Hydrodynamics of Young Supernova Remnants and the Implications for their Gamma-ray emission

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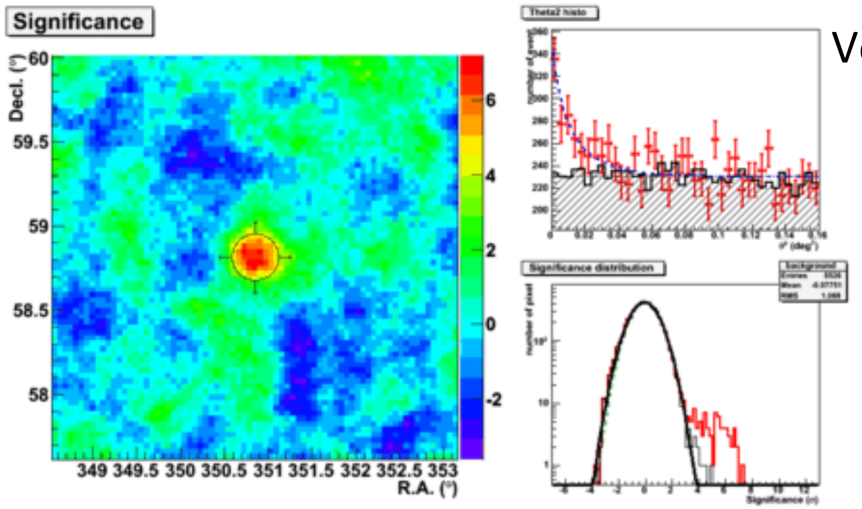
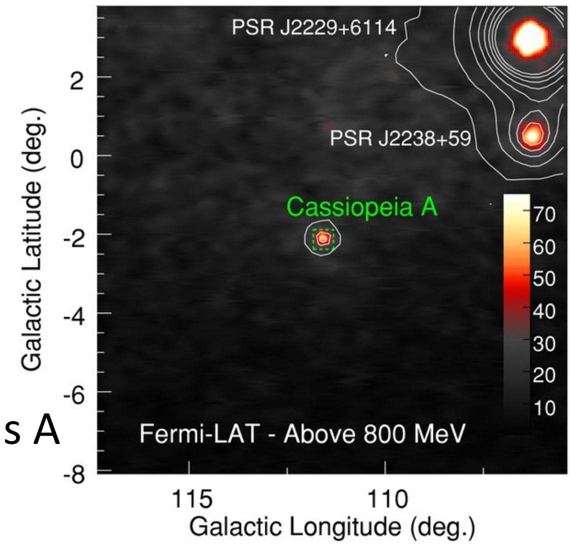
VHE Emission from Young SNRs

- Only a few young SNRs are seen at high energies – partly due to the fact that few young SNRs are known in general.
- Objects include Tycho, SN 1006 (Type Ia), Cas A (core-collapse), RCW 86, RXJ 1713 etc.
- Important: These are all in the ejecta dominated stage, and far from the Sedov phase. Therefore we need to consider both the ejecta dynamics and the ambient medium structure.
- The SN Environment is very important

