Time-dependent cosmic-ray feedback on shocks

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The cosmic-ray spectrum
Overview

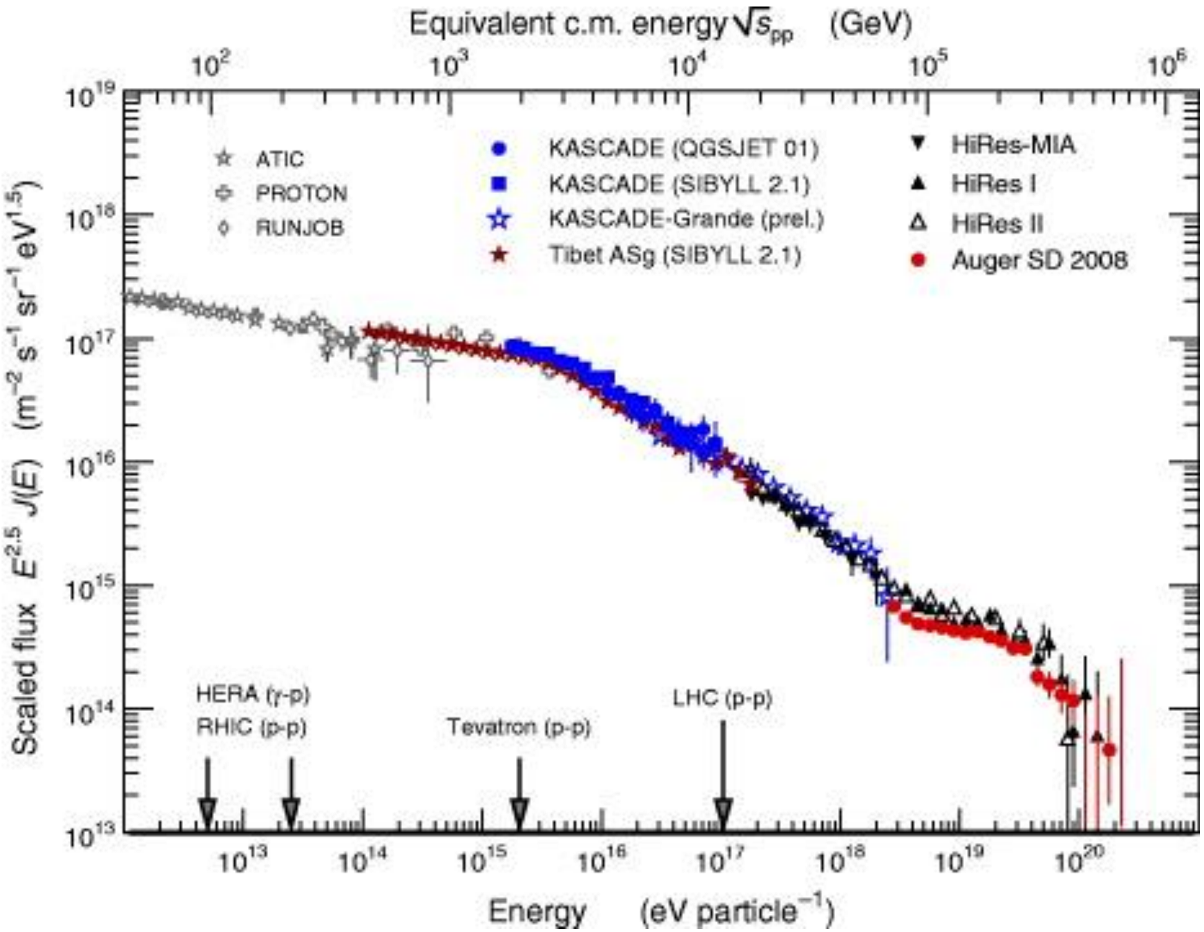


Figure: The cosmic ray spectrum

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

Signatures of cosmic-ray acceleration

Overview

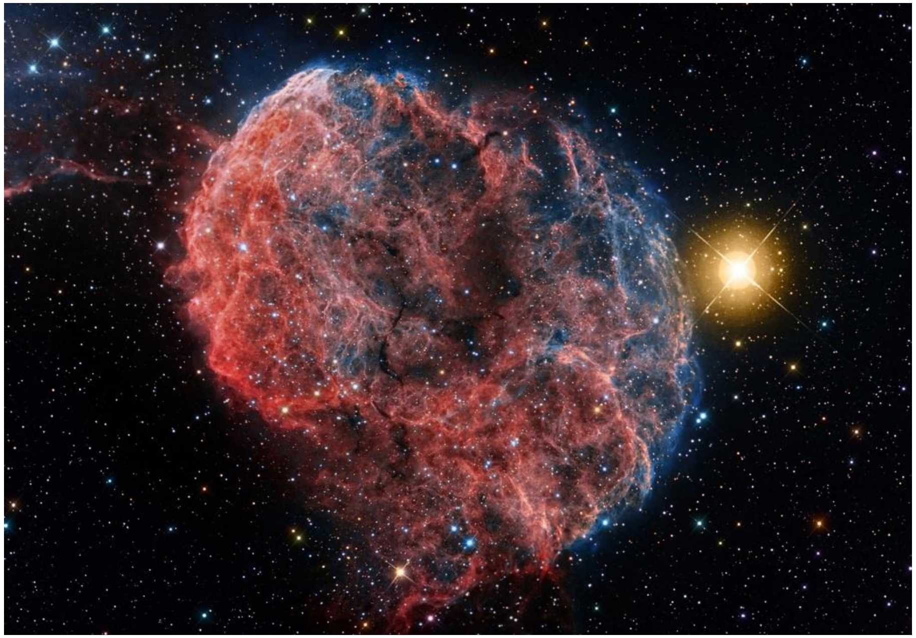
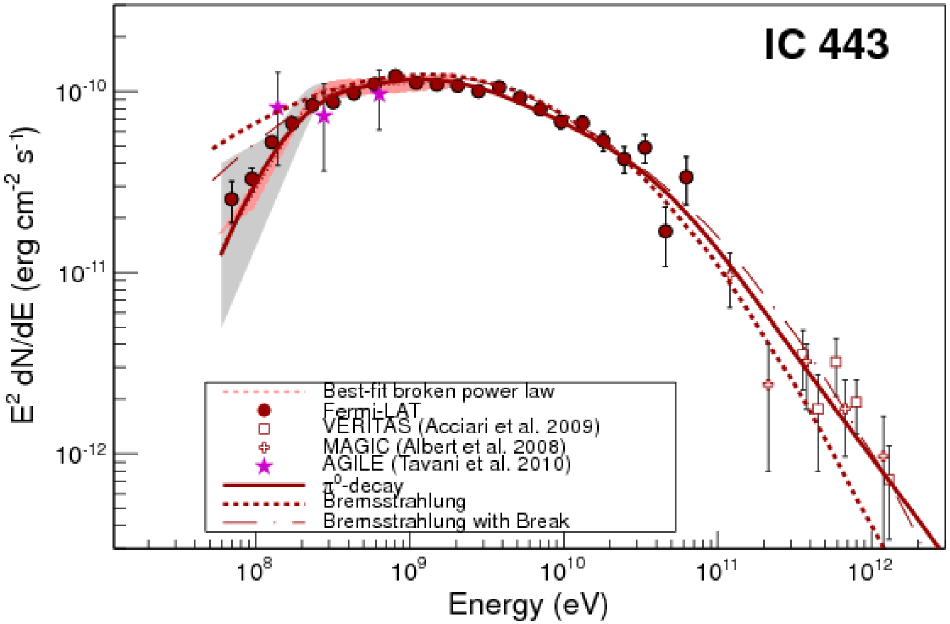


