Cosmic ray physics in AREPO

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in collaboration with

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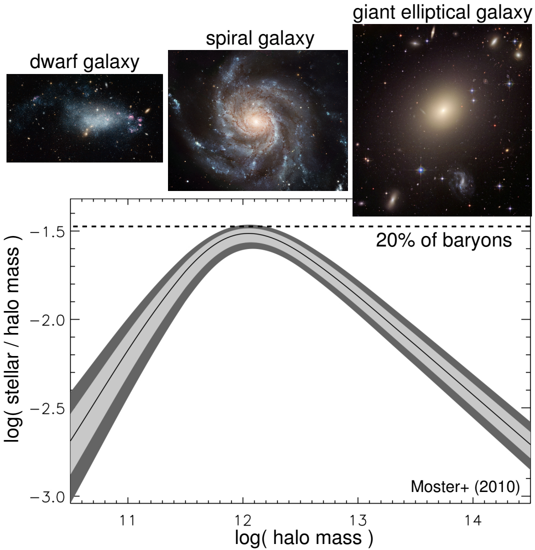
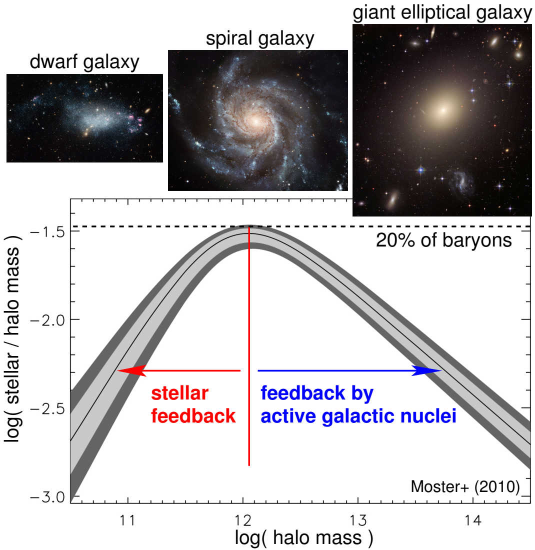
Puzzles in galaxy formation



Puzzles in galaxy formation



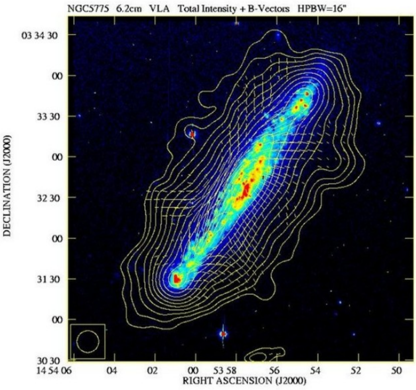
How are galactic winds driven?

observed energy equipartition between cosmic rays (CRs), thermal gas and magnetic fields

$\rightarrow$ suggests self-regulated feedback loop with CR driven winds

Why are CRs important for wind formation?

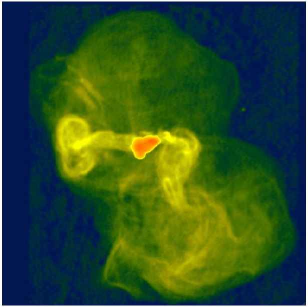
Radio halos in disks: CRs and magnetic fields exist at the disk-halo interface



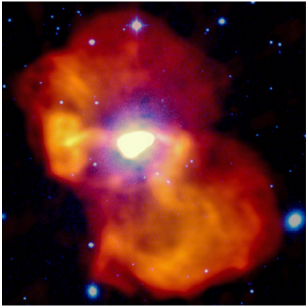
Tüllmann+ (2000)

- CR pressure drops less quickly than thermal pressure ($P \propto \rho^{\gamma}$)
- CRs cool less efficiently than thermal gas
- CR pressure energizes the wind $\rightarrow$ "CR battery"
- poloidal ("open") field lines at wind launching site $\rightarrow$ CR-driven Parker instability

AGN feedback: M87 at radio wavelengths



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



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

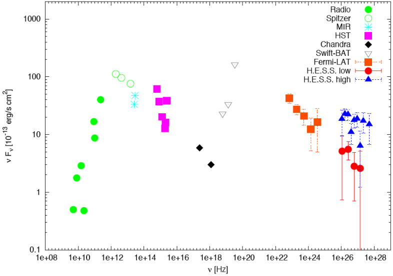
- high-ν: freshly accelerated CR electrons
  low-ν: fossil CR electrons $\rightarrow$ time-integrated AGN feedback!
- LOFAR: same picture $\rightarrow$ puzzle of "missing fossil electrons"
- solution: electrons are fully mixed with the dense cluster gas and cooled through Coulomb interactions

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 (?)

