The dynamical impact of Cosmic-ray feedback on galaxy evolution

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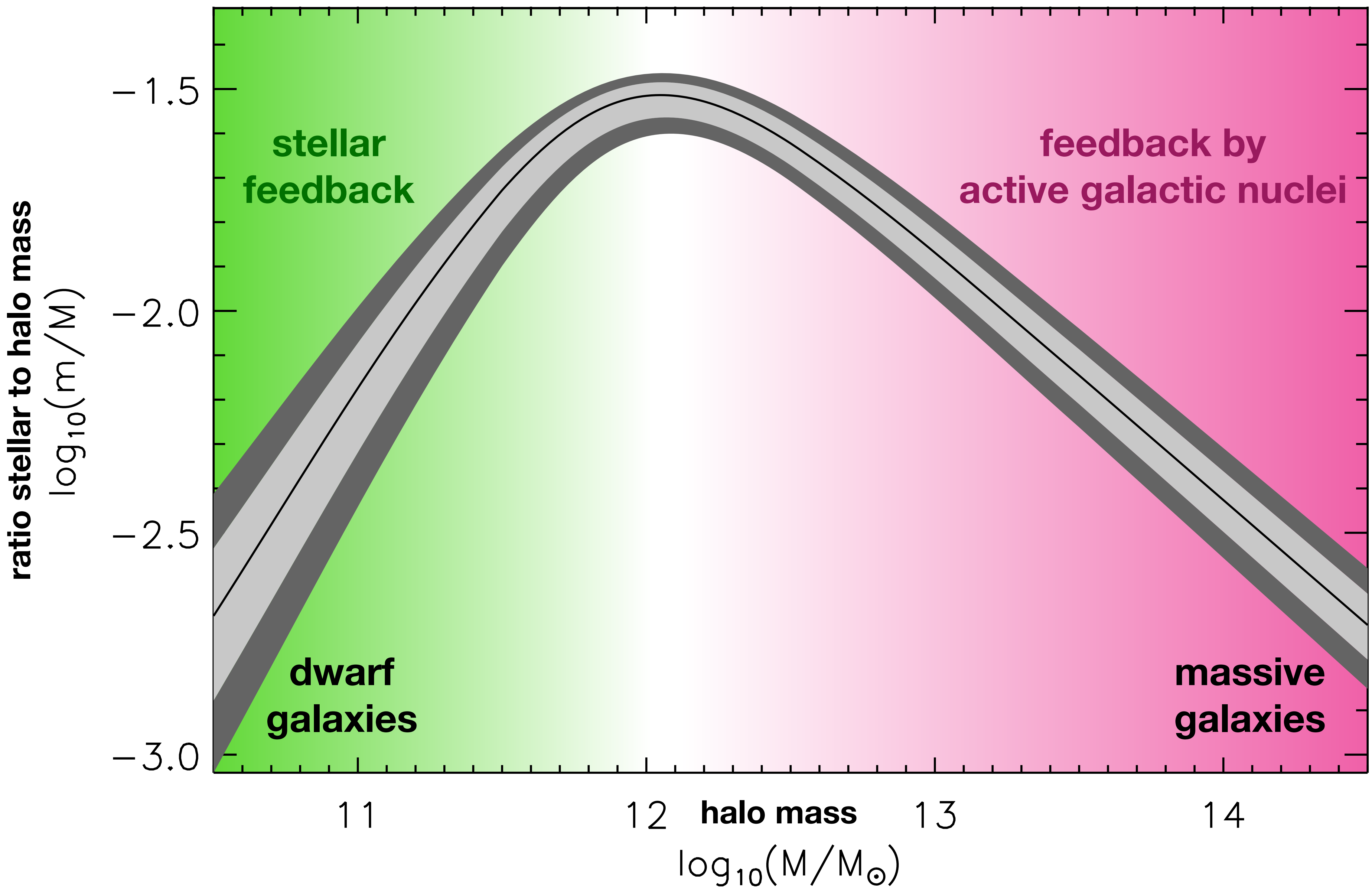
Low stellar masses in galaxies

stellar mass to halo mass ratio (Moster et al. 2010)



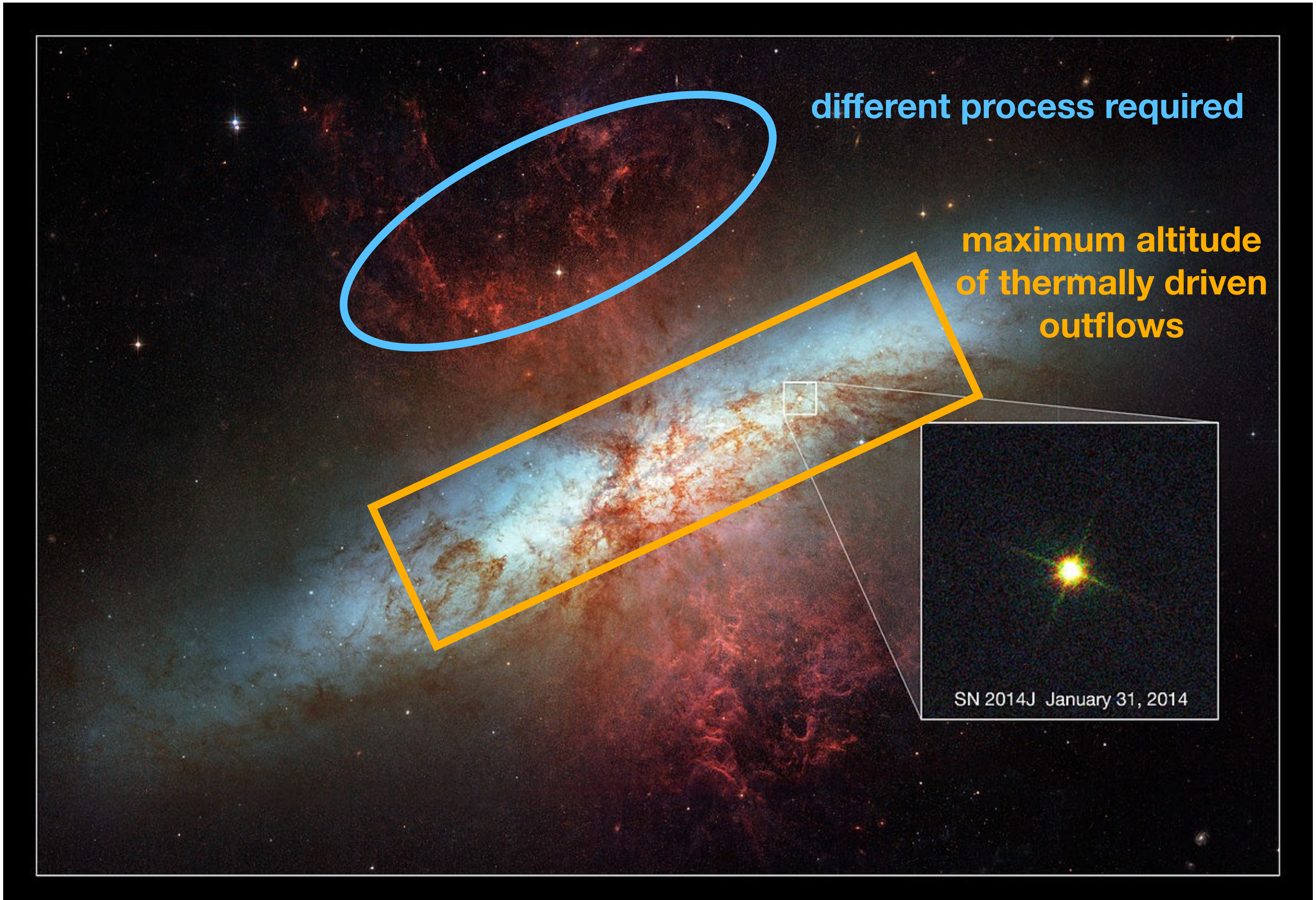
How do galaxies lose their mass?

Motivation for Cosmic Rays

strong outflows in all phases

Thermal energy cools too fast

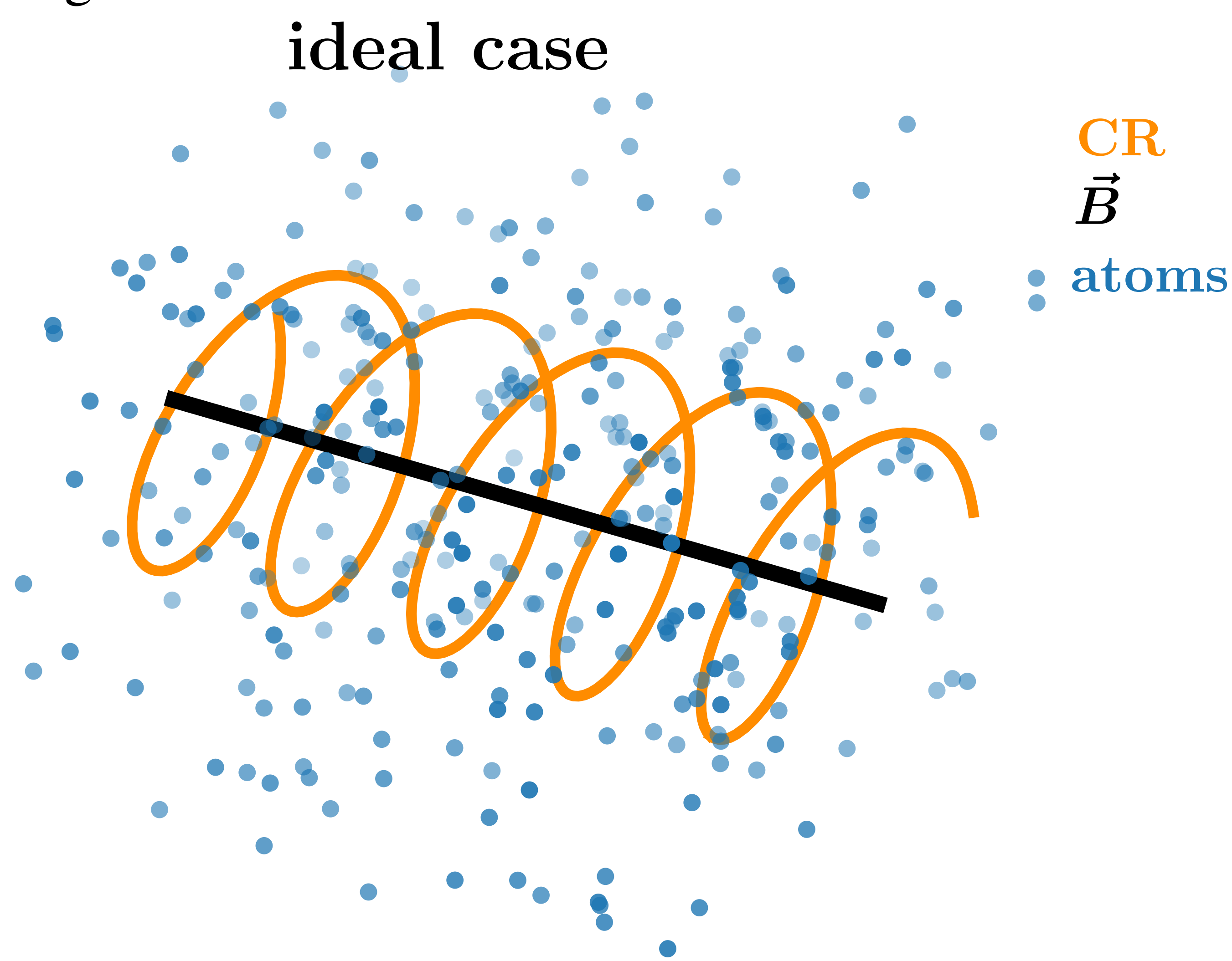
classical stellar feedback too weak (SNe, winds, radiation)



Cosmic ray basics

reviews:
Grenier, Black, Strong 2015
Zweibel 2013, 2017
Ruszkowski & Pfrommer 2023

- CRs: mainly high-energy protons
- accelerated in strong shocks: supernova remnants
- inefficient cooling (compared to thermal gas)
  $\Rightarrow$ long lived
- in galaxy: $E_{\rm cr} \sim E_{\rm kin} \sim E_{\rm therm} \sim E_{\rm mag}$
- transport
  - advection with gas
  - diffusion relative to gas
  - back-reaction onto B & gas



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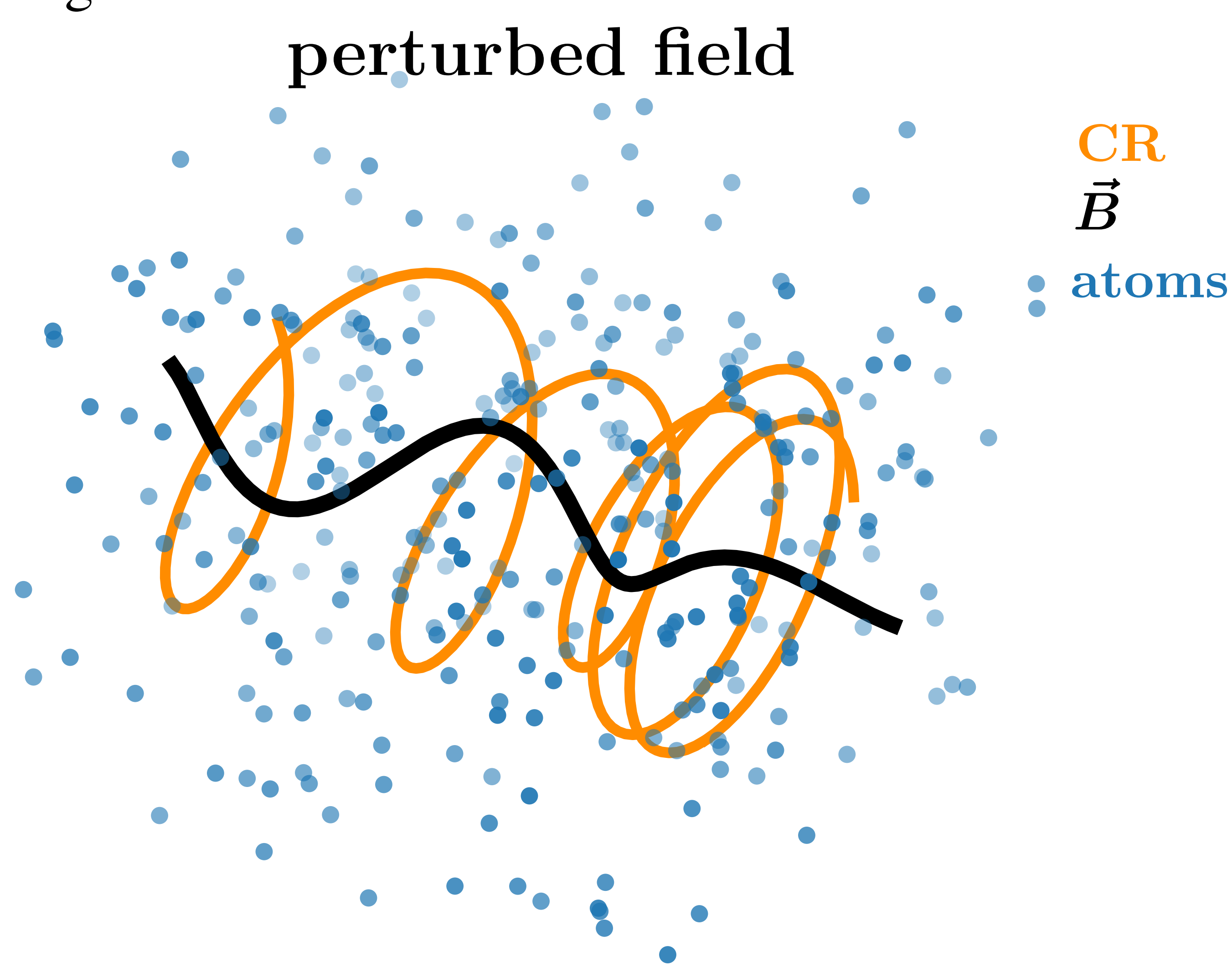

