Cosmic ray heating in cool core clusters

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in collaboration with

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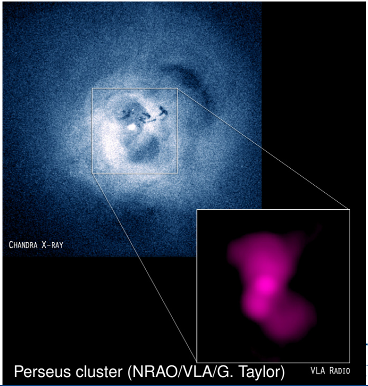
Outline

1. Active galactic nuclei
   - Feedback
   - Magnetic fields
   - Open questions
2. Cosmic ray feedback
   - Observations of M87
   - Cosmic ray heating
   - Local stability
3. Diversity of cool cores
   - Steady state solutions
   - Non-thermal emission
   - AREPO Simulations

Radio mode feedback by AGN

Paradigm: super-massive black holes with $M \sim (10^9 \ldots 10^{10})\mathrm{M}_\odot$ 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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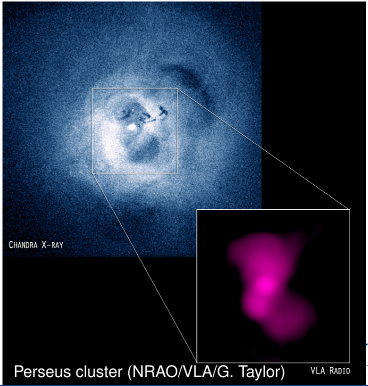
- energy source: release of non-gravitational energy due to accretion on a black hole and its spin
- jet interaction with magnetized cluster medium → turbulence
- jet accelerates relativistic particles (cosmic rays, CRs) → release from bubbles provides source of heat
- self-regulated heating mechanism to avoid overcooling



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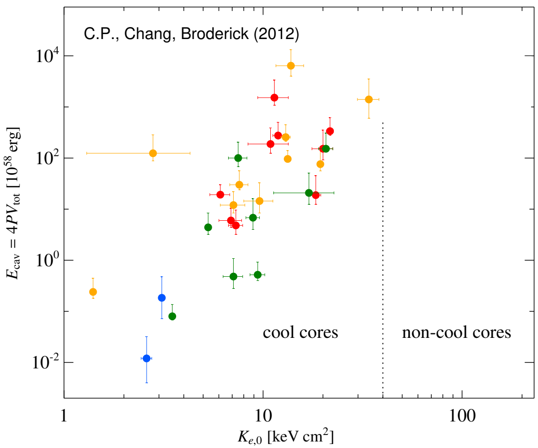
How efficient is heating by AGN feedback?



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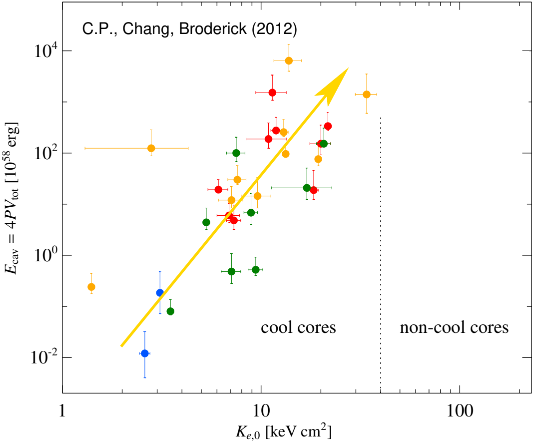

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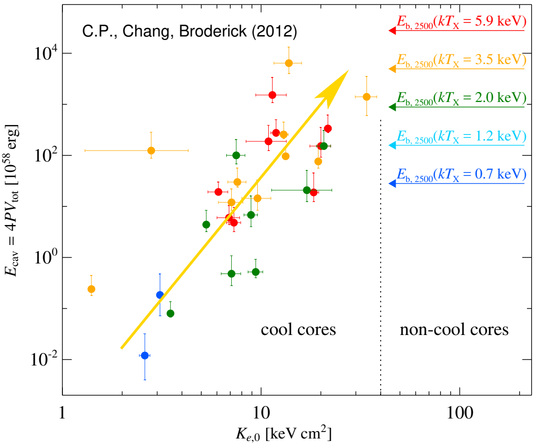

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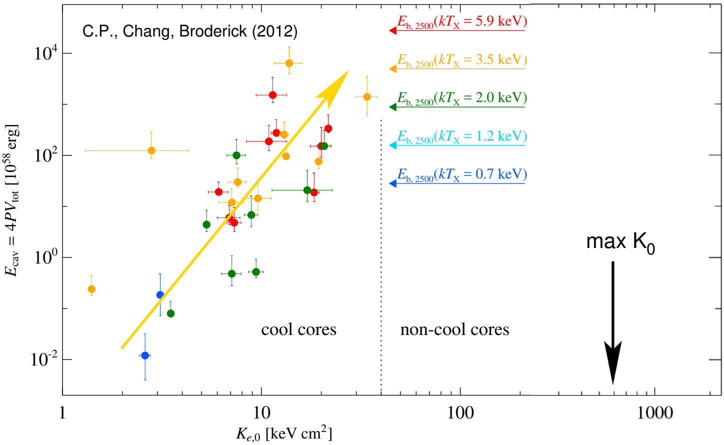
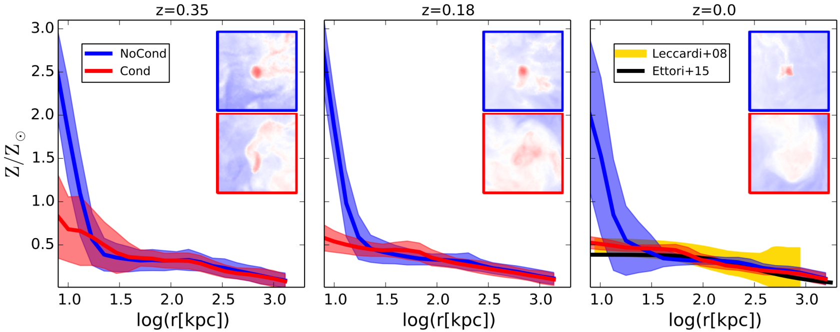

C.P., Chang, Broderick (2012)

AGNs cannot transform CC to NCC clusters (on a buoyancy timescale)

