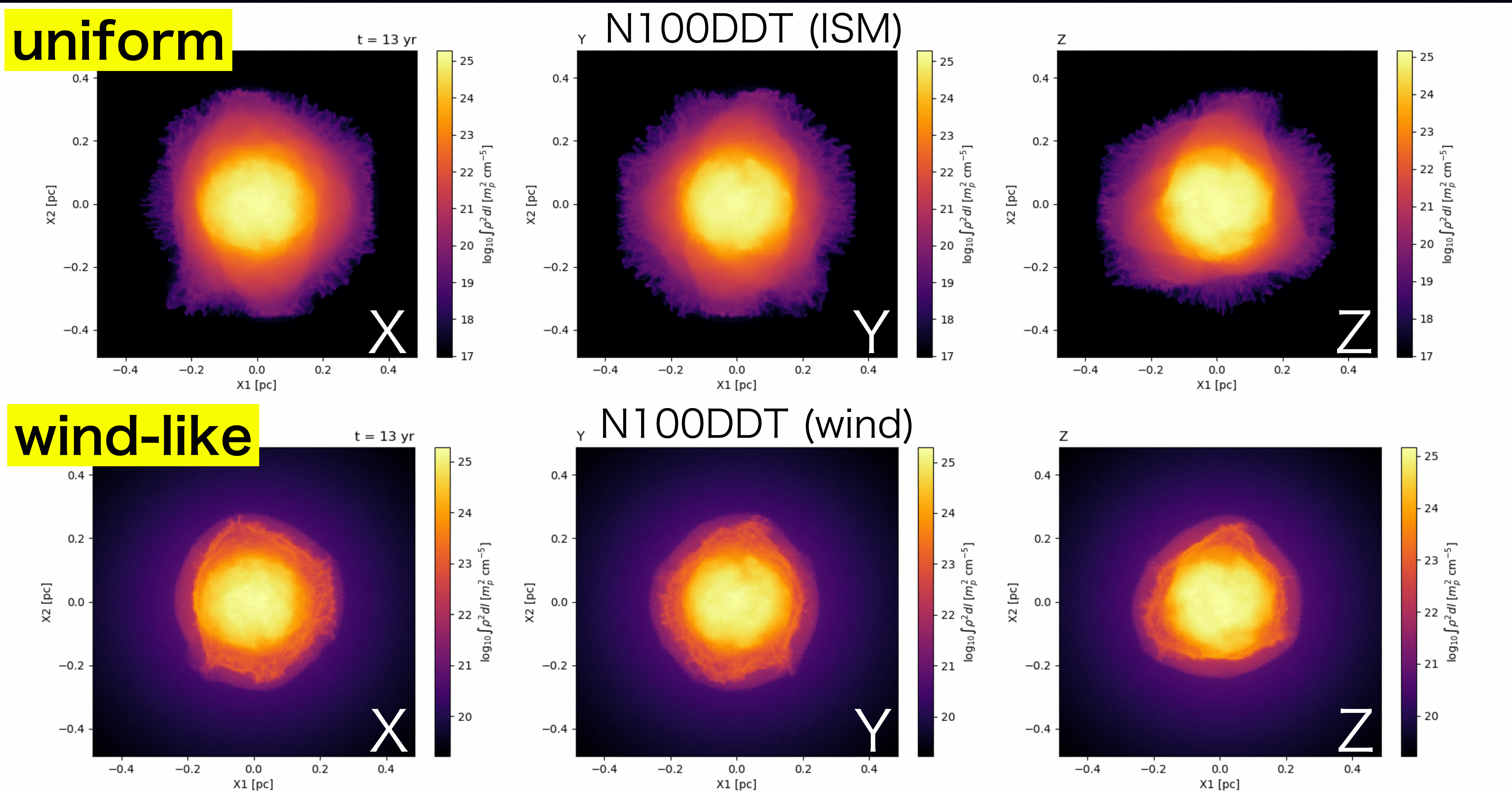
N=5



Example: diversity of Ia SNRs

