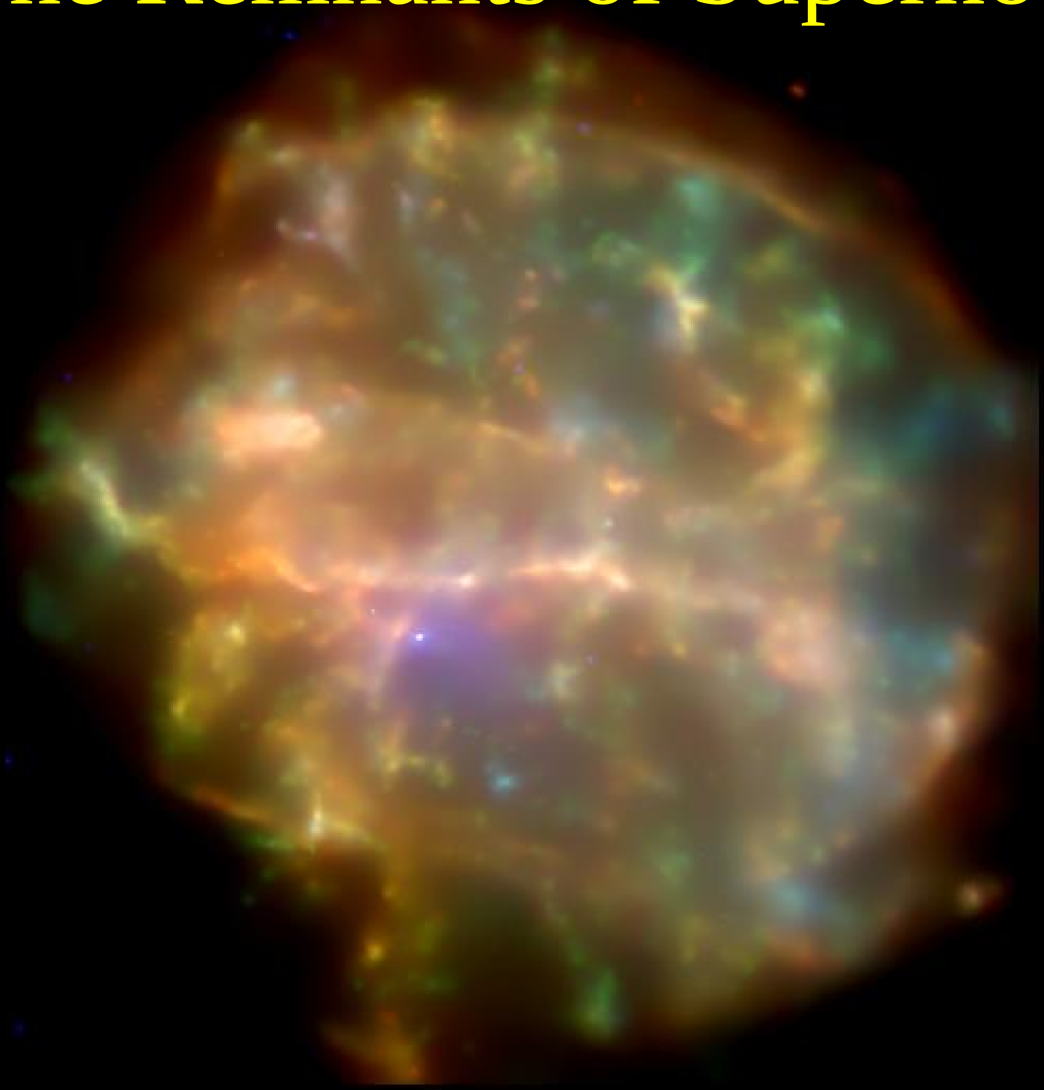
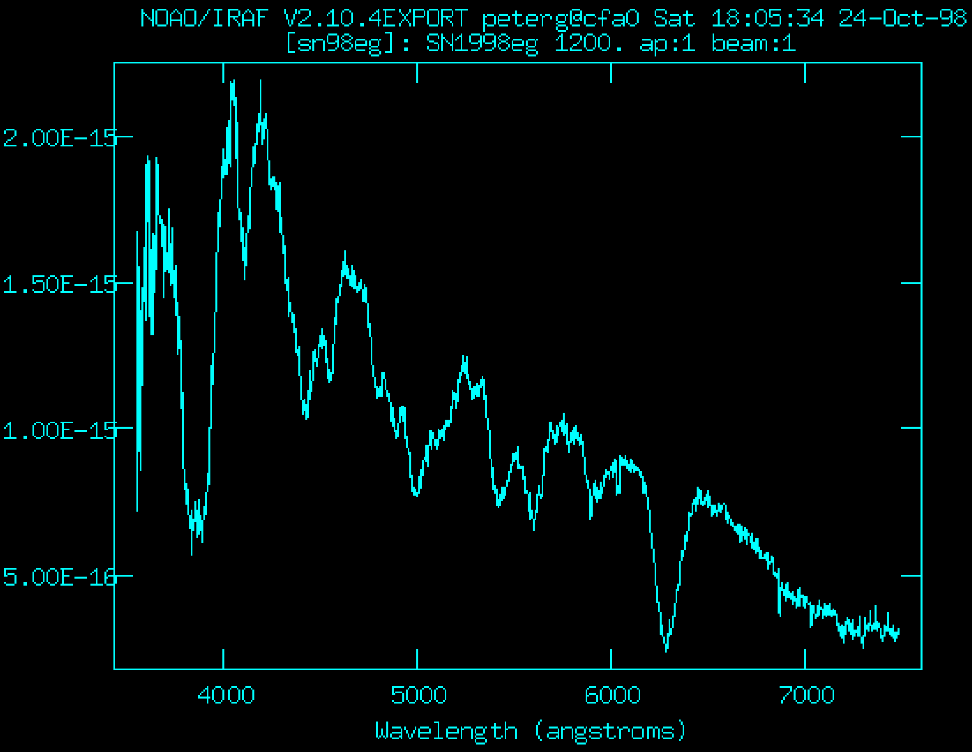
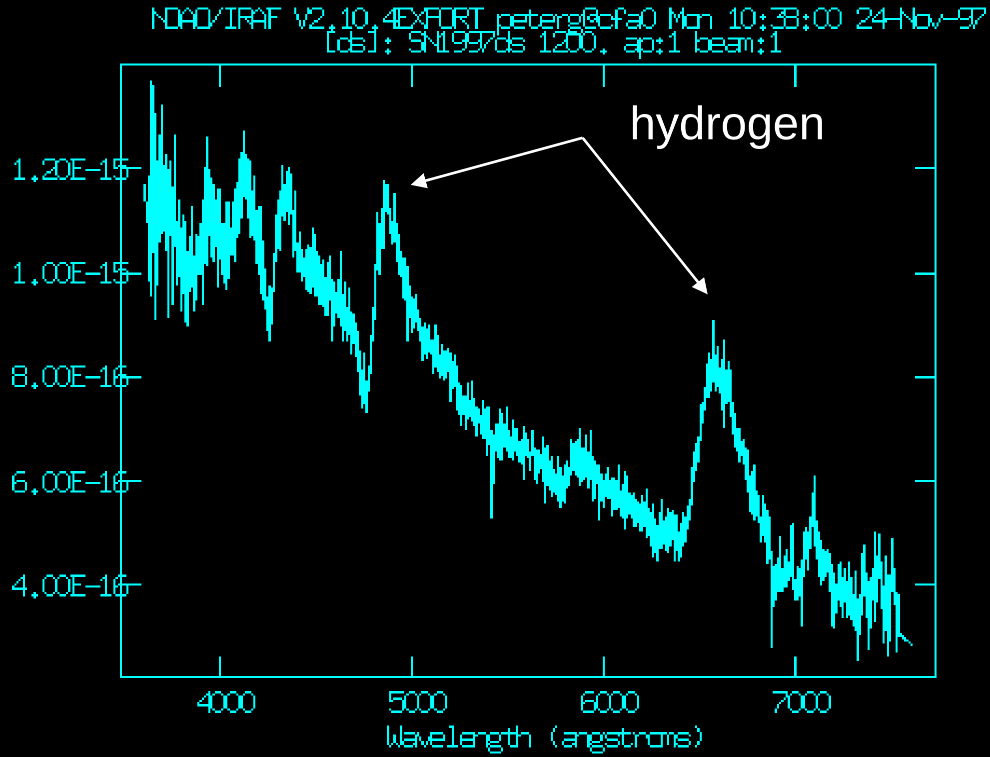
The Remnants of Supernovae



The Starting Point: Supernovae



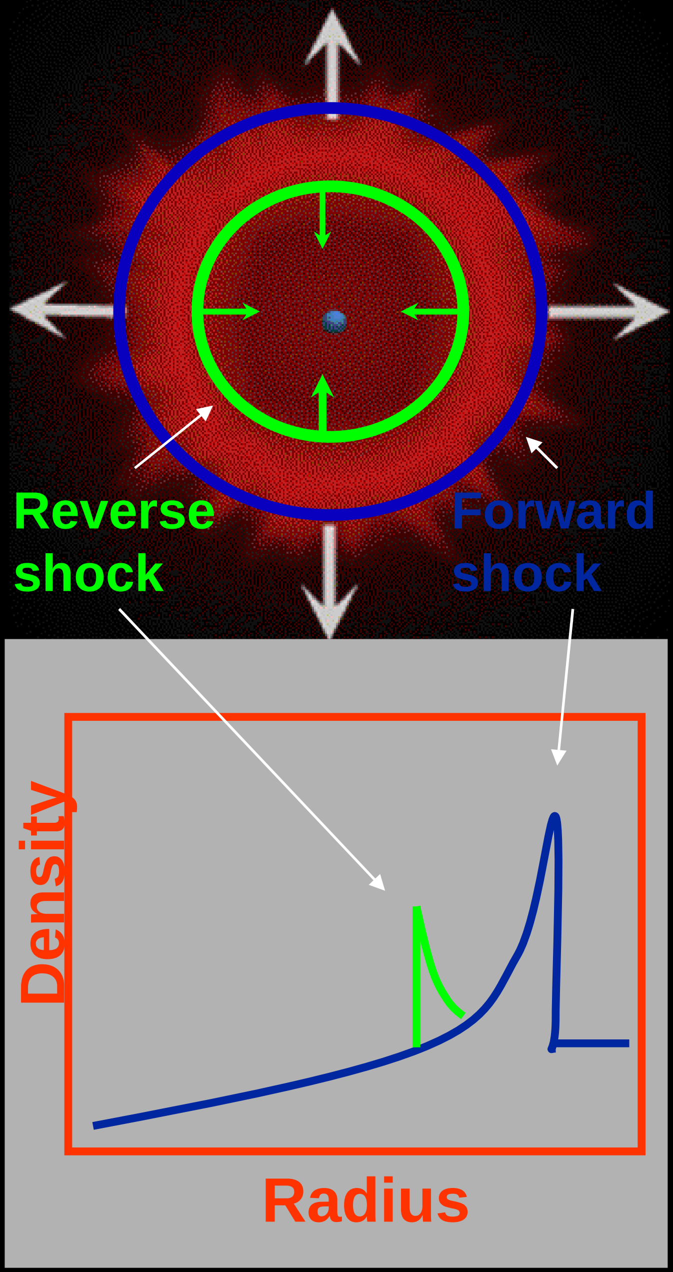


- **Type Ia** characterized by lack of hydrogen in spectrum
- Presumably from accretion onto WD

- **Type Ibc/II** associated with collapse of massive star
- **Comprise ~85% of SNe**

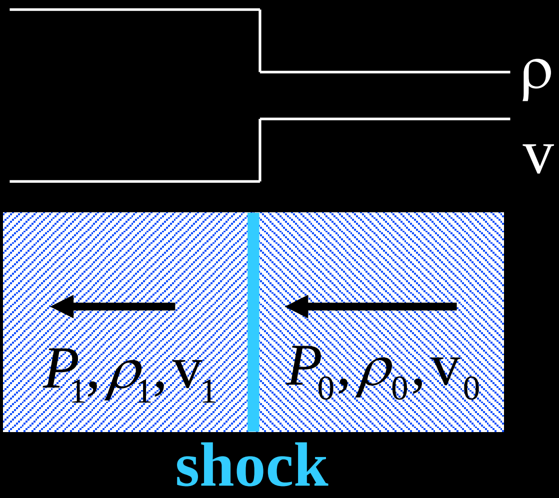
Overall SN rate is about 1 per 40 years

Supernova Remnants



- Explosion blast wave sweeps up CSM/ISM in forward shock
  - spectrum shows abundances consistent with solar or with progenitor wind
- As mass is swept up, forward shock decelerates and ejecta catches up; reverse shock heats ejecta
  - spectrum is enriched w/ heavy elements from hydrostatic and explosive nuclear burning

