# Coupling energy-dependent transport of cosmic rays to ISM simulations with Piernik MHD code

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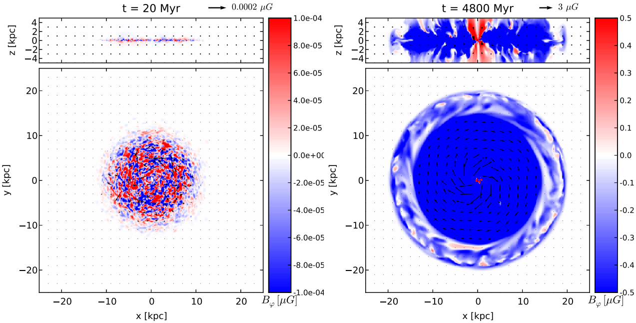
## Two approaches to CR propagation in the ISM

- GALPROP (Strong & Moskalenko) and similar codes.
  - Careful treatment of CR electron & nucleon transport in energy-dependent manner.
  - CR acceleration, radiative processes, spallation, radioactive decay, production of secondary CRs, etc.
  - use diffusion, convection and magnetic field as parameterized ingredients.
  - do not include the dynamical interaction of CRs with the ISM.
- Grid MHD codes: PIERNIK (Hanasz et al 2009, 2013), FLASH extensions (Girichidis et al 2016), RAMSES (Dubois & Commercon 2016), AREPO (Pfrommer et al 2017), PLUTO, ...
  - treat cosmic rays as a separate (single) relativistic fluid in the MHD framework, dynamically coupled to ISM gas.
  - transported by advection, diffusion, streaming.
  - Neglect spectral evolution of CR nucleons and electrons.

## Cosmic Ray driven dynamo in disk galaxies

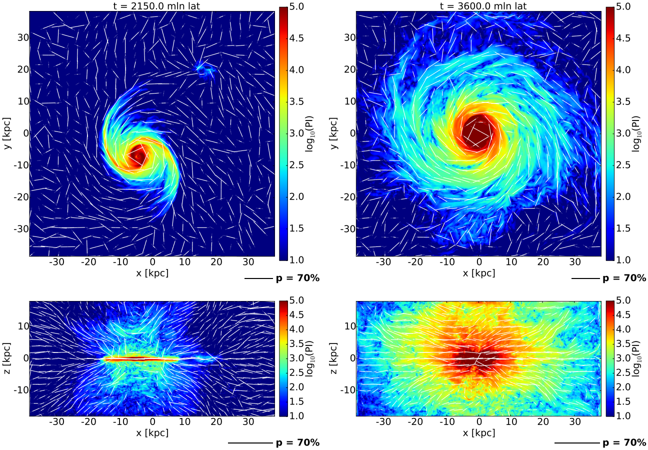
**Hanasz, Woltański, Kowalik 2009, ApJ 706L, 155**




Azimuthal magnetic field blue: $B_\varphi < 0$, red: $B_\varphi > 0$

## SPIRAL GALAXIES – SYNTHETIC RADIO-MAPS

Assumption: CR electron energy density is proportional to CR proton energy density (simulation by Dominik Wóltanski)




Polarised synchrotron emission + polarisation vectors.

**BUT: CR electrons cool down in energy-dependent manner,**

⇒ **radioemission maps look different at different radio-frequencies**

Fletcher et al. (2011)

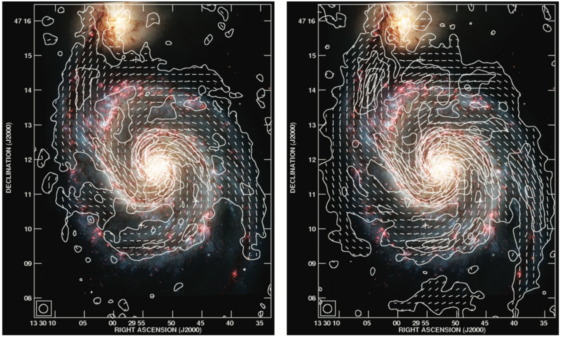



**Figure 2.** (a) $\lambda$3 cm (left) and (b) $\lambda$6 cm (right) polarized radio emission at 15 arcsec resolution from VLA and Effelsberg observations, overlaid on the same optical image as in Fig. 1. Polarized intensity contours in both maps are at 3, 9, 15, 21 times the noise level of 8 μJy beam$^{-1}$ at $\lambda$3 cm and 10 μJy beam$^{-1}$ at $\lambda$6 cm. Also shown are the *B*-vectors of polarized emission: the position angle of the polarized electric field rotated by 90°, not corrected for Faraday rotation, with the length proportional to the polarized intensity PI and only plotted where $P \geq 3\sigma_{\mathrm{PI}}$.

