An introduction to cosmic rays

A bit of theory and simulations

Philipp Girichidis, 13.02.2024

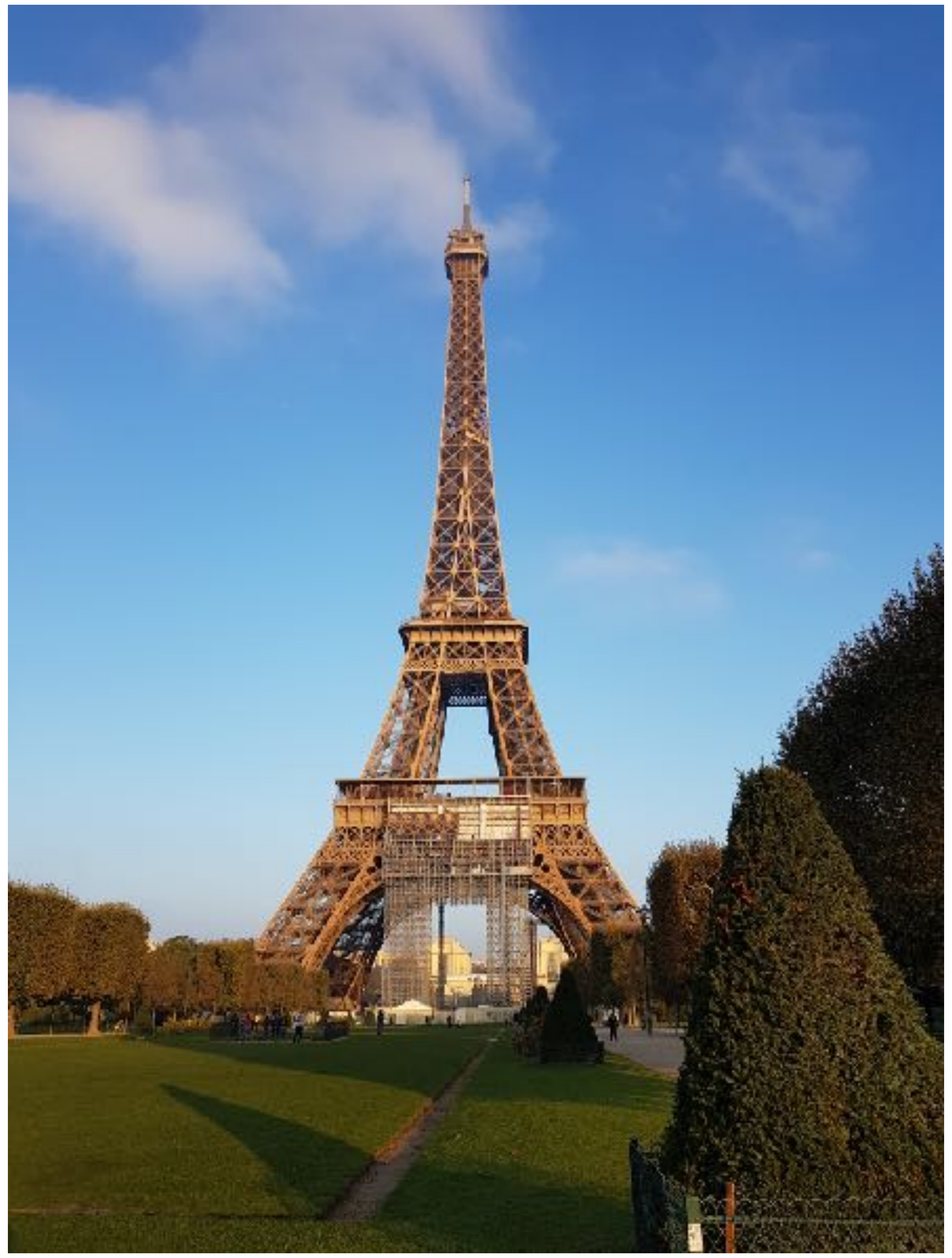
Overview

- What are cosmic rays (CRs)
- basics of interactions and transport (microscopic perspective)
- particle acceleration and CR origin
- fluid approaches (macroscopic perspective)
- CR-MHD fluids and numerical models / applications in galaxies and the ISM

What are Cosmic Rays

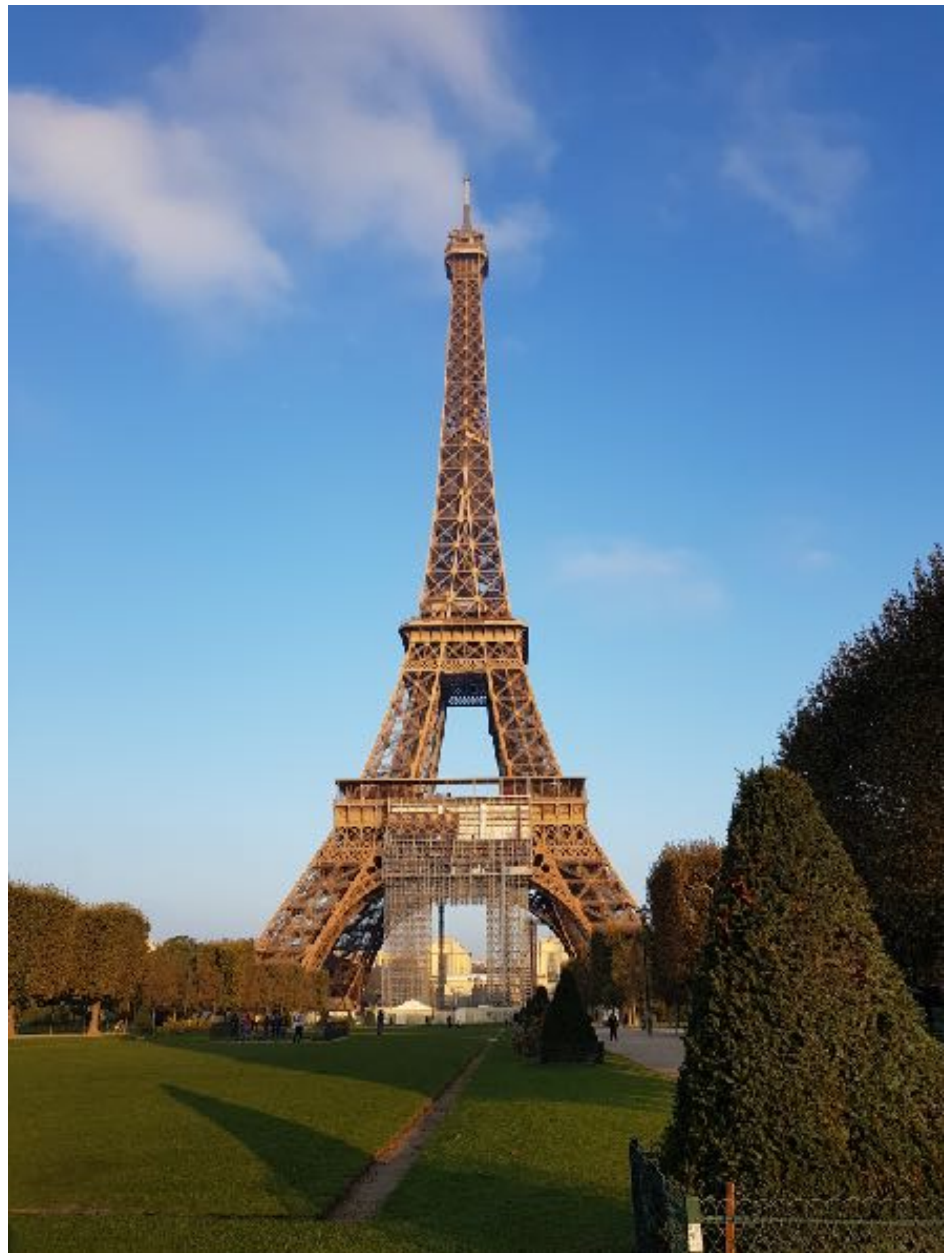
Historical notes

- 1909: Theodor Wulf invents electrometer and finds increasing radiation on top of Eiffel Tower
- 1911: Domenico Pacini: experiments at sea level and below (higher radiation at sea level)
- Discovered in 1912 by Victor Hess during balloon-borne experiments: radiation increases with altitude



Historical notes

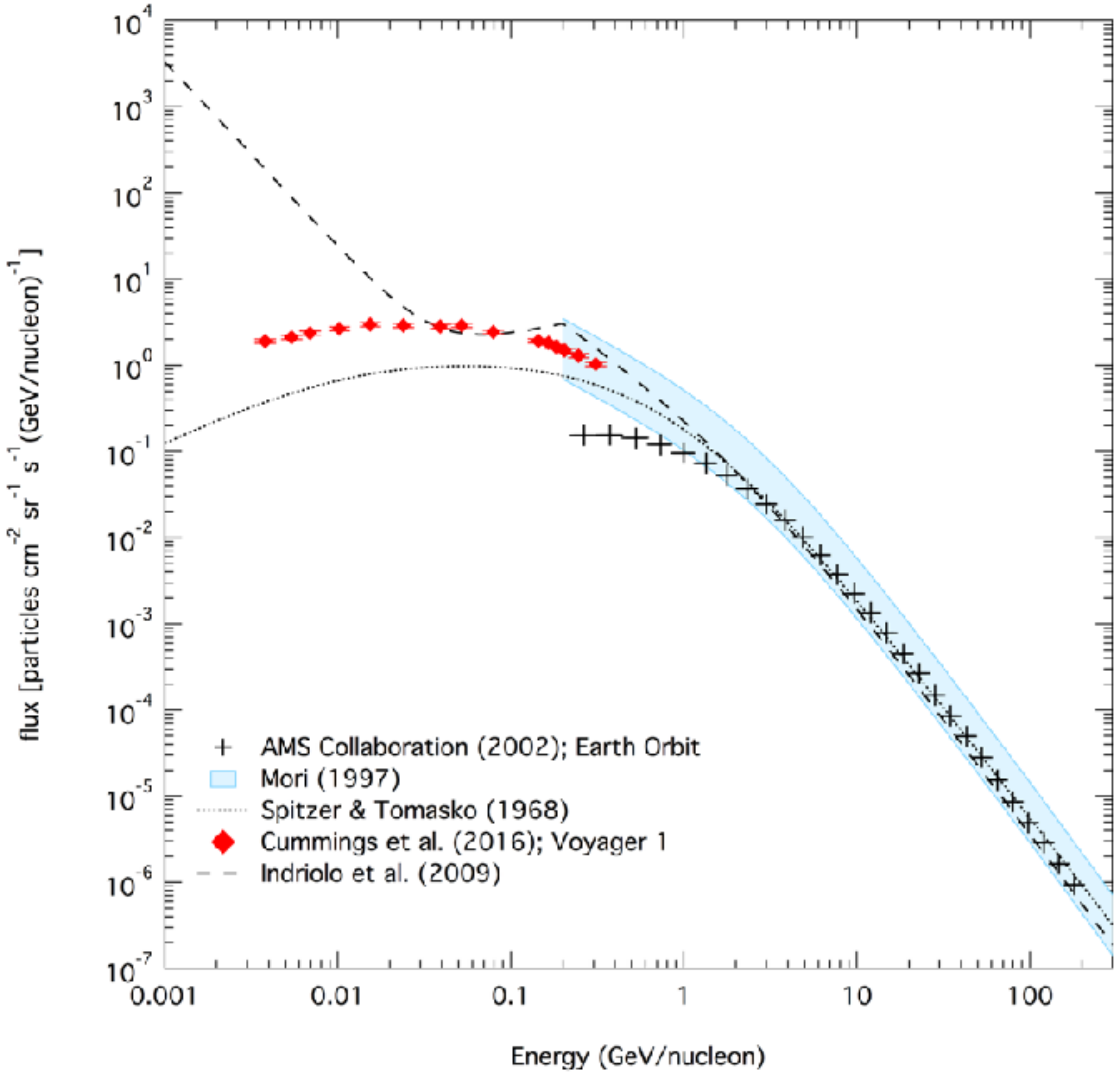
- 1909: Theodor Wulf invents electrometer and finds increasing radiation on top of Eiffel Tower
- 1911: Domenico Pacini: experiments at sea level and below (higher radiation at sea level)
- Discovered in 1912 by Victor Hess during balloon-borne experiments: radiation increases with altitude
- "Solid knowledge" about cosmic rays (Millikan 1926 Proc. NAS, 12, 48)
  "We can draw some fairly reliable conclusions of a general sort as to the origin of these very penetrating and high frequency rays"
- Now known to be highly energetic charged particles
  (p, e-, e+, α, heavy bare nuclei)

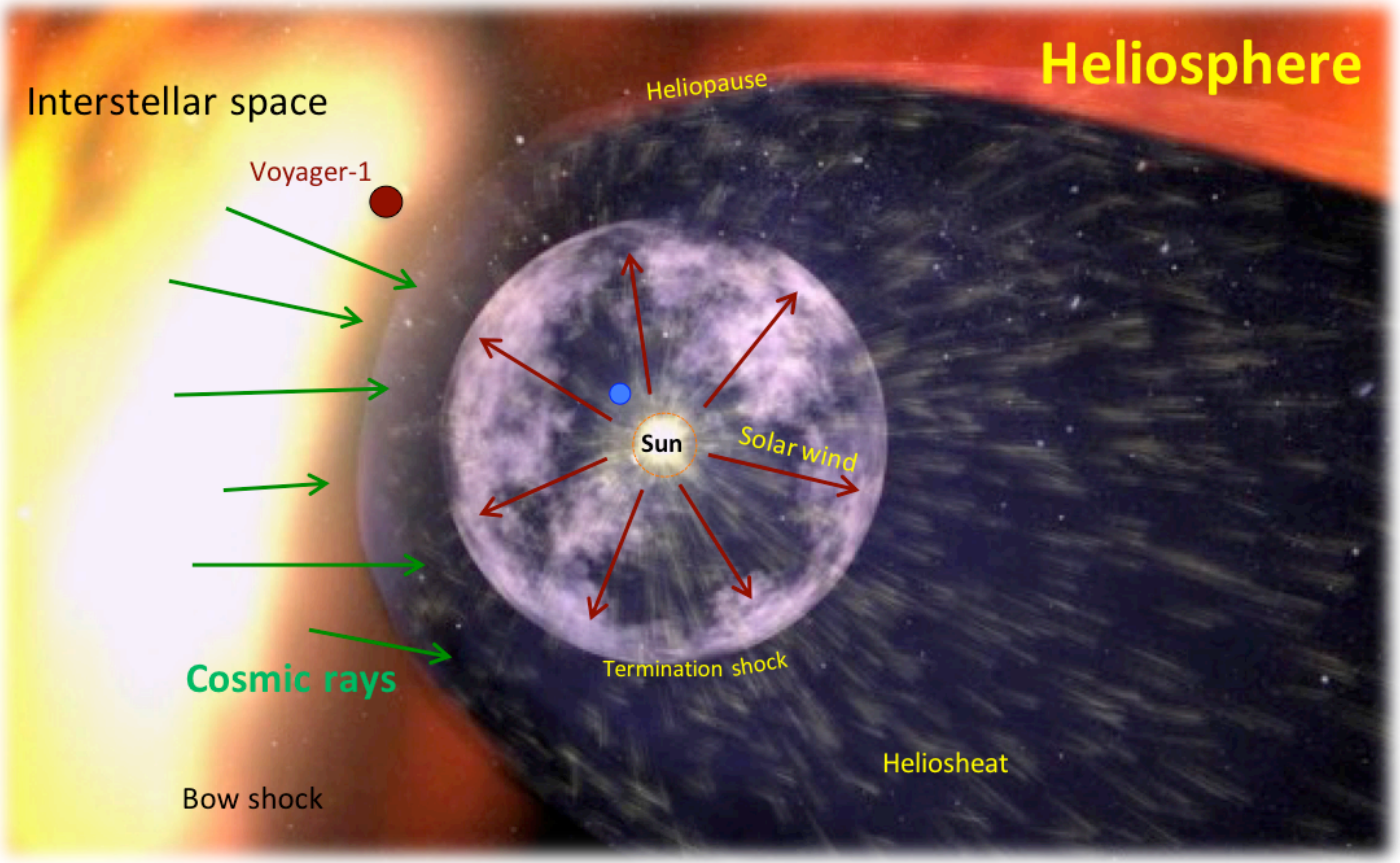


Cosmic ray energy distribution

low energies

- low-E ($\lesssim 1\ \mathrm{GeV}$) spectrum poorly constrained: solar modulation





https://matisse.web.cern.ch

Cosmic ray energy distribution

intermediate and high energies

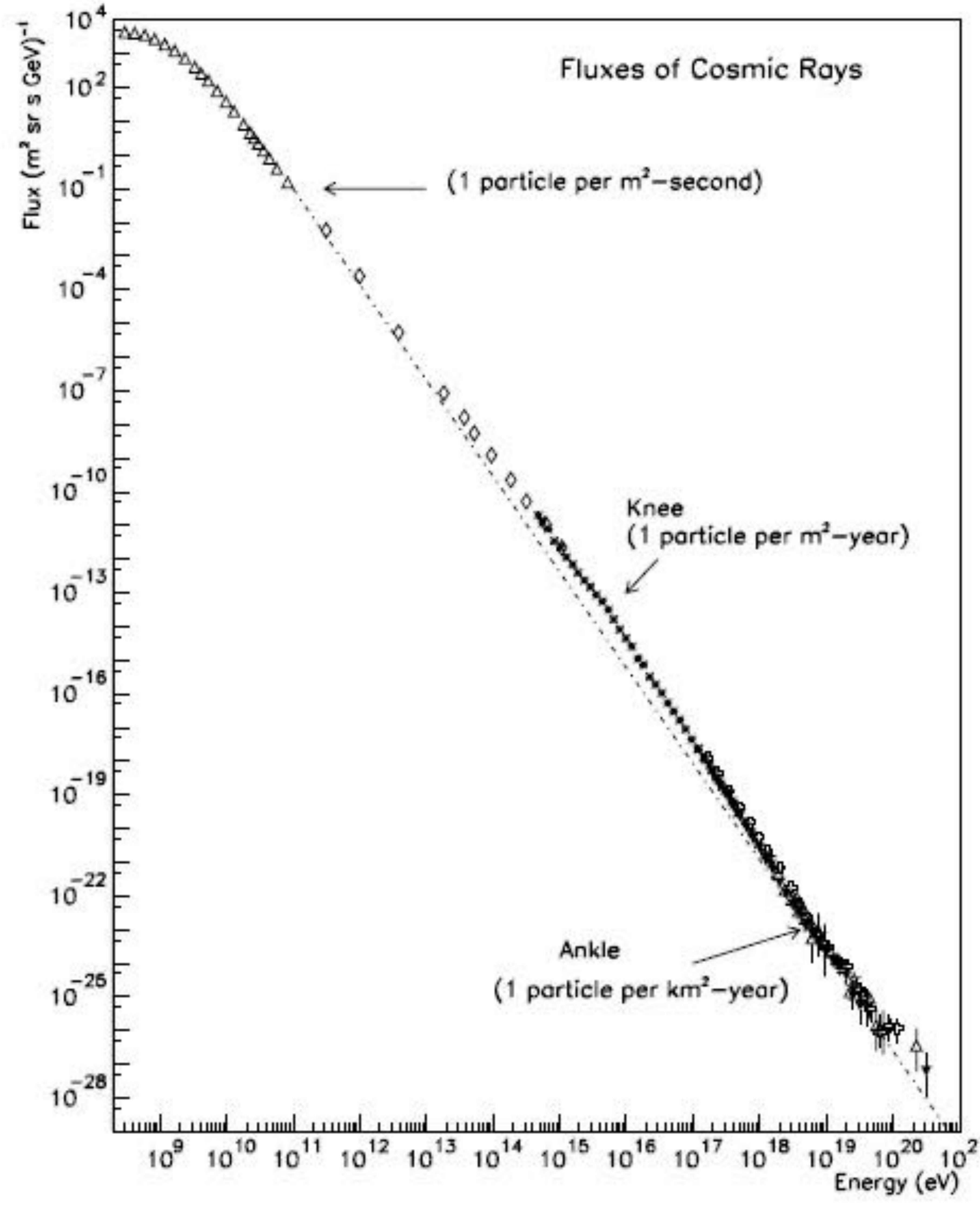
- $100\ \mathrm{GeV} \lesssim E \lesssim 10^{16}\ \mathrm{eV}$
  power law $n(E)\mathrm{d}E \propto E^{-2.7}$

- “knee” at $10^{15}\,\mathrm{eV}$
  “end” of galactic CRs

- $10^{16}\ \mathrm{eV} \lesssim E \lesssim 10^{19}\ \mathrm{eV}$
  power law $n(E)\mathrm{d}E \propto E^{-3}$

- “ankle” at $10^{19}\,\mathrm{eV}$

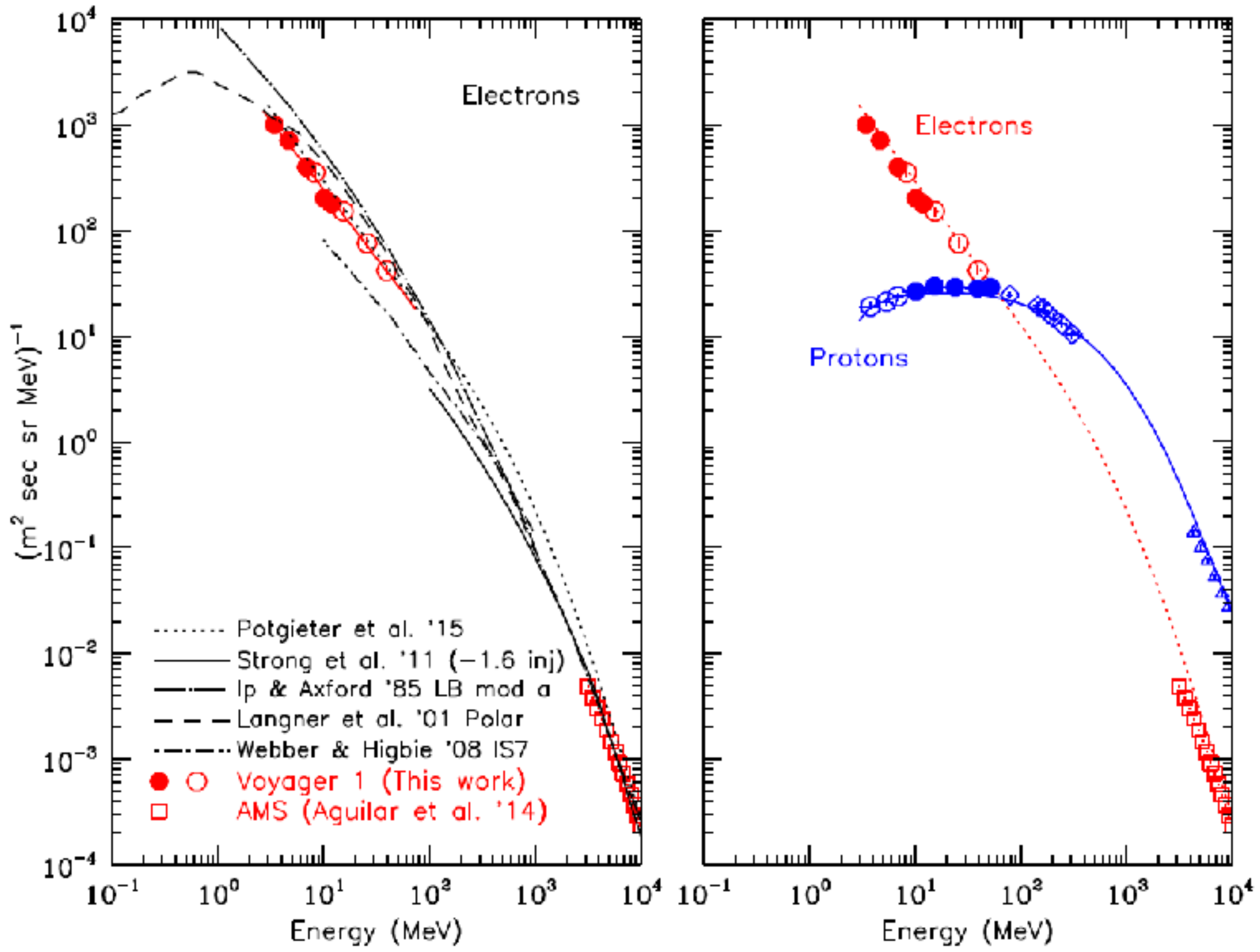
- $\sim 10^{20}\,\mathrm{eV}$: GZK (Greisen-Zatsepin-Kuzmin) cutoff: theoretical upper limit (efficient losses due to interaction with CMB radiation)



Swordy 2001, Space Sci. Rev., 99, 85

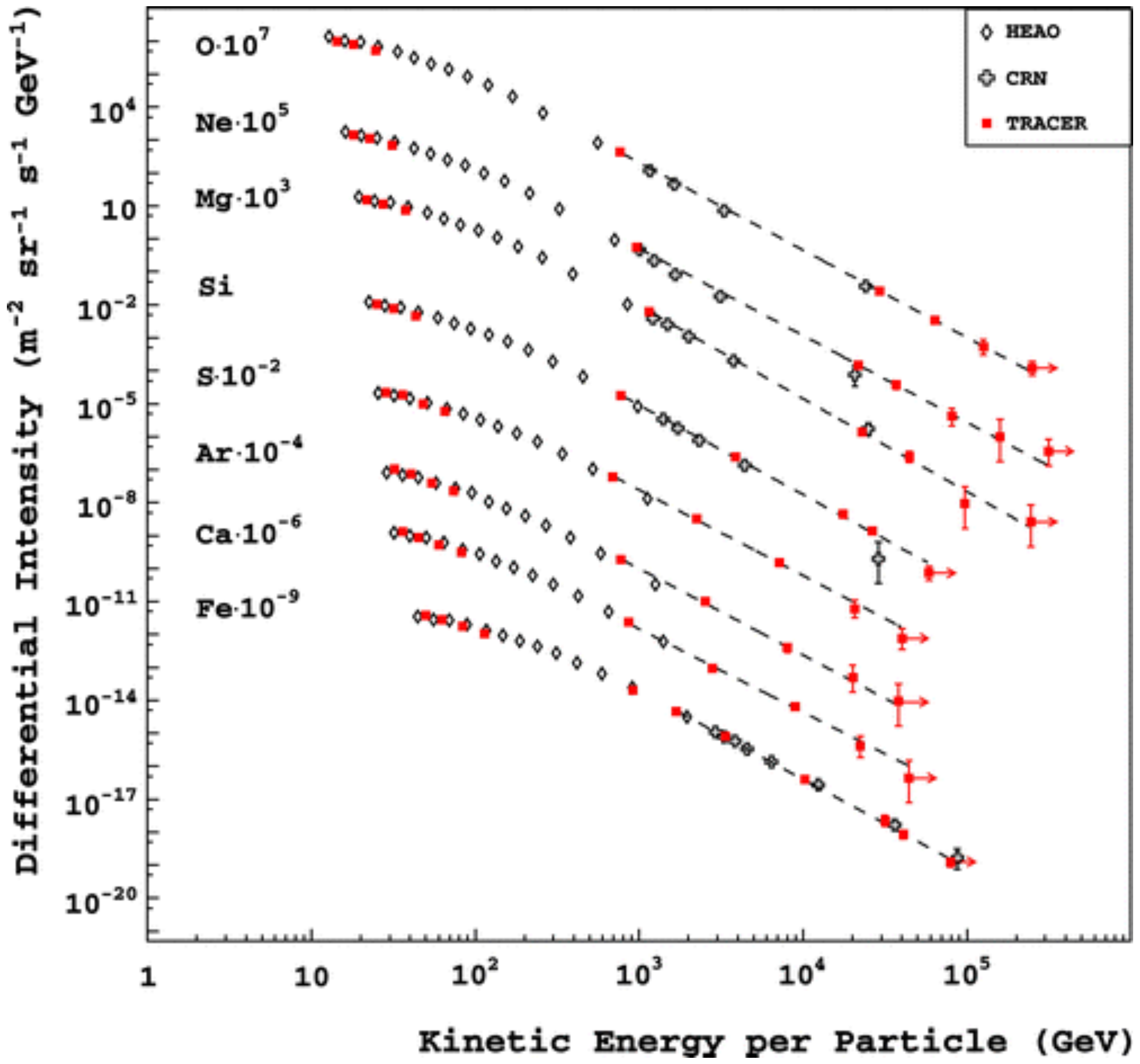
Composition

- e^- dominate at low E, p at high E



Cummings et al. 2016, ApJ, 831, 18

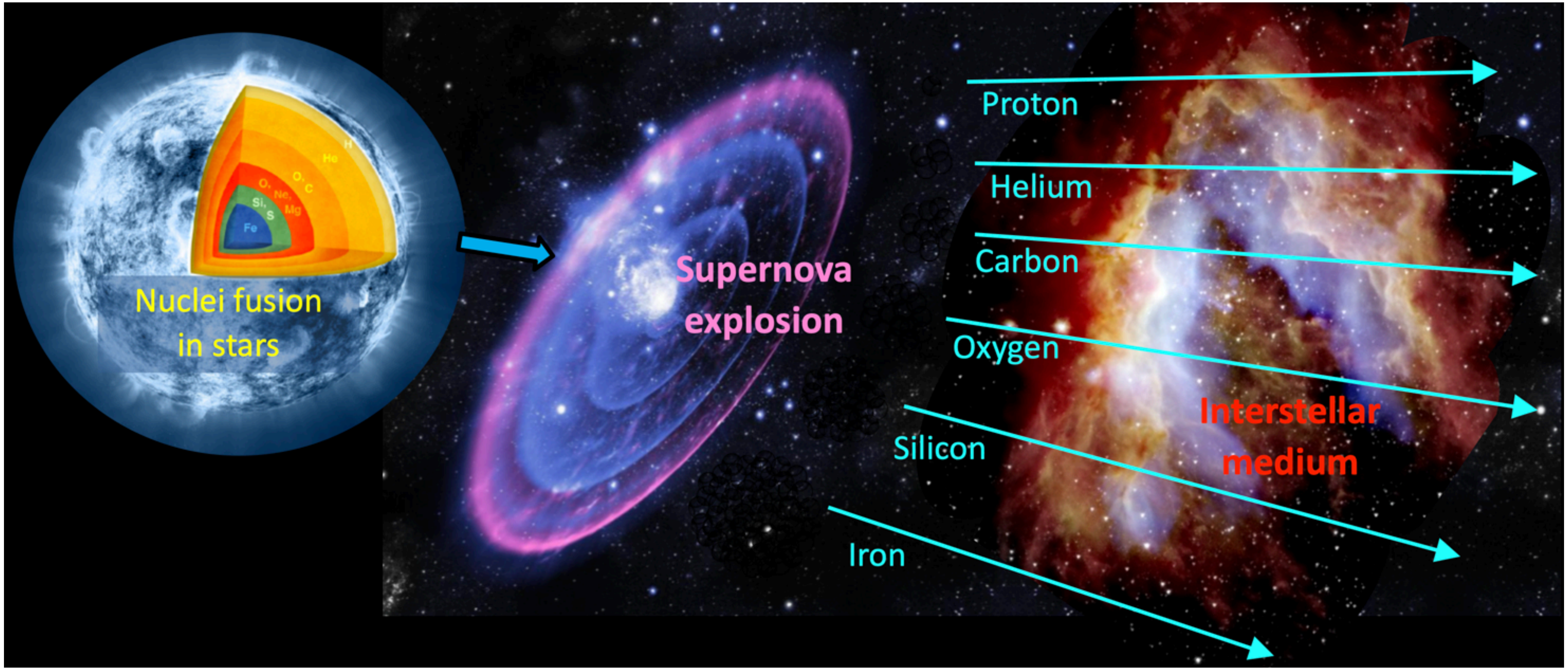
- in addition heavy nuclei
- abundances are above solar
- spectral shape is similar
  ⇒ hints to universal acceleration



Ave et al. 2008, ApJ, 678, 262

Composition: primaries

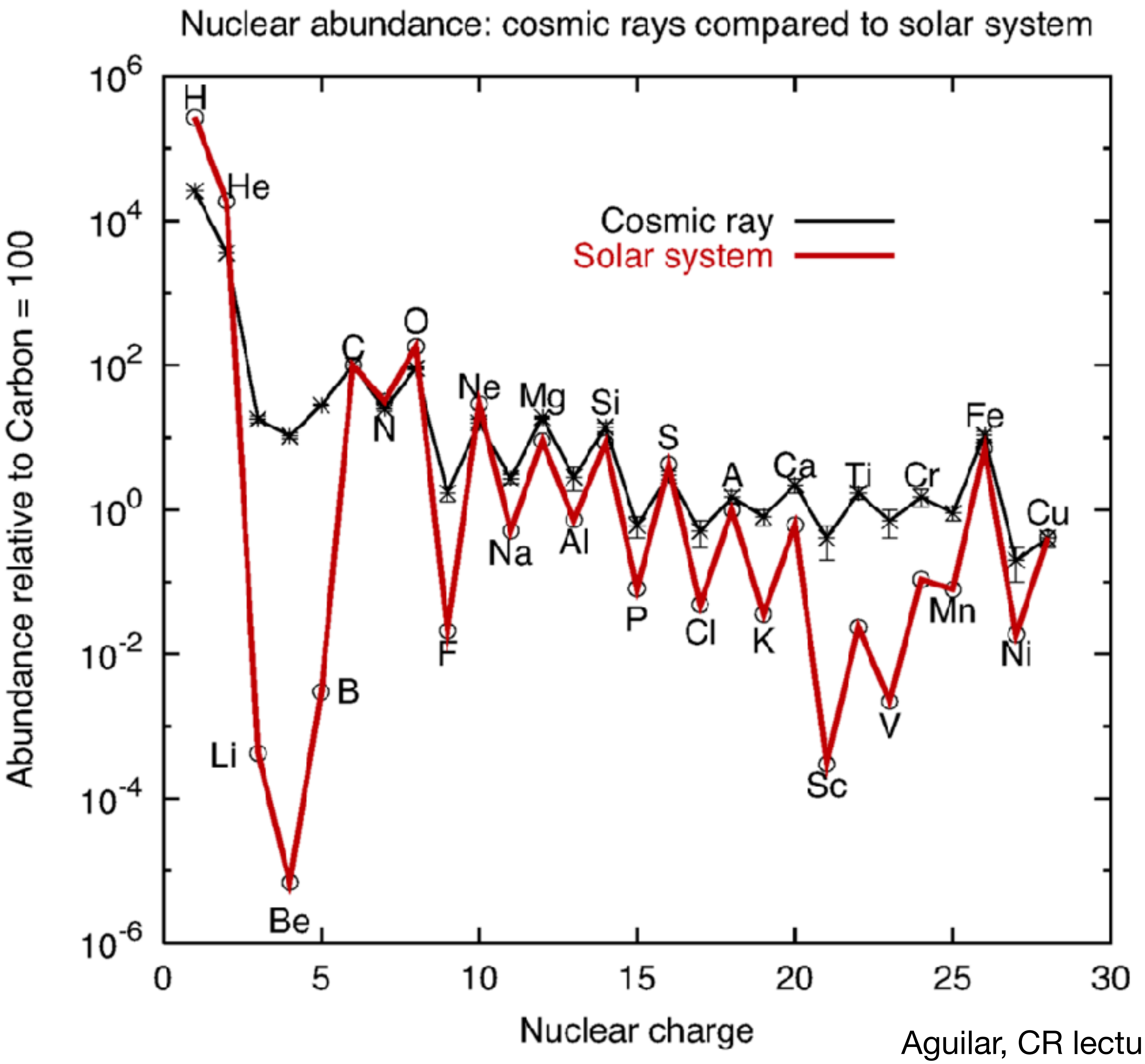
- primaries produced during lifetime of stars and accelerated at SNe
- p, He, C, O, …, Fe (dominated by alpha elements)
- fundamental to understanding of origin, acceleration, propagation through ISM



credit:
Mike Capell

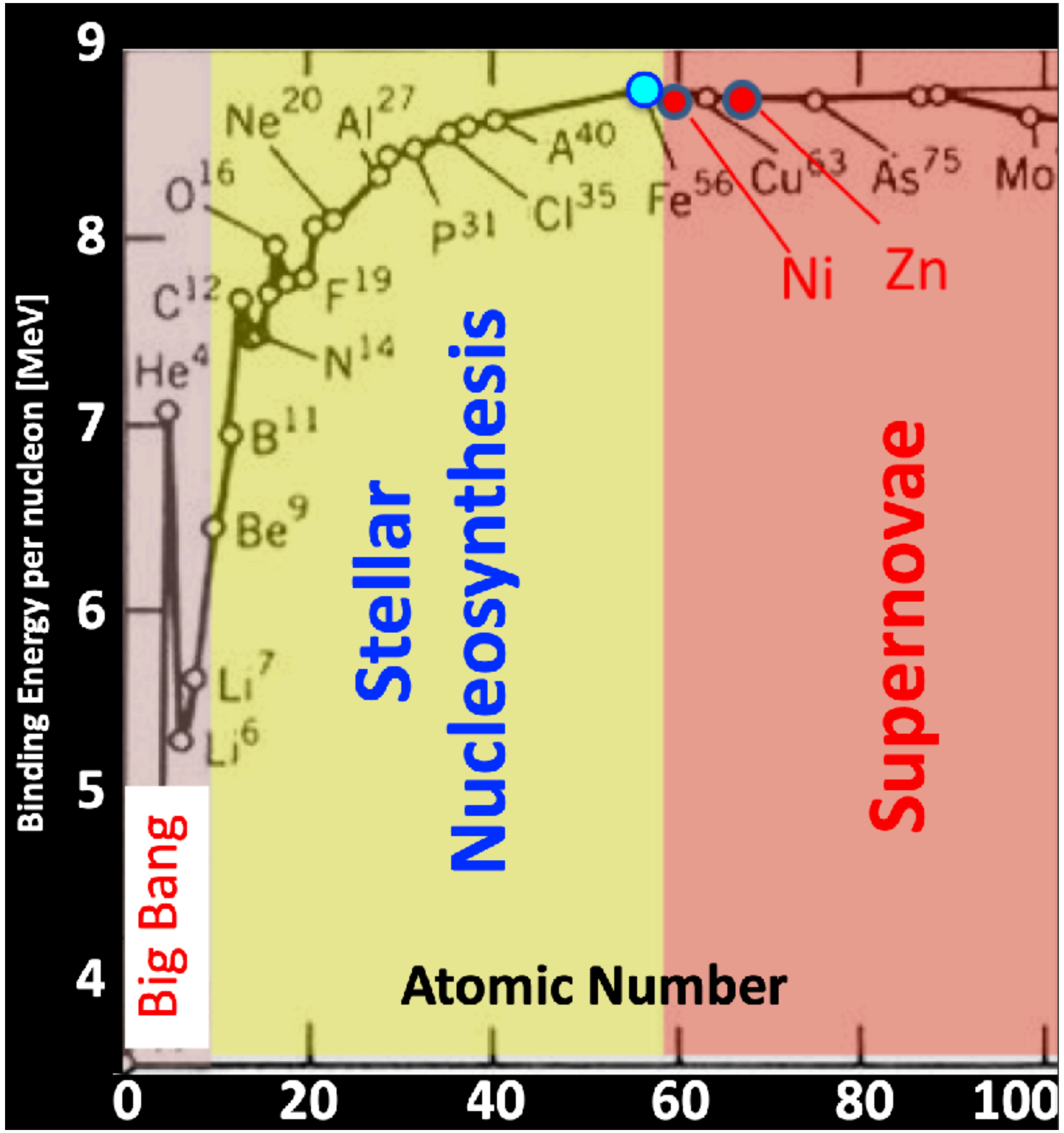
Origin of elements

- high abundances of alpha elements (p, He, C, O, …, Fe)



