Cosmic rays and magnetic fields in galaxies

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in collaboration with

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Jul 1, 2015 / Ringberg Castle: *Cosmic Magnetic Fields*

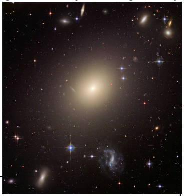
Outline

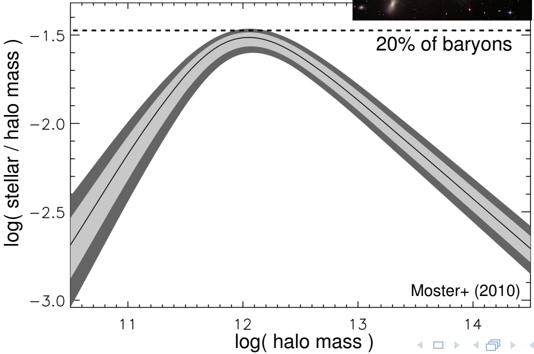
Puzzles in galaxy formation

dwarf galaxy

spiral galaxy

giant elliptical galaxy





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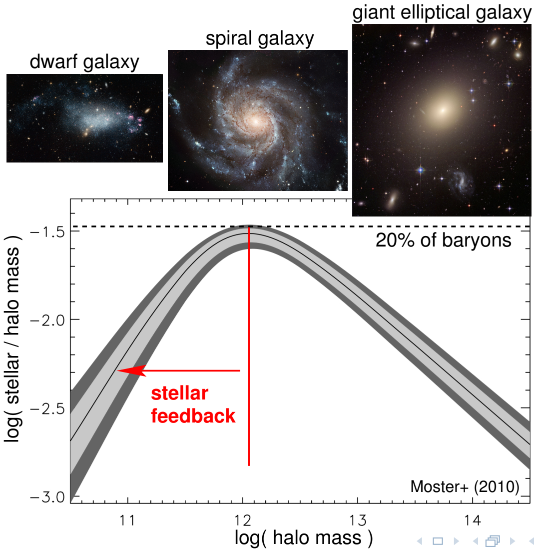
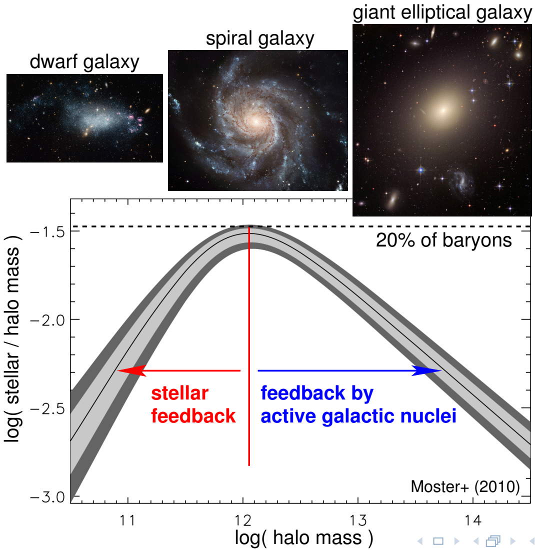
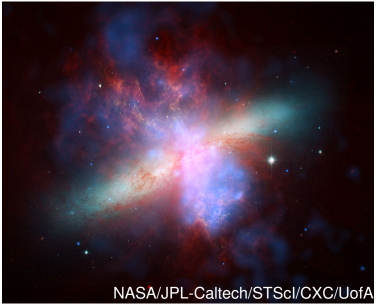


Puzzles in galaxy formation



How are galactic winds driven?



super wind in M82

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

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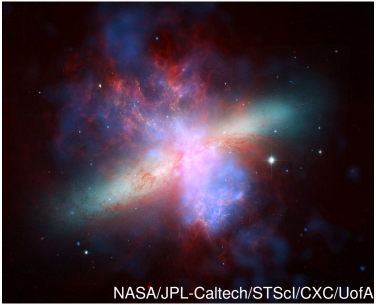

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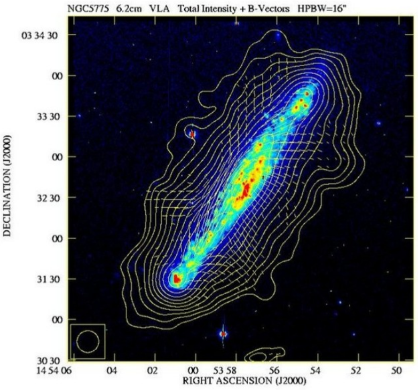
observed energy equipartition between cosmic rays, thermal gas and magnetic fields
$\rightarrow$ suggests self-regulated feedback loop with CR driven winds

Why are CRs important for wind formation?

