Particle Escape from post-adiabatic SNRs

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The cosmic-ray spectrum

The Plot I

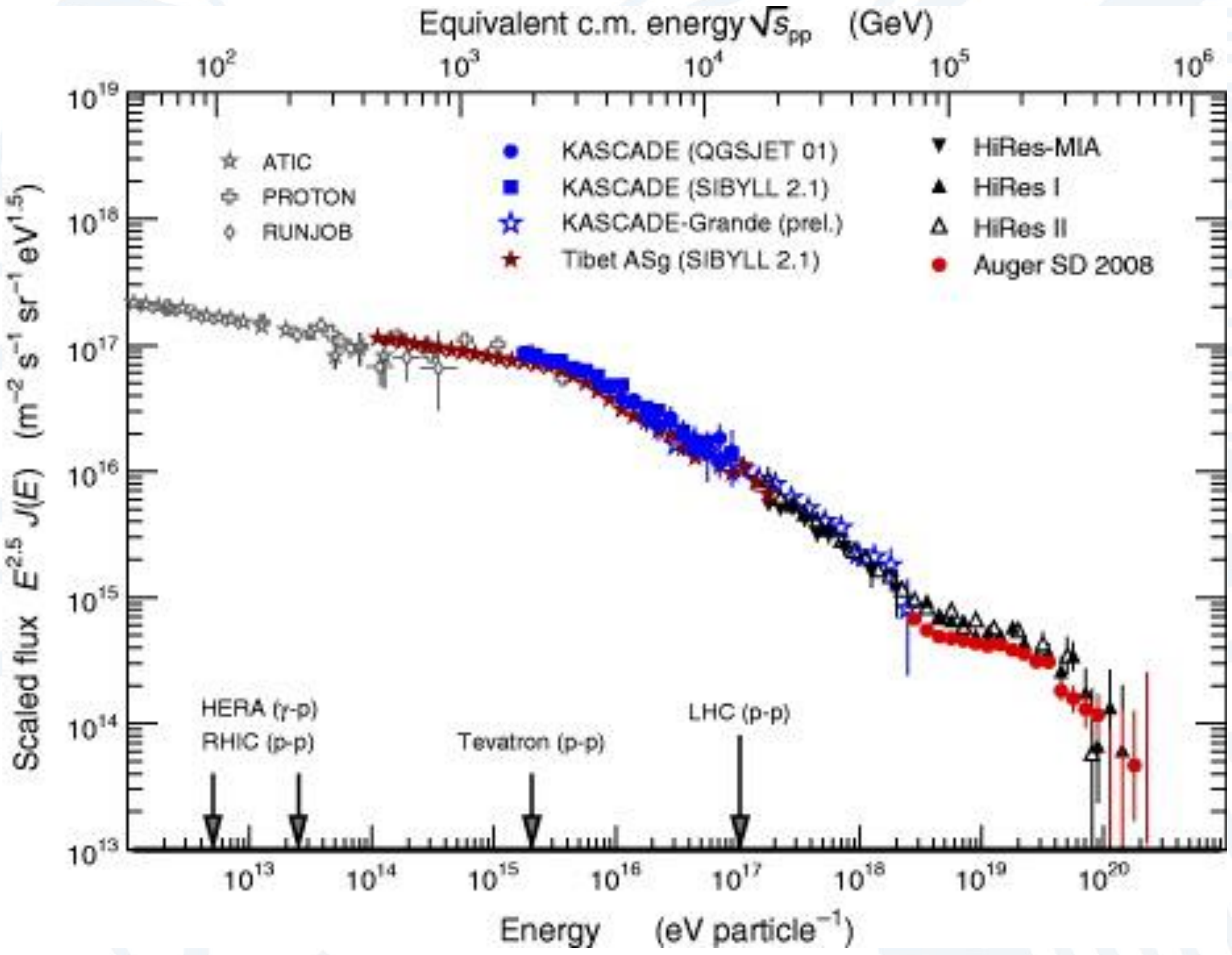


Figure: The cosmic ray spectrum (Blümer et al. 2019)

What is the origin of galactic cosmic rays?
Supernova remnants?

