# *The role of cosmic-rays and magnetic fields in galaxy formation*

Christoph Pfrommer[1]

in collaboration with

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Postdocs: T. Berlok[1], T. Buck[1], P. Girichidis[1], M. Shalaby[1], M. Sparre[2,1],
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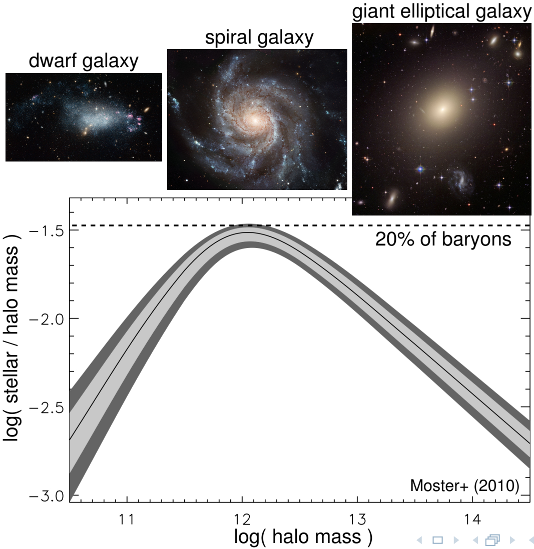
*Max Planck Princeton Center – Workshop,* Göttingen, Jan 2020

# Do cosmic rays matter in galaxy formation?

# Puzzles in galaxy formation



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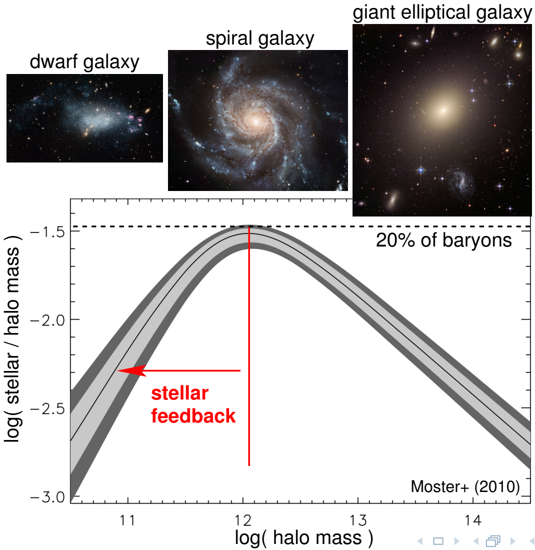

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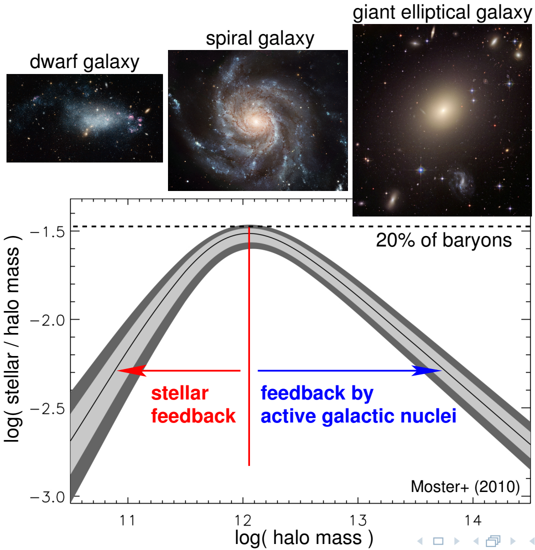
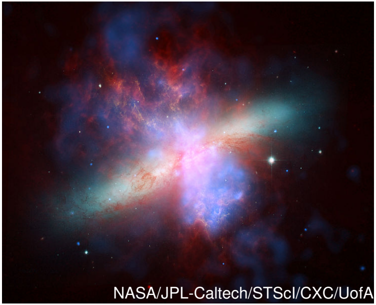


# How are galactic winds driven?




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?

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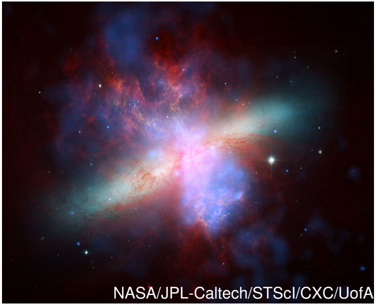


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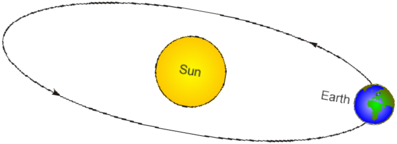
observed energy equipartition between cosmic rays, thermal gas and magnetic fields not a coincidence
$\rightarrow$ suggests self-regulated feedback loop with CR driven winds

AIP

# Outline

# Cosmic ray transport: an extreme multi-scale problem




Milky Way-like galaxy:

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

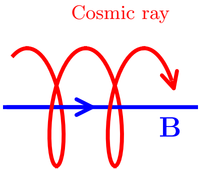
gyro-orbit of GeV cosmic ray:

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

$\Rightarrow$ 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

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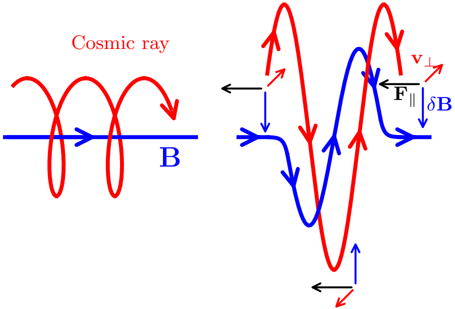