Shocks in SNRs



- **Expanding blast wave moves supersonically through CSM/ISM; creates shock**
  - **mass, momentum, and energy conservation across shock give (with γ=5/3)**

$$\rho_1 = \frac{\gamma+1}{\gamma-1}\rho_0 = 4\rho_0$$

$$v_1 = \frac{\gamma-1}{\gamma+1}v_0 = \frac{v_0}{4}$$

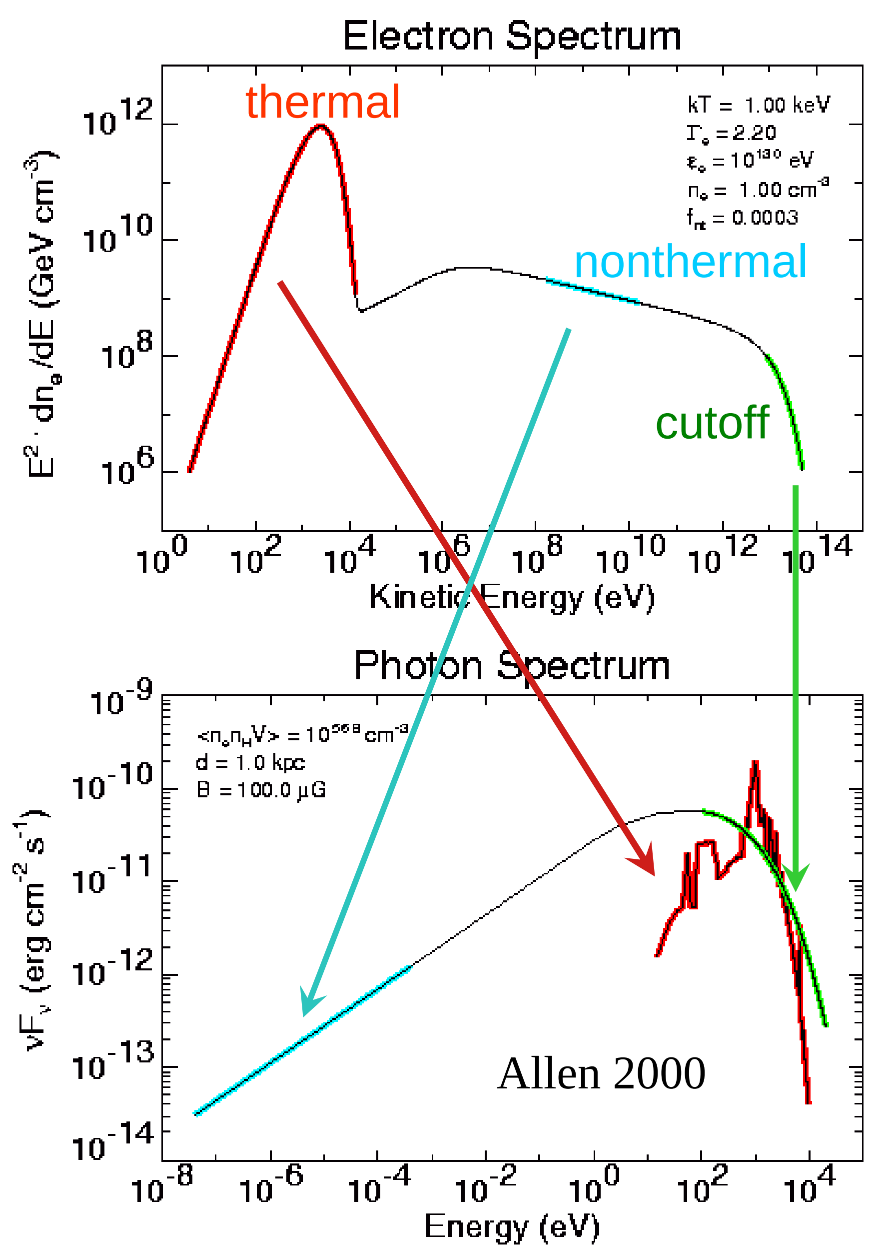
$$v_{ps} = \frac{3v_s}{4}$$

$$T_1 = \frac{2(\gamma-1)}{(\gamma+1)^2}\frac{\mu}{k}m_H v_0^2 = 1.3\times10^7 v_{1000}^2 \text{ K}$$

X-ray emitting temperatures

- **Shock velocity gives temperature of gas**
  - **note effects of electron-ion equilibration timescales**

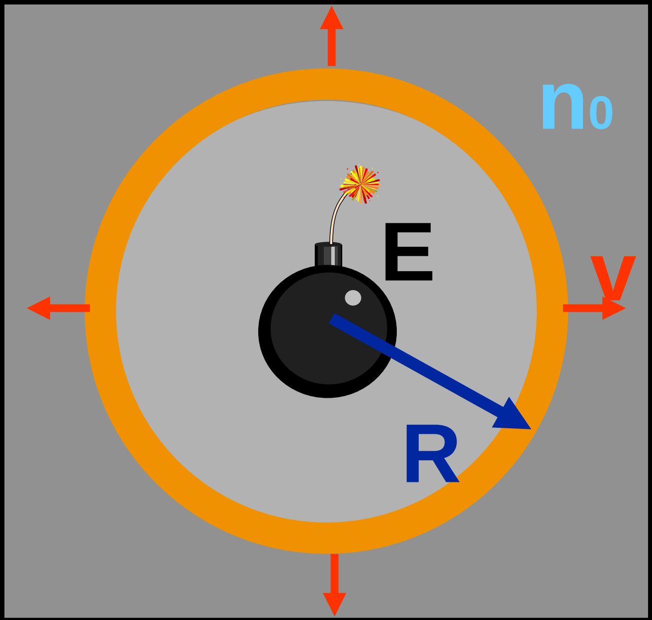
- **If another form of pressure support is present (e.g. cosmic rays), the temperature will be lower than this**



Shocked Electrons and their Spectra

- **Forward shock sweeps up ISM; reverse shock heats ejecta**
- **Thermal electrons produce line-dominated x-ray spectrum with bremsstrahlung continuum**
  - **yields kT, ionization state, abundances**
- **nonthermal electrons produce synchrotron radiation over broad energy range**
  - **responsible for radio emission**
- **high energy tail of nonthermal electrons yields x-ray synchrotron radiation**
  - **rollover between radio and x-ray spectra gives exponential cutoff of electron spectrum, and a limit to the energy of the associated cosmic rays**
  - **large contribution from this component modifies dynamics of thermal electrons**

SNR Evolution: The Ideal Case



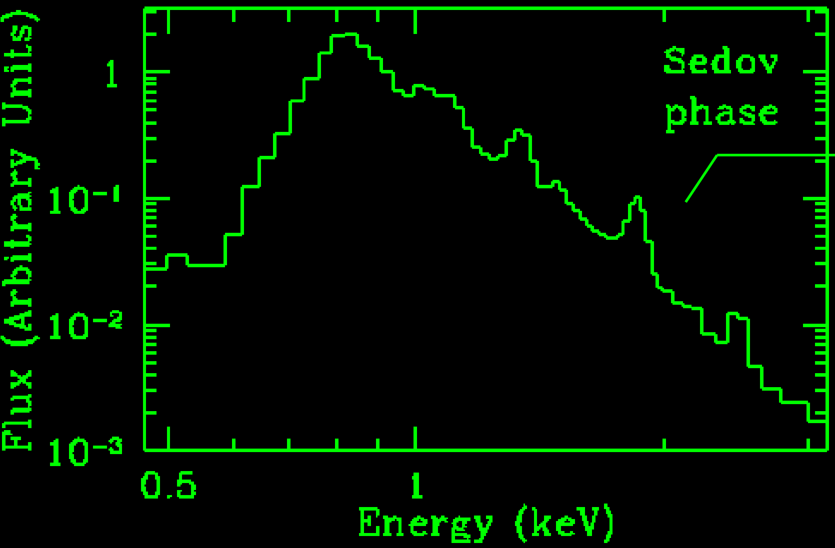
- **Once sufficient mass is swept up (> 1-5 Mej) SNR enters Sedov phase of evolution**

$$v_s = \frac{2}{5}\frac{R_s}{t} \qquad \frac{E_{51}}{\rho_0} = 0.49 R_s^5 t^{-2}$$

- **X-ray measurements can provide temperature and density**

$$EM = \int n_H n_e dV \qquad T_x = 1.28 T_{shock}$$

from spectral fits

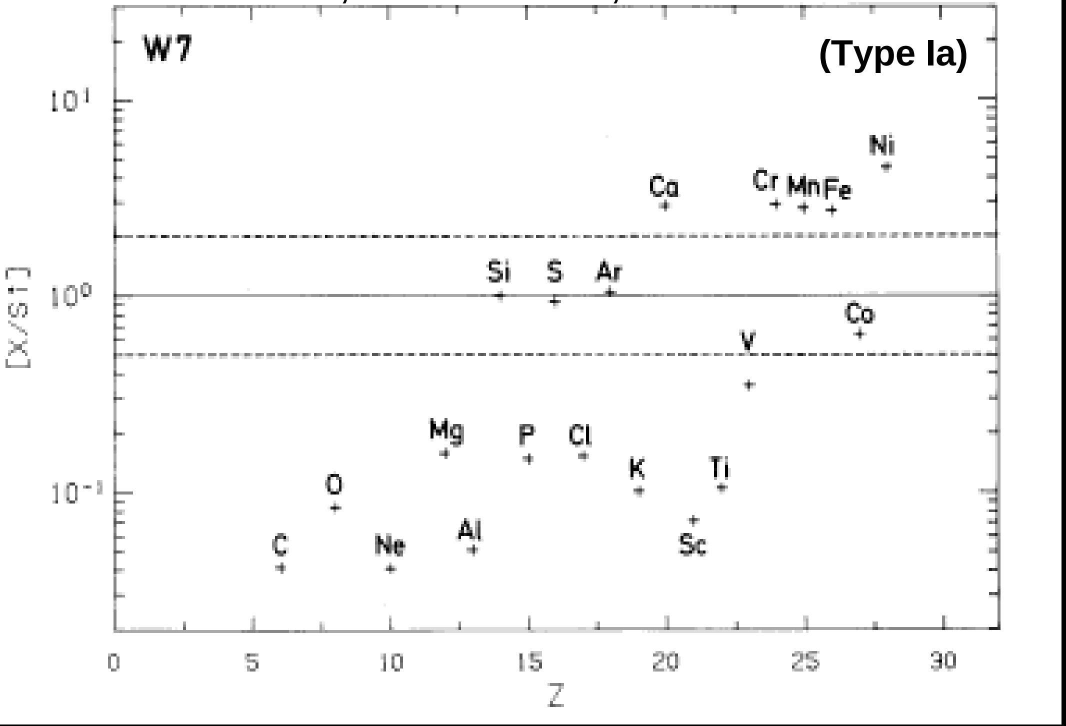


- **Sedov phase continues until kT ~ 0.1 keV**

$$t_{rad} \approx 2.4 \times 10^4 \left(\frac{E_{51}}{n_0}\right)^{1/3} yr$$

Nucleosynthesis: Probing the Progenitor Core

Nomoto, Thielemann, & Yokoi 1984



- **X-ray spectra of young SNRs reveal composition and abundances of stellar ejecta**
  - e.g. Type Ia progenitors yield more Si, S, Ar, Fe than Type II

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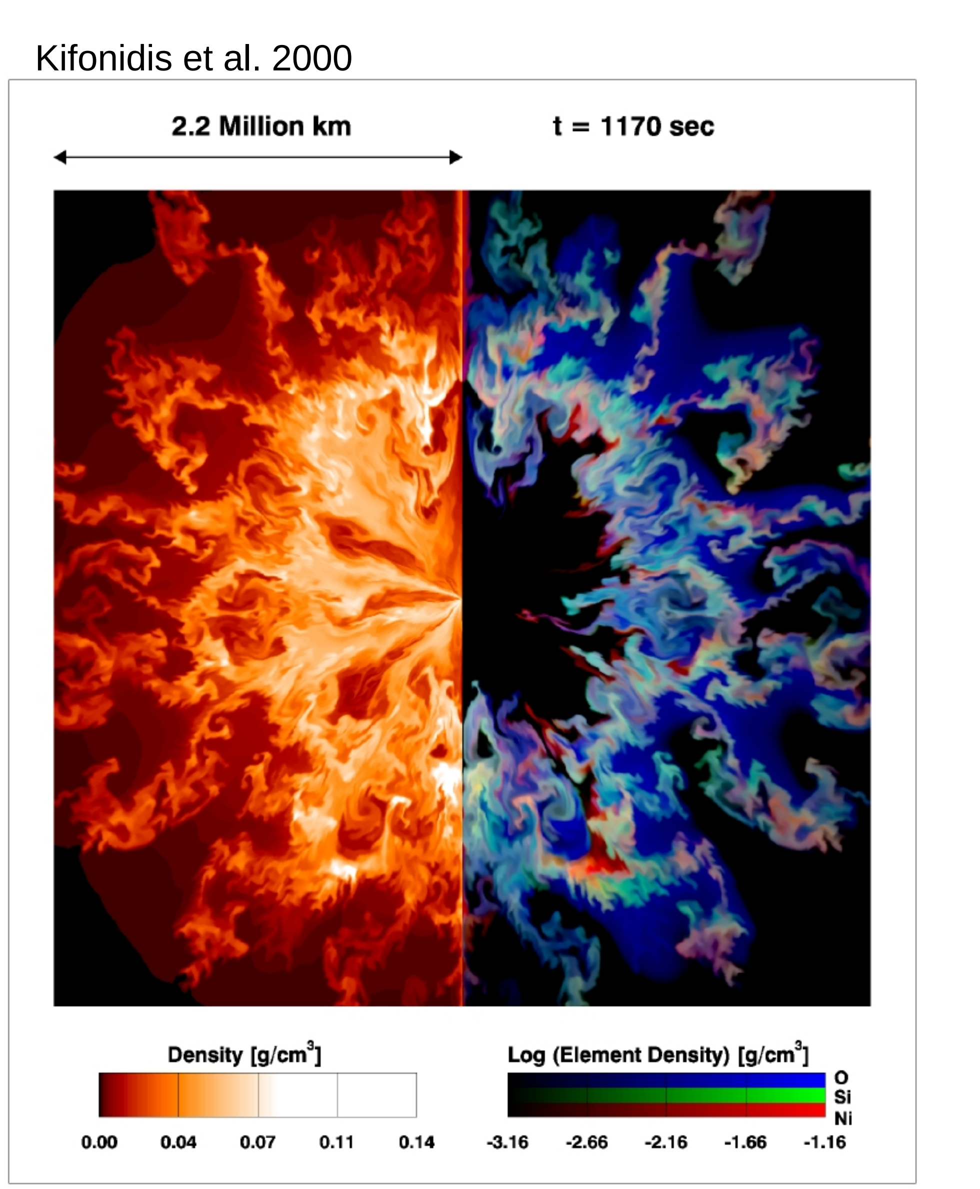

