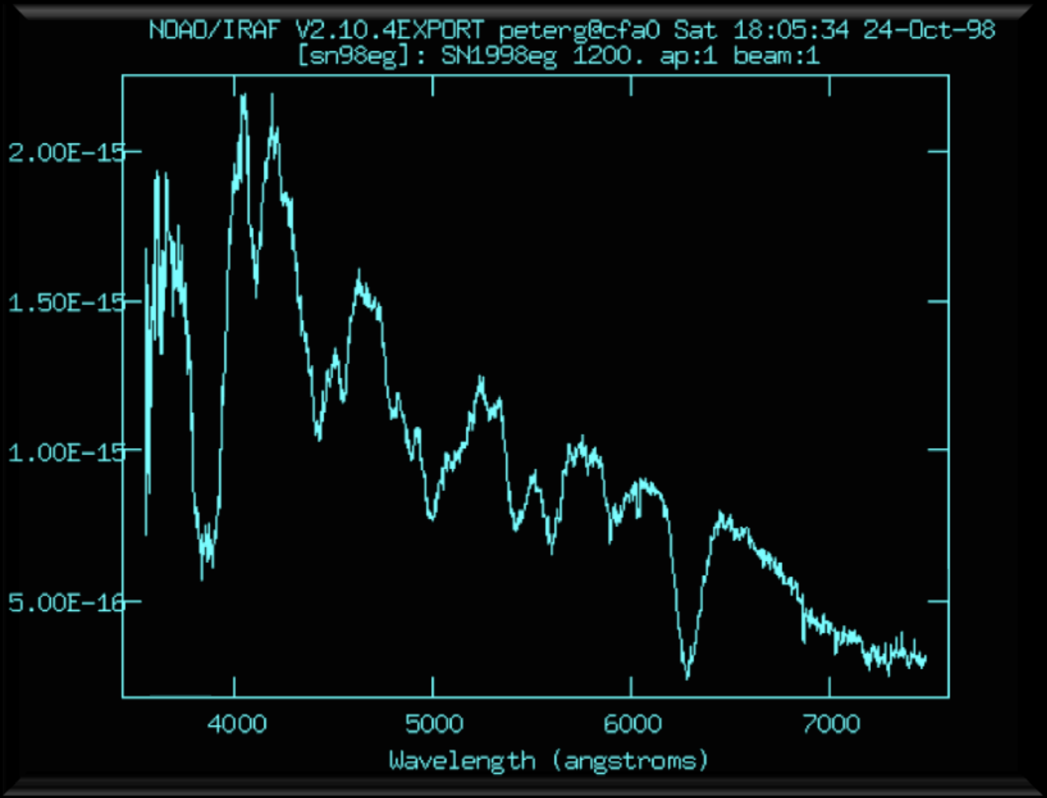
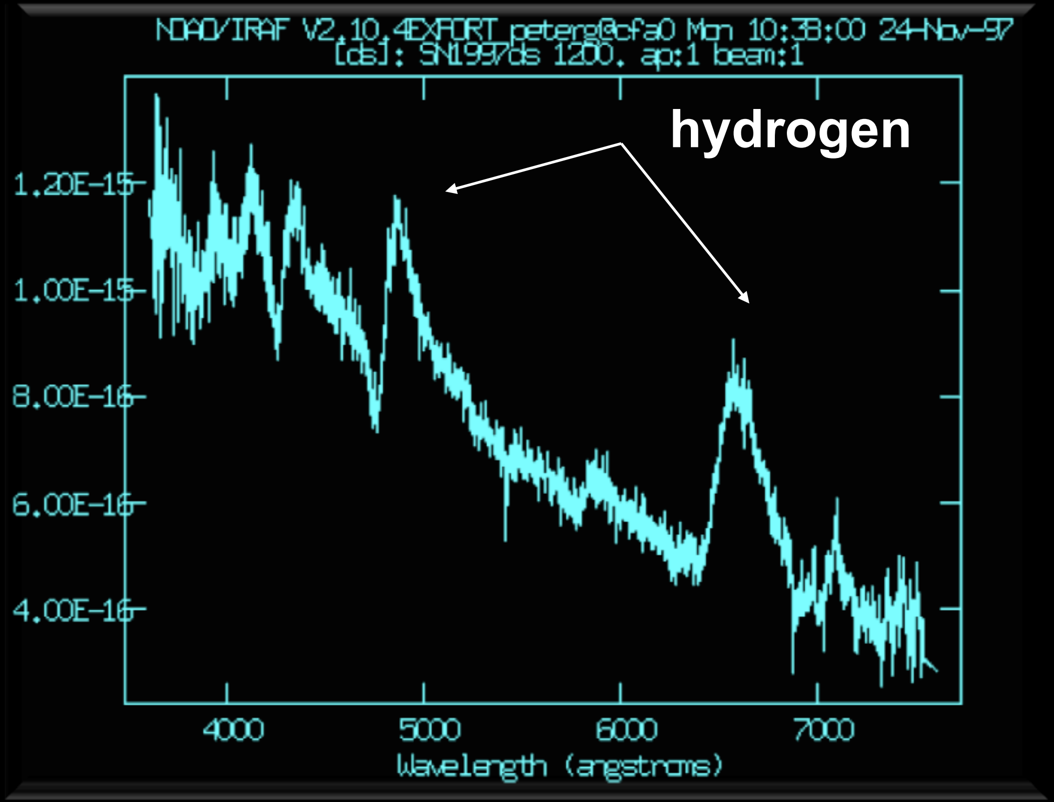
Supernova Remnants:

The Starting Point: Supernovae





- **Type I** characterized by lack of hydrogen in spectrum
- **Type II** characterized by presence of strong hydrogen in spectrum

Overall SN rate is about 1 per 40 years

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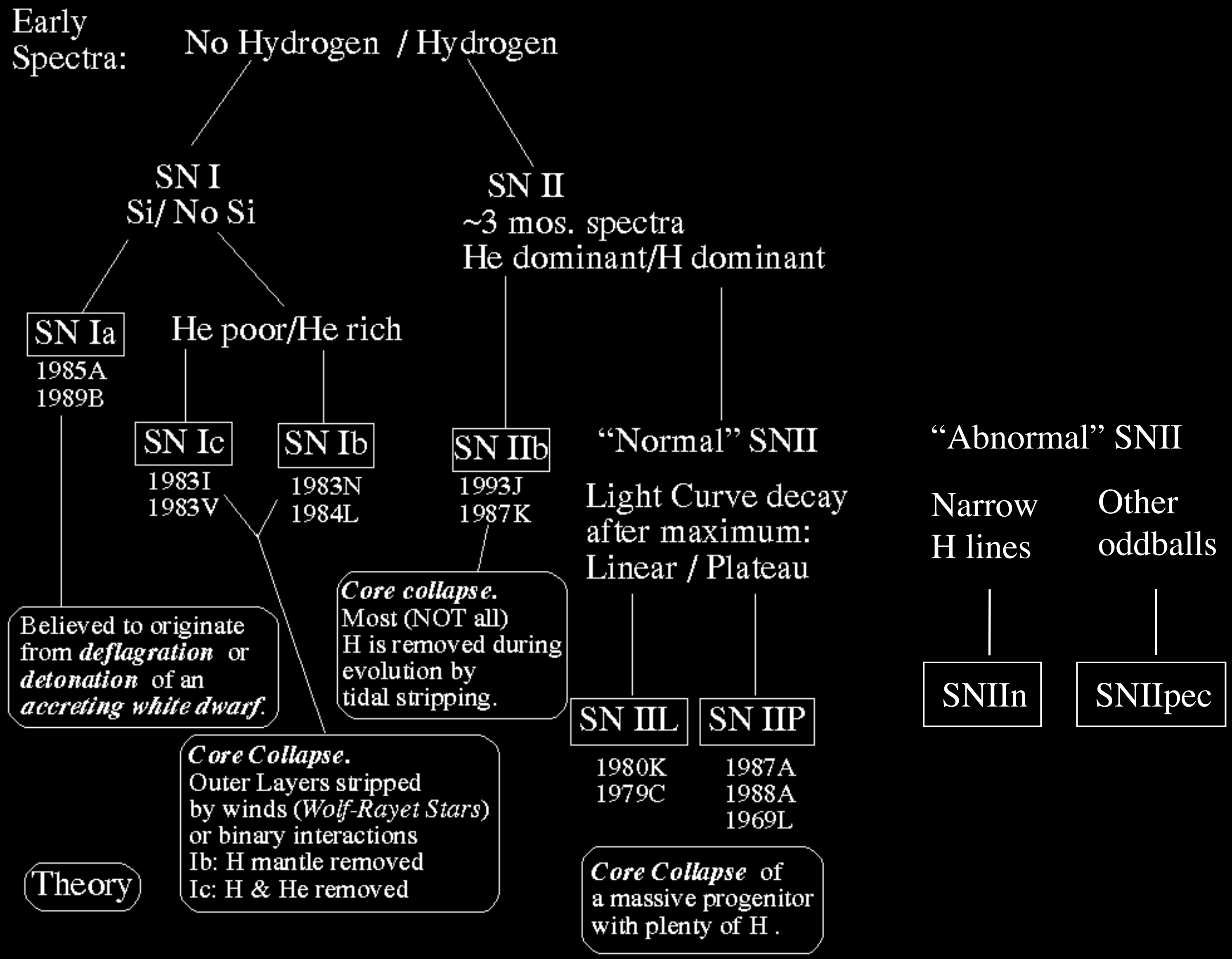


Early Spectra: No Hydrogen / Hydrogen

SN I
Si/ No Si

SN II
~3 mos. spectra
He dominant/H dominant

SN Ia
1985A
1989B

He poor/He rich

SN Ic
1983I
1983V

SN Ib
1983N
1984L

SN IIb
1993J
1987K

"Normal" SNII

Light Curve decay after maximum:
Linear / Plateau

SN IIL
1980K
1979C

SN IIP
1987A
1988A
1969L

"Abnormal" SNII

Narrow H lines

SNIIn

Other oddballs

SNIIpec

Believed to originate from ***deflagration*** or ***detonation*** of an ***accreting white dwarf.***

Core Collapse.
Outer Layers stripped by winds (*Wolf-Rayet Stars*) or binary interactions
Ib: H mantle removed
Ic: H & He removed

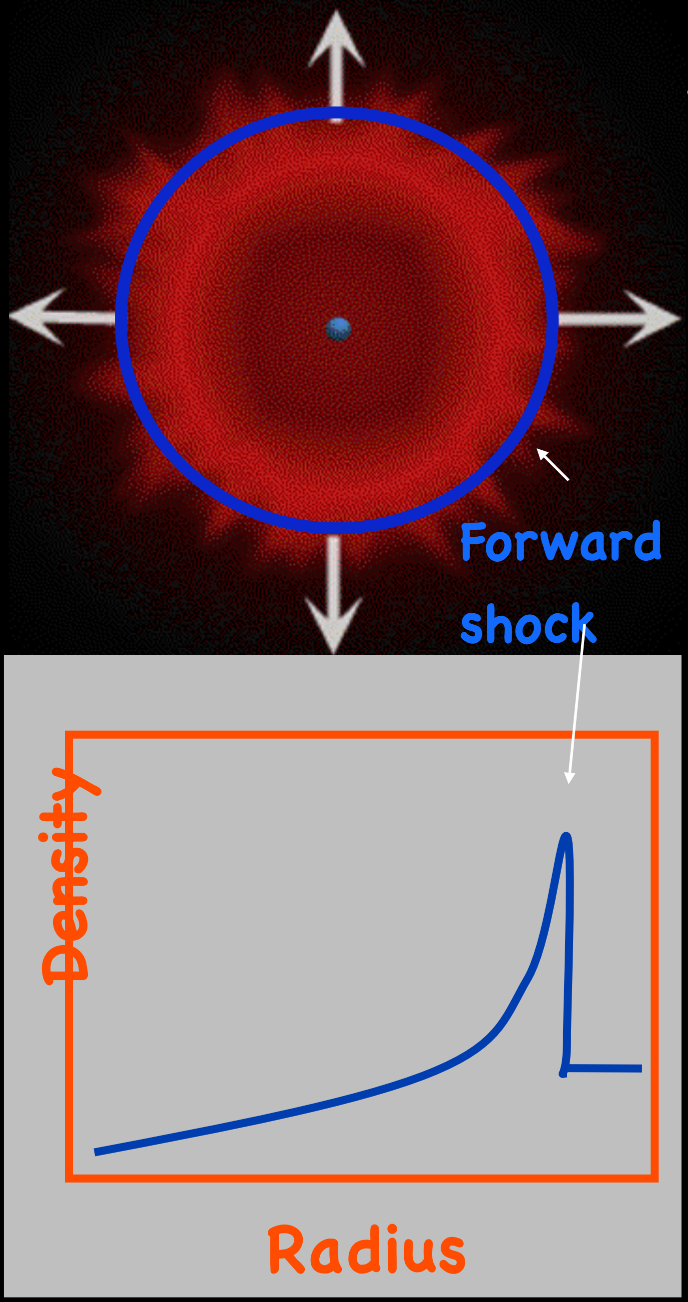
Core collapse.
Most (NOT all) H is removed during evolution by tidal stripping.

Core Collapse of a massive progenitor with plenty of H .

Theory

M. Montes

Supernova Remnants



- Explosion blast wave sweeps up CSM/ISM in forward shock and heats to x-ray emitting temperatures (> 10 million degrees)
  - spectrum shows abundances consistent with solar or with progenitor wind

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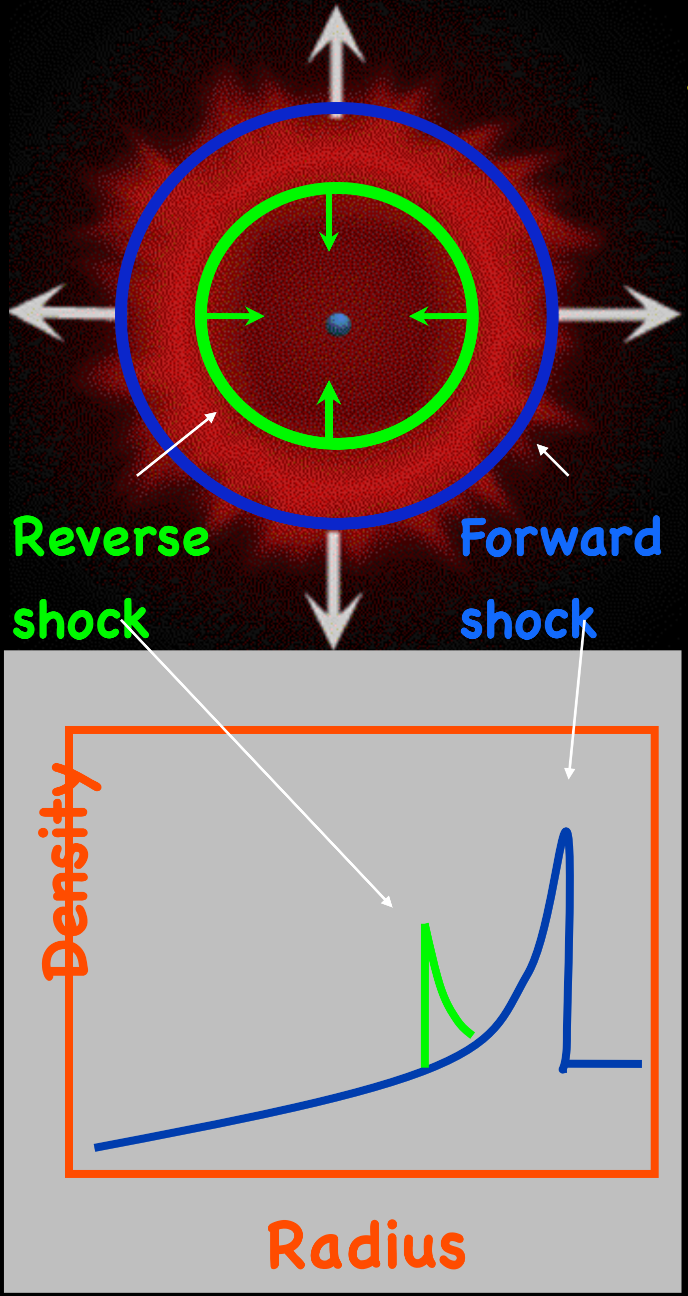

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- As mass is swept up, forward shock decelerates and ejecta catches up; **reverse shock** heats ejecta
  - spectrum is enriched w/ heavy elements from hydrostatic and explosive nuclear burning

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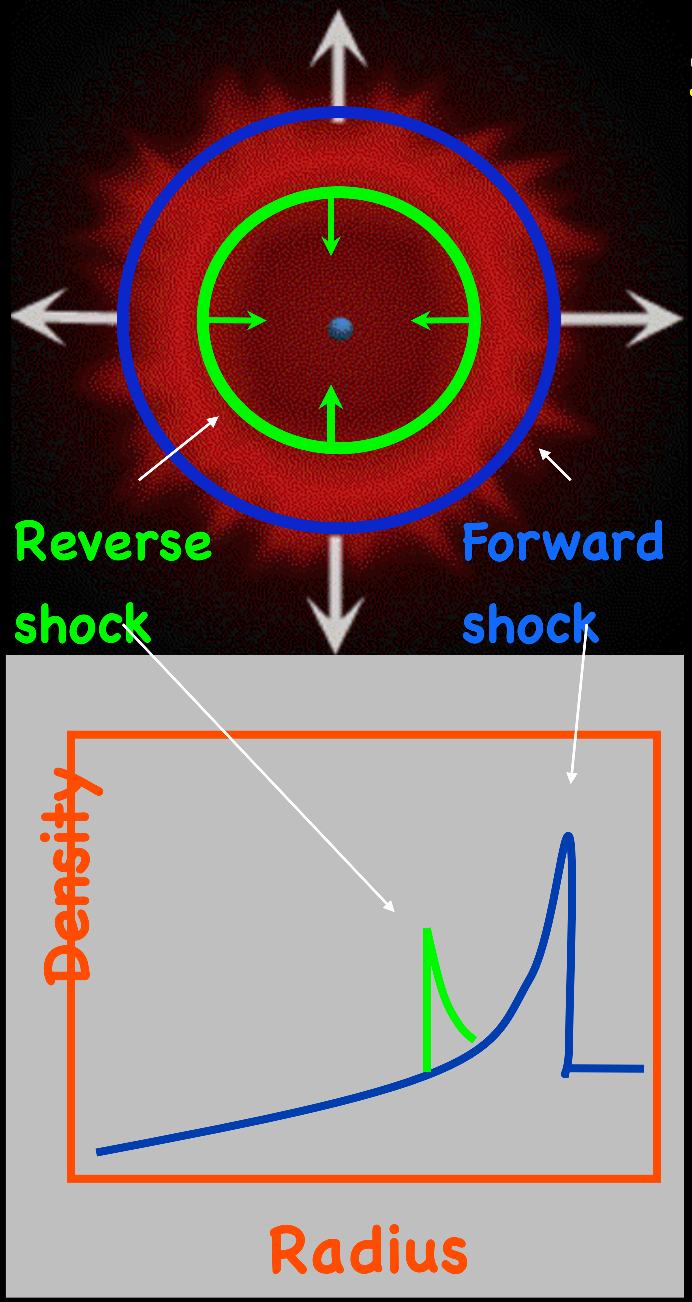

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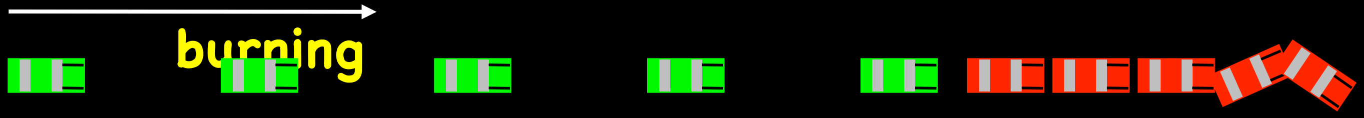

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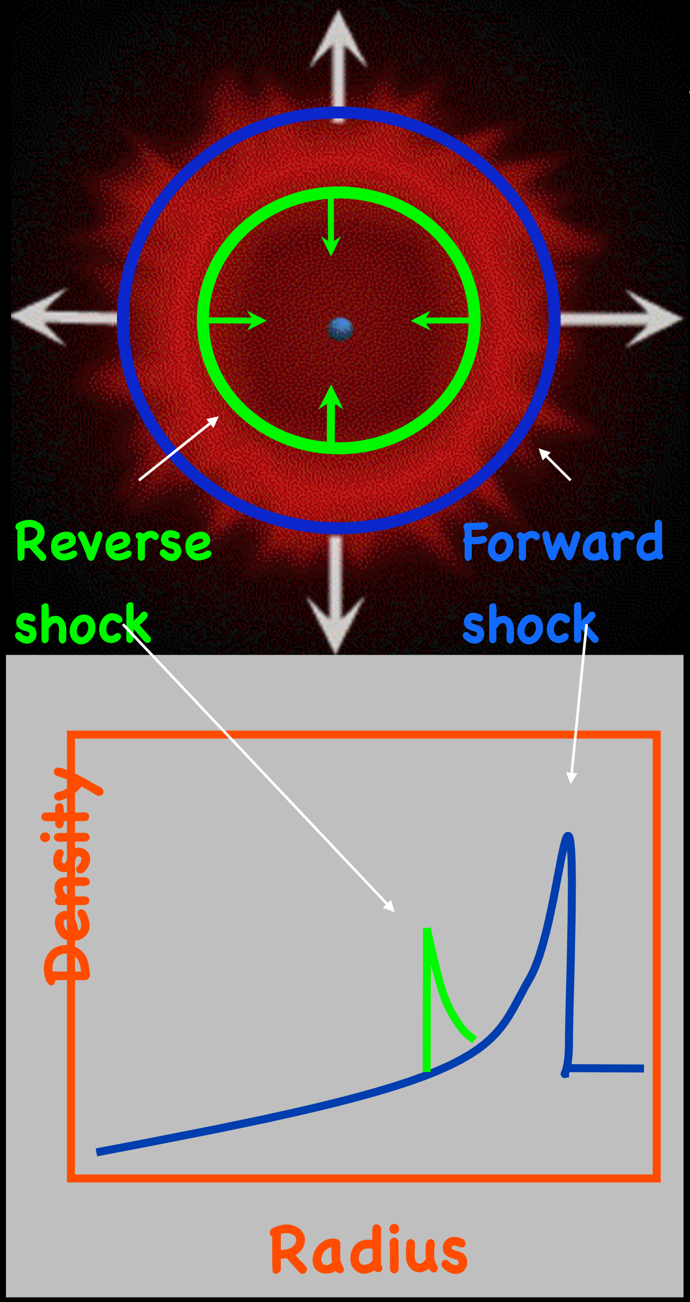

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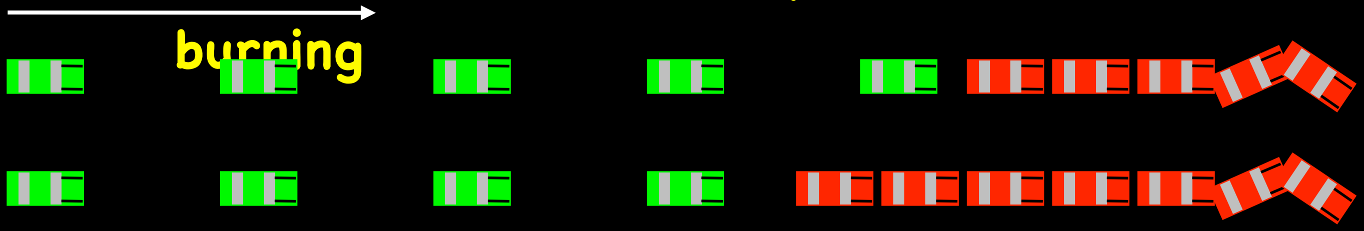

