Particle Escape from post-adiabatic SNRs

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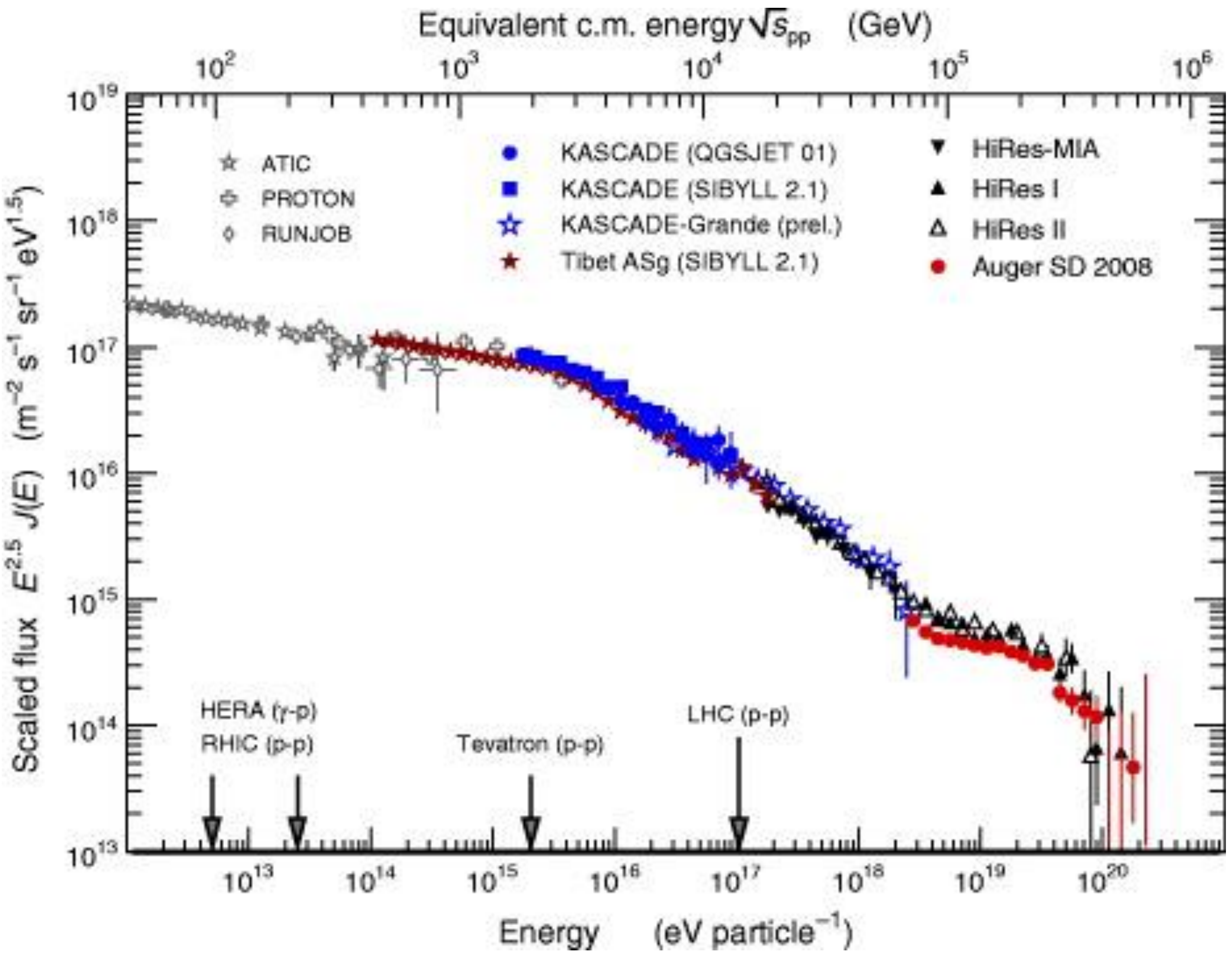
HELMHOLTZ ASSOCIATION

DESY

The cosmic-ray spectrum

The Plot I



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

Figure:

The cosmic ray spectrum (Blümer et al. 2019)

Why supernova remnants?

