Cosmic rays in galaxies: plasma instabilities, transport, and observations

Christoph Pfrommer[1]

in collaboration with

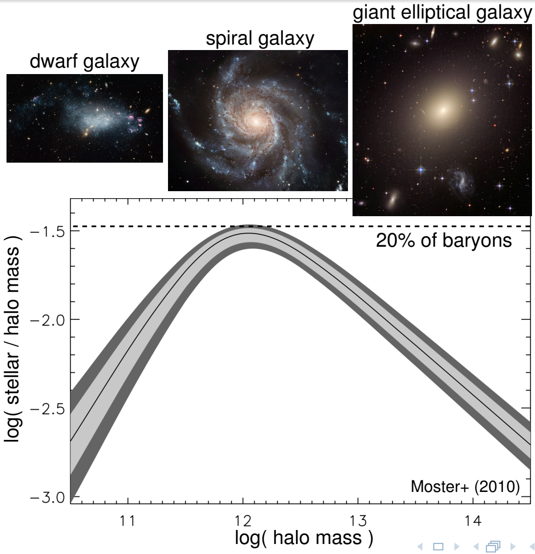
T. Thomas[1], M. Werhahn[1], M. Shalaby[1], P. Girichidis[1],
E. Puchwein[1], G. Winner[1], T. Enßlin[2], R. Pakmor[2]

[1]AIP Potsdam, [2]MPA Garching

Astrophysics Seminar, Würzburg University, May 2021

Puzzles in galaxy formation

Puzzles in galaxy formation



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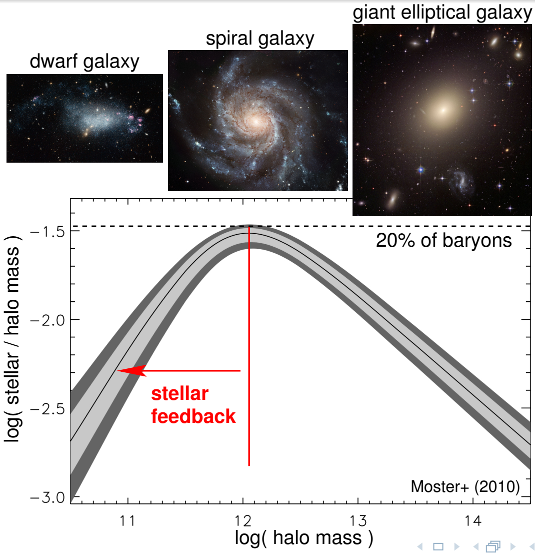
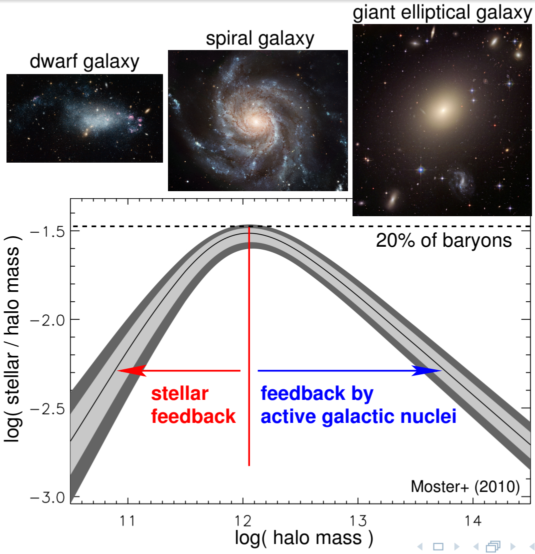


Puzzles in galaxy formation



Feedback

feedback n -s often attrib:

1. the return to the input of a part of the output of a machine, system, or process
2. the partial reversion of the effects of a given process to its source or to a preceding stage so as to reinforce or modify this process

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2. the partial reversion of the effects of a given process to its source or to a preceding stage so as to reinforce or modify this process
3. the solution of all problems in galaxy formation

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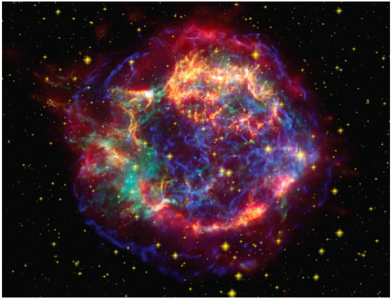
Cosmic ray transport and feedback in galaxies



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

Cosmic ray transport and feedback in galaxies

super wind in M82

NASA/JPL-Caltech/STScI/CXC/UofA

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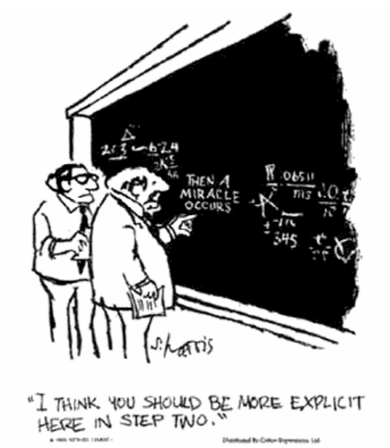

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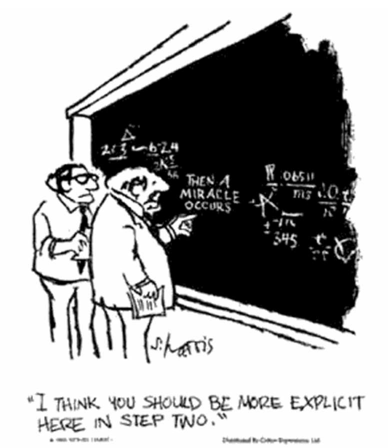

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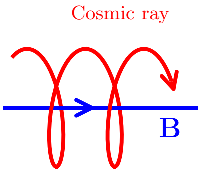
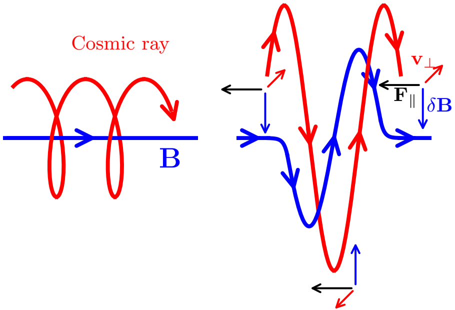
- supernovae, radiation and cosmic rays (CRs) drive gas out of galaxies via outflows
- critical for explaining low star conversion efficiency in dwarfs $\rightarrow$ physics of galaxy formation
- need to study cosmic-ray driven plasma instabilities $\rightarrow$ CR acceleration, transport and feedback

Interactions of CRs and magnetic fields



sketch: Jacob

Interactions of CRs and magnetic fields



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- **gyro resonance:** $\omega - k_{||} v_{||} = n\Omega$

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

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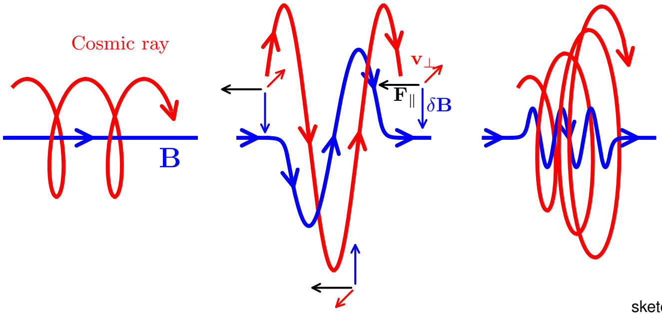

