A pedagogical introduction to cosmic rays, magnetic fields and galaxy formation

Part 3: Cosmic ray transport and non-thermal emission

Christoph Pfrommer

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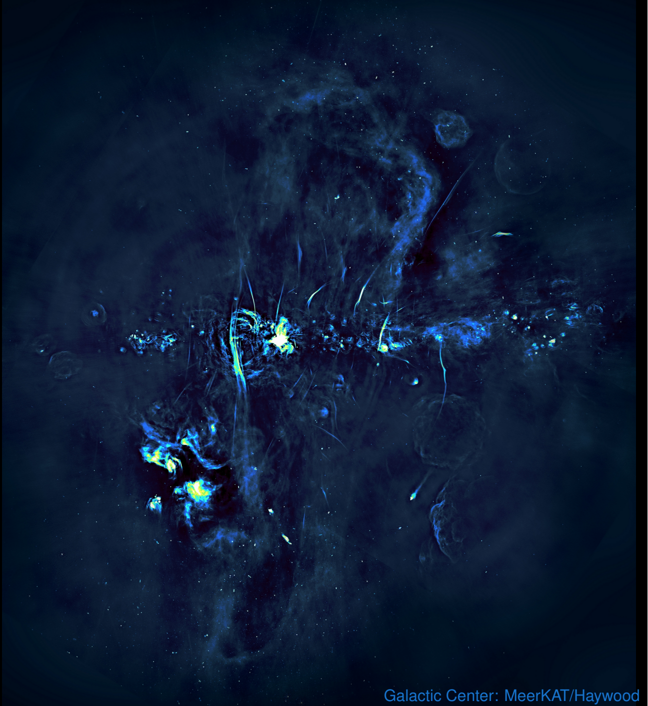
2nd International Astronomy Winter School
NCTS/UCAT/NTHU, Taiwan



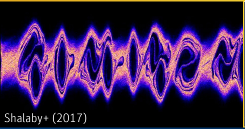
Galactic Center: MeerKAT/Haywood

Outline of the topics of the four lectures:

- **Magnetic fields**
  - * Properties and observables of astrophysical magnetic fields
  - * Generation and evolution of magnetic fields
- **Cosmic ray acceleration and observables**
  - * Properties of Galactic cosmic rays
  - * Cosmic ray acceleration by shocks and turbulence
- **Cosmic ray transport and non-thermal emission**
  - * Cosmic ray transport and particle-wave interactions
  - * Non-thermal emission processes from radio to gamma rays
- **The physics of galaxy formation**
  - * Puzzles in galaxy formation
  - * Feedback by stars and active galactic nuclei

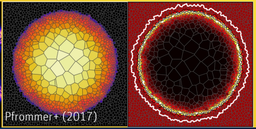
A multiscale approach to cosmic rays in galaxies

PIC – fluid PIC



Shalaby+ (2017)

cosmic ray MHD



Pfrommer+ (2017)

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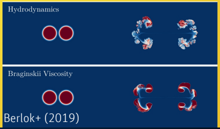
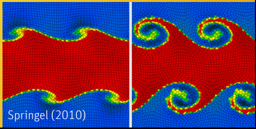


Berlok+ (2019)

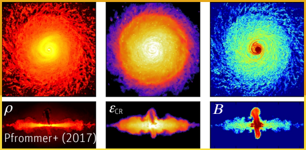
Cosmological moving mesh code



Springel (2010)

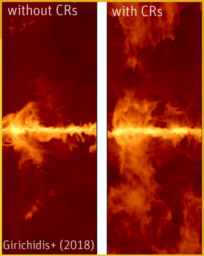
A multiscale approach to cosmic rays in galaxies

CR feedback



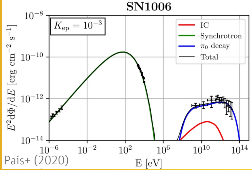
Pfrommer+ (2017)

CR transport in the ISM



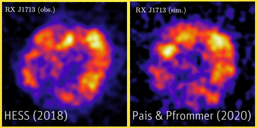
Girichidis+ (2018)

CR observables



Pais+ (2020)

CR shock acceleration: SNR



HESS (2018)

Pais & Pfrommer (2020)

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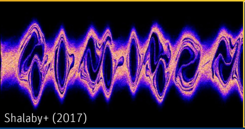

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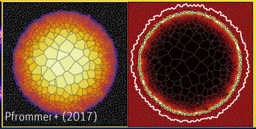

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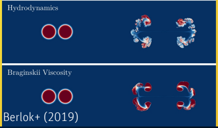

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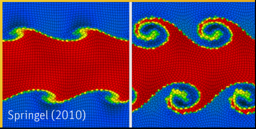
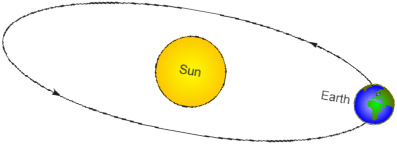


Springel (2010)

Cosmic ray transport: an extreme multi-scale problem



Milky Way-like galaxy:

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

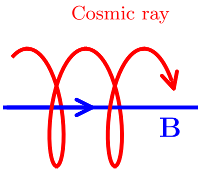
gyro-orbit of GeV CR:

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

⇒ 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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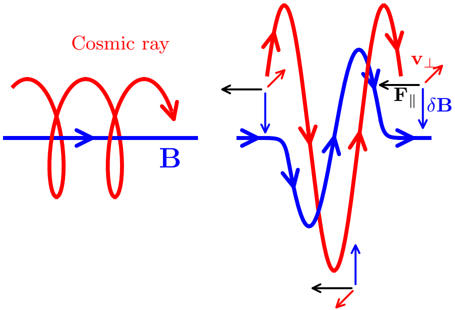

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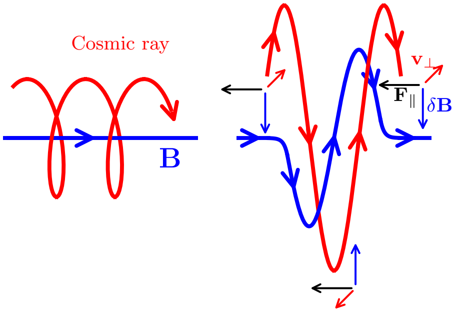

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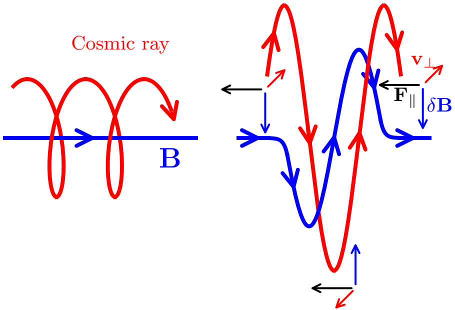

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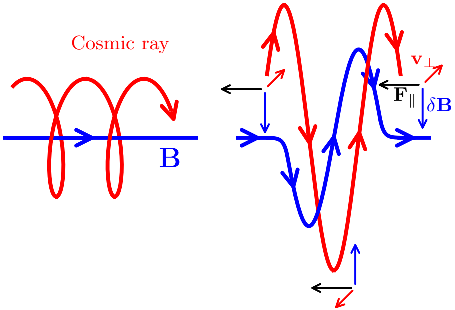

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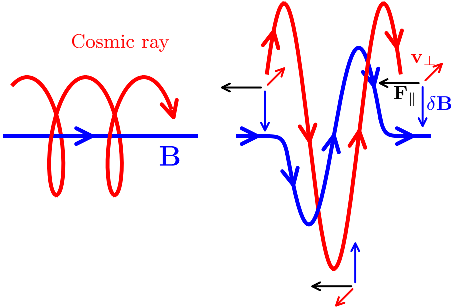
- work out **Lorentz forces on CRs** in wave frame: $\boldsymbol{F}_\mathrm{L}=Ze\dfrac{\boldsymbol{v}\times\boldsymbol{B}}{c}$
- Lorentz force depends on **relative phase of CR gyro orbit and wave:**
  - sketch: decelerating Lorentz force along CR orbit → $p_\parallel$ decreases
  - phase shift by 180°: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

Interactions of CRs and magnetic fields



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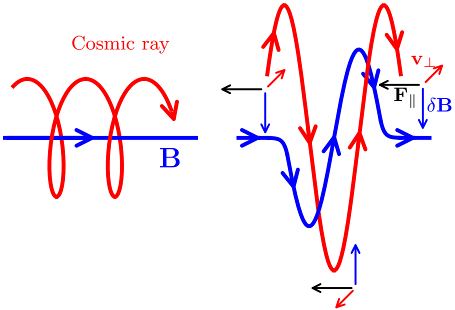

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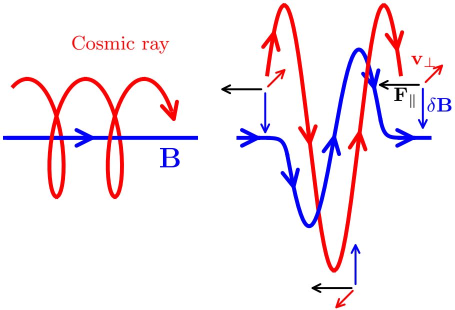

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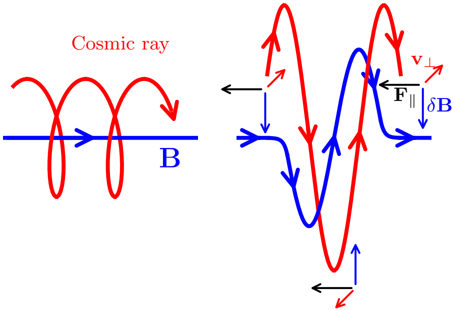

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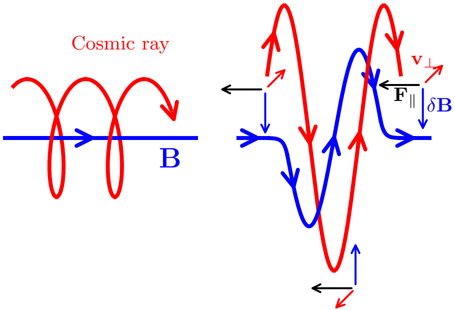
- this increases the CR pitch angle cosine $\mu = \cos\theta = \dfrac{\boldsymbol{B}}{|\boldsymbol{B}|}\cdot\dfrac{\boldsymbol{p}}{|\boldsymbol{p}|}$

Interactions of CRs and magnetic fields



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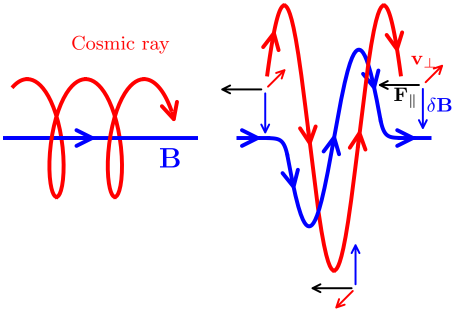

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- **CRs resonantly interact with Alfvén waves** so that the wavelength equals the gyro-radius:

$$L_\parallel = r_g = \frac{p_\perp c}{ZeB}$$

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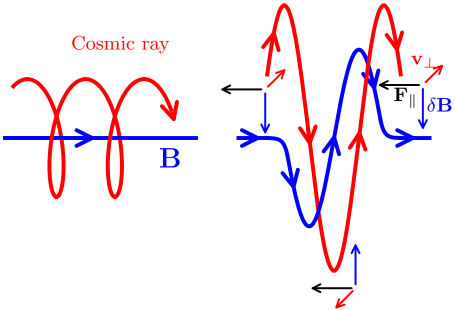

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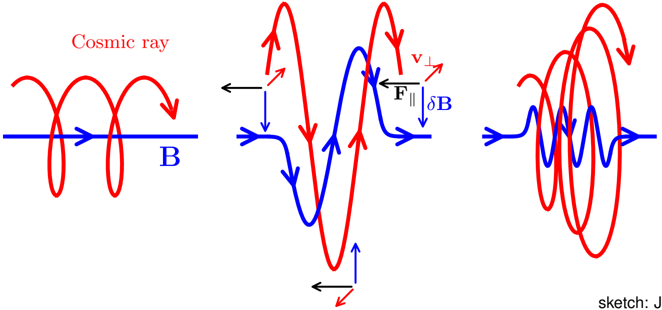

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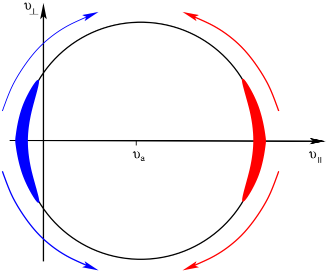
AIP

Pitch angle scattering isotropizes CRs



- 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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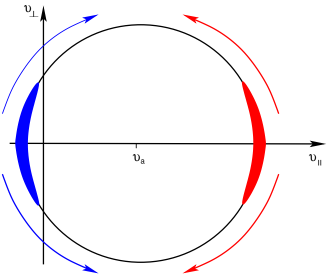

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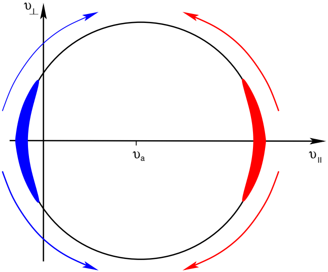

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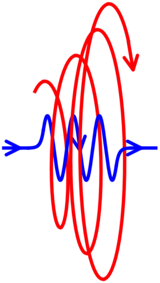
- CR scattering with Alfvén waves can be described as random walk in μ, which on average reduces $v_\parallel$ (provided $v_\parallel > v_a$ initially) and ***conserves the particle energy in the Alfvén wave rest frame***
- ***diffusion process in μ along the equal-energy circle*** in velocity space with scattering frequency $\nu(p,\mu) \Rightarrow$ homogeneous μ distribution:

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

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 $\sim v_{\mathrm{a}}$
  - wave damping: transfer of CR energy and momentum to the thermal gas



