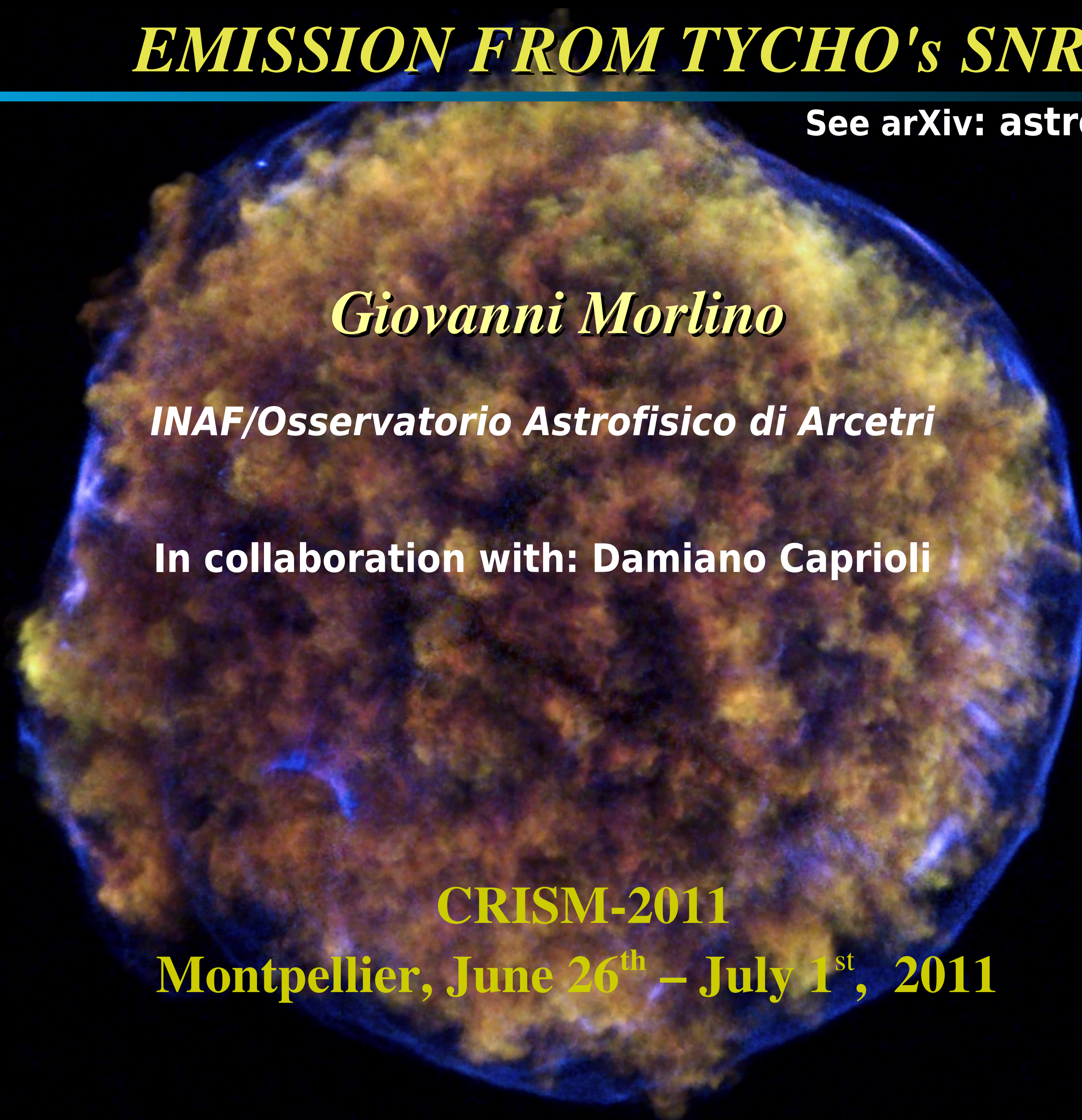
COSMIC RAY PRODUCTION AND GAMMA-RAY EMISSION FROM TYCHO's SNR

See arXiv: astro-ph 1105.6342



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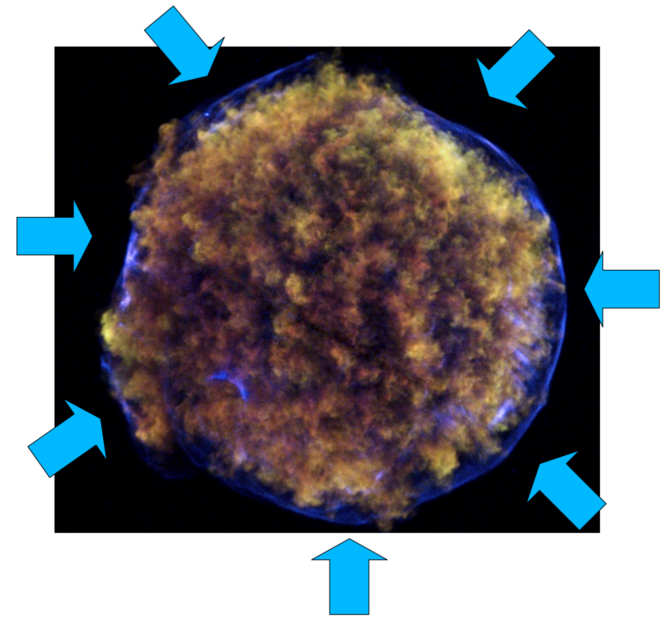
Hints of efficient acceleration in Tycho

Tycho's SNR presents several hints of efficient hadronic acceleration:

1) Thin non-thermal X-ray filaments → evidence for magnetic field amplification (B~200-300 μG)

[Hwang el al(2002); Bamba et al (2005)]



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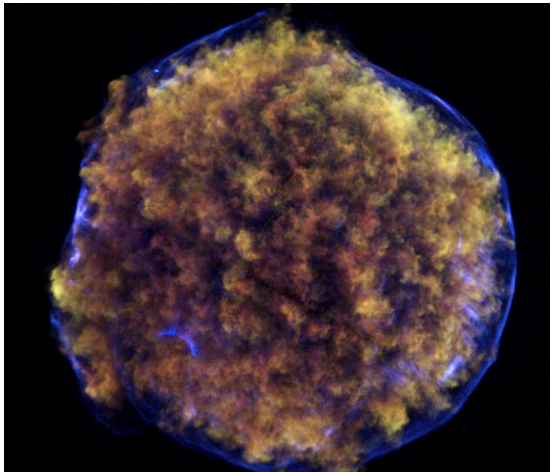

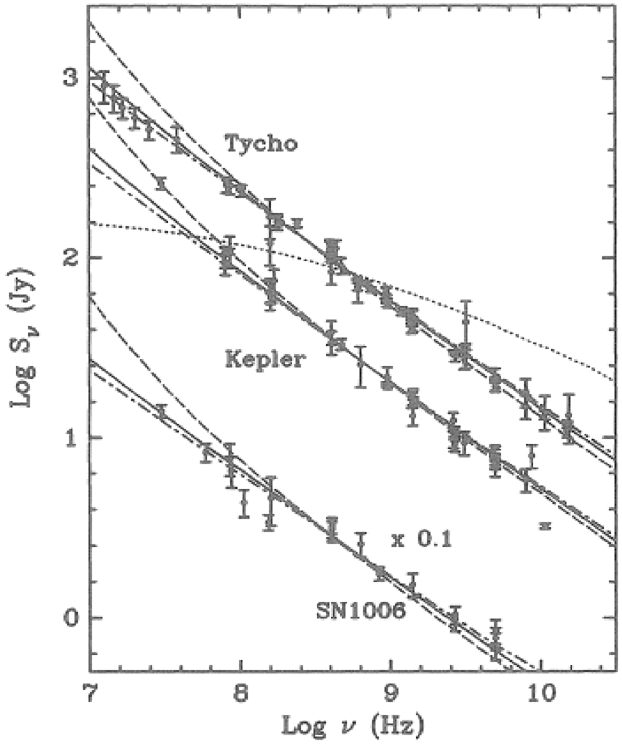

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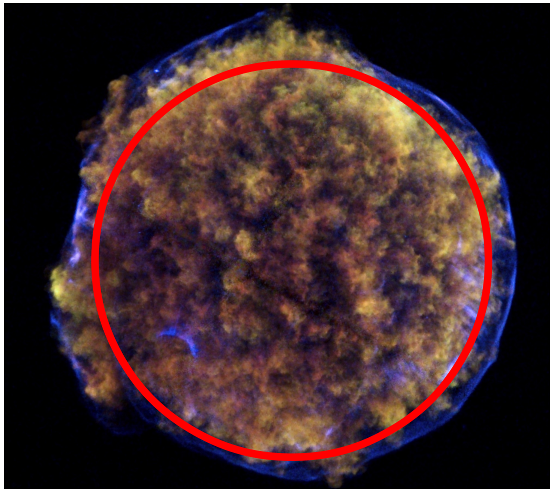

