Cooler and smoother – the impact of cosmic rays on the phase structure of galactic outflows

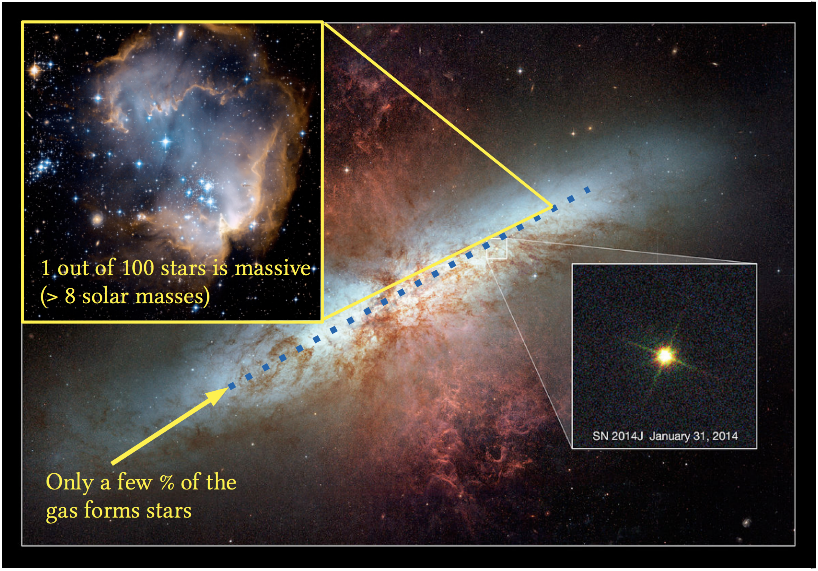
Philipp Girichidis

Georg Winner, Christoph Pfrommer (AIP)
Thorsten Naab (MPA Garching),
Stefanie Walch (University of Cologne)
Michał Hanasz (Copernicus University Torun)

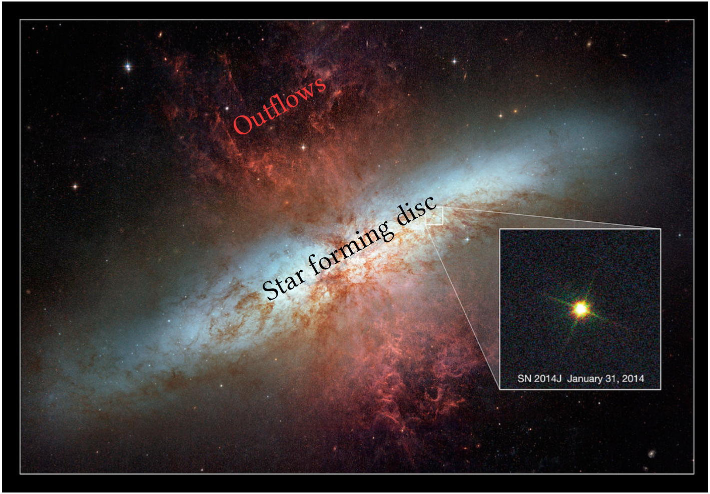
AIP Potsdam

September 5, 2018

Observations: starburst galaxy M82 (Hubble)



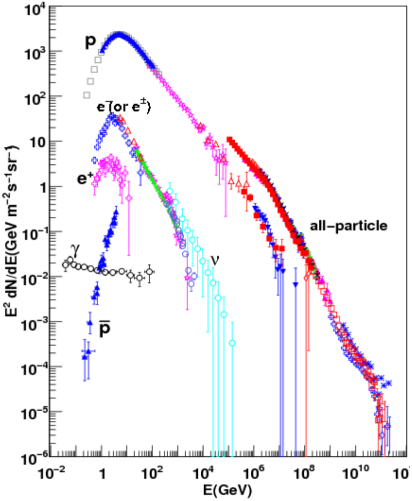
Observations: starburst galaxy M82 (Hubble)



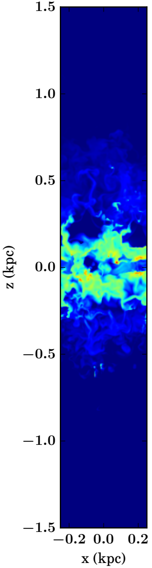
- strong outflows with $\eta = \dot{M}_{\mathrm{outflow}} / \dot{M}_{*}$ of a few
- outflows in all chemical phases (ionized – molecular)

