Magnetic dynamo in galaxies and the origin of the far-infrared–radio correlation

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in collaboration with

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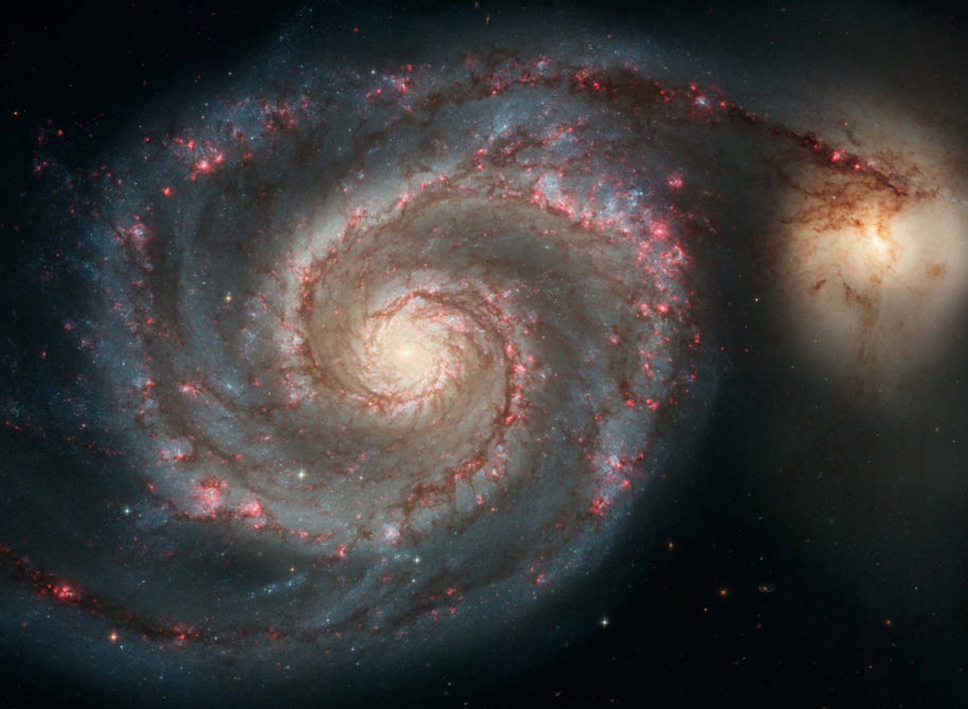
Building Galaxies from Scratch, Vienna, Feb 2024



Outline

1. Galactic magnetic dynamos
   - Magnetic growth and saturation
   - Identifying main growth phases
   - Small-scale dynamo
2. Cosmic rays and radio emission
   - Steady-state modeling and cosmic rays
   - Far-infrared–radio correlation
   - Radio spectra

Origin and growth of magnetic fields

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

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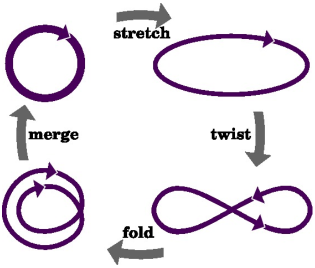

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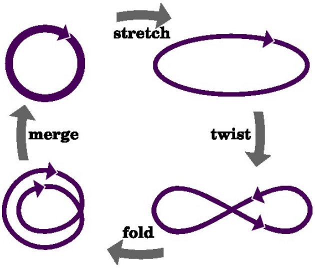
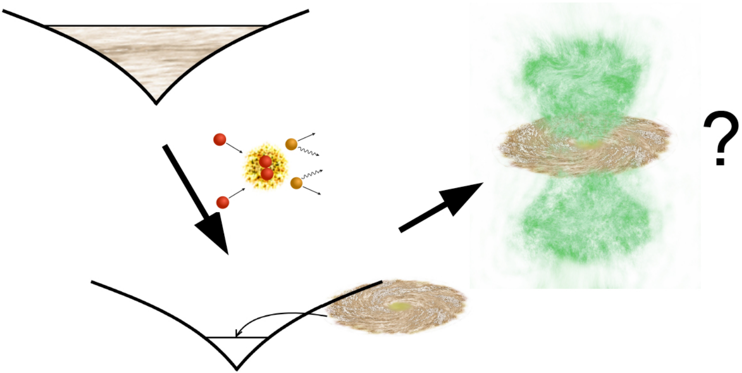
- ***Growth.*** A small-scale (fluctuating) dynamo is an MHD process, in which the kinetic (turbulent) energy is converted into magnetic energy: the mechanism relies on magnetic fields to become stronger when the field lines are stretched
- ***Saturation.*** Field growth stops at a sizeable fraction of the turbulent energy when magnetic forces become strong enough to resist the stretching and folding motions



