Cosmic ray feedback: the dynamical impact

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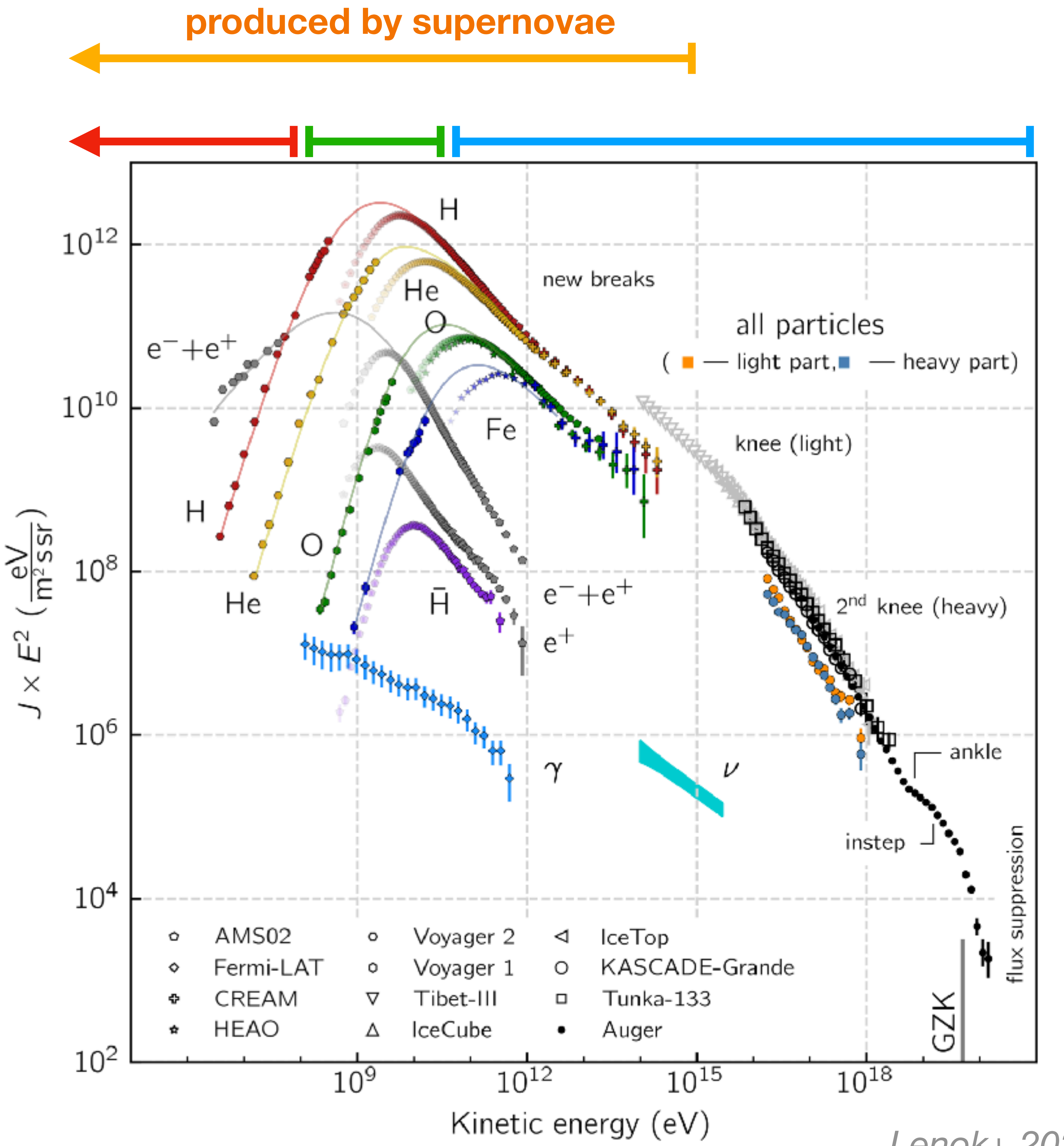
TOSCA-2024
Siena, Italy
October 29, 2024

CR energy ranges

- **low-E CRs** *Padovani+ 2020*
  Large cross section with gas, strong losses
  heating of dense star forming regions

- **GeV CRs** *Ferriere 2001, Ruszkowski & Pfrommer 2023*
  Most of energy (weak losses)
  Dynamically relevant via pressure:
  in ISM: $e_{\mathrm{cr}} \sim e_{\mathrm{kin}} \sim e_{\mathrm{therm}} \sim e_{\mathrm{mag}}$

- **high-E CRs** *Kotera & Olinto 2011*
  Low integrated energy
  Extragalactic
  important as **observational diagnostics**

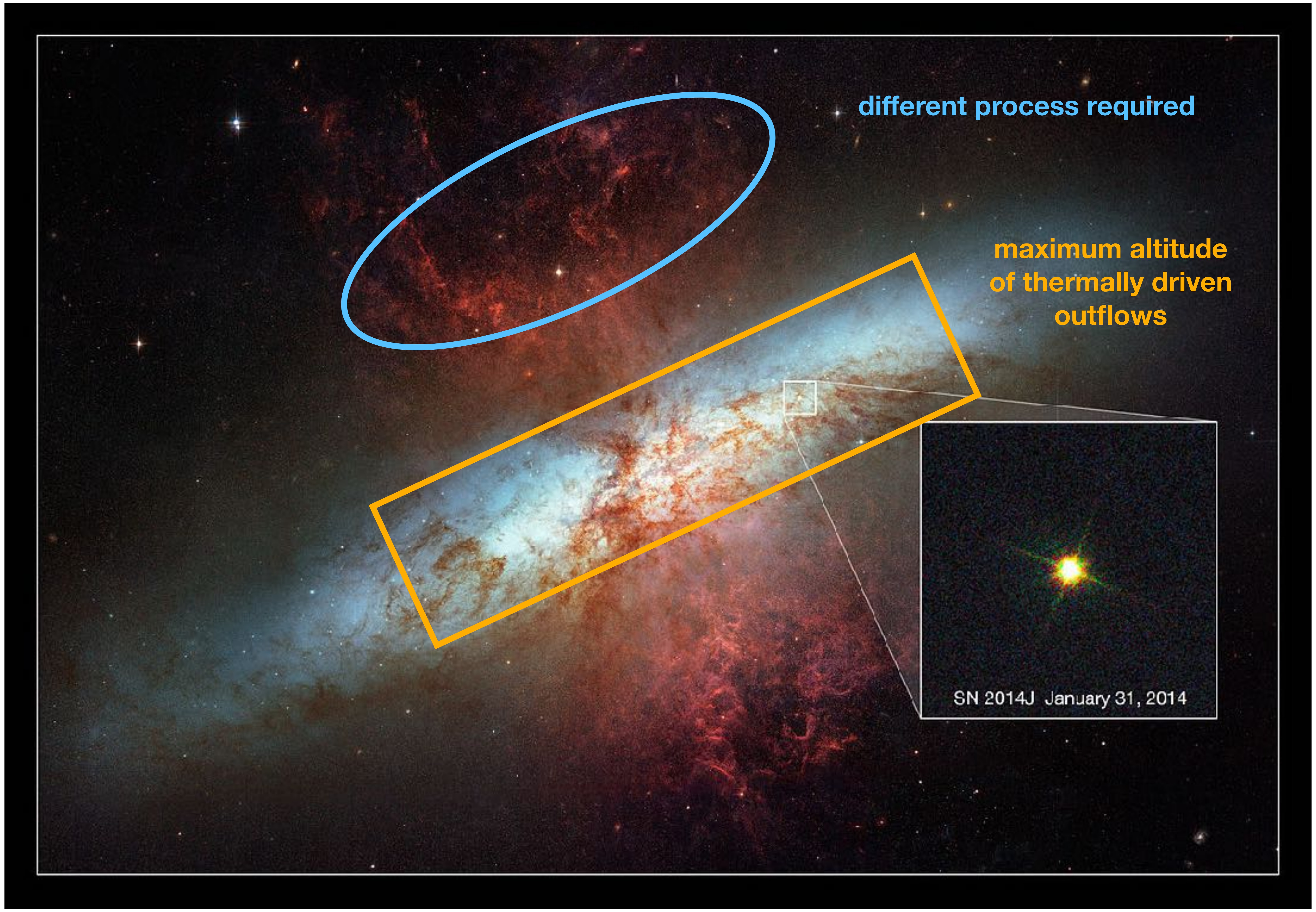


Lenok+ 2022

Motivation for CRs in the ISM of galaxies

classical stellar feedback too weak

reviews: *Zweibel 2017, Recchia 2020, Ruszkowski&Pfrommer 2023*



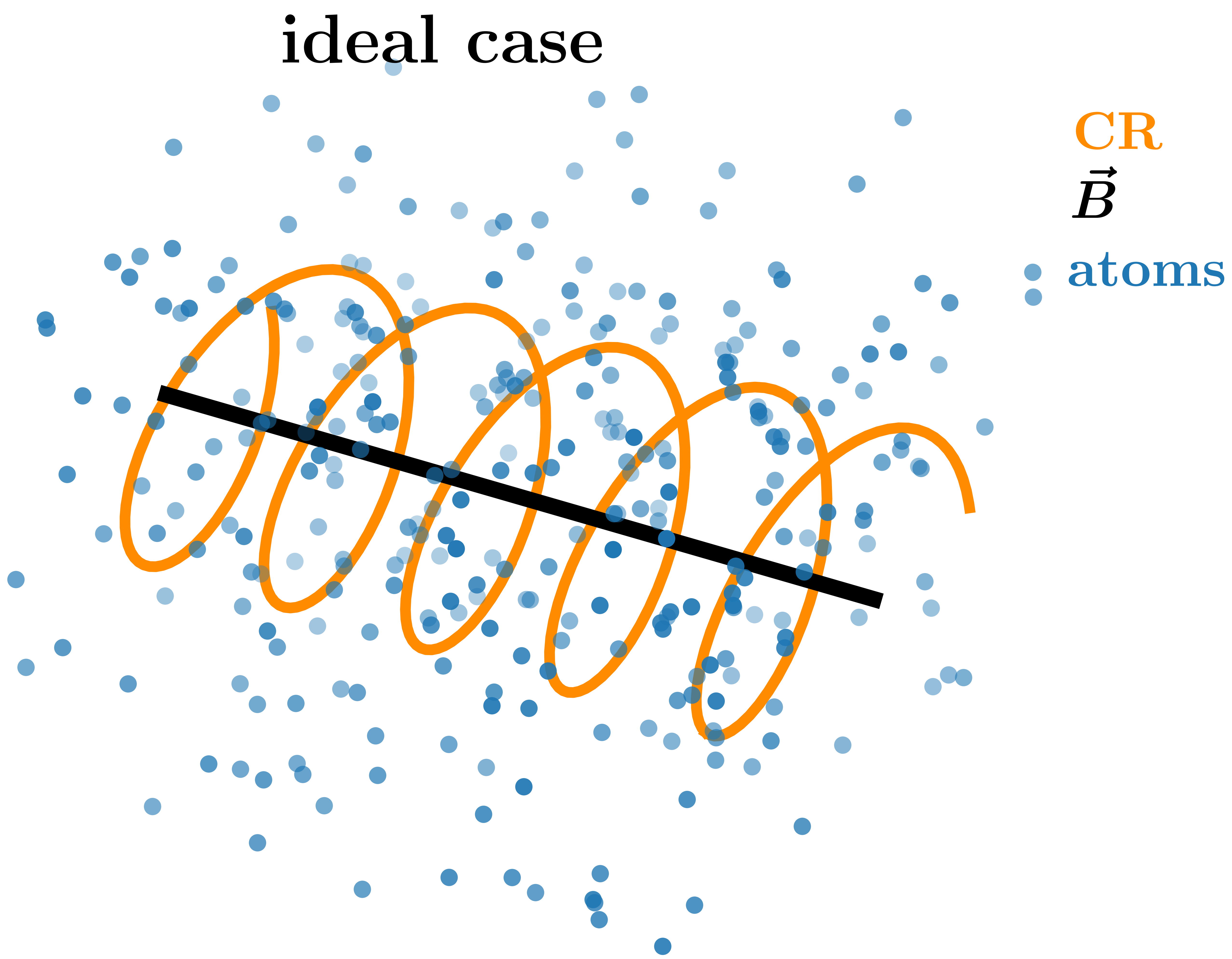
- evidence for strong outflows in all phases, H^+, H, H_2
- classical stellar feedback
  - cools too fast (SNe)
  - does not couple enough (γ)
  - too weak (winds, protost. outflows)
- CRs are **fast** & **cool inefficiently** (energy can reach large heights)

reviews: *Zweibel 2013, Amato&Blasi 2018*
Ruszkowski&Pfrommer 2023
numerics: *Hanasz+ 2021*

CR Transport illustrated

Advection

- CR gyrate around B
- no direct particle-particle interaction
- vertical motions of B
  $\Rightarrow$ coupled to motions of CRs
- gas (partially) ionized
- B frozen in gas, ideal MHD
- CR $\leftrightarrow$ B $\leftrightarrow$ gas
- advection with the gas



reviews: *Zweibel 2013, Amato&Blasi 2018*
Ruszkowski&Pfrommer 2023
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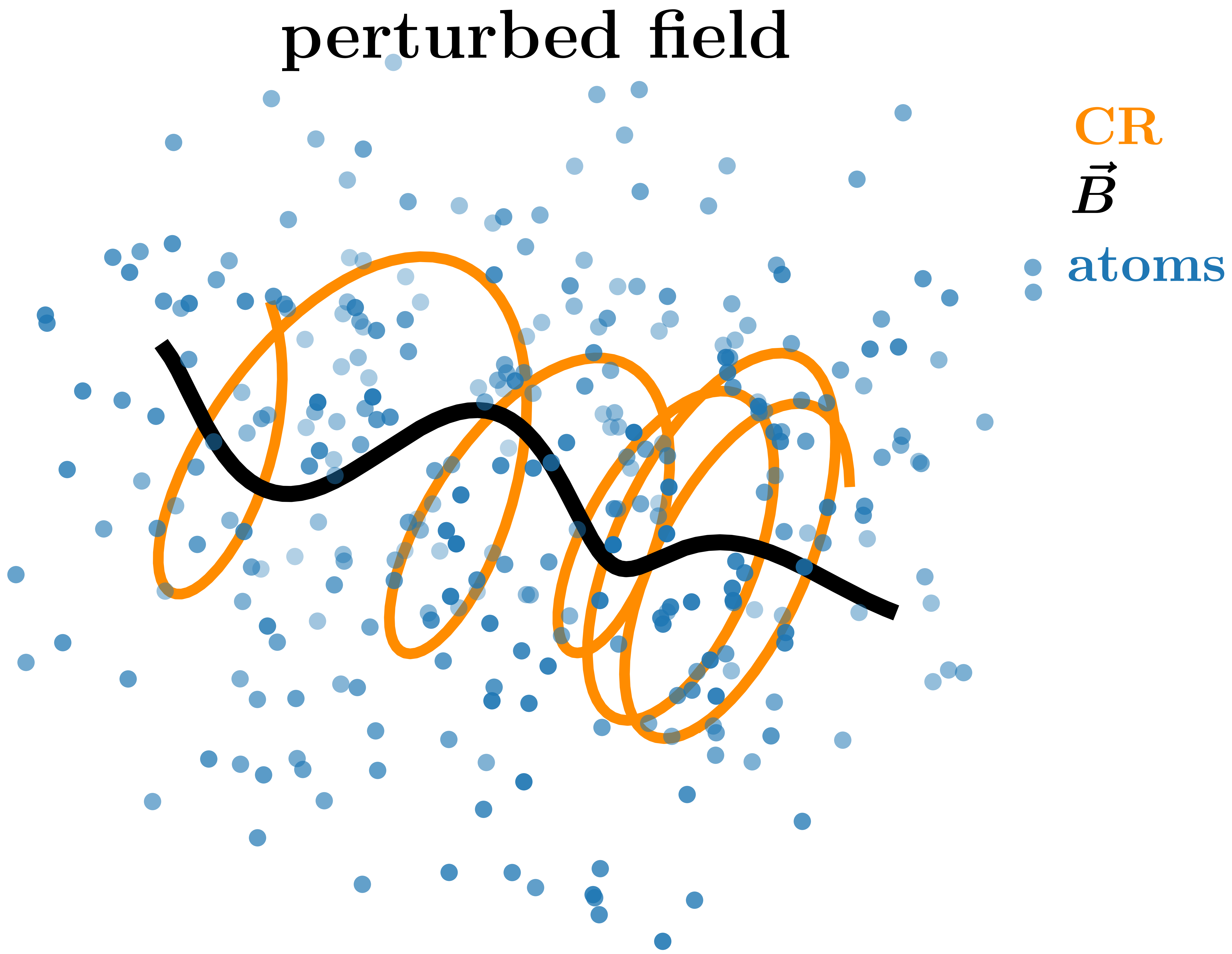
CR Transport illustrated

Diffusion

- perturbed field,
  turbulent environment
- scattering off of B irregularities
- elastic scattering ⇒ diffusion
- diffusion relative to the gas
- diffusion mainly along B



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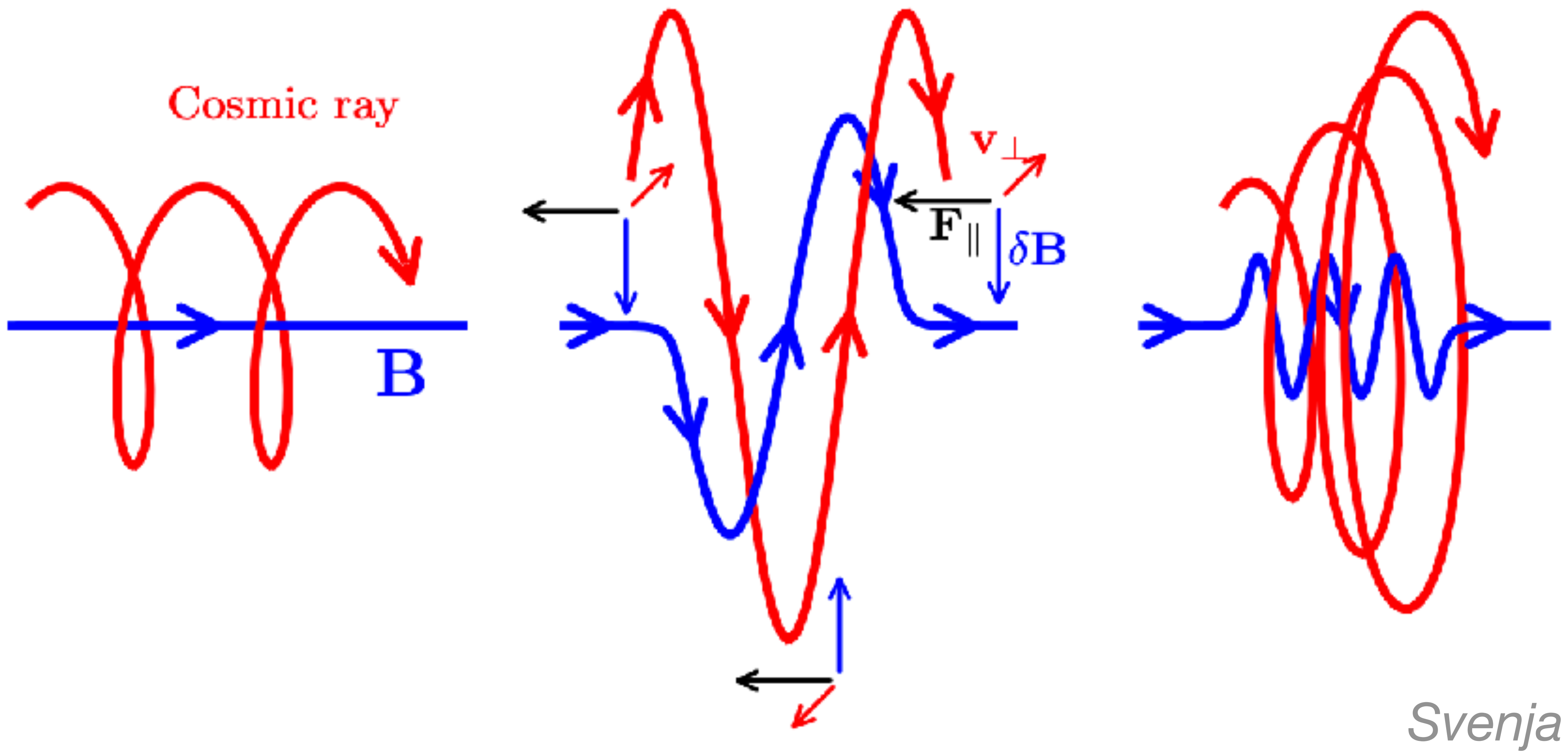
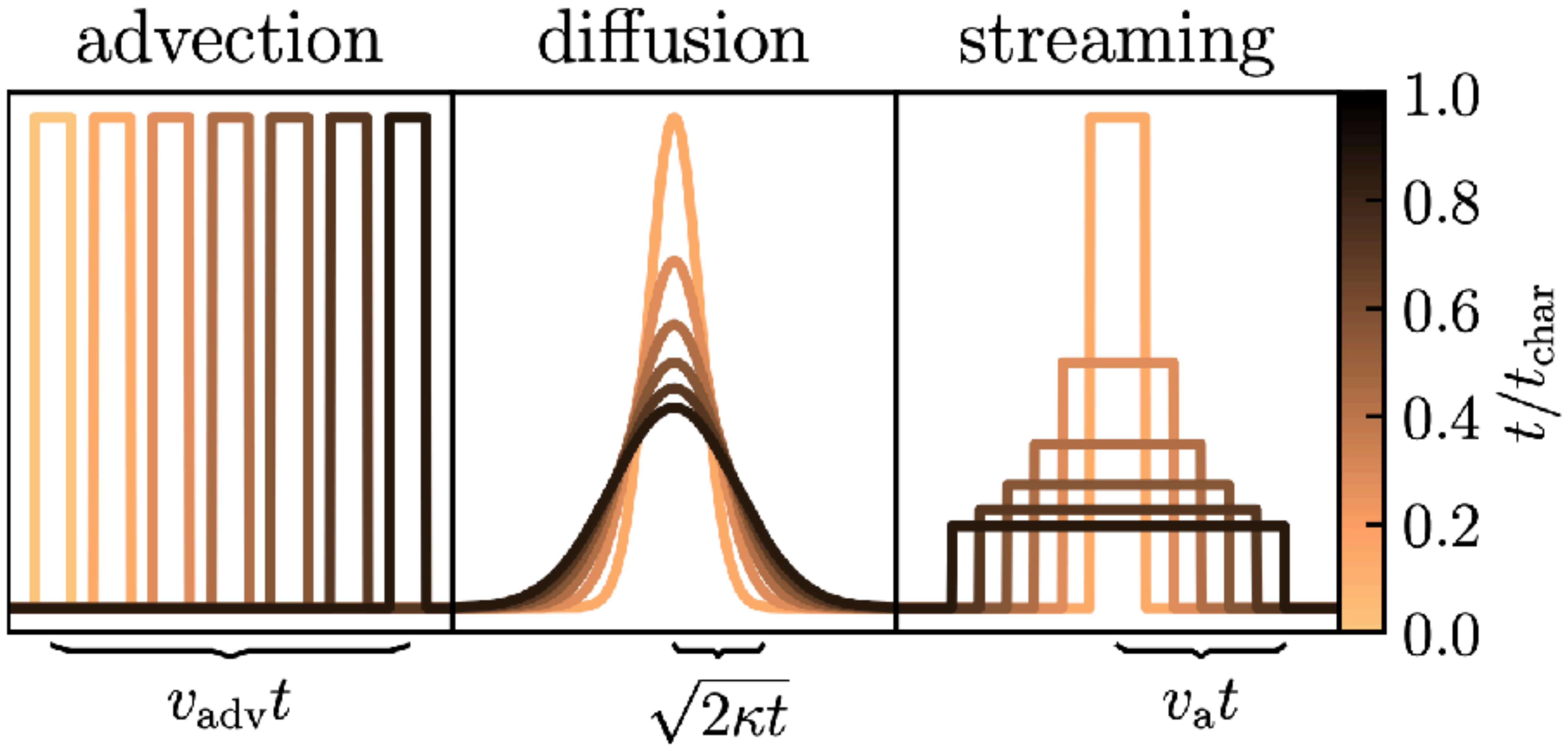
Back reaction CR $\leftrightarrow B$