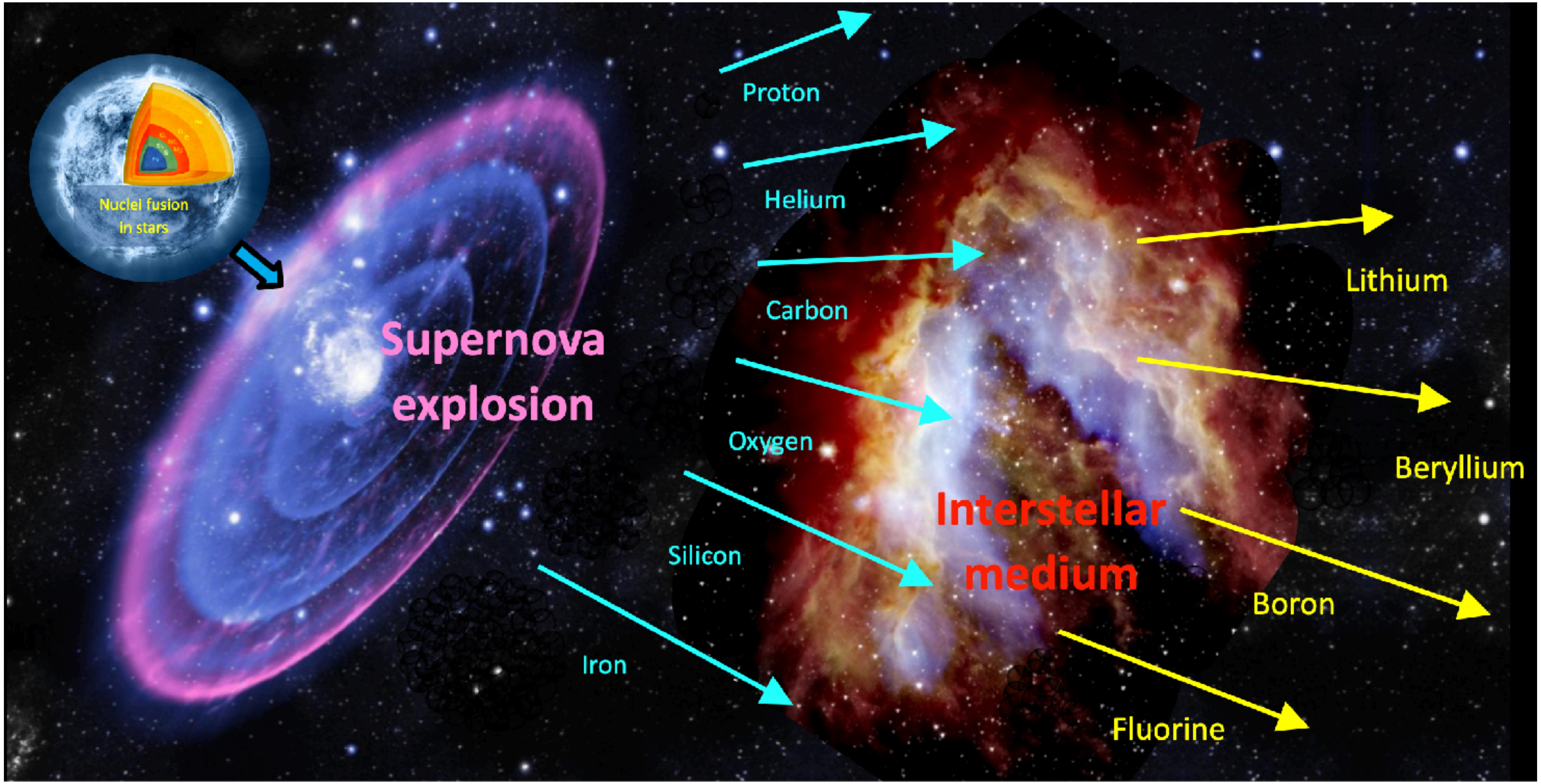
Aguilar, CR lecture

credit: Mike Capell



Composition: secondaries

- secondaries (Li, Be, B, F) produced by collision of primaries with ISM
- fundamental to understanding of propagation through ISM



credit:
Mike Capell

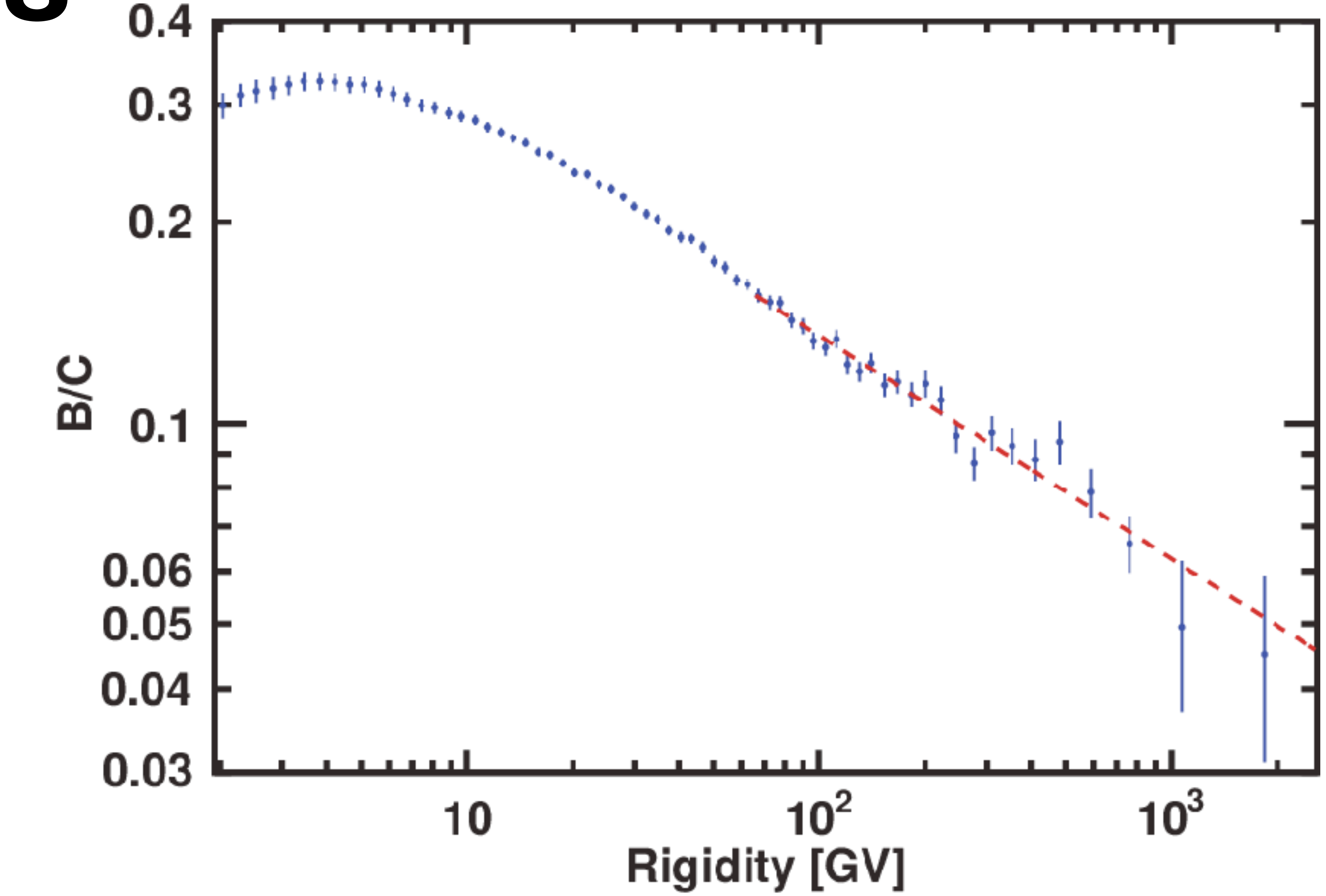
see reviews Strong+ 2007, Grenier+ 2015

Primaries to secondaries

example B/C ratio

- assume CRs are universally accelerated from ISM
- expect similar composition as in stars/ISM (very abundant alpha elements!)
- but observed relative overabundance of light elements (e.g. B)
- B must be produced while travelling through ISM
- less B, shorter travel distance through ISM

Aguilar et al. 2016



- B/C smaller for larger E
- rigidity $R = \frac{pc}{Ze}$, energy per charge
- larger E escape faster

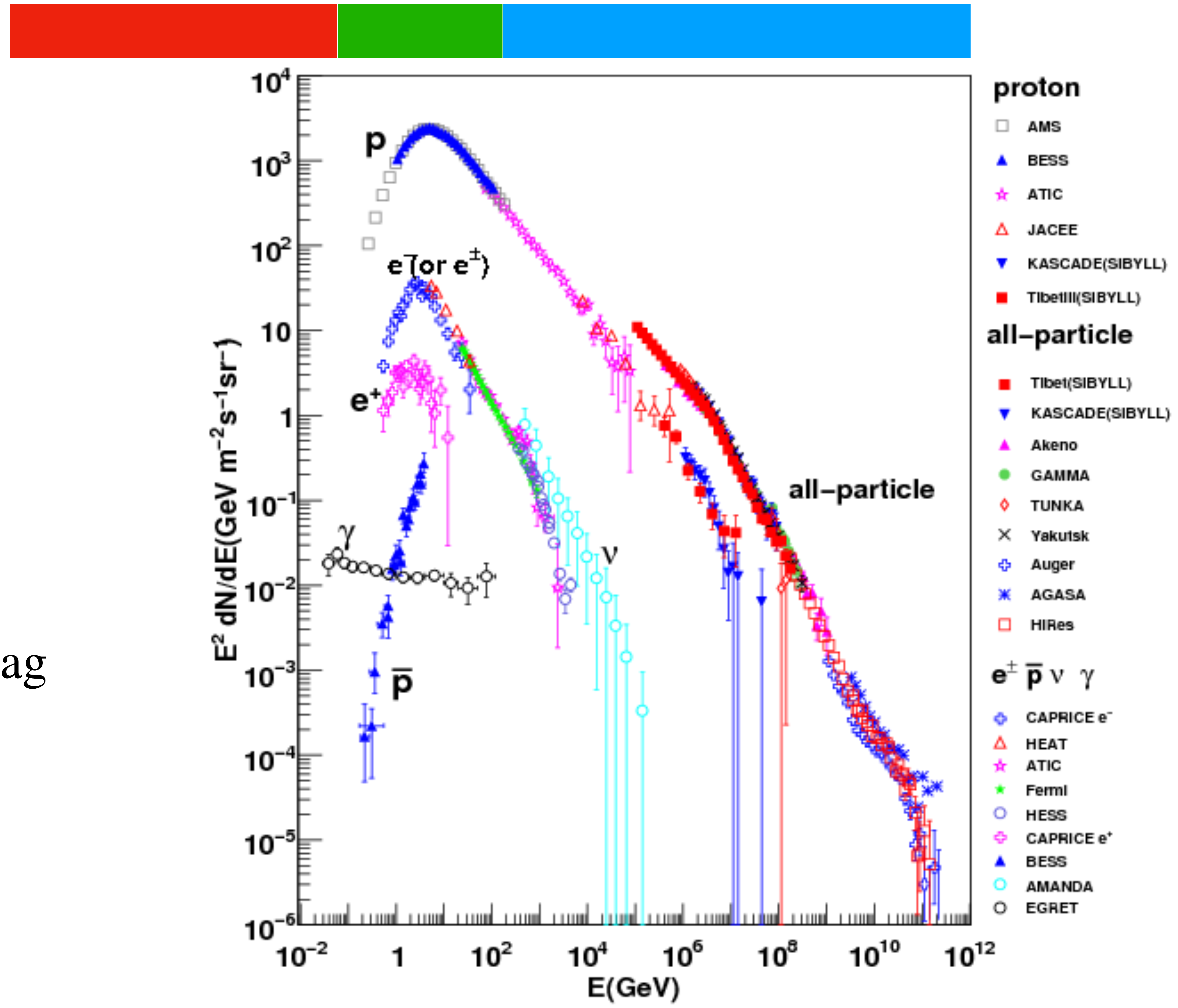
Basics:
interaction and transport

Three different energy regimes

- **low-E CRs** (see Padovani+2020)
  Large cross section with gas
  Strong losses
  heating of dense star forming regions

- **GeV CRs** (see Ferriere 2001)
  Most of energy (weak losses)
  Dynamically relevant via pressure:
  similar E-densities: $e_{\rm cr} \sim e_{\rm kin} \sim e_{\rm therm} \sim e_{\rm mag}$

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



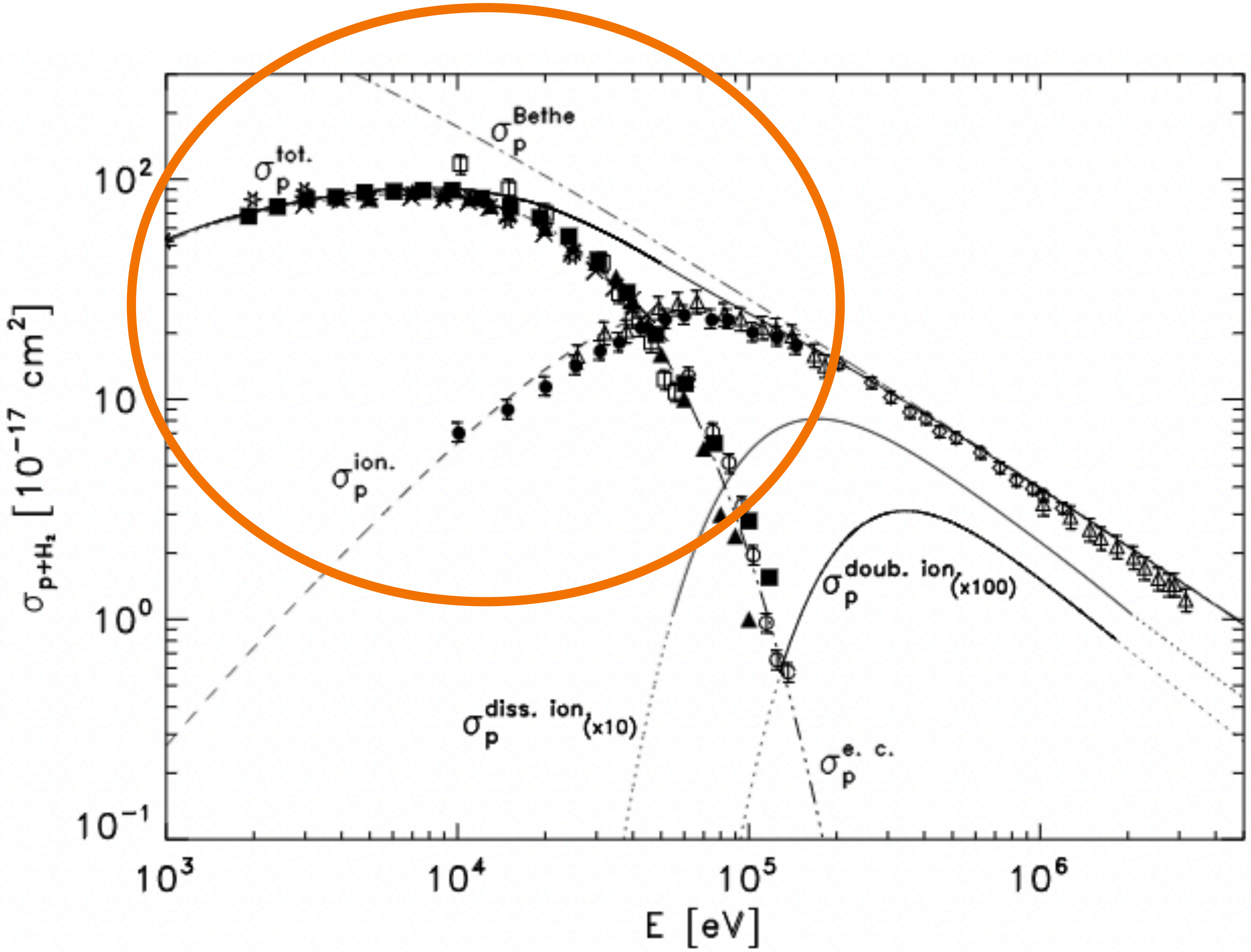
Hu et al. (2009)

Cross section

relatively large cross sections for low E responsible for ionisation in dense gas

⇒ temperature floor

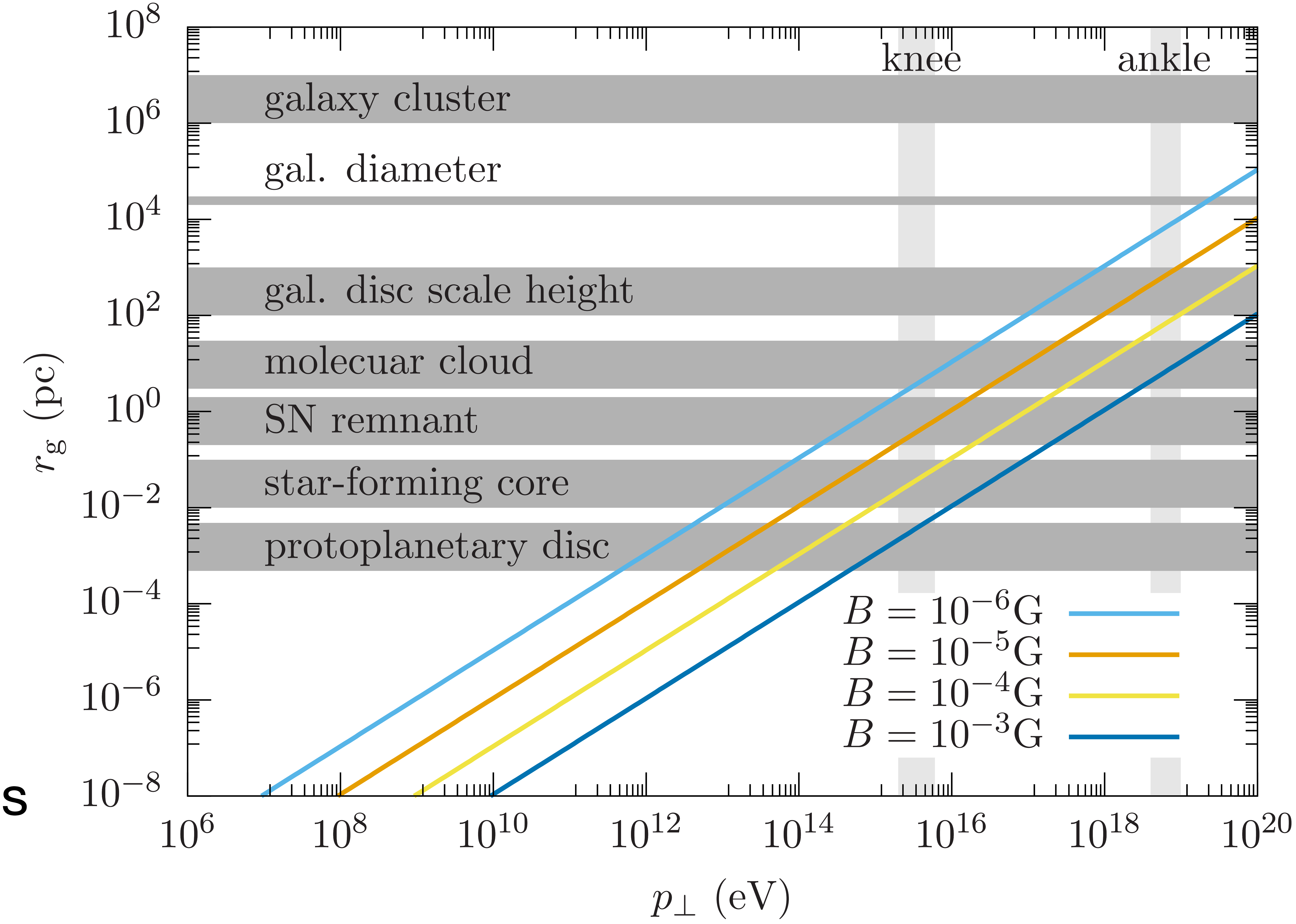
- cross section is small and decreases with E
  Bethe cross section: $\sigma \propto E^{-1}$
- most CRs do not interact directly with gas, no particle-particle collisions
- interaction via magnetic field:
  - gyration around field lines
  + (non-)resonant scattering interactions



Padovani et al. (2009)

Gyro radius

- gyro radius
  $$r_{\mathrm{g}} = \frac{p_\perp}{|q|B}$$
- most cases: $r_{\mathrm{g}} \ll L_{\mathrm{system}}$
- low E: frequent gyration
  “frequent scattering”
  $\Rightarrow$ fluid approximation
- high E: $r_{\mathrm{g}} \sim L_{\mathrm{system}}$
  need to follow individual trajectories

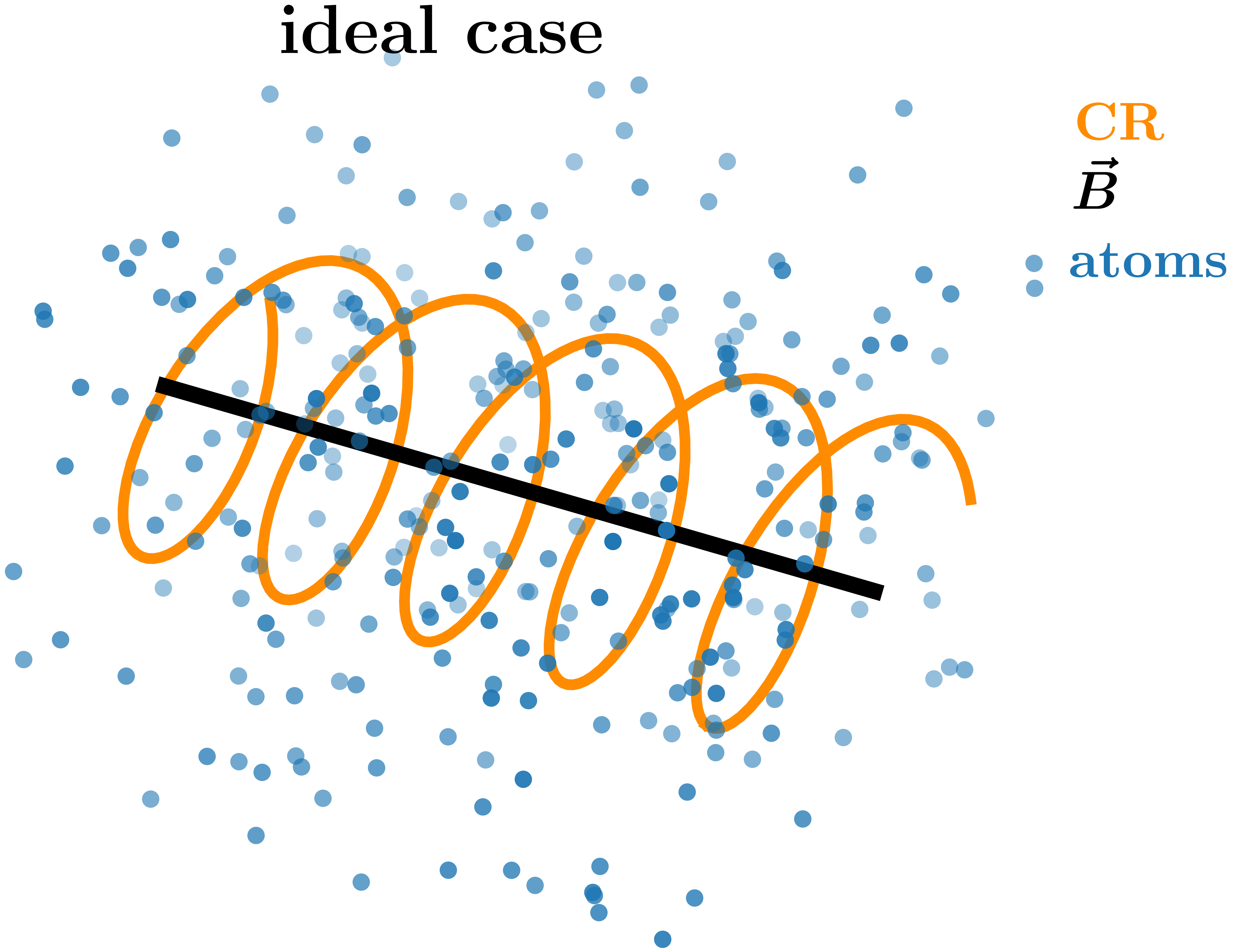


Hanasz, Strong, Girichidis (2021)

CR Transport illustrated

Advection

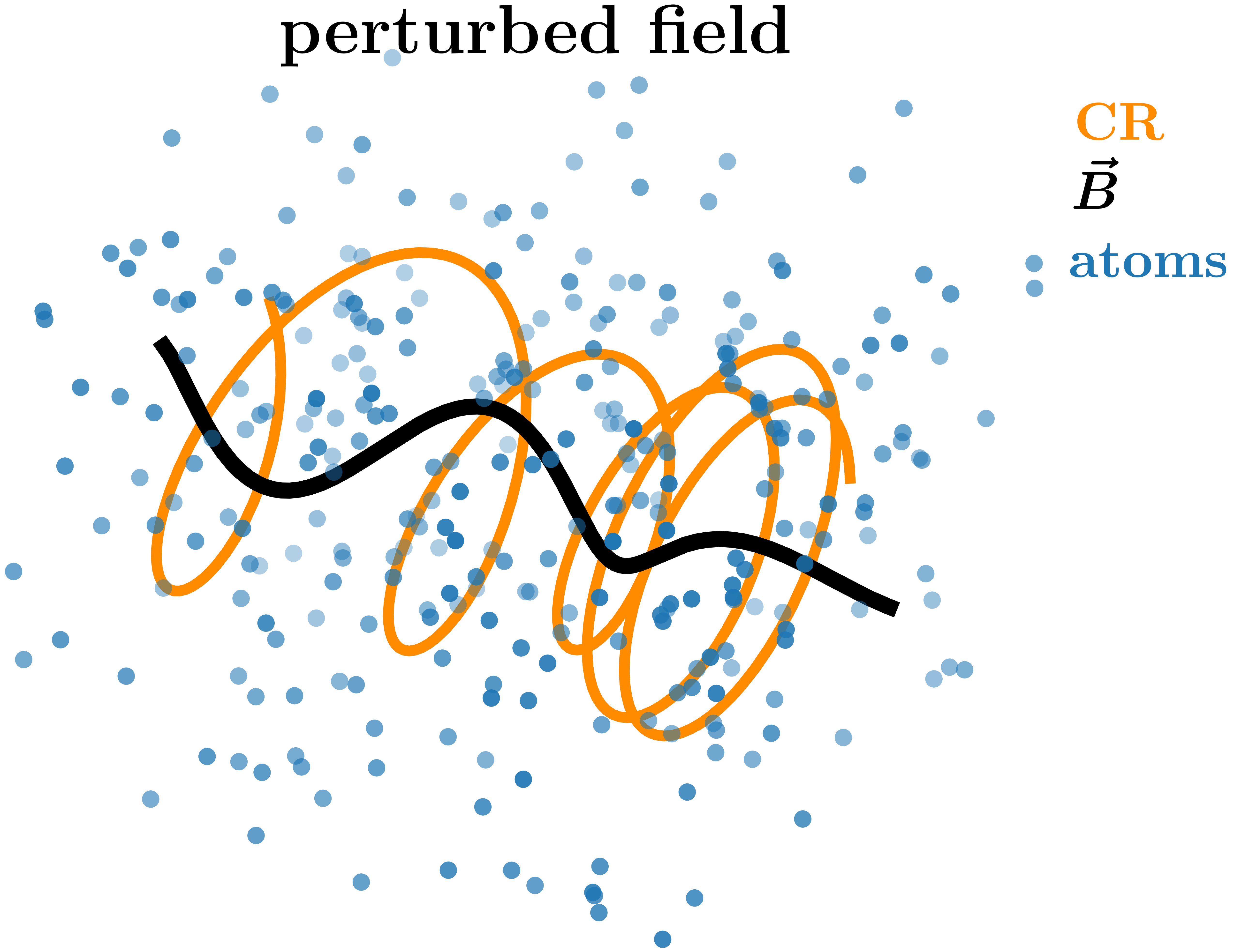
- CR gyrate around B
- vertical motions of B
  $\Rightarrow$ coupled to motions of CRs
- gas (partially) ionized
- ideal MHD, B frozen in gas
- CR $\Leftrightarrow$ B $\Leftrightarrow$ gas
- advection with the gas



CR Transport illustrated

Diffusion

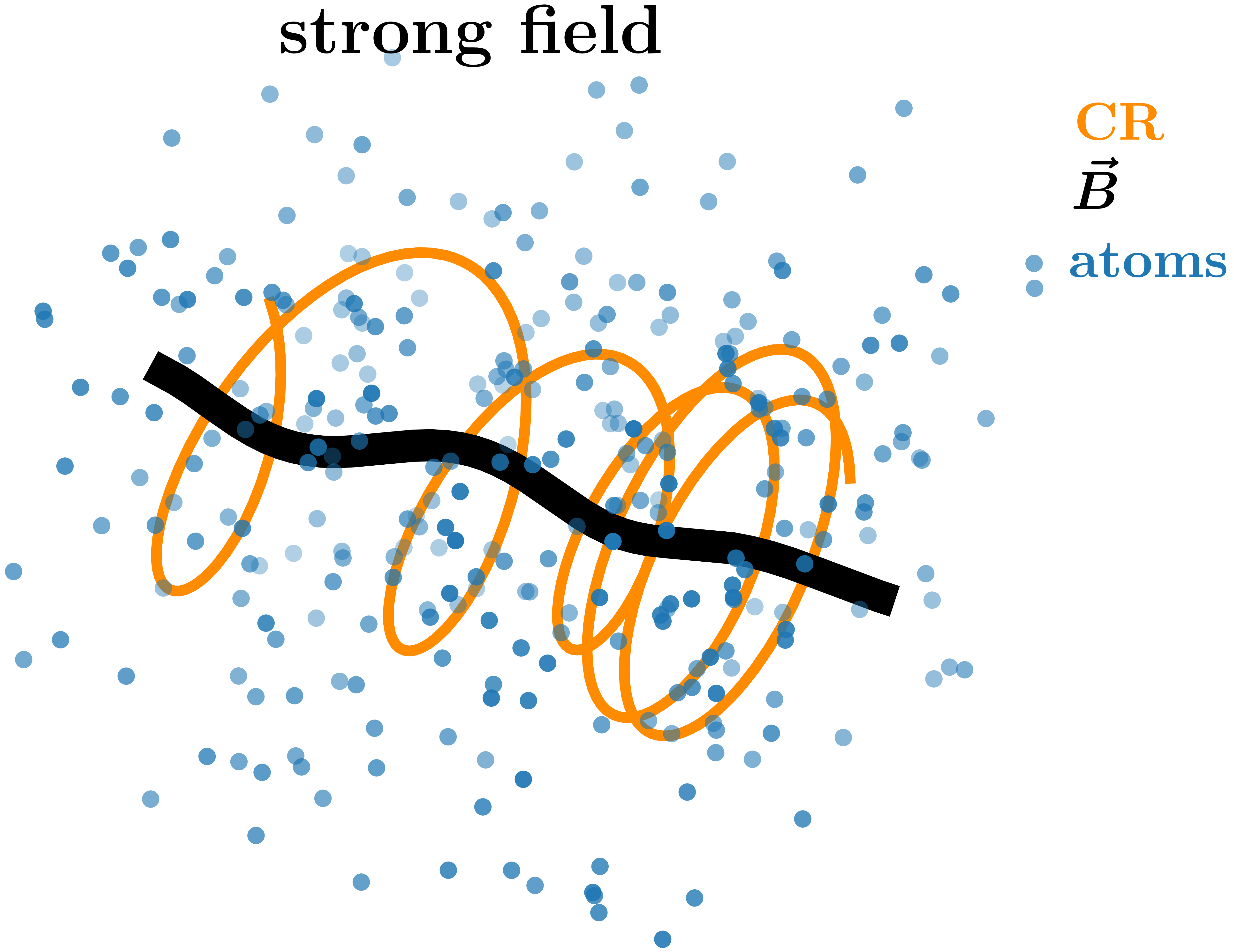
- perturbed field
- scattering off of B irregularities
- elastic scattering ⇒ diffusion
- realistic environment:
  turbulent 3D
- diffusion relative to the gas
- diffusion mainly along B



CR Transport illustrated

Back reaction from CRs onto B

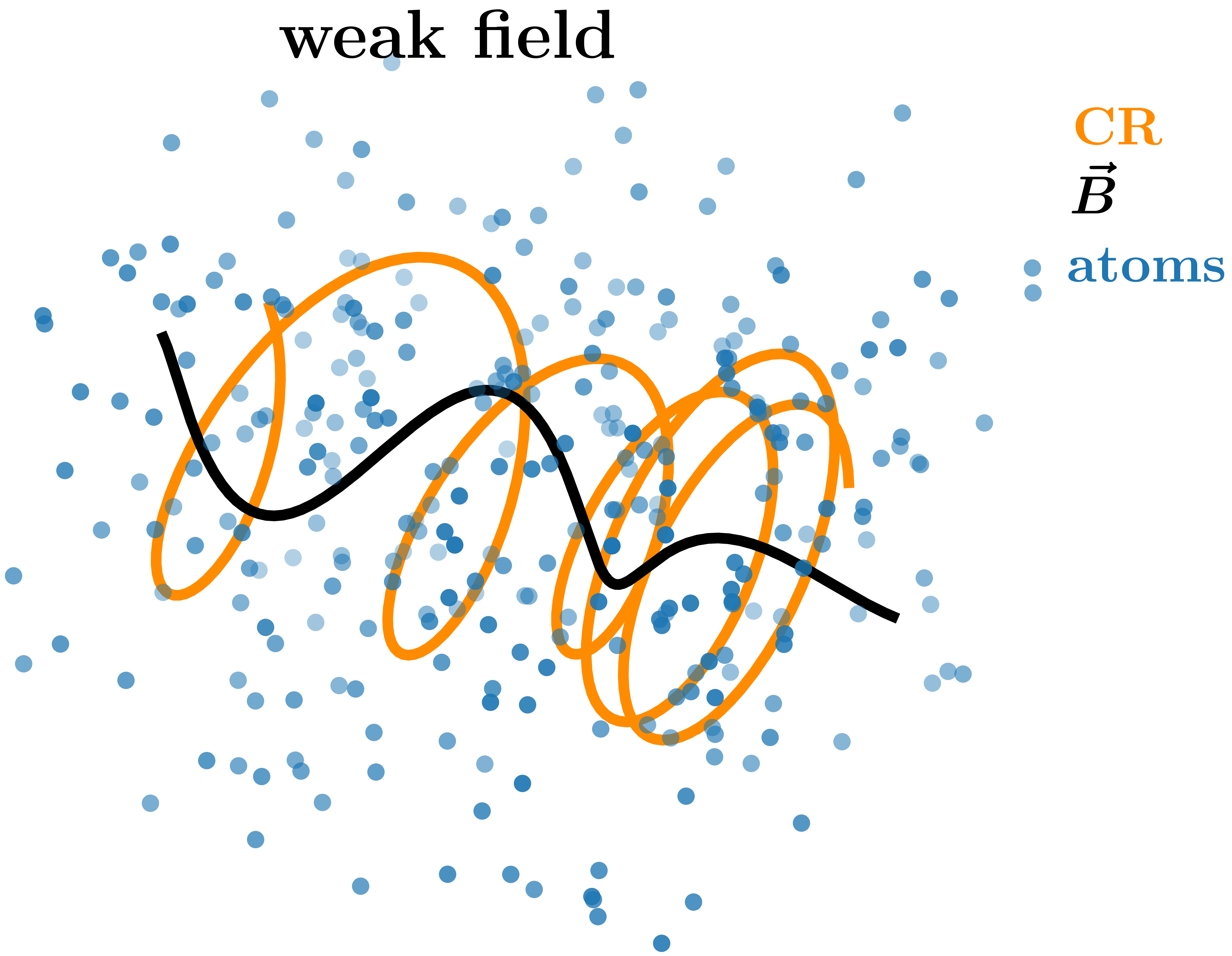
- perturbed field
- elastic scattering ⇒ diffusion
  depends on total energy ratio
  B / CR resonances
- case 1: strong B field
- little back reaction of CRs onto B



CR Transport illustrated

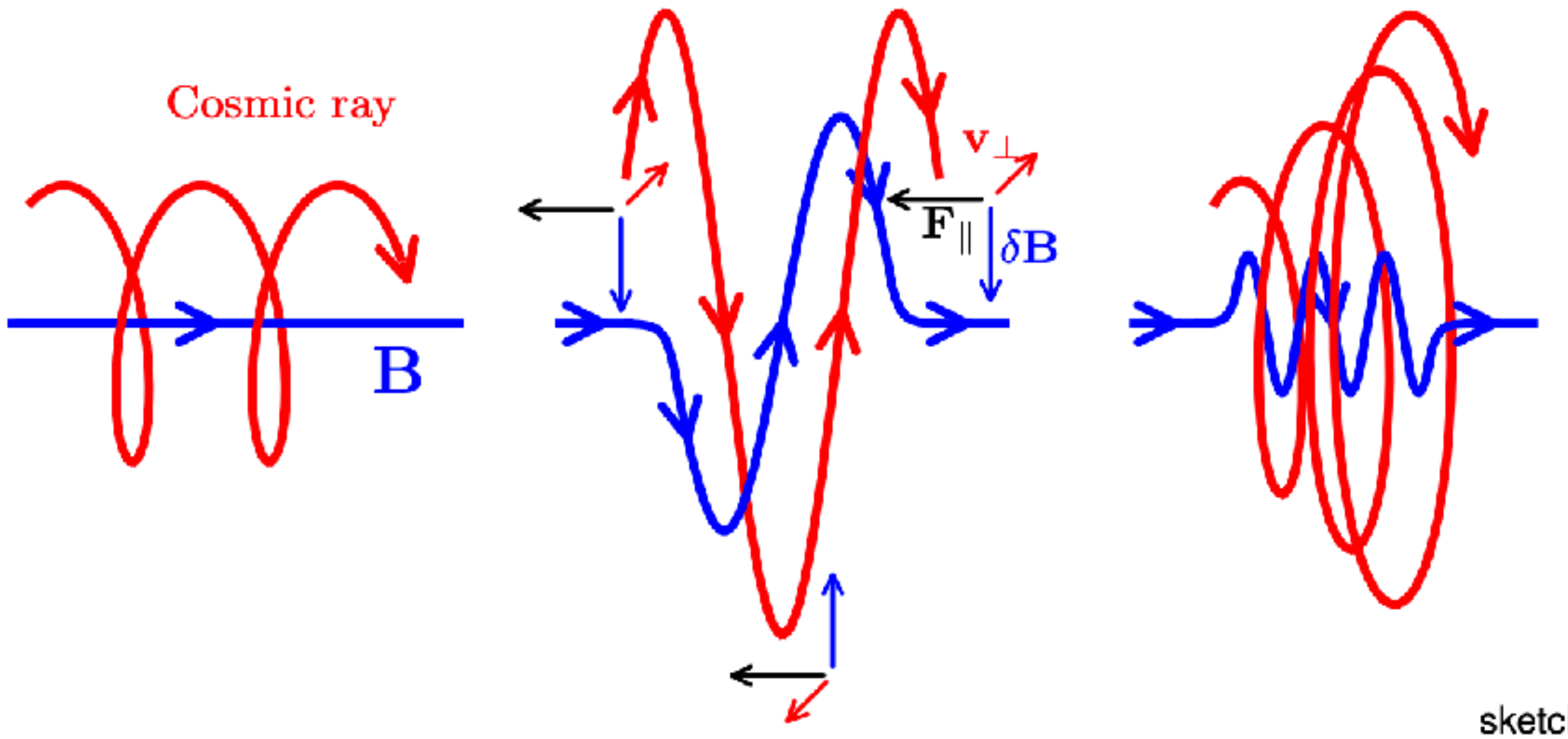
Back reaction from CRs onto B

- perturbed field
- elastic scattering ⇒ diffusion depends on total energy ratio B / CR resonances
- case 2: weak B field
- strong back reaction of CRs onto B



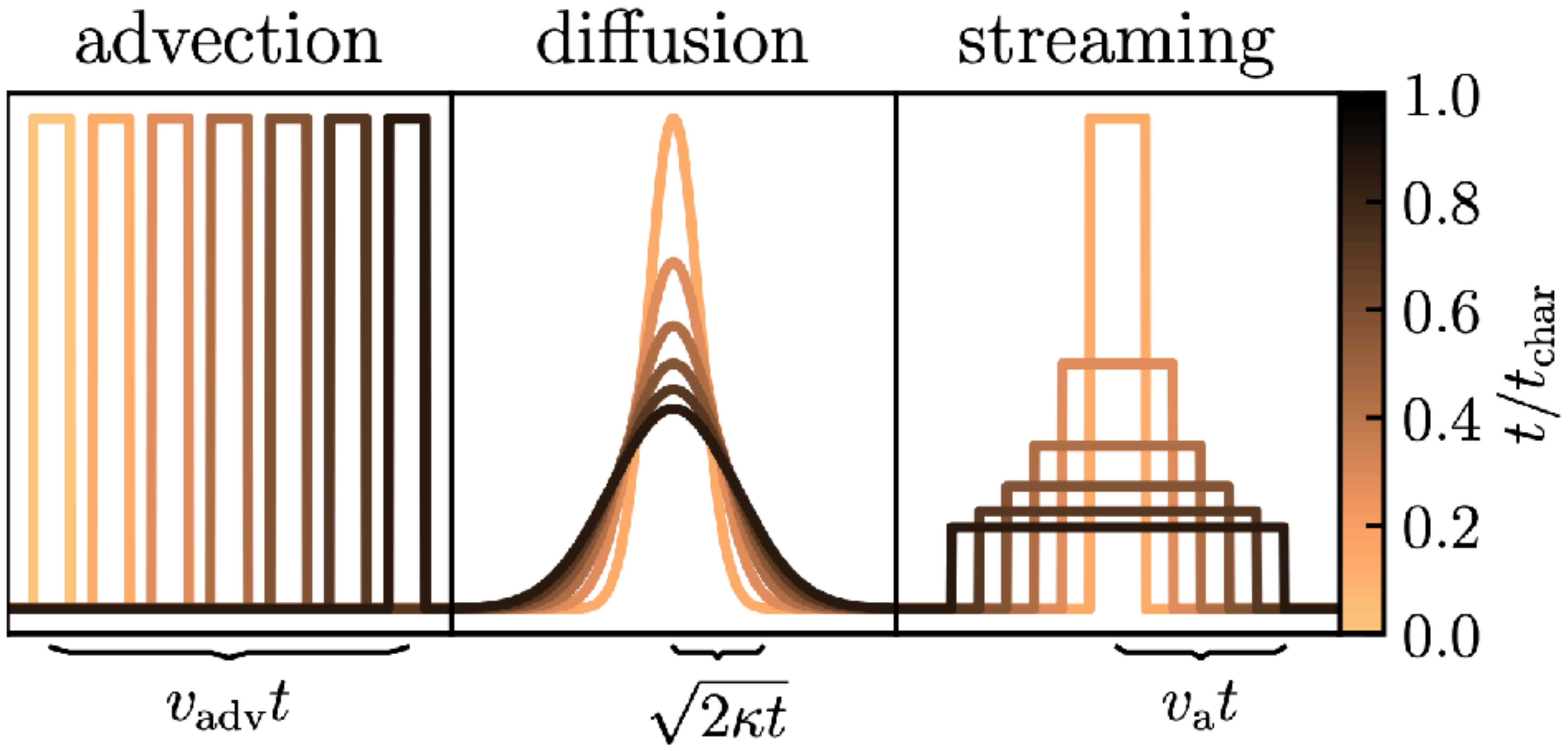
Gyro resonance

Streaming instability (Skilling 1975)



sketch: Jacob

- important: gyro resonances
- depend on CR energy, B properties at different scales, MHD waves
- depend on
  - CR energy
  - spectrum of B-field
  - turbulence spectrum
- macroscopically: bulk of CRs streams with Alfvén speed

