Cosmic-ray transport from acceleration at SNRs to galactic scales

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in collaboration with

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CRATER 2018, L'Aquila – May 2018

Outline

Outline

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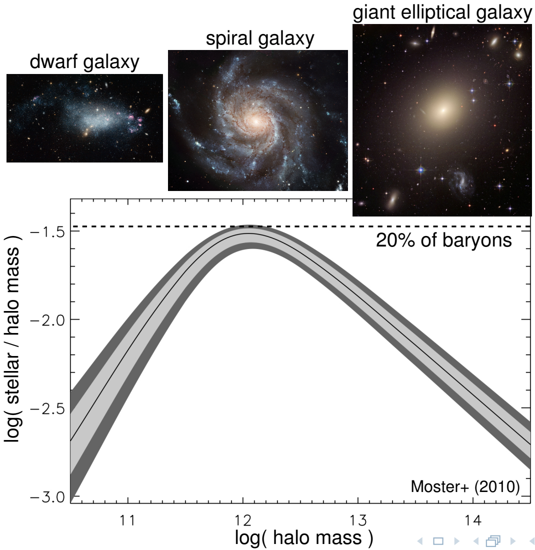
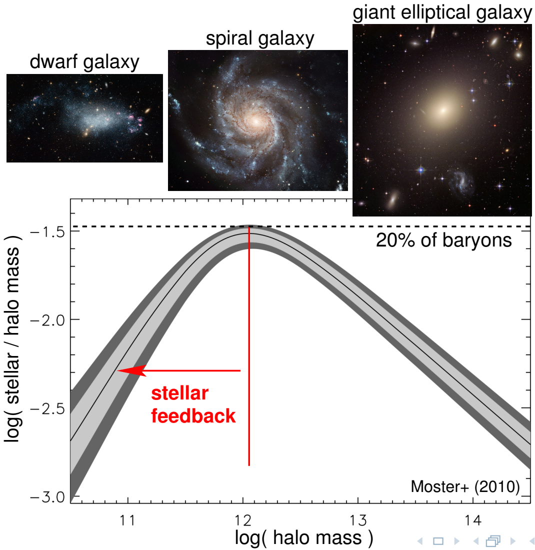
Puzzles in galaxy formation

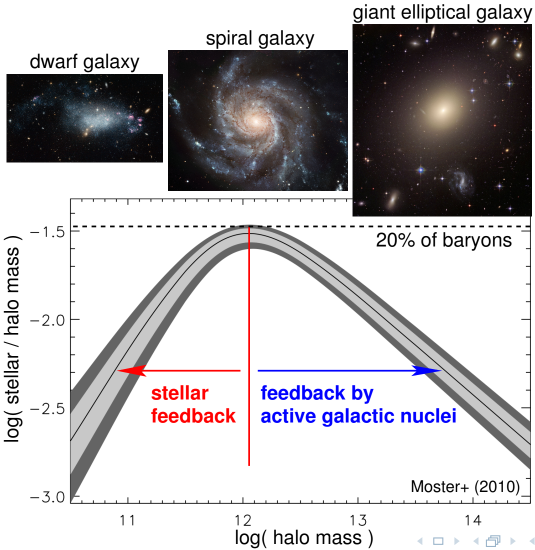
Puzzles in galaxy formation



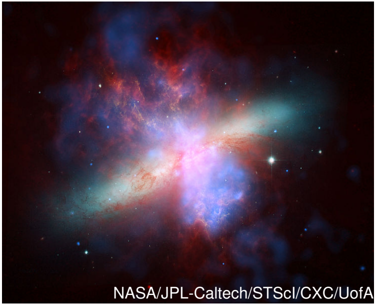
Puzzles in galaxy formation



Puzzles in galaxy formation



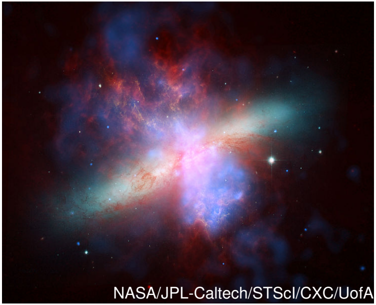
How are galactic winds driven?



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?

How are galactic winds driven?



super wind in M82

- thermal pressure provided by supernovae or AGNs?
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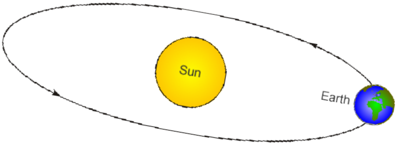
observed energy equipartition between cosmic rays, thermal gas and magnetic fields
$\rightarrow$ suggests self-regulated feedback loop with CR driven winds

Cosmic ray feedback: an extreme multi-scale problem



Milky Way-like galaxy:

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

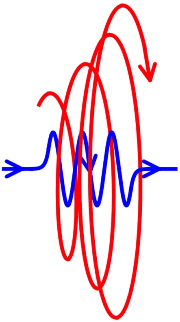
gyro-orbit of GeV cosmic ray:

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

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

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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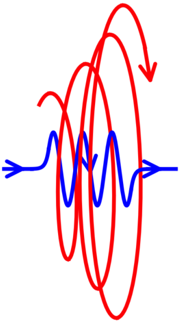

$\rightarrow$ CRs exert a pressure on the thermal gas by means of scattering off of Alfvén waves

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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- CRs stream down their own pressure gradient relative to the gas, CRs diffuse in the wave frame due to pitch angle scattering by MHD waves (both transports are along the local direction of $\boldsymbol{B}$):

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

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

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

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

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

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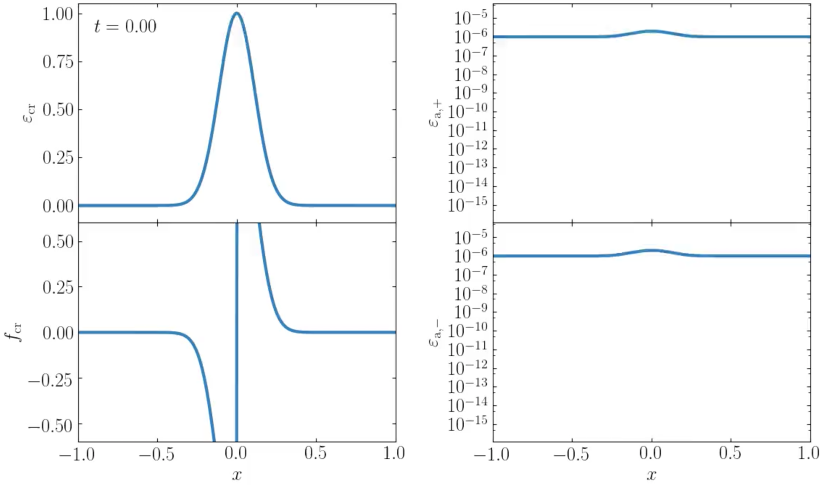
- energy equations with $\varepsilon = \varepsilon_{\rm th} + \rho v^2/2$:

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

Non-equilibrium CR streaming and diffusion

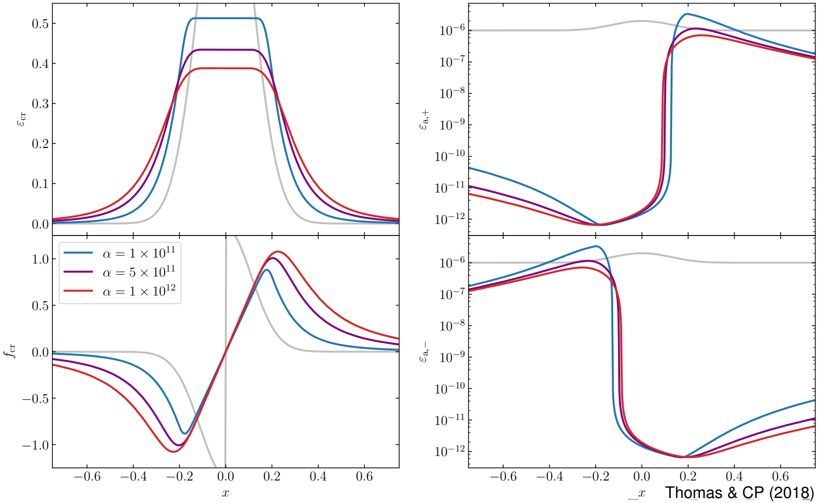
Coupling the evolution of CR and Alfvén wave energy densities



Thomas & CP (2018)

Non-equilibrium CR streaming and diffusion

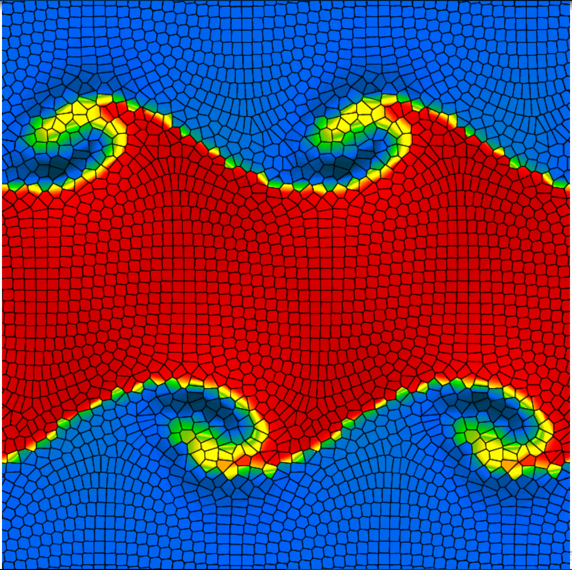
Varying damping rate of Alfvén waves modulates the diffusivity of solution



