Particle acceleration
Theory and astrophysical observations

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- Introduction on galactic cosmic rays and supernova remnants
- Diffusive shock acceleration: nonlinear physicsfrom theory to observations
- Conclusions

Introduction: origin of cosmic rays

Energy

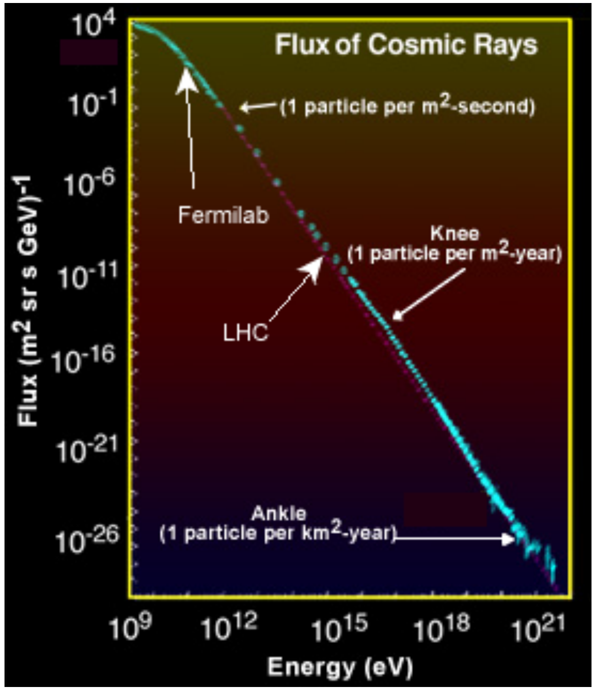
- What powers the accelerator and how does it work?
- Why its spectrum is very close to a power law over so many decades in particle energy ?

Acceleration process

- Over what energy range does the accelerator work?
- What spectral form does it produce?
- Can one mechanism explain all the data ?

Origin of the accelerated particles ?

- How much of the observed cosmic ray spectrum is of Galactic origin?
- Out of what component of the Galaxy does the accelerator select particles to turn into cosmic rays?
- How many different types of accelerator are required?



See, e.g. Drury et al. 2001, Blasi 2013

Introduction: origin of galactic cosmic rays

Source of energy for the bulk of galactic cosmic rays

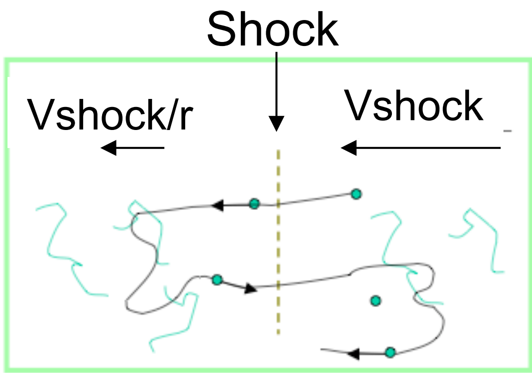
- Supernova explosions: 10% of their kinetic energy can maintain the population of Galactic Cosmic rays up to the knee at ~3 10^{15} eV

  (Baade & Zwicky 1934, …)

Acceleration process

Charged particles can be energetized at high Mach number shocks in supernova remnants (SNRs) **through diffusive shock acceleration**

(Krymskii, 1977; Blandford and Ostriker, 1978; Axford et al, 1977; Bell, 1978a,b; Blandford & Eichler 1987)



First order Fermi acceleration

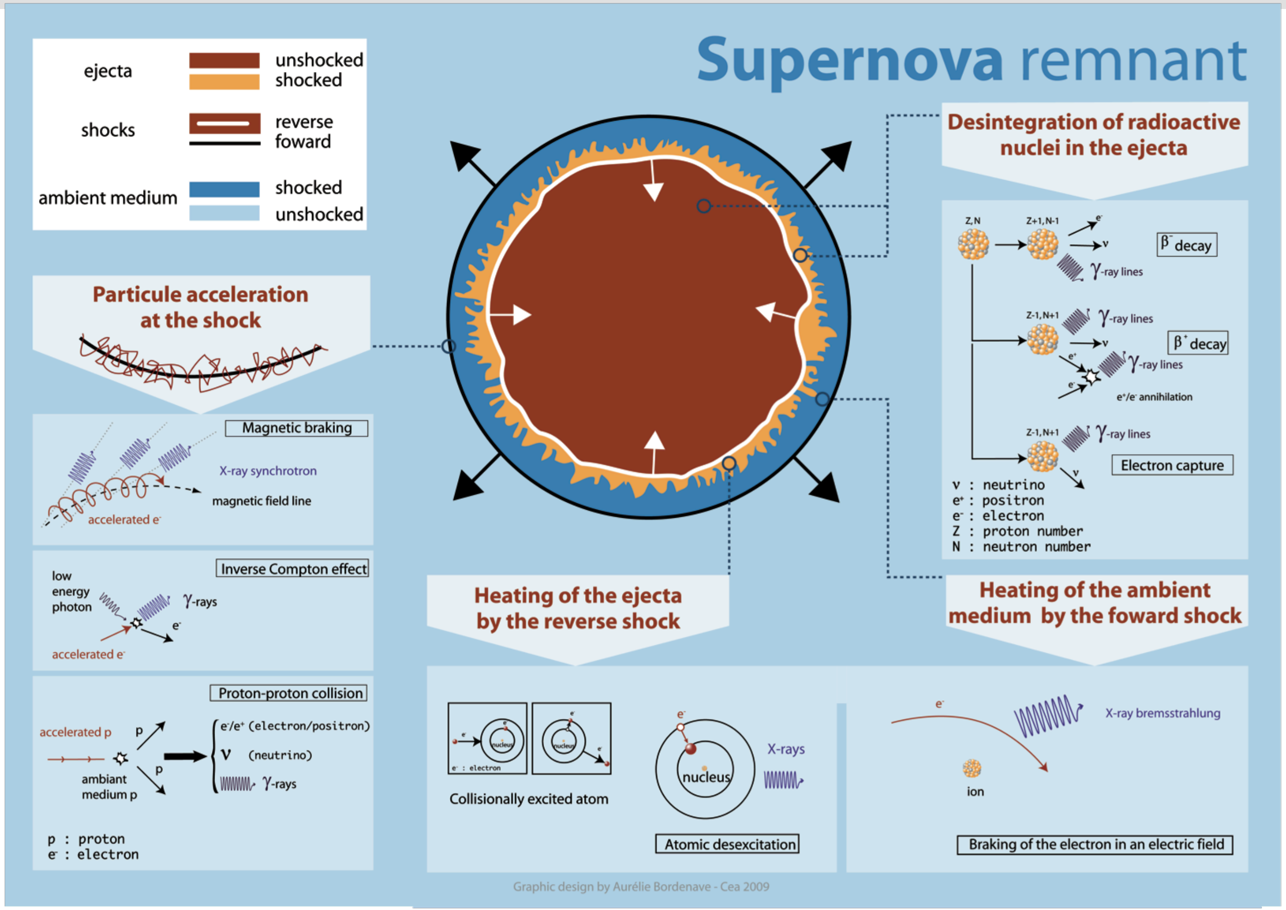
Spectrum of accelerated particles: power law in momentum with a slope α that only depends on the shock compression ratio *r*

$$\alpha = 3r/(r-1)$$

Maximum energy achieved in a SNR shock expanding in the ISM

- finite time of acceleration: age of the remnant
- existence of a spatial boundary (leak out of the particle from the system)

Shock structure in a young supernova remnant: Origin of the accelerated particles ?



Nonthermal emission from radio to very high energy gamma-ray emission

VLA,..

