Cosmic rays in the interstellar medium and their dynamical impact

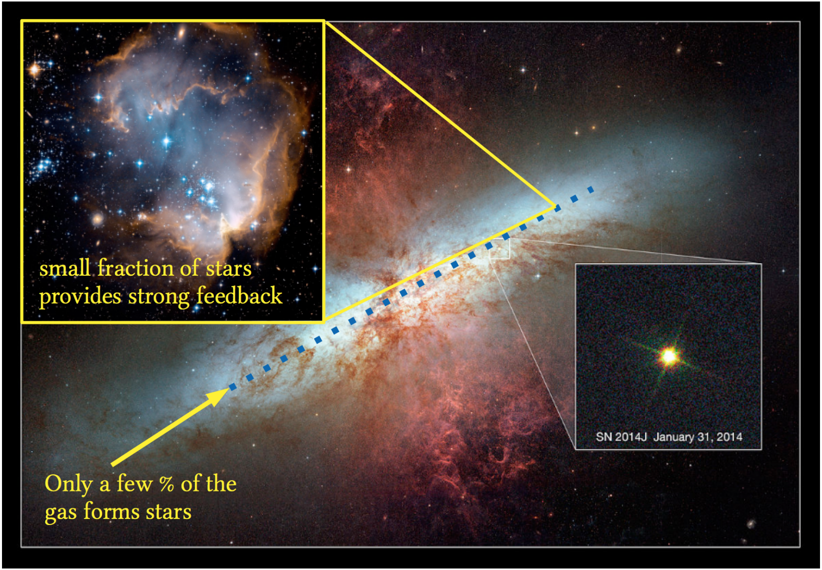
Philipp Girichidis

Christoph Pfrommer, Thorsten Naab, Michał Hanasz, Stefanie Walch, Daniel Seifried, Georg Winner, Maria Werhahn

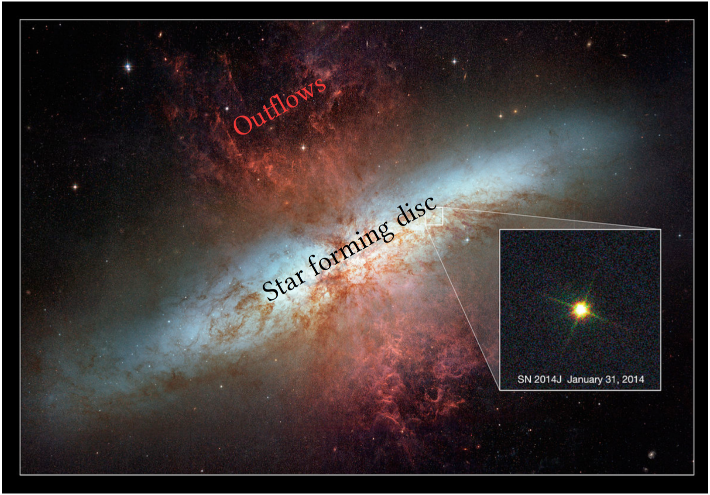
AIP Potsdam

October 15, 2019

Starburst galaxy M82 (Hubble)

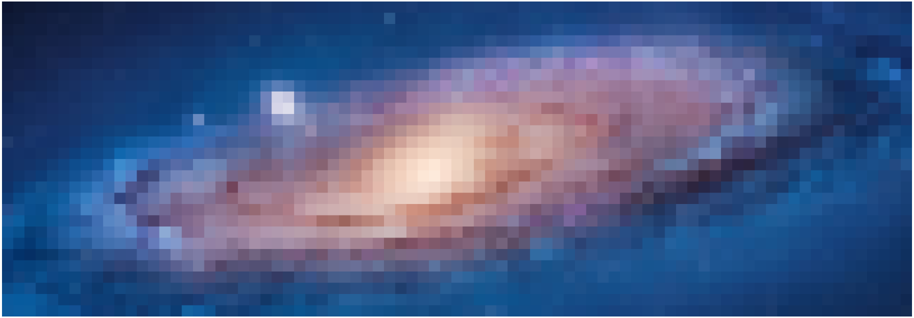


Starburst galaxy M82 (Hubble)



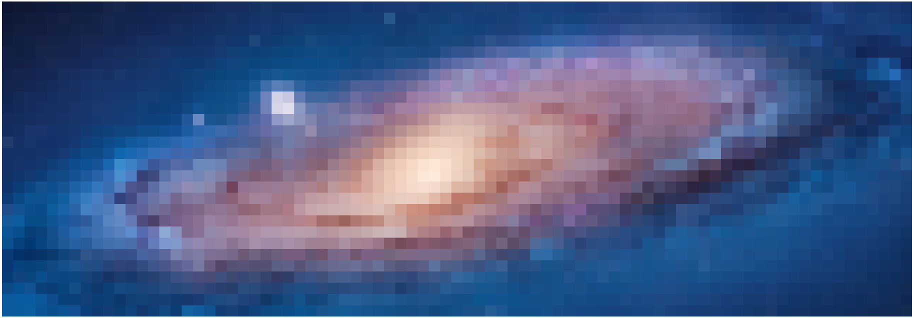
- strong outflows with $\eta = \dot{M}_{\mathrm{outflow}}/\dot{M}_*$ of a few
- outflows in all chemical phases (ionized – molecular)

