Cosmic rays in galaxy formation: acceleration, transport, feedback

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in collaboration with

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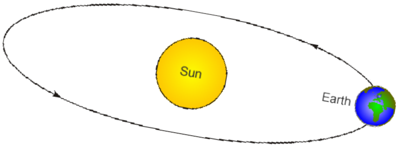
Outline

1. Cosmic rays in galaxies
   - Cosmic ray transport
   - Global galaxy models
2. AGN feedback
   - Cosmic ray heating
   - Cosmic rays in jets

Cosmic ray feedback: an extreme multi-scale problem



Milky Way-like galaxy:

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

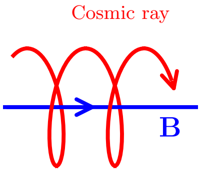
gyro-orbit of GeV cosmic ray:

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

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

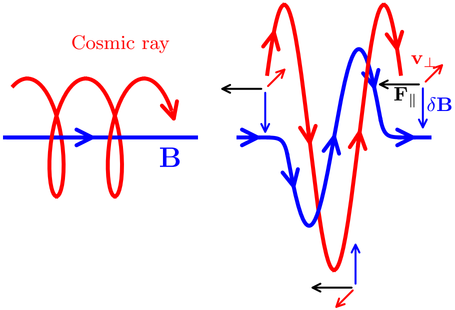
Zweibel (2017), Jiang & Oh (2018), Thomas & CP (2018)

Interactions of CRs and magnetic fields



sketch: Jacob

Interactions of CRs and magnetic fields

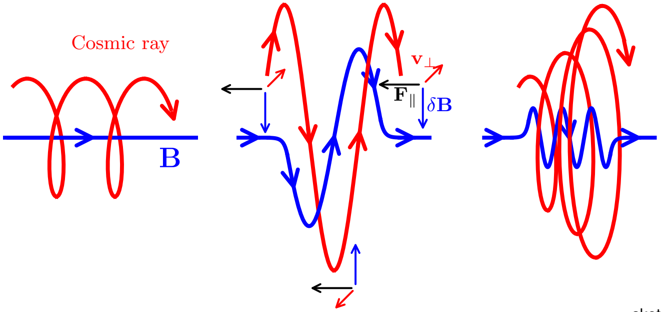


sketch: Jacob

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

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

Interactions of CRs and magnetic fields

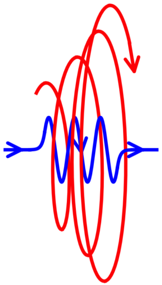


sketch: Jacob

- **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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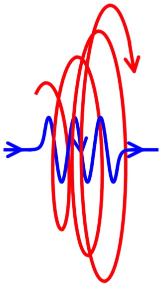

$\rightarrow$ *CRs exert pressure on thermal gas via scattering on Alfvén waves*

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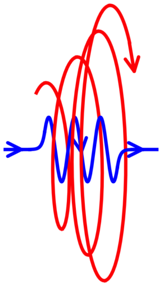
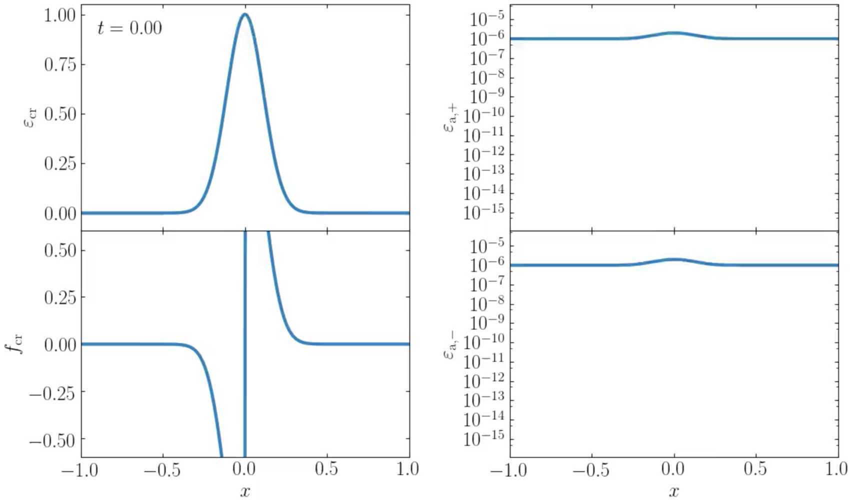


