Three-dimensional numerical investigations of the morphology of Type Ia SNRs

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Anything without citation is
from Warren & Blondin (2013)

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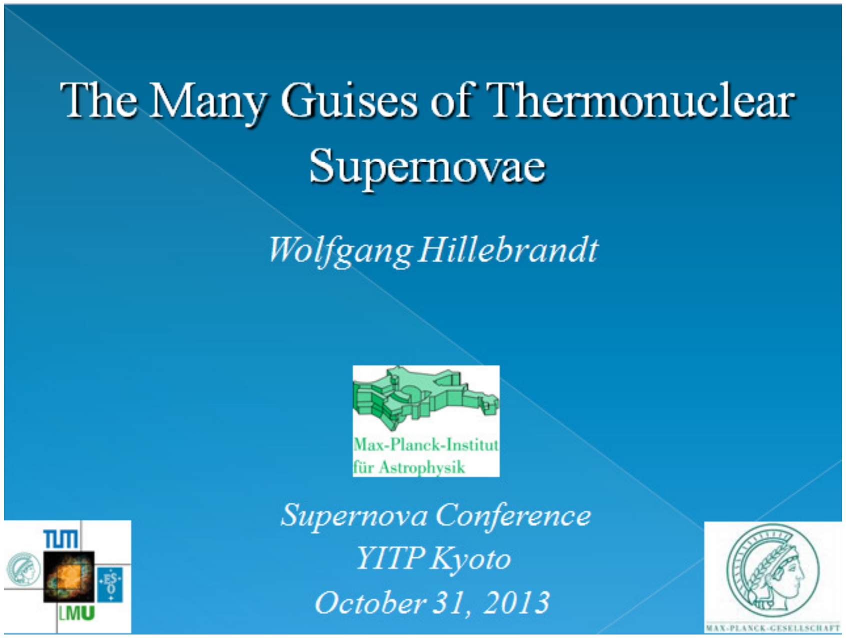


The Many Guises of Thermonuclear Supernovae

Wolfgang Hillebrandt

Max-Planck-Institut für Astrophysik

Supernova Conference
YITP Kyoto
October 31, 2013

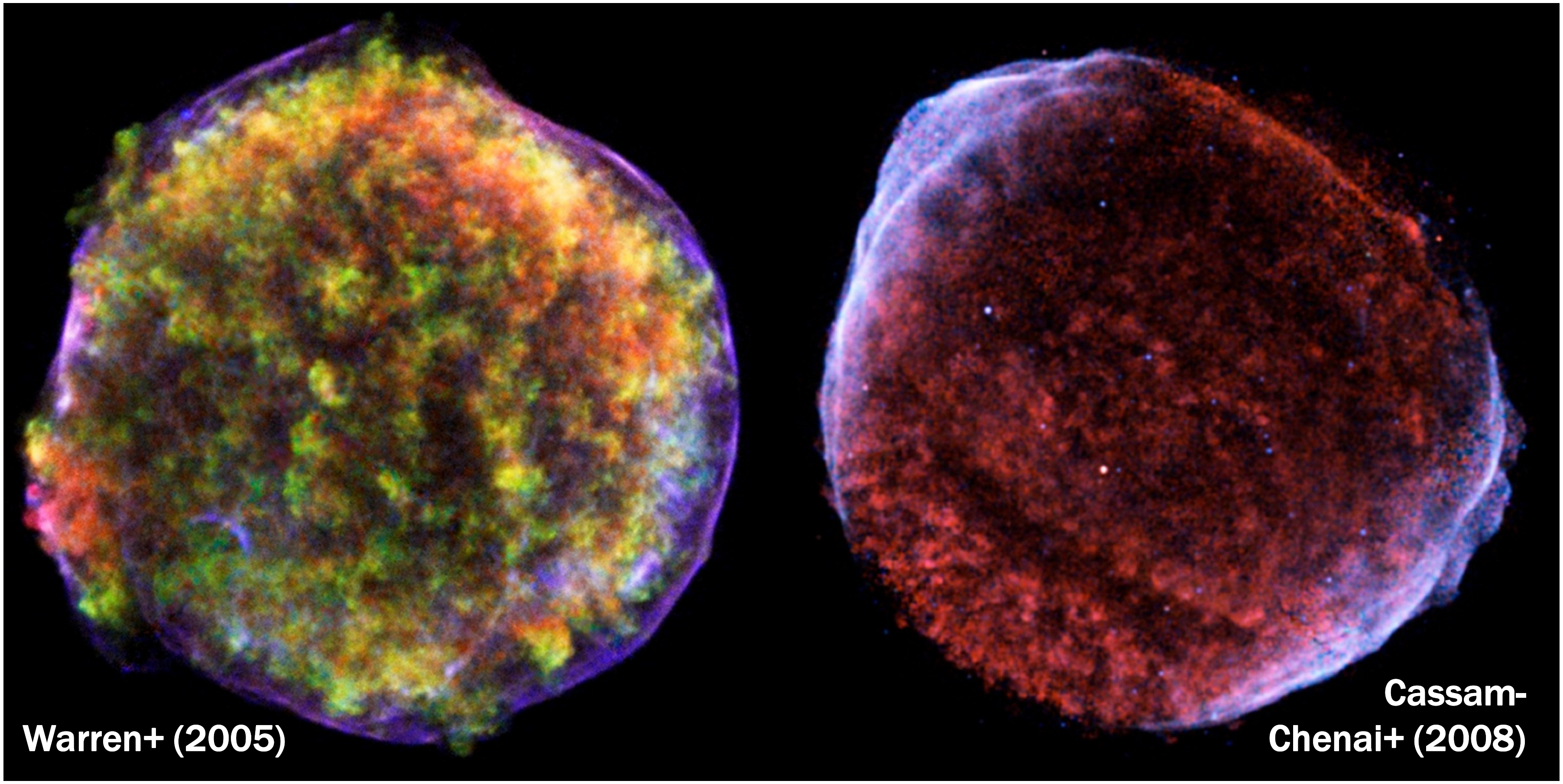
Thanks to W. Hillebrandt!

Outline

- Motivation
- Numerical model / setup
- Output
- Implications for Tycho’s SNR & SNR 1006
- Conclusions

Motivation

- X-ray images of Tycho’s SNR and SN 1006 show lots of structure. Can simple hydrodynamics do this, or do we need more physics?



Tycho’s SNR

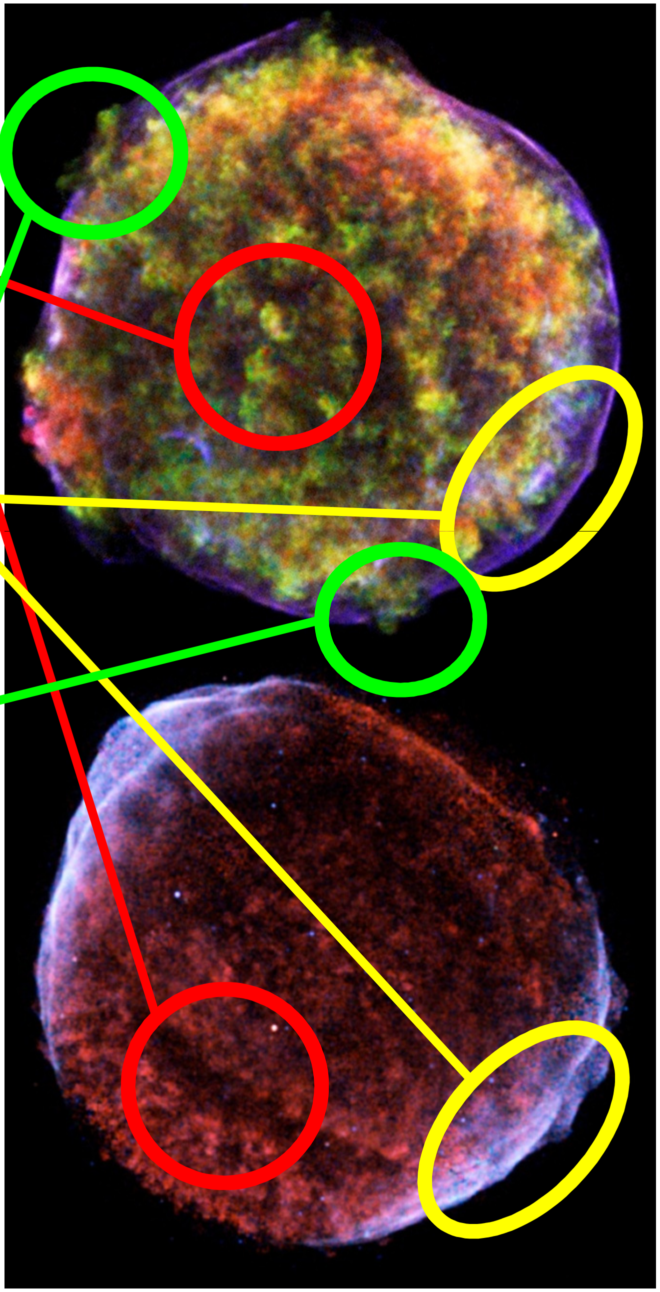
SN 1006

Warren+ (2005)

Cassam-Chenai+ (2008)

Motivation

- Points of interest:
  - Ejecta structures in central regions
  - Close proximity of ejecta to forward shock
  - Knots of ejecta ahead of forward shock?
- Can we infer dynamical age of both SNRs?