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  Doppler-shifted MHD frequency is a multiple of the CR gyrofrequency
- CRs scatter on magnetic fields $\rightarrow$ isotropization of CR momenta

Coupling of CRs to the background plasma

- extrinsic confinement: scattering off of turbulence cascaded from large scales via supernovae, stellar winds, etc.
  $\Rightarrow$ important for confinement of TeV CRs

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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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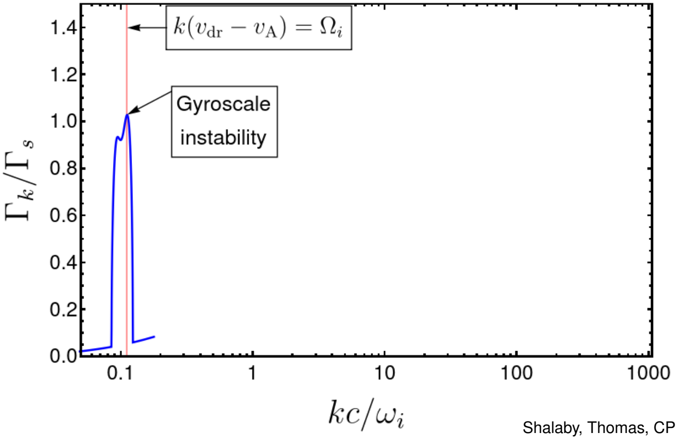
- dispersion relation ($\Omega_{e,0} = -m_i/m_e \times \Omega_{i,0}$, $\alpha = n_{\rm cr}/n_{\rm i}$):
  CR ion + electron beam propagates in background plasma

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

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

$$\text{CRi} \Rightarrow \quad + \frac{\alpha\omega_i^2}{\gamma_i\omega^2}\left\{\frac{\omega - kv_{\rm dr}}{kv_{\rm dr} - \omega \pm \Omega_i} - \frac{v_\perp^2\left(k^2c^2 - \omega^2\right)/c^2}{2\left(kv_{\rm dr} - \omega \pm \Omega_i\right)^2}\right\}$$

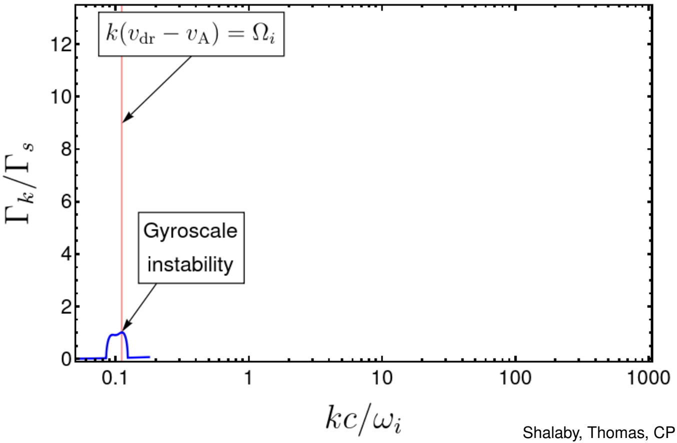
CR driven instabilities – growth rates



Shalaby, Thomas, CP (2021)

- gyro-resonant instability of gyrotropic CR population

CR driven instabilities – growth rates



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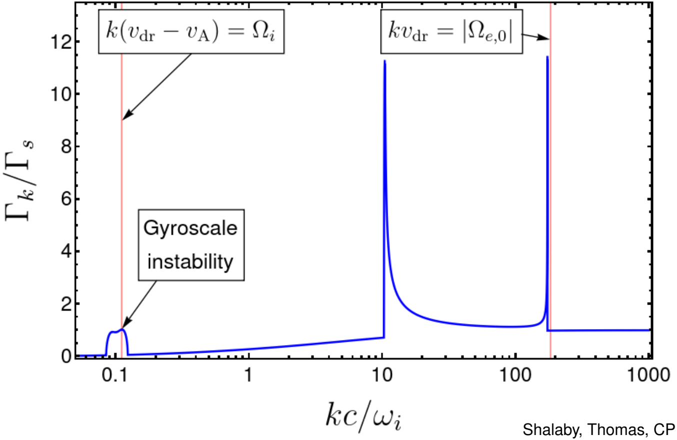

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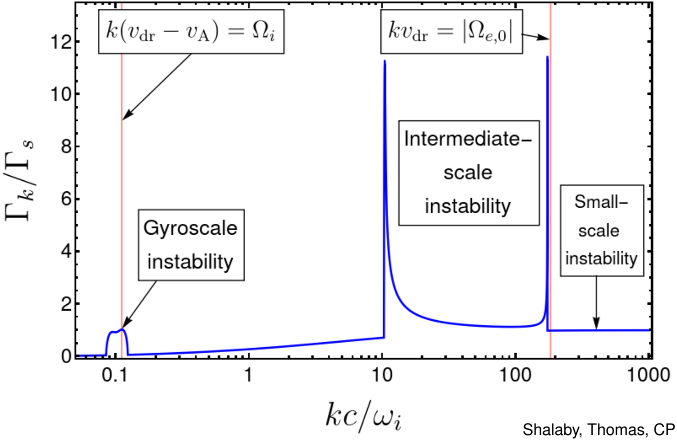

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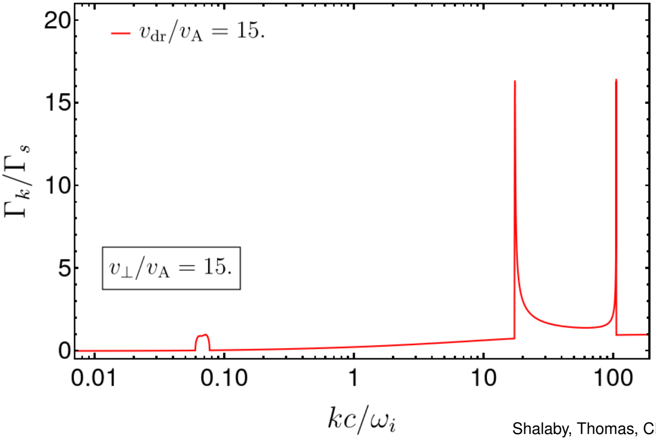
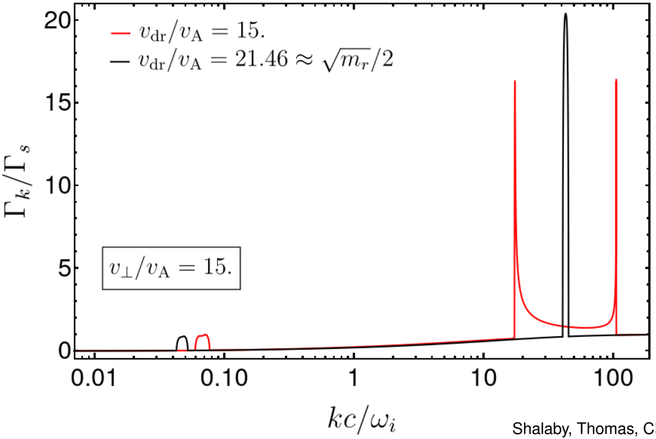
CR driven intermediate-scale instability



