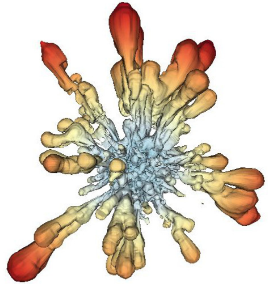
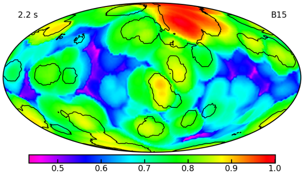
3D long-term evolution of CCSN





Michael Gabler
B. Giudici, H.T. Janka

University of Valencia

Distinguished researcher Plan
Gen—T

11.06.2024

SNR - an Odyssey in space after stellar death III, Chania, Greece, 9-15 June, 2024

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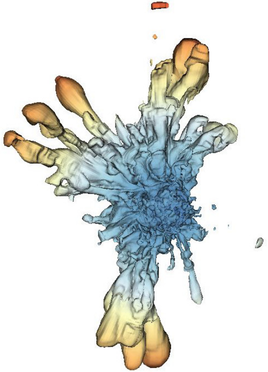

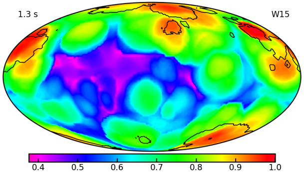

Anisotropy drivers in Core-Collapse Supernovae

- Progenitor
- Hydrodynamic-Explosion instabilities (Convection, SASI)
- Magneto-rotational instabilities
- Propagation (RTI) instabilities
- Interaction with reverse shocks
- β decay
- Interaction with interstellar medium

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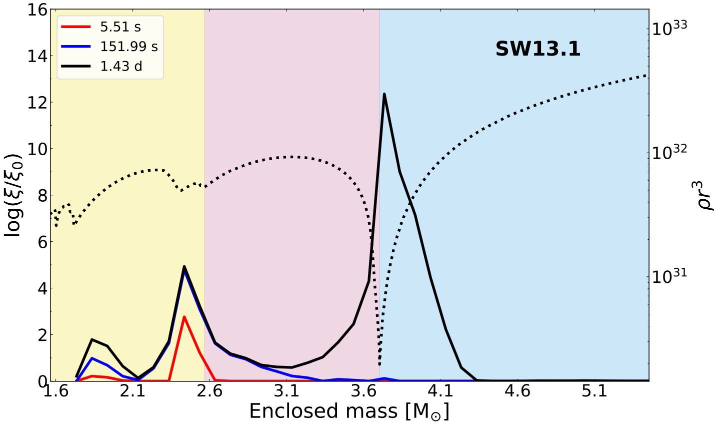
PROMETHEUS-HOTB

3D long-time simulations (with simplified neutrino transport)

From explosion to shock breakout - Rayleigh Taylor Instabilities

- Propagation of shock and ejecta through progenitor star
- Shock (and ejecta) decelerate/accelerate when $\rho = \rho_0(r/r_0)^n$, $n > -3$ or $n < -3$



⇒See Poster by B. Giudici

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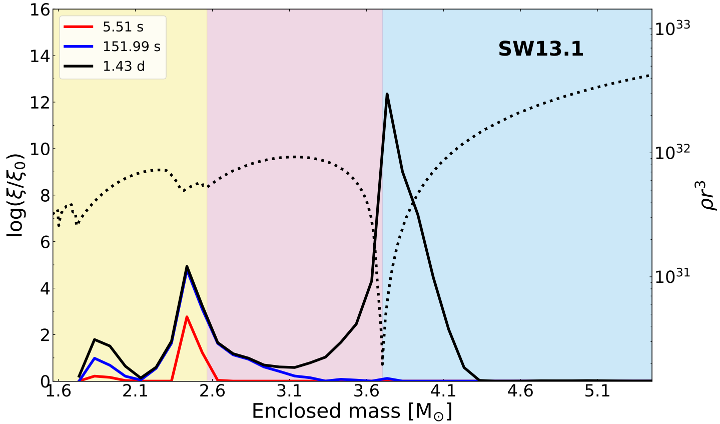
- Shock (and ejecta) decelerate/accelerate when $\rho = \rho_0 (r/r_0)^n$, $n > -3$ or $n < -3$
- Rayleigh-Taylor instabilities $\sigma = \sqrt{-\frac{p}{\rho}\frac{\partial \ln p}{\partial r}\frac{\partial \ln \rho}{\partial r}}$