Figure: IC443 – multi wavelength image

Figure: IC443 – gamma ray emission



NDSA-theories
Overview

Ingredients

- Hydro evolution of the specific SNR
- Solve the cosmic ray transport equation for protons and electrons
- Account for magnetic field amplification and magnetic turbulence

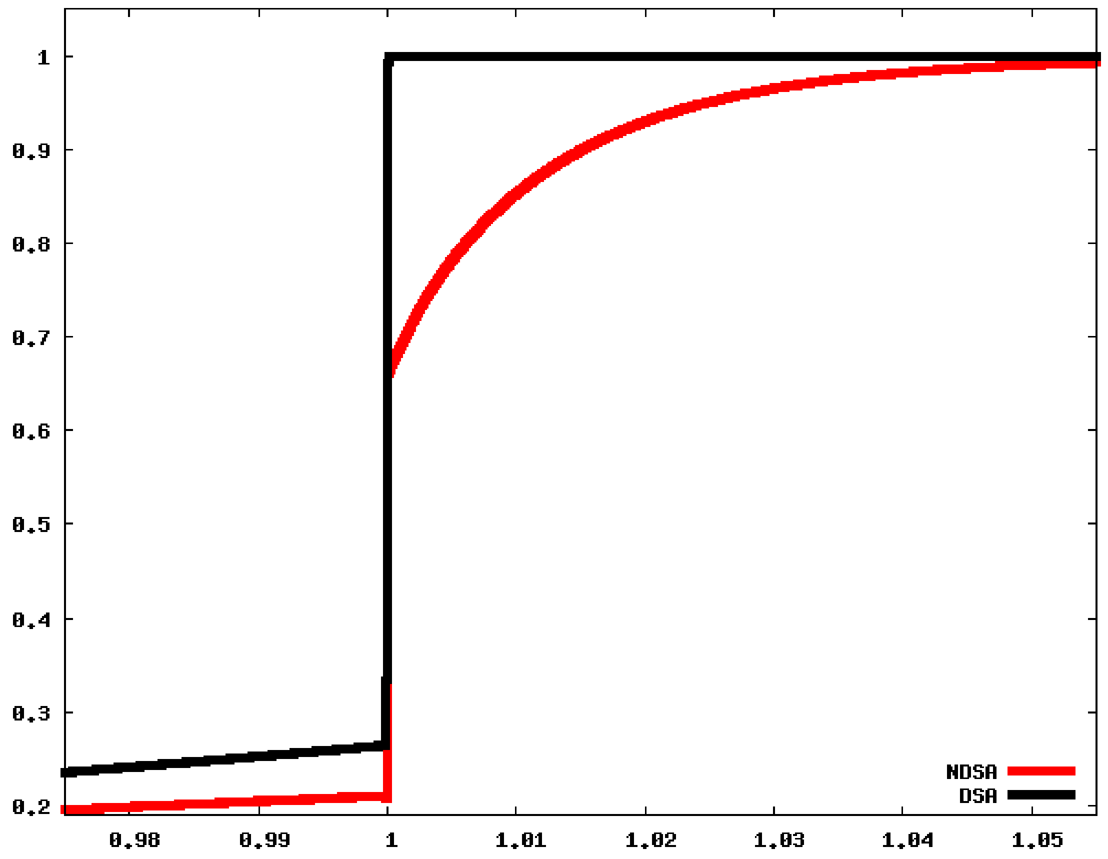
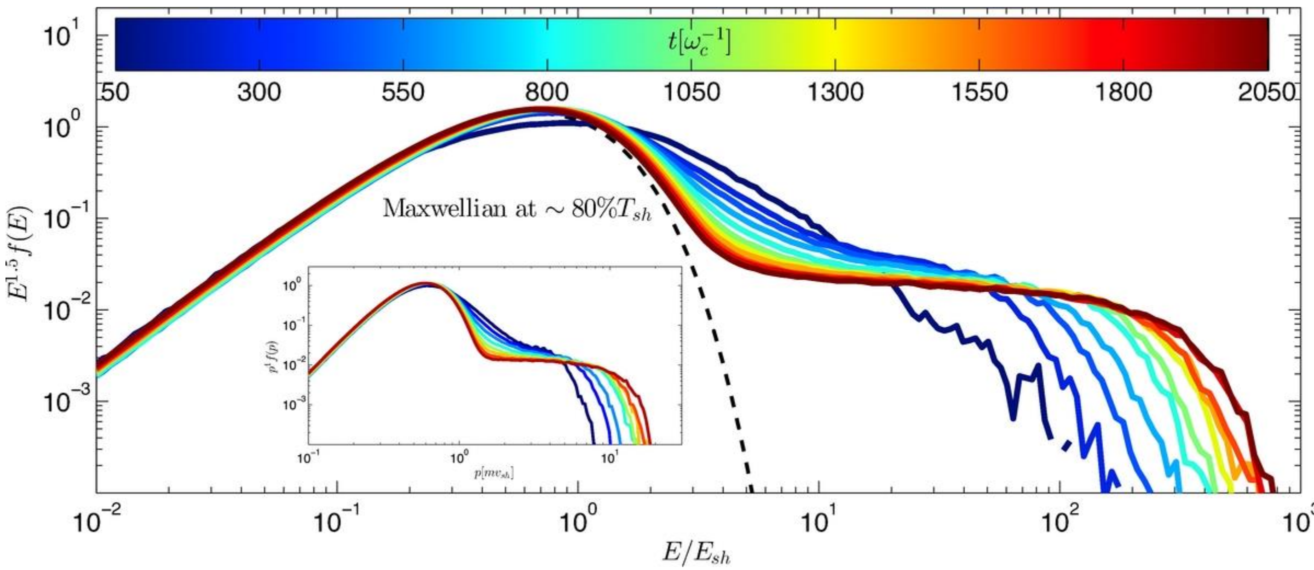