Chandra, XMM-Newton

Fermi, HESS

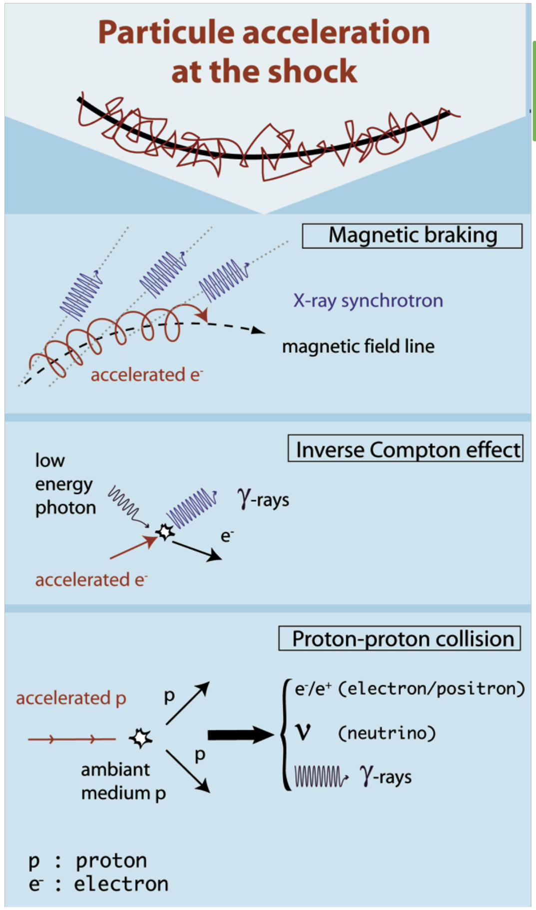
Gamma-ray nuclear emission lines

Integral, Nustar

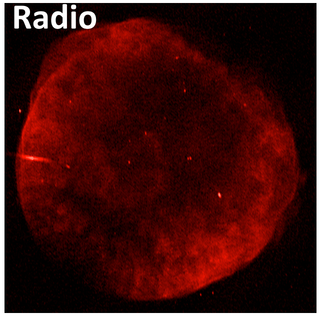
X-ray bremsstrahlung and emission lines

XMM-Newton, Chandra, …

Nonthermal emission of supernova remnants

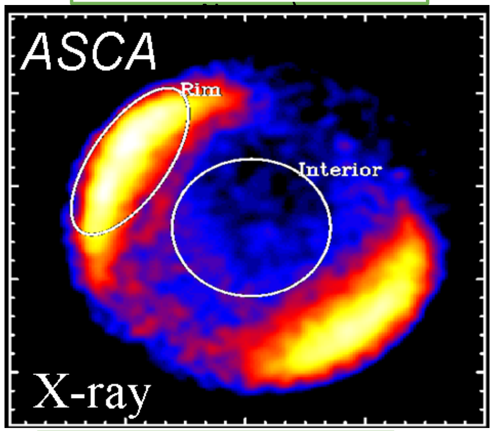


1952 : radio synchrotron emission (Tycho's SNR)



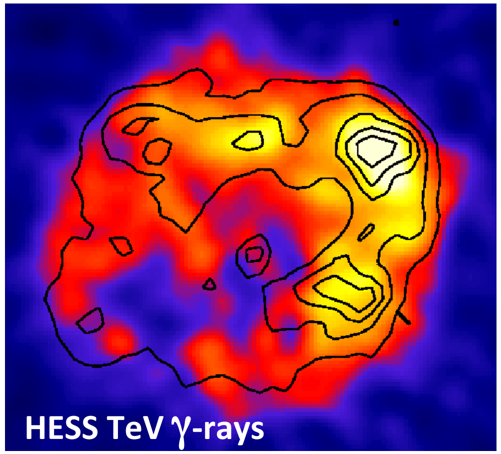
=> GeV electrons

1995 : X-ray synchrotron emission in SN 1006 (Koyama et al.



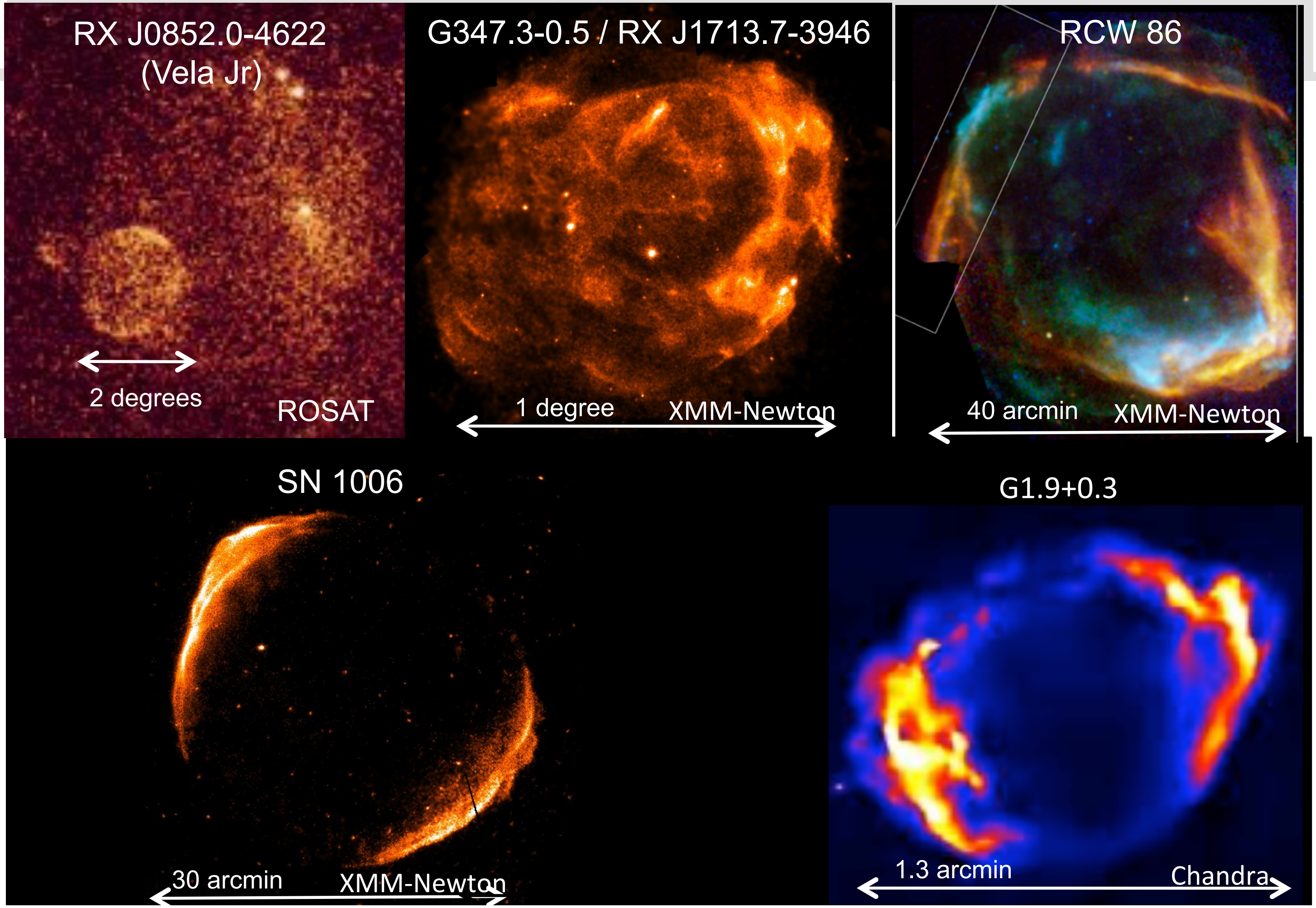
=> TeV electrons

2000-2004: gamma-ray emission in RXJ17-13 (Muraishi et al., Enomoto et al., Cangaroo; Aharonian et al., Nature)



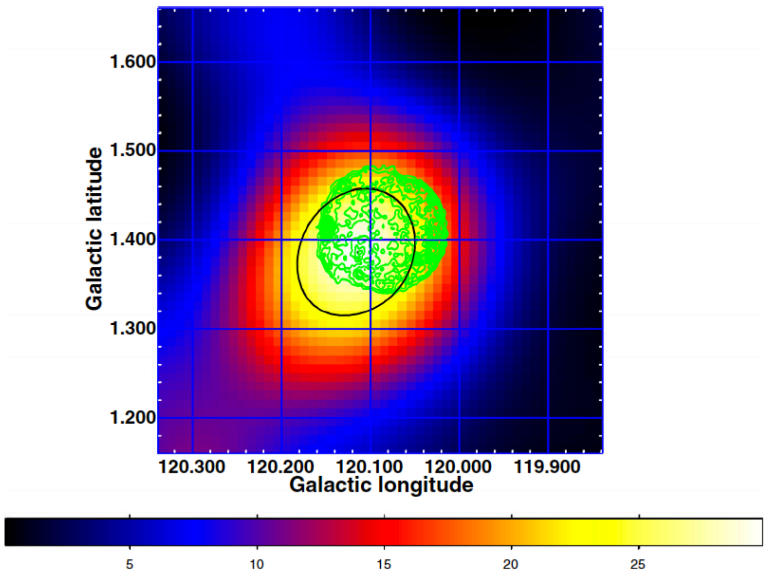
=> TeV particles (electrons ? Protons ?)