Streaming instability (Skilling 1975)

- back-reaction onto B-field, gyro-resonances
  $\Rightarrow$ no simple diffusion
  $\Rightarrow$ transport + E-transfer $E_{\rm cr} \leftrightarrow E_{\rm mag}$
- bulk of CRs streams with Alfvén speed, Alfvén heating
- equate growth and damping *Wiener+ 2013*
  $$\Gamma_{\rm growth} = \Gamma_{\rm NLLD} + \Gamma_{\rm in}$$
  $$\Rightarrow H = -\mathbf{v}_{\rm A} \cdot \nabla P_{\rm cr}$$
- but: active development of PIC numerics & self-consistent plasma models
  e.g. Holcomb+2019, Shalaby et al. 2021/2023, Lemmerz et al. 2024



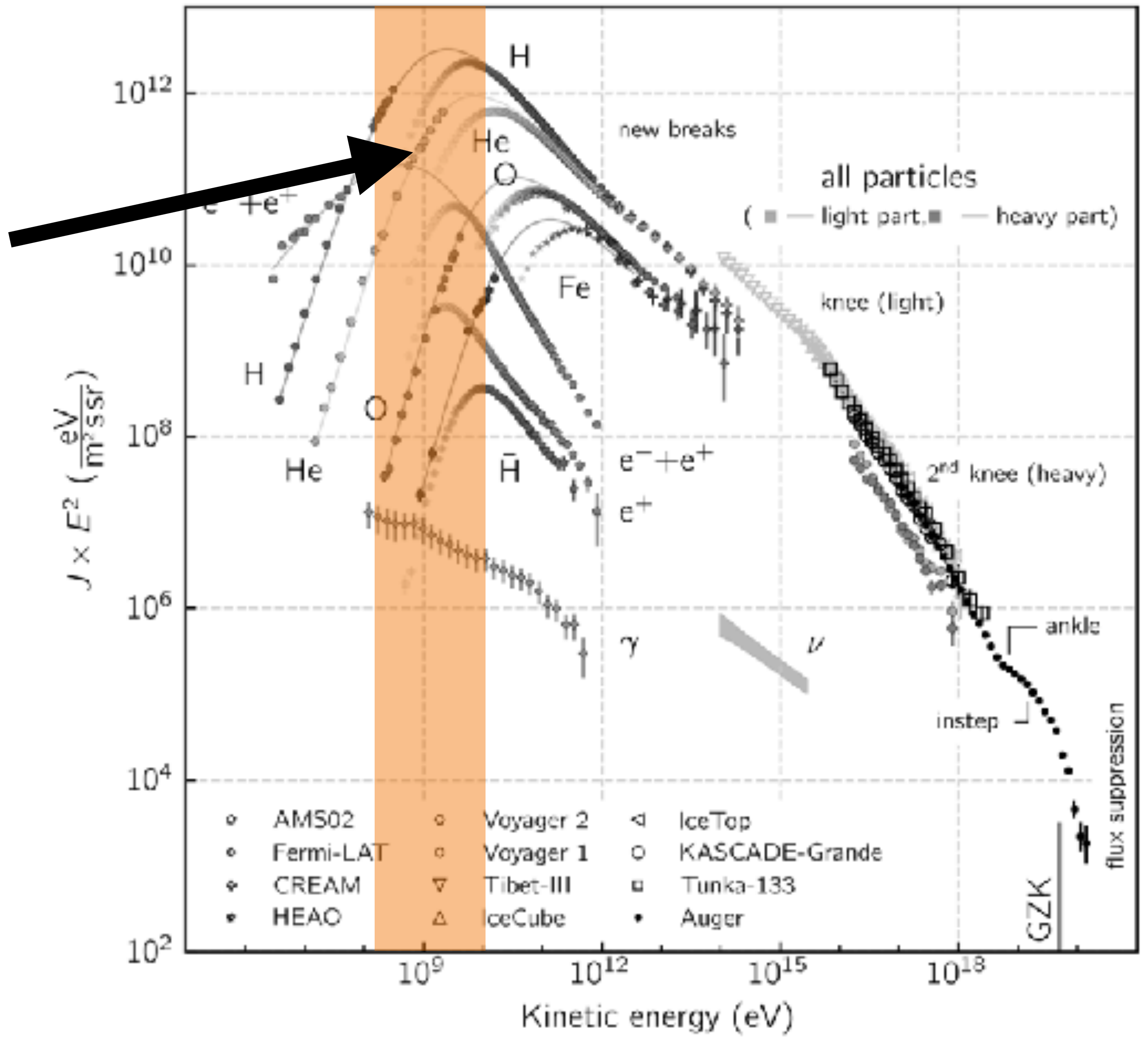
Svenja Jacob



Thomas, Pfrommer, Enßlin 2020

CR+MHD (in grey approximation)

only integrated energy



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

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

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

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

advection $\quad \frac{\partial e_{\mathrm{cr}}}{\partial t} + \nabla \cdot \left(e_{\mathrm{cr}} \mathbf{v} \right) = -p_{\mathrm{cr}} \nabla \cdot \mathbf{v}$ adiabatic

$- \nabla F_{\mathrm{st}} - \Lambda_{\mathrm{cr}}$ streaming

$+ \nabla \cdot \left(\mathsf{K} \cdot \nabla e_{\mathrm{cr}} \right)$ diffusion

$+ Q_{\mathrm{cr}}$ sources/sinks

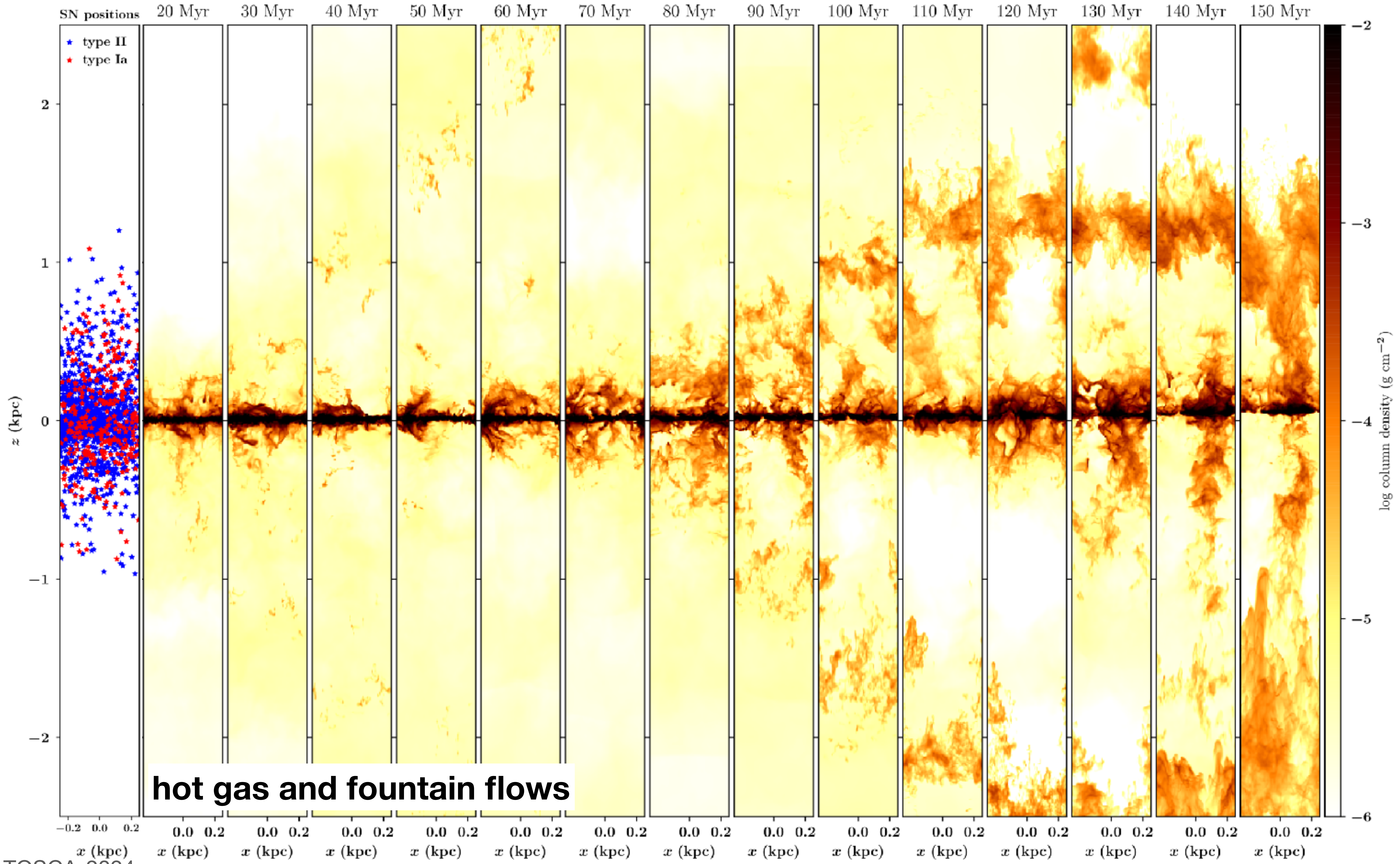
$$p_{\mathrm{tot}} = p_{\mathrm{therm}} + p_{\mathrm{mag}} + p_{\mathrm{cr}}$$

Piernik: *Hanasz+2003*
FLASH: *Girichidis+2014,2016a*
Arepo: *Pfrommer+2017, Pakmor+2016,2017, Thomas+2021*
RAMSES: *Dubois+2016, Commercon+2019*

review on numerics: *Hanasz+ 2021*

ISM evolution without CRs

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



ISM evolution (therm+CRs)

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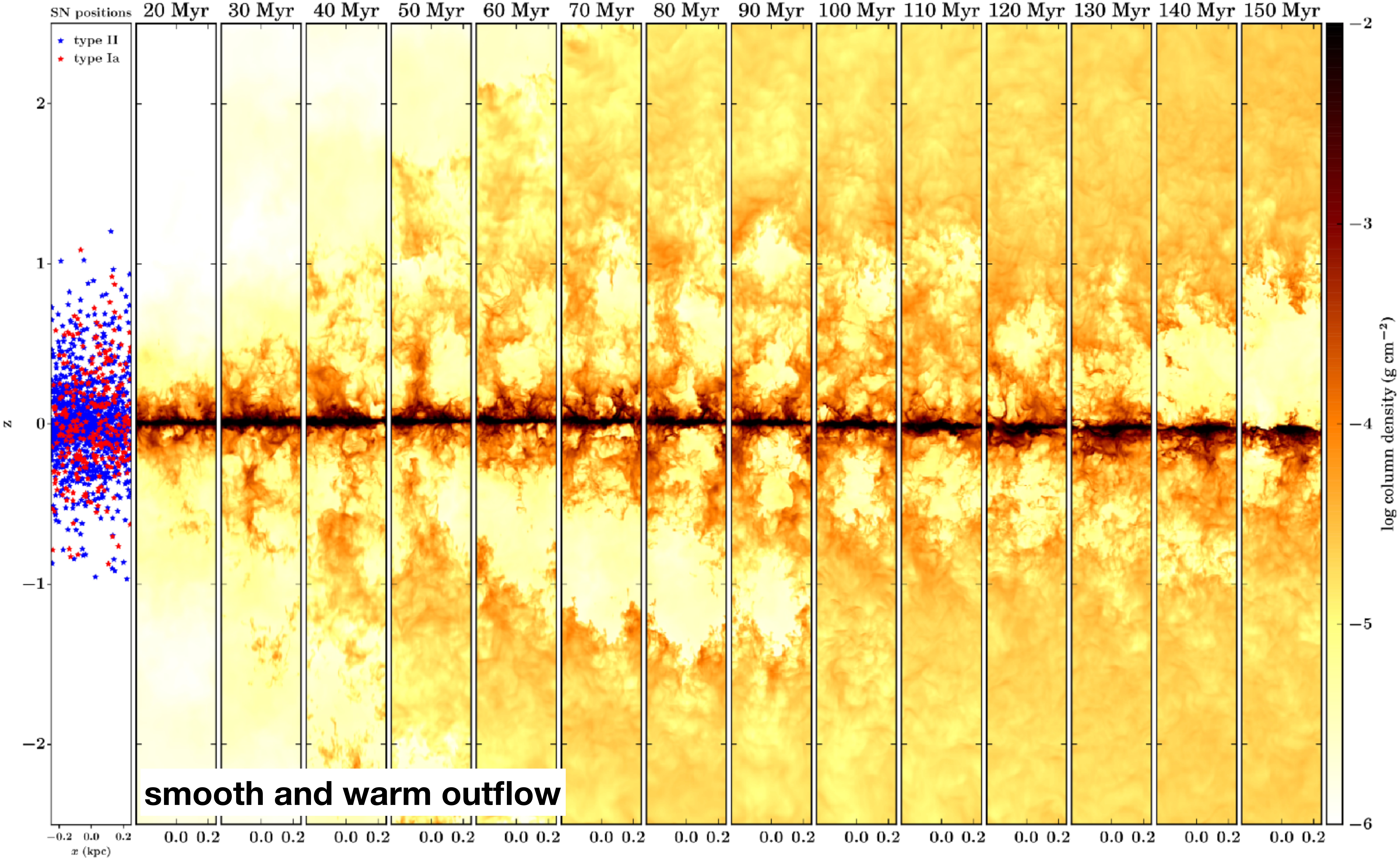

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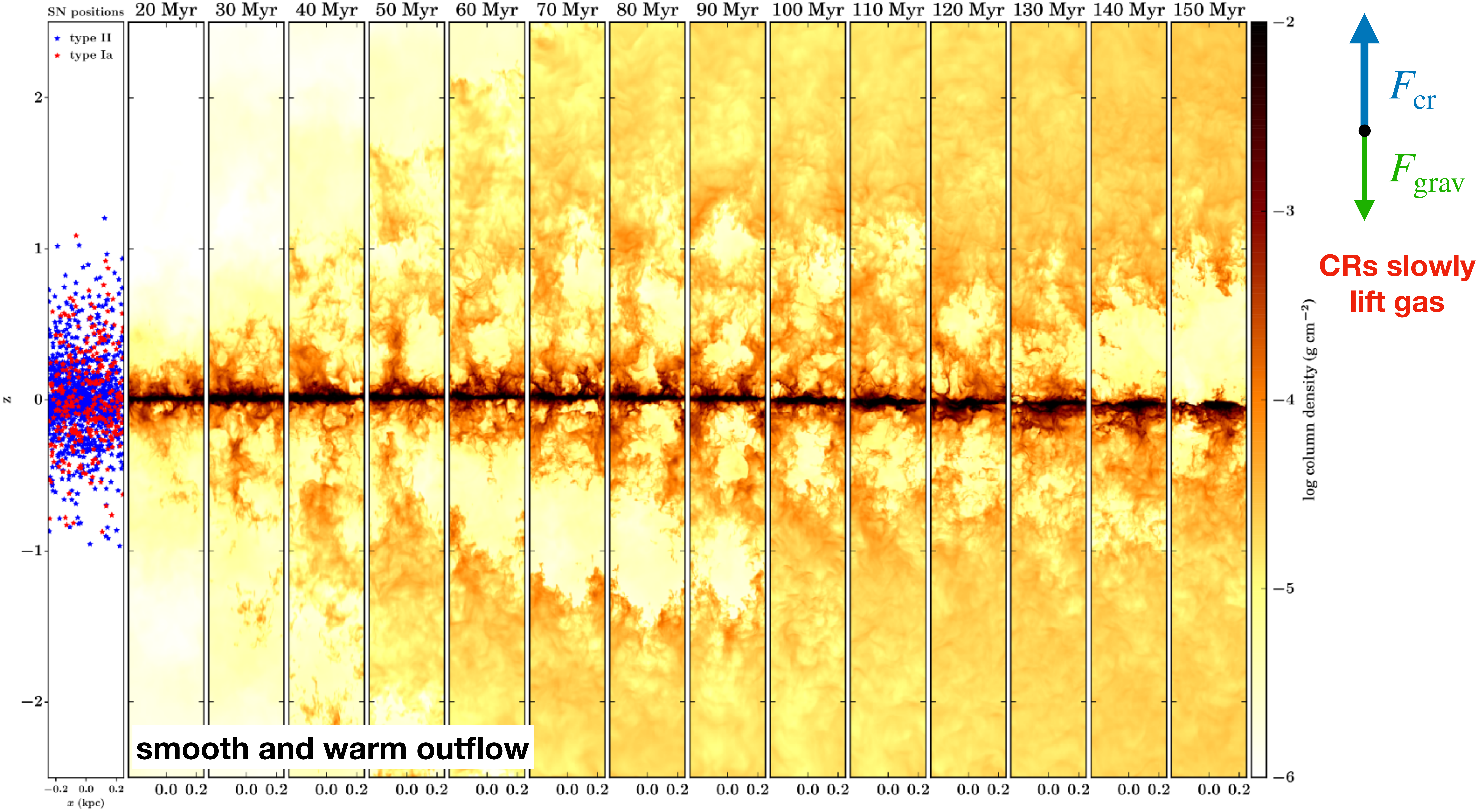
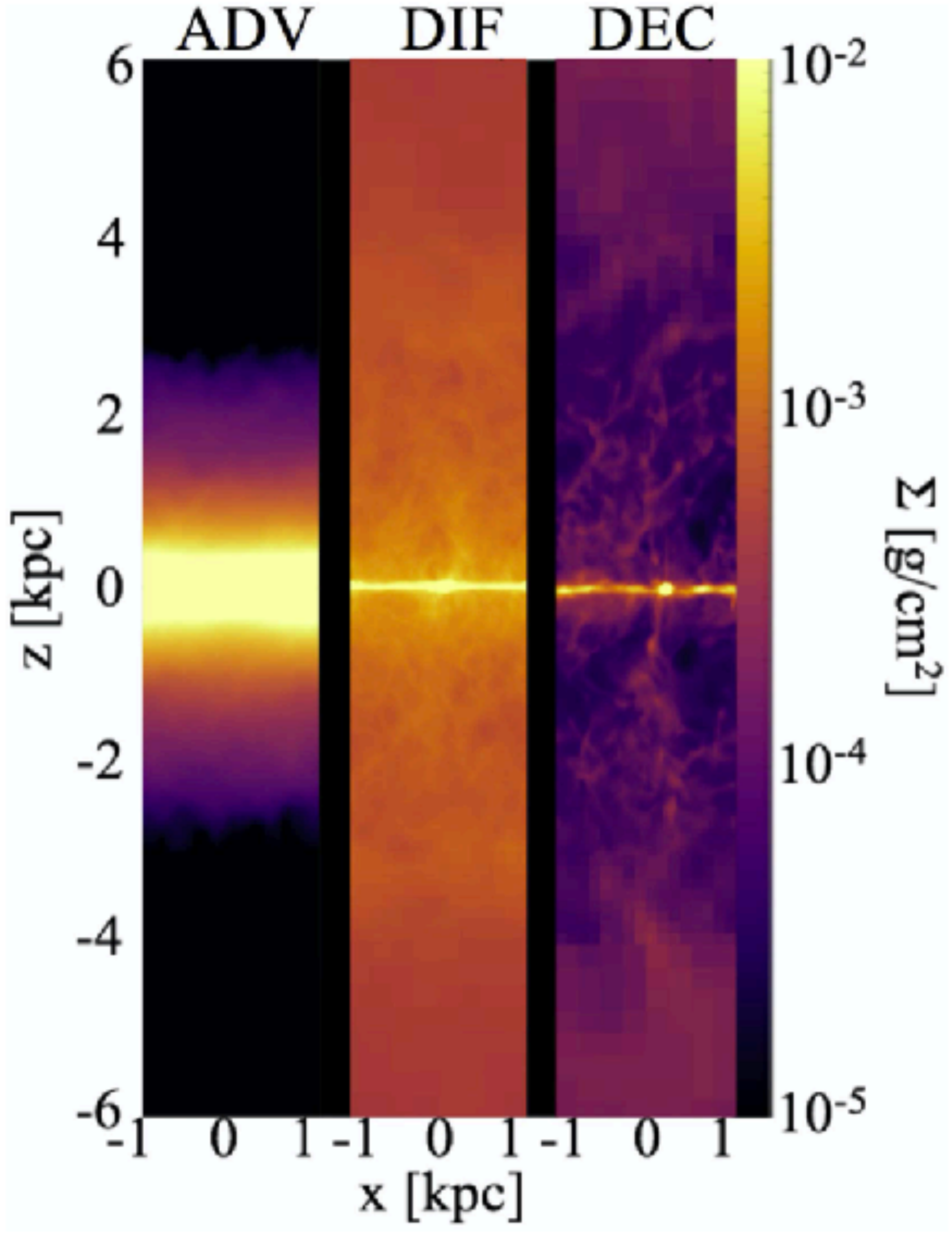


CRs slowly lift gas

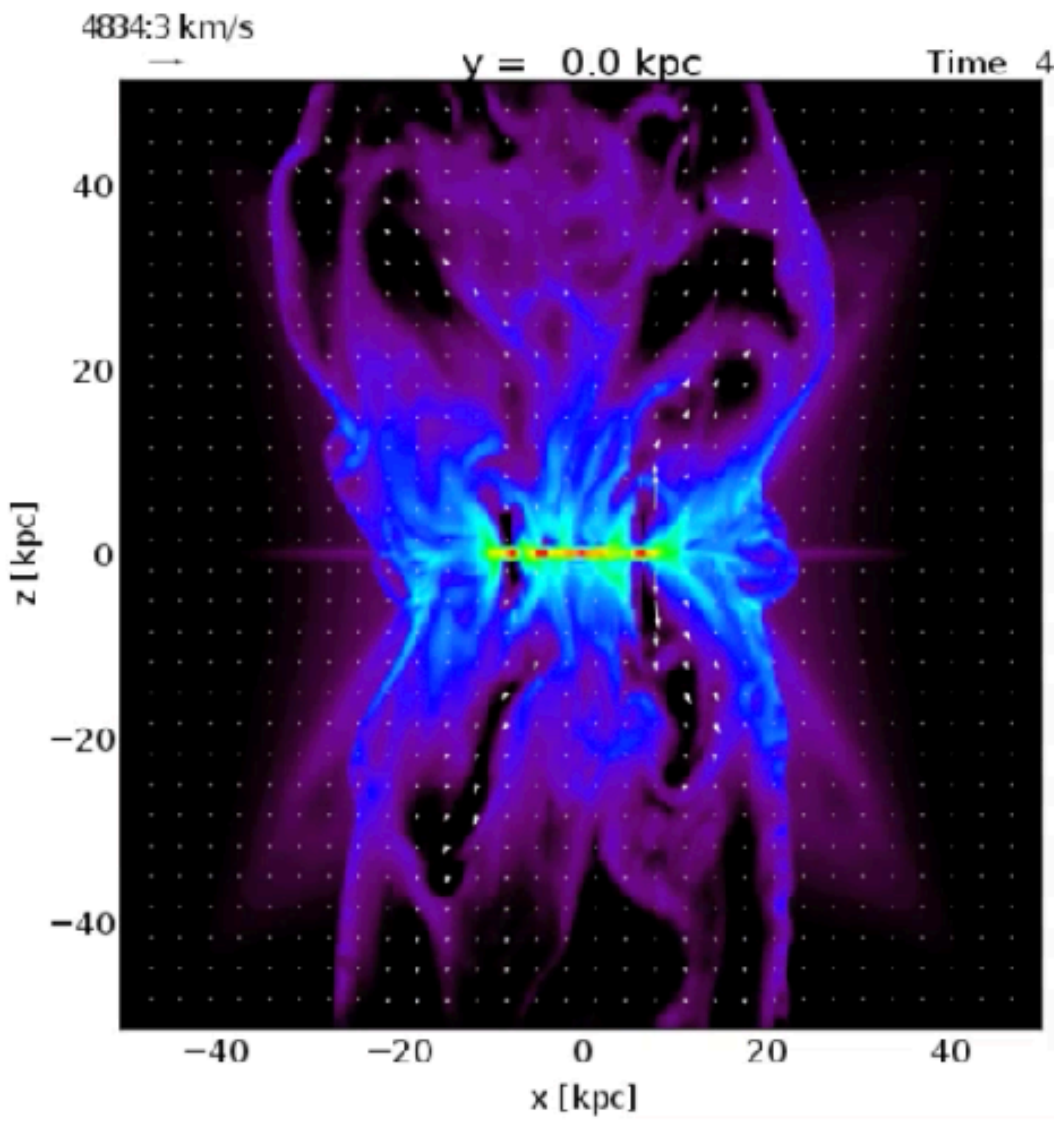
Different setups, similar conclusion

stratified boxes (ISM)



