Trends in Supernova Remnant Research

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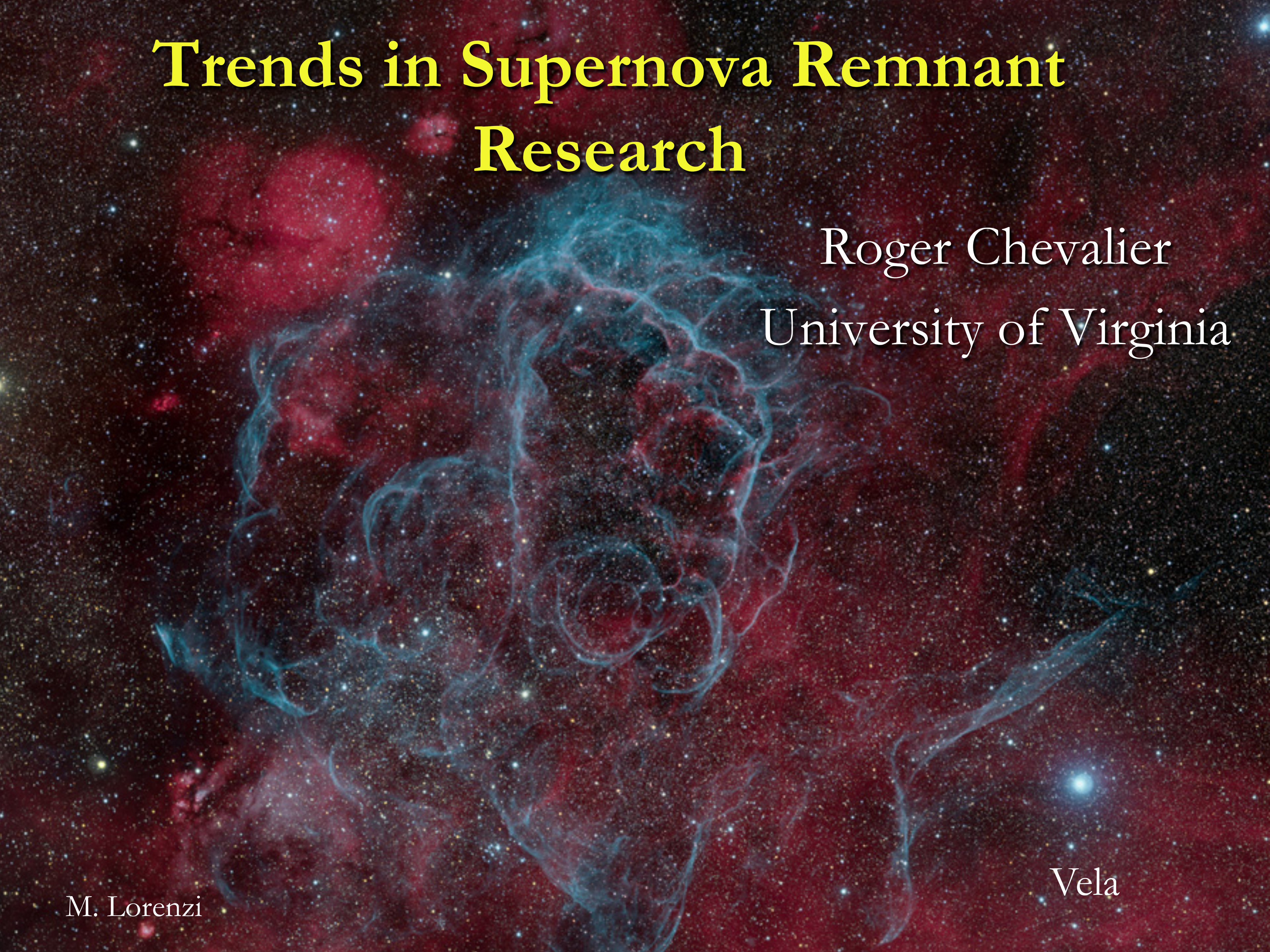
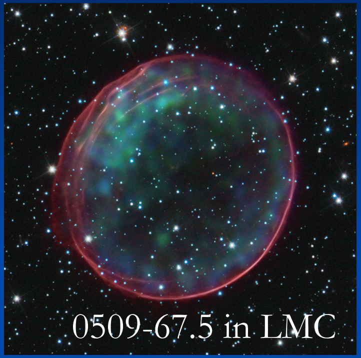
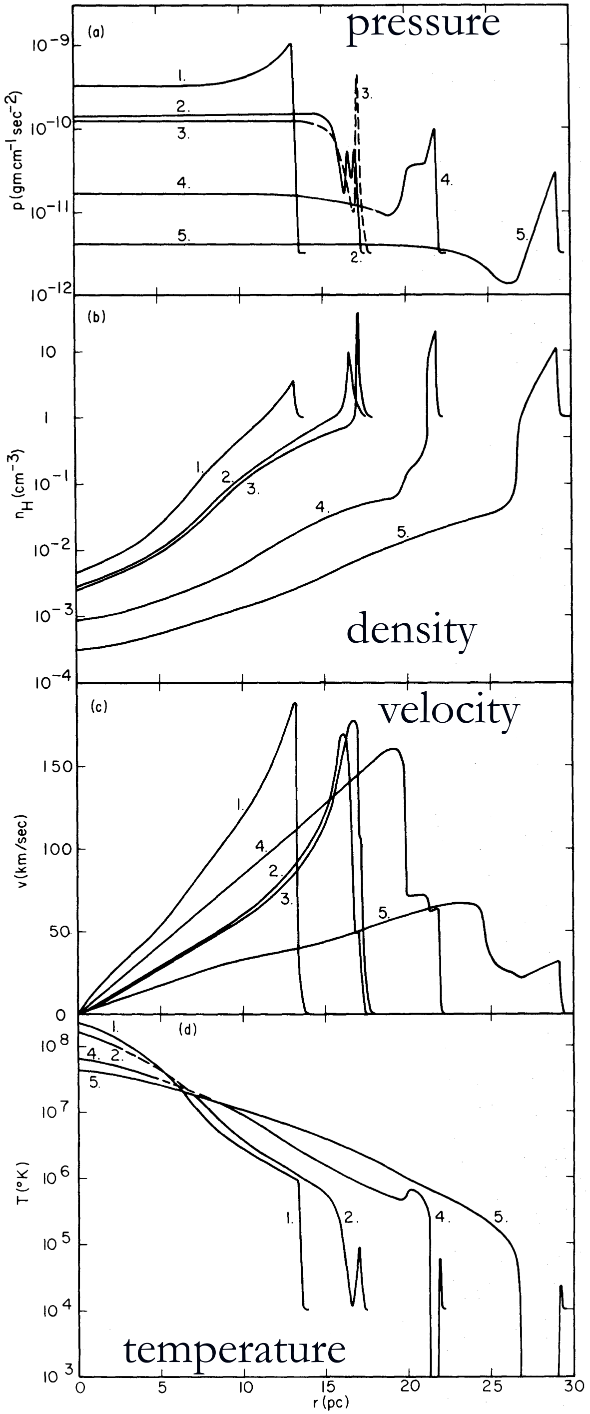
University of Virginia



Evolution stages in uniform medium
(Spitzer 1968, Woltjer 1972,…)

- Ejecta- dominated
  - up to ~10^3 years
- Nonradiative Sedov blast wave
  - up to ~10^4 years
- Radiative shell
  - up to ~10^{5-6} years
- Return to interstellar medium