Nonthermal X-rays in synchrotron-dominated supernova remnants



Direct signature from TeV energies

Unique domain where the emission can be dominated by the hadrons



Tycho SNR
FERMI LAT + XMM X-ray contours
(Giordano et al. 2012)

- **TeV Gamma-ray emission from Tycho's SNR**, mostly of hadronic origin

(e.g.,Morlino & Caprioli 2012 ; Atoyan & Dermer 2012 ; Berezhko et al. 2013 ; Zhang et al. 2013; Slane et al. 2014)

- **Hadronic TeV emission detected in a number of older SNRs interacting with molecular clouds**

(e.g., Giordano et al. 2012, Acciari et al. 2011, Katagiri et al. 2016,..)

Non linear diffusive shock acceleration

If efficient ion diffusive shock acceleration =>
non linear theory of diffusive shock acceleration

(eg, Malkov and Drury 2001, Drury 1983, Blasi 2013)

Dynamical reaction of accelerated particle

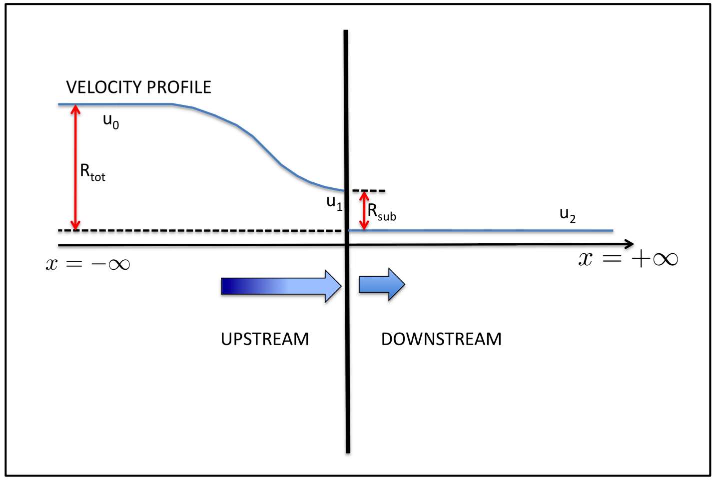
Pressure exerted by accelerated particles on the plasma at the shock modifies the shock dynamics and acceleration process

Magnetic field amplification

Accelerated particles induce plasma instabilities and magnetic amplification at the shock

Dynamical reaction of the amplified magnetic field

The amplified magnetic field affects the compression ratio at the shock, then the spectrum and level of magnetic amplification



From Blasi 2013

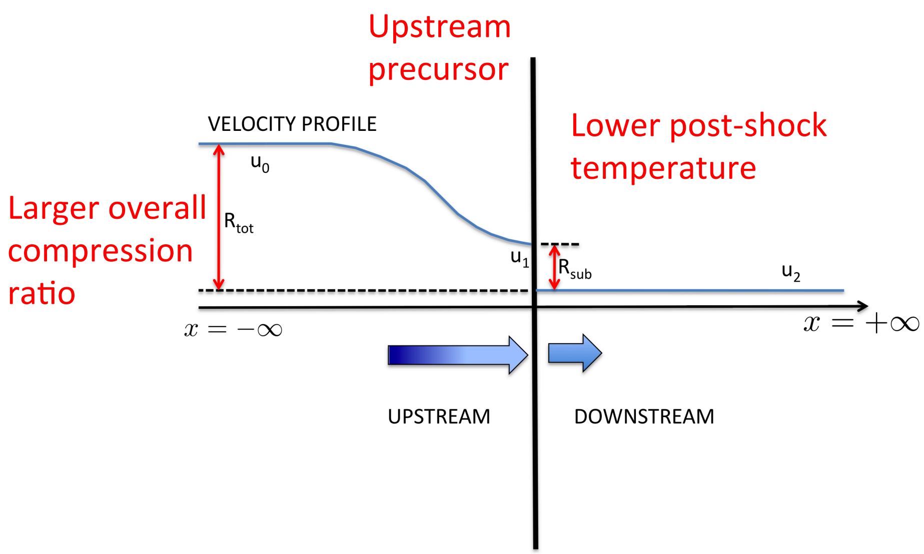
What is the efficiency of particle acceleration ? What is the level of magnetic field amplification at the shock ? What is the maximum energy of the accelerated particles ?

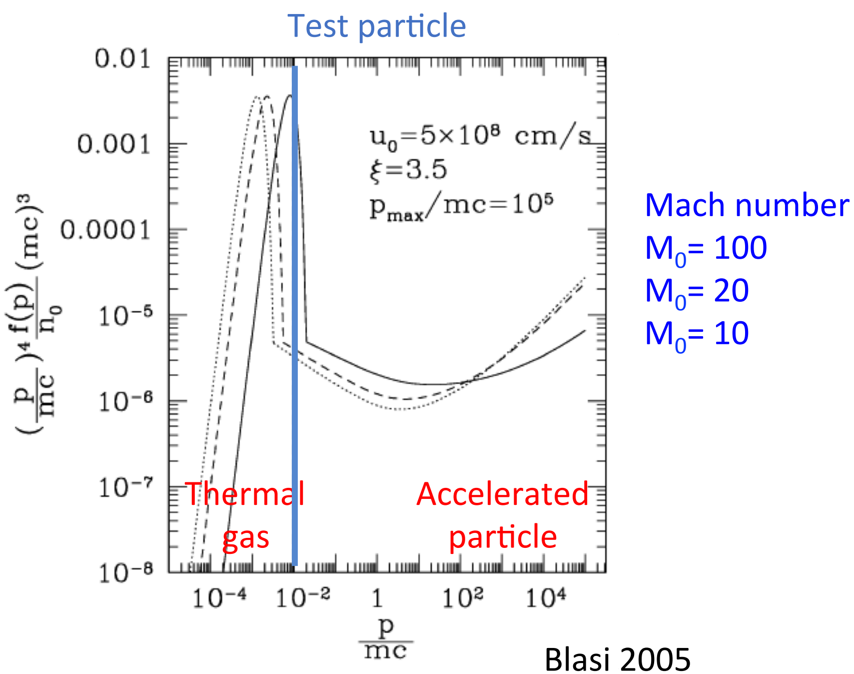
NL DSA
A. Dynamical reaction of accelerated particles

Modification of the shock structure by efficient ion acceleration => modification of the spectrum

1. Curvature of the particle spectra instead of a perfect power law

(Ellison & Reynolds 91, Berezhko et al. 1994; Berezhko & Völk 1997; Berezhko & Ellison 1999; Malkov 1999; Blasi 2002).