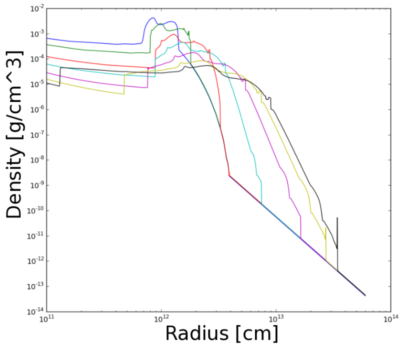
$\Rightarrow$ Strong mixing of ejecta

- Shocks form at the interfaces



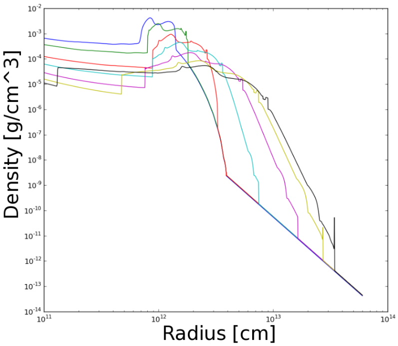
$\Rightarrow$See Poster by B. Giudici

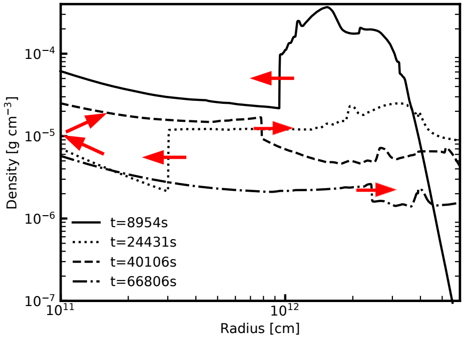
Shocks, Reverse shocks and self-reflected reverse shocks



- (Reverse)Shock form at interfaces and CSM-interaction
- The shock from the He/H interface heats up material at small radii

Shocks, Reverse shocks and self-reflected reverse shocks





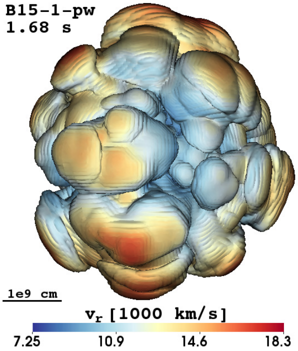
- (Reverse)Shock form at interfaces and CSM-interaction
- The shock from the He/H interface heats up material at small radii