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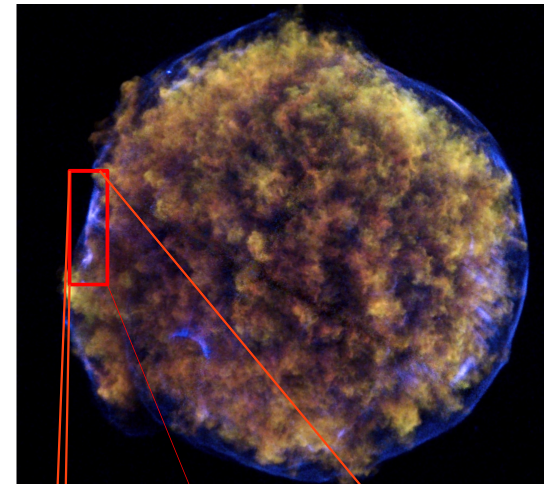
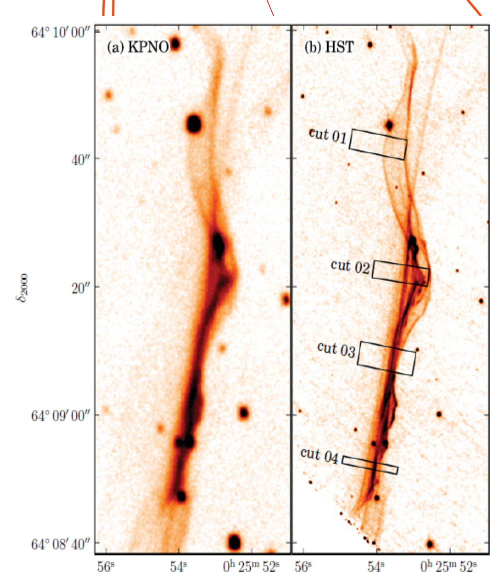
4) Detection of Balmer lines in the region ahead of the shock → has been interpreted as neutral hydrogen heated in the CR-induced precursor

[Lee et al. (2010)]

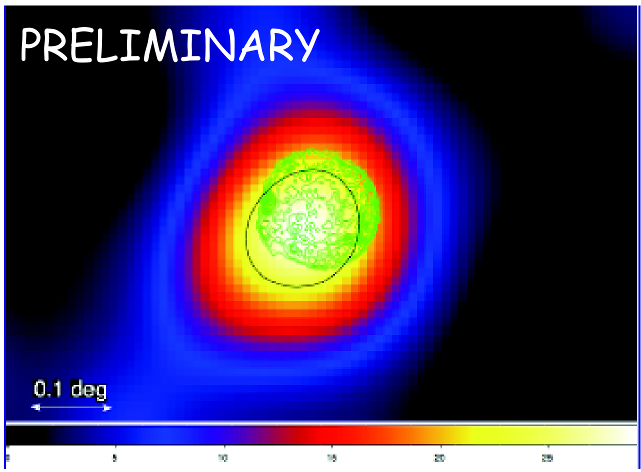




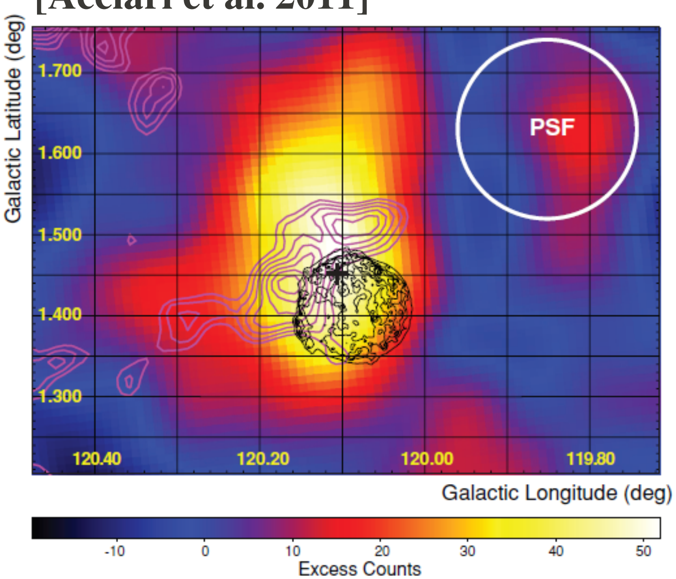
Hubble space telescope

Tycho detection in gamma emission

Fermi TS map 1-100 GeV
[Giordano's talk]

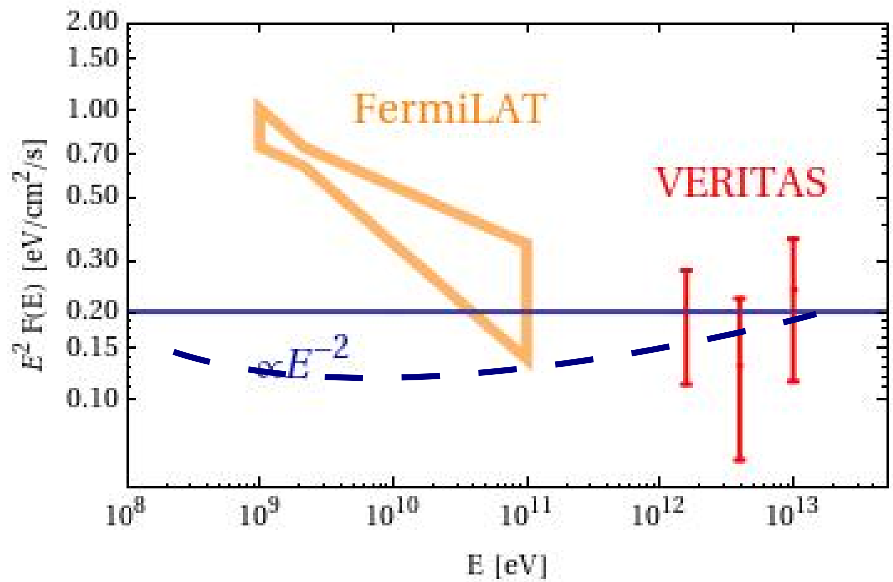


VERITAS map $E > 1$ TeV
[Acciari et al. 2011]



Measured spectral slope in gamma-rays:

FermiLAT $\Gamma = 2.3 \pm 0.1$ (PRELIMINARY) [Giodano et al. 2011]
VERITAS $\Gamma = 1.95 \pm 0.51_{stat} \pm 0.30_{sys}$ [Acciari et al. 2011]



Linear theory → $f_p(E) \propto E^{-2} \Rightarrow F(\pi_0 \to \gamma\gamma) \propto E^{-2}$

Non-linear theory → $f_p(E) \propto E^{-\Gamma}, \quad \Gamma > 2$

Is it possible to build a model able to explain the γ-ray spectrum and contemporary all the other spectral and morphological properties?

