The size of PeV sources

Philipp Mertsch
with Hanno Jacobs, Marco Kuhlen and Minh Phan

HONEST2: PeVatrons and their environment
30 November 2022

Institute for Theoretical Particle Physics and Cosmology
RWTH AACHEN UNIVERSITY

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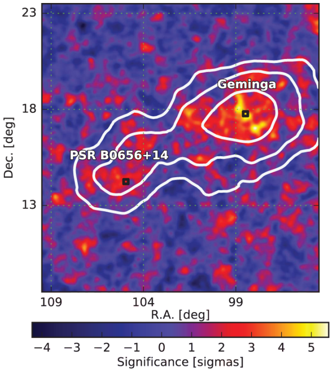
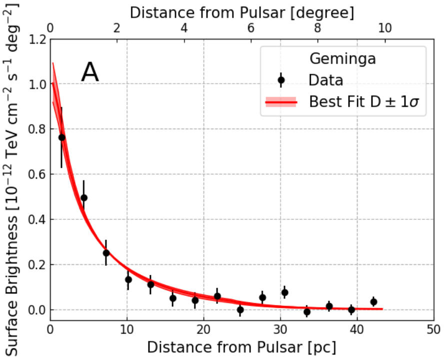
Gamma-ray halos

Abeysekara *et al.* (2017)





- Gamma-ray emission around two nearby pulsars
- Emission from $\mathrm{e}^{\pm}$ much more confined than expected

$\rightarrow$ Ambient diffusion coefficient suppressed by factor ~ 100

- Self-confinement of high-energy $\mathrm{e}^{\pm}$

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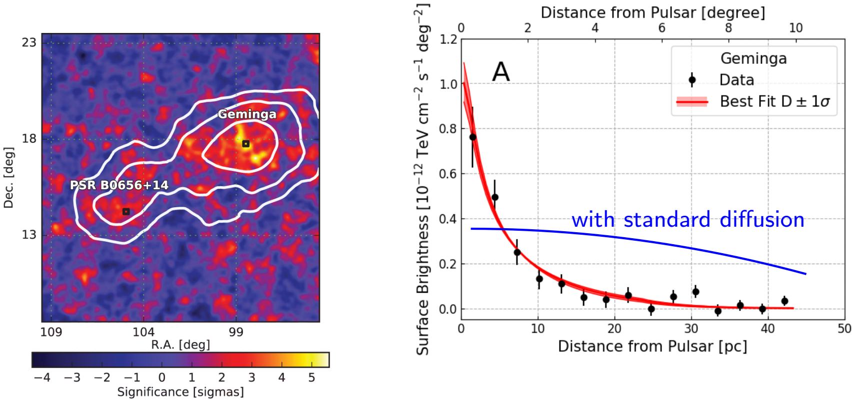

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Cosmic ray self-confinement

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 $I(k)$

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

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

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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:

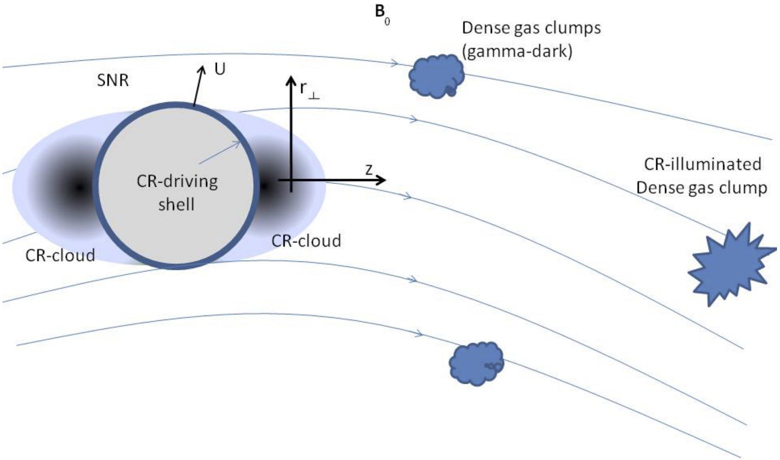
Evoli, Linden, Morlino (2018), Linden & Mukhopadhyay (2022)