Experimental evidence

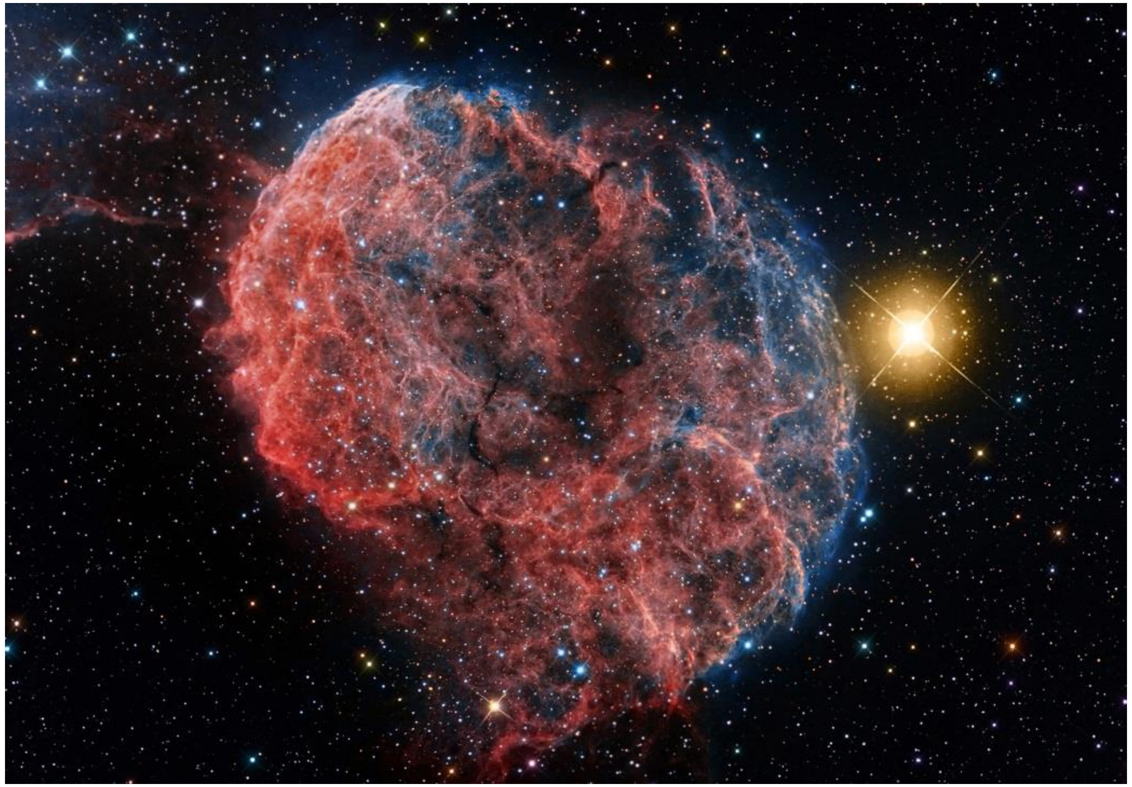
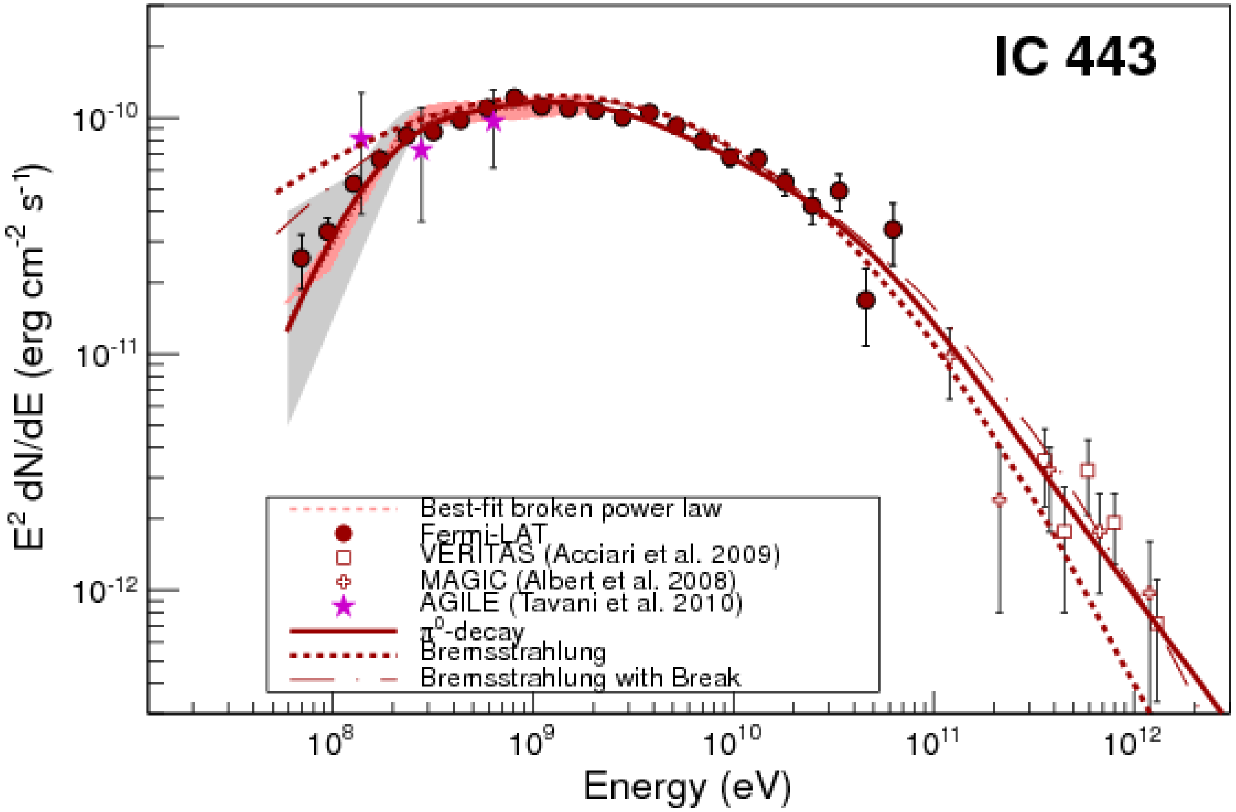


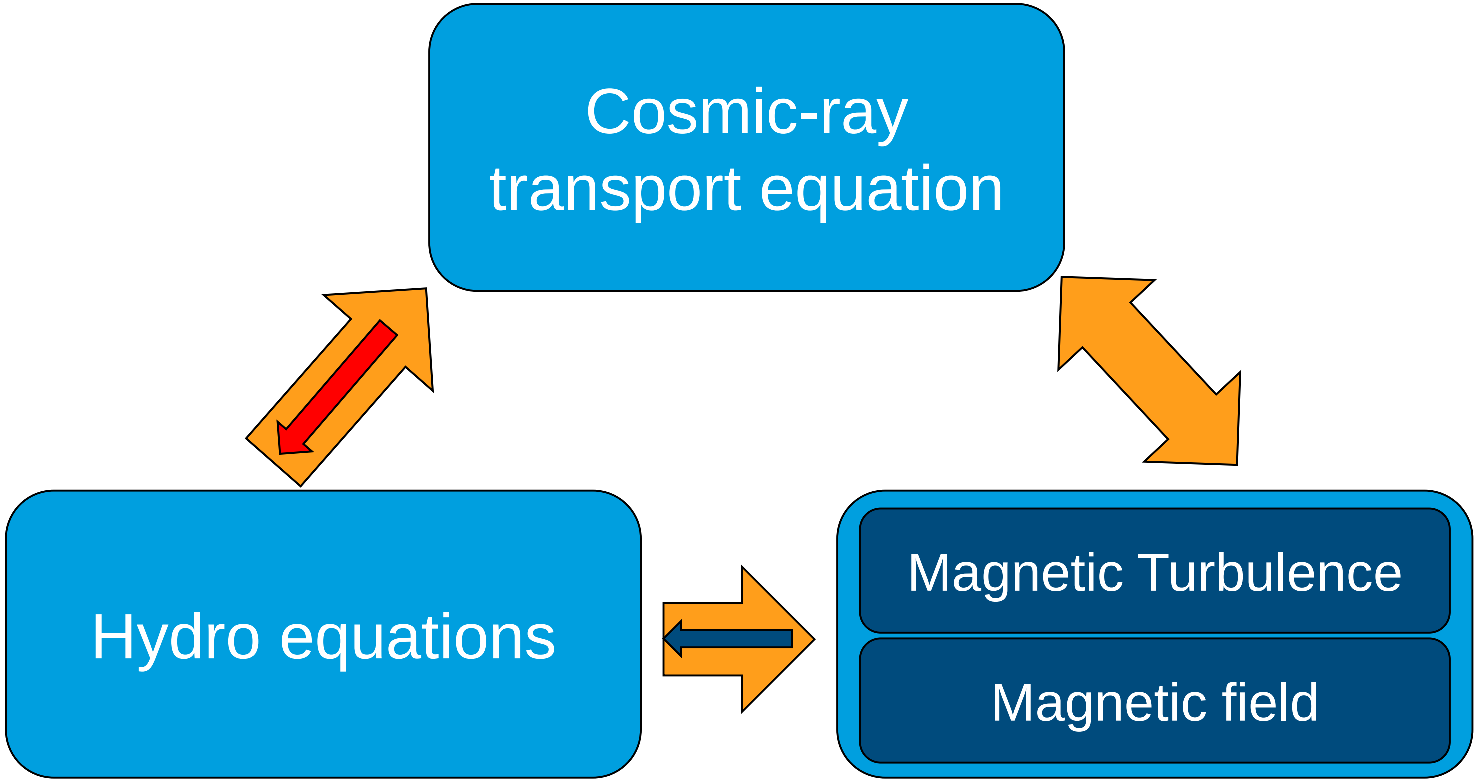
Figure: IC443 – multi wavelength image (credit: Dieter Willasch)

