Self-confinement of low-energy cosmic rays around supernova remnants

Philipp Mertsch
with Hanno Jacobs, Minh Phan

Cosmic rays 2: The salt of the star formation recipe
8 November 2022

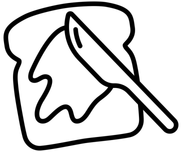
Institute for Theoretical Particle Physics and Cosmology
RWTH AACHEN UNIVERSITY

Roles of cosmic rays

Cosmic rays as salt

- Provide pressure support
- Provide heating
- Ionise molecular clouds
- Regulate coupling of gas and magnetic field
- ...

Roles of cosmic rays



Cosmic rays as salt

- Provide pressure support
- Provide heating
- Ionise molecular clouds
- Regulate coupling of gas and magnetic field
- ...

Cosmic rays as bread and butter

- Produce local fluxes

cosmic ray origin

sources

"What is accelerating up to $E_{\mathrm{knee}} \sim 3 \times 10^{15}\,\mathrm{eV}$?"

transport

"How are diffusion, radiative losses etc. shaping the spectrum?"

cosmic ray origin

sources

“What is accelerating up to $E_{\text{knee}} \sim 3 \times 10^{15}\,\text{eV}$?”

transport

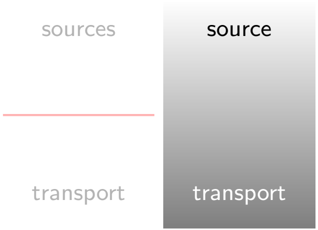
“How are diffusion, radiative losses etc. shaping the spectrum?”

A grey area

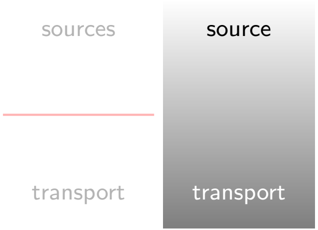
sources

transport

A grey area



A grey area



"Reacceleration"

- 2nd-order Fermi acceleration
- Better fit to boron-to-carbon Strong & Moskalenko (1998)
- Too much power from turbulence? Drury & Strong (2016)

Escape from shock

- Confinement by **B**-fields

→ Escape probability function of rigidity and time

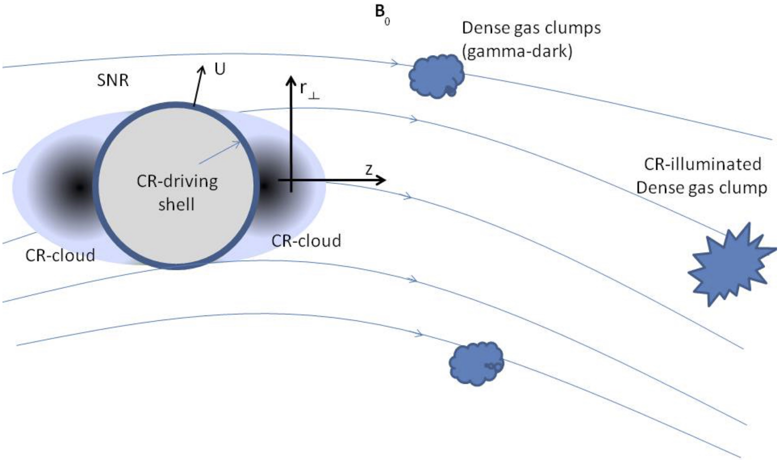
- Time-integrated spectrum? gamma-rays?