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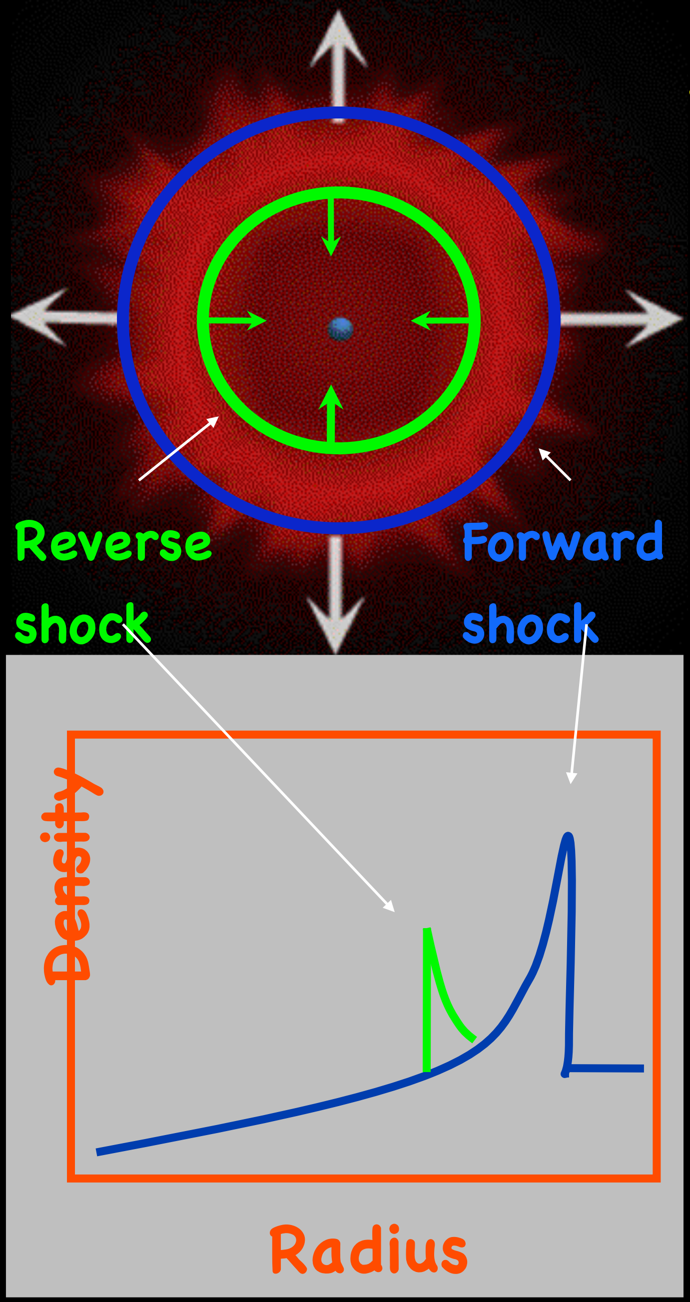

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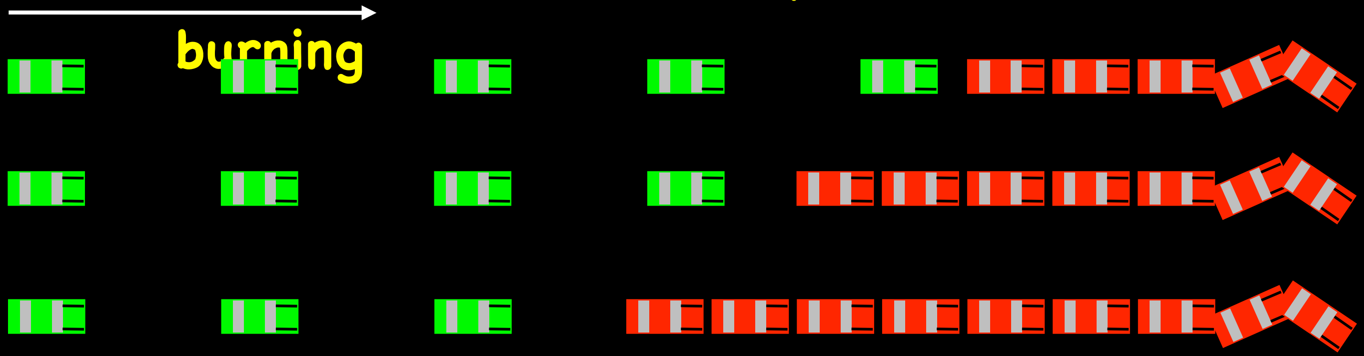
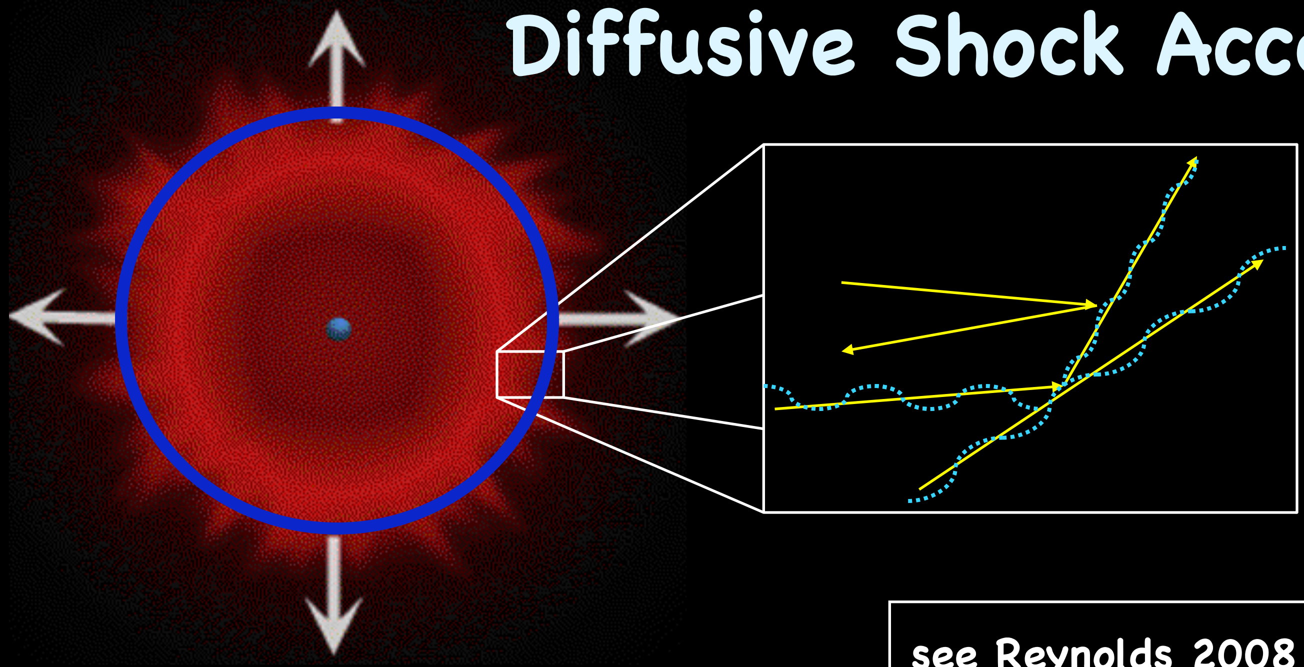


Diffusive Shock Acceleration



- Particles scatter from MHD waves in background plasma
  - pre-existing, or generated by turbulence from streaming

see Reynolds 2008

- Maximum energies determined by either:

age – finite age of SNR (and thus of acceleration)

$$E_{\max}(\text{age}) \sim 0.5 \mathrm{v}_8^2 t_3 B_{\mu G} (\eta R_J)^{-1} \,\text{TeV}$$

r

$$E_{\max}(\text{loss}) \sim 100 \mathrm{v}_8 (B_{\mu G} \eta R_J)^{-1/2} \,\text{TeV}$$

ns)

$$E_{\max}(\text{escape}) \sim 20 B_{\mu G} \lambda_{17} \,\text{TeV}$$

escape – scattering efficiency decreases w/ energy

Electrons:

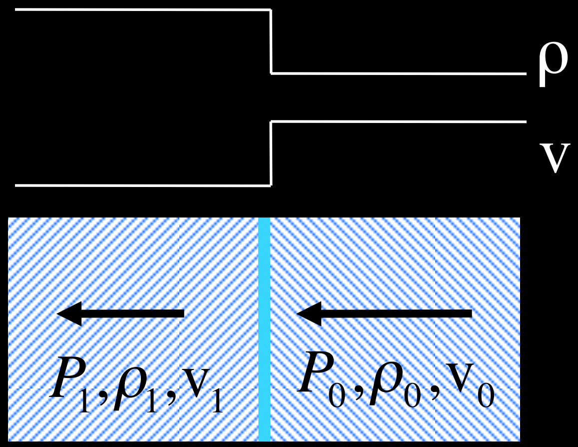
- large B lowers max energy due to synch. losses

Ions:

- large B increases max energy (needed to get to hadrons to knee of CR spectrum)

Current observations suggest high B fields

Shocks in SNRs



shock

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

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

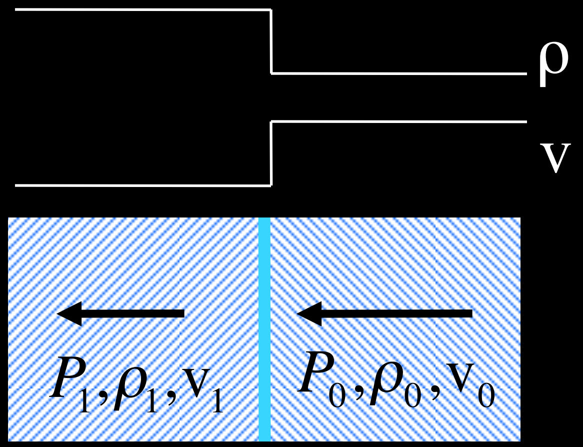
$$v_1 = \frac{\gamma-1}{\gamma+1}v_0 = \frac{v_0}{4}$$

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

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

X-ray emitting temperatures

Shocks in SNRs



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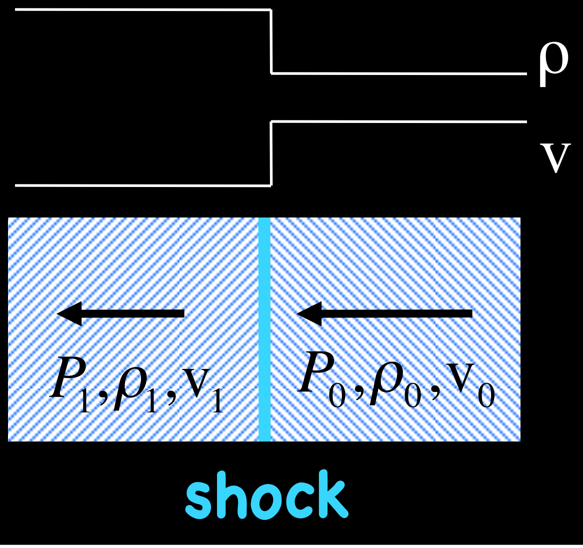
- Shock velocity gives temperature of gas
  - note effects of electron-ion equilibration timescales

Shocks in SNRs



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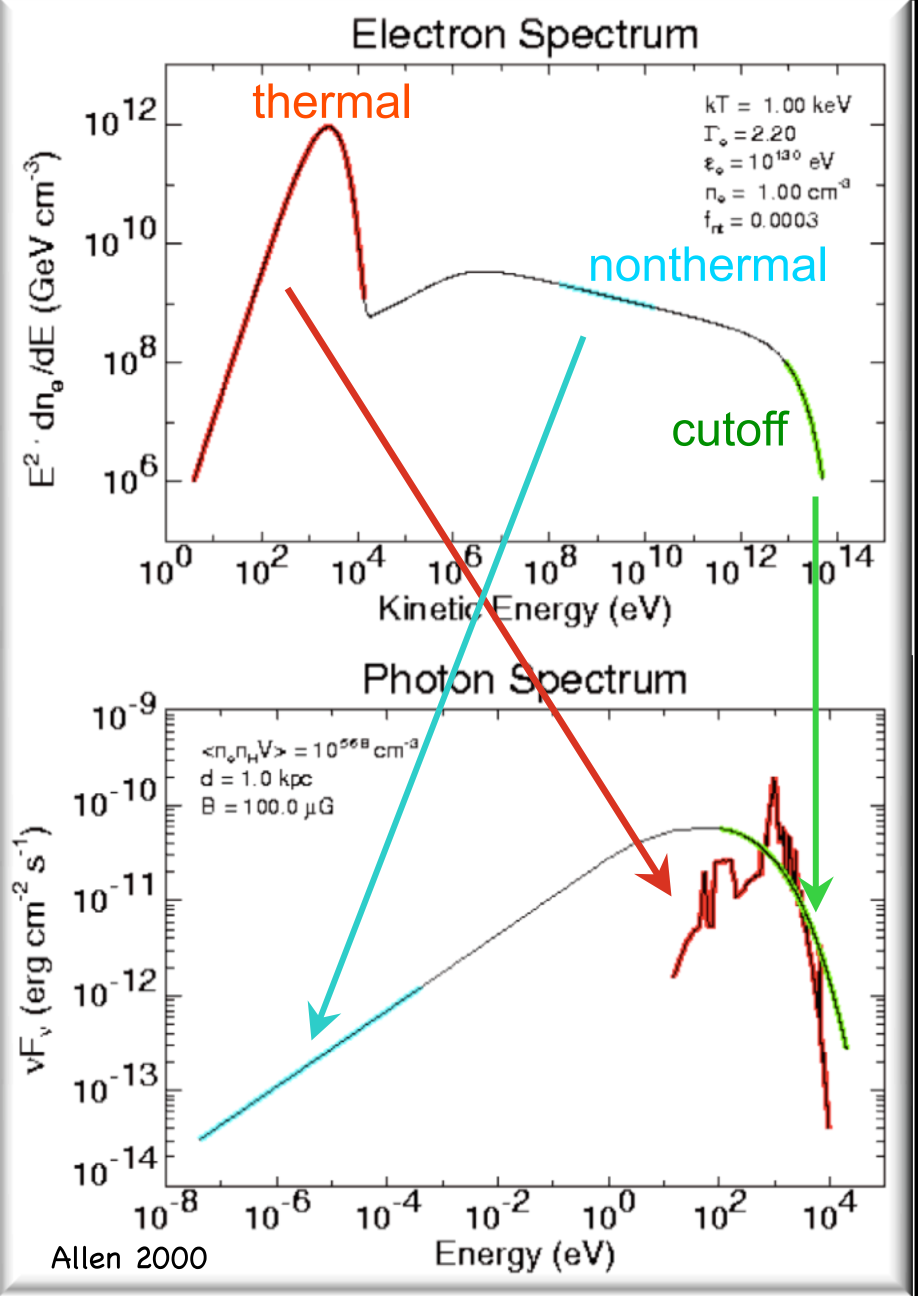
X-ray emitting temperatures

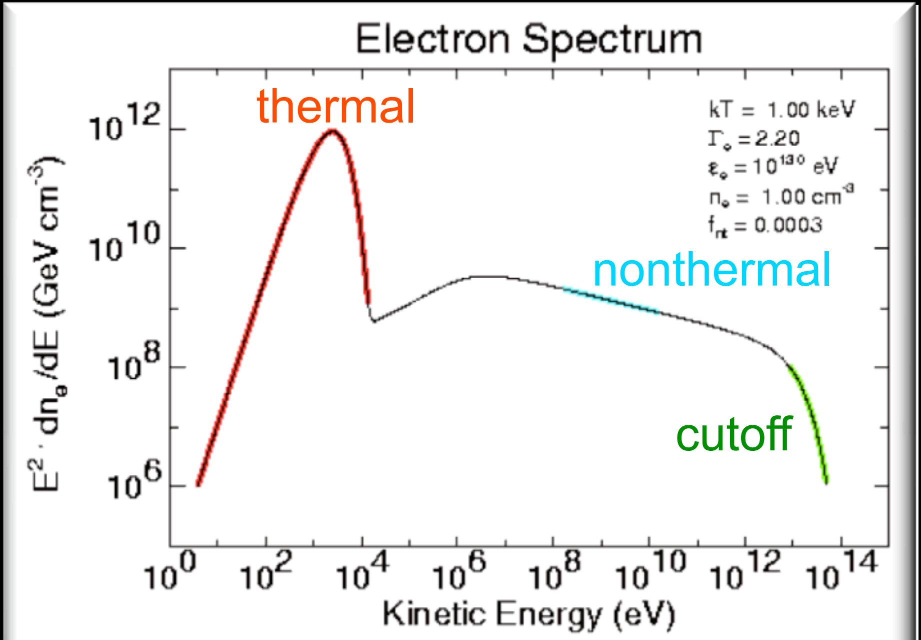
- Shock velocity gives temperature of gas
  - note effects of electron-ion equilibration timescales
- If another form of pressure support is present (e.g., cosmic rays), the temperature will be lower than this

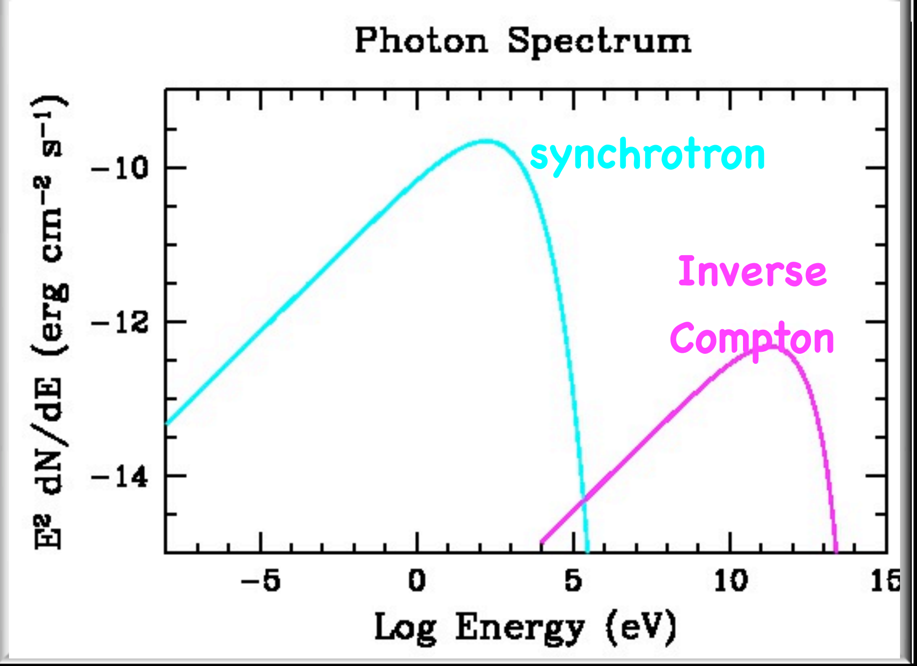


Allen 2000

Shocked Electrons and their Spectra

- 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 **limits on energy of associated cosmic rays**
  - large contribution from this component **modifies dynamics** of thermal electrons





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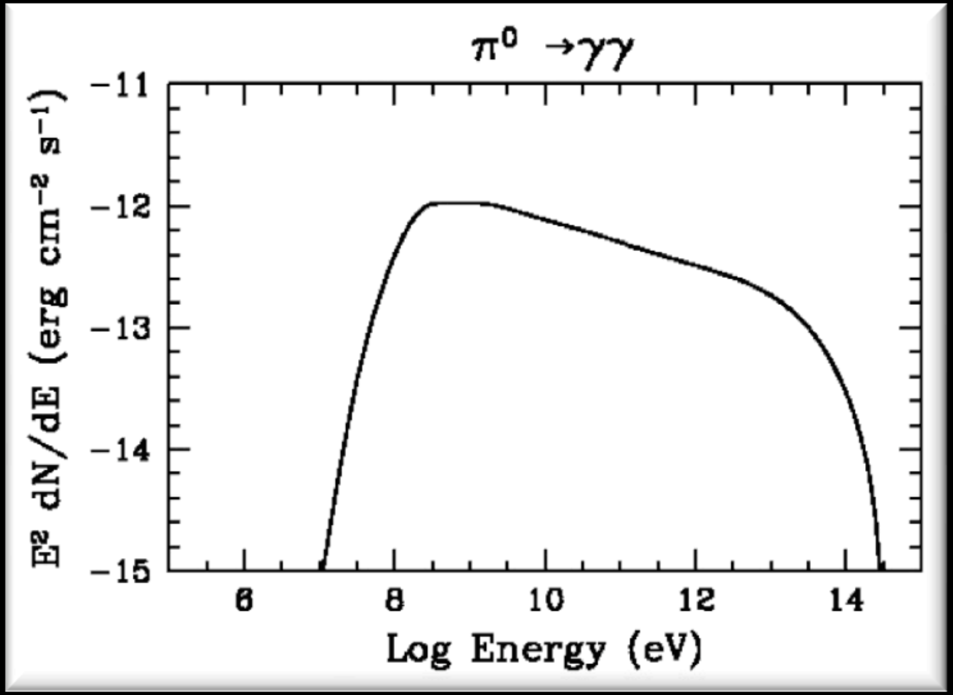
  - rollover between radio and x-ray spectra gives exponential cutoff of electron spectrum, and limits on energy of associated cosmic rays
  - large contribution from this component modifies dynamics of thermal electrons
- energetic electrons upscatter ambient photons through inverse-Compton scattering
  - source of GeV/TeV γ-rays
  - field photons include CMB, starlight, dust IR

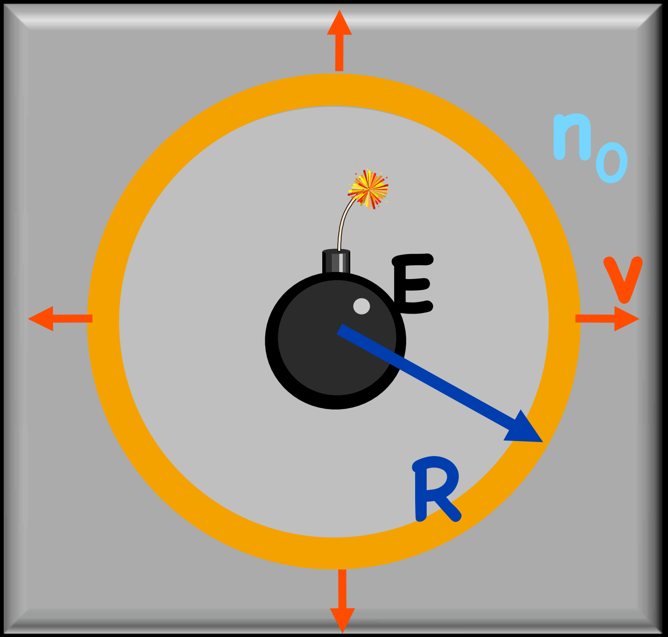
Shocked Protons and Their Spectra

- Protons (and other ions) are inefficient radiators
  - large mass reduces synchrotron and IC emission relative to electrons
  - difficult to detect (but hugely important, because they carry virtually all of the energy!)



