Cosmic Rays and Magnetic Fields in Galaxy Formation

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in collaboration with

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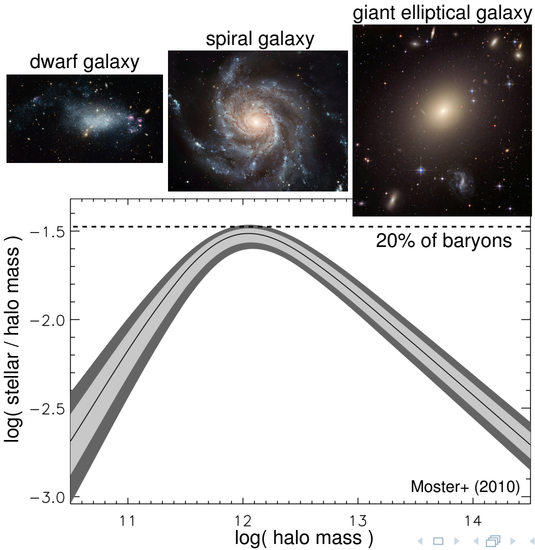
Mike Norman Festschrift, Kloster Seeon, June 2023

Puzzles in galaxy formation



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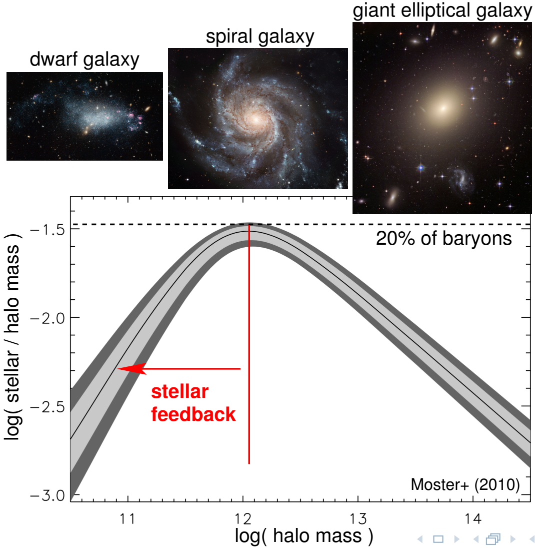

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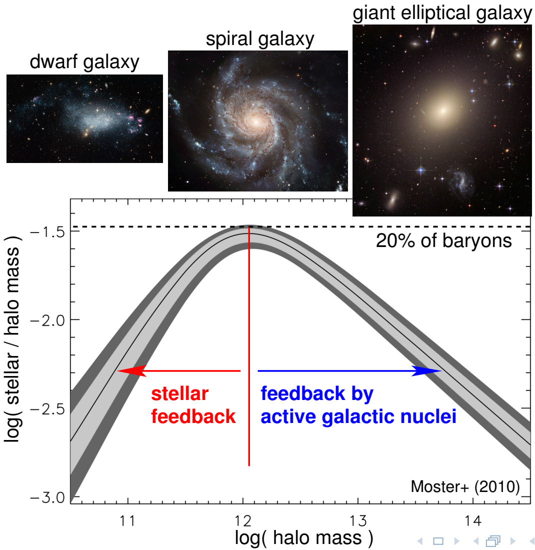


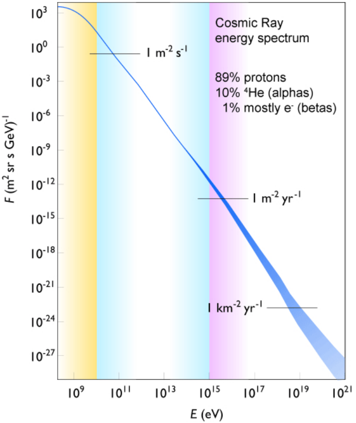
Stellar feedback

super wind in M82

NASA/JPL-Caltech/STScI/CXC/UofA

- thermal pressure provided by supernovae or active galactic nuclei?
- radiation pressure and photoionization by massive stars and quasars?
- pressure of cosmic rays (CRs) that are accelerated at supernova shocks?

Galactic cosmic ray spectrum



data compiled by Swordy

- spans more than 33 decades in flux and 12 decades in energy
- "knee" indicates characteristic maximum energy of galactic accelerators
- CRs beyond the "ankle" have extra-galactic origin

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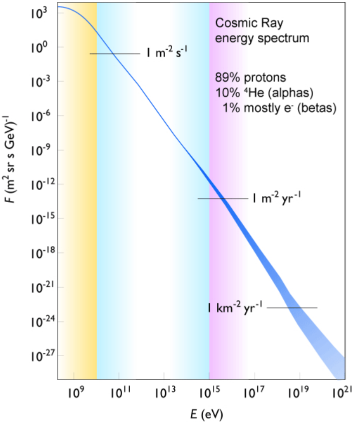

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- spans more than 33 decades in flux and 12 decades in energy
- "knee" indicates characteristic maximum energy of galactic accelerators
- CRs beyond the "ankle" have extra-galactic origin
- energy density of cosmic rays, magnetic fields, and turbulence in the interstellar gas all similar

Review on cosmic ray feedback

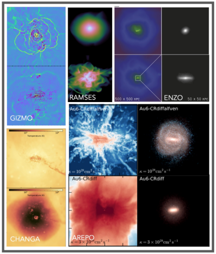
The Astronomy and Astrophysics Review manuscript No.
(will be inserted by the editor)

Cosmic ray feedback in galaxies and galaxy clusters

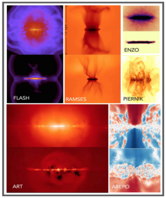
A pedagogical introduction and a topical review of the acceleration, transport, observables, and dynamical impact of cosmic rays

Mateusz Ruszkowski[1,3,*], Christoph Pfrommer[2,*]

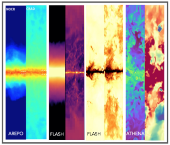
COSMO



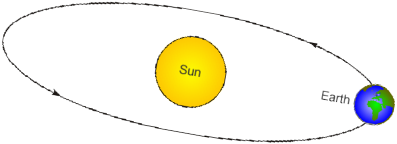
GLOBAL



ZOOM



Cosmic ray transport: an extreme multi-scale problem



Milky Way-like galaxy:

$$r_{\text{gal}} \sim 10^4 \text{ pc}$$

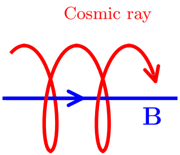
gyro-orbit of GeV CR:

$$r_{\text{cr}} = \frac{p_\perp}{e\,B_{\mu\text{G}}} \sim 10^{-6} \text{ pc} \sim \frac{1}{4} \text{ AU}$$