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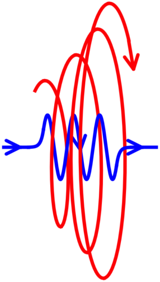

→ *CRs exert pressure on thermal gas via scattering on Alfvén waves*

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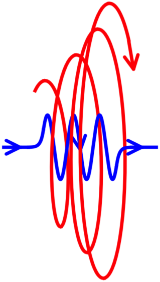
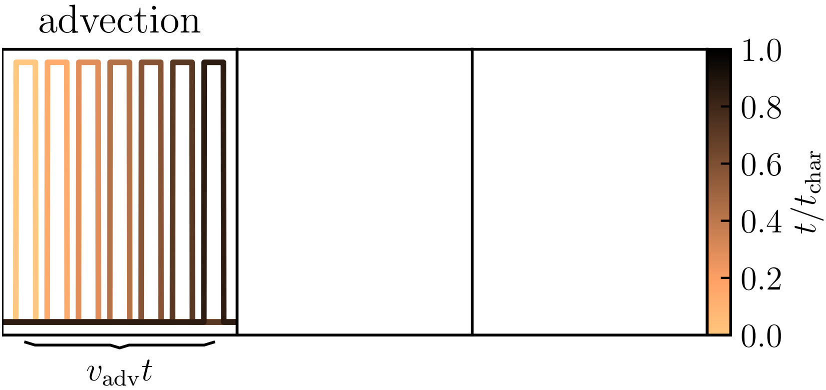


→ *CRs exert pressure on thermal gas via scattering on Alfvén waves*

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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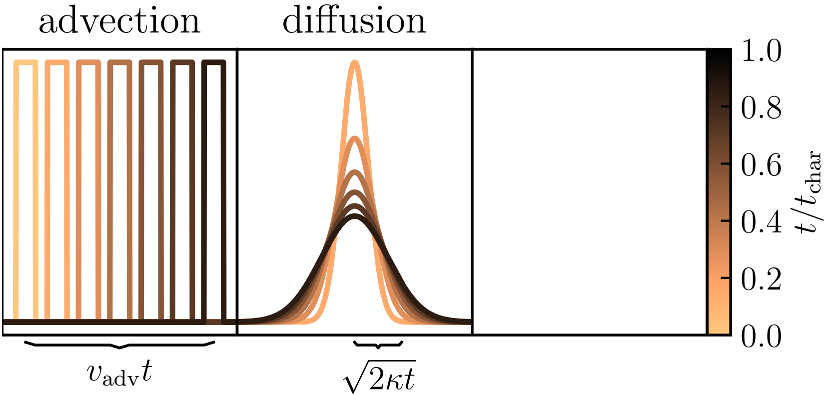

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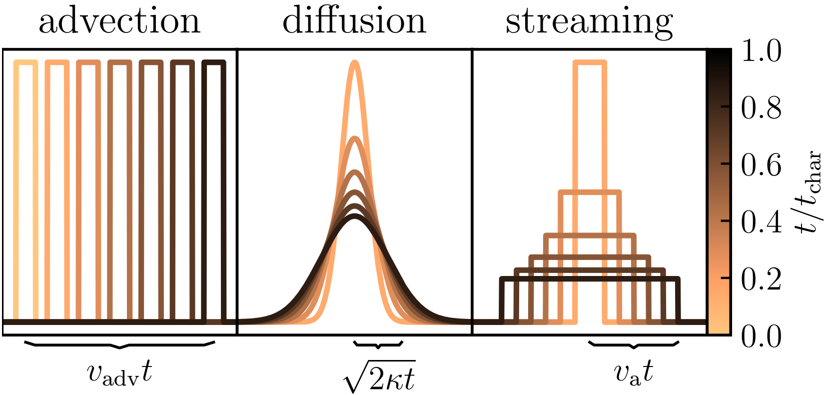

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1-moment CR hydrodynamics (steady-state flux)

- total CR velocity $\boldsymbol{v}_{\mathrm{cr}} = \boldsymbol{v} + \boldsymbol{v}_{\mathrm{st}} + \boldsymbol{v}_{\mathrm{di}}$ (where $\boldsymbol{v} \equiv \boldsymbol{v}_{\mathrm{gas}}$)

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- energy equations with $\varepsilon = \varepsilon_{\mathrm{th}} + \rho v^2/2$:

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1-moment CR hydrodynamics (steady-state flux)

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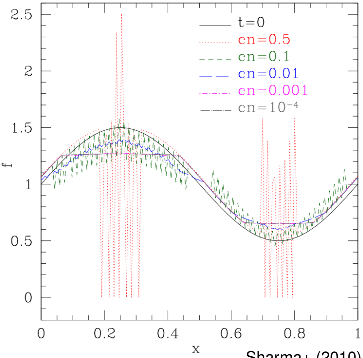
\frac{\partial \varepsilon_{\mathrm{cr}}}{\partial t} + \boldsymbol{\nabla} \cdot [P_{\mathrm{cr}} \boldsymbol{v}_{\mathrm{st}} + \varepsilon_{\mathrm{cr}}(\boldsymbol{v} + \boldsymbol{v}_{\mathrm{st}} + \boldsymbol{v}_{\mathrm{di}})] &= -P_{\mathrm{cr}} \boldsymbol{\nabla} \cdot \boldsymbol{v} + \boldsymbol{v}_{\mathrm{st}} \cdot \boldsymbol{\nabla} P_{\mathrm{cr}} \\
\Longleftrightarrow \quad \frac{\partial \varepsilon_{\mathrm{cr}}}{\partial t} + \boldsymbol{\nabla} \cdot [\varepsilon_{\mathrm{cr}}(\boldsymbol{v} + \boldsymbol{v}_{\mathrm{st}} + \boldsymbol{v}_{\mathrm{di}})] &= -P_{\mathrm{cr}} \boldsymbol{\nabla} \cdot (\boldsymbol{v} + \boldsymbol{v}_{\mathrm{st}})
\end{aligned}$$

Modeling CR streaming

A challenging hyperbolic/parabolic problem



Sharma+ (2010)

- streaming equation (no heating):

$$\frac{\partial \varepsilon_{\rm cr}}{\partial t} + \boldsymbol{\nabla} \cdot [(\varepsilon_{\rm cr} + P_{\rm cr})\boldsymbol{v}_{\rm st}] = 0$$

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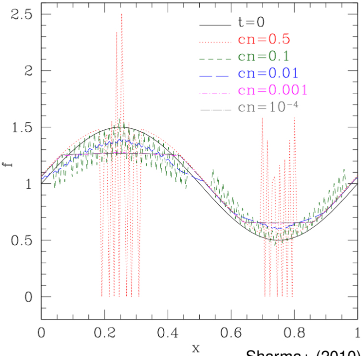
- CR streaming $\sim$ CR advection with the Alfvén speed
- at local extrema, CR energy can overshoot and develop unphysical oscillations

Modeling CR streaming

A challenging hyperbolic/parabolic problem



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- CR streaming $\sim$ CR advection with the Alfvén speed
- at local extrema, CR energy can overshoot and develop unphysical oscillations

- idea: regularize equations, similar to adding artificial viscosity

Modeling CR streaming – regularization

- 1D streaming equation (no heating):

$$\frac{\partial \varepsilon_{\mathrm{cr}}}{\partial t} + \frac{\partial}{\partial x}\left[(\varepsilon_{\mathrm{cr}} + P_{\mathrm{cr}})v_{\mathrm{st}}\right] = 0$$

$$v_{\mathrm{st}} = -v_{\mathrm{a}}\mathrm{sgn}\left(\frac{\partial \varepsilon_{\mathrm{cr}}}{\partial x}\right) \quad \rightarrow \quad \tilde{v}_{\mathrm{st}} = -v_{\mathrm{a}}\tanh\left(\frac{1}{\delta}\frac{\partial \varepsilon_{\mathrm{cr}}}{\partial x}\right)$$

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- regularized 1D streaming equation (no heating):

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$$\frac{\partial \varepsilon_{\mathrm{cr}}}{\partial t} + \tilde{v}_{\mathrm{st}} \frac{\partial}{\partial x}(\varepsilon_{\mathrm{cr}} + P_{\mathrm{cr}}) - \kappa_{\mathrm{reg}} \frac{\partial^2 \varepsilon_{\mathrm{cr}}}{\partial x^2} = 0,$$

where $\kappa_{\mathrm{reg}} = v_{\mathrm{a}} \gamma_{\mathrm{cr}} \varepsilon_{\mathrm{cr}} \frac{1}{\delta} \mathrm{sech}^2\left(\frac{1}{\delta}\frac{\partial \varepsilon_{\mathrm{cr}}}{\partial x}\right)$ (Sharma+ 2010)

- regularized equation is advective at gradients and diffusive at extrema

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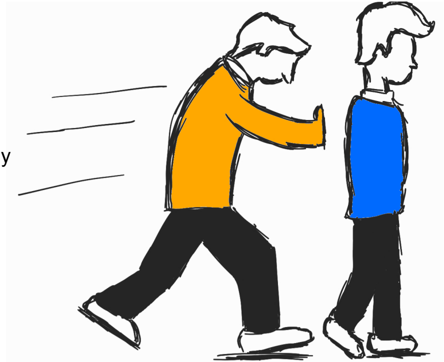
- regularized equation is advective at gradients and diffusive at extrema
- ***but:*** *numerical diffusion dominates for CR sources on a background*

CR interactions with Alfvén waves



acceleration
+ energy transfer

CRs

are … fast
will … lose energy

Alfvén waves

are … slow
will … gain energy

slide concept Thomas

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

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

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

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

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

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

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

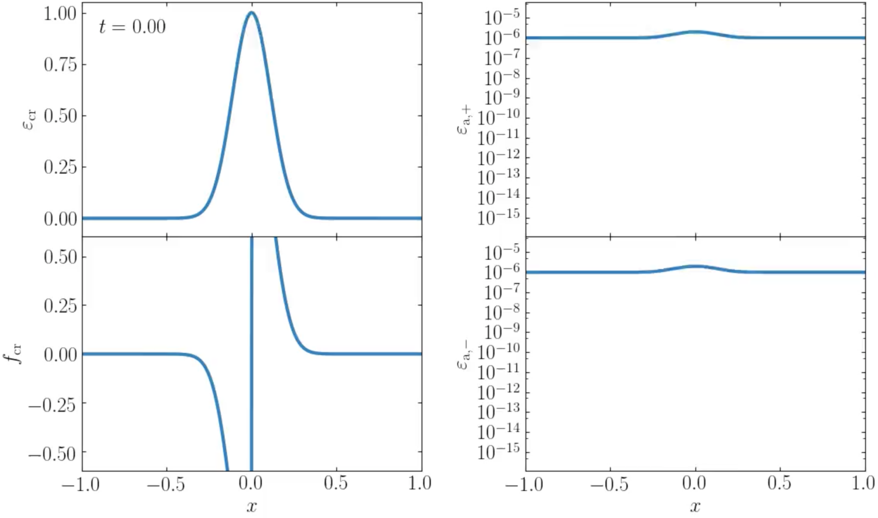
$$\begin{aligned}\frac{\partial \varepsilon_{\mathrm{cr}}}{\partial t} &+ \boldsymbol{\nabla}\cdot\left[\boldsymbol{v}(\varepsilon_{\mathrm{cr}}+P_{\mathrm{cr}})+\boldsymbol{b}f_{\mathrm{cr}}\right] = \boldsymbol{v}\cdot\boldsymbol{\nabla}P_{\mathrm{cr}} \\ &- \frac{v_{\mathrm{a}}}{3\kappa_+}\left[f_{\mathrm{cr}}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

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

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

Non-equilibrium CR streaming and diffusion

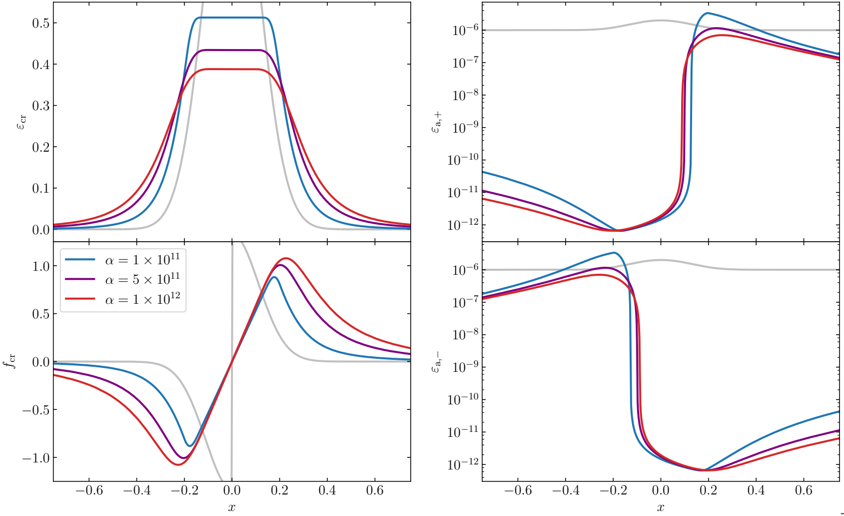
Coupling the evolution of CR and Alfvén wave energy densities



Thomas & CP (2019)

Non-equilibrium CR streaming and diffusion

Varying damping rate of Alfvén waves modulates the diffusivity of solution

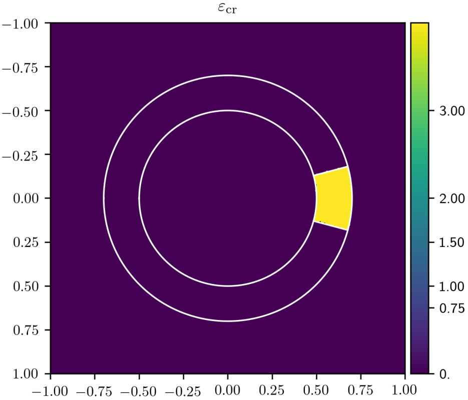


Thomas & CP (2019)

