Stars: Their Life and Afterlife

Supernova Remnants and Cosmic Rays

Brian Humensky

68th Series, Compton Lecture #5

November 8, 2008

Outline

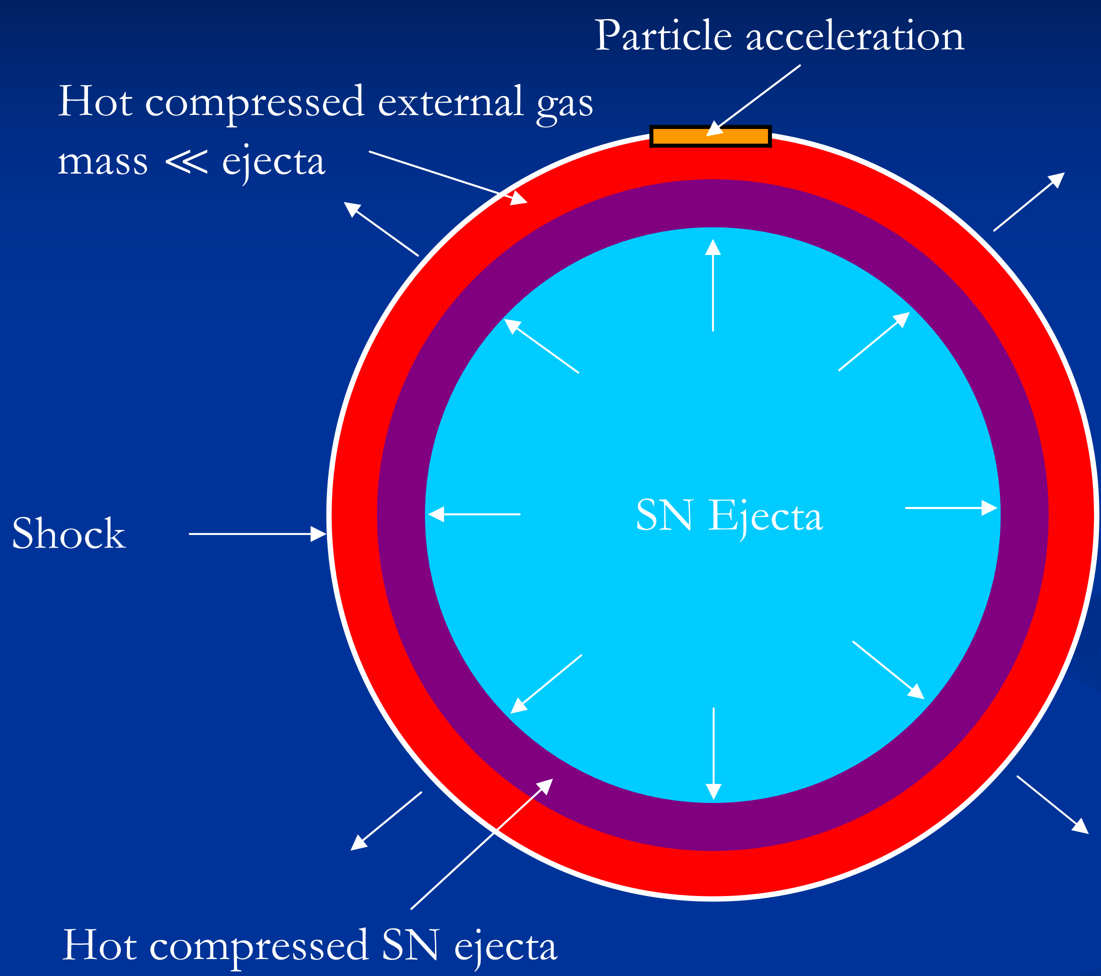
- Evolution of Supernova Remnants
- Cosmic Rays
- Supernova Remnants and their Radiation

Key Points to Take Away

- SNRs produce many kinds of thermal and nonthermal radiation
  - Each tells us something about conditions in progenitor, SN, or SNR
- Cosmic rays bombard the earth all the time, and carry a significant fraction of the energy budget of the galaxy
- SNRs long thought to be the source of cosmic rays but definitive proof is still lacking
- Shock acceleration seems the likely mechanism, but…
  - Max energy?
  - Unambiguous proof of nuclear cosmic ray acceleration?

Evolution of Supernova Remnants

The Free Expansion Phase



Interstellar gas
(Type Ia)

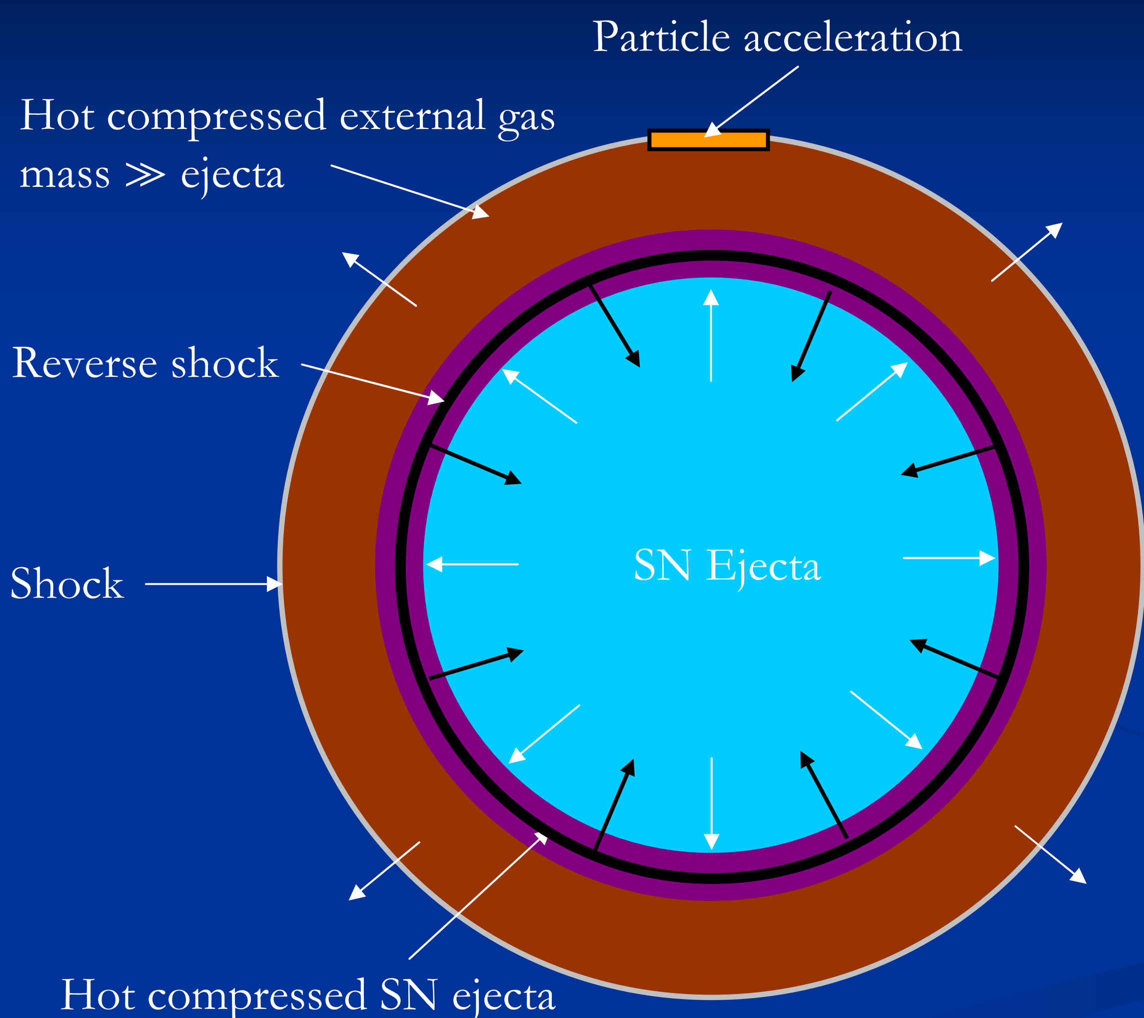
OR

Wind from exploded star,
with compressed gas shells
(Type Ib/c or Type II)