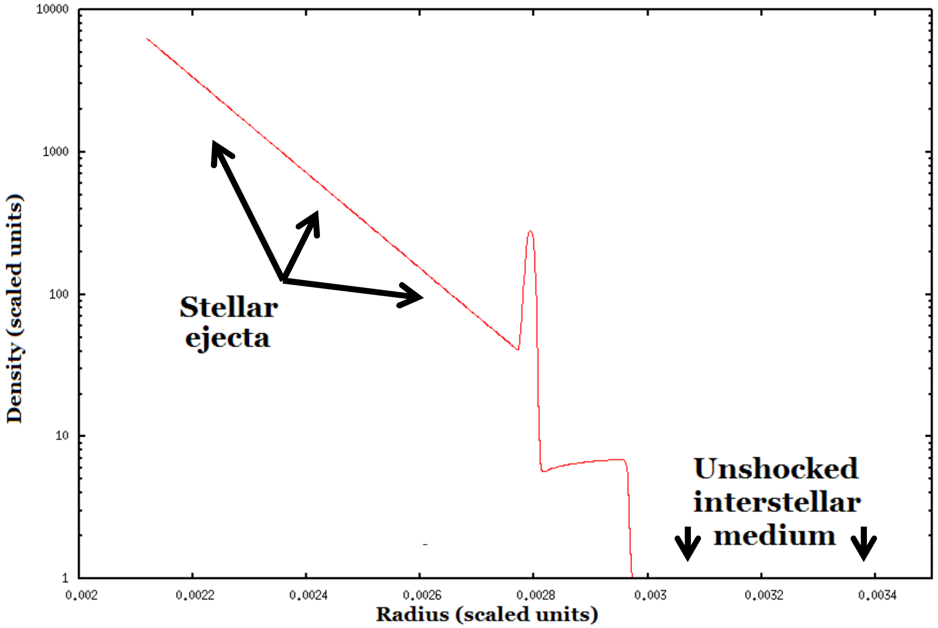


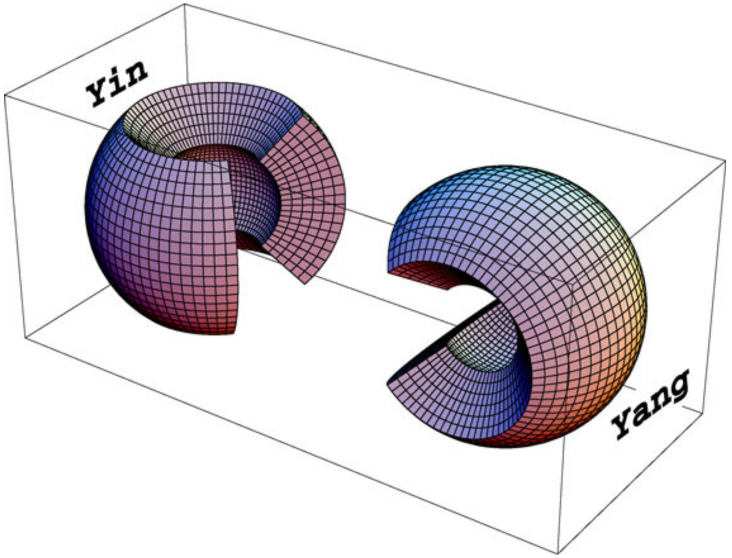
Numerical model

- **Used exponential radial density profile**
  (Dwarkadas & Chevalier 1998)

$$\rho_{\mathrm{SN}} = At^{-3}\mathrm{e}^{-v/v_e}$$

- **Swept out across full 4π steradians using “Yin-Yang” grid**
  (Kageyama & Sato 2004)

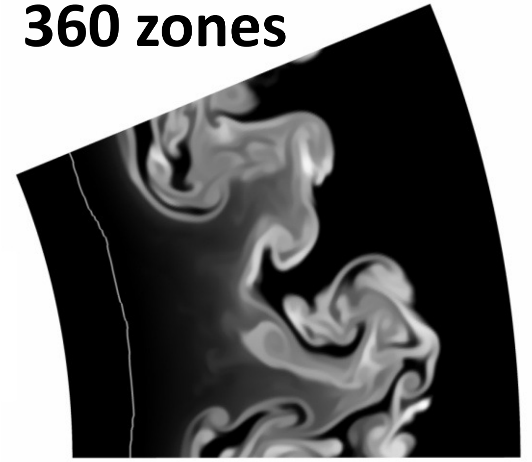




Numerical model

- 3-D grid size
  (r x θ x φ x YY): 360 x 360 x 1080 x 2

360 zones



- Tracked ionization timescale and ejecta fraction

- To approximate efficiency of CR acceleration, ran three different simulations with differing adiabatic indices: γ_{eff} = 5/3, γ_{eff} = 4/3, & γ_{eff} = 6/5
  (c.f. Blondin & Ellison 2001)

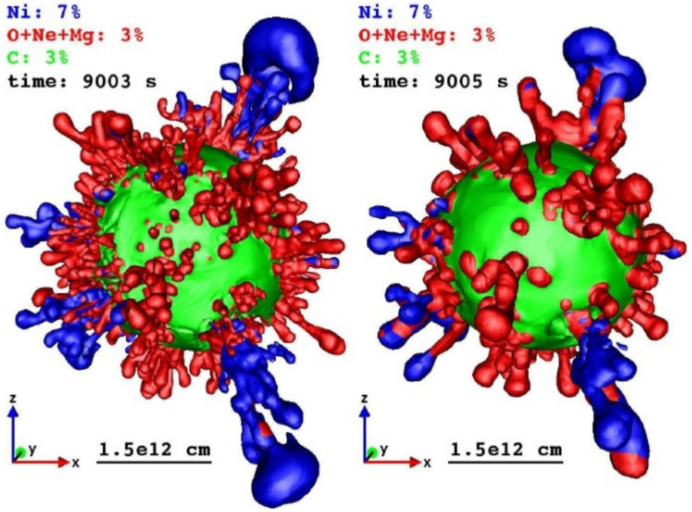
Brief aside

- 2-D runs showed 3 “epochs” regarding fluid instabilities like R-T fingers:
  - Growth
  - Saturation
  - “Freeze-out”

- Saturation period very important to our results, so need to start early enough to reach it (one big difference between our paper and Orlando+ 2012)

Brief aside

- Effect of saturation: initial instability seed irrelevant (for small initial perturbations)
- Initially smooth ejecta generates all structures to follow

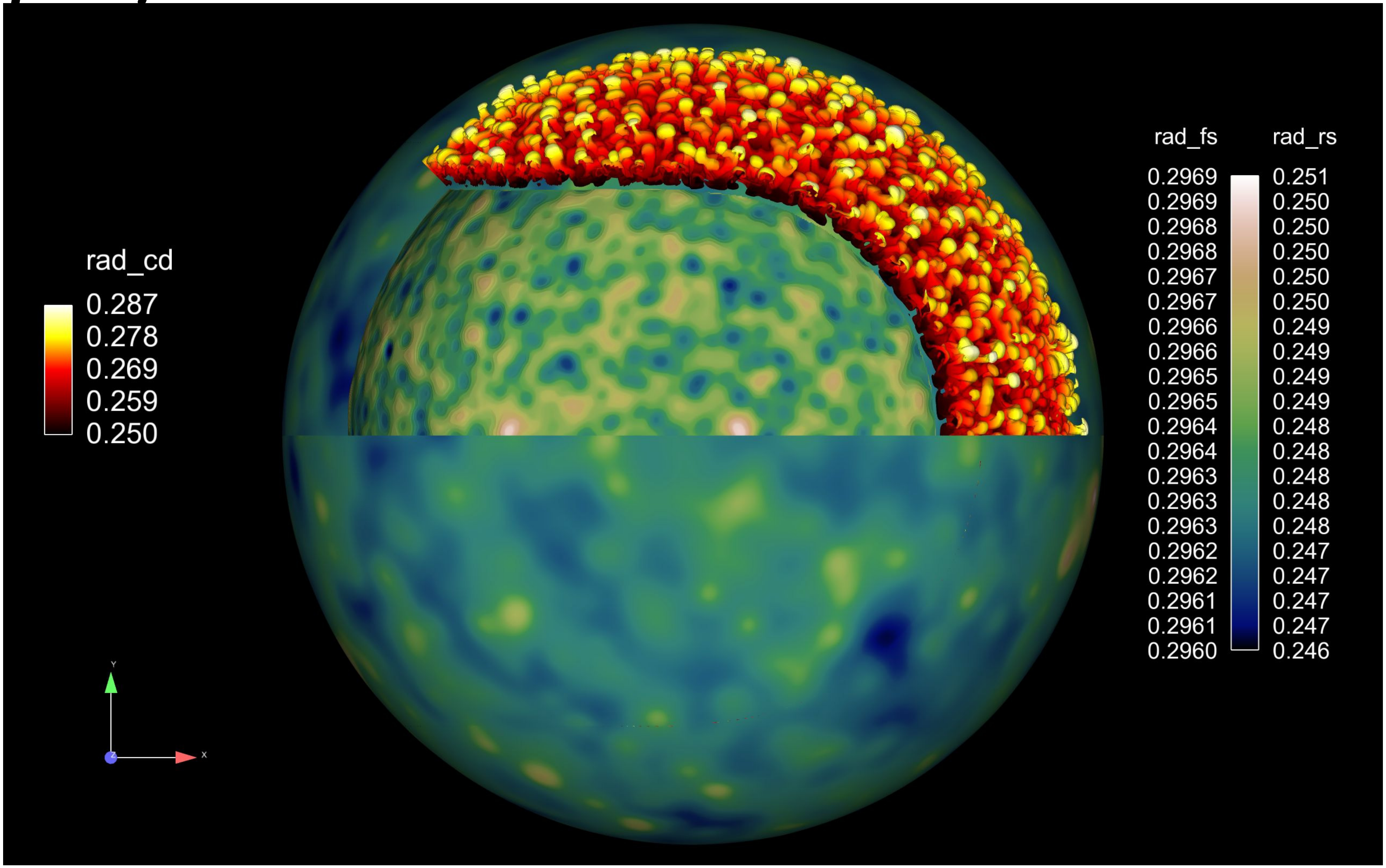


NOT small

Thanks to A. Wongwathanarat!