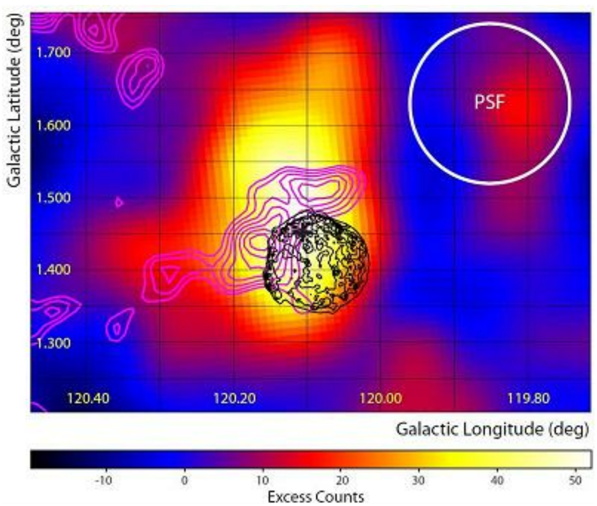
Gamma-Ray observations of SNRs



Veritas – Cas A

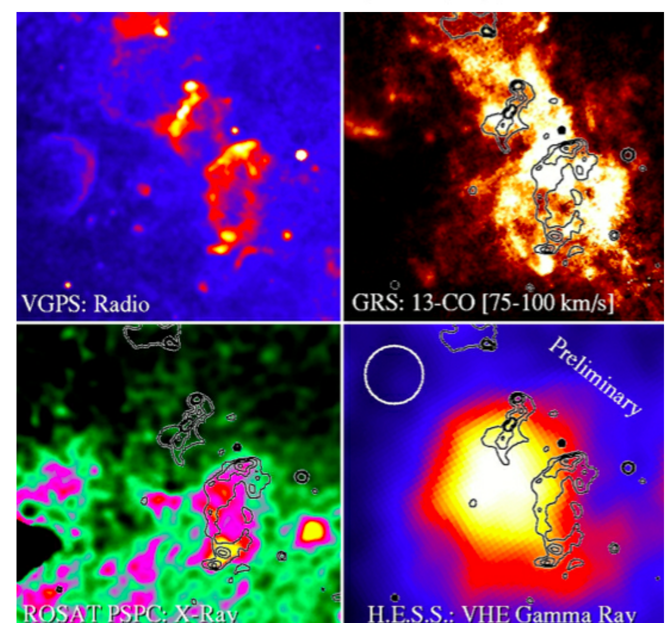


Fermi – Cas A



Veritas – Tycho's SNR

HESS – Kes 78



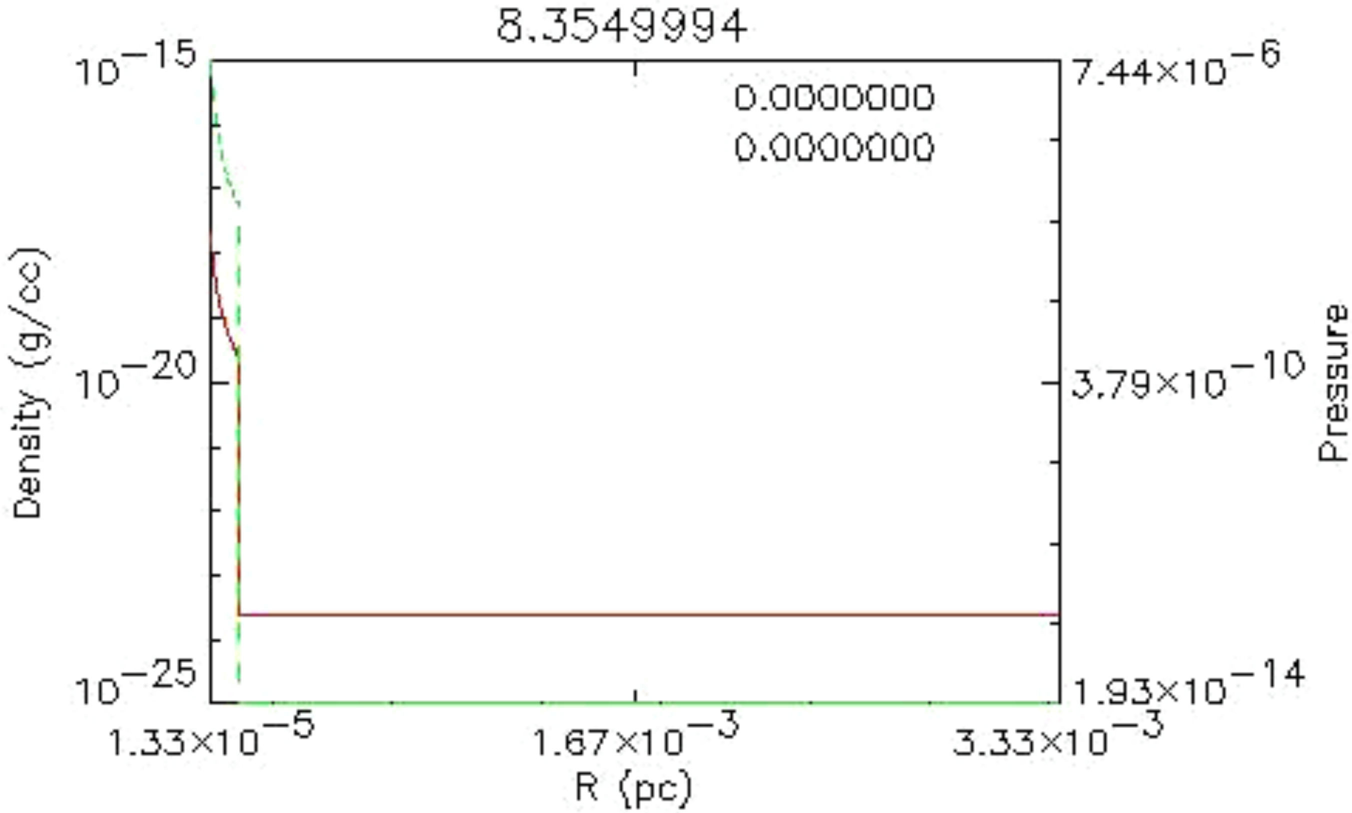
Core-Collapse Supernovae

- Core-collapse SNe arise from massive stars.
- These stars start their lives as O, B stars.
- After spending most of their lifetime on the Main Sequence, burning H, they exit the MS, undergo a Helium flash, and form Red Supergiants.
- Stars with initial mass below 30 M_o end their lives as red supergiants, forming **Type IIP Sne**.
- Stars with $M > 30\ M_o$ lose their H and perhaps He envelopes, becoming W-R stars. These will explode to form SNe of **Type Ib/Ic**.
- Massive stars lose a considerable amount of mass via winds, especially in the post-MS phases. It is in this wind-blown ambient region that the SN shock will evolve.