Shock expands at 10-20 * 10^3 km/s
⇒few % speed of light (3 * 10^5 km/s)

Ambient matter is swept up,
compressed, and heated

The Taylor-Sedov Phase



Interstellar gas
(Type Ia)

OR

Wind from exploded star, with compressed gas shells (Type Ib/c or Type II)

Shock slows to few * 10^3 km/s
⇒ Ejecta compressed, heated
⇒ Reverse shock propagates back into ejecta

The "Snow Plow" or Radiative Phase

- When the SNR's shell cools to $\lesssim 10^6$ K, electrons begin to recombine with heavy atoms (oxygen, silicon, …) to form ions
  - Enhances SNR's ability to cool by radiating
  - As cooling continues, more and more ions form ⇒ more cooling ⇒ snowball effect
- Shell shrinks, gets denser ⇒ expansion slows, stops
- Phase lasts a few hundred thousand years

  (few * 10^5 years)
- Shell visible in radio (synchrotron) and optical (synch, thermal)

Dispersal…

- Eventually expansion speed drops below sound speed in ISM (~20 km/s)
  - no longer a "shock"
- Random motions of ISM disrupt SNR
  - SNR gradually mixes with ISM
  - Heavy elements synthesized in supernova enrich the ISM

Cosmic Rays

What are Cosmic Rays?

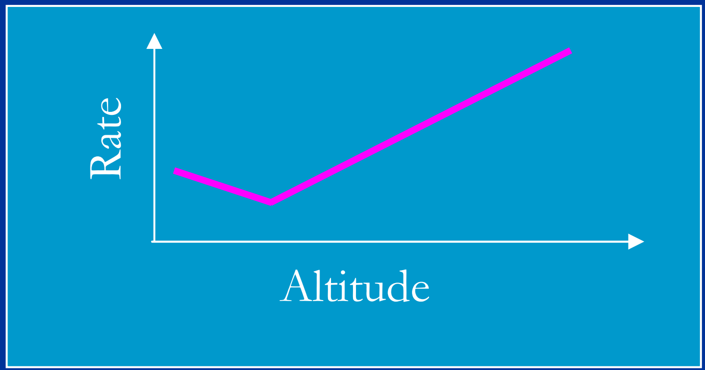
- Cosmic rays are high-energy charged particles that strike the earth from all directions
  - ~85% protons, ~12% helium nuclei, ~1% heavier nuclei, ~2% electrons and positrons
- Why are they interesting?
  - Sample of matter from outside our Solar System
  - Teach us about the composition, evolution, dynamics of the galaxy
  - Particle physics discoveries

Charged Particles Surround Us

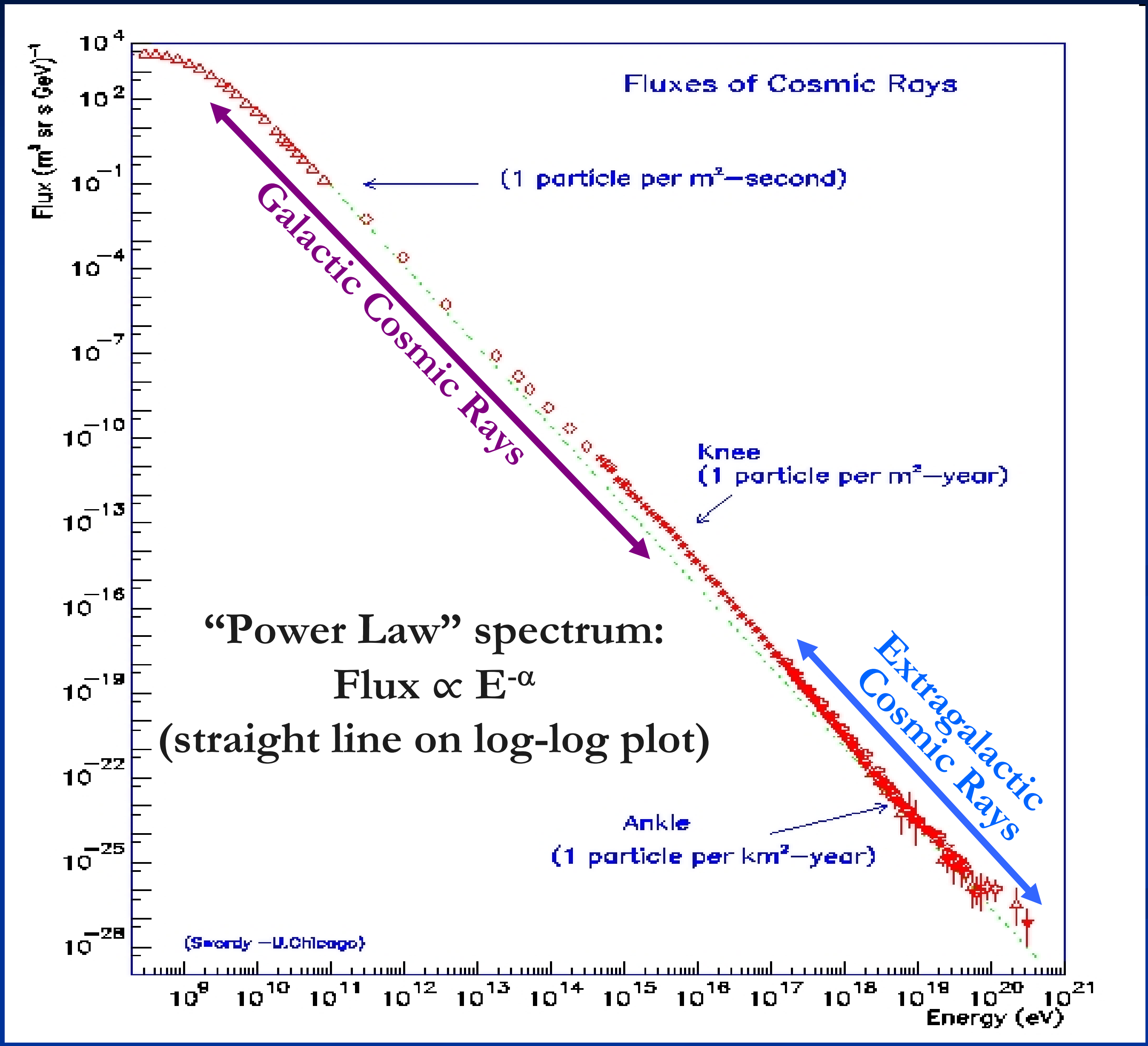
- Early 1900's: Radioactivity recently discovered
- Natural radioactivity exists in the earth all around us
  - X-rays, gamma rays, electrons/positrons, protons, neutrons, alpha particles
  - Produced by smoke detectors, bananas, radon, and other every-day items
- Energetic particles ionize atoms that they interact with ⇒ "ionizing radiation"

Discovering Cosmic Rays

- Ionizing radiation from natural radioactivity should decrease with altitude
  - Air provides insulation
- Viktor Hess tested this with a balloon flight in 1912
  - Up to 5 km
  - Rate of ionizing radiation dropped till 1.5 km, then began rising again!
- Radiation coming from space!
- Coined “cosmic rays” by Robert Millikan in 1925



Fast Forward ~90 Years: CR Spectrum



Where Do They Come From?

