How cosmic rays shape galaxies and galaxy clusters

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in collaboration with

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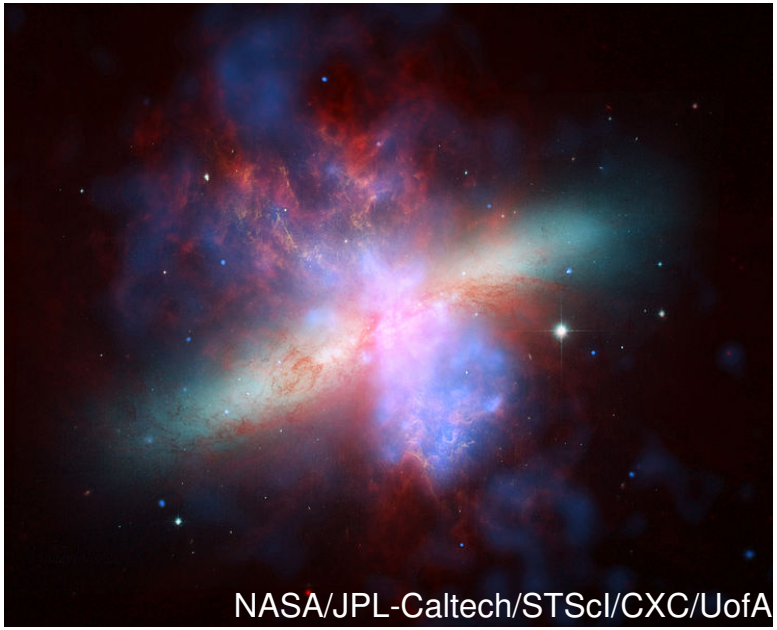
CLUES meeting, Teneriffe – Jun 2018

Outline

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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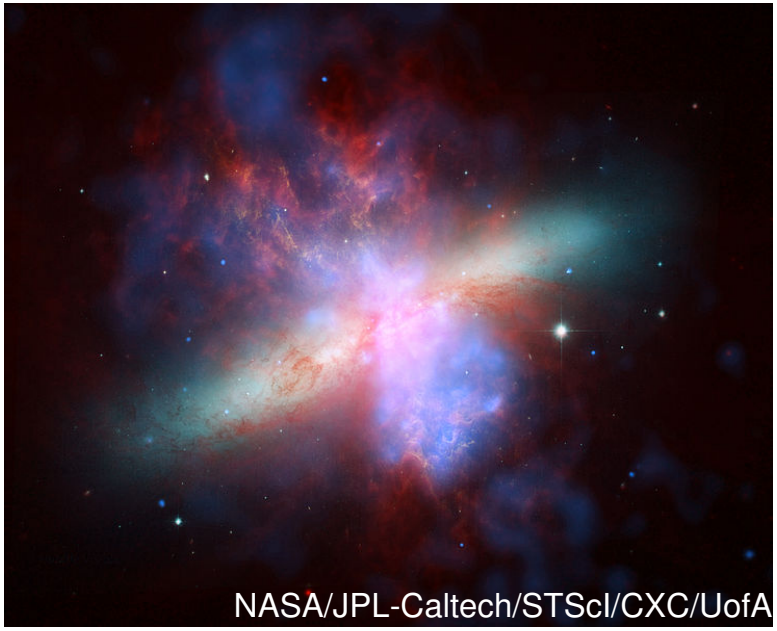

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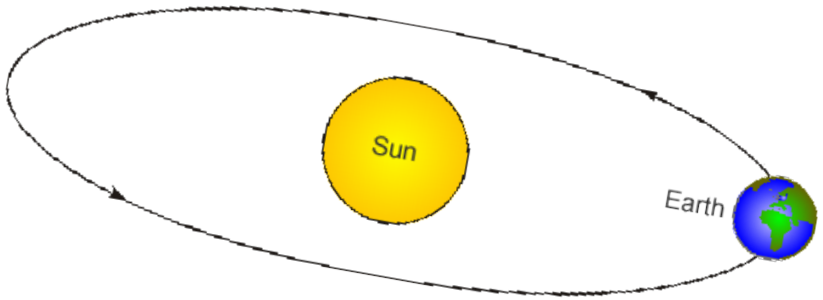
observed energy equipartition between cosmic rays, thermal gas and magnetic fields
$\rightarrow$ suggests self-regulated feedback loop with CR driven winds

Cosmic ray feedback: an extreme multi-scale problem



Milky Way-like galaxy:

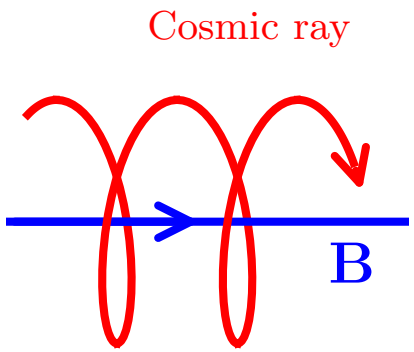
$$r_{\rm gal} \sim 10^4 \text{ pc}$$

gyro-orbit of GeV cosmic ray:

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

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

Interactions of CRs and magnetic fields



sketch: Jacob

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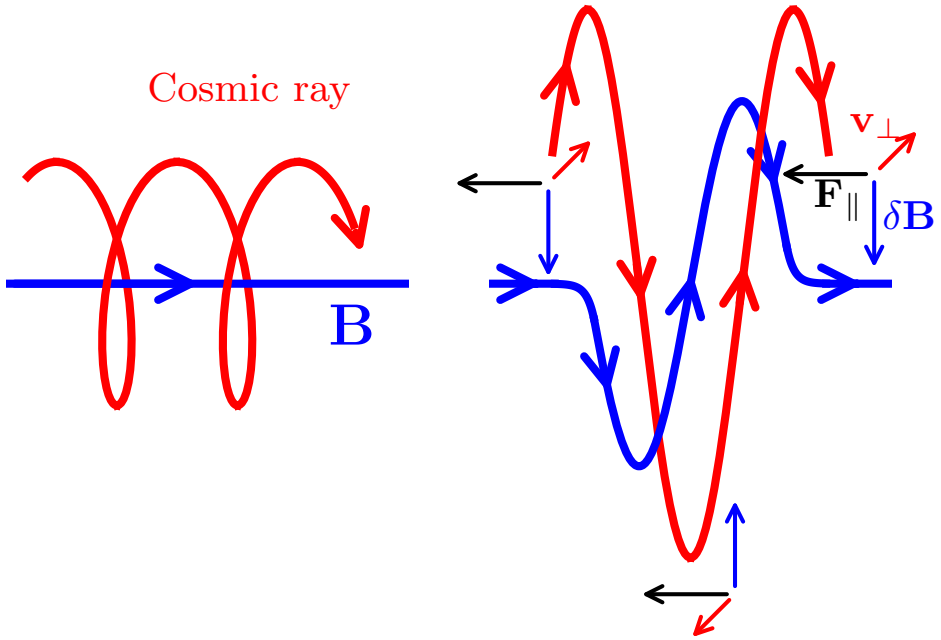

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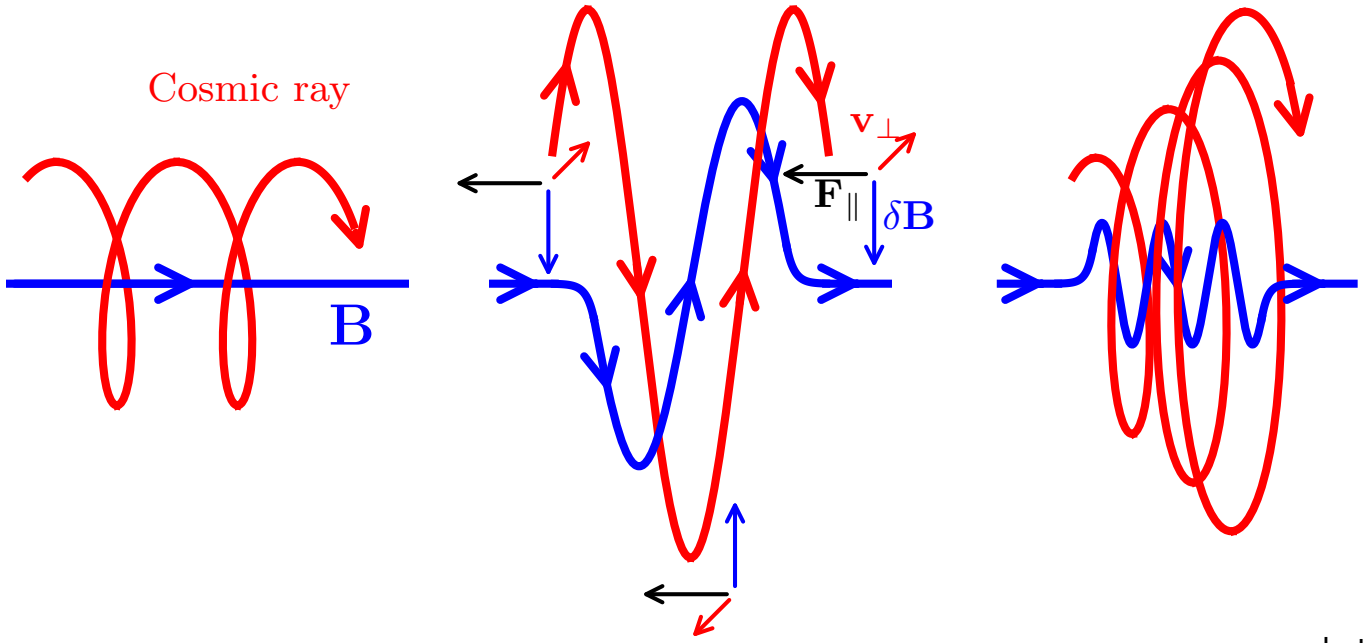
- **gyro resonance:** $\omega - k_\parallel v_\parallel = n\Omega$

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

Interactions of CRs and magnetic fields

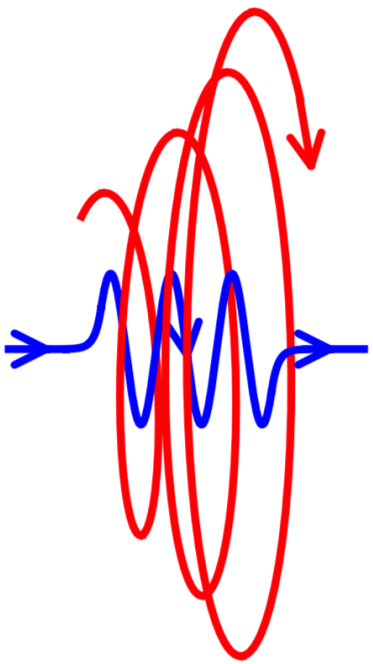


sketch: Jacob

- **gyro resonance:** $\omega - k_\parallel v_\parallel = n\Omega$
  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 $v_{\rm cr} > v_{\rm A}$, 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 $\sim v_{\rm A}$
  - wave damping: transfer of CR energy and momentum to the thermal gas



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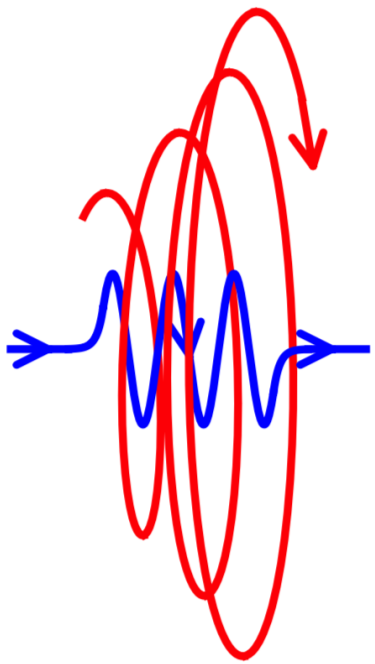

$\rightarrow$ **CRs exert a pressure on the thermal gas by means of scattering off of Alfvén waves**

CR transport in steady state

- total CR velocity $\boldsymbol{v}_{\rm cr} = \boldsymbol{v} + \boldsymbol{v}_{\rm st} + \boldsymbol{v}_{\rm di}$ (where $\boldsymbol{v} \equiv \boldsymbol{v}_{\rm gas}$)

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$$\boldsymbol{v}_{\rm st} = \boldsymbol{v}_{\rm A}\,\frac{\bar{\nu}_+ - \bar{\nu}_-}{\bar{\nu}_+ + \bar{\nu}_-}, \quad \boldsymbol{v}_{\rm di} = -\kappa_{\rm di}\boldsymbol{b}\,\frac{\boldsymbol{b}\cdot\boldsymbol{\nabla}\varepsilon_{\rm cr}}{\varepsilon_{\rm cr}}, \quad \kappa_{\rm di} = \frac{c^2}{3(\bar{\nu}_+ + \bar{\nu}_-)}$$

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

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

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$$\begin{aligned}
\frac{\partial\varepsilon}{\partial t} + \boldsymbol{\nabla}\cdot\left[(\varepsilon + P_{\rm th} + P_{\rm cr})\boldsymbol{v}\right] &= P_{\rm cr}\boldsymbol{\nabla}\cdot\boldsymbol{v} - \boldsymbol{v}_{\rm st}\cdot\boldsymbol{\nabla}P_{\rm cr} \\
\frac{\partial\varepsilon_{\rm cr}}{\partial t} + \boldsymbol{\nabla}\cdot\left[P_{\rm cr}\boldsymbol{v}_{\rm st} + \varepsilon_{\rm cr}(\boldsymbol{v} + \boldsymbol{v}_{\rm st} + \boldsymbol{v}_{\rm di})\right] &= -P_{\rm cr}\boldsymbol{\nabla}\cdot\boldsymbol{v} + \boldsymbol{v}_{\rm st}\cdot\boldsymbol{\nabla}P_{\rm cr}
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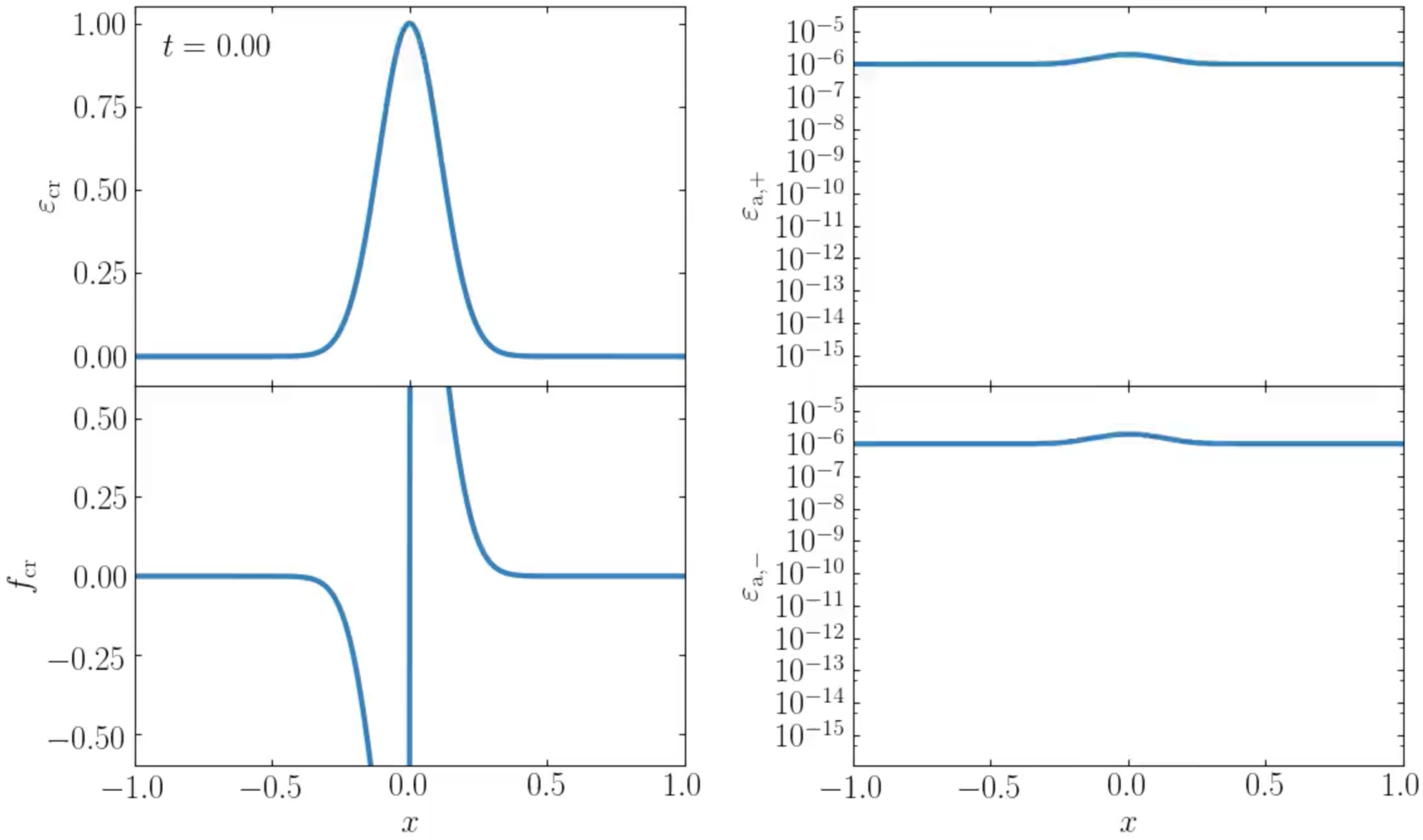
\end{aligned}$$

Non-equilibrium CR streaming and diffusion

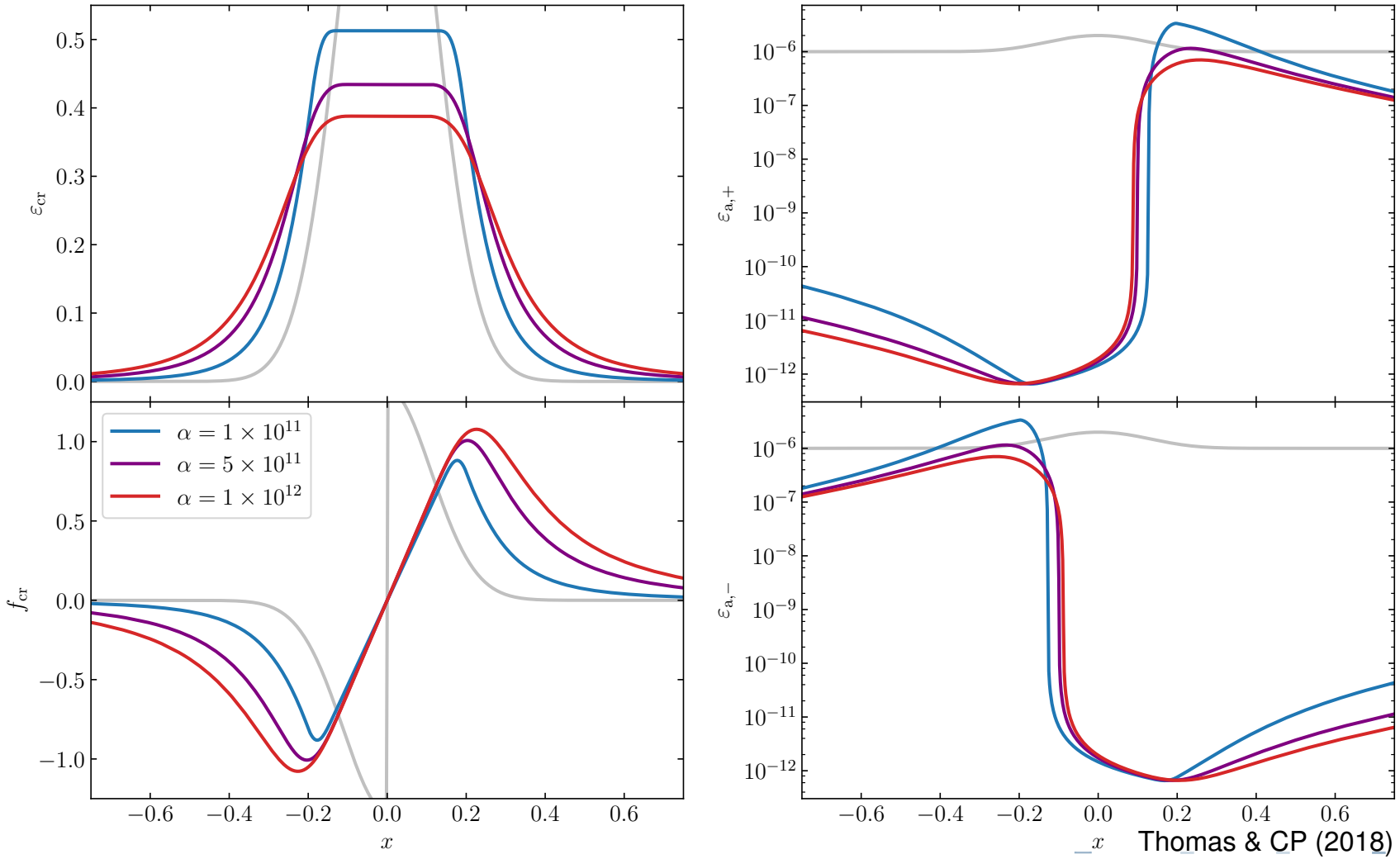
Coupling the evolution of CR and Alfvén wave energy densities



