Cosmic ray feedback in galaxies and cool core clusters

Christoph Pfrommer

in collaboration with

M. Uhlig, M. Sharma, B. Nath, T. Enßlin, V. Springel
(cosmic-ray driven winds)

1Heidelberg Institute for Theoretical Studies, Germany

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1. Puzzles in galaxy formation

2. Driving galactic winds
   - Galactic winds and cosmic rays
   - Mass loss and star formation
   - Cosmic-ray heating

3. AGN feedback
   - Observations of M87
   - Cosmic-ray heating
   - Conclusions
Puzzles in galaxy formation

- Driving galactic winds
- AGN feedback

![Graph showing log(halo mass) vs. log(stellar/halo mass) for dwarf galaxy, spiral galaxy, and giant elliptical galaxy. The graph indicates that 20% of baryons are concentrated in the halo mass range of 10^11 to 10^14.]

Moster+ 2010

Chiristoph Pfrommer: Cosmic ray feedback in galaxies and cool core clusters
Puzzles in galaxy formation

- Driving galactic winds
- AGN feedback

- log( halo mass )
- log( stellar / halo mass )
- feedback
- stellar
- 20% of baryons
- Moster+ 2010
- giant elliptical galaxy
- dwarf galaxy
- spiral galaxy

- Cosmic ray feedback in galaxies and cool core clusters
Puzzles in galaxy formation

Driving galactic winds
AGN feedback

Puzzles in galaxy formation

log( halo mass )

log( stellar / halo mass )

black hole feedback

supermassive

20% of baryons

Moster+ 2010

giant elliptical galaxy
dwarf galaxy

spiral galaxy

feedback

stellar

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Cosmic ray feedback in galaxies and cool core clusters
Puzzles in galaxy formation

Bright-end of luminosity function:

- **astrophysical solutions:**
  - AGN/quasar feedback, . . .

![Graph showing luminosity function with labels for dwarf galaxy, spiral galaxy, giant elliptical galaxy, and stellar feedback.]
Puzzles in galaxy formation

Bright-end of luminosity function:

- **astrophysical solutions:**
  - AGN/quasar feedback, . . .

Faint-end of luminosity function:

- **dark matter (DM) solutions:**
  - warm DM, interacting DM, DM from late decays, large annihilation rates, . . .
Puzzles in galaxy formation

Bright-end of luminosity function:

- **astrophysical solutions:**
  - AGN/quasar feedback, . . .

Faint-end of luminosity function:

- **dark matter (DM) solutions:**
  - warm DM, interacting DM, DM from late decays, large annihilation rates, . . .
  - **astrophysical solutions:**
    - preventing gas from falling into DM potential wells:
      - increasing entropy by reionization, blazar heating . . .
    - preventing gas from forming stars in galaxies:
      - suppress cooling (photoionization, low metallicities), . . .
    - pushing gas out of galaxies:
      - supernova/quasar feedback $\rightarrow$ **galactic winds**
Galactic winds

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

supernova Cassiopeia A

Galactic winds

- galactic supernova remnants drive shock waves, turbulence, accelerate electrons + protons, amplify magnetic fields
- star formation and supernovae drive gas out of galaxies by galactic super winds

super wind in M82

NASA/JPL-Caltech/STScI/CXC/UofA
Galactic winds

- Galactic supernova remnants drive shock waves, turbulence, accelerate electrons + protons, amplify magnetic fields.
- Star formation and supernovae drive gas out of galaxies by galactic super winds.
- Critical for understanding the physics of galaxy formation → may explain puzzle of low star conversion efficiency in dwarf galaxies.

Super wind in M82

NASA/JPL-Caltech/STScI/CXC/UofA
Galactic winds

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

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supernova remnant shocks amplify magnetic fields and accelerate CR electrons up to $\sim 100$ TeV (narrow X-ray synchrotron filaments observed by *Chandra*)
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pion bump provides evidence for CR proton acceleration (Fermi/AGILE $\gamma$-ray spectra)

Fermi observations of W44:

Ackermann+ (2013)
The role of supernova remnants

- supernova remnant shocks amplify magnetic fields and accelerate CR electrons up to $\sim 100$ TeV (narrow X-ray synchrotron filaments observed by Chandra)
- pion bump provides evidence for CR proton acceleration ($\text{Fermi}/\text{AGILE} \ \gamma$-ray spectra)
- shell-type SNRs show evidence for efficient shock acceleration beyond $\sim 100$ TeV (HESS TeV $\gamma$-ray observations)