$\rightarrow$ *CRs exert pressure on thermal gas via scattering on Alfvén waves*

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

Non-equilibrium CR streaming and diffusion

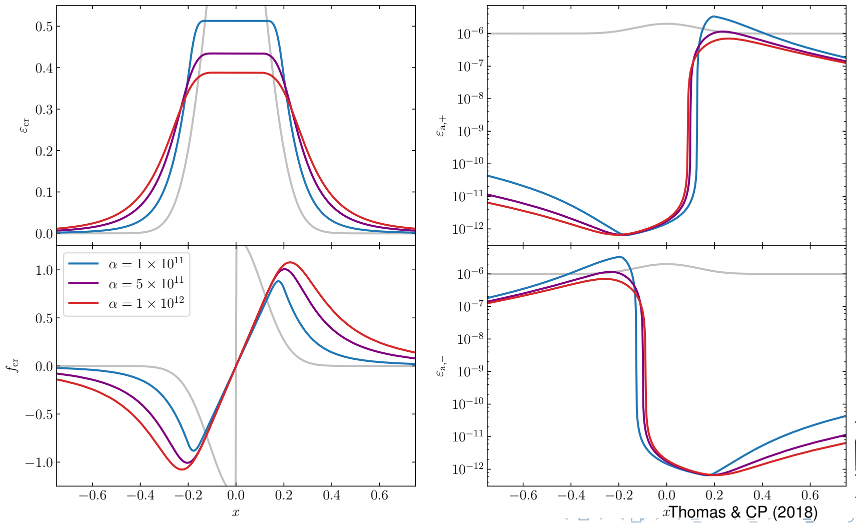
Coupling the evolution of CR and Alfvén wave energy densities



Thomas & CP (2018)

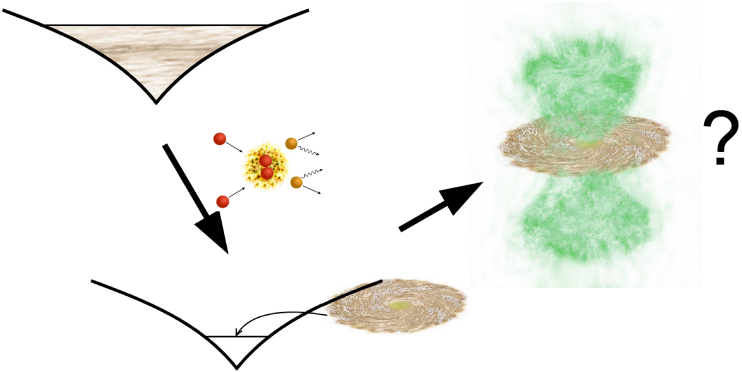
Non-equilibrium CR streaming and diffusion

Varying damping rate of Alfvén waves modulates the diffusivity of solution



Thomas & CP (2018)

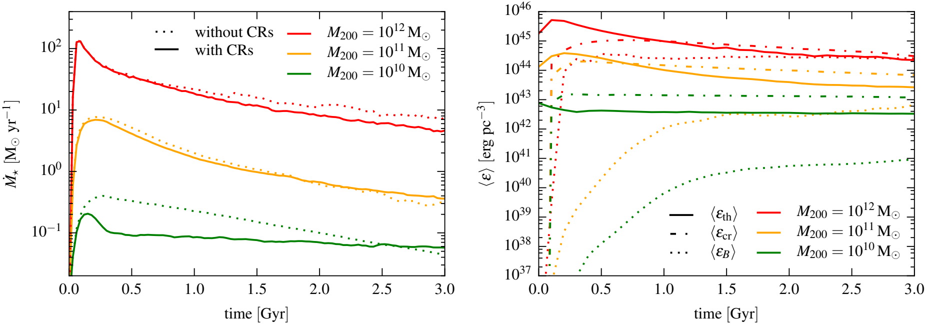
Galaxy simulation setup: 1. cosmic ray advection