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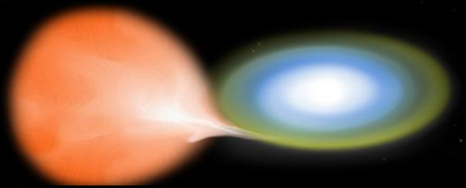
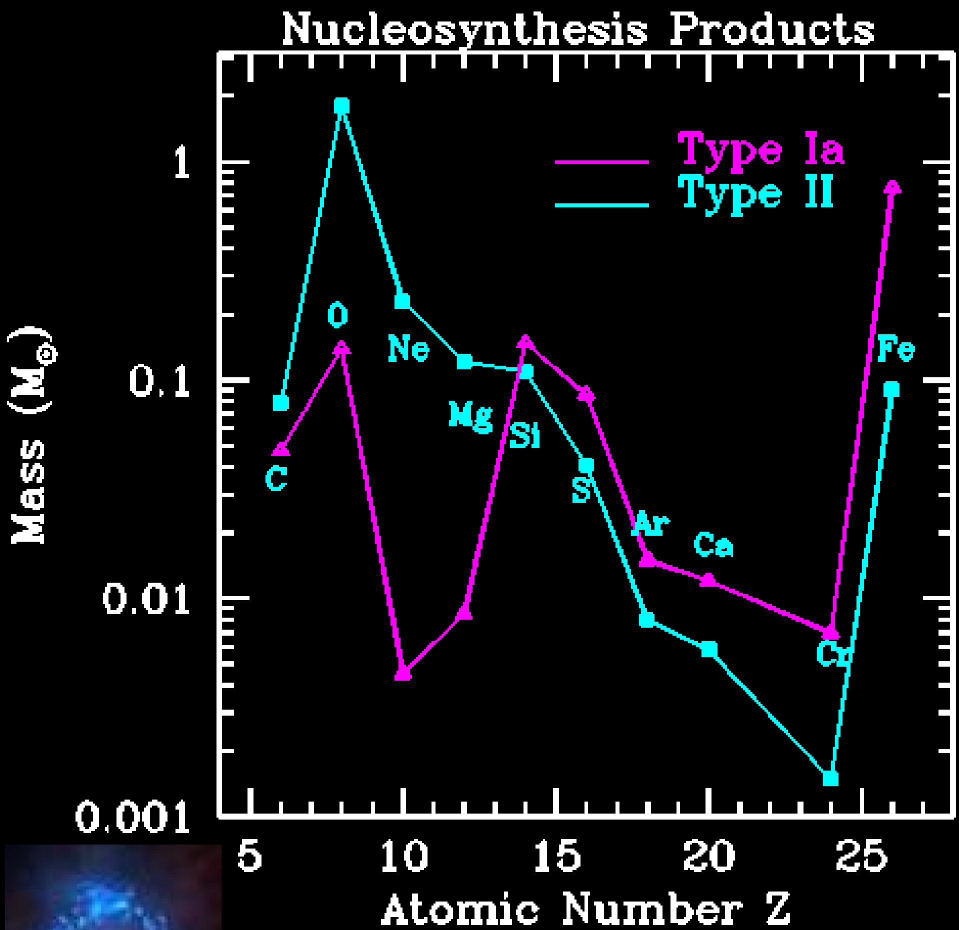
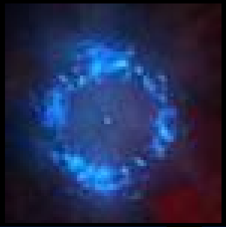
- **Distribution of ejecta material provides details of explosion and nucleosynthesis**
  - turbulent mixing of ejecta evident in models; do we see stratification or mixing in real remnants?



SNRs: Tracking the Ejecta





Type Ia:

- Complete burning of 1.4 $M_\odot$ C-O white dwarf
- Produces mostly Fe-peak nuclei (Ni, Fe, Co) with some intermediate mass ejecta (O, Si, S, Ar…)
  - very low O/Fe ratio
- Si-C/Fe sensitive to transition from deflagration to detonation; probes density structure
  - X-ray spectra constrain burning models
- Products stratified; preserve burning structure

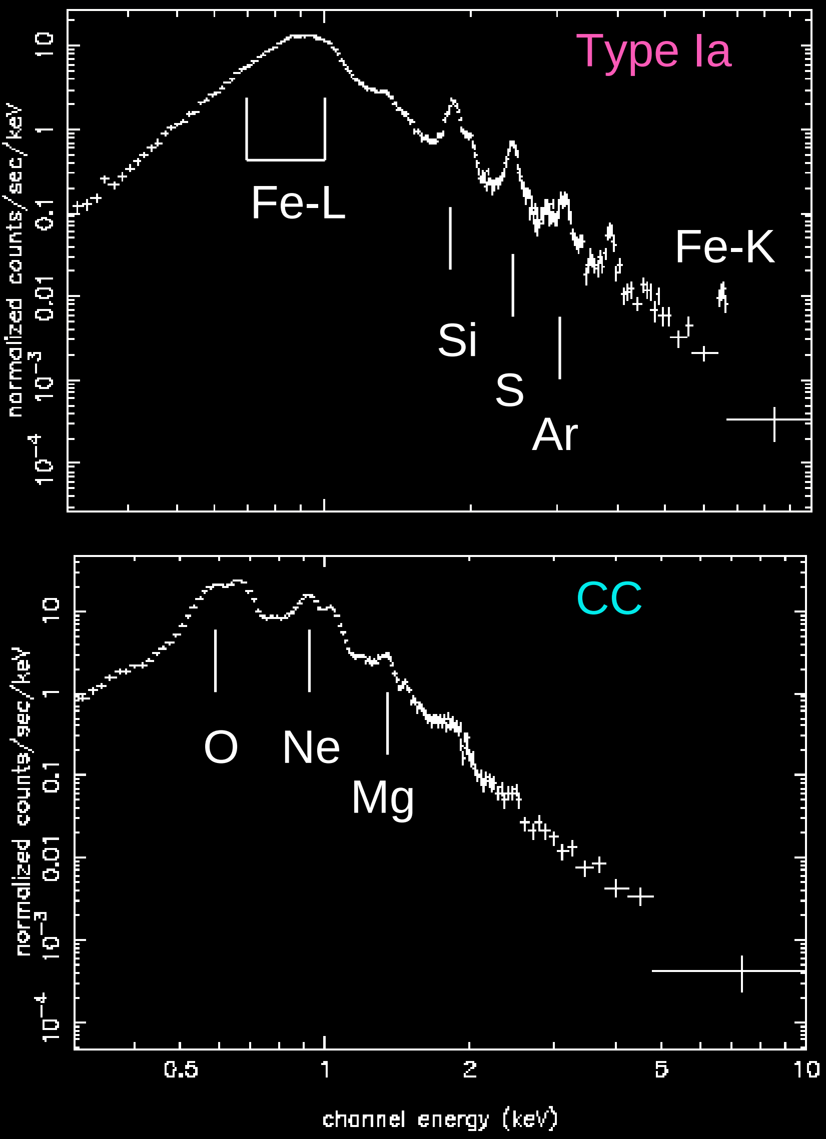
Core Collapse:

- Explosive nucleosynthesis builds up light elements
  - very high O/Fe ratio
  - explosive Si-burning: "Fe", alpha particles
  - incomplete Si-burning: Si, S, Fe, Ar, Ca
  - explosive O-burning: O, Si, S, Ar, Ca
  - explosive Ne/C-burning: O, Mg, Si, Ne

T

- Fe mass probes mass cut
- O, Ne, Mg, Fe very sensitive to progenitor mass
- Ejecta distribution probes mixing by instabilities

SNRs: Tracking the Ejecta



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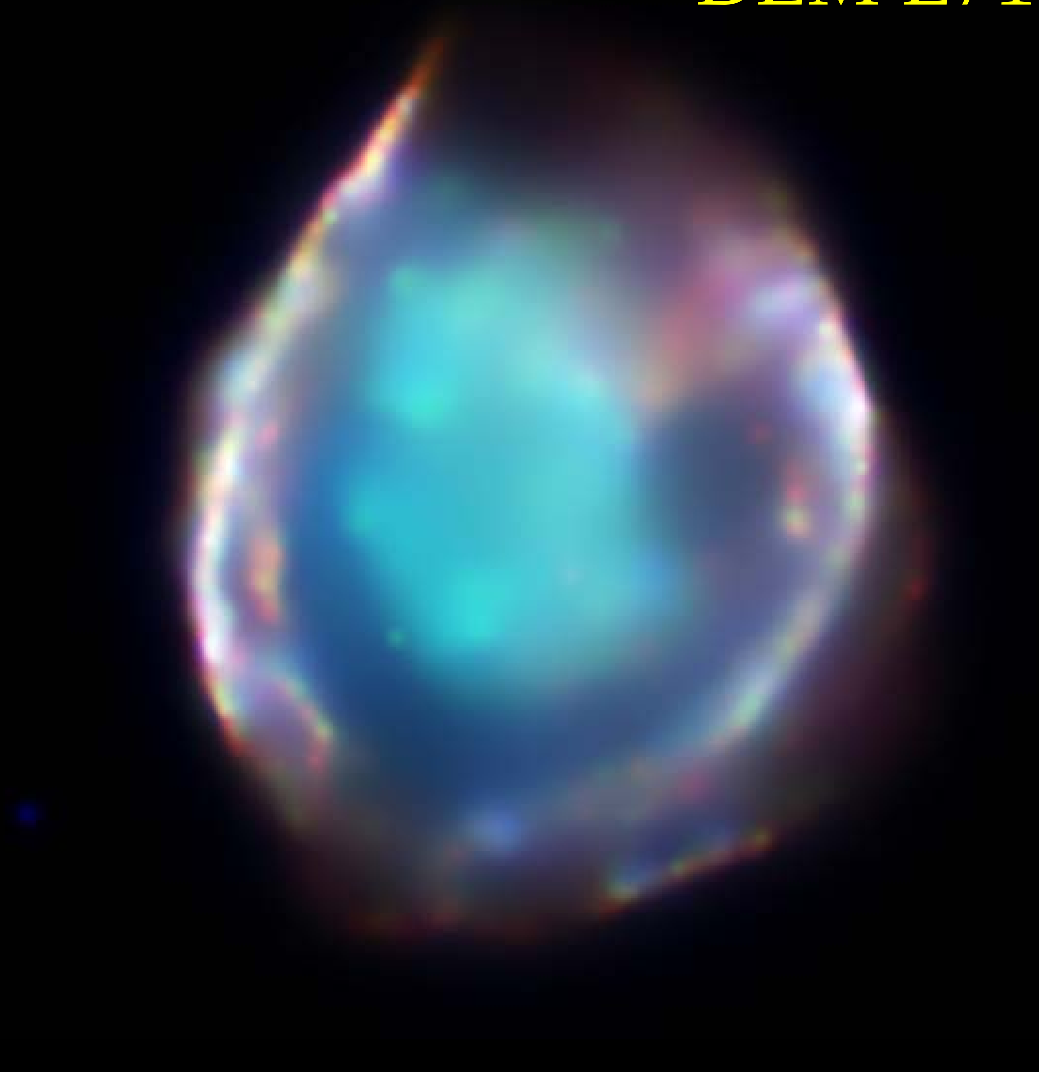
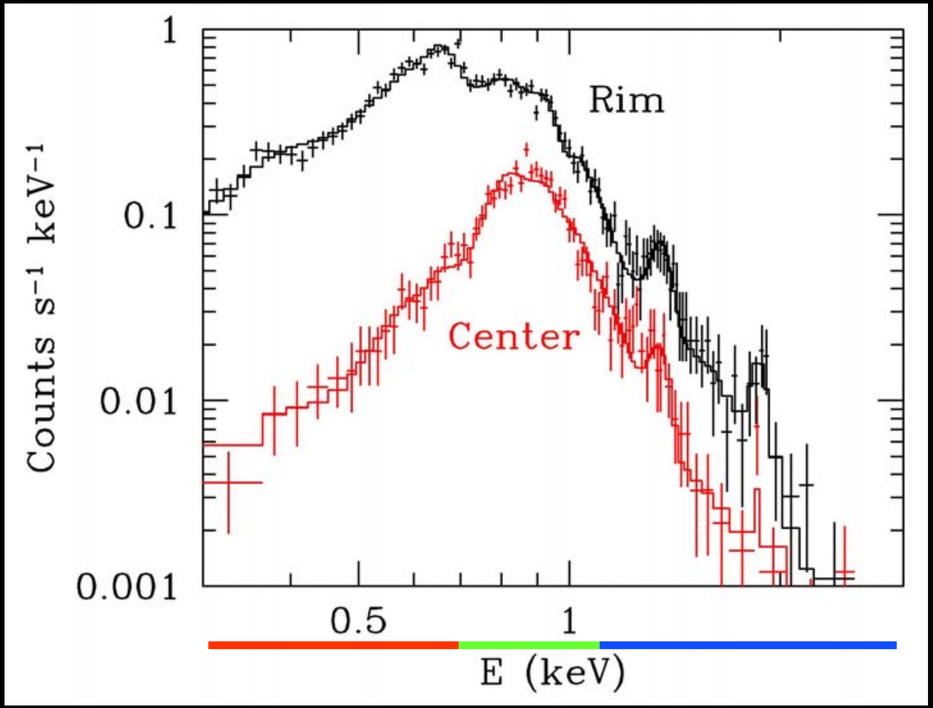
DEM L71: a Type Ia





