Cosmic rays in galaxy formation

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in collaboration with

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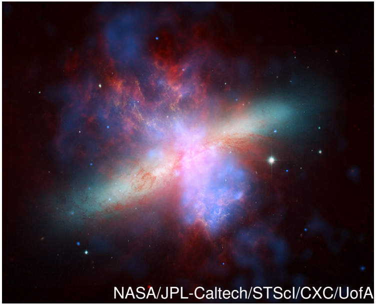
Computational Galaxy Formation, Ringberg – Mar 2018

Outline

1. Cosmic ray feedback
   - Cosmic ray transport
   - Galactic winds
   - Gamma-rays
2. AGN feedback
   - Introduction
   - Steady state solutions
   - Cosmic ray jet simulations

Outline

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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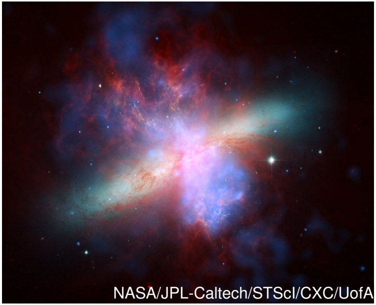

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- thermal pressure provided by supernovae or AGNs?
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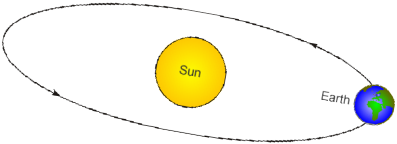
- cosmic-ray pressure and Alfvén wave heating of CRs accelerated at supernova shocks?

observed energy equipartition between cosmic rays, thermal gas and magnetic fields
→ suggests self-regulated feedback loop with CR driven winds

Cosmic ray feedback: an extreme multi-scale problem



Milky Way-like galaxy:

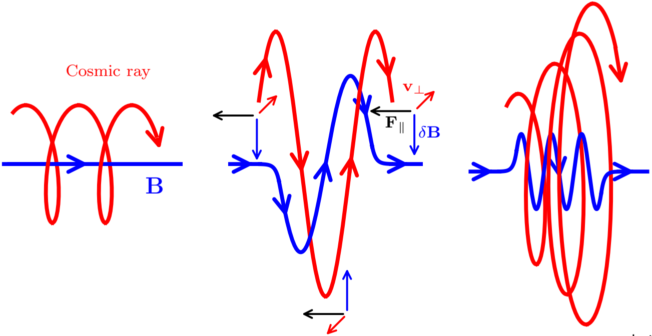
$$r_{\mathrm{gal}} \sim 10^4 \text{ pc}$$

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!**

Interactions of CRs and magnetic fields



sketch: Jacob

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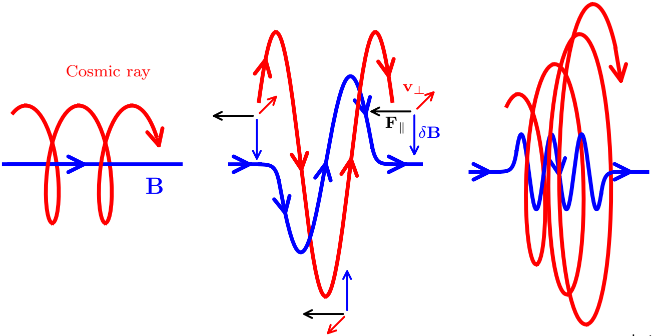

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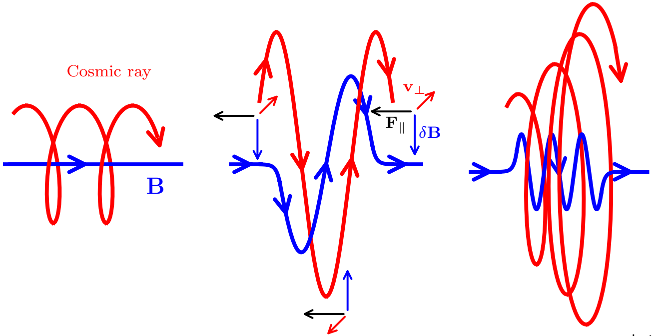
- **gyro resonance:** $\omega - k_\parallel v_\parallel = n\Omega$

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

Interactions of CRs and magnetic fields



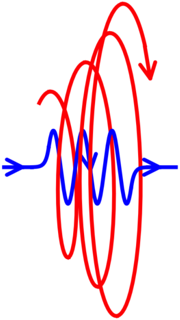
sketch: Jacob

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

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

CR streaming

- **CR streaming instability:** Kulsrud & Pearce 1969
  - if $v_{\mathrm{cr}} > v_{\mathrm{A}}$, CR current provides steady driving force, which 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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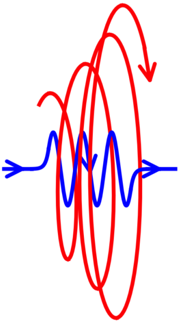

→ **CRs exert a pressure on the thermal gas by means of scattering off of Alfvén waves**

CR transport

- 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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$$\boldsymbol{v}_{\rm st} = -\boldsymbol{v}_{\rm A} \frac{\boldsymbol{b} \cdot \nabla P_{\rm cr}}{|\boldsymbol{b} \cdot \nabla P_{\rm cr}|}, \qquad \boldsymbol{v}_{\rm di} = -\kappa_{\rm di} \boldsymbol{b} \frac{\boldsymbol{b} \cdot \nabla \varepsilon_{\rm cr}}{\varepsilon_{\rm cr}},$$

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- energy equations with $\varepsilon = \varepsilon_{\rm th} + \rho v^2/2$:

$$\frac{\partial\varepsilon}{\partial t} + \nabla\cdot\left[(\varepsilon + P_{\rm th} \qquad)\boldsymbol{v}\right] = 0$$

