Cosmic rays in galaxy formation: instabilities, transport and feedback

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in collaboration with

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Outline

1. Cosmic ray driven instabilities
   - Introduction
   - Intermediate instability
   - Overview and applications
2. Cosmic ray transport
   - CR propagation
   - CR hydrodynamics
   - Radio synchrotron harps
3. Galaxy formation
   - Cosmic ray driven winds
   - Non-thermal emission
   - Conclusions

AIP

Does plasma physics matter in galaxy formation?

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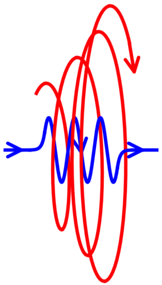
Can (sub-)galactic observations teach us plasma physics?

CR streaming instability

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



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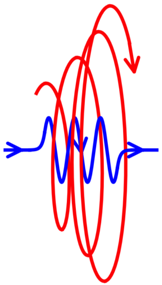

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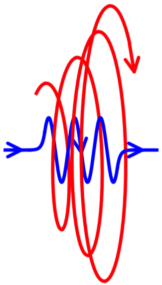

→ *CRs exert pressure on thermal gas via scattering on Alfvén waves*

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

Coupling of CRs to the background plasma

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- intrinsic confinement: CRs drive unstable plasma wave modes (e.g., Alfvén waves), and then scatter off of them
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- dispersion relation ($\Omega_{e,0} = -m_i/m_e \times \Omega_{i,0}$, $\alpha = n_{\mathrm{cr}}/n_{\mathrm{i}}$): gyrotropic CR ion + electron beam propagates in background plasma

$$\frac{k^2c^2}{\omega^2} - 1 = \frac{\omega_i^2}{\omega\left(-\omega \pm \Omega_{i,0}\right)} + \frac{\omega_e^2}{\omega\left(-\omega \pm \Omega_{e,0}\right)} \quad \Leftarrow \text{ background}$$

$$\text{CRe} \Rightarrow \quad + \frac{\alpha\omega_e^2}{\gamma_e\omega^2}\left\{\frac{\omega - kv_{\mathrm{dr}}}{kv_{\mathrm{dr}} - \omega \mp \Omega_{e,0}/\gamma_e}\right\}$$

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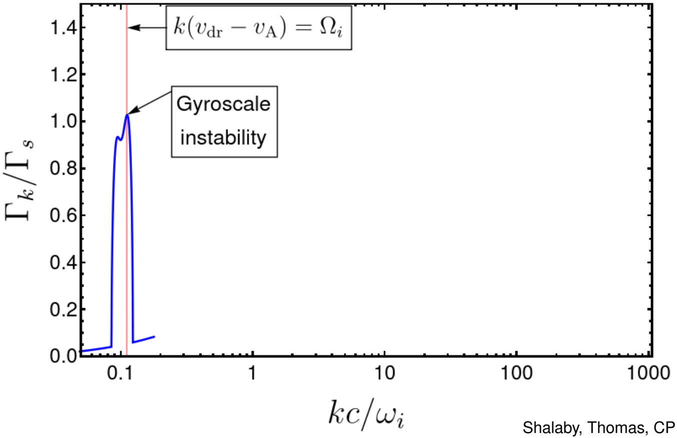
CR driven instabilities – growth rates



Shalaby, Thomas, CP (2021)

- gyro-resonant instability of gyrotropic CR population

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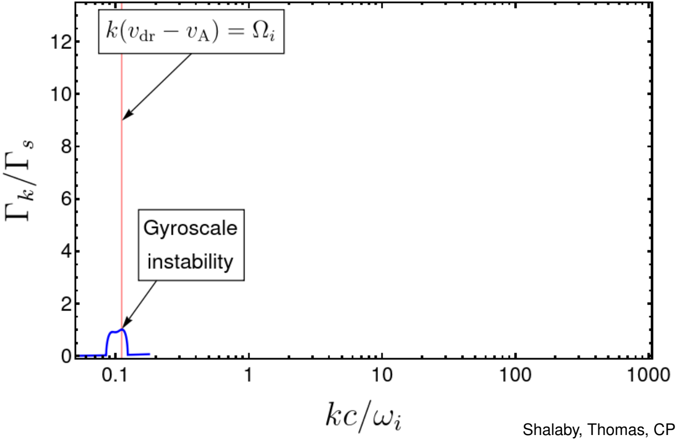

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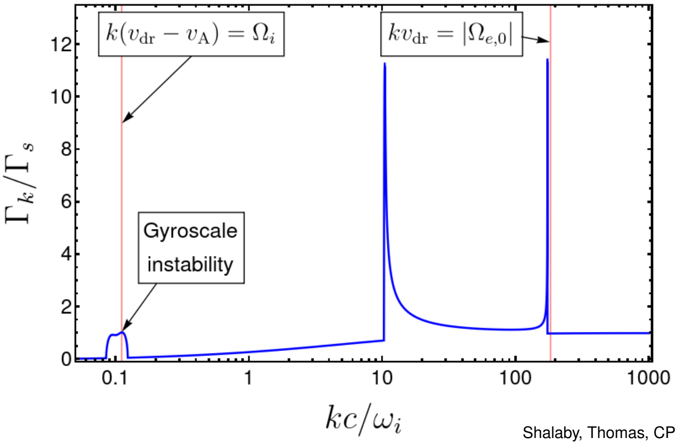

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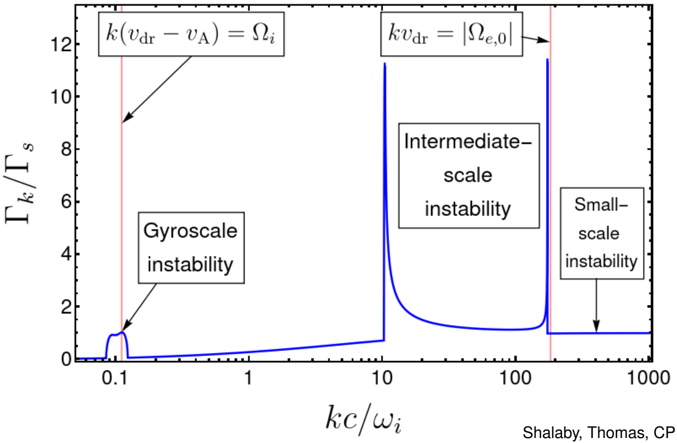

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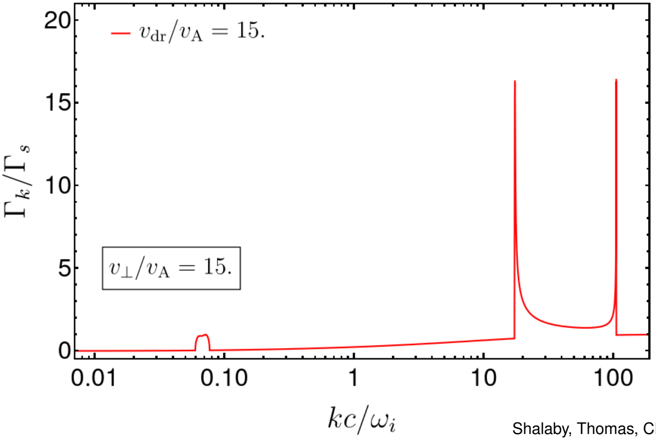
CR driven intermediate-scale instability