Thomas & CP (2018)

Non-equilibrium CR streaming and diffusion

Varying damping rate of Alfvén waves modulates the diffusivity of solution

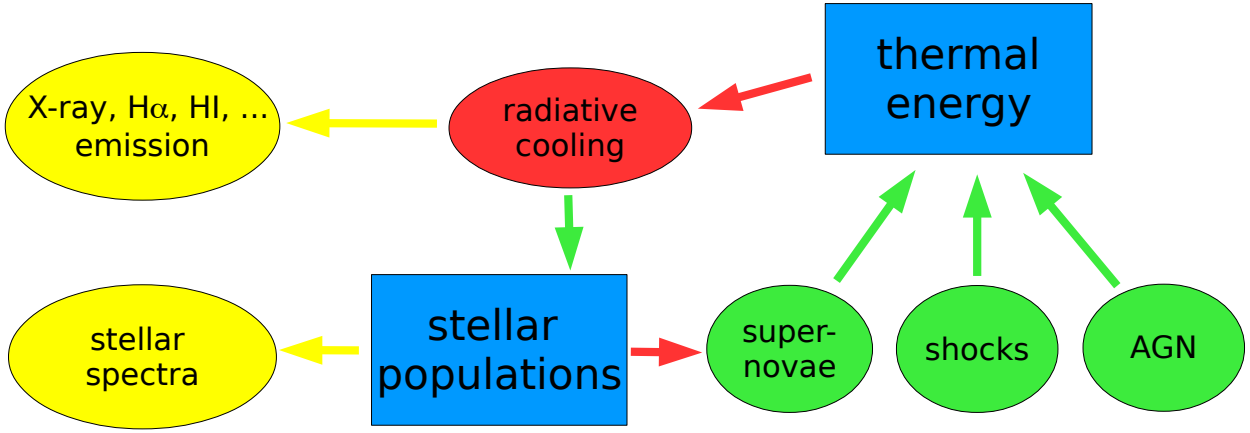


Thomas & CP (2018)

Simulations – flowchart

observables:

physical processes:



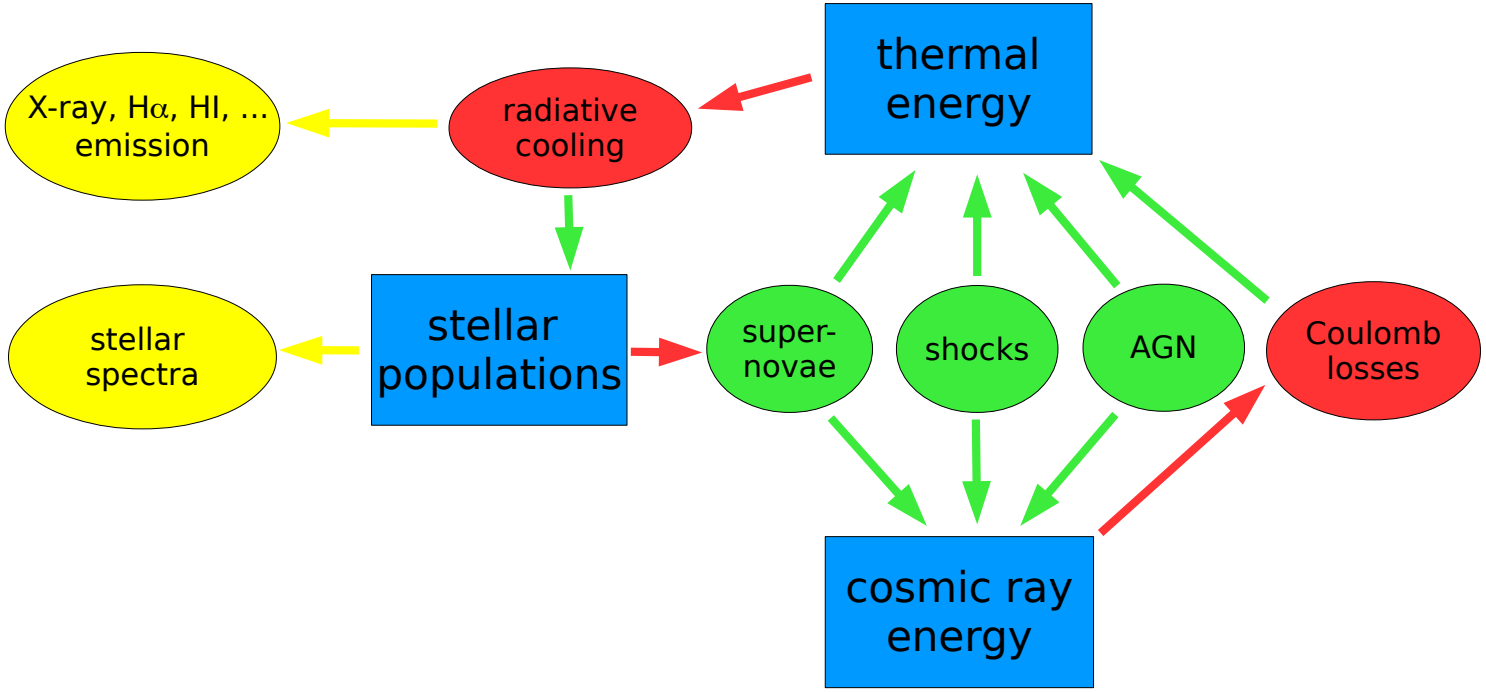
loss processes
gain processes
observables
populations

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

Simulations with cosmic ray physics

observables:

physical processes:



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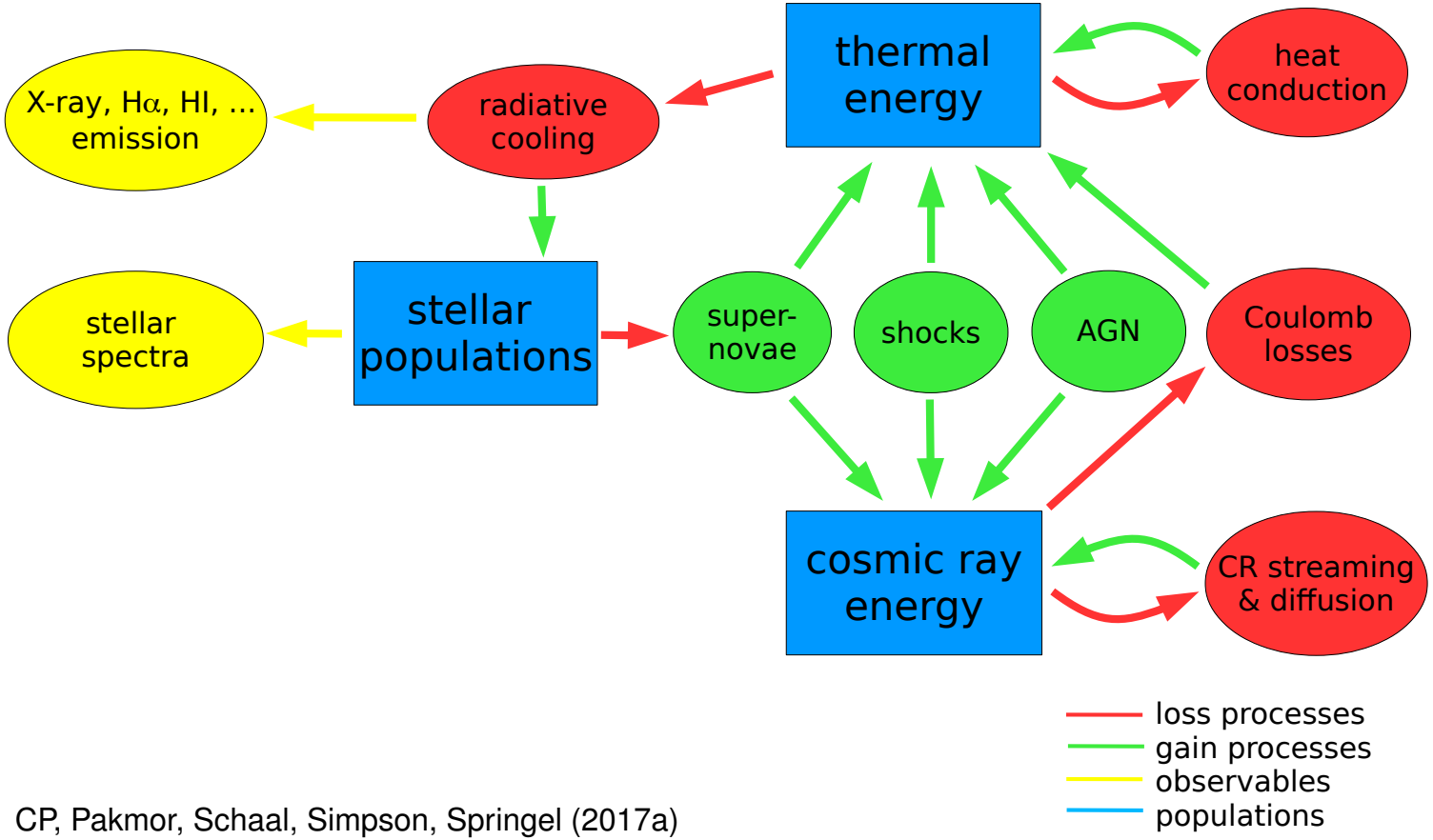

CP, Pakmor, Schaal, Simpson, Springel (2017a)

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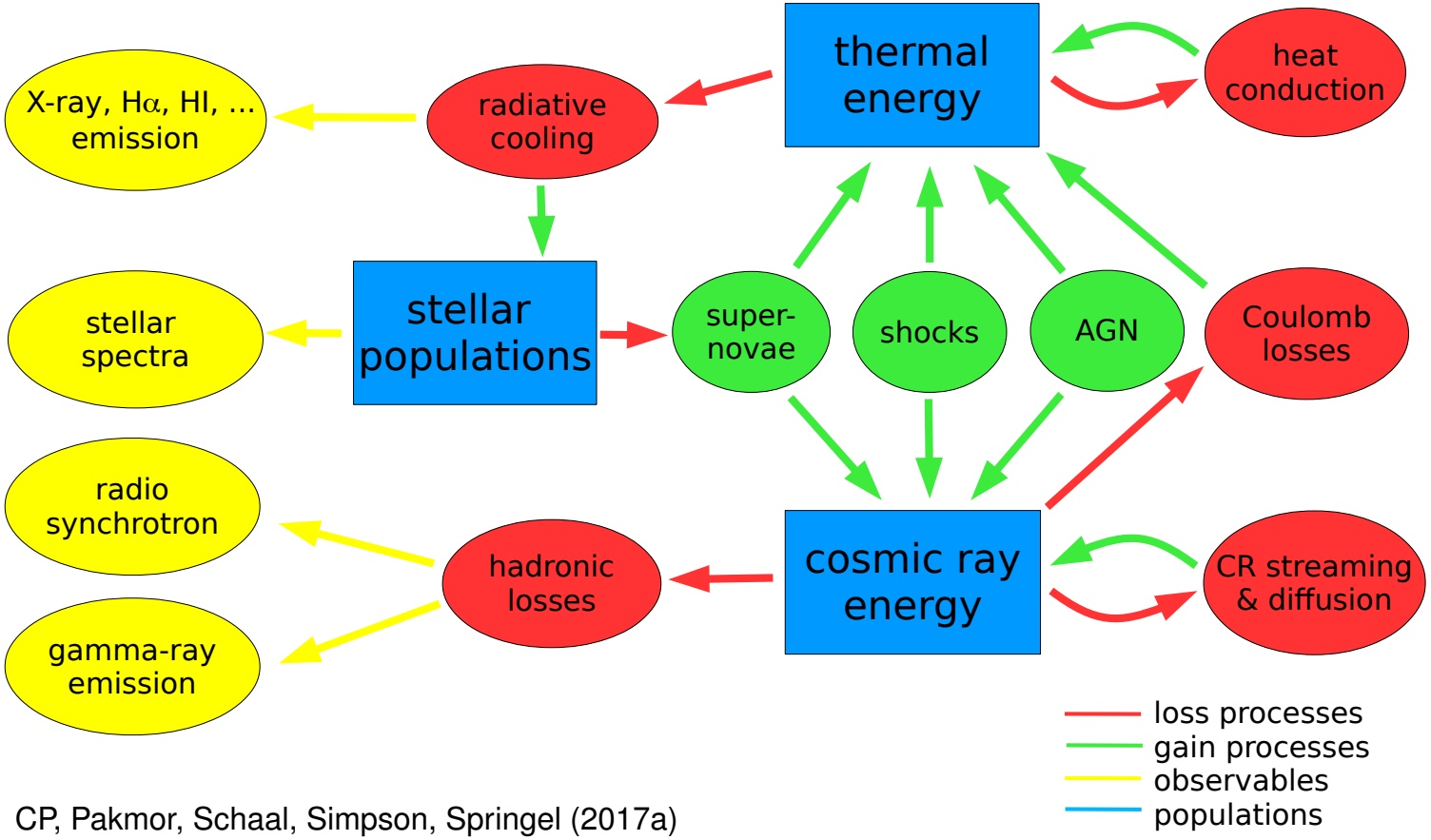
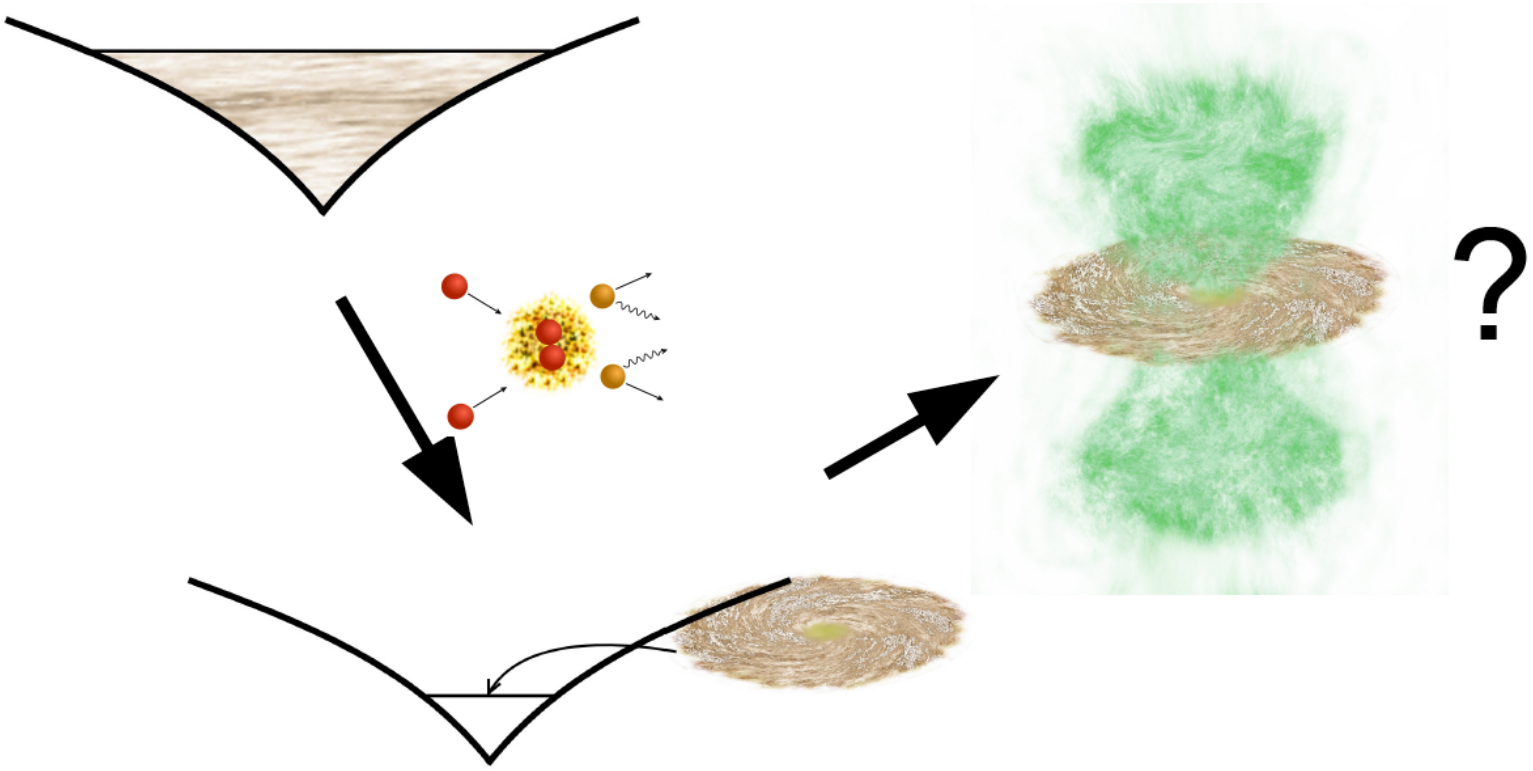


CP, Pakmor, Schaal, Simpson, Springel (2017a)

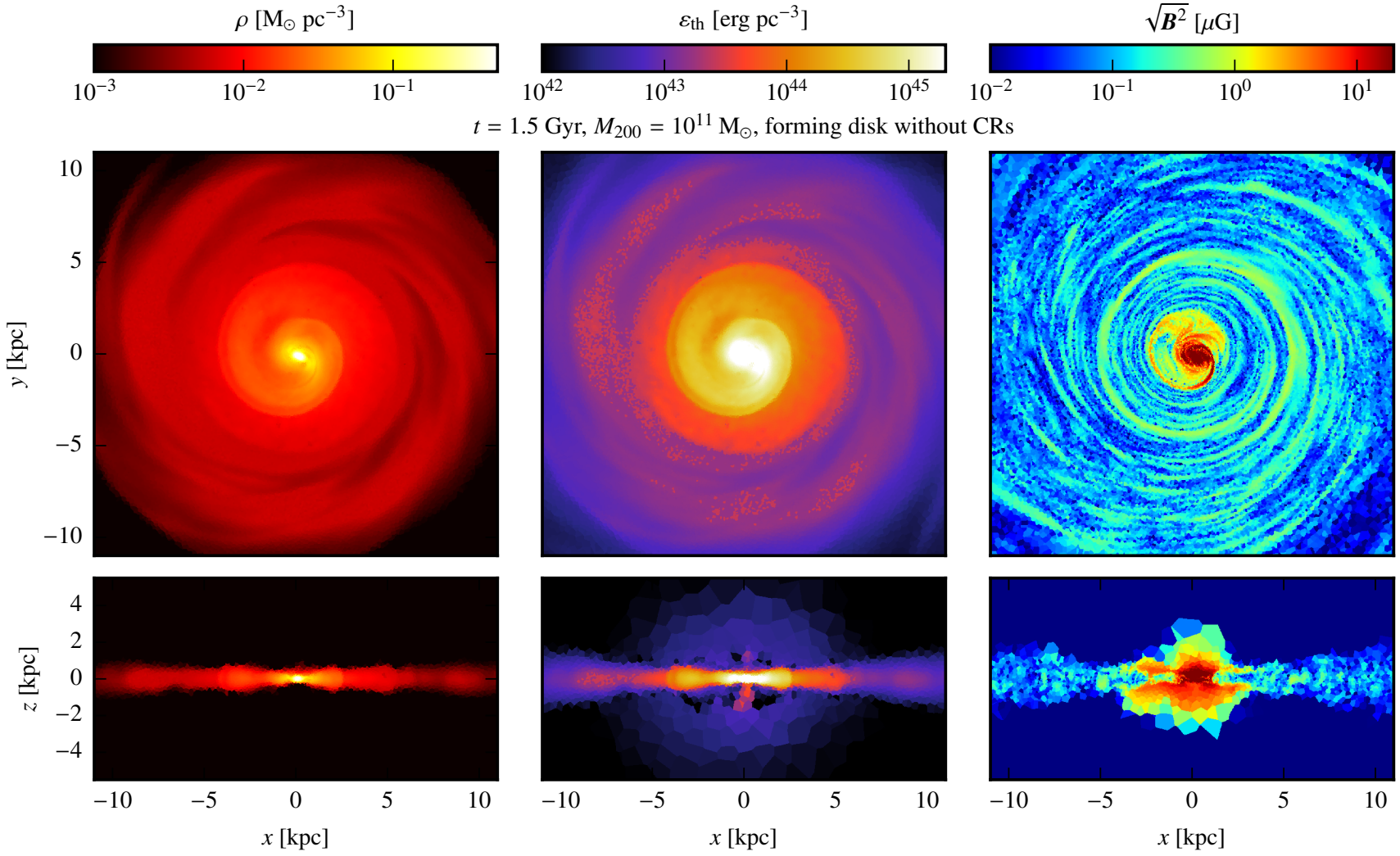
Galaxy simulation setup: 1. cosmic ray advection



