Spectrally resolved cosmic rays in galaxy simulations

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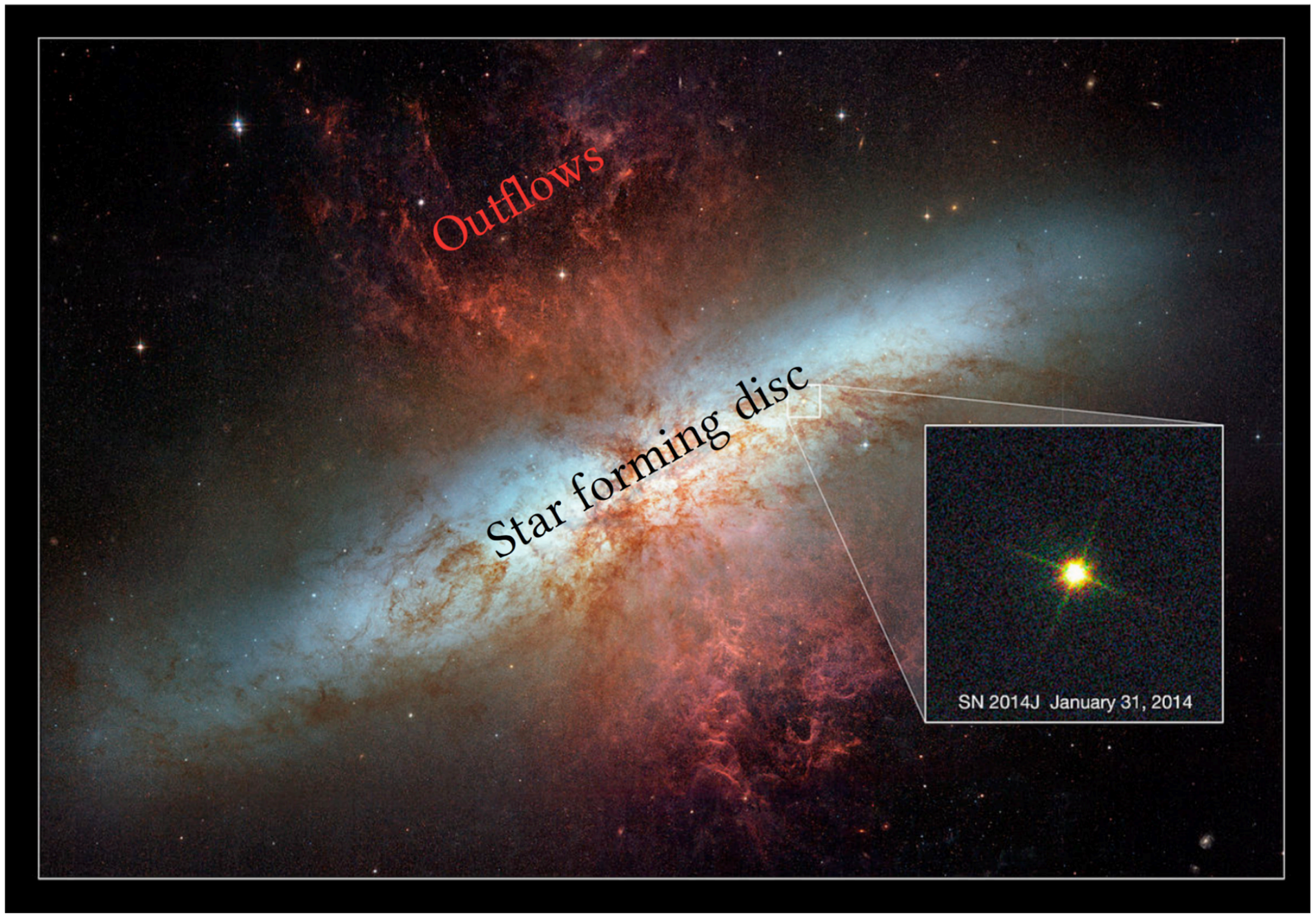
Strong outflows



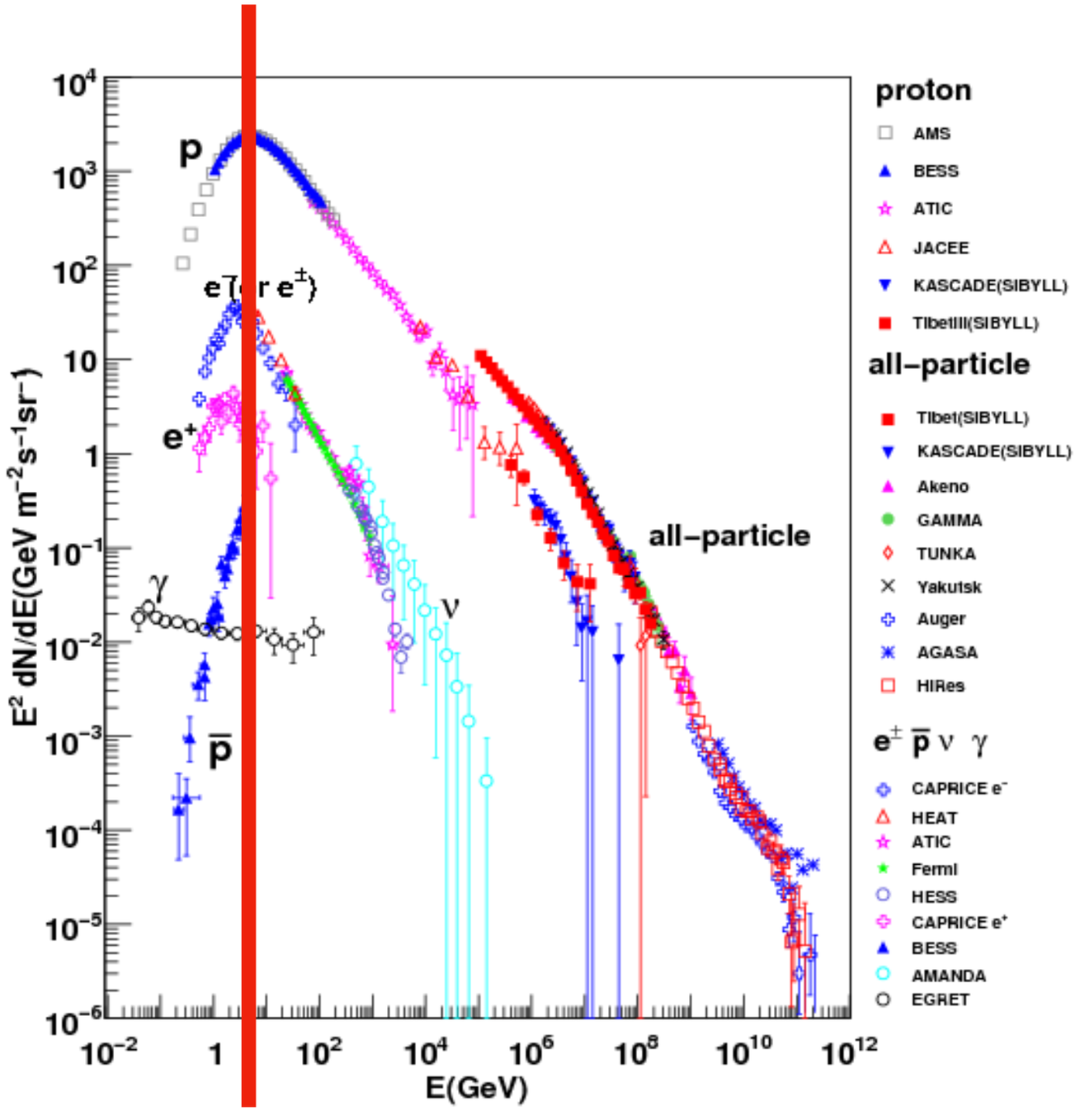
- strong outflows in all chemical phases (H^+, H, H_2)
- CRs are likely to play a non-negligible role