**Fermi observations of W44:**

- $E^2 dN/dE \ (\text{erg cm}^{-2} \text{s}^{-1})$
- Energy (eV)

**HESS observations of shell-type SNRs:**

- RCW 86
- RX J1713.7-3946
- RX J0852.0-4622

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Cosmic ray feedback in galaxies and cool core clusters
Galactic cosmic ray spectrum

- spans more than 33 decades in flux and 12 decades in energy
- "knee" indicates characteristic maximum energy of galactic accelerators
- CRs beyond the "ankle" have extra-galactic origin

data compiled by Swordy
Galactic cosmic ray spectrum

- spans more than 33 decades in flux and 12 decades in energy
- "knee" indicates characteristic maximum energy of galactic accelerators
- CRs beyond the "ankle" have extra-galactic origin
- energy density of cosmic rays, magnetic fields, and turbulence in the interstellar gas all similar
Galactic wind in the Milky Way?
Diffuse X-ray emission in our galaxy

...as suggested by Everett+ (2008) and Everett, Schiller, Zweibel (2010)
How are galactic winds driven?

- 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?

super wind in M82

NASA/JPL-Caltech/STScI/CXC/UofA
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Observed energy equipartition between cosmic rays, thermal gas and magnetic fields
→ 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

- CR pressure drops less quickly than thermal pressure \((P \propto \rho \gamma)\)
- CRs cool less efficiently than thermal gas
- CR pressure energizes the wind → “CR battery”
- Poloidal (“open”) field lines at wind launching site → CR-driven Parker instability

Tüllmann+ (2000)
Interactions of CRs and magnetic fields

- CRs scatter on magnetic fields → isotropization of CR momenta

- **CR streaming instability**: Kulsrud & Pearce 1969
  - if $v_{cr} > v_A$, 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 $\sim v_A$
  - wave damping: transfer of CR energy and momentum to the thermal gas
CRs scatter on magnetic fields → isotropization of CR momenta

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- wave damping: transfer of CR energy and momentum to the thermal gas

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

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

\[
\mathbf{v}_{\text{st}} = -v_A \frac{\nabla P_{\text{cr}}}{|\nabla P_{\text{cr}}|} \quad \text{with} \quad v_A = \sqrt{\frac{B^2}{4\pi \rho}} , \quad \mathbf{v}_{\text{di}} = -\kappa_{\text{di}} \frac{\nabla P_{\text{cr}}}{P_{\text{cr}}} ,
\]
CR transport

- total CR velocity $v_{cr} = v + v_{st} + v_{di}$ (where $v \equiv v_{gas}$)

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

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

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

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- energy equations with $\varepsilon = \varepsilon_{\text{th}} + \rho \mathbf{v}^2/2$ (neglecting CR diffusion):
  
  $$\frac{\partial \varepsilon}{\partial t} + \nabla \cdot [(\varepsilon + P_{\text{th}} + P_{\text{cr}}) \mathbf{v}] = P_{\text{cr}} \nabla \cdot \mathbf{v} + |\mathbf{v}_{\text{st}} \cdot \nabla P_{\text{cr}}|$$
  
  $$\frac{\partial \varepsilon_{\text{cr}}}{\partial t} + \nabla \cdot (\varepsilon_{\text{cr}} \mathbf{v}) + \nabla \cdot [(\varepsilon_{\text{cr}} + P_{\text{cr}}) \mathbf{v}_{\text{st}}] = -P_{\text{cr}} \nabla \cdot \mathbf{v} - |\mathbf{v}_{\text{st}} \cdot \nabla P_{\text{cr}}|$$

  $$\iff \frac{\partial \varepsilon_{\text{cr}}}{\partial t} + \nabla \cdot [\varepsilon_{\text{cr}} (\mathbf{v} + \mathbf{v}_{\text{st}})] = -P_{\text{cr}} \nabla \cdot (\mathbf{v} + \mathbf{v}_{\text{st}})$$
Puzzles in galaxy formation
Driving galactic winds
AGN feedback
Mass loss and star formation
Cosmic-ray heating

Simulations – flowchart

ISM observables:
- X-ray, Hα, HI, ...
- stellar spectra

Physical processes in the ISM:
- radiative cooling
- thermal energy
- supernovae
- shocks
- AGN