Description of the model: remnant evolution

Type Ia SN
Detected echo light (Krause et al., 2008)

$$E_{SN} = 10^{51}\,erg$$
$$M_{eje} = 1\,M_{sol}$$
$$T_{SNR} = 439\,yr$$
$$f(v) \propto (v/v_{eje})^{-7}$$

Expansion in homogeneous ISM
Tian & Leahy (2011) analysed the 21 cm continuum, the HI and ^{12}CO-line data, concluding that there are no evidences of direct interaction between the shock and a MC.

$$n_0 = 0.3\,proton/cm^3 \quad \text{(free parameter)}$$
$$T_0 = 10^4\,K$$

Tycho is at the end of the free expansion phase

$$T_{ST} = 463\,yr > T_{SNR}$$

Analytic solution for ejecta dominated phase [Truelove & McKee 1999]

$$R_{sh}(t) = 4.06\left(\frac{t}{T_{ST}}\right)^{4/7} pc$$
$$V_{sh}(t) = 4875\left(\frac{t}{T_{ST}}\right)^{-3/7} km/s$$

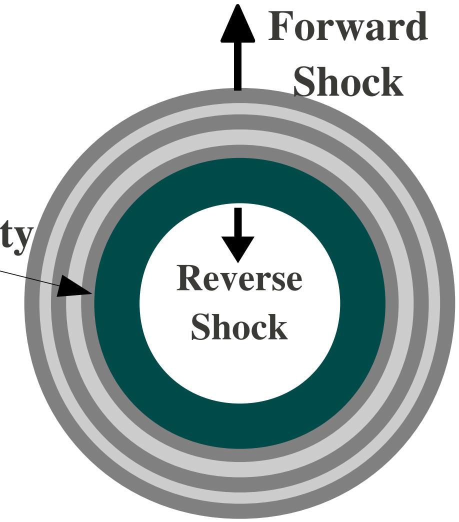
$$R_{sh}(T_{SNR}) = 3.94\,pc \rightarrow d = 3.3\,kpc$$
$$V_{sh}(T_{SNR}) = 4990\,km/s$$

Compatible with all existing estimates

Description of the model: particle acceleration

We couple the remnant evolution to the stationary Non Linear Diffusive Shock Acceleration (NLDSA)

The remnant evolution is divided in several time steps Δt and for each time step we apply the stationary shock acceleration theory .



In order to compute the evolution of the *downtream* plasma (thermal fluid+ CRs component) we assume:

→ entropy conservation within each single shell

→ pressure equilibration between close shells

For particle acceleration we adopt the semi-analytical framework from Amato & Blasi (2006) and Caprioli et al. (2010)

- *Thermal leakage*: We assume that all particle with momentum > ξ_{inj} times the thermal momentum can cross back the shock and are injected in the acceleration mechanism.

- *Diffusion*: Accelerated particles diffuse with Bohm-like diffusion coefficient in the self-generate magnetic turbulence via **resonant streaming instability**

- *Escape boundary*: particles escape from the accelerator at each time when they reach a distance $d \sim \chi_{esc} R_{SNR}$ with $\chi_{esc} \sim 10\%$ → this fix the maximum energy.

Magnetic field amplification and damping

<u>UPSTREAM</u>: growth and transport of magnetic turbulence with resonant amplification

$$\frac{dF_w}{dx} = u(x)\frac{dP_w}{dx} + v_A\frac{dP_{cr}}{dx} \quad \Rightarrow \quad P_w(x) = \frac{B_1(x)^2}{8\pi\rho_0 V_{sh}} \simeq \frac{1+U(x)}{4M_A(x)U(x)}P_{cr}(x)$$

<u>DOWNSTREAM</u>: transport with adiabatic losses and damping

Non-linear Landau damping
(Ptuskin & Zirakashvili, 2003):

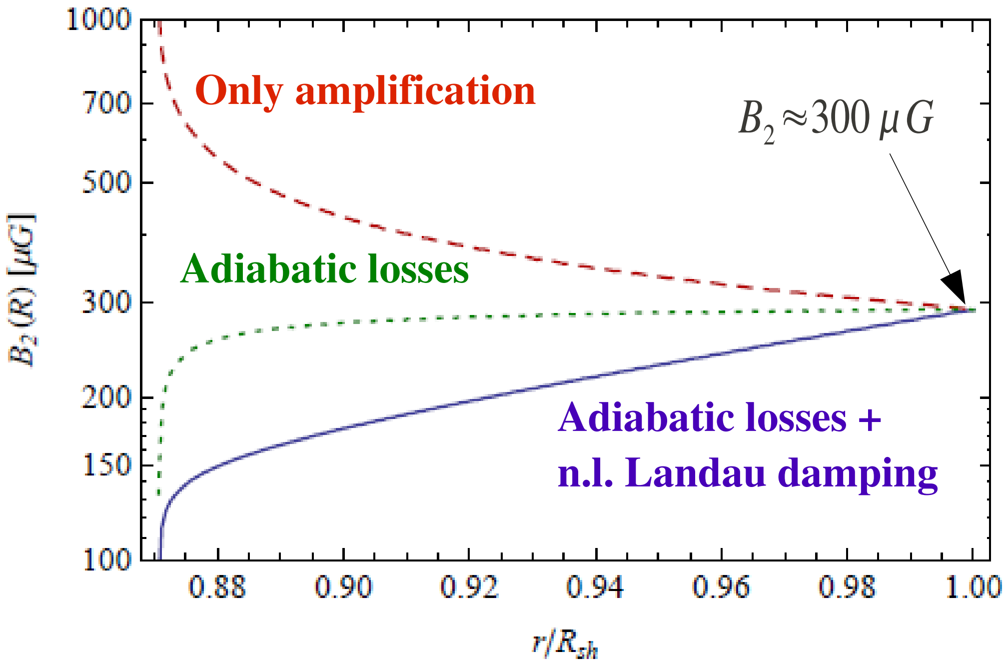
$$\Gamma_{nl} \simeq 0.05\,k_{min}v_A \simeq 0.05\frac{v_A}{r_L(p_{max})}$$ Damping rate averaged on the different scales

$$\lambda_{nl} \simeq \frac{u_2}{\Gamma_{nl}} \approx 3.5\,pc$$ Damping scale

$$L(t_0,t) = \left[\rho(t)/\rho_0\right]^{1/3}$$ Adiabatic losses

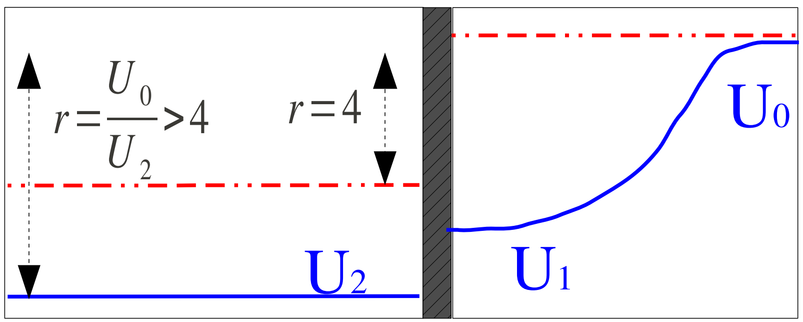
$$B_2(x) = B_2(t_0)L(t_0,t)^2 \exp\left[-\frac{R_{sh}-x}{\lambda_{nl}}\right]$$

Downstream profile of magnetic field

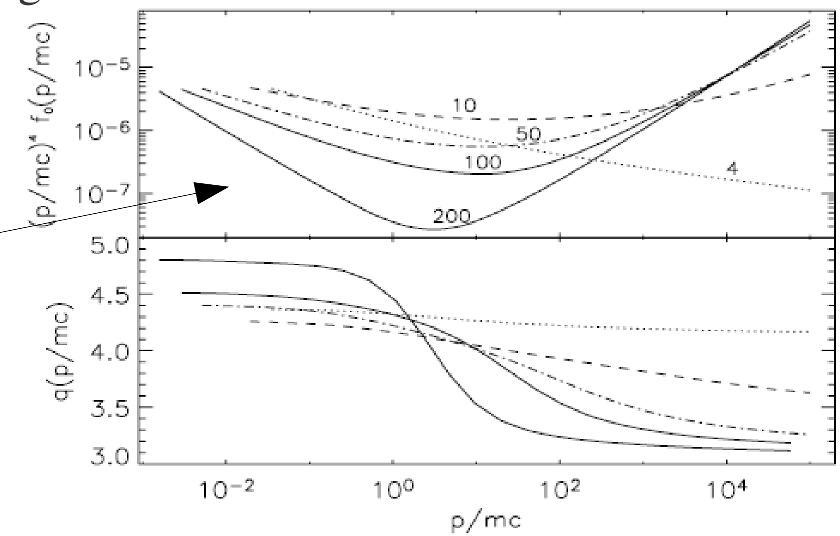


The role of scattering centers in presence of strong magnetic amplification

In the standard NLDSA the CR pressure modifies the shock structure in such a way to produce concave particle spectra with spectral slope > 2 at higher energies