CR spectrum, grey approx.

- total energy

$$e = \int_0^\infty 4\pi p^2 T(p) f(p) dp$$

- dominated by GeV protons
- effective cooling (assuming steady state)
- effective diffusive transport (at mean energy):
  $D_{xx} \sim 10^{28}\,\mathrm{cm}^2\,\mathrm{s}^{-1}$
- $P_{\mathrm{CR}} = (\gamma_{\mathrm{CR}} - 1) e_{\mathrm{CR}}$
- $\gamma_{\mathrm{CR}} = 4/3$



Combined MHD-CR equ.

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

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

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

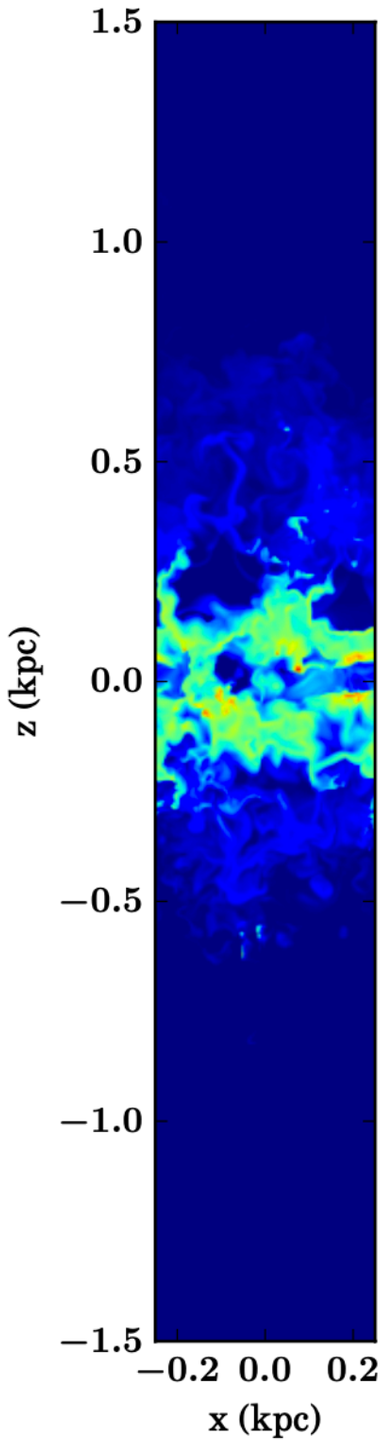
$$\frac{\partial \mathbf{B}}{\partial t} - \nabla \times (\mathbf{v} \times \mathbf{B}) = 0$$

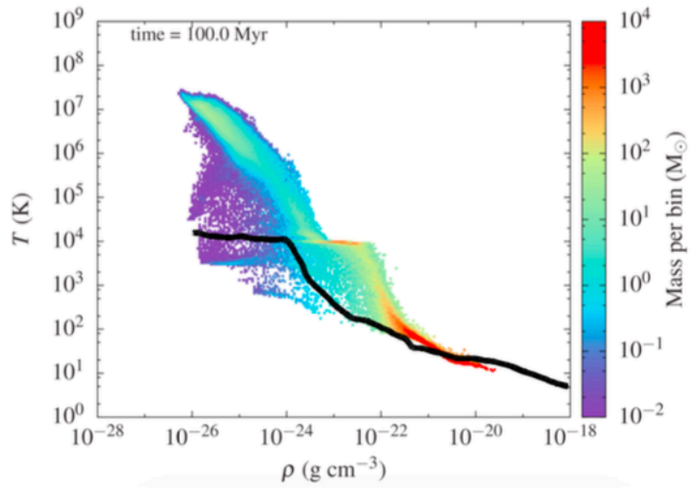
$$\frac{\partial e_{\rm cr}}{\partial t} + \nabla \cdot (e_{\rm cr} \mathbf{v}) = -p_{\rm cr} \nabla \cdot \mathbf{v} + \nabla \cdot (\mathsf{K} \cdot \nabla e_{\rm cr}) + Q_{\rm cr}$$

Hanasz & Lesch 2003, Girichidis et al. 2016, Pfrommer et al. 2017
recent review on num. methods: Hanasz, Strong, Girichidis arxiv:2106.08426

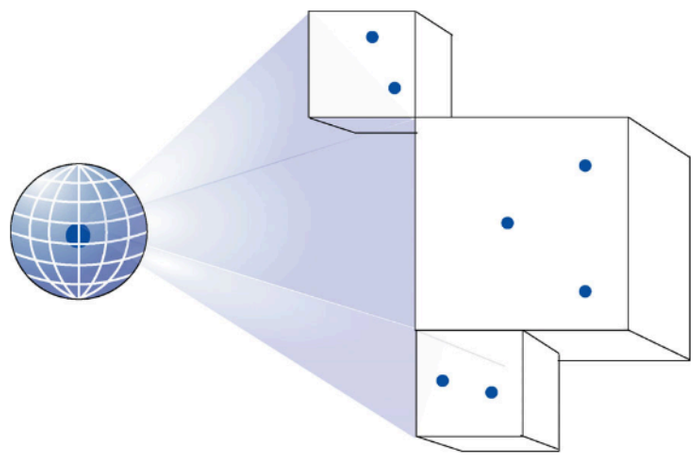
ISM simulations

- 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: $10\,\frac{M_\odot}{pc^2}$, $Z_\odot$





(Gatto et al. 2015)