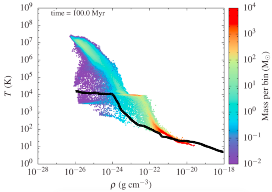
- CRs: $E_{\rm CR} \sim E_{\rm mag} \sim E_{\rm th} \lesssim E_{\rm kin}$ (Ferriere 2001)
- inefficient cooling (contrast to gas) different transport properties
- couple to gas via magnetic fields
- advection-diffusion approximation
- Galactic CRs generated in SN remnants (DSA, Axford et al. 1977; Krymskii 1977; Bell 1978; Blandford & Ostriker1978; Malkov & OC Drury 2001, Caprioli & Spitkovsky 2014)
- efficiency: 10% of SN energy

CR spectrum (Hu+ 2009)

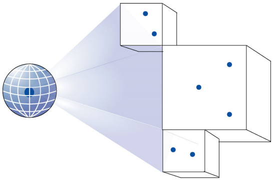


- stratified box (deAvillez+2004, 2005, Kim & Ostriker+ 2013 - 2018, Hennebelle & Iffrig 2015)
- external potential (ρ_*, DM)
- **Magneto**hydrodynamics
- atomic, mol., metal cooling (follow H^+, H, H_2, C^+, CO) (Glover et al. 2012, Walch et al. 2015)
- shielding effects ($A_V > 1$)
- stellar feedback (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)

Combined MHD-CR equations (Girichidis+2016a)

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

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

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

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

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

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

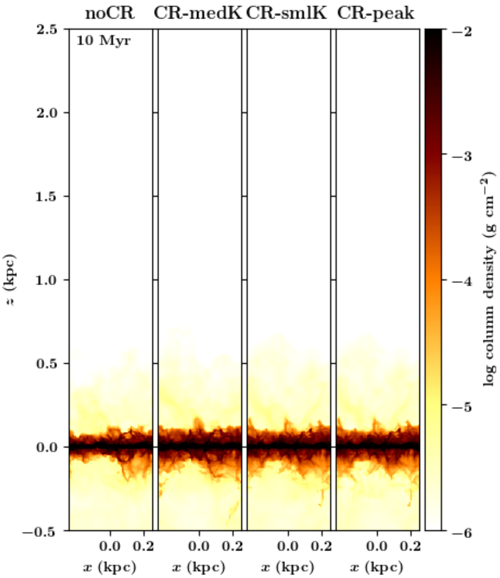
similar to Hanasz & Lesch 2003, Pfrommer et al. 2017

Time evolution with and without CRs (Girichidis+ 2018a)

- same SN rate

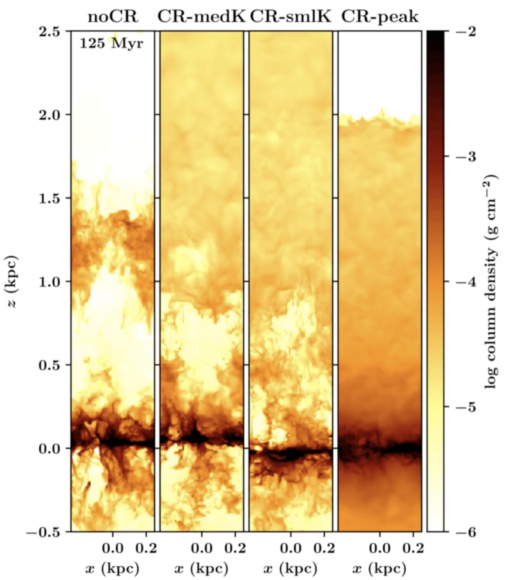
- left: no CRs
- middle: CRs
  – medK: $K_{\parallel} = 3 \times 10^{28}\,\frac{\mathrm{cm}^2}{\mathrm{s}}$
  – smlK: $K_{\parallel} = 1 \times 10^{28}\,\frac{\mathrm{cm}^2}{\mathrm{s}}$
- right: CRs, SNe in peaks
  assume SNe explode where stars formed

- data publicly available:
  girichidis.com
  https://silcc.mpa-garching.mpg.de



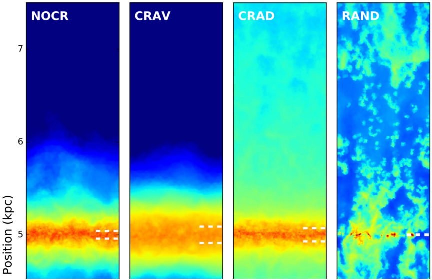
Time evolution with and without CRs (Girichidis+ 2018a)

- same SN rate
- left: no CRs
- middle: CRs
  – medK: $K_{\|} = 3 \times 10^{28}\ \frac{\mathrm{cm}^2}{\mathrm{s}}$
  – smlK: $K_{\|} = 1 \times 10^{28}\ \frac{\mathrm{cm}^2}{\mathrm{s}}$
- right: CRs, SNe in peaks
  assume SNe explode where stars formed
- data publicly available:
  girichidis.com
  https://silcc.mpa-garching.mpg.de