On Galaxy scales:

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

The cosmic ray cloud

Malkov *et al.* (2013)



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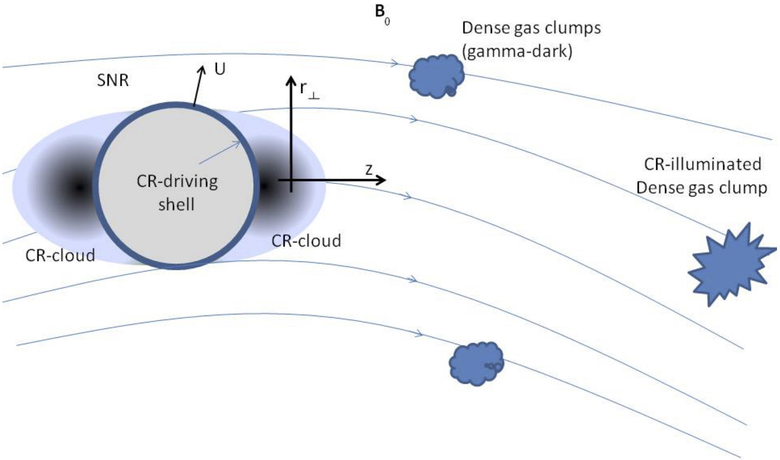


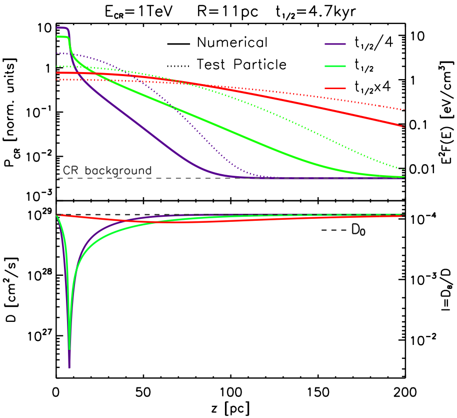
Validity of flux tube approximation?

Schroer *et al.* (2021) and others

Previous work

Nava *et al.* (2016)

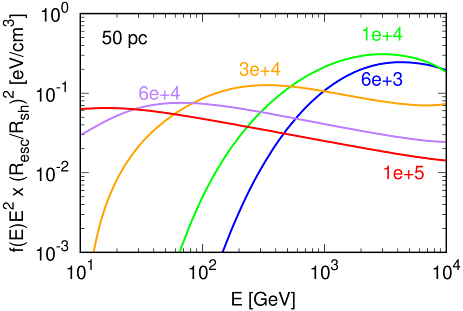
- Consider warm neutral medium (WNM) and warm ionised medium (WIM)
- ion-neutral damping and Farmer-Goldreich damping

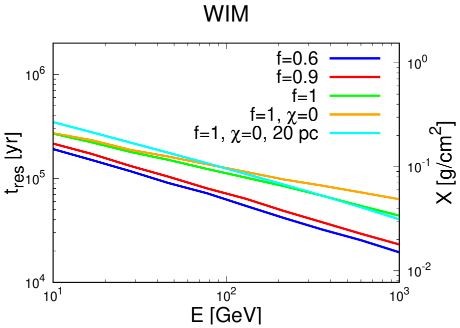


- $t_{1/2}$ is the time after which more than half of the CRs initially in the cloud have diffused away
- of the order a few tens of kyr
- $P_{\rm CR}$ significantly modified wrt to test-particle for $t \lesssim t_{1/2}$
- diffusion coefficient can be locally suppressed by factor 100

Previous work

Nava *et al.* (2016, 2019); Brahimi *et al.* (2020); Recchia *et al.* (2021)





- No transport in p, but Coulomb and ionisation losses important at energies below 10 GeV
- No transport in k but cascading from large to small scales

