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CR transport and feedback in galaxies

Timon Thomas
with Christoph Pfrommer, Rüdiger Pakmor

For GeV CRs that interact via the gyroresonant streaming instability

.. evolve energy contained in CRs $\varepsilon_{\mathrm{cr}}$

.. evolve energy flux for CRs f_{cr}

.. evolve energy contained in gyroresonant Alfvén waves ε_{a}

CR diffusion coefficient given by $$\frac{1}{\kappa} = \frac{27\pi}{16} \frac{\Omega}{3c^2} \frac{\varepsilon_{\mathrm{a}}}{\varepsilon_{\mathrm{B}}}$$

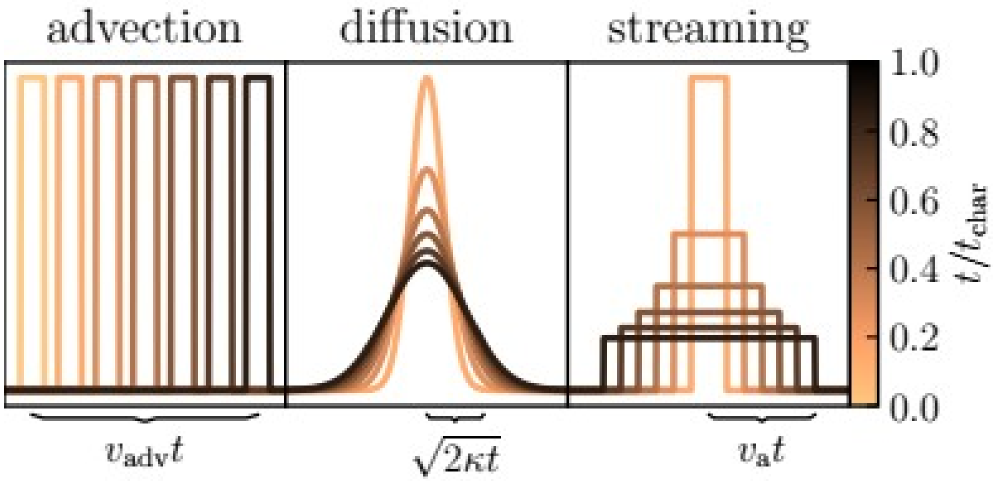
Streaming instability: $$v_{\mathrm{cr}} = \frac{f_{\mathrm{cr}}}{\varepsilon_{\mathrm{cr}} + P_{\mathrm{cr}}} > v_{\mathrm{a}}$$