- ~5000 yr old LMC SNR
- Outer shell consistent with swept-up ISM
  - LMC-like abundances
- Central emission evident at E>0.7 keV
  - primarily Fe-L
  - Fe/O > 5 times solar; typical of Type Ia

Hughes, Ghavamian, Rakowski, & Slane 2003, ApJ, 582, L95

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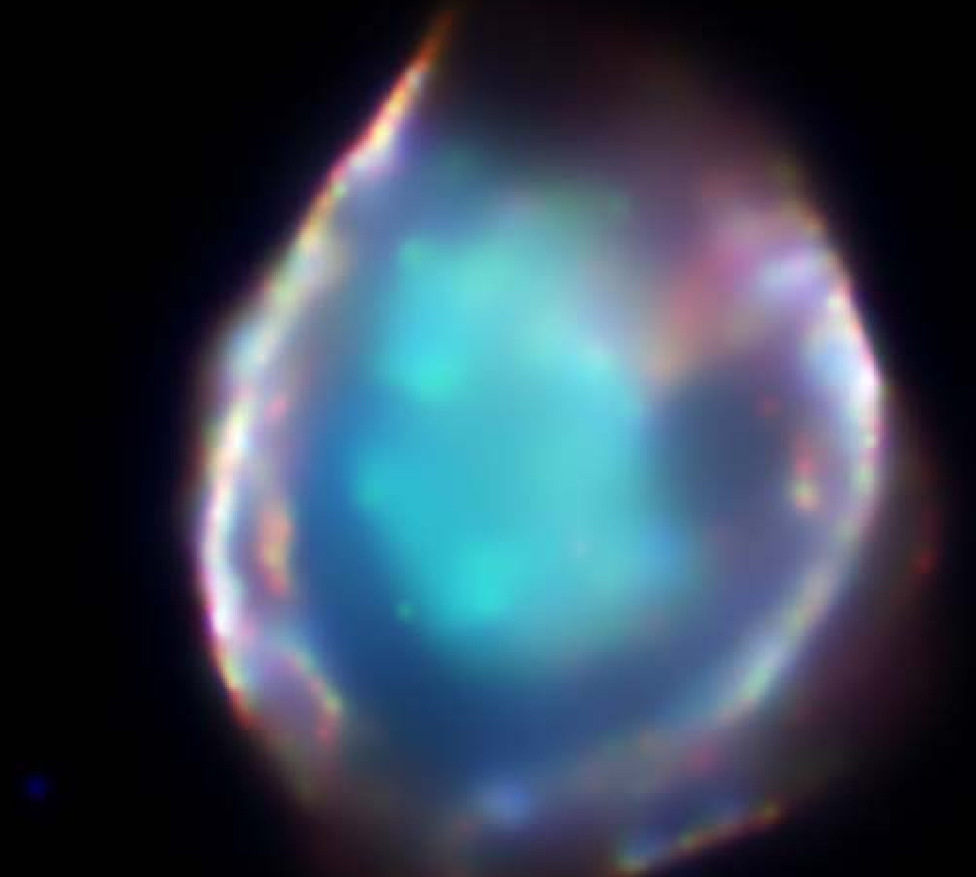
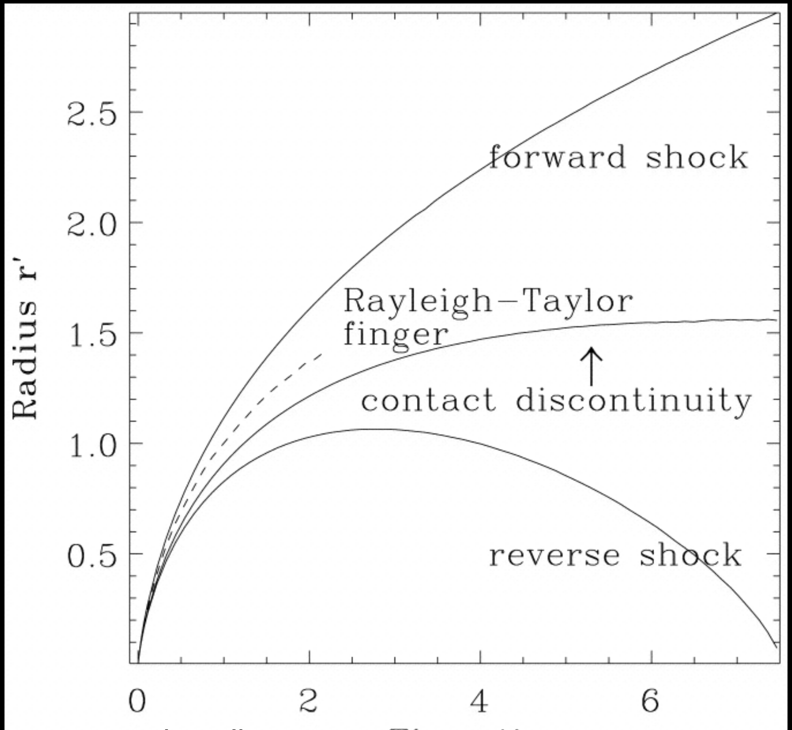




Wang & Chevalier 2001

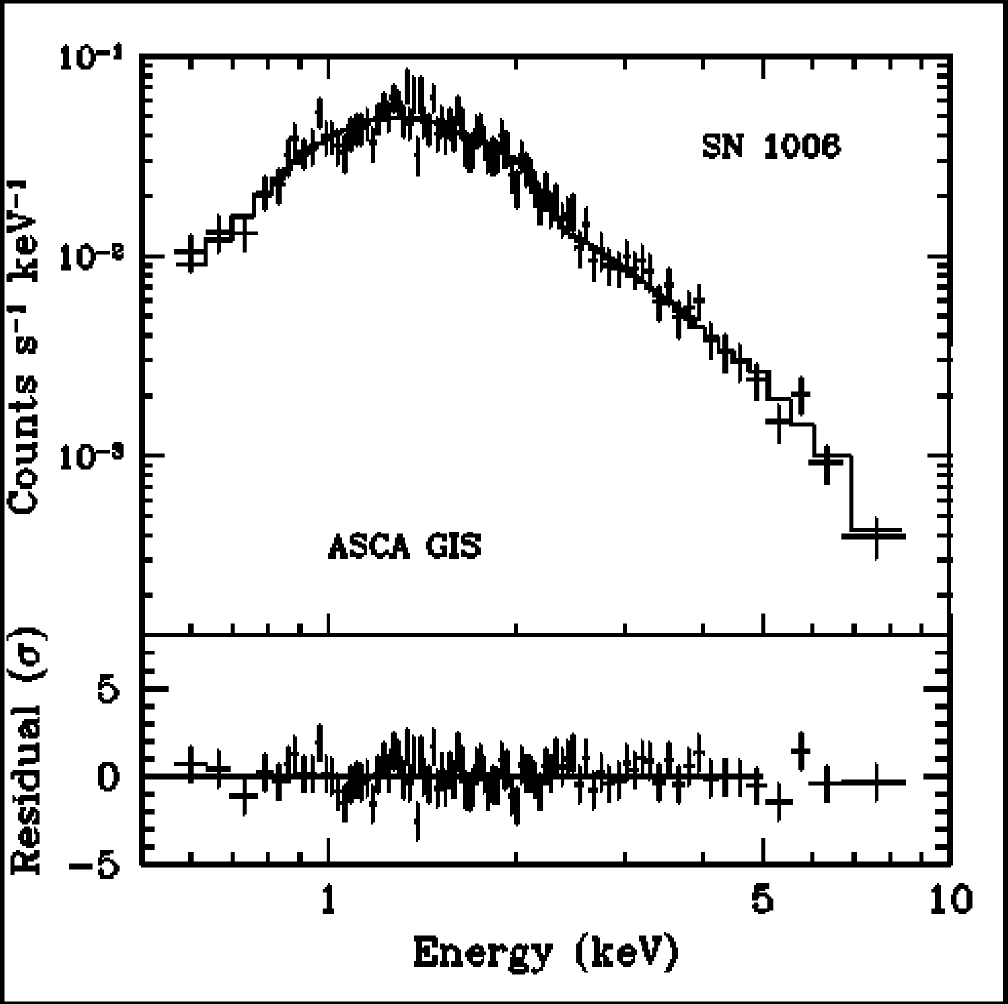
- Spectra and morphology place contact discontinuity at ~R/2; or r' = 3 where

$$M_{ej} = M_{Ch} n_0 \left(\frac{r_{pc}}{2.19 r'} \right)$$

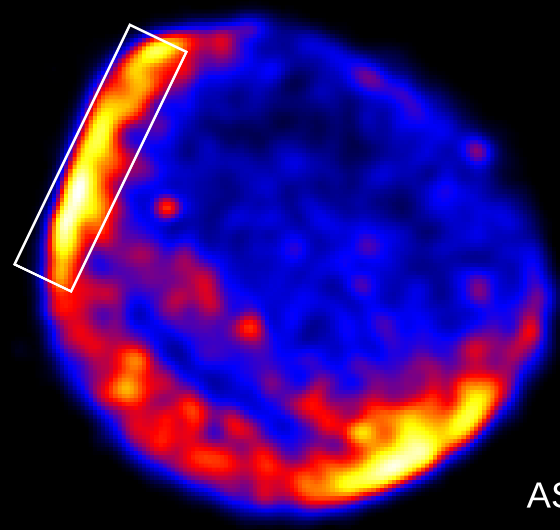
Hughes, Ghavamian, Rakowski, & Slane 2003, ApJ, 582, L95

- Total ejecta mass is thus ~1.5 solar masses
  - reverse shock has heated all ejecta
- Spectral fits give $M_{Fe} \sim 0.8$-$1.5\ M_{\odot}$ and $M_{Si} \sim 0.12$-$0.24\ M_{\odot}$
  - consistent w/ Type Ia progenitor

Particle Acceleration in SN 1006



- **Spectrum of limb dominated by <u>nonthermal emission</u> (Koyama et al. '96)**
  - keV photons imply $E_e \approx 100\,\mathrm{TeV}$
  - TeV γ-ray emission might be expected, but source is not currently detected