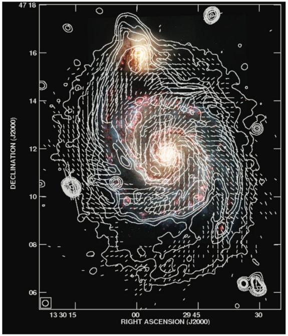



**Figure 3.** Contours of $\lambda$20 cm total radio emission at 15 arcsec resolution, overlaid on the same optical image as in Fig. 1. Total intensity contours are at 6, 12, 24, 36, 48, 96, 192 times the noise level of 20 μJy beam$^{-1}$. Also shown are the *B*-vectors of polarized emission: the plane of polarization of

An opportunity to confront magnetic field amplification and CR propagation models with data (radio, gamma)
– if we have proper CR simulation tools.

The idea is to add the CR transport equation (e.g. Skilling 1975, Blandford & Eichler 1987 ) to the system of MHD equations and solve the whole system in a quasi-conservative manner in the 4D space of spatial coordinates $(x, y, z, p)$ and particle momentum.

$$\frac{\partial f}{\partial t} = -\boldsymbol{u} \cdot \nabla f + \nabla(\kappa \nabla f) + \frac{1}{3}(\nabla \cdot \boldsymbol{u}) p \frac{\partial f}{\partial p} + \frac{1}{p^2} \frac{\partial}{\partial p} \left[ p^2 b_l f + D_p \frac{\partial f}{\partial p} \right] + j \quad (1)$$

where:

$f(\boldsymbol{x}, \boldsymbol{p})$ — distribution function of CR particles,
$u$ — velocity field of thermal gas (e.g. ISM),
$\kappa$ and $D_p$ — diffusion coefficients in space and momentum,
$b_l(\boldsymbol{x}, \boldsymbol{p})$ — loss term and $j(\boldsymbol{x}, \boldsymbol{p})$ — CR sources.

We assume that $f$ is isotropic and $D_p = 0$ (neglect particle accelleration).

**The core of the algorithm is based on:**
**Miniati, Computer Physics Communications 141, 17, 2001**

Piecewise power-law distribution function

$$f(p) = f_{i-\frac{1}{2}} \left( \frac{p}{p_{i-\frac{1}{2}}} \right)^{-q_i}, \qquad (2)$$

$f_{i-\frac{1}{2}}$ – distribution function amplitudes.
CR number density

$$n_i = 4\pi f_{i-\frac{1}{2}} p^3_{i-\frac{1}{2}} \times \frac{\left( p_{i+\frac{1}{2}} / p_{i-\frac{1}{2}} \right)^{3-q_i} - 1}{3 - q_i} \qquad (3)$$

CR energy density: assume relativistic limit: $p \gg mc$, $T \simeq pc$

$$e_i = 4\pi c f_{i-\frac{1}{2}} p^4_{i-\frac{1}{2}} \times \frac{\left( p_{i+\frac{1}{2}} / p_{i-\frac{1}{2}} \right)^{4-q_i} - 1}{4 - q_i} \qquad (4)$$

The whole spectrum of CR particles can be described equivalently by two sets of discretised quantities

$$(n_i, e_i) \Leftrightarrow (f_{i-\frac{1}{2}}, q_i), \qquad i = 1, n_{\text{bin}}, \tag{5}$$

The slopes $q_i$ are computed by numerical (Newton-Raphson) solution of

$$\frac{e_i}{n_i \; p_{i-\frac{1}{2}} \; c} = \frac{3 - q_i}{4 - q_i} \frac{\left(p_{i+\frac{1}{2}} / p_{i-\frac{1}{2}}\right)^{4-q_i} - 1}{\left(p_{i+\frac{1}{2}} / p_{i-\frac{1}{2}}\right)^{3-q_i} - 1} \tag{6}$$

Particle density evolution equation

$$\boxed{n_i^{t+\Delta t} = n_i^t - \left(F^n_{i+\frac{1}{2}}(\Delta t) - F^n_{i-\frac{1}{2}}(\Delta t)\right)} \tag{7}$$