Shock modified by CRs



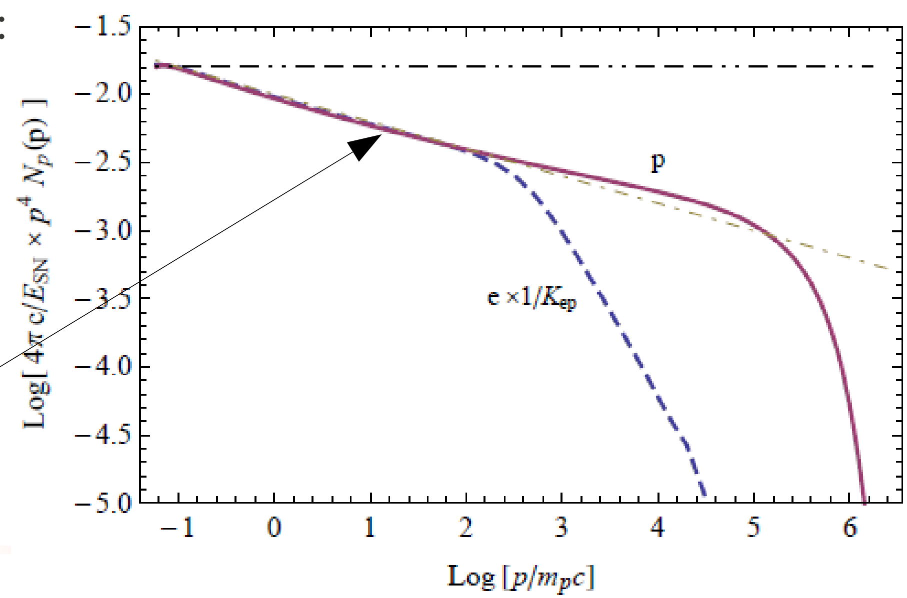
When the magnetic field is strongly amplified the Alfvén speed upstream can become a non negligible fraction of the shock speed. In this case the effective compression ratio is:

$$r = \frac{u_1 - v_{A,1}}{u_2 \pm v_{A,2}} \simeq \frac{u_1 - v_{A,1}}{u_2}$$

Downstream $v_{A,2} \approx 0$ because of helicity mixing.

In the case of Tycho:

$$v_{A,1} = \frac{B_1}{\sqrt{4\pi\rho_1}} \approx 0.15 V_{sh} \rightarrow s = \frac{r+2}{r-1} \simeq 4.2 \quad \text{(2.2 in energy)}$$



Electron spectrum

Electron spectrum at the shock position
from Zirakashvily & Aharonian (2007)

$$f_{e,0}(p) = K_{ep} \times f_{p,0}(p)\left[1+0.523\left(p/p_{e,max}\right)^{9/4}\right]^2 \exp\left[-p^2/p^2_{e,max}\right]$$

The maximum energy is determined by synchrotron losses which produces a quadratic exponential cut-off

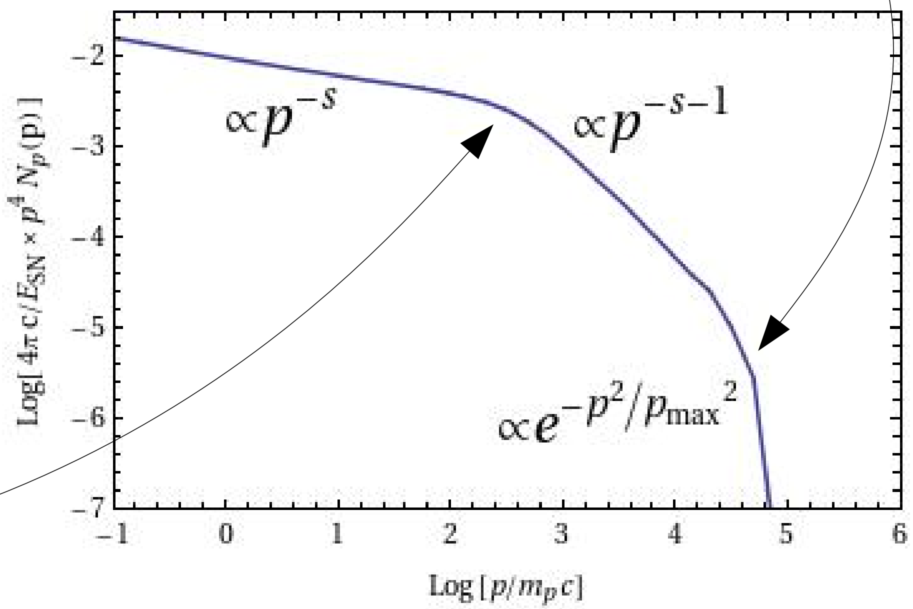
$$\tau_{loss}(p_{max}, B) = t_{acc}(p_{max}, B)$$

Evolution of electron energy downstream of the shock
from Reynolds (1988)

$$\frac{dE}{dt} = -\frac{4}{3}\sigma_T\left(\frac{E}{m_e c^2}\right)^2 \frac{B_{eff}^{\;2}}{8\pi} - \frac{E}{L}\frac{dL}{dt}$$

Synchrotron + Inverse Compton losses

Adiabatic losses



Synchrotron losses downstream determines a slope change for $p > p_{roll}$

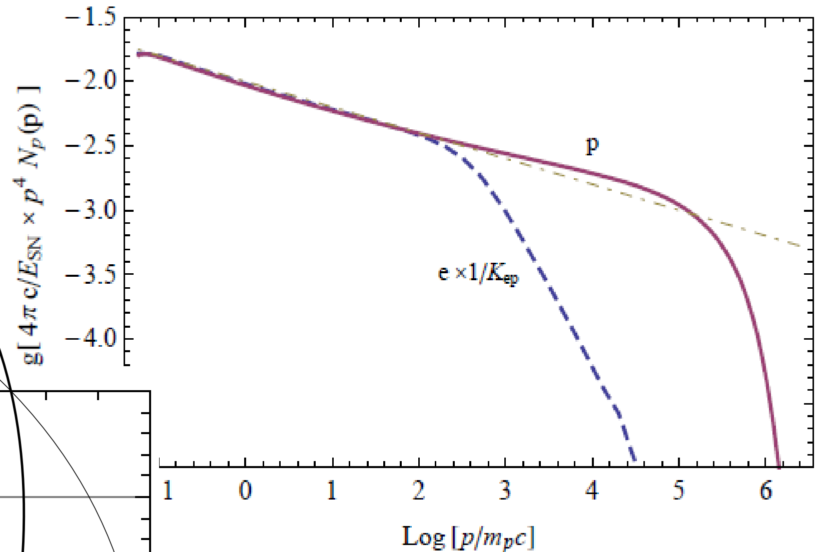
$$\tau_{loss}(p_{roll}, B_2) = T_{SNR}$$

