Recent results on particle acceleration
Part II

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Introduction

We apply our insights to Supernova remnants

We discuss their structure and properties

We perform radiation modeling

Question

Where can we best study particle acceleration?

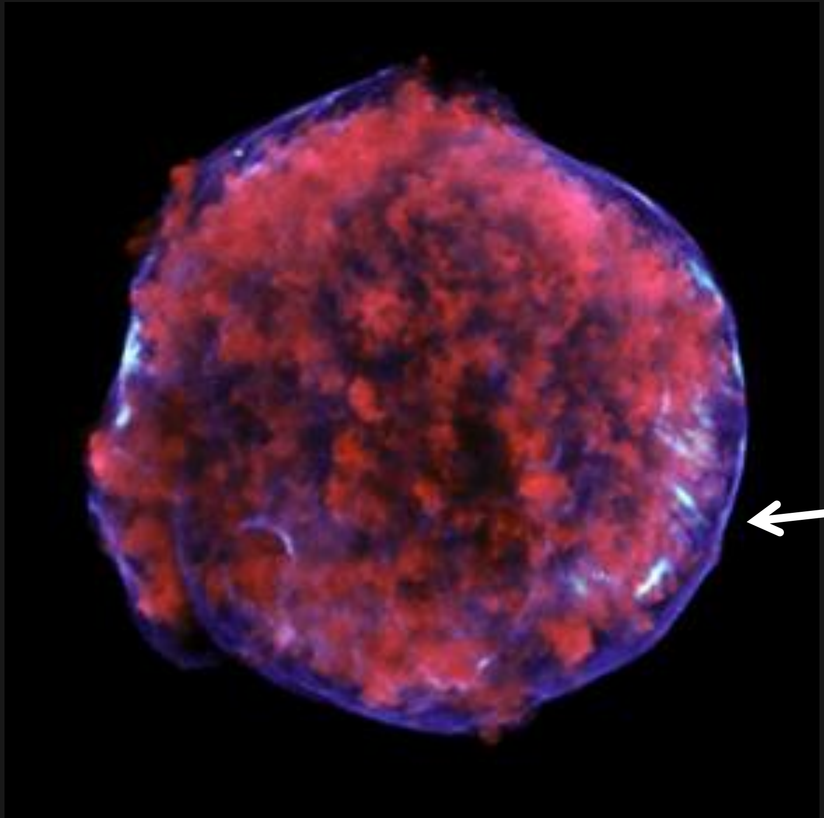
Persistence
Resolvability
Brightness

➔ **Supernova remnants**

Supernova remnants

Tycho‘s SNR in X rays

Red: Hot gas



Narrow filaments

Blue: Synchrotron

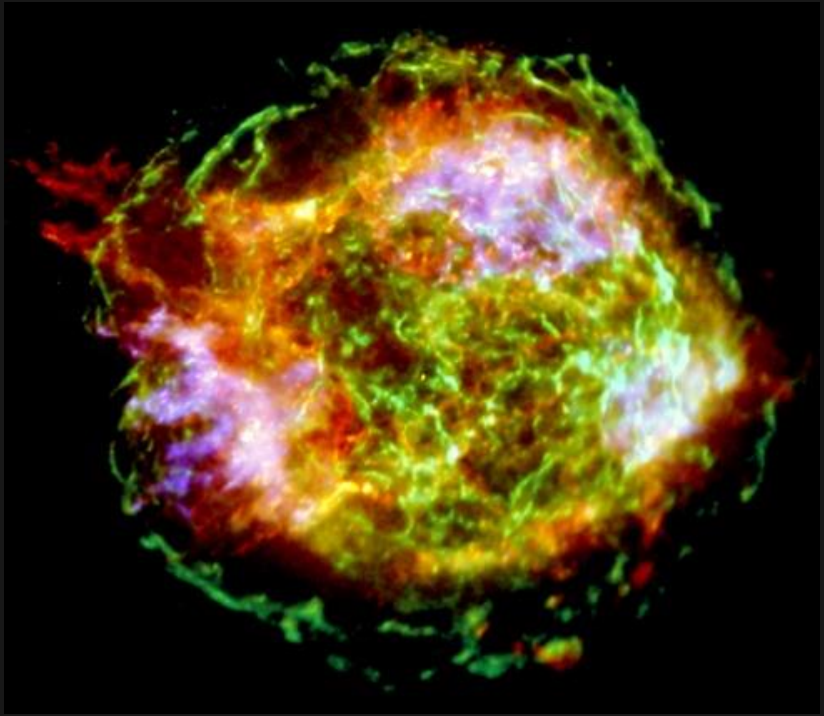
Supernova remnants

Cassiopeia A

