The role of cosmic rays in driving outflows

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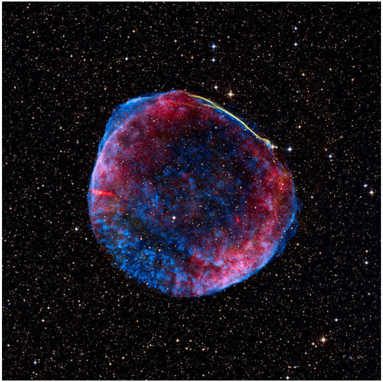
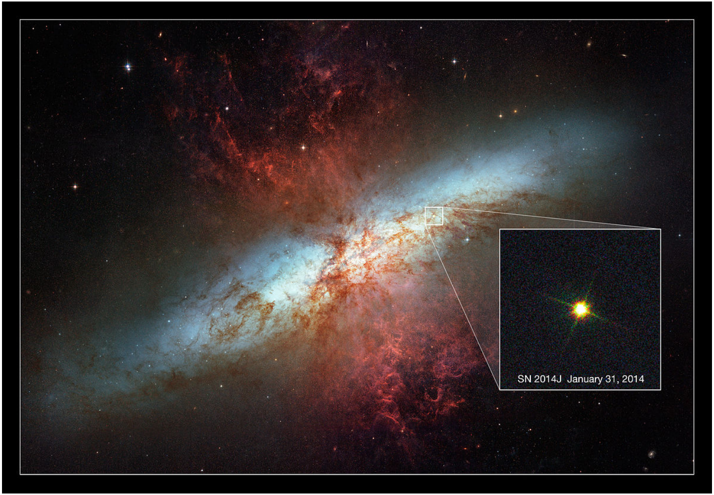
Observations: supernovae as dynamical drivers

Ackermann et al. 2013



- individual supernova ($1\,\mathrm{pc}$)
- explosion of star with $M > 8\,M_\odot$ after a life time of $4 - 30\,\mathrm{Myr}$.
- dynamical drivers ($10^{51}\,\mathrm{erg}$)
- production sites of CRs ($10^{50}\,\mathrm{erg}$)

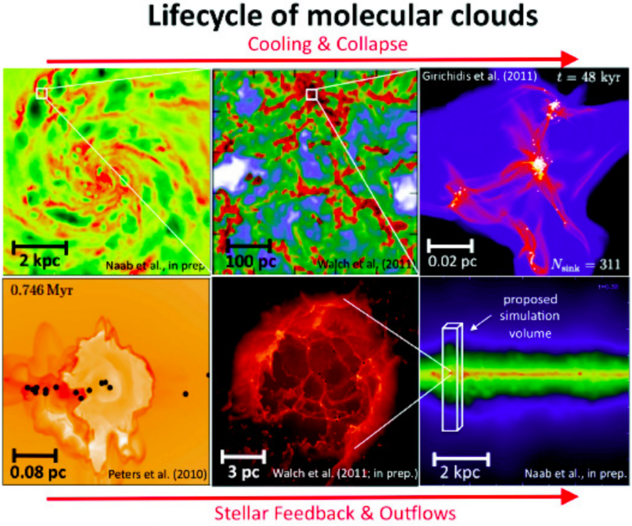
Observations: starburst galaxy M82 (Hubble)



- starburst galaxy $(50,000\,\mathrm{pc})$
- strong outflows with $\eta = \dot{M}_\mathrm{outflow}/\dot{M}_*$ of a few

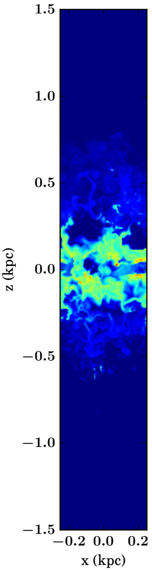
ISM details on different scales

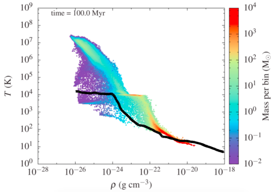
SILCC: SImulating the LifeCycle of molecular Clouds