⇒ Temperature and entropy increase

⇒ Outwards moving shock formed

- Reverse shocks compress ejecta
- Outwards moving shock accelerate ejecta

From explosion to shock breakout - 3% Ni surfaces

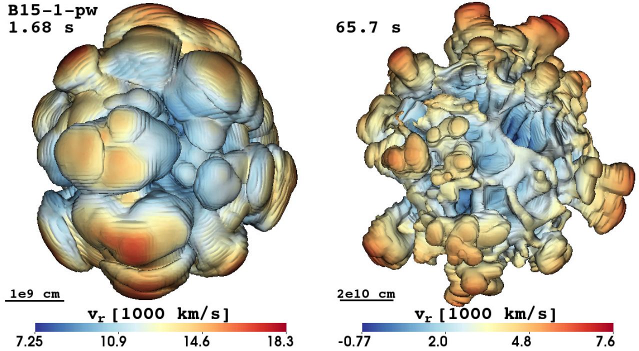


Model B15 - Ni surfaces

- Initial big plumes created by hydrodynamic instabilities during explosion

Wongwathanarat et al. 2014

From explosion to shock breakout - 3% Ni surfaces



Model B15 - Ni surfaces

- Initial big plumes created by hydrodynamic instabilities during explosion
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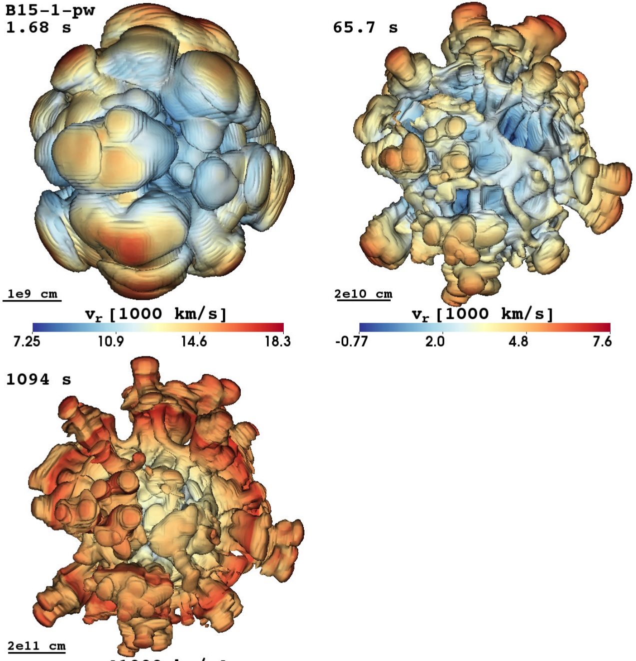
Wongwathanarat et al. 2014

From explosion to shock breakout - 3% Ni surfaces



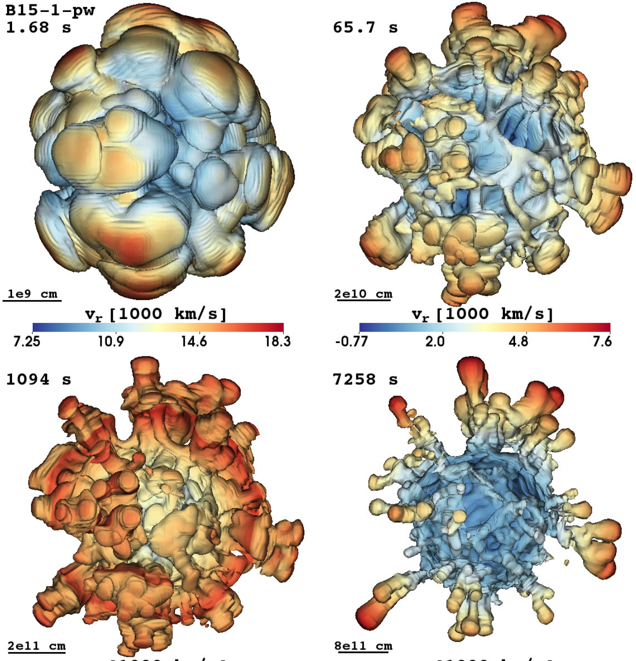
Model B15 - Ni surfaces

- Initial big plumes created by hydrodynamic instabilities during explosion
- First Rayleigh-Taylor phase with starting fragmentation of initial plumes
- Reverse shock passes through the ejecta (red color in bottom left panel)

$\Rightarrow$ compresses central ejecta

Wongwathanarat et al. 2014

From explosion to shock breakout - 3% Ni surfaces



Model B15 - Ni surfaces

- Initial big plumes created by hydrodynamic instabilities during explosion
- First Rayleigh-Taylor phase with starting fragmentation of initial plumes
- Reverse shock passes through the ejecta (red color in bottom left panel)

