RIKEN — RESCEU Joint Seminar 2016 @ U-Tokyo
Jul. 2016, 26th

Multi-Dimensional Numerical Modeling of Supernova Remnants

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Kyushu Univ. → RIKEN (from this fall)

Collaboration with Astrophysical Big-Bang Laboratory (ABBL, RIKEN)

Supernovae to Supernova remnants

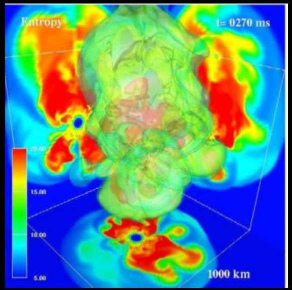
Supernova explosions

Explosive nucleosynthesis

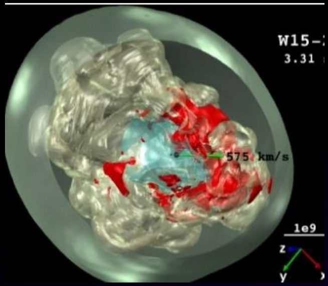
Mixing

Supernovae

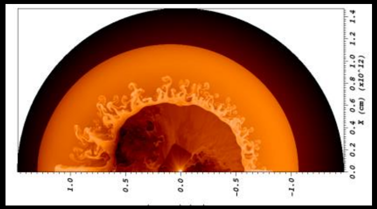
Supernova remnant



T. Takiwaki

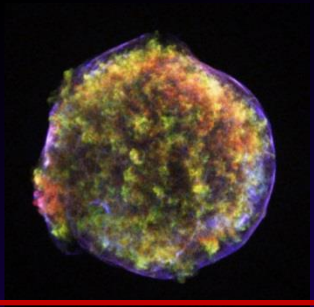


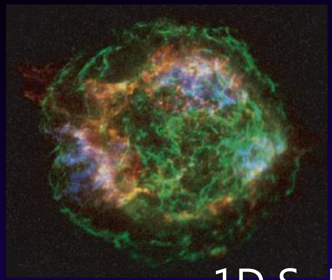
A. Wongwathanarat

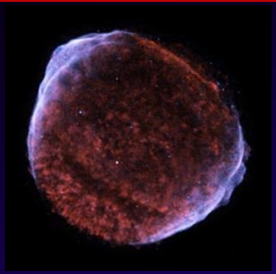


MO and J. Mao

Multi-D (MO)



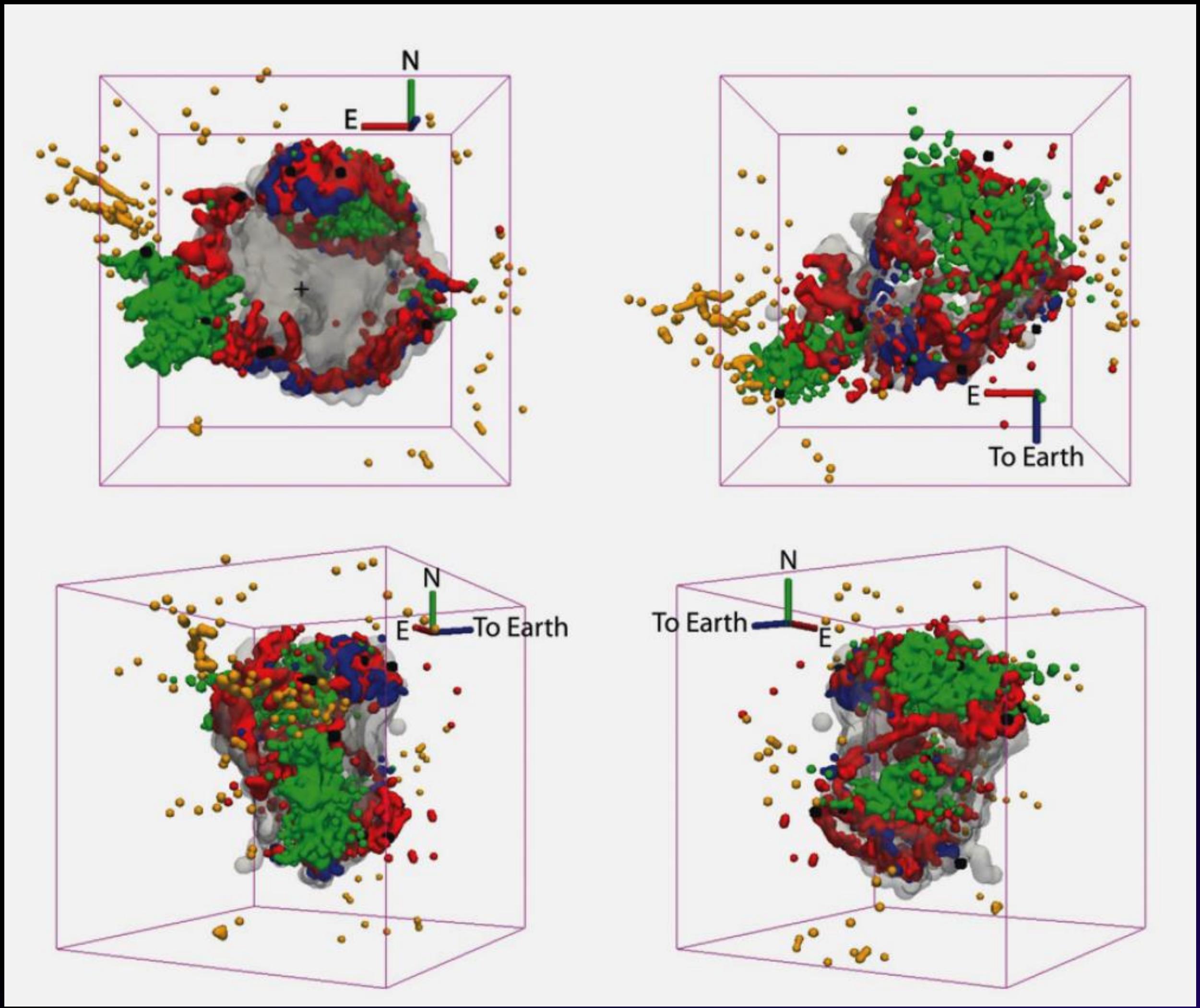




1D S.-H., Lee (Herman)

3D structure of Cas A

Delaney et al. 2010



Chandra 's X-rays

Spitzer 's infrared

Green: X-ray Fe-K

Black: X-ray Si XIII

Red: IR [Ar II]

Blue: high [Ne II]/[Ar II] ratio

Grey: IR [Si II]

Yellow: optical outer ejecta

Asymmetries in core-collapse supernovae from maps of radioactive ^{44}Ti in Cas A

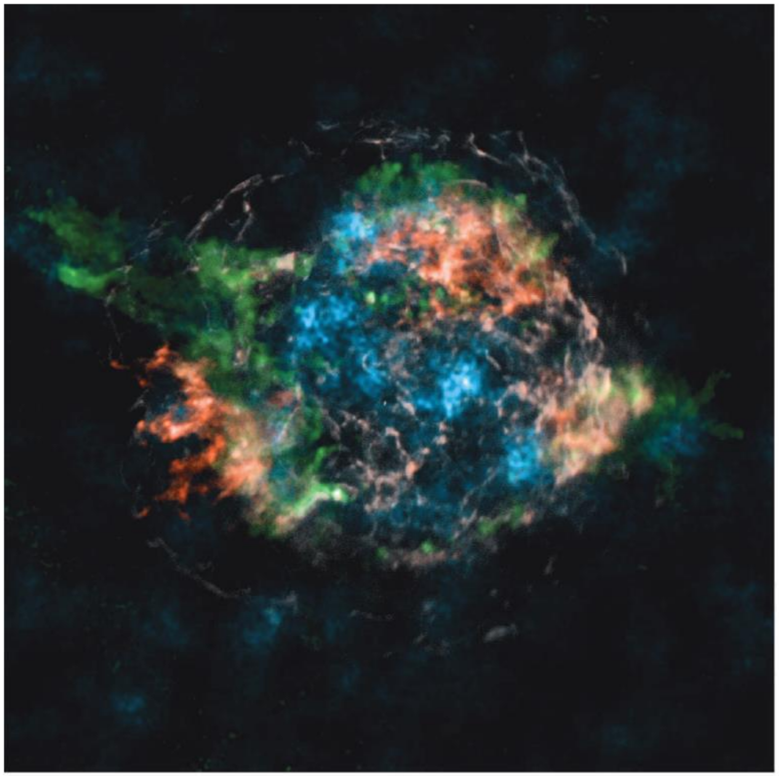


Figure 3 | A comparison of the spatial distribution of ^{44}Ti with known Fe K-shell emission in Cas A. We reproduce the spatial distributions shown in Fig. 2 and add the 4–6-keV continuum emission (white) and the spatial distribution of X-ray-bright Fe (red) seen by Chandra (Fe distribution courtesy of U. Hwang). We find that the ^{44}Ti does not follow the distribution of Fe K-shell X-ray emission, suggesting either that a significant amount of Fe remains unshocked and therefore does not radiate in the X-ray, or that the Fe/Ti ratio in the ejecta deviates from the expectation of standard nucleosynthesis models.