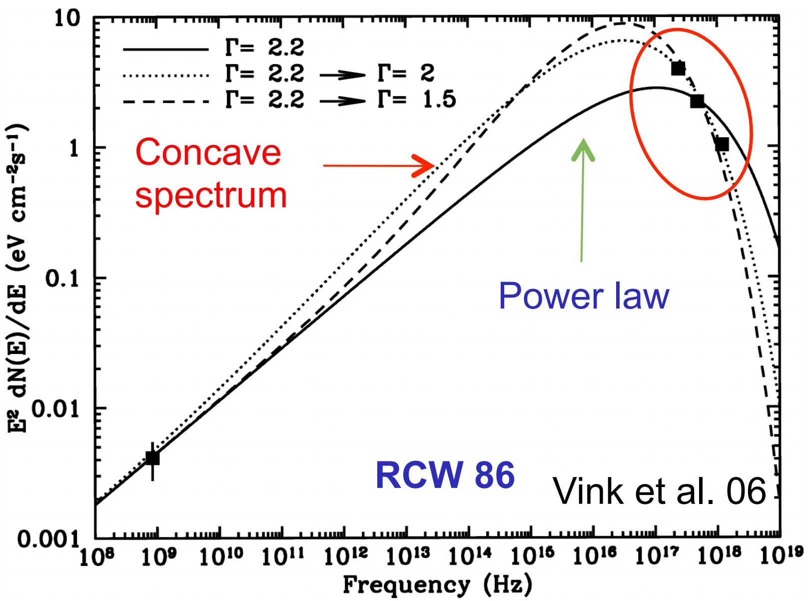


Blasi 2005

NL DSA

A. Dynamical reaction of accelerated particles

Observational indications of the curvature of the electron spectrum in a few SNRs



For example,

SN 1006: combining radio and X-ray data (Allen et al. 08)

RCW 86: combining radio and X-ray data (Vink et al. 06)

Cas A: from infrared data (Jones et al. 03)

Tycho and Kepler: from radio data (Reynolds & Ellison 92)

NL DSA
A. Dynamical reaction of accelerated particles

Modification of the shock structure by efficient ion acceleration =>

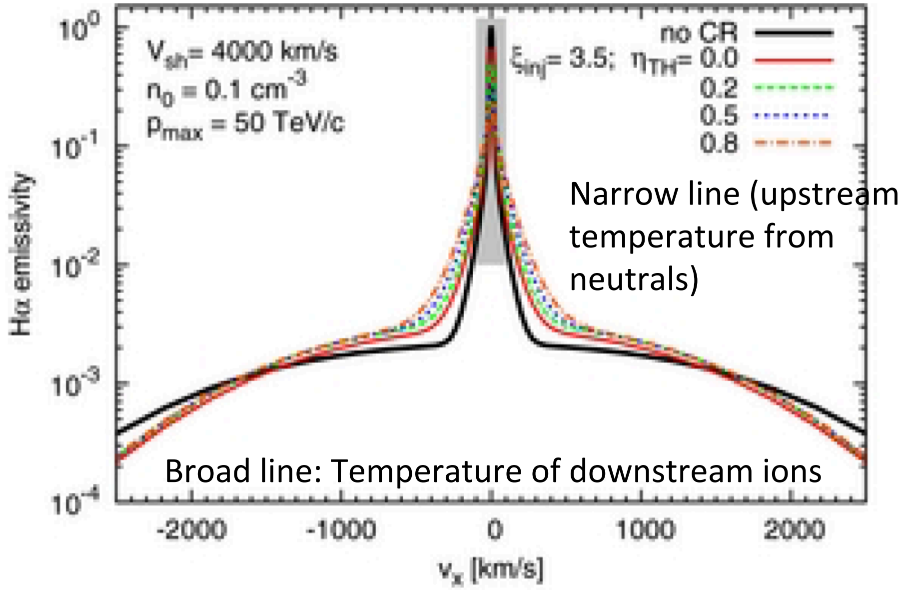
2. Larger compression ratio and lower post-shock temperature than in the test particle case

Difficult measurements due to shock velocity determination

- **RCW 86**: post-shock proton temperature from Hα broad line and shock velocity from X-ray proper motion (Helder et al. 09) indicating efficient particle acceleration => revised (Helder et al. 13)
- **1E0102**: post-shock electron temperature from X-rays and shock velocity from X-ray proper motion (Hughes et al. 00) => revised (Xi et al. 2019)

- **Possible use of Balmer-dominated Hα lines** (Knežević et al. 2017) => CR precursor in Tycho

Shape of the Balmer line emission
Modification with acceleration



Morlino et al. 2013

NL DSA
A. Dynamical reaction of accelerated particles

If efficient ion acceleration =>

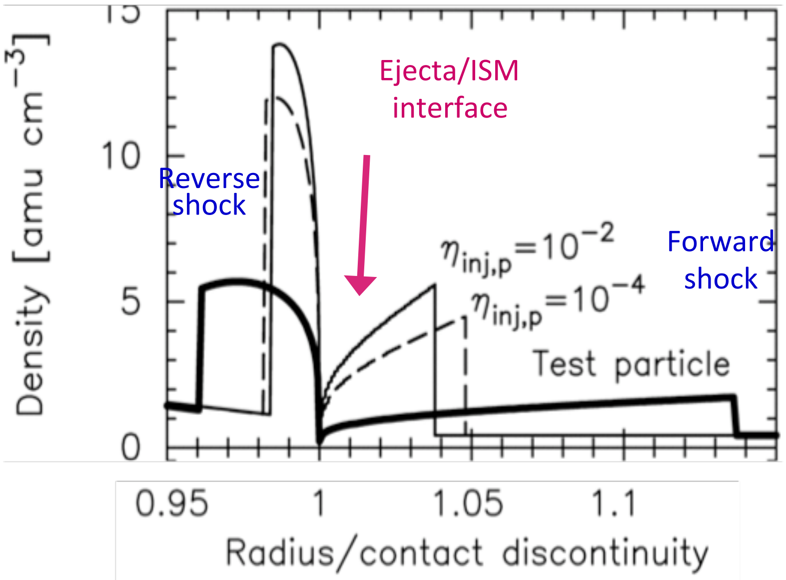
3. Shrinking of the shocked region compared to test particle case

(Chevalier 1983, Decourchelle et al. 2000)

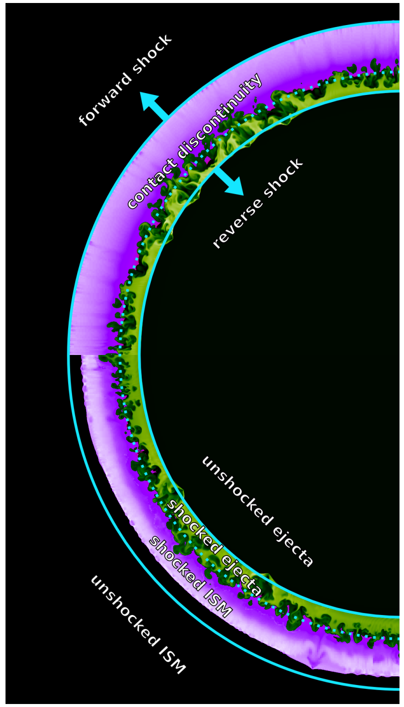
larger ion injection ($n_{inj,p}$)

=> larger compression ratio (> 4 at the shock)

=> larger backreaction on the hydrodynamics structure



1D SNR density and mean temperature profiles with NL DSA
(Decourchelle, Ballet, Ellison 2000)



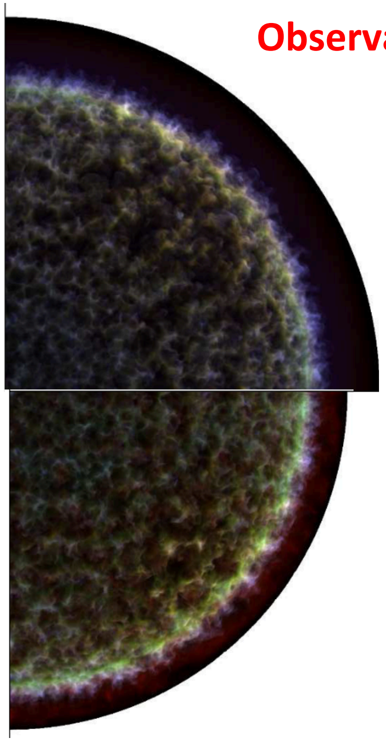
Slice in density

3D SNR simulations with NL DSA
(Ferrand et al. 2010)

