Cosmic rays in galaxy formation

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in collaboration with

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Virgo Consortium meeting, Durham, Jan 2020

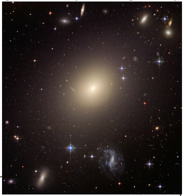
Do cosmic rays matter in galaxy formation?

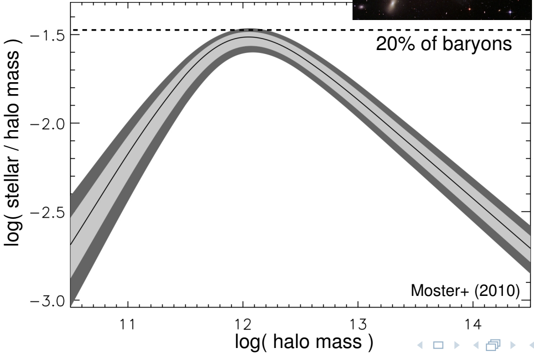
Puzzles in galaxy formation

dwarf galaxy

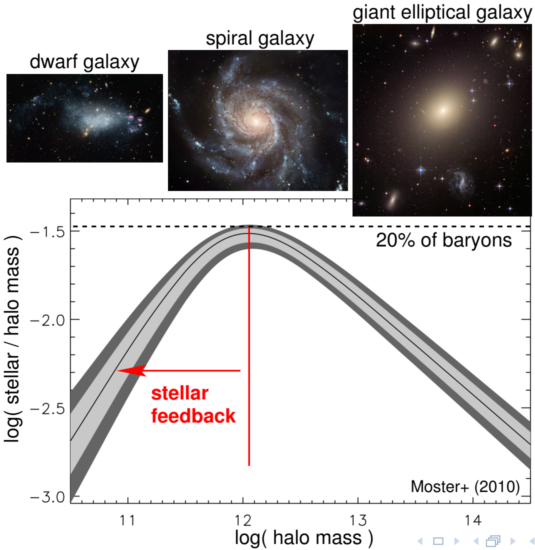
spiral galaxy

giant elliptical galaxy

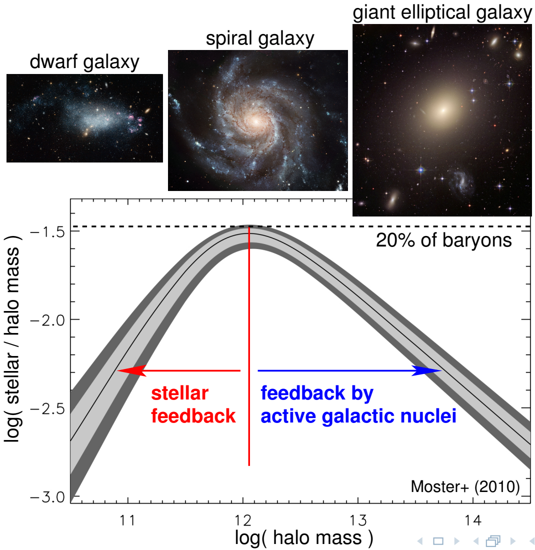




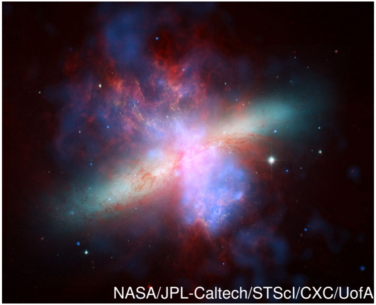
Puzzles in galaxy formation



Puzzles in galaxy formation



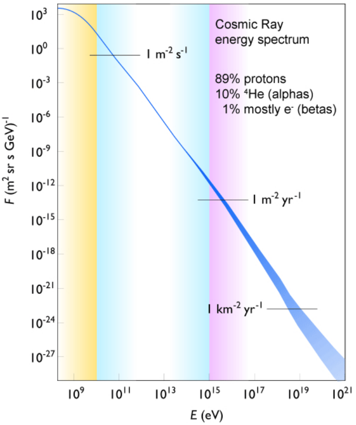
How are galactic winds driven?



super wind in M82

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

Galactic cosmic ray spectrum



data compiled by Swordy

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

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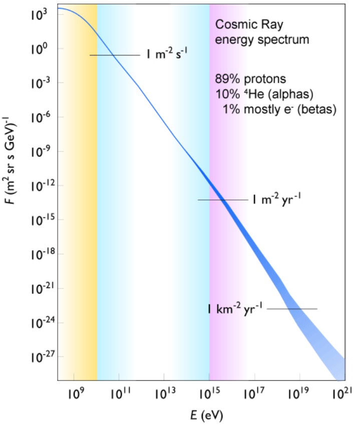

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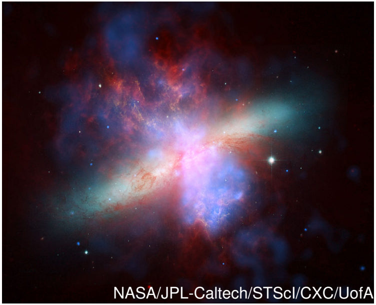
- spans more than 33 decades in flux and 12 decades in energy
- "knee" indicates characteristic maximum energy of galactic accelerators
- CRs beyond the "ankle" have extra-galactic origin
- energy density of cosmic rays, magnetic fields, and turbulence in the interstellar gas all similar

How are galactic winds driven?



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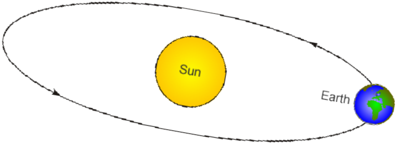
observed energy equipartition between cosmic rays, thermal gas and magnetic fields not a coincidence
→ suggests self-regulated feedback loop with CR driven winds

Outline

1. Cosmic ray transport
   - Introduction
   - CR hydrodynamics
   - Observational tests

2. Cosmic ray feedback
   - Modeling physics
   - Galaxy simulations
   - Galaxy cluster physics

Cosmic ray transport: an extreme multi-scale problem



Milky Way-like galaxy:

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

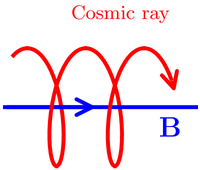
gyro-orbit of GeV cosmic ray:

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

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

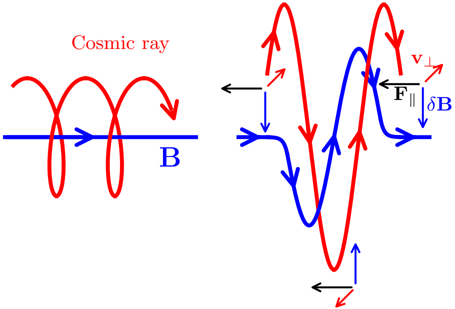
Zweibel (2017), Jiang & Oh (2018), Thomas & CP (2019)