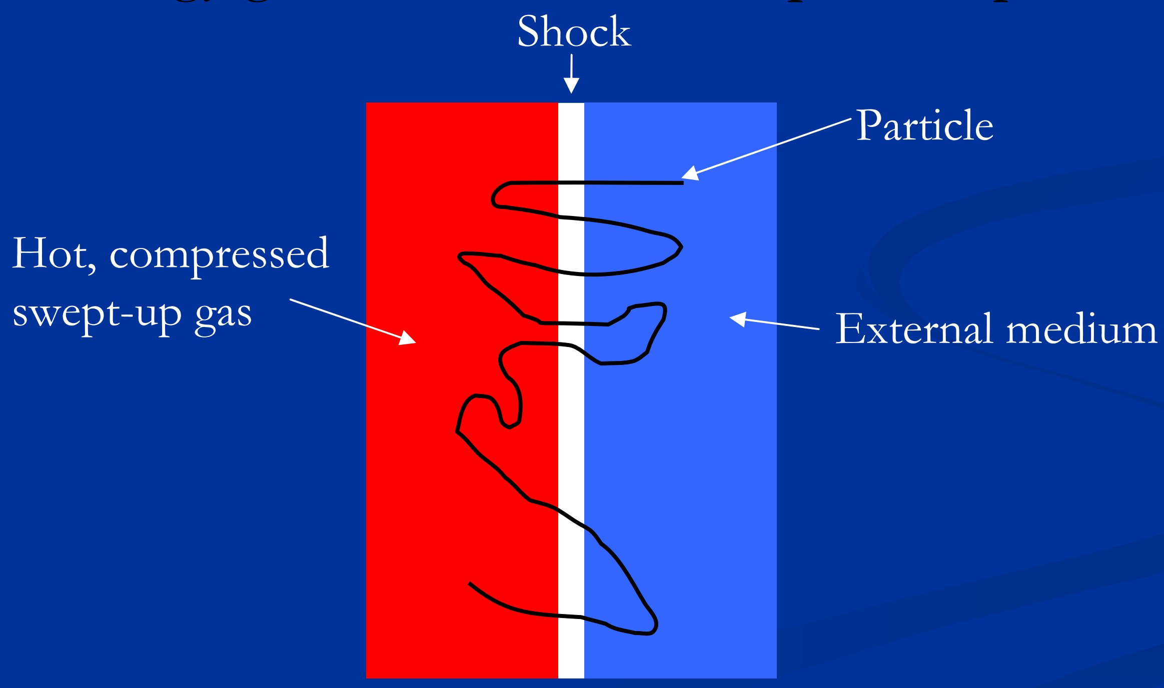
- (Nuclear) cosmic rays are a major component of the galaxy's energy budget!
- They diffuse slowly from their sources through the galaxy in a random walk.
- And gradually leak out of the galaxy, with a typical timescale of ~ 10 million years
  - ⇒ CR power loss ~ $5 * 10^{40}$ erg/s
- Can be supplied by SNe: luminosity of ~ 10^{42} erg/s on average
  - ~10^{51} erg released in SN / 50 yrs ~ 10^{9} s

Radiation	Energy Density (eV/cm^3)
Cosmic Rays	1.0
Star Light	0.3
Cosmic Microwave Background	0.3
Galactic Magnetic Fields	0.2

⇒ Can we prove that cosmic-ray nuclei are accelerated in SNRs?

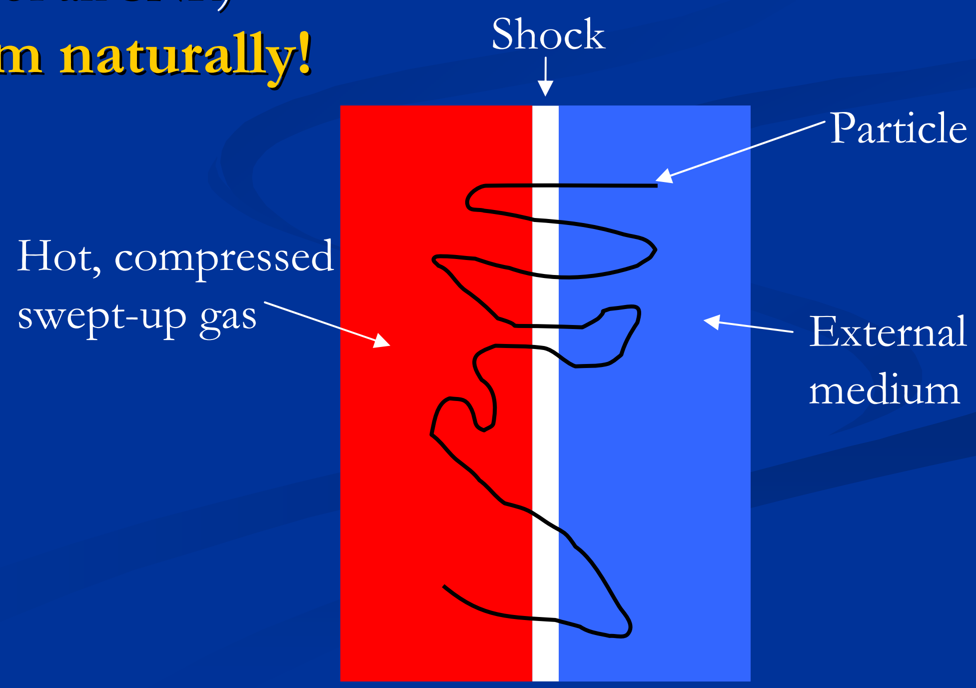
Shock Acceleration

- Shock waves + strong magnetic fields increase the energy of cosmic rays over time
  - From particle's perspective, each time it crosses the shock it experiences a head-on collision with magnetic domains
  - Energy gain **$\Delta E/E$** $\propto$ shock speed / speed of light **~ 1 %**



Shock Acceleration

- Cosmic ray gains ~ 1 % energy on each crossing
- Confined near shock: scatters off turbulent magnetic fields
- Can cross 1000's of times!
- Timescales: for a 10 μG magnetic field and 10^3 km/s shock speed, can accelerate a proton to
  - 1 GeV in ~ 1 month
  - 1 TeV in ~ 100 years
  - 1 PeV in ~ 10^5 years (~lifetime of an SNR)
- **Predicts power-law spectrum naturally!**
- Acceleration is faster for
  - stronger magnetic fields
  - faster shock speeds
- **Maybe can reach "knee" of CR spectrum?!? Hard to say…**

