Open problems for modelling cosmic rays in galaxy formation

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in collaboration with

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Max-Planck-Princeton Research Center for Plasma Physics – 2017

Outline

1. Introduction
   - Puzzles in galaxy formation
   - Feedback in galaxies
   - Cosmic rays
2. Galactic winds
   - Cosmic ray advection
   - Cosmic ray diffusion
   - Open problems
3. Active galactic nuclei
   - Feedback
   - Cosmic ray heating
   - 3D MHD simulations

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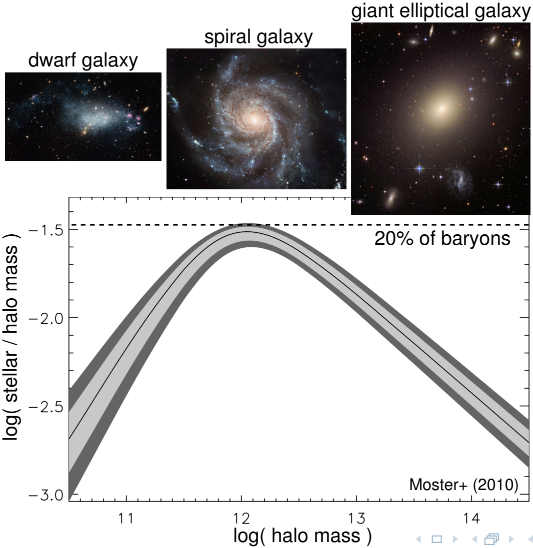
Puzzles in galaxy formation


Puzzles in galaxy formation



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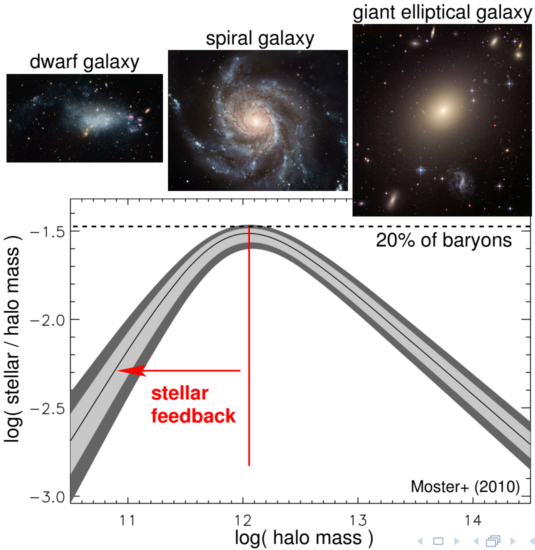
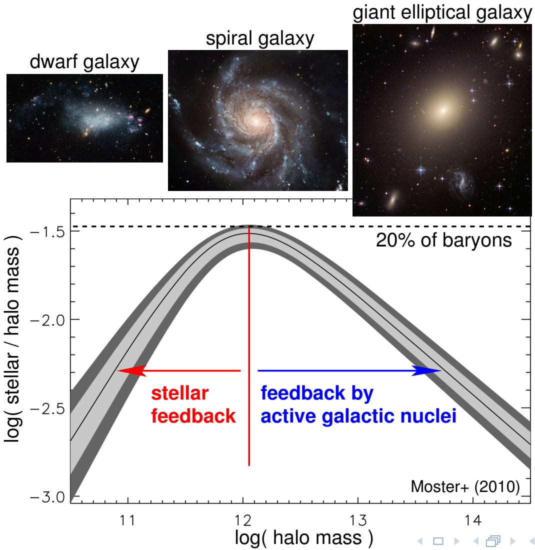
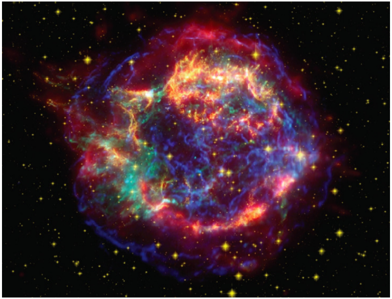
Puzzles in galaxy formation



Puzzles in galaxy formation



Feedback by galactic winds



supernova Cassiopeia A

X-ray: NASA/CXC/SAO; Optical: NASA/STScI;
Infrared: NASA/JPL-Caltech/Steward/O.Krause et al.

- galactic supernova remnants drive shock waves, turbulence, accelerate electrons + protons, amplify magnetic fields

Feedback by galactic winds

super wind in M82

NASA/JPL-Caltech/STScI/CXC/UofA

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- critical for understanding the physics of galaxy formation $\rightarrow$ may explain puzzle of low star conversion efficiency in dwarf galaxies

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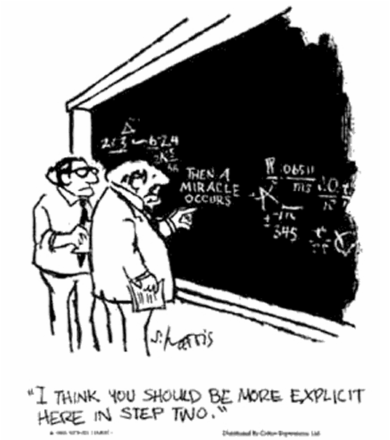
Feedback by galactic winds



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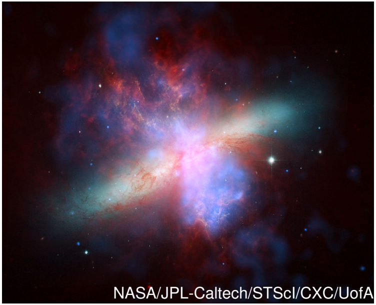
How are galactic winds driven?



super wind in M82

- thermal pressure provided by supernovae or AGNs?
- radiation pressure and photoionization by massive stars and QSOs?
- cosmic-ray (CR) pressure and Alfvén wave heating of CRs accelerated at supernova shocks?