Interactions of CRs and magnetic fields



sketch: Jacob

Interactions of CRs and magnetic fields



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

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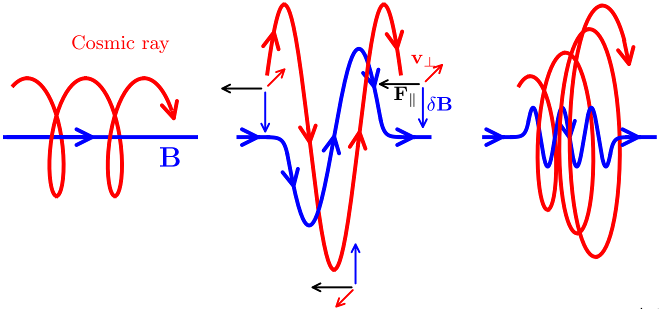

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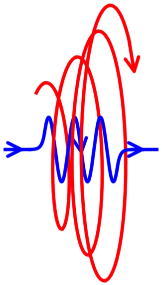
- **gyro resonance:** $\omega - k_{\parallel} v_{\parallel} = n\Omega$
  Doppler-shifted MHD frequency is a multiple of the CR gyrofrequency
- CRs scatter on magnetic fields → isotropization of CR momenta

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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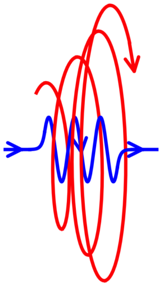

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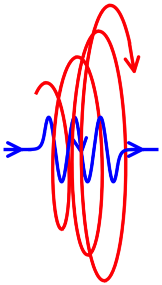

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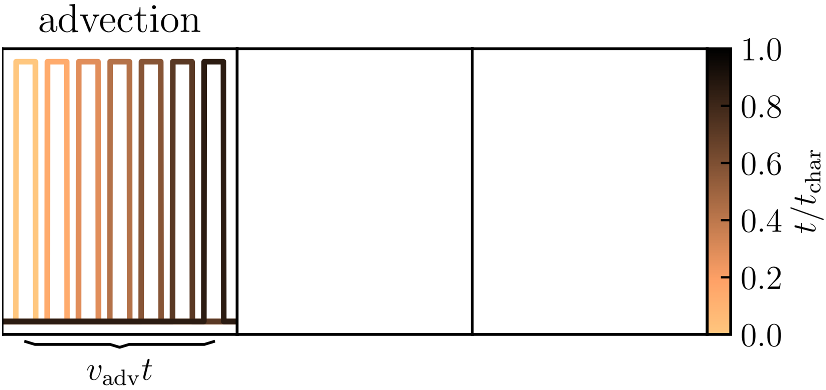
weak wave damping: strong coupling $\rightarrow$ CR stream with waves
strong wave damping: less waves to scatter $\rightarrow$ CR diffusion prevails

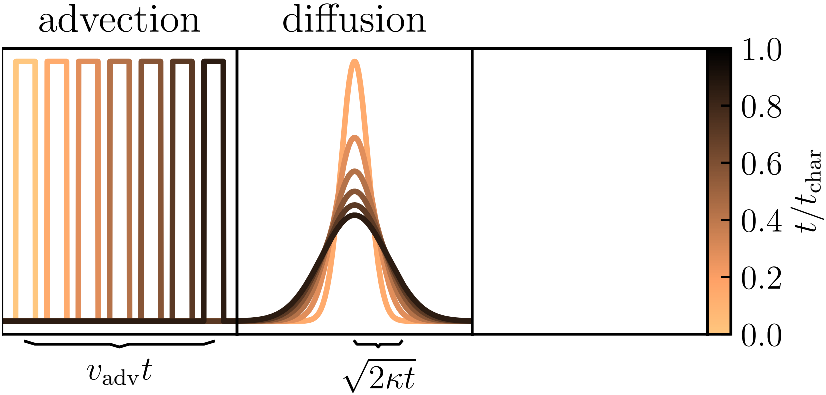
AIP

Modes of CR propagation



Thomas, CP, Enßlin (2020)

Modes of CR propagation



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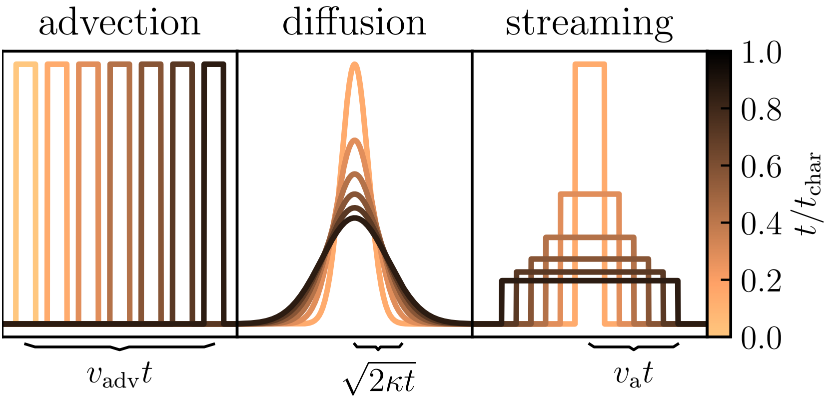

Thomas, CP, Enßlin (2020)

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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Alfvén wave velocity in lab frame: $\boldsymbol{w}_{\pm} = \boldsymbol{v} \pm \boldsymbol{v}_{\mathrm{a}}$,
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- lab-frame equ's for radiation energy and momentum density, ε and $\boldsymbol{f}/c^2$
  (Mihalas & Mihalas, 1984, Lowrie+ 1999):

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

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

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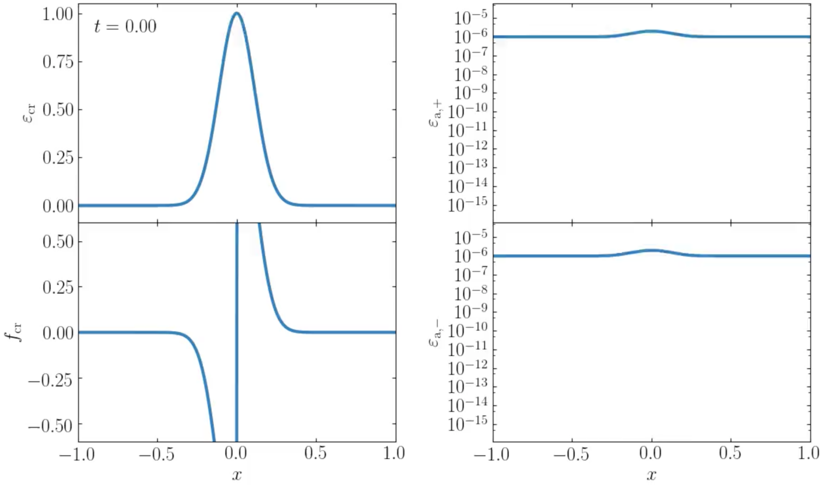
- ***solution:*** *transform in comoving frame and project out gyrokinetics!*