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- **gyro resonance:** $\omega - k_\parallel v_\parallel = n\Omega$

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

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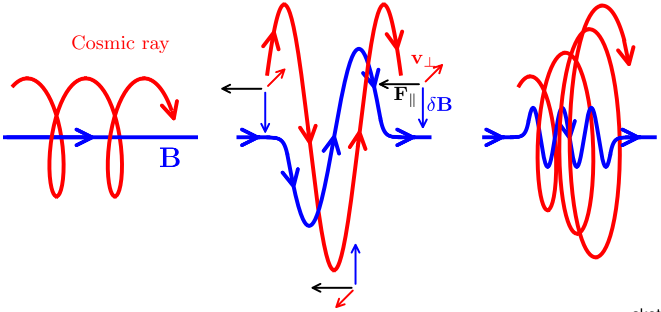
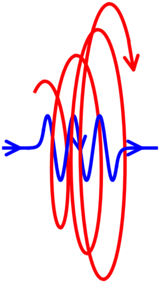



sketch: Jacob

- **gyro resonance:** $\omega - k_{\|} v_{\|} = n\Omega$
  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 $v_{\rm cr} > v_{\rm a}$, 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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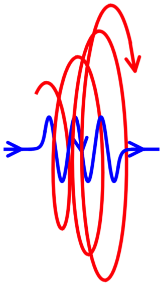

→ *CRs exert pressure on thermal gas via scattering on Alfvén waves*

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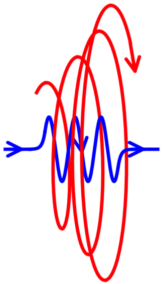
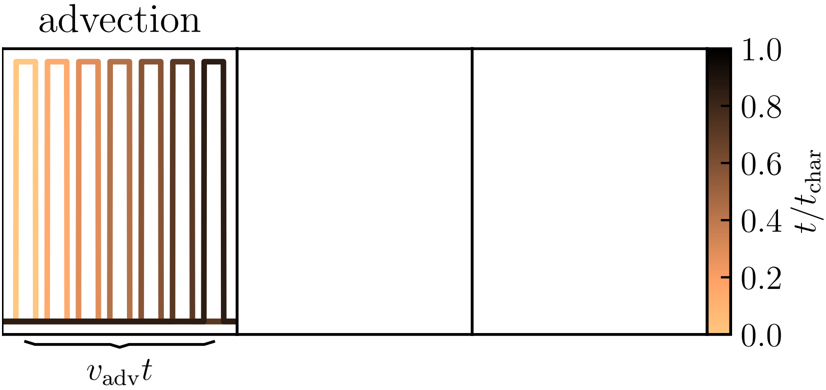


$\rightarrow$ *CRs exert pressure on thermal gas via scattering on Alfvén waves*

**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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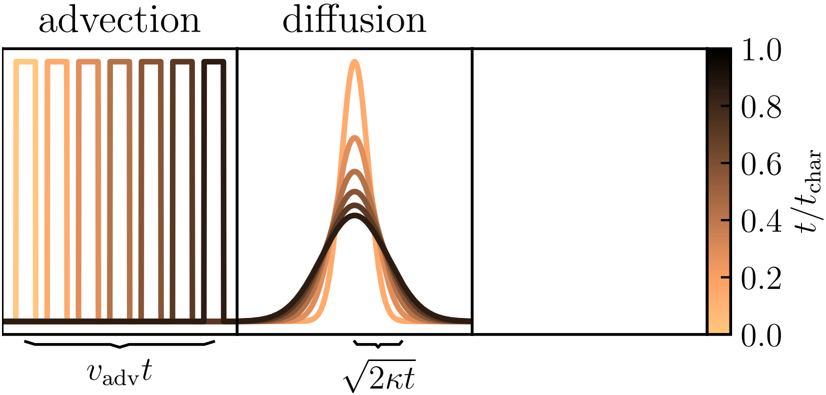


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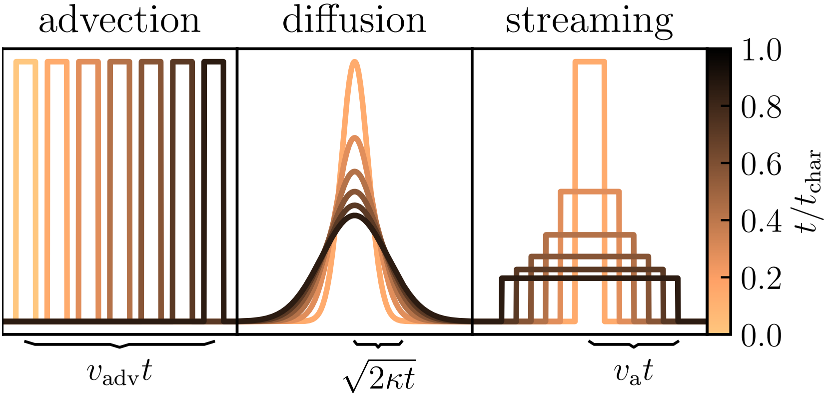


Thomas, CP, Enßlin (2020)

