Dynamical impact of cosmic rays on the ISM and Galactic outflows

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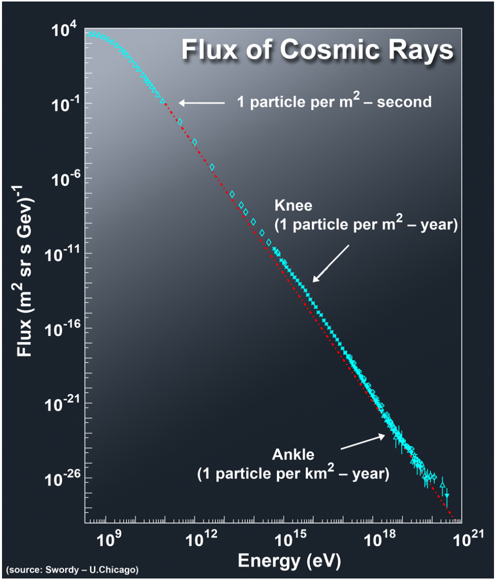
Why Cosmic Rays?

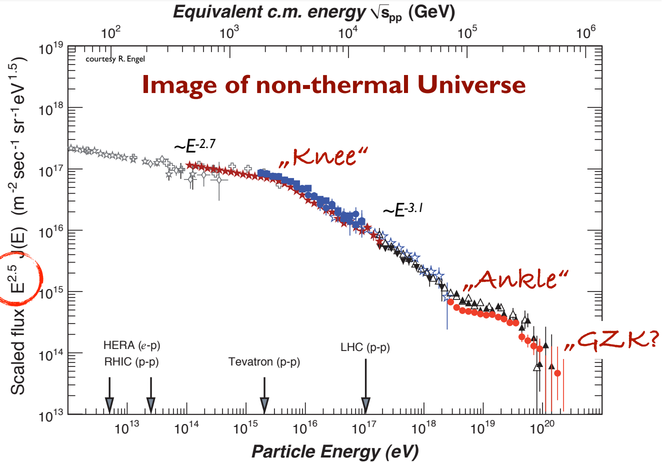
- What are Cosmic Rays?
  - high energy particles (non-thermal energies)
  - mostly protons, smaller fraction of electrons and heavier nuclei
  - have comparable energy densities to magnetic energy and thermal energy in the Galaxy
- Why do we care about them?
  - They have comparable energy densities in the ISM
  - They have different interaction processes with gas

What is the energy spectrum?



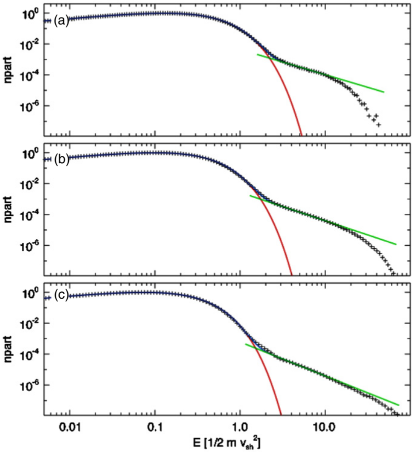
How and where are they created?

- depends on the energy range:
  1. below $\sim 1\mathrm{GeV}$: thermal conditions in SN shells
  2. up to $\lesssim 10^{15}\,\mathrm{eV}$: Galactic origin (Shock acceleration)
  3. above: assumed to be of extra-galactic origin



Shock acceleration and resulting spectrum?

- Strongest shocks are Supernova shells
- CR are accelerated via DSA (Axford et al. 1977; Krymskii 1977; Bell 1978; Blandford & Ostriker 1978; Malkov & OC Drury 2001)
- acceleration depends on shock properties: $\mathcal{M}, \rho, T, B$
- Expected energy input $E_{\rm CR} \sim 0.1\, E_{\rm SN}$ (Hillas 2005)