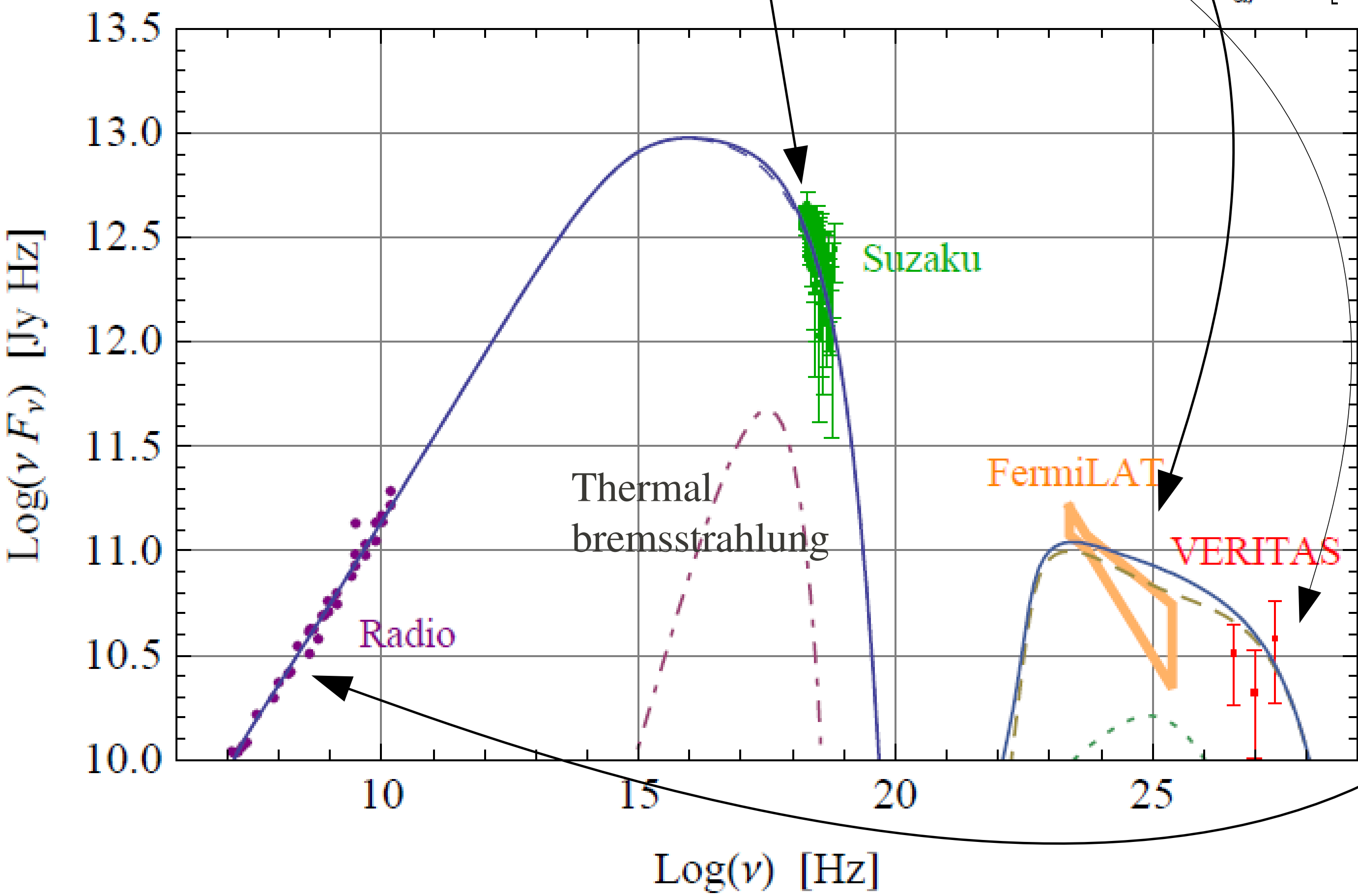
Multi-wavelength spectrum

Our model has only four free parameters

1) **ISM density**
2) **Injection efficiency of protons**
3) **Free escape boundary**
4) **Normalization of electrons**

$$n_0 = 0.3\, p/cm^3$$
$$\xi_{inj} = 3.7$$
$$\chi_{esc} = 0.1\, R_{sh}$$
$$K_{ep} = 1.6\times10^{-3}$$





The radio slope (~0.6) and normalization are well fitted without tuning additional parameters.

Gamma spectrum

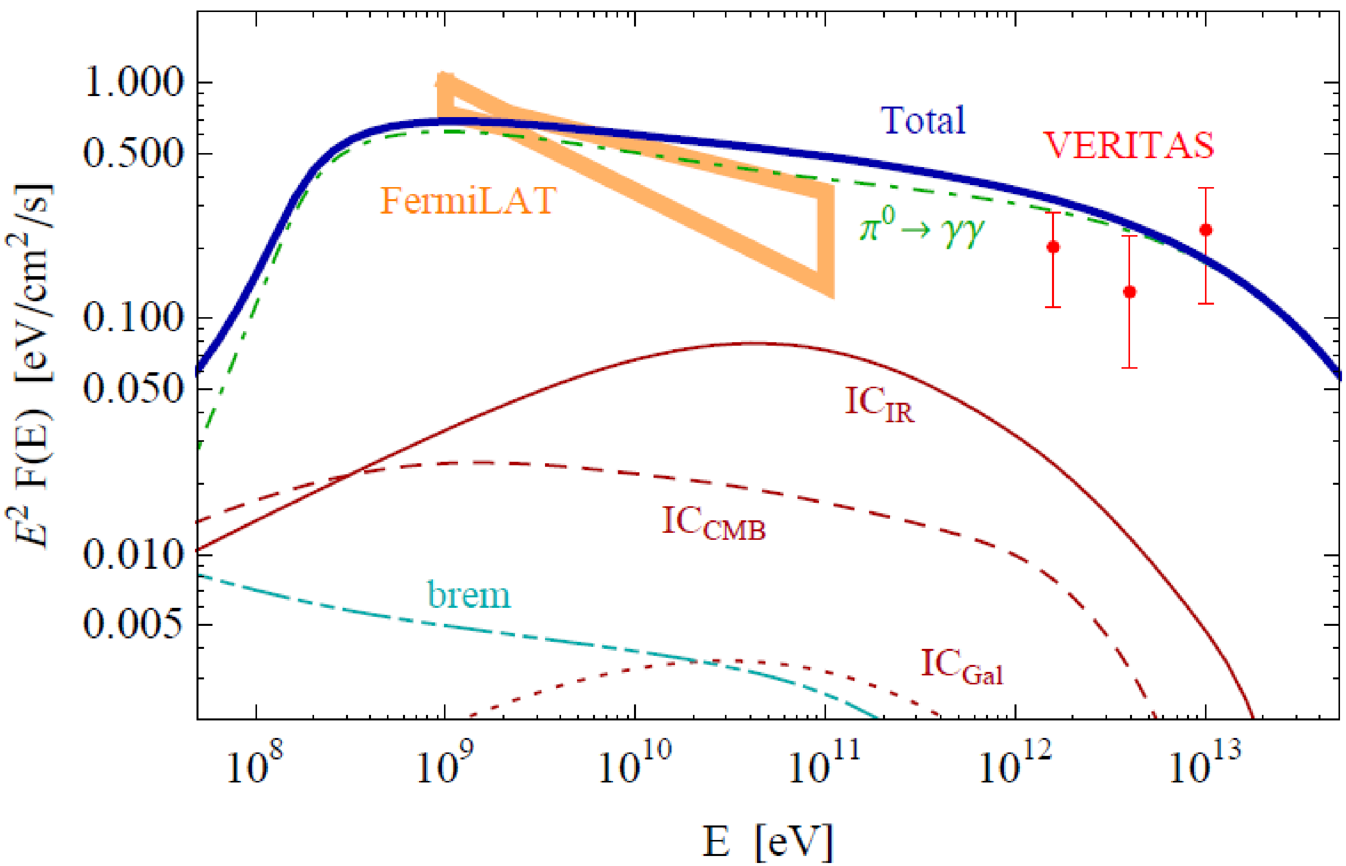
The dominant process in the GeV-TeV range is the pion decay produced in hadronic collisions

Maximum proton energy: $p_{max} = 470 \ TeV/c$ Kinetic energy converted into CRs : $\epsilon_{CR} = 0.12$