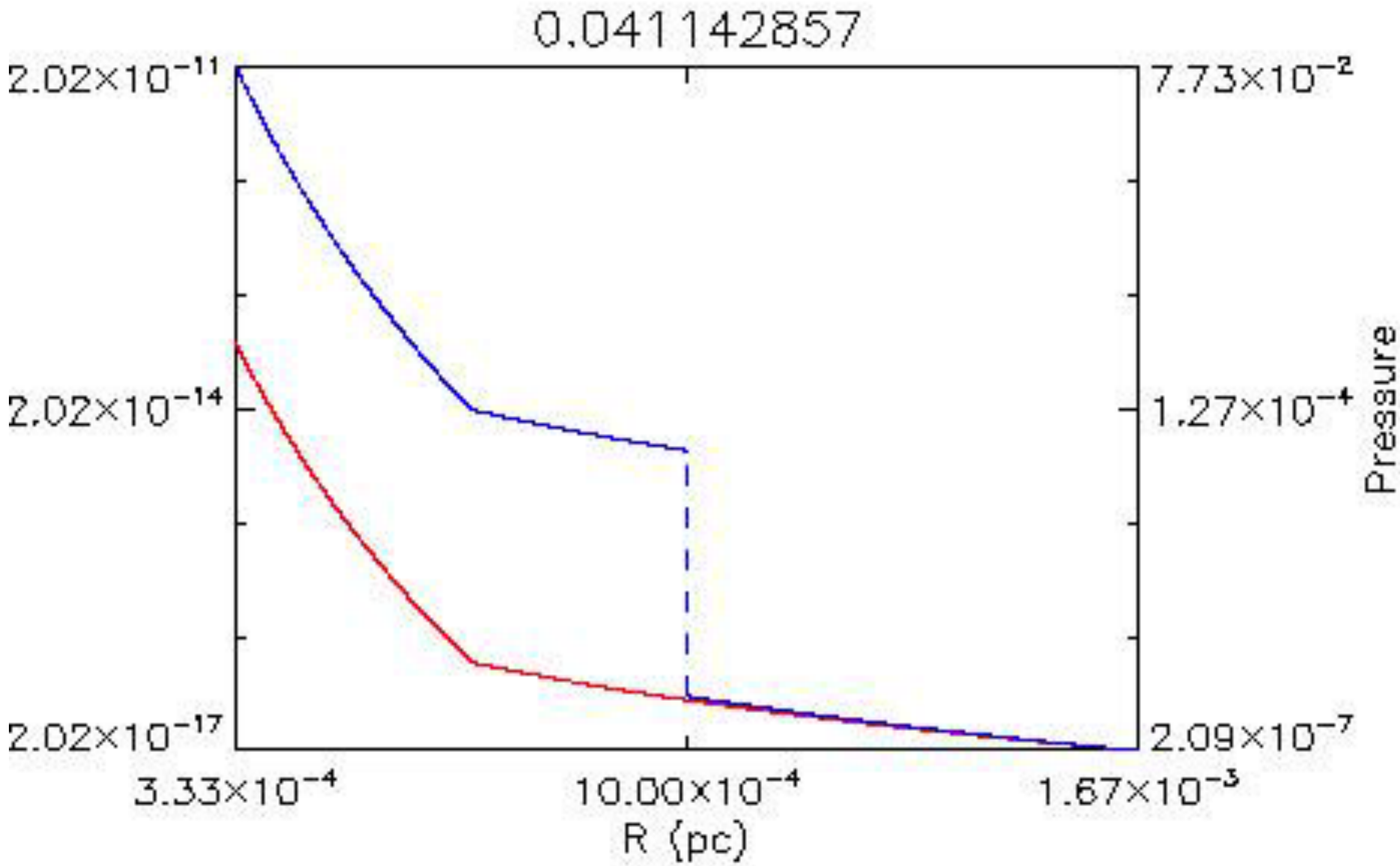
Young SNRs

- To understand the SNR dynamics, it is important to know the structure of the environment into which the SNR is expanding.
- With core-collapse SNR in winds, it can take thousands of years for the SN to reach the Sedov stage (Note: Contrary to general expectation, the Sedov stage is NOT reached when swept-up mass = ejecta mass, but when swept-up mass = 20-30 ejecta mass [Gull 1973, Dwarkadas & Chevalier 1998])

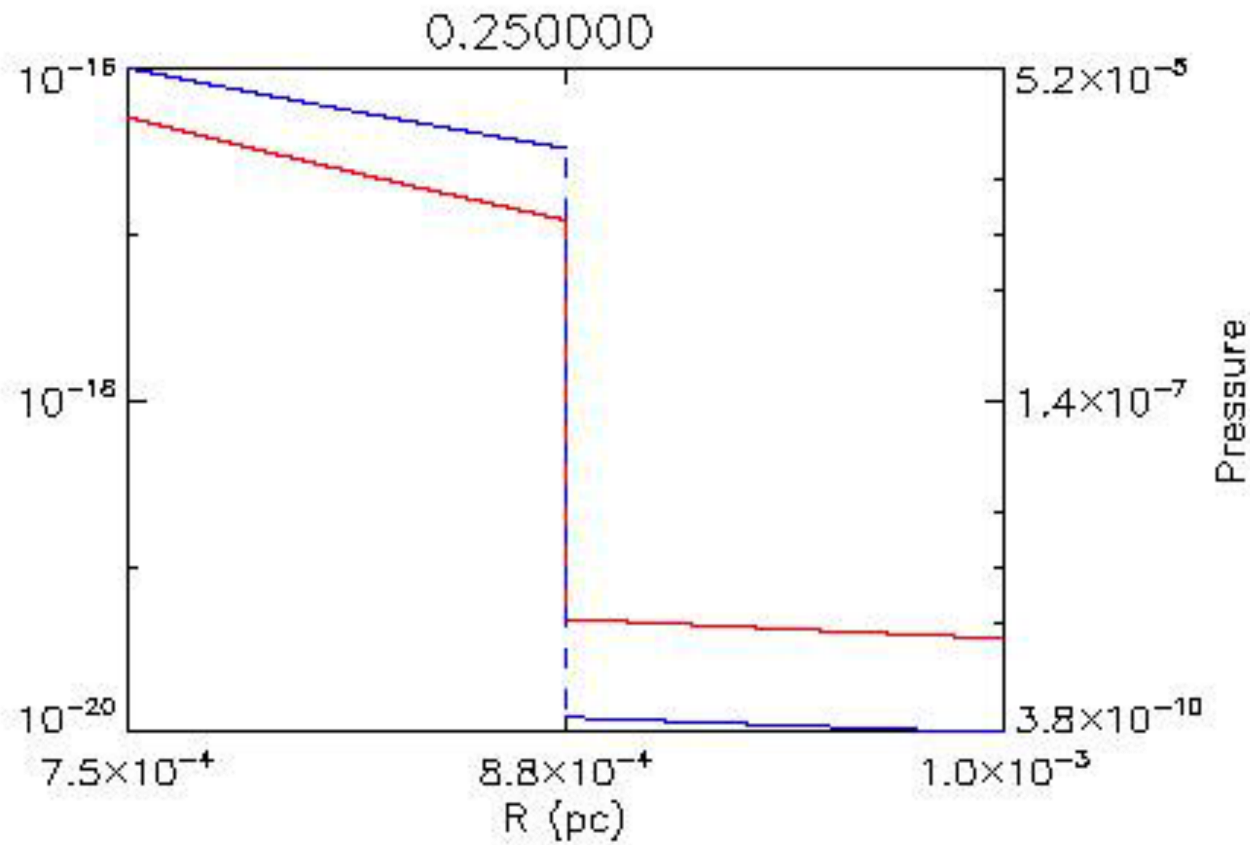
Circumstellar Medium Profile



Type IIP SN


0.041142857
2.02×10^-11
2.02×10^-14
2.02×10^-17
7.73×10^-2
1.27×10^-4
2.09×10^-7
Pressure
3.33×10^-4
10.00×10^-4
1.67×10^-3
R (pc)

