Cosmic ray transport near particle accelerators

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Introduction

Cosmic-ray transport proceeds by diffusion and by advection

Advection: determined by gas flow, modified by cosmic-ray pressure gradient

Diffusion: determined by plasma turbulence, driven by the cosmic rays

Introduction

Cosmic-ray transport equation with diffusion coefficient D_r and flow speed u

$$\frac{\partial N}{\partial t} = \nabla(D_r \nabla N - \mathbf{u}N) - \frac{\partial}{\partial p}\left((N\dot{p}) - \frac{\nabla \cdot \mathbf{u}}{3} N p\right) + Q$$

Far from sources and shocks, the system approaches an equilibrium

In the Galaxy (u=0): $N \propto (H - z)$

Upstream of a shock (in shock frame): $N \propto \exp\left(-\int_{x_{sh}}^{x} dr\, \frac{v_{sh}}{D_r}\right)$

Introduction

Driving of turbulence with growth rate Γ

Resonant: $\Gamma \propto D_r \frac{dN_{CR}}{dx}$ $= D_r \frac{N_{CR,mean}}{H}$ on galactic scale

Nonresonant: $\Gamma \propto N_{CR} v_{sh}$ $= N_{CR,sh} v_{sh}$ near shock

Driving is balanced by damping and nonlinear interactions

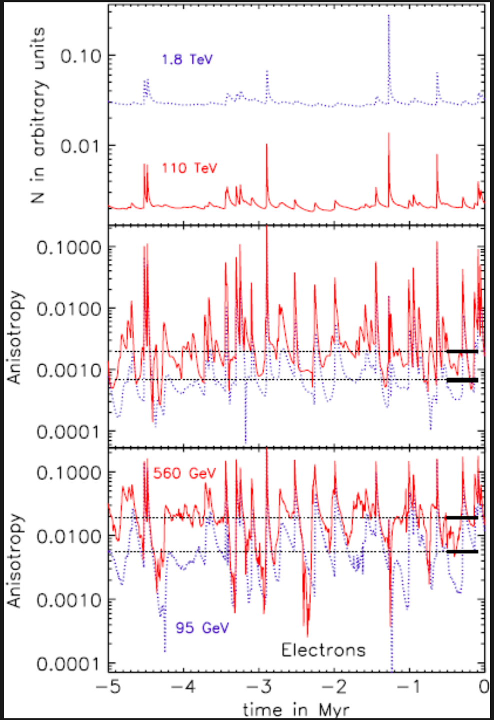
Local gradients

Cosmic ray distribution for random localized sources
(MP & Eichler 2013)

Local gradients are much stronger than global gradients

Wave driving is local, and so is wave damping

The diffusion coefficient will strongly vary with location



Introduction

Solar-system constraints measure „average" cosmic-ray transport

Reality is a patchwork of strongly variable conditions in space and time

How can we physically model cosmic-ray transport?

Driving on large scales and cascades → Don't work well (Hopkins et al. 2021)

Self-confinement of cosmic rays → Tend to flip-flop behavior (Brose et al. 2016)

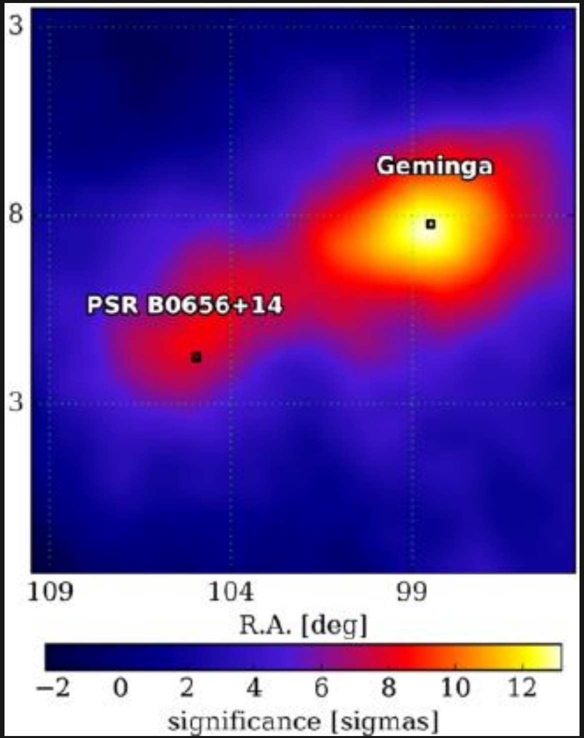
Geminga halo

TeV halo around Geminga (HAWC coll. 2017)

Diffusion coefficent only 0.1% of Galactic mean

Electron energy density 0.01 eV/cc

Only 30x mean CR energy density at same energy
Is that enough? We have that around each SNR.