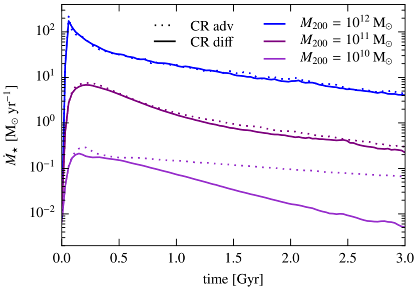
Galaxy simulations with cosmic rays



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: $\{10^{10}, 10^{11}, 3\times10^{11}, 10^{12}\}\ M_\odot$

Time evolution of SFR and energy densities



CP+ (2022)

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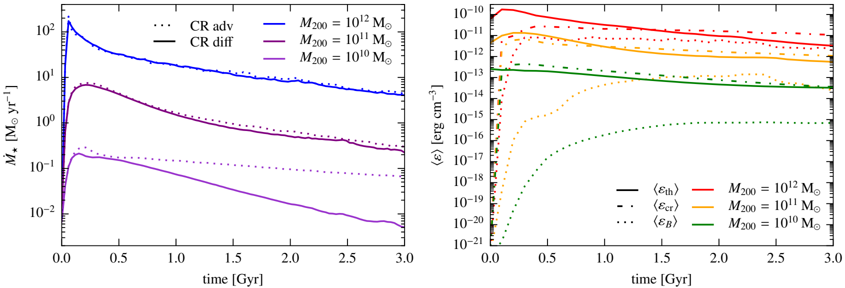
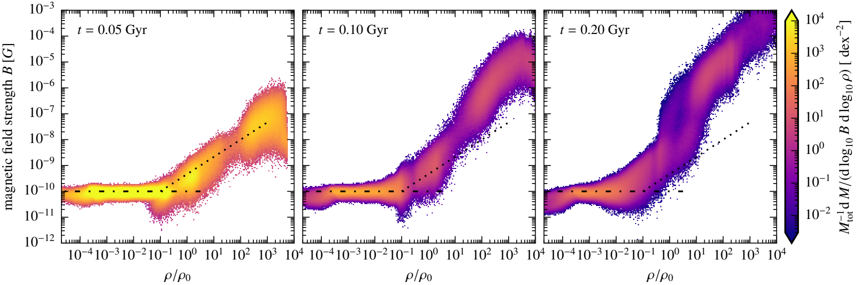


CP+ (2022)

- 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 galaxies than in dwarfs

Identifying different growth phases



CP+ (2022)

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

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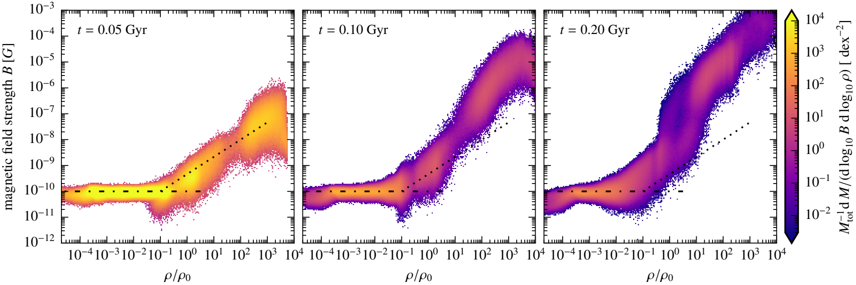

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- *2nd phase:* additional growth at high density ρ with small dynamical times $t_{\rm dyn} \sim (G\rho)^{-1/2}$

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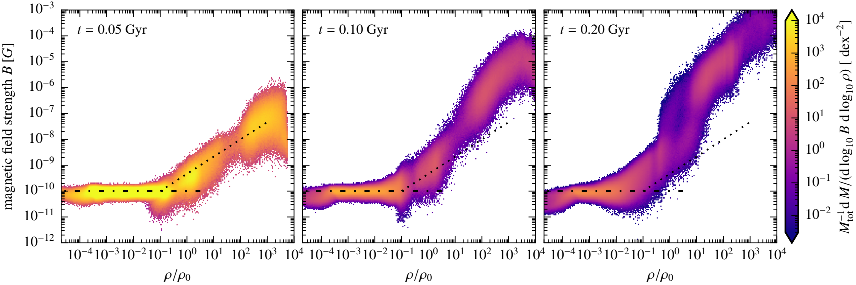

