Dynamical impact of CRs in the ISM and the launching of outflows

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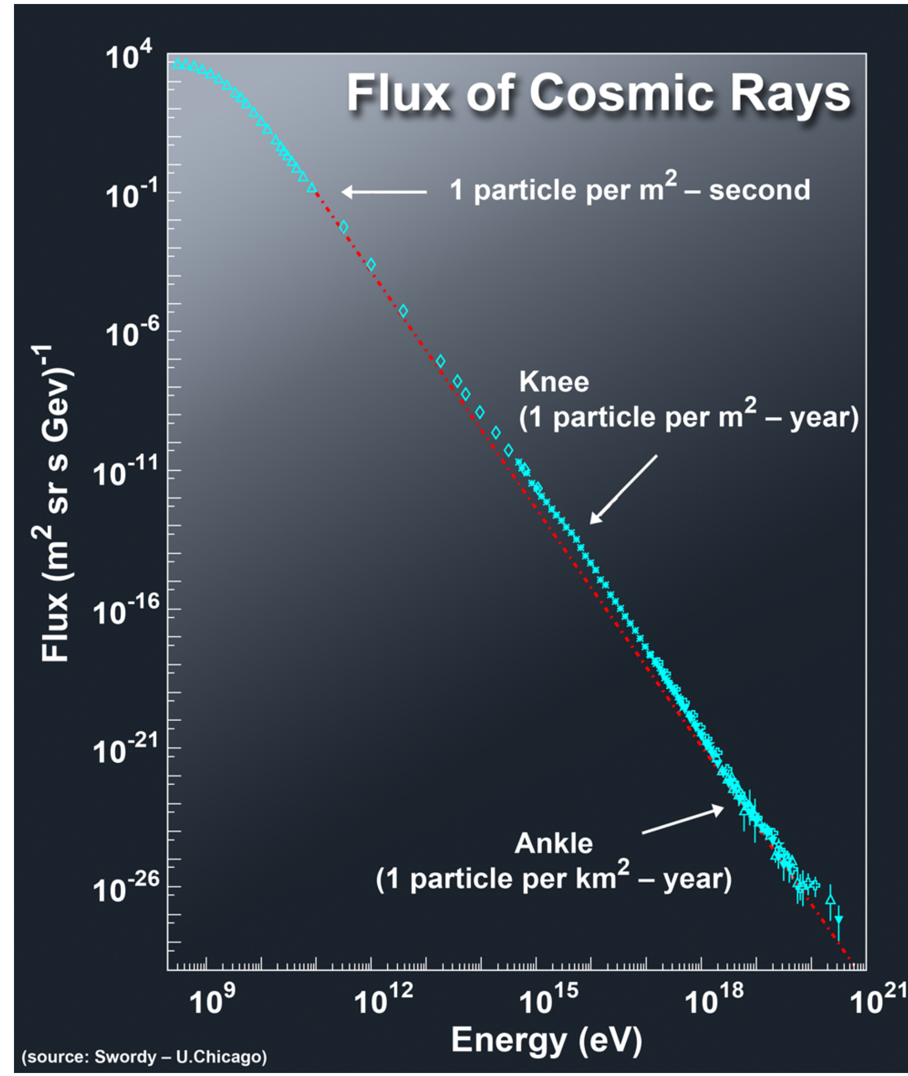
CRs in the ISM

- CRs: similar energy densities as turbulence and magnetic fields (Ferriere 2001)
- Very inefficient cooling (compared to gas) and different transport properties
- CRs couple to gas via magnetic fields, no direct pp collisions
- Galactic CRs generated mostly in SN remnants (DSA, Axford et al. 1977; Krymskii 1977; Bell 1978; Blandford & Ostriker1978; Malkov & OC Drury 2001, Ackermann et al. 2013)
- Efficiency: 0.01-0.3 of thermal SN energy
- CRs are effectively a second relativistic fluid
- Advection-diffusion approximation (anisotropic: $K_{\|}=10^{28}$-10^{29} cm^2/s)



MHD-CR equations

Similar to Hanasz & Lesch 2003, based on HLLR3 (Bouchut 2007, 2010, Waagan 2009)