Thomas & CP (2018)

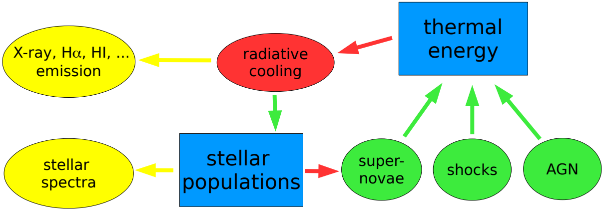
Outline

Cosmological moving-mesh code AREPO (Springel 2010)



Simulations – flowchart

observables: physical processes:



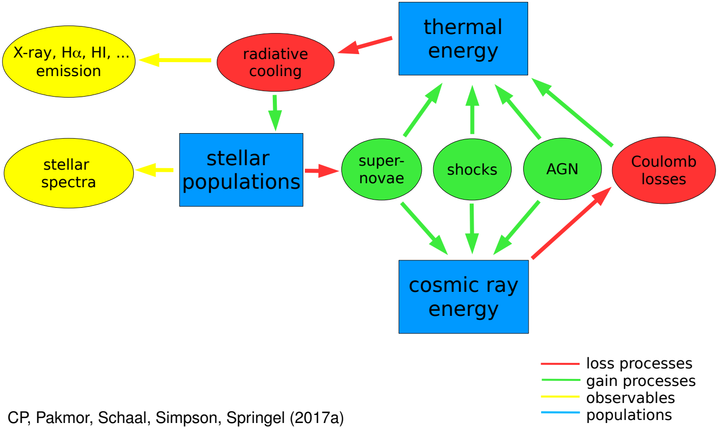
loss processes
gain processes
observables
populations

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

Simulations with cosmic ray physics

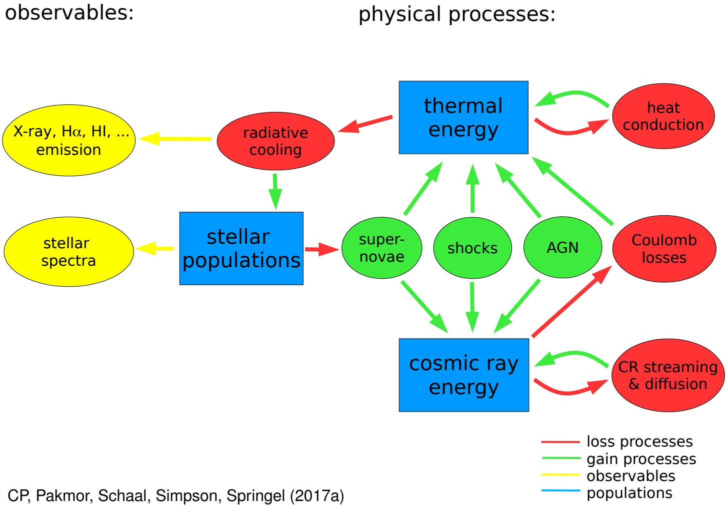
observables:

physical processes:



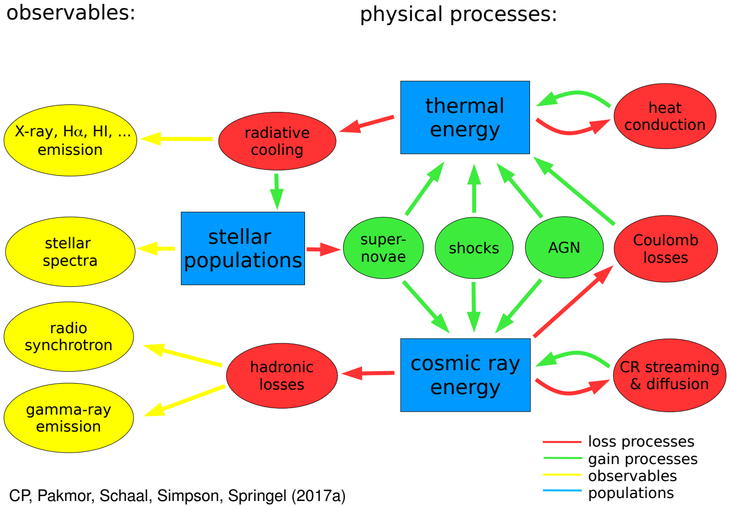
CP, Pakmor, Schaal, Simpson, Springel (2017a)

Simulations with cosmic ray physics



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

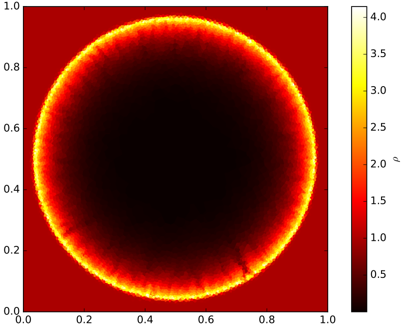
Simulations with cosmic ray physics



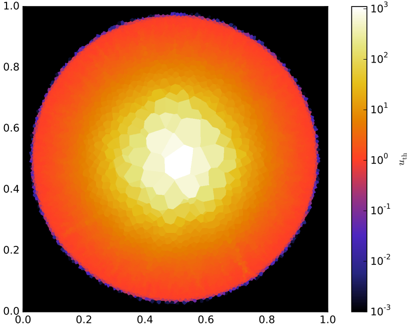
CP, Pakmor, Schaal, Simpson, Springel (2017a)

Sedov explosion

density

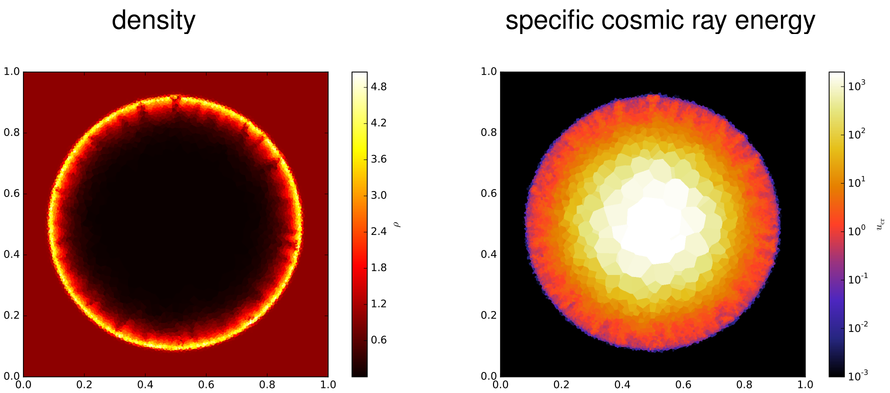


specific thermal energy



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

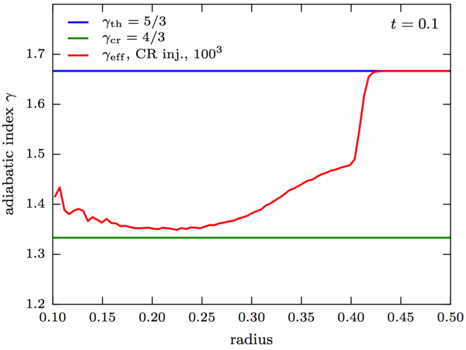
Sedov explosion with CR acceleration



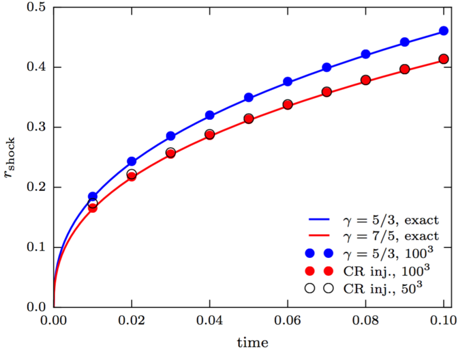
CP, Pakmor, Schaal, Simpson, Springel (2017a)

Sedov explosion with CR acceleration

adiabatic index



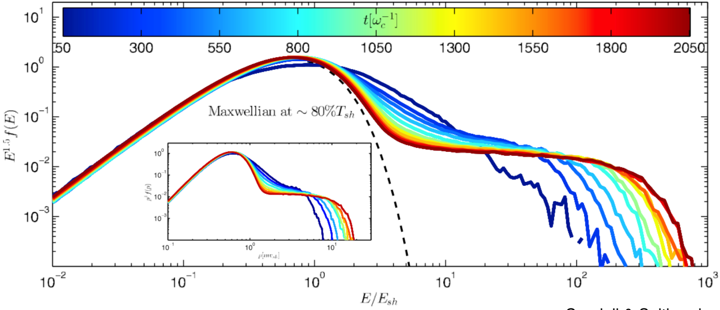
shock evolution



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

Ion spectrum

Non-relativistic *parallel shock* in long-term hybrid simulation



Caprioli & Spitkovsky (2014)

- quasi-parallel shocks ($\boldsymbol{B} \parallel \boldsymbol{n}_s$) efficiently accelerate ions
- quasi-perpendicular shocks ($\boldsymbol{B} \perp \boldsymbol{n}_s$) cannot
- model magnetic obliquity in AREPO simulations