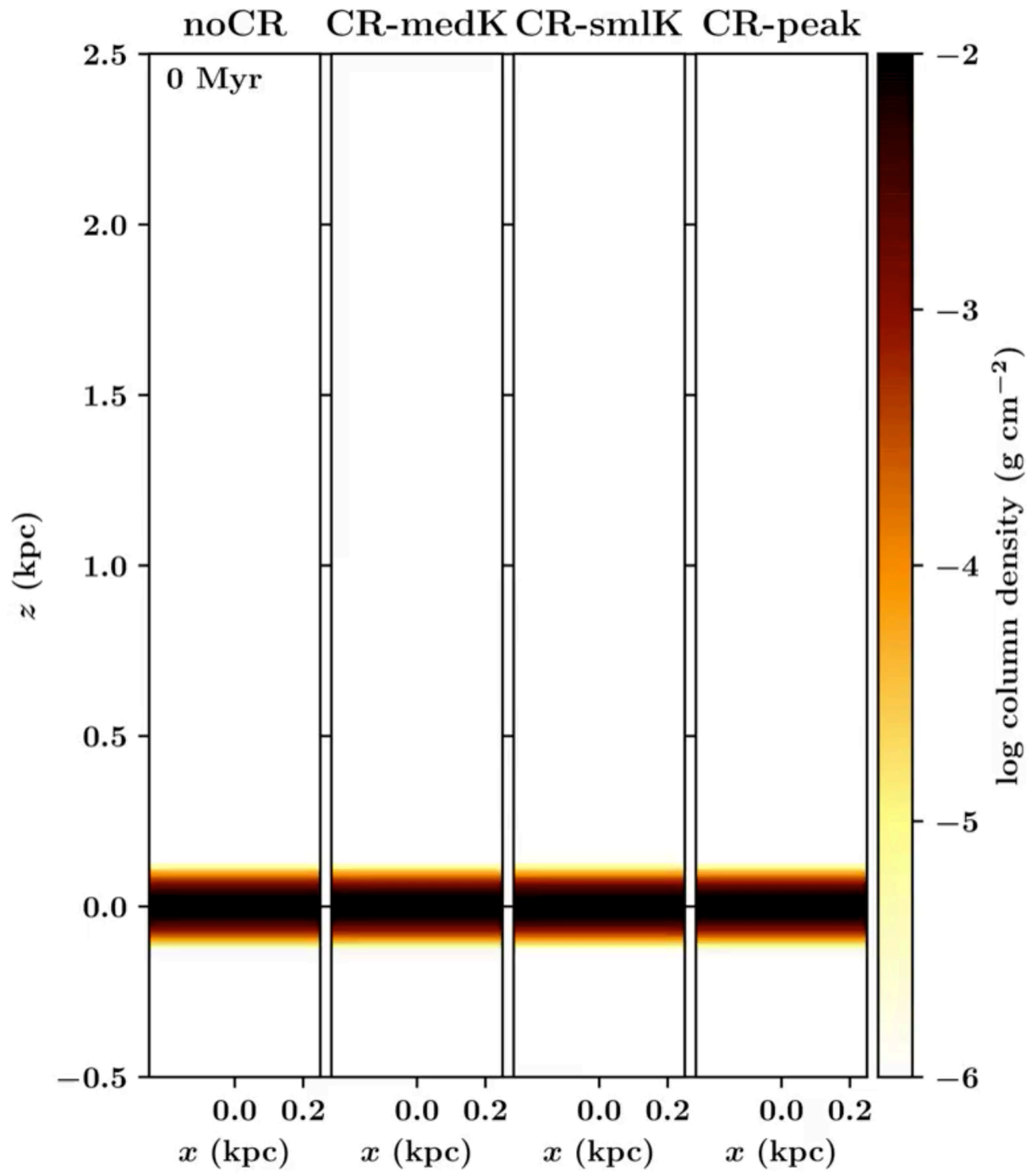


(Clark et al. 2012, Wünsch et al. 2018)