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

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

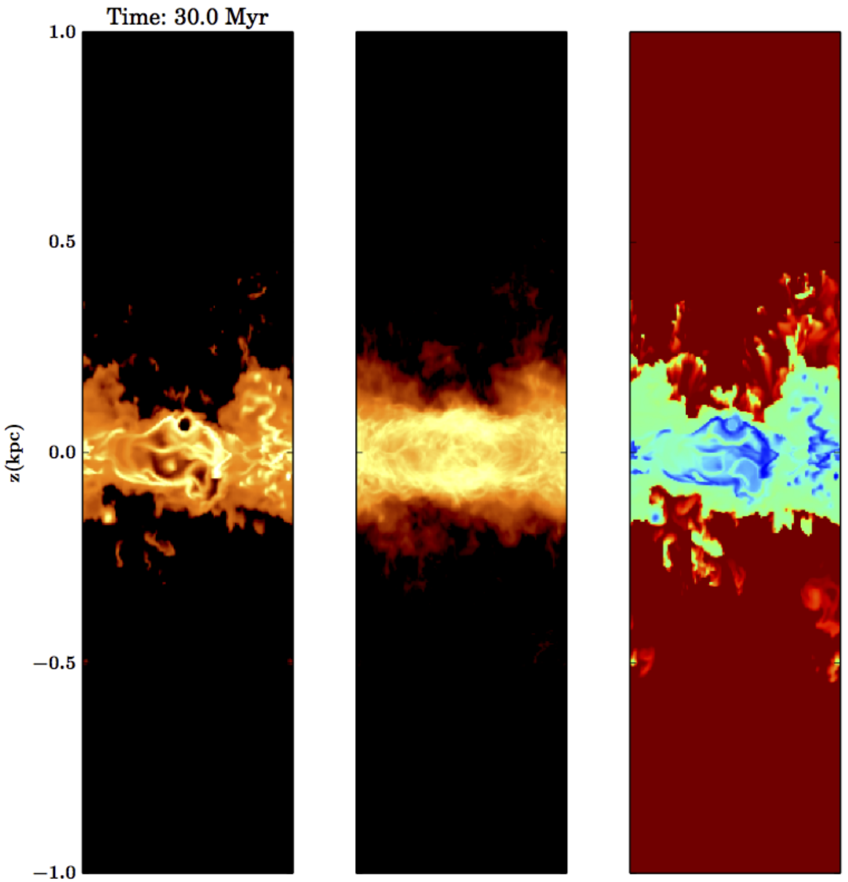
$$\frac{\partial e_{\mathrm{tot}}}{\partial t} + \nabla \cdot \left[(e_{\mathrm{tot}} + p_{\mathrm{tot}})\, \mathbf{v} - \frac{\mathbf{B}(\mathbf{B} \cdot \mathbf{v})}{4\pi} \right] = \rho \mathbf{v} \cdot \mathbf{g} + \nabla \cdot (\mathsf{K} \cdot \nabla e_{\mathrm{cr}})$$

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

