# Spectral evolution of CR electrons and their synchrotron emission in live MHD models of spiral galaxies

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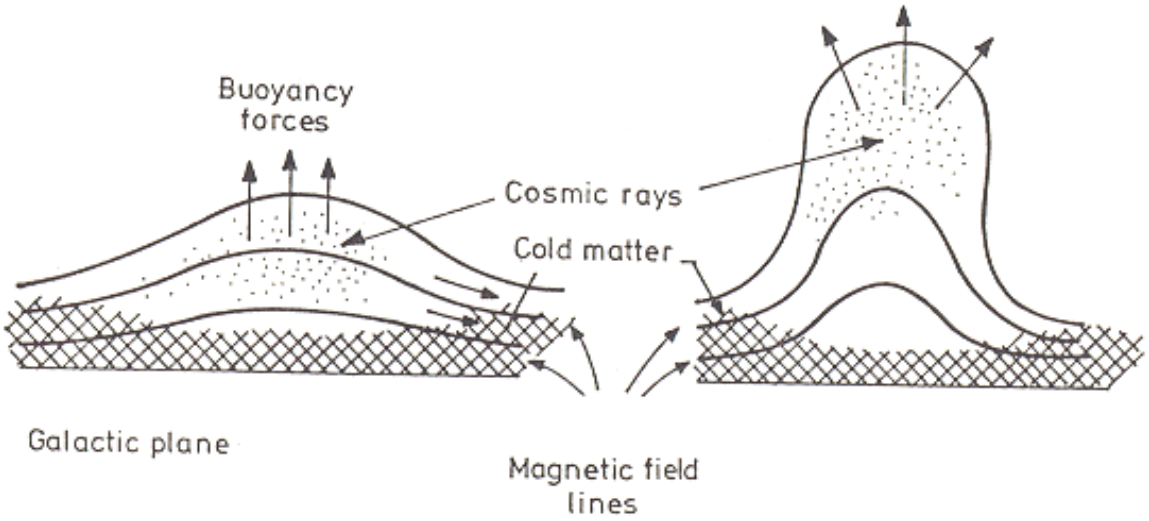
Parker instability in the ISM (Parker 1966, 1967 )




(from *High Energy Astrophysics, M. Longair, 2011, p. 522)*

- Cosmic ray gas: an important ISM ingredient - accelerated in SN remnants (see e.g. Hillas 2005, Ackermann et al. 2013)
- Kinetic energy of SN II explosion $\sim 10^{51}$erg $\Rightarrow$ 10 % of $E_{\mathrm{SN}} \rightarrow$ acceleration of cosmic rays - charged particles (protons, electrons) accelerated in shocks to relativistic energies
- $\Rightarrow$ strong buoyancy effects due to relativistic weightless CR gas.

CR TRANSPORT EQUATION – CRs added as second fluid to the system of MHD equations

Diffusion - advection approximation

(e.g. Schlickeiser & Lerche 1985,
Hanasz& Lesch 2003 – numerical algorithm)

$$\frac{\partial e_{\rm cr}}{\partial t} + \nabla(e_{\rm cr}\boldsymbol{V}) = -p_{\rm cr}\nabla\boldsymbol{V} + \nabla(\hat{K}\nabla e_{\rm cr}) \qquad (1)$$

$$+ \text{ CR sources (SN remnants)}$$

$$p_{\rm cr} = (\gamma_{\rm cr} - 1)e_{\rm cr} \qquad (2)$$

Anisotropic diffusion of CRs

(Giaccalone & Jokipii 1998 , Jokipii 1999, Ryu et al. 2003)

$$K_{ij} = K_\perp \delta_{ij} + (K_\parallel - K_\perp)n_i n_j, \quad n_i = B_i/B, \qquad (3)$$