ELECTRONIC PROCESSES:

Non-thermal bremsstrahlung is totally negligible

Inverse Compton with photon background:
1) CMB
2) Galactic light (opt+IR)
3) local dust-IR radiation



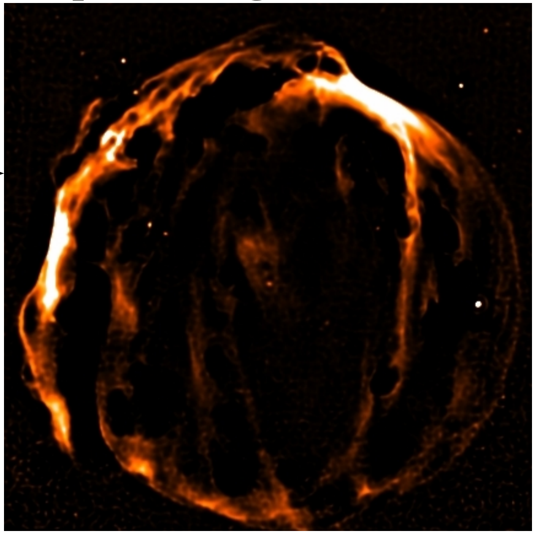
Contribution of IR dust emission to inverse Compton scattering

IR radiation has two different component:

1) **Cold component** (T ~ 20 K) correlated with the position of CO molecular cloud → non related to the remnant

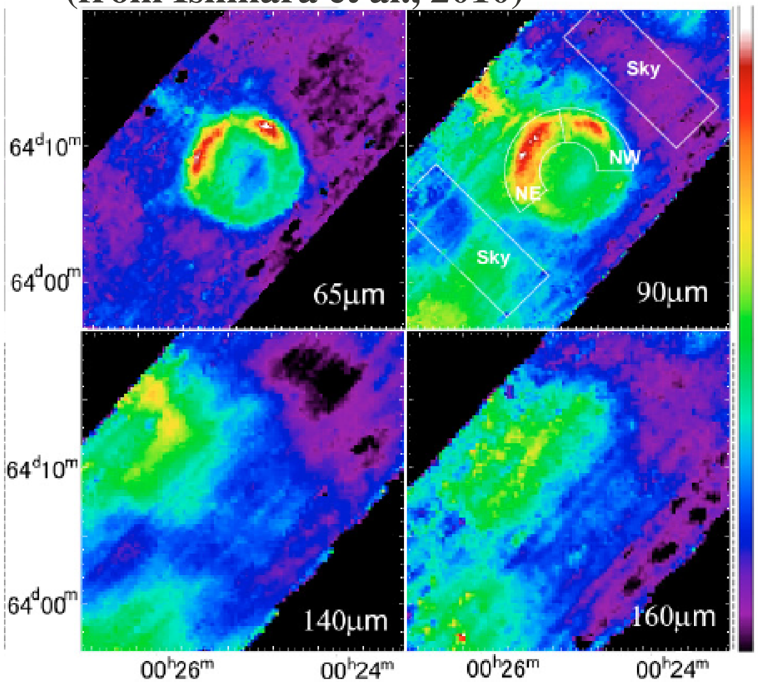
2) **Warm component** (T ~ 100 K) due to local ISM dust heated downstream of the shock (local photon energy density 3.1 eV/cm^3) →

Spitzer image at 24 μm



The warm IR photons dominate the IC scattering over CMB and Galactic background light

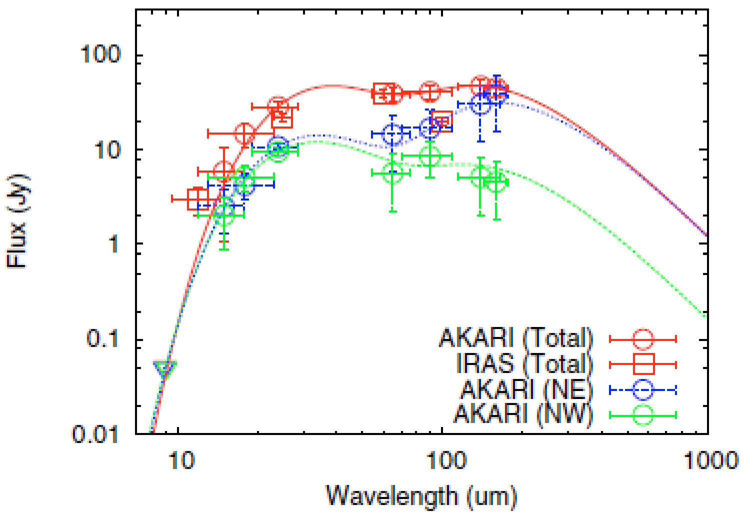
AKARI map at different wavelength (from Ishihara et al., 2010)



Warm component

Cold component

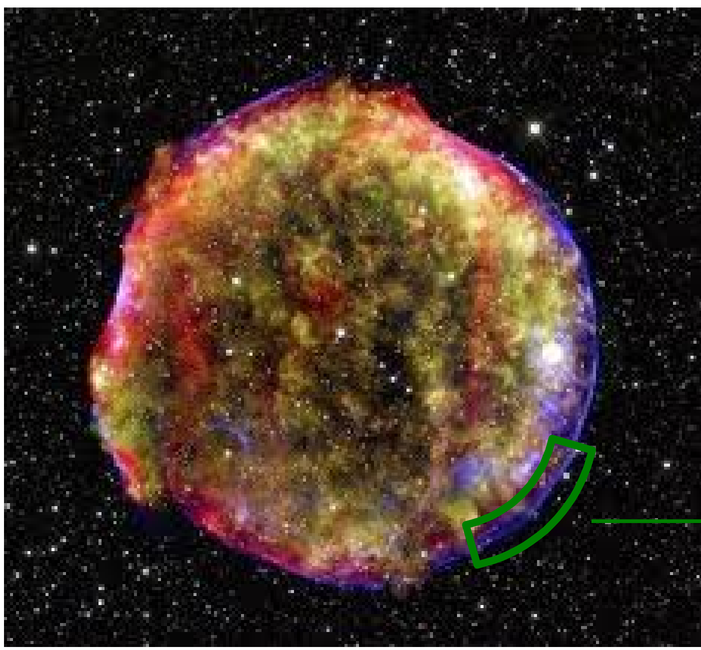
→



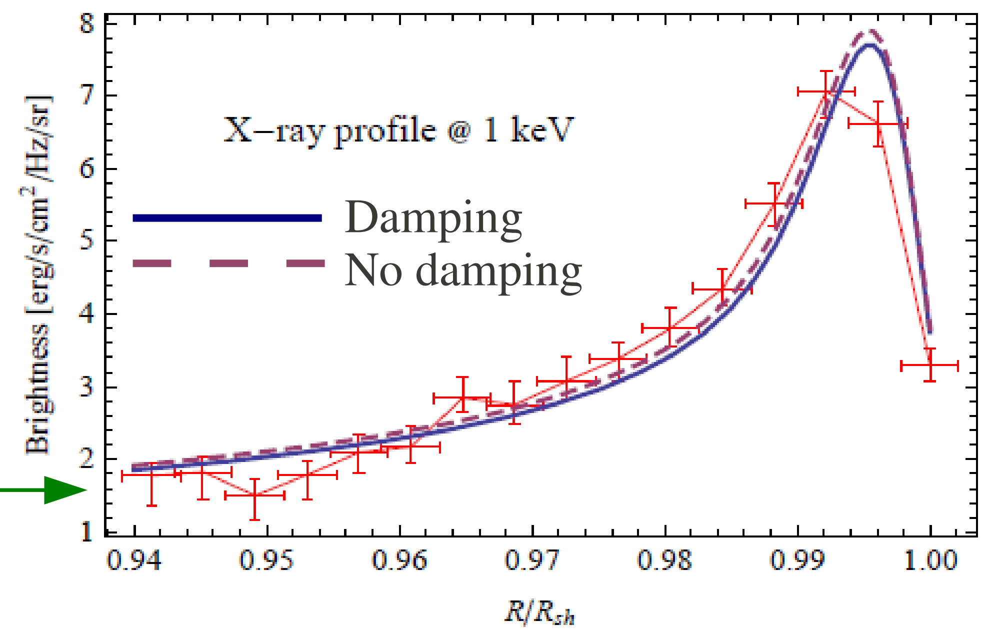
Radial profile of X-ray emission

Filamentary structure of non-thermal X-ray emission is well reproduced by our calculations.