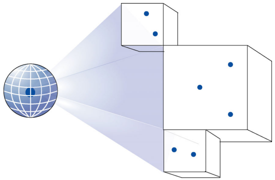
Setup for ISM simulations

- stratified box (deAvillez+2004, 2005, Kim & Ostriker+ 2013, 2014, 2015, Hennebelle & Iffrig 2015)
- external potential (ρ_*)
- **Magneto**hydrodynamics
- atomic, mol., metal cooling (follow H^+, H, H_2, C^+, CO) (Glover et al. 2012, Walch et al. 2015)
- shielding effects (high optical depth)
- feedback from stars (SNe)
- cosmic rays (second part)
- MW conditions: $10\,\frac{M_\odot}{\mathrm{pc}^2}$, $Z_\odot$



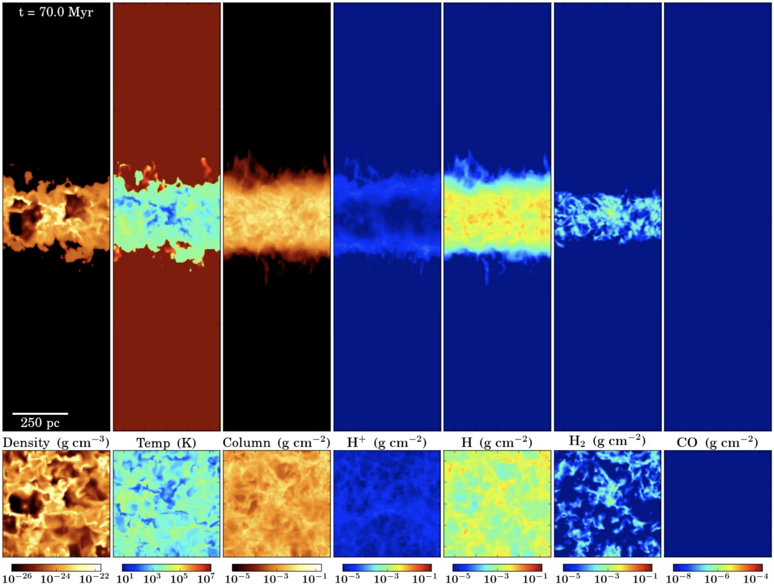


(Gatto et al. 2015)

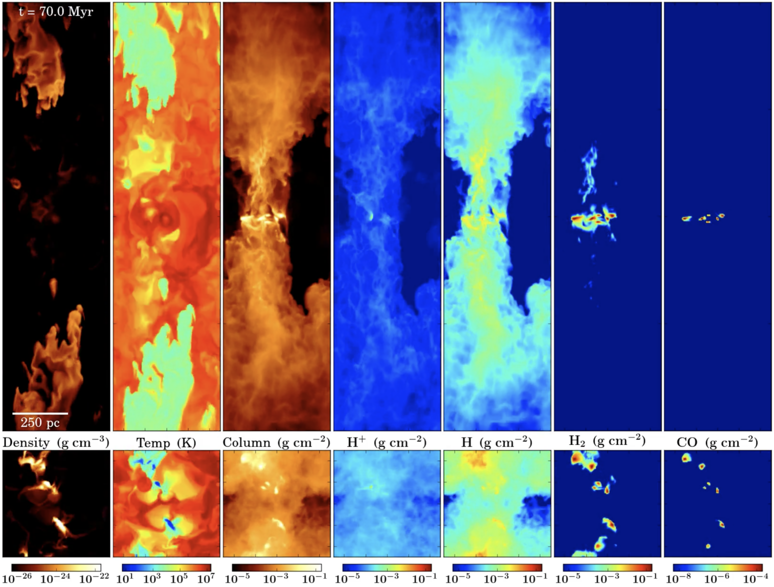


(Clark et al. 2012, Wünsch et al. in prep.)