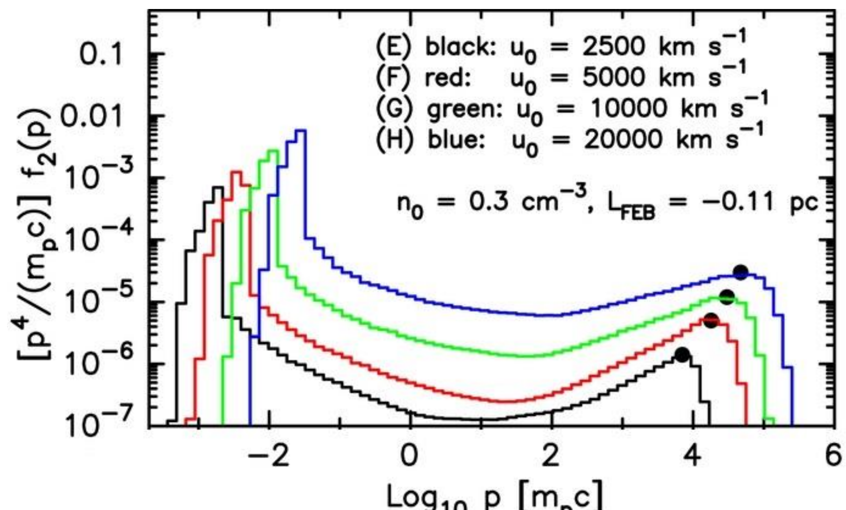
Figure: Flow profiles of a modified and a unmodified shock

