The impact of magnetic turbulence spectrum on particle acceleration in SNR IC443

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Particle acceleration in IC443
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DESY

Outline

- Particle acceleration
  - transport equation
  - diffusion coefficient and turbulence
- Magnetic turbulence spectrum
  - typical view
  - calculation
  - first results
  - approximations
- Model of supernova remnant IC443. First results.
  - (not so) known parameters
  - modeling
  - first results
- Summary

Particle acceleration: transport equation

- Assuming:
  - particles scatter elastically
  - their distribution is isotropic ($v_{CR} >> v_{shock}$)

- Cosmic-rays evolution can be described by diffusion-advection equation:

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

  - N – energy differential number density of CRs
  - D – energy dependent diffusion coefficient
  - u – plasma flow velocity
  - p_t – energy losses
  - Q – source of thermal particles

Particle acceleration: diffusion coefficient and turbulence

- diffusion coefficient, D, defines:
  - injection of particles from thermal pool
  - acceleration efficiency and E_{max} (small **D** ➔ large CR's residence time ➔ high CR's E_{max})
  - number and spectral shape of escaping particles
- escaping particles
  - produce magnetic turbulence that scatters next generation of injected particles
  - re-fill Galactic
- diffusion coeff

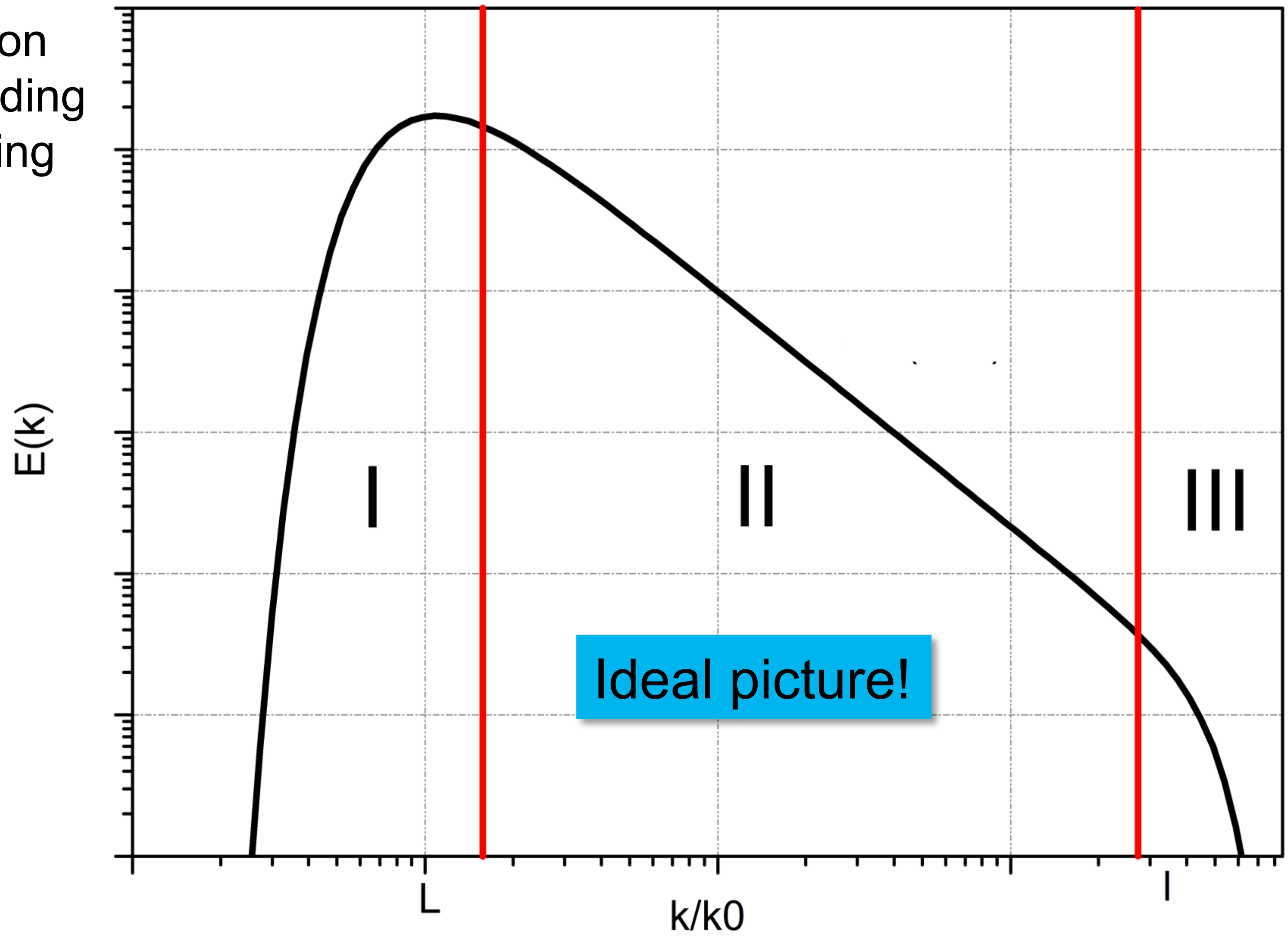
assuming η = const (or E_w = const) is strong (wrong) assumption!

$$D = \eta \frac{v r_g}{3} \qquad \eta = \frac{B_0^2}{\delta B^2} \qquad \delta B^2(k) = B_0^2 \frac{dW(k)}{dk} k$$

$$\delta B^2(k) = B_0^2 \frac{dE_w(k)}{d \ln k} \rightarrow B_0^2 E_w(k) \qquad D = \frac{1}{E_w(k)} \frac{v r_g}{3} \qquad k = \frac{1}{r_g}$$

Magnetic turbulence spectrum: typical view

I injection
II cascading
III damping



Magnetic turbulence spectrum: calculation

- Evolution of magnetic turbulence energy density is given by transport equation:

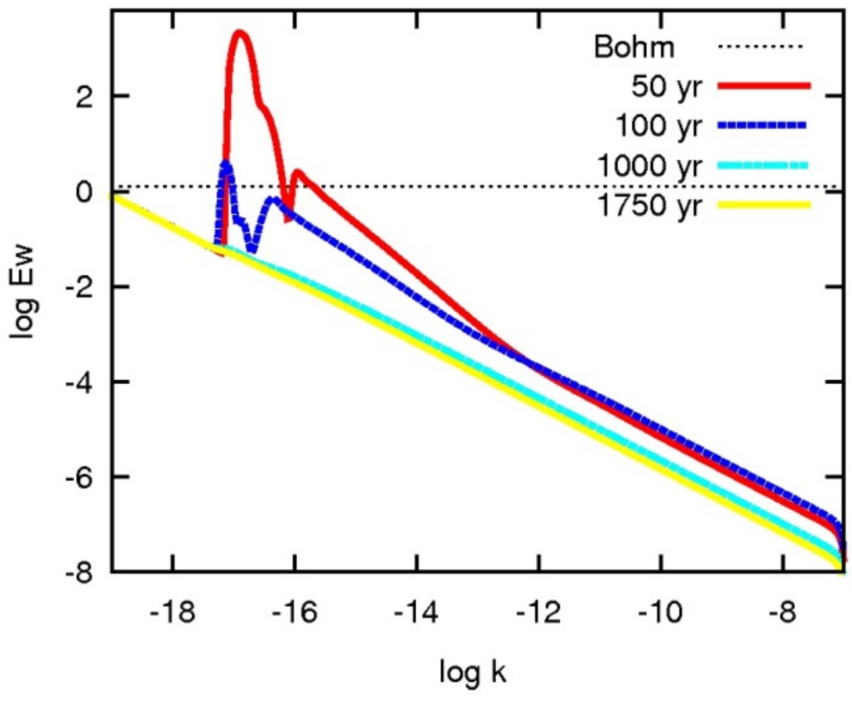
$$\frac{\partial E_w}{\partial t} = k \frac{\partial}{\partial k} k^2 D_k \frac{\partial}{\partial k} \frac{E_w}{k^3} - \nabla(\vec{u} E_w) + (\Gamma_g - \Gamma_d) E_w$$

$$D_k = k^3 v_a \sqrt{\frac{E_w}{2U}} \qquad \Gamma_g = \frac{v_a p v_{cr}}{3U} \frac{\partial N}{\partial x}$$