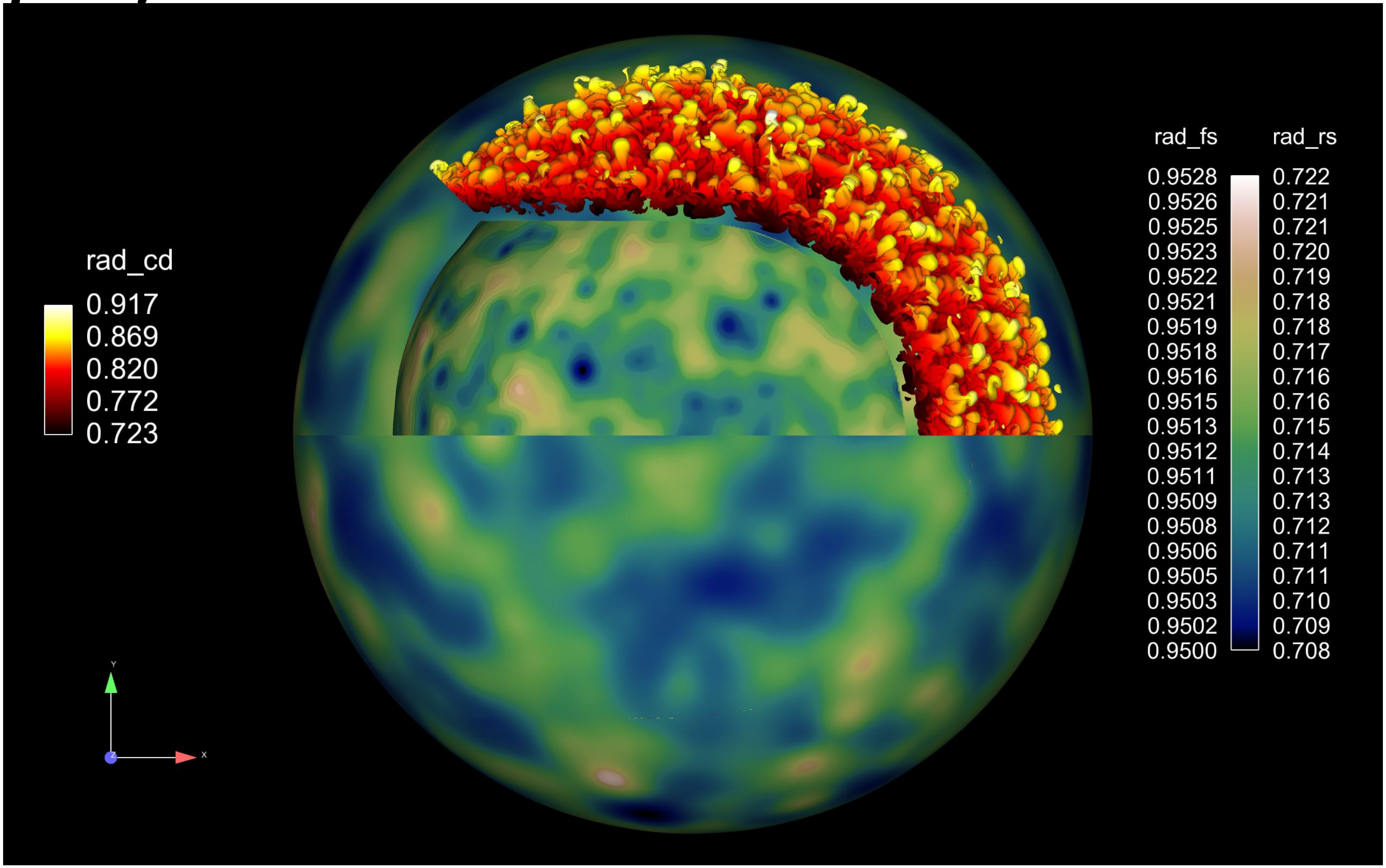
Output

- *γ* = 5/3 run at t = 0.12



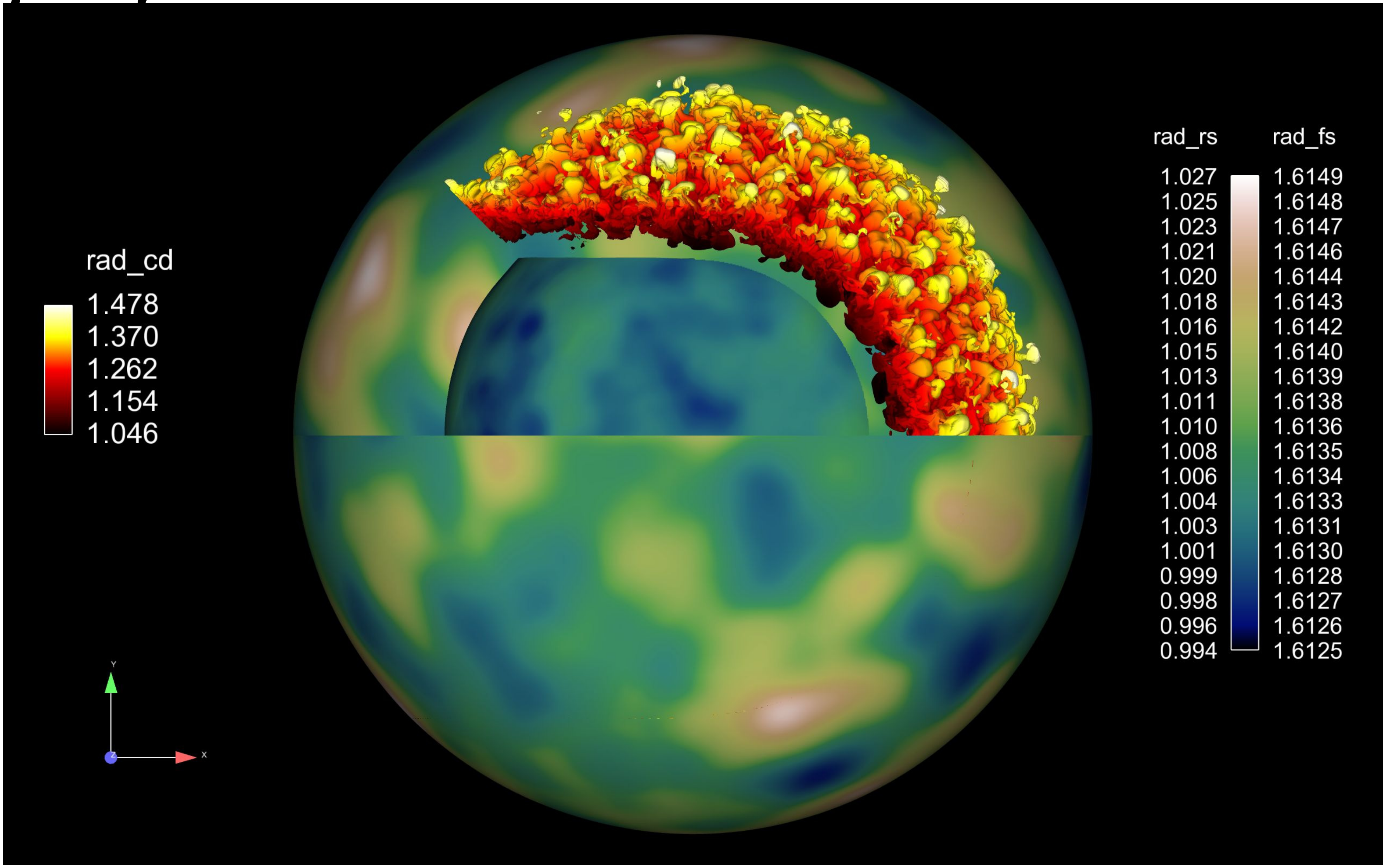
Output

- $\gamma = 5/3$ run at t = 0.75



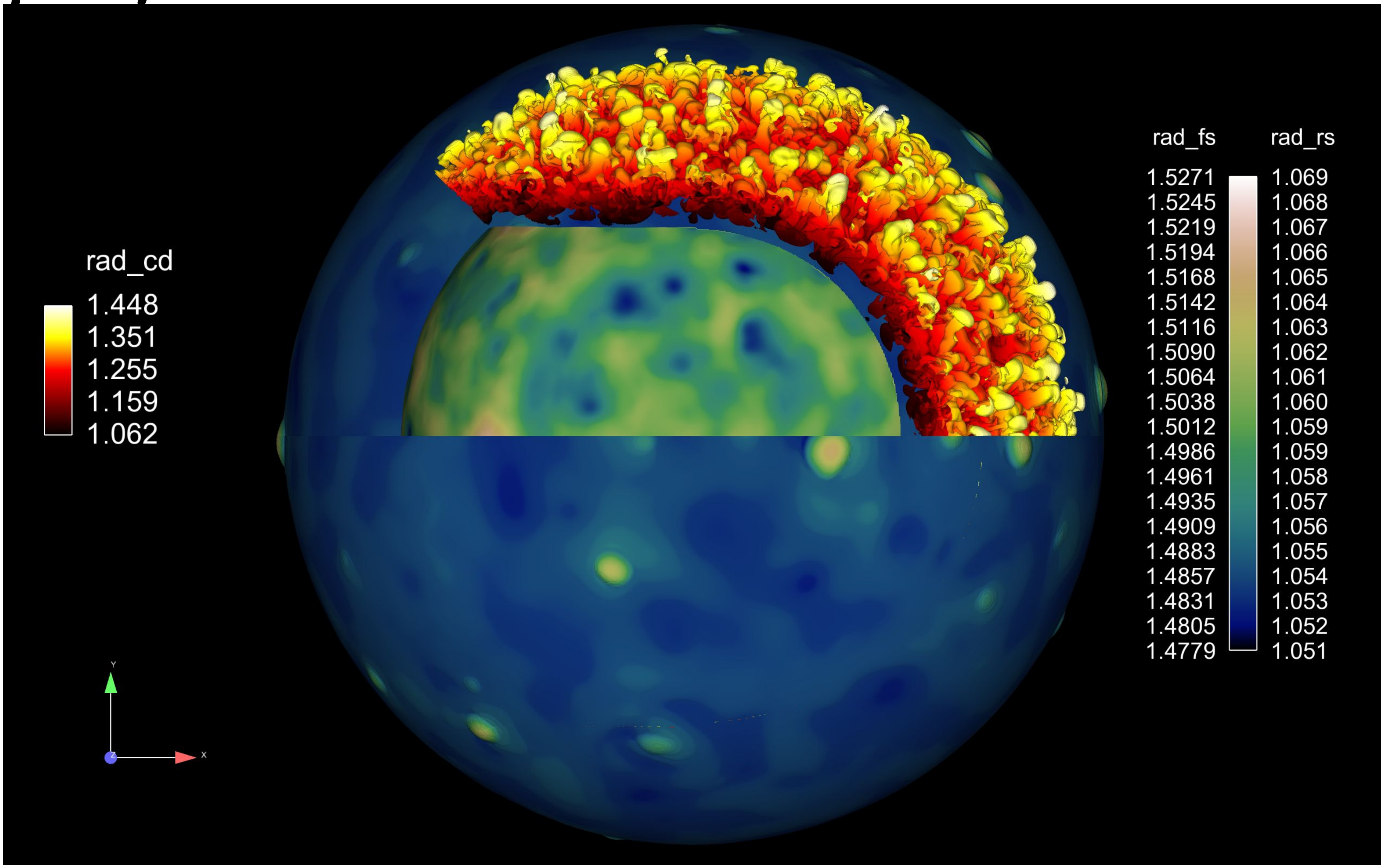
Output

- $\gamma = 5/3$ run at t = 2.0



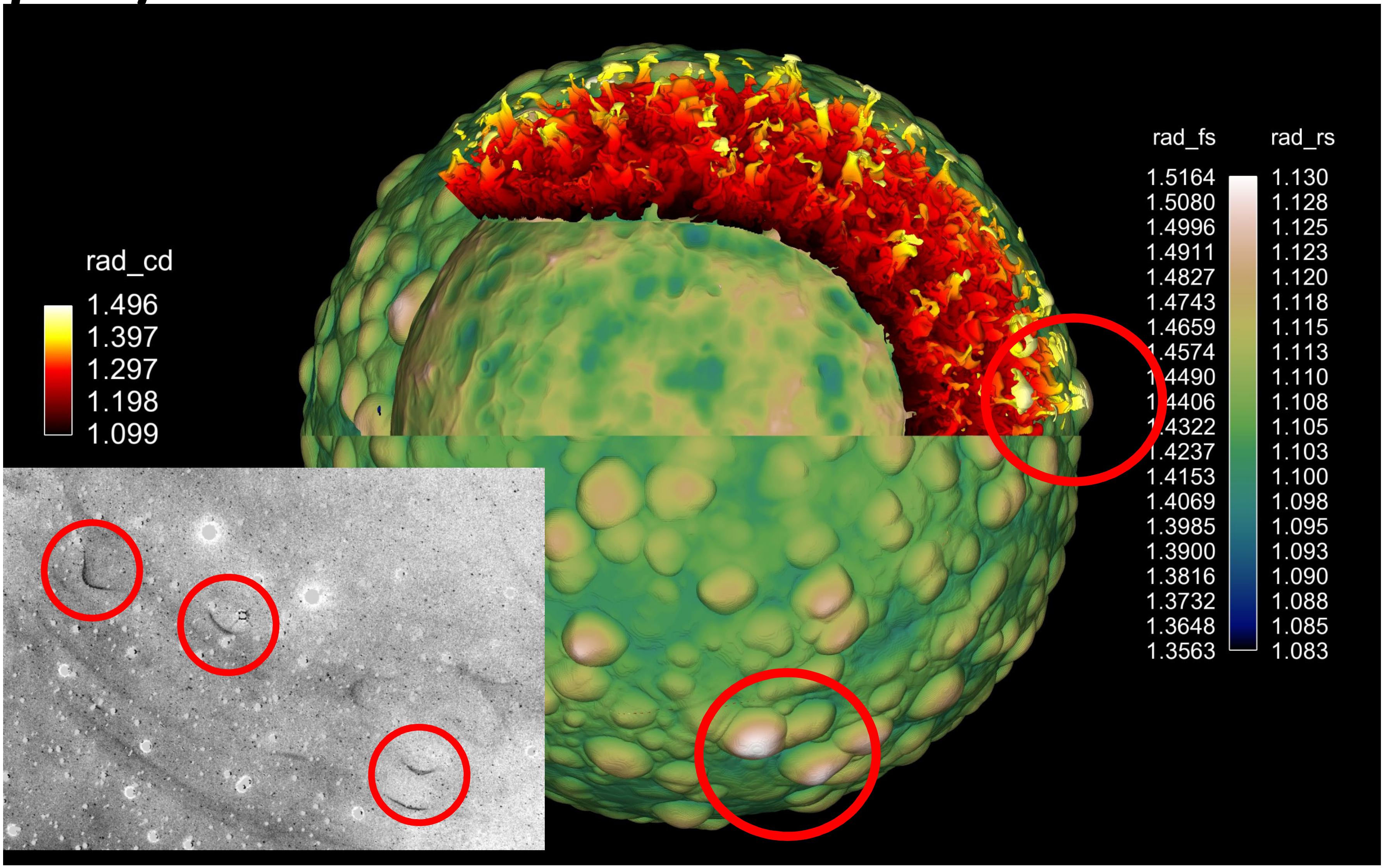
Output

- $\gamma = 4/3$ run at $t = 2.0$



Output

- γ = 6/5 run at t = 2.0



