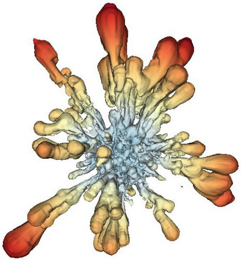
# The infancy of supernova remnants: evolving a supernova into its remant in 3D



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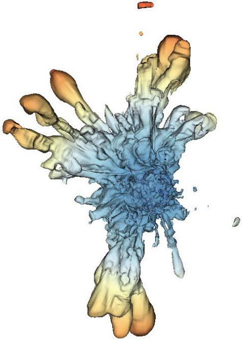

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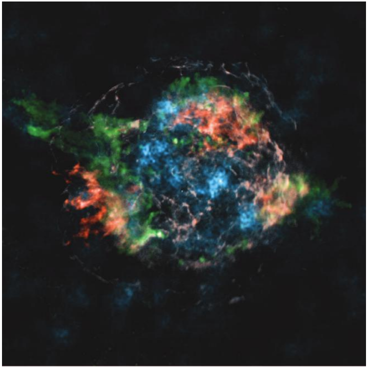
# SNR Observations - Cas A

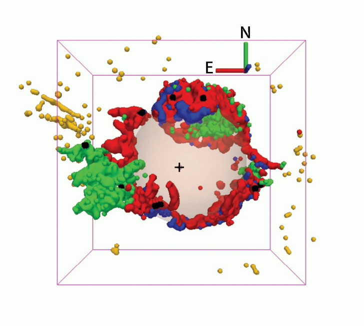
The observation of asymmetries in the supernova ejecta

- High ratio of Ti44/Ni56 emission (Nagataki et al. 1998)
- Optical light echoes (Rest et al. 2011)
- Jet-like features in the X-ray and optical ejecta (Hwang et al. 2004, Fesen et al. 2006)



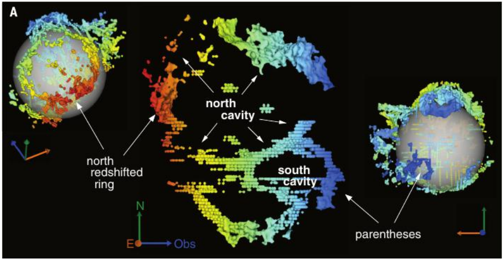
- Spatially resolved X-ray emission (Grefenstette et al. 2014, Milisavljevic et al. 2015)
  - Spatial distribution of Ti44 (blue)
  - Si/Mg (green)
  - Fe (red)

# Bubbles, Cavities, Protrusions ('jets')

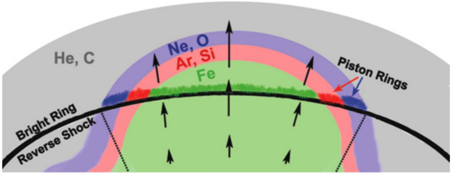



- DeLaney et al. 2010
- Infrared [Ar II] (red), high infrared [Ne III]/[Ar II] ratio (blue), X-ray Si XIII (black), X-ray Fe-K (green), outer optical ejecta (yellow), fiducial reverse shock (sphere), and CCO (cross)

- Milisavljevic & Fesen (2015)
- Doppler reconstruction of [S III] emission
- Color coding: velocity



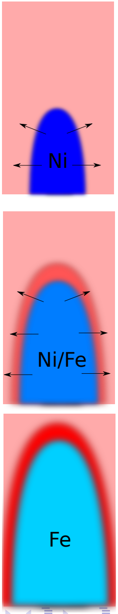
# Piston vs. Ni-bubble



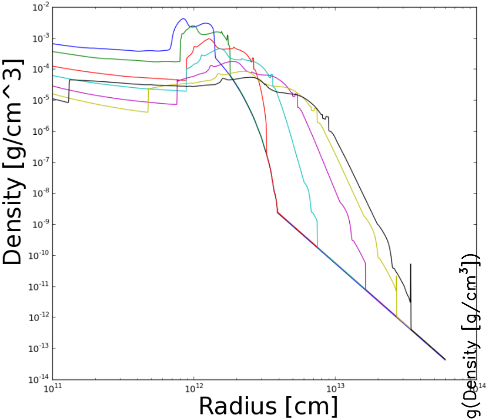

DeLaney et al. 2010

- Piston with high velocity creates regions with different composition at a given radius
- Reverse shock heats part of Fe that is enclosed by rings of Ar/Si and Ne/O emission