C.P., Enßlin, Springel (2008)
Simulations with cosmic ray physics

ISM observables:

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Physical processes in the ISM:

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ISM observables:
- X-ray, Hα, HI, ...
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Physical processes in the ISM:
- radiative cooling
- stellar populations
- supernovae
- shocks
- AGN
- Coulomb losses
- heat conduction
- cosmic ray energy
- CR streaming

C.P., Enßlin, Springel (2008)
Simulations with extended cosmic ray physics

ISM observables:
- X-ray, Hα, HI, ... emission
- stellar spectra
- radio synchrotron
- gamma-ray emission

Physical processes in the ISM:
- Radiative cooling
- Stellar populations
- Supernovae
- Cosmic ray energy
- Shocks
- AGN
- Coulomb losses
- CR streaming
- Heat conduction

Loss processes:
- Hadronic losses

Gain processes:
- Radiative cooling

Observables:
- X-ray, Hα, HI, ...
- Stellar spectra
- Radio synchrotron
- Gamma-ray emission

C.P., Enßlin, Springel (2008)
Gamma-ray emission of the Milky Way

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Cosmic ray feedback in galaxies and cool core clusters
Simulation setup


*Galactic winds driven by cosmic-ray streaming*
CR streaming drives winds

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Cosmic ray feedback in galaxies and cool core clusters
Cosmic ray driven wind: mechanism

Puzzles in galaxy formation
Driving galactic winds
AGN feedback
Galactic winds and cosmic rays
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Cosmic-ray heating

Wind velocity profile along the symmetry axis

\[
M_{\text{halo}} = 10^9 \, h^{-1} \, M_\odot \\
M_{\text{halo}} = 10^{10} \, h^{-1} \, M_\odot \\
M_{\text{halo}} = 10^{11} \, h^{-1} \, M_\odot
\]

- \(10^9 - 10^{10} \, M_\odot\): accelerating wind due to a continuous CR momentum and energy deposition during the ascent of the wind in the gravitational potential
  → different from traditional energy- or momentum-driven winds!

- \(10^{11} \, M_\odot\): wind stalls in halo and falls back onto the disk
  → fountain flow
Gas mass loss within the virial radius

- after initial phase (~ 2.5 Gyr), only winds driven by CR streaming overcome the ram pressure of infalling gas and expel gas from the halo
- mass loss rate increases with CR injection efficiency $\zeta_{SN}$ (left) and toward smaller galaxy masses (right)
Page dimensions: 362.8x272.1

Star formation histories (SFHs)

- CR feedback suppresses star formation
- $10^9 M_\odot$: CR advection-only (green, yellow): oscillating SFH
  - CR streaming (red, blue): suppressed smooth SFH
- $10^{10} M_\odot$: suppressed smooth SFH
Temperature structure due to CR heating

- Halo temperatures scale as $kT \propto v_{\text{wind}}^2 \sim v_{\text{esc}}^2$

- $10^9 \rightarrow 10^{10} \, M_\odot$: transition of isotropic to bi-conical wind; in these cones, CR wave heating overcomes radiative cooling

- $10^{10} \rightarrow 10^{11} \, M_\odot$: broadening of hot temperature structure due to inability of CR streaming to drive a sustained wind; instead, fountain flows drive turbulence, thereby heating larger regions
Gas temperature: observation vs. simulation

M82 observation

CR streaming \( (10^{10} \, M_\odot) \)
CR-driven winds: analytics versus simulations
Bernoulli theorem along streamlines: wind speeds and mass loading factors

- winds speeds increase with galaxy mass as \( v_{\text{wind}} \propto v_{\text{circ}} \propto M_{200}^{1/3} \)
  until they cutoff around \( 10^{11} M_\odot \) due to a fixed wind base height (set by radiative physics)

- mass loading factor \( \eta = \dot{M}/\text{SFR} \) decreases with galaxy mass
Conclusions on cosmic-ray driven winds in galaxies

- galactic winds are naturally explained by CR streaming (known energy source and plasma physics)
- CR streaming heating can explain observed hot wind regions above disks
- substantial mass losses of low mass galaxies → opportunity for understanding the physics at the faint end of galaxy luminosity function

outlook: improved hydrodynamics (AREPO), including MHD (anisotropic transport), improved modeling of plasma physics, cosmological settings, . . .