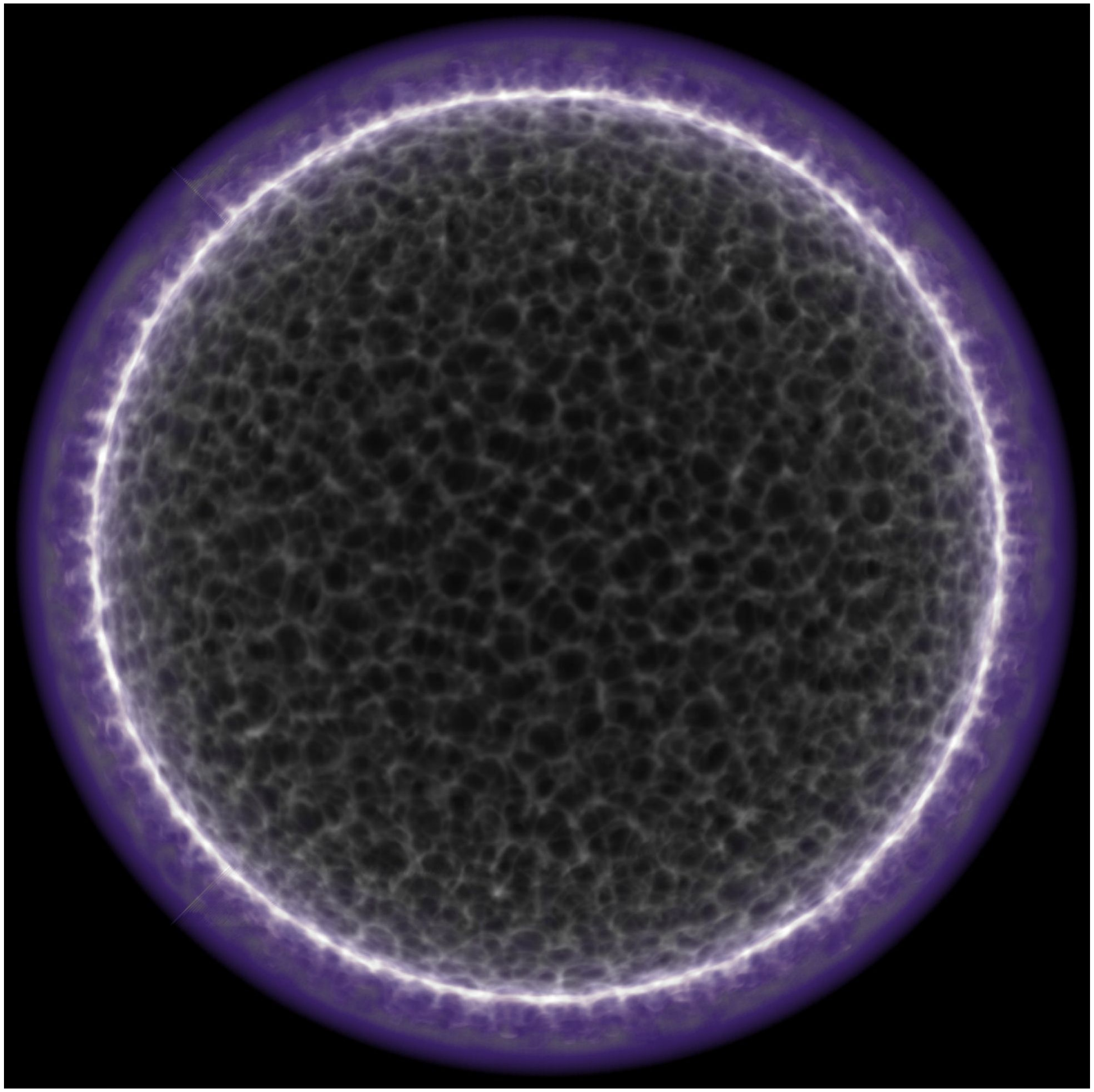
Thanks to F. Winkler!

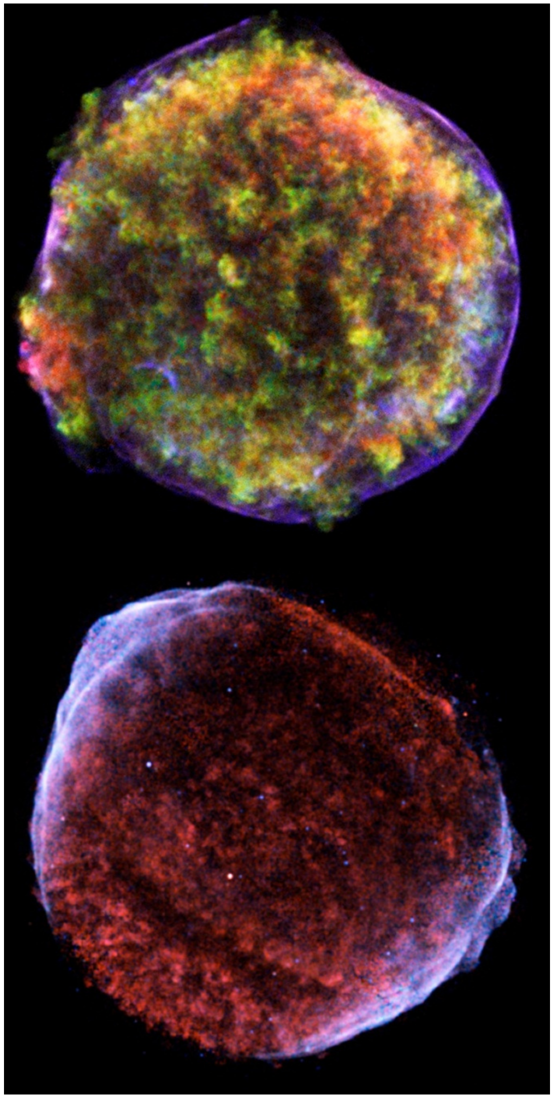
Output

- To directly compare against observations, we also generated line-of-sight projections
- Ejecta contributes as n^2 (i.e. thermal emission)
- Shocked ISM contributes radio synchrotron (so shocked ISM region broader than for X-ray synchrotron)