- Ni56 clumps are mixed to large radii
- Surrounding medium expands freely
- Beta decay of Ni heats up Ni-bubble that expands
- Inside bubble density decreases
- Outside shell of swept up material

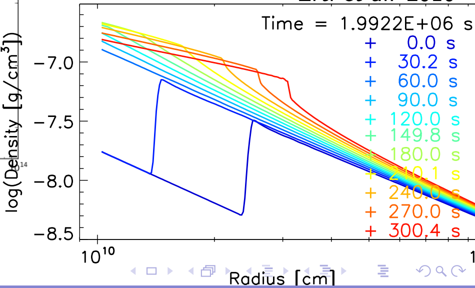


# Reverse shock and Rayleigh-Taylor instabilities

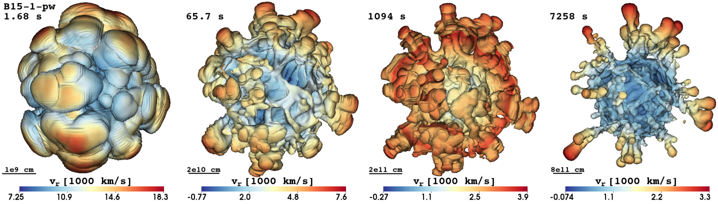


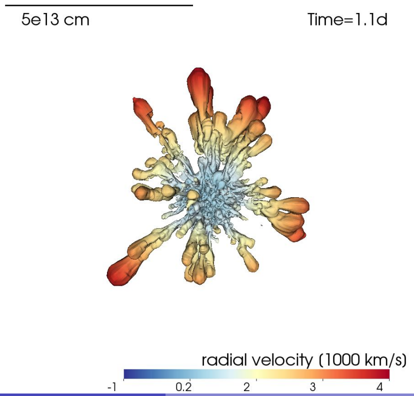

- Reverse shock usually forms when ejecta are decelerated
- Here at $r \sim 10^{12}$cm
- Rayleigh Taylor instabilities where $\frac{\partial \rho}{\partial r}\frac{\partial p}{\partial r} < 0$
- New outwards shock builds up