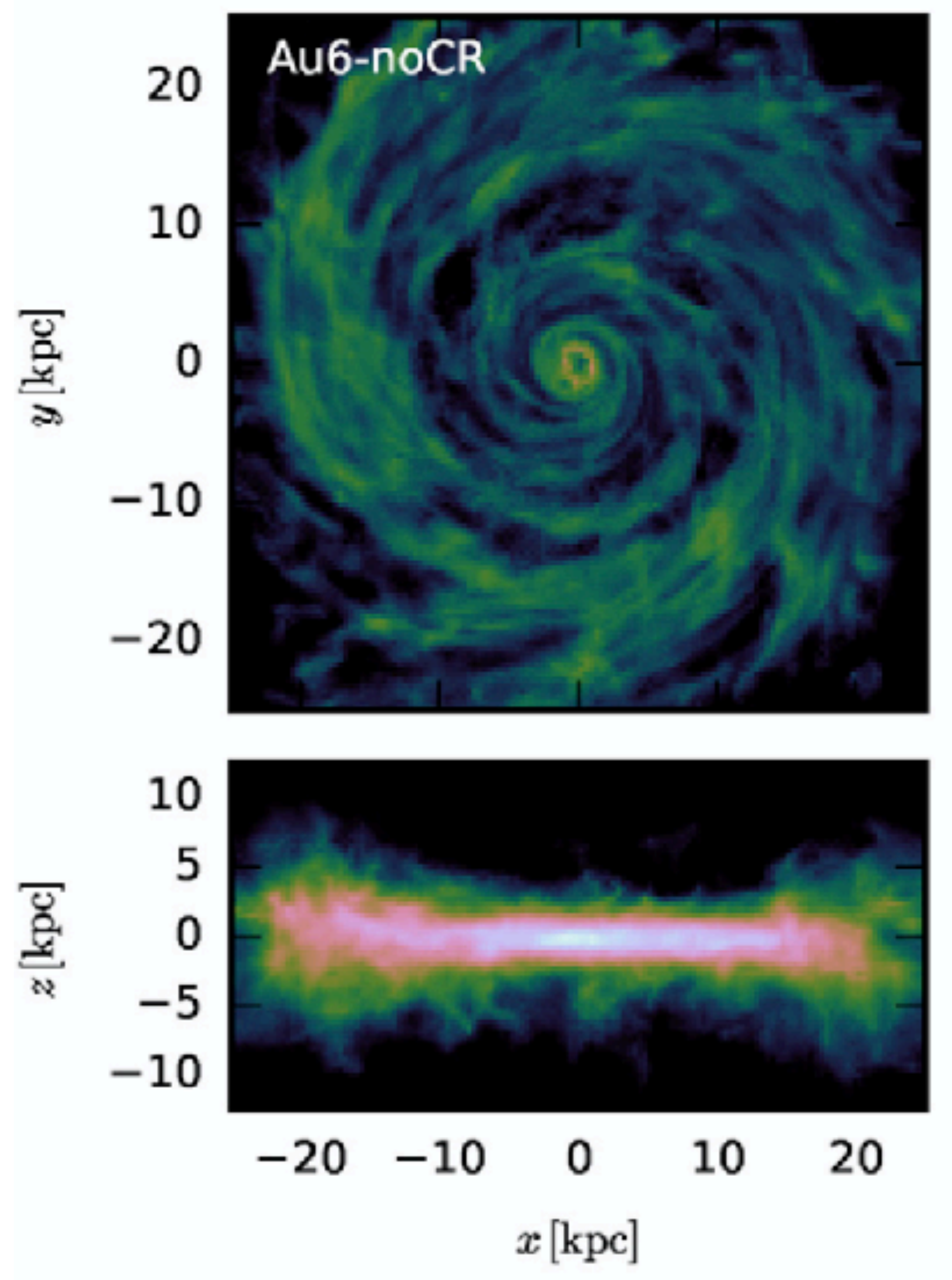
Hanasz+ 2003, Girichidis+ 2016,2018, Simpson+ 2016, Dubois+ 2016, Farber+ 2018, Armillotta+ 18,21,23 Commercon+ 2019, Butsky+ 2020, Rathjen+ 2021,2022, Armillotta+ 2024

isolated galaxies



Booth+ 2013, Ruszkowski+ 2017a, Pakmor+ 2016, Pfrommer+ 2017, Jacob+ 2018, Dashyan+ 2020, Semenov+ 2021, Girichidis+ 2022/24, Thomas+ 2021,2023, Farcy+ 2022, Nunez-Castineyra+ 2022, Peschken+ 2023

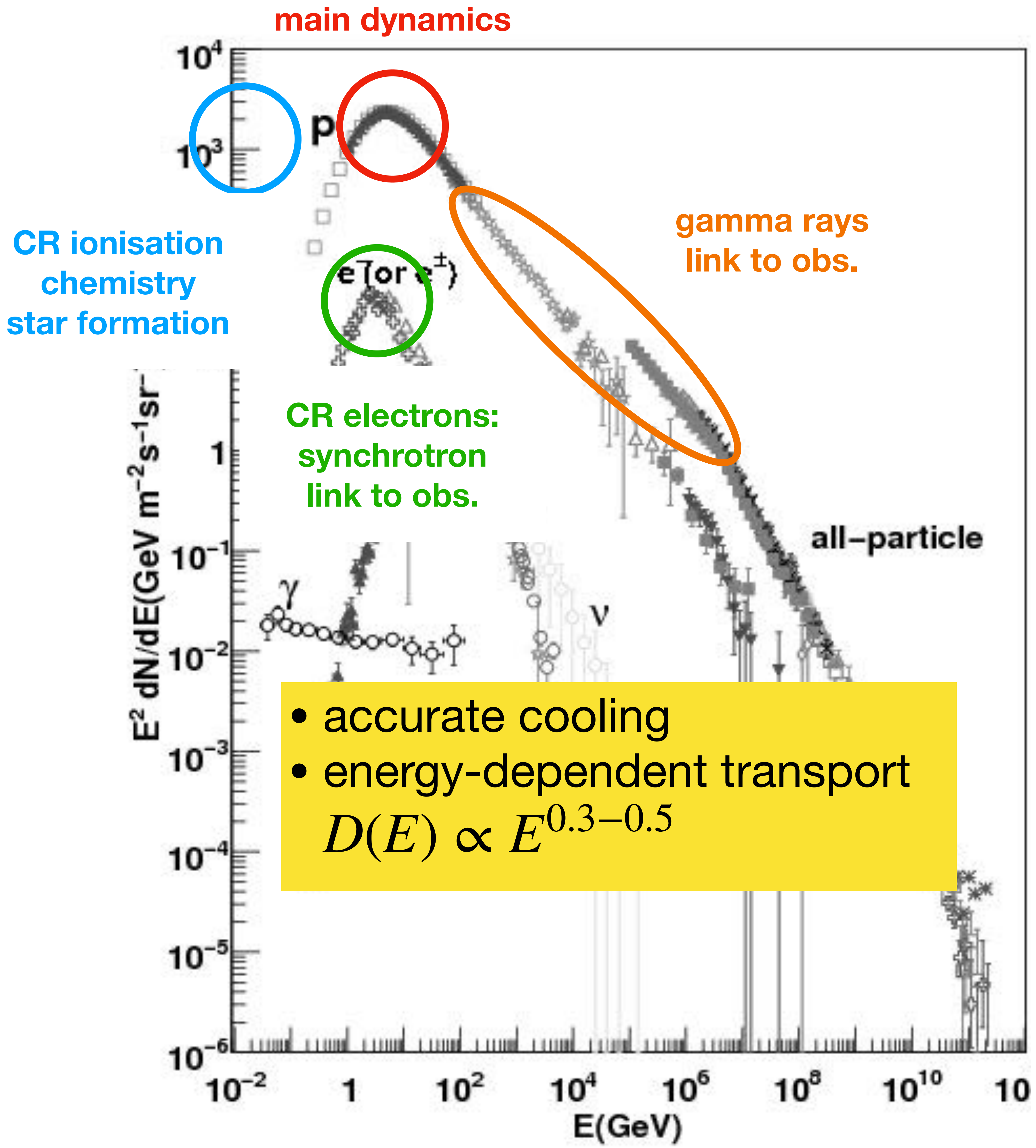
cosmological galaxies



Jubelgas+ 2008, Salem+ 2014, Chan+ 2018, Hopkins+ 2020/2021/2022, Buck+2020, Ji+2020, Böss+ 2023, Rodriguez Montero+ 2023

CRs are good candidate to drive outflows! **Details are complicated…**

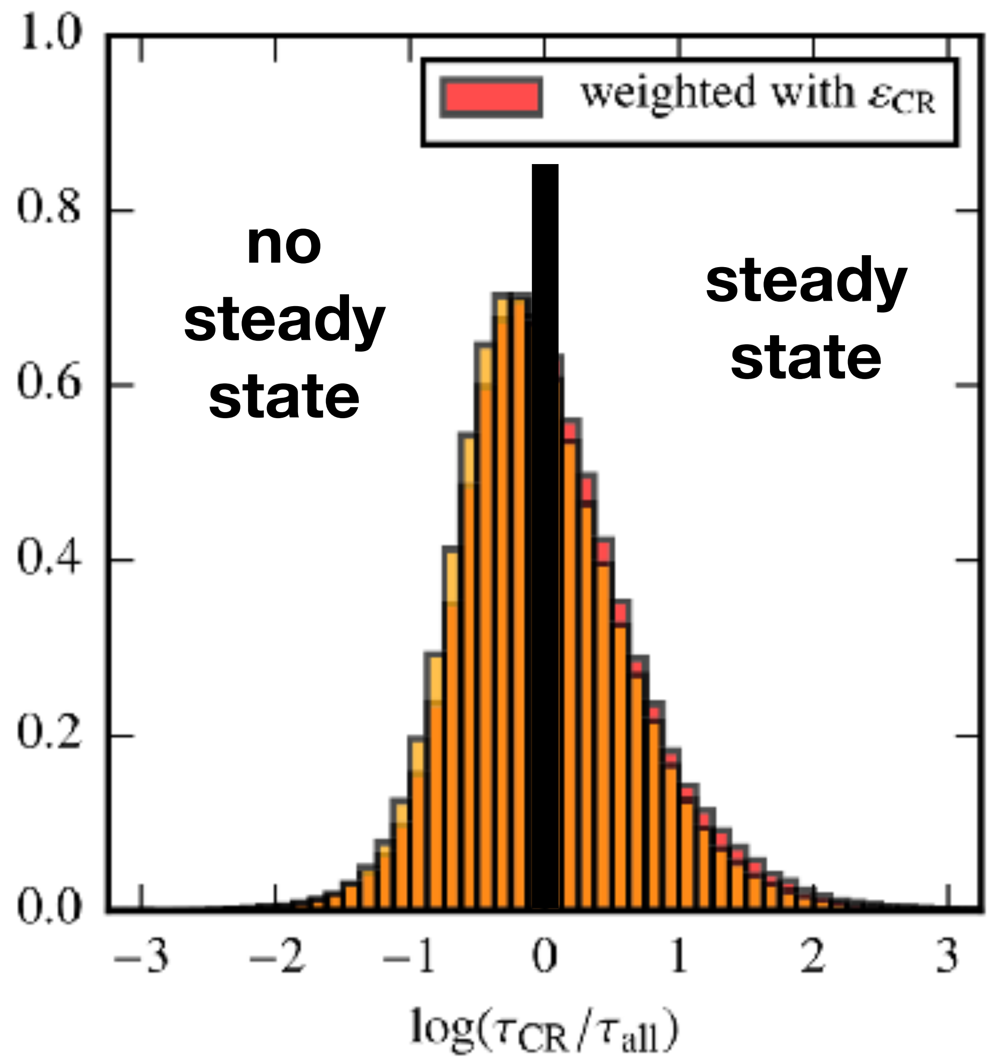
Extension to full CR spectrum

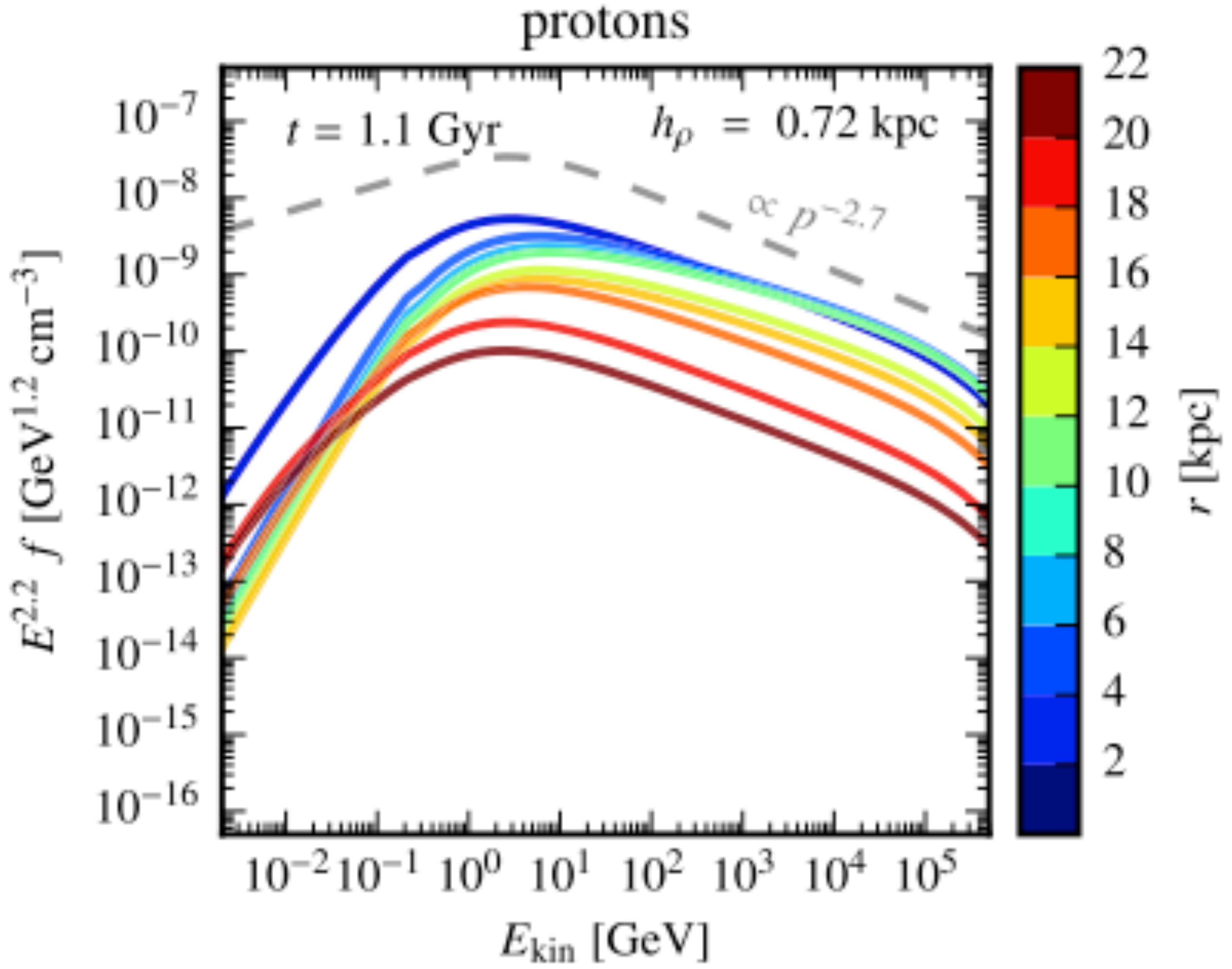


- accurate cooling
- energy-dependent transport $D(E) \propto E^{0.3-0.5}$

validity of steady state

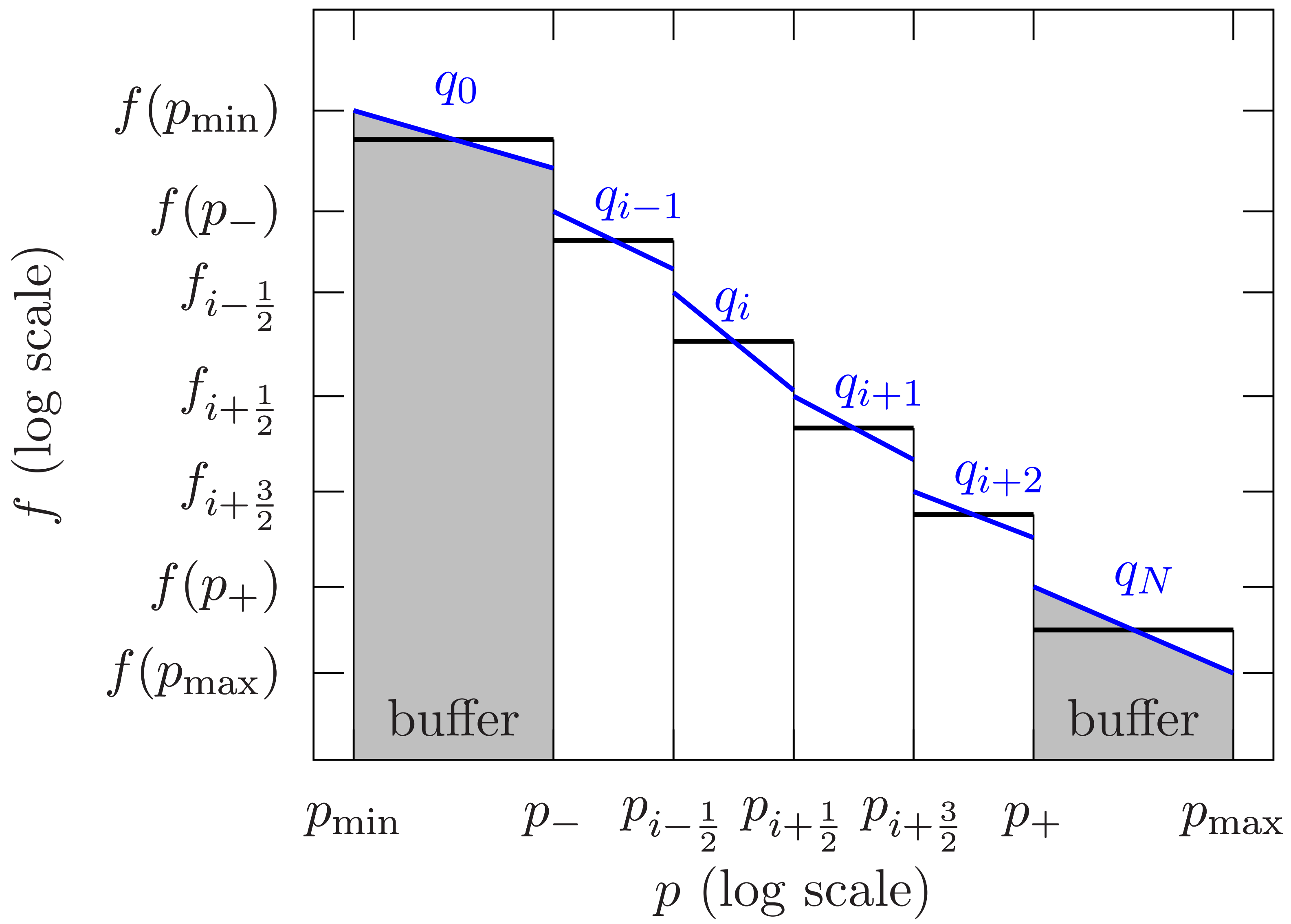
Werhahn et al. 2021a





numerical scheme to couple MHD and live spectra

Girichidis et al. 2020, 2022, 2024

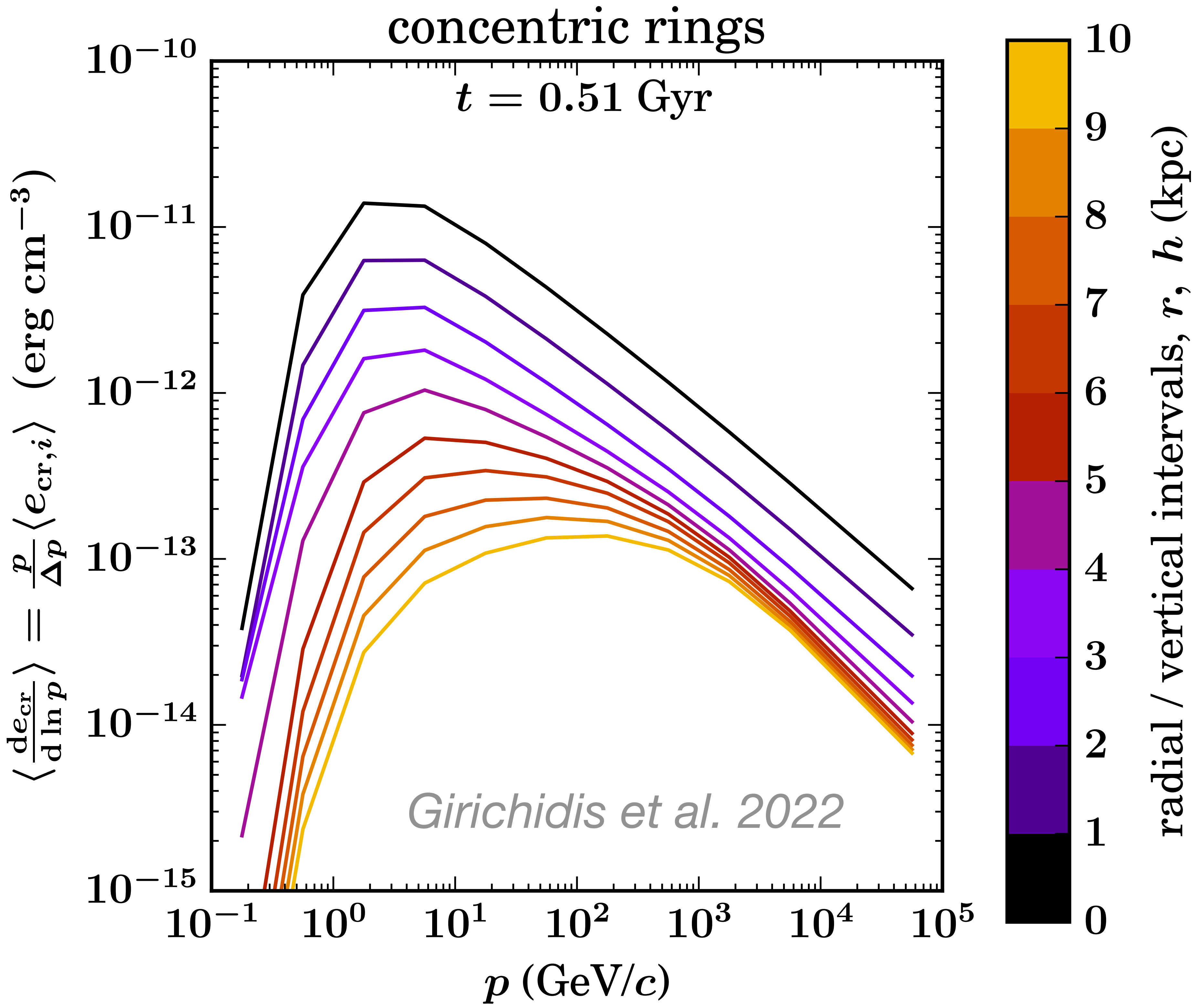


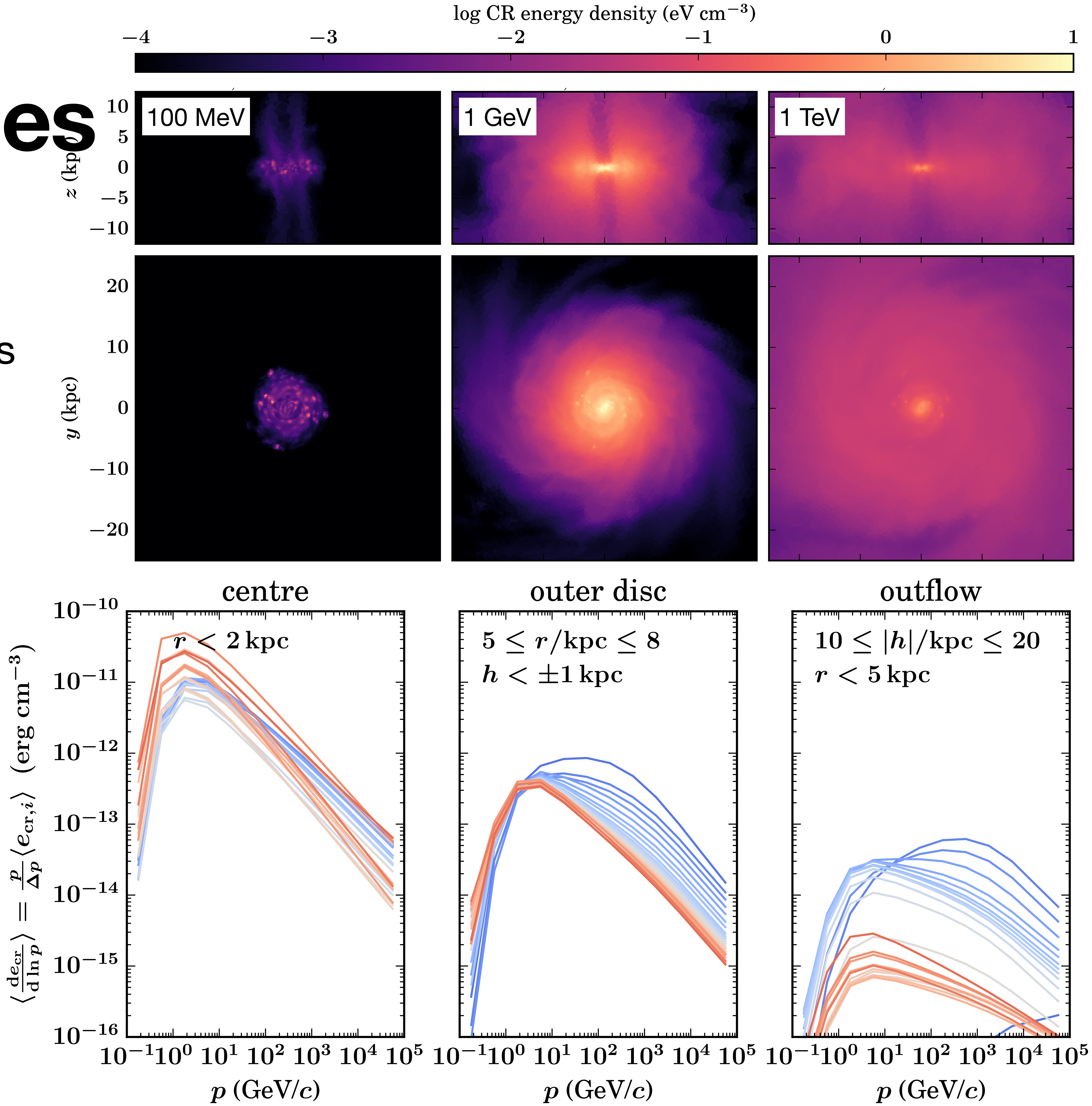
- often no steady state
- spectral variations important