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

Simulations of stratified discs with SNe

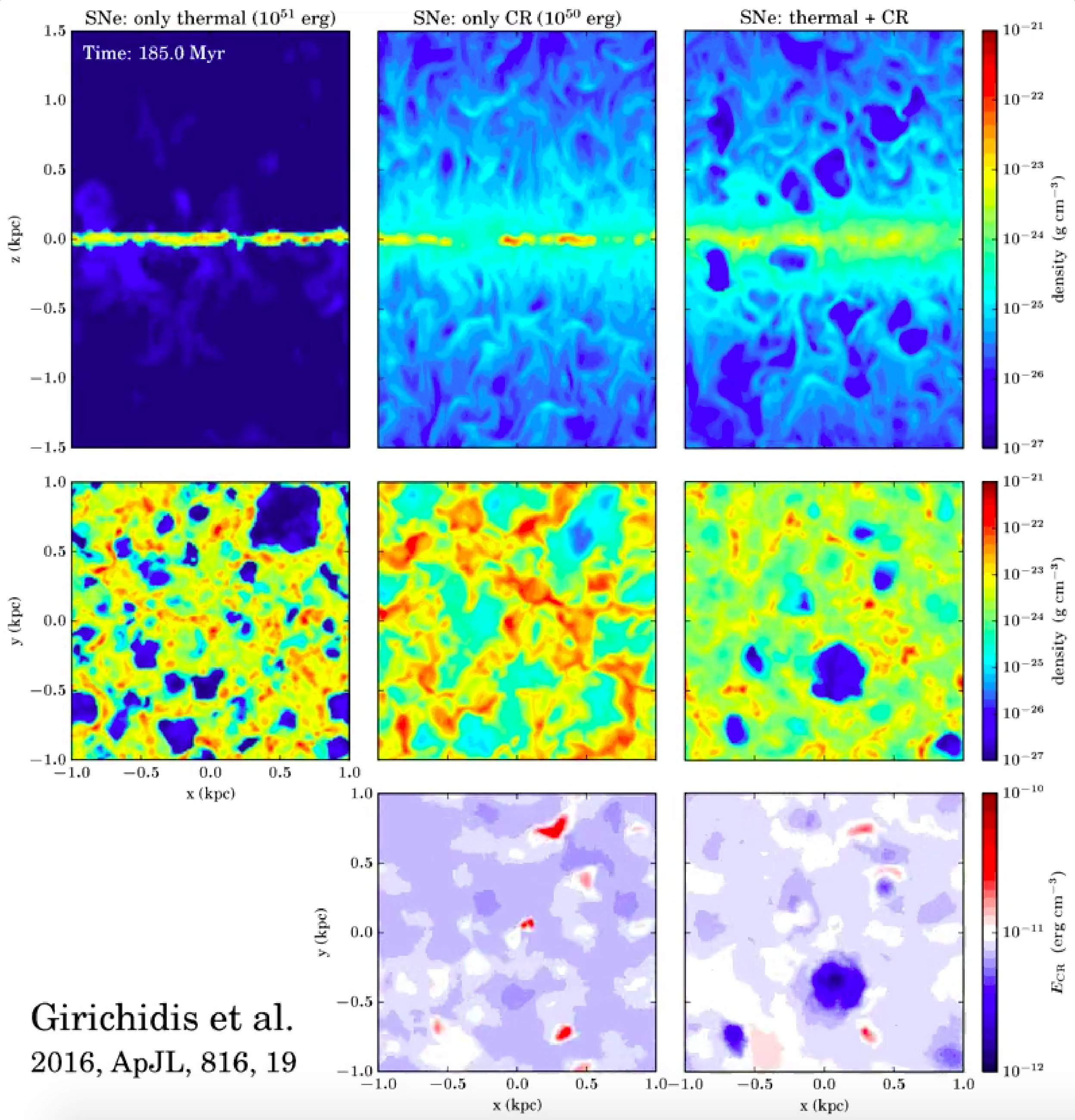
- Stratified disc 2x2x40kpc
- Include SNe at fixed rate (momentum and thermal energy), Gatto+2014
- Include chemical evolution (H+, H, H2, CO, C+) Glover+2012, Walch+2015
- Include shielding of the gas (attenuation of ISRF), TreeCol (Clark+2012, Wünsch+ in prep.)
- Milky Way conditions (10 Msol/pc^2, solar Z)