“Radio-mode” AGN feedback
Messier 87 at radio wavelengths

\[ \nu = 1.4 \text{ GHz (Owen+ 2000)} \]

- **high-\(\nu\):** freshly accelerated CR electrons
- **low-\(\nu\):** fossil CR electrons \(\rightarrow\) time-integrated AGN feedback!
Messier 87 at radio wavelengths

- high-\( \nu \): freshly accelerated CR electrons
- low-\( \nu \): fossil CR electrons \( \rightarrow \) time-integrated AGN feedback!

- LOFAR: halo confined to same region at all frequencies and no low-\( \nu \) spectral steepening \( \rightarrow \) puzzle of “missing fossil electrons”
Solutions to the “missing fossil electrons” problem

solutions:

- special time: M87 turned on
  - \( \sim 40 \text{ Myr ago} \) after long silence
  - \( \Leftrightarrow \) conflicts order unity duty cycle inferred from stat. AGN feedback studies (Birzan+ 2012)
Solutions to the “missing fossil electrons” problem

solutions:

- special time: M87 turned on ∼ 40 Myr ago after long silence
  ⇔ conflicts order unity duty cycle inferred from stat. AGN feedback studies (Birzan+ 2012)

- Coulomb cooling removes fossil electrons
  → efficient mixing of CR electrons and protons with dense cluster gas
  → predicts γ rays from CRp-p interactions:
  \[ p + p \rightarrow \pi^0 + \ldots \rightarrow 2\gamma + \ldots \]
The gamma-ray picture of M87

- high state is time variable
  → jet emission

- low state:
  (1) steady flux
  (2) $\gamma$-ray spectral index (2.2)
    $= \text{CRp index}$
    $= \text{CRE injection index as probed by LOFAR}$
  (3) spatial extension is under investigation (?)

→ confirming this triad would be smoking gun for first $\gamma$-ray signal from a galaxy cluster!
Estimating the CR pressure in M87

hypothesis: low state of $\gamma$-ray emission traces $\pi^0$ decay in ICM:

- X-ray data $\rightarrow$ $n$ and $T$ profiles
- assume steady-state CR streaming: $P_{\text{cr}} \propto \rho^{\gamma_{\text{cr}}/2} \propto P_{\text{th}}$
- $F_\gamma \propto \int dV P_{\text{cr}} n$ enables to estimate $X_{\text{cr}} = P_{\text{cr}}/P_{\text{th}} = 0.31$ (allowing for Coulomb cooling with $\tau_{\text{Coul}} = 40$ Myr)

$\rightarrow$ in agreement with non-thermal pressure constraints from dynamical potential estimates (Churazov+ 2010)
Cosmic-ray heating vs. radiative cooling (1)

**CR Alfvén-wave heating:**
(Loewenstein, Zweibel, Begelman 1991, Guo & Oh 2008, Enßlin+ 2011)

\[ \mathcal{H}_{\text{cr}} = -v_A \cdot \nabla P_{\text{cr}} = -v_A \left( X_{\text{cr}} \nabla r \langle P_{\text{th}} \rangle \Omega + \frac{\delta P_{\text{cr}}}{\delta l} \right) \]

- Alfvén velocity \( v_A = B / \sqrt{4\pi \rho} \) with \( B \sim B_{\text{eq}} \) from LOFAR and \( \rho \) from X-ray data
- \( X_{\text{cr}} \) inferred from \( \gamma \) rays
- \( P_{\text{th}} \) from X-ray data
- pressure fluctuations \( \delta P_{\text{cr}} / \delta l \) (e.g., due to weak shocks of \( M \sim 1.1 \))
Cosmic-ray heating vs. radiative cooling (1)

**CR Alfvén-wave heating:**
(Loewenstein, Zweibel, Begelman 1991, Guo & Oh 2008, Enßlin+ 2011)

\[
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- Alfvén velocity \( v_A = B/\sqrt{4\pi \rho} \) with \( B \sim B_{eq} \) from LOFAR and \( \rho \) from X-ray data
- \( X_{cr} \) inferred from \( \gamma \) rays
- \( P_{th} \) from X-ray data
- pressure fluctuations \( \delta P_{cr}/\delta l \) (e.g., due to weak shocks of \( M \sim 1.1 \))

**radiative cooling:**

\[
c_{rad} = n_e n_i \Lambda_{cool} (T, Z)
\]