Spectral CR in galaxies

full spectrum in every cell

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

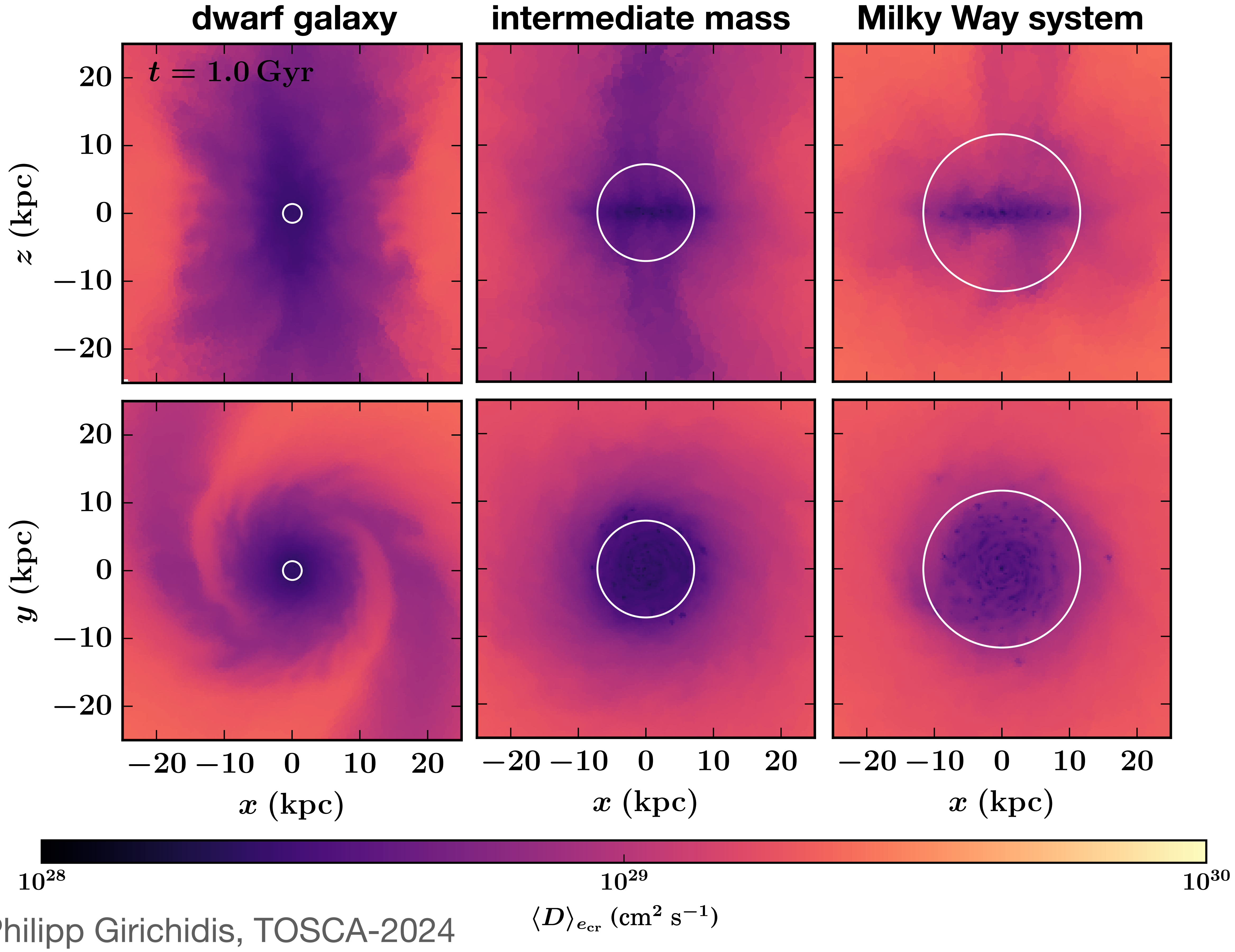


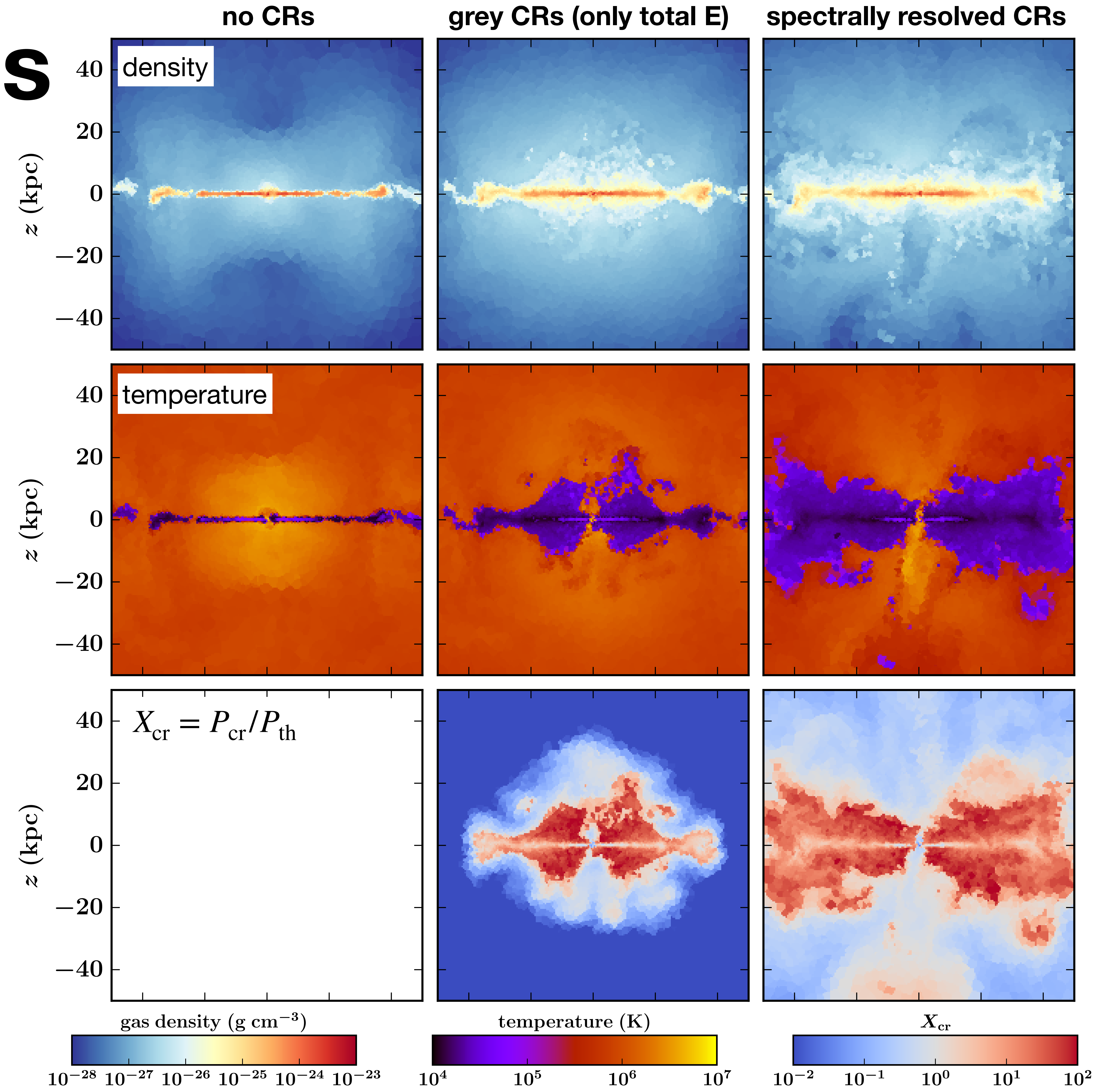


Girichidis et al. 2022, 2024

Spectrally resolved CRs

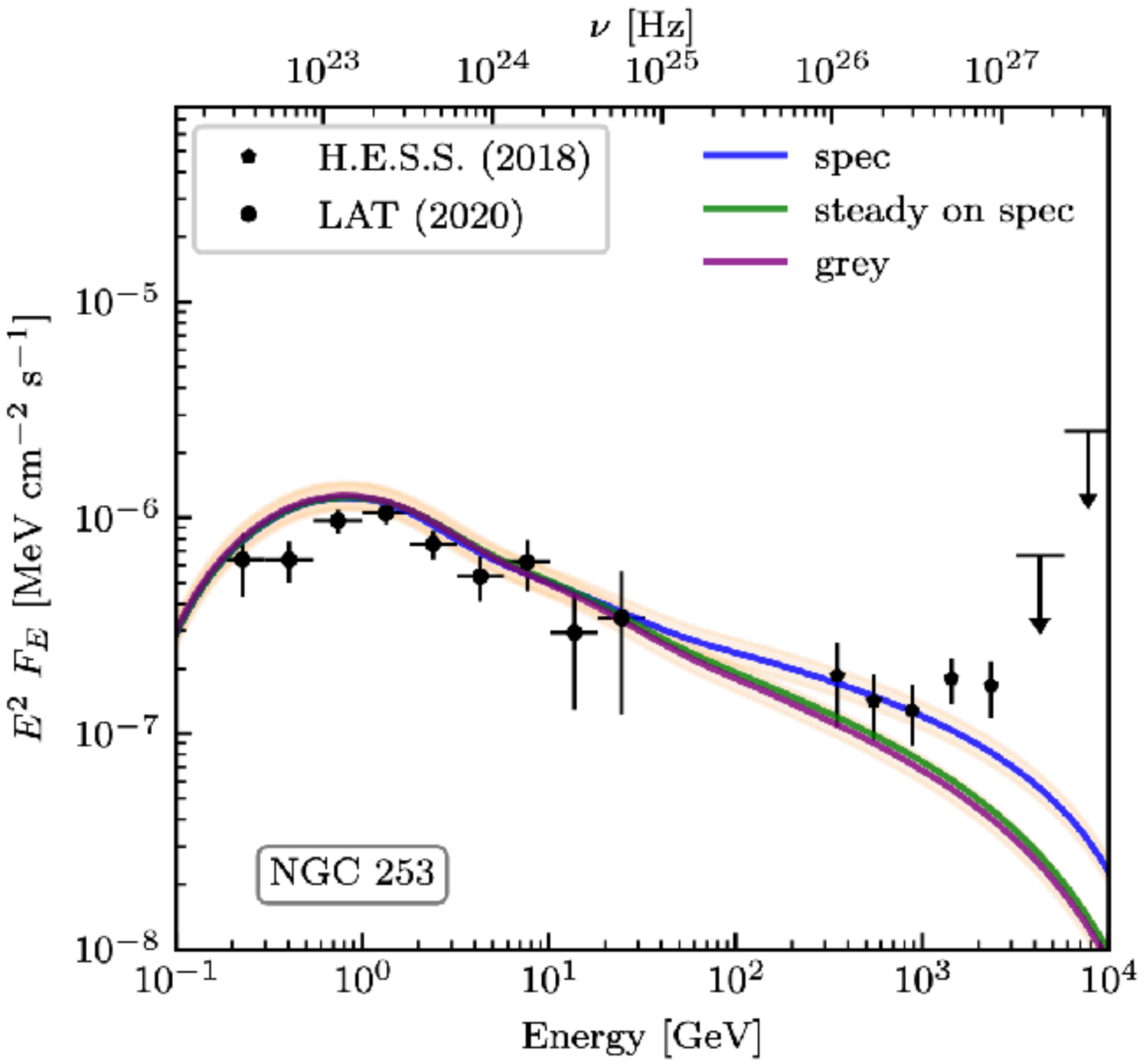
- variations in spectra ⇒ variations in diffusion
- large region of cold CGM, cold gal. fountain
- large region with CR dominated pressure

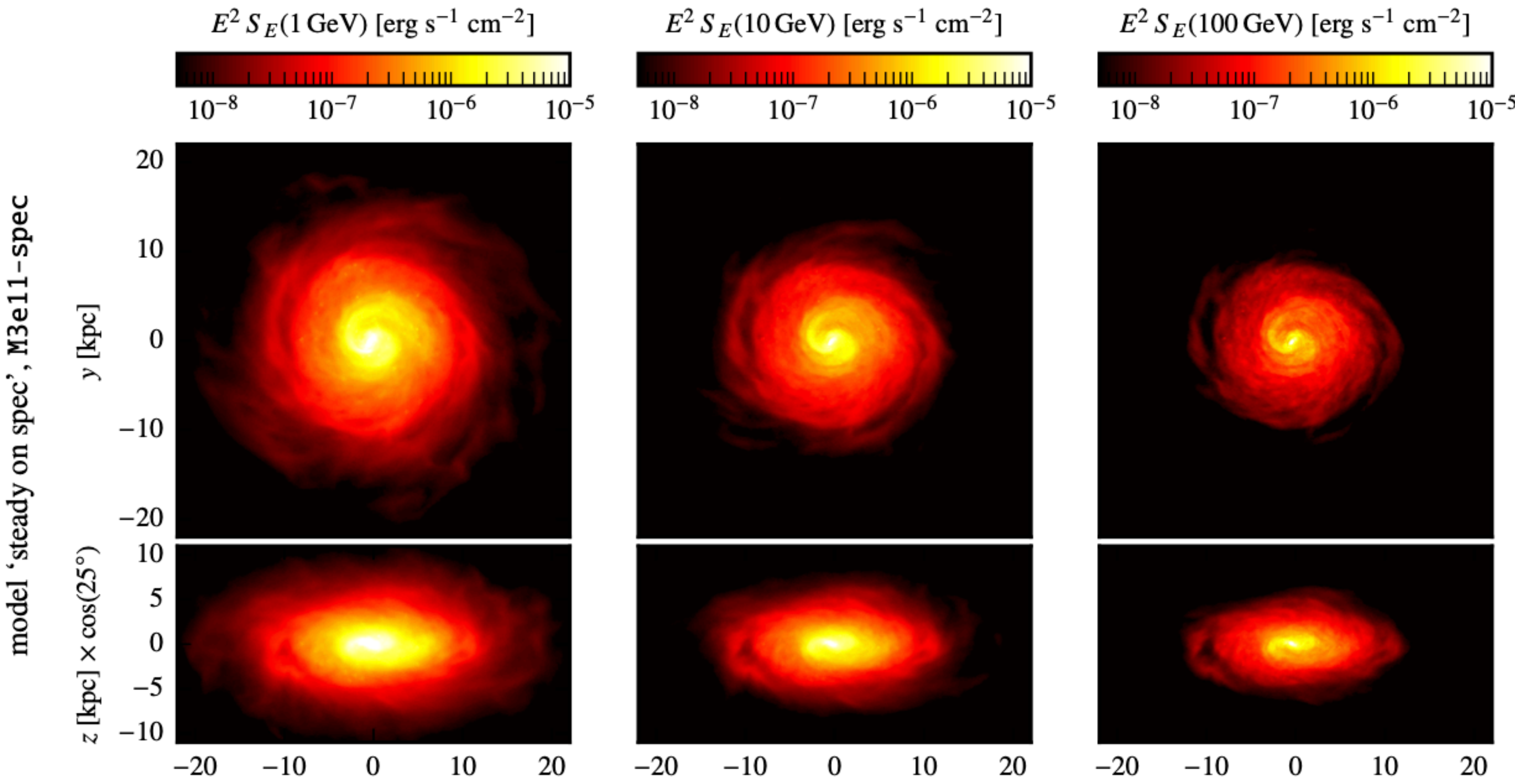




Connection to gamma rays

- Steady state vs. full spectrum *Werhahn+ 2021abc, 2023*
- Variations in Milky-Way models / Galactic center / Fermi bubbles *Kjellgren et al., Peschken et al.*





- spectral model: better fit to spectra

strong differences between energy ranges

Werhahn et al. 2023

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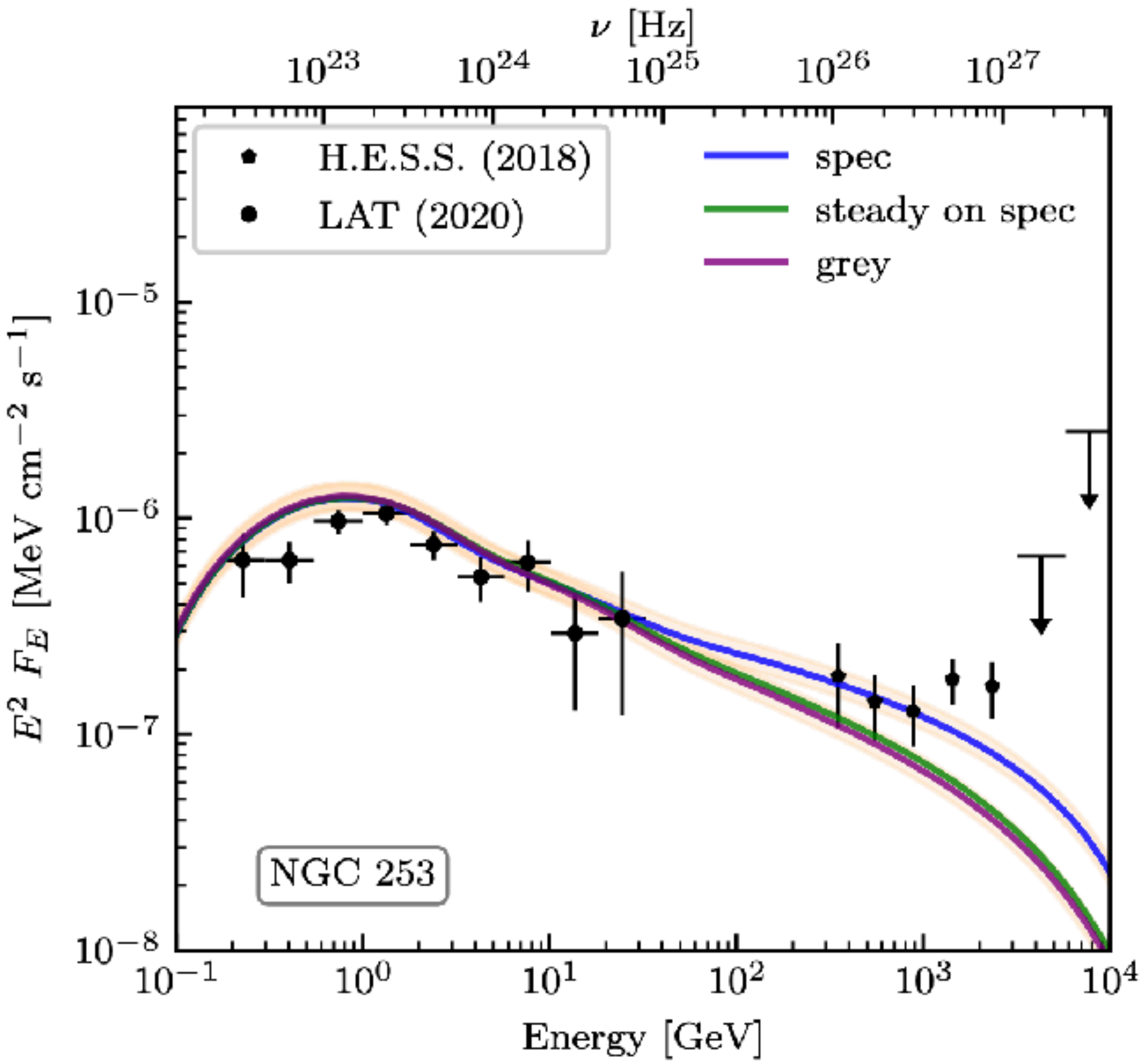