Non-equilibrium CR streaming and diffusion

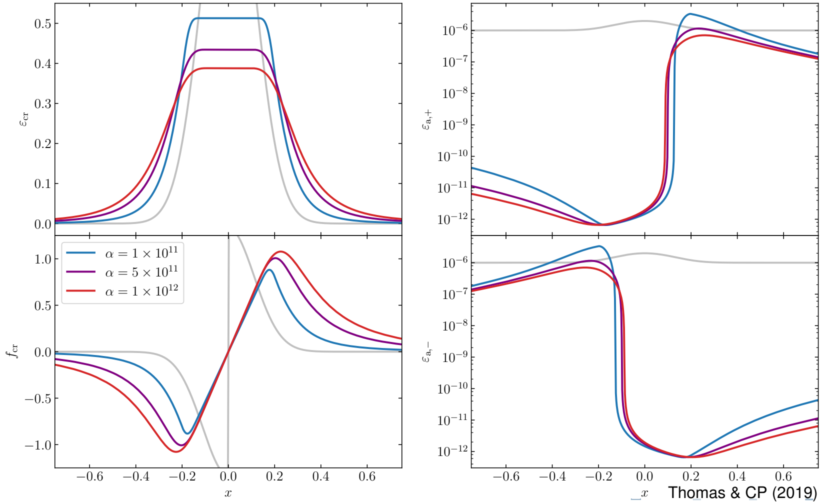
Coupling the evolution of CR and Alfvén wave energy densities



Thomas & CP (2019)

Non-equilibrium CR streaming and diffusion

Varying damping rate of Alfvén waves modulates the diffusivity of solution

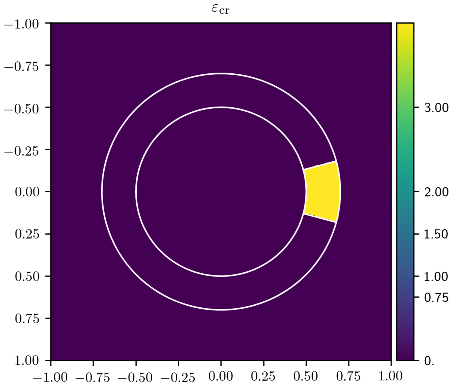


Thomas & CP (2019)

Anisotropic CR streaming and diffusion – AREPO

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

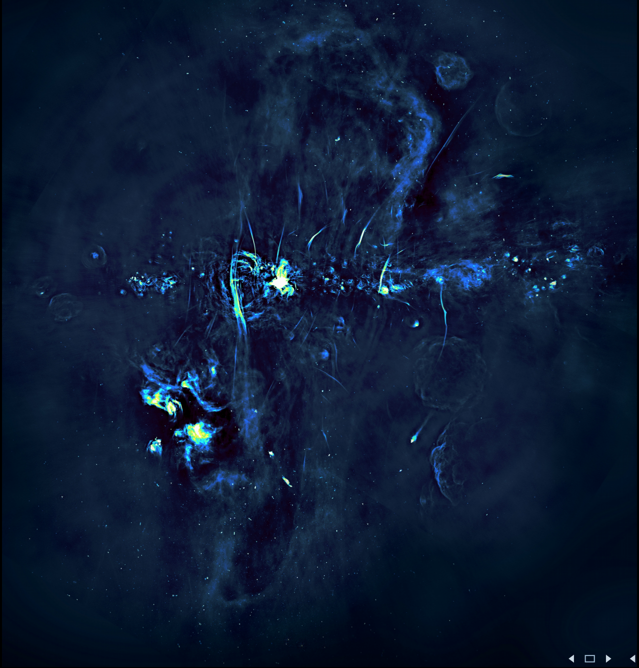
- CR streaming and diffusion along magnetic field lines in the self-confinement picture
- moment expansion similar to radiation hydrodynamics
- accounts for kinetic physics: non-linear Landau damping, gyro-resonant instability, ...
- Galilean invariant and causal transport
- energy and momentum conserving



Thomas, Pakmor, CP (in prep.)

MeerKAT image of the Galactic Center

Haywood+ (Nature, 2019)



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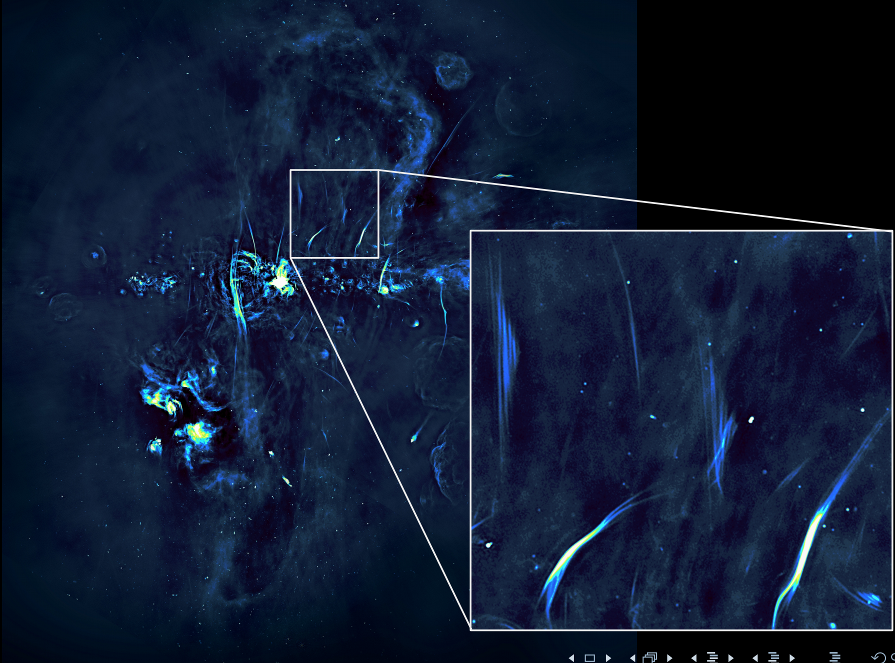
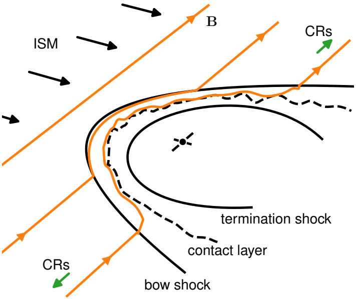


