Cosmic ray feedback and magnetic dynamos in the interstellar medium

Christoph Pfrommer[1]

in collaboration with

PhD students: L. Jlassi[1], R. Lemmerz[1], L. Tevlin[1], M. Weber[1], J. Whittingham[1]
Postdocs: T. Berlok[2], V. Bresci[1], L. M. Perrone[1], M. Shalaby[1], M. Sparre[3,1], T. Thomas[1], **M. Werhahn**[4]
Faculty: E. Puchwein[1], R. Pakmor[4], V. Springel[4], T. Enßlin[4]

[1]AIP Potsdam, [2]Niels Bohr Inst., [3]U of Potsdam, [4]MPA Garching

Annual meeting of the German Astronomical Society, Berlin, 2023

Origin and growth of magnetic fields

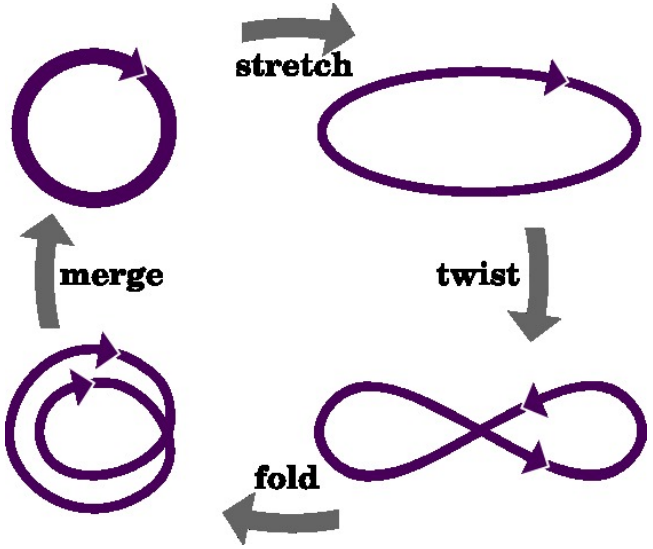
The general picture:

- ***Origin.*** Magnetic fields are generated by 1. electric currents sourced by a phase transition in the early universe or 2. by the Biermann battery

Origin and growth of magnetic fields

The general picture:

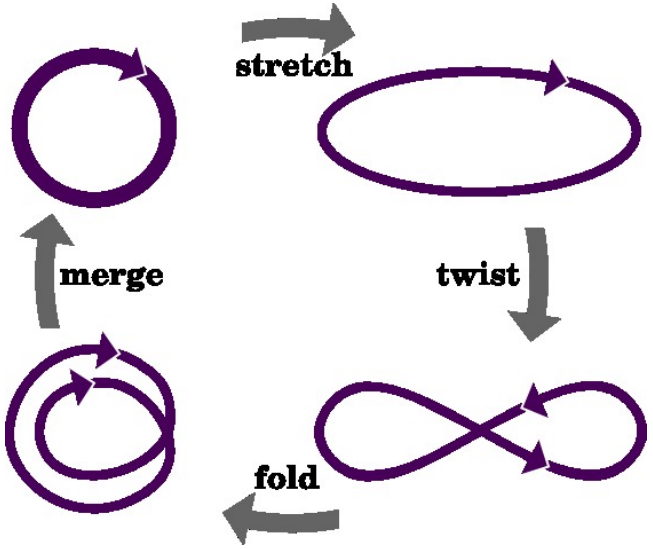
- ***Origin.*** Magnetic fields are generated by 1. electric currents sourced by a phase transition in the early universe or 2. by the Biermann battery
- ***Growth.*** A small-scale (fluctuating) dynamo is an MHD process, in which the kinetic (turbulent) energy is converted into magnetic energy: the mechanism relies on magnetic fields to become stronger when the field lines are stretched



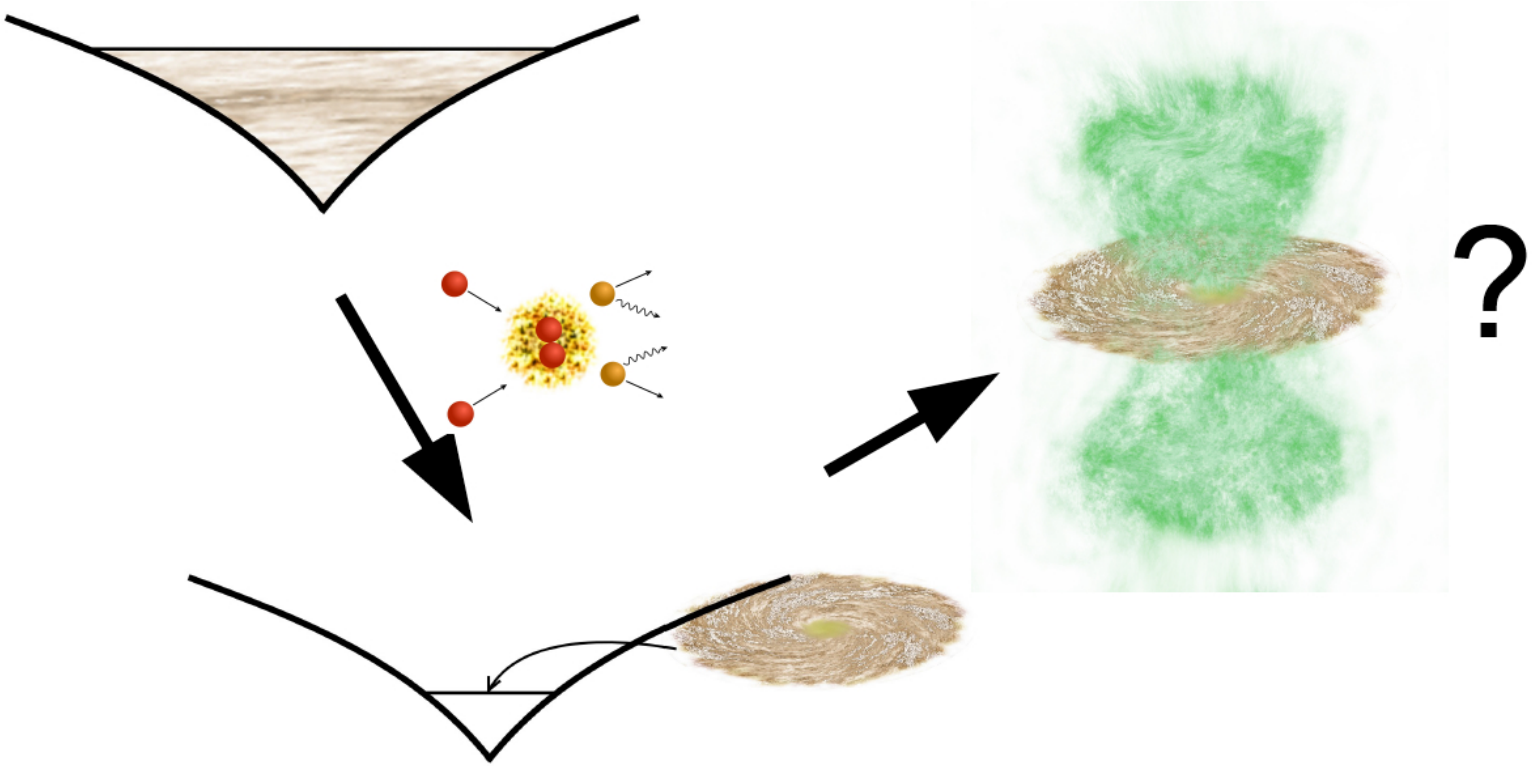
Origin and growth of magnetic fields

The general picture:

- ***Origin.*** Magnetic fields are generated by 1. electric currents sourced by a phase transition in the early universe or 2. by the Biermann battery
- ***Growth.*** A small-scale (fluctuating) dynamo is an MHD process, in which the kinetic (turbulent) energy is converted into magnetic energy: the mechanism relies on magnetic fields to become stronger when the field lines are stretched
- ***Saturation.*** Field growth stops at a sizeable fraction of the turbulent energy when magnetic forces become strong enough to resist the stretching and folding motions



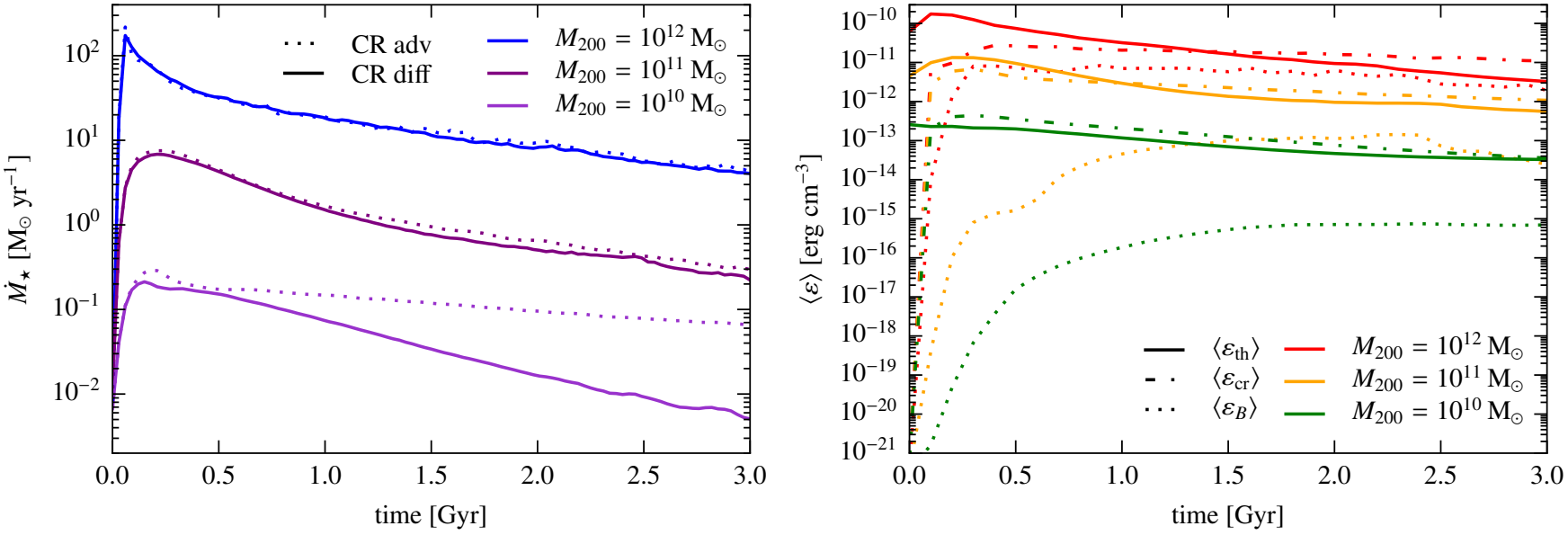
1. Magnetic dynamo in MHD galaxy simulations



CP, Werhahn, Pakmor, Girichidis, Simpson (2022)
Simulating radio synchrotron emission in star-forming galaxies: small-scale magnetic dynamo and the origin of the far-infrared–radio correlation

MHD + cosmic ray advection + diffusion: $\{10^{10}, 10^{11}, 3 \times 10^{11}, 10^{12}\}\ \mathrm{M}_\odot$

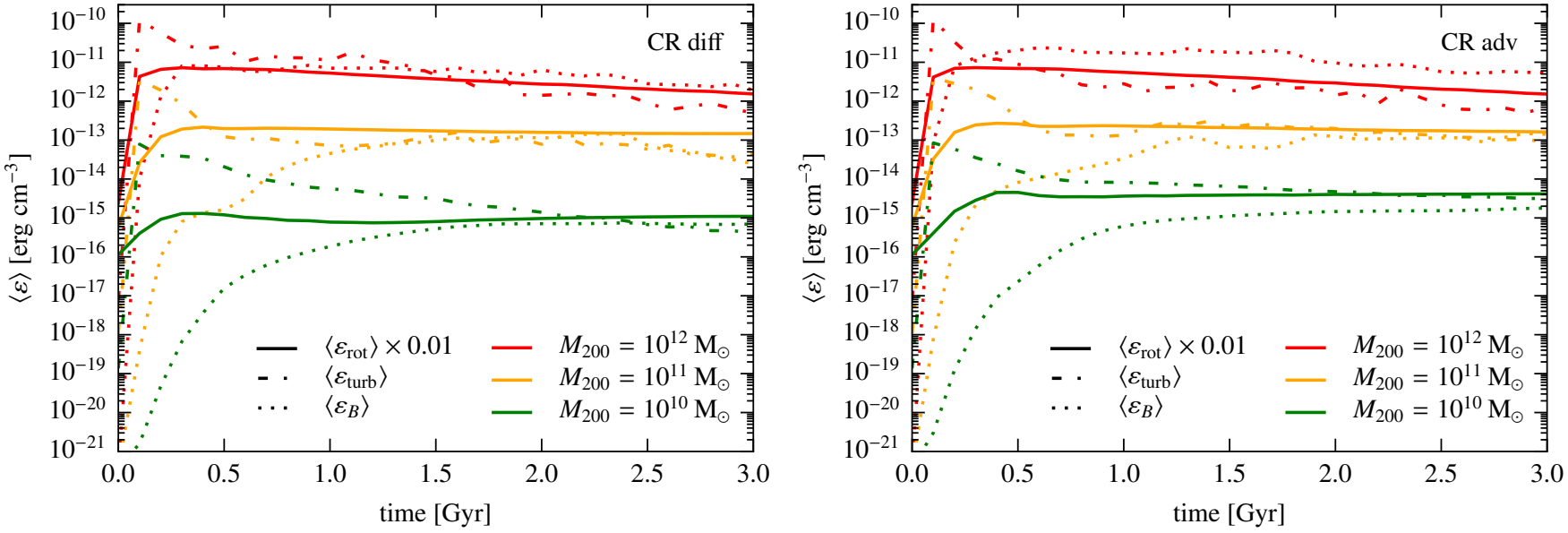
Time evolution of SFR and energy densities



CP+ (2022)

- cosmic ray (CR) pressure feedback suppresses SFR more in smaller galaxies
- energy budget in disks is dominated by CR pressure
- magnetic growth faster in Milky Way (MW) galaxies than in dwarfs and saturate at equipartition in MWs but not in dwarfs

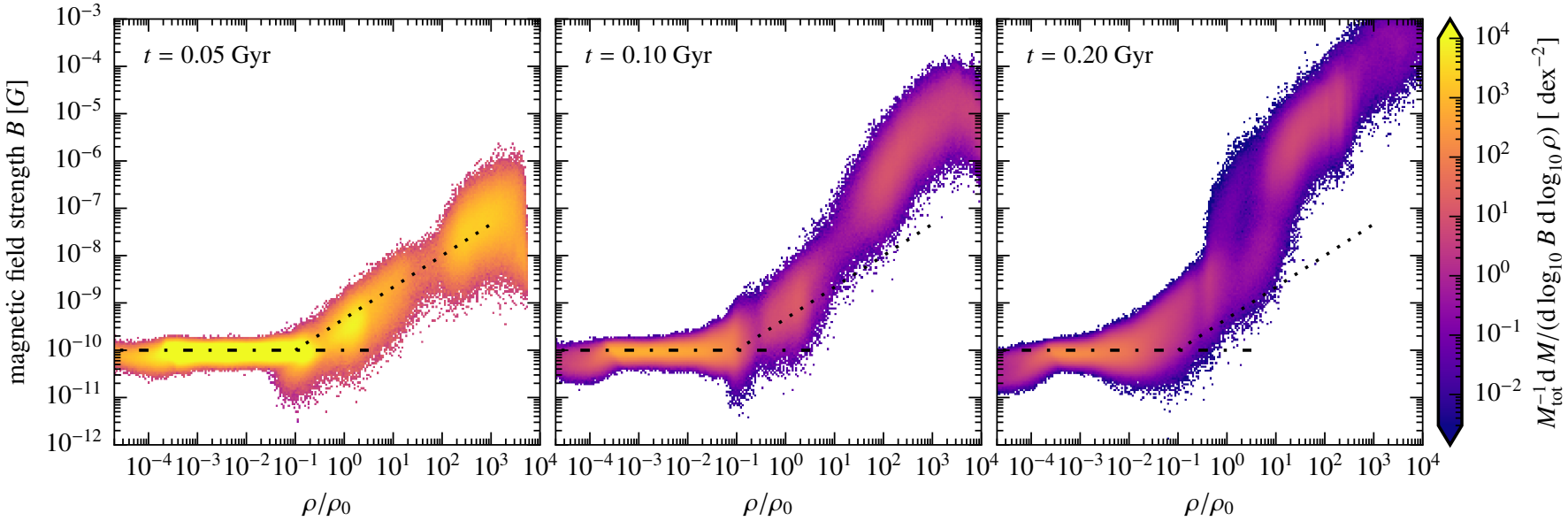
Comparing turbulent and magnetic energy densities



CP+ (2022)

- magnetic energy saturates at the turbulent energy, $\varepsilon_B \sim \varepsilon_{\rm turb} = \rho\delta v^2/2$ (averaged over the disk)
- saturation level similar for CR models with diffusion (left) and without (right)
- rotation dominates: $\varepsilon_{\rm rot} = \rho v_\varphi^2/2 \sim 100\varepsilon_{\rm turb}$

