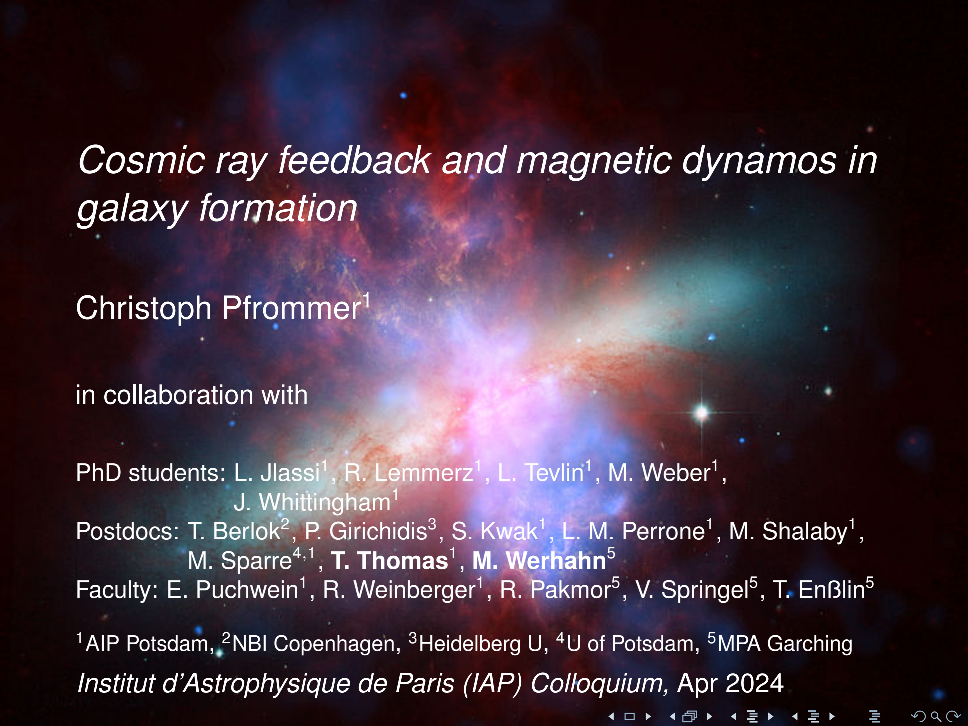

# *Cosmic ray feedback and magnetic dynamos in galaxy formation*

Christoph Pfrommer[1]

in collaboration with

PhD students: L. Jlassi[1], R. Lemmerz[1], L. Tevlin[1], M. Weber[1],
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Postdocs: T. Berlok[2], P. Girichidis[3], S. Kwak[1], L. M. Perrone[1], M. Shalaby[1],
M. Sparre[4,1], **T. Thomas**[1], **M. Werhahn**[5]
Faculty: E. Puchwein[1], R. Weinberger[1], R. Pakmor[5], V. Springel[5], T. Enßlin[5]

[1]AIP Potsdam, [2]NBI Copenhagen, [3]Heidelberg U, [4]U of Potsdam, [5]MPA Garching

*Institut d'Astrophysique de Paris (IAP) Colloquium,* Apr 2024

# Outline

1. Introduction
   - Puzzles in galaxy formation
   - Galaxy formation paradigm
   - Cosmic ray population
2. Cosmic ray transport
   - Wave-particle interactions
   - CR hydrodynamics
   - Radio harps
3. Cosmic rays in galaxy formation
   - Cosmic ray driven winds
   - Galactic magnetic dynamo
   - Cosmic rays and non-thermal emission

AIP

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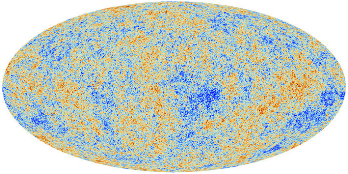
AIP

# Cosmological structure formation



ESA/Planck Collaboration (2013)

- small fluctuations in cosmic microwave background are initial conditions for structure formation

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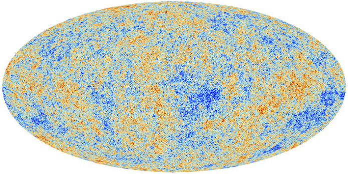

ESA/Planck Collaboration (2013)

dropping pebbles into the pond generates expanding waves that interfere with each other

- small fluctuations in cosmic microwave background are initial conditions for structure formation
- galaxies and clusters form at sites of constructive interference of those primordial waves

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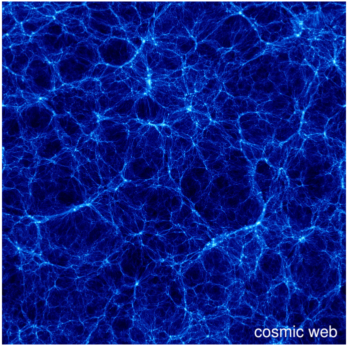

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- cosmic matter assembles in the "cosmic web" through gravitational instability
- galaxies form as "beats on a string" along the cosmic filaments
- galaxy clusters form at the knots of the cosmic web by mergers of galaxies and galaxy groups

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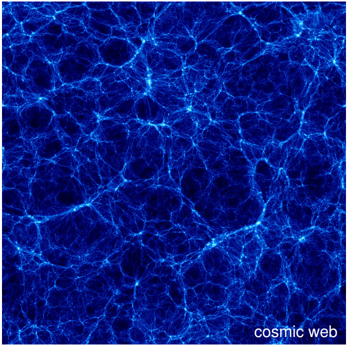

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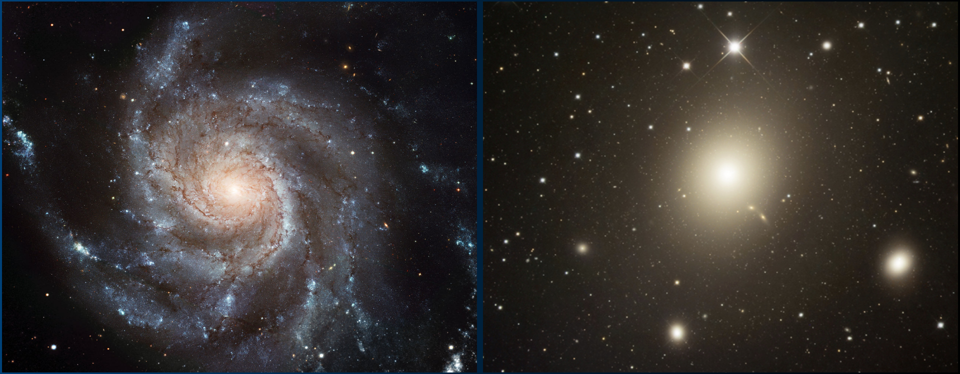
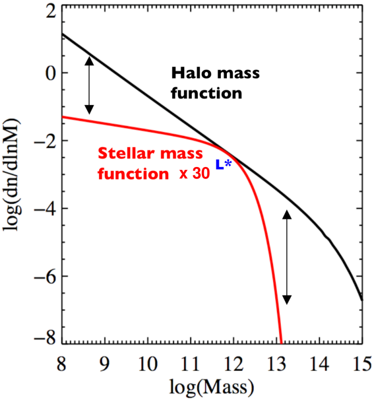


# Galaxy formation in dark matter halos



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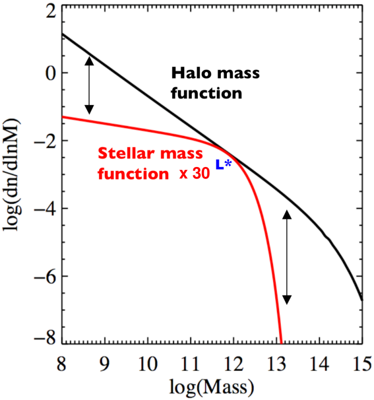

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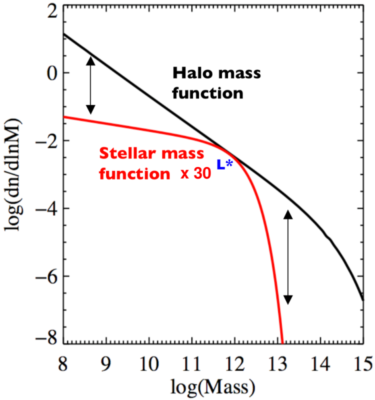
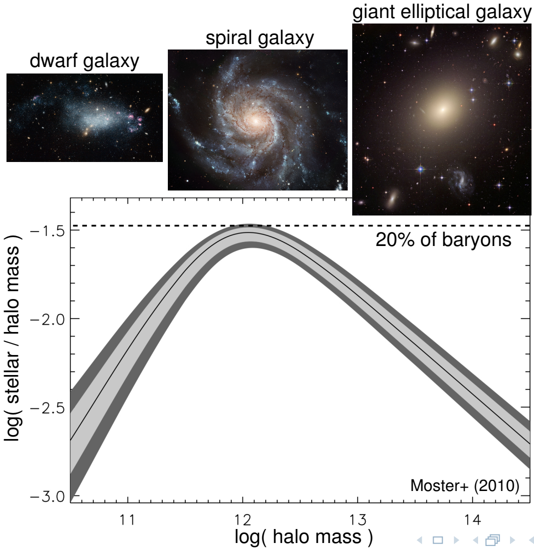


- the number of galaxies in dark matter (DM) halos of mass $\gtrsim 10^{12}\,\mathrm{M}_\odot$ is exponentially suppressed
  → some non-gravitational process introduces a new scale of galaxy formation
- discrepancy of the power-law slopes at the faint end
  → some process lowers the star conversion rate in smaller halos
  or the DM halo mass function is wrong (warm DM?)

# Puzzles in galaxy formation



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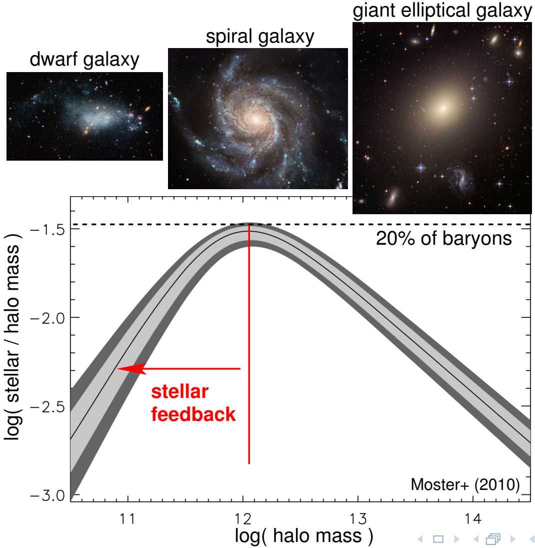

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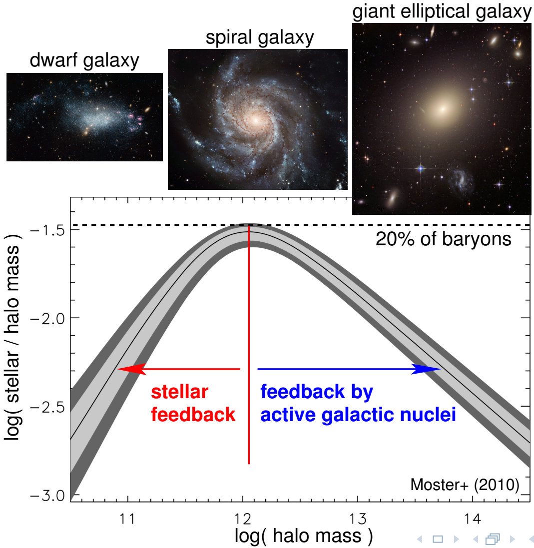
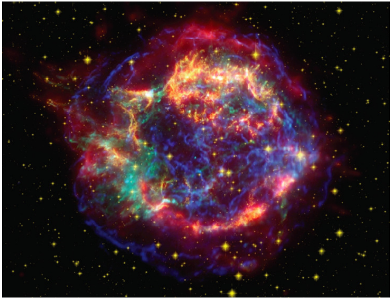


# Feedback by galactic winds



supernova Cassiopeia A

X-ray: NASA/CXC/SAO; Optical: NASA/STScI;
Infrared: NASA/JPL-Caltech/Steward/O.Krause et al.