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- *3rd phase:* growth migrates to lower ρ on larger scales $\propto \rho^{-1/3}$

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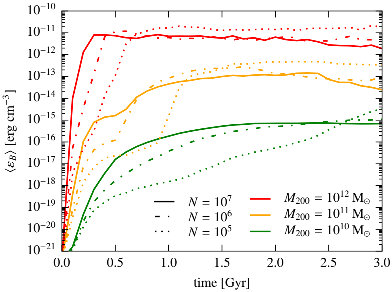
Studying growth rate with numerical resolution



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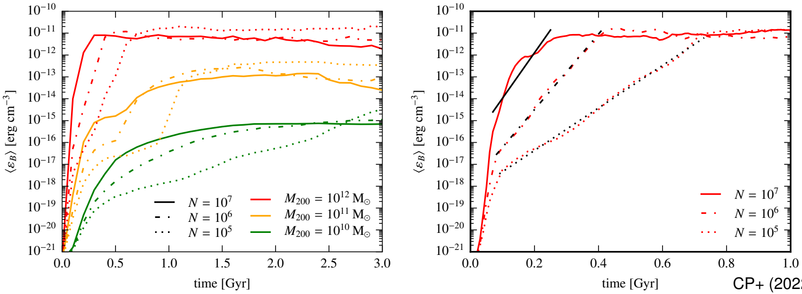

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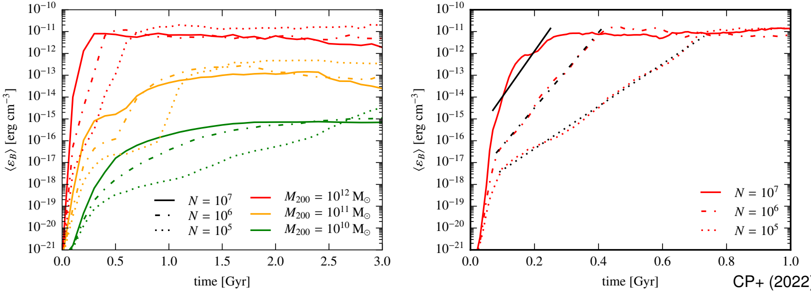


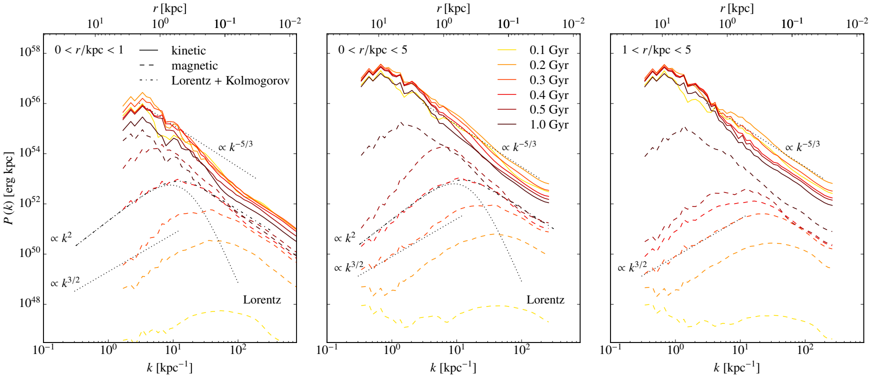
CP+ (2022)