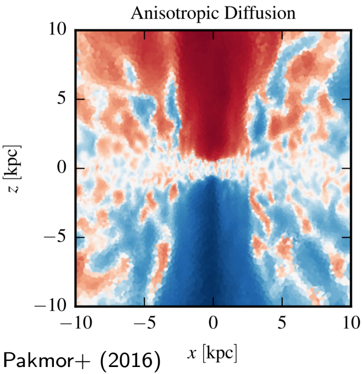


Other studies

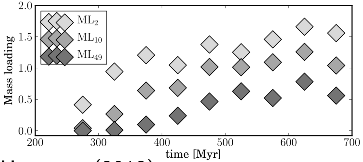
- ISM: Hanasz+ (2009), Simpson+ (2016), Ruszkowsky+ (2017), Farber+ (2018)
- Galaxy (isotropic diff.): Booth+ (2013), Salem+ (2014), Pakmor+ (2016), Jacob+ (2018)
- Galaxy (anisotropic diff.): Yang+ (2012), Hanasz+ (2013), Pakmor+ (2016), Pfrommer+ (2017)



Simpson+ (2016)

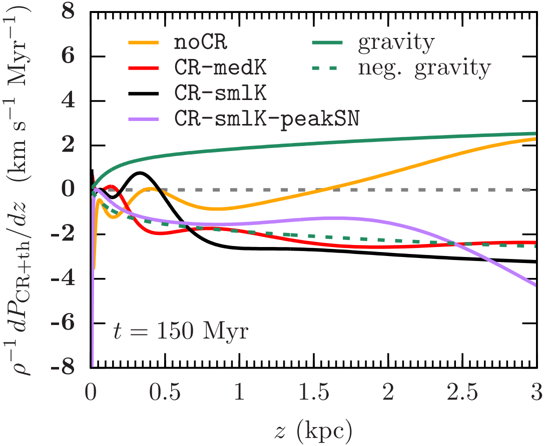


Pakmor+ (2016)



Hanasz+ (2013)

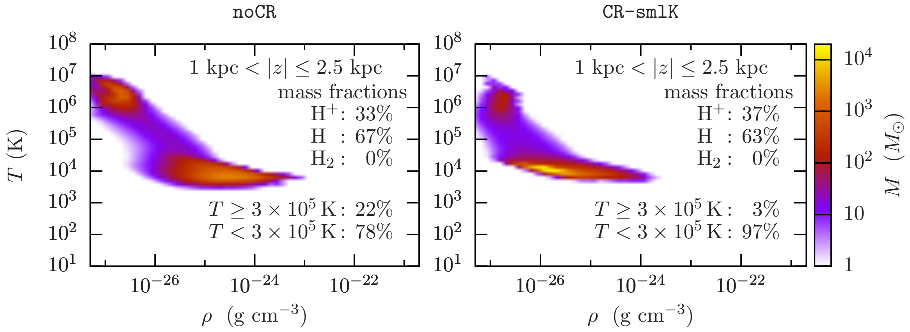
Net force balance



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

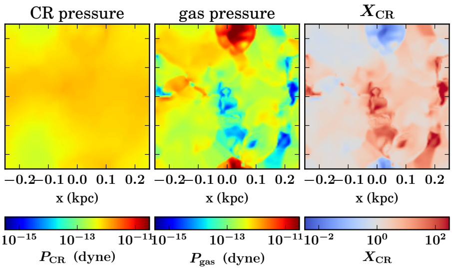
Outflow strength and composition

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

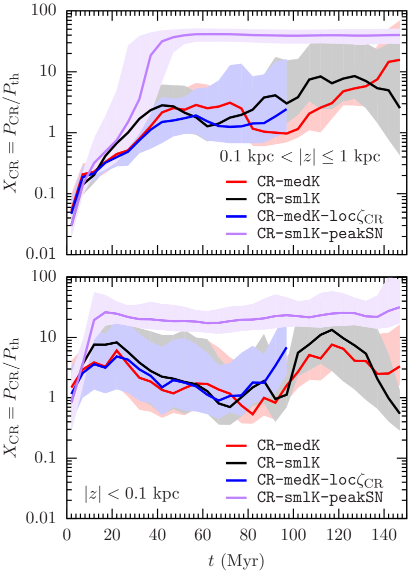


- Thermal run produces more hot gas.
- CR-driven outflows have same ionisation degree.