Anisotropic thermal conduction

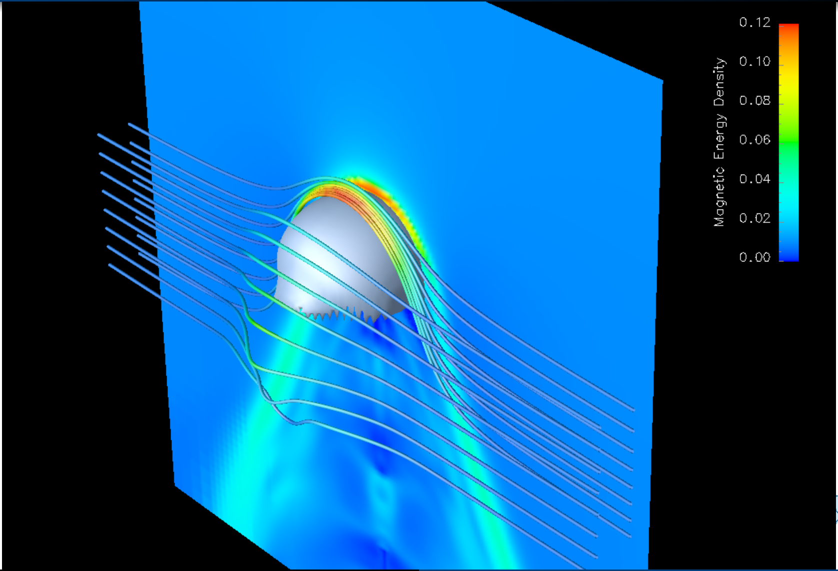
Increasing AGN feedback induced quenching and metal mixing



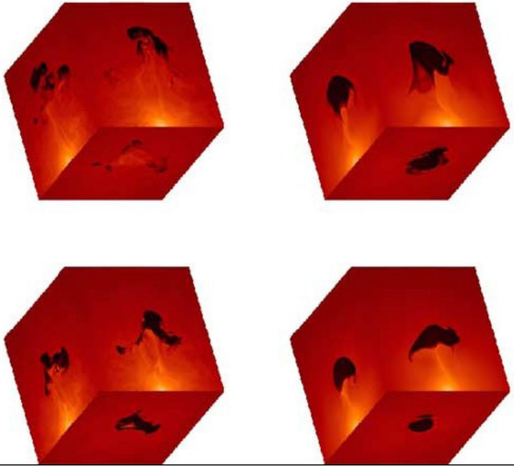
Kannan+ (2016)

Anisotropic thermal conduction changes buoyant response of ICM: increased mixing efficiently isotropizes the injected feedback energy at less energy cost!

Magnetic draping around rising bubbles

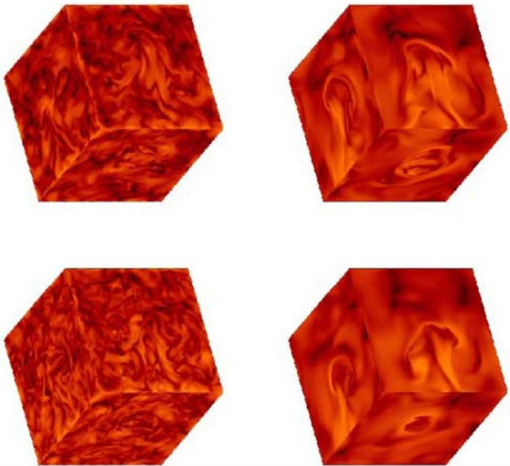


Magnetic draping at bubbles: density



log ρ, non-draping versus draping case (Ruszkowski+ 2007)

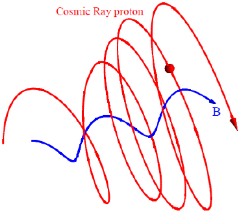
Magnetic draping at bubbles: magnetic pressure



log B^2, non-draping versus draping case (Ruszkowski+ 2007)

Interactions of CRs and magnetic fields

- CRs scatter on magnetic fields → isotropization of CR momenta
- **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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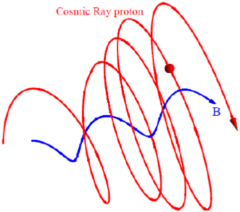


→ **CRs exert a pressure on the thermal gas by means of scattering off of Alfvén waves**

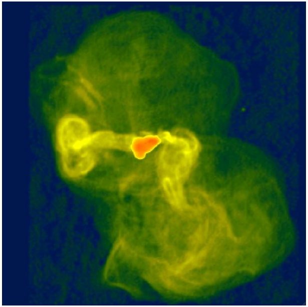
Open questions on radio mode AGN feedback

- how is accretion output thermalized?
  - dissipation of waves, turbulence, releasing potential energy, thermal conduction, cosmic-ray heating
- is heating/cooling balance thermally stable?
  - no: turbulence dissipation, conduction
  - yes: cosmic-ray heating
- how is the accretion rate tuned?
  - Schwarzschild radius

$$r_\mathrm{SMBH} = \frac{2GM_\mathrm{SMBH}}{c^2} \simeq 10^{15} \left(\frac{M_\mathrm{SMBH}}{5\times 10^9\,\mathrm{M}_\odot} \right)\ \mathrm{cm}$$

  - cooling radius (30 kpc) $\sim 10^8$ Schwarzschild radii

Messier 87 at radio wavelengths



$\nu = 1.4$ GHz (Owen+ 2000)

- high-ν: freshly accelerated CR electrons
  low-ν: fossil CR electrons → time-integrated AGN feedback!

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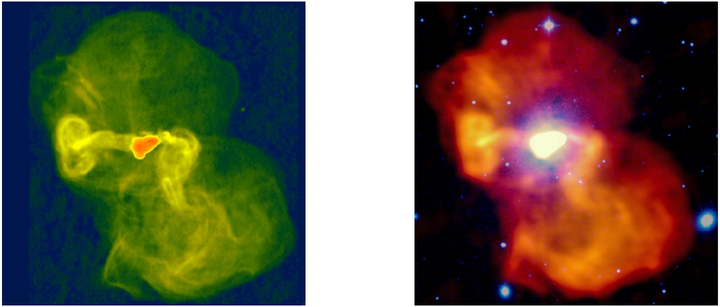


$\nu = 1.4$ GHz (Owen+ 2000)

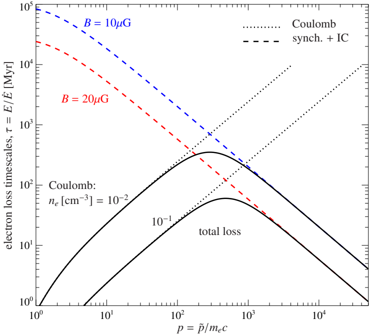
$\nu = 140$ MHz (LOFAR/de Gasperin+ 2012)

- high-ν: freshly accelerated CR electrons
  low-ν: fossil CR electrons → time-integrated AGN feedback!
- LOFAR: halo confined to same region at all frequencies and no low-ν spectral steepening → puzzle of “missing fossil electrons”

Solution to the “missing fossil electrons” problem

solution:

- Coulomb cooling removes fossil electrons
  → efficient mixing of CR electrons and protons with dense cluster gas
  → predicts γ rays from CRp-p interactions:
  $p + p \rightarrow \pi^0 + \ldots \rightarrow 2\gamma + \ldots$



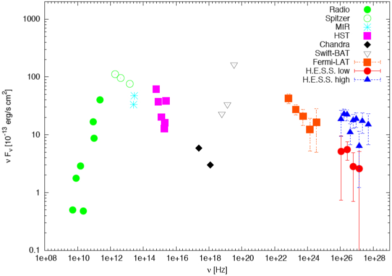
C.P. (2013)

The gamma-ray picture of M87

- high state is time variable
  $\rightarrow$ jet emission
- low state:
  (1) steady flux

  (2) γ-ray spectral index (2.2)
  $=$ CRp index
  $=$ CRe injection index as probed by LOFAR

  (3) spatial extension is under investigation (?)