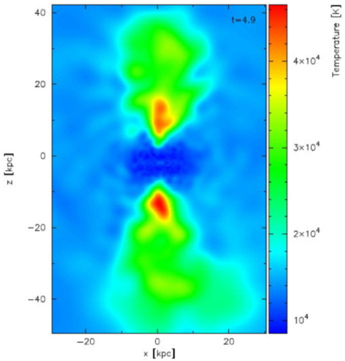
Radio halos in disks: CRs and magnetic fields exist at the disk-halo interface



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

Cosmic-ray driven winds – literature

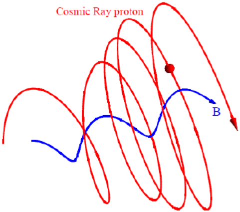


Uhlig, C.P.+ (2012)

- previous theoretical works:
  Ipavich (1975), Breitschwerdt+ (1991), Zirakashvili+ (1996), Ptuskin+ (1997), Breitschwerdt+ (2002), Socrates+ (2008), Everett+ (2008, 2010), Samui+ (2010), Dorfi & Breitschwerdt (2012)
- previous 3D simulations:
  CR streaming: Uhlig, C.P.+ (2012)
  CR diffusion: Booth+ (2013), Hanasz+ (2013), Salem & Bryan (2014)

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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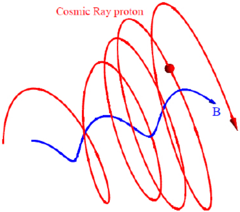

$\rightarrow$ **CRs exert a pressure on the thermal gas by means of scattering off of Alfvén waves**

CR transport

- total CR velocity $\boldsymbol{v}_{\mathrm{cr}} = \boldsymbol{v} + \boldsymbol{v}_{\mathrm{st}} + \boldsymbol{v}_{\mathrm{di}}$ (where $\boldsymbol{v} \equiv \boldsymbol{v}_{\mathrm{gas}}$)
- 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 $\boldsymbol{B}$):

$$\boldsymbol{v}_{\mathrm{st}} = -v_{\mathrm{A}} \frac{\boldsymbol{\nabla} P_{\mathrm{cr}}}{|\boldsymbol{\nabla} P_{\mathrm{cr}}|} \text{ with } v_{\mathrm{A}} = \sqrt{\frac{\boldsymbol{B}^2}{4\pi\rho}}, \qquad \boldsymbol{v}_{\mathrm{di}} = -\kappa_{\mathrm{di}} \frac{\boldsymbol{\nabla} P_{\mathrm{cr}}}{P_{\mathrm{cr}}},$$

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

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

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

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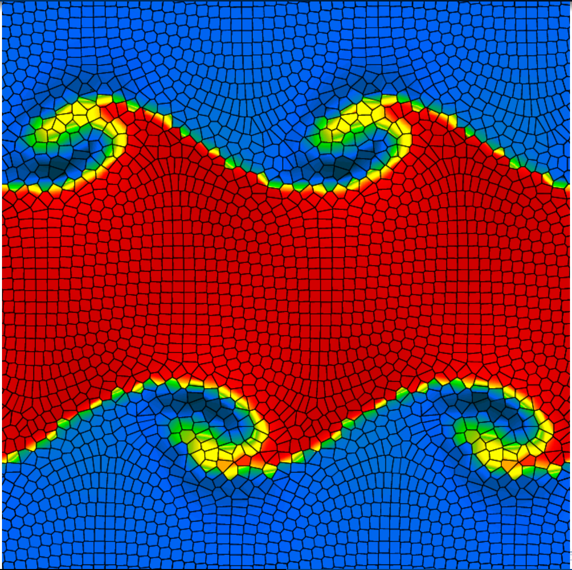
$$\Longleftrightarrow \quad \frac{\partial \varepsilon_{\rm cr}}{\partial t} + \boldsymbol{\nabla} \cdot [\varepsilon_{\rm cr}(\boldsymbol{v} + \boldsymbol{v}_{\rm st})] = -P_{\rm cr} \boldsymbol{\nabla} \cdot (\boldsymbol{v} + \boldsymbol{v}_{\rm st})$$

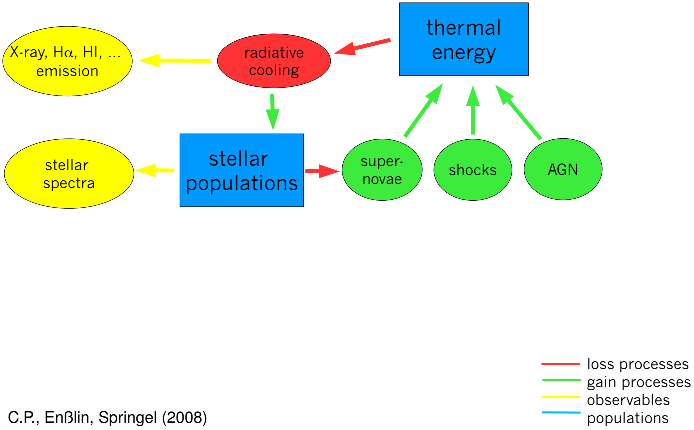
Cosmological moving-mesh code AREPO (Springel 2010)



Simulations – flowchart

ISM observables:

Physical processes in the ISM:



C.P., Enßlin, Springel (2008)

Simulations with cosmic ray physics

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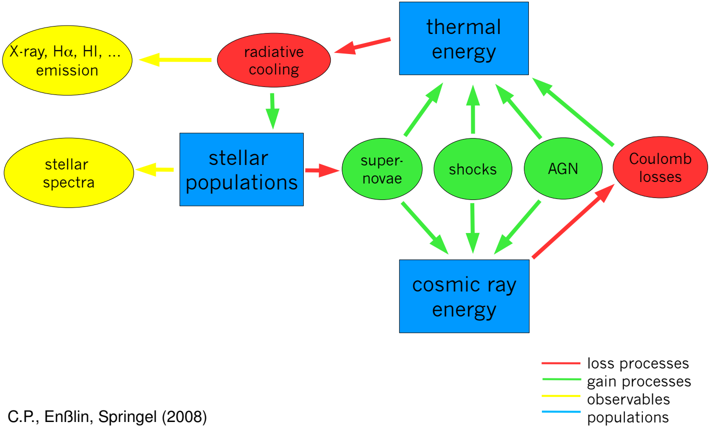