- galactic supernova remnants drive shock waves, turbulence, accelerate electrons + protons, amplify magnetic fields

# Feedback by galactic winds

super wind in M82

NASA/JPL-Caltech/STScI/CXC/UofA

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- star formation and supernovae drive gas out of galaxies by galactic super winds

# Feedback by galactic winds

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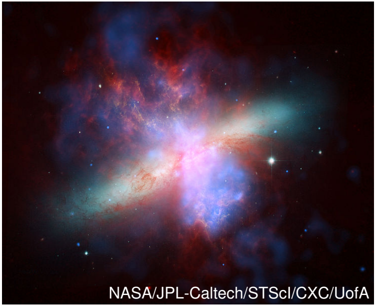
- galactic supernova remnants drive shock waves, turbulence, accelerate electrons + protons, amplify magnetic fields
- star formation and supernovae drive gas out of galaxies by galactic super winds
- critical for understanding the physics of galaxy formation → may explain puzzle of low star conversion efficiency in dwarf galaxies

# How are galactic winds driven?



super wind in M82

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

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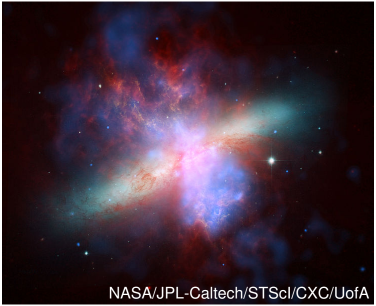
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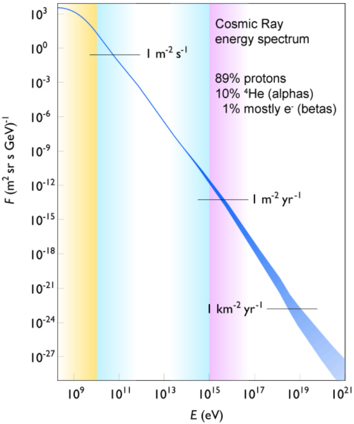
observed energy equipartition between cosmic rays, thermal gas and magnetic fields

→ may suggest self-regulated feedback loop with CR driven winds

# 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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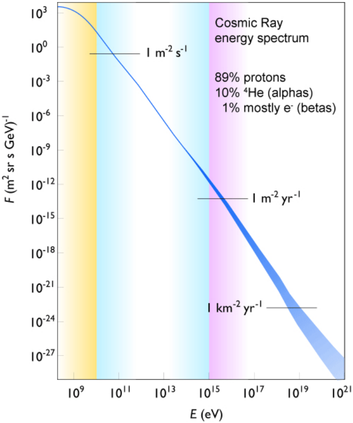

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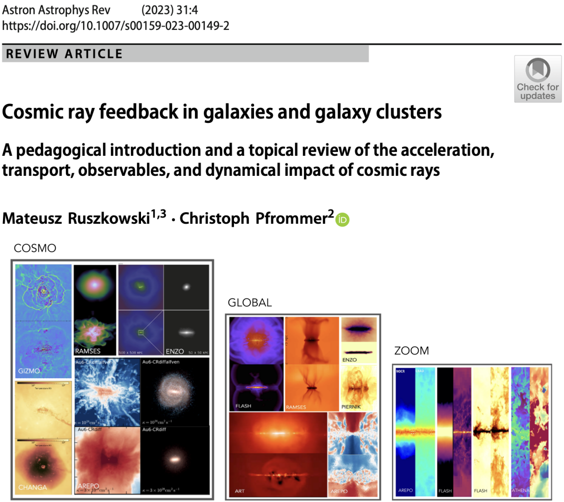
- spans more than 33 decades in flux and 12 decades in energy
- “knee” indicates characteristic maximum energy of galactic accelerators
- CRs beyond the “ankle” have extra-galactic origin
- energy density of cosmic rays, magnetic fields, and turbulence in the interstellar gas all similar

# Review on cosmic ray feedback



Astron Astrophys Rev (2023) 31:4
https://doi.org/10.1007/s00159-023-00149-2

**REVIEW ARTICLE**

Check for updates

## 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]**

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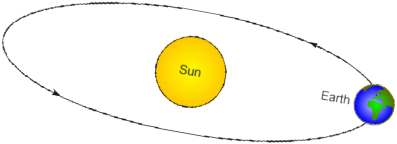
# Cosmic ray transport: an extreme multi-scale problem



Milky Way-like galaxy:

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

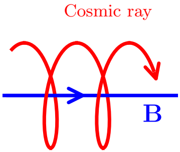
gyro-orbit of GeV CR:

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

$\Rightarrow$ 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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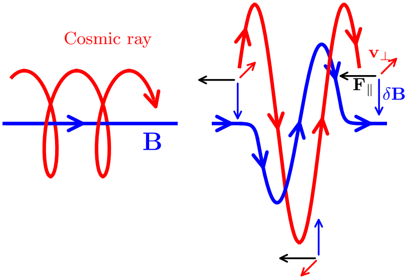

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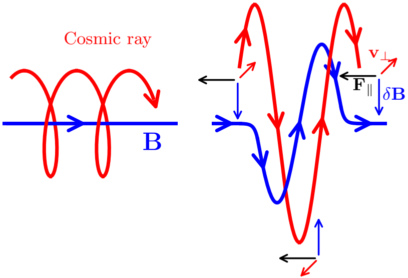

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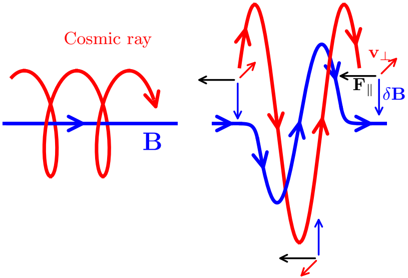

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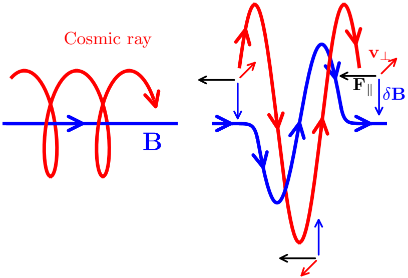

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- work out **Lorentz forces on CRs** in wave frame: $\boldsymbol{F}_\mathrm{L} = Ze\dfrac{\boldsymbol{v} \times \boldsymbol{B}}{c}$
- Lorentz force depends on **relative phase of CR gyro orbit and wave:**
  - sketch: decelerating Lorentz force along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

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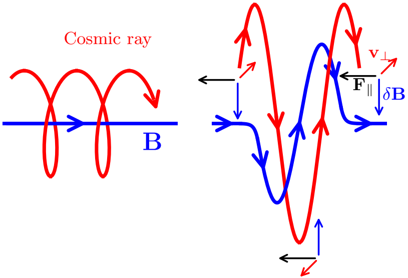

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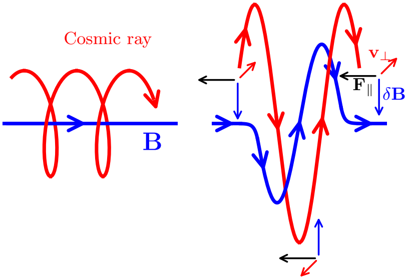

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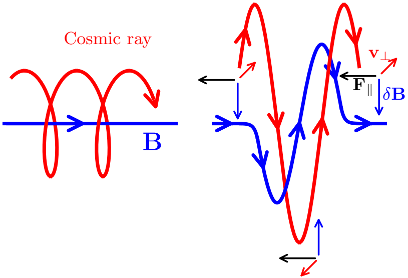

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- this increases the CR pitch angle cosine $\mu = \cos\theta = \frac{\boldsymbol{B}}{|\boldsymbol{B}|} \cdot \frac{\boldsymbol{p}}{|\boldsymbol{p}|}$

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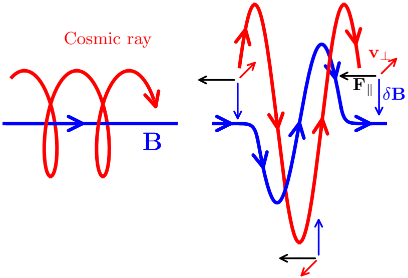

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$$L_\parallel = r_\mathrm{g} = \frac{p_\perp c}{ZeB}$$

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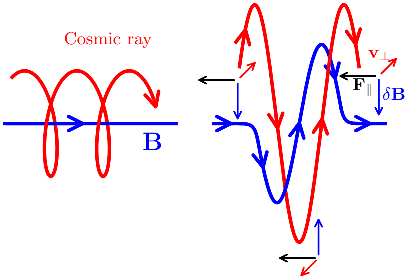

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  Doppler-shifted MHD frequency is a multiple $n$ of the CR gyrofrequency

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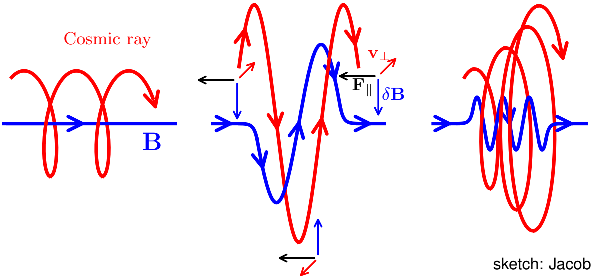

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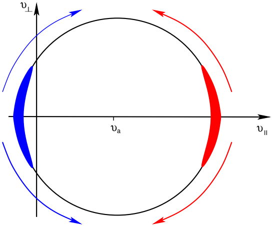

- an anisotropic CR distribution moving rightwards (red) or leftwards (blue) has initially values of the pitch angle cosine $|\mu| = |v_\parallel / v| \lesssim 1$

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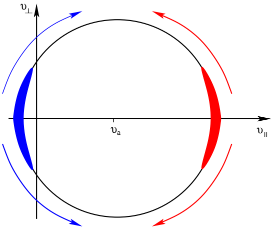

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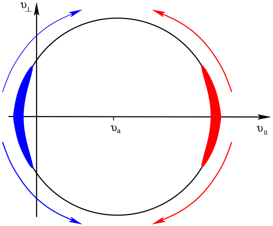

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- CR scattering at Alfvén waves can be described as a random walk in $\mu$, which ***conserves the particle energy in the Alfvén wave rest frame***
- ***diffusion process in $\mu$ along the equal-energy circle*** in velocity space with scattering frequency $\nu(p, \mu) \Rightarrow$ homogeneous $\mu$ distribution:

$$\left.\frac{\partial f}{\partial t}\right|_{\text{scatt}} = \frac{\partial}{\partial \mu}\left[\frac{1-\mu^2}{2}\,\nu(p,\mu)\,\frac{\partial}{\partial \mu} f\right]$$

# CR streaming and diffusion

- **CR streaming instability:** Kulsrud & Pearce 1969
  - if $v_{\mathrm{cr}} > v_{\mathrm{a}}$, 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 $\sim v_{\mathrm{a}}$
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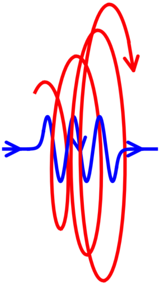

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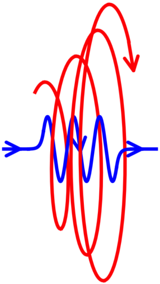

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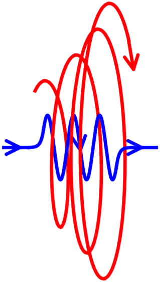