Radio synchrotron harps: the model

shock acceleration scenario



Thomas, CP, Enßlin (2020)

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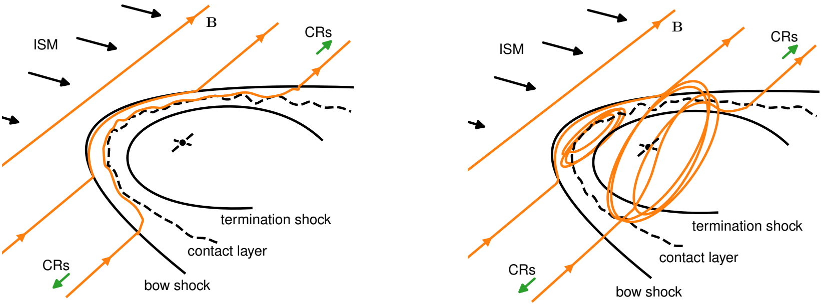
magnetic reconnection at pulsar wind



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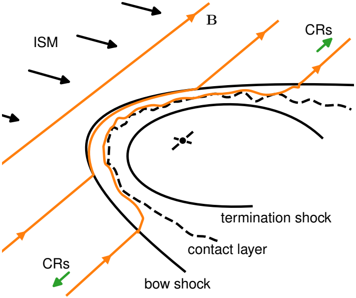
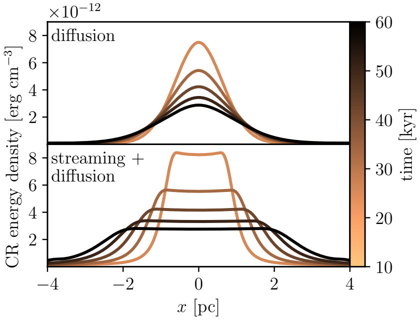
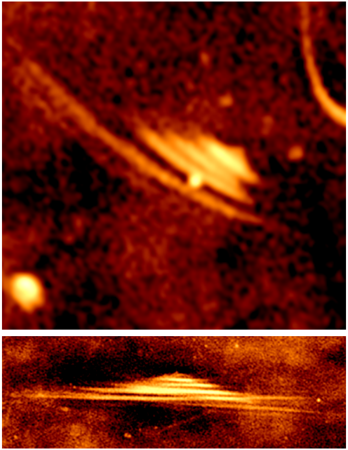


Thomas, CP, Enßlin (2020)

CR diffusion vs. streamig + diffusion



Radio synchrotron harps: testing CR propagation



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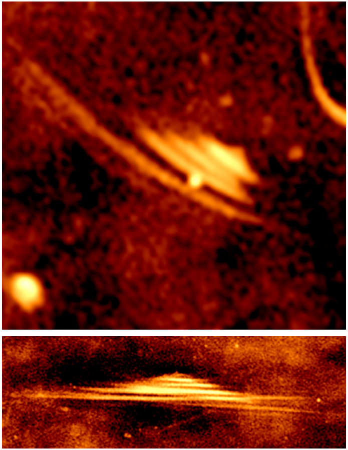

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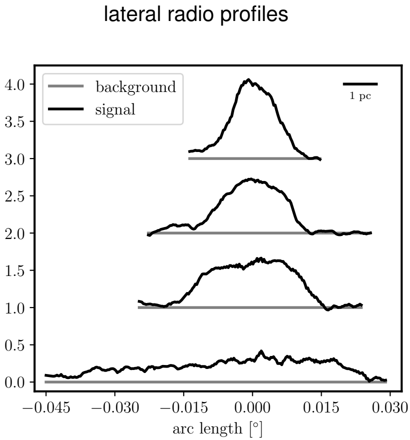

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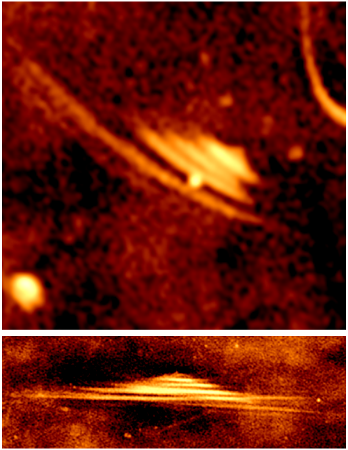

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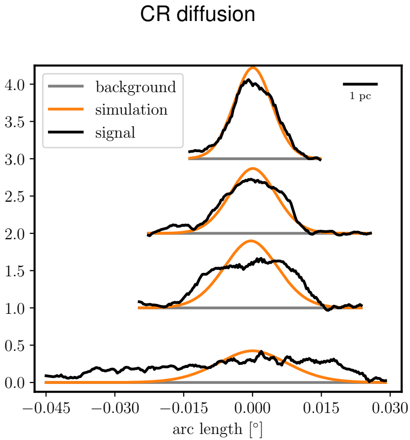

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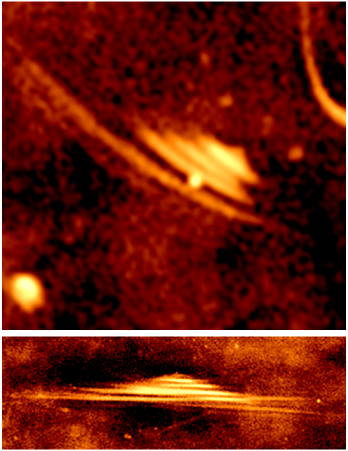

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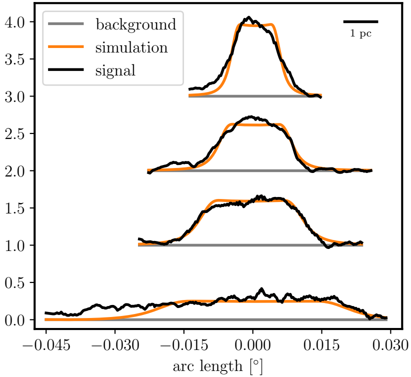
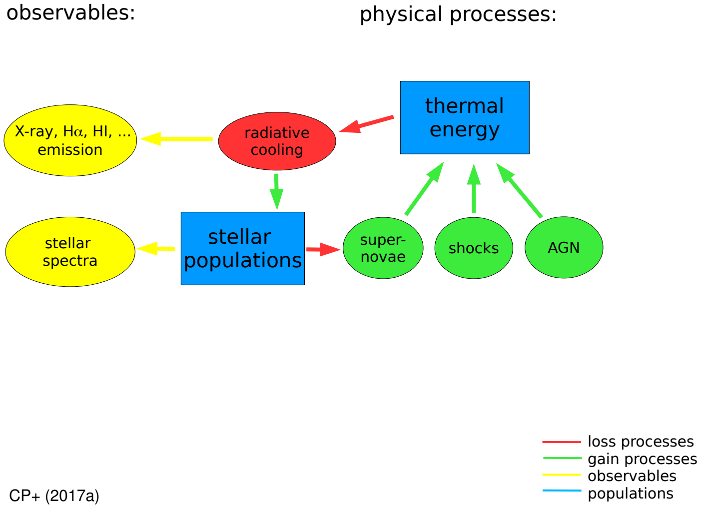
CR streaming and diffusion