Output

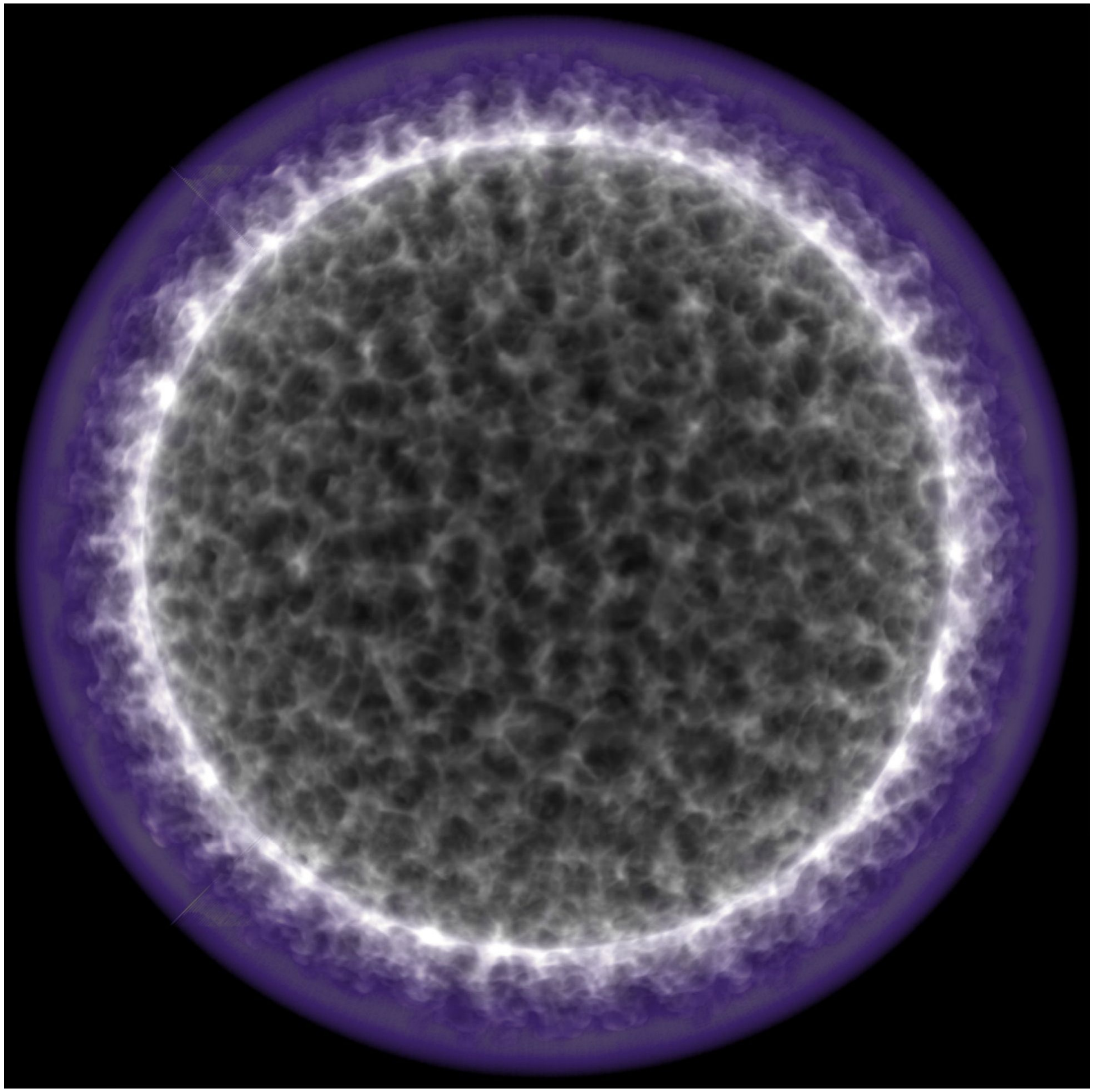
- More images: $\gamma = 5/3$ run at $t = 0.12$

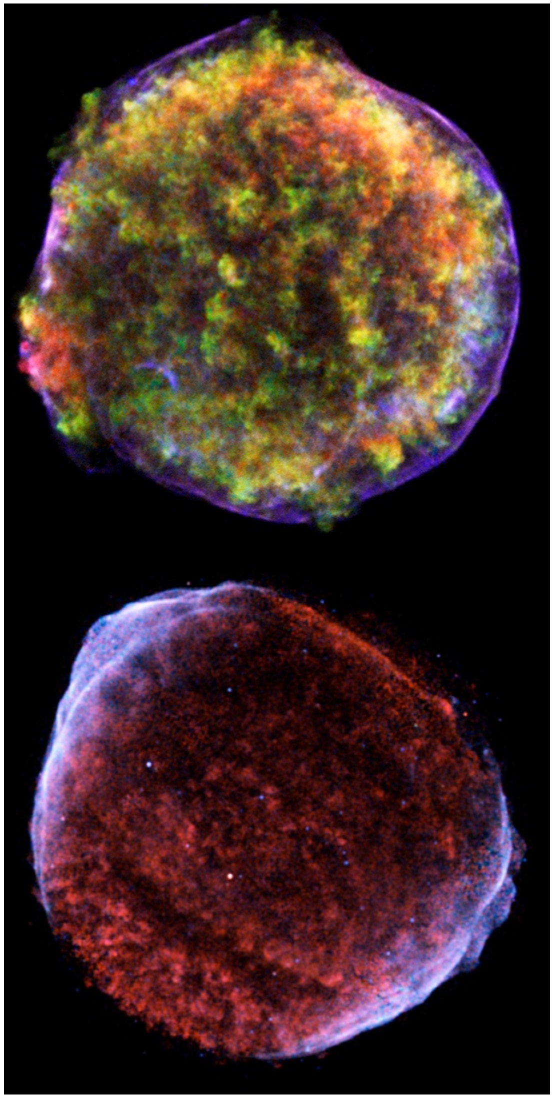




Output

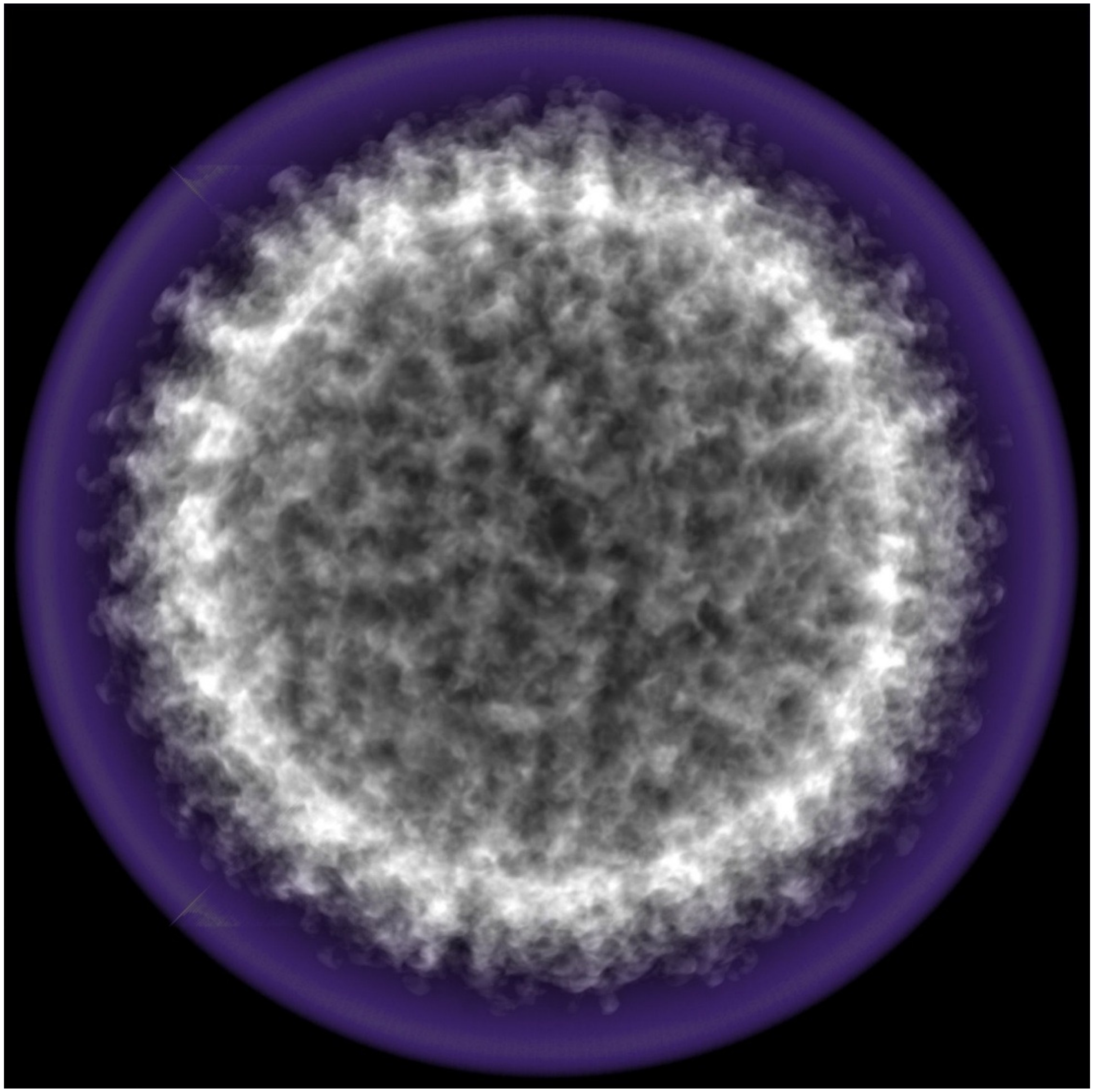
- More images: $\gamma = 5/3$ run at $t = 0.75$