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



Fermi acceleration

Coupled equations



Standard DSA

Non-linear DSA

NDSA + high MF

Fermi acceleration

The equations

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

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

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

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

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

Model Parameters

Hydrodynamics:

- Type1a explosion
  - $n_0 = 0.3\ cm^{-3}$, $T_{ISM} = 40000K$, $E_{expl} = 10^{51}$ erg, $M_{ej} = 1.4\ M_{sol}$
- $B_0 = 5\ \mu G$, Compressed field

Cosmic rays:

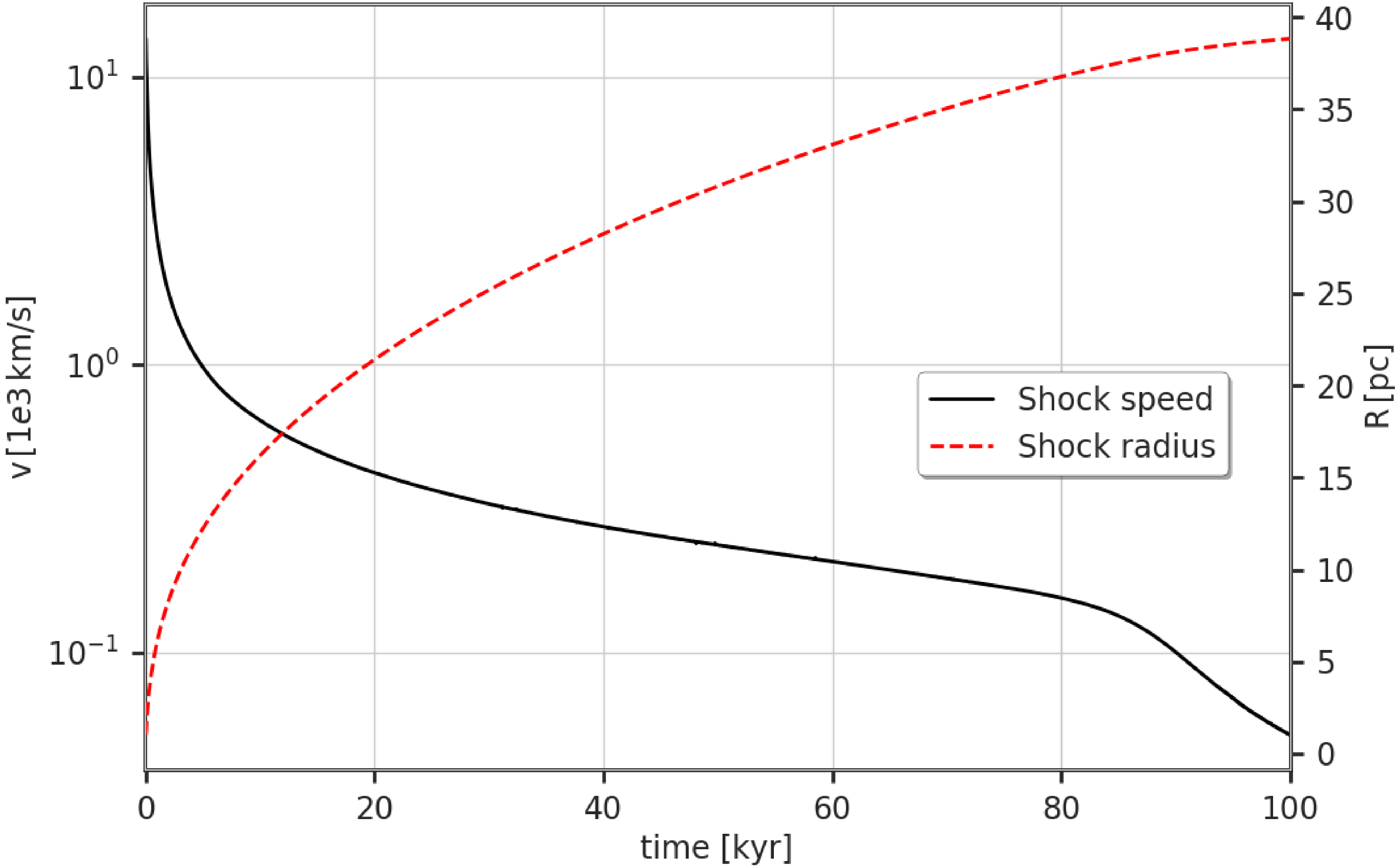
- Electrons and protons
- Two diffusion models:
  - Bohm-like diffusion (no time evolution)
  - Alfvenic diffusion (time-dependent diffusion coefficient)

Cosmic-ray escape

Hydrodynamic evolution

100kyrs of SNR evolution:

- Free-expansion end: 1.3kyrs
  - $v_{sh} = 2350$ km/s
- Sedov-phase end: 35kyrs
  - $v_{sh} = 300$ km/s
- Shell formation starts after 85kyrs
  - $v_{sh} = 130$ km/s
  - Compression ratio drops to 3.15 at end of simulation