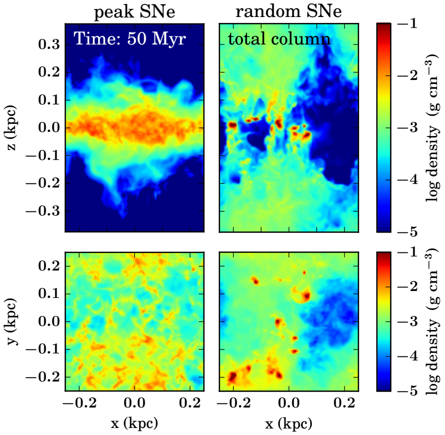
SNe in density peaks (Walch+2015, Girichidis+2016a)

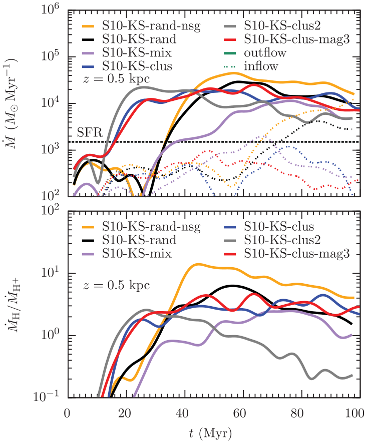


SNe at random positions (Walch+2015, Girichidis+2016a)



Structure of the ISM and the disk

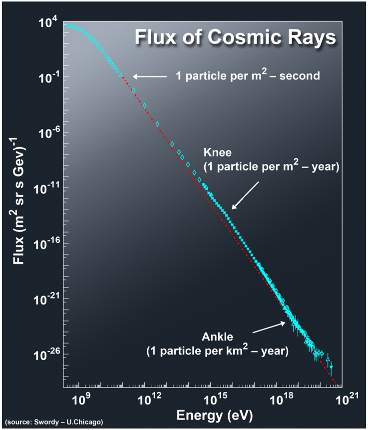




- peak SNe: only warm gas, no outflows
- random SNe: hot gas channels, outflows
- low-density SNe locally reach mass loading factors of 10

CRs in the ISM

- CRs: similar energy densities as turbulence and magn. fields (Ferriere 2001)
- inefficient cooling (comp. to gas)
- different transport properties
- couple to gas via magnetic fields
- Galactic CRs generated in SN remnants (DSA, Axford et al. 1977; Krymskii 1977; Bell 1978; Blandford & Ostriker1978; Malkov & OC Drury 2001, Ackermann et al. 2013)
- efficiency: 10% of thermal SN energy
- advection-diffusion approximation



Combined MHD-CR equations

based on MHD-Solver HLLR3 (Bouchut et al. 2007, 2010, Waagan et al. 2009, 2011)

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

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

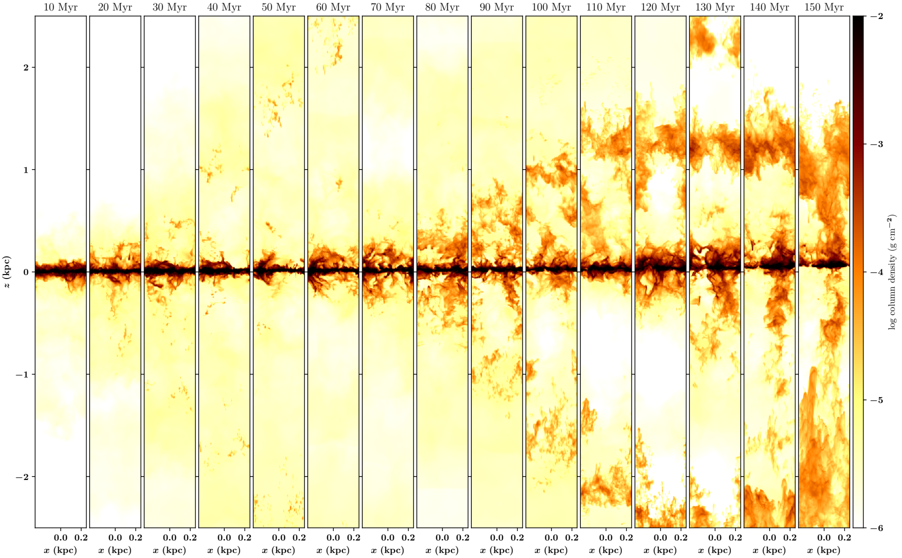
$$\frac{\partial e_{\mathrm{tot}}}{\partial t} + \nabla \cdot \left[(e_{\mathrm{tot}} + p_{\mathrm{tot}})\, \mathbf{v} - \frac{\mathbf{B}(\mathbf{B} \cdot \mathbf{v})}{4\pi} \right] = \rho \mathbf{v} \cdot \mathbf{g} + \nabla \cdot (\mathsf{K} \cdot \nabla e_{\mathrm{cr}})$$