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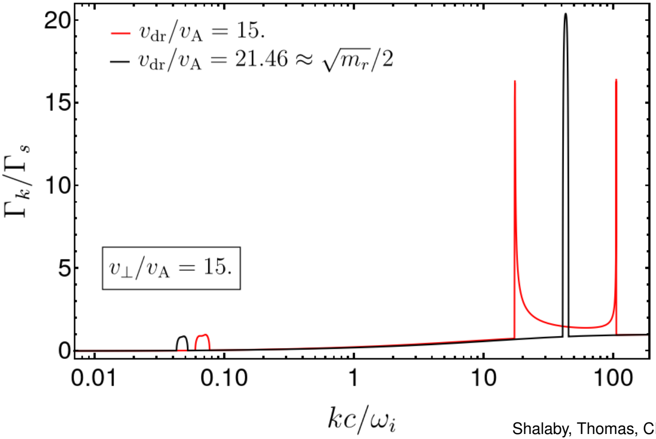
- low CR drift speed: two instability peaks

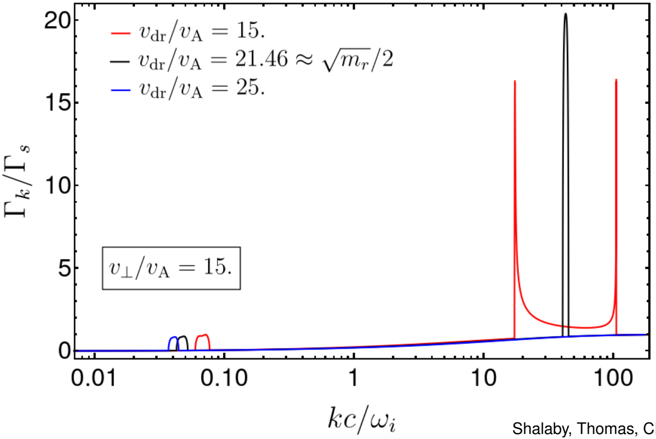
CR driven intermediate-scale instability



Shalaby, Thomas, CP (2021)

- for CR drift speed $v_{dr} \approx \sqrt{\frac{m_i}{m_e}} \frac{v_A}{2}$: two instability peaks merge

CR driven intermediate-scale instability

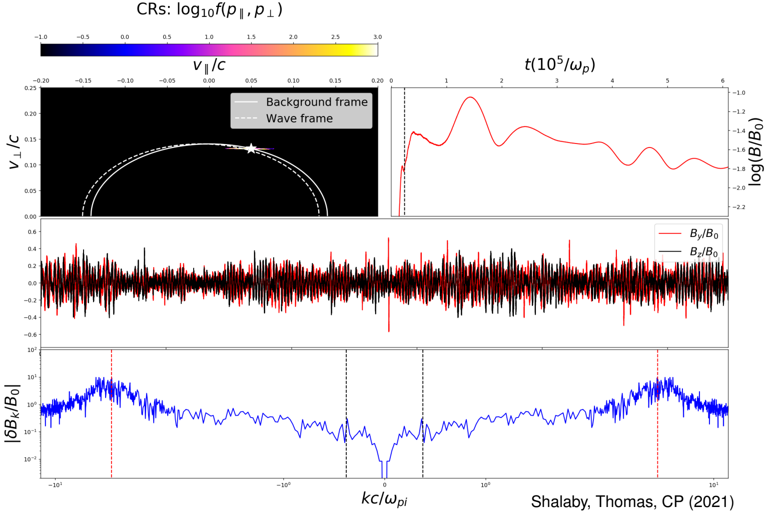


Shalaby, Thomas, CP (2021)

- for $v_{\rm dr} > \sqrt{\frac{m_{\rm i}}{m_{\rm e}}}\frac{v_{\rm A}}{2}$: intermediate-scale instability quenched

Cosmic ray driven instabilities

Growth of the intermediate-scale and the gyro-resonant instability



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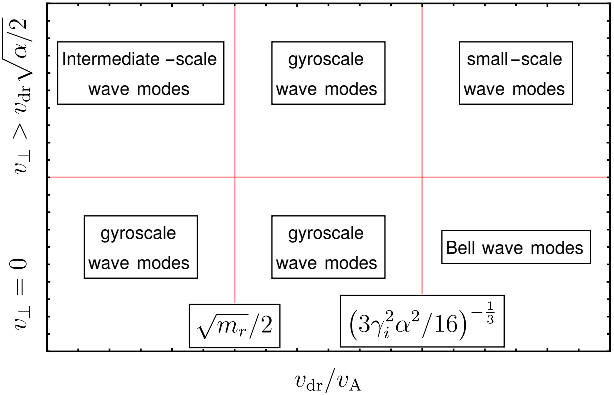
Regimes of CR driven instabilities



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- where $\alpha = \frac{n_{\rm cr}}{n_{\rm i}}$ is the CR number fraction, $m_{\rm r} = \frac{m_{\rm i}}{m_{\rm e}}$ is the mass ratio, and $\gamma_{\rm i}$ is the Lorentz factor of CR ions

The intermediate-scale instability

Properties of the intermediate-scale instability:

- growth rate $\Gamma_{\rm inter} \gg \Gamma_{\rm gyro}$ and excites broad spectral support
- unstable modes are background ion-cyclotron waves in the comoving CR frame
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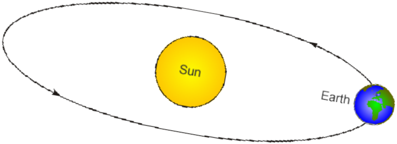
Possible implications of this new instability:

- couples CRs more tightly to background plasma and strengthens CR feedback in galaxies and galaxy clusters
- enables electron heating at shocks and injection into diffusive shock acceleration
- slows down CR escape from the sites of particle acceleration $\rightarrow$ brighter gamma-ray halos

Cosmic ray transport: an extreme multi-scale problem



Milky Way-like galaxy:

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

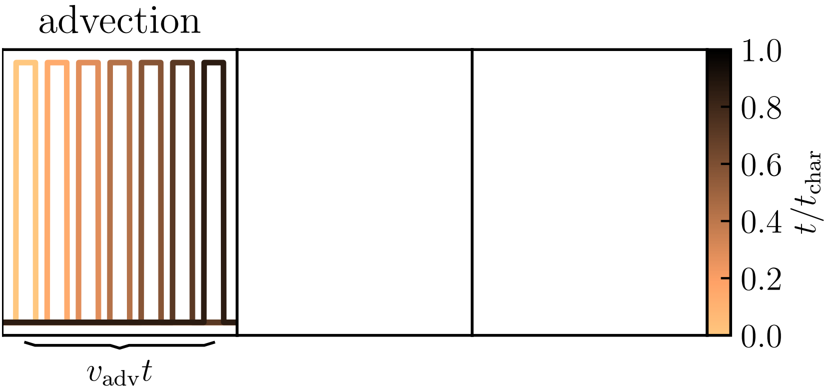
gyro-orbit of GeV cosmic ray:

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

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

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

Modes of CR propagation



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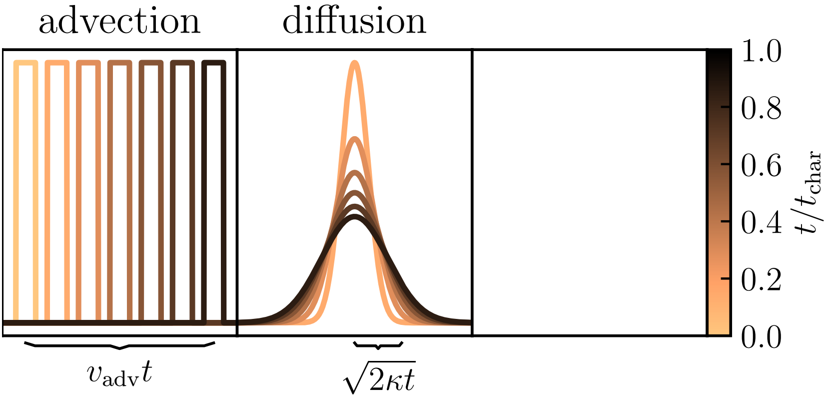