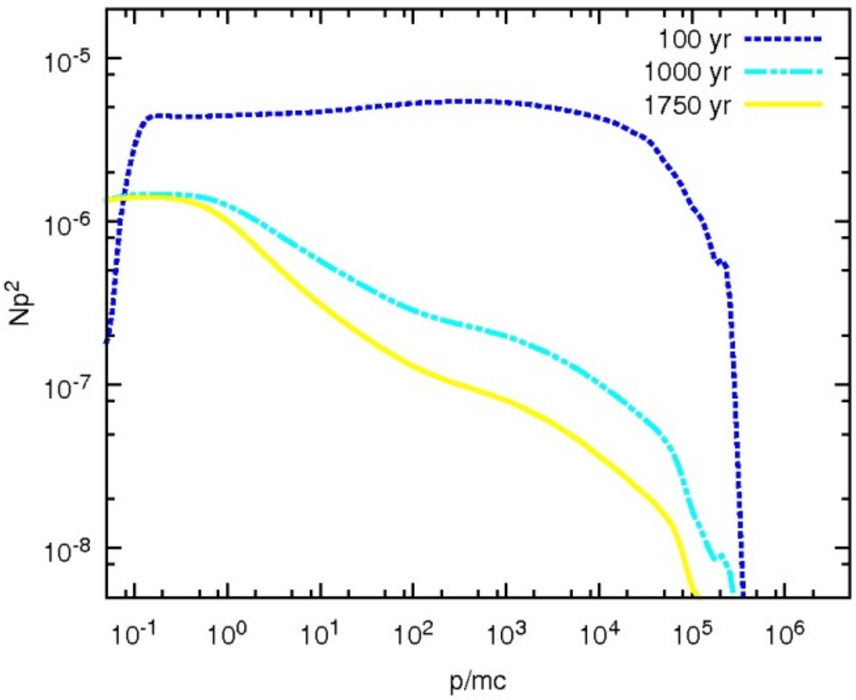
  - E_w – differential (per *ln*k) energy density of magnetic turbulence
  - D_k – cascading coefficient (Zhou & Matthaeus 1990)
  - U – energy density of background magnetic field
  - u – plasma flow velocity
  - v_a – Alfven velocity
  - Γ_g – resonant mode growth rate (Bell 1978)
  - Γ_d – turbulence damping rate
  - N – energy differential number density of CRs