- proton-proton collisions produce pions; neutral pions decay to γ-rays
  - for regions of high density, this component can dominate γ-ray emission, providing "direct" evidence of energetic hadrons
  - note that this has consequences for thermal X-ray emission as well

SNR Evolution: The Ideal Case



- Once sufficient mass is swept up (> 1-5 M_{ej})

  SNR enters Sedov phase of evolution

$$t_{yr} = 470 R_{pc} T_7^{-1/2}$$

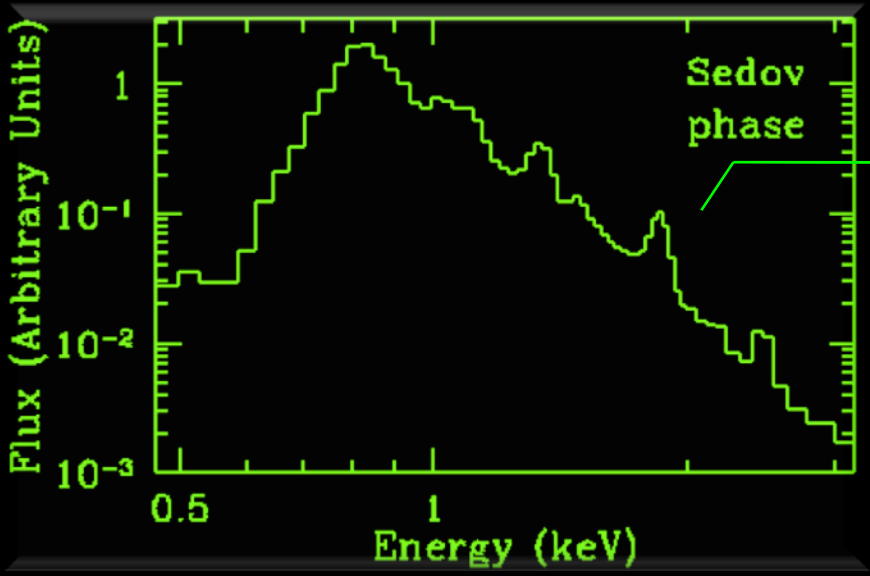
$$\frac{E_{51}}{n_0} = 340 R_{pc}^5 t_{yr}^{-2}$$

- X-ray measurements can provide temperature and density

$$EM = \int n_H n_e dV$$

$$T_x = 1.28 T_{shock}$$

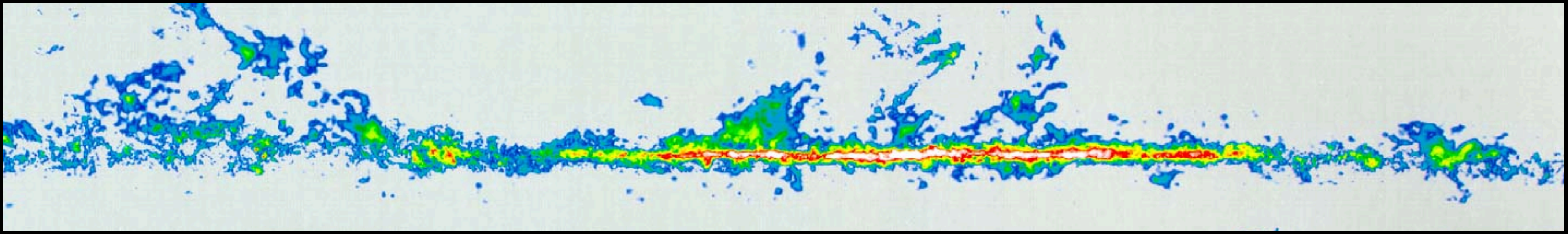
from spectral fits



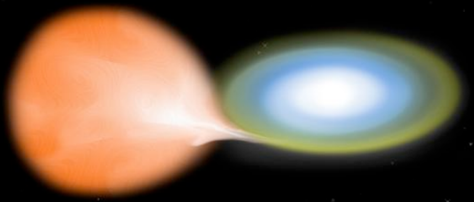
- Sedov phase continues until kT ~ 0.1 keV

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

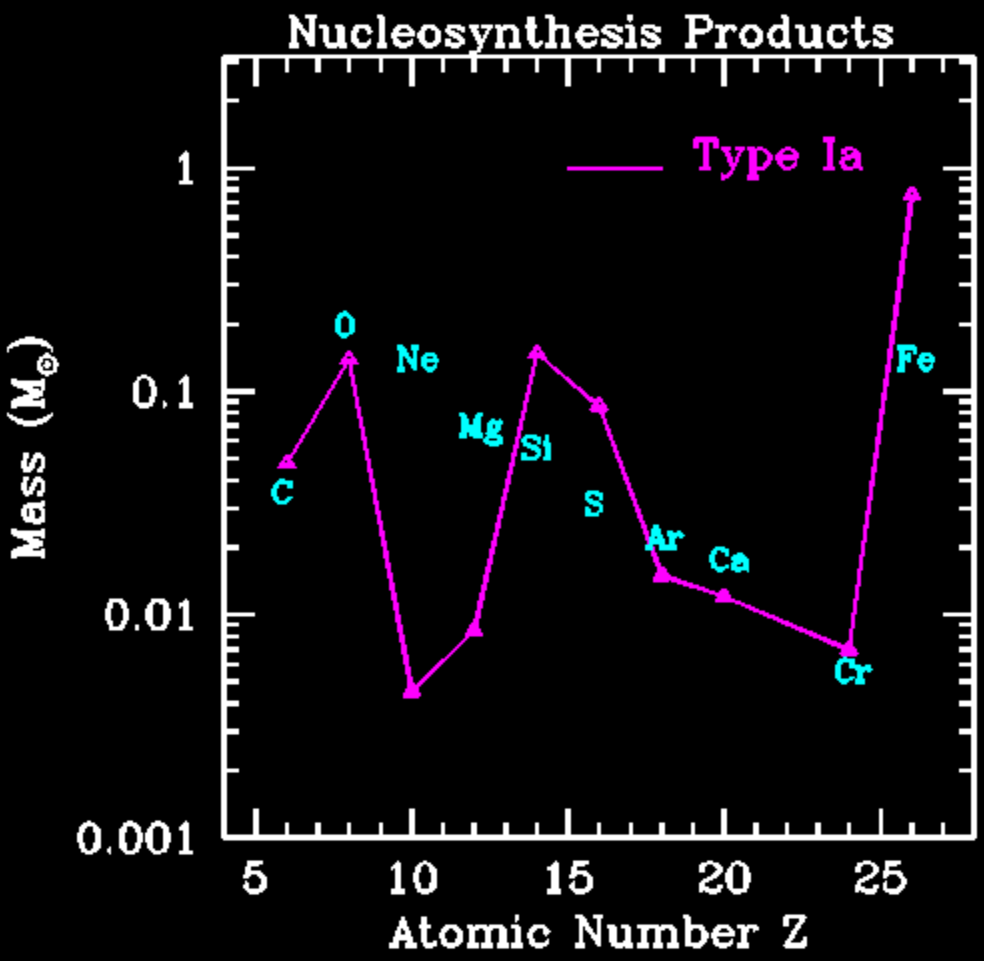
SNR Evolution: The Harsh Reality



- Massive stars die near their birth sites
- Surrounding medium is complex; molecular clouds complicate morphology, evolution, shocks
- In short, we are virtually always looking at modifications to ideal Sedov evolution…



SNRs: Tracking the Ejecta



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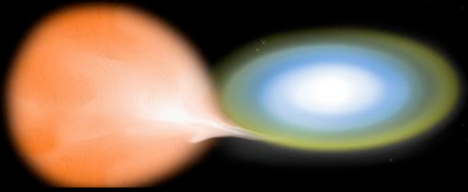

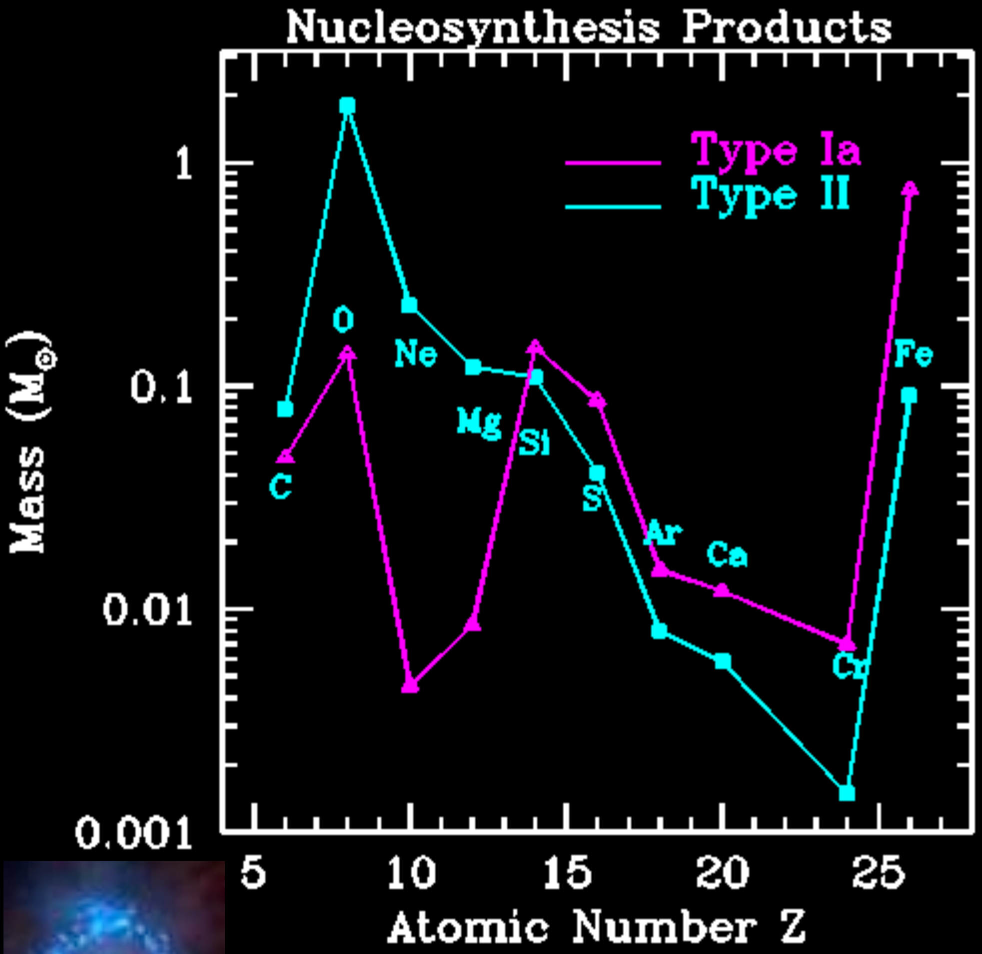

Type Ia:

- Complete burning of 1.4 M_{sun} 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
- Fe mass probes mass cut
- O, Ne, Mg, Fe very sensitive to progenitor mass
- Ejecta distribution probes mixing by instabilities

↑ *T*

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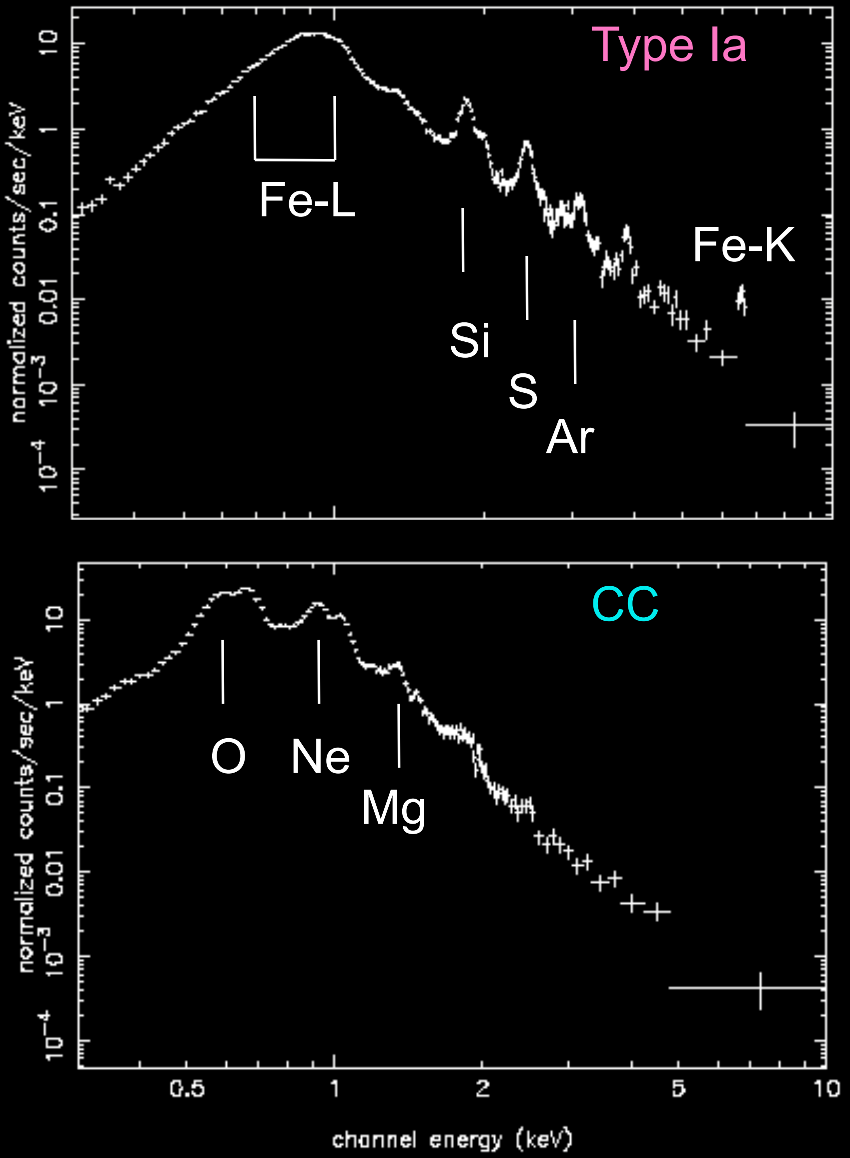

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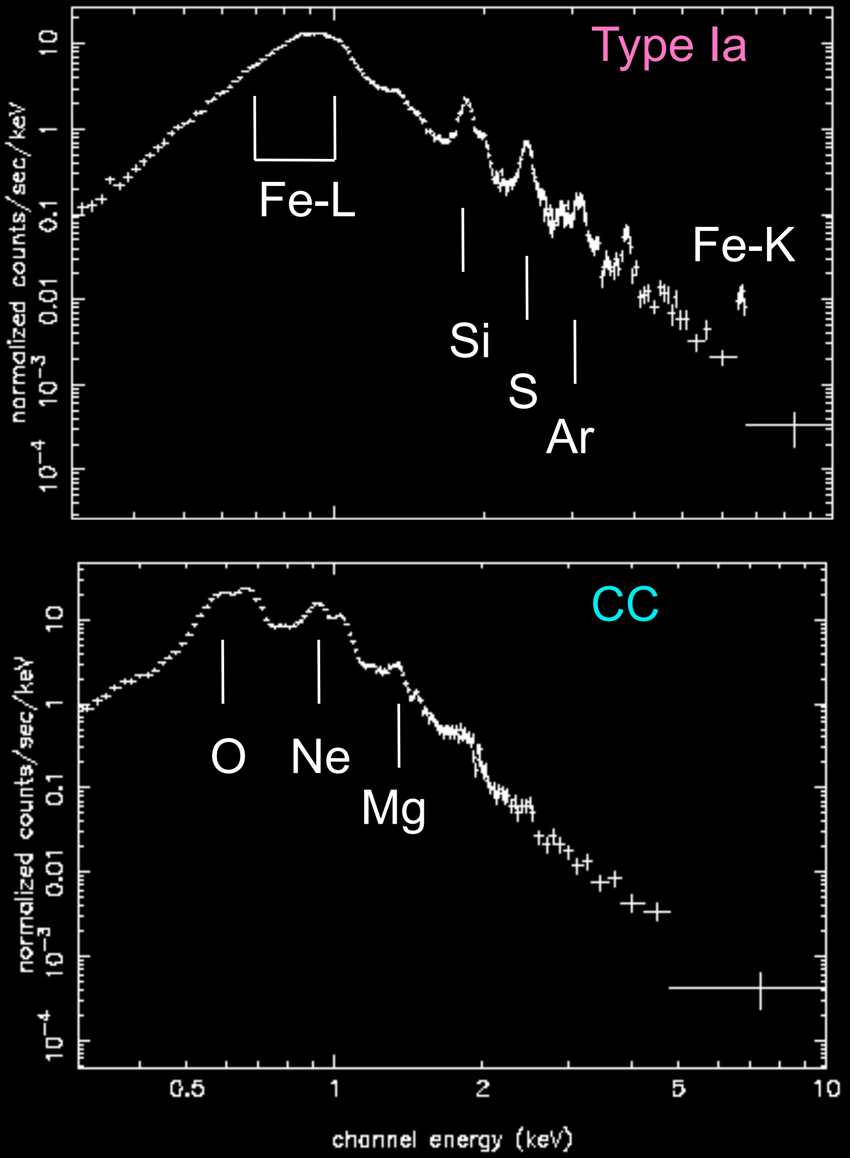

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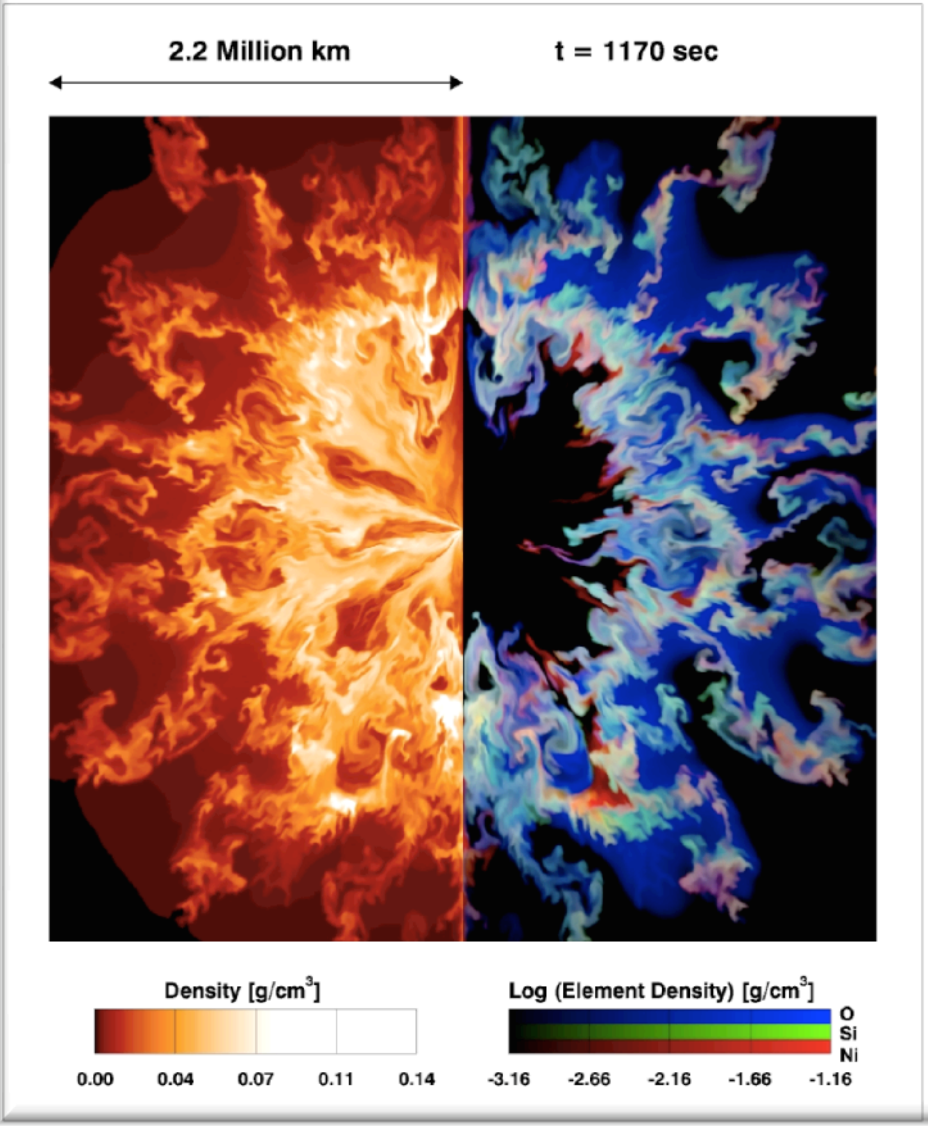
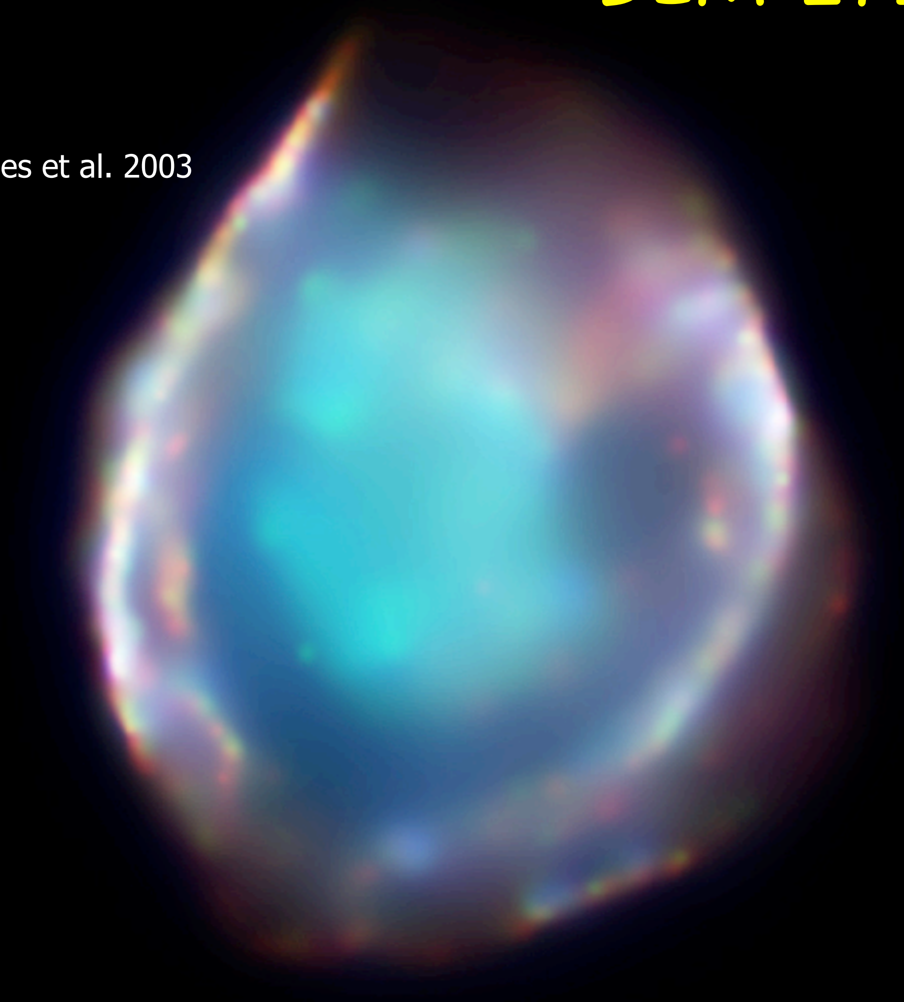
Nucleosynthesis: Probing the Progenitor

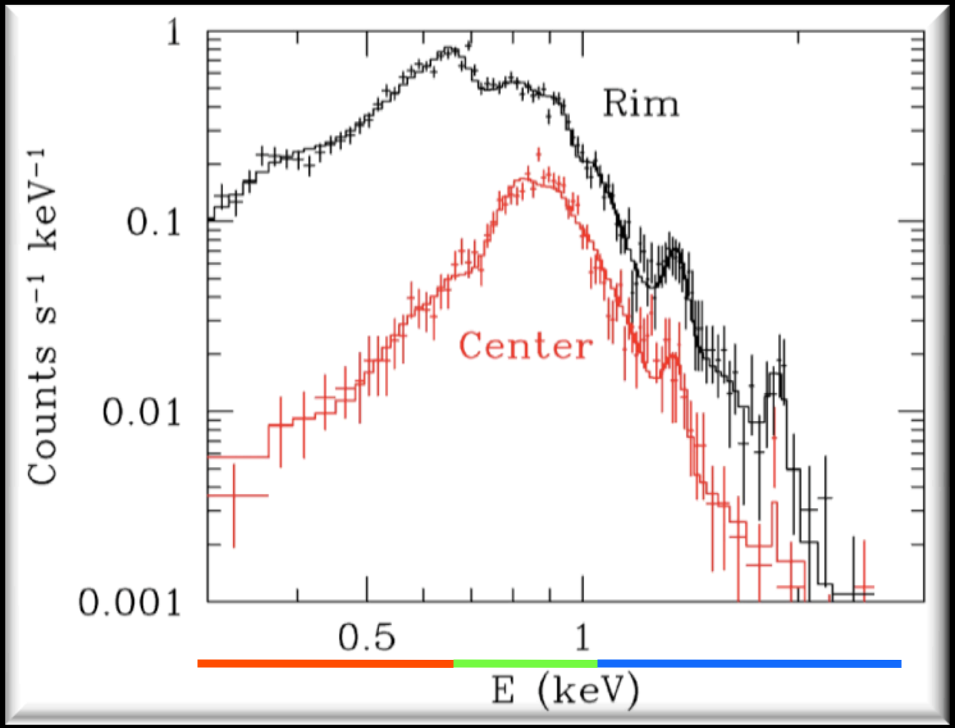

Kifonidis et al. 2000

- 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?