Near-source confinement

- Resonant streaming instability
- Self-similar solution Malkov et al. (2013)
- Strong dependence on ionisation Nava *et al.* (2016, 2019), Recchia *et al.* (2021)

The cosmic ray cloud

Malkov *et al.* (2013)



Cosmic ray self-confinement

Ptuskin, Zirakashvili, Plesser (2008); Malkov *et al.* (2013); Nava *et al.* (2016)

$$\partial_t P_{\mathrm{CR}} + v_{\mathrm{A}} \partial_z P_{\mathrm{CR}} = \partial_z \left(D_{zz}(z,p) \partial_z P_{\mathrm{CR}} \right)$$

$$D_{zz}(z,p) \sim \left. \frac{D_B(p)}{I(k)} \right|_{k=1/r_g}$$

- CR pressure $P_{\mathrm{CR}} = p^4 f$
- Diffusion coefficient $D_{zz}(z,p)$
- Bohm value $D_{\mathrm{B}}(p)$
- Turbulence spectral energy density $I(k)$

Cosmic ray self-confinement

Ptuskin, Zirakashvili, Plesser (2008); Malkov *et al.* (2013); Nava *et al.* (2016)

$$\partial_t P_{\mathrm{CR}} + v_{\mathrm{A}} \partial_z P_{\mathrm{CR}} = \partial_z \left(D_{zz}(z, p) \partial_z P_{\mathrm{CR}} \right)$$

$$D_{zz}(z, p) \sim \left. \frac{D_B(p)}{I(k)} \right|_{k=1/r_g}$$

$$\Gamma_{\mathrm{CR}}(z, k) = -\frac{v_{\mathrm{A}}}{I} \partial_z P_{\mathrm{CR}}$$

$$\partial_t I + v_{\mathrm{A}} \partial_z I = 2\Gamma_{\mathrm{CR}}(z, k) I - 2\Gamma_d I + Q$$

- CR pressure $P_{\mathrm{CR}} = p^4 f$
- Diffusion coefficient $D_{zz}(z, p)$
- Bohm value $D_{\mathrm{B}}(p)$
- Turbulence spectral energy density $I(k)$
- Growth rate $\Gamma_{\mathrm{CR}}(z, k)$
- Damping rate Γ_d

Cosmic ray self-confinement

Ptuskin, Zirakashvili, Plesser (2008); Malkov *et al.* (2013); Nava *et al.* (2016)

$$\partial_t P_{\mathrm{CR}} + v_{\mathrm{A}} \partial_z P_{\mathrm{CR}} = \partial_z \left(D_{zz}(z,p) \partial_z P_{\mathrm{CR}} \right)$$

$$D_{zz}(z,p) \sim \left. \frac{D_B(p)}{I(k)} \right|_{k=1/r_g}$$

$$\Gamma_{\mathrm{CR}}(z,k) = -\frac{v_{\mathrm{A}}}{I} \partial_z P_{\mathrm{CR}}$$

$$\partial_t I + v_{\mathrm{A}} \partial_z I = 2\Gamma_{\mathrm{CR}}(z,k) I - 2\Gamma_d I + Q$$

- CR pressure $P_{\mathrm{CR}} = p^4 f$
- Diffusion coefficient $D_{zz}(z,p)$
- Bohm value $D_{\mathrm{B}}(p)$
- Turbulence spectral energy density $I(k)$
- Growth rate $\Gamma_{\mathrm{CR}}(z,k)$
- Damping rate Γ_d

Around supernova remnants:

Nava & Gabici (2013), D'Angelo *et al.* (2016, 2018), Nava *et al.* (2019), Brahimi *et al.* (2020), Brose *et al.* (2021), Schroer *et al.* (2021), Recchia *et al.* (2022), Jacobs, Mertsch, Phan (2022)

Around pulsar wind nebulae:

Evoli, Linden, Morlino (2018), Linden & Mukhopadhyay (2022)

On Galaxy scales:

Amato, Blasi, Serpico (2012), Evoli *et al.* (2016)

The phases of the ISM

Phase	T [K]	n [cm^{-3}]	filling factor	ionisation fraction	neutrals	ions
HIM	10^6	10^{-2}	0.5	1	-	H^+
WIM	8000	0.35	0.25	0.6-0.9	H, He	H^+
WNM	8000	0.35	0.25	10^{-2}	H, He	H^+
CNM	80	35	~ 0	10^{-3}	H, He	C^+
DiM	50	300	~ 0	10^{-4}	H_2, He	C^+

Most of the ISM mass in molecular clouds, but filling factor tiny.