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$$\frac{\partial\varepsilon}{\partial t} + \nabla\cdot[(\varepsilon + P_{\rm th} + P_{\rm cr})\boldsymbol{v}] = P_{\rm cr}\nabla\cdot\boldsymbol{v} - \boldsymbol{v}_{\rm st}\cdot\nabla P_{\rm cr}$$

$$\frac{\partial\varepsilon_{\rm cr}}{\partial t} + \nabla\cdot[P_{\rm cr}\boldsymbol{v}_{\rm st} + \varepsilon_{\rm cr}(\boldsymbol{v} + \boldsymbol{v}_{\rm st} + \boldsymbol{v}_{\rm di})] = -P_{\rm cr}\nabla\cdot\boldsymbol{v} + \boldsymbol{v}_{\rm st}\cdot\nabla P_{\rm cr}$$

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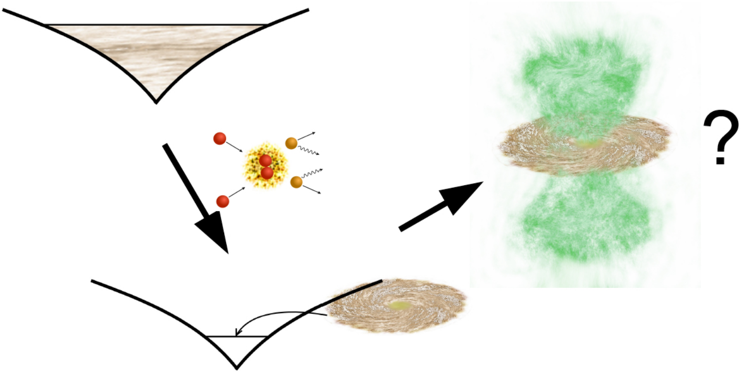
$$\Longleftrightarrow \quad \frac{\partial \varepsilon_{\rm cr}}{\partial t} + \nabla \cdot [\varepsilon_{\rm cr}(\boldsymbol{v} + \boldsymbol{v}_{\rm st} + \boldsymbol{v}_{\rm di})] = -P_{\rm cr} \nabla \cdot (\boldsymbol{v} + \boldsymbol{v}_{\rm st})$$

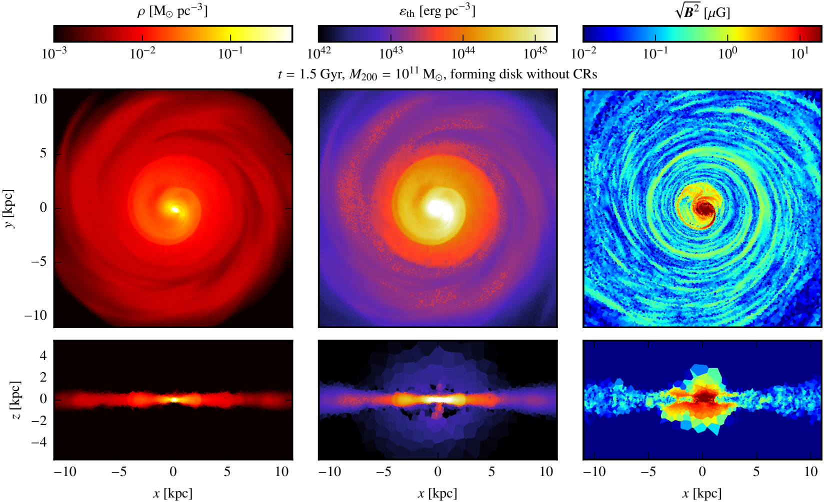
Galaxy simulation setup: 1. cosmic ray advection



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

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

MHD galaxy simulation without CRs



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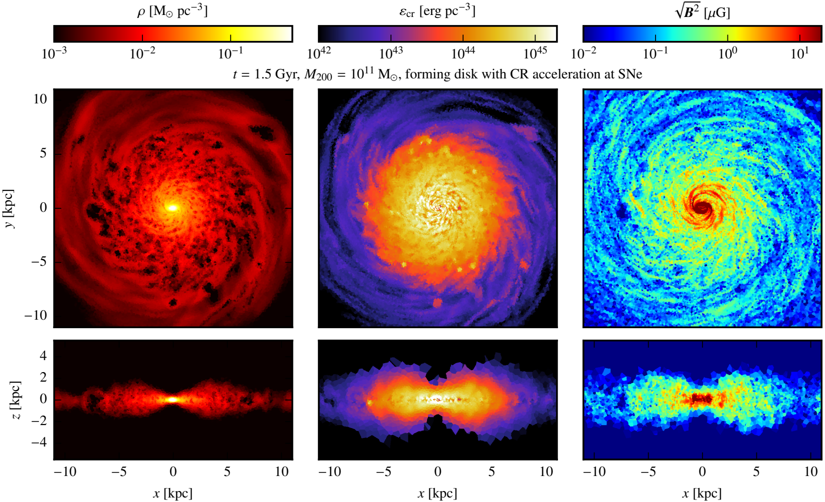
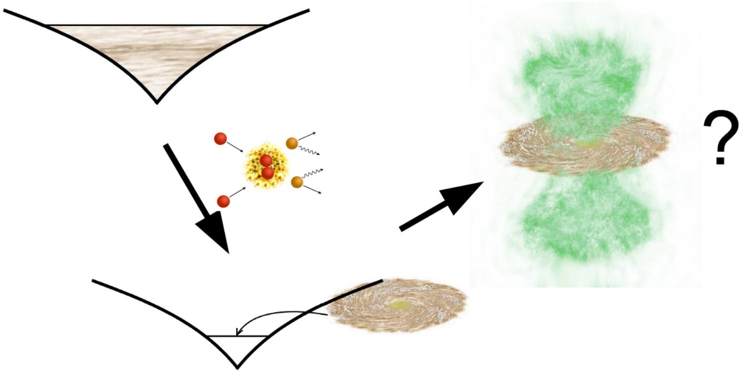


C.P., Pakmor, Schaal, Simpson, Springel (2017)