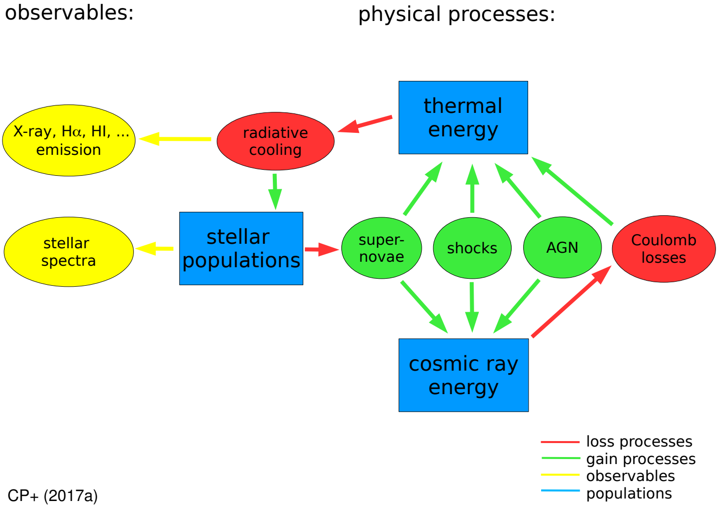
Thomas, CP, Enßlin (2020)

Simulations – flowchart



CP+ (2017a)

Simulations with cosmic ray physics



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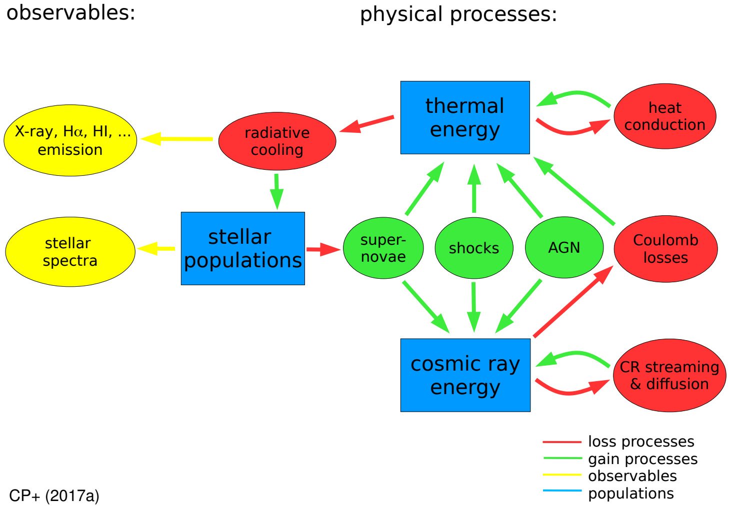

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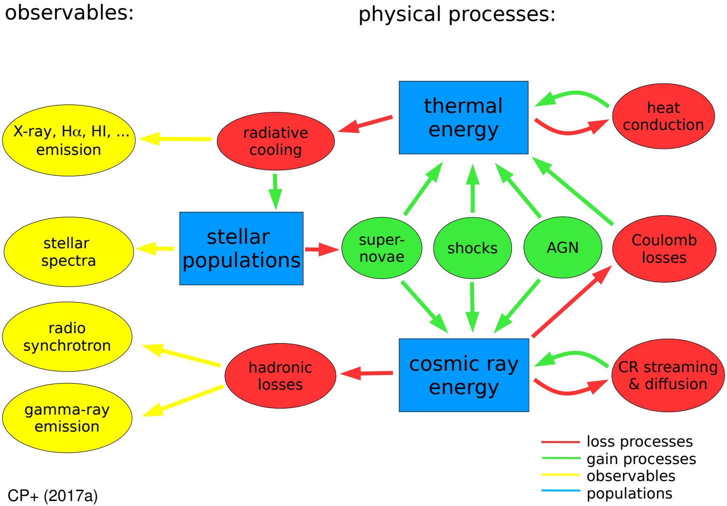

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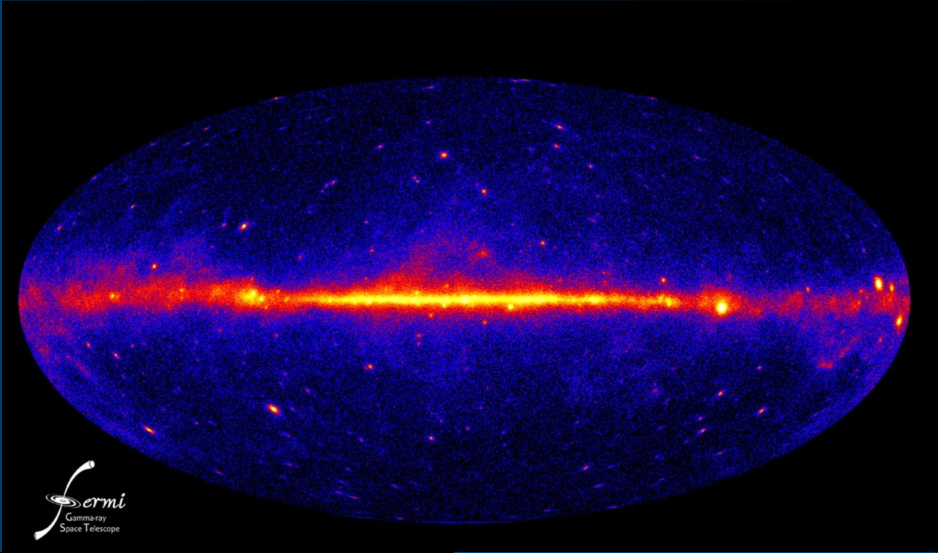
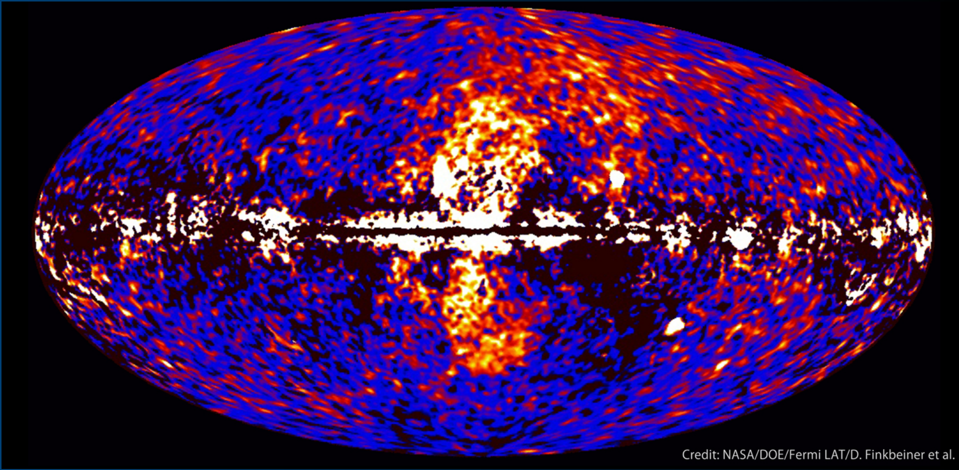
Gamma-ray emission of the Milky Way