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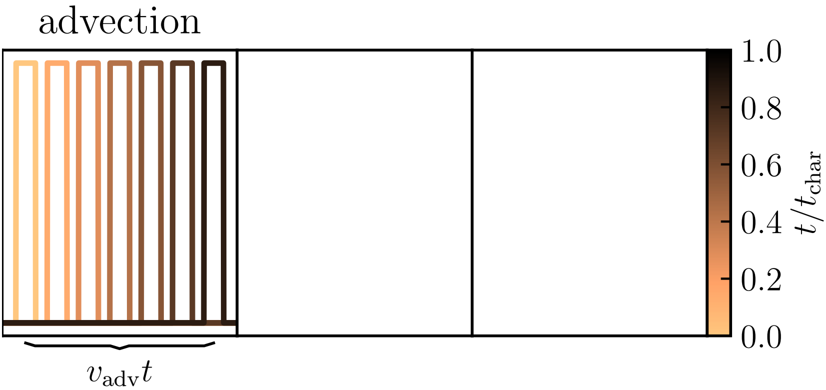
**weak wave damping:** strong coupling → CR stream with waves
**strong wave damping:** less waves to scatter → CR diffusion prevails

# Modes of CR propagation



Thomas, CP, Enßlin (2020)

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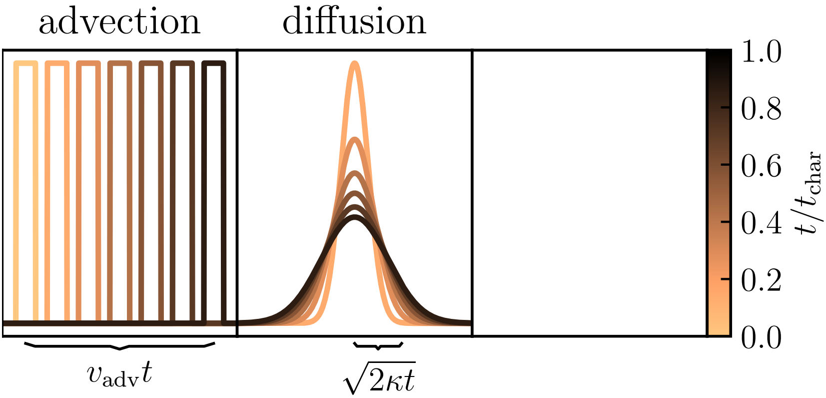

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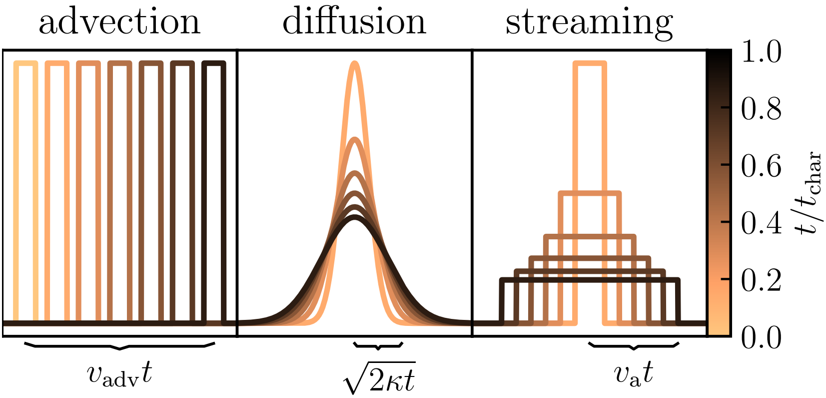

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# Analogies of CR and radiation hydrodynamics

## CRs and radiation are relativistic fluids

| regime | CR transport | radiation HD analogy |
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| • weak scattering | CR streaming and diffusion | flux-limited diffusion with $\tau \sim 1$ |

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|---|---|---|
| • tangled ***B***, strong scattering | CR diffusion | diffusive transport in clumpy medium |
| • resolved ***B***, strong scattering | CR streaming with $\boldsymbol{v}_\mathrm{a}$ | Thomson scattering ($\tau \gg 1$) → advection with $\boldsymbol{v}$ |
| • weak scattering | CR streaming and diffusion | flux-limited diffusion with $\tau \sim 1$ |
| • no scattering | CR propagation with $c$ | vacuum propagation |

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

# Analogies of CR and radiation hydrodynamics

## CRs and radiation are relativistic fluids

| regime | CR transport | radiation HD analogy |
|---|---|---|
| • tangled ***B***, strong scattering | CR diffusion | diffusive transport in clumpy medium |
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| • no scattering | CR propagation with *c* | vacuum propagation |

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

***but:*** *CR hydrodynamics is charged RHD*
→ ***account for Lorentz force and anisotropic transport along B***

# CR vs. radiation hydrodynamics

- capitalize on analogies of CR and radiation hydrodynamics (Jiang & Oh 2018)
  derive two-moment equations from CR Vlasov equation (Thomas & CP 2019)

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$$\begin{aligned}
\frac{\partial \varepsilon_\mathrm{cr}}{\partial t} + \boldsymbol{\nabla}\cdot\boldsymbol{f}_\mathrm{cr} &= -\boldsymbol{w}_\pm \cdot \frac{\boldsymbol{bb}}{3\kappa_\pm}\cdot\left[\boldsymbol{f}_\mathrm{cr} - \boldsymbol{w}_\pm(\varepsilon_\mathrm{cr} + P_\mathrm{cr})\right] - \boldsymbol{v}\cdot\boldsymbol{g}_\mathrm{Lorentz} + S_\varepsilon \\
\frac{1}{c^2}\frac{\partial \boldsymbol{f}_\mathrm{cr}}{\partial t} + \boldsymbol{\nabla}\cdot\mathbf{P}_\mathrm{cr} &= -\frac{\boldsymbol{bb}}{3\kappa_\pm}\cdot\left[\boldsymbol{f}_\mathrm{cr} - \boldsymbol{w}_\pm(\varepsilon_\mathrm{cr} + P_\mathrm{cr})\right] - \boldsymbol{g}_\mathrm{Lorentz} + \boldsymbol{S}_f
\end{aligned}$$

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

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\frac{1}{c^2}\frac{\partial \boldsymbol{f}}{\partial t} + \boldsymbol{\nabla}\cdot\mathbf{P} &= -\sigma_\mathrm{s} \left[\boldsymbol{f} - \boldsymbol{v}\cdot(\varepsilon\mathbf{1} + \mathbf{P})\right] + S_\mathrm{a}\boldsymbol{v}
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\end{aligned}$$

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

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\end{aligned}$$

- ***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 $f_{\mathrm{cr}}/c^2$, and Alfvén-wave energy densities $\varepsilon_{\mathrm{a},\pm}$ (Thomas & CP 2019)

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

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

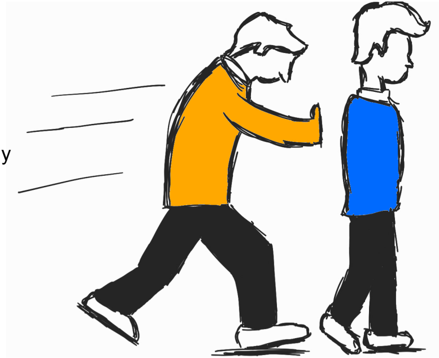
$$\begin{aligned}\frac{\partial \varepsilon_{\mathrm{a},\pm}}{\partial t} &+ \boldsymbol{\nabla}\cdot\left[\boldsymbol{v}(\varepsilon_{\mathrm{a},\pm}+P_{\mathrm{a},\pm}) \pm v_{\mathrm{a}}\boldsymbol{b}\varepsilon_{\mathrm{a},\pm}\right] = \boldsymbol{v}\cdot\boldsymbol{\nabla} P_{\mathrm{a},\pm} \\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

# 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
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**Alfvén waves**

are … fast
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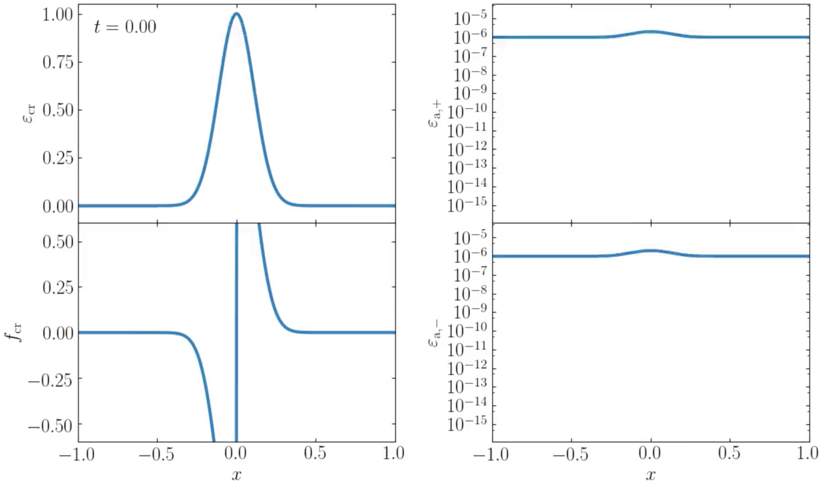
slide concept Thomas

# Non-equilibrium CR streaming and diffusion

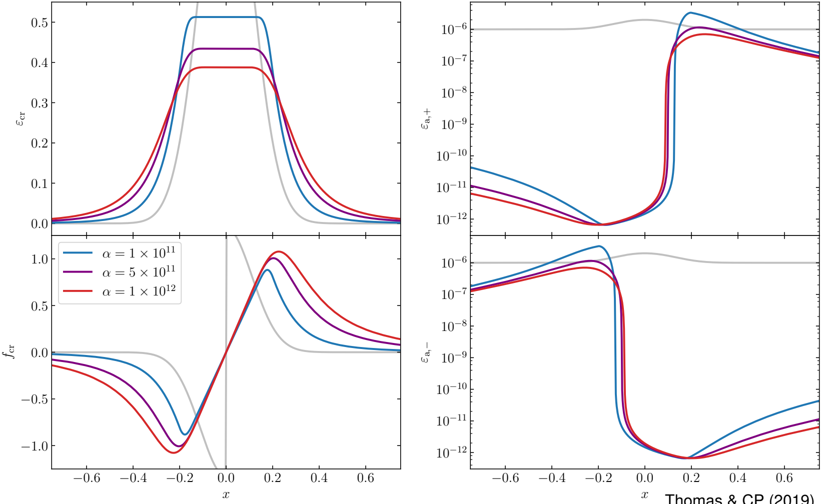
## Coupling the evolution of CR and Alfvén wave energy densities



Thomas & CP (2019)

# Non-equilibrium CR streaming and diffusion

## Varying damping rate of Alfvén waves modulates the diffusivity of solution

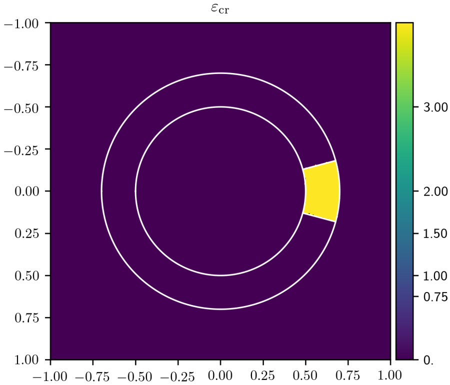


Thomas & CP (2019)