Shalaby, Thomas, CP (2021)

- low CR drift speed: two instability peaks

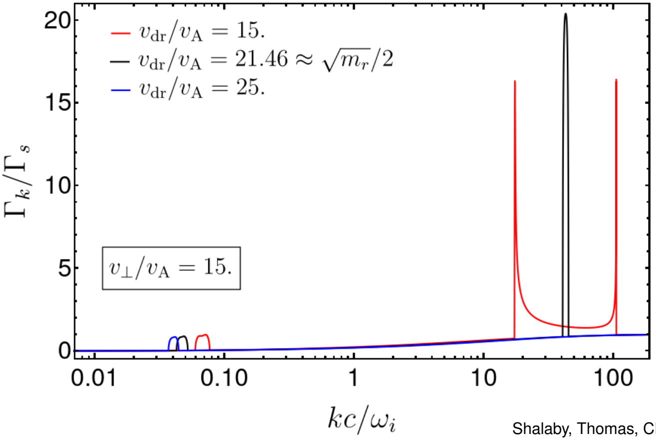
CR driven intermediate-scale instability



Shalaby, Thomas, CP (2021)

- for CR drift speed $v_{\rm dr} \approx \sqrt{\frac{m_{\rm i}}{m_{\rm e}}}\frac{v_{\rm A}}{2}$: two instability peaks merge

CR driven intermediate-scale instability

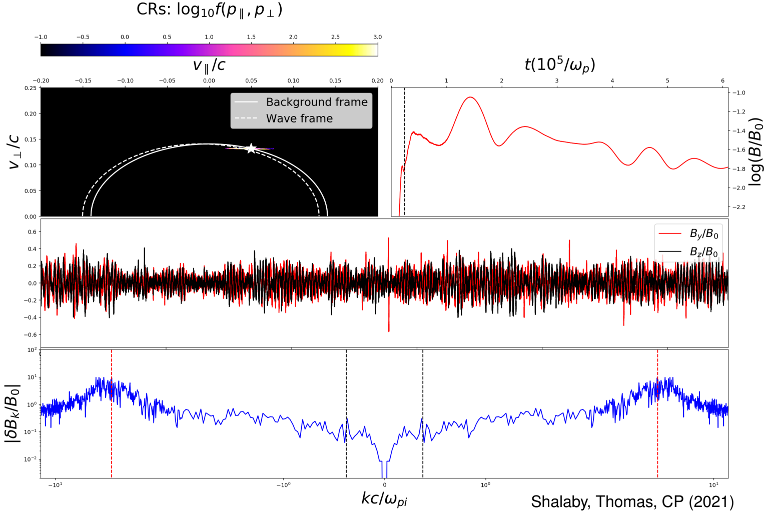


Shalaby, Thomas, CP (2021)

- for $v_{dr} > \sqrt{\frac{m_i}{m_e}} \frac{v_A}{2}$: intermediate-scale instability quenched

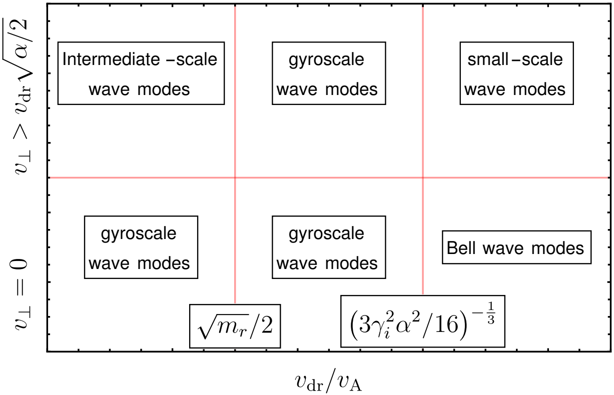
Cosmic ray driven instabilities

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



Shalaby, Thomas, CP (2021)

Regimes of CR driven instabilities



Shalaby, Thomas, CP (2021)

- 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 $\Gamma_{\mathrm{inter}} \gg \Gamma_{\mathrm{gyro}}$ and excites broad spectral support
- unstable modes are background ion-cyclotron waves in the comoving CR frame
- condition for growth: $$\frac{v_{\mathrm{dr}}}{v_{\mathrm{A}}} < \frac{1}{2}\sqrt{\frac{m_{\mathrm{i}}}{m_{\mathrm{e}}}}$$

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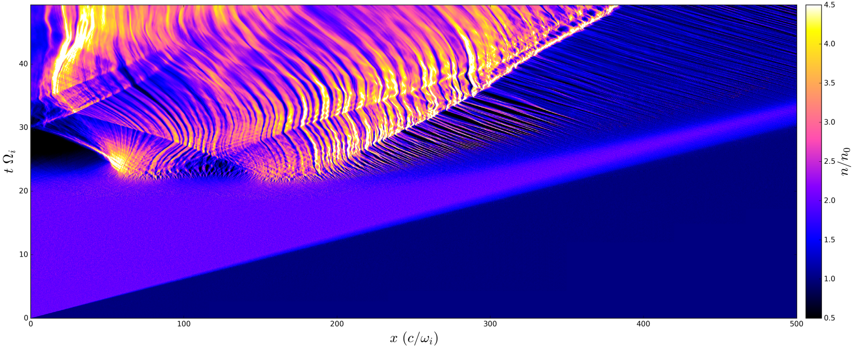
Implication of this new instability:

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

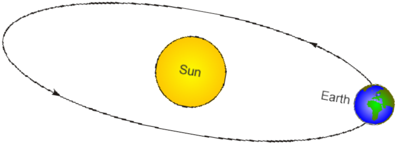
The intermediate-scale instability

Electron heating and injection into diffusive shock acceleration



Shalaby+ (in prep.)

Cosmic ray transport: an extreme multi-scale problem



Milky Way-like galaxy:

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

gyro-orbit of GeV cosmic ray:

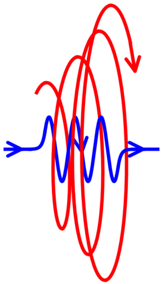
$$r_{\mathrm{cr}} = \frac{p_\perp}{e\,B_{\mu\mathrm{G}}} \sim 10^{-6} \text{ pc} \sim \frac{1}{4} \text{ AU}$$

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

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

CR streaming and diffusion

- **CR streaming instability:** Kulsrud & Pearce 1969
  - if $v_{cr} > v_a$, 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 $\sim v_a$
  - wave damping: transfer of CR energy and momentum to the thermal gas



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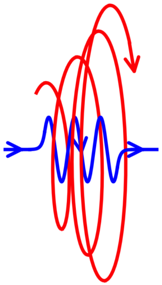