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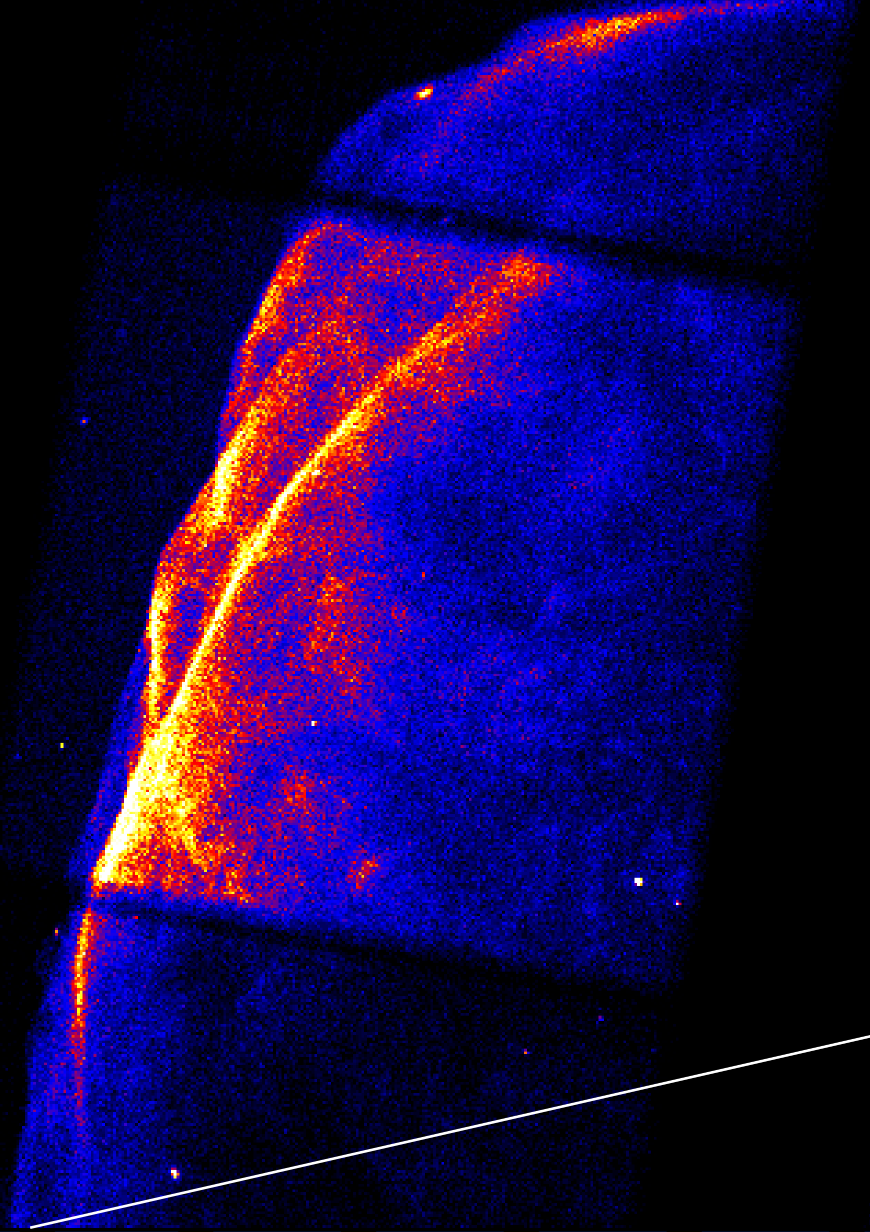

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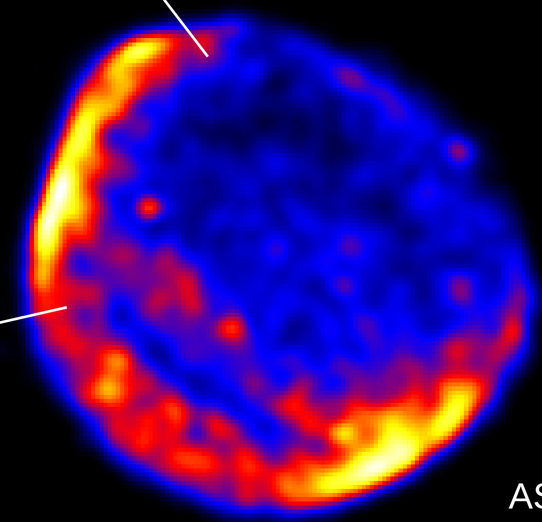
- ***Chandra* observations show distinct shock structure in shell**



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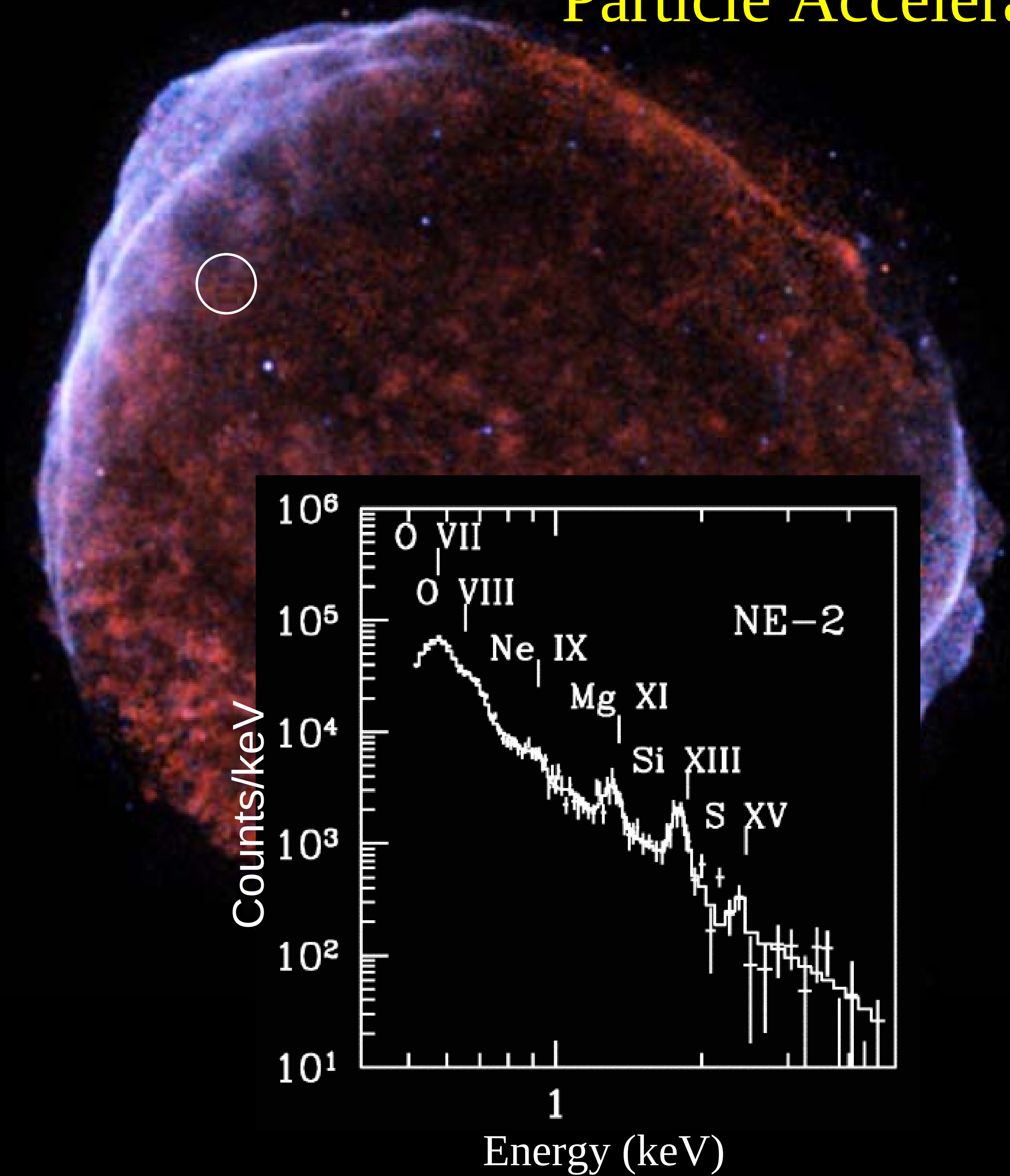

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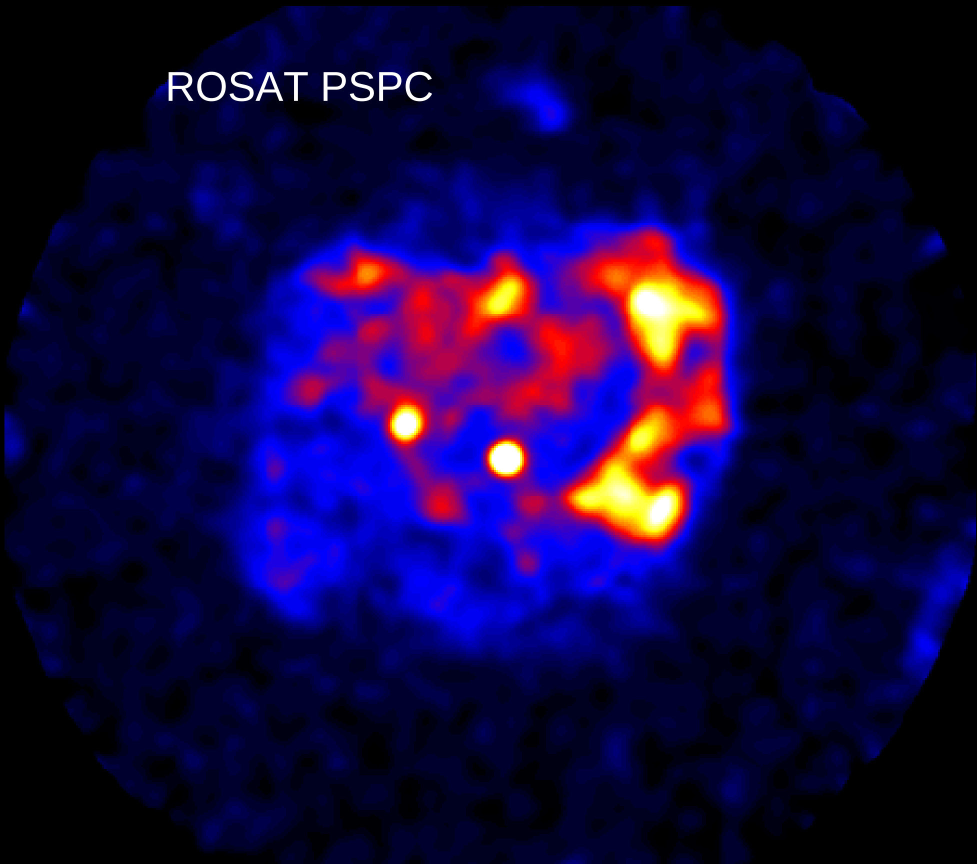
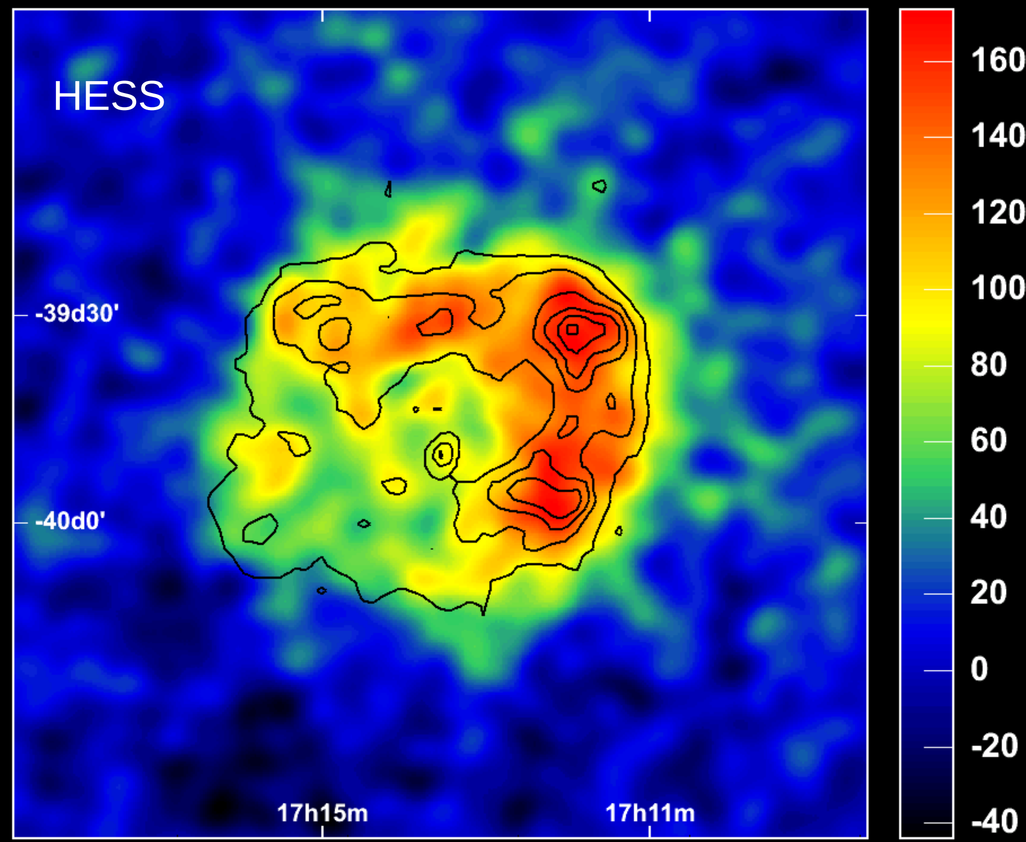
- ***Chandra* observations show distinct shock structure in shell**

- **Interior of SNR shows thermal ejecta**
  - knots near rim are not rich in Fe as expected for a Type Ia
  - stratification showing outer regions of explosive nucleosynthesis in WD?