Iron and ^{44}Ti have different distributions

$$^{44}\mathrm{Ti} \rightarrow {}^{44}\mathrm{Sc} \rightarrow {}^{44}\mathrm{Ca}$$

$T_{1/2}$ = 60 yr $T_{1/2}$ = 4 h

Blue: ^{44}Ti

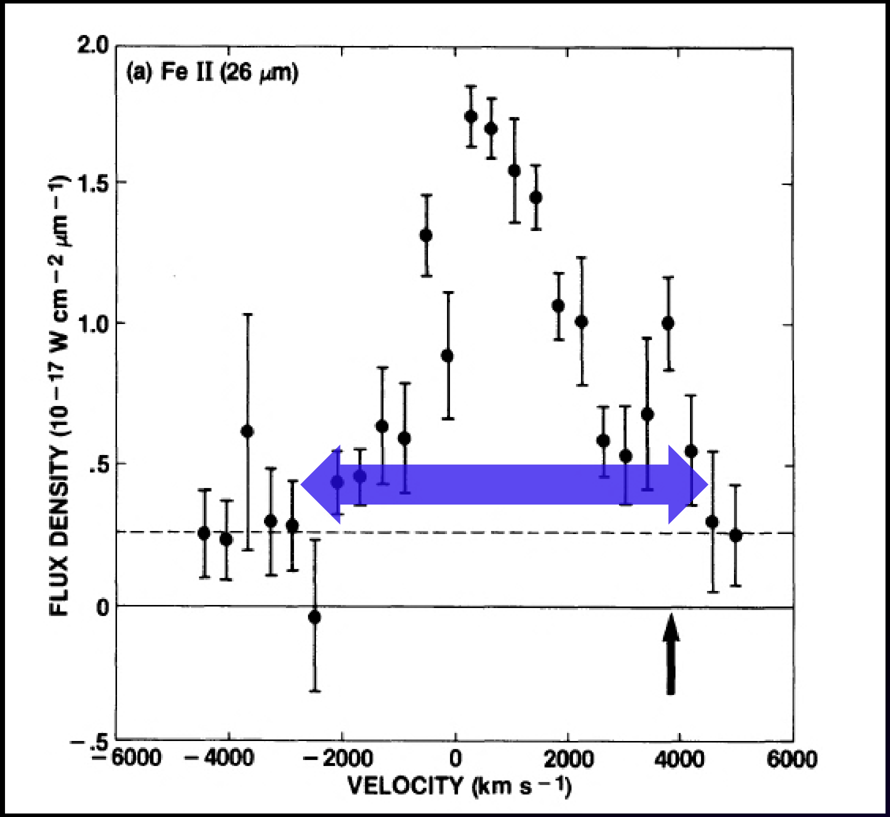
Green: Si/Mg band

Red: Fe

Grefenstette+14, Nature, 506, 339

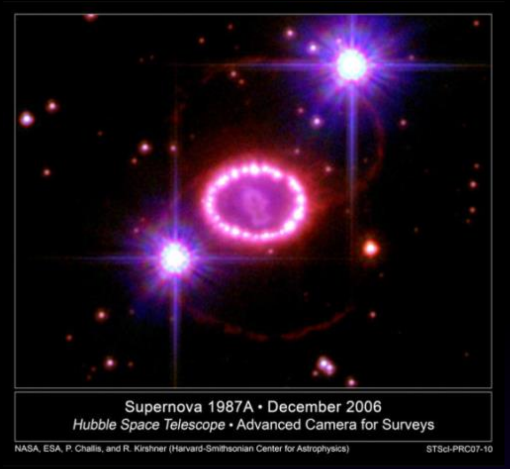
Broadened line profile of [Fe II] in SN 1987A

[Fe II] line profile (Haas et al. 1990)



Doppler velocity 4000 km s^{-1}

SN 1987A



$^{56}Ni \rightarrow {}^{56}Co \rightarrow {}^{56}Fe$

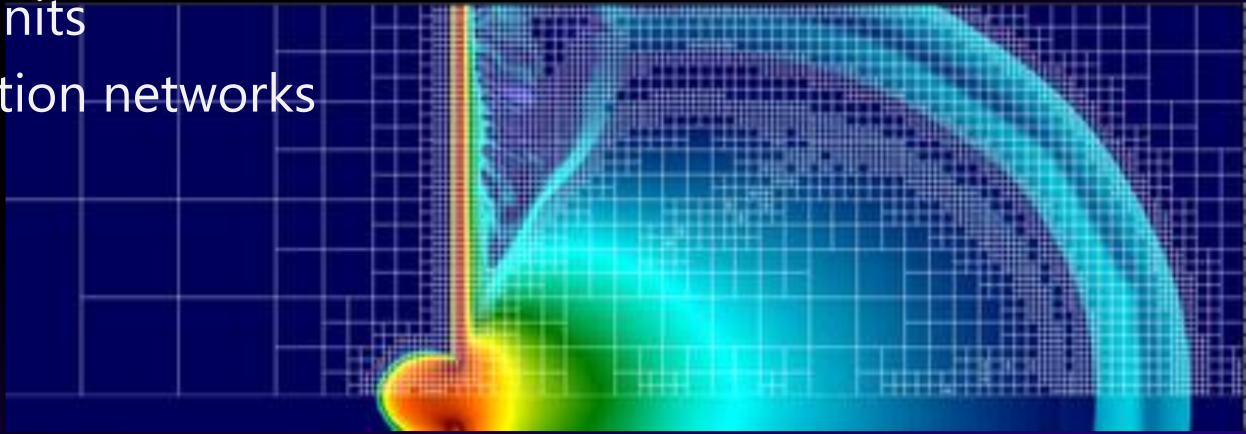
$T_{1/2}$ = 6.1 d $T_{1/2}$ = 77 d

FLASH Code

Flash Center for computational science

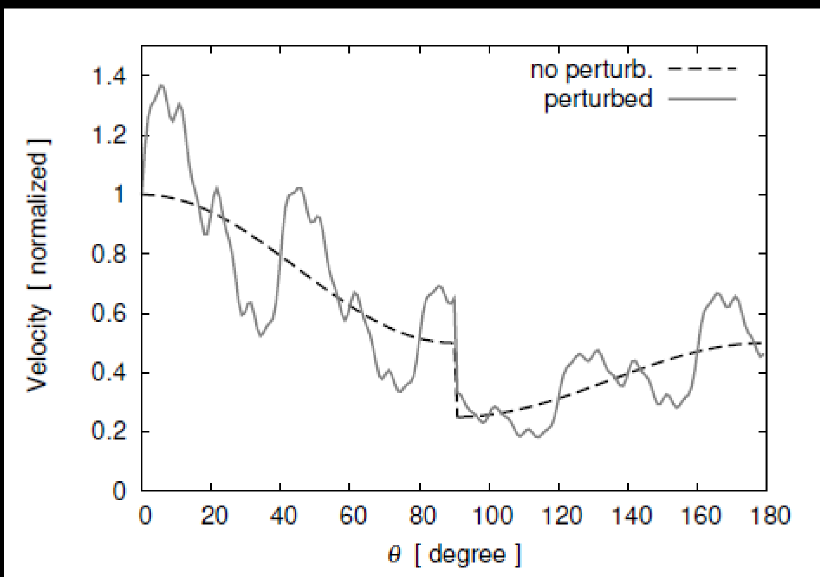
The FLASH code is a modular, parallel multiphysics simulation code capable of handling general compressible flow problems found in many astrophysical environment (Fryxell et al. 2000)

- Eulerian hydrodynamic code
  - Piecewise Parabolic Method (PPM)
  - Unsplit solver, MHD, RHD
- AMR (Adaptive mesh refinement)
  - Reduce numerical costs
- Many optional units
  - Nuclear reaction networks (7-19 nuclei)