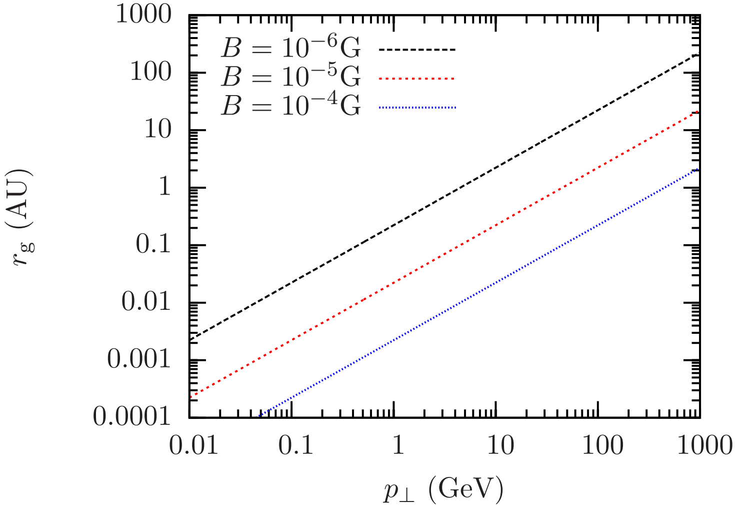
Gargate, Spitkovsky 2012

Why are they important?

- large mean free paths = small cross sections with the gas
- they do not interact locally with the gas
  1. CR can escape from the acceleration regions (cooling of SN regions)
  2. CR can penetrate into high density material (heating of molecular clouds)
- connection CR–gas mediated by magnetic fields
  1. CR are redirected by magnetic fields
  2. CR can deposit energy into magnetic fields (B field amplification)

Physics from small to large scales

- CR are charged particles that gyrate around magnetic field lines



Fluid approach for CR

- main assumption: effective mean free path ($\hat{=}$ particles' gyroradius) is small compared to computational cell
- particles travel relative to magnetic field lines due to inelastic effects in principle: work out diffusive effects and use diffusion process
- K depends on energy e_{cr} (Castellina & Donato 2011)

$$K(E) = 10^{28}\,\mathrm{cm}^2\,\mathrm{s}^{-1}\left(\frac{E}{10\,\mathrm{GeV}}\right)^{0.5}$$

- K depends on position in space ($\Rightarrow$ diffusion tensor) diffusion tensor depends on direction of magnetic field

$$\frac{\partial e_{\mathrm{cr}}(\mathbf{r},t)}{\partial t} = \sum_{i=1}^{3}\sum_{j=1}^{3}\frac{\partial}{\partial x_i}\left[K_{ij}(e_{\mathrm{cr}},\mathbf{r},\mathbf{B})\frac{\partial e_{\mathrm{cr}}(\mathbf{r},t)}{\partial x_j}\right]$$

- CR diffusion is different along and perpendicular to field lines

$$K_{\|} \sim (10-100)K_{\perp}$$

coupling gas ⇒ CR

- How to couple CR and gas?
- assume ideal MHD: magnetic field lines are frozen in the gas
  ⇒ magnetic field is *advected/compressed* with the gas
- assume that the perpendicular diffusion coefficient is small
  ⇒ strong coupling of CR to the field lines
  ⇒ CR are *advected* with the gas
- *advection-diffusion approximation*

$$
\underbrace{\partial_t e_{\rm cr} + \nabla(e_{\rm cr}\mathbf{v})}_{\text{advection}} = - \underbrace{p_{\rm cr}\nabla\cdot\mathbf{v}}_{\text{compression of gas (CR are trapped)}} + \underbrace{\nabla\cdot(\mathsf{K}\cdot\nabla e_{\rm cr})}_{\text{diffusion (anisotropic)}} + \underbrace{Q_{\rm cr}}_{\text{source terms}}
$$

CR spectra

- so far, only total CR considered
- strongly varying diffusion coefficient (Berezinskii et al. 1990; Castellina & Donato 2011)

$$K_{\parallel}(E) = K_{\parallel,0}\left(\frac{E}{10\,\mathrm{GeV}}\right)^{0.5}, \qquad K_{\perp} \sim 0.01 K_{\parallel}$$