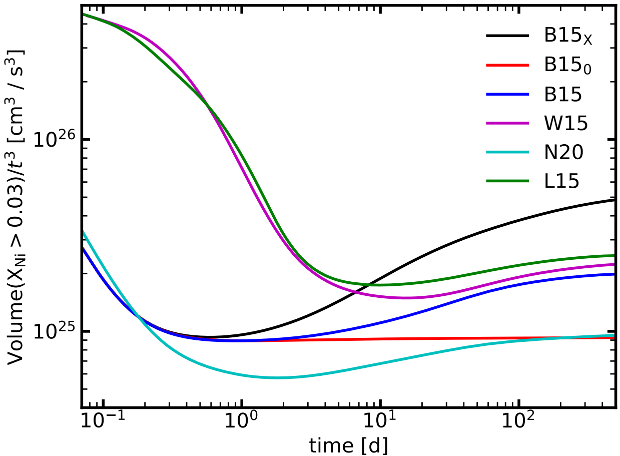
$\Rightarrow$ compresses central ejecta

- Few strongly fragmented RT fingers stick out

Wongwathanarat et al. 2014

From shock break out towards homology - Expansion of 3%-Ni surfaces

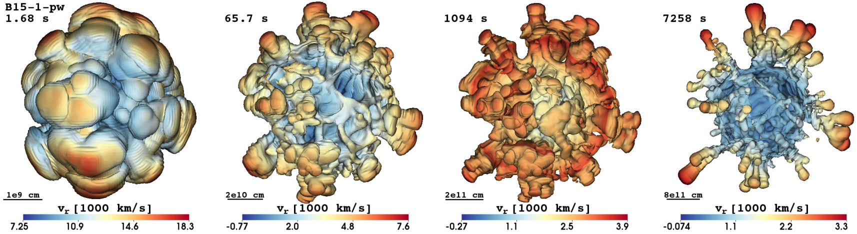
Homologous expansion: $V \sim r^3 \xrightarrow[Expansion]{Homologous} V/t^3 = \mathrm{const.}$



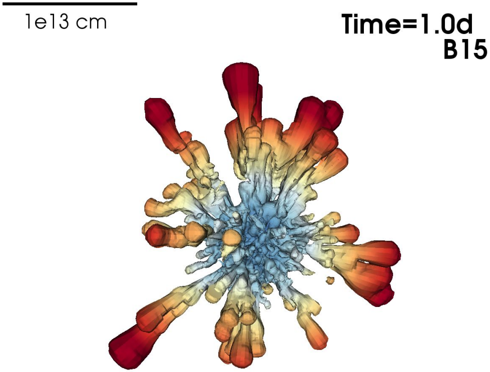
Compared to homologous expansion (horizontal line)

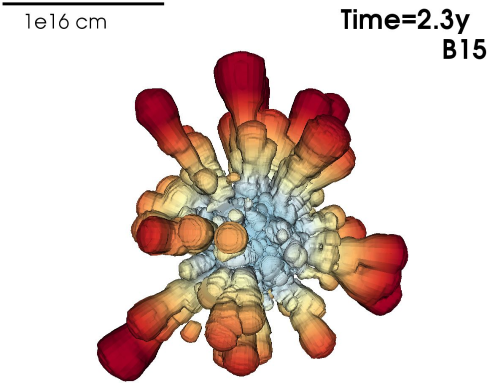
- Initially:
  slow expansion due to reverse shock
- Hours/days:
  inflation due to self-reflected shock and β-decay
- 100d - 1yr:
  β-decay ceases, additional inflation stops