Propagation of low energetic protons

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

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

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

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

Improvements

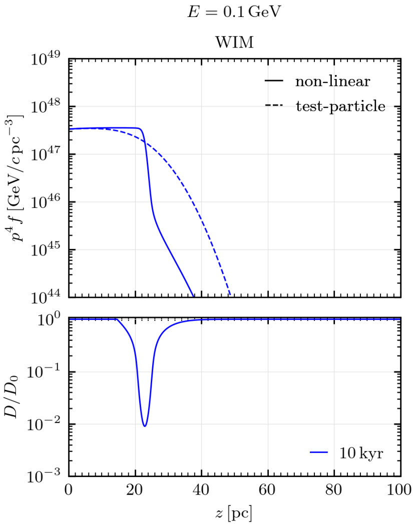
- Energy losses important $E < 10\,\mathrm{GeV}$
  - Ionisation
  - Cloulomb
  - Pion production
- Spatial dependent $v_A(z)$
- Non linear cascade in wave-number

(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 $1\,\mathrm{Myr}$



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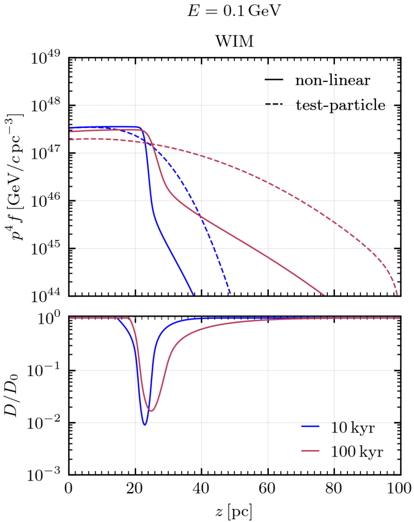

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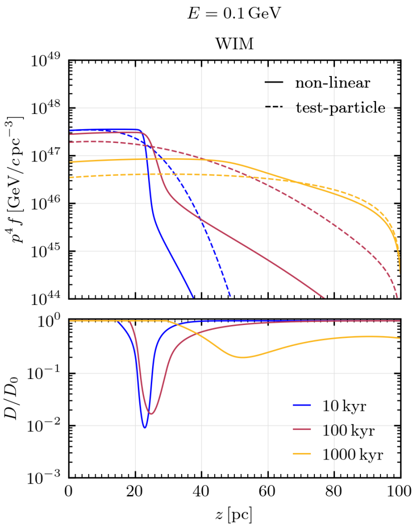


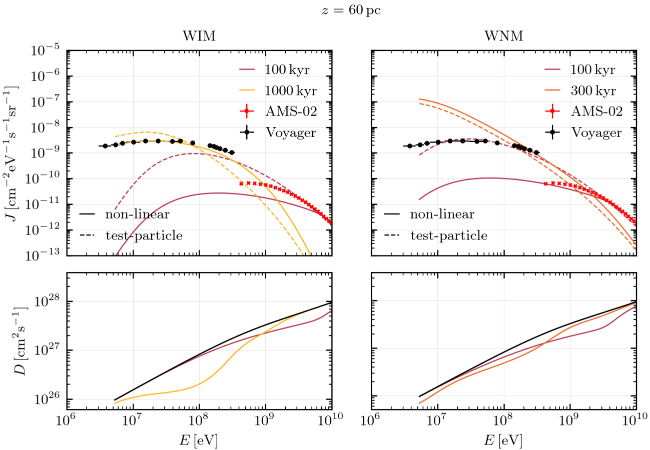
Spectral dependence

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)

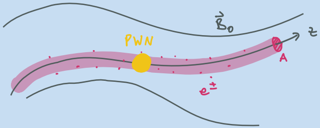
(More results → Appendix)



NOT the conflict

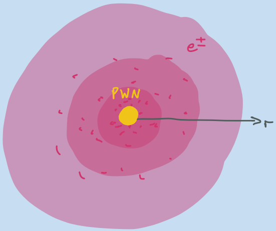
Evoli, Linden, Morlino (2018), Linden & Mukhopadhyay (2022)