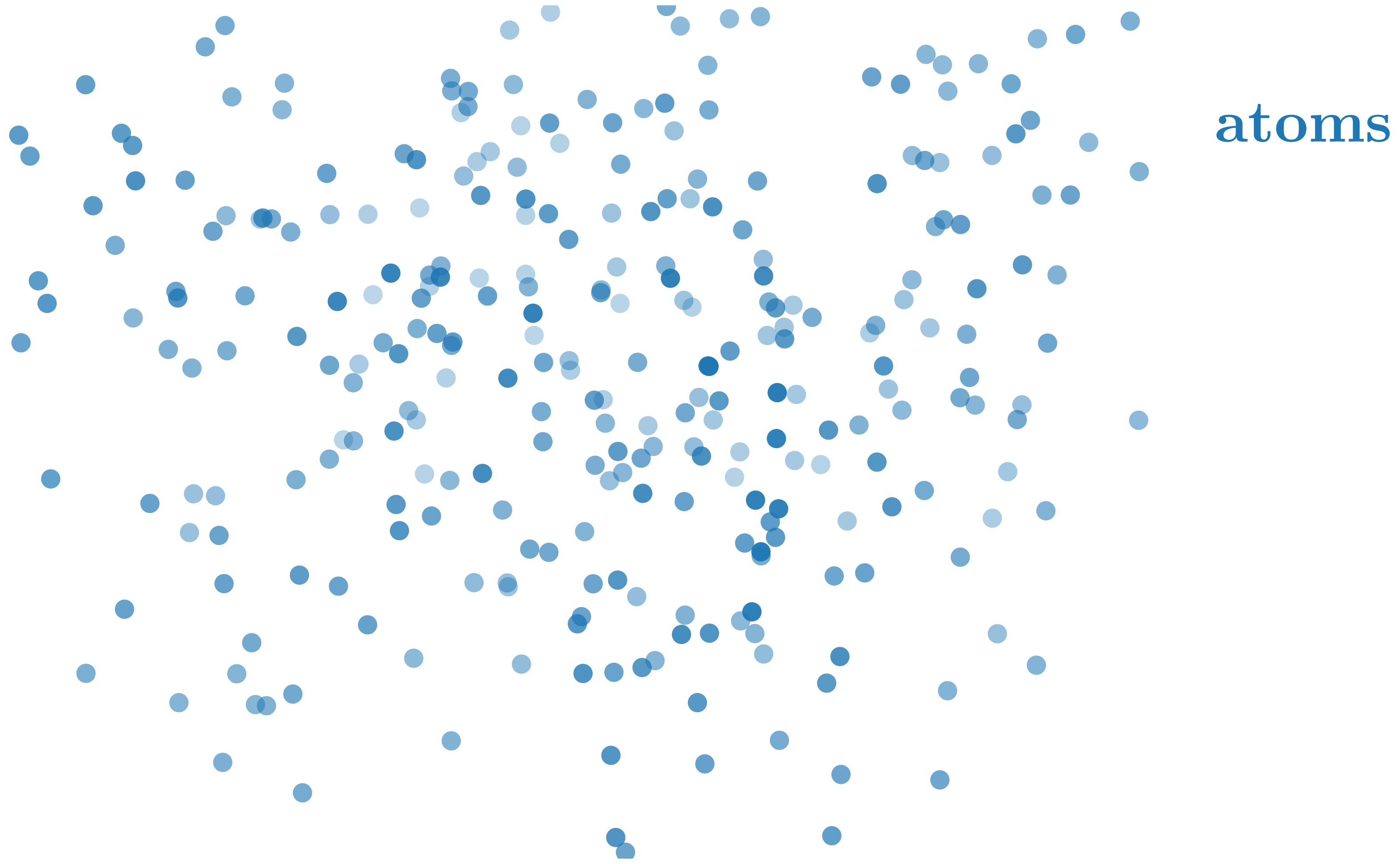


Thomas, CP, Enßlin (2020)

CRs as a fluid? Yes, with some differences

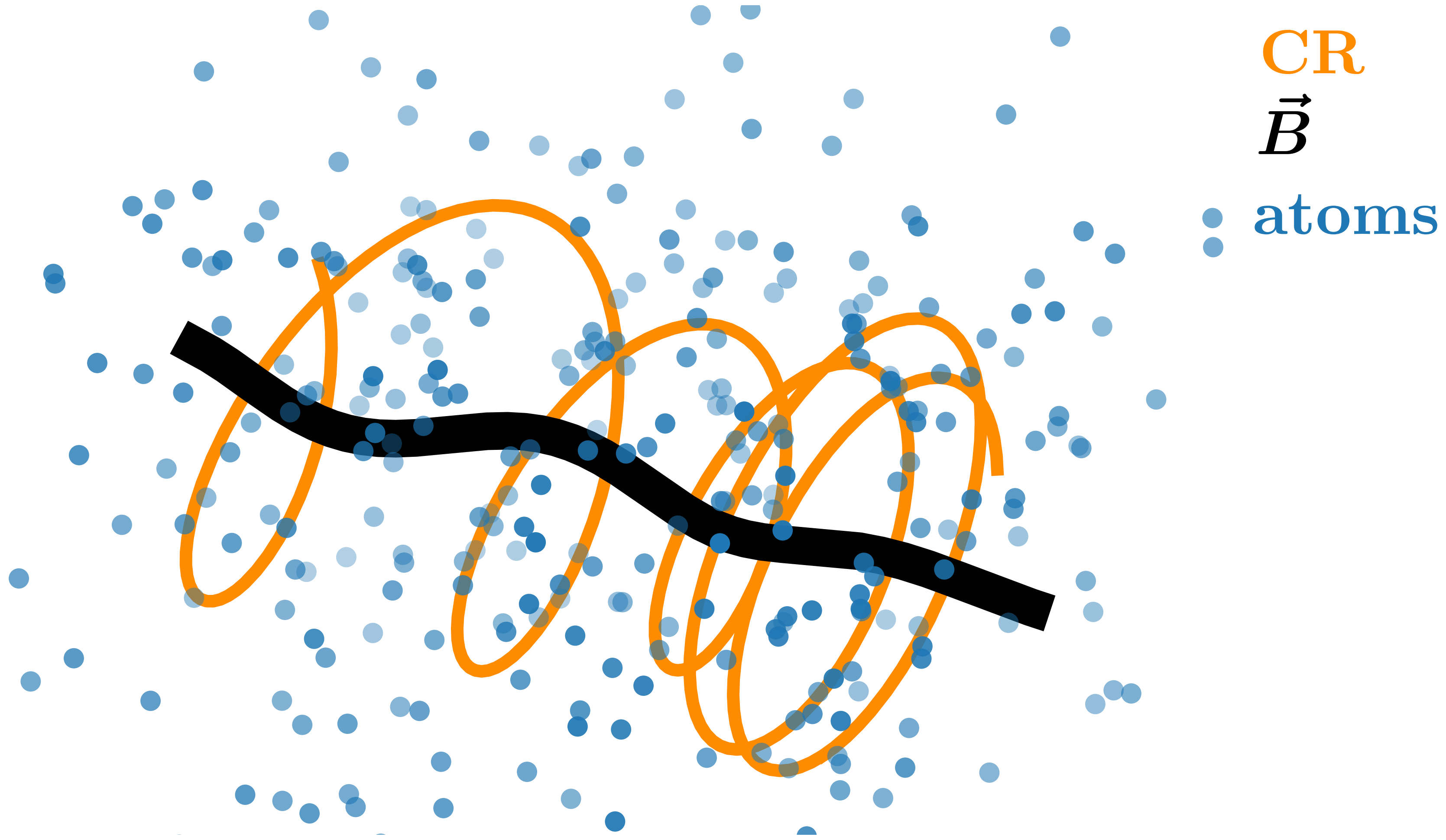
thermal fluid

- direct particle collisions
- fast thermalisation (Maxwellian distribution)
- isotropic distribution function, isotropic pressure



CR fluid

- interaction via B field
- complicated / slow energy transfer (distribution function not universal)
- anisotropic contribution due to coupling with B field orientation

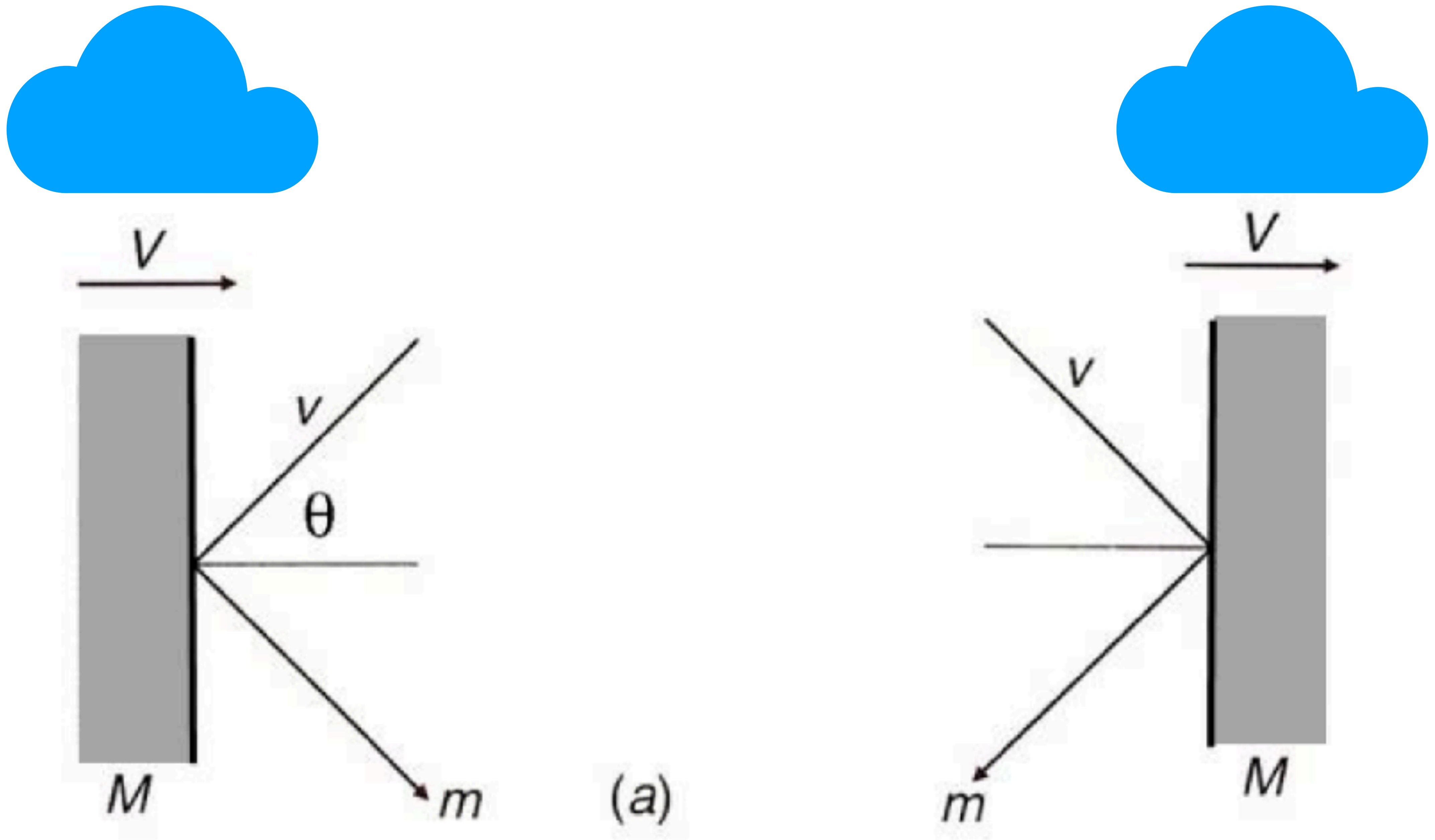


Origin / Acceleration

Fermi acceleration

Fermi-II

- Fermi 1949: stochastic scattering of particles between clouds (magn. mirrors)
- particles see head-on and following collisions
- random orientation: average over θ
- second order process
- exponential increase over time



$$\Delta E = E'' - E = E\left[\frac{2Vv\cos\theta}{c^2} + 2\left(\frac{V}{c}\right)^2\right]$$

$$\left\langle \frac{\Delta E}{E} \right\rangle = \frac{2}{3}\left(\frac{V}{c}\right)^2$$

see e.g. Longair: High energy astrophysics, 2011

Spectrum in steady state

- change in energy over time

$$\frac{\mathrm{d}E}{\mathrm{d}t} = \frac{4}{3}\left(\frac{V^2}{cL}\right) E = \alpha E$$

- diff-loss-eq.

$$\frac{\mathrm{d}N}{\mathrm{d}t} = D\nabla^2 N + \frac{\partial}{\partial E}[b(E)N(E)] - \frac{N}{\tau_{\mathrm{esc}}} + Q(E)$$

- assume steady state

$$\cancel{\frac{\mathrm{d}N}{\mathrm{d}t}} = D\cancel{\nabla^2} N + \frac{\partial}{\partial E}[b(E)N(E)] - \frac{N}{\tau_{\mathrm{esc}}} + \cancel{Q(E)}$$

- reorder

$$-\frac{\mathrm{d}}{\mathrm{d}E}[\alpha E N(E)] - \frac{N(E)}{\tau_{\mathrm{esc}}} = 0 \qquad \frac{\mathrm{d}N(E)}{\mathrm{d}E} = -\left(1 + \frac{1}{\alpha\tau_{\mathrm{esc}}}\right)\frac{N(E)}{E}$$

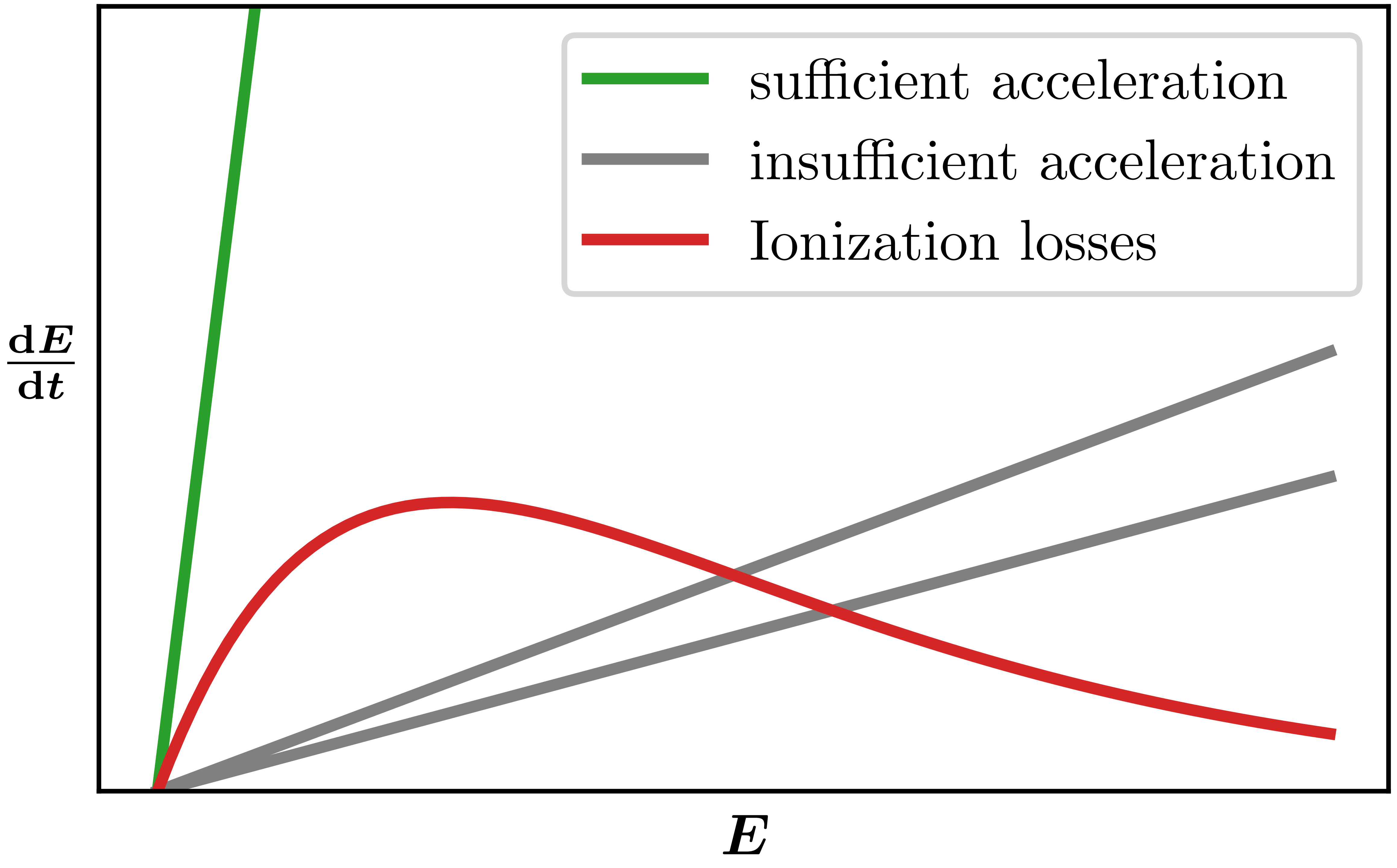
- solve: **power law in E**

$$N(E) = \mathrm{constant} \times E^{-x} \qquad x = 1 + (\alpha\tau_{\mathrm{esc}})^{-1}$$

see e.g. Longair: High energy astrophysics, 2011

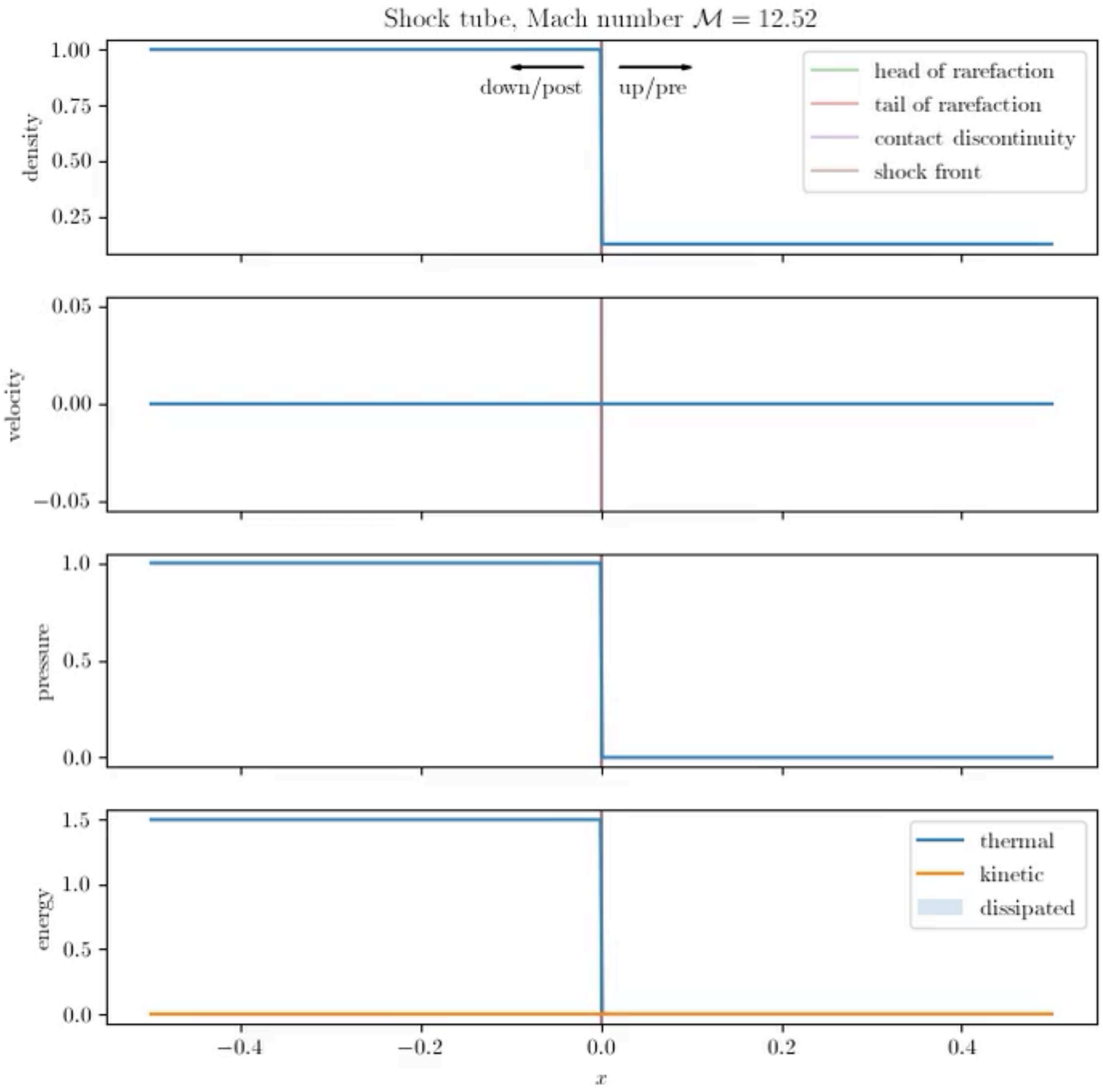
Problems with Fermi-II acceleration

- gain in energy is too slow: $\left(\frac{V}{c}\right)^2$
- random V are too small (10 km/s)
- distance between clouds too large (~pc)
- collisions/losses usually take over
- effectively very unlikely to be relevant acceleration mechanism



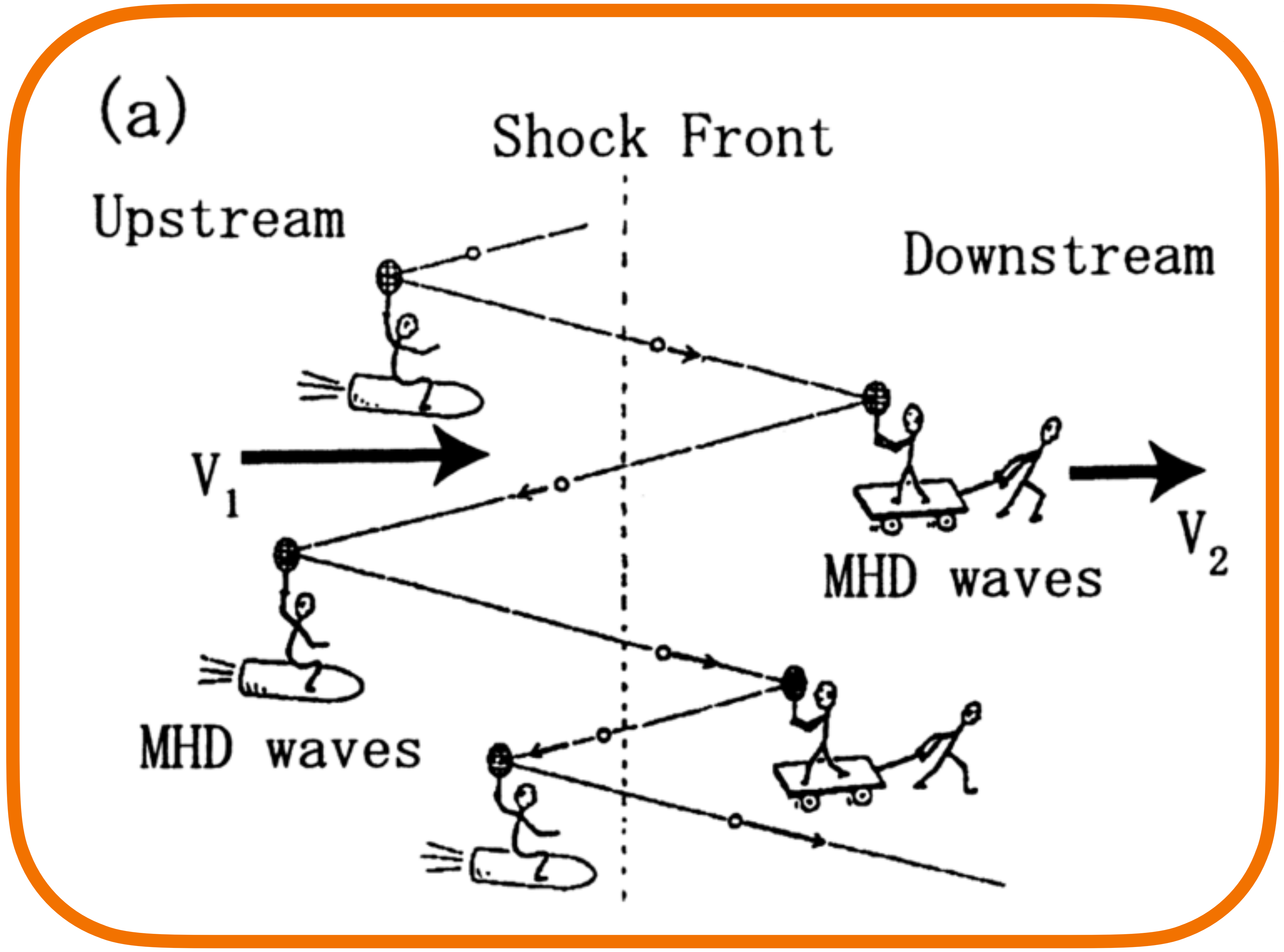
Shocks

- fluid dynamics: discontinuity arises if material moves faster than speed of sound
- Rankine-Hugoniot jump conditions
- distinguish between shocks and contact discontinuity

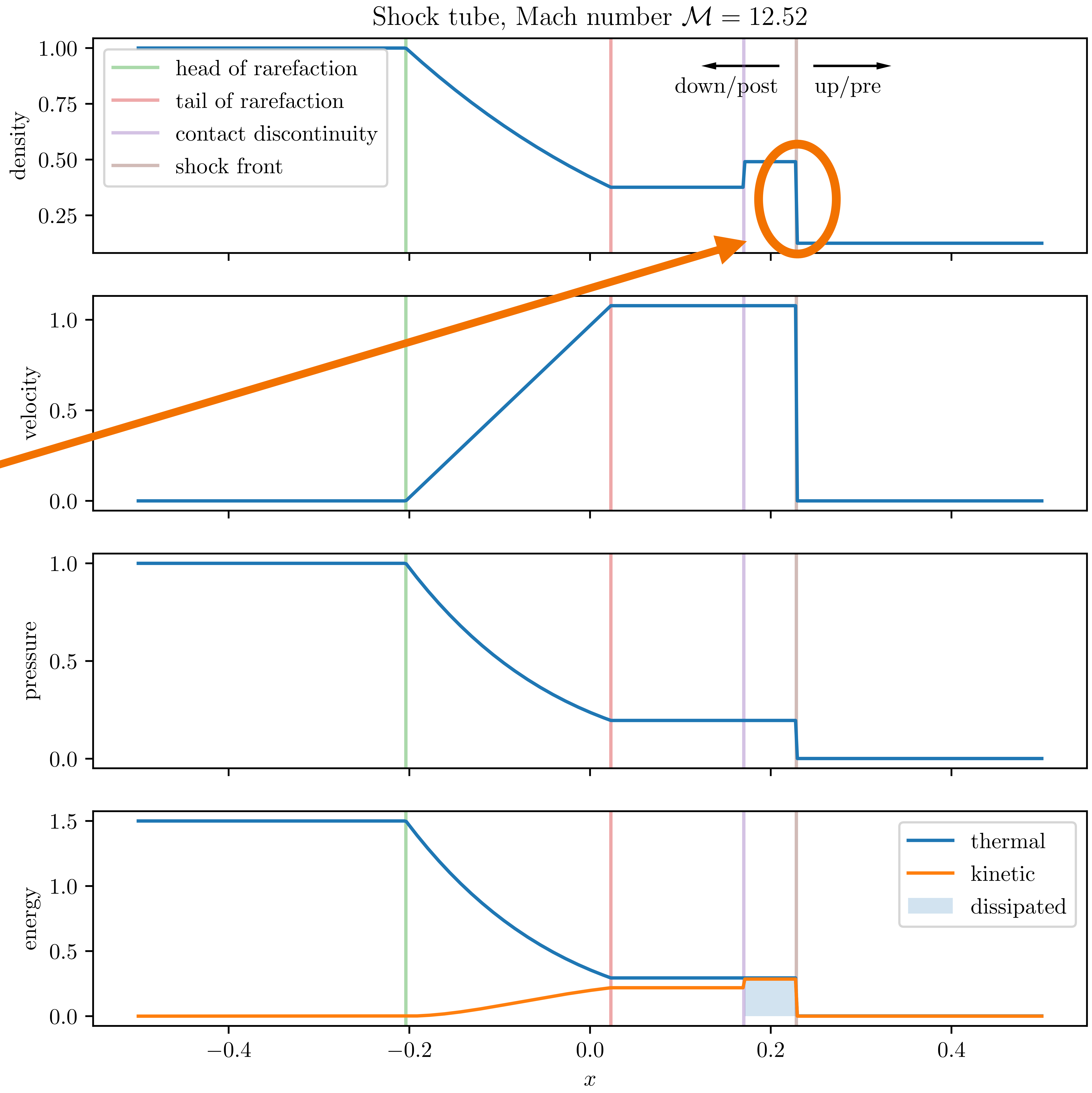


Shocks

1. particle encounter in shock
2. scattering
3. energy gain
4. repeated acceleration
5. escape



M. Scholer



Diffusive shock acceleration (DSA)

Blandford & Ostriker 1978
Bell 1978

- $E = \beta E_0$: avg. energy of particle after collision
- P: probab. that particle remains in acc. region
- after k collisions: $N = N_0 P^k$ particles with energies $E = E_0 \beta^k$
- eliminate k

$$\frac{N}{N_0} = \left(\frac{E}{E_0}\right)^{\ln P / \ln \beta}$$

- differentiating $dN(E) \propto E^{-1+(\ln P/\ln \beta)} dE$

- strong shock: $\rho_2/\rho_1 = 4$, $v_2 = (1/4) v_1$
- Lorentz transformation, derive ΔE
- $\left\langle \frac{\Delta E}{E} \right\rangle = \frac{2}{3}\frac{v}{c}$
- first-order in v/c (due to coherent and converging motions)
- non-relativistic shock: $\ln P/\ln \beta \approx -1$ $\mathrm{d}N(E)/\mathrm{d}E \propto E^{-2}$
- or in units of of the shock velocities $\mathrm{d}N(E)/\mathrm{d}E \propto E^{-s}$ with $s = \frac{v_1/v_2 + 2}{v_1/v_2 - 1} \rightarrow 2$

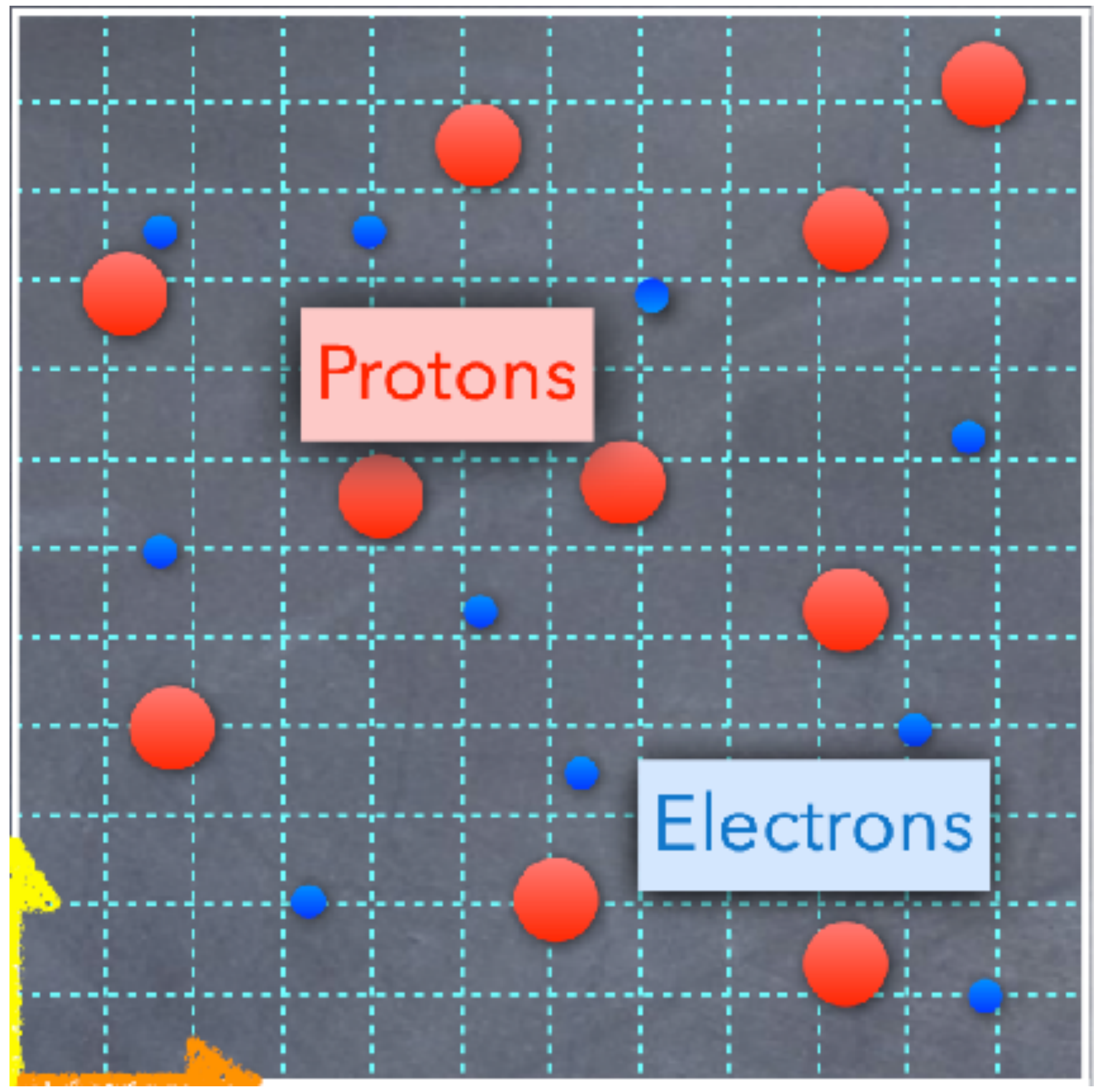
DSA: from paper to simulations

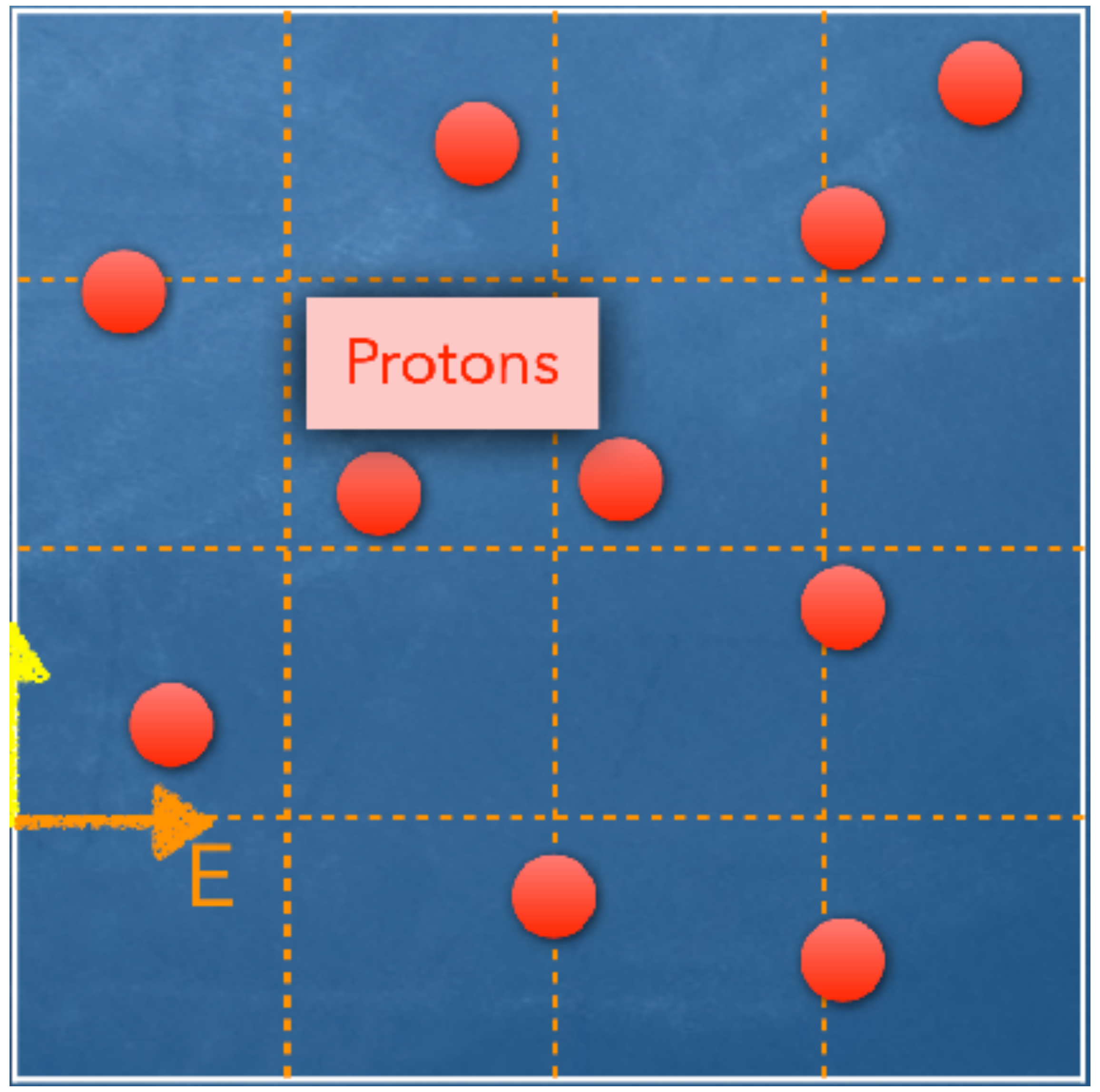
Particle in cell simulations (PIC)

- Ingredients:
  - back-reaction onto the fluid
  - real shock is not infinitely sharp
  - magnetic fields (vector field)
- simulations:
  particle-in-cell (PIC)
- compute Lorentz force and particle trajectories

(Winske & Omidi; Burgess et al., Lipatov 2002; Giacalone et al. 1993,1997,2004-2013; Caprioli & Spitkovsky 2013-2015, …)

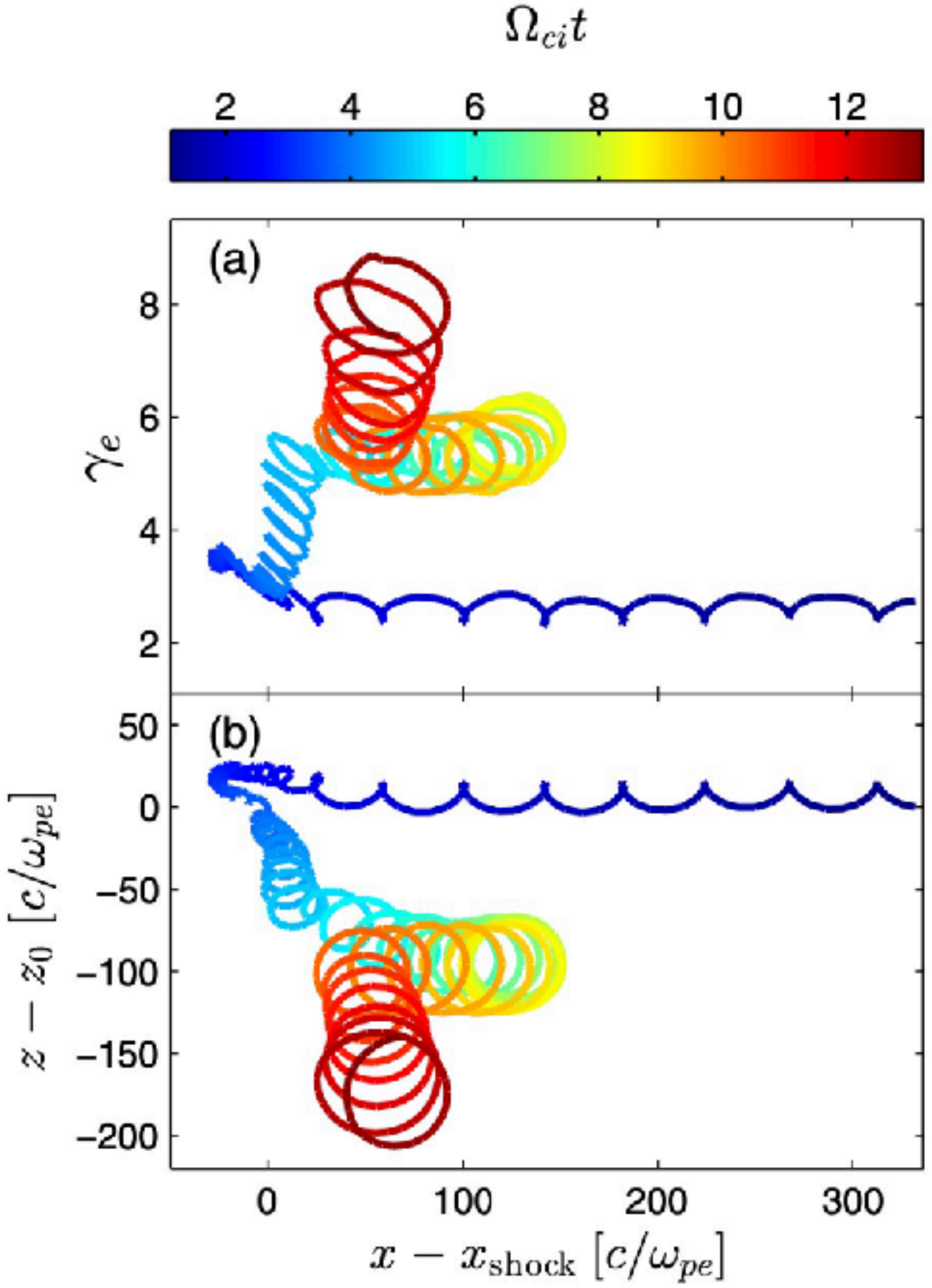
- EM field on grid
- Full-PIC: p and e^- as (macro) particles
  - challenge: small gyro radii for e^-
- Hybrid: fluid-e^-, kinetic p