Global ISM properties



density	$1\,\mathrm{cm}^{-3}$
temperature	$10^4\,\mathrm{K}$
magnetic fields	$5\,\mu\mathrm{G}$
turbulence	$10\,\mathrm{km\,s}^{-1}$
cosmic rays	$1\,\mathrm{eV\,cm}^{-3}$

Global ISM properties

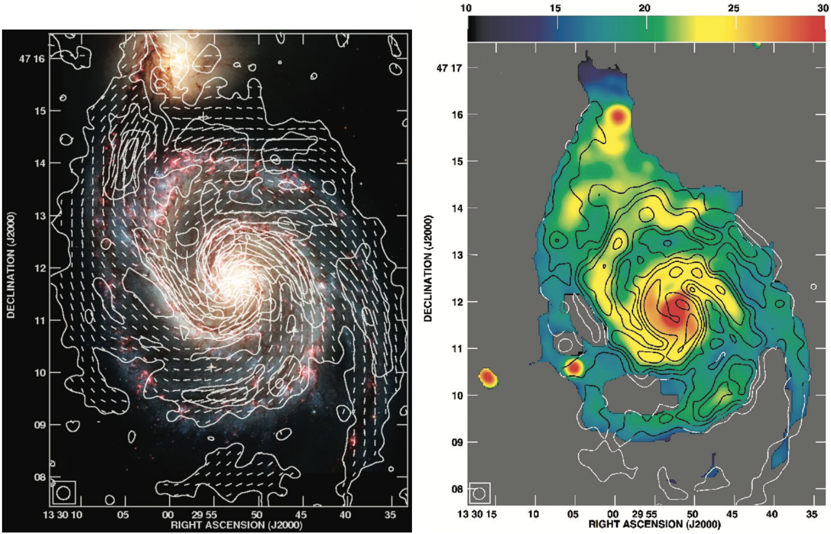


density	$1\,\mathrm{cm}^{-3}$	$1\,\mathrm{cm}^{-3}$
temperature	$10^4\,\mathrm{K}$	$1\,\mathrm{eV\,cm}^{-3}$
magnetic fields	$5\,\mu\mathrm{G}$	$1\,\mathrm{eV\,cm}^{-3}$
turbulence	$10\,\mathrm{km\,s}^{-1}$	$1\,\mathrm{eV\,cm}^{-3}$
cosmic rays	$1\,\mathrm{eV\,cm}^{-3}$	$1\,\mathrm{eV\,cm}^{-3}$

Global ISM properties

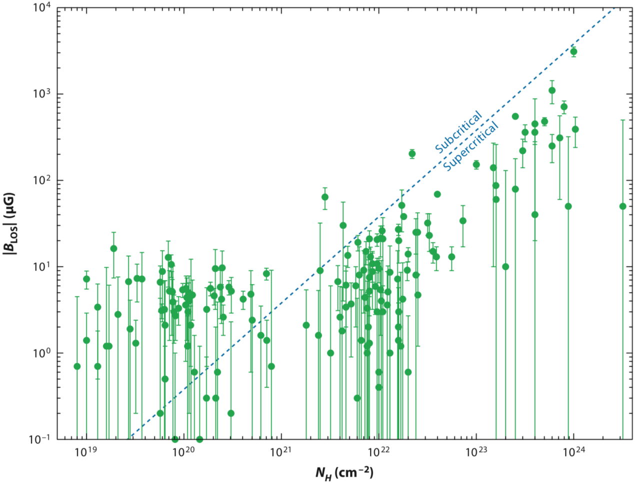
density	$1\,\mathrm{cm}^{-3}$	$1\,\mathrm{cm}^{-3}$	$10^{-4} - 10^{6}\,\mathrm{cm}^{-3}$
temperature	$10^{4}\,\mathrm{K}$	$1\,\mathrm{eV\,cm}^{-3}$	$10 - 10^{8}\,\mathrm{K}$
magnetic fields	$5\,\mu\mathrm{G}$	$1\,\mathrm{eV\,cm}^{-3}$	$0.1 - 10^{3}\,\mu\mathrm{G}$
turbulence	$10\,\mathrm{km\,s}^{-1}$	$1\,\mathrm{eV\,cm}^{-3}$	$0.1 - 10^{3}\,\mathrm{km\,s}^{-1}$
cosmic rays	$1\,\mathrm{eV\,cm}^{-3}$	$1\,\mathrm{eV\,cm}^{-3}$	$1\,\mathrm{eV\,cm}^{-3}$

Magnetic fields in galaxies (M51)