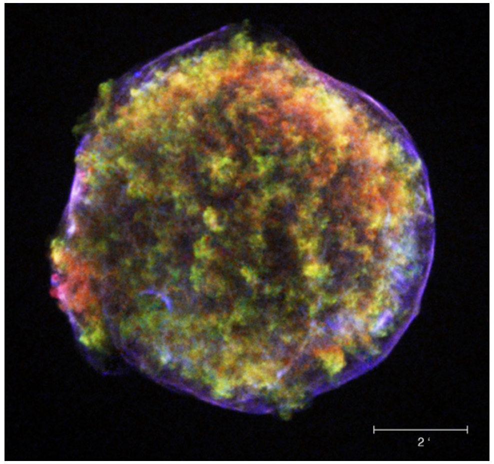
NL DSA
A. Dynamical reaction of accelerated particles

Observational X-ray diagnostic: shock very close to interface: $R_{shock}/R_{interface} < 1.1$

=> efficient particle acceleration



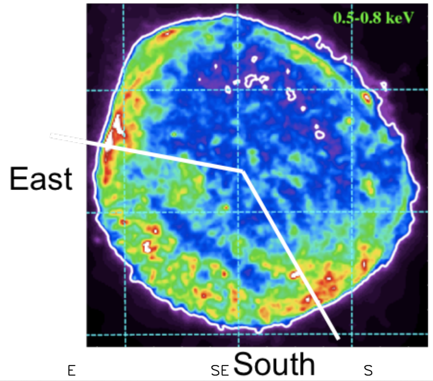
3D SNR simulations with NL DSA model: thermal X-ray emission (Ferrand et al. 2012)

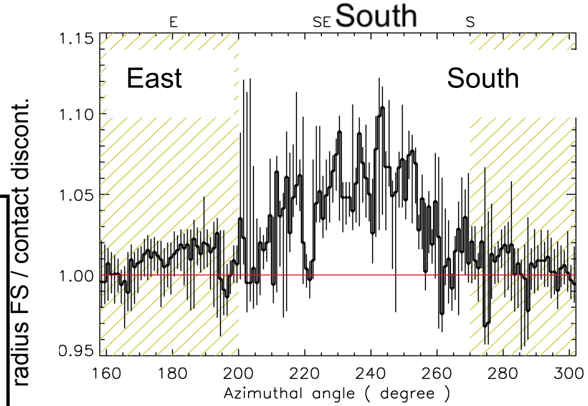


Tycho (Warren et al. 05, Decourchelle et al. 04)

SN 1006 (Miceli et al. 09, Cassam-Chenaï et al. 08)

Cas A: X-ray proper motion & morphology (Patnaude et al. 09)





Cassam-Chenaï et al. 08

NL DSA
B. Plasma instabilities induced by accelerated particles

Magnetic field amplification

- Shock corrugation => amplification in the downstream region when inhomogeneous medium

(e.g., Giacalone & Jokipii 2007)

- Streaming instability of accelerated particles => amplification upstream of the shock

(e.g., Schure et al. 2012 for a review)

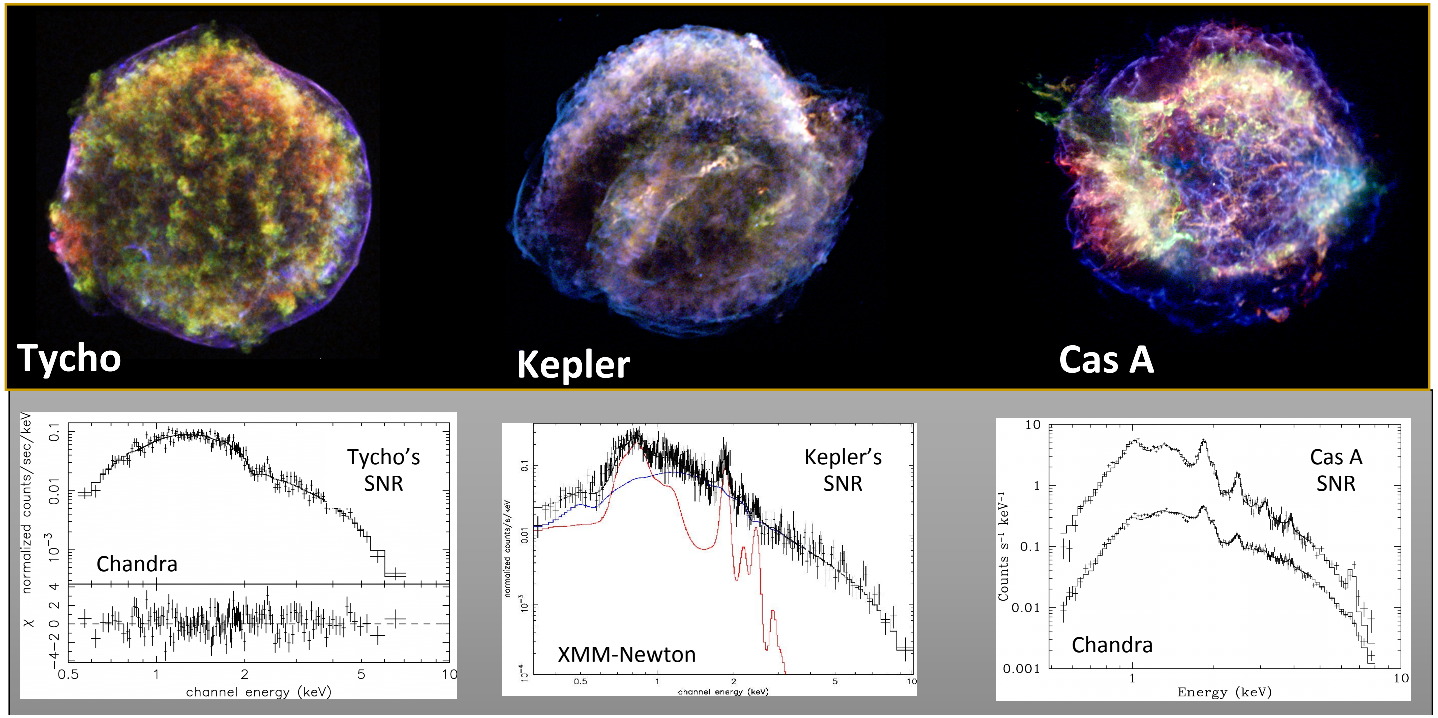
=> diffusive confinement of CRs close to the shock surface shortens the acceleration time and should make it possible for the maximum energy to rise up to 10^{15} - 10^{16} eV

NL DSA
B. Plasma instabilities induced by accelerated particles

Narrow nonthermal synchrotron filaments at the shock in young SNRs (eg., Vink 2012, Ballet 2006)