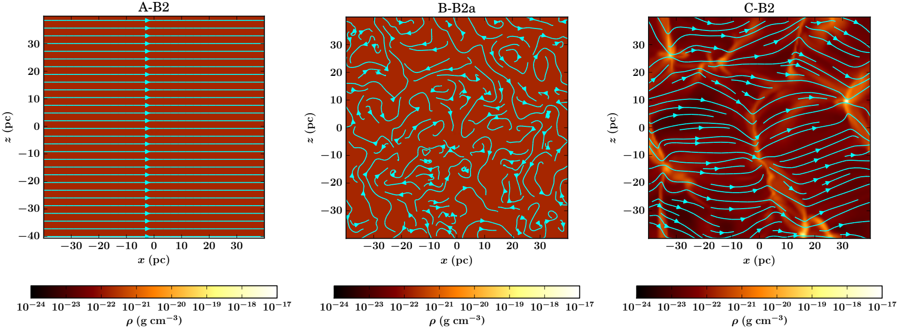
- follow CRs of different energies separately (full spectrum)
  we use 10 different bins (different $\gamma_{\mathrm{CR}}(E)$)

$$\partial_t e_{\mathrm{cr}} + \nabla\cdot(e_{\mathrm{cr}}\mathbf{v}) = -p_{\mathrm{cr}}\nabla\cdot\mathbf{v} + \nabla\cdot(\mathsf{K}\cdot\nabla e_{\mathrm{cr}}) + Q_{\mathrm{cr}}$$
$$\partial_t e_{\mathrm{cr},i} + \nabla\cdot(e_{\mathrm{cr},i}\mathbf{v}) = -p_{\mathrm{cr},i}\nabla\cdot\mathbf{v} + \nabla\cdot(\mathsf{K}_i(e_i)\cdot\nabla e_{\mathrm{cr},i}) + Q_{\mathrm{cr},i}$$

- include adiabatic gains and losses in momentum space
- Girichidis, Naab, Walch, Hanasz (arXiv:1406.4861)

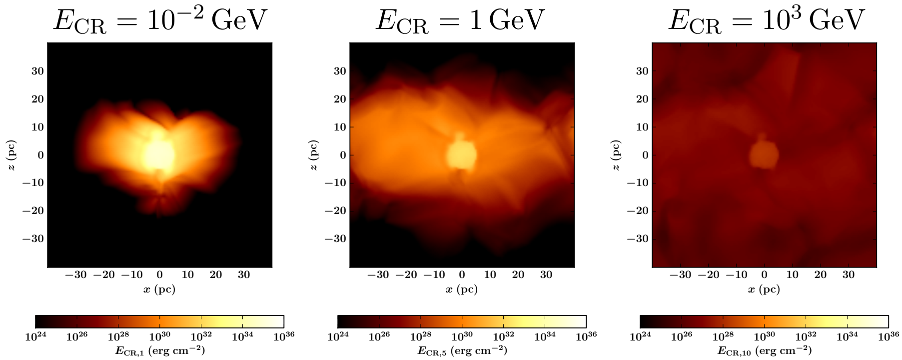
Test and realistic setups

- vary density and magnetic field configuration
- realistic setup: initial homogeneous $\mathbf{B}$ field, turbulence, gravity