SN observed in 17th century

Advantages of SNRs

Persistence
Resolvable in nearly all wavebands



Standard process

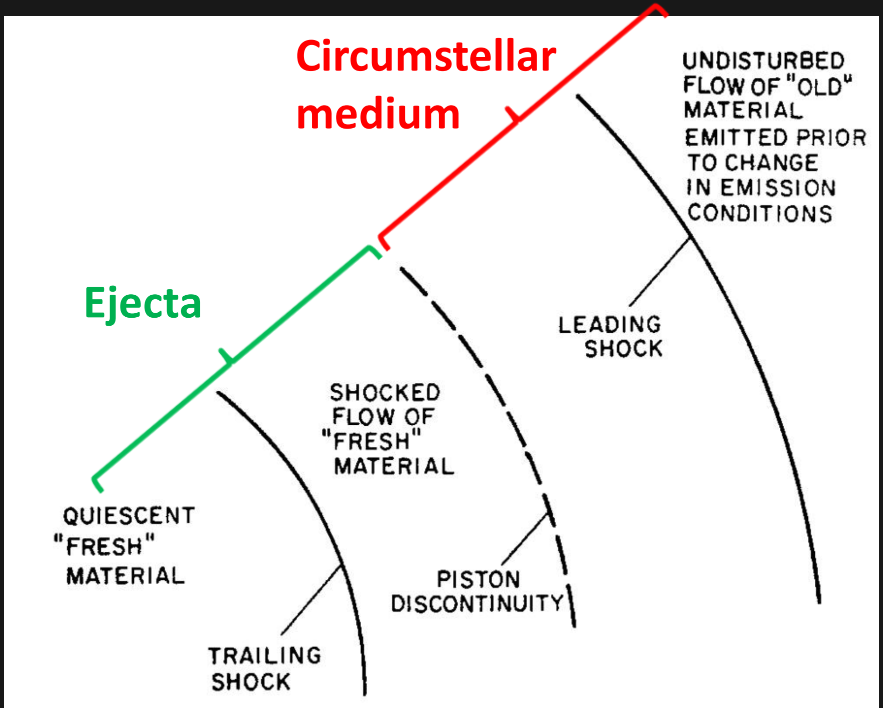
What are supernova remnants?

A blast wave driven by a stellar explosion

Inside: stellar ejecta

Outside: interstellar gas

Shock speed ~4000 km/s



Supernovae

There are two types of supernovae,
type Ia (white dwarf collapse) and core collapse (death of massive star)

and hence two types of remnants

- Type Ia: Outflow into interstellar medium, no central object
- All other types: Outflow into wind bubble, possibly central pulsar