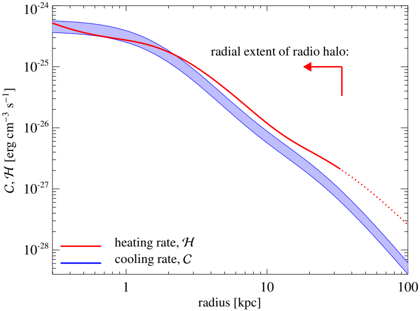
hypothesis: low state γ-ray emission traces CRp-p interactions

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

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

(Loewenstein, Zweibel, Begelman 1991, Guo & Oh 2008, Enßlin+ 2011)

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



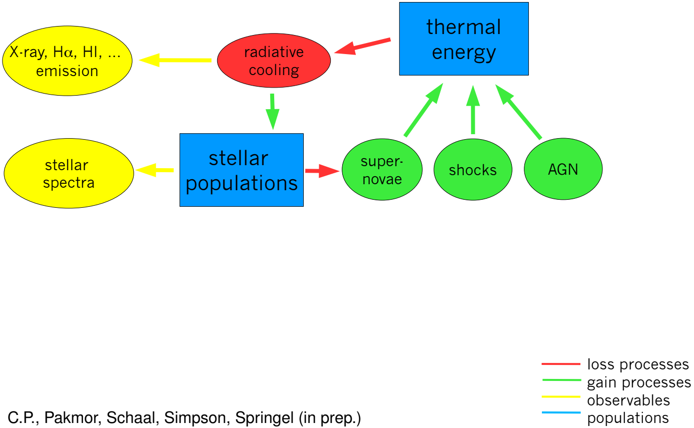
C.P. (2013)

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

Simulations – flowchart

ISM observables:

Physical processes in the ISM:



C.P., Pakmor, Schaal, Simpson, Springel (in prep.)

Simulations with cosmic ray physics

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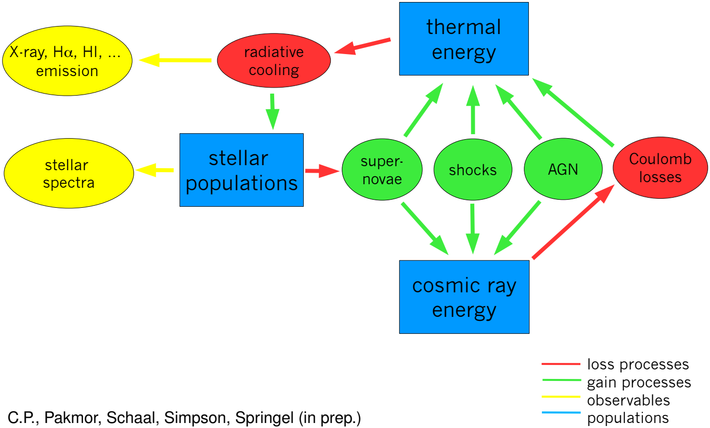

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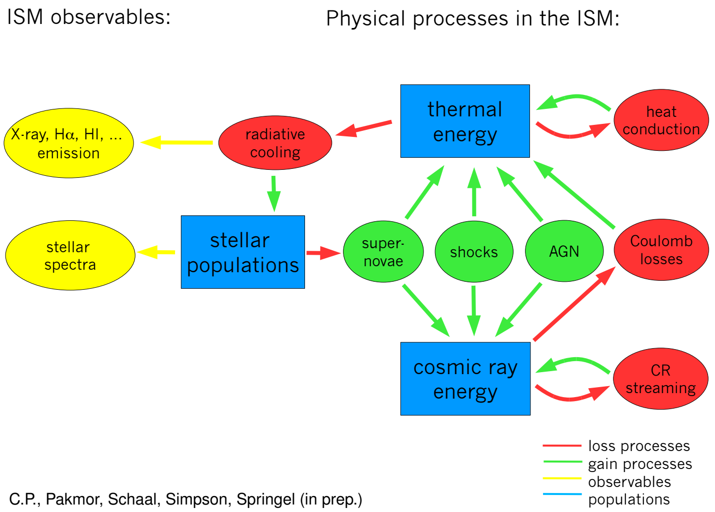