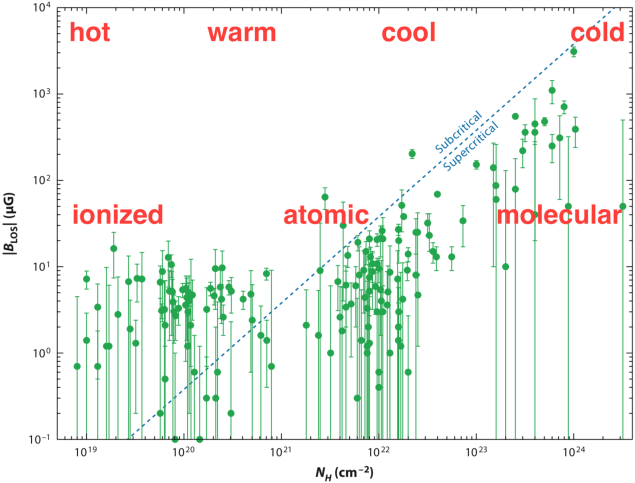
Fletcher+ (2011)

Magnetic fields in the interstellar medium



Crutcher (2012)

Magnetic fields in the interstellar medium



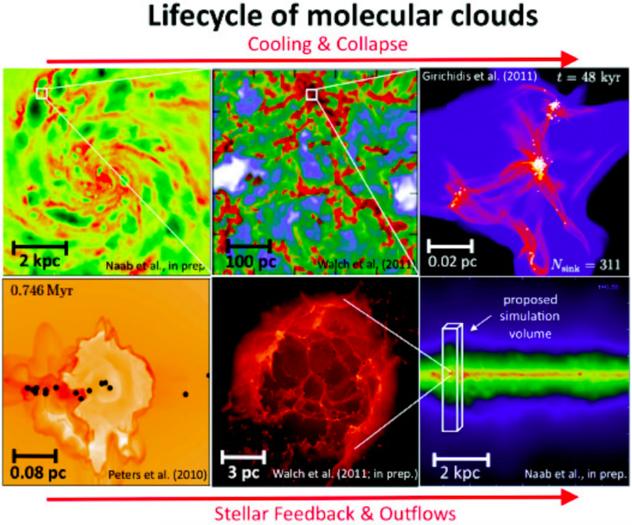
Crutcher (2012)

SILCC: ISM details on different scales

SILCC: SImulating the LifeCycle of molecular Clouds

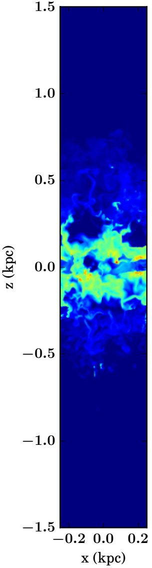
Walch+2015,

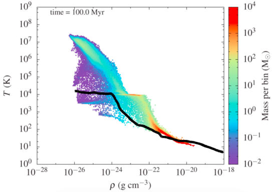
Girichidis+2016b



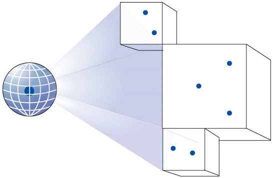
Setup for ISM simulations

- stratified box (deAvillez+2004, 2005, Kim & Ostriker+ 2013 - 2018, Hennebelle & Iffrig 2015)
- external potential (ρ_*, DM)
- MHD
- atomic, mol., metal cooling (follow H^+, H, H_2, C^+, CO) (Glover et al. 2012, Walch et al. 2015)
- shielding effects ($A_V > 1$)
- stellar feedback (SNe, CRs)
- MW conditions: $10\ \frac{M_\odot}{\mathrm{pc}^2}$, $Z_\odot$



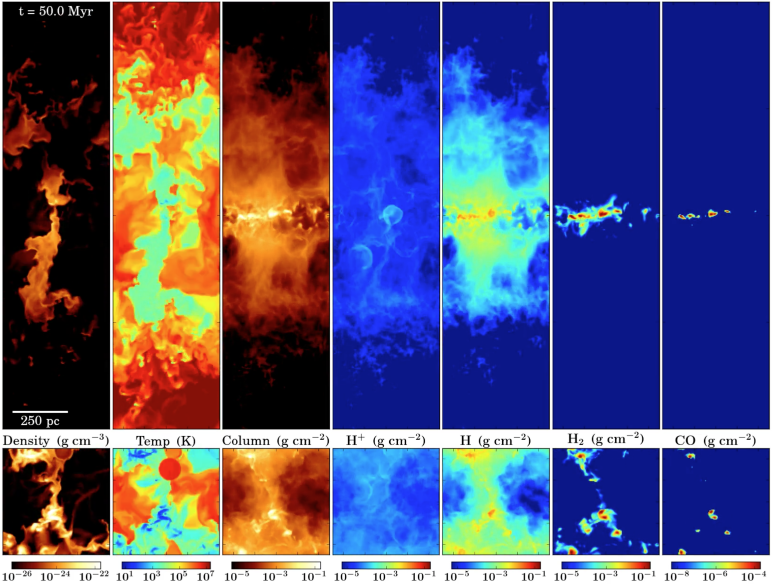


(Gatto et al. 2015)