Radiative remnant

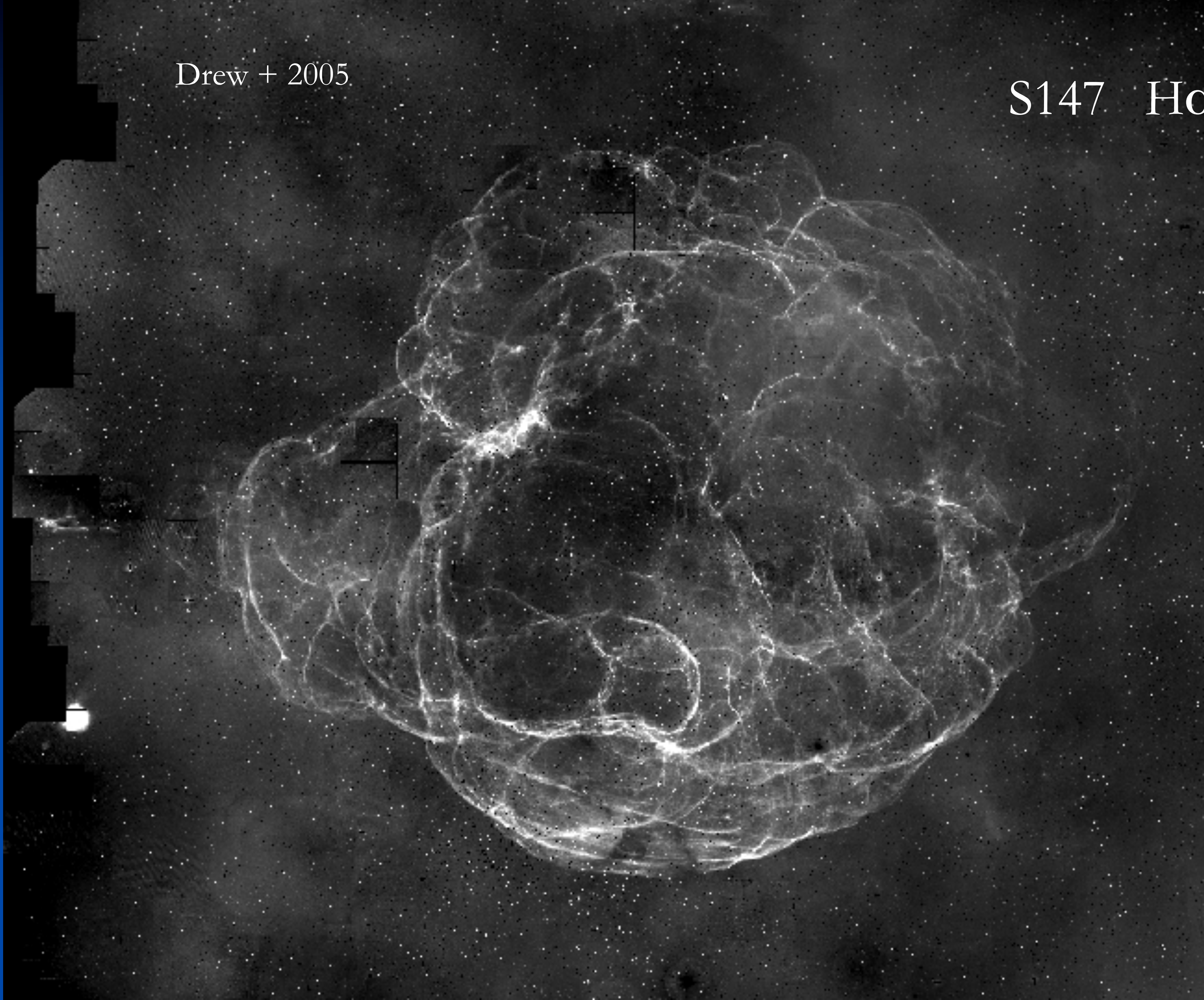
1 Nonradiative Sedov-Taylor

2,3 Shell formation

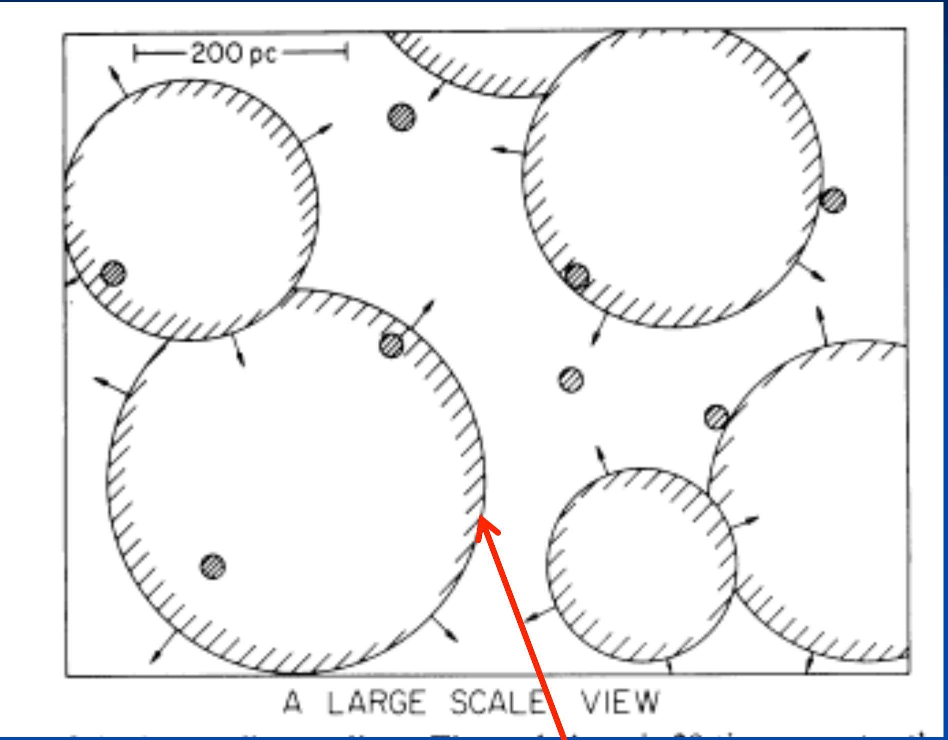
4,5 Cool, dense shell with hot interior

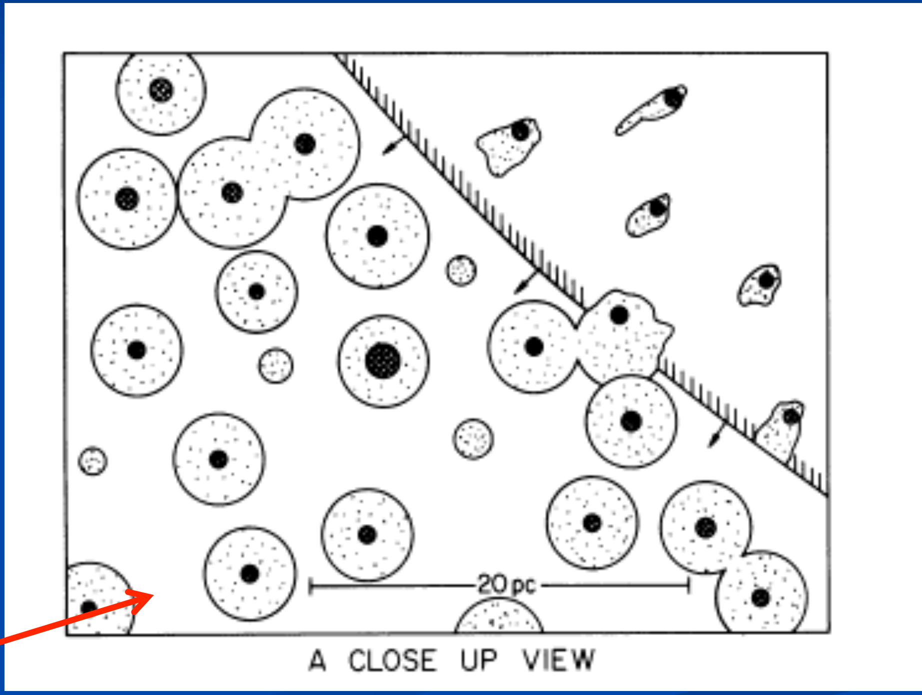
3×10^{50} erg, 1 part./cm^3

RAC 1974


Drew + 2005
S147 Hα

Crushed cloud model for SNRs



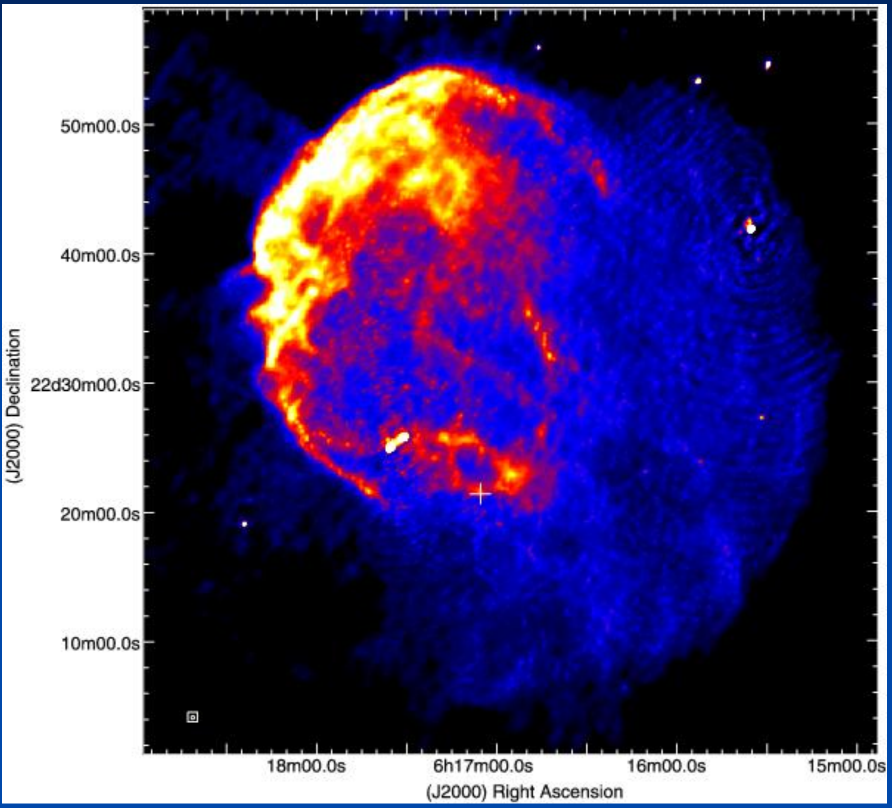


Nonradiative shock

Hot ISM

McKee & Ostriker 1977

IC 443

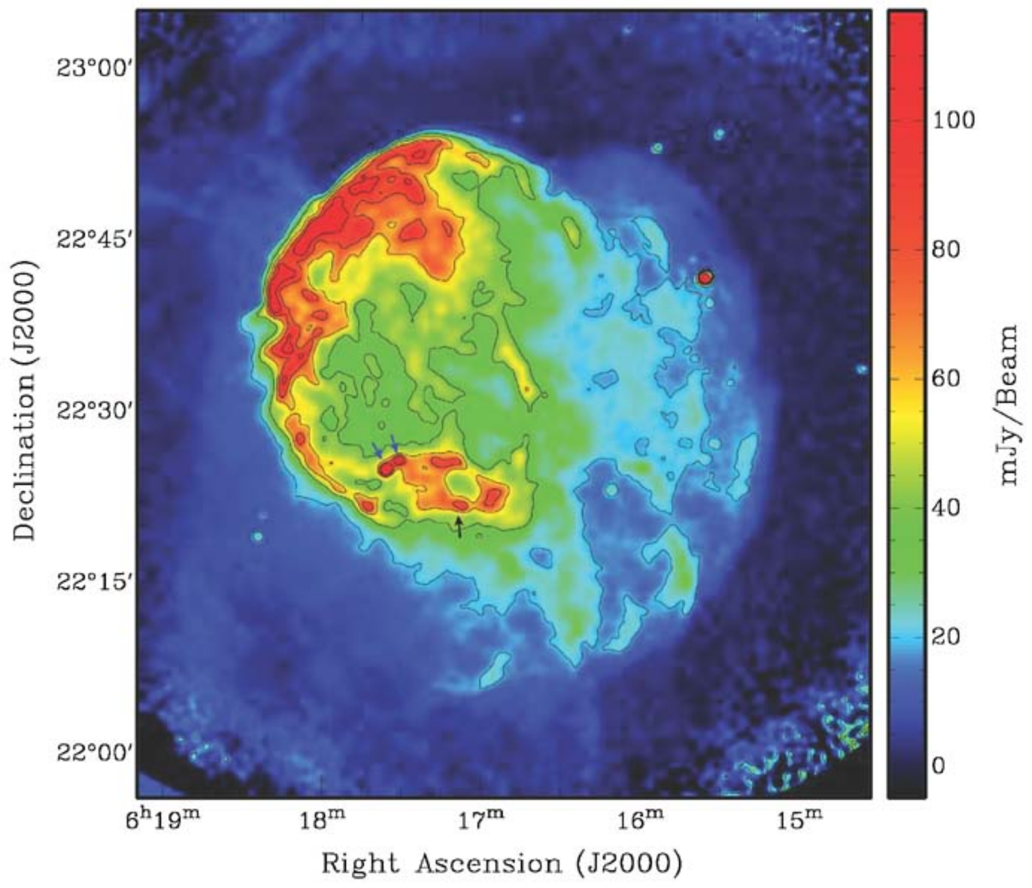


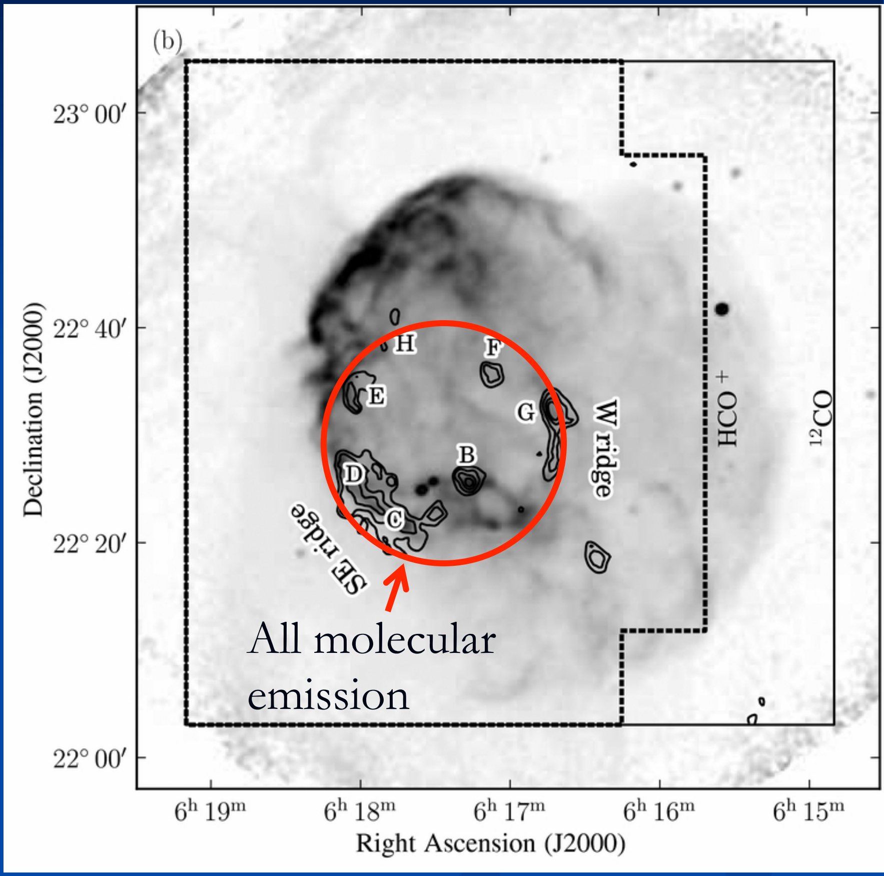
Radio (Lee+ 2008)

Optical Hα

Duin & van der Laan (1975) showed detailed correspondence and developed model of radio from compressed IS fields and particles

