Is cosmic ray heating relevant in cool core clusters?

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in collaboration with

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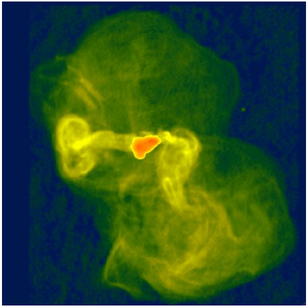
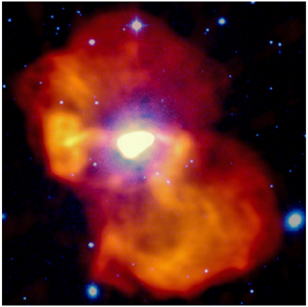
Outline

1. Cosmic ray feedback
   - Observations of M87
   - Cosmic ray heating
   - Local stability
2. Diversity of cool cores
   - Steady state solutions
   - Non-thermal emission
   - Simulations

Messier 87 at radio wavelengths



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



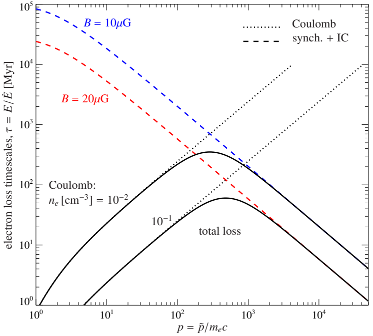
$\nu = 140$ MHz (LOFAR/de Gasperin+ 2012)

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

Solution to the “missing fossil electrons” problem

solution:

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



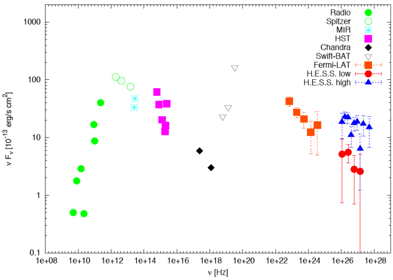
C.P. (2013)

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 (?)

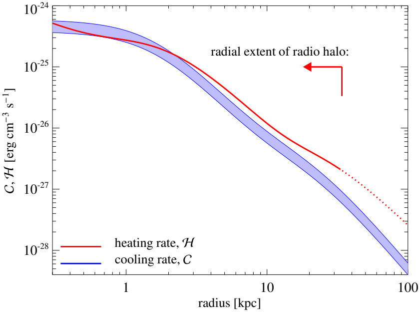
hypothesis: low state γ-ray emission traces π^0 decay within cluster

- cosmic rays excite Alfvén waves that dissipate the energy $\rightarrow$ 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)

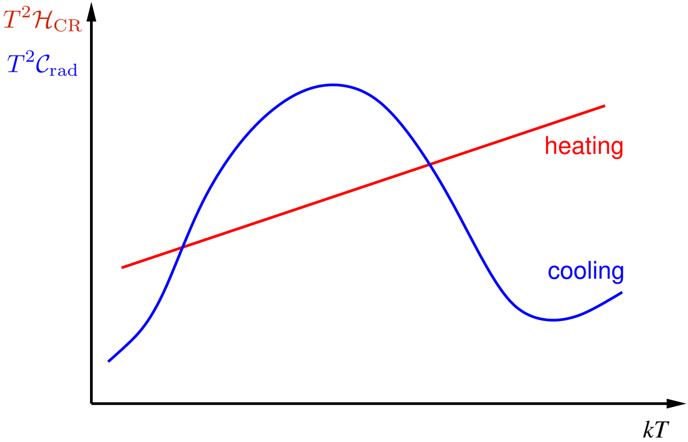
- calibrate $P_{\rm cr}$ to γ-ray emission and $\boldsymbol{v}_{\rm A}$ to radio/X-ray emission $\rightarrow$ spatial heating profile



C.P. (2013)

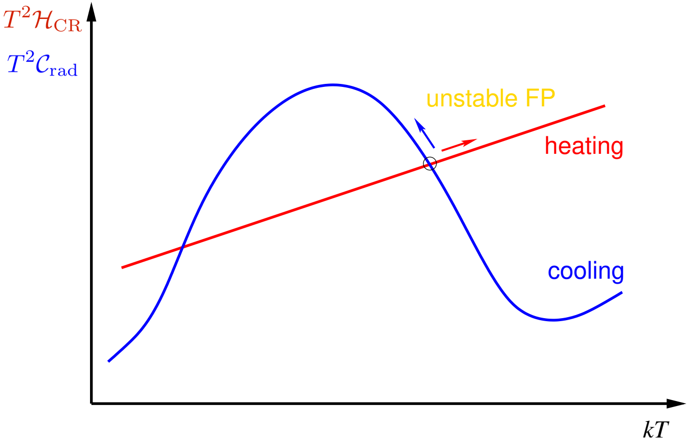
$\rightarrow$ cosmic-ray heating matches radiative cooling (observed in X-rays) and may solve the famous "cooling flow problem" in galaxy clusters!