Rieger & Aharonian (2012)

$\rightarrow$ **confirming this triad would be smoking gun for first γ-ray signal from a galaxy cluster!**

AGN feedback = cosmic ray heating (?)

hypothesis: low state γ-ray emission traces π^0 decay within cluster

- cosmic rays excite Alfvén waves that dissipate the energy → heating rate

$$\mathcal{H}_{\rm cr} = |\boldsymbol{v}_{\rm A} \cdot \nabla P_{\rm cr}|$$

(Loewenstein+ 1991, Guo & Oh 2008, Enßlin+ 2011, Wiener+ 2013, C.P. 2013)

- calibrate $P_{\rm cr}$ to γ-ray emission and $\boldsymbol{v}_{\rm A}$ to radio/X-ray emission → spatial heating profile

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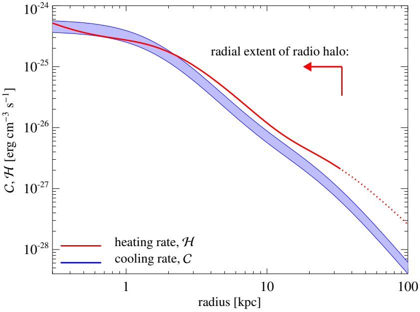
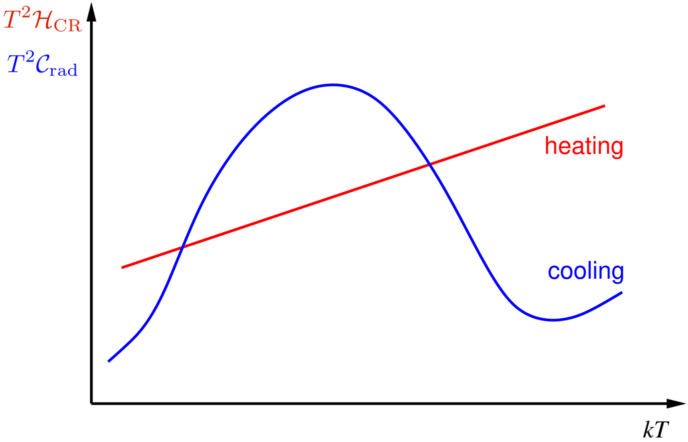


C.P. (2013)

→ cosmic-ray heating matches radiative cooling (observed in X-rays) and may solve the famous “cooling flow problem” in galaxy clusters!

Local stability analysis (1)



- isobaric perturbations to global thermal equilibrium
- CRs are adiabatically trapped by perturbations

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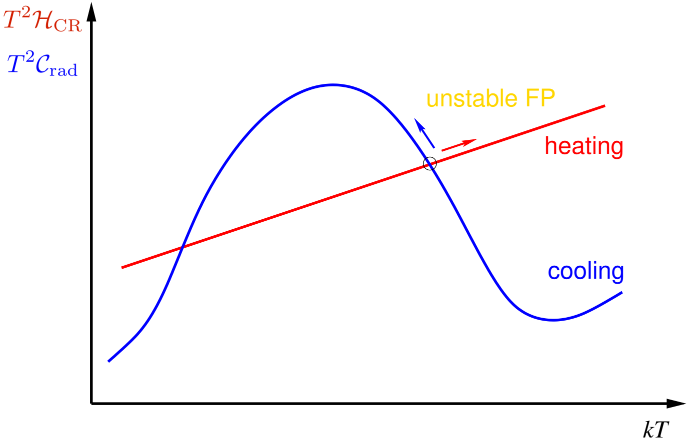

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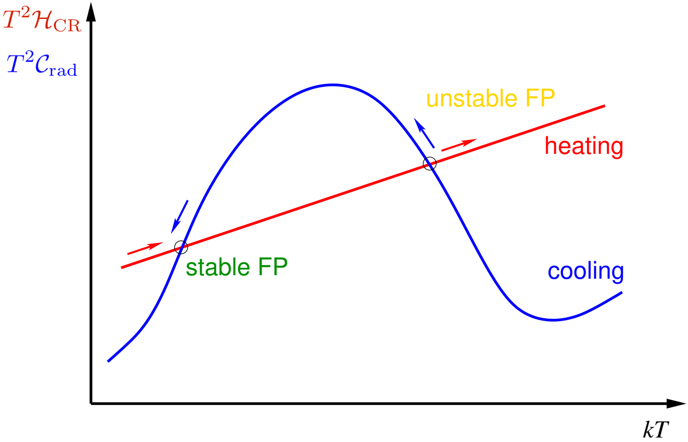

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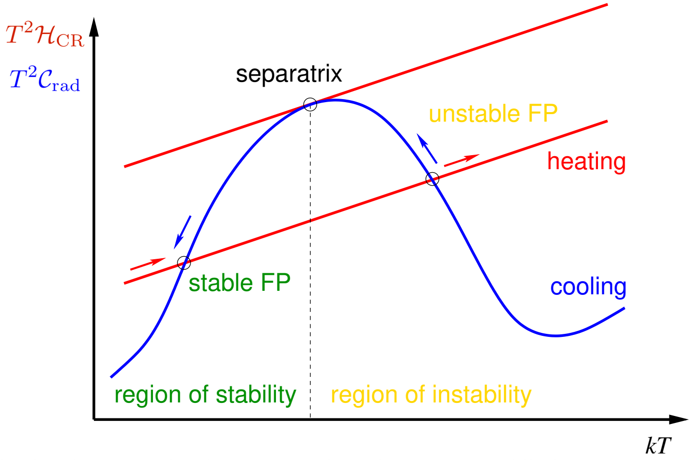

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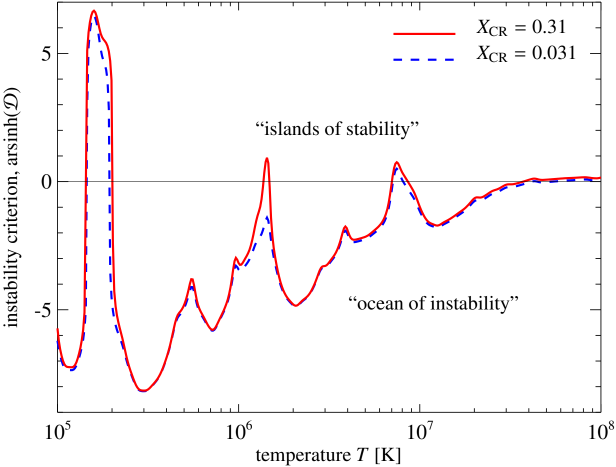
Local stability analysis (2)

