Dynamical and chemical impact of cosmic rays on the ISM

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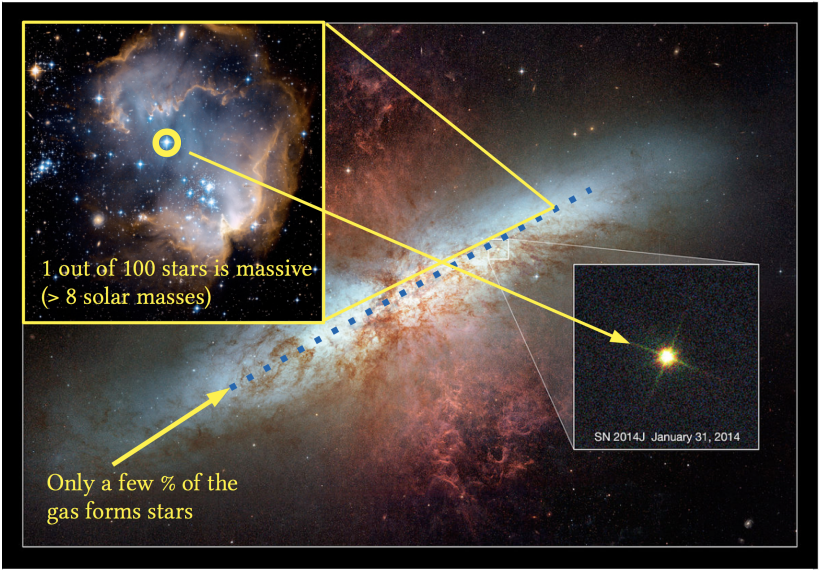
Observations: starburst galaxy M82 (Hubble)



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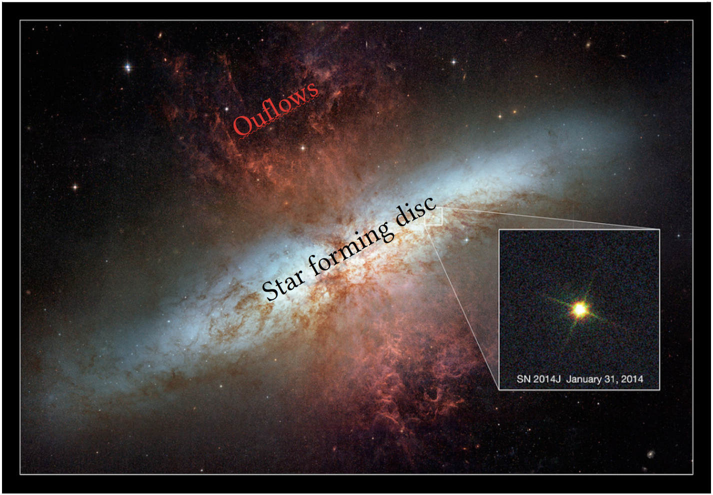


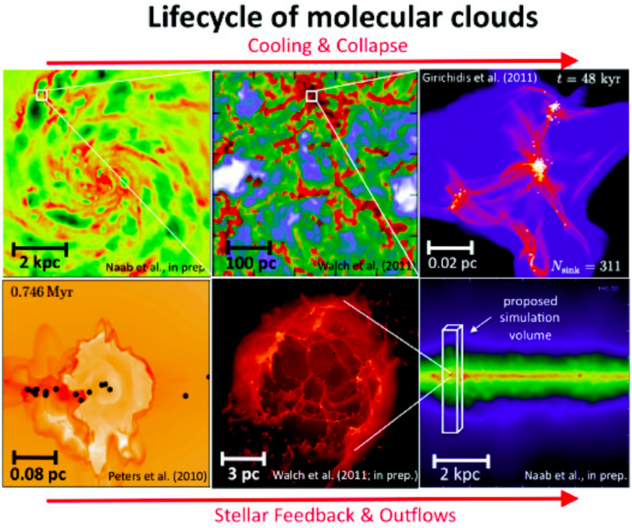
- strong outflows with $\eta = \dot{M}_{\mathrm{outflow}}/\dot{M}_{*}$ of a few
- *big problem in galaxy formation and evolution!*