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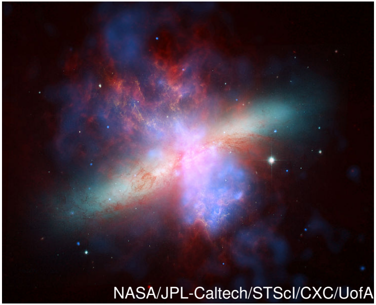

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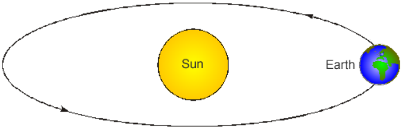
observed energy equipartition between cosmic rays, thermal gas and magnetic fields
→ suggests self-regulated feedback loop with CR driven winds

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!**

Cosmic ray interactions with the plasma

individual particles:

- ***electrons/positrons:***
  - synchrotron
  - inverse Compton
  - bremsstrahlung
- ***ions:***
  - hadronic interaction $\rightarrow \gamma$ rays, ν, $e^{\pm}$
  - collisional ionization and Coulomb heating of the interstellar medium by MeV particles

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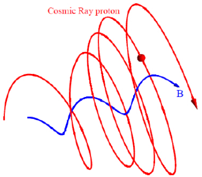
collective:

- ***microscales:***
  kinetic instabilities and damping
- ***mesoscales:***
  structure of collisionless shocks
- ***macroscales:***
  interstellar, circumgalactic, intracluster plasma dynamics
  - outflows
  - equilibrium + stability
  - collisionless heating

Cosmic ray transport: two pictures

self-confinement:

- Alfvén waves are generated by streaming cosmic rays themselves
- gyroresonant interaction
  $\omega - k\,v_{\parallel} = \pm n\,\omega_{\mathrm{c}}, \quad n \in \mathbb{Z}$
- grow rate balanced by (non-linear Landau & turbulent) damping



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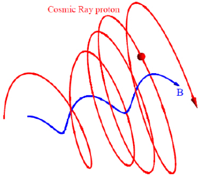
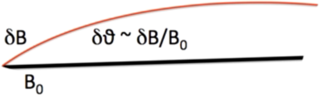


extrinsic confinement:

- waves are present as part of a turbulent cascade
- random walk of particles with nearly elastic scatterings
- diffusion process with scattering frequency

$$\nu \sim \frac{\langle(\delta\vartheta)^2\rangle}{\delta t} \sim \omega_{\mathrm{c}} \left(\frac{\delta B}{B_0}\right)^2$$



Cosmic-ray (CR) transport: streaming vs. diffusion

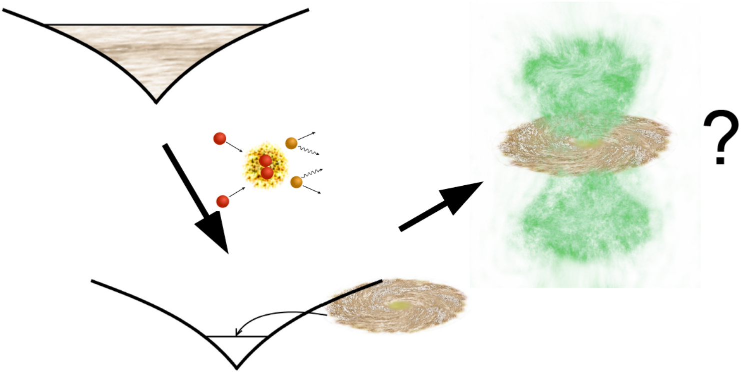
- total CR velocity $\boldsymbol{v}_{\rm cr} = \boldsymbol{v} + \boldsymbol{v}_{\rm st} + \boldsymbol{v}_{\rm di}$ (where $\boldsymbol{v} \equiv \boldsymbol{v}_{\rm gas}$)
- CRs stream down their own pressure gradient relative to the gas, CRs diffuse in the wave frame due to pitch angle scattering by MHD waves (both transports are along the local direction of $\boldsymbol{B}$):

$$\boldsymbol{v}_{\rm st} = -\frac{\boldsymbol{B}}{\sqrt{4\pi\rho}} \frac{\boldsymbol{b}\cdot\nabla P_{\rm cr}}{|\boldsymbol{b}\cdot\nabla P_{\rm cr}|}, \qquad \boldsymbol{v}_{\rm di} = -\kappa_{\rm di}\boldsymbol{b}\,\frac{\boldsymbol{b}\cdot\nabla\varepsilon_{\rm cr}}{\varepsilon_{\rm cr}},$$

- CR streaming adiabatically transports CR energy with $\sim v_{\rm A}$ CR diffusion irreversibly disperses the CR energy

Outline

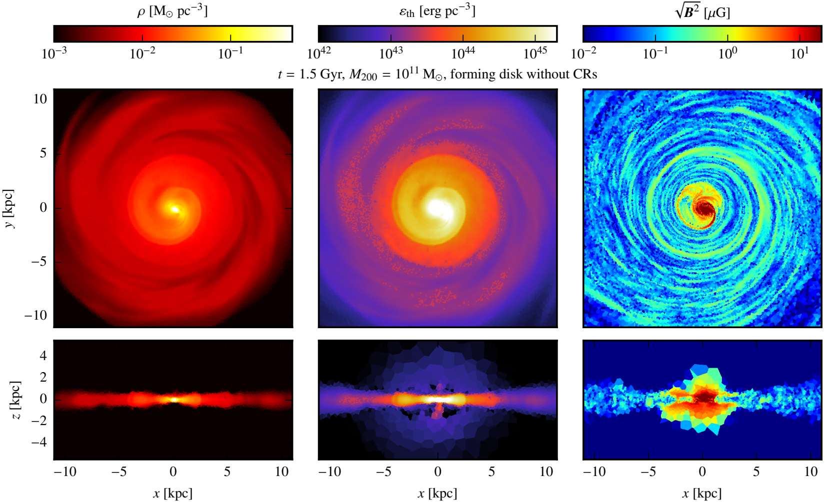
Galaxy simulation setup: 1. cosmic ray advection