From shock break out towards homology - 3% Ni surfaces

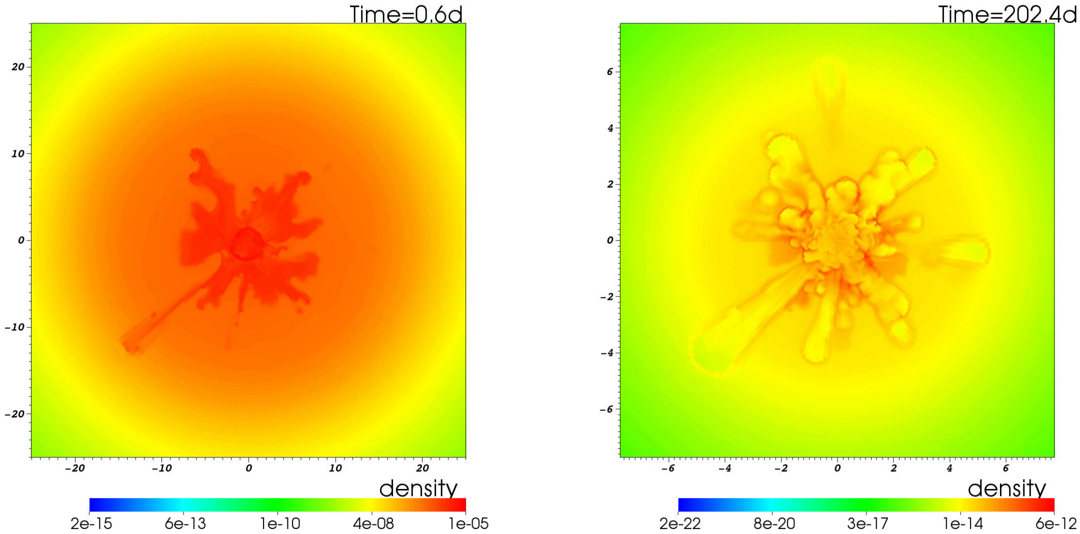


Wongwathanarat et al. 2014

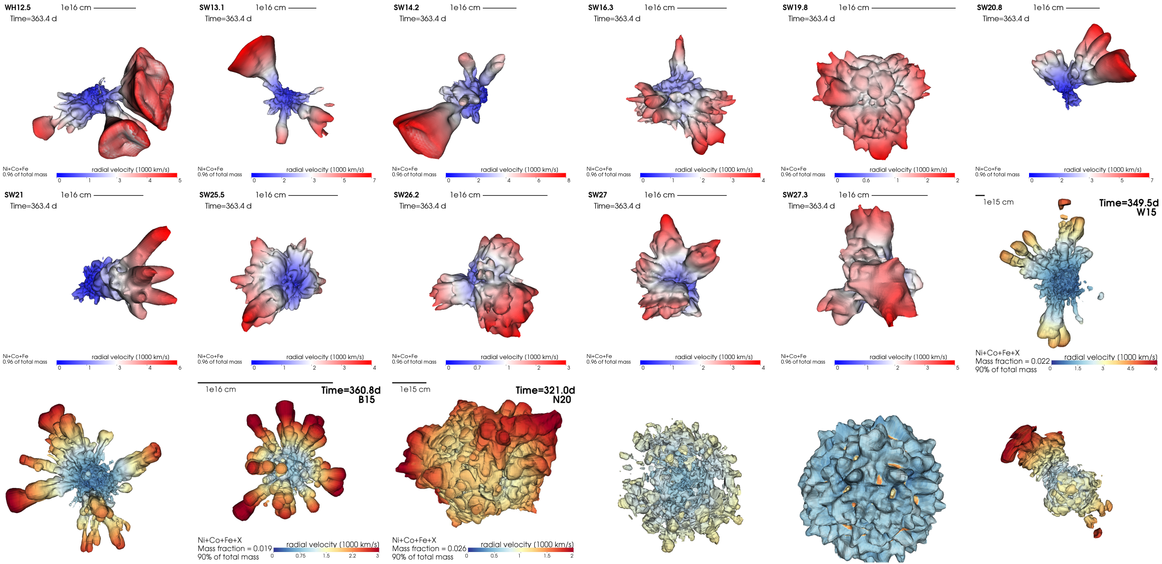




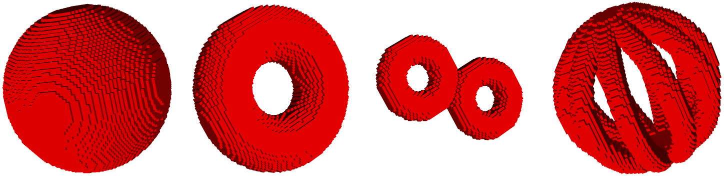
Density slice (model B15)



Different 3D models at 1 year



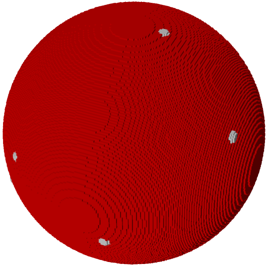
Genus g = topologically invariant property of a surface



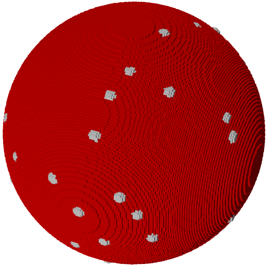
$g = 0$ $g = 1$ $g = 2$ $g = 8$

- Negative for several isolated surfaces
- 1 shell: $g = -1$
- n spheres: $g = -n + 1$
- n shells: $g = -2n + 1$
- n detached tori: $g = 1$
- 2 touching tori: $g = 2$
- n touching tori: $g = n$
- Genus = 'number of holes' = 'number of handles'
- Application in 2D - Tycho's SNR, Sato et al., 2019