$\rightarrow$ *CRs exert pressure on thermal gas via scattering on Alfvén waves*

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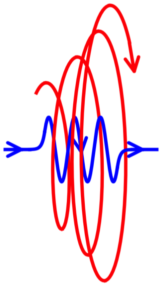
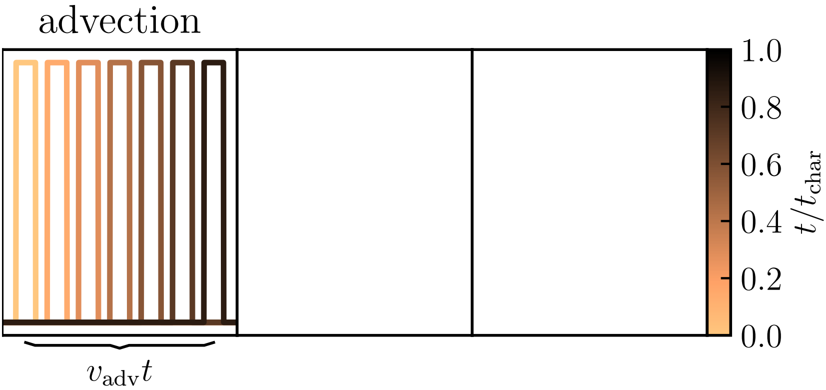


$\rightarrow$ *CRs exert pressure on thermal gas via scattering on Alfvén waves*

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

Modes of CR propagation



Thomas, CP, Enßlin (2020)

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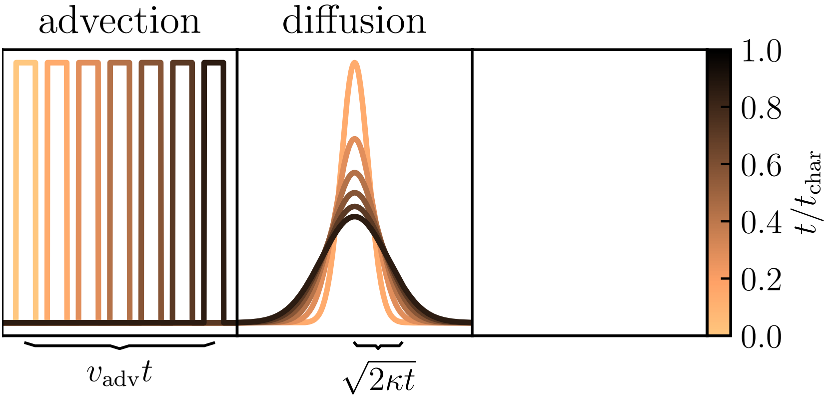

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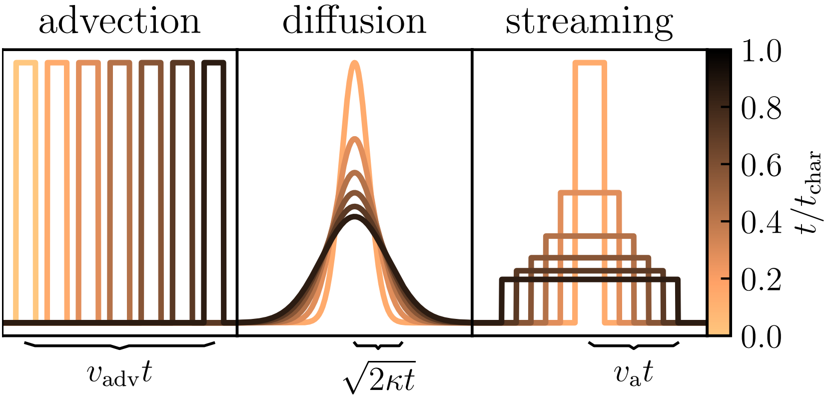

Thomas, CP, Enßlin (2020)

Analogies of CR and radiation hydrodynamics

CRs and radiation are relativistic fluids

regime	CR transport	radiation HD analogy
• tangled $\boldsymbol{B}$, strong scattering	CR diffusion	diffusive transport in clumpy medium
• resolved $\boldsymbol{B}$, strong scattering	CR streaming with $\boldsymbol{v}_\mathrm{a}$	Thomson scattering ($\tau \gg 1$) $\rightarrow$ advection with $\boldsymbol{v}$
• weak scattering	CR streaming and diffusion	flux-limited diffusion/ M1 closure ($\tau \gtrsim 1$)
• no scattering	CR propagation with c	vacuum propagation

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

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

but: *CR hydrodynamics is charged RHD*

$\rightarrow$ ***account for Lorentz force and anisotropic transport along B***

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CR vs. radiation hydrodynamics

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

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

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

AIP

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

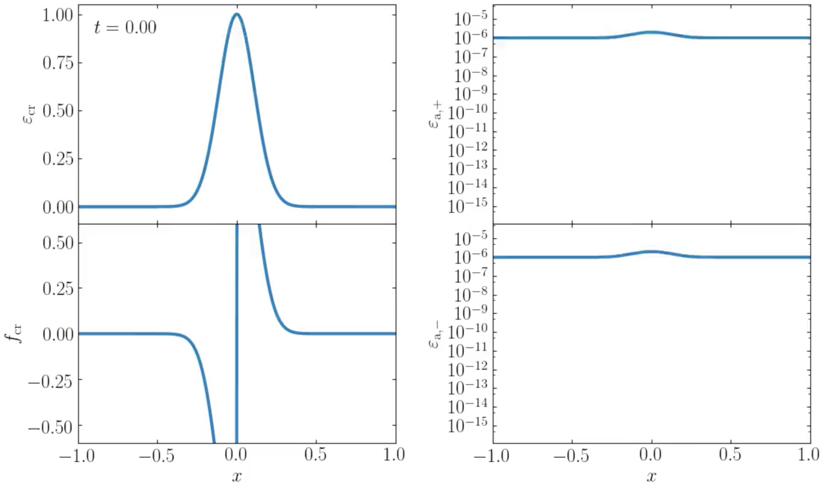
$$\frac{\partial \varepsilon_{\rm cr}}{\partial t} + \nabla\cdot\left[\boldsymbol{v}(\varepsilon_{\rm cr}+P_{\rm cr}) + \boldsymbol{b} f_{\rm cr}\right] = \boldsymbol{v}\cdot\nabla P_{\rm cr} - \frac{v_{\rm a}}{3\kappa_+}\left[f_{\rm cr} - v_{\rm a}(\varepsilon_{\rm cr}+P_{\rm cr})\right] + \frac{v_{\rm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

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

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

Non-equilibrium CR streaming and diffusion

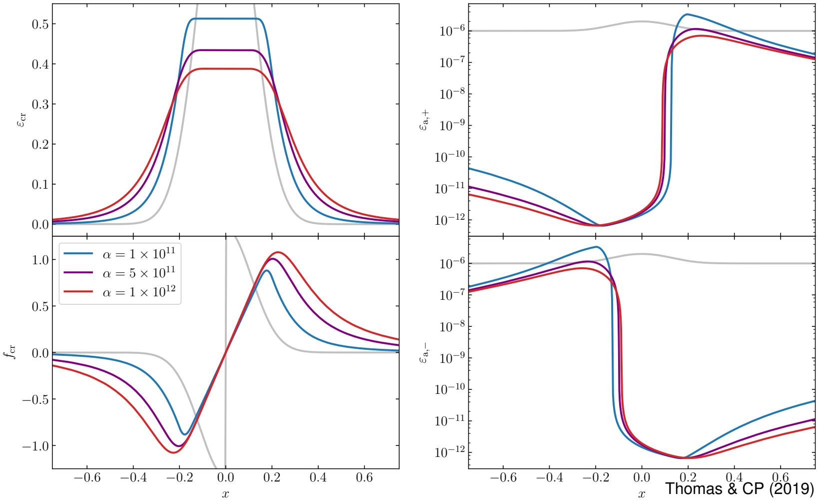
Coupling the evolution of CR and Alfvén wave energy densities