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

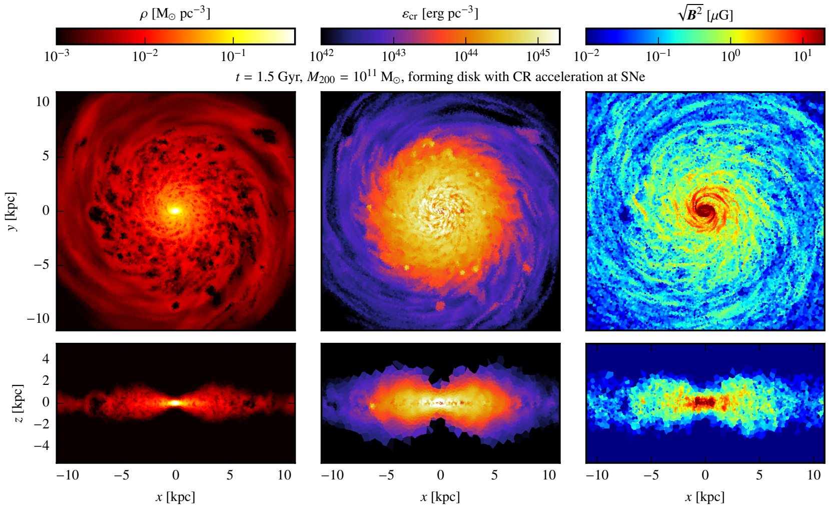
MHD + cosmic ray advection: $\{10^{10}, 10^{11}, 10^{12}\}\ M_\odot$

MHD galaxy simulation without CRs



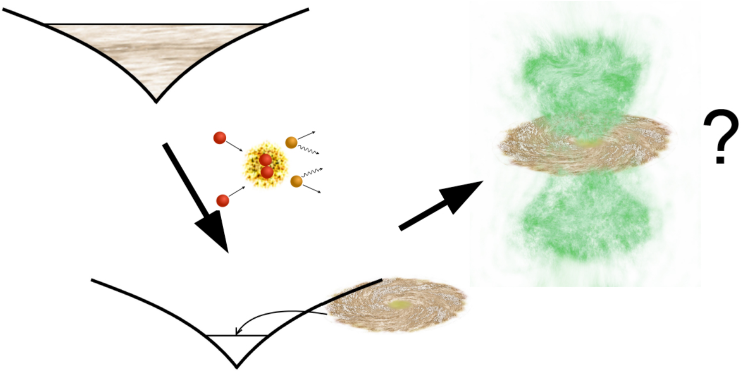
C.P., Pakmor, Schaal, Simpson, Springel (2017)

MHD galaxy simulation with CRs



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

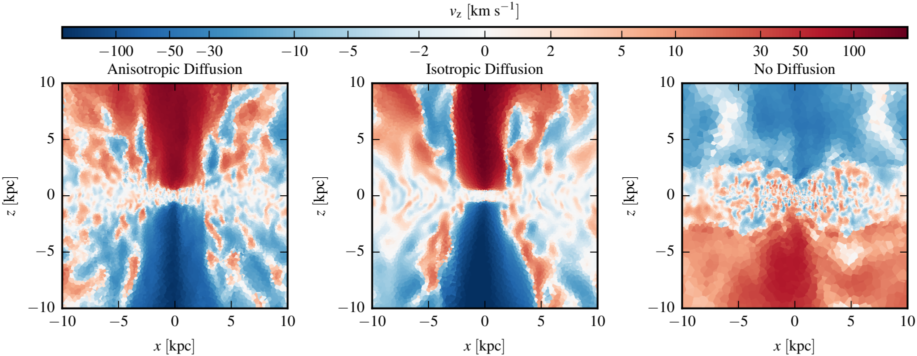
Galaxy simulation setup: 2. cosmic ray diffusion



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} $M_\odot$

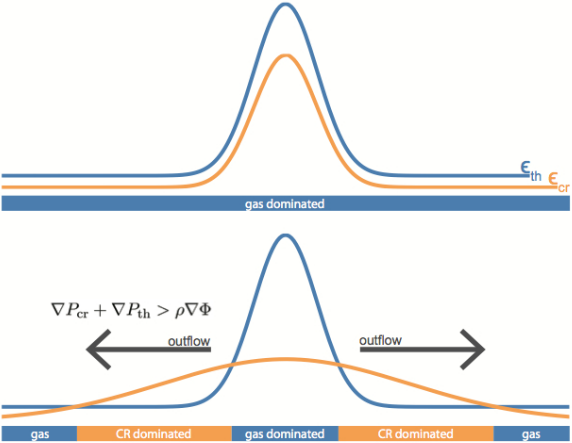
MHD galaxy simulation with CR diffusion



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

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

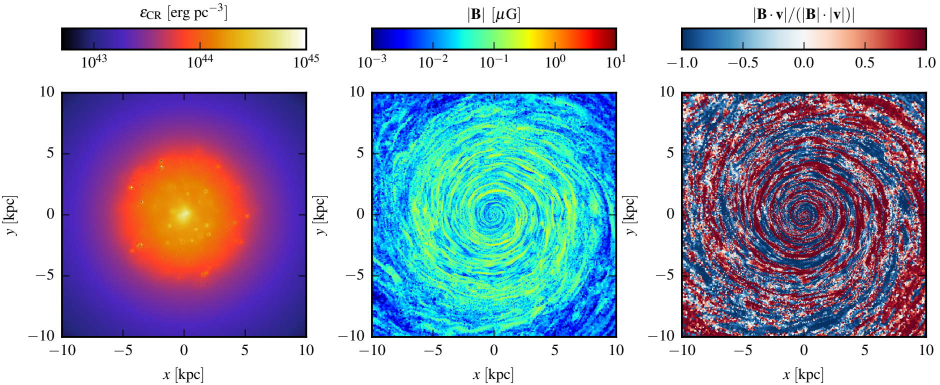
Cosmic ray driven wind: mechanism



CR streaming: Uhlig, C.P.+ (2012)