The cosmic-ray spectrum
Experimental evidence

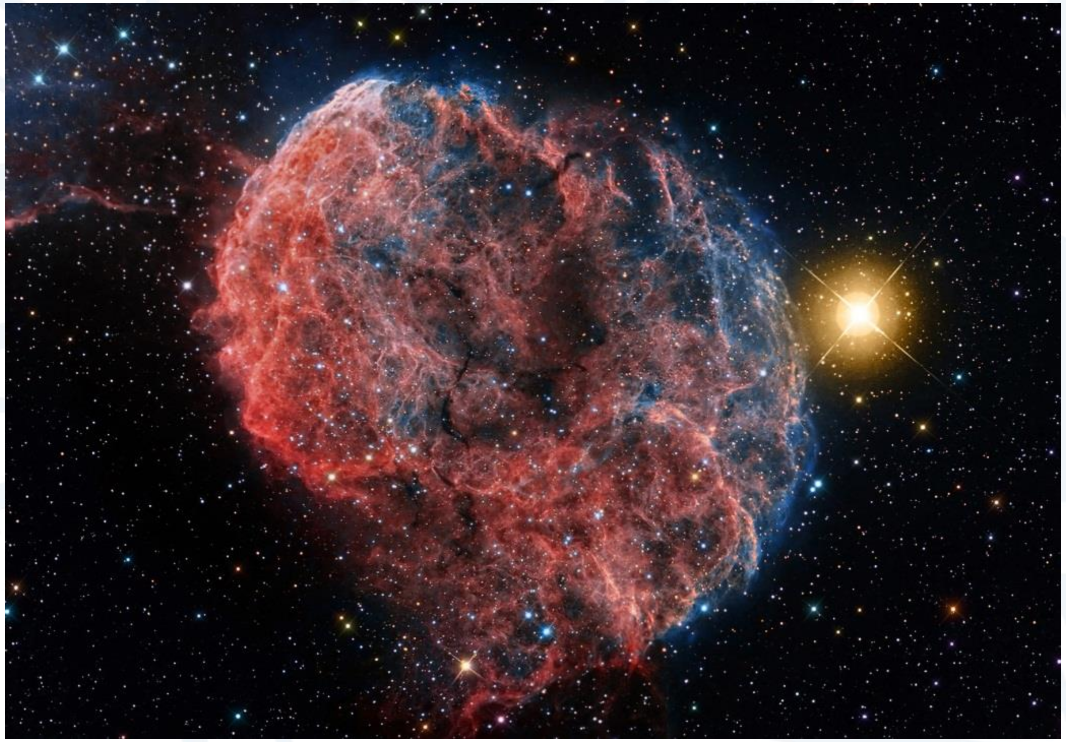
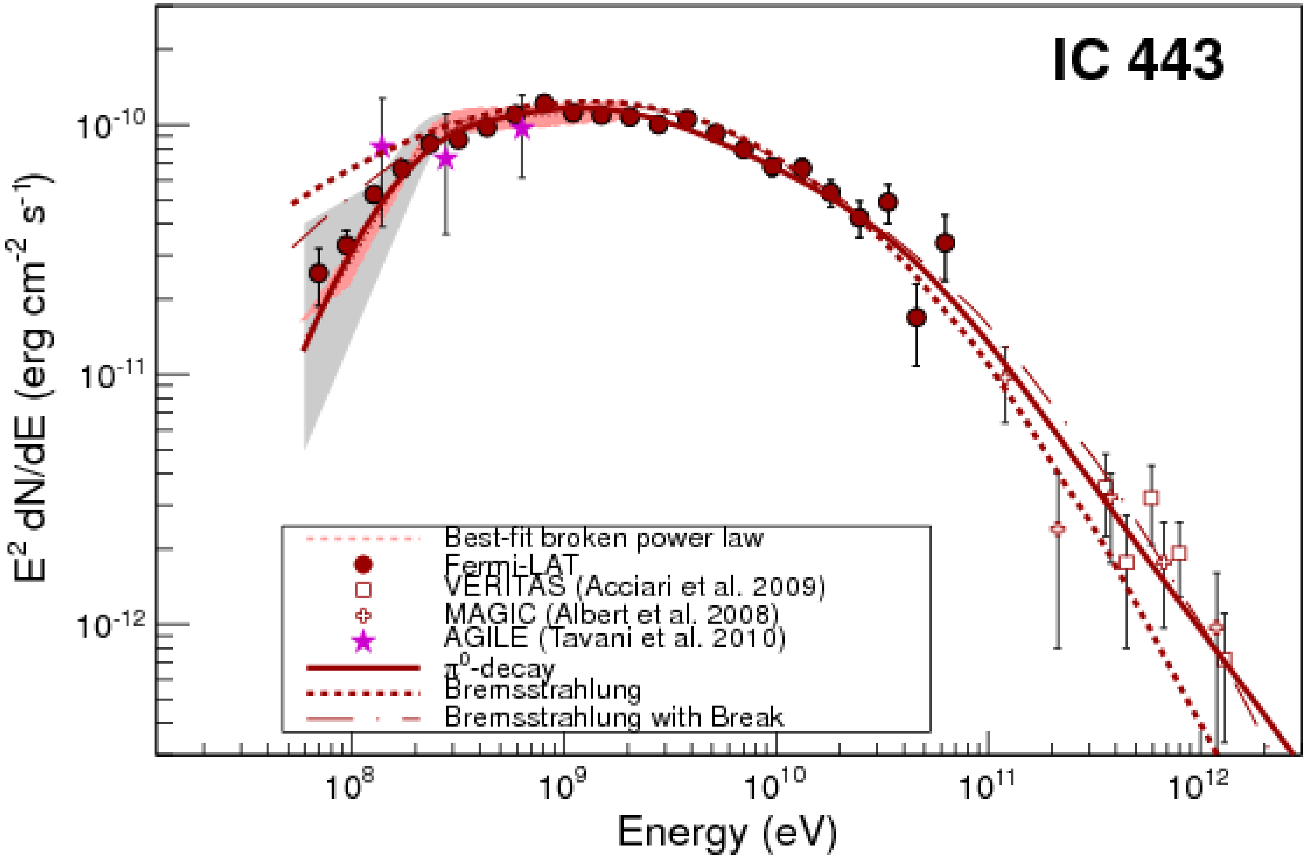
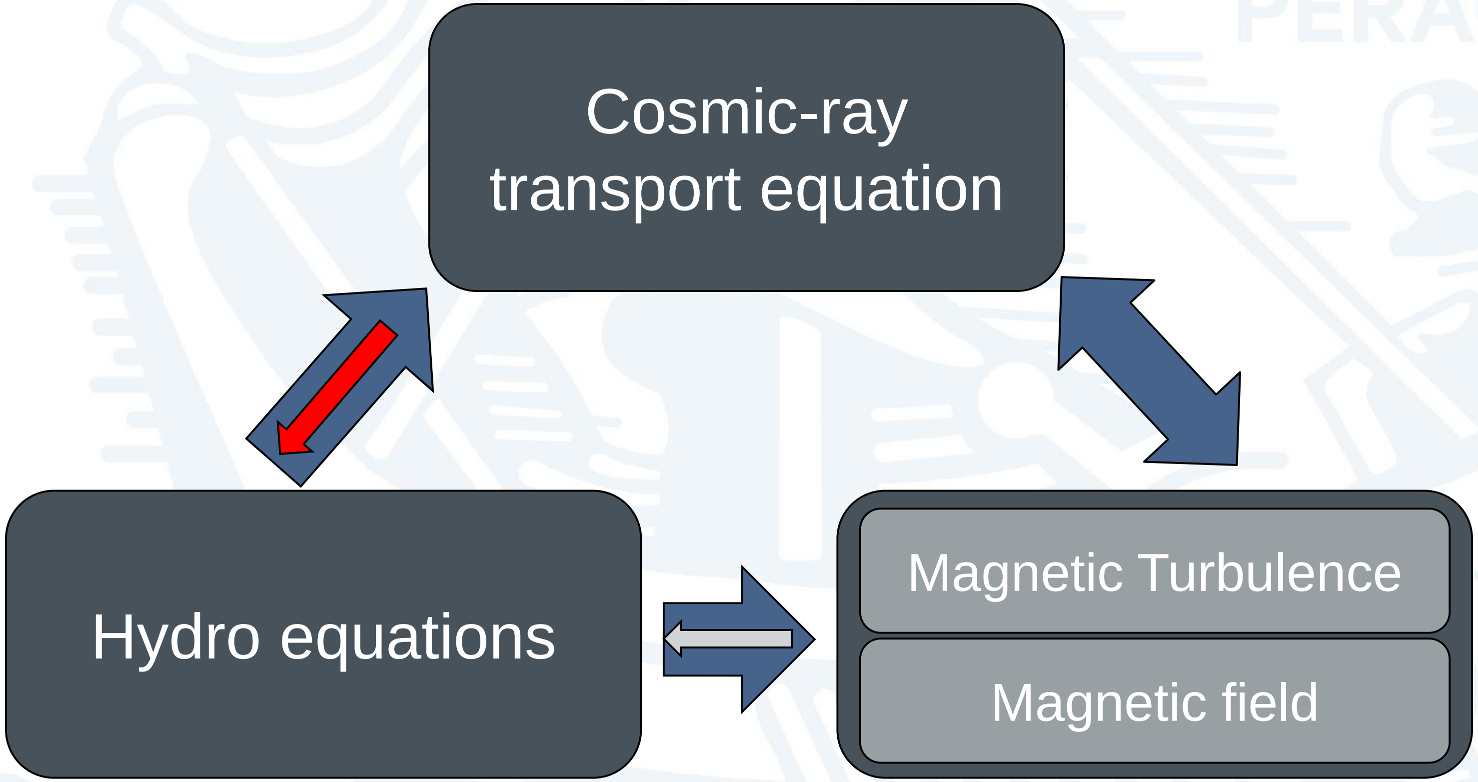