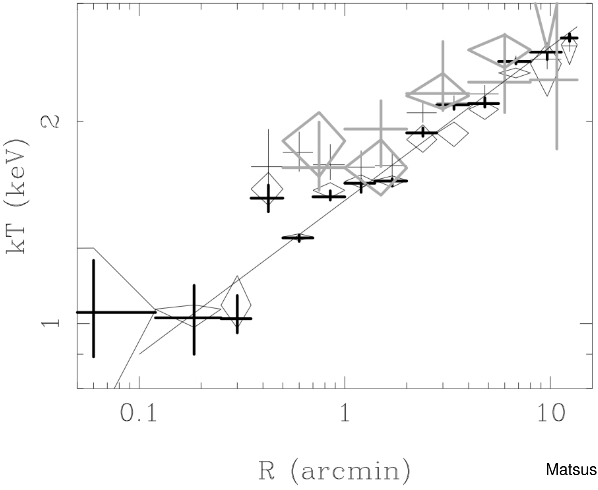
Theory predicts observed temperature floor at $kT \simeq 1$ keV



C.P. (2013)

Virgo cluster cooling flow: temperature profile

X-ray observations confirm temperature floor at $kT \simeq 1$ keV



Matsushita+ (2002)

How universal is CR heating in cool core clusters?

- no γ rays observed from other clusters → P_{cr} unconstrained
- **strategy:**

  (1) construct large sample of 39 cool cores

  (2) search for spherically symmetric, steady-state solutions:

  CR heating ($\mathcal{H}_{\mathrm{cr}}$) $+$ conductive heating ($\mathcal{H}_{\mathrm{th}}$) $\approx$ cooling ($\mathcal{C}_{\mathrm{rad}}$)

  (3) calculate hadronic radio and γ-ray flux $\mathcal{F}_{\mathrm{had}}$ and compare to observed fluxes $\mathcal{F}_{\mathrm{obs}}$

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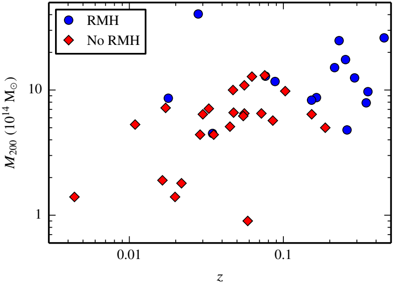
  (3) calculate hadronic radio and γ-ray flux $\mathcal{F}_{\mathrm{had}}$ and compare to observed fluxes $\mathcal{F}_{\mathrm{obs}}$
- **consequences:**
  ⇒ if $\mathcal{H}_{\mathrm{cr}} + \mathcal{H}_{\mathrm{th}} \approx \mathcal{C}_{\mathrm{rad}}\ \forall\ r$ and $\mathcal{F}_{\mathrm{had}} \leq \mathcal{F}_{\mathrm{obs}}$: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

Sample selection

select 39 cool cores (CCs):

- brightest 23 CCs from X-ray flux-limited sample (HIFLUGCS) that are also in ACCEPT
- 10 high-resolution Chandra data (Vikhlinin+ 2006)
- 15 clusters with radio-mini halos (RMHs) (Giacintucci+ 2014)
- add Virgo + A2597



Jacob & C.P. (2016a)

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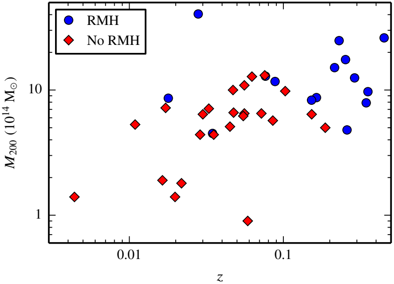

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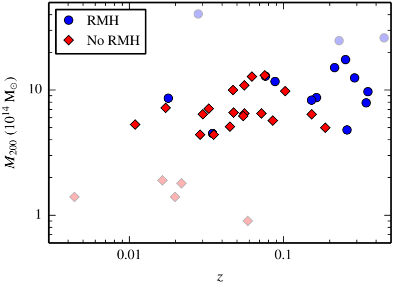

Jacob & C.P. (2016a)

⇒ RMH clusters show selection bias towards high-z and being more massive (fixed surface brightness limit)

⇒ study ***sub-sample that is unbiased in*** M_{200} and ***entire sample***

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

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

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

- 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 $S_\mathrm{cr} = -\frac{\nu\varepsilon_\mathrm{cr}\dot{M}c^2}{4\pi r_\mathrm{cr}^3}\left(\frac{r}{r_\mathrm{cr}}\right)^{-3-\nu}\left(1-e^{-(r/r_\mathrm{cr})^2}\right)$

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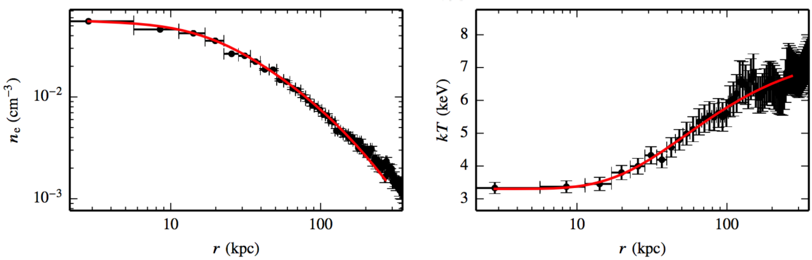
$$\frac{\mathrm{d}e_\mathrm{cr}}{\mathrm{d}t} + \gamma_\mathrm{cr} e_\mathrm{cr} \boldsymbol{\nabla} \cdot \boldsymbol{v} = -\boldsymbol{\nabla} \cdot \boldsymbol{F}_\mathrm{cr} - \mathcal{H}_\mathrm{cr} + S_\mathrm{cr}$$

- 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 $\mathcal{H}_\mathrm{cr} = -\boldsymbol{v}_\mathrm{st} \cdot \boldsymbol{\nabla} P_\mathrm{cr}$

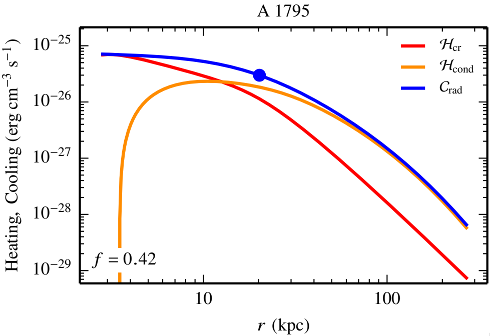
Case study A1795: density and temperature



Jacob & C.P. (2016a)

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

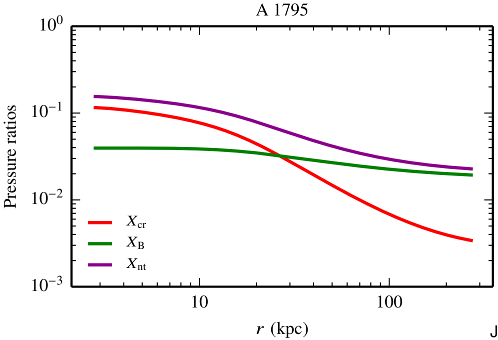
Case study A1795: heating and cooling



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}

Case study A1795: CR and *B* pressure ratios



Jacob & C.P. (2016a)