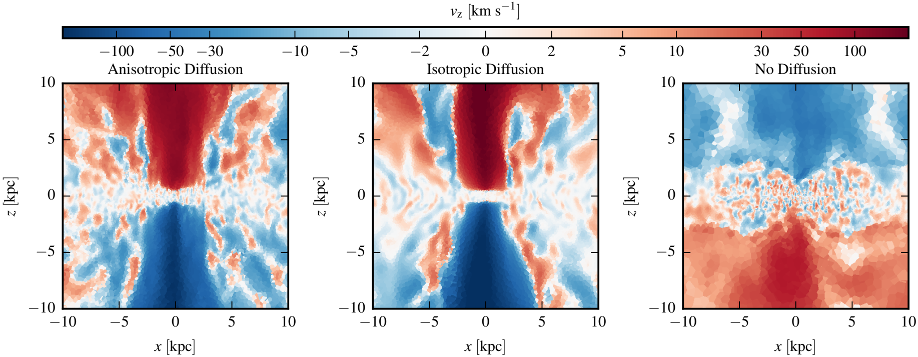
Galaxy simulation setup: 2. cosmic ray diffusion



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

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

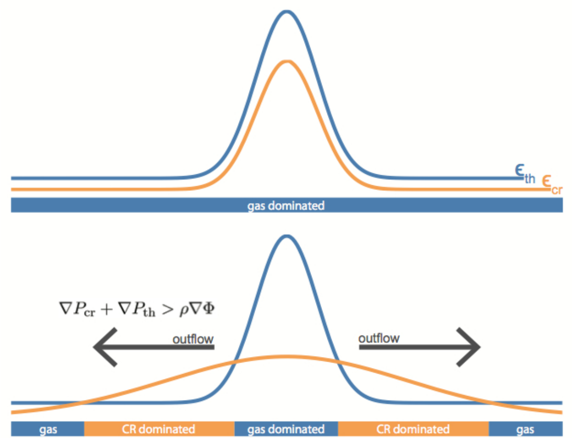
MHD galaxy simulation with CR diffusion



Pakmor, C.P., Simpson, Springel (2016)

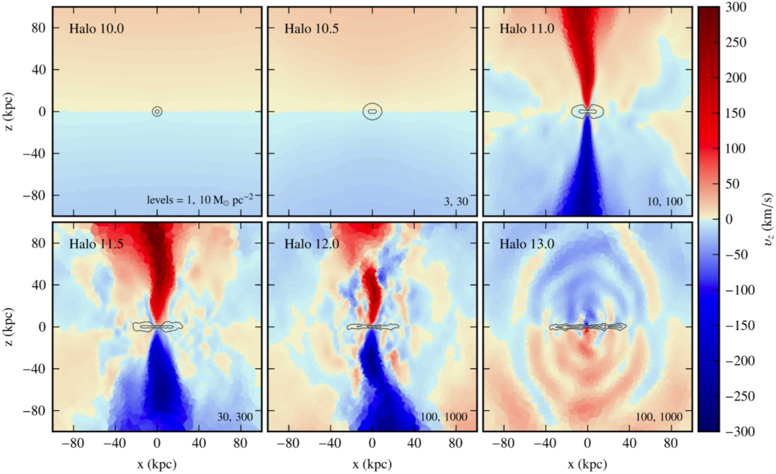
- CR diffusion launches powerful winds
- simulation without CR diffusion exhibits only weak fountain flows

Cosmic ray driven wind: mechanism



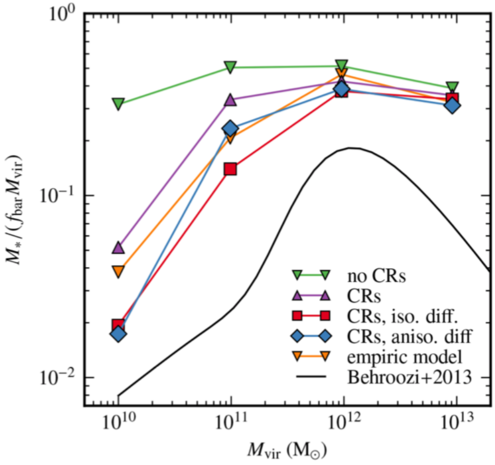
CR streaming in 3D simulations: Uhlig, C.P.+ (2012), Ruszkowski+ (2017)
CR diffusion in 3D simulations: Jubelgas+ (2008), Booth+ (2013), Hanasz+ (2013), Salem & Bryan (2014), Pakmor, C.P.+ (2016), Simpson+ (2016), Girichidis+ (2016), Dubois+ (2016), C.P.+ (2017), Jacob+ (2018)

CR-driven winds: dependence on halo mass



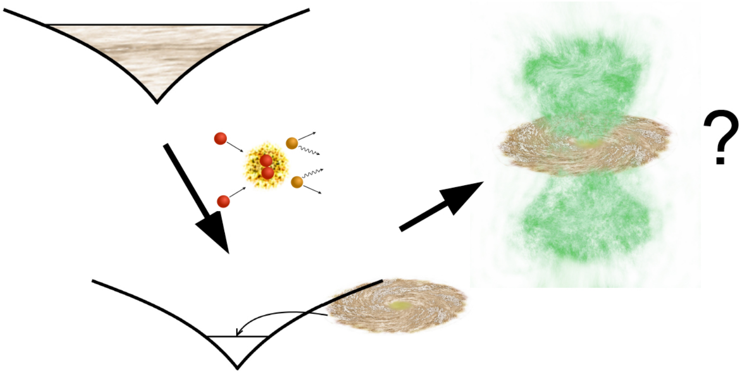
Jacob+ (2018)

CR-driven winds: suppression of star formation



Jacob+ (2018)