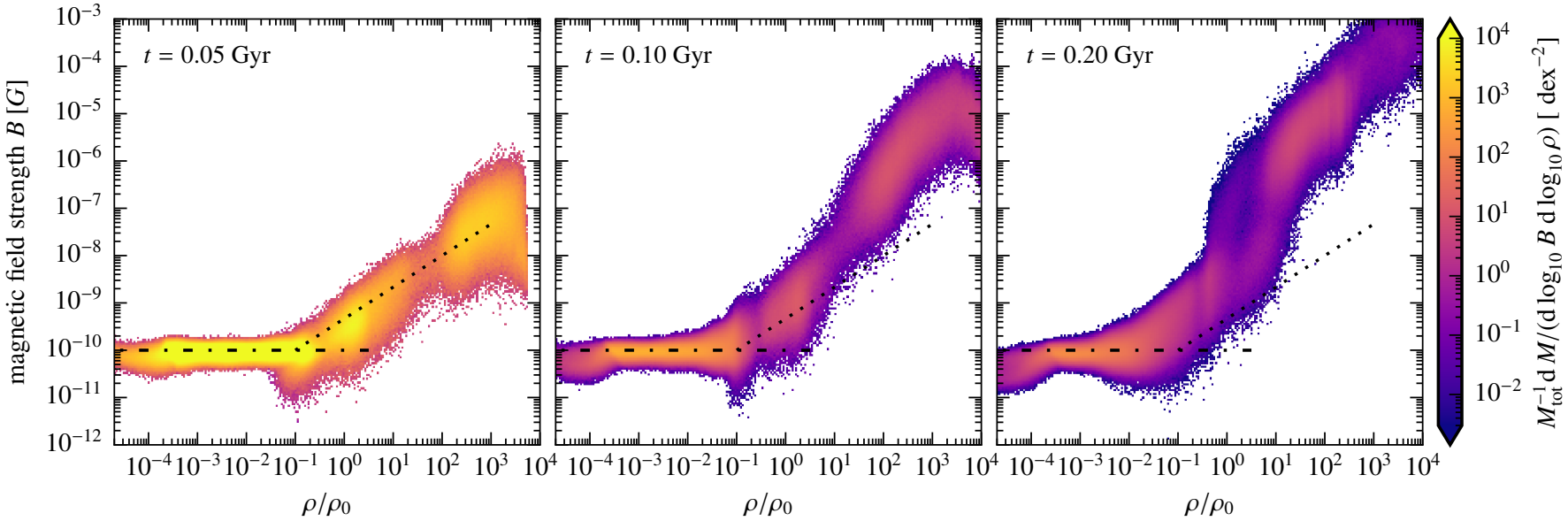
Identifying different growth phases



CP+ (2022)

- *1st phase:* adiabatic growth with $B \propto \rho^{2/3}$ (isotropic collapse)

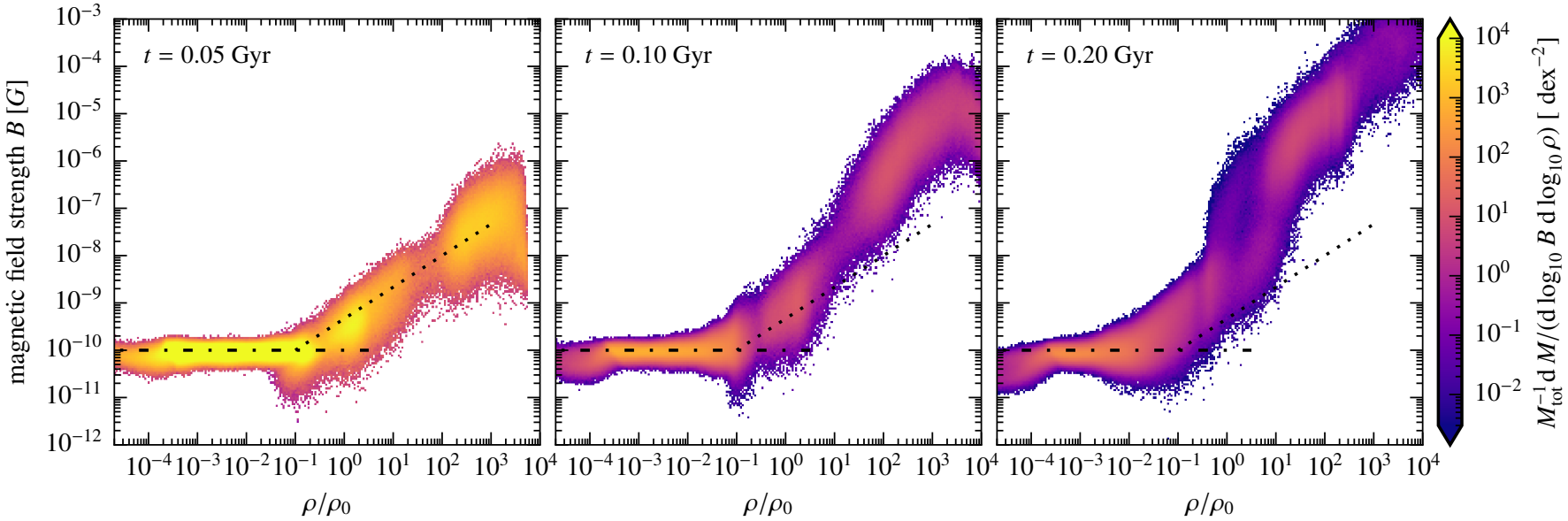
Identifying different growth phases



CP+ (2022)

- *1st phase:* adiabatic growth with $B \propto \rho^{2/3}$ (isotropic collapse)
- *2nd phase:* additional growth at high density ρ with small dynamical times $t_{\rm dyn} \sim (G\rho)^{-1/2}$

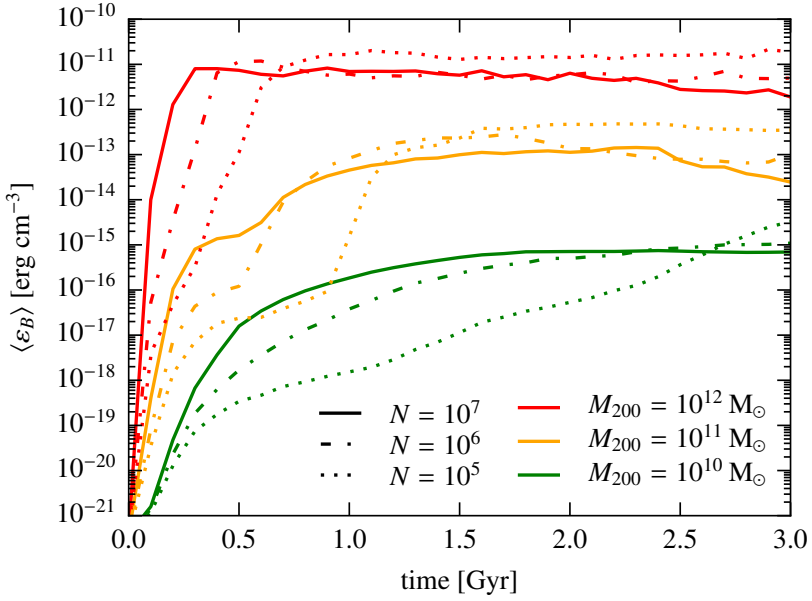
Identifying different growth phases



CP+ (2022)

- *1st phase:* adiabatic growth with $B \propto \rho^{2/3}$ (isotropic collapse)
- *2nd phase:* additional growth at high density ρ with small dynamical times $t_{\rm dyn} \sim (G\rho)^{-1/2}$
- *3rd phase:* growth migrates to lower ρ on larger scales $\propto \rho^{-1/3}$

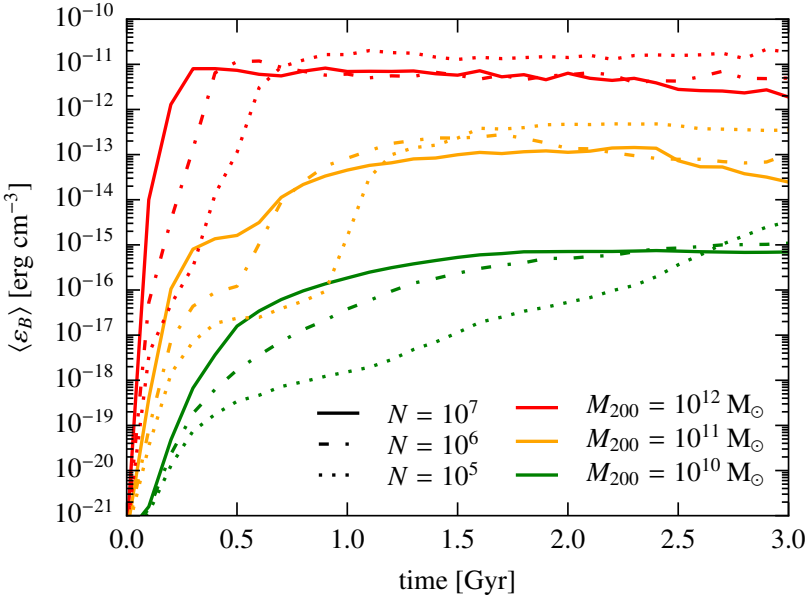
Studying growth rate with numerical resolution

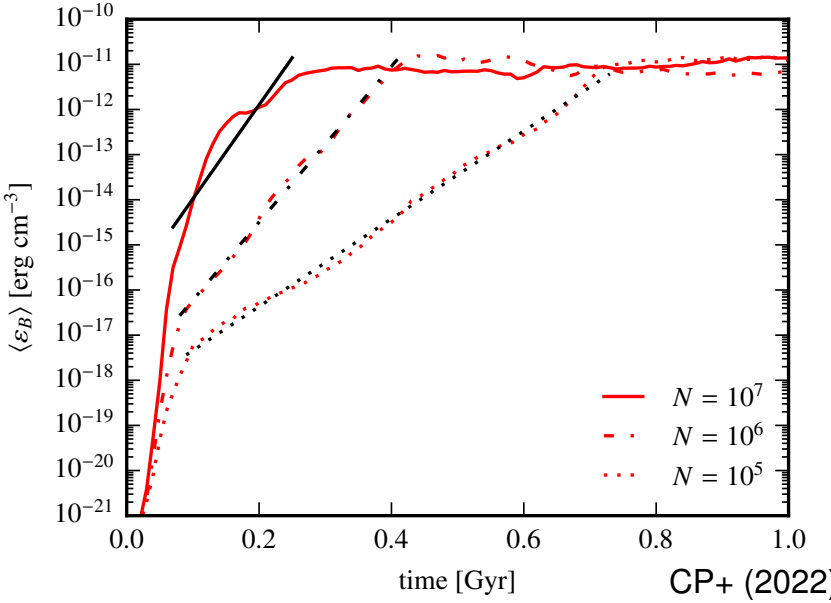


CP+ (2022)

- ***faster magnetic growth in higher resolution simulations and larger halos,*** numerical convergence for $N \gtrsim 10^6$

Studying growth rate with numerical resolution

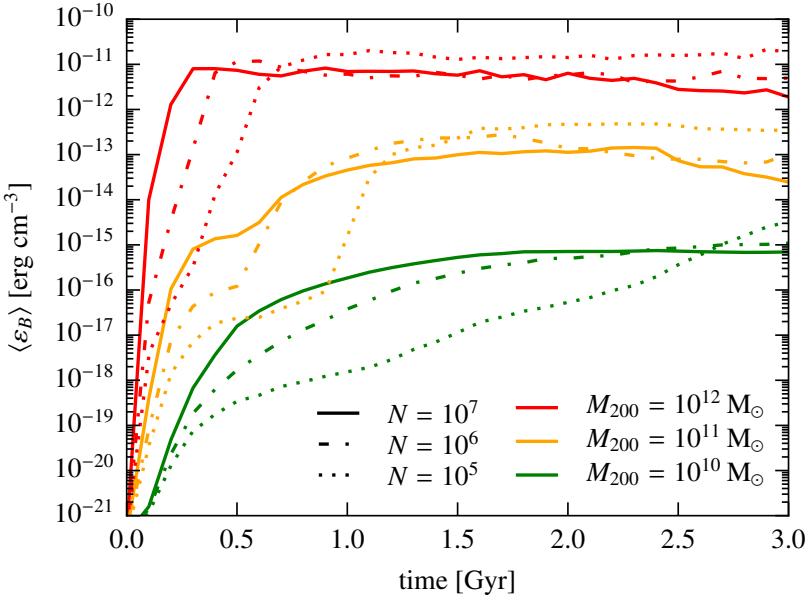


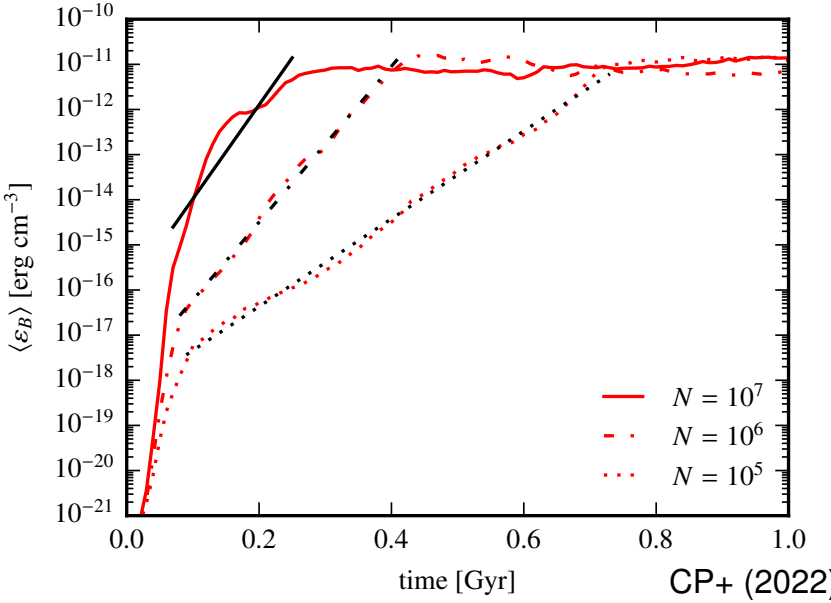


CP+ (2022)

- ***faster magnetic growth in higher resolution simulations and larger halos,*** numerical convergence for $N \gtrsim 10^6$
- *1st phase:* adiabatic growth (independent of resolution)

Studying growth rate with numerical resolution



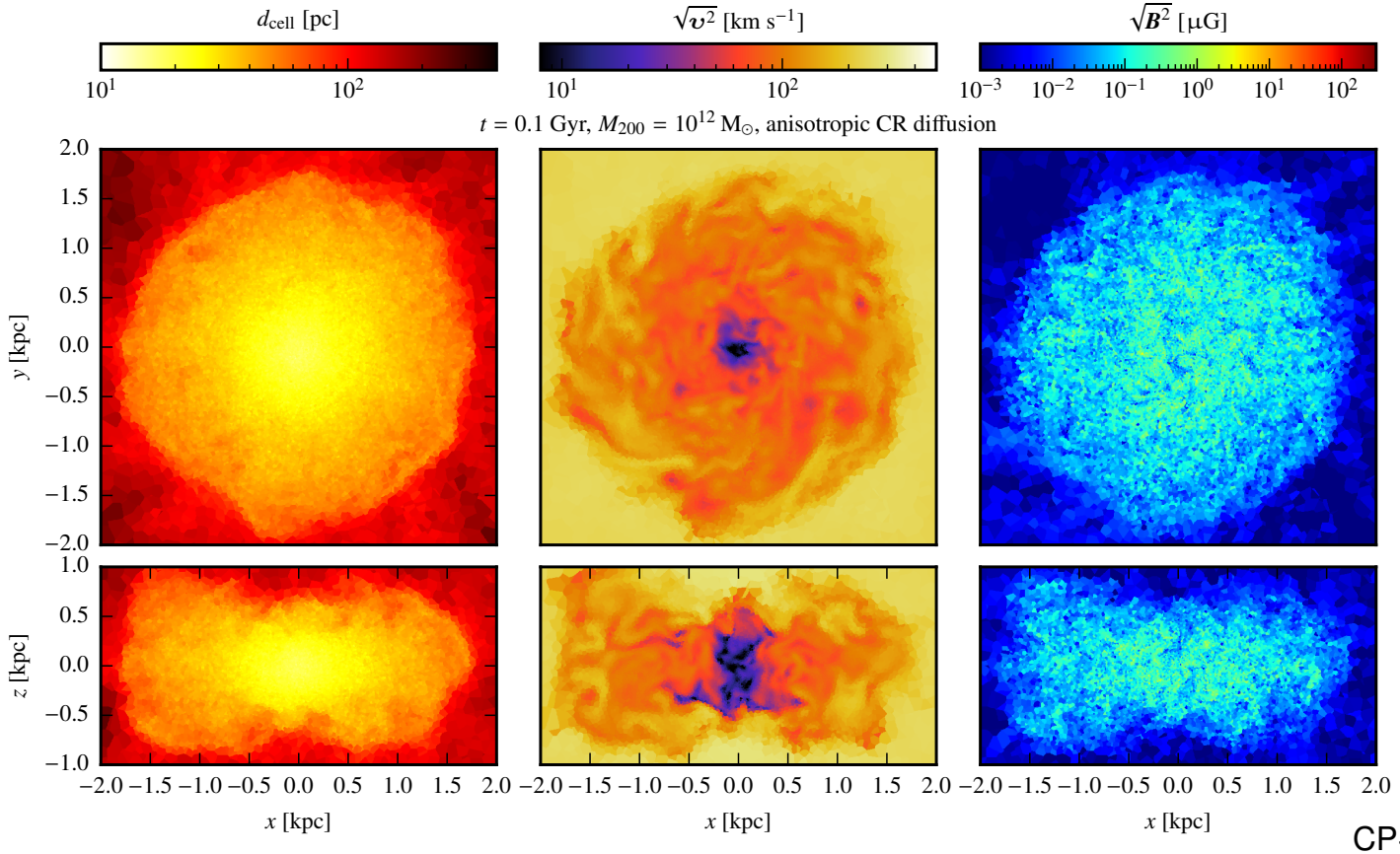


CP+ (2022)