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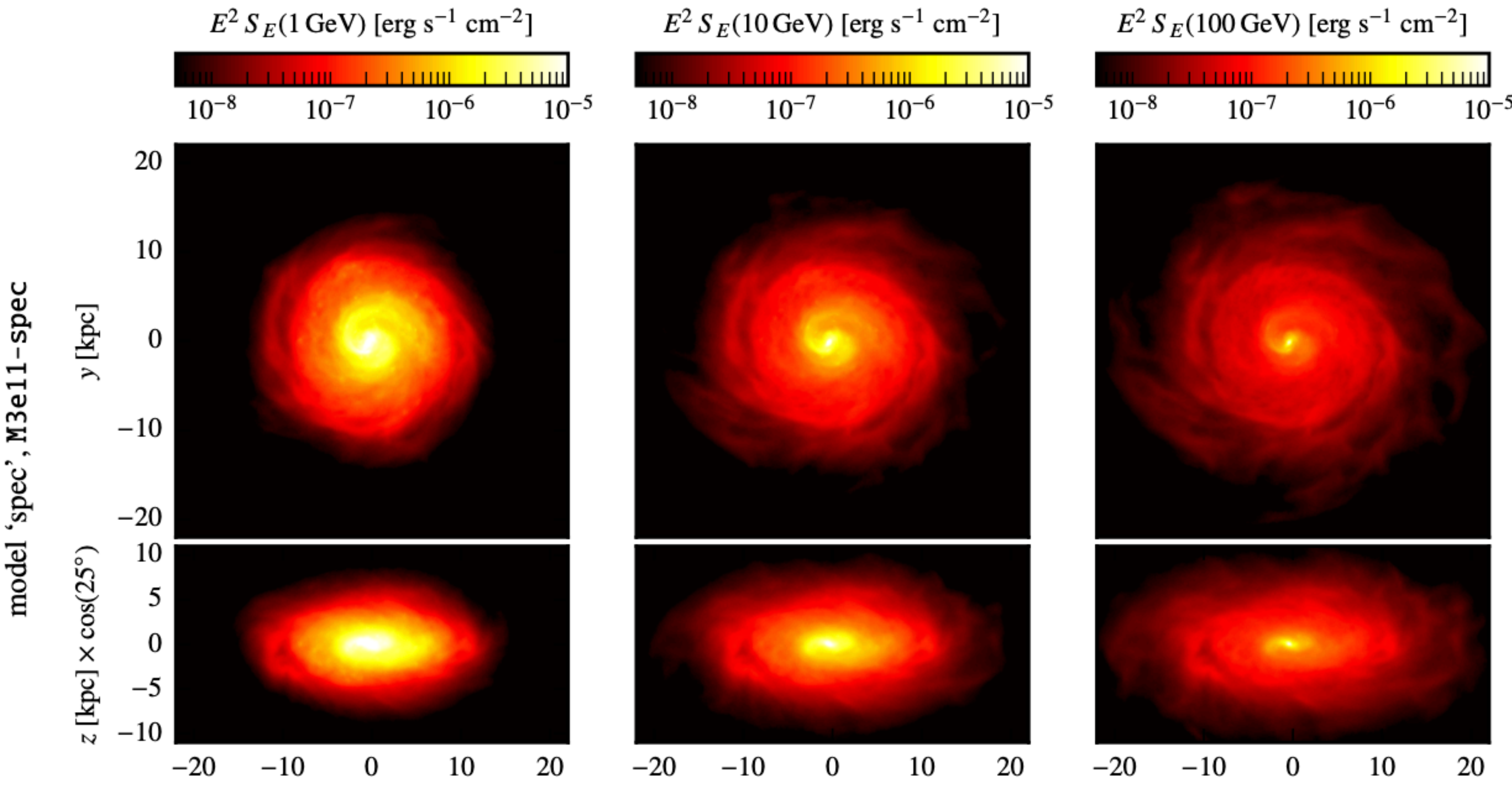


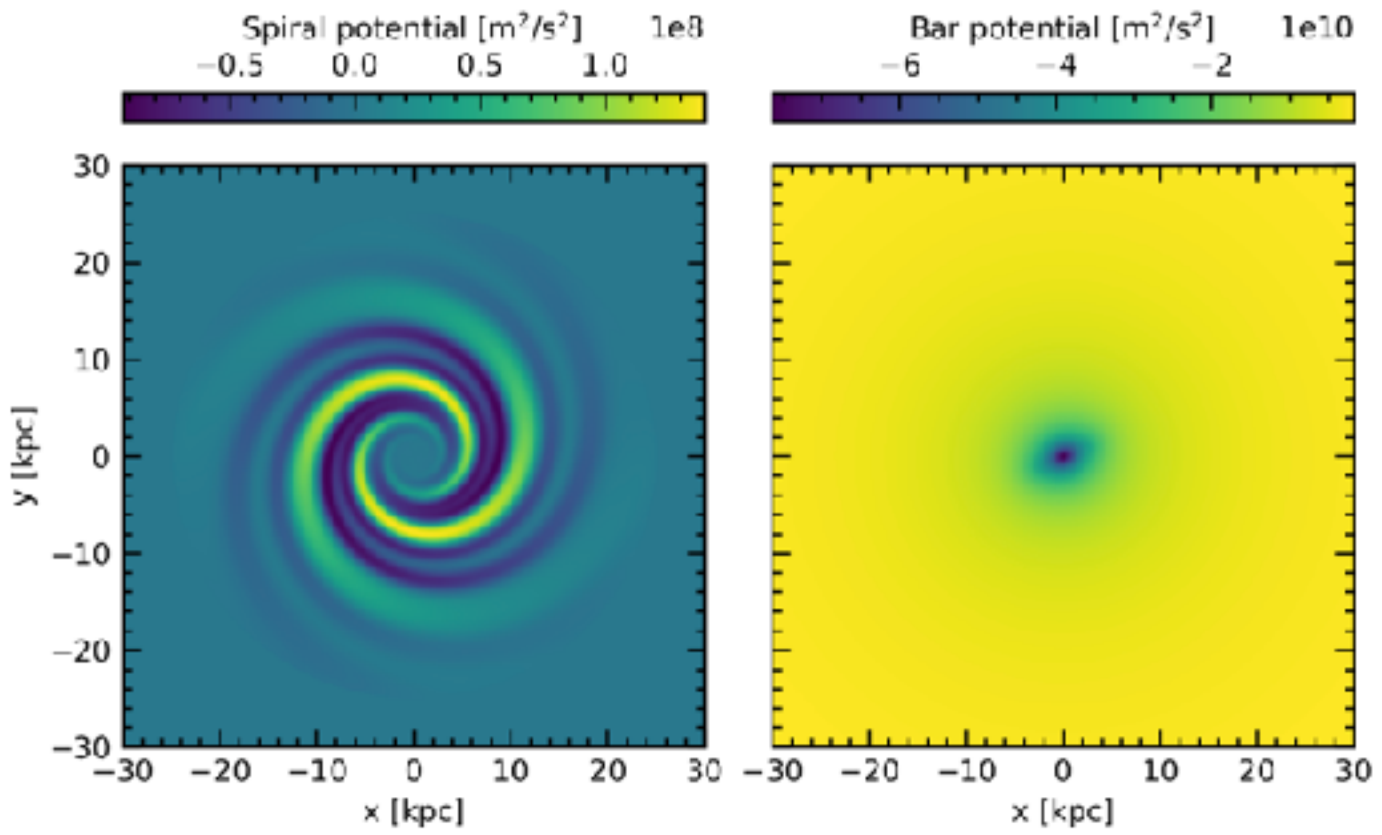
strong differences between energy ranges

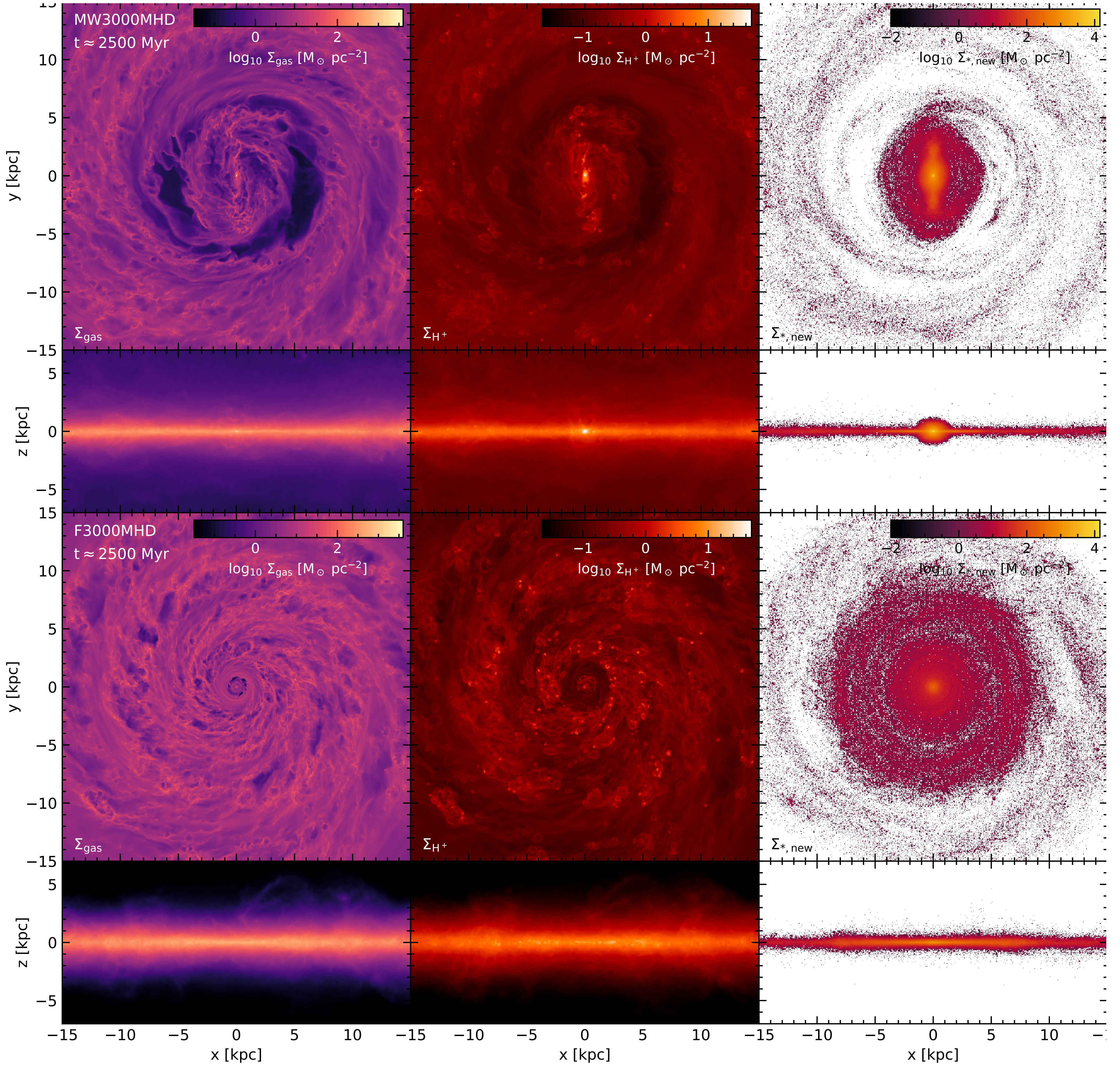
Werhahn et al. 2023

Our isolated MW

basis: Rhea simulations (Göller+, subm.)

- MW galaxy: $M_{\rm gas} = 10^{10}\,{\rm M}_\odot$
  halo indirect, $10^{12}\,{\rm M}_\odot$ via external potential
  bar, bulge, spiral potential *Hunter+ 2024*
- Arepo *(Springel 2010, Pakmor+ 2013, Weinberger+ 2020)*
- chemistry: non-eq for H, C
  Glover+ 2007,2012, Nelson & Langer 97
- star particles: *Göller+ subm.*
  compute probability for collapse
  convert (part of) cell into star clusters
  draw massive stars from IMF with indiv. life times
- feedback:
  currently: SNe after life time of massive stars
  next: live radiation using SWEEP *(Peter+ 2024)*
- Cosmic rays (advection-diffusion + streaming losses)
  currently: grey *(Pfrommer+ 2017, Pakmor+ 2016)*
  next: spectral *(Girichidis+ 2020,2022)*

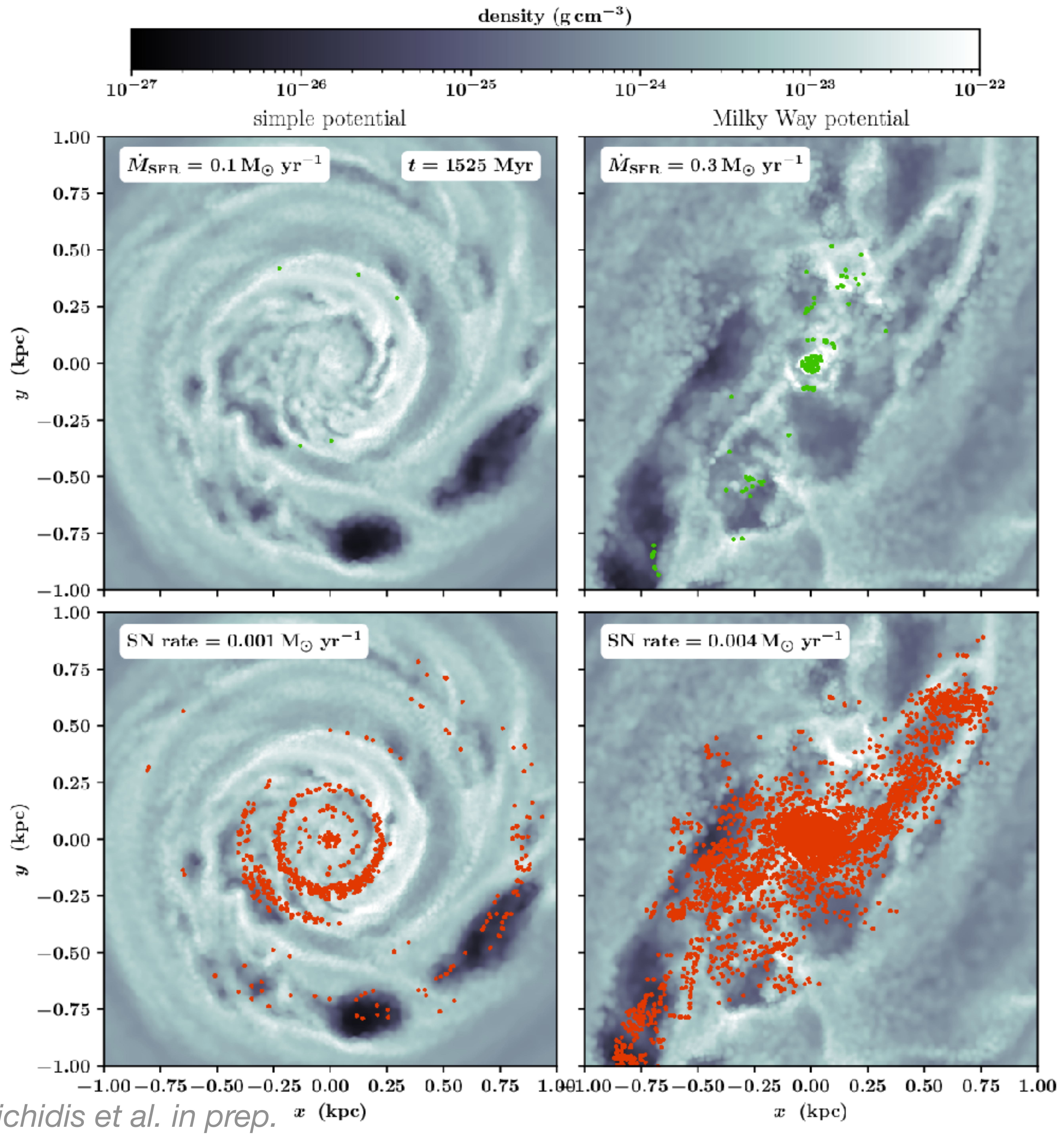




central SN feedback

most SF in centre

- collective energy input
- SFR: $\sim 0.1\,\mathrm{M_\odot\ yr^{-1}}$
- SNR: $\sim 0.001\,\mathrm{yr^{-1}} = 10^3\,\mathrm{Myr^{-1}}$
- E input:
  $E_{\mathrm{inj}} = 10^{54}\,\mathrm{erg\,Myr^{-1}}$
  $P_{\mathrm{inj}} \sim 3\times10^{40}\,\mathrm{erg\ s^{-1}}$



Girichidis et al. in prep.

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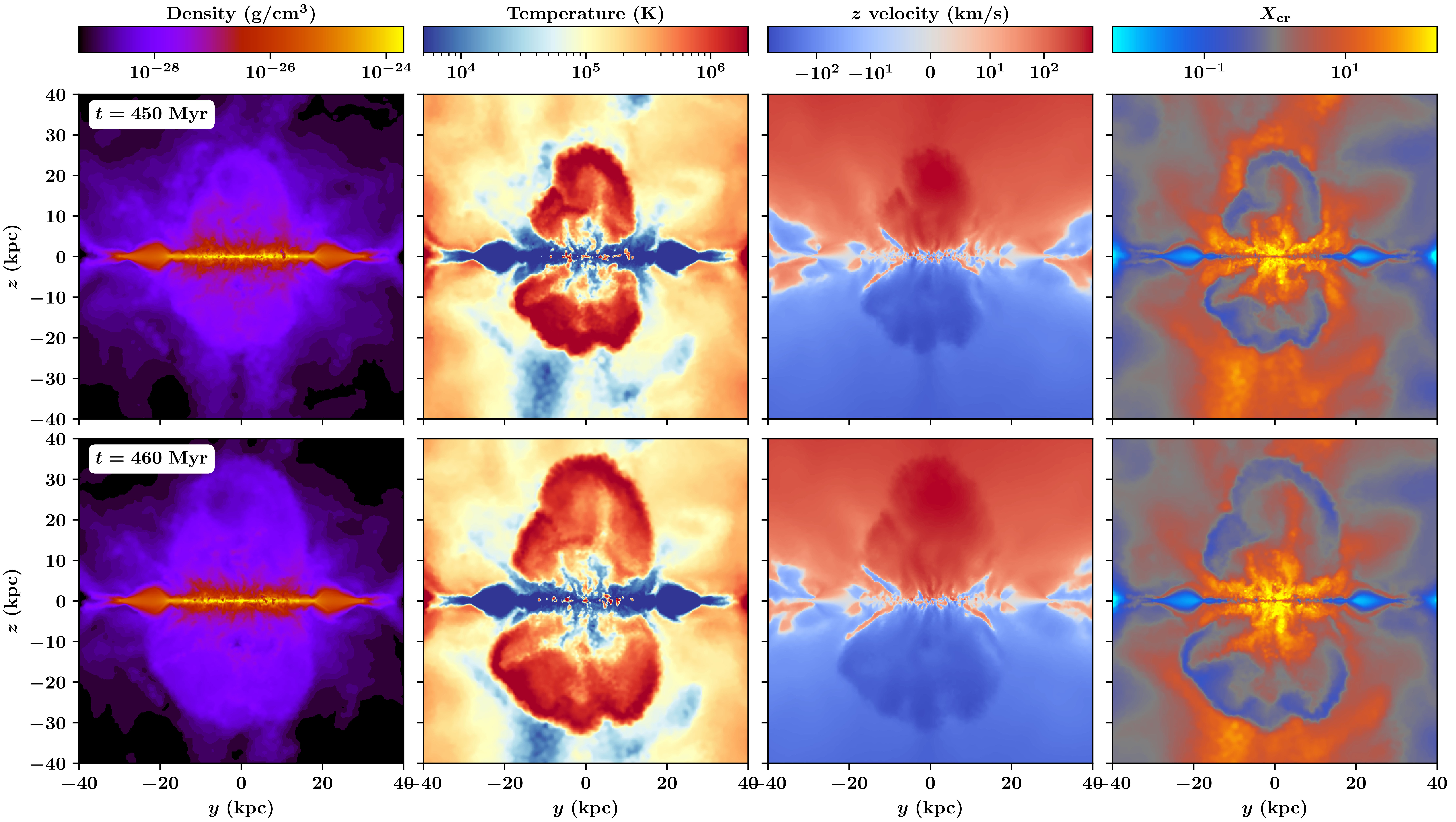


Philipp Girichidis, TOSCA-2024

The Fermi/eRosita bubble

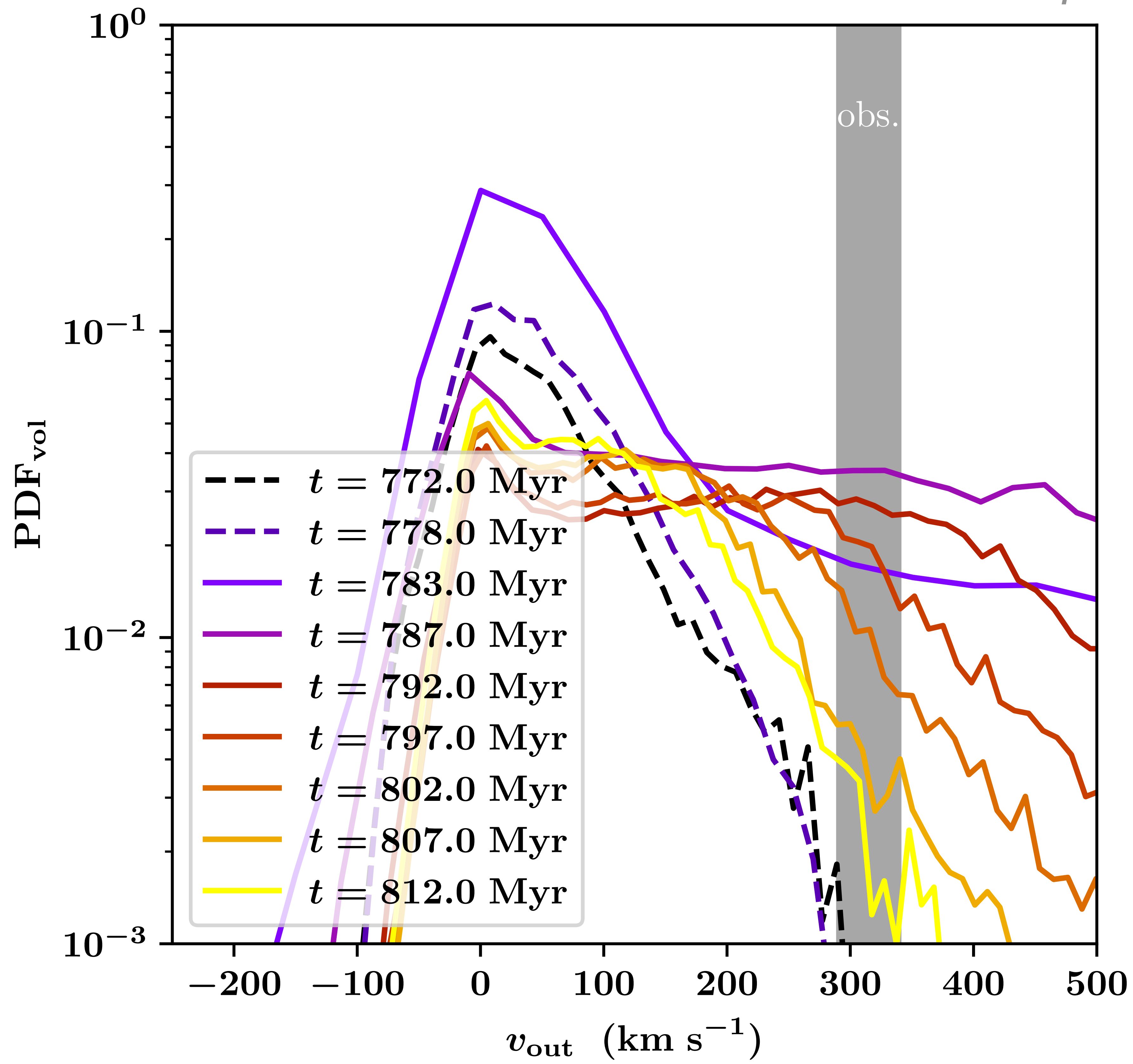
- $T_{\text{bubble}} = 3 \times 10^6\,\text{K},\ T_{\text{CGM}} = 2 \times 10^6\,\text{K}$
  Kataoka et al. (2013, 2015) and LaRocca et al. (2020)
  Henley & Shelton (2010, 2013), Miller & Bregman (2015)