Issues

What is the effect of cosmic-ray pressure?

Do PWNs also release hadrons that drive turbulence?

Is the turbulence really fully due to cosmic-ray streaming?

Shouldn‘t there be bright haloes around each SNR?

Can I really model the situation without modeling the accelerator?

Issues

What is the effect of cosmic-ray pressure?

Negligible, if that is only 0.01 eV/cc

Do PWNs also release hadrons that drive turbulence?

That might provide significant pressure

Is the turbulence really fully due to cosmic-ray streaming?

Shouldn‘t there be bright haloes around each SNR?

Can I really model the situation without modeling the accelerator?

Issues

What is the effect of cosmic-ray pressure?

Do PWNs also release hadrons that drive turbulence?

Is the turbulence really fully due to cosmic-ray streaming?

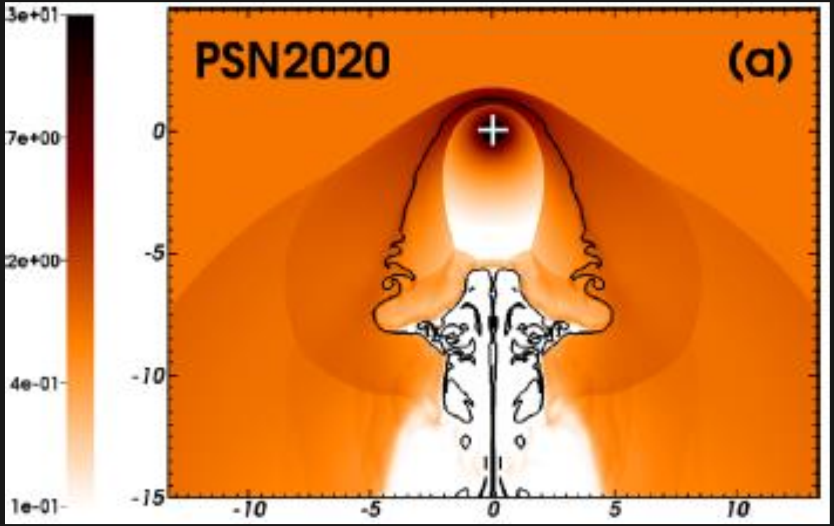
Remember the wind bubble …

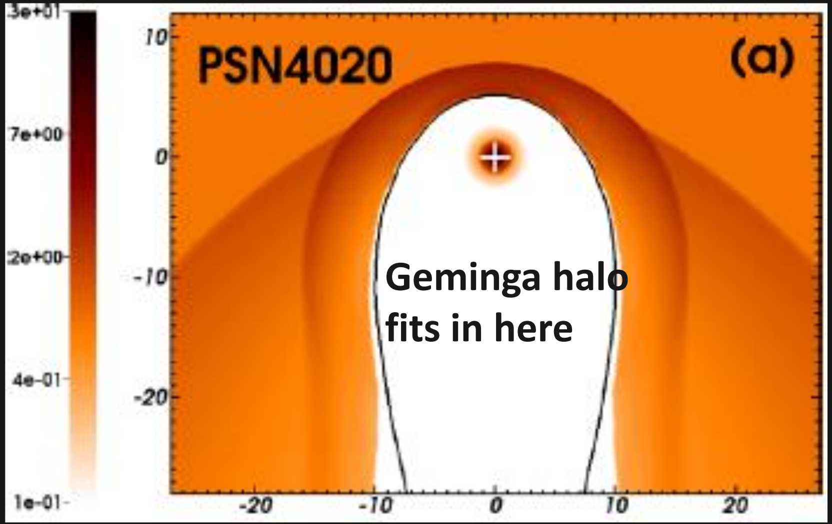
Shouldn‘t there be bright haloes around each SNR?

Can I really model the situation without modeling the accelerator?