- width determined by synchrotron losses of ultrarelativistic electrons

=> high value of $B_{downstream}$(~ 50-500 μG) => large amplified magnetic field



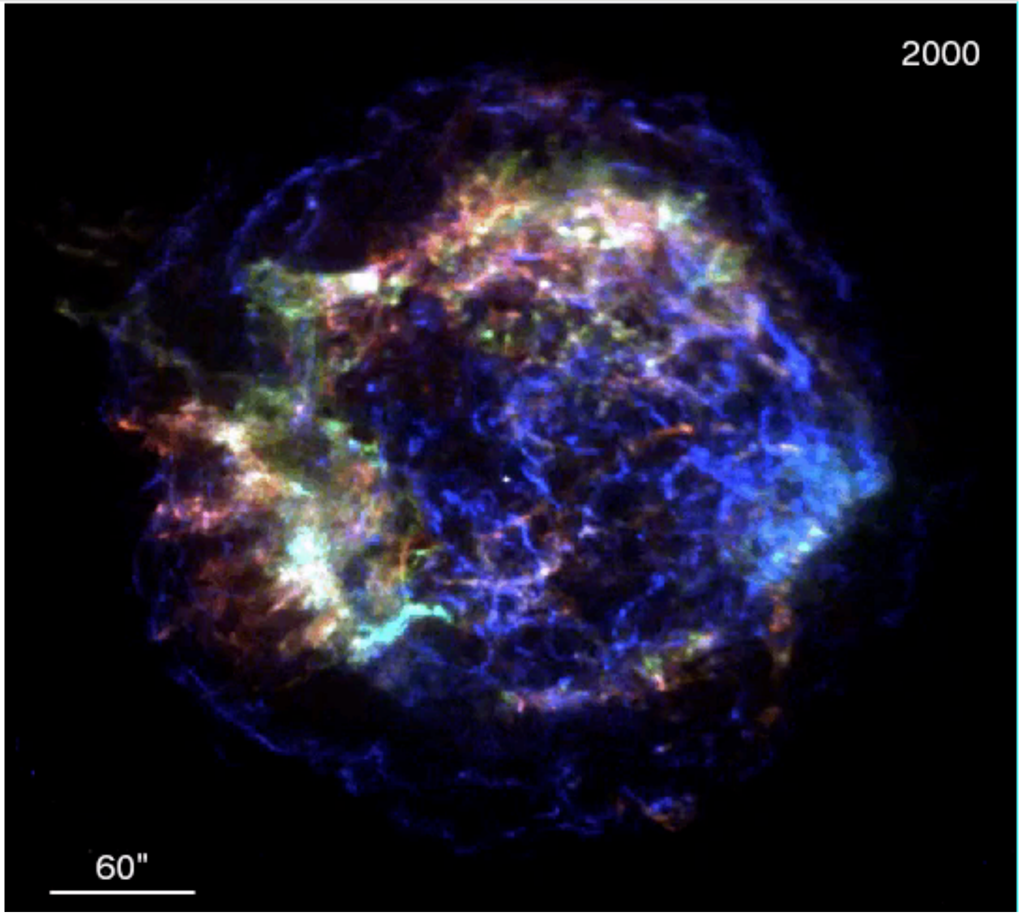
Additional support from

- Fast variability of the brightness of these filaments (eg. Cas A, RXJ17.13)
- Broad band modeling of the nonthermal emission

How large is the magnetic field ? Is it very turbulent ? Is it amplified ?

The magnetic field is a crucial parameter :

- for understanding particle acceleration
- For the maximum energy of accelerated particles
- for interpreting the origin of TeV γ-rays : leptonic versus hadronic

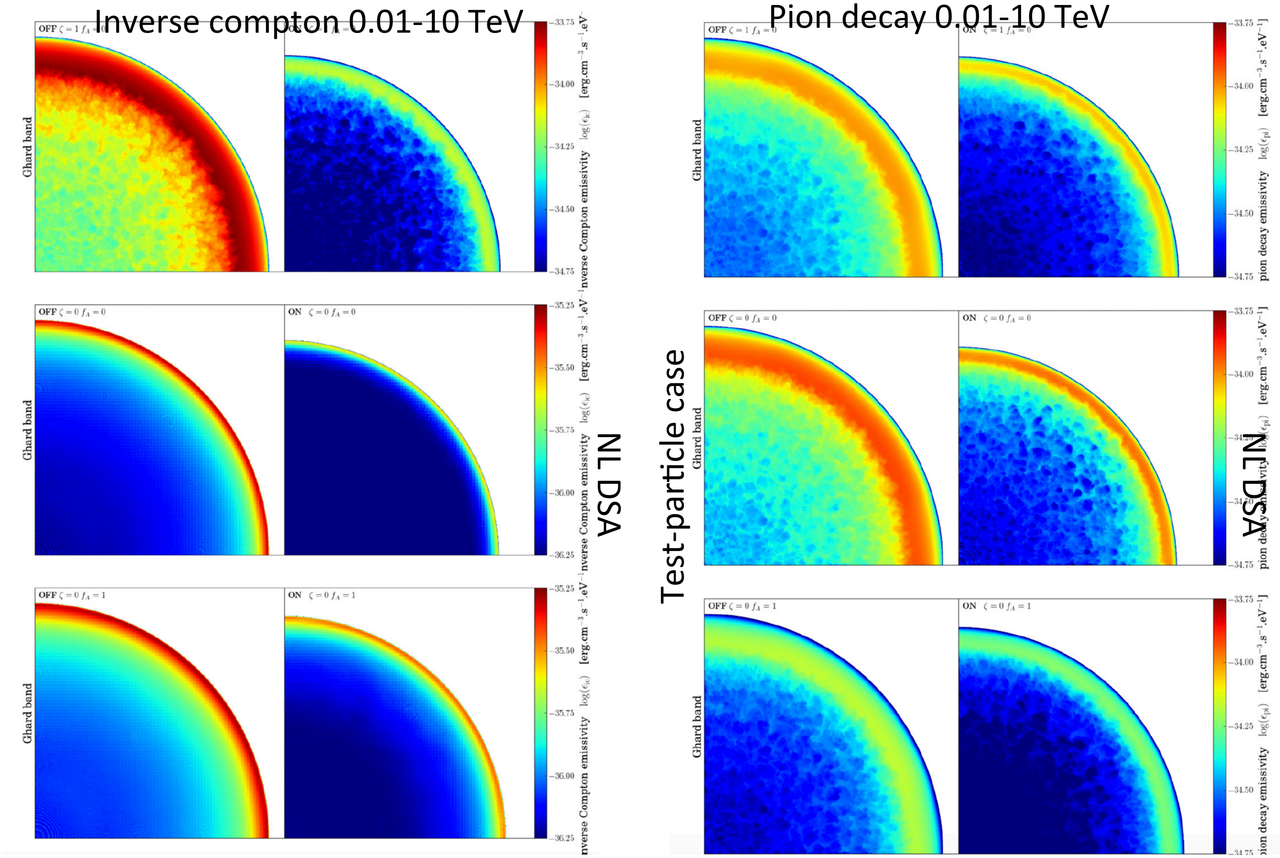


Patnaude et al. 09

NL DSA
C. Dynamical reaction of the amplified magnetic field

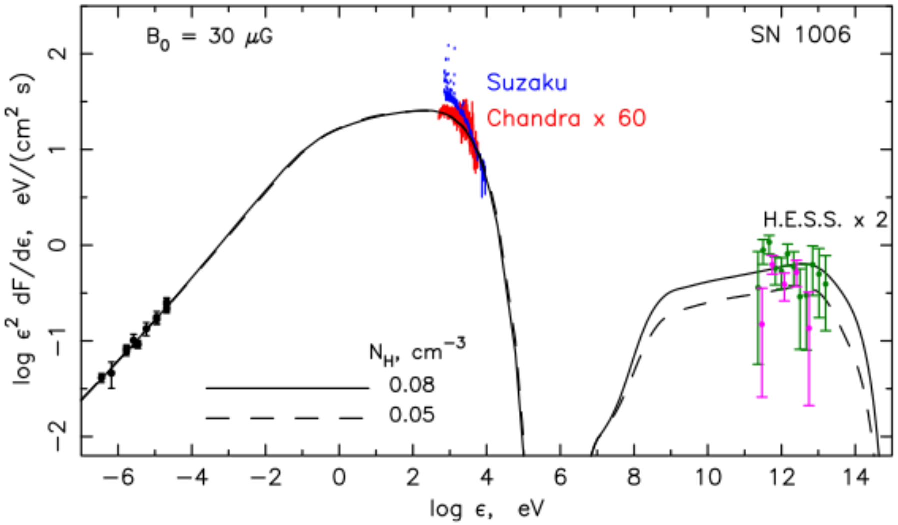
- Non linearity due to the dynamical reaction of magnetic fields produced by CRs upstream on the shock itself (Caprioli et al. 2008, 2009)