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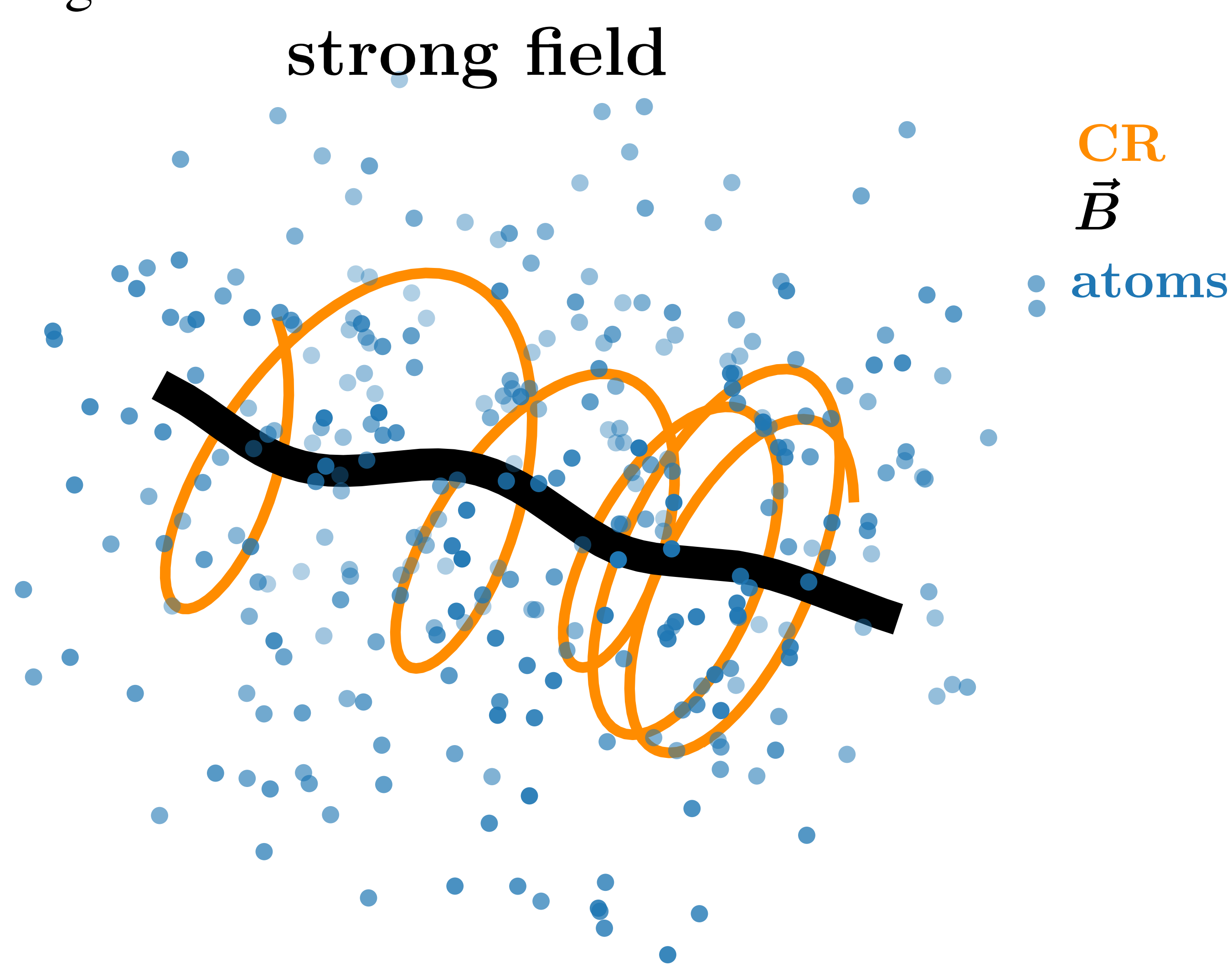

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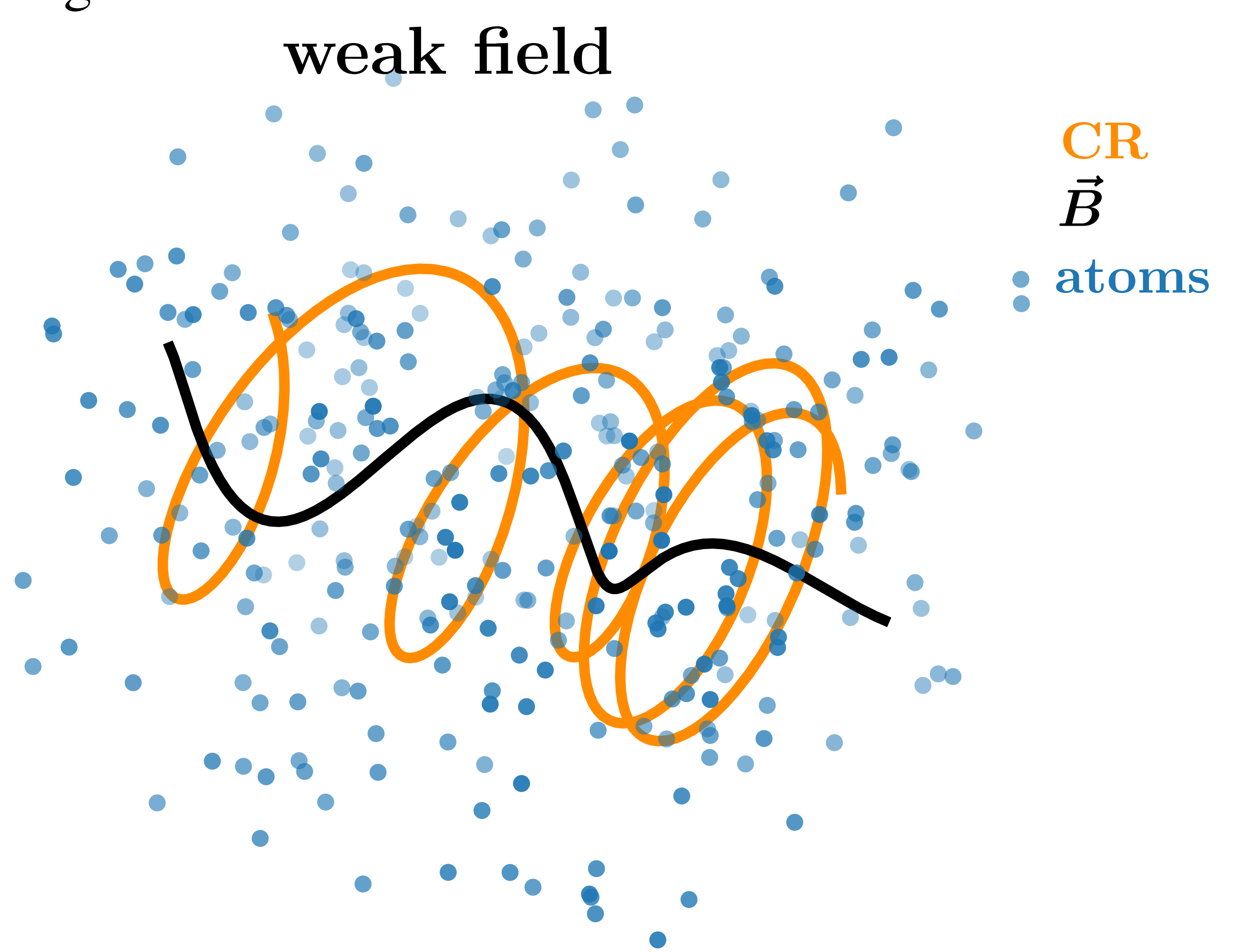
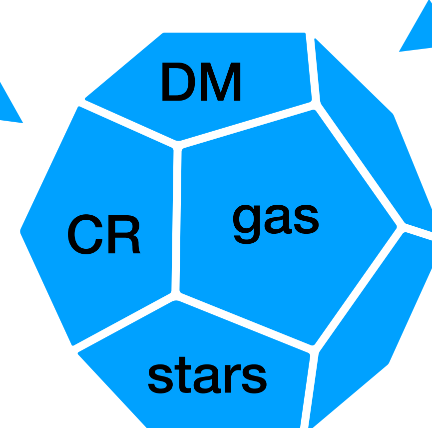


Merge CR physics and galaxy astro

CR/particle physics

$$\frac{\partial \mathcal{N}}{\partial t} = q(\boldsymbol{r}, p) + \boldsymbol{\nabla} \cdot (D_{xx} \boldsymbol{\nabla} \mathcal{N} - \boldsymbol{V} \mathcal{N}) + \frac{\partial}{\partial p} p^2 D_{pp} \frac{\partial}{\partial p} \frac{1}{p^2} \mathcal{N}$$
$$- \frac{\partial}{\partial p} \left[\dot{p} \mathcal{N} - \frac{p}{3} (\boldsymbol{\nabla} \cdot \boldsymbol{V}) \mathcal{N} \right] - \frac{1}{\tau_f} \mathcal{N} - \frac{1}{\tau_r} \mathcal{N} \, ,$$



cosmology

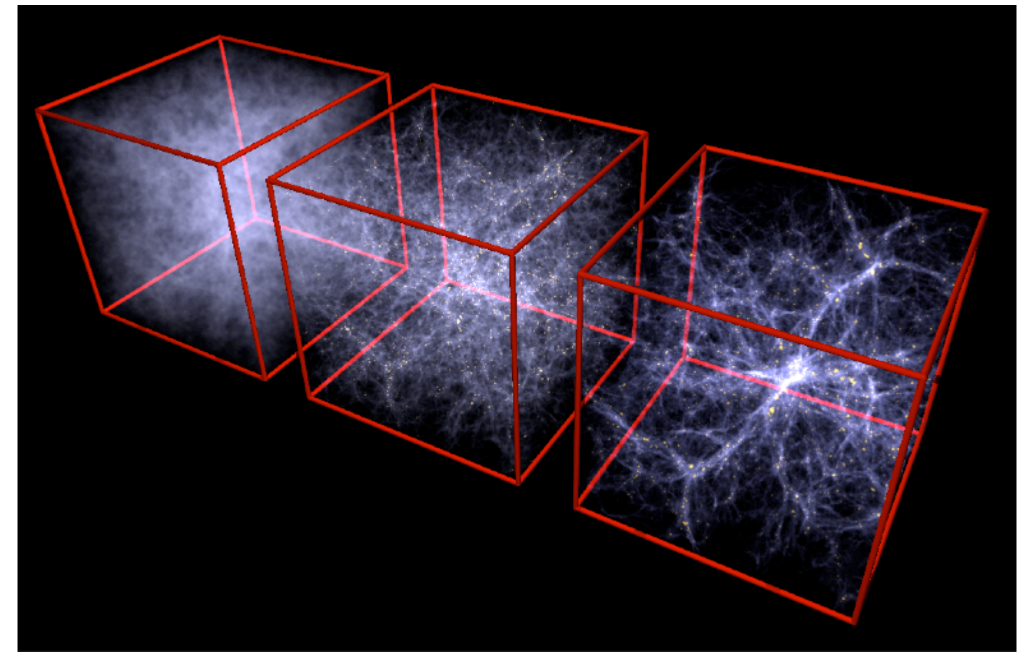
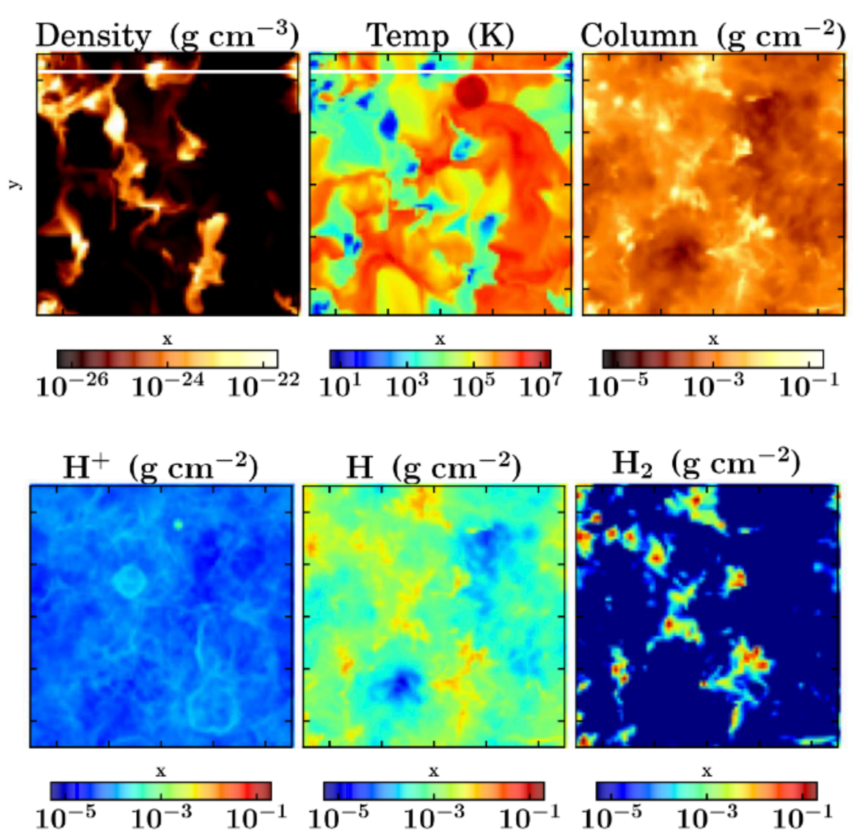


