The formation of gamma-ray halos around supernova remnants through particle escape

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Introduction and model

Supernova remnants are known to accelerate particles to relativistic energies on account of their non-thermal emission. The observational progress reveals more and more morphological features that need to be accounted for when modeling the emission from those objects.

Radiation **A**cceleration **T**ransport **Pa**rallel **C**ode (RATPaC) – a numerical toolset to study particle acceleration in SNRs [1]

Hydrodynamics:

- Gasdynamical equations solved in 1D for a Type-Ia SNR in a uniform ambient medium

Cosmic rays:

- Kinetic test-particle approach, solved in 1D spherical symmetry
- Synchrotron and IC-cooling for electrons

Magnetic turbulence:

- Passively transported large-scale field
- Self-consistent amplification of Alfvenic turbulence

Gamma-ray morphology

- The **gamma-ray morphology** strongly depends on the age and the emission process – strongly **different** for **inverse-Compton** (IC) **and Pion-decay** (PD) emission
- **PD-emission** remains mostly **shell-like** → depends strongly on target-material distribution
- **IC-emission evolves** from shell-like to center filled → uniform target-photon distribution
- **After 2,000yrs**: an **extensive IC-halo** is formed → detectable with current or next-generation instruments
- PD halo present as well but much fainter

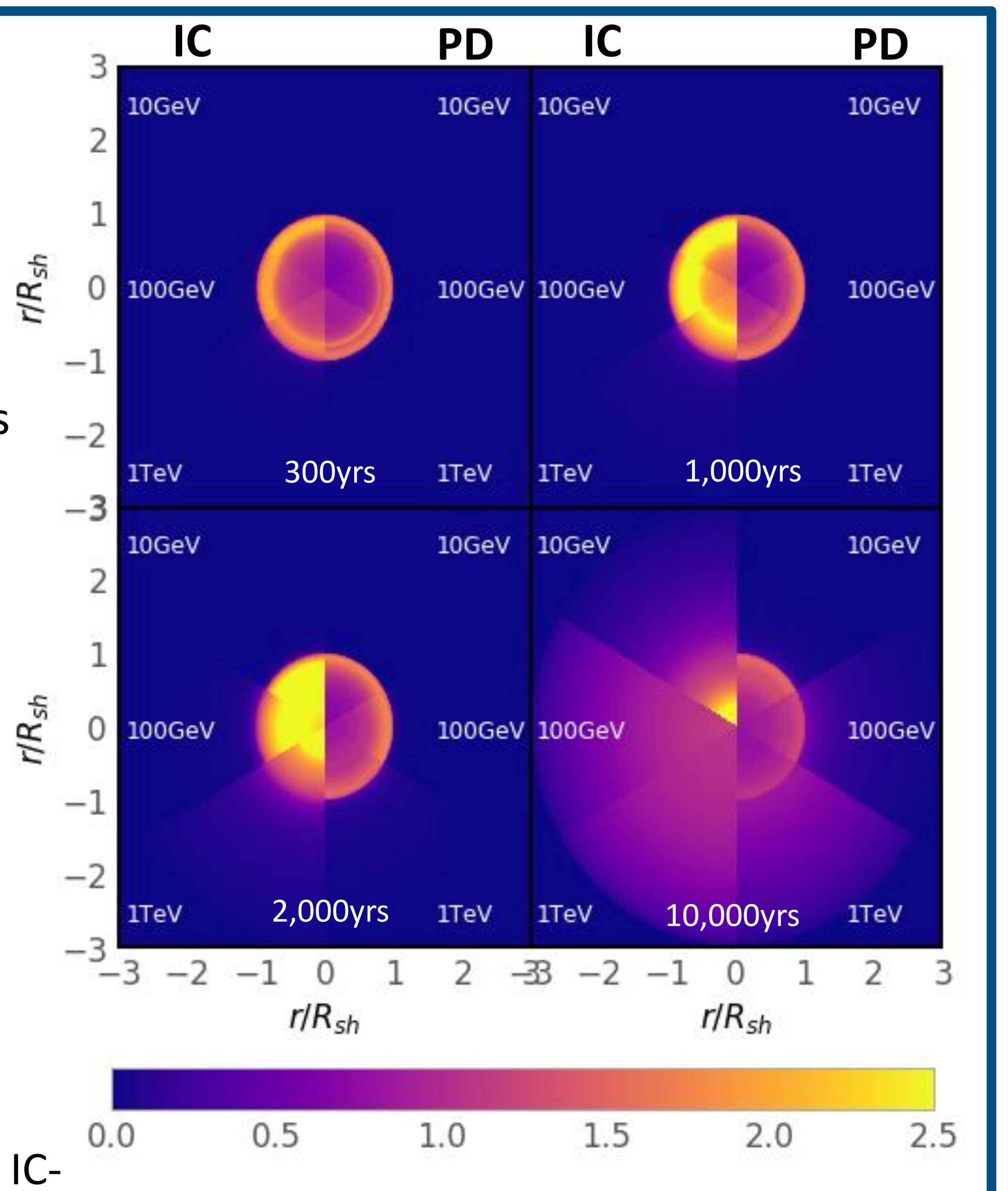


Figure 2: Gamma-ray emission morphology for 300, 1000, 2000 and 10000 yrs. Left hemispheres show the IC-emission and right hemispheres the PD-emission [4].

Spectral evolution

Pion-decay emission:

- PD-spectra soften over time (see Figure 1)
- Lack of ambient target material → Emission always dominated by SNR

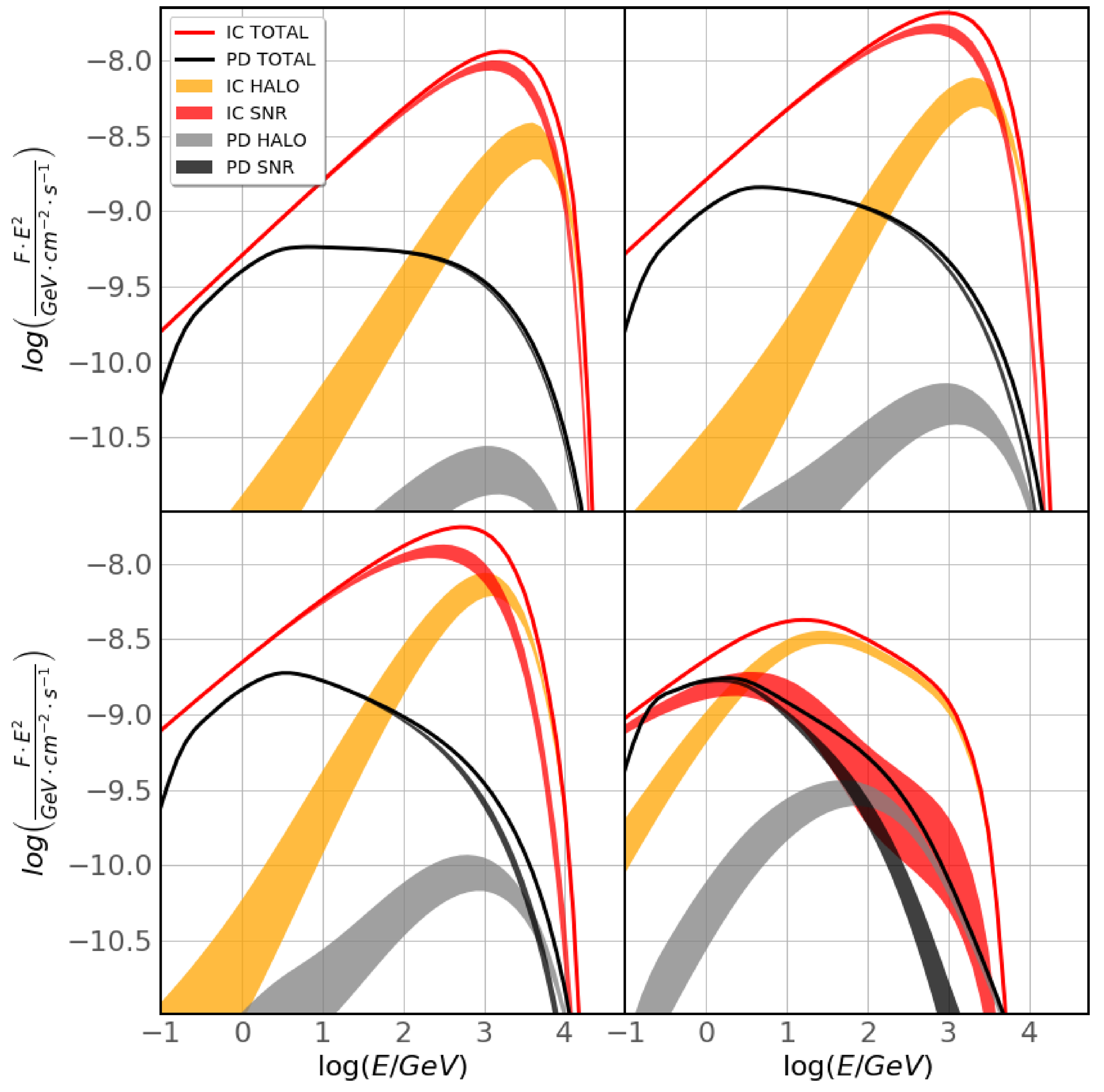
Inverse-Compton emission:

- Synchrotron-cooling important for electrons from 1-2kyrs → visible cooling break afterwards
- Brighter IC-halo compared to PD-halo (see Figure 1)
- Halo dominates emission later

Observational prospects:

- IC-emission from brightest known SNRs likely to contain halo-contribution
- Halo-spectra are generally harder than spectra from inside the SNR
- Projection effect complicates everything → sources with favorable morphology needed, e.g. SN 1006

Figure 3: Comparison of emission-spectra for IC (red) and PD (black) emission. Emission from the SNR is filled-black and filled-red for PD and IC-emission respectively. The halo-emission is filled-orange and filled-gray for IC and PD-emission respectively. Times as in Figure 2. The upper (lower) boundaries of the SNR emission represent spectra including (absent of) the project effect. The situation is inverted for emission from the Halo. [4]



Particle escape

- Evolved SNRs tend to show **soft gamma-ray spectra** including **spectral breaks**
- Non-linear acceleration theory predicts a hardening at the highest energies and concave spectra

How to get spectral breaks?

- E_{max} of the SNR rapidly **decreases** as it enters the Sedov-Taylor phase
- The shock-surface keeps increasing → **more particles** are **accelerated later** in the evolution
- The superposition of the spectra produced at different times have a **break at the current E_{max}** and are **softer at high energies** (red line→)

How does the particle escape (from deep downstream) work?

- The decrease in E_{max} is accompanied by an decrease of the diffusion coefficient for the highest energetic particles
- High **energy particles** start to **diffusively escape** from the interior, produce less gamma-rays and leave behind an even softer spectrum (blue line→)