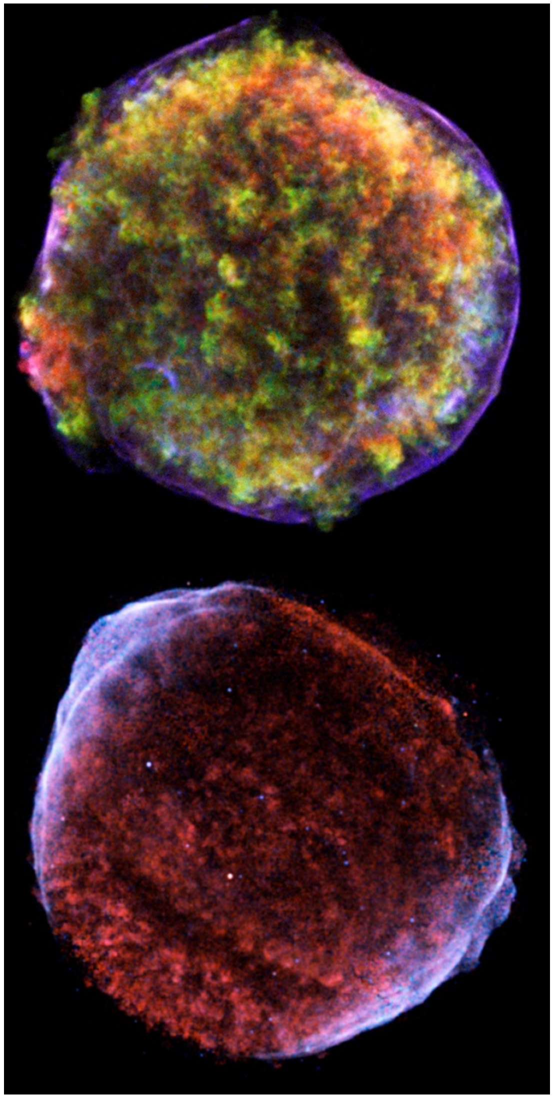




Output

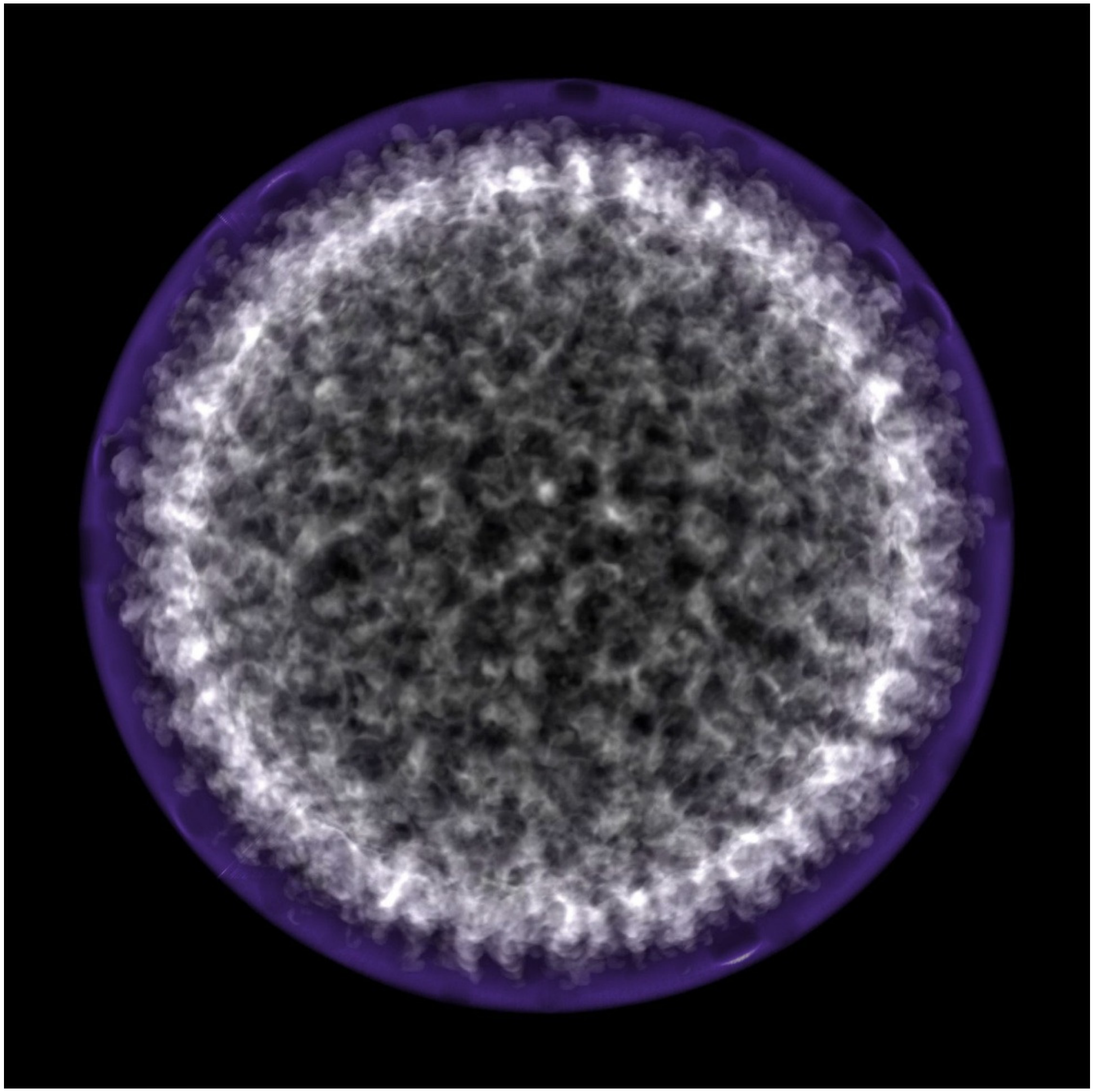
- More images: $\gamma = 5/3$ run at t = 2.0

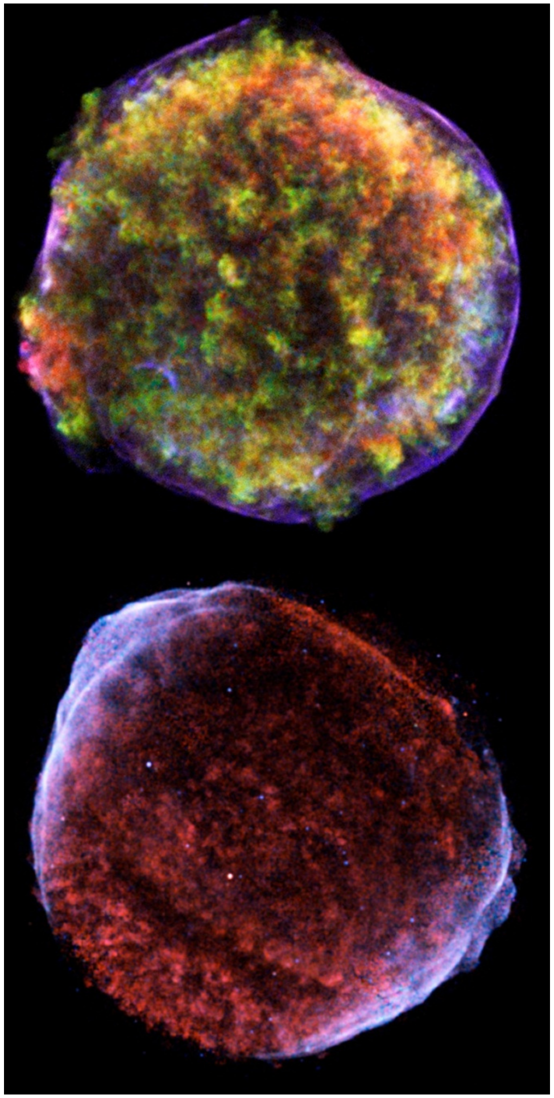




Output

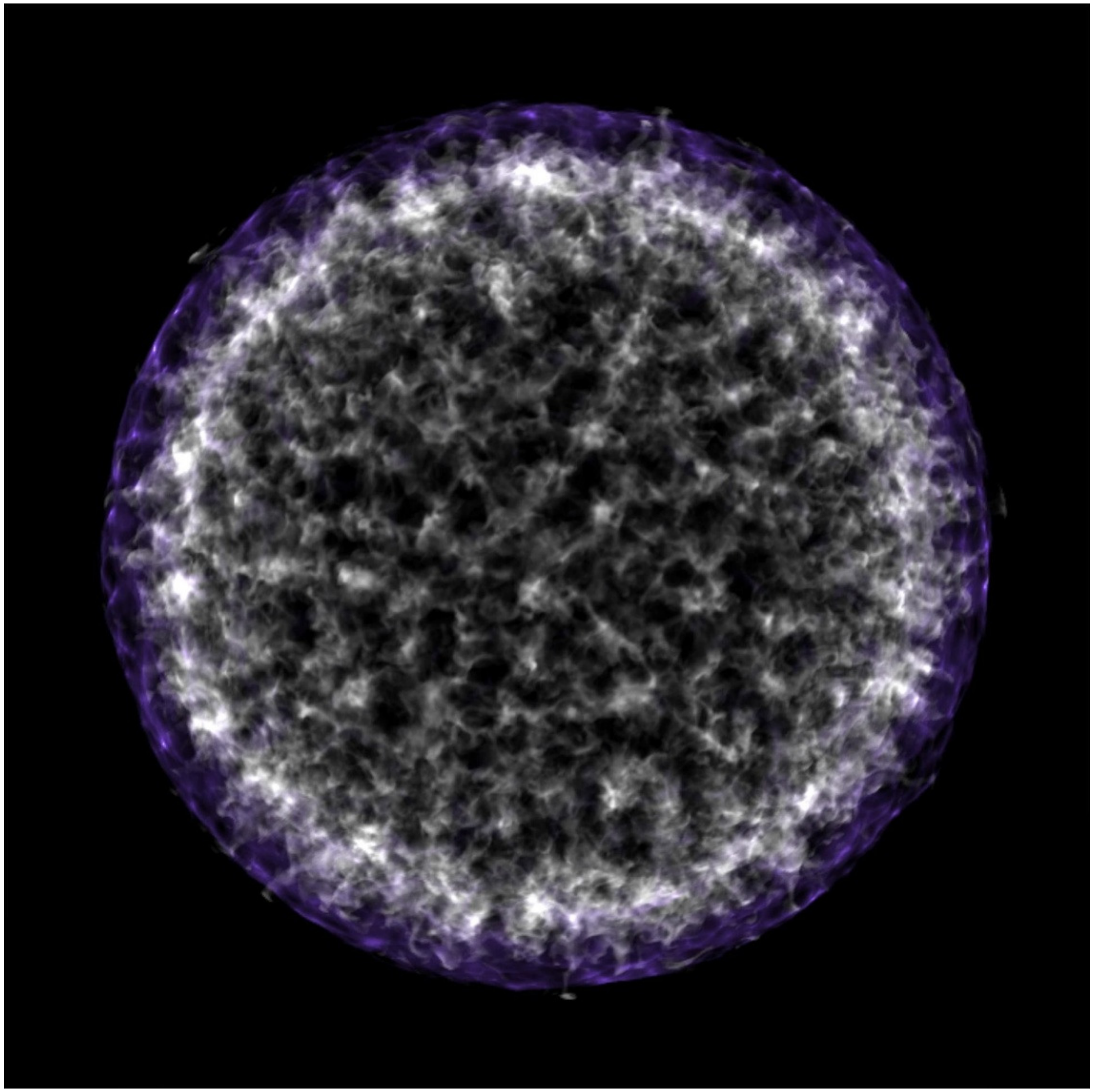
- More images: $\gamma = 4/3$ run at $t = 2.0$