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

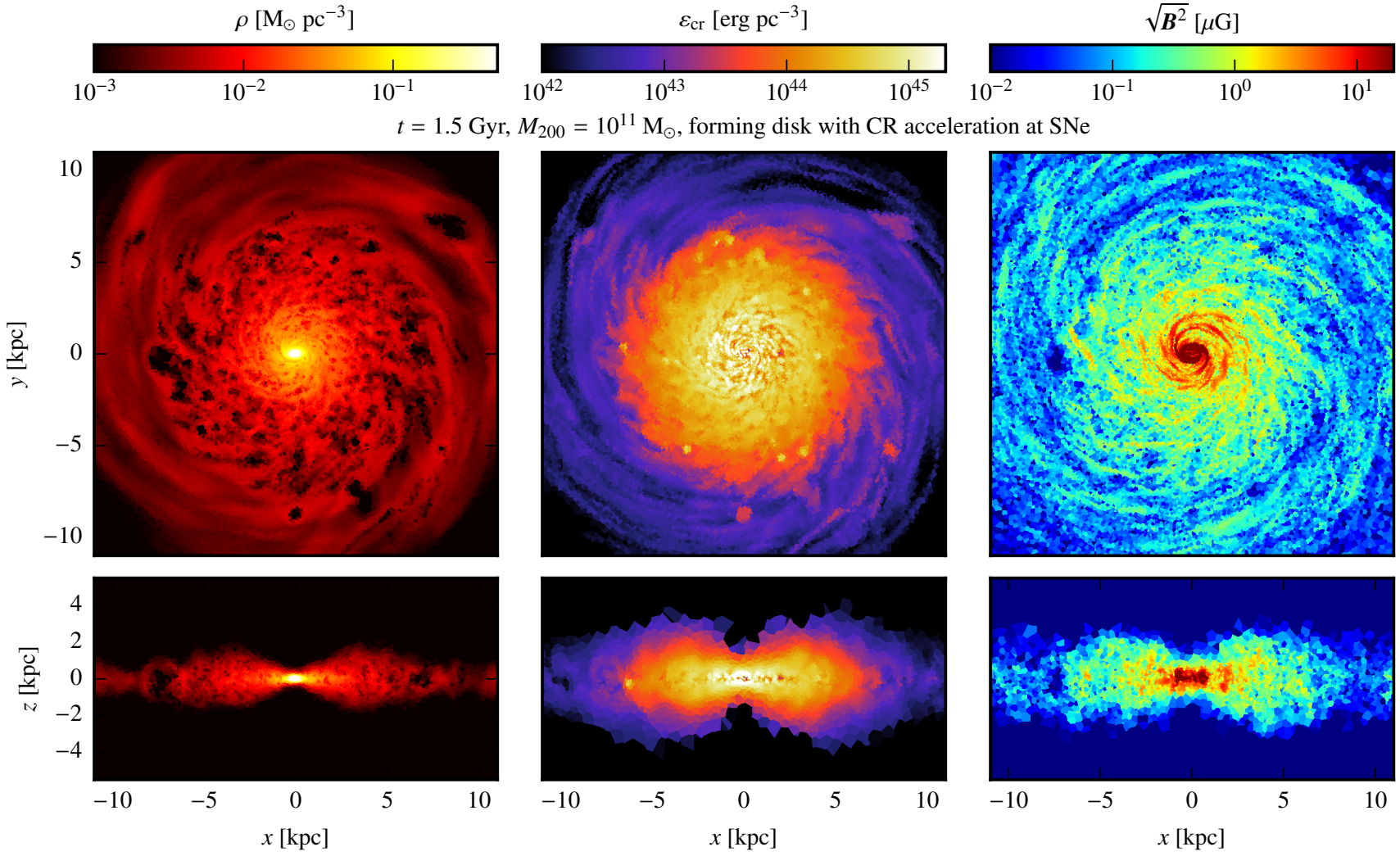
MHD + cosmic ray advection: $\{10^{10}, 10^{11}, 10^{12}\}\ M_\odot$

MHD galaxy simulation without CRs



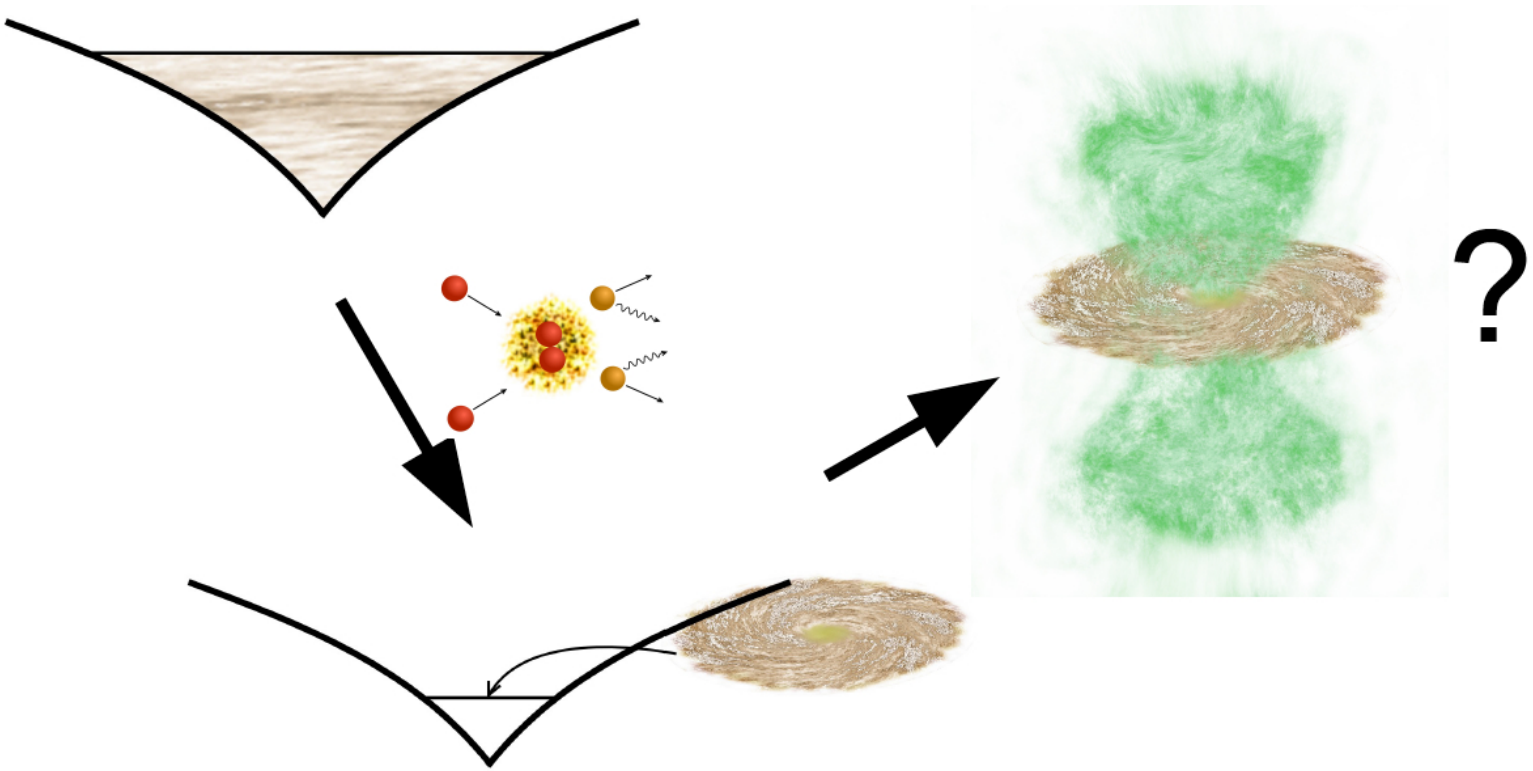
CP, Pakmor, Schaal, Simpson, Springel (2017a)

MHD galaxy simulation with CRs



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

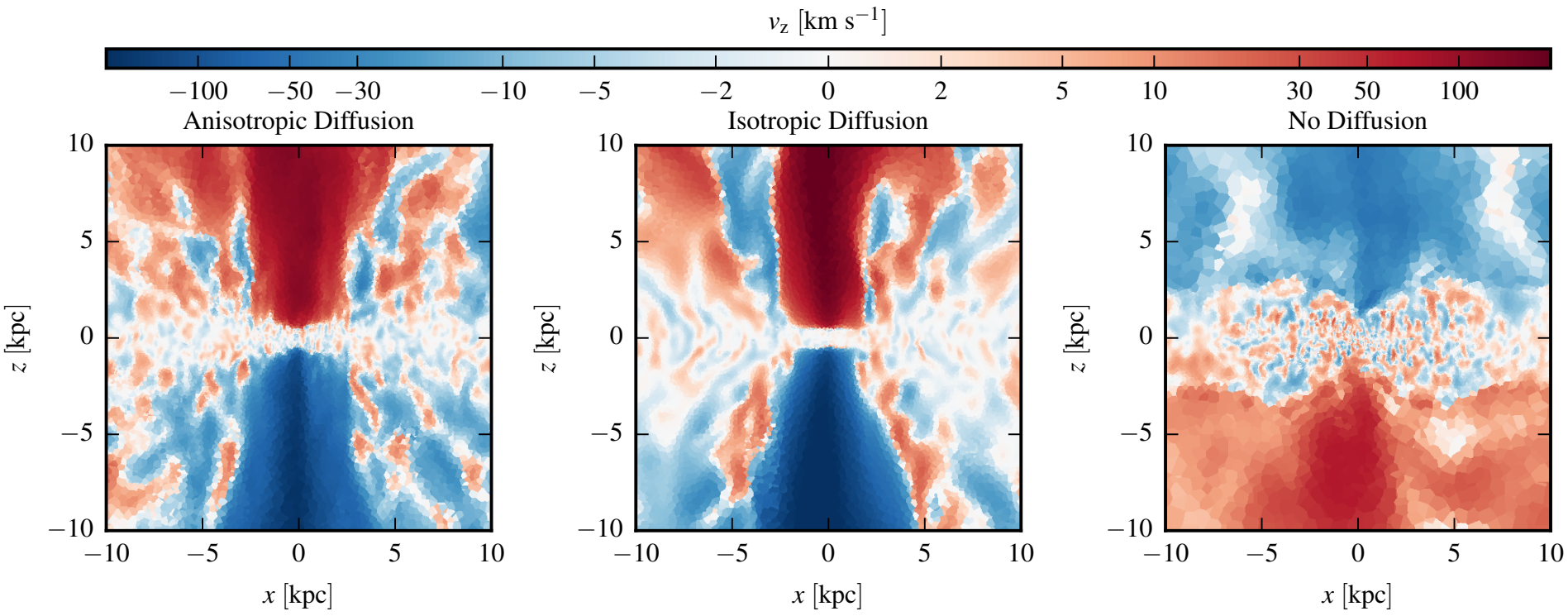
Galaxy simulation setup: 2. cosmic ray diffusion



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

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

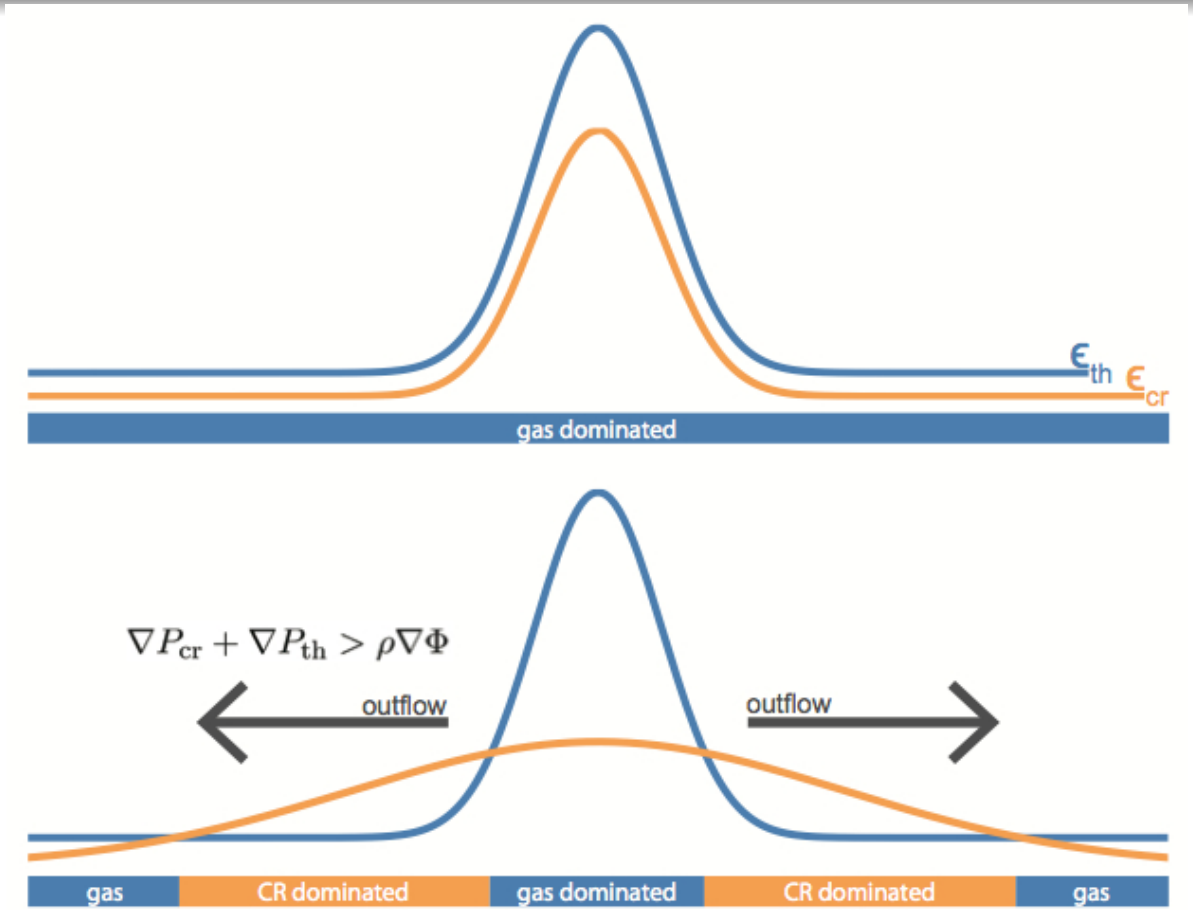
MHD galaxy simulation with CR diffusion



Pakmor, CP, Simpson, Springel (2016)

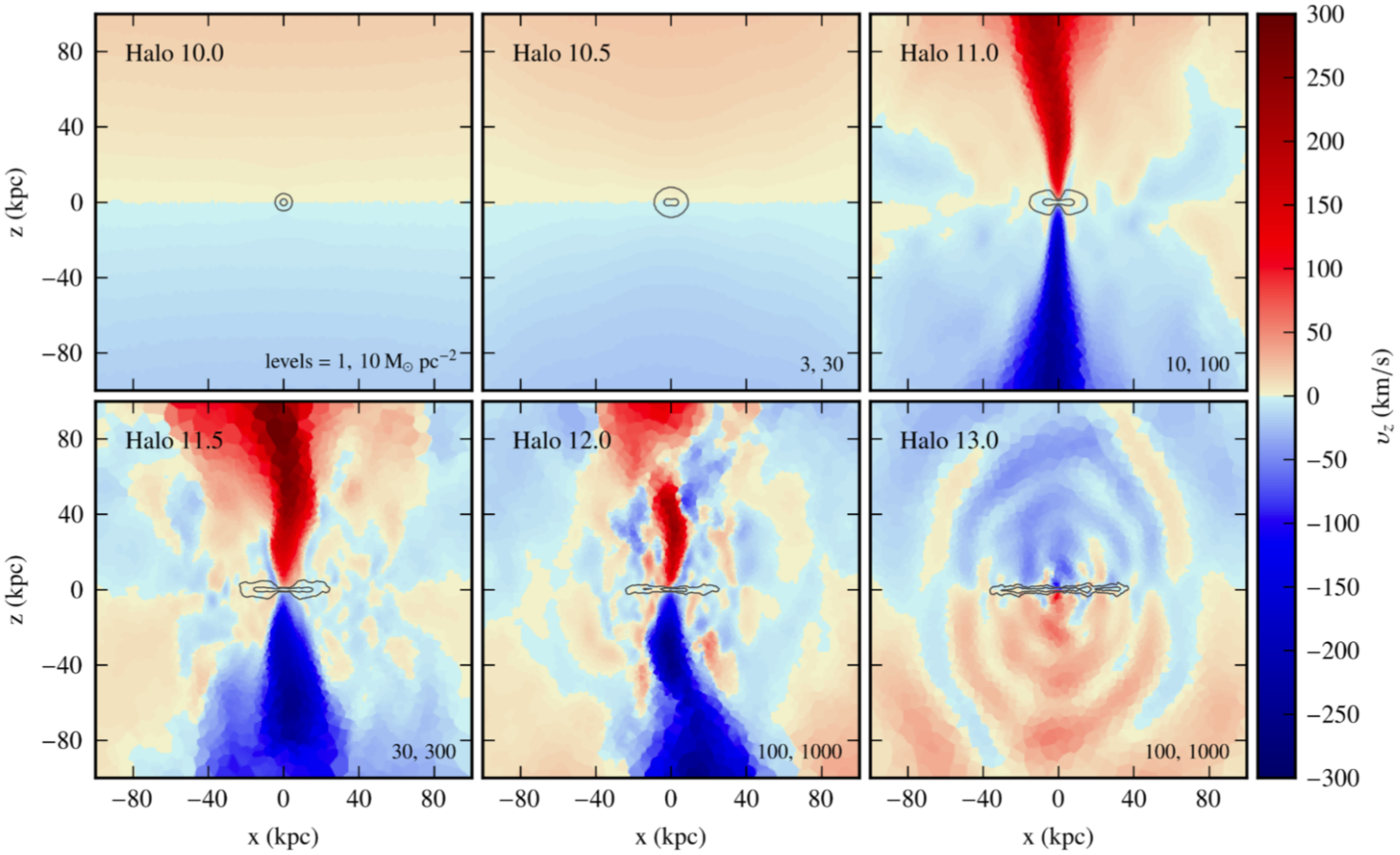
- CR diffusion launches powerful winds
- simulation without CR diffusion exhibits only weak fountain flows