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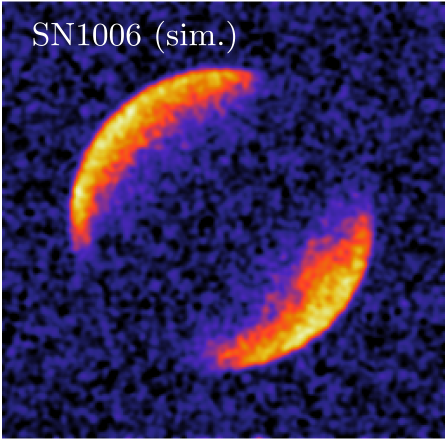
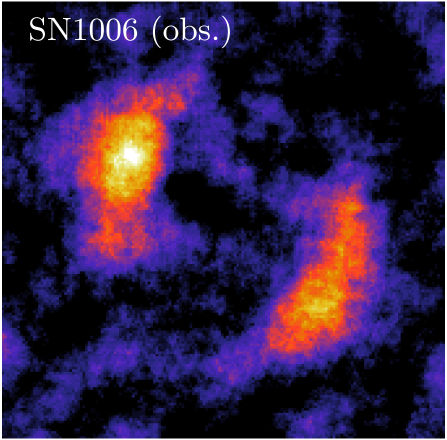
TeV γ rays from shell-type SNRs: SNR 1006

H.E.S.S. observation



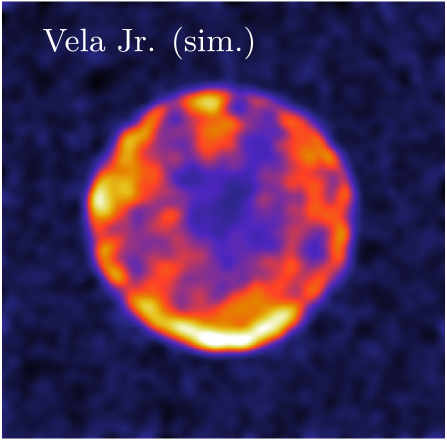
AREPO simulation



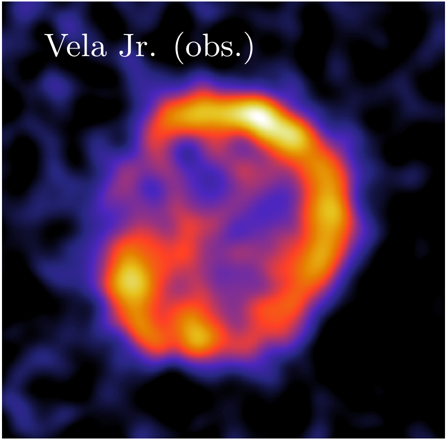
Pais, CP, Ehlert (2018)

TeV γ rays from shell-type SNRs: Vela Junior

H.E.S.S. observation



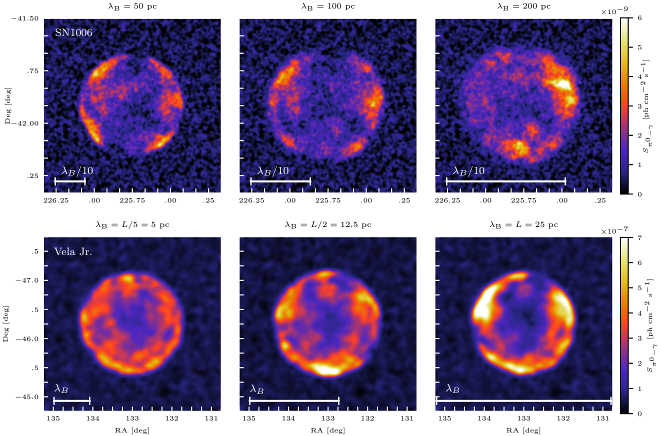
AREPO simulation



Pais, CP, Ehlert (2018)

TeV γ rays from shell-type supernova remnants

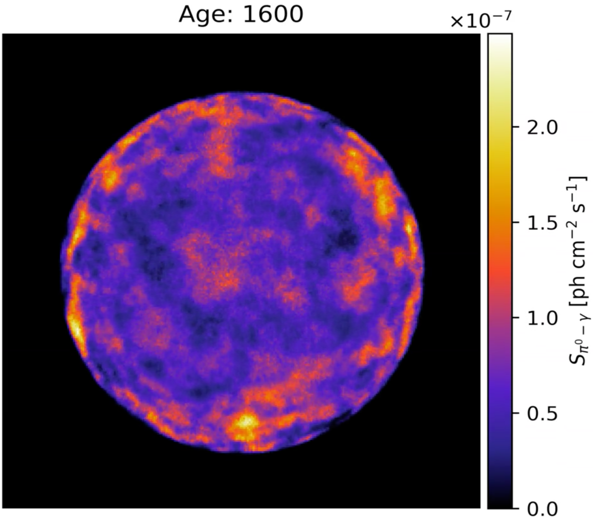
Varying magnetic coherence scale in simulations of SN1006 and Vela Junior



Pais, CP, Ehlert (2018)

SNR 1006: $\lambda_B > 200^{+10}_{-60}$ pc Vela Junior: $\lambda_B = 8^{+15}_{-6}$ pc

TeV γ rays from shell-type SNRs: Vela Junior



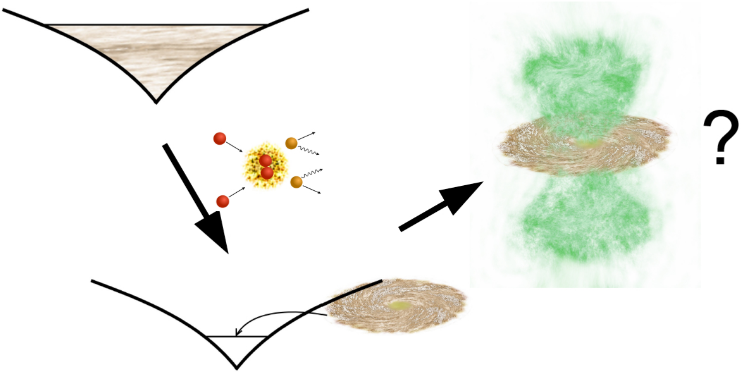
Pais, CP, Ehlert (2018)

Outline

1. Introduction
   - Puzzles
   - Galactic winds
   - Cosmic ray transport
2. Small galactic scales
   - Modelling physics in galaxies
   - Supernova explosions
   - Particle acceleration
3. Simuating galaxies and clusters
   - Global galaxy models
   - Radio and gamma-rays
   - AGN jets in galaxy clusters

AIP

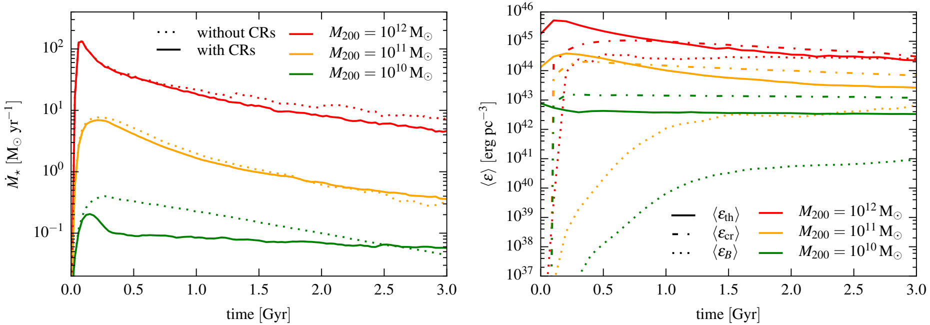
Galaxy simulation setup: 1. cosmic ray advection



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

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

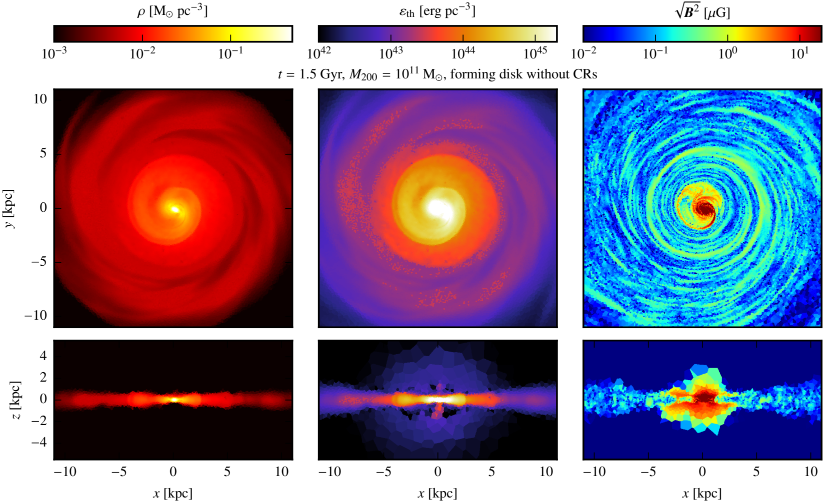
Time evolution of SFR and energy densities