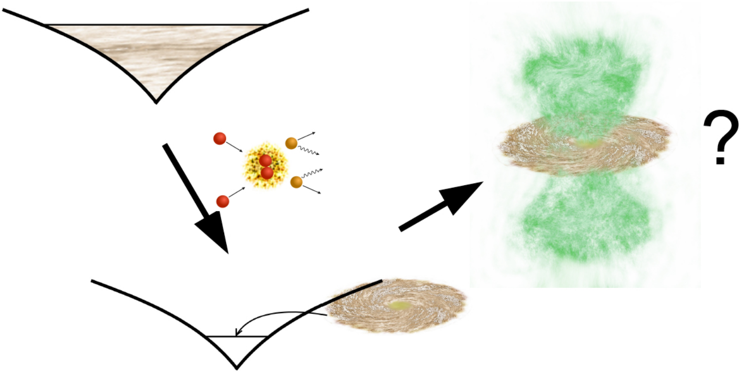


Galactic wind in the Milky Way?

Fermi gamma-ray bubbles



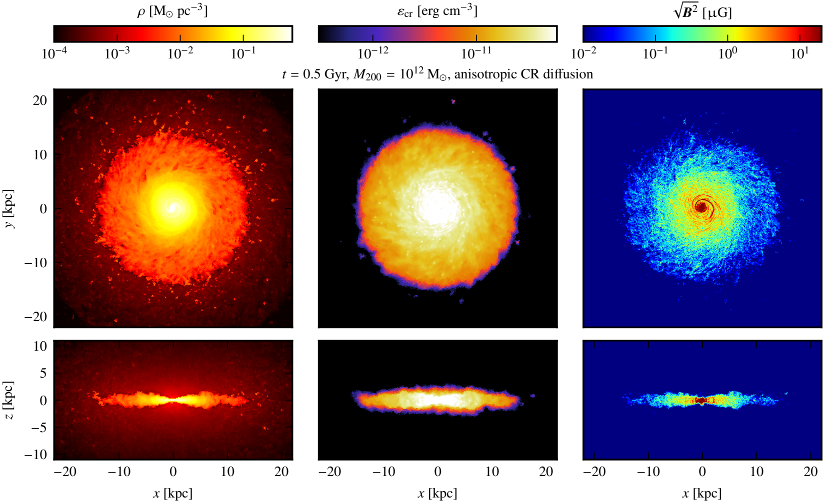
1. Galaxy formation in idealized halos



CP, Pakmor, Simpson, Springel (2017b)
Simulating gamma-ray emission in star-forming galaxies
MHD + CR advection + anisotropic diffusion, $\{10^{10}, 10^{11}, 10^{12}\}\ M_\odot$

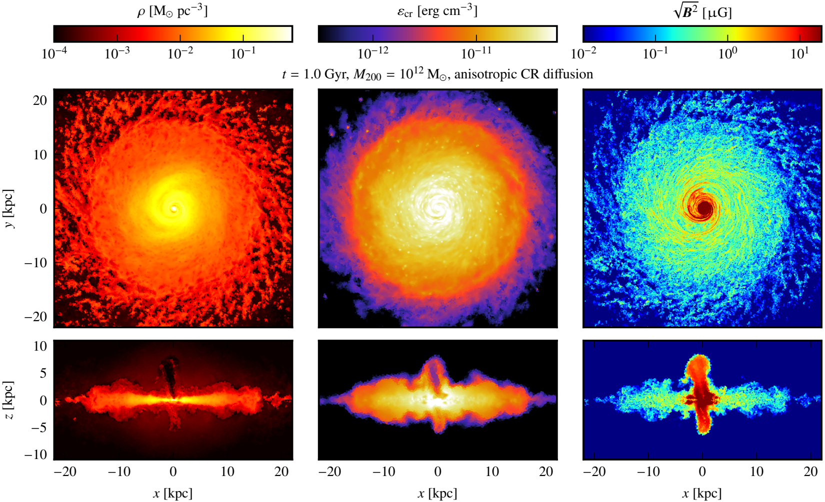
AIP

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



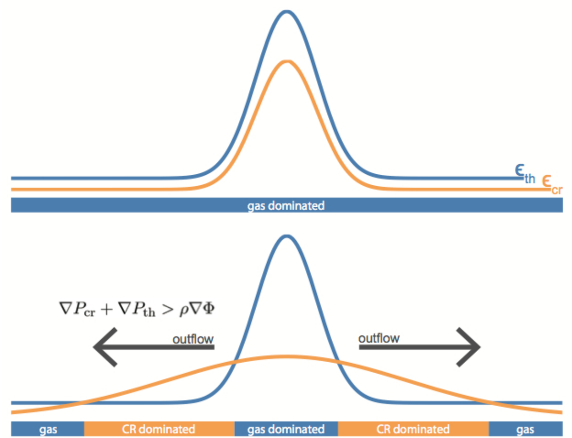
CP+ (2017b)

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



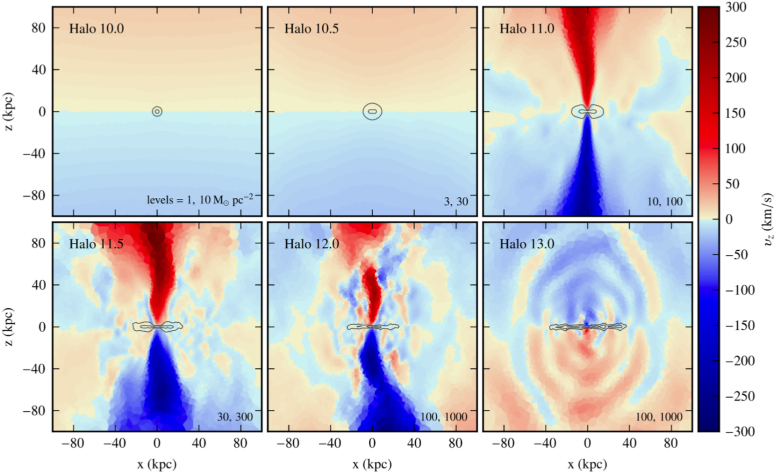
CP+ (2017b)

