Cosmic ray feedback and magnetic dynamos in galaxy formation

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in collaboration with

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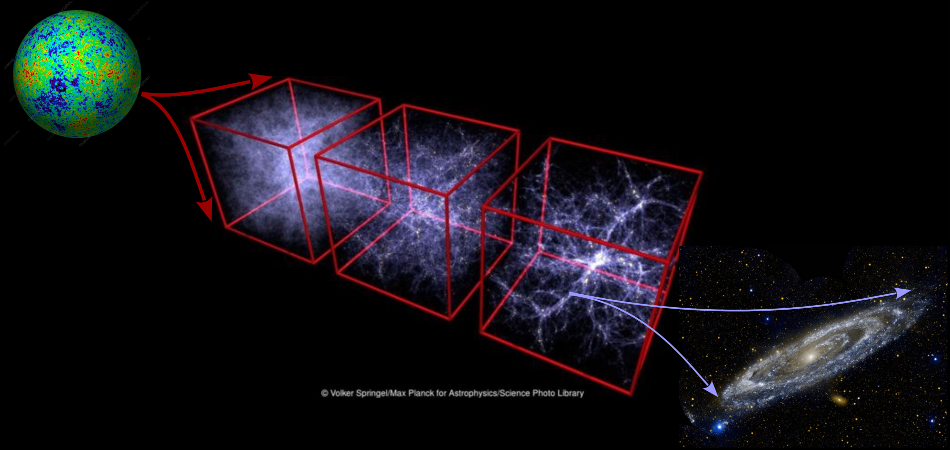
IAP Conference on galaxy formation, Paris, Dec 2023

Cosmological galaxy formation



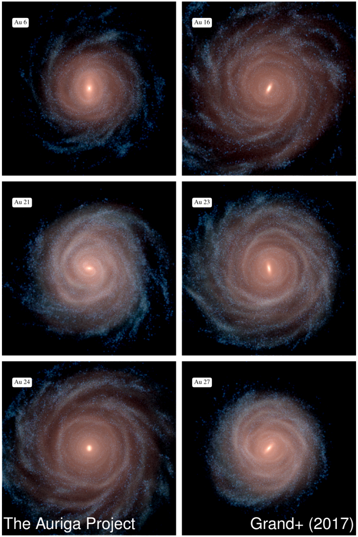
Cosmic rays in cosmological galaxy simulations

The galaxy formation model

- primordial and metal line cooling
- sub-resolution model for star formation (Springel+ 03)
- mass and metal return from stars to ISM
- cold dense gas stabilised by pressurised ISM
- thermal and kinetic energy from supernovae modelled by isotropic wind – launched outside of SF region
- black hole seeding and accretion model (Springel+ 05)
- thermal feedback from AGN in radio and quasar mode
- uniform magnetic field of 10^{-10} G seeded at $z = 128$

Simulation suite (Buck, CP+ 2020)

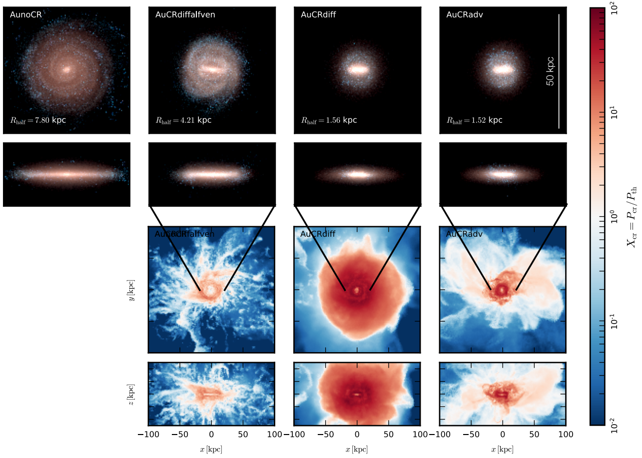
- 2 galaxies, baryons with $5 \times 10^4\,M_\odot$ $\sim 5 \times 10^6$ resolution elements in halo, 2×10^6 star particles
- 4 models with different CR physics for each galaxy:
  - no CRs
  - CR advection
  - + CR anisotropic diffusion
  - + CR Alfvén wave cooling



The Auriga Project Grand+ (2017)

Cosmic rays in cosmological galaxy simulations

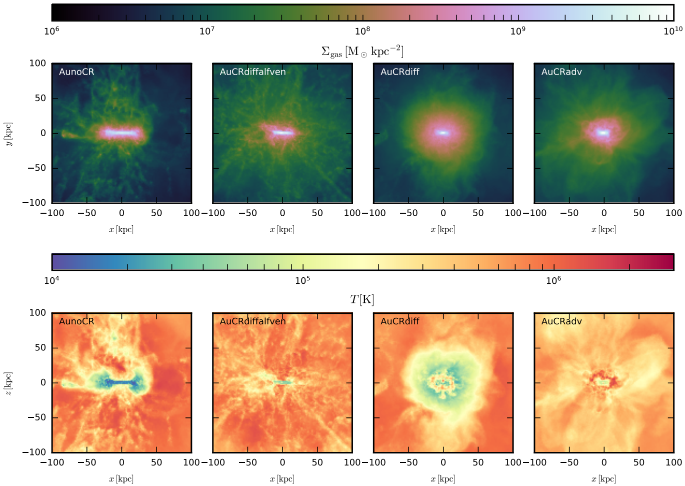
Auriga MHD models: CR transport changes disk sizes