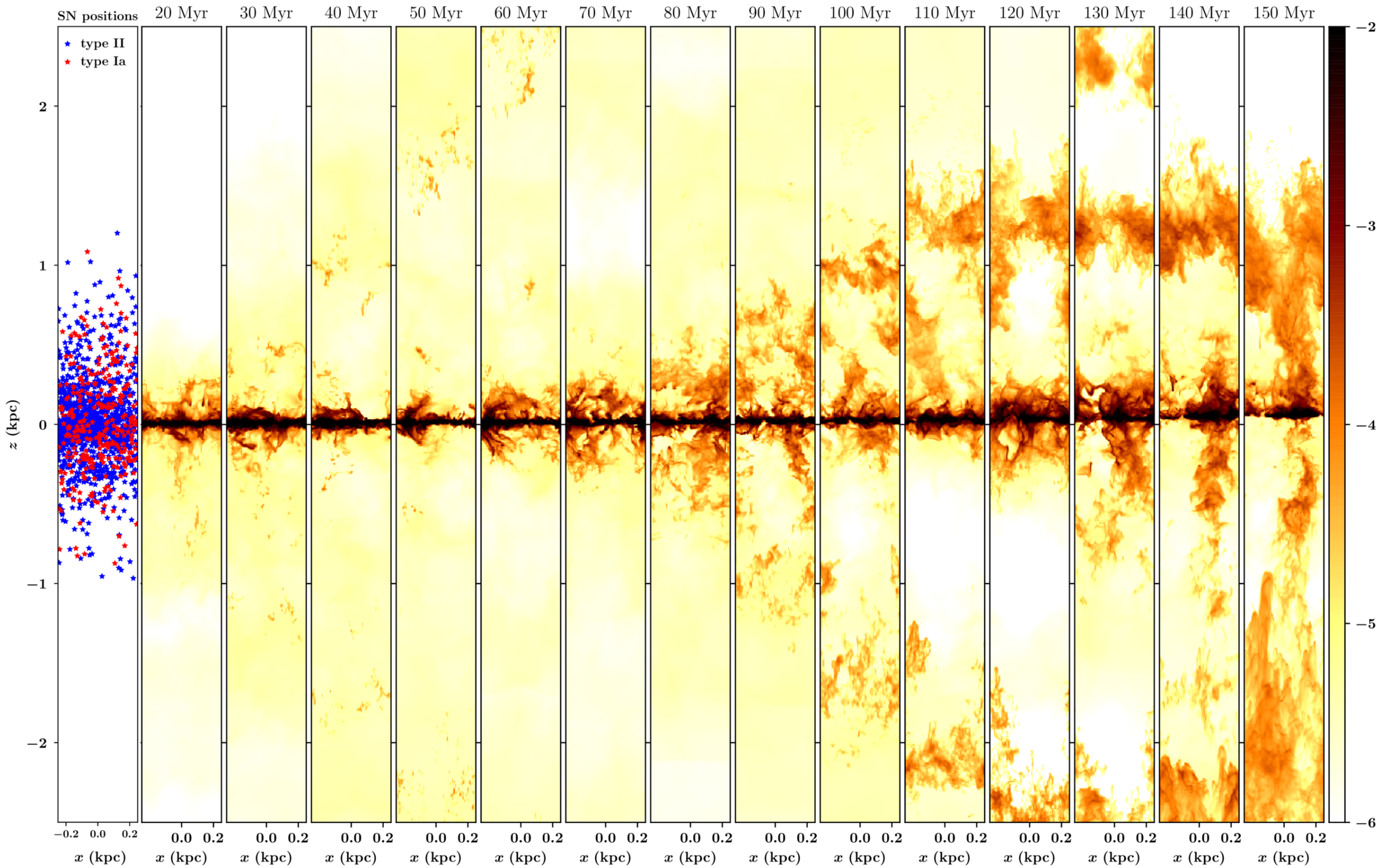
dynamical impact of CRs

- 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

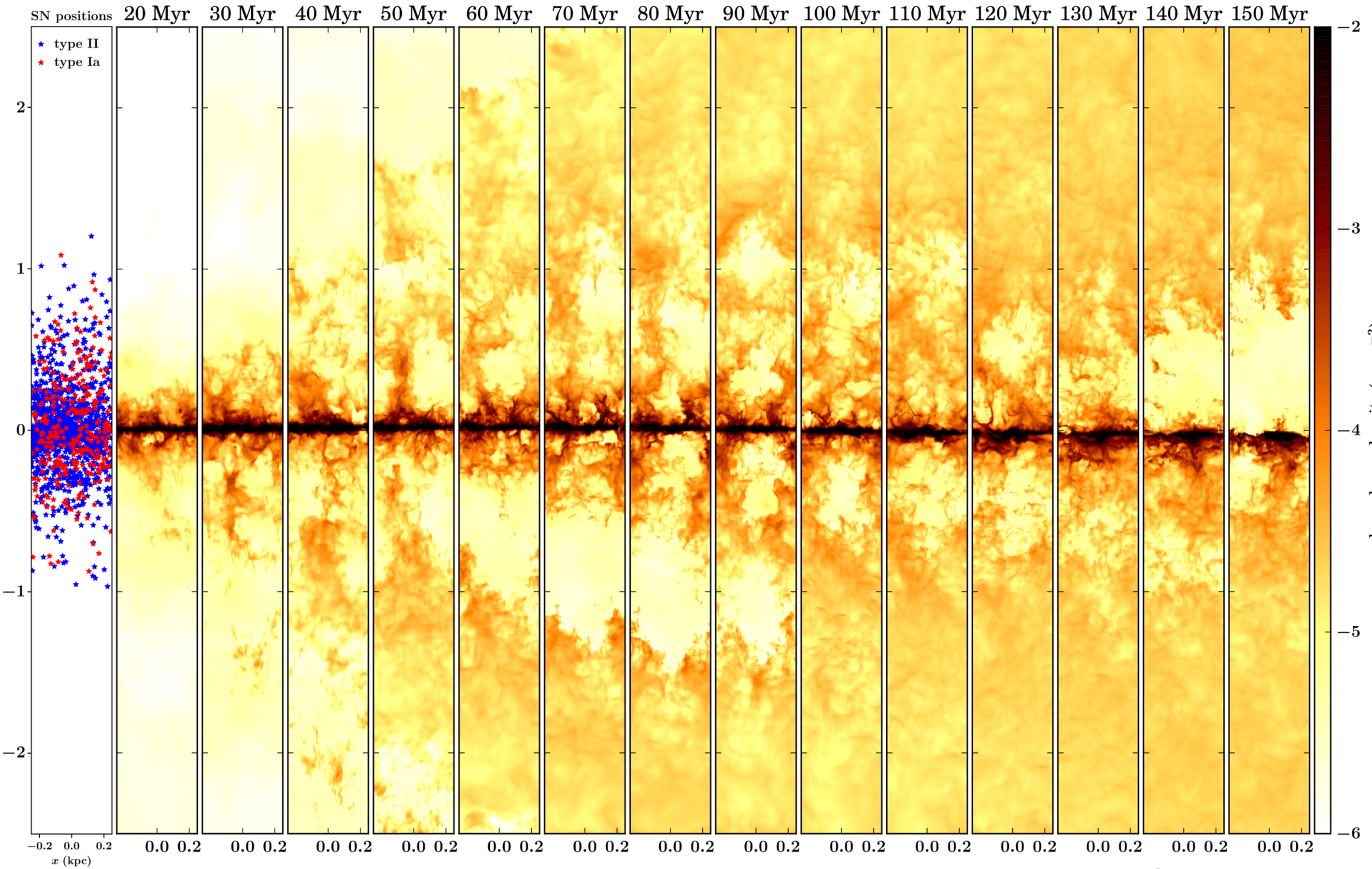


Time evolution w/o CRs



Girichidis et al. 2018a