Transfer of energy from CRs to gyroresonant Alfvén waves
→ CRs are slowed down

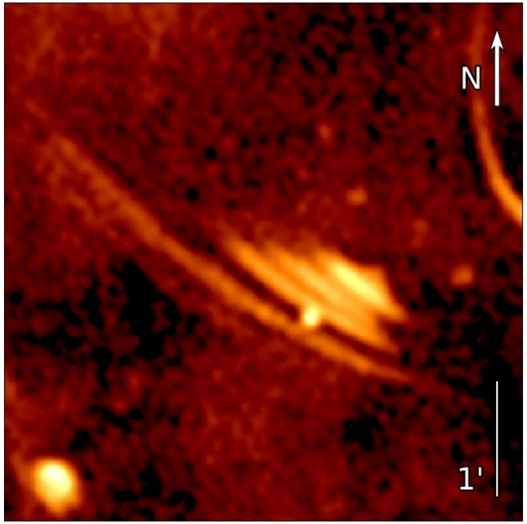
Reversible process → Fermi II

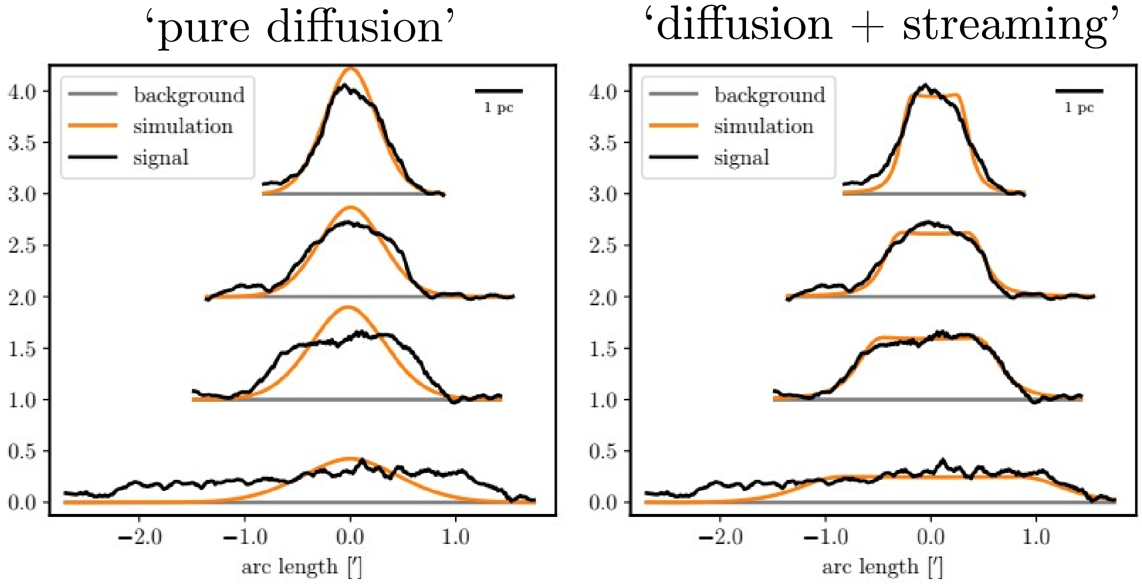
See also Thomas, Pfrommer 2018

Thomas, Pfrommer, Ensslin, 2020

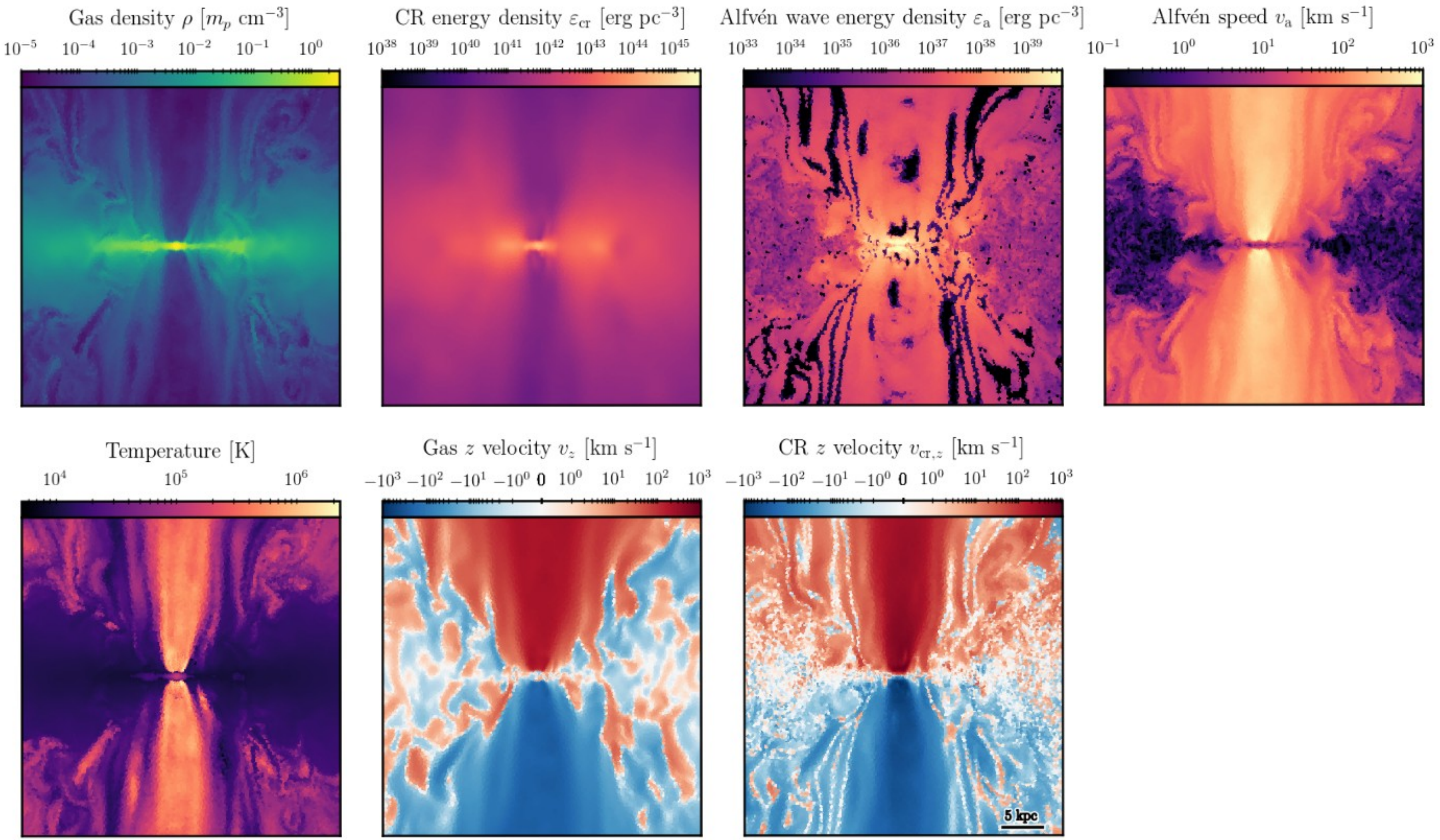


Heywood+, 2019



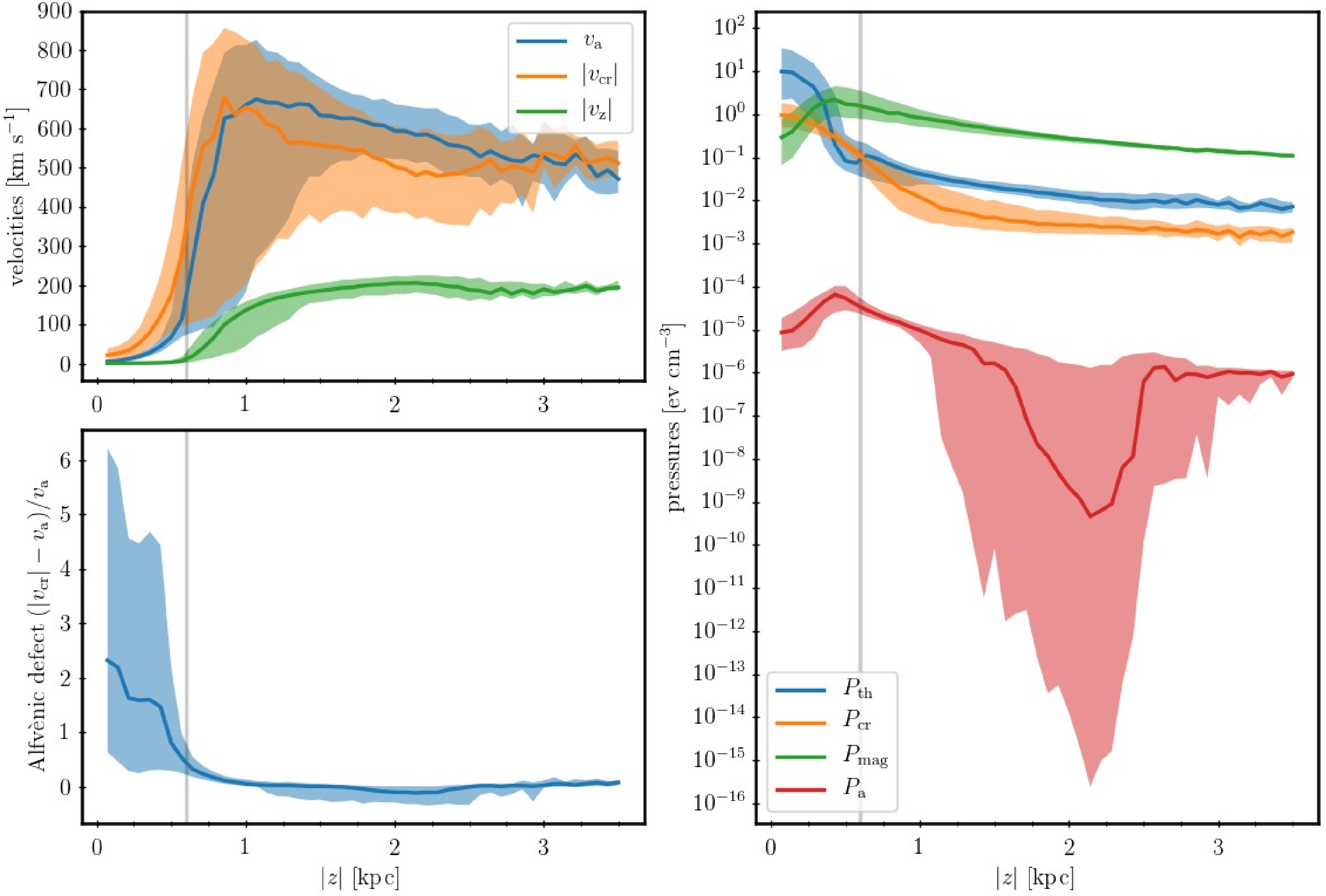