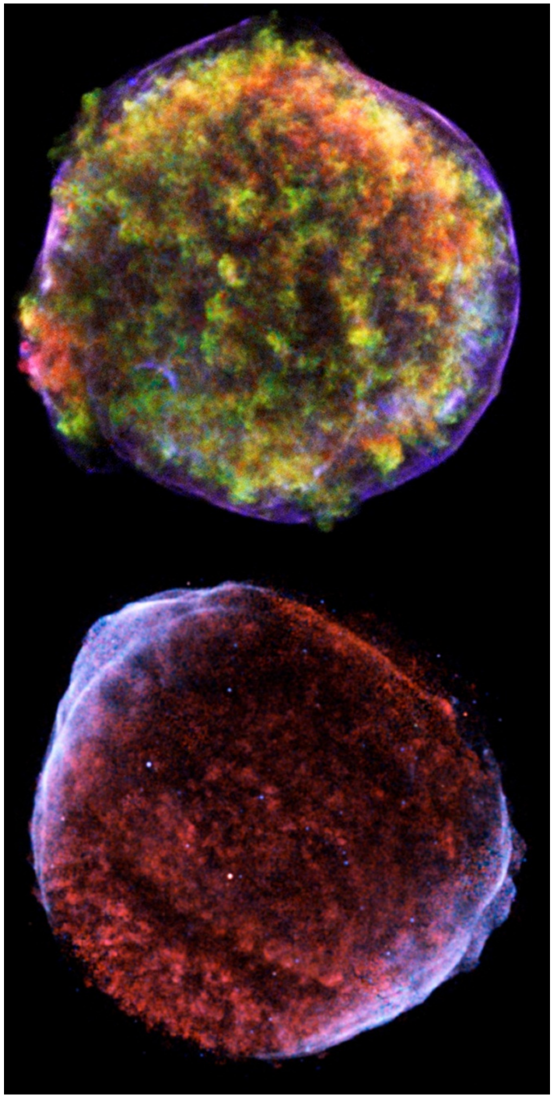




Output

- More images: $\gamma = 6/5$ run at $t = 2.0$





Output

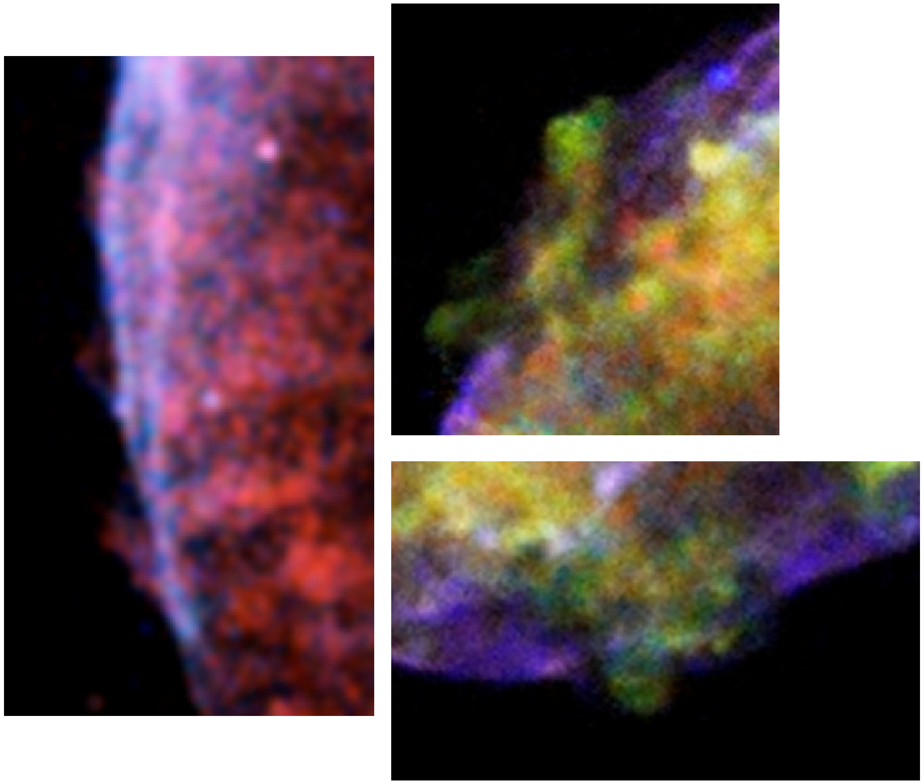
- Key results:
  - Smooth ejecta <u>can</u> generate structures seen in Tycho and SN 1006 – no physics beyond fluid instabilities needed
  - Long simulation duration washes out small initial instabilities
  - Remnants look very different at different times, or with different compressibilities

Output

- Key results:
  - Increase age → increase size of RT structures
  - Change γ → change shape of RT structures
  - Decrease γ → make observed forward shock filamentary
  - Decrease γ → dramatically reduce separation between ejecta and forward shock
  - Hydrodynamics simulations give *amazingly* pretty results

Output

- Ejecta knots ahead of forward shock is projection effect combined with faint forward shock



3D morphology of Ia SNRs 3107

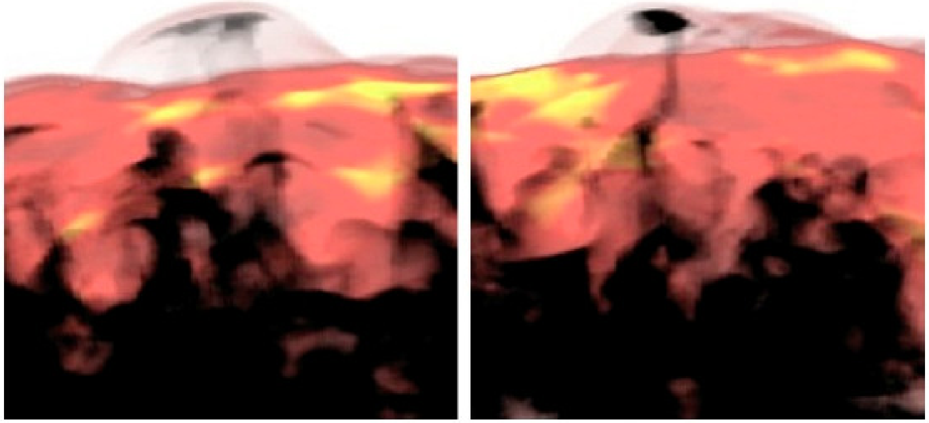
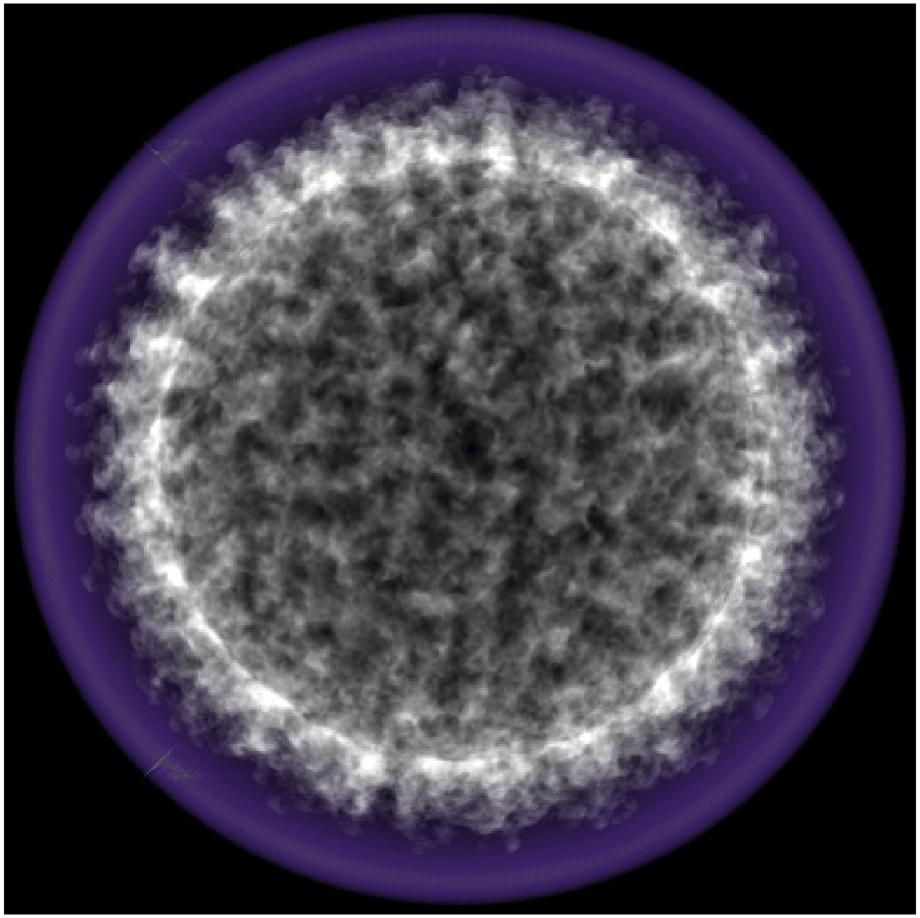


Figure 10. Magnified views of two locations from the $\gamma = 6/5$ run where knots of ejecta seem to have overtaken the forward shock.