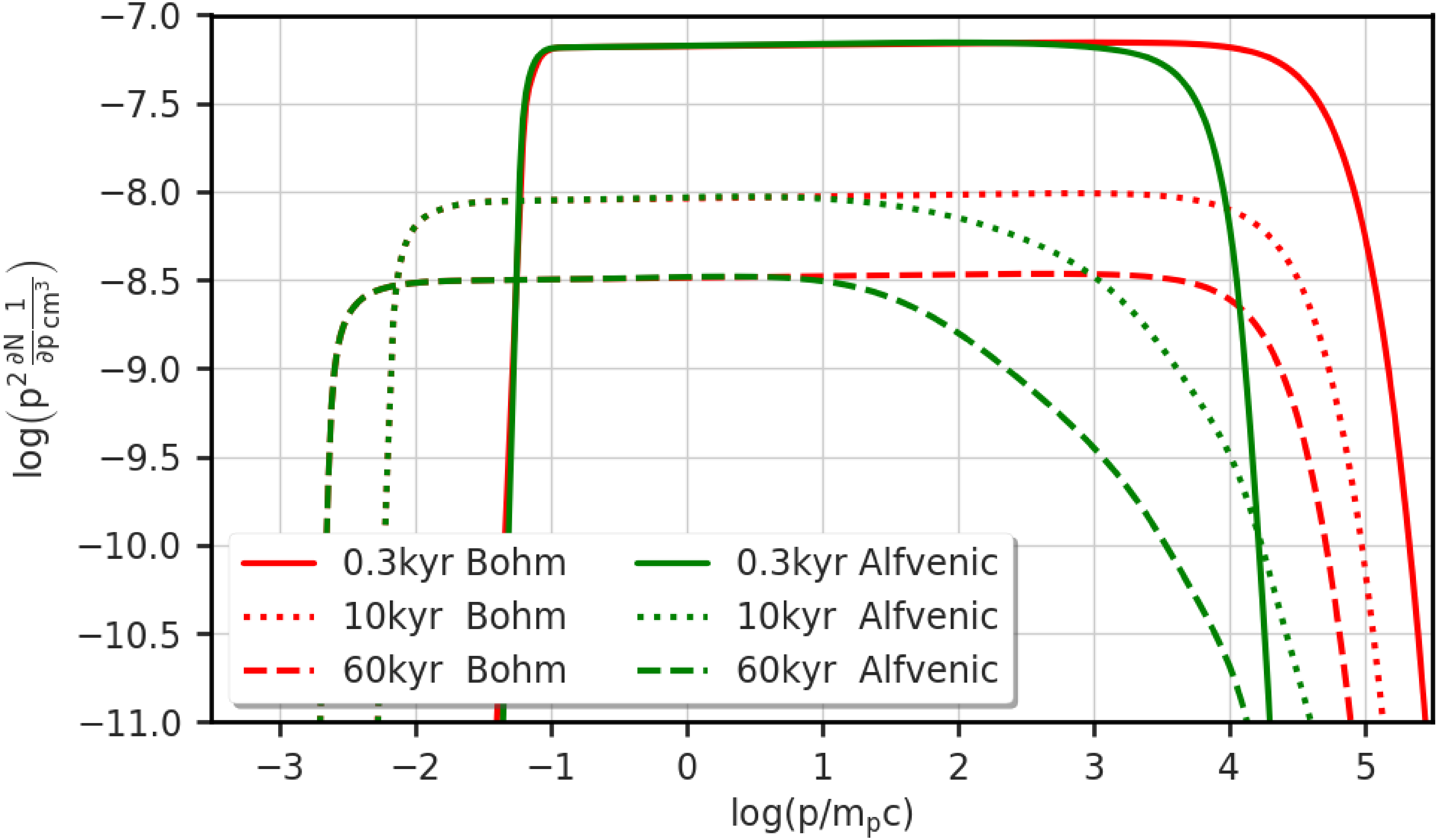


Cosmic-ray escape

Downstream spectra

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

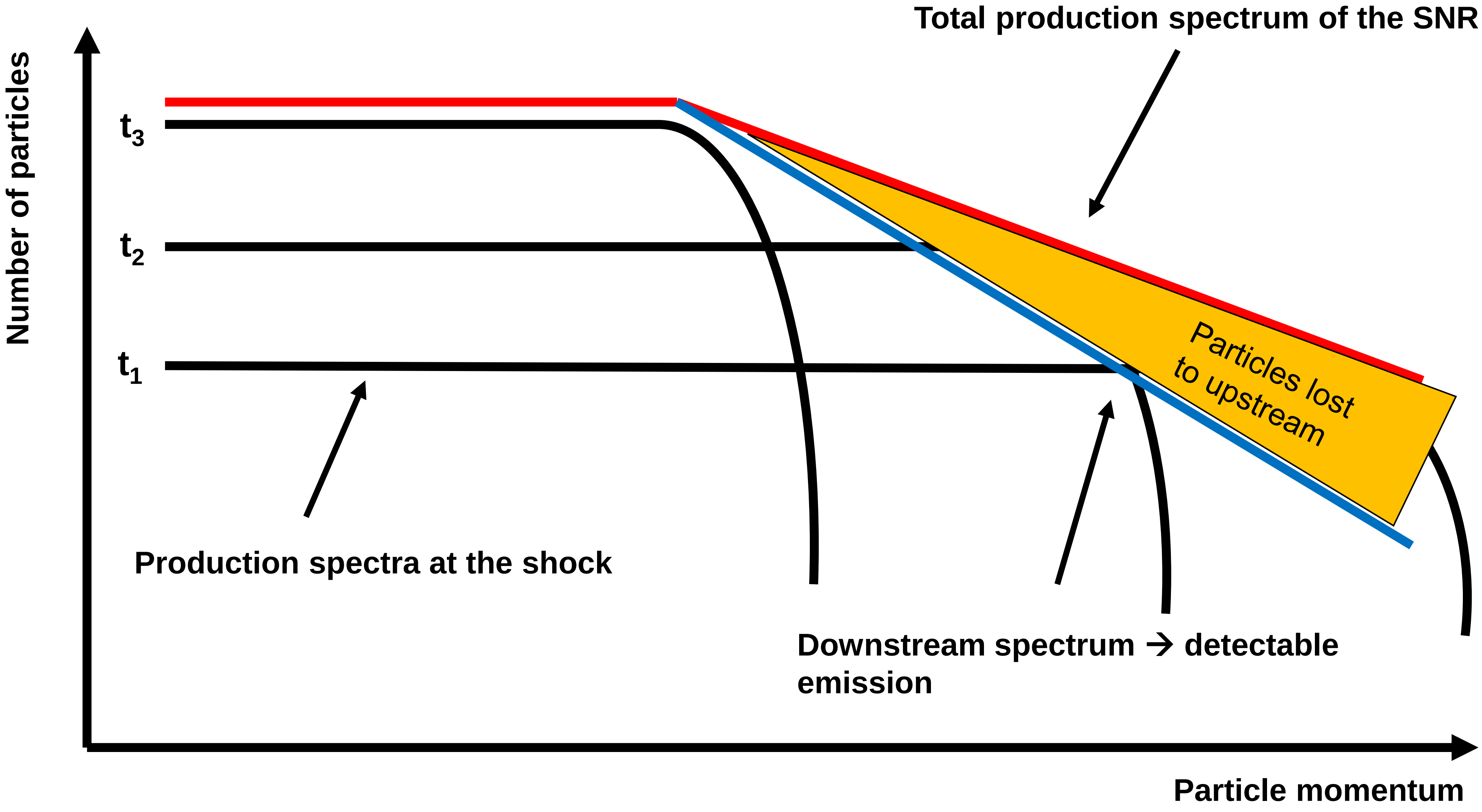
Alfvenic diffusion:
- Maximum energy strongly time-dependent → decrease by factor ~1000
- Spectra get soft at high energies
- A spectral break at 1-10GeV forms