- ***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

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

Kinetic and magnetic power spectra

Fluctuating small-scale dynamo in different analysis regions



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

Steady-state cosmic ray spectra

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

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

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

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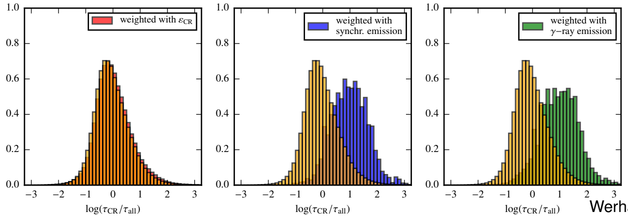
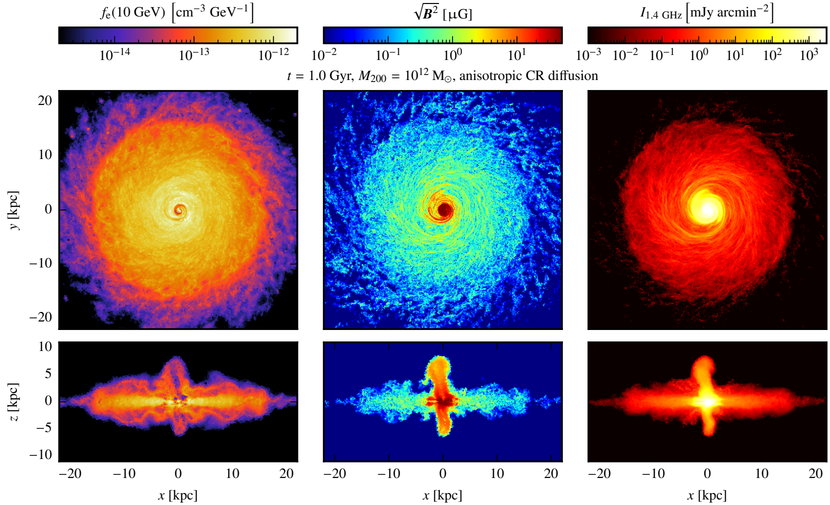
- steady state assumption is fulfilled in disk and in regions dominating the non-thermal emission but not at low densities, at SNRs and in outflows



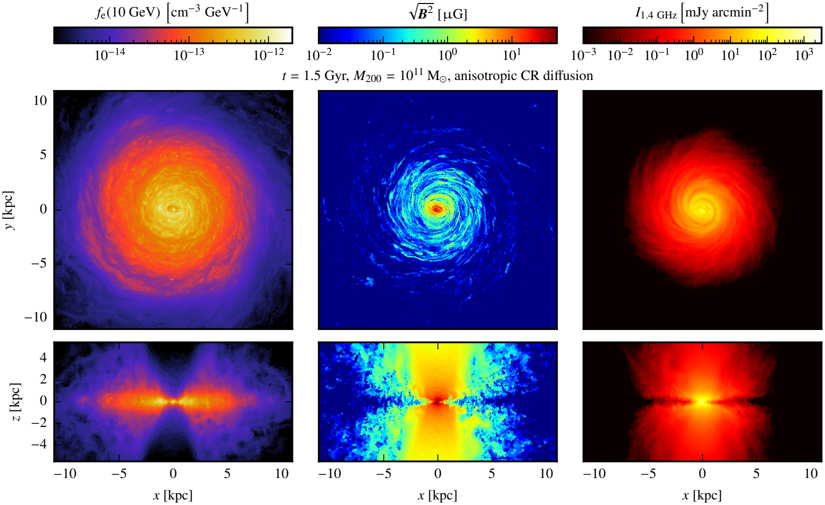
Werhahn+ (2021a)

Simulated radio emission: $10^{12}\,\mathrm{M}_\odot$ halo



CP+ (2022)

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



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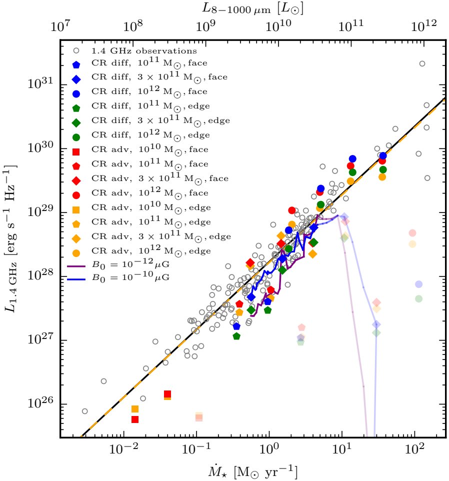
Far infra-red – radio correlation

Universal conversion: star formation → cosmic rays → radio



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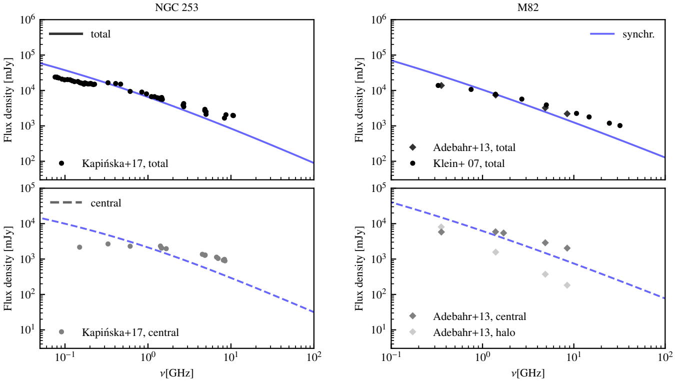
Radio-ray spectra of starburst galaxies