Simplified flow model

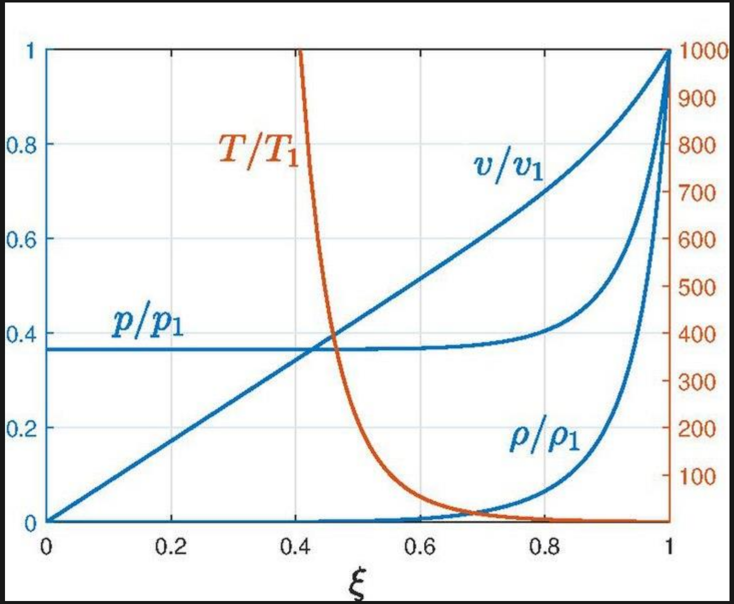
Type Ia: Outflow decelerates and turns into Sedov solution

Reverse shock disappeared

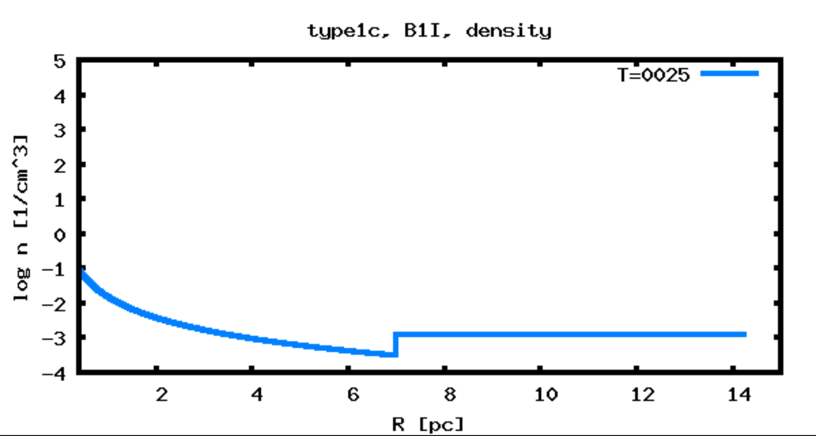
Accumulated mass large

$R_s \sim t^{0.4}$

$v_s \sim t^{-0.6}$



Simplified flow model

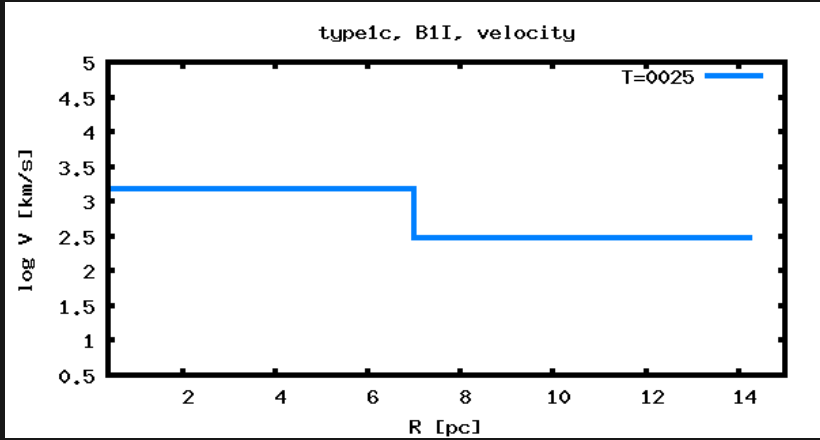


Shock development
can be complicated,
even under spherical symmetry …

Typ Ic: Wolf-Rayet progenitor

Core-collapse and wind bubble

No Sedov transition visible



Supernova remnants

Expect shock acceleration of cosmic rays

- Spatial transport is advective and diffusive
- Rate of acceleration depends on turbulence spectrum
- Efficient acceleration should modify shock … not observed as expected

Supernova remnants

1. Flow profiles from hydrodynamical simulations

2. Calculate particle transport on flow profiles

$$\frac{\partial N}{\partial t} = \nabla(D\nabla N - \vec{v}N) - \frac{\partial}{\partial p}\left((N\dot{p}) - \frac{\nabla\vec{v}}{3}Np\right) + Q$$