Figure: IC443 – multi wavelength image (credit: Dieter Willasch)

Figure: IC443 – gamma ray emission (Funk et al. 2013)



Fermi acceleration
Coupled equations



Standard DSA | Non-linear DSA | NDSA + high MF

DIAS
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Fermi acceleration

The equations

$$\frac{\partial N}{\partial t} = \underbrace{\nabla D_r \nabla N}_{\text{Diffusion}} - \underbrace{\nabla v N}_{\text{Advection}} - \frac{\partial}{\partial p}\Big(\underbrace{N\dot{p}}_{\text{Cooling}} - \underbrace{\frac{v}{3} N p}_{\text{Acceleration}}\Big) + \underbrace{Q}_{\text{Injection}}$$

$$\frac{\partial E_W}{\partial t} = - \underbrace{(v\nabla_r E_W + c\nabla_r v E_W)}_{\text{Advection + Compression}} + \underbrace{k^3 \nabla_k D_k \nabla_k \frac{E_W}{k^3}}_{\text{Cascading}} + \underbrace{2(\Gamma_g - \Gamma_d) E_W}_{\text{Growth + Damping}}$$

$$\frac{\partial}{\partial t}\begin{pmatrix} \varrho \\ \boldsymbol{m} \\ E \end{pmatrix} + \nabla \begin{pmatrix} \varrho \boldsymbol{v} \\ \boldsymbol{m}\boldsymbol{v} + (P + P_{CR})\boldsymbol{I} \\ (E + P + P_{CR})\boldsymbol{v} \end{pmatrix} = \begin{pmatrix} 0 \\ 0 \\ L \end{pmatrix}$$

$$\frac{\rho v^2}{2} + \frac{P}{\gamma - 1} = E$$

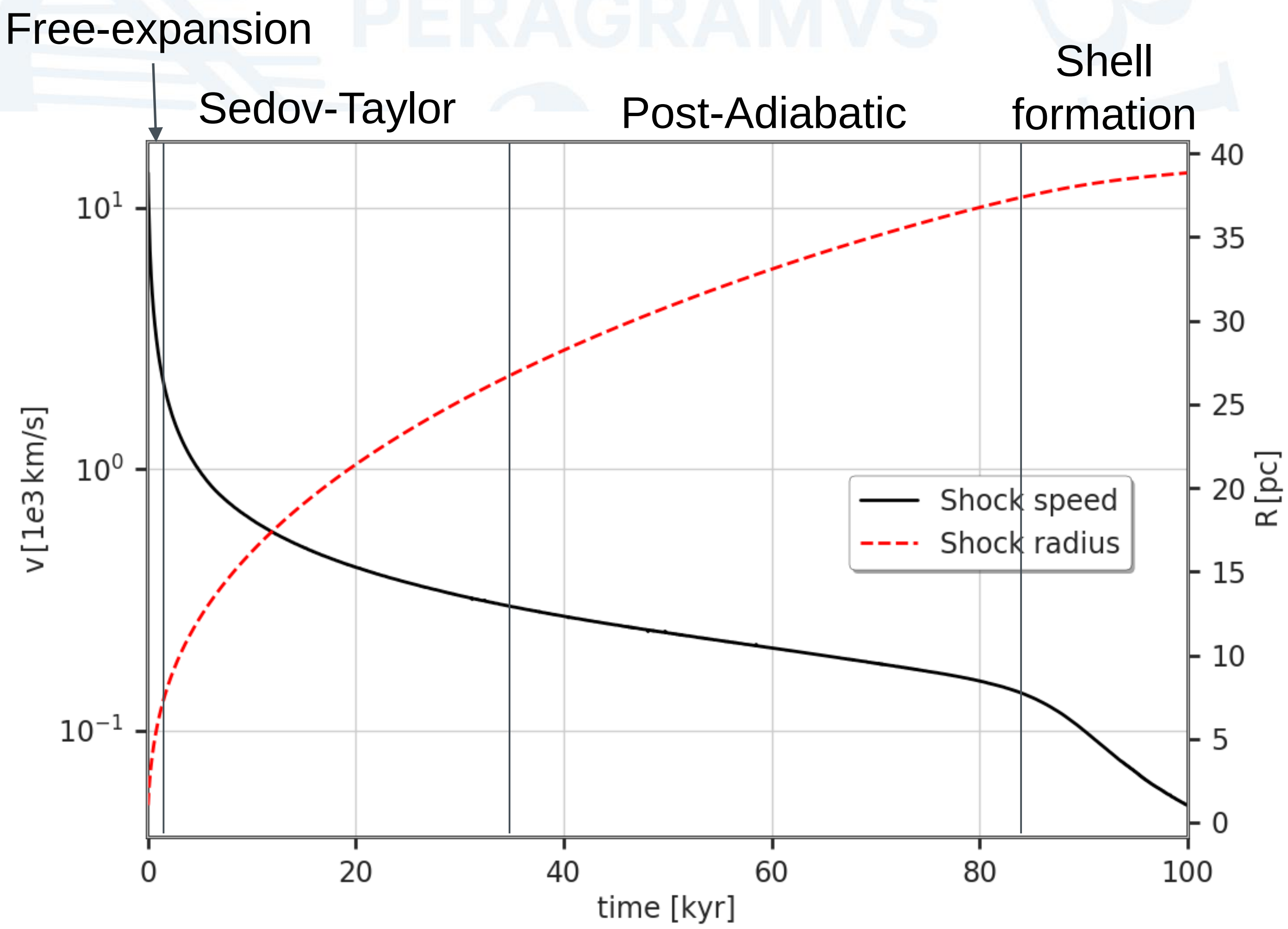
The equations are solved:

- One dimensional
- Assuming spherical symmetry
- Including Synchrotron cooling for electrons
- On a comoving, expanding grid for turbulence and CRs → no free escape boundary

Cosmic-ray escape
Model Parameters and Hydrodynamic evolution

Hydrodynamics:
- Type-Ia explosion
  - $n_0 = 0.3\ cm^{-3}$, $T_{ISM} = 40000K$, $E_{expl} = 10^{51}$ erg, $M_{ej} = 1.4\ M_{sol}$
- $B_0 = 5\ \mu G$, Transported field

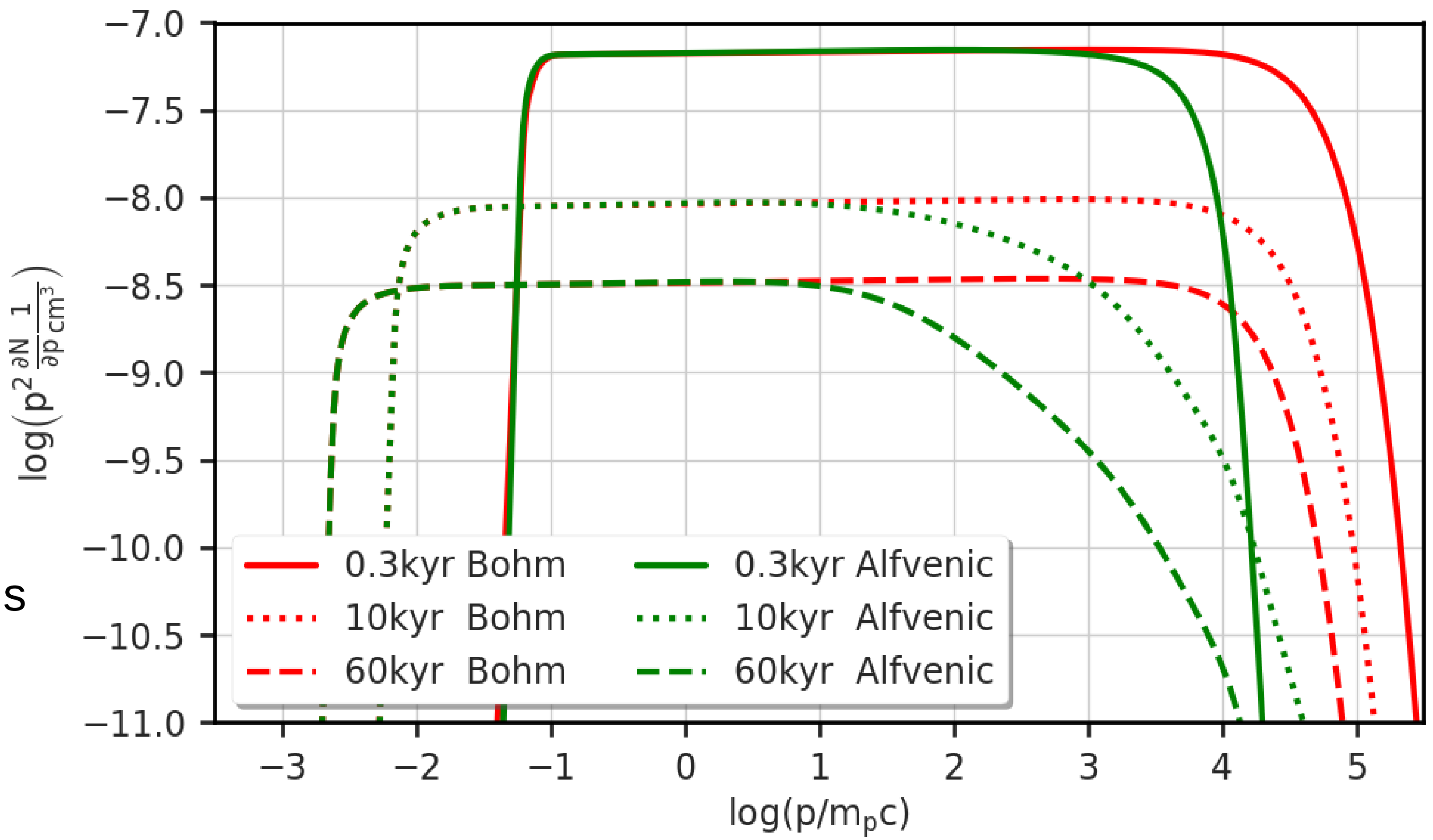
Cosmic rays:
- Electrons and protons
- Two diffusion models:
  - Bohm-like diffusion (no time evolution)
  - Alfvenic diffusion (time-dependent diffusion coefficient)