- ***faster magnetic growth in higher resolution simulations and larger halos,*** numerical convergence for $N \gtrsim 10^6$
- *1st phase:* adiabatic growth (independent of resolution)
- *2nd phase:* small-scale dynamo with resolution-dep. growth rate

$$\Gamma = \frac{\mathcal{V}}{\mathcal{L}} \mathrm{Re}_{\mathrm{num}}^{1/2}, \quad \mathrm{Re}_{\mathrm{num}} = \frac{\mathcal{L}\mathcal{V}}{\nu_{\mathrm{num}}} = \frac{3\mathcal{L}\mathcal{V}}{d_{\mathrm{cell}}\, v_{\mathrm{th}}}$$

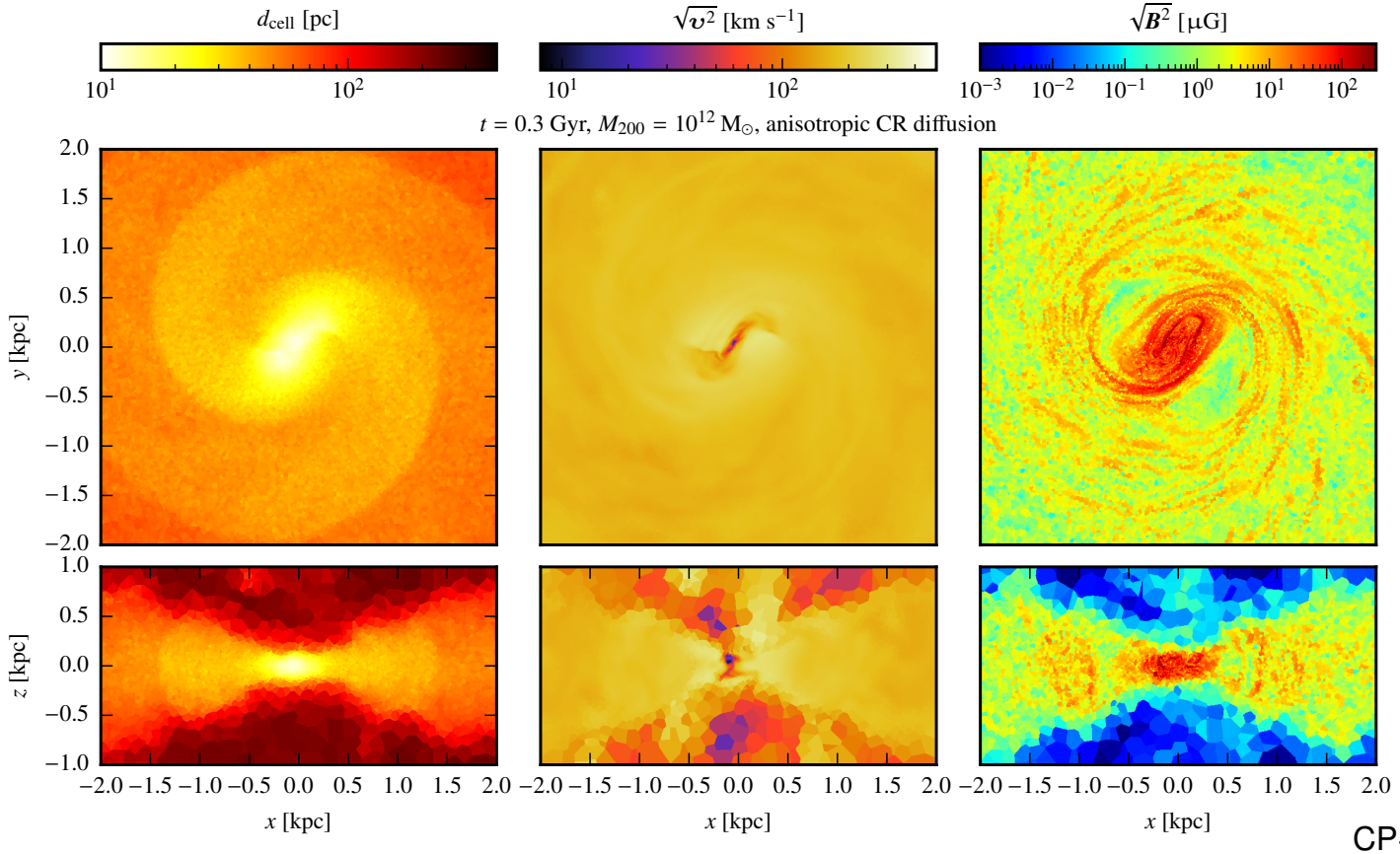
Exponential field growth in kinematic regime



CP+ (2022)

- ***corrugated accretion shock*** dissipates kinetic energy from gravitational infall, injects vorticity that decays into turbulence, and drives a small-scale dynamo

Dynamo saturation on small scales while λ_B increases

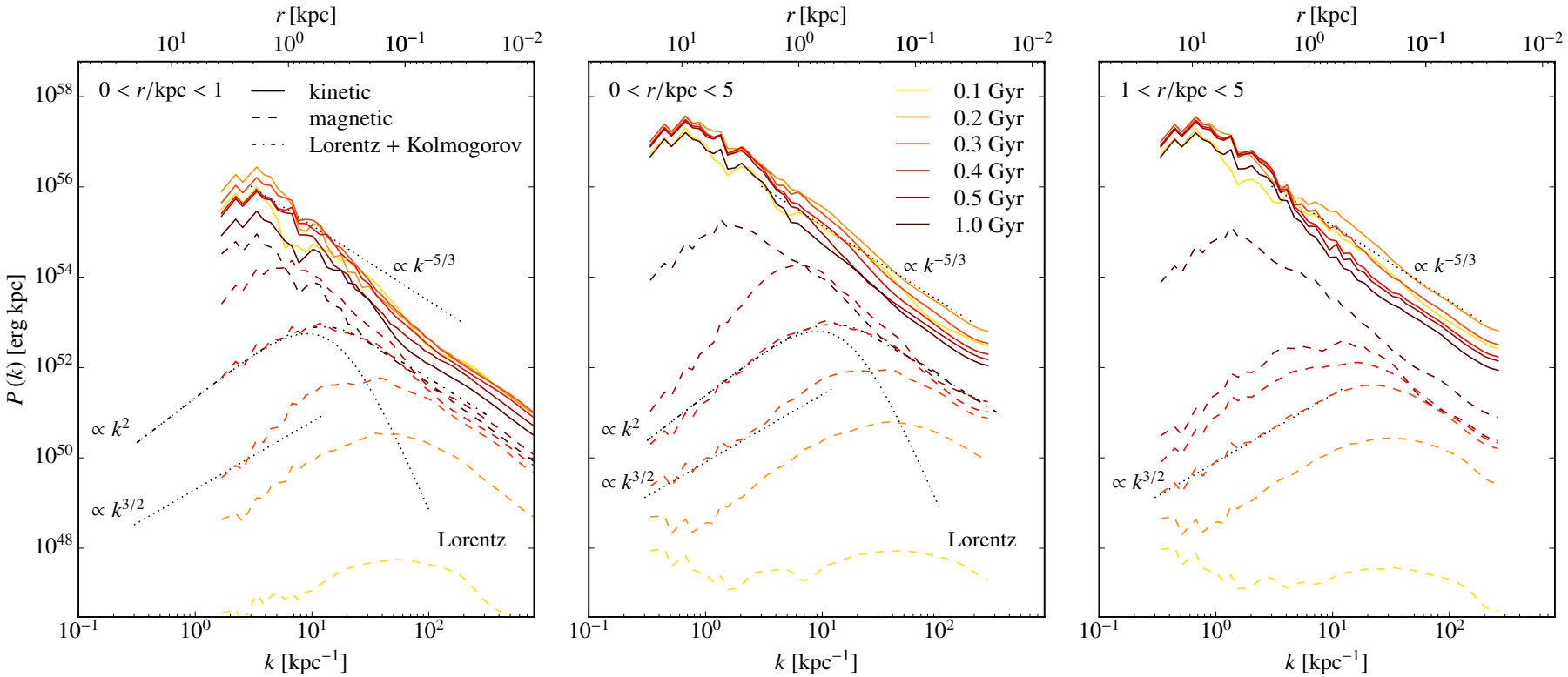


CP+ (2022)

- ***supersonic velocity shear*** between the rotationally supported cool disk and hotter CGM: excitation of Kelvin-Helmholtz body modes that interact and drive a small-scale dynamo

Kinetic and magnetic power spectra

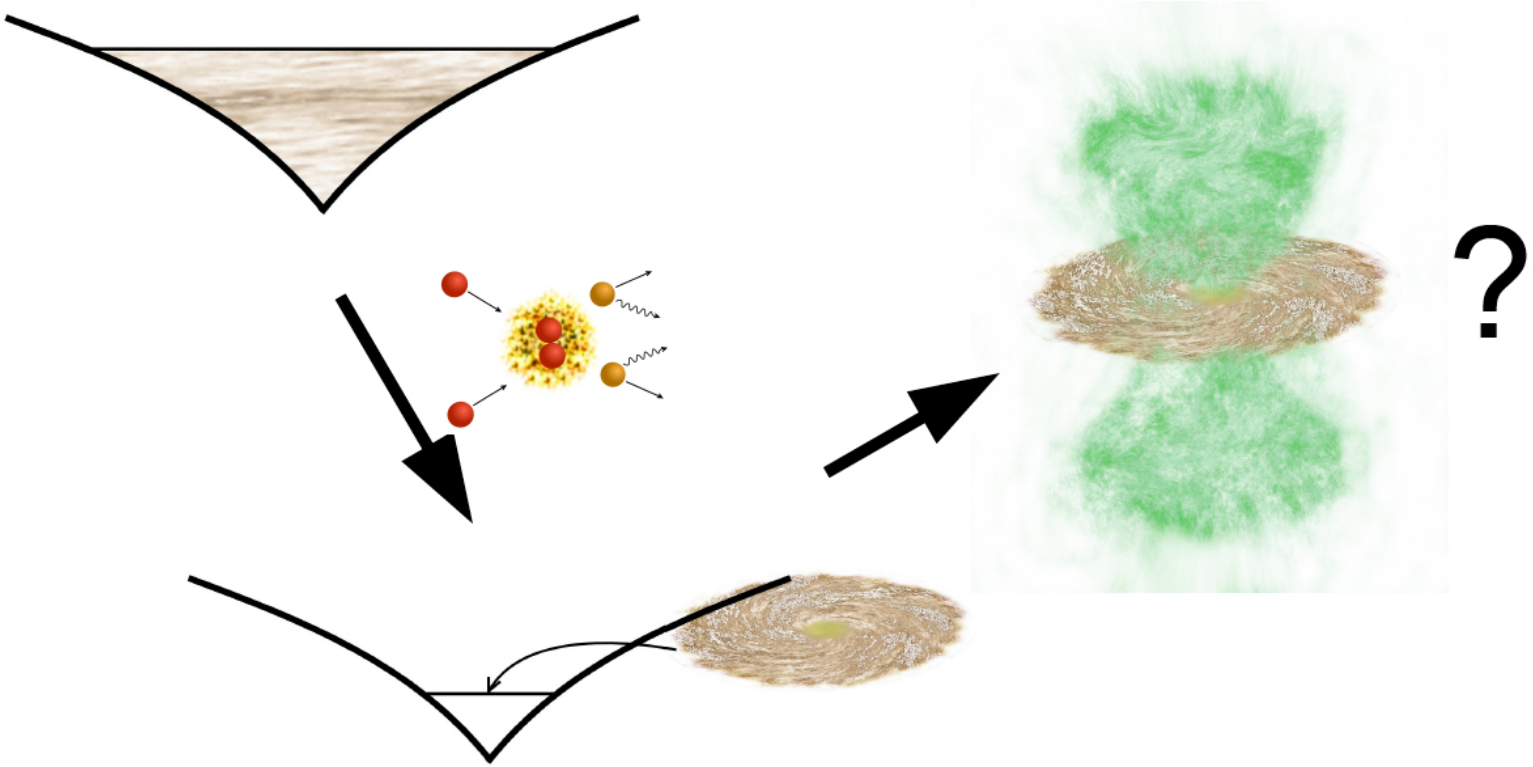
Fluctuating small-scale dynamo in different analysis regions



CP+ (2022)

- $E_B(k)$ superposition of form factor and turbulent spectrum
- pure turbulent spectrum outside steep central B profile

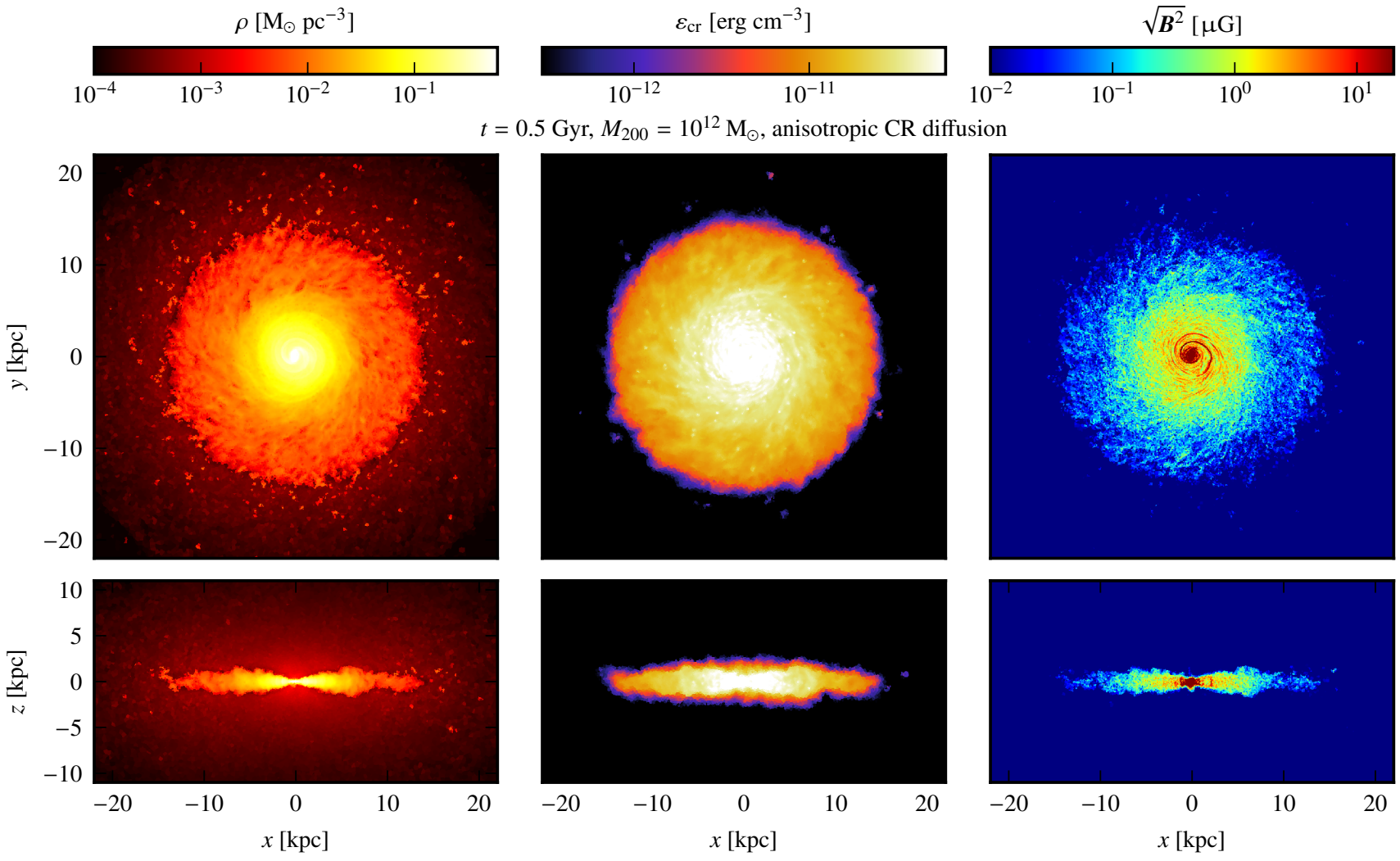
2. Cosmic ray driven winds in galaxy simulations



CP, Pakmor, Simpson, Springel (2017)
Simulating gamma-ray emission in star-forming galaxies