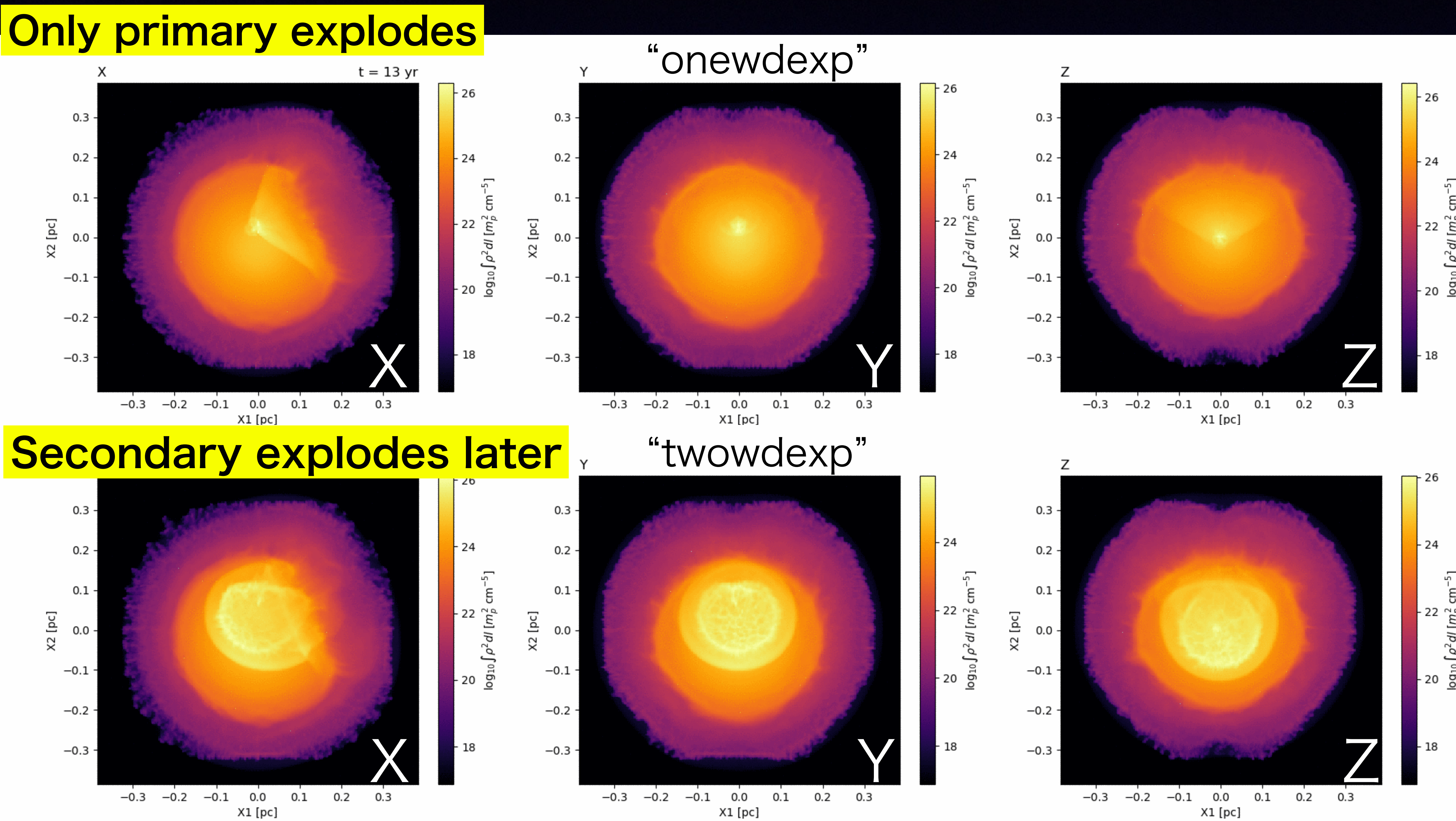
III. Environment: uniform ISM vs wind cavity