Buck, CP, Pakmor, Grand, Springel (2020)

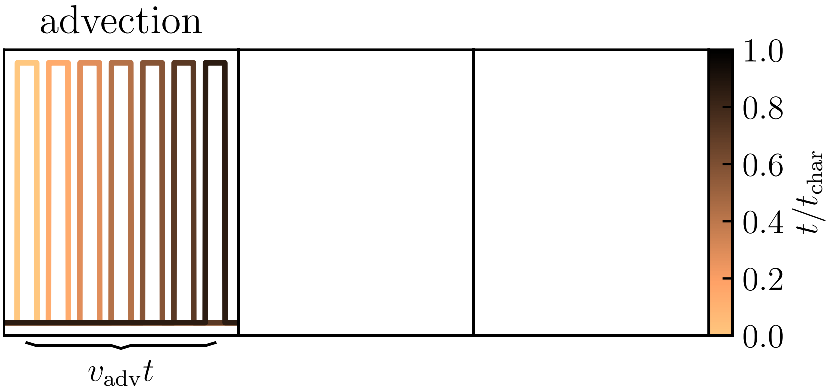
Cosmic rays in cosmological galaxy simulations

Auriga MHD models: CR transport modifies the circum-galactic medium



Buck, CP, Pakmor, Grand, Springel (2020)

Modes of CR propagation



Thomas, CP, Enßlin (2020)

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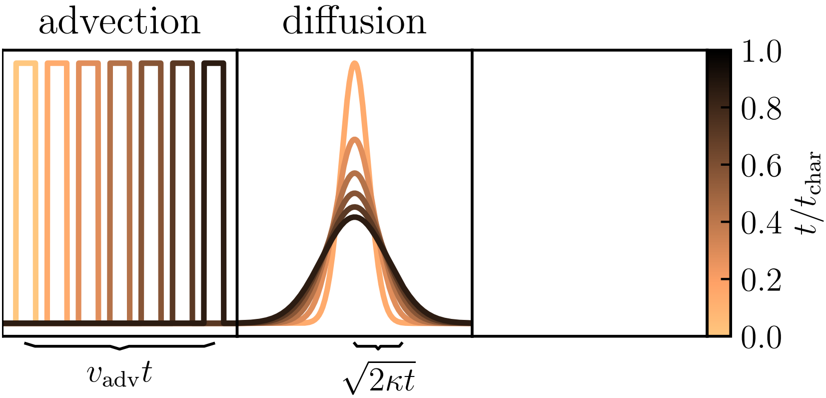

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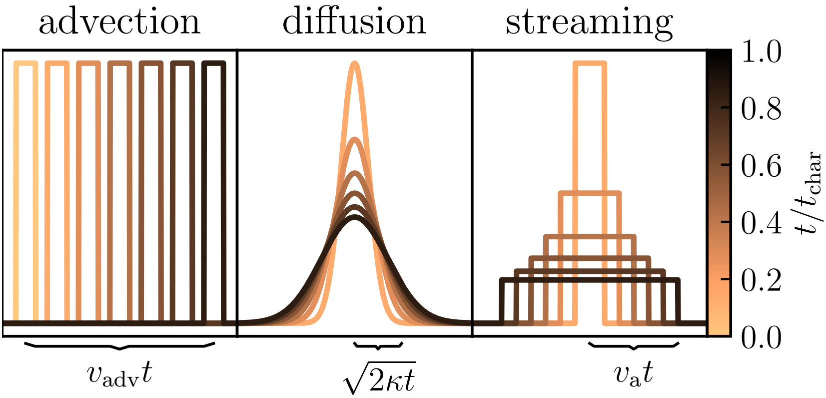


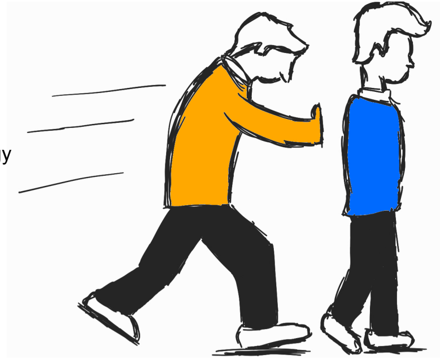
Thomas, CP, Enßlin (2020)