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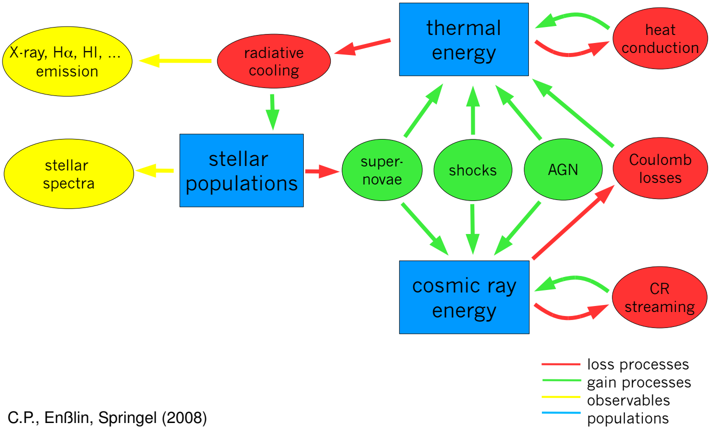

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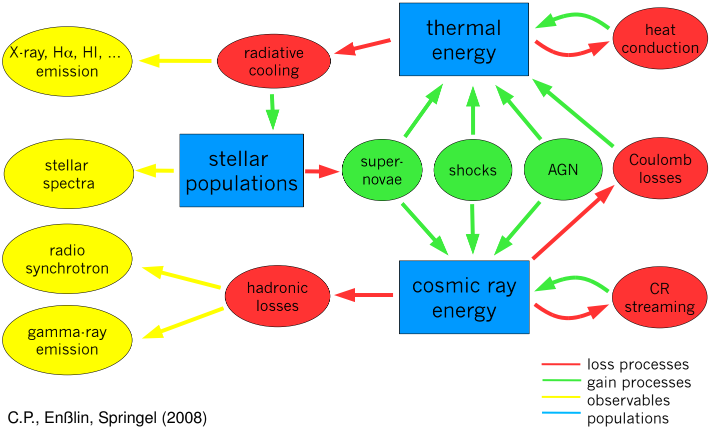

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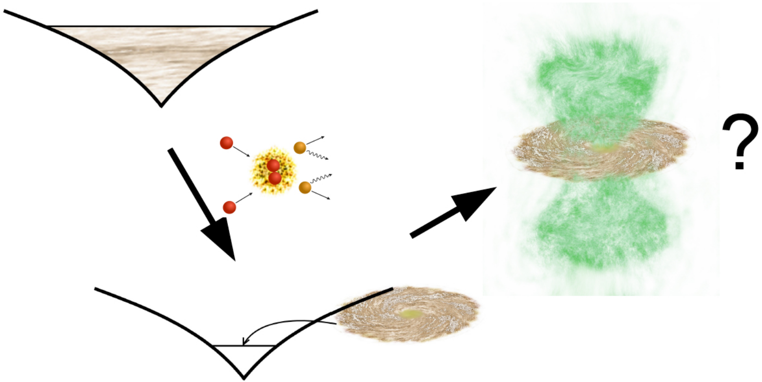
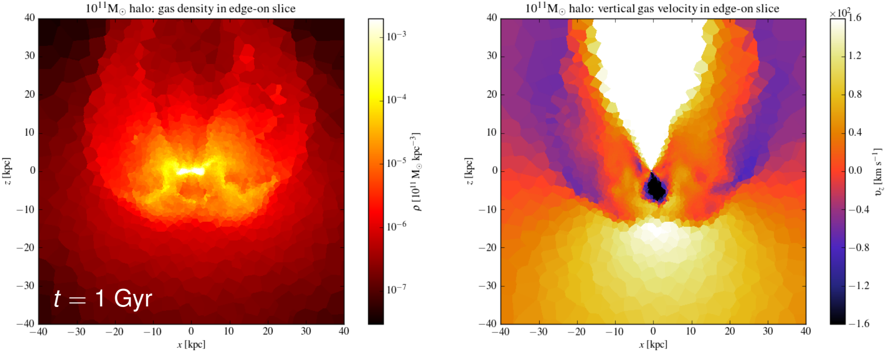
Simulation setup



Pfrommer, Pakmor, Springel, in prep.

note: MHD + CR physics with isotropic CR diffusion

CR driven winds: density and vertical velocity



- CR pressure launches super wind that escapes from the halo
- forming disk collimates the wind into a biconical morphology with a time-varying opening angle

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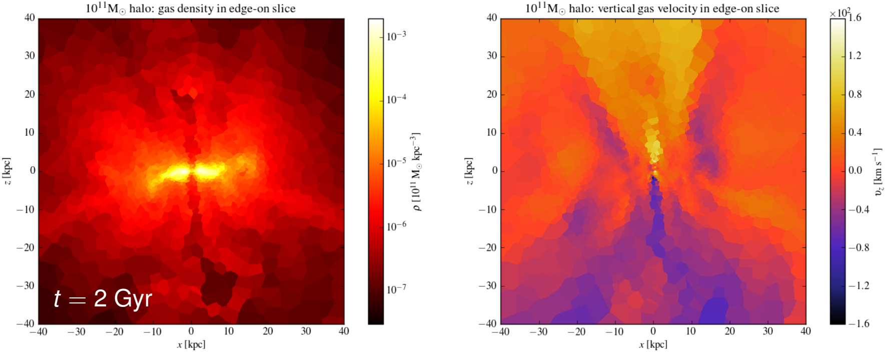