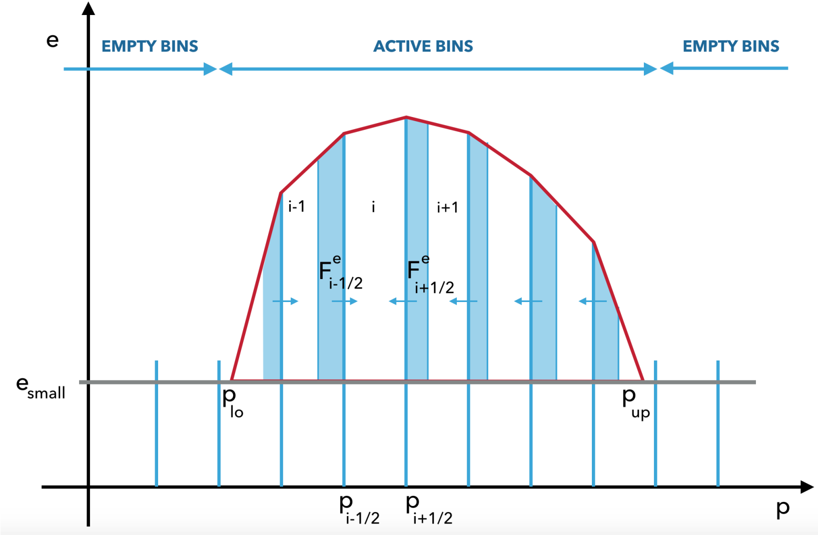
Energy density evolution equation

$$\boxed{e_i^{t+\Delta t} = e_i^t - \left(F^e_{i+\frac{1}{2}}(\Delta t) - F^e_{i-\frac{1}{2}}(\Delta t)\right) - \frac{1}{2}\Delta t\, R_i \left(e_i^{t+\Delta t} + e_i^t\right)} \tag{8}$$

where:

$R_i = \frac{1}{e_i}\int_{p_{i-\frac{1}{2}}}^{p_{i+\frac{1}{2}}} 4\pi p^2 f(p) b(p) dp$ – energy losses,

$F^n_{i+\frac{1}{2}}(\Delta t)$, $F^e_{i+\frac{1}{2}}(\Delta t)$ are inter-bin fluxes of $n$ and $e$.


e
EMPTY BINS
ACTIVE BINS
EMPTY BINS
i-1
i
i+1
$F^e_{i-1/2}$
$F^e_{i+1/2}$
$e_{small}$
$p_{lo}$
$p_{up}$
$p_{i-1/2}$
$p_{i+1/2}$
p

Adiabatic compression/expansion

$$\frac{dp}{dt} = b_{ad}(p) \equiv \frac{1}{3}(\nabla \cdot \boldsymbol{v})\, p \tag{9}$$

where $v$ – velocity field of thermal gas.
Synchrotron losses

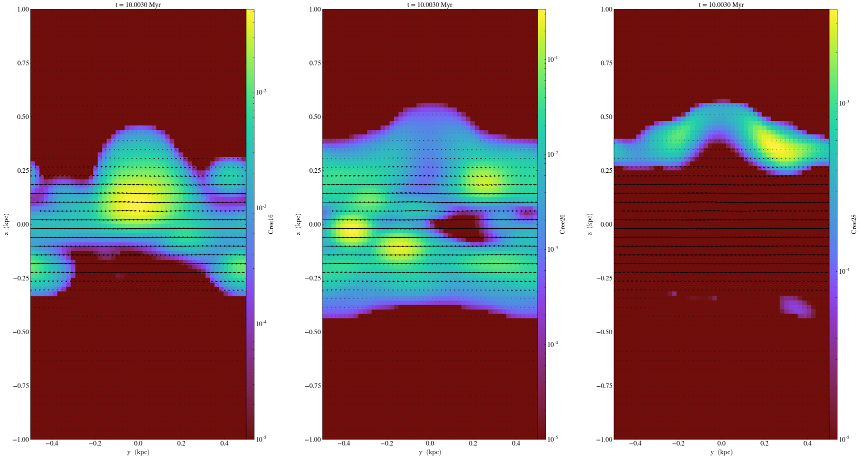
$$\frac{dp}{dt} = b_{syn}(p) \equiv -\frac{4}{3}\frac{\sigma_T}{m_e^2 c} u_B\, p^2 \tag{10}$$

where $u_B$ – magnetic energy density.