Acceleration

3. Consider transport of magnetic field

Advantages:

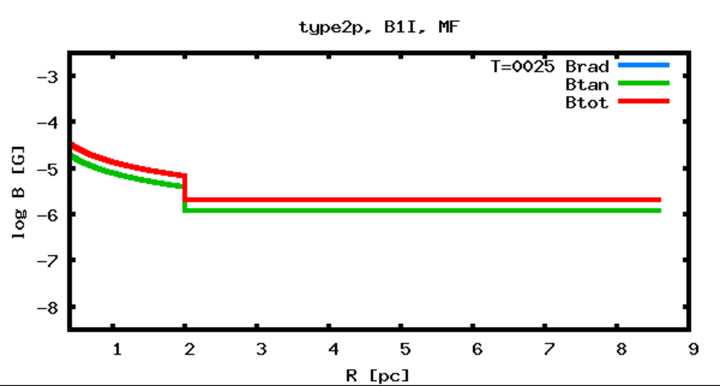
- Accurate treatment of acceleration and transport
- Self-consistent treatment of escape possible

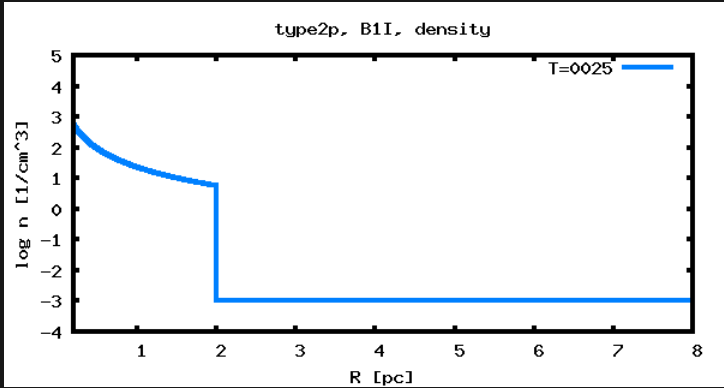
Magnetic-field profile

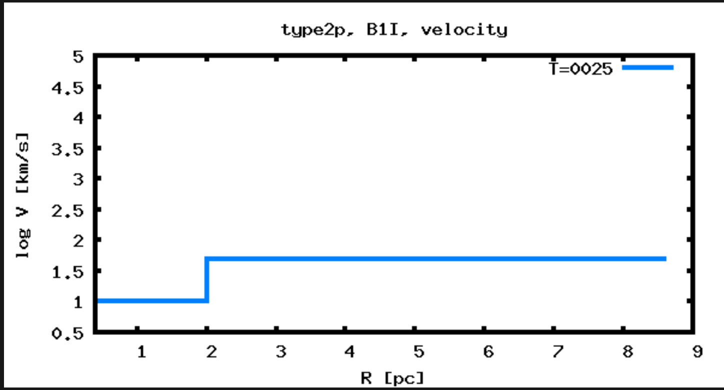
Dynamically unimportant

Induction equation $$\frac{\partial \vec{B}}{\partial t} = \vec{\nabla} x (\vec{v} x \vec{B})$$

Here for Type 2p (RSG progenitor)







Radiation modeling

One zone modeling is insufficient

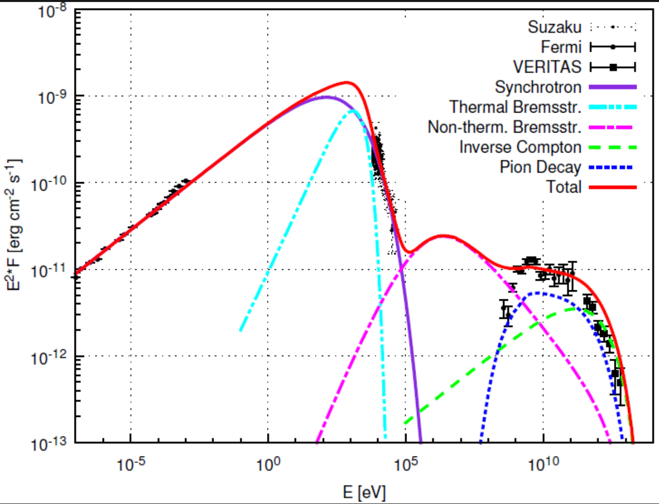
All parameters depend on location and time