Local stability analysis (1)



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

Local stability analysis (1)



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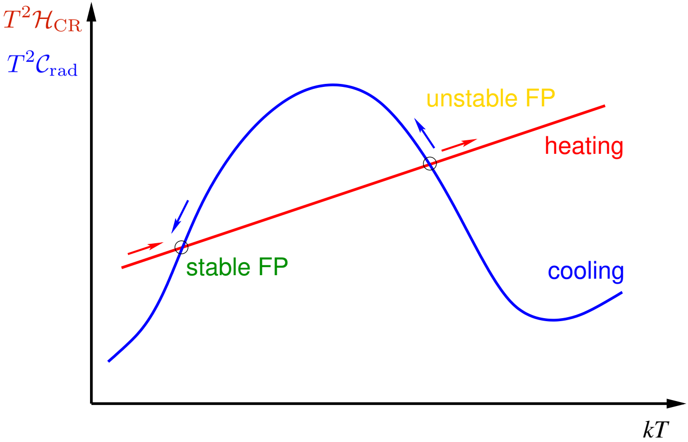

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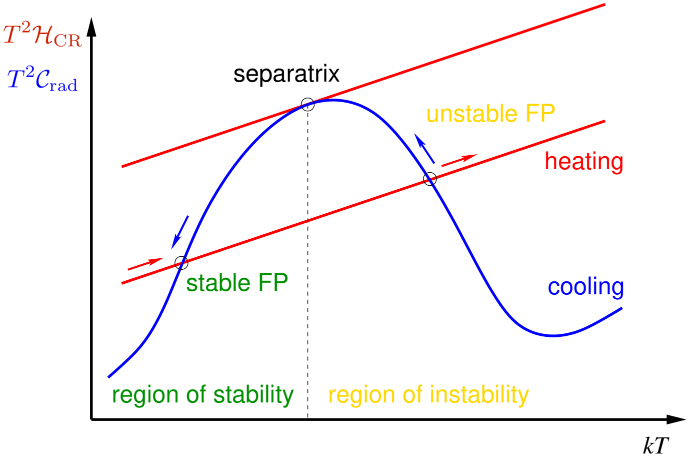

- isobaric perturbations to global thermal equilibrium
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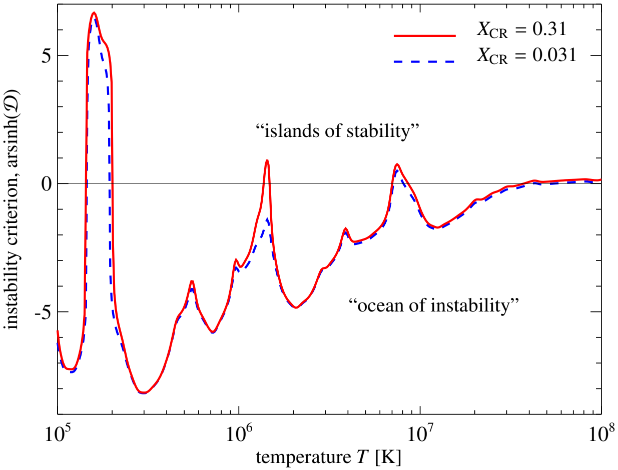
Local stability analysis (2)

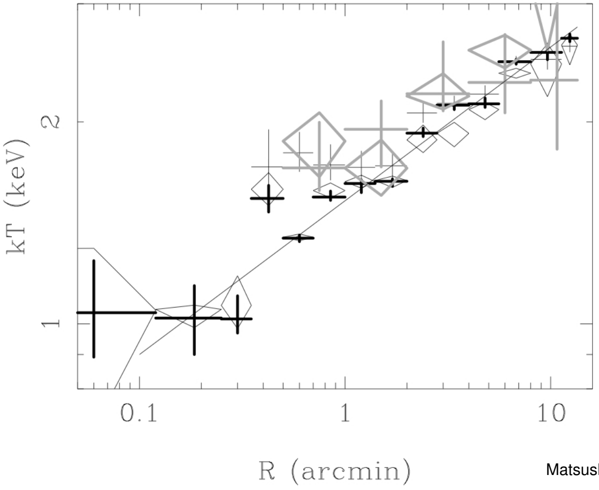
Theory predicts observed temperature floor at $kT \simeq 1$ keV