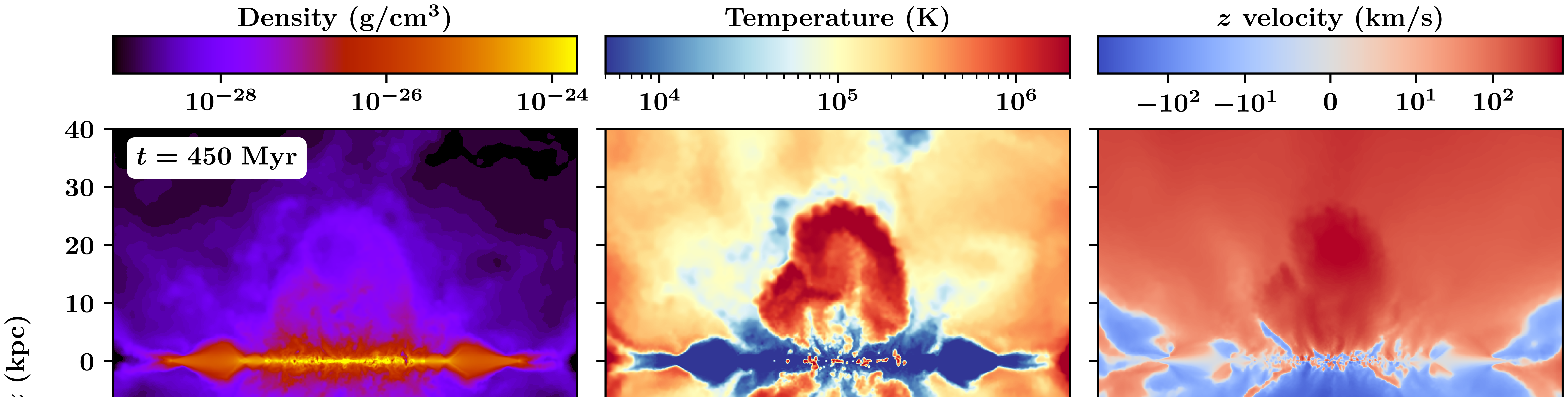
- size: $L = 10 - 15\,\text{kpc}$ at age $t \approx 20\,\text{Myr}$
  Predehl+ 2020, review by Sarkar 2024

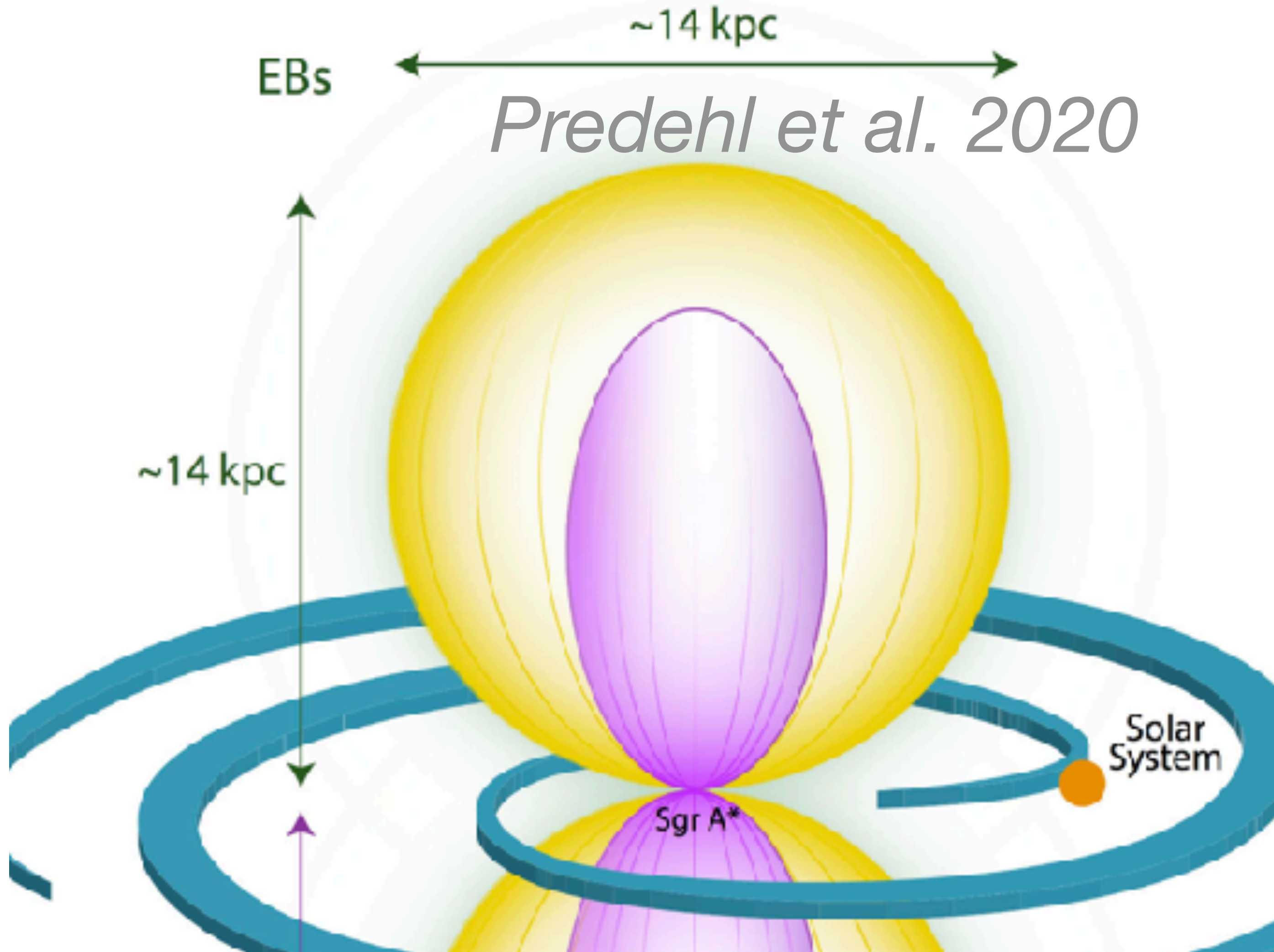
- inferred: $\mathscr{M} = 1.4,\ v_s \approx 320\,\text{km s}^{-1}$,
  $n \sim 4 - 5 \times 10^{-27}\,\text{g cm}^{-3}$

- thermal energy: $E_{\text{th}} \sim 10^{56}\,\text{erg}$
  Kataoka et al. 2013, 2015; Predehl et al. 2020

Girichidis et al. in prep.



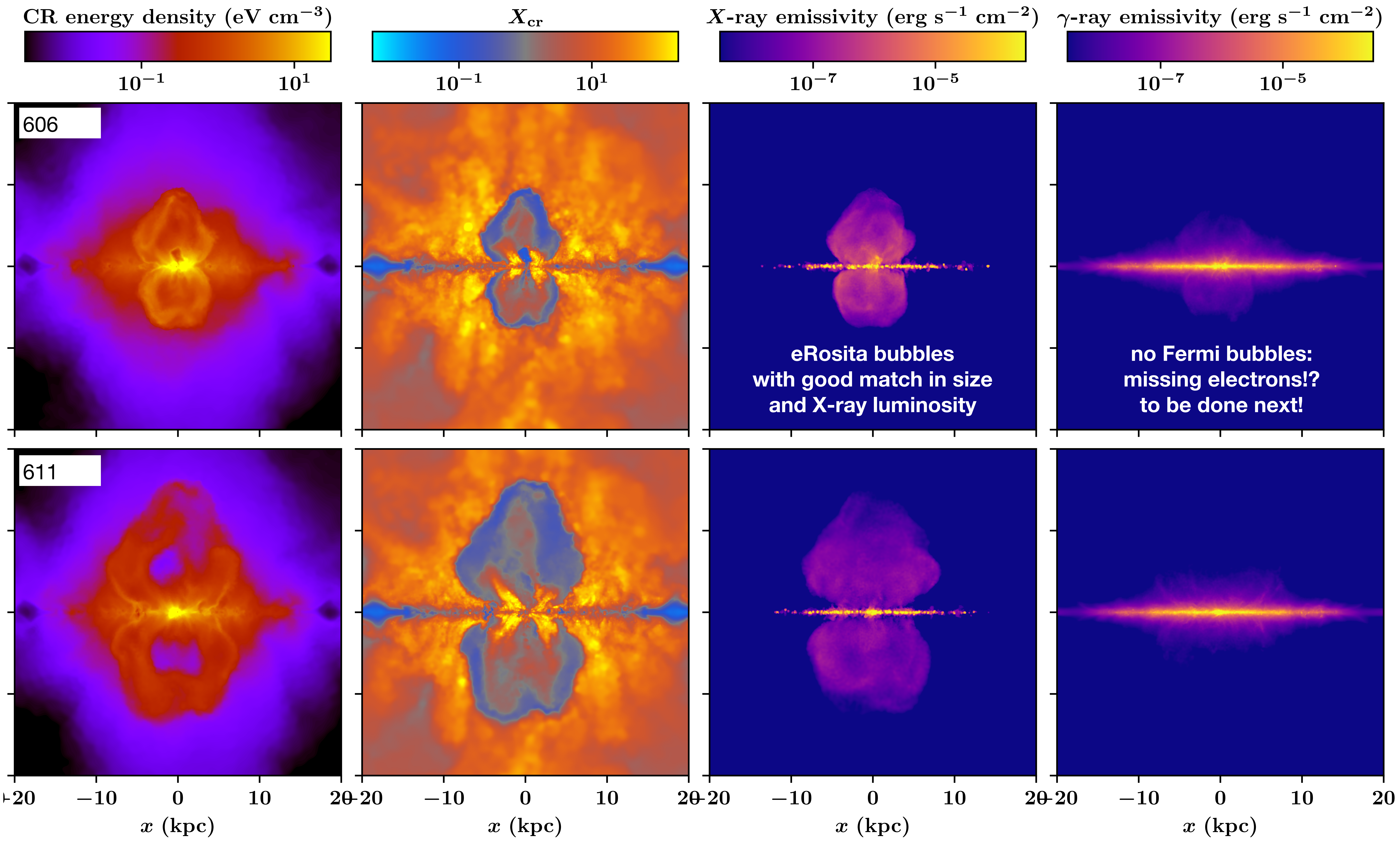




Predehl et al. 2020

bubble evolution with X & γ-ray emission

Girichidis et al. in prep.

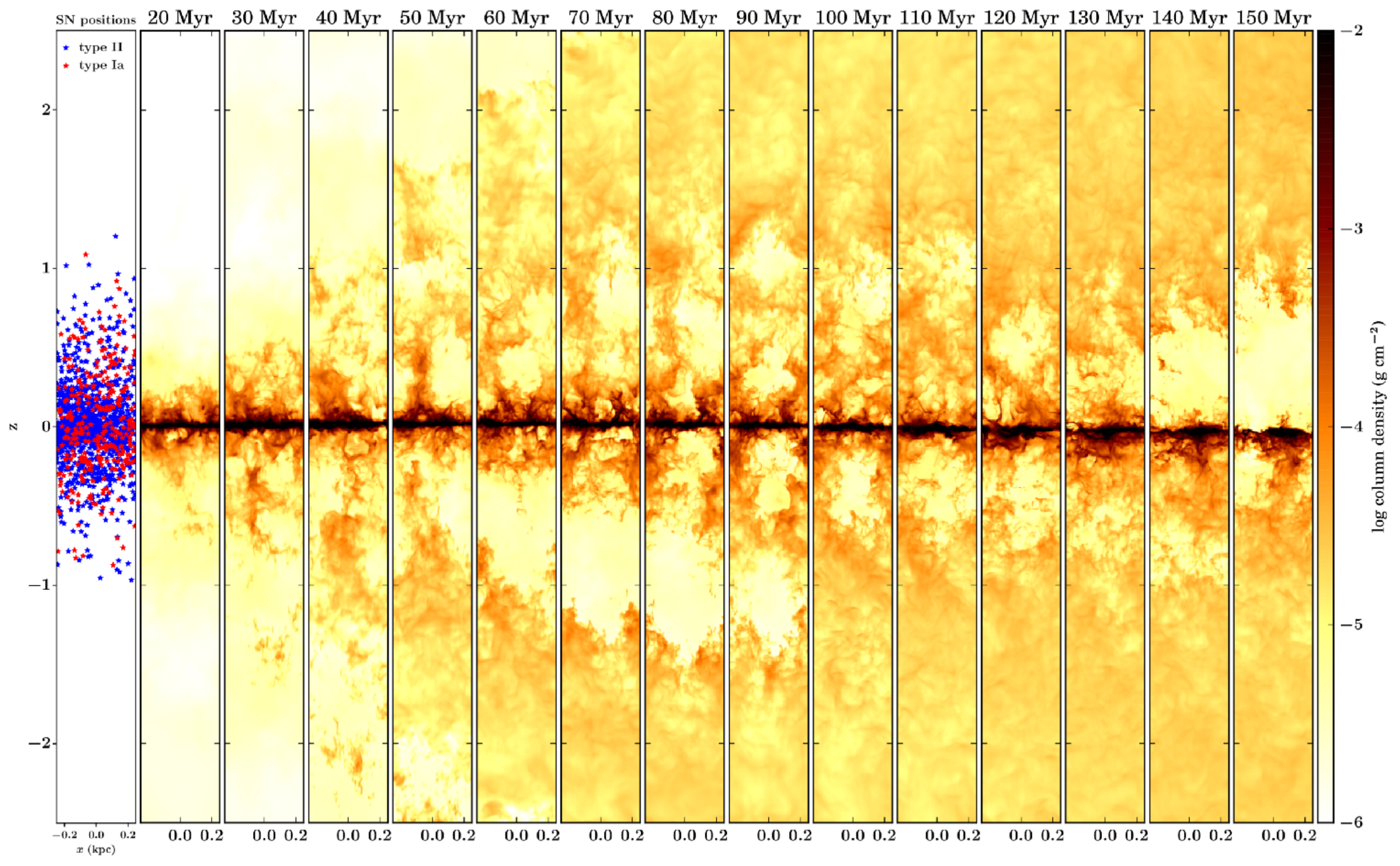


Take home points

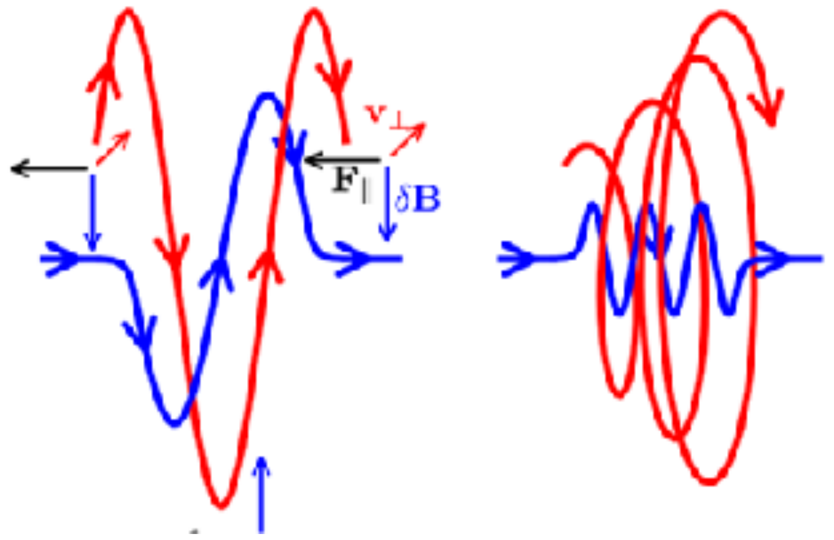
- CRs $\leftrightarrow$ B field
  adv. + diffusion/streaming along B

- ISM: $e_{\rm cr} \sim e_{\rm kin} \sim e_{\rm therm} \sim e_{\rm mag}$

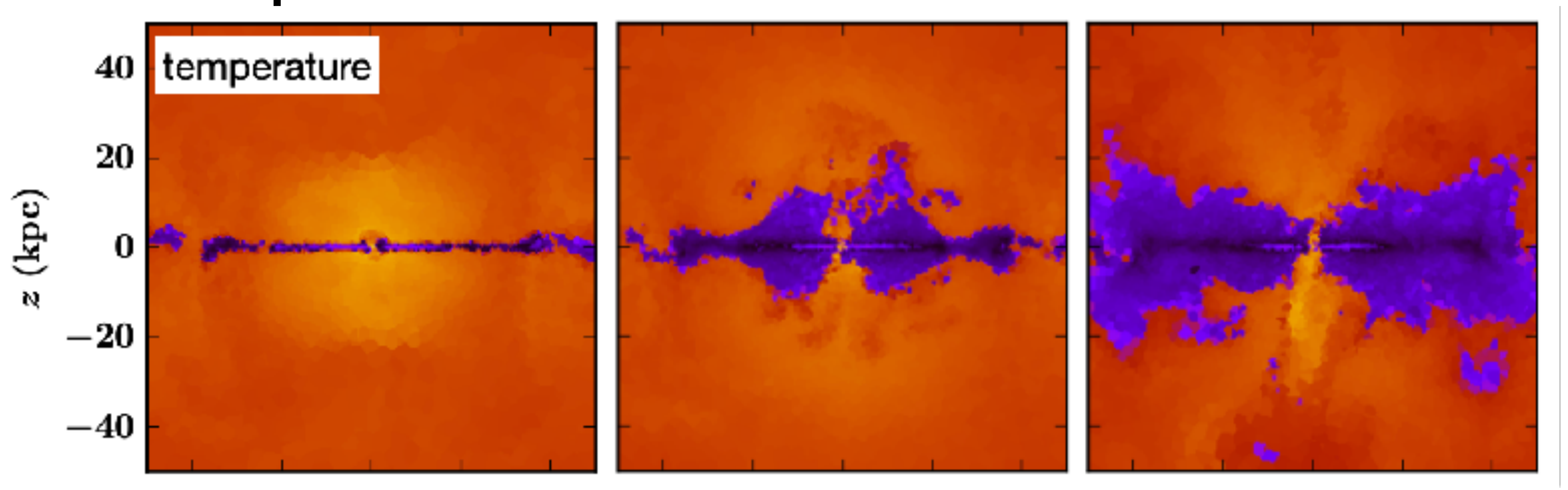
- CR drive warm and smooth outflows



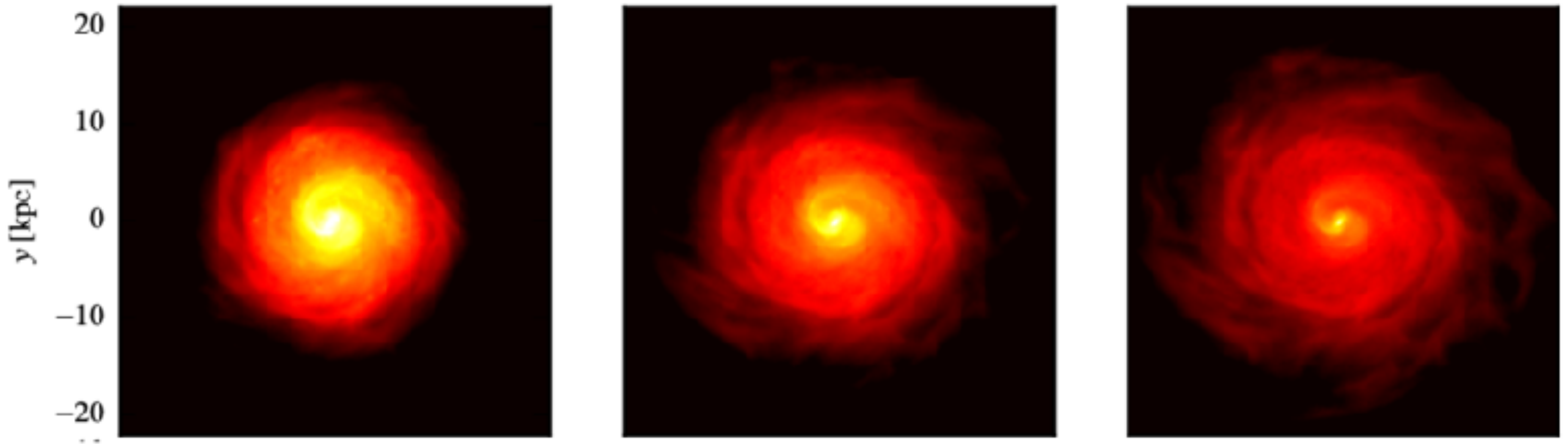
- todo: new plasma transport models



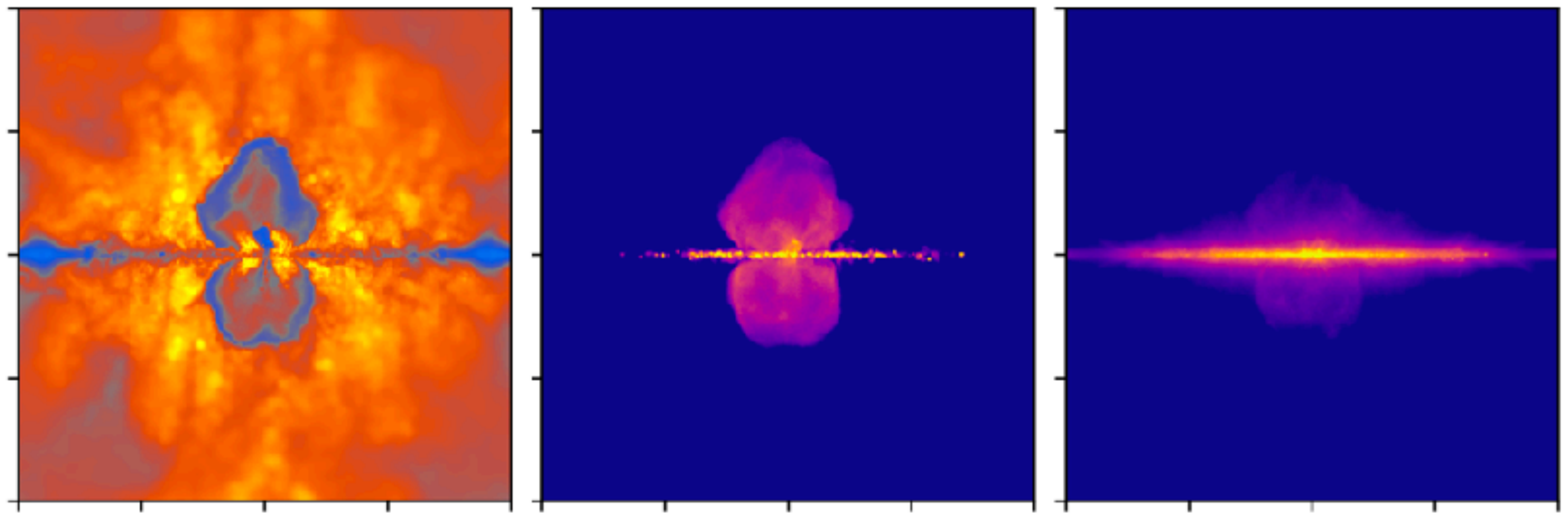
- live spectra: different CGM / outflows



- live spectra: better fit to γ-ray obs.