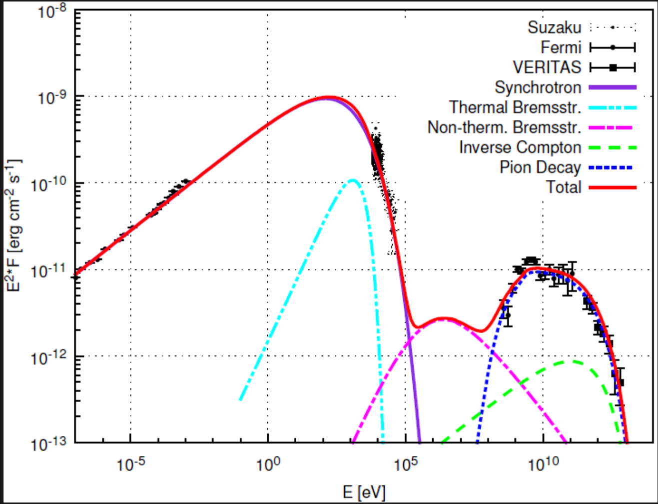
That includes the particle spectra

We do know the radiation processes

Radiation modeling

Weaker magnetic field | **Cas A** | **Stronger magnetic field**





Electrons: magenta and green **Hadrons: blue**

Relative role depends on magnetic-field strength

Radiation modeling

Despite the limitations on the one-zone models, we can say some things

1) There is no evidence for strong cosmic-ray modification of shocks

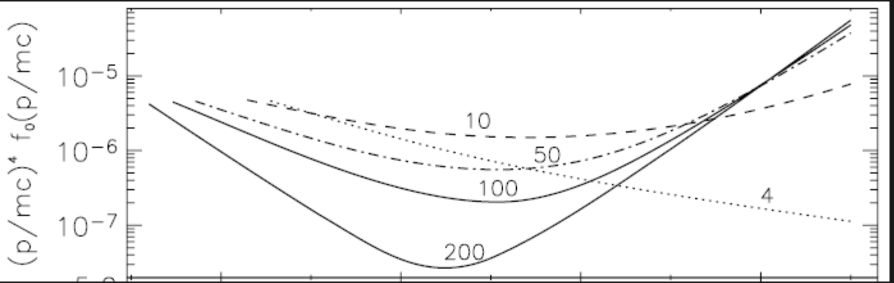
Cosmic-ray feedback

Hard spectra expected in the TeV band

… not really seen, spectra tend to be soft

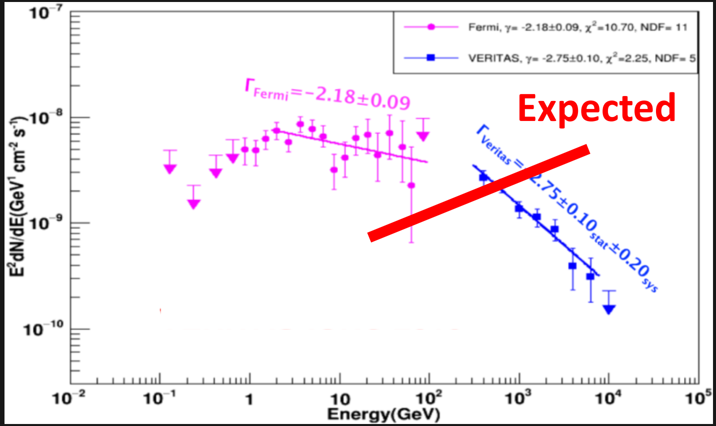
Cosmic-ray spectra