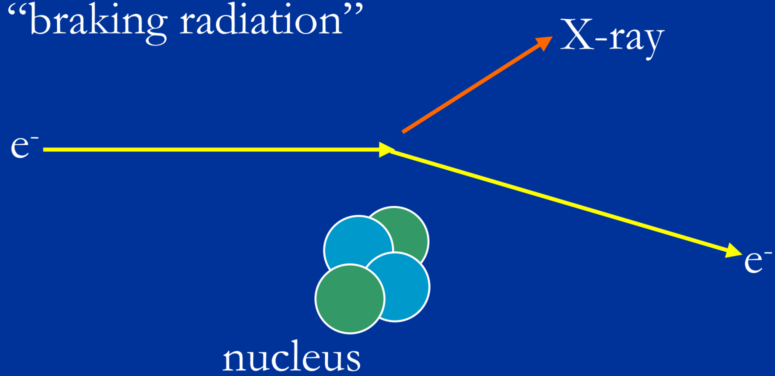


Radiation from Supernova Remnants

Bremsstrahlung and Synchrotron Radiation

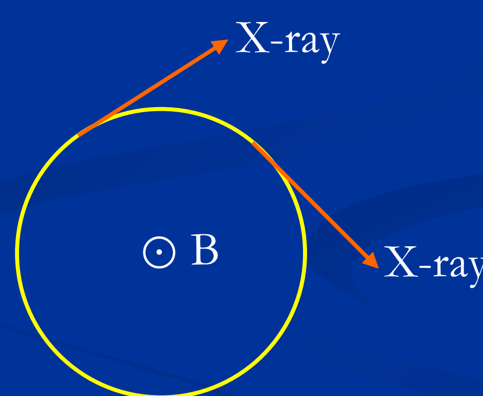
- Charged particles radiate when they are accelerated

Bremsstrahlung: radiation when an electron passes through the electric field of an atom
"braking radiation"



Produced by electrons in hot ($\gtrsim 10^6$ K) gas
⇒ "thermal" bremsstrahlung
⇒ X-rays
⇒ Useful for extracting temperature, density of gas in SNRs

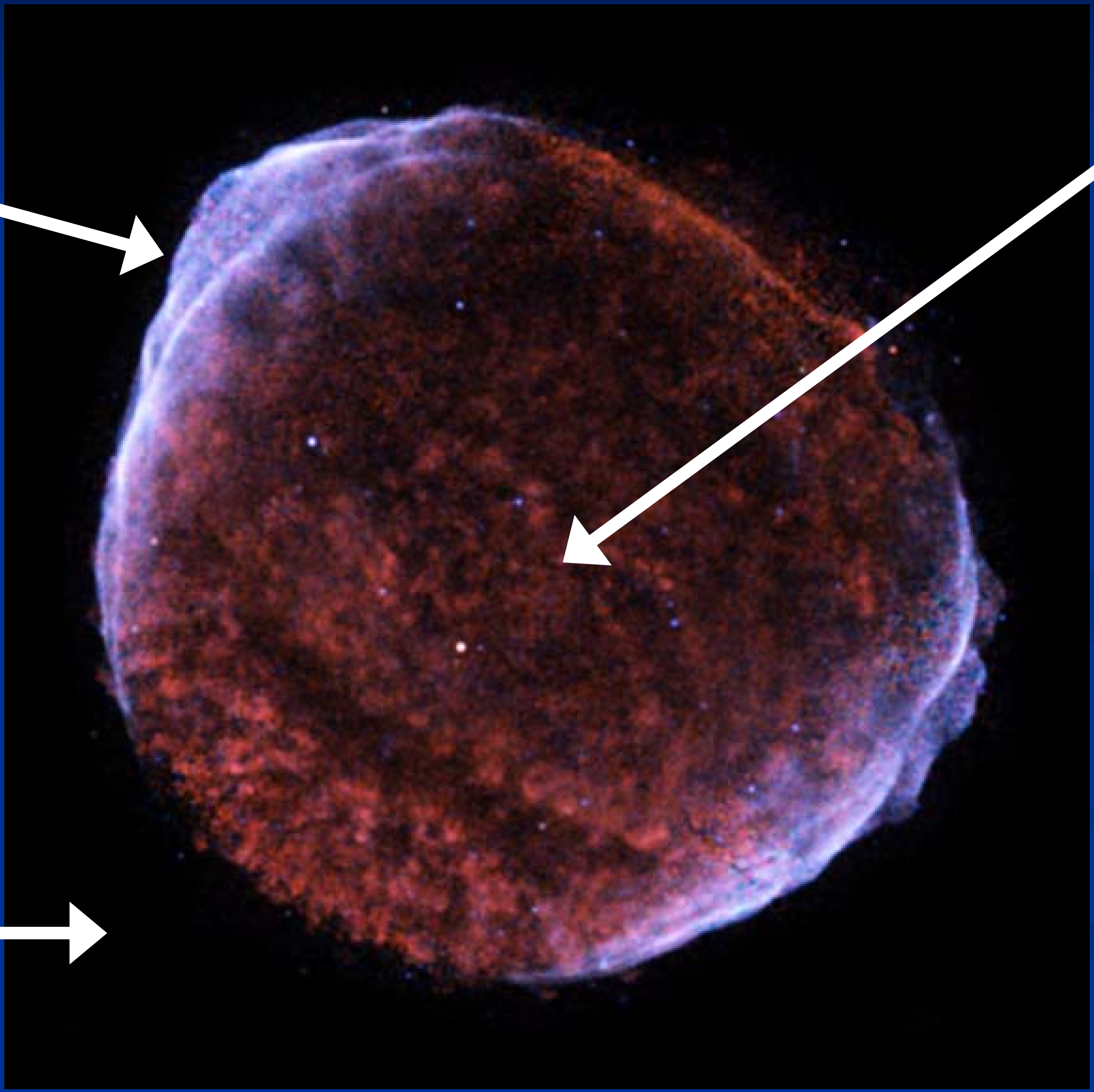
Synchrotron: radiation when an electron's path is curved by a magnetic field



Produced by cosmic-ray electrons
Very efficient cooling mechanism!
⇒ Multi-TeV electrons produce X-rays
⇒ cool quickly – radiate at acceleration site
⇒ MeV/GeV electrons produce radio
⇒ cool slowly – electrons can diffuse