Thomas & CP (2019)

Non-equilibrium CR streaming and diffusion

Varying damping rate of Alfvén waves modulates the diffusivity of solution

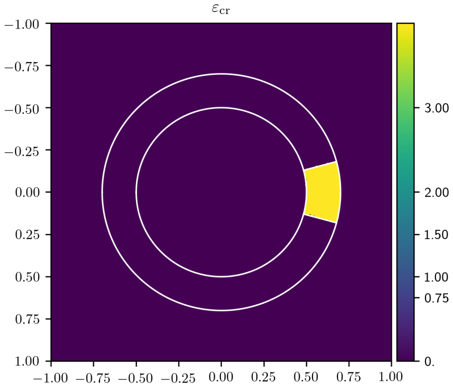


Thomas & CP (2019)

Anisotropic CR streaming and diffusion – AREPO

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

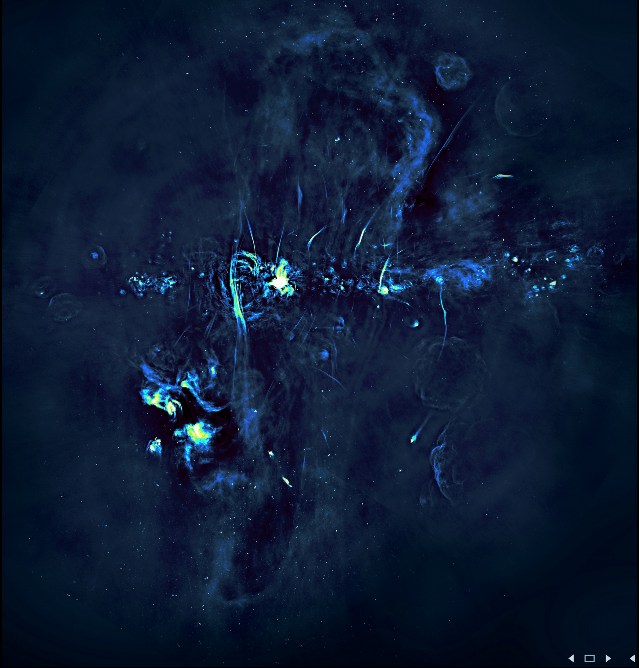
- CR streaming and diffusion along magnetic field lines in the self-confinement picture
- moment expansion similar to radiation hydrodynamics
- accounts for kinetic physics: non-linear Landau damping, gyro-resonant instability, . . .
- Galilean invariant and causal transport
- energy and momentum conserving



Thomas, CP, Pakmor (2021)

MeerKAT image of the Galactic Center

Haywood+ (Nature, 2019)



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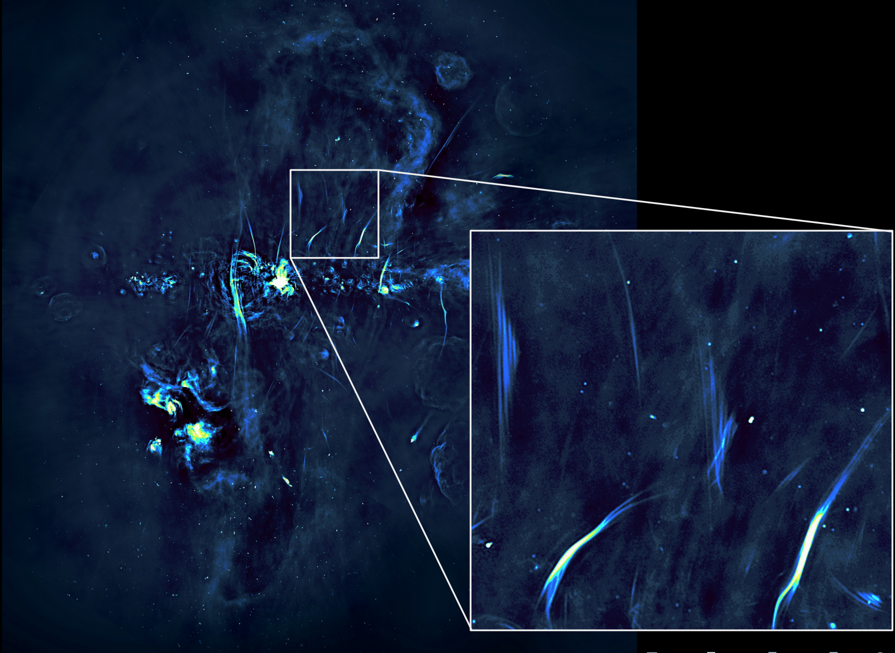
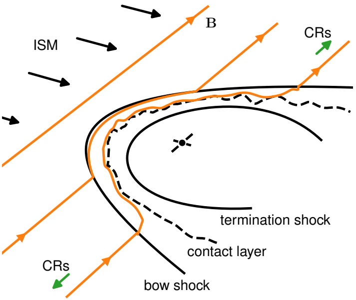


Radio synchrotron harps: the model

shock acceleration scenario



Thomas, CP, Enßlin (2020)

Radio synchrotron harps: the model

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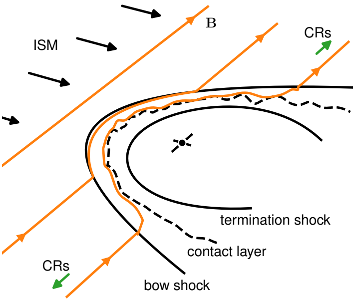
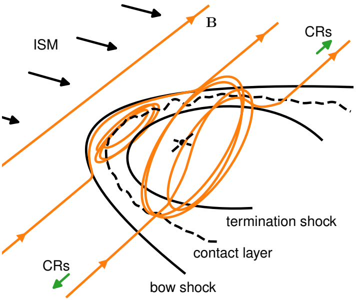


magnetic reconnection at pulsar wind



Thomas, CP, Enßlin (2020)

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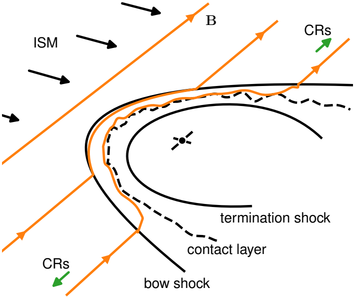
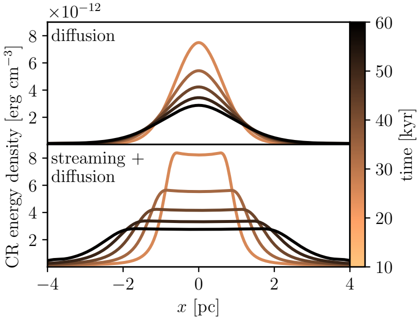
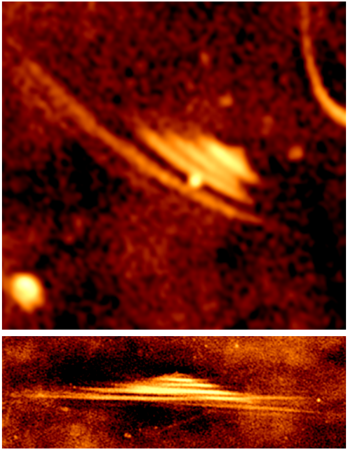