$\Rightarrow$ need to develop a **fluid theory for a collisionless, non-Maxwellian component!**

Zweibel (2017), Jiang & Oh (2018), Thomas & CP (2019)

Interactions of CRs and magnetic fields



sketch: Jacob & CP

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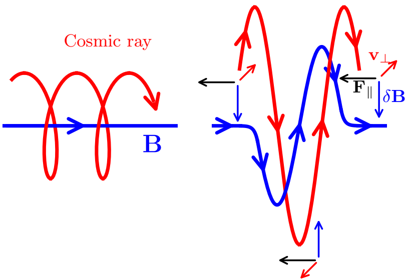

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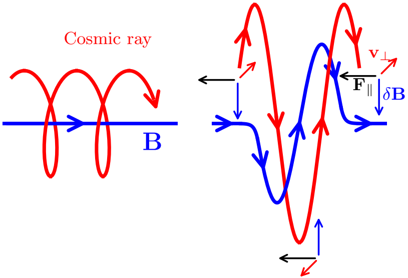

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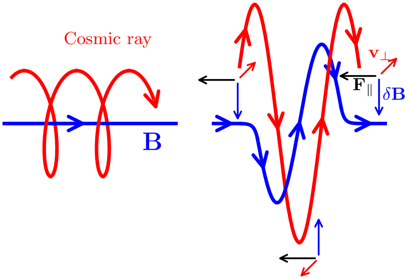

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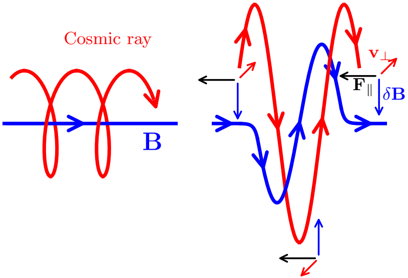

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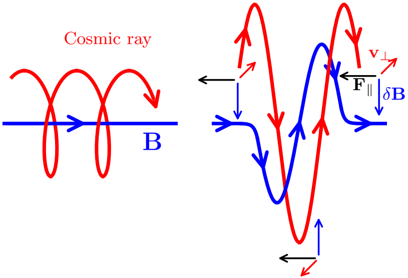
- work out **Lorentz forces on CRs** in wave frame: $\boldsymbol{F}_\mathrm{L} = q\dfrac{\boldsymbol{v} \times \boldsymbol{B}}{c}$
- Lorentz force depends on **relative phase of CR gyro orbit and wave:**
  - sketch: decelerating Lorentz force along CR orbit $\rightarrow p_\parallel$ decreases
  - phase shift by 180°: accelerating Lorentz force $\rightarrow p_\parallel$ increases

Interactions of CRs and magnetic fields



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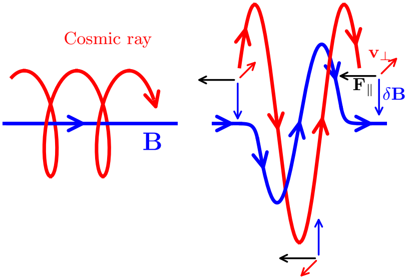

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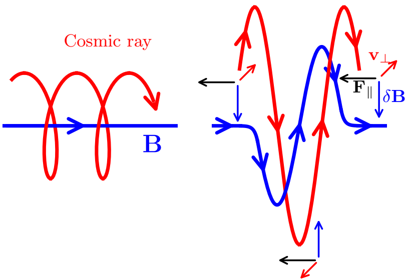

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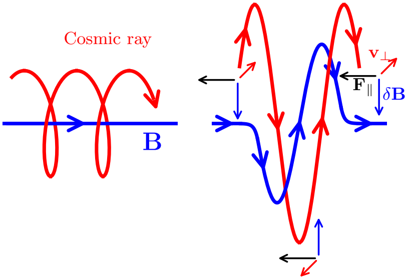
- this increases the CR pitch angle cosine $\mu = \cos\theta = \frac{\boldsymbol{B}}{|\boldsymbol{B}|} \cdot \frac{\boldsymbol{p}}{|\boldsymbol{p}|}$

Interactions of CRs and magnetic fields



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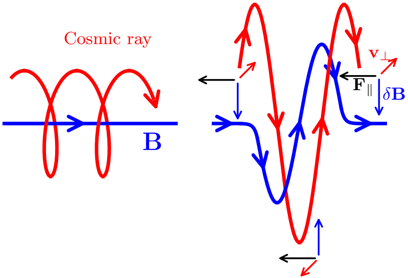
$$L_{\parallel} = r_{\rm g} = \frac{p_{\perp} c}{qB}$$

Interactions of CRs and magnetic fields



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Doppler-shifted MHD frequency is a multiple n of the CR gyrofrequency

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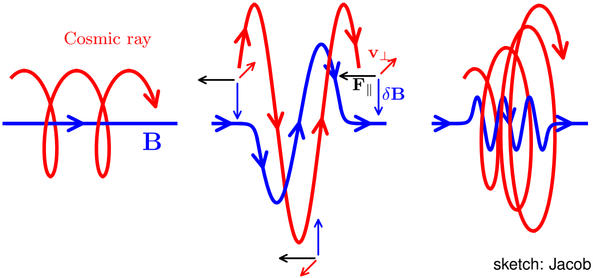

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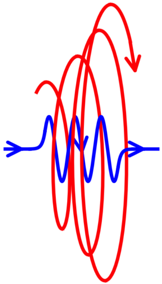
Cosmic ray streaming and diffusion

- **CR streaming instability:** Kulsrud & Pearce 1969
  - if $v_{\rm cr} > v_{\rm a}$, CR flux excites and amplifies an Alfvén wave field in resonance with the gyroradii of CRs
  - scattering off of this wave field limits the (GeV) CRs' bulk speed $\sim v_{\rm a}$
  - wave damping: transfer of CR energy and momentum to the thermal gas



AIP

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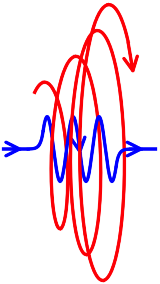

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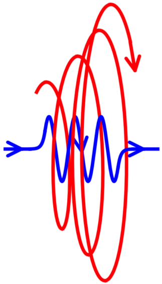