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 $\rightarrow$ 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 $\mathcal{F}_{\mathrm{obs}}$
- **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

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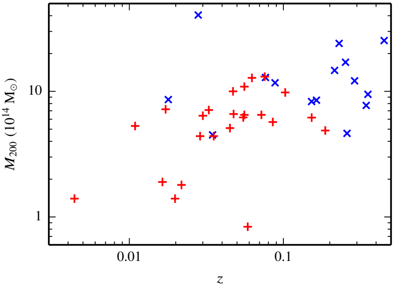
Sample selection

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)

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

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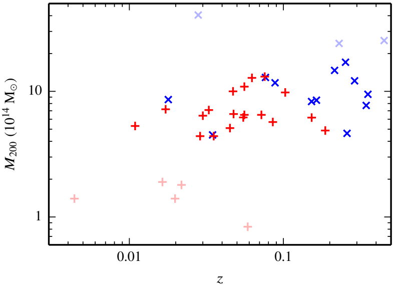

Jacob & C.P. (2016a)

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

$\Rightarrow$ 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:

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

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

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

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Governing equations

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

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

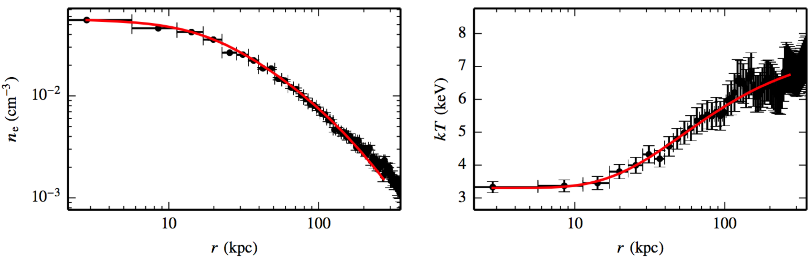
$$\rho\frac{\mathrm{d}\boldsymbol{v}}{\mathrm{d}t} = -\boldsymbol{\nabla}\left(P_{\mathrm{th}} + P_{\mathrm{cr}}\right) - \rho\boldsymbol{\nabla}\phi$$

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

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

- 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 $\boldsymbol{v}_{\mathrm{st}} = -v_{\mathrm{A}}\dfrac{\boldsymbol{\nabla}P_{\mathrm{cr}}}{|\boldsymbol{\nabla}P_{\mathrm{cr}}|}$
- 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

Note: 3D model vs. projected 2D kT profiles
Wish to X-ray community: update ACCEPT + include 3D kT profiles

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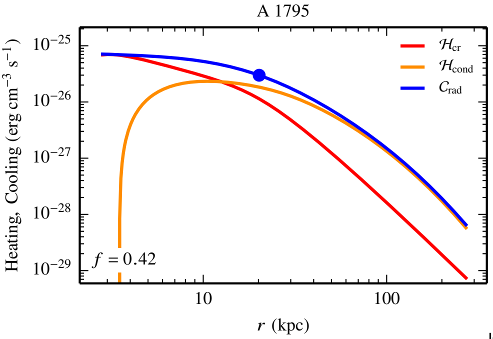
Case study A1795: heating and cooling



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}

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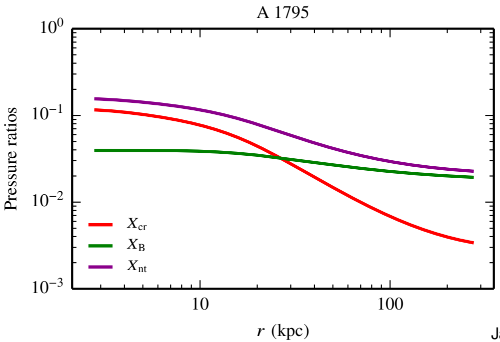
Case study A1795: CR and B pressure ratios



Jacob & C.P. (2016a)

- define $X_{\rm cr} = P_{\rm cr}/P_{\rm th}$, $X_B = P_B/P_{\rm th}$, $X_{\rm nt} = P_{\rm nt}/P_{\rm th}$
- $X_{\rm cr} \approx$ const. in center: $\Delta\varepsilon_{\rm th} = -\tau_{\rm A} \boldsymbol{v}_{\rm st} \cdot \boldsymbol{\nabla} P_{\rm cr} \approx P_{\rm cr} = X_{\rm cr} P_{\rm th}$
- adopt B model from Faraday rotation studies:

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

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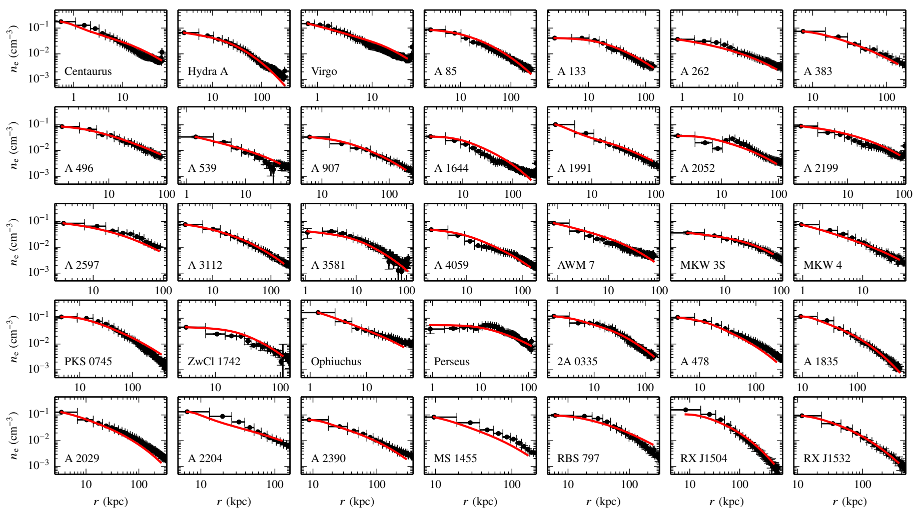
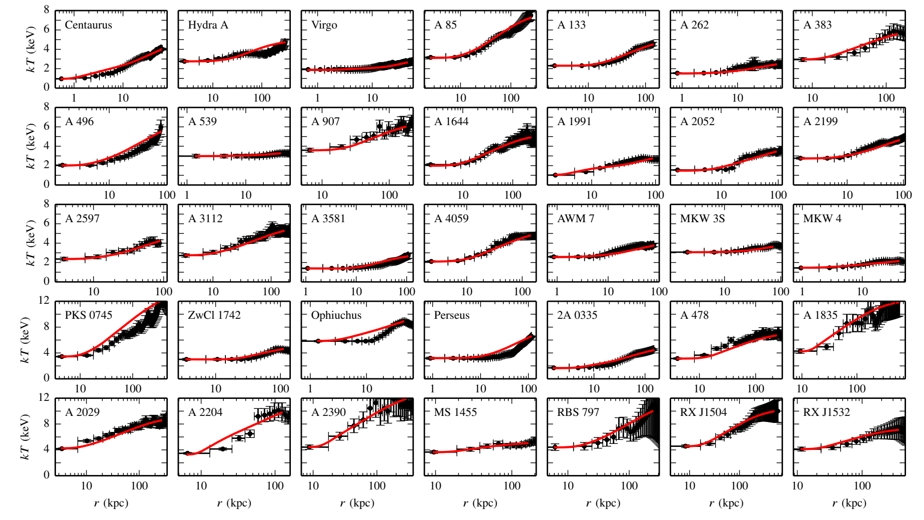
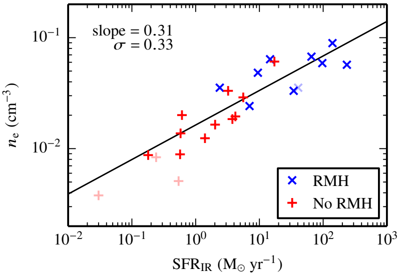
Gallery of solutions: density profiles