Cosmic ray driven wind: mechanism



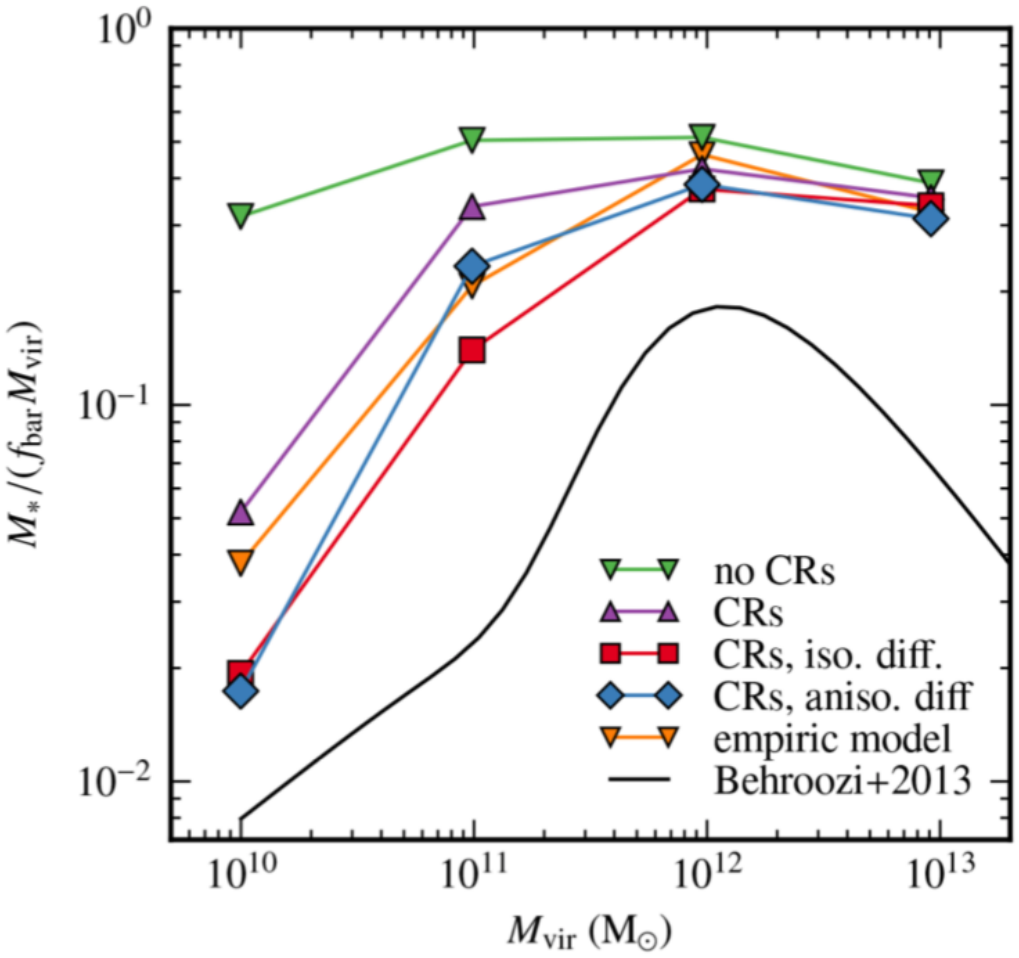
CR streaming in 3D simulations: Uhlig, CP+ (2012), Ruszkowski+ (2017)
CR diffusion in 3D simulations: Jubelgas+ (2008), Booth+ (2013), Hanasz+ (2013), Salem & Bryan (2014), Pakmor, CP+ (2016), Simpson+ (2016), Girichidis+ (2016), Dubois+ (2016), CP+ (2017b), Jacob+ (2018)

CR-driven winds: dependence on halo mass



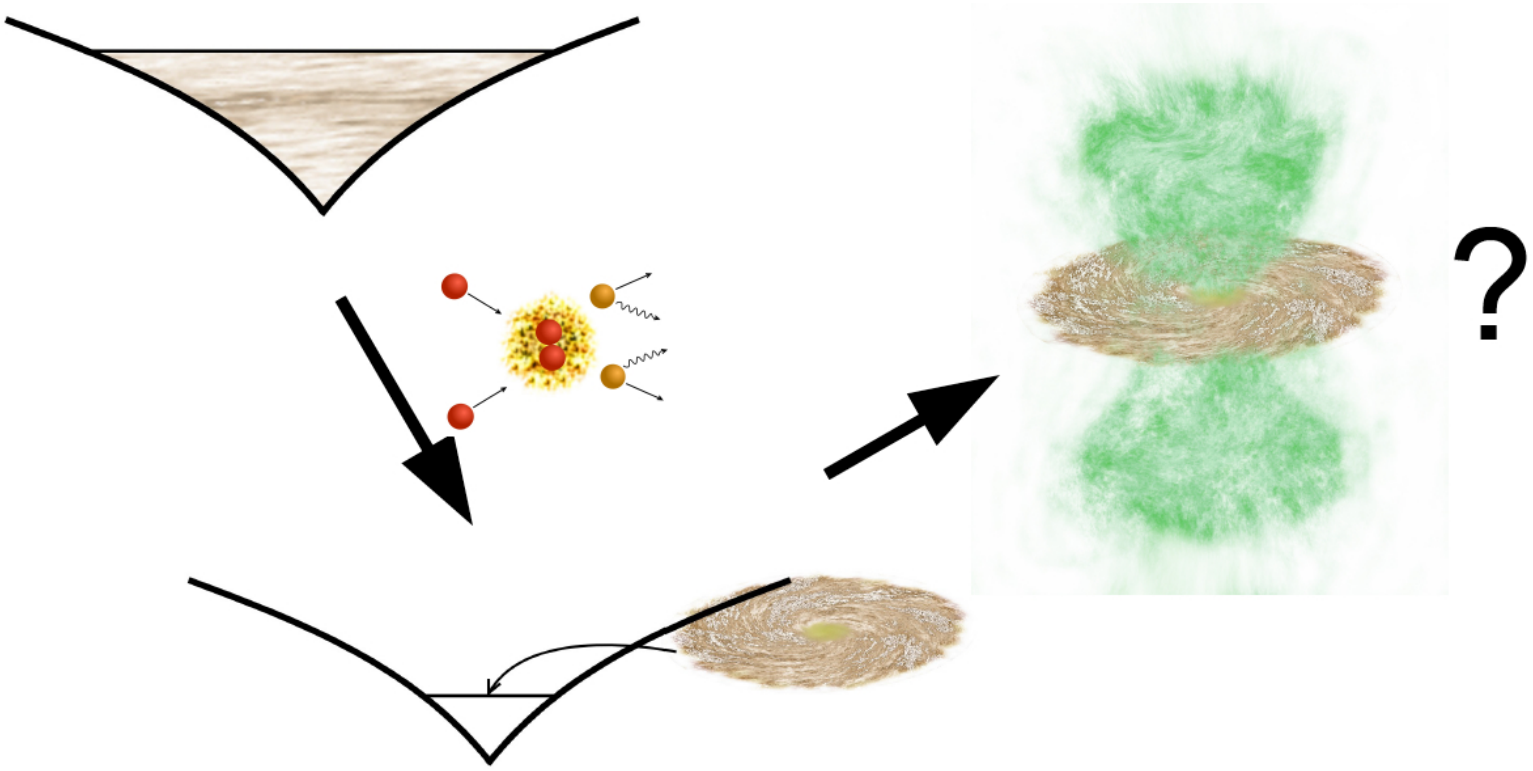
Jacob+ (2018)

CR-driven winds: suppression of star formation



Jacob+ (2018)

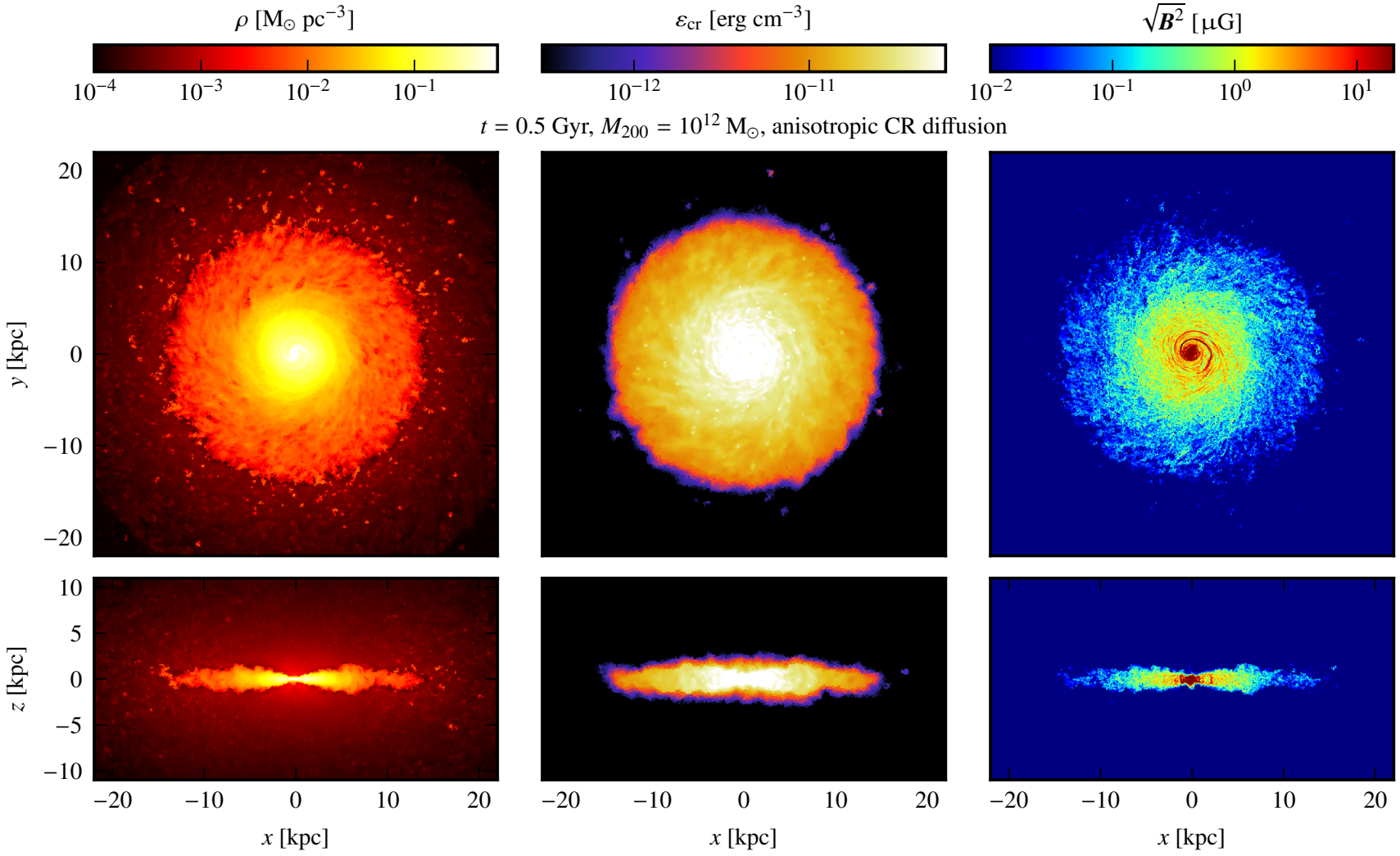
Galaxy simulation setup: 3. non-thermal emission



CP, Pakmor, Simpson, Springel (2017b, 2018)
Simulating radio synchrotron and gamma-ray emission in galaxies

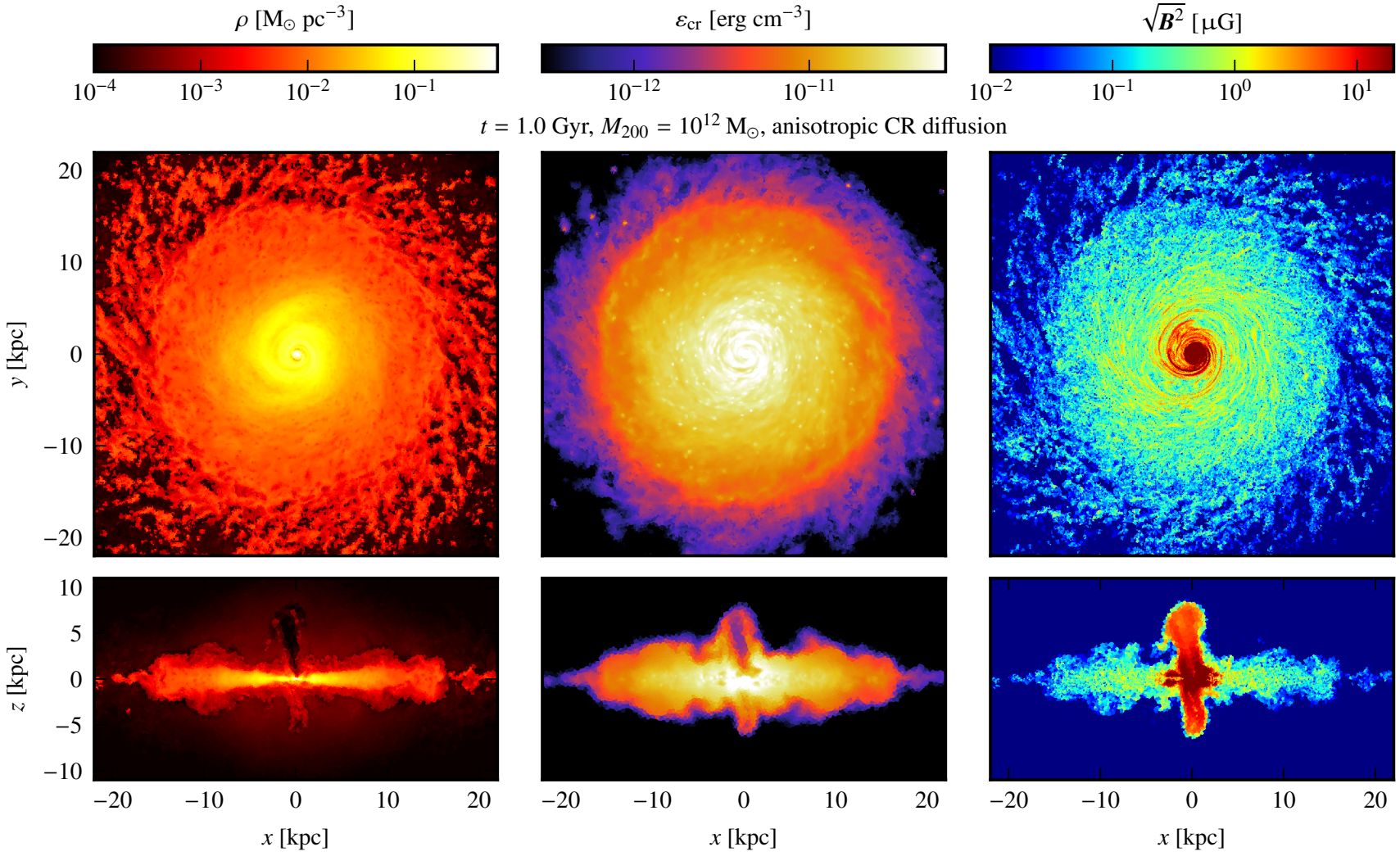
MHD + CR advection + diffusion: $\{10^{10}, 10^{11}, 10^{12}\}\ M_\odot$

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



CP+ (2017b, 2018)

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



CP+ (2017b, 2018)

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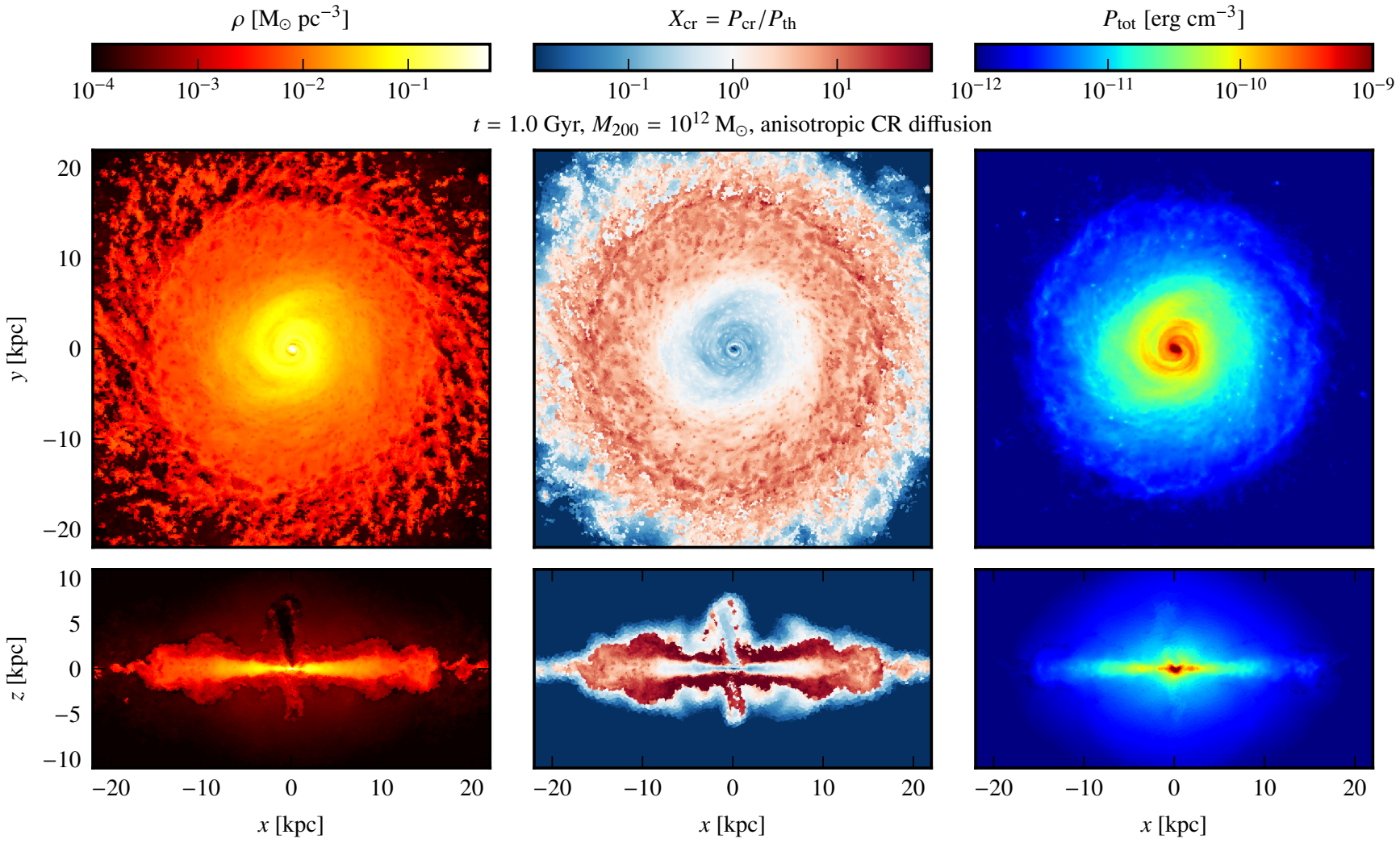
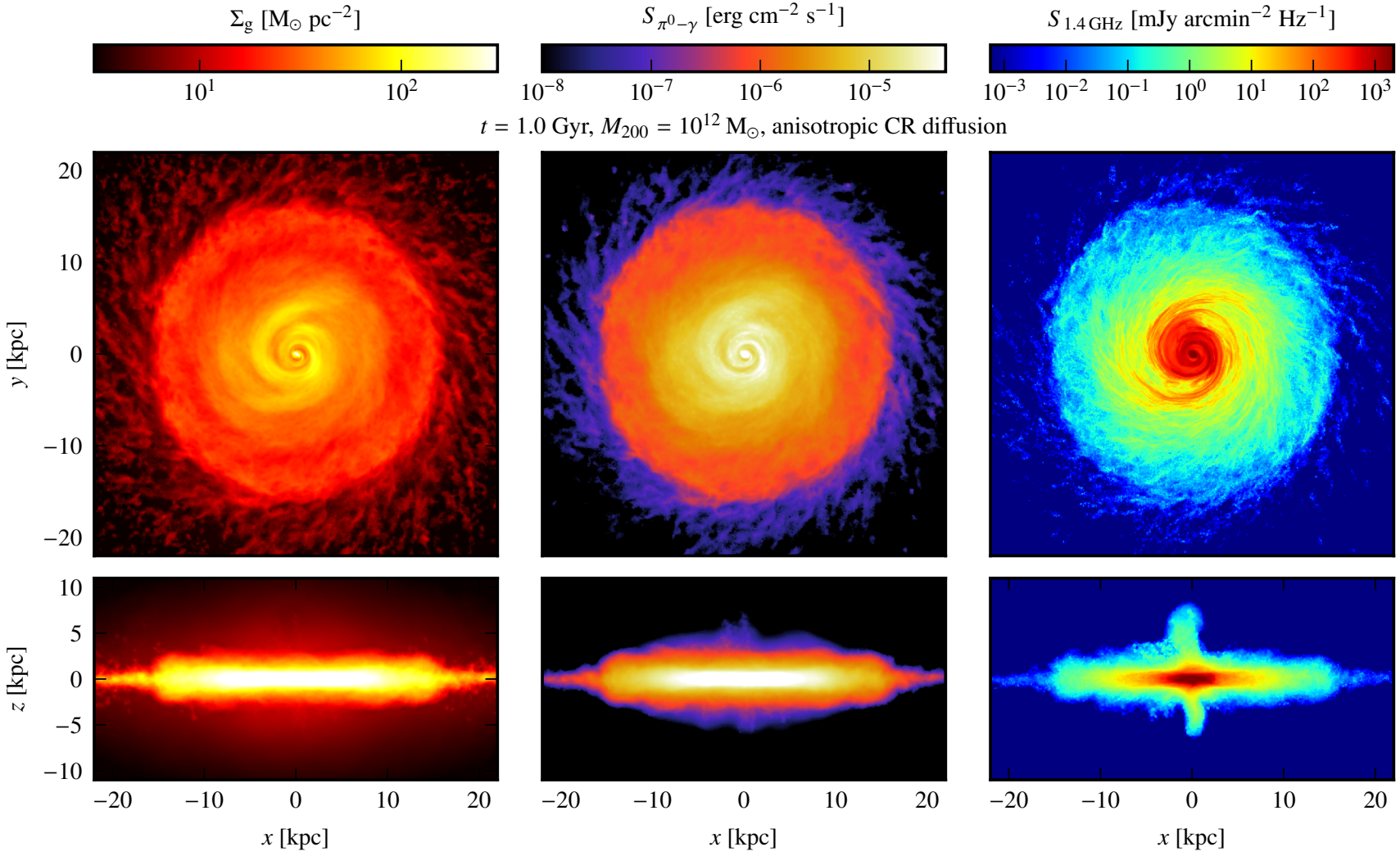