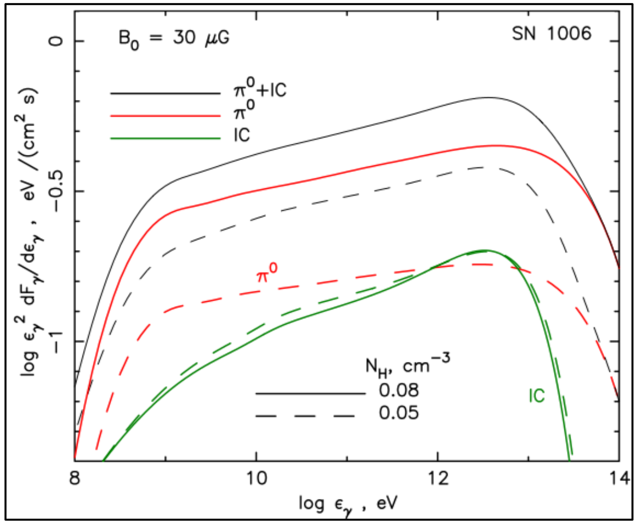
=> less modified shocks, less concave spectra of accelerated particles making them closer to power laws



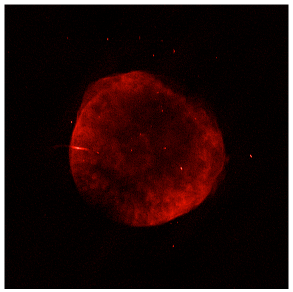
Ferrand et al. 2014

Broadband modeling of the nonthermal emission of SN 1006

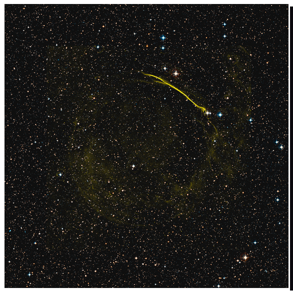




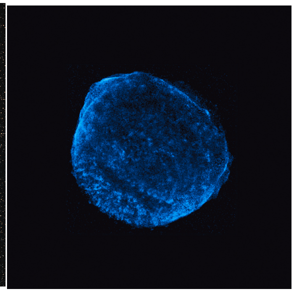
Berezhko et al. 2012



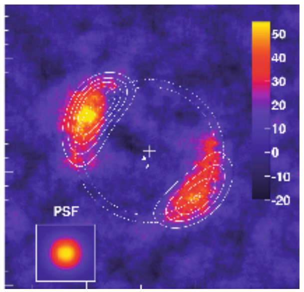
radio



optical

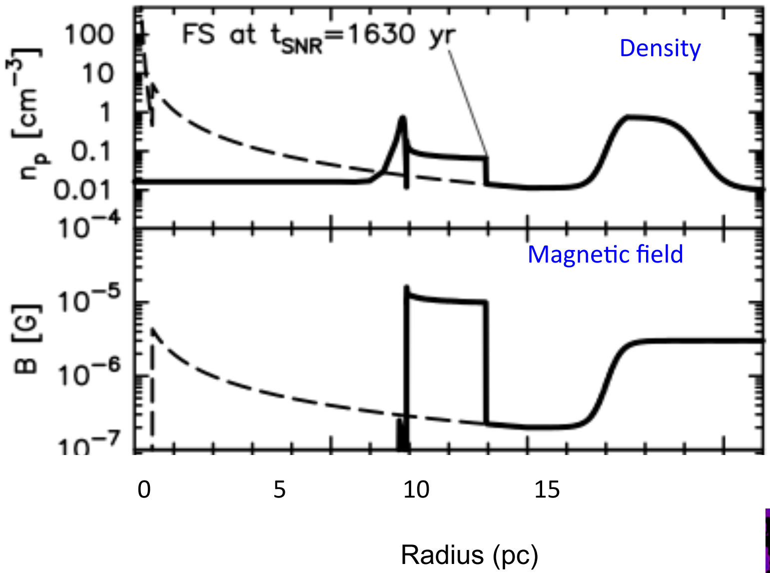


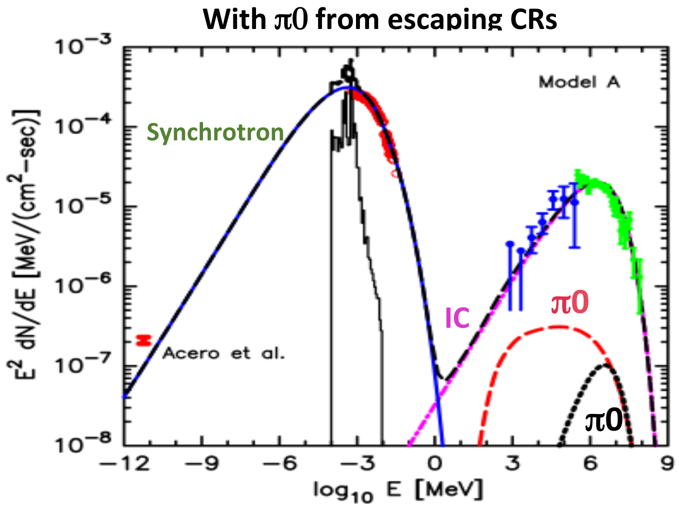
X-rays



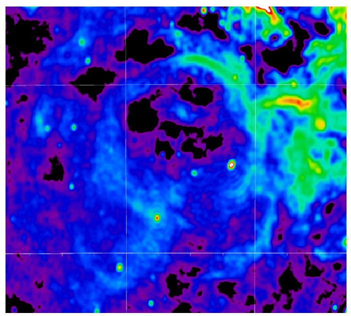
gamma rays

Broadband modeling of the emission of G347.3-0.5

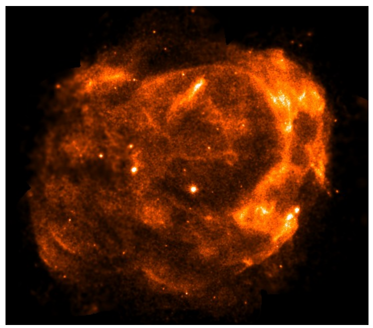




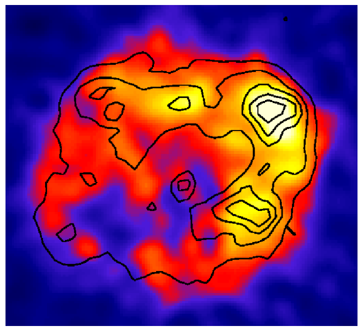
Ellison et al. 2012



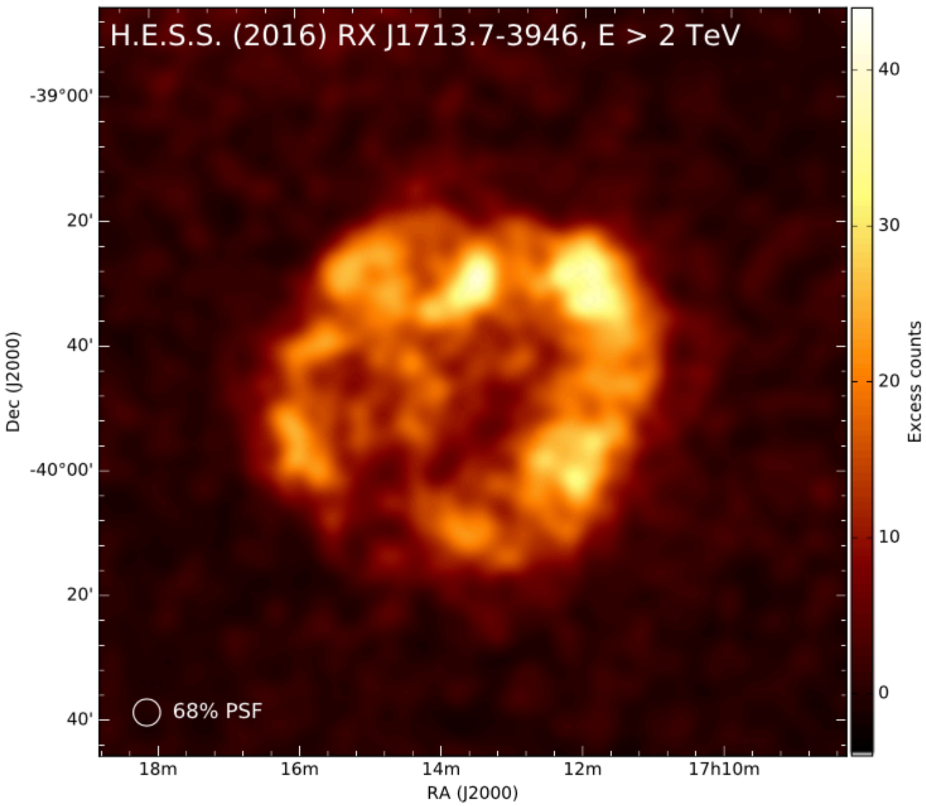
Radio - ATCA

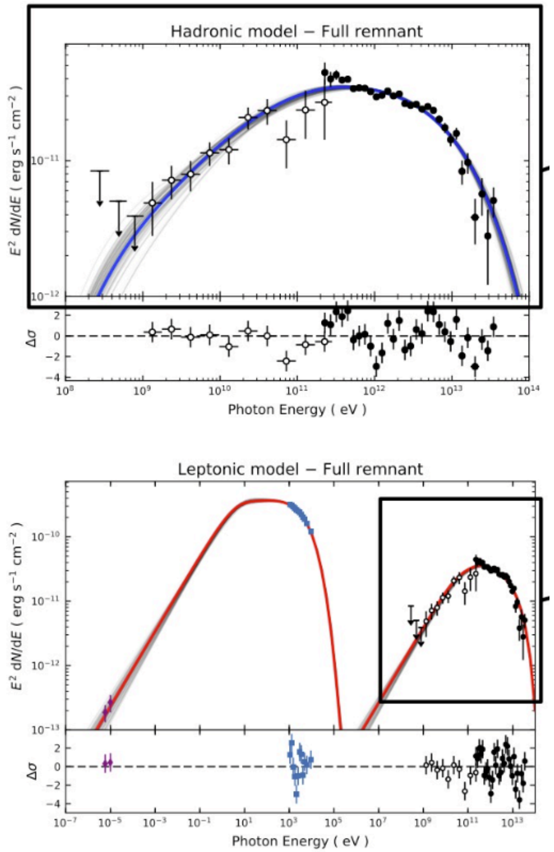


X-rays - XMM-Newton



Gamma rays - HESS





HESS collaboration 2018, A&A

Expectations with CTA

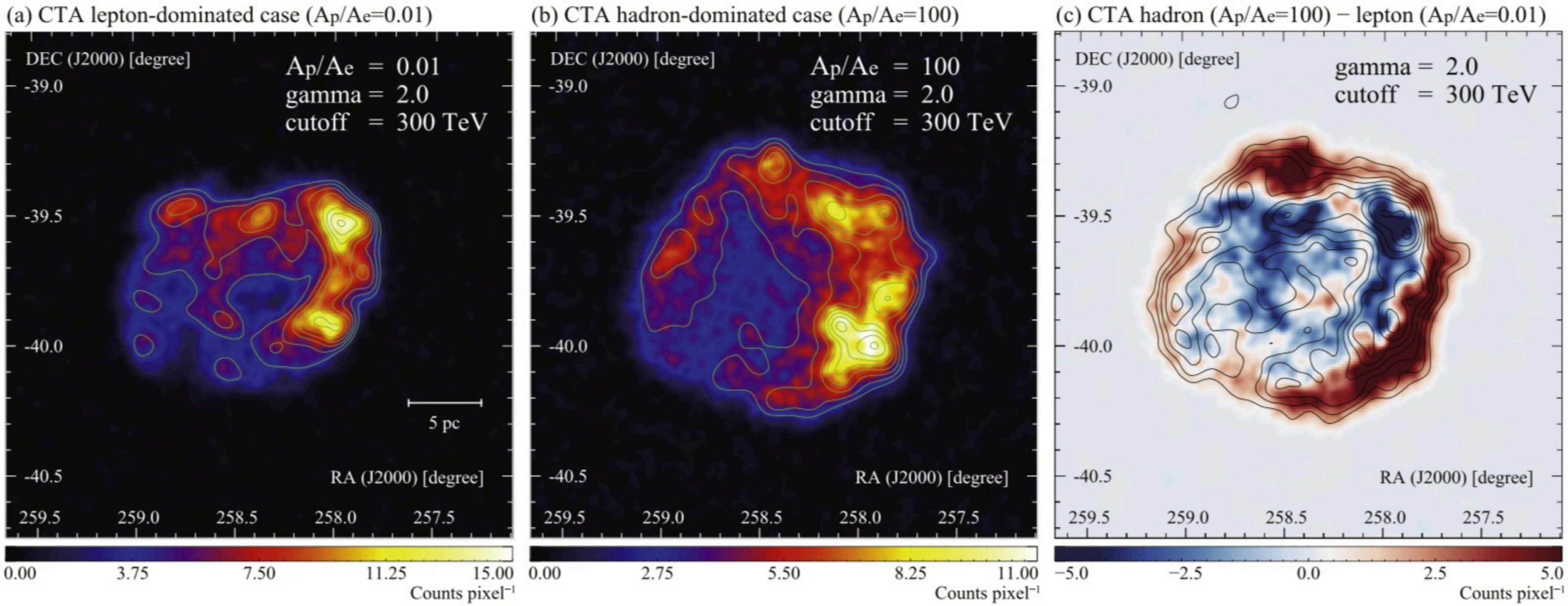


Figure 1. Simulated gamma-ray images of (a) $A_p/A_e = 0.01$ (lepton-dominated case) and (b) $A_p/A_e = 100$ (hadron-dominated case) with $\Gamma_p = 2.0$ and $E_c^p = 300$ TeV. The green contours show (a) *XMM-Newton* X-ray intensity (e.g., Acero et al. 2009) and (b) total interstellar proton column density (Fukui et al. 2012) smoothed to match the PSF of CTA. The subtracted image of (b) − (a) is also shown in (c). The black contours correspond to the H.E.S.S. VHE gamma rays (Aharonian et al. 2007a). The unit of color axis is counts pixel^{-1} for all panels.

Conclusions

Impressive discoveries in the last 20 years regarding particle acceleration

