# Tracing the origin of low diffusivity and CR bubbles around sources

Benedikt Schroer

Oreste Pezzi, Damiano Caprioli, Colby Haggerty, Pasquale Blasi

July 12th – 23rd, 2021

GRAN SASSO SCIENCE INSTITUTE

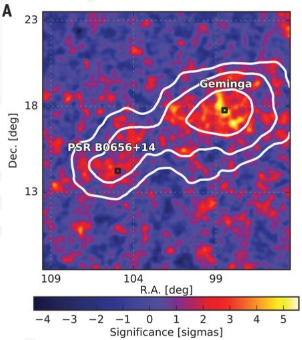
www.gssi.it

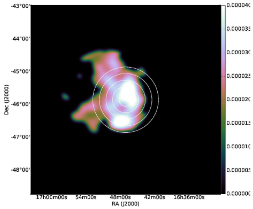
# Content



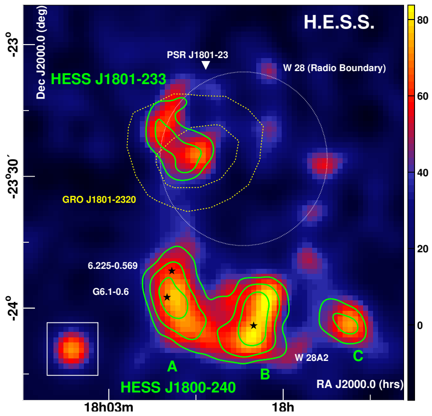
G S
S I

# Introduction




1



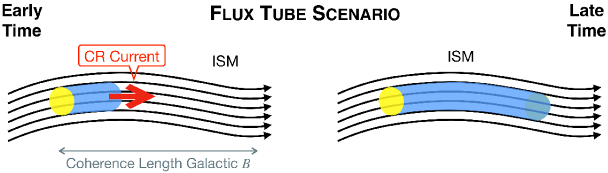

2

- Hints for strongly reduced diffusion coefficient observed near SNR, stellar clusters and pulsars

[1] [Abeysekara et al., 2017; Aharonian et al., 2019]
[2] [Aharonian et al., 2008]

# Standard picture of CR escape

- interstellar magnetic field is coherent on scales of $\sim$ 10-50 pc
- particles mainly diffuse parallel to the magnetic field




$\Rightarrow$ on these scales particles fill a flux tube and the problem can be regarded 1D

- flux given by: $\phi_{CR}(E > E_0) = n_{CR}(E > E_0)v_D = \frac{L_{CR}}{2\pi R_s^2 \Lambda E_0}$
- In this configuration CRs will excite a resonant streaming instability, hindering their escape
- Less efficient for high-energy particles [3]

[3] [Nava et al., 2016, D'Angelo et al. 2016]

# Formation of CR bubbles

# Bell instability [4]

Did we miss something?

[4] [Bell, 2004]

# Bell instability [4]

Did we miss something? $\Rightarrow$ non-resonant streaming instability

- large growth rate $\gamma_{max}$
- on scale $k^{-1} \ll r_L \Rightarrow$ does not affect the CR current at first
- until saturation at $\sim 5 - 10\gamma_{max}^{-1}$, then cascades to larger scales

[4] [Bell, 2004]

# Bell instability [4]

Did we miss something? $\Rightarrow$ non-resonant streaming instability

- large growth rate $\gamma_{max}$
- on scale $k^{-1} \ll r_L \Rightarrow$ does not affect the CR current at first
- until saturation at $\sim 5 - 10\gamma_{max}^{-1}$, then cascades to larger scales
- $$D = \frac{1}{3}\frac{v r_L}{P(k_{res})} \sim \frac{B_0^2}{\delta B^2}$$ $\rightarrow$ affects transport and enables strong particle scattering
- Condition:

$$\frac{\phi_{CR}(E > E_0)}{c} E_0 \gg \frac{B_0^2}{4\pi}$$

- This instability is often excited at SNR shocks

[4] [Bell, 2004]

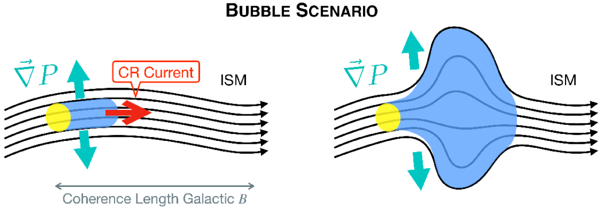
# Source in the ISM

- Bell condition for SNR: $\boxed{\dfrac{4\pi\phi_{CR}}{cB_0^2} \approx 100}$, $\gamma_{max}^{-1} \approx 1.1(\mathrm{E}/2.5\mathrm{TeV})\,\mathrm{yr}$
- Easy to see: Flux at SNR shock = flux of escaping particles, the condition holds at the shock $\Rightarrow$ it holds in the flux tube