Thomas, CP, Enßlin (2020)

CR diffusion vs. streaming + diffusion

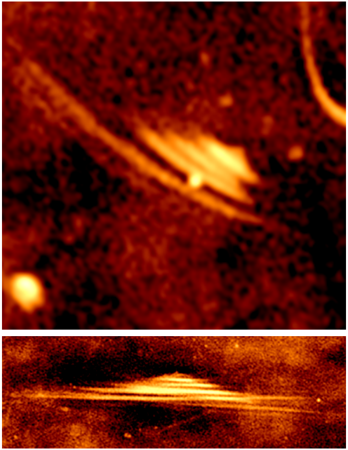


Radio synchrotron harps: testing CR propagation



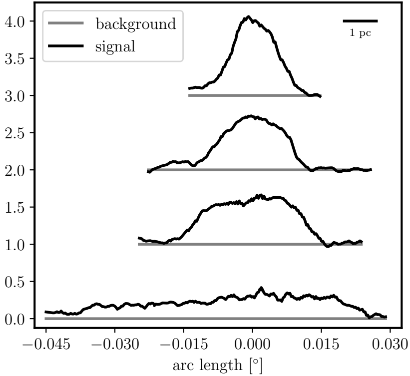
Haywood+ (Nature, 2019)

Radio synchrotron harps: testing CR propagation



Haywood+ (Nature, 2019)

lateral radio profiles



Thomas, CP, Enßlin (2020)

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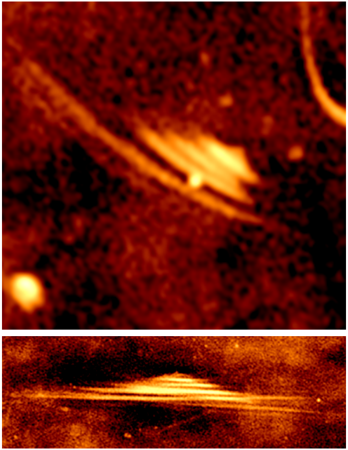
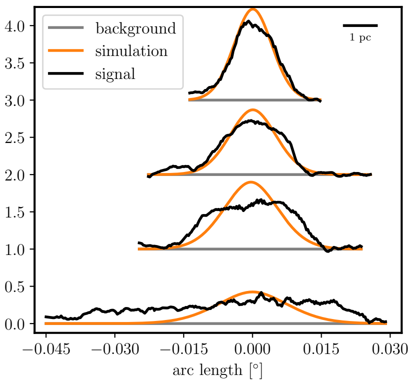


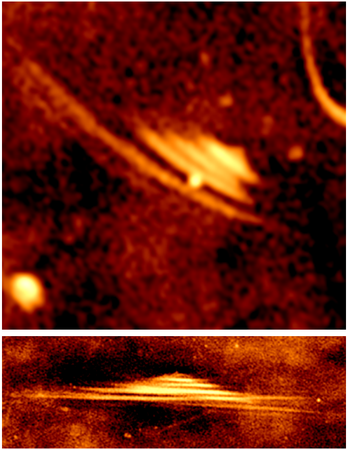
Haywood+ (Nature, 2019)

CR diffusion

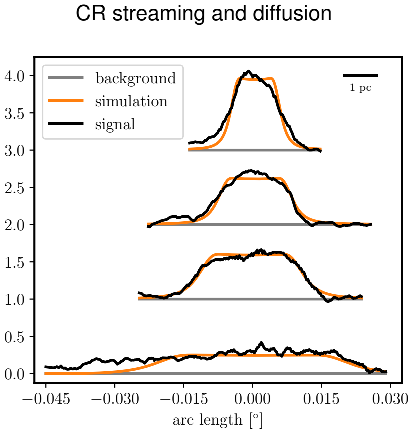


Thomas, CP, Enßlin (2020)

Radio synchrotron harps: testing CR propagation

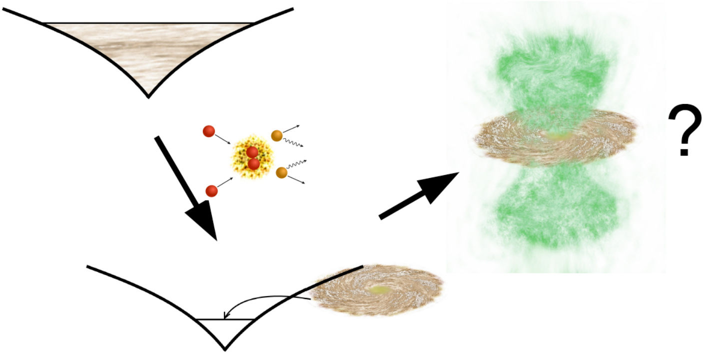


Haywood+ (Nature, 2019)



Thomas, CP, Enßlin (2020)

Cosmic rays in galaxy formation



Werhahn, CP, Girichidis+ (2021)

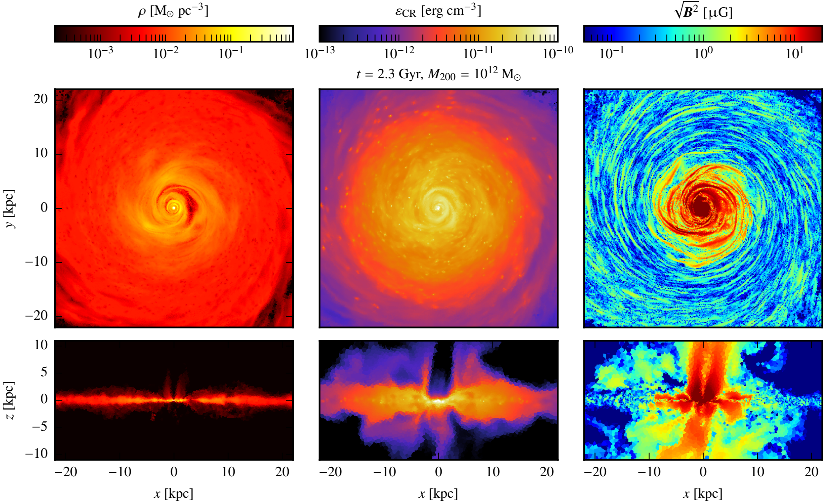
Cosmic rays and non-thermal emission in simulated galaxies: I. & II.