CP, Pakmor, Schaal, Simpson, Springel (2017)
Simulating cosmic ray physics on a moving mesh

MHD + cosmic ray advection: $\{10^{10}, 10^{11}, 10^{12}\}\ M_\odot$

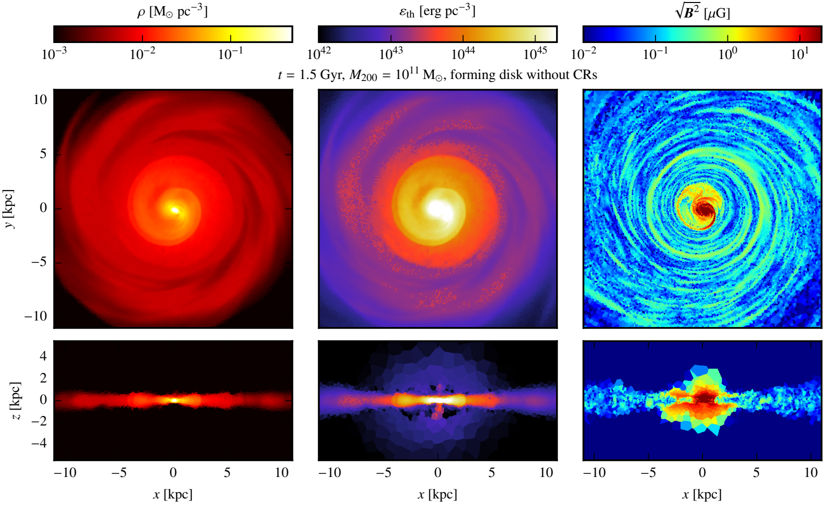
Time evolution of SFR and energy densities



CP, Pakmor, Schaal, Simpson, Springel (2017)

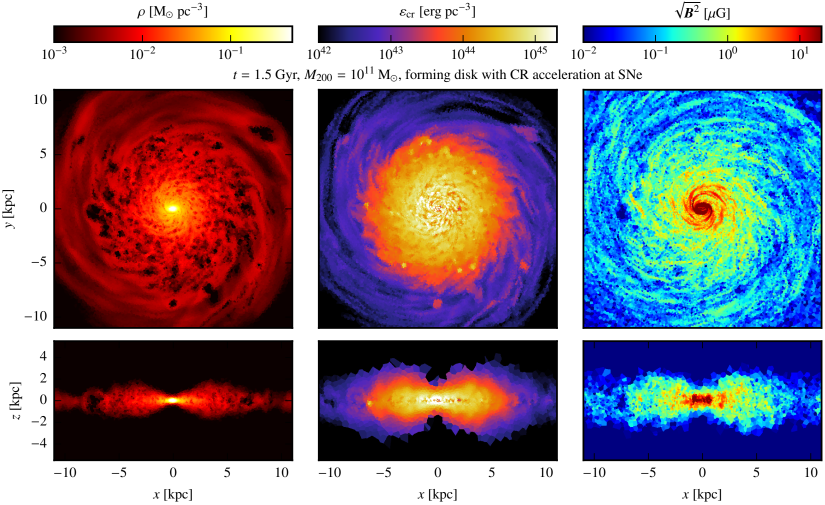
- CR pressure feedback suppresses SFR more in smaller galaxies
- energy budget in disks is dominated by CR pressure
- magnetic dynamo faster in Milky Way galaxies than in dwarfs