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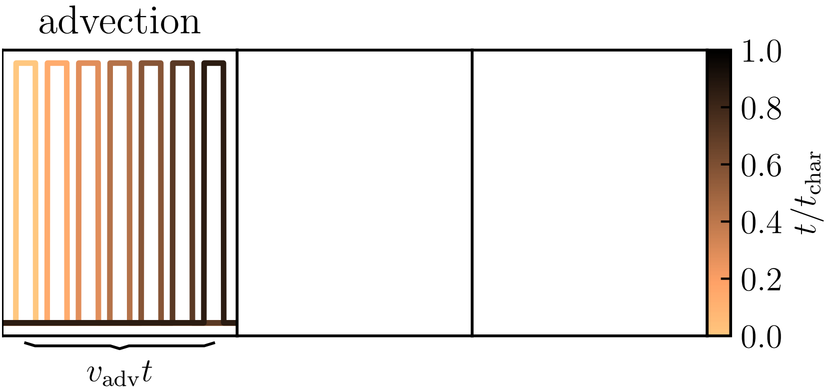
weak wave damping: strong coupling $\rightarrow$ CR stream with waves
strong wave damping: less waves to scatter $\rightarrow$ CR diffusion prevails

Modes of CR propagation



Thomas, CP, Enßlin (2020)

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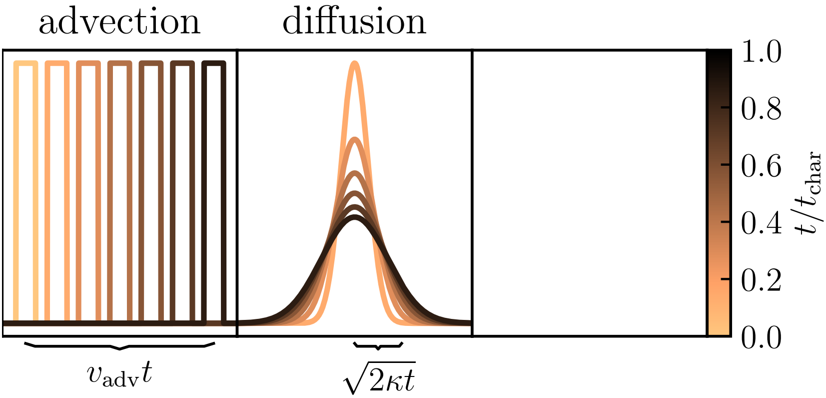

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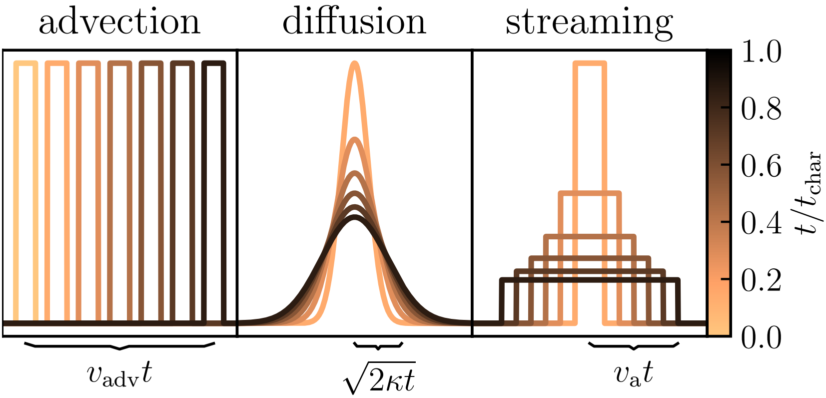

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$$\frac{\partial \varepsilon_{\rm cr}}{\partial t} + \boldsymbol{\nabla}\cdot\boldsymbol{f}_{\rm cr} = -\boldsymbol{w}_\pm \cdot \frac{\boldsymbol{bb}}{3\kappa_\pm}\cdot\left[\boldsymbol{f}_{\rm cr} - \boldsymbol{w}_\pm(\varepsilon_{\rm cr} + P_{\rm cr})\right] - \boldsymbol{v}\cdot\boldsymbol{g}_{\rm Lorentz} + S_\varepsilon$$

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Alfvén wave velocity in lab frame: $\boldsymbol{w}_\pm = \boldsymbol{v} \pm \boldsymbol{v}_{\rm a}$, CR pressure tensor $\mathbf{P}_{\rm cr} = P_{\rm cr}\mathbf{1}$, CR scattering frequency $\bar{\nu}_\pm = c^2/(3\kappa_\pm)$

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- lab-frame equ's for radiation energy and momentum density, ε and $\boldsymbol{f}/c^2$
  (Mihalas & Mihalas 1984, Lowrie+ 1999):

$$\frac{\partial \varepsilon}{\partial t} + \boldsymbol{\nabla} \cdot \boldsymbol{f} = -\sigma_{\mathrm{s}} \boldsymbol{v} \cdot [\boldsymbol{f} - \boldsymbol{v} \cdot (\varepsilon\mathbf{1} + \mathbf{P})] + S_{\mathrm{a}}$$

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- ***problem:*** *CR lab-frame equation requires resolving rapid gyrokinetics!*

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- ***solution:*** *transform in comoving frame and project out gyrokinetics!*

Alfvén-wave regulated CR transport

- comoving equ's for CR energy and momentum density (along $\boldsymbol{B}$), $\varepsilon_{\mathrm{cr}}$ and f_{cr}/c^2, and Alfvén-wave energy densities $\varepsilon_{\mathrm{a},\pm}$ (Thomas & CP 2019)

$$
\begin{aligned}
\frac{\partial \varepsilon_{\mathrm{cr}}}{\partial t} &+ \boldsymbol{\nabla}\cdot\left[\boldsymbol{v}(\varepsilon_{\mathrm{cr}}+P_{\mathrm{cr}})+\boldsymbol{b}f_{\mathrm{cr}}\right] = \boldsymbol{v}\cdot\boldsymbol{\nabla}P_{\mathrm{cr}} \\
&- \frac{v_{\mathrm{a}}}{3\kappa_+}\left[f_{\mathrm{cr}}-v_{\mathrm{a}}(\varepsilon_{\mathrm{cr}}+P_{\mathrm{cr}})\right] + \frac{v_{\mathrm{a}}}{3\kappa_-}\left[f_{\mathrm{cr}}+v_{\mathrm{a}}(\varepsilon_{\mathrm{cr}}+P_{\mathrm{cr}})\right],
\end{aligned}
$$

$$
\begin{aligned}
\frac{\partial f_{\mathrm{cr}}/c^2}{\partial t} &+ \boldsymbol{\nabla}\cdot\left(\boldsymbol{v}f_{\mathrm{cr}}/c^2\right) + \boldsymbol{b}\cdot\boldsymbol{\nabla}P_{\mathrm{cr}} = -(\boldsymbol{b}\cdot\boldsymbol{\nabla}\boldsymbol{v})\cdot(\boldsymbol{b}f_{\mathrm{cr}}/c^2) \\
&- \frac{1}{3\kappa_+}\left[f_{\mathrm{cr}}-v_{\mathrm{a}}(\varepsilon_{\mathrm{cr}}+P_{\mathrm{cr}})\right] - \frac{1}{3\kappa_-}\left[f_{\mathrm{cr}}+v_{\mathrm{a}}(\varepsilon_{\mathrm{cr}}+P_{\mathrm{cr}})\right],
\end{aligned}
$$