- cooling function \( \Lambda_{cool} \) with \( Z \sim Z_{\odot} \),
- all quantities determined from X-ray data
Cosmic-ray heating vs. radiative cooling (2)
Global thermal equilibrium on all scales in M87

\[ C_{\text{rad}}, H_{\text{CR}} \text{ [ergs cm}^{-3} \text{s}^{-1}] \]

- \( H_{\text{CR}}, P_{\text{smooth}} + \delta P \)
- \( H_{\text{CR}}, P_{\text{smooth}} \)
- \( C_{\text{rad}}(0.7 Z_\odot \lesssim Z \lesssim 1.3 Z_\odot) \)

radial extent of radio halo:

C.P. (2013)
is this global thermal equilibrium a coincidence in Virgo?
Cosmic-ray heating vs. radiative cooling (3)

is this global thermal equilibrium a coincidence in Virgo?

- CCs typically show a steep central density profile: \( n \propto r^{-1} \)
- central temperature profile rises slowly: \( T \propto r^\alpha \), with \( \alpha \lesssim 0.3 \)
- assume \( v_A = \text{const.} \) and steady-state CR streaming, \( P_{cr} \propto \rho^{\gamma_{cr}/2} \propto P_{th} \) (also required for self-consistency):

\[
\mathcal{H}_{cr} \propto \frac{\partial}{\partial r} P_{th} \propto \frac{\partial}{\partial r} r^{\alpha-1} \propto r^{\alpha-2}
\]

\[
C_{\text{rad}} \propto n^2 \propto r^{-2}
\]
Cosmic-ray heating vs. radiative cooling (3)

is this global thermal equilibrium a coincidence in Virgo?

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- central temperature profile rises slowly: \( T \propto r^\alpha \), with \( \alpha \lesssim 0.3 \)
- assume \( v_A = \text{const.} \) and steady-state CR streaming, \( P_{cr} \propto \rho \gamma_{cr}^{-2} \propto P_{th} \) (also required for self-consistency):

\[
\begin{align*}
\mathcal{H}_{cr} & \propto \frac{\partial}{\partial r} P_{th} \propto \frac{\partial}{\partial r} r^{\alpha-1} \propto r^{\alpha-2} \\
\mathcal{C}_{\text{rad}} & \propto n^2 \propto r^{-2}
\end{align*}
\]

(1) identical radial profiles expected for \( T \simeq \text{const.} \) (\( \alpha \simeq 0 \))
(2) for a smoothly rising temperature profile, heating is slightly favored over cooling at larger radii \( \rightarrow \) onset of cooling is smoothly modulated from the outside in
Cosmic-ray heating vs. radiative cooling
Global thermal equilibrium on all scales in M87

\[ C_{\text{rad}}, H_{\text{CR}} \text{ [ergs cm}^{-3}\text{ s}^{-1}] \]

radial extent of radio halo:

\[ H_{\text{CR}}, P_{\text{smooth}} + \delta P \]
\[ H_{\text{CR}}, P_{\text{smooth}} \]
\[ C_{\text{rad}}(0.7 Z_{\odot} \lesssim Z \lesssim 1.3 Z_{\odot}) \]

C.P. (2013)
Local stability analysis (1)

- isobaric perturbations to global thermal equilibrium
- CRs are adiabatically trapped by perturbations
Local stability analysis (1)

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Local stability analysis (1)

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

\[ T^2 \mathcal{H}_{CR} \]
\[ T^2 \mathcal{C}_{rad} \]

stable FP
unstable FP
region of stability
region of instability
separatrix
heating
cooling
Local stability analysis (2)

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

![Graph showing the instability criterion, $\text{arsinh}(D)$, and the 'islands of stability' and 'ocean of instability' at different X_Cr values.](image)

- $X_{CR} = 0.31$
- $X_{CR} = 0.031$

C.P. (2013)
Virgo cluster cooling flow: temperature profile

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

$kT$ (keV) vs $R$ (arcmin)

Matsushita+ (2002)
Critical length scale of the instability ($\sim$ Fields length)

- CR streaming transfers energy to a gas parcel with the rate
  \[
  \mathcal{H}_{cr} = -v_A \cdot \nabla P_{cr} \sim f_s v_A |\nabla P_{cr}|,
  \]
  where $f_s$ is the magnetic suppression factor.
- line and bremsstrahlung emission radiate energy with a rate $C_{rad}$
Critical length scale of the instability (∼ Fields length)