Magnetic turbulence spectrum: first results

Turbulence spectrum

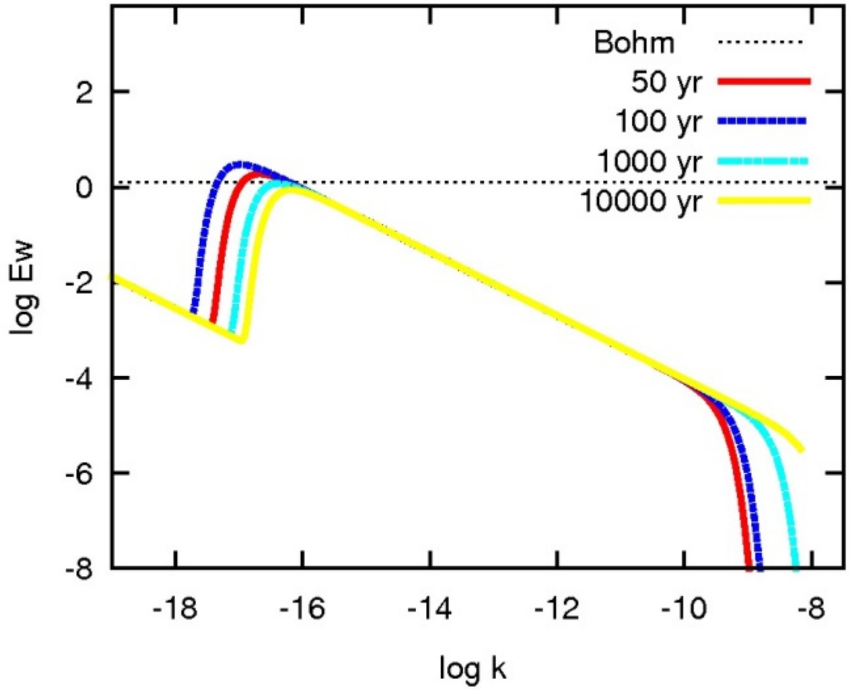


Particle spectrum

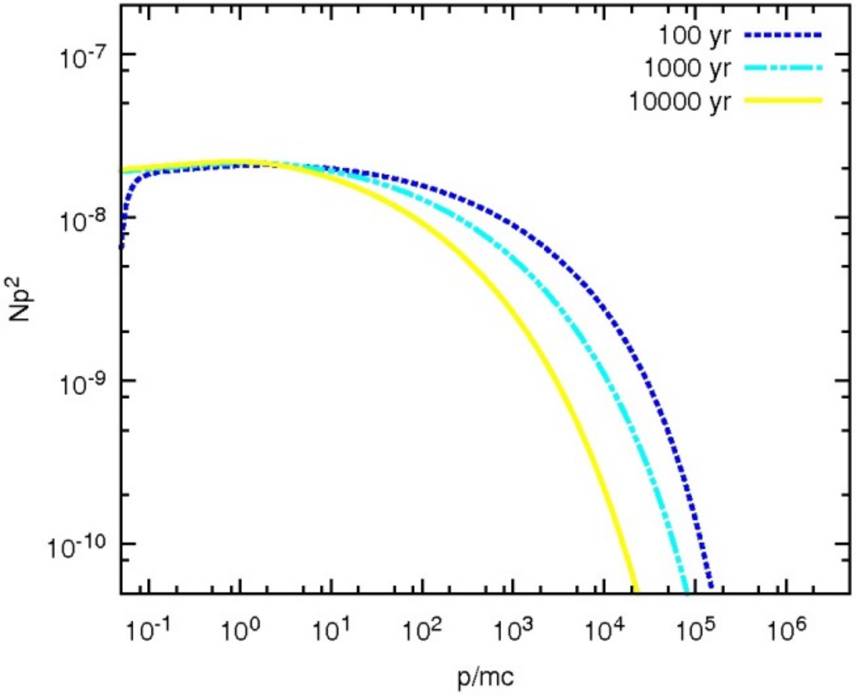


Magnetic turbulence spectrum: analytic approximations

Turbulence spectrum

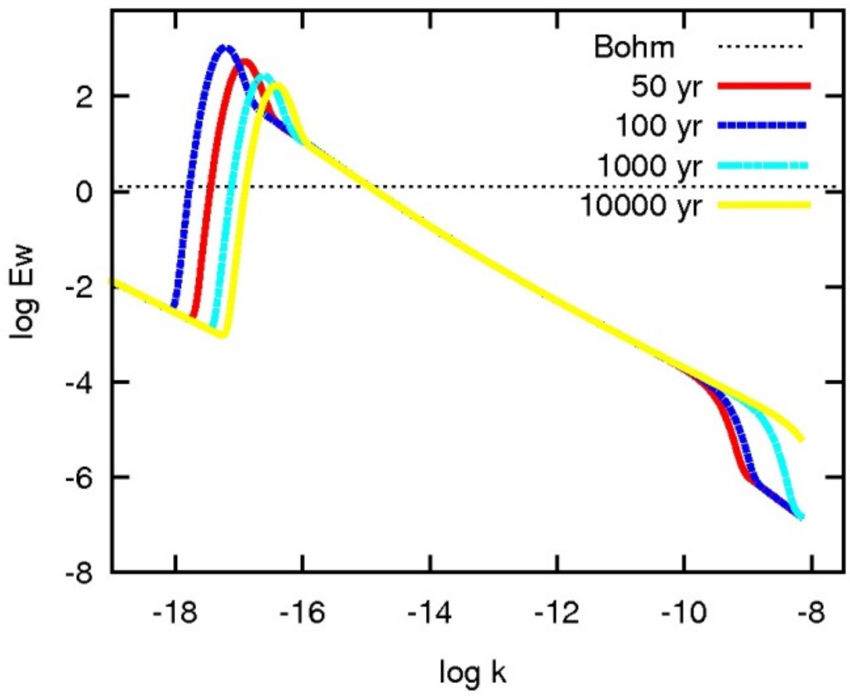


Particle spectrum

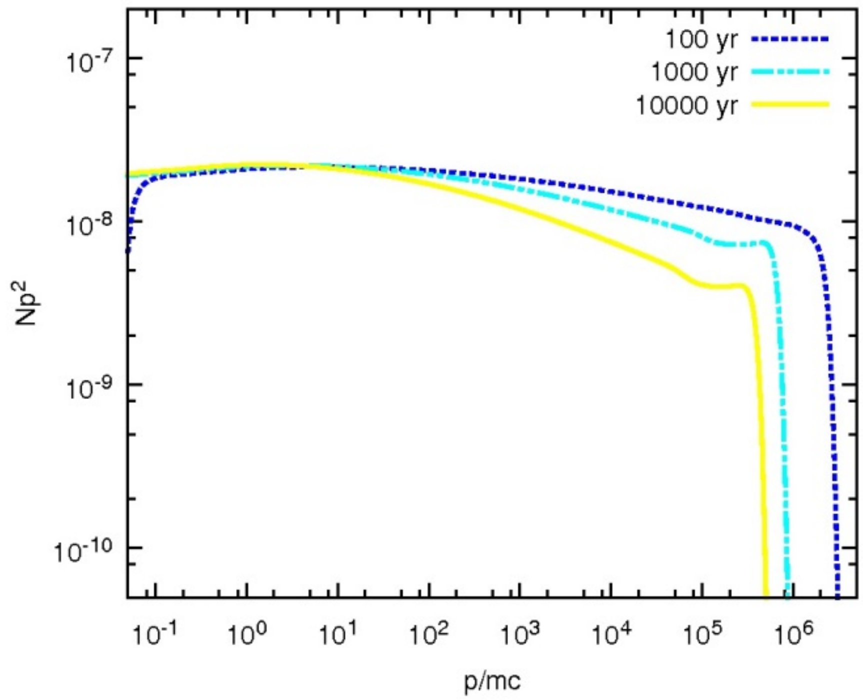