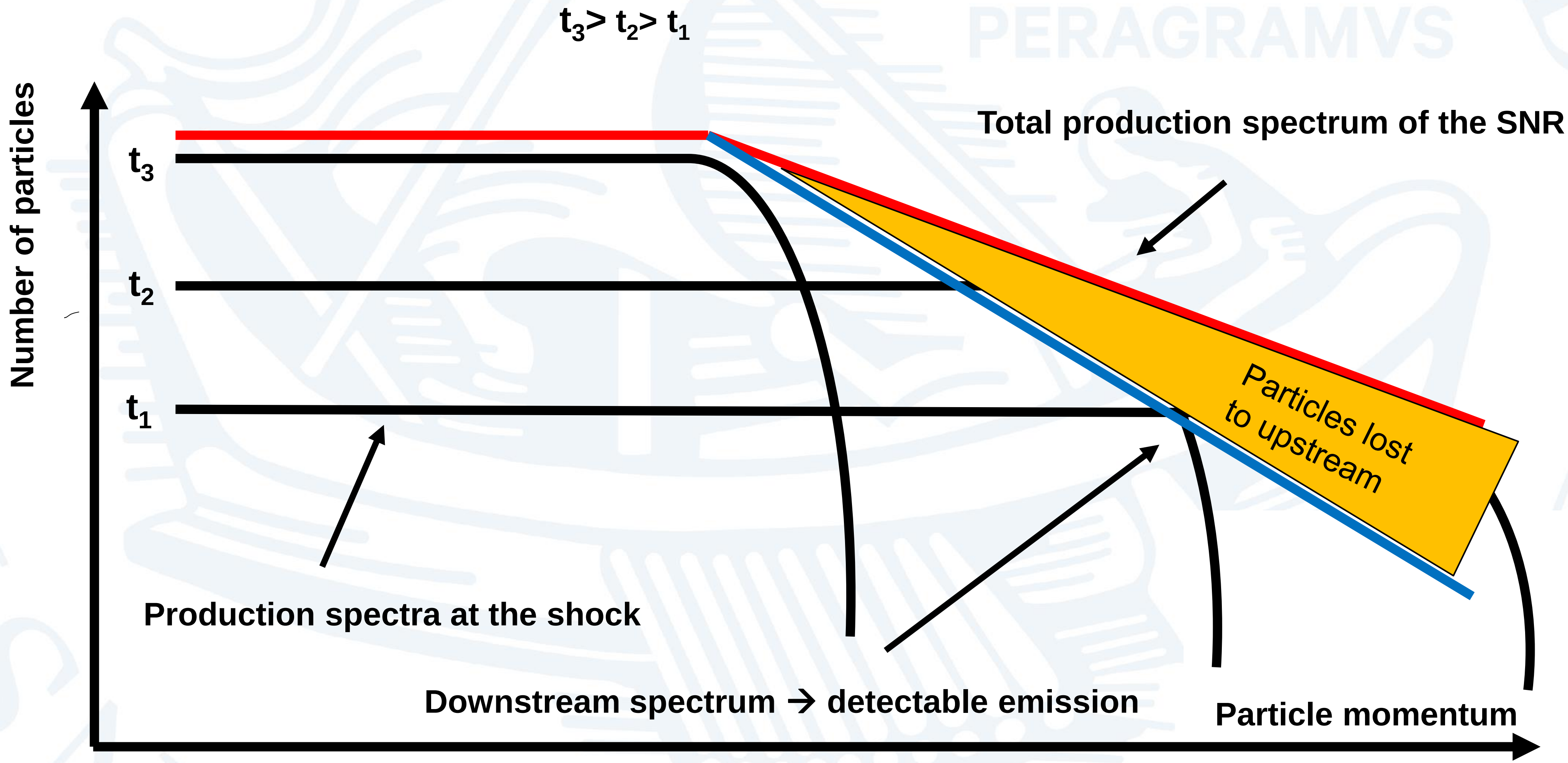
Cosmic-ray escape
Downstream spectra

Bohm-diffusion:
- Spectra are s=-2 power-laws
- Maximum energy decreases by factor ~10

Alfvenic diffusion:
- Maximum energy strongly time-dependent → decrease by factor ~1000
- Spectra get soft at high energies
- A spectral break at 1-10GeV forms