CR interactions with Alfvén waves

acceleration
+ energy transfer

CRs

are … fast
will … lose energy



Alfvén waves

are … slow
will … gain energy

slide concept Thomas

CR interactions with Alfvén waves

acceleration
+ energy transfer

Alfvén waves

are … fast
will … lose energy

CRs

are … slow
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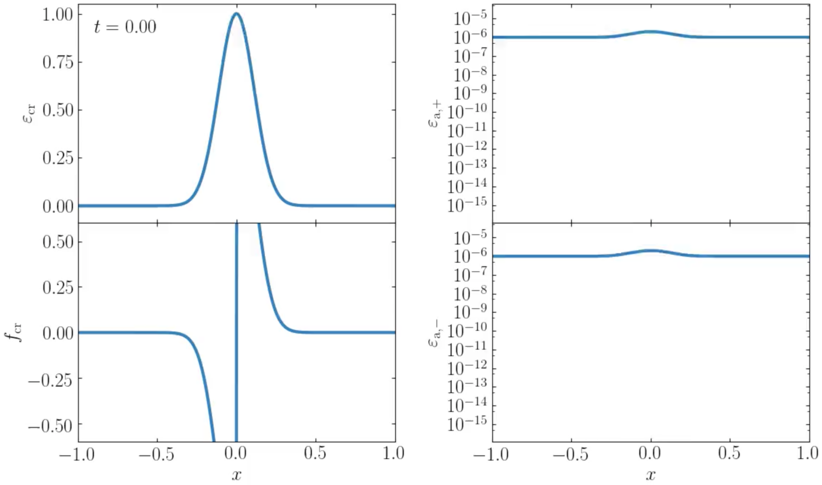
slide concept Thomas

Non-equilibrium CR streaming and diffusion

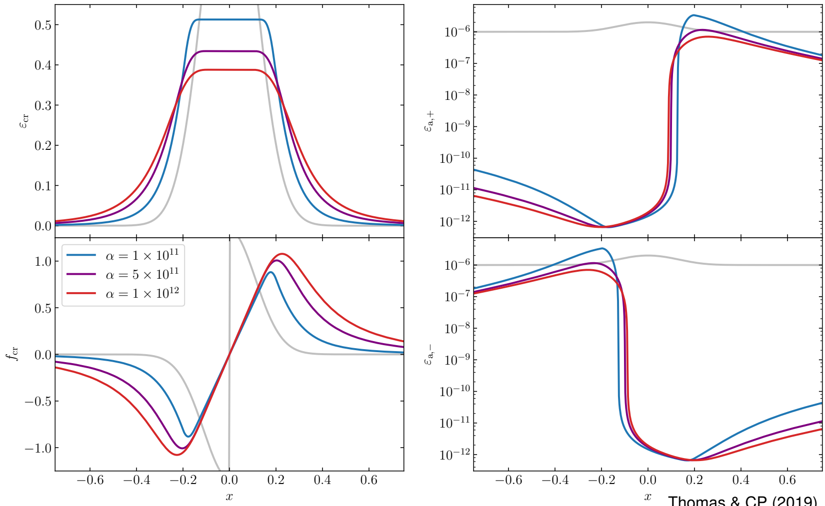
Coupling the evolution of CR and Alfvén wave energy densities



Thomas & CP (2019)

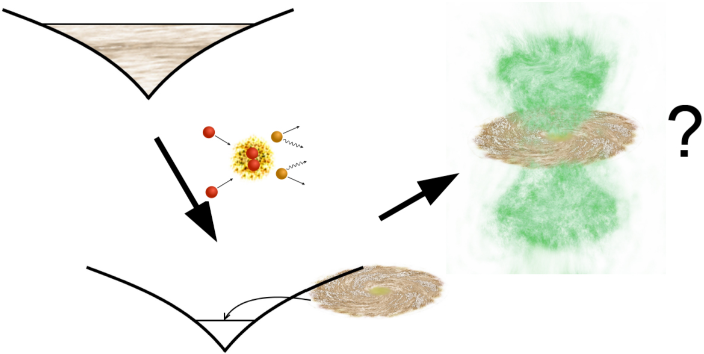
Non-equilibrium CR streaming and diffusion

Varying damping rate of Alfvén waves modulates the diffusivity of solution



Thomas & CP (2019)

1. Galaxy simulations with cosmic ray feedback

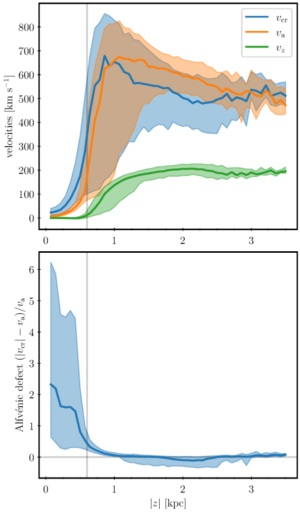


Thomas, CP, Pakmor (2023)
Cosmic ray-driven galactic winds: transport modes of cosmic rays and Alfvén-wave dark regions

MHD + Alfvén wave regulated CR hydrodynamics: $10^{11}\,\mathrm{M}_\odot$ halo

AIP

Wind launching



Thomas, CP, Pakmor (2023)