https://hera.ph1.uni-koeln.de/~silcc/
https://silcc.mpa-garching.mpg.de

Walch+ 2015 (MNRAS 454, 238)
Girichidis+ 2016 (MNRAS 456, 3432)

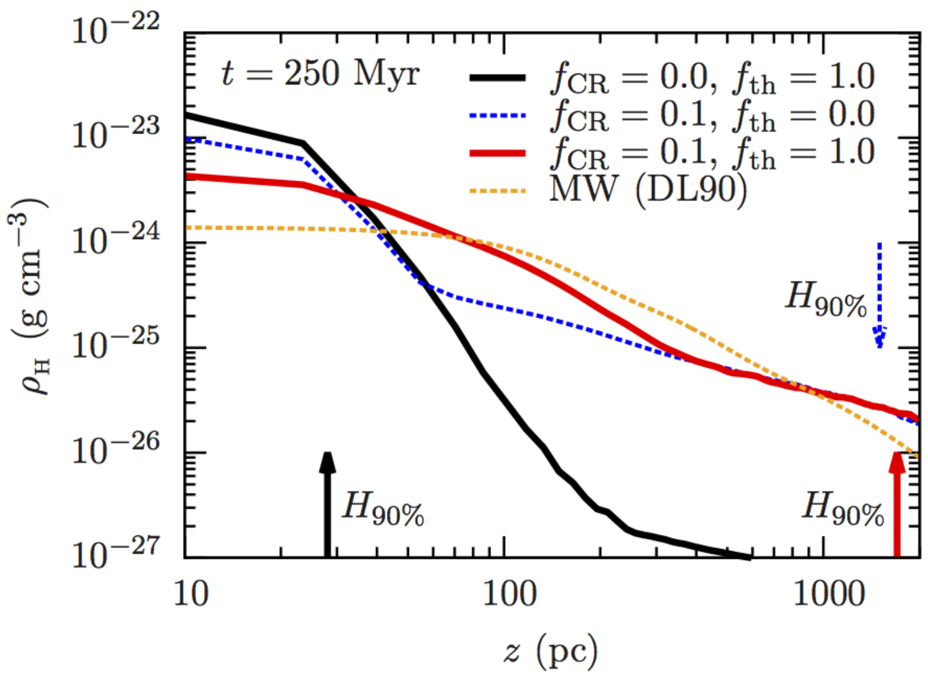
ISM simulations including CRs



Scale heights of the disc

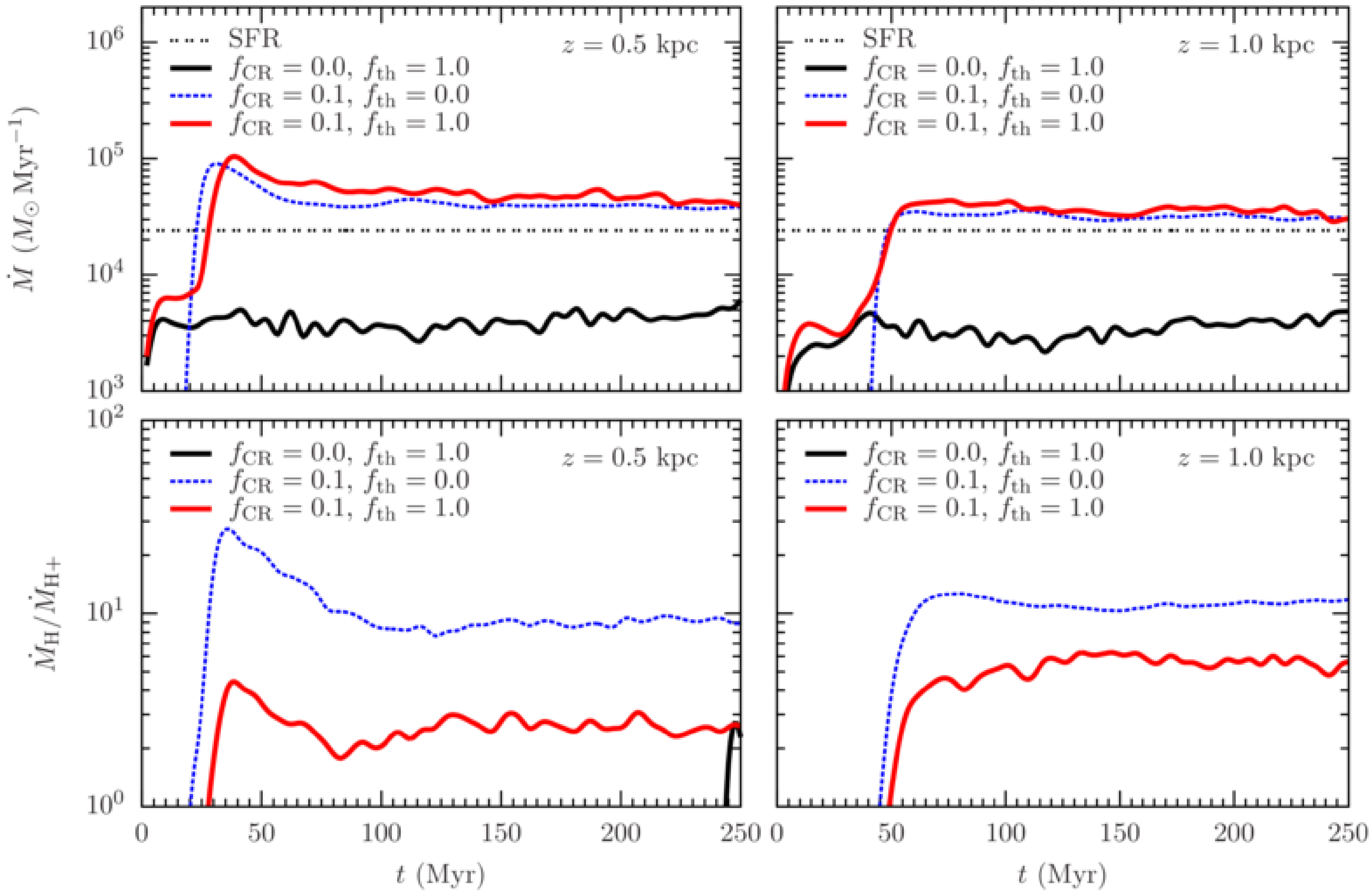
- CRs quickly diffuse throughout the disk
- CRs do not cool efficiently
- Can build up a long-lived, large-scale pressure gradient
- Gas is lifted to heights of several hundred pc
- Thicker disc with CRs
- CRs allow for gradual lift, not like a hot SN shock

- Magnetic fields are not enough (Hill et al. 2012)



- Gas can reach 50 kpc height (Hanasz et al 2013, Booth et al. 2013, Salem & Bryan 2014, Pakmor et al. 1016)