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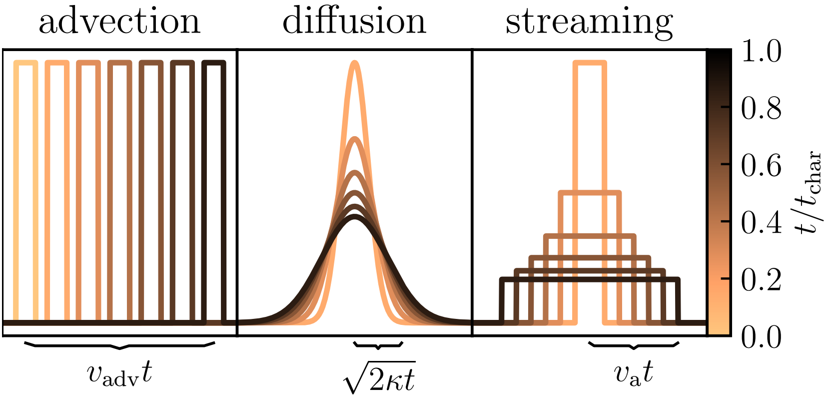

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1-moment CR hydrodynamics (steady-state flux)

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

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

AIP

Alfvén-wave regulated CR transport

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

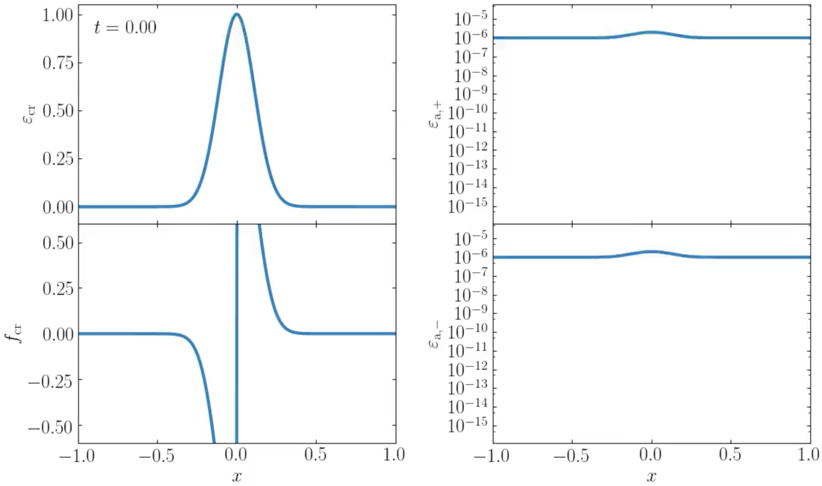
$$\frac{\partial \varepsilon_{\rm cr}}{\partial t} + \boldsymbol{\nabla}\cdot[\boldsymbol{v}(\varepsilon_{\rm cr}+P_{\rm cr}) + \boldsymbol{b} f_{\rm cr}] = \boldsymbol{v}\cdot\boldsymbol{\nabla} P_{\rm cr} - \frac{v_{\rm a}}{3\kappa_+}[f_{\rm cr} - v_{\rm a}(\varepsilon_{\rm cr}+P_{\rm cr})] + \frac{v_{\rm a}}{3\kappa_-}[f_{\rm cr} + v_{\rm a}(\varepsilon_{\rm cr}+P_{\rm cr})],$$

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

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

Non-equilibrium CR streaming and diffusion

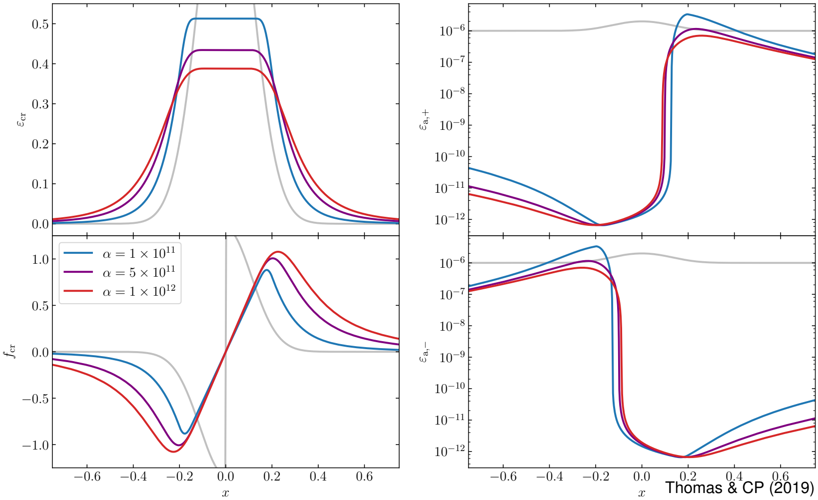
Coupling the evolution of CR and Alfvén wave energy densities



Thomas & CP (2019)

Non-equilibrium CR streaming and diffusion

Varying damping rate of Alfvén waves modulates the diffusivity of solution

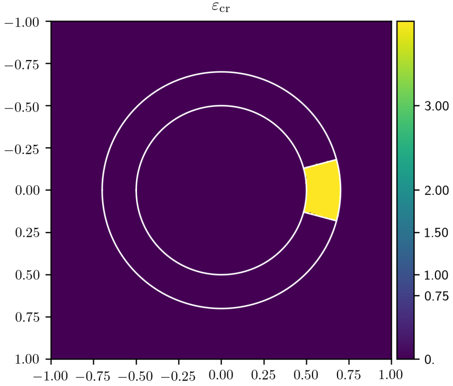


Thomas & CP (2019)

Anisotropic CR streaming and diffusion – AREPO

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

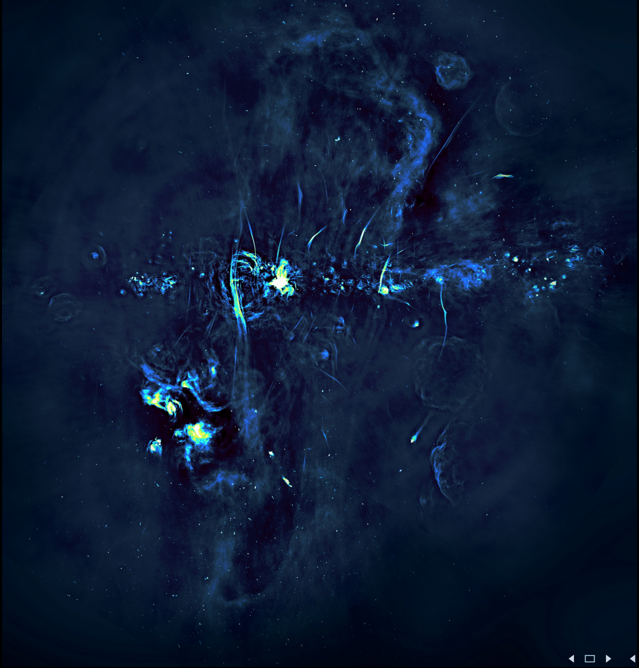
- CR streaming and diffusion along magnetic field lines in the self-confinement picture
- moment expansion similar to radiation hydrodynamics
- accounts for kinetic physics: non-linear Landau damping, gyro-resonant instability, ...
- Galilean invariant and causal transport
- energy and momentum conserving



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

MeerKAT image of the Galactic Center

Haywood+ (Nature, 2019)