Cosmic ray driven wind: mechanism



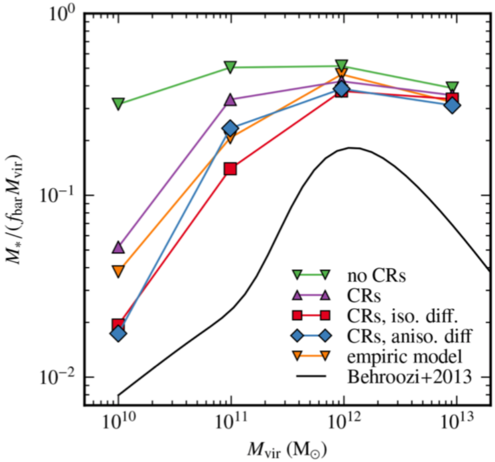
CR streaming in 3D simulations: Uhlig, CP+ (2012), Ruszkowski+ (2017)
CR diffusion in 3D simulations: Jubelgas+ (2008), Booth+ (2013), Hanasz+ (2013), Salem & Bryan (2014), Pakmor, CP+ (2016), Simpson+ (2016), Girichidis+ (2016), Dubois+ (2016), CP+ (2017b), Jacob+ (2018), . . .

CR-driven winds: dependence on halo mass



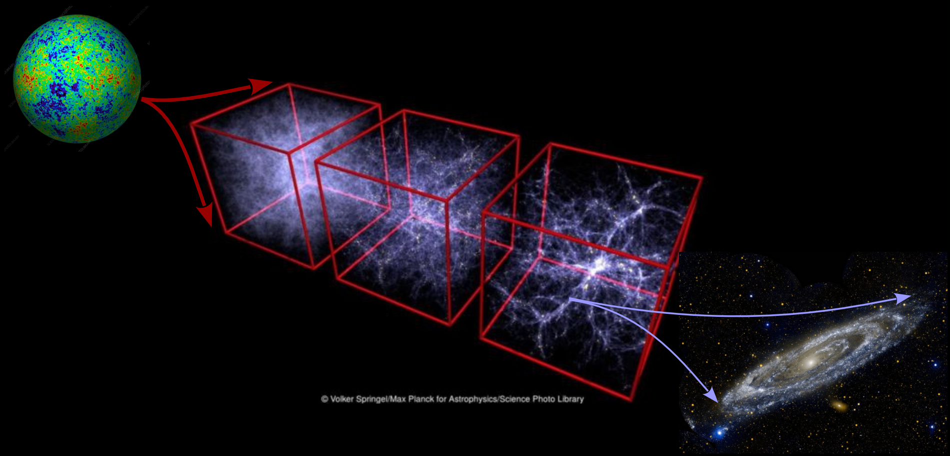
Jacob+ (2018)

CR-driven winds: suppression of star formation



Jacob+ (2018)

2. Cosmological galaxy formation



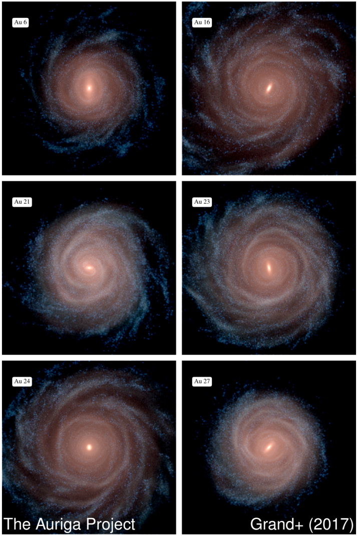
Cosmic rays in cosmological galaxy simulations

The galaxy formation model

- primordial and metal line cooling
- sub-resolution model for star formation (Springel+ 03)
- mass and metal return from stars to ISM
- cold dense gas stabilised by pressurised ISM
- thermal and kinetic energy from supernovae modelled by isotropic wind – launched outside of SF region
- black hole seeding and accretion model (Springel+ 05)
- thermal feedback from AGN in radio and quasar mode
- uniform magnetic field of 10^{-10} G seeded at $z = 128$

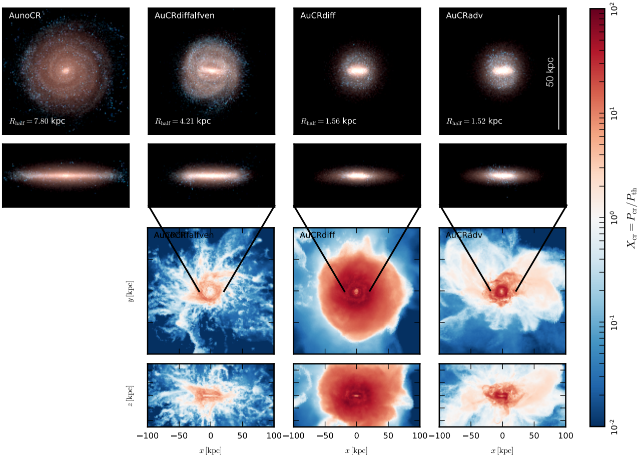
Simulation suite (Buck+ 2019)

- 2 galaxies, baryons with $5 \times 10^4\,M_\odot \sim 5 \times 10^6$ resolution elements in halo, 2×10^6 star particles
- 4 models with different CR physics for each galaxy:
  - no CRs
  - CR advection
  - + CR anisotropic diffusion
  - + CR Alfvén wave cooling



Cosmic rays in cosmological galaxy simulations

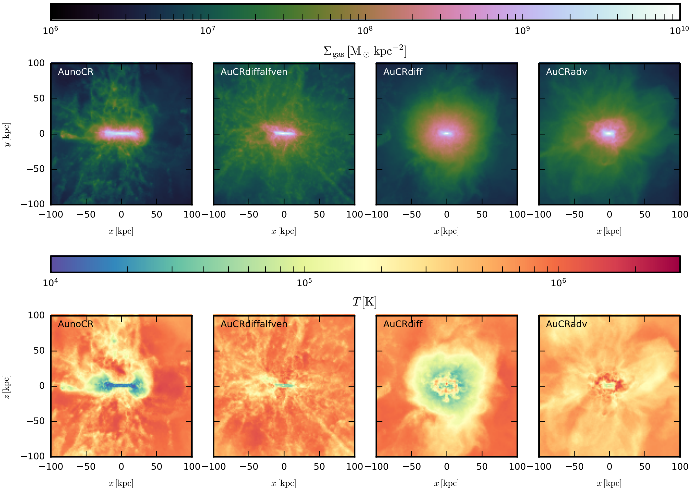
Auriga MHD models: CR transport changes disk sizes