Magnetic turbulence spectrum: analytic approximations

Turbulence spectrum

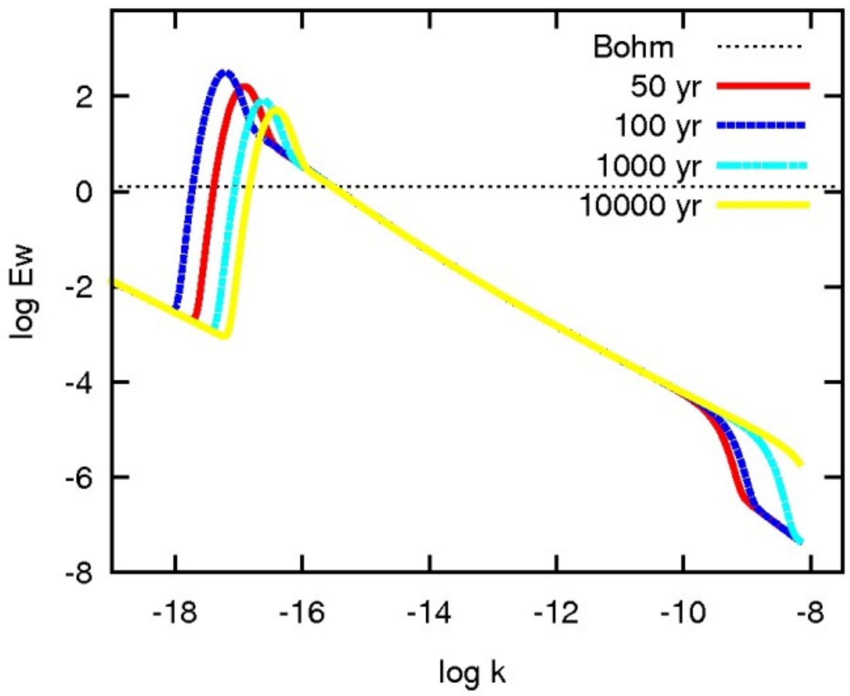


Particle spectrum

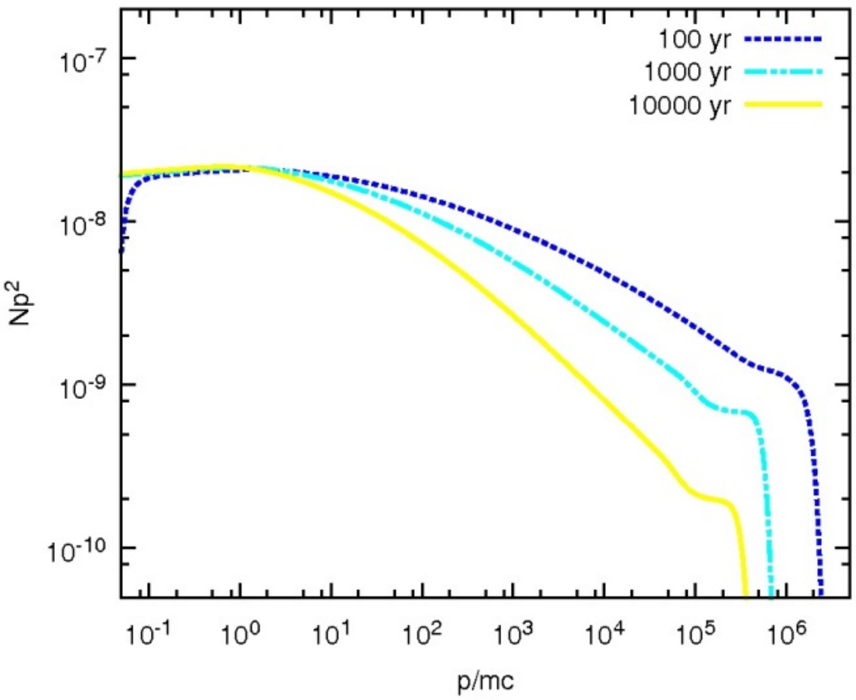


Magnetic turbulence spectrum: analytic approximations

Turbulence spectrum

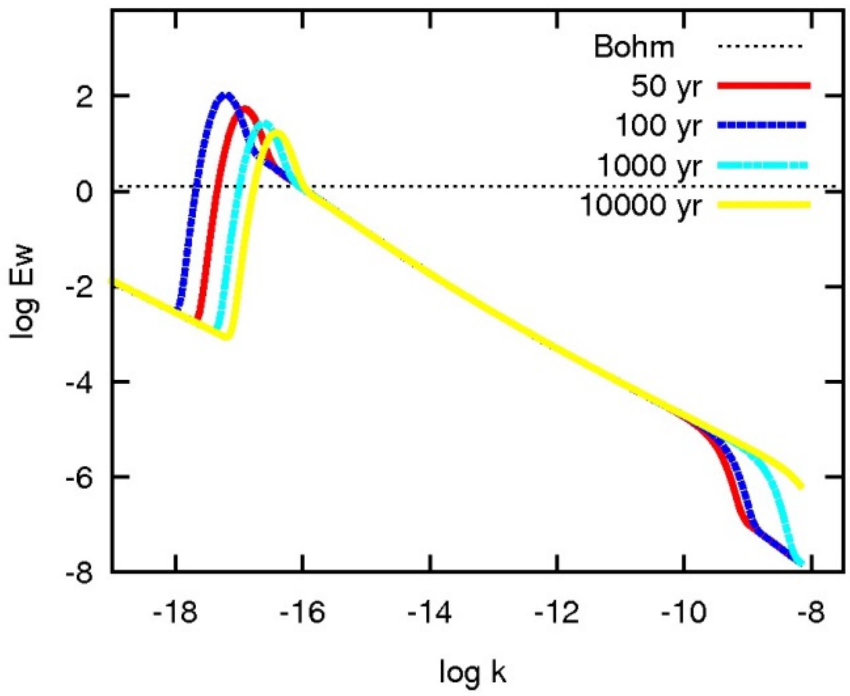


Particle spectrum