- Prompted by observations (notably XMM-Newton, Chandra, HESS, Fermi)
- Theoretical developments on nonlinear diffusive shock acceleration
- Broad band modelling

A number of open questions remains: highest energy achievable in SNRs ? Escape ?

- Complex physics of collisionless shocks,

  dependent of the SNR and ambient medium properties (shock velocity, density, magnetic field orientation, level of ionization, level of inhomogeneities,..)

- Non linear coupling between shock properties, accelerated particles, magnetic field (amplification) and thermal gas properties and accelerated particles

- Different types of SNRs (thermonuclear and core collapse)

  Large range of environments depending on progenitors

  For core collapse SNe, circumstellar medium (stellar wind, bubbles), cloud interaction

Prospects

- Detailed observations of supernova remnants with next generation instruments
  - In gamma-rays with CTA ; **spatially resolved spectrum** ; **very high energy**
  - In X-rays with Athena ; **spatially resolved high-resolution spectroscopy** of the shock

- Theory and multiwavelength modelling
  - **Spatially resolved** broadband modelling of **thermal and nonthermal** emission in prototype supernova remnants including back reaction of accelerated particles, non equilibrium ionization, non equipartition temperatures

    => dependence of the acceleration on the environment

- Discovery space with CTA
  - Individual SNR accelerating CRs up to the knee ?
  - New SNRs in the process of accelerating particles and larger samples of TeV SNRs