- define $X_{\rm cr} = P_{\rm cr}/P_{\rm th}$, $X_B = P_B/P_{\rm th}$, $X_{\rm nt} = P_{\rm nt}/P_{\rm th}$

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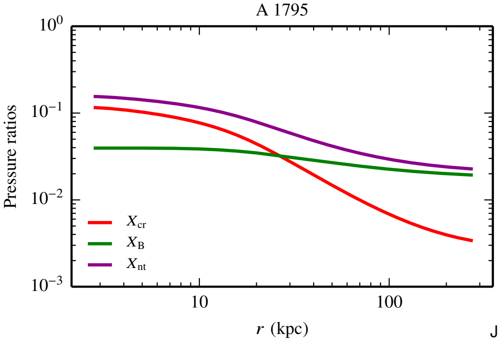

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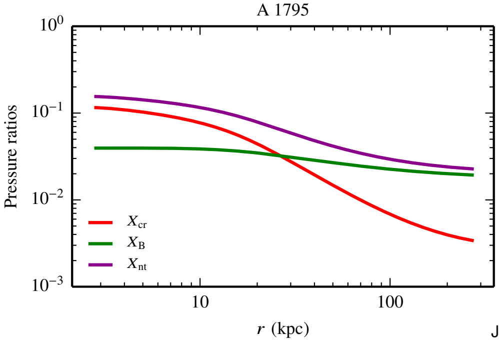

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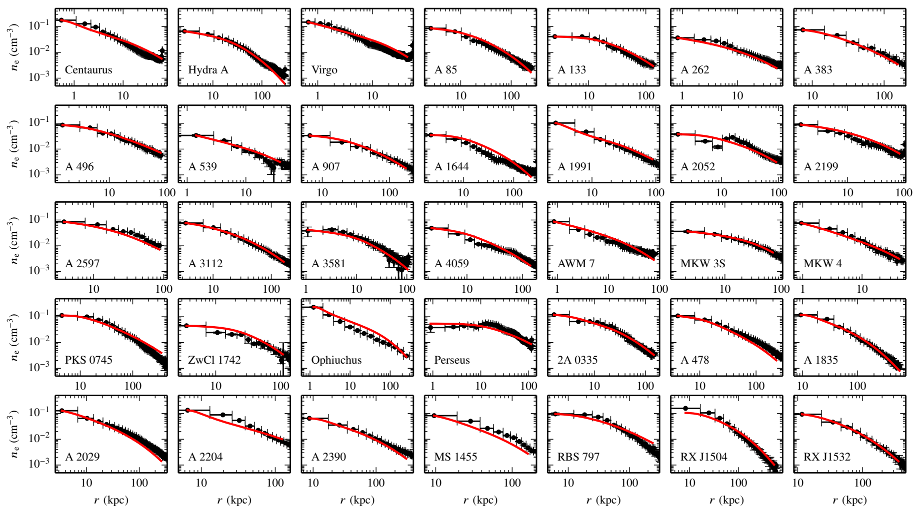
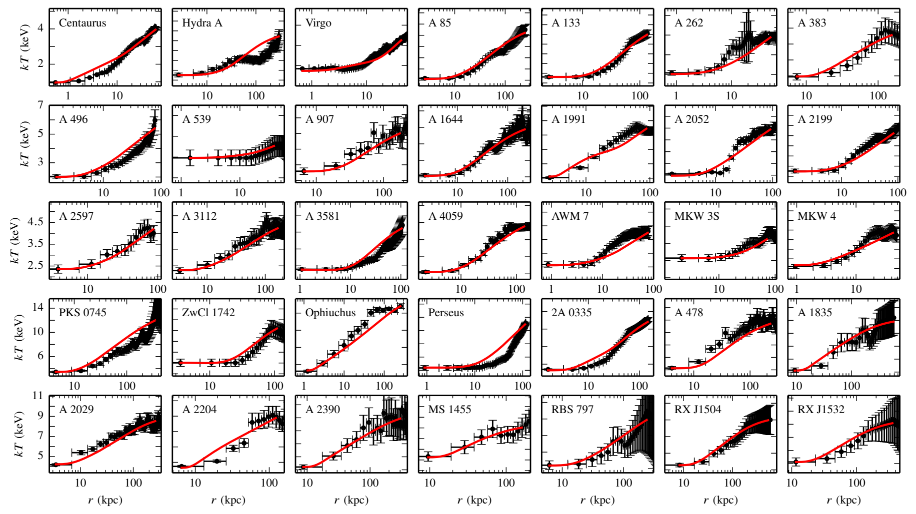
- adopt B model from Faraday rotation studies:

$$B = 10\,\mu\mathrm{G}\times\left(n/0.01\,\mathrm{cm}^{-3}\right)^{0.5}$$

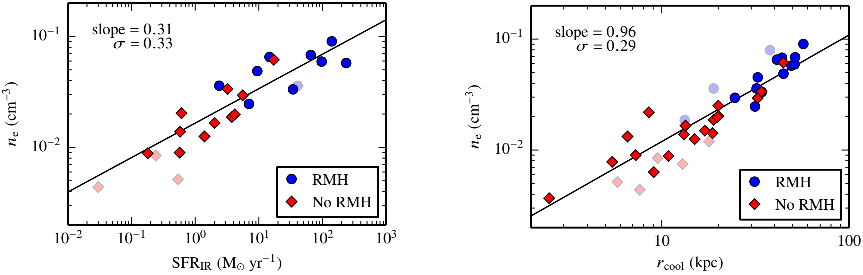
Gallery of solutions: density profiles



Gallery of solutions: temperature profiles



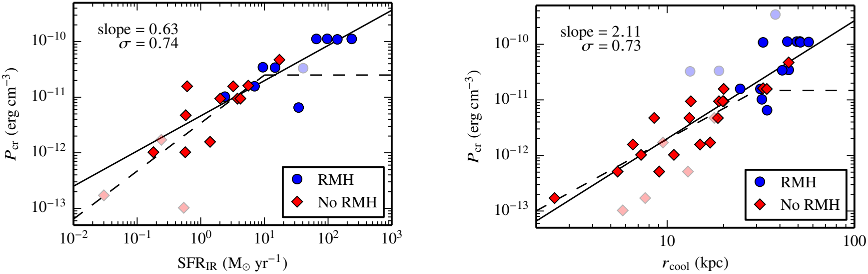
Steady state solutions: density correlations



Jacob & C.P. (2016b)

- tight correlation of gas density $n_e(30\text{ kpc})$ with SFR and with 1 Gyr cooling radius
- RMH clusters are on average denser, show larger SFRs and cooling radii