MHD galaxy simulation without CRs



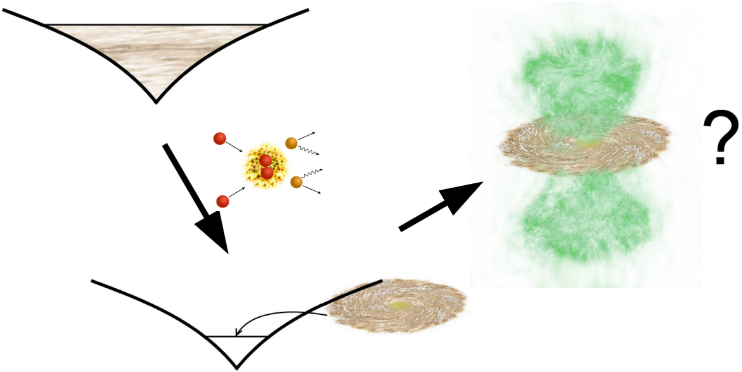
CP, Pakmor, Schaal, Simpson, Springel (2017)

MHD galaxy simulation with CRs



CP, Pakmor, Schaal, Simpson, Springel (2017)

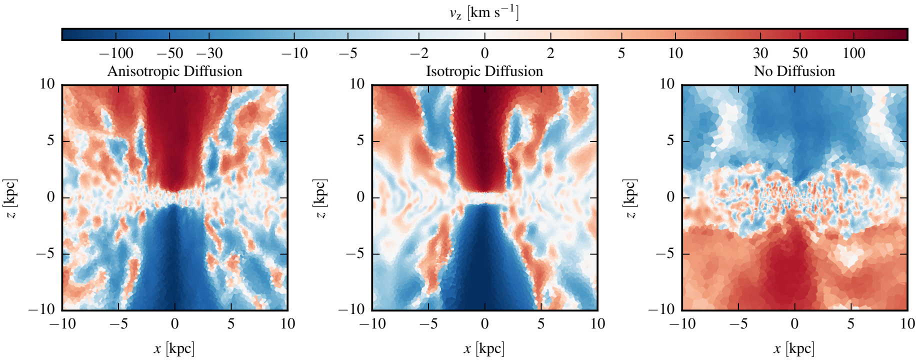
Galaxy simulation setup: 2. cosmic ray diffusion



Pakmor, CP, Simpson, Springel (2016)
Galactic winds driven by isotropic and anisotropic cosmic ray diffusion in isolated disk galaxies

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

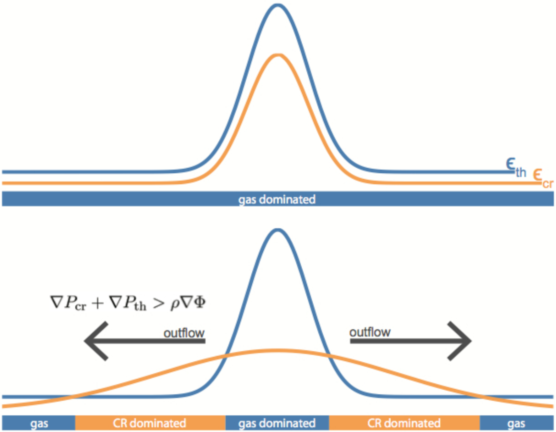
MHD galaxy simulation with CR diffusion



Pakmor, CP, Simpson, Springel (2016)