Gallery



Gas density ρ [m_p cm^{-3}]
10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1} 10^{0}
CR energy density ε_{cr} [erg pc^{-3}]
10^{38} 10^{39} 10^{40} 10^{41} 10^{42} 10^{43} 10^{44} 10^{45}
Alfvén wave energy density ε_a [erg pc^{-3}]
10^{33} 10^{34} 10^{35} 10^{36} 10^{37} 10^{38} 10^{39}
Alfvén speed v_a [km s^{-1}]
10^{-1} 10^{0} 10^{1} 10^{2} 10^{3}
Temperature [K]
10^{4} 10^{5} 10^{6}
Gas z velocity v_z [km s^{-1}]
-10^{3} -10^{2} -10^{1} -10^{0} 0 10^{0} 10^{1} 10^{2} 10^{3}
CR z velocity $v_{cr,z}$ [km s^{-1}]
-10^{3} -10^{2} -10^{1} -10^{0} 0 10^{0} 10^{1} 10^{2} 10^{3}
5 kpc

Wind launching



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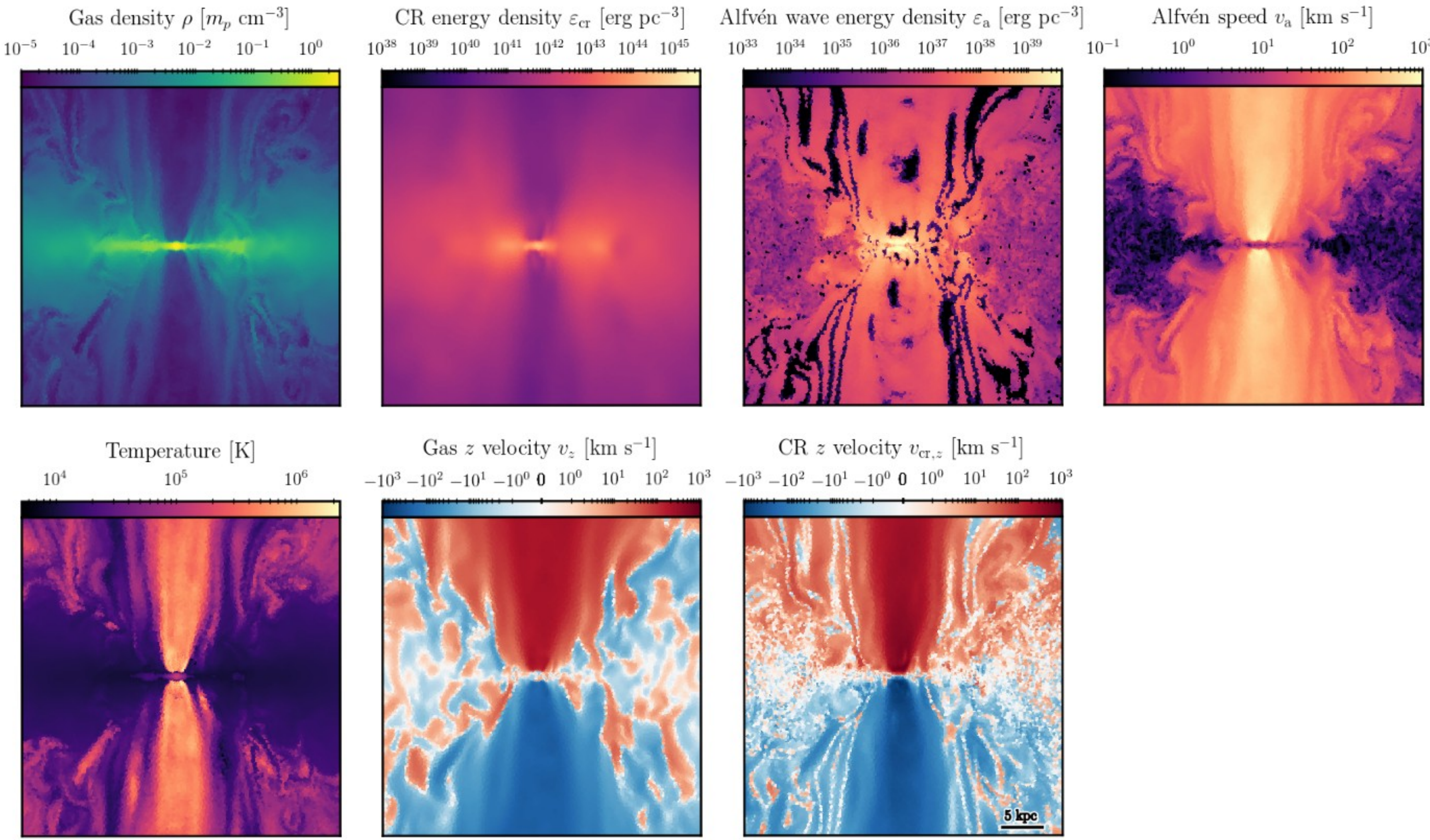