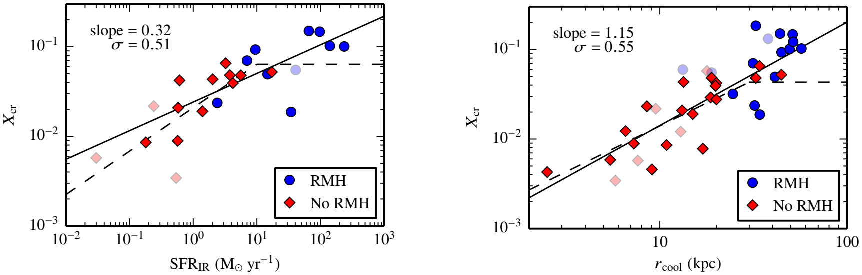
Steady state solutions: $P_{\rm cr}$ correlations



Jacob & C.P. (2016b)

- strong correlation of CR pressure $P_{\rm cr}$ with SFR and $r_{\rm cool}$
- strongly cooling RMH clusters require larger CR heating rates, $\mathcal{H}_{\rm cr} \propto P_{\rm cr}$, and thus CR pressure values to balance cooling
- $P_{\rm cr}$ correlations significantly steeper than $n_{\rm e}$ correlations

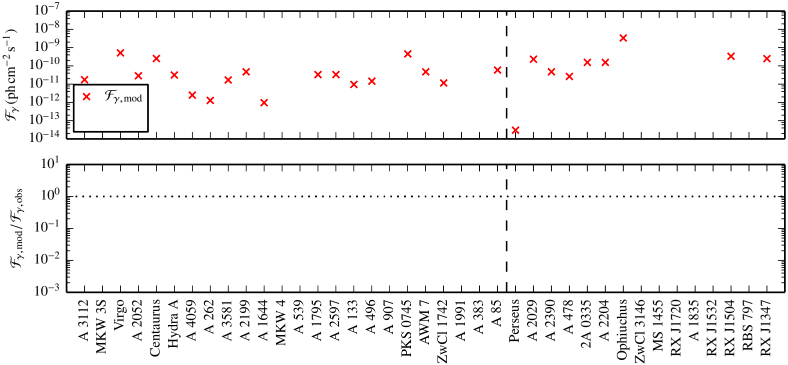
Steady state solutions: $X_{\rm cr}$ correlations



Jacob & C.P. (2016b)

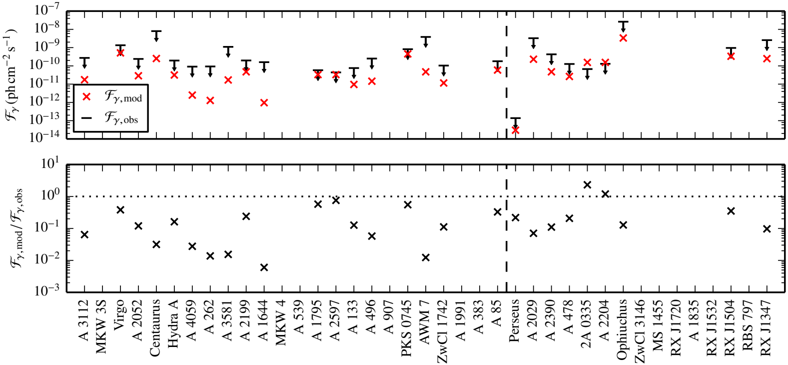
- remainder made up by correlation of CR-to-thermal pressure ratio $X_{\rm cr} = P_{\rm cr}/(nkT)$ with SFR and $r_{\rm cool}$
- strongly cooling RMH clusters require not only larger $P_{\rm cr}$ but also larger $X_{\rm cr}$ to balance cooling

Hadronic gamma-ray emission



Jacob & C.P. (2016b)

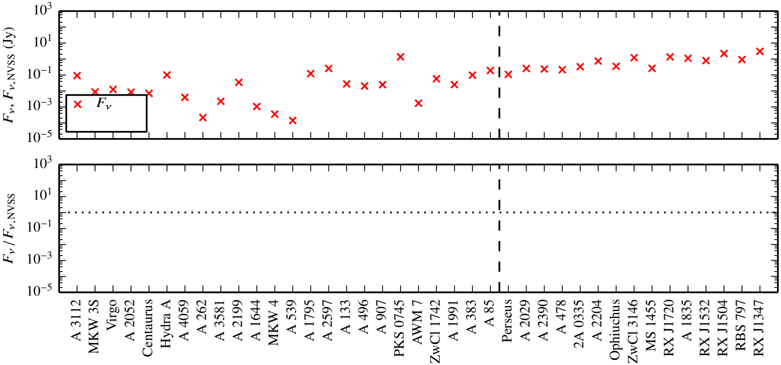
Hadronic gamma-ray emission: observational limits



Jacob & C.P. (2016b)

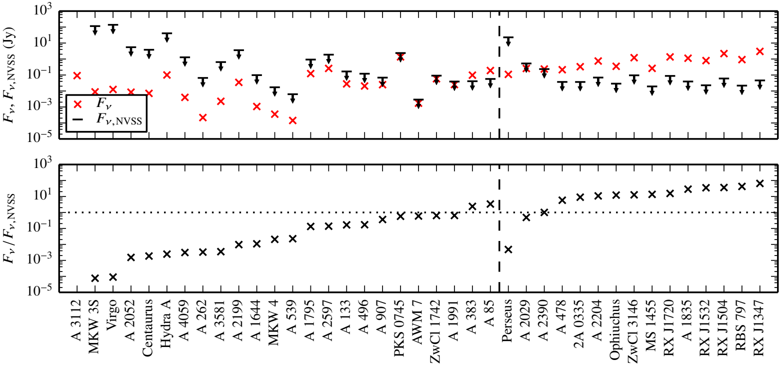
- predictions close to observational limits
- sensitivity not sufficient to be constraining

Hadronically induced radio emission



Jacob & C.P. (2016b)

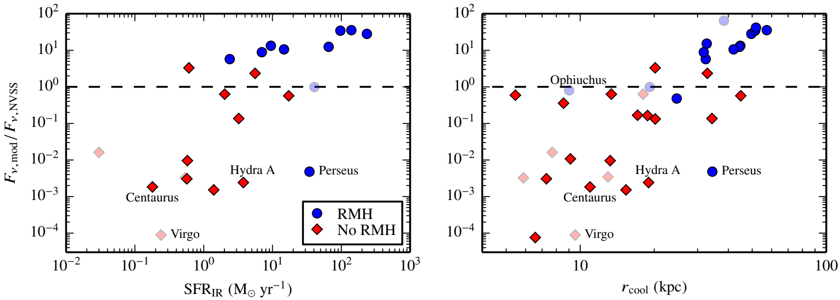
Hadronically induced radio emission: NVSS limits



Jacob & C.P. (2016b)