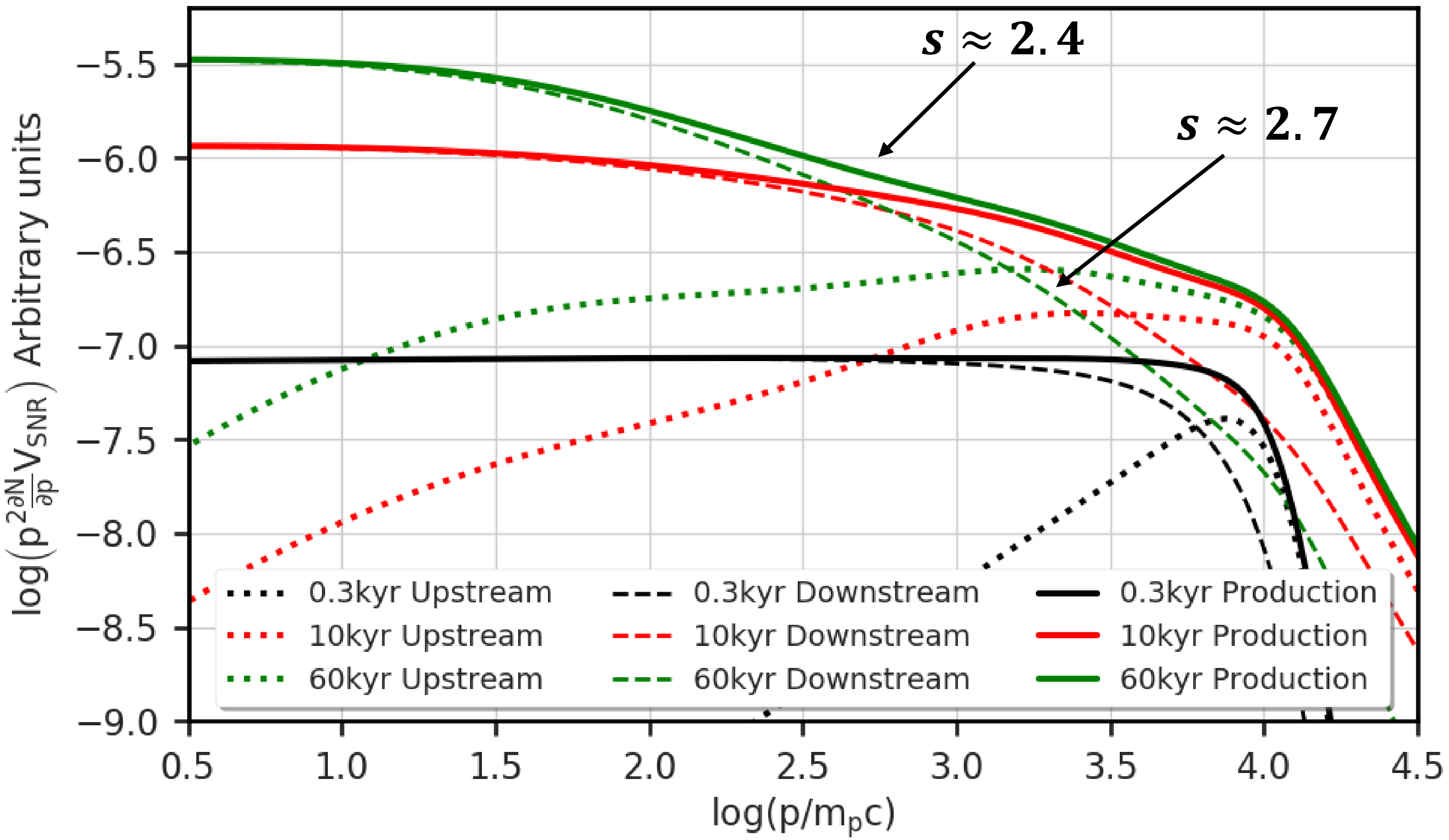
Cosmic-ray escape
The mechanism



Cosmic-ray escape

Production spectra

- The production spectrum agrees roughly with galactic propagation models
- The downstream spectra are softer than the production spectra
- Particles “escape” from deep downstream to upstream