Signatures of cosmic-ray acceleration
Overview



Hybrid model by Caprioli & Spitkovsky 2014

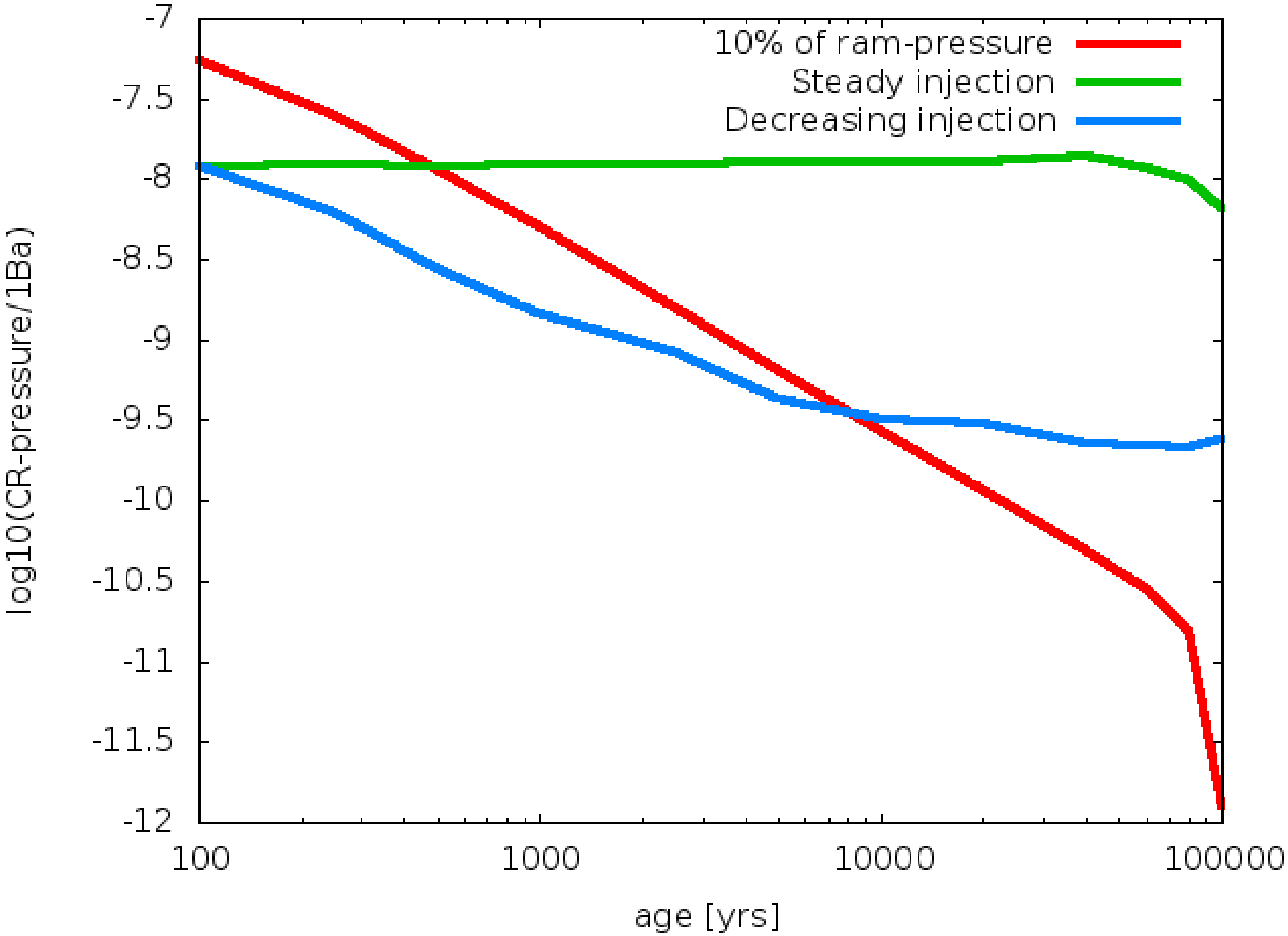
Steady-state model by Bykov et al. 2014



The need for NDSA-models

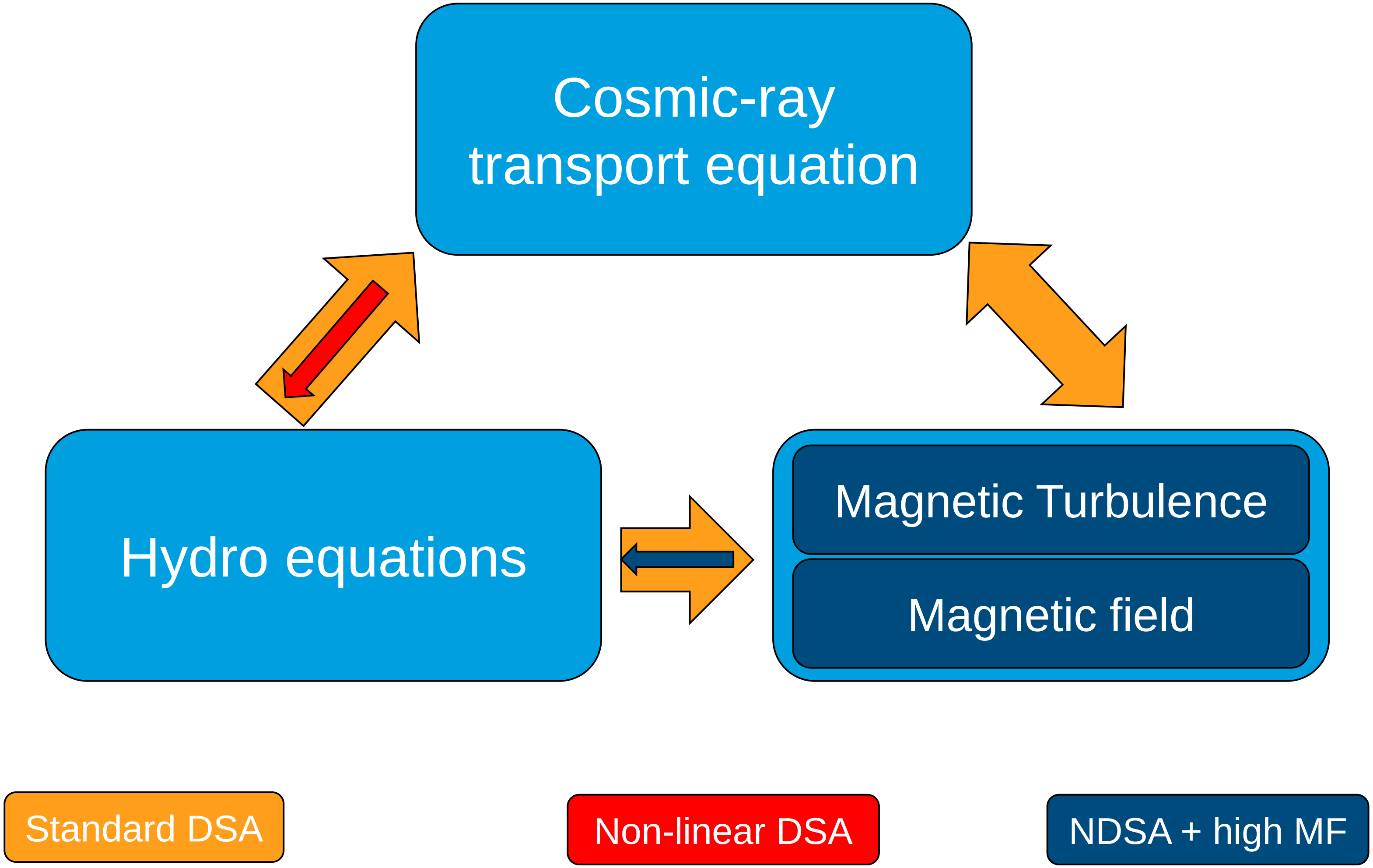
The CR-pressure falls slower than the ram-pressure

Feedback has to become important at some point!



Fermi acceleration

Coupled equations



Fermi acceleration

Transport equation for cosmic rays

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

The equation is solved:

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

Fermi acceleration

Hydrodynamical equations

Hydro modeling:

- Solving the standard gas-dynamical equations
- 1D and spherically symmetric
- Modeled as type1a-explosion in a uniform medium

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

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

Fermi acceleration
Numerics

Resolutions:

- $10^{-6} R_{Shock}$ for the cosmic-ray grid → $\Delta r \approx 10^{12}$cm
- $\sim 10^{5}$ Cells for the whole grid → $\Delta r \approx 10^{13}$cm

Length scales:

- $\sim 10^{15}$cm for 1TeV Protons
- $\sim 10^{12}$cm for 1GeV Protons

$$r = \frac{\rho_d}{\rho_u} = \frac{u_u}{u_d}$$

$$s = \frac{r+2}{r-1}$$

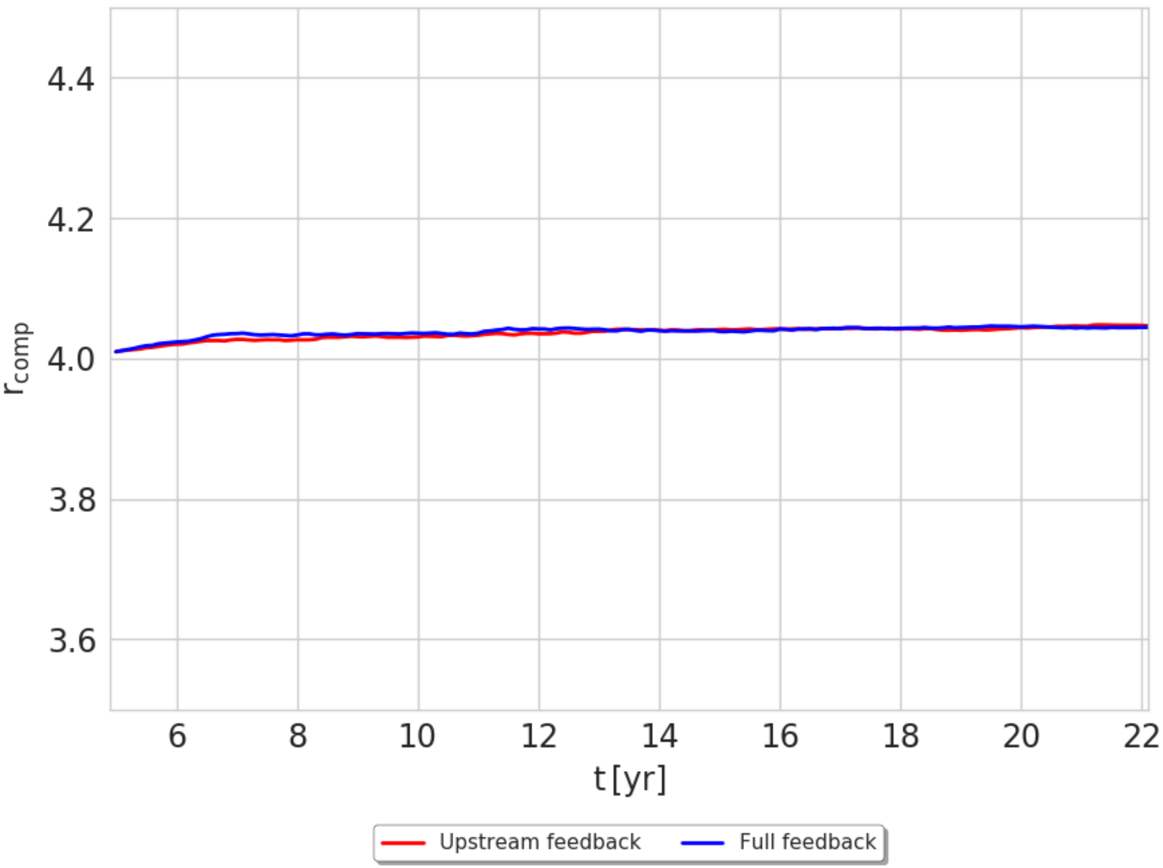
Results 0

Unmodified shock

Observation:

- $\frac{P_{CR}}{P_{Ram}} \approx 10\%$ → Compression ratio ≈ 4
- Confirms Kang et al. 2010
- Higher CR-pressure needed → more injection
- Leads to standard DSA-spectra with $s \approx 2$

Figure: Compression ratio over time



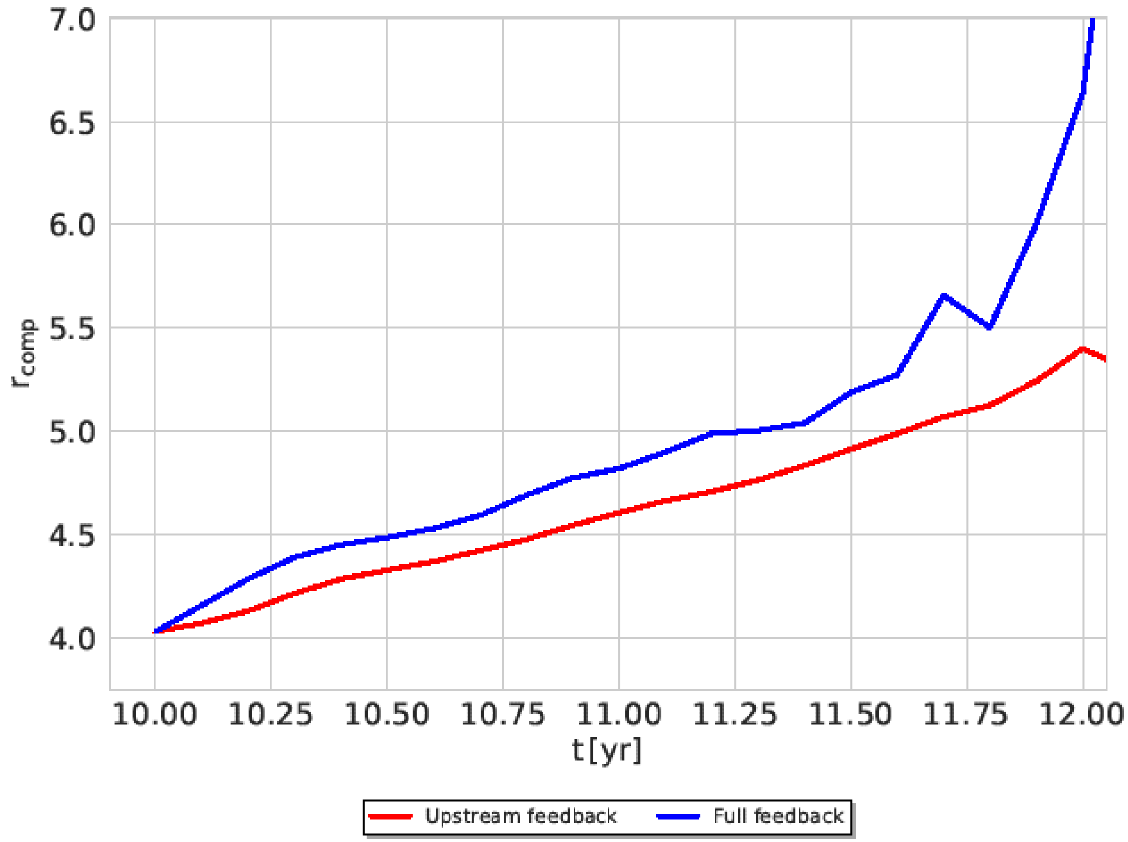
Results I

Poor resolution: Numeric unstable situation

Observation:

- More injection: $\frac{P_{CR}}{P_{Ram}} > 15\%$
- Behaves like a relativistic fluid → Compression ratio grows to values >> 4
- Feedback mechanism: growing CR-pressure increases compression ratio → increasing CR-pressure