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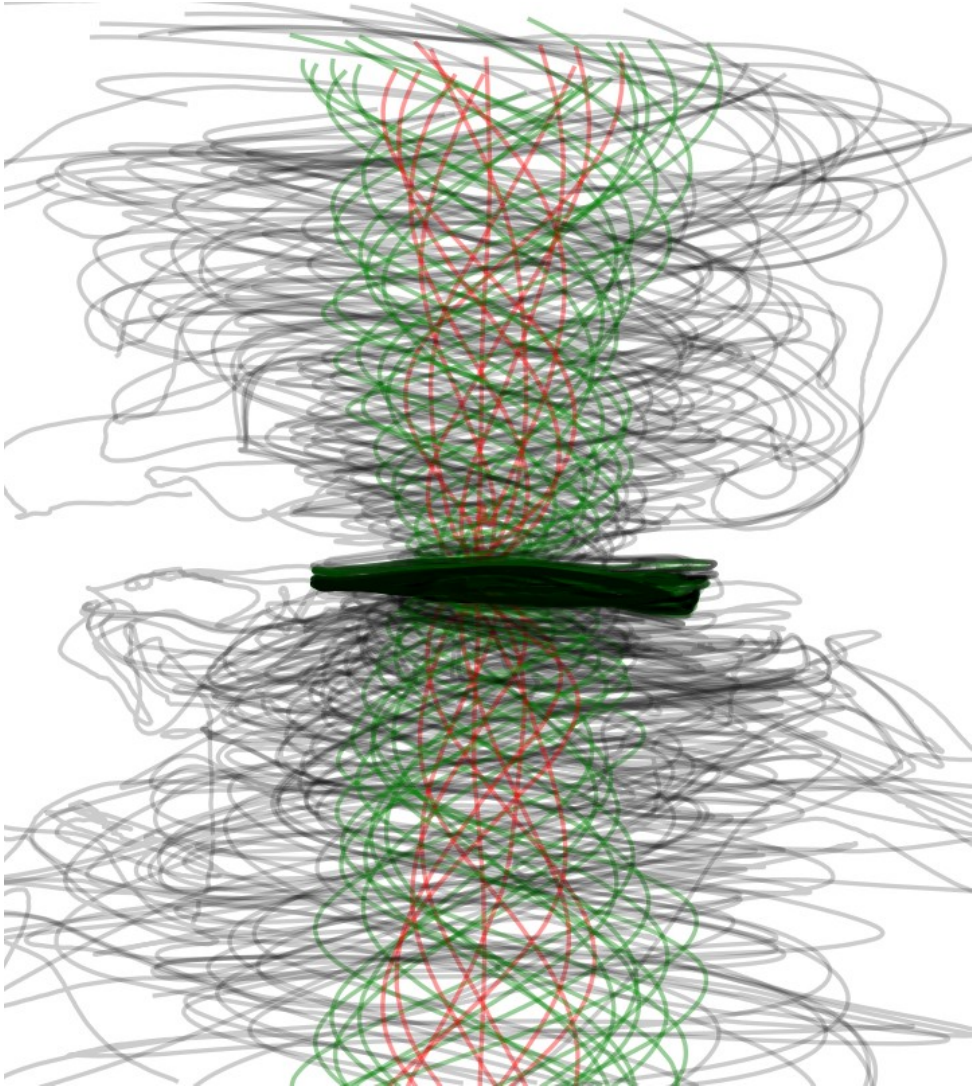