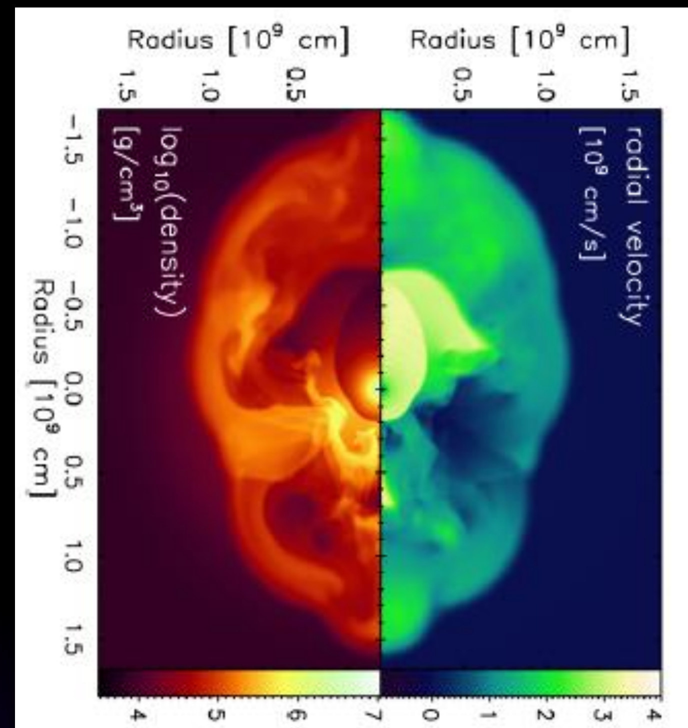


Mimicking the neutrino-driven explosions

Initial radial velocity

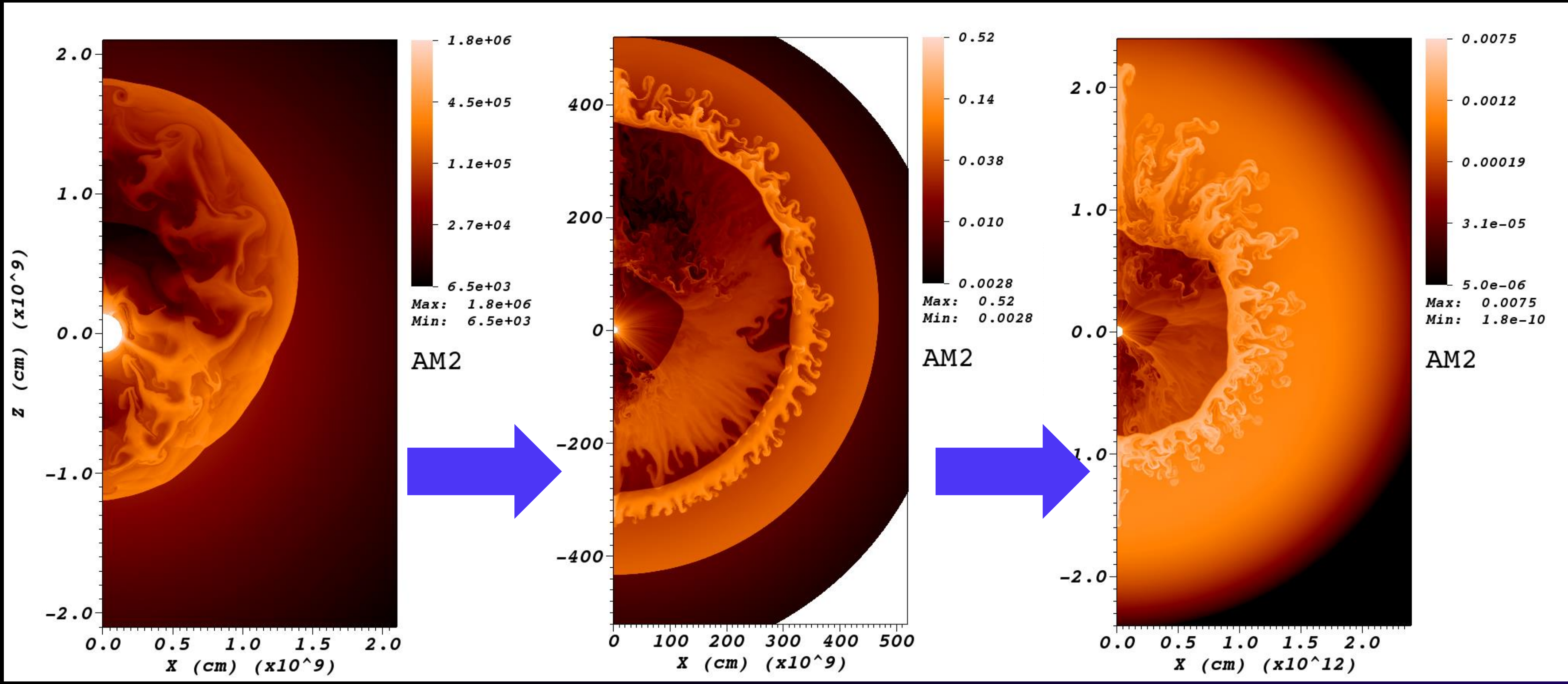


$$1 + \sum_{n=1}^{4} \frac{\epsilon}{2^{(n-1)}} \sin(m\, n\, \theta),$$



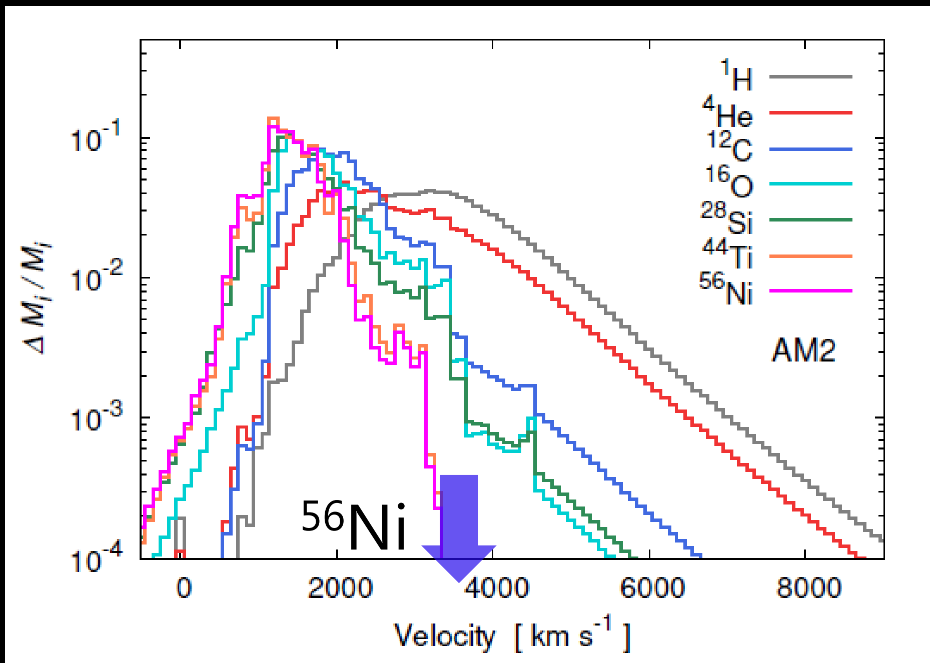
Scheck+04

Aspherical explosion with clumpy structure + RT instability



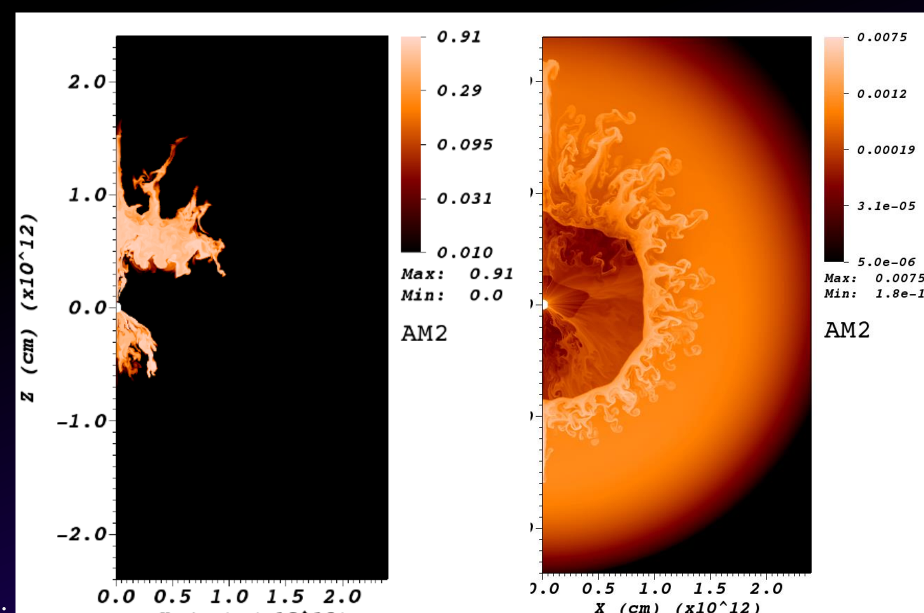
0.53 s   288 s   5752 s

Radial velocity distributions of the best model in this study



Maximum 3000 km s^{-1}

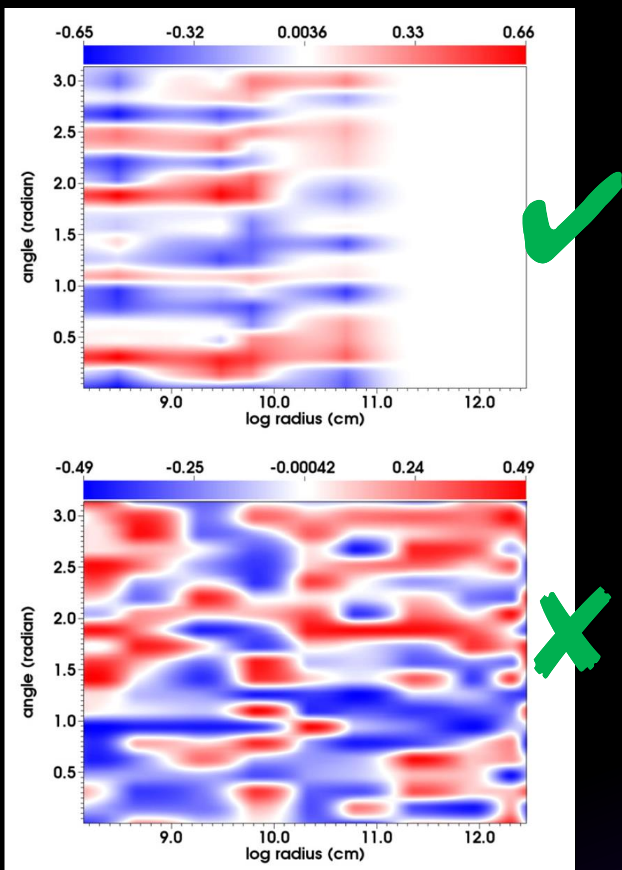
- Relatively high velocity (3000 km s^{-1}) of ^{56}Ni
- Mass of ^{56}Ni with ~ 3000 km s^{-1} : 1.4 x 10^{-3} $M_\odot$

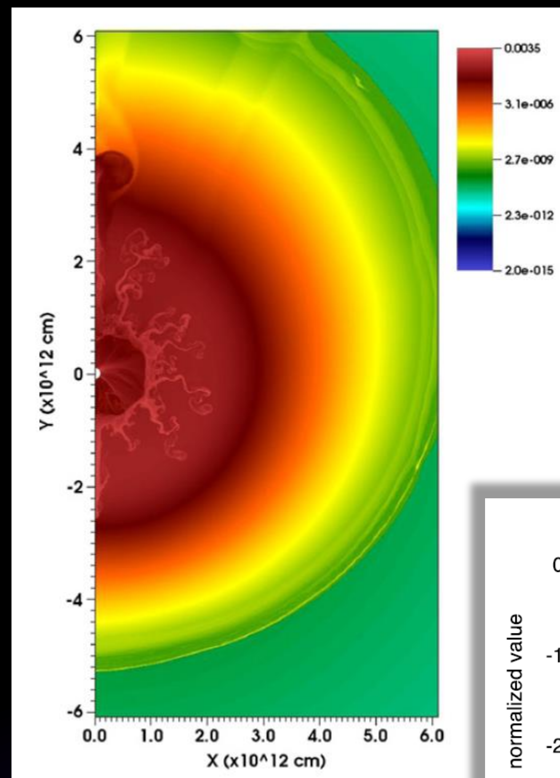


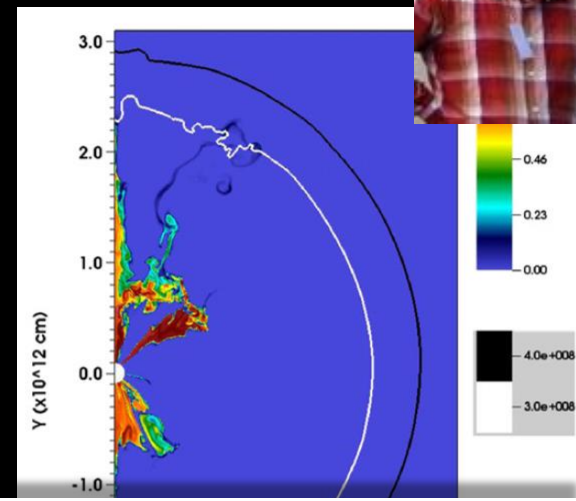
Large density fluctuations at the end of a star