Output

- Haven’t mentioned ionization age yet
- Instituting minimum τ for emission excludes freshly shocked ejecta
- Changes location & shape of reverse shock



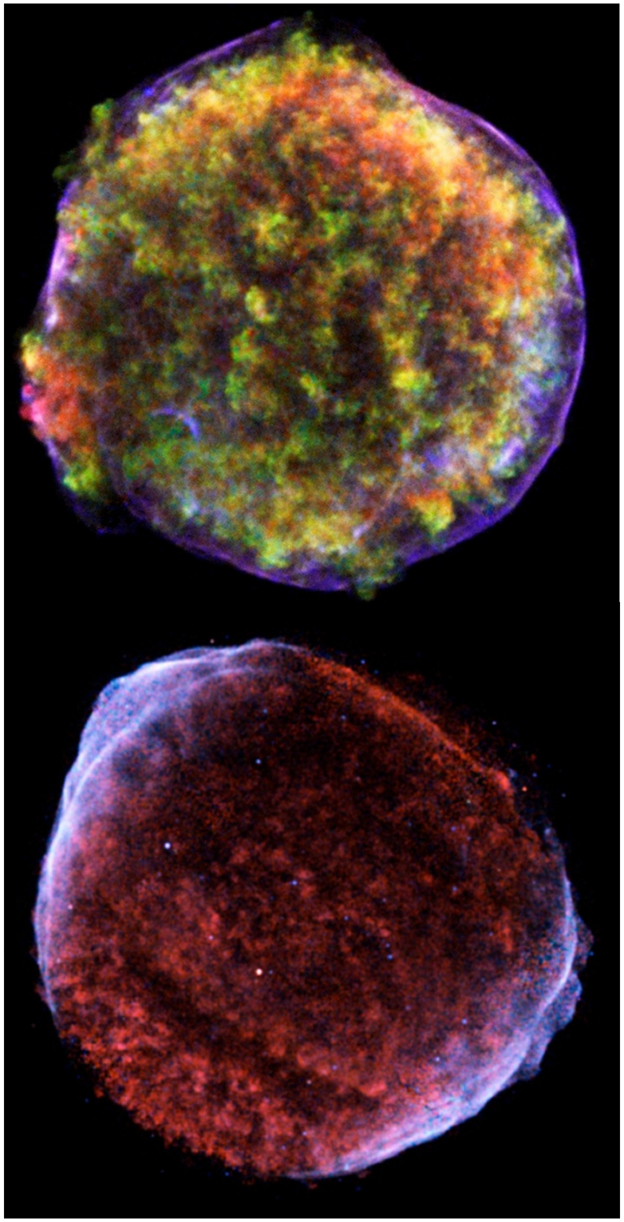
Implications for Tycho & SN1006

- Ejecta structures larger in Tycho than SN1006; larger dynamical age for Tycho?
- Also, exponential model governed by 3 parameters – M_e/M_{Ch}, E_{51}, and n_0. Can we determine those?

$$R' = \left(\frac{M_e}{4/3\pi\rho_{am}}\right)^{1/3} \approx 2.19 \left(\frac{M_e}{M_{Ch}}\right)^{1/3} n_0^{-1/3}\ \mathrm{pc},$$

$$V' = \left(\frac{2E}{M_e}\right)^{1/2} \approx 8.45 \times 10^3 \left(\frac{E_{51}}{M_e/M_{Ch}}\right)^{1/2}\ \mathrm{km\,s^{-1}},$$

$$T' = \frac{R'}{V'} \approx 248 \left(\frac{M_e}{M_{Ch}}\right)^{5/6} E_{51}^{-1/2} n_0^{-1/3}\ \mathrm{yr},$$



Implications for Tycho & SN1006

- Methods available to determine these quantities:
  - Shock separation
  - Fluid/shock velocities
  - (Mostly) known distance/size information

Implications for Tycho & SN1006

- Ratio R_{RS}/R_{CD} for Tycho with (good) assumption that $\gamma = 5/3$ for ejecta gives estimate of $t = 1.6$
- Can also use R_{RS}/R_{FS} (as in Warren+ 2005), but requires extra assumption about compressibility of material at forward shock
- Assuming $\gamma_{FS} \geq 4/3$ also gives $t = 1.6$

Implications for Tycho & SN1006

- SN1006 reverse shock speed of 7026 km/s (Hamilton+ 2007) suggests *t* = 1.0

- Tycho Fe Kα line speed of 4000 km/s (Hayato+ 2010) suggests *t* = 1.1
- Tycho ejecta expansion velocity of 4700 km/s (Hayato+ 2010) suggests *t* = 1.0

- Mystery: Tycho’s velocities and radial profile each internally consistent, but don’t mutually agree

Implications for Tycho & SN1006

- For SN1006 have good idea of distance, 2.18 kpc (Winkler+ 2003)
- Angular size means $r = 9.19$ pc
- Best estimate: $n_0 = 0.019$, $E_{51} = 1.4$ (or $n_0 = 0.03$, $E_{51} = 2.1$ if $M_e/M_{Ch} = 1.5$)

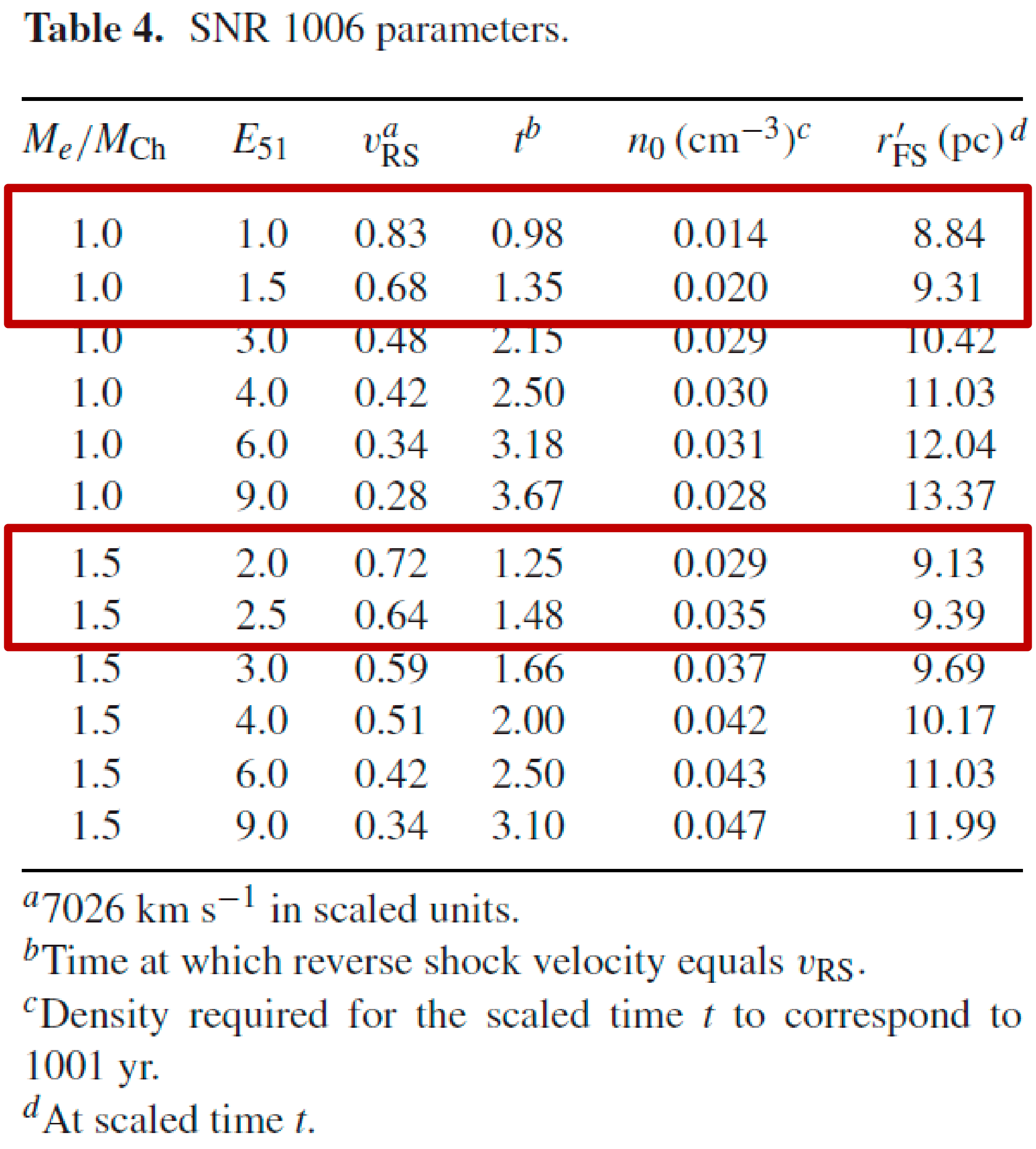


Table 4. SNR 1006 parameters.

$M_e/M_{\rm Ch}$	E_{51}	$v^a_{\rm RS}$	t^b	n_0 (cm^{-3})^c	$r'_{\rm FS}$ (pc)^d
1.0	1.0	0.83	0.98	0.014	8.84
1.0	1.5	0.68	1.35	0.020	9.31
1.0	3.0	0.48	2.15	0.029	10.42
1.0	4.0	0.42	2.50	0.030	11.03
1.0	6.0	0.34	3.18	0.031	12.04
1.0	9.0	0.28	3.67	0.028	13.37
1.5	2.0	0.72	1.25	0.029	9.13
1.5	2.5	0.64	1.48	0.035	9.39
1.5	3.0	0.59	1.66	0.037	9.69
1.5	4.0	0.51	2.00	0.042	10.17
1.5	6.0	0.42	2.50	0.043	11.03
1.5	9.0	0.34	3.10	0.047	11.99

[a] 7026 km s^{-1} in scaled units.

[b] Time at which reverse shock velocity equals $v_{\rm RS}$.

[c] Density required for the scaled time t to correspond to 1001 yr.

[d] At scaled time t.

Implications for Tycho & SN1006

- With n_0 = 0.019, E_{51} = 1.4 and M_e/M_{Ch} = 1, dynamical age of SN1006 is t = 1.3
- Measured R_{CD}/R_{FS} gives $\gamma_{eff} \approx 6/5$

- Less information for Tycho, but best guess is that t = 1.0 and γ_{eff} slightly higher than 4/3
- Reason for larger ejecta structures unclear

Conclusions

- Morphology of Tycho & SN 1006 consistent with significant energy loss to CRs at forward shock
- Smooth ejecta sufficient to generate observed ejecta, forward shock structures
- Dynamical ages of Tycho, SN 1006 both ≈ 1, but evidence for Tycho inconsistent
- Much work to be done on both remnants