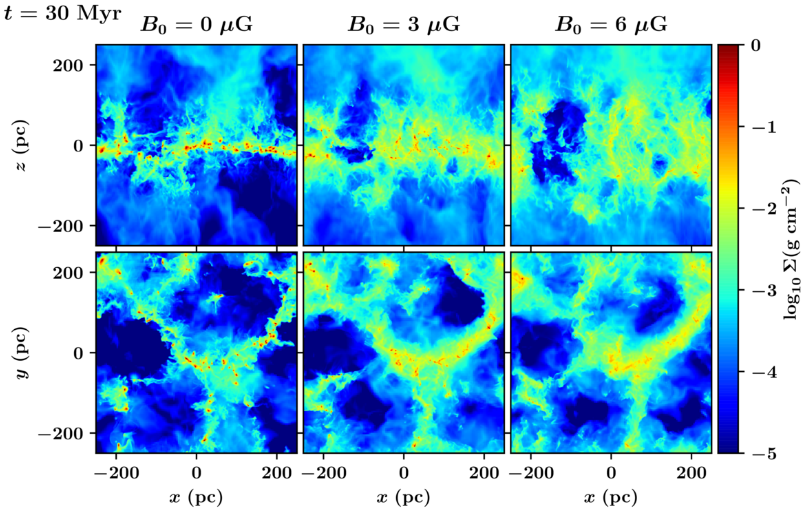


(Clark et al. 2012, Wünsch et al. 2018)

SN-driven ISM (Walch+2015, Girichidis+2016a)



Dynamical impact of magnetic fields (Girichidis+ 2018b)



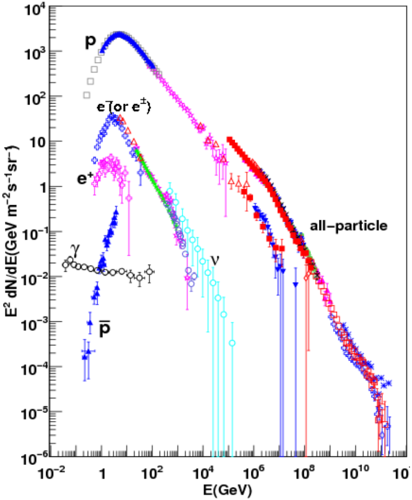
Girichidis et al. 2018, MNRAS, 480, 3511

magnetic fields result in more diffuse gas

Cosmic rays

- CRs: $E_{\mathrm{CR}} \sim E_{\mathrm{mag}} \sim E_{\mathrm{th}} \lesssim E_{\mathrm{kin}}$
  (Ferriere 2001)
- primary source: shocks: DSA
  Axford+ 1977; Krymskii 1977; Bell 1978; Blandford & Ostriker1978; Malkov+ 2001, Caprioli & Spitkovsky 2014
- mainly SN remnants
- efficiency 10% (10^{50} erg/SN)
- stellar wind shocks

CR spectrum (Hu+ 2009)



Combined MHD-CR equations (Girichidis+2016a, Girichidis+2018a)

based on MHD-Solver HLLR3 (Bouchut+ 2007, 2010, Waagan+ 2009, 2011)

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0$$

$$\frac{\partial \rho \mathbf{v}}{\partial t} + \nabla \cdot \left(\rho \mathbf{v}\mathbf{v} - \frac{\mathbf{B}\mathbf{B}}{4\pi} \right) + \nabla p_{\mathrm{tot}} = \rho \mathbf{g}$$

$$\frac{\partial e_{\mathrm{tot}}}{\partial t} + \nabla \cdot \left[(e_{\mathrm{tot}} + p_{\mathrm{tot}})\, \mathbf{v} - \frac{\mathbf{B}(\mathbf{B} \cdot \mathbf{v})}{4\pi} \right] = \rho \mathbf{v} \cdot \mathbf{g} + \nabla \cdot (\mathsf{K} \cdot \nabla e_{\mathrm{cr}}) + Q_{\mathrm{cr}}$$

$$\frac{\partial \mathbf{B}}{\partial t} - \nabla \times (\mathbf{v} \times \mathbf{B}) = 0$$

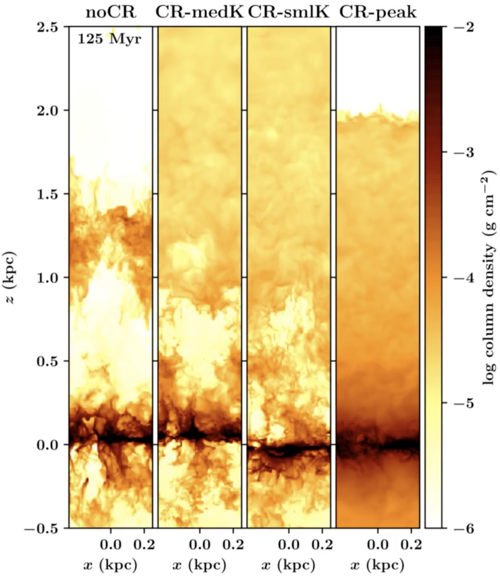
$$\frac{\partial e_{\mathrm{cr}}}{\partial t} + \nabla \cdot (e_{\mathrm{cr}} \mathbf{v}) = -p_{\mathrm{cr}} \nabla \cdot \mathbf{v} + \nabla \cdot (\mathsf{K} \cdot \nabla e_{\mathrm{cr}}) + Q_{\mathrm{cr}}$$