# CR vs. radiation hydrodynamics

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  derive two-moment equations from CR Vlasov equation (Thomas & CP 2019)

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

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Alfvén wave velocity in lab frame: $\boldsymbol{w}_\pm = \boldsymbol{v} \pm \boldsymbol{v}_{\rm a}$,
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  (Mihalas & Mihalas, 1984, Lowrie+ 1999):

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

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

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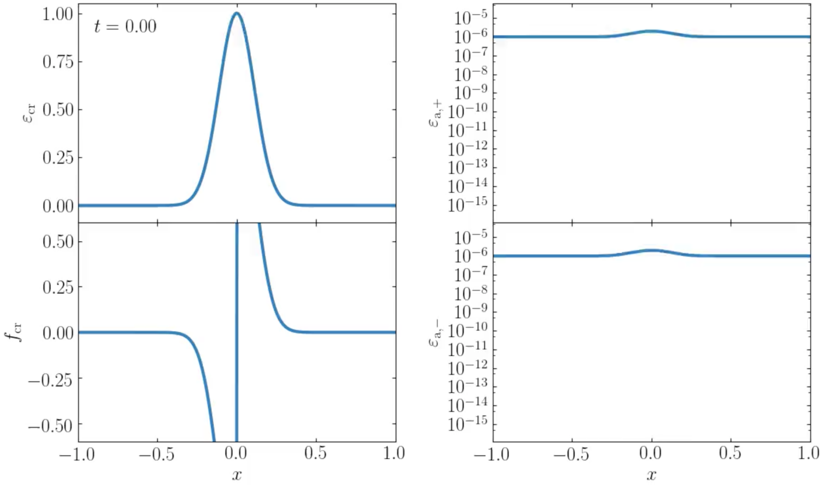
- ***solution:*** *transform in comoving frame and project out gyrokinetics!*

AIP

# Non-equilibrium CR streaming and diffusion

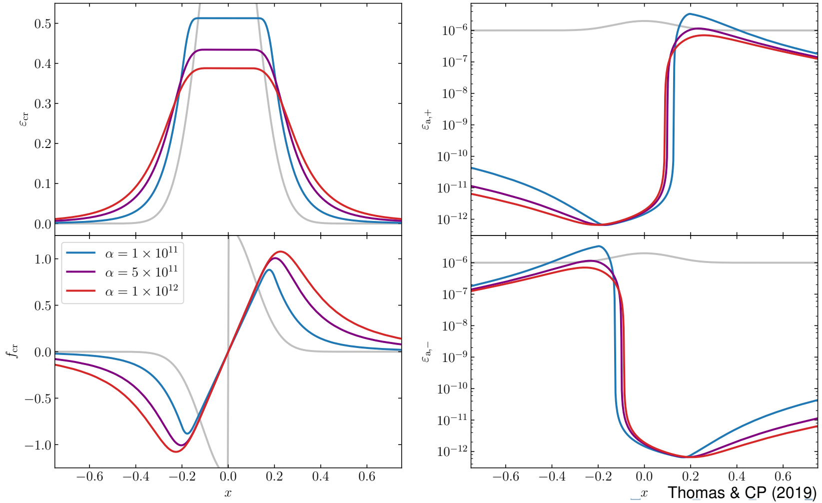
## Coupling the evolution of CR and Alfvén wave energy densities




Thomas & CP (2019)

# Non-equilibrium CR streaming and diffusion

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

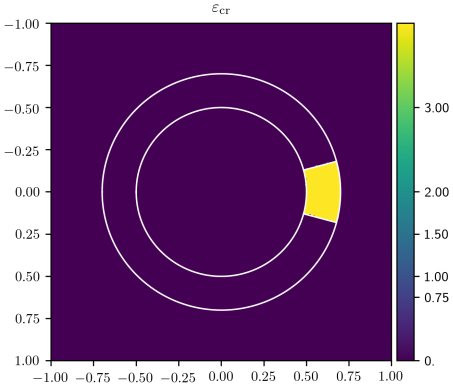



Thomas & CP (2019)

# Anisotropic CR streaming and diffusion – AREPO

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

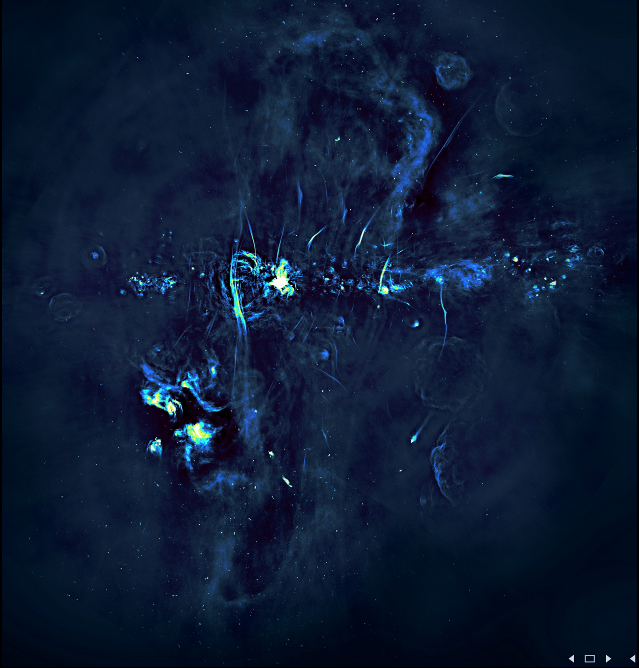
- CR streaming and diffusion along magnetic field lines in the self-confinement picture
- moment expansion similar to radiation hydrodynamics
- accounts for kinetic physics: non-linear Landau damping, gyro-resonant instability, . . .
- Galilean invariant and causal transport
- energy and momentum conserving




Thomas, Pakmor, CP (in prep.)