CP+ (2017b, 2018)

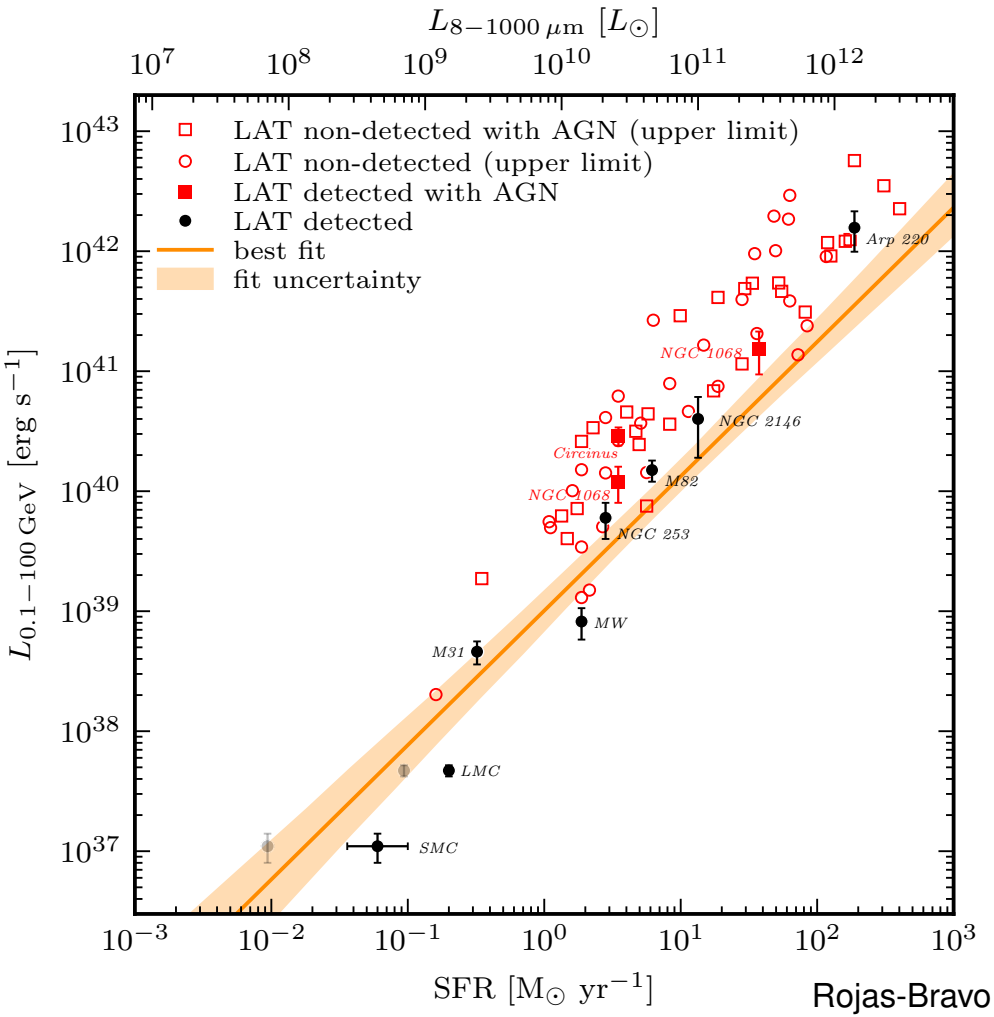
γ-ray and radio emission of Milky Way-like galaxy



CP+ (2017b, 2018)

Far infra-red – gamma-ray correlation

Universal conversion: star formation → cosmic rays → gamma rays



Rojas-Bravo & Araya (2016)

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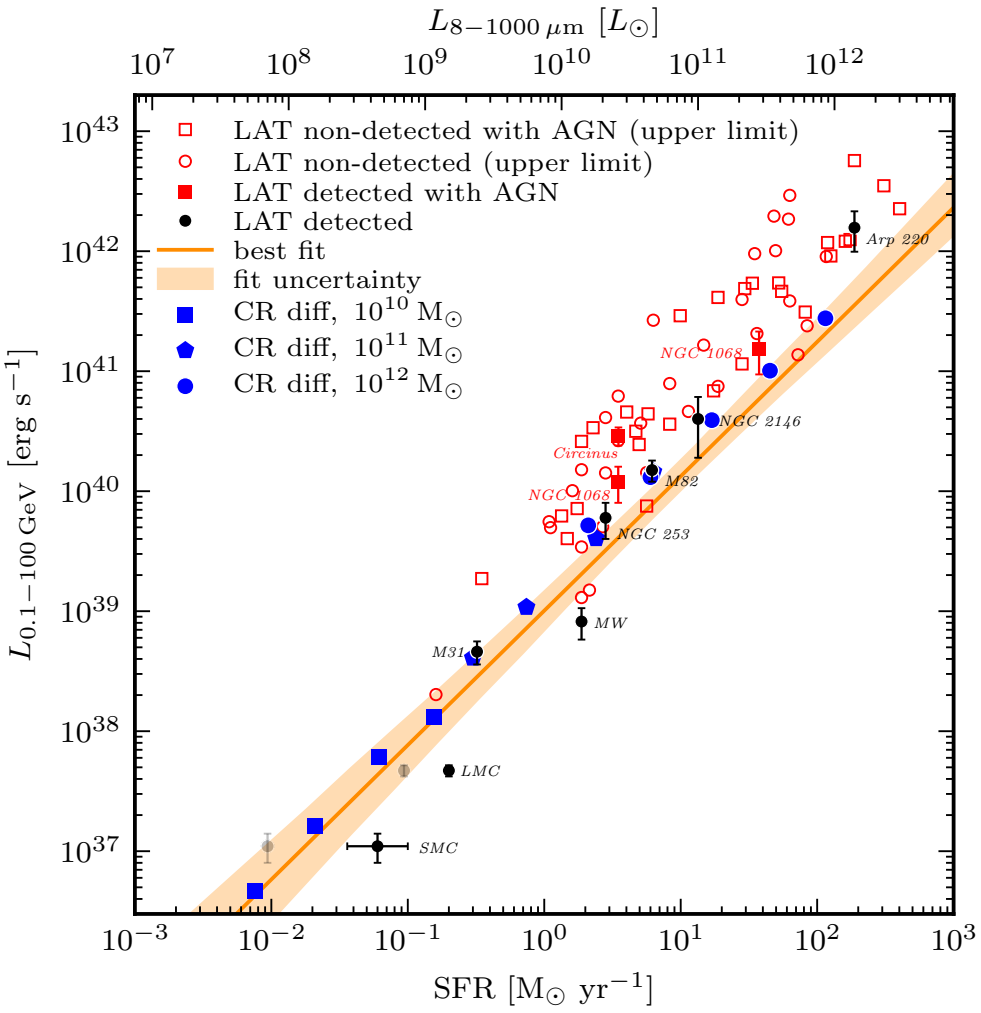

CP+ (2017b)

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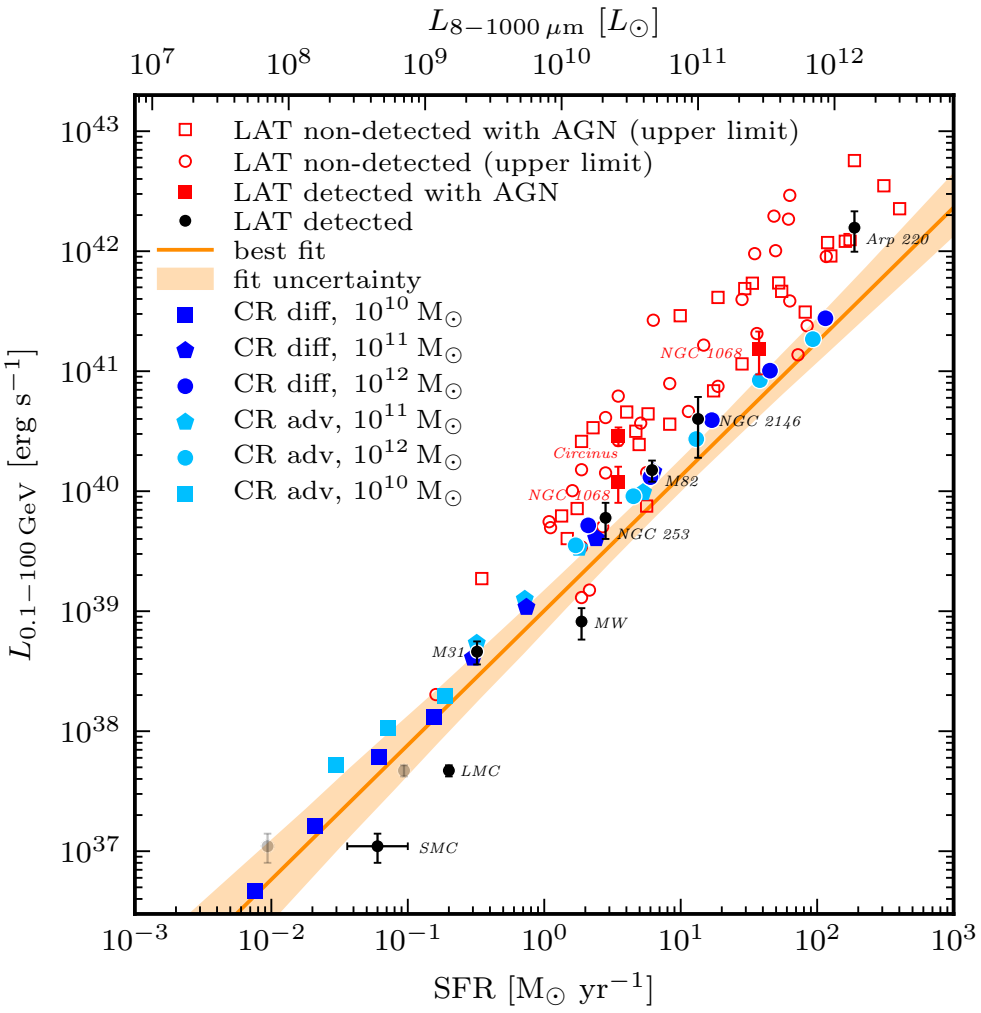

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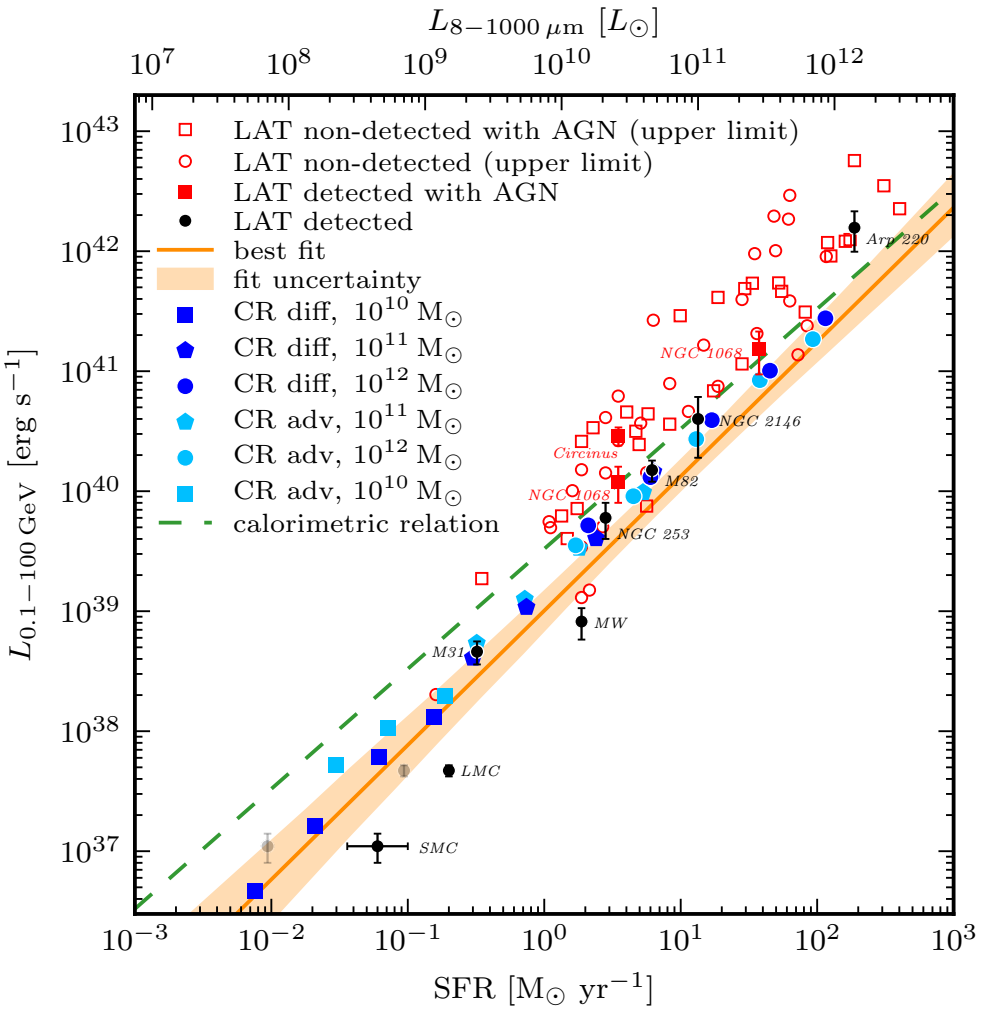


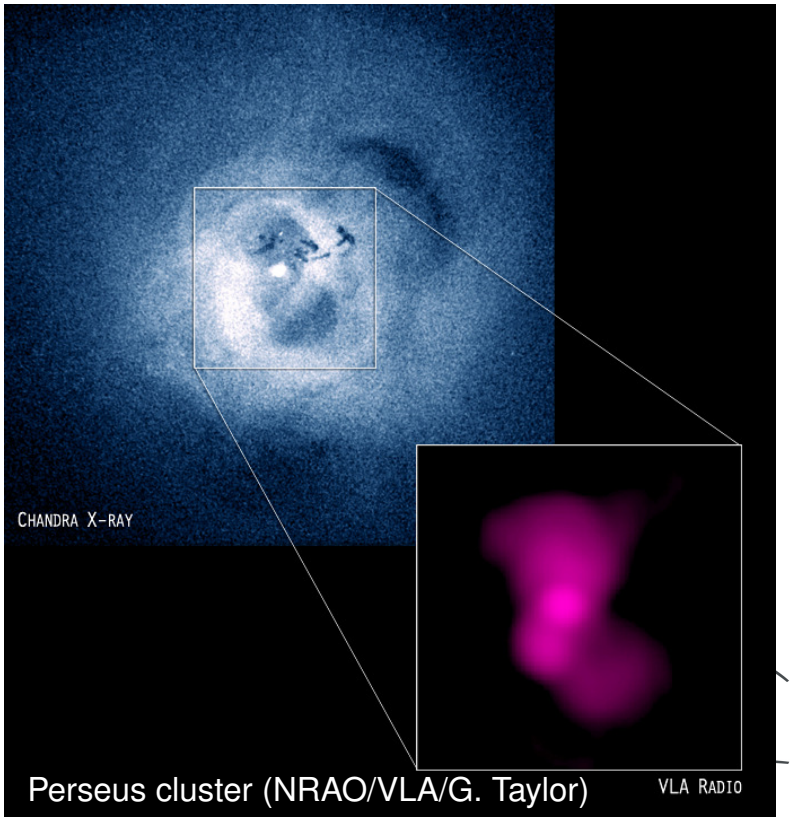
CP+ (2017b)

Outline

Feedback by active galactic nuclei

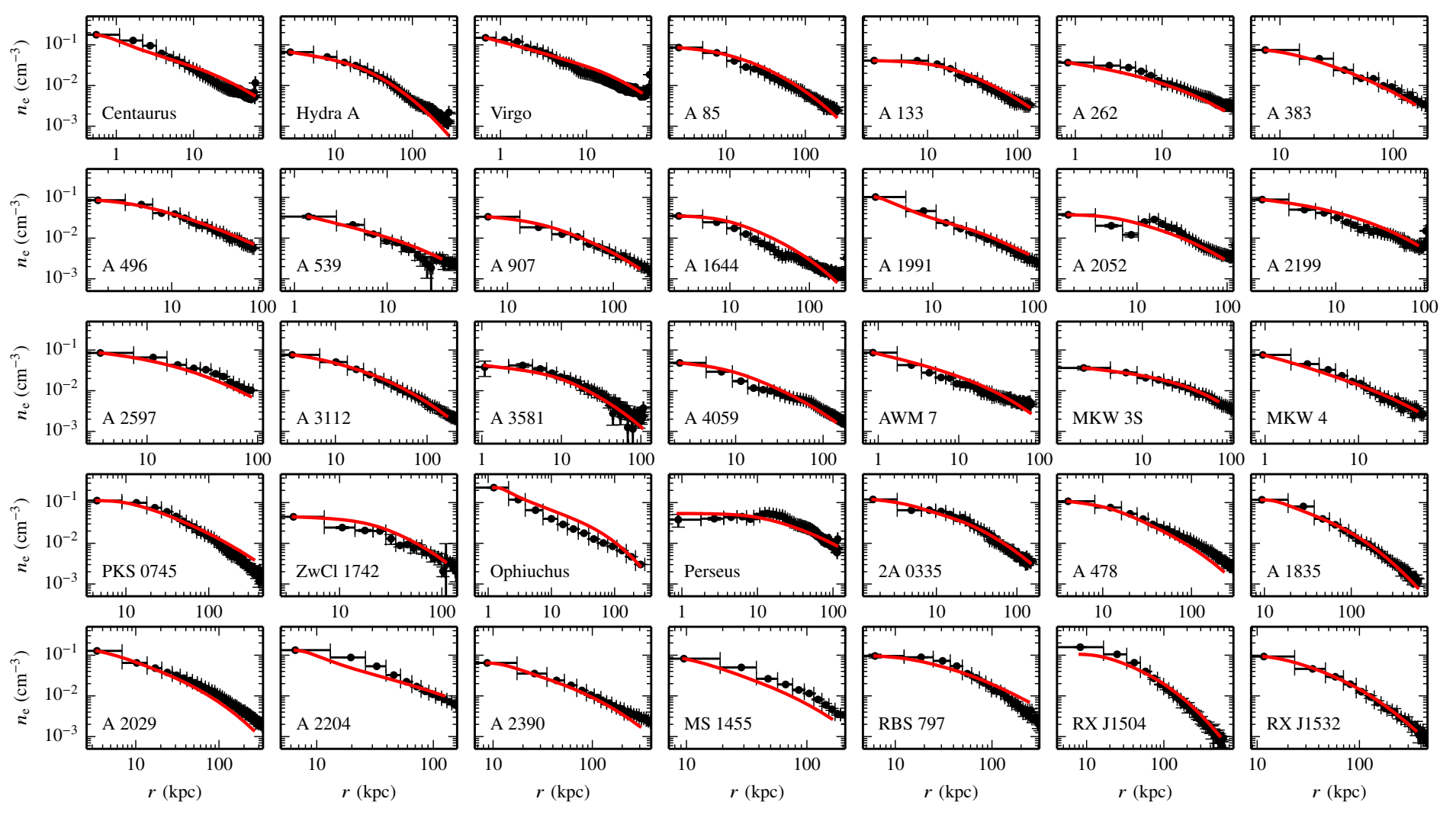
Paradigm: accreting super-massive black holes at galaxy cluster centers launch relativistic jets, which provide energetic feedback to balance cooling $\Rightarrow$ **but how?**