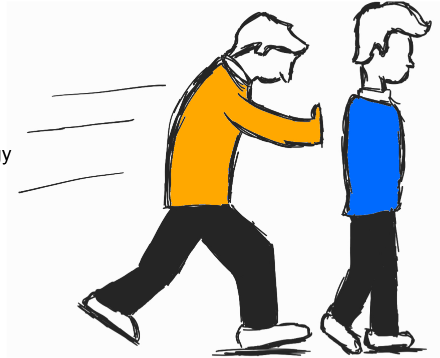
$$
\begin{aligned}
\frac{\partial \varepsilon_{\mathrm{a},\pm}}{\partial t} &+ \boldsymbol{\nabla}\cdot\left[\boldsymbol{v}(\varepsilon_{\mathrm{a},\pm}+P_{\mathrm{a},\pm}) \pm v_{\mathrm{a}}\boldsymbol{b}\varepsilon_{\mathrm{a},\pm}\right] = \boldsymbol{v}\cdot\boldsymbol{\nabla}P_{\mathrm{a},\pm} \\
&\pm \frac{v_{\mathrm{a}}}{3\kappa_\pm}\left[f_{\mathrm{cr}}\mp v_{\mathrm{a}}(\varepsilon_{\mathrm{cr}}+P_{\mathrm{cr}})\right] - S_{\mathrm{a},\pm}.
\end{aligned}
$$

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

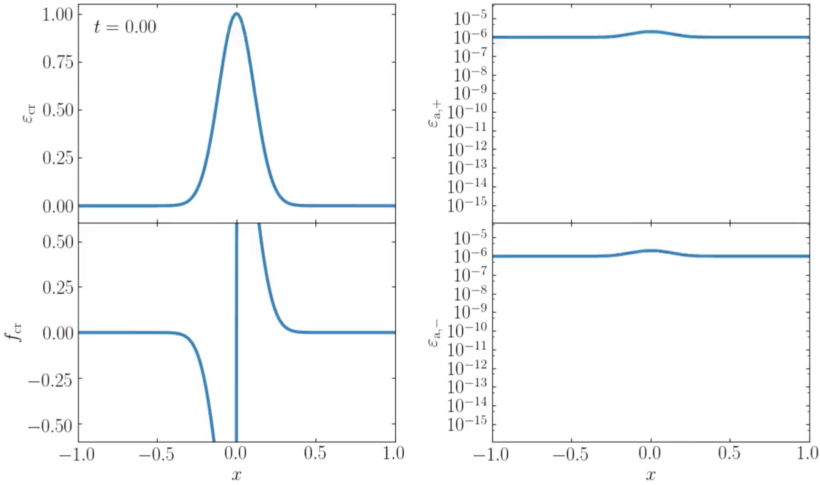
CRs

are … slow
will … gain energy

slide concept Thomas

Non-equilibrium CR streaming and diffusion

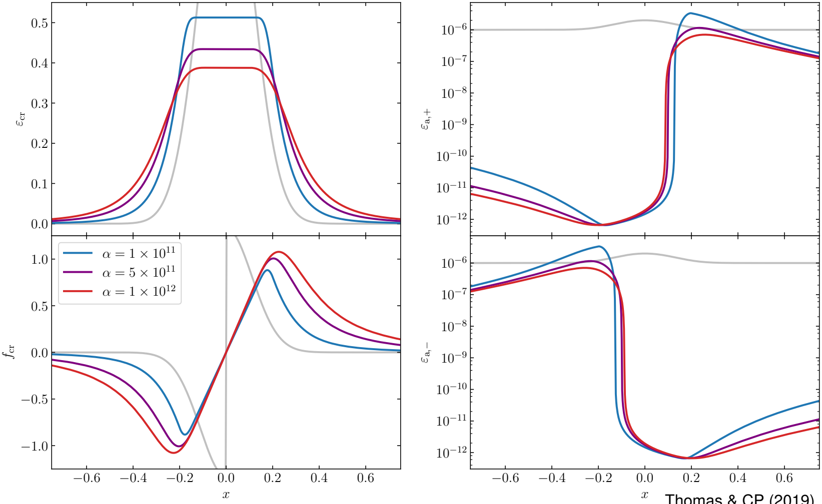
Coupling the evolution of CR and Alfvén wave energy densities



Thomas & CP (2019)

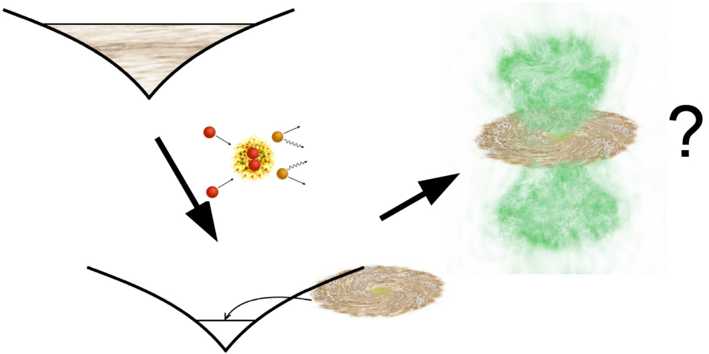
Non-equilibrium CR streaming and diffusion

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

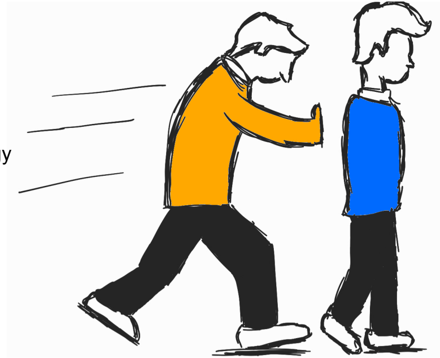
MHD + Alfvén wave regulated CR hydrodynamics: $10^{11}\,M_\odot$ halo