CR pressure and $X_{\rm CR}$

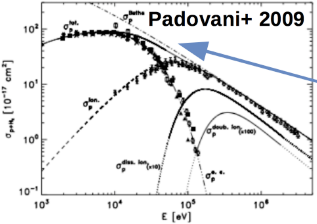


- smooth energy CR distribution
- CR pressure dominates in the disk
- region above the disk: equipartition
- locally varying $\zeta_{\rm CR}$ no effect

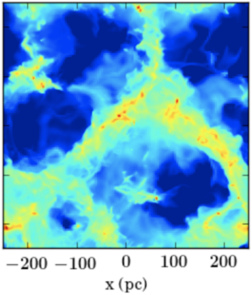


CR spectrum

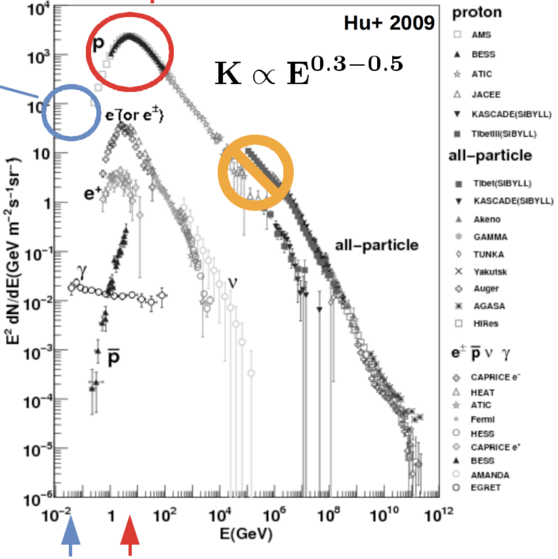
CR-gas interaction



- 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

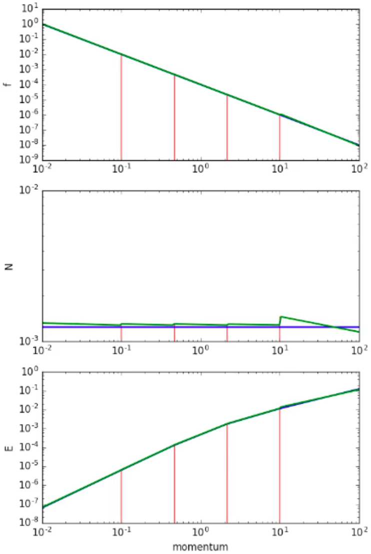
$$f(p) = f_{\mathrm{f}}\left(\frac{p}{p_{\mathrm{f}}}\right)^{q_i},$$

- derive number density and energy density

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

- see also Miniati 2001, Yang+ 2017

Spectral grid

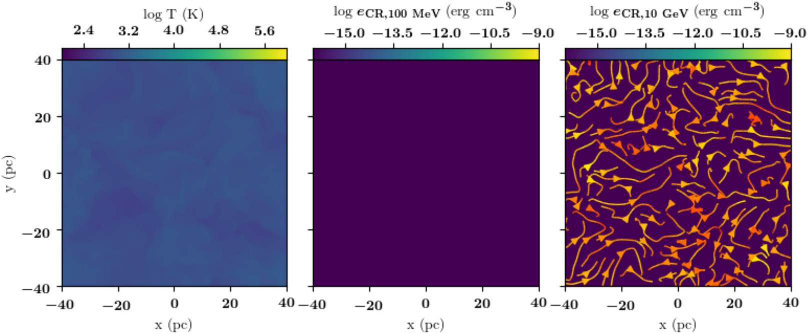


- chose logarithmic bins in p
- compute spectrum in every cell
- compute changes of n and e
- reconstruct distribution function f, q

- standalone code
  coupled to FLASH (Fryxell+2000) and
  Arepo (Springel 2010)

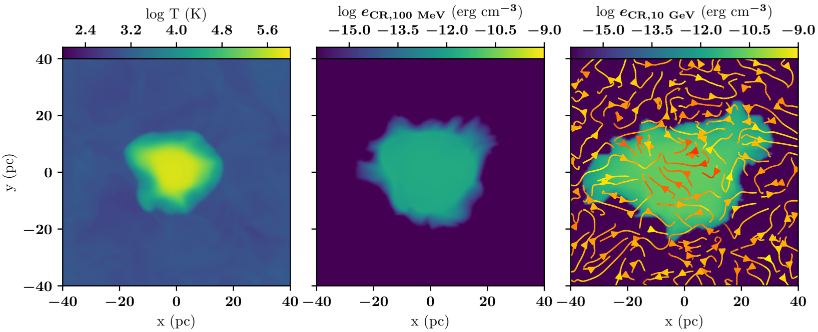
SN with the full spectral code

- turbulent box with tangled magnetic field
- explode SN in the centre of the box



SN with the full spectral code

- turbulent box with tangled magnetic field
- explode SN in the centre of the box



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 ($T \sim 10^4\,\mathrm{K}$) outflows
4. Spectrally resolved CR: more physics and better comparison to observations

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