[Schroer et al., 2021]

# Source in the ISM

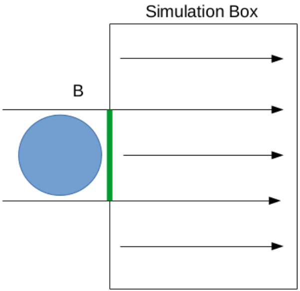
- Bell condition for SNR: $\boxed{\frac{4\pi\phi_{CR}}{cB_0^2} \approx 100}$, $\gamma_{max}^{-1} \approx 1.1(\mathrm{E}/2.5\mathrm{TeV})\,\mathrm{yr}$
- Easy to see: Flux at SNR shock = flux of escaping particles, the condition holds at the shock $\Rightarrow$ it holds in the flux tube
- mean free path $\lambda = \frac{3D}{v} \approx 1 \cdot E_{\mathrm{GeV}}^{1/2}\,\mathrm{pc} \Rightarrow$ high-energy CR escape ballistically
- Flux $\phi_{CR}(E > E_0) = n_{CR}(E > E_0)v_D$ conserved, but $v_D$ decreases as particles start to transition to diffusive behavior
- $\Rightarrow P_{CR} \gg P_{gas} \rightarrow$ tube will expand in transverse direction, breaks 1D geometry



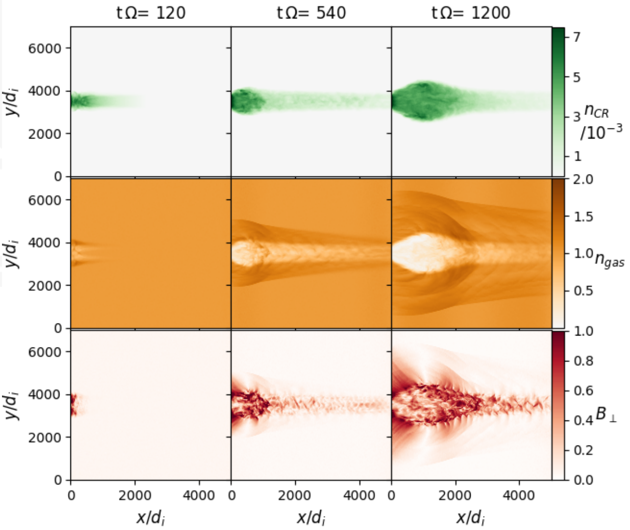

[Schroer et al., 2021]

# Simulation

- Hybrid particle-in-cell simulation with dHybridR
- Solve Maxwell equations and equations of motion for macroparticles
- Electromagnetic fields due to moving particles

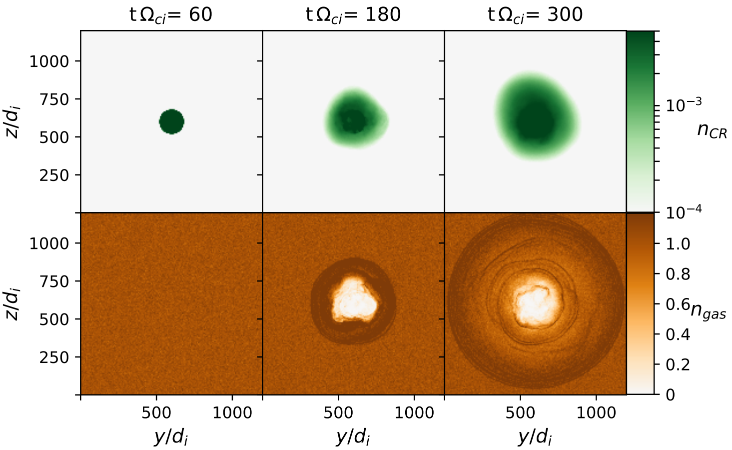


# 2D Simulation




[Schroer et al., 2021]

# 3D Simulation



# Conclusion

# Conclusion

new insights about escape of CRs from their sources:

- current of escaping particles generate a non-resonant instability which slows down their escape
- leads to formation of CR bubbles around sources with reduced diffusivity
- Important implications:
  - enhanced $\gamma$-ray emission from circumsource region
  - accumulated grammage of trapped CRs might be significant for secondary-to-primary ratios
  - electrons get trapped as well so that energy losses become important