The phases of the ISM

Phase	T [K]	n [cm^{-3}]	filling factor	ionisation fraction	neutrals	ions
HIM	10^6	10^{-2}	0.5	1	-	H^+
WIM	8000	0.35	0.25	0.6-0.9	H, He	H^+
WNM	8000	0.35	0.25	10^{-2}	H, He	H^+
CNM	80	35	~ 0	10^{-3}	H, He	C^+
DiM	50	300	~ 0	10^{-4}	H_2, He	C^+

Most promising at low energies

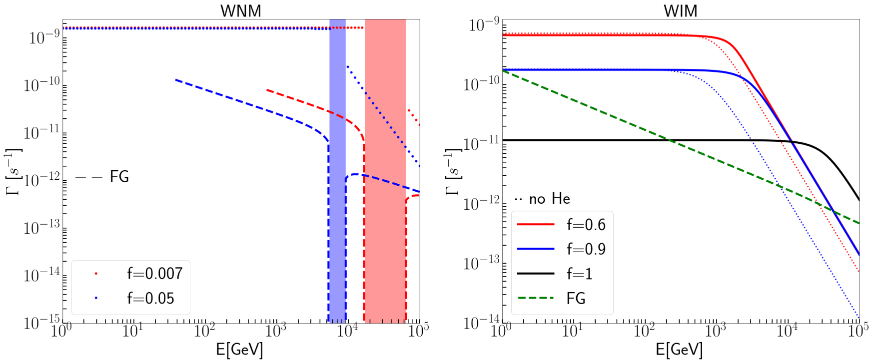
Most of the ISM mass in molecular clouds, but filling factor tiny.

- Focus on WIM with ionisation fraction 0.9 and WNM
- Alfvén speed v_A larger in WNM due to inefficient coupling of neutrals at low energies

Damping Processes

- Ion-neutral damping (momentum transfer to neutrals)
- Farmer-Goldreich damping (interaction with external turbulence)
- Non-linear Landau damping (interaction of beat of waves with background plasma)

Recchia *et al.*(2021)



Propagation of low energetic protons

$$\partial_t f_{\rm CR} = \partial_z \left(D_{zz}(z,p) \partial_z f_{\rm CR} \right) - \frac{1}{p^2} \partial_p \left(\dot{p} p^2 f(z,p) \right)$$

$$D_{zz}(z,p) \sim \left. \frac{D_B(p)}{k W(k)} \right|_{k=1/r_g}$$

$$\Gamma_{\rm CR}(z,k) = -\frac{v_A}{kW} \partial_z p^4 f_{\rm CR}$$

$$\partial_t W + \partial_k \left(D_{kk} \partial_k W(z,k) \right) = \left(\Gamma_{\rm CR}(z,k) - \Gamma_D \right) W$$

Improvements

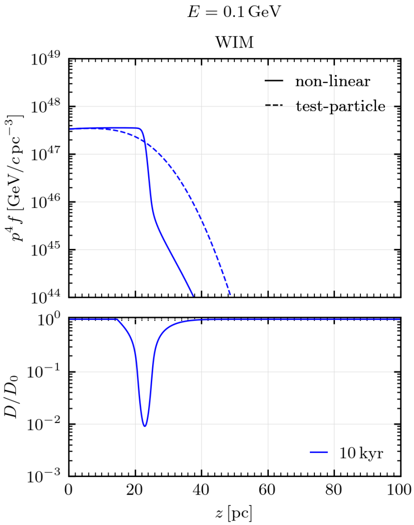
- Energy losses important $E < 10\,\mathrm{GeV}$
  - Ionisation
  - Cloulomb
  - Pion production
- Spatial dependent $v_A(z)$
- Non linear cascade in wave-number

(Details → Appendix)