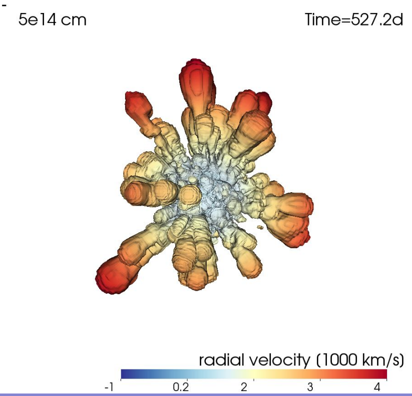
Ertl et al. 2016



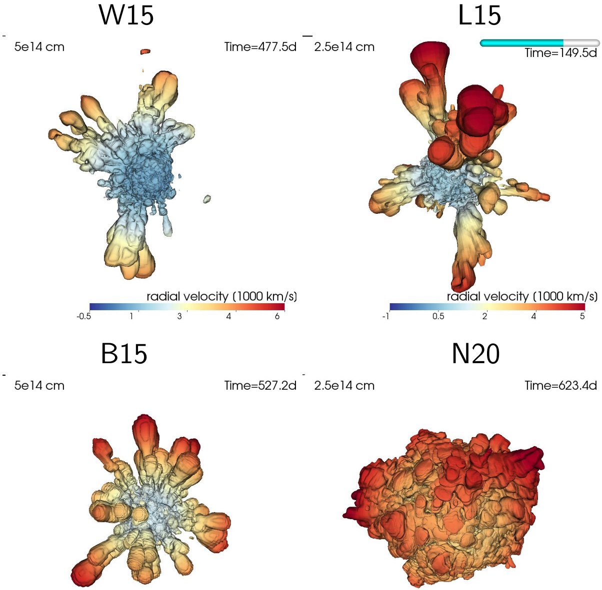
# From shock break out towards homology



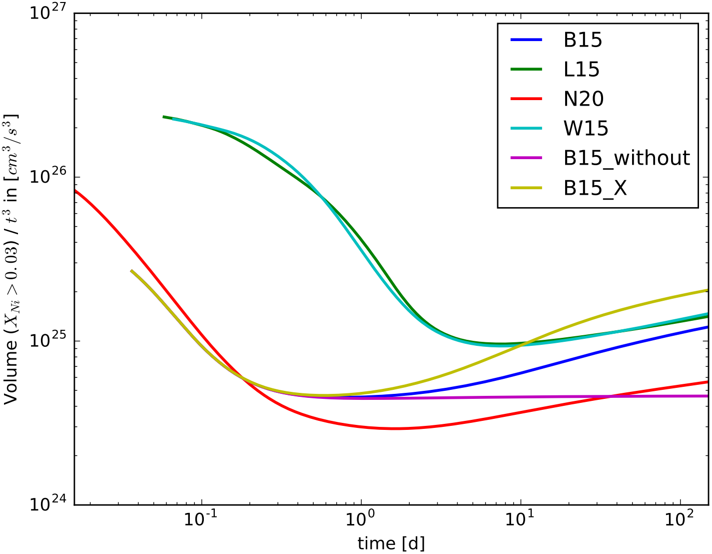



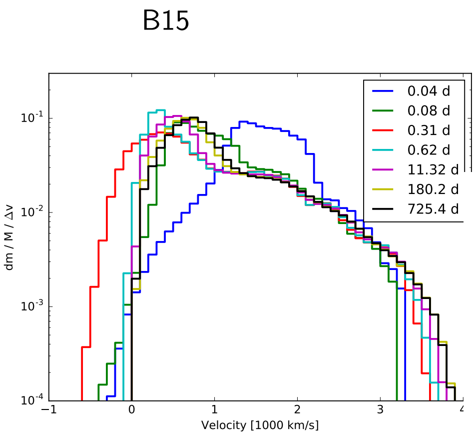
# Comparing different models



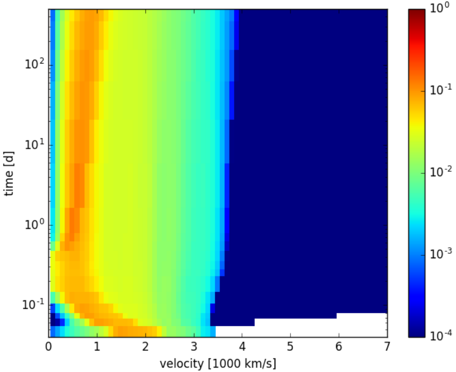
# Expansion of 3%-Ni fractions: $V/t^3$



# Velocities of Ni56



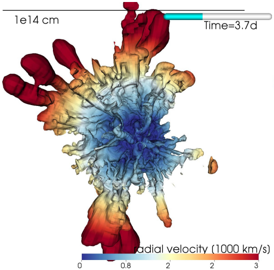

- High velocity material slowed down by reverse shock (and shut off of $\nu$-driven wind)
- Formation of new outward shock accelerates at $t \sim 0.5 \ldots 5\,\mathrm{d}$