similar to Hanasz & Lesch 2003, Pfrommer et al. 2017

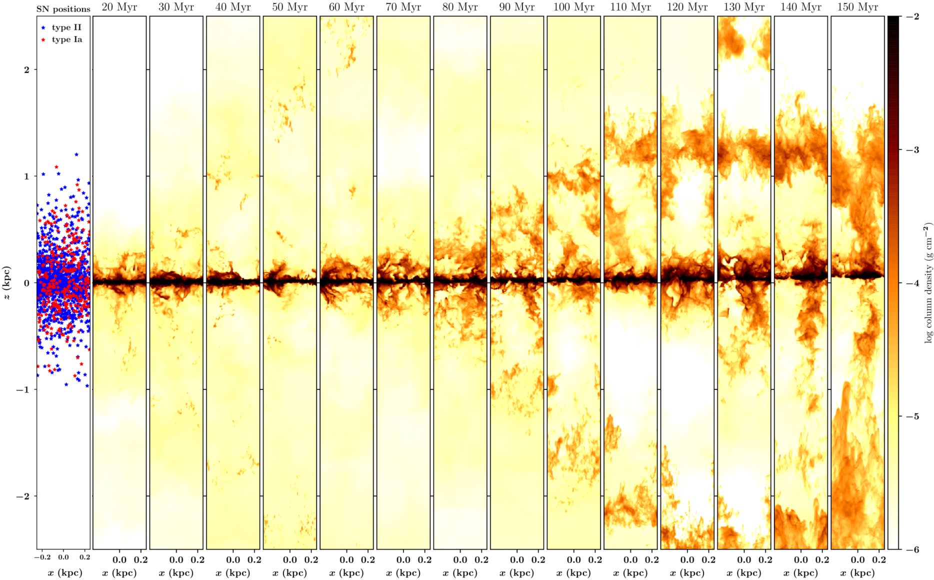
dynamical impact of CRs

- Galactic CRs: SNe (DSA, Axford et al. 1977; Krymskii 1977; Bell 1978)
- 10% of SN energy
- dynamical impact (Girichidis+ 2018a)
    - no CRs
    - $\mathsf{K}_{\parallel} = 3 \times 10^{28}\ \frac{\mathrm{cm}^2}{\mathrm{s}}$
    - $\mathsf{K}_{\parallel} = 1 \times 10^{28}\ \frac{\mathrm{cm}^2}{\mathrm{s}}$
    - SNe in peaks
- data publicly available: girichidis.com