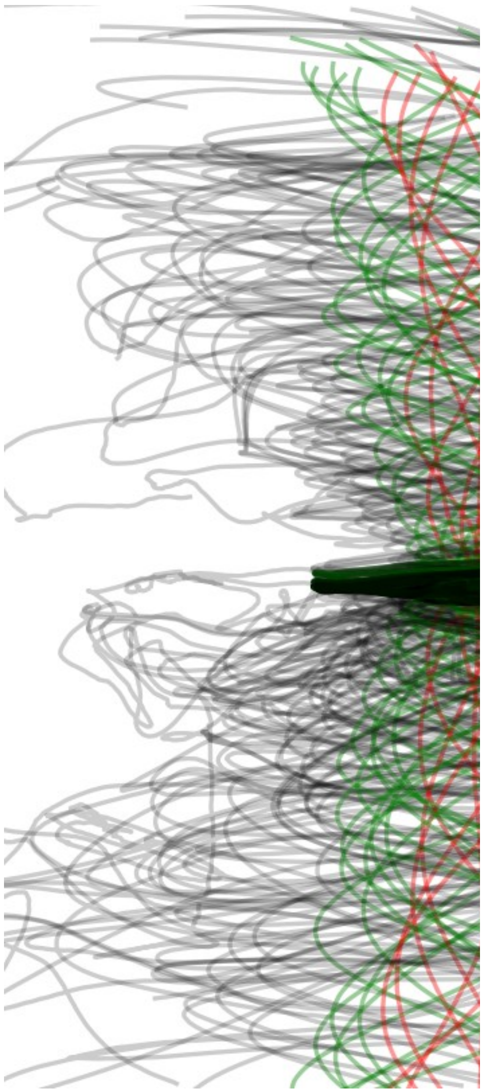
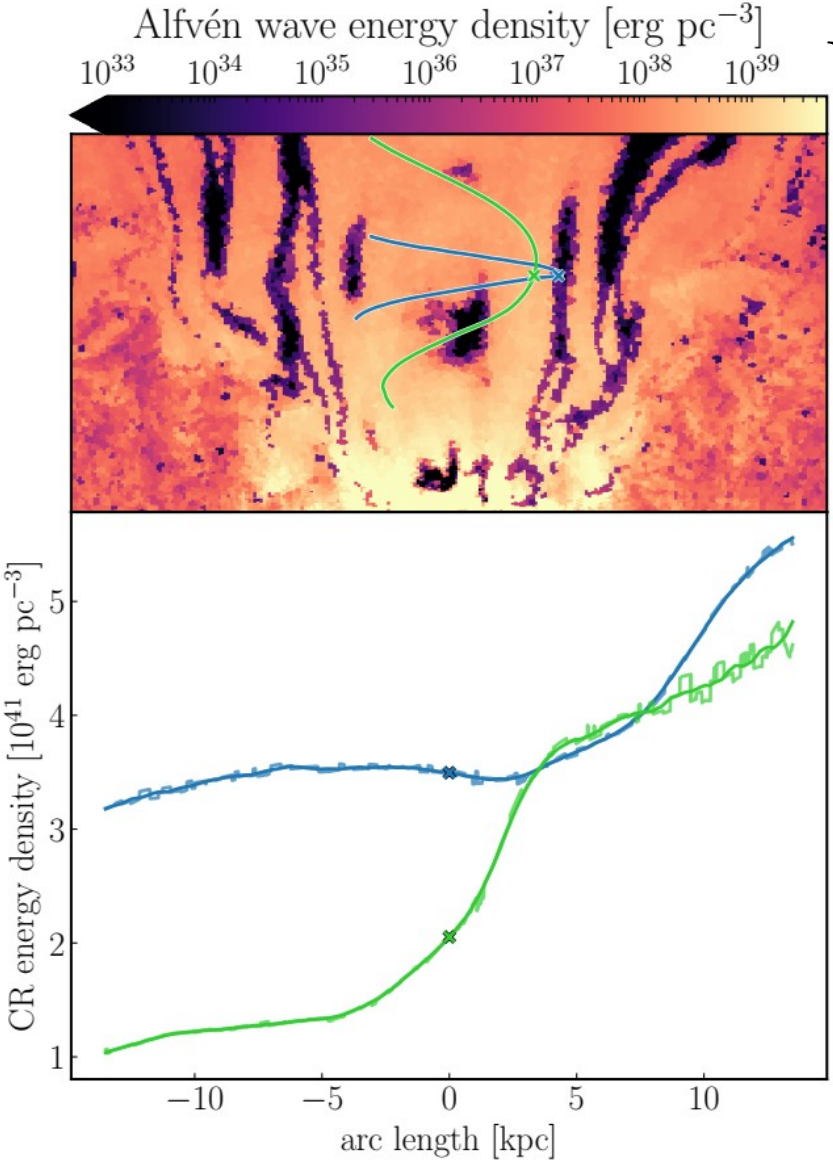