1D



- Growth rate: $\Gamma_{1D} \propto \frac{\partial f}{\partial z}$
- Volume occupied: $V_{1D} \sim A \left\langle (\Delta z)^2 \right\rangle^{1/2}$

3D



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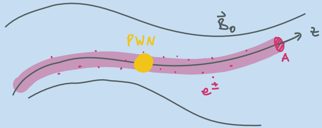

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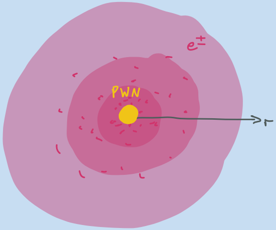

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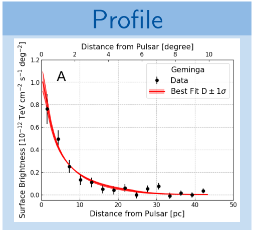
Locally, transport is **not** isotropic

See Lopez-Coto and Giacinti (2019) though

The conflict



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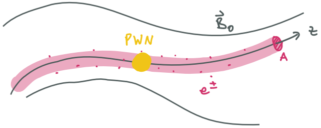
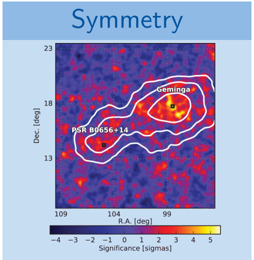
Suppression of diffusion



$$\kappa_\perp \ll \kappa_\parallel \quad \Leftrightarrow \quad \delta B^2 \ll B_0^2$$



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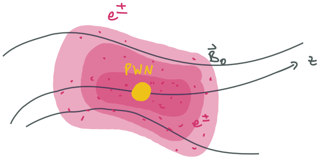
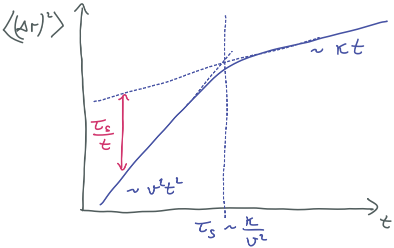
Spherical distribution



$$\kappa_\perp \sim \kappa_\parallel \quad \Leftrightarrow \quad \delta B^2 \gg B_0^2$$

Are $e^{\pm}$ diffusing?

$$\sigma^2 \equiv \left\langle (\Delta r)^2 \right\rangle \propto t^{\alpha} \quad \rightarrow \quad \begin{cases} \alpha < 1 & \text{sub-diffusion} \\ \alpha = 1 & \text{diffusion} \\ \alpha > 1 & \text{super-diffusion} \\ \alpha = 2 & \text{ballistic} \end{cases}$$



$$\sigma \sim v \tau_s \sim \frac{\kappa}{v} \simeq 30\,\mathrm{pc} \left(\frac{\kappa(1\,\mathrm{GeV})}{3 \times 10^{28} \mathrm{cm}^2\,\mathrm{s}^{-1}} \right) \left(\frac{E}{\mathrm{PeV}} \right)^{1/3}$$

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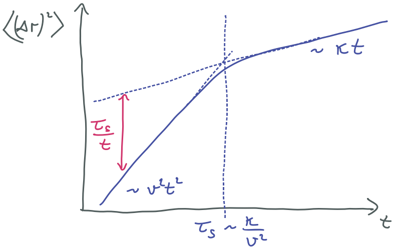

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Overestimation of σ^2

1. More peaked profile

→ No need for suppressed diffusion?