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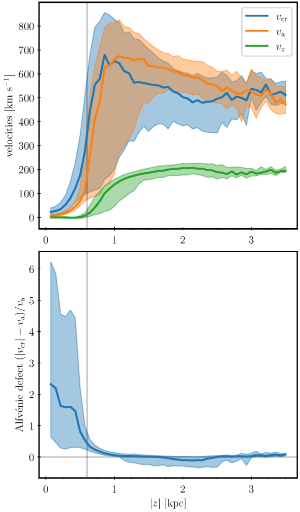

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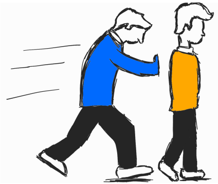
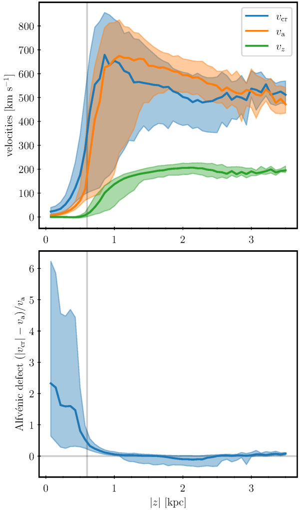


- CRs faster than Alfvén waves
  $\Rightarrow$ Alfvén waves gain energy

Wind launching



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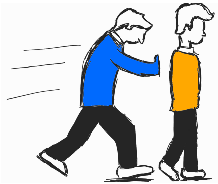
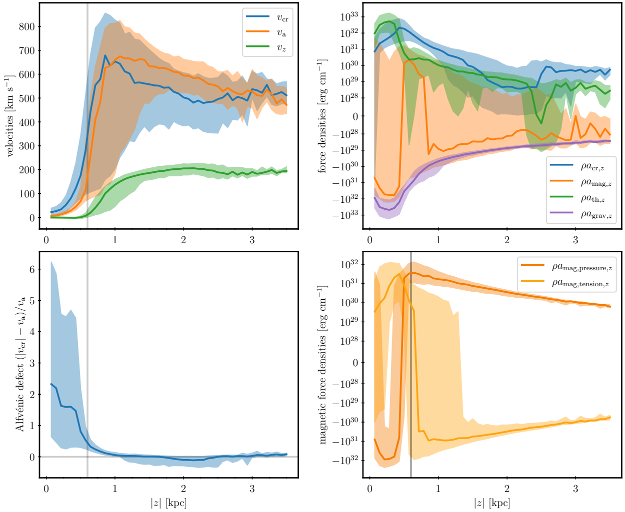


- CRs faster than Alfvén waves
  ⇒ Alfvén waves gain energy
- Alfvén waves are supported by thermal plasma
  ⇒ plasma gets accelerated

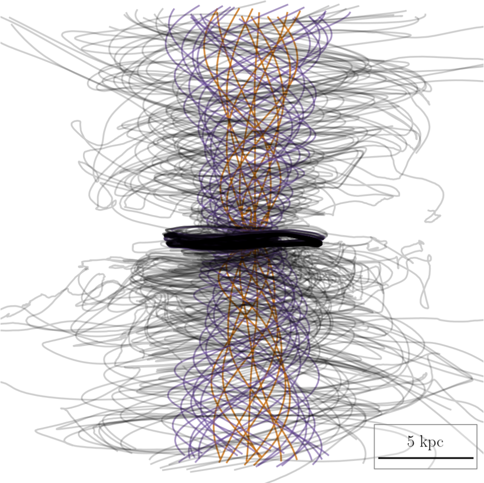
AIP

Wind launching



Thomas, CP, Pakmor (2023)

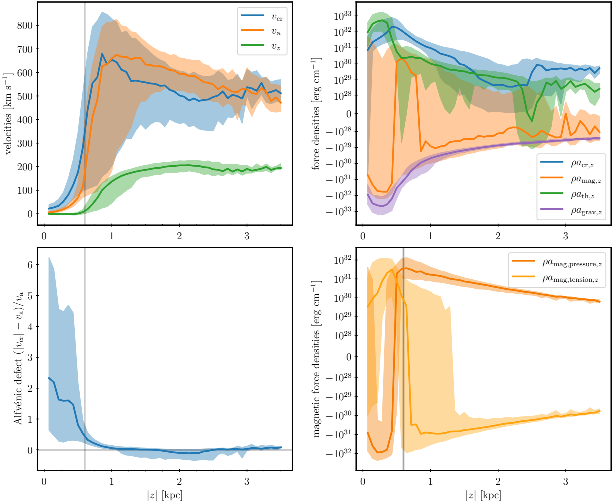
Magnetic field topology



Thomas, CP, Pakmor (2023)