CR-driven outflows



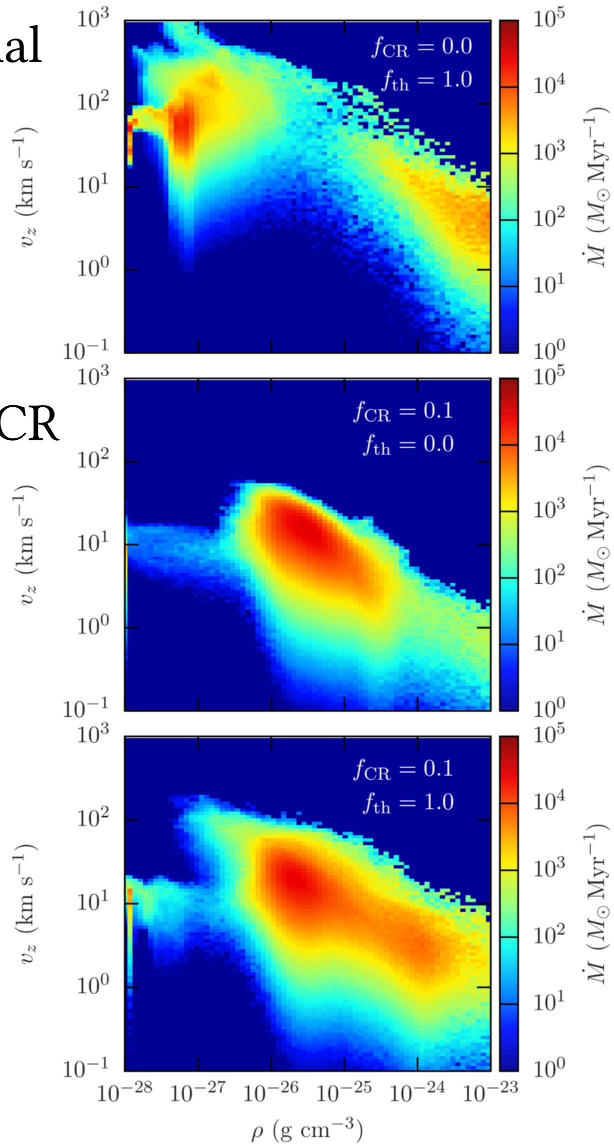
- CRs create dense atmosphere
- CRs drive vertical motions with mass loading of order unity

Velocity and Density of the outflow

thermal

Only CR

both



- Thermal SNe: fast expanding shells, fast outflows at low-density
- Type Ia SNe in high altitudes are not shielded and can ionize the outflows

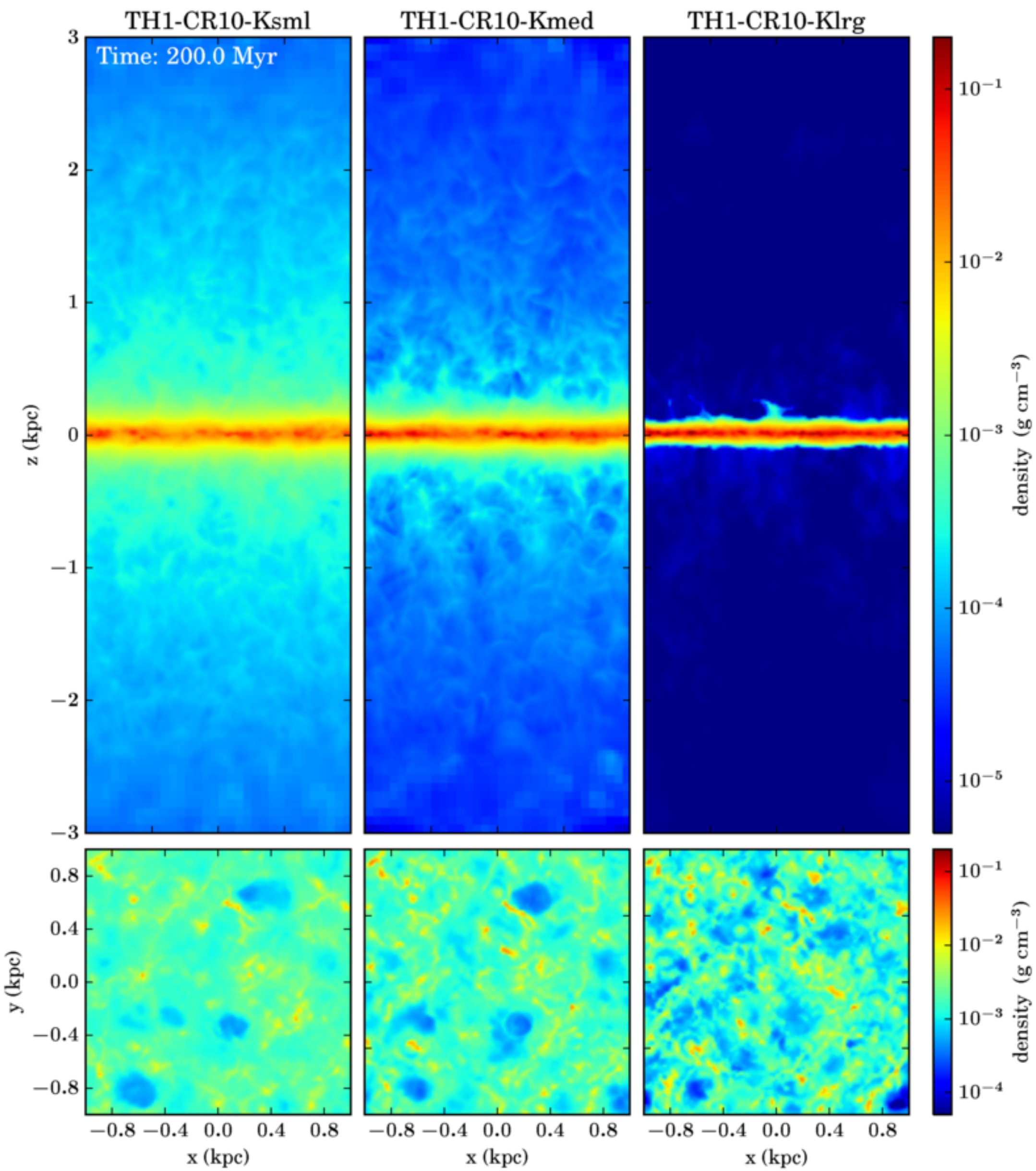
- Only CRs: Slow, smooth, dense outflow
- Only atomic gas in outflow