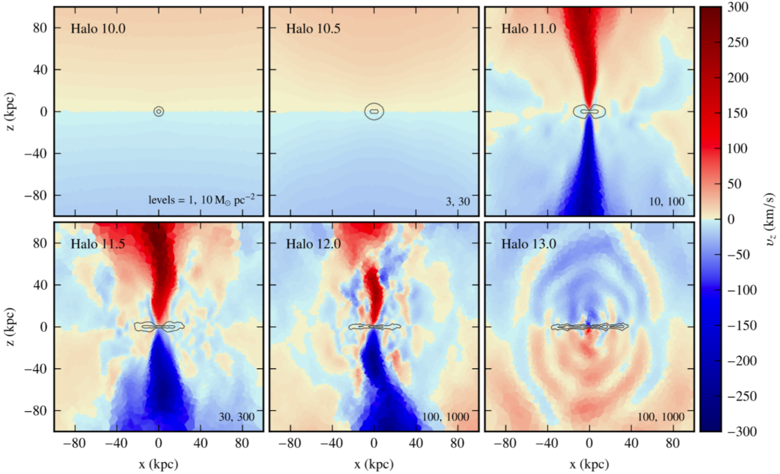
- CR diffusion launches powerful winds
- simulation without CR diffusion exhibits only weak fountain flows

Cosmic ray driven wind: mechanism



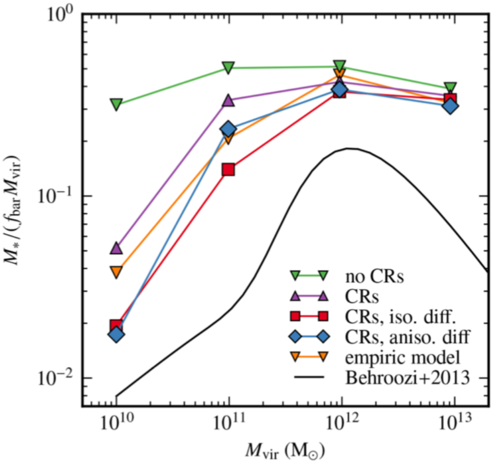
CR streaming in 3D simulations: Uhlig, CP+ (2012), Ruszkowski+ (2017)
CR diffusion in 3D simulations: Jubelgas+ (2008), Booth+ (2013), Hanasz+ (2013), Salem & Bryan (2014), Pakmor, CP+ (2016), Simpson+ (2016), Girichidis+ (2016), Dubois+ (2016), CP+ (2017), Jacob+ (2018)

CR-driven winds: dependence on halo mass



Jacob+ (2018)

CR-driven winds: suppression of star formation

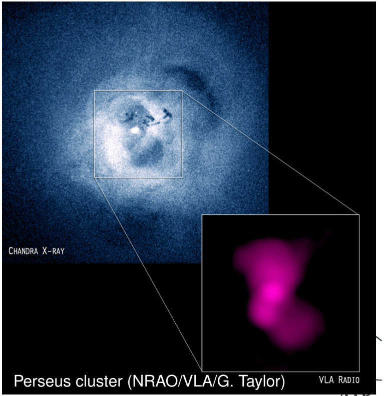


Jacob+ (2018)

Feedback by active galactic nuclei

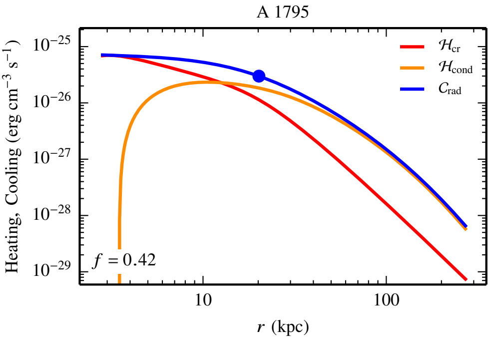
Paradigm: accreting super-massive black holes at galaxy cluster centers launch relativistic jets, which provide energetic feedback to balance cooling $\Rightarrow$ **but how?**

- Jacob & CP (2017a,b): study large sample of 40 cool core clusters
- spherically symmetric steady-state solutions where cosmic ray heating balances radiative cooling



Perseus cluster (NRAO/VLA/G. Taylor)