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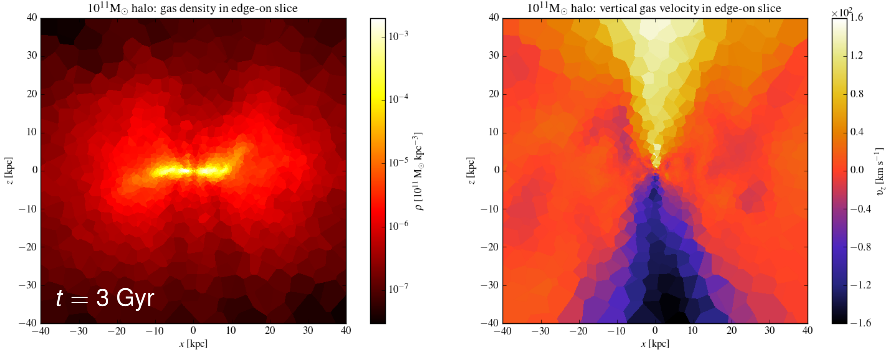

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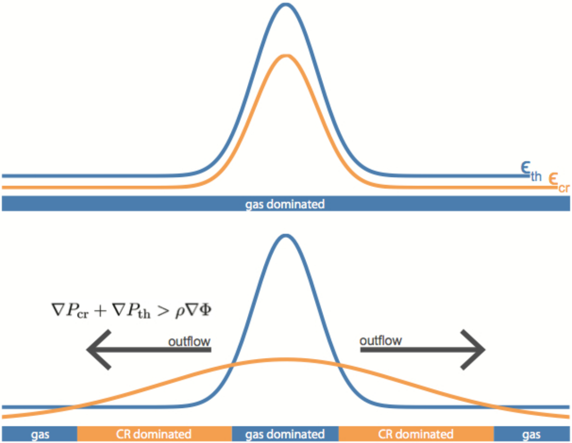
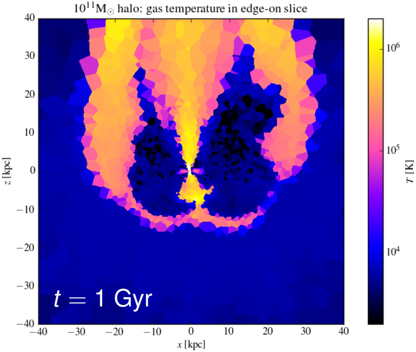
Cosmic ray driven wind: mechanism

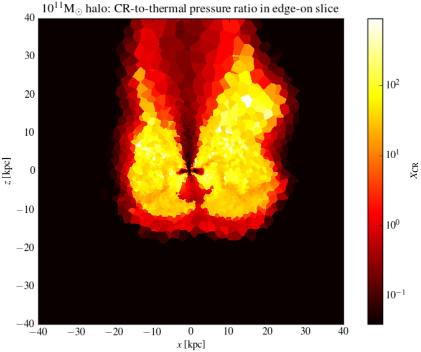


CR streaming: Uhlig, C.P.+ (2012)

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

CR driven winds: temperature and $X_{cr} = P_{cr}/P_{th}$





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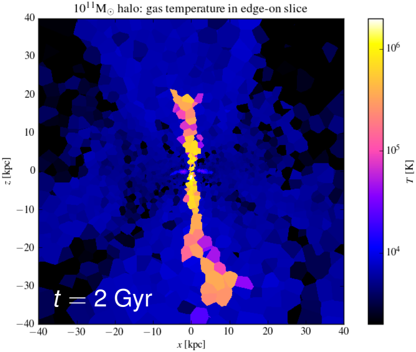

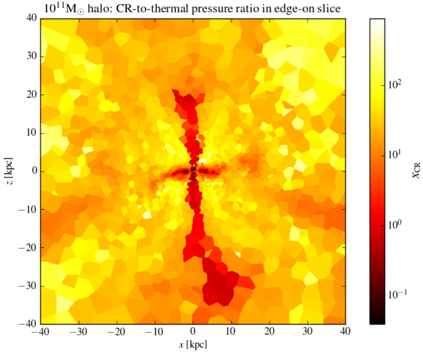

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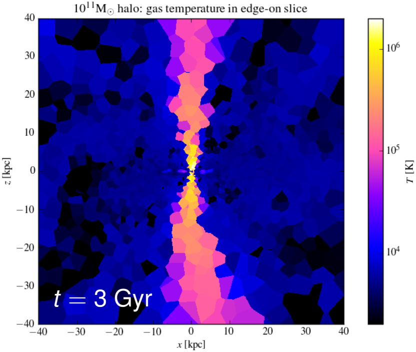