HESS Observations of G347.3-0.5

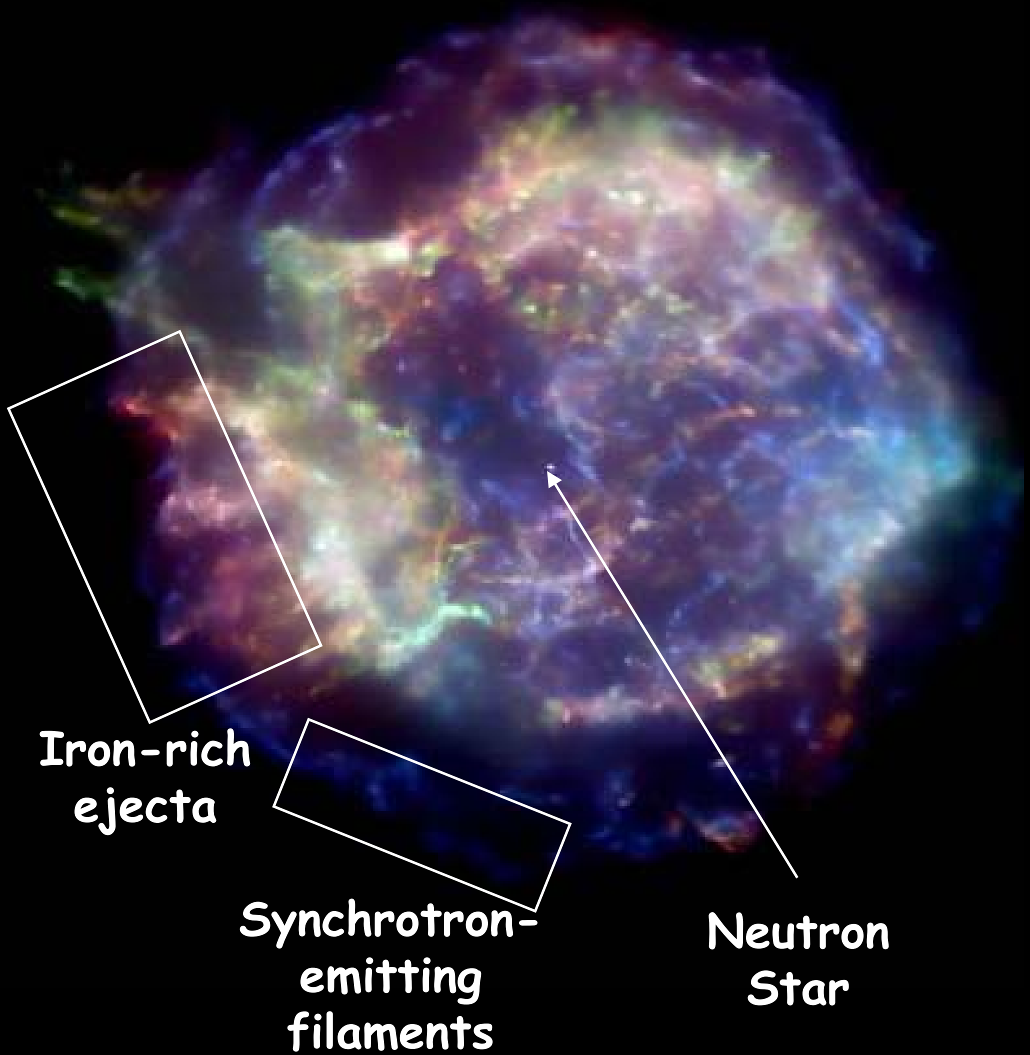


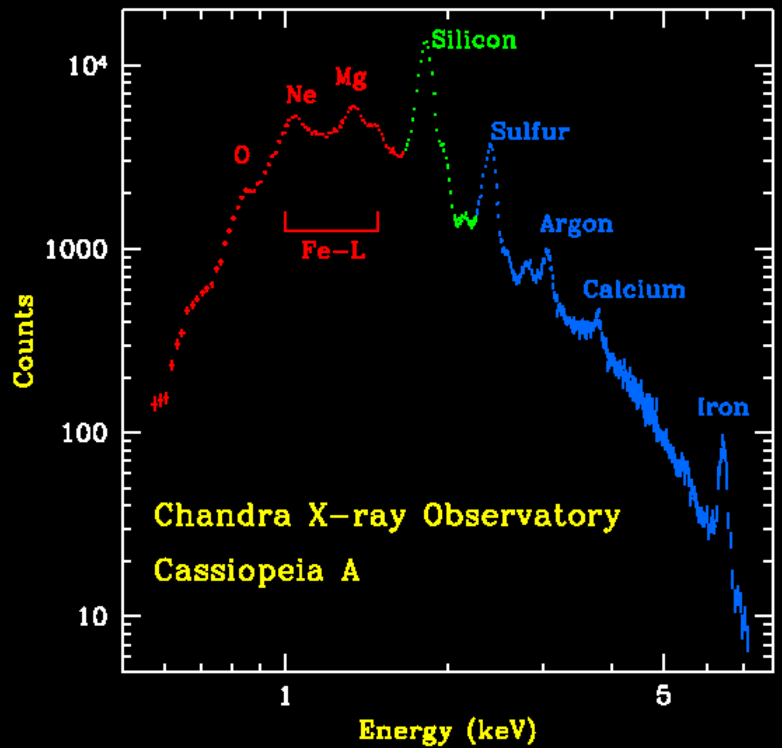


- X-ray observations reveal a nonthermal spectrum everywhere in G347.3-0.5
  - evidence for cosmic-ray acceleration
  - based on X-ray synchrotron emission, infer electron energies of ~100 TeV

- This SNR is detected directly in TeV gamma-rays, by HESS
  - first resolved image of an SNR at TeV energies

Cassiopeia A: A Young Core-Collapse SNR

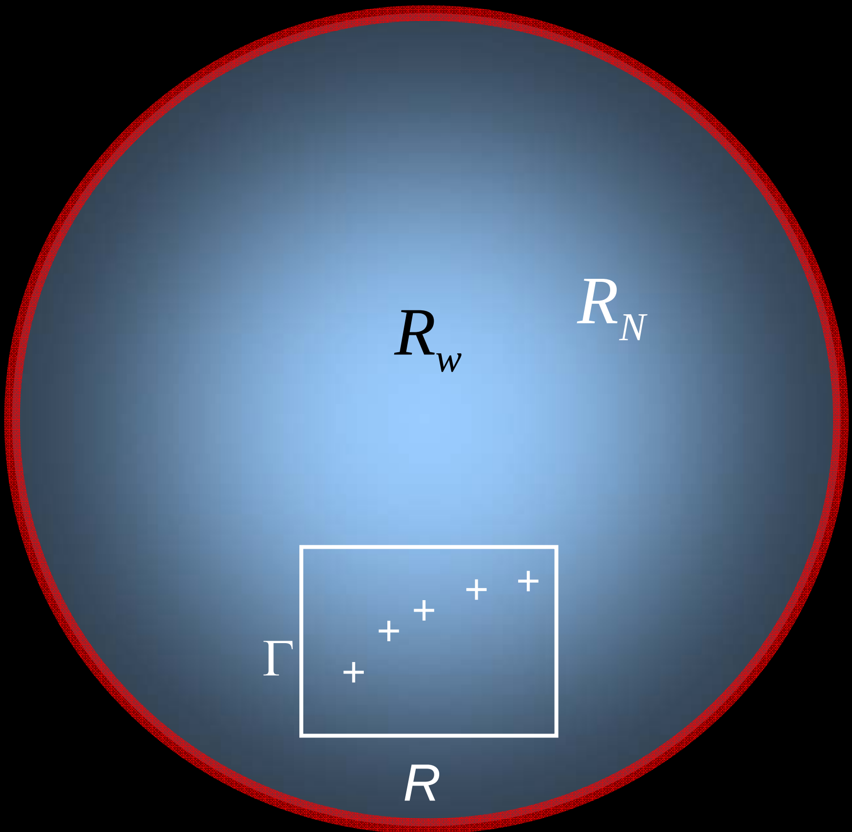




- **Complex ejecta distribution**
  - Fe formed in core, but found near rim
- **Nonthermal filaments**
  - cosmic-ray acceleration
- **Neutron star in interior**
  - no pulsations or wind nebula observed

Hughes, Rakowski, Burrows, & Slane 2000, ApJ, 528, L109
Hwang, Holt, & Petre 2000, ApJ, 537, L119

Pulsar Wind Nebulae



- **Pulsar wind inflates bubble of energetic particles and magnetic field**
  - pulsar wind nebula
  - synchrotron radiation; at high frequencies, index varies with radius (burn-off)

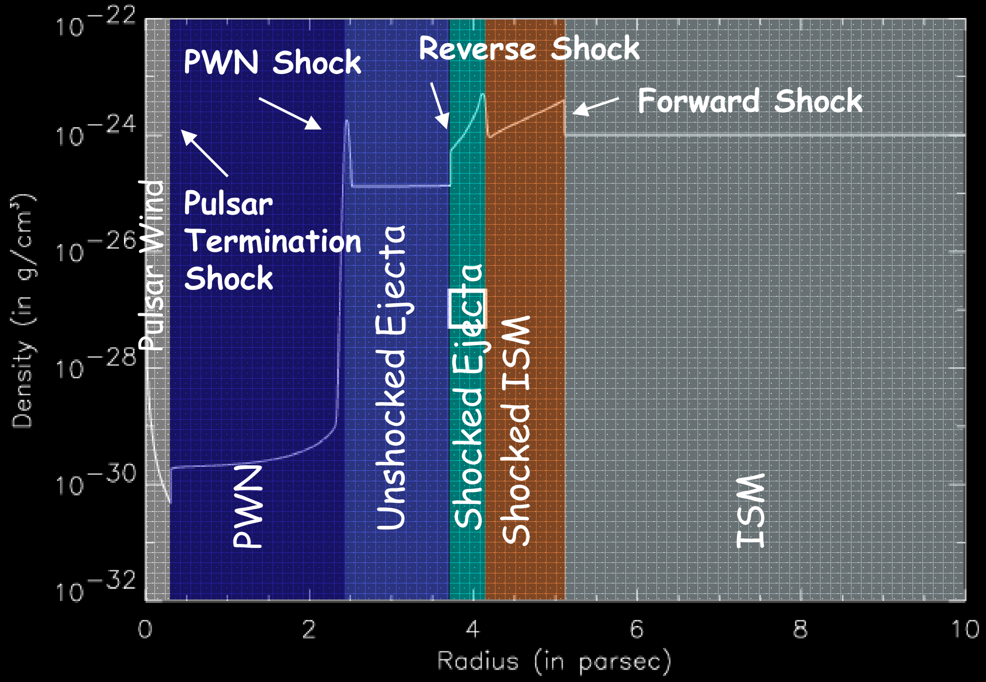
- **Expansion boundary condition at R_w forces wind termination shock at R_N**
  - wind goes from $v \approx c/3$ inside R_w to $v \approx R_N / t$ at outer boundary