Spatial dependence

H. Jacobs, P. Mertsch, M. Phan, JCAP 05 (2022) 05, 024 [arXiv:2112.09708]

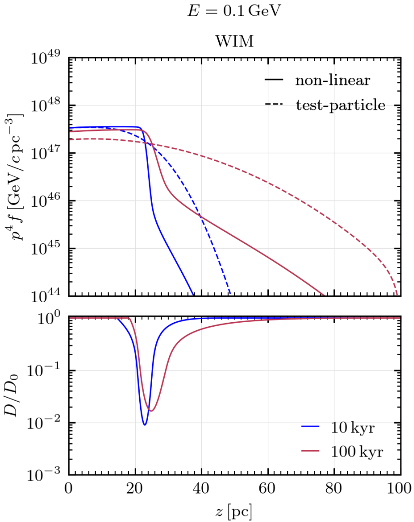
- Initially top hat profile
- Test particle solution approximately gaussian
- Particles confined longer in non-linear simulation
- Diffusion coefficient suppressed up to $\mathcal{O}(100)$
- Suppression lasts $1\,\mathrm{Myr}$



Spatial dependence

H. Jacobs, P. Mertsch, M. Phan, JCAP 05 (2022) 05, 024 [arXiv:2112.09708]

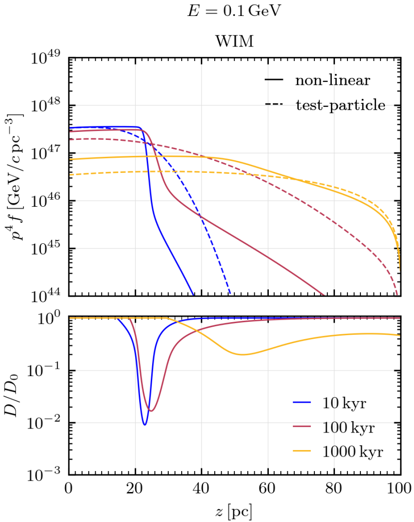
- Initially top hat profile
- Test particle solution approximately gaussian
- Particles confined longer in non-linear simulation
- Diffusion coefficient suppressed up to $\mathcal{O}(100)$
- Suppression lasts $1\,\mathrm{Myr}$



Spatial dependence

H. Jacobs, P. Mertsch, M. Phan, JCAP 05 (2022) 05, 024 [arXiv:2112.09708]

- Initially top hat profile
- Test particle solution approximately gaussian
- Particles confined longer in non-linear simulation
- Diffusion coefficient suppressed up to $\mathcal{O}(100)$
- Suppression lasts $1\,\mathrm{Myr}$



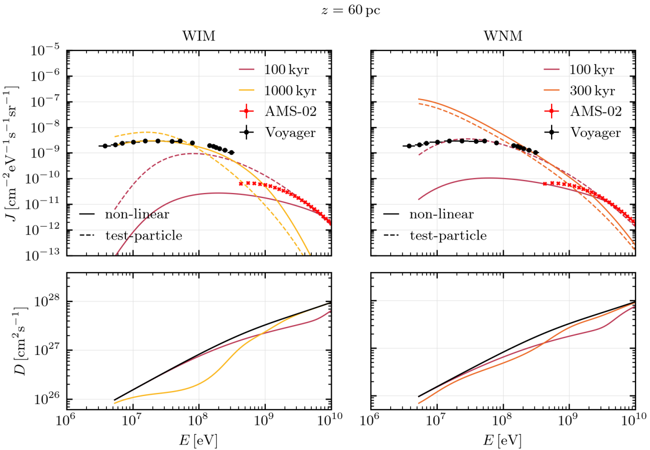
Spectral dependence

H. Jacobs, P. Mertsch, M. Phan, JCAP 05 (2022) 05, 024 [arXiv:2112.09708]

- Softer spectrum at later times
- More flux at later times
- Spectral break closer to Voyager than test particle solution
- Can explain Voyager1 and AMS02 data with two fine tuned sources
- Need statistical approach