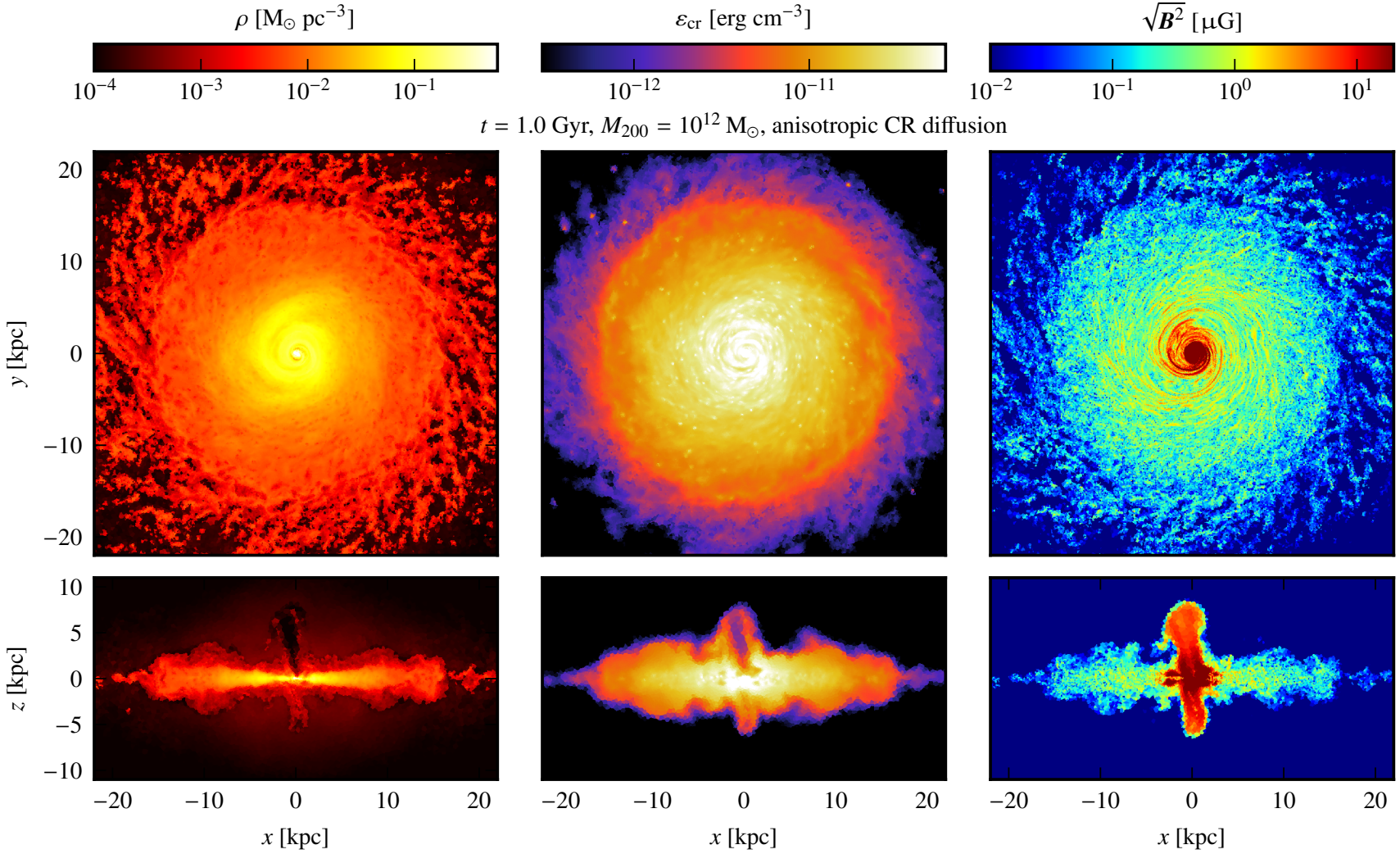
MHD + CR advection + anisotropic diffusion, $\{10^{10}, 10^{11}, 10^{12}\}\ M_\odot$

Simulation of Milky Way-like galaxy, $t = 0.5$ Gyr



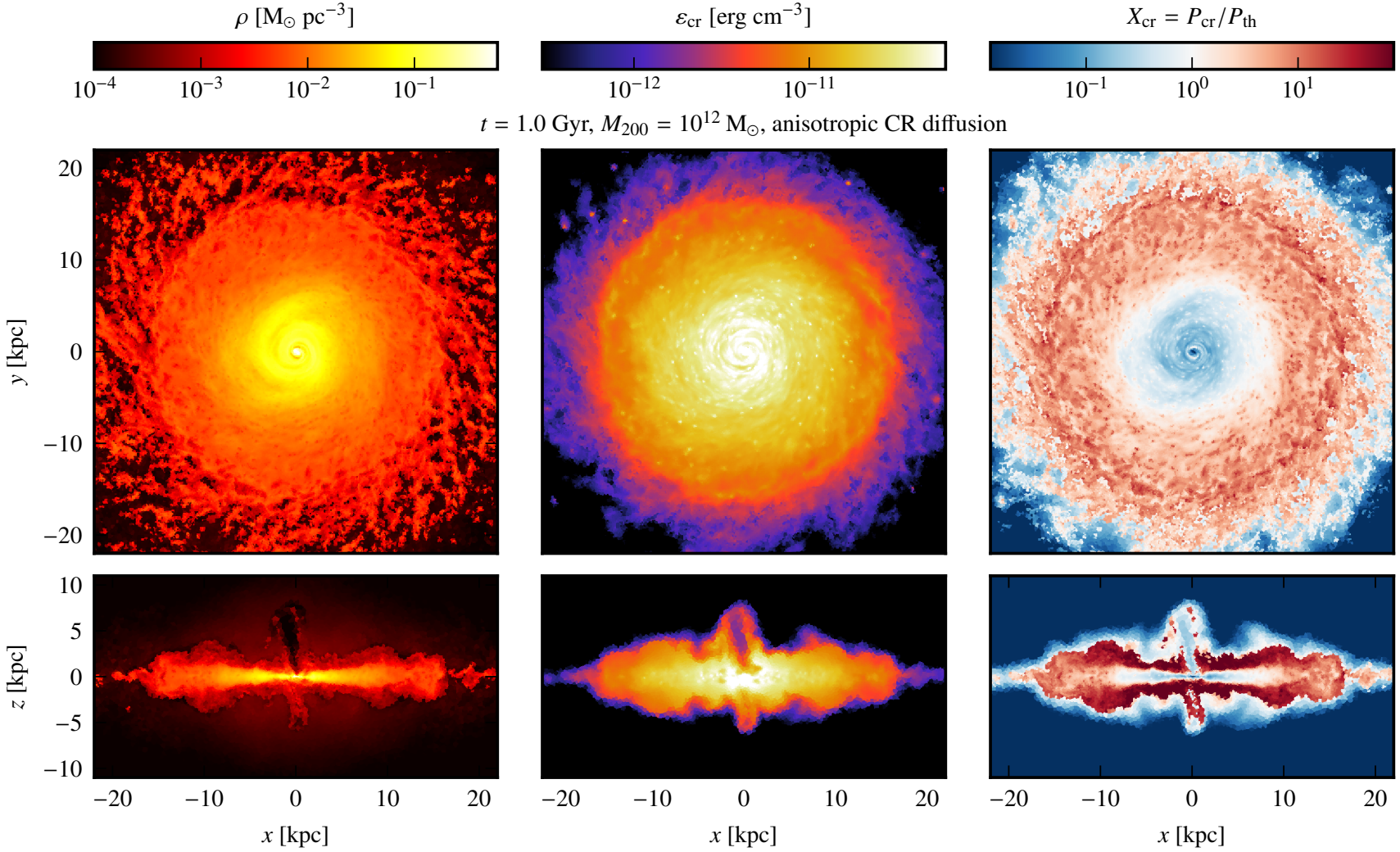
CP+ (2017)

Simulation of Milky Way-like galaxy, $t = 1.0$ Gyr



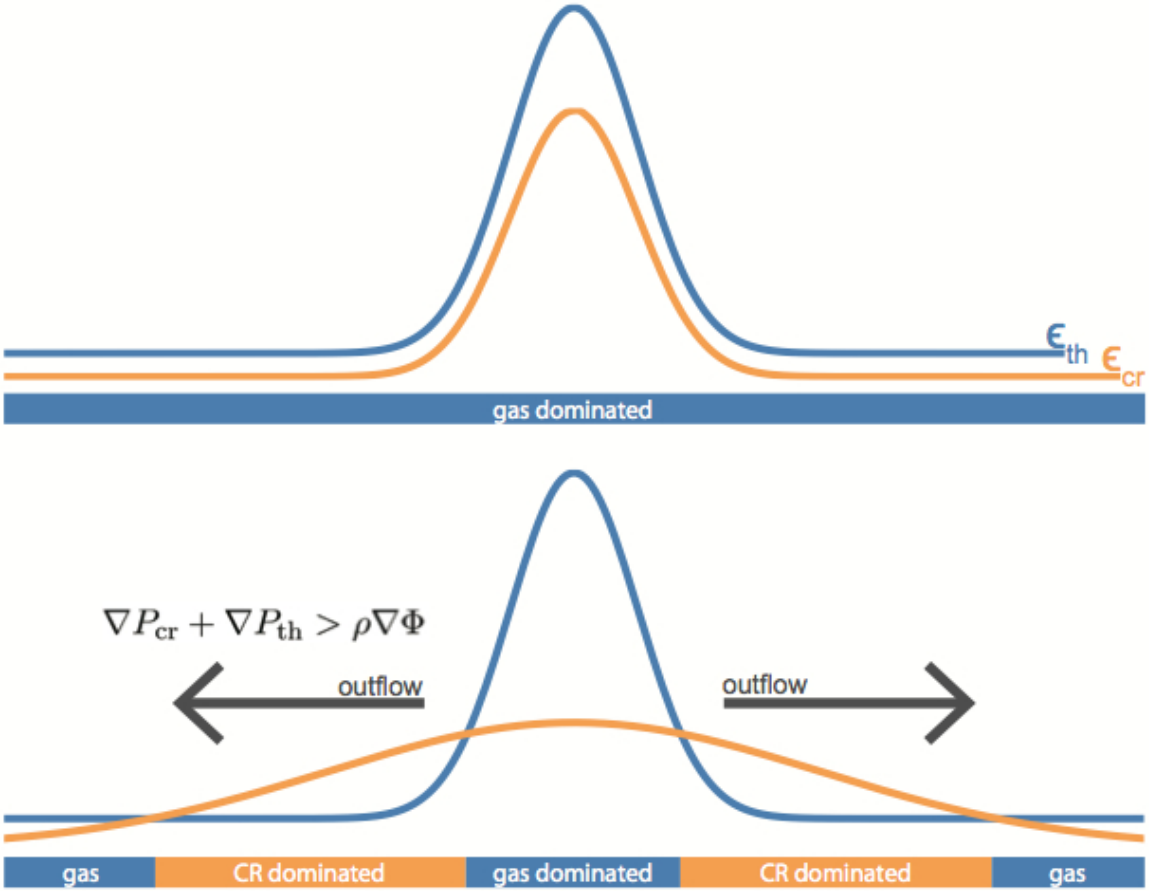
CP+ (2017)

Simulation of Milky Way-like galaxy, $t = 1.0$ Gyr



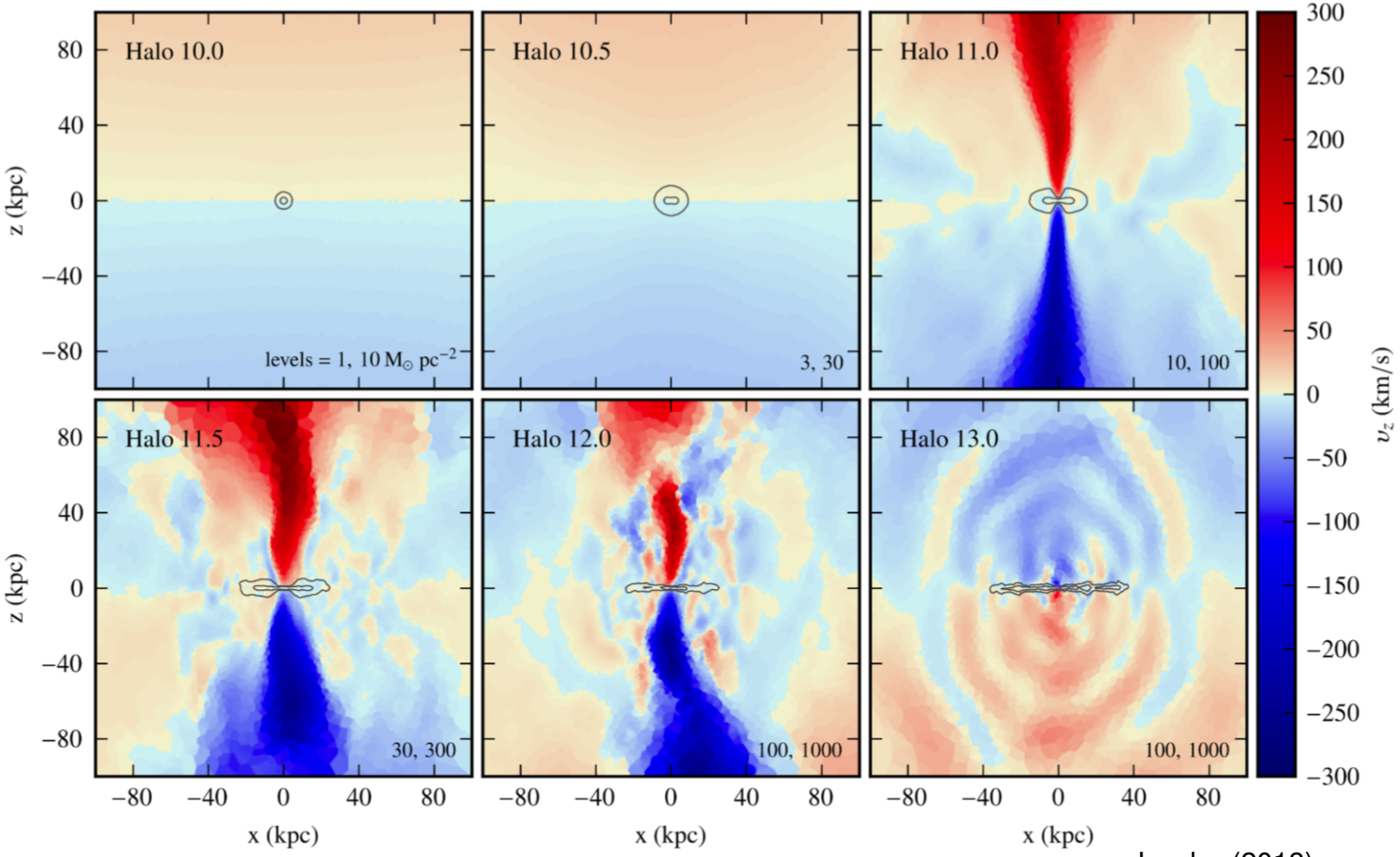
CP+ (2017)

Cosmic ray driven wind: mechanism



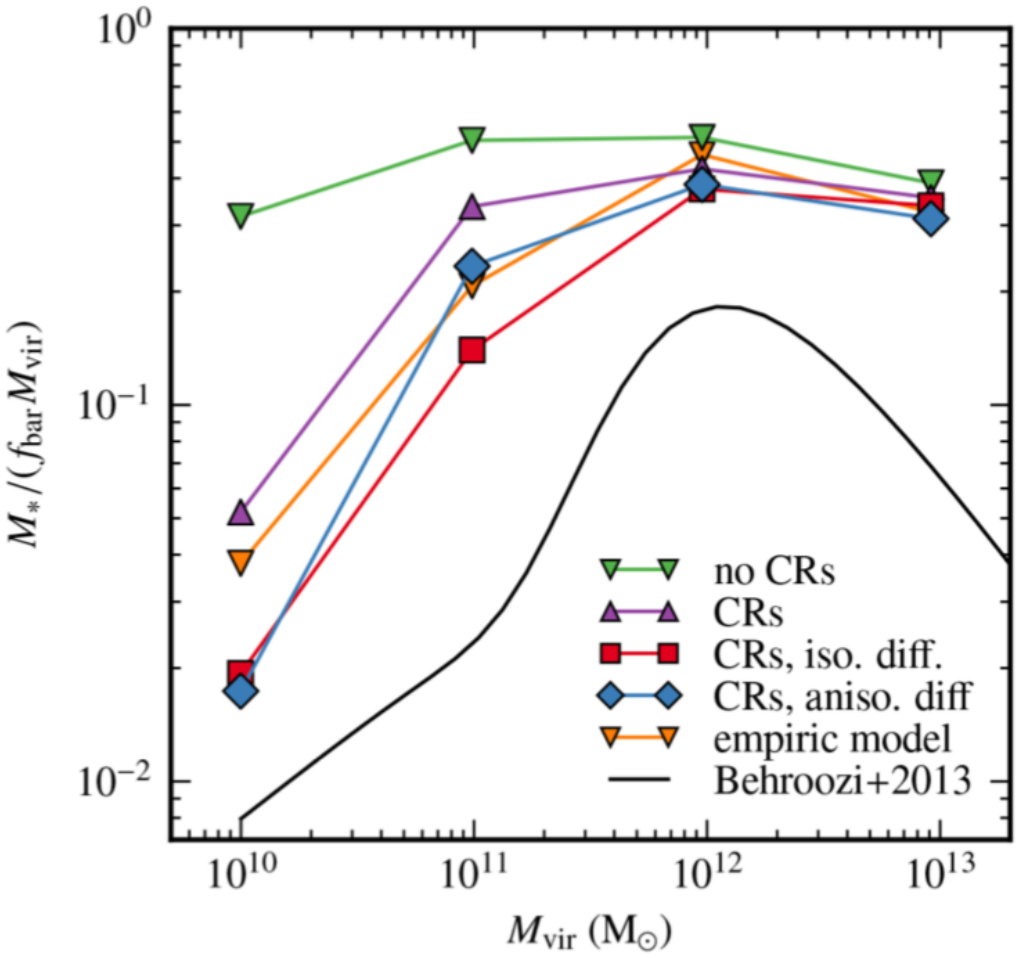
CR streaming in 3D simulations: Uhlig, CP+ (2012), Ruszkowski+ (2017)
CR diffusion in 3D simulations: Jubelgas+ (2008), Booth+ (2013), Hanasz+ (2013), Salem & Bryan (2014), Pakmor, CP+ (2016), Simpson+ (2016), Girichidis+ (2016), Dubois+ (2016), CP+ (2017), Jacob+ (2018), . . .