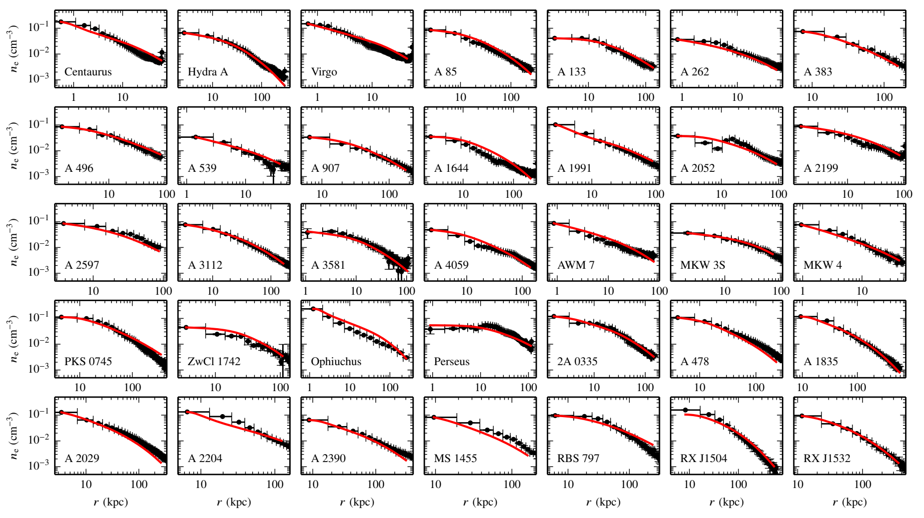
Case study A1795: heating and cooling



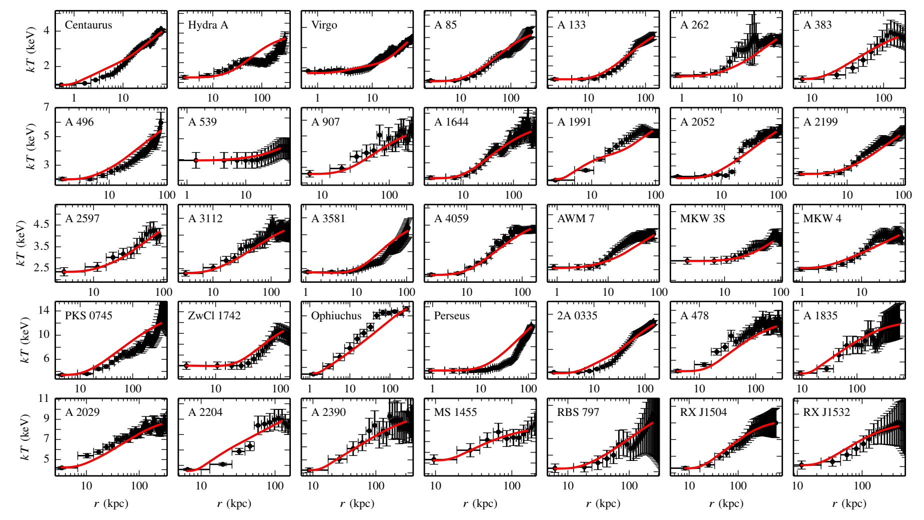
Jacob & CP (2016a)

- CR heating dominates in the center
- conductive heating takes over at larger radii, $\kappa = 0.42\kappa_{\rm Sp}$
- $\mathcal{H}_{\rm cr} + \mathcal{H}_{\rm cond} \approx \mathcal{C}_{\rm rad}$: modest mass deposition rate of 1 $M_\odot$ yr^{-1}