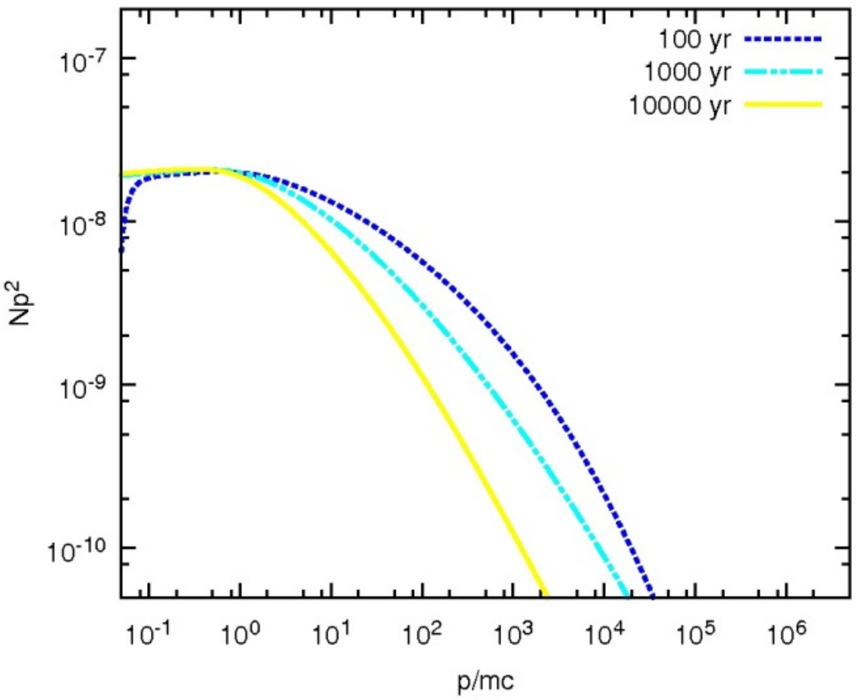


Magnetic turbulence spectrum: analytic approximations

Turbulence spectrum



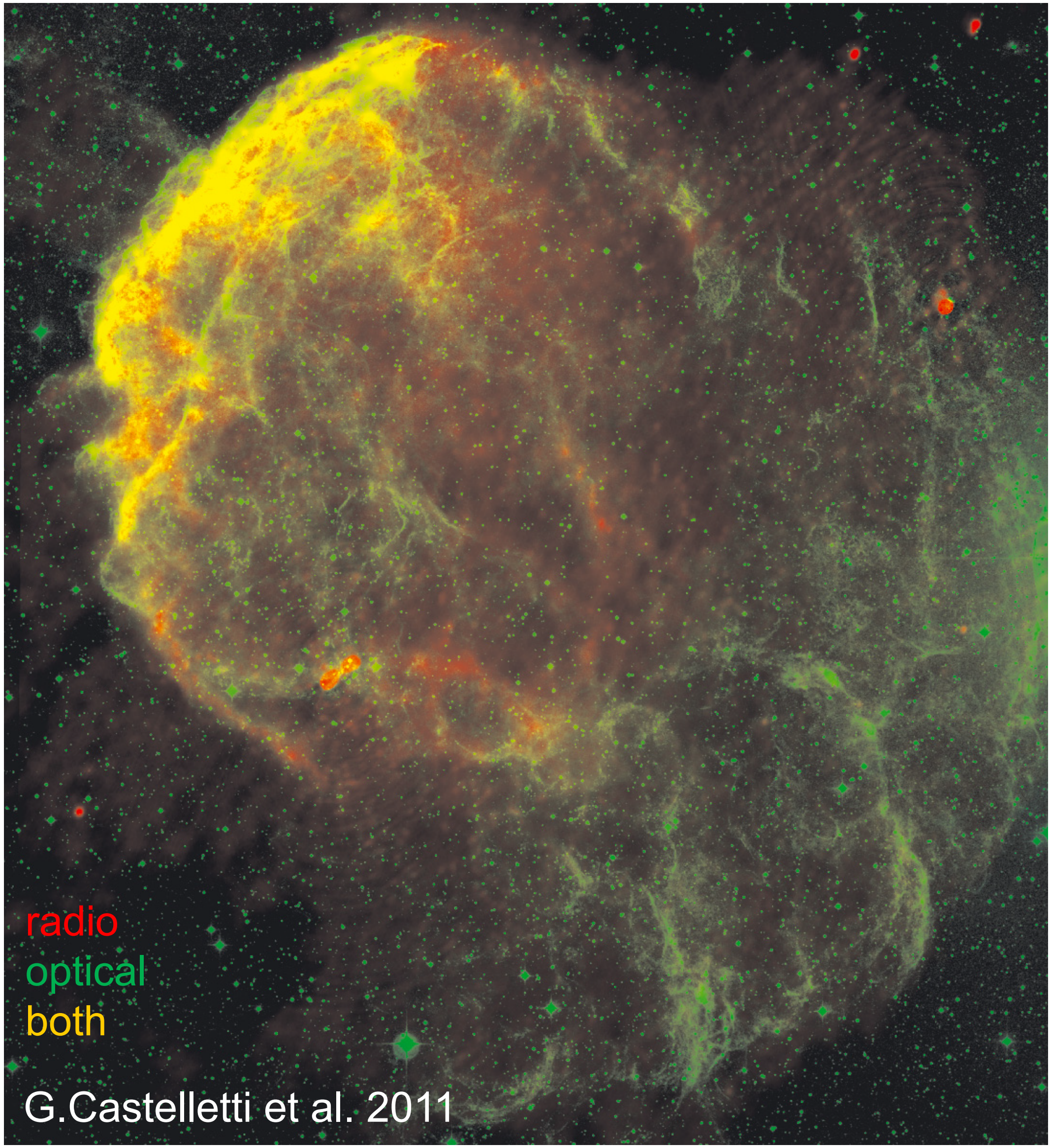
Particle spectrum



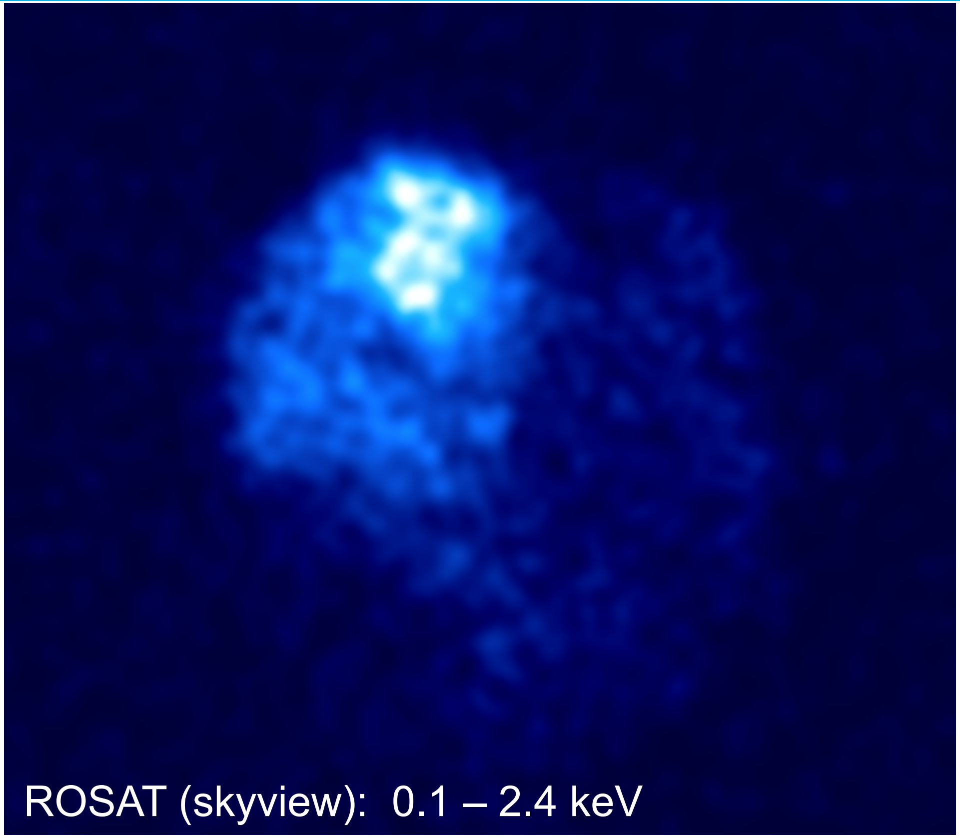
IC443: wide view

Credit: Giovanni Benintende.

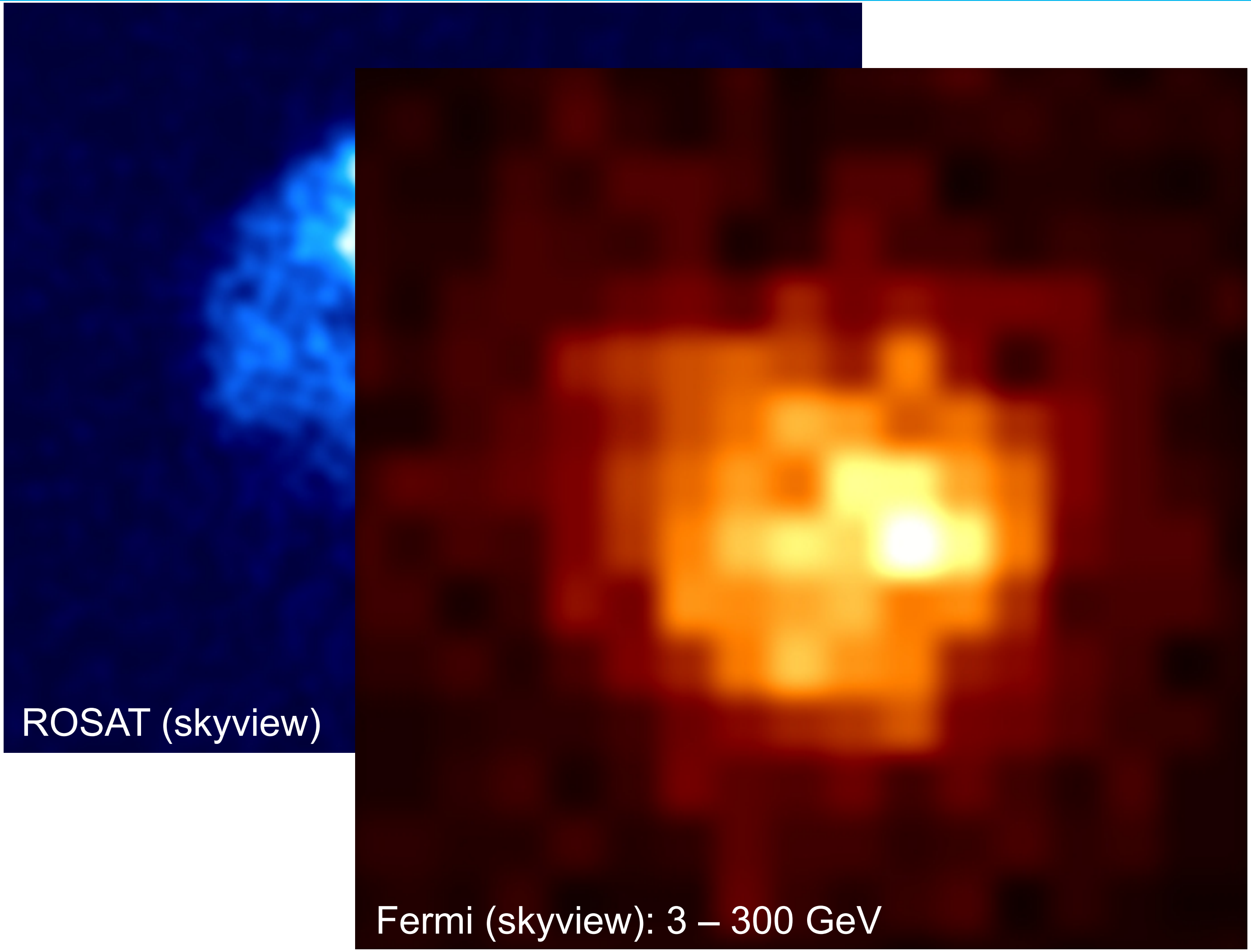
IC443: multi-wavelength source, radio/optical