CR diffusion: Booth+ (2013), Hanasz+ (2013), Salem & Bryan (2014)

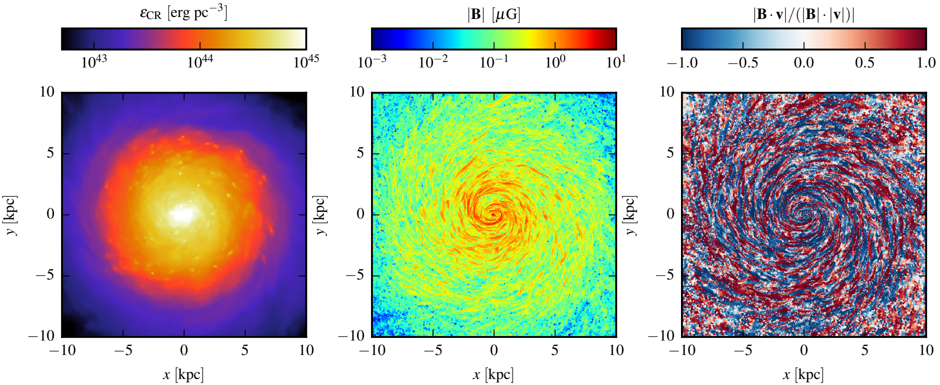
MHD galaxy simulation with CR isotropic diffusion



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

- CR diffusion strongly suppresses SFR
- strong outflow quenches magnetic dynamo to yield $B \sim 0.1\,\mu$G

MHD galaxy simulation with CR anisotropic diffusion



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

- anisotropic CR diffusion also suppresses SFR
- reactivation of magnetic dynamo: growth to observed strengths

Open problems on cosmic ray-driven galactic winds

- improved plasma physics modeling of CR transport:
  streaming vs. diffusion
  $\rightarrow$ scaling of wind properties with halo mass ($\dot{M}$, $v_{\mathrm{wind}}, \ldots$)
  $\rightarrow$ magnetic dynamo (non-linear back-reaction on CR transport)

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Open problems on cosmic ray-driven galactic winds

- improved plasma physics modeling of CR transport:
  streaming vs. diffusion
  $\rightarrow$ scaling of wind properties with halo mass ($\dot{M}$, $v_{\rm wind}$, ...)
  $\rightarrow$ magnetic dynamo (non-linear back-reaction on CR transport)
- follow CR spectra:
  $\rightarrow$ improved cooling and (energy-dependent) transport
- interplay of CRs with supernovae and radiation feedback:
  $\rightarrow$ which epoch? which halo mass?
  $\rightarrow$ active driver vs. preventive feedback?
- impact of cosmological environment

Outline

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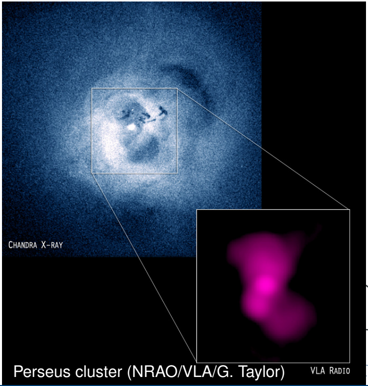
Radio mode feedback by AGN

Paradigm: super-massive black holes with $M \sim (10^9 \ldots 10^{10}) M_\odot$ co-evolve with their hosting cD galaxies at the centers of galaxy clusters; they launch relativistic jets that blow bubbles and provide energetic feedback to balance cooling



Perseus cluster (NRAO/VLA/G. Taylor)

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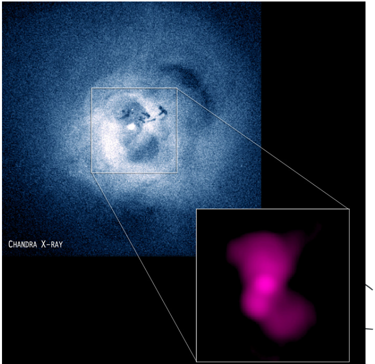
- energy source: release of non-gravitational energy due to accretion on a black hole and its spin
- self-regulated heating mechanism to avoid overcooling



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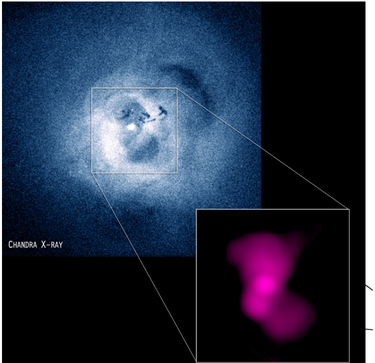
- energy source: release of non-gravitational energy due to accretion on a black hole and its spin
- self-regulated heating mechanism to avoid overcooling
- jet interaction with magnetized cluster medium $\rightarrow$ turbulence
- jet accelerates relativistic particles (cosmic rays, CRs) $\rightarrow$ release from bubbles provides source of heat



Perseus cluster (NRAO/VLA/G. Taylor)

How universal is CR heating in cool core clusters?