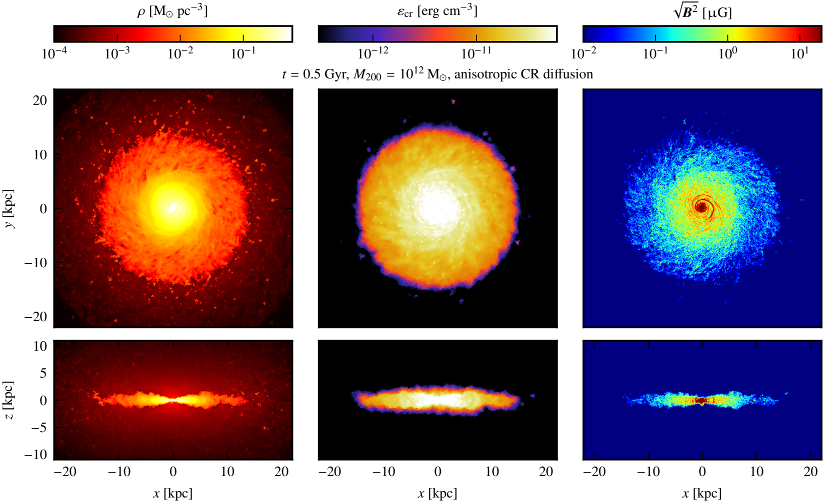
Galaxy simulation setup: 3. non-thermal emission



C.P., Pakmor, Simpson, Springel (2017a,b)
Simulating radio synchrotron and gamma-ray emission in galaxies

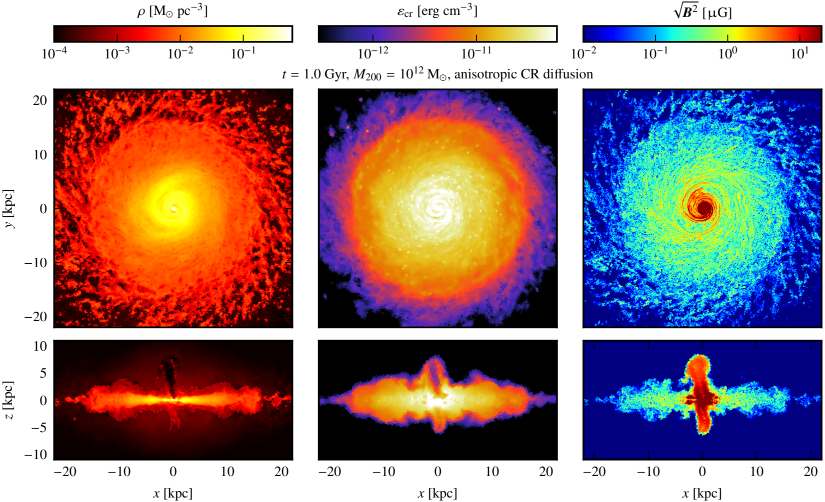
MHD + CR advection + diffusion: $\{10^{10}, 10^{11}, 10^{12}\}$ $M_\odot$

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



C.P.+ (2017a,b)

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



C.P.+ (2017a,b)

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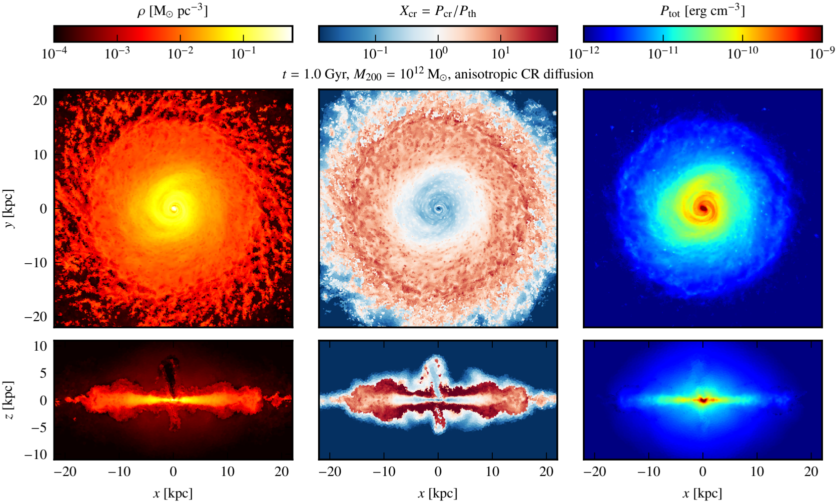
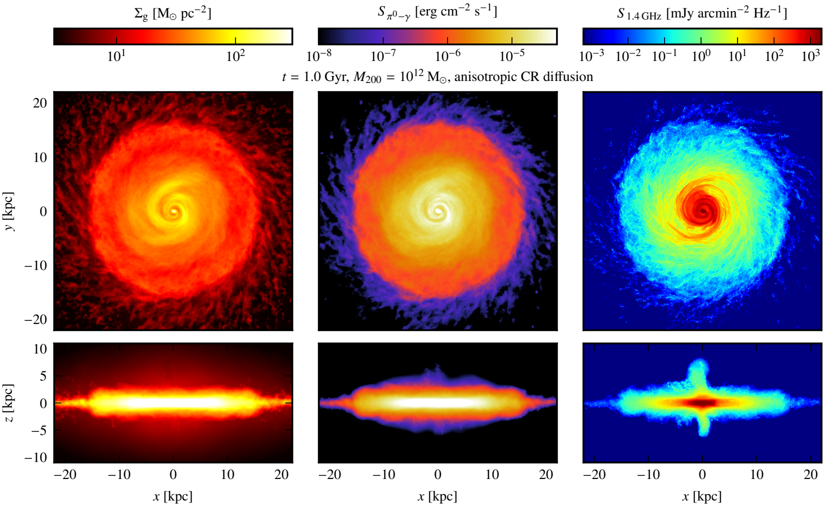


C.P.+ (2017a,b)