AIP

Wind launching



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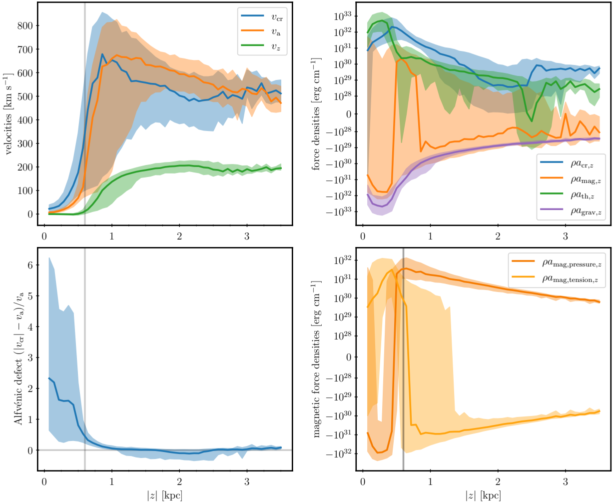

$$\rho \boldsymbol{a}_{\text{mag,pressure}} = -\nabla \boldsymbol{B}^2/2$$
$$\rho \boldsymbol{a}_{\text{mag,tension}} = +(\boldsymbol{B}\cdot\nabla)\,\boldsymbol{B}$$

Thomas, CP, Pakmor (2023)

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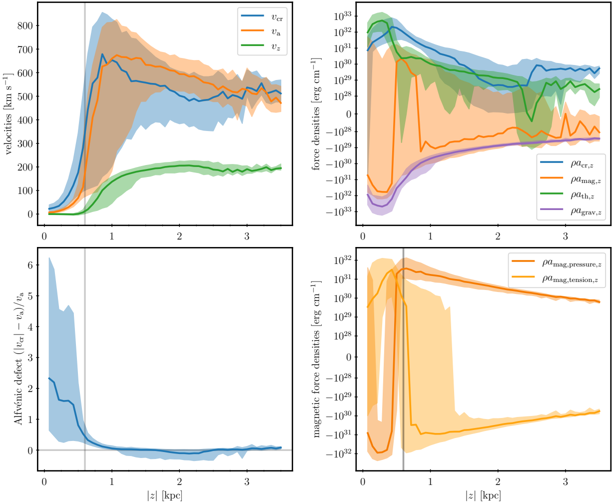

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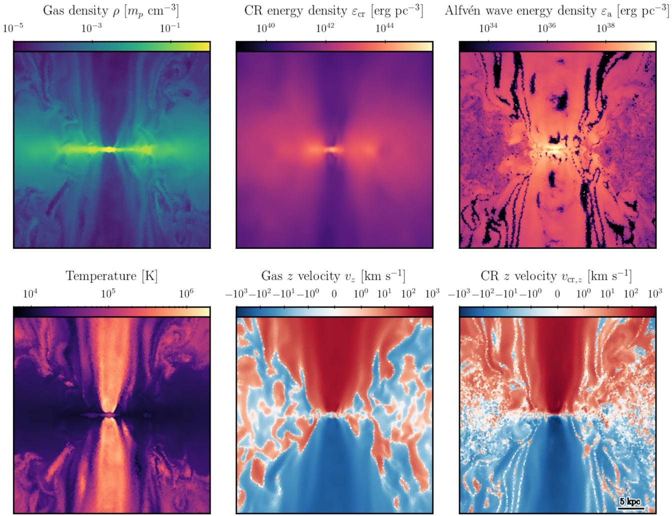
$$\rho \boldsymbol{a}_{\text{mag,tension}} = +(\boldsymbol{B} \cdot \boldsymbol{\nabla})\, \boldsymbol{B}$$

ignoring toroidal field components:

$$\rho a_{\text{mag,pressure},z} = -(\partial_z B_z) B_z$$
$$\rho a_{\text{mag,tension},z} = +B_z (\partial_z B_z)$$

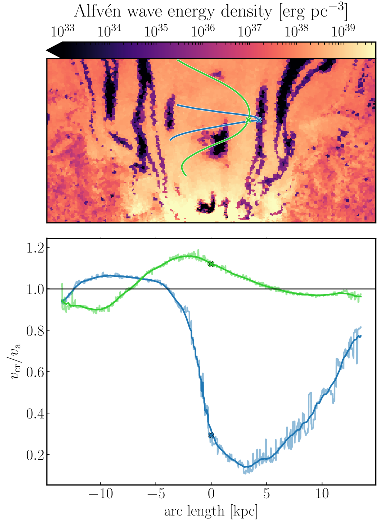
Thomas, CP, Pakmor (2023)

Wind properties



Thomas, CP, Pakmor (2023)

What is the origin of the Alfvén wave dark regions?



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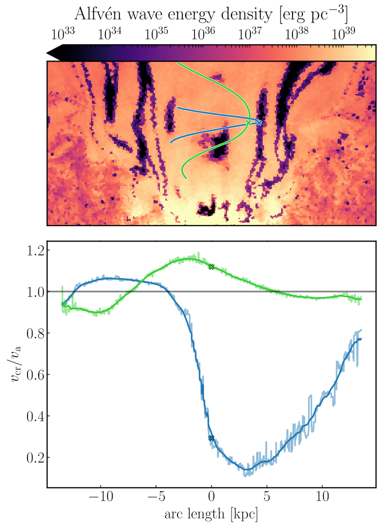

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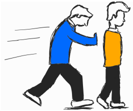