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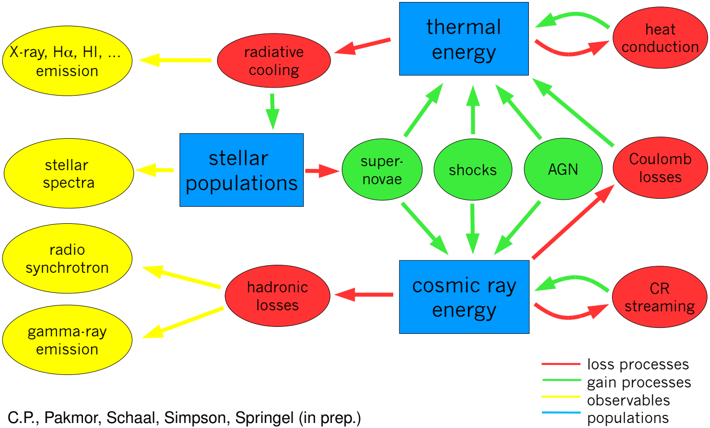

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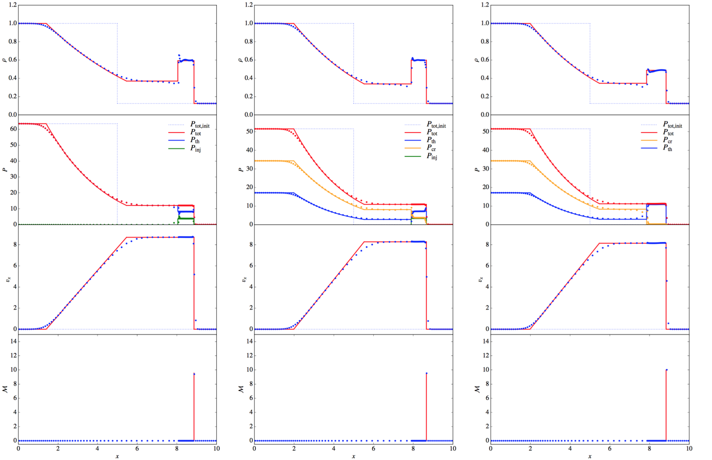
CR shock acceleration

Comparing simulations to novel exact solutions that include CR acceleration



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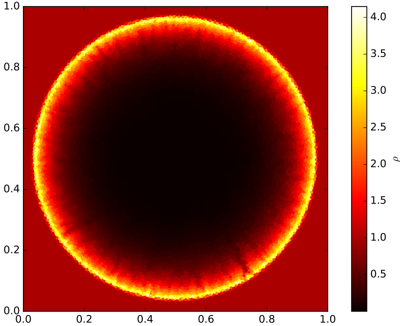
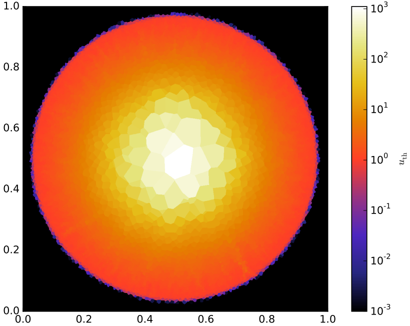
Sedov explosion

density



specific thermal energy



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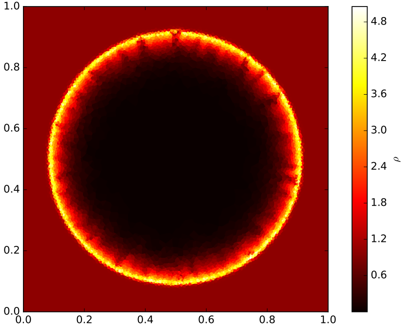
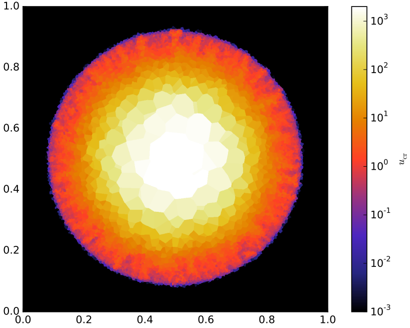
Sedov explosion with CR acceleration

