Cosmic ray feedback in galaxies and cool core clusters

Christoph Pfrommer[1]

in collaboration with

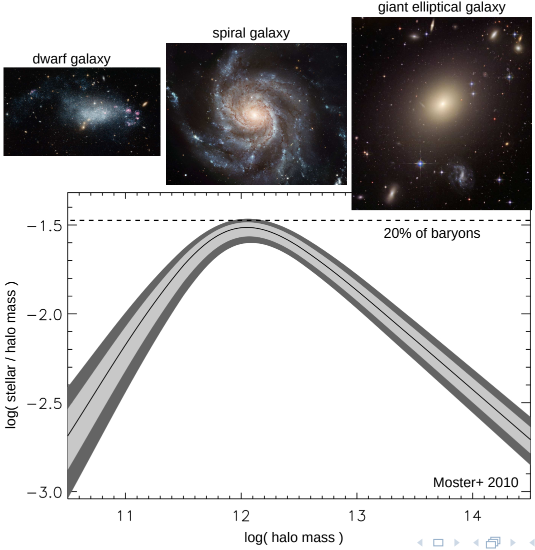
M. Uhlig, M. Sharma, B. Nath, T. Enßlin, V. Springel
(cosmic-ray driven winds)

[1] Heidelberg Institute for Theoretical Studies, Germany

Apr 21, 2015 / Perimeter Institute, Waterloo: *Colloquium*

Outline

Puzzles in galaxy formation

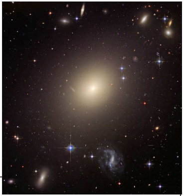


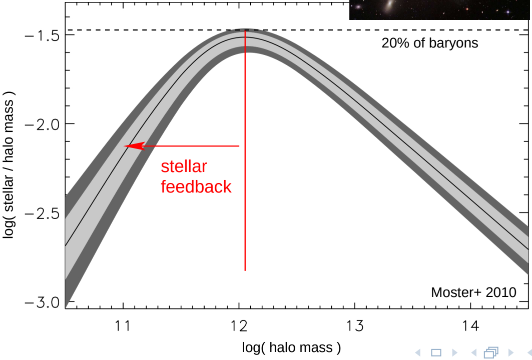
Puzzles in galaxy formation

dwarf galaxy

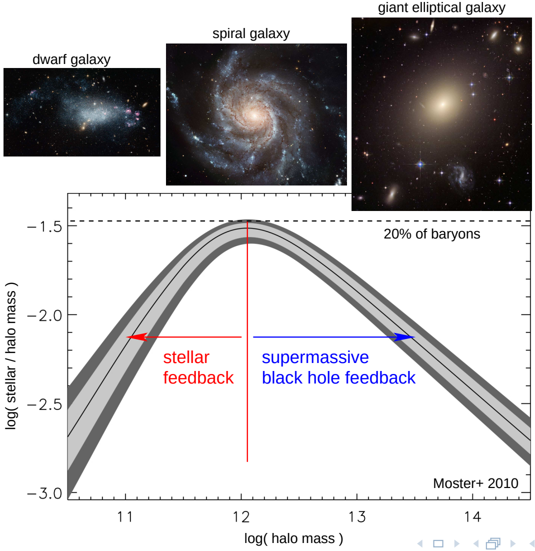
spiral galaxy

giant elliptical galaxy





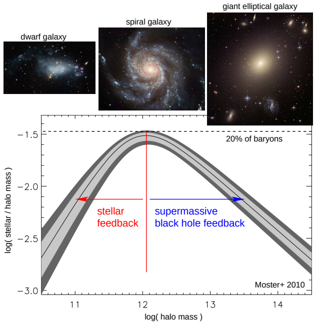
Puzzles in galaxy formation



Puzzles in galaxy formation

Bright-end of luminosity function:

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



Puzzles in galaxy formation

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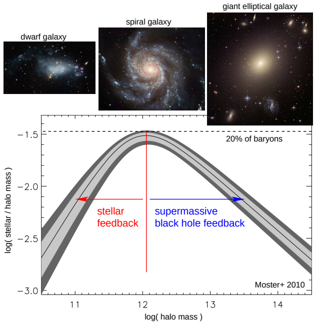
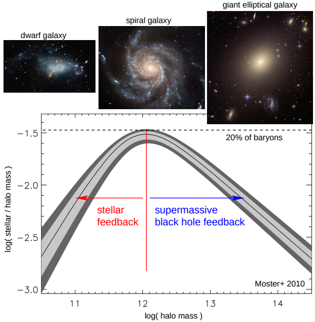
Faint-end of luminosity function:

- dark matter (DM) solutions: warm DM, interacting DM, DM from late decays, large annihilation rates, . . .