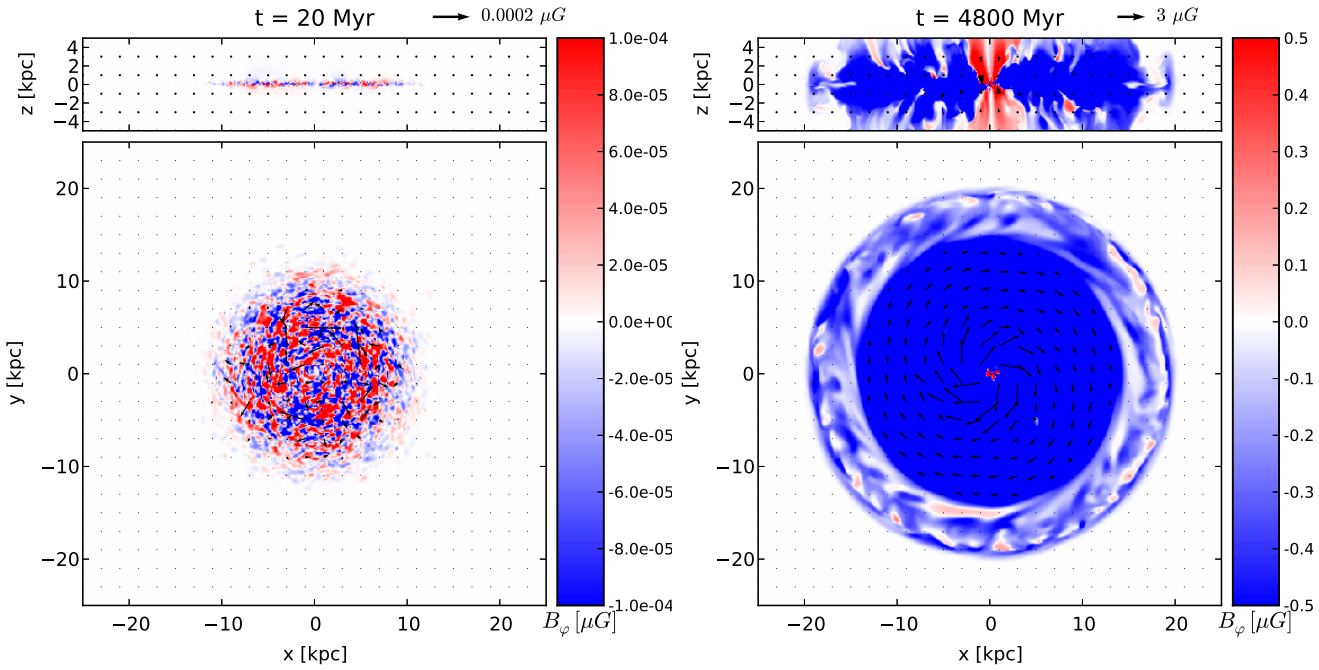
$$K_\parallel = 3\cdot 10^{28}\mathrm{cm}^2\mathrm{s}^{-1}, \qquad K_\perp = (1-10)\%\,(K_\parallel)$$

## CR-DRIVEN GALACTIC DYNAMO MODEL

(Hanasz et al 2009, ApJ 706L, 155)

**Inspired by Gene's Parker (1992) idea of galactic dynamo driven by cosmic rays.**

- Galactic gravitational potential: halo+bulge+disk: analytical model (Allen & Santillan 1991)
- Interstellar gas: Global model of ISM for the Milky Way (Ferriere 1998)
- **Schmidt-Kennicutt law:** SFR $\propto$ (gas density)$^{1.4}$
- SNR $\propto$ SFR
- 10% of SN energy output converts to CR energy.
- **No magnetic field at** $t = 0$
- **weak ($10^{-4}\mu$G) dipolar, small scale ($r \sim 50$pc ) randomly oriented magnetic field is supplied locally in 10% of SN remnants (Krab type)**




Colours: – azimuthal (toroidal) magnetic field blue: $B_\varphi < 0$, red: $B_\varphi > 0$
Exploding magnetised stars spread weak irregular magnetic fields in the ISM

- **Cosmic-ray driven dynamo due to buoyancy, Coriolis force and disk differential rotation $\Rightarrow$ amplification of regular magnetic fields on timescales $\sim T_{rot}$** (Hanasz et al 2004, 2009; Kulpa-Dybel et al 2011, 2015; Siejkowski et al 2014, 2018; see also Pfrommer et al 2022)
- **CR-driven galactic winds** , (Ipavich 1975; ... Jubelgas et al 2008; Uhlig at al 2012; Hanasz at al, 2013; Booth et al 2014; Salem&Brian 2014; Pakmor et al 2016; Girichidis et al 2016, 2018, Hopkins et al 2021 and many others)

**Our goal is: to confront models of magnetic fields amplification and CR propagation against observations of real galaxies**