Haloes around SNRs

Wind bubble size depends on the progenitor mass





20 M_{sol} at 20 km/s

Density maps

40 M_{sol} at 20 km/s

Meyer et al. 2015

Issues

What is the effect of cosmic-ray pressure?

Do PWNs also release hadrons that drive turbulence?

Is the turbulence really fully due to cosmic-ray streaming?

Shouldn‘t there be bright haloes around each SNR?

Likely yes

Can I really model the situation without modeling the accelerator?

Probably not

SNR modeling

Modeling cosmic rays, turbulence, and hydrodynamics in parallel

$$\frac{\partial}{\partial t}\begin{pmatrix} \rho \\ \mathbf{m} \\ E \end{pmatrix} + \nabla \begin{pmatrix} \rho \mathbf{v} \\ \mathbf{m}\mathbf{v} + P\mathbf{I} \\ (E+p)\mathbf{v} \end{pmatrix}^T = \begin{pmatrix} 0 \\ 0 \\ L \end{pmatrix}$$

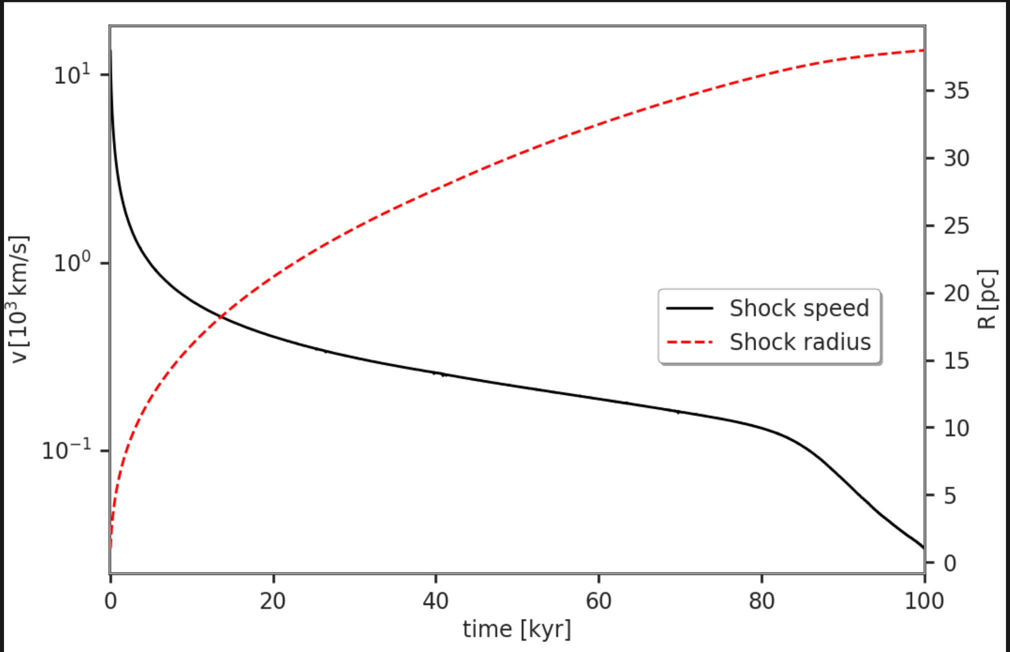
$$\frac{\rho \mathbf{v}^2}{2} + \frac{P}{\gamma - 1} = E,$$

$$\frac{\partial N}{\partial t} = \nabla(D_r \nabla N - \mathbf{u}N) - \frac{\partial}{\partial p}\left((N\dot{p}) - \frac{\nabla \cdot \mathbf{u}}{3} N p\right) + Q$$

$$\frac{\partial E_w}{\partial t} + \cdot\nabla(\mathbf{u}E_w) + k\frac{\partial}{\partial k}\left(k^2 D_k \frac{\partial}{\partial k}\frac{E_w}{k^3}\right) = 2(\Gamma_g - \Gamma_d)E_w.$$

Today: Type-Ia only (Brose et al. 2020, 2021)

SNR modeling



Geminga halo is deeply inside late SNR

What is left of the SNR-produced turbulence?