$\int \rho^2 d\ell$



Example: diversity of Ia SNRs

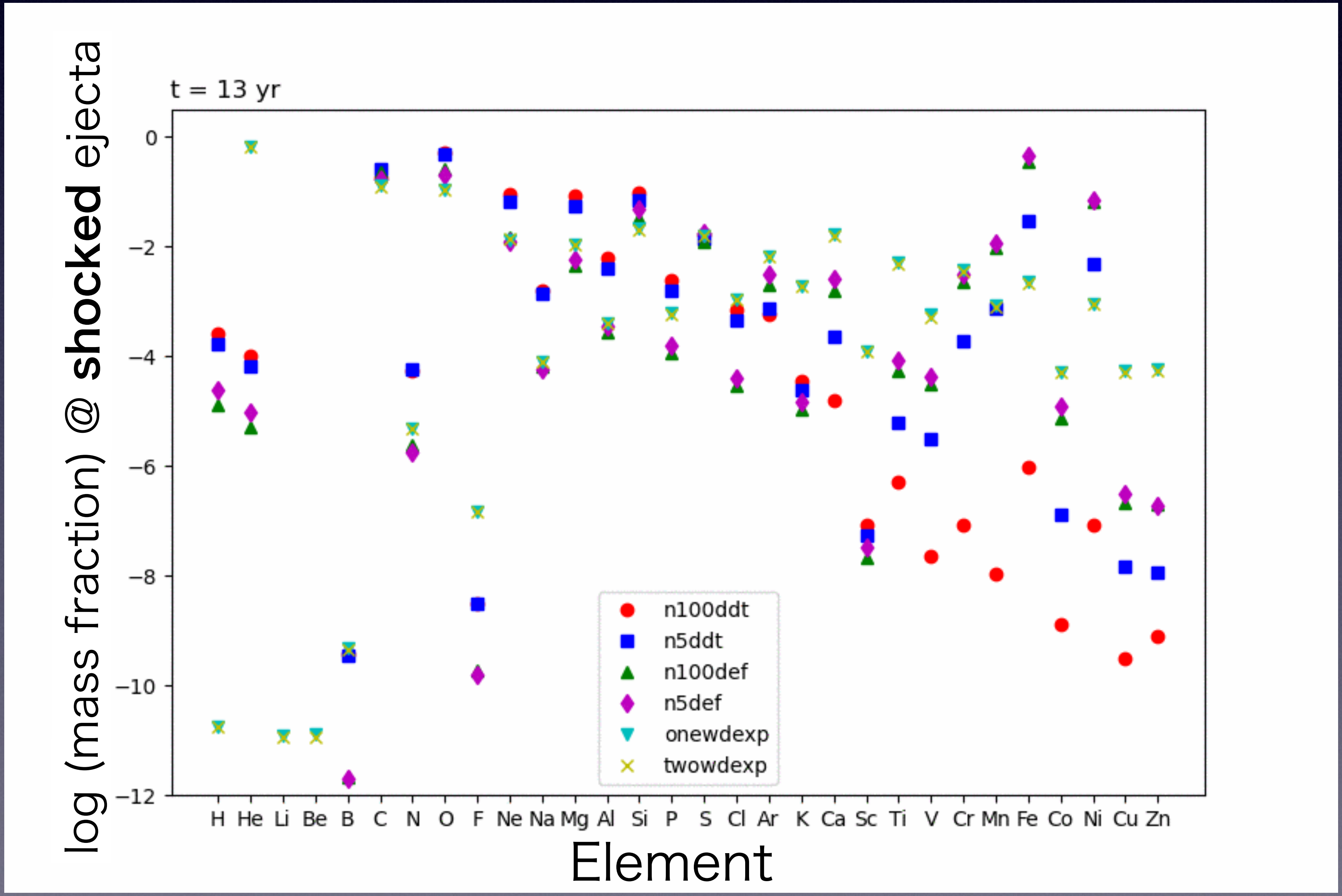
IV. DD: single vs double WD explosion (Pakmor+ 2022)