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

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

AIP

Simulation of a starburst galaxy



Werhahn, CP+ (2021)

Steady-state cosmic ray spectra

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

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

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

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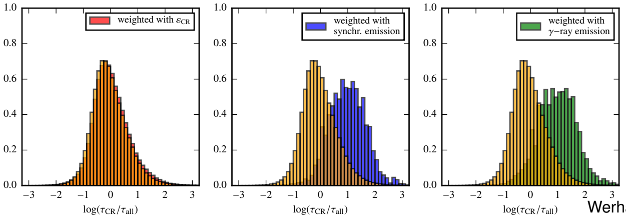
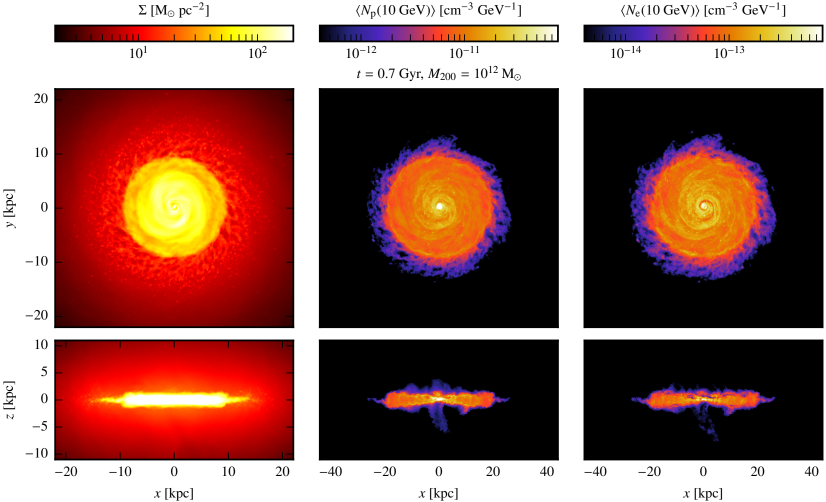
- electrons: Coulomb, bremsstr., IC, synchrotron and escape losses
  - primaries (re-normalized using $K_{\rm ep} = 0.02$)
  - secondaries
- steady state assumption is fulfilled in disk and in regions dominating the non-thermal emission but not at low densities, at SNRs and in outflows



Werhahn+ (2021a)

From a starburst galaxy to a Milky Way analogy



Werhahn, CP+ (2021)

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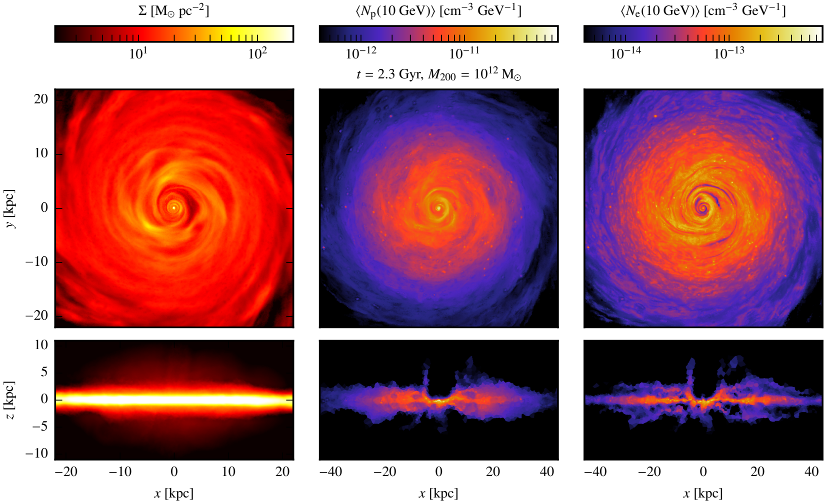
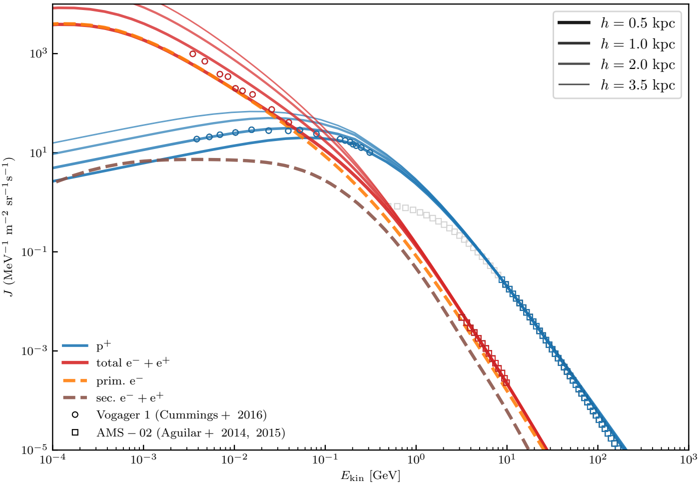


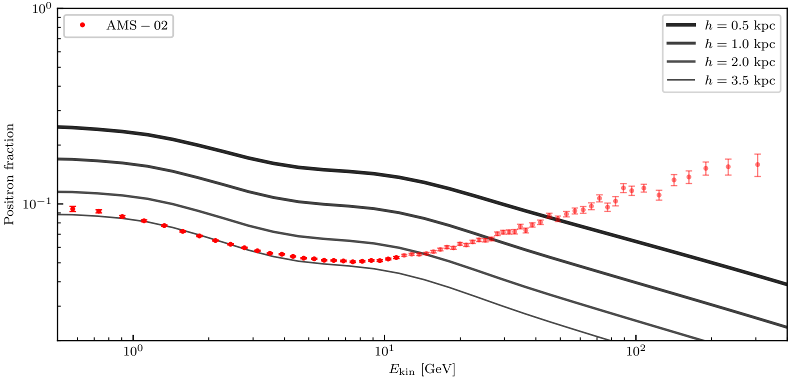
Werhahn, CP+ (2021)

Comparing CR spectra to Voyager and AMS-02 data



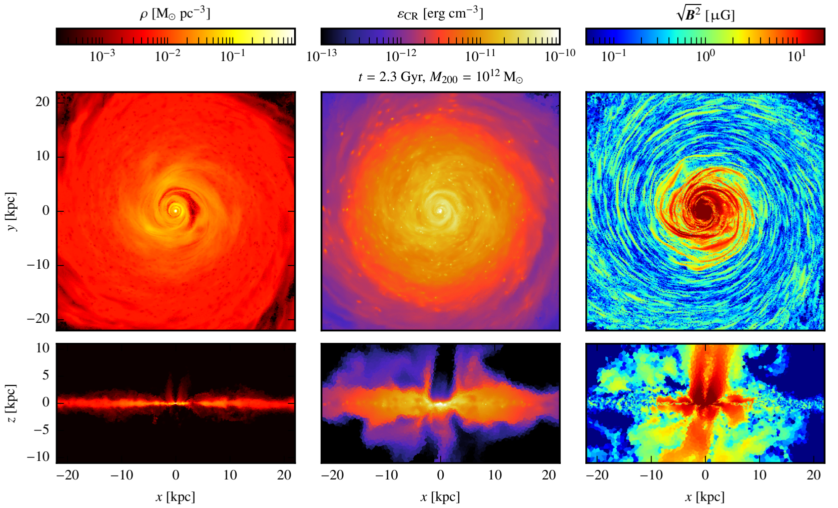
Werhahn, CP+ (2021)