# MeerKAT image of the Galactic Center

Haywood+ (Nature, 2019)



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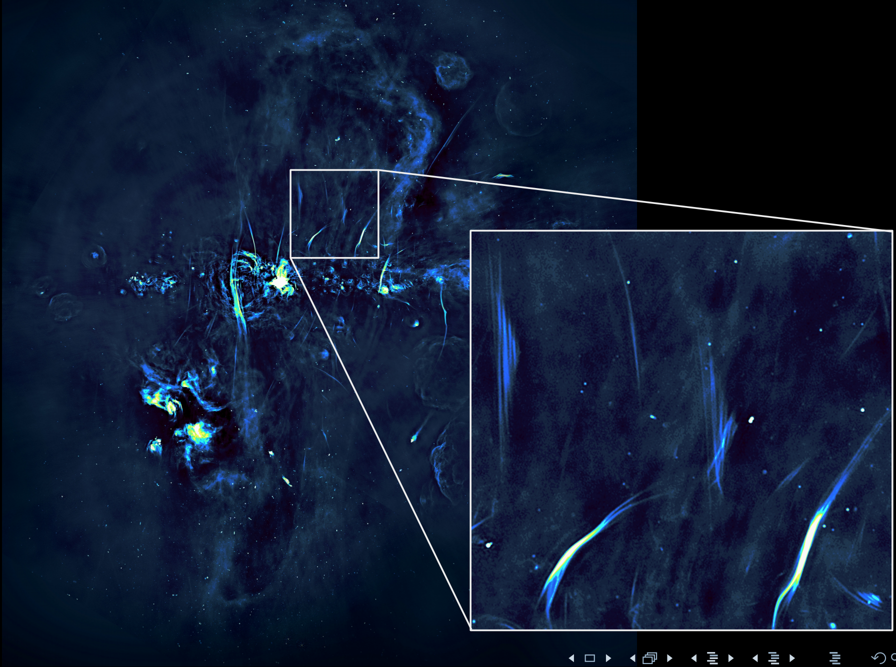
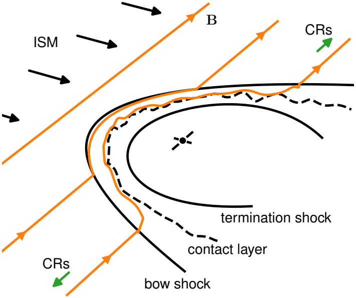


# Radio synchrotron harps: the model

shock acceleration scenario




Thomas, CP, Enßlin (2020)

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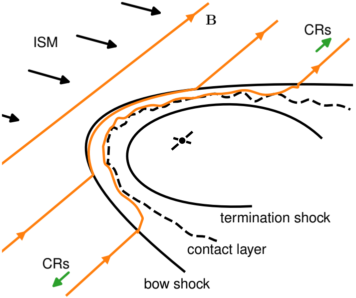
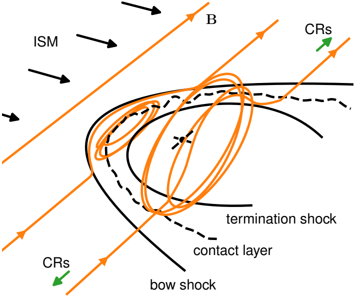
magnetic reconnection at pulsar wind

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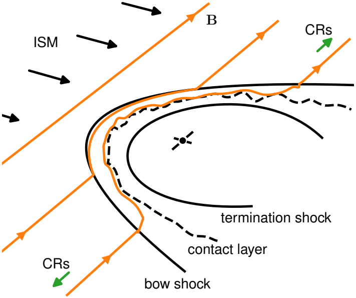
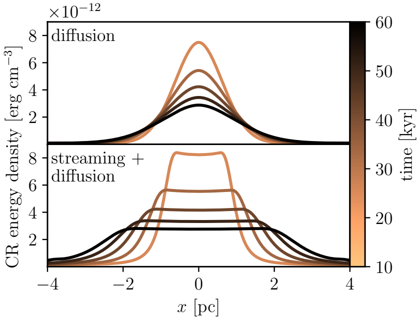
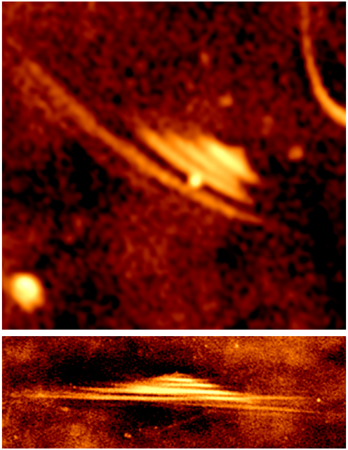



Thomas, CP, Enßlin (2020)