Anisotropic CR streaming and diffusion – AREPO

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

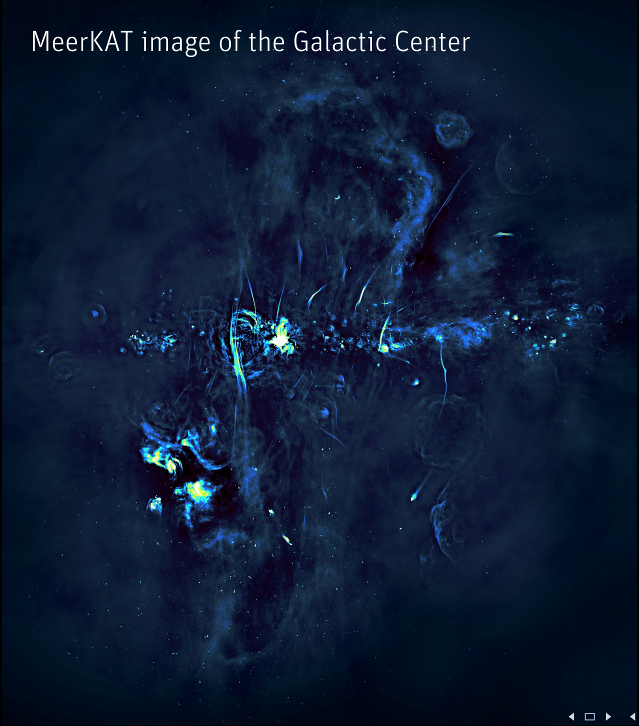
- CR streaming and diffusion along magnetic field lines in the self-confinement picture
- moment expansion similar to radiation hydrodynamics
- accounts for kinetic physics: non-linear Landau damping, gyro-resonant instability, . . .
- Galilean invariant and causal transport
- energy and momentum conserving



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

MeerKAT image of the Galactic Center

Haywood+ (Nature, 2019)



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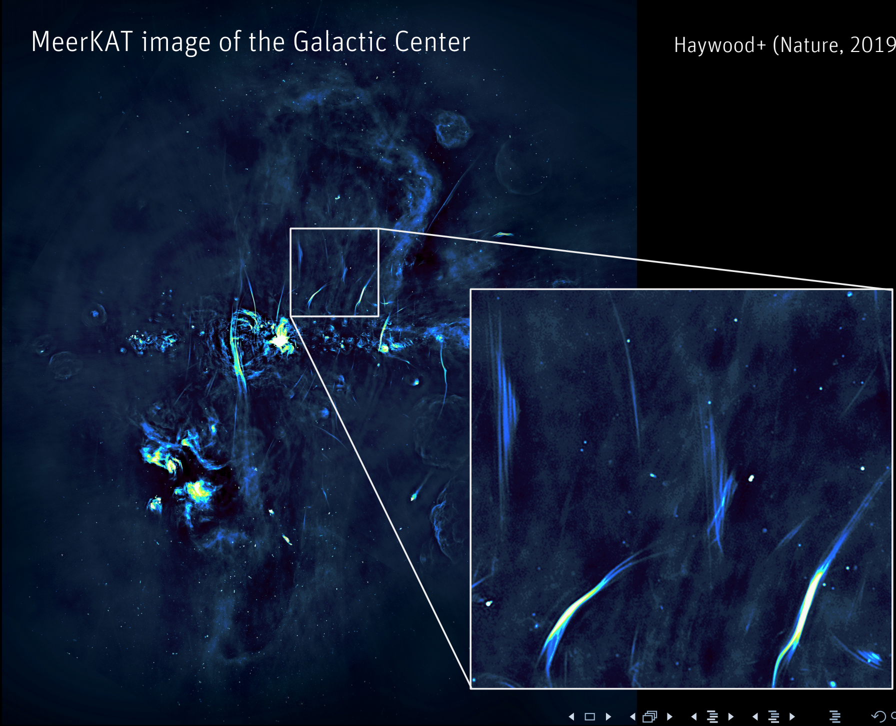
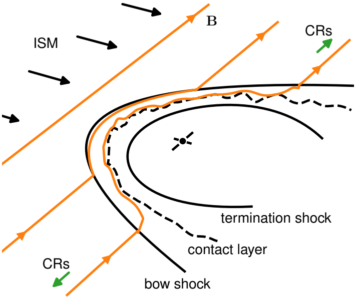


Radio synchrotron harps: the model

shock acceleration scenario



Thomas, CP, Enßlin (2020)

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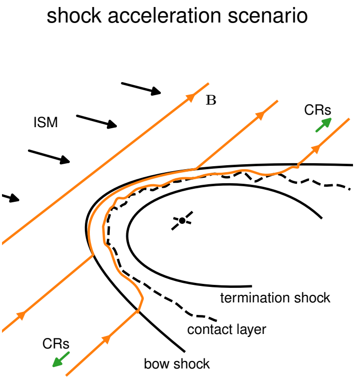

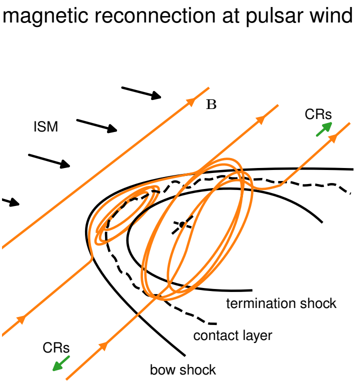

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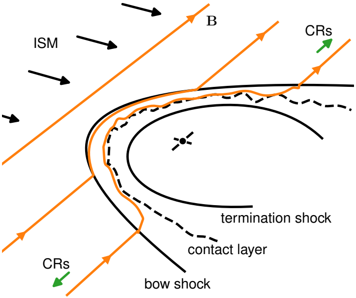
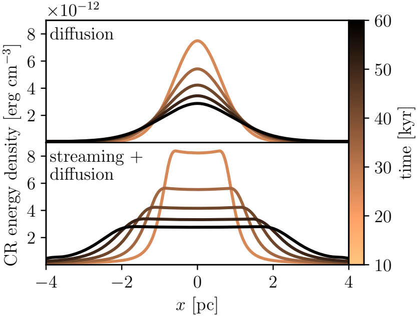
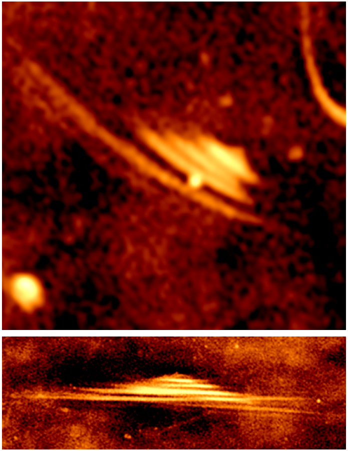


Thomas, CP, Enßlin (2020)

CR diffusion vs. streaming + diffusion



Radio synchrotron harps: testing CR propagation



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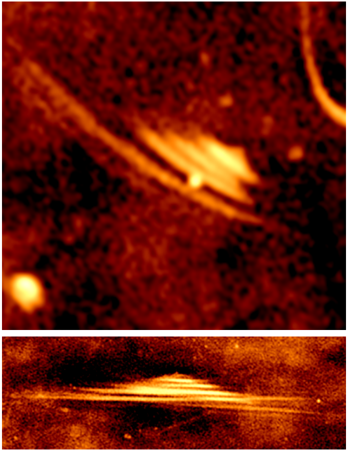

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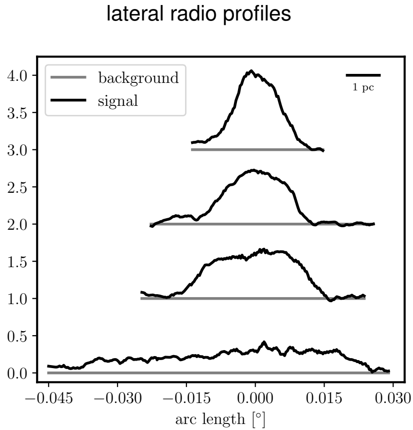

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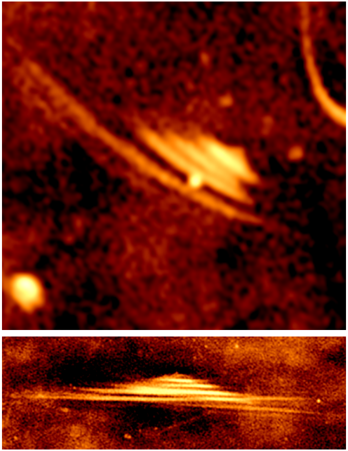

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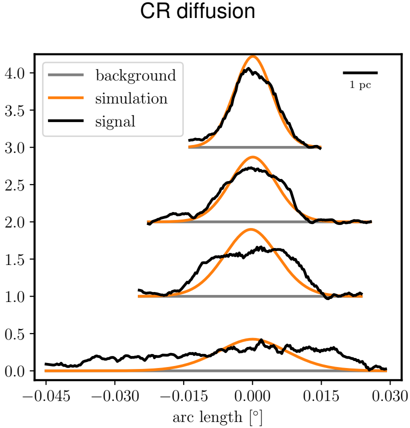

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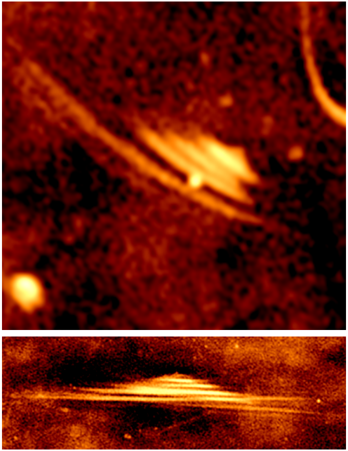
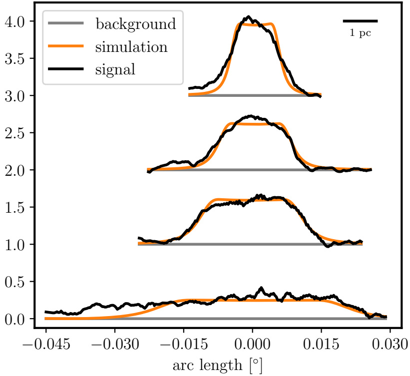


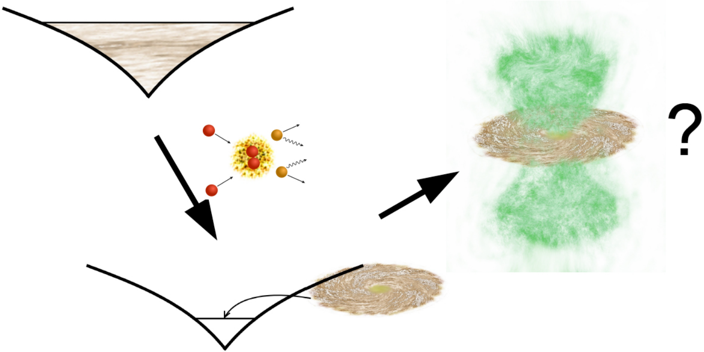
Haywood+ (Nature, 2019)

CR streaming and diffusion



Thomas, CP, Enßlin (2020)

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

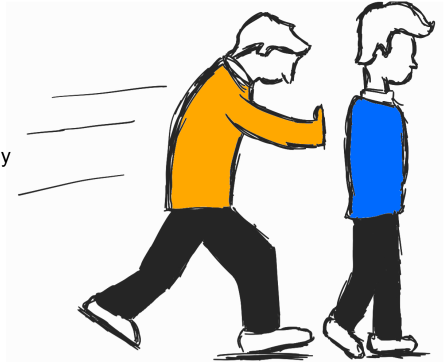
MHD + Alfvén wave regulated (2-moment) CR hydrodynamics:
galaxy forming in a $10^{11}\,M_\odot$ halo

CR interactions with Alfvén waves

acceleration
+ energy transfer

CRs

are … fast
will … lose energy

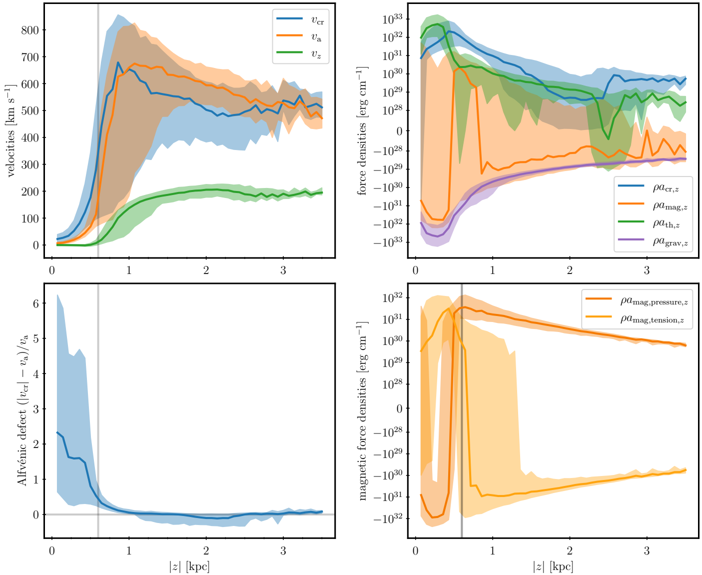


Alfvén waves

are … slow
will … gain energy

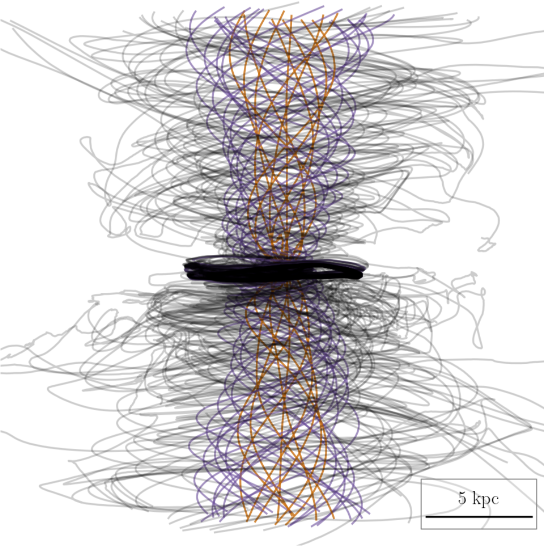
slide concept Thomas

Wind launching



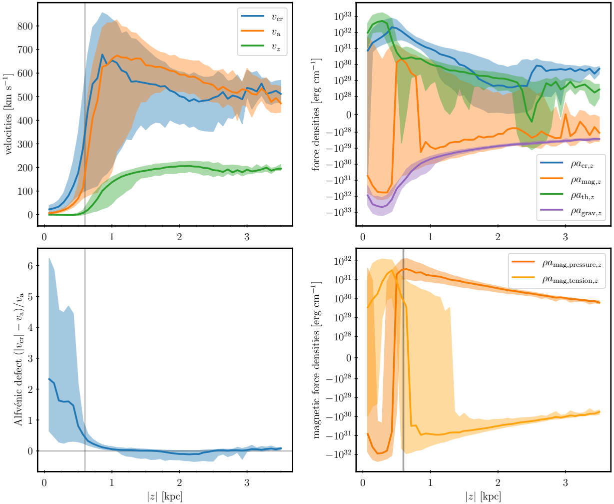
Thomas, CP, Pakmor (2023)