CR-driven winds: dependence on halo mass



Jacob+ (2018)

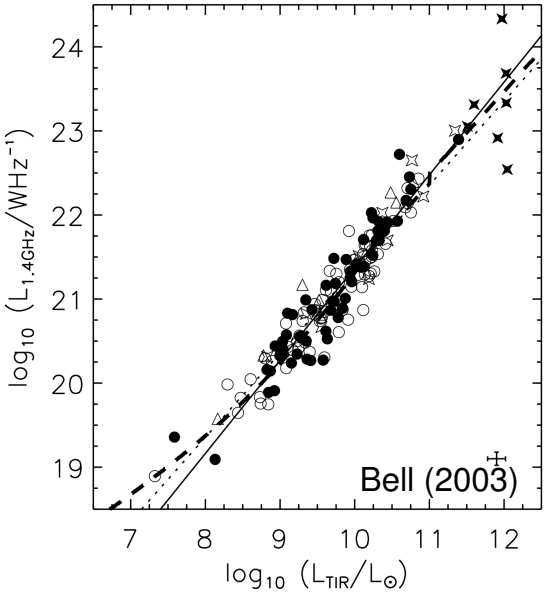
CR-driven winds: suppression of star formation

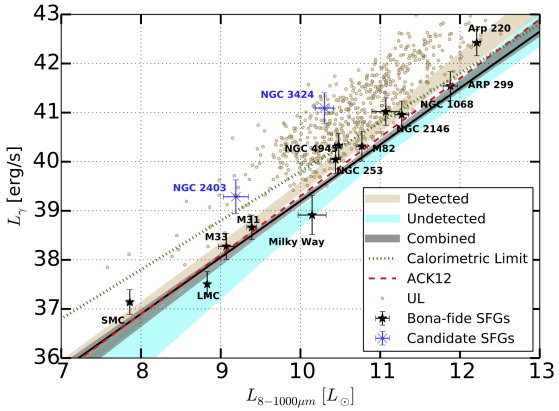


Jacob+ (2018)

Non-thermal emission in star-forming galaxies

- ***previous theoretical modeling:***
  - one-zone steady-state models (Lacki+ 2010, 2011, Yoast-Hull+ 2013)
  - 1D transport models (Heesen+ 2016)
  - static Milky Way models (Strong & Moskalenko 1998, Evoli+ 2008, Kissmann 2014)

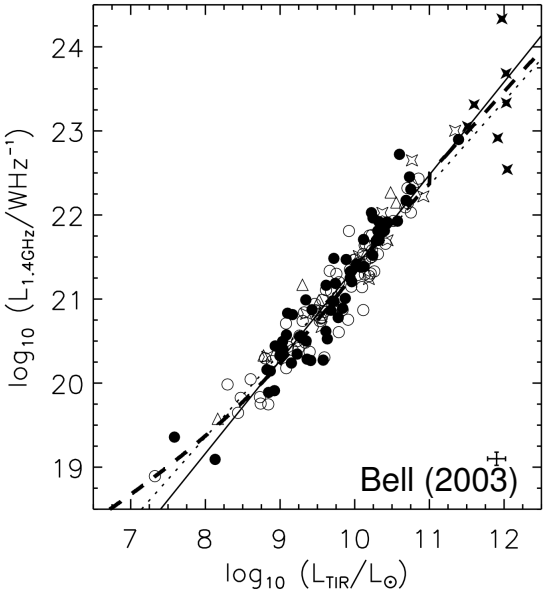


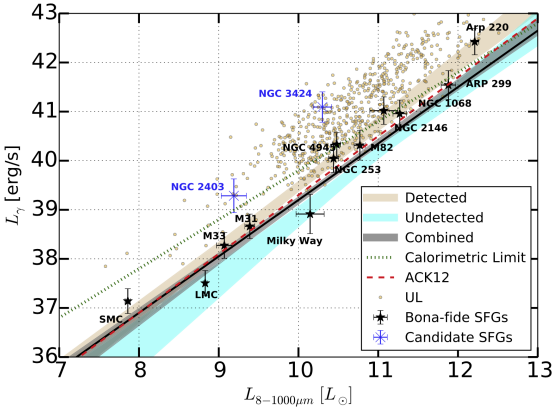


Ajello+ (2020)

Non-thermal emission in star-forming galaxies

- ***previous theoretical modeling:***
  - one-zone steady-state models (Lacki+ 2010, 2011, Yoast-Hull+ 2013)
  - 1D transport models (Heesen+ 2016)
  - static Milky Way models (Strong & Moskalenko 1998, Evoli+ 2008, Kissmann 2014)
- ***our theoretical modeling:***
  - run MHD-CR simulations of galaxies at different halos masses and SFRs
  - model steady-state CRs: protons, primary and secondary electrons
  - model all radiative processes from radio to gamma rays
  - gamma rays: understand pion decay and leptonic inverse Compton emission
  - radio: understand magnetic dynamo, primary and secondary electrons





Ajello+ (2020)

Steady-state cosmic ray spectra

- solve the steady-state equation in every cell for each CR population:

$$\frac{N(E)}{\tau_{\rm esc}} - \frac{\rm d}{{\rm d}E}\left[N(E)b(E)\right] = Q(E)$$

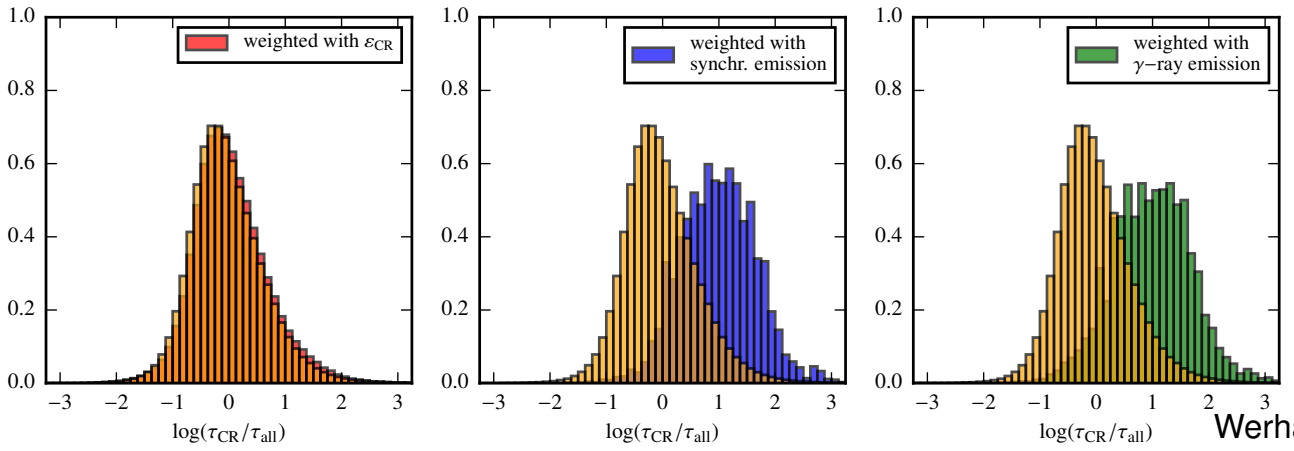
- protons: Coulomb, hadronic and escape losses (re-normalized to $\varepsilon_{\rm cr}$)
- electrons: Coulomb, bremsstr., IC, synchrotron and escape losses
  - primaries (re-normalized using $K_{\rm ep} = 0.02$)
  - secondaries

Steady-state cosmic ray spectra

- solve the steady-state equation in every cell for each CR population:

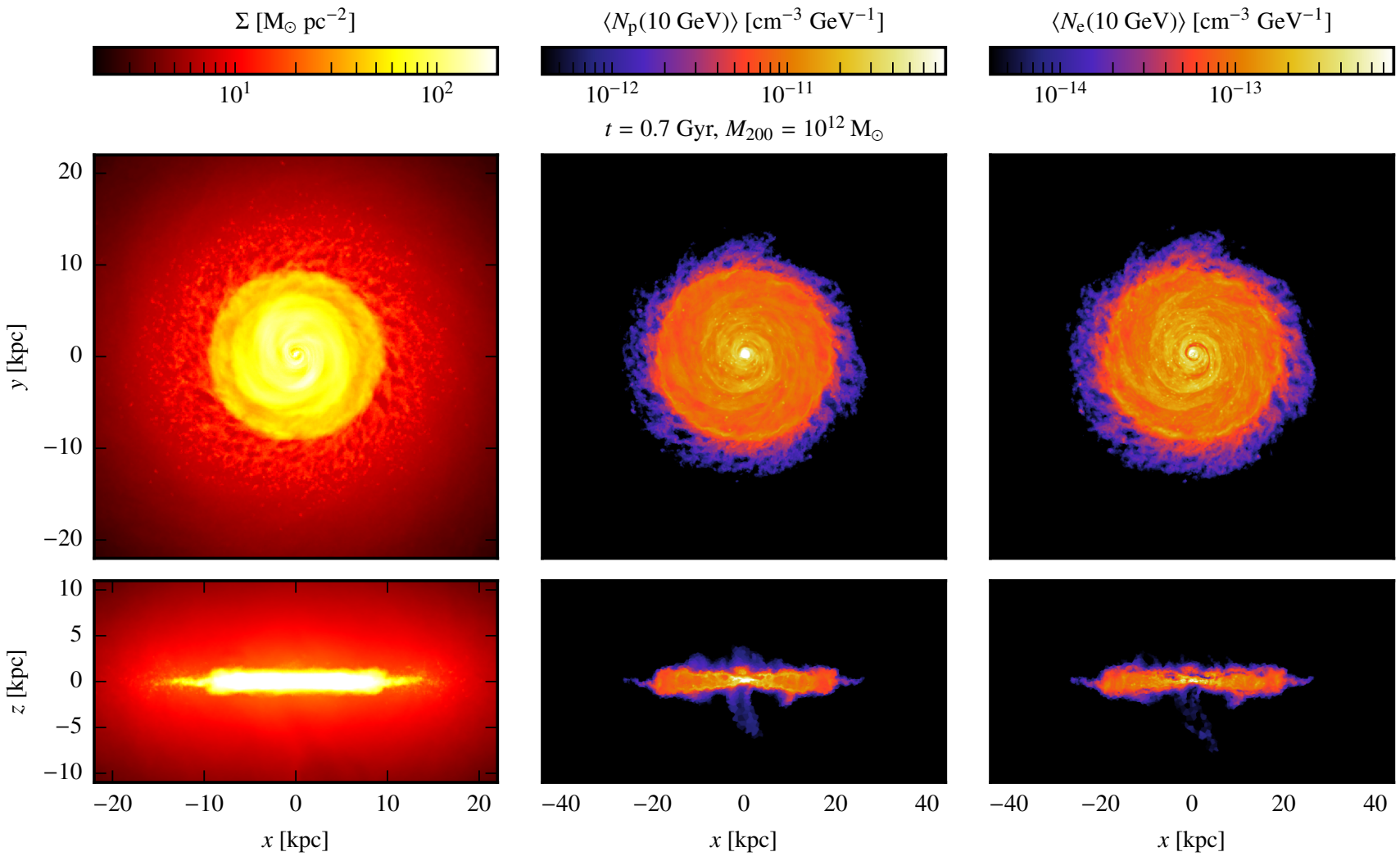
$$\frac{N(E)}{\tau_{\rm esc}} - \frac{\rm d}{{\rm d}E}\left[N(E)b(E)\right] = Q(E)$$

- protons: Coulomb, hadronic and escape losses (re-normalized to $\varepsilon_{\rm cr}$)
- electrons: Coulomb, bremsstr., IC, synchrotron and escape losses
  - primaries (re-normalized using $K_{\rm ep} = 0.02$)
  - secondaries
- steady state assumption is fulfilled in disk and in regions dominating the non-thermal emission but not at low densities, at SNRs and in outflows



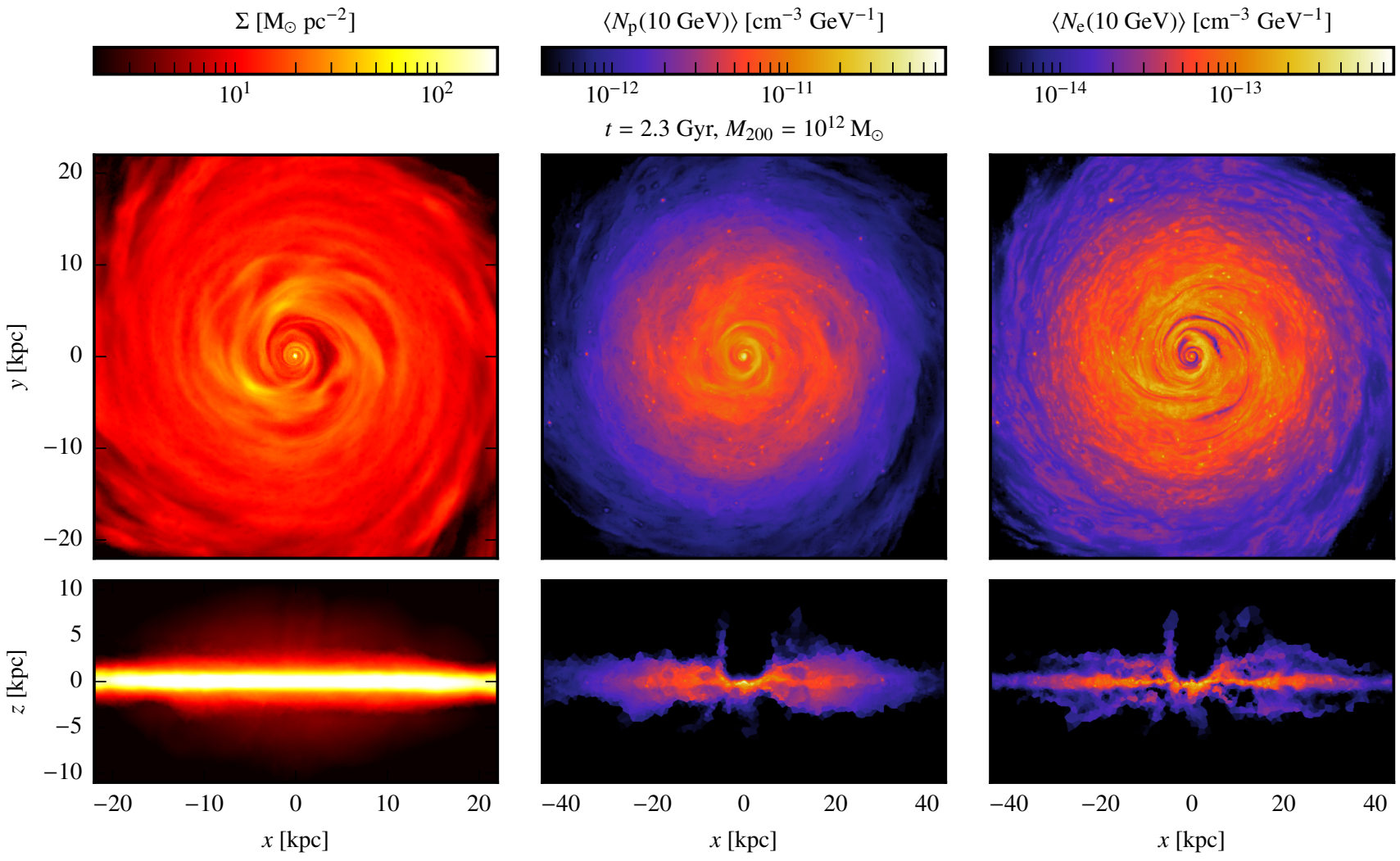
Werhahn+ (2021a)