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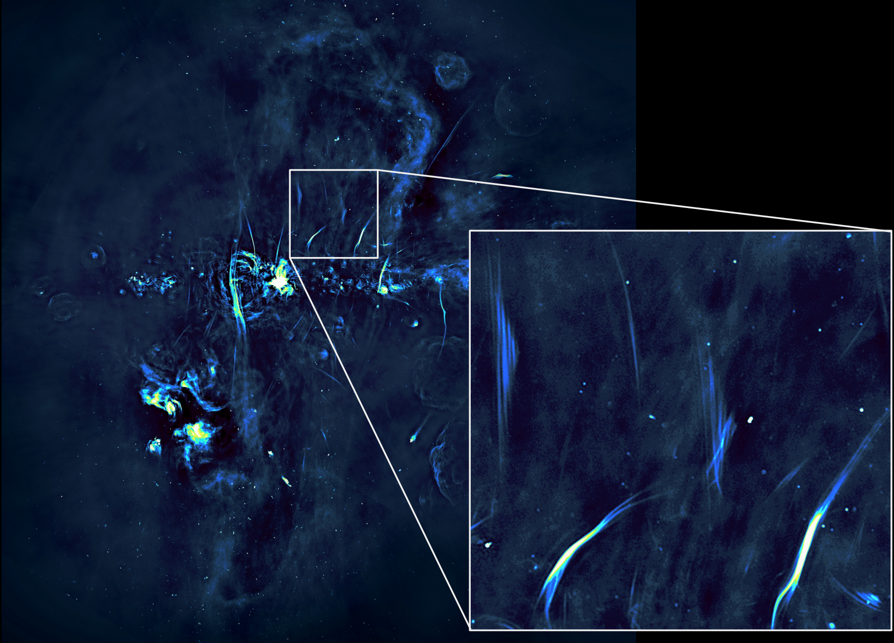
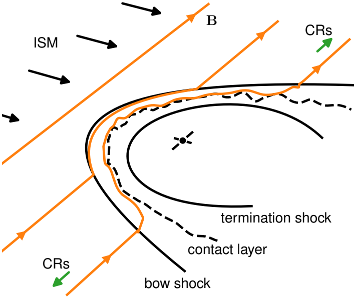


Radio synchrotron harps: the model

shock acceleration scenario



Thomas, CP, Enßlin (2020)

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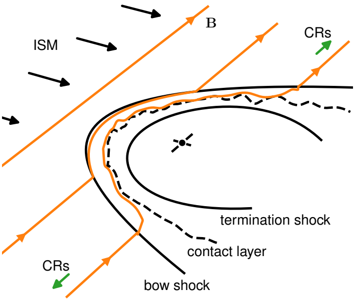
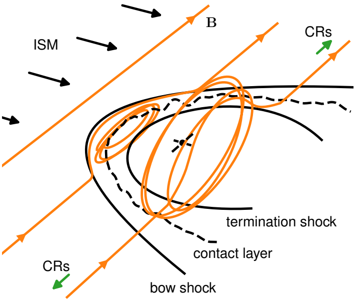
shock acceleration scenario



magnetic reconnection at pulsar wind



Thomas, CP, Enßlin (2020)

Radio synchrotron harps: the model

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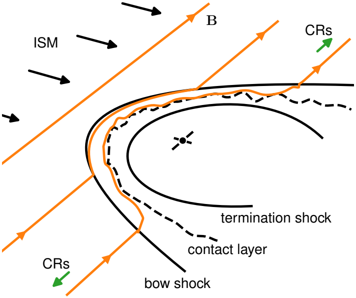
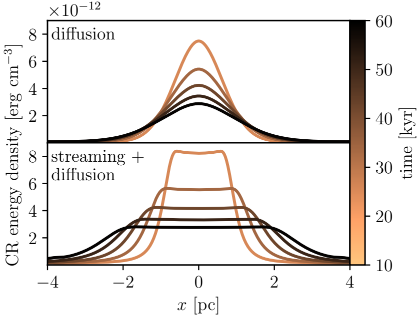
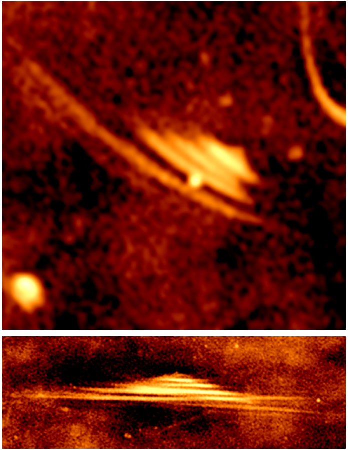


Thomas, CP, Enßlin (2020)

CR diffusion vs. streamig + diffusion

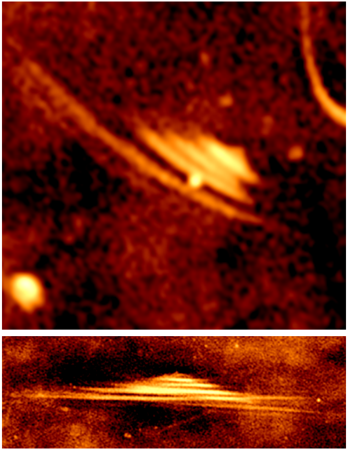


Radio synchrotron harps: testing CR propagation



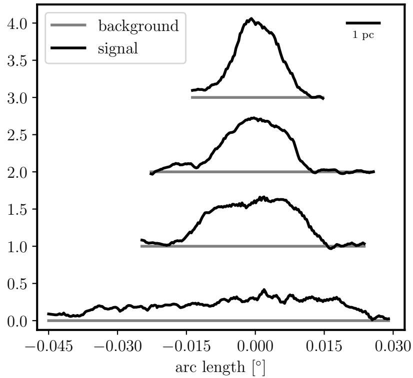
Haywood+ (Nature, 2019)

Radio synchrotron harps: testing CR propagation



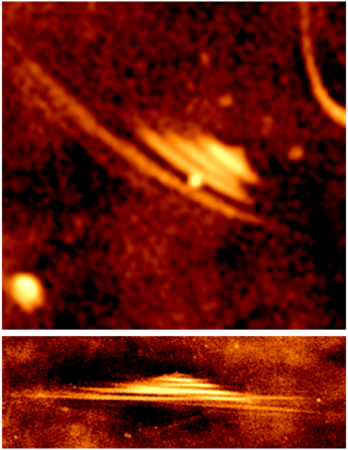
Haywood+ (Nature, 2019)

lateral radio profiles



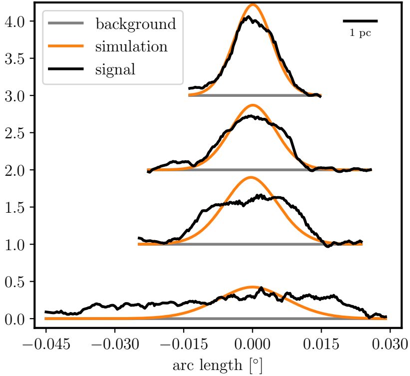
Thomas, CP, Enßlin (2020)

Radio synchrotron harps: testing CR propagation



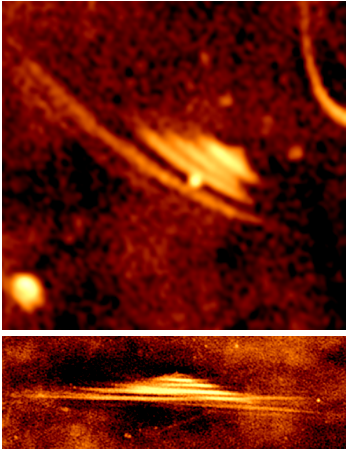
Haywood+ (Nature, 2019)

CR diffusion



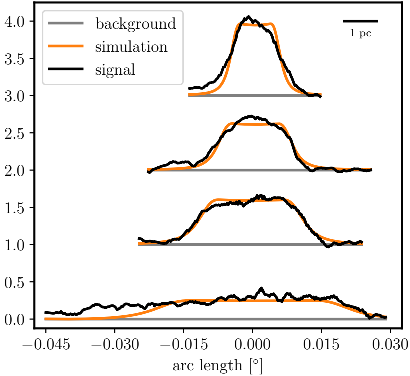
Thomas, CP, Enßlin (2020)