# Essential elements of the algorithm:

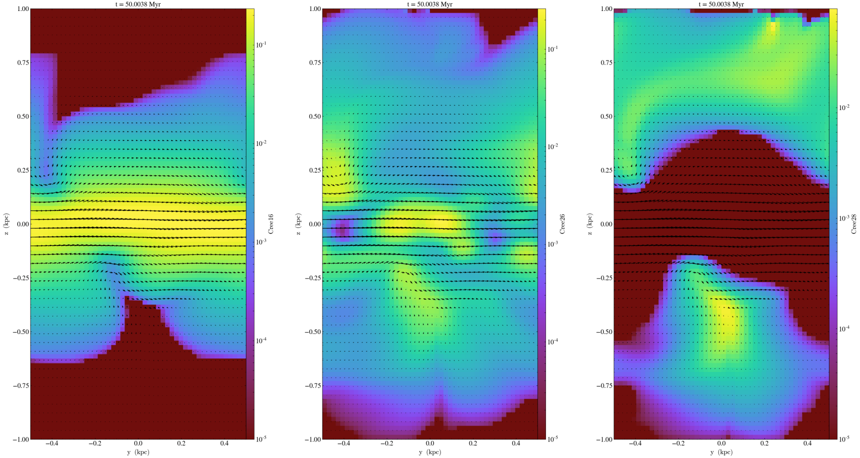
- uniform mesh in $\log p$
- the spectrum $(n_i, e_i)$ extends between $p_{lo}$ and $p_{up}$ (active bins)
- $p_{lo}$ and $p_{up}$ are estimated at the beginning of each timestep
- anisotropic CR diffusion, algorithm by (Hanasz & Lesch A&A 412, 331, 2003),
- $K_{||}(p) \propto p^{0.5}$, $K_{\perp}(p) =$ a few % of $K_{||}(p)$
- CR spectrum evolution and diffusion steps are executed between MHD steps.
- initial CR spectrum – power law – injected instantaneously in SN remnants.

Early phase (10 Myr) of random CR injection in a stratified disk.
Low, mid and high energy bins of electron spectrum – 1st, 2nd, 3rd panels



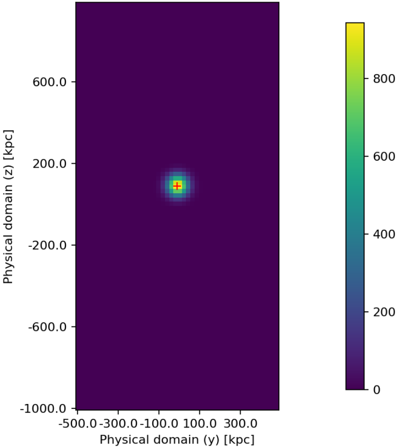
## CR ELECTRON MAPS

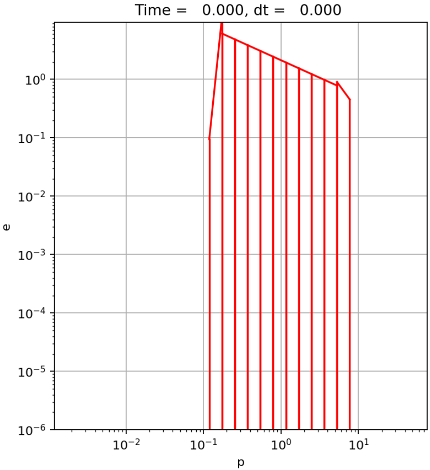
Advanced phase (50 Myr) of random CR injection in a stratified disk.
Low, mid and high energy bins of electron spectrum – 1st, 2nd, 3rd panels