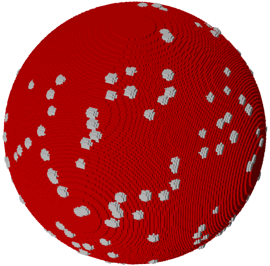
Genus statistic - Shell with holes



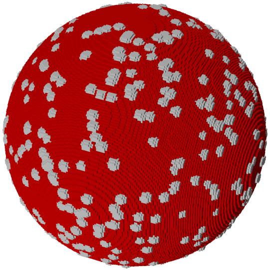
10 holes $g = 7$



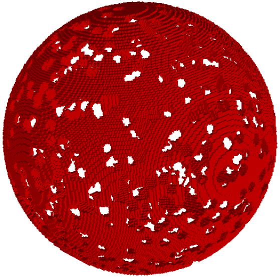
50 holes $g = 38$



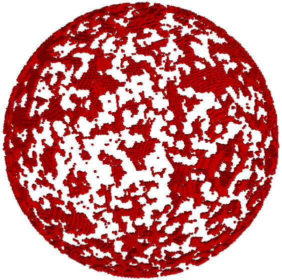
200 holes $g = 133$



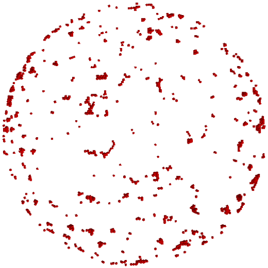
500 holes $g = 182$



1k holes $g = 48$

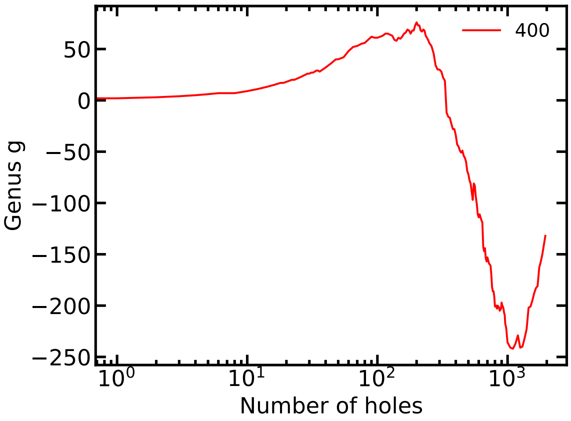


3k holes $g = -988$