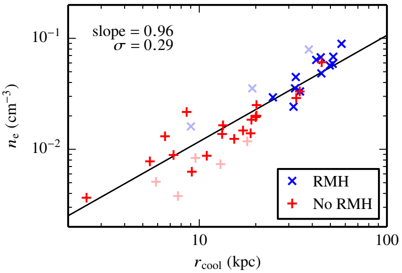


Gallery of solutions: temperature profiles



Steady state solutions: density correlations

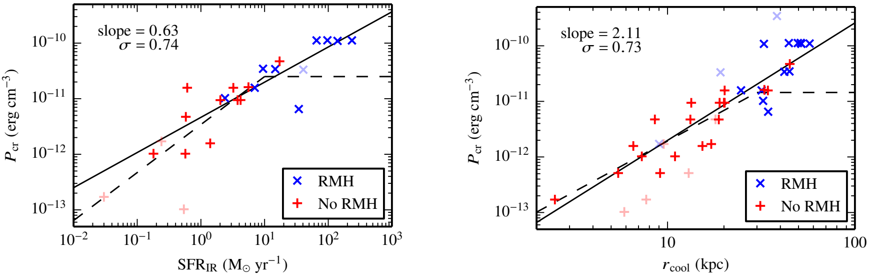




Jacob & C.P. (2016b)

- tight correlation of gas density n_e(30 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_{cr} correlations



Jacob & C.P. (2016b)

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

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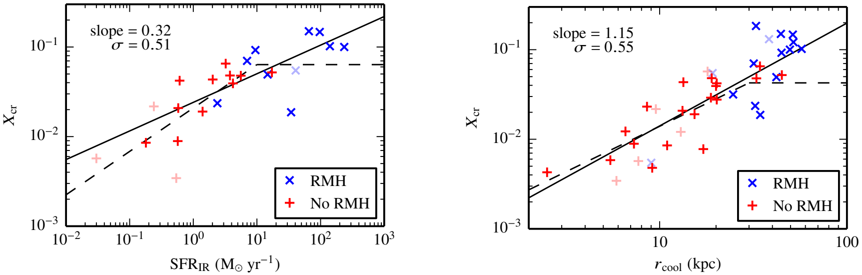
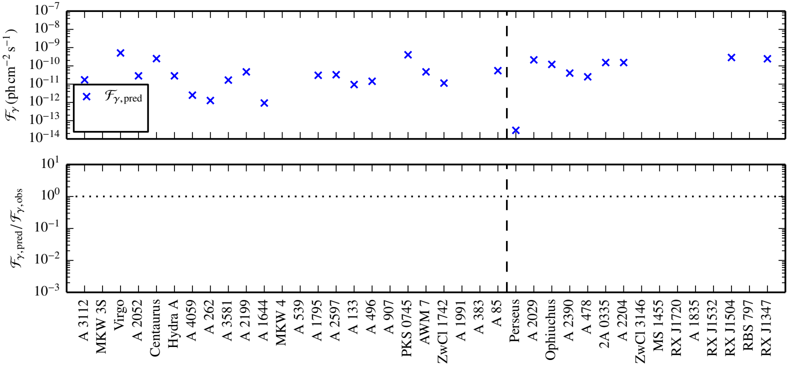
Steady state solutions: $X_{\rm cr}$ correlations



Jacob & C.P. (2016b)

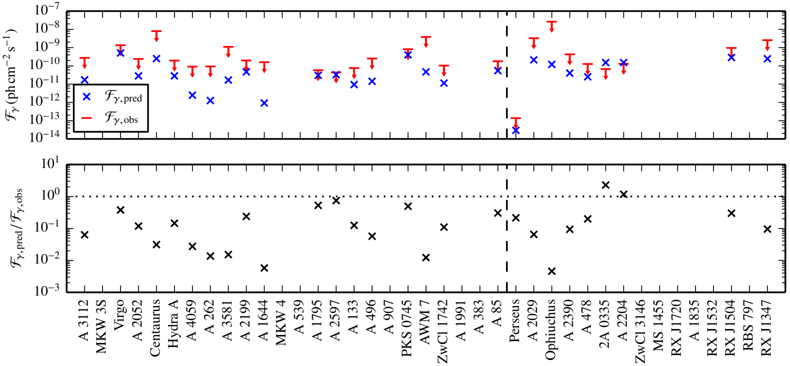
- remainder made up by correlation of CR-to-thermal pressure ratio $X_{\rm cr} = P_{\rm cr}/(nkT)$ with SFR and $r_{\rm cool}$
- strongly cooling RMH clusters require not only larger $P_{\rm cr}$ but also larger $X_{\rm cr}$ to balance cooling

Hadronic gamma-ray emission



Jacob & C.P. (2016b)