IC 443 – a molecular cloud interactor





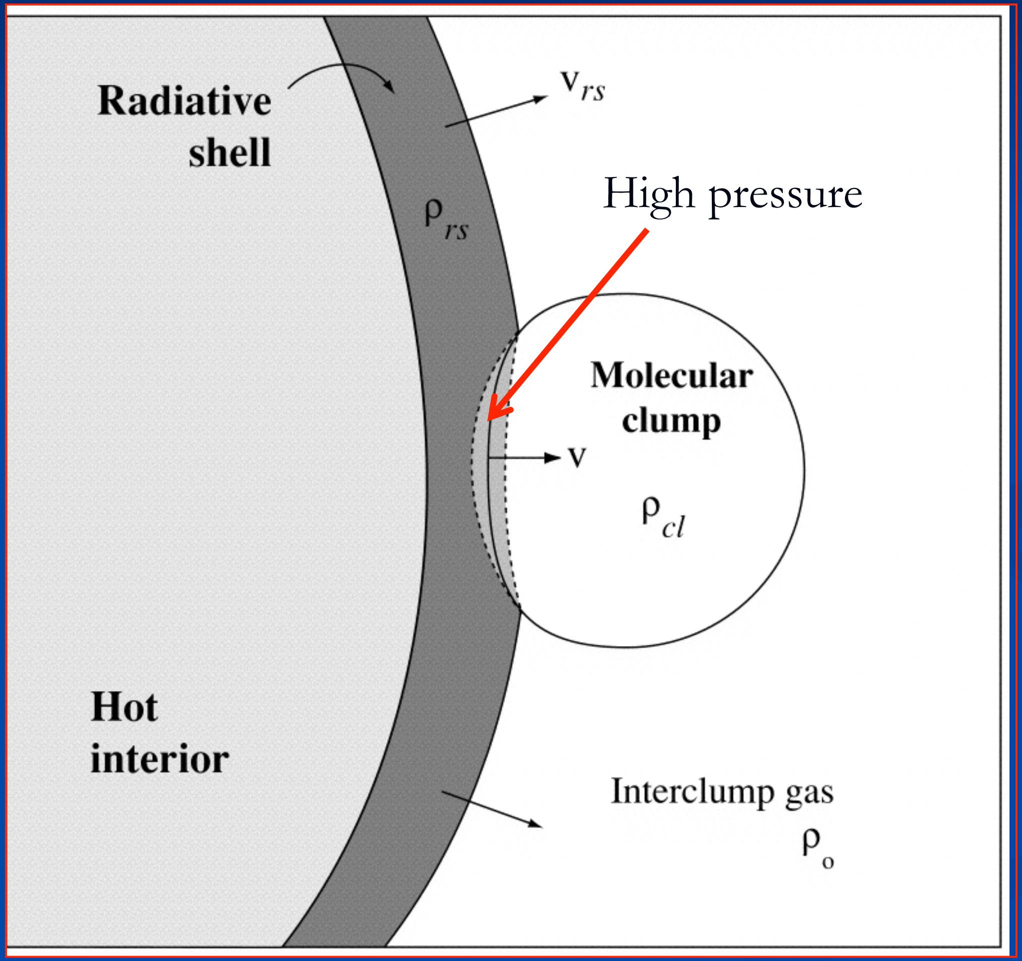
21 cm continuum emission

Lee et al. 2008

Radio continuum
Shocked CO contours
Lee et al. 2012

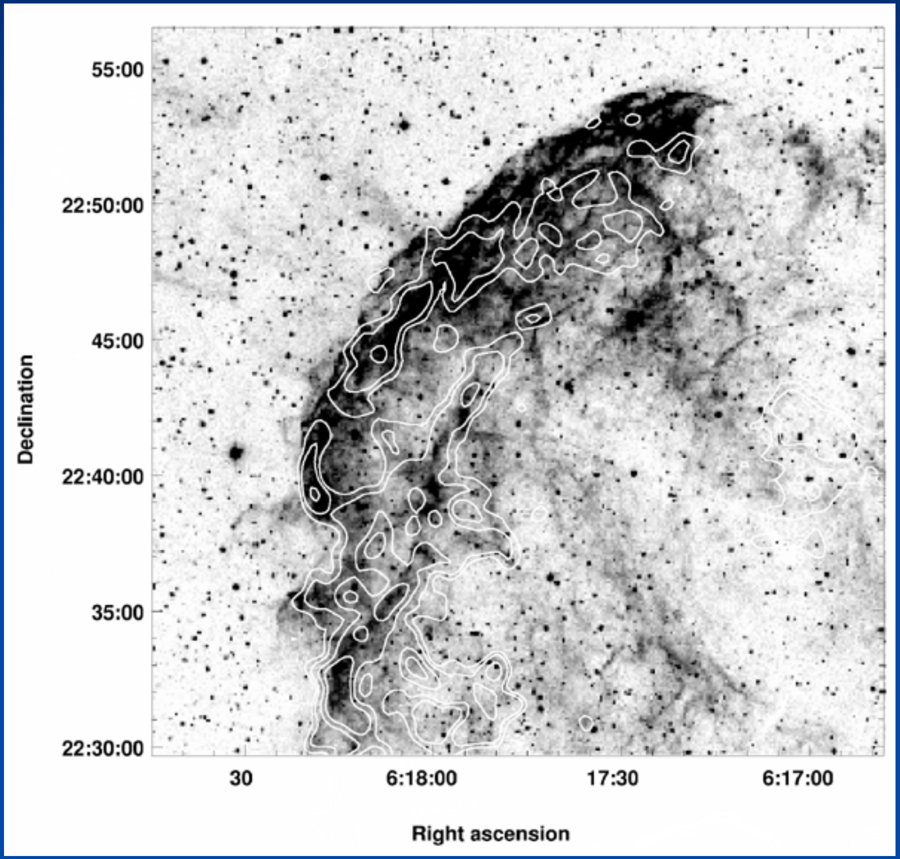
- Early B star (B2, B3) on main sequence (8, 10 $M_{\odot}$) can result in a supernova that interacts with its parent molecular cloud
- Molecular cloud structure
  - Interclump medium $n \sim 10\ cm^{-3}$
  - Clump $n \sim 10^{3}\ cm^{-3}$
  - Dense core $n \sim 10^{5-6}\ cm^{-3}$

Radiative shell/clump interaction model (RAC 99)



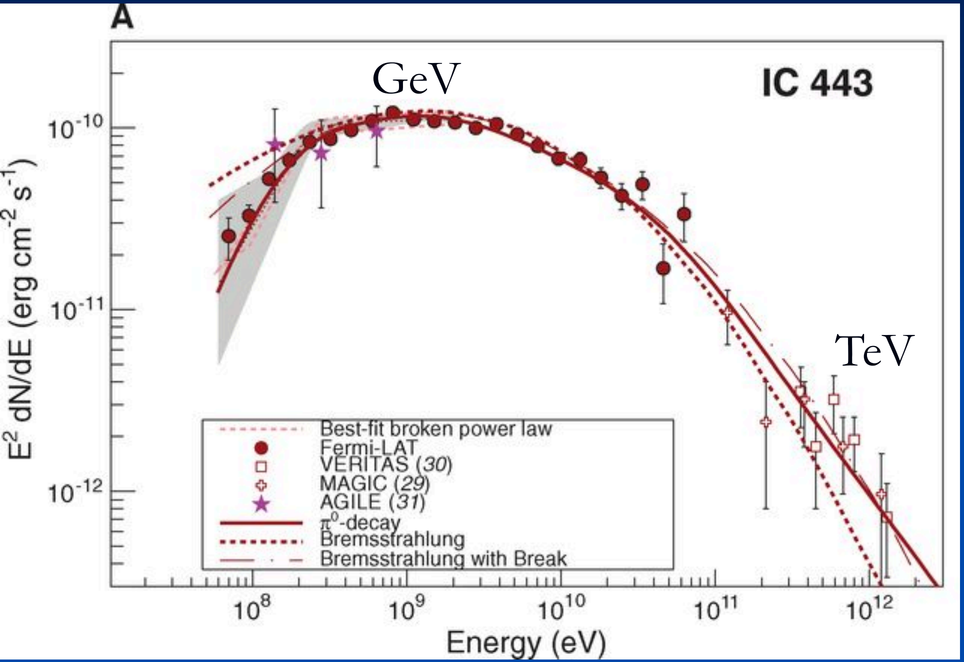
Applied to IC 443, W44, 3C 391

Competing model: nonradiative blast wave in intercloud region (Reach + 2005, Uchiyama + 2010)

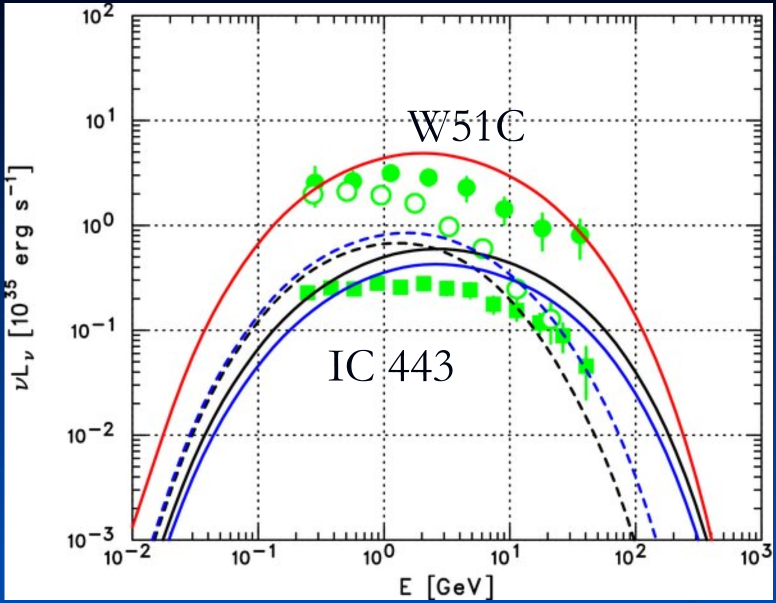


Shocked HI contours on optical image
Lee et al. 2008

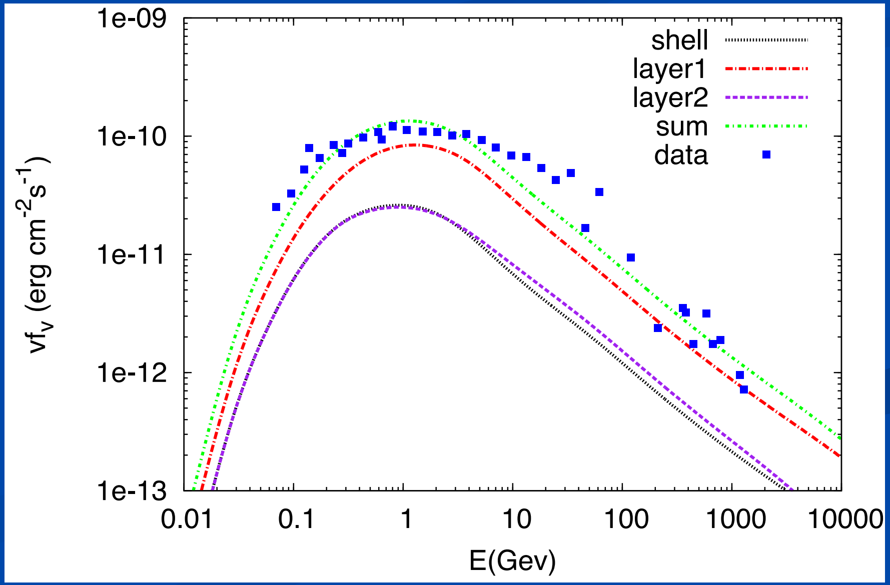
- Column density of HI is about as expected for radiative shell in 10 cm^{-3} gas



Ackermann+ 2013



Uchiyama+ 2010



Tang & RAC 2014

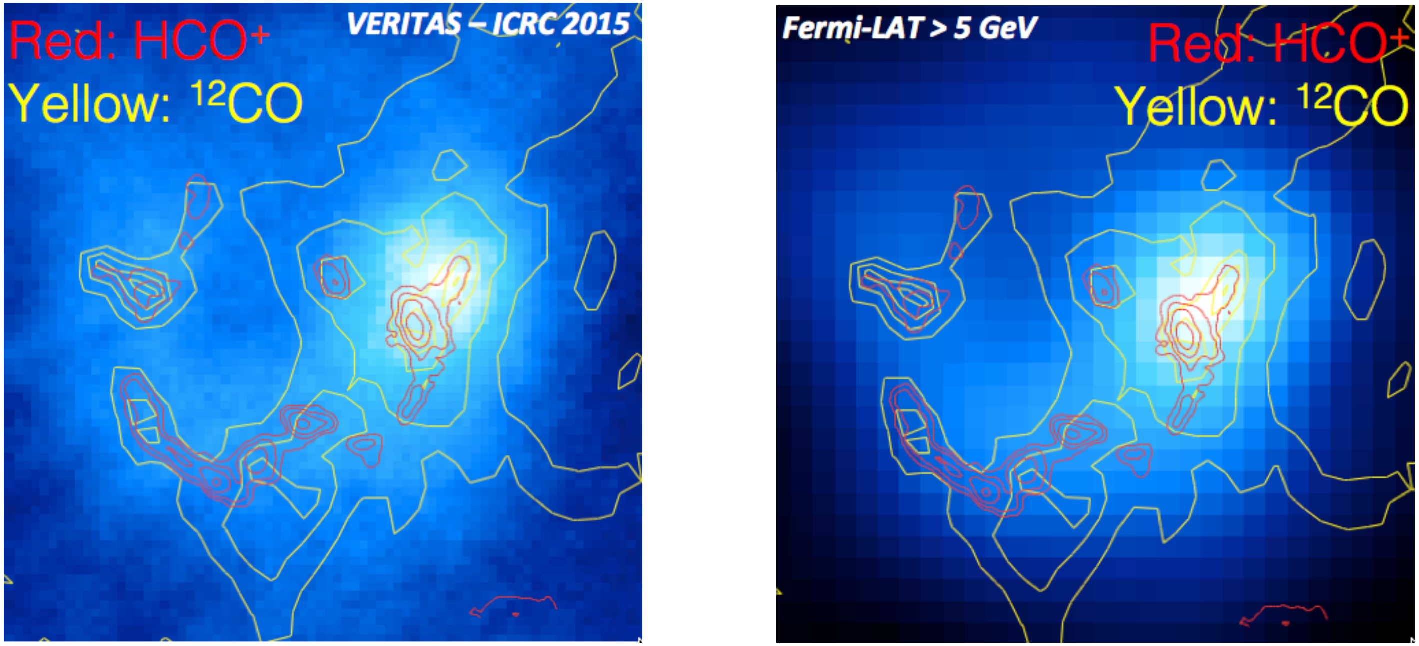


Figure 5: (left) VERITAS excess map with contours of two tracers of shocked gas, HCO^+ (red) and ^{12}CO (yellow) overlaid. (right) The *Fermi*-LAT counts map, with the same contours overlaid.