- Significant fraction of atomic hydrogen
- SNe embedded in this thicker layer of dense gas are less efficient in ionizing the gas

Effect of the diffusion coefficient

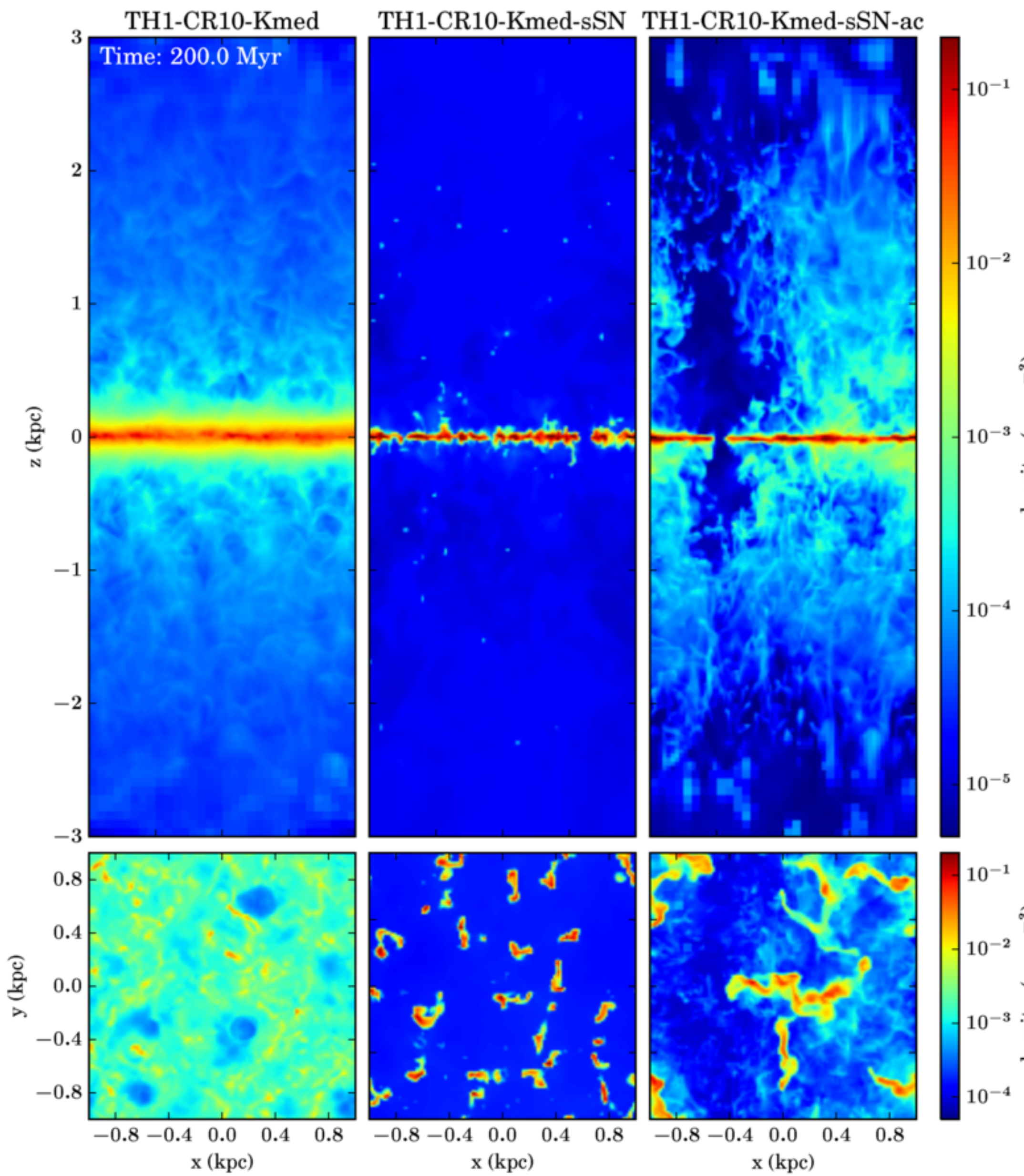
- Higher diffusion speeds
- Faster removal of CR energy
- Shallower CR energy gradients
- Less dense atmosphere
- But slightly faster outflow