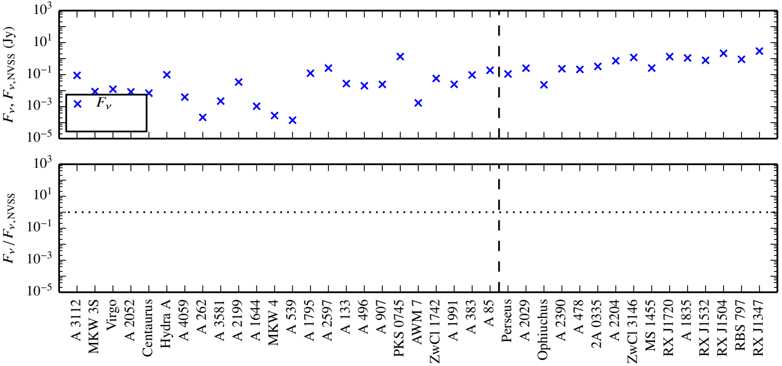
Hadronic gamma-ray emission: observational limits



Jacob & C.P. (2016b)

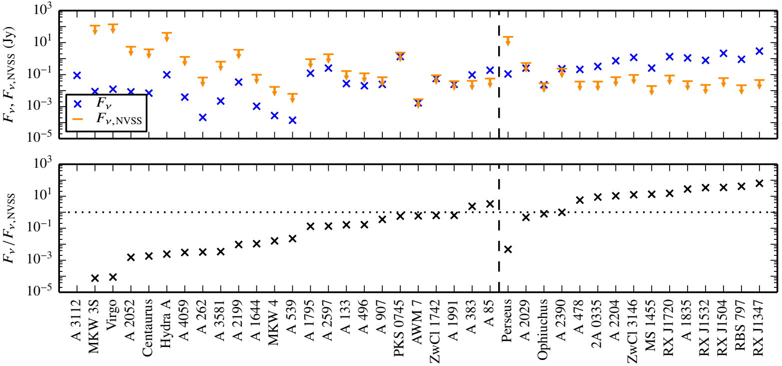
- predictions close to observational limits
- sensitivity not sufficient to be constraining

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

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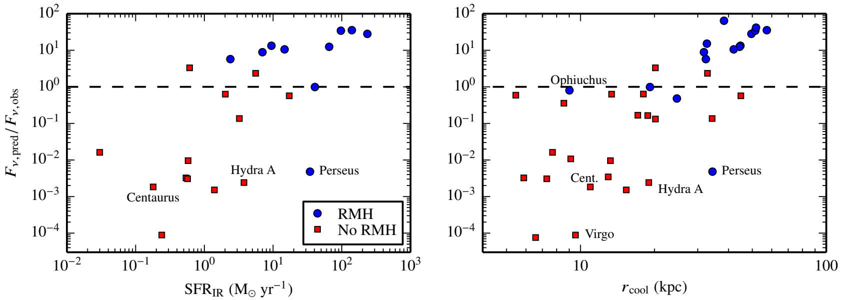
Self-regulated heating/cooling cycle in cool cores



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
  $\Rightarrow$ predicting existence of **radio micro halos** in CR heated clusters

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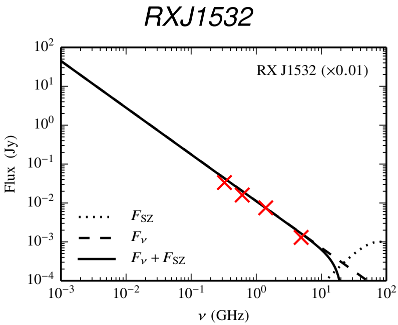
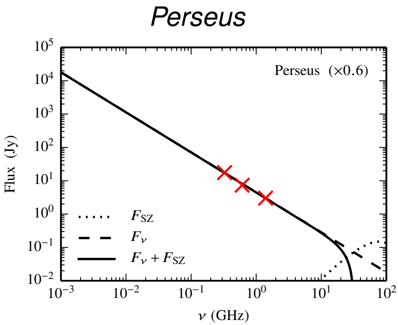
Radio mini halos





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

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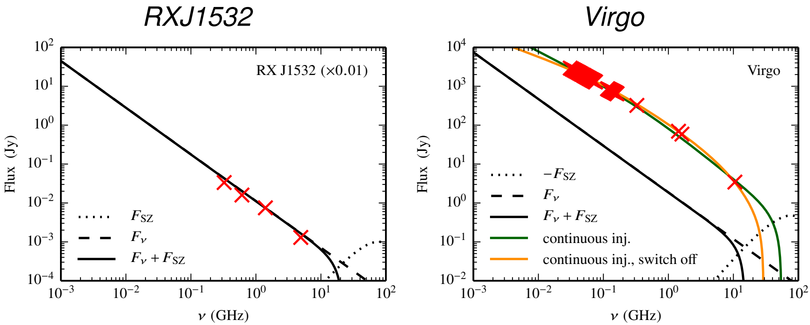
Predicting radio micro halos