Radio synchrotron harps: testing CR propagation



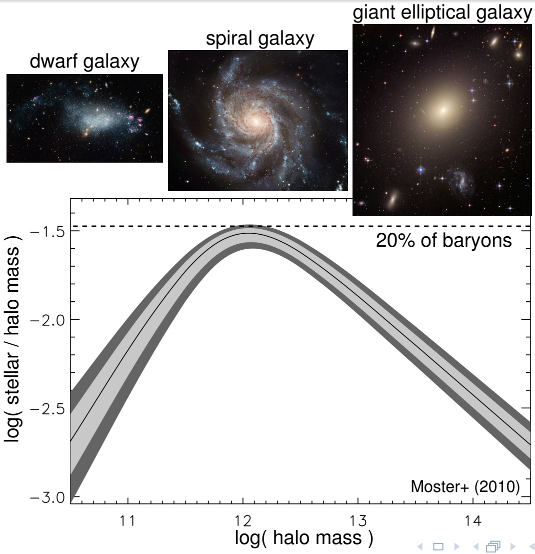
Haywood+ (Nature, 2019)

CR streaming and diffusion

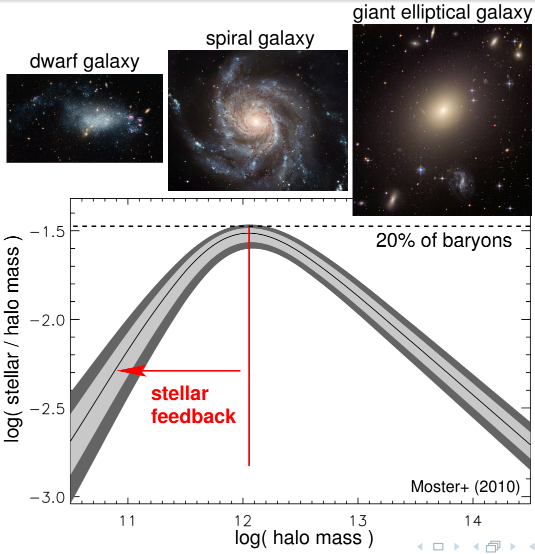


Thomas, CP, Enßlin (2020)

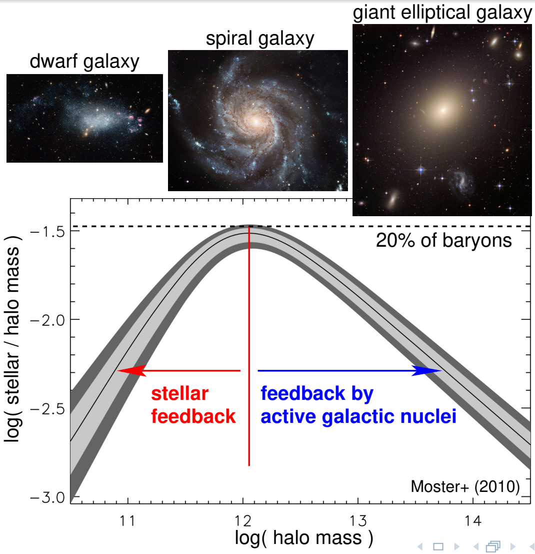
Puzzles in galaxy formation



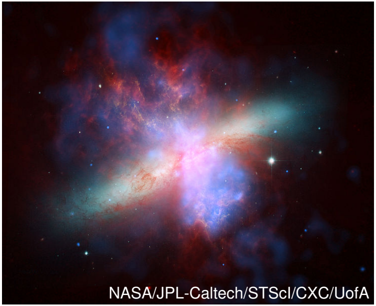
Puzzles in galaxy formation



Puzzles in galaxy formation



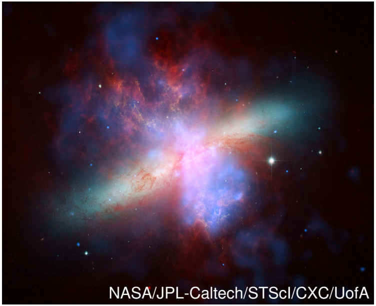
How are galactic winds driven?



super wind in M82

- thermal pressure provided by supernovae or AGNs?
- radiation pressure and photoionization by massive stars and QSOs?
- cosmic-ray (CR) pressure and Alfvén wave heating of CRs accelerated at supernova shocks?

How are galactic winds driven?



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- thermal pressure provided by supernovae or AGNs?
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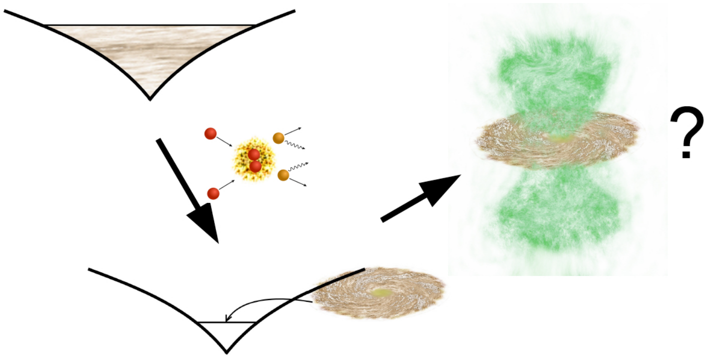
- cosmic-ray (CR) pressure and Alfvén wave heating of CRs accelerated at supernova shocks?

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

$\rightarrow$ suggests self-regulated feedback loop with CR driven winds

1. Cosmic ray feedback in galaxy formation

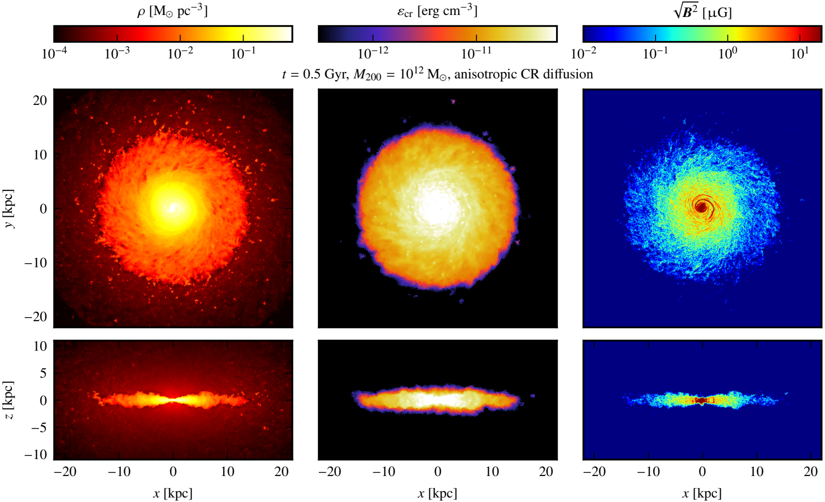


Pakmor, CP+ (2016), CP+ (2017b)