Figure: Compression ratio over time



Resolving the resolution issue

Ways to disentangle Hydro and cosmic rays:

- Increase the hydro resolution → Expensive, works only up to a point
- Smear CR-pressure to hydro resolution
- Increase the precursor scale:
  - Decrease the shock speed: $L_{Precursor} = {}^{D}/{v_{Shock}}$
  - Increase the diffusion coefficient; Change the energy dependence of the diffusion coefficient → Energy independent up to 500 GeV

- Change to a comoving coordinate system for Hydro-grid too

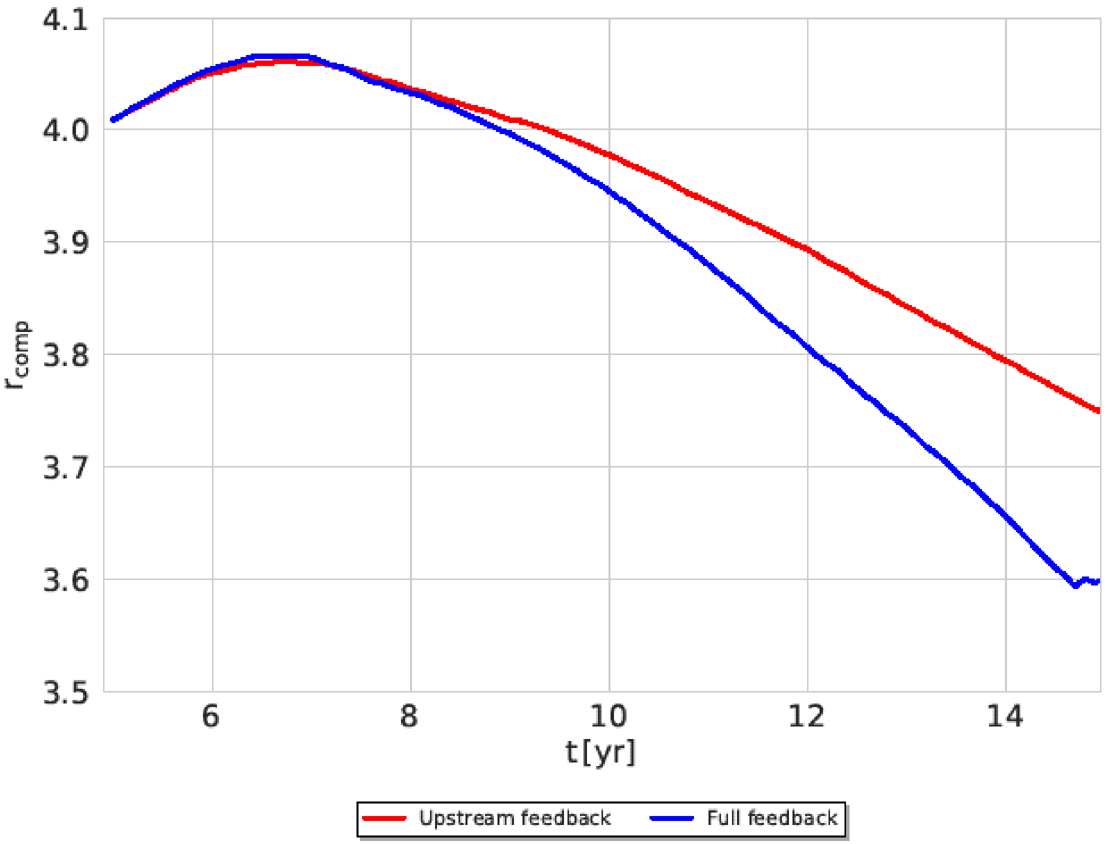
Results

Downstream feedback

Sufficient resolution:

- The Compression ratio decreases with increasing CR-pressure, as expected
- Systems with and without feedback behave differently: Downstream feedback effects!