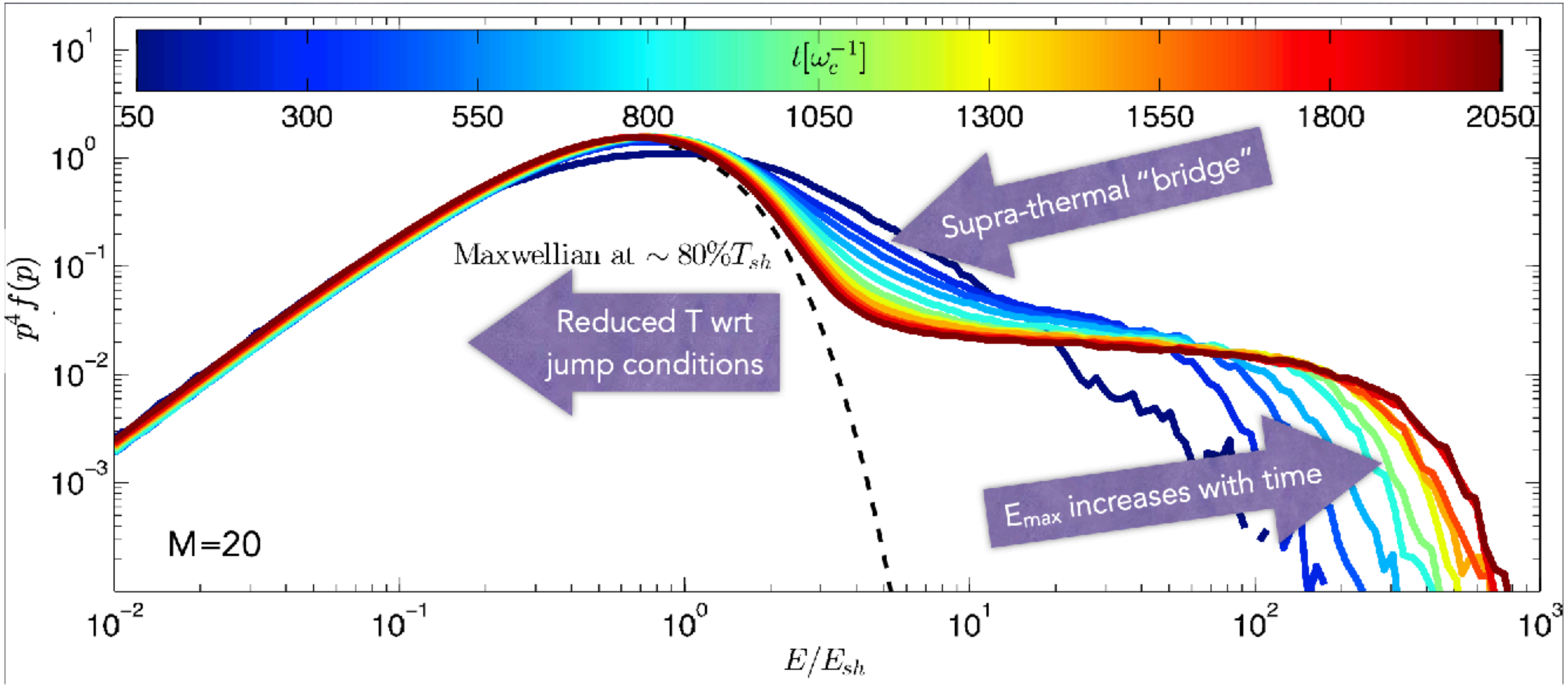
PIC and hybrid simulations

Guo et al. 2014



- energy increases in every gyration

Caprioli & Spitkovsky 2014

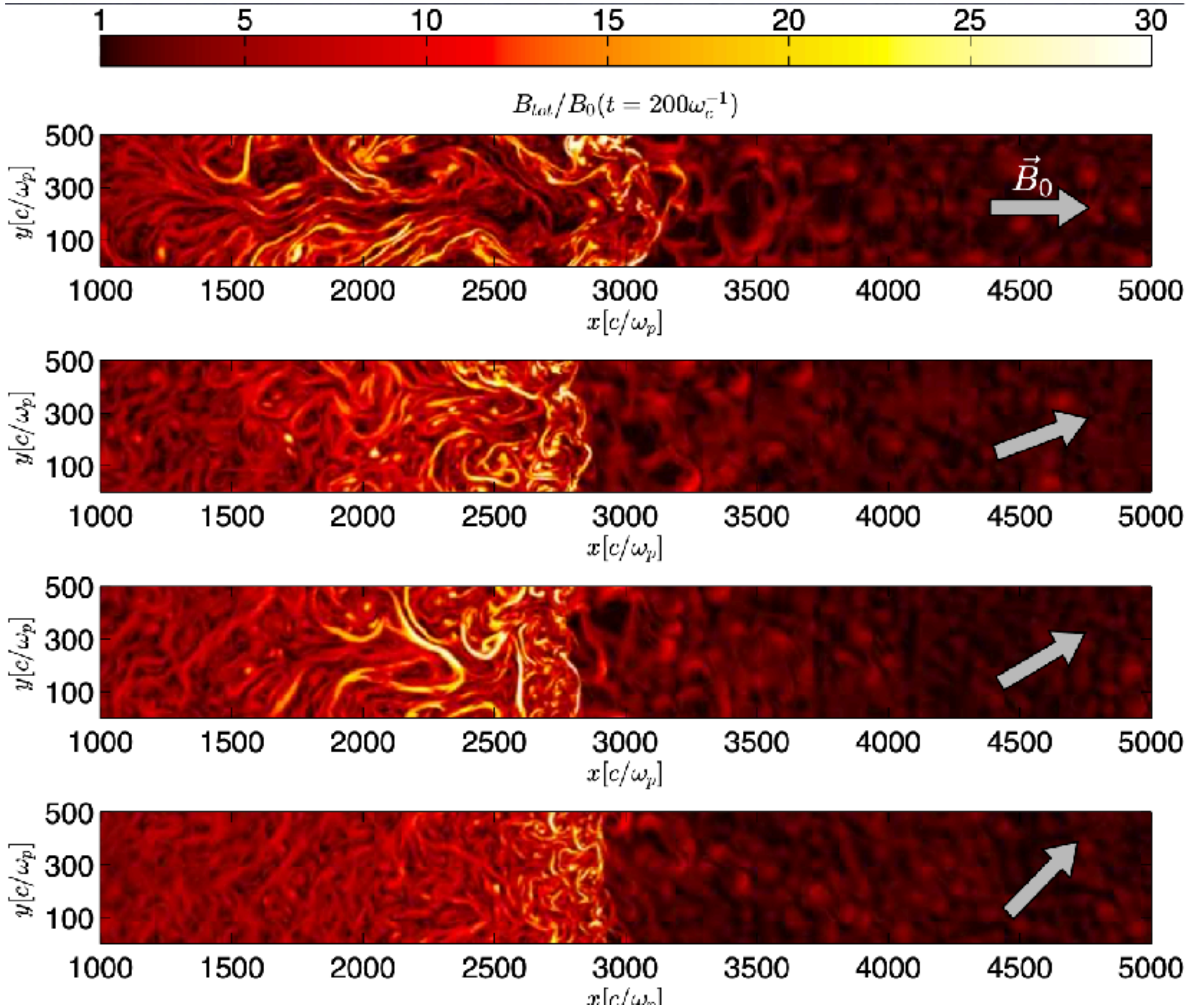


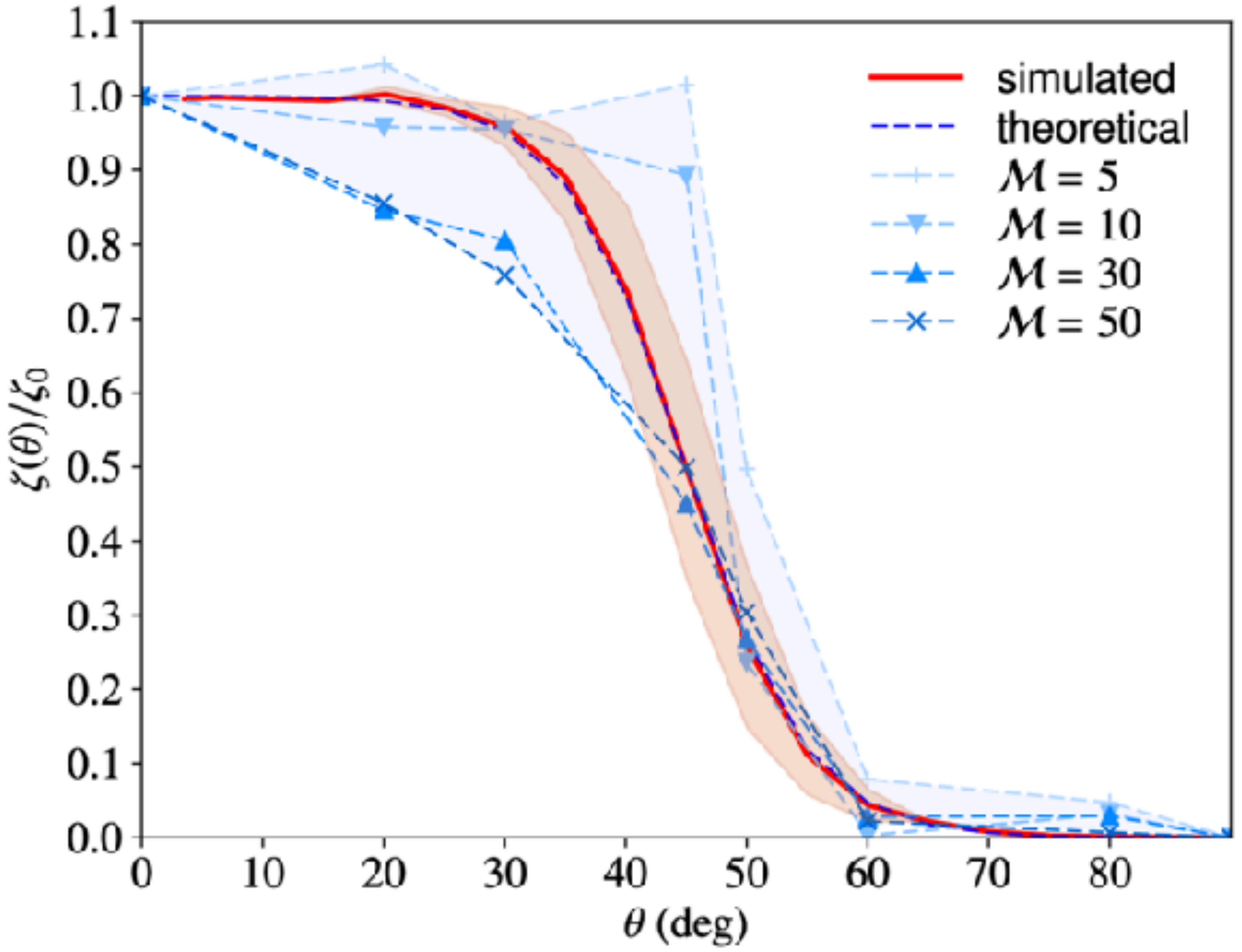
- non-thermal tail develops
- $E_{\max}$ increases over time
- steep spectrum: ordinate is $p^4 f(p)$ and $f(p)$ is flat, so $f(p) \propto p^{-4}$

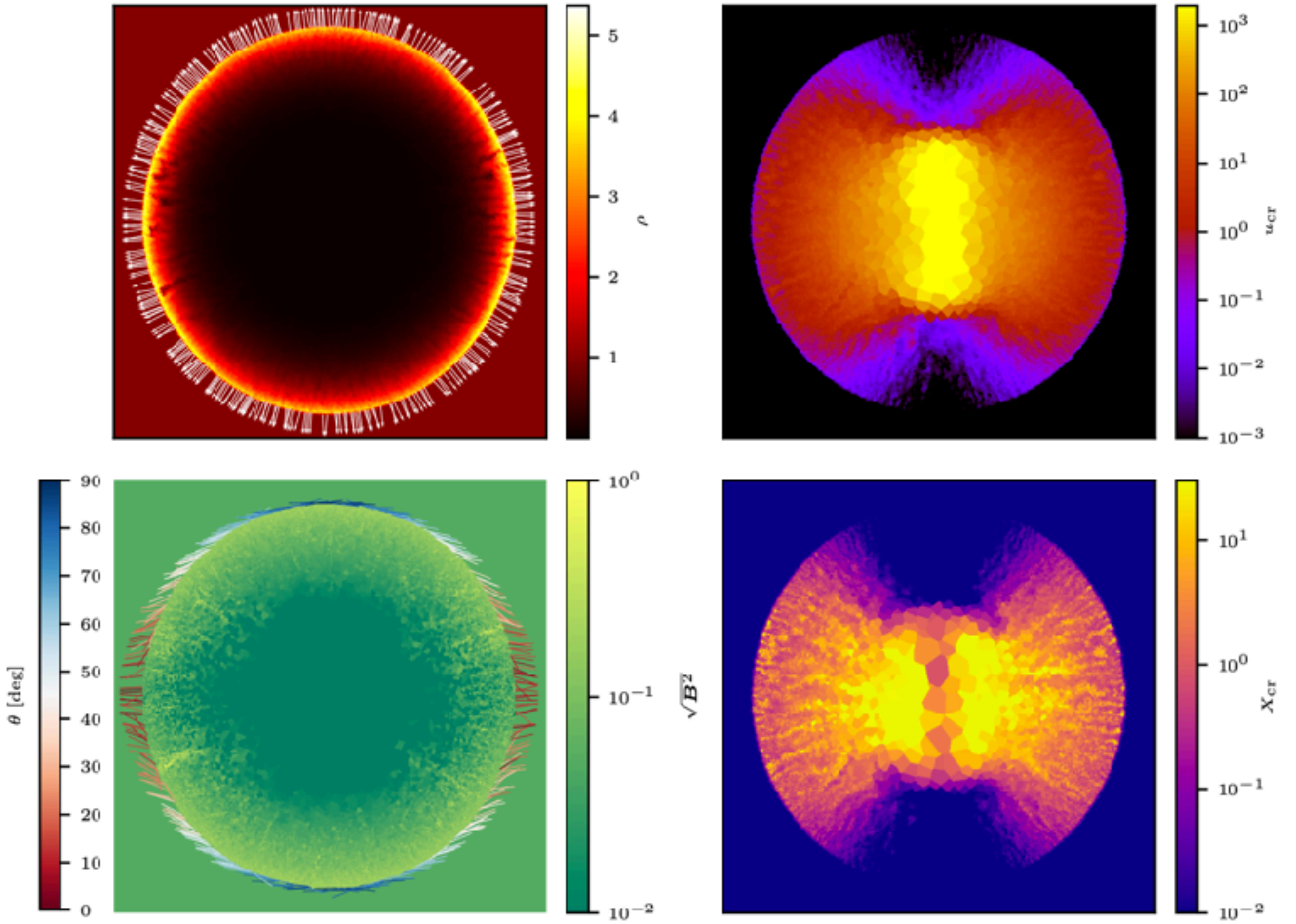
Obliquity dependence

acceleration depends on B orientation

- magnetic orientation alters turbulence and B-field amplification



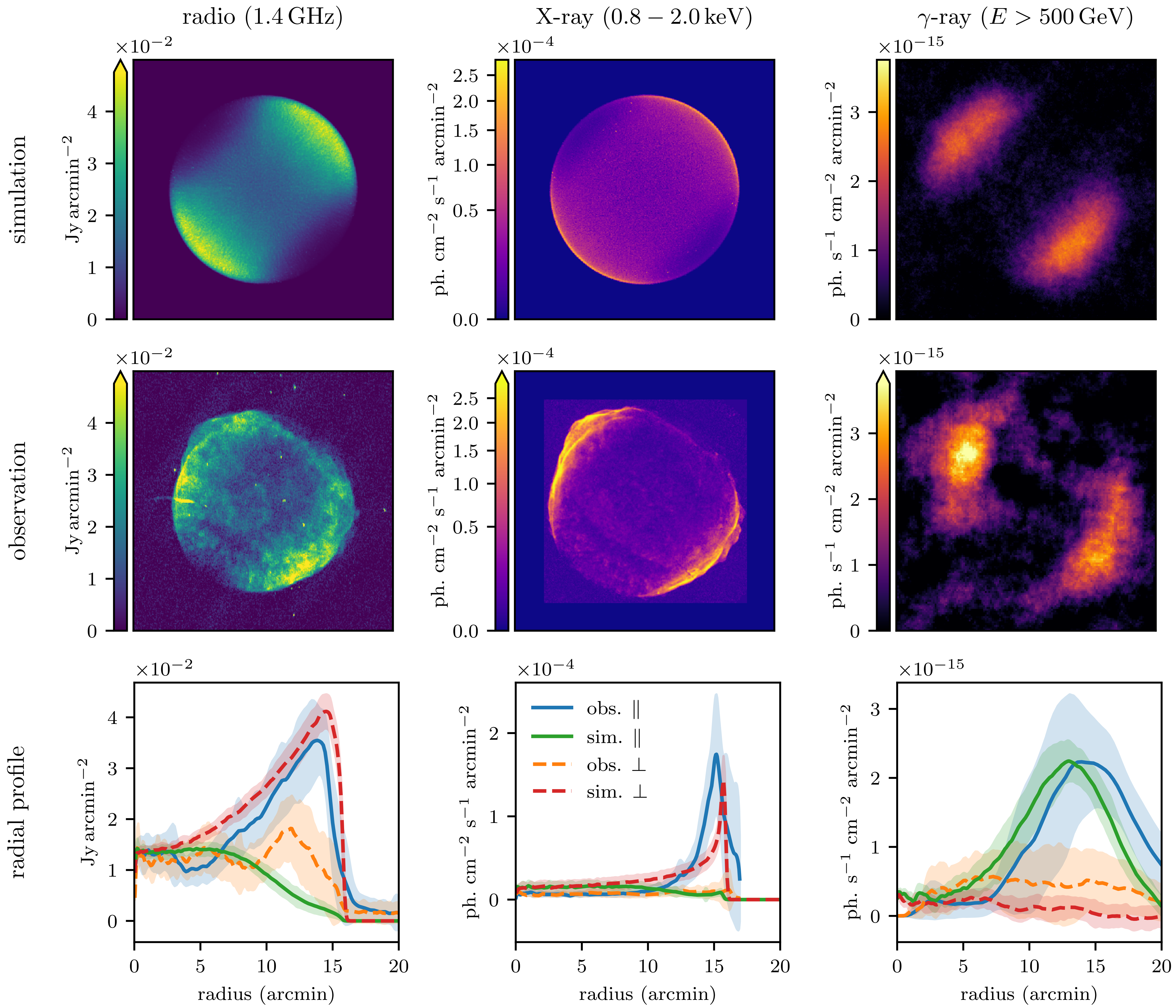




Caprioli & Spitkovsky 2014, Pais et al. 2018

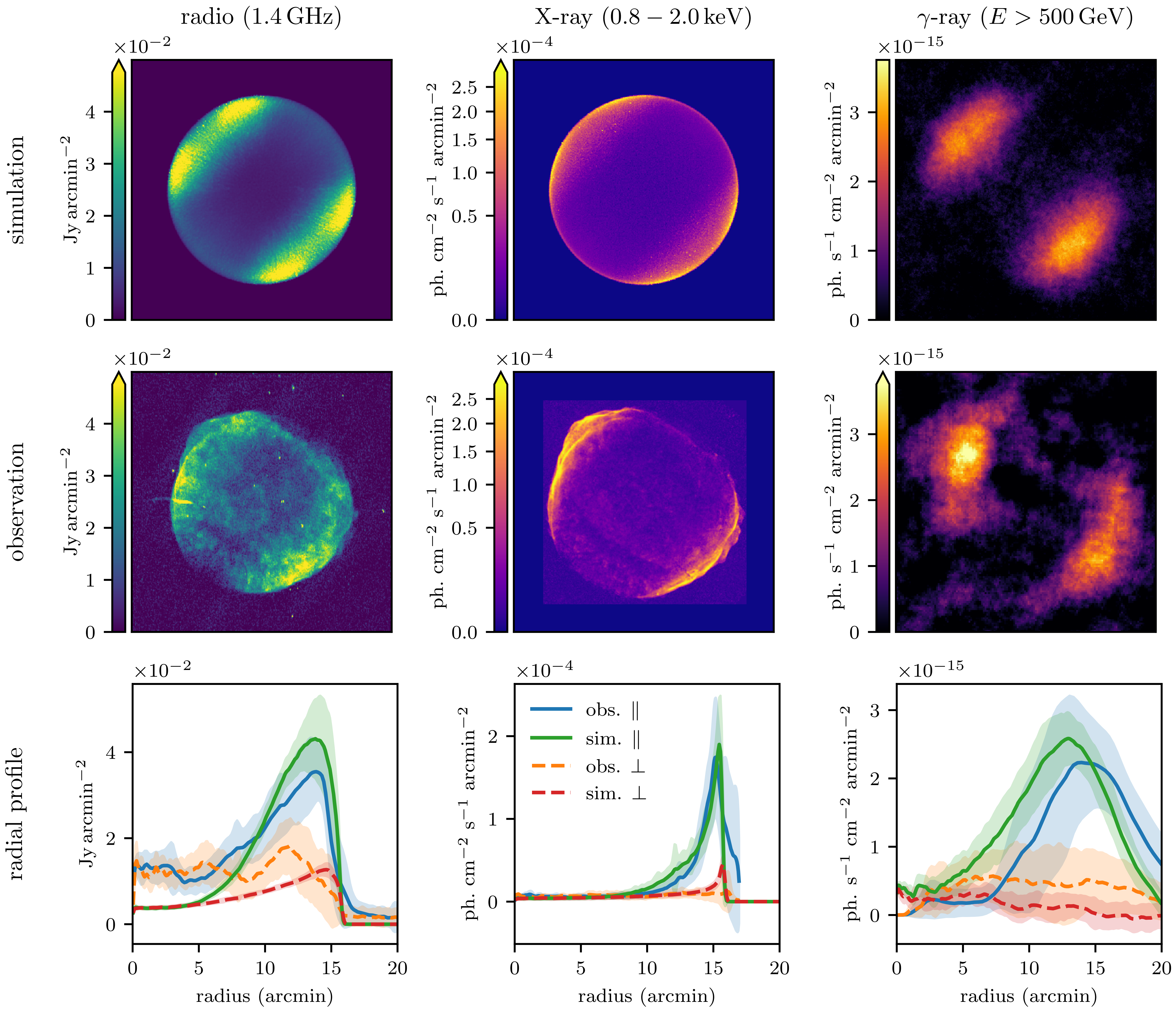
Check simulations vs. observations (SN 1006)

obliquitiy *in*dependent acceleration



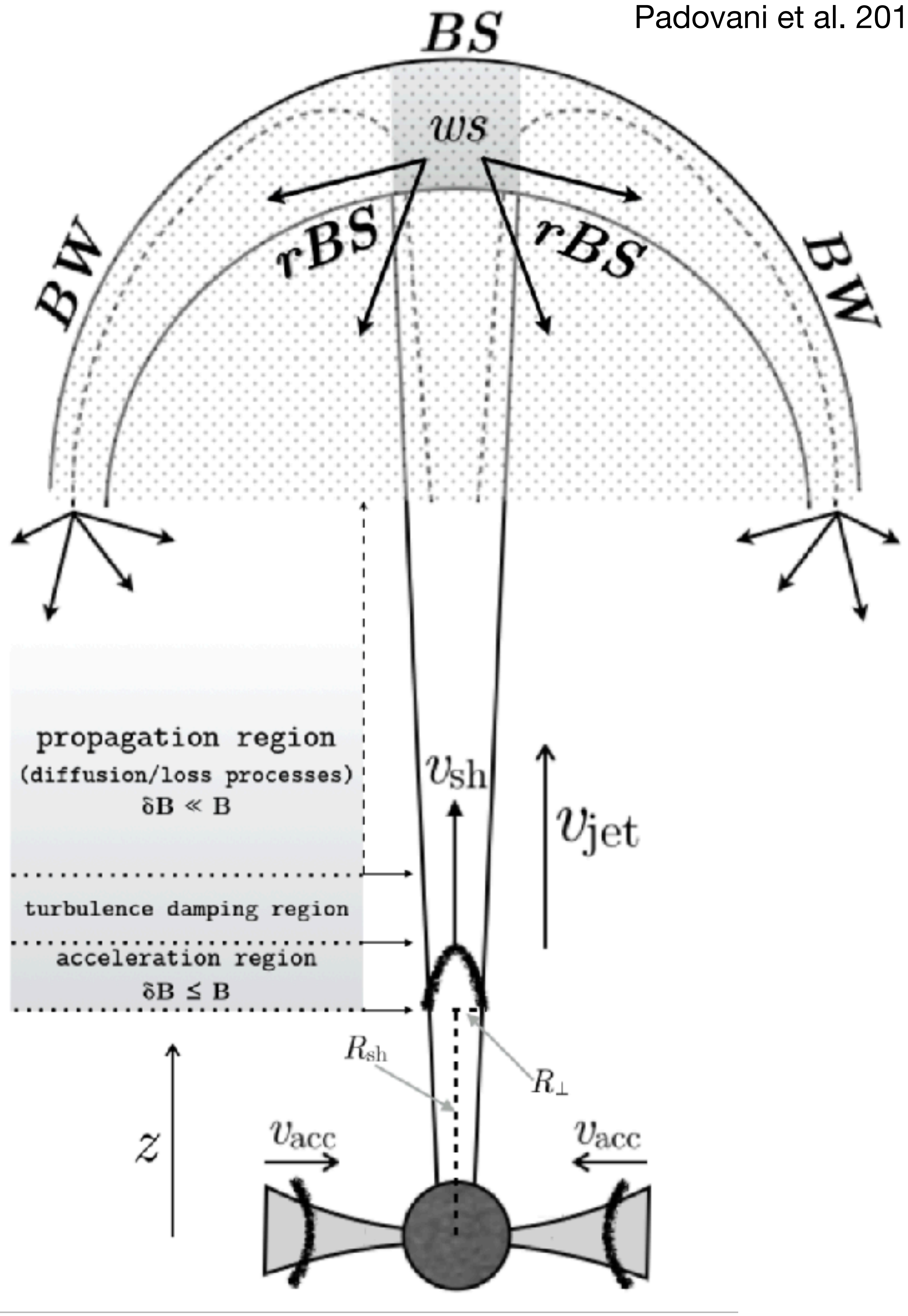
obliquitiy dependent acceleration

Winner et al. 2020



Astrophysical accelerators

- low-energies $< \mathrm{GeV}$: all kinds of shocks (ISM, stellar winds, accretion shocks, outflows)
- up to $\sim 10^{15}\,\mathrm{GeV}$: SNe during free expansion phase and Sedov phase
- global energetic arguments: 10% of SN energy into CRs ($\sim 10^{50}\,\mathrm{erg}$)

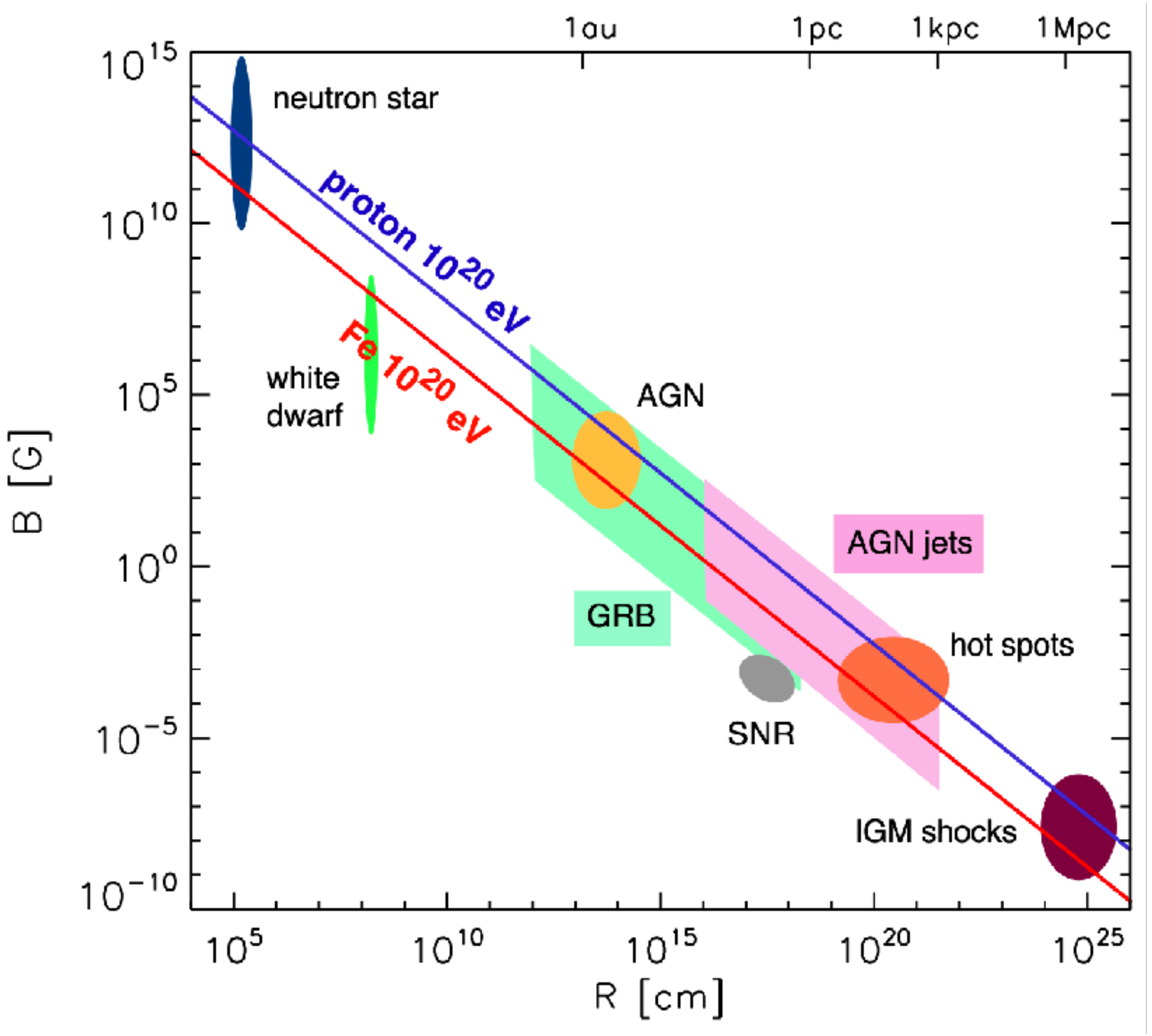


Padovani et al. 2016

Astrophysical accelerators II

$$r_{\mathrm{g}} = \frac{p_\perp}{|q|B}$$

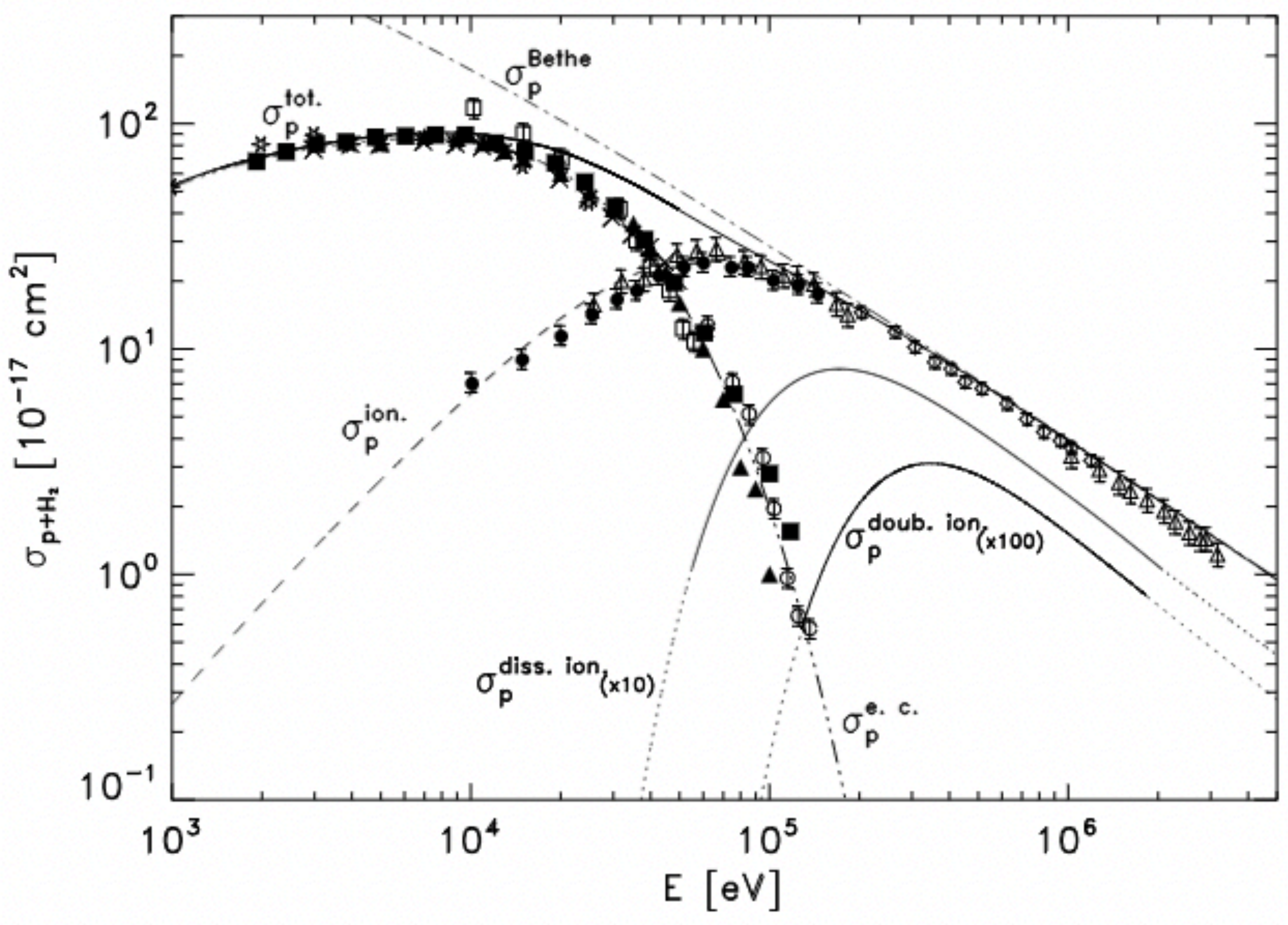
- beyond $\sim 10^{15}\,\mathrm{GeV}$: SNe not powerful enough
- follow global arguments of confinement, r_{g}
- “Hillas plot” (Hillas 1984, originally by Fermi)
  “exclusion plot”
- CRs above the line are confined
  (how strong does B need to be)
- candidate sources
  - AGN (relativistic conditions)
  - GRB (multiple shocks)
  - neutron stars (strong B-fields)

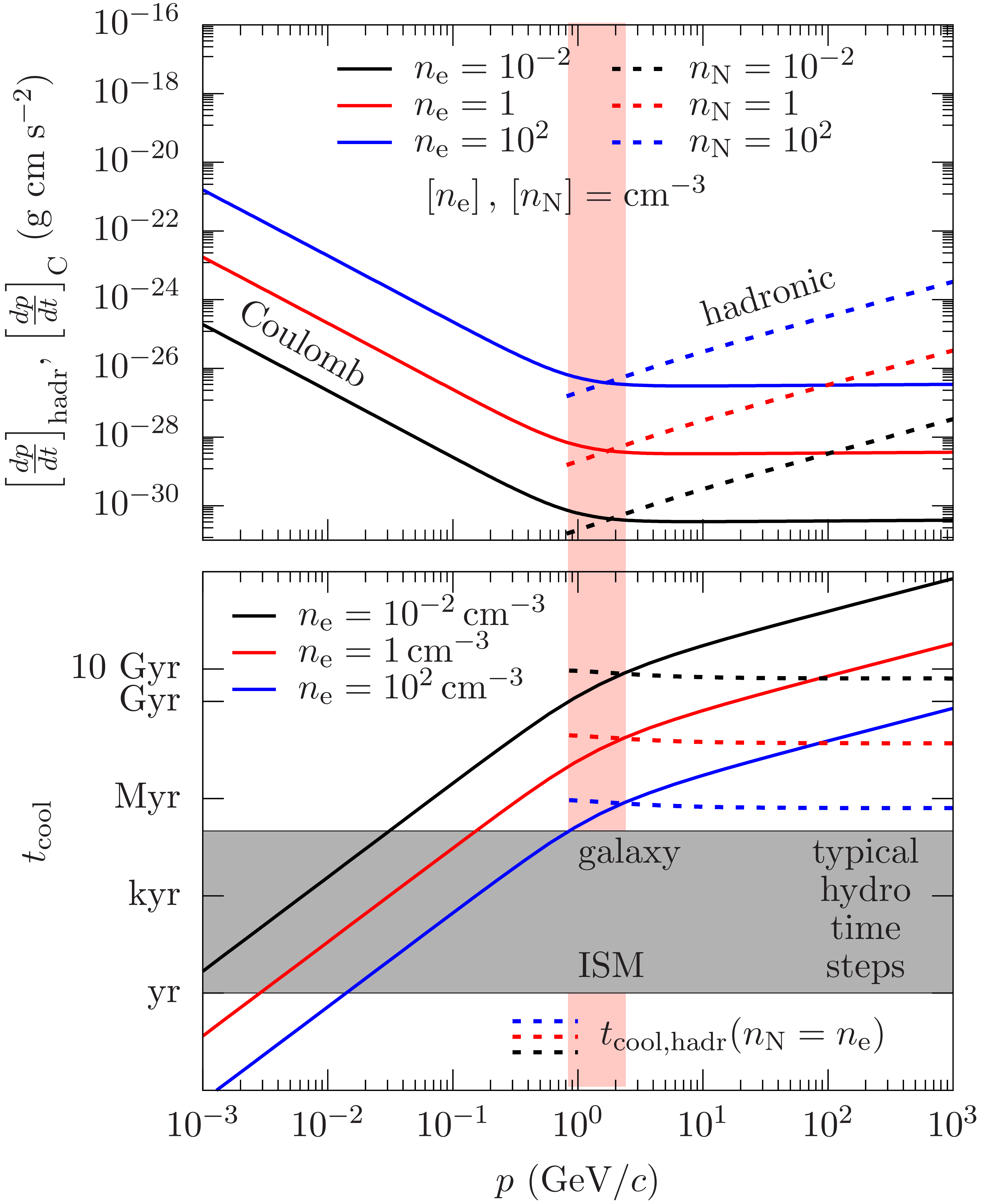


from Kotera & Olinto 2011

CR-MHD fluid theory

Energy dependent losses

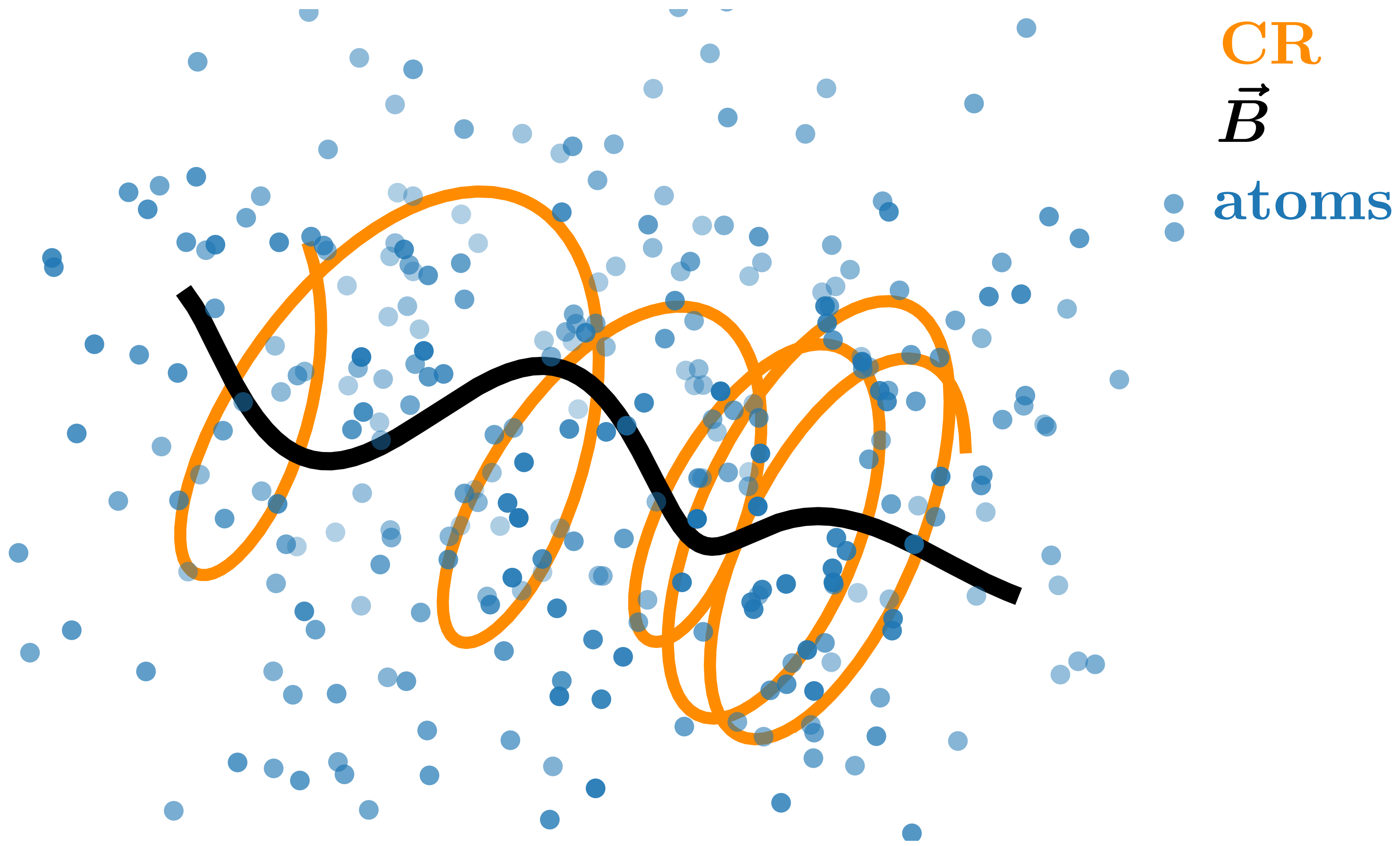




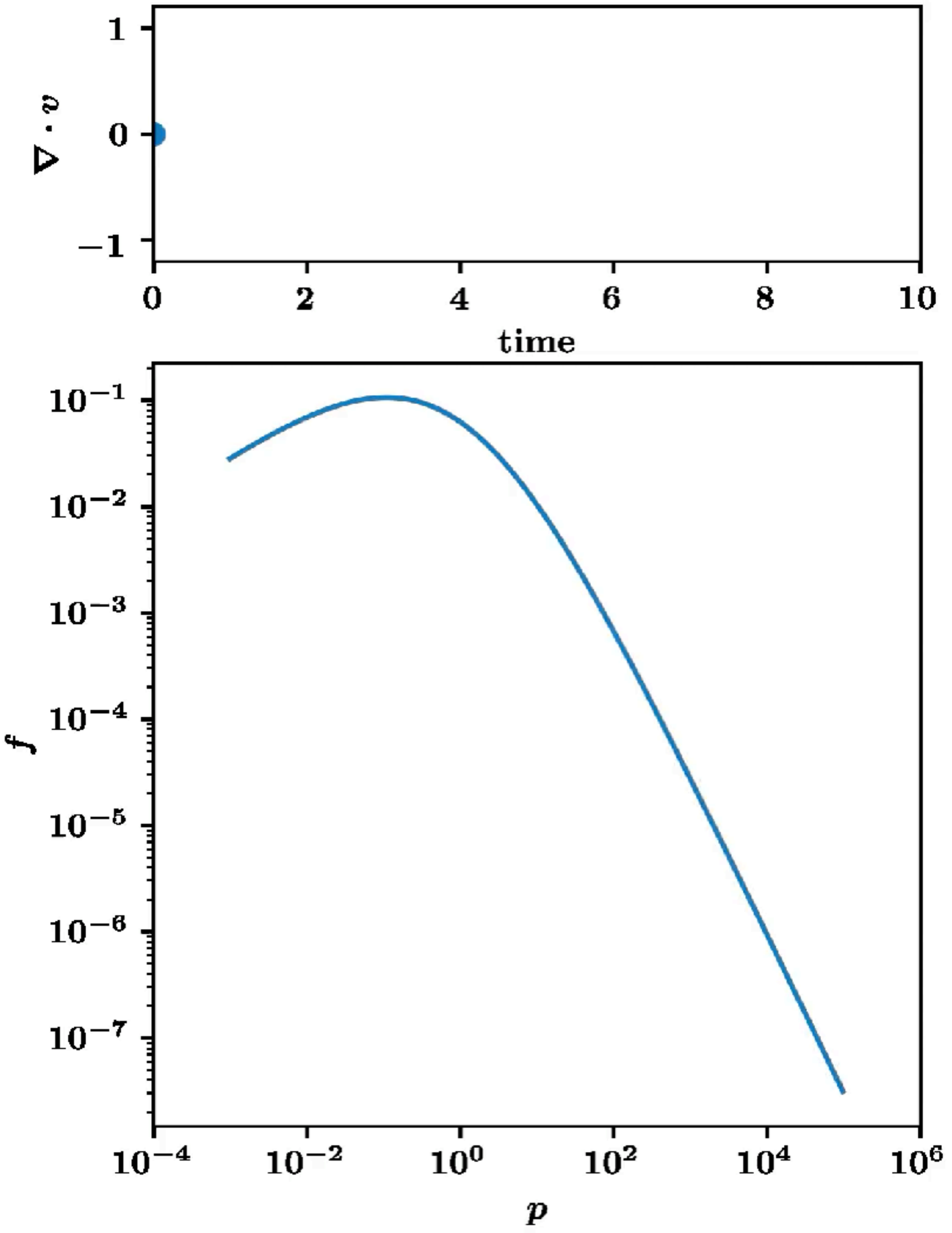
- Coulomb and ionisation losses (low-E CRs)
- hadronic losses via $\mathrm{CR} + p \to \pi^0 \to 2\gamma$ above threshold for π^0 $(0.78\,\mathrm{GeV})$
- GeV CRs cool least efficient, GeV peak with most energy
- cooling time Myr - Gyr

Adiabatic gains/losses

Shift of the spectrum



- adiabatic process $\left(\frac{\partial f}{\partial t}\right)_{\mathrm{ad}} = -\left(\frac{1}{3}\boldsymbol{\nabla}\cdot\boldsymbol{u}\right)\frac{\partial f}{\partial \ln p}$
- in log-log space $y \equiv \ln(f) \quad x \equiv \ln(p)$
- advection in ln p $\frac{\partial y}{\partial t} = -\frac{1}{3}\left(\boldsymbol{\nabla}\cdot\boldsymbol{u}\right)\frac{\partial y}{\partial x}$
- keeps the spectral shape!!