ISM details on different scales

SILCC: SImulating the LifeCycle of molecular Clouds

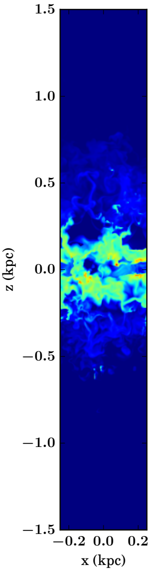
Walch+2015,

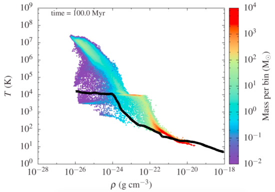
Girichidis+2016b



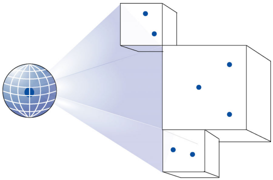
Setup for ISM simulations

- stratified box (deAvillez+2004, 2005, Kim & Ostriker+ 2013 - 2018, Hennebelle & Iffrig 2015)
- external potential (ρ_*)
- **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 + CRs)
- MW conditions: $10\,\frac{M_\odot}{\mathrm{pc}^2}$, $Z_\odot$





(Gatto et al. 2015)

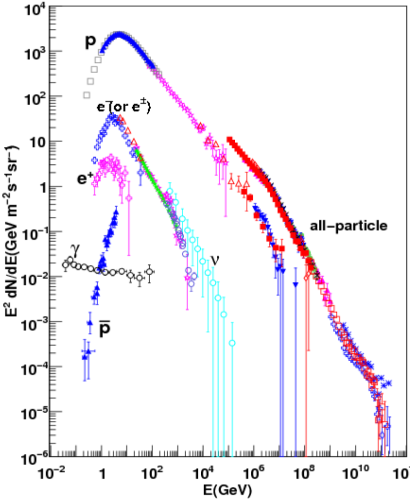


(Clark et al. 2012, Wünsch et al. 2018)

CRs in the ISM

- CRs: similar energy densities as turbulence and magn. fields (Ferriere 2001)
- inefficient cooling (contrast to gas) different transport properties
- couple to gas via magnetic fields
- advection-diffusion approximation
- Galactic CRs generated in SN remnants (DSA, Axford et al. 1977; Krymskii 1977; Bell 1978; Blandford & Ostriker1978; Malkov & OC Drury 2001, Caprioli & Spitkovsky 2014)
- efficiency: 10% of SN energy

CR spectrum (Hu+ 2009)



Combined MHD-CR equations (Girichidis+2016a)

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

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

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

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

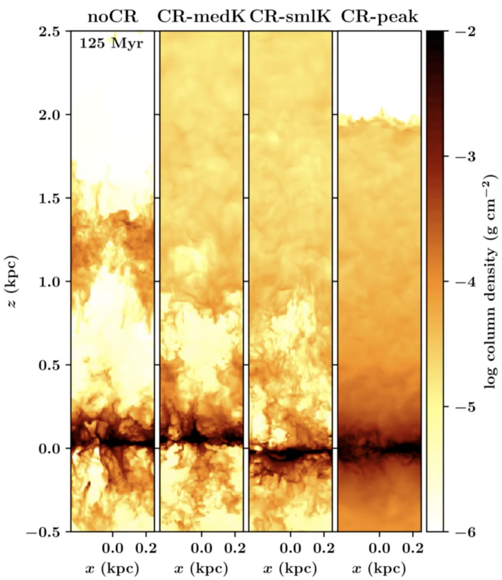
$$\frac{\partial \mathbf{B}}{\partial t} - \nabla \times (\mathbf{v} \times \mathbf{B}) = 0$$