- CRs in GC: eRosita/Fermi bubbles

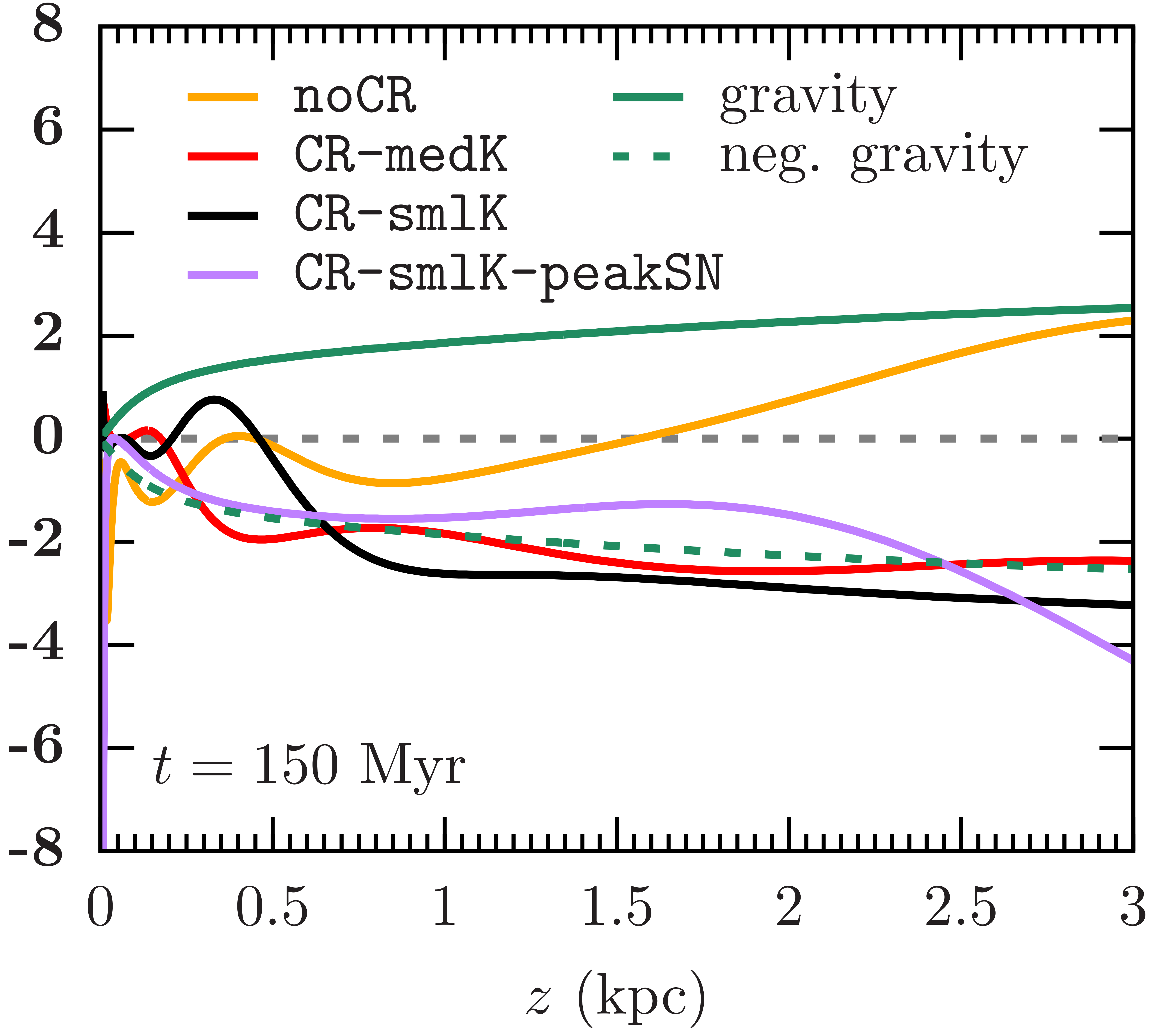


Backup slides

Girichidis et al. 2018a

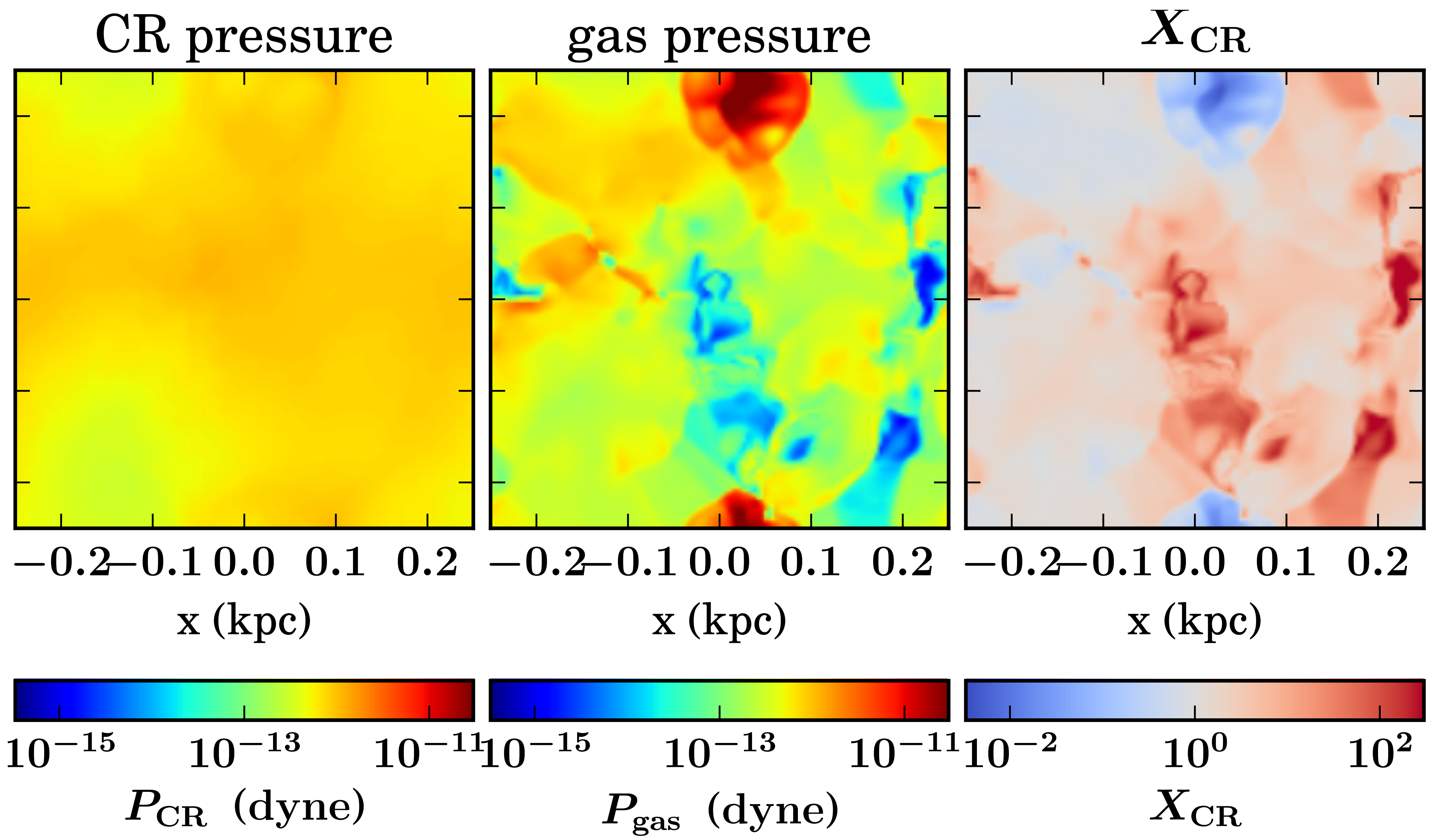
Force balance

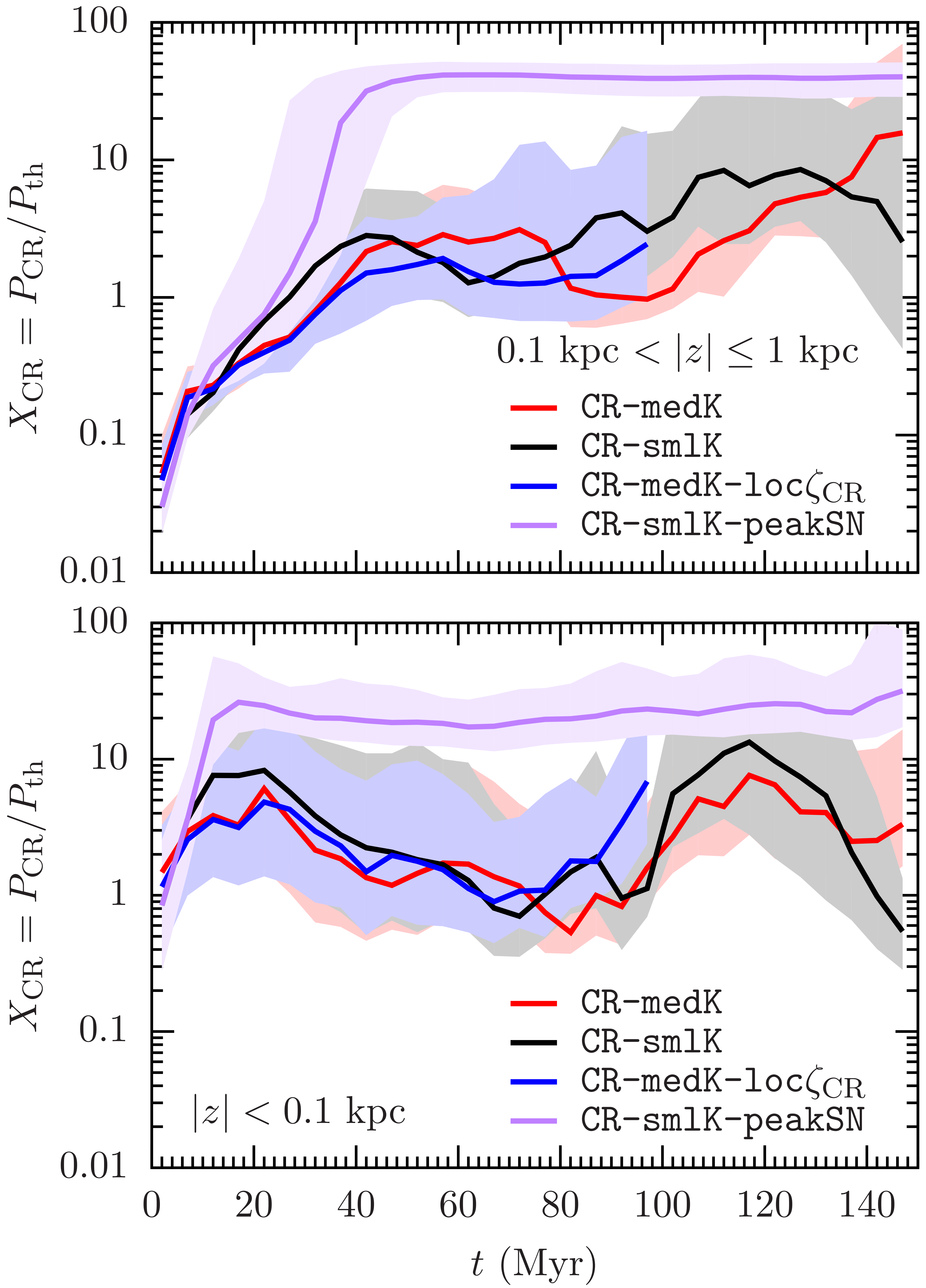
- CR pressure gradient over-compensates gravitational attraction
- force-free motions of gas into halo
- slowly lift the gas, not shooting



CR pressure

- CRs in approximate equipartition in ISM consistent with obs. (Ferriere 2001, Cox 2005)
- fast diffusion (faster than gas motions) CR pressure is almost uniform
- weak gradients compared to $\nabla P_{\rm therm}$



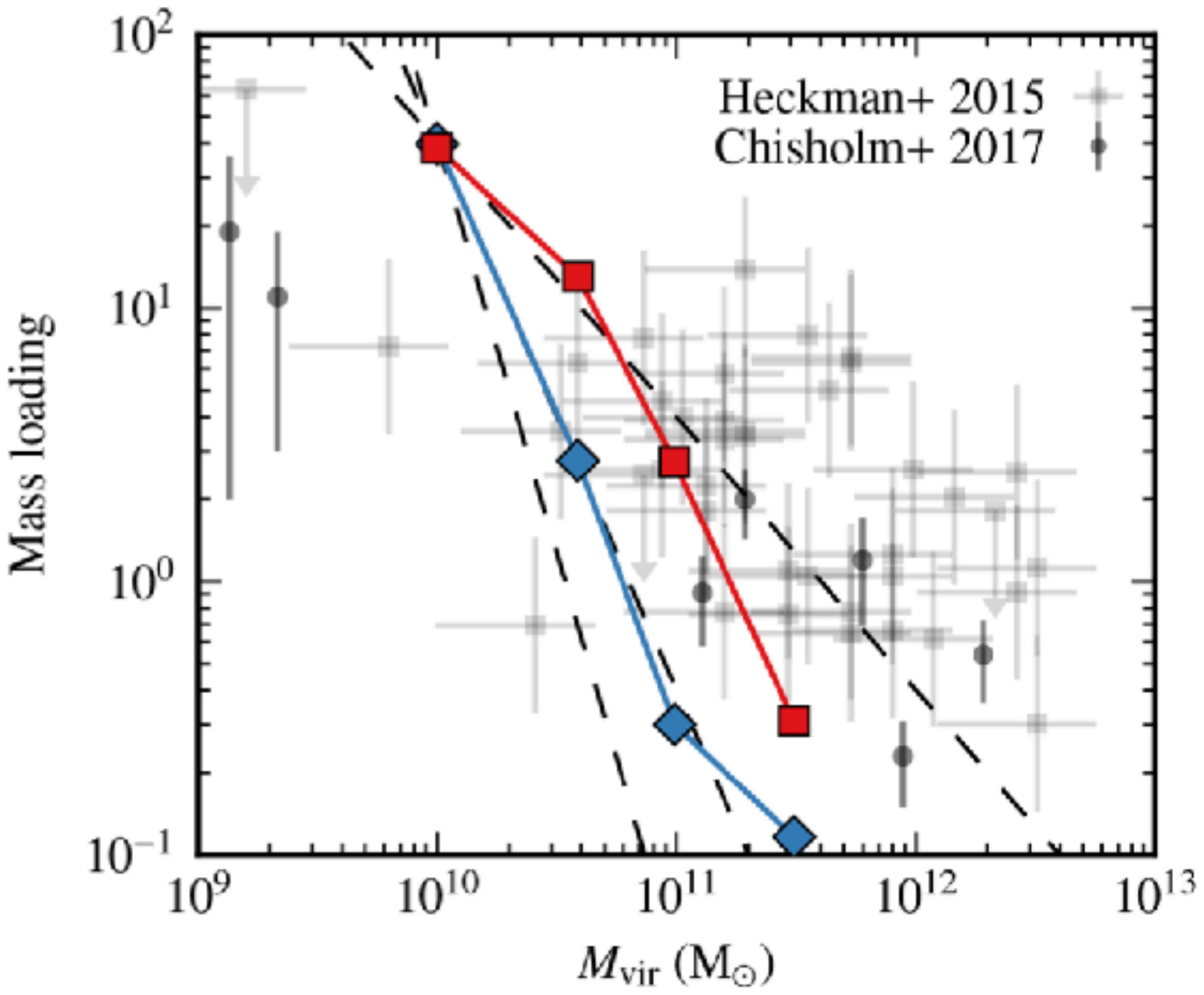


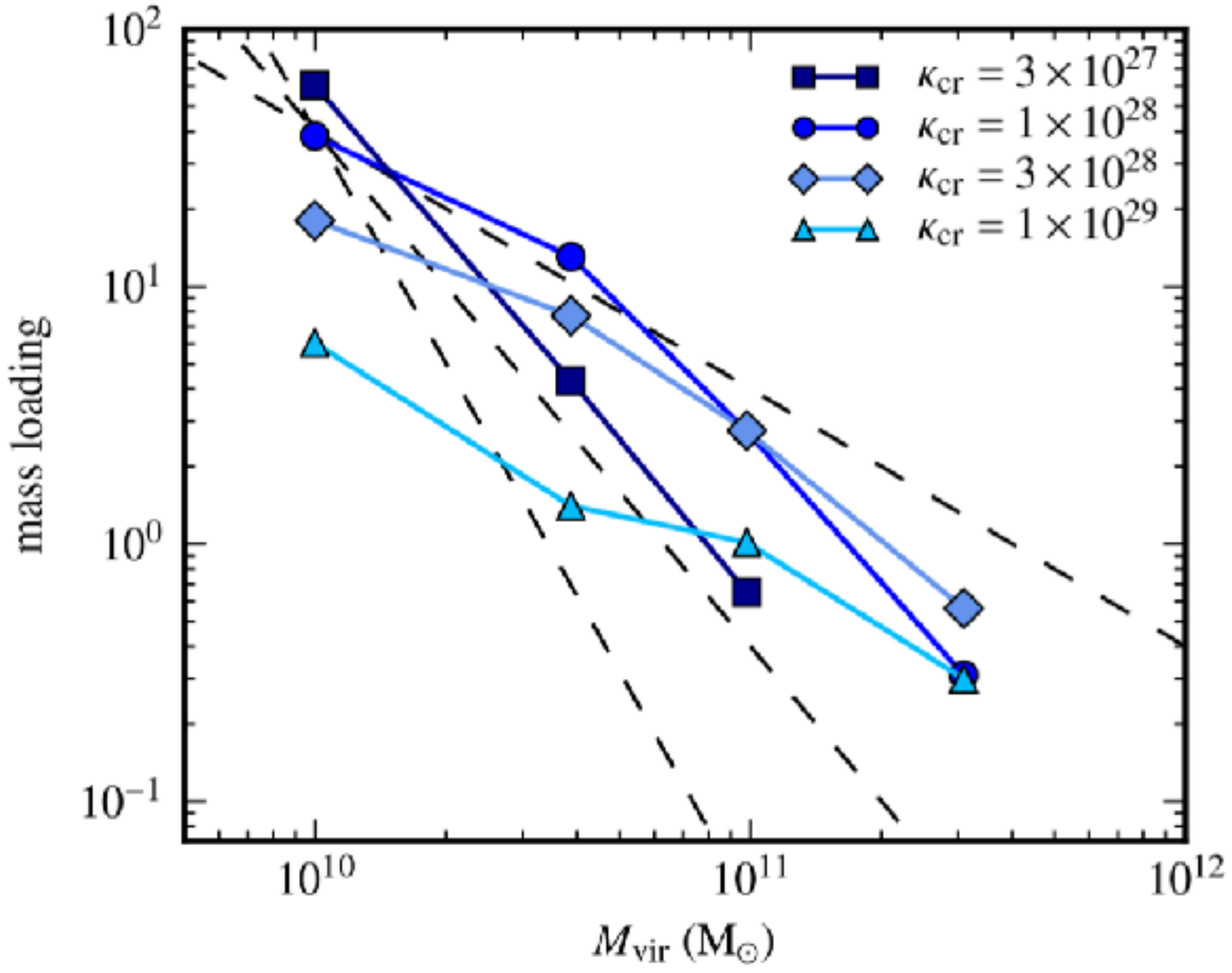
Halo mass dependence

- CR power for outflows is limited
- above $M \sim 3 \times 10^{11}\,\mathrm{M}_\odot$ no outflows
- depends on injection efficiency
- high diffusivity, weaker mass loading

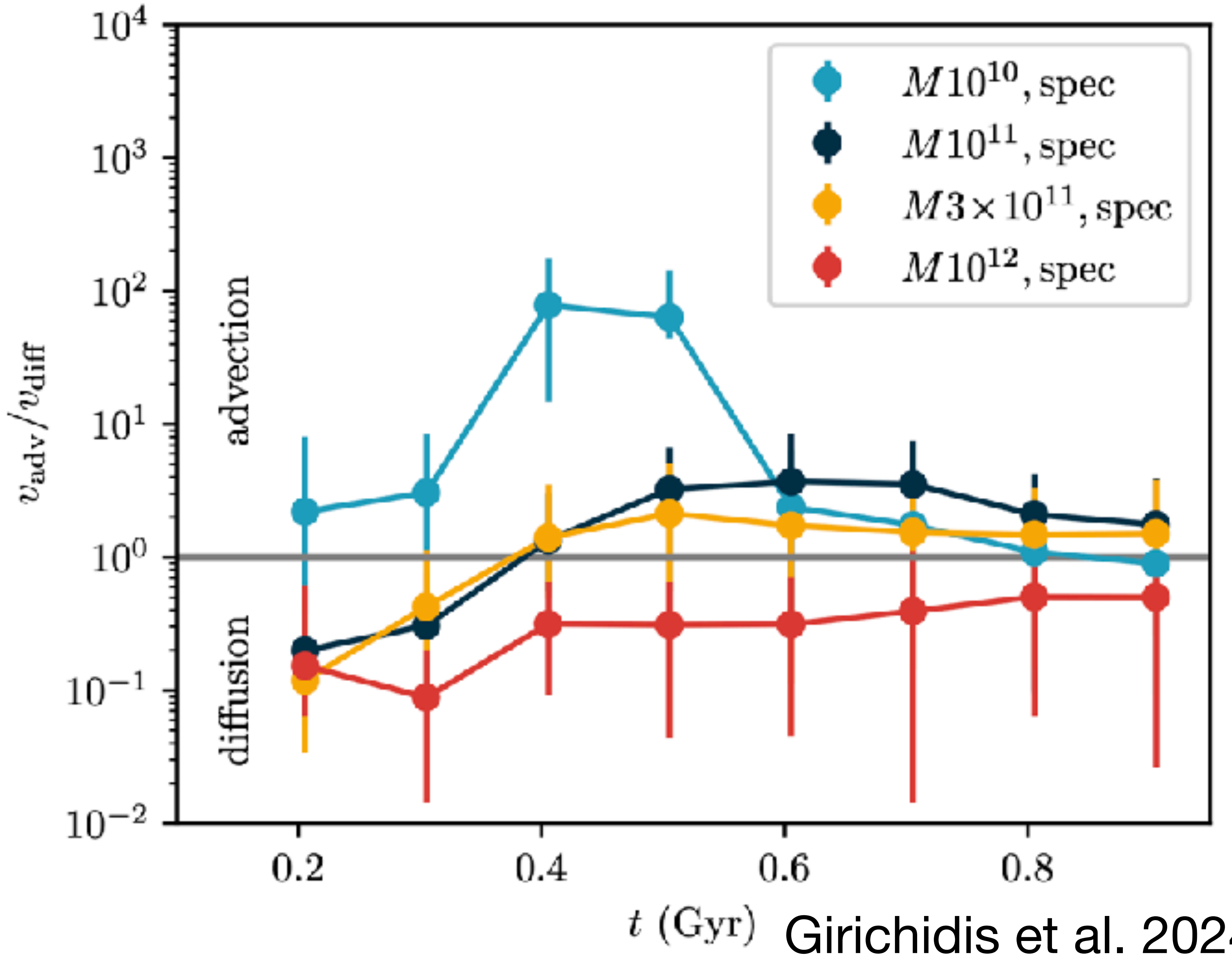
- in dwarf:
  CR transport mainly advective