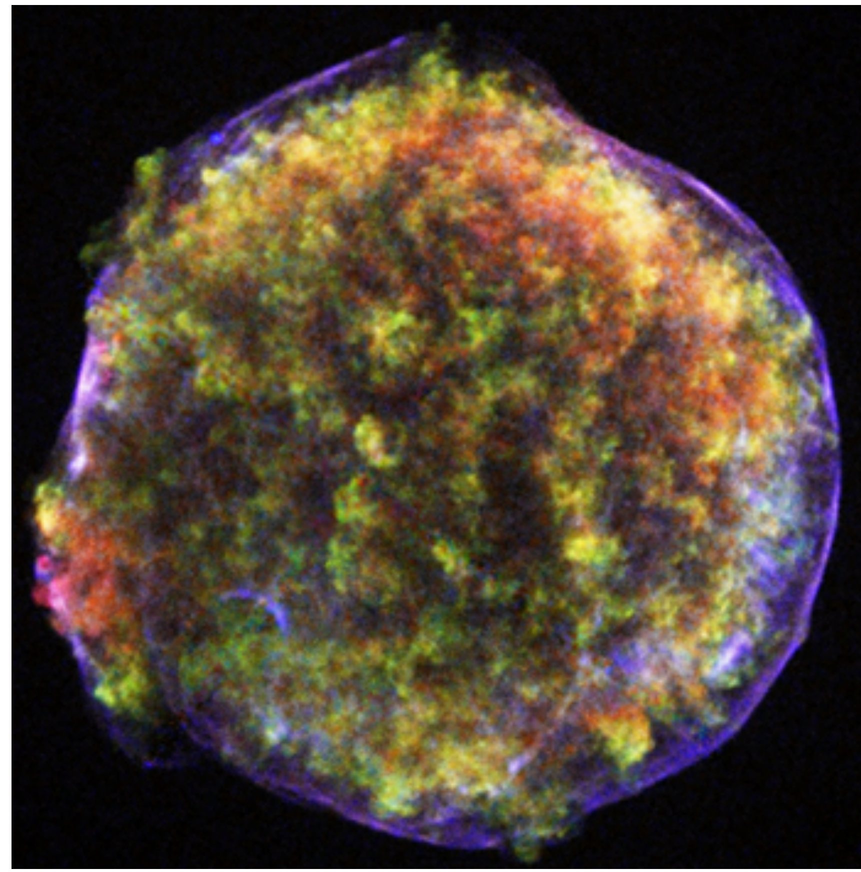
Type Ic SN



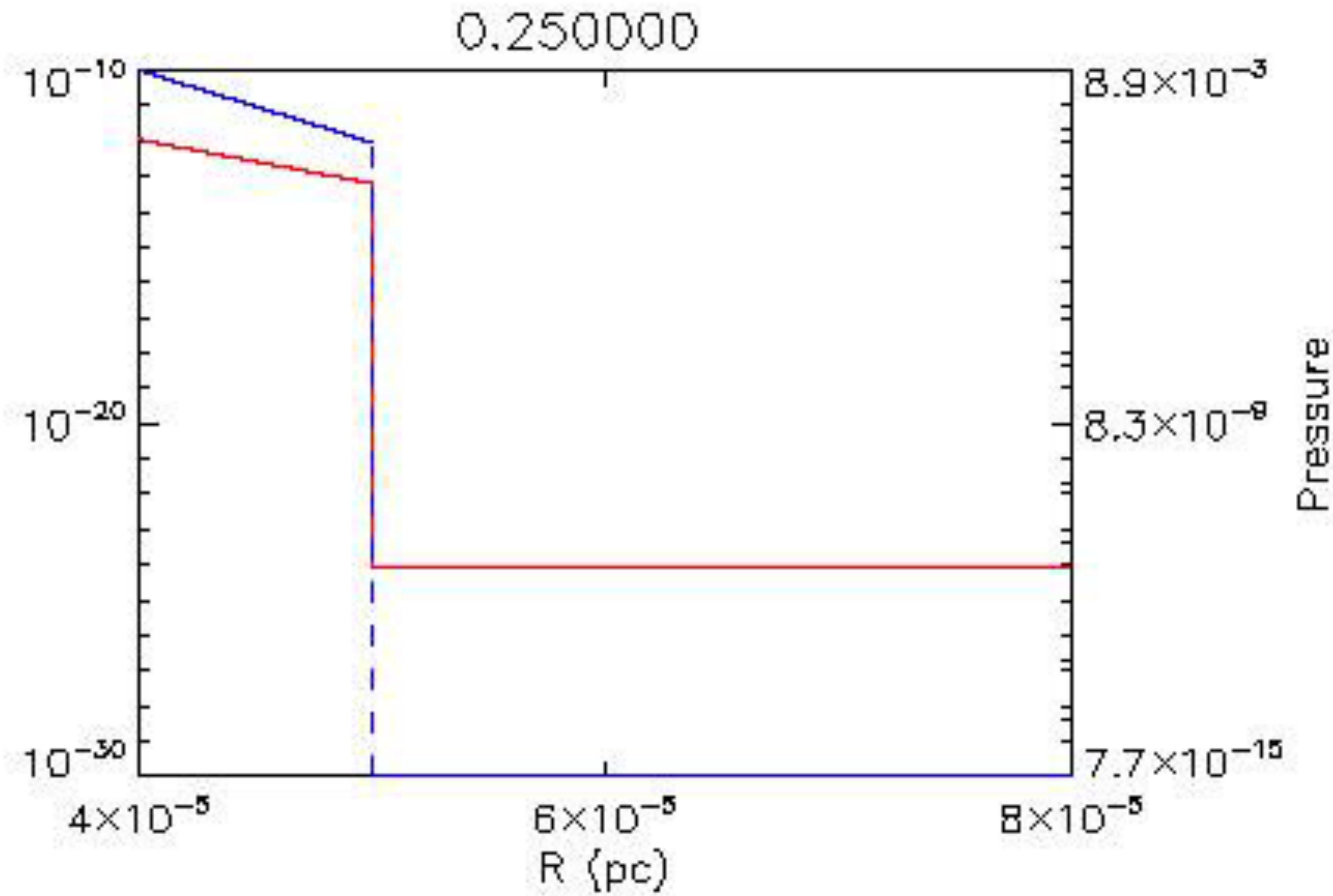
0.250000
10^{-16}
10^{-18}
10^{-20}
5.2×10^{-5}
1.4×10^{-7}
3.8×10^{-10}
Pressure
7.5×10^{-4}
8.8×10^{-4}
1.0×10^{-3}
R (pc)

Type Ia SNe

- Arise from low mass progenitors (< 8 solar masses)
- Appear to be expanding into a mainly constant density medium (Badenes et al)



Interaction of Type Ia Ejecta with Constant-Density ISM



Simple Analytic Model
(Dwarkadas, 2013, MNRAS,434, 3368)

$$F_\gamma(>E_o, t) = \frac{q_\gamma}{4\pi d^2} \frac{M(t)}{\mu m_{\rm p}} \left[\frac{\epsilon_{CR}}{V}\right]$$

(Drury, Aharonian & Volk 1994)