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

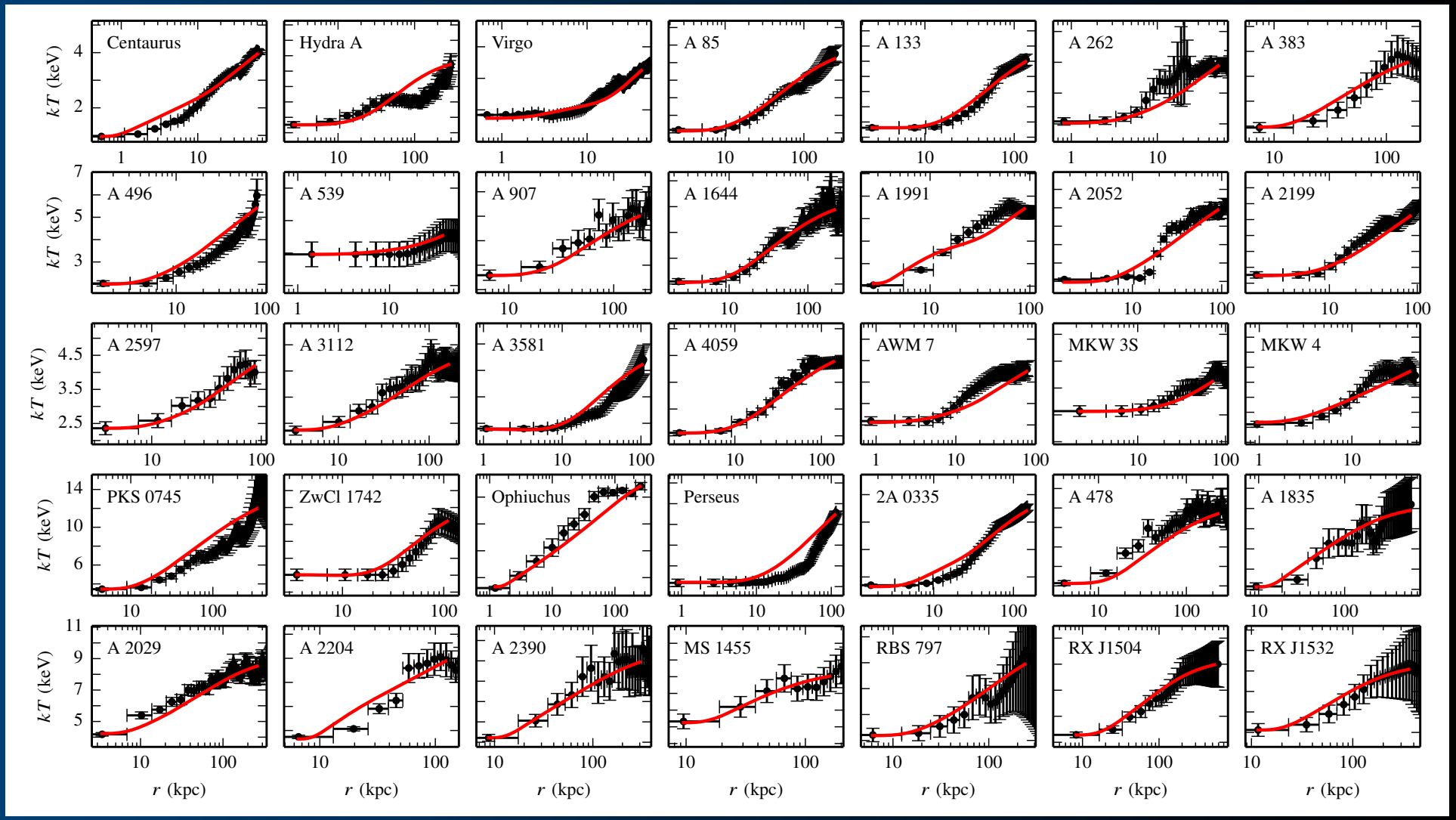


Perseus cluster (NRAO/VLA/G. Taylor)

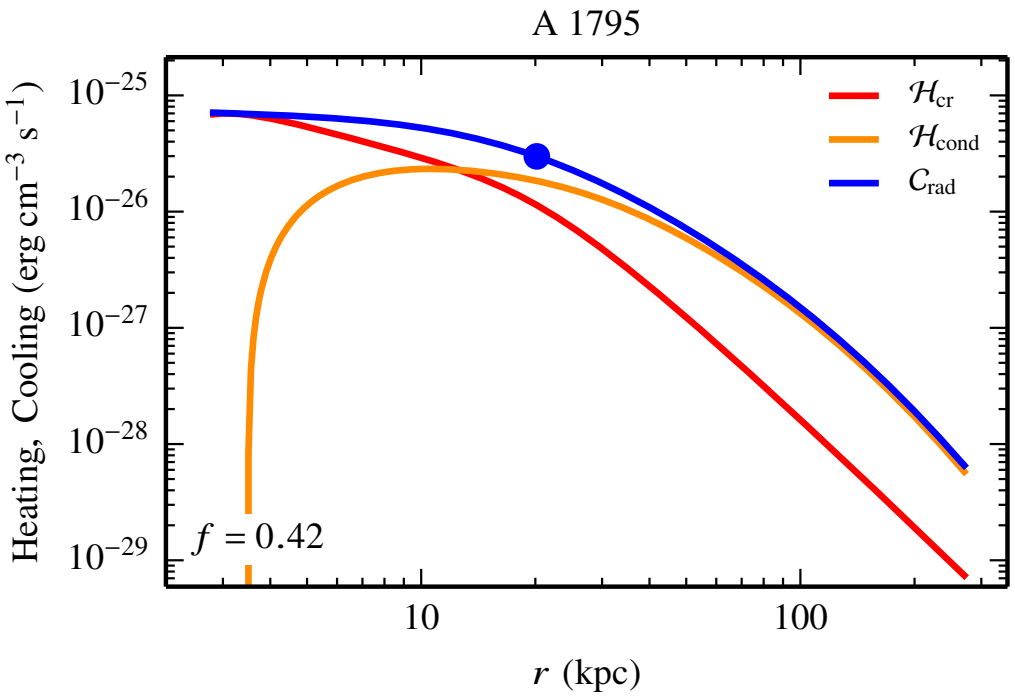
Gallery of solutions: density profiles



Gallery of solutions: temperature profiles



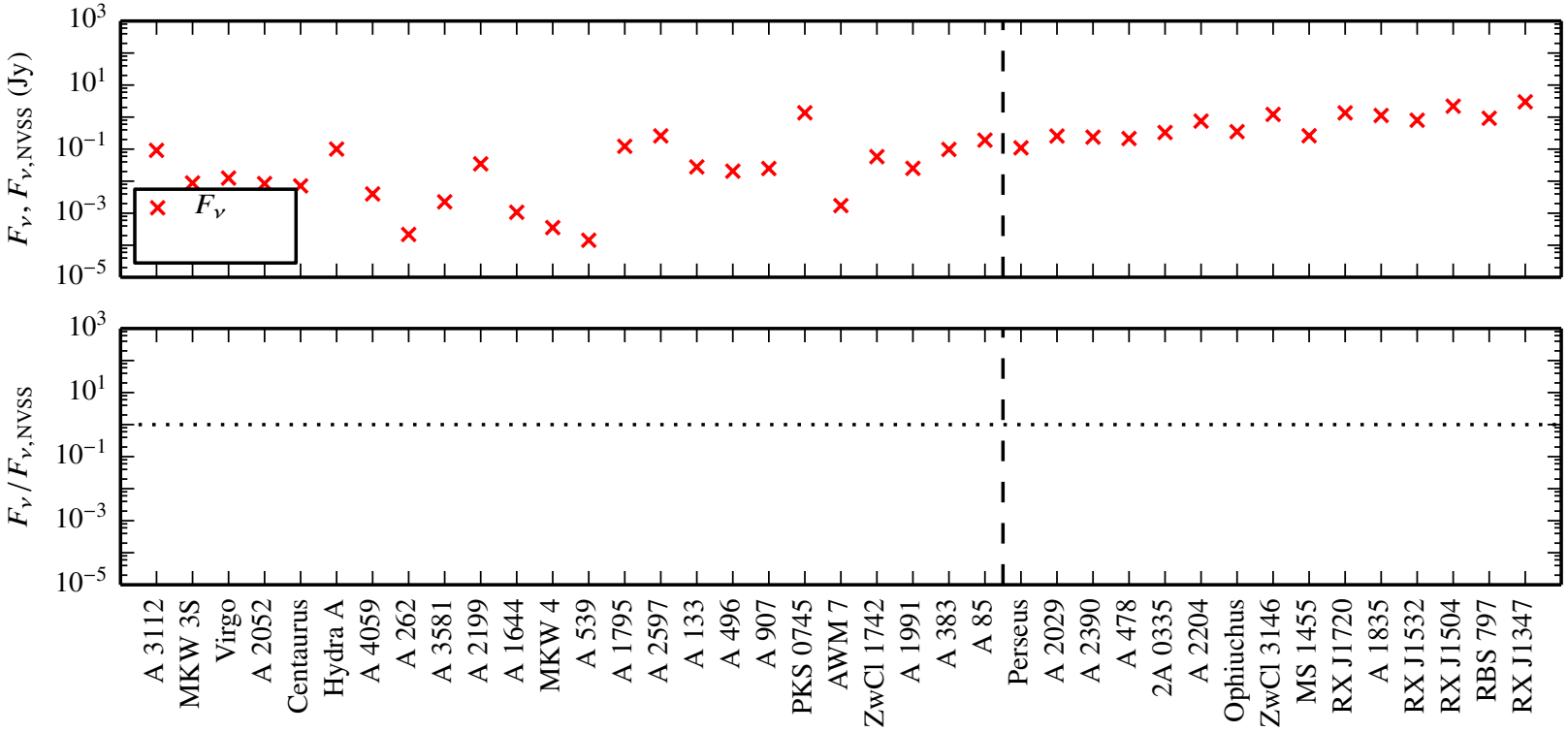
Case study A1795: heating and cooling



Jacob & CP (2016a)

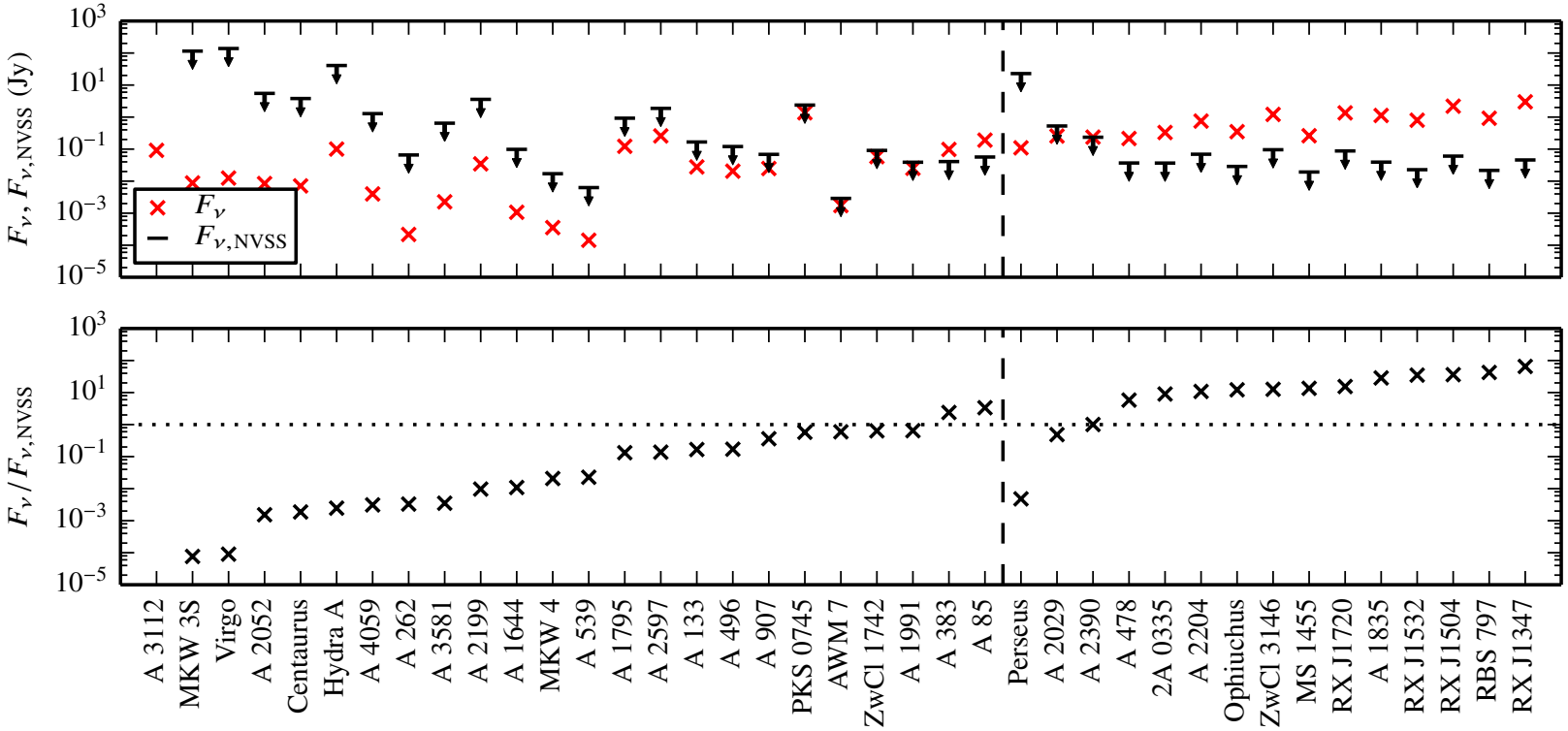
- CR heating dominates in the center
- conductive heating takes over at larger radii, $\kappa = 0.42\kappa_{Sp}$
- $\mathcal{H}_{cr} + \mathcal{H}_{cond} \approx \mathcal{C}_{rad}$: modest mass deposition rate of 1 $M_\odot$ yr^{-1}

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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radio mini halo

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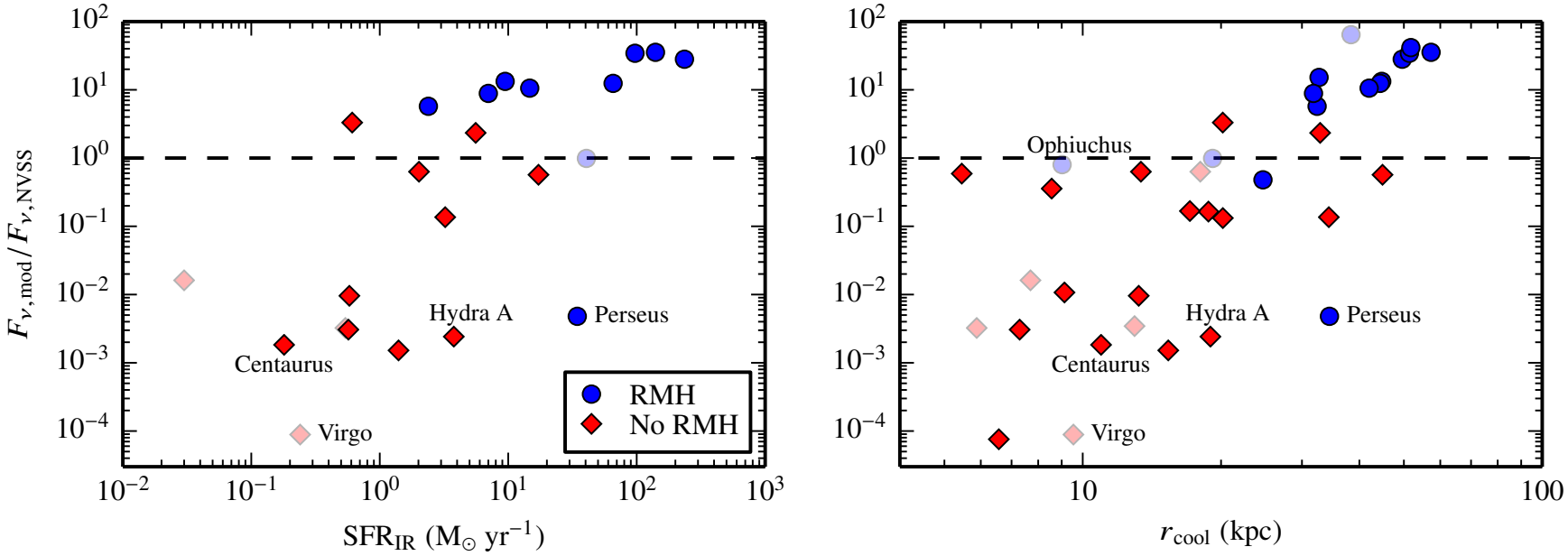
↑

Self-regulated heating/cooling cycle in cool cores

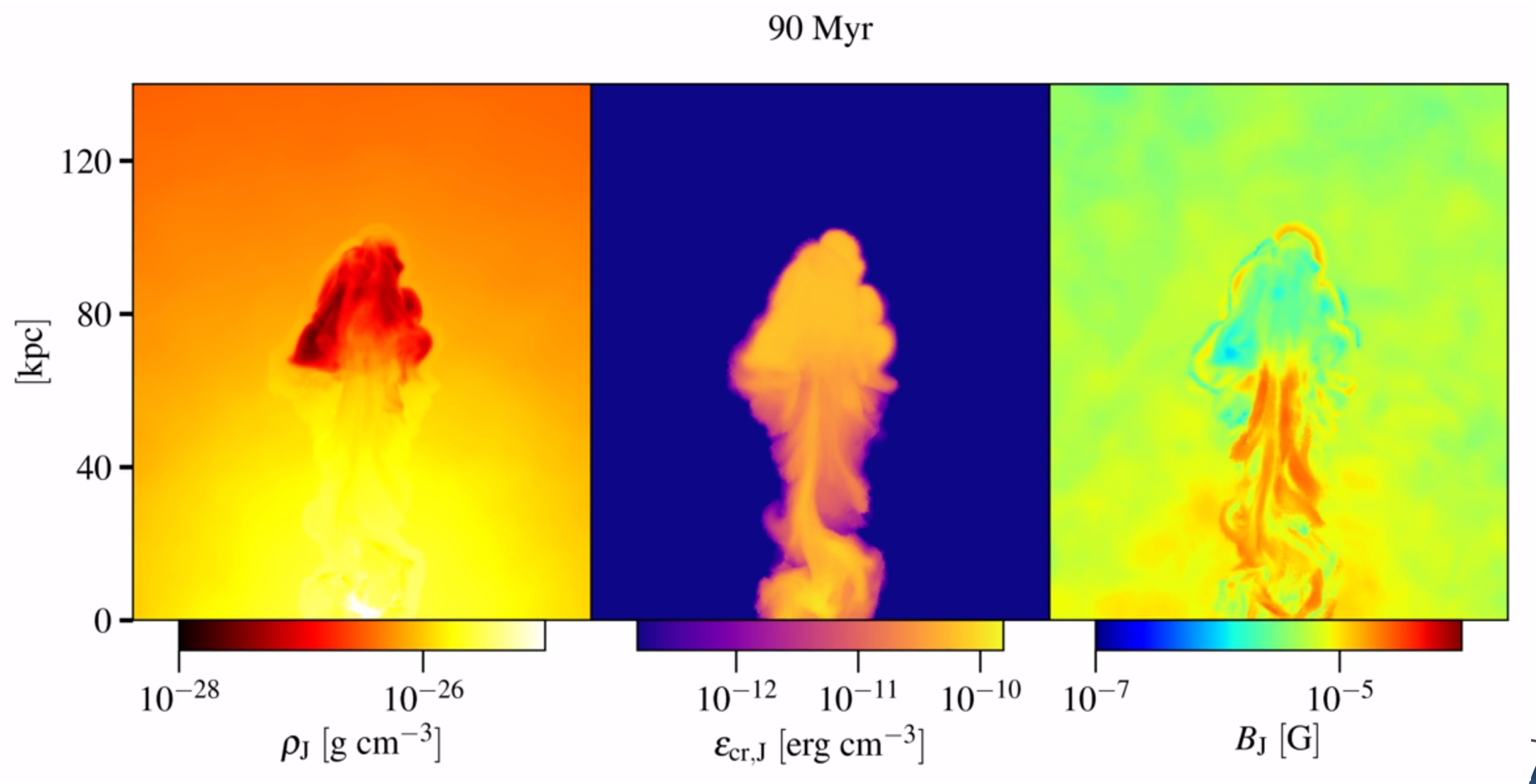


Jacob & CP (2017b)