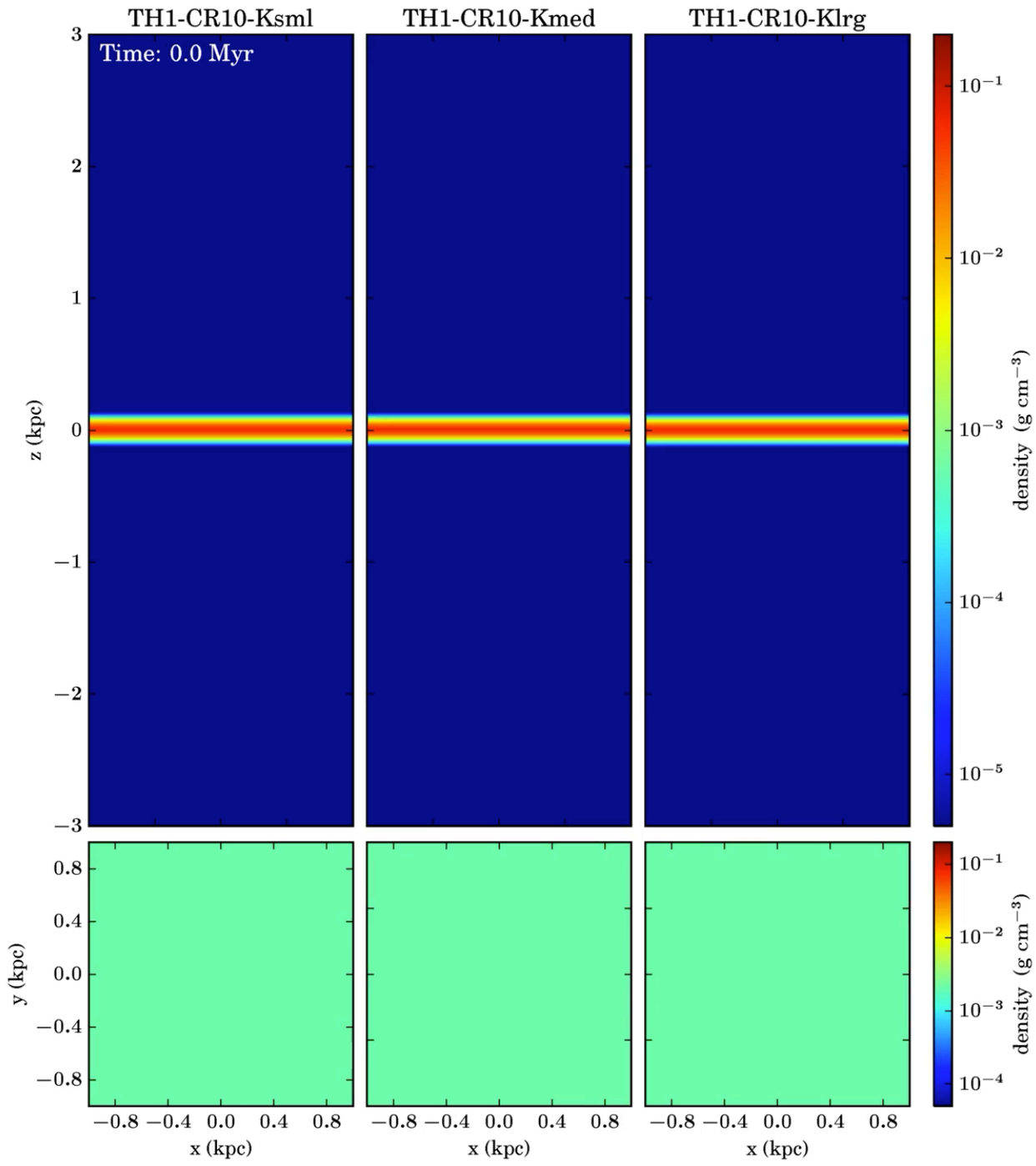
Time evolution with CRs



Girichidis et al. 2018a

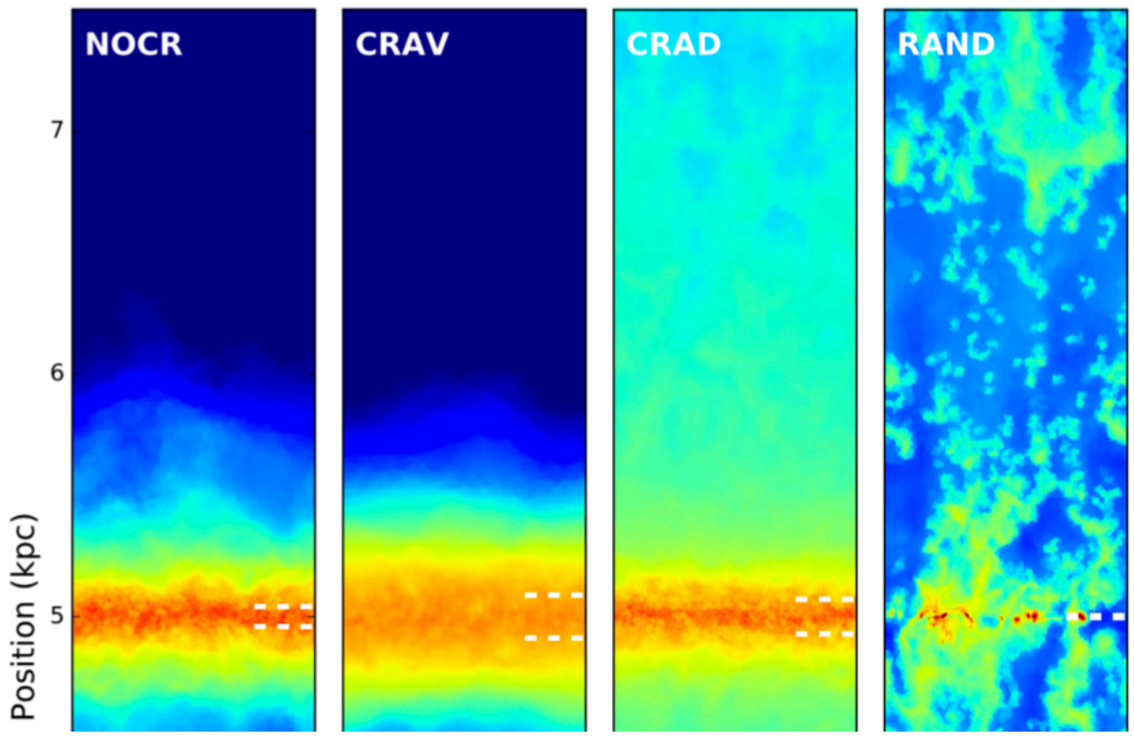
different diff. coefficients

- 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)