Galactic winds driven by CR diffusion in isolated disk galaxies

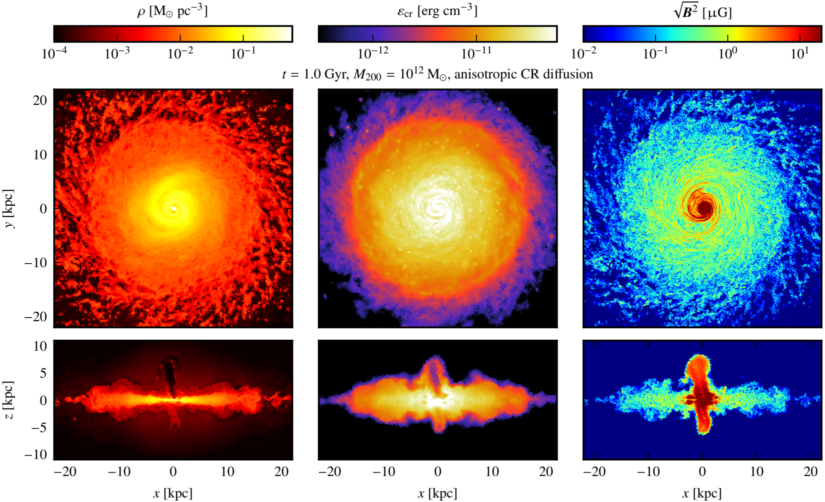
MHD + CR advection + anisotropic diffusion, $\{10^{10}, 10^{11}, 10^{12}\}$ $M_\odot$

Simulation of Milky Way-like galaxy, $t = 0.5$ Gyr



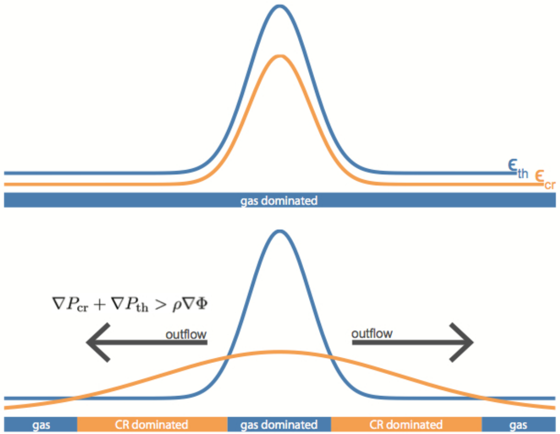
CP+ (2017b)

Simulation of Milky Way-like galaxy, $t = 1.0$ Gyr



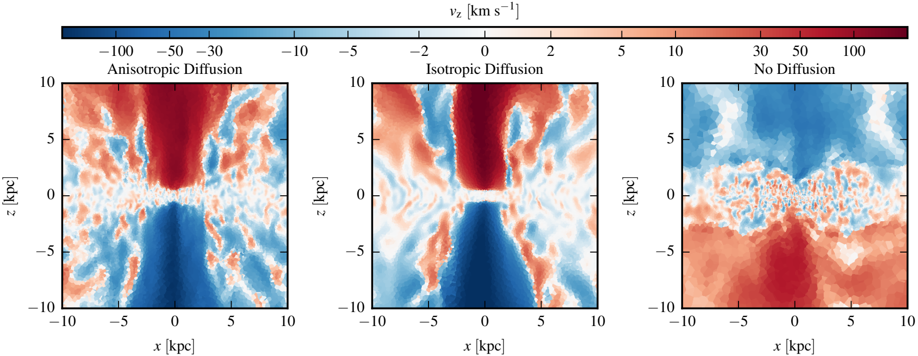
CP+ (2017b)

Cosmic ray driven wind: mechanism



CR streaming in 3D simulations: Uhlig, CP+ (2012), Ruszkowski+ (2017)
CR diffusion in 3D simulations: Jubelgas+ (2008), Booth+ (2013), Hanasz+ (2013), Salem & Bryan (2014), Pakmor, CP+ (2016), Simpson+ (2016), Girichidis+ (2016), Dubois+ (2016), CP+ (2017b), Jacob+ (2018), . . .

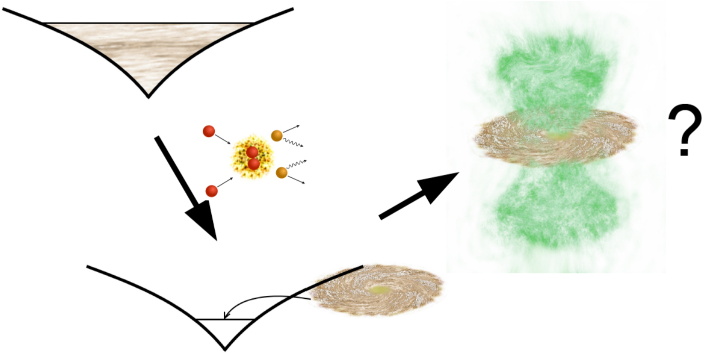
CR diffusion vs. advection



Pakmor, CP, Simpson, Springel (2016)

- CR diffusion launches powerful winds
- simulation without CR diffusion exhibits only weak fountain flows

2. Cosmic rays and non-thermal emission



Werhahn, CP+ (2021a, b, c), CP, Werhahn+ (2021)
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

AIP

Steady-state cosmic ray spectra

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

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

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

Steady-state cosmic ray spectra

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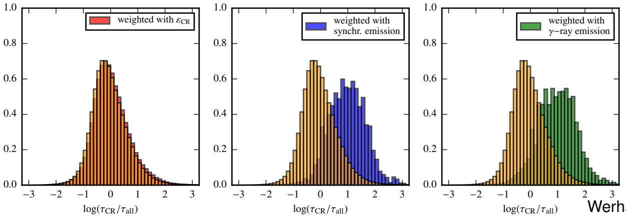
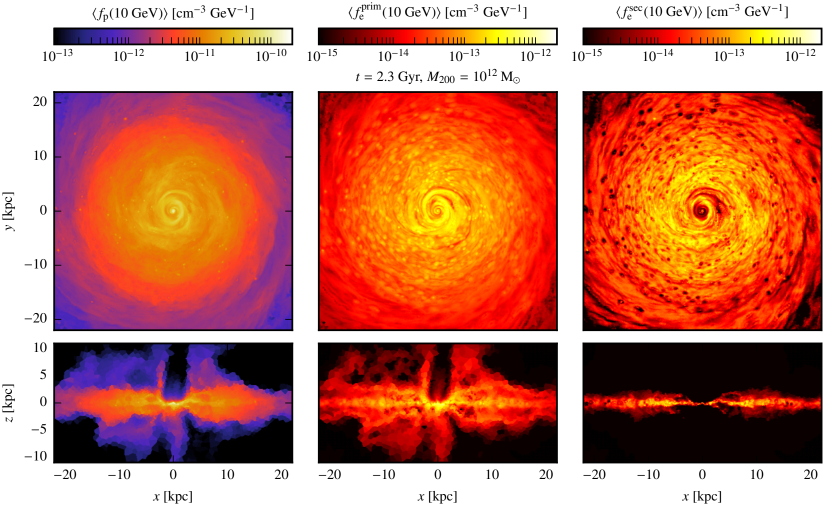
- electrons: Coulomb, bremsstr., IC, synchrotron and escape losses
  - primaries (re-normalized using $K_{\rm ep} = 0.02$)
  - secondaries
- steady state assumption is fulfilled in disk and in regions dominating the non-thermal emission but not at low densities, at SNRs and in outflows



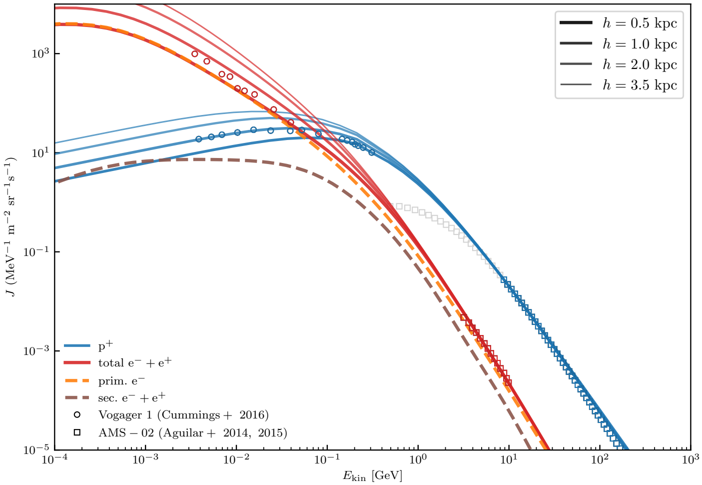
Werhahn+ (2021a)