Puzzles in galaxy formation



Bright-end of luminosity function:

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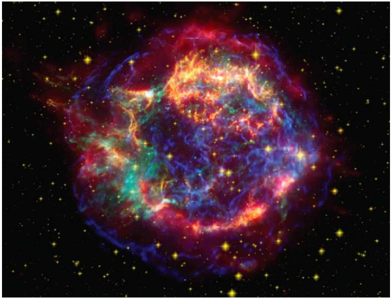
Faint-end of luminosity function:

- 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 $\longrightarrow$ **galactic winds**

Galactic winds



supernova Cassiopeia A

X-ray: NASA/CXC/SAO; Optical: NASA/STScI;
Infrared: NASA/JPL-Caltech/Steward/O.Krause et al.

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

Galactic winds

super wind in M82

NASA/JPL-Caltech/STScI/CXC/UofA

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NASA/JPL-Caltech/STScI/CXC/UofA

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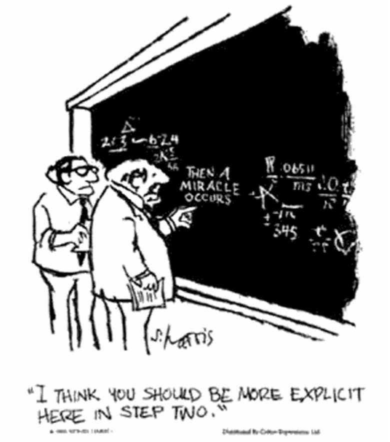
Galactic winds



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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*)

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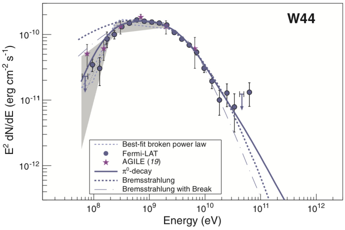
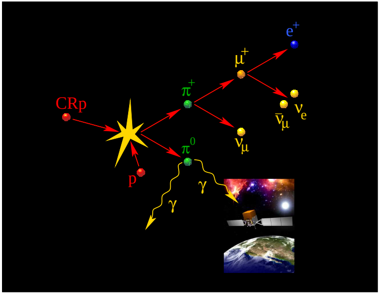
Fermi observations of W44:



Ackermann+ (2013)



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- shell-type SNRs show evidence for efficient shock acceleration beyond $\sim$ 100 TeV (HESS TeV γ-ray observations)

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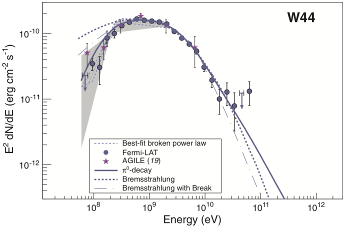

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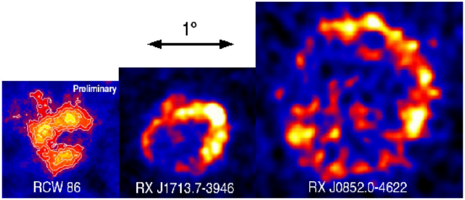
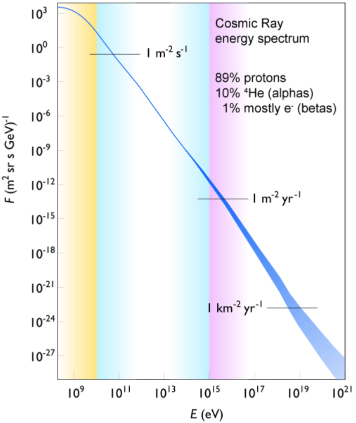
HESS observations of shell-type SNRs:



Hinton (2009)

Galactic cosmic ray spectrum



data compiled by Swordy

- 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

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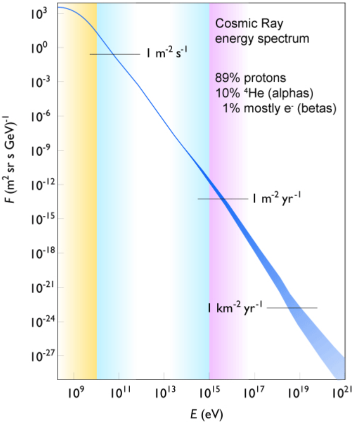