The VHE gamma-ray luminosity

The VHE gamma-ray luminosity

The Plot II

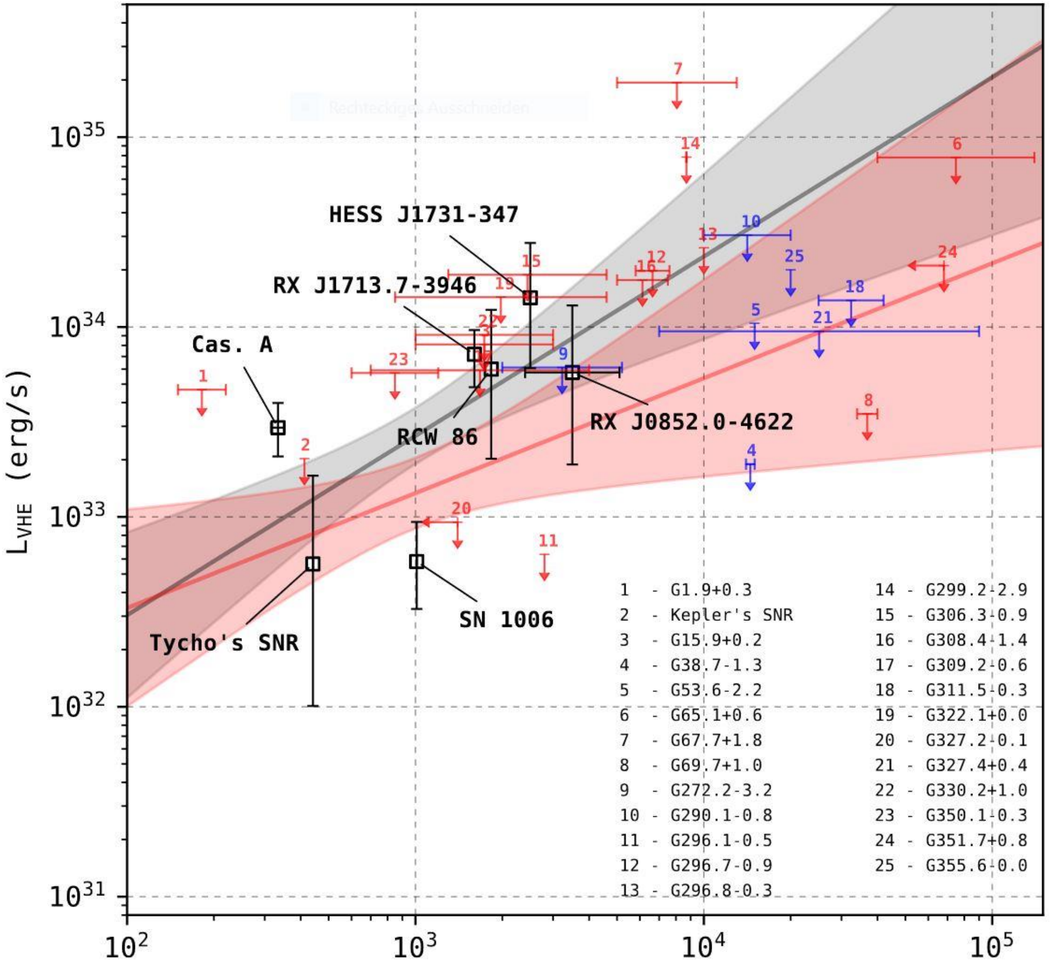
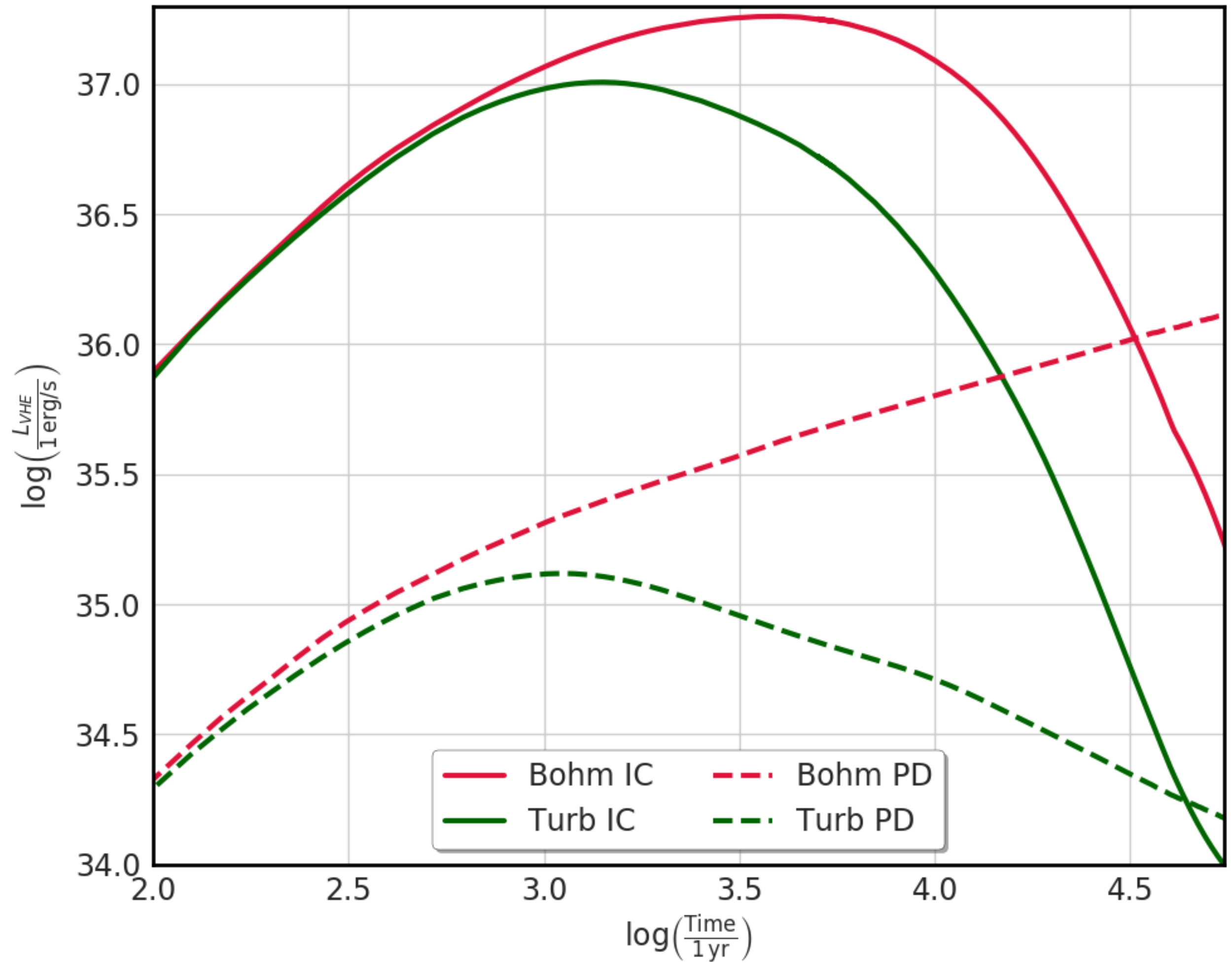


Figure: H.E.S.S. 2018

Why are there no remnants older than a few kyrs detected?

The VHE gamma-ray luminosity

Gamma-ray emission



IC:

- Specta are comparable for both diffusion regimes

PD:

- Luminosity keeps increasing in the Bohm-case
- Particle escape reduces luminosity in the Alfvenic case