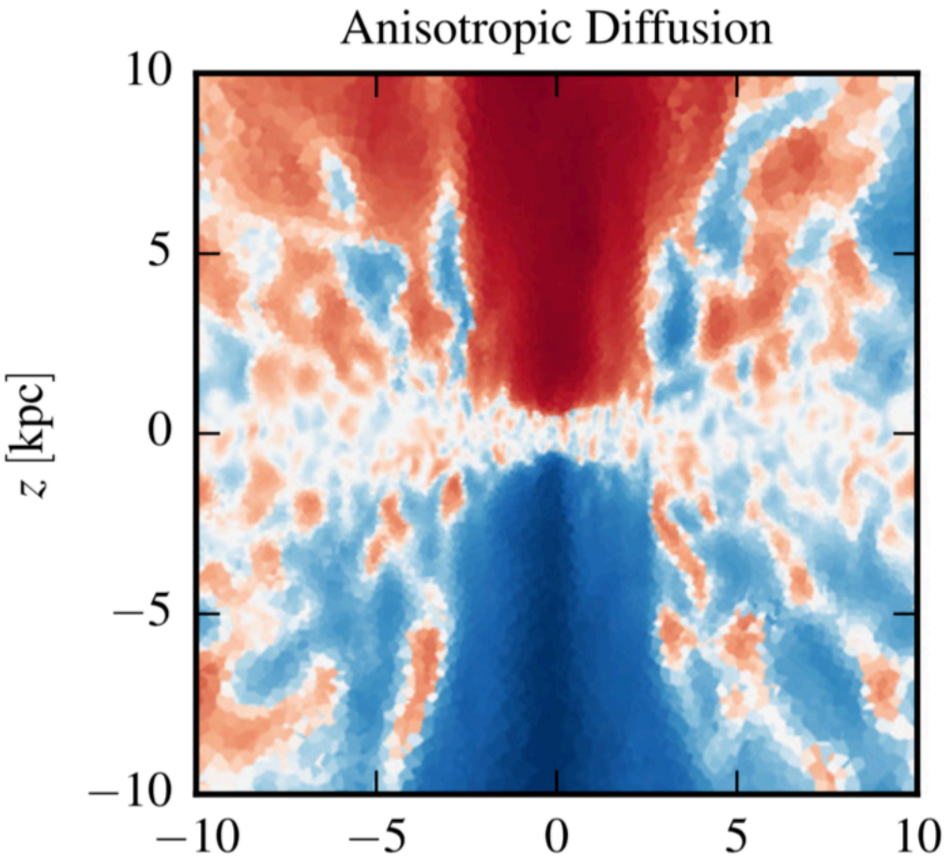


Other studies

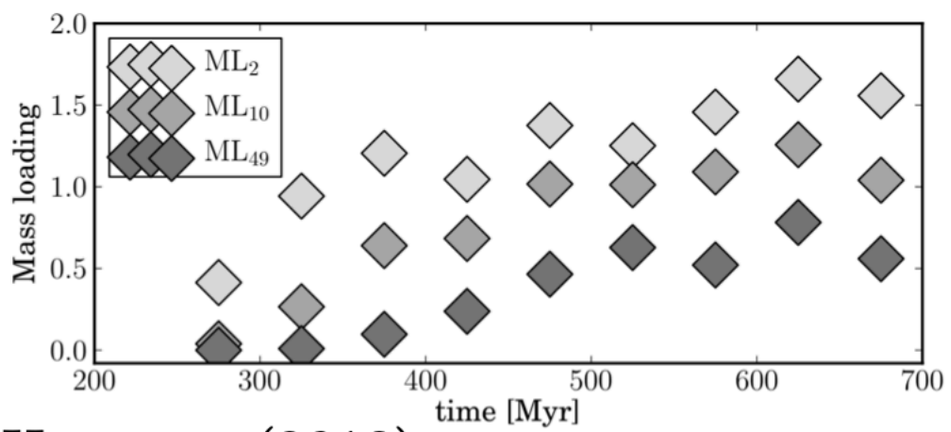
- ISM: Hanasz+ (2009), Simpson+ (2016), Ruszkowsky+ (2017), Farber+ (2018)
- Galaxy: Booth+ (2013), Hanasz+ (2013), Salem+ (2014), Pakmor+ (2016), Pfrommer+ (2017), Jacob+ (2018), Hopkins+ (2020)



Simpson+ (2016)



Pakmor+ (2016)



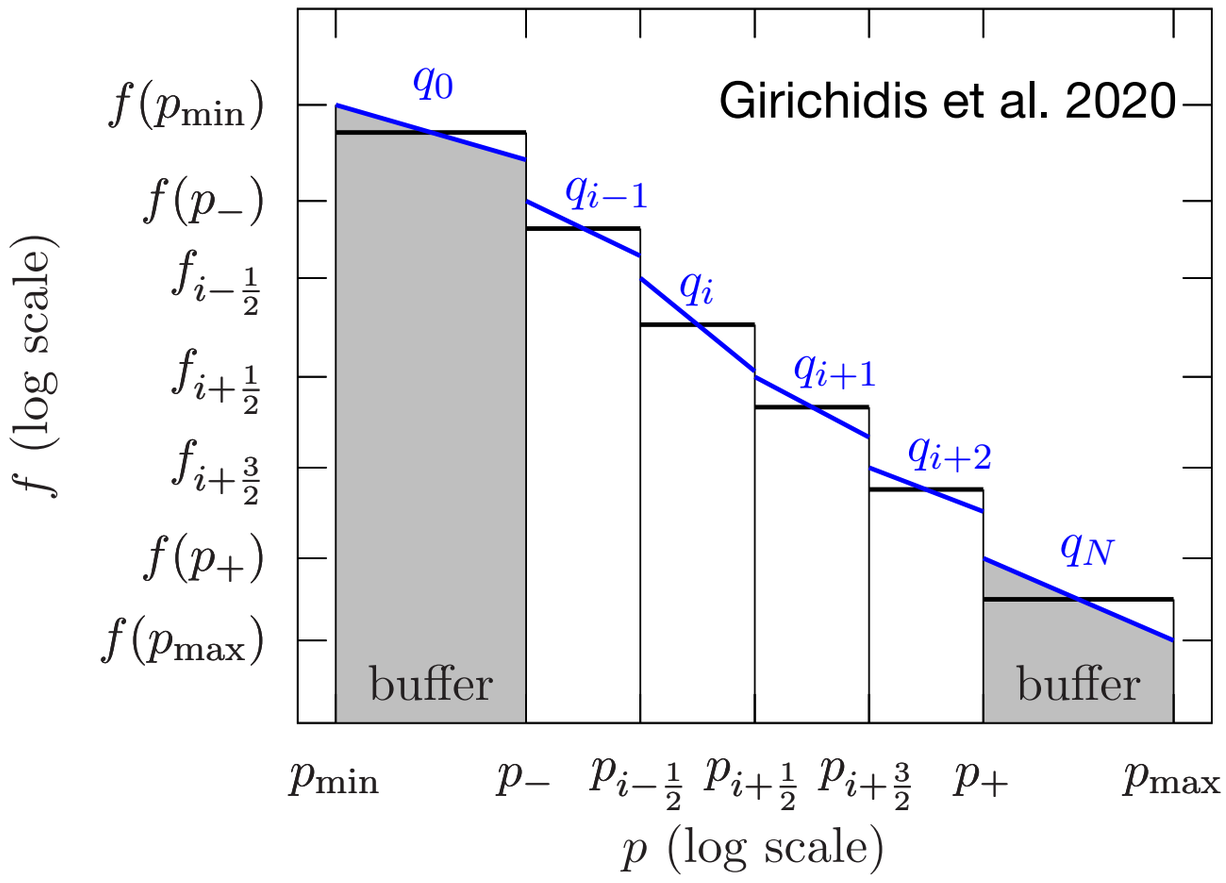
Hanasz+ (2013)