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

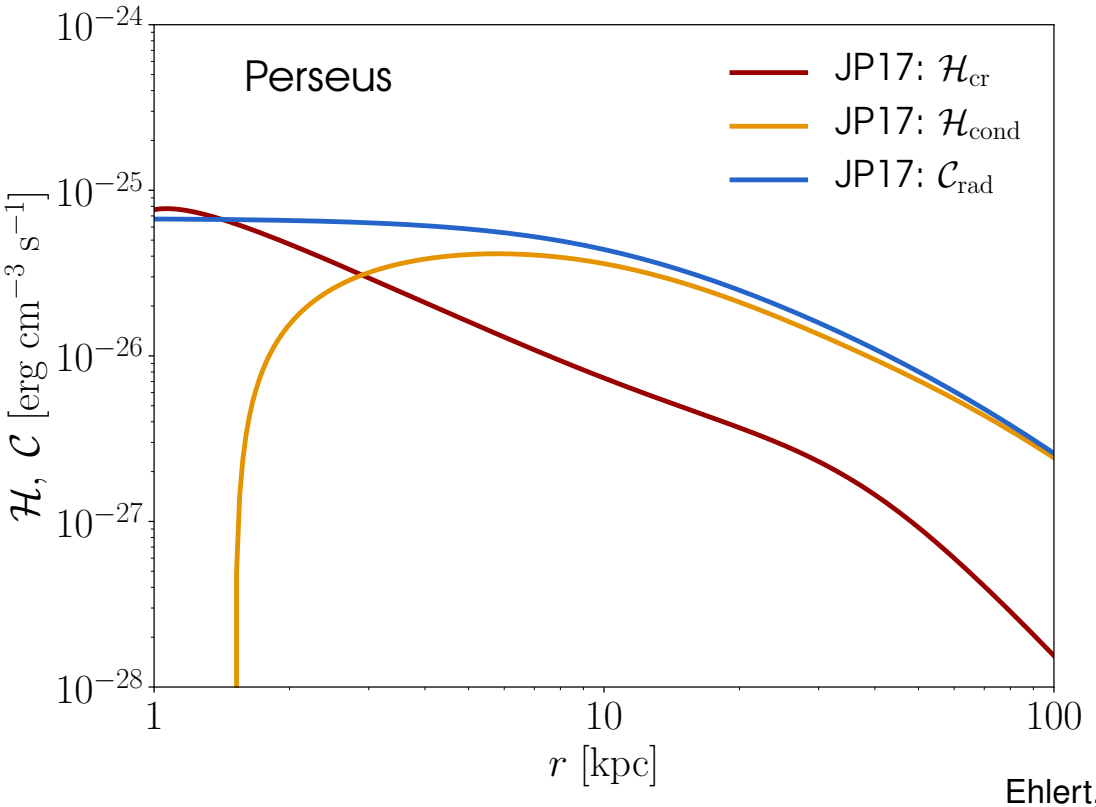
- simmering SF: CR heating is effectively balancing cooling
- abundant SF: heating/cooling out of balance

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



Ehlert, Weinberger, CP+ (2018)

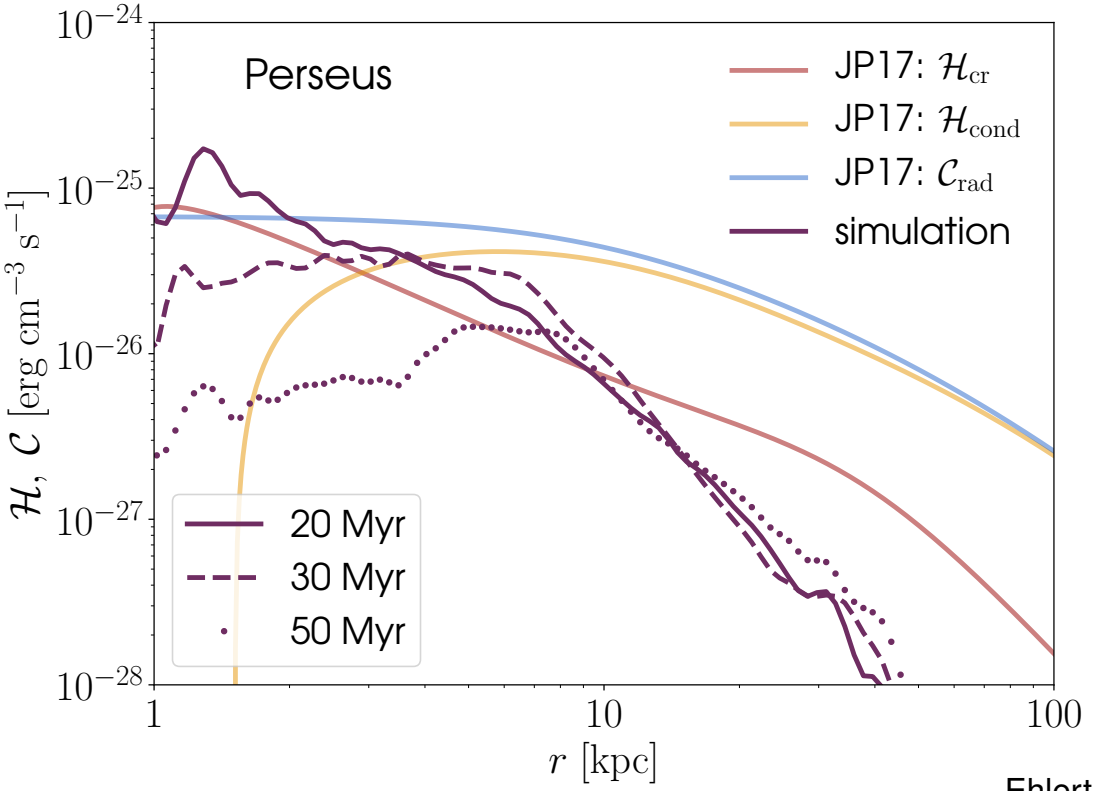
Perseus cluster – heating vs. cooling: theory



Ehlert, Weinberger, CP+ (2018)

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

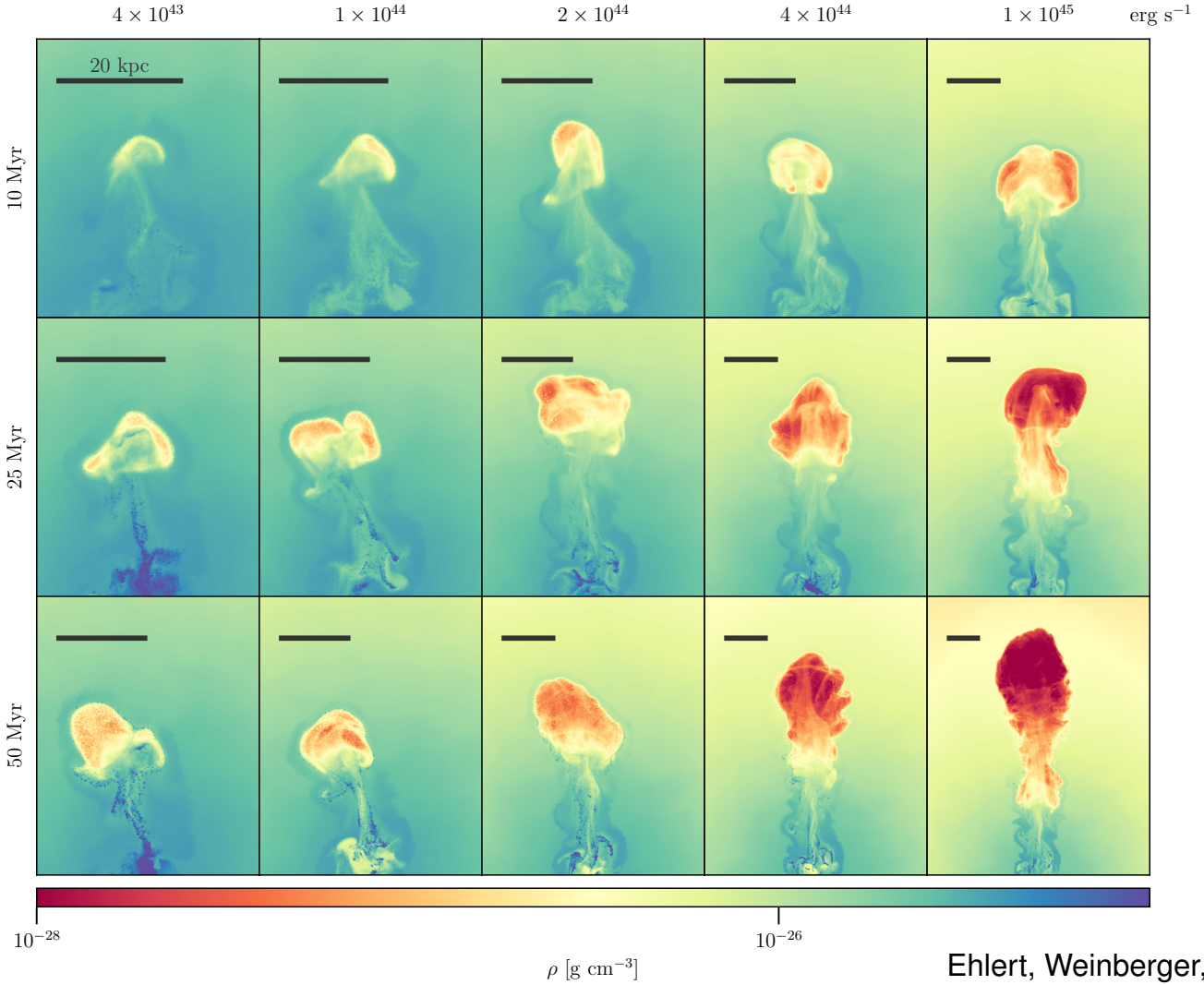
Perseus cluster – heating vs. cooling: simulations



Ehlert, Weinberger, CP+ (2018)

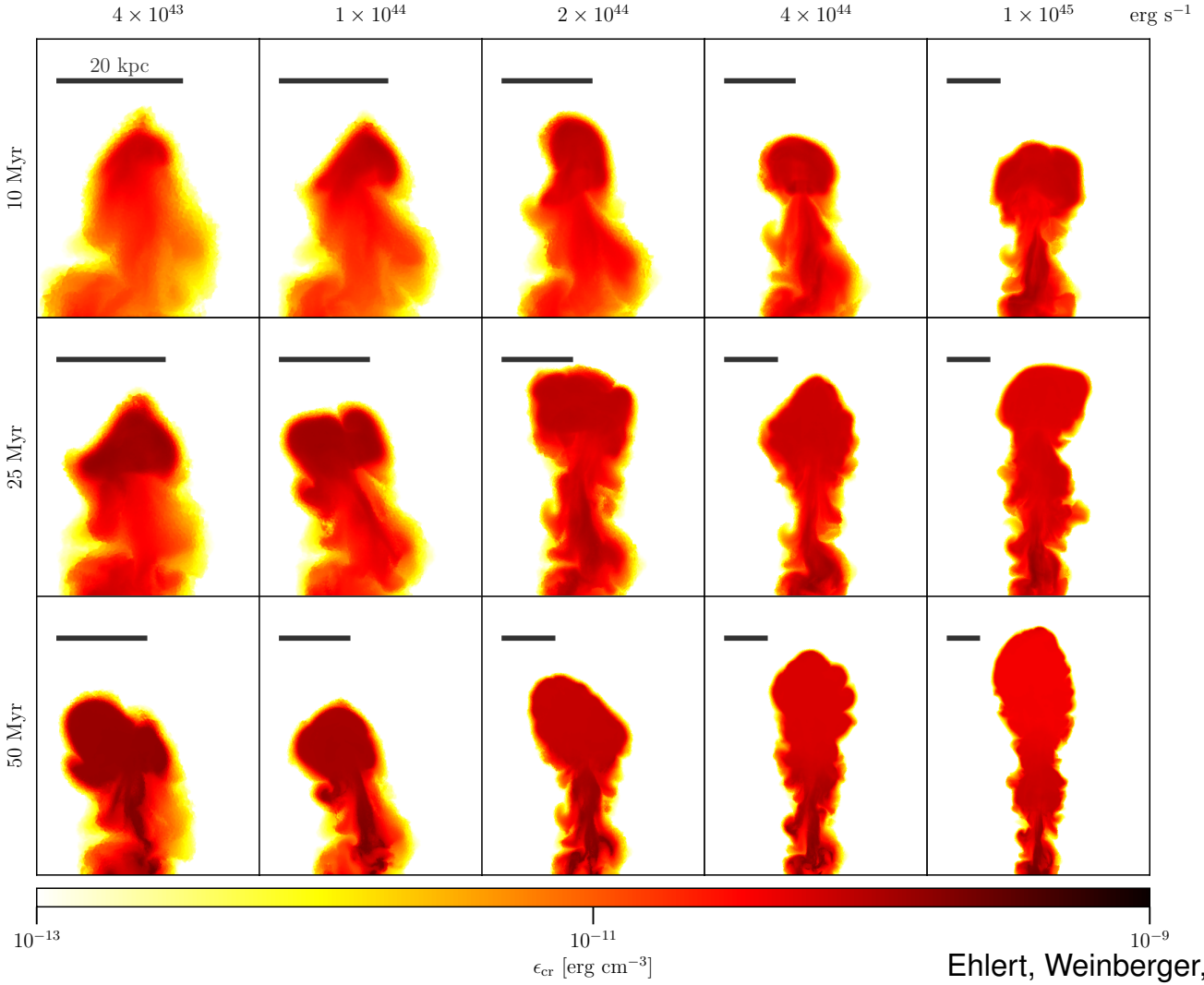
- CR and conductive heating balance radiative cooling: $\mathcal{H}_{\rm cr} + \mathcal{H}_{\rm cond} \approx \mathcal{C}_{\rm rad}$: modest mass deposition rate of 1 $M_\odot$ yr^{-1}
- **simulated CR heating rate matches 1D steady state model**

Matrix of jet simulations: density at 70 Myrs



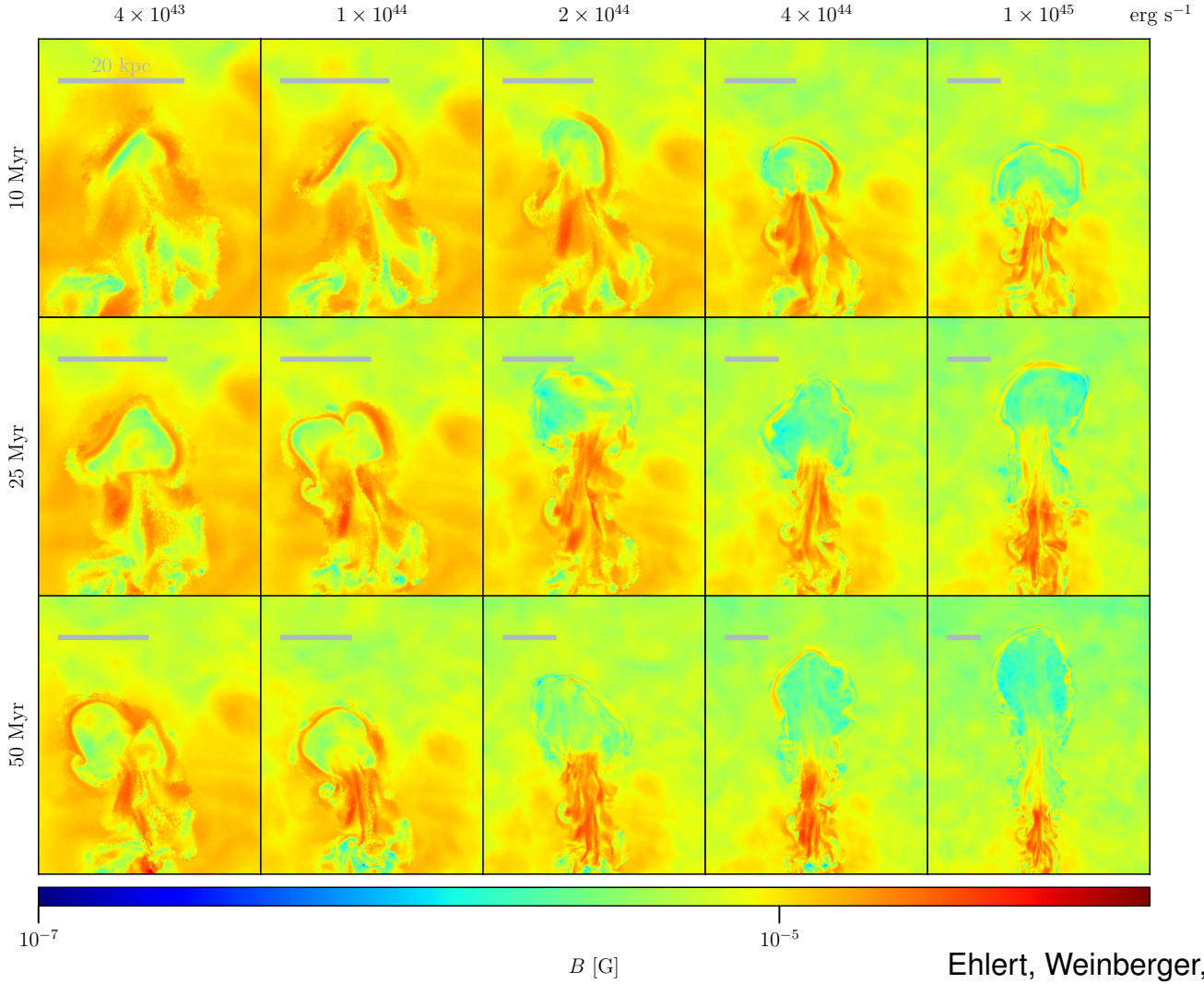
Ehlert, Weinberger, CP+ (2018)

Matrix of jet simulations: CR energy density at 70 Myrs



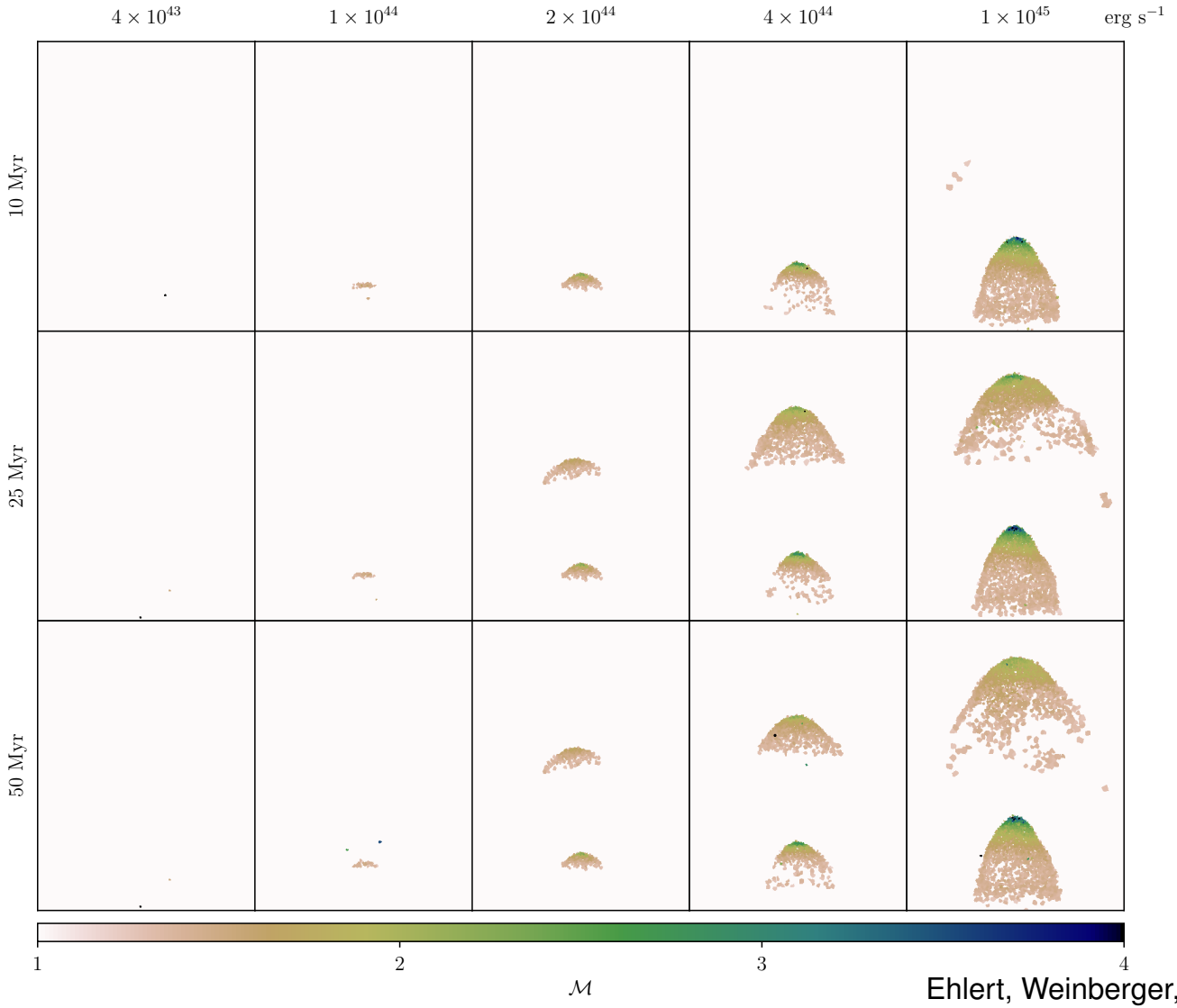
Ehlert, Weinberger, CP+ (2018)

Matrix of jet simulations: magnetic field at 70 Myrs



Ehlert, Weinberger, CP+ (2018)

Matrix of jet simulations: shock strengths at 70 Myrs



Ehlert, Weinberger, CP+ (2018)

Conclusions on CR feedback in galaxies and clusters

- CR pressure feedback slows down star formation
- galactic winds are naturally explained by CR diffusion & streaming

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Conclusions on CR feedback in galaxies and clusters

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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 – 1

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.