Tracing abundance pattern in the shocked plasma in real time

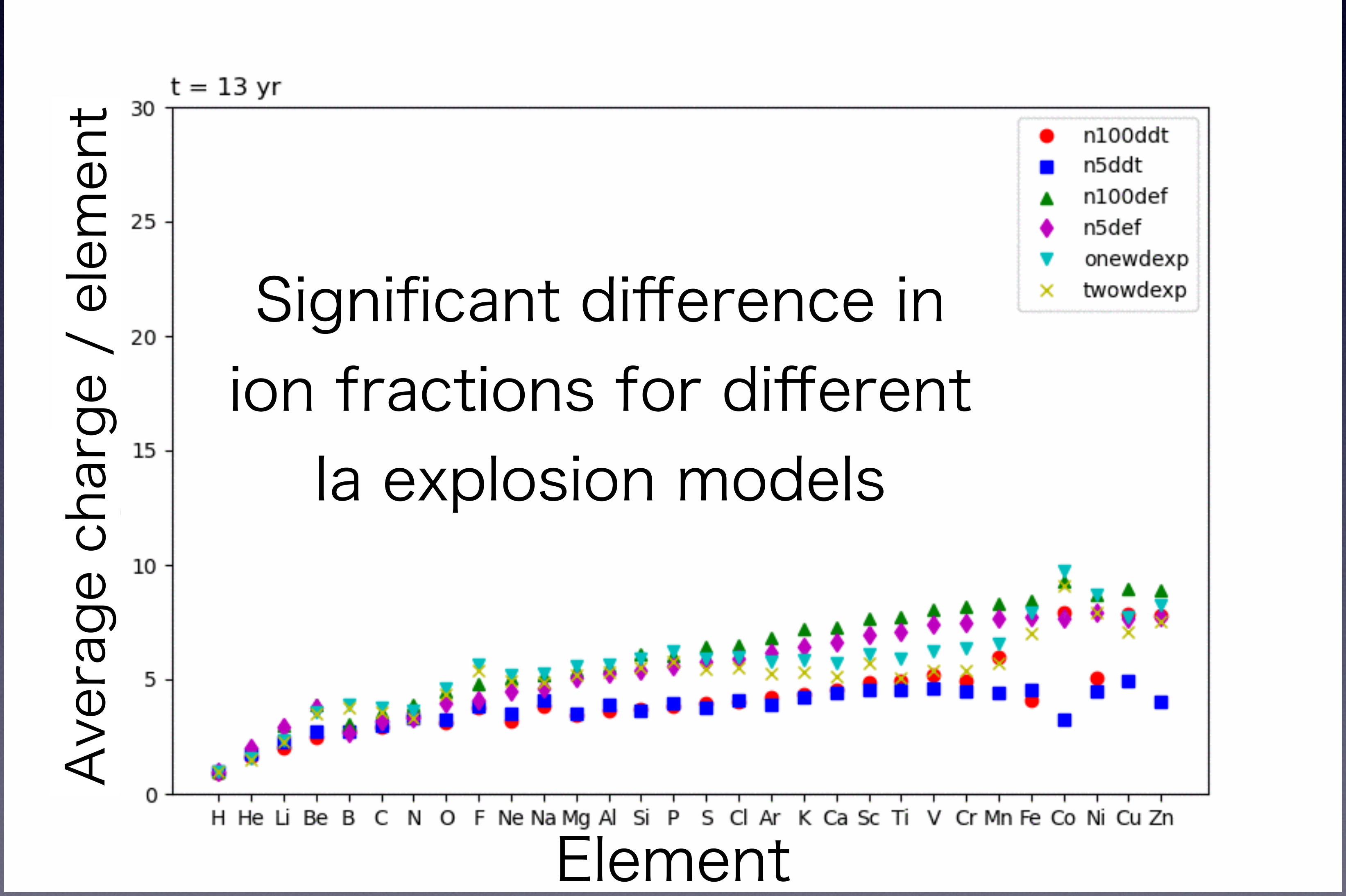
Shock dynamics taken into account

= a better test against observed values than SN model yields



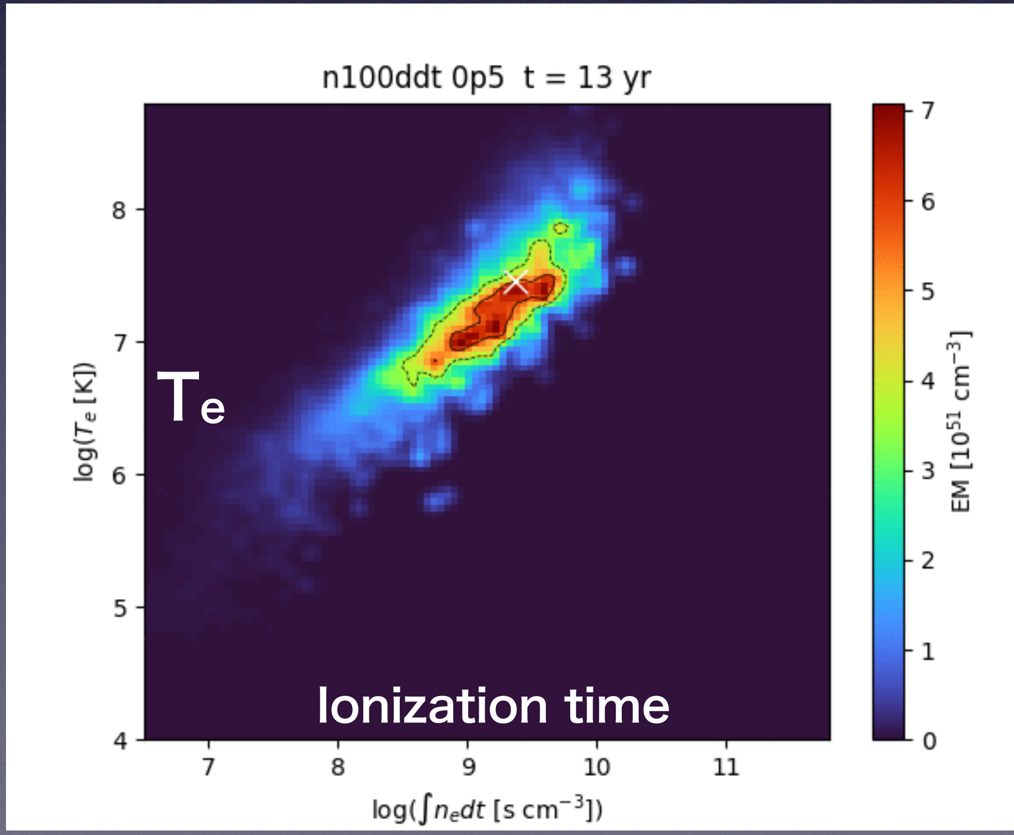
Tracing plasma state of the shocked materials in real time

3-D distributions of ion states, emission measures, temperatures and velocities allow direct comparison with (LOS-specific) spectra @ XRISM resolution



Plasma diagnosis

Ionization time $\int n_e dt$ vs T_e



Future works
(a.k.a. projects for graduate students)

- Go diverse: work on SNRs from different progenitor systems, including the “rarer” ones (various SESN, ECSN, LMCCSN, SLSN, P… various Ia’s, etc…) (see talks by Ken, Dan, Tomoya, Hideyuki a… …ers)
- Go broadband: non-thermal emission, dust em… (see Ono-san’s talk), nebular optical lines, nuclear lines?
- Go extra 3-D: 3-D CSM e.g., pre… …lar evolution (see Hirai-san’s talk on binary models), inhomog… …ISM e.g., pre-existing dense clouds
- Go detailed: charge… …ge, resonant scattering, improved atomic physics, electr… …g & cooling physics, magnetic fields, …
- Intern… …g sources / central engine? PWNe, ^{56}Ni, magnetar…
- Lo… absorption? cold ejecta, CSM

As long as: without making the code too slow