# Anisotropic CR streaming and diffusion – AREPO

## CR transport mediated by Alfvén waves and coupled to magneto-hydrodynamics

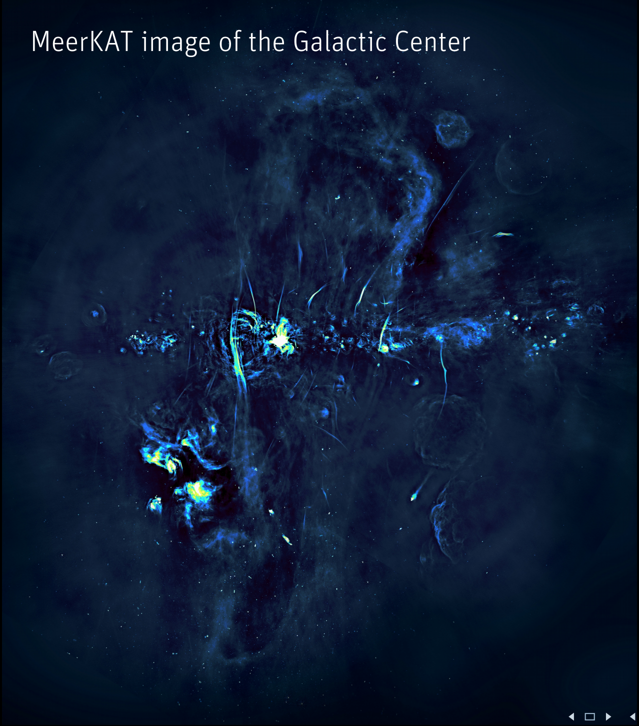
- CR streaming and diffusion along magnetic field lines in the self-confinement picture
- moment expansion similar to radiation hydrodynamics
- accounts for kinetic physics: non-linear Landau damping, gyro-resonant instability, . . .
- Galilean invariant and causal transport
- energy and momentum conserving



Thomas, CP, Pakmor (2021), Thomas & CP (2022)

# MeerKAT image of the Galactic Center

Haywood+ (Nature, 2019)



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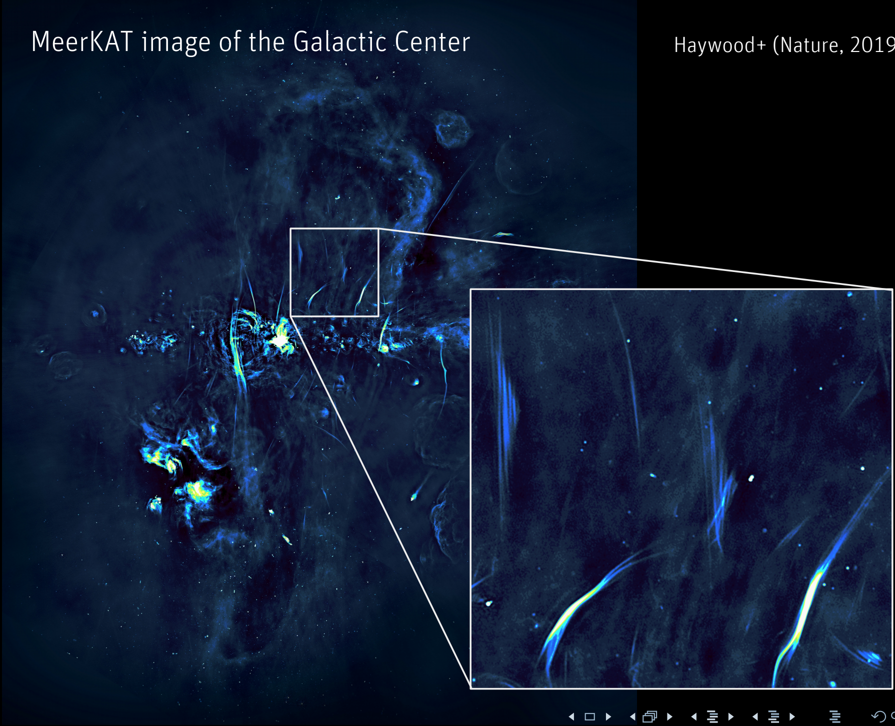
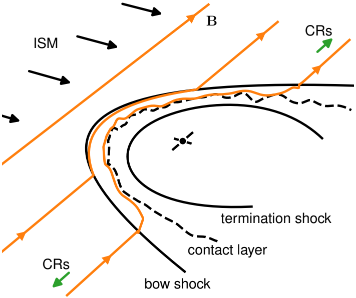


# Radio synchrotron harps: the model

shock acceleration scenario



Thomas, CP, Enßlin (2020)

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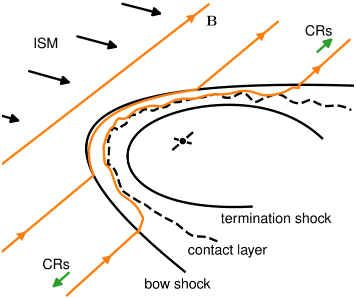
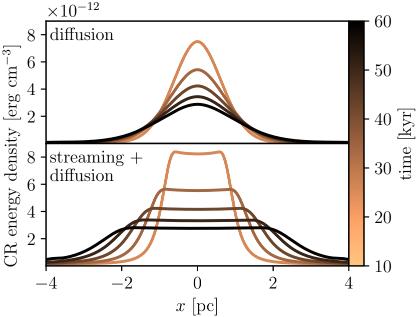
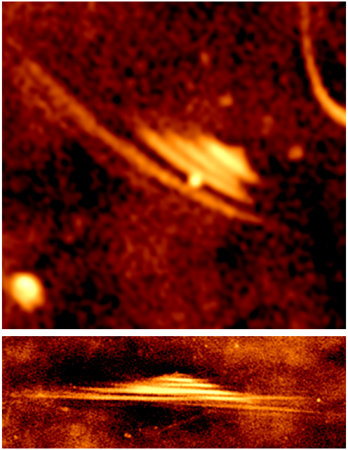


Thomas, CP, Enßlin (2020)

CR diffusion vs. streaming + diffusion



# Radio synchrotron harps: testing CR propagation



Haywood+ (Nature, 2019)

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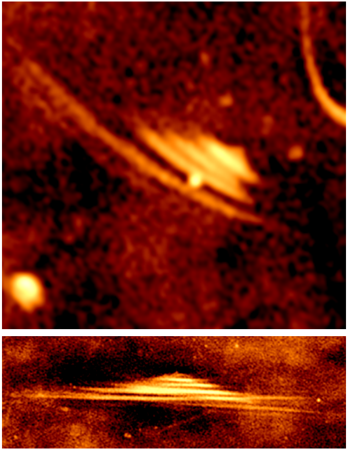
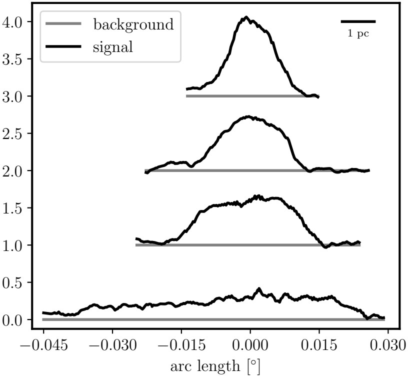


Haywood+ (Nature, 2019)

lateral radio profiles



Thomas, CP, Enßlin (2020)

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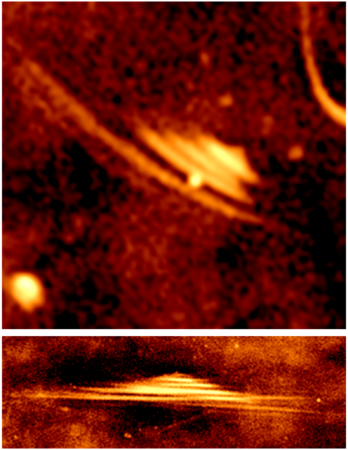

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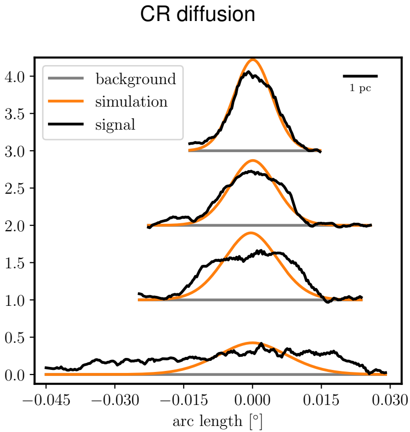

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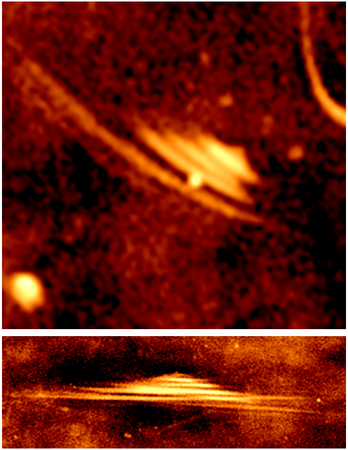

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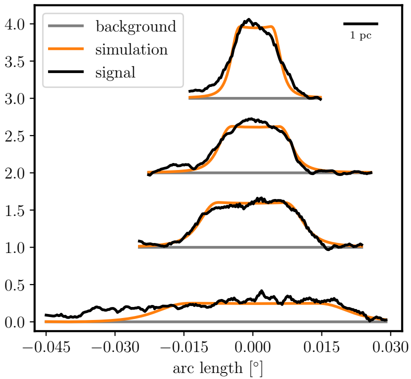


CR streaming and diffusion

Thomas, CP, Enßlin (2020)

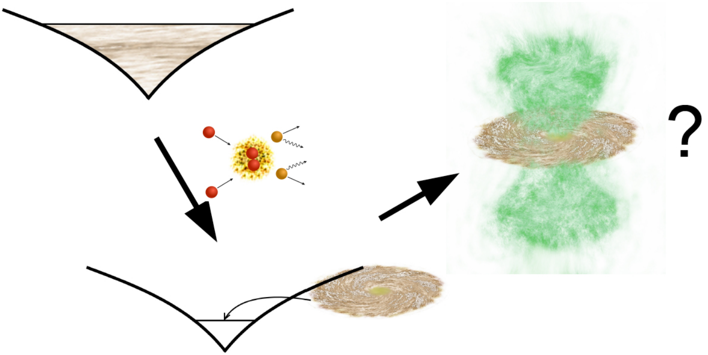
# Outline

1 Introduction
- Puzzles in galaxy formation
- Galaxy formation paradigm
- Cosmic ray population

2 Cosmic ray transport
- Wave-particle interactions
- CR hydrodynamics
- Radio harps

3 Cosmic rays in galaxy formation
- Cosmic ray driven winds
- Galactic magnetic dynamo
- Cosmic rays and non-thermal emission

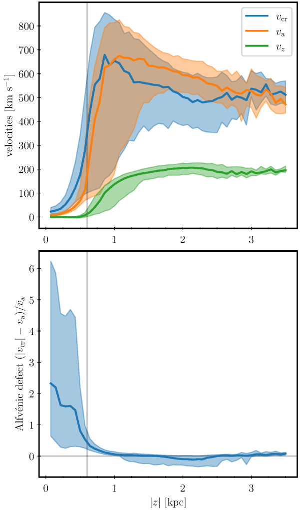
# 1. Galaxy simulations with cosmic ray feedback



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

# Wind launching



Thomas, CP, Pakmor (2023)

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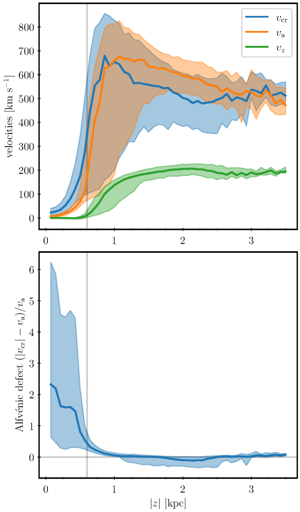
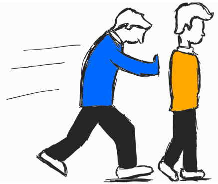
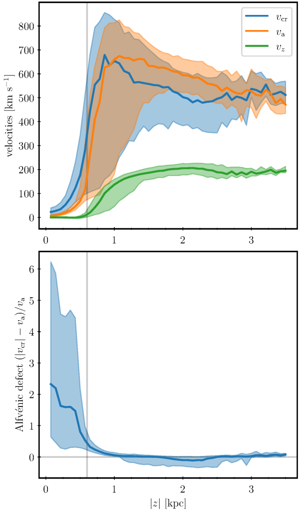