Figure: Compression ratio over time



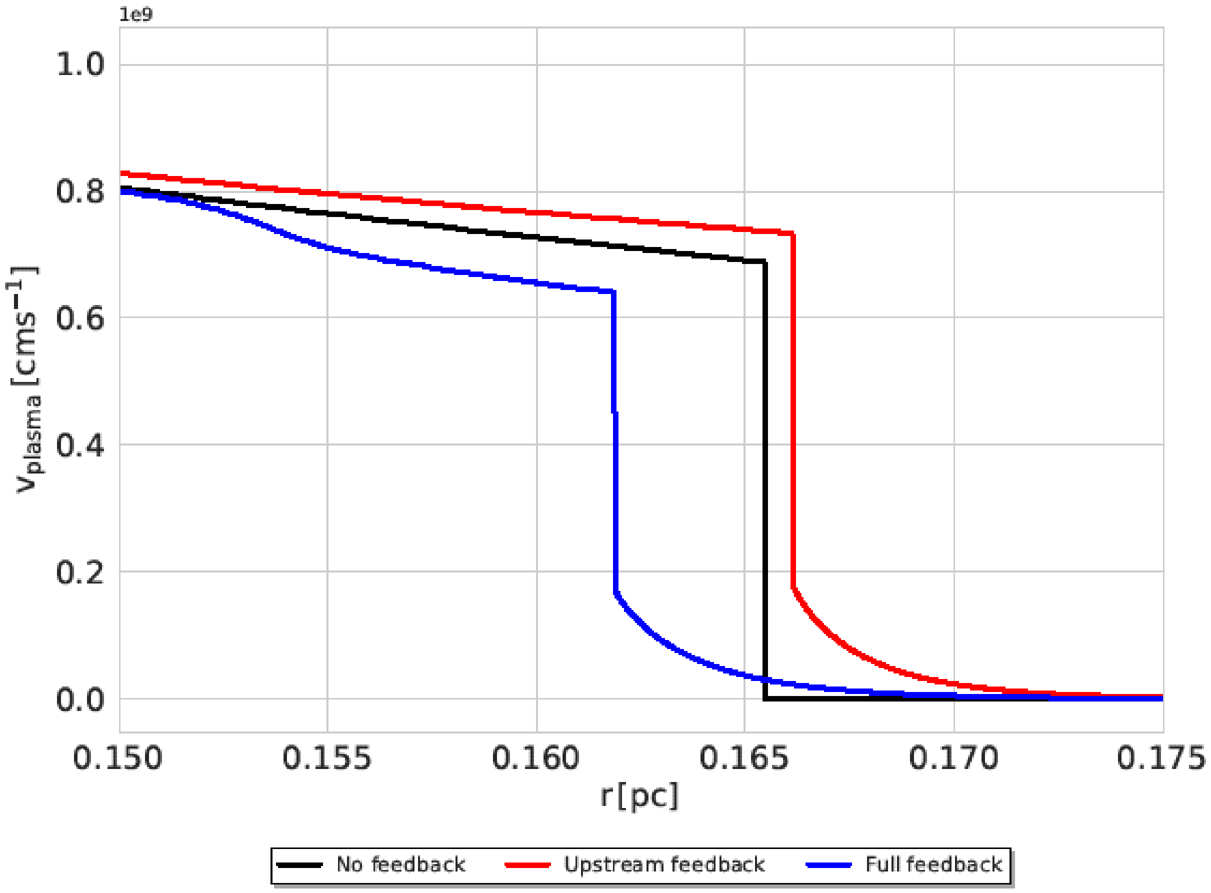
Results

Downstream feedback

Reason:

- The downstream CR-gradient slows down the flow behind the shock and the shock itself

Figure: Flow profile – observer frame

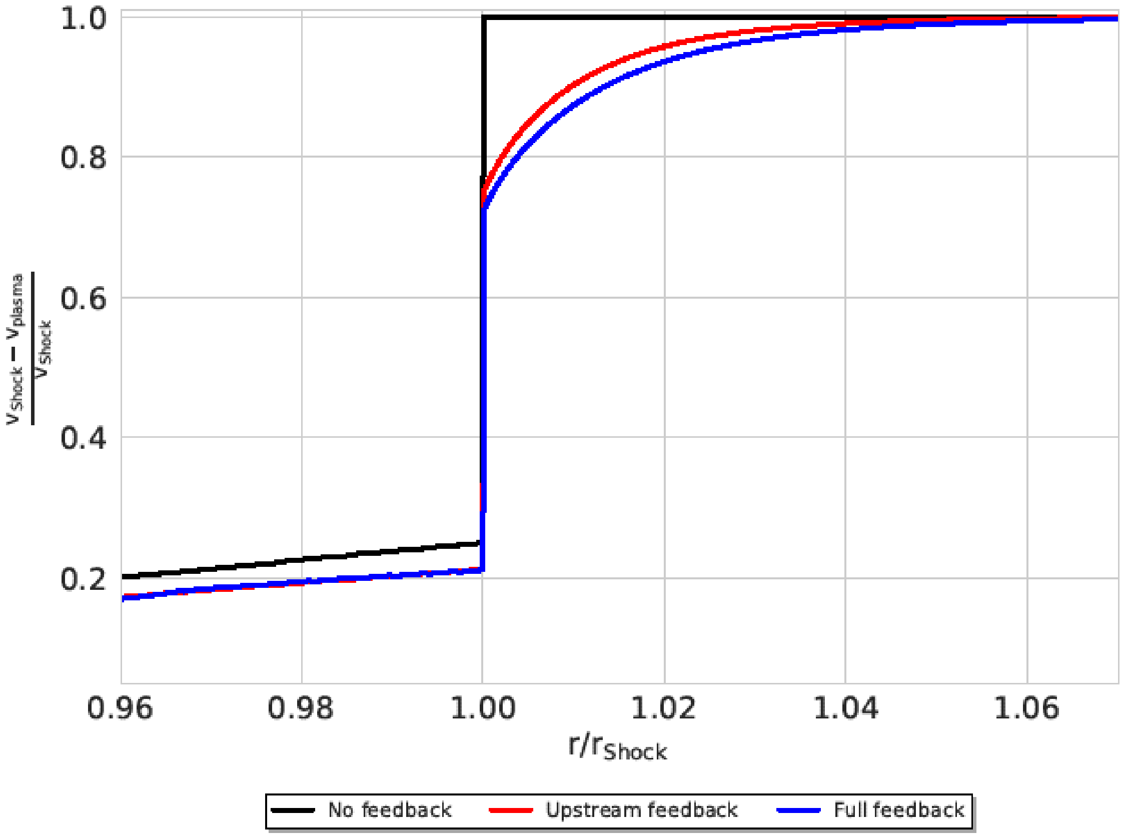


Results

Downstream feedback

- Flow profiles are similar in the shock-rest frame
- Precursor scale and change in velocity slightly larger in the case with downstream feedback