Geminga halo likely not entirely due to e^{+-} streaming

SNR modeling

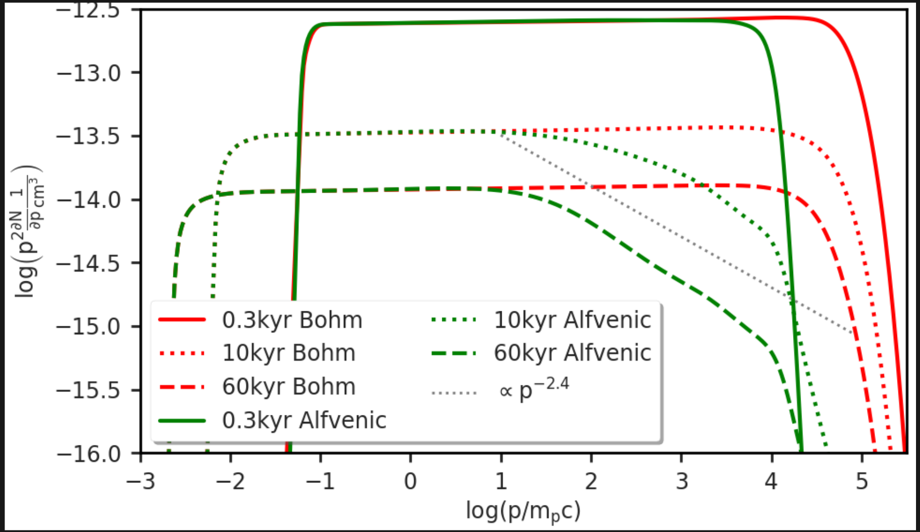
Turbulence modeling matters: Volume-integrated proton spectra

Decreasing CR density reduces turbulence driving and E_{max}

Total production spectra above 10 GeV are soft

Consistent with data!

Electron spectra cut off earlier



SNR modeling

Models decisively depend on the injection efficiency

Its scaling behavior is unknown

Initially: Bohm-like diffusion and efficient acceleration

Later: Larger diffusion coefficients and inefficient acceleration

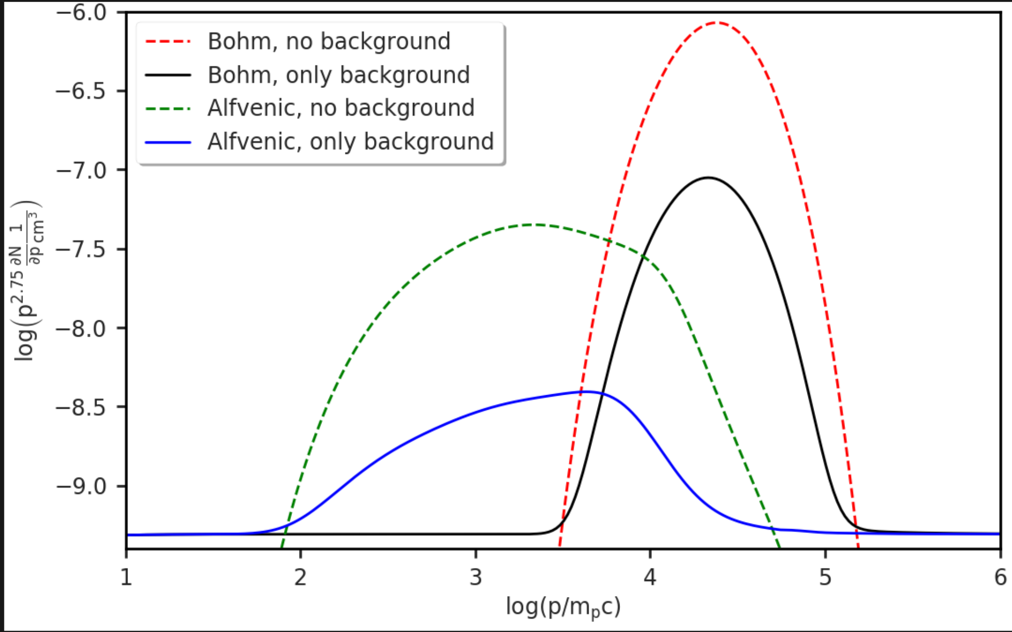
Cosmic rays tend to be dynamically important only late in the evolution

Haloes around SNRs

Spectra 7.5pc ahead of the forward shock after 37 kyr.