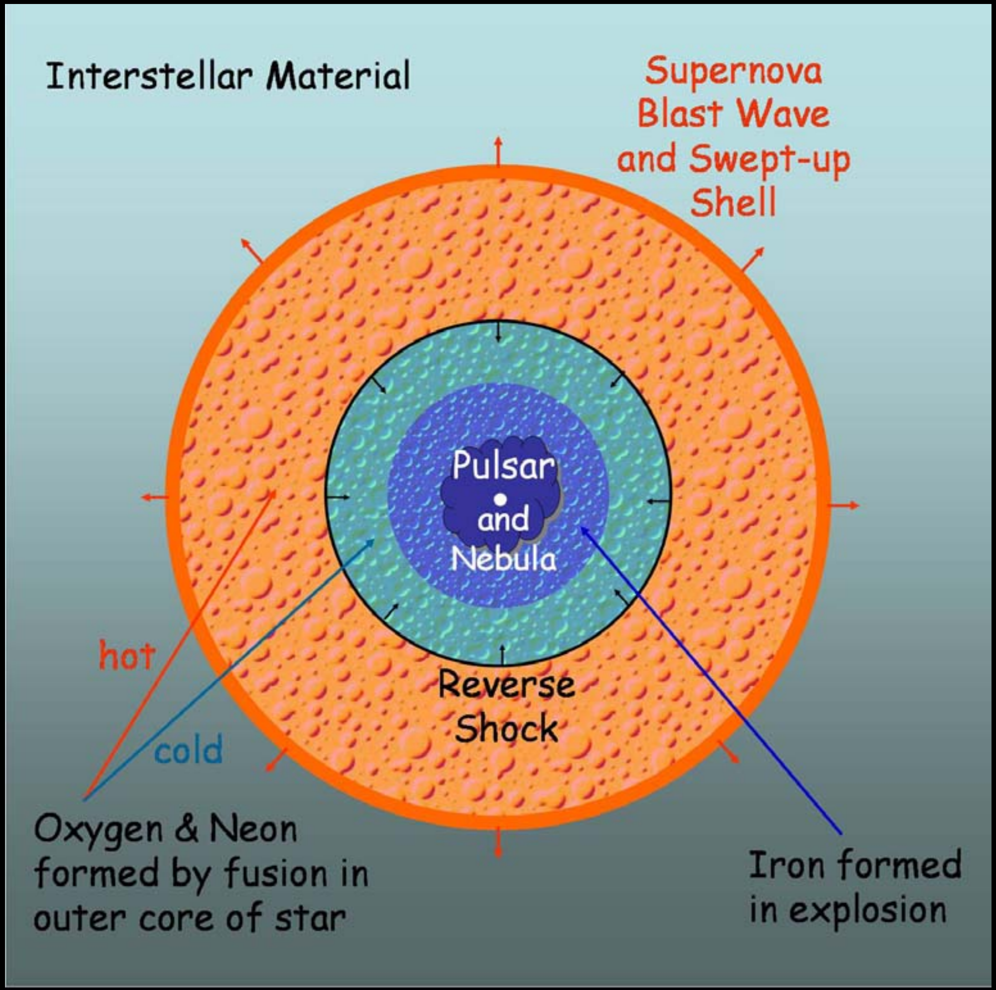
- **Pulsar wind is confined by pressure in nebula**

$$\frac{\dot{E}}{4\pi R_w^2 c} = P_{neb}$$

obtain by integrating radio spectrum

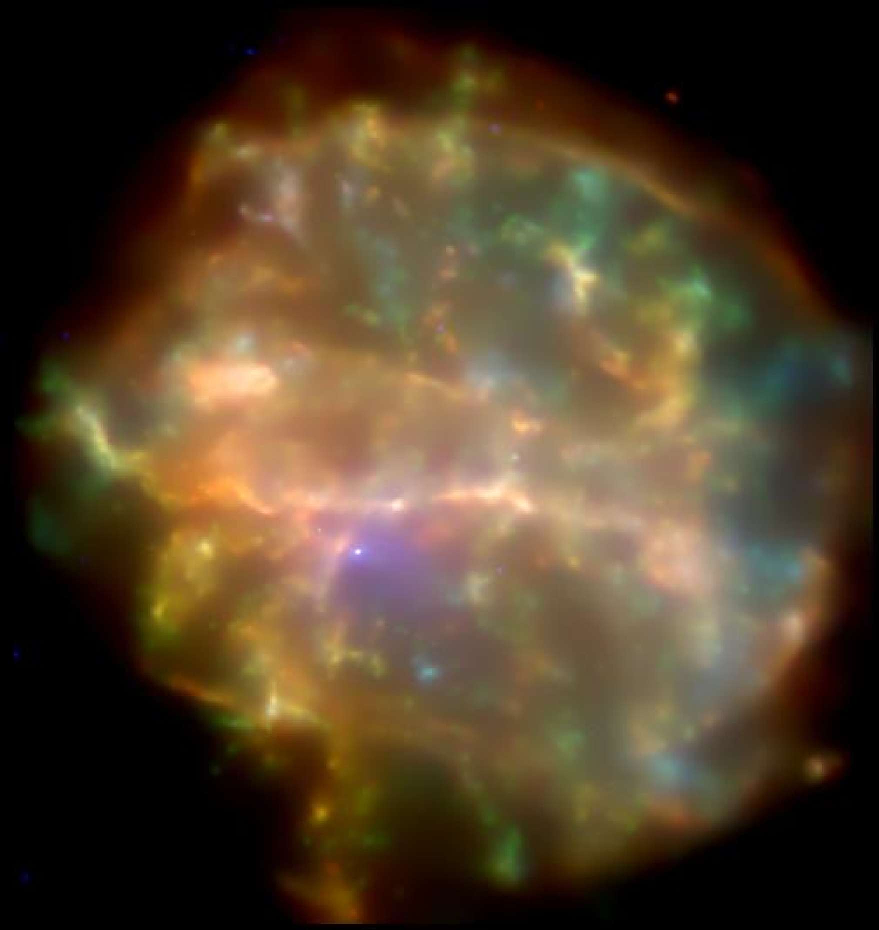
Putting it Together: Composite SNRs

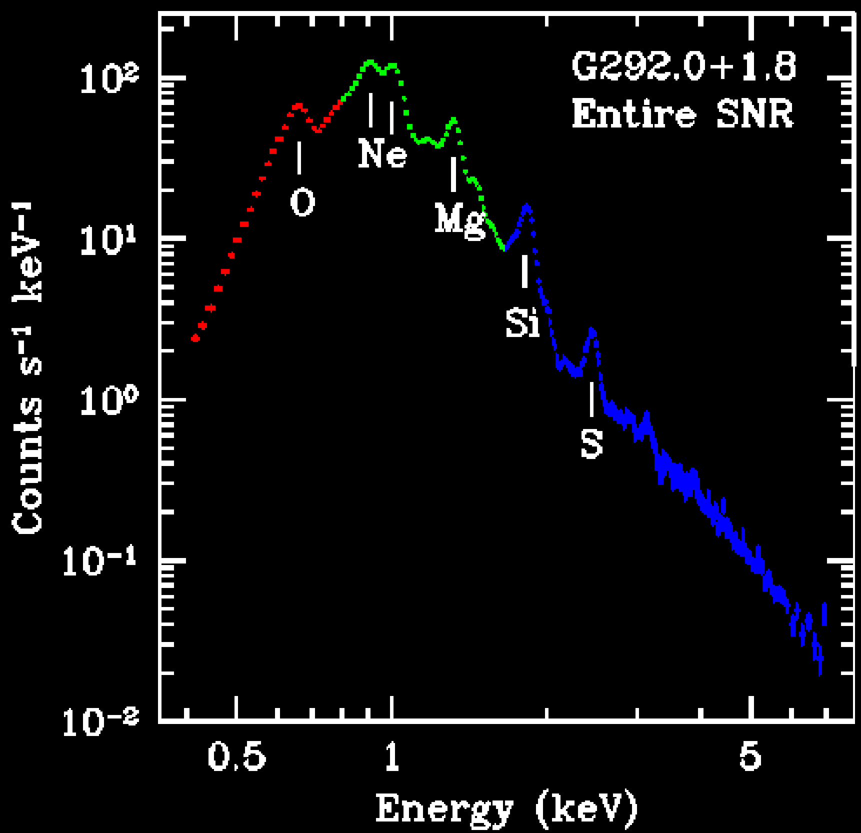




- **Pulsar Wind**
  - sweeps up ejecta; termination shock decelerates flow; PWN forms
- **Supernova Remnant**
  - sweeps up ISM; reverse shock heats ejecta; ultimately compresses PWN

G292.0+1.8: O-Rich and Composite

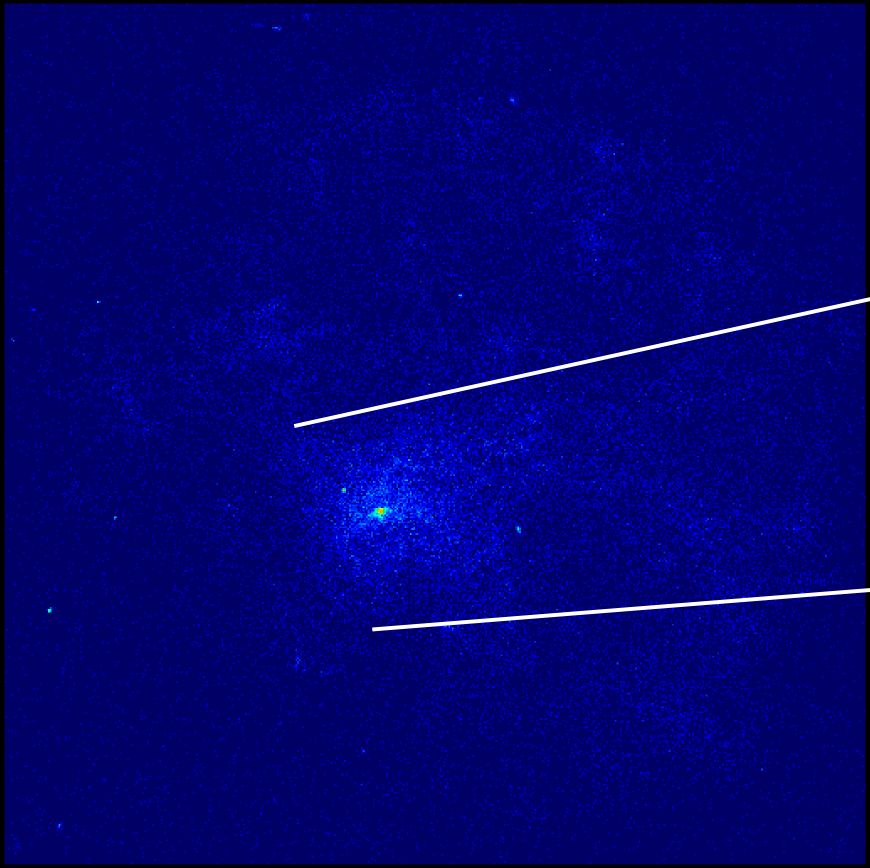




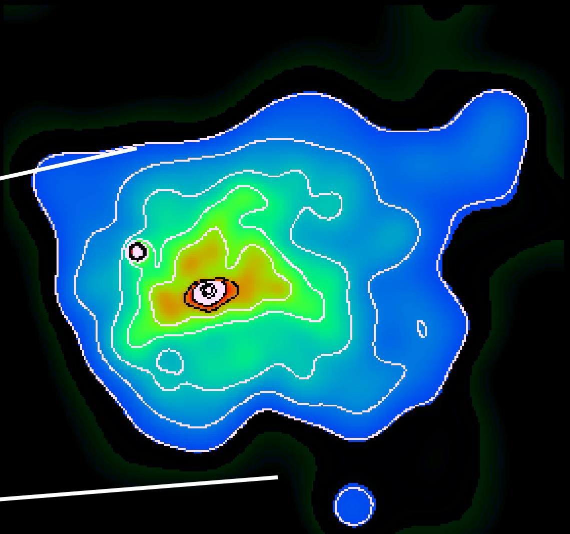
- Oxygen-rich SNR; massive star progenitor
  - dynamical age ~2000 yr
  - O & Ne dominate Fe-L, as expected

Park, et al. 2002, ApJ, 564, L39

G292.0+1.8: O-Rich and Composite



Hughes, et al. 2001, ApJ, 559, L153

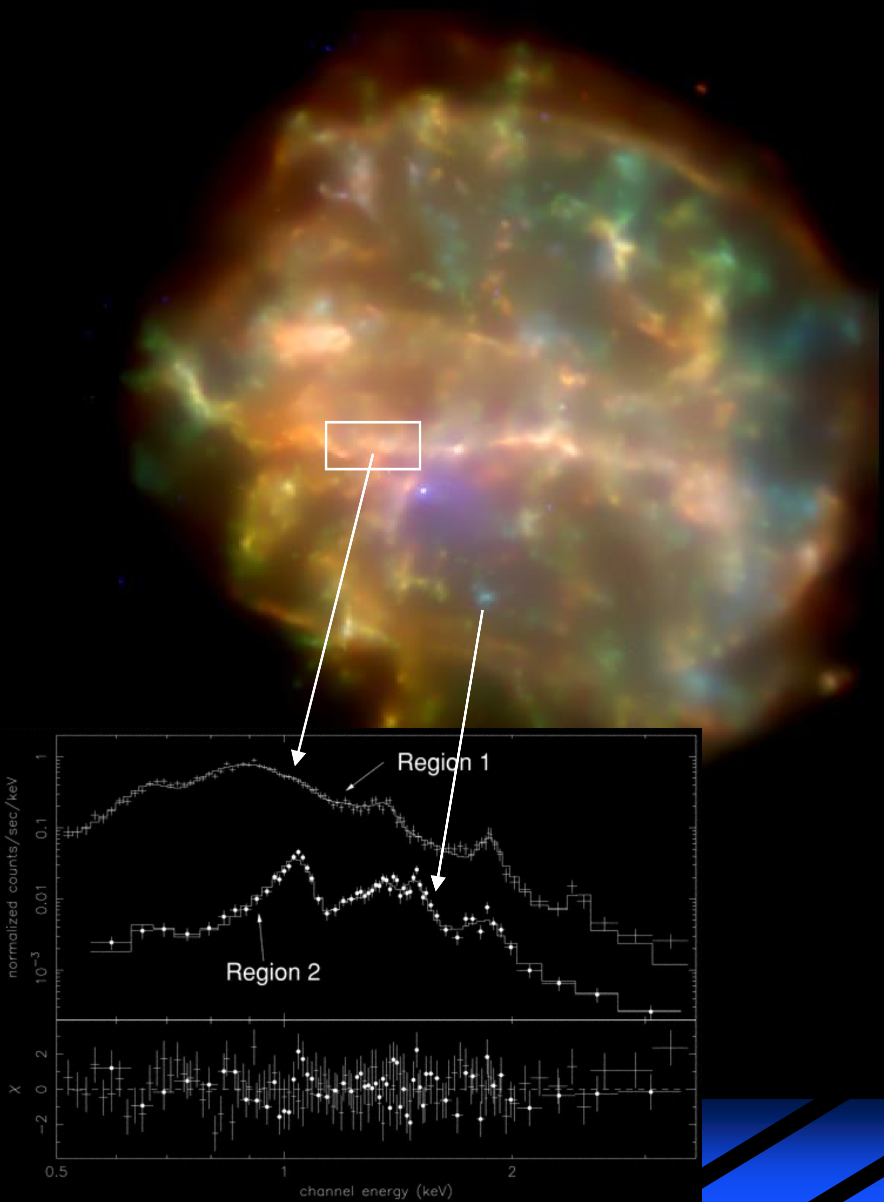


- Compact source surrounded by diffuse emission seen in hard band
  - pulsar (Camillo et al. 2002) and PWN
  - 135 ms pulsations confirmed in X-rays

- Compact source extended
  - evidence of jets/torus?