CR interactions with Alfvén waves

acceleration
+ energy transfer

CRs

are … fast
will … lose energy

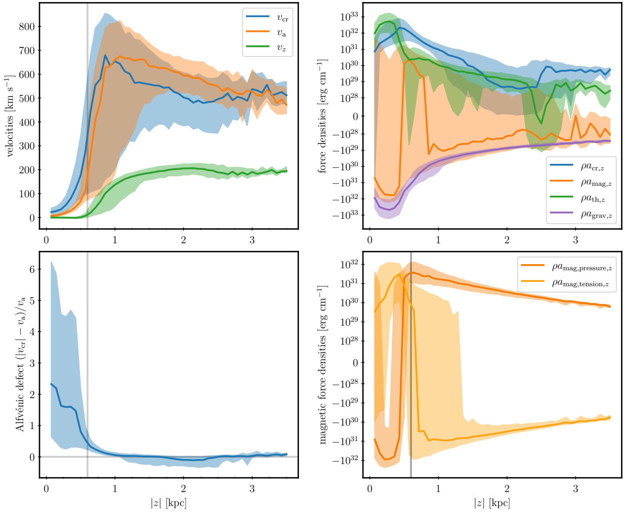


Alfvén waves

are … slow
will … gain energy

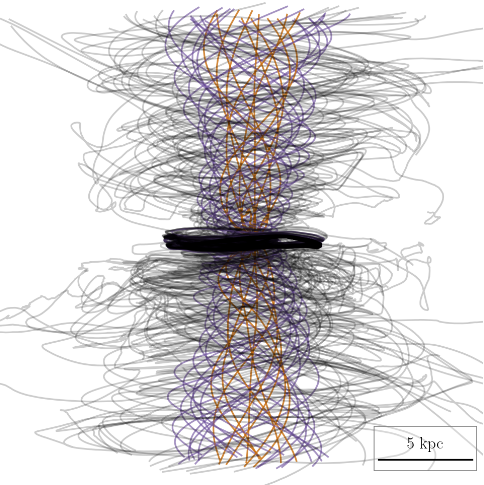
slide concept Thomas

Wind launching



Thomas, CP, Pakmor (2023)

Magnetic field topology



Thomas, CP, Pakmor (2023)

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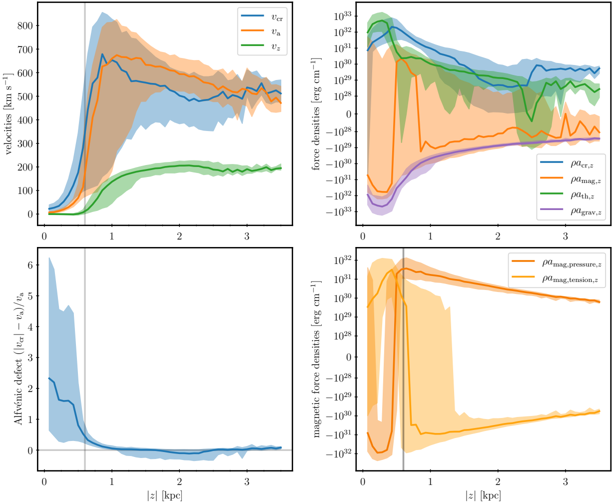

Thomas, CP, Pakmor (2023)

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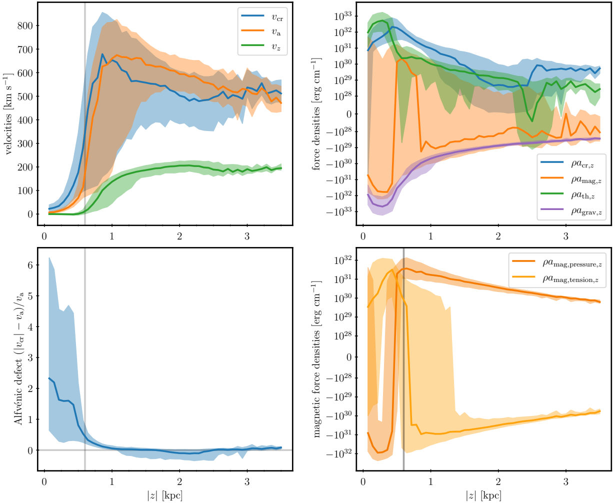

$$\rho \boldsymbol{a}_{\text{mag,pressure}} = -\boldsymbol{\nabla} \boldsymbol{B}^2/2$$
$$\rho \boldsymbol{a}_{\text{mag,tension}} = +(\boldsymbol{B} \cdot \boldsymbol{\nabla})\, \boldsymbol{B}$$

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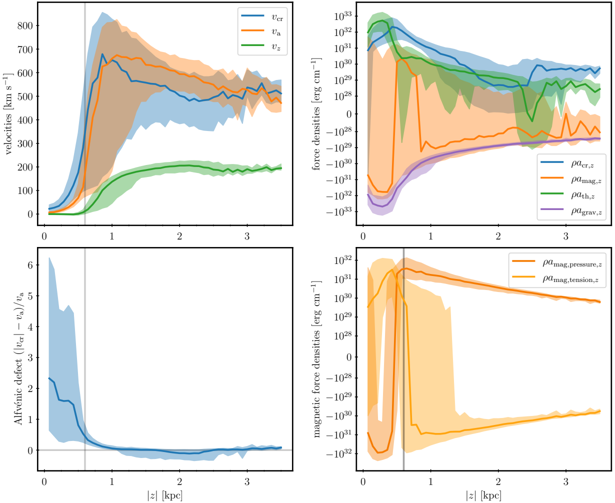

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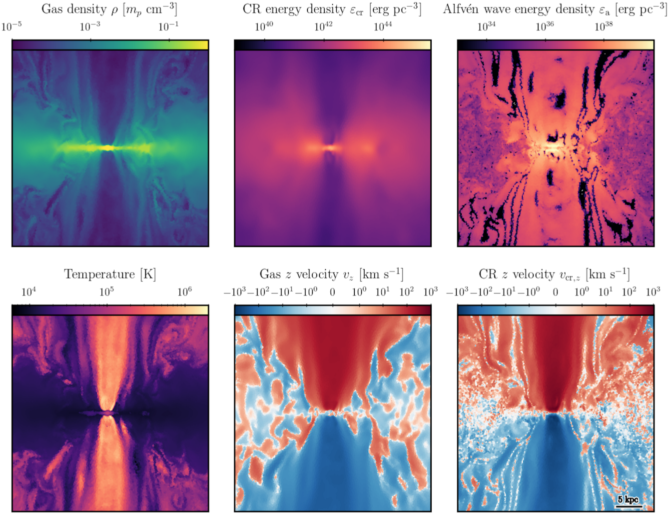
ignoring toroidal field components:

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

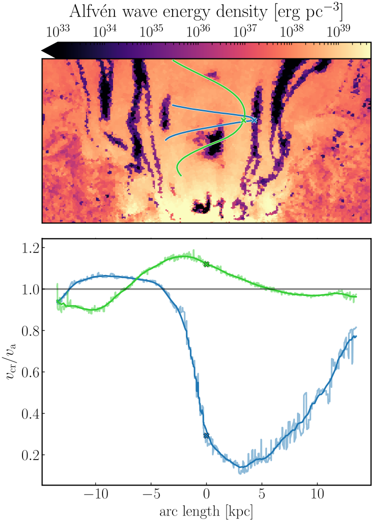
Thomas, CP, Pakmor (2023)

Wind properties



Thomas, CP, Pakmor (2023)

What is the origin of the Alfvén wave dark regions?