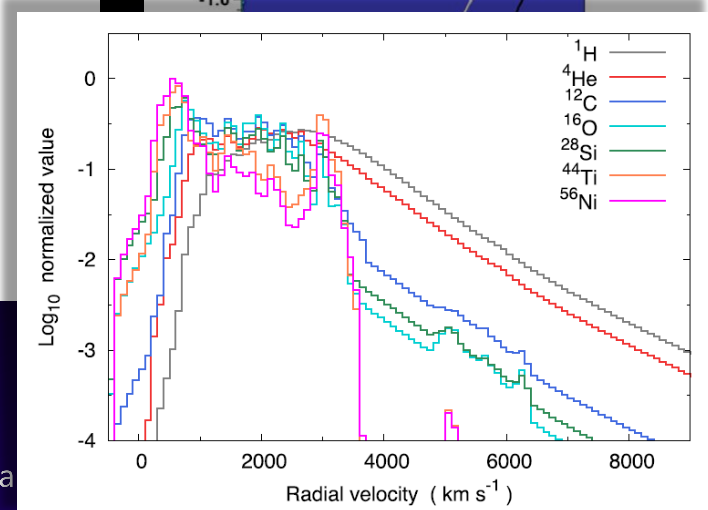
Distribution of the fluctuations

J. Mao, MO et al. 2015

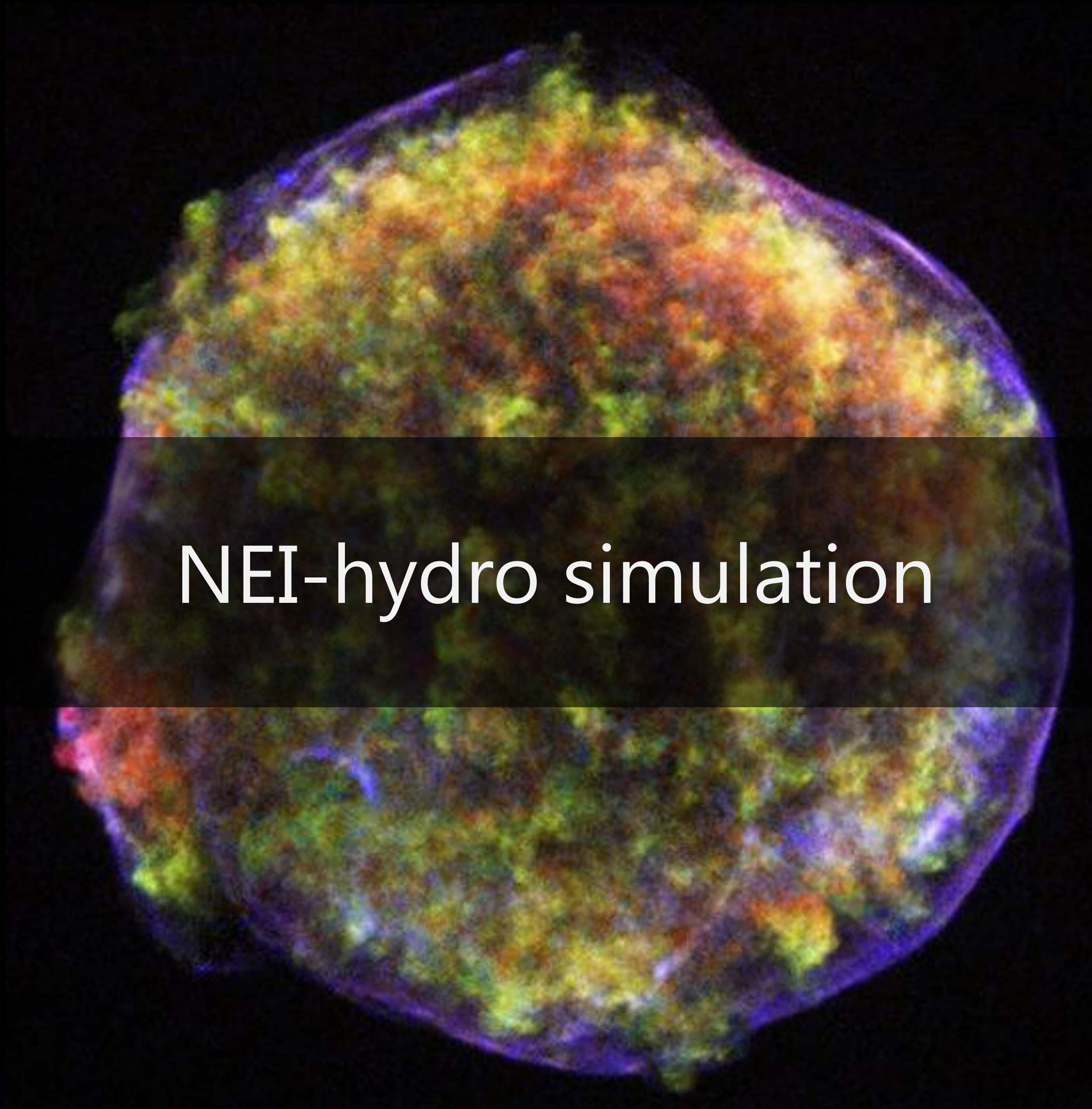








Asph+SC1p25m20(**)



NEI-hydro simulation

Multi-D SNR simulation with a realistic Type Ia explosion model

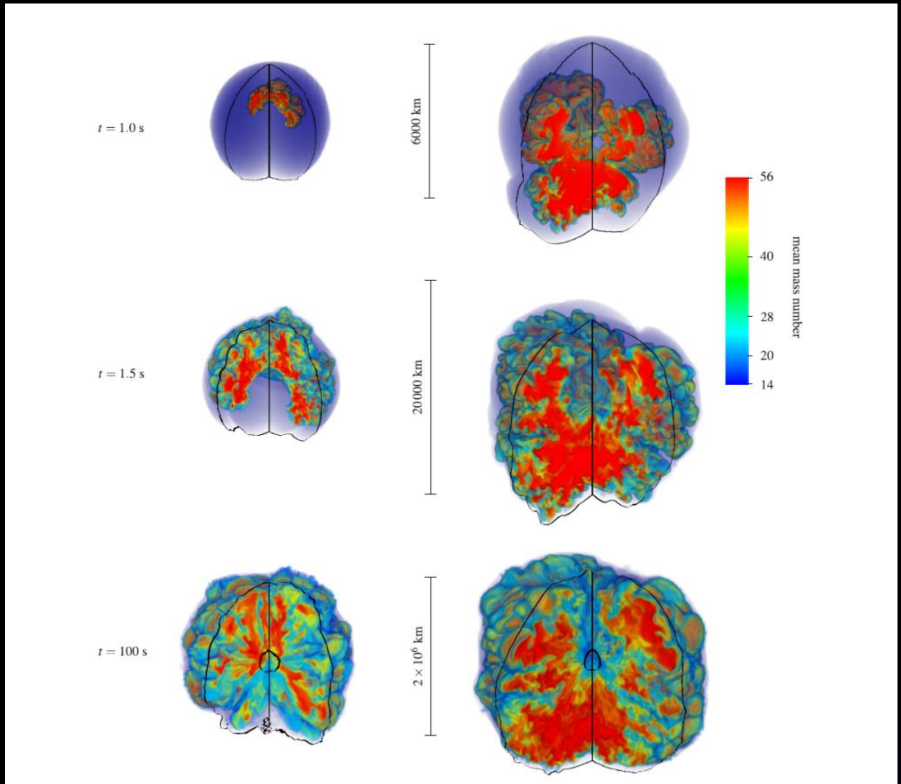


Figure 2. Explosion evolution for models N1def (left-hand column) and N20def (right-hand column). Colour coded is the mean mass number calculated from the reduced set of species in the hydrodynamic simulation. In the volume renderings a 90° wedge is cut out in the front part of the ejecta. The times after explosion initiation are from top to bottom: $t = 0.5$, 1.0, 1.5 and 100 s (for each time the length-scale along the middle axis of the plots is given in the centre). At $t = 100$ s, the innermost black contours mark the outer edges of the regions which do not become gravitationally unbound.

Taken from Flink et al. 2014

Collaboration with F. Röpke (MPA), K. Maeda, S. Nagataki, S.-H. Lee

- 2-3D pure deflagration of C+O WD with nucleosynthesis
- What happen if we use this as an input of Multi-D SNR simulations?

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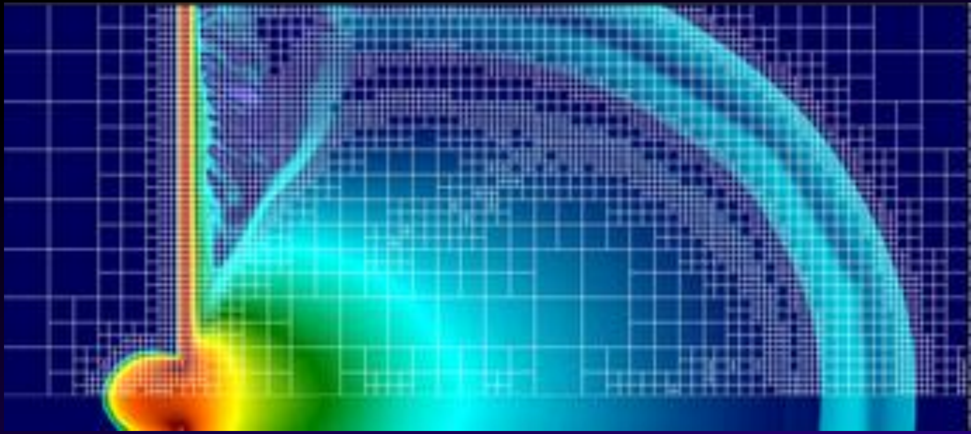
  - Piecewise Parabolic Method (PPM)
  - Unsplit MHD solver, RHD
- AMR (Adaptive mesh refinement)
  - Reduce numerical costs
- Many optional units
  - Ionization
  - 3T (2T) hydro (electron/ion/~~radiation~~)
  - Heatexchange



Basic equations

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \boldsymbol{v}) = 0 \quad (1)$$

$$\frac{\partial}{\partial t}(\rho \boldsymbol{v}) + \nabla \cdot (\rho \boldsymbol{v}\boldsymbol{v}) + \nabla P_{\mathrm{tot}} = 0, \quad (2)$$

$$\frac{\partial}{\partial t}(\rho E_{\mathrm{tot}}) + \nabla \cdot [(\rho E_{\mathrm{tot}} + P_{\mathrm{tot}})\, \boldsymbol{v}] = 0, \quad (3)$$

$$P_{\mathrm{tot}} = P_{\mathrm{ion}} + P_{\mathrm{ele}}, \quad E_{\mathrm{tot}} = \frac{1}{2}\boldsymbol{v}^2 + e_{\mathrm{ion}} + e_{\mathrm{ele}},$$

$$\frac{\partial}{\partial t}(\rho e_{\mathrm{ion}}) + \nabla \cdot (\rho e_{\mathrm{ion}} \boldsymbol{v}) + P_{\mathrm{ion}} \nabla \cdot \boldsymbol{v} = \rho \frac{c_{v,\mathrm{ele}}}{\tau_{\mathrm{ei}}} (T_{\mathrm{ele}} - T_{\mathrm{ion}}),$$

$$\frac{\partial}{\partial t}(\rho e_{\mathrm{ele}}) + \nabla \cdot (\rho e_{\mathrm{ele}} \boldsymbol{v}) + P_{\mathrm{ele}} \nabla \cdot \boldsymbol{v} = \rho \frac{c_{v,\mathrm{ele}}}{\tau_{\mathrm{ei}}} (T_{\mathrm{ion}} - T_{\mathrm{ele}}),$$

$$\frac{\partial}{\partial t}(\rho s_{\mathrm{ele}}) + \nabla \cdot (\rho s_{\mathrm{ele}} \boldsymbol{v}) = 0. \quad (4)$$

1 Solve equations (1), (2), (3), (4)

2 Compute the total specific internal energy: $e_{\mathrm{tot}} = E_{\mathrm{tot}} - \frac{1}{2}\boldsymbol{v}^2$

3 Compute the electron specific internal energy using 3T EoS: $e_{\mathrm{ele}} = e_{\mathrm{ele}}(\rho, s_{\mathrm{ele}}, e_{\mathrm{tot}})$