- **strategy:**
  (1) construct large sample of 39 cool cores
  (2) search for spherically symmetric, steady-state solutions:
  CR heating ($\mathcal{H}_{\rm cr}$) $+$ conductive heating ($\mathcal{H}_{\rm th}$) $\approx$ cooling ($\mathcal{C}_{\rm rad}$)
  (3) calculate hadronic radio and γ-ray flux $\mathcal{F}_{\rm had}$ and compare to observed fluxes $\mathcal{F}_{\rm obs}$

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  (3) calculate hadronic radio and γ-ray flux $\mathcal{F}_{\mathrm{had}}$ and compare to observed fluxes $\mathcal{F}_{\mathrm{obs}}$
- **consequences:**
  $\Rightarrow$ if $\mathcal{H}_{\mathrm{cr}} + \mathcal{H}_{\mathrm{th}} \approx \mathcal{C}_{\mathrm{rad}}\ \forall\ r$ and $\mathcal{F}_{\mathrm{had}} \leq \mathcal{F}_{\mathrm{obs}}$:
  successful CR heating model that is locally stable at 1 keV
  $\Rightarrow$ otherwise ***CR heating ruled out*** as dominant heating source

Governing equations

- conservation of mass, momentum, thermal and CR energy:

$$\frac{\mathrm{d}\rho}{\mathrm{d}t} + \rho\boldsymbol{\nabla}\cdot\boldsymbol{v} = 0$$

$$\rho\frac{\mathrm{d}\boldsymbol{v}}{\mathrm{d}t} = -\boldsymbol{\nabla}\left(P_{\mathrm{th}} + P_{\mathrm{cr}}\right) - \rho\boldsymbol{\nabla}\phi$$

$$\frac{\mathrm{d}e_{\mathrm{th}}}{\mathrm{d}t} + \gamma_{\mathrm{th}} e_{\mathrm{th}}\boldsymbol{\nabla}\cdot\boldsymbol{v} = -\boldsymbol{\nabla}\cdot\boldsymbol{F}_{\mathrm{th}} + \mathcal{H}_{\mathrm{cr}} - \rho\mathcal{L}$$

$$\frac{\mathrm{d}e_{\mathrm{cr}}}{\mathrm{d}t} + \gamma_{\mathrm{cr}} e_{\mathrm{cr}}\boldsymbol{\nabla}\cdot\boldsymbol{v} = -\boldsymbol{\nabla}\cdot\boldsymbol{F}_{\mathrm{cr}} - \mathcal{H}_{\mathrm{cr}} + S_{\mathrm{cr}}$$

- Lagrangian derivative $\mathrm{d}/\mathrm{d}t = \partial/\partial t + \boldsymbol{v}\cdot\boldsymbol{\nabla}$
- equations of state:

$$P_{\mathrm{th}} = (\gamma_{\mathrm{th}} - 1)e_{\mathrm{th}}$$

$$P_{\mathrm{cr}} = (\gamma_{\mathrm{cr}} - 1)e_{\mathrm{cr}}$$

Governing equations

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$$\frac{\mathrm{d}e_\mathrm{cr}}{\mathrm{d}t} + \gamma_\mathrm{cr} e_\mathrm{cr}\boldsymbol{\nabla}\cdot\boldsymbol{v} = -\boldsymbol{\nabla}\cdot\boldsymbol{F}_\mathrm{cr} - \mathcal{H}_\mathrm{cr} + S_\mathrm{cr}$$

- gravitational potential $\phi = -\frac{GM_\mathrm{s}}{r}\ln\left(1 + \frac{r}{r_\mathrm{s}}\right) + v_\mathrm{c}^2\ln\left(\frac{r}{r_0}\right)$
- radiative cooling $\rho\mathcal{L} = n_\mathrm{e}^2\left(\Lambda_\mathrm{l} + \Lambda_\mathrm{b} T^{1/2}\right)$
- CR source $S_\mathrm{cr} = -\frac{\nu\varepsilon_\mathrm{cr}\dot{M}c^2}{4\pi r_\mathrm{cr}^3}\left(\frac{r}{r_\mathrm{cr}}\right)^{-3-\nu}\left(1 - e^{-(r/r_\mathrm{cr})^2}\right)$

Governing equations

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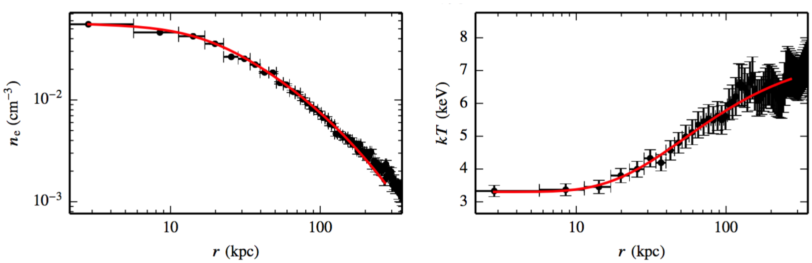
$$\frac{\mathrm{d}e_{\mathrm{cr}}}{\mathrm{d}t} + \gamma_{\mathrm{cr}}e_{\mathrm{cr}}\boldsymbol{\nabla}\cdot\boldsymbol{v} = -\boldsymbol{\nabla}\cdot\boldsymbol{F}_{\mathrm{cr}} - \mathcal{H}_{\mathrm{cr}} + S_{\mathrm{cr}}$$

- thermal heat flux $\boldsymbol{F}_{\mathrm{th}} = -\kappa\boldsymbol{\nabla}T$
- CR streaming flux $\boldsymbol{F}_{\mathrm{cr}} = (e_{\mathrm{cr}} + P_{\mathrm{cr}})\boldsymbol{v}_{\mathrm{st}}$ with $\boldsymbol{v}_{\mathrm{st}} = -v_{\mathrm{A}}\frac{\boldsymbol{\nabla}P_{\mathrm{cr}}}{|\boldsymbol{\nabla}P_{\mathrm{cr}}|}$
- CR heating rate $\mathcal{H}_{\mathrm{cr}} = -\boldsymbol{v}_{\mathrm{st}}\cdot\boldsymbol{\nabla}P_{\mathrm{cr}}$