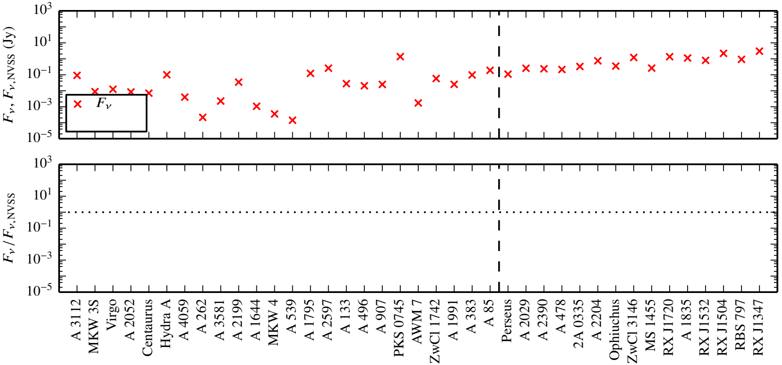
Gallery of solutions: density profiles



Gallery of solutions: temperature profiles

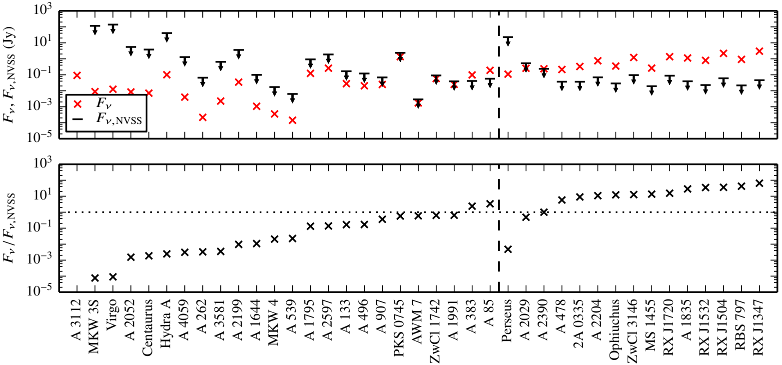


Hadronically induced radio emission



Jacob & CP (2017b)

Hadronically induced radio emission: NVSS limits



Jacob & CP (2017b)

- continuous sequence in $F_{\nu,\mathrm{pred}}/F_{\nu,\mathrm{NVSS}}$
- CR heating viable solution for non-RMH clusters
- CR heating solution ruled out in radio mini halos (RMHs)

How can we explain these results?

- self-regulated feedback cycle driven by CRs

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CRs stream outwards and become too dilute to heat the cluster

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CRs stream outwards and become too dilute to heat the cluster

↘

radio mini halo

How can we explain these results?

- self-regulated feedback cycle driven by CRs

AGN injects CRs → CR heating balances cooling

↓

cluster cools and triggers AGN activity ← CRs stream outwards and become too dilute to heat the cluster

↘

radio mini halo

How can we explain these results?

- self-regulated feedback cycle driven by CRs

AGN injects CRs → CR heating balances cooling

↓

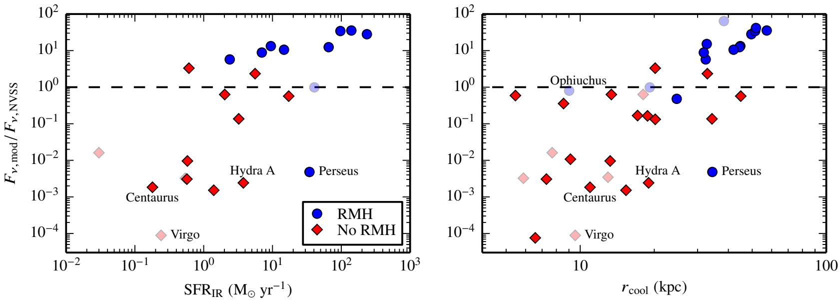
CRs stream outwards and become too dilute to heat the cluster

← cluster cools and triggers AGN activity

↑ (back to AGN injects CRs)