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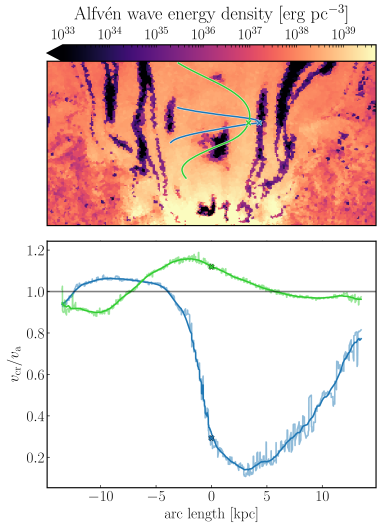
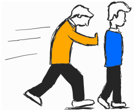


Thomas, CP, Pakmor (2023)



CRs faster than AWs
AWs gain energy

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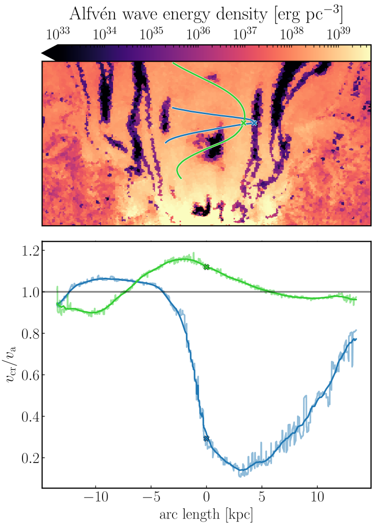
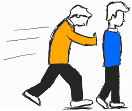


Thomas, CP, Pakmor (2023)



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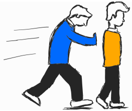

CRs slower than AWs
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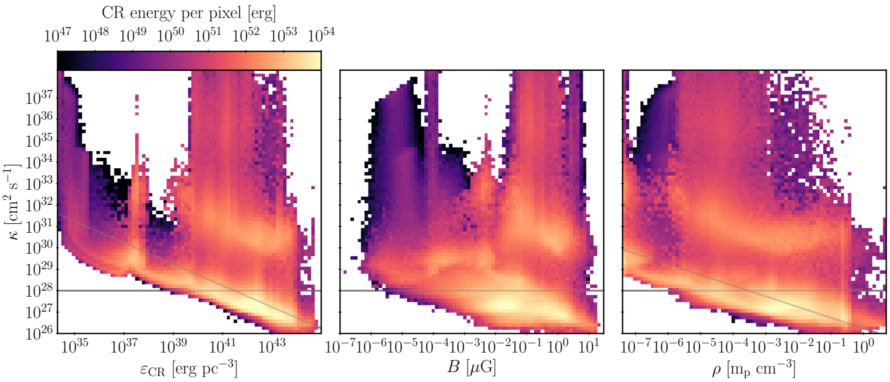
Parallel CR diffusion coefficient



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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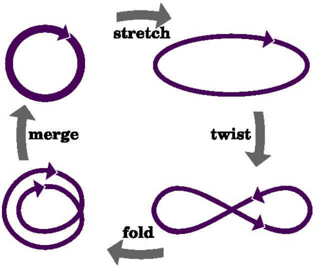

AIP

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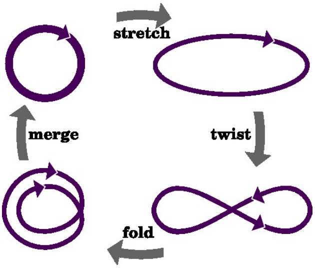
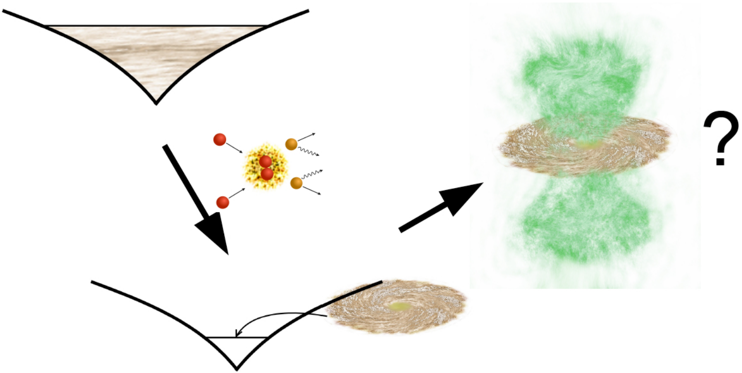
- ***Saturation.*** Field growth stops at a sizeable fraction of the turbulent energy when magnetic forces become strong enough to resist the stretching and folding motions



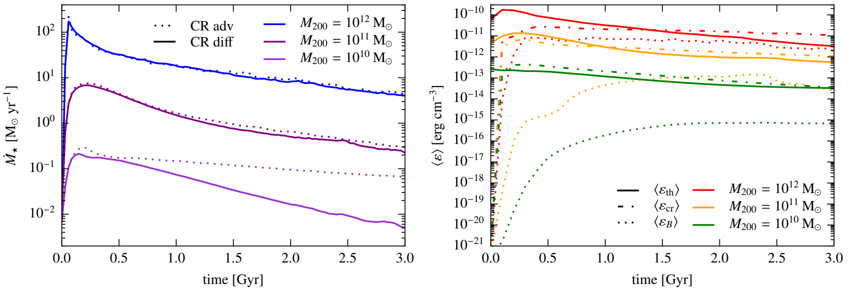
2. Galactic magnetic dynamo



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: $\{10^{10}, 10^{11}, 3\times10^{11}, 10^{12}\}\ \mathrm{M}_\odot$