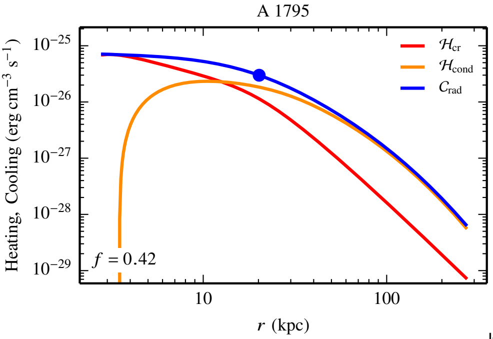
Case study A1795: density and temperature



Jacob & C.P. (2017a)

- beautiful match of steady-state solutions to observed profiles
- pure NFW mass profile in A1795

Case study A1795: heating and cooling



Jacob & C.P. (2017a)

- 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 $1\,{\rm M}_\odot\,{\rm yr}^{-1}$

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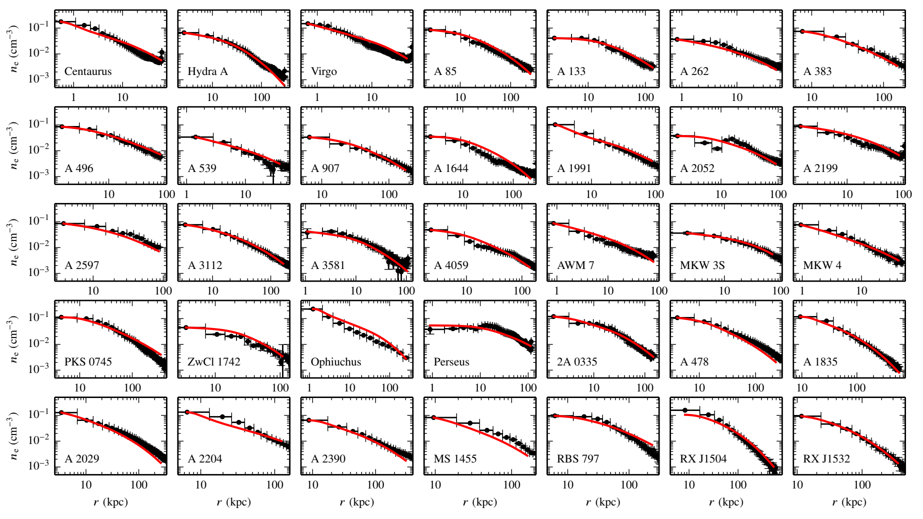
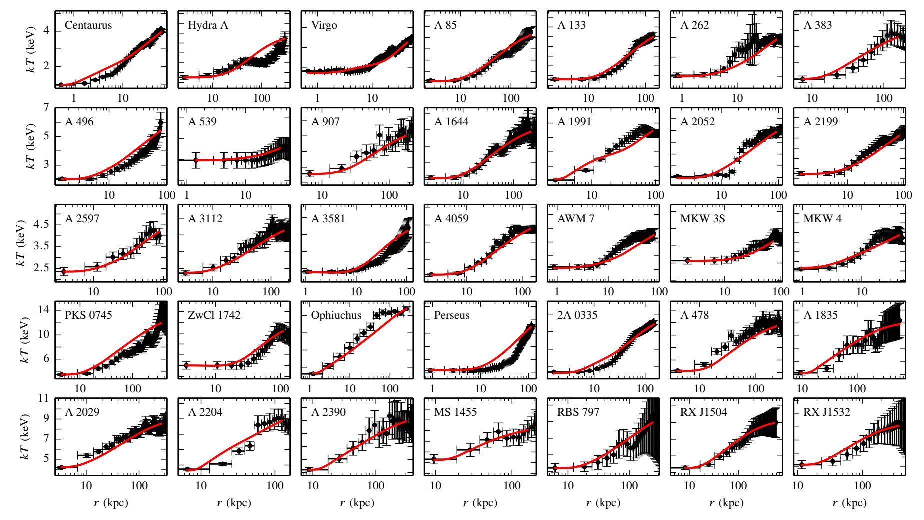
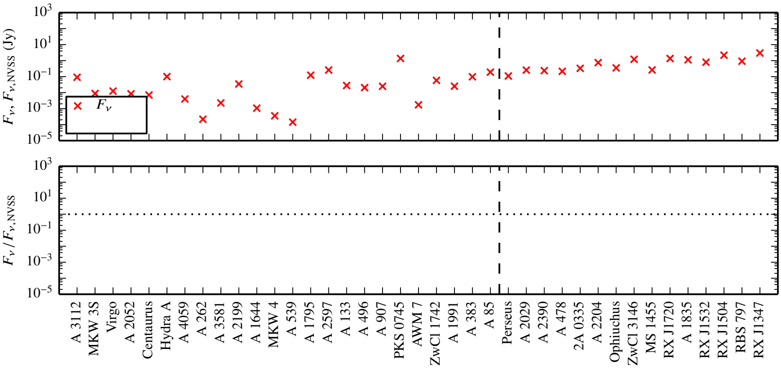
Gallery of solutions: density profiles



Gallery of solutions: temperature profiles

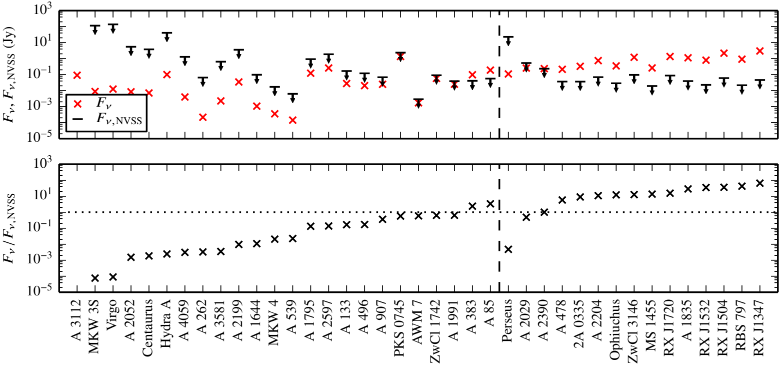


Hadronically induced radio emission



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 solution ruled out in radio mini halos
- CR heating viable solution for non-RMH clusters