Magnetic field topology



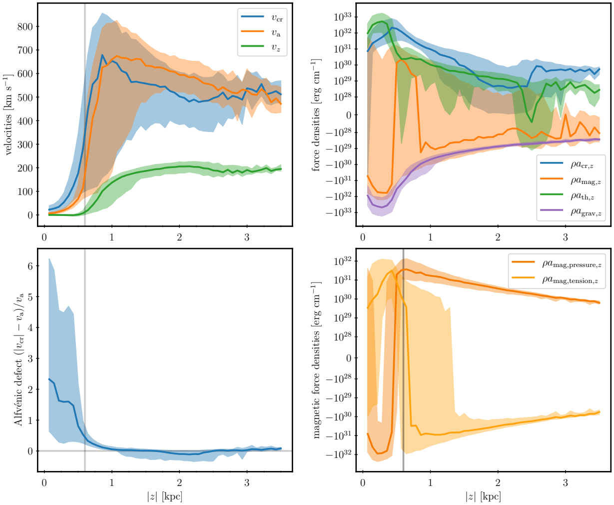
Thomas, CP, Pakmor (2023)

Wind launching



Thomas, CP, Pakmor (2023)

Wind launching



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

Thomas, CP, Pakmor (2023)

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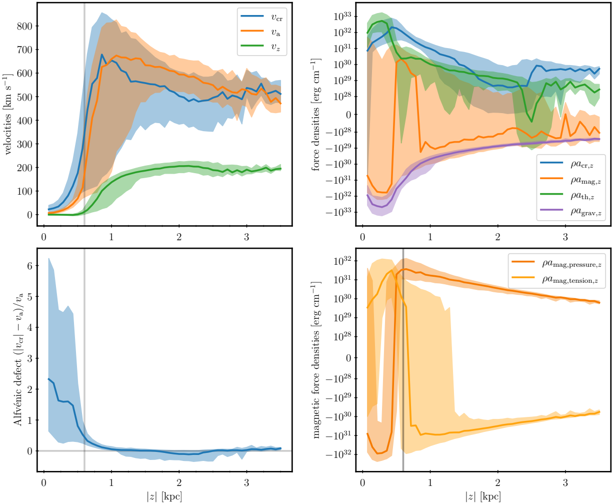

Thomas, CP, Pakmor (2023)

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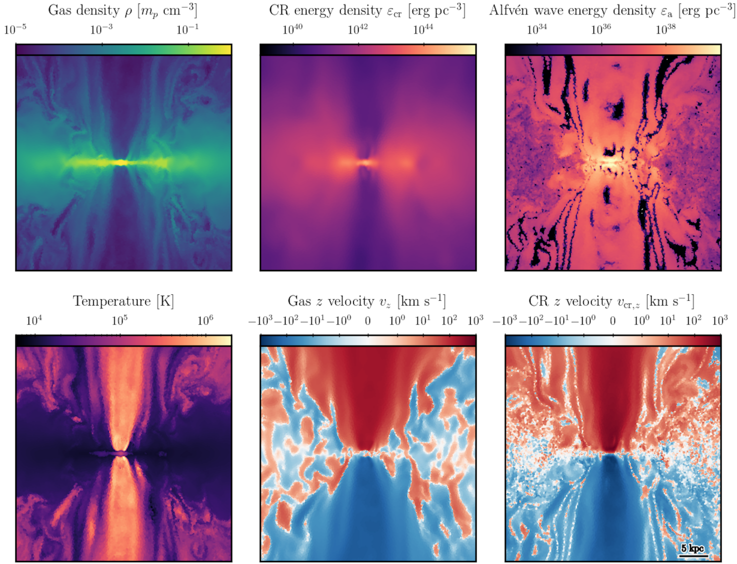
ignoring toroidal field components:

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

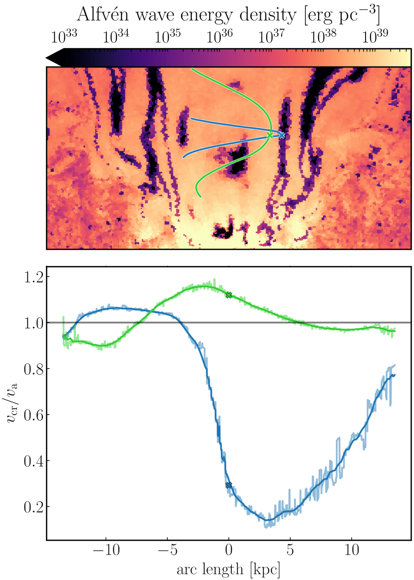
$$\rho a_{\text{mag,tension},z} = +B_z (\partial_z B_z)$$

Wind properties



Thomas, CP, Pakmor (2023)

What is the origin of the Alfvén dark regions?



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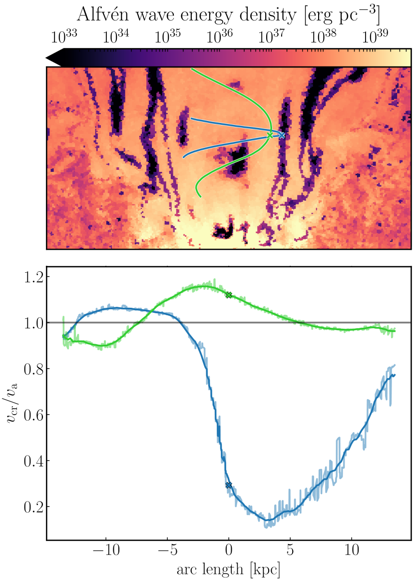

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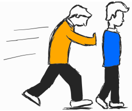

CRs faster than AWs
AWs gain energy

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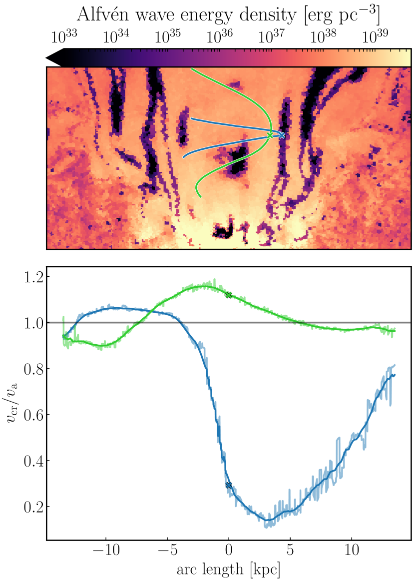
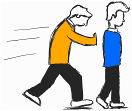


Thomas, CP, Pakmor (2023)



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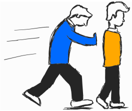
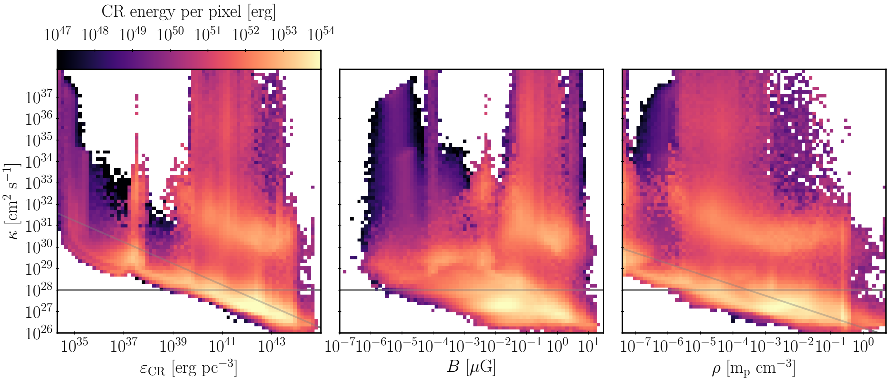


CRs slower than AWs
AWs lose energy

Parallel CR diffusion coefficient



Thomas, CP, Pfrommer (2023)

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

Non-thermal emission processes

Complementary information to CRs: electro-magnetic emission points back to origin

hadronic processes:

- pion decay:

$$\mathrm{p{+}ion} \rightarrow \left\{ \begin{array}{ccl} \pi^0 & \rightarrow & \gamma\gamma \\ \pi^\pm & \rightarrow & \mathrm{e}^\pm + 3\nu \end{array} \right.$$

- photo-meson production:

$$\mathrm{p} + \gamma \rightarrow \left\{ \begin{array}{ccl} \pi^0 & \rightarrow & \gamma\gamma \\ \pi^\pm & \rightarrow & \mathrm{e}^\pm + 3\nu \end{array} \right.$$

- Bethe-Heitler pair production:

$$\mathrm{p} + \gamma \rightarrow \mathrm{p} + e^+ + e^-$$

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leptonic processes:

- inverse Compton:

$$\mathrm{e}^* + \gamma \rightarrow \mathrm{e} + \gamma^*$$

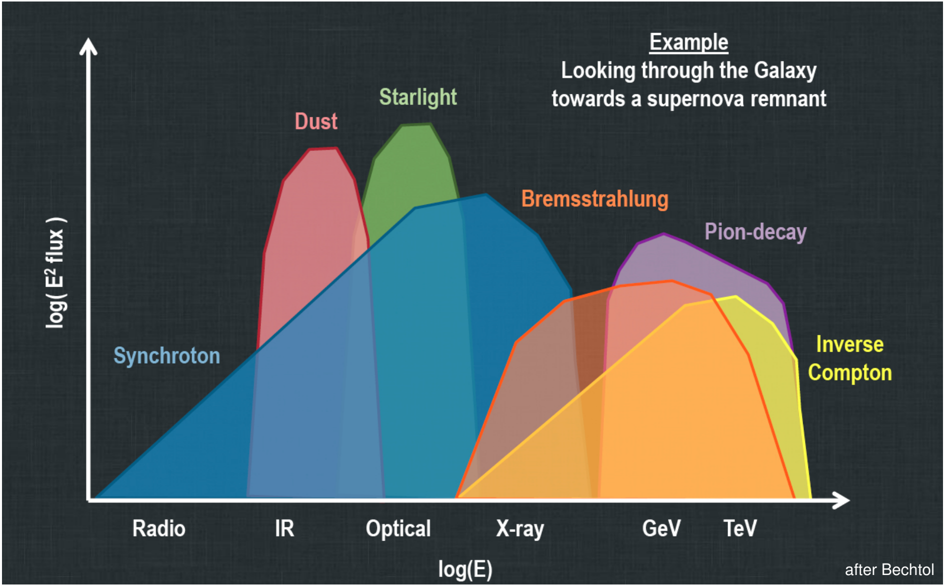
- synchrotron radiation:

$$\mathrm{e}^* + B \rightarrow \mathrm{e} + B + \gamma^*$$

- bremsstrahlung:

$$\mathrm{e}^* + \mathrm{ion} \rightarrow \mathrm{e} + \mathrm{ion} + \gamma^*$$

A sketch of the non-thermal emission



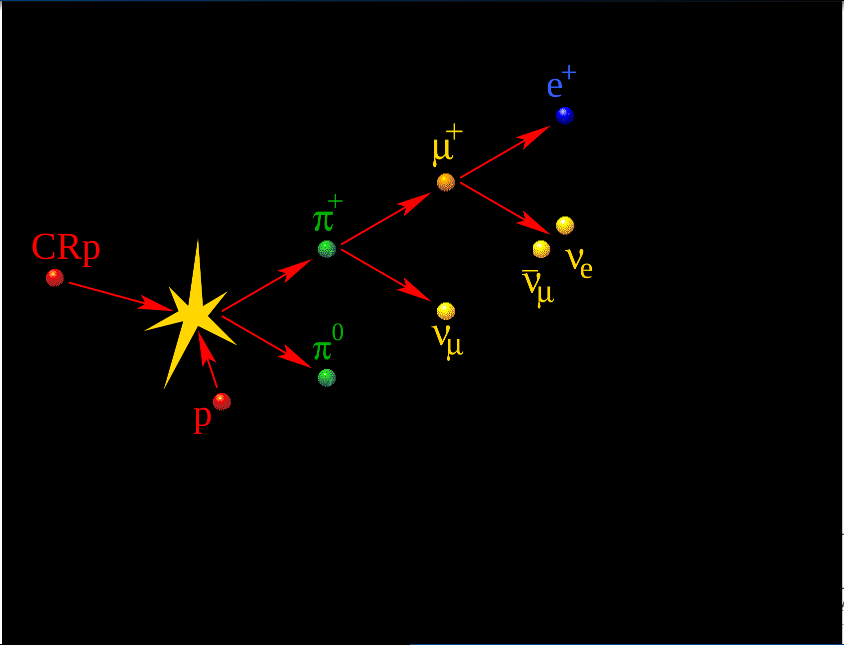
after Bechtol

CR protons vs. CR electrons

CR protons:

- diffusive shock acceleration, Fermi II acceleration via MHD-wave interactions
- can provide substantial pressure support $\Rightarrow$ modifies gas dynamics and shocks
- Coulomb/MHD wave interactions $\rightarrow$ modifies thermal gas energy
- radiative losses negligible – suppressed by $(m_\mathrm{e}/m_\mathrm{p})^2$,
- visible through hadronic interaction and pion-decay gamma rays

Hadronic cosmic ray proton interaction



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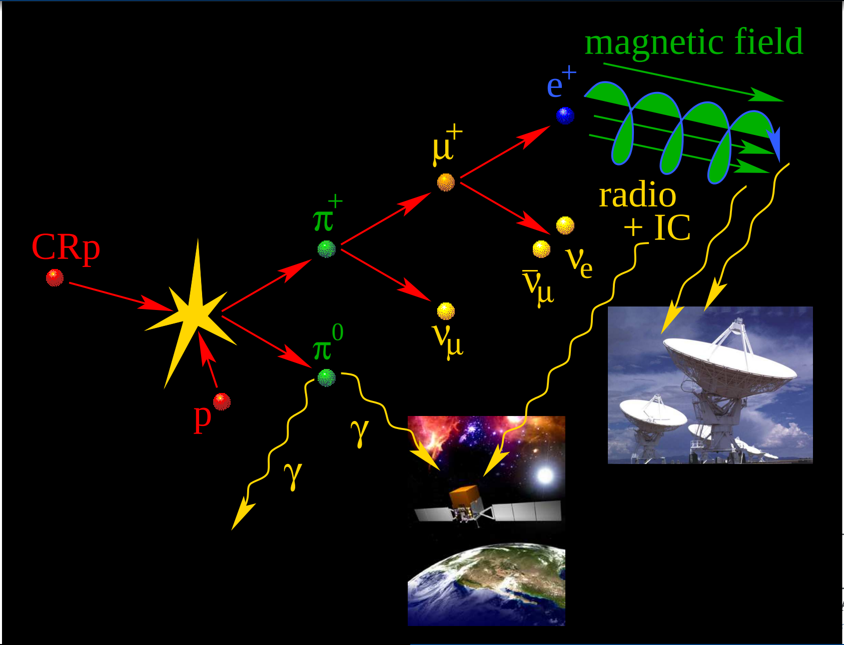

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- negligible pressure support
- radiative losses important: we can observe them in the radio, X-rays and γ rays!

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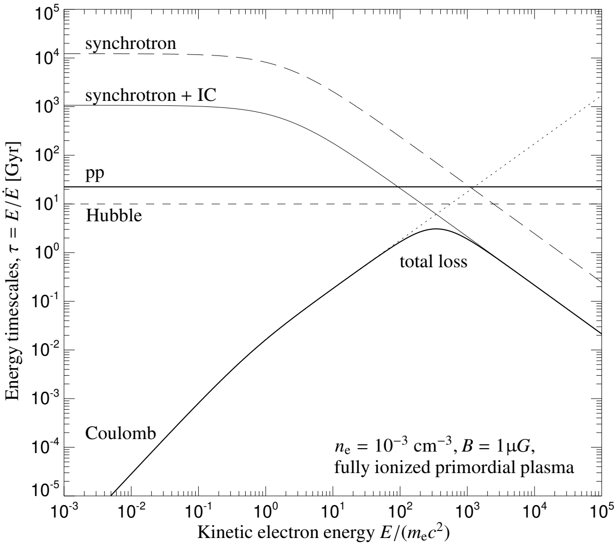
CRs are accelerated by astrophysical shocks of . . .

- supernovae and stellar winds in the interstellar medium
- pulsar wind nebulae
- jets in active galactic nuclei
- galactic superwinds
- cosmological structure formation shocks

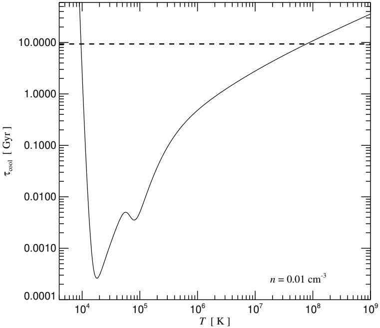
Cooling time scales of CR electrons



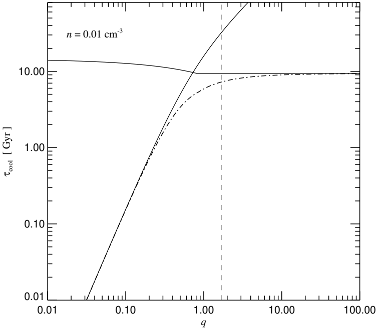
Pfrommer+ (2008)

Cooling time scales: thermal gas vs. CR protons

Cooling of primordial gas:



Cooling of cosmic rays:



Jubelgas+ (2008)

- ***thermal gas*** radiates its energy quickly away

Cooling time scales: thermal gas vs. CR protons

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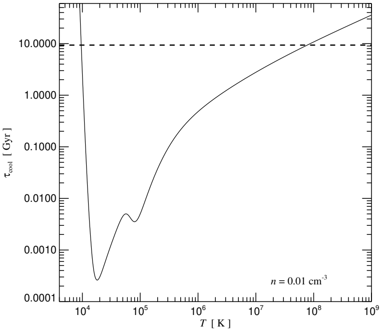

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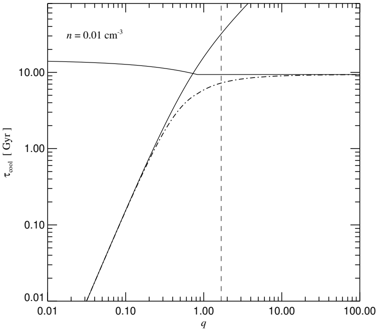

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Cooling time scales: thermal gas vs. CR protons

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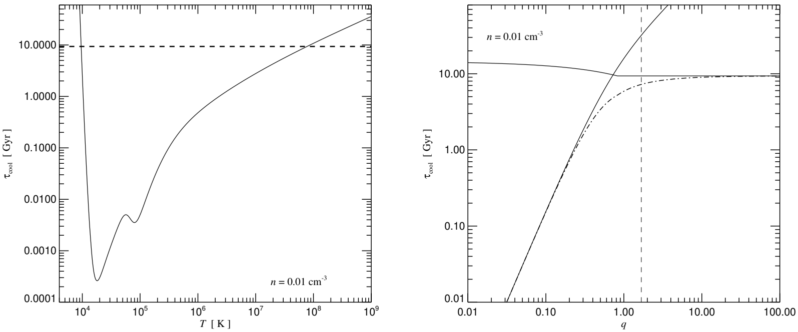

Jubelgas+ (2008)

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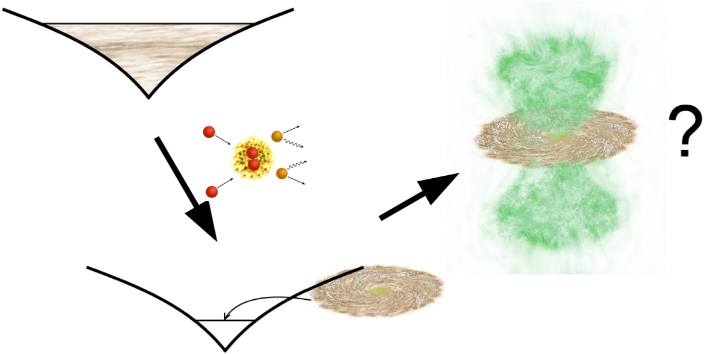
  ⇒ non-thermal pressure support of interstellar and circum-galactic gas
  ⇒ CR pressure gradient accelerates gas and drives galactic winds
  ⇒ CRs excite Alfvén waves that dissipate energy and heat gas in galaxies & galaxy clusters

2. Galaxy simulations: CRs and non-thermal emission



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

MHD + cosmic ray advection + diffusion:
$\{10^{10}, 10^{11}, 3\times10^{11}, 10^{12}\}\ \mathrm{M}_\odot$
steady-state spectra of CR protons, primary & secondary electrons

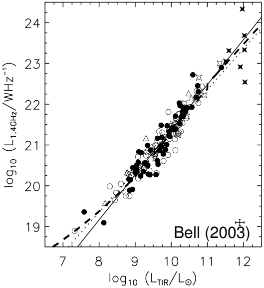
Non-thermal emission in star-forming galaxies

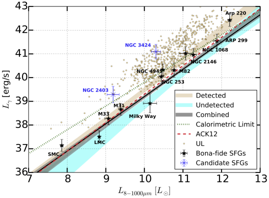
- ***observations:***
  - global far infrared (FIR)-radio correlation

    (van der Kruit 1971, Condon 1992, Yun+ 2001, Bell 2003)
  - local FIR-radio correlation

    (M31: Hoernes+ 1998, M33: Hippelein+ 2003, LMC: Hughes+ 2006)
  - global FIR-gamma-ray correlation

    (Ackermann+ 2012, Rojas-Bravo & Araya 2016, Linden 2017, Ajello+ 2020)
  - spectra in radio and gamma rays

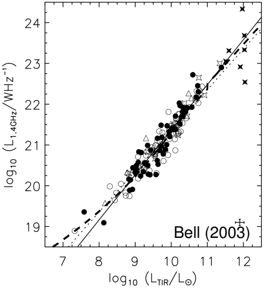


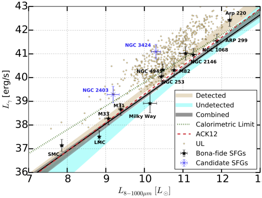


Ajello+ (2020)

Non-thermal emission in star-forming galaxies

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





Ajello+ (2020)

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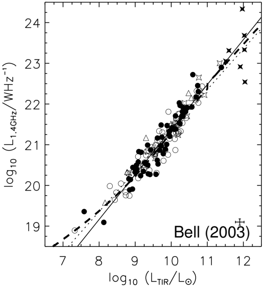
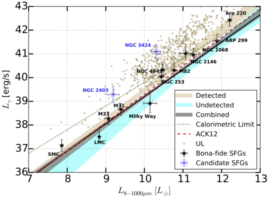
  - 1D transport models (Heesen+ 2016)
  - static Milky Way models (Strong & Moskalenko 1998, Evoli+ 2008, Kissmann 2014)
- ***state-of-the-art theoretical modeling:***
  - run MHD simulations of galaxies at different halos masses and star formation rates
  - model cosmic rays: protons, primary and secondary electrons
  - model all radiative processes from radio to gamma rays
  - gamma rays: understand pion decay and leptonic inverse Compton emission
  - radio: understand magnetic dynamo, primary and secondary electrons





Ajello+ (2020)

Steady-state cosmic ray spectra

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

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

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

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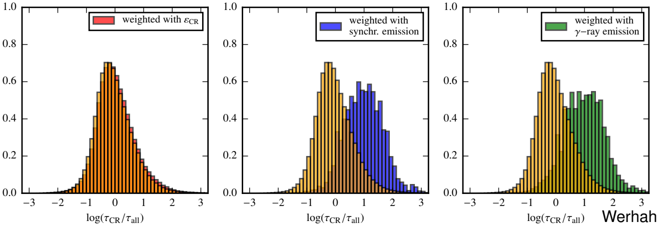
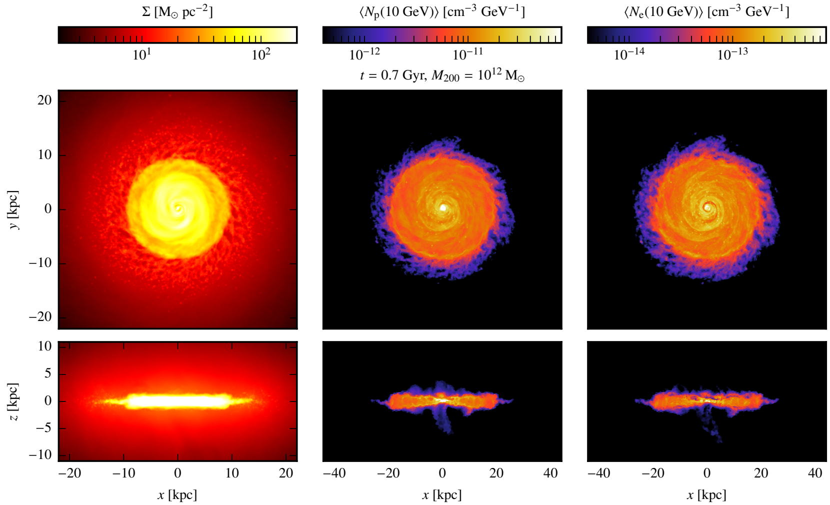
  - secondaries
- steady state assumption is fulfilled in disk and in regions dominating the non-thermal emission but not at low densities, at SNRs and in outflows



Werhahn+ (2021a)