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

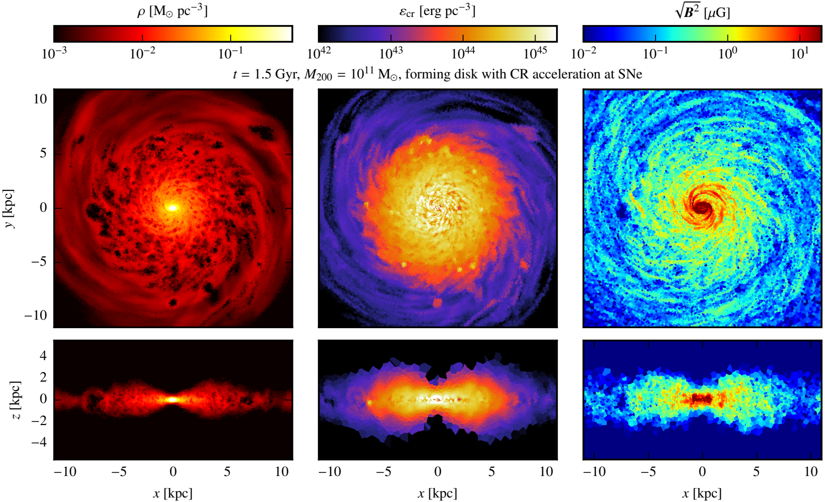
- CR pressure feedback suppresses SFR more in smaller galaxies
- energy budget in disks is dominated by CR pressure
- magnetic dynamo faster in Milky Way galaxies than in dwarfs

MHD galaxy simulation without CRs



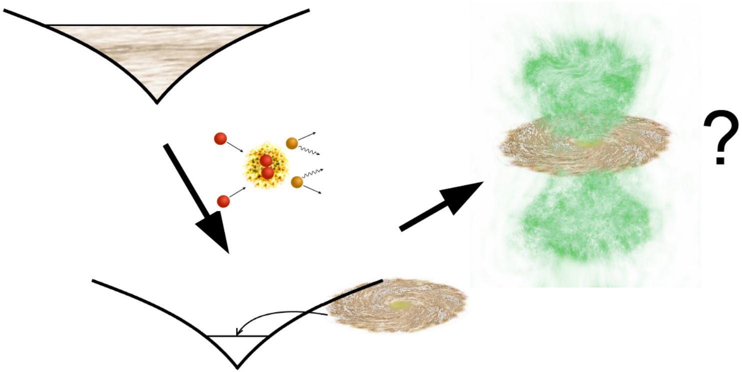
CP, Pakmor, Schaal, Simpson, Springel (2017a)

MHD galaxy simulation with CRs



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

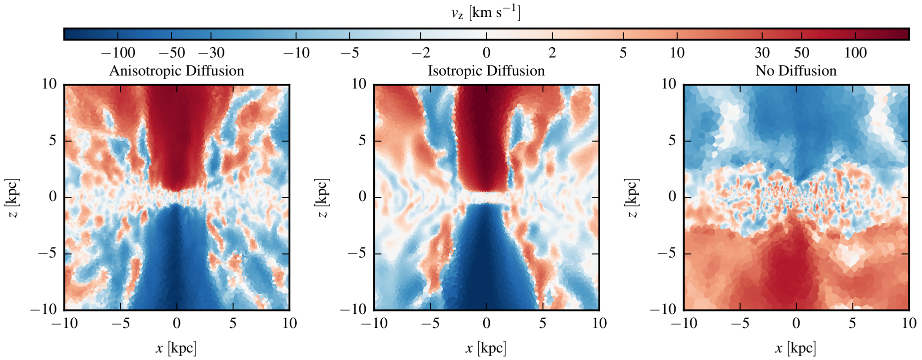
Galaxy simulation setup: 2. cosmic ray diffusion



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} $M_{\odot}$

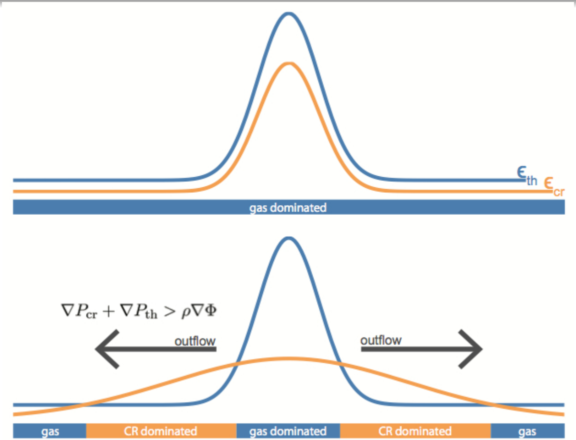
MHD galaxy simulation with CR diffusion



Pakmor, CP, Simpson, Springel (2016)

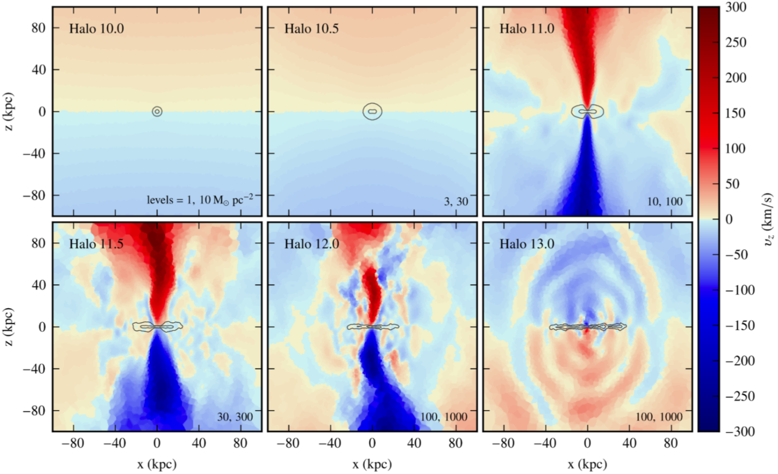
- CR diffusion launches powerful winds
- simulation without CR diffusion exhibits only weak fountain flows

Cosmic ray driven wind: mechanism



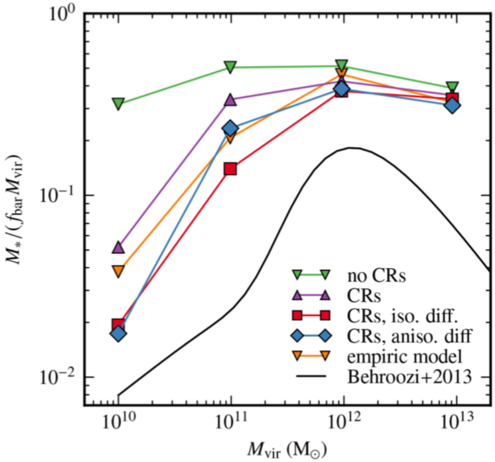
CR streaming in 3D simulations: Uhlig, CP+ (2012), Ruszkowski+ (2017)
CR diffusion in 3D simulations: Jubelgas+ (2008), Booth+ (2013), Hanasz+ (2013), Salem & Bryan (2014), Pakmor, CP+ (2016), Simpson+ (2016), Girichidis+ (2016), Dubois+ (2016), CP+ (2017b), Jacob+ (2018)

CR-driven winds: dependence on halo mass



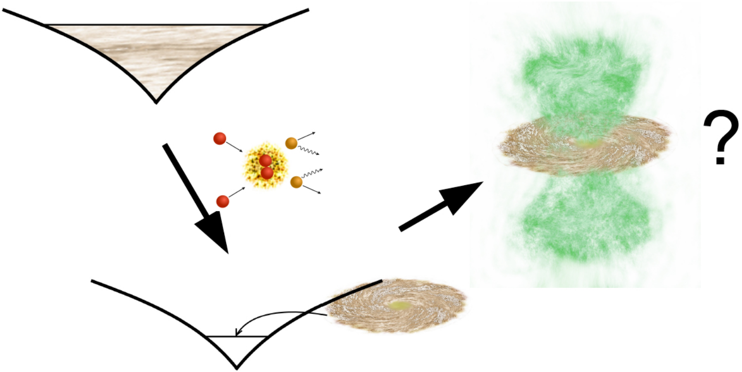
Jacob+ (2018)

CR-driven winds: suppression of star formation



Jacob+ (2018)

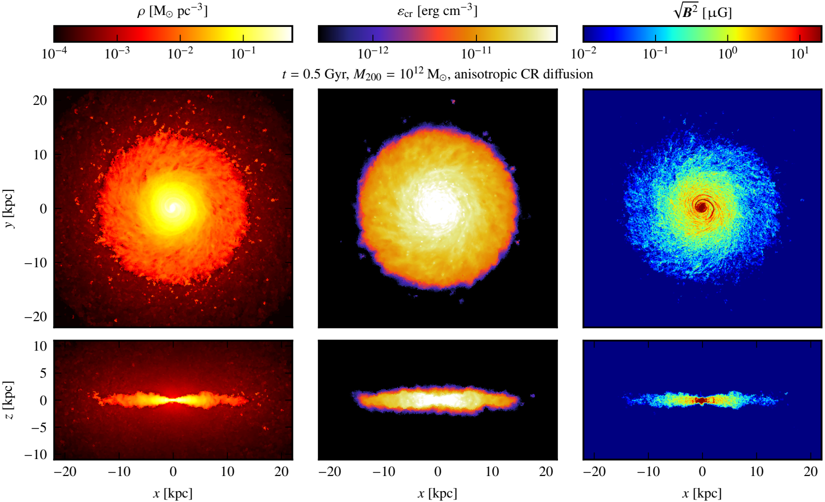
Galaxy simulation setup: 3. non-thermal emission