4 Compute the ion specific internal energy: $e_{\mathrm{ion}} = e_{\mathrm{tot}} - e_{\mathrm{ele}}$

Heat exchange between ions and electrons due to Coulomb interaction

$$\frac{dT_{\mathrm{e}}}{dt} = \frac{1}{\tau_{\mathrm{ei}}}(T_{\mathrm{i}} - T_{\mathrm{e}})$$

$$\tau_{\mathrm{ei}} = \frac{3k_B^{3/2}}{8\sqrt{2\pi}e^4}\frac{(m_{\mathrm{i}}T_{\mathrm{e}} + m_{\mathrm{e}}T_{\mathrm{i}})^{3/2}}{(m_{\mathrm{e}}m_{\mathrm{i}})^{1/2}\bar{z}^2 n_{\mathrm{i}} \ln\Lambda_{\mathrm{ei}}}$$

$$\sim \left(\frac{\boxed{10^{12}\mathrm{s}}}{Z^2 \ln\Lambda_{\mathrm{ei}}/10}\right)\left[\frac{(k_B T_{\mathrm{e}}/1\ \mathrm{keV})^{3/2}}{n_{\mathrm{i}}/1\ \mathrm{cm}^{-3}}\right]$$

Non-equilibrium ionization

- Non-equilibrium ionization (NEI) for the element *Z*

$$\frac{\partial n_i^Z}{\partial t} = n_\mathrm{e}\left[n_{i+1}^Z \alpha_{i+1}^Z + n_{i-1}^Z S_{i-1}^Z - n_i^Z(\alpha_i^Z + S_i^Z)\right]$$

i : i-th ionization state

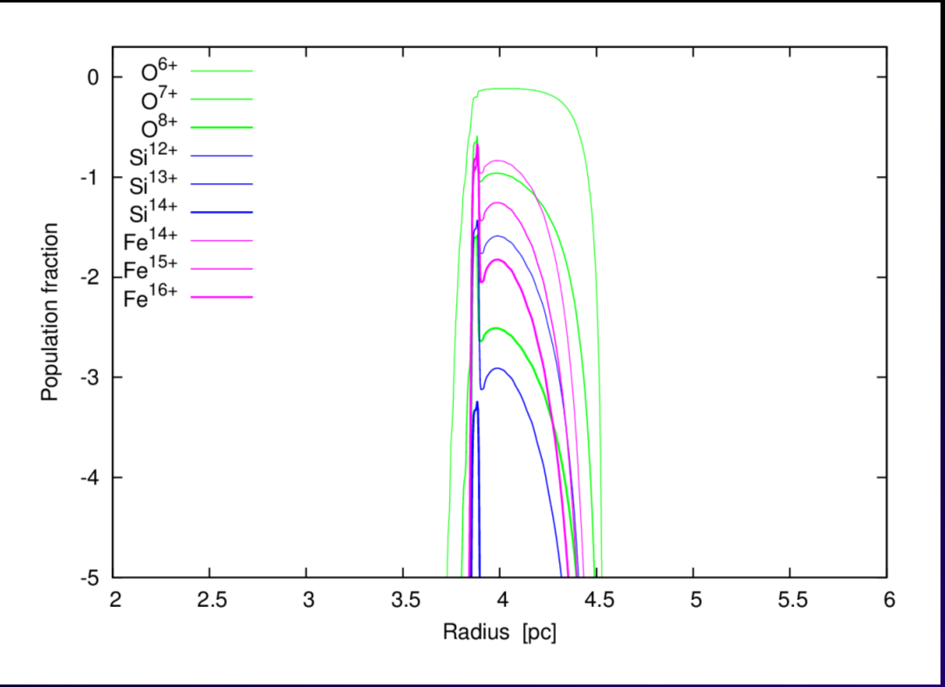
Ionization rates

$$S_i^Z = S(n_\mathrm{e}, T_\mathrm{e})$$

Recombination rates

$$\alpha_i^Z = \alpha(n_\mathrm{e}, T_\mathrm{e})$$

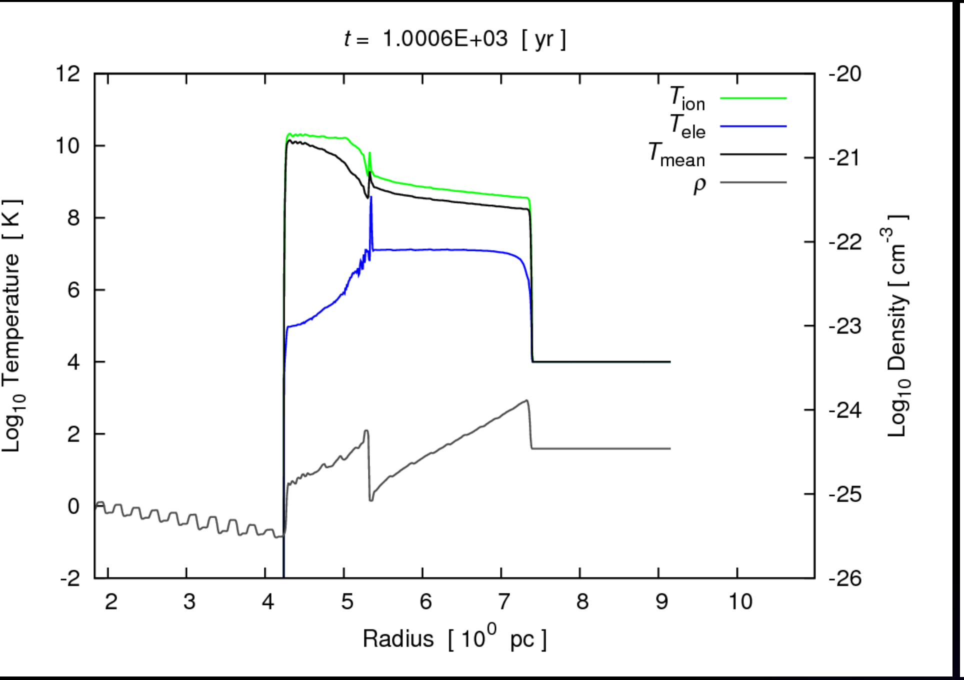
Collisional ionization
Excited autoionization
Radiative recombination
Dielectronic recombination

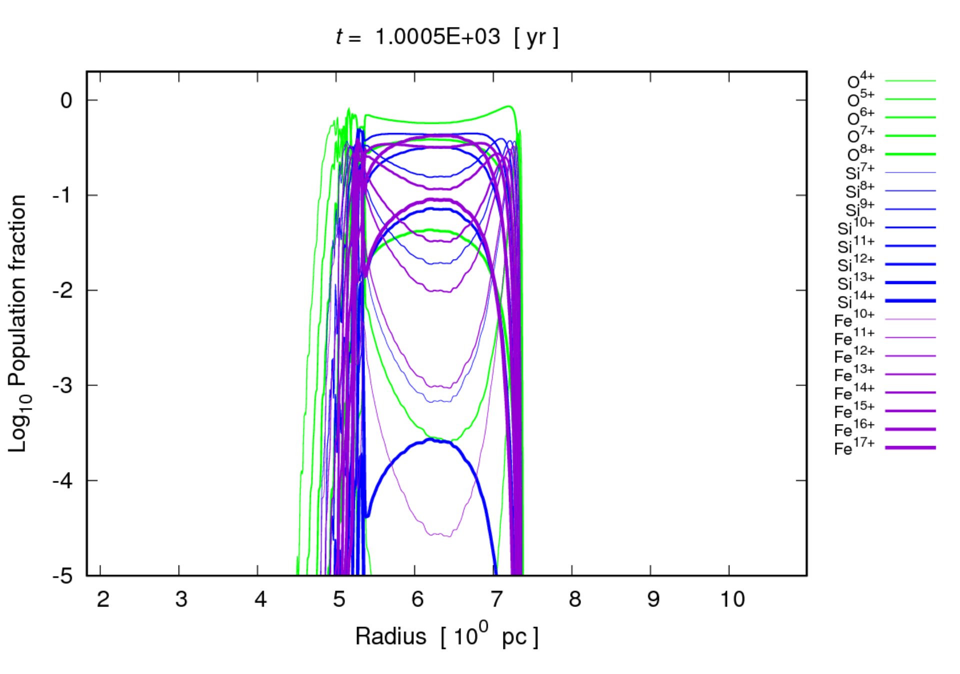


Test 1D hydro with NEI

Radial profiles of temp., ionization

50% of ions are singly ionized (except for hydrogen)





Efficient collisionless heating of electrons at RS

- X-ray observations of Tycho by SUZAKU
  - Fe K_{α}, Fe K_{β}

beta = T_e/T_{ion}

- If beta = m_e/m_{ion}, beta ∼ 10^{-5}
- beta = 0.01 is required for Tycho
- Possible mechanism
  - Cross-shock potential?