From a paper published in 2006



Energy in TeV 0.1 1 10

Gamma-ray spectra



Radiation modeling

Despite the limitations on the one-zone models, we can say some things

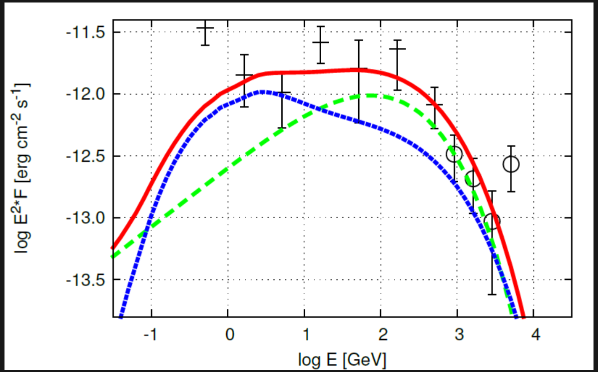
1) There is no evidence for strong cosmic-ray modification of shocks

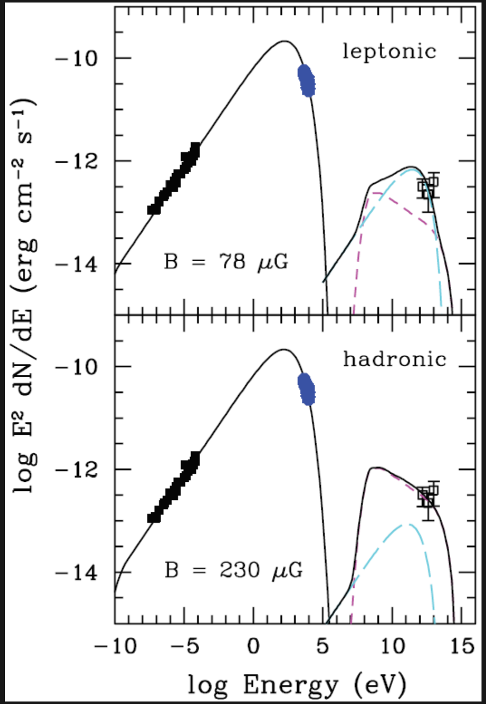
2) The mean magnetic field is much stronger than by compression alone

Radiation modeling

Tycho's SN remnant:
Model-independent estimate of average magnetic field

With damping B>170 μG





Magnetic field must be amplified!

Radiation modeling

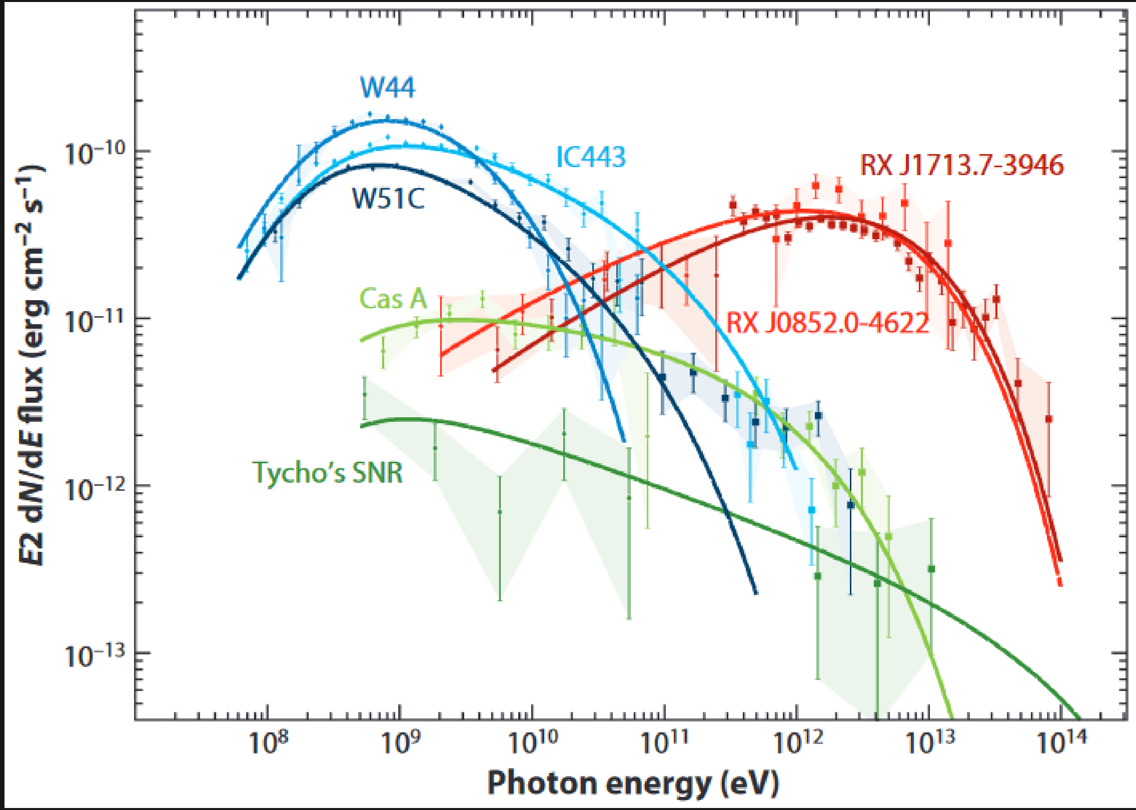
Despite the limitations on the one-zone models, we can say some things