From a starburst galaxy to a Milky Way analogy



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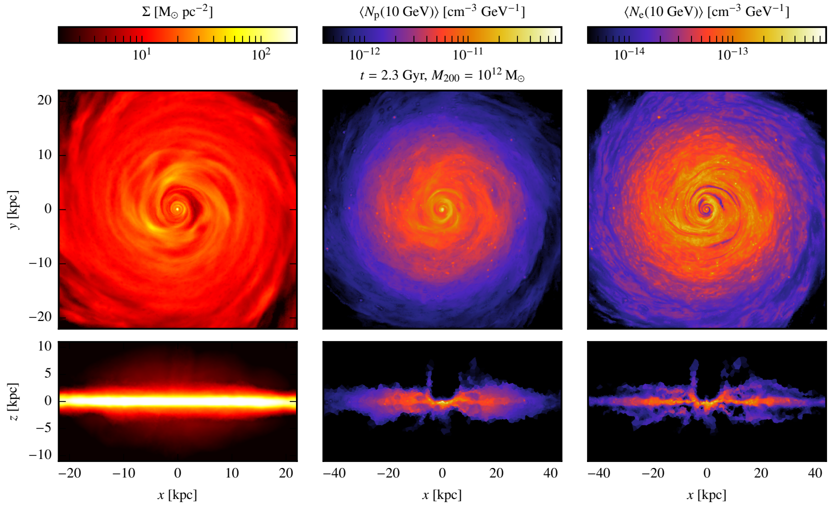
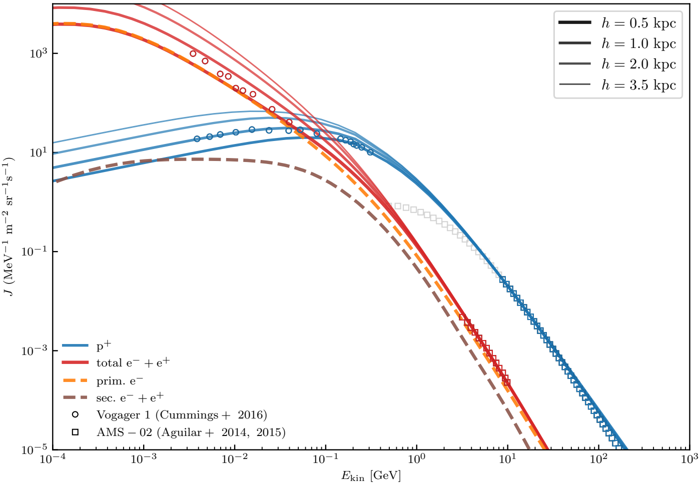


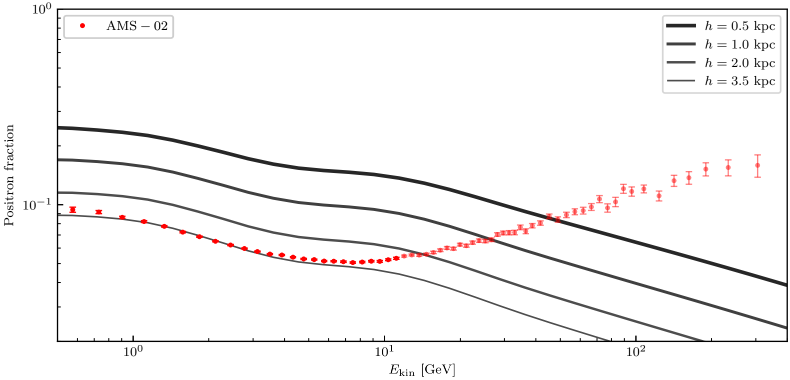
Werhahn, CP+ (2021a)

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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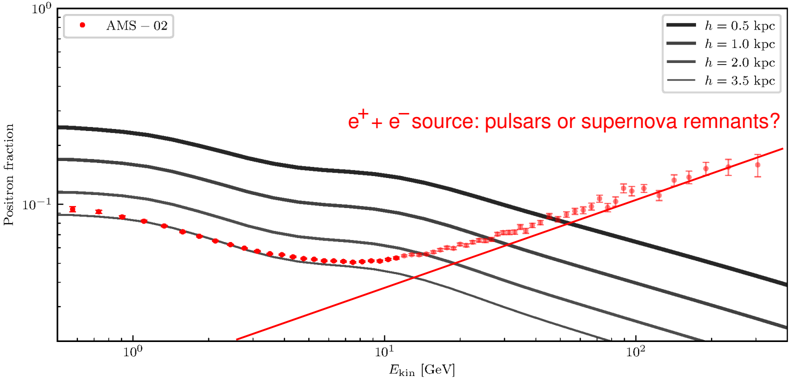
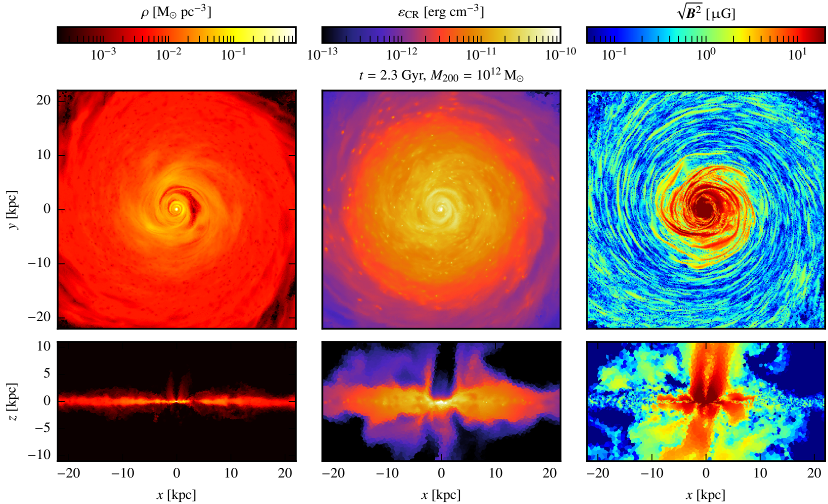


$e^+ + e^-$ source: pulsars or supernova remnants?

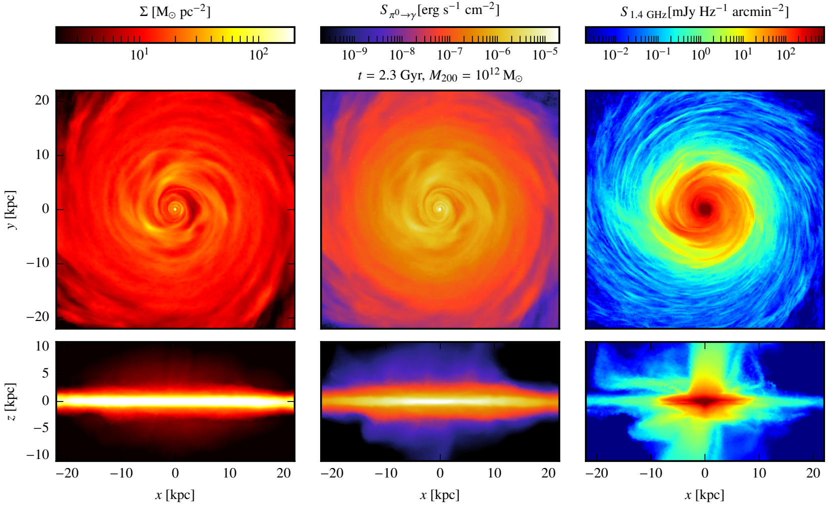
Werhahn, CP+ (2021a)

Simulation of a starburst galaxy



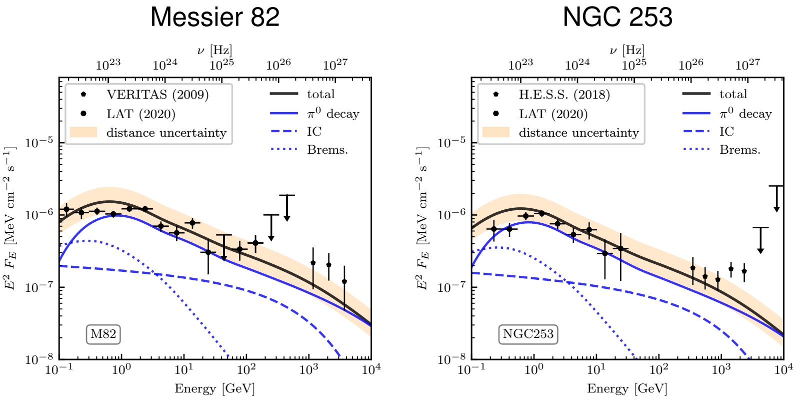
Werhahn, CP+ (2021b)

Simulation of a starburst galaxy



Werhahn, CP+ (2021b, c)

Gamma-ray spectra of starburst galaxies



Messier 82

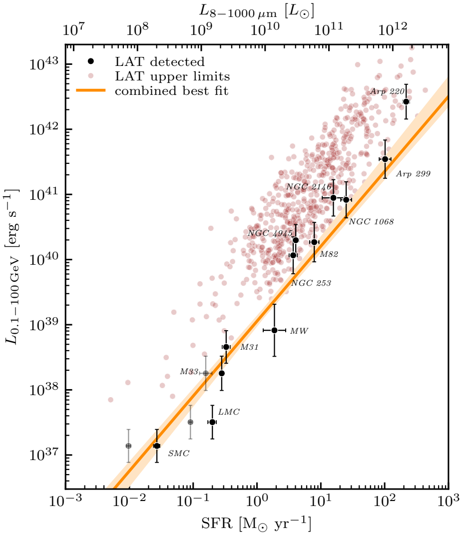
NGC 253

Werhahn, CP+ (2021b)

- gamma-ray spectra in starbursts dominated by pion decay
- CR protons propagate in Kolmogorov turbulence: $\kappa \propto E^{0.3}$

Far infra-red – gamma-ray correlation

Universal conversion: star formation → cosmic rays → gamma rays



Ajello+ (2020)

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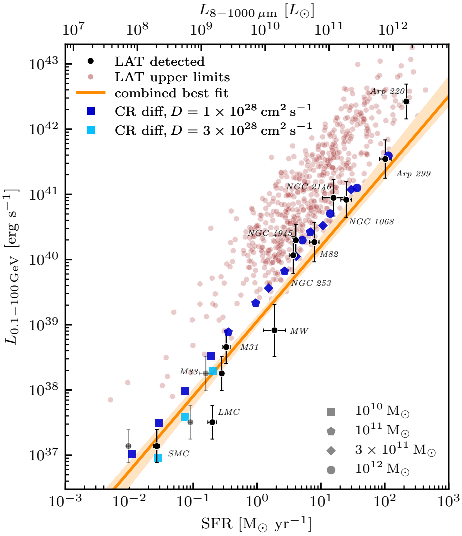

Werhahn, CP+ (2021b)

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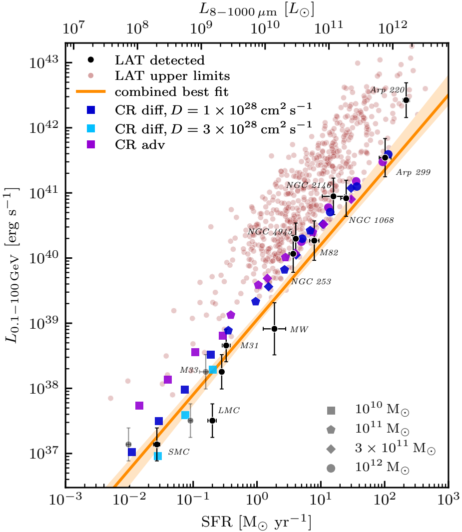

Werhahn, CP+ (2021b)

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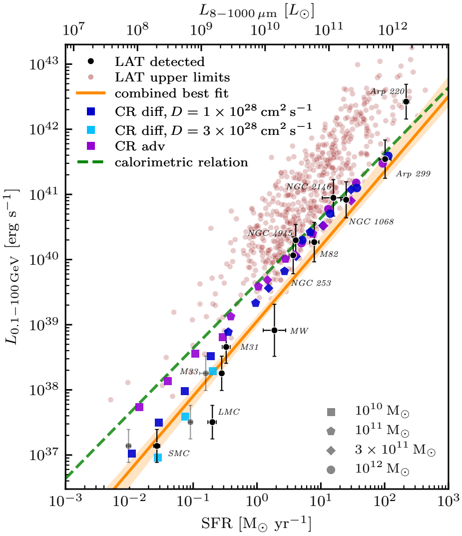
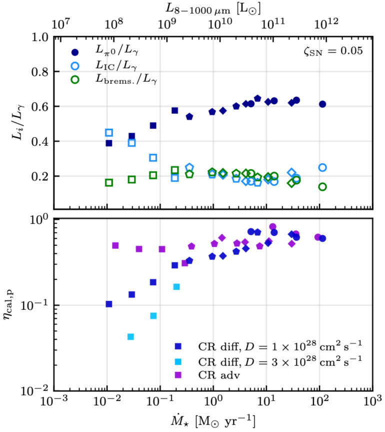


Werhahn, CP+ (2021b)

Far infra-red – gamma-ray correlation

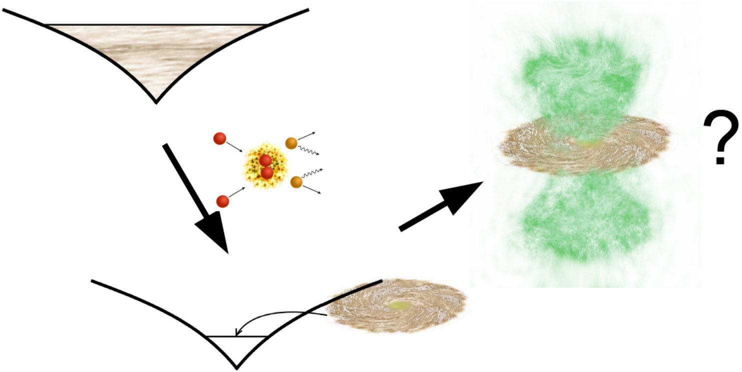
Hadronic vs. leptonic emission and calorimetric fraction across galaxy scales



Werhahn, CP+ (2021b)

- pion decay dominates gamma-ray emission in starbursts
- leptonic component (primarily inverse Compton) dominates at low star formation rates
- calorimetric energy fraction in starbursts $\eta_{\text{cal,p}} \approx 0.5$: half of the energy available for CR feedback
- faster CR diffusion decreases calorimetric fraction at low star formation rates