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

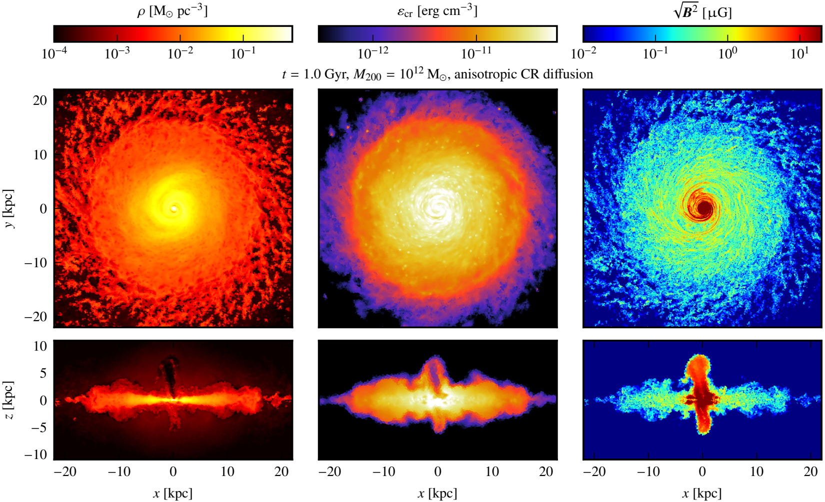
MHD + CR advection + diffusion: $\{10^{10}, 10^{11}, 10^{12}\}\ M_\odot$

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



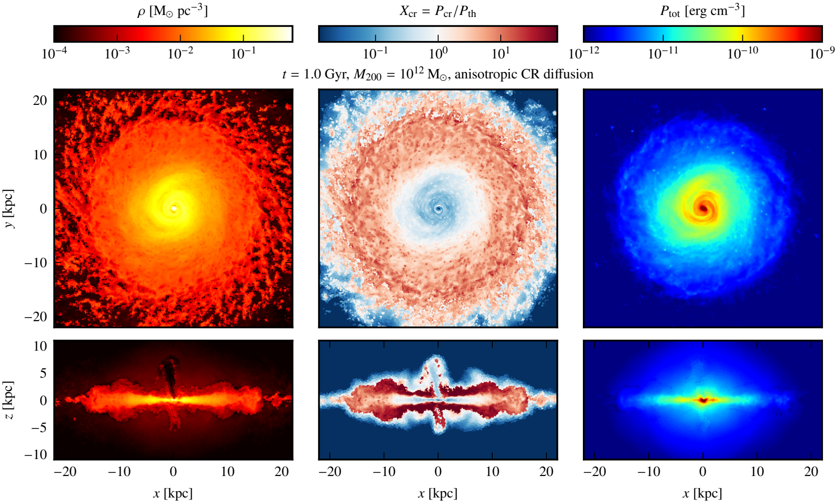
CP+ (2017b, 2018)

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



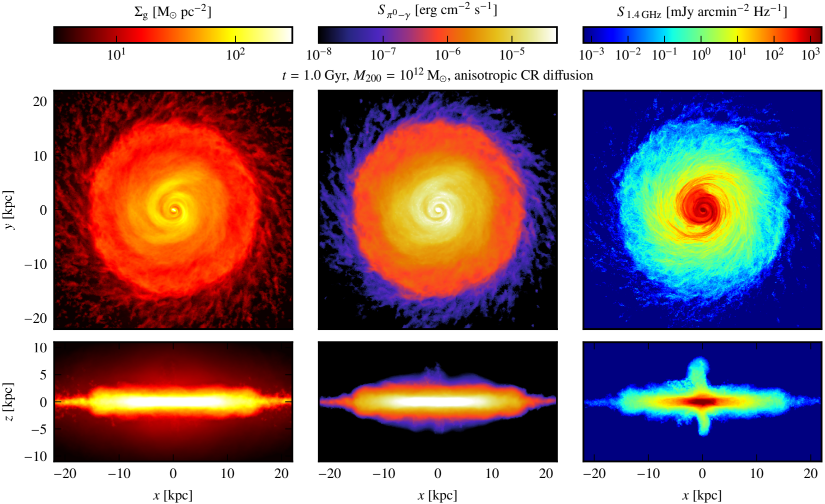
CP+ (2017b, 2018)

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



CP+ (2017b, 2018)

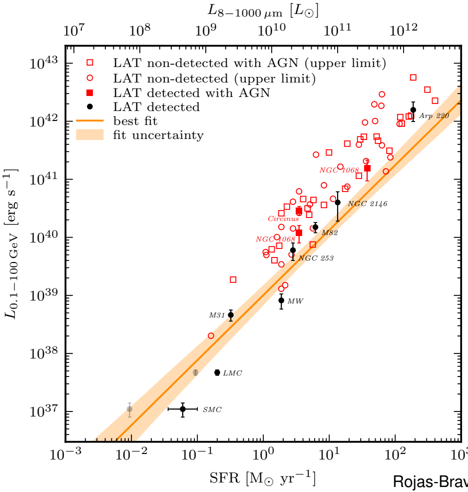
γ-ray and radio emission of Milky Way-like galaxy



CP+ (2017b, 2018)

Far infra-red – gamma-ray correlation

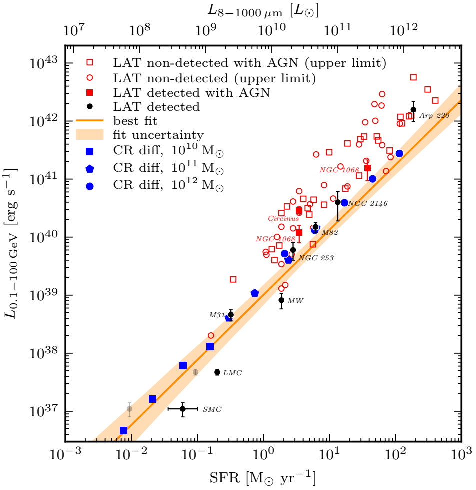
Universal conversion: star formation → cosmic rays → gamma rays



Rojas-Bravo & Araya (2016)

Far infra-red – gamma-ray correlation

Universal conversion: star formation → cosmic rays → gamma rays

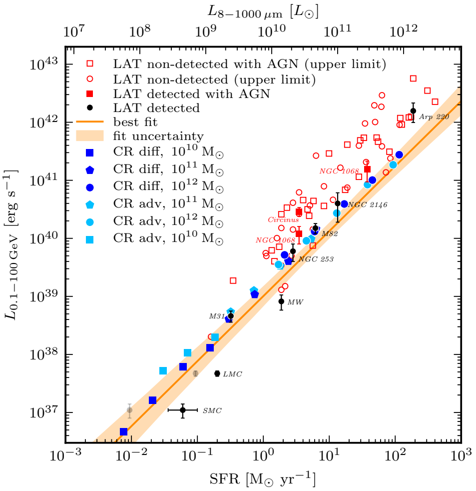


CP+ (2017b)

AIP

Far infra-red – gamma-ray correlation

Universal conversion: star formation → cosmic rays → gamma rays



CP+ (2017b)

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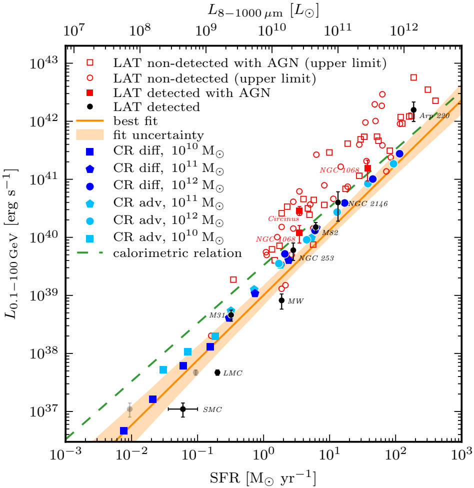
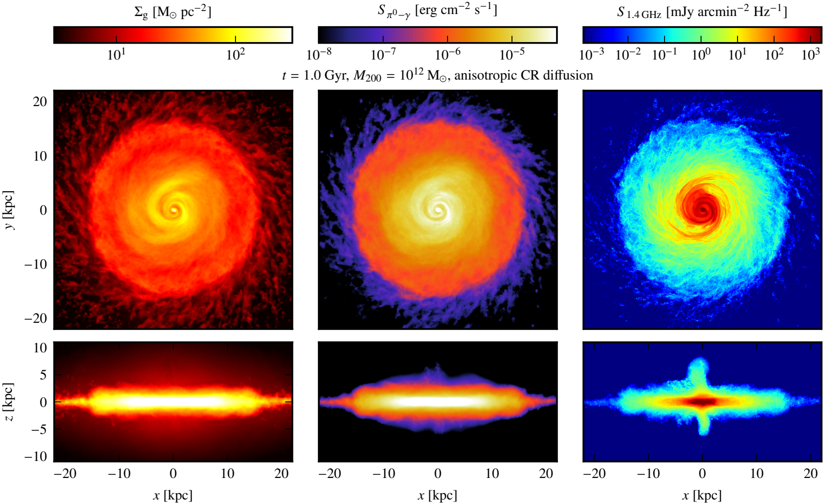


CP+ (2017b)

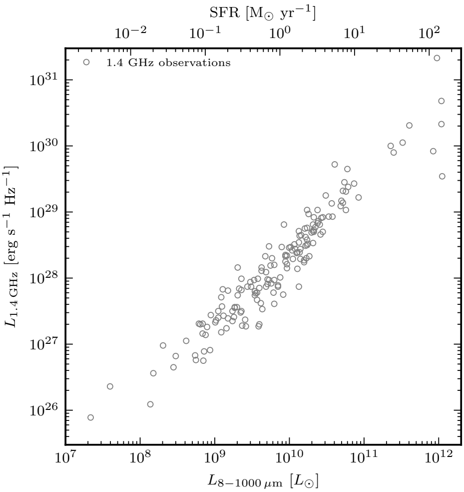
γ-ray and radio emission of Milky Way-like galaxy