image credit: V. Springel

interstellar medium



Girichidis et al. 2016

galactic dynamics

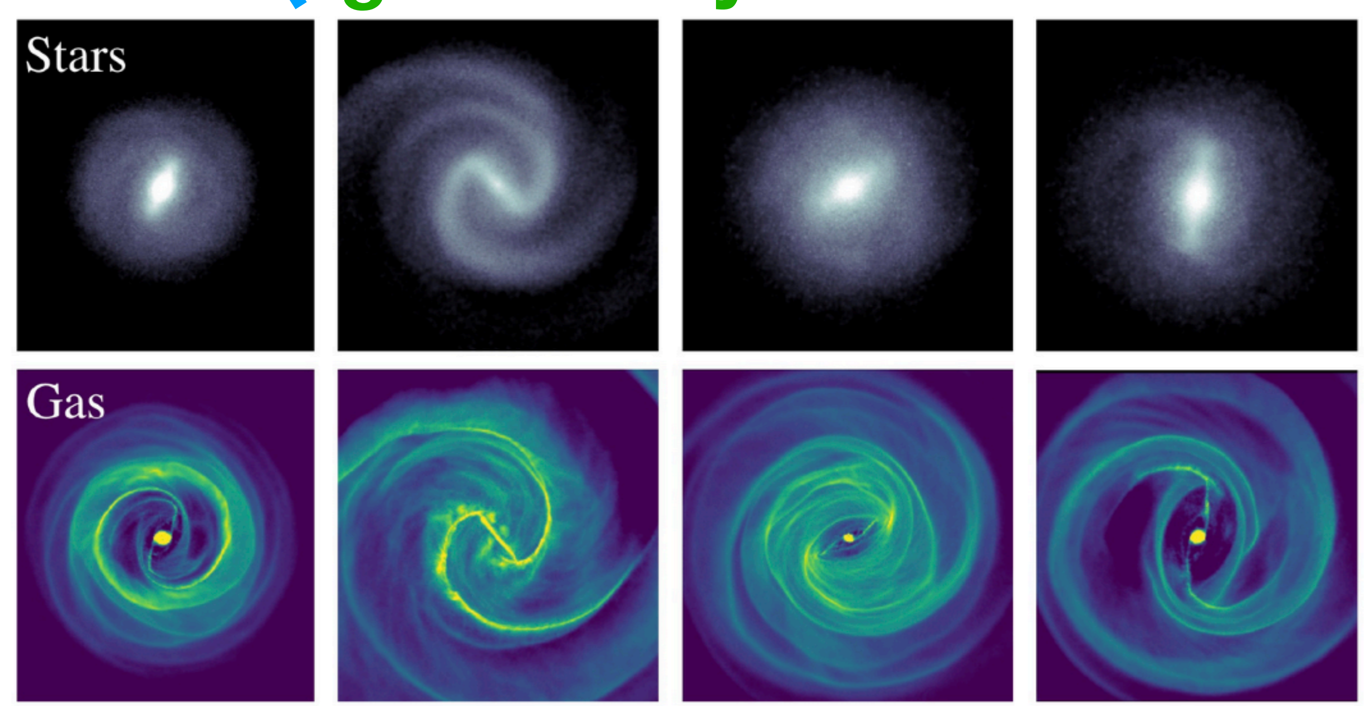


image credit: A. Pettitt

CRs in a grey approximation

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

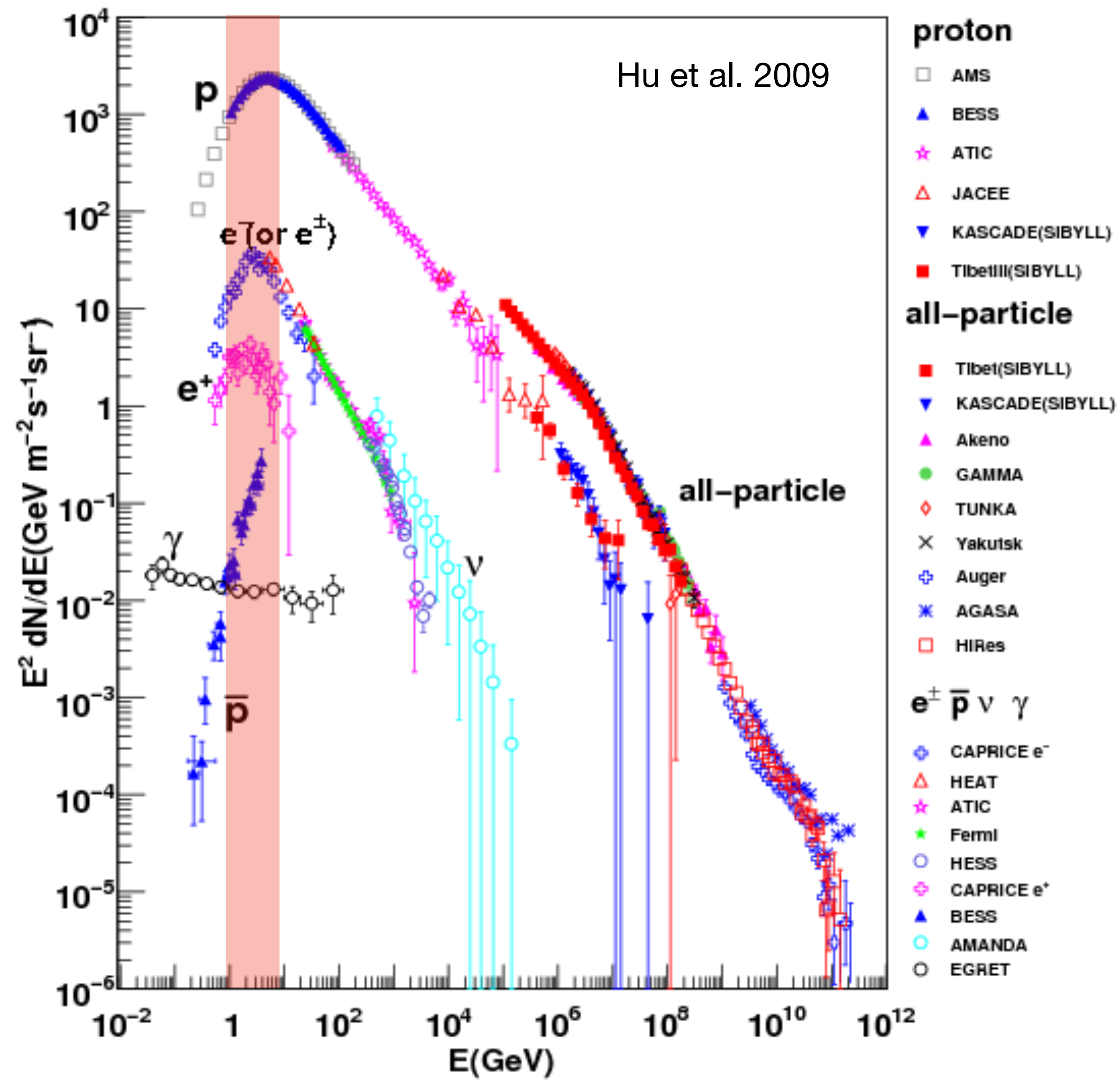
- dominated by GeV protons

- effective cooling

- effective diffusive transport (at median energy): $D_{xx} \sim 10^{28}\,\mathrm{cm^2\,s^{-1}}$

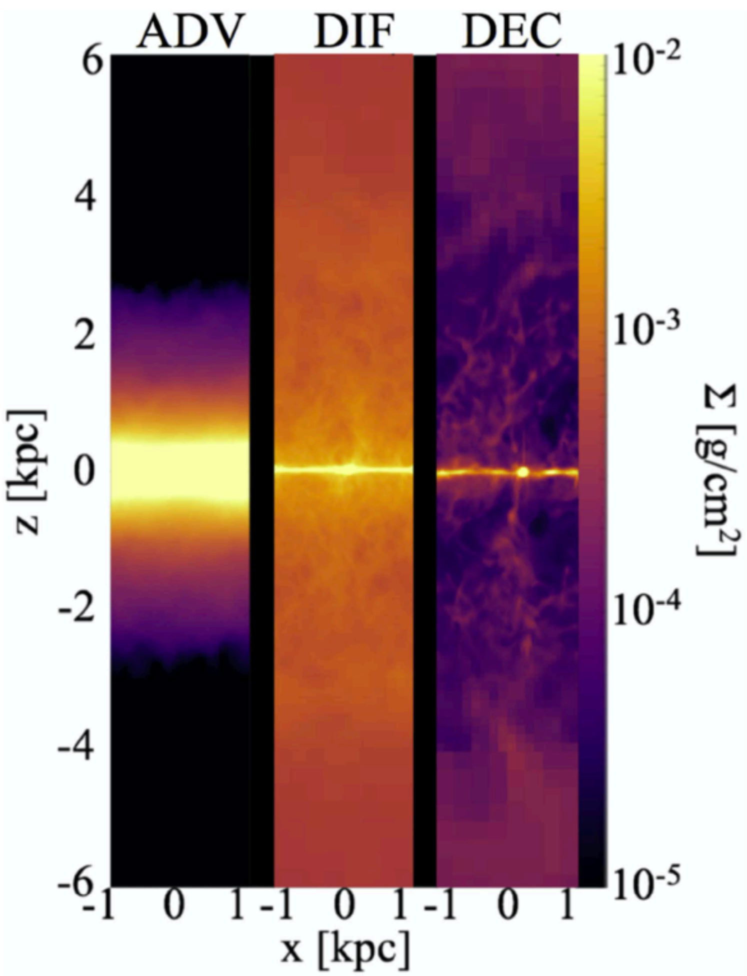
- $P_{\rm CR} = (\gamma_{\rm CR} - 1) e_{\rm CR}$

- $\gamma_{\rm CR} = 4/3$



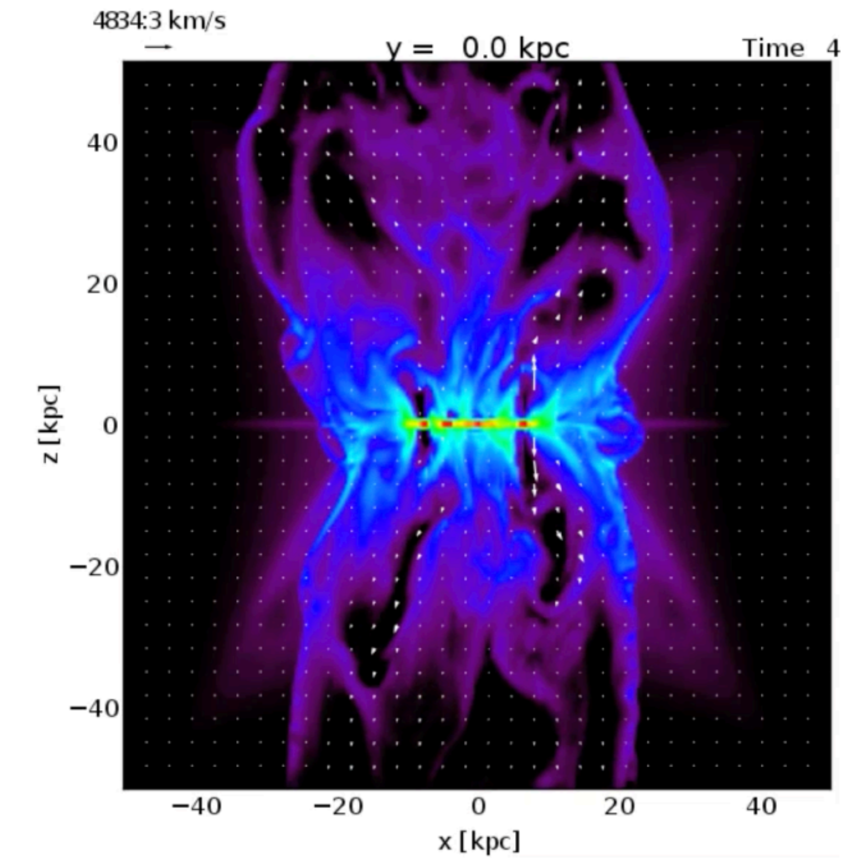
CRs in numerical simulations

stratified boxes (ISM)



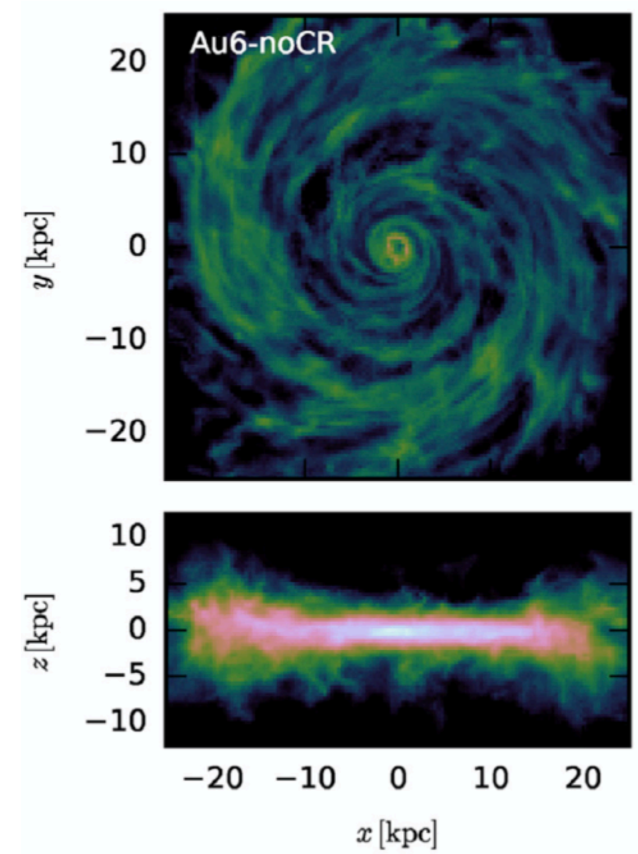
Hanasz+ 2003, Girichidis+16,18, Simpson+ 2016, Dubois+ 2016, Farber+ 2018, Armillotta+18,21, Commercon+2019, Butsky+2020, Rathjen+ 2021,2022

isolated galaxies



Booth+ 2013, Ruszkowski+ 2017a, Pakmor+2016, Pfrommer+2017, Jacob+ 2018, Dashyan+ 2020, Semenov+ 2021, Girichidis+ 2022, Thomas+2022,2023, Peschken+ 2023

cosmological galaxies



Jubelgas+ 2008, Salem+ 2014, Chan+ 2018, Hopkins+ 2020/2021, Buck+2020, Ji+2021

CRs in ISM simulations

based on SILCC setup (Walch+2015, Girichidis+2016)
also Simpson+2016, Farber+2018, Armillotta+ 2021

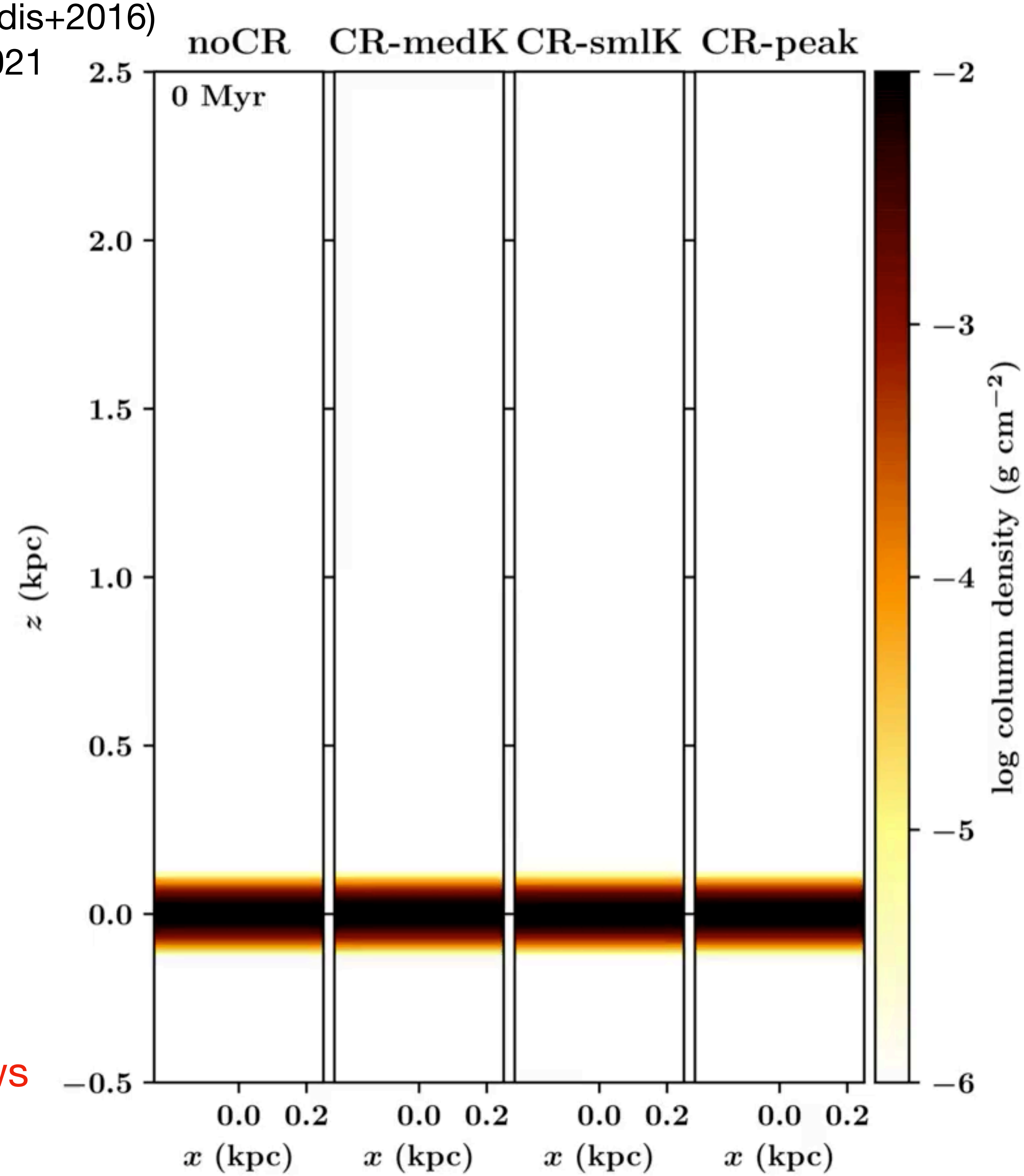
- 10% of SN energy
  (therm: 10^{51} erg, CR: 10^{50} erg)
  but see also Pais+ 2018 (only 5%)

- SN models:
  - 20% type Ia
  - 80% type II
    - 48% clustered
    - 32% runaway (random)