DEM L71: a Type Ia

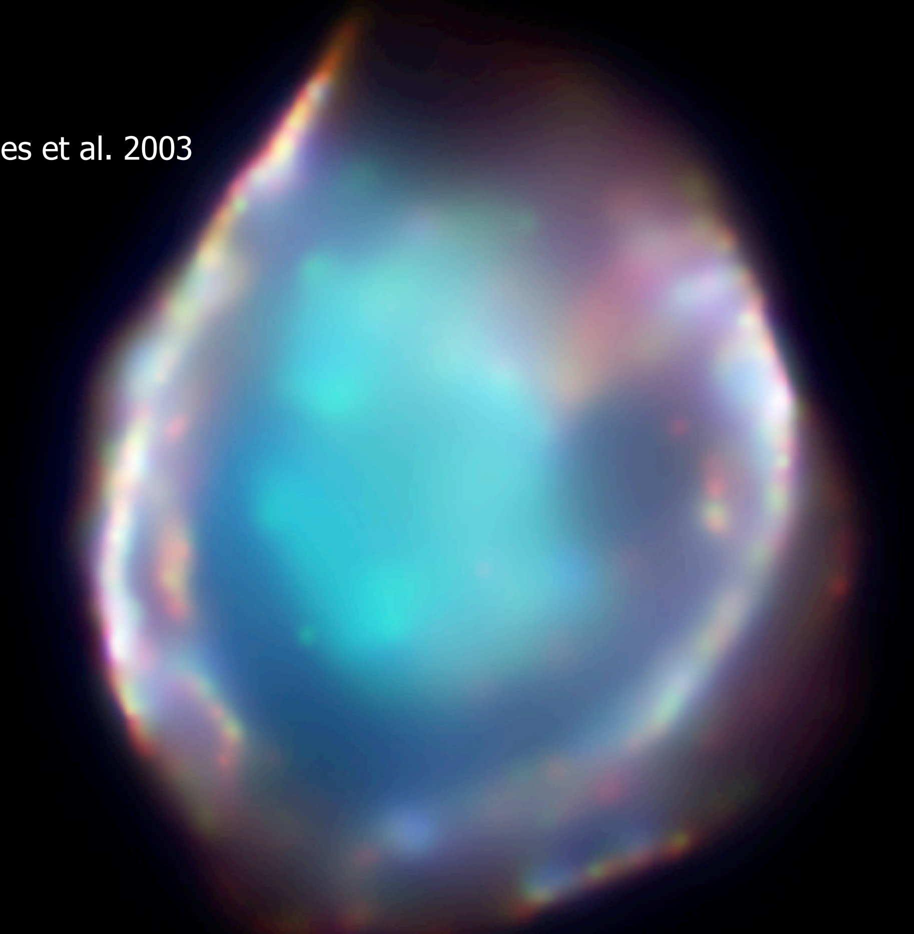
Hughes et al. 2003





- ~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

DEM L71: a Type Ia



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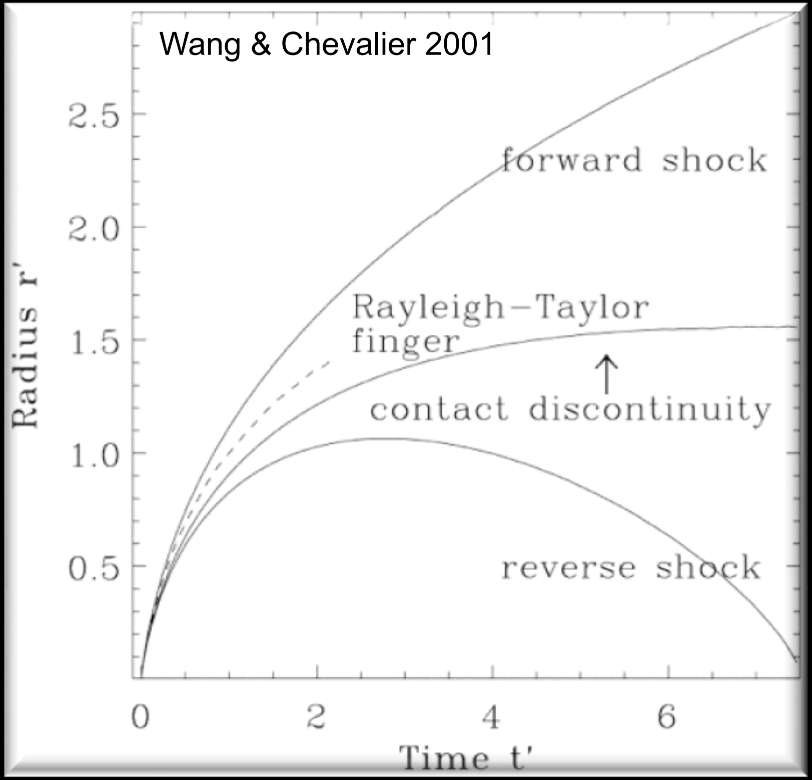


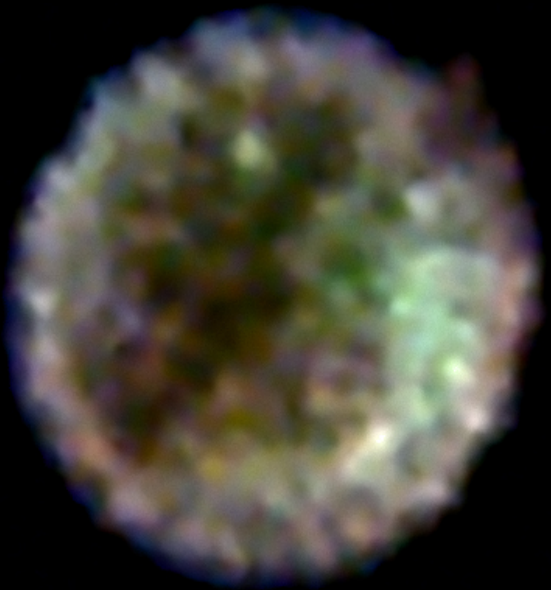
Wang & Chevalier 2001

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

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

- Total ejecta mass is thus ~1.5 solar masses
  - reverse shock has heated all ejecta
- Spectral fits give M_{Fe} ~ 0.8-1.5 M_{sun} and

SNR 0509-67.5

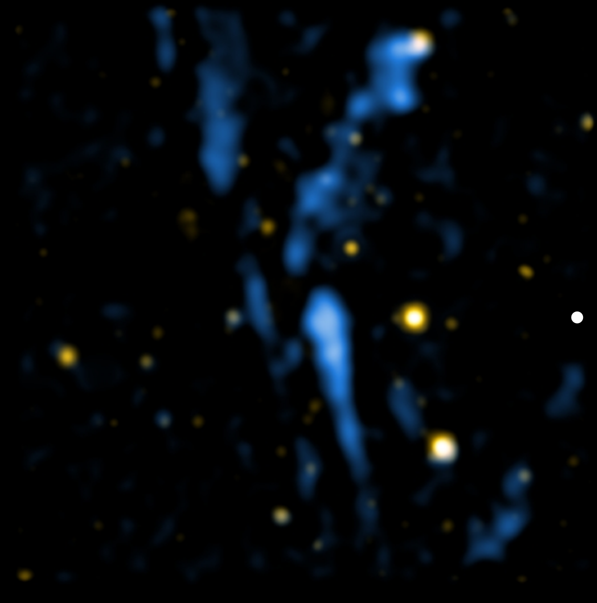


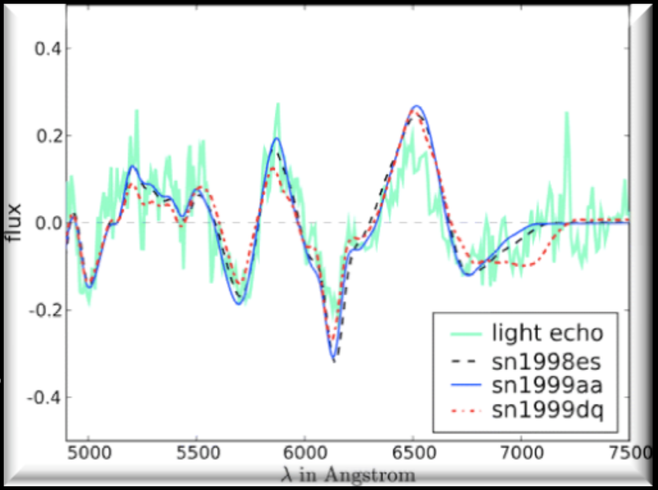
- SNR 0509-67.5 is a young SNR in the LMC
  - identified as Type Ia based on ASCA spectrum (Hughes et al. 1995)

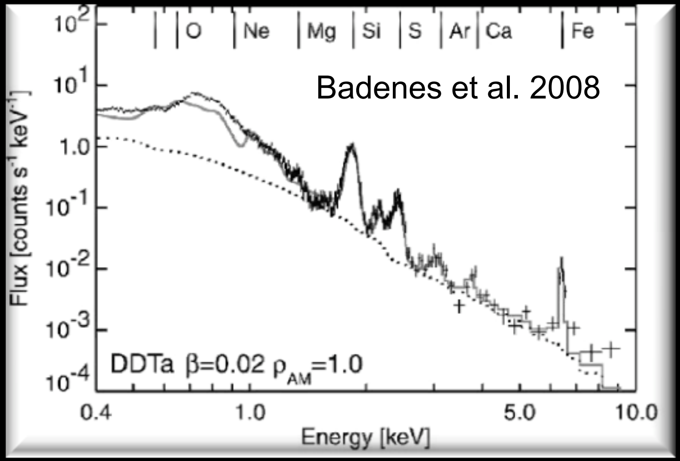
- Observations of optical light echoes establish age as ~400 yr
  - spectra of light echoes indicate that SNR is result of an SN 1991T-like (bright, highly energetic, Type Ia) SN (Rest et al. 2008)

- Comparison of hydrodynamic and non-equilibrium ionization models for emission from Type Ia events with X-ray image and spectrum indicates E = 1.4 x 10^{51} erg s^{-1} and M(^{56}Ni)=0.97 $M_\odot$ (i.e. energetic,

Rest et al. 2005






Badenes et al. 2008

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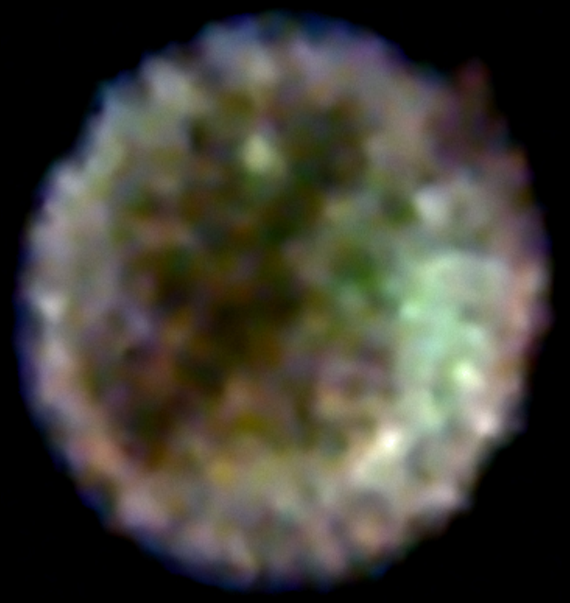

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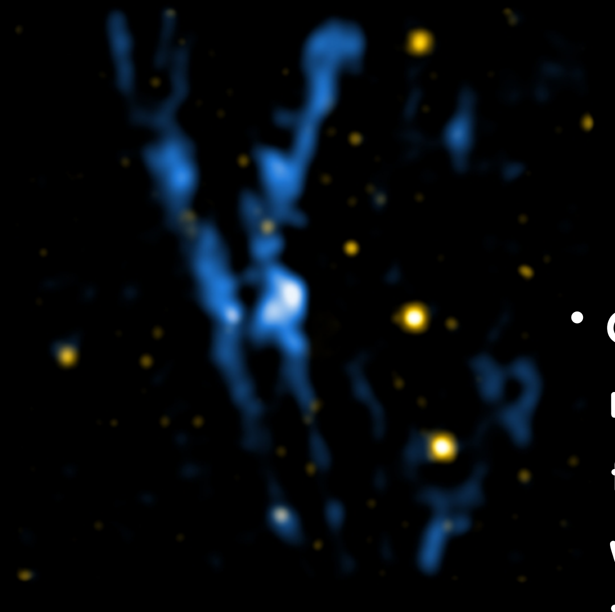

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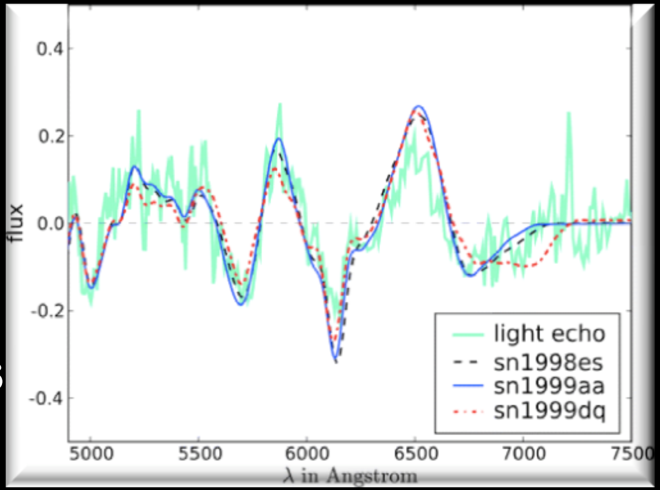
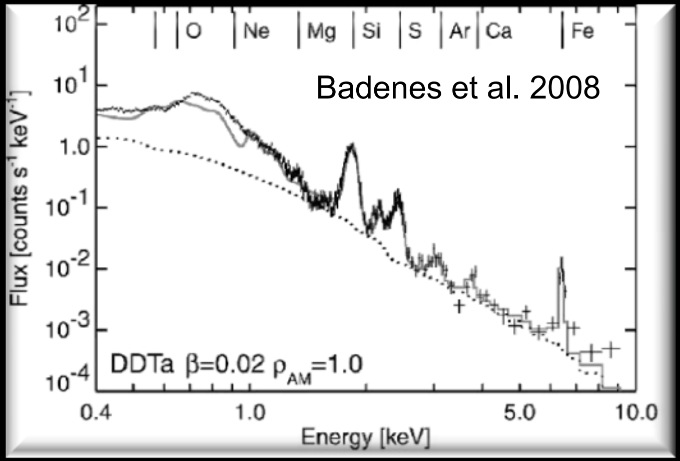
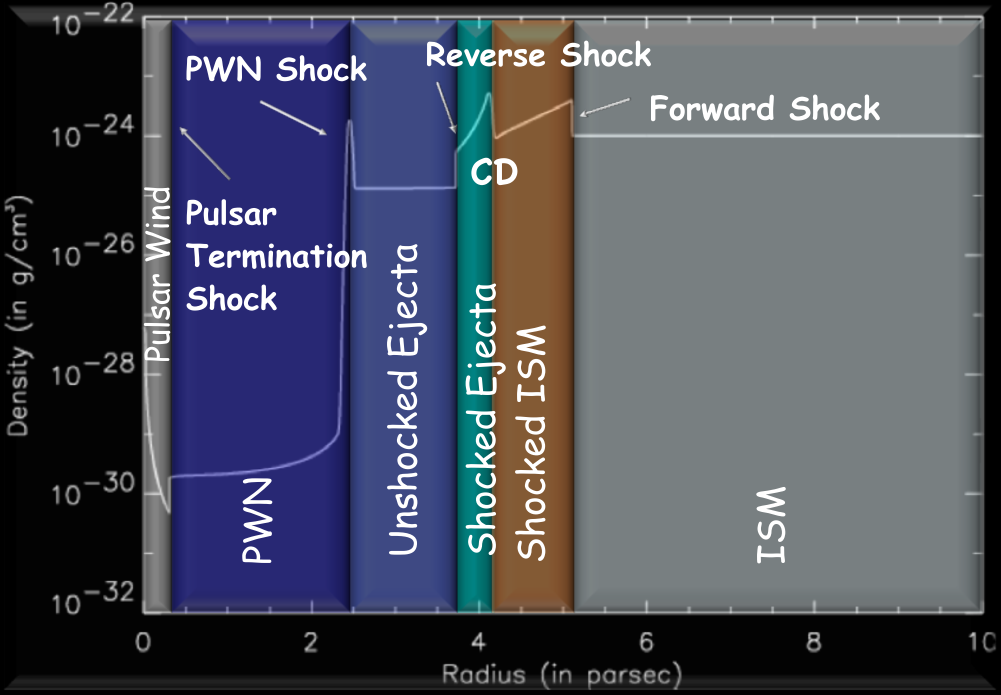
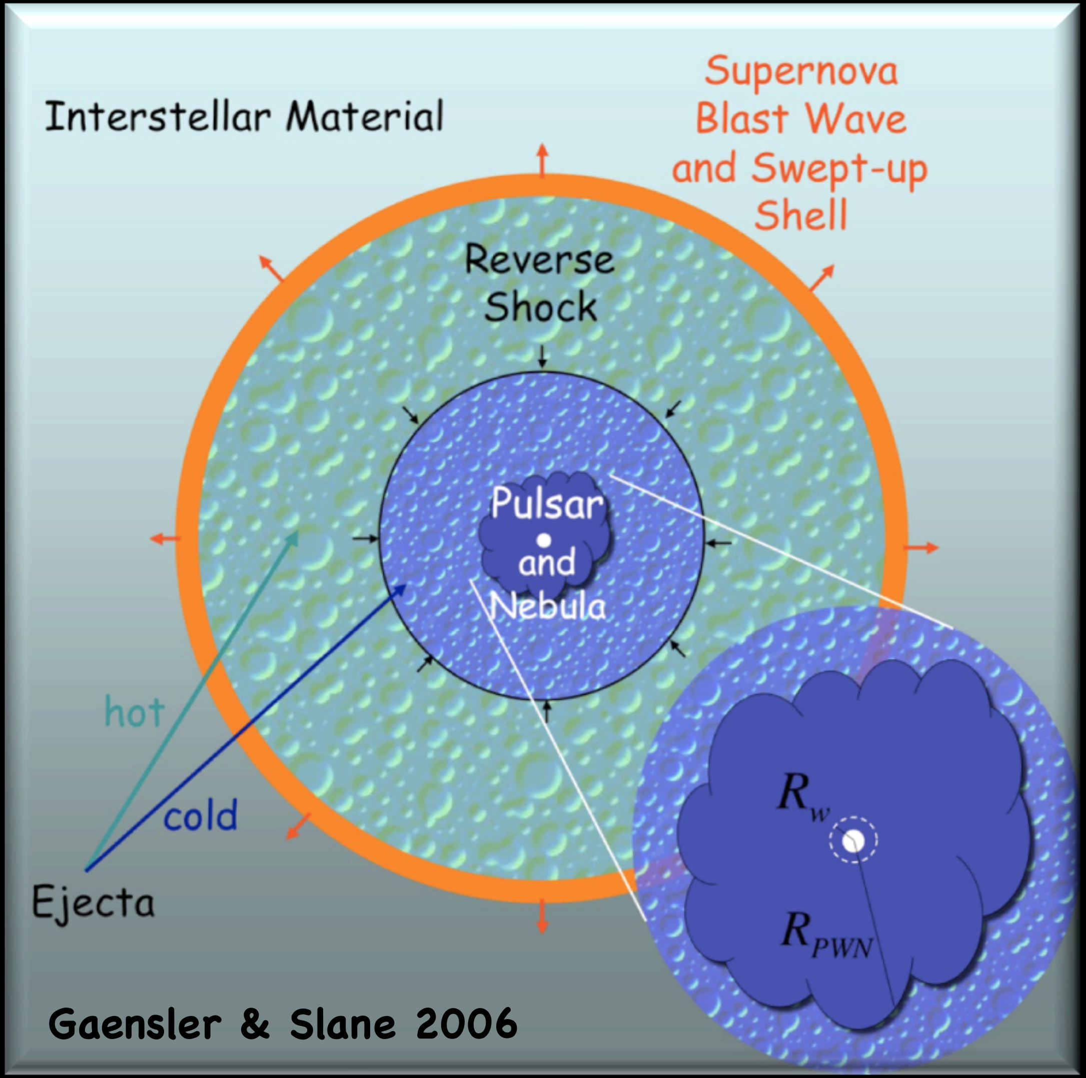




Badenes et al. 2008

Composite SNRs





Gaensler & Slane 2006

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

Composite SNR Evolution

$$\dot{E} = I\Omega\dot{\Omega} = \dot{E}_0\left[1+\frac{t}{\tau}\right]^{-\frac{n+1}{n-1}}$$

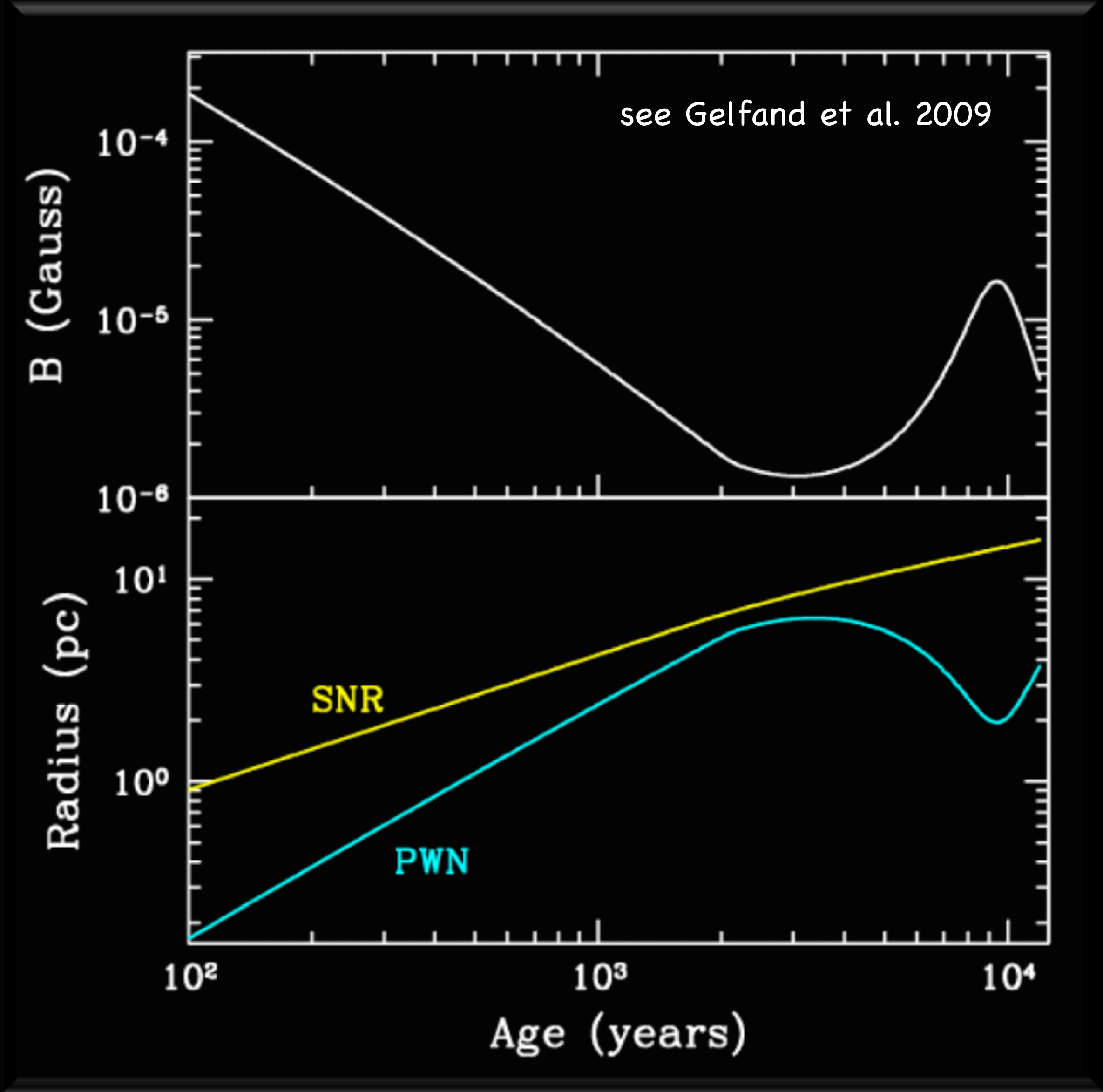
$$\frac{dM}{dt} = 4\pi R^2 \rho_{SN}(\mathrm{v} - R/t)$$

energy input and swept-up ejecta mass

$$\frac{d\left[\frac{4\pi R^3}{3}p_i\right]}{dt} = \dot{E} - p_i 4\pi R^2 \frac{dR}{dt}$$

$$M\frac{d\mathrm{v}}{dt} = 4\pi R^2\left[p_i - \rho_{SN}(\mathrm{v}-R/t)^2\right]$$