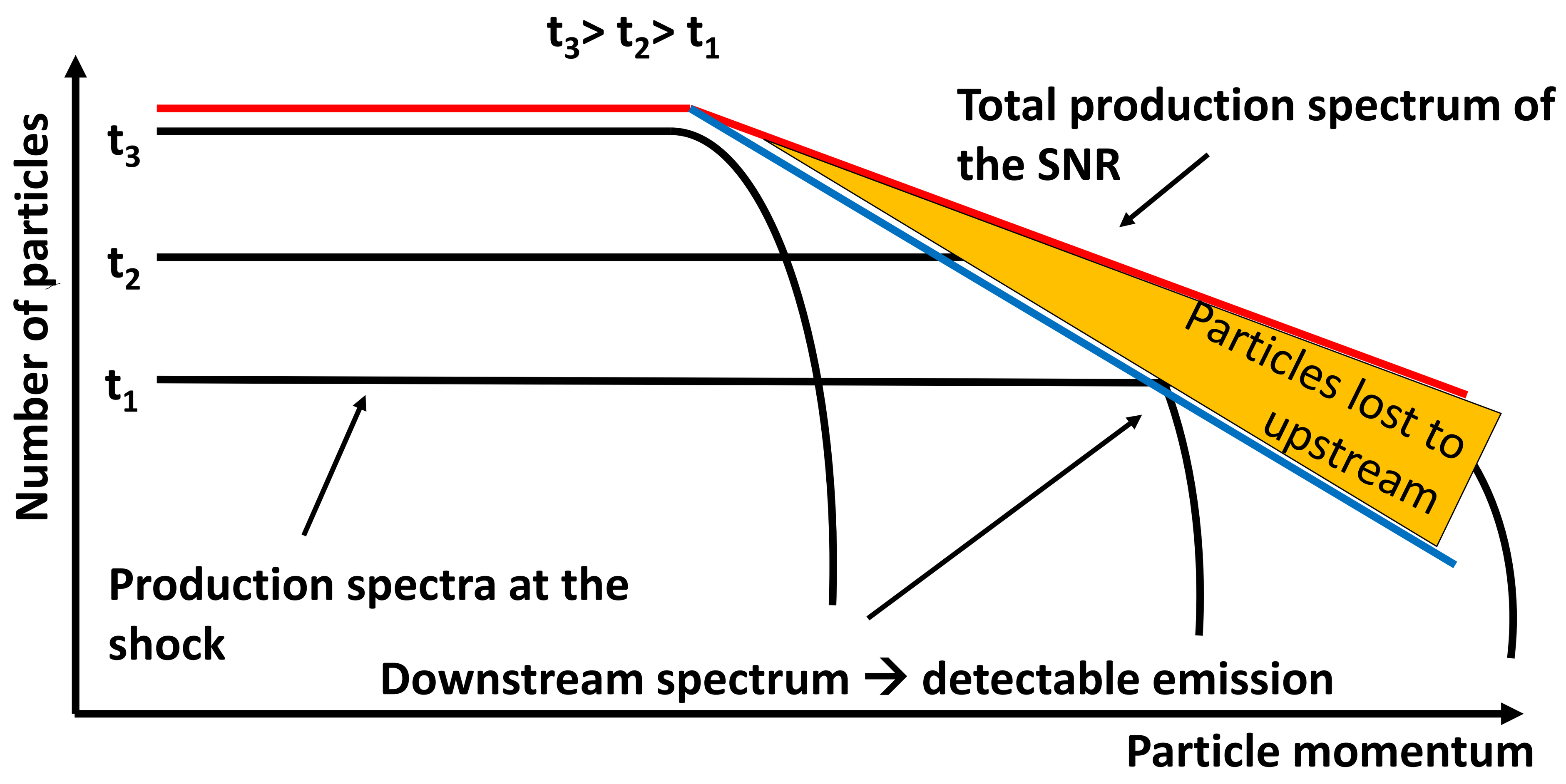


Figure 1: Sketch of spectra close to the shock for different times (black), the total spectrum produced (red) and the spectrum of particles that remains inside the SNR (blue) [2,3].

Conclusions

- PD and IC emission produce different morphologies for evolved remnants
- IC-halos are brighter and more likely to be detected even by current-generation instruments

Check out the papers ← →

Selected Publications

1. Brose, R., Telezhinsky, I., & Pohl, M. 2016, A&A, 593, A20
2. Brose, R., Pohl, M., Sushch, I., Petruk, O., & Kuzyo, T. 2020, A&A, 634, A59
3. Brose, R., Pohl, M., Sushch, I., 2021, A&A, 654, A139

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