Use Chevalier (1982) self-similar solution (n>5, s=0 for constant density, s=2 for wind)

$$\rho_{SN} = At^{-3}v^{-n}$$

$$\rho_{cs} = Br^{-s}$$

$$R_{sh} = \left(\frac{\alpha A}{B}\right)^{\frac{1}{n-s}} t^{\frac{n-3}{n-s}} \propto t^m$$

Simple Analytic Model
(Dwarkadas, 2013, MNRAS,434, 3368)

$$F_\gamma(>E_o, t) = \frac{q_\gamma}{4\pi d^2} \frac{M(t)}{\mu m_{\mathrm{p}}} \left[\frac{\epsilon_{CR}}{V}\right]$$ (Drury, Aharonian & Volk 1994)

Mass = Swept-up mass

$$M_{\mathrm{sw}} = \int_0^R 4\pi r^2 B r^{-s} \mathrm{d}r = \frac{4\pi B}{3-s} R^{3-s}$$

Energy in Cosmic Rays = Some fraction of available shock energy at timestep

$$\epsilon_{\mathrm{CR}} = 2\pi \int_0^t \xi R_{\mathrm{sh}}^2 \rho_{\mathrm{sh}} V_{\mathrm{sh}}^3 \,\mathrm{d}t \quad = \frac{2\pi B \xi (\kappa C_1)^{5-s} m^3}{5m - ms - 2} t^{5m-ms-2}$$

For s=0 (constant density), $E_{CR} \sim t^{5m-2}$, for m> 2/5, increases with time.
For s=2 (wind), $E_{CR} \sim 3m - 2$, increases for m>2/3 (Sedov value)
Energy available at shock front equal total SN energy ONLY at Sedov stage.

Simple Analytic Model

$$F_\gamma(>E_o, t) = \frac{3q_\gamma B^2 \xi (\kappa C_1)^{5-2s} m^3}{2(3-s)(5m-ms-2)\beta \mu m_{\rm p} d^2} t^{5m-2ms-2}$$

Core-collapse SNe, evolve in stellar winds. If steady wind, s=2

$$F_\gamma(>E_o, t) = \frac{3q_\gamma \xi (\kappa C_1) m^3}{32\pi^2(3m-2)\beta \mu m_{\rm p} d^2} \left[\frac{\dot{M}}{v_{\rm w}}\right]^2 t^{m-2}$$

Note that, since m < 1, the emission is decreasing with time, after an early approach to maximum energy.

Simple Analytic Model

Constant density medium, s=0 (Type Ia Sne)

$$F_\gamma(>E_o, t) = \frac{3q_\gamma \xi (\kappa C_1)^5 m^3}{6(5m-2)\beta \mu m_\mathrm{p} d^2} \rho_{am}^2 t^{5m-2}$$

If m> 2/5 , which it should be if the remnant has not yet reached the Sedov phase, then the emission is always increasing with time.
Note: Emission proportional to density squared, not simply density, as in older SNRs.