CRs faster than AWs
AWs gain energy

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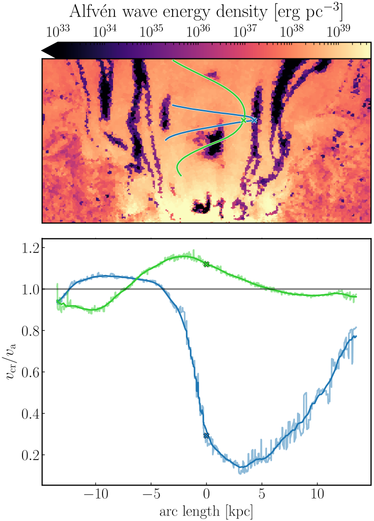

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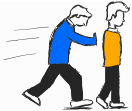

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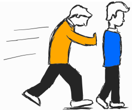
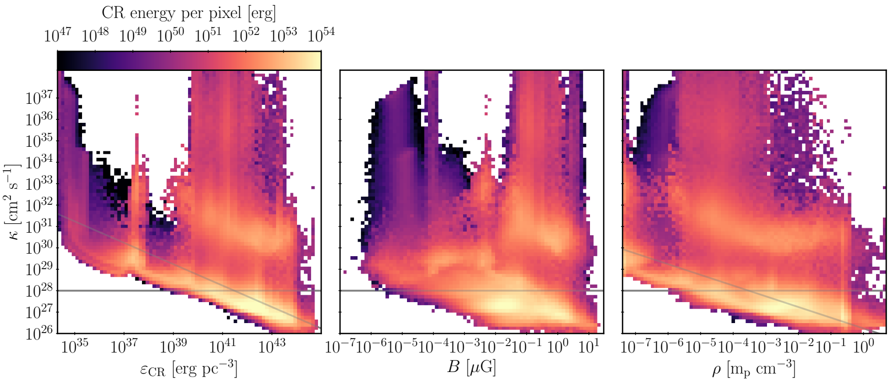


CRs slower than AWs
AWs lose energy

Parallel CR diffusion coefficient



Thomas, CP, Pakmor (2023)

- ***The CR diffusion coefficient is not constant*** but strongly depends on environment!

AIP

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

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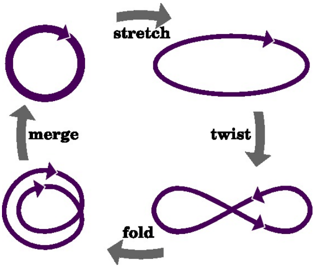

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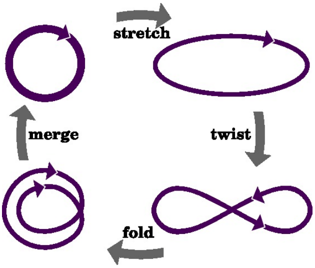
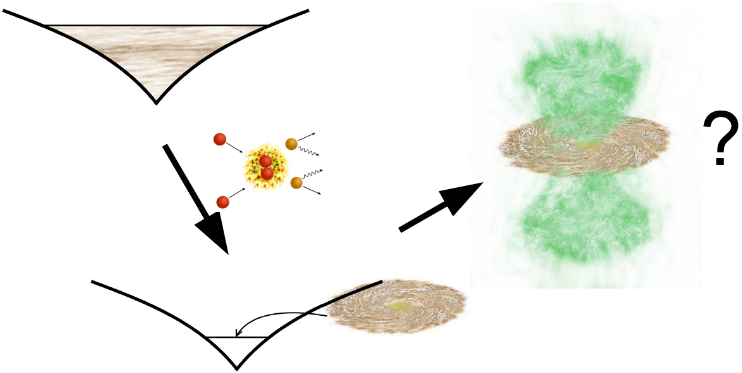
- ***Saturation.*** Field growth stops at a sizeable fraction of the turbulent energy when magnetic forces become strong enough to resist the stretching and folding motions



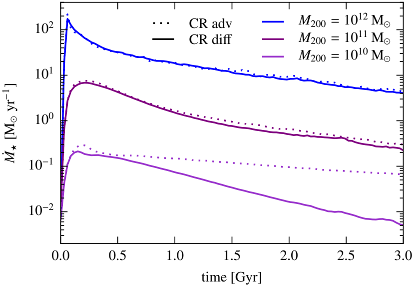
2. Galactic magnetic dynamo

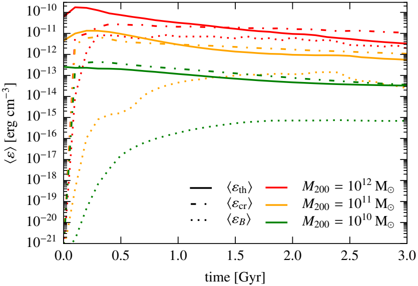


CP, Werhahn, Pakmor, Girichidis, Simpson (2022)
Simulating radio synchrotron emission in star-forming galaxies: small-scale magnetic dynamo and the origin of the far-infrared–radio correlation

MHD + cosmic ray advection + diffusion: $\{10^{10}, 10^{11}, 3\times10^{11}, 10^{12}\}\ \mathrm{M}_\odot$