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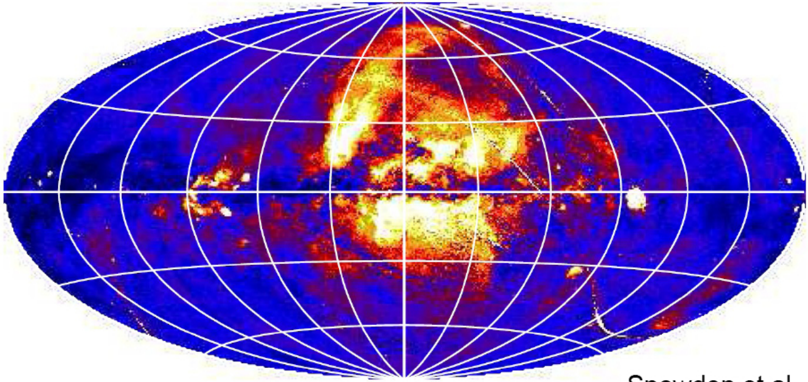
- spans more than 33 decades in flux and 12 decades in energy
- "knee" indicates characteristic maximum energy of galactic accelerators
- CRs beyond the "ankle" have extra-galactic origin
- energy density of cosmic rays, magnetic fields, and turbulence in the interstellar gas all similar

Galactic wind in the Milky Way?

Diffuse X-ray emission in our galaxy



Snowden et al., 2007

. . . as suggested by Everett+ (2008) and Everett, Schiller, Zweibel (2010)

How are galactic winds driven?

super wind in M82

- 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?

How are galactic winds driven?


NASA/JPL-Caltech/STScI/CXC/UofA

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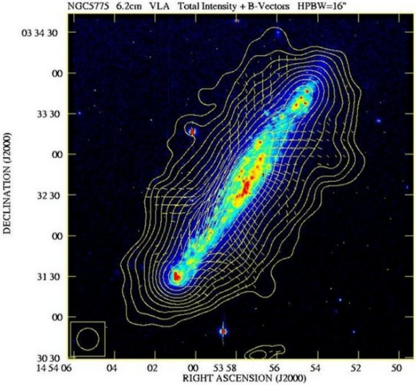
observed energy equipartition between cosmic rays, thermal gas and magnetic fields

→ 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

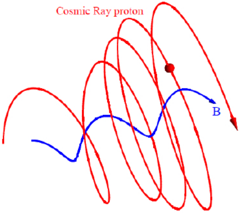


Tüllmann+ (2000)

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

Interactions of CRs and magnetic fields

- CRs scatter on magnetic fields $\rightarrow$ 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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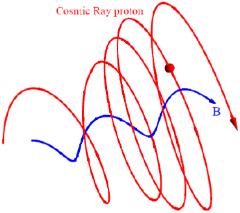

→ **CRs exert a pressure on the thermal gas by means of scattering off of Alfvén waves**

CR transport

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

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

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

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

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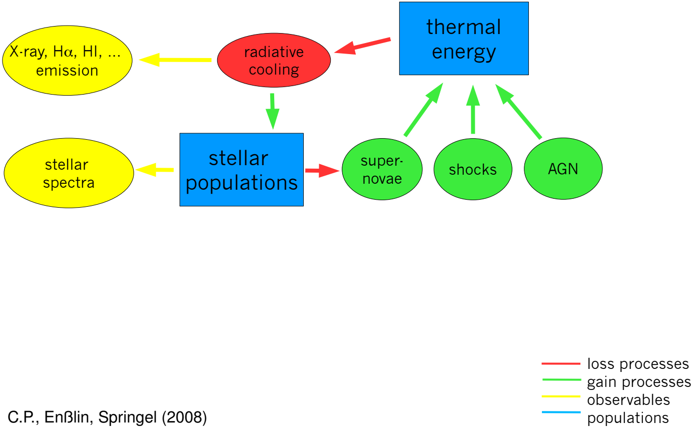
\Longleftrightarrow \quad \frac{\partial \varepsilon_{\rm cr}}{\partial t} + \boldsymbol{\nabla} \cdot [\varepsilon_{\rm cr}(\boldsymbol{v} + \boldsymbol{v}_{\rm st})] &= -P_{\rm cr} \boldsymbol{\nabla} \cdot (\boldsymbol{v} + \boldsymbol{v}_{\rm st})
\end{aligned}$$