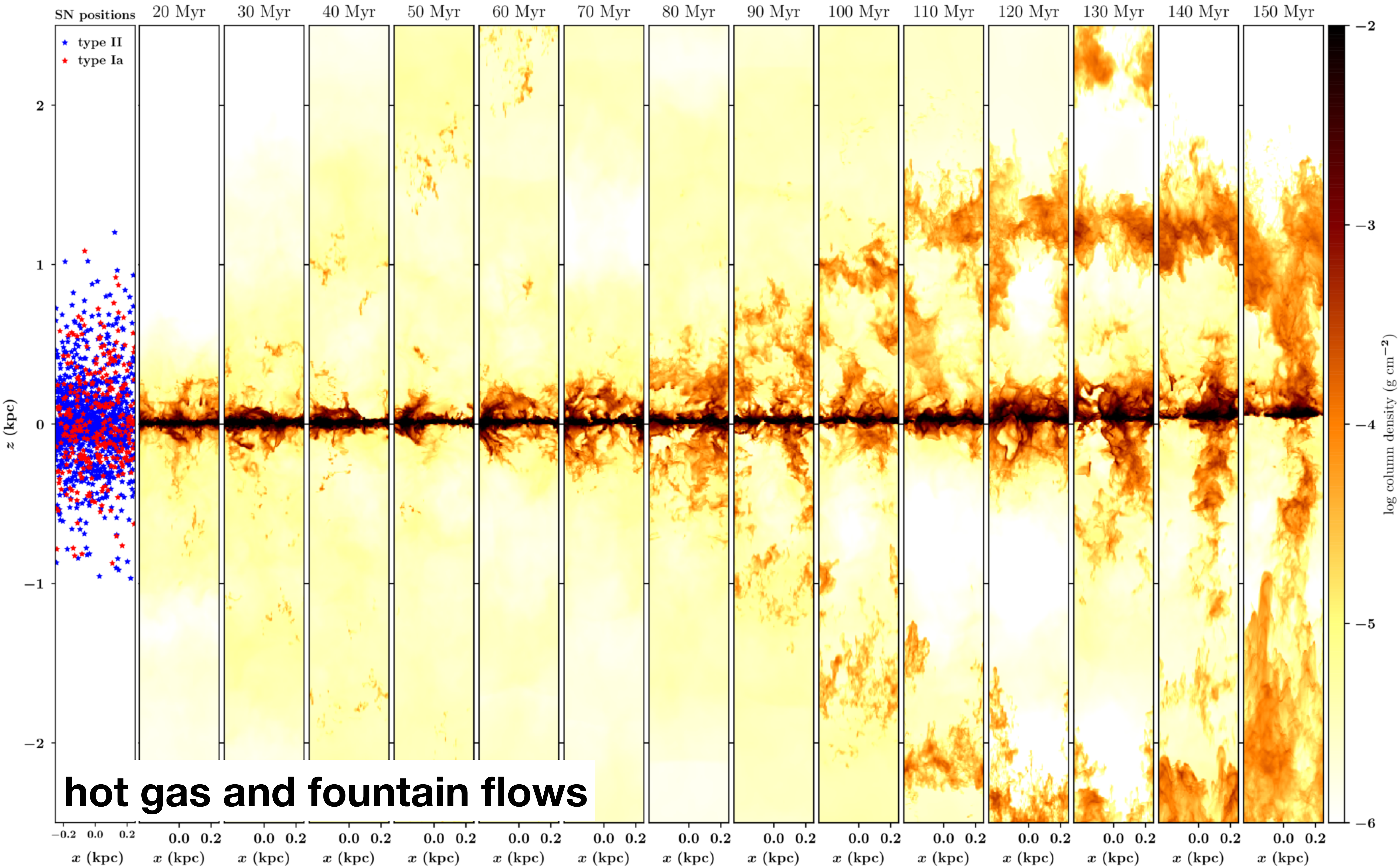
- dynamical impact
  - no CRs
  - medium diff $\left(\mathrm{K}_{\parallel} = 3 \times 10^{28} \, \frac{\mathrm{cm}^2}{\mathrm{s}}\right)$
  - small diff $\left(\mathrm{K}_{\parallel} = 1 \times 10^{28} \, \frac{\mathrm{cm}^2}{\mathrm{s}}\right)$
  - all SNe exploding in dense gas

CRs are able to drive and sustain outflows with mass loading of order unity

Girichidis et al. 2016a, 2018a

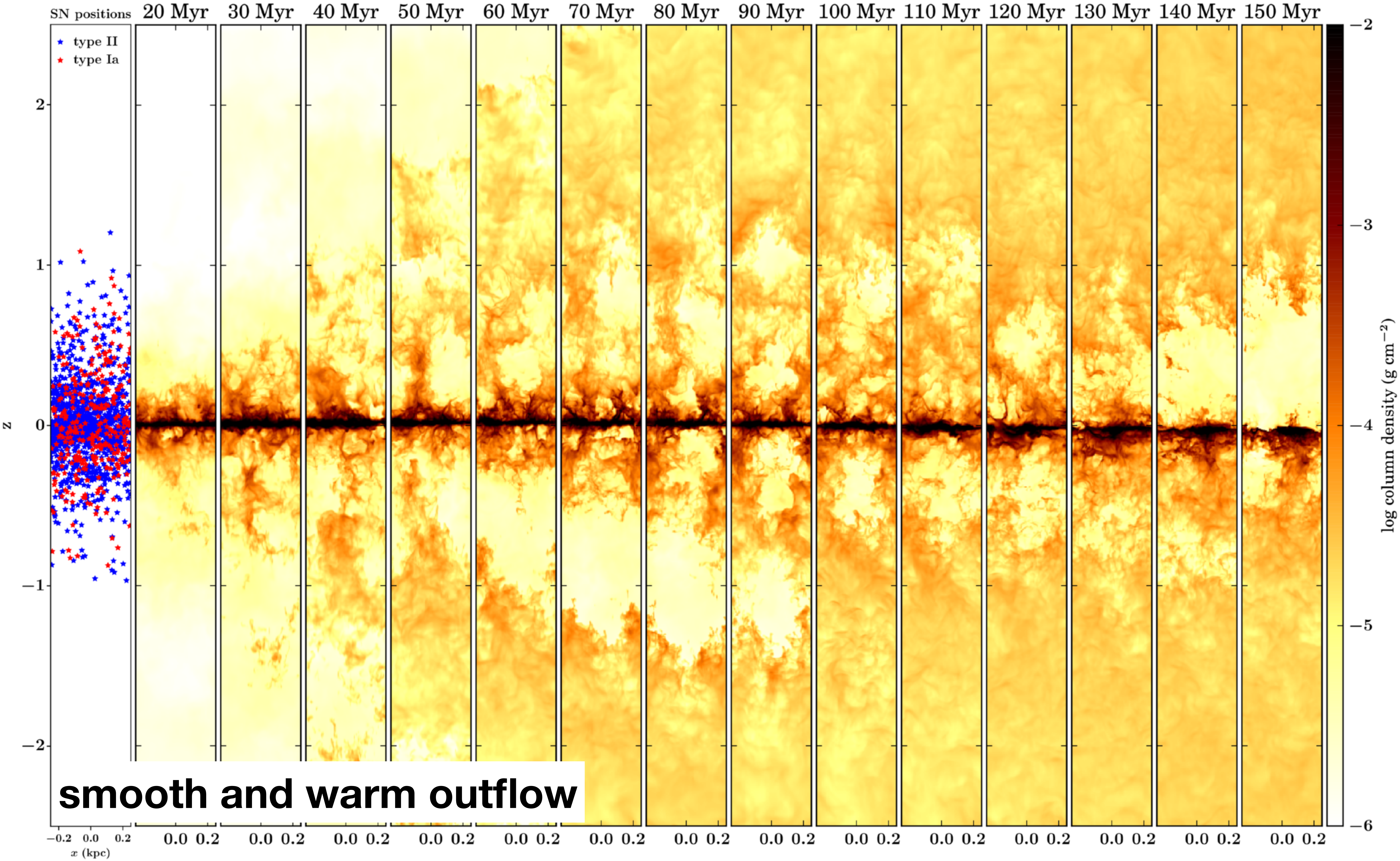


ISM evolution without CRs (only thermal)



Girichidis et al. 2018a, based on SILCC setup (Walch+ 2015, Girichidis+2016)

ISM evolution including CRs (+ thermal)

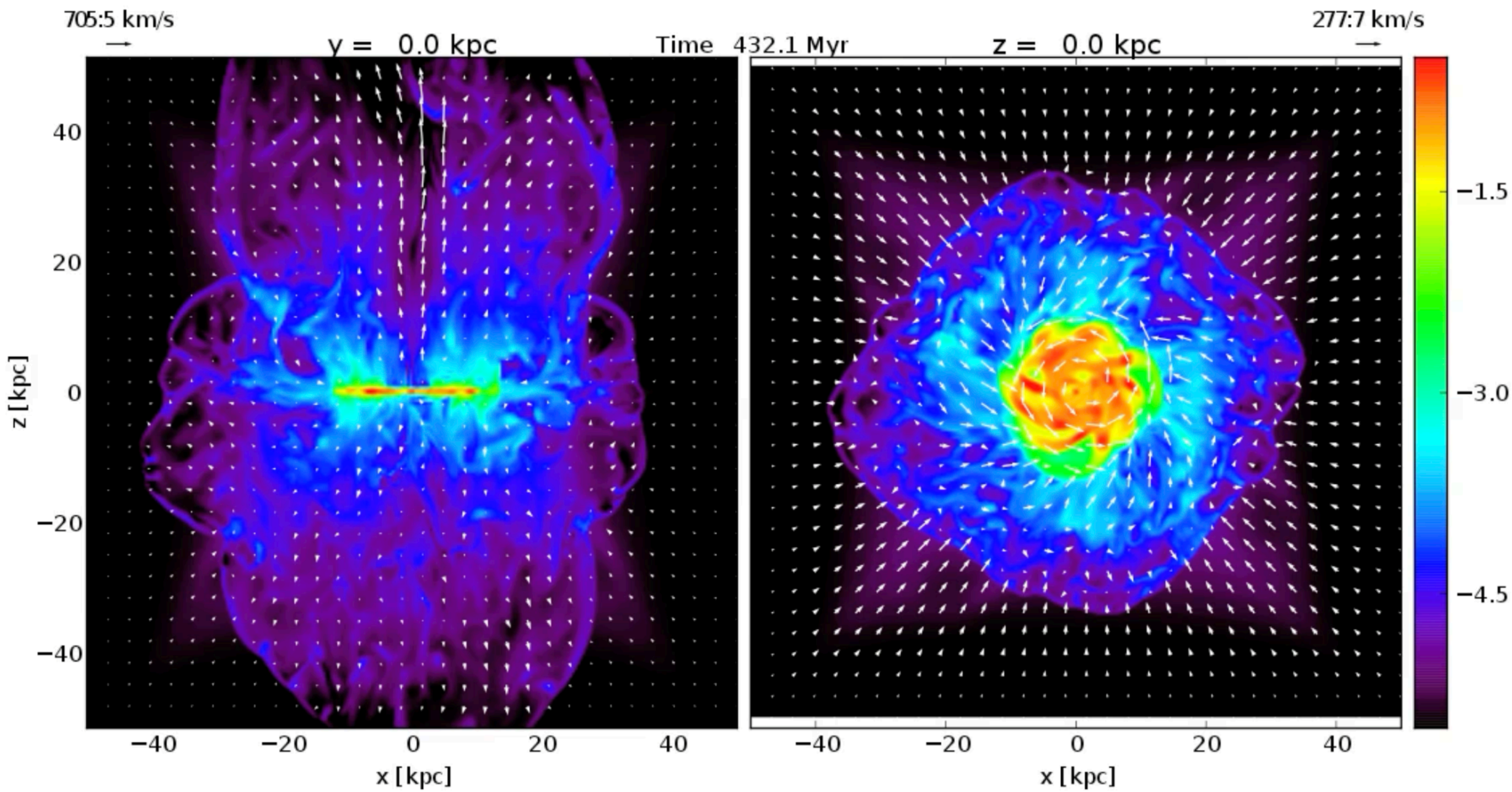


Girichidis et al. 2018a, based on SILCC setup (Walch+ 2015, Girichidis+2016)

MHD, anisotropic diffusion, isothermal

Hanasz et al. (2013)

- isolated galaxy, isothermal gas, only CR injection with supernovae

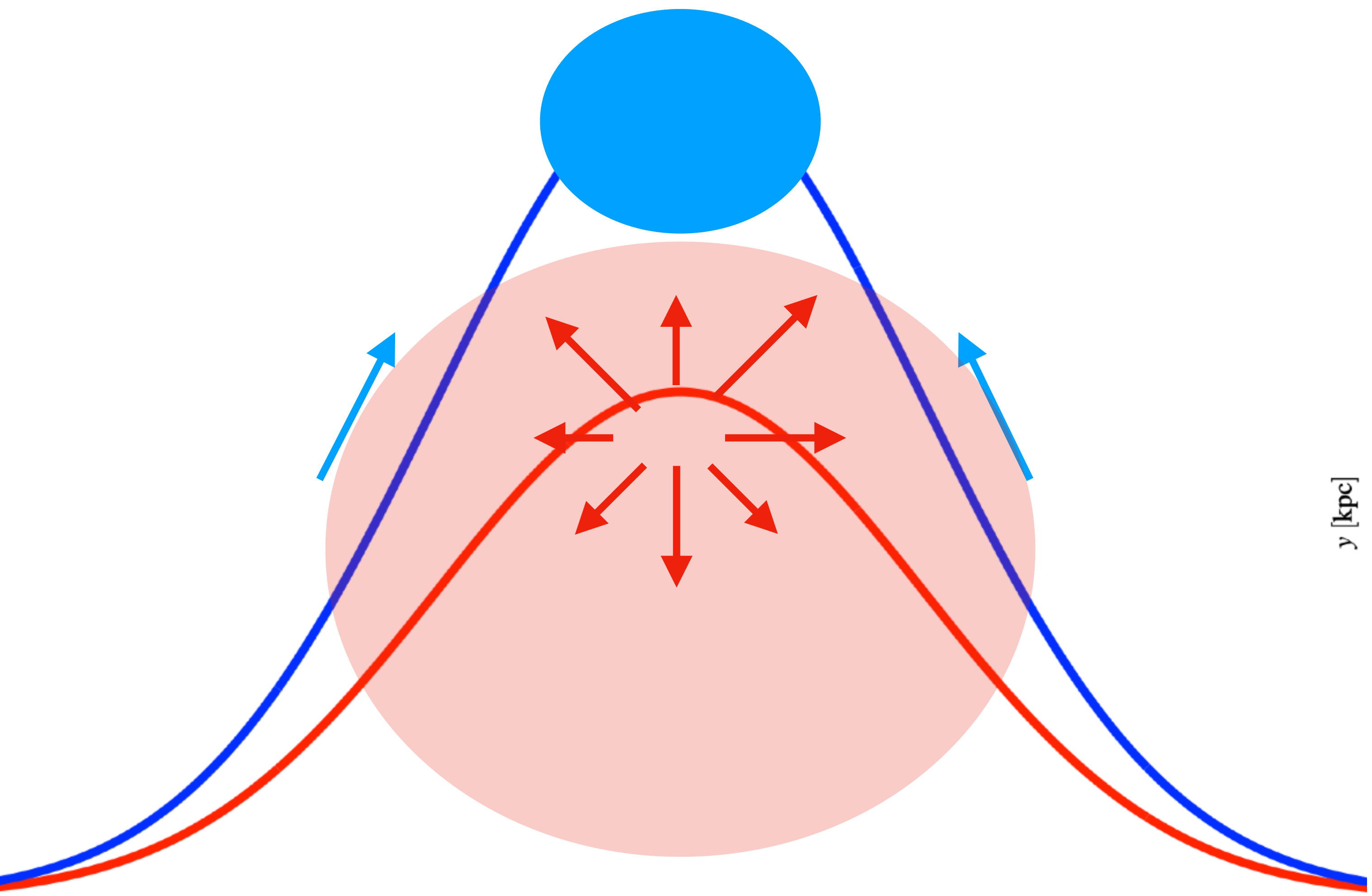


CRs alone are able to drive winds!