Humensky +Veritas 2015

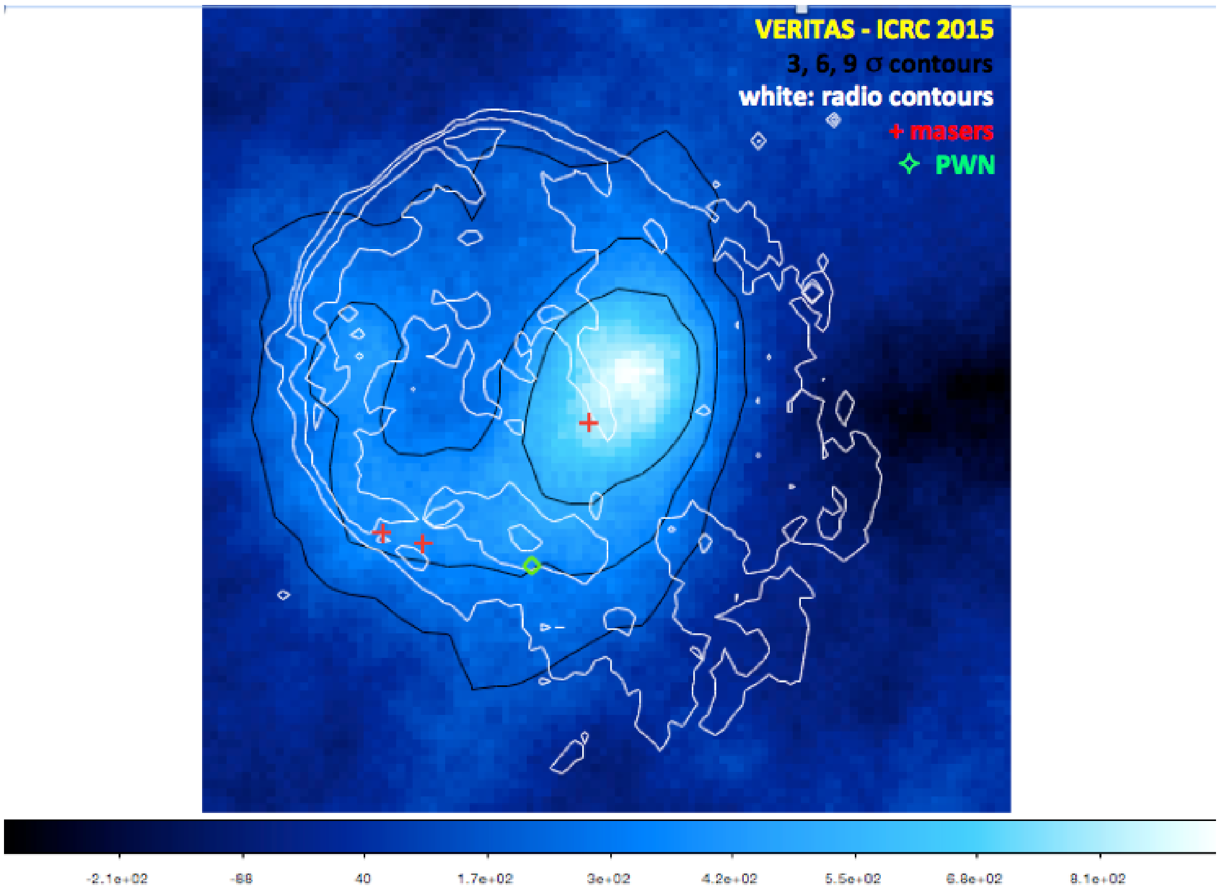
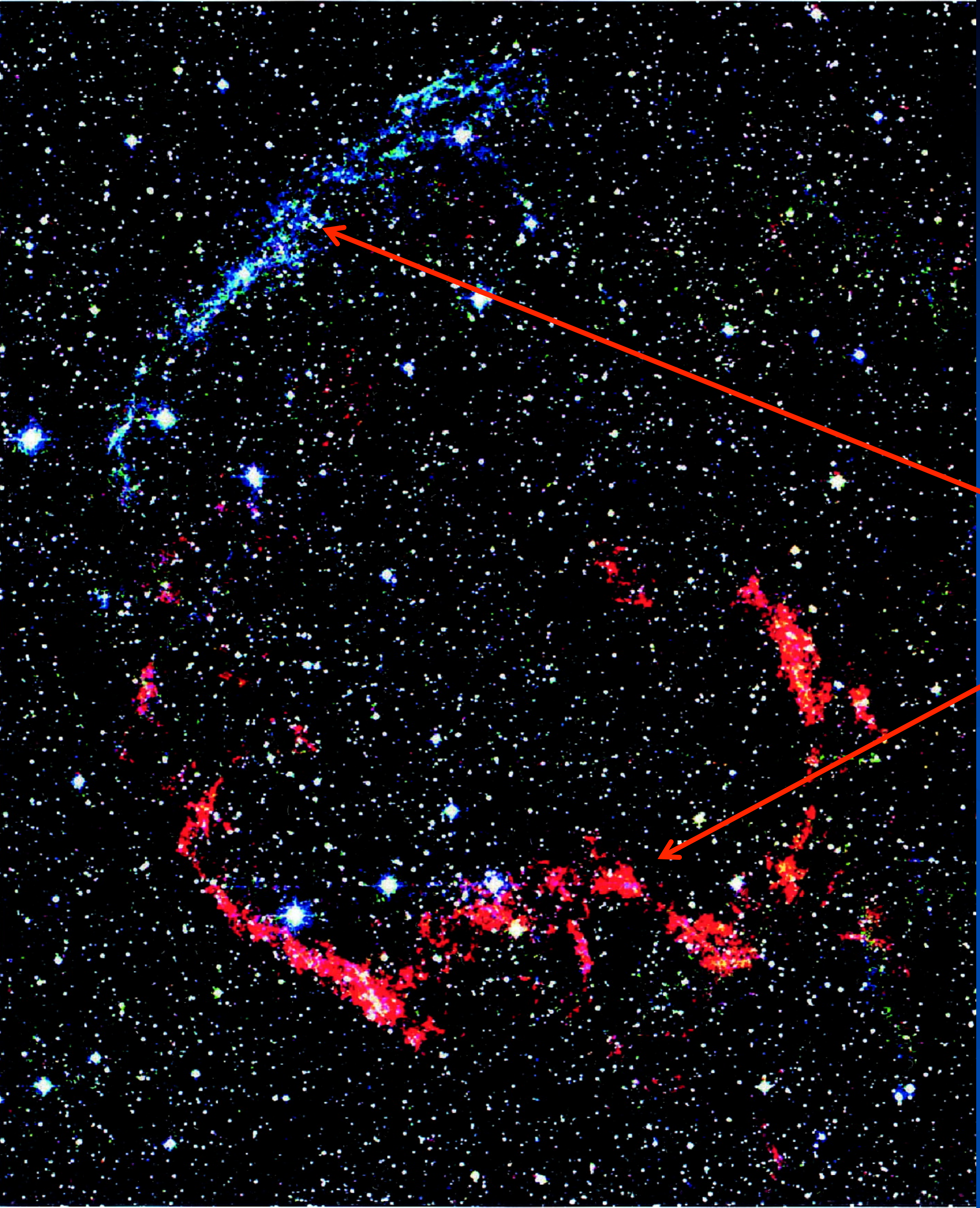


Figure 1: Excess map for the field including IC 443, with the color scale indicating counts integrated within a radius of 0.09° about each point. White contours indicate the radio shell and black contours indicate the significance of the VERITAS observations at the 3, 6, and 9 σ levels. Locations of maser emission are marked in red, while the location of a likely pulsar wind nebula is marked in green.

Humensky +Veritas 2015

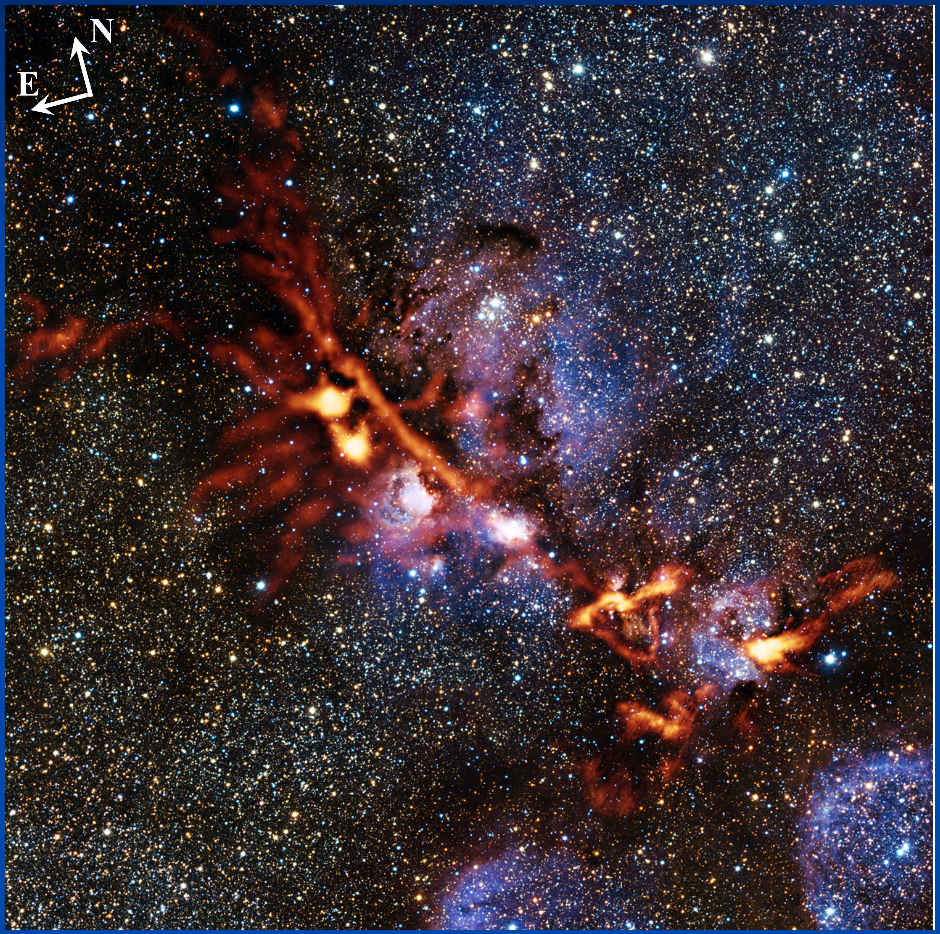


2Mass

Blue, J band, ionic emission from shocks

Red, K band, H_2 emission from shocks

Rho et al. 2001



350 μ dust emission Andre + 2016

Filament in NGC 6334
0.1 pc width
~ 10 pc long
Massive star forming region

Models for "mixed morphology" remnants (IC 443, W44,…)