From a starburst galaxy to a Milky Way analogy



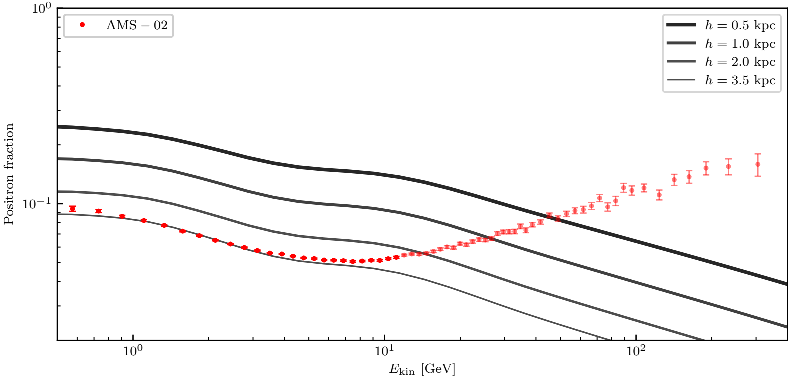
Werhahn, CP+ (2021b)

Comparing CR spectra to Voyager and AMS-02 data



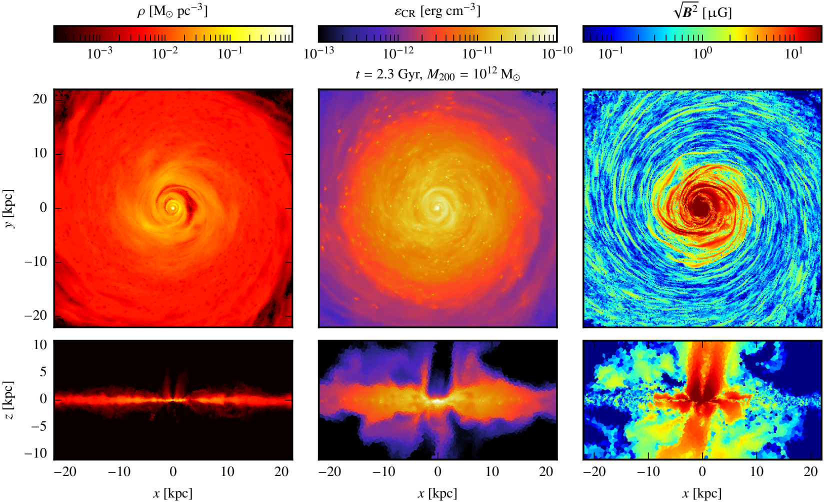
Werhahn, CP+ (2021a)

Comparing the positron fraction to AMS-02 data



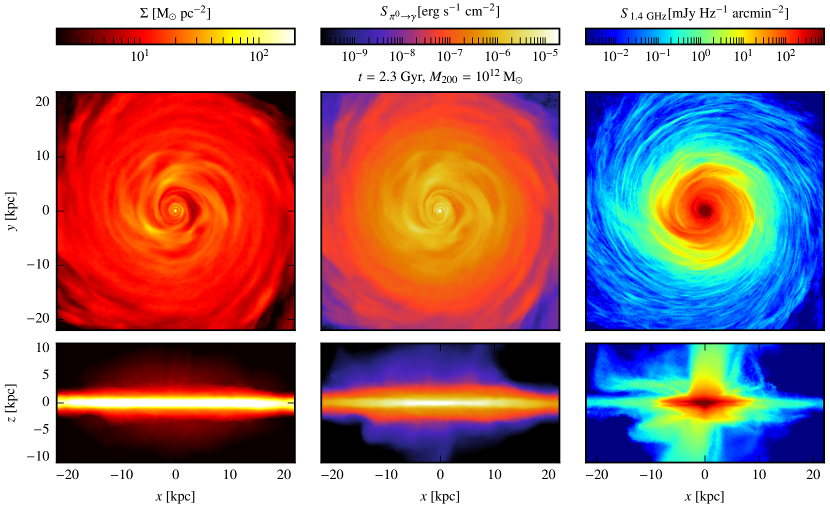
Werhahn, CP+ (2021a)

Simulation of a starburst galaxy



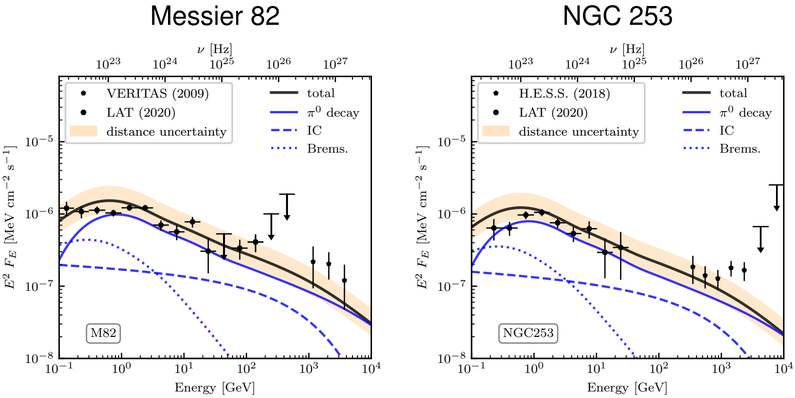
Werhahn, CP+ (2021b, c)

Simulation of a starburst galaxy



Werhahn, CP+ (2021b, c)

Gamma-ray spectra of starburst galaxies

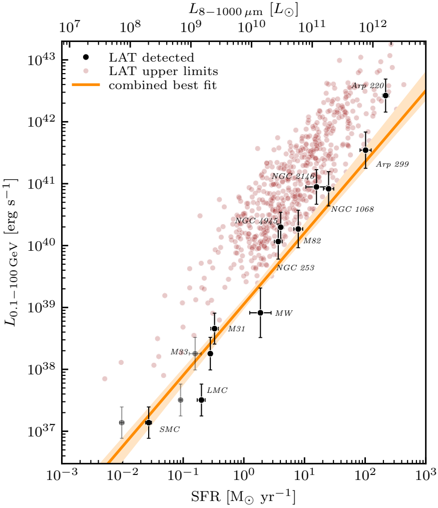


Werhahn, CP+ (2021b)

- 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

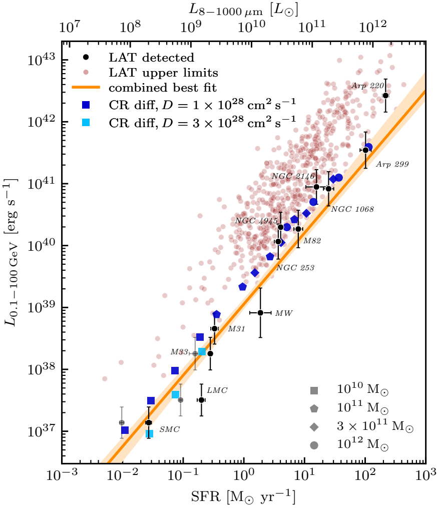
Universal conversion: star formation → cosmic rays → gamma rays



Ajello+ (2020)