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

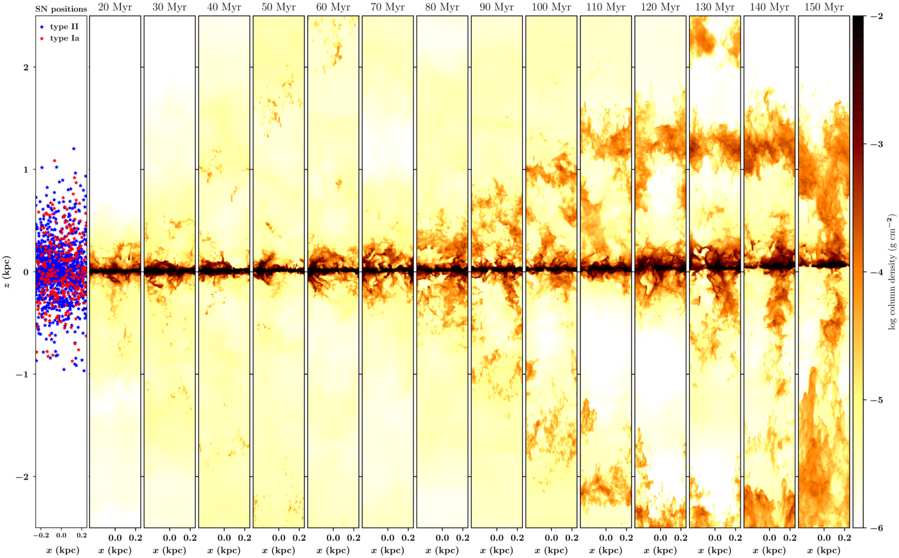
similar to Hanasz & Lesch 2003, Pfrommer et al. 2017

Time evolution with and without CRs

- left: no CRs
- middle: CRs
  - medK: $K_{\parallel} = 3 \times 10^{28}\, \frac{\mathrm{cm}^2}{\mathrm{s}}$
  - smlK: $K_{\parallel} = 1 \times 10^{28}\, \frac{\mathrm{cm}^2}{\mathrm{s}}$
- right: CRs, SNe in peaks
  assume SNe explode where stars formed
- color: column density
- same SN rate



Time evolution without CRs (Girichidis+, subm.)



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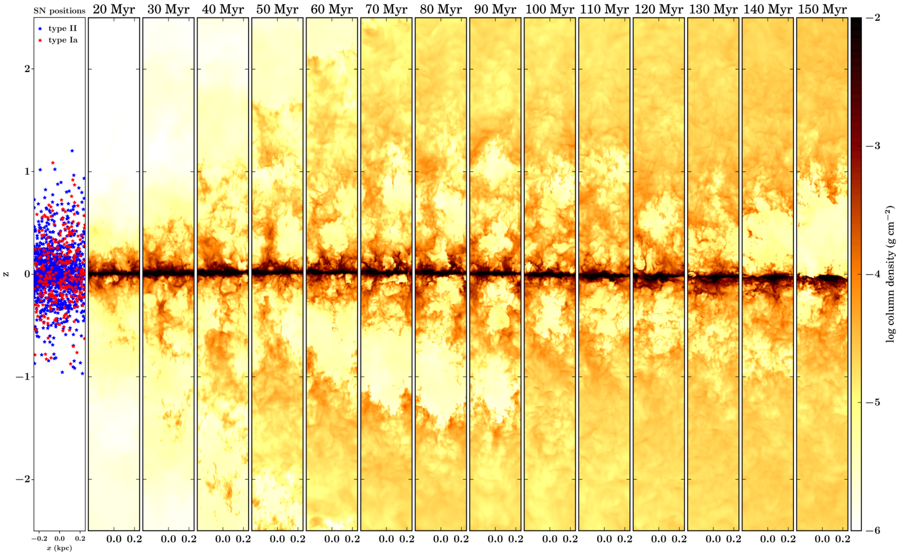
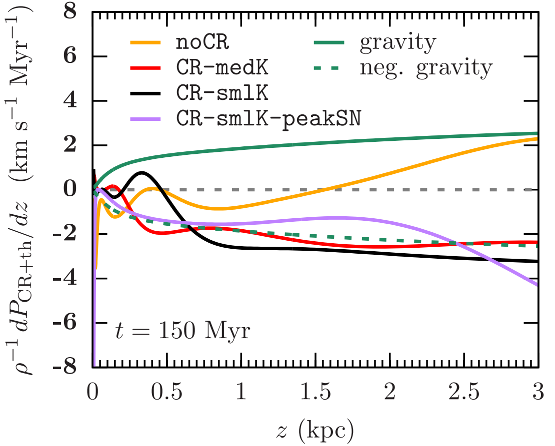
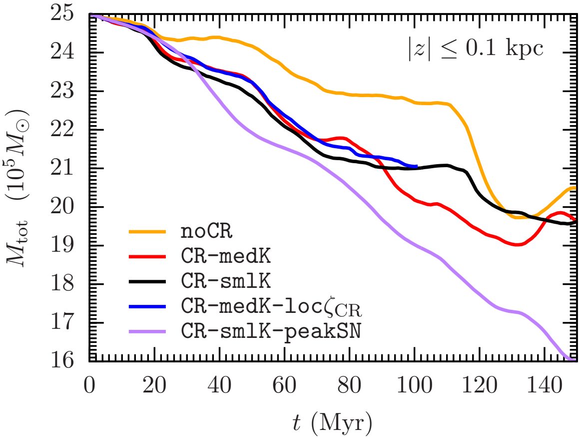