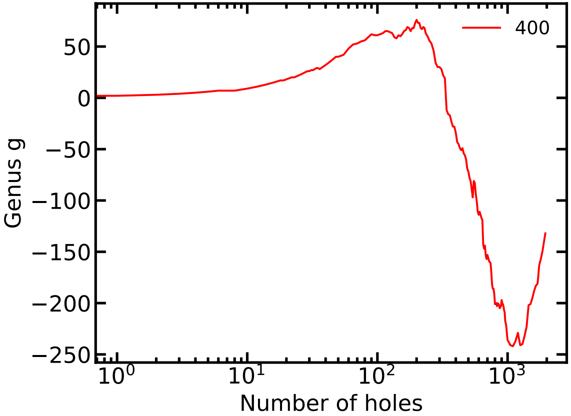


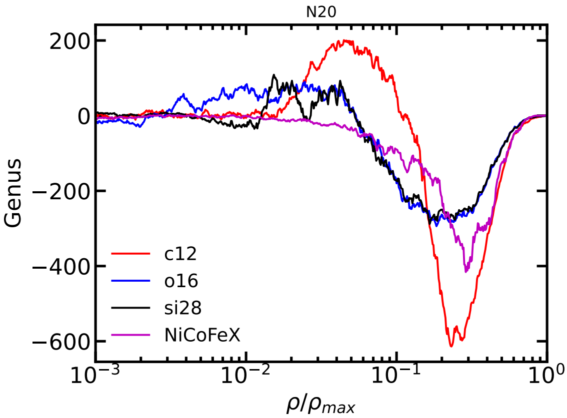
10k holes $g = -440$

Genus of shell with holes vs models



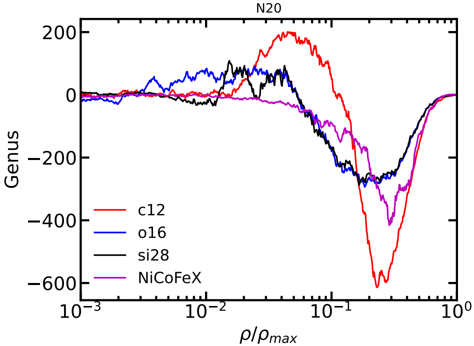
Genus of shell with holes vs models

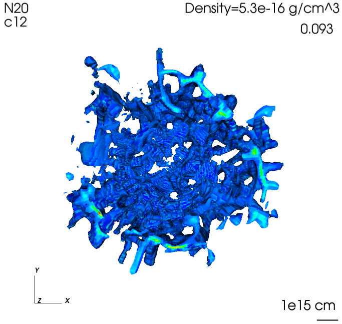


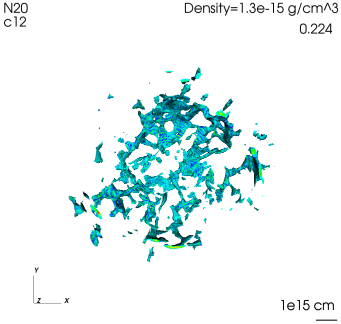


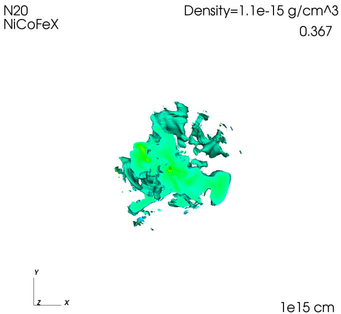
- Genus of ^{12}C very similar to shell with holes
- Genus of NiCoFeX always negative