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
- predicting radio micro halos of primary origin in CR-heated CCs: CR electrons that escaped from AGN; subdominant hadronic emission

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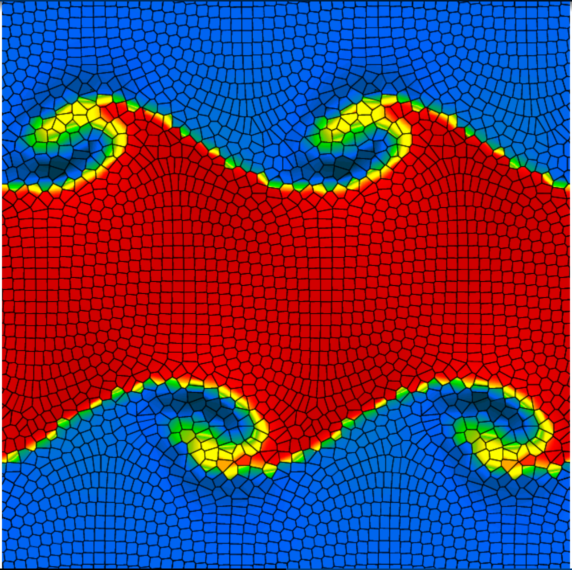
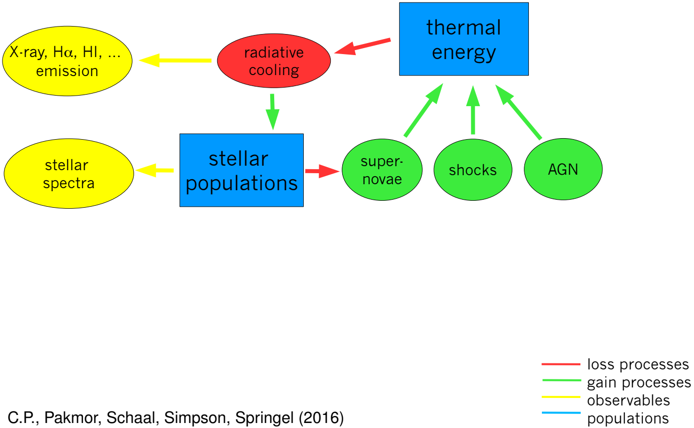
Cosmological moving-mesh code AREPO (Springel 2010)



Simulations – flowchart

ISM observables:

Physical processes in the ISM:



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

Simulations with cosmic ray physics

ISM observables:

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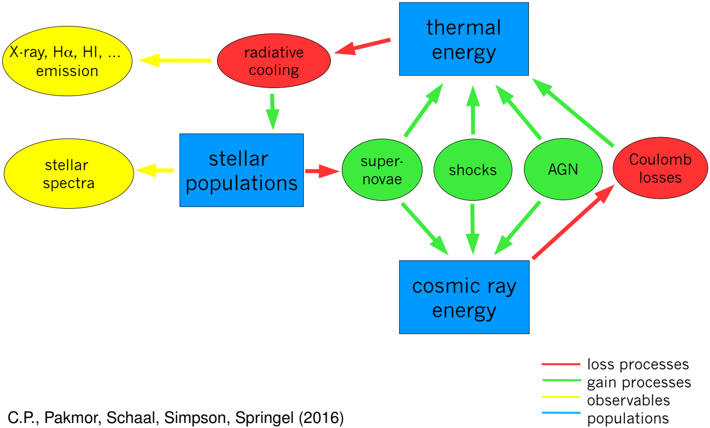

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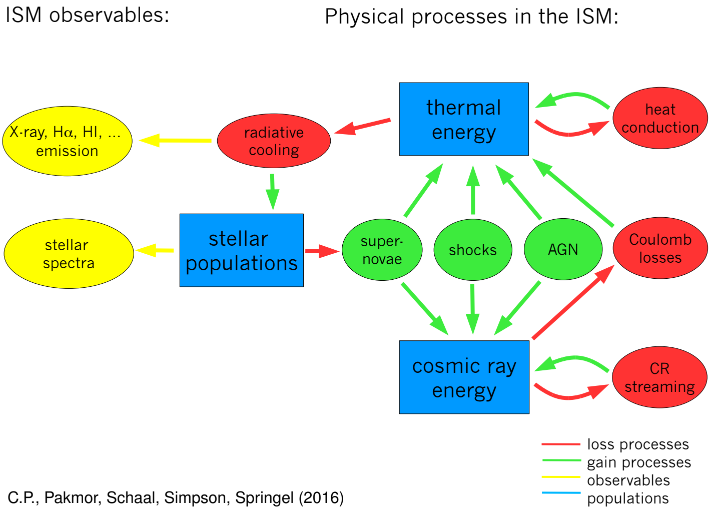
Simulations with cosmic ray physics