From a starburst galaxy to a Milky Way analogy



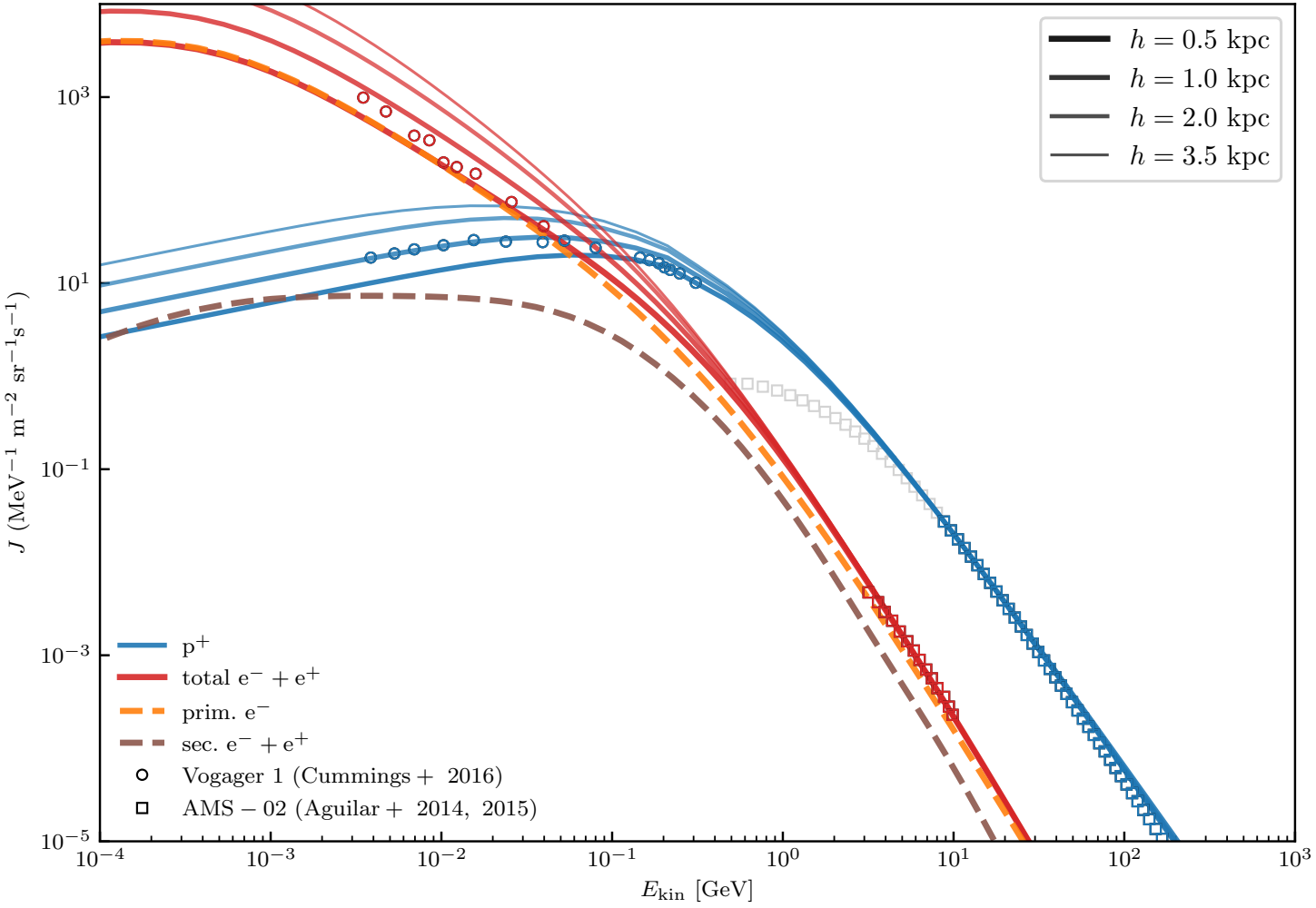
Werhahn, CP+ (2021a,b)

From a starburst galaxy to a Milky Way analogy



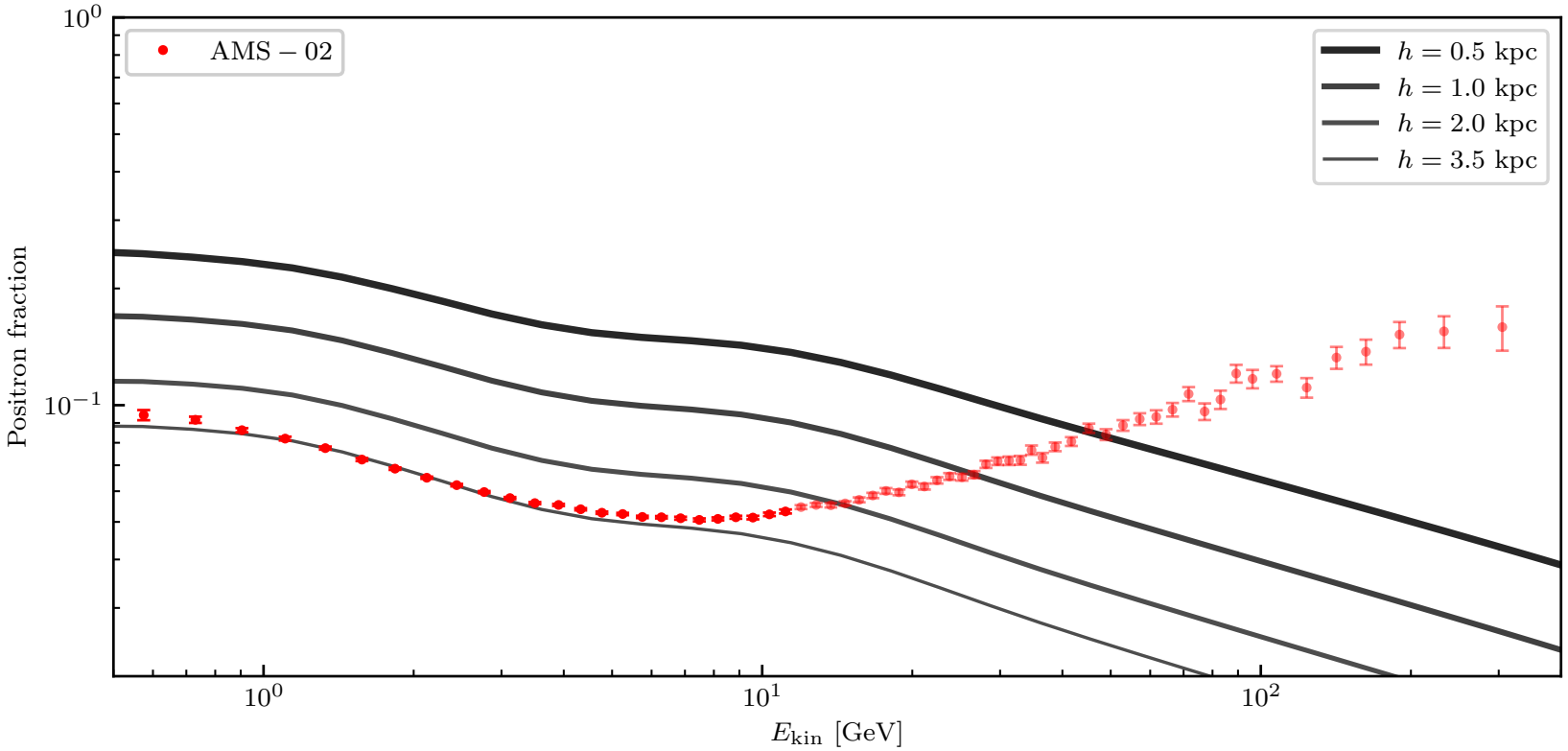
Werhahn, CP+ (2021a,b)

Comparing CR spectra to Voyager and AMS-02 data



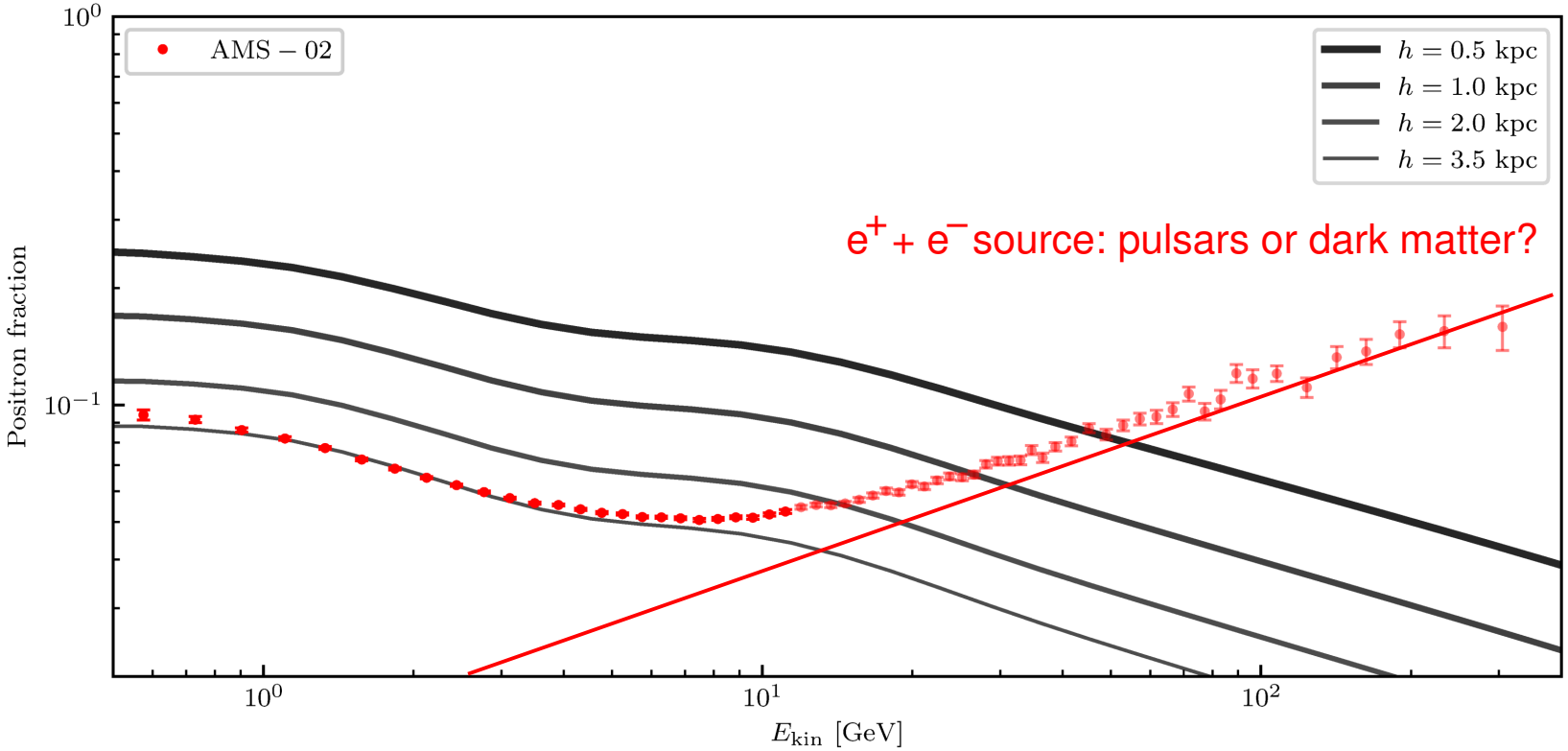
Werhahn, CP+ (2021a)

Comparing the positron fraction to AMS-02 data



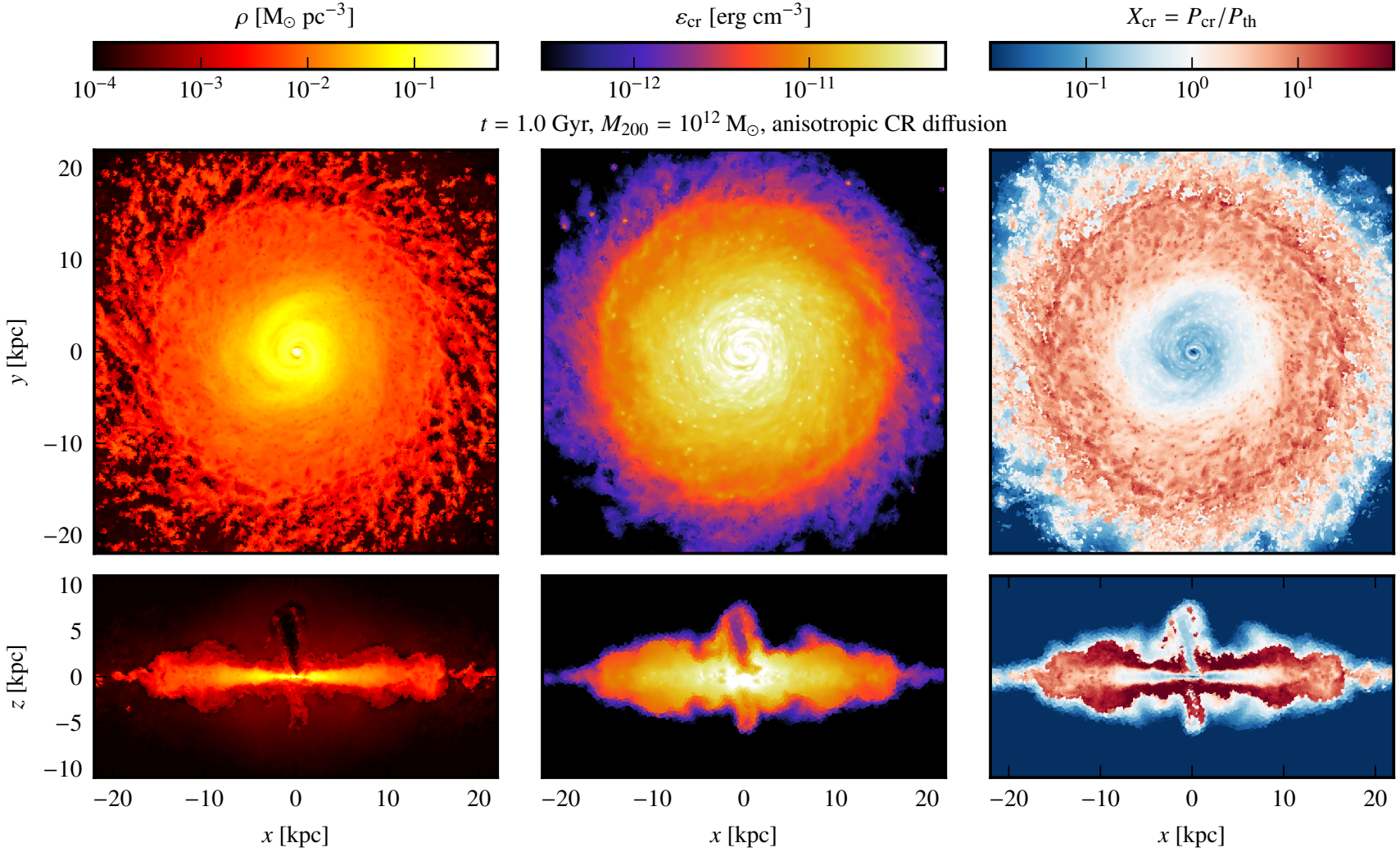
Werhahn, CP+ (2021a)

Comparing the positron fraction to AMS-02 data



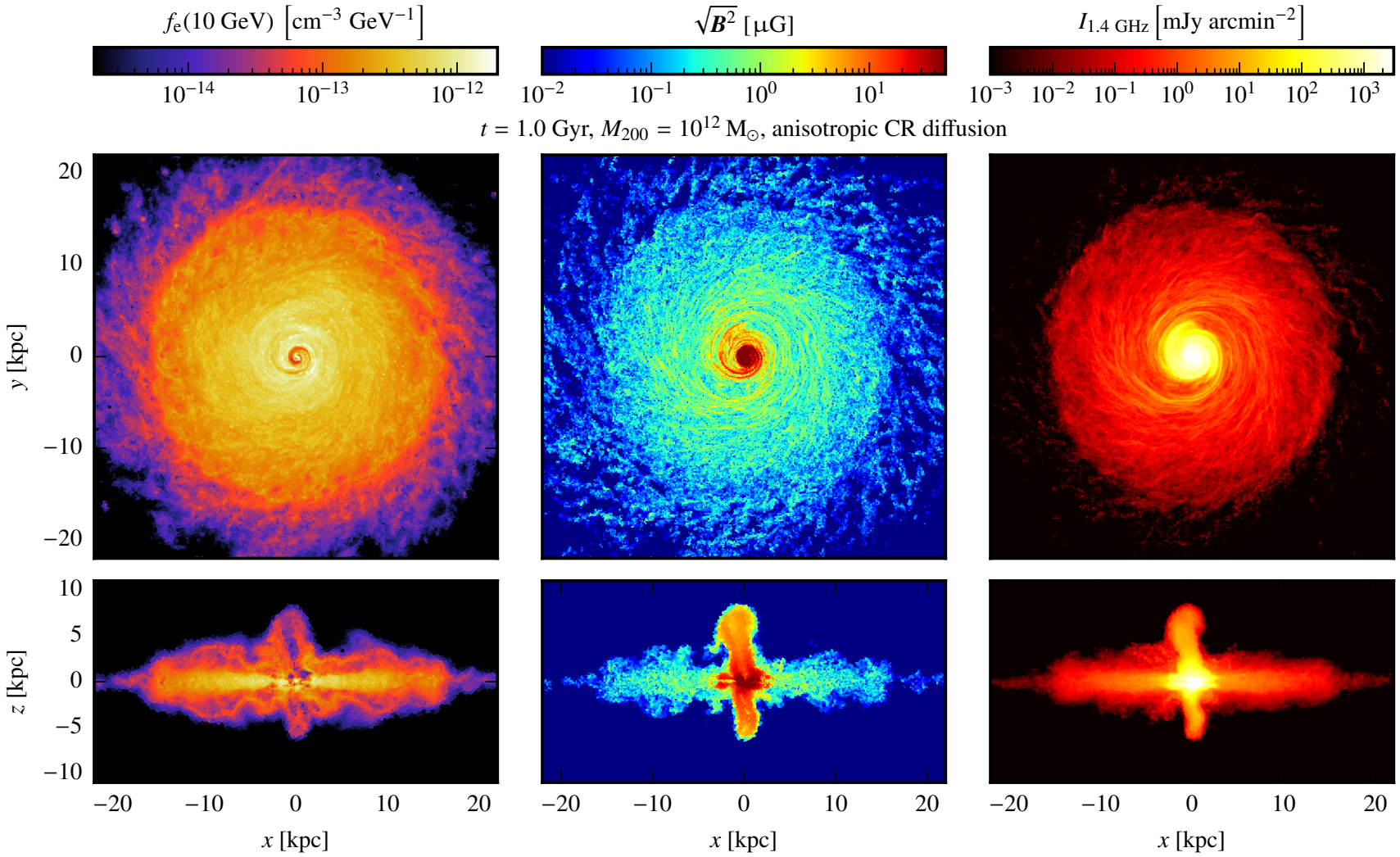
Werhahn, CP+ (2021a)