- The small filaments' thickness is a consequence of rapid synchrotron losses in a strong magnetic field ($B_2 \approx 300\ \mu$G).
- Non-linear Landau damping plays a minor role because the damping scale is large, $\lambda \sim 3$ pc.

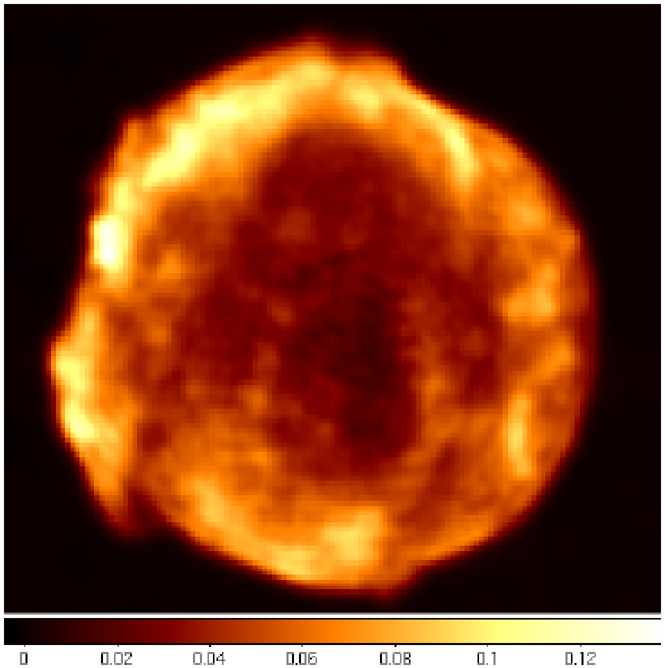


Chandra X-ray map.
Data for the green sector are from Cassam-Chenaï et al (2007)

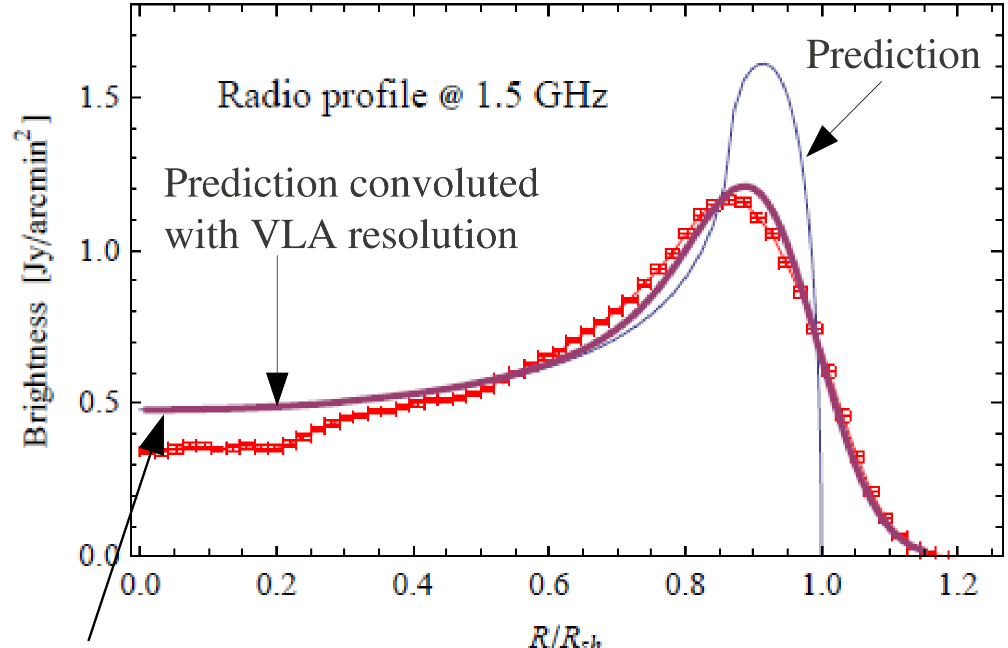


Radial profile of radio emission

• Electron spectrum and magnetic field strength in the downstream well reproduce the morphology of radio synchrotron emission.
• For the radio emission we need the damping otherwise we over predict the flux by a factor ~5



Radio map at 1.5 GHz from NRAO/VLA archive Survey



The excess in the inner part of the remnant could be due to small deviation from perfect spherical symmetry

We find no evidence of efficient particle acceleration at the reverse shock

Position of *contact discontinuity*

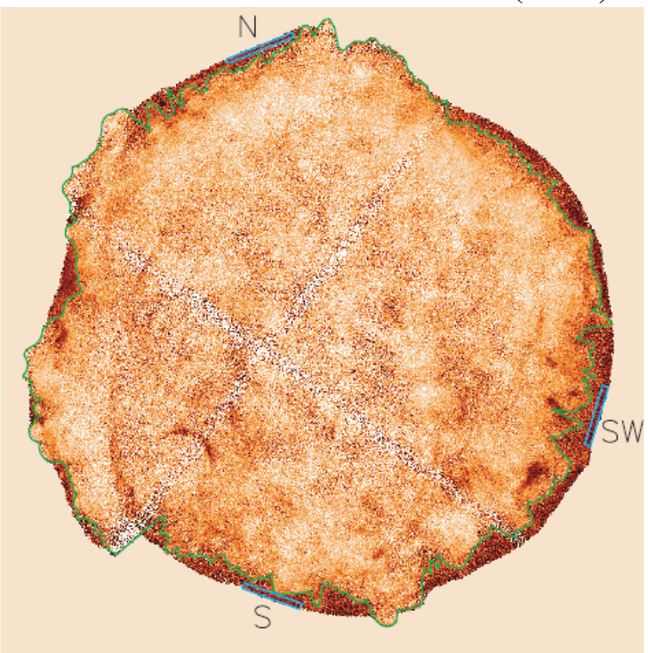
Comparing thermal and non-thermal X-ray emission, Warren et al. (2005) measured the position of CD and FS concluding that they are too close to be described by purely gaseous hydrodynamical models.

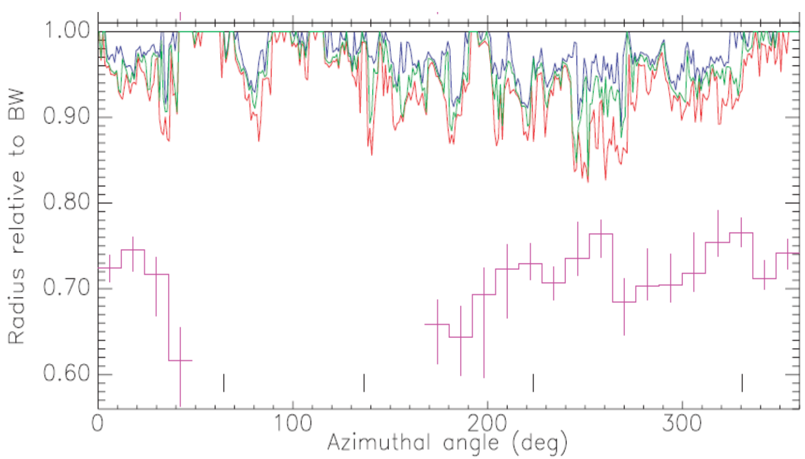
The presence of a non-negligible population of relativistic particles makes the shocked plasma more compressible and can explain this effect .