Far infra-red – gamma-ray correlation

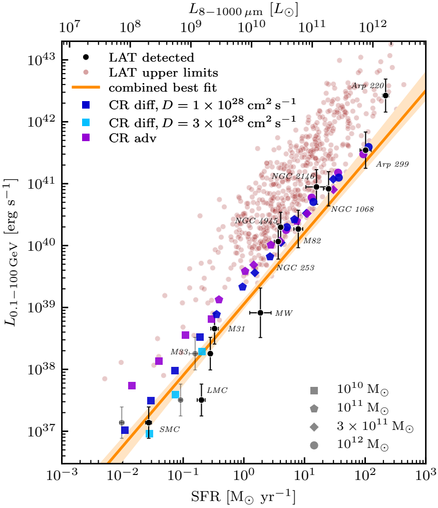
Universal conversion: star formation → cosmic rays → gamma rays



Werhahn, CP+ (2021b)

Far infra-red – gamma-ray correlation

Universal conversion: star formation → cosmic rays → gamma rays



Werhahn, CP+ (2021b)

Far infra-red – gamma-ray correlation

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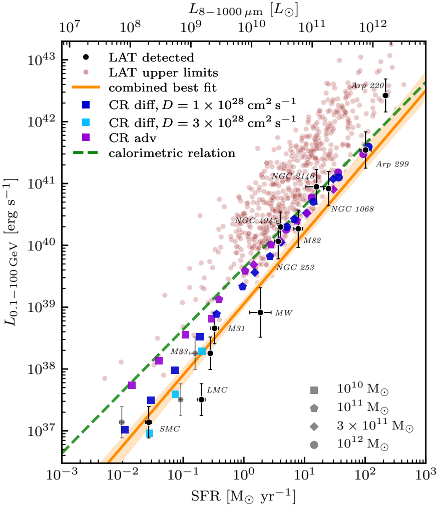
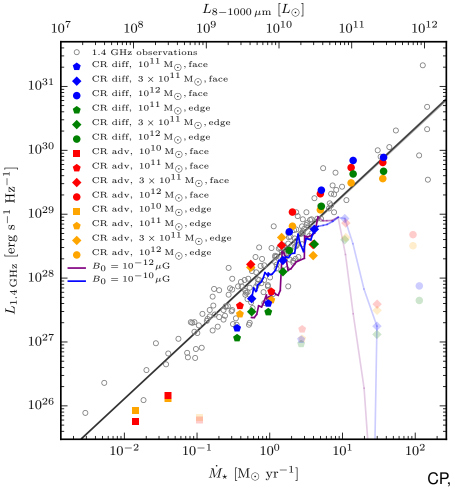


Werhahn, CP+ (2021b)

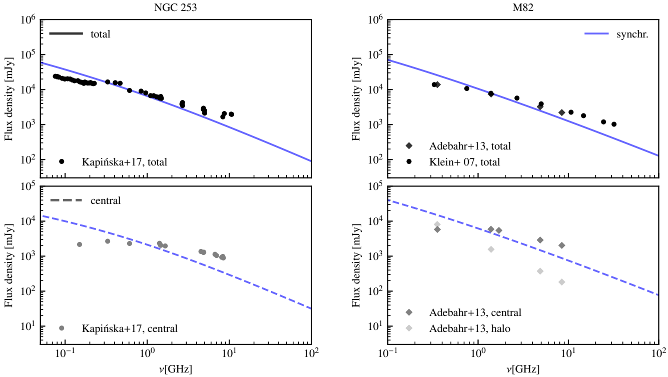
Far infra-red – radio correlation

Universal conversion: star formation → cosmic rays → radio



CP, Werhahn+ (2021)

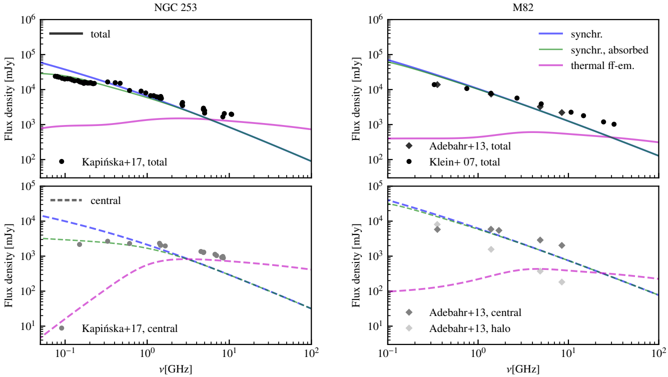
Radio spectra of starburst galaxies



Werhahn, CP+ (2021c)

- steep synchrotron spectra demonstrate electron calorimetry

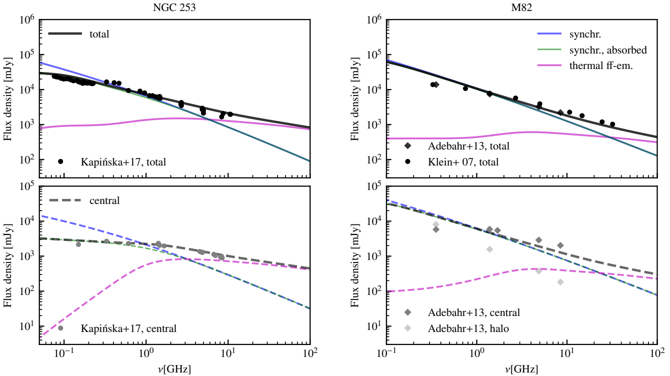
Radio spectra of starburst galaxies



Werhahn, CP+ (2021c)

- steep synchrotron spectra demonstrate electron calorimetry
- free-free absorption/emission flatten spectra at low/high frequencies

Radio spectra of starburst galaxies



Werhahn, CP+ (2021c)

- steep synchrotron spectra demonstrate electron calorimetry
- free-free absorption/emission flatten spectra at low/high frequencies to match observations

Conclusions

CR-driven plasma instabilities:

- discovery of new *intermediate-scale instability*, which grows faster than the gyro-resonant instability
- implications for CR transport in galaxies, electron heating and injection into diffusive shock acceleration, and CR escape from acceleration sites

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- synchrotron harps: CR streaming dominates over diffusion

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CR transport in galaxies:

- novel theory of CR transport mediated by Alfvén waves and coupled to magneto-hydrodynamics
- synchrotron harps: CR streaming dominates over diffusion

CR-induced signatures in galaxies

- CR feedback drives galactic winds & slows down star formation
- 3D MHD simulations reproduce CR, gamma-ray and radio spectra & FIR radio/gamma-ray correlations

AIP

CRAGSMAN: The Impact of Cosmic RAys on Galaxy and CluSter 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 CRAGSMAN–646955).

Literature for the talk – 1

Cosmic ray driven instabilities:

- Shalaby, Thomas, Pfrommer, *A new cosmic ray-driven instability,* 2021, ApJ.

Cosmic ray transport:

- Pfrommer, Pakmor, Schaal, Simpson, Springel, *Simulating cosmic ray physics on a moving mesh,* 2017a, MNRAS.
- Thomas & Pfrommer, *Cosmic-ray hydrodynamics: Alfvén-wave regulated transport of cosmic rays,* 2019, MNRAS.
- Thomas, Pfrommer, Enßlin, *Probing cosmic ray transport with radio synchrotron harps in the Galactic center,* 2020, ApJL.
- Thomas, Pfrommer, Pakmor, *A finite volume method for two-moment cosmic-ray hydrodynamics on a moving mesh,* 2021, MNRAS
- Thomas & Pfrommer, *Comparing different closure relations for cosmic ray hydrodynamics,* 2021, MNRAS

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Literature for the talk – 2

Cosmic ray feedback in galaxies:

- Pakmor, Pfrommer, Simpson, Springel, *Galactic winds driven by isotropic and anisotropic cosmic ray diffusion in isolated disk galaxies,* 2016, ApJL.

Cosmic rays and non-thermal emission in galaxies:

- Pfrommer, Pakmor, Simpson, Springel, *Simulating gamma-ray emission in star-forming galaxies,* 2017b, ApJL.
- 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
- 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
- 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
- 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,* 2021