CR diffusion vs. streamig + diffusion



# Radio synchrotron harps: testing CR propagation



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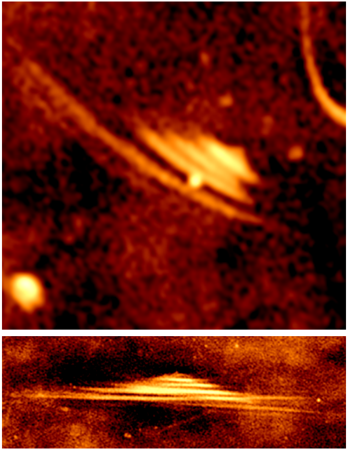
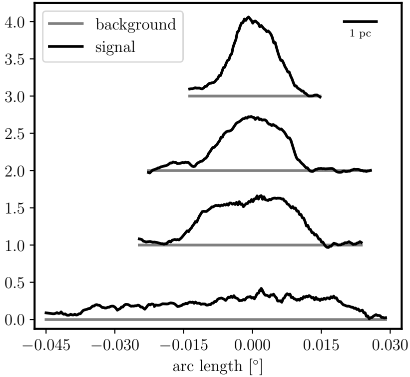


Haywood+ (Nature, 2019)

lateral radio profiles

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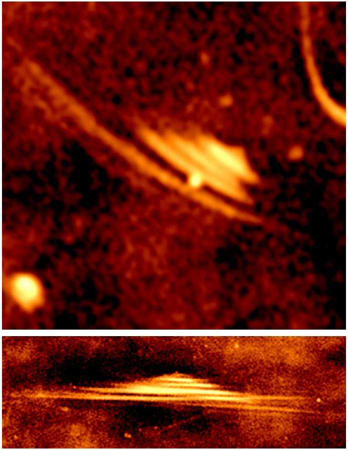

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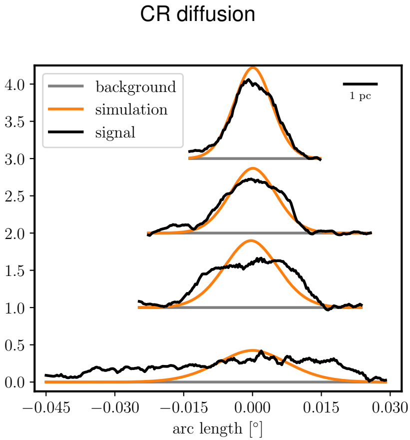


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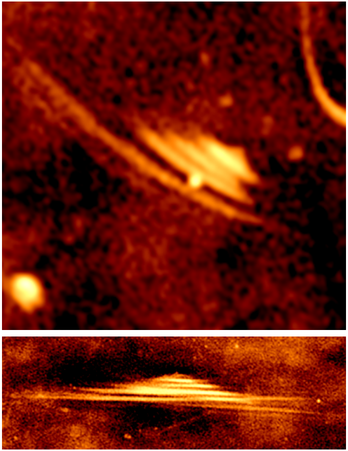

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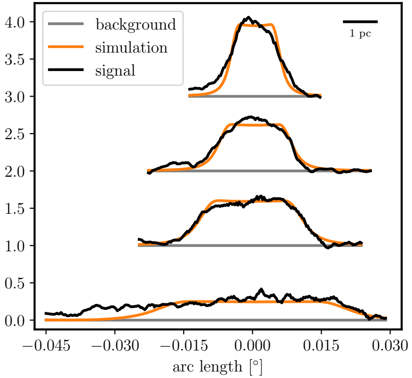
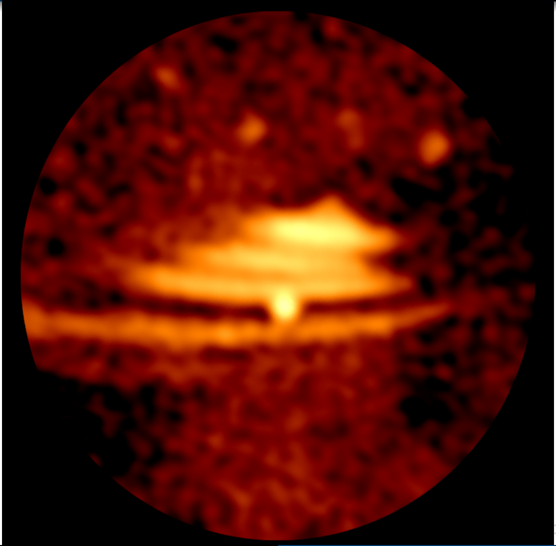
CR streaming and diffusion



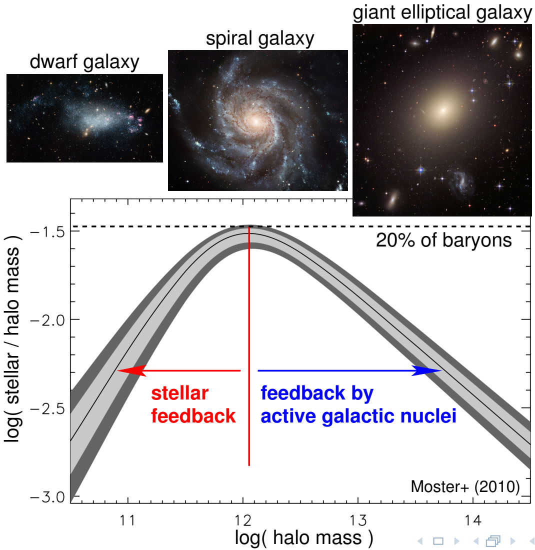

Thomas, CP, Enßlin (2020)