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

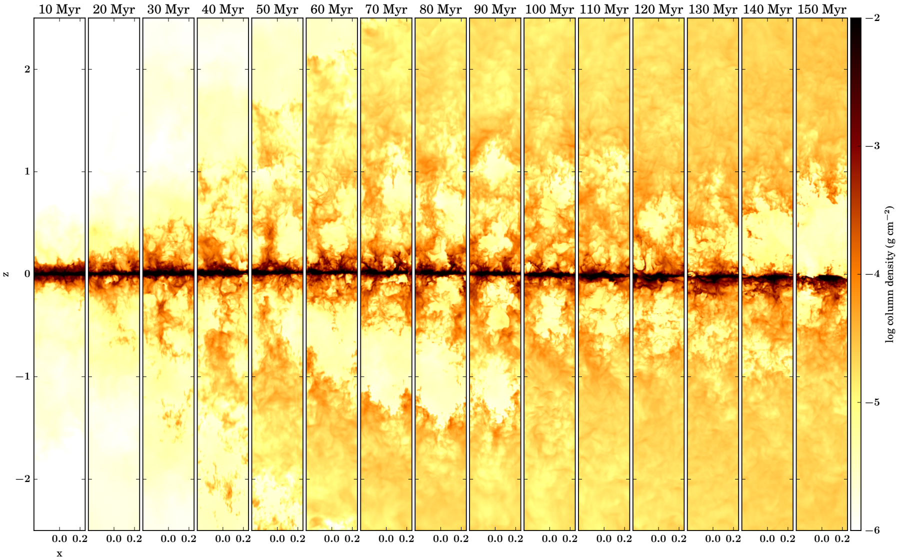
$$\frac{\partial e_{\mathrm{cr}}}{\partial t} + \nabla \cdot (e_{\mathrm{cr}} \mathbf{v}) = -p_{\mathrm{cr}} \nabla \cdot \mathbf{v} + \nabla \cdot (\mathsf{K} \cdot \nabla e_{\mathrm{cr}}) + Q_{\mathrm{cr}}$$

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

Time evolution without CRs (Girichidis+, subm.)

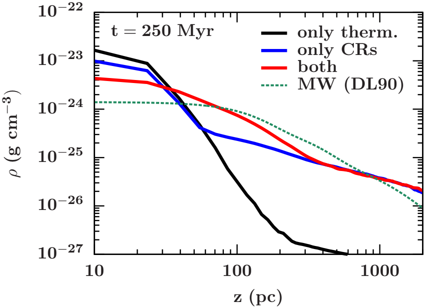


Time evolution including CRs (Girichidis+, subm.)