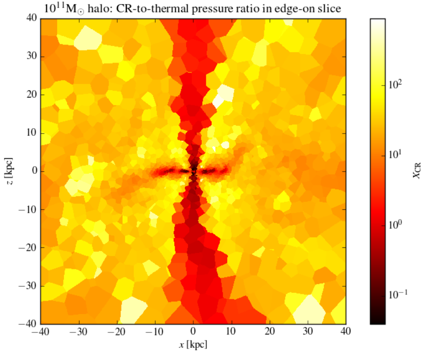

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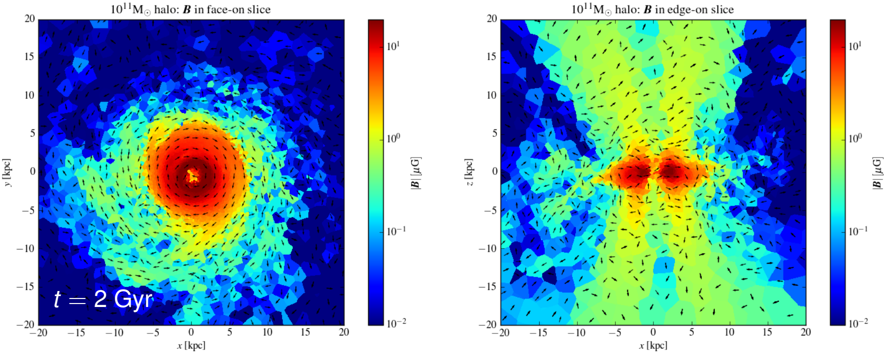
CR driven winds: ***B*** field, face and edge-on view



- disk: magnetic shear amplification aligns ***B*** with velocity field
- halo: X-shaped ***B*** morphology due to time varying collimation
- narrower wind → faster outflow → lower density channel

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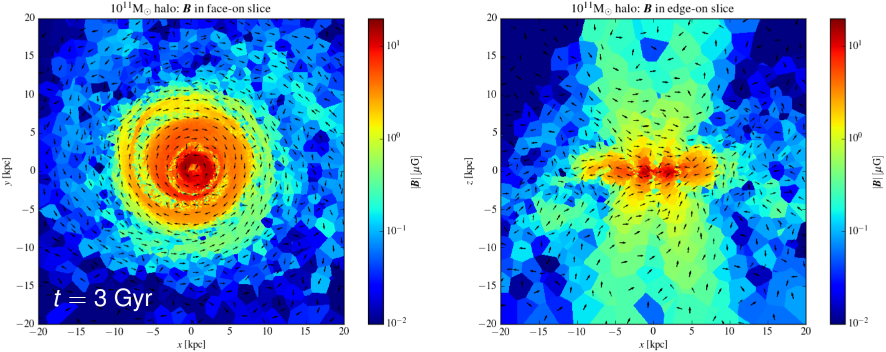

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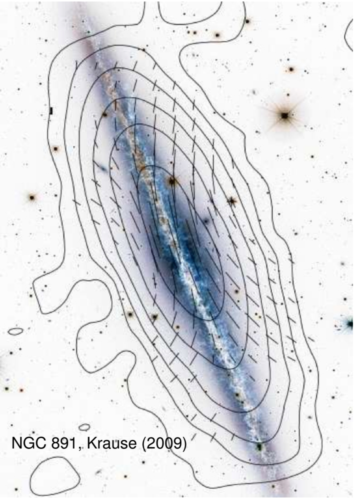
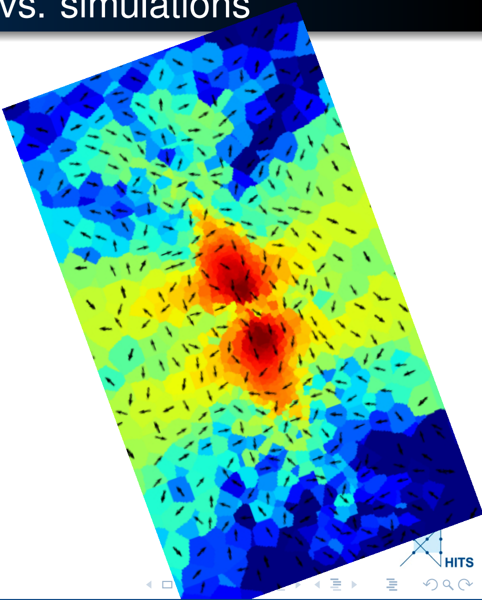
Halo *B* field: observations vs. simulations





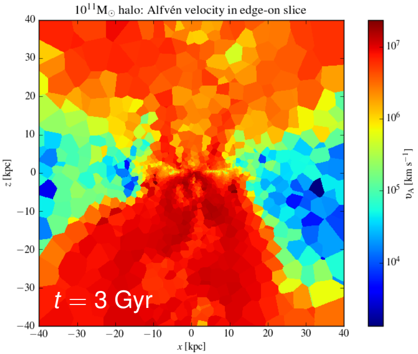
CR streaming vs. diffusion: estimates

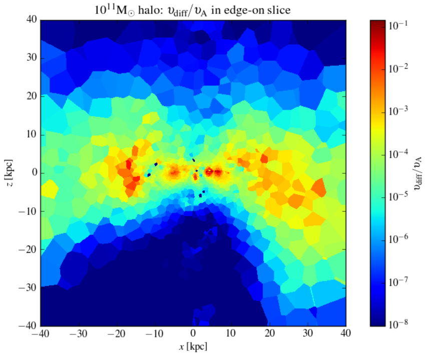
- CRs cannot be transported faster than the Alfvén speed over macroscopic distances:

$$v_{\rm diff} \equiv \kappa \frac{|\nabla P_{\rm cr}|}{\varepsilon_{\rm cr} + P_{\rm cr}} \stackrel{!}{<} v_{\rm A}$$

$\Rightarrow$ limit on diffusion coefficient κ (varies spatially and temporarily)

CR driven winds: v_A and v_{diff}/v_A





- 3 Gyr: stationary outflow with thick CR disk $\rightarrow$ $v_{diff}/v_A < 1$
  (using a Galactic diffusion coefficient $\kappa \simeq 10^{28}\,\mathrm{cm}^2\,\mathrm{s}^{-1}$)