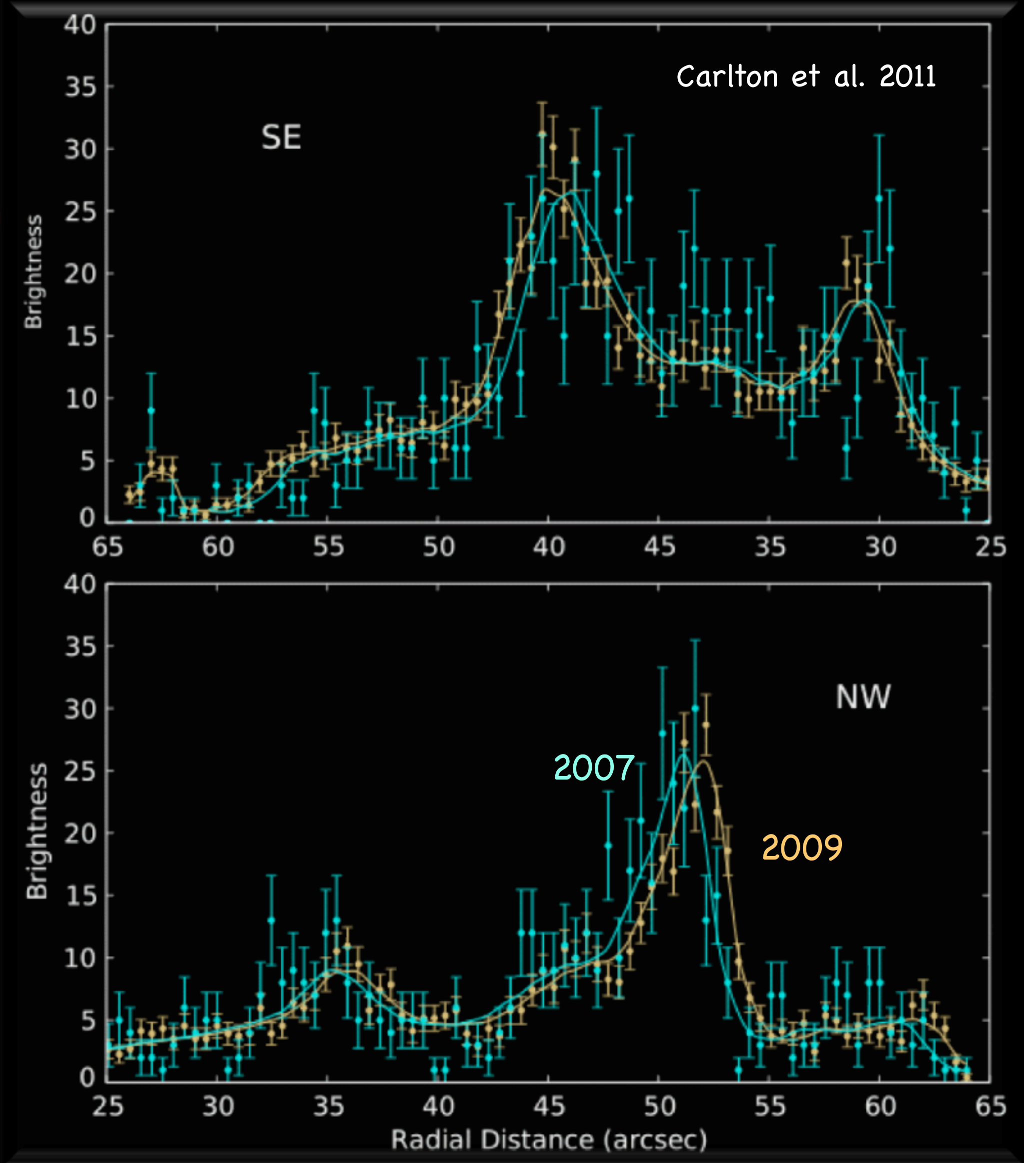
PWN evolution



Expansion of SNRs

G1.9+0.3

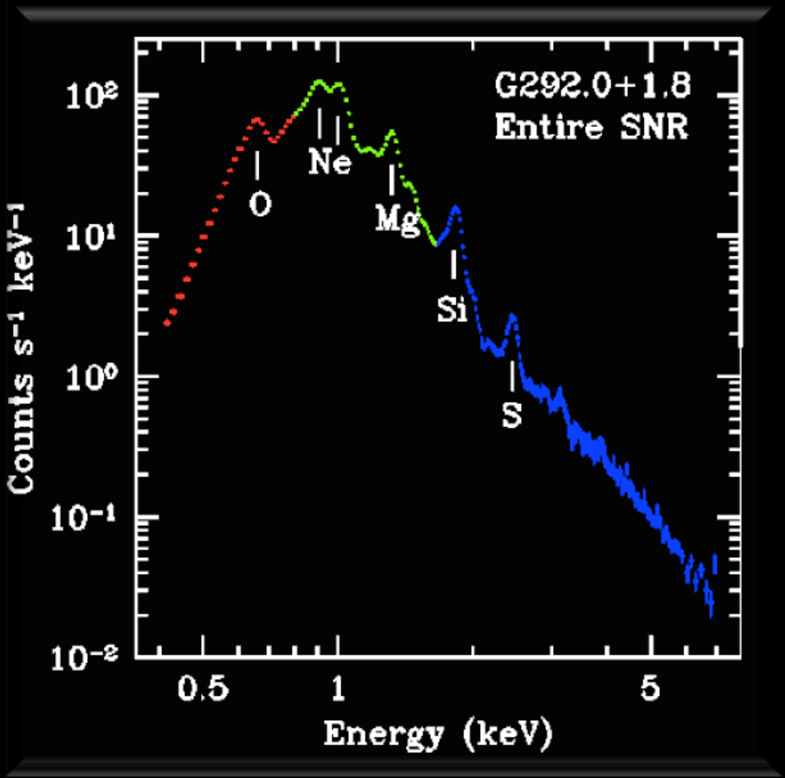
Reynolds et al. 2008



- Youngest known SNR in Galaxy
- $v_{exp} \approx 13{,}000 - 16{,}000$ km s^{-1}
  - deceleration observed!

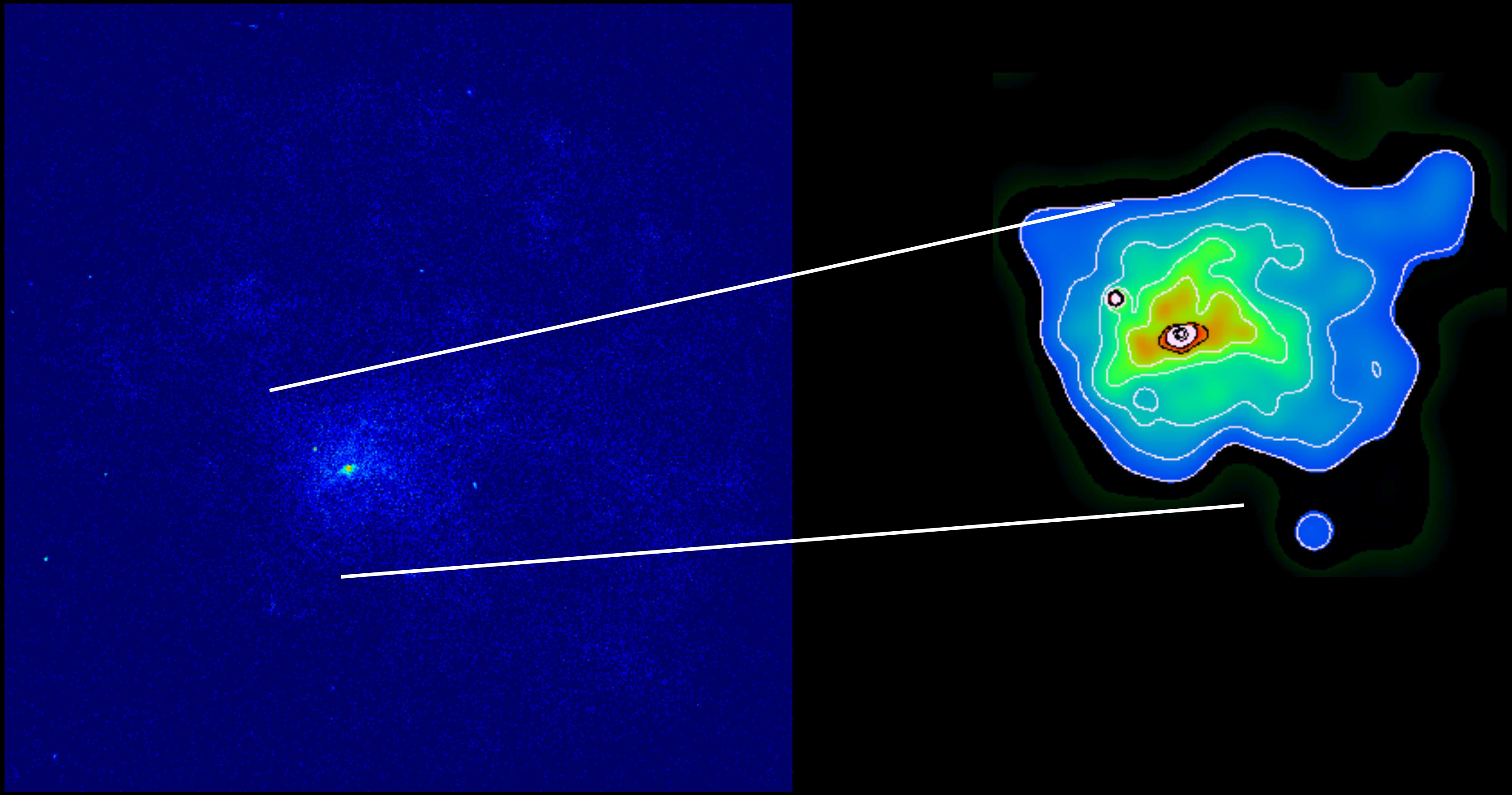
G292.0+1.8: O-Rich and Composite

Park, et al. 2002



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

G292.0+1.8: O-Rich and Composite



Hughes, et al. 2001

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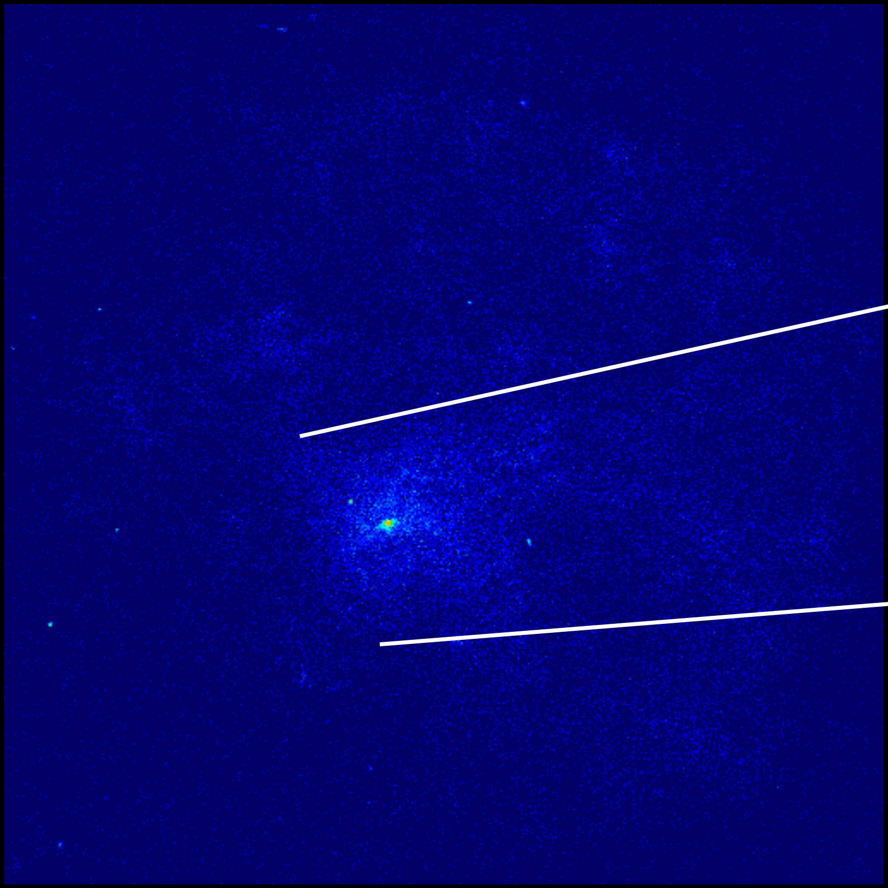
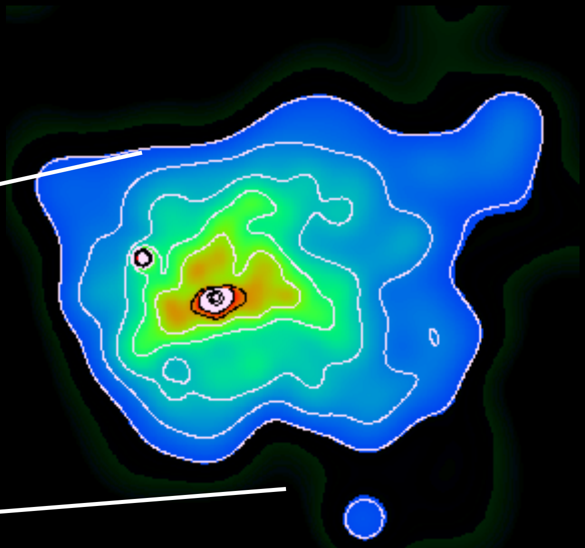


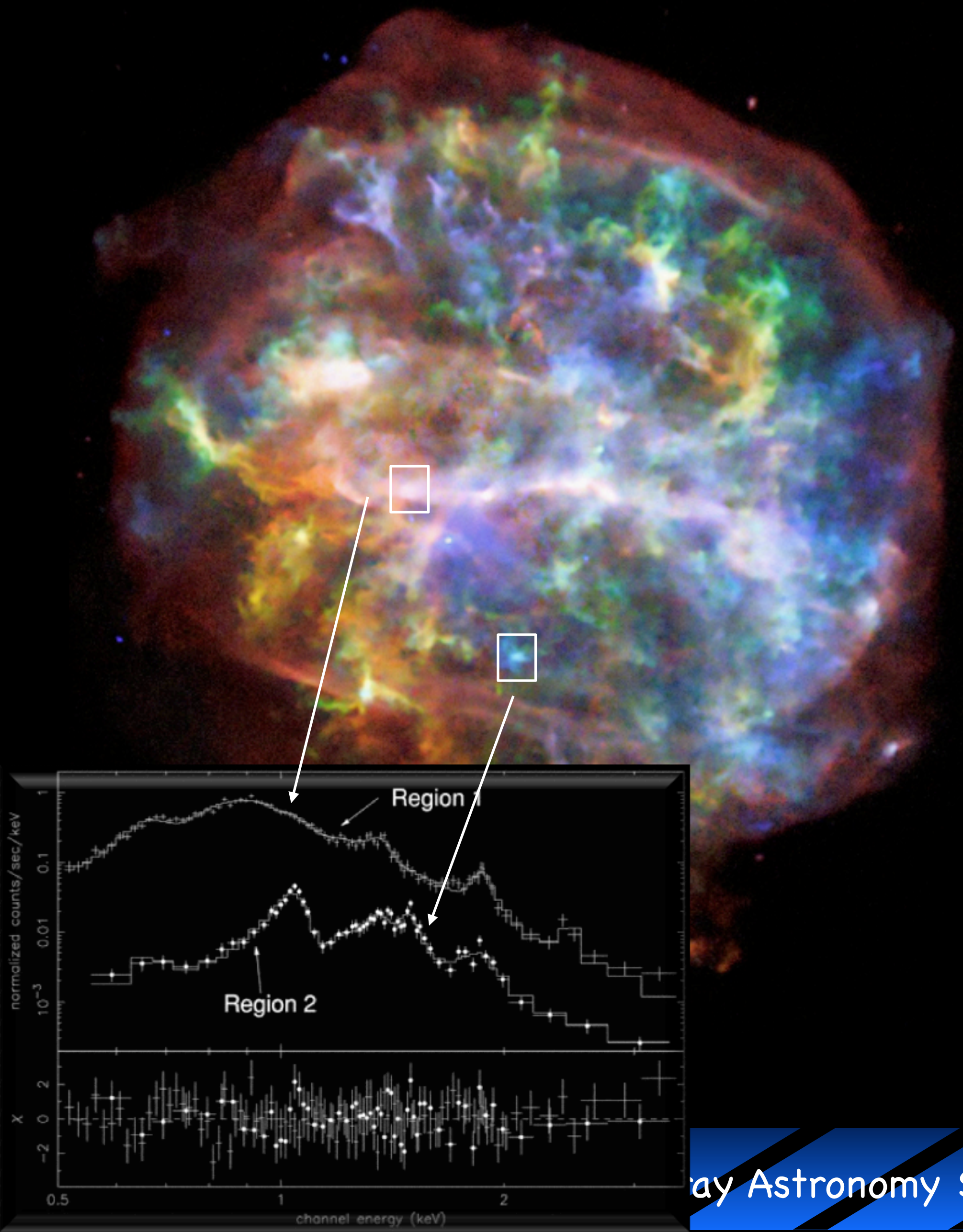


Hughes, et al. 2001

- 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?

G292.0+1.8: Sort of Shocking…



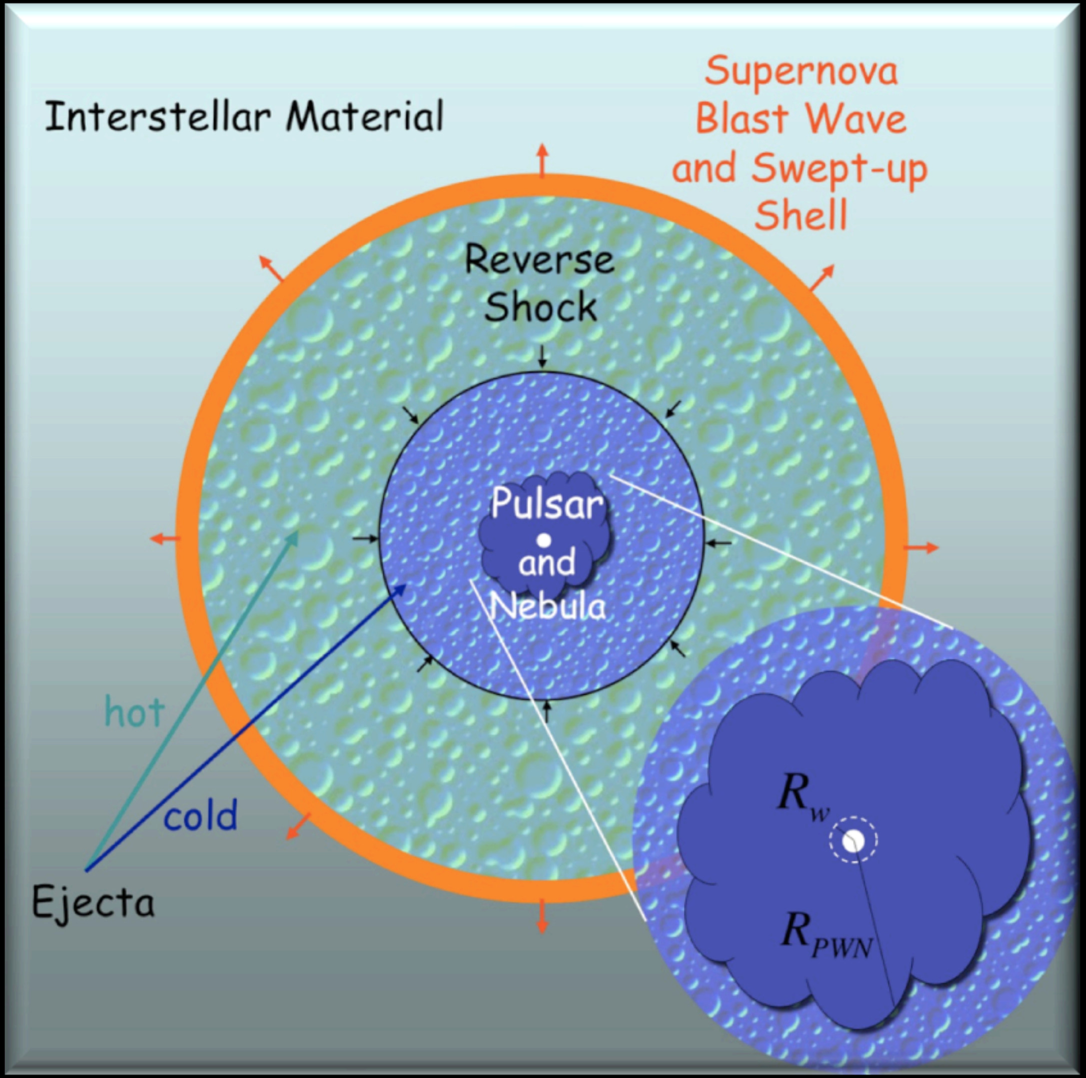
- Individual knots rich in ejecta

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

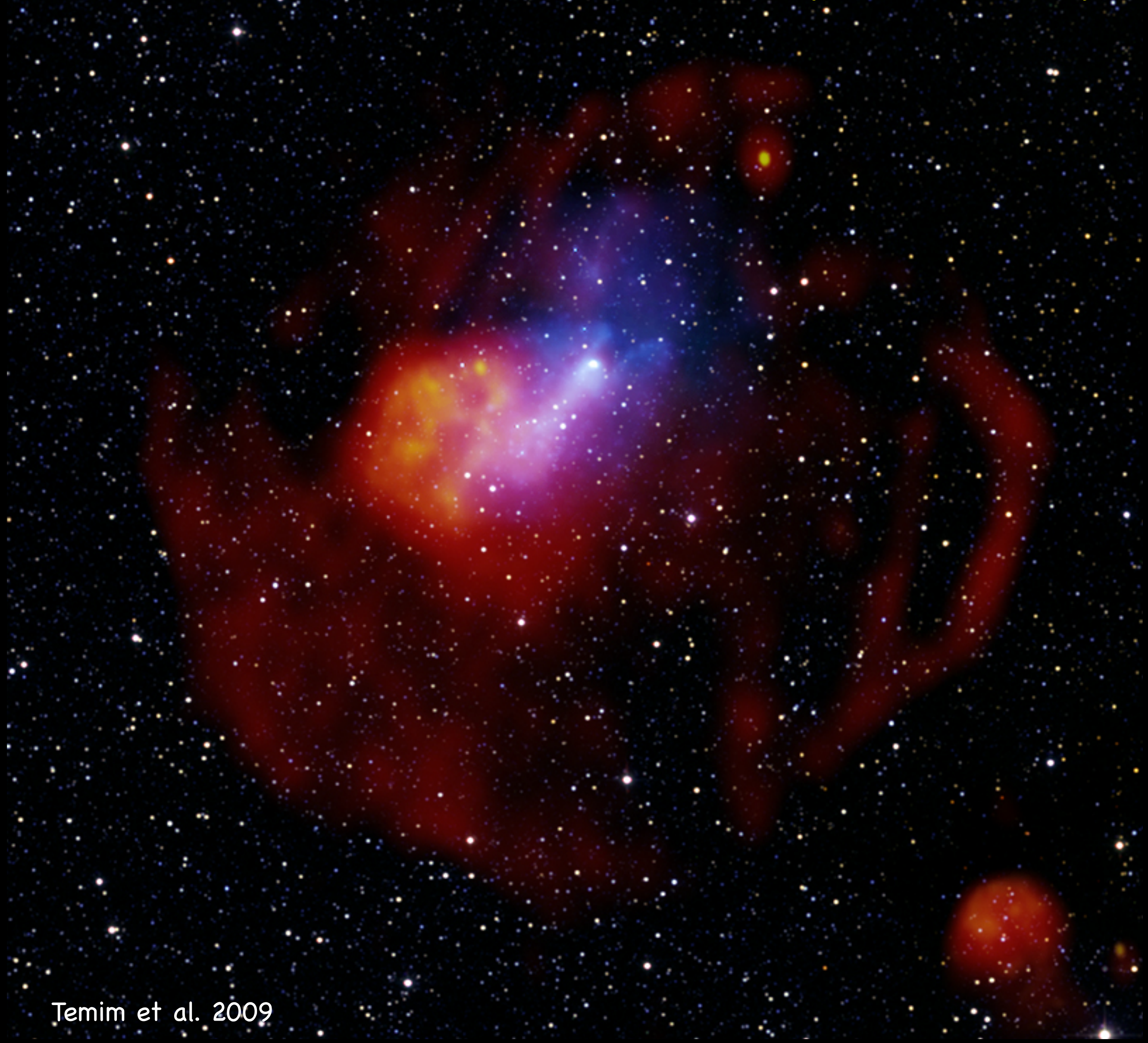
- High abundance of O and NE detected in ejecta; very little iron observed
  - reverse shock appears to still be progressing toward center; not all material synthesized in explosion has been shocked
    ➔ reverse shock hasn't yet reached PWN?