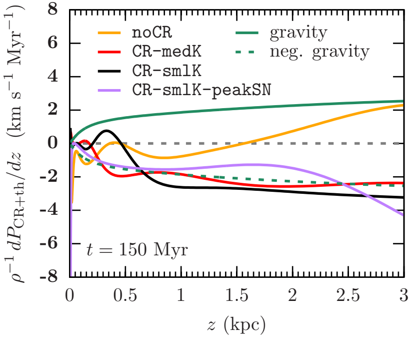
Scale height of the disk

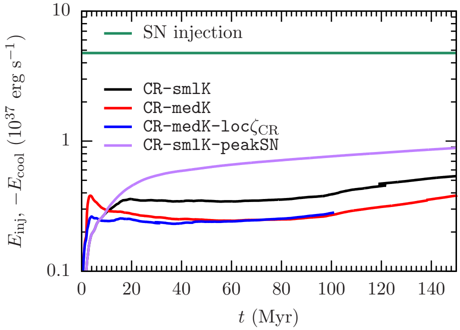
- CRs quickly diffuse throughout the disk
- CRs do not cool as fast as gas
- can build up a long-lived, large-scale pressure gradient along z-direction
- ∇P_{cr} counteracts gravity
- gas is lifted to heights of several 100 pc
- CRs allow for gradual lift, not like a hot SN shock



- gas can reach 50 kpc height (Hanasz et al 2013, Booth et al. 2013, Salem & Bryan 2014, Pakmor et al. 2016)

Force balance and losses

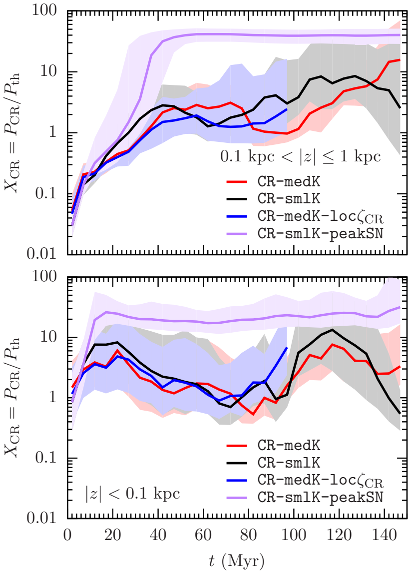


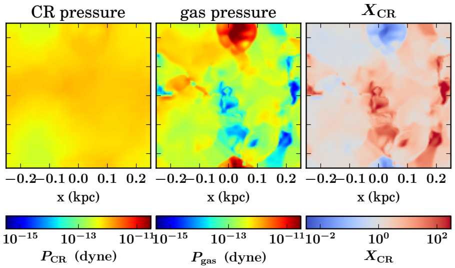


- thermal SNe: locally strong accelerations
- incl. CR: smooth forces
- for slow CR diffusion: net pressure gradient exceeds gravity

- $5 - 25\%$ of CR energy are lost
- higher loss rates for slower diffusion
- even all SNe in density peaks: only 25% losses

pressure ratios

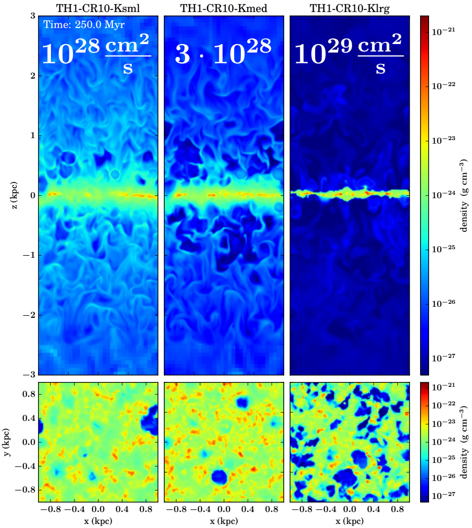




- CR pressure dominates in the disk
- region above the disk: equipartition

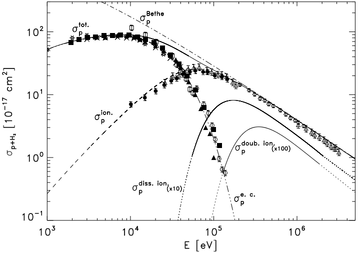
Effect of the diffusion coefficient

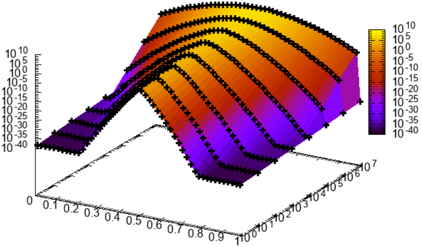
- higher diffusion speeds
- faster removal of CR energy
- shallower CR energy gradients
- less dense atmosphere



- CRs have a large range of energies/momenta
- $p \sim \mathrm{GeV}/c$: peak of total CR energy, direct dynamical impact
- $p < \mathrm{MeV}/c$: important for CR ionisation rate
- adiabatic process changes CR momentum
- increase of CR energy in shocks
- transport properties depend on energy
    - diffusion coefficient $K(E) \sim E^{0.5}$
    - streaming vs. diffusion process
- $\Rightarrow$ spectral distribution!