Multibin CRs

- full CR spectrum in every cell
- solve FP equation

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

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



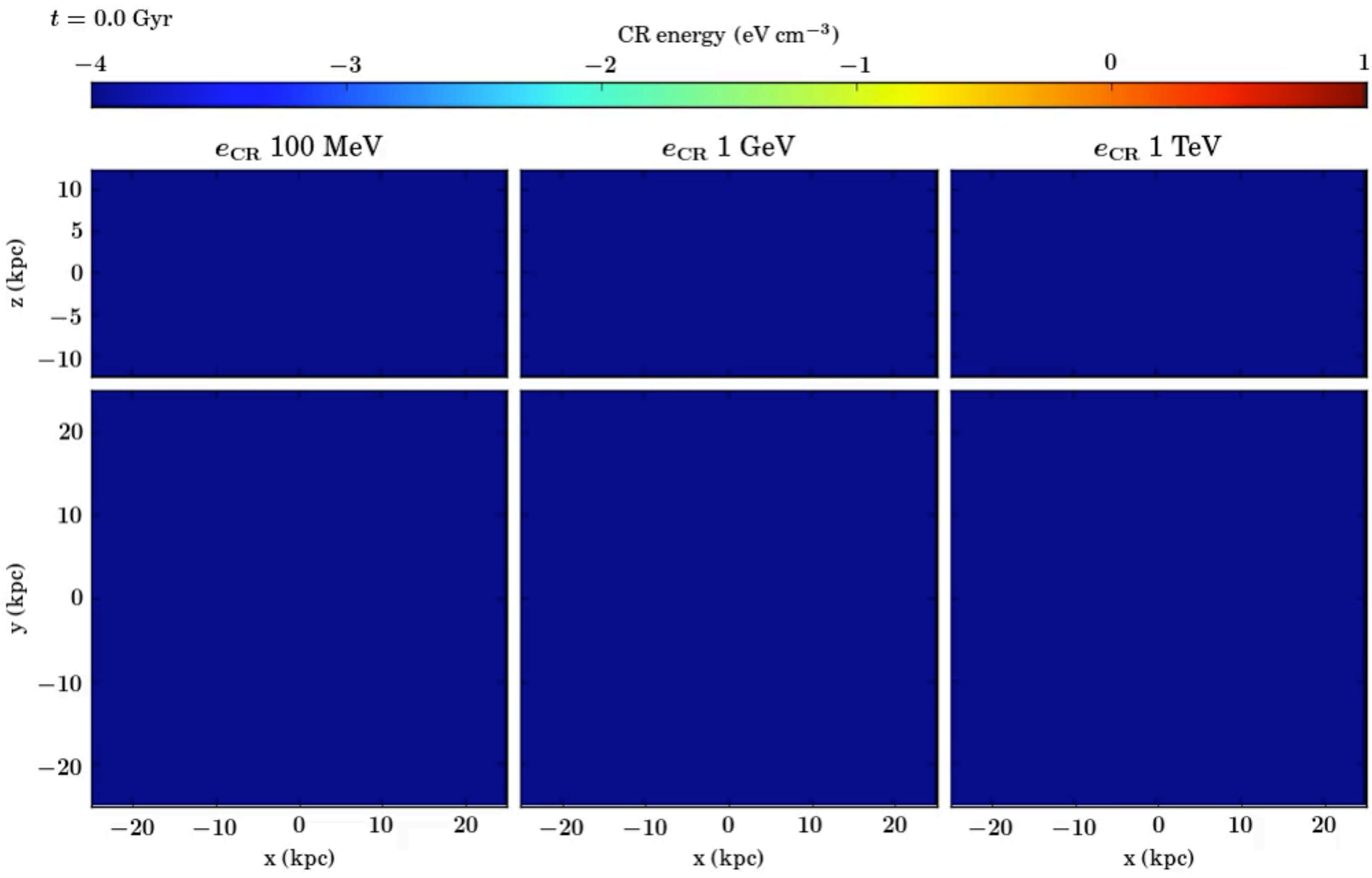
- chose piecewise power law

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

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

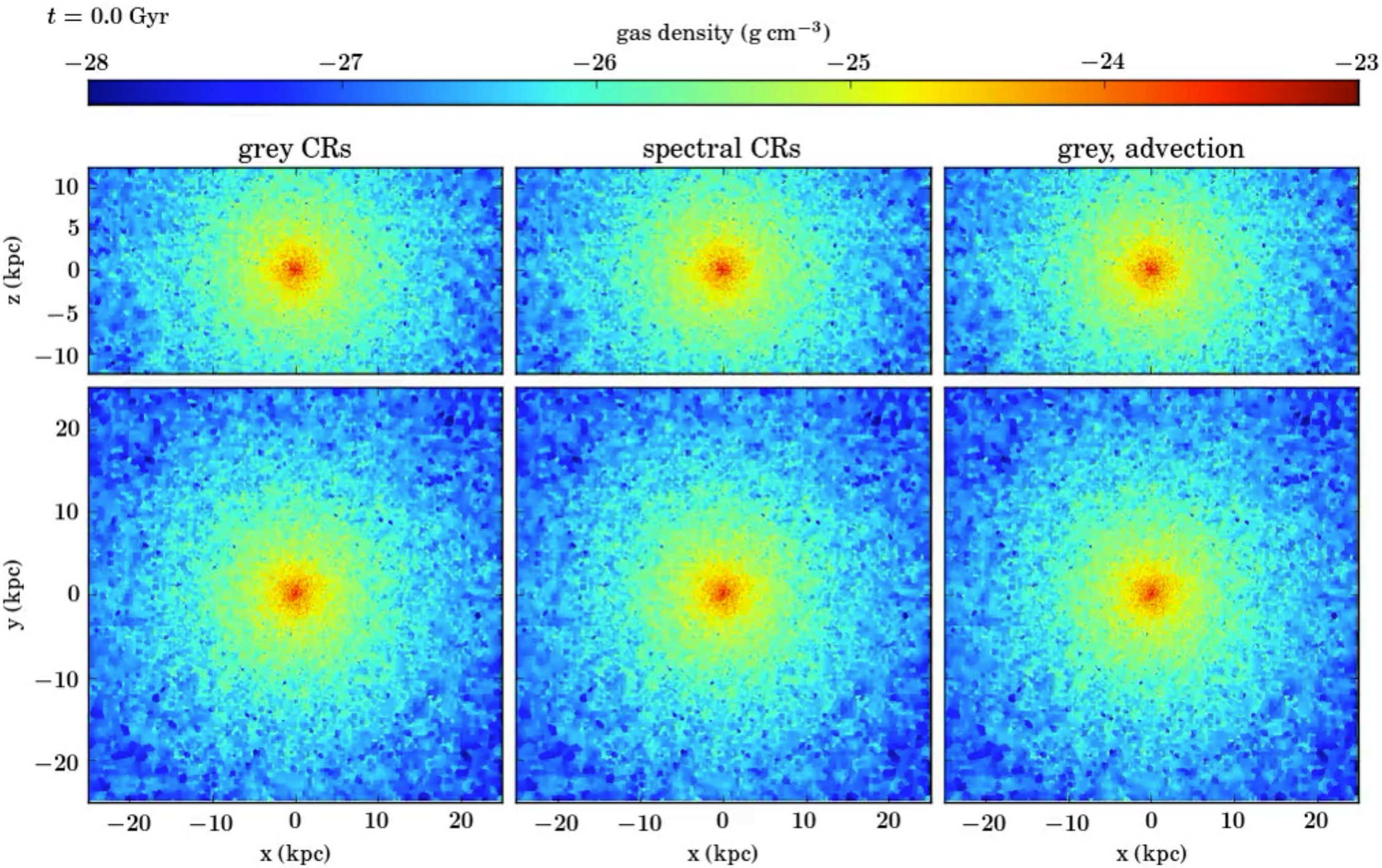
Miniati 2001, Yang et al. 2017, Girichidis et al. 2020, Ogrodnik et al. 2021