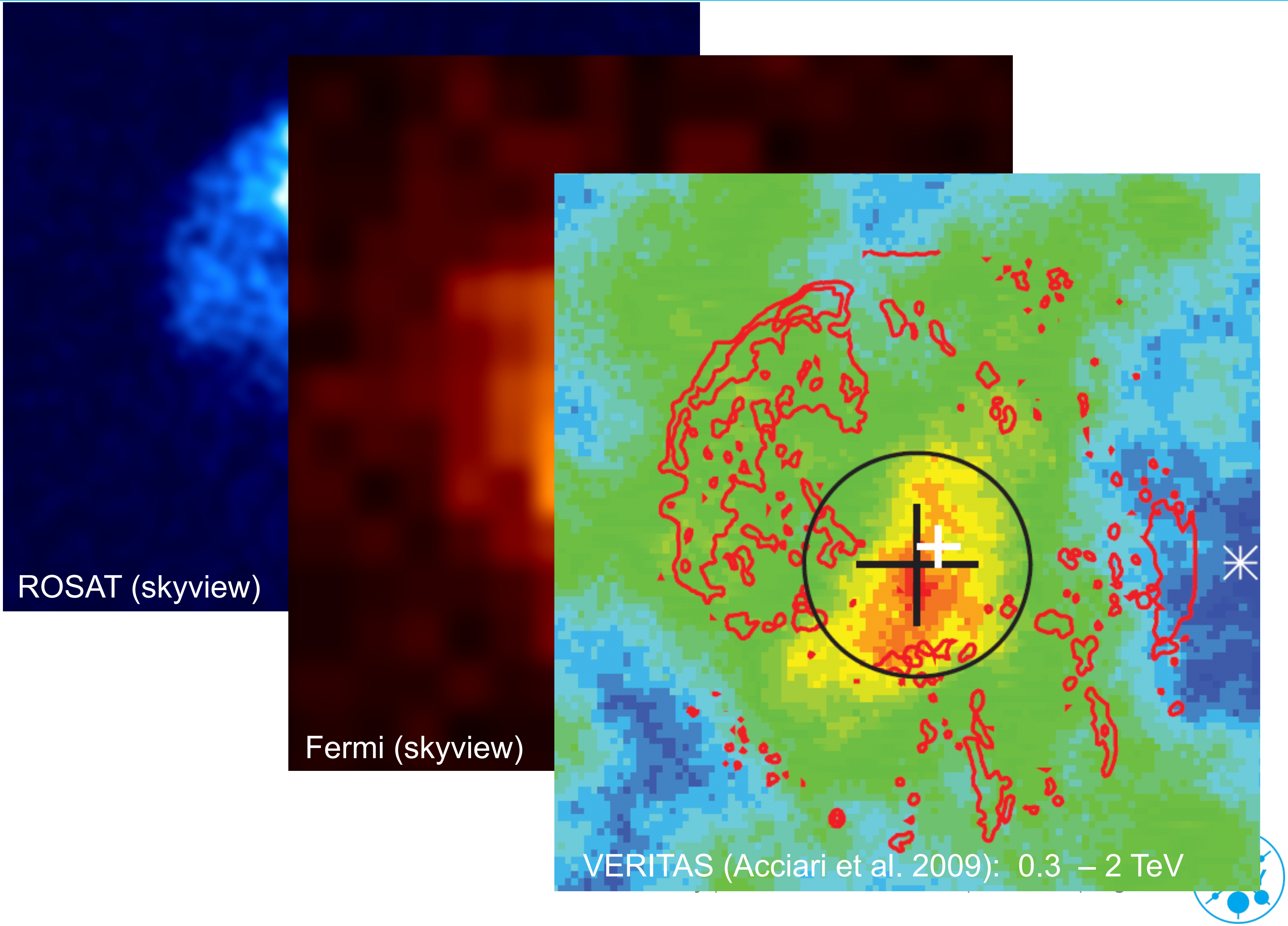
IC443: multi-wavelength source – x-rays



IC443: multi-wavelength source – x-rays, HE γ-rays



IC443: multi-wavelength source – x-rays, HE, VHE γ-rays



IC443: parameters

- type: mixed-morphology
  - radio shell, center-filled X-rays
- age (unclear): 3-30 kyr
- distance: 1.5 kpc
- size: 45’ -> 20 pc
  - two half-spheres: R_1 = 7.7 pc, R_2 = 12.1 pc
- indications of interaction with dense material
  - $n = 10 - 10^4$ cm^{-3}
- radiative stage of evolution?
  - slow shocks

IC443: modeling HD and CRs

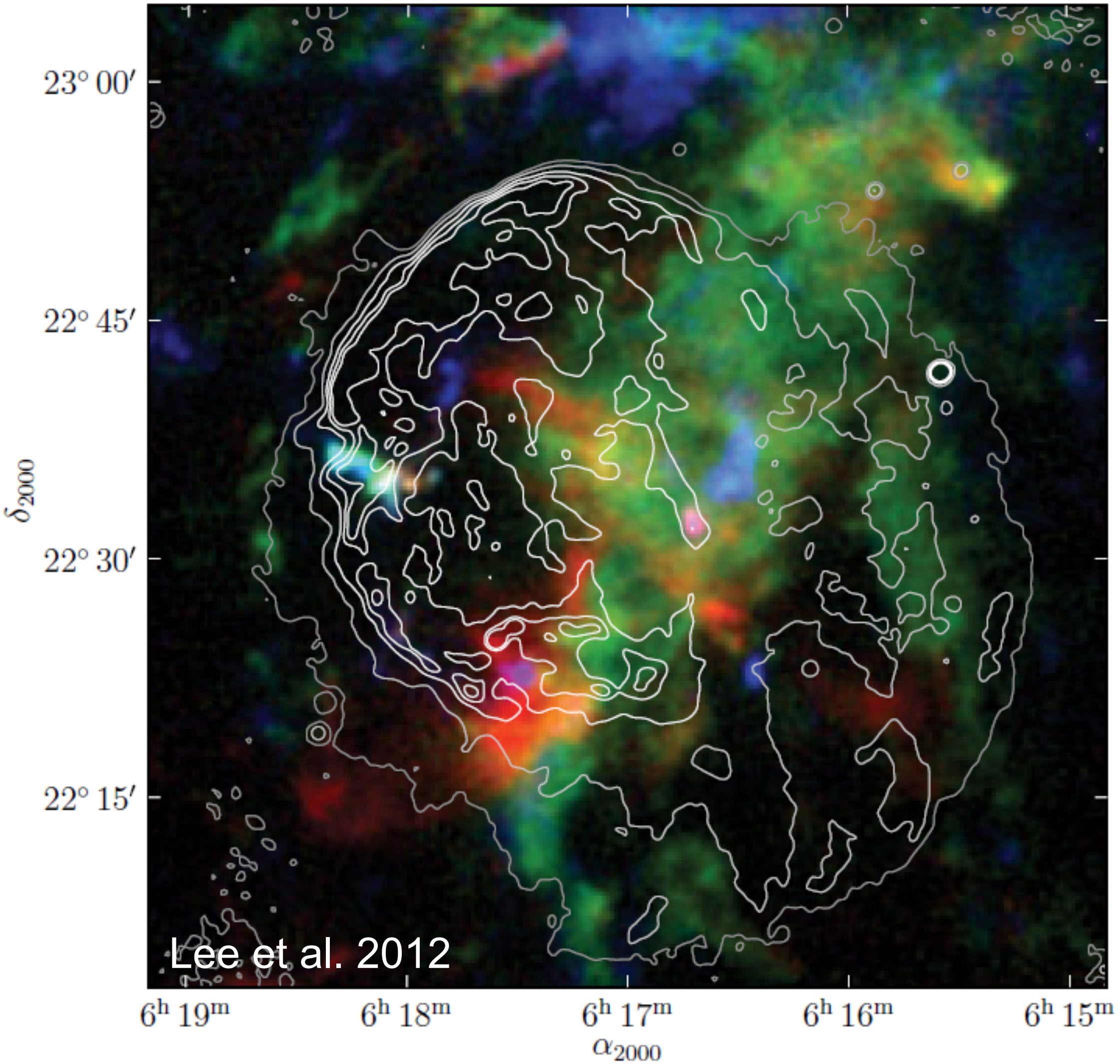
- $t = 12500$ yr
- $E_{SN} = 1e51$ ergs
- $n_1 = 12$ cm^{-3} ➔ $R_1(t) = 7.7$ pc
  - $t_{tr} = 7780$ yr, $V_{sh} = 0.5V_{sh}(t_{tr}) = 170$km/s
- $n_2 = 1.9$ cm^{-3} ➔ $R_2(t) = 12.1$ pc
- $B_{0,1} = 20\ \mu$G
- $B_{0,2} = 6\ \mu$G
- D is calculated from analytically assumed turbulence spectrum
- Consider injected + background galactic CRs
- $E_{CR} = 0.05\ E_{SN}$