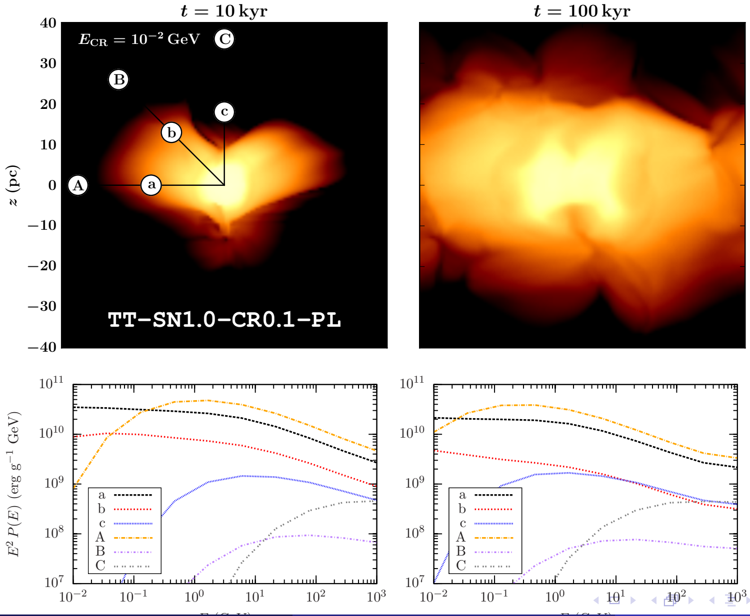


Realistic ISM conditions

- CR diffusion $10\,\mathrm{kyr}$ after the SN explosion



Realistic ISM conditions

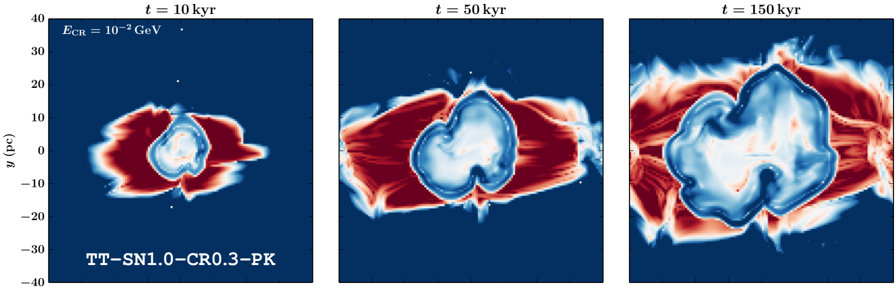


Ratio of the pressure gradients

- pressure gradients are accelerating the gas
- ratio of pressure gradients

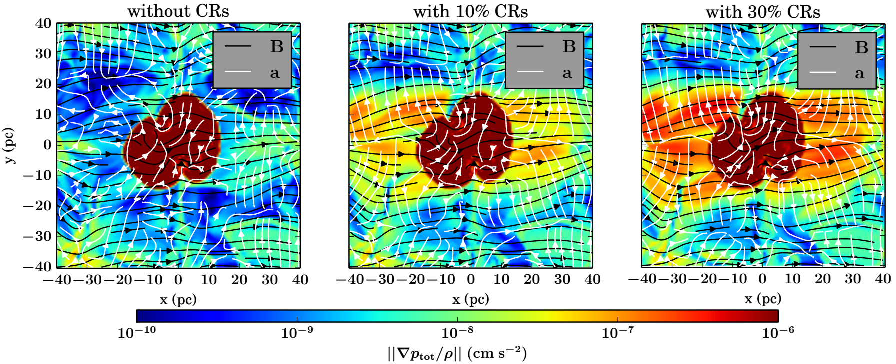
$$\frac{|\nabla P_{\rm CR}|}{|\nabla P_{\rm gas}|}$$

shows, where CRs are the dominant driver of acceleration



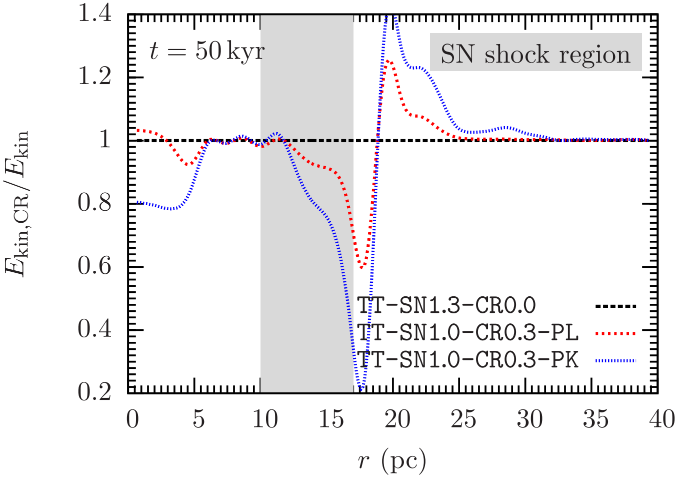
Net acceleration

- net acceleration of the gas
- mostly perpendicular to the magnetic field lines



Energy in the shock region

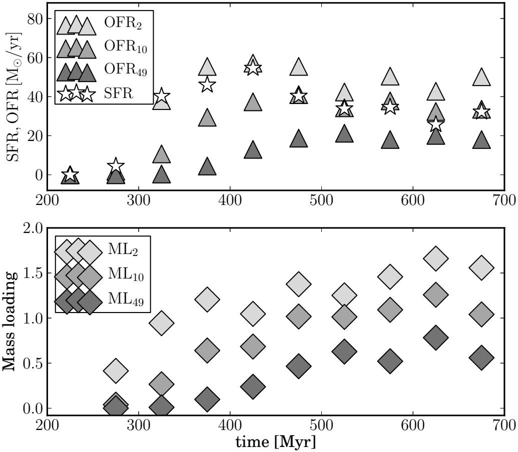
- compare run SN+CR (1.0+0.3) to purely thermal run (1.3+0.0)