Simulations – flowchart

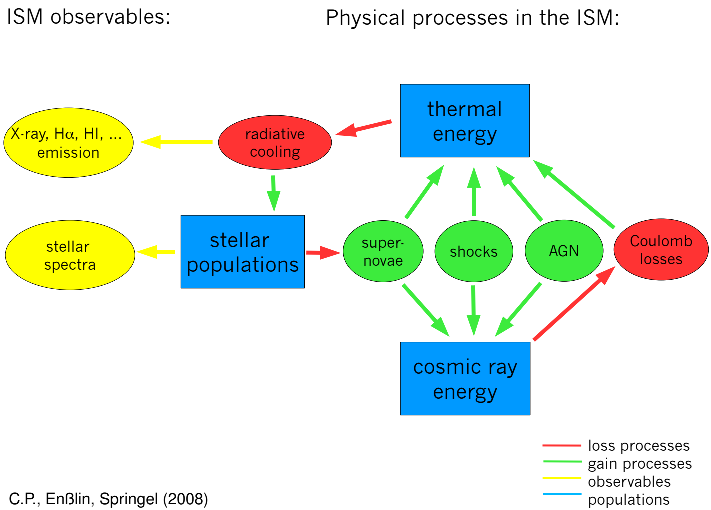
ISM observables:

Physical processes in the ISM:



C.P., Enßlin, Springel (2008)

Simulations with cosmic ray physics



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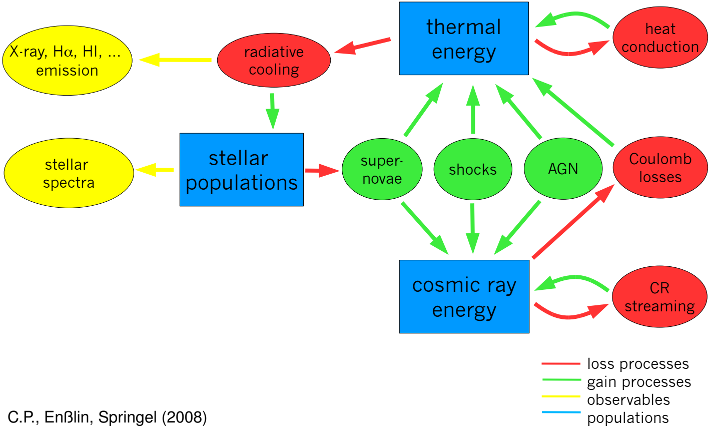

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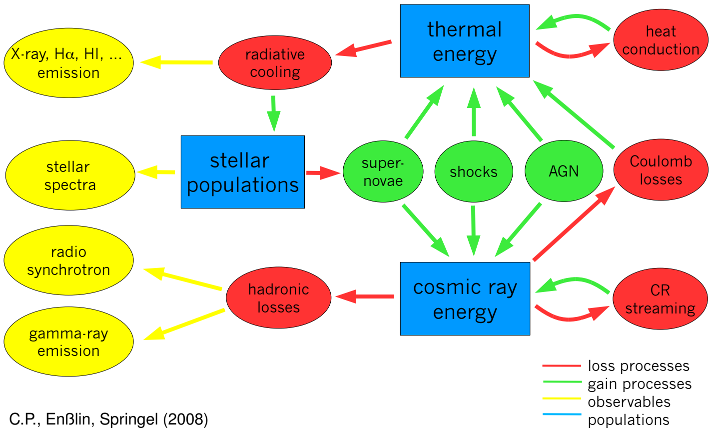
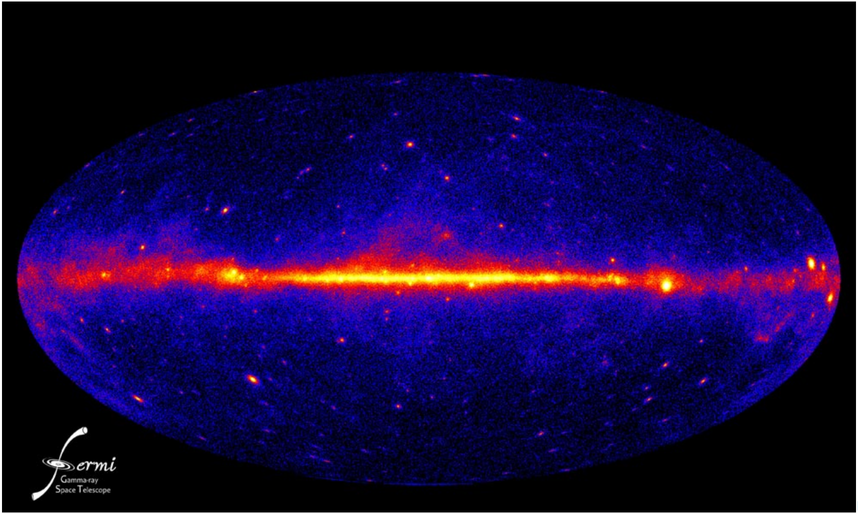
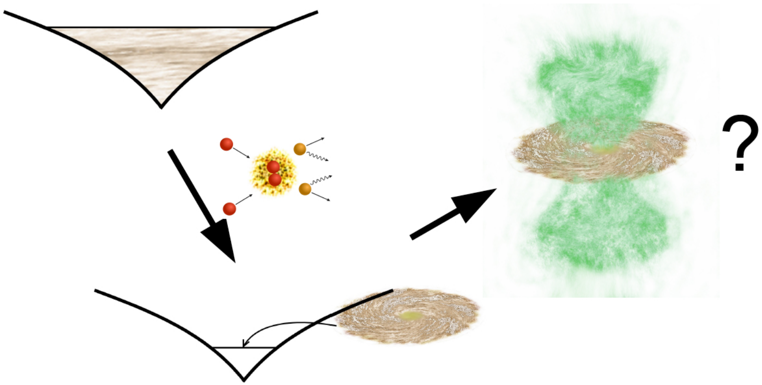