- in MW:
  CR transport mainly diffusive





Jacob et al. 2018

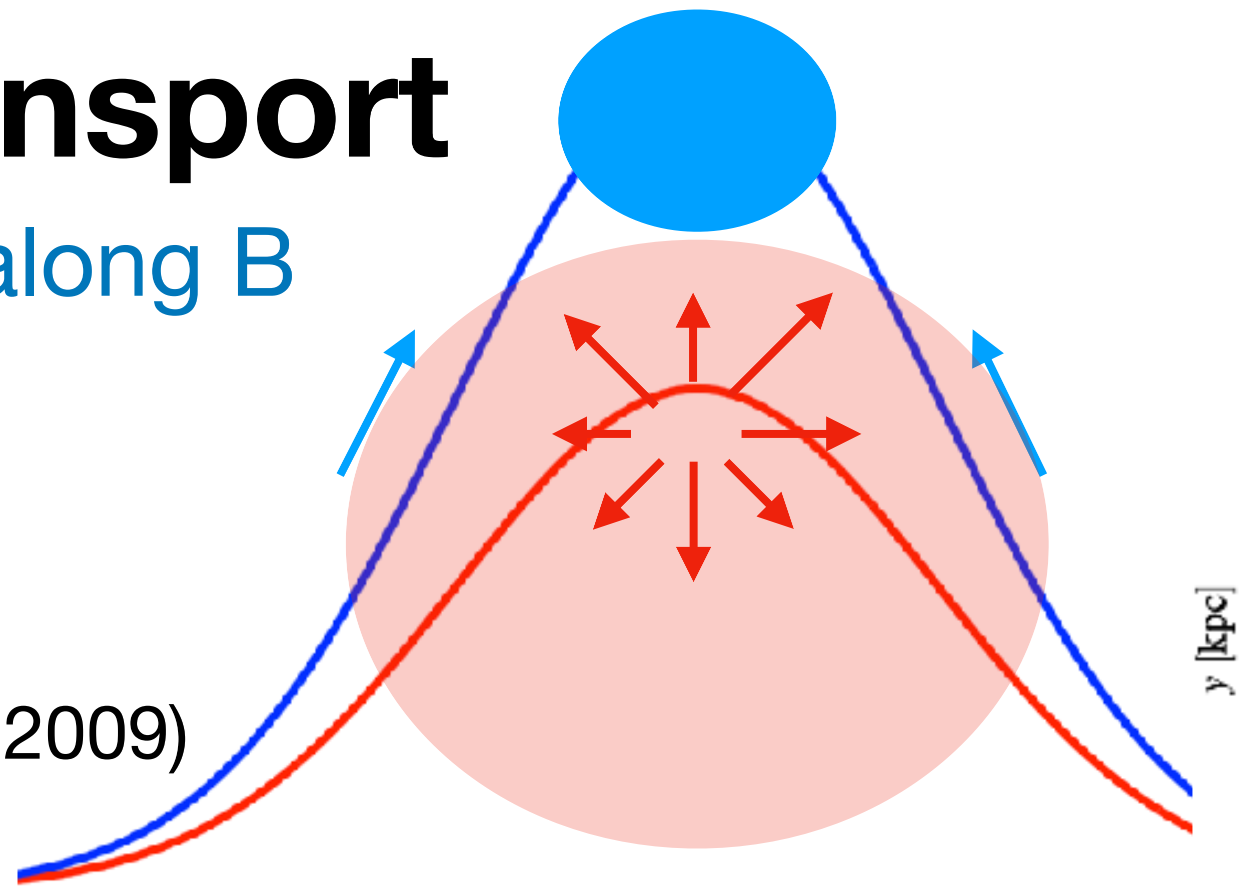


Girichidis et al. 2024

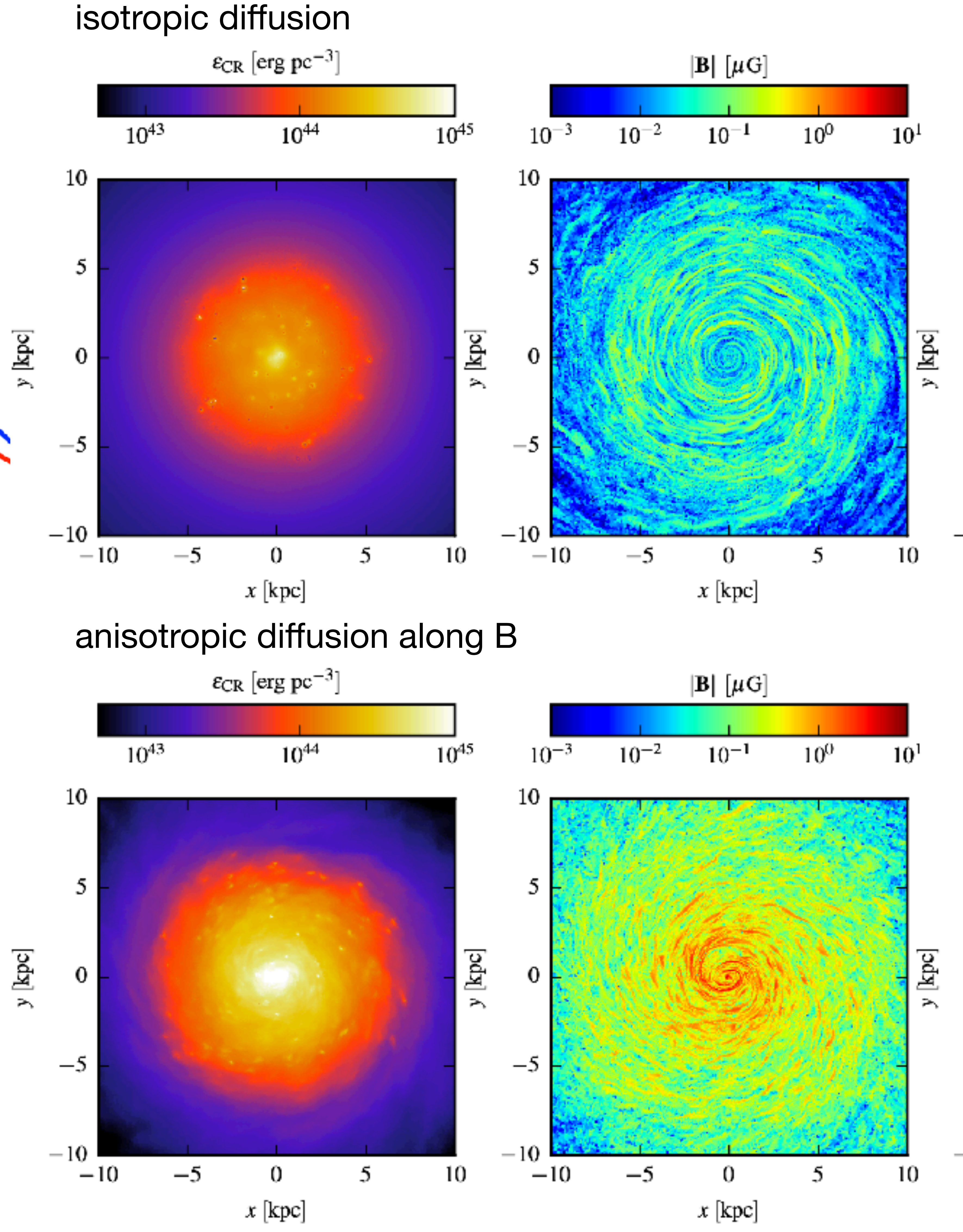
CR-driven dynamo

isotropic vs. anisotropic transport

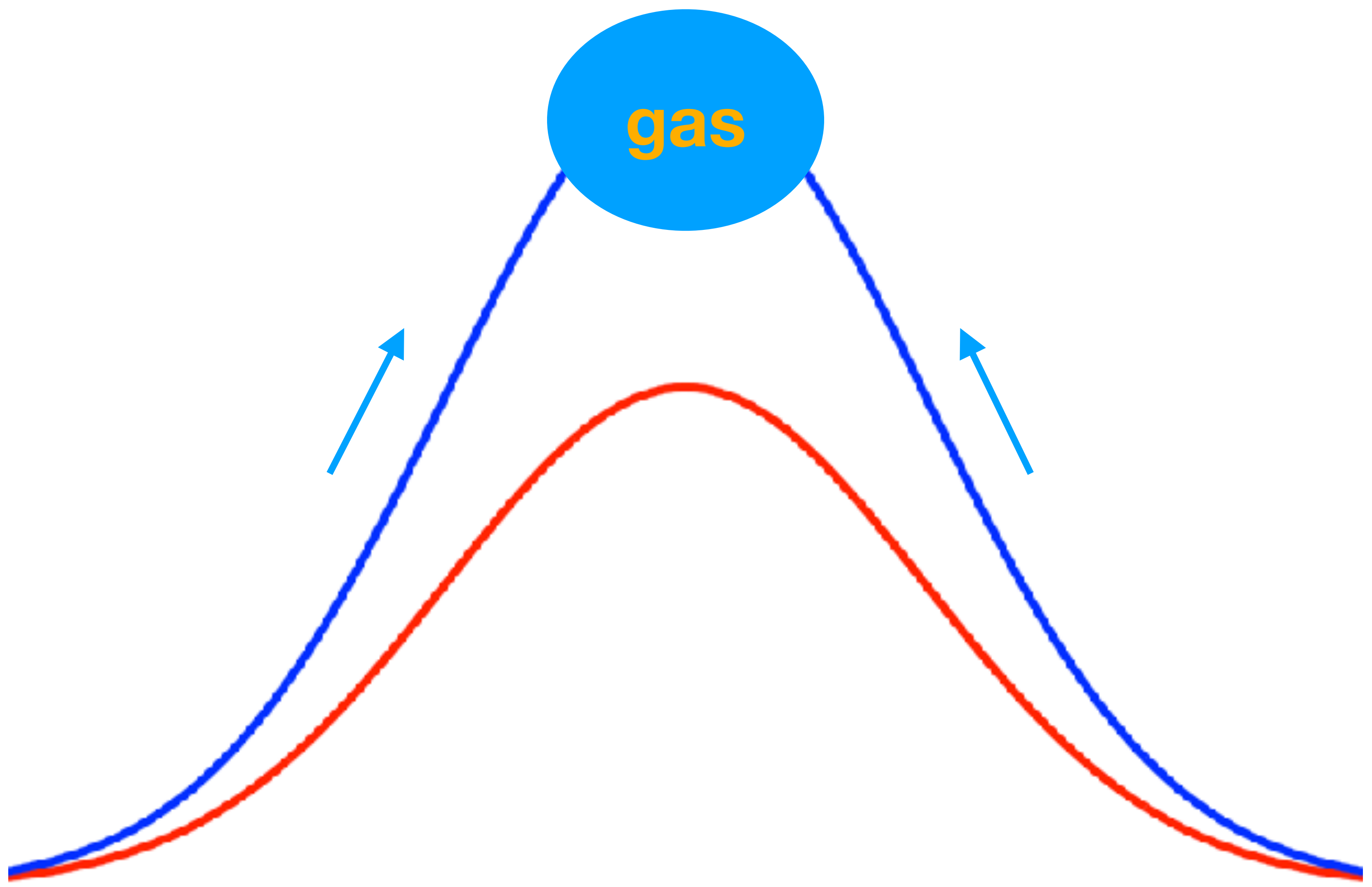
- isotropic diffusion vs. anisotropic diffusion along B
- impact on B-field strength
  enhance Parker loops (Parker 1992)
- stronger α effect in large scale dynamo
  (Hanasz & Lesch 2000, Lesch & Hanasz 2003, Hanasz+ 2009)



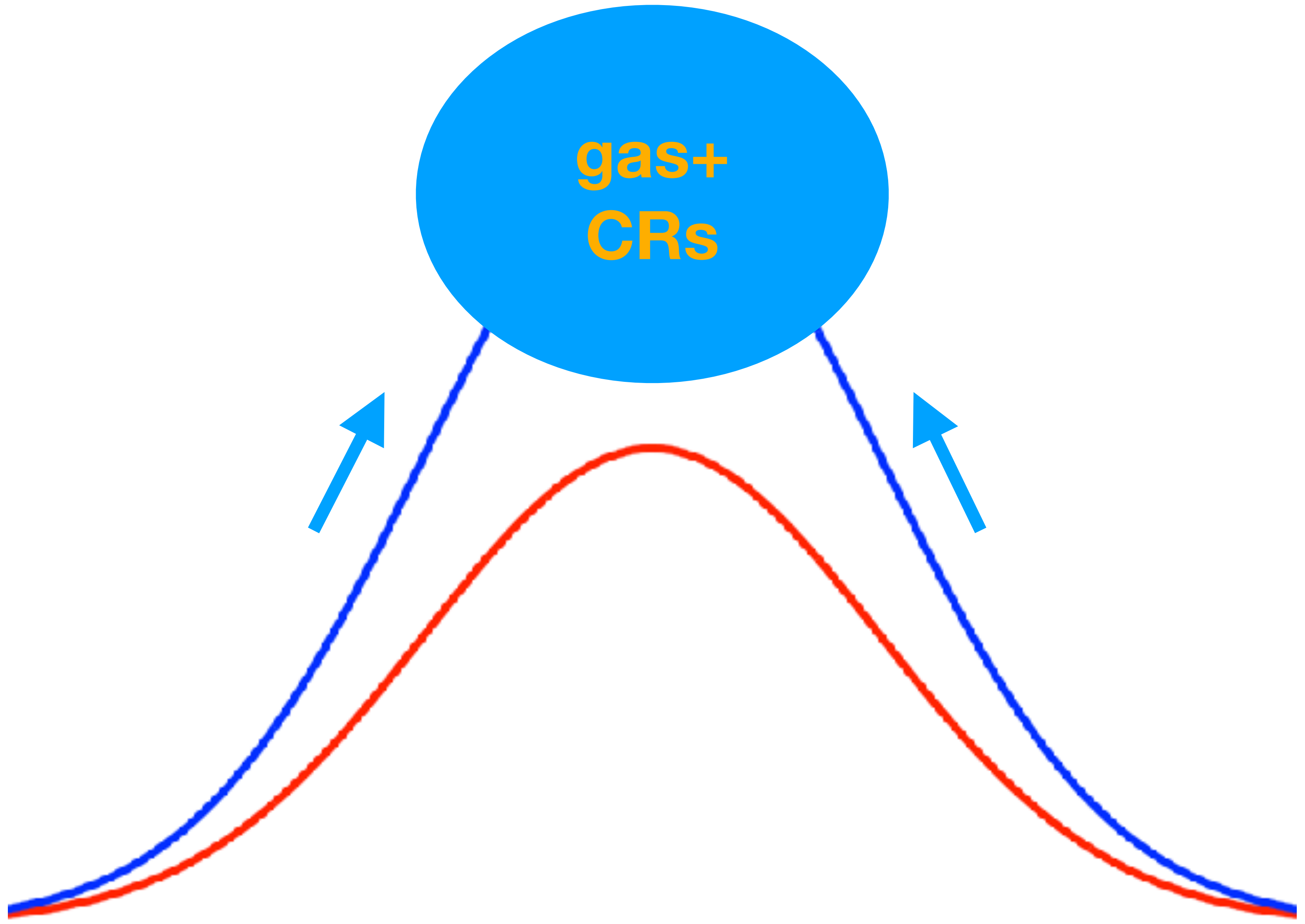
Pakmor et al. 2016



thermal Parker loop

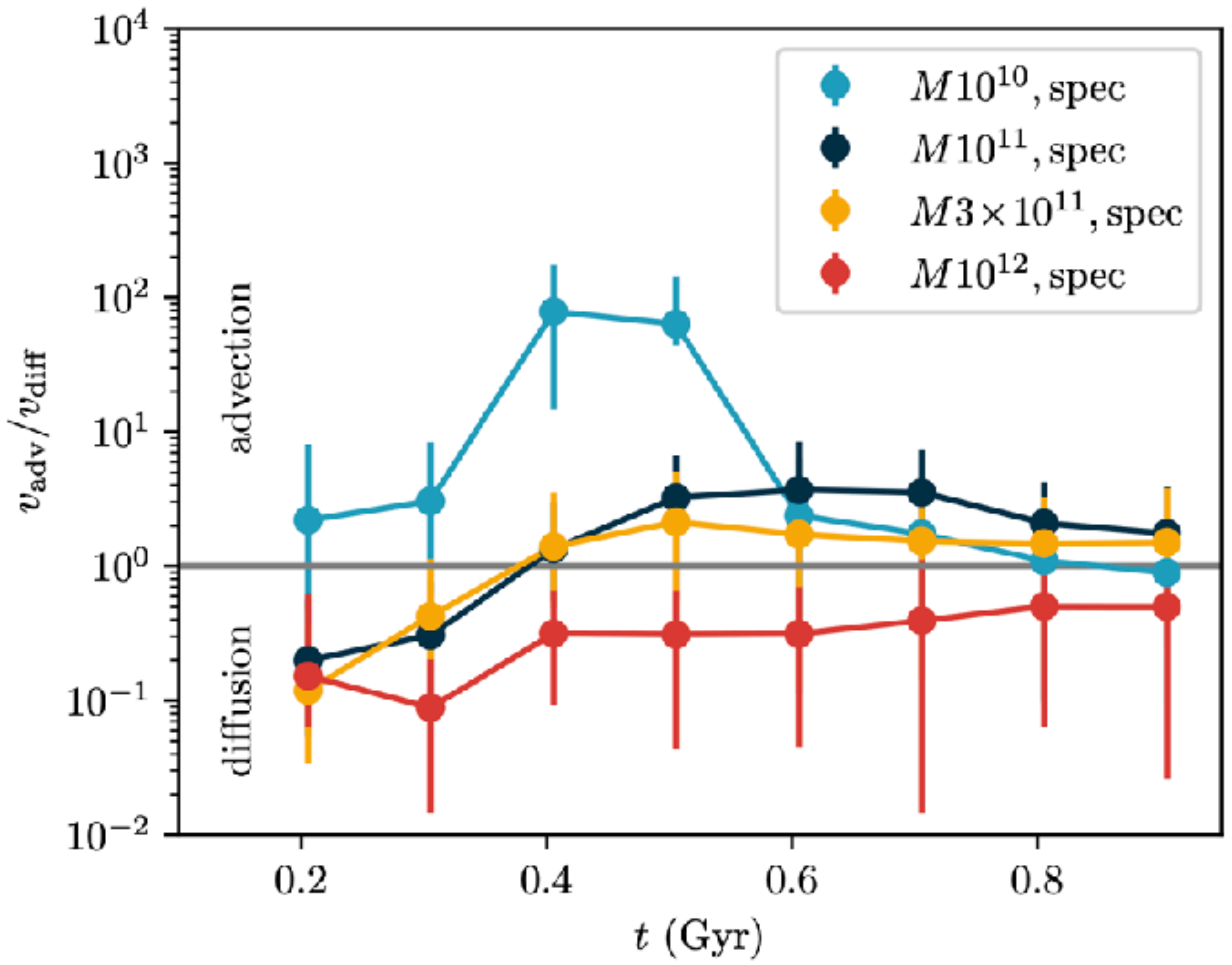


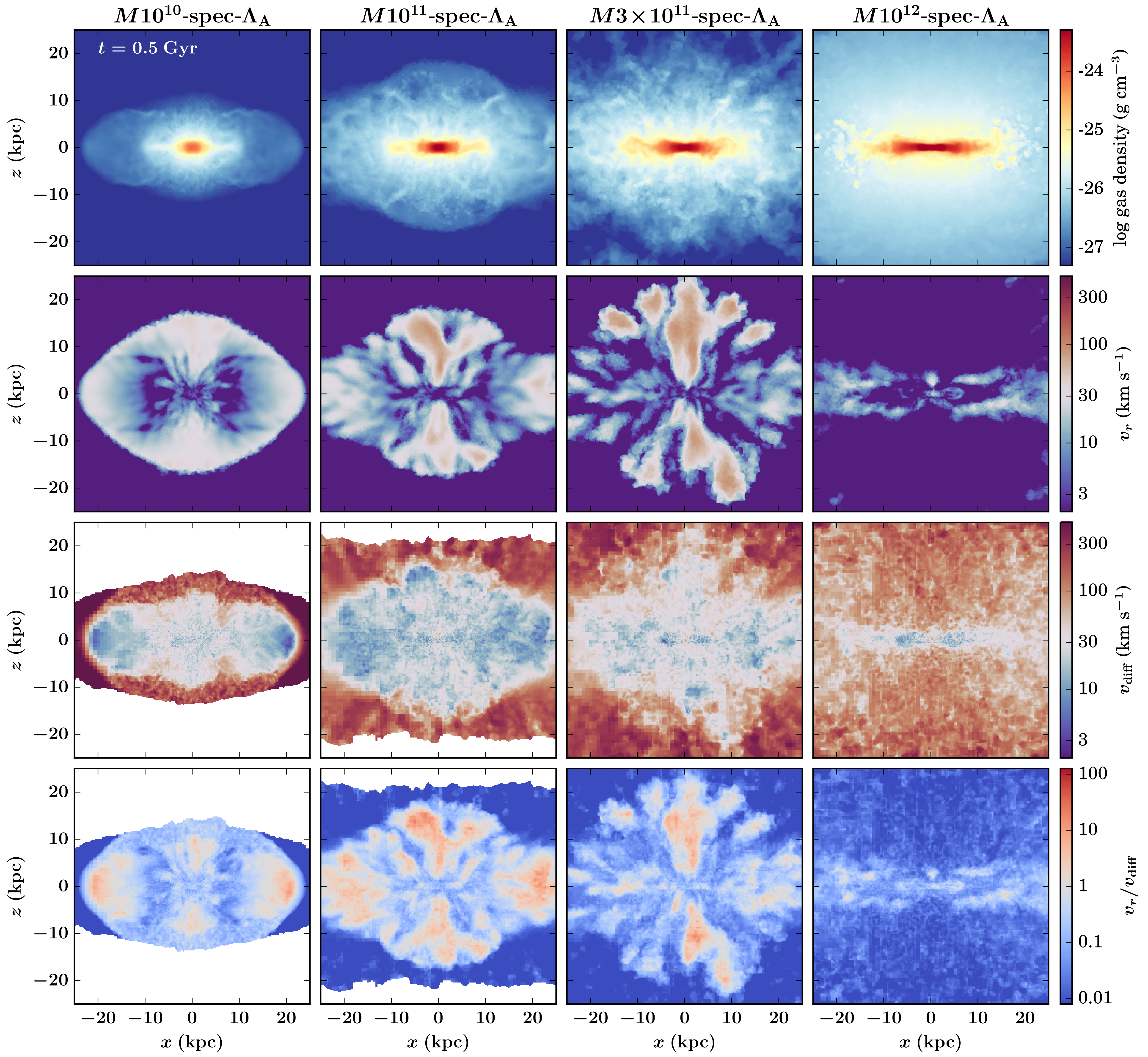
CR enhanced Parker loop



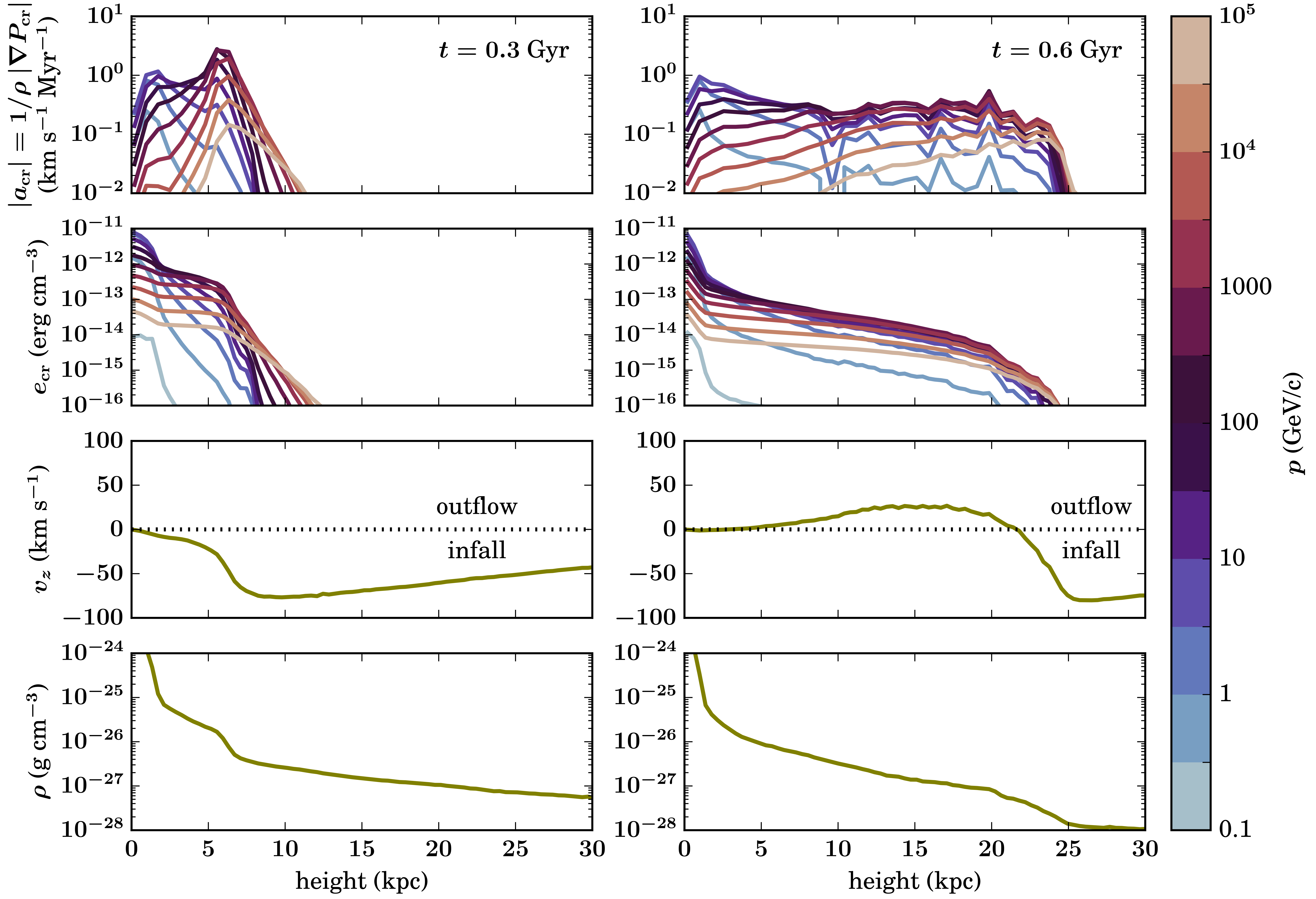
Advection vs. diffusion

- dwarfs: dominated by advection
- Milky Way dominated by diffusion





Advection vs. diffusion in spectra (dwarf)



Advection vs. diffusion in spectra (MW)