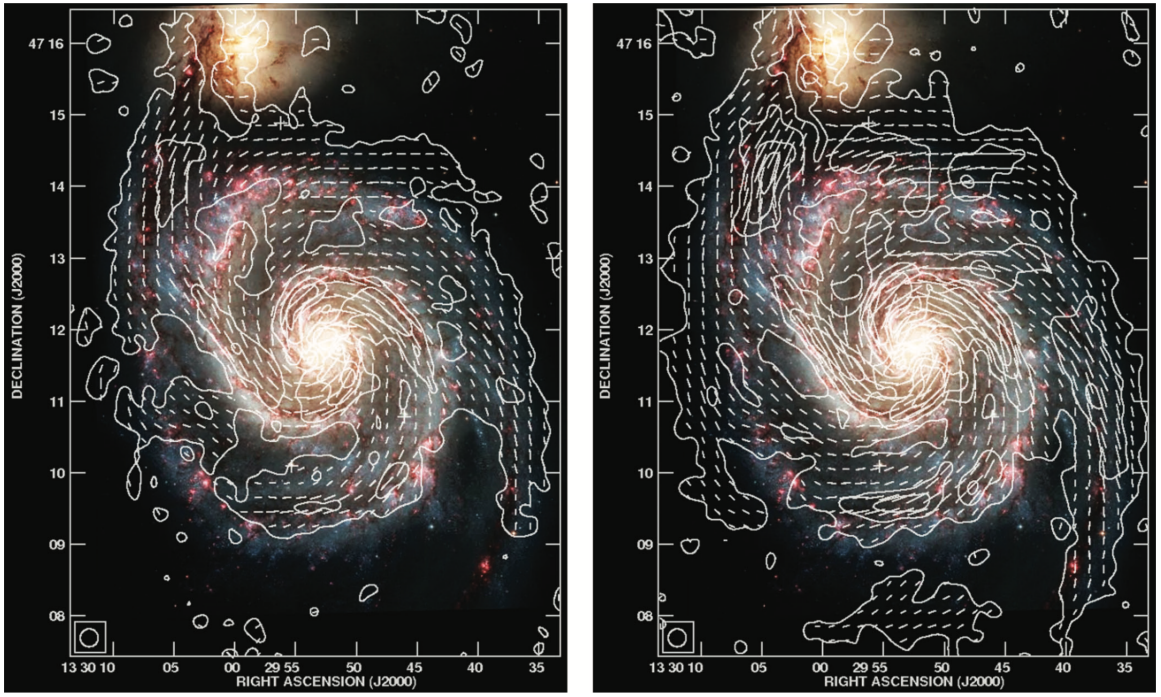



**Figure 2.** (a) λ3 cm (left) and (b) λ6 cm (right) polarized radio emission at 15 arcsec resolution from VLA and Effelsberg observations, overlaid on the same optical image as in Fig. 1. Polarized intensity contours in both maps are at 3, 9, 15, 21 times the noise level of 8 μJy beam$^{-1}$ at λ3 cm and 10 μJy beam$^{-1}$ at λ6 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 $P \geq 3\sigma_{\mathrm{PI}}$.

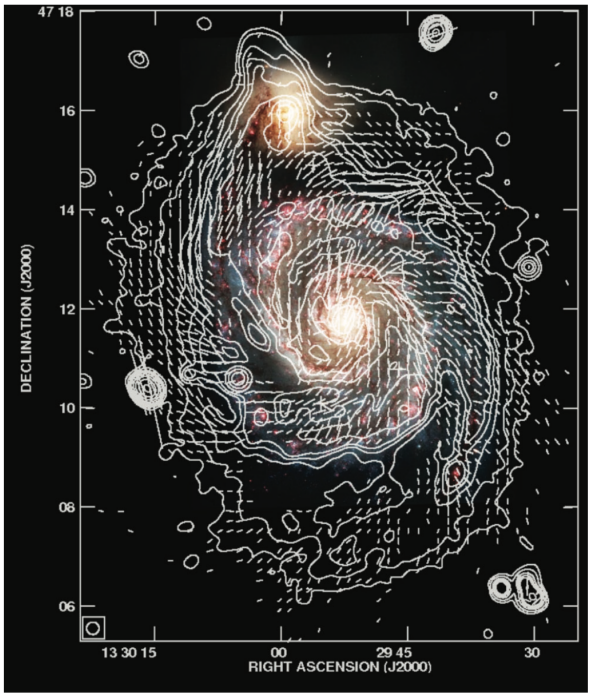



**Figure 3.** Contours of λ20 cm total radio emission at 15 arcsec resolution, overlaid on the same optical image as in Fig. 1. Total intensity contours are at 6, 12, 24, 36, 48, 96, 192 times the noise level of 20 μJy beam$^{-1}$. Also shown are the *B*-vectors of polarized emission: the plane of polarization of

(Fletcher et al. 2011)

**We need synthetic maps of synchrotron radio emission generated for numerical simulation models.**

**We add momentum-dependent diffusion-advection equation for CR electrons (Skilling 1975)**, and solve the whole system:

**(MHD, CR protons) + electrons in 4D space** $(x, y, z, p)$

$$\frac{\partial f}{\partial t} = -\boldsymbol{u}\cdot\nabla f + \nabla(\kappa\nabla f) + \frac{1}{3}(\nabla\cdot\boldsymbol{u})p\frac{\partial f}{\partial p} + \frac{1}{p^2}\frac{\partial}{\partial p}\left[p^2 b_l f + D_p\frac{\partial f}{\partial p}\right] + j \quad (4)$$

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.