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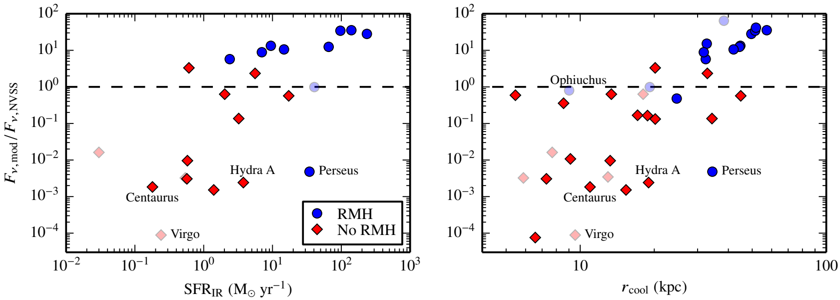
Self-regulated heating/cooling cycle in cool cores

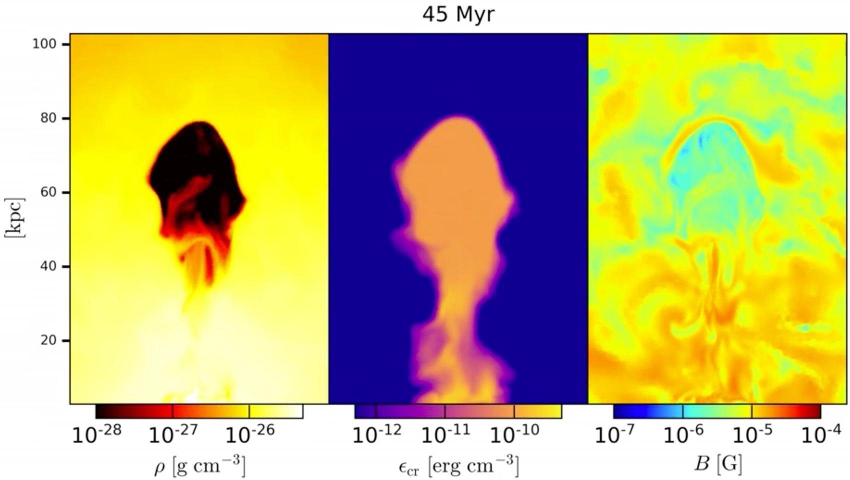


Jacob & C.P. (2017b)

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

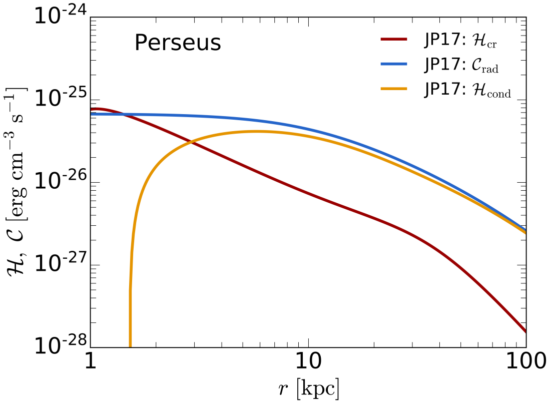
- simmering SF: CR heating is effectively balancing cooling
- abundant SF: heating/cooling out of balance

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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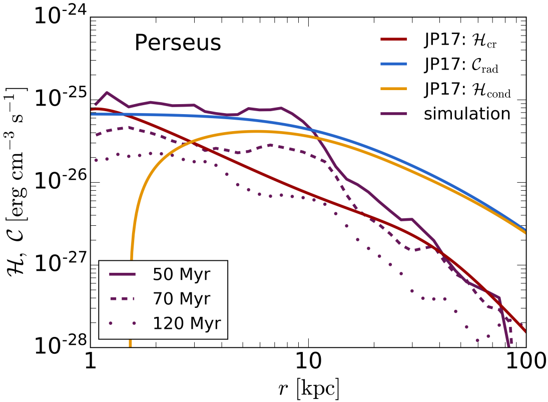
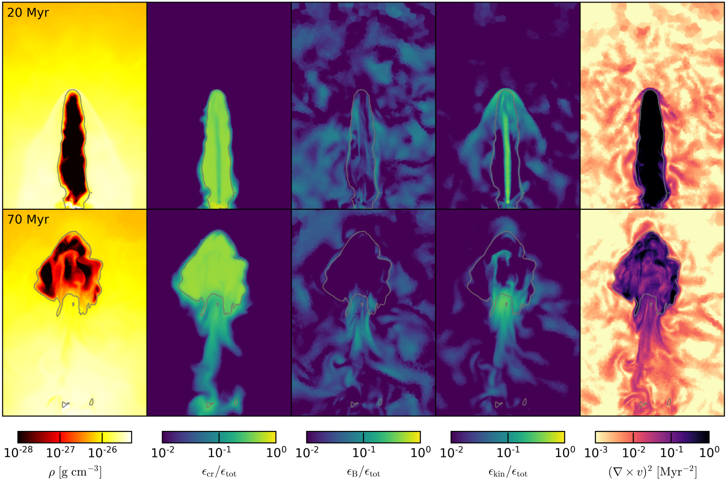
Perseus cluster – heating vs. cooling: simulations



Ehlert+ in prep.