Galaxy simulation with cosmic ray-driven wind



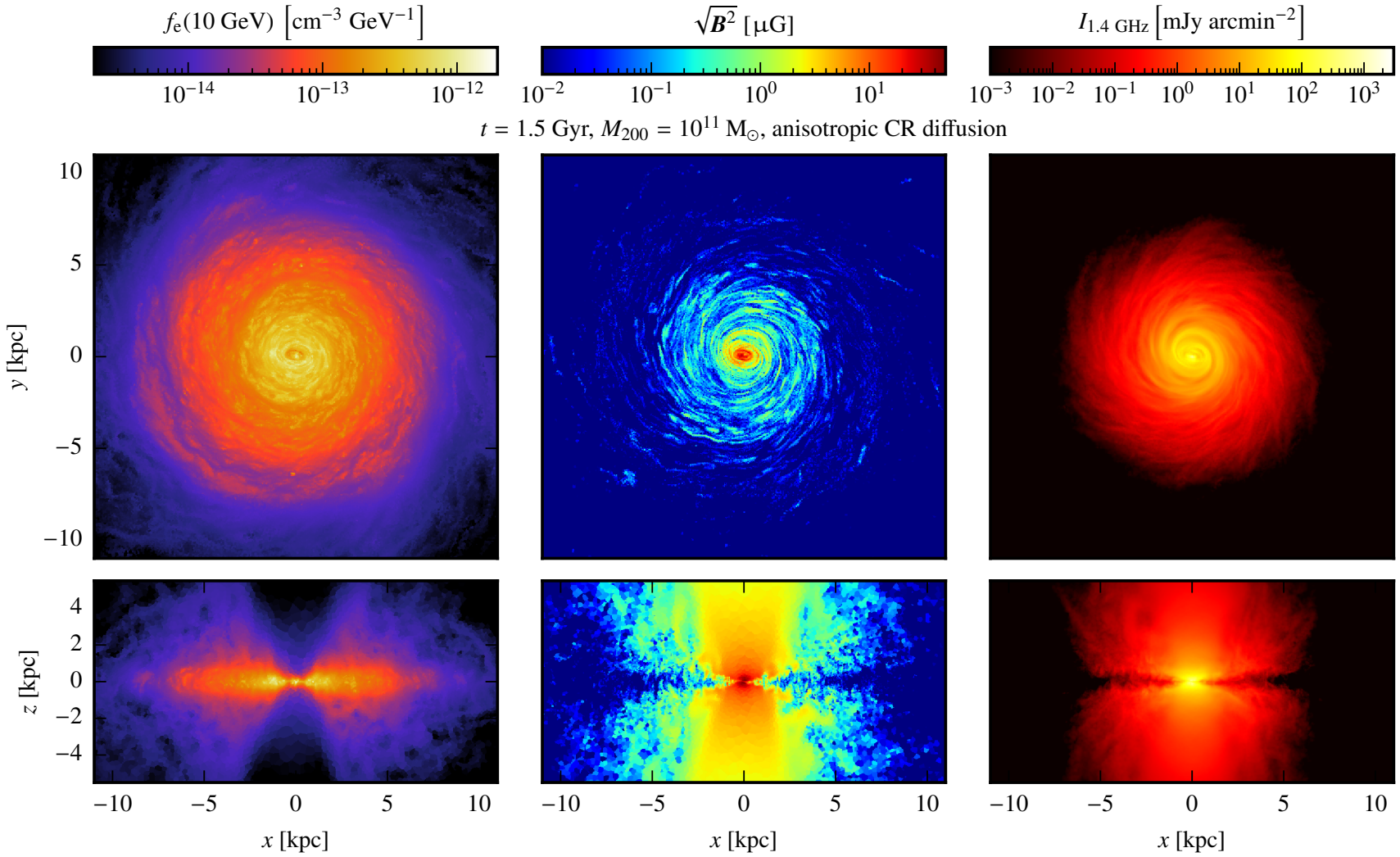
CP+ (2017)

Simulated radio emission: $10^{12}\,M_\odot$ halo



CP+ (2022)

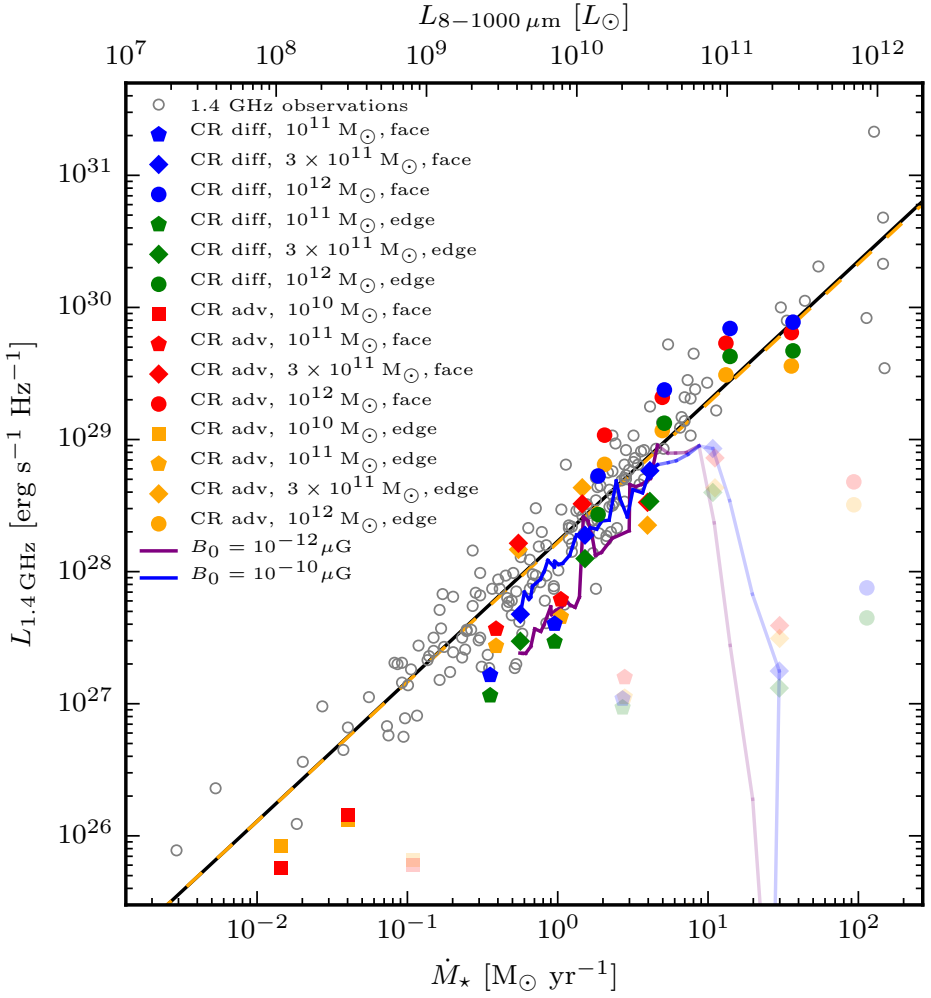
Simulated radio emission: 10^{11} $M_\odot$ halo



CP+ (2022)

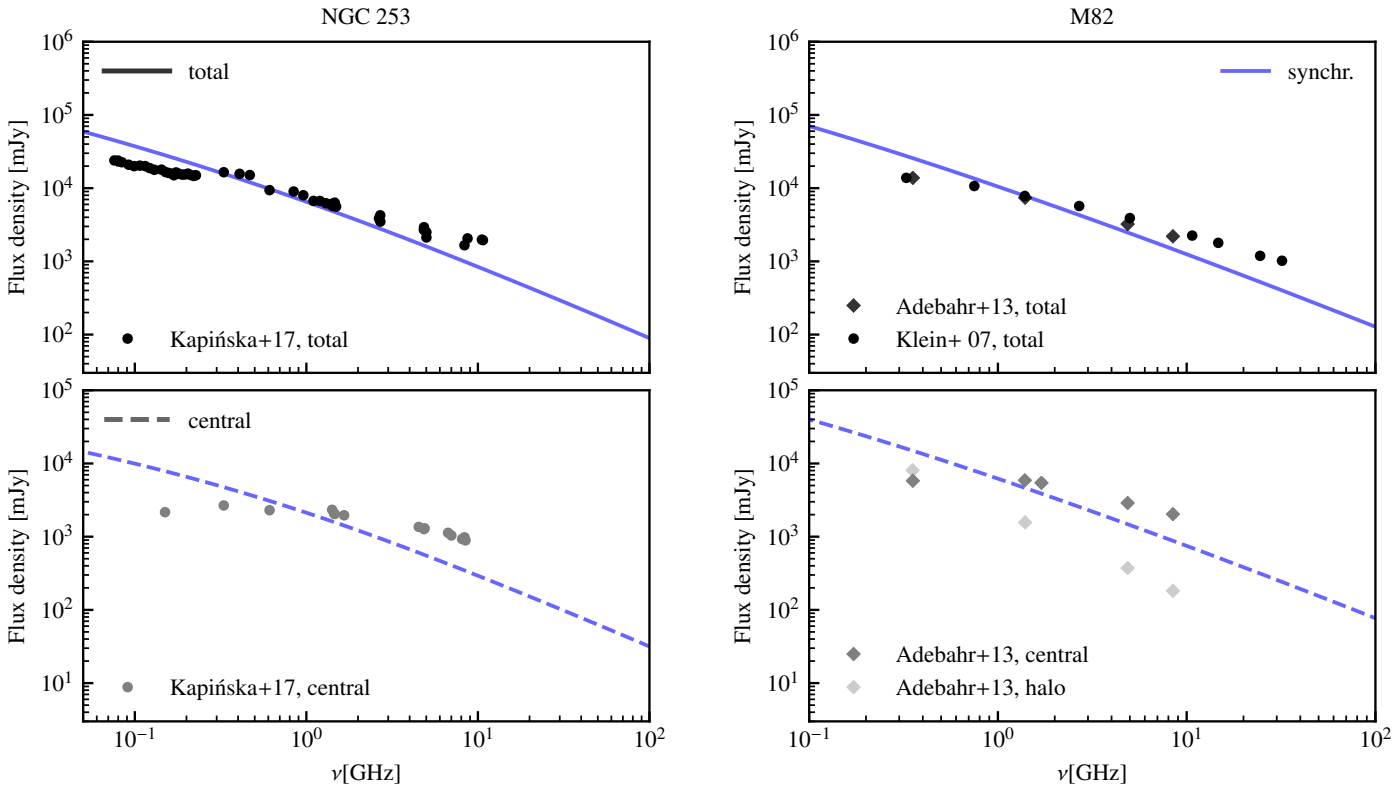
Far infra-red – radio correlation

Universal conversion: star formation → cosmic rays → radio



CP+ (2022)

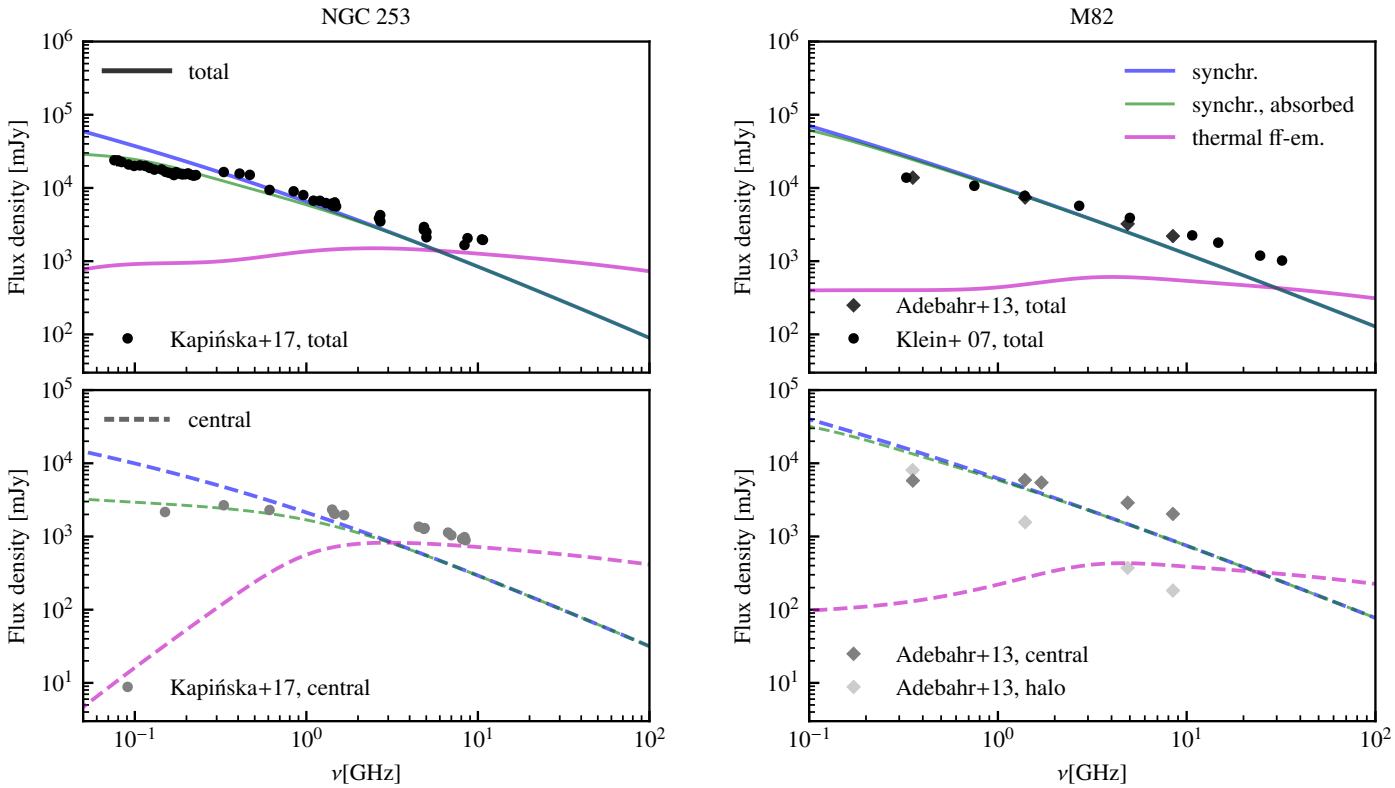
Radio-ray spectra of starburst galaxies



Werhahn, CP+ (2021c)

- synchrotron spectra too steep (cooling + diffusion losses)

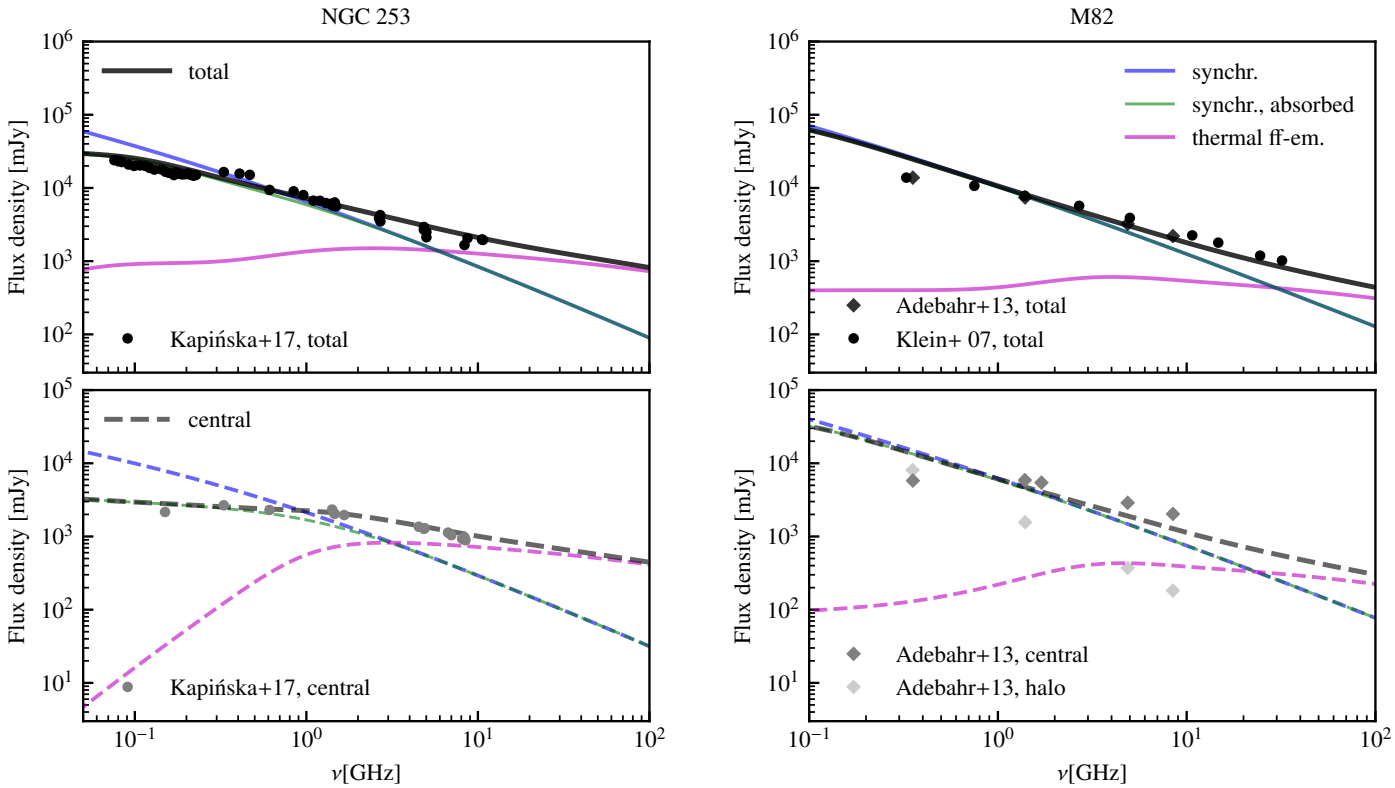
Radio-ray spectra of starburst galaxies



Werhahn, CP+ (2021c)