SN 1006 Today: X-rays

Rims: synchrotron radiation from electrons accelerated by the shock front

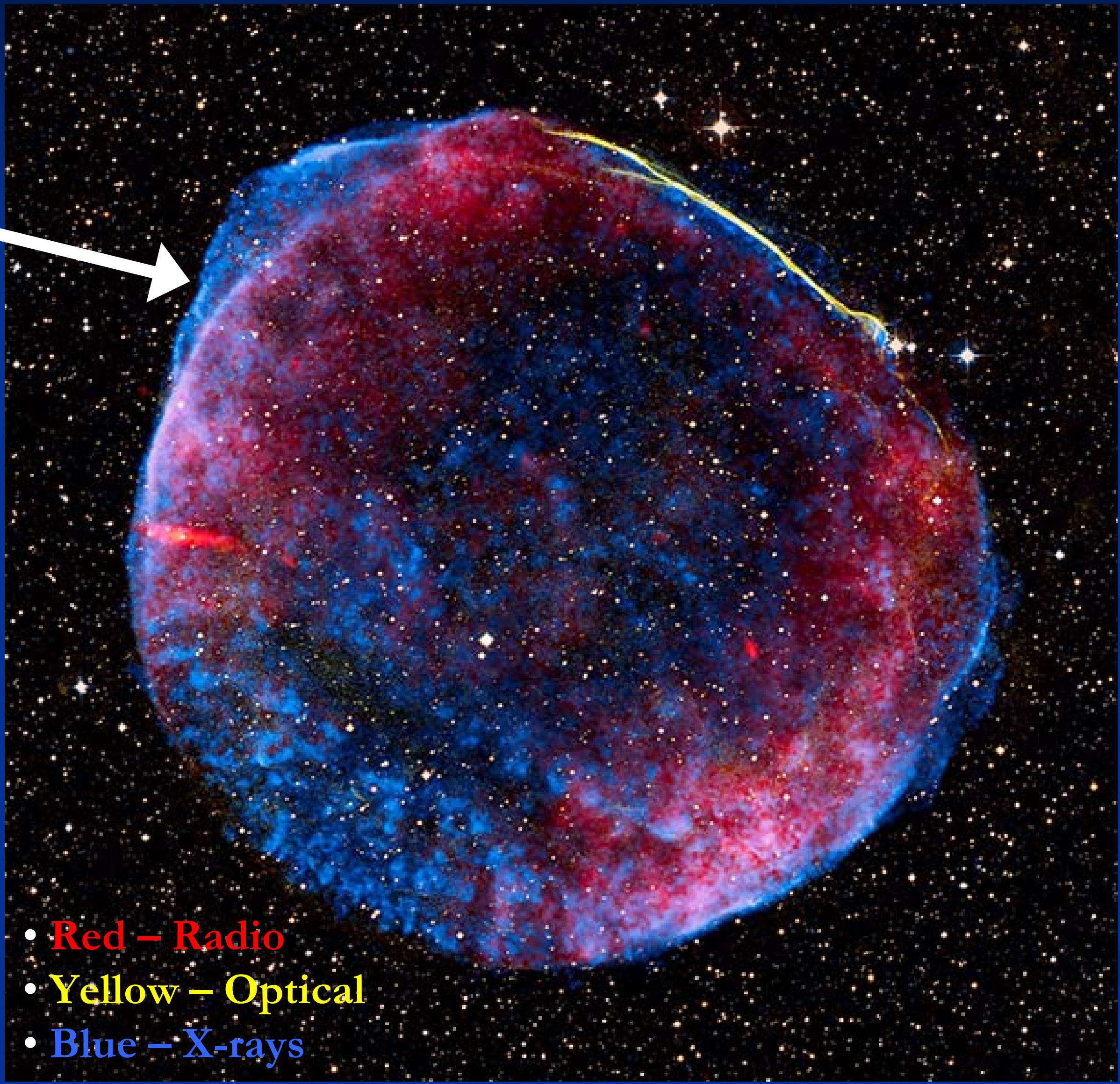


Interior: filled with hot gas - multimillion degrees

Exterior: low-density interstellar medium

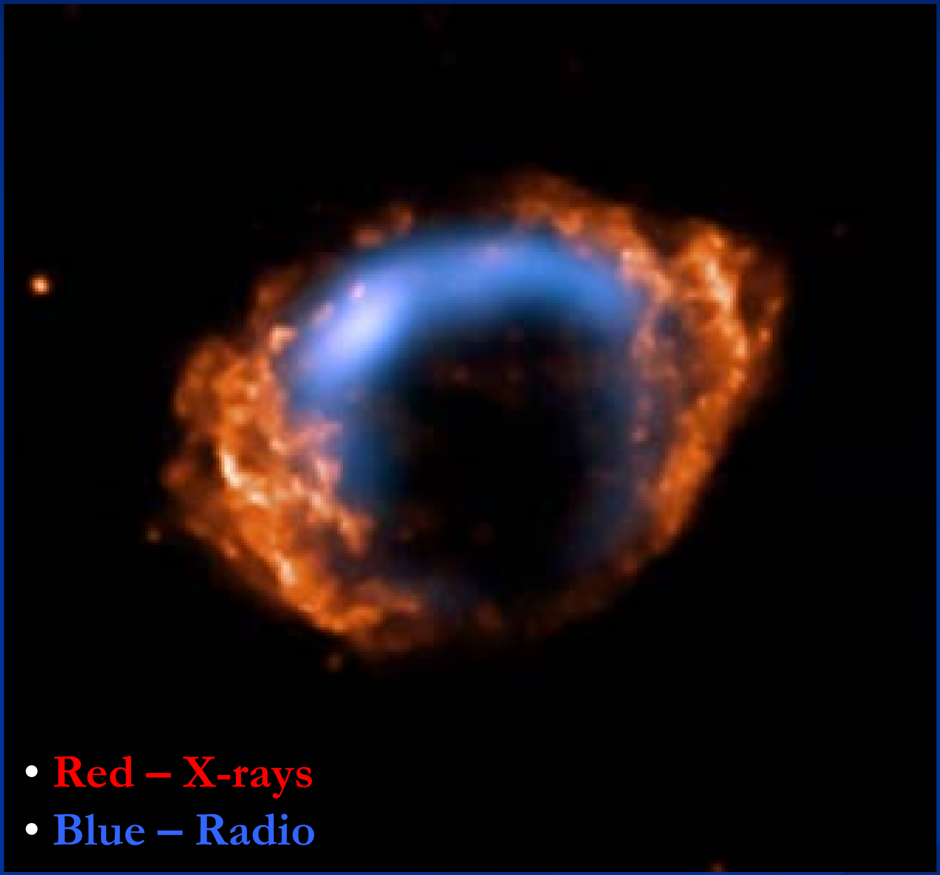
SN 1006 Composite Image

X-rays show thin, sharp filaments in contrast to “fuzzy” radio intensity – related to electron energy



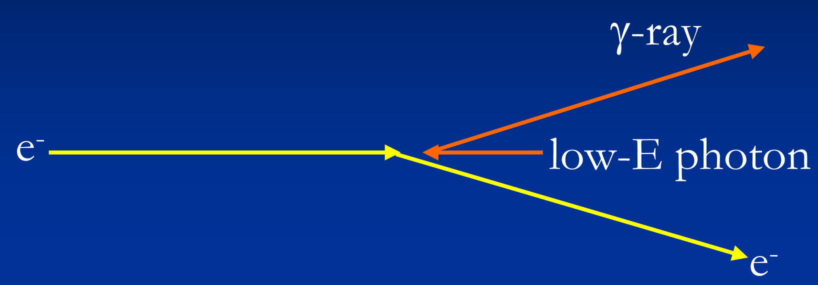
SNR G1.9+0.3: The Baby of the Galaxy

- Near the galactic center, ~ 28k light years away.
- Young! ~100-150 yrs old
- Dust and absorption made the SN itself undetectable
- Expanding at ~14 * 10^3 km/s – fastest known SNR
- Diameter ~ 7 light years
- Very bright synchrotron radiation – accelerating electrons
- No thermal bremsstrahlung observed yet
- No TeV gamma-ray signal seen (or expected yet)

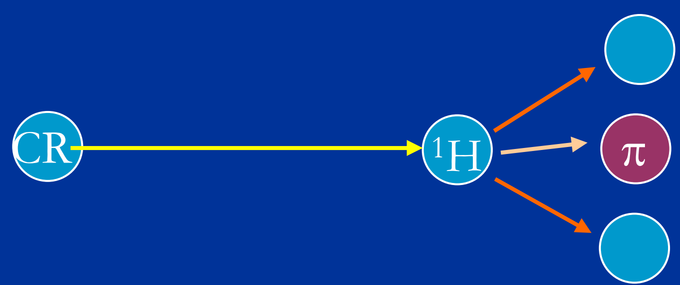


Very High Energy Radiations

- Inverse Compton Scattering: cosmic-ray electrons



- Pion production / decay: cosmic-ray nuclei



$$\pi^0 \rightarrow \gamma + \gamma$$
$$\pi^\pm \rightarrow \mu^\pm + \nu$$
$$\hookrightarrow e^\pm + \nu$$

* Gamma rays and neutrinos provide a smoking gun for acceleration of cosmic ray nuclei in SNRs!