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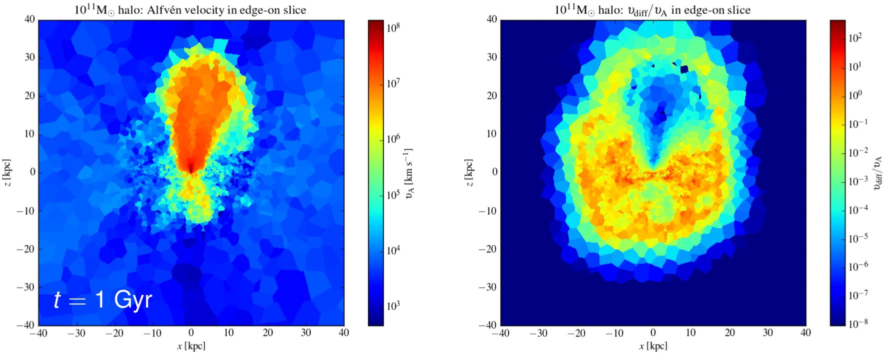

- 3 Gyr: stationary outflow with thick CR disk $\rightarrow v_{diff}/v_A < 1$
  (using a Galactic diffusion coefficient $\kappa \simeq 10^{28}\,\mathrm{cm^2\,s^{-1}}$)
- < 2 Gyr: small CR injection regions $\rightarrow v_{diff}/v_A \gg 1$!

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- what happens during CR injection at a supernova remnant?

$$v_{\rm diff} \sim \frac{\kappa}{4L_{\rm cr}} \sim 10^3 \text{ km s}^{-1} \; \kappa_{28} L_{\rm cr,10 \text{ pc}}^{-1} \sim 100 v_{\rm A}$$

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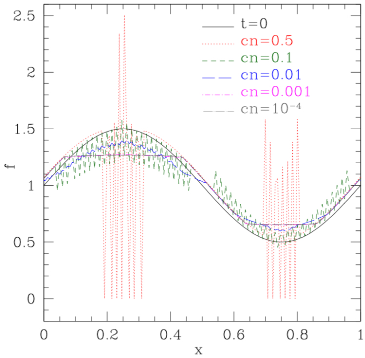
$\Rightarrow$ flux-limited CR diffusion: prohibitively expensive because of von-Neumann-type time step constraint ($\Delta t \propto \Delta x^2/\kappa$), even for implicit solvers

$\Rightarrow$ simulate CR streaming!

Modeling CR streaming

A challenging hyperbolic/parabolic problem



Sharma+ (2010)

- streaming equation (no heating):

$$\frac{\partial \varepsilon_{\mathrm{cr}}}{\partial t} + \nabla \cdot [(\varepsilon_{\mathrm{cr}} + P_{\mathrm{cr}})\boldsymbol{v}_{\mathrm{st}}] = 0$$

$$\boldsymbol{v}_{\mathrm{st}} = -\mathrm{sgn}(\mathbf{B} \cdot \nabla P_{\mathrm{cr}})\boldsymbol{v}_{\mathrm{A}}$$

- CR streaming $\sim$ CR advection with the Alfvén speed
- at local extrema, CR energy can overshoot and develop unphysical oscillations

- idea: regularize equations, similar to adding artificial viscosity
  $\rightarrow$ diffusive at extrema, advective at gradients

HITS

AREPO MHD simulations of CR driven galactic winds

the good: CR diffusion successfully launches super winds that

- expel a large fraction of gas from the halo
- heat the halo gas and circumgalactic medium $\rightarrow$ X-rays?
- enrich halo/circumgalactic medium with X-shaped $\boldsymbol{B}$ fields
- suppress subsequent star formation

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the bad: constant (Galactic) diffusivity too simplified:

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- fails for non-equilibrium conditions during disk formation

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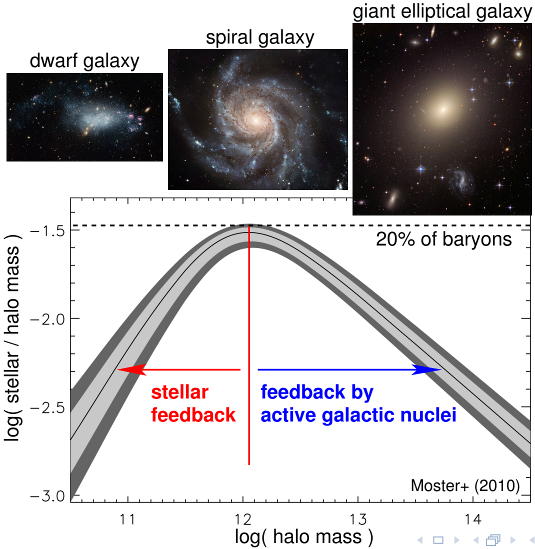
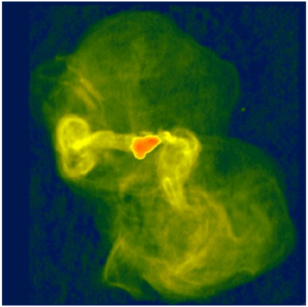
the ugly: CR streaming is a challenging hyperbolic/parabolic problem

Puzzles in galaxy formation



Feedback heating: M87 at radio wavelengths



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

- high-ν: freshly accelerated CR electrons
  low-ν: fossil CR electrons $\rightarrow$ time-integrated AGN feedback!