Our method attempts to extend the GALPROP-type approach (Strong, Moskalenko 1998, see also Orlando & Strong 2013 ) assuming a static or stationary ISM model.

**Description of the method: Ogrodnik et al (2021)** based on Miniati, COSMOCR algorithm (2001)

**Piecewise power-law distribution function:**10-20 momentum bins is enough to cover a few decades of the CR energy spectrum:

$$f(p) = f_{i-\frac{1}{2}} \left( \frac{p}{p_{i-\frac{1}{2}}} \right)^{-q_i}, \tag{5}$$

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

**Two-moment approach:** The algorithm evolves number and energy spectral densities of CRs particles $n_i$ and $e_i$.

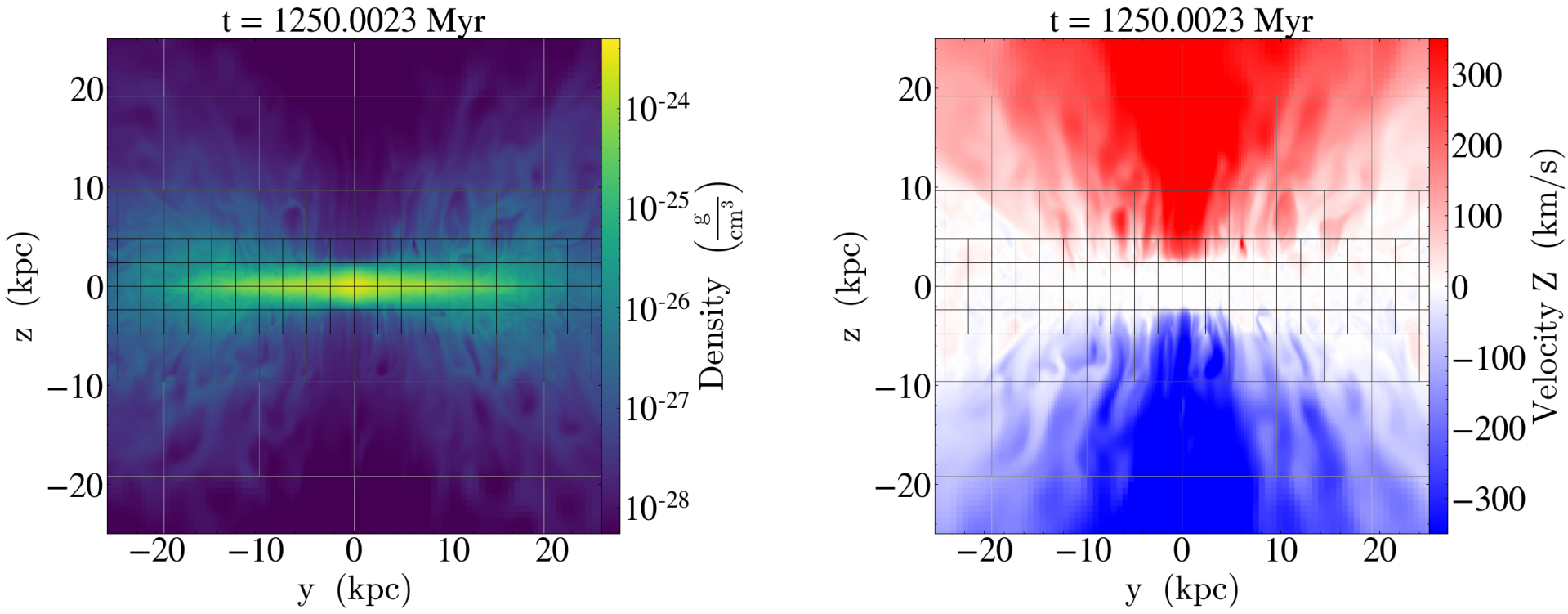
**We take into account:** adiabatic cooling/heating, synchrotron losses combined with energy-dependent diffusion and advection and coupled to MHD evolution of the gaseous component of the ISM.

Algorithm: **C**osmic **R**ay **E**nergy **SP**ectrum (CRESP) (Ogrodnik et al. 2021) module of PIERNIK code (poster by Mateusz Ogrodnik et al.).