Thomas, CP, Pakmor (2023)

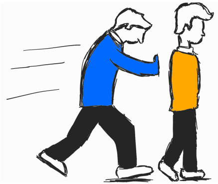


- CRs faster than Alfvén waves
  $\Rightarrow$ Alfvén waves gain energy

# Wind launching

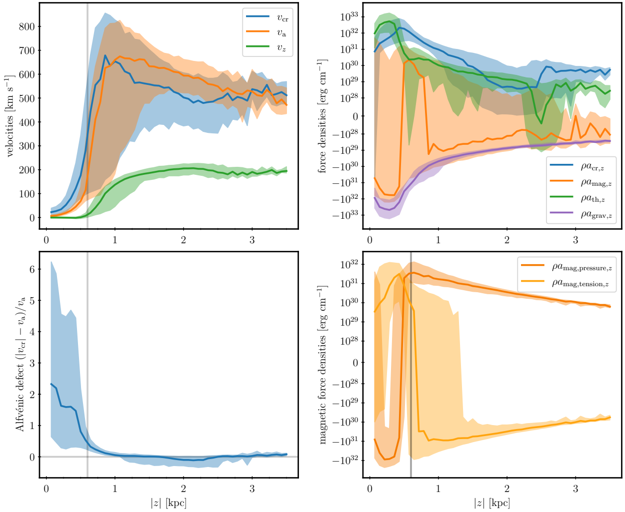


Thomas, CP, Pakmor (2023)



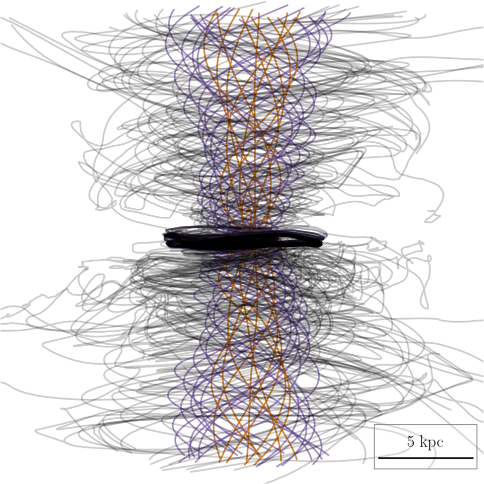
- CRs faster than Alfvén waves
  ⇒ Alfvén waves gain energy
- Alfvén waves are supported by thermal plasma
  ⇒ plasma gets accelerated

# Wind launching



Thomas, CP, Pakmor (2023)

# Magnetic field topology



Thomas, CP, Pakmor (2023)

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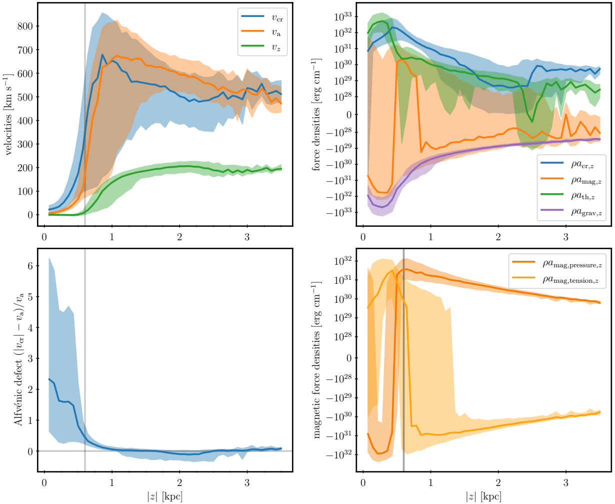

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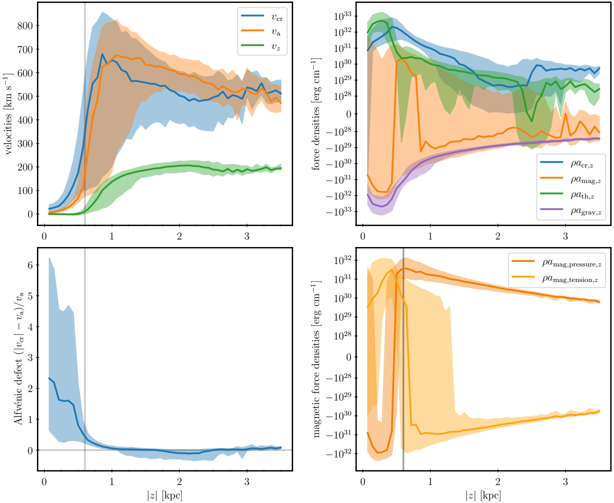
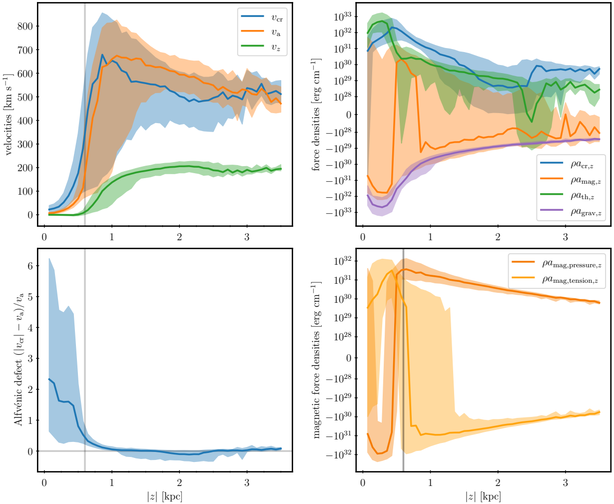


$$\rho \boldsymbol{a}_{\text{mag,pressure}} = -\boldsymbol{\nabla} \boldsymbol{B}^2/2$$

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

Thomas, CP, Pakmor (2023)

# Wind launching



$$\rho \boldsymbol{a}_{\text{mag,pressure}} = -\boldsymbol{\nabla} \boldsymbol{B}^2/2$$

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

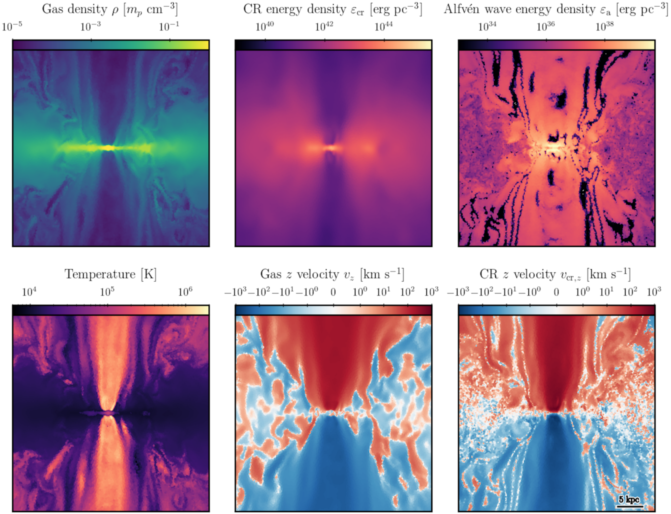
ignoring toroidal field components:

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

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

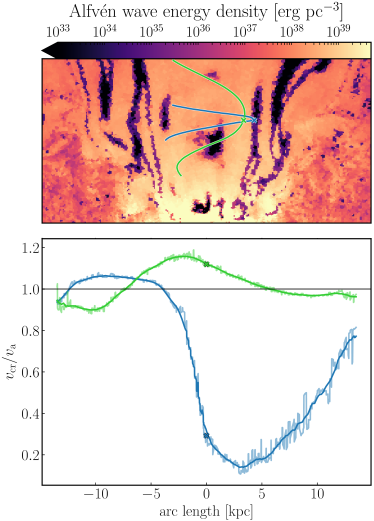
Thomas, CP, Pakmor (2023)

# Wind properties



Thomas, CP, Pakmor (2023)

# What is the origin of the Alfvén wave dark regions?



Thomas, CP, Pakmor (2023)

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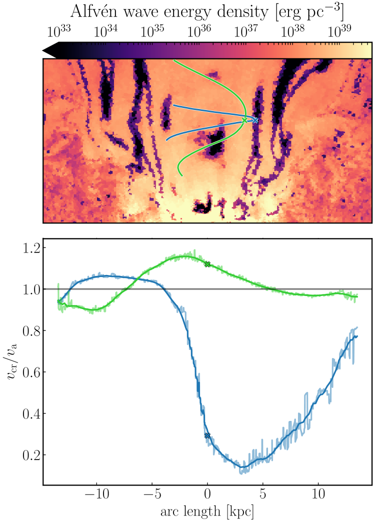

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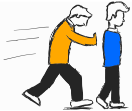

CRs faster than AWs
AWs gain energy

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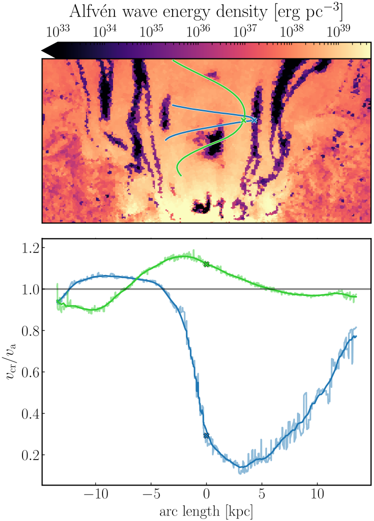

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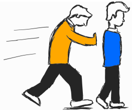

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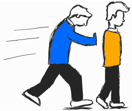
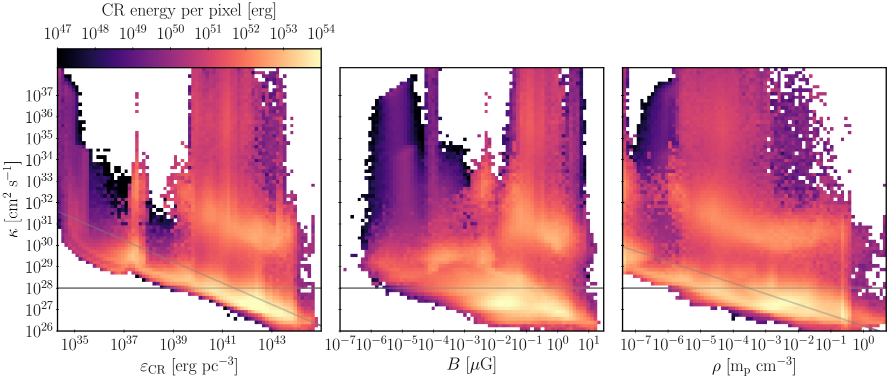


CRs slower than AWs
AWs lose energy

# Parallel CR diffusion coefficient



Thomas, CP, Pakmor (2023)

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

# 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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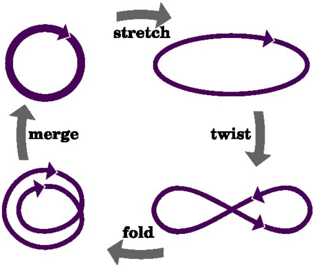
- ***Growth.*** A small-scale (fluctuating) dynamo is an MHD process, in which the kinetic (turbulent) energy is converted into magnetic energy: the mechanism relies on magnetic fields to become stronger when the field lines are stretched