Yamaguchi et al. 2014

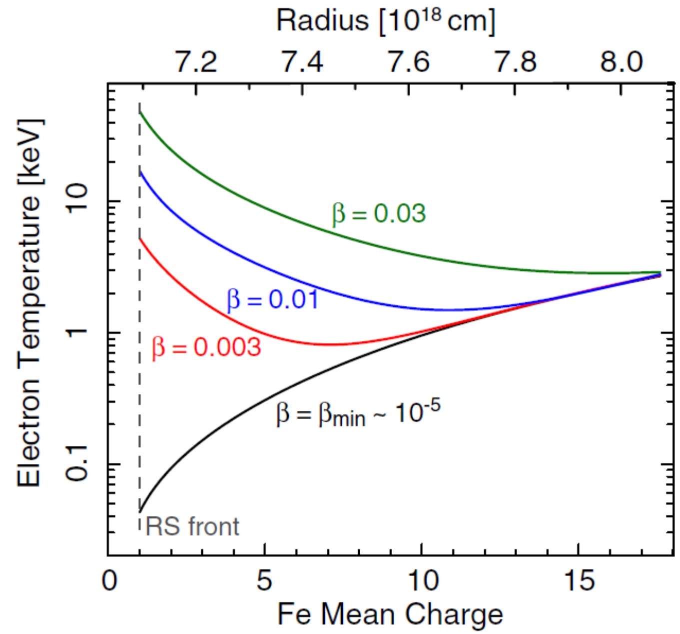
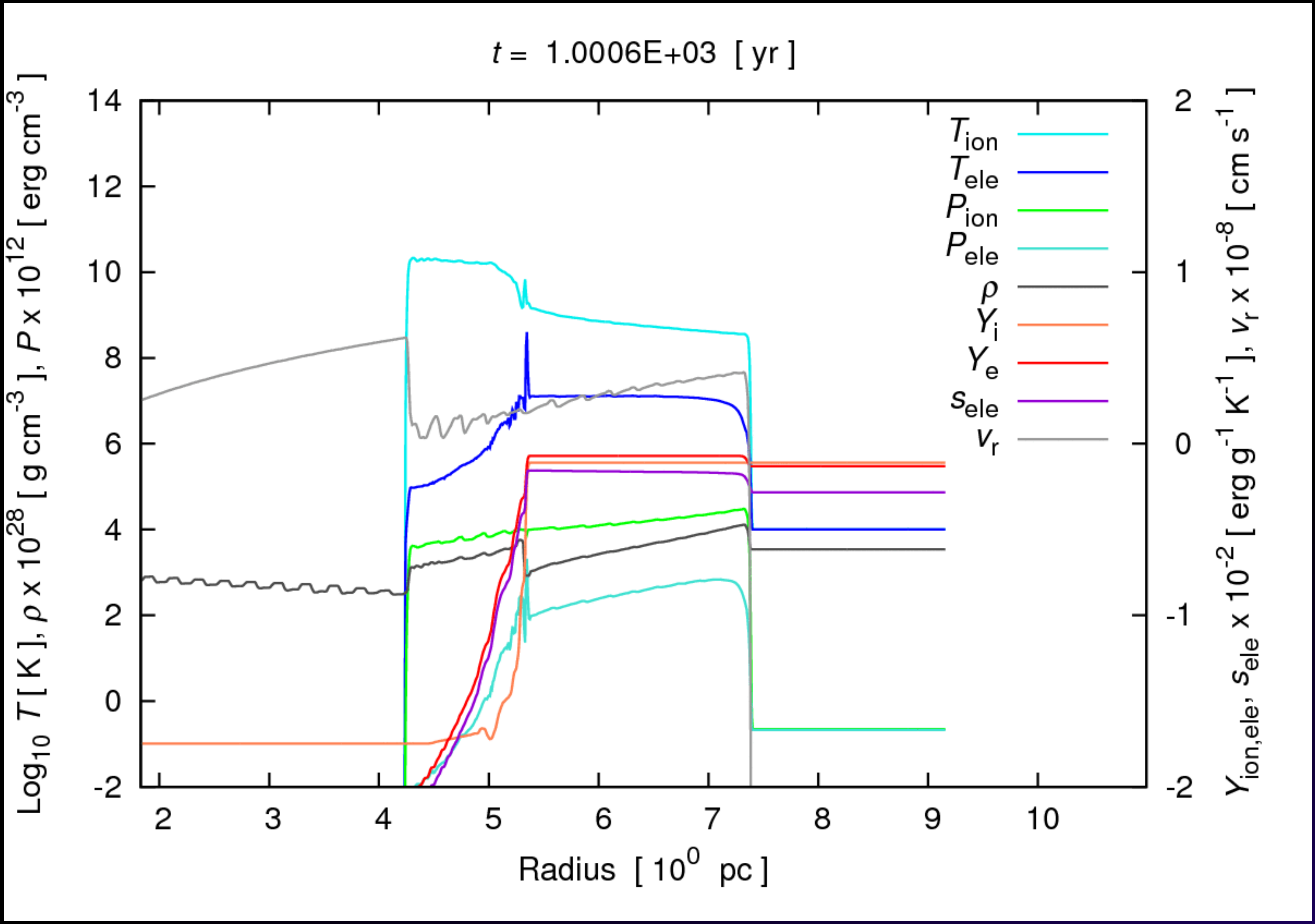


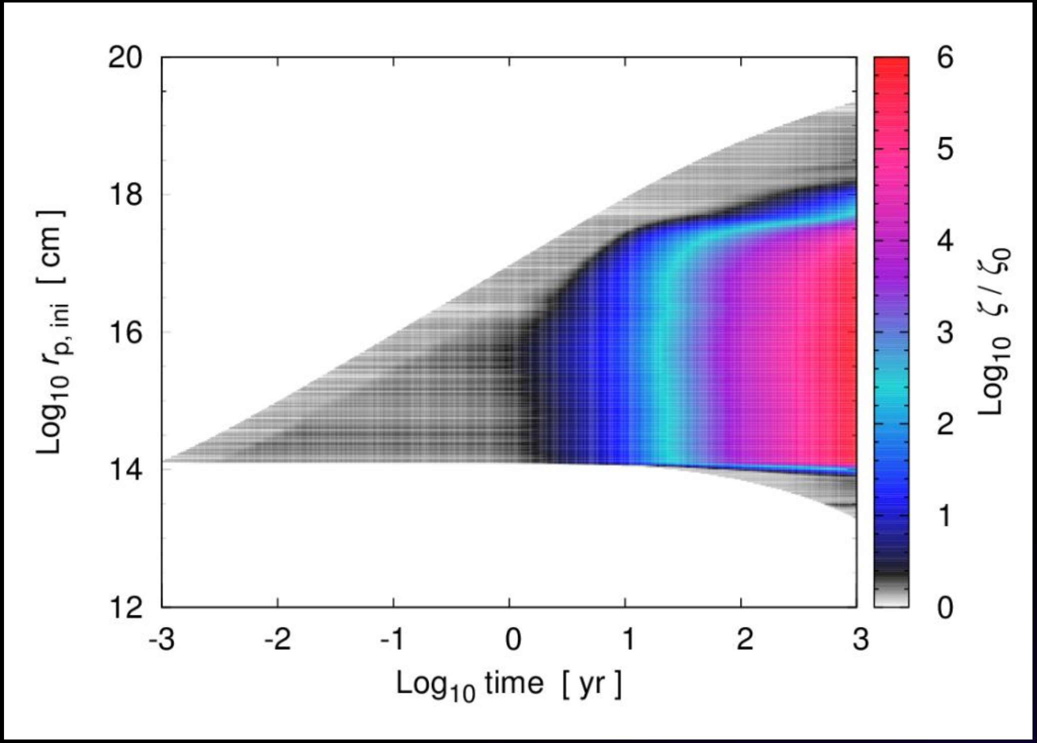
Figure 7. Electron temperature as a function of the mean charge of Fe ions from our hydrodynamical simulations. The corresponding radius is also given above. The black curve is the β_{min} model where no collisionless electron heating is assumed. The temperature ratio between the electrons and ions at the RS front is, therefore, set by their mass ratio. The models represented by the red, blue, and green curves assume that collisionless electron heating occurs at the RS, parameterized by ($\beta = T_e/T_{ion}$) with values set to 0.003, 0.01, and 0.03, respectively.

Evolution of physical quantities



Evolution of RT stability

Lines are initial position of Lagrange particle



RT growth rate

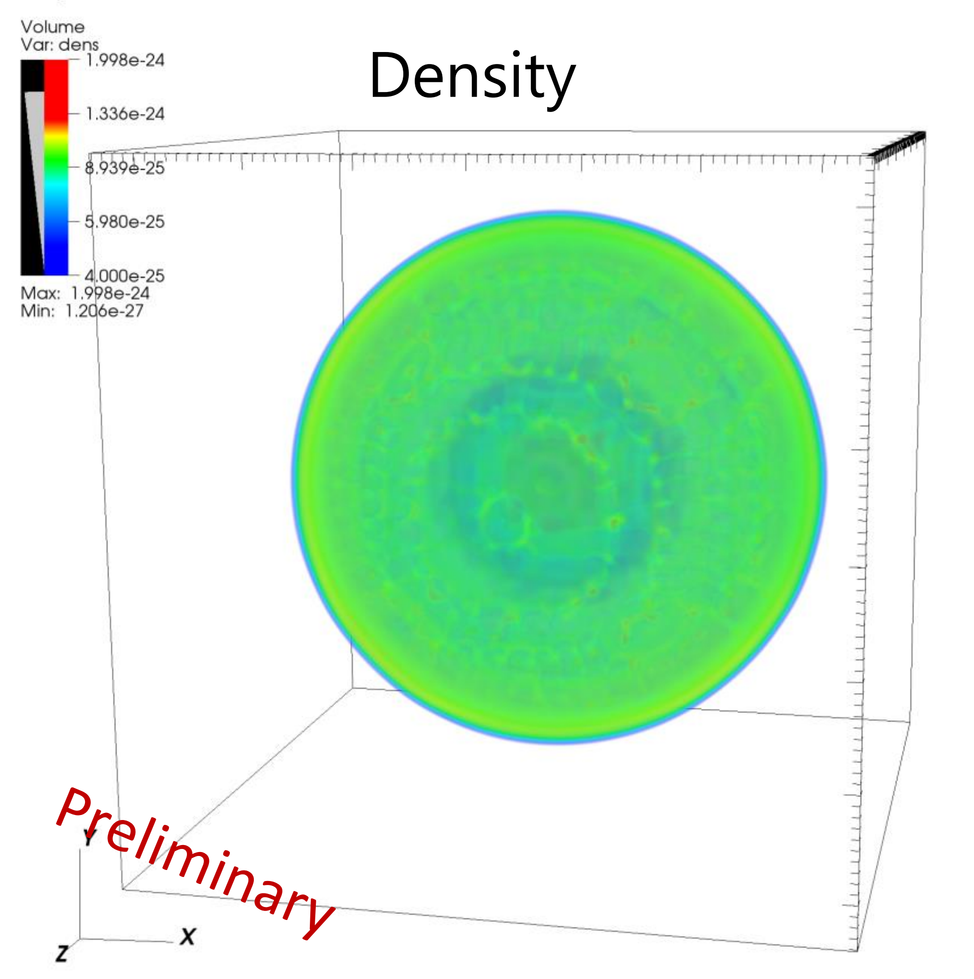
$$\sigma = \sqrt{-\frac{P}{\rho}\mathscr{P}\mathscr{R}},$$