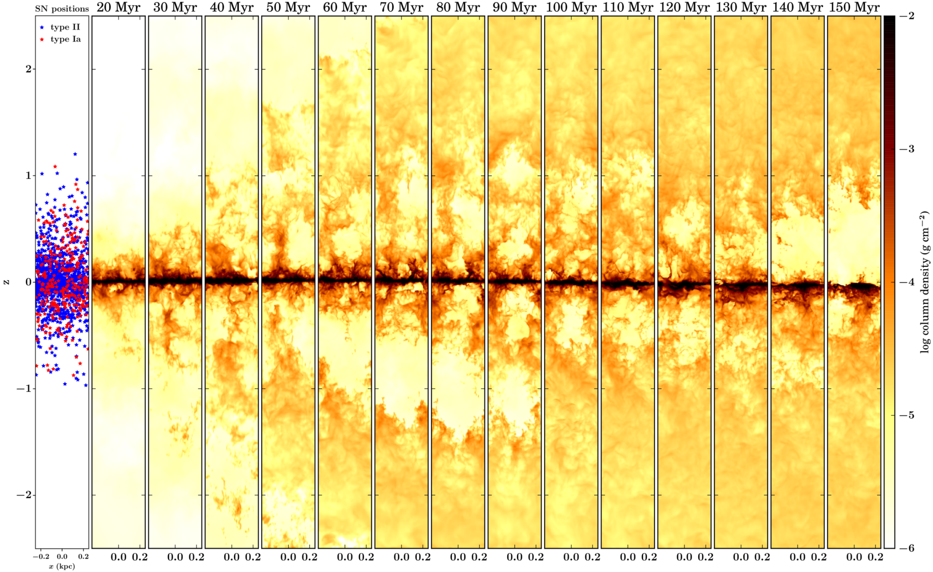
  http://silcc.mpa-garching.mpg.de



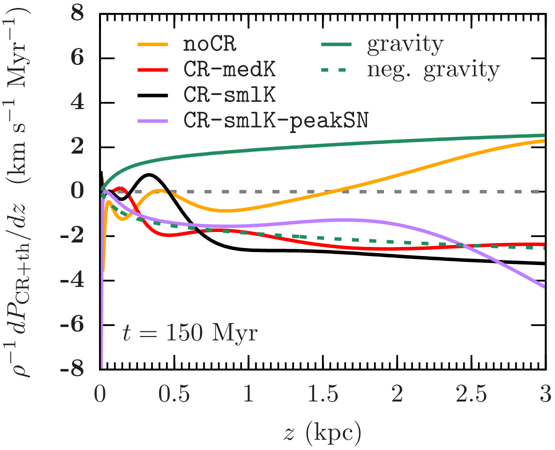
time evolution without CRs



time evolution including CRs



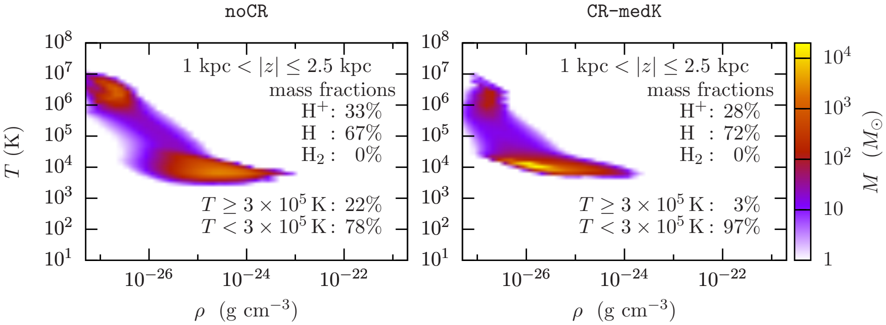
Net force balance



- thermal SNe: locally strong accelerations, temporal fluctuations
- incl. CR: smoother forces, net outward pointing force
- for slow CR diffusion: net pressure gradient exceeds gravity

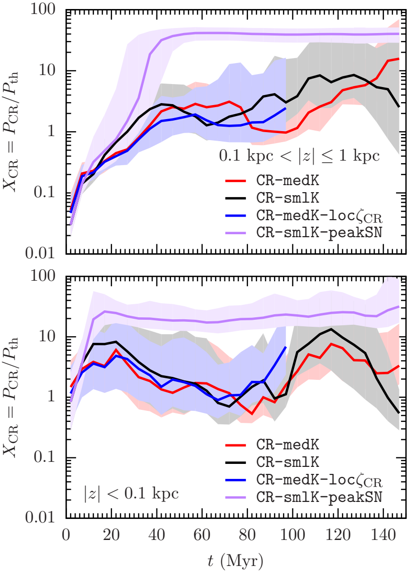
Outflow strength and composition

- CRs drive stronger outflows from the disk
- effective mass loading factors maesured at 2.5 kpc
  $\eta_{\rm therm} \approx 0.1$ (Kim+2018), $\eta_{\rm cr} \sim 0.7 - 1.4$ (Mao+2018)

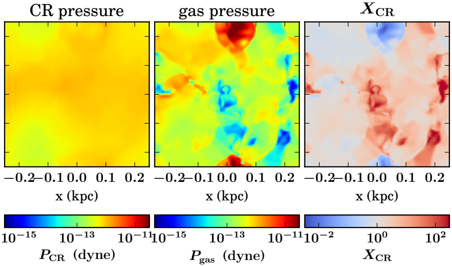


- Thermal run produces more hot gas.
- CR-driven outflows have same ionisation degree.

CR pressure and X_{CR}

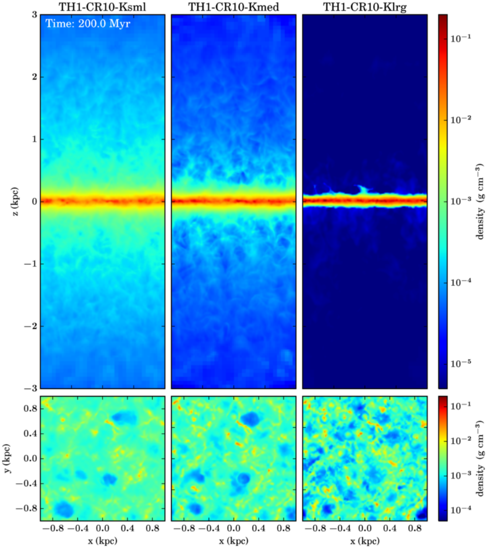


- smooth CR energy distribution
- CR pressure dominates in the disk
- region above the disk: equipartition

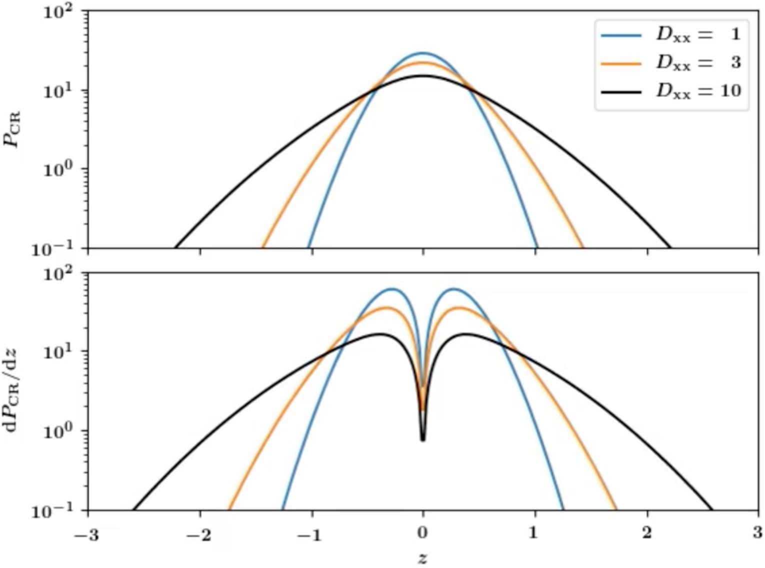


Dependence on the diffusion coefficient

- high diffusion speeds
- fast removal of CR energy
- shallow CR energy gradients
- less dense atmosphere
- slightly faster outflow (Dorfi & Breitschwerdt 2012)
- large differences between isotropic vs. anisotropic (Pakmor et al. 2016)