- CR: shock weaker, energy can be pushed to larger radii

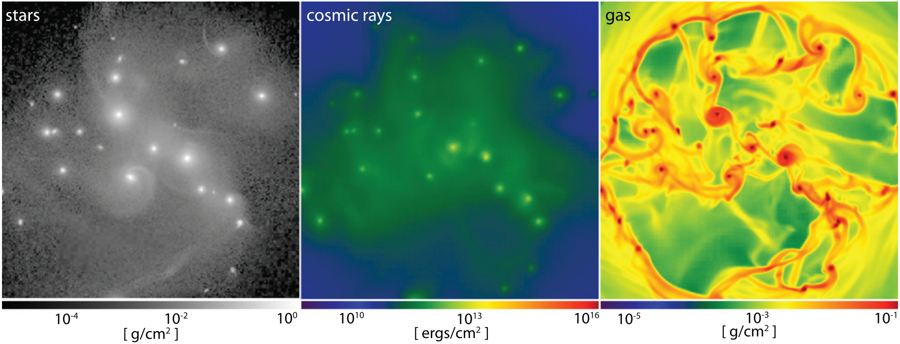
Galactic Scales

- Hanasz et al. (2013): entire galaxy, including magnetic fields
- only CR input from SN, no thermal contribution
- conclusion: CR energy alone is enough to drive outflows



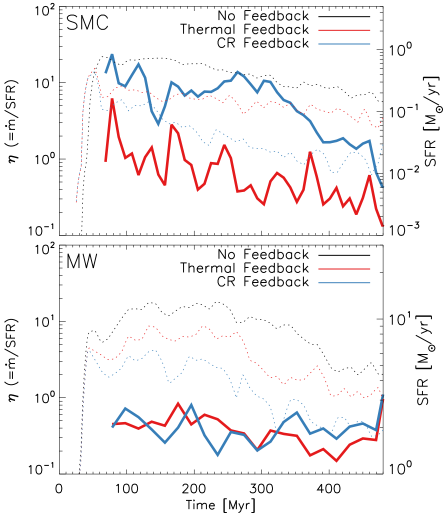
Galactic Scales

- Salem et al. (2013)
- entire Galaxy with thermal and CR impact of SN
- no magnetic fields, no anisotropic diffusion
- conclusion: CRs suppress SF and drive winds



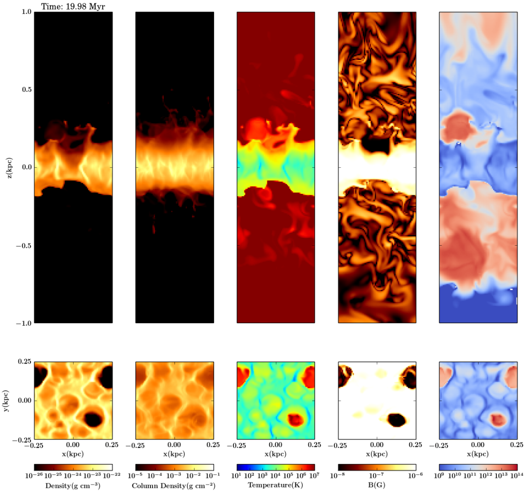
Galactic Scales

- Booth et al. (2013)
- entire galaxy
    - SMC (75 kpc)
    - MW (150 kpc)
- SN with thermal and CR feedback
- isotropic diffusion (no $\mathbf{B}$)
- conclusions: CR suppress SF (add. pressure), drive winds



Stratified box

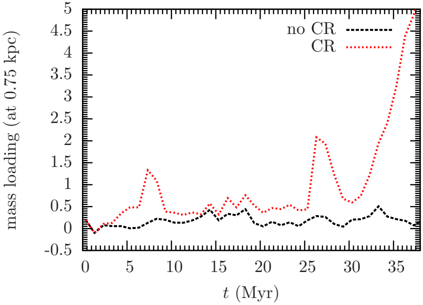
- Girichidis, SILCC collaboration, MacLow
- stratified box: $0.5 \times 0.5 \times 40\,\mathrm{kpc}^3$
- $\Sigma = 10\,M_\odot\,\mathrm{pc}^{-2}$
- chemical network with H^+, HI, H_2, CO, C^+ Glover et al. 2010
- shielding using TreeCol (Clark et al. 2010, Wünsch et al. in prep.)