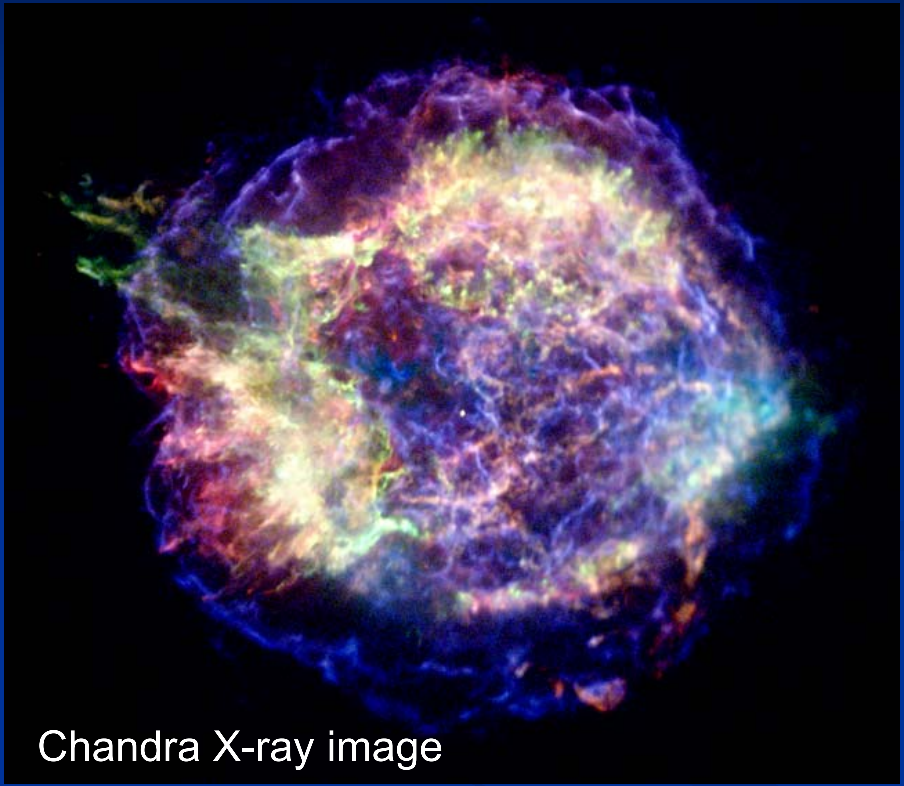
Caveats:

⇒ Gamma signal can be faked by cosmic-ray electrons

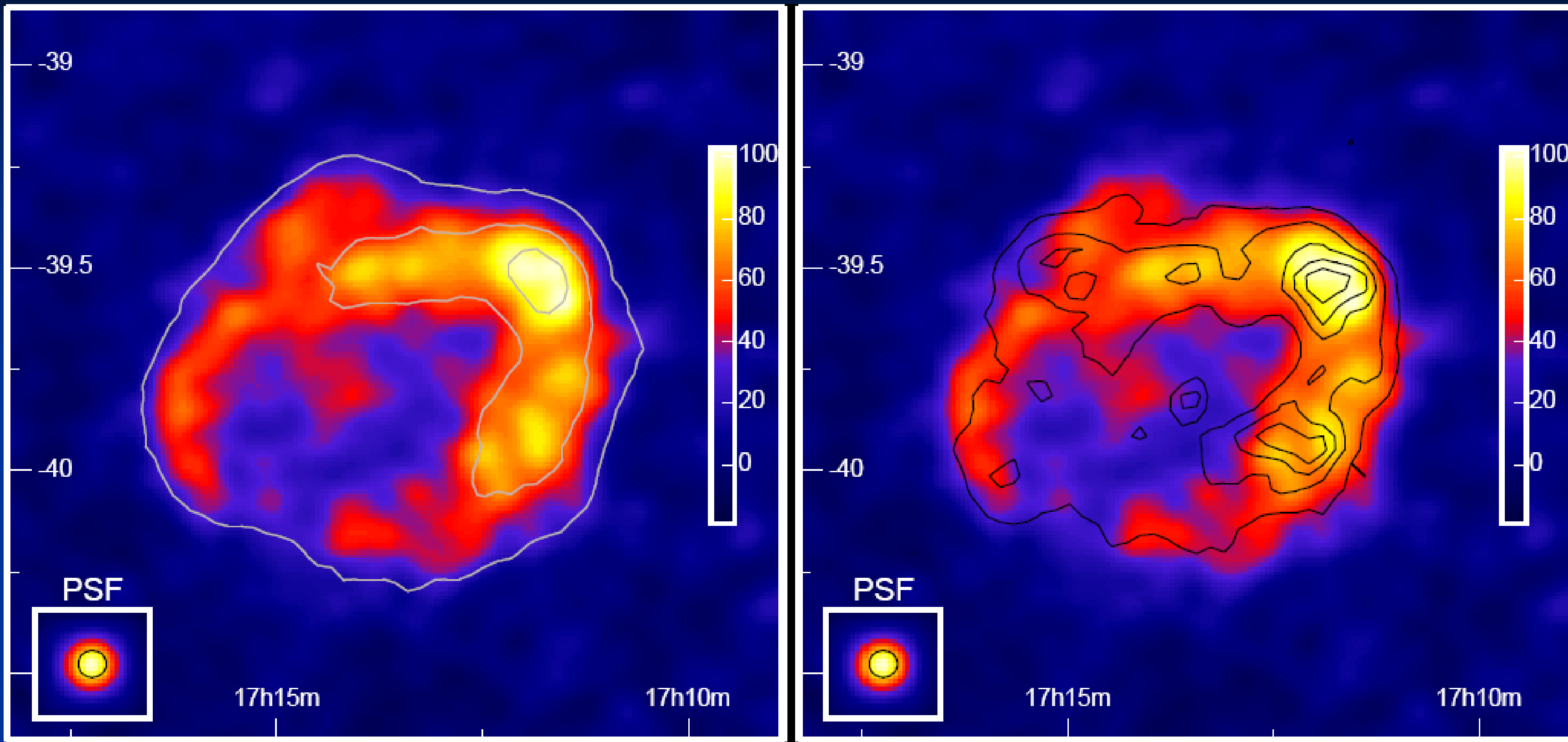
⇒ Neutrino signal not yet detected

Cas A and Cosmic Rays

- Cassiopeia A is a young SNR, ~ 320 yrs old
- First SNR detected in TeV gamma rays! By HEGRA in 2001
  - since detected by VERITAS and MAGIC as well
- Still not clear whether it accelerates nuclei or only electrons.