CP+ (2017b, 2018)

Far infra-red – radio correlation

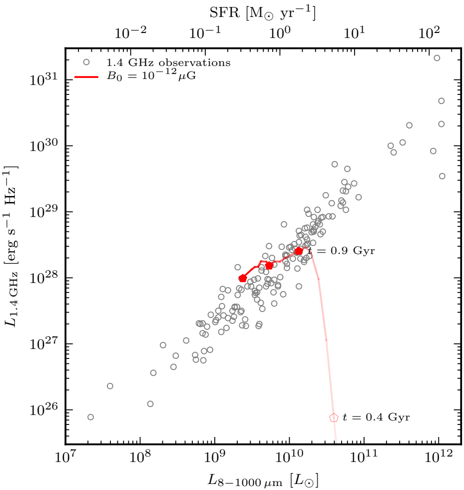
Universal conversion: star formation → cosmic rays → radio



Bell (2003)

Far infra-red – radio correlation

Universal conversion: star formation → cosmic rays → radio



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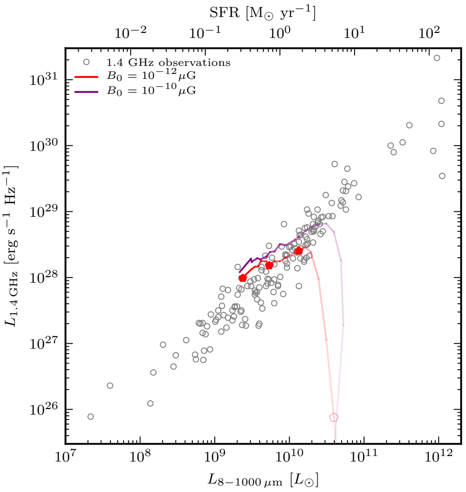

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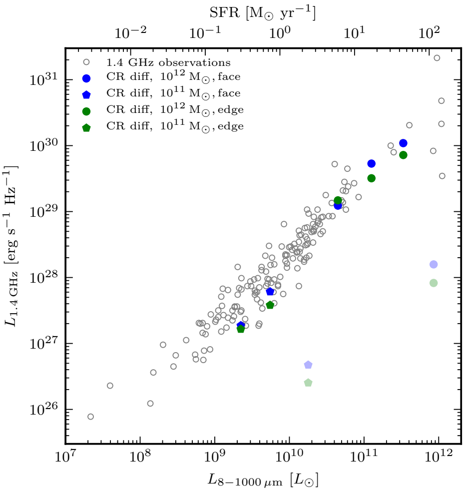

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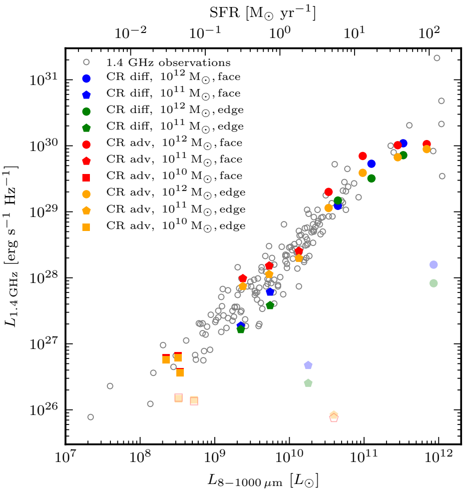

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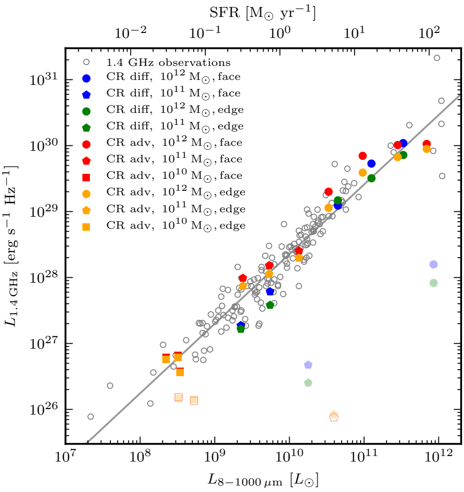
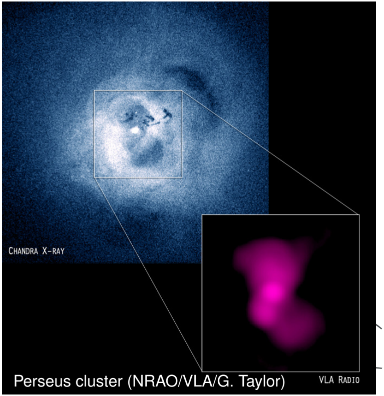


CP+ (2018)

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 ⇒ **but how?**



Perseus cluster (NRAO/VLA/G. Taylor)

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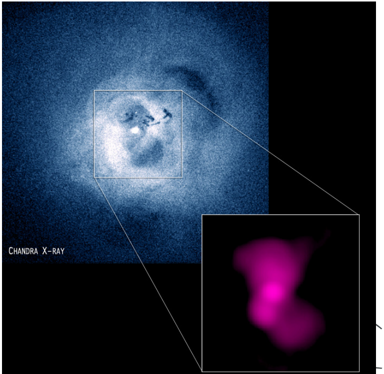
- energy source: release of non-gravitational energy due to accretion on a black hole and its spin
- self-regulated heating mechanism to avoid overcooling



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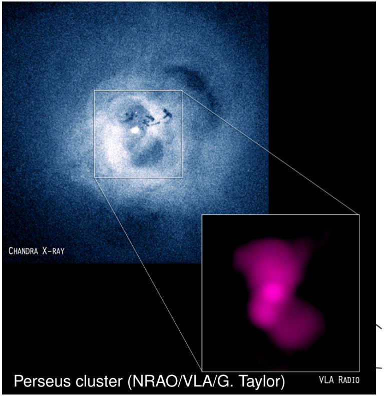
- energy source: release of non-gravitational energy due to accretion on a black hole and its spin
- self-regulated heating mechanism to avoid overcooling
- jet interaction with magnetized cluster medium → turbulence
- jet accelerates cosmic rays → release from bubbles provides source of heat

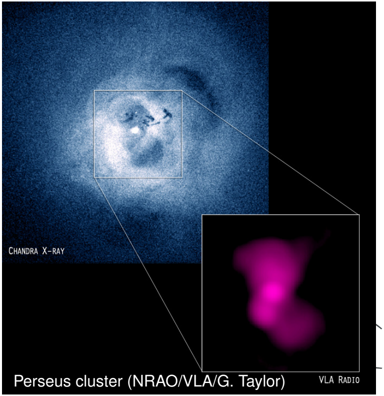


Perseus cluster (NRAO/VLA/G. Taylor)

Feedback by active galactic nuclei

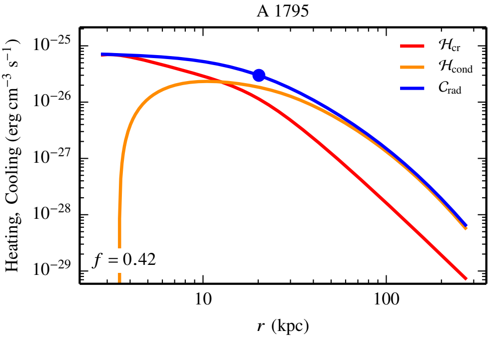
Paradigm: accreting super-massive black holes at galaxy cluster centers launch relativistic jets, which provide energetic feedback to balance cooling ⇒ **but how?**