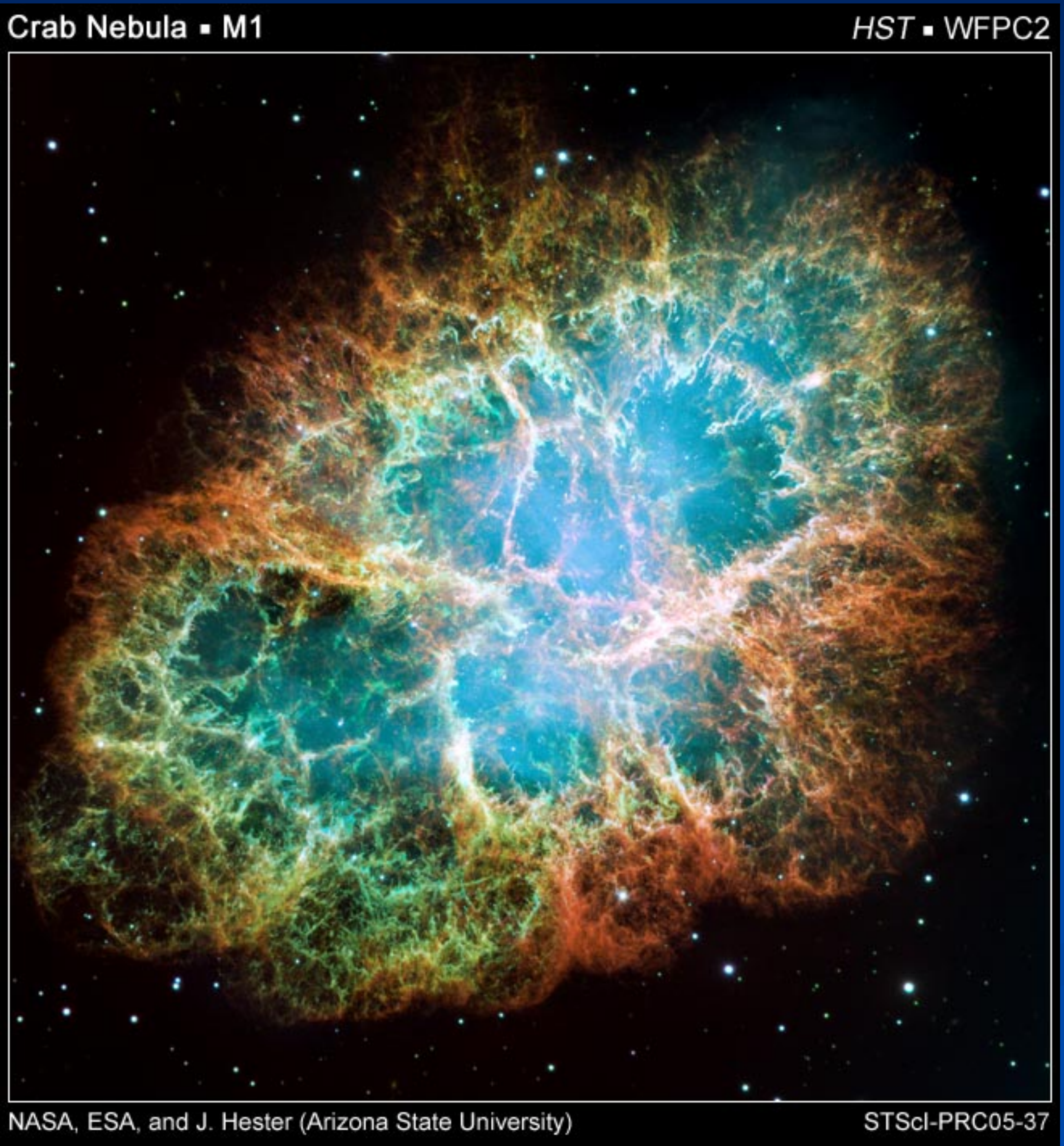
Crushed cloud model

- X-rays indicate current shock velocity
- Mostly nonradiative shock
- Ages 10^3' s of years
- White & Long 1991

Radiative shell model

- X-rays from earlier phase and left in interior
- Mostly radiative shock
- Ages 10^4' s of years
- Chevalier 1999, Shelton, Cox…

Pulsar wind in SN ejecta: the Crab

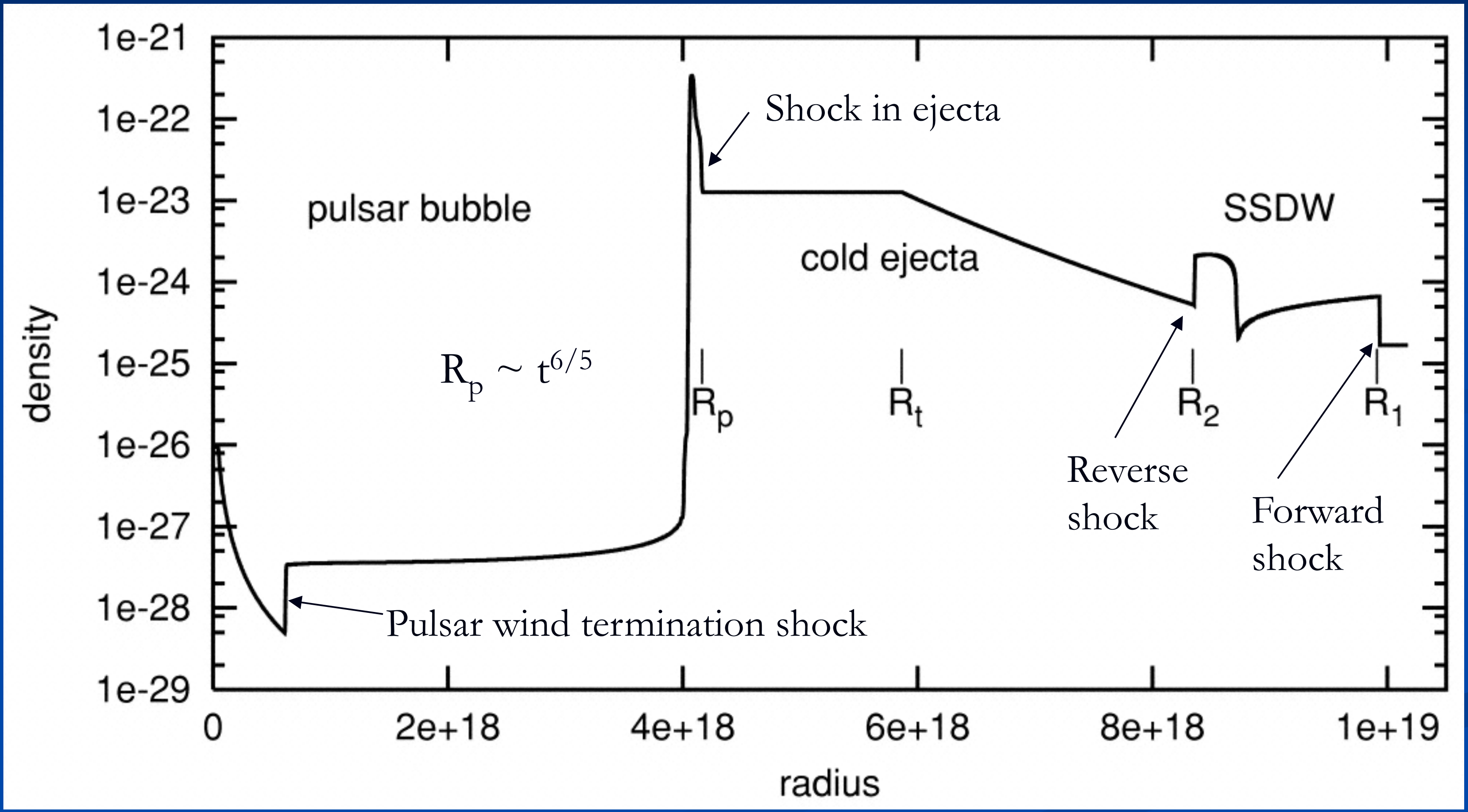


Shell driven by the pulsar bubble in freely expanding ejecta is accelerated and subject to Rayleigh-Taylor instability

Assuming a normal SN energy, SNR shock is at large radius

RAC 1977

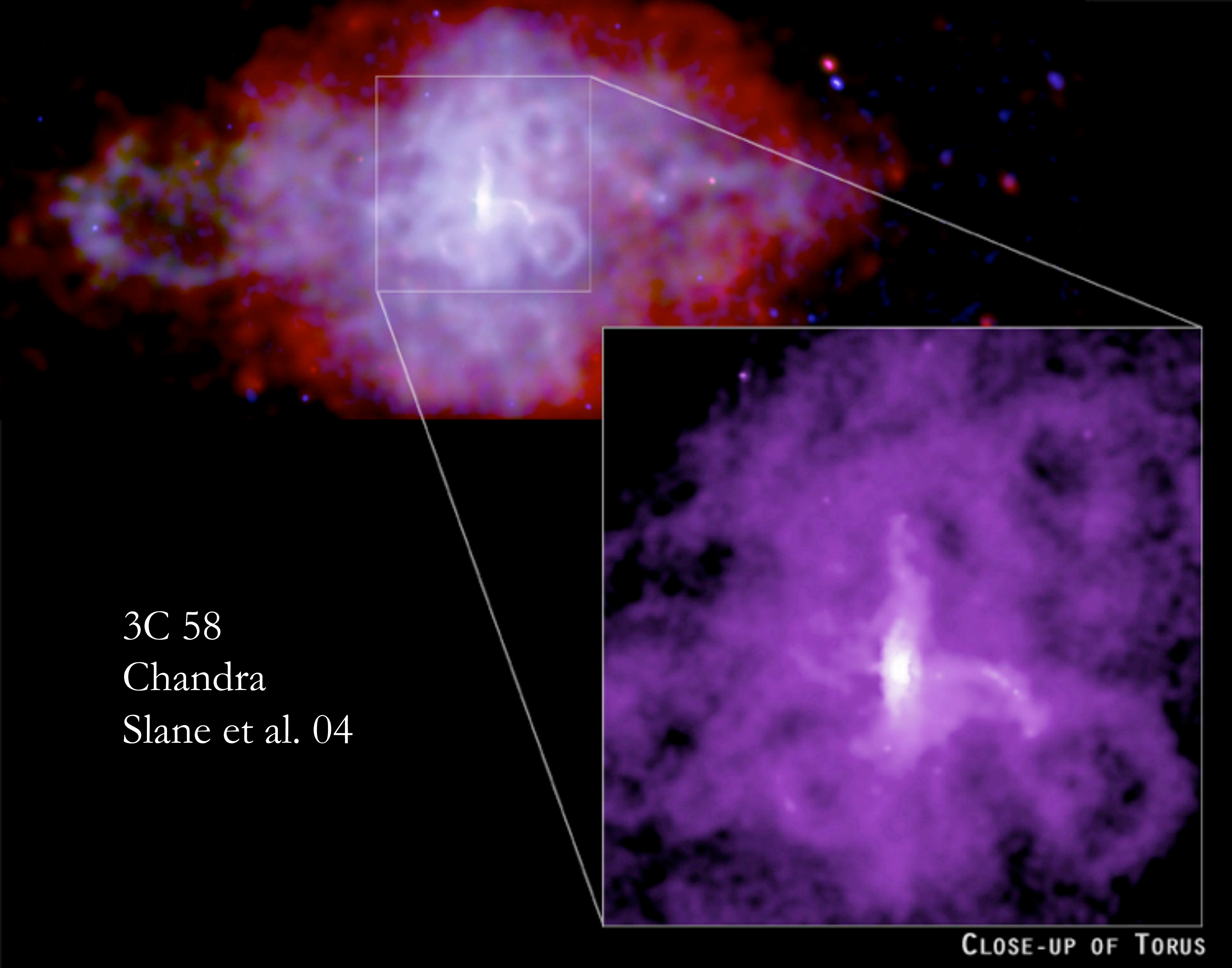
Inner and outer interaction



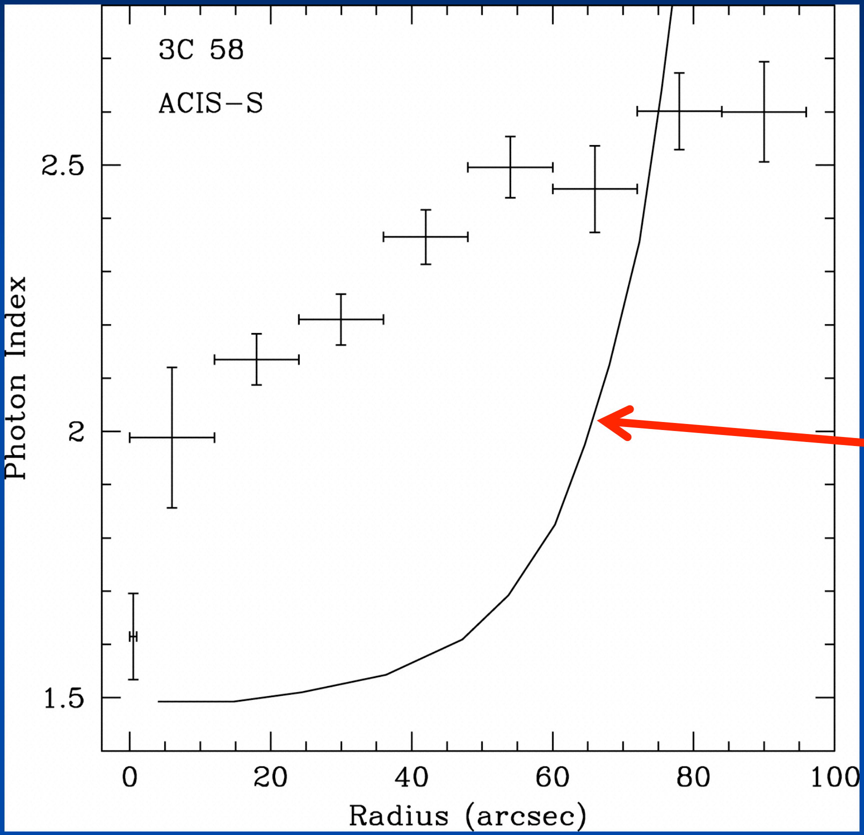
Blondin, RAC, Frierson 01

Chandra, HST


NASA/Spitzer/Gehrz
Infrared



3C 58
Chandra
Slane et al. 04

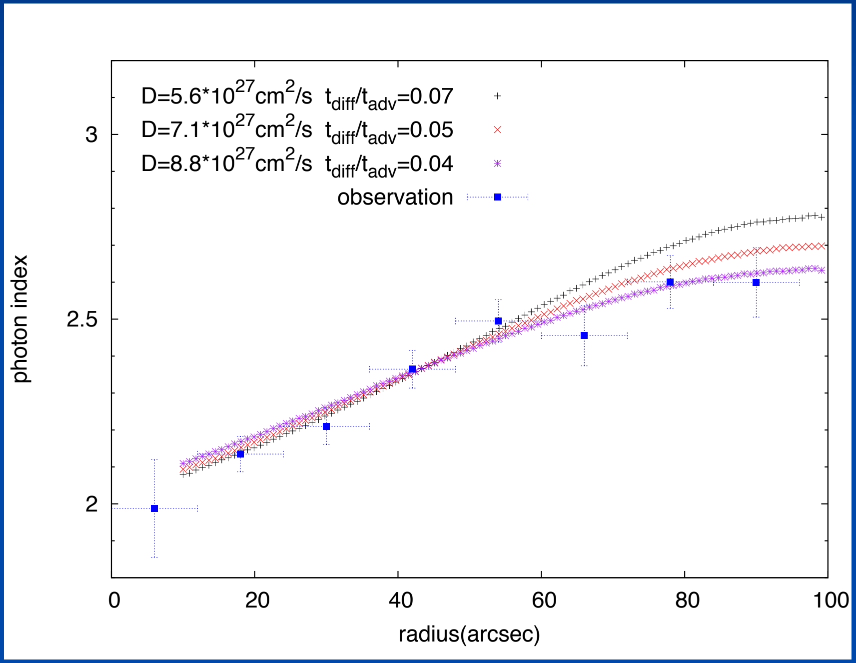


3C 58

X-ray photon index based on KC 84 MHD model

Slane et al. 04 (also Reynolds 03)