What causes Alfvén waves to vanish?





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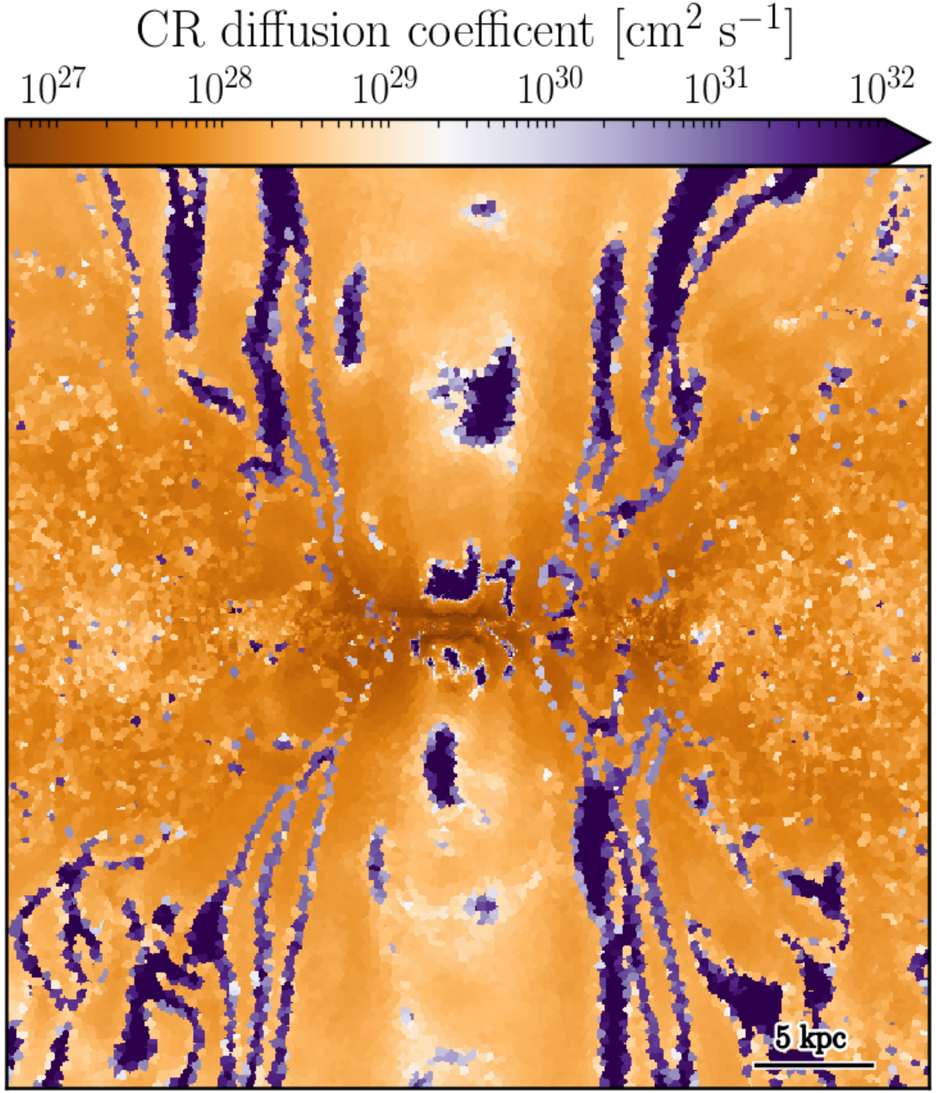
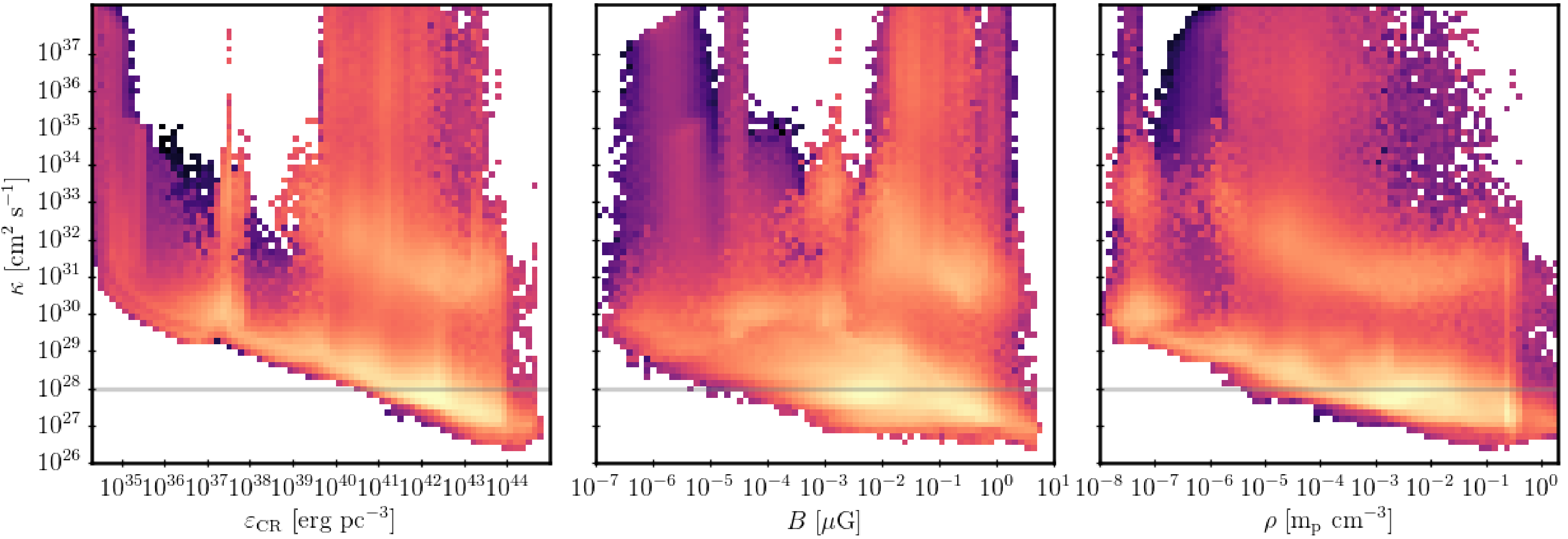