Cosmic-ray escape

The mechanism

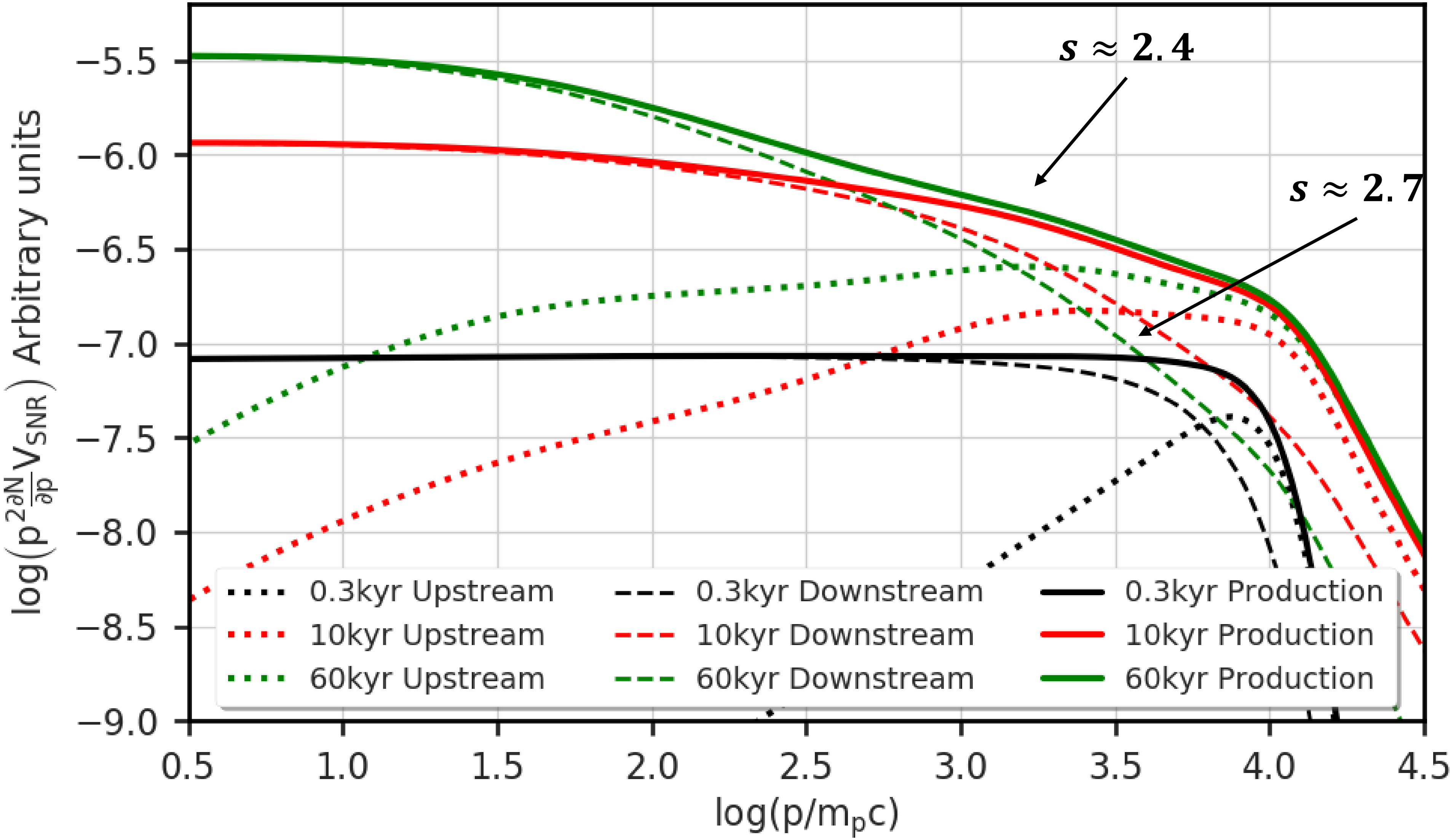
$t_3 > t_2 > t_1$



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

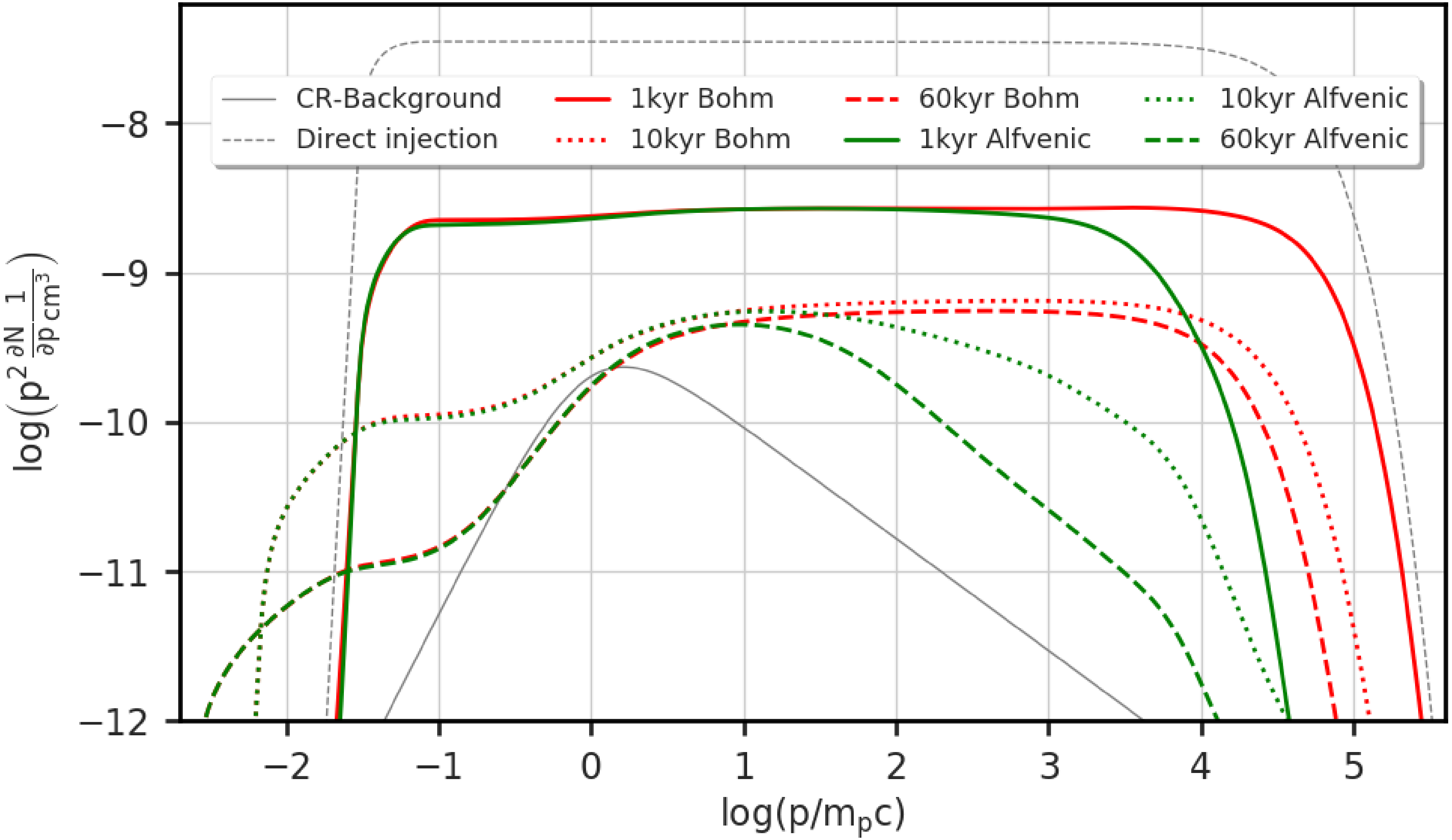


CR reacceleration

Cosmic-ray reacceleration