Padovani et al. 2009





CR equations

- start with Fokker-Planck equation

$$\frac{\partial f}{\partial t} = \underbrace{-\mathbf{u} \cdot \nabla f}_{\text{advection}} + \underbrace{\nabla \left(\kappa \nabla f\right)}_{\text{diffusion}} + \underbrace{\frac{1}{3} \left(\nabla \cdot \mathbf{u}\right) p \frac{\partial f}{\partial p}}_{\text{adiabatic process}} \tag{1}$$

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

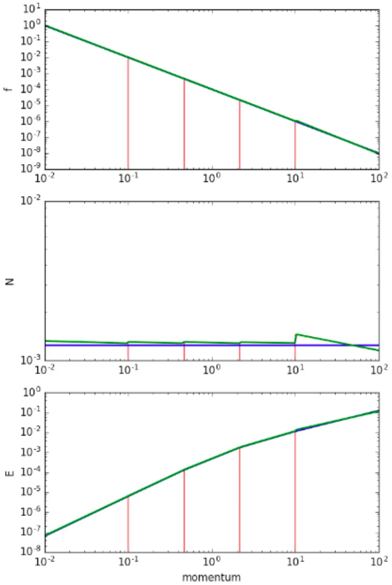
- chose piecewise powerlaws for f

$$f(p) = f_f \left(\frac{p}{p_f} \right)^{q_i}, \tag{3}$$

- derive number density and energy density

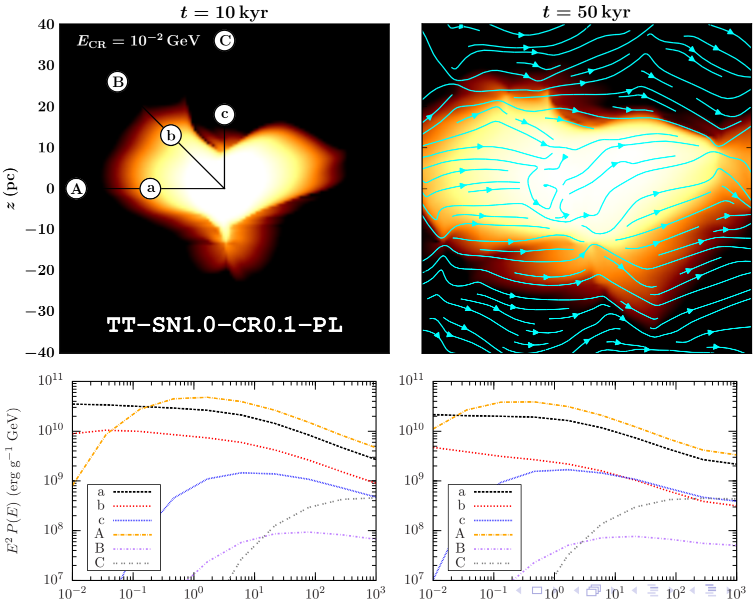
$$n_i = \int 4\pi p^2 f(p)\, dp \qquad e_i = \int 4\pi p^2 f(p) T(p)\, dp \tag{4}$$

Spectral grid



- chose logarithmic bins in p
- compute spectrum in every cell
- We can only afford a few bins (~ 10)
- compute changes of n and e

different spectra at different positions



Conclusions

- SN positioning has big impact on shock efficiency and galactic dynamics
- CRs thicken the disk (influence on GMC formation, SN efficiency)
- CRs alone can drive and sustain outflows (mass loading ~ 1)
- CRs driven outflows are smooth and warm
- We need spectral CR transport