Time evolution of SFR and energy densities



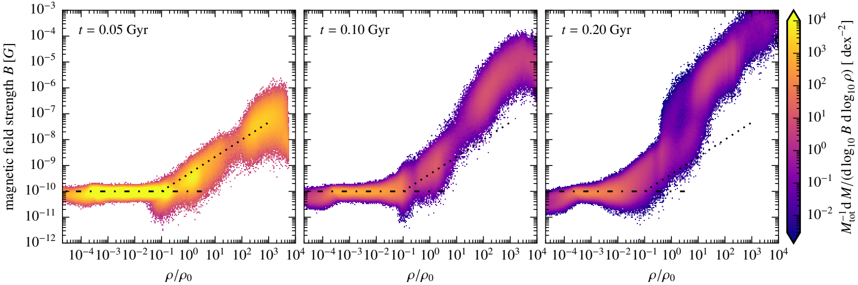


CP+ (2022)

- 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 galaxies than in dwarfs

AIP

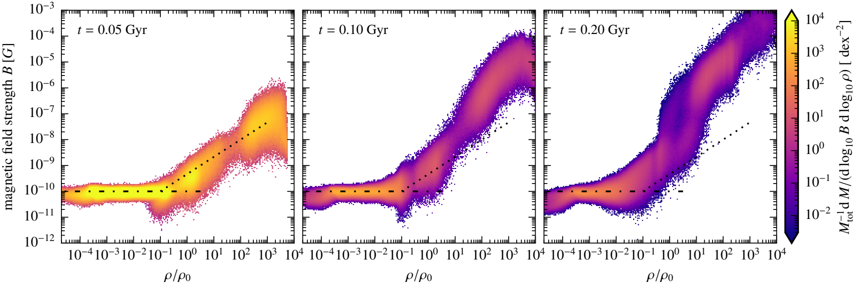
Identifying different growth phases



CP+ (2022)

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

Identifying different growth phases



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

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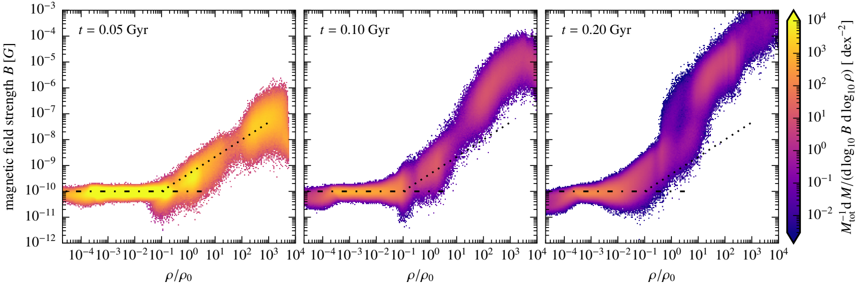
Identifying different growth phases



CP+ (2022)

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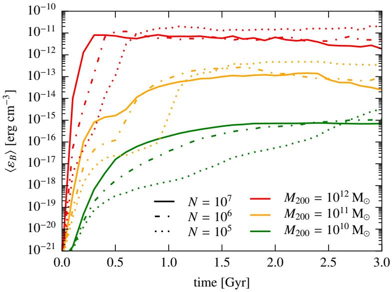
- *2nd phase:* additional growth at high density ρ with small dynamical times $t_{\rm dyn} \sim (G\rho)^{-1/2}$
- *3rd phase:* growth migrates to lower ρ on larger scales $\propto \rho^{-1/3}$

AIP

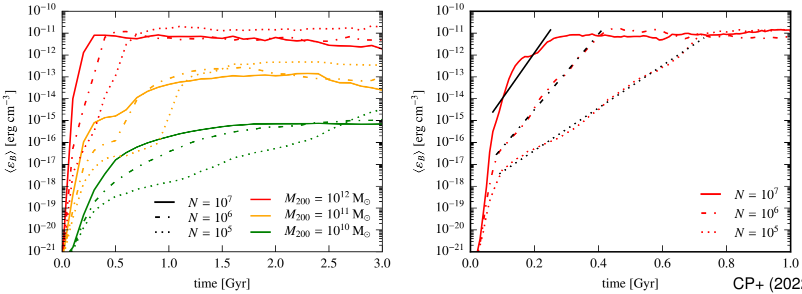
Studying growth rate with numerical resolution



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



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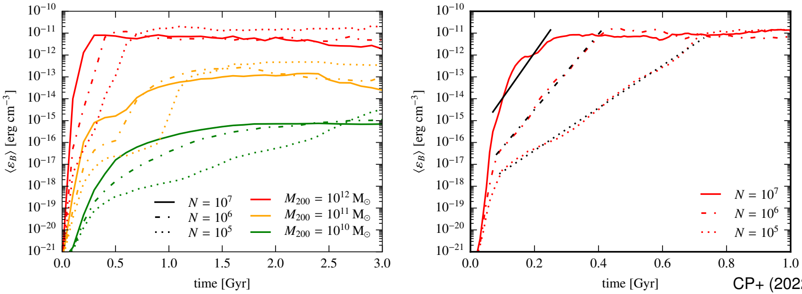
Studying growth rate with numerical resolution