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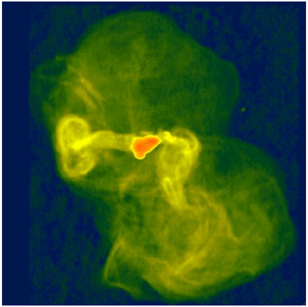

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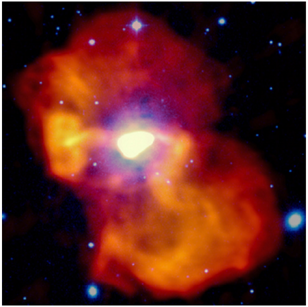


$\nu = 140$ MHz (LOFAR/de Gasperin+ 2012)

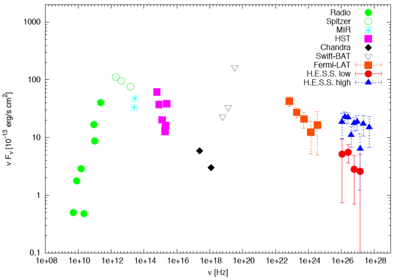
- high-ν: freshly accelerated CR electrons
  low-ν: fossil CR electrons $\rightarrow$ time-integrated AGN feedback!
- LOFAR: same picture $\rightarrow$ puzzle of “missing fossil electrons”
- solution: electrons are fully mixed with the dense cluster gas and cooled through Coulomb interactions

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 π^0 decay within cluster

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

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

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

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

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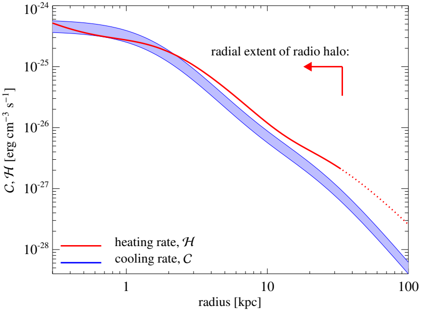
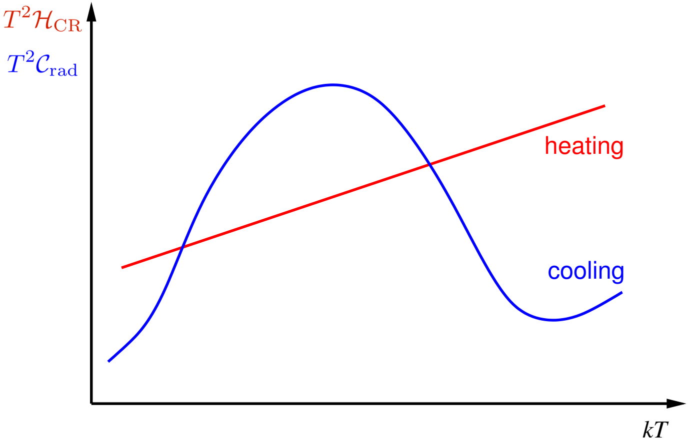


C.P. (2013)

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

HITS

Local stability analysis (1)



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

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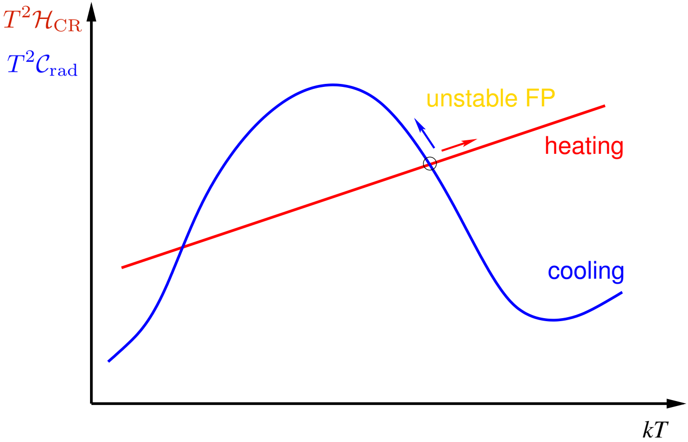

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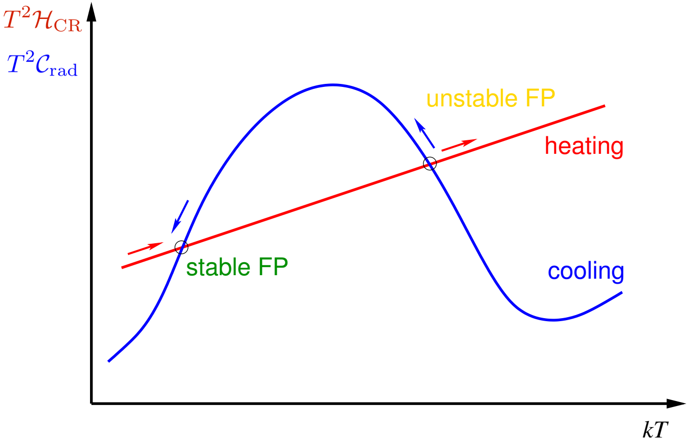