  (Dorfi & Breitschwerdt 2012)
- Large differences between isotropic vs. anisotropic (Pakmor et al. 2016)



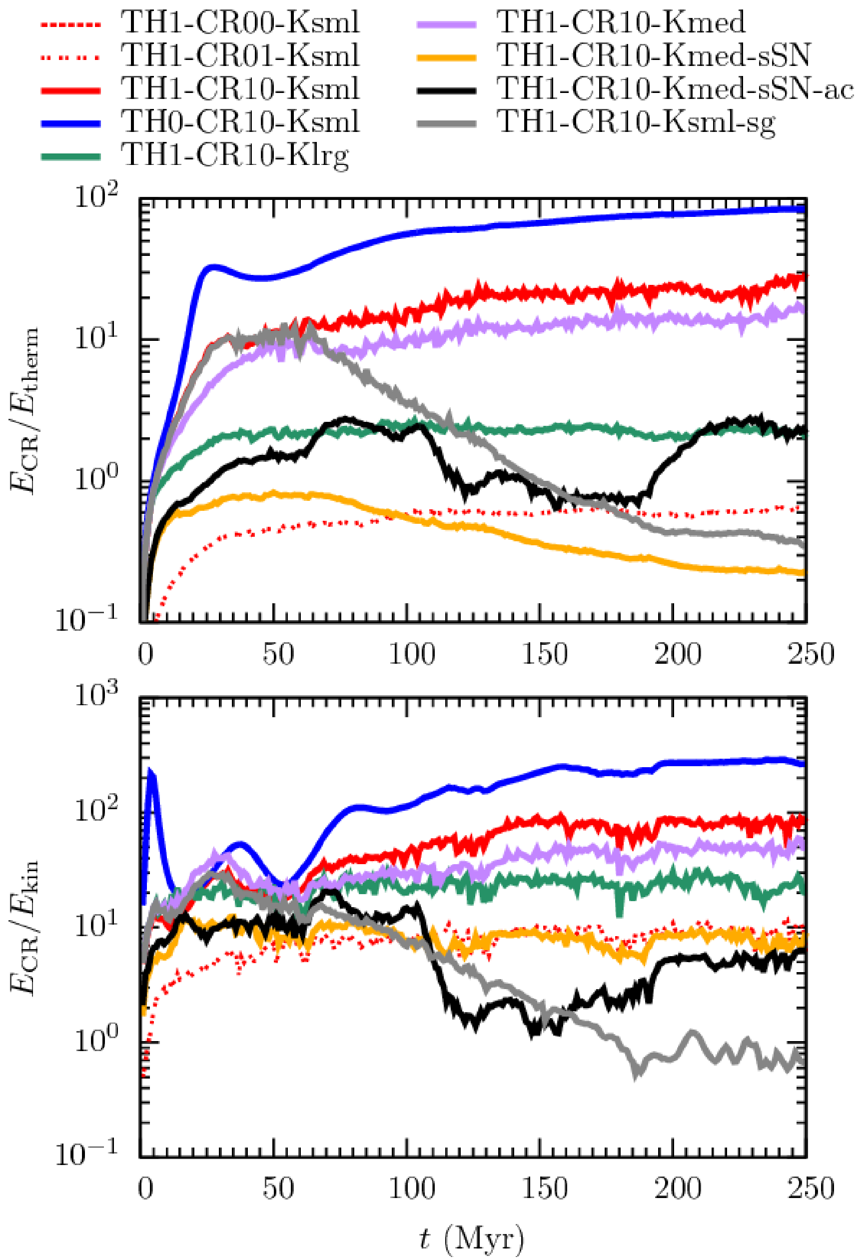
Effect of SN positioning

- Details of SN positions are important (Hill et al. 2012, Walch et al. 2015, Girichidis et al. 2016, Kim & Ostriker 2015, 2016)
- SNe in density peaks are very inefficient, even with resolved Sedov phase!
- SNe are clustered
- 20% of the SNe as type Ia with larger scale height
- Use active clusters (clusters of SNe placed in dense peaks)



Energy ratios in the ISM (<0.5 kpc)

- Small diffusion coefficients (10^{28} cm^2/s) result in high CR energy density
- Fiducial diffusion ($3\text{x}10^{28}$ cm^2/s) + clustered SNe + some runaway SNe + type Ia SNe + resolved Sedov phase = equipartion
- Degeneracy: diffusion speed vs. CR injection efficiency