Fokker-Planck equation for CRs

- investigate particle distribution (bulk of CRs)
- time evolution: Fokker-Planck equation for CRs
  (Skilling 1971, 1975a,b,c)

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

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

- CRs couple efficiently
  ⇒ advection with the gas
- scattering along the magnetic field:
  ⇒ anisotropic diffusion along B
- coupled fluid (gas+CRs):
  ⇒ adiabatic expansion/compression
- losses
  (Coulomb, Ionisation, Hadronic)
- sources
  (e.g. shock injection)

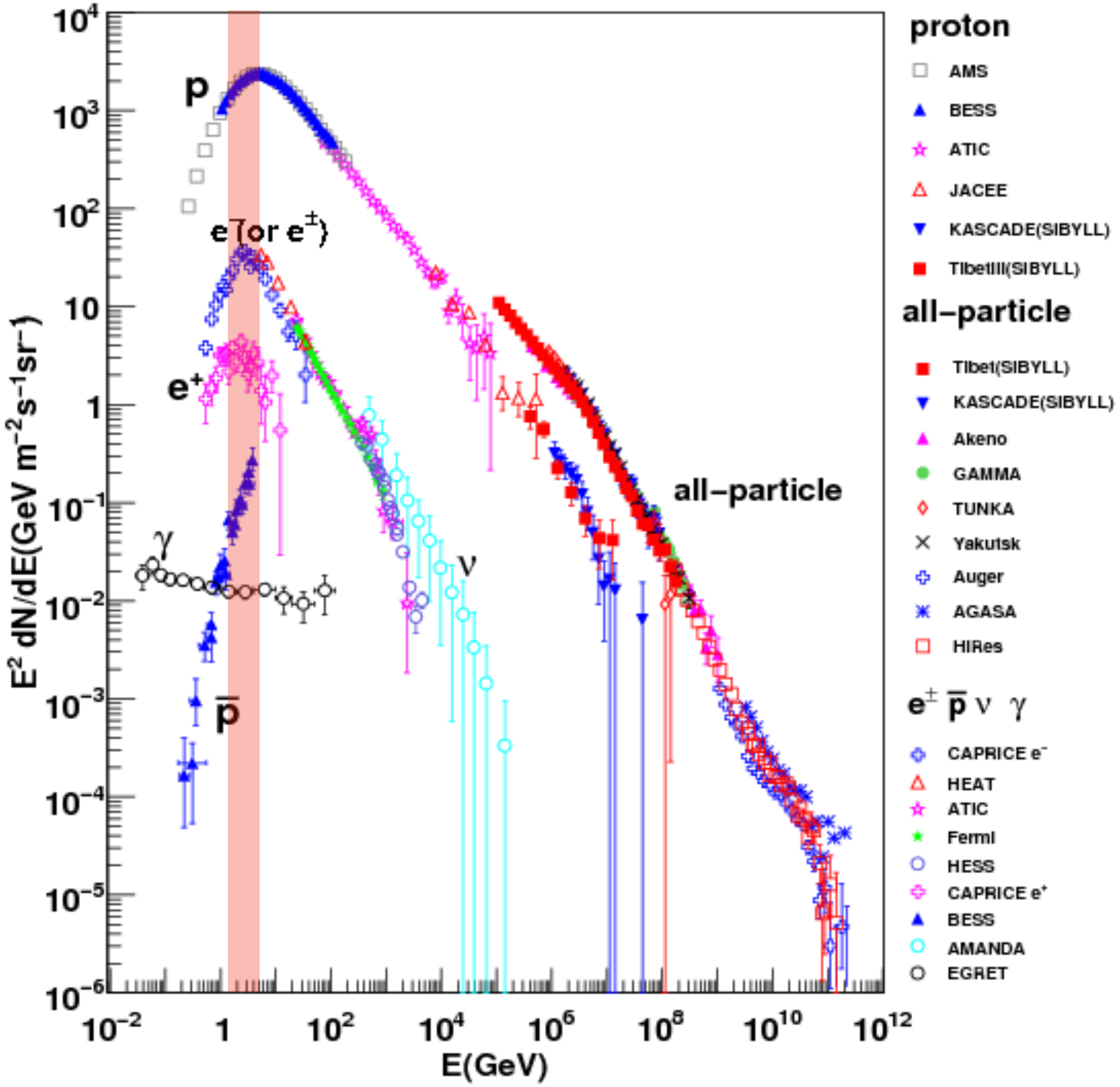
Grey approximation

- 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): $D_{xx} \sim 10^{28-29}\,\mathrm{cm}^2\,\mathrm{s}^{-1}$
- $P_{\rm CR} = (\gamma_{\rm CR} - 1) e_{\rm CR},\ \gamma_{\rm CR} = 4/3$

assumes universal spectrum, not just steady state



Combined CR-MHD equations (2-fluid)

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

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

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

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

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

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

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

Applications

CR facts to remember

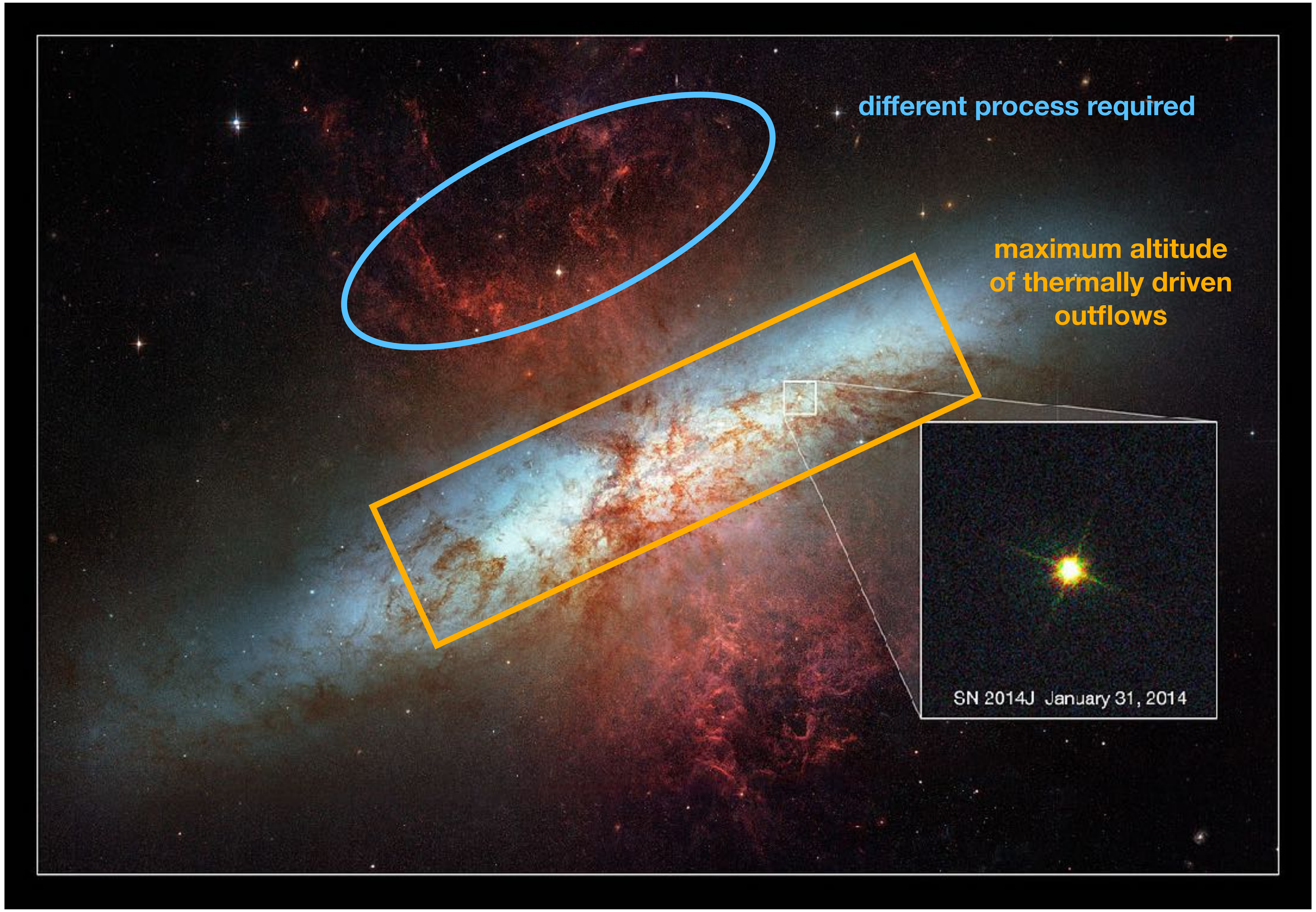
- CR diffuse fast
- diffusion is energy dependent $D(E) \propto E^{0.3-0.5}$
- CR cool less efficiently than gas

Motivation for CRs in galaxies

strong outflows in all phases

Thermal energy cools too fast

classical stellar feback too weak (SN, winds, radiation)

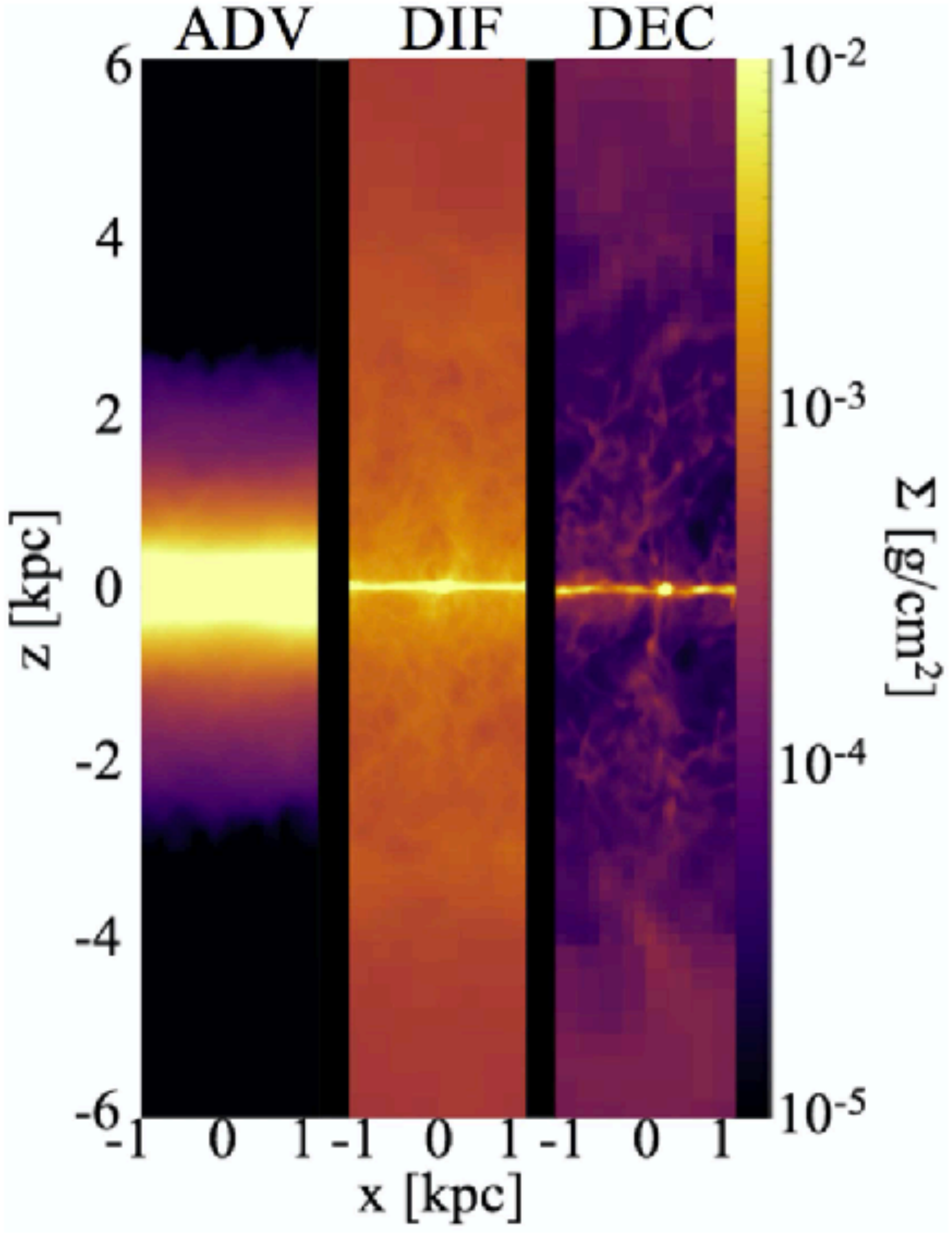


different process required

maximum altitude
of thermally driven
outflows

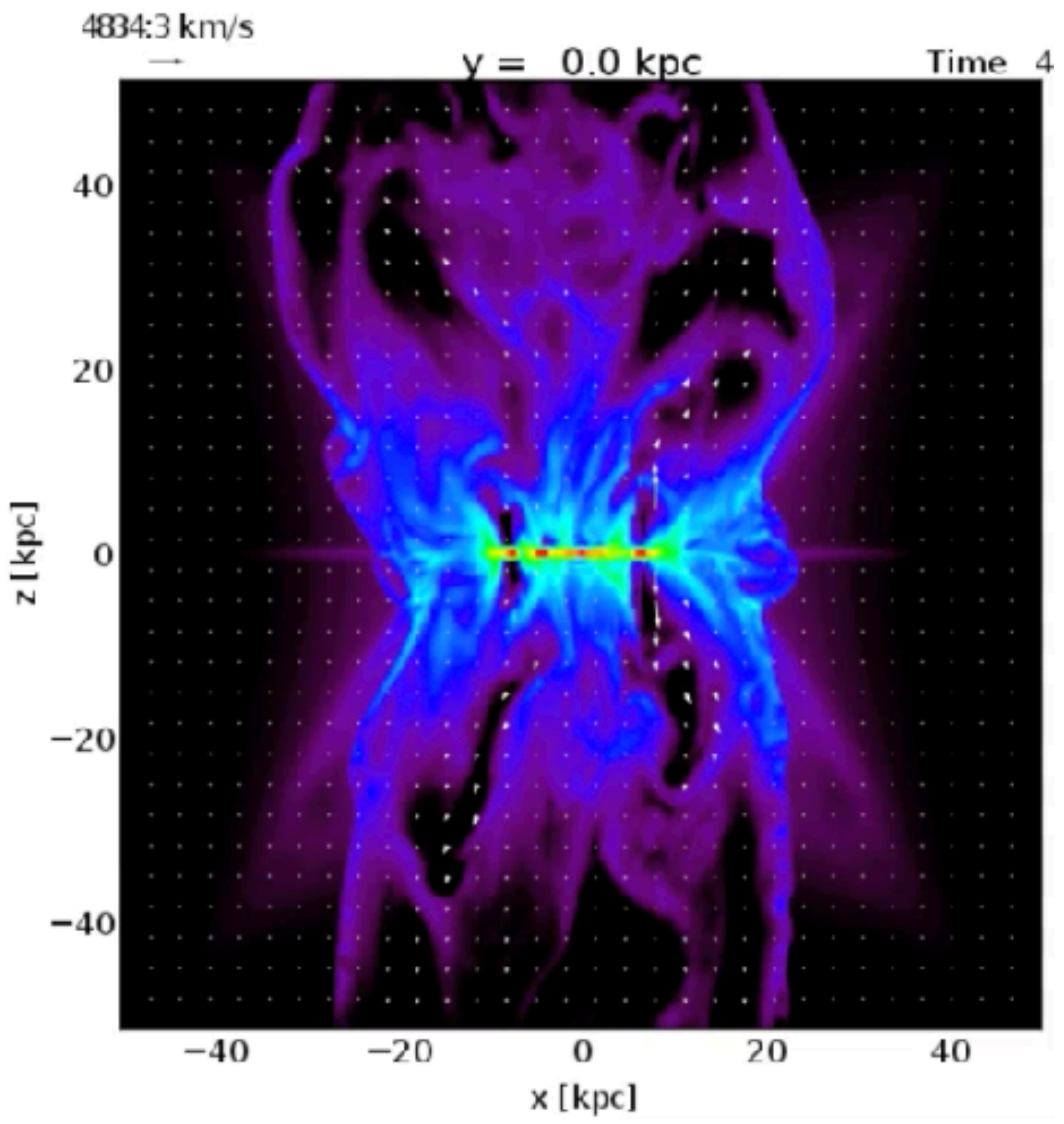
different setups

stratified boxes (ISM)



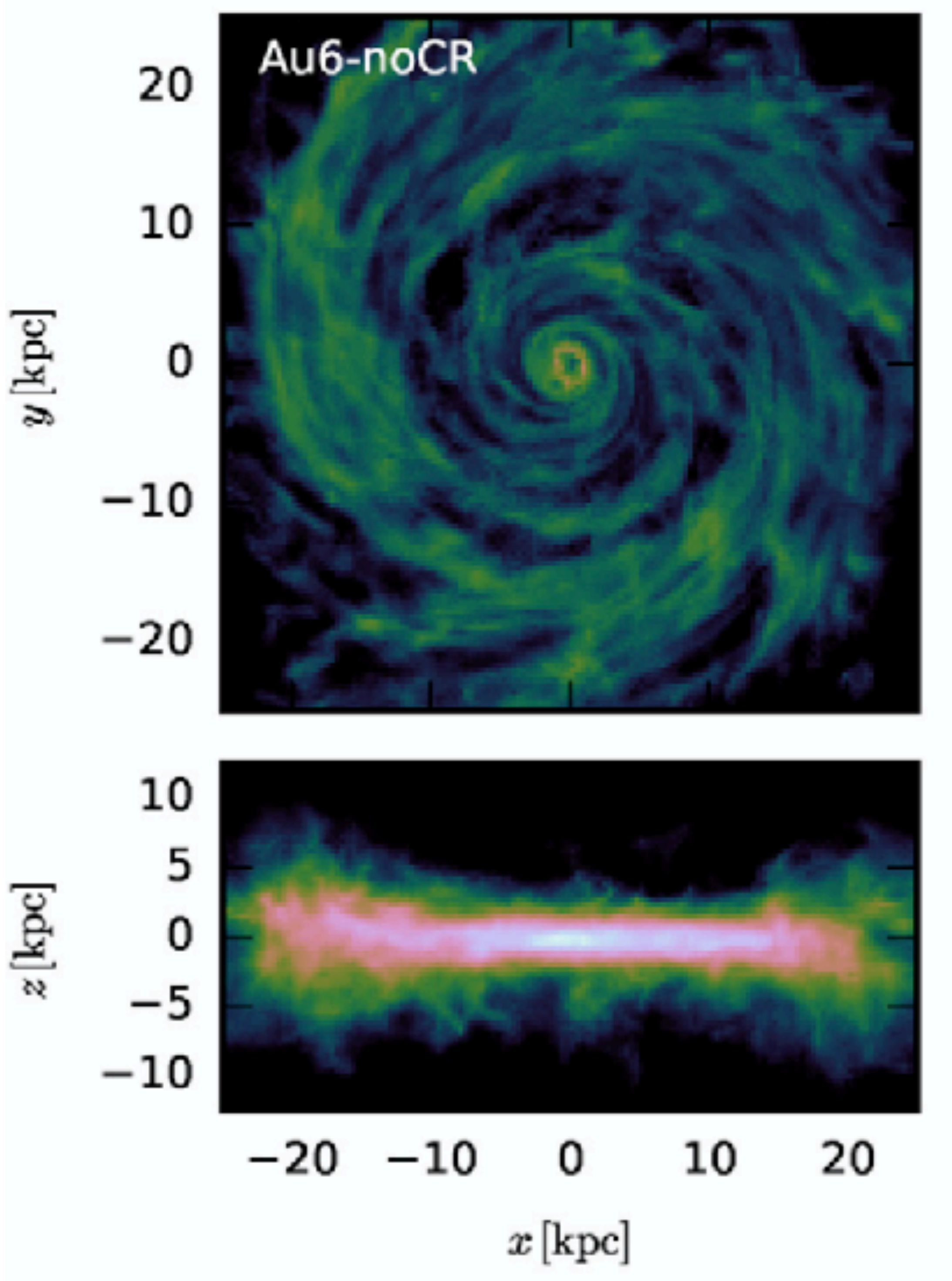
Hanasz+ 2003, Girichidis+16,18, Simpson+ 2016, Dubois+ 2016, Farber+ 2018, Armillotta+18,21, Commercon+2019, Butsky+2020, Rathjen+ 2021,2022

isolated galaxies



Booth+ 2013, Ruszkowski+ 2017a, Pakmor+2016, Pfrommer+2017, Jacob+ 2018, Dashyan+ 2020, Semenov+ 2021, Girichidis+ 2022/23, Thomas+2022,2023, Nunez-Castineyra+2022, Peschken+ 2023

cosmological galaxies



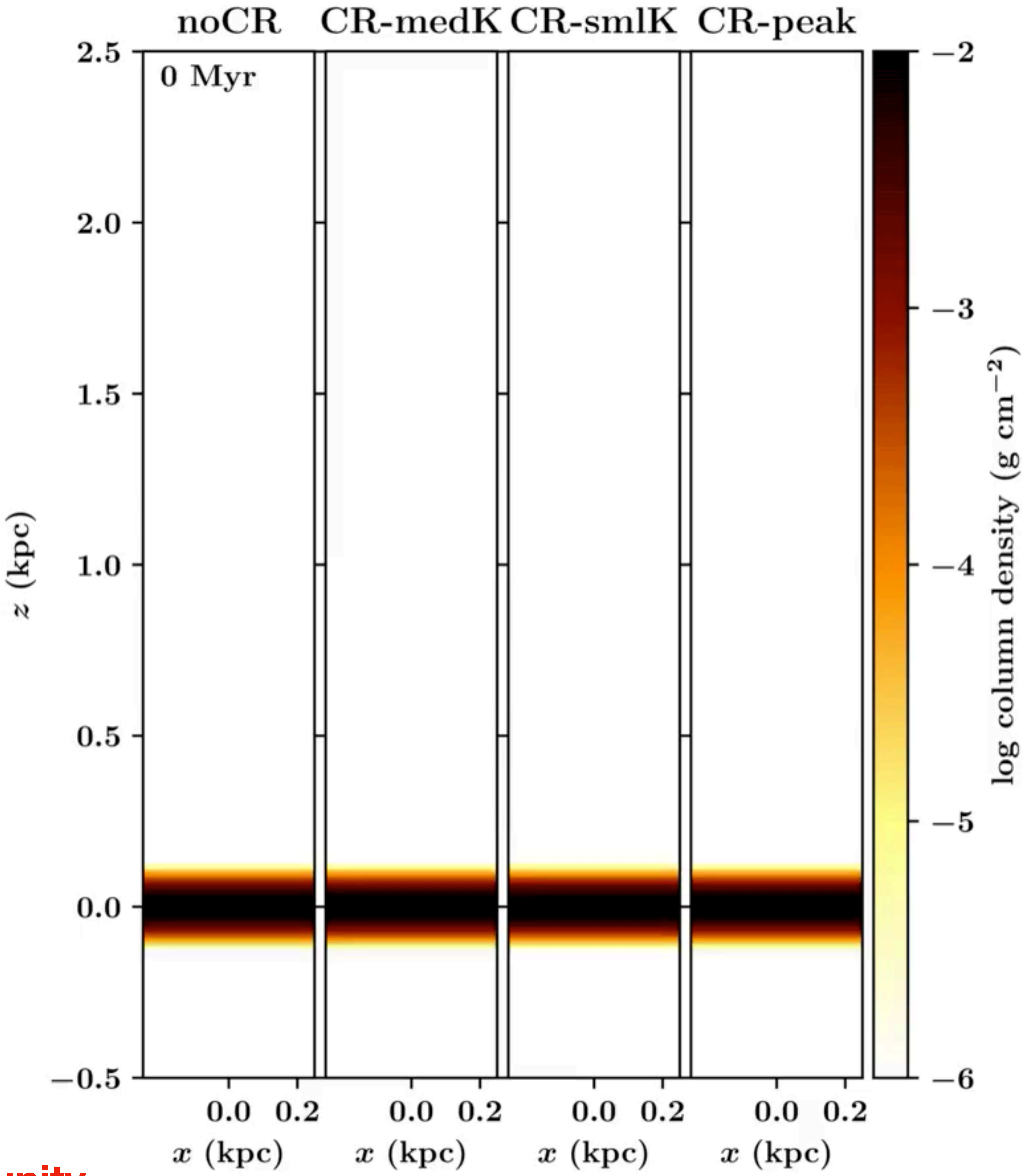
Jubelgas+ 2008, Salem+ 2014, Chan+ 2018, Hopkins+ 2020/2021, Buck+2020, Ji+2021, Farcy+ 2022, Böss+ 2023, Rodriguez Montero+ 2023

Girichidis et al. 2016a, 2018a

Stratified box simulations

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

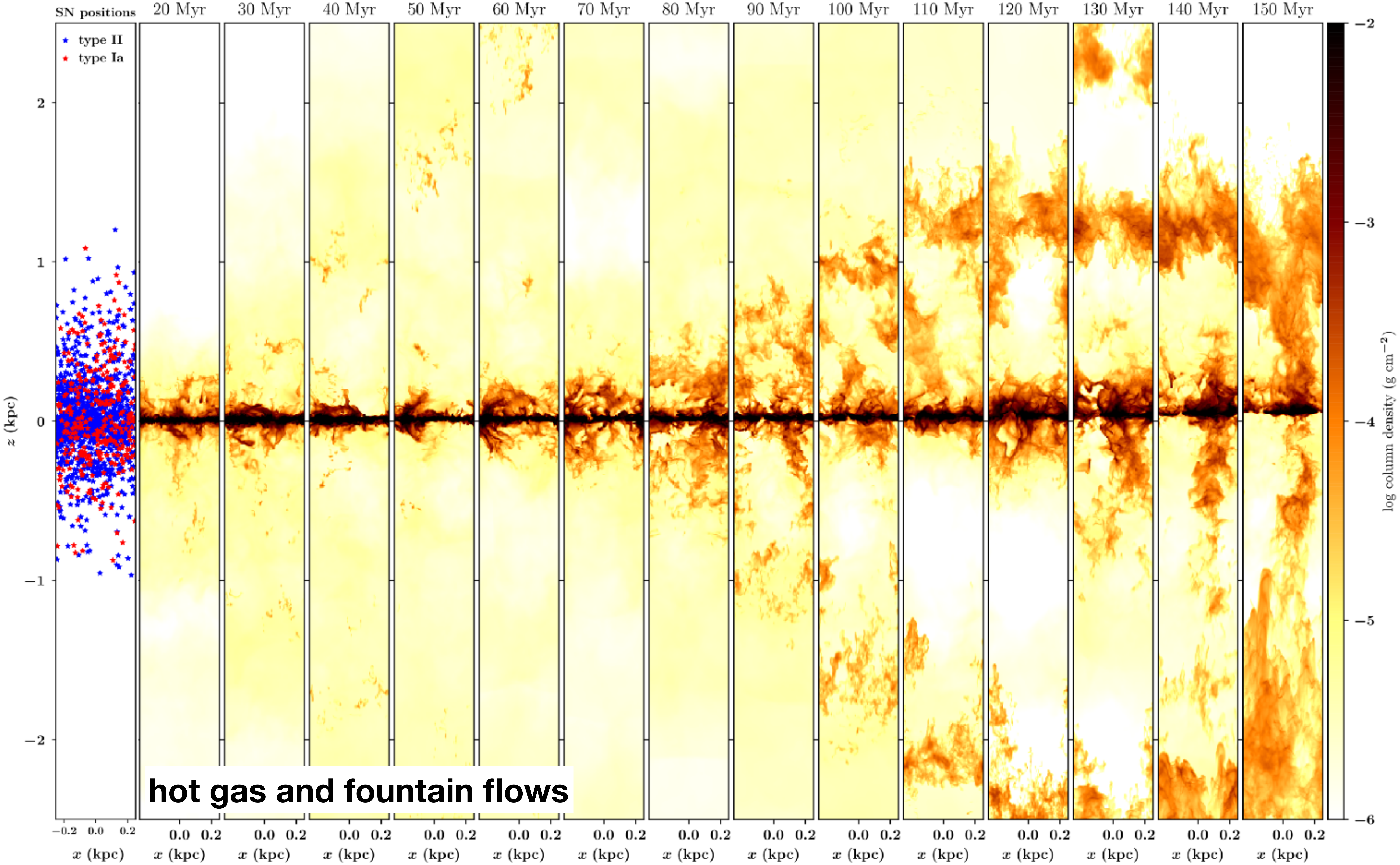
- “precomputed star formation and SNe”
  - therm: 10^{51} erg, CR: 10^{50} erg
    but see also Pais+ 2018 (only 5% of CRs)
- SN models:
  - 20% type Ia
  - 80% type II (48% clustered, 32% runway)
- 4 models
  - no CRs
  - medium diff $\left(K_{\parallel} = 3 \times 10^{28}\,\frac{\mathrm{cm}^2}{\mathrm{s}}\right)$
  - small diff $\left(K_{\parallel} = 1 \times 10^{28}\,\frac{\mathrm{cm}^2}{\mathrm{s}}\right)$
  - all SNe exploding in dense gas



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

ISM evolution without CRs

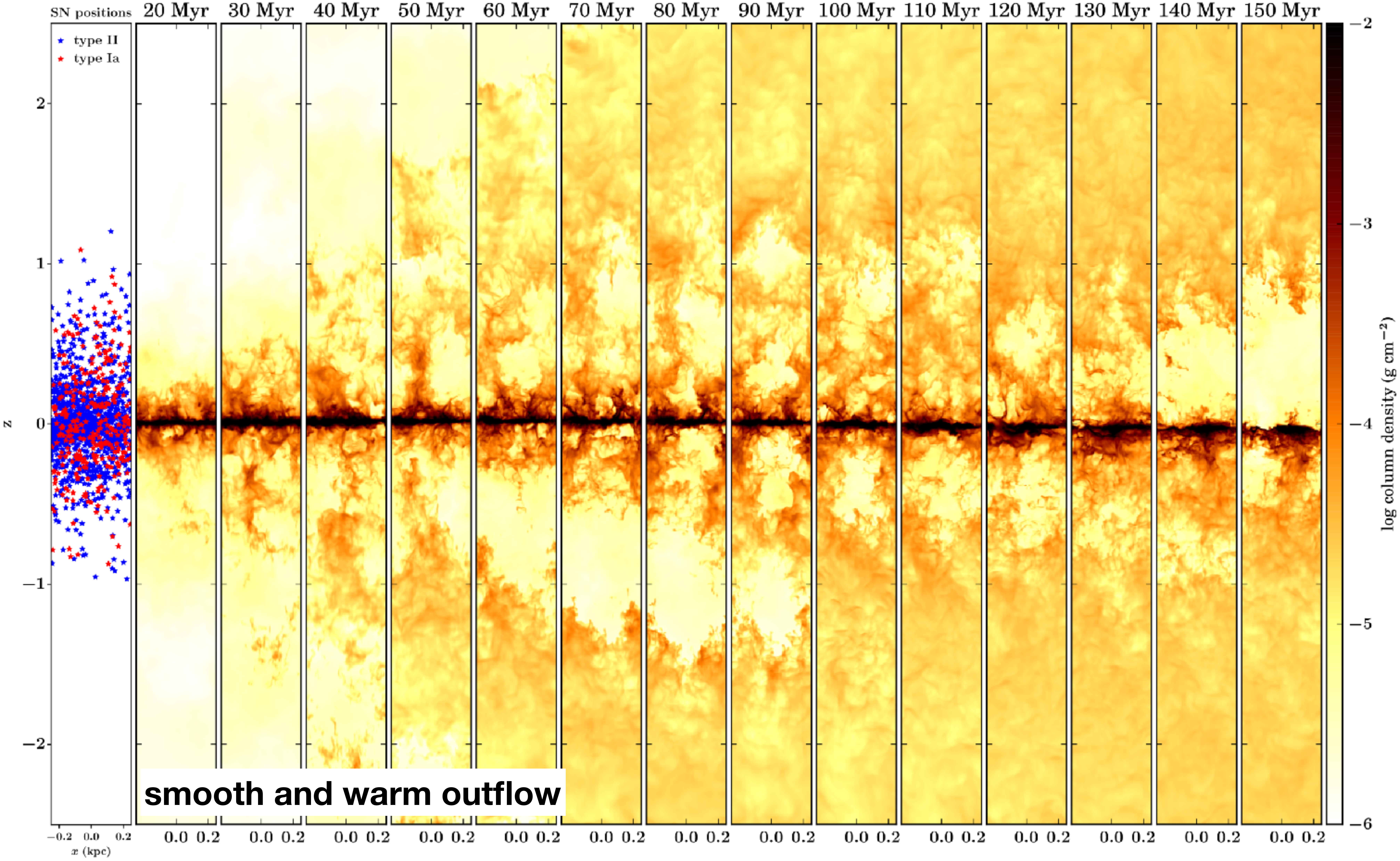
Girichidis et al. 2018a, based on SILCC setup (Walch+ 2015, Girichidis+2016)



hot gas and fountain flows

ISM evolution (therm+CRs)