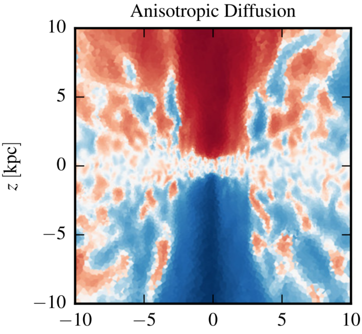


Dependence on the diffusion coefficient

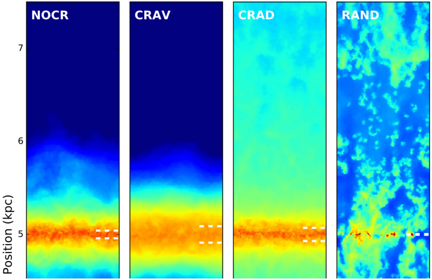


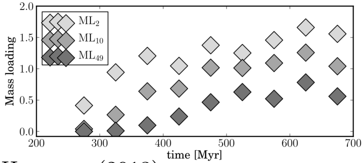
Other studies

- ISM: Hanasz+ (2009), Simpson+ (2016), Farber+ (2018)
- Galaxy (isotropic diff.): Booth+ (2013), Salem+ (2014), Pakmor+ (2016), Jacob+ (2018)
- Galaxy (anisotropic diff.): Hanasz+ (2013), Pakmor+ (2016), Pfrommer+ (2017)
- Galaxy (streaming): Uhlig+ (2012), Ruszkowski+ (2017)



Pakmor+ (2016)

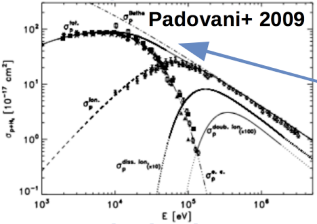




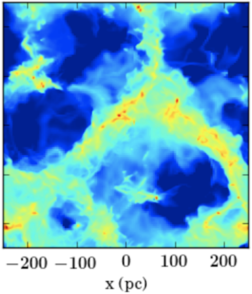
Hanasz+ (2013)

CR spectrum

CR-gas interaction

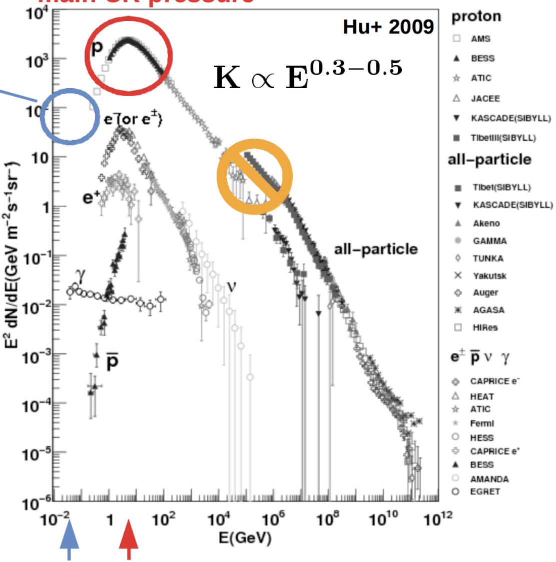


- CR ionisation rate
- CR losses

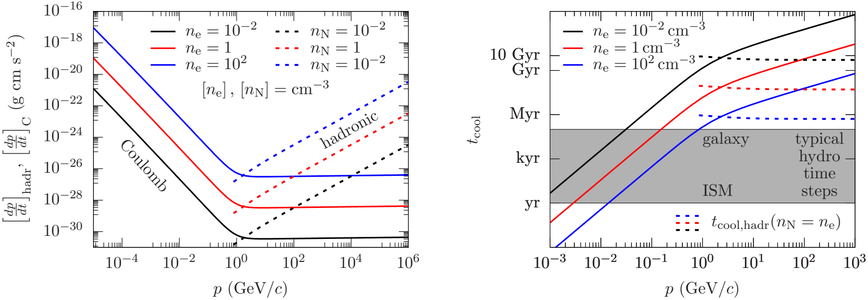


main CR pressure

$$K \propto E^{0.3-0.5}$$



CR cooling



- Coulomb losses important for low-E CRs
- hadronic losses: $\mathrm{CR} + p \rightarrow \pi^0 \rightarrow 2\gamma$
- spectra will not be steady state spectra

Fokker-Planck equations for CRs

- start with Fokker-Planck equation

$$\frac{\partial f}{\partial t} = \underbrace{-\mathbf{v}\cdot\nabla f}_{\text{advection}} + \underbrace{\nabla\cdot(\mathsf{K}\cdot\nabla f)}_{\text{diffusion}} + \underbrace{\frac{1}{3}(\nabla\cdot\mathbf{v})\,p\frac{\partial f}{\partial p}}_{\text{adiabatic process}}$$

$$+ \underbrace{\frac{1}{p^2}\frac{\partial}{\partial p}\left[p^2\left(b_l f + D_{pp}\frac{\partial f}{\partial p}\right)\right]}_{\text{other losses and Fermi II acceleration}} + \underbrace{j}_{\text{sources}}$$