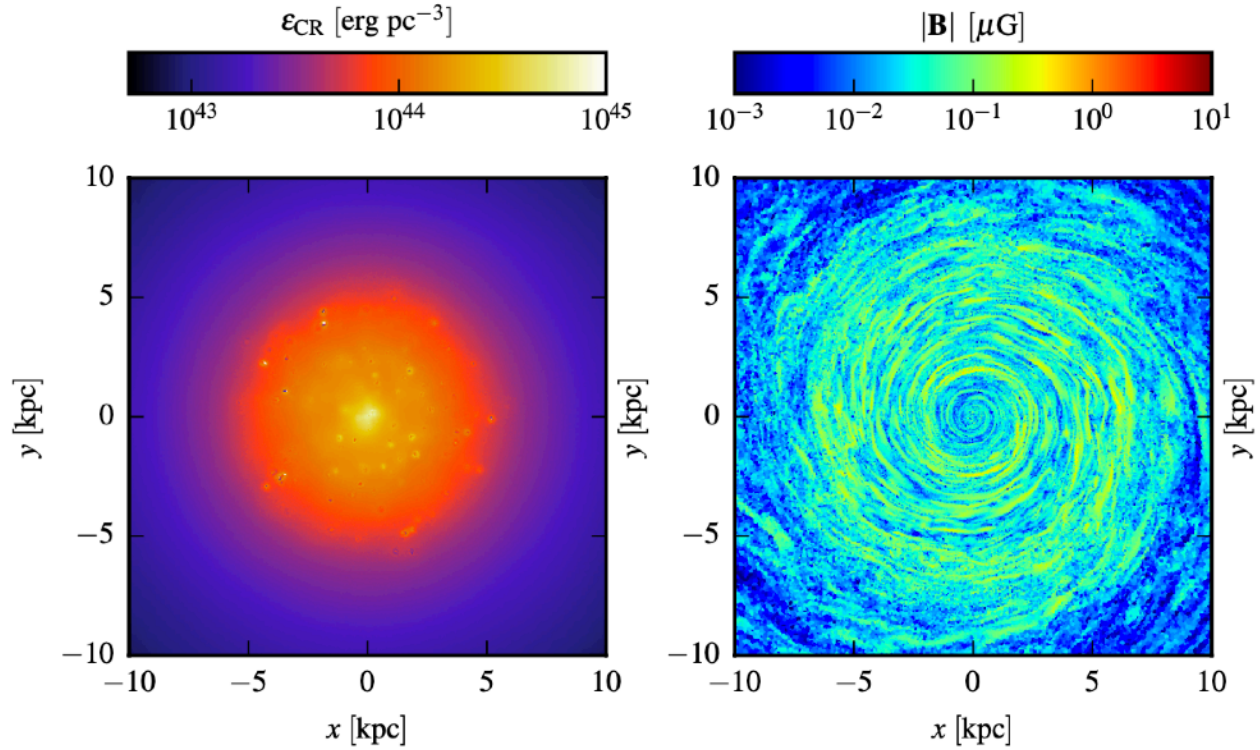
Isotropic vs. anisotropic diffusion

Pakmor et al. (2016)

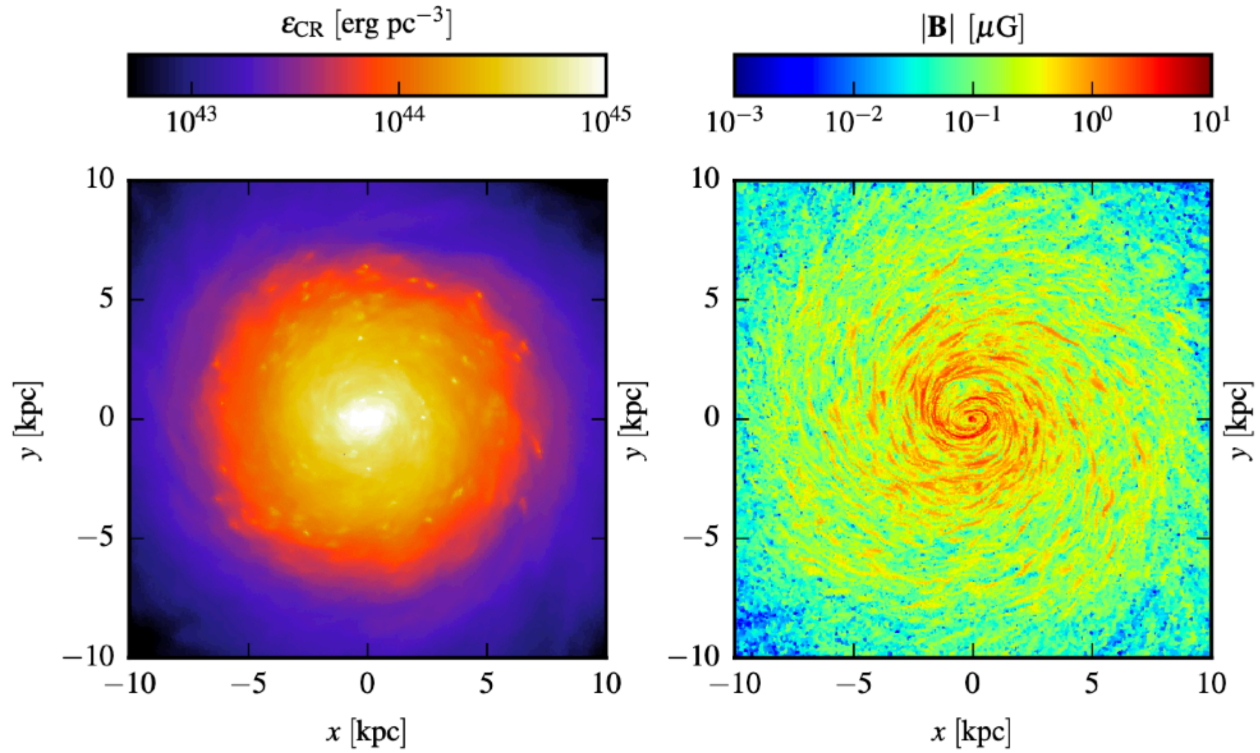
- isolated cooling halo
- simplified model for interstellar medium
- compare
  - isotropic diffusion
  - anisotropic diffusion along field lines
- impact on B-field strength
  enhance Parker loops



isotropic diffusion



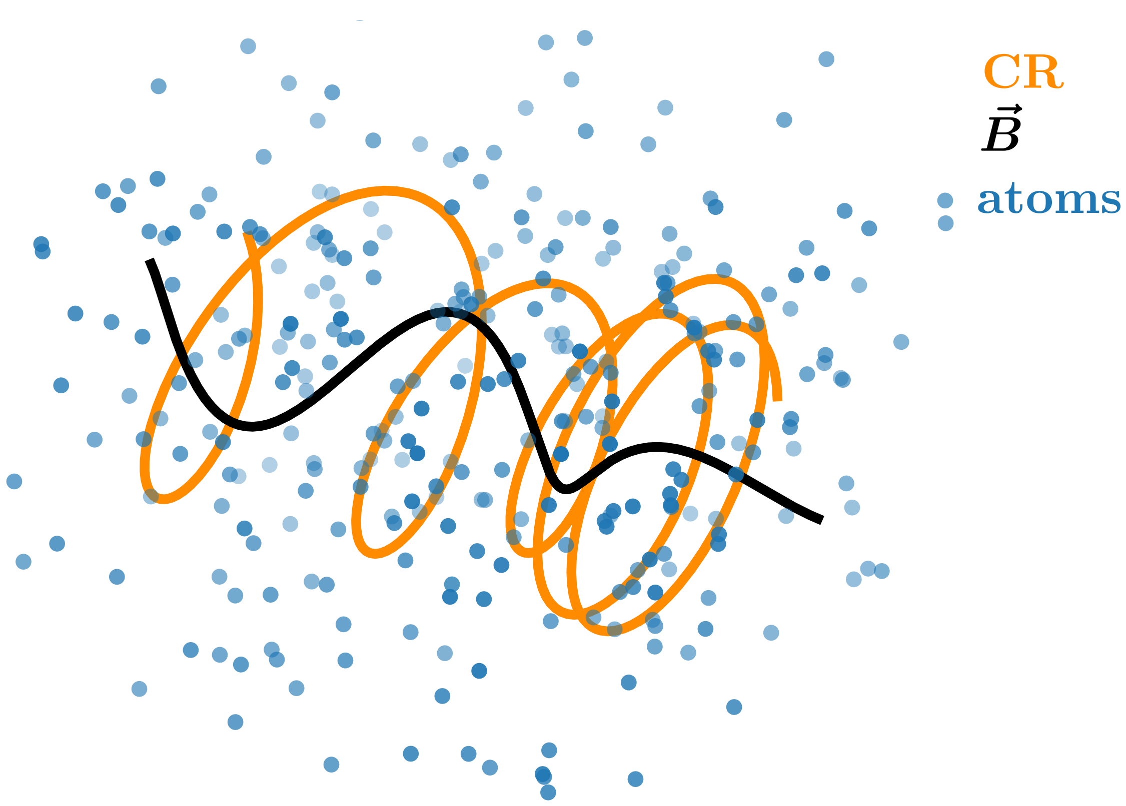
anisotropic diffusion along B

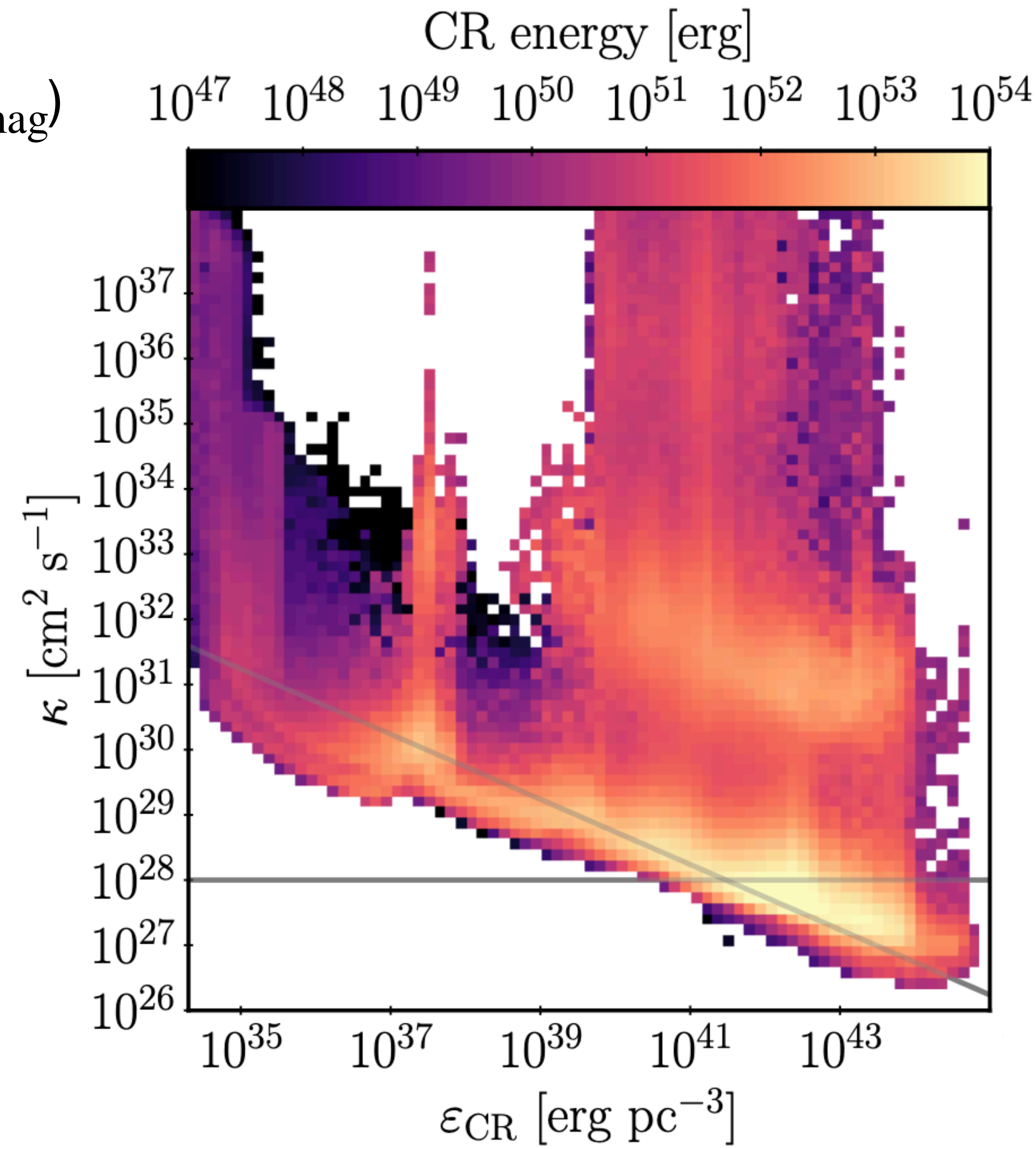


Anisotropic diffusion is important!

More accurate coupling CR ⇔ gas+B

- total CR energy high, $E_{\rm cr} \sim E_{\rm mag}$
- CRs: back-reaction onto B-field
  ⇒ no simple diffusion (energy-conserving)
  ⇒ complex transport (E-transfer $E_{\rm cr} \leftrightarrow E_{\rm mag}$)
  (Thomas & Pfrommer 2019,2021,2022,
  see also Hopkins+ 2021, Shalaby+ 2021,2022)
- bulk of CRs streams with Alfvén speed,
  Alfvén heating (e.g. Wiener+ 2013)