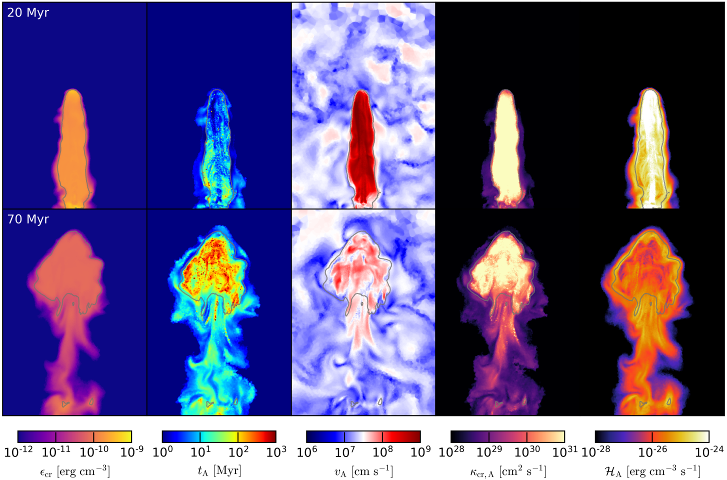
- CR and conductive heating balance radiative cooling: $\mathcal{H}_{\rm cr} + \mathcal{H}_{\rm th} \approx \mathcal{C}_{\rm rad}$: modest mass deposition rate of 1 $M_\odot$ yr^{-1}
- **simulated CR heating rate matches 1D steady state model**

AGN Simulations: energy densities



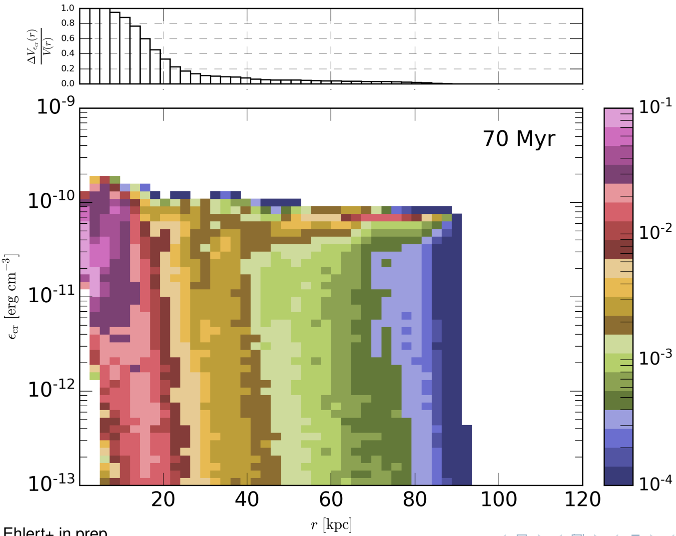
Ehlert+ in prep.

AGN Simulations: cosmic-ray transport



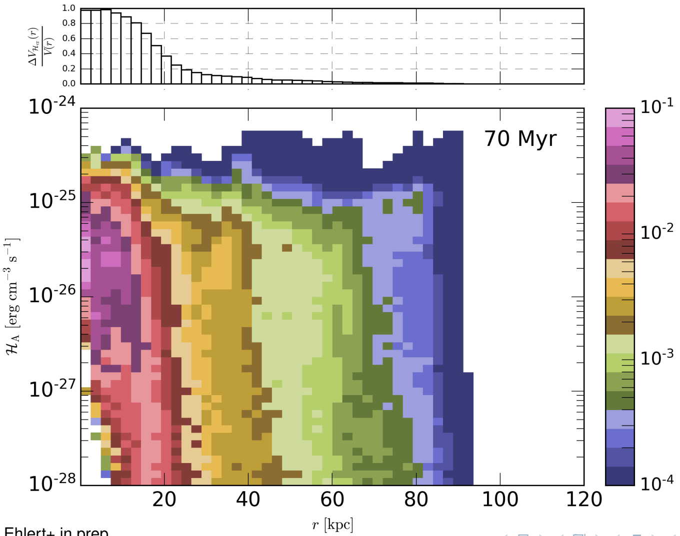
Ehlert+ in prep.

AGN Simulations: cosmic ray distribution



Ehlert+ in prep.

AGN Simulations: cosmic-ray heating rate



Ehlert+ in prep.

Conclusions on AGN feedback by cosmic-ray heating

Large sample of cool cores $\Rightarrow$ self-regulation cycle

- *low-density cool cores:* possibly stably heated by cosmic rays
- *radio mini halo clusters:* cosmic-ray heating ruled out
  systems are strongly cooling and form stars at large rates

AIP

Conclusions on AGN feedback by cosmic-ray heating

Large sample of cool cores ⇒ self-regulation cycle

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  systems are strongly cooling and form stars at large rates

3D MHD simulations with cosmic rays

- isotropic cosmic-ray distribution in inner 10s of kpc
- 3D cosmic-ray heating rate matches 1D steady state models
- *macro-scale constraints on effective transport coefficients and plasma physics (provided this picture is correct)*

Open problems on active galactic nuclei feedback

- improved plasma physics modeling of CR transport:
  streaming vs. diffusion
  $\rightarrow$ CR heating efficiency and isotropy
  $\rightarrow$ radial profile of heating rate

Open problems on active galactic nuclei feedback

- improved plasma physics modeling of CR transport:
  streaming vs. diffusion
  $\rightarrow$ CR heating efficiency and isotropy
  $\rightarrow$ radial profile of heating rate
- understanding duty cycle of active galactic nuclei:
  $\rightarrow$ quasi-steady vs. intermittent heating
- interplay of CR and mechanical heating (turbulence, shocks):
  $\rightarrow$ in which clusters (strong vs. weak cool cores)?
- impact of cosmological environment

CRAGSMAN: The Impact of Cosmic RAys on Galaxy and CluSter ForMAtioN

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Literature for the talk

Cosmic-ray driven galactic winds:

- 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.

AGN feedback by cosmic rays:

- 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, Springel, *Simulating active galactic nuclei feedback with cosmic rays,* in prep.