1) There is no evidence for strong cosmic-ray modification of shocks

2) The mean magnetic field is much stronger than by compression alone

3) The total cosmic-ray spectra are soft and do not extend to a PeV

Radiation modeling



Magnetic-field strength

Can we measure where magnetic field is amplified?

What is its amplitude?

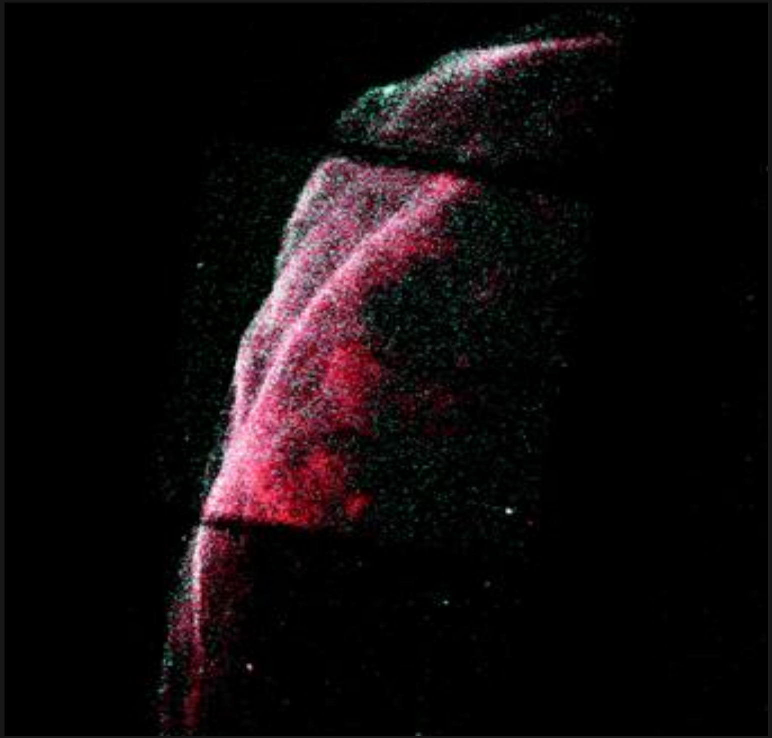
Magnetic-field strength

Observation:

Nonthermal X-rays in filaments

Requires strong magnetic field

Magnetic turbulence related to particle acceleration?



SN 1006

Magnetic-field strength

X-ray filaments involve strong magnetic field

Origin unknown — Shock? Energetic particles? → should be turbulent

Fate unknown — If persisting, magnetic field must be very strong

Turbulent field should cascade away …

Not seen in radio polarimetry…

How strong and where is it?