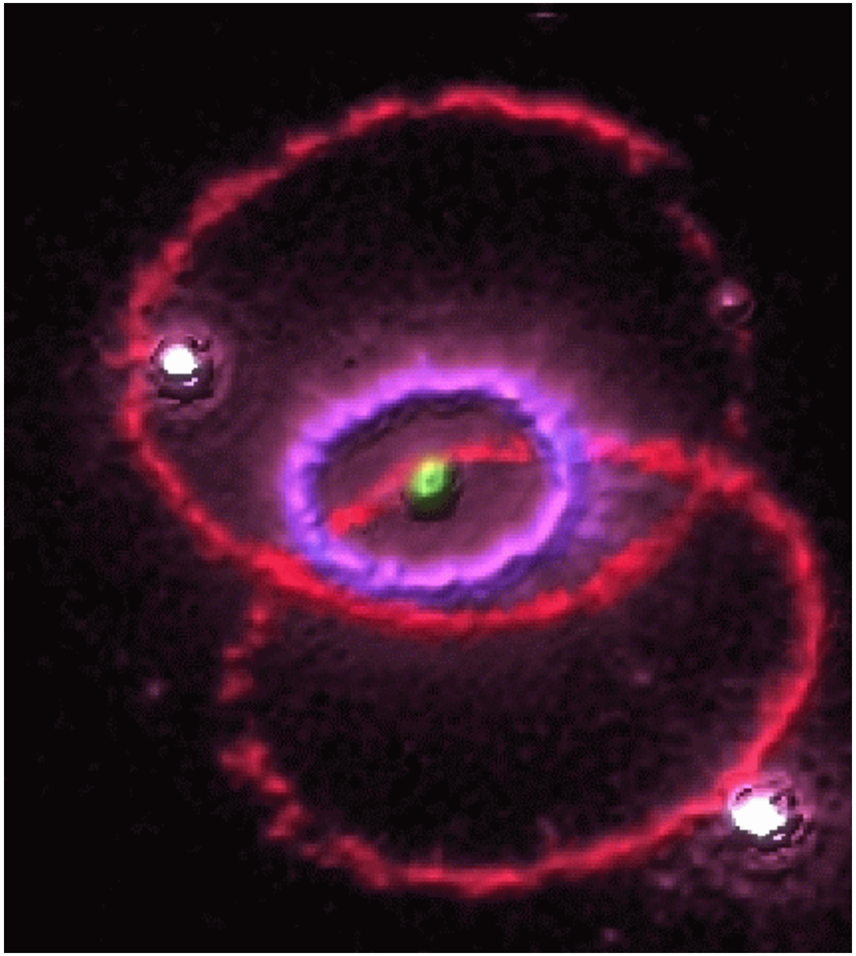
Application to Cas A

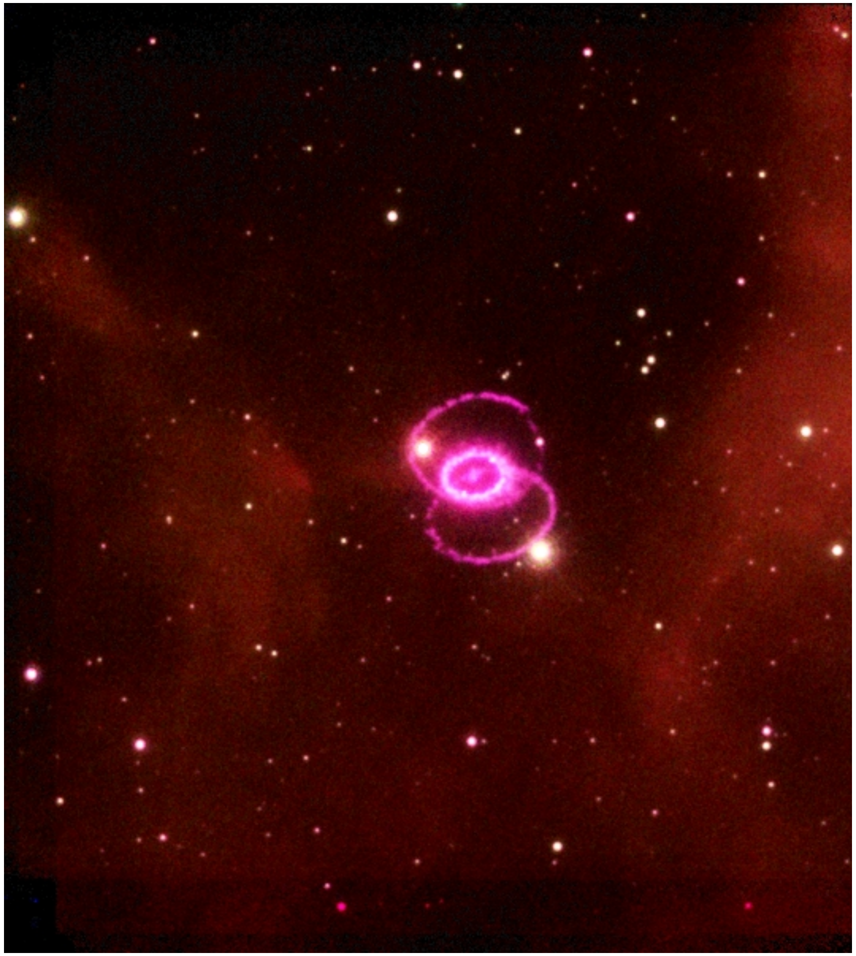
- A SNR expanding in a dense RSG wind.
- Mass-loss rate - 2 * 10^{-5} Msun/yr, wind velocity 10 km/s, E_{SN}= 4. * 10^{51} ergs, n=10.12 (Chevalier & Oishi)
- $F_{\gamma(CasA)}$(> 100 MeV) = 5.5 x 10^{-8} $cm^{-2}s^{-1}$
- Fermi best fit suggests only 2% energy in cosmic rays, explosion energy 2.*10^{51} ergs
- Then: $F_{\gamma(87A)}$(> 100 MeV) = 1.1 x 10^{-8} $cm^{-2}s^{-1}$
- Comparable to Fermi result. Suggests hadronic emission for Cas A.

SN 1987A

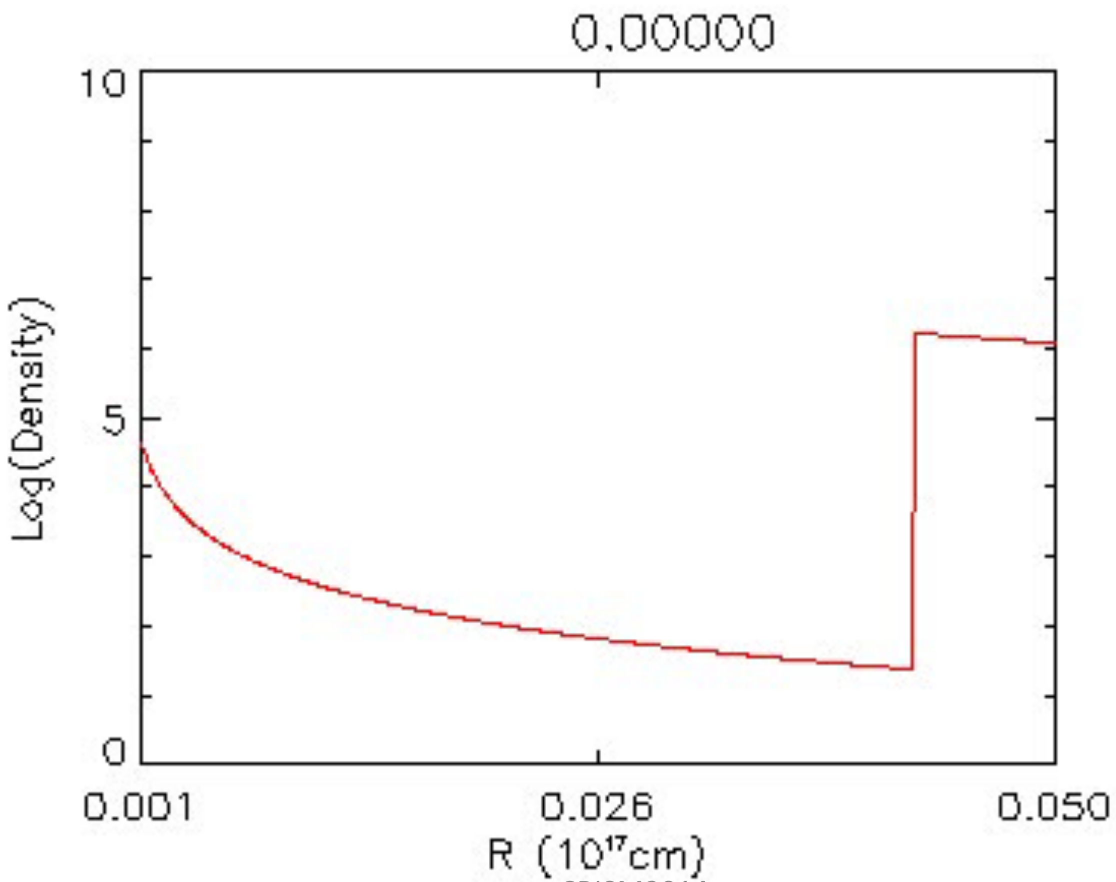
- The closest SN in over 300 years
- Hubble images show an interesting structure, with an equatorial ring and two rings at higher latitudes.
- The increasing X-ray and radio emission after 3 years indicated the presence of an HII region interior to the ring (Chevalier & Dwarkadas 1995).
- We can model the interaction within the equatorial plane and outside the equatorial plane (no ring interaction).