- Jacob & 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}

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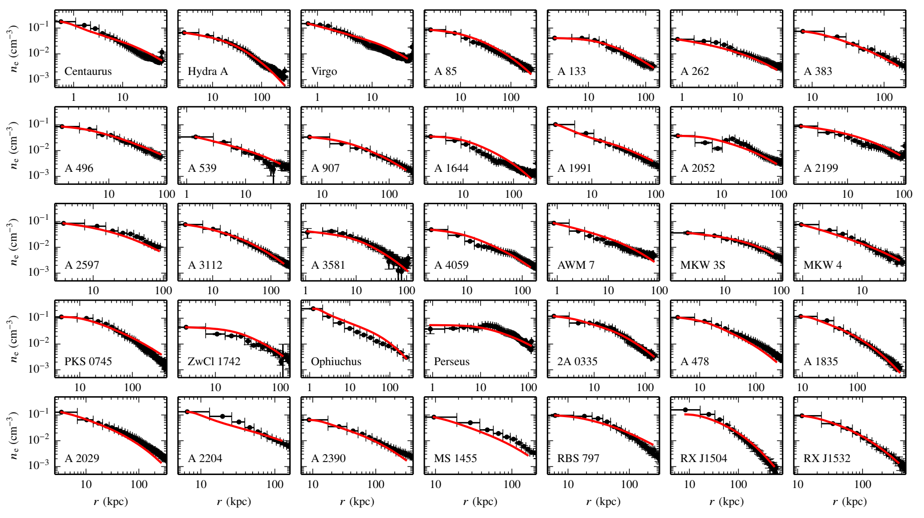
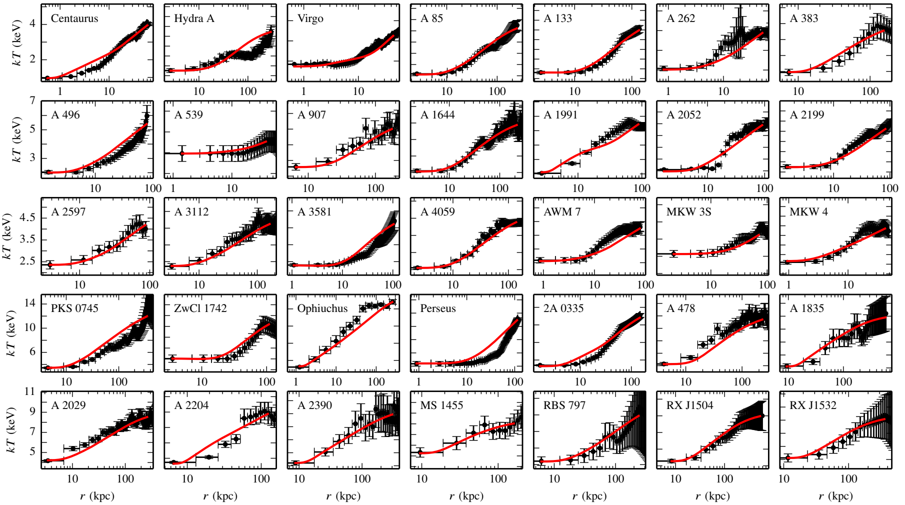
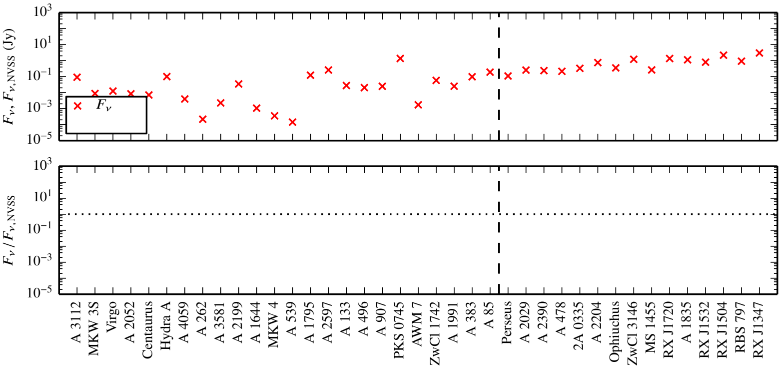
Gallery of solutions: density profiles



Gallery of solutions: temperature profiles

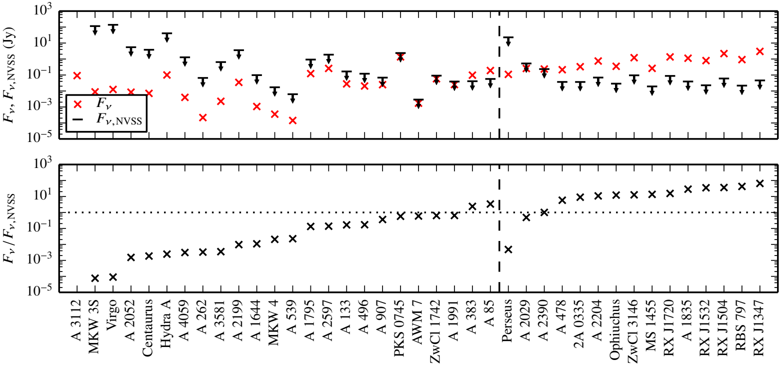


Hadronically induced radio emission



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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AGN injects CRs

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radio mini halo

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↘

radio mini halo

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- self-regulated feedback cycle driven by CRs

AGN injects CRs → CR heating balances cooling

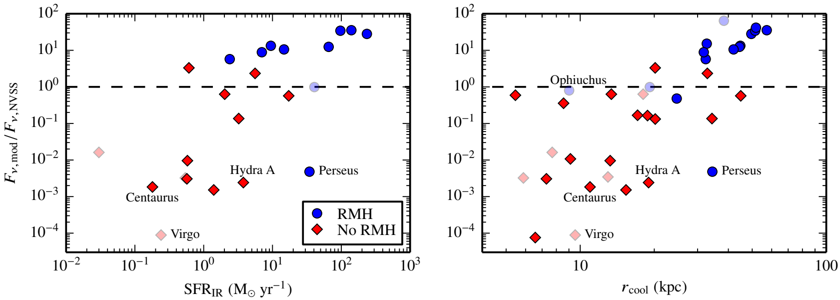
↑ ↓

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

↘

radio mini halo

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

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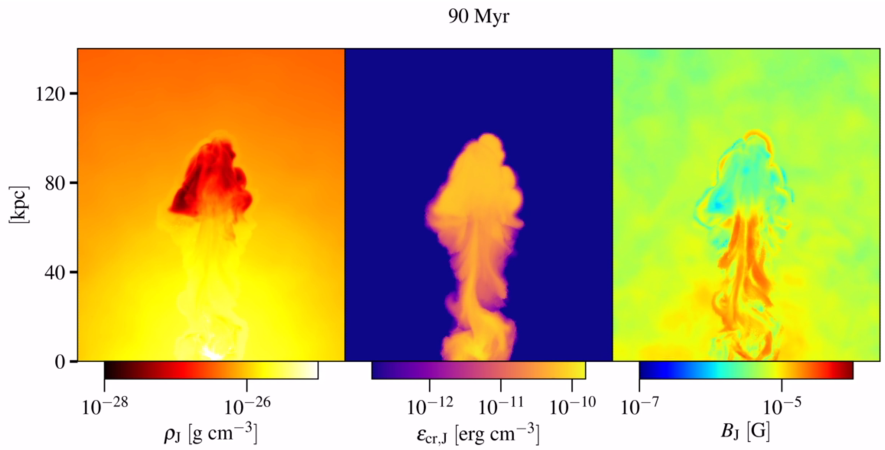
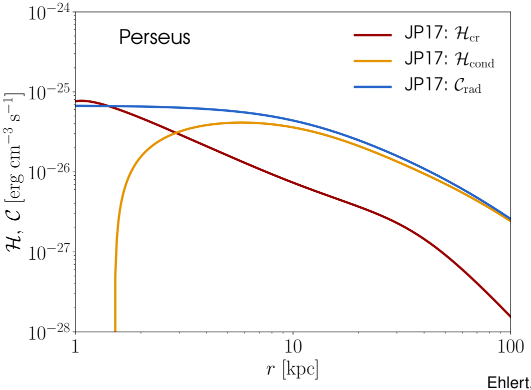
Jet simulation: gas density, CR energy density, *B* field



Ehlert, Weinberger, CP+ (2018)

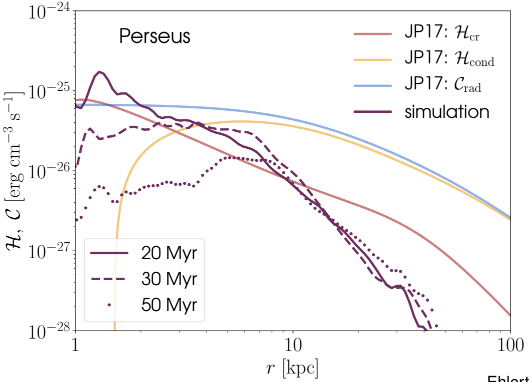
Perseus cluster – heating vs. cooling: theory



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}

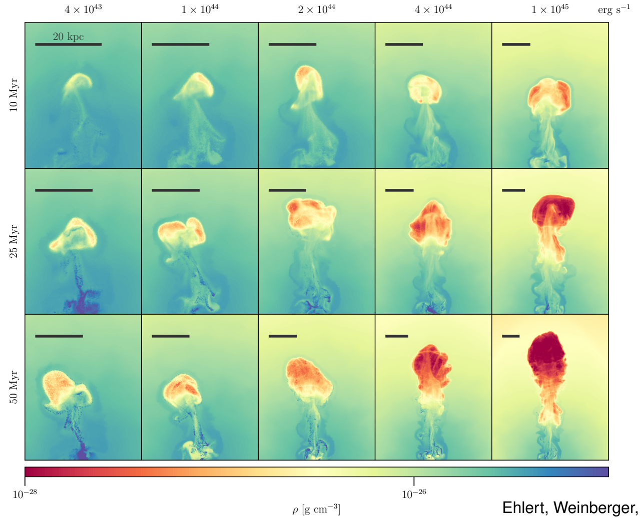
Perseus cluster – heating vs. cooling: simulations



Ehlert, Weinberger, CP+ (2018)

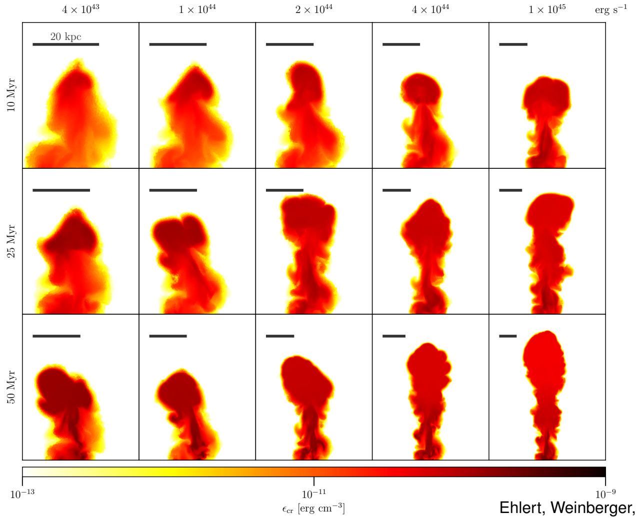
- CR and conductive heating balance radiative cooling: $\mathcal{H}_{\rm cr} + \mathcal{H}_{\rm cond} \approx \mathcal{C}_{\rm rad}$: modest mass deposition rate of 1 $M_\odot$ yr^{-1}
- **simulated CR heating rate matches 1D steady state model**