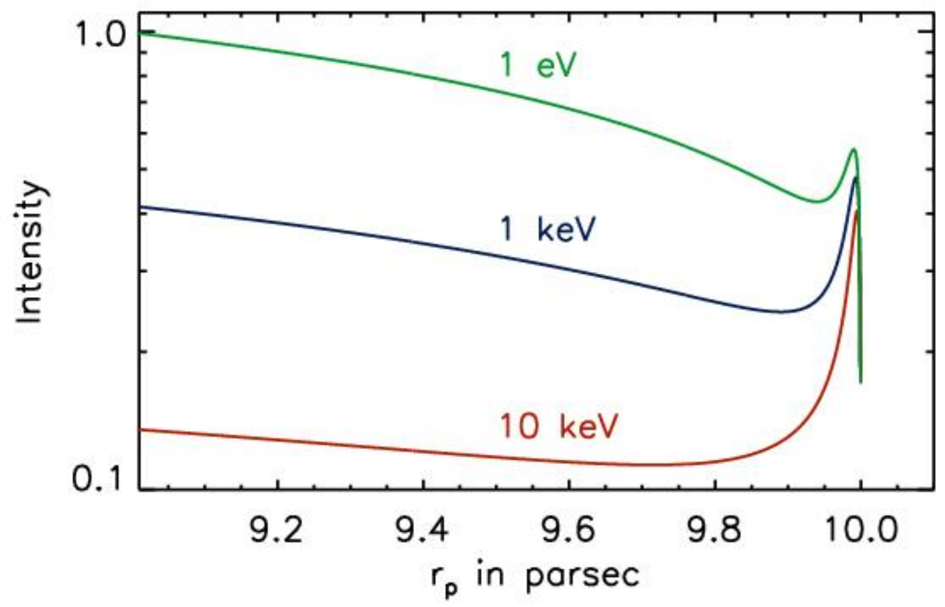
Magnetic-field strength

A) Filaments are loss limited ➔ gives magnetic field strength

B) Filaments are magnetic structures

Caused by damping of turbulence!

δB not determined



Magnetic-field strength

Clues from X-ray variability?

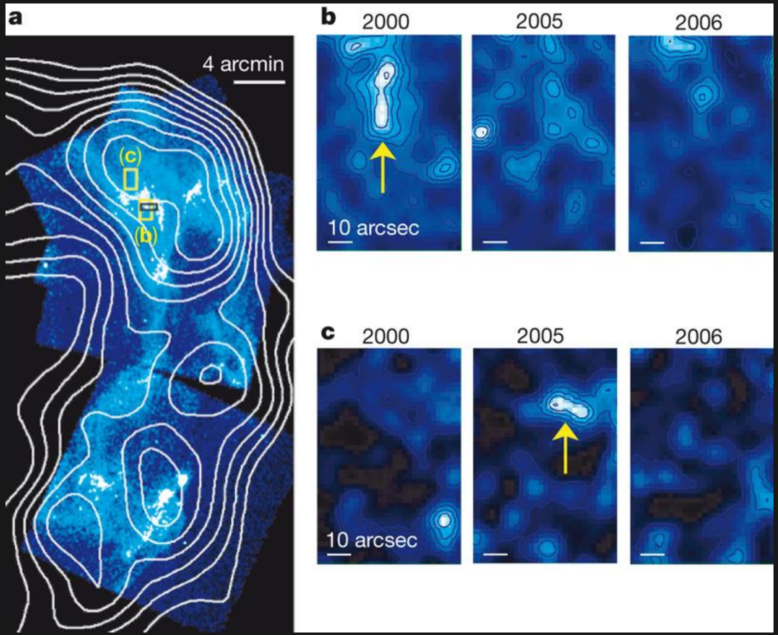
Energy losses require a few milliGauss!

BUT:

Damping gives same timescale

Short-lived spikes in turbulent field

May give too many secondary electrons



Summary Part II

Supernova remnants have given many important insights

- the type and internal structure matters
- No evidence for cosmic ray feedback
- No evidence for acceleration up to PeV scale
- Magnetic field amplification, but where and how strong?