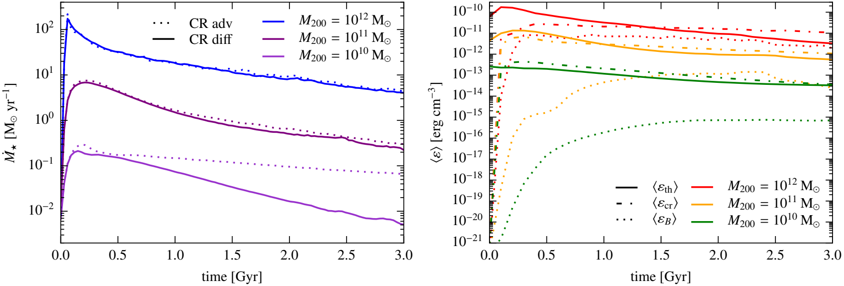
3. Galaxy simulations: CRs and non-thermal emission



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

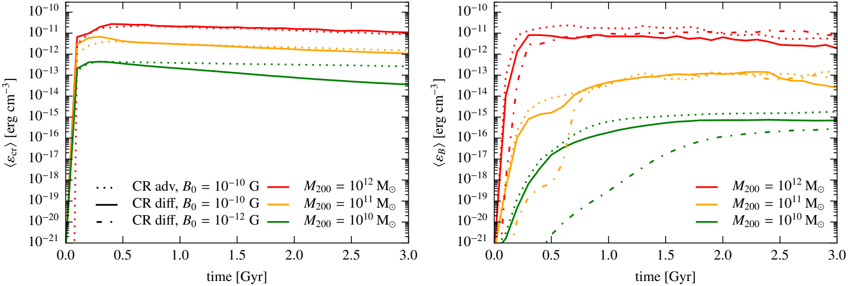
Time evolution of SFR and energy densities



CP+ (2022)

- CR pressure feedback suppresses star formation rate (SFR) more in smaller galaxies
- energy budget in disks is dominated by CR pressure
- magnetic growth faster in Milky Way galaxies than in dwarfs

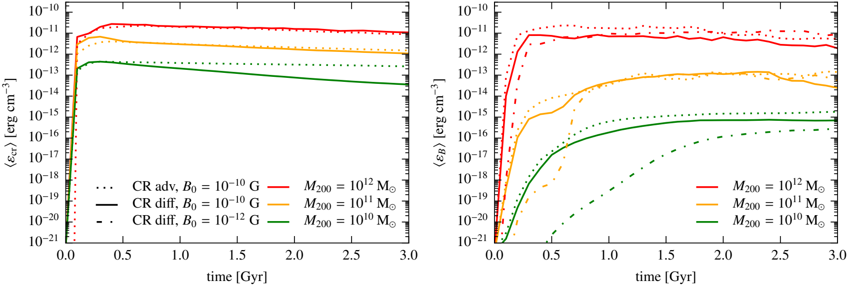
Time evolution of CR and magnetic energy densities



CP+ (2022)

- CRs diffuse out of galaxies ⇒ lowers $\varepsilon_{\rm cr}$ in disk
- CR diffusion slows magnetic field growth ⇒ lowers ε_B
- both effects decrease synchrotron emissivity
- magnetic field reaches saturation after initial growth phase

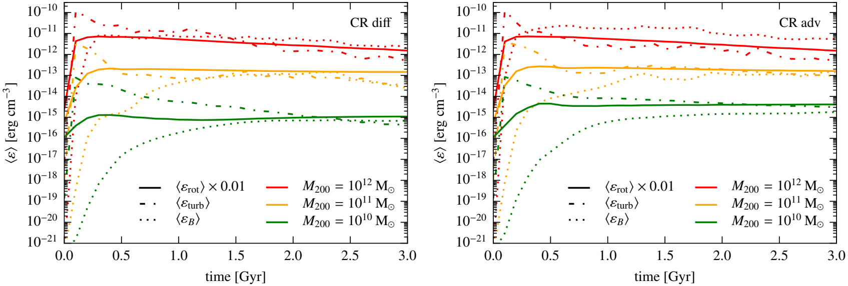
Time evolution of CR and magnetic energy densities



CP+ (2022)

- CRs diffuse out of galaxies ⇒ lowers $\varepsilon_{\rm cr}$ in disk
- CR diffusion slows magnetic field growth ⇒ lowers ε_B
- both effects decrease synchrotron emissivity
- magnetic field reaches saturation after initial growth phase
  ⇒ study saturation stage!

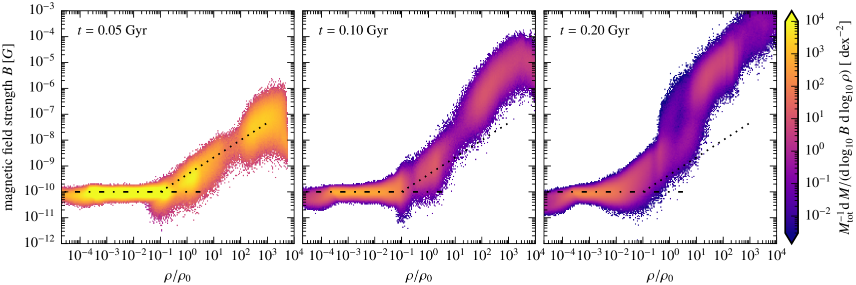
Comparing turbulent and magnetic energy densities



CP+ (2022)

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

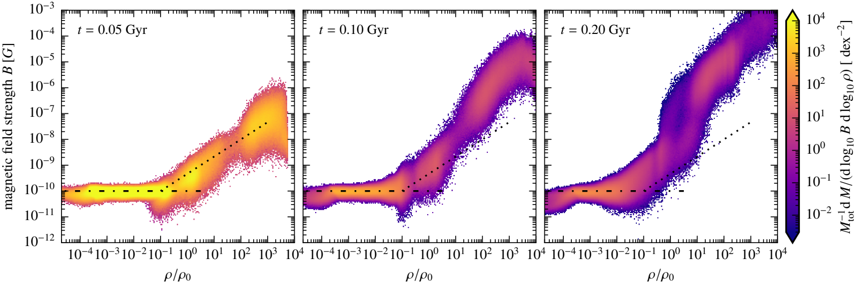
Identifying different growth phases



CP+ (2022)

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

Identifying different growth phases



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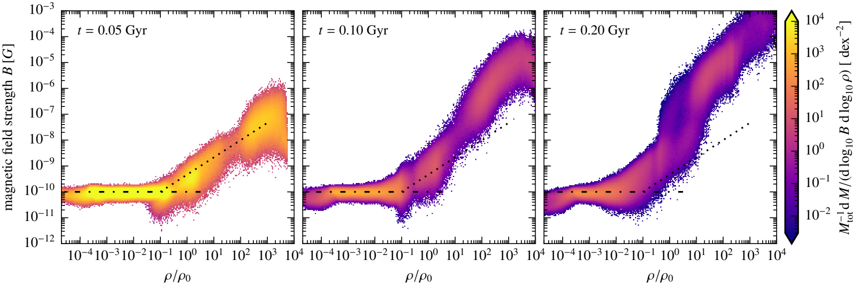
Identifying different growth phases



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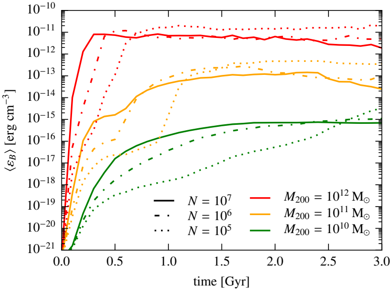
- *3rd phase:* growth migrates to lower ρ on larger scales $\propto \rho^{-1/3}$

Studying growth rate with numerical resolution



CP+ (2022)

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

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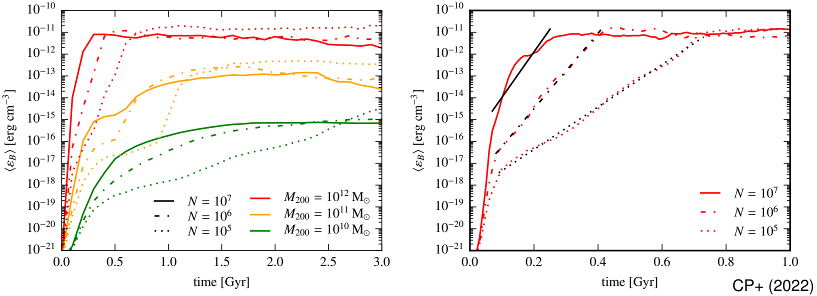

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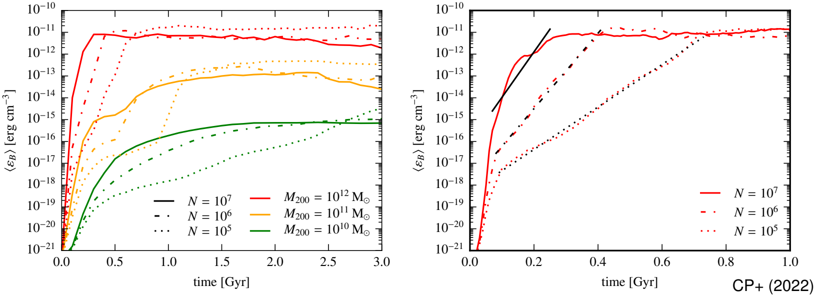
Studying growth rate with numerical resolution

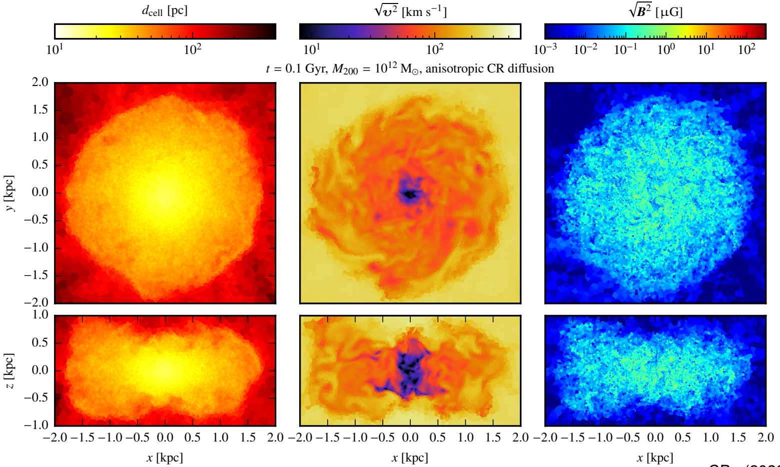


CP+ (2022)

- ***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

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

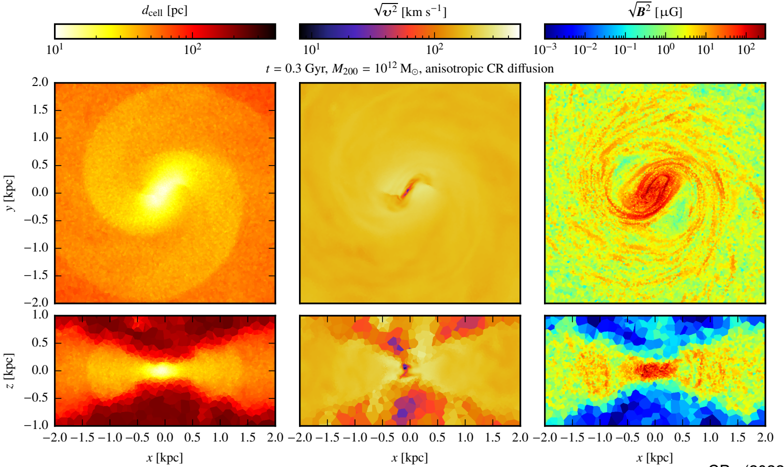
Exponential field growth in kinematic regime



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 λ_B increases

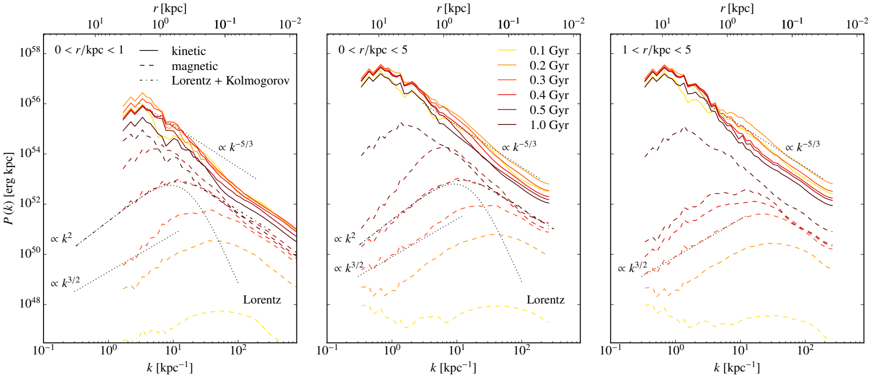


CP+ (2022)

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

Kinetic and magnetic power spectra

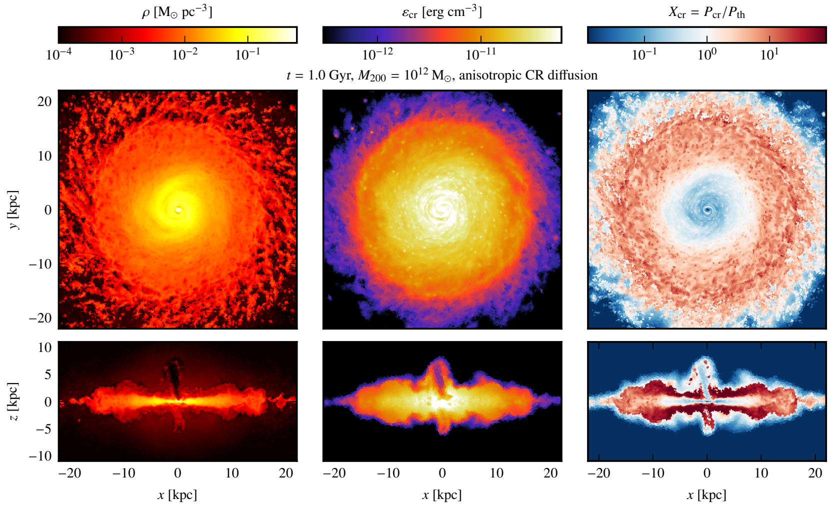
Fluctuating small-scale dynamo in different analysis regions