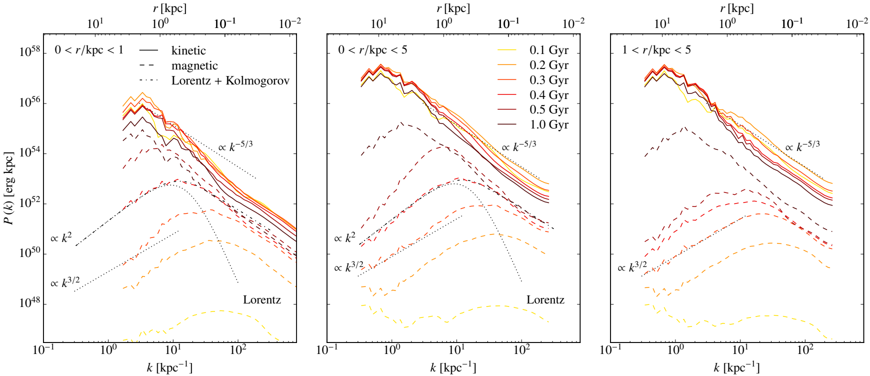
CP+ (2022)

- ***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

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

Kinetic and magnetic power spectra

Fluctuating small-scale dynamo in different analysis regions



CP+ (2022)

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

Conclusions for cosmic ray physics in galaxies

CR transport:

- CRs modify galaxy disk sizes and the circumgalactic medium
- accruate modeling requires CR transport mediated by Alfvén waves and coupled to magneto-hydrodynamics
- Diffusion coefficient emerges from CR-wave interactions

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CRs and magnetic fields in galaxy formation:

- small-scale dynamo grows magnetic field to equipartition with turbulent energy density
- CR feedback drives galactic winds & slows down star formation

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

CR hydrodynamics:

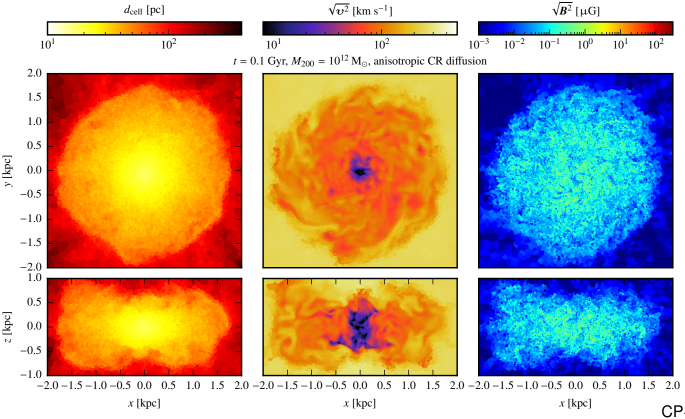
- Pfrommer, Pakmor, Schaal, Simpson, Springel, *Simulating cosmic ray physics on a moving mesh,* 2017, MNRAS, 465, 4500.
- Thomas & Pfrommer, *Cosmic-ray hydrodynamics: Alfvén-wave regulated transport of cosmic rays,* 2019, MNRAS, 485, 2977.
- Thomas, Pfrommer, Pakmor, *A finite volume method for two-moment cosmic-ray hydrodynamics on a moving mesh,* 2021, MNRAS, 503, 2242.
- Thomas & Pfrommer, *Comparing different closure relations for cosmic ray hydrodynamics,* 2022, MNRAS, 509, 4803.

Magnetic dynamos and CR feedback in galaxy formation:

- Buck, Pfrommer, Pakmor, Grand, Springel, *The effects of cosmic rays on the formation of Milky Way-mass galaxies in a cosmological context,* 2020, MNRAS, 497, 1712.
- 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.
- Thomas, Pfrommer, Pakmor, *Cosmic ray-driven galactic winds: transport modes of cosmic rays and Alfvén-wave dark regions,* 2023, MNRAS, 521, 3023.

Additional slides

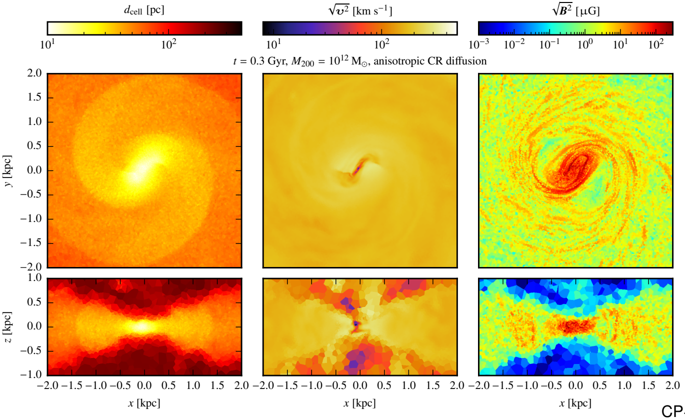
Exponential field growth in kinematic regime



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