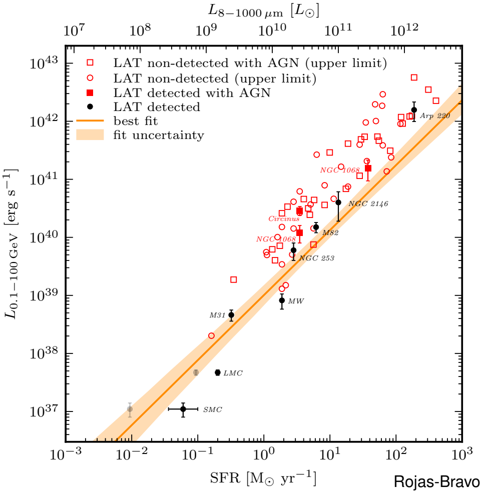
γ-ray and radio emission of Milky Way-like galaxy



C.P.+ (2017a,b)

Far infra-red – gamma-ray correlation

Universal conversion: star formation → cosmic rays → gamma rays



Rojas-Bravo & Araya (2016)

Far infra-red – gamma-ray correlation

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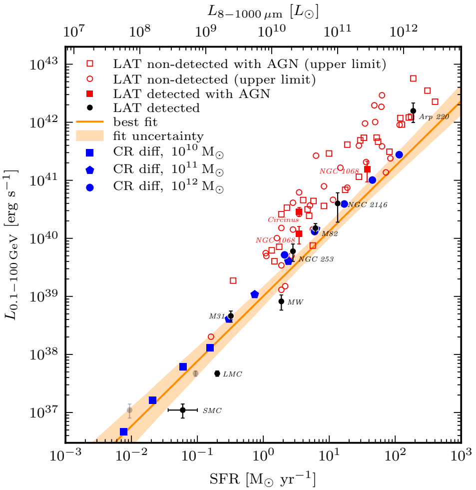

C.P.+ (2017a)

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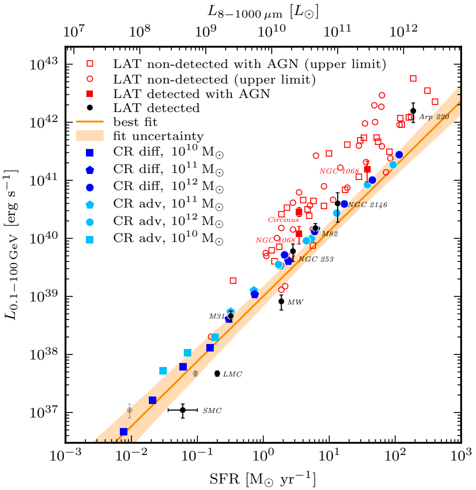

C.P.+ (2017a)

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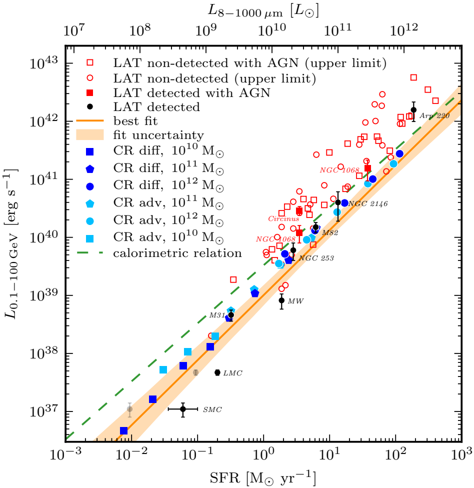

C.P.+ (2017a)

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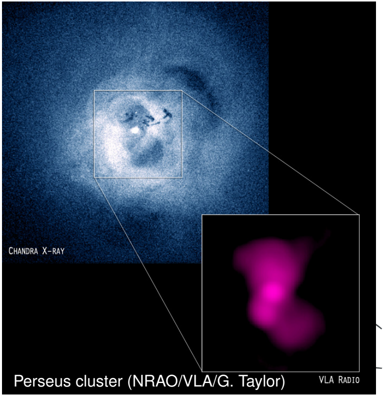
Feedback by active galactic nuclei

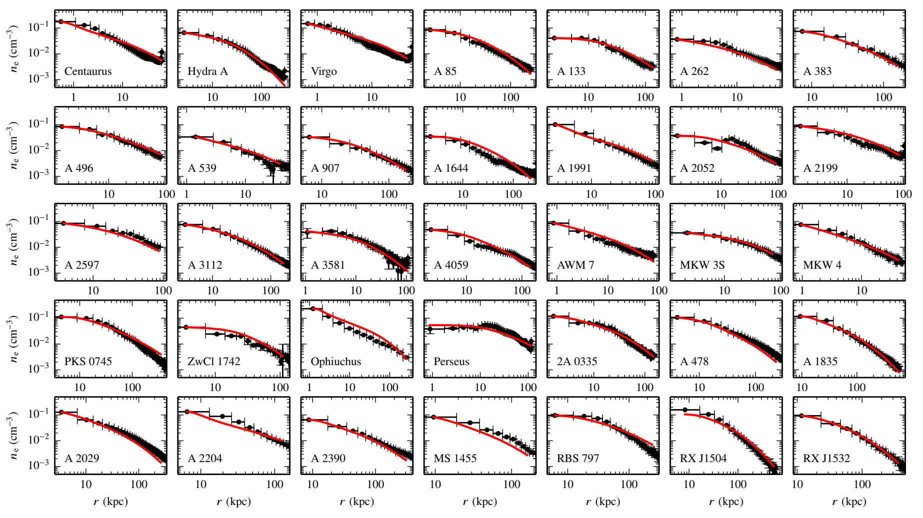
Paradigm: accreting super-massive black holes at galaxy cluster centers launch relativistic jets, which provide energetic feedback to balance cooling ⇒ **but how?**