Diffusion Coefficient

$$\frac{1}{\kappa} = \frac{27\pi}{16} \frac{\Omega}{3c^2} \frac{\varepsilon_\mathrm{a}}{\varepsilon_\mathrm{B}}$$

Diffusion Coefficient



Transport Classification

CR Energy weighted

73%	non steady-state transport
6%	advection
18%	streaming + diffusion
1%	diffusion
11%	streaming

Mass weighted

67%	non steady-state transport
18%	advection
12%	streaming + diffusion
7%	diffusion
1%	streaming

Volume weighted

41%	non steady-state transport
30%	advection
26%	streaming + diffusion
19%	diffusion
1%	streaming

Define steady state transport using 4 categories:

advection

$$f_{\mathrm{cr}} = 0$$

streaming

$$f_{\mathrm{cr}} = v_{\mathrm{a}}(\varepsilon_{\mathrm{cr}} + P_{\mathrm{cr}})$$

diffusion

$$f_{\mathrm{cr}} = -\kappa \mathbf{b} \cdot \nabla \varepsilon_{\mathrm{cr}}$$

streaming + diffusion

$$f_{\mathrm{cr}} = v_{\mathrm{a}}(\varepsilon_{\mathrm{cr}} + P_{\mathrm{cr}}) - \kappa \mathbf{b} \cdot \nabla \varepsilon_{\mathrm{cr}}$$

Allow for 10% deviations to count towards a category

Takeaways

- First simulation of a galactic wind with a two moment approximation for CR transport with consistently coarse-grained plasma physics

- CR transport is non-steady state in galactic winds

- CR diffusion coefficient is $\langle \kappa \rangle \sim 1 \times 10^{28} \mathrm{cm}^2 \mathrm{s}^{-1}$

<u>What's next?</u>

- include more plasma physics (Mohamad Shalaby's talk)

- more faithful representation of CRs (Philipp Girichidis's talk)

- observational impact (Maria Werhahn's talk)

- other applications (Kristian Ehlert's talk)