Figure: Flow profile – shock frame

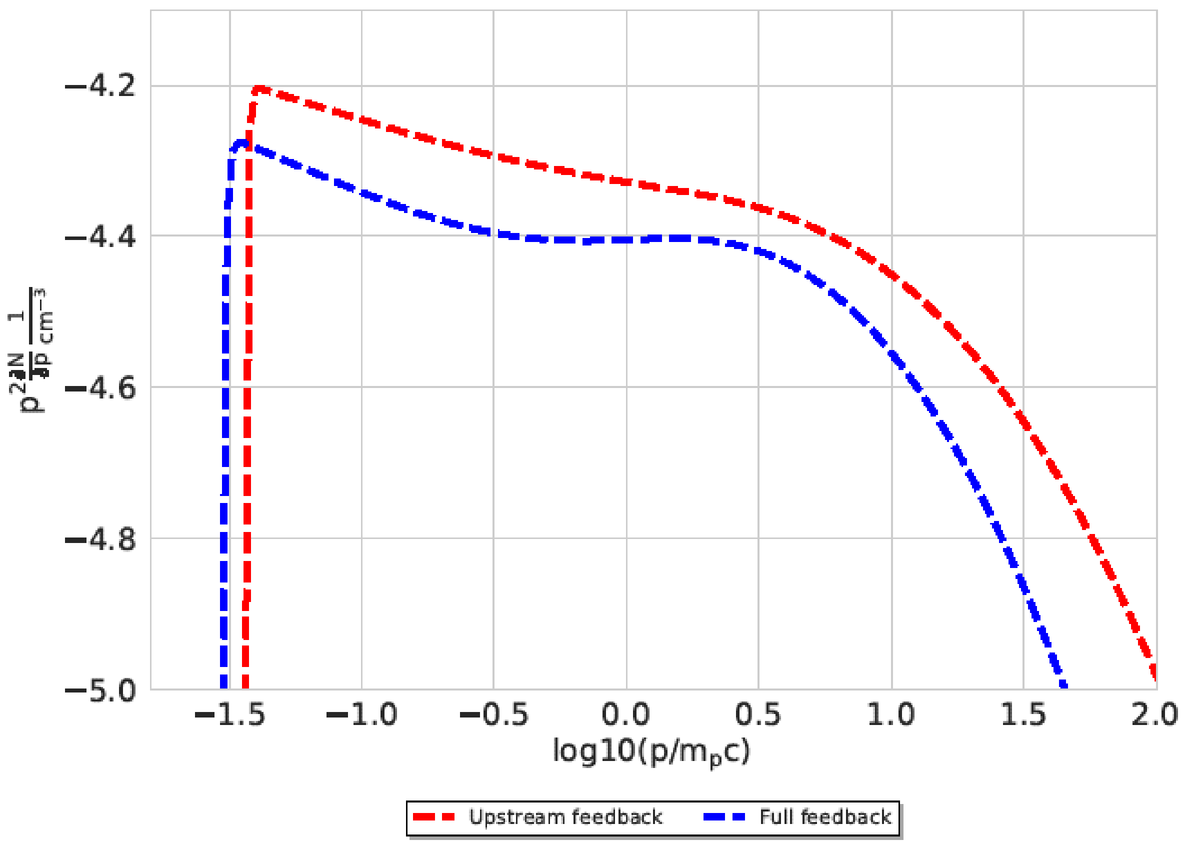


Results

Downstream feedback

- Cosmic ray spectra differ too
- Reason: different shock speeds → stage of evolution
- No curved spectra yet → CR-cutoff energy still below turning point in diffusion coefficient

Figure: CR-spectra at t=14yrs



Results

Downstream feedback

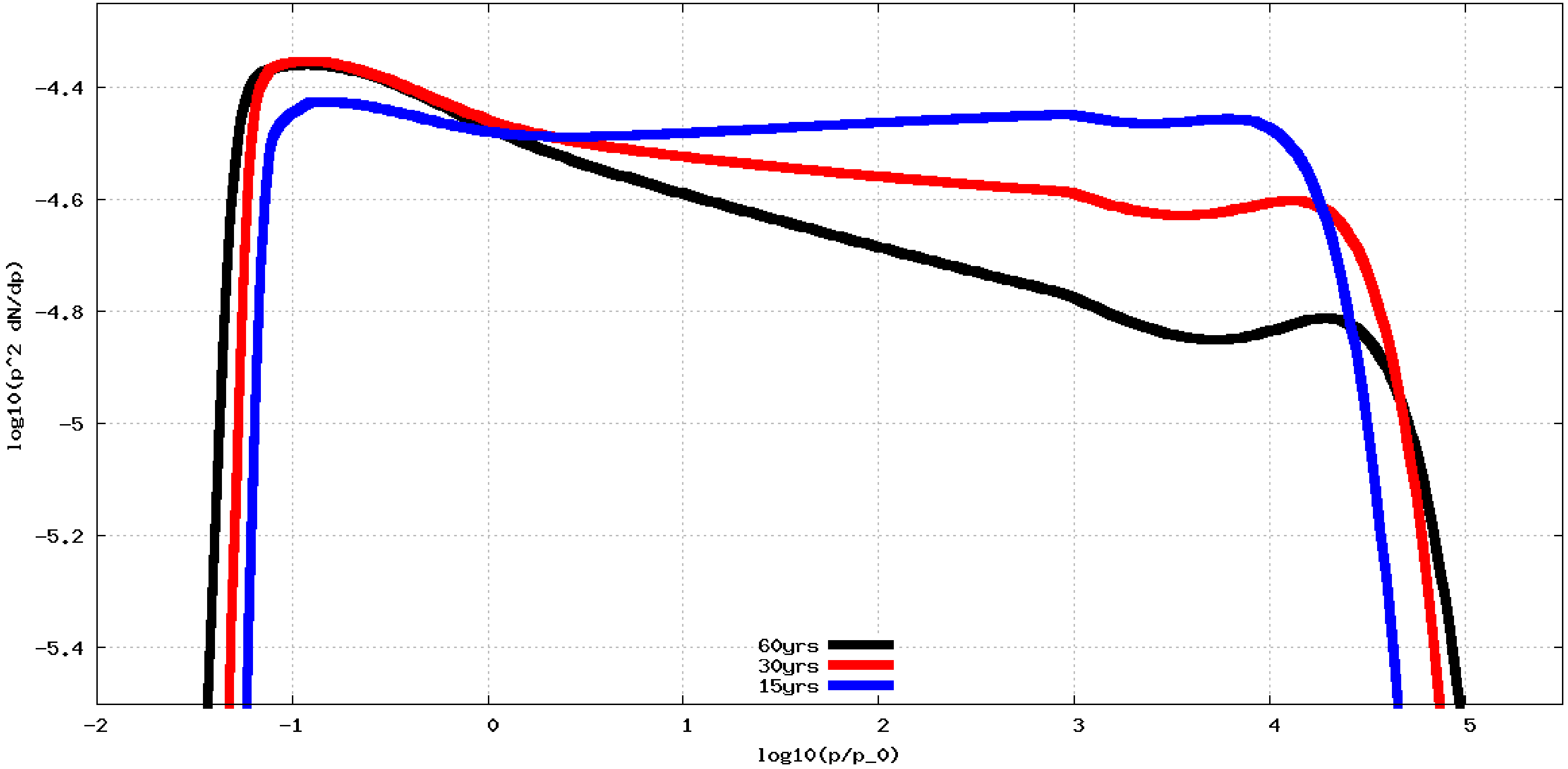


Figure: CR-spectra for different times

Summary

- Test-particle limit applicable as long as $\frac{P_{CR}}{P_{Ram}} \leq 10\%$
- There are still “new” aspects in NDSA to discover: Downstream feedback in spherical symmetric systems
- Simulations are numerically challenging and require compromises: e.g. changed diffusion coefficients
- Curved NDSA-spectra are obtained but shape differs due to changed diffusion coefficient

Thank you for your attention!

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