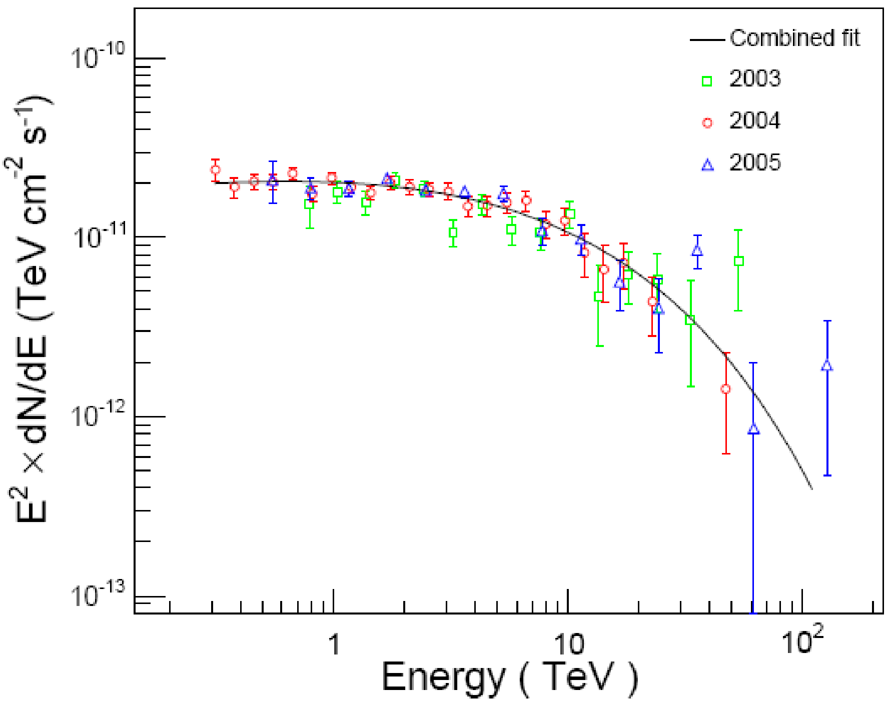


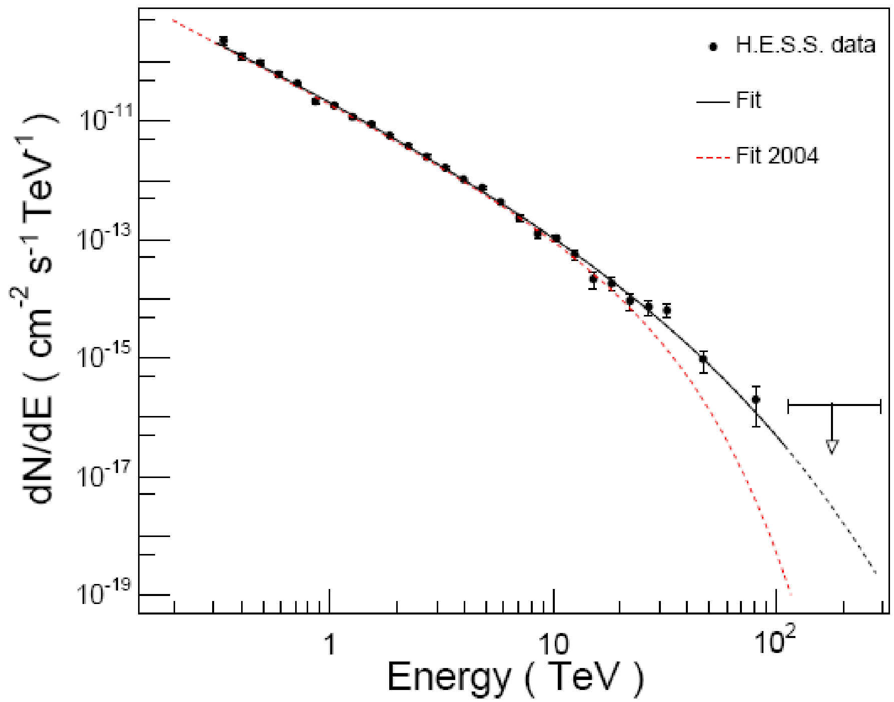
TeV Gamma Rays from SNRs: RX J1713



- ~ 1000-yr-old SNR about 3300 light years away
- 1° diameter
- Observed by the HESS gamma-ray observatory 2003-2005
- First time detailed images of an extended object made in TeV gamma rays! (several more since)

TeV Gamma Rays from SNRs: RX J1713





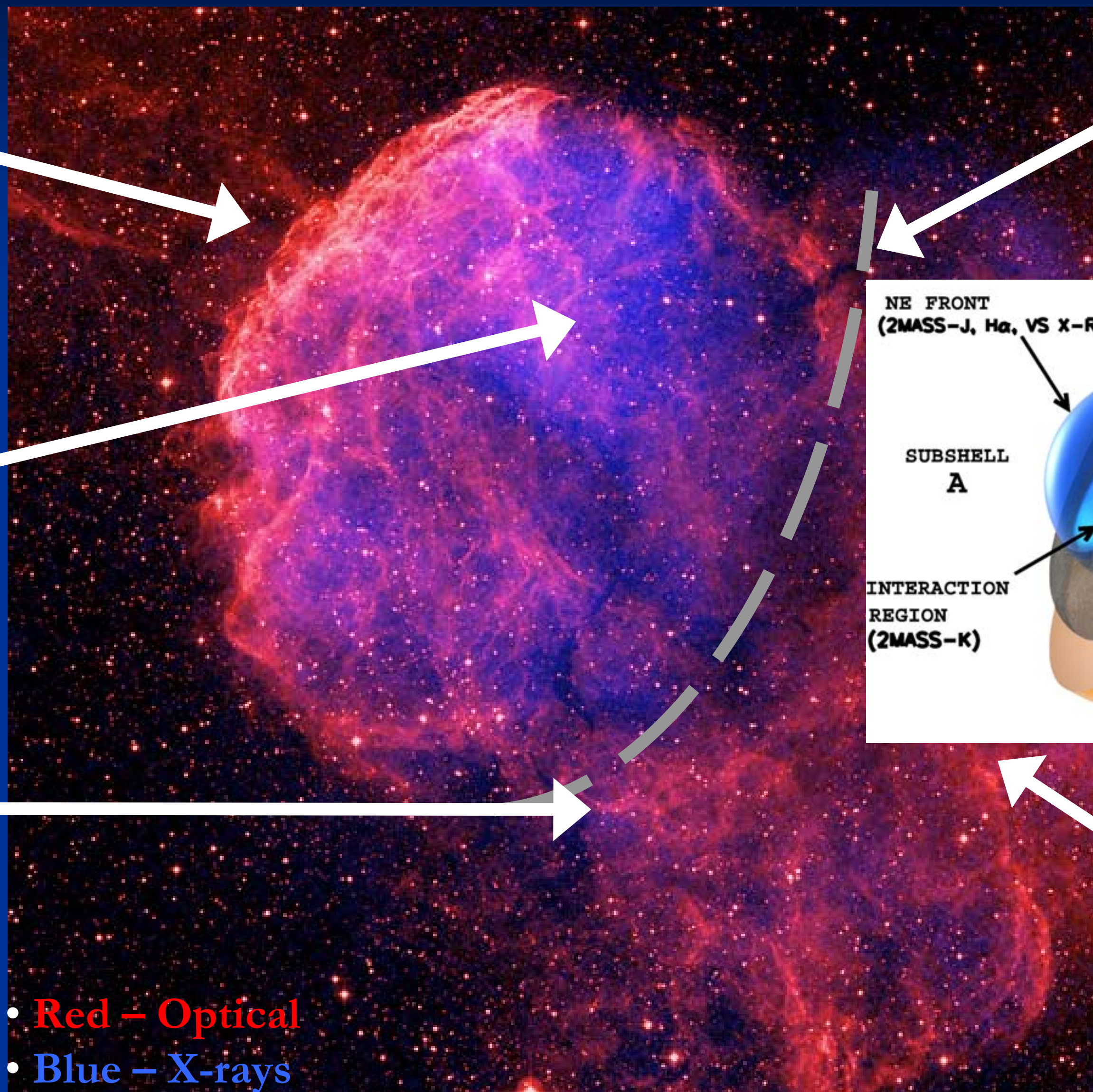
- Spectrum of TeV gamma rays produced by the cosmic rays in the SNR
- Follows power law up to few TeV, and then softens – reaching maximum energy of cosmic rays in RX J1713?
- Key question: are the cosmic rays electrons or protons?
  - Hard to answer conclusively! Need to extend spectrum to higher AND lower energies!