Diffusion/Advection Model (Tang+RAC 12)



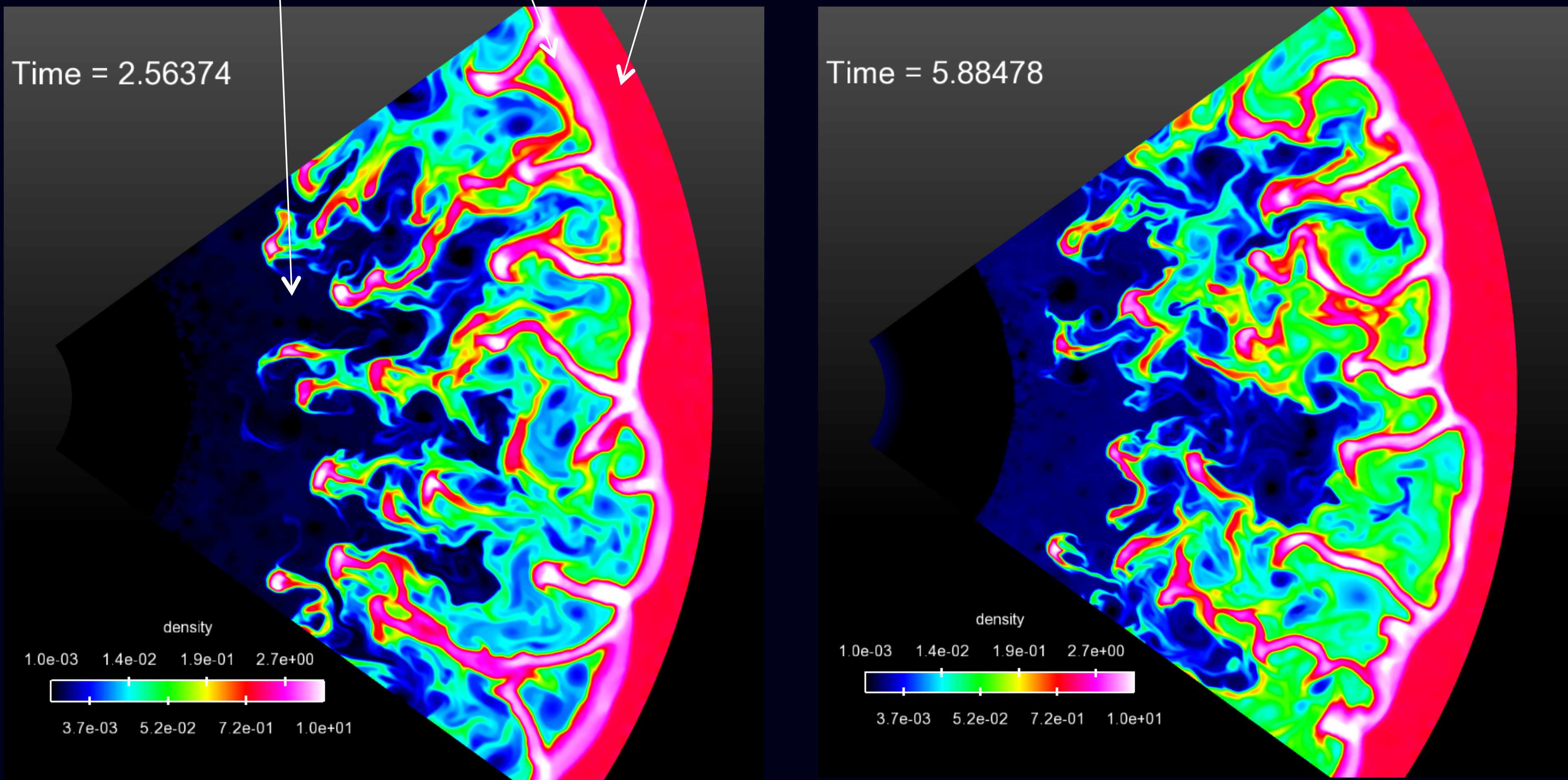
3C 58

- Analytical and Monte Carlo models
- Reflecting outer boundary tends to flatten outer index profile
- Diffusion length < observed filament length