Matrix of jet simulations: density at 70 Myrs



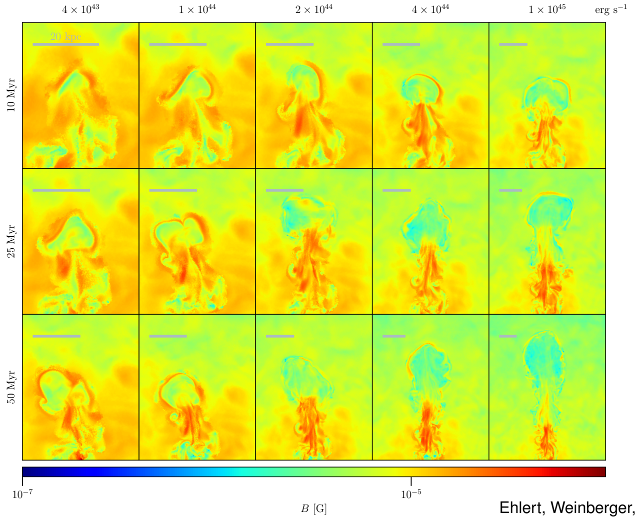
Ehlert, Weinberger, CP+ (2018)

Matrix of jet simulations: CR energy density at 70 Myrs



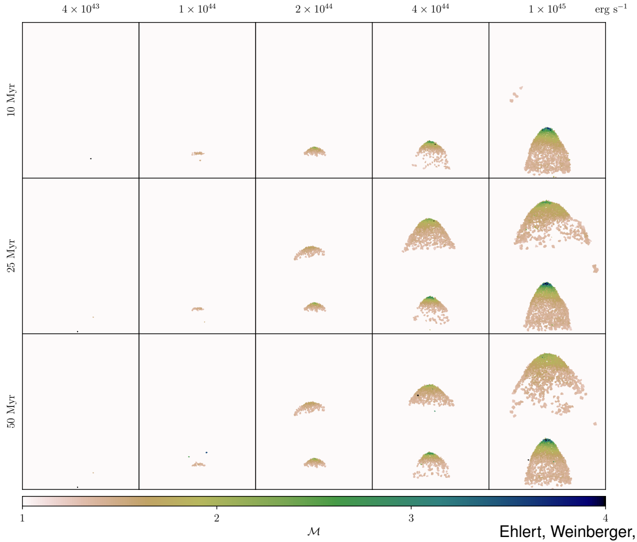
Ehlert, Weinberger, CP+ (2018)

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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- $L_{\rm FIR} - L_\gamma$ correlations enable us to test the calorimetric assumption and magnetic dynamo theories
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Conclusions on CR feedback in galaxies and clusters

- CR pressure feedback slows down star formation
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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

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 acceleration and transport:

- Thomas, Pfrommer, *Cosmic-ray hydrodynamics: Alfvén-wave regulated transport of cosmic rays,* 2018.
- *Constraining the coherence scale of the interstellar magnetic field using TeV gamma-ray observations of supernova remnants,* 2018.
- Pais, Pfrommer, Ehlert, Pakmor, *The effect of cosmic-ray acceleration on supernova blast wave dynamics,* 2018, MNRAS.

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.

AIP

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.

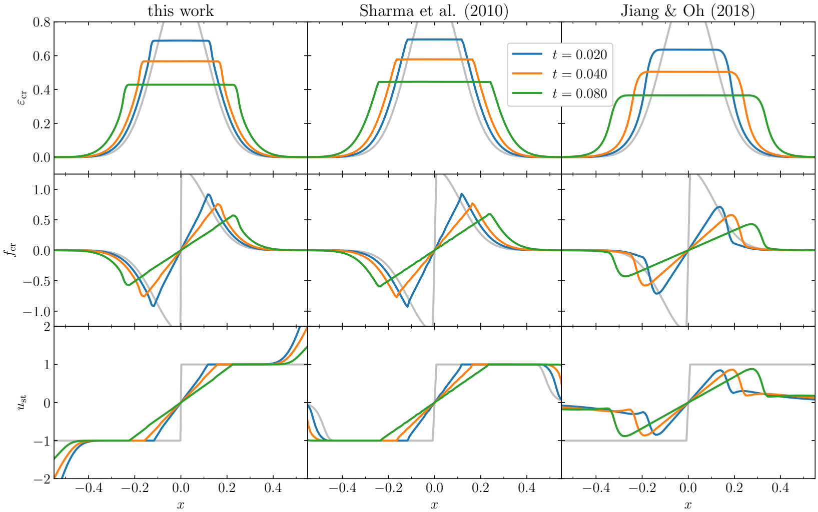
Cosmic ray heating in clusters:

- 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.

AIP

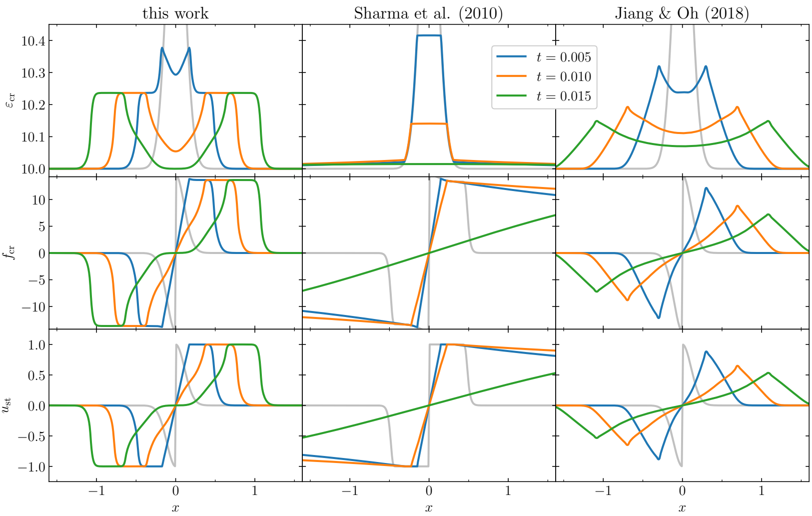
Additional slides

CR transport – evolution of isolated Gaussian



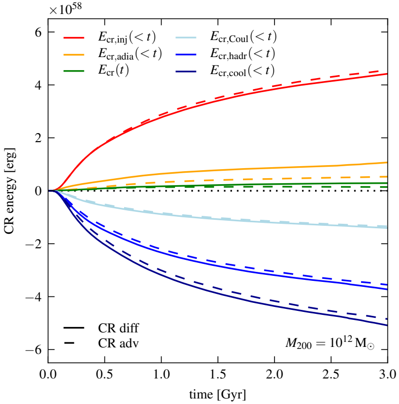
Thomas & CP (2018)

CR transport – evolution of Gaussian with background



Thomas & CP (2018)

Time evolution of CR energies



CP+ (2017b)

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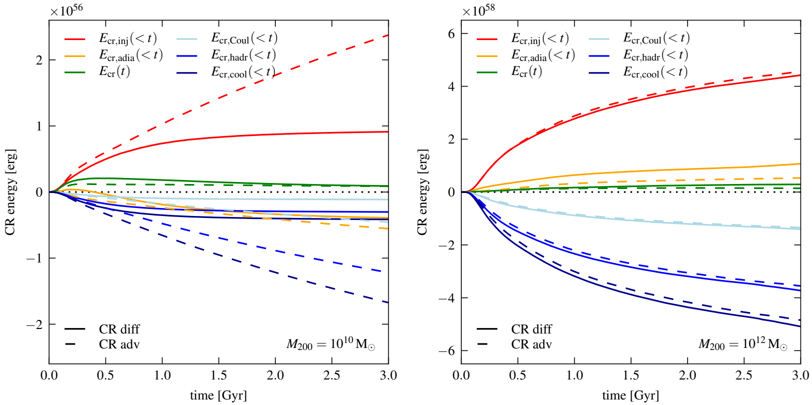

CP+ (2017b)

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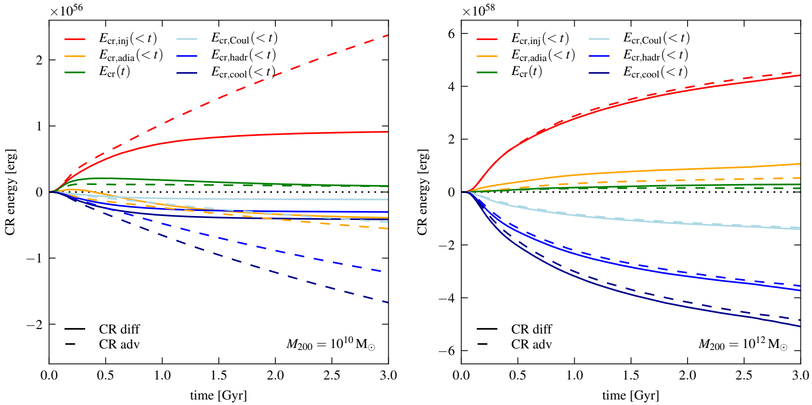

CP+ (2017b)

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