Park, et al. 2004

G292.0+1.8: Sort of Shocking...



G327.1-1.1: More (Reverse) Shocking Results


Temim et al. 2009

- G327.1-1.1 is a composite SNR for which radio morphology suggests PWN/RS interaction
- Chandra observations show an offset compact source w/ trail of nonthermal emission extending back to radio PWN
  - compact source is extended and embedded in bowshock-structure
  - prong-like structures extend from source, inflating bubble in region cleared out by RS

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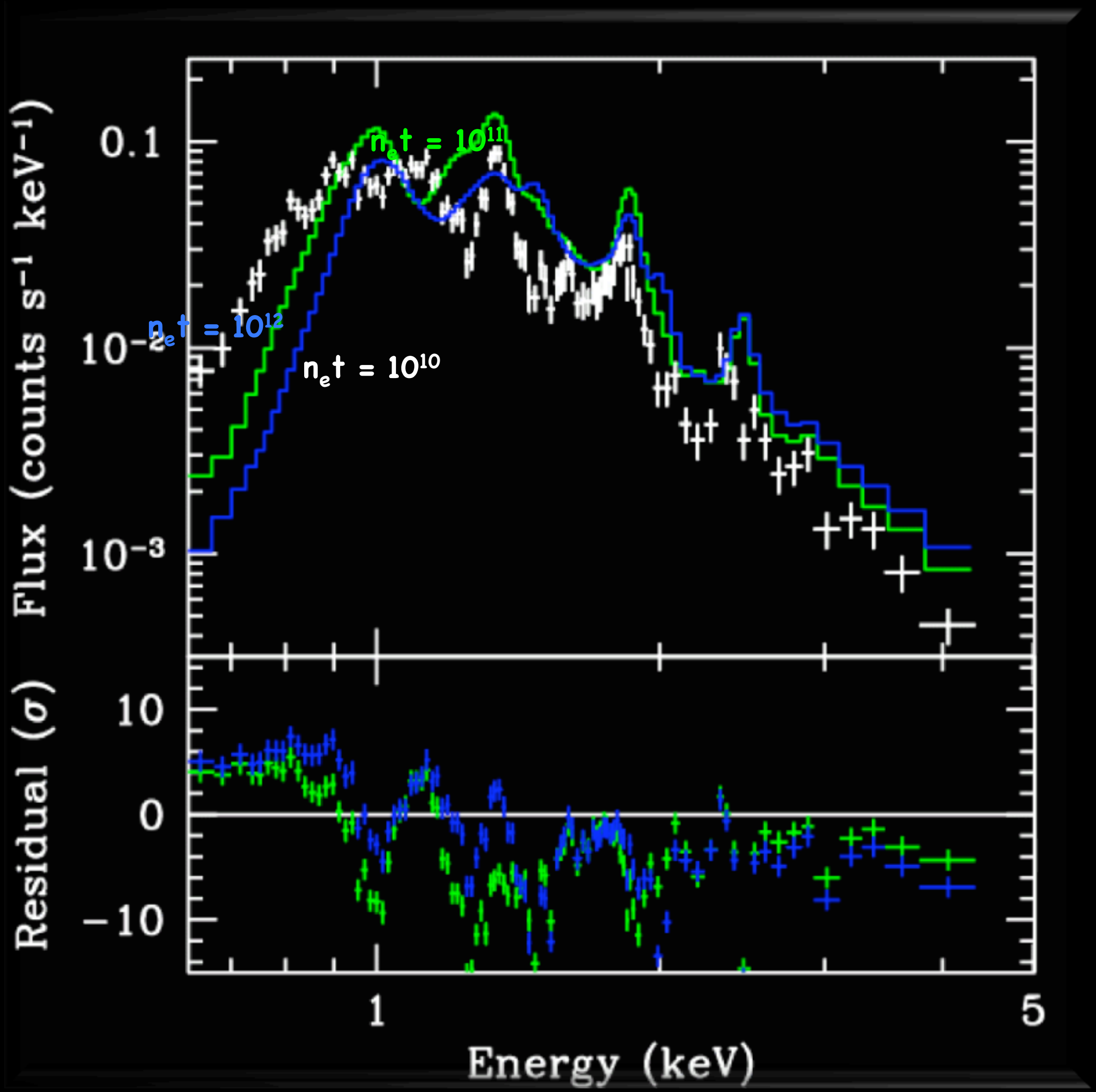
Details of X-ray Spectra of SNRs

- **NEI vs. CIE**
- kT_e vs. kT_p
- CR effects
- Overionized plasmas



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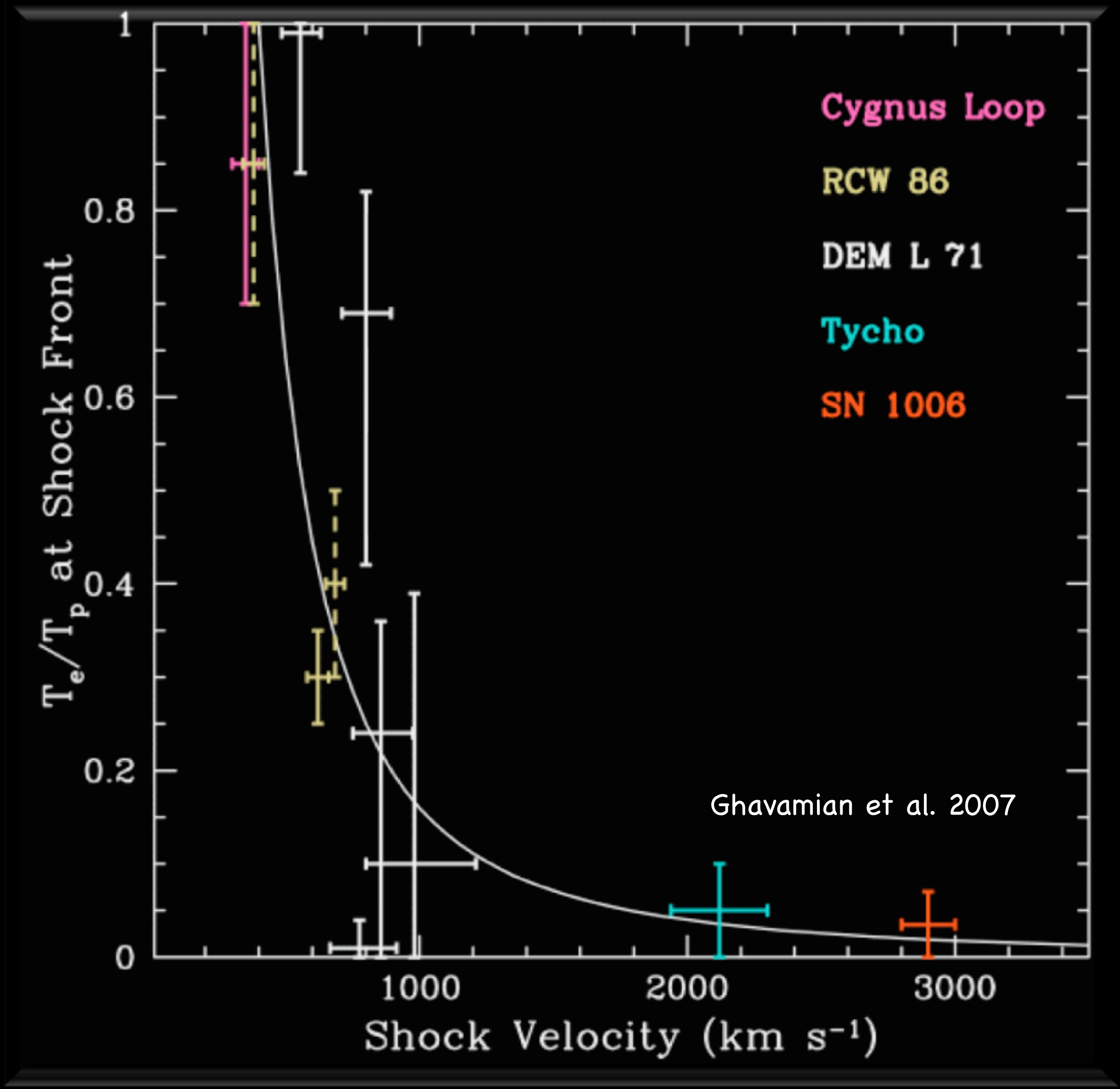

Ghavamian et al. 2007

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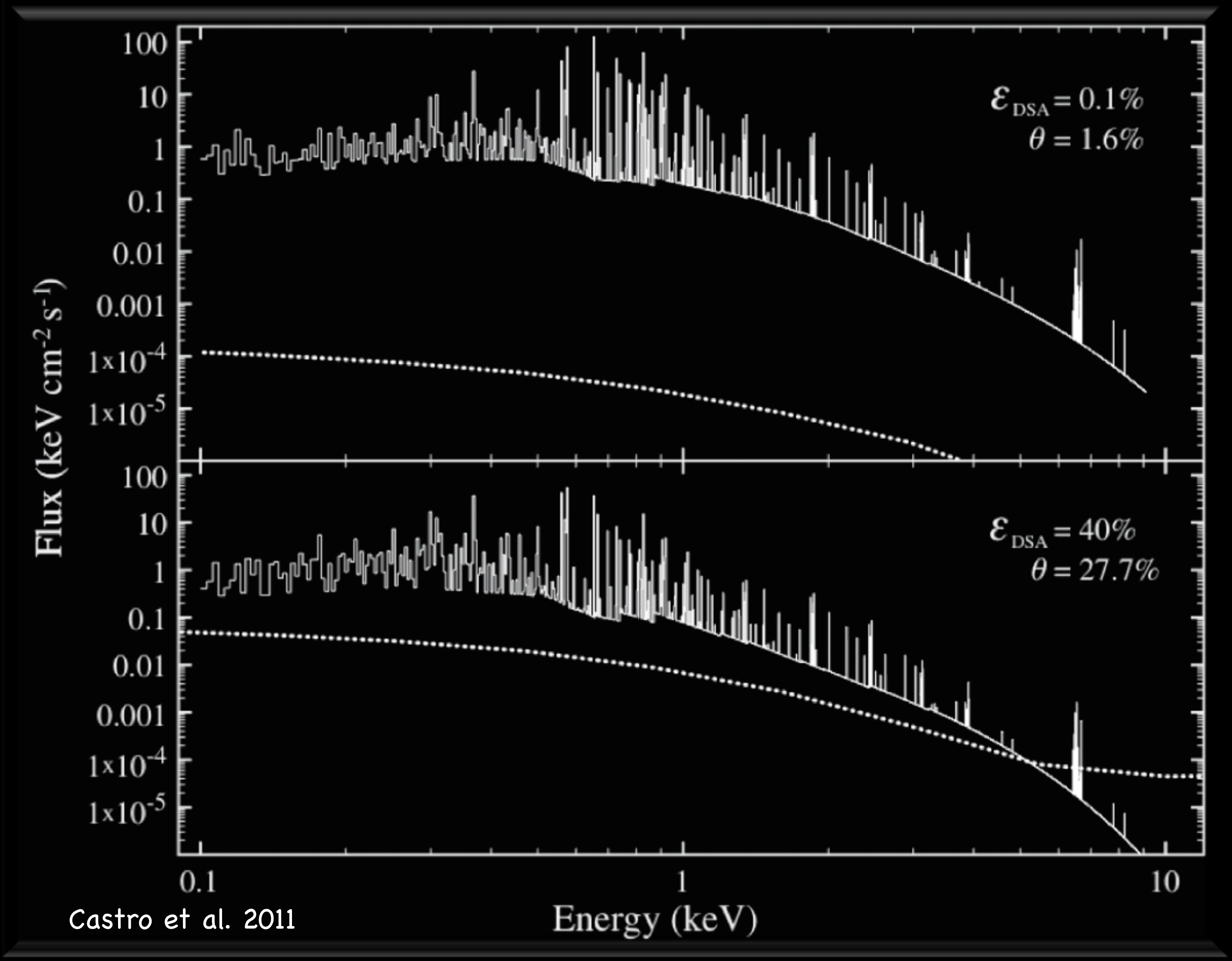

Castro et al. 2011

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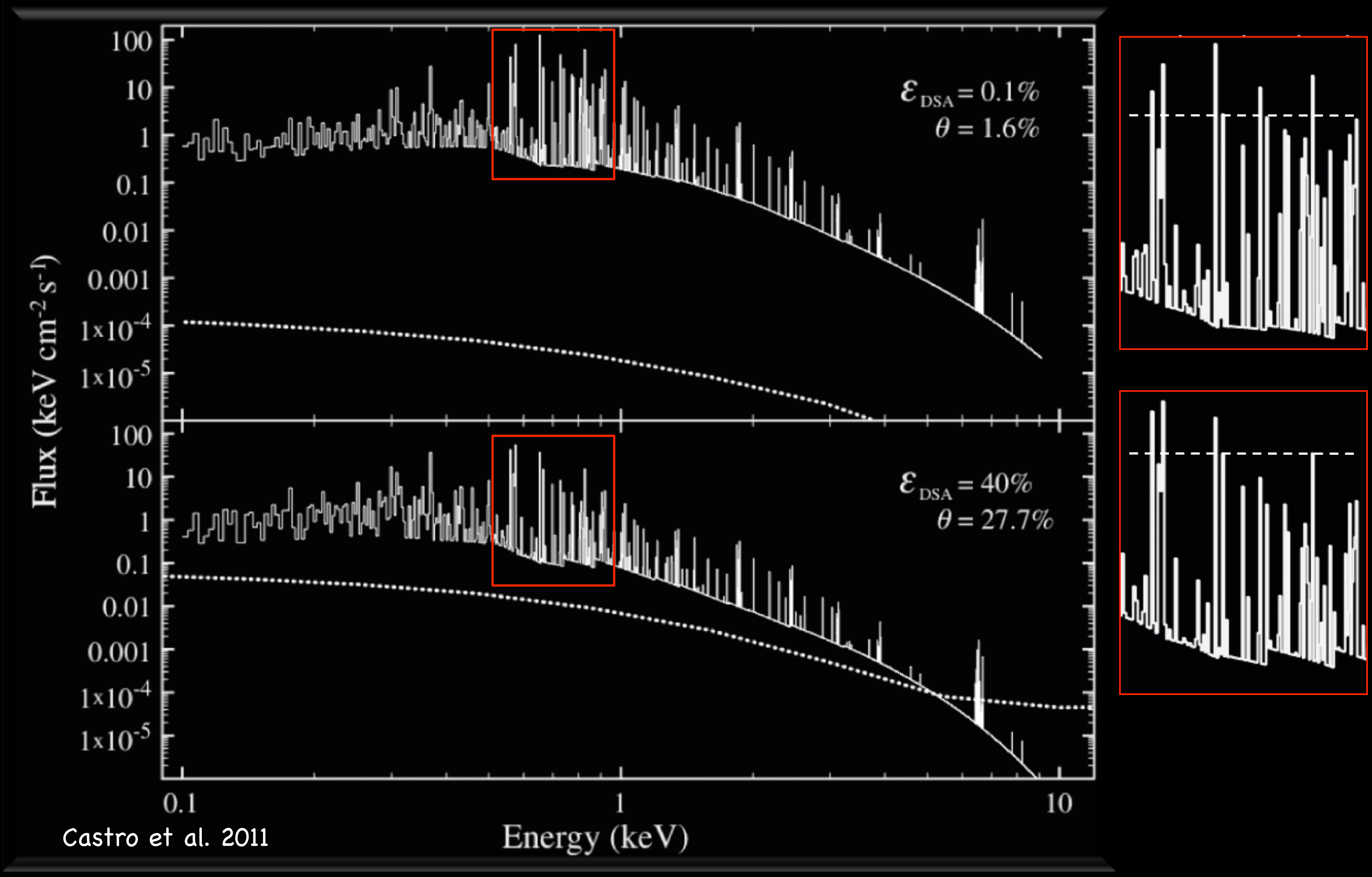

Castro et al. 2011

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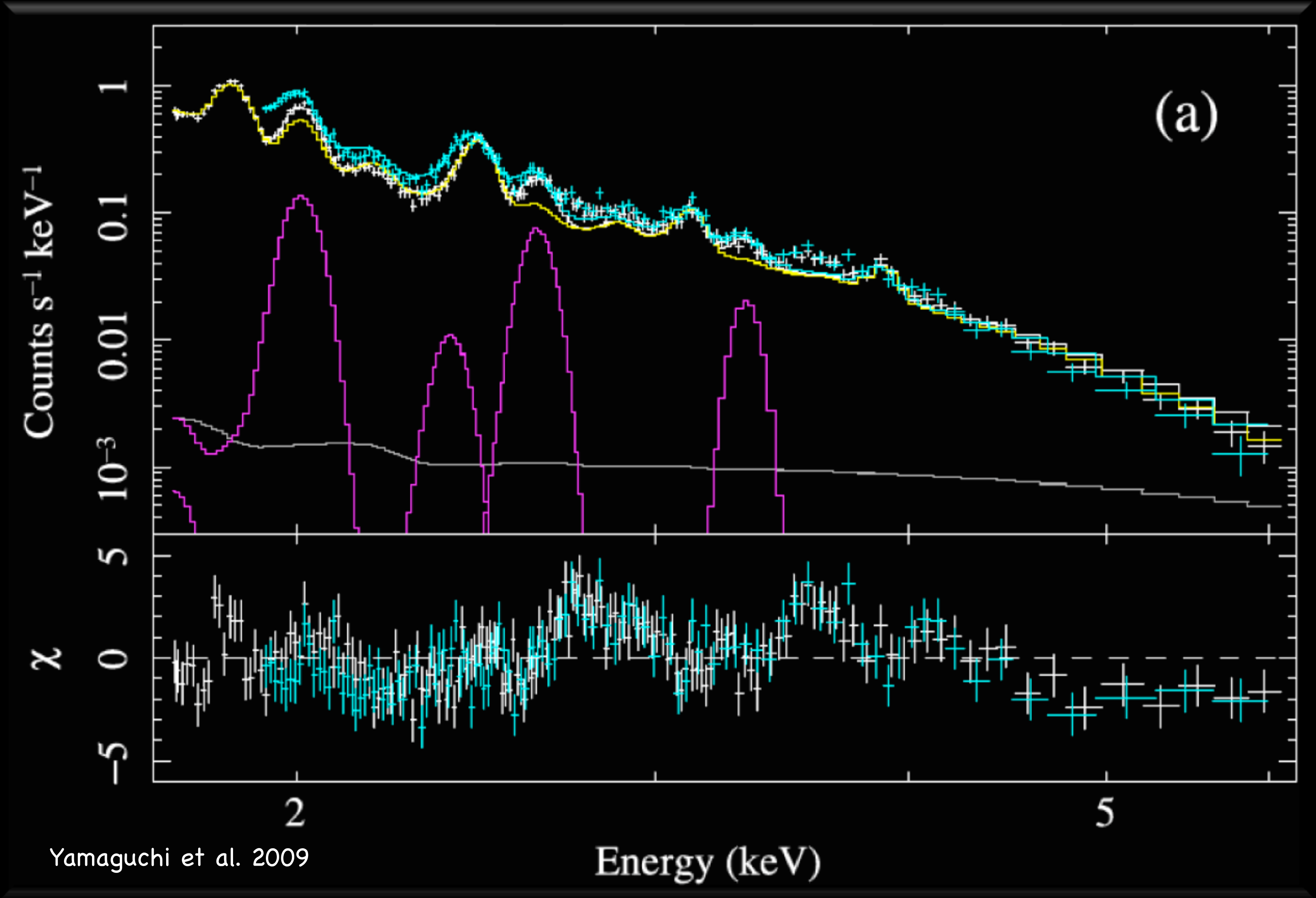
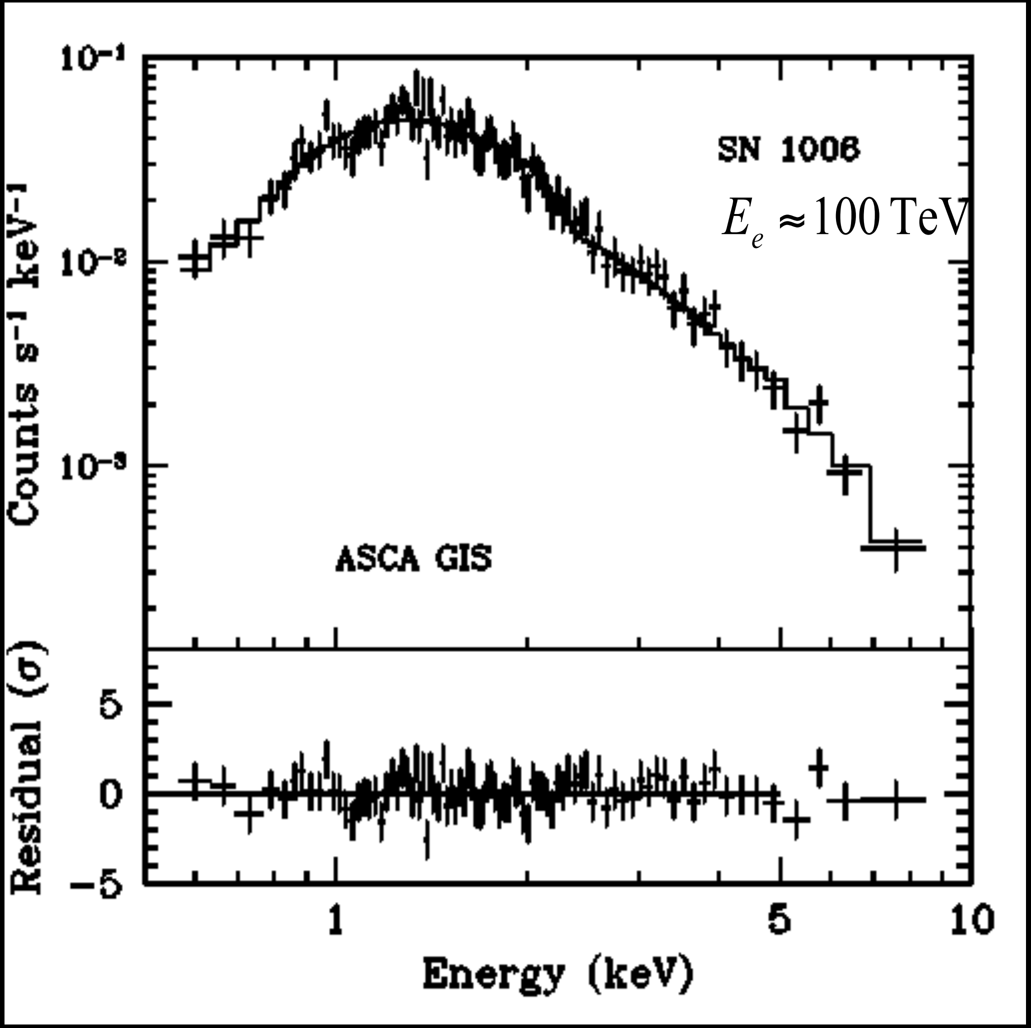
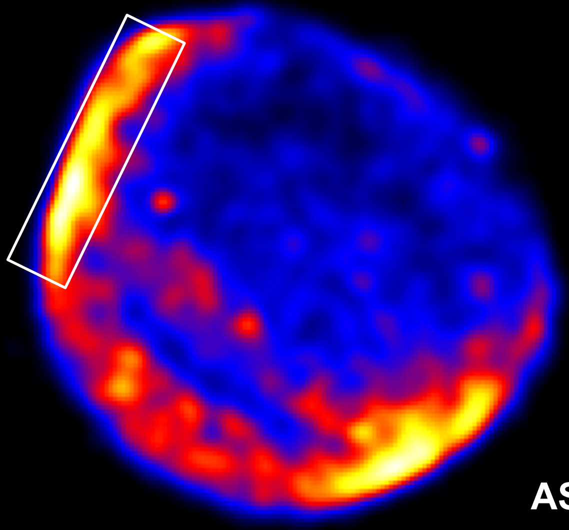