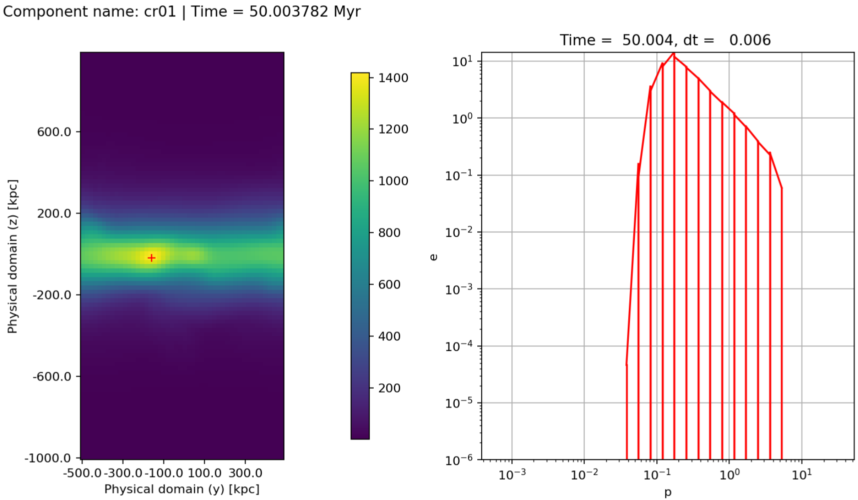
## CR ELECTRON SPECTRA

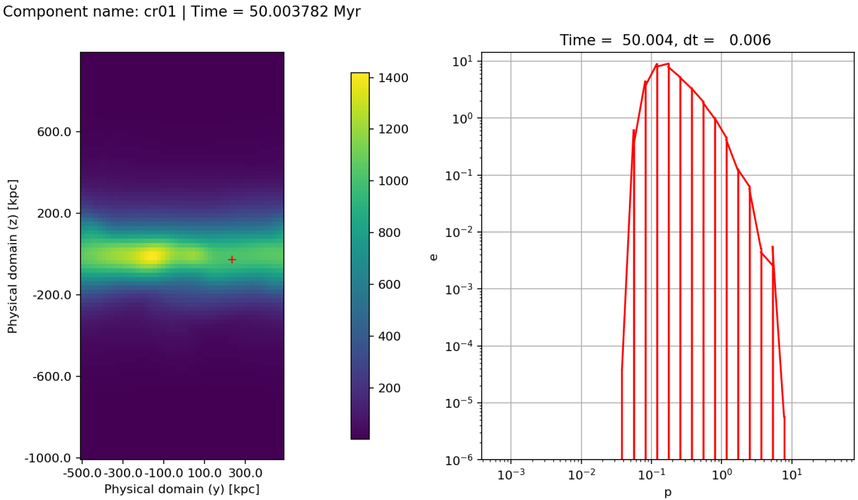
Component name: cr01 | Time = 0.000000 Myr



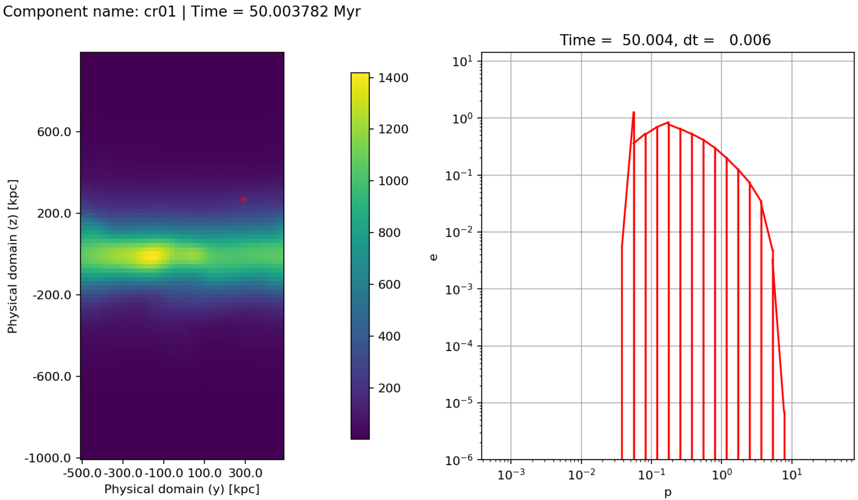



## CR ELECTRON SPECTRA




Component name: cr01 | Time = 50.003782 Myr
Physical domain (z) [kpc]
600.0
200.0
-200.0
-600.0
-1000.0
-500.0 -300.0 -100.0 100.0 300.0
Physical domain (y) [kpc]
1400
1200
1000
800
600
400
200
Time = 50.004, dt = 0.006
e
$10^{1}$
$10^{0}$
$10^{-1}$
$10^{-2}$
$10^{-3}$
$10^{-4}$
$10^{-5}$
$10^{-6}$
$10^{-3}$
$10^{-2}$
$10^{-1}$
$10^{0}$
$10^{1}$
p

## CR ELECTRON SPECTRA



- We have incorporated CR energy dependent transport of CR electrons into PIERNIK MHD code.
- The extended code can be used for modeling evolution of CR population subject to synchrotron and adiabatic losses.
- Other physical interaction mechanisms for CR electrons and nucleons can be introduced in a similar way.
- Next target: simulations of galactic synchrotron emission and confrontation of our MHD models to real galaxies observed in radio-range.