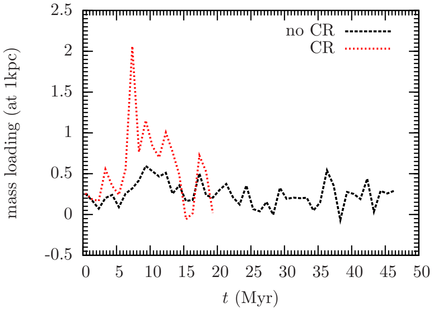
Galactic Scales

- place SNe at random positions
- different scale heights for type I (300 pc) and type II (80 pc) SNe
- clustering of type II SNe
- initially ordered magnetic field $B_x = 3\mu\text{G}$

- 1/3 KS SFR

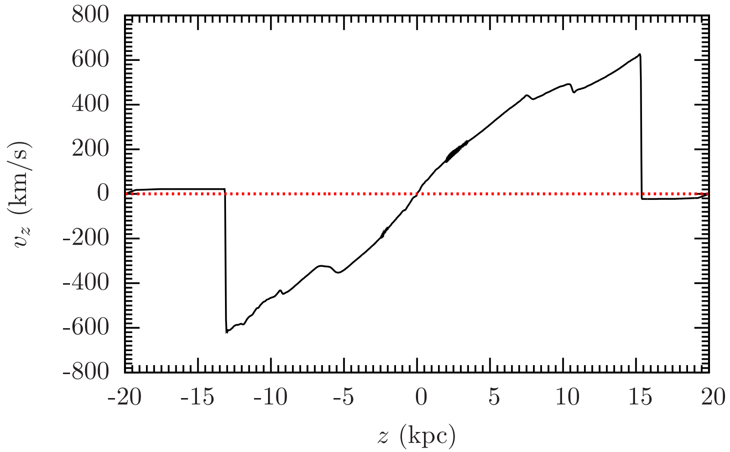


- KS SFR



Larger altitudes

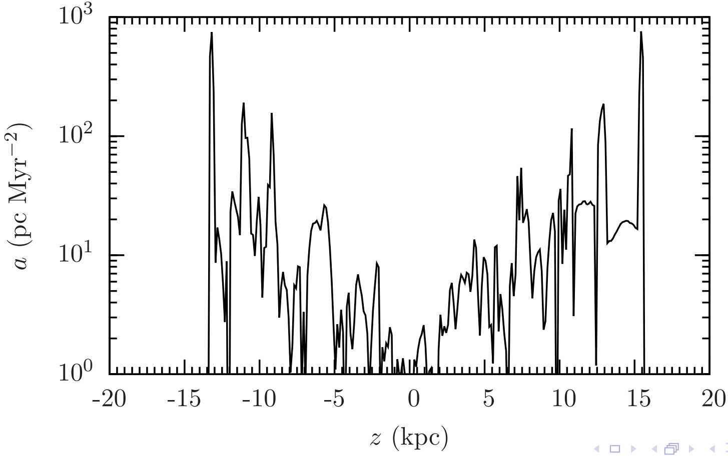
- CR drive gas at high velocities
- total mass transfer exceeds mass loading of unity



Larger altitudes

- acceleration of the gas

$$a = \frac{1}{\rho} \nabla P_{\mathrm{tot}}$$



Conclusions

- CRs quickly diffuse through the ISM along magnetic field lines
- CRs increase E_{kin} ahead of the SN shell (locally $20 - 40\%$)
- acceleration of gas due to CRs is strong in low-density environments
- acceleration details and ionisation depend on CR source spectrum
- CRs have enough energy to drive Galactic outflows