Genus of Model N20



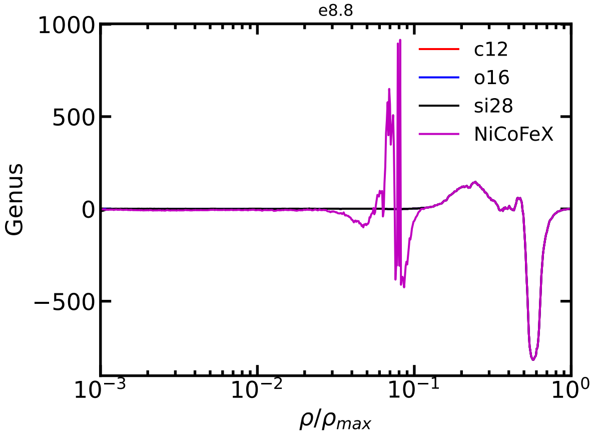


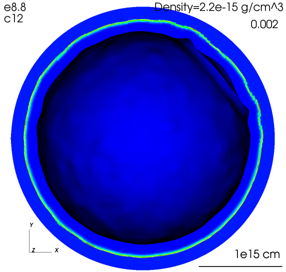


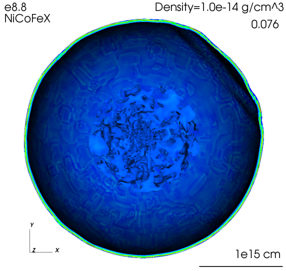


- ^{12}C disrupted shell with holes
- Solid structures of NiCoFeX

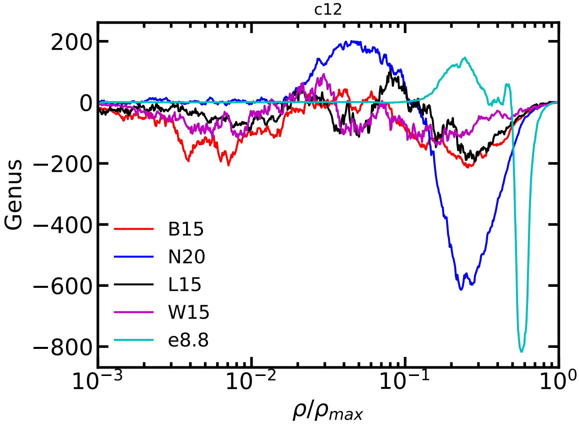
Genus of model e8.8

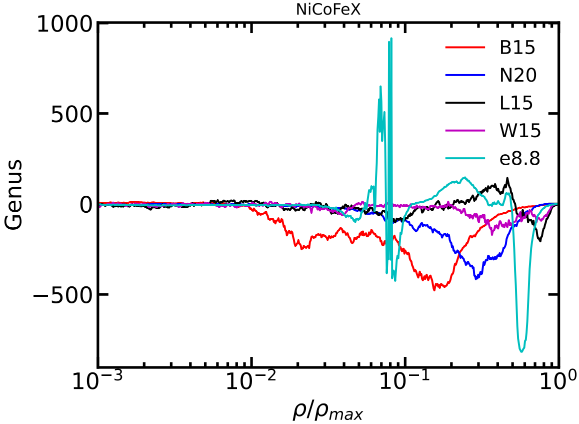






- ^{12}C spherical shell no matter in center
- NiCoFeX spherical shell and matter in center





- ^{12}C generally similar behaviour
- NiCoFeX similar
- But ^{12}C different from NiCoFeX
- ^{28}Si depend on the model

Conclusions

- **Asymmetries are seeded during explosion** $t \lesssim 1s$ (or even from progenitor)
- Final morphology carry imprints from initial assymetries
- **Progenitor structure** determines conditions for **RTI** $\Rightarrow$ determines **mixing of ejacta during propagation through progenitor**

  Poster by B. Giudici
- Quantitative analysis shows significant differences between models: clump numbers, clump sizes, separation, spherical harmonics, ...
- **Genus statistics** potential to **characterize different morphologies** in the ejecta