Turbulence modeling shapes cosmic rays that drive the waves

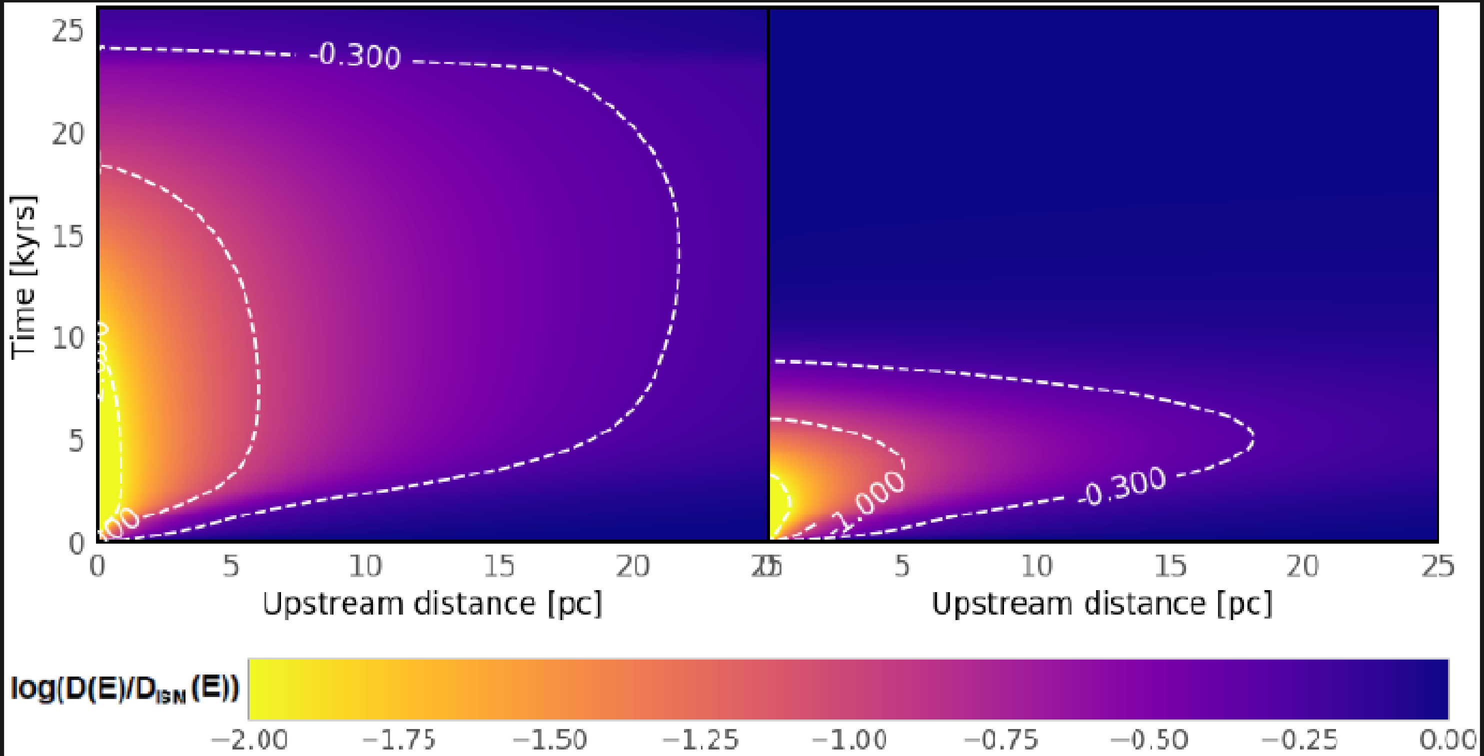
Haloes cannot be modeled without considering the accelerator