Net force balance



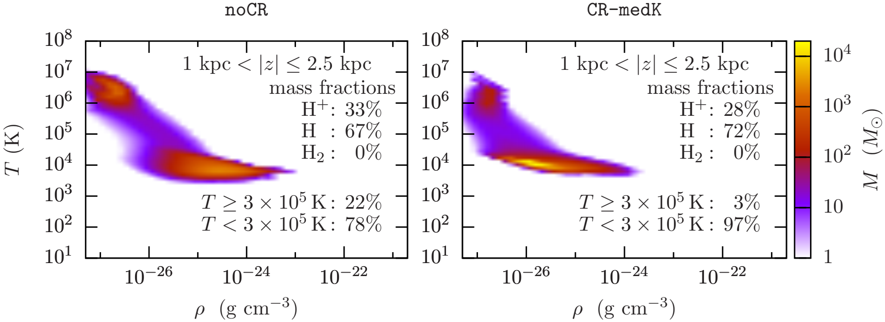
- thermal SNe: locally strong accelerations, temporal fluctuations
- incl. CR: smoother forces, net outward pointing force
- for slow CR diffusion: net pressure gradient exceeds gravity

Outflow rates



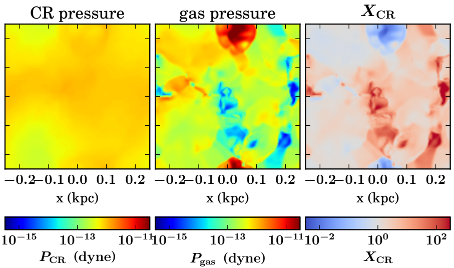
- CRs drive stronger outflows from the disk
- effective mass loading factors maesured at $2.5\,\mathrm{kpc}$
  $\eta_{\mathrm{therm}} \approx 0.1$ (Kim+2018), $\eta_{\mathrm{cr}} \sim 0.7 - 1.4$ (Mao+2018)

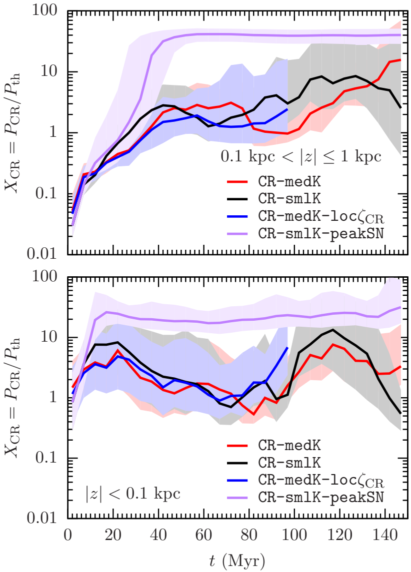
Composition of the outflow



- Thermal run produces more hot gas.
- CR-driven outflows are warm.