density



specific cosmic ray energy



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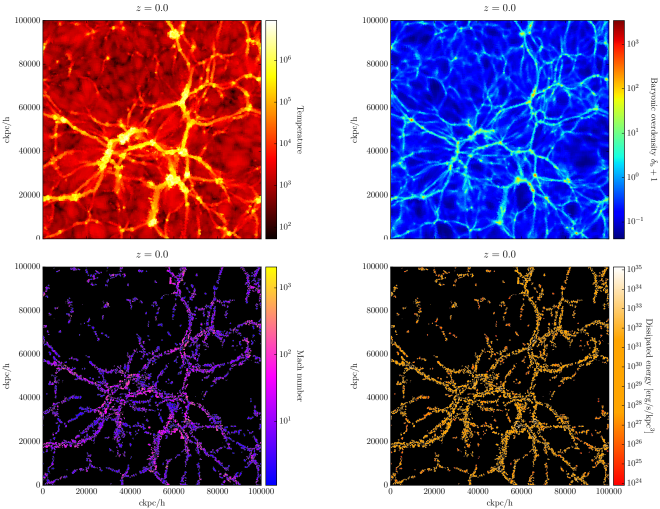
Cosmological simulations with cosmic rays



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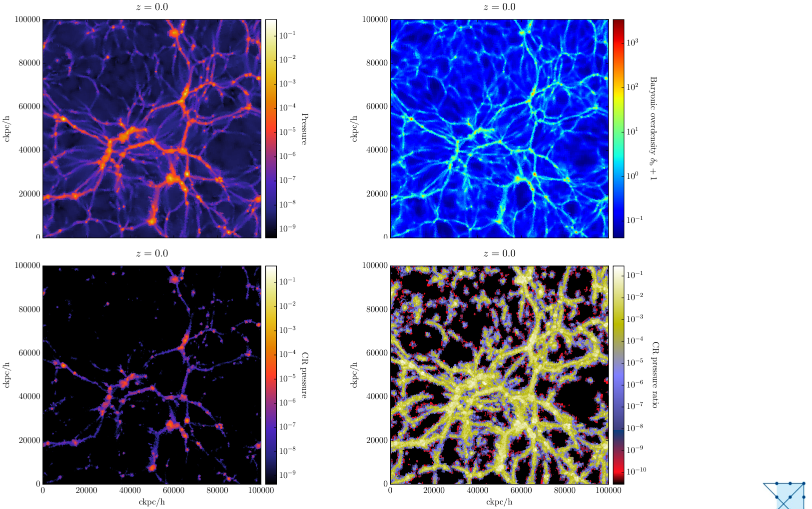

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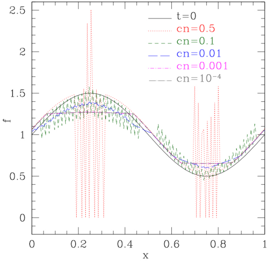
Modeling CR streaming

A challenging hyperbolic/parabolic problem

streaming equation:

$$\frac{\partial \varepsilon_{\rm cr}}{\partial t} + \nabla \cdot [(\varepsilon_{\rm cr} + P_{\rm cr})\boldsymbol{v}_{\rm st}] = \boldsymbol{v}_{\rm st} \cdot \nabla P_{\rm cr}, \quad \boldsymbol{v}_{\rm st} = -\mathrm{sgn}(\mathbf{B} \cdot \nabla P_{\rm cr})\boldsymbol{v}_{\rm A}$$



Sharma+ (2010)

- CR streaming ~ CR advection with the Alfvén speed
- at local extrema, CR energy overshoots and develops unphysical grid oscillations

Modeling CR streaming

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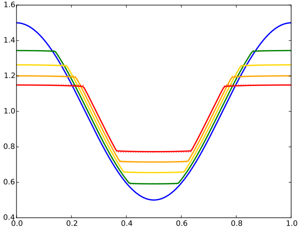

C.P., Pakmor, Springel (in prep.)

- CR streaming $\sim$ CR advection with the Alfvén speed
- at local extrema, CR energy overshoots and develops unphysical grid oscillations
- regularize equations: diffusive at extrema, advective at gradients

- problem: stability criterium requires $\Delta t \propto \Delta x^3$
  $\Rightarrow$ implicit non-linear solver