CRs stream outwards … ↘ radio mini halo

Self-regulated heating/cooling cycle in cool cores

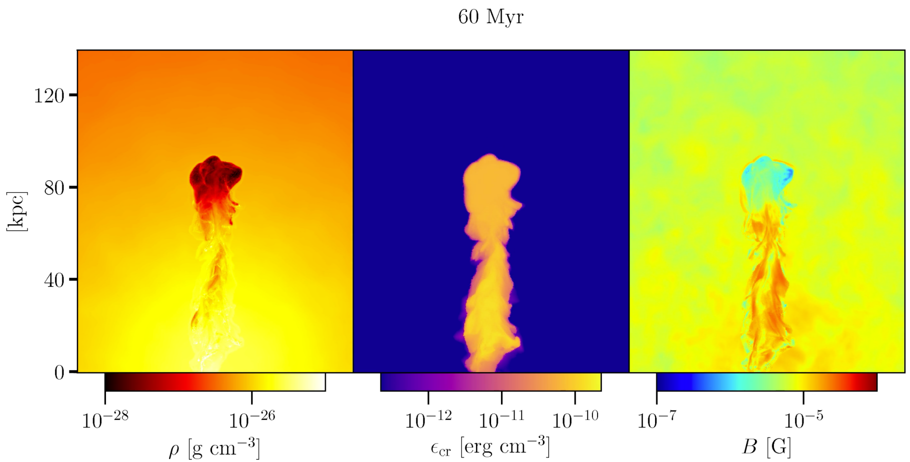


Jacob & CP (2017b)

possibly CR-heated cool cores vs. radio mini halo clusters:

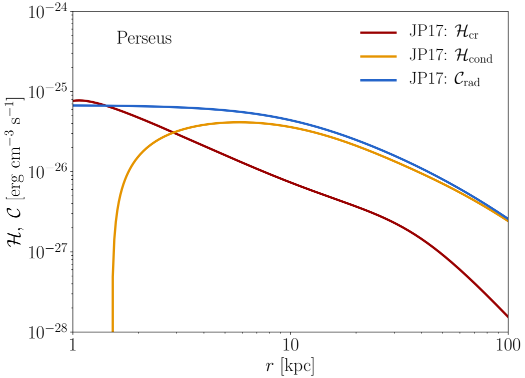
- simmering SF: CR heating is effectively balancing cooling
- abundant SF: heating/cooling out of balance

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



Ehlert, Weinberger, CP+ (2018)

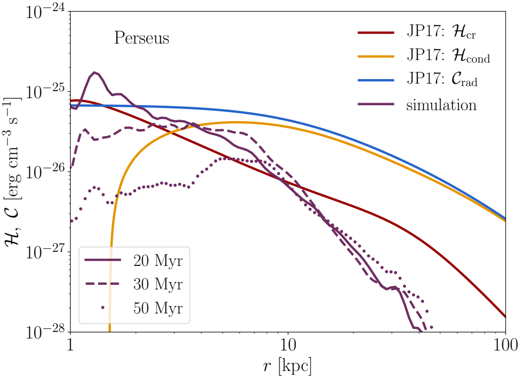
Perseus cluster – heating vs. cooling: theory



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**

Conclusions on CR feedback in galaxies and clusters

- CR pressure feedback slows down star formation
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AIP

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outlook: improved modeling of plasma physics, follow CR spectra, cosmological settings

need: comparison to resolved radio/γ-ray observations $\rightarrow$ **SKA/CTA**

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).

AIP

Literature for the talk

Cosmic ray transport:

- Thomas, Pfrommer, *Cosmic-ray hydrodynamics: Alfvén-wave regulated transport of cosmic rays,* 2018.

Cosmic ray feedback in galaxies:

- Pfrommer, Pakmor, Schaal, Simpson, Springel, *Simulating cosmic ray physics on a moving mesh,* 2017a, MNRAS.
- Pakmor, Pfrommer, Simpson, Springel, *Galactic winds driven by isotropic and anisotropic cosmic ray diffusion in isolated disk galaxies,* 2016, ApJL.
- Jacob, Pakmor, Simpson, Springel, Pfrommer, *The dependence of cosmic ray driven galactic winds on halo mass,* 2018, MNRAS.

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.