# Origin and growth of magnetic fields

## The general picture:

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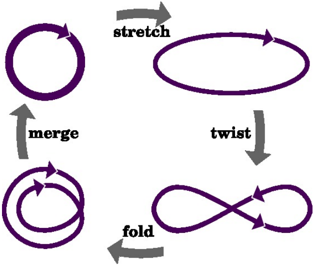
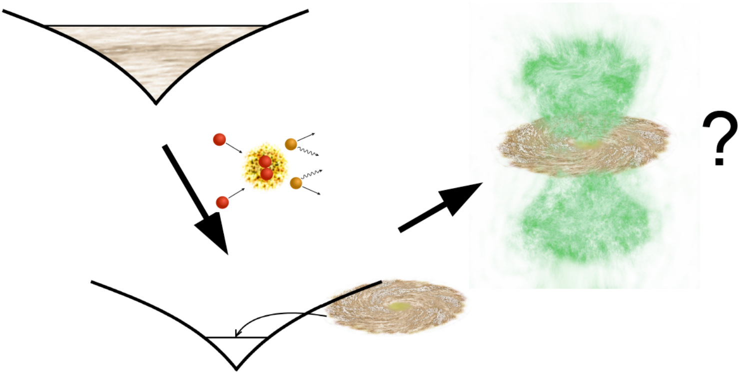
- ***Growth.*** A small-scale (fluctuating) dynamo is an MHD process, in which the kinetic (turbulent) energy is converted into magnetic energy: the mechanism relies on magnetic fields to become stronger when the field lines are stretched
- ***Saturation.*** Field growth stops at a sizeable fraction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



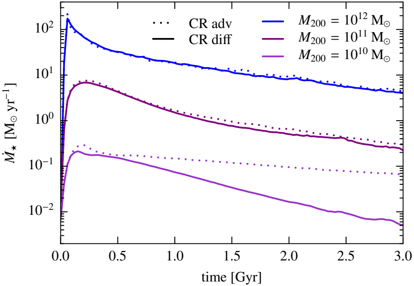
# 2. Galactic magnetic dynamo



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

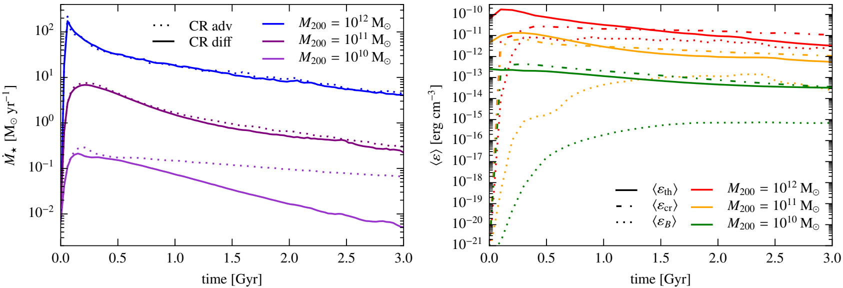
# Time evolution of SFR and energy densities



CP+ (2022)

- cosmic ray (CR) pressure feedback suppresses SFR more in smaller galaxies

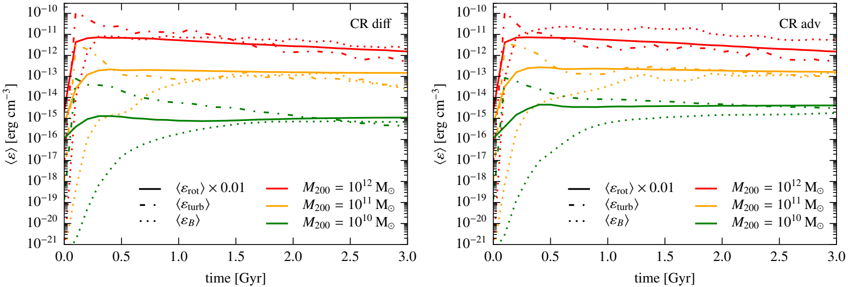
# Time evolution of SFR and energy densities



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

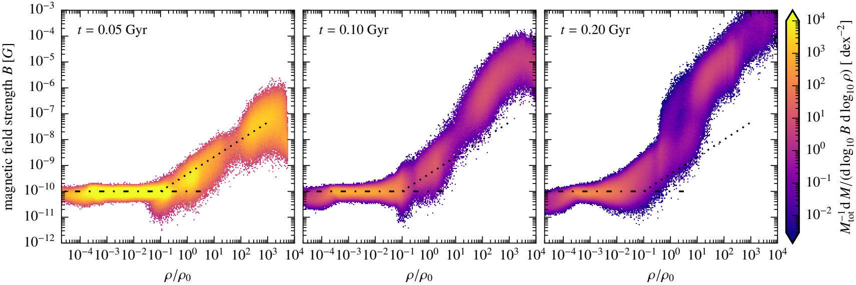
# Comparing turbulent and magnetic energy densities



CP+ (2022)

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

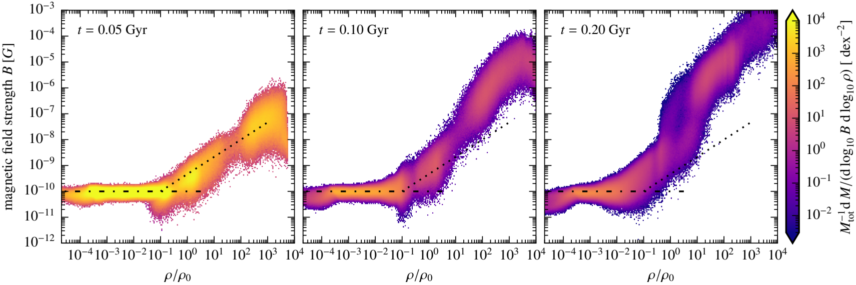
# Identifying different growth phases



CP+ (2022)

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

# Identifying different growth phases



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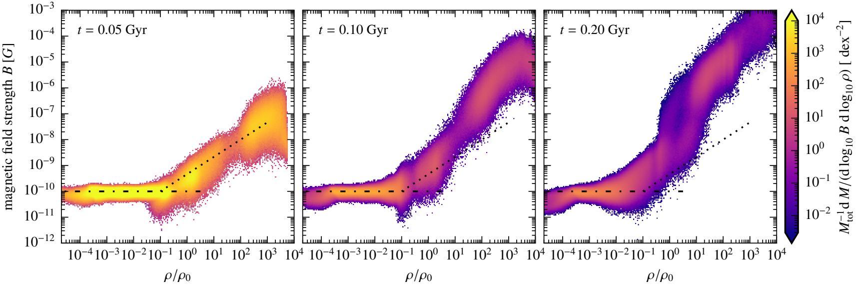
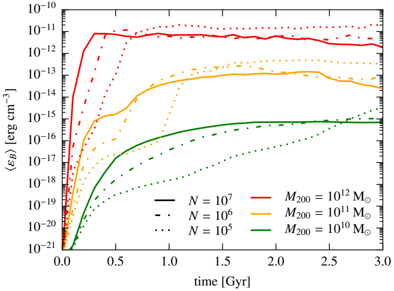


CP+ (2022)

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

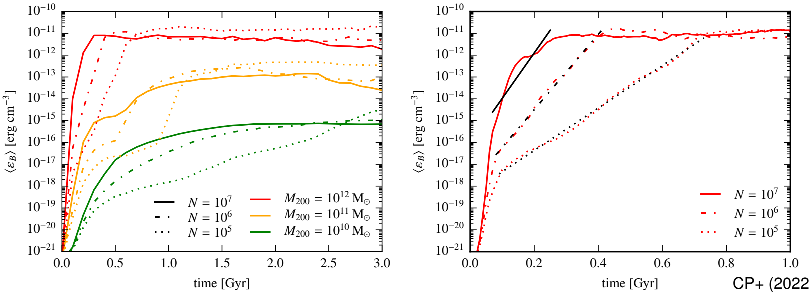
# Studying growth rate with numerical resolution



CP+ (2022)

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

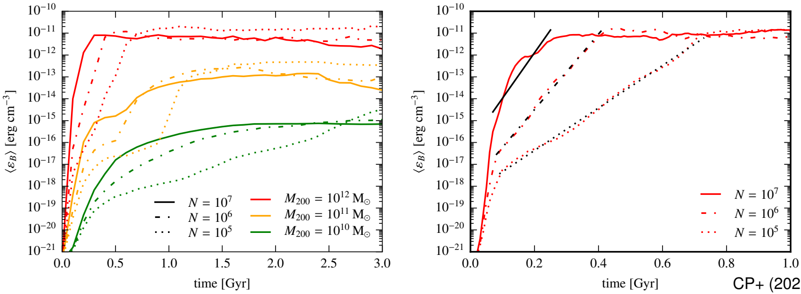
# Studying growth rate with numerical resolution



CP+ (2022)

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

# Studying growth rate with numerical resolution

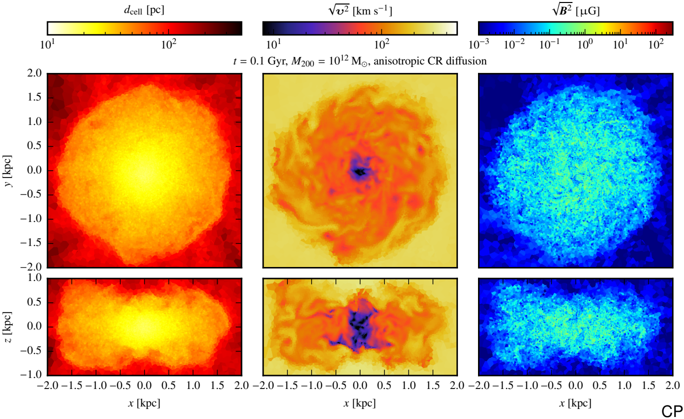


CP+ (2022)

- ***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

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

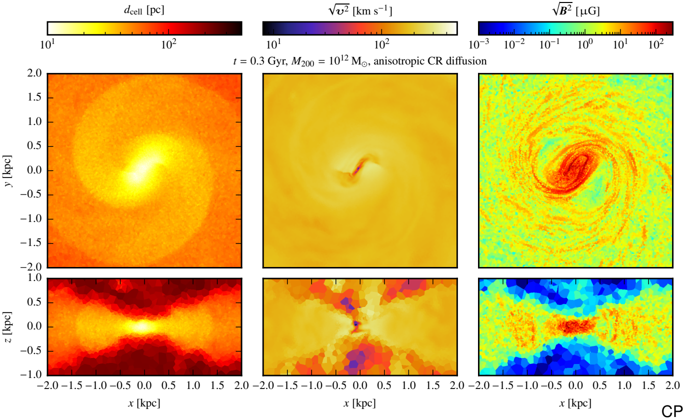
# Exponential field growth in kinematic regime



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 $\lambda_B$ increases

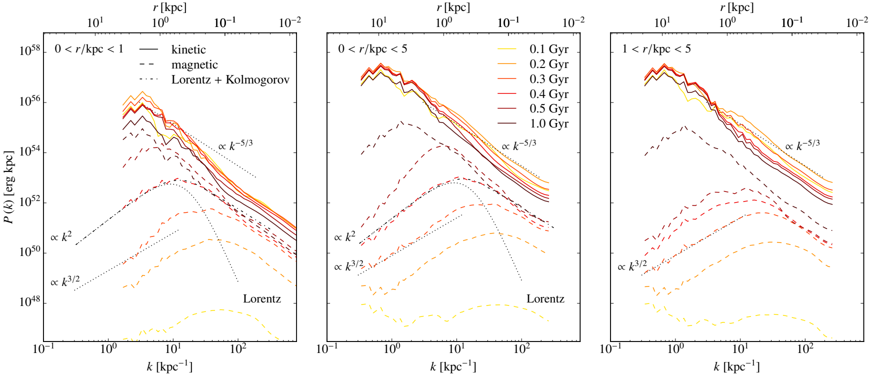


CP+ (2022)

- ***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

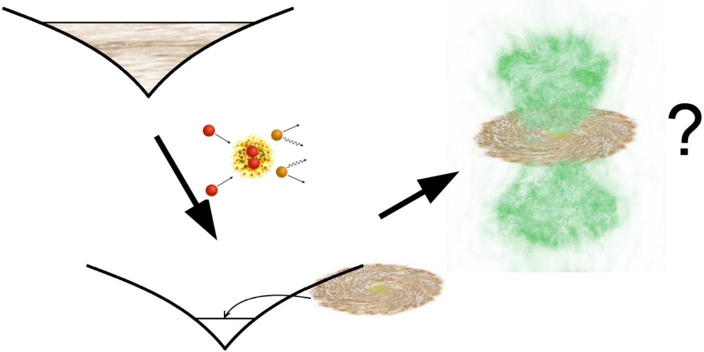
## Fluctuating small-scale dynamo in different analysis regions