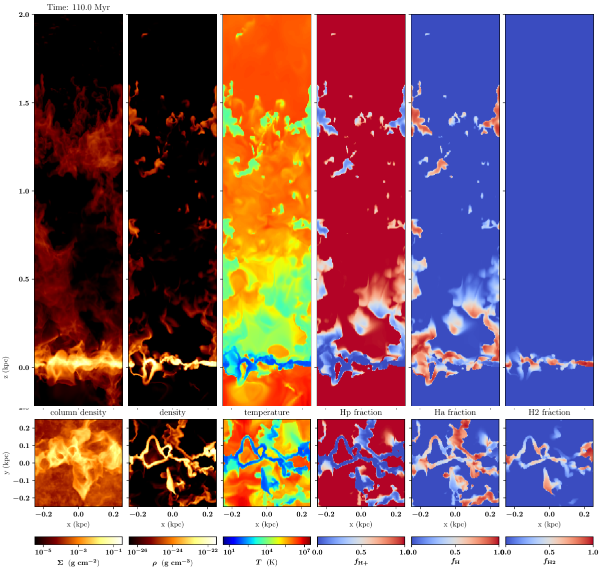
CR pressure and X_{CR}

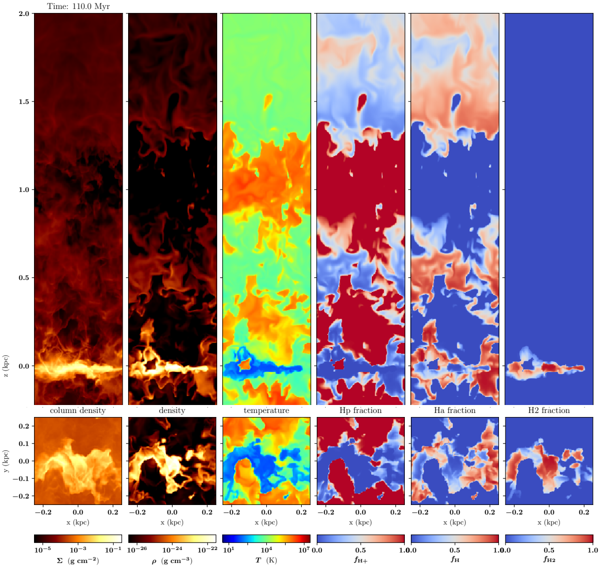




- smooth energy CR distribution
- CR pressure dominates in the disk
- region above the disk: equipartition
- locally varying ζ_{CR} no effect

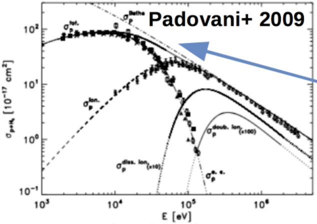
chemical composition without CRs



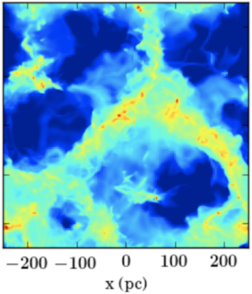

Time: 110.0 Myr
z (kpc)
2.0
1.5
1.0
0.5
0.0
column density
density
temperature
Hp fraction
Ha fraction
H2 fraction
y (kpc)
0.2
0.1
0.0
−0.1
−0.2
x (kpc)
−0.2
0.0
0.2
10^{-5} 10^{-3} 10^{-1}
Σ (g cm^{-2})
10^{-26} 10^{-24} 10^{-22}
ρ (g cm^{-3})
10^{1} 10^{4} 10^{7}
T (K)
0.0 0.5 1.0
f_{H+}
f_{H}
f_{H2}