Yamaguchi et al. 2009

Particle Acceleration in SN 1006

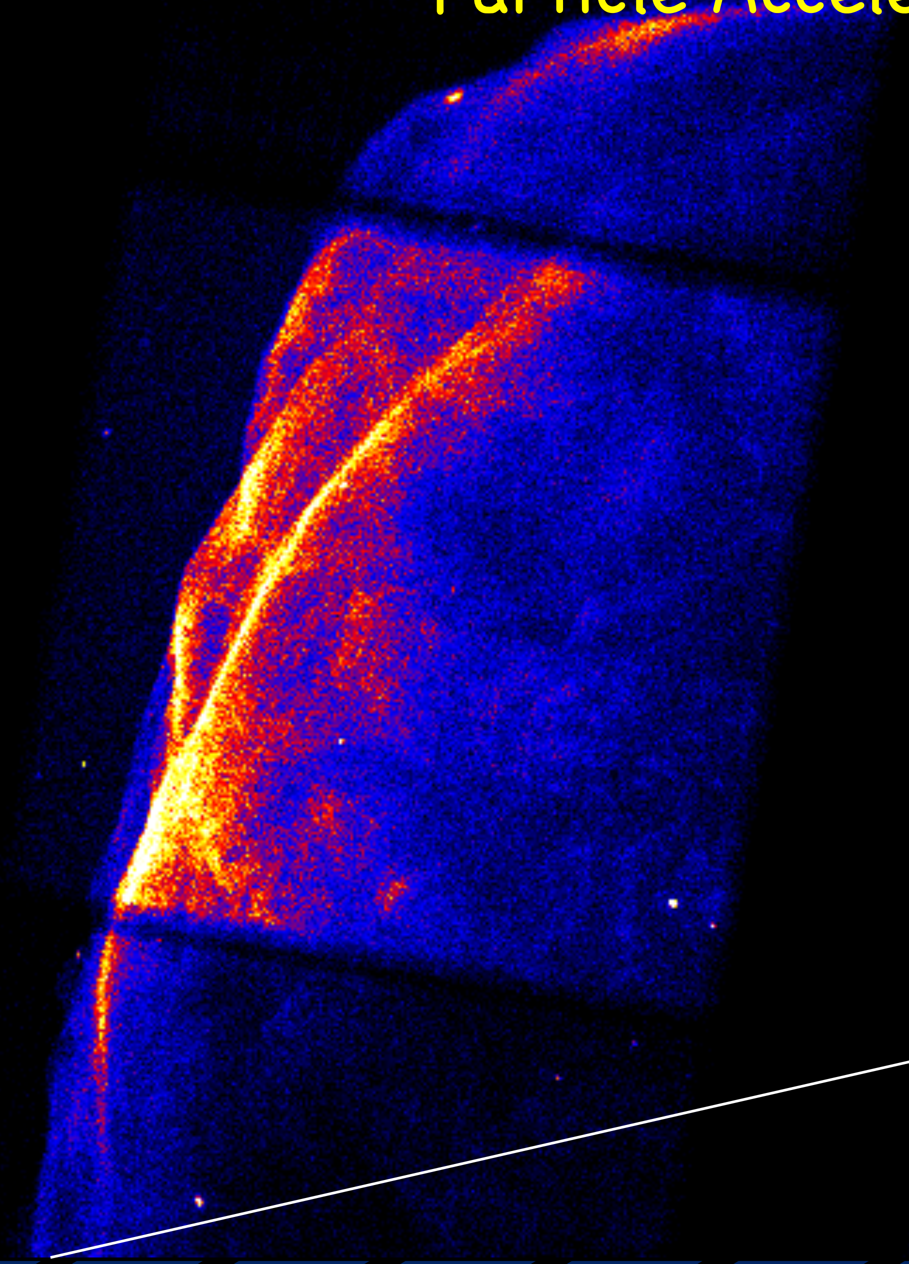


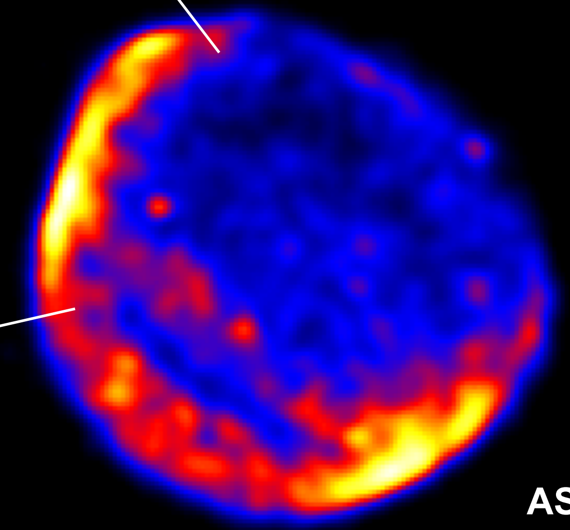
- Spectrum of limb dominated by <u>nonthermal emission</u> (Koyama et al. '96)
  - keV photons imply $E_e \approx 100$ TeV
  - TeV γ-ray emission also detected


ASCA

Particle Acceleration in SN 1006

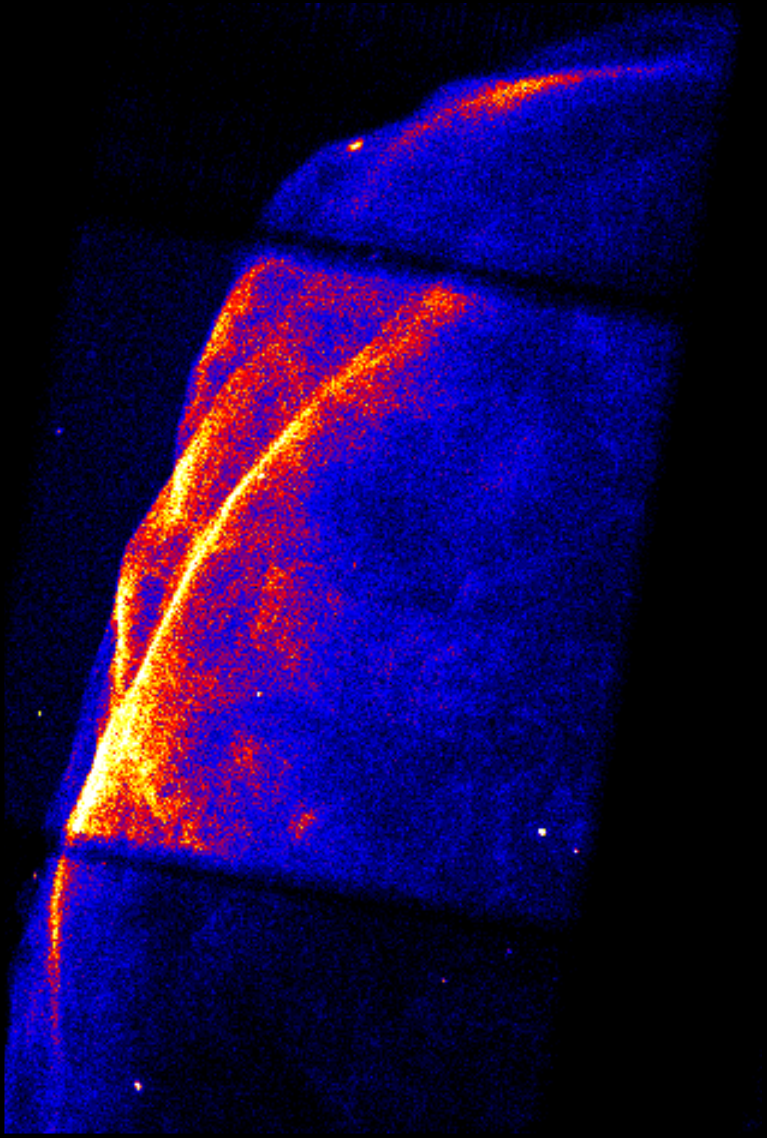
- Spectrum of limb dominated by nonthermal emission (Koyama et al. '96)
  - keV photons imply $E_e \approx 100$ TeV
  - TeV γ-ray emission also detected
- Chandra observations show distinct shock structure in shell





ASCA

Thin Filaments: B Amplification?

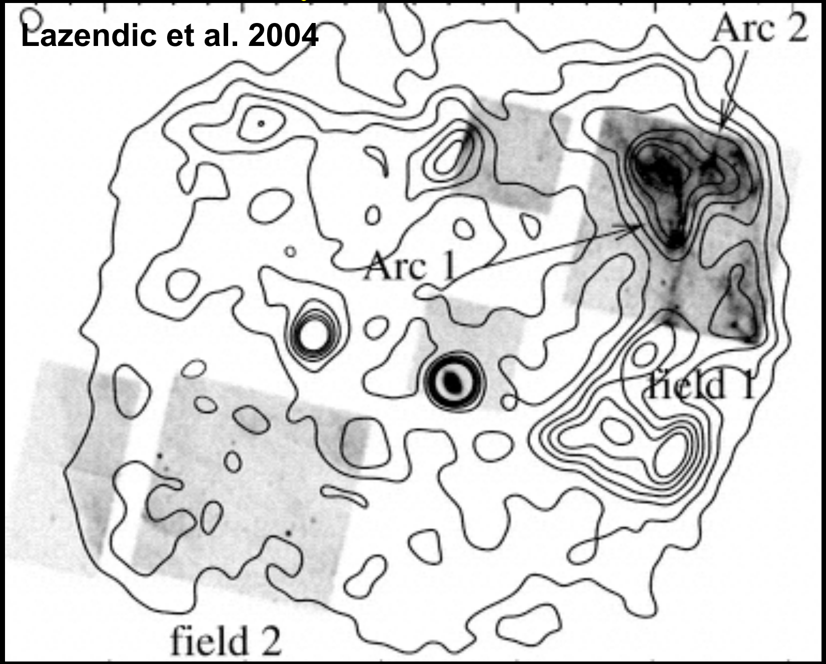


- Thin nonthermal X-ray filaments are now observed in many SNRs, including SN 1006, Cas A, Kepler, Tycho, RX J1713, and others
  - observed drop in synchrotron emissivity is too rapid to be the result of adiabatic expansion

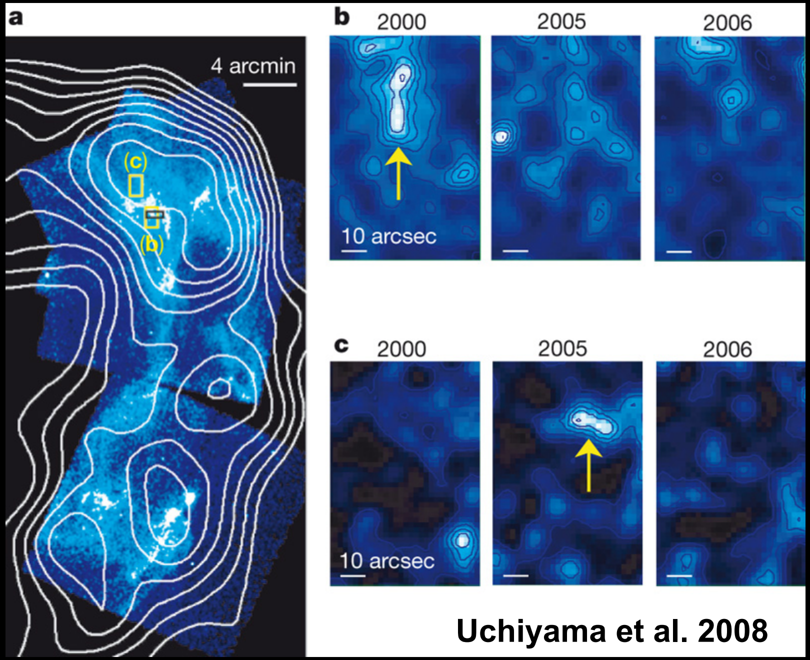
- Vink & Laming (2003) and others argue that this suggests large $B \sim 200 \mathrm{v}_8^{2/3} \left(\frac{l}{0.01 pc} \right)^{-2/3} \mu G$ trong magnetic field:

- Diffusion length upstr $l_D \sim \frac{\kappa}{\mathrm{v}}, \text{ but } \kappa \propto B^{-1}$ very small as well (Bamba et al. 2003)
  - we don't see a "halo" of synchrotron emission in the upstream region

Rapid Time Variability: B Amplification?



Lazendic et al. 2004



Uchiyama et al. 2008

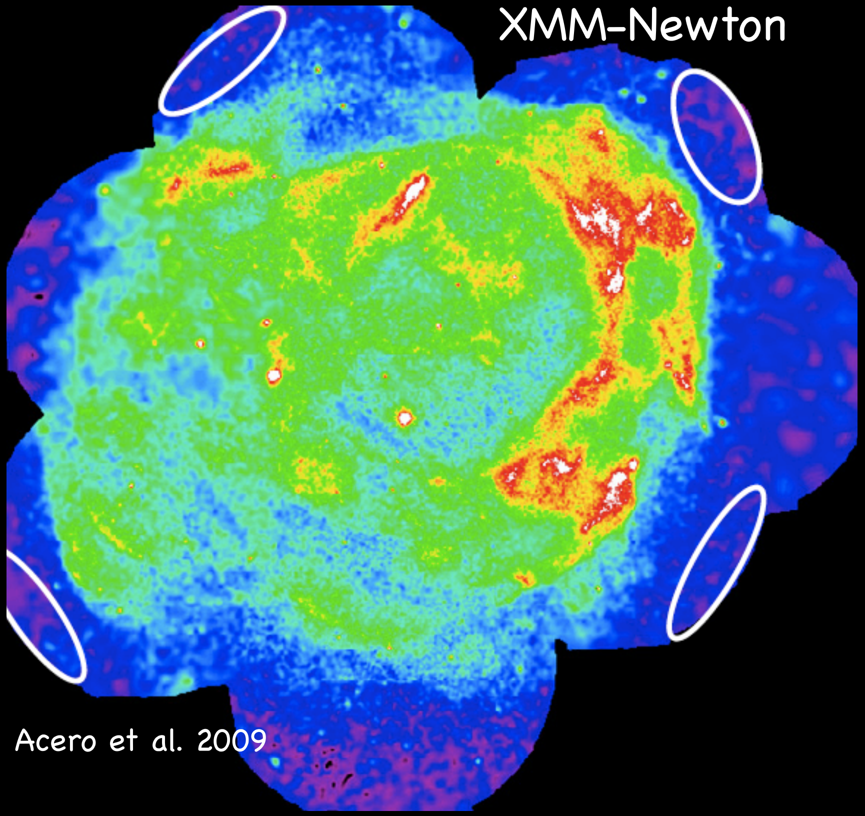
- Along NW rim of G347.3-0.5, brightness variations observed on timescales of ~1 yr
  - if interpreted as synchrotron-loss or acceleration timescales, B is huge: B ~ 1 mG

$$t_{syn} \sim 1.5 B_{mG}^{-3/2} \varepsilon_{keV}^{-1/2} \mathrm{yr} \qquad t_{acc} \sim 9 B_{mG}^{-3/2} \varepsilon_{keV}^{1/2} v_{1000}^{-2} \mathrm{yr}$$

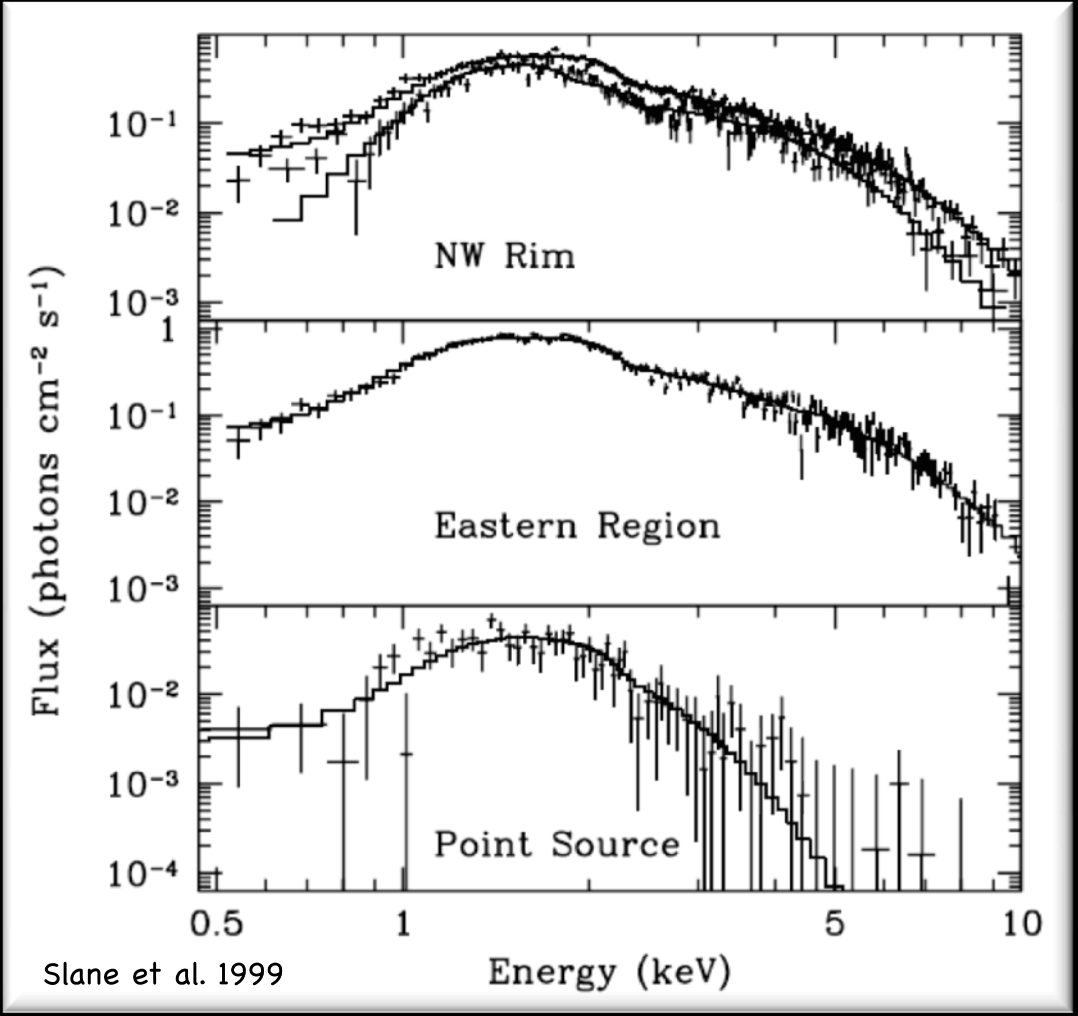
- This, along with earlier measurements of the nonthermal spectrum in Cas A, may support the notion of magnetic field amplification => potential high energies for ions

- Similar behavior seen in Cas A

G347.3-0.5/RX J1713.7-3946



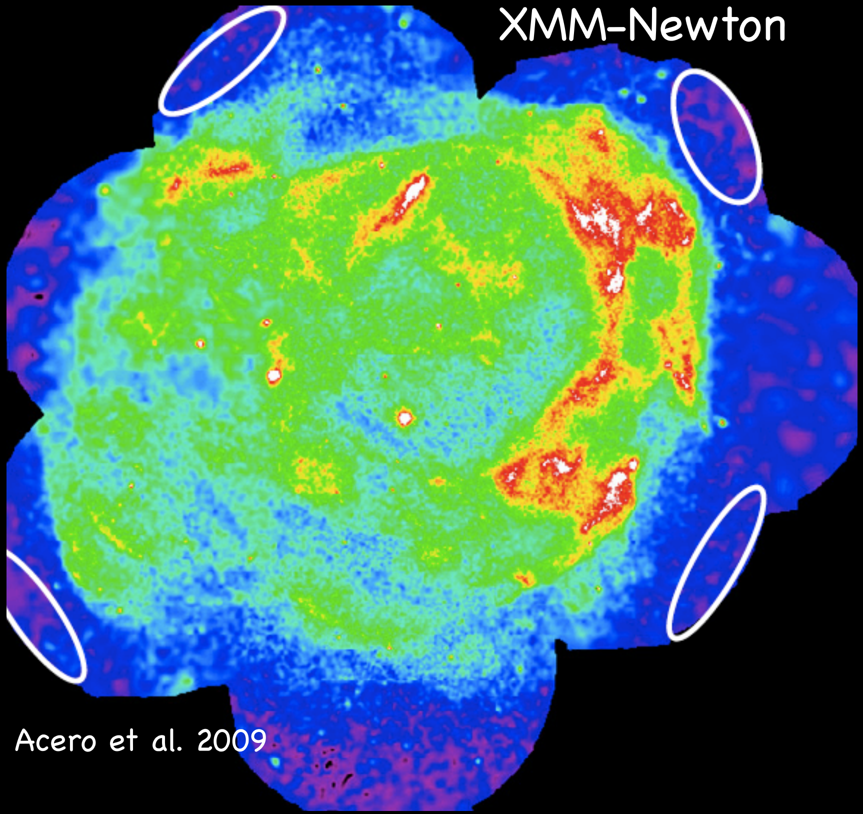
Acero et al. 2009



Slane et al. 1999

- **X-ray spectrum from SNR is completely nonthermal**
  - upper limits on thermal emission place strong constraints on density

G347.3-0.5/RX J1713.7-3946



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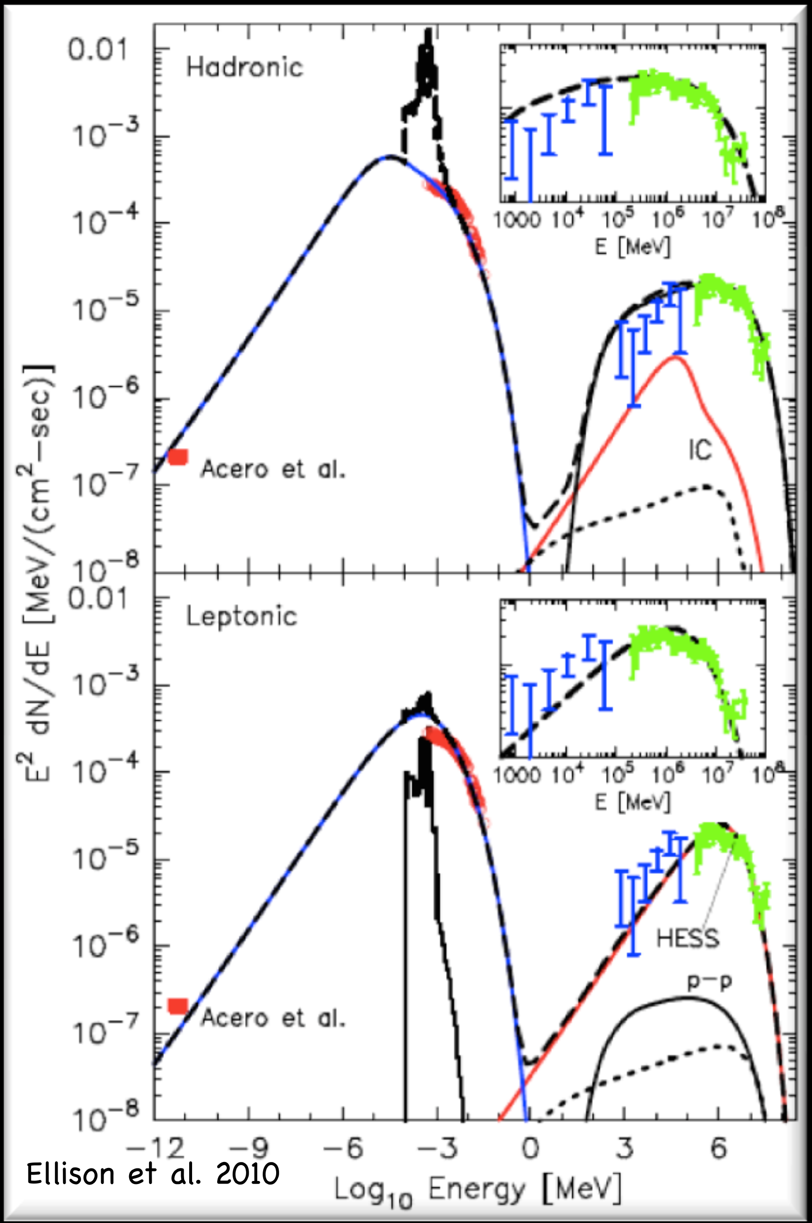