- 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

Self-regulated heating/cooling cycle in cool cores

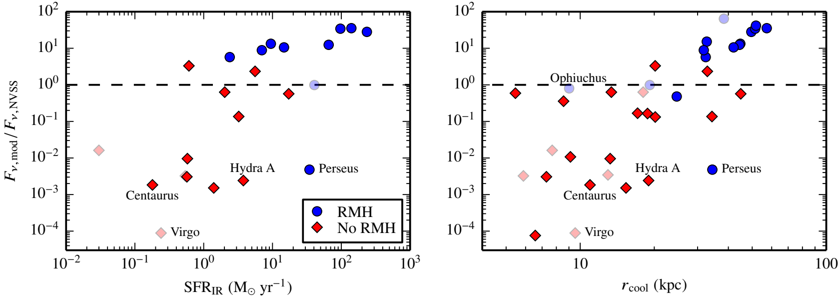


Jacob & C.P. (2016b)

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

Self-regulated heating/cooling cycle in cool cores

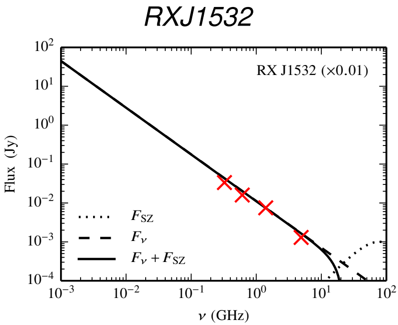


Jacob & C.P. (2016b)

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

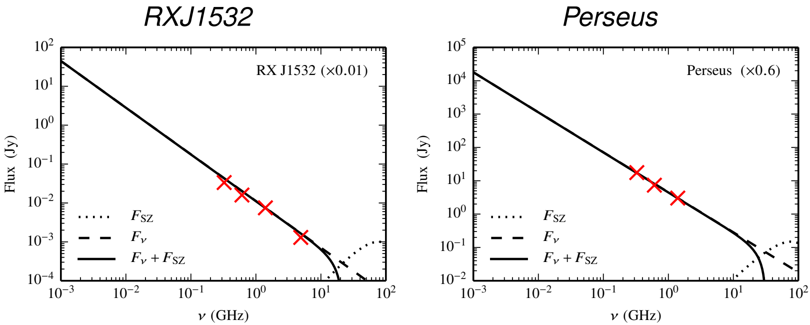
- simmering SF: CR heating is effectively balancing cooling
- abundant SF: heating/cooling out of balance
- $F_{\nu,\mathrm{obs}} > F_{\nu,\mathrm{pred}}$: strong radio source = abundant injection of CRs
  ⇒ predicting existence of **radio micro halos** in CR heated clusters

Radio mini halos



- radio mini halos may be of hadronic origin: CR protons from AGN that have streamed outwards and cooled via Alfvén-wave excitation
- *RXJ1532:* dying radio mini halo

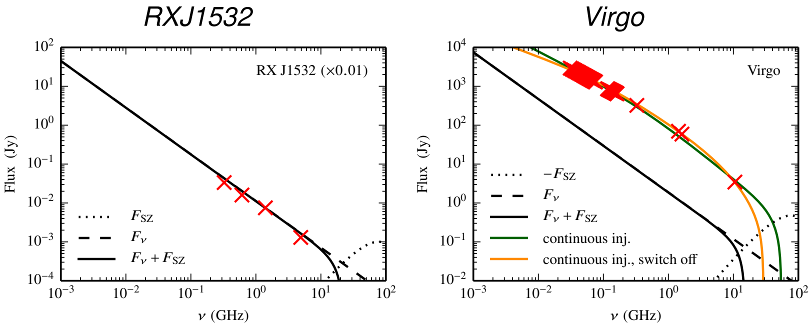
Radio mini halos



Jacob & C.P. (2016a)

- radio mini halos may be of hadronic origin: CR protons from AGN that have streamed outwards and cooled via Alfvén-wave excitation
- *RXJ1532:* dying radio mini halo
  Perseus: transitional object, was CR heated until recently

Predicting radio micro halos

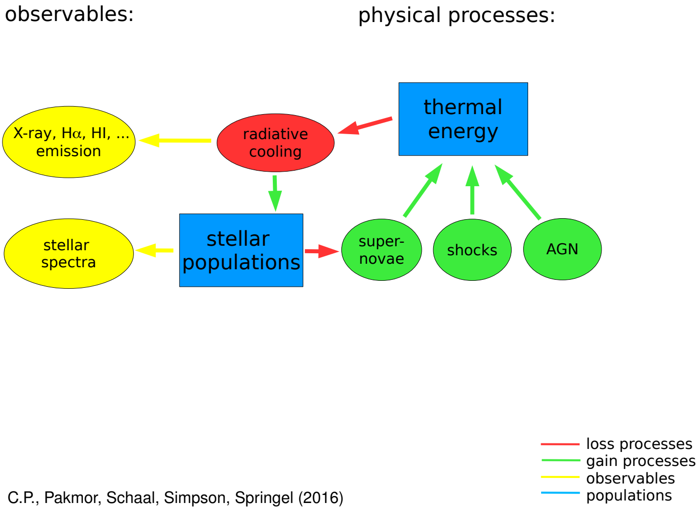


RXJ1532 *Virgo*

Jacob & C.P. (2016a)

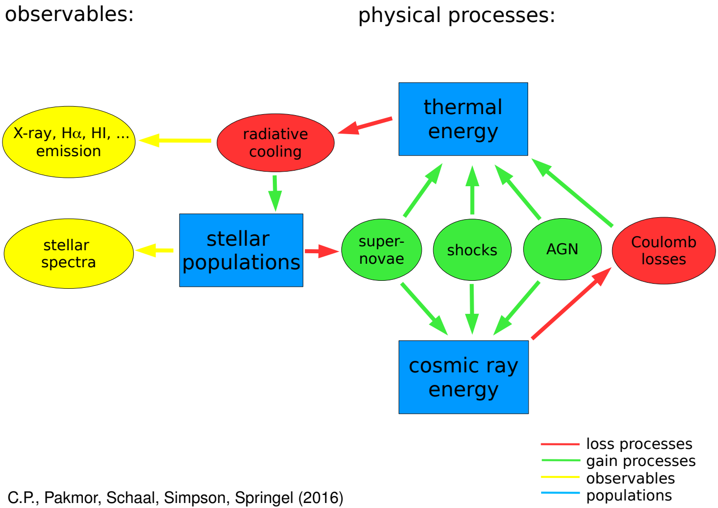
- radio mini halos may be of hadronic origin: CR protons from AGN that have streamed outwards and cooled via Alfvén-wave excitation
- predicting radio micro halos of primary origin in CR-heated CCs: CR electrons that escaped from AGN; subdominant hadronic emission