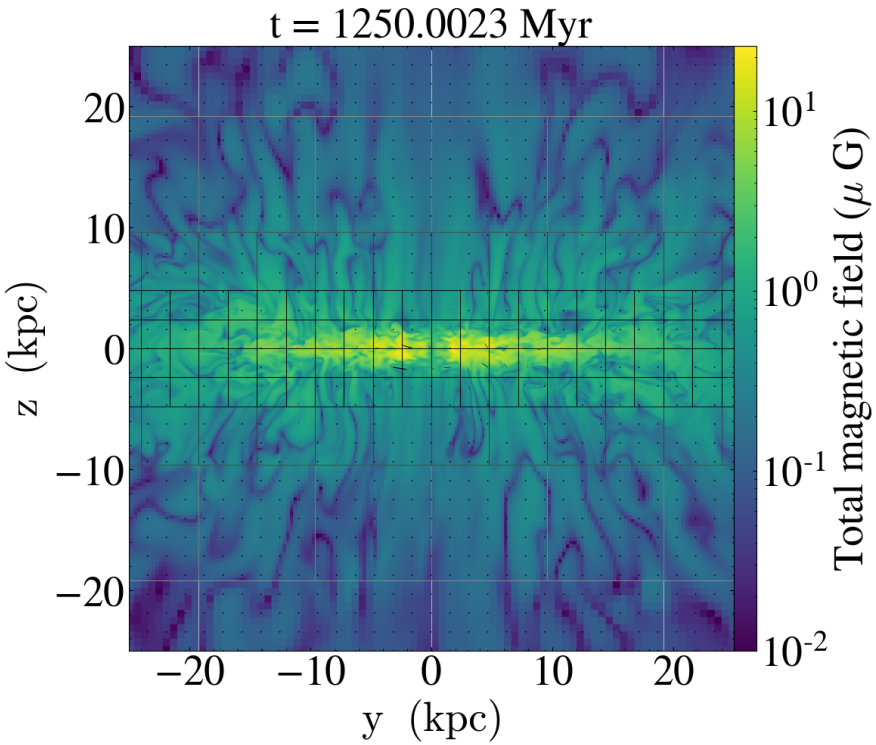
We assume:

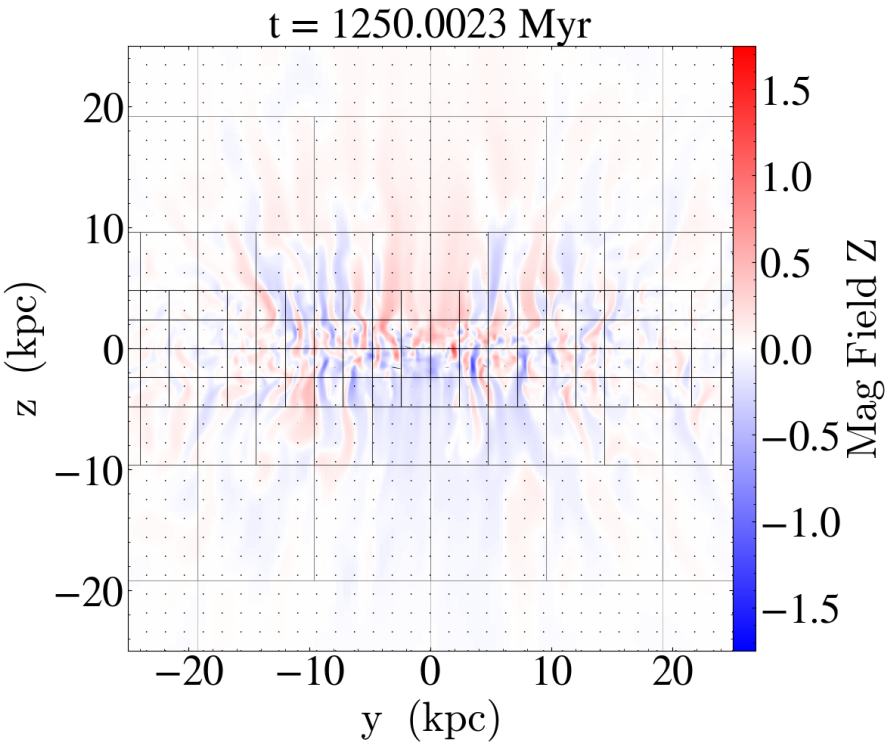
- A galaxy similar to NGC891 (Mulcahy et al (2018), see also poster by Mateusz Ogrodnik et al. and upcoming paper by Ogrodnik et al.)
- We take into account only the CR feedback and neglect thermal and kinetic effects of SNe.
- SN inject 10% of explosion energy in CR protons and 0.1% in CR electrons.
- CR protons diffuse anizotropically along magnetic field lines and are dynamically coupled to the thermal gas, $K_{||}(p) \propto p^{0.5}$ $(= 3 \cdot 10^{28} \mathrm{cm}^2 \mathrm{s}^{-1}$ at 10 GeV) , $K_{\perp}(p) = 1$ % of $K_{||}(p)$
- Eulerian nested grid of spanning $L_x \times L_y \times L_z = 76$ kpc $\times 76$ kpc $\times 38$ kpc in $x$, $y$, $z$ directions, minimum cell size $\Delta x = \Delta y = \Delta z = 75$pc
- CR electron spectrum is distributed over 16 bins spanning the energy range of $(10 - 10^5) m_e c^2$.