- synchrotron spectra too steep (cooling + diffusion losses)
- synchrotron absorption (low-ν) and thermal free-free emission (high-ν)

Radio-ray spectra of starburst galaxies



Werhahn, CP+ (2021c)

- synchrotron spectra too steep (cooling + diffusion losses)
- synchrotron absorption (low-ν) and thermal free-free emission (high-ν) required to match (total and central) spectra

Conclusions

- energy budget in large galaxies is dominated by CR pressure
  $\Rightarrow$ CRs suppress star formation and launch galactic winds
- small-scale dynamo grows magnetic fields in isolated galaxies: driven by (i) corrugated accretion shock and (ii) Kelvin-Helmholtz body modes excited by disk-halo velocity shear
- small-scale dynamo clearly identified via growth rates, saturation at $\varepsilon_B \sim \varepsilon_{\rm turb}$, power spectra, magnetic curvature statistics

Conclusions

- energy budget in large galaxies is dominated by CR pressure
  $\Rightarrow$ CRs suppress star formation and launch galactic winds
- small-scale dynamo grows magnetic fields in isolated galaxies: driven by (i) corrugated accretion shock and (ii) Kelvin-Helmholtz body modes excited by disk-halo velocity shear
- small-scale dynamo clearly identified via growth rates, saturation at $\varepsilon_B \sim \varepsilon_{\rm turb}$, power spectra, magnetic curvature statistics
- magnetic fields saturate close to equipartition in Milky Way centers and sub-equipartition at larger radii and in dwarfs
  $\Rightarrow$ too simplified ISM modeling?
- global $L_{\rm FIR} - L_{\rm radio}$ reproduced for galaxies with saturated magnetic fields, scatter due to viewing angle and CR transport
- synchrotron absorption (low-ν) and thermal free-free emission (high-ν) required to flatten cooled radio synchrotron spectra

PICOGAL: From Plasma KInetics to COsmological GALaxy Formation

This project has received funding from the European Research Counsil (ERC) under the European Union's Horizon 2020 research and innovation program (grant agreement No PICOGAL–101019746).

AIP

Additional slides

Lorentz force: magnetic curvature and pressure

- Lorentz force density, expressed in terms of $\boldsymbol{B}$ in the MHD approximation:

$$\boldsymbol{f}_{\mathrm{L}} = \frac{1}{c}\boldsymbol{j} \times \boldsymbol{B} = \frac{1}{4\pi}(\nabla \times \boldsymbol{B}) \times \boldsymbol{B} = \frac{1}{4\pi}(\boldsymbol{B} \cdot \nabla)\boldsymbol{B} - \frac{1}{8\pi}\nabla B^2,$$

two terms on RHS are ***not*** magnetic curvature and pressure forces!

Lorentz force: magnetic curvature and pressure

- Lorentz force density, expressed in terms of $\boldsymbol{B}$ in the MHD approximation:

$$\boldsymbol{f}_\mathrm{L} = \frac{1}{c}\boldsymbol{j}\times\boldsymbol{B} = \frac{1}{4\pi}\left(\boldsymbol{\nabla}\times\boldsymbol{B}\right)\times\boldsymbol{B} = \frac{1}{4\pi}\left(\boldsymbol{B}\cdot\boldsymbol{\nabla}\right)\boldsymbol{B} - \frac{1}{8\pi}\boldsymbol{\nabla}B^2,$$

  two terms on RHS are ***not*** magnetic curvature and pressure forces!
- define $\boldsymbol{B} = B\boldsymbol{b}$, where $\boldsymbol{b}$ is the unit vector along $\boldsymbol{b}$ and rewrite $\boldsymbol{f}_\mathrm{L}$:

$$\begin{aligned}\boldsymbol{f}_\mathrm{L} &= \frac{B^2}{4\pi}\left(\boldsymbol{b}\cdot\boldsymbol{\nabla}\right)\boldsymbol{b} + \frac{1}{8\pi}\boldsymbol{b}(\boldsymbol{b}\cdot\boldsymbol{\nabla})B^2 - \frac{1}{8\pi}\boldsymbol{\nabla}B^2\\ &= \frac{B^2}{4\pi}\left(\boldsymbol{b}\cdot\boldsymbol{\nabla}\right)\boldsymbol{b} - \frac{1}{8\pi}\boldsymbol{\nabla}_\perp B^2 \equiv \boldsymbol{f}_\mathrm{c} + \boldsymbol{f}_\mathrm{p},\end{aligned}$$

  where $\boldsymbol{\nabla}_\perp = (\mathbf{1} - \boldsymbol{bb})\cdot\boldsymbol{\nabla}$ is the perpendicular gradient

Lorentz force: magnetic curvature and pressure

- Lorentz force density, expressed in terms of $\boldsymbol{B}$ in the MHD approximation:

$$\boldsymbol{f}_\mathrm{L} = \frac{1}{c}\boldsymbol{j}\times\boldsymbol{B} = \frac{1}{4\pi}(\boldsymbol{\nabla}\times\boldsymbol{B})\times\boldsymbol{B} = \frac{1}{4\pi}(\boldsymbol{B}\cdot\boldsymbol{\nabla})\,\boldsymbol{B} - \frac{1}{8\pi}\boldsymbol{\nabla}B^2,$$

  two terms on RHS are ***not*** magnetic curvature and pressure forces!

- define $\boldsymbol{B} = B\boldsymbol{b}$, where $\boldsymbol{b}$ is the unit vector along $\boldsymbol{b}$ and rewrite $\boldsymbol{f}_\mathrm{L}$:

$$\begin{aligned}\boldsymbol{f}_\mathrm{L} &= \frac{B^2}{4\pi}(\boldsymbol{b}\cdot\boldsymbol{\nabla})\,\boldsymbol{b} + \frac{1}{8\pi}\boldsymbol{b}(\boldsymbol{b}\cdot\boldsymbol{\nabla})B^2 - \frac{1}{8\pi}\boldsymbol{\nabla}B^2\\ &= \frac{B^2}{4\pi}(\boldsymbol{b}\cdot\boldsymbol{\nabla})\,\boldsymbol{b} - \frac{1}{8\pi}\boldsymbol{\nabla}_\perp B^2 \equiv \boldsymbol{f}_\mathrm{c} + \boldsymbol{f}_\mathrm{p},\end{aligned}$$

  where $\boldsymbol{\nabla}_\perp = (\mathbf{1} - \boldsymbol{bb})\cdot\boldsymbol{\nabla}$ is the perpendicular gradient

  $\Rightarrow$ $\boldsymbol{f}_\mathrm{c}$ is the magnetic curvature force and $\boldsymbol{f}_\mathrm{p}$ is $\perp$ mag. pressure force

Lorentz force: magnetic curvature and pressure

- Lorentz force density, expressed in terms of $\boldsymbol{B}$ in the MHD approximation:

$$\boldsymbol{f}_\mathrm{L} = \frac{1}{c}\boldsymbol{j}\times\boldsymbol{B} = \frac{1}{4\pi}(\boldsymbol{\nabla}\times\boldsymbol{B})\times\boldsymbol{B} = \frac{1}{4\pi}(\boldsymbol{B}\cdot\boldsymbol{\nabla})\,\boldsymbol{B} - \frac{1}{8\pi}\boldsymbol{\nabla}B^2,$$

  two terms on RHS are ***not*** magnetic curvature and pressure forces!

- define $\boldsymbol{B} = B\boldsymbol{b}$, where $\boldsymbol{b}$ is the unit vector along $\boldsymbol{b}$ and rewrite $\boldsymbol{f}_\mathrm{L}$:

$$\begin{aligned}\boldsymbol{f}_\mathrm{L} &= \frac{B^2}{4\pi}(\boldsymbol{b}\cdot\boldsymbol{\nabla})\,\boldsymbol{b} + \frac{1}{8\pi}\boldsymbol{b}(\boldsymbol{b}\cdot\boldsymbol{\nabla})B^2 - \frac{1}{8\pi}\boldsymbol{\nabla}B^2\\ &= \frac{B^2}{4\pi}(\boldsymbol{b}\cdot\boldsymbol{\nabla})\,\boldsymbol{b} - \frac{1}{8\pi}\boldsymbol{\nabla}_\perp B^2 \equiv \boldsymbol{f}_\mathrm{c} + \boldsymbol{f}_\mathrm{p},\end{aligned}$$

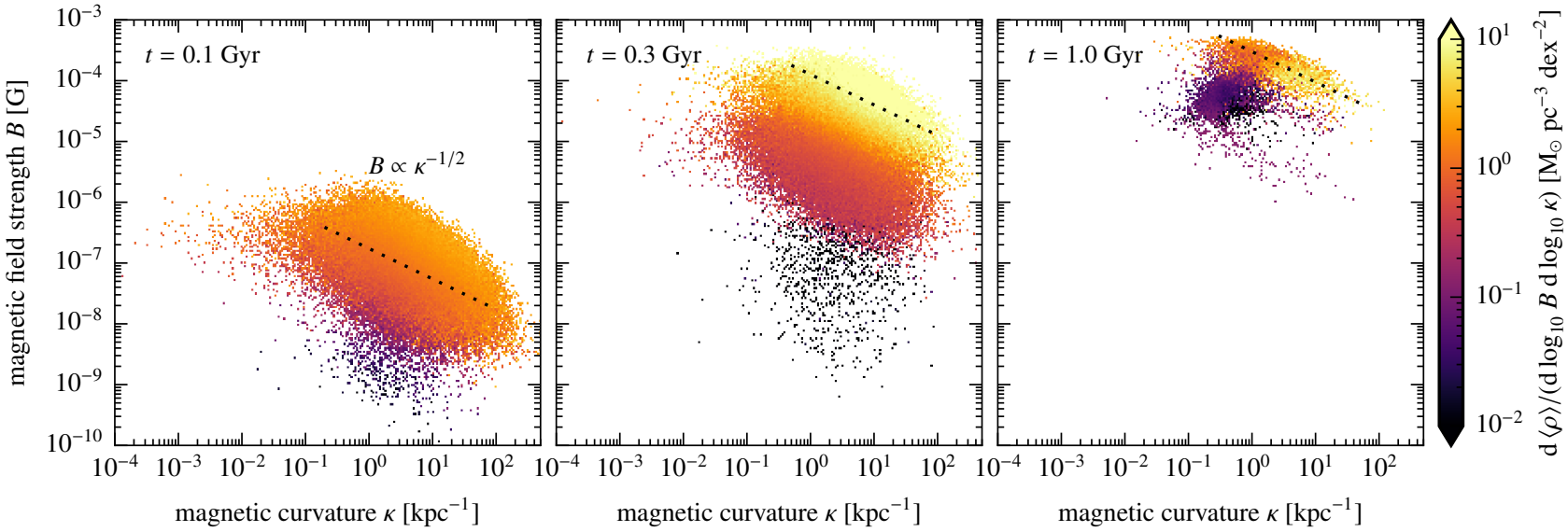
  where $\boldsymbol{\nabla}_\perp = (\mathbf{1} - \boldsymbol{bb})\cdot\boldsymbol{\nabla}$ is the perpendicular gradient

  $\Rightarrow$ $\boldsymbol{f}_\mathrm{c}$ is the magnetic curvature force and $\boldsymbol{f}_\mathrm{p}$ is $\perp$ mag. pressure force

- define a magnetic curvature:

$$\boldsymbol{\kappa} \equiv (\boldsymbol{b}\cdot\boldsymbol{\nabla})\boldsymbol{b} = \frac{(\mathbf{1} - \boldsymbol{bb})\cdot(\boldsymbol{B}\cdot\boldsymbol{\nabla})\,\boldsymbol{B}}{B^2} = \frac{4\pi\,\boldsymbol{f}_\mathrm{c}}{B^2},$$

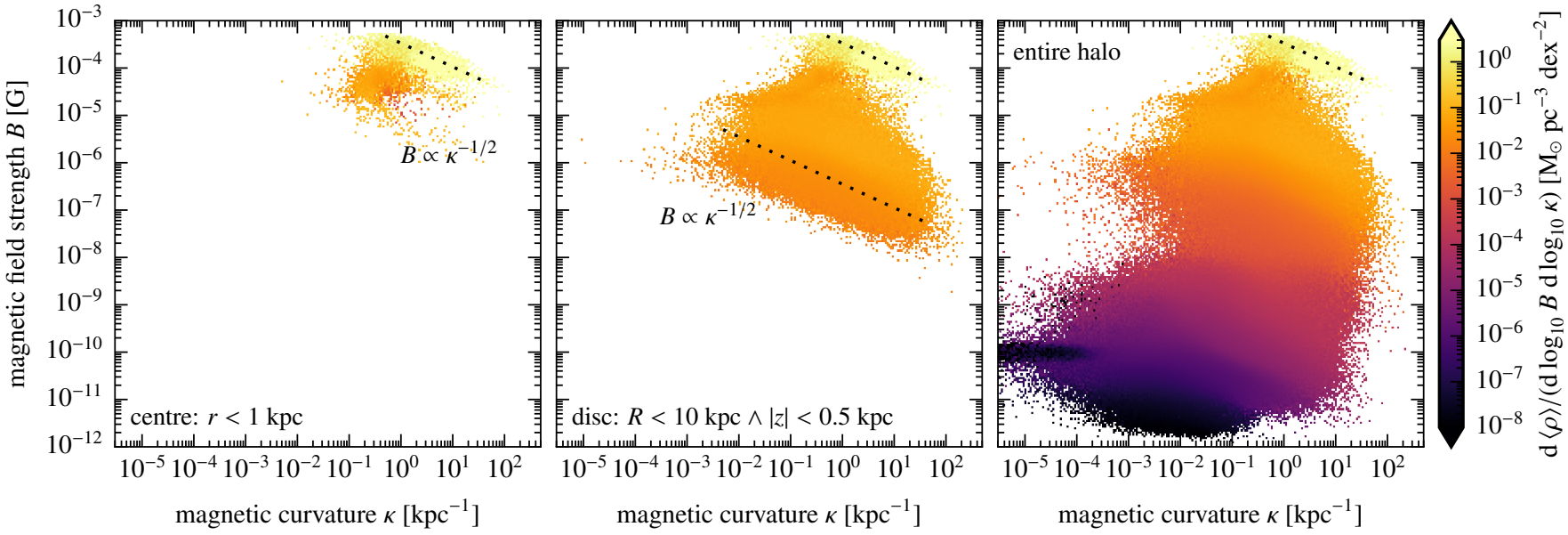
Correlating magnetic curvature to field strength – 1



CP+ (2022)

- emergence of magnetic field and curvature in the galaxy centre
- panels show from left to right:
  - (i) exponential growth phase in the kinematic regime
  - (ii) growth of the magnetic coherence scale
  - (iii) saturation phase of the magnetic dynamo

Correlating magnetic curvature to field strength – 2



CP+ (2022)

- separating different dynamo processes by spatial cuts during saturated phase
- superposition of different small-scale dynamos
- each dynamo grows at a different characteristic density or eddy turnover time

Literature for the talk

Cosmic rays, magnetic dynamo, and radio emission in galaxies:

- Pfrommer, Werhahn, Pakmor, Girichidis, Simpson, *Simulating radio synchrotron emission in star-forming galaxies: small-scale magnetic dynamo and the origin of the far infrared-radio correlation,* 2022, MNRAS, 515, 4229.
- Werhahn, Pfrommer, Girichidis, Puchwein, Pakmor, *Cosmic rays and non-thermal emission in simulated galaxies. I. Electron and proton spectra explain Voyager-1 data,* 2021a, MNRAS 505, 3273.
- Werhahn, Pfrommer, Girichidis, Winner, *Cosmic rays and non-thermal emission in simulated galaxies. II. γ-ray maps, spectra and the far infrared-γ-ray relation,* 2021b, MNRAS, 505, 3295.
- Werhahn, Pfrommer, Girichidis, *Cosmic rays and non-thermal emission in simulated galaxies. III. probing cosmic ray calorimetry with radio spectra and the FIR-radio correlation,* 2021c, MNRAS, 508, 4072.
- Pfrommer, Pakmor, Simpson, Springel, *Simulating gamma-ray emission in star-forming galaxies,* 2017, ApJL, 847, L13.
- Pfrommer, Pakmor, Schaal, Simpson, Springel, *Simulating cosmic ray physics on a moving mesh,* 2017, MNRAS, 465, 4500.