Hughes, Slane, Roming, & Burrows 2003, ApJ

G292.0+1.8: Sort of Shocking…



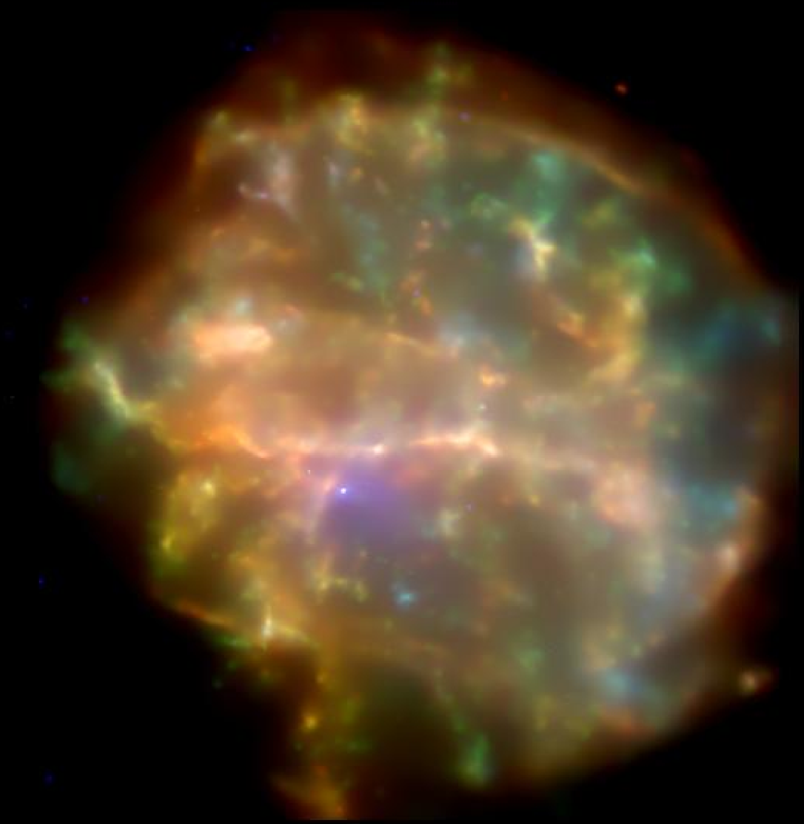
- Individual knots rich in ejecta

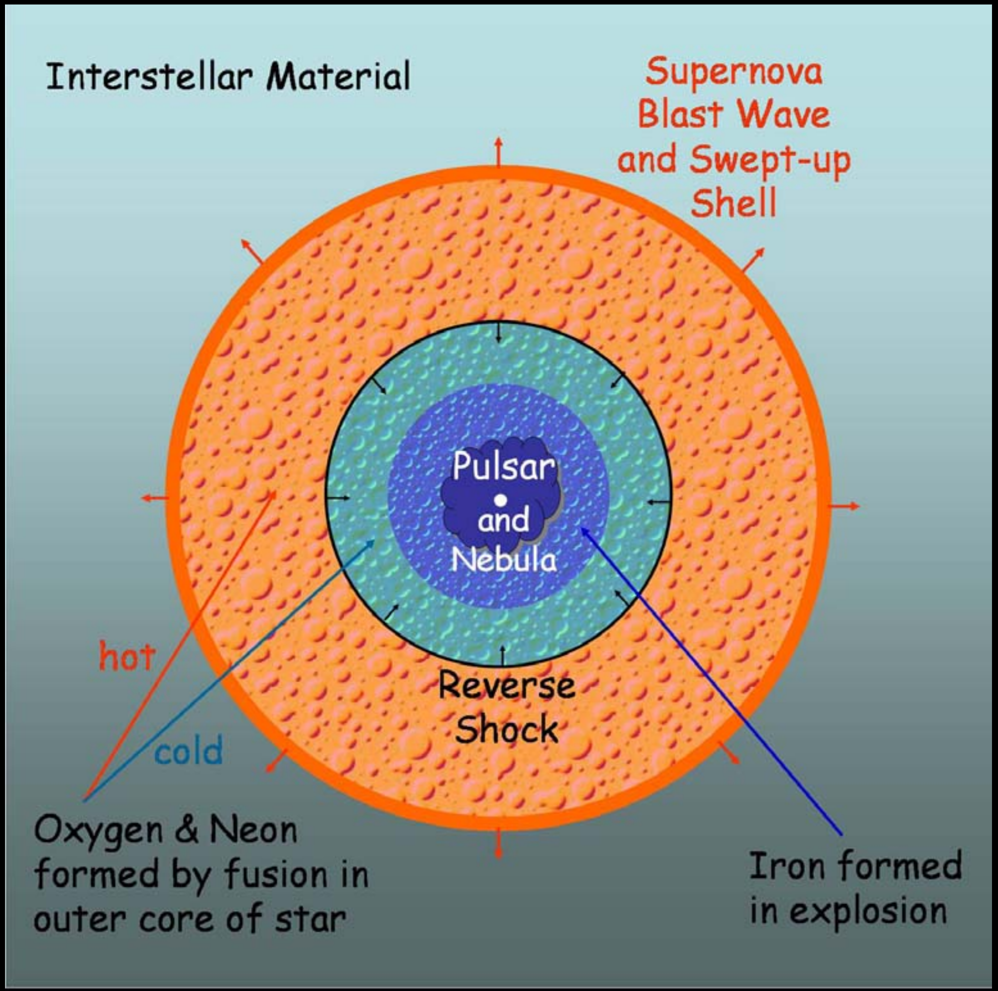
- Spectrum of central bar and outer ring show ISM-like abundances
  - relic structure from equatorially-enhanced stellar wind?

- Oxygen and Neon abundances seen in ejecta are enhanced above levels expected; very little iron observed
  - reverse shock appears to still be progressing toward center; not all material synthesized in center of star has been shocked
  - pressure in PWN is lower than in ejecta as well ➔ reverse shock hasn't reached PWN?

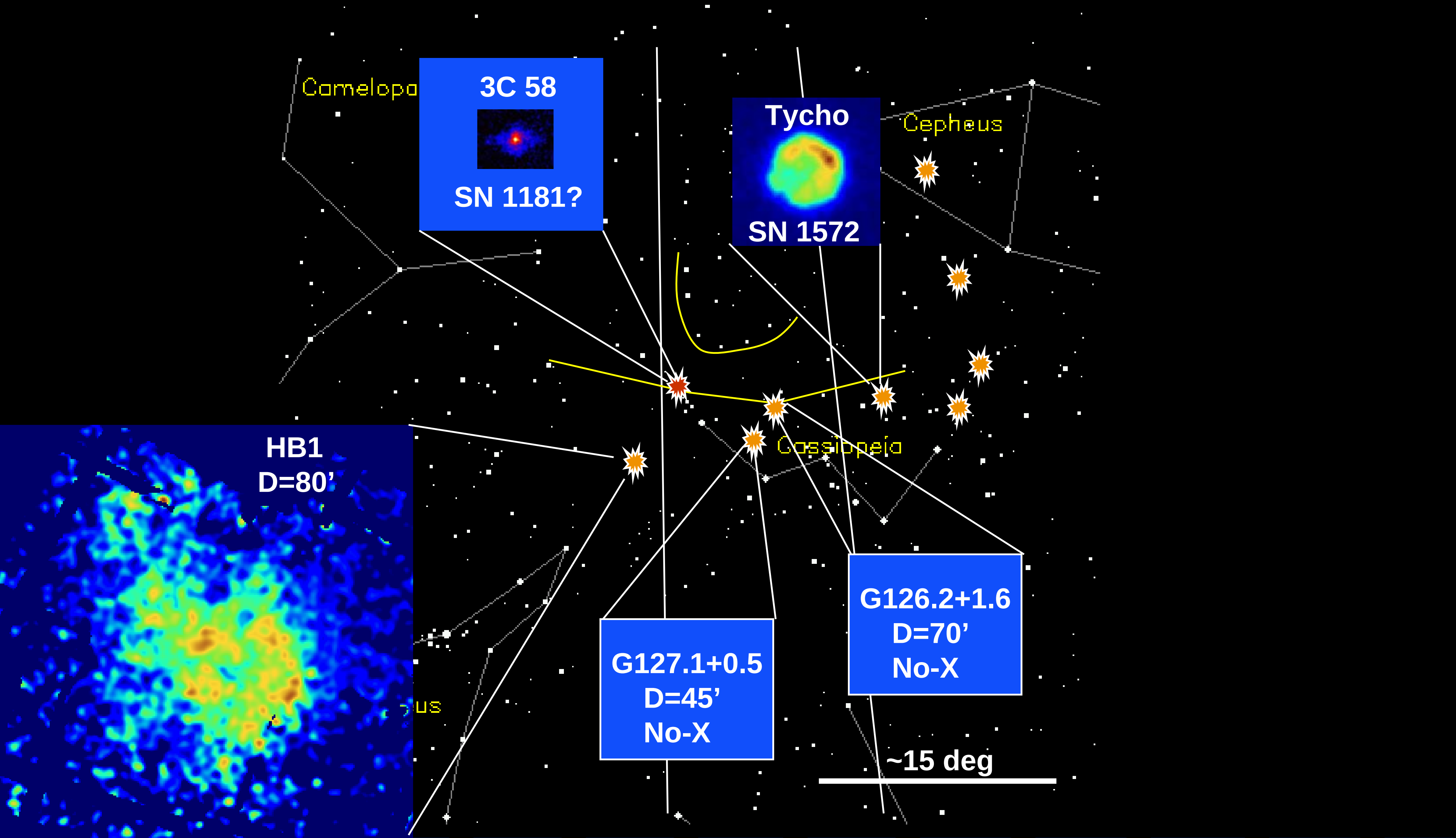
Park, et al. 2004, ApJ, 602, L33

G292.0+1.8: Sort of Shocking…

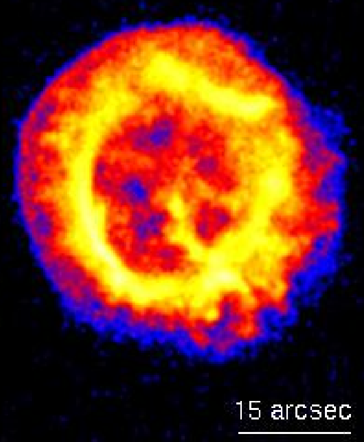




Is 3C 58 The Relic of SN 1181?



Evolution and Dynamics of 1E 0102.2-7219



See Hughes, Rakowski, & Decourchelle 2000, ApJ, 543, L61

1E 0102.2-7219 (Figure 1) is an oxygen-rich supernova remnant in the Small Magellanic Cloud. X-ray observations reveal the blast wave andyield a shock radius of 22 arcseconds at the 60 kpc distance of the SMC. The spectrum of the blast wave yields a temperature of $kT_x = 0.8$ keV and an ionization timescale $n_e t \sim 1 \times 10^{11}$ cm^{-3}s.

1. Based on the temperature, what is the shock velocity? Assuming the SNR is in the Sedov phase of evolution, calculate the age. How does this compare with the age under the assumption of free expansion?

2. Expansion measurements from X-ray observations at different epochs yield a blast wave velocity of v_s = 6200 (+1500 -1600) km/s. What temperature does this correspond to? If this velocity is correct, what is the age under Sedov and free-expansion assumptions? How can we reconcile these temperature values?

3. Note that the heating timescale for postshock electrons via Coulomb collisions gives

$$\frac{dT_e}{dn_e t} = 0.13 \frac{T_p - T_e}{T_e^{3/2}}.$$

Rearrange the above and estimate the upper limit on the electron temperature assuming that the expansion velocity gives the proton temperature. Can the temperature discrepancy be reconciled in this way? What else might be going on? Comment on potential ramifications for determining neutron star ages through SNR associations.