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

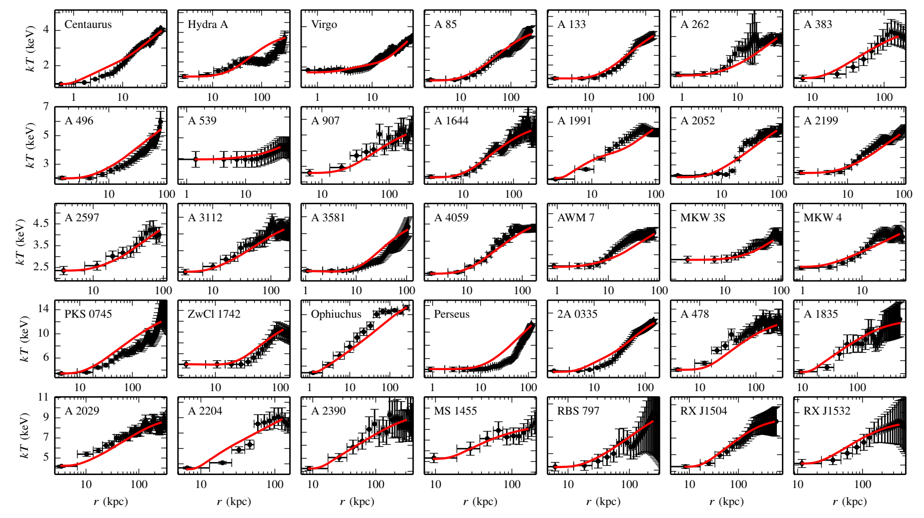


Perseus cluster (NRAO/VLA/G. Taylor)

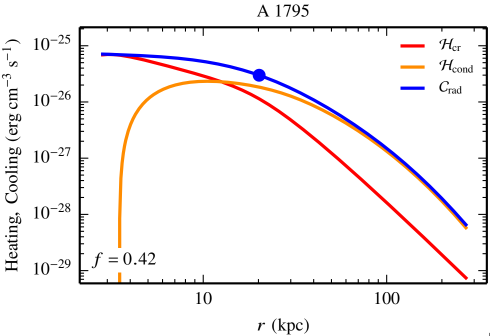
Gallery of solutions: density profiles



Gallery of solutions: temperature profiles



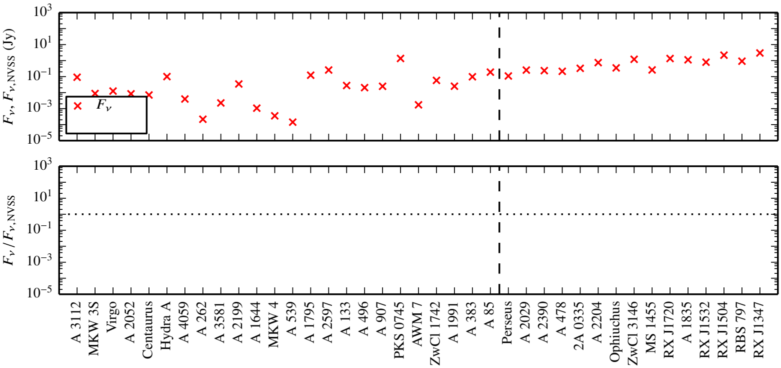
Case study A1795: heating and cooling



Jacob & C.P. (2016a)

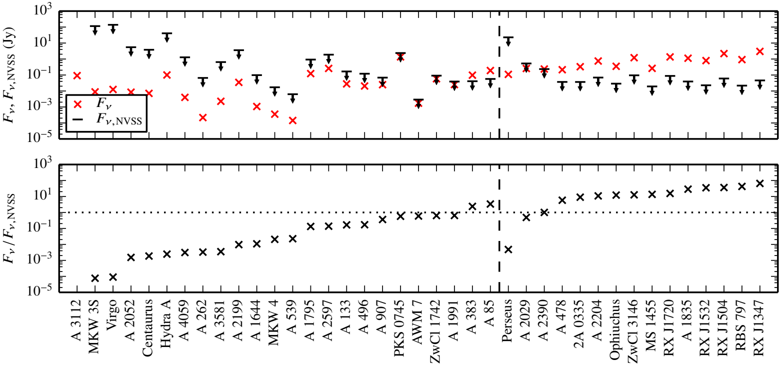
- CR heating dominates in the center
- conductive heating takes over at larger radii, $\kappa = 0.42\kappa_{\rm Sp}$
- $\mathcal{H}_{\rm cr} + \mathcal{H}_{\rm th} \approx \mathcal{C}_{\rm rad}$: modest mass deposition rate of 1 $M_\odot$ yr^{-1}

Hadronically induced radio emission



Jacob & C.P. (2017b)

Hadronically induced radio emission: NVSS limits



Jacob & C.P. (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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AGN injects CRs

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AGN injects CRs → CR heating balances cooling

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CRs stream outwards and become too dilute to heat the cluster

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radio mini halo

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

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radio mini halo

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↑		↓
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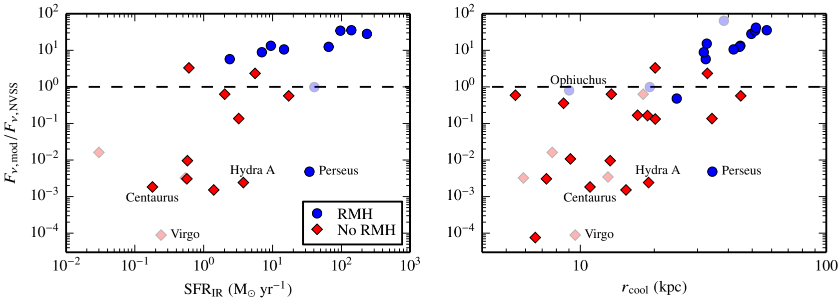
		↘
		radio mini halo