CR spectrum

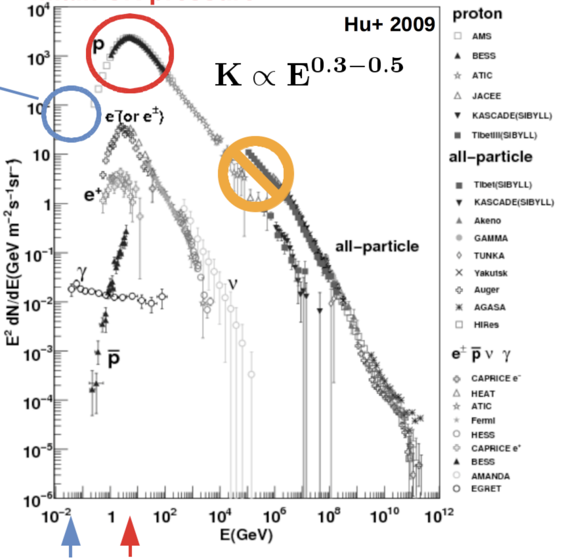
CR-gas interaction



- CR ionisation rate
- CR losses



main CR pressure



CR equations

- start with Fokker-Planck equation

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

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

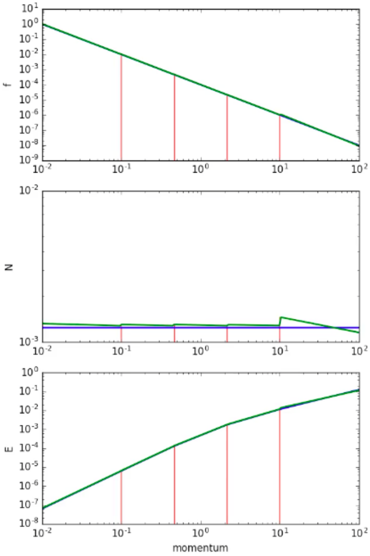
- chose piecewise powerlaws for f

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

- derive number density and energy density

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

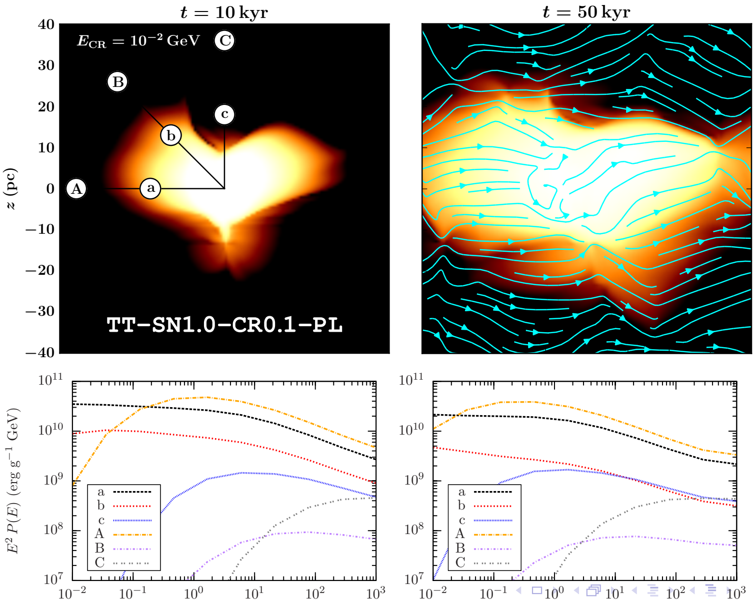
Spectral grid



- chose logarithmic bins in p
- compute spectrum in every cell
- compute changes of n and e
- reconstruct distribution function f, q

- standalone code
  coupled to FLASH and Arepo

different spectra at different positions



Conclusions

1. CRs thicken the disk (influence on GMC formation, SN efficiency)
2. CRs alone can drive and sustain outflows (mass loading ~ 1)
3. CRs create smooth and warm ($T \sim 10^4\,\mathrm{K}$) gas (disc & outflows)
4. We need spectrally resolved CR transport