# “Fir tree in space” Süddeutsche Zeitung, 24. 12. 2019

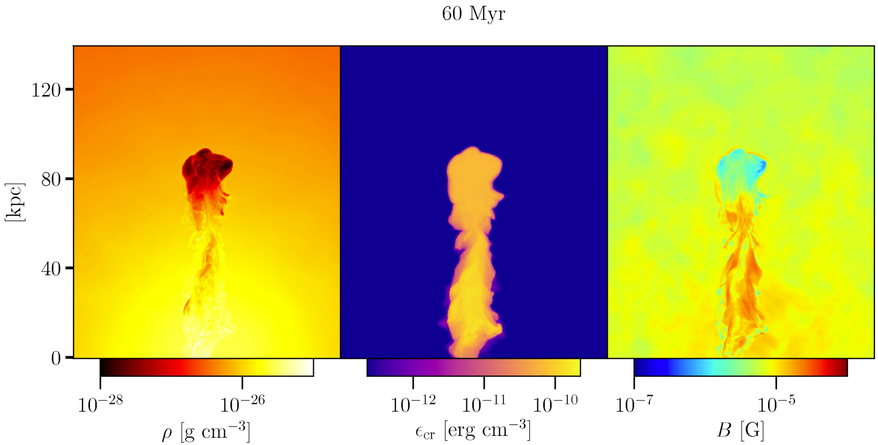
## Of harps, Christmas trees, a wandering star and the mysterious streams of cosmic rays



# Puzzles in galaxy formation: galaxy clusters

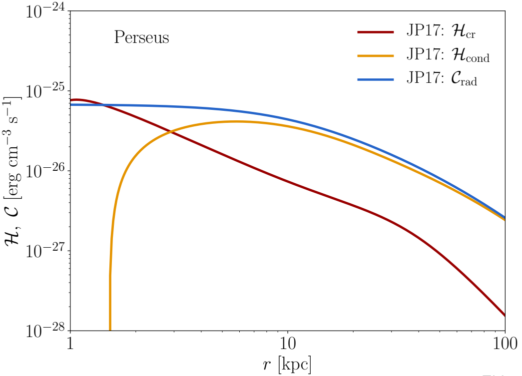


# Jet simulation: gas density, CR energy density, *B* field




Ehlert, Weinberger, CP+ (2018)

# Perseus cluster – heating vs. cooling: theory




Ehlert, Weinberger, CP+ (2018)

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

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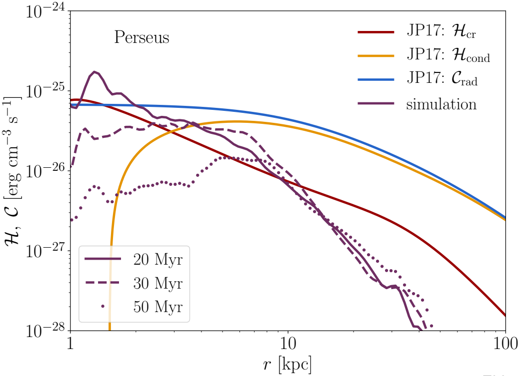


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- CR and conductive heating balance radiative cooling: $\mathcal{H}_{\rm cr} + \mathcal{H}_{\rm cond} \approx \mathcal{C}_{\rm rad}$: modest mass deposition rate of 1 $M_\odot$ yr$^{-1}$
- **simulated CR heating rate matches 1D steady state model**