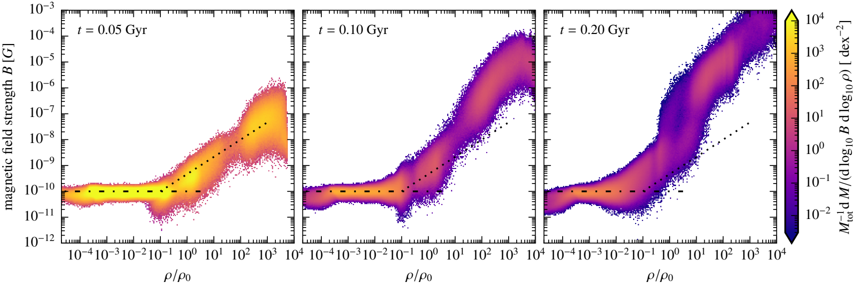
Time evolution of SFR and energy densities



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

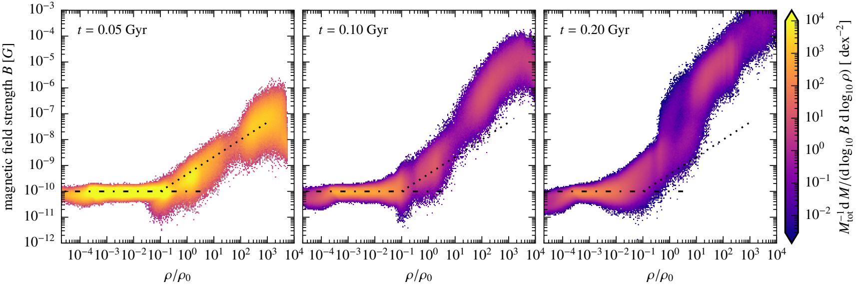
Identifying different growth phases



CP+ (2022)

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

Identifying different growth phases



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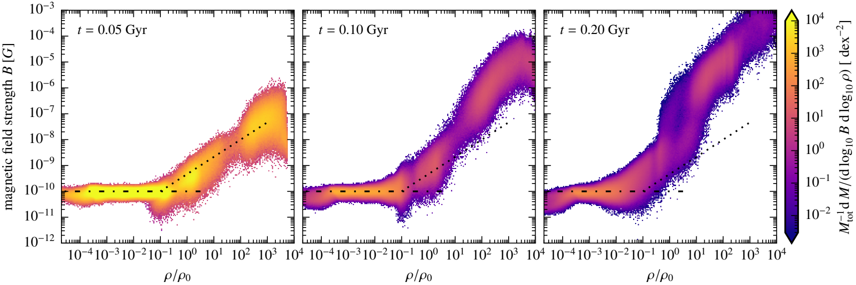

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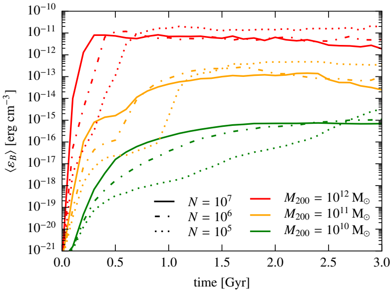
- *2nd phase:* additional growth at high density ρ with small dynamical times $t_{\rm dyn} \sim (G\rho)^{-1/2}$
- *3rd phase:* growth migrates to lower ρ on larger scales $\propto \rho^{-1/3}$

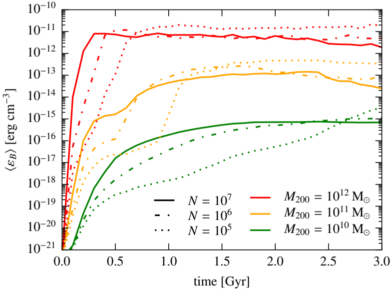
Studying growth rate with numerical resolution

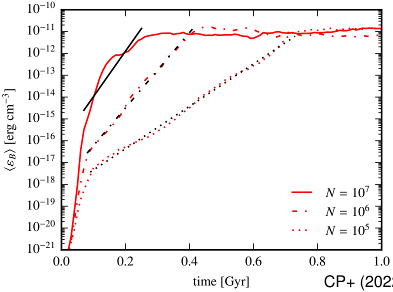


CP+ (2022)

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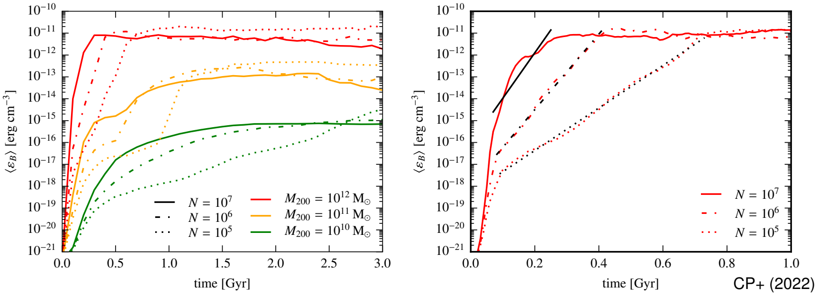
- ***faster magnetic growth in higher resolution simulations and larger halos,*** numerical convergence for $N \gtrsim 10^6$
- *1st phase:* adiabatic growth (independent of resolution)

Studying growth rate with numerical resolution



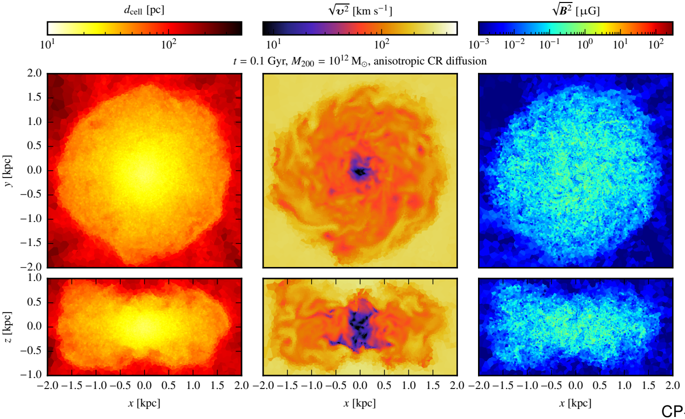
CP+ (2022)

- ***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

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

AIP

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

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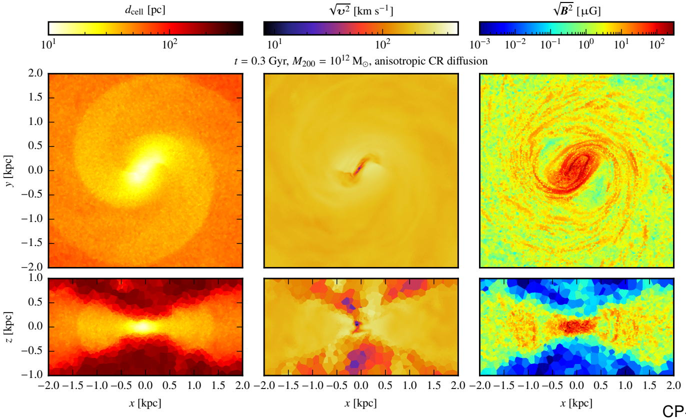
Dynamo saturation on small scales while λ_B increases