IC443: modeling emission

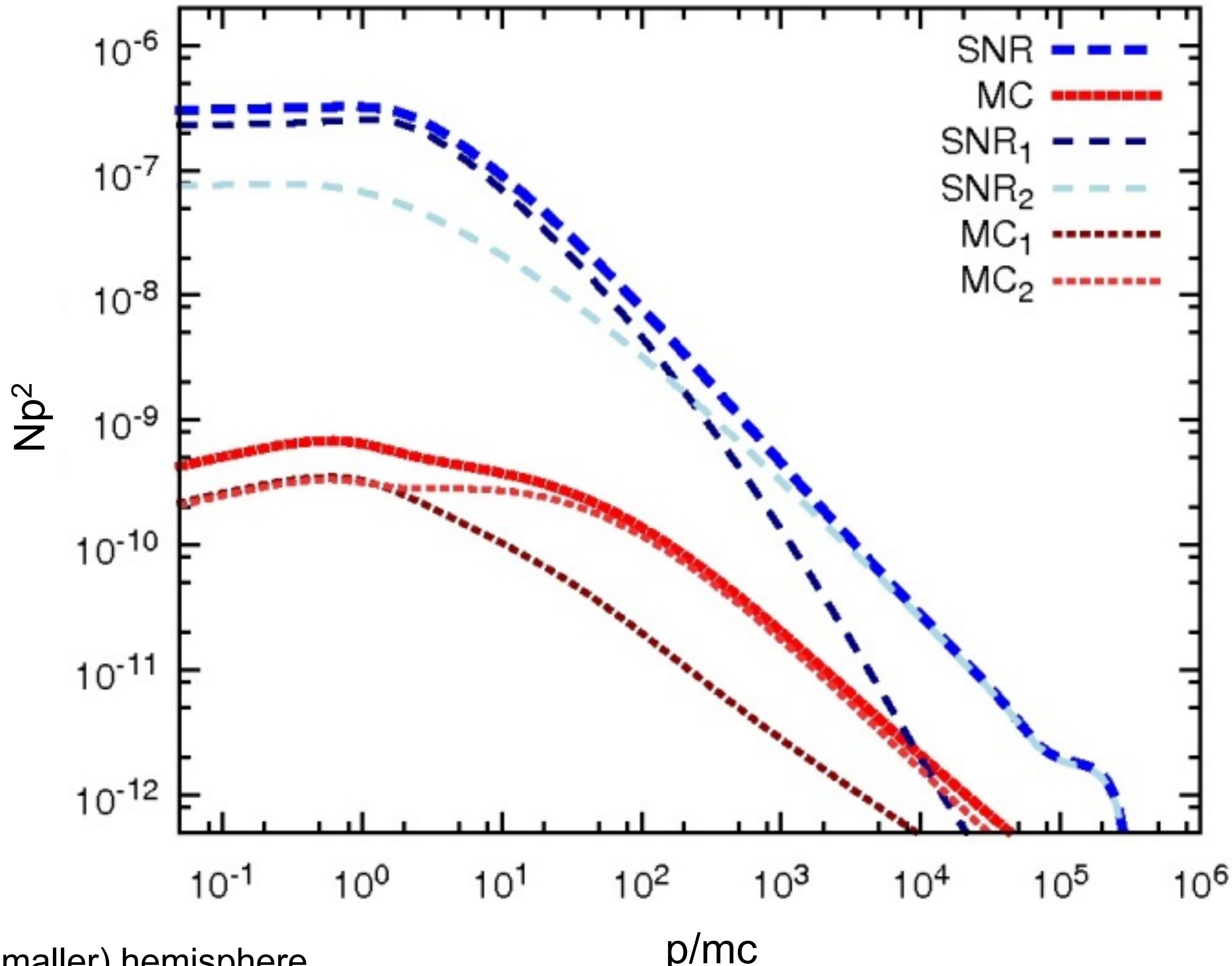
- ^{12}CO image traces dense material

- Molecular cloud:
  - d_{MC} ~ 13 pc
  - R_{MC} ~ 3 pc
  - M_{MC} ~ 10^5 M_{Sun}

- pion-decay
  - two SNR hemispheres
  - dense material illuminated by escaped CRs