Self-regulated heating/cooling cycle in cool cores

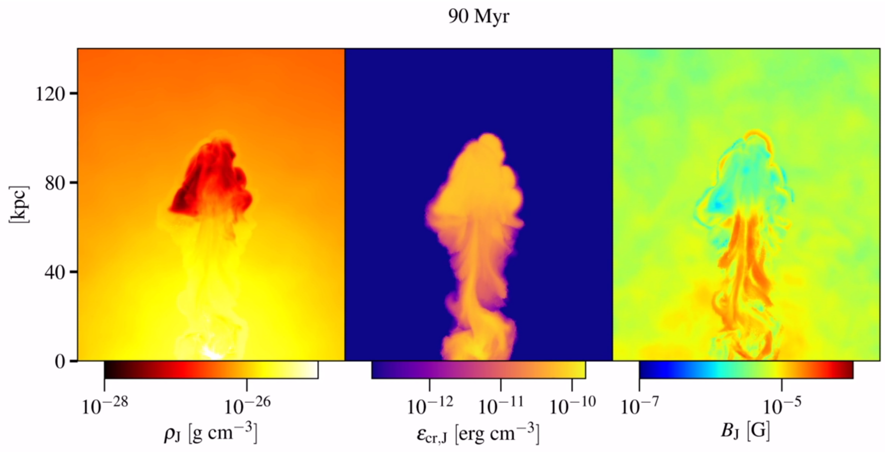


Jacob & C.P. (2017b)

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

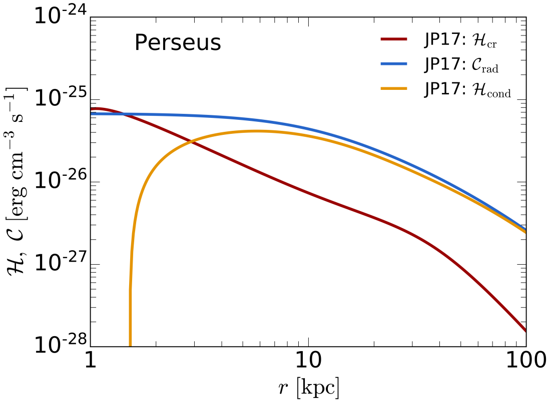
- simmering SF: CR heating is effectively balancing cooling
- abundant SF: heating/cooling out of balance

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



Ehlert+ in prep.

Perseus cluster – heating vs. cooling: theory



Ehlert+ in prep.

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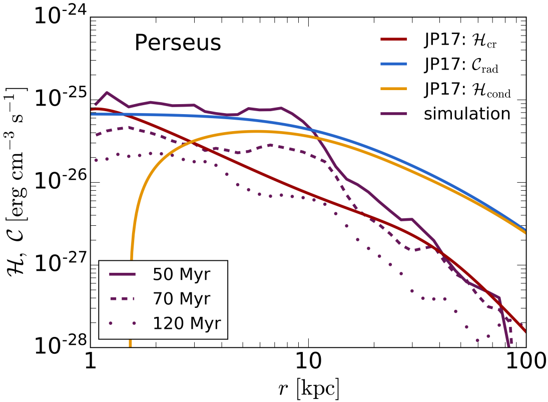
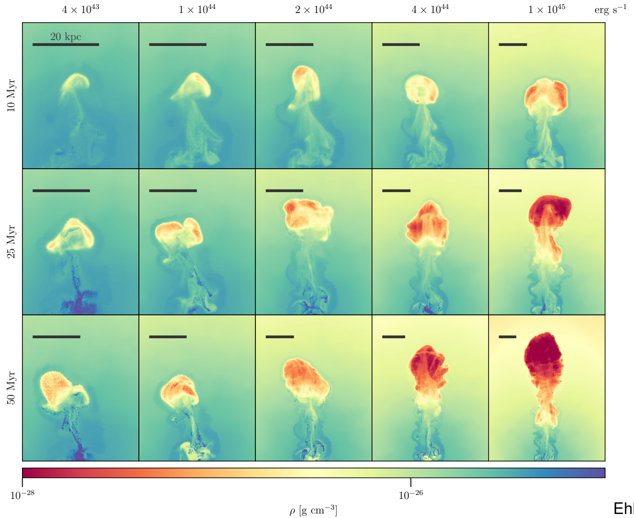
Perseus cluster – heating vs. cooling: simulations



Ehlert+ in prep.

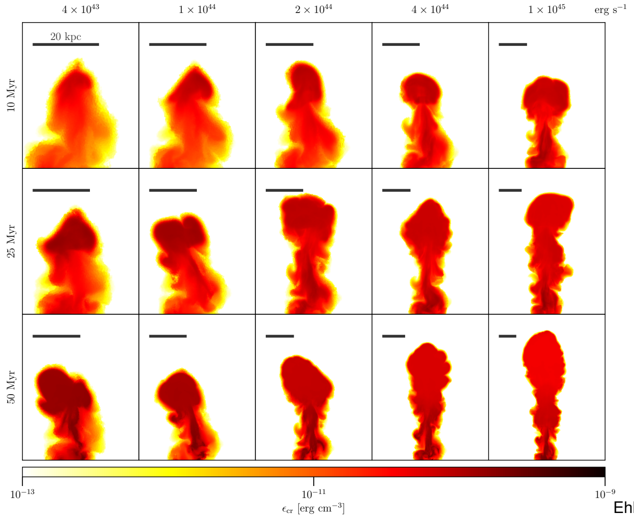
- CR and conductive heating balance radiative cooling: $\mathcal{H}_{\rm cr} + \mathcal{H}_{\rm th} \approx \mathcal{C}_{\rm rad}$: modest mass deposition rate of 1 $M_\odot$ yr^{-1}
- **simulated CR heating rate matches 1D steady state model**

Matrix of jet simulations: density at 70 Myrs



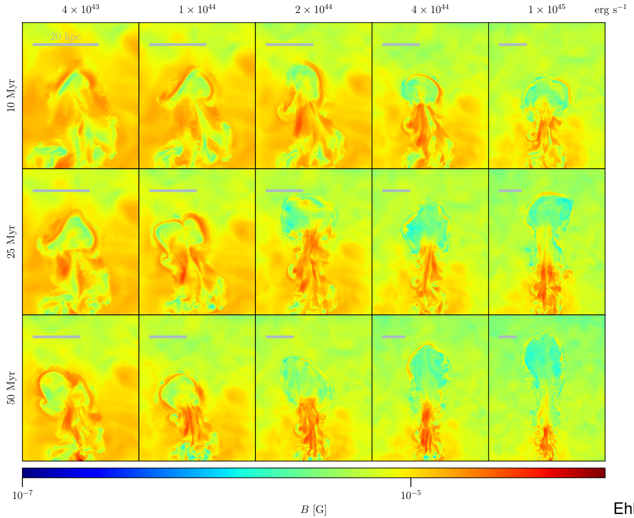
Ehlert+ in prep.