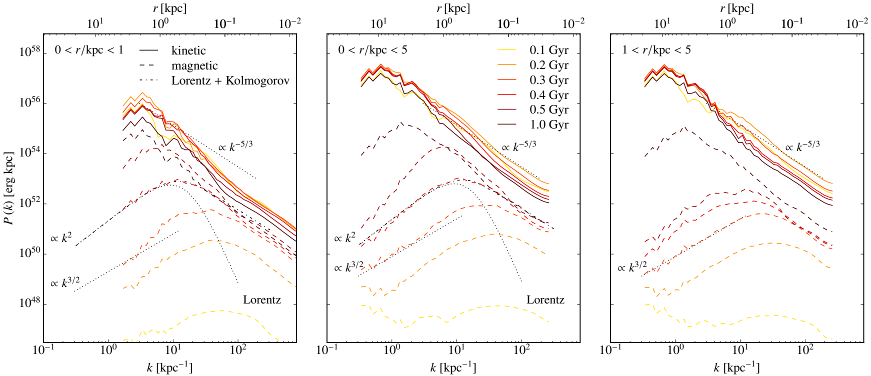


CP+ (2022)

- ***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

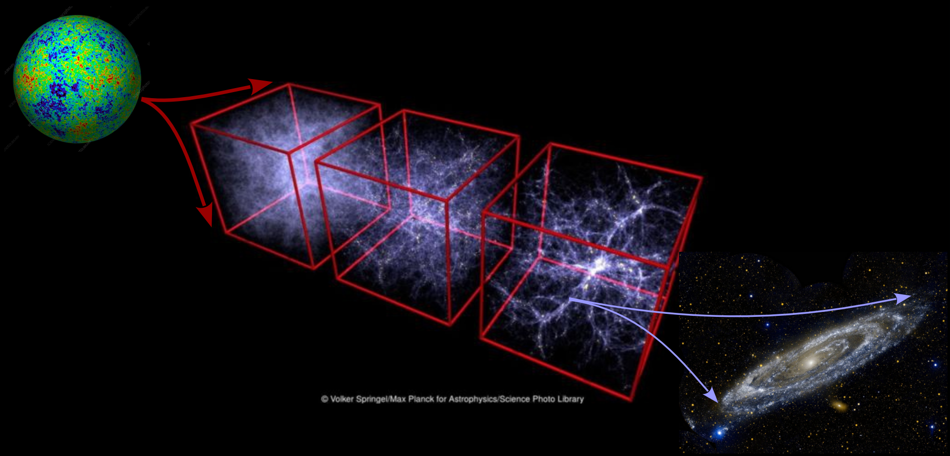
Fluctuating small-scale dynamo in different analysis regions



CP+ (2022)

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

3. Cosmological galaxy formation



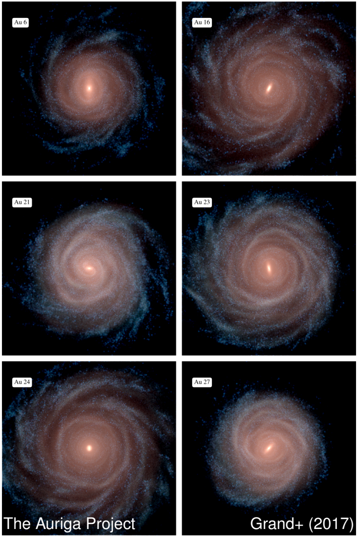
Cosmic rays in cosmological galaxy simulations

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 $z = 128$

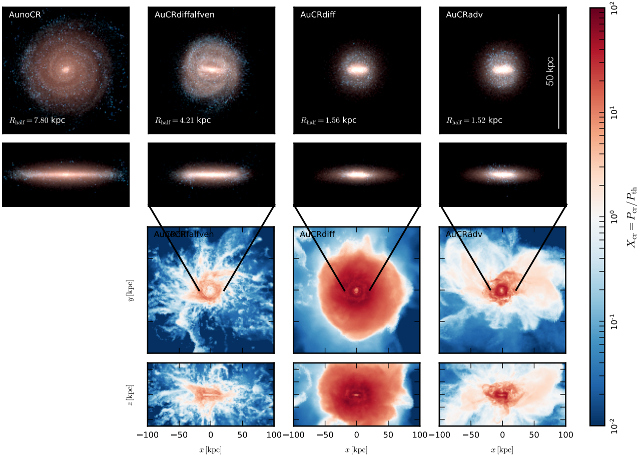
Simulation suite (Buck, CP+ 2020)

- 2 galaxies, baryons with $5 \times 10^4\,\mathrm{M}_\odot$ $\sim 5 \times 10^6$ 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



Cosmic rays in cosmological galaxy simulations

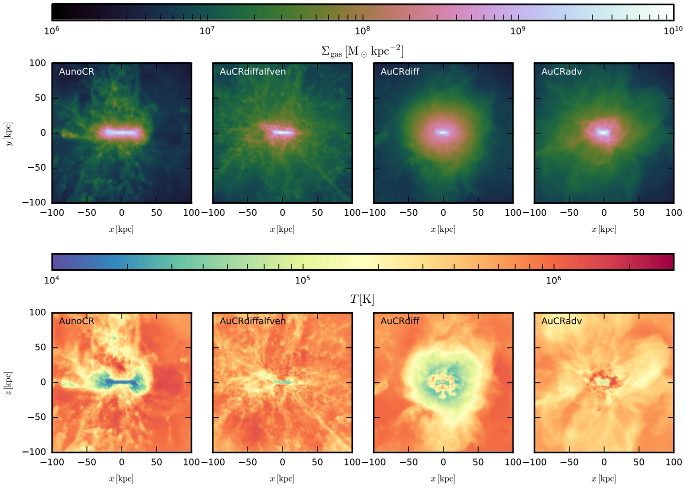
Auriga MHD models: CR transport changes disk sizes



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)

Conclusions for cosmic ray physics in galaxies

CR hydrodynamics:

- moment expansion similar to radiation hydrodynamics
- novel theory of 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
- CRs modify galaxy disk sizes and the circumgalactic medium

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

Literature for the talk

CR hydrodynamics:

- Pfrommer, Pakmor, Schaal, Simpson, Springel, *Simulating cosmic ray physics on a moving mesh,* 2017a, 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:

- 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.

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