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Simulations with cosmic ray physics

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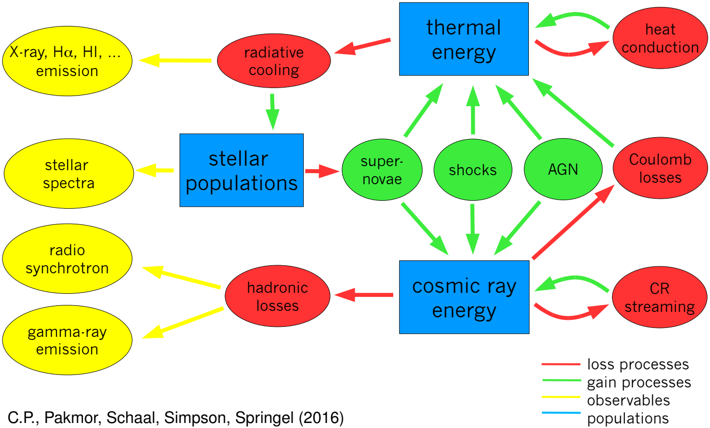
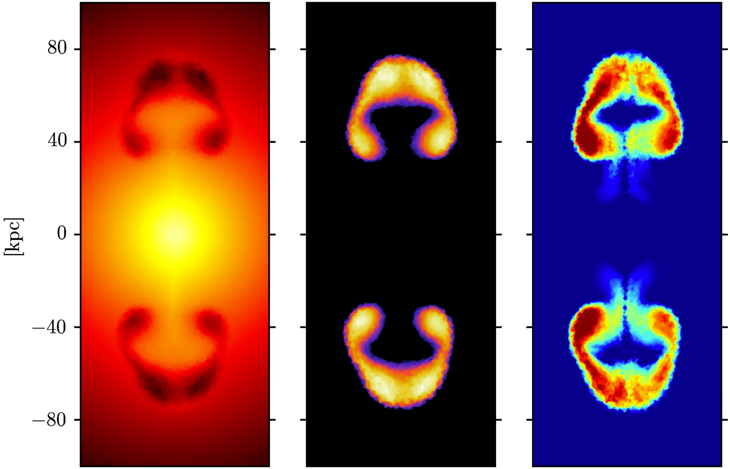


C.P., Pakmor, Schaal, Simpson, Springel (2016)

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

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

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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.
- S. Jacob & C. Pfrommer, *Cosmic ray heating in cool core clusters I: diversity of steady state solutions*, 2016a, in prep.
- S. Jacob & C. Pfrommer, *Cosmic ray heating in cool core clusters II: self-regulation cycle and non-thermal emission*, 2016b, in prep.

Cosmic ray simulations with AREPO:

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

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Additional slides

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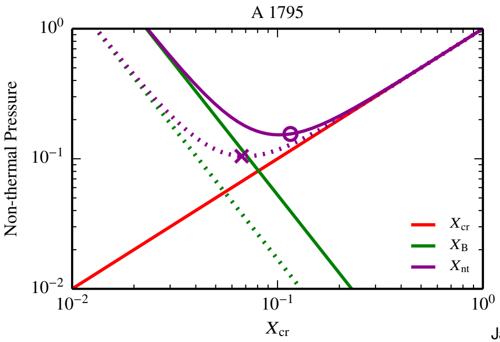
Case study A1795: non-thermal pressure balance



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

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

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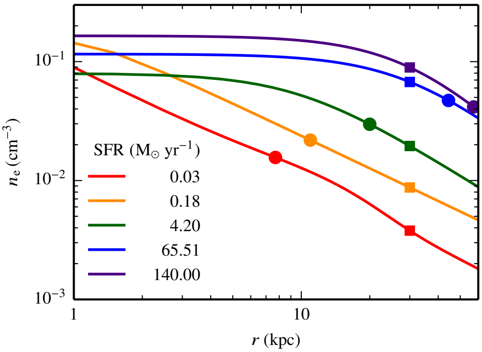
Steady state solutions: origin of density correlations



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

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