CR spectra

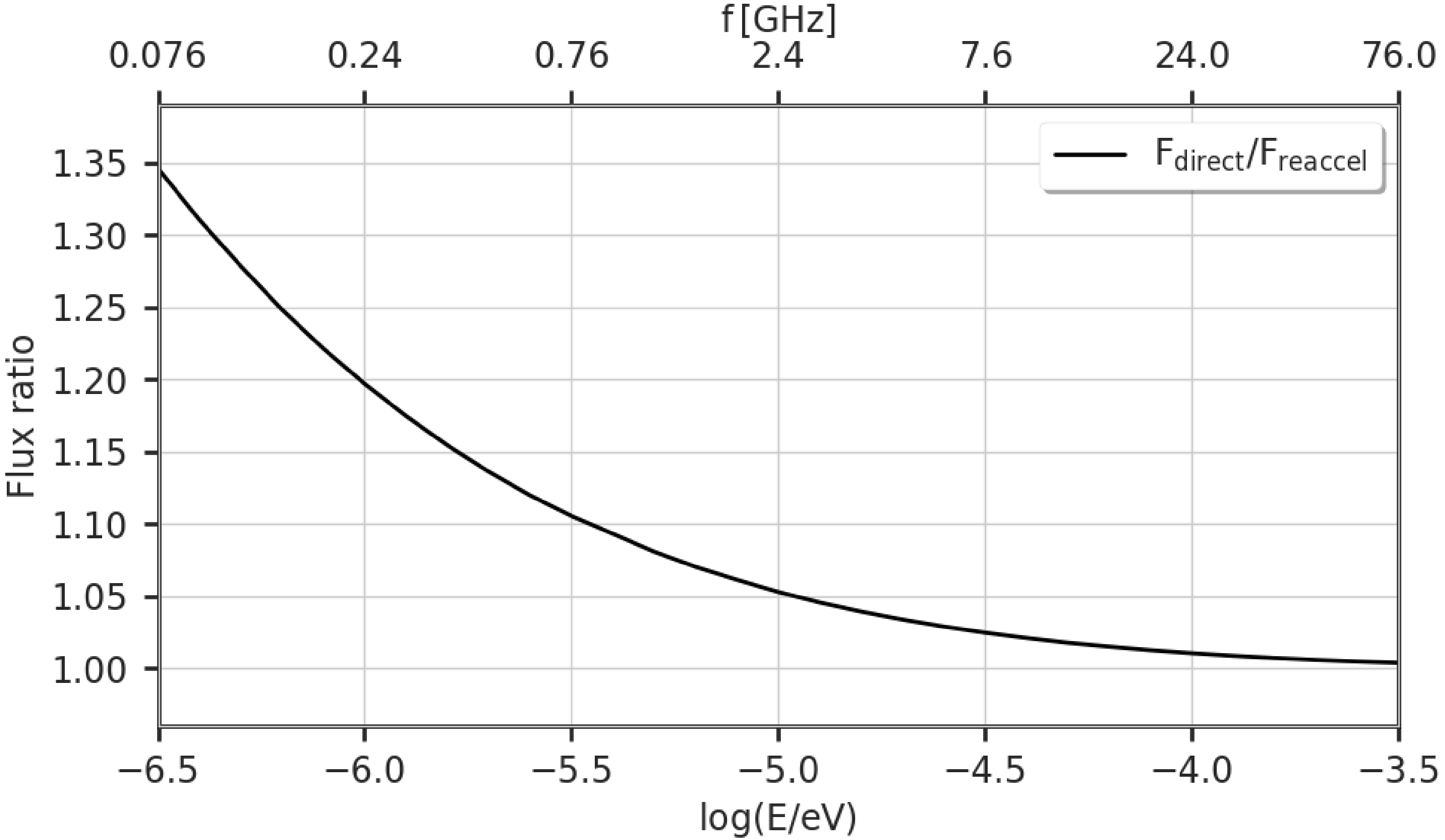
- We artificially decreased injection with time → background CRs dominate from ~2kyrs onwards
- Particle spectra above a few GeV are indistinguishable from direct acceleration scenario