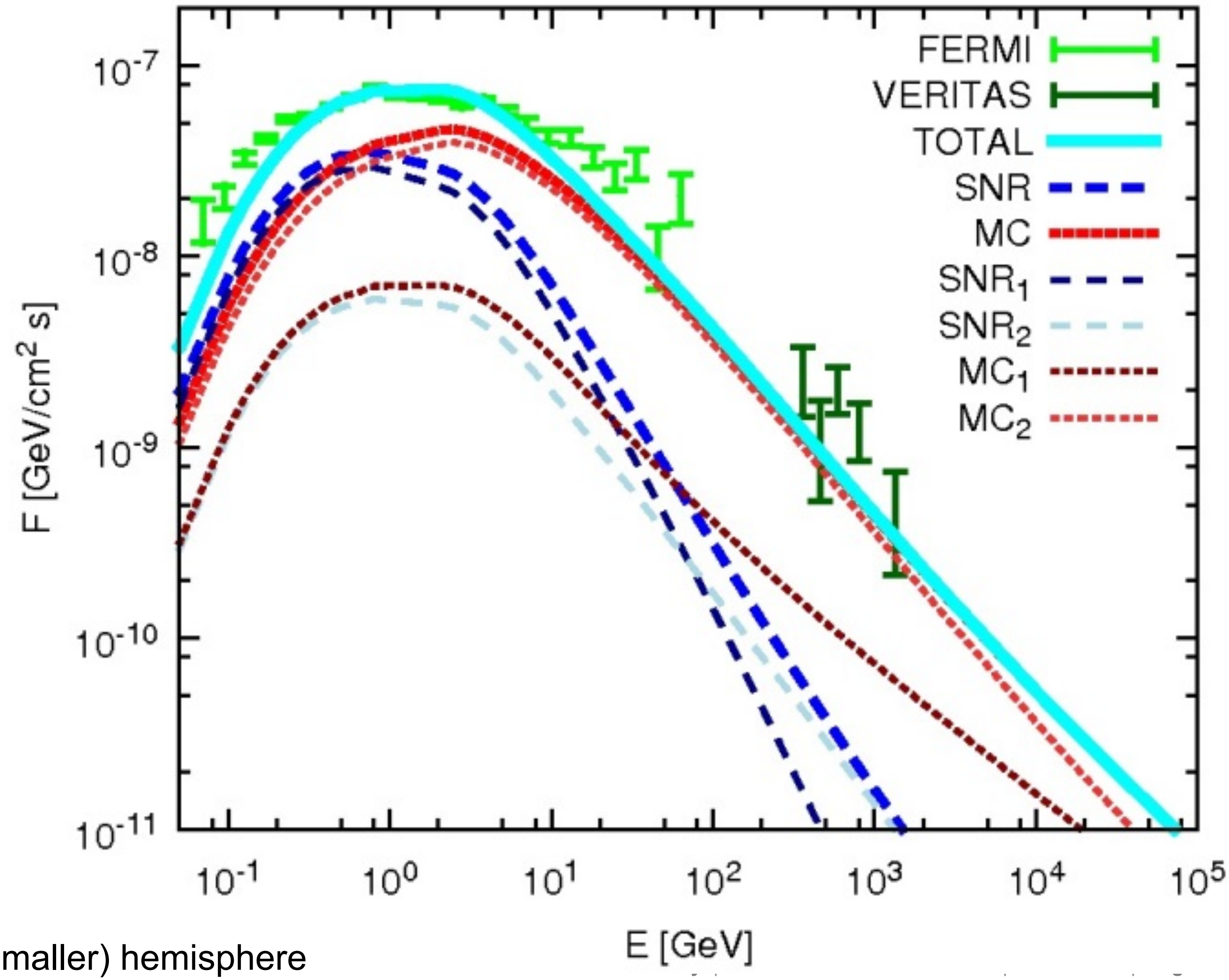


IC443: first results – proton spectra



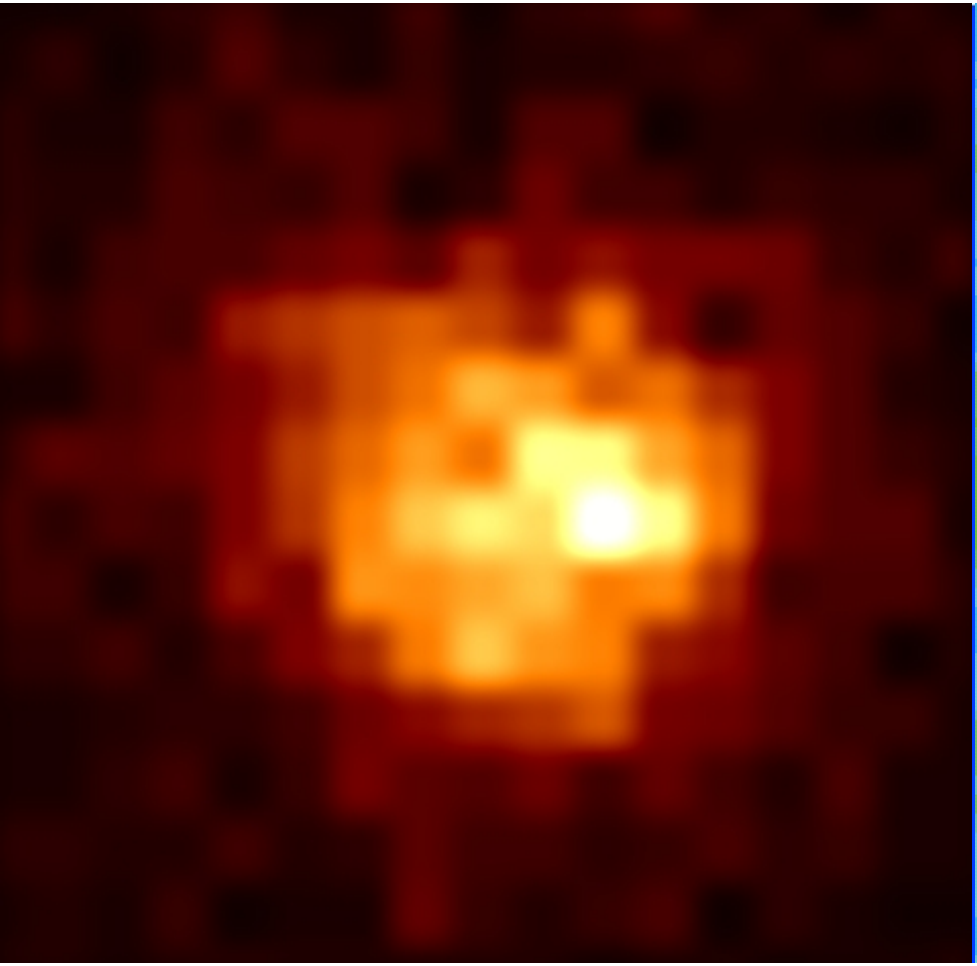
1 – NE (smaller) hemisphere
2 – SW (larger) hemisphere

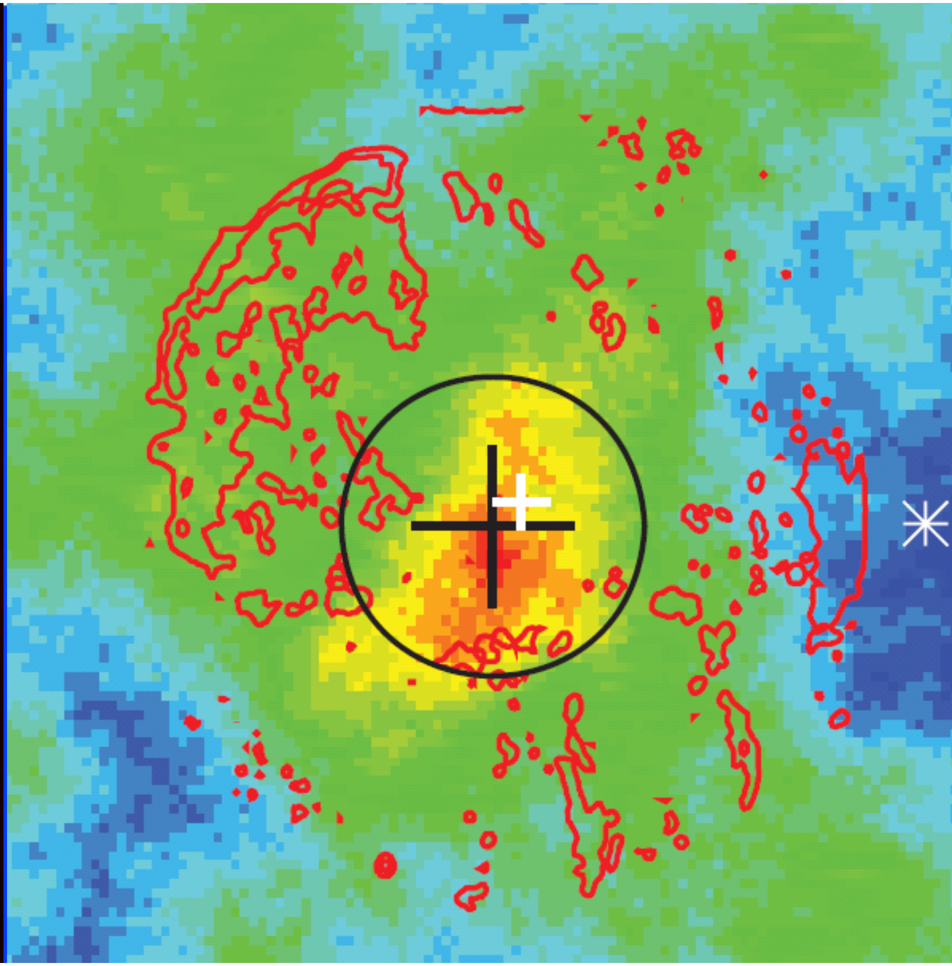
IC443: first results – radiation spectra



1 – NE (smaller) hemisphere
2 – SW (larger) hemisphere

IC443: first results – radiation maps





Summary

- Magnetic turbulence spectrum is not “white noise”
  - details on the spectral shape are not known
  - requires coupling and simultaneous solution of both turbulence and particle transport equations
- If taken into account, turbulence spectrum affects particle diffusion, which modifies CR distributions
  - inside the SNR (downstream of the shock)
  - at the position of target material (escaped particles)
- Observed spectral breaks may be naturally obtained
- The proposed model may explain HE/VHE data on IC443
  - thorough analysis of dense matter distribution around SNR is required to build realistic emission models