- CR streaming transfers energy to a gas parcel with the rate
  \[ \mathcal{H}_{cr} = -v_A \cdot \nabla P_{cr} \sim f_s v_A |\nabla P_{cr}|, \]
  where \( f_s \) is the magnetic suppression factor.
- line and bremsstrahlung emission radiate energy with a rate \( C_{\text{rad}} \).
- limiting size of unstable gas parcel since CR Alfvén-wave heating smooths out temperature inhomogeneities on small scales:
  \[ \lambda_{\text{crit}} = \frac{f_s v_A P_{cr}}{C_{\text{rad}}} \]
  however: unstable wavelength must be supported by the system
  \( \rightarrow \) constraint on magnetic suppression factor \( f_s \)

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Critical length scale of the instability ($\sim$ Fields length)

$$\lambda_{\text{crit}} = r$$

unstable wavelength
larger than system

thermally unstable

stabilized by CR streaming

$ f_{\text{sup}} = 1.0, Z = 0.7 \, Z_\odot$

$ f_{\text{sup}} = 1.0, Z = 1.3 \, Z_\odot$

$ f_{\text{sup}} = 0.3, Z = 0.7 \, Z_\odot$

$ f_{\text{sup}} = 0.3, Z = 1.3 \, Z_\odot$
CR heating dominates over thermal conduction

\[ \frac{\mathcal{H}_{CR}}{\mathcal{H}_{\text{cond}}} \]

where

\[ \mathcal{H}_{CR} = P_{\text{smooth}} + \delta P \]

C.P. (2013)

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Cosmic ray feedback in galaxies and cool core clusters
(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
→ 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: $P_{\text{cr}}/P_{\text{cr},0} = \delta^{4/3} \sim 20$ for compression factor $\delta = 10$

(3) CR escape and outward streaming → CR Alfvén-wave heating
Prediction: flattening of high-$\nu$ radio spectrum

![Graph showing the prediction of flattening in the radio spectrum of galaxies. The graph plots flux density in units of Jy against frequency in MHz. Lines represent different scenarios: continuous injection, continuous injection with switch off, and hadronically induced emission. Data points are also shown.](image-url)
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 $\gamma$ rays identified with low state of M87 → estimate CR-to-thermal pressure of $X_{cr} = 0.31$
- 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 $kT \approx 1$ keV

Outlook: simulate steaming CRs coupled to MHD, cosmological cluster simulations, improve $\gamma$-ray and radio observations . . .
Cosmic ray-driven winds in galaxies:


AGN feedback by cosmic rays:

Puzzles in galaxy formation
Driving galactic winds
AGN feedback
Observations of M87
Cosmic-ray heating
Conclusions

Additional slides

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Cosmic ray feedback in galaxies and cool core clusters
Self-consistent CR pressure in steady state

- CR streaming transfers energy per unit volume to the gas as

\[ \Delta \varepsilon_{\text{th}} = -\tau_A \mathbf{v}_A \cdot \nabla P_{\text{cr}} \approx P_{\text{cr}} = X_{\text{cr}} P_{\text{th}}, \]

where \( \tau_A = \delta l / v_A \) is the Alfvén crossing time and \( \delta l \) the CR pressure gradient length

- comparing the first and last term suggests that a constant CR-to-thermal pressure ratio \( X_{\text{cr}} \) is a necessary condition if CR streaming is the dominant heating process

→ thermal pressure profile adjusts to that of the streaming CRs!
Impact of varying Alfvén speed on CR heating

**global thermal equilibrium:**

**local stability criterion:**

parametrize $B \propto \rho^{\alpha_B}$, which implies $v_A = B/\sqrt{4\pi\rho} \propto \rho^{\alpha_B - 1/2}$:

- $\alpha_B = 0.5$ is the geometric mean, implying $v_A = \text{const}$.
- $\alpha_B = 0$ for collapse along $B$, implying $v_{A,\parallel} \propto \rho^{-1/2}$
- $\alpha_B = 1$ for collapse perpendicular to $B$, implying $v_{A,\perp} \propto \rho^{1/2}$
**CR streaming: Gadget-2 versus 1-d grid solver**

Evolution of the specific CR energy due to streaming in a medium at rest

Uhlig+ (2012)
Puzzles in galaxy formation
Driving galactic winds
AGN feedback
Observations of M87
Cosmic-ray heating
Conclusions

CR-driven wind simulations: resolution study

- our results winds driven by CR streaming are converged with respect to particle resolution (left) and time step of the explicit streaming solver (right)