Buck, CP, Pakmor, Grand, Springel (2019)

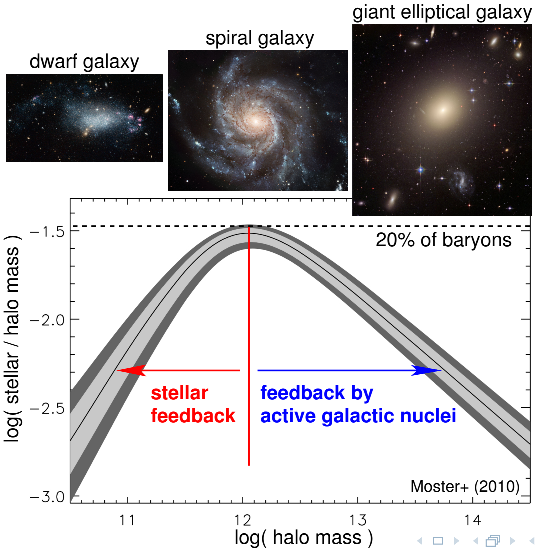
Cosmic rays in cosmological galaxy simulations

Auriga MHD models: CR transport modifies the circum-galactic medium

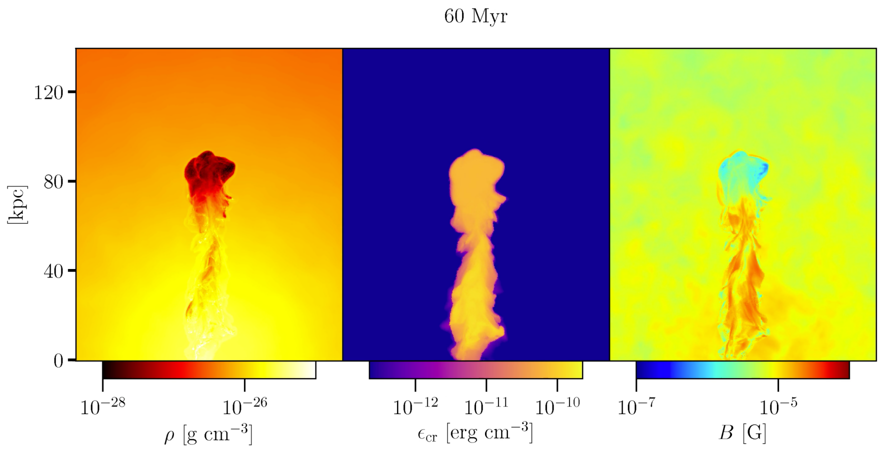


Buck, CP, Pakmor, Grand, Springel (2019)

Puzzles in galaxy formation: galaxy clusters

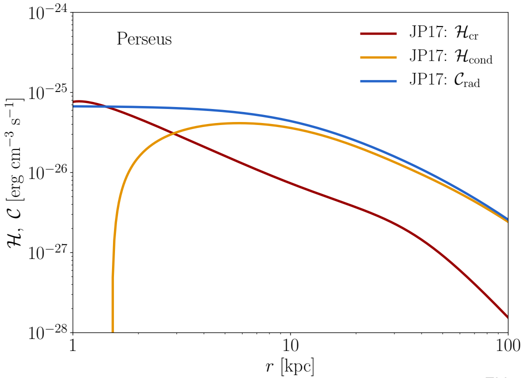


Jet simulation: gas density, CR energy density, *B* field



Ehlert, Weinberger, CP+ (2018)

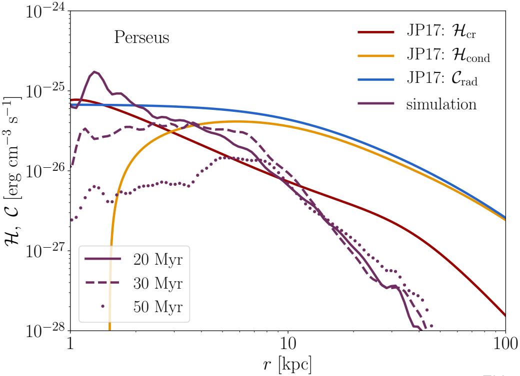
Perseus cluster – heating vs. cooling: theory



Ehlert, Weinberger, CP+ (2018)

- CR and conductive heating balance radiative cooling: $\mathcal{H}_{\rm cr} + \mathcal{H}_{\rm th} \approx \mathcal{C}_{\rm rad}$: modest mass deposition rate of 1 $M_\odot$ yr^{-1}

Perseus cluster – heating vs. cooling: simulations



Ehlert, Weinberger, CP+ (2018)

- CR and conductive heating balance radiative cooling: $\mathcal{H}_{\rm cr} + \mathcal{H}_{\rm th} \approx \mathcal{C}_{\rm rad}$: modest mass deposition rate of 1 $M_\odot$ yr^{-1}
- **simulated CR heating rate matches 1D steady state model**

AIP

Conclusions for cosmic ray physics in galaxies

CR hydrodynamics:

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

AIP

Conclusions for cosmic ray physics in galaxies

CR hydrodynamics:

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

CR feedback in galaxy formation:

- CR feedback drives galactic winds & slows down star formation
- CRs modify disk sizes and the circumgalactic medium
- CR heating may balance radiative cooling in cluster cooling flows

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 transport:

- 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, submitted.

Cosmic ray feedback in galaxy clusters:

- Jacob & Pfrommer, *Cosmic ray heating in cool core clusters I: diversity of steady state solutions*, 2017a, MNRAS.
- Jacob & Pfrommer, *Cosmic ray heating in cool core clusters II: self-regulation cycle and non-thermal emission*, 2017b, MNRAS.
- Ehlert, Weinberger, Pfrommer, Pakmor, Springel, *Simulations of the dynamics of magnetised jets and cosmic rays in galaxy clusters,* 2018, MNRAS.

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.
- Pfrommer, Pakmor, Schaal, Simpson, Springel, *Simulating cosmic ray physics on a moving mesh,* 2017a, MNRAS.
- Pfrommer, Pakmor, Simpson, Springel, *Simulating gamma-ray emission in star-forming galaxies,* 2017b, ApJL.
- Jacob, Pakmor, Simpson, Springel, Pfrommer, *The dependence of cosmic ray driven galactic winds on halo mass,* 2018, MNRAS.
- Buck, Pfrommer, Pakmor, Grand, Springel, *The effects of cosmic rays on the formation of Milky Way-like galaxies in a cosmological context,* 2019, subm.