X-ray measurement (Warren et al. 2005)	$R_{CD}/R_{FS} = 0.93 \pm 2\%$	
1-D hydrodynamical simulation (Wang & Chevalier 2001)	$R_{CD}/R_{FS} = 0.77 \rightarrow$	< 0.87
Our prediction	$R_{CD}/R_{FS} = 0.87 \rightarrow$	~ 0.91

The estimated efficiency ~12% well account for the CD/FS observed distance, taking into account also the effect of Raileigh-Taylor instability at the CD.

From Warren et al. (2005)





Conclusions

Using NLDSA we showed that γ-ray emission (from GeV to TeV) is well accounted for by hadronic interactions

$$E_{max}\ (\text{protons}) \simeq 470\ \text{TeV}; \qquad \epsilon_{CR} \simeq 12\%$$

The NLDSA includes

- Back reaction of accelerated particles
- Self-generation of magnetic field (streaming instability)
- Dynamical role of amplified magnetic filed
- Modified speed of scattering centers induced by magnetic amplification ($v_A \sim 0.1\ V_{sh}$)

crucial effect → effective compression factor < 4 and $s \simeq 4.2$ (*more investigation needed*)

Using a model with only 4 free parameters we can account for:

- Flux and spectral shape of GeV-TeV emission
- Non-thermal X-ray emission
- Total flux and spectral index of radio emission
- Thickness of X-ray filaments
- Morphology of radio emission
- Distance between CD and FS

We are unable to explain gamma-ray emission using leptonic processes and simultaneously account for observations in other wavelengths

We consider Tycho the first clear example of young SNR able to accelerate hadrons efficiently

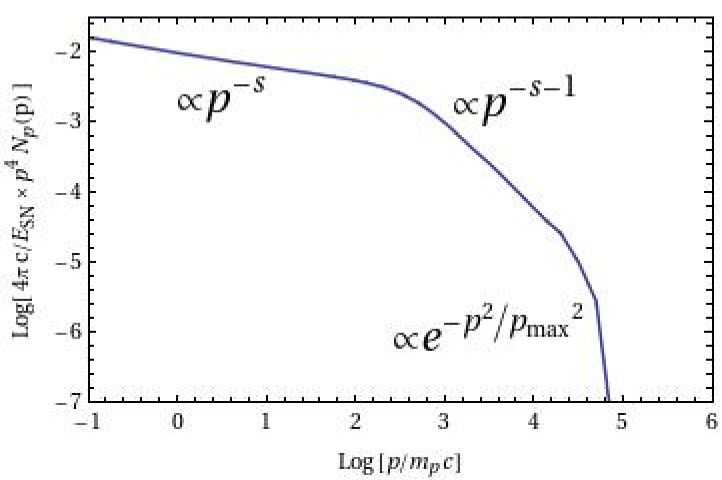
Synchrotron emission as a hint of magnetic field amplification

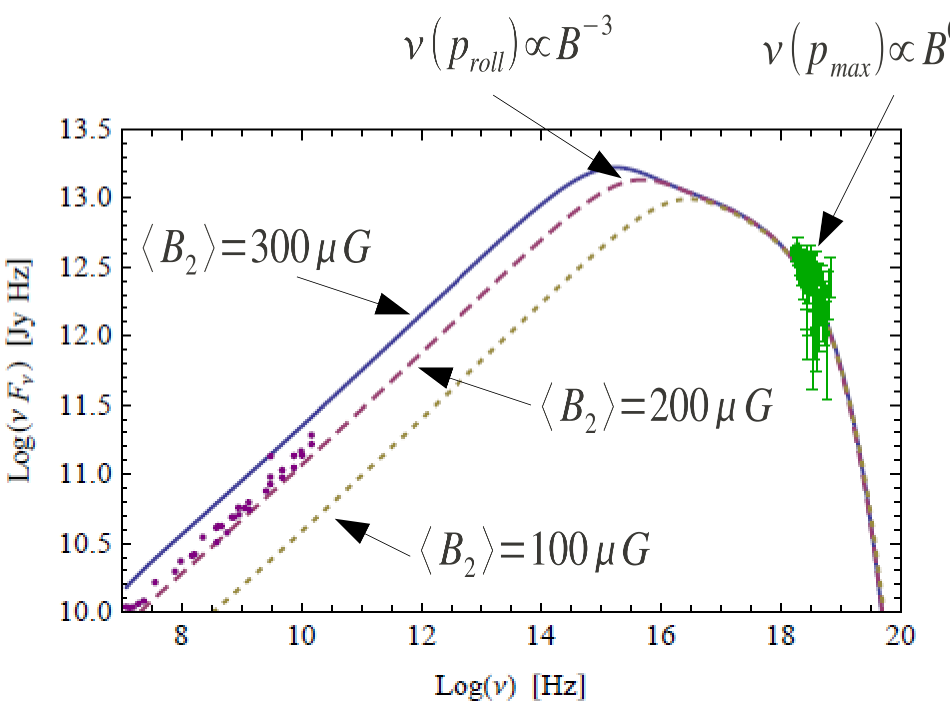
Beyond the X-ray filament thickness, a second independent proof of magnetic field amplification is provided by the simultaneous fit of radio and X-ray data.

From radio data → the electron slope $s = 2.2$
From X-ray data → normalization $K_{ep} = 1.6 \times 10^{-3}$
The position of the p_{roll} is uniquely determined
p_{roll} determines the mean magnetic field

$$\tau_{loss}(p_{roll}, \langle B \rangle) = T_{SNR}$$

Electron equilibrium spectrum

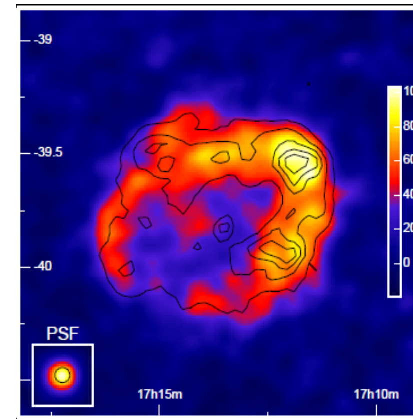




Do young SNRs accelerate efficiently CRs?

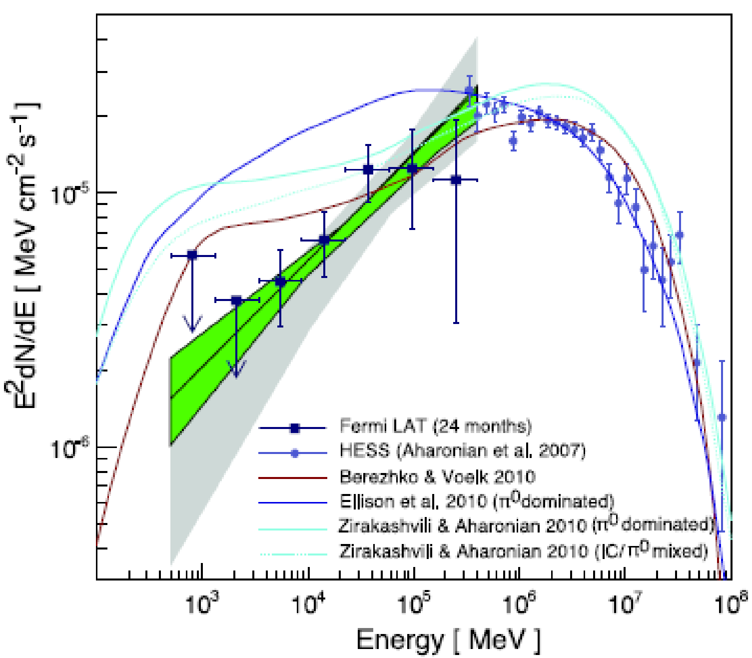
We still lack of a direct proof of hadronic acceleration
➔Gamma-ray detection so far did not provide solid evidences for efficient hadronic acceleration

The remnant **RX J1713.7-3946** has been considered the most promising candidate to prove the existence of accelerated hadrons
FermiLAT revealed a probable leptonic origin



RX J1713.7-3946 detected by HESS

Hadronic model: $\pi^0 \rightarrow \gamma\gamma$



Leptonic model: inverse Compton scattering