The VHE gamma-ray luminosity

Spectral evolution

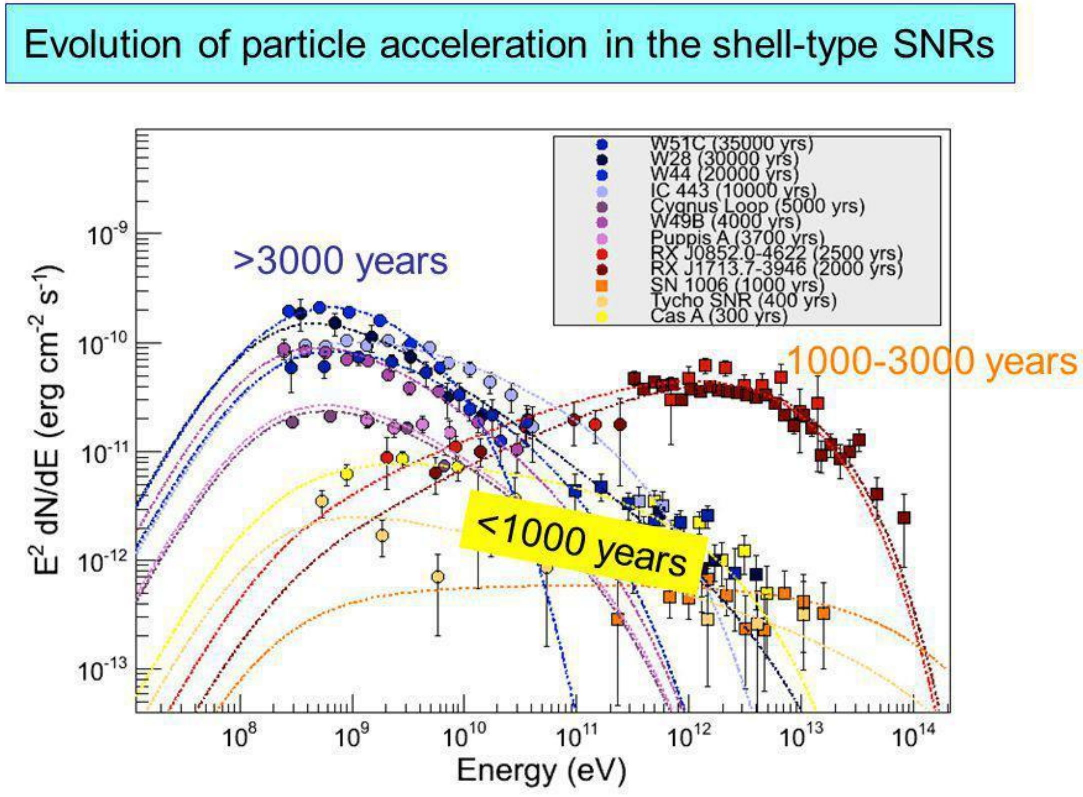
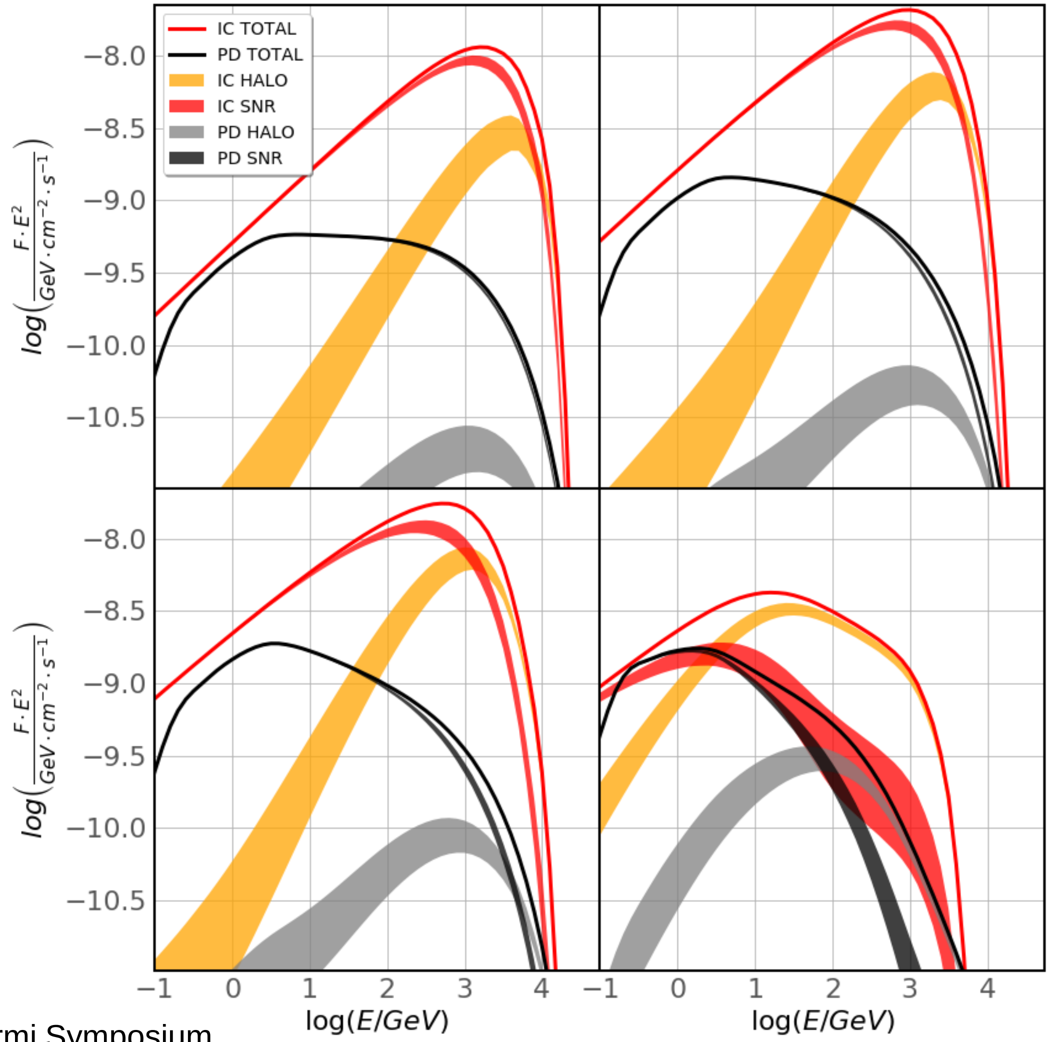


Figure: Gamma-ray flux from various SNRs (Funk, TeVPa 2011)



Conclusions

- A strong evolution of E_{max} results in **soft production spectra** even if the acceleration mechanism is standard DSA
- The spectral index of the production spectra is $\boldsymbol{s \approx 2.4}$ **is close to the predictions by galactic propagation models** ($s = 2.2 - 2.4$)
- Particle **escape** of the highest energetic CRs **forms soft spectra at high energies** and spectral breaks between 1-10GeV

- Efficient CR **reacceleration** might work and will be detectable by **breaks in the Radio-spectrum**

- CR **escape reduces** the VHE gamma-ray luminosity **of old SNRs** in hadronic scenarios
- The VHE peak-**IC luminosity is higher for remnants in low-density environments** → the most luminous known SNRs expand in low-density environments

Brose et al. 2020, doi:10.1051/0004-6361/201936567

Thank you for your attention!