Simulations by Mateusz Ogrodnik.

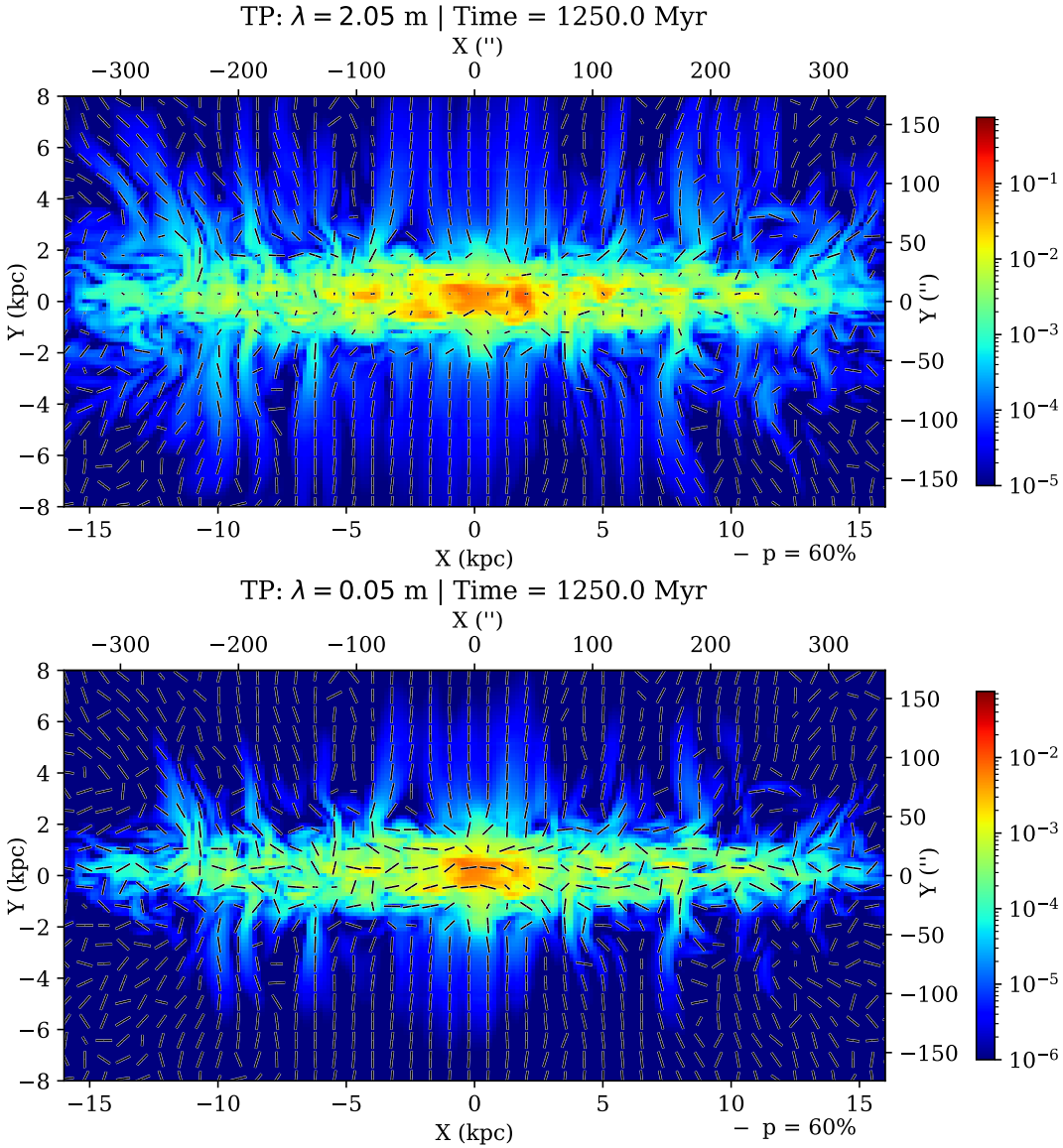



Vertical slices through the computational domain
gas density distribution (left), vertical velocity component (right).