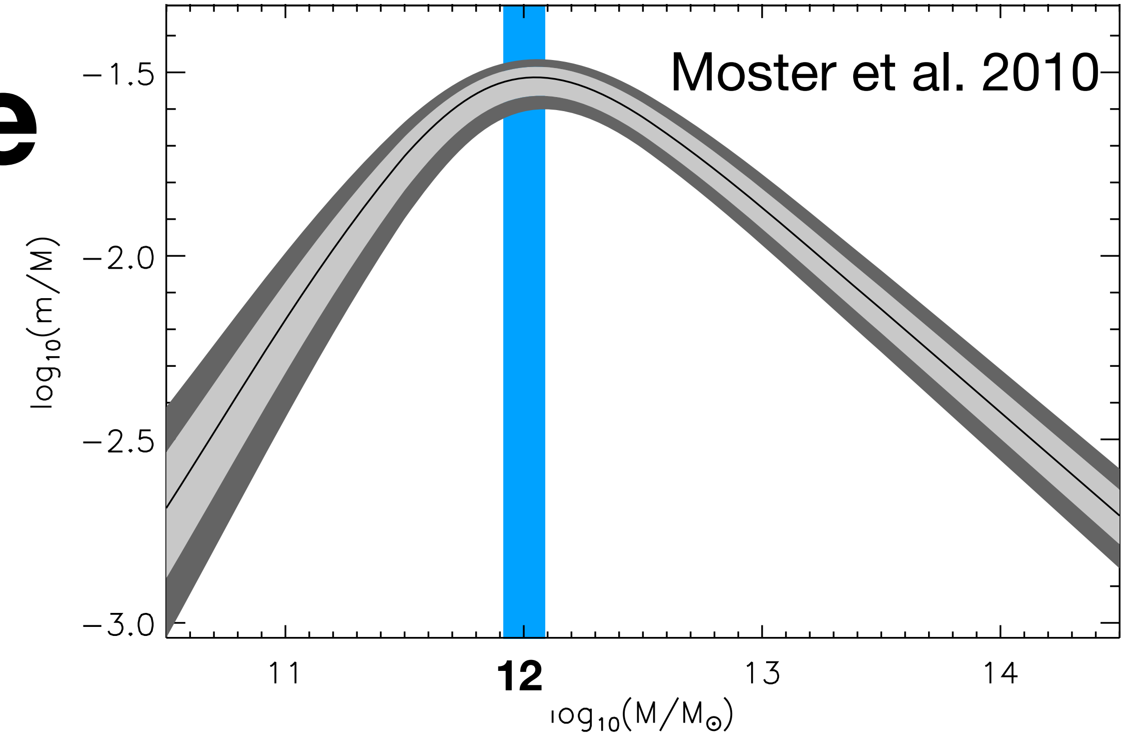


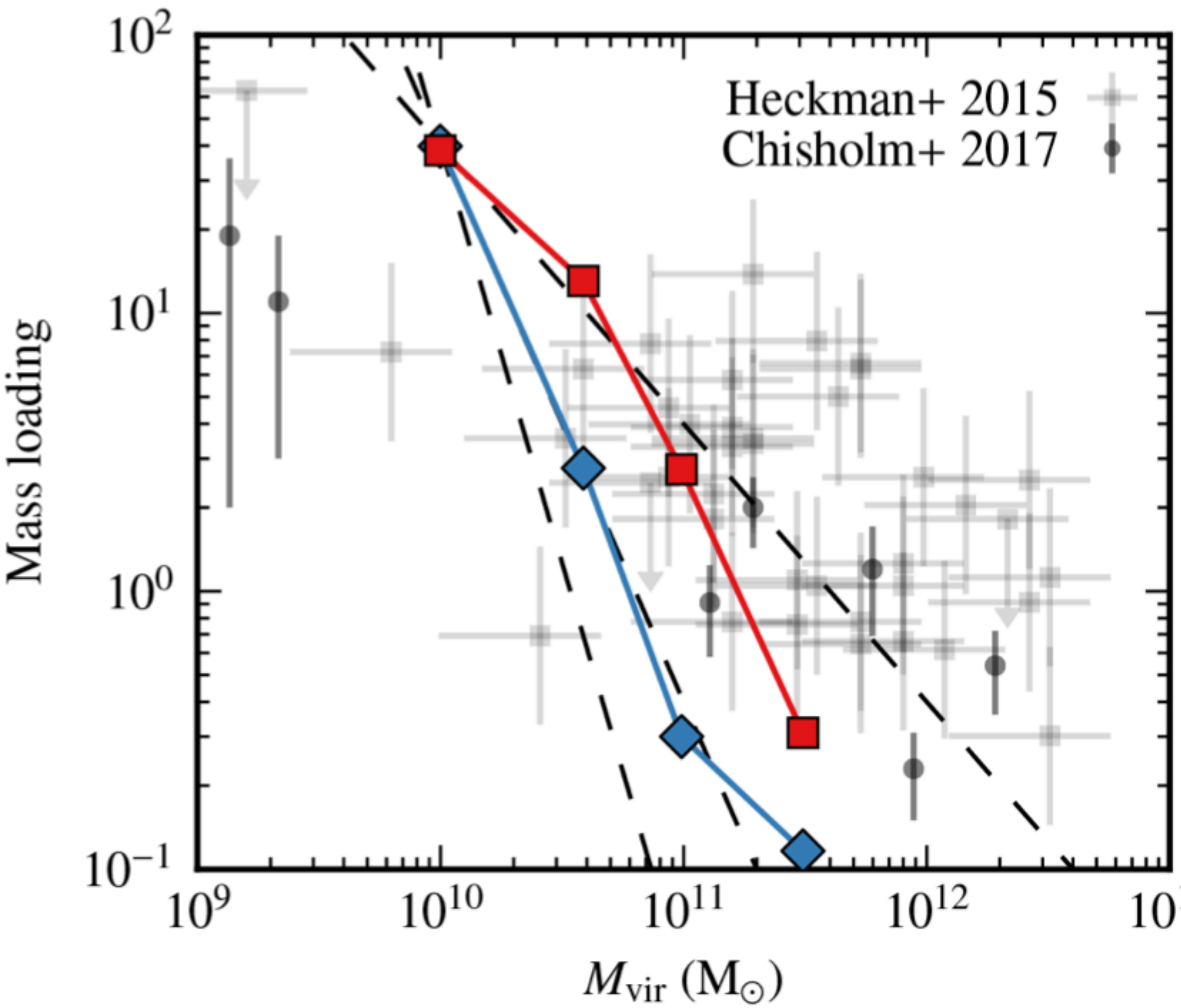
Thomas et al. 2022

Halo mass dependence

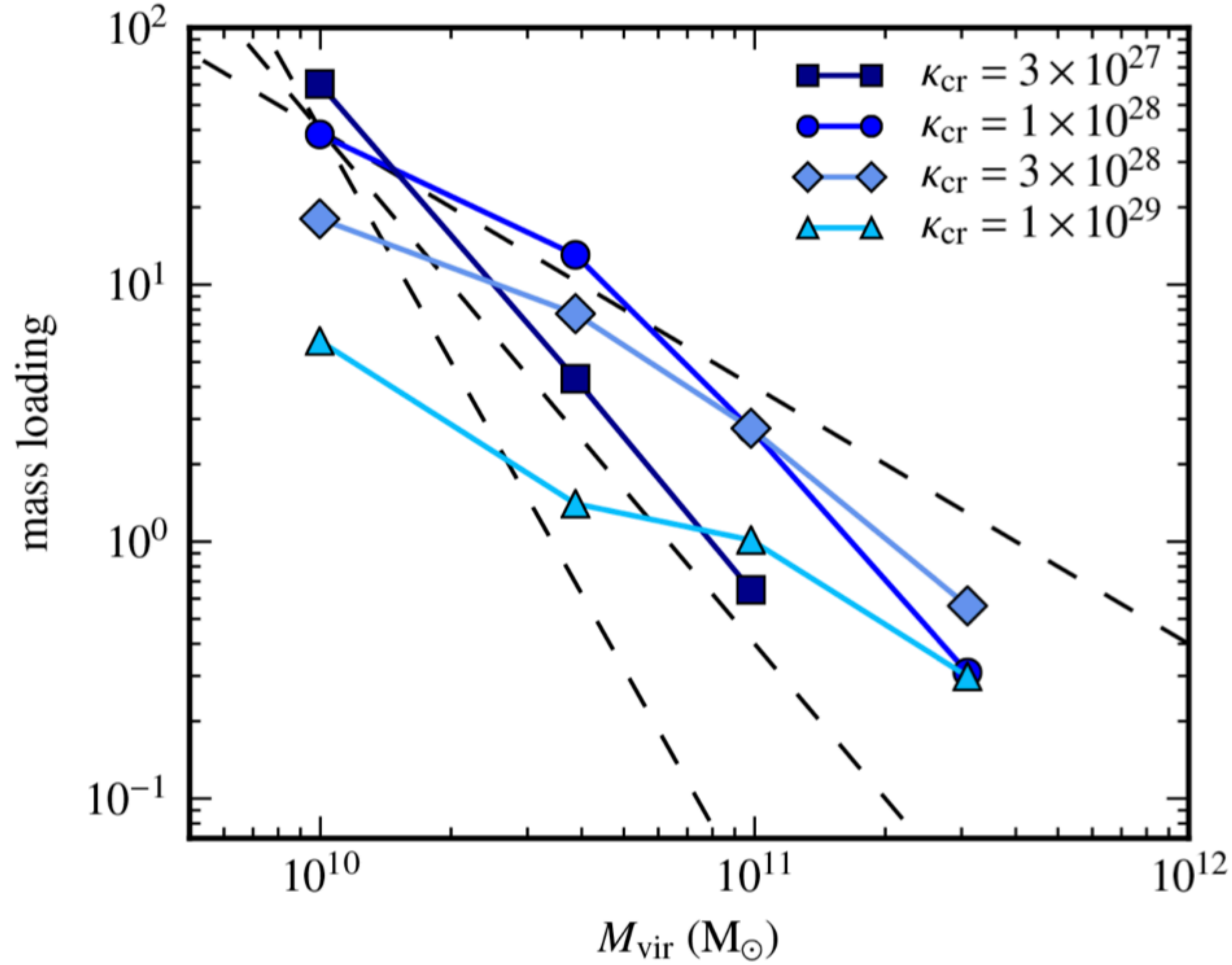
Jacob+ 2018, Girichidis+ 2023

- **outflow strength depends on halo mass**
- above $M \sim 3 \times 10^{11}\,\mathrm{M}_\odot$ no outflows
- depends on injection efficiency
- high diffusivity, weaker mass loading





Jacob et al. 2018



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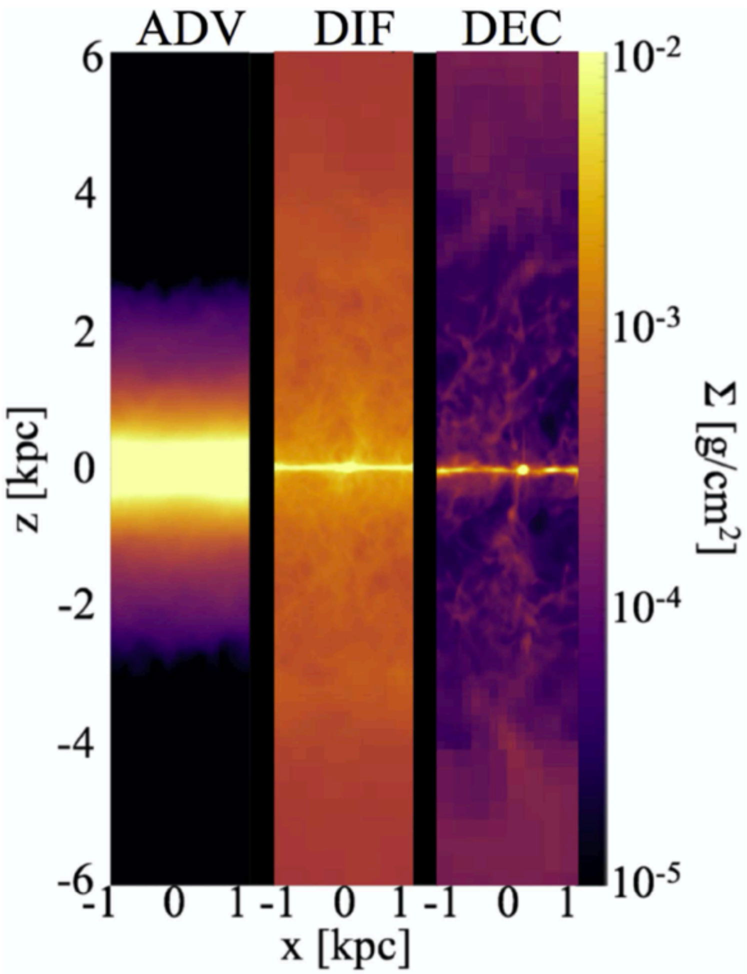

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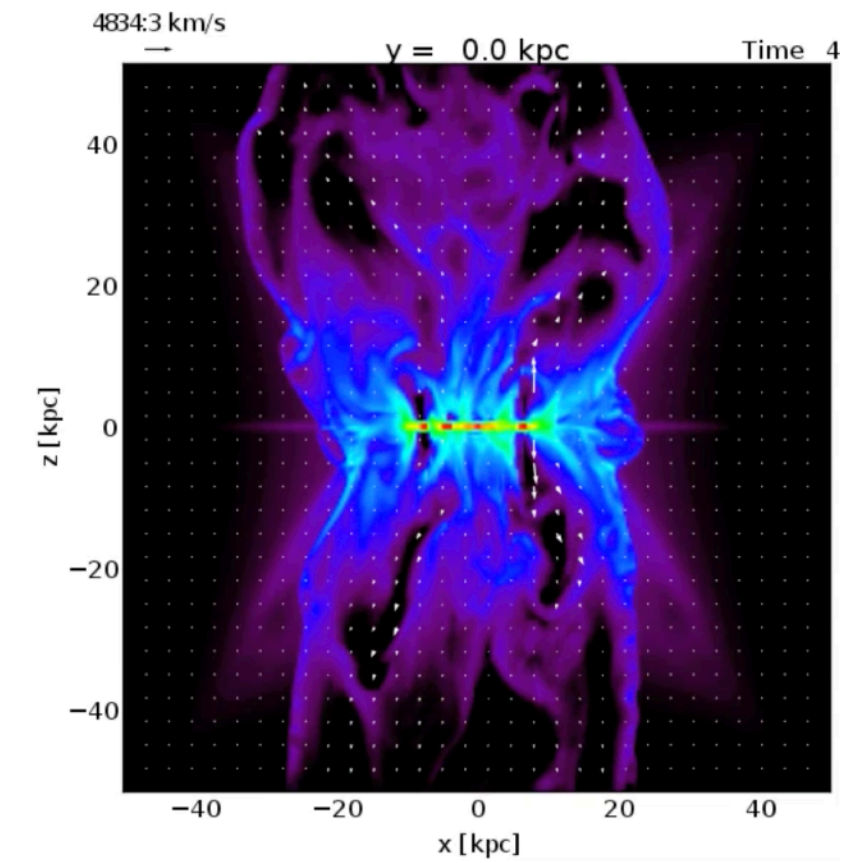

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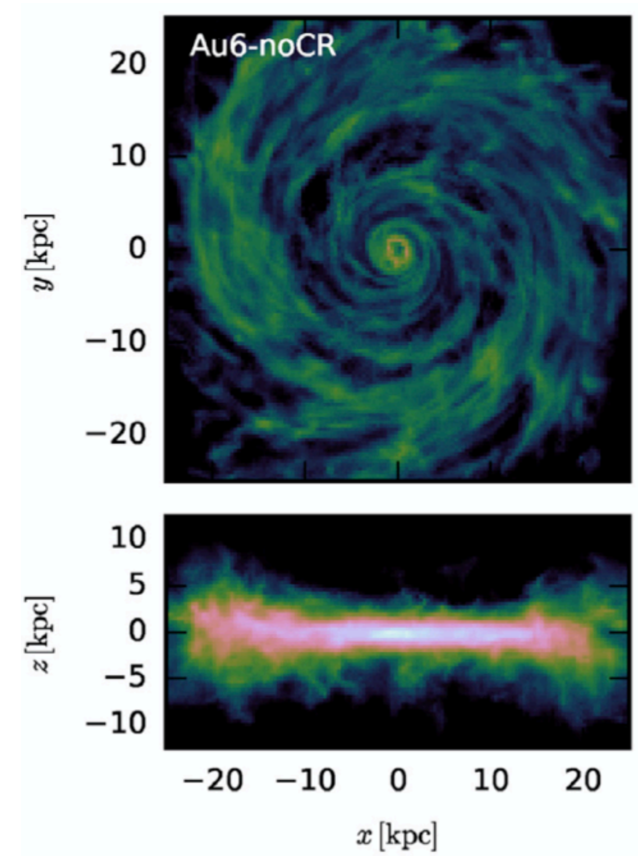

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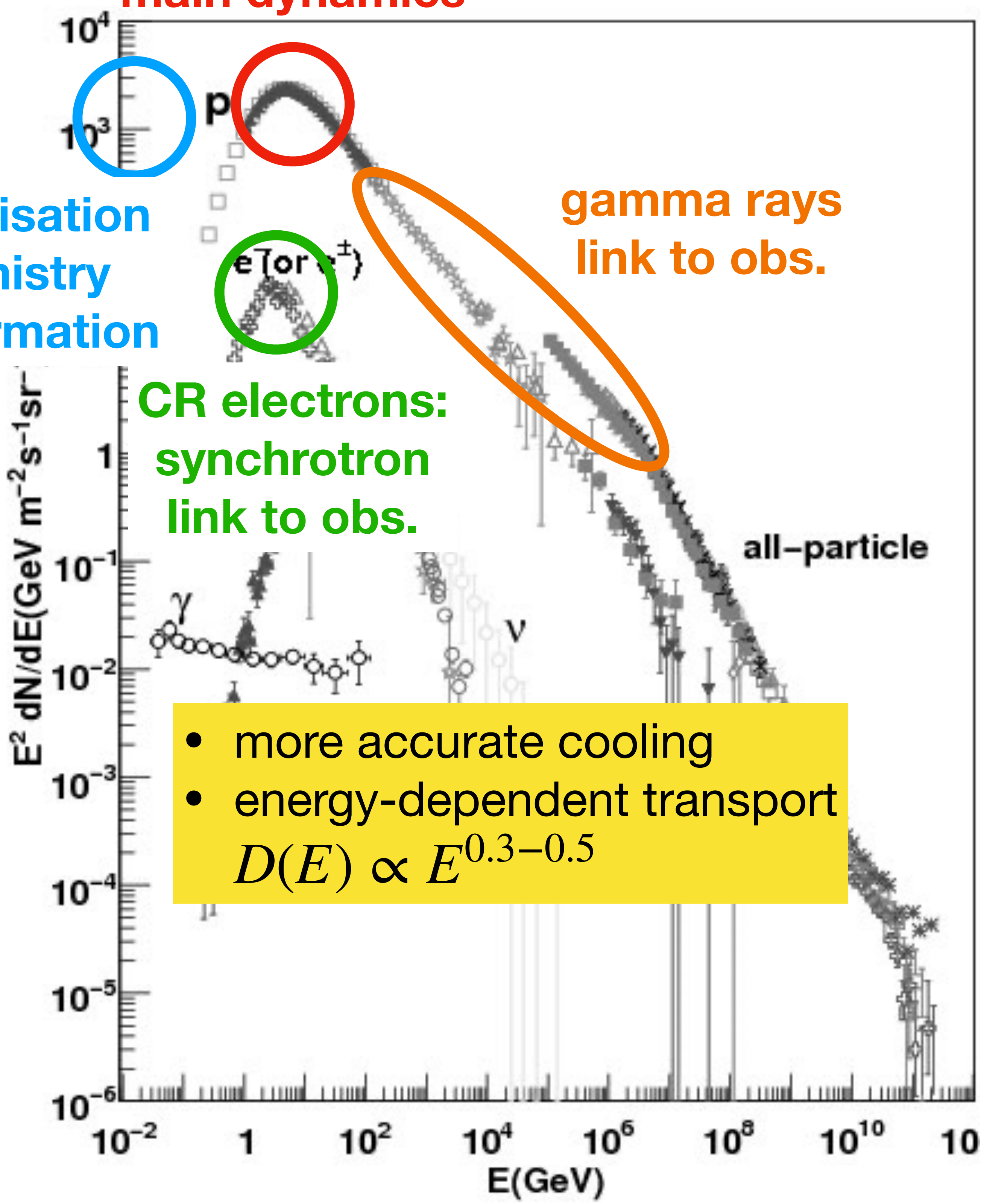
CRs are dynamically important! Details in transport etc. matter!