CP+ (2022)

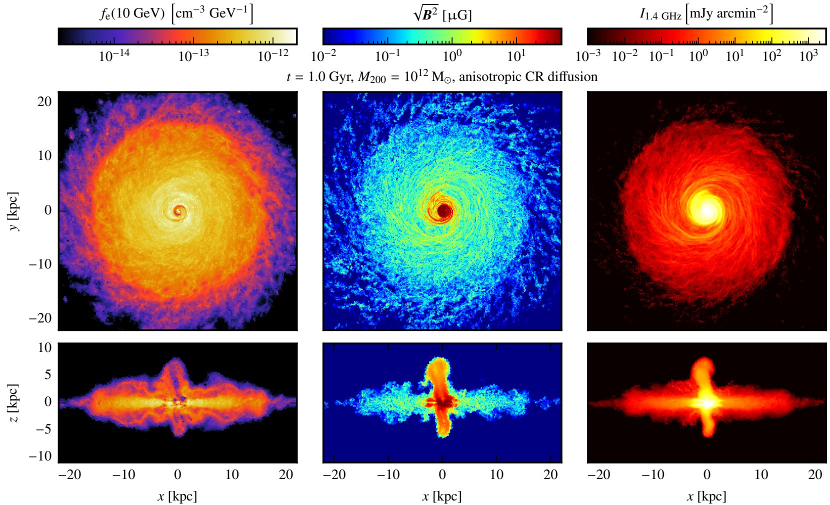
- $E_B(k)$ superposition of form factor and turbulent spectrum
- pure turbulent spectrum outside steep central B profile

Galaxy simulation with cosmic ray-driven wind



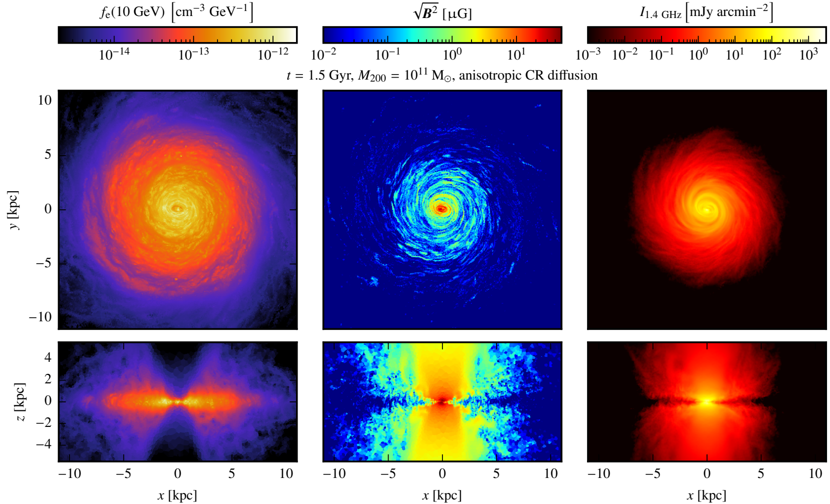
CP+ (2017)

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



CP+ (2022)

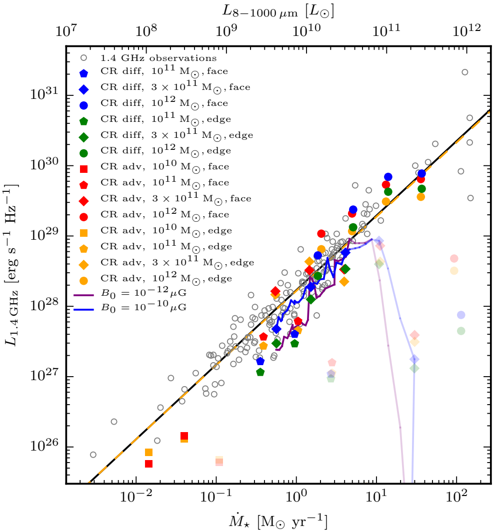
Simulated radio emission: 10^{11} $M_\odot$ halo



CP+ (2022)

Far infra-red – radio correlation

Universal conversion: star formation → cosmic rays → radio



CP+ (2022)

Equilibrium distribution of CR electrons

- **CR electron acceleration.** In galaxies, CR electrons are either directly accelerated at supernova remnant shocks or in hadronic CR proton interactions → source function $s_\mathrm{e} = CE_\mathrm{e}^{-\alpha_\mathrm{e}}$, with $\alpha_\mathrm{e} \simeq 2 - 2.4$

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- CR electron cooling. At high energies, synchrotron and inverse Compton (IC) interactions with starlight & cosmic microwave background (CMB) photons dominate the losses:

$$-\dot{E}_\mathrm{e}(E_\mathrm{e}) = \frac{4\,\sigma_\mathrm{T}\,c}{3\,m_\mathrm{e}^2\,c^4}\,[\varepsilon_B + \varepsilon_\mathrm{ph}]\;E_\mathrm{e}^2$$

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- In steady state, CR electron acceleration balances cooling via synchrotron and IC processes:

$$\frac{\partial}{\partial E_\mathrm{e}}\left[\dot{E}_\mathrm{e}(E_\mathrm{e}) f_\mathrm{e}(E_\mathrm{e})\right] = s_\mathrm{e}(E_\mathrm{e})$$

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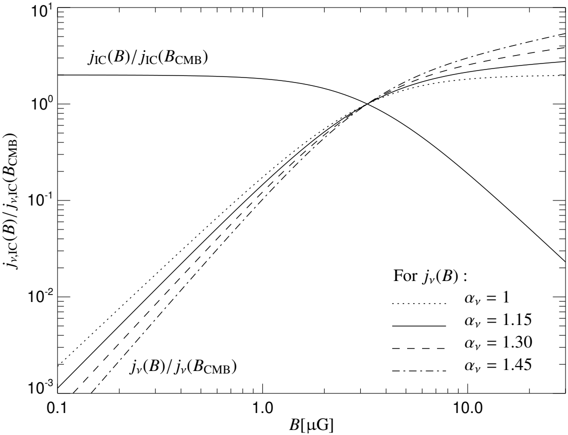
- Solution. For $\dot{E}_\mathrm{e}(E_\mathrm{e}) < 0$, this equation is solved by

$$f_\mathrm{e}(E_\mathrm{e}) = \frac{1}{|\dot{E}_\mathrm{e}(E_\mathrm{e})|}\int_{E_\mathrm{e}}^{\infty} \mathrm{d}E_\mathrm{e}' s_\mathrm{e}(E_\mathrm{e}') = \frac{C}{(\alpha_\mathrm{e} - 1)\,|\dot{E}_\mathrm{e}(E_\mathrm{e})|}\,E_\mathrm{e}^{1-\alpha_\mathrm{e}} \propto E_\mathrm{e}^{-\alpha_\mathrm{e}-1}$$

where we assumed synchrotron/IC loss processes in the last step.

Synchrotron vs. inverse Compton emissivity

In steady state, the emissivity in the IC/synchrotron regime is nearly independent of B

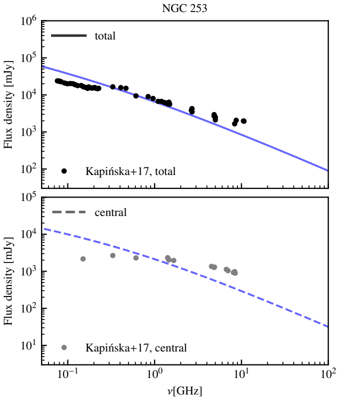


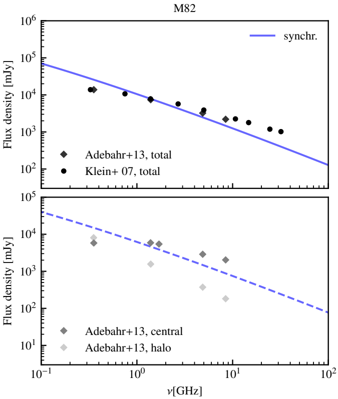
CP+ (2008)

inverse Compton cooling regime: $B < B_{\mathrm{CMB}} \simeq 3.2\,(1+z)^2\,\mu\mathrm{G}$

synchrotron cooling regime: $B > B_{\mathrm{CMB}}$

Radio spectra of starburst galaxies





Werhahn, CP+ (2021c)

- synchrotron spectra too steep (cooling + diffusion losses)

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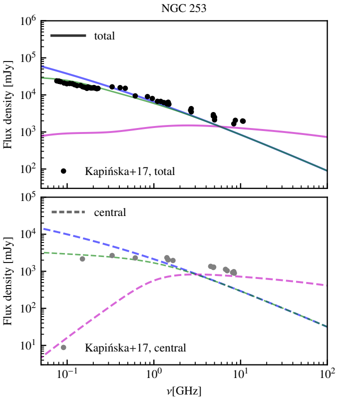

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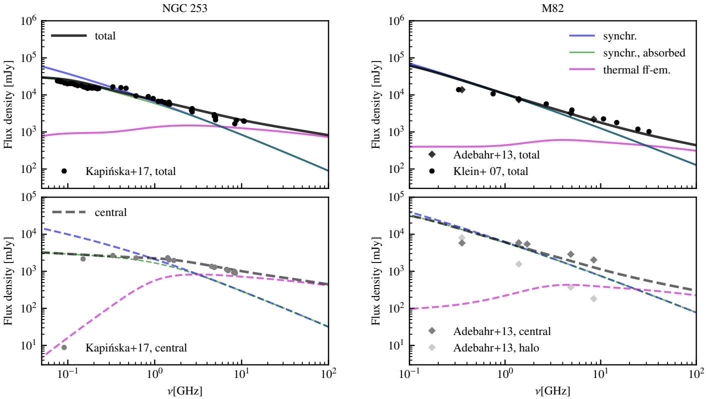

Werhahn, CP+ (2021c)

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

Cosmic ray transport and non-thermal emission – 1

Recap of today's lecture

- **Cosmic ray transport:**
  - * an extreme multi-scale problem ⇒ need to develop a fluid theory for a collisionless, non-Maxwellian component
  - * CRs exert pressure on thermal gas via scattering on Alfvén waves
  - * *weak wave damping:* strong coupling → CR stream with waves
  - * *strong wave damping:* less waves to scatter → CR diffusion prevails

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  - * synchrotron harps: CR streaming dominates over diffusion

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- **Cosmic ray feedback in galaxy formation:**
  - * CRs drive galactic winds and accelerate the gas in a $10^{11}\ \mathrm{M}_\odot$ halo beyond the escape speed
  - * CRs suppress star formation through additional pressure and by moving gas from the disk into the halo
  - * CR diffusion coefficient strong function of position (very large in Alfvén dark regions) → need for self-consistent modeling

Cosmic ray transport and non-thermal emission – 2

Recap of today's lecture

- **Magnetic dynamo in galaxies:**
  * magnetic growth faster in Milky Way galaxies than in dwarfs
  * adiabatic compression and turbulent small-scale dynamo grows magnetic fields in galaxies to saturation
  * magnetic energy saturate close to equipartition with the turbulent energy

Cosmic ray transport and non-thermal emission – 2

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- **Magnetic dynamo in galaxies:**
  - * magnetic growth faster in Milky Way galaxies than in dwarfs
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  - * magnetic energy saturate close to equipartition with the turbulent energy
- **Non-thermal emission in galaxies:**
  - * global $L_{\mathrm{FIR}} - L_\gamma$ correlation matches observational data and enables us to test the calorimetric assumption: half of CR energy available for feedback in in starbursts and more at low star formation rates
  - * global $L_{\mathrm{FIR}} - L_{\mathrm{radio}}$ correlation reproduced for galaxies with saturated magnetic fields, scatter due to viewing angle and CR transport
  - * synchrotron absorption (low-ν) and thermal free-free emission (high-ν) required to flatten cooled radio synchrotron spectra

Literature for general reading

There are many excellent texts on cosmic ray astrophysics. If I had to select three I would probably pick these ones that range from a basic introduction to numerical modeling to a solid review:

- **This review paper connects the kinetic theory to the classical theory of cosmic ray hydrodynamics:**
  The basis for cosmic ray feedback: Written on the wind, Zweibel, 2017, PhPl, 24, 5402
  `https://aip.scitation.org/doi/10.1063/1.4984017`
- **This review summarizes numerical methods for simulating CR propagation on macroscopic scales:**
  Simulations of cosmic ray propagation, Hanasz, Strong, Girichidis, 2021, LRCA, 7, 2
  `https://link.springer.com/article/10.1007%2Fs41115-021-00011-1`
- **Excellent book on the transport theory of gases, plasmas, and photons:**
  Transport Processes in Space Physics and Astrophysics, Zank,
  `https://link.springer.com/book/10.1007%2F978-1-4614-8480-6`

If you want to refresh your memory on the derivation of the hydrodynamic equations, of shock waves and hydrodynamic turbulence, I suggest to read Section 3.1 of my

- **Lecture notes that cover many topics in theoretical astrophysics:**
  The Physics of Galaxy Clusters, Pfrommer,
  `https://pages.aip.de/pfrommer/Lectures/clusters.pdf`

Literature for the lecture – 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, Pakmor, Simpson, Springel, *Simulating gamma-ray emission in star-forming galaxies,* 2017b, ApJL, 847, L13.
- 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, 508, 4072.
- Werhahn, Pfrommer, Girichidis, Winner, *Cosmic rays and non-thermal emission in simulated galaxies. II. γ-ray maps, spectra and the far infrared-γ-ray relation,* 2021b, MNRAS, 505, 3295.
- Werhahn, Pfrommer, Girichidis, *Cosmic rays and non-thermal emission in simulated galaxies. III. probing cosmic ray calorimetry with radio spectra and the FIR-radio correlation,* 2021c, MNRAS, 508, 4072.
- Pfrommer, 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.