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



smooth and warm outflow

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

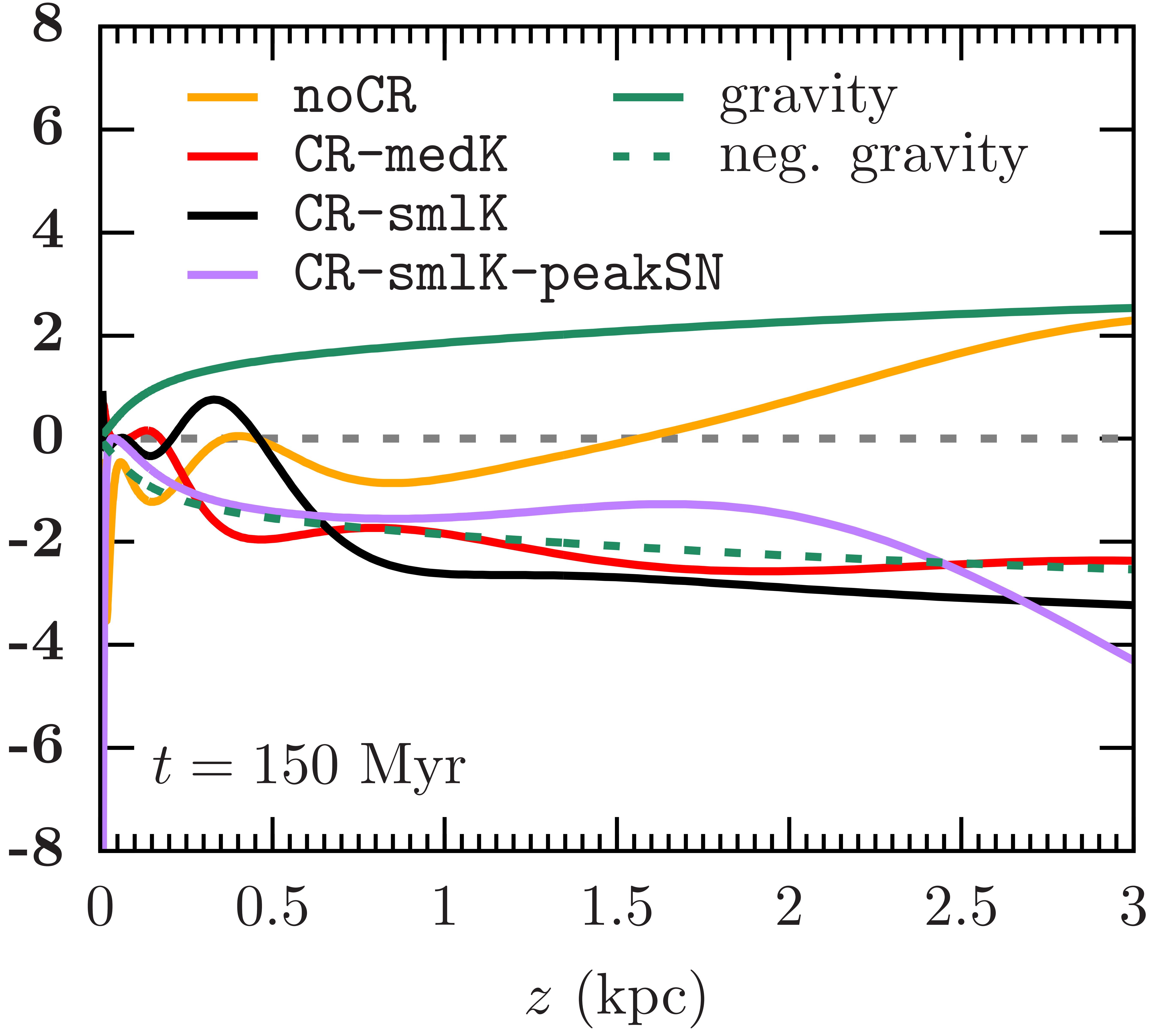
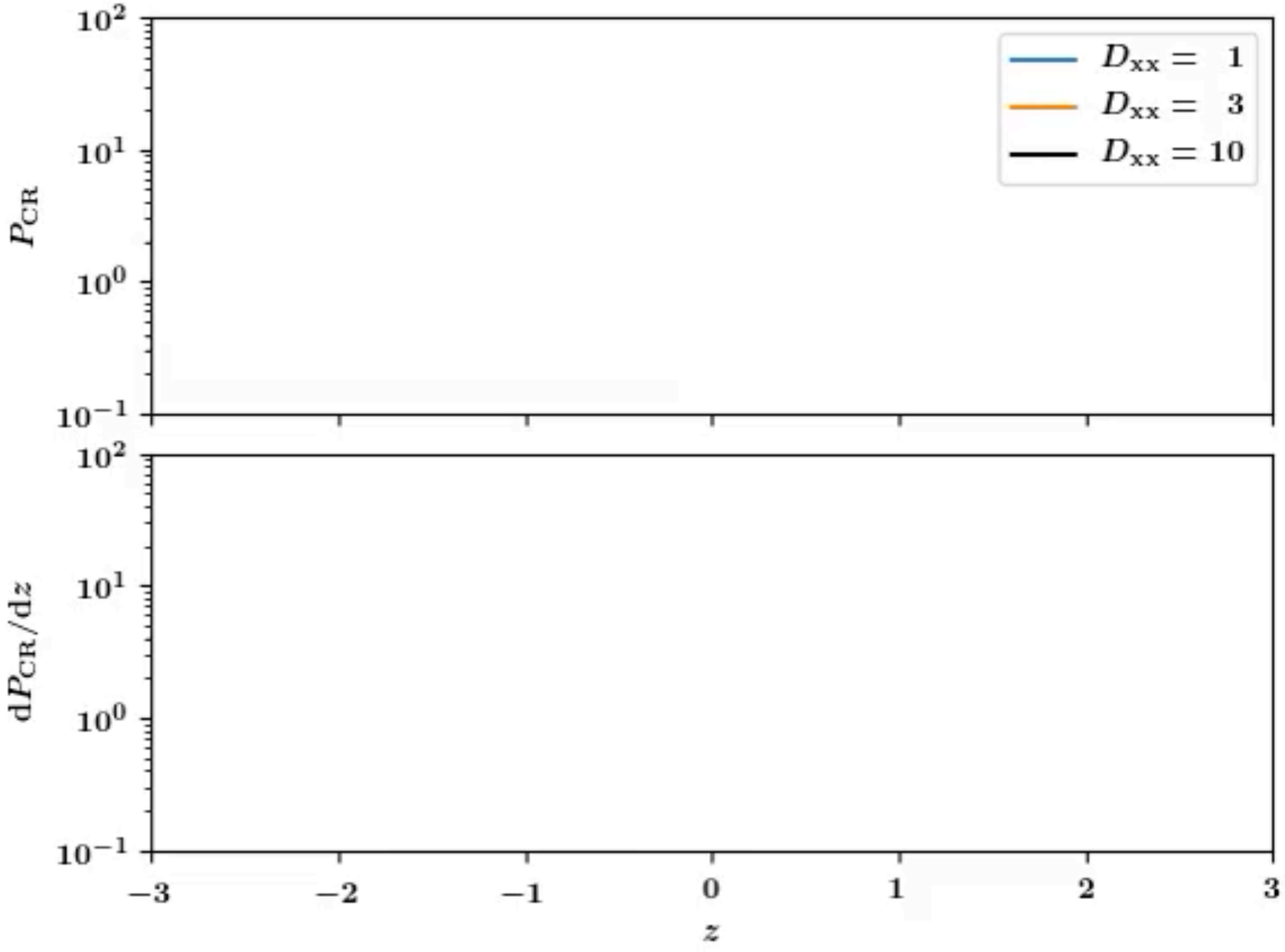
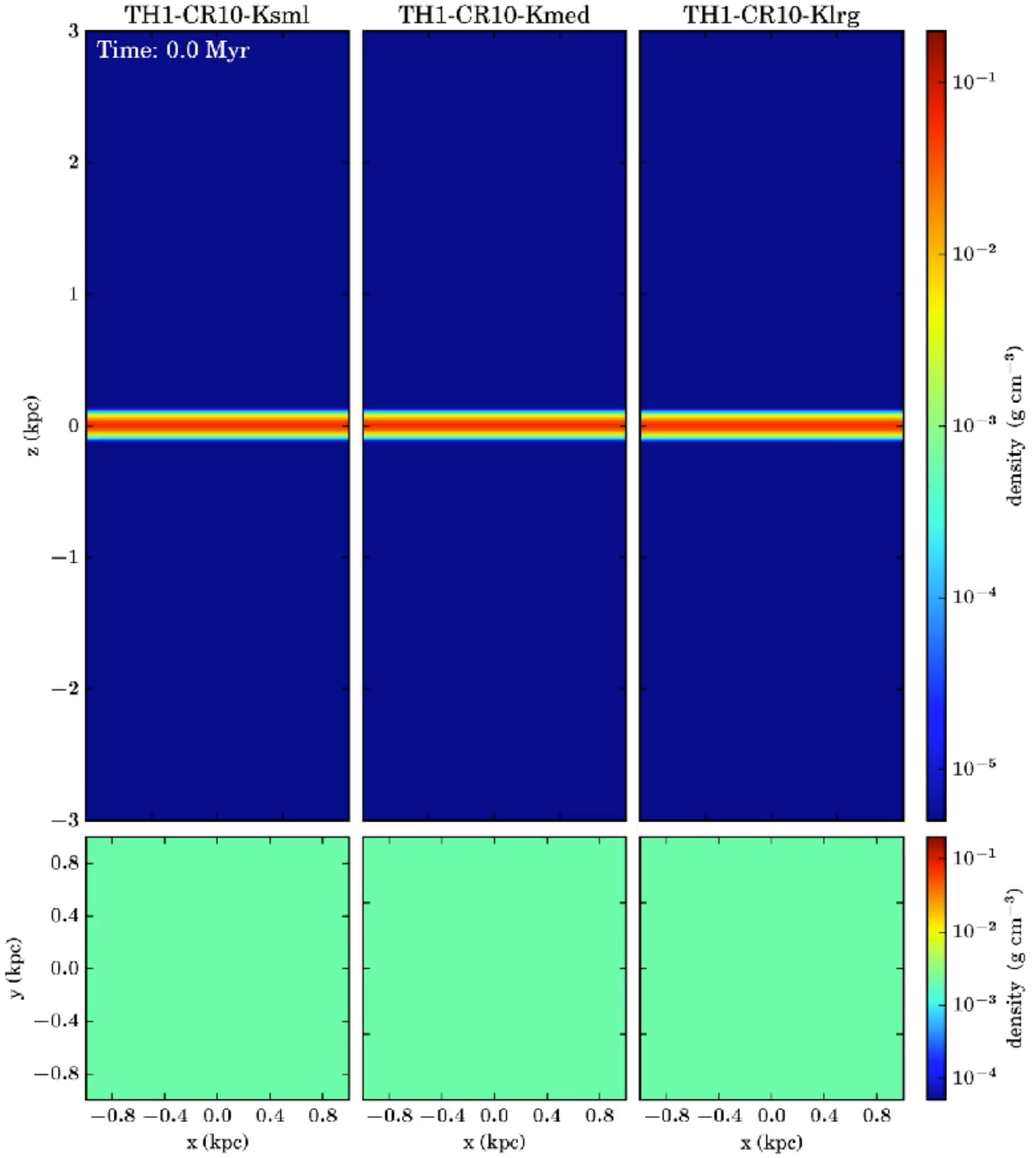


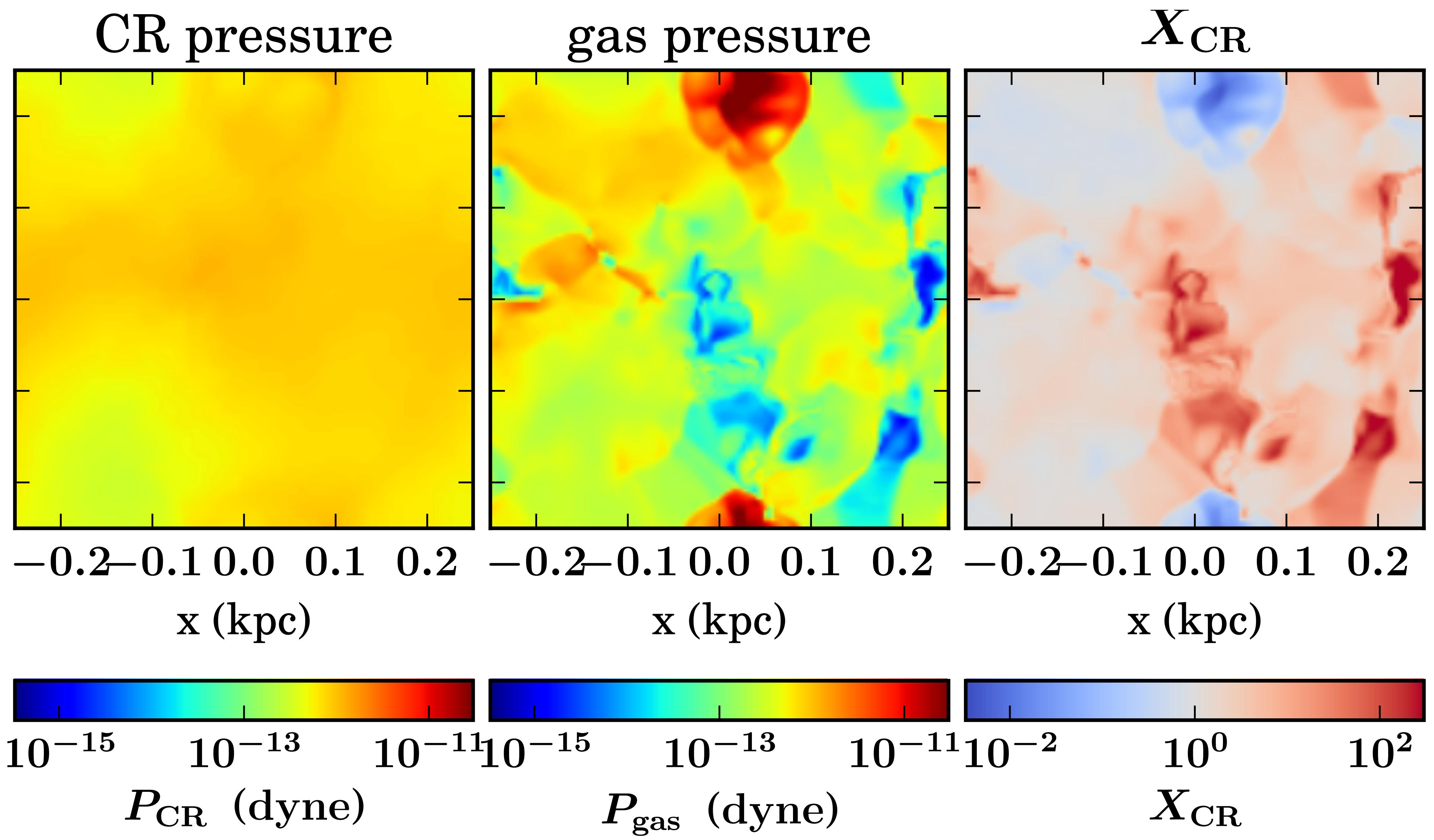
Illustration of different diffusion speeds

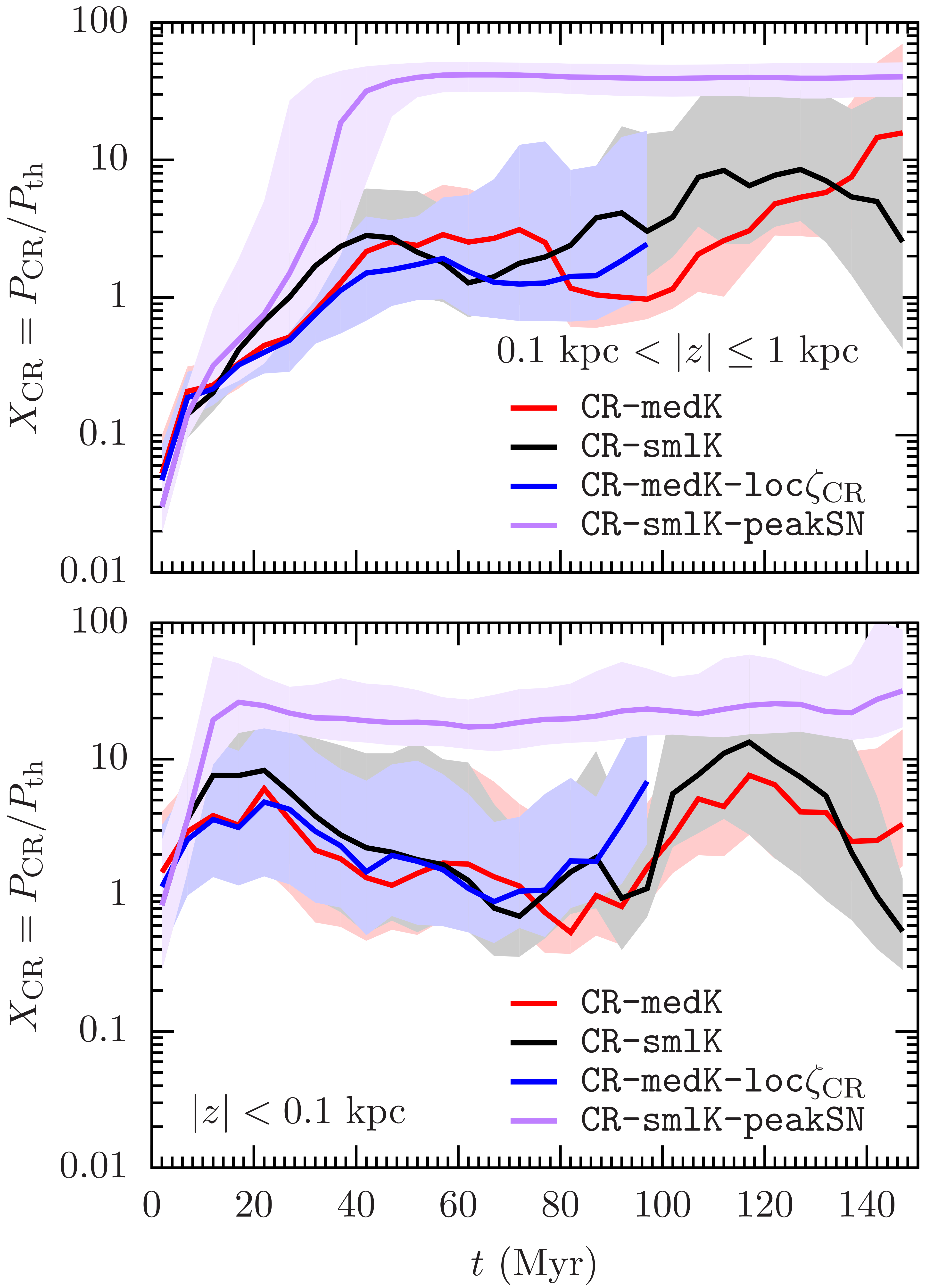




CR pressure

- 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 $\nabla P_{\rm therm}$

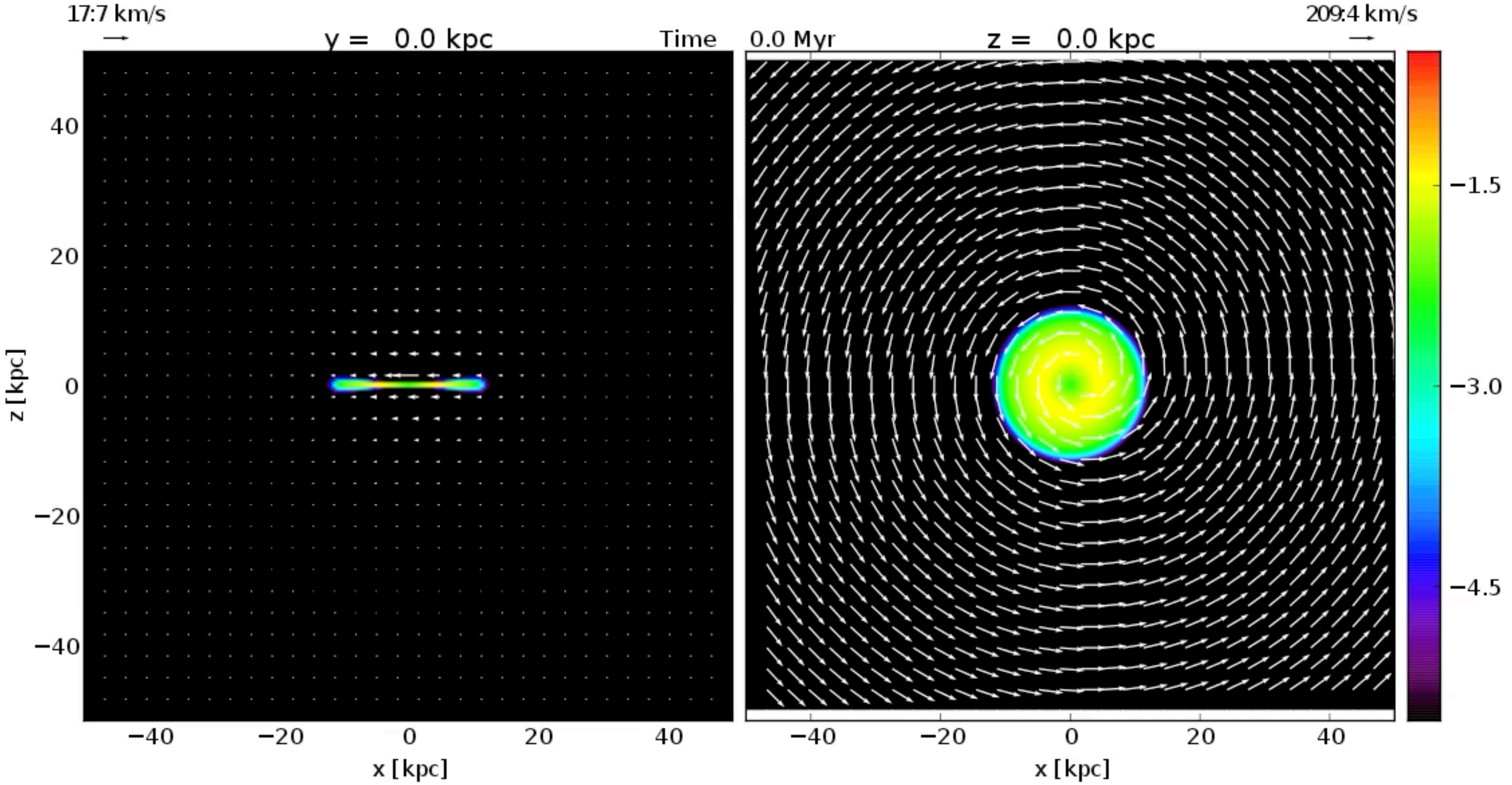




MHD, anisotropic diffusion, isothermal

Hanasz et al. (2013)

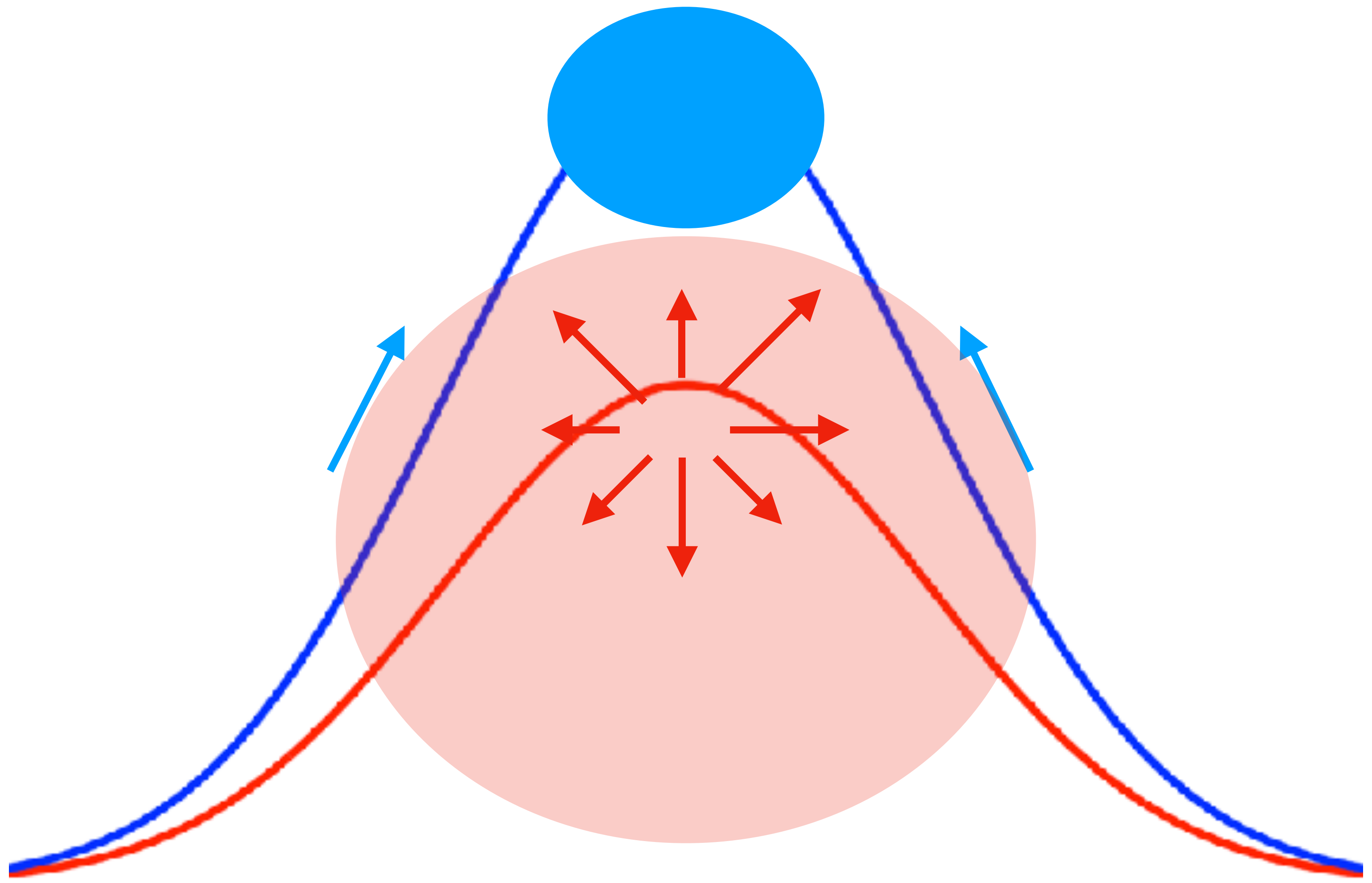
- isolated galaxy
- isothermal gas
- only CR injection with SNe
- **CRs alone are able to drive winds**



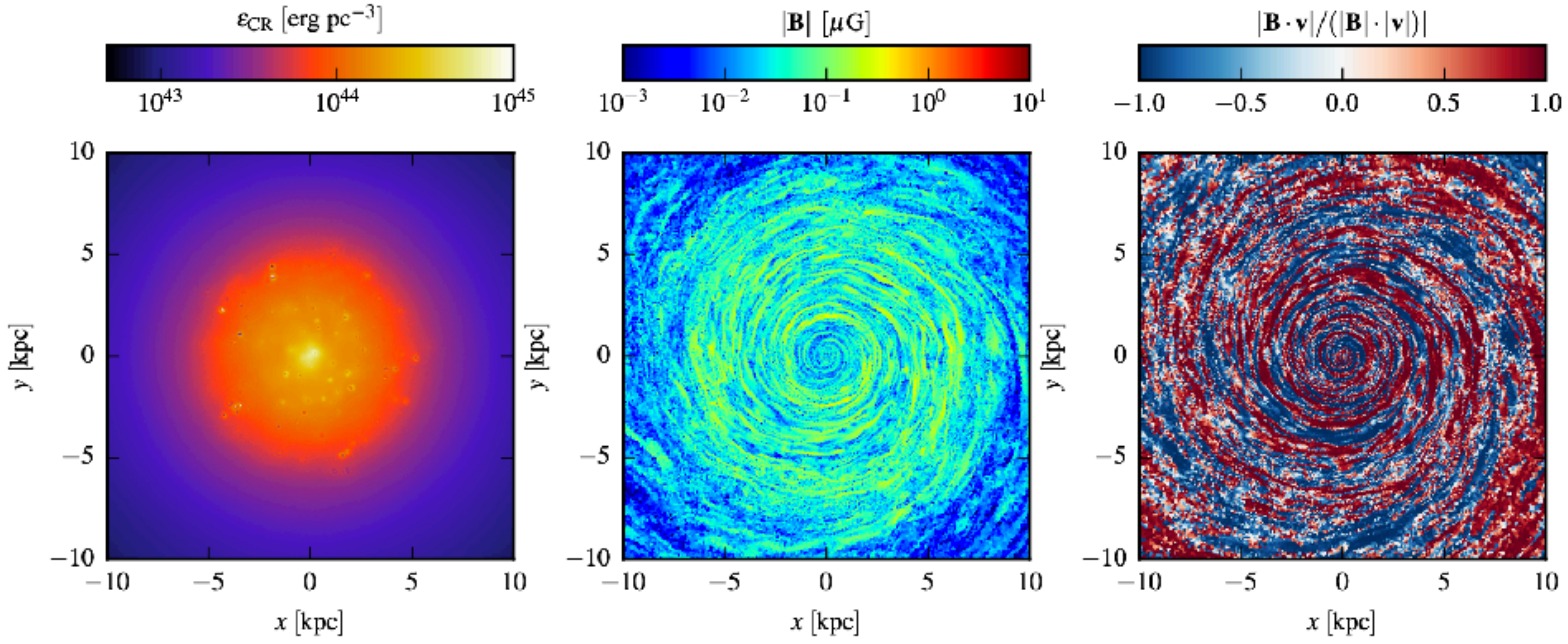
Isotropic vs. anisotropic diffusion

Pakmor et al. (2016)

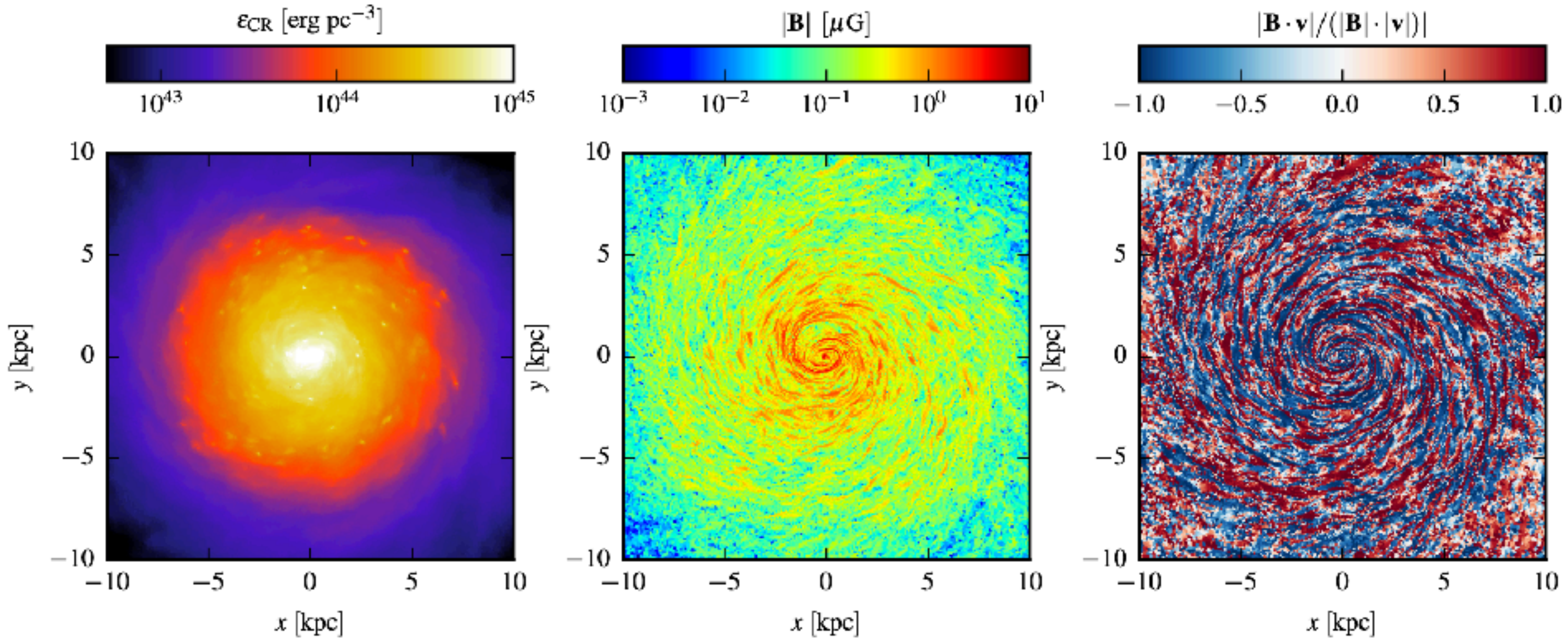
- isolated cooling halo
- simplified model for interstellar medium
- compare
  - isotropic diffusion
  - anisotropic diffusion along field lines
- impact on B-field strength
  enhance Parker loops



isotropic diffusion



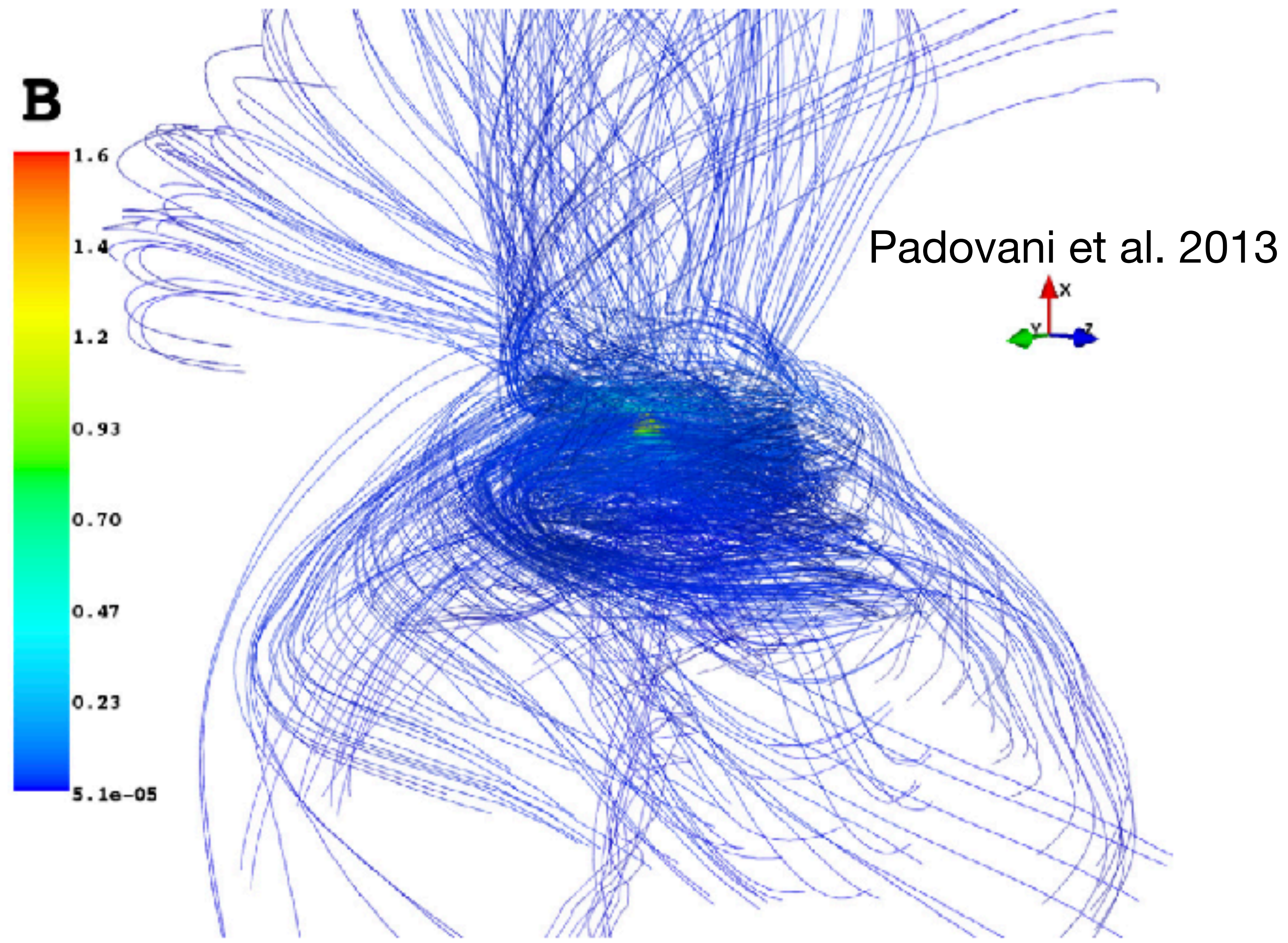
anisotropic diffusion along B



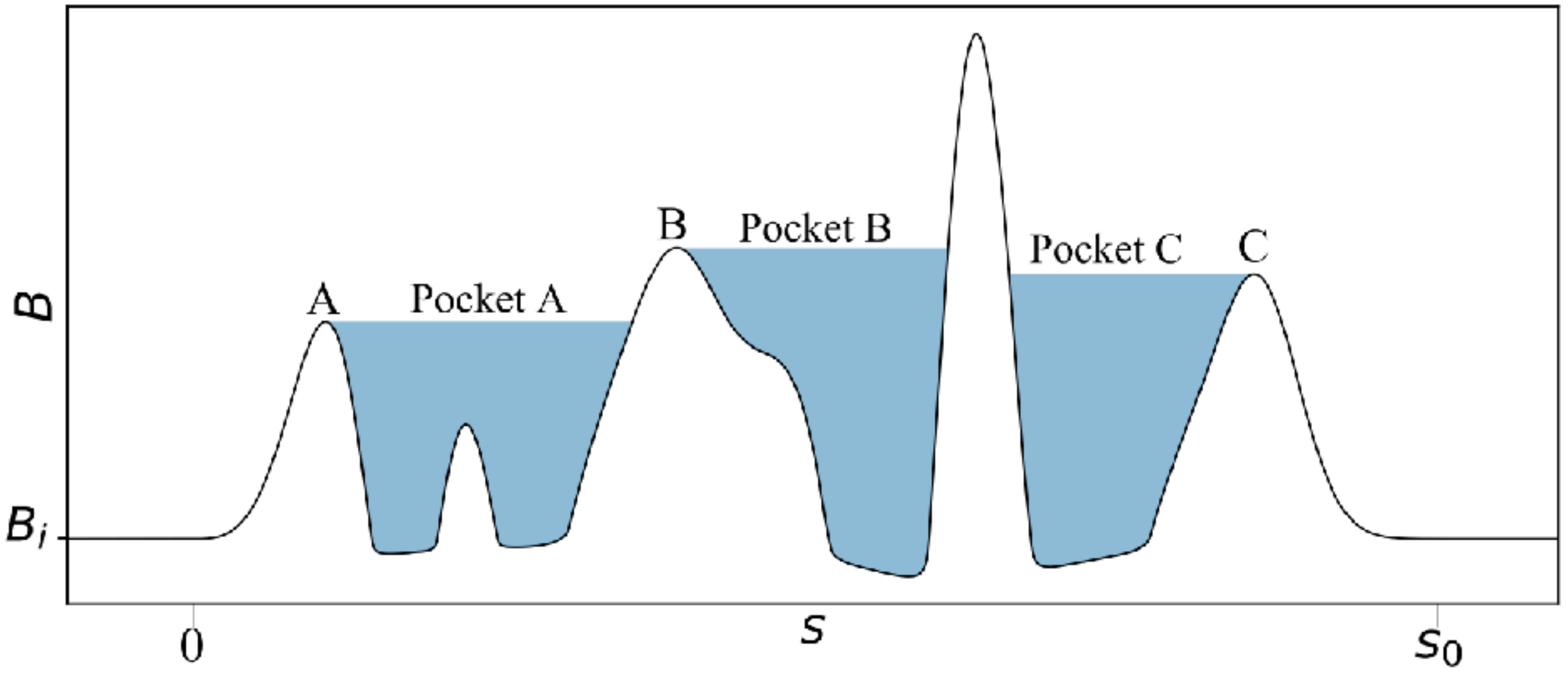
Simultions on small scales

focus on low energy CRs, ionisation

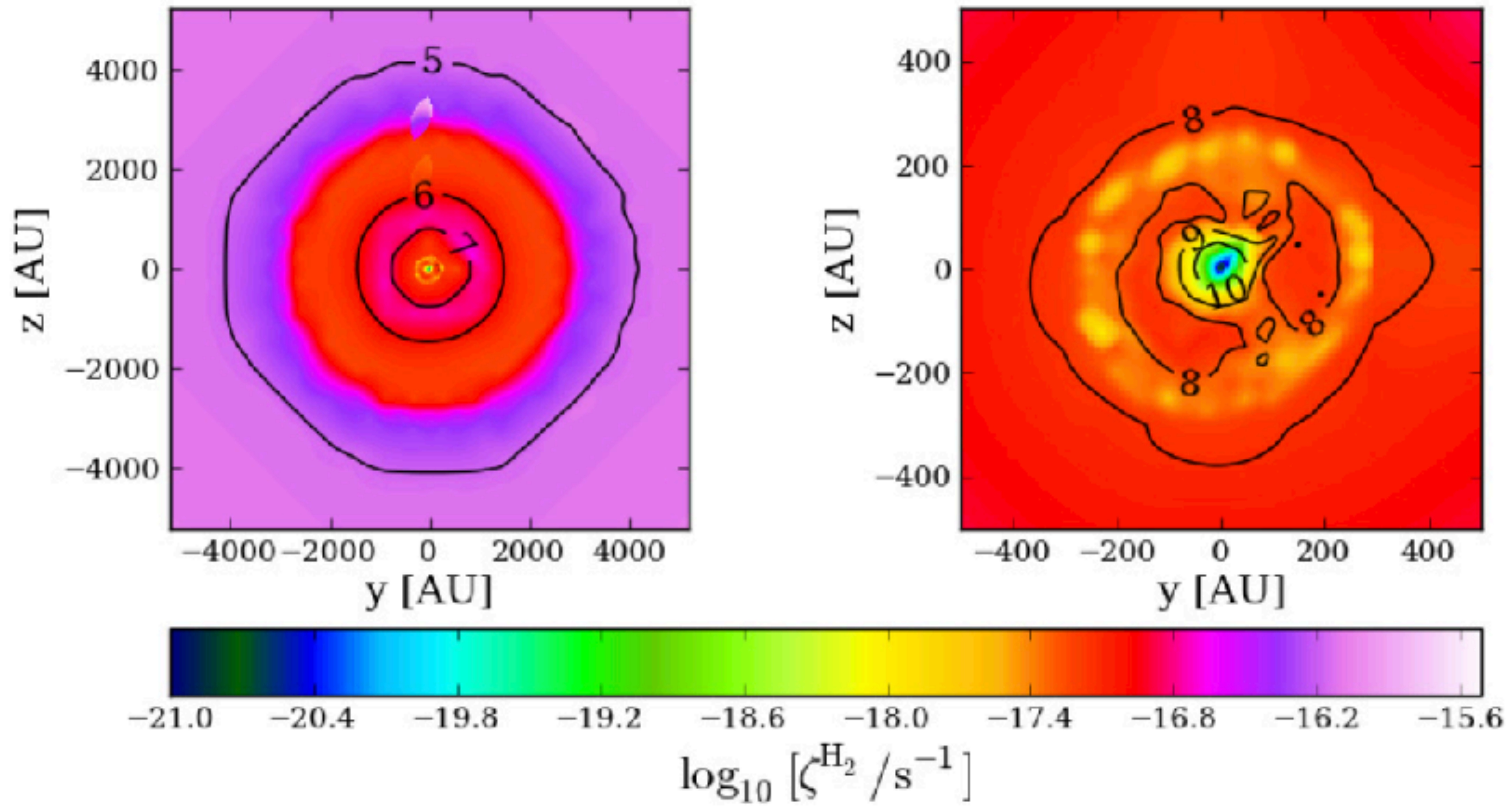
- CRs move fast, relatively uniform distribution of CR pressure
- low-energy CRs provide CR ionisation
- investigate CRs penetrating into cores