Galaxy model with multibin CRs



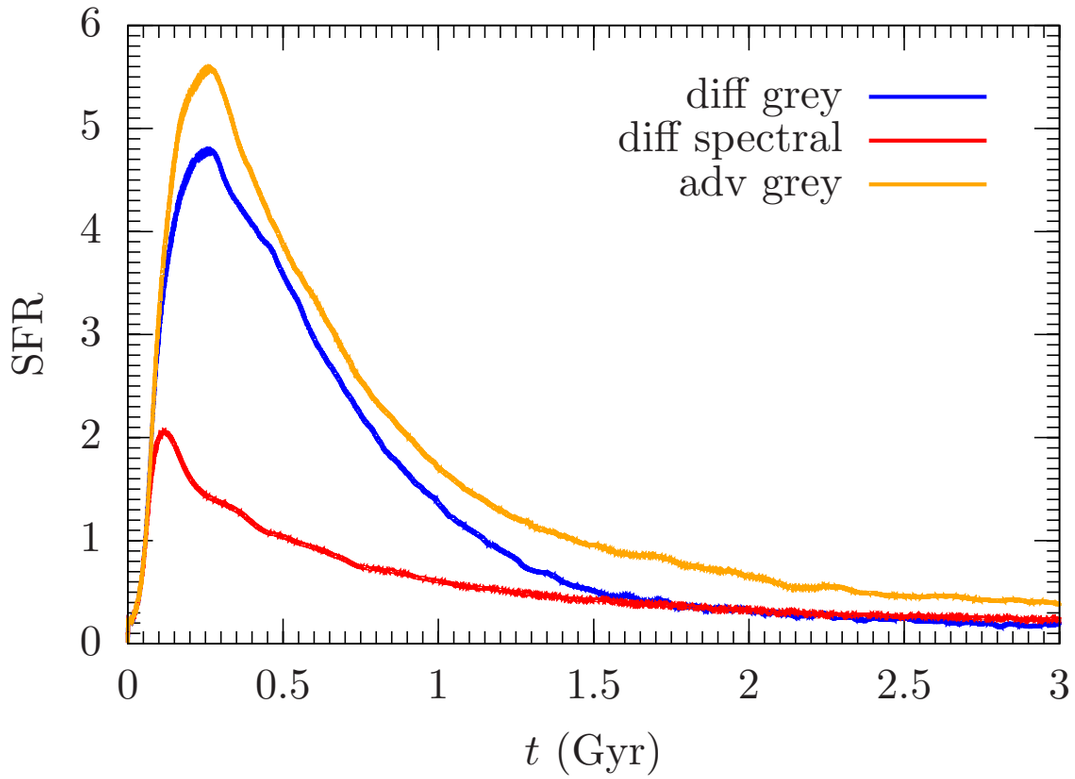
Girichidis et al. in prep.

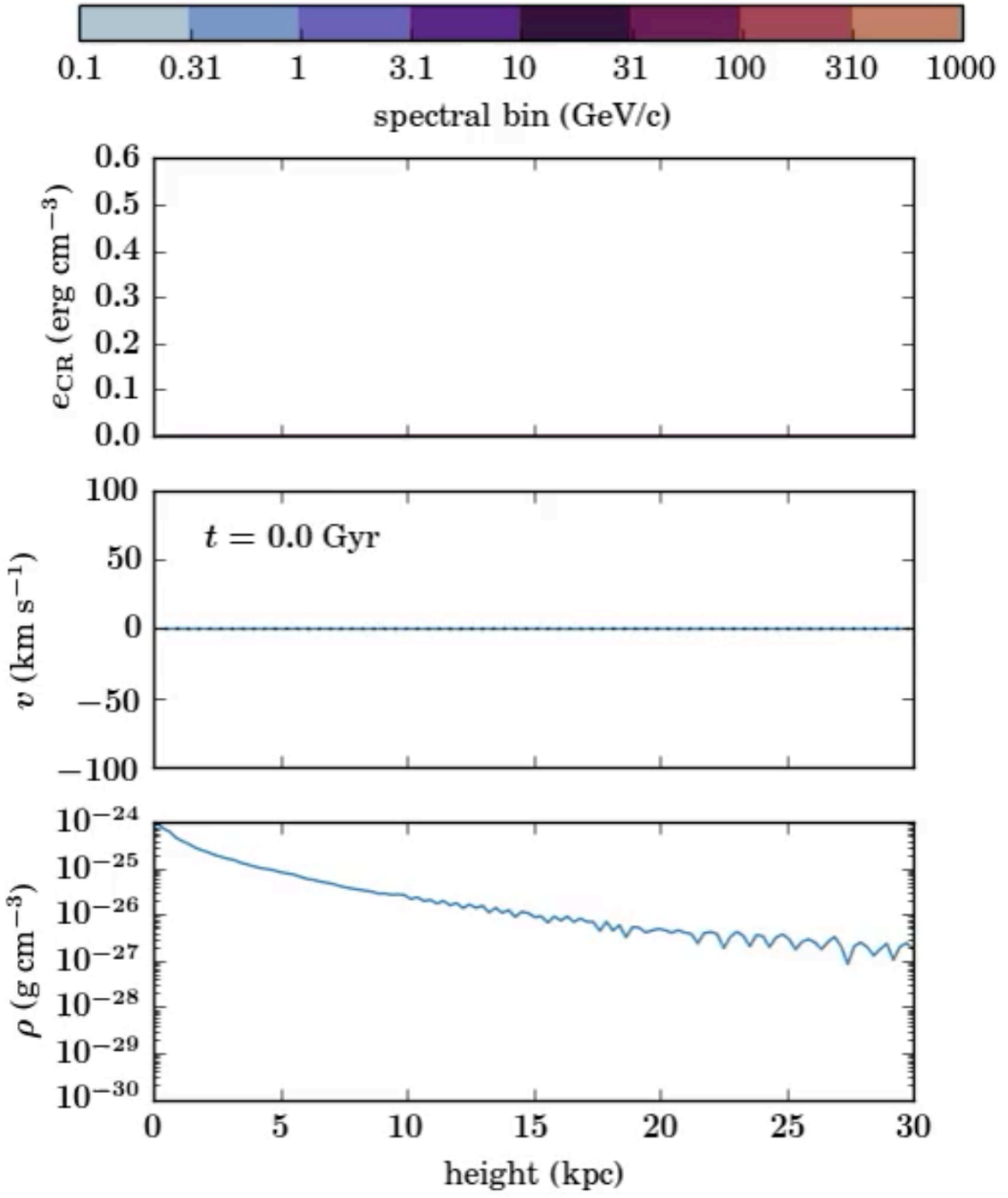
Galaxy model with multibin CRs



Girichidis et al. in prep.

SFR and outflows





Girichidis et al. in prep.

Conclusions for MHD-CR simulations

- CRs are dynamically relevant
- CRs can drive outflows
- many details matter:
  - accurate transport (diffusion vs. streaming)
  - spectrally resolved CRs
  - accurate losses and transfer of energy to gas/B-field