C.P., Enßlin, Springel (2008)

Gamma-ray emission of the Milky Way

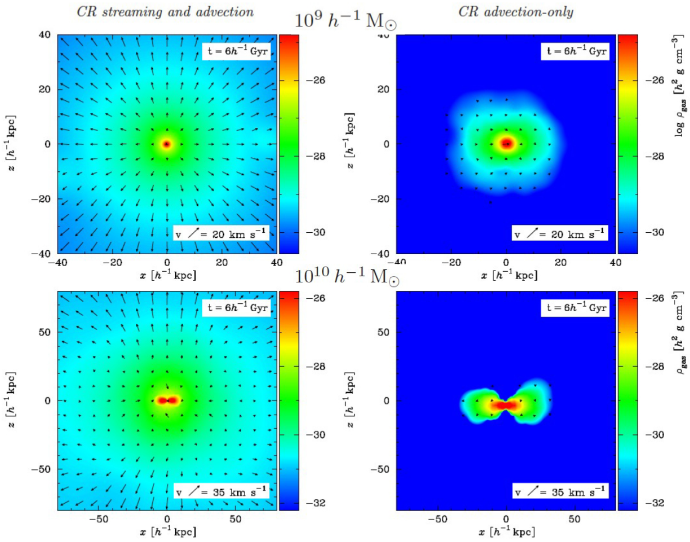


Simulation setup

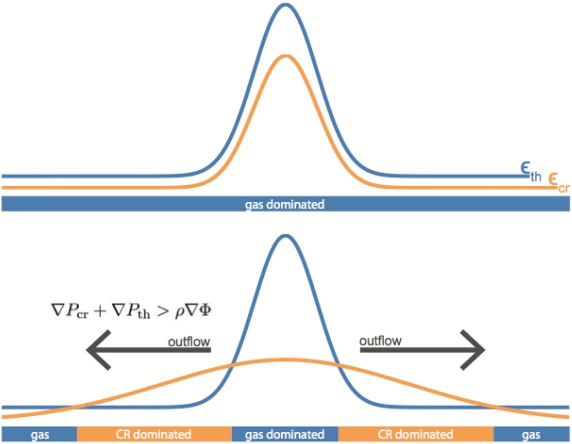


Uhlig, C.P., Sharma, Nath, Enßlin, Springel, *MNRAS* **423**, 2374 (2012)
Galactic winds driven by cosmic-ray streaming

CR streaming drives winds



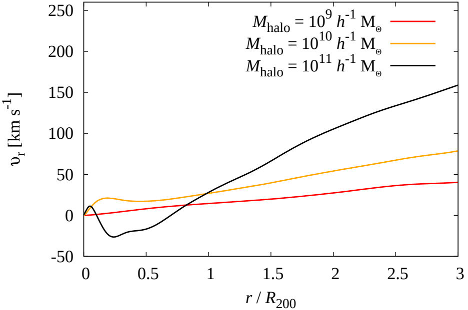
Cosmic ray driven wind: mechanism



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

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