Padovani et al. 2013



Silvbee et al. 2018



New improvements I
CR transport / coupling

More accurate coupling CR ⇔ gas+B

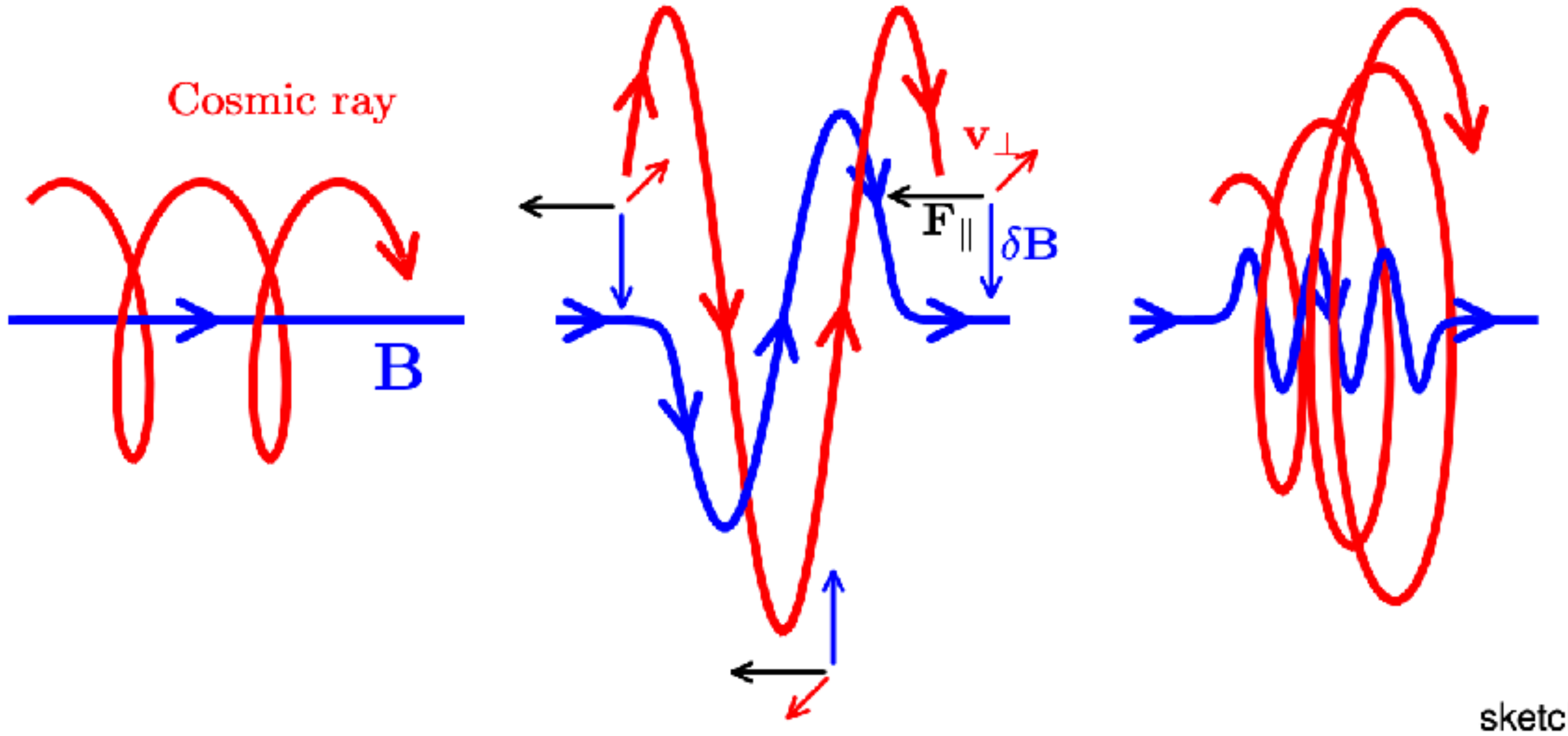
- CRs: back-reaction onto B-field, gyro-resonances
  ⇒ no simple diffusion
  ⇒ complex transport (E-transfer $E_\mathrm{cr} \leftrightarrow E_\mathrm{mag}$)
- Streaming instability (Kulsrud+1975)
- bulk of CRs streams with Alfvén speed, Alfvén heating
- equate growth and damping (Wiener+ 2013)

$$\boxed{\Gamma_\mathrm{growth} = \Gamma_\mathrm{NLLD} + \Gamma_\mathrm{in}}$$

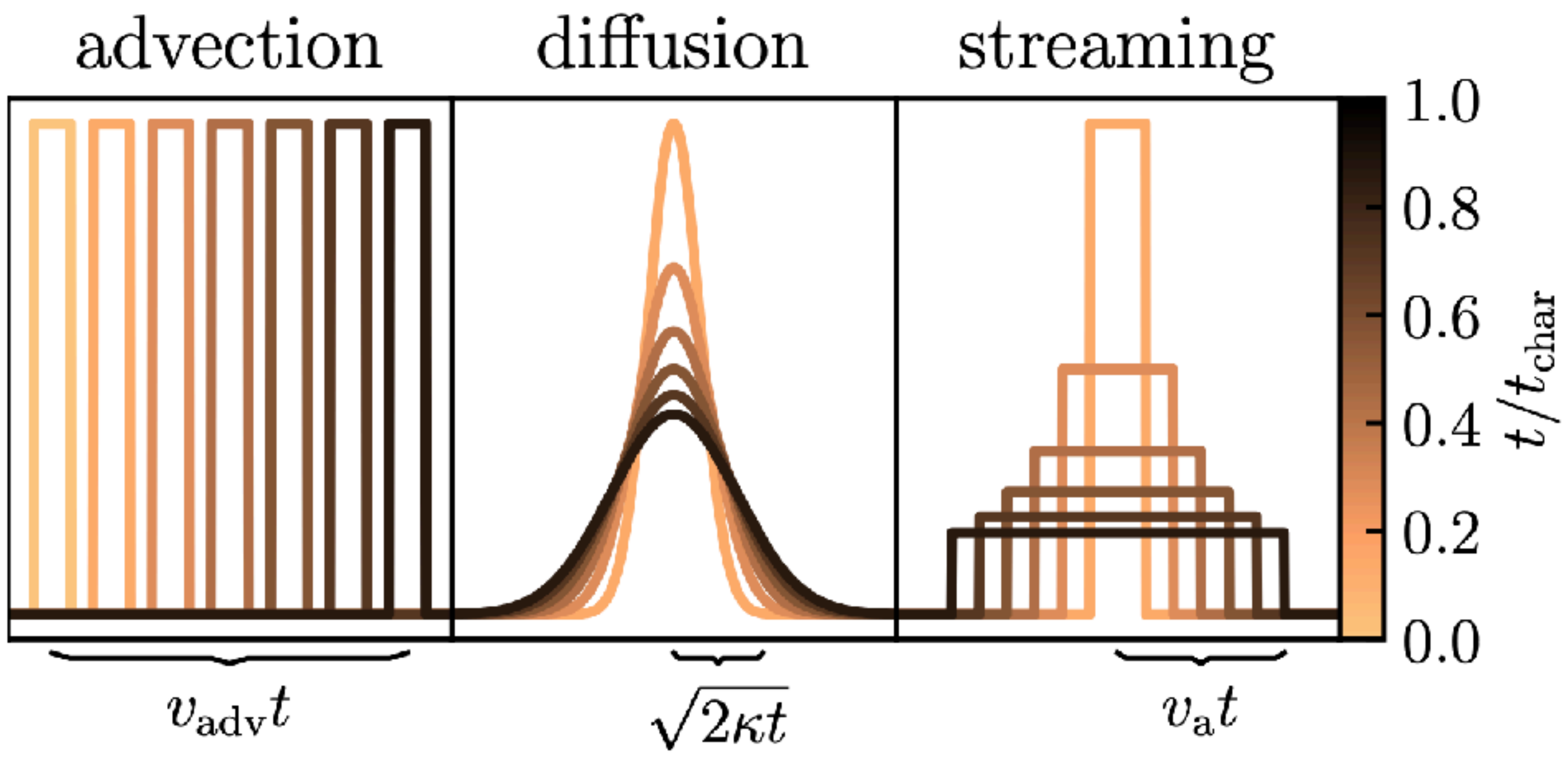
depend on effective turbulence model, effective B-field $\delta B/B$, fixed B spectrum

$$\Rightarrow H = -\mathbf{v}_\mathrm{A} \cdot \nabla P_\mathrm{cr}$$

- new self-consistent PIC models (Shalaby et al. 2021/2023)
- ⇒ many unknowns concerning
  - transport speeds
  - energy exchange



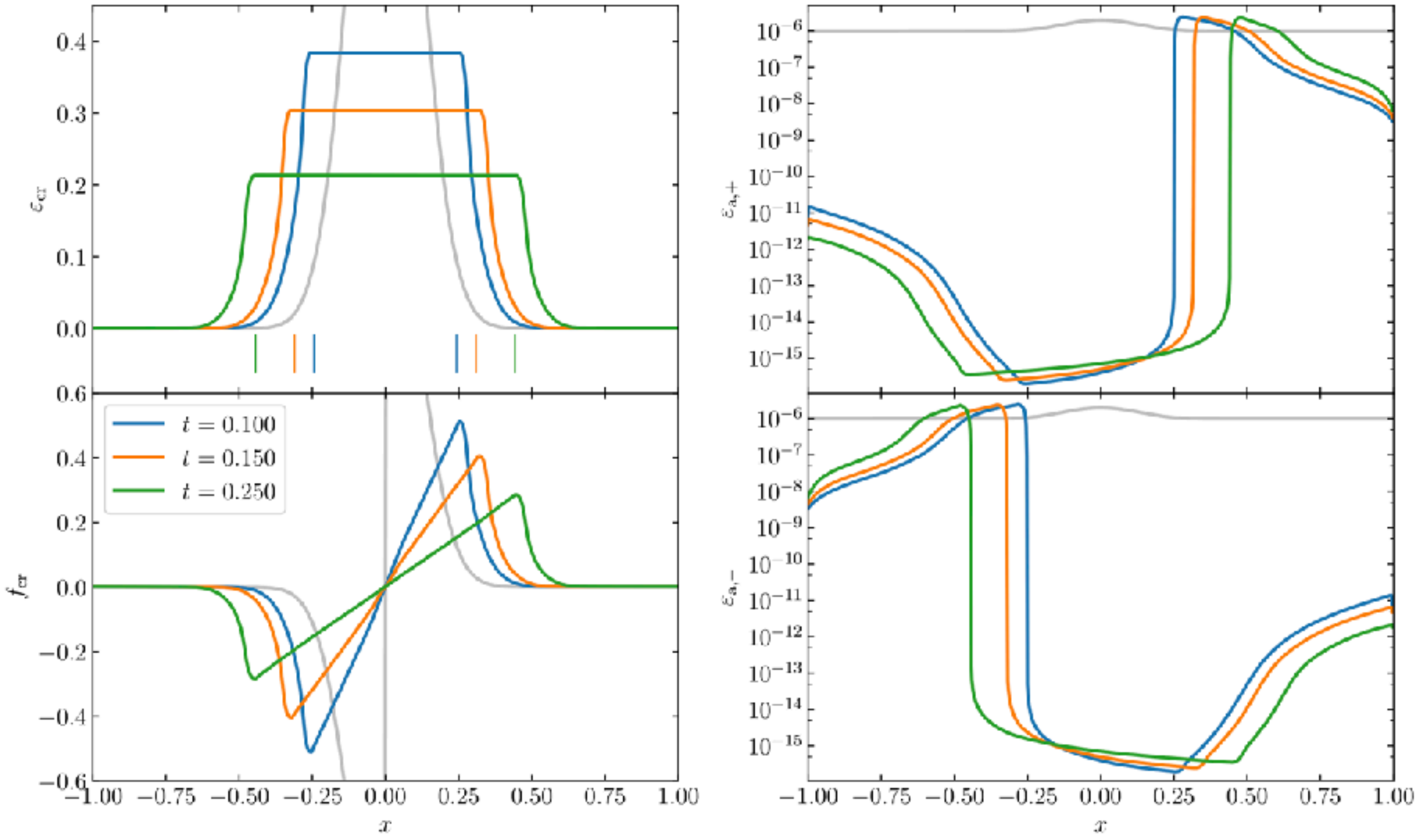
sketch: Jacob

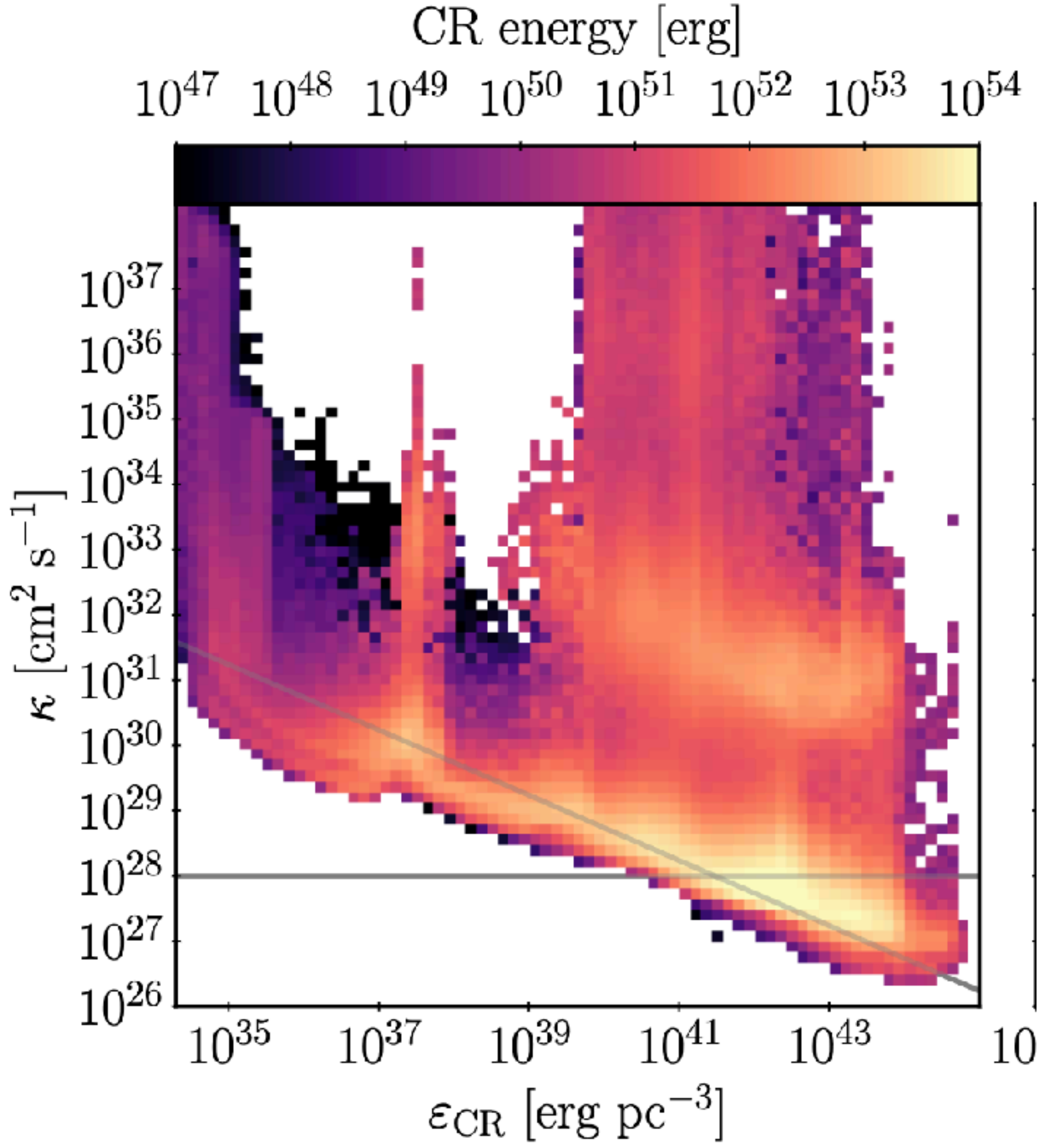


Thomas, CP, Enßlin (2020)

More accurate coupling CR ⇔ gas+B

- new approach in fluid approximation
- Thomas+ 2019,2021,2022:
  - follow CR energy AND energy in magnetic waves
  - averaged over p, given fixed spectrum



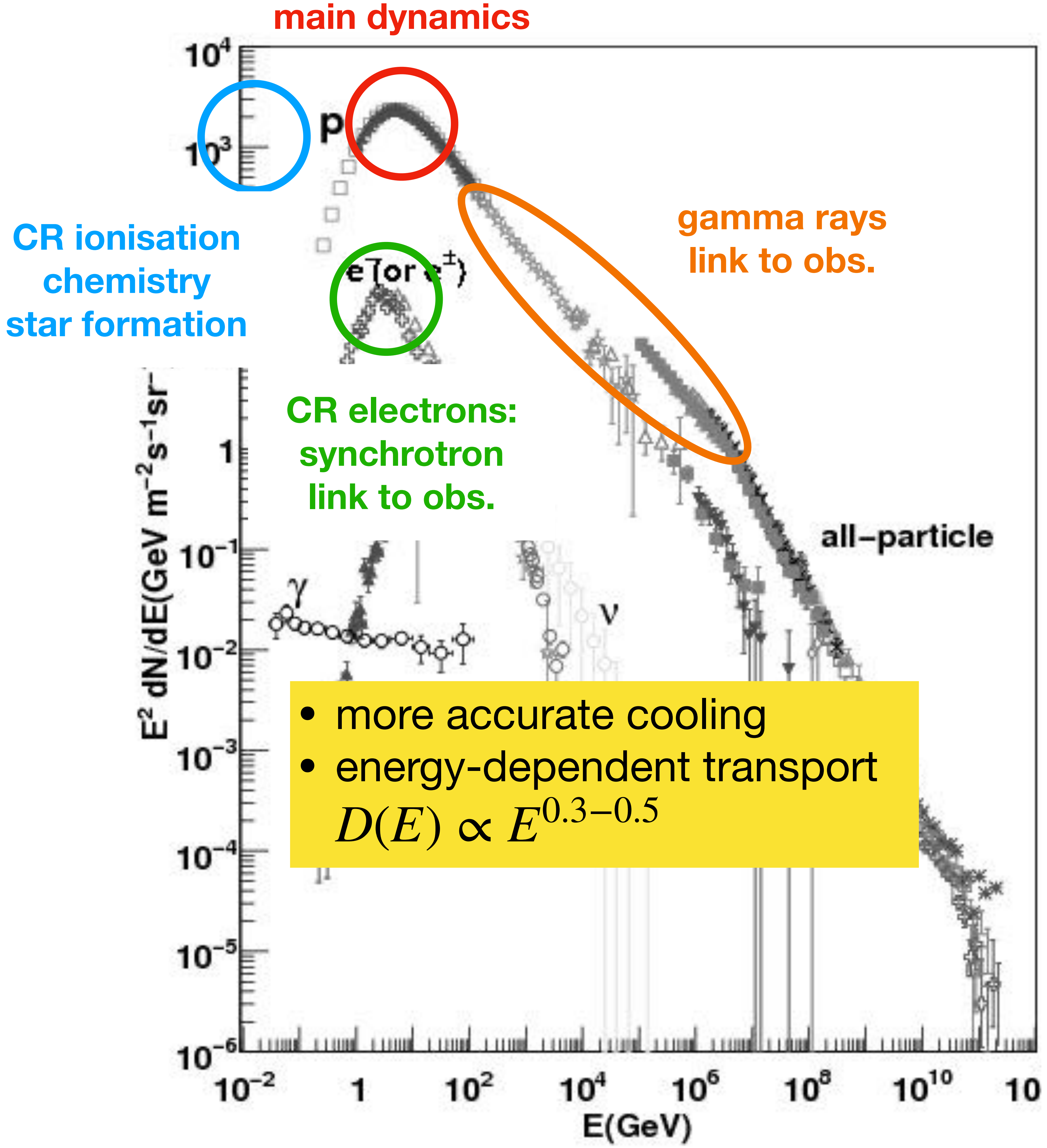


Thomas et al. 2022

New improvements II
Spectral MHD models

Extension to spectral code

just total energy is not enough



main dynamics

CR ionisation
chemistry
star formation

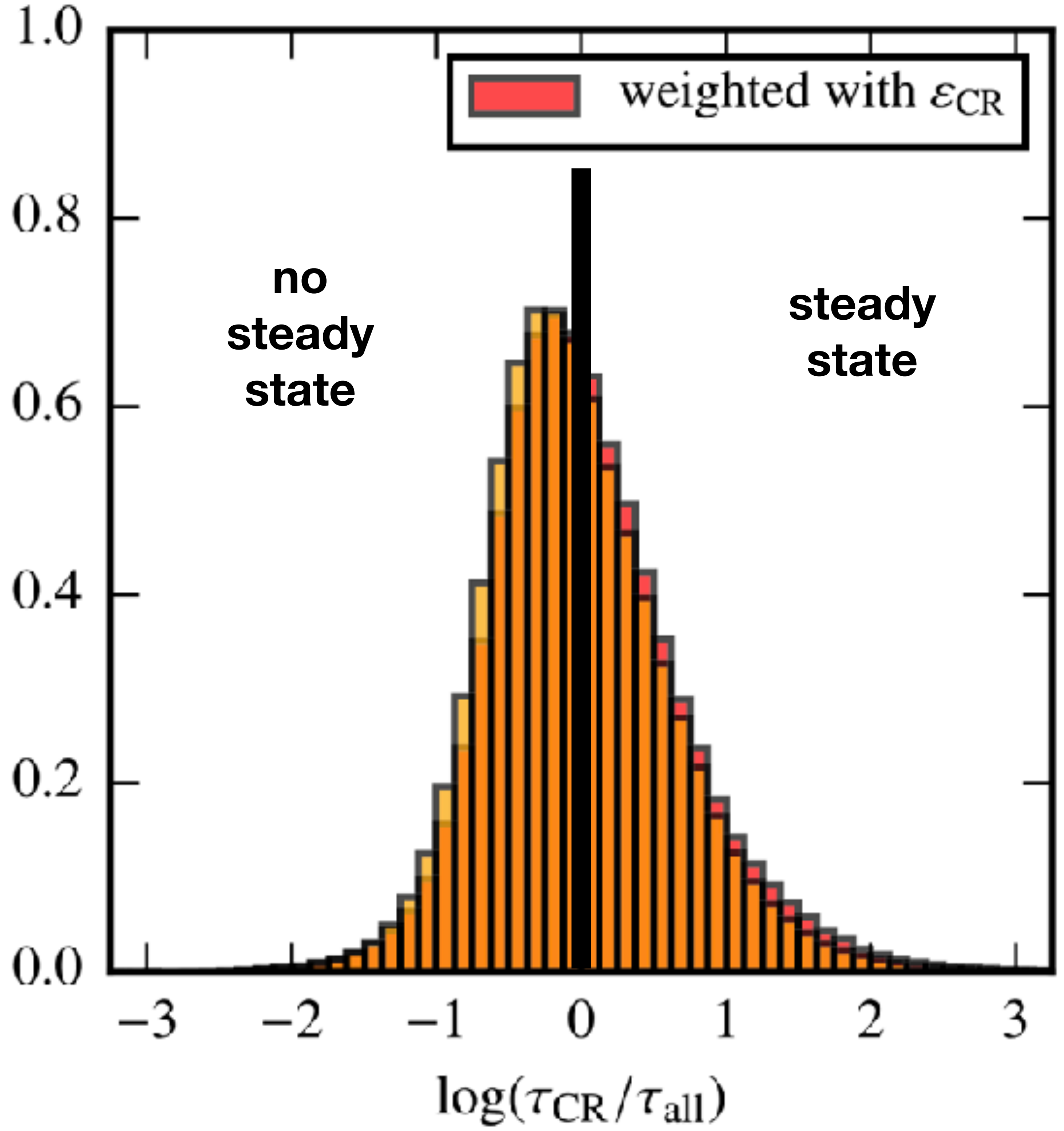
CR electrons:
synchrotron
link to obs.

gamma rays
link to obs.

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

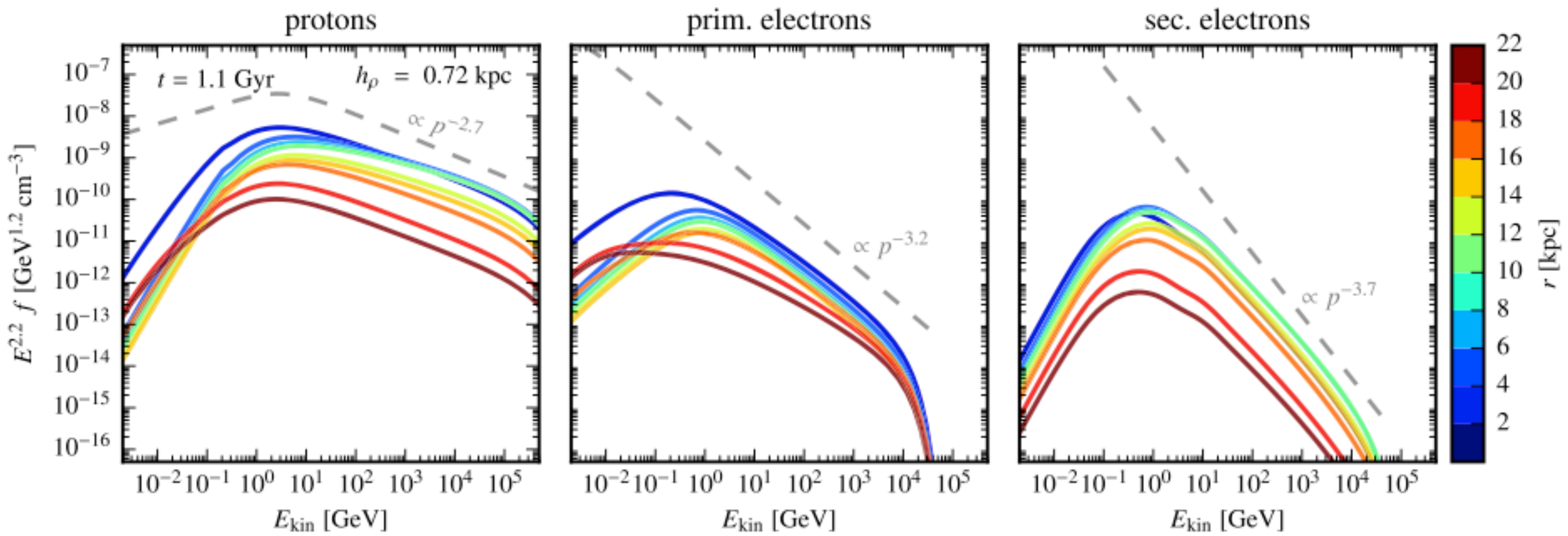
- in large fraction of galaxy no steady state
- spectral variations are important

Werhahn et al. 2021



no
steady
state

steady
state

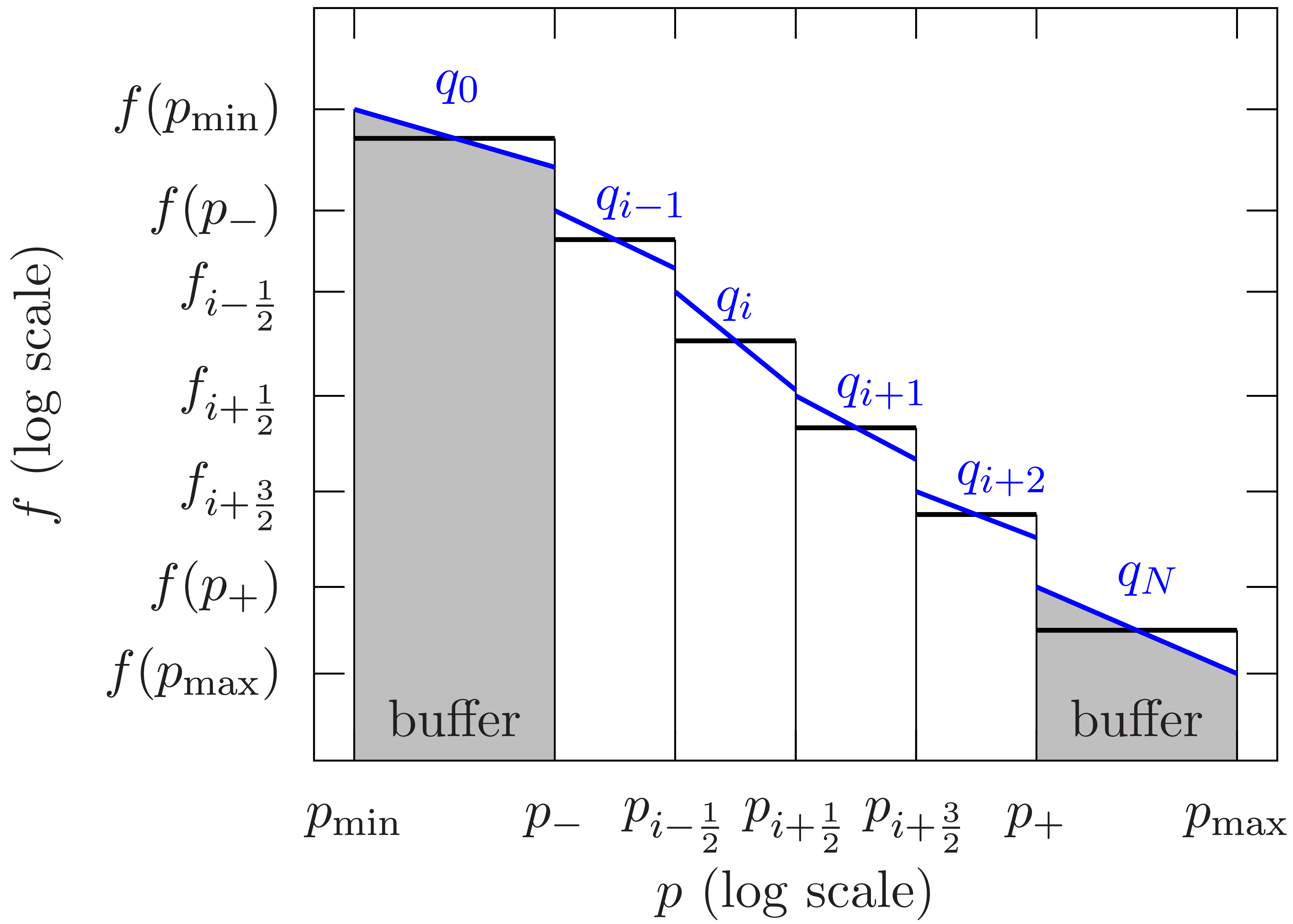


Multibin CR solver

basic idea

- full spectrum in every cell: low N_{spec}
- solve Fokker-Planck equation
- large dynamic range:
  use piecewise powerlaws
  two degrees of freedom per bin
- couple to MHD via two moments, n and e

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



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

Miniati 2001, Jones&Kand 2005, Yang et al. 2017, Girichidis et al. 2020,2022, Ogrodnik et al. 2021

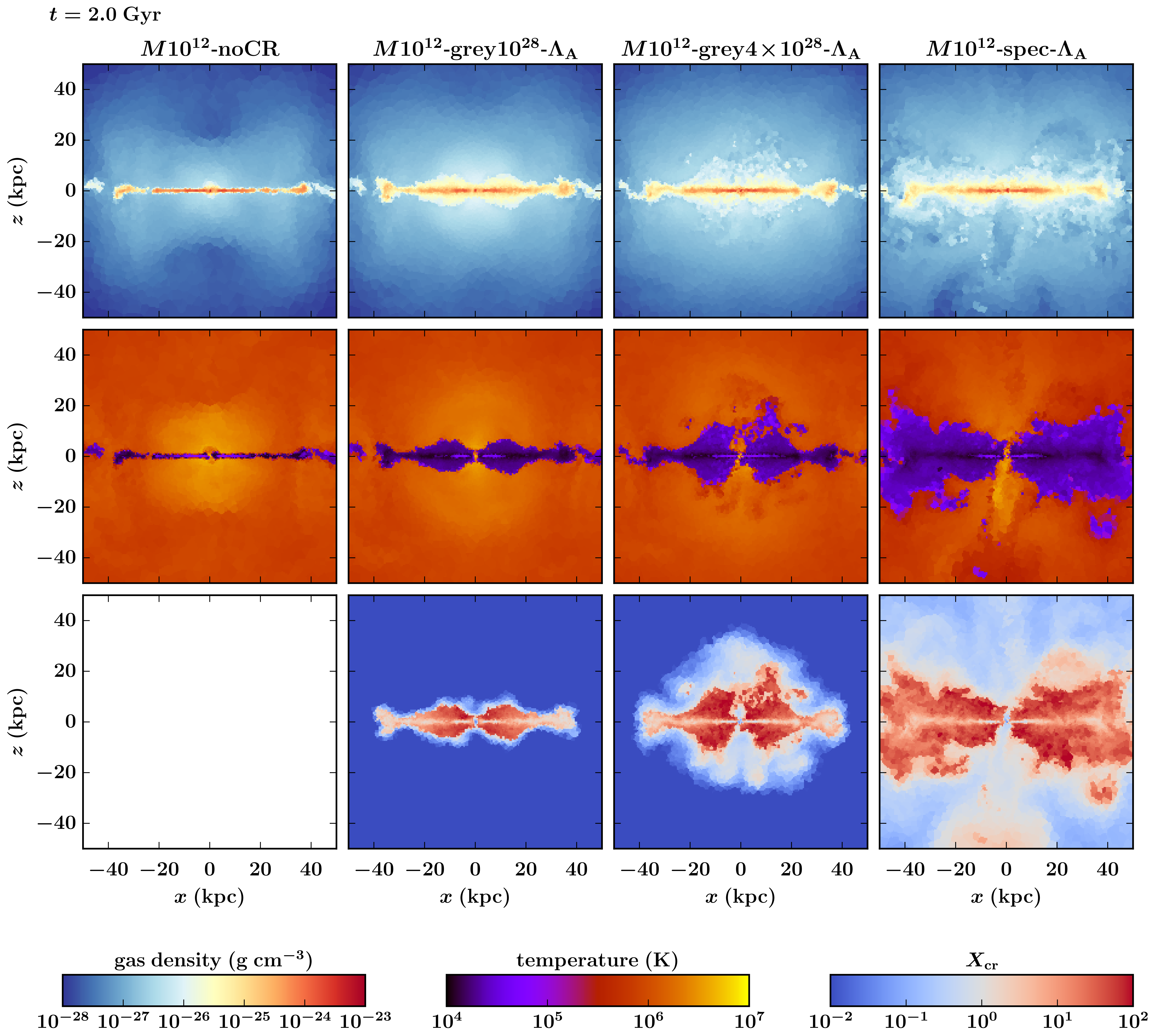
Application to isolated galaxies

Girichidis et al. 2022, 2023

temperature and CR content

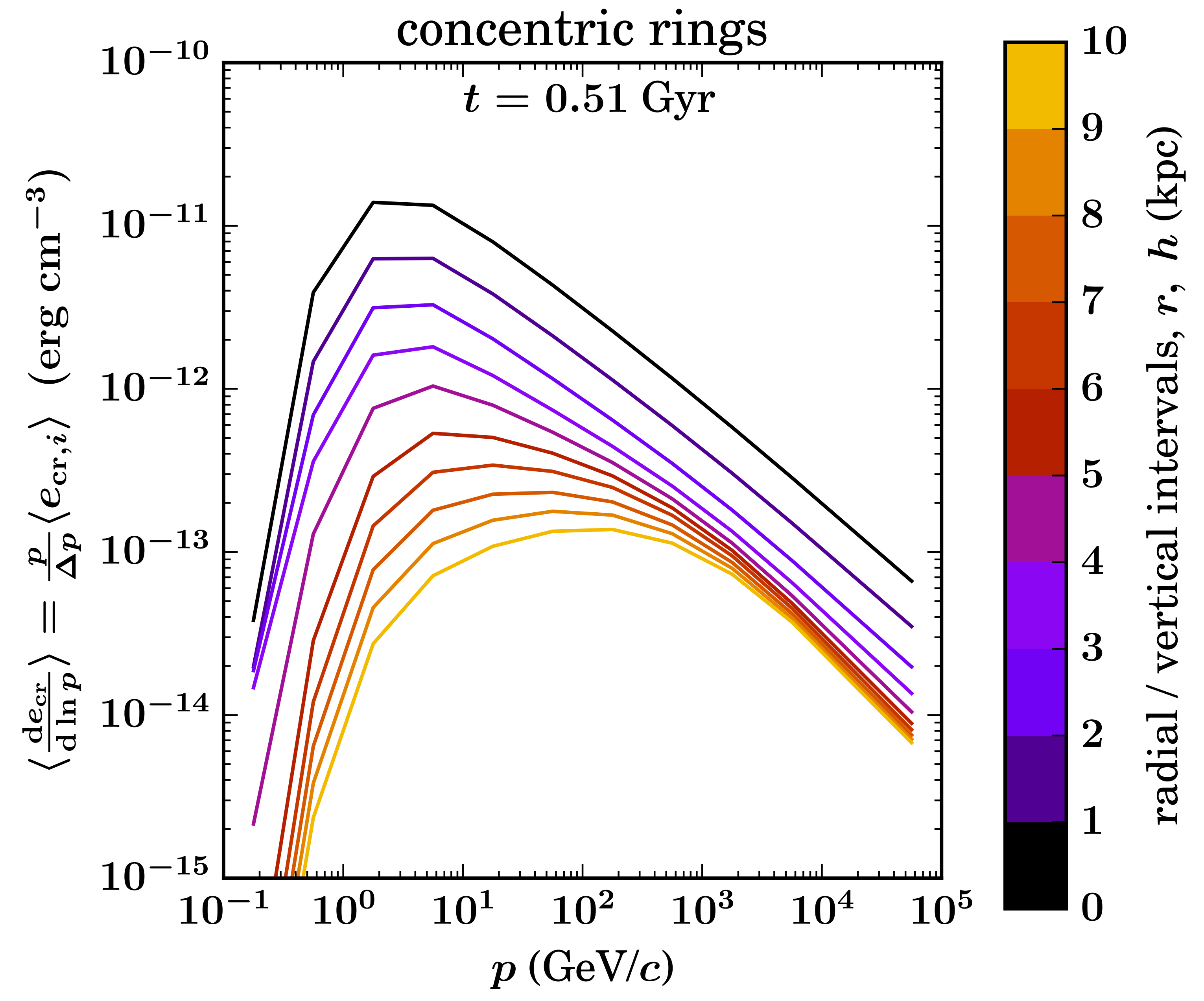
- isolated halo,
  rotating gas cloud
- Arepo
  (Springel '10, Weinberger+ '19)
- CRs (Pakmor+'16, Pfrommer+'17)
- spectral CRs (Girichidis+ '20)
- CRs: 10% of SN energy

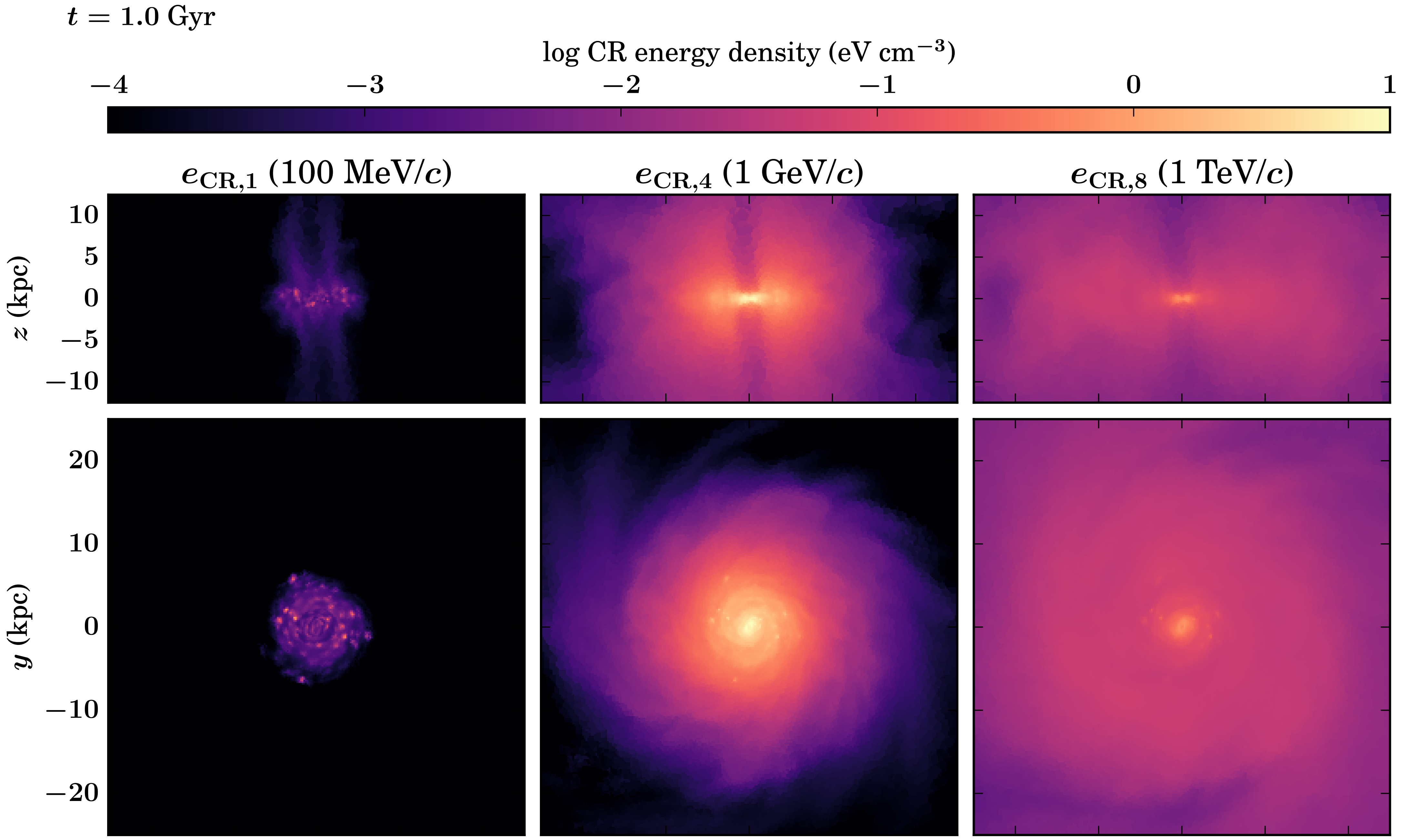
- high-E CRs escape faster
- larger region of cold CGM
  impact on gal. fountain
- larger region with CR dominated pressure