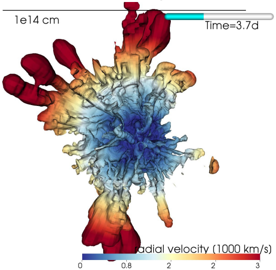

- Late acceleration due to beta decay $d \gtrsim 7\,\mathrm{d}$

# Different elements - 25% enclosed mass

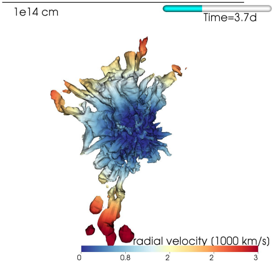
C



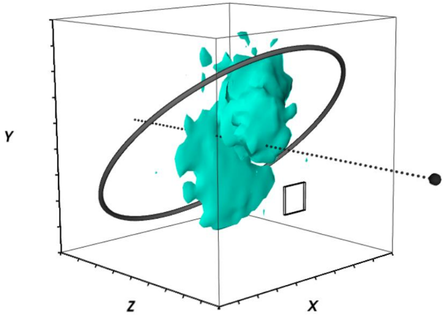

O




Si

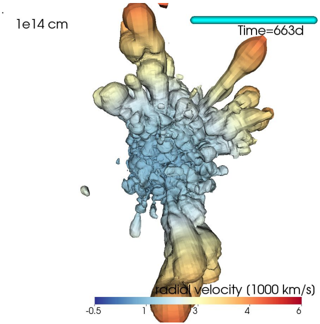


# Tentative comparison to observations



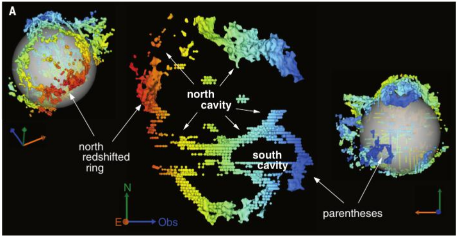

3D isosurface of [Si I]+[Fe II] emission of SN87A

Larsson et al. 2016

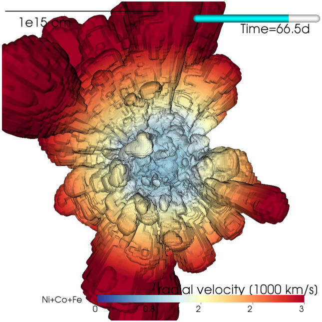



3% mass fraction of X56 of W15

# Tentative comparison to observations

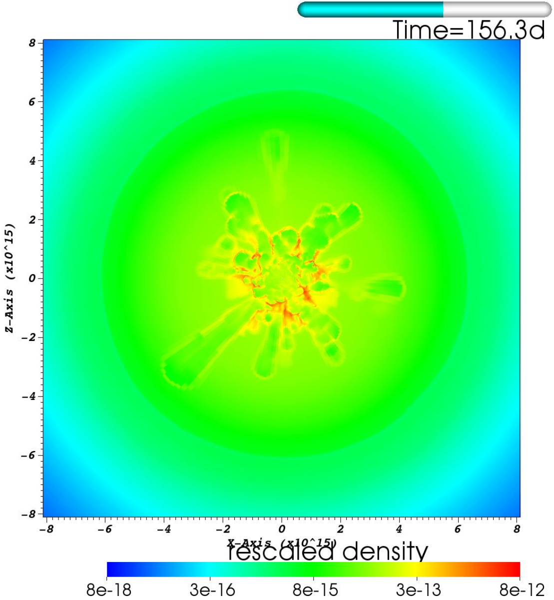



Milisavljevic & Fesen (2015) ([S III] emission)

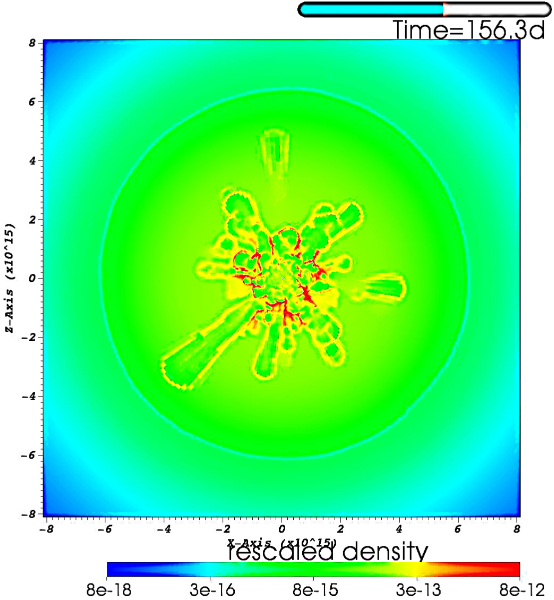



75% of all C12 (model W15)

# Density slice (model B15)



# Density slice (model B15)



# Conclusions

- Asymmetries are seeded during epxlosion ($t \lesssim 1s$)
- Rayleigh-Taylor instabilities change their shape and may cause fragmentation into smaller 'fingers'
- Growth of 'RT-fingers' depends on progenitor structure
- Newly formed outwards shock accelerates innermost ejecta
- Beta decay 'smears' small RT-fingers and causes merging of fine structures
- Homology (fine structures do longer change) reached after several beta-decay timescales ($\sim 1/2$y)
- Direct comparison to observations not straight forward (molecule formation, dust, emission mechanism)
  (But see Wongwathanarat et al. 2016 for Ti44)