Literature for the talk – 2

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

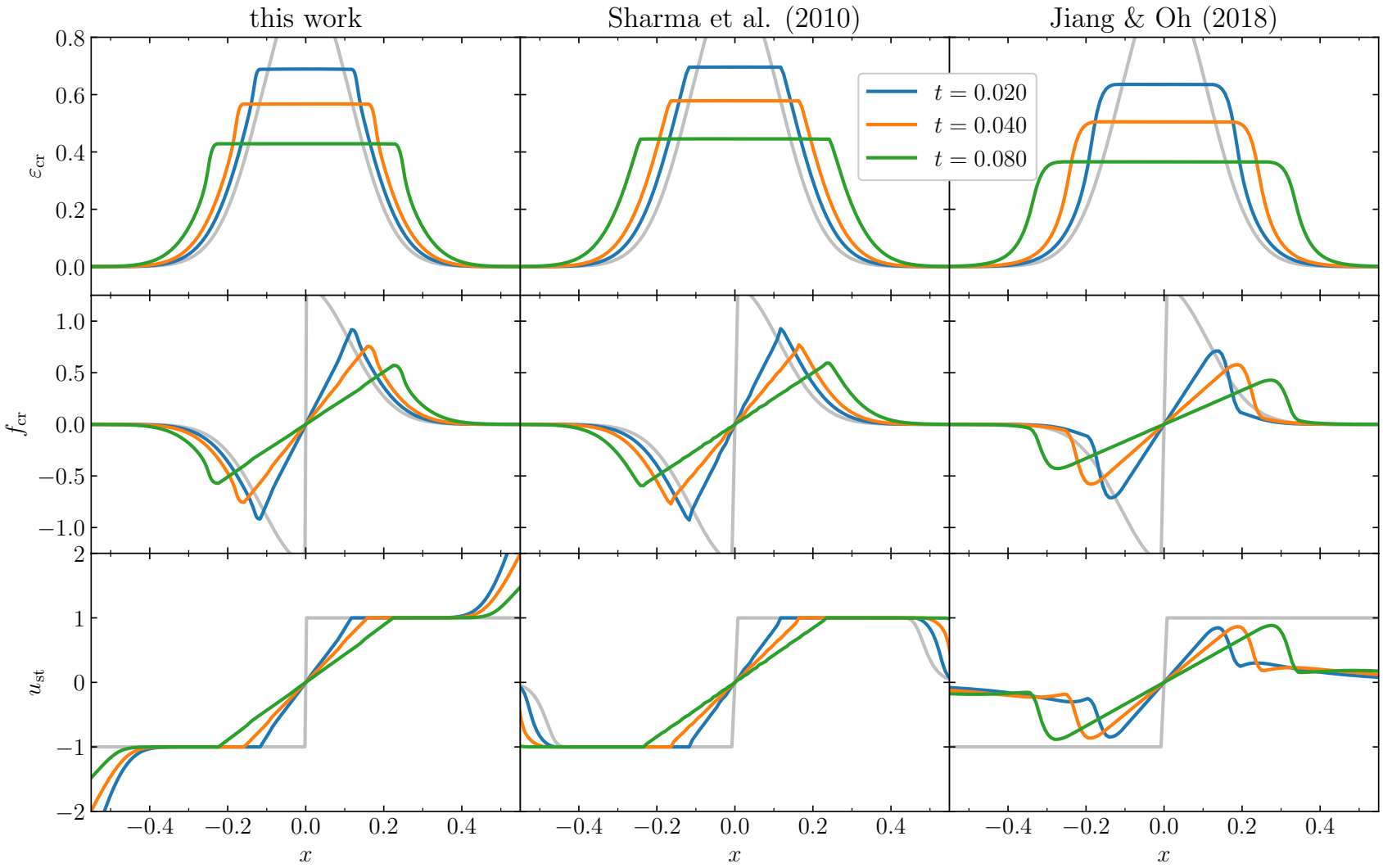
- Pfrommer, Pakmor, Simpson, Springel, *Simulating Gamma-ray Emission in Star-forming Galaxies,* 2017b, ApJL.
- Pfrommer, Pakmor, Simpson, Springel, *Simulating Radio Synchrotron Emission in Galaxies: the Origin of the Far Infrared–Radio Correlation,* 2018.

Cosmic ray heating in clusters:

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

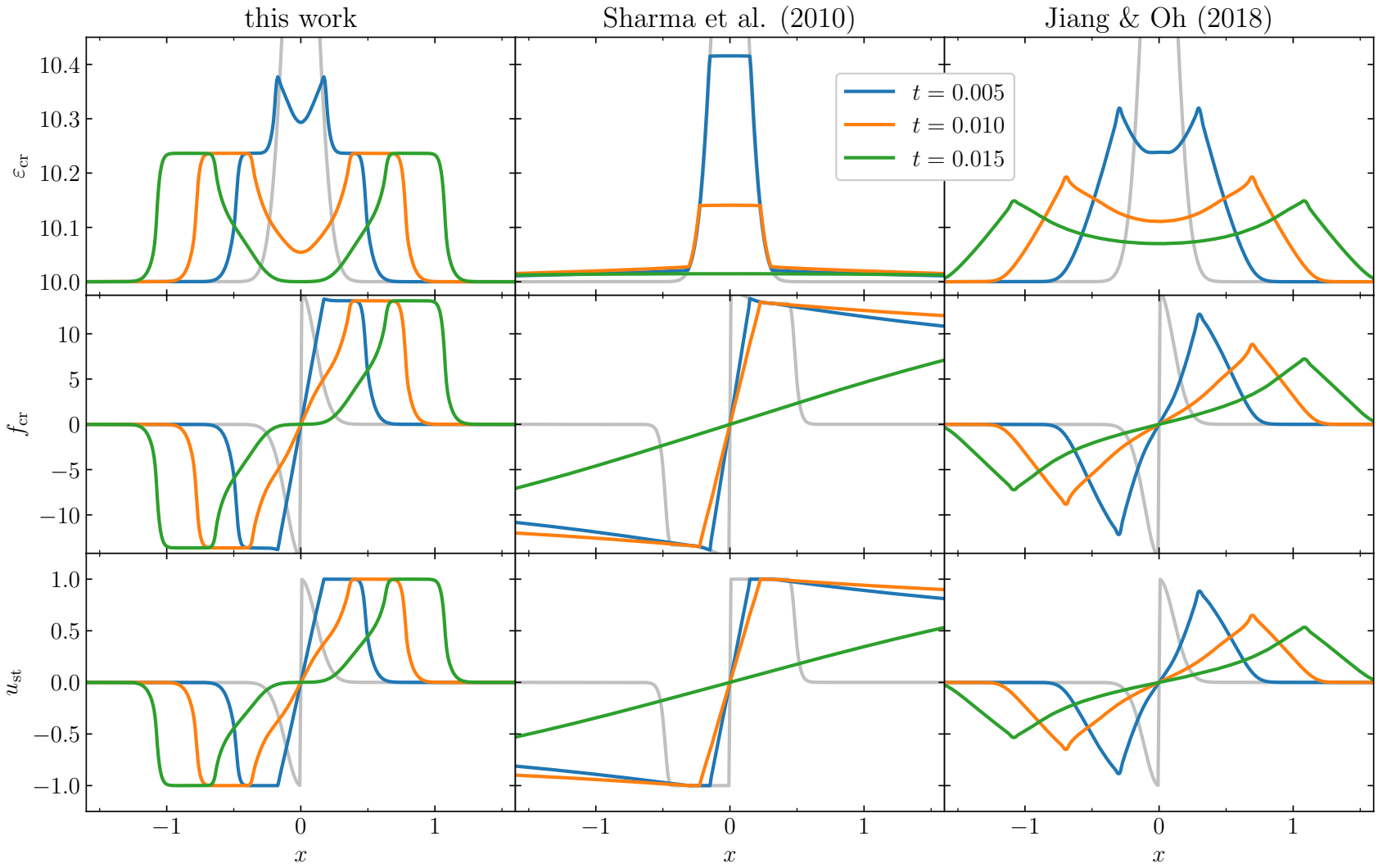
Additional slides

CR transport – evolution of isolated Gaussian



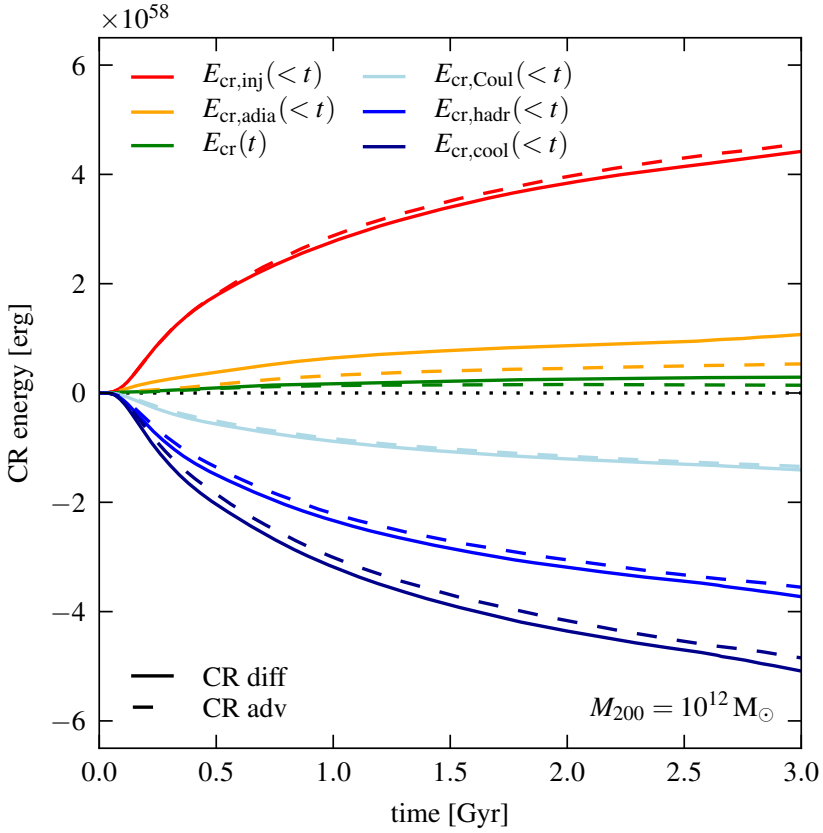
Thomas & CP (2018)

CR transport – evolution of Gaussian with background



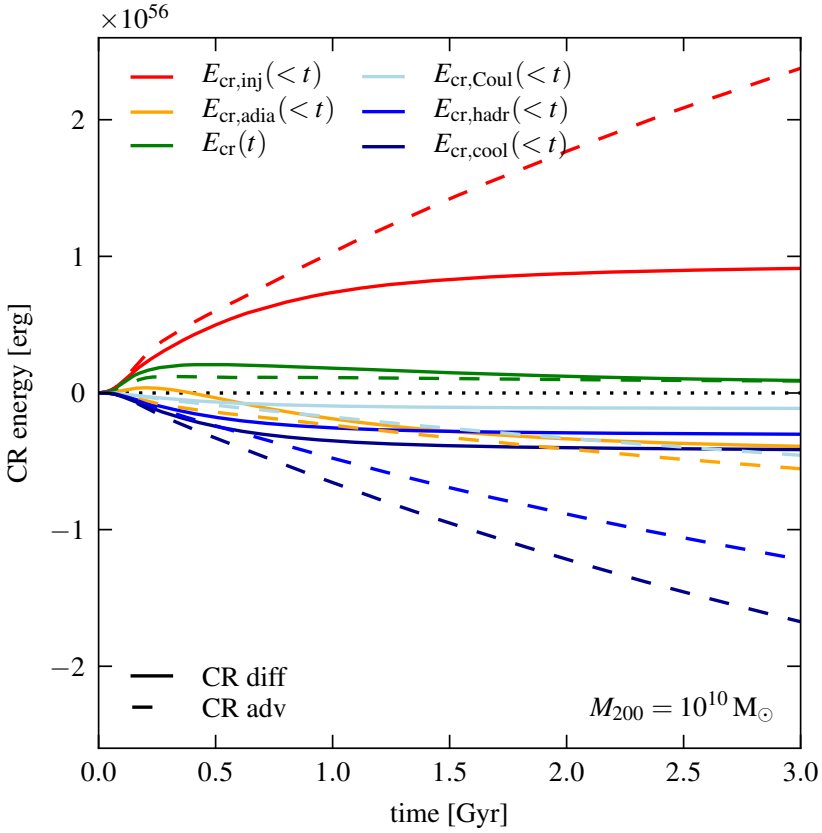
Thomas & CP (2018)

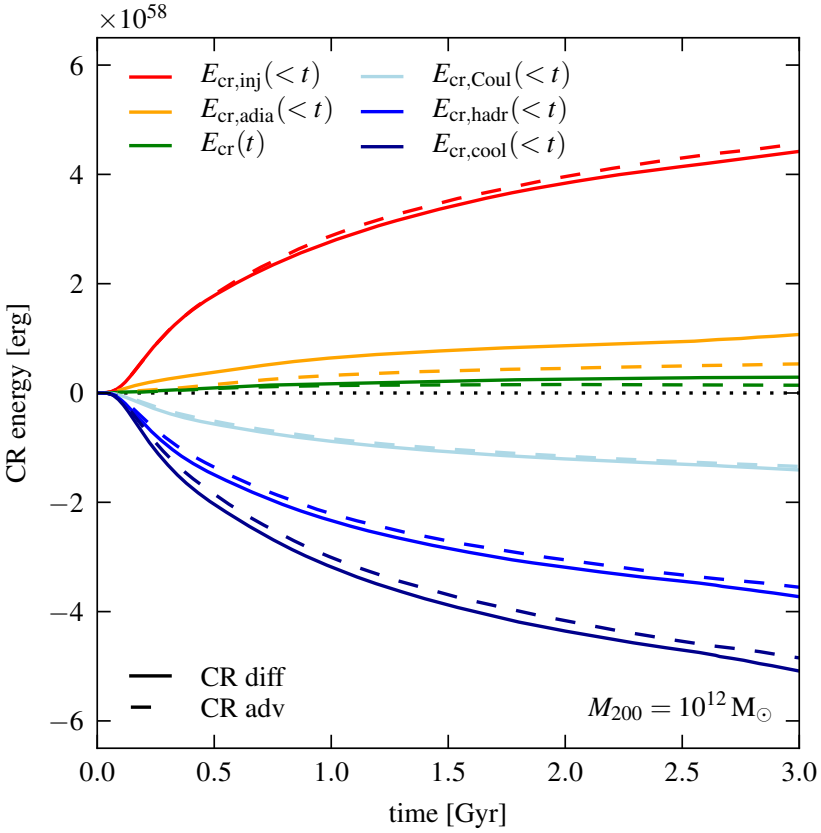
Time evolution of CR energies



CP+ (2017b)

Time evolution of CR energies





CP+ (2017b)

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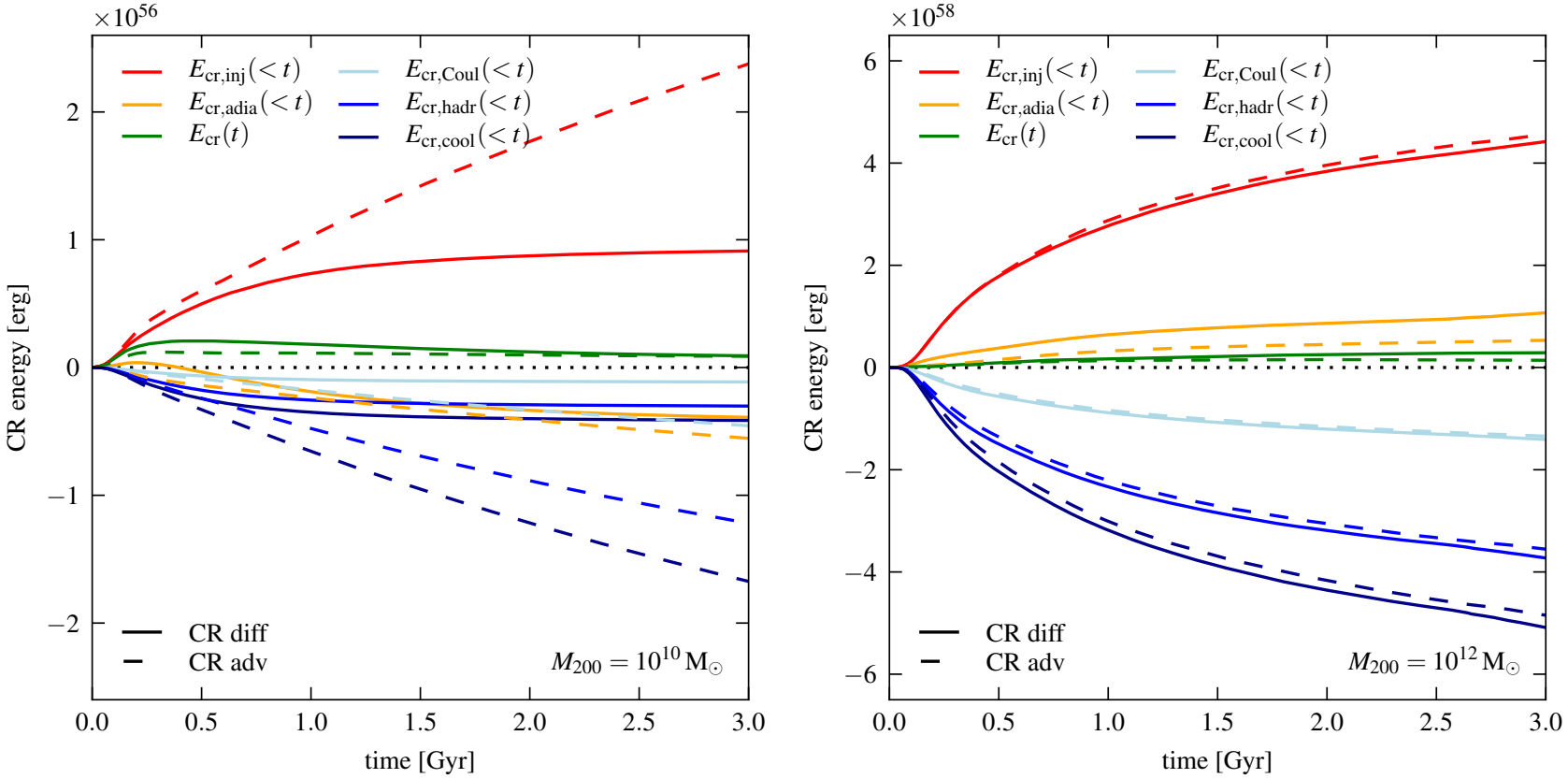

CP+ (2017b)

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