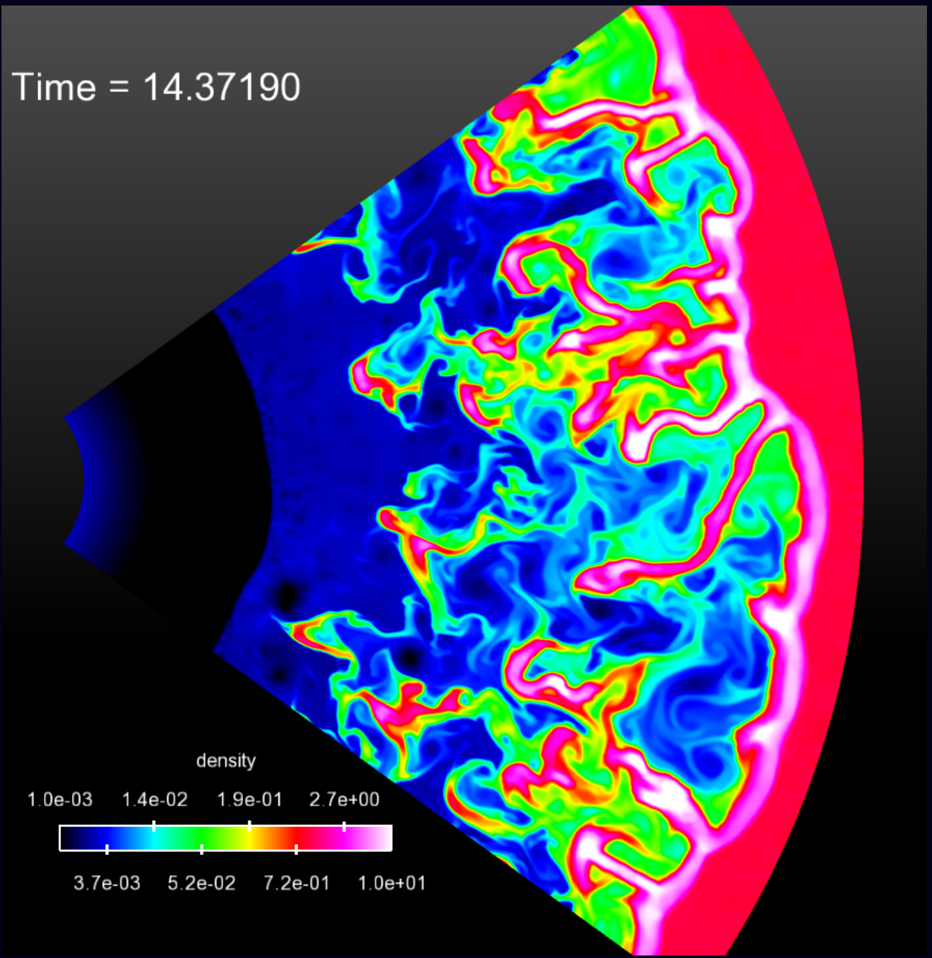
Swept up shell

Shocked pulsar wind

Uniform ejecta



John Blondin, RAC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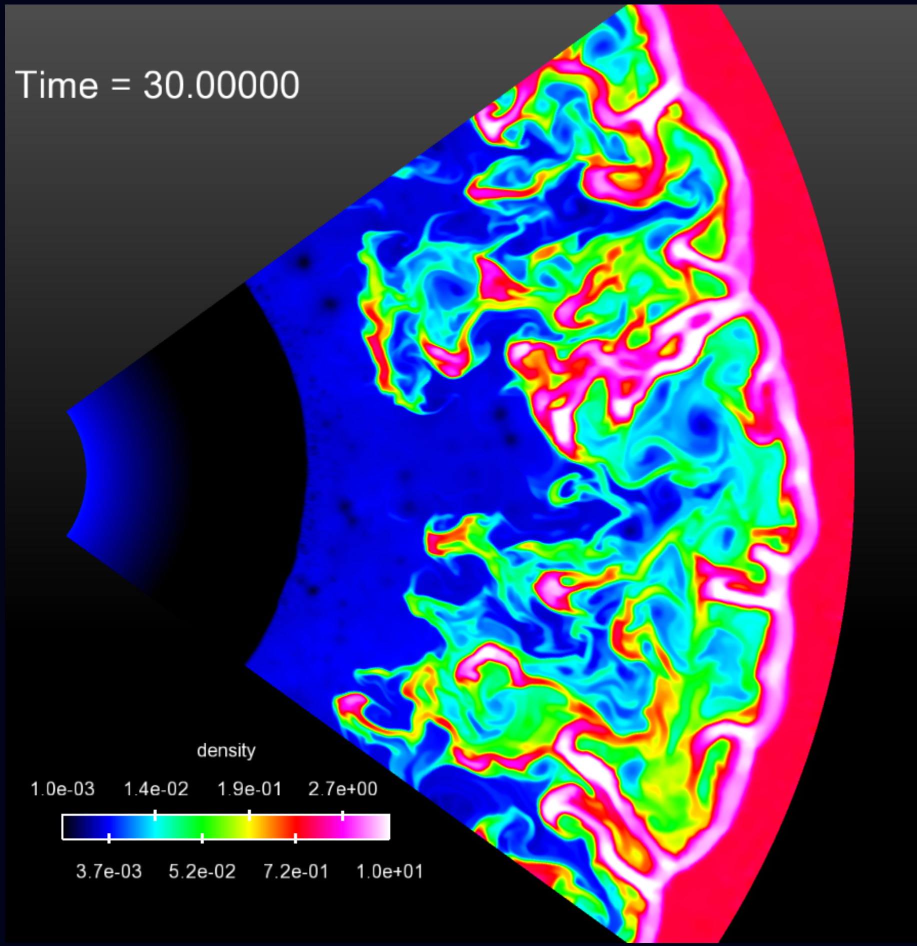
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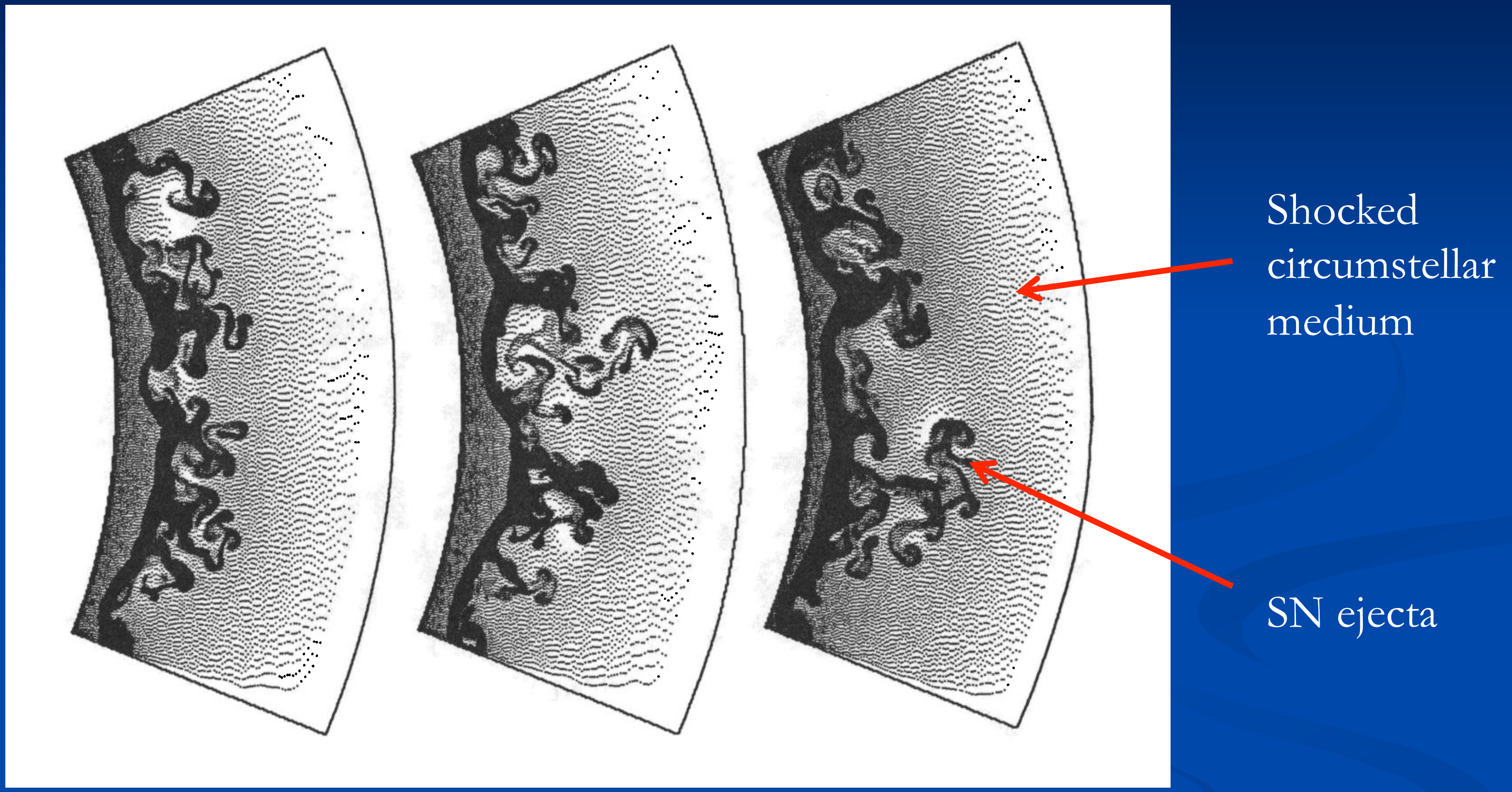
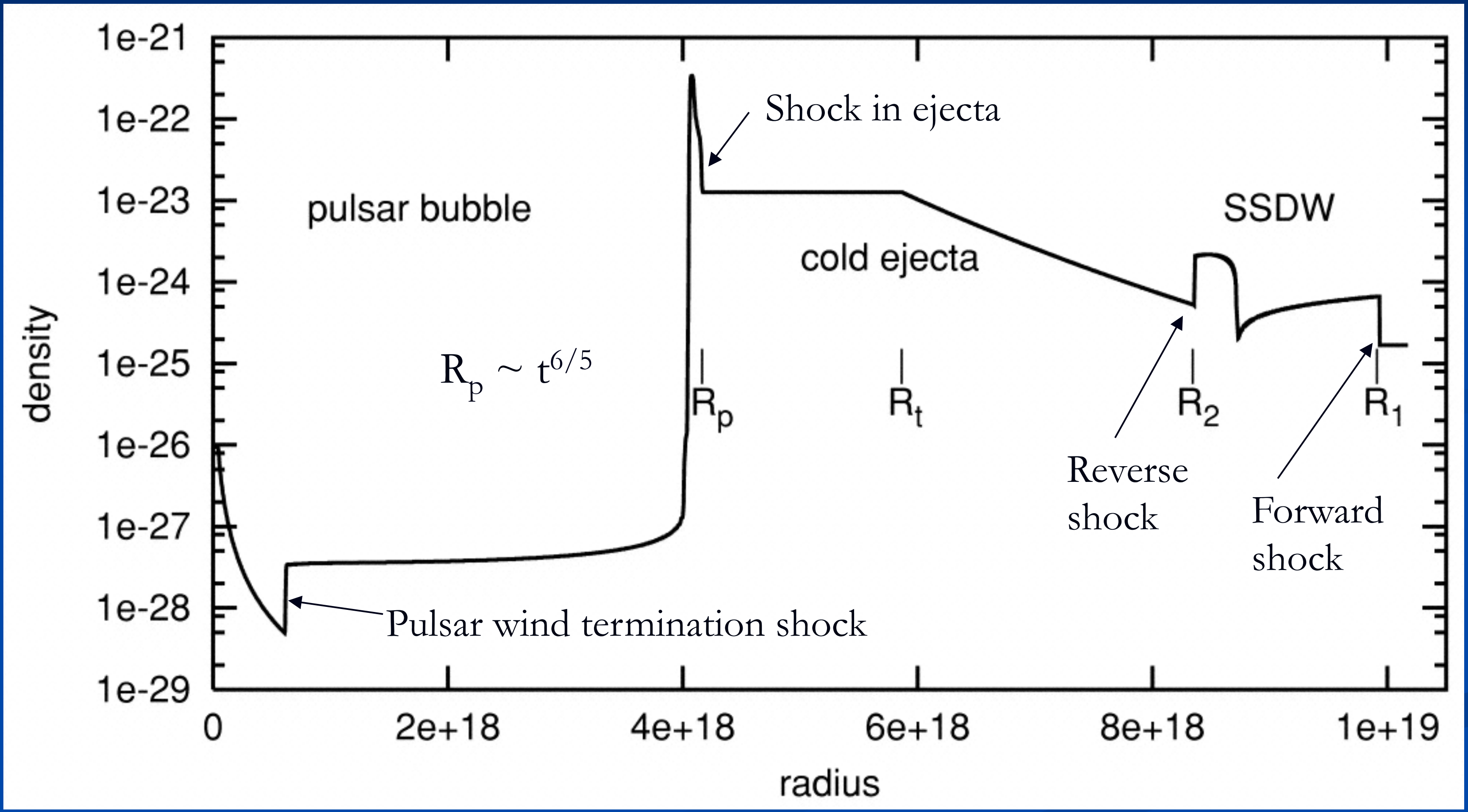
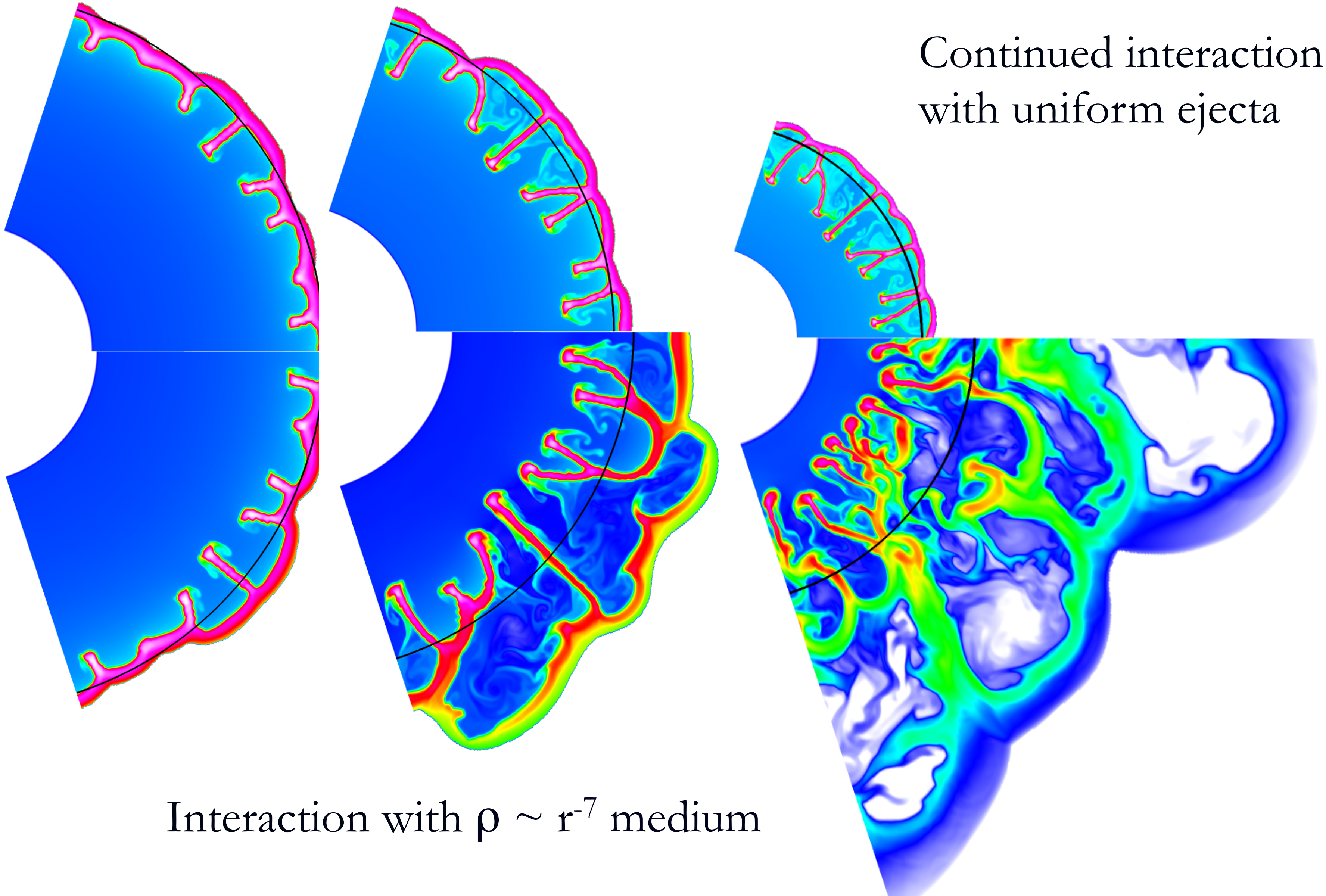