Diffusion

100 GeV

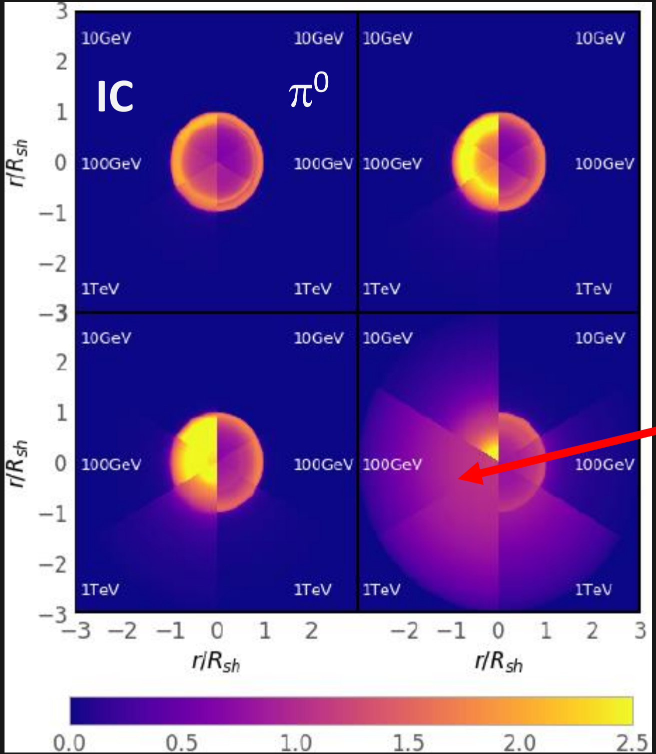
3 TeV



Intensity around SNRs

300 yrs

1000 yrs



2000 yrs

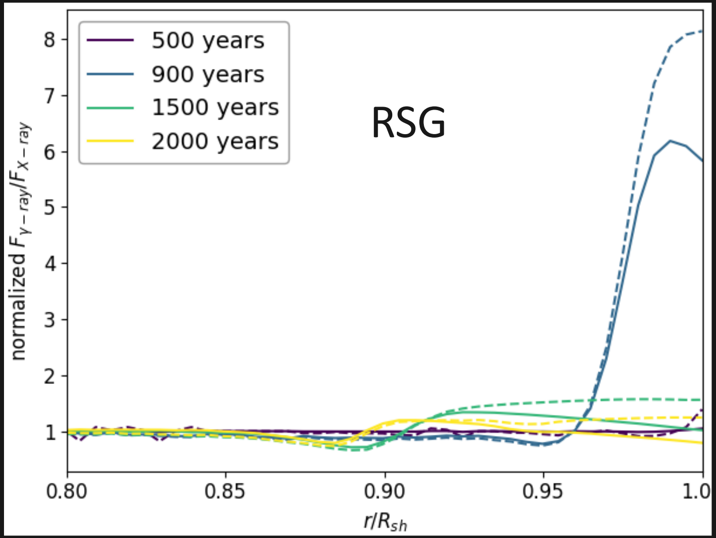
10,000 yrs

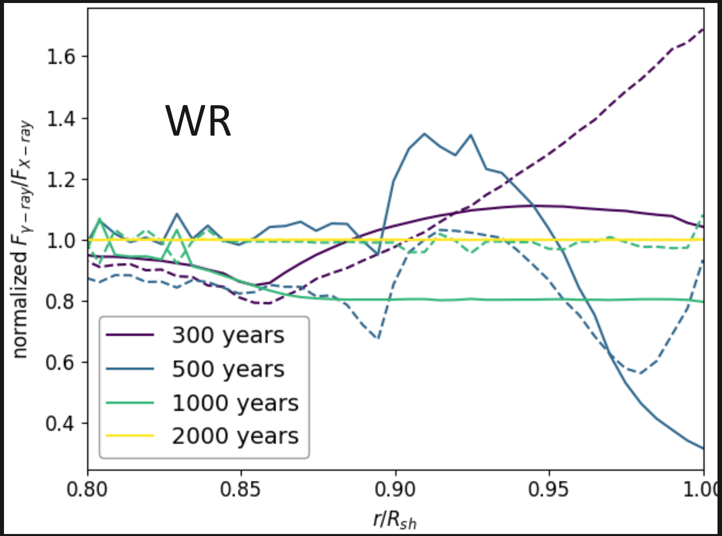
Haloes evident after 10,000 yrs

Always a thin shell in X rays

Young type-II SNRs

Do not assume a spatial correlation between X-ray and IC γ-ray intensity





Sushch et al.
2111.06946

Conclusions

- Haloes around cosmic-ray accelerator are a natural feature
- Proper modeling requires simultaneous accounting for the accelerator
- Reduced diffusivity results from cosmic-ray streaming
- Diffusion coefficients are strongly variable in time and space
- At least for SNRs, the source is brighter than the halo
- Modeling of type-II SNRs and PWNs inside SNRs is still to be done