Simulations – flowchart



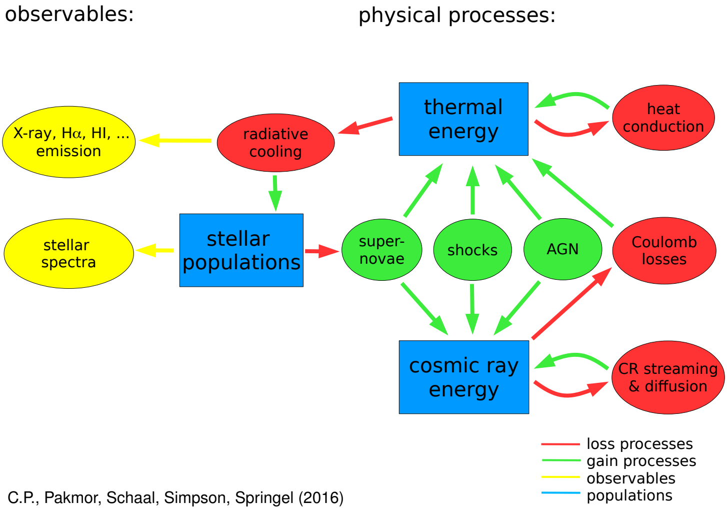
C.P., Pakmor, Schaal, Simpson, Springel (2016)

Simulations with cosmic ray physics



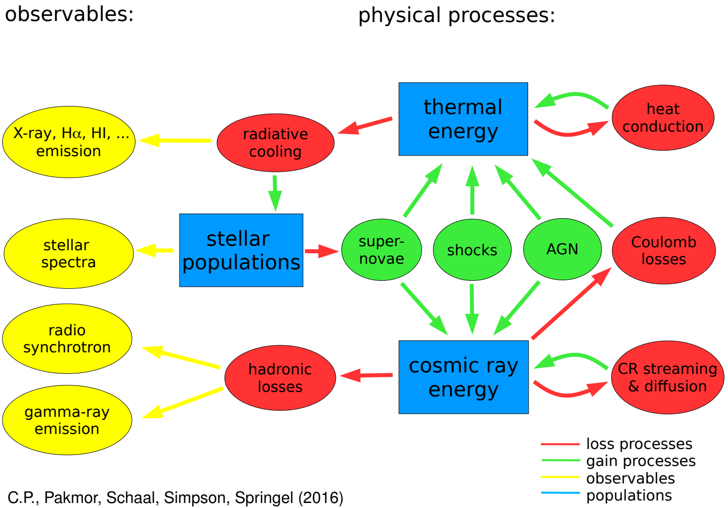
C.P., Pakmor, Schaal, Simpson, Springel (2016)

Simulations with cosmic ray physics



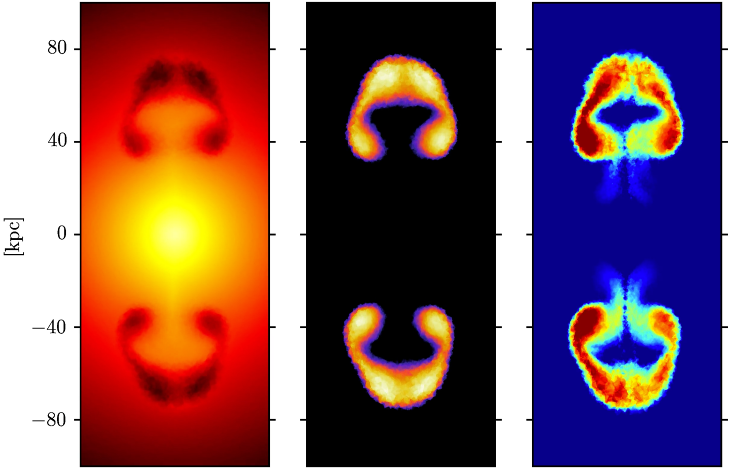
C.P., Pakmor, Schaal, Simpson, Springel (2016)

Simulations with cosmic ray physics



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

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



Weinberger+ in prep.

Conclusions on AGN feedback by cosmic-ray heating

cosmic-ray heating in M87:

- radio and γ-ray data of M87 imply CR mixing with dense cluster gas with a CR-to-thermal pressure ratio of $X_{\rm cr} = 0.3$
- CR Alfvén wave heating balances radiative cooling on all scales within the central radio halo ($r < 35$ kpc)
- local thermal stability analysis predicts observed temperature floor at $kT \simeq 1$ keV

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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
- predicting continuous sequence of diffuse radio emission in *all* cool cores: from radio micro to mini halos

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).

Literature for the talk

AGN feedback by cosmic rays:

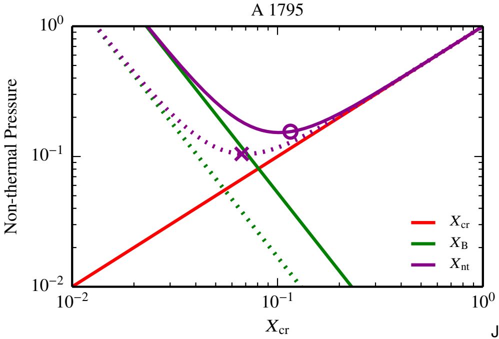
- Pfrommer, *Toward a comprehensive model for feedback by active galactic nuclei: new insights from M87 observations by LOFAR, Fermi and H.E.S.S.*, 2013, ApJ, 779, 10.
- Jacob & Pfrommer, *Cosmic ray heating in cool core clusters I: diversity of steady state solutions*, 2016a, submitted.
- Jacob & Pfrommer, *Cosmic ray heating in cool core clusters II: self-regulation cycle and non-thermal emission*, 2016b, submitted.

Cosmic ray simulations with AREPO:

- Pfrommer, Pakmor, Schaal, Simpson, Springel, *Simulating cosmic ray physics on a moving mesh,* 2016, submitted.

Additional slides

Case study A1795: non-thermal pressure balance

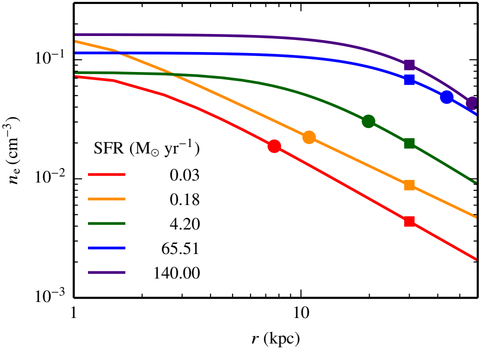


Jacob & C.P. (2016a)

- define $X_{\rm cr} = P_{\rm cr}/P_{\rm th}$ and $X_B = P_B/P_{\rm th}$
- CR heating rate: $\mathcal{H}_{\rm cr} = -\boldsymbol{v}_{\rm st} \cdot \nabla P_{\rm cr} \propto X_B^{0.5} X_{\rm cr}$
- non-thermal pressure at fixed heating rate:

$$X_{\rm nt} \equiv (X_B + X_{\rm cr})|_{\mathcal{H}_{\rm cr}} = A X_{\rm cr}^{-2} + X_{\rm cr} \quad \rightarrow \quad X_{\rm cr,min} = (2A)^{1/3}$$

Steady state solutions: origin of density correlations



Jacob & C.P. (2016a)

- tight correlation of gas density n_e(30 kpc) (squares) with SFR and with 1 Gyr cooling radius r_{cool} (circles)
- clusters with larger SFRs are on average denser and show larger r_{cool}: more cool gas available for star formation