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

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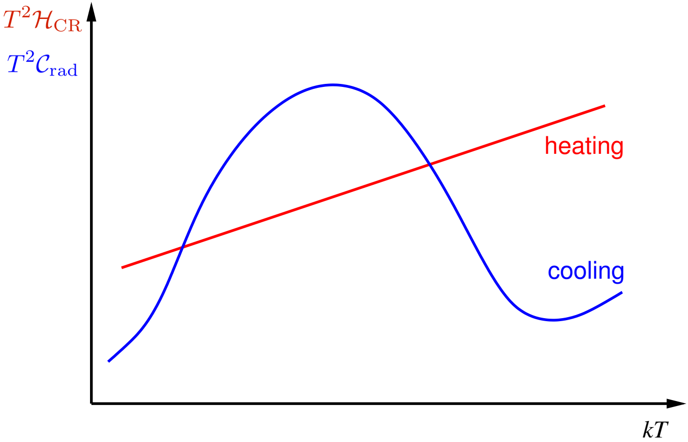
Additional slides

Local stability analysis (1)



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

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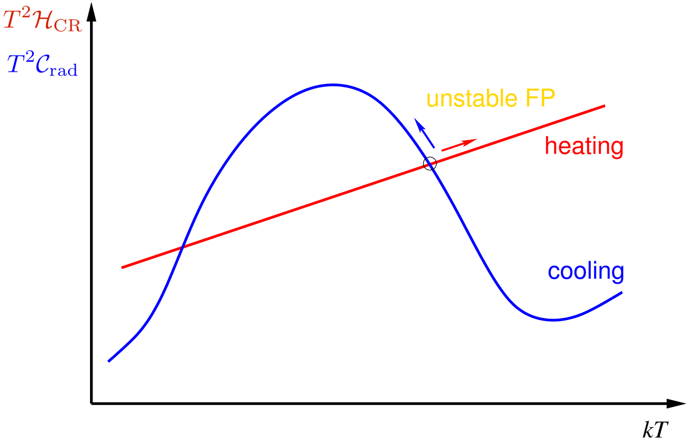

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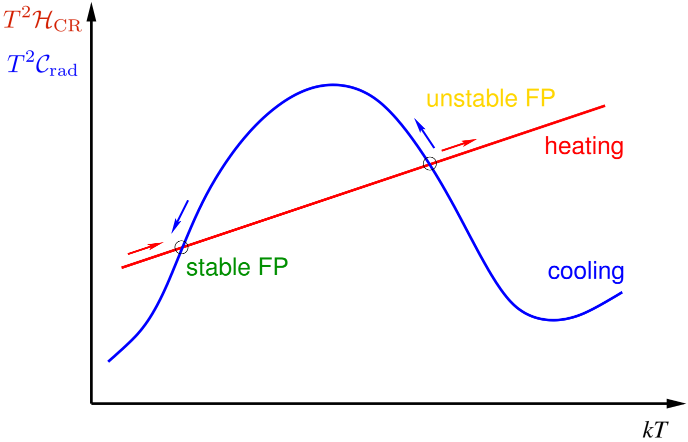

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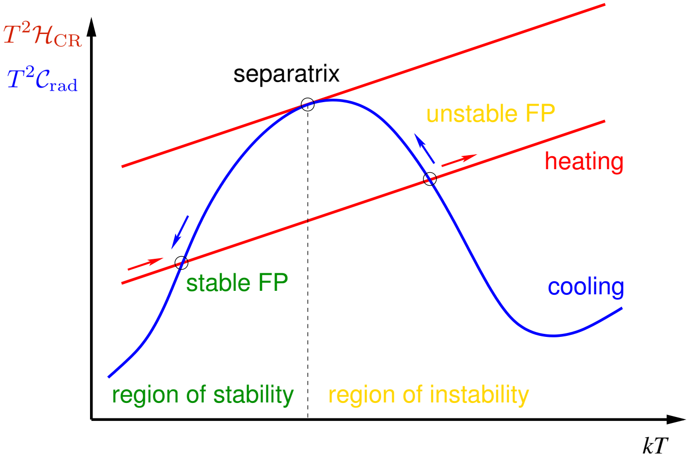

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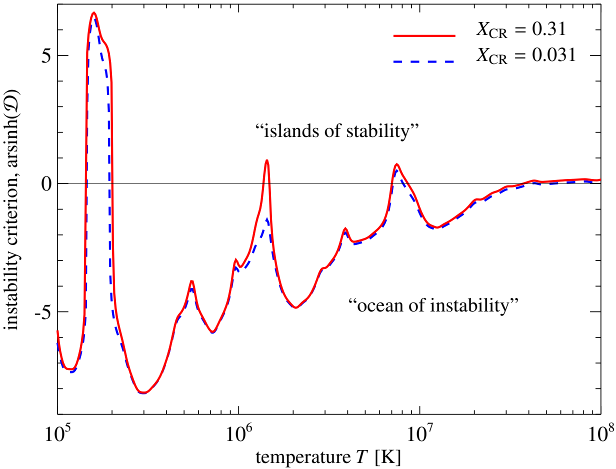
Local stability analysis (2)