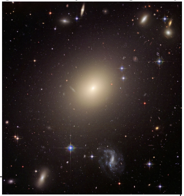
AIP

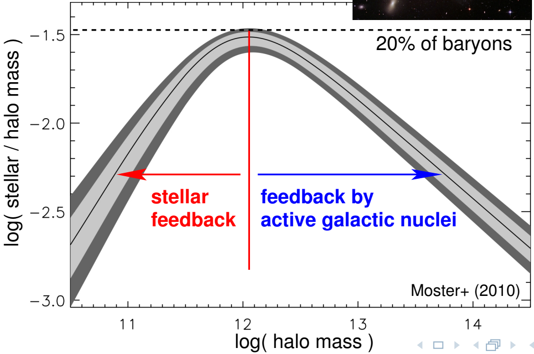
# Puzzles in galaxy formation

dwarf galaxy

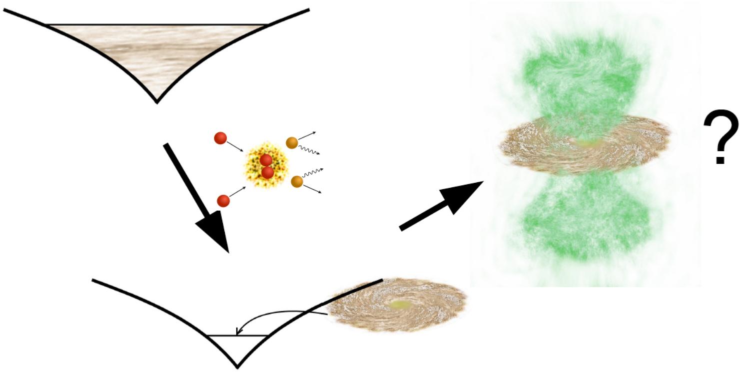
spiral galaxy

giant elliptical galaxy



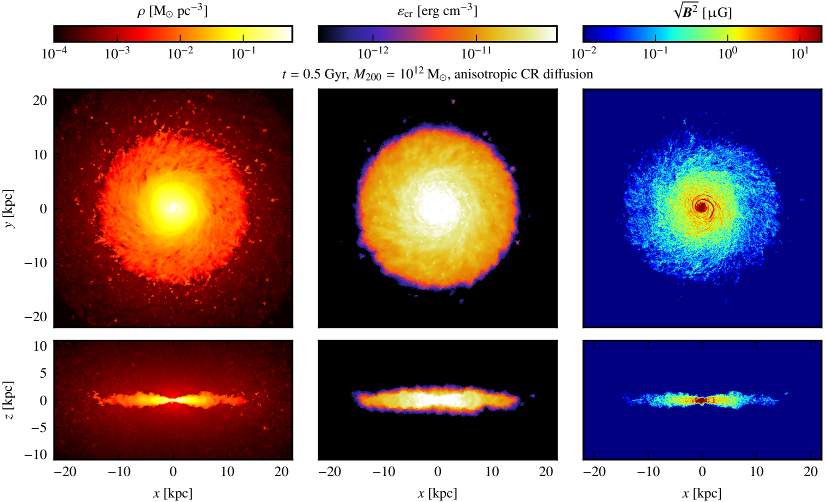


# 1. Galaxy formation in idealized halos



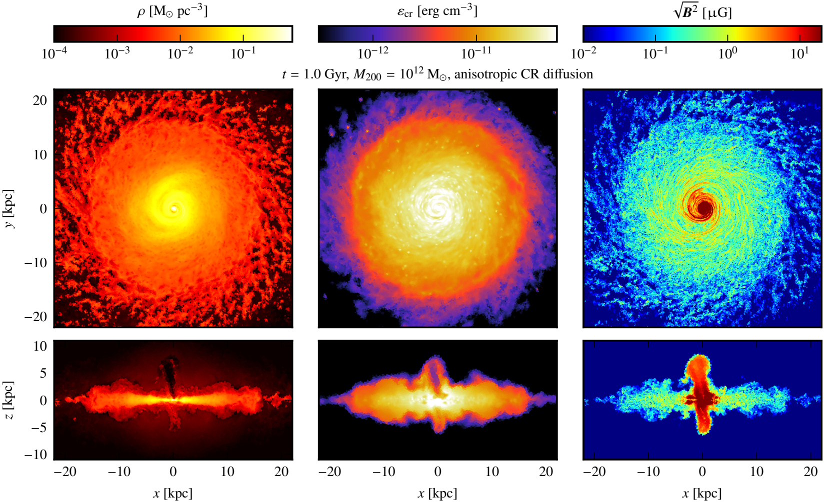

CP, Pakmor, Simpson, Springel (2017b)
*Simulating gamma-ray emission in star-forming galaxies*
MHD + CR advection + anisotropic diffusion, $\{10^{10}, 10^{11}, 10^{12}\}\ M_\odot$

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



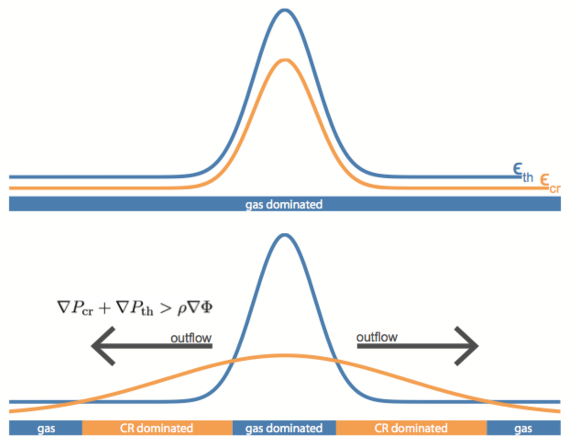

CP+ (2017b)

# 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), . . .

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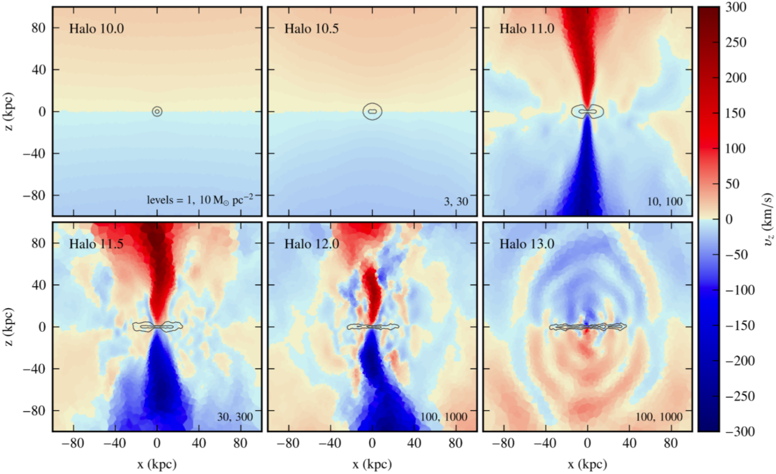
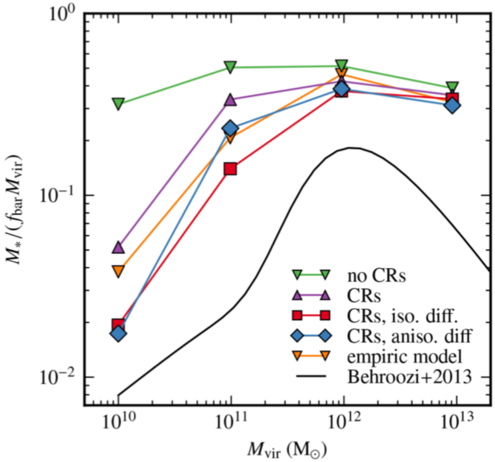
# CR-driven winds: dependence on halo mass