Recchia *et al.* (2021)

2. Underestimation of growth rate:

$$\Gamma_{3D} \propto \max \frac{\partial f}{\partial r} \propto \left(\sigma^2 \right)^{-2}$$

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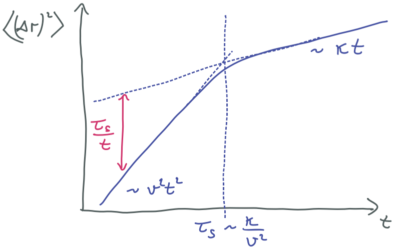

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Test particle simulations

Kuhlen, Mertsch, Phan (2022) [arXiv:2211.05881]; also Mertsch (2019)

- Reduced rigidity: $\frac{r_{\mathrm{g}}}{L_{\mathrm{c}}}$
- Turbulence level: $\eta = \frac{\delta B^2}{B_0^2 + \delta B^2}$

- Isotropic turbulence
- Kolmogorov power spectrum $P(k) \propto k^{-5/3}$
- Running diffusion coefficients:

$$d_{\parallel}(t) \equiv \frac{1}{2} \frac{\mathrm{d}}{\mathrm{d}t} \langle (\Delta z)^2 \rangle$$

$$d_{\perp}(t) \equiv \frac{1}{4} \frac{\mathrm{d}}{\mathrm{d}t} \left(\langle (\Delta x)^2 \rangle + \langle (\Delta y)^2 \rangle \right)$$

(So, $\quad \langle (\Delta z)^2 \rangle = 2 \int_0^t \mathrm{d}t' d_{\parallel}(t') \quad$ etc.)

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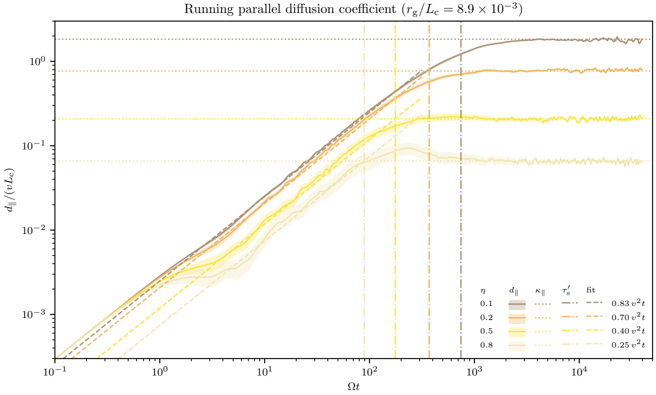

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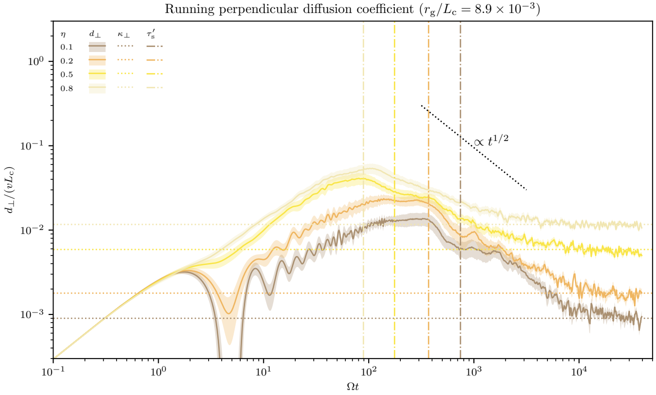


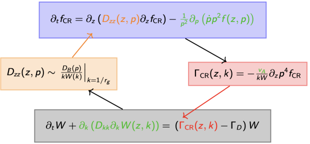
1. $d_{||}$ smaller than $v^2 t$ $\Rightarrow$ $\langle (\Delta z)^2 \rangle$ even smaller $\Rightarrow$ Larger Γ_{1D}
2. $d_\perp$ enhanced at intermediate times $\Rightarrow$ Larger perpendicular spread

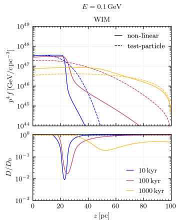
Health and safety

Test particle simulations
↯
Non-linear transport

Summary

Coupled evolution of CR density and magnetic turbulence





Propagation at GeV energies

- Suppression of diffusion
- Longer residence times
- Spectral features

Test particle simulations at PeV energies: slower diffusion, more spread