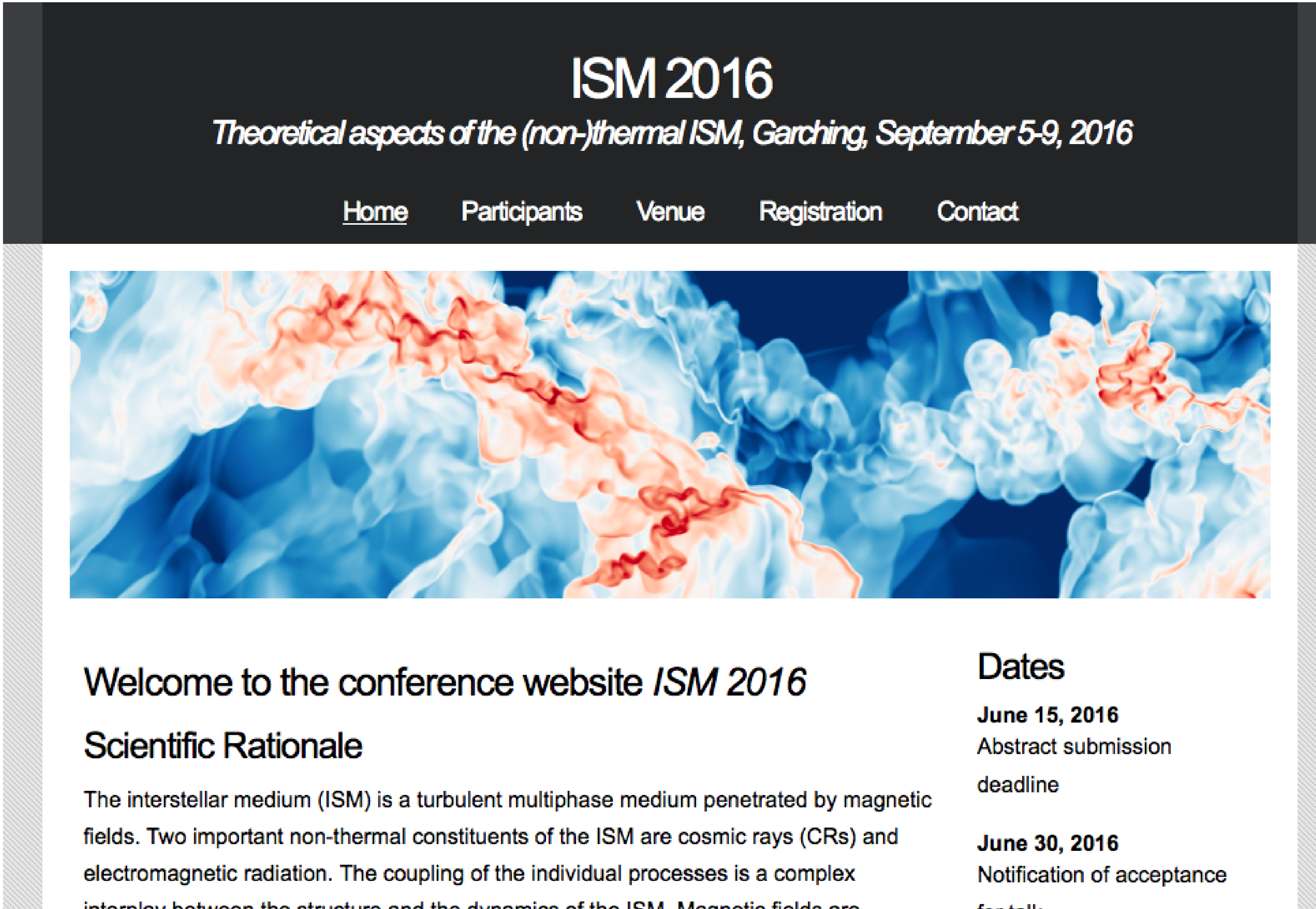
Summary

- CRs thicken the disc and are likely to influence GMC formation
- CRs alone can drive and sustain outflows (mass loading ~ 1)
- CRs delay the formation of structures and dense gas

CRs seem to be dynamically important (1-10^3 pc)

- Tricky degeneracies (f_{CR}, K tensor, **B** structure)

Non-thermal ISM (girichidis.de/ism2016)



ISM 2016

Theoretical aspects of the (non-)thermal ISM, Garching, September 5-9, 2016

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Scientific Rationale

The interstellar medium (ISM) is a turbulent multiphase medium penetrated by magnetic fields. Two important non-thermal constituents of the ISM are cosmic rays (CRs) and electromagnetic radiation. The coupling of the individual processes is a complex interplay between the structure and the dynamics of the ISM. Magnetic fields are

Dates

June 15, 2016
Abstract submission deadline

June 30, 2016
Notification of acceptance for talk