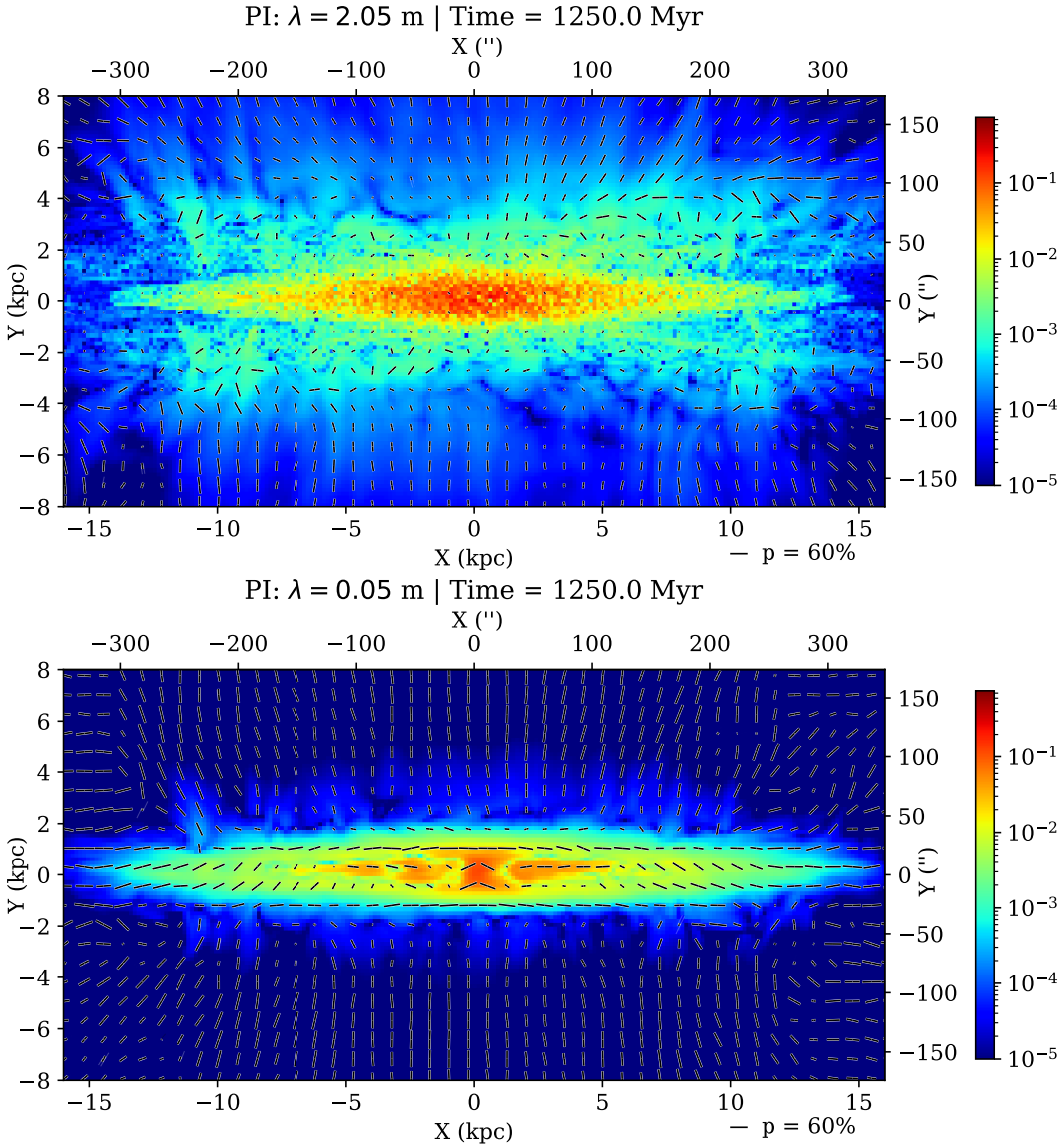


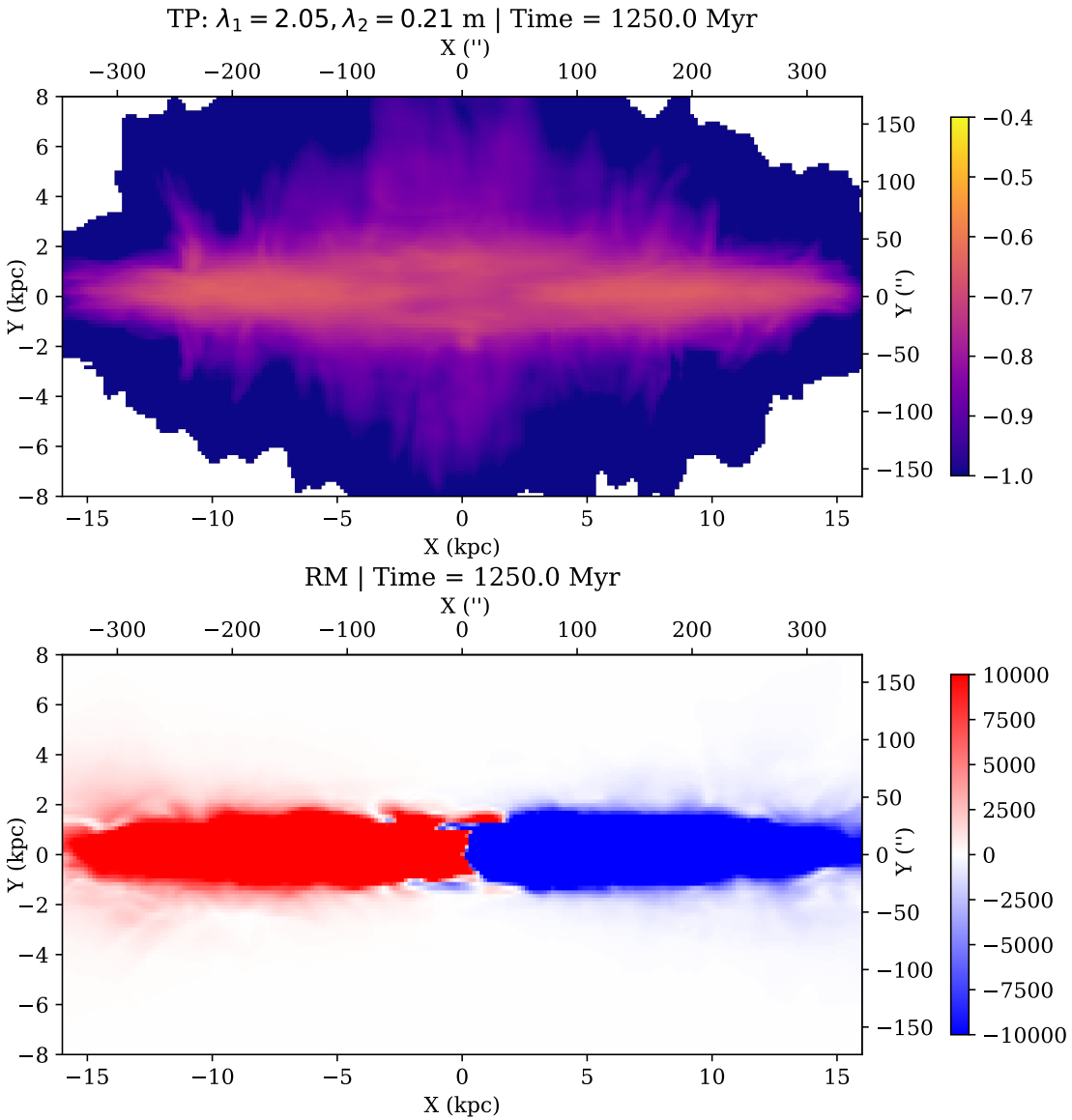

Vertical slices of the computational domain:
Total magnetic field $|B|$ (left), vertical magnetic field component |Bz| (right).




Total power (TP) at 146 MHz and 6 GHz – layer depth 1 kpc around galactic center




Polarized intensity (PI) at 146 MHz and 6 GHz – full depth along the line of sight




Spectral index between 146 MHz and 1421 MHz – full depth along the line of sight and rotation measure

- In CRESP module we have incorporated CR energy dependent transport of CR electrons into PIERNIK MHD code.
- The code can be used for modeling evolution of CR electron energy spectrum combined with MHD simulations.
- Currently available: momentum-dependent diffusion, adiabatic cooling/heating, synchrotron losses as well as momentum-dependent propagation of multiple CR species including primary and secondary CRs.
- Time-dependent simulations of CR electron spectrum evolution, coupled to MHD evolution, in global galactic scales are feasible.
- Synthetic synchrotron radio-maps of PI, TP, RM, spectral index can be generated through post-processing of simulation results.

**The main message:**
**interstellar medium driven by supernovae and CRs is highly structured and variable $\Rightarrow$ propagation of CRs coupled to the evolving MHD system is strongly influenced by the ISM dynamics.**