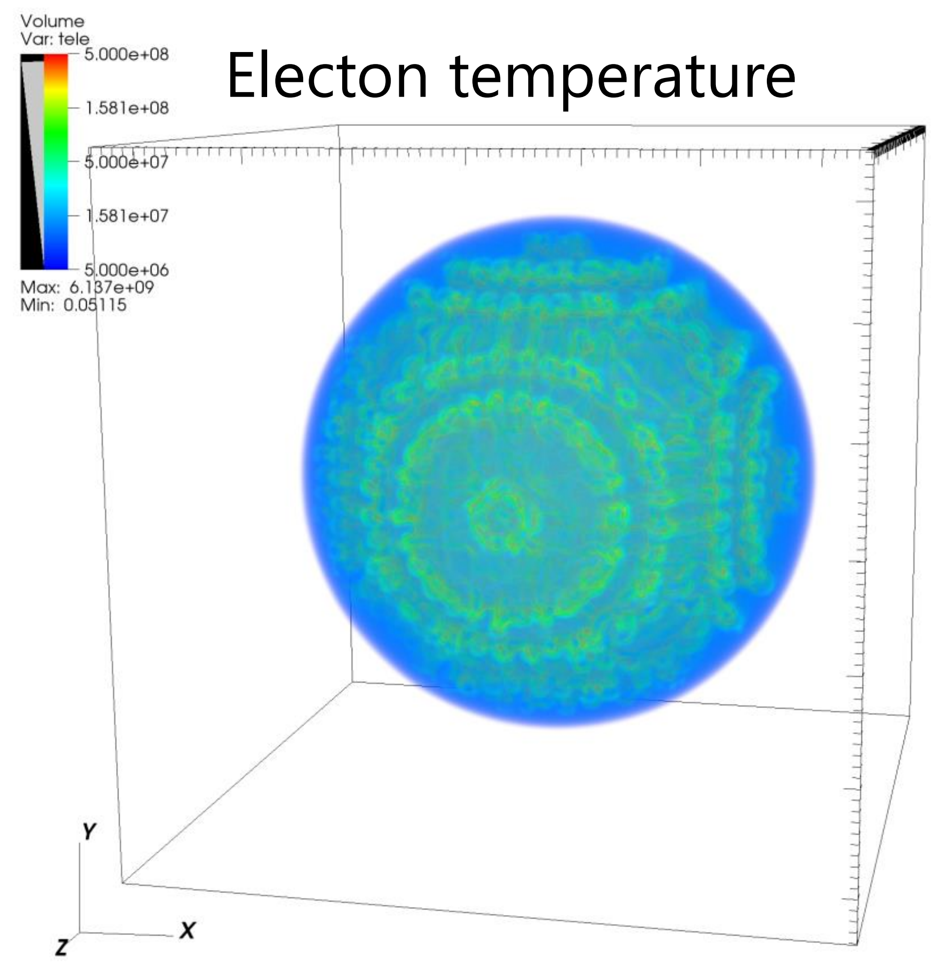
$$\mathscr{P} = \partial \ln P / \partial r \text{ and } \mathscr{R} = \partial \ln \rho / \partial r$$

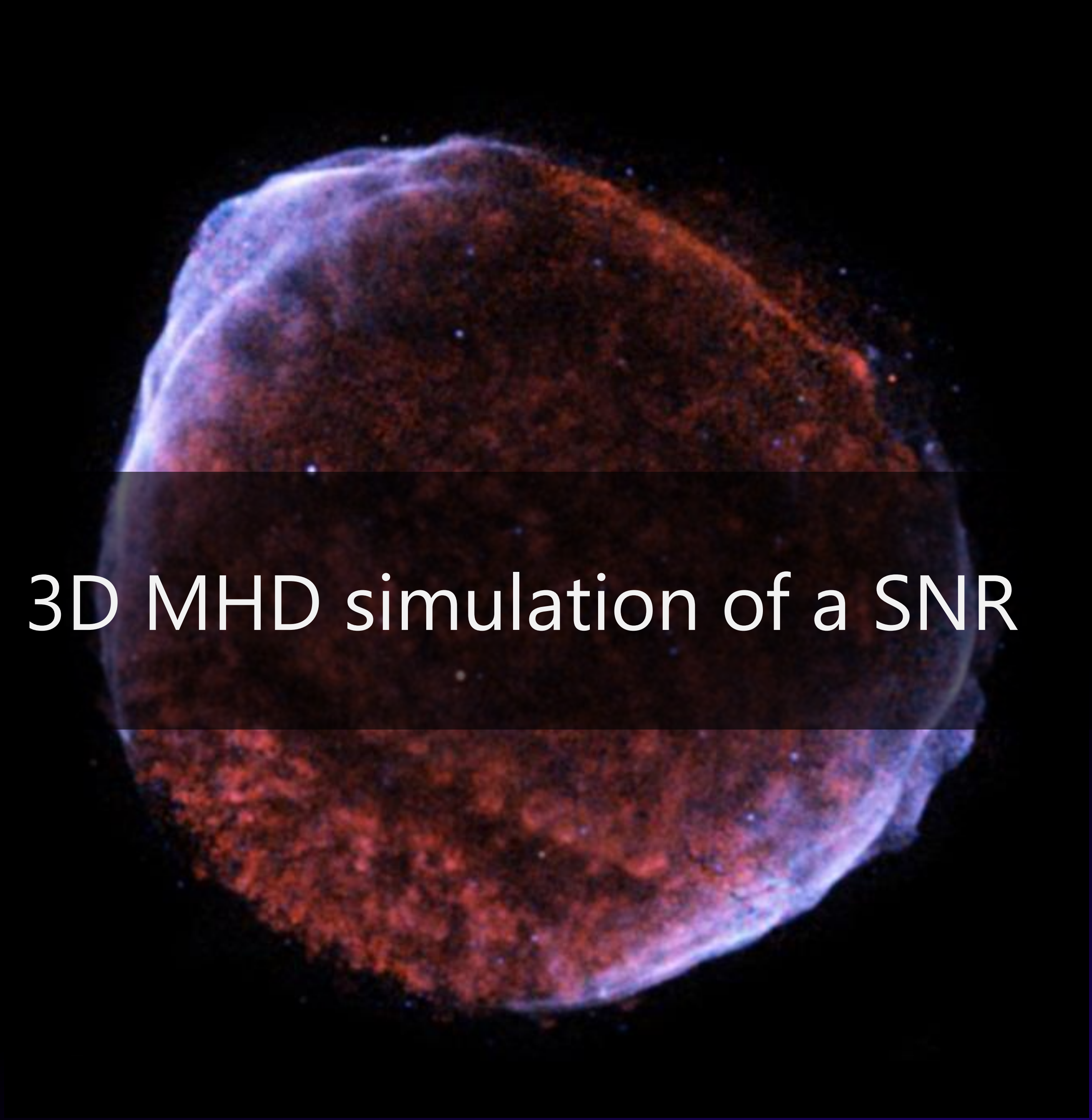
Growth factor

$$\frac{\zeta}{\zeta_0} = \exp\left(\int_0^t \mathrm{Re}\,[\,\sigma\,]\,\mathrm{d}t'\right),$$

Test 3D calculation

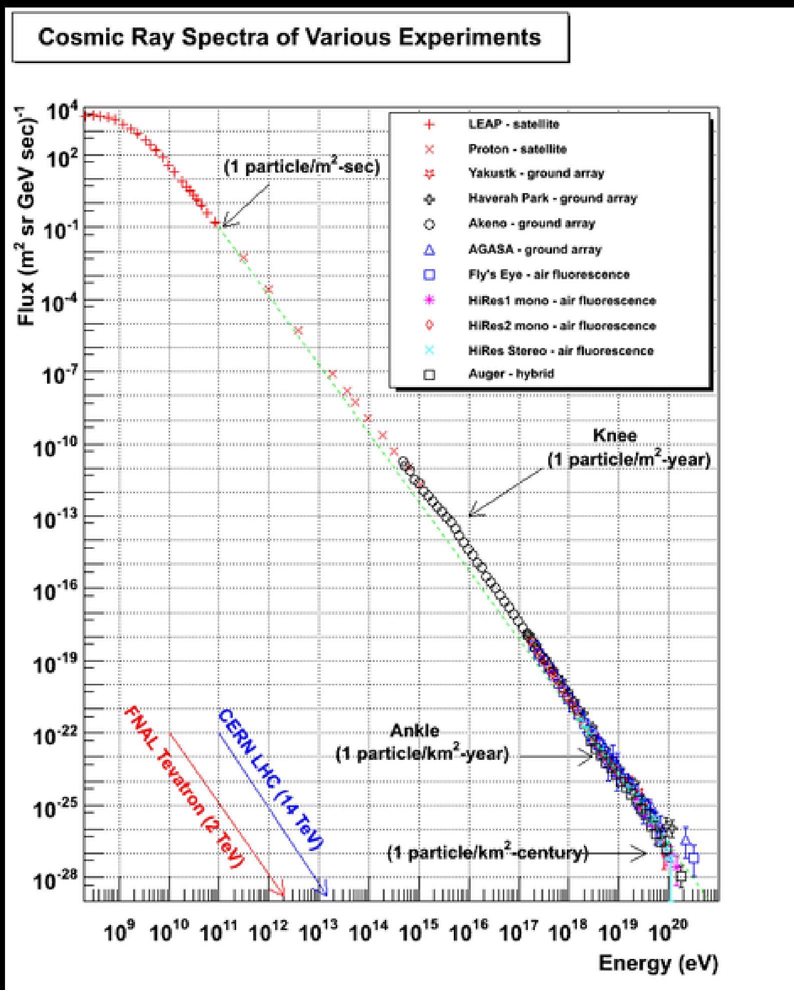






3D MHD simulation of a SNR

Ultra high-energy cosmic-rays (UHECRs)

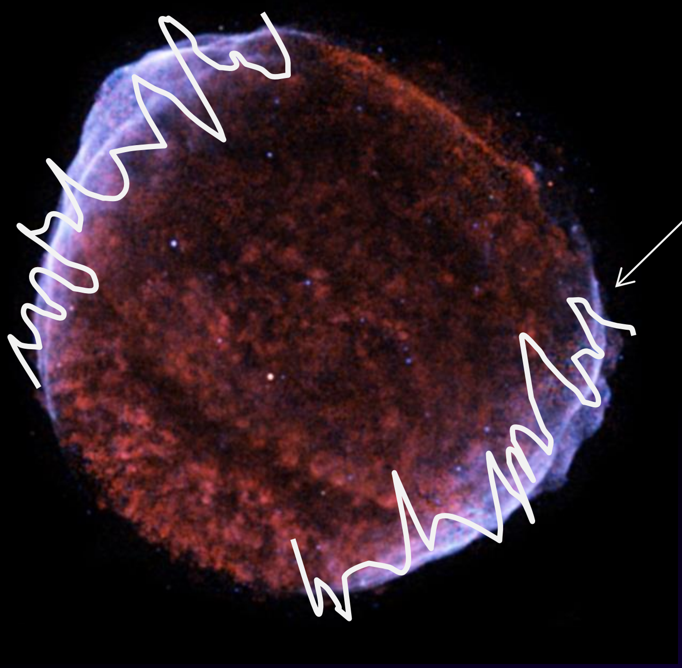


- Energy spectrum
- Composition
  - Proton or Iron?
- Anisotropy (arrival direction)
  - Correlation with AGN?
  - Correlation with LSS?

http://www.physics.utah.edu/~whanlon/spectrum.html

Cosmic-ray (CR) acceleration in SNRs

- Acceleration of cosmic-ray in SNRs
  - Up to 10^{15} eV or more ?
  - Magnetic field is key ingredient



Synchrotron radiation from accelerated electrons

SN1006 (Chandra: X-ray)

Amplified strong magnetic field ?