CP+ (2022)

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

# 3. Cosmic rays and non-thermal emission



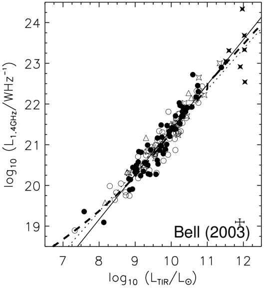
Werhahn, CP, Girichidis+ (2021a,b,c)
*Cosmic rays and non-thermal emission in simulated galaxies*

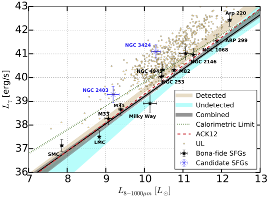
MHD + CR advection + anisotropic diffusion: $\{10^{10}, 10^{11}, 10^{12}\}\ \mathrm{M}_\odot$

steady-state spectra of CR protons, primary & secondary electrons

# 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

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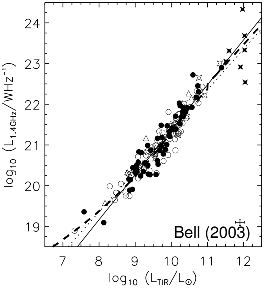
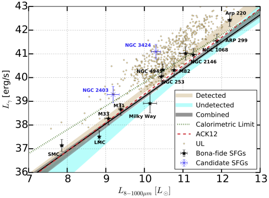
  - 1D transport models (Heesen+ 2016)
  - static Milky Way models (Strong & Moskalenko 1998, Evoli+ 2008, Kissmann 2014)
- ***our theoretical modeling:***
  - run MHD-CR simulations of galaxies at different halos masses and SFRs
  - model steady-state CRs: protons, primary and secondary electrons
  - 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



Bell (2003)



Ajello+ (2020)

# Steady-state cosmic ray spectra

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

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

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

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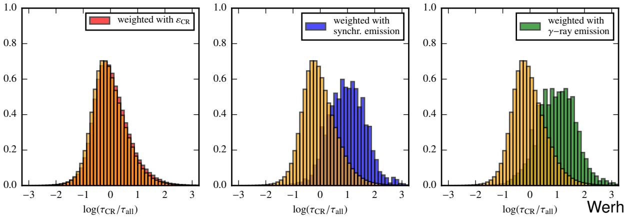
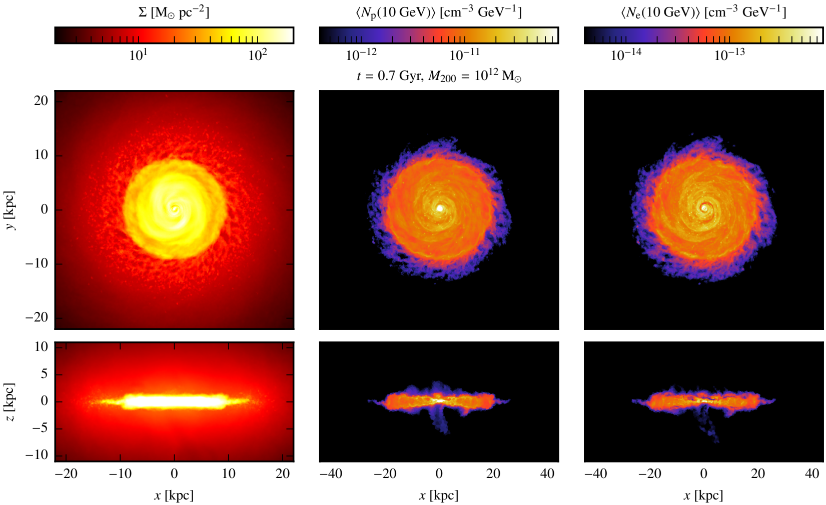
- electrons: Coulomb, bremsstr., IC, synchrotron and escape losses
  - primaries (re-normalized using $K_{\mathrm{ep}} = 0.02$)
  - secondaries
- steady state assumption is fulfilled in disk and in regions dominating the non-thermal emission but not at low densities, at SNRs and in outflows



Werhahn+ (2021a)

# From a starburst galaxy to a Milky Way analogy



Werhahn, CP+ (2021a,b)

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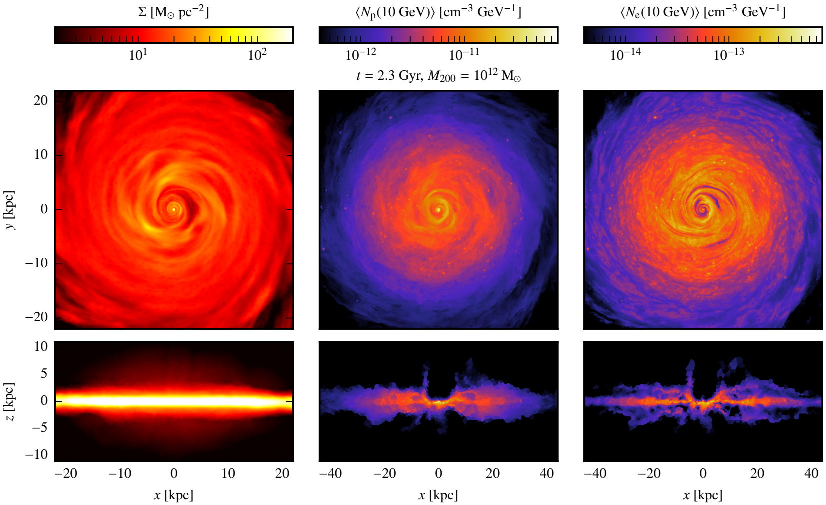
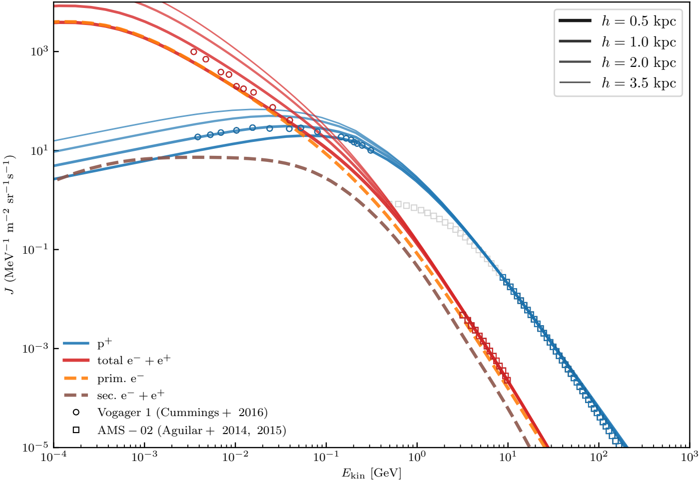


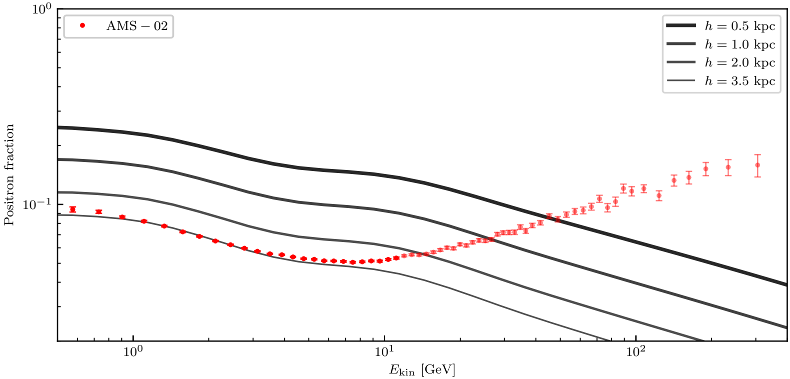
Werhahn, CP+ (2021a,b)

# Comparing CR spectra to Voyager and AMS-02 data



Werhahn, CP+ (2021a)

# Comparing the positron fraction to AMS-02 data



Werhahn, CP+ (2021a)

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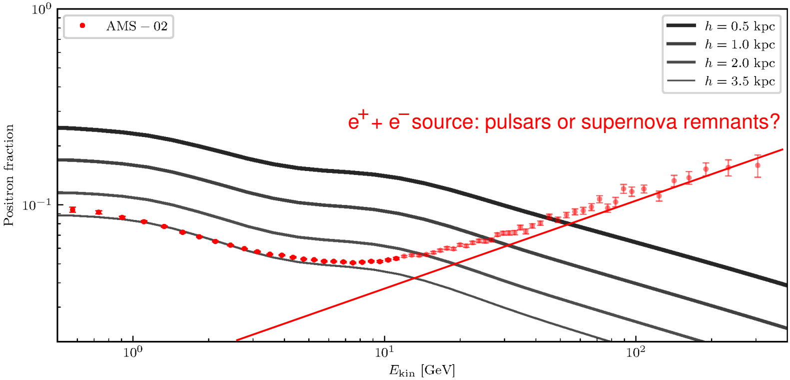
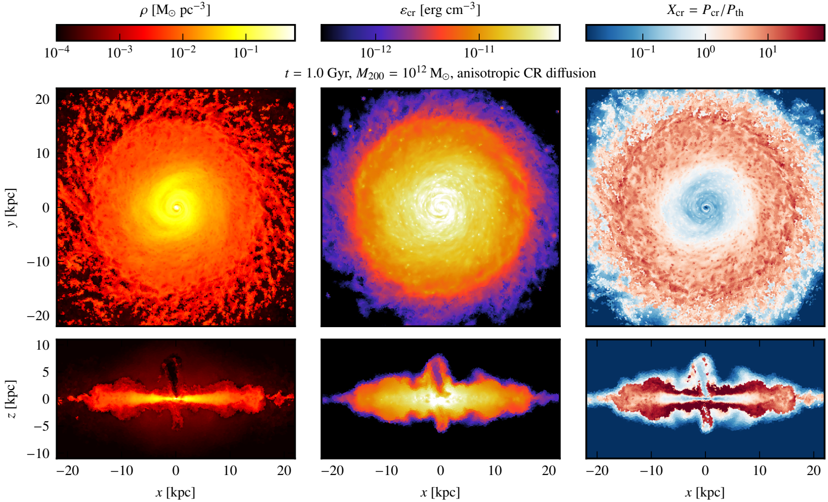


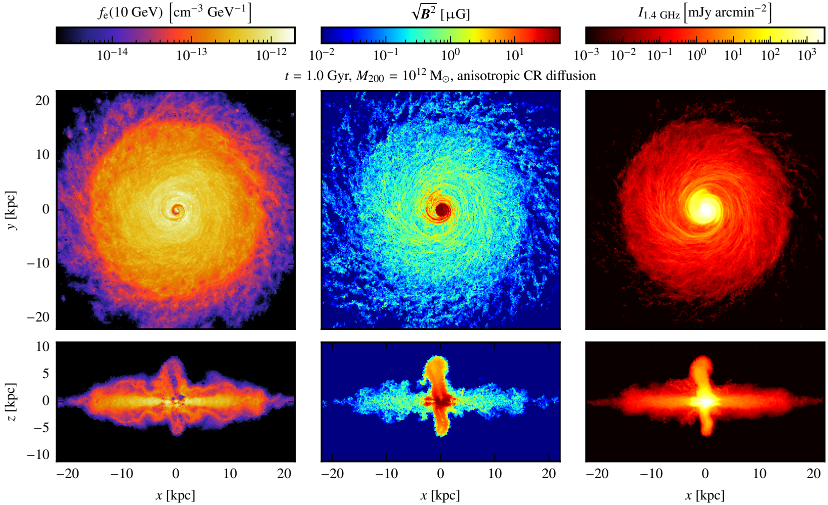
Werhahn, CP+ (2021a)