Matrix of jet simulations: CR energy density at 70 Myrs



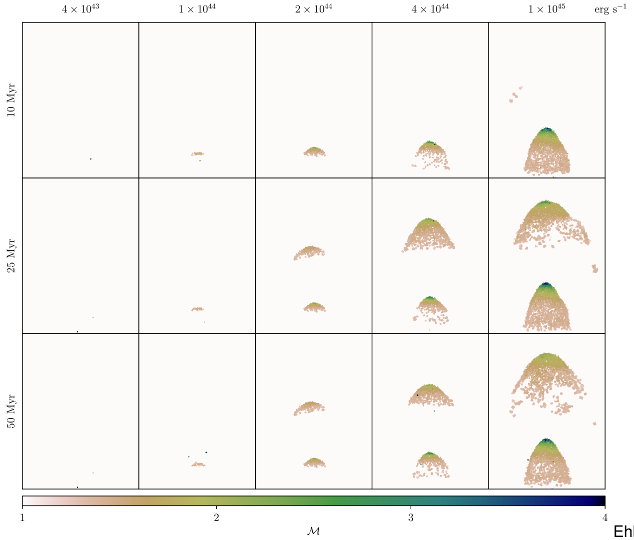
Ehlert+ in prep.

Matrix of jet simulations: magnetic field at 70 Myrs



Ehlert+ in prep.

Matrix of jet simulations: shock strengths at 70 Myrs



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Conclusions on CR feedback in galaxies and clusters

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- galactic winds are naturally explained by CR diffusion & streaming

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- $L_{\mathrm{FIR}} - L_\gamma$ correlations enable us to test the calorimetric assumption and magnetic dynamo theories
- MHD simulations of AGN jets: CR heating can solve the “cooling flow problem” in galaxy clusters

Conclusions on CR feedback in galaxies and clusters

- CR pressure feedback slows down star formation
- galactic winds are naturally explained by CR diffusion & streaming
- $L_{\mathrm{FIR}} - L_\gamma$ correlations enable us to test the calorimetric assumption and magnetic dynamo theories
- MHD simulations of AGN jets: CR heating can solve the "cooling flow problem" in galaxy clusters

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

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Literature for the talk

Non-thermal radio and gamma-ray emission in galaxies:

- Pfrommer, Pakmor, Simpson, Springel, *Simulating Gamma-ray Emission in Star-forming Galaxies,* 2017, ApJL.
- Pfrommer, Pakmor, Simpson, Springel, *Simulating Radio Synchrotron Emission in Galaxies: the Origin of the Far Infrared–Radio Correlation,* 2017b, in prep.

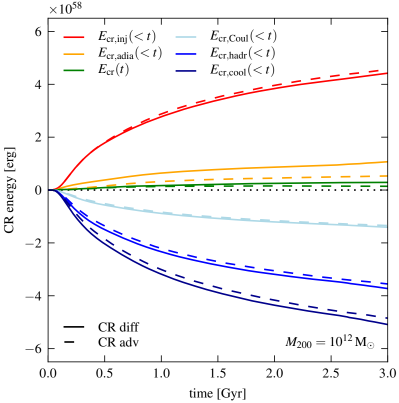
Cosmic ray feedback in galaxies:

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

AIP

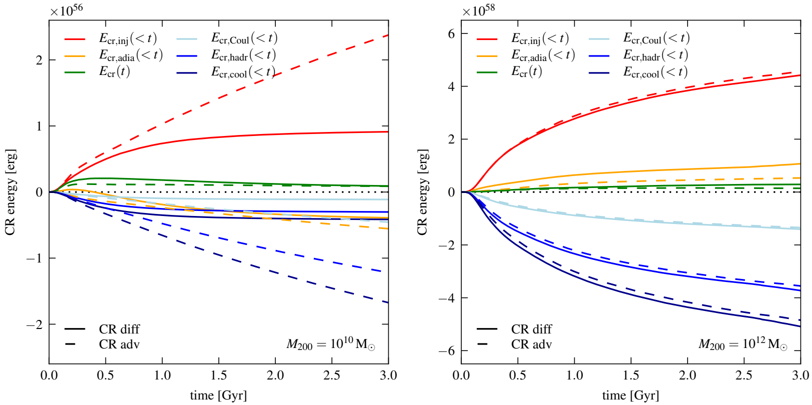
Additional slides

Time evolution of CR energies



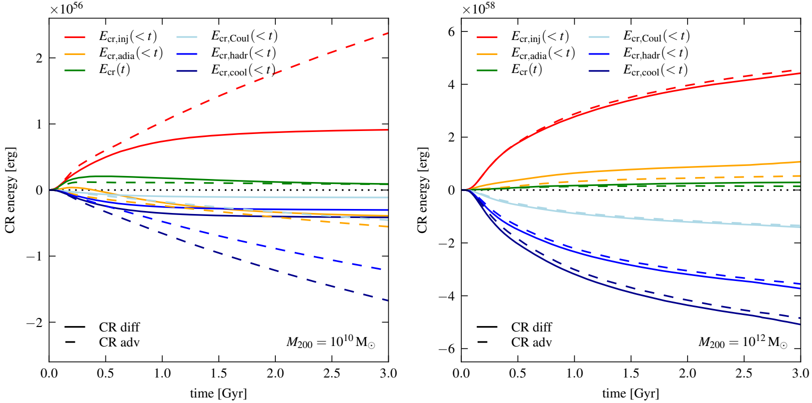
C.P.+ (2017a)

Time evolution of CR energies



C.P.+ (2017a)

Time evolution of CR energies



C.P.+ (2017a)

- adiabatic CR losses are significant in small galaxies
  ⇒ deviation from calorimetric relation at small SFRs

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