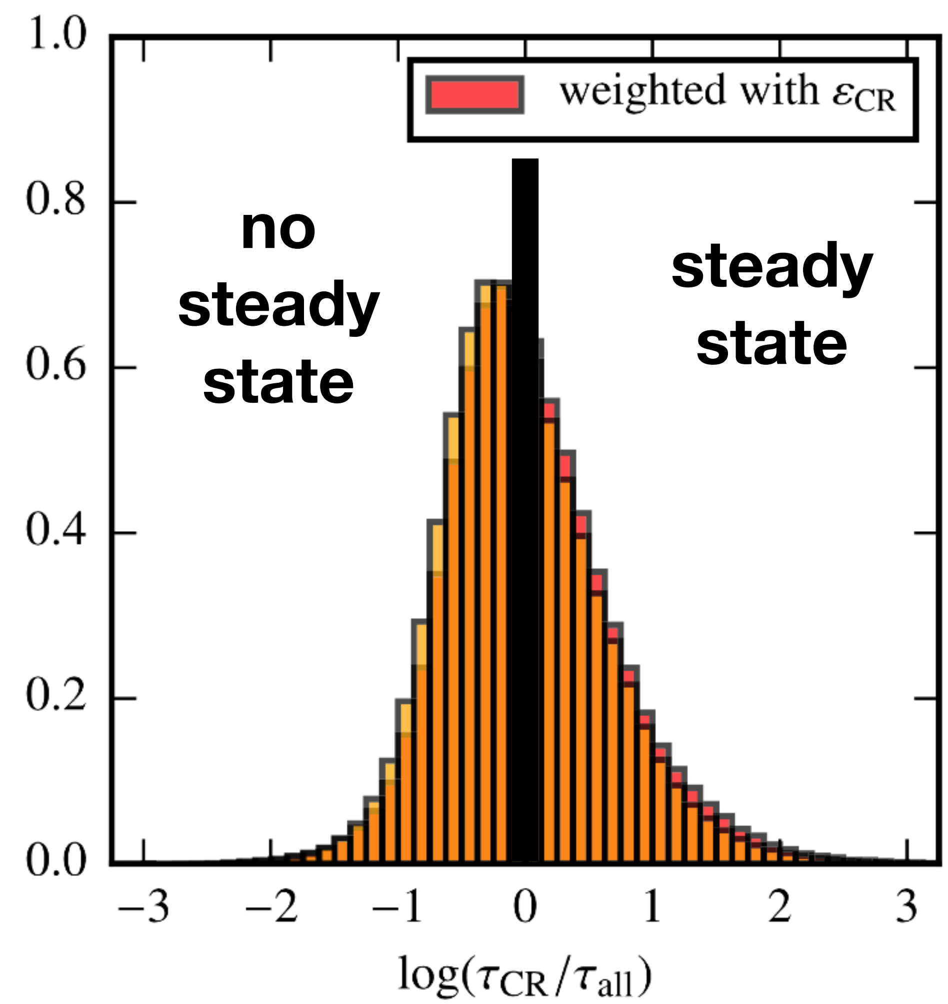
Extension to spectral code

just total energy is not enough



- more accurate cooling
- energy-dependent transport $D(E) \propto E^{0.3-0.5}$

Werhahn+ 2021a



- in large fraction of galaxy no steady state
- spectral variations are important

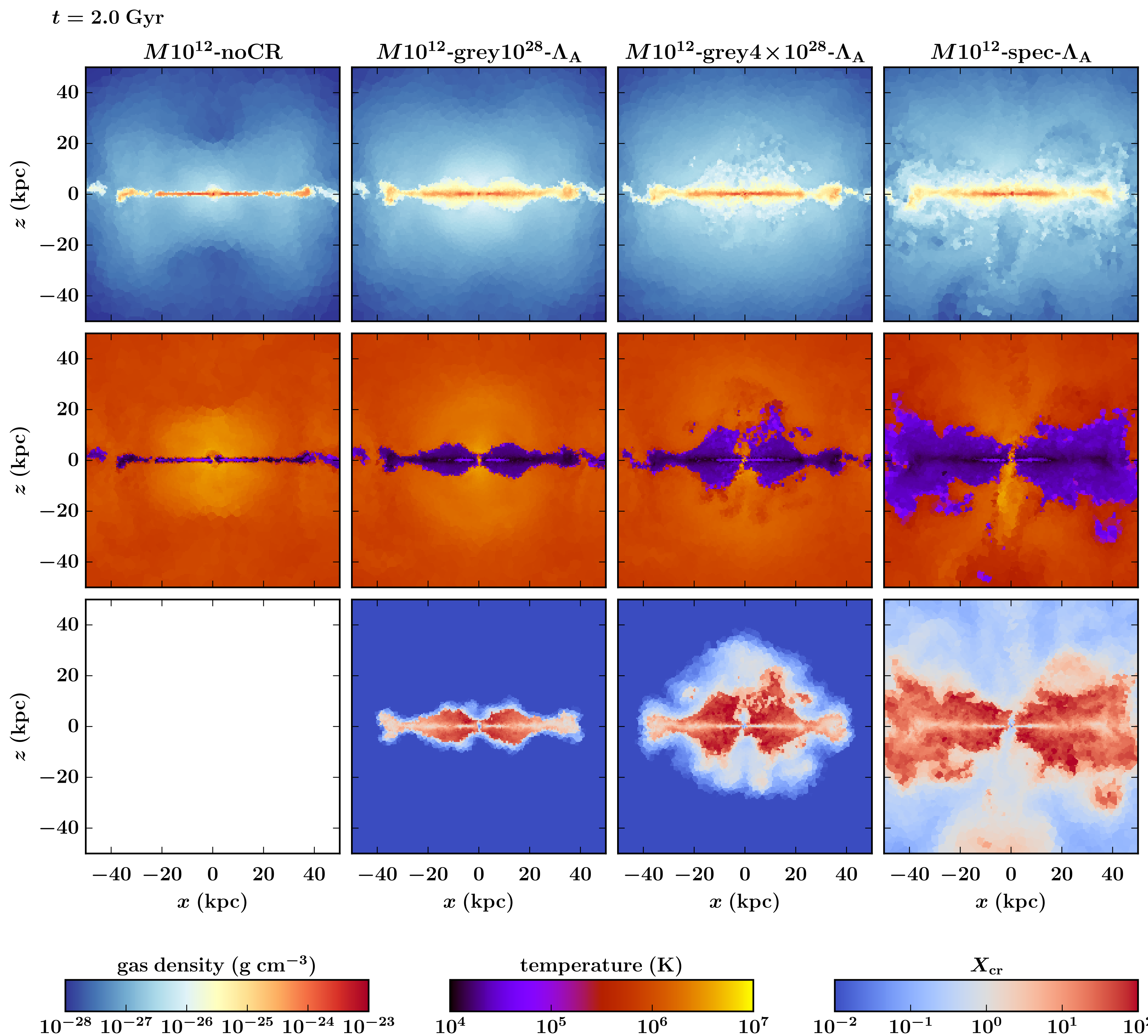
Galaxy setup with spectral CRs

temperature and CR content

Girichidis et al. 2022, 2023

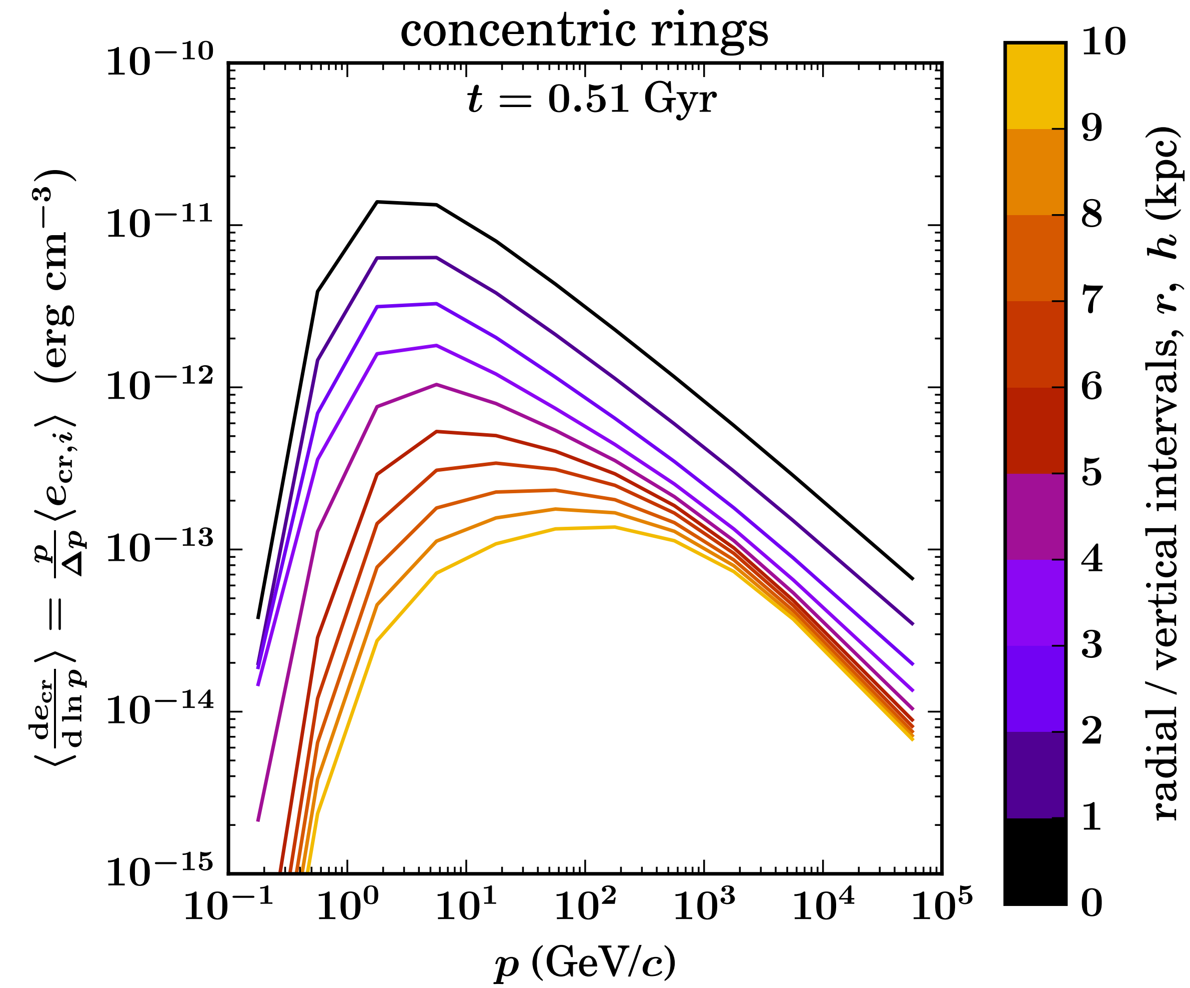
- isolated halo, rotating gas cloud
- Arepo (Springel '10, Weinberger+ '19)
- CRs (Pakmor+'16, Pfrommer+'17)
- spectral CRs (Girichidis+ '20)
- CRs: 10% of SN energy

- high-E CRs escape faster
- larger region of cold CGM impact on gal. fountain
- larger region with CR dominated pressure

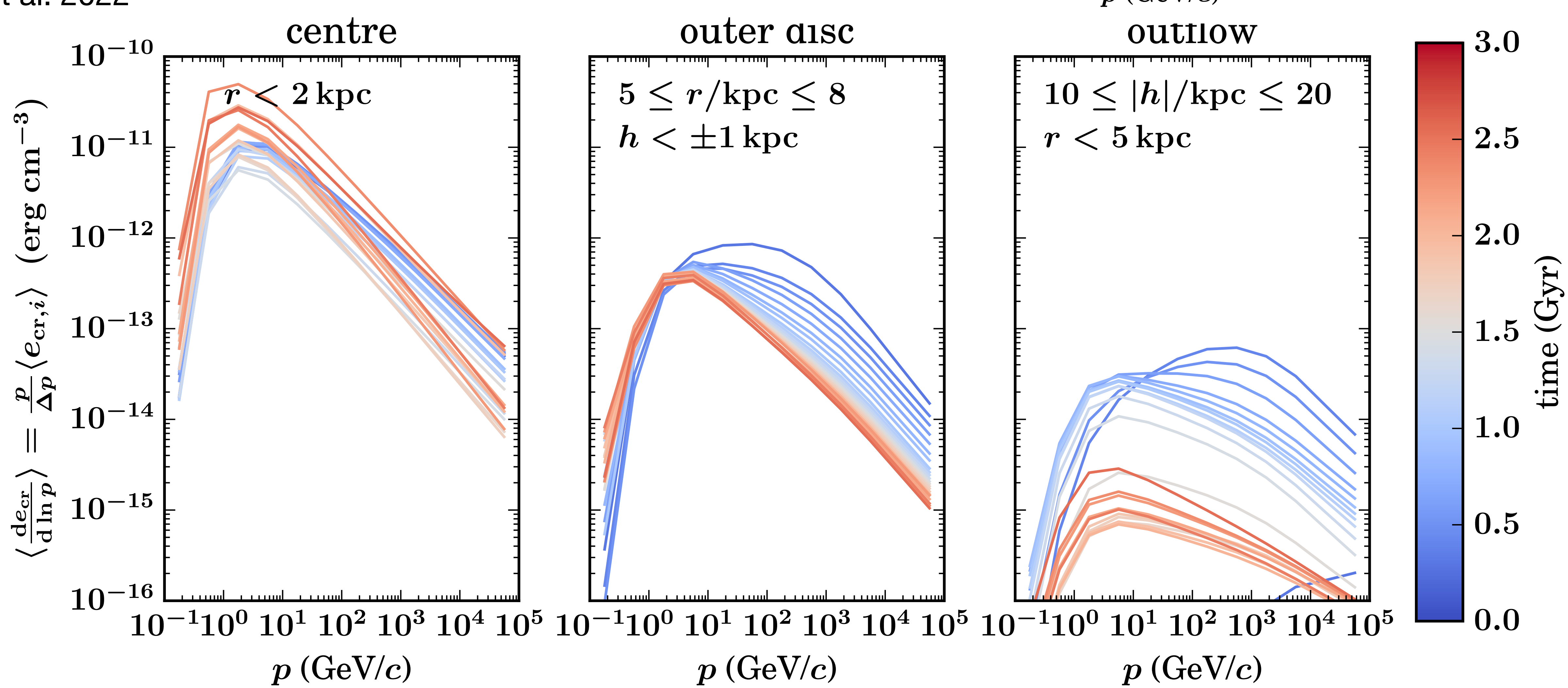


CR spectra
spatial and temporal variations

- spectra at large distance: more high-E CRs
- larger distance -> lower total CR energy
- many regions: no steady state spectrum



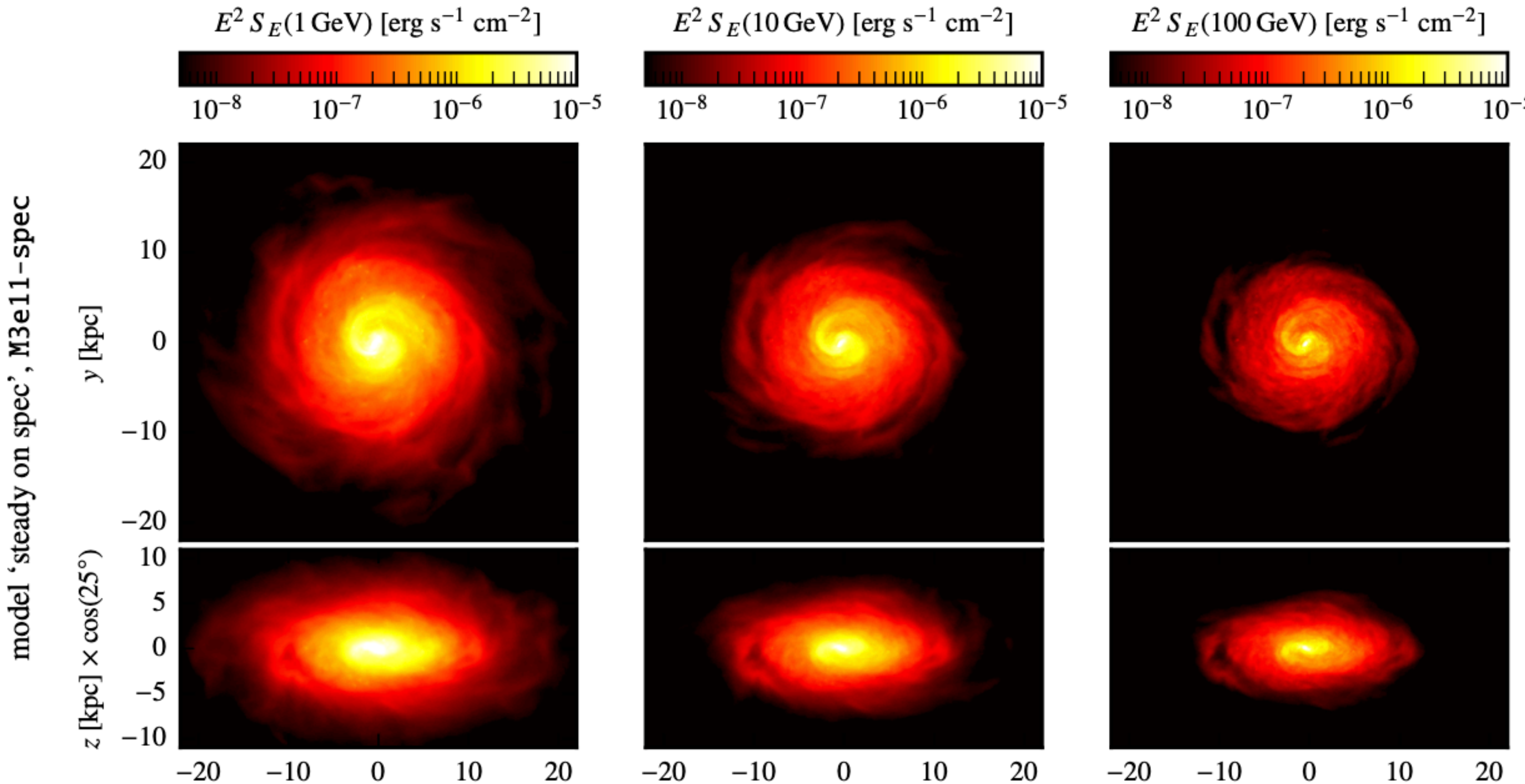
Girichidis et al. 2022



Connection to Gamma-ray obs.