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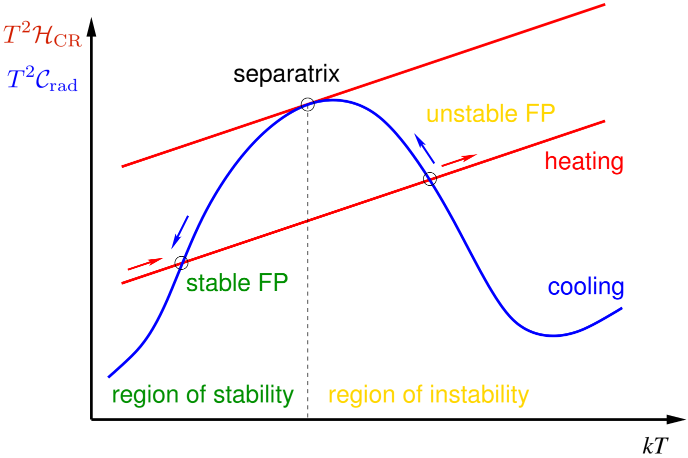

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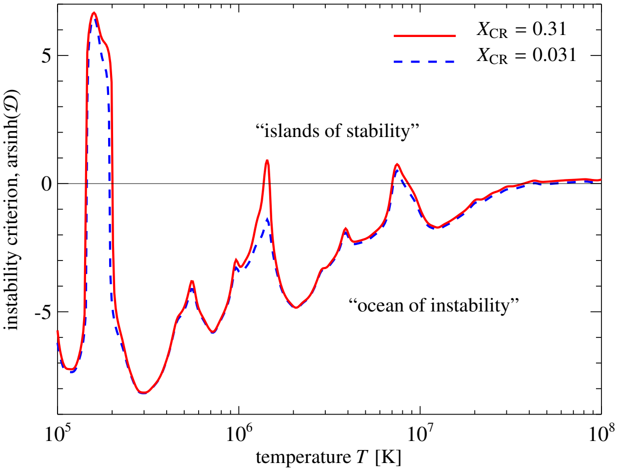
Local stability analysis (2)

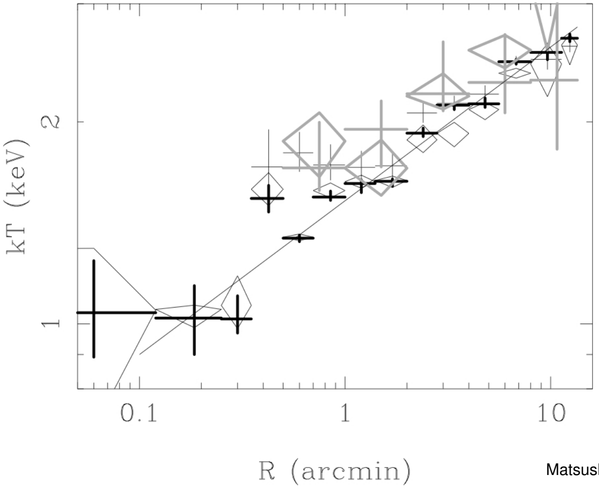
Theory predicts observed temperature floor at $kT \simeq 1$ keV



C.P. (2013)

Virgo cluster cooling flow: temperature profile

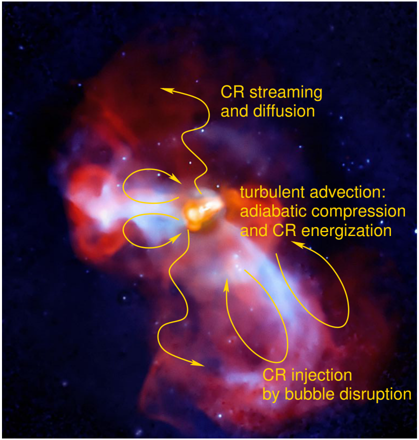
X-ray observations confirm temperature floor at $kT \simeq 1$ keV



Matsushita+ (2002)

Emerging picture of CR feedback by AGNs

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

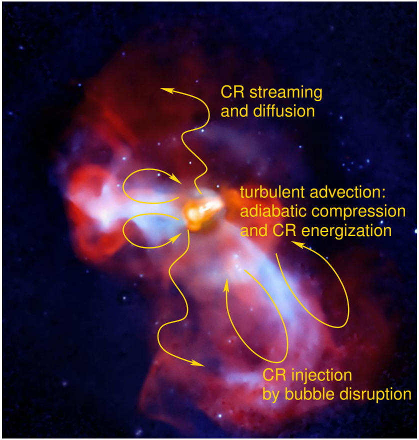


Emerging picture of CR feedback by AGNs

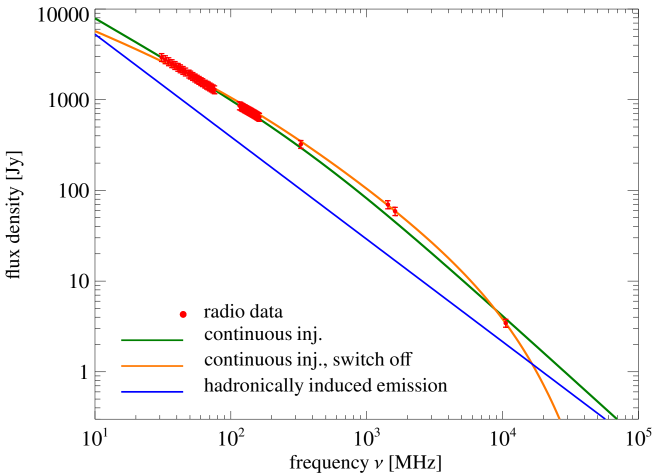
(1) during buoyant rise of bubbles: CRs diffuse and stream outward
$\rightarrow$ CR Alfvén-wave heating

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

(3) CR escape and outward streaming $\rightarrow$ CR Alfvén-wave heating



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 ...