- chose piecewise powerlaws for f

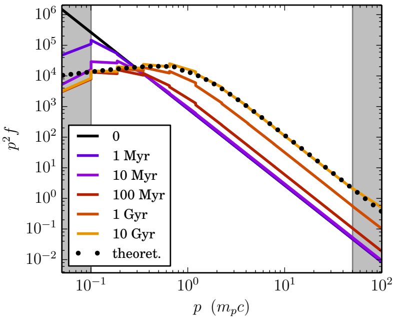
$$f(p) = f_{i-1/2}\left(\frac{p}{p_{i-1/2}}\right)^{q_i},$$

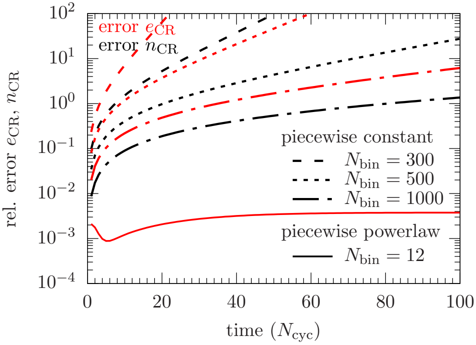
- derive number density and energy density

$$n_i = \int_{p_{i-1/2}}^{p_{i+1/2}} 4\pi p^2 f(p)\,dp \qquad e_i = \int_{p_{i-1/2}}^{p_{i+1/2}} 4\pi p^2 f(p) T(p)\,dp$$

- see also Miniati 2001, Yang+ 2017, Girichidis+2019

Spectral discretisation tests



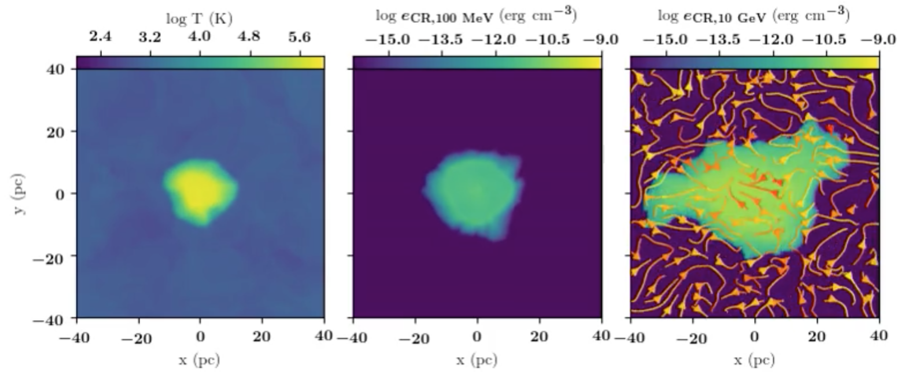


- steady state spectrum with only 10 bins.

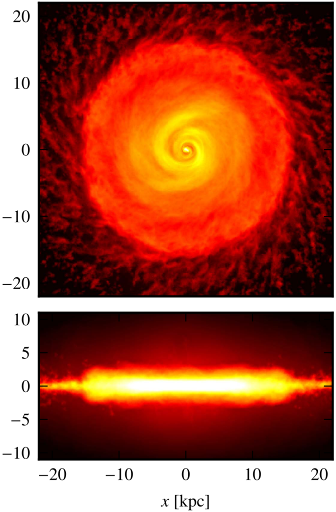
- periodic compression/expansion
- need large number of bins for classical approach
- new method: rel. error 10^{-4}

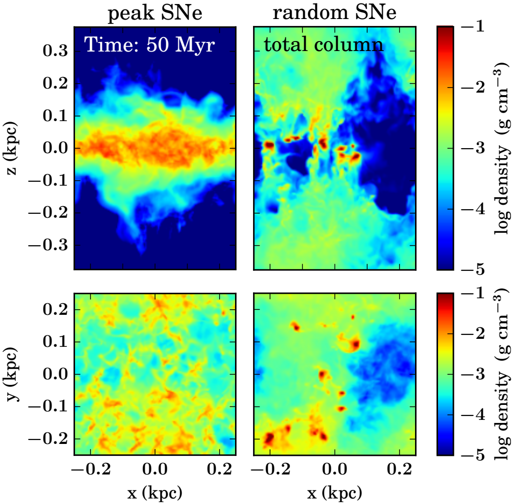
Application

- explode SN with typical CR spectrum
- adiabatic gains/losses, energy dependent diffusion



spectral CRs in two setups


Pfrommer+ 2017


local ISM setup

Conclusions

- magnetic fields keep more gas in diffuse state
- cosmic rays can drive outflows with mass loading of order unity
- cosmic ray-driven outflows are warm and smooth, slowly lifted
- spectral distribution of CRs in hydro simulations
    - more accurate transport
    - better connection to observations

This project has received funding from the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme (grant agreement No CRAGSMAN-646955)