SN 1987A - 3 Ring Circus

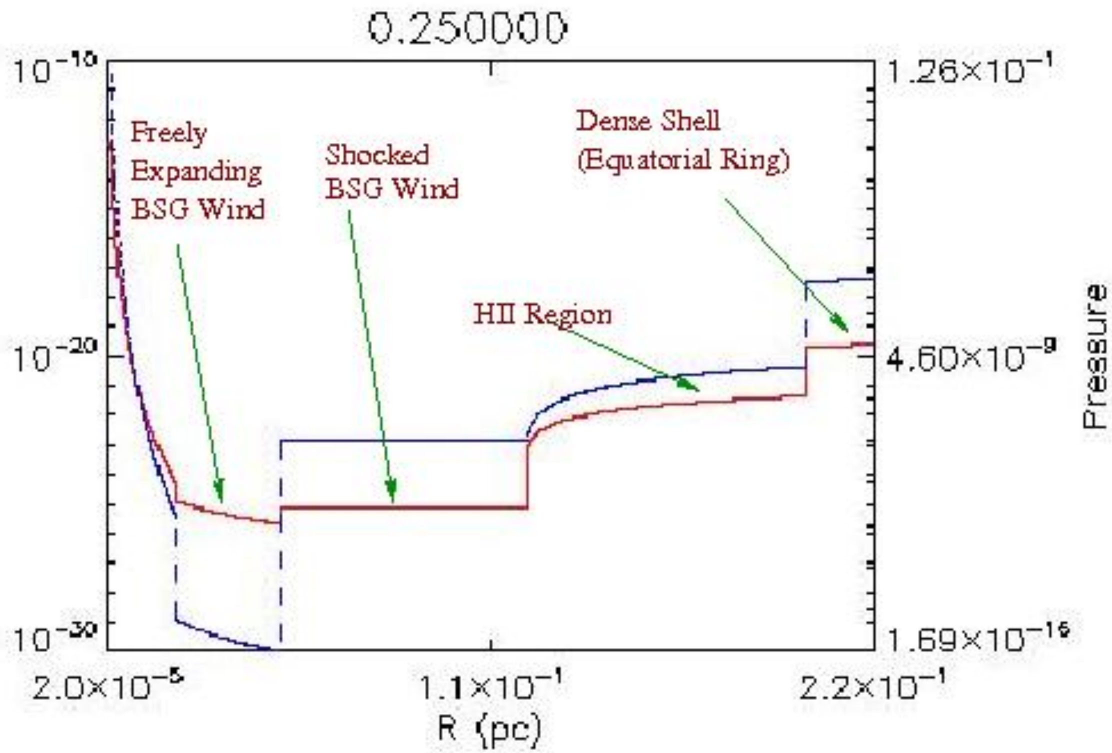




Formation of SN 1987A CSM

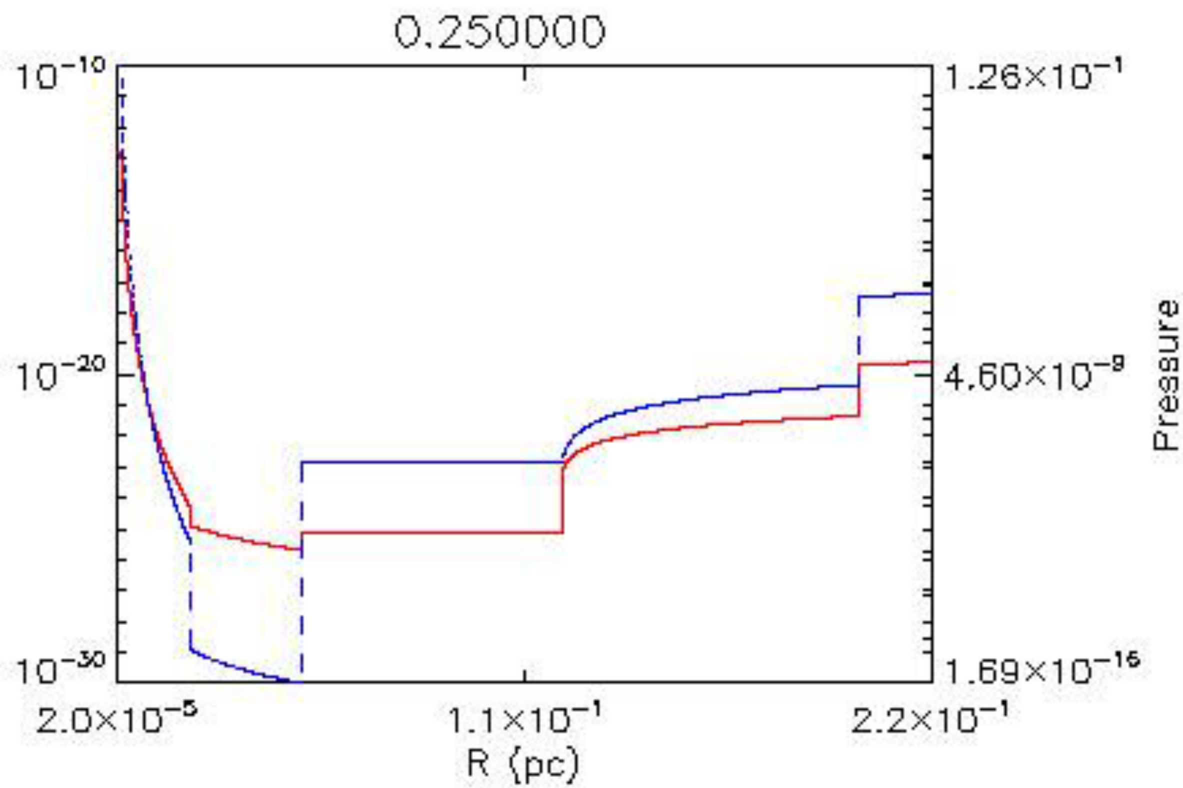


SN 1987A



0.250000
10^{-10}
10^{-20}
10^{-30}
1.26×10^{-1}
4.60×10^{-9}
1.69×10^{-16}
2.0×10^{-5}
1.1×10^{-1}
2.2×10^{-1}
R (pc)
Pressure
Freely Expanding BSG Wind
Shocked BSG Wind
Dense Shell (Equatorial Ring)
HII Region