Comparing the positron fraction to AMS-02 data



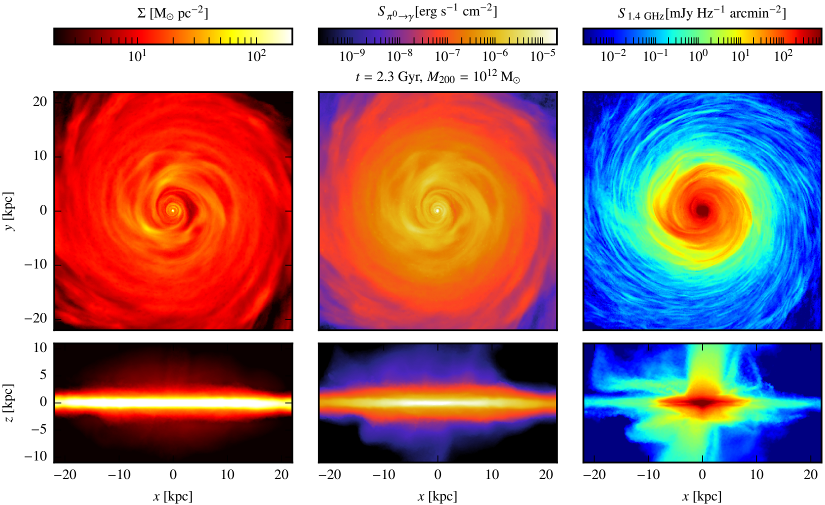
Werhahn, CP+ (2021)

Simulation of a starburst galaxy



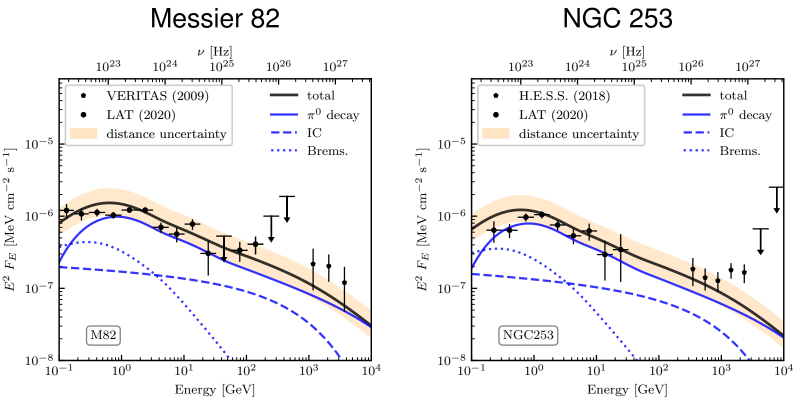
Werhahn, CP+ (2021)

Simulation of a starburst galaxy



Werhahn, CP+ (2021)

Gamma-ray spectra of starburst galaxies

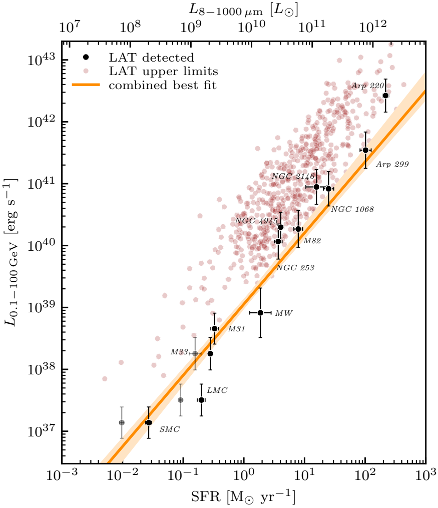


Werhahn, CP+ (2021)

- 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

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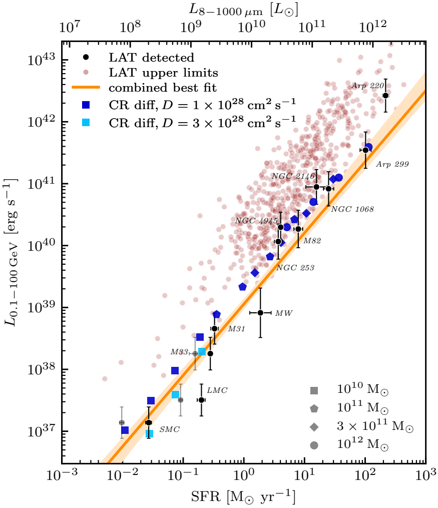

Werhahn, CP+ (2021)

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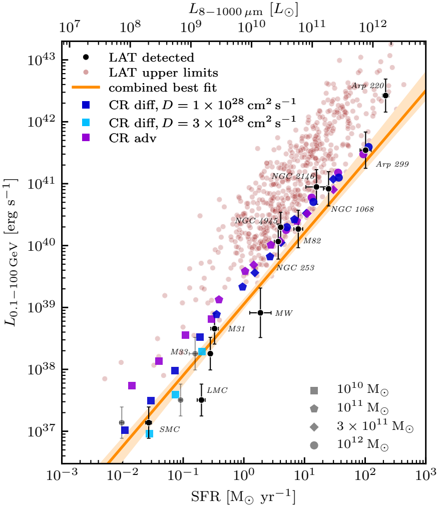

Werhahn, CP+ (2021)

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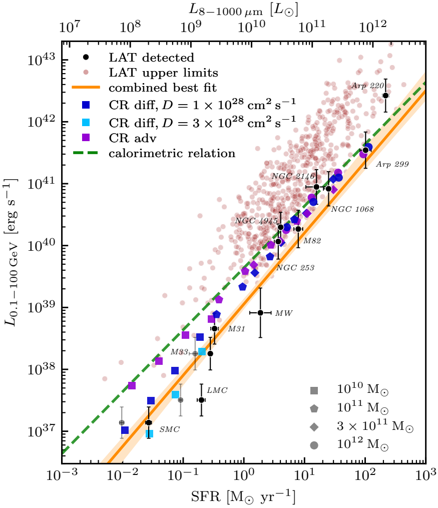
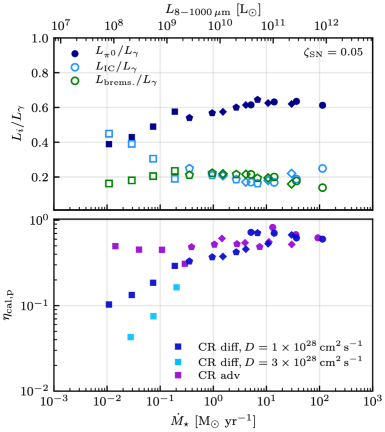


Werhahn, CP+ (2021)

Far infra-red – gamma-ray correlation

Hadronic vs. leptonic emission and calorimetric fraction across galaxy scales



Werhahn, CP+ (2021)

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

Conclusions

CR-driven plasma instabilities:

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

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- novel theory of CR transport mediated by Alfvén waves and coupled to magneto-hydrodynamics
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CR transport in galaxies:

- novel theory of CR transport mediated by Alfvén waves and coupled to magneto-hydrodynamics
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CR-induced signatures in galaxies

- Voyager's high electron-to-proton ratio at low energies explained by Coulomb losses of steady-state spectra
- leptonic gamma-ray contribution important at low star formation rates

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

Cosmic ray instabilities and transport:

- Shalaby, Thomas, Pfrommer, *A new cosmic ray-driven instability,* 2021, ApJ, 908, 206.
- 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.

Cosmic rays in galaxies:

- Werhahn, Pfrommer, Girichidis, Puchwein, Pakmor, *Cosmic rays and non-thermal emission in simulated galaxies. I. Electron and proton spectra explain Voyager-1 data,* 2021
- 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,* 2021