Uchiyama et al. 2007, Nature, 4469 576

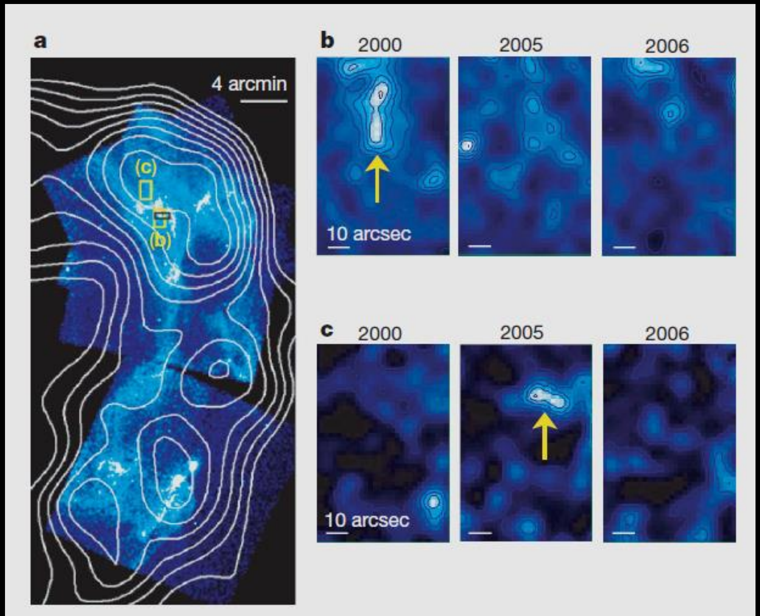


Figure 1 | Chandra X-ray images of the western shell of SNR RX J1713.7−3946. **a**, A Chandra X-ray mosaic image is overlaid with TeV γ-ray contours from HESS measurements[26]. North is up and east is to the

Variations of X-ray hot spots on a 1 yr timescale

Strong amplified magnetic field (∼ 100 μ G)?

Bohm-diffusion limit

$$t_{\rm synch} \approx 1.5\,(B/{\rm mG})^{-1.5}\,(\epsilon/{\rm keV})^{-0.5}\,{\rm yr} \qquad \eta \approx 1$$

$$t_{\rm acc} \approx 1\,\eta\,(\epsilon/{\rm keV})^{0.5}\,(B/{\rm mG})^{-1.5}\,(v_{\rm s}/3,000\,{\rm km\,s^{-1}})^{-2}\,{\rm yr}$$

Magnetic field amplification

- Interaction between accelerated CRs and background fluid
  - Bell instability (Bell 2004)
  - Cosmic-ray current accelerates background plasma
  - $\boldsymbol{j}_{\mathrm{CR}} \times \boldsymbol{B}$ force
  - hybrid (MHD/particle) simulation
  - *B*-field can be amplified by several orders

- Hydrodynamic instability
  - Richtmyer-Meshkov instability
  - Rayleigh-Taylor instability ?

Magnetic field is important for the acceleration of CRs and non-thermal emission

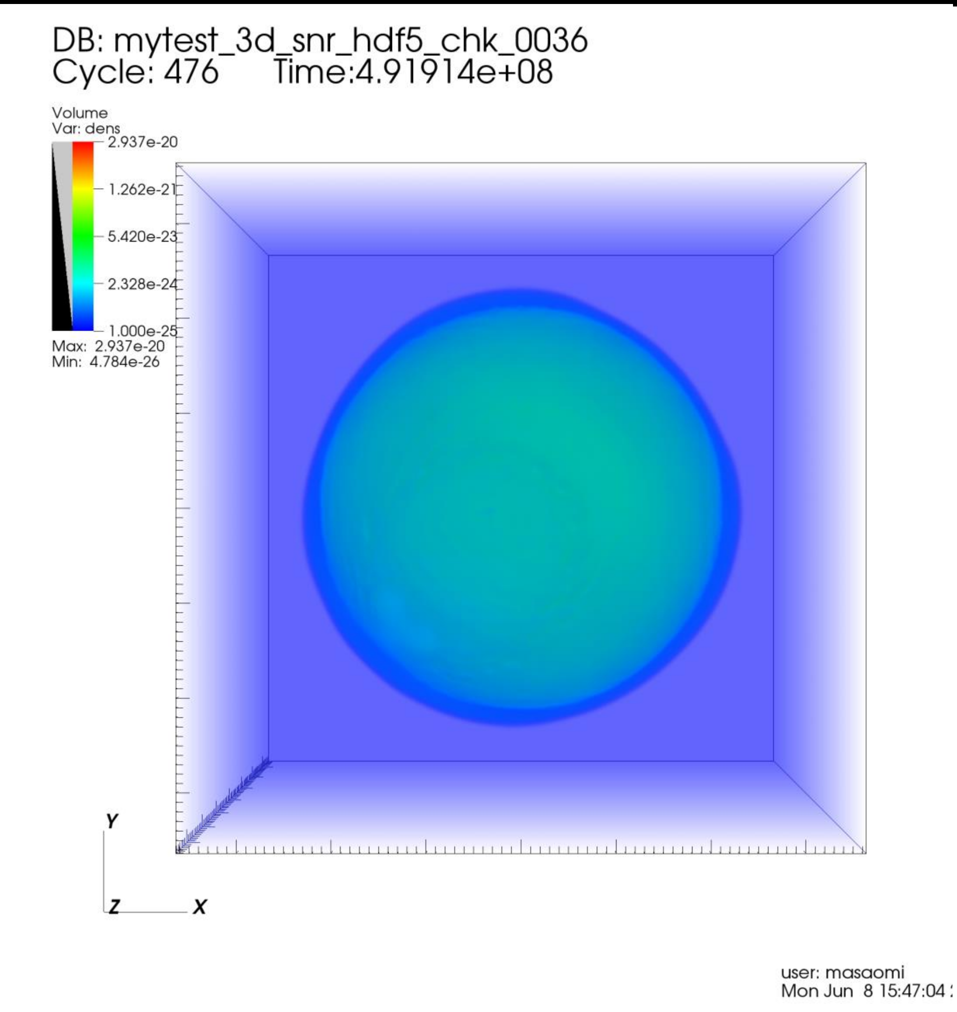
Test 3D simulation

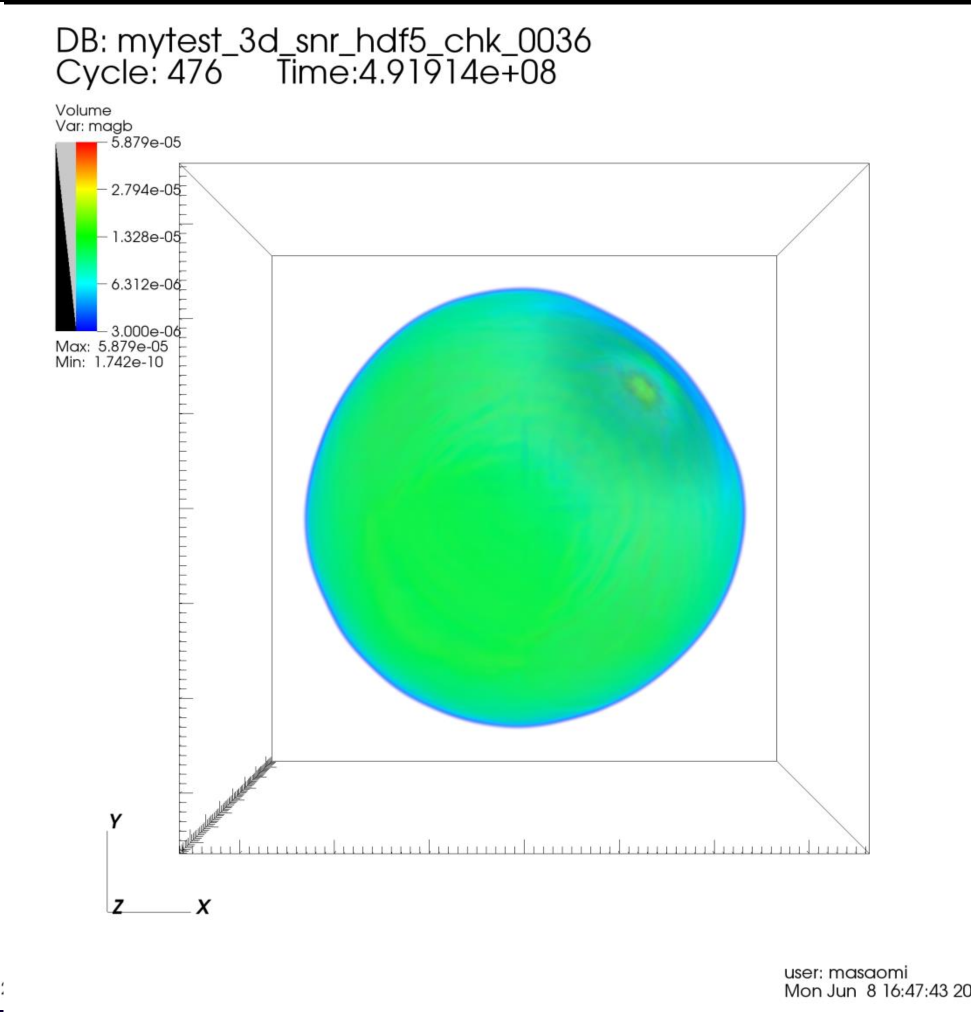
- Setup
  - Exponential ejecta profile
  - M_{ej} = 1.4 $M_{\odot}$, E_{ej} = 1.5 x 10^{51} erg
  - ISM density n_0 = 5 x 10^{-2}, 1 x 10^{-1} [cm^{-3}]
  - Simulation stars from 1 x 10^{-3} yr
- Effective gamma
  - Arbitral effect of particle acceleration on SNR dynamics

$$\gamma_{\rm eff} = \gamma - (\gamma - \gamma_{\rm min}) \left\{ 1 - e^{-t/t_{\rm acc}} \right\}$$

$$\gamma = 5/3,\ \gamma_{\rm min} = 1.1,\ t_{\rm acc} = 10\ {\rm yr}$$

3D MHD simulation (on going…)





As a summary: the prospects of multi-D (M)HD simulation

- Multi-dimensional (magneto) hydrodynamics
- Non-equilibrium ionization (NEI)
  - H, He, C, N, Ne, Mg, Si, S, Ar, Ca, Fe, Ni
- Heat exchange between ions and electrons due to Coulomb interaction
- From supernova explosions with realistic explosion model to supernova remnants to be compared with observation directly

- In future
  MHD simulation with non-linear acceleration of CRs

How RT instability and asymmetric explosions affect the element distribution, *B*-field amplification, particle acceleration, thermal and non-thermal emission ?