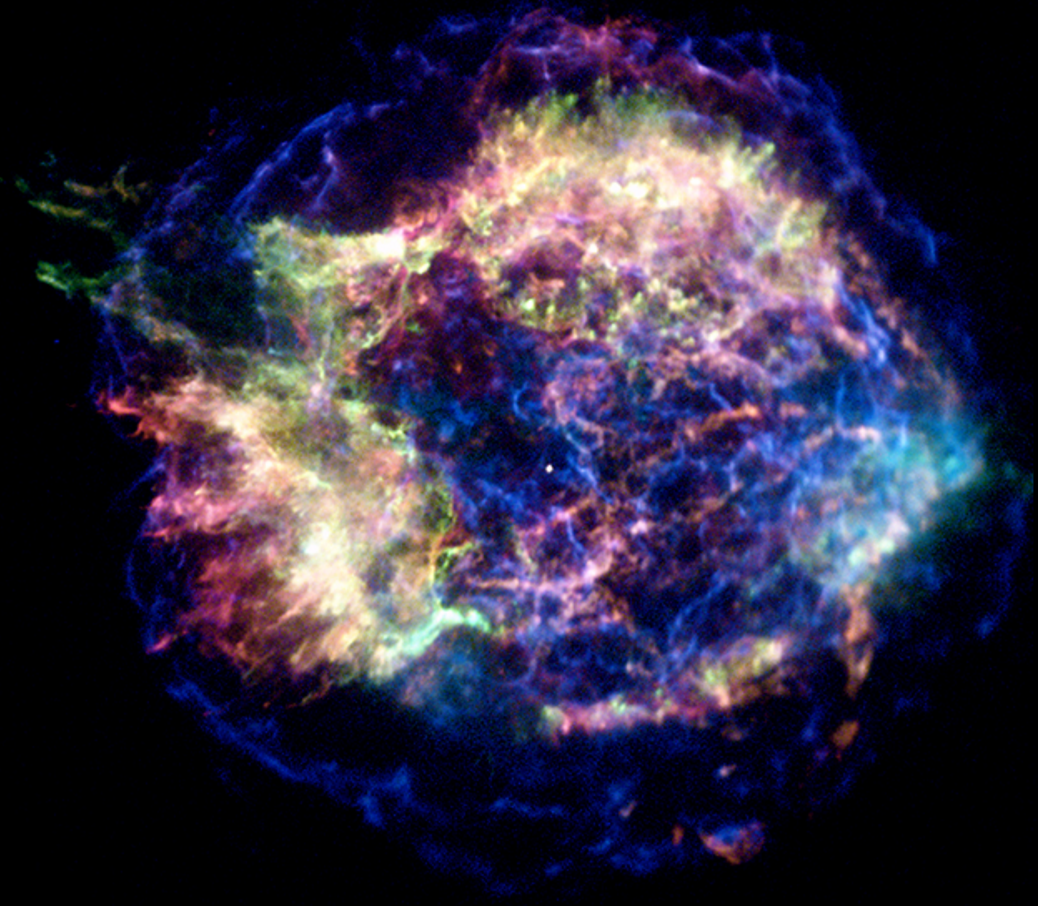
Ellison et al. 2010

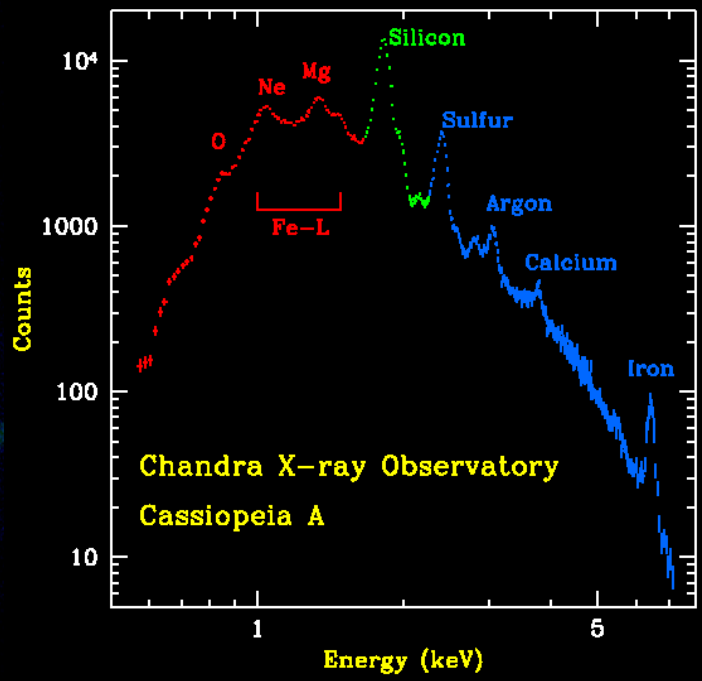
- **Broadband modeling shows that, for expansion into a uniform ISM, γ-ray emission must be leptonic in origin**
  - **NOTE: This does NOT mean that energetic hadrons are not produced in such a model; they ARE!**

(Some of the) Open Issues

- Electron-ion temperature equilibration
- Details of particle acceleration
- Ejecta Mixing
- Connection between SN type and NS class
- Structure of shock precursor
- Acceleration at reverse shock
- X-ray heating/destruction of SN dust
- Models vs. observations…

Exercise: Spectra of Cas A and its CCO





ACIS-S Observation:

3-color image in soft/ medium/hard bands (ds9)

Spectra of discrete regions from the SNR (specextract)

Spectral fitting (xspec/ sherpa, NEI models w/ variable abundances; power law model; blackbody model)

- **Complex ejecta distribution**
- **Nonthermal filaments**
- **Neutron star in interior**

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

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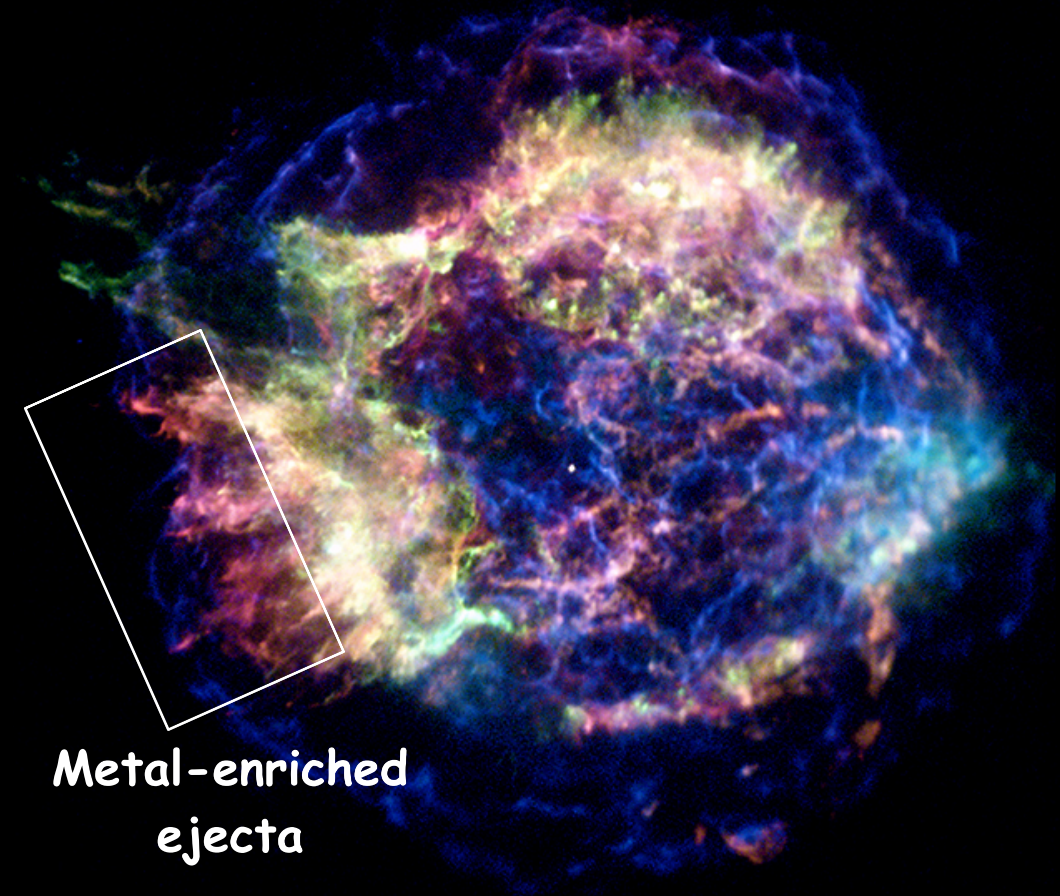

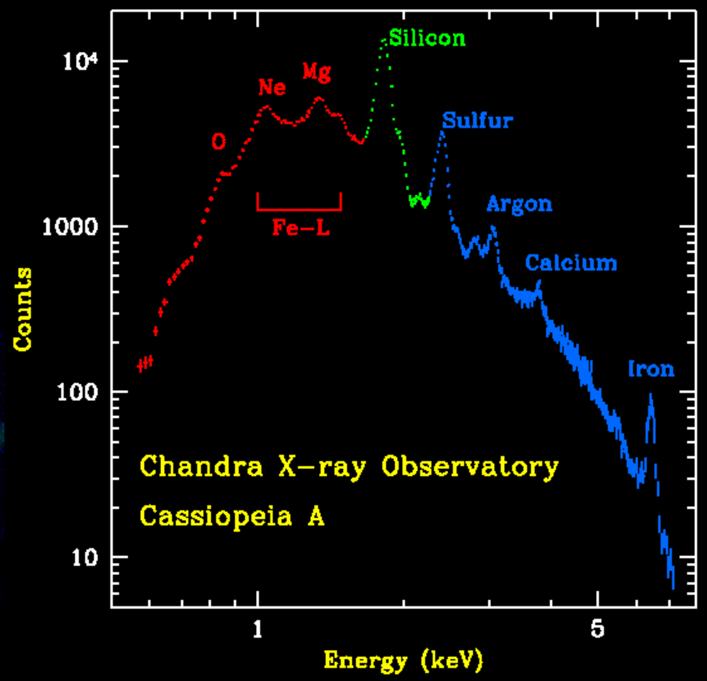

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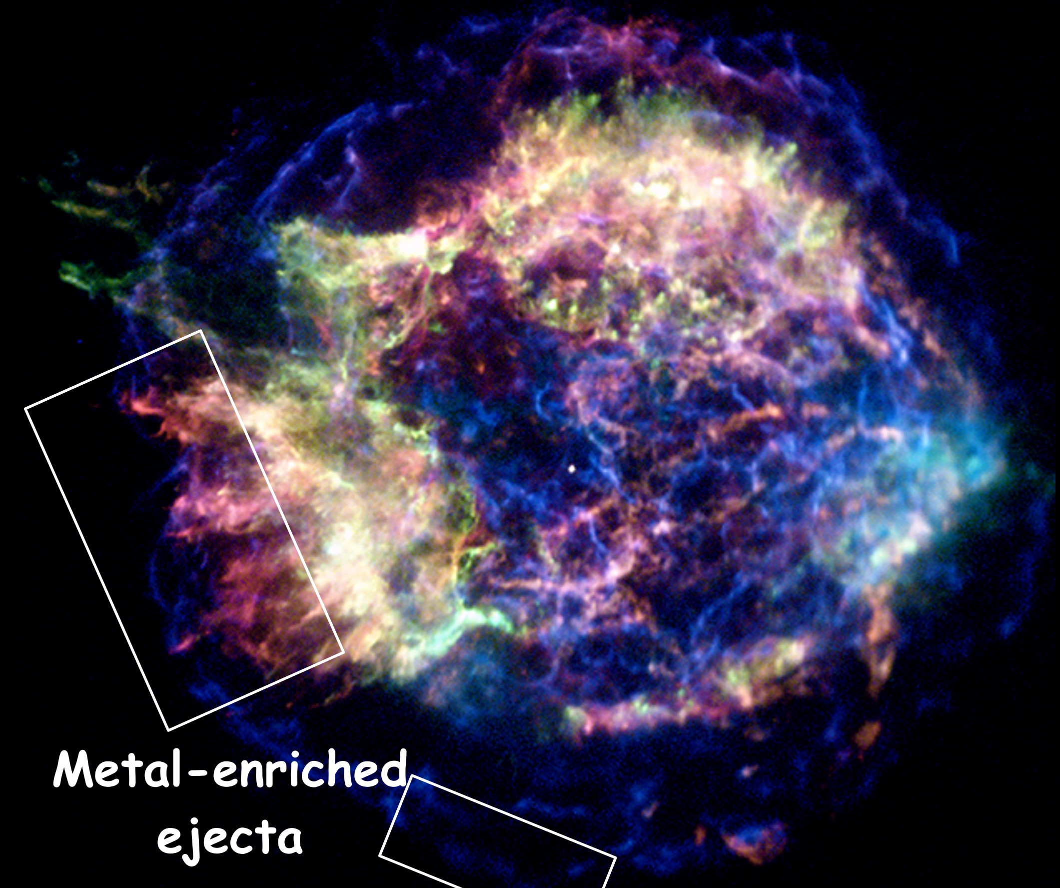

Metal-enriched ejecta

Synchrotron-emitting filaments

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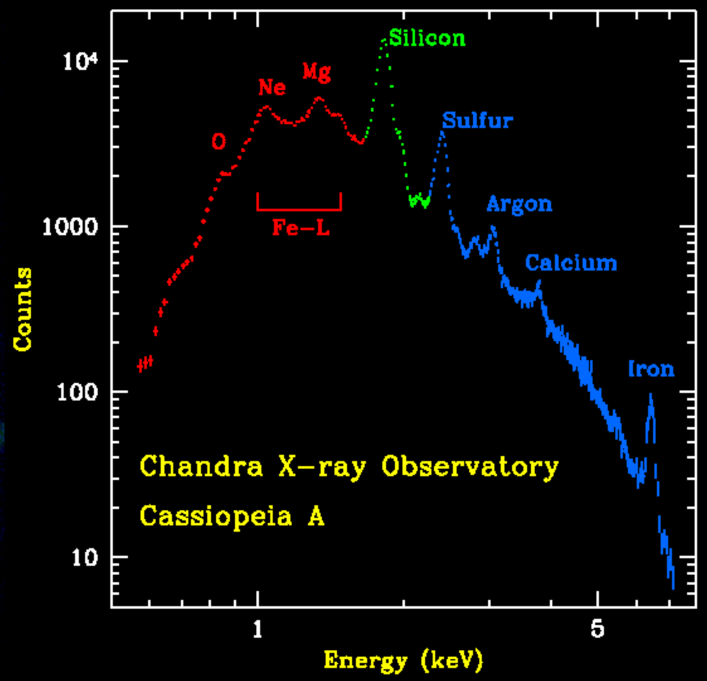

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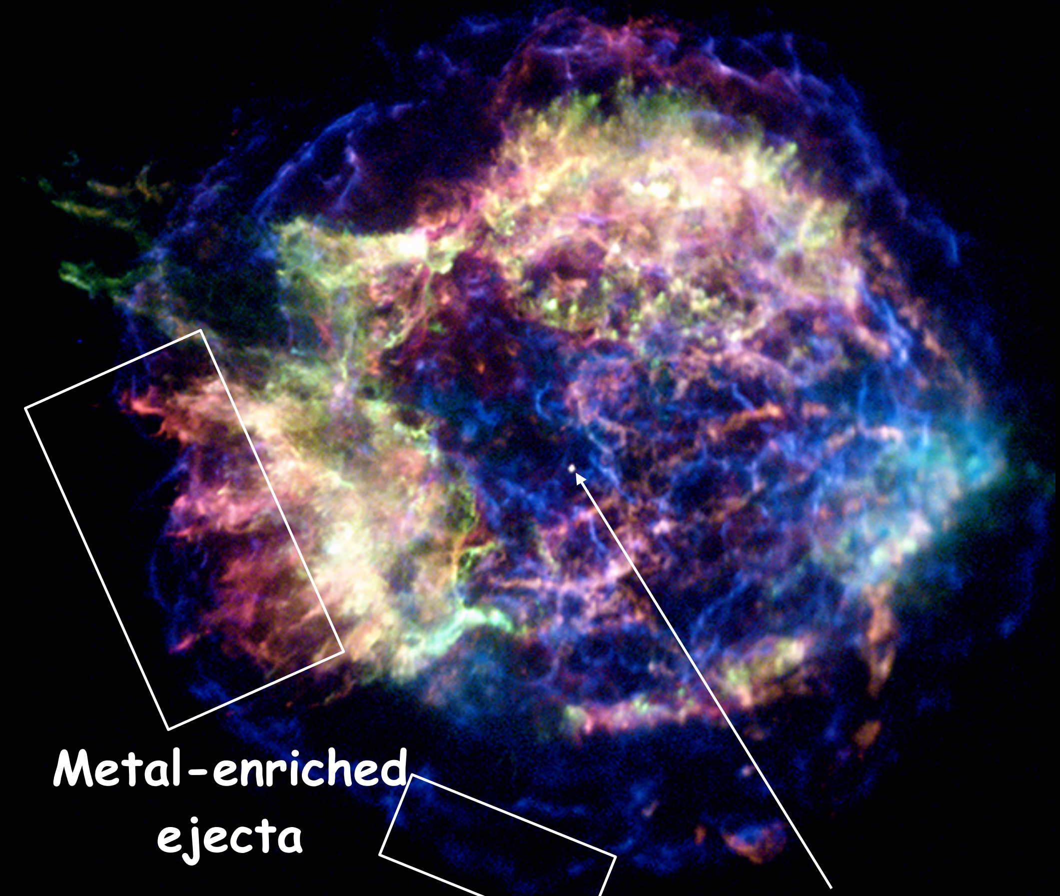
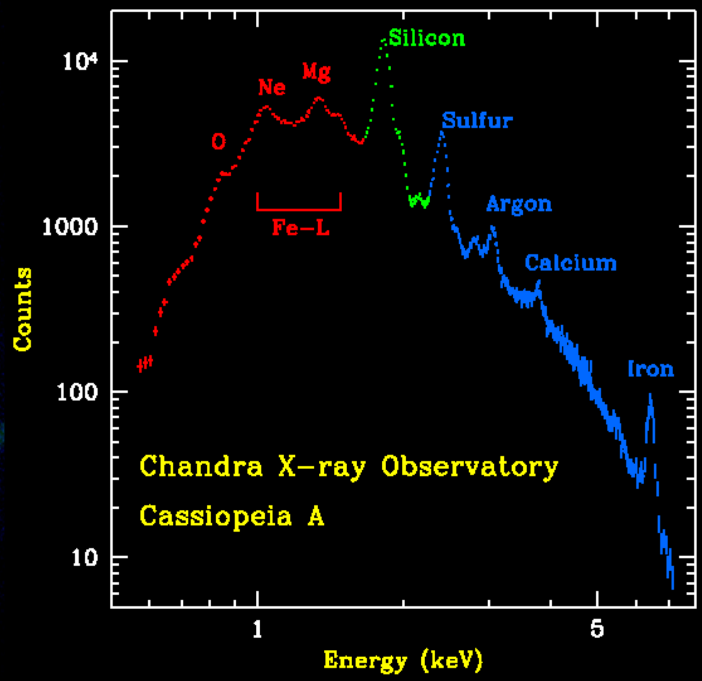


Metal-enriched ejecta

Synchrotron-emitting filaments

Neutron Star



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Exercise: Spectra of Cas A and its CCO

Introduction:

Cas A is a young, ejecta-dominated supernova remnant located at a distance of about 3.4 kpc. It is thought to be the result of a stellar explosion in about the year 1680. In the X-ray band, Cas A is characterized by a complex shell of X-ray emitting material that is dominated by shock-heated stellar ejecta. A thin shell of hard X-ray emission surrounds the remnant, and a compact neutron star resides at its center.

In this exercise, you will use Chandra data to derive rough estimates of the dynamical properties of Cas A, investigate variations in the composition of the shock-heated ejecta, determine the nature of the emission from the thin shell, and investigation the emission properties of the central compact object.

1. From the Chandra archive, download data from a Cas A observation carried out with ACIS-S. An observation of about 20 ks is more than adequate for this investigation.

2. Using ds9, create a 3-color image of Cas A. Reasonable energy bands are the following:

red: 0.6-1.65 keV
green: 1.65-2.25 keV
blue: 2.25-7.5 keV

a) What is the physical radius of Cas A?

b) Given its age, what is the mean expansion velocity of Cas A? What is the corresponding proton temperature?

c) Assuming the Galactic average of n_0 ~ 0.3 cm^{-3} for the ambient density, how much mass has Cas A swept up? Do you expect the X-ray emission to be dominated by the CSM/ISM or the ejecta

3. Using the 3-color image, identify four spectral regions for study:

i) The tip of one of the red-colored fingers in the outer southeastern region.

ii) A compact blue-green emission interior to the southeastern shell.

iii) A blue filament along the outer southeastern boundary.

iv) The central compact object.

Choose an appropriate region outside the SNR for a background spectrum.

4) Extract the spectrum of the central compact object. Use an absorbed blackbody model (tbabs*bbodyrad) to fit the spectrum.

a) What is the temperature of the neutron star?

b) Using the distance to Cas A, and the normalization from the best-fit spectrum, what is the radius of the emitting area on the neutron star? How does this compare to the expected size of a neutron star?

c) Suppose the neutron star is rotating, and that the magnetic axis is inclined relative to the spin axis. What does the size measured above suggest about the possible pulsed fraction for emission from the source? How could you test this with an X-ray observation?

Exercise: Spectra of Cas A and its CCO

5) Extract spectra from the red and blue-green knots in the southeastern region of Cas A. Compare the two spectra. They are complex, and you will not be able to get good fits with simple models, but some key features are discernible:

a) What dominates the emission of the red knot?

b) What elements are particularly over-abundant in the blue-green knot?

c) In the nucleosynthesis process of the progenitor and explosion, iron is formed nearest the center of the explosion, interior to where Si is formed, for example. Comment on the spatial location of the two knots in this context.

d) What is the approximate temperature of the plasma? How does this compare with the estimated proton temperature above? Comment.

6) Extract the spectrum from thin filament region in southeast.

a) Does the spectrum look like ejecta-dominated material?

b) Use an absorbed power-law to fit the spectrum. What is the spectral index? Based on these data, estimate a lower limit to the maximum energy of the synchrotron emission. By some estimates, the magnetic field in Cas A may be as high as 1 mG. If this is the case, what is the mean electron energy corresponding to the highest-energy (observed) synchrotron photons? What might this suggest about gamma-ray emission from Cas A?

References:

Pavlov et al. 2000, ApJ, 531, L53

Hughes et al. 2000, ApJ, 528, L109

Uchiyama & Aharonian 2008, ApJ, 677, L105

Ghavamian et al. 2007, ApJ, 654, L69

Murray et al. 2002, ApJ, 566, 1039