Shocked region driven by the supernova
RAC, Blondin + 92

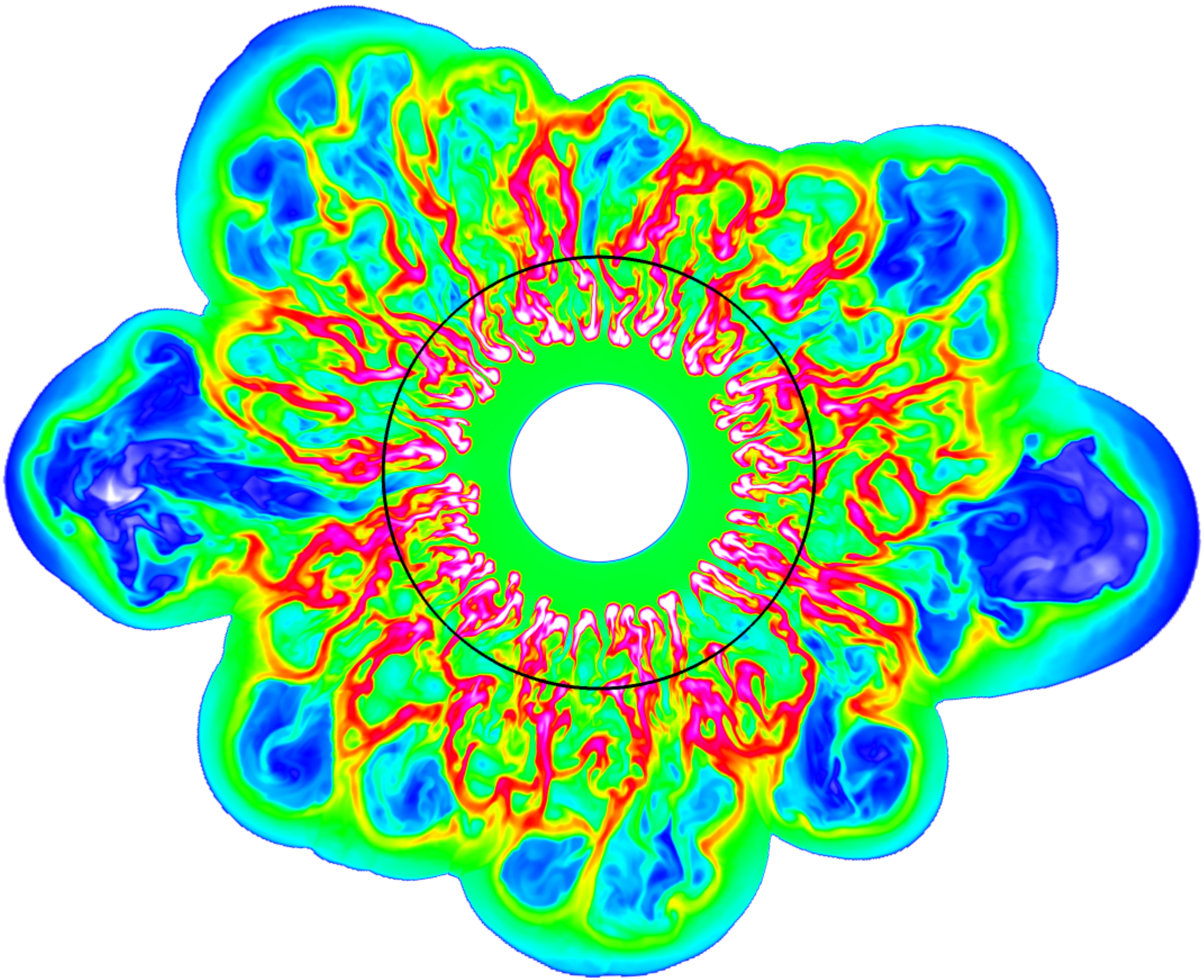


Blondin, RAC, Frierson 01



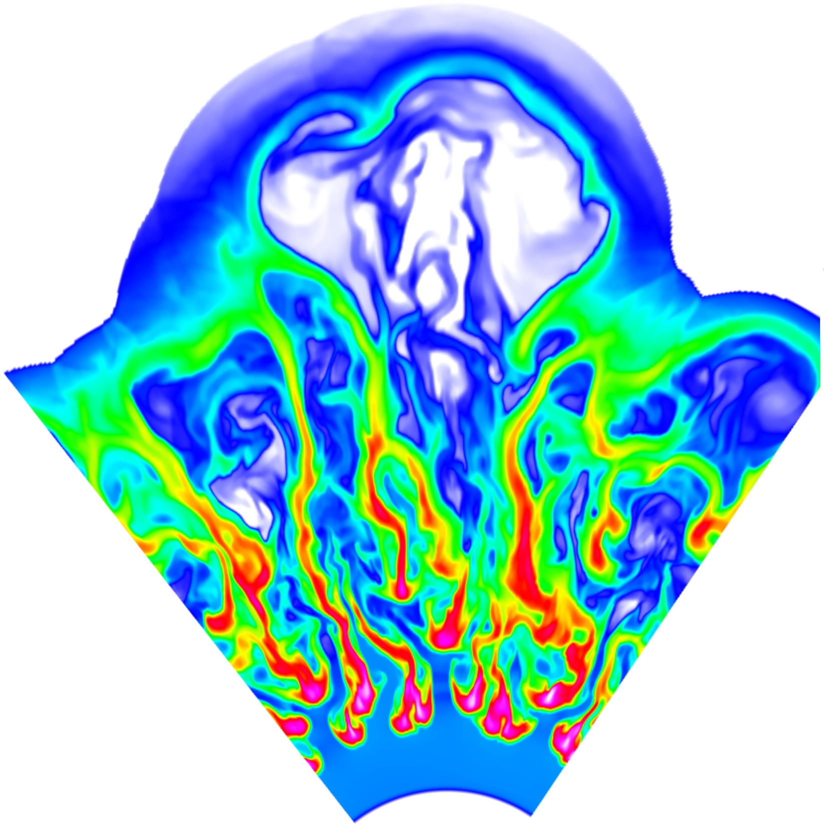
Continued interaction with uniform ejecta

Interaction with $\rho \sim r^{-7}$ medium

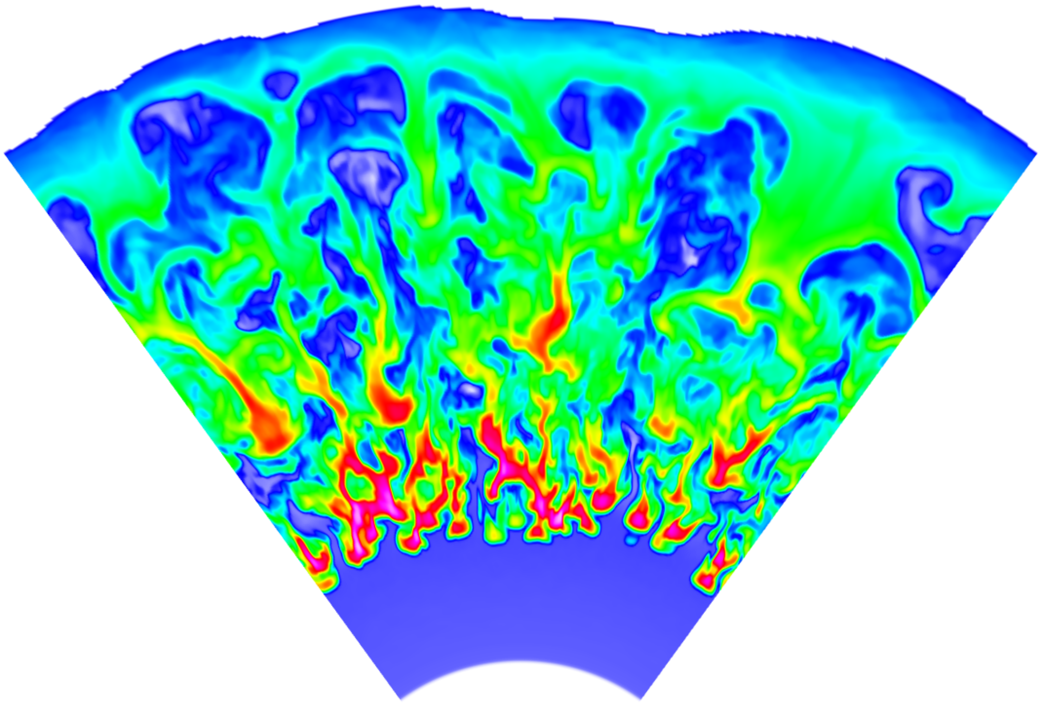


2 D

Post-blowout phase



2-dimensional

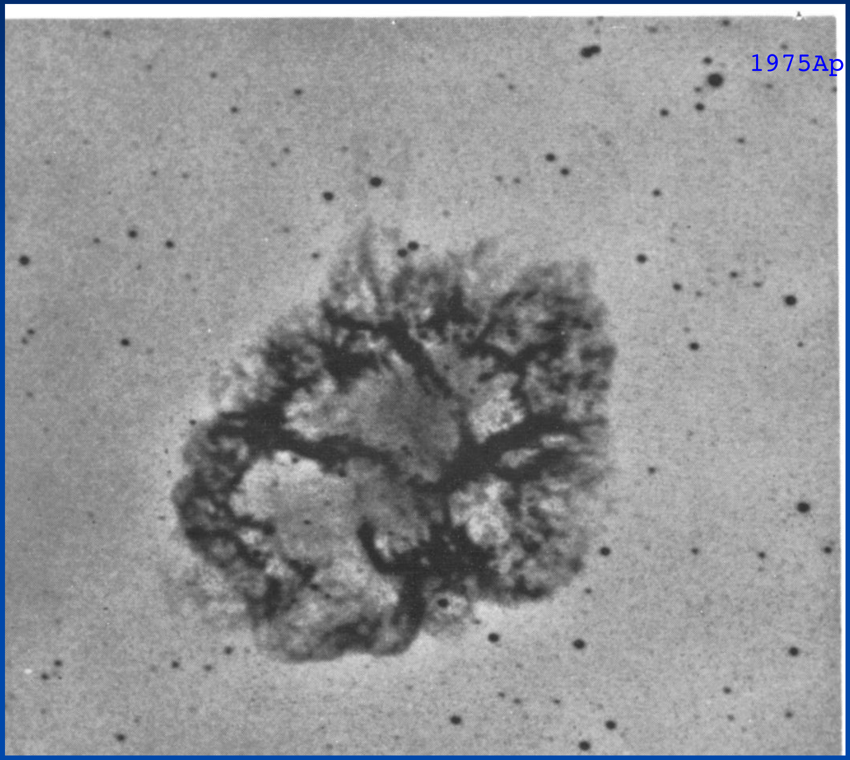


3-dimensional

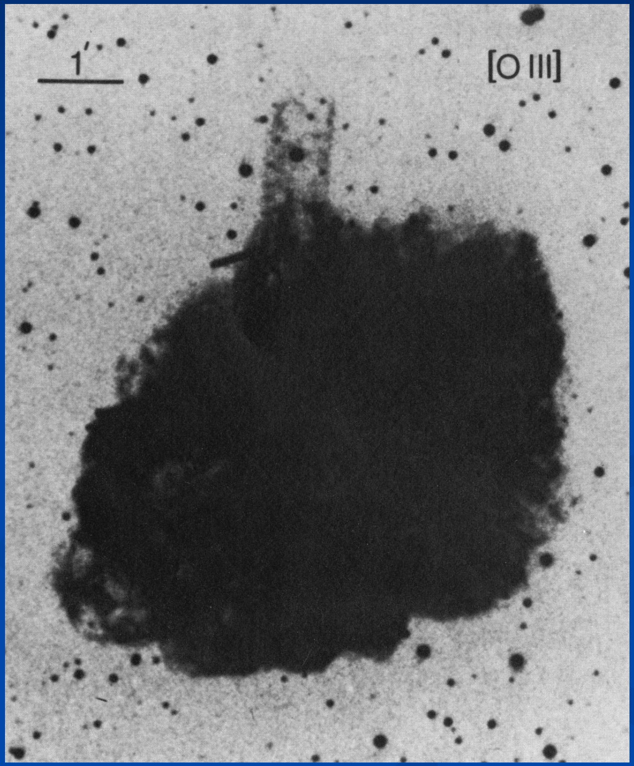
- The approximate condition for the blow-out to occur is that the deposited pulsar spin down energy be > than the SN energy E_{SN}
  - If E_{SN} is 10^{51} erg, an initial pulsar period in the msec range is needed. May apply to magnetar model for superluminous supernovae (Chen + 16)
  - If E_{SN} is 10^{50} erg, the period can be $3\times$ higher.

- If Crab were a normal 10^{51} erg supernova, would expect to see external signs
- Constraints on the Crab
  - Abundances suggest 8-10 $M_\odot$ progenitor
  - Velocity, age, radius, mass of the nebula
- Most consistent with a low energy ($\sim 10^{50}$ erg) supernova
  - Acceleration, mass, cooling shock

(Yang + RAC 15)

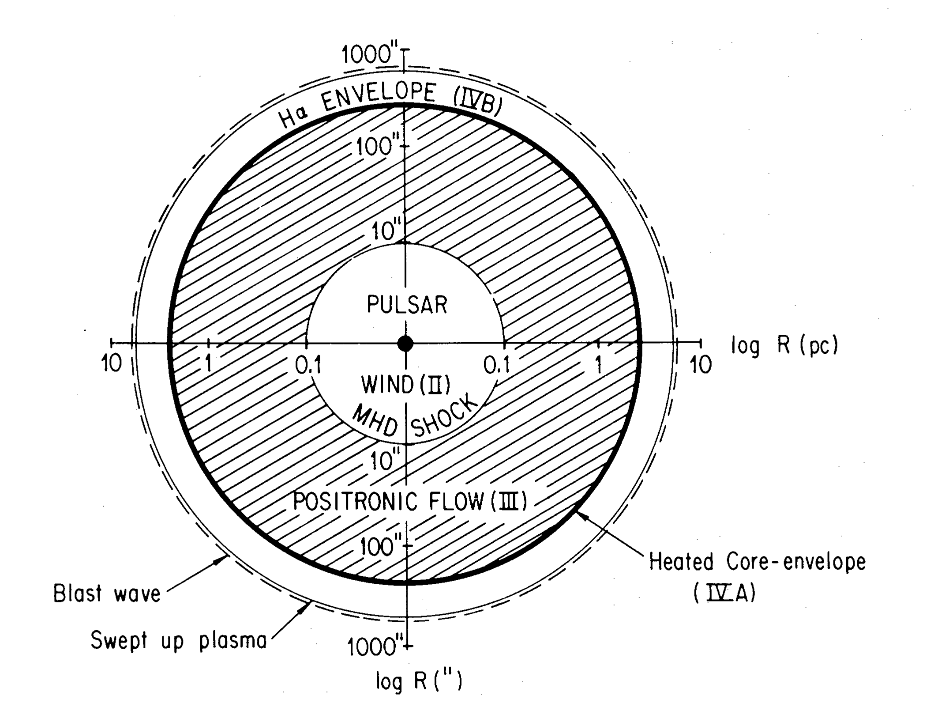


RAC Gull 75



Gull Fesen 82

- After > 40 years, many mysteries still persist and new ones have come along



Shocked MHD flow model
Toroidal magnetic field
Advective flow of particles, with B field

Kennel & Coroniti 84