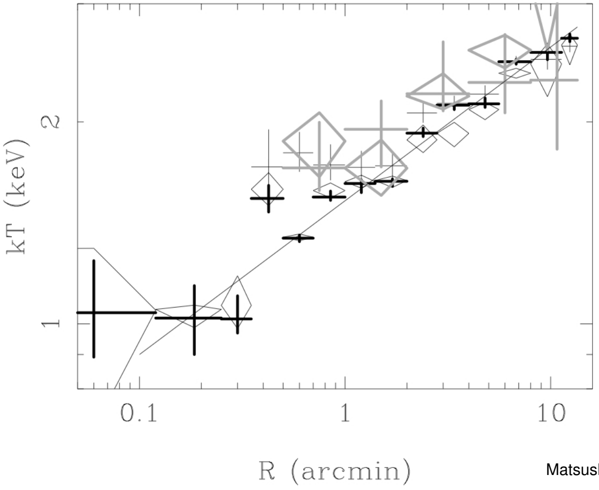
Theory predicts observed temperature floor at $kT \simeq 1$ keV



C.P. (2013)

Virgo cluster cooling flow: temperature profile

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



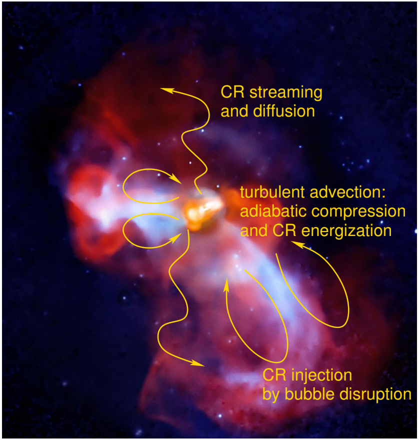
Matsushita+ (2002)

Emerging picture of CR feedback by AGNs

(1) during buoyant rise of bubbles: CRs diffuse and stream outward
→ CR Alfvén-wave heating

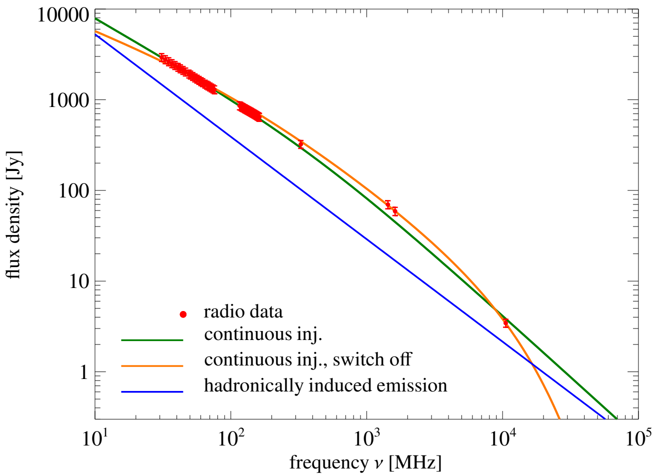
(2) if bubbles are disrupted, CRs are injected into the ICM and caught in a turbulent downdraft that is excited by the rising bubbles
→ CR advection with flux-frozen field
→ adiabatic CR compression and energizing: $P_{\mathrm{cr}}/P_{\mathrm{cr},0} = \delta^{4/3} \sim 20$ for compression factor $\delta = 10$

(3) CR escape and outward streaming → CR Alfvén-wave heating



HITS

Prediction: flattening of high-ν radio spectrum



C.P. (2013)

Conclusions on AGN feedback by cosmic-ray heating

- LOFAR puzzle of “missing fossil electrons” solved by mixing with dense cluster gas and Coulomb cooling
- predicted γ rays identified with low state of M87 $\rightarrow$ estimate CR-to-thermal pressure of $X_{\mathrm{cr}} = 0.31$
- CR Alfvén wave heating balances radiative cooling on all scales within the radio halo ($r < 35$ kpc)
- local thermal stability analysis predicts observed temperature floor at $kT \simeq 1$ keV

outlook: simulate steaming CRs coupled to MHD, cosmological cluster simulations, improve γ-ray and radio observations . . .