IC 443 – A "Snow Plow" Remnant

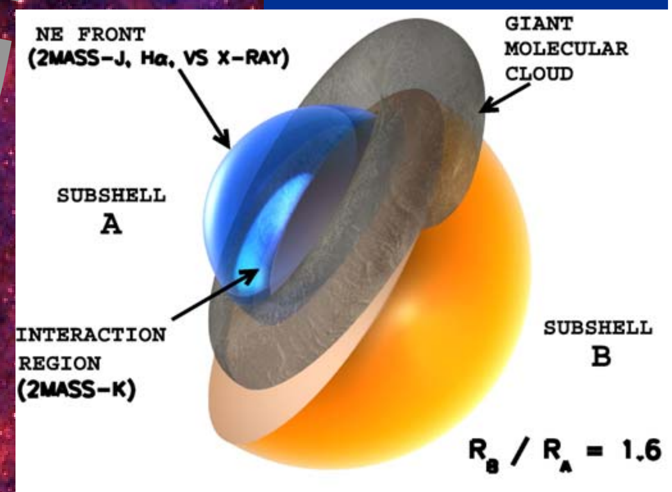
expanding shell impacting a cloud of atomic hydrogen

hot gas fills the interior

pulsar wind nebula



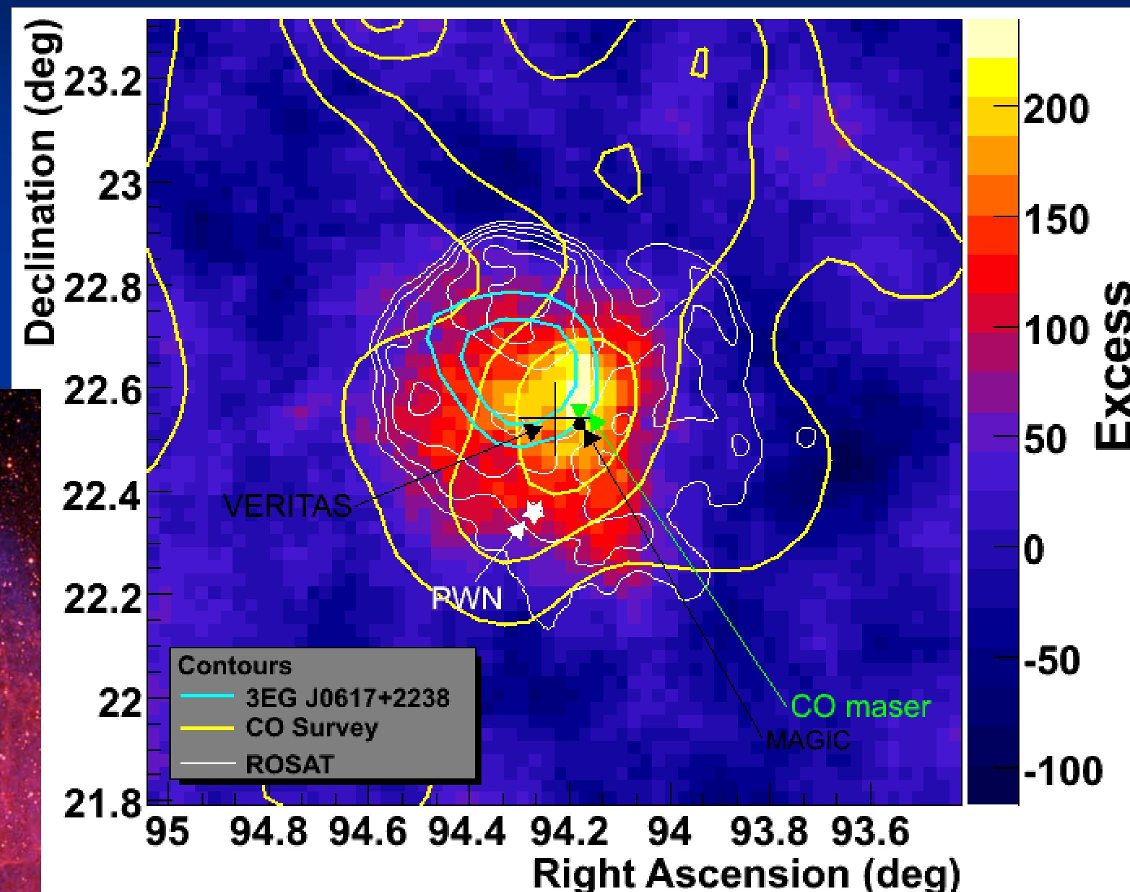
giant molecular cloud

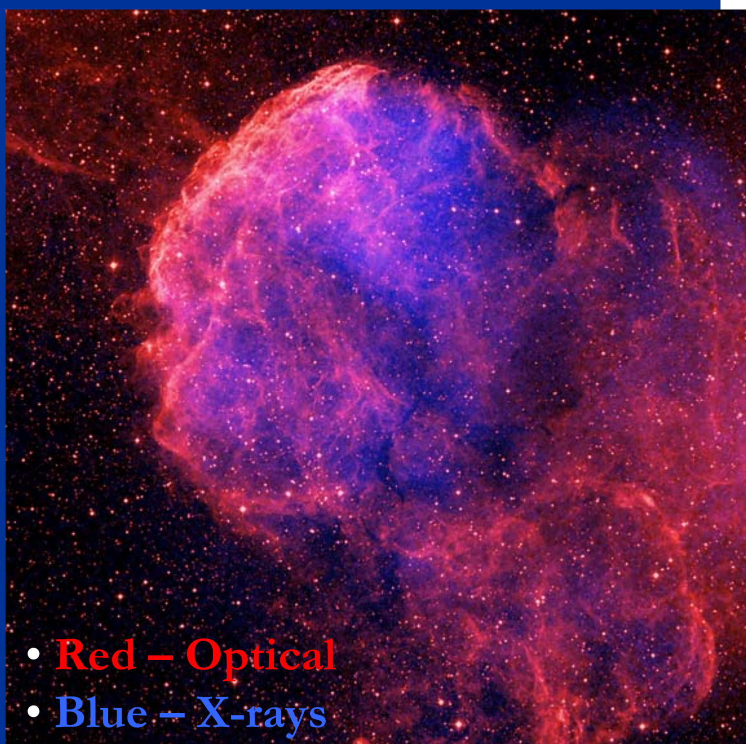


breakout into lower-density region

What Kinds of CRs does IC 443 Accelerate?

VERITAS TeV gamma-ray observations combined with multiwavelength observations:





Summary

- SNRs produce many kinds of thermal and nonthermal radiation
  - Each tells us something about conditions in progenitor, SN, or SNR
- Cosmic rays bombard the earth all the time, and carry a significant fraction of the energy budget of the galaxy
- SNRs long thought to be the source of cosmic rays but definitive proof is still lacking
- Shock acceleration seems the likely mechanism, but…
  - Max energy?
  - Unambiguous proof of nuclear cosmic ray acceleration?
- SNRs inject a large quantity of power (kinetic energy, cosmic rays, heat) into the Interstellar Medium, with strong impacts on the local environment and the galaxy – Next Week!