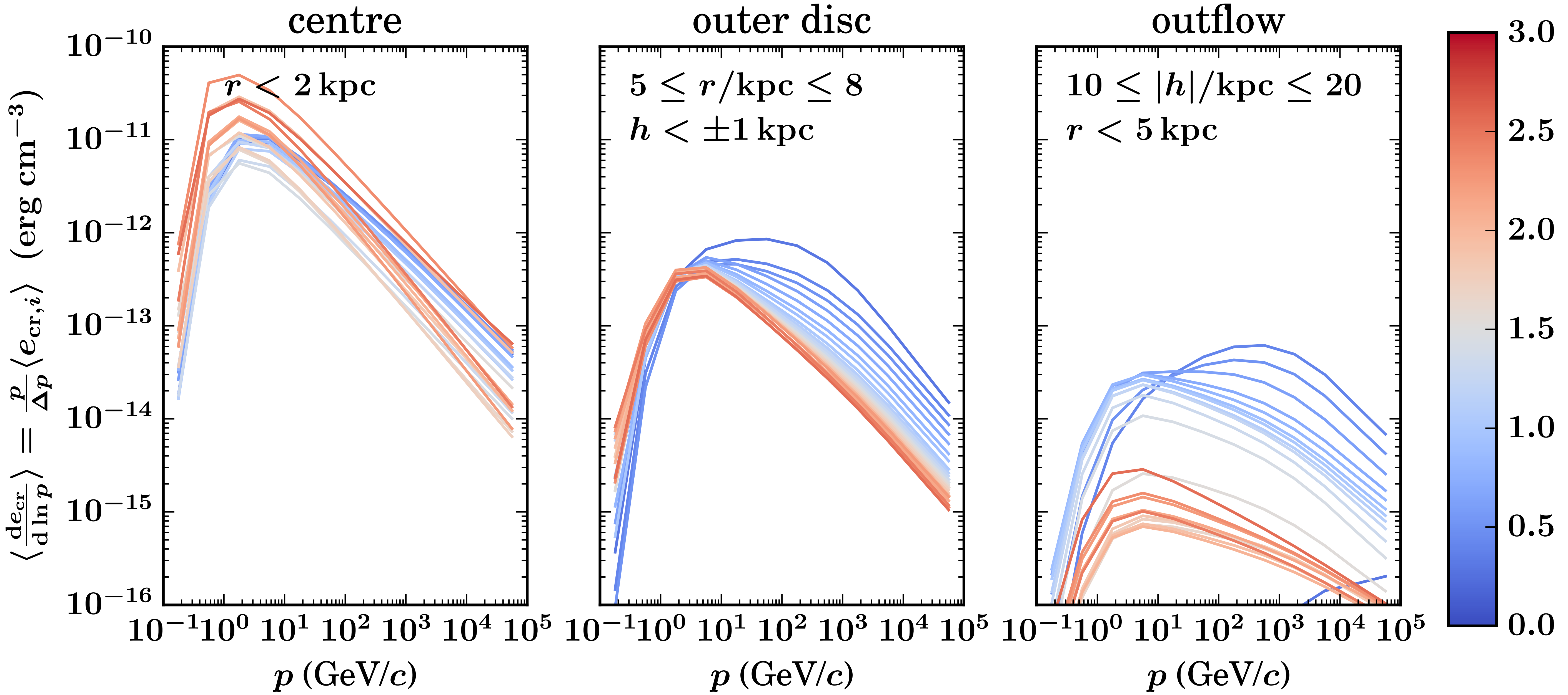


Spectral shapes

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





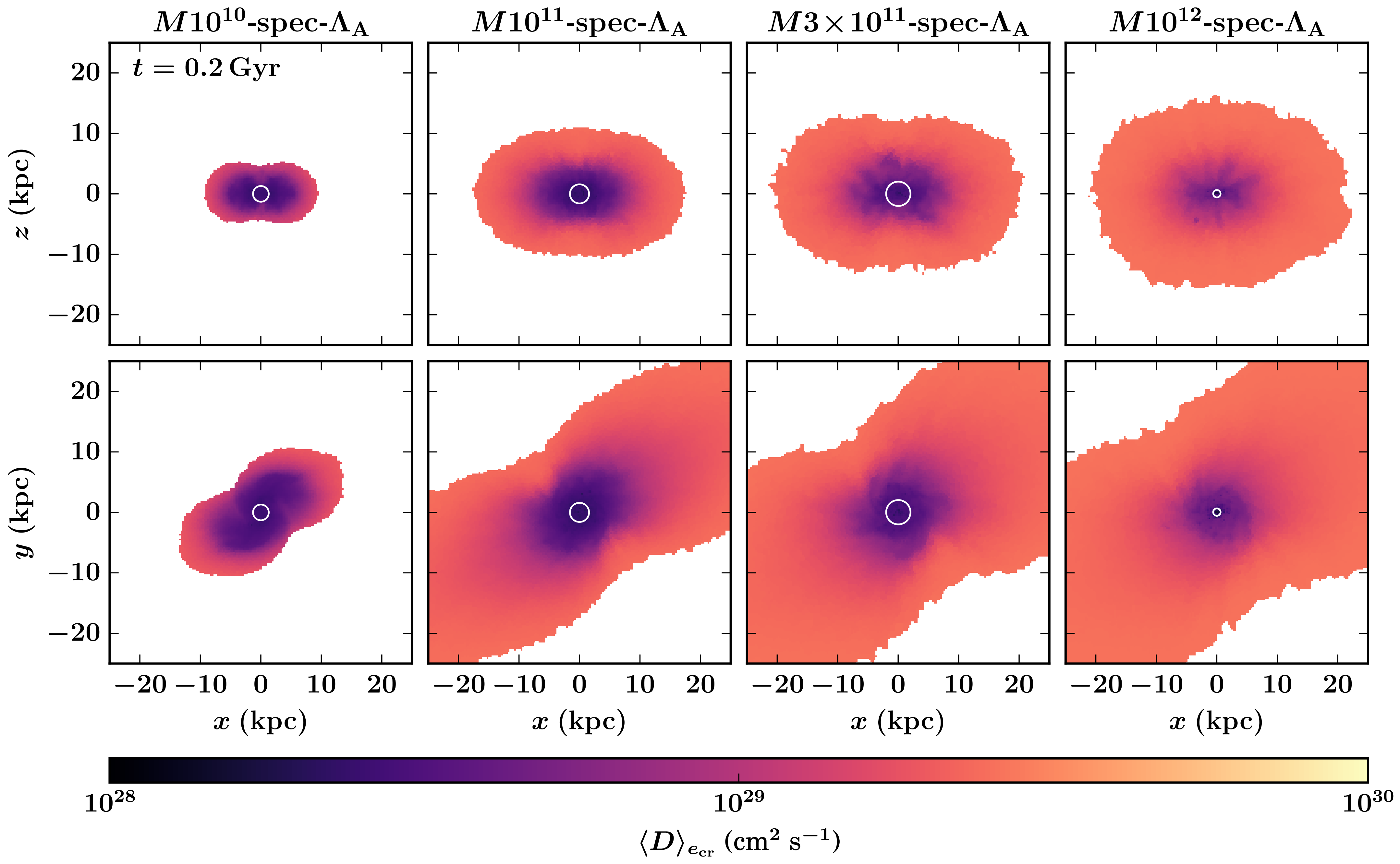


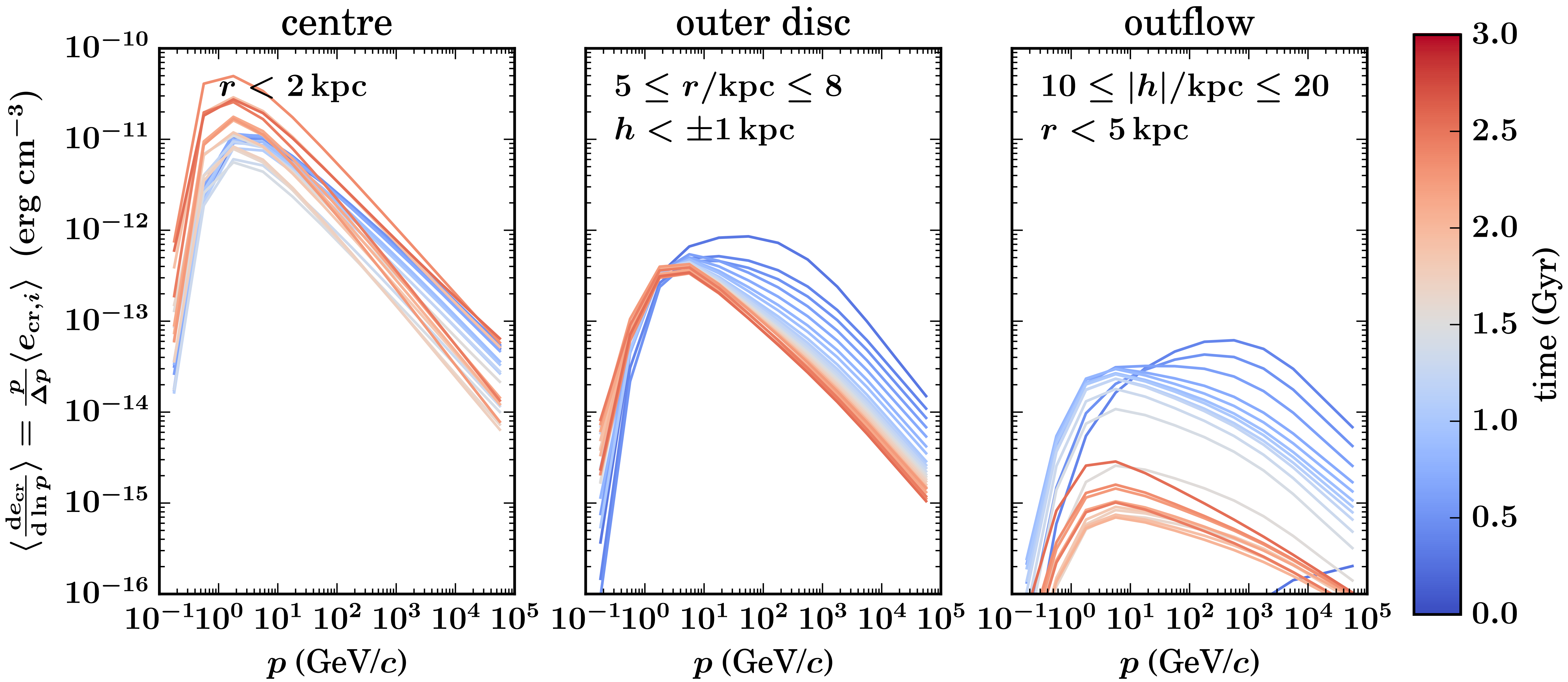
Girichidis et al. 2022

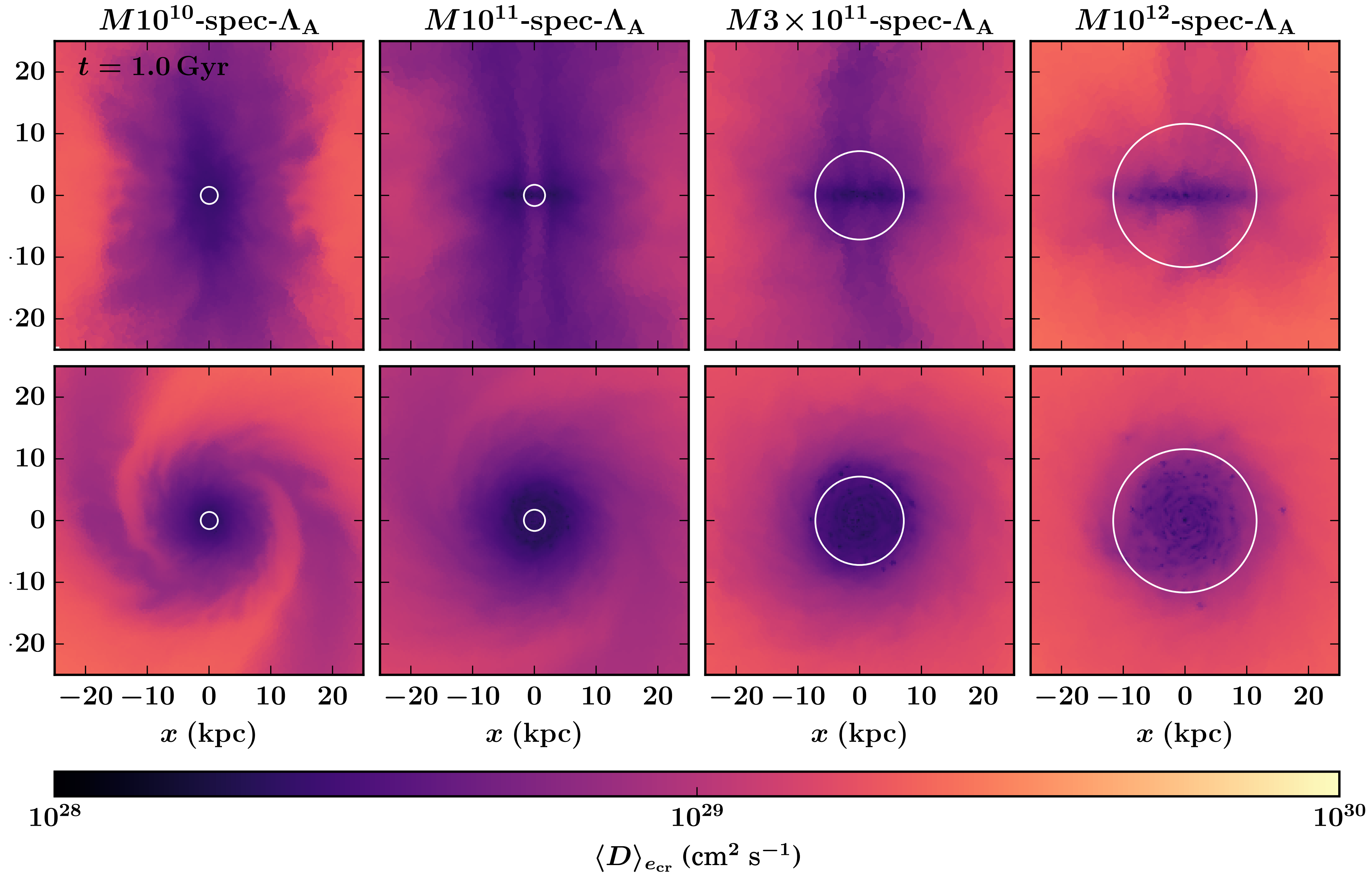
Effective diffusion speed

- $D(E) \propto E^s,\ s = 0.3 - 0.6$
- effective net diffusion of bulk of CR energy

$$\langle D \rangle = \frac{1}{e_\mathrm{cr}} \int_{p_\mathrm{min}}^{p_\mathrm{max}} \frac{\partial e_\mathrm{cr}}{\partial p} D(p)\mathrm{d}p$$

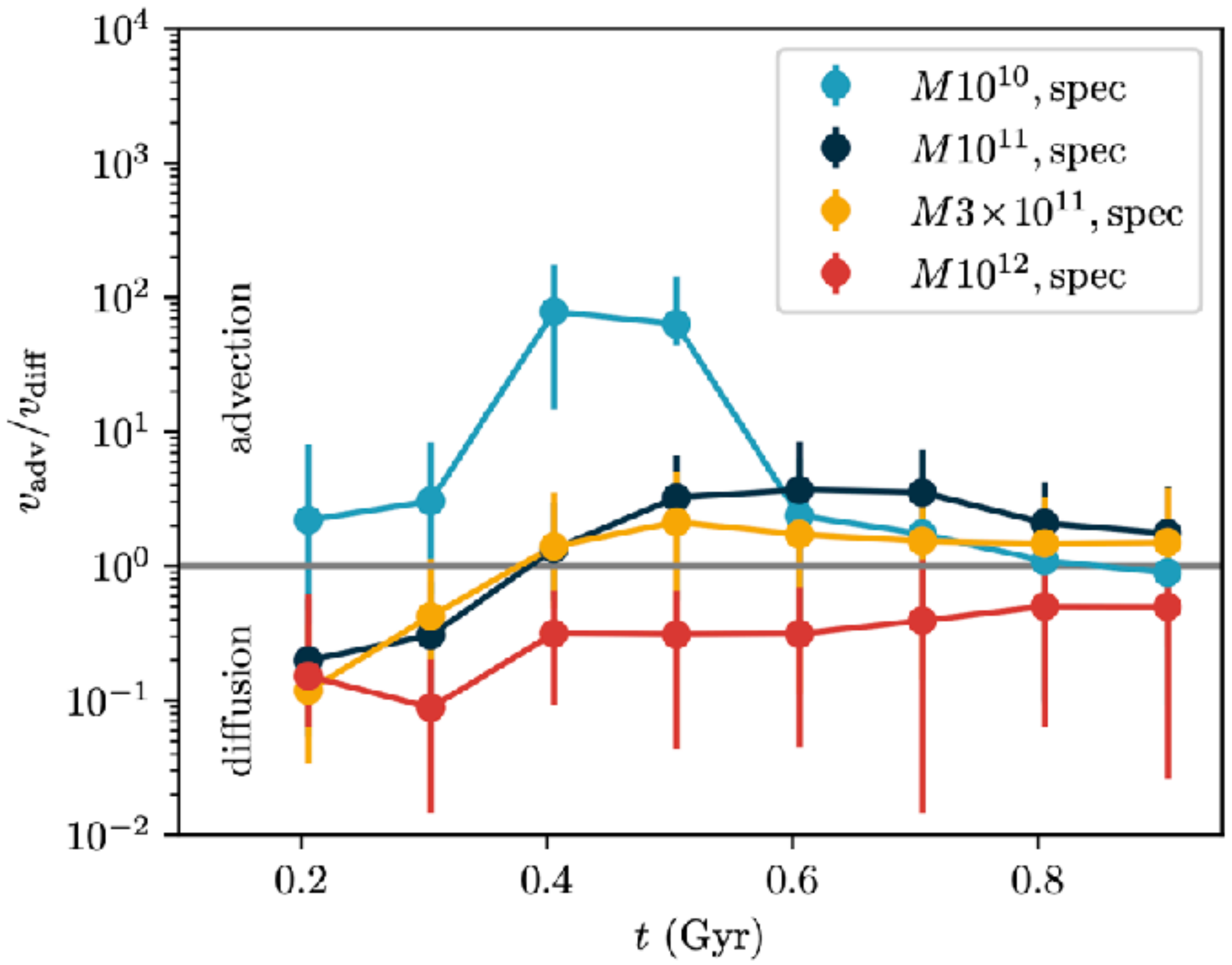


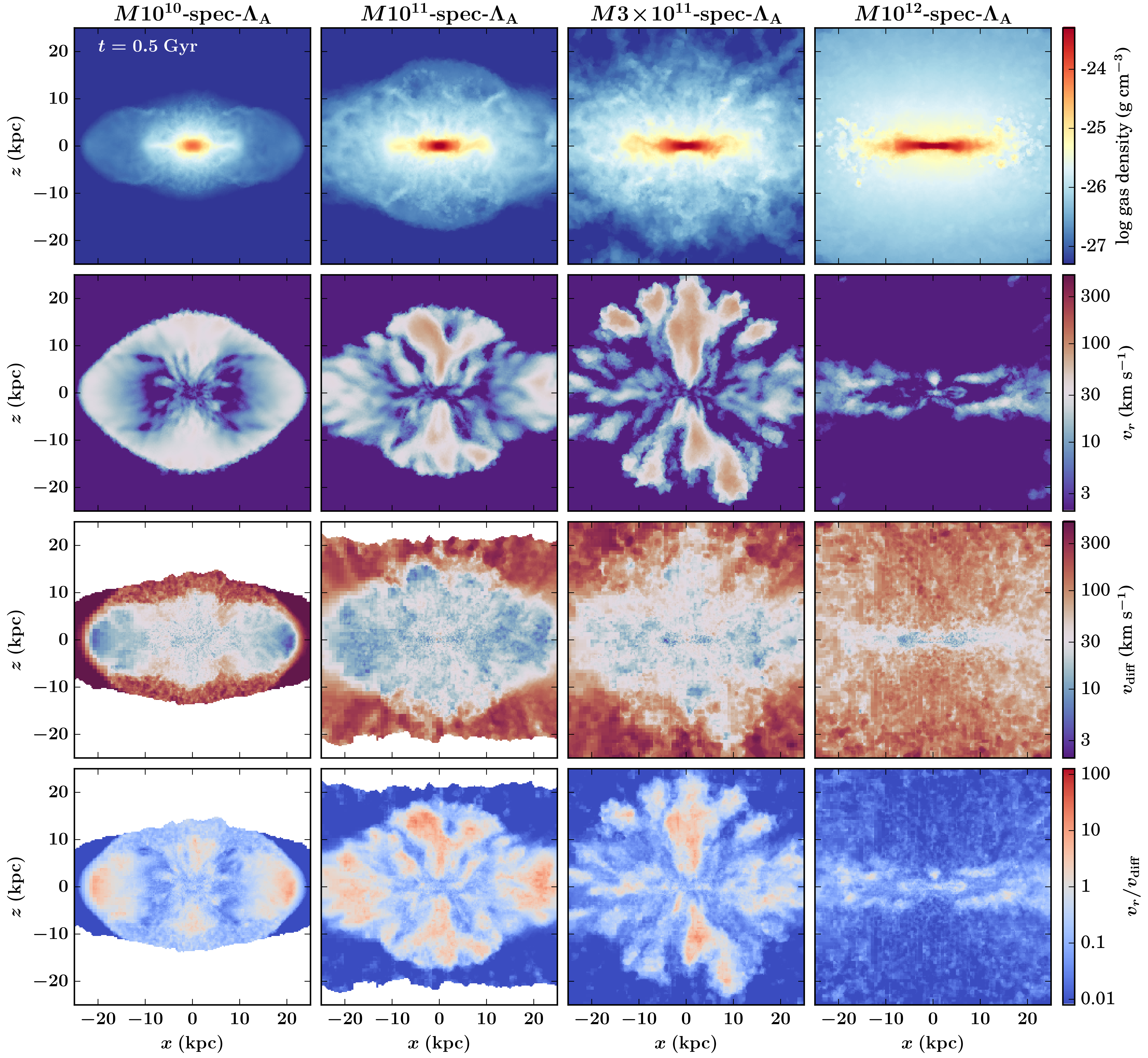




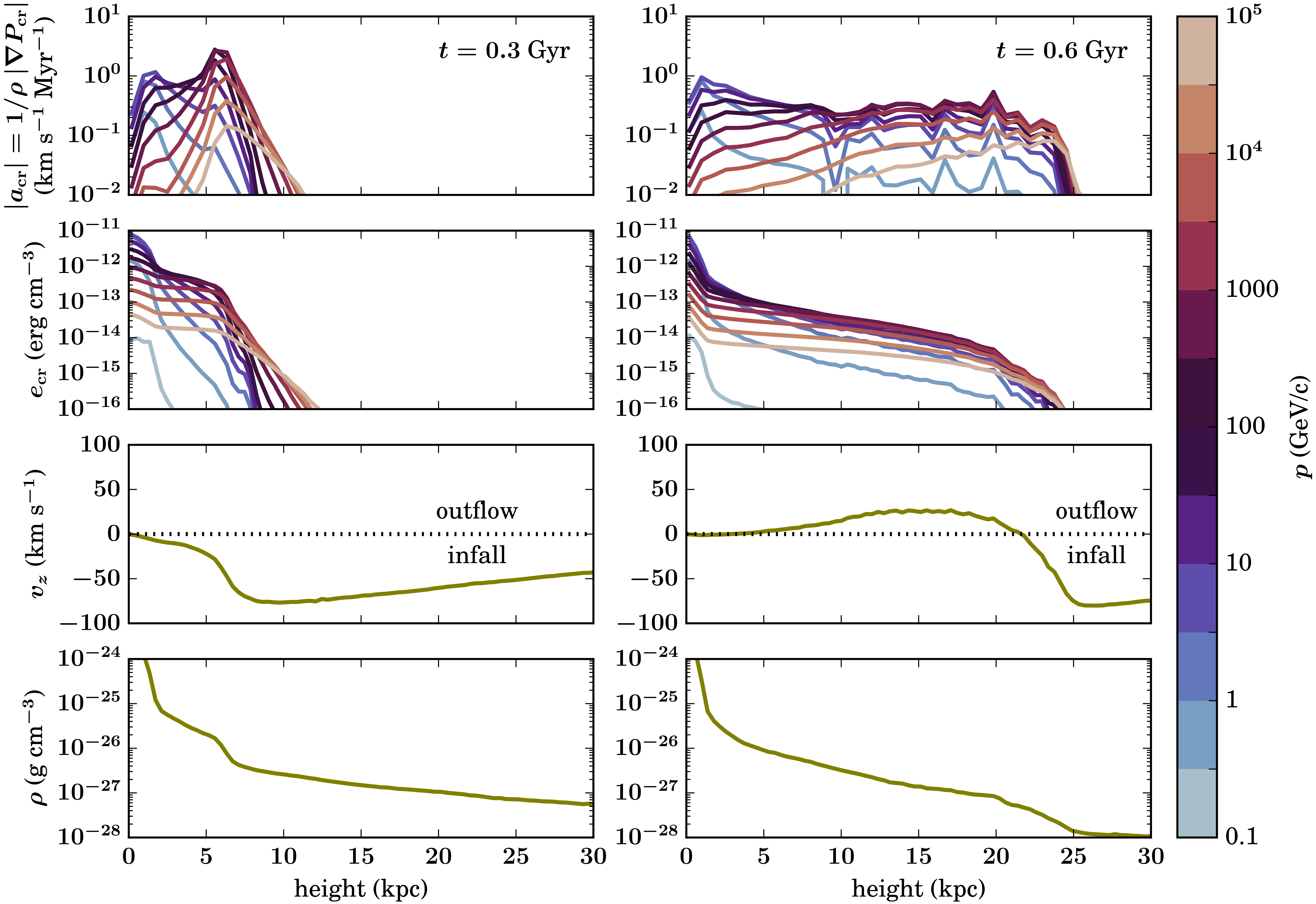
Advection vs. diffusion

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

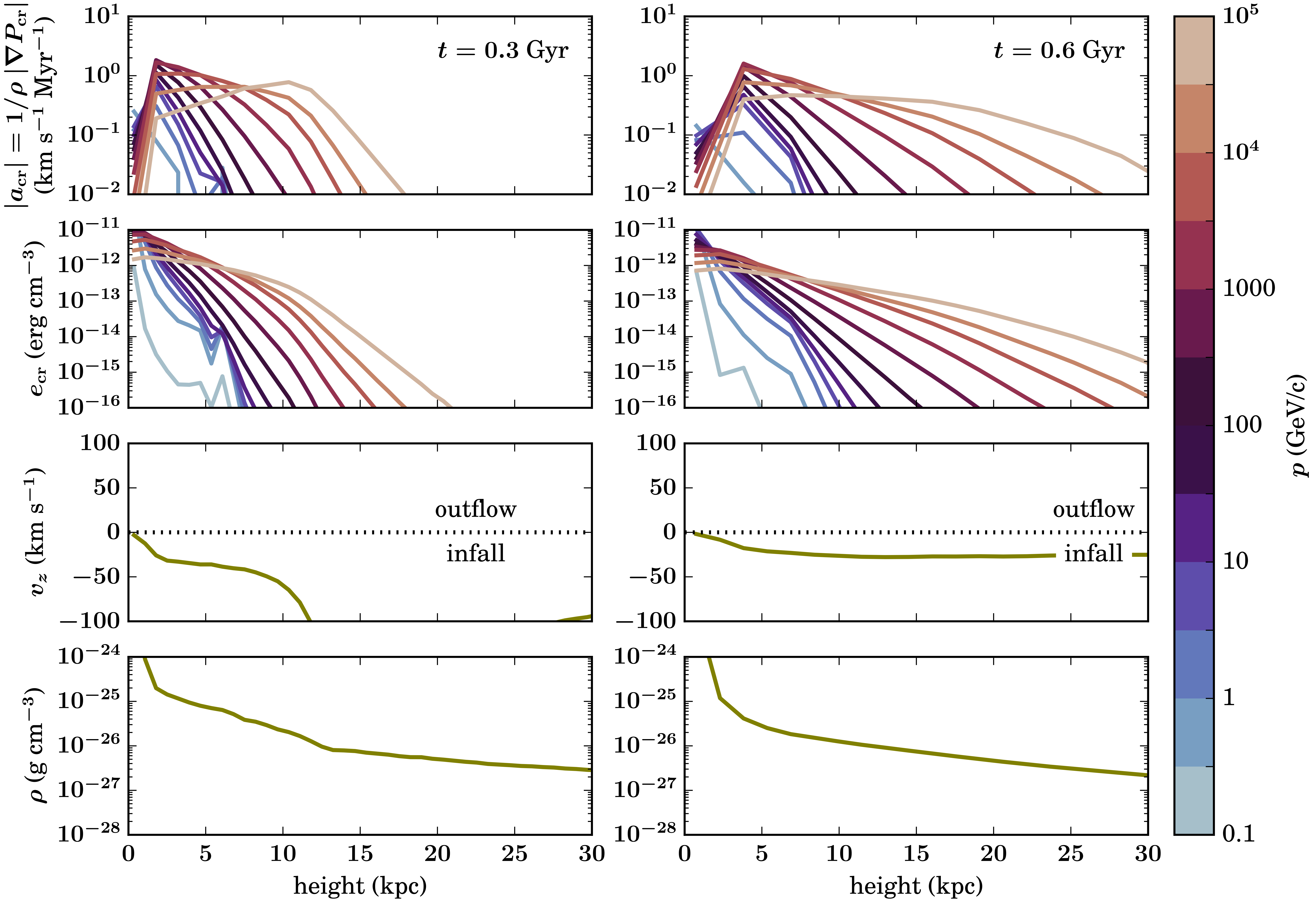




Advection vs. diffusion in spectra (dwarf)

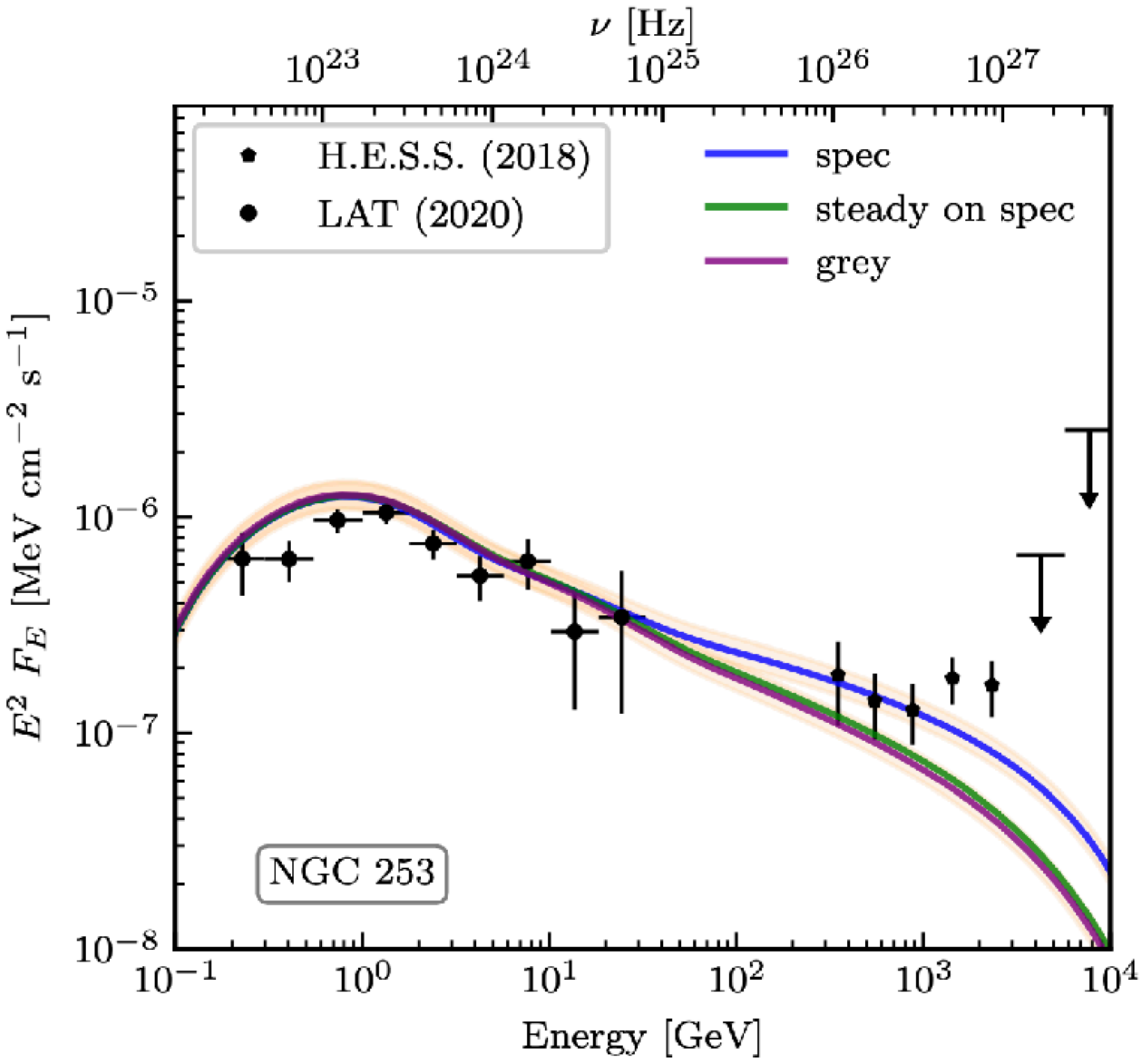


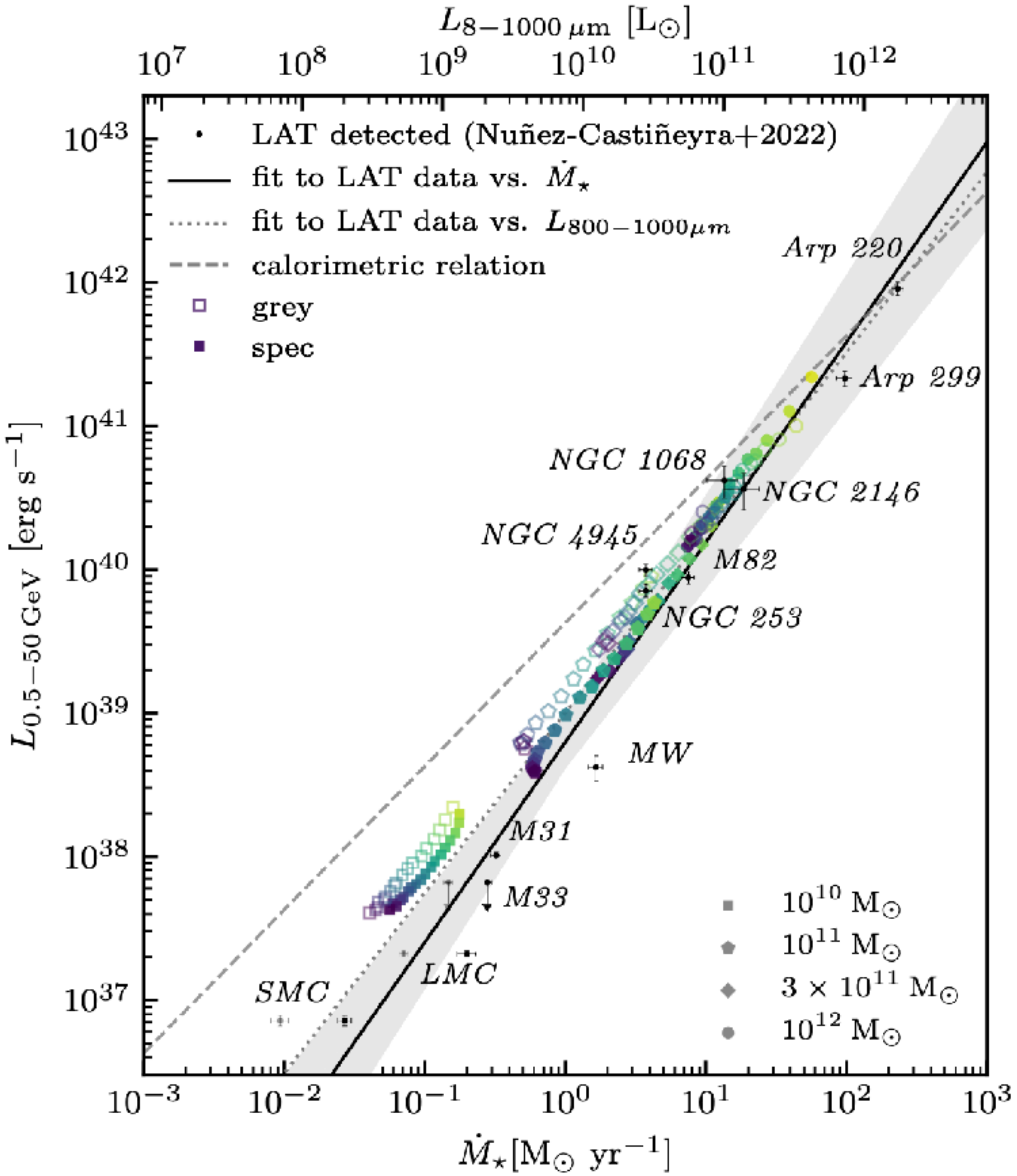
Advection vs. diffusion in spectra (MW)



Connection to gamma rays

Werhahn et al. 2023

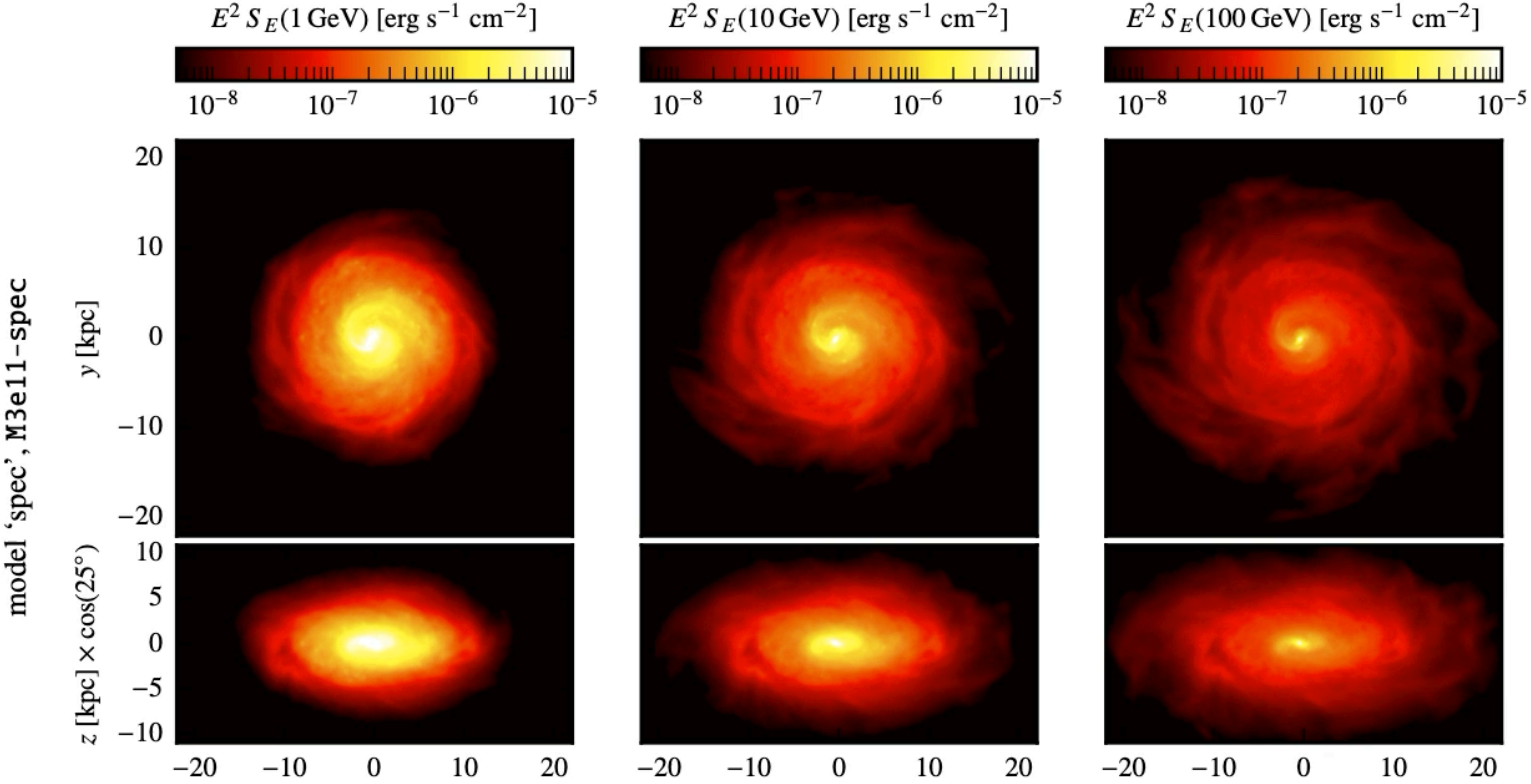




- spectral model: better fit to spectra and SFR-γ luminosity

Gamma rays II

- Steady state vs. full spectrum (Werhahn+ 2021abc, 2023)



Take home points

- CRs are relativistic particles
- most energy in protons with GeV energies
- accelerated mostly in SN remnants
- CR energy comparable to other energies in ISM
  - CR drive outflows from disk (comparable to star formation rate)
- big questions in CR physics
  - transport details (diffusion/streaming, transport speed)
  - details of the spectrum (high-E ⇔ γ-rays, low-E ⇔ ionisation rate)