Cosmic-ray reacceleration

Radio spectra

- Background CR and electron spectra are hard below a few GeV → spectral slope is conserved
- Transition between background spectral indexes observable at Radio-frequencies

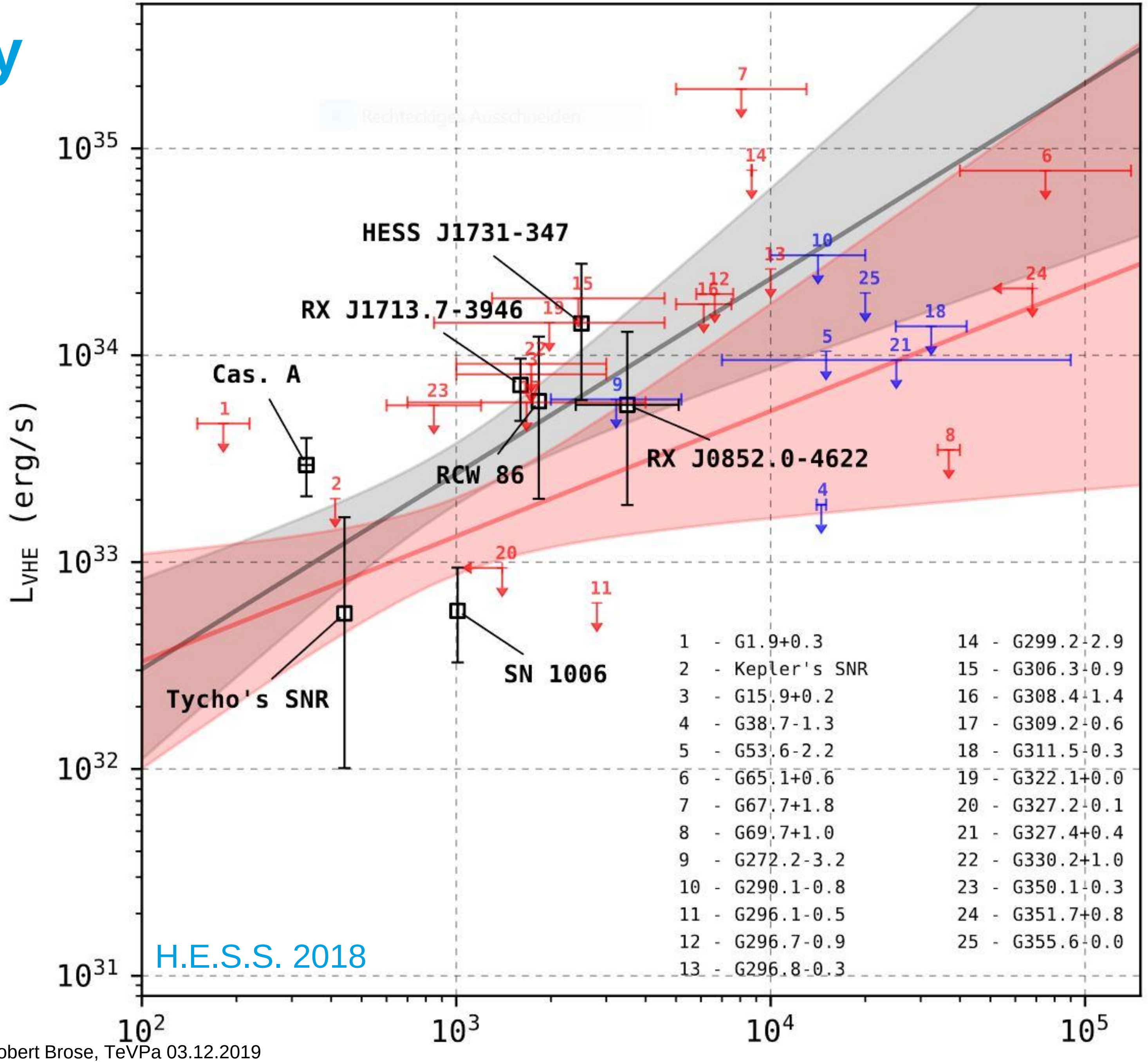


The VHE gamma-ray luminosity

The VHE gamma-ray luminosity

The plot II

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



Gamma-ray emission

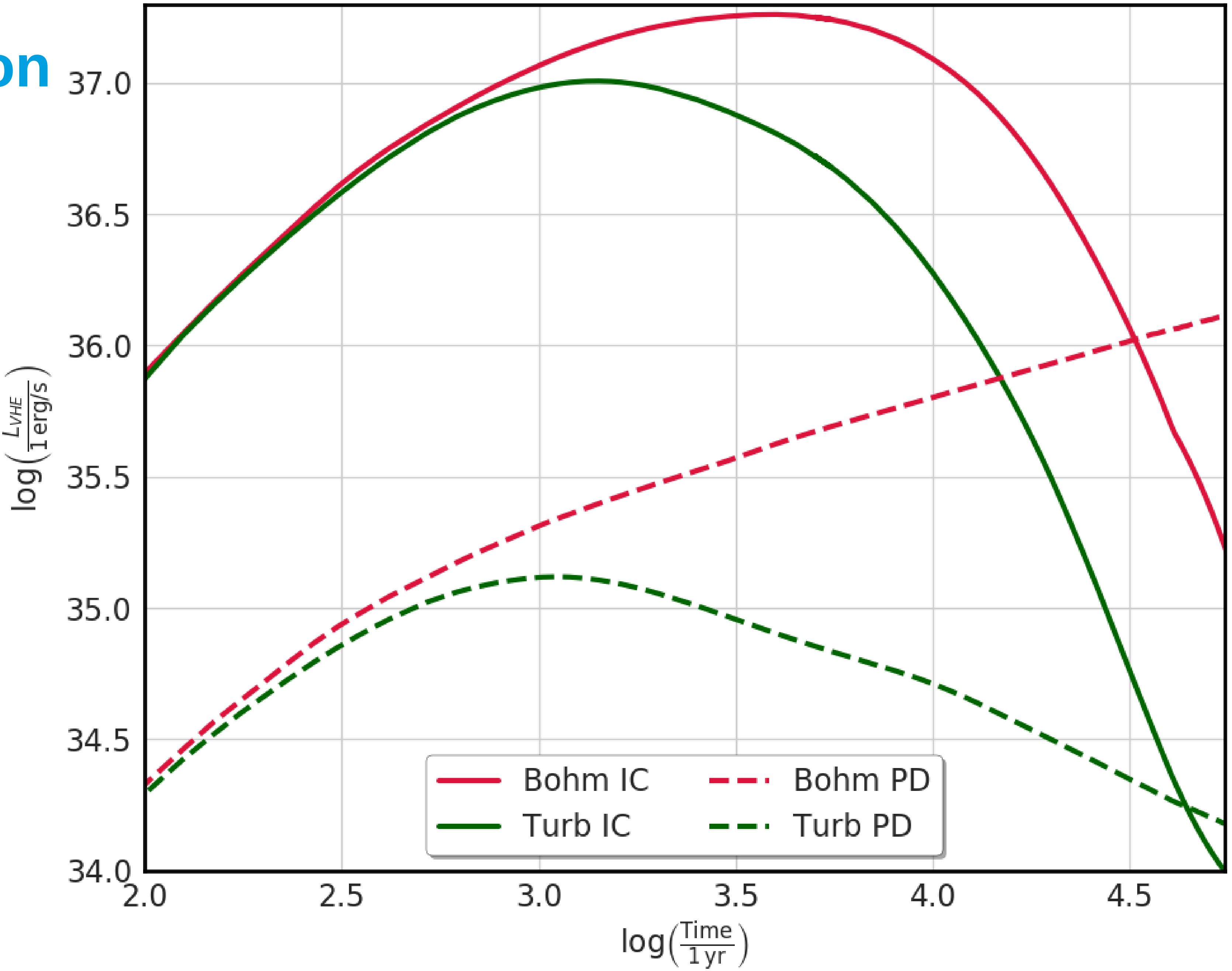
The VHE-luminosity

IC:

- specta are comparable for both diffusion regimes

PD:

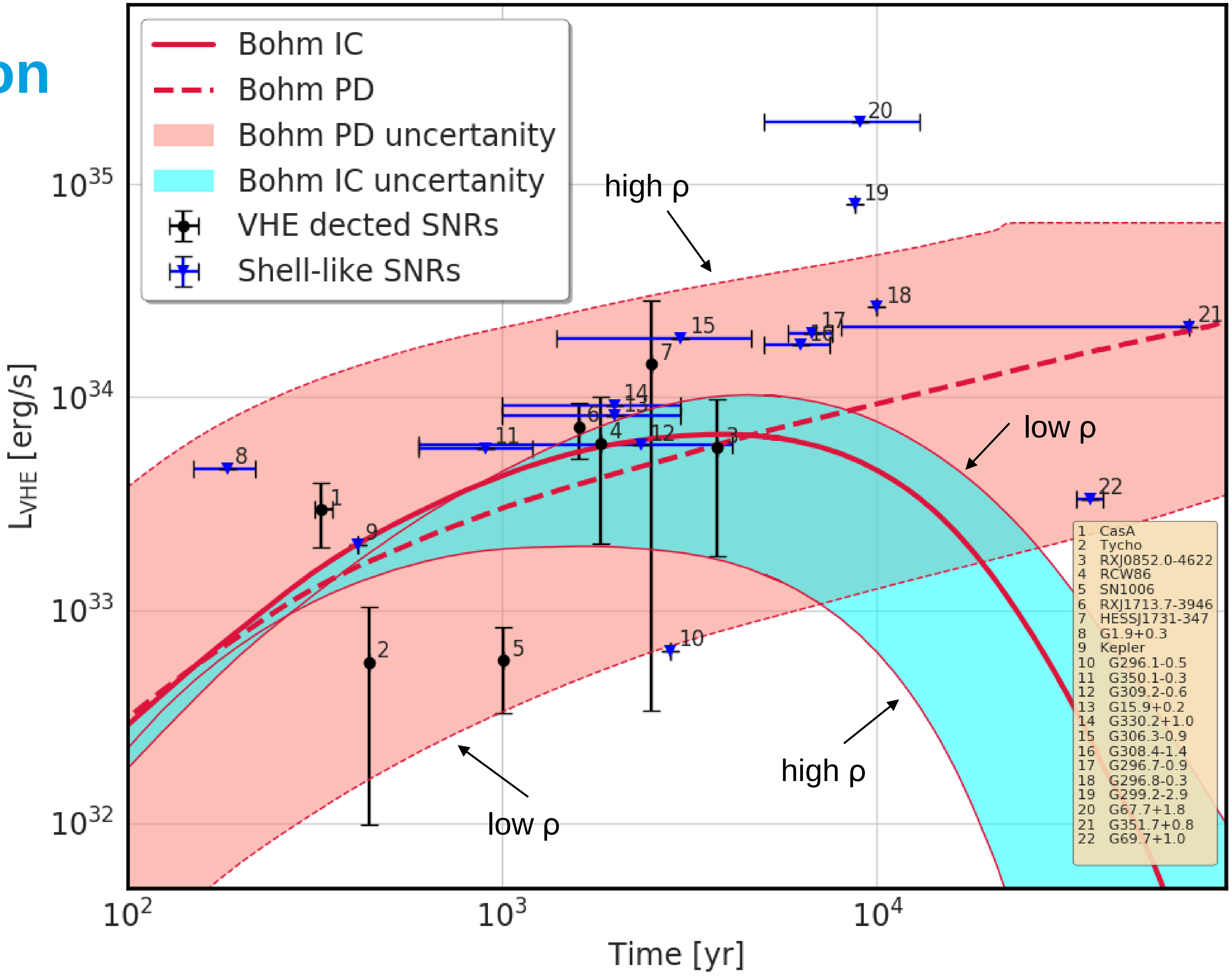
- luminosity keeps increasing in the Bohm-case
- Particle escape reduces luminosity in the Alfvenic case



Gamma-ray emission

The VHE-luminosity

- Remnants expanding in low density environment reach higher peak IC-luminosities
- RXJ1713, Vela Jr., RCW86, HESSJ1731 → The brightest known remnants expand in low-density environments!
- No non-interacting remnant detected older than a few kyrs → synchrotron cooling



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 $s \approx 2.4$ 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 will reduce the VHE gamma-ray luminosity of 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

Thank you for your attention!