- gamma rays differ: steady state vs. full spectrum (Werhahn+ 2021abc, 2022)

assuming steady state spectra using spectrally resolved simulations



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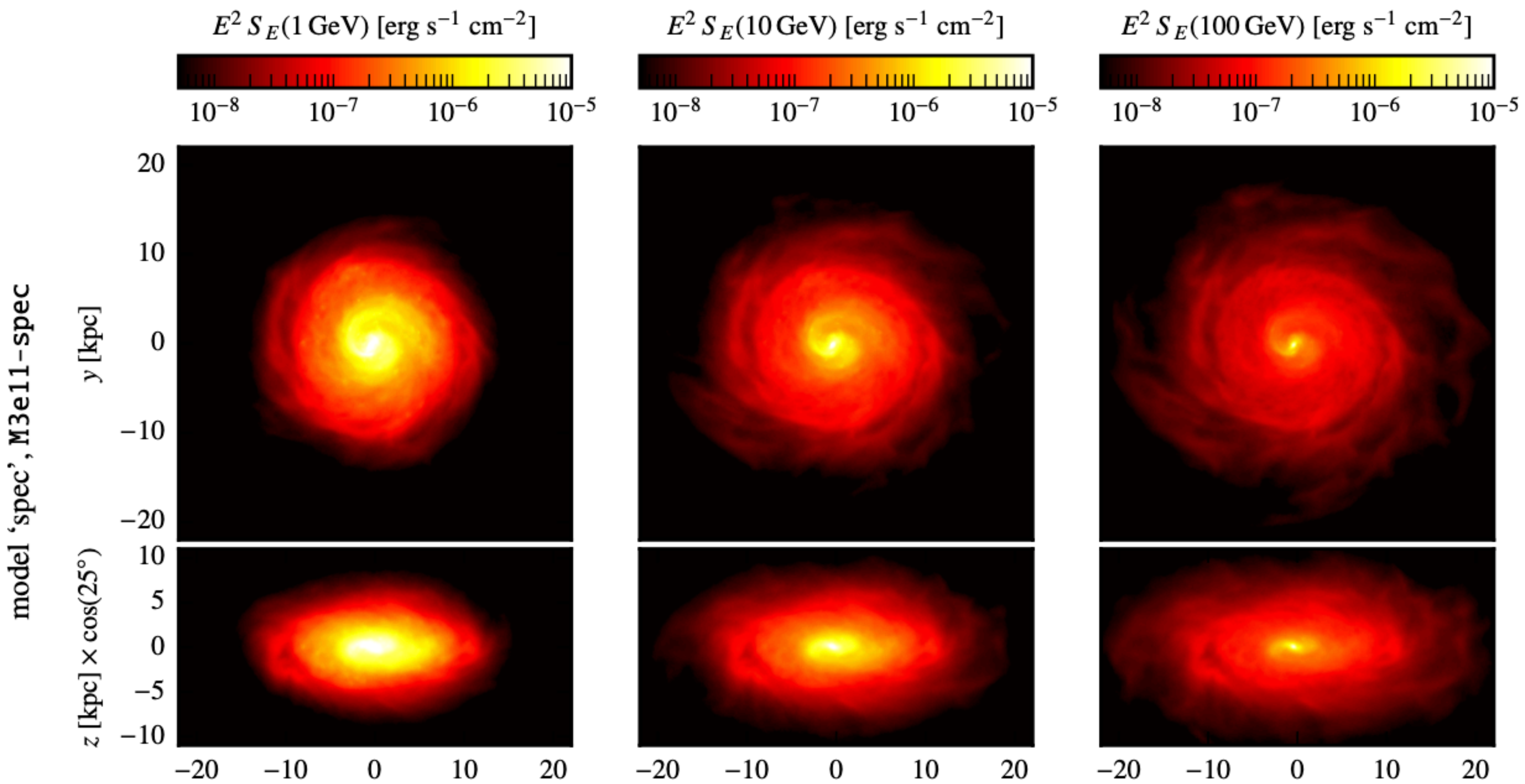
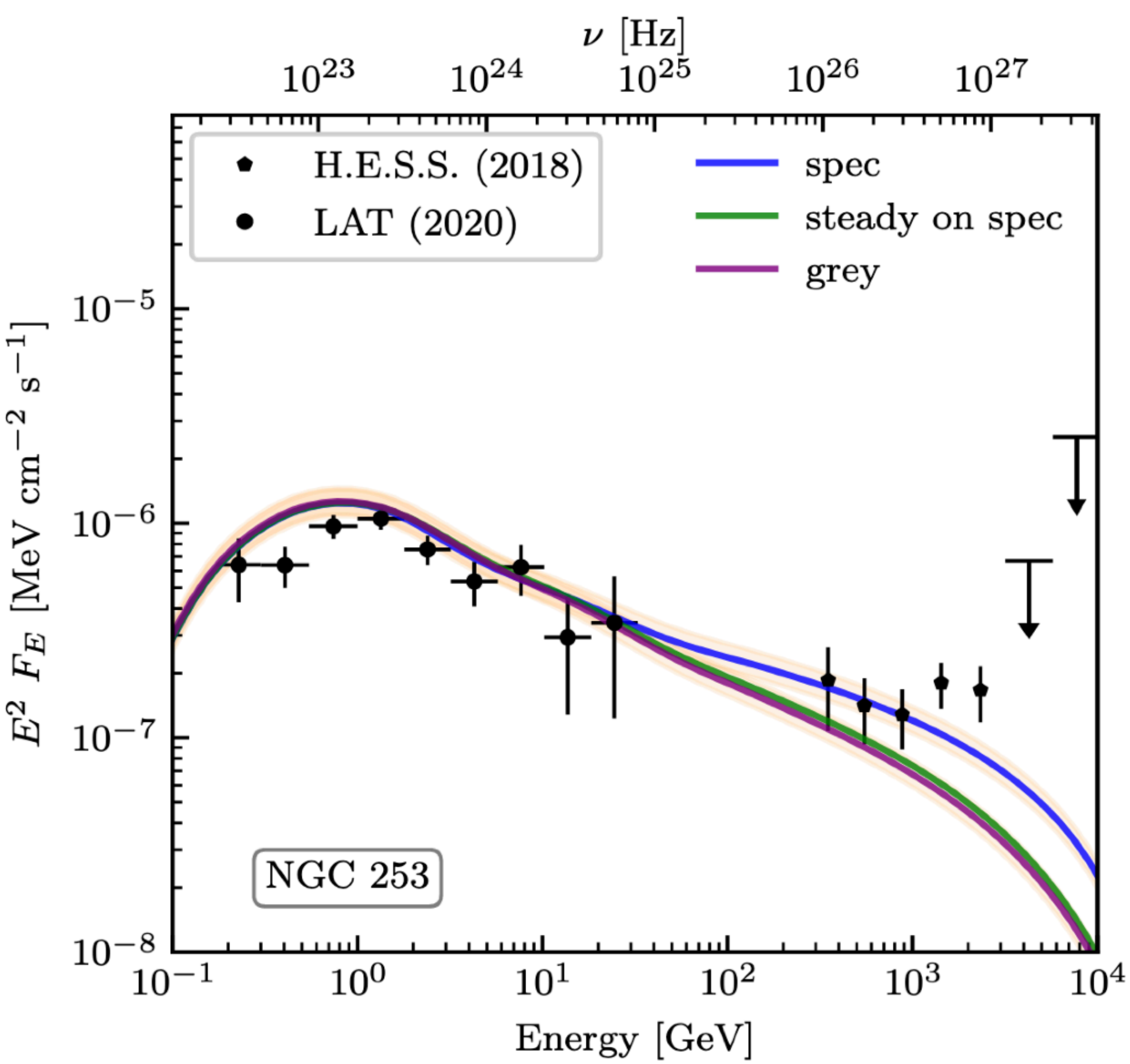
“true” spectra of the spectrally resolved simulations

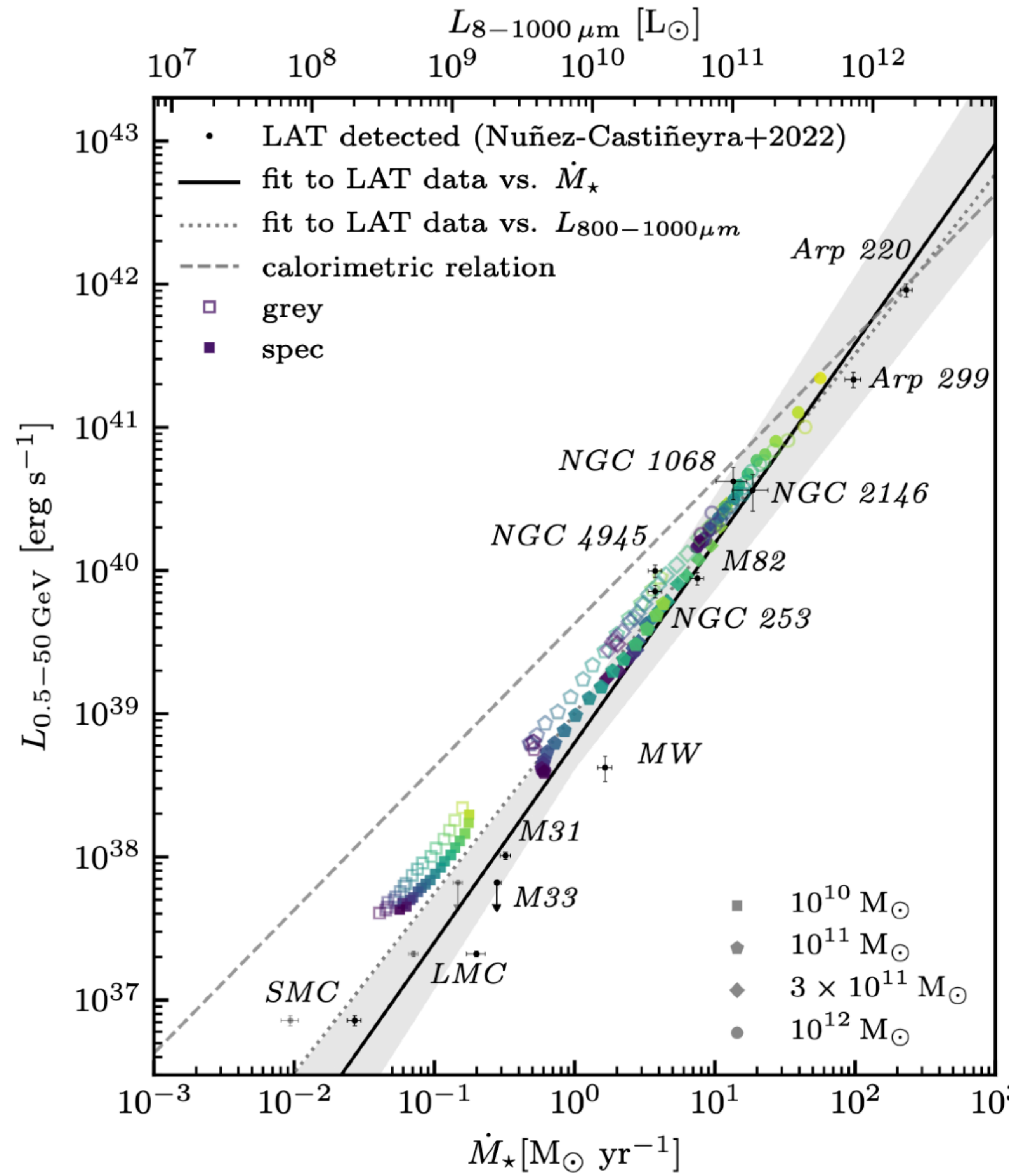


Gamma rays II

comp. to observations

Werhahn et al. 2022



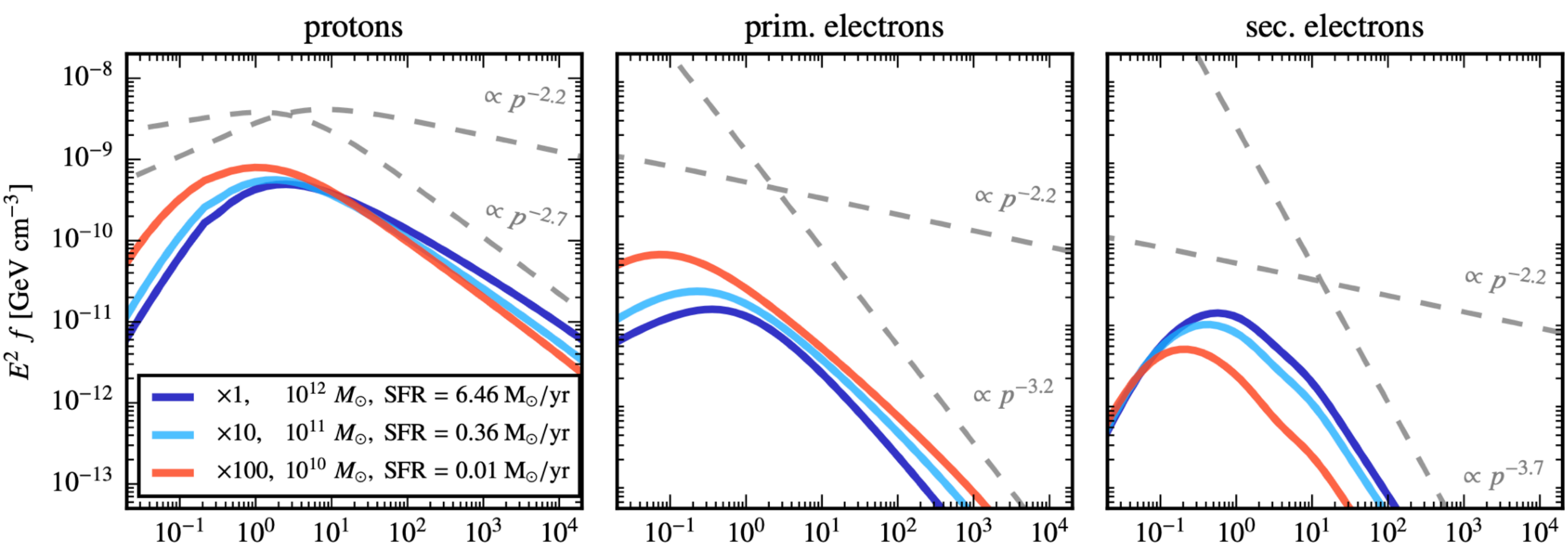


- spectral model: better fit to spectra and SFR-γ luminosity

Beyond CR protons

Werhahn+ in prep
Whittingham+ in prep
Ljassi+ in prep

- include CR electrons as tracer particles
- compute electron losses spectrally resolved (Winner+ 2019,2020)
- compute secondary electrons
- compute synchrotron radiation self-consistently



Summary and Conclusions

- *cosmic rays are dynamically important*
  → thicken the disk
  → drive smooth and warm outflows
  → at mass loading factors of order unity

- *spectrally resolved CRs*
  → change the temperature of the circum-galactic medium
  → alter the onset of outflows
  → provide accurate link to observations
    → via gamma rays (spectral models: better fit)
    → via radio synchrotron (electrons) (work in progress)