SN 1987A



0.250000
10^{-10}
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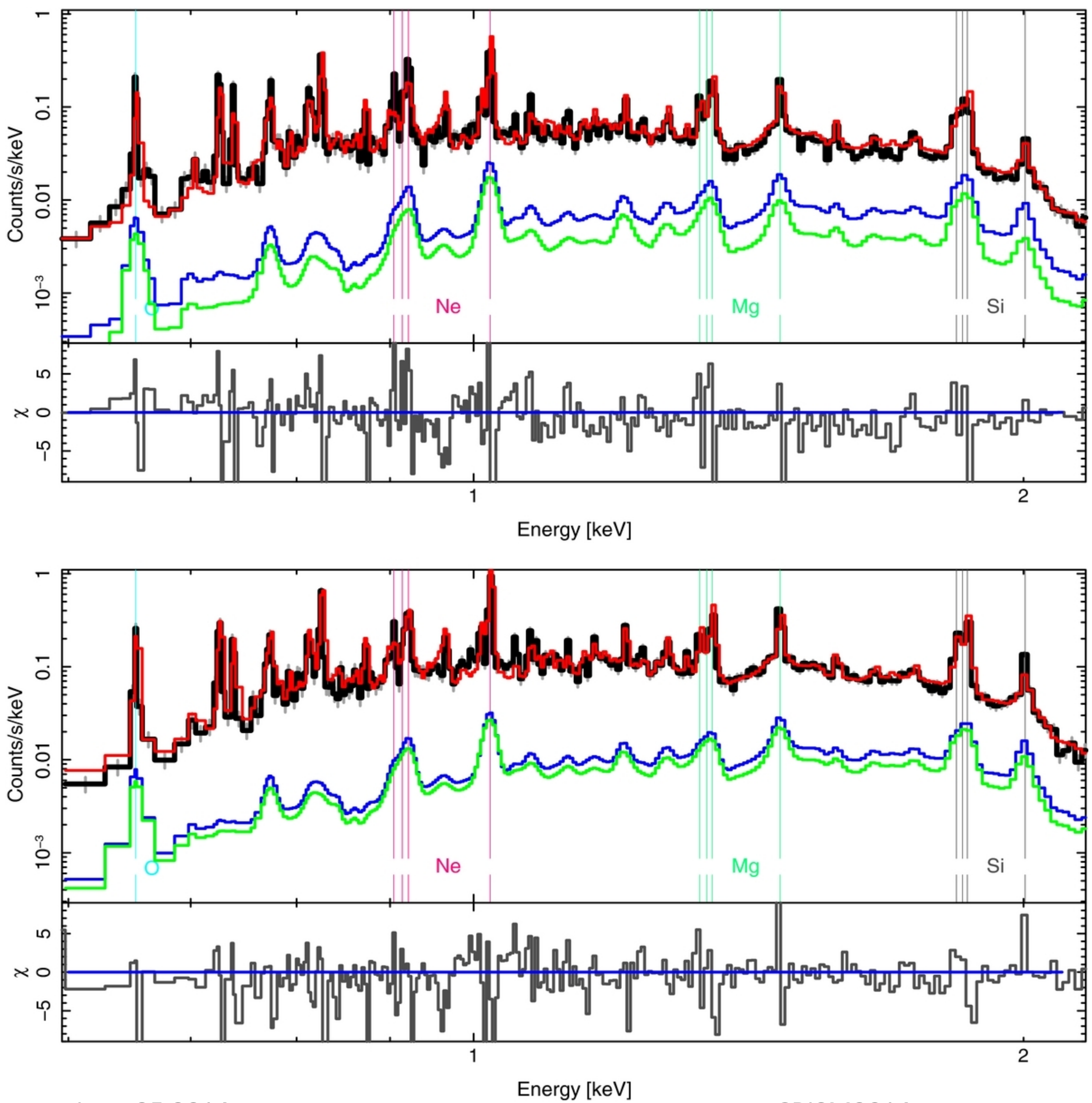
1.69×10^{-16}
Pressure
2.0×10^{-5}
1.1×10^{-1}
2.2×10^{-1}
R (pc)

D. Dewey et al. 2012 ApJ 752 103 doi:10.1088/0004-637X/752/2/103



HETG(MEG) spectra and full hydrodynamics-based models. The HETG-07 (top) and HETG-11 (bottom) data (black) are reasonably fit by the total (HII plus nominal clumped-ER) model spectra (red). The HII-shocked-CSM (blue) and the HII-shocked-ejecta (green) components are also shown individually.

(Dewey, Dwarkadas et al. 2012, ApJ, 752, 103)

Progenitor BSG: Wind velocity ~500 km/s, Mass-loss rate < 10^{-8} msun/yr.

SN 1987A

- Assuming the parameters in Dewey et al (2012), n=9, we get
- $F_{\gamma(87A)}(> 100\ \mathrm{MeV}) = 4.04 \times 10^{-10}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$
- If we assume a spectral index close to the shock of 2, and emissivity $q_\gamma=10^{-17}$, then the TeV flux is given by:
- $F_{\gamma(87A)}(> 1\ \mathrm{TeV}) = 8.1 \times 10^{-14}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$
- This I think is a few times smaller than can be detected by HESS currently.

SN 1987A

- But the SN shock is currently interacting with the equatorial ring, and sweeping up high density material.
- If it sweeps up a large amount of high density material, then the mass with which the accelerated electrons are interacting increases and the level of hadronic emission increases.
- In the year 2023:
- $F_{\gamma(87A)}(> 100\ \mathrm{MeV}) = 1.9 \times 10^{-08}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$
- $F_{\gamma(87A)}(> 1\ \mathrm{TeV}) = 3.8 \times 10^{-12}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$
- This should be detectable by HESS and CTA
- Note (several approximations made, especially that although shock moving through different density media, self-similar solutions still apply).

Summary & Conclusions

- SN Environment is very important!!!!
- Young core-collapse SN will typically interact with the freely expanding wind of the progenitor star first, followed by a constant density region.
- The density may decrease considerably in Type IIP SNe, or increase some in Type Ic.
- A simple estimate can be made of the hadronic flux using DAV 1994, the Chevalier self-similar solutions, and some approximations.
- Suggests that Cas A emission is hadronic, and that 87A may be detectable in a few years.