Werhahn, CP+ (2021c)

- synchrotron spectra too steep (cooling + diffusion losses)

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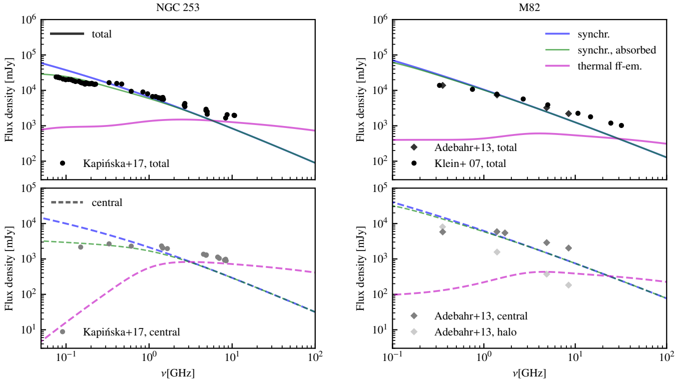

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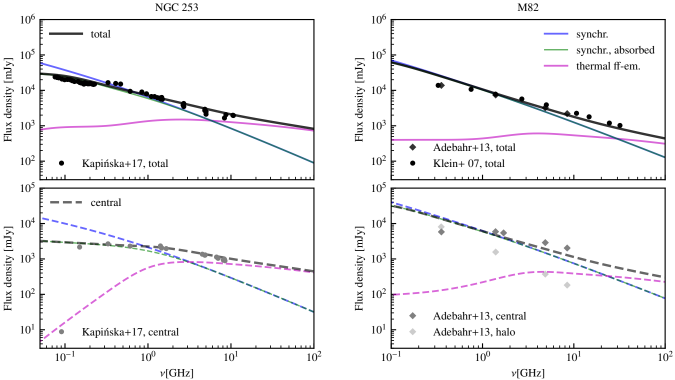

Werhahn, CP+ (2021c)

- 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

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Conclusions

- energy budget is dominated by CR pressure
  $\Rightarrow$ CRs suppress star formation and launch galactic winds
- small-scale dynamo clearly identified via growth rates, saturation at $\varepsilon_B \sim \varepsilon_{\mathrm{turb}}$, 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?

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Conclusions

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- 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).

Literature for the talk

Cosmic rays and non-thermal 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.

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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!

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

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

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

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

- define a magnetic curvature:

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

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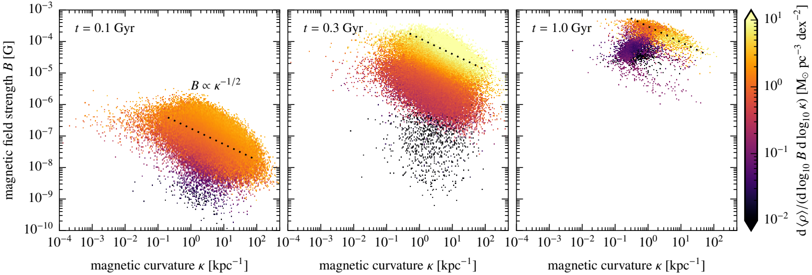
Correlating magnetic curvature to field strength – 1

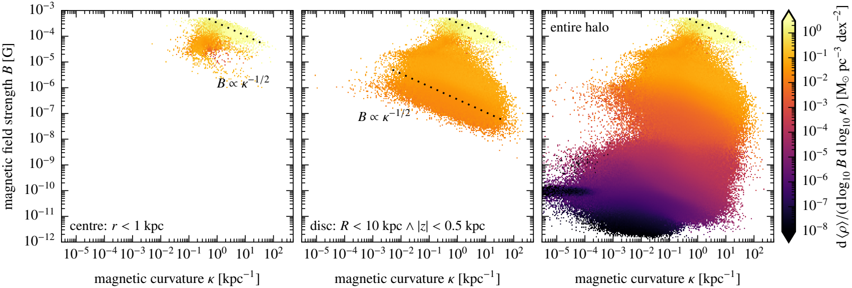


CP+ (2022)

- 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

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