# Galaxy simulation with cosmic ray-driven wind



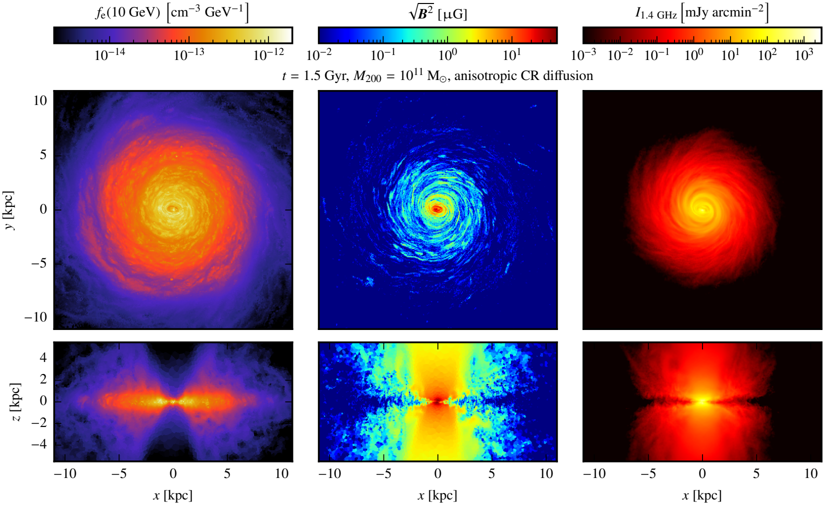
CP+ (2017)

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



CP+ (2022)

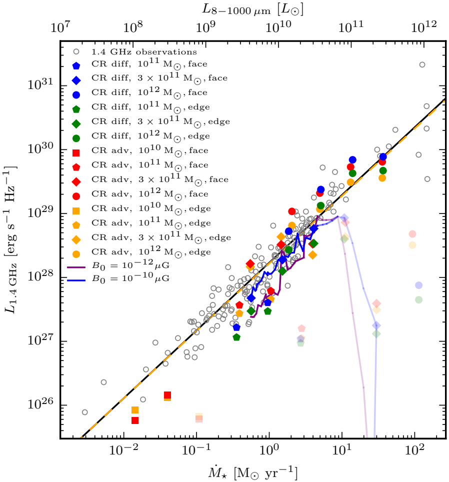
# Simulated radio emission: $10^{11}$ $\mathrm{M}_\odot$ halo



CP+ (2022)

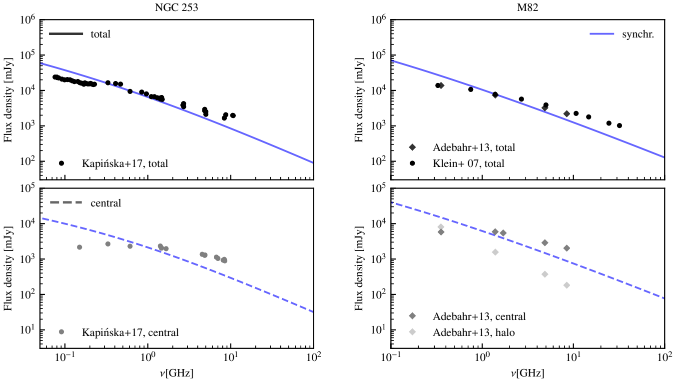
# Far infra-red – radio correlation

## Universal conversion: star formation → cosmic rays → radio



CP+ (2022)

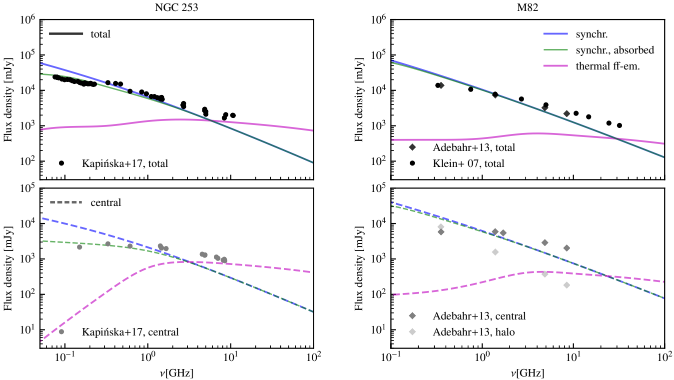
# Radio-ray spectra of starburst galaxies



Werhahn, CP+ (2021c)

- synchrotron spectra too steep (cooling + diffusion losses)

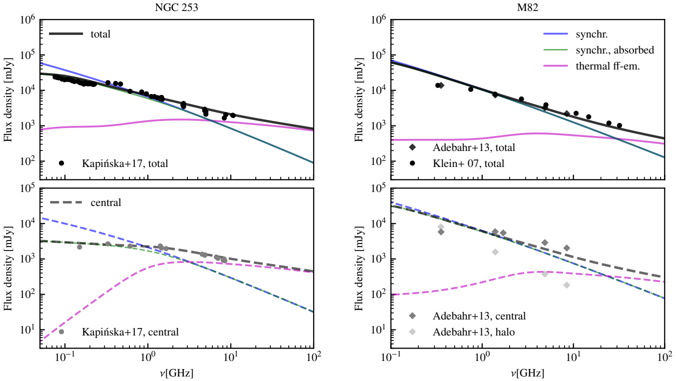
# Radio-ray spectra of starburst galaxies



Werhahn, CP+ (2021c)

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

# Radio-ray spectra of starburst galaxies



Werhahn, CP+ (2021c)

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

# 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
- synchrotron harps: CR streaming dominates over diffusion

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**CR hydrodynamics:**

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- synchrotron harps: CR streaming dominates over diffusion

**CR acceleration and feedback in galaxy formation:**

- small-scale dynamo grows magnetic field to equipartition with turbulent energy density
- CR feedback drives galactic winds & slows down star formation
- global $L_{\mathrm{FIR}} - L_{\mathrm{radio}}$ reproduced for galaxies with saturated magnetic fields, scatter due to viewing angle and CR transport
- synchrotron absorption (low-$\nu$) and thermal free-free emission (high-$\nu$) 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 – 1

## Cosmic ray hydrodynamics:

- Pfrommer, Pakmor, Schaal, Simpson, Springel, *Simulating cosmic ray physics on a moving mesh,* 2017a, MNRAS, 465, 4500.
- Jiang, Oh, *A New Numerical Scheme for Cosmic-Ray Transport,* 2018, ApJ, 854, 5.
- Thomas & Pfrommer, *Cosmic-ray hydrodynamics: Alfvén-wave regulated transport of cosmic rays,* 2019, MNRAS, 485, 2977.
- Thomas, Pfrommer, Enßlin, *Probing cosmic ray transport with radio synchrotron harps in the Galactic center,* 2020, ApJL, 890, L18.
- 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.
- Thomas, Pfrommer, Pakmor, *Cosmic ray-driven galactic winds: transport modes of cosmic rays and Alfvén-wave dark regions,* 2023, MNRAS.

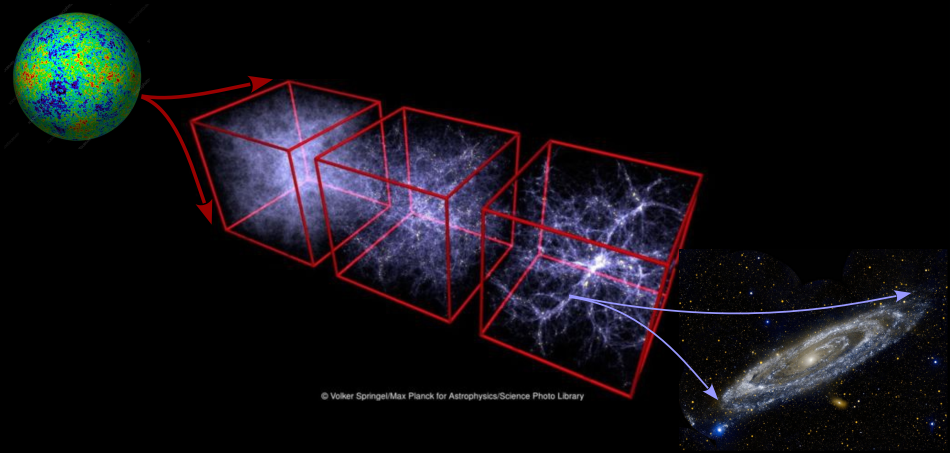
# Literature for the talk – 2

## 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. $\gamma$-ray maps, spectra and the far infrared-$\gamma$-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.

# Additional slides

# Cosmological galaxy formation



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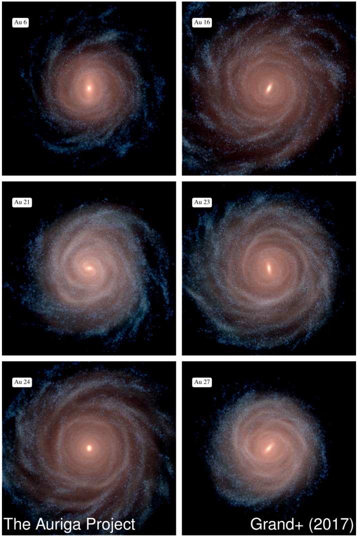
# Cosmic rays in cosmological galaxy simulations

## 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 stabilized by pressurized ISM
- thermal and kinetic energy from supernovae modeled 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, $2 \times 10^6$ star particles
- 4 models with different CR physics for each galaxy:
  - no CRs
  - CR advection
  - + CR anisotropic diffusion
  - + CR Alfvén wave cooling

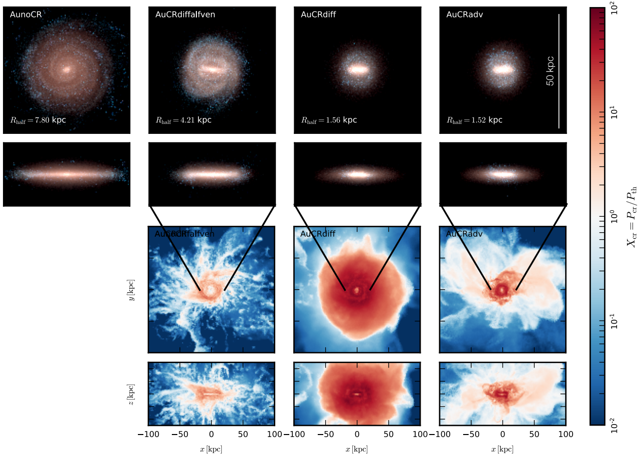


The Auriga Project

Grand+ (2017)

# Cosmic rays in cosmological galaxy simulations

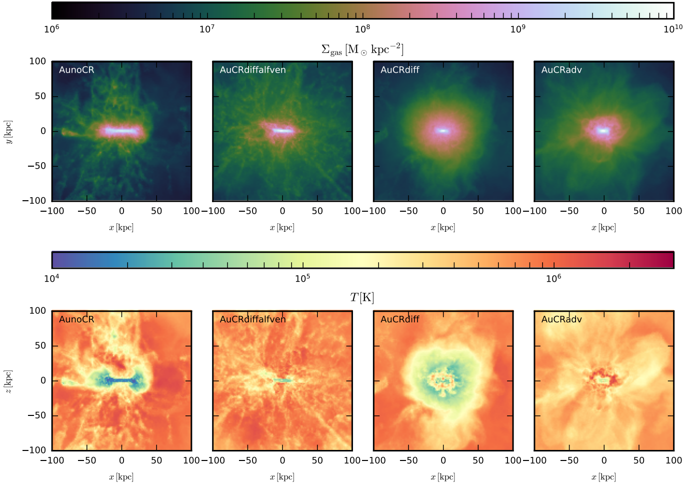
## Auriga MHD models: CR transport changes disk sizes



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)