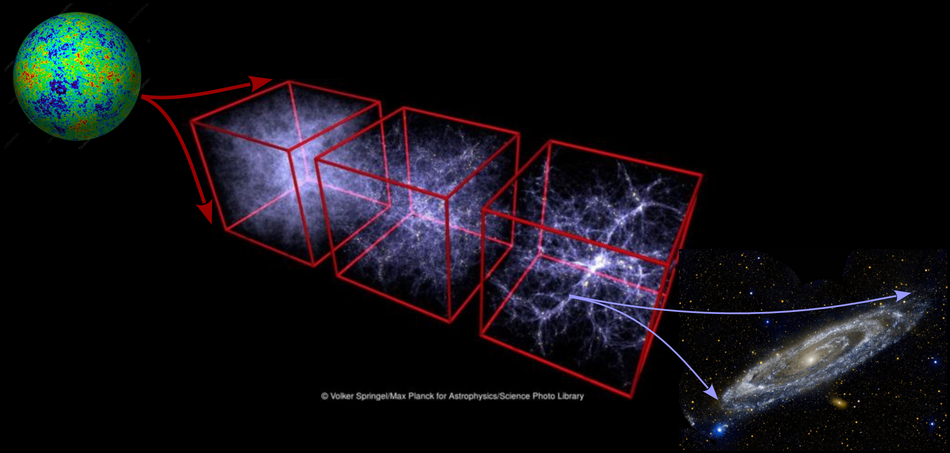

Jacob+ (2018)

# CR-driven winds: suppression of star formation




Jacob+ (2018)

# 2. Cosmological galaxy formation



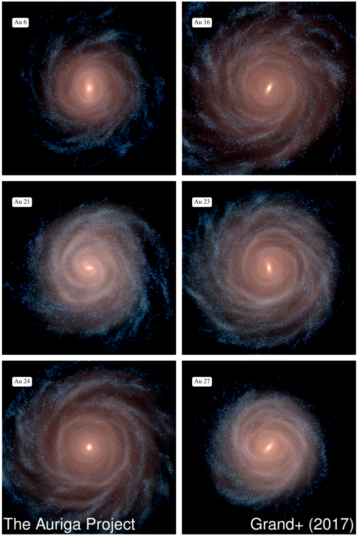
# Cosmic rays in cosmological galaxy simulations

## 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 $z = 128$

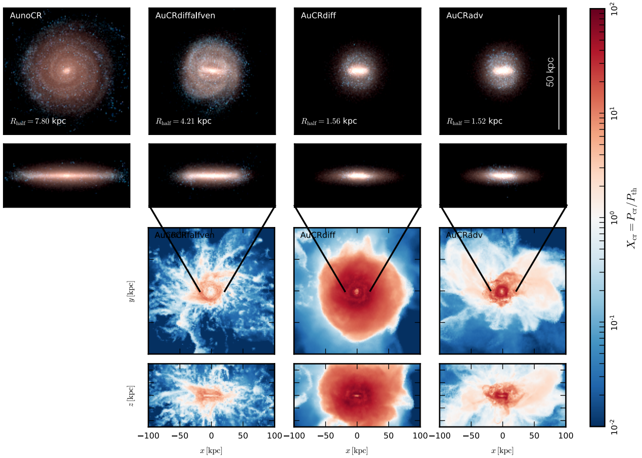
## Simulation suite (Buck+ 2019)

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



# Cosmic rays in cosmological galaxy simulations

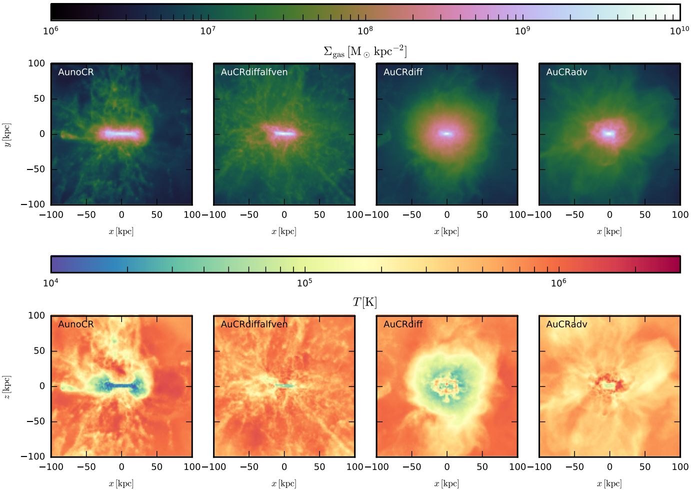
## Auriga MHD models: CR transport changes disk sizes




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)

# Conclusions for cosmic ray physics in galaxies

**CR hydrodynamics:**

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

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**CR hydrodynamics:**

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**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).

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# 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, ApJL.

## 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.

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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.
- 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.