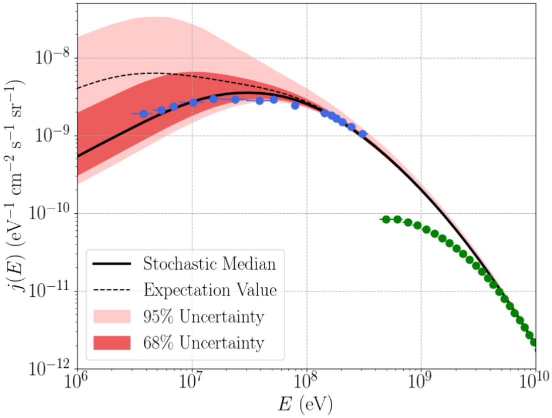
  M. Phan, F. Schulze, P. Mertsch, S. Recchia, S. Gabici (2021)

(More results → Appendix)



Stochasticity

M. Phan, F. Schulze, P. Mertsch, S. Recchia, S. Gabici (2021)



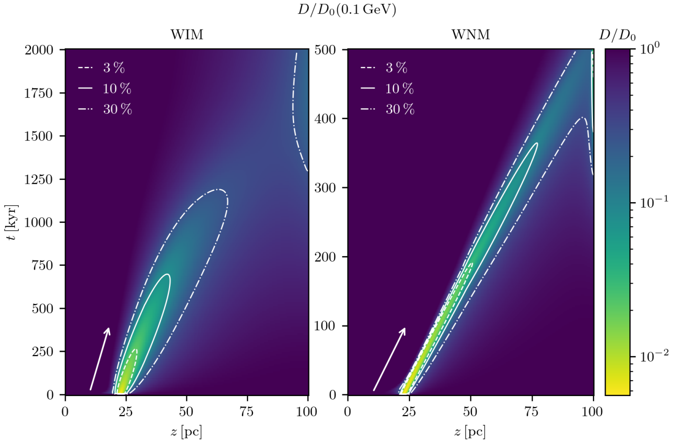
- Combine stochasticity and non-linear approach

$\rightarrow$ Minh Phan's talk today

Diffusion coefficient

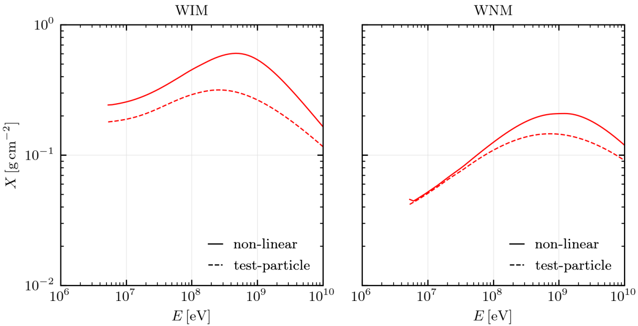
H. Jacobs, P. Mertsch, M. Phan, JCAP 05 (2022) 05, 024 [arXiv:2112.09708]

- Low diffusion zone advected with gradient of CR (arrow)
- WIM: suppression lasting over $1\,\mathrm{Myr}$
- WNM: suppression advected to boundary at $500\,\mathrm{kyr}$
- Instantaneous transition from 1D to 3D at boundary overestimation



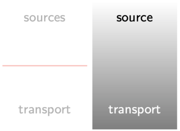
Grammage

H. Jacobs, P. Mertsch, M. Phan, JCAP 05 (2022) 05, 024 [arXiv:2112.09708]



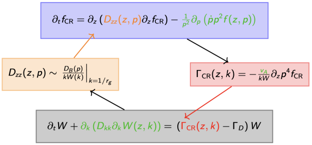
- Increased by factor 3
- Similar results to Recchia *et al.* (2021) (fig. 4) at $10\,\mathrm{GeV}$
- WIM: Constant at lowest energies
- WNM: Advection dominated at lowest energies

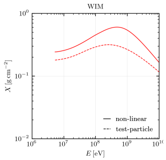
Summary



CR density $\neq$ (source) $\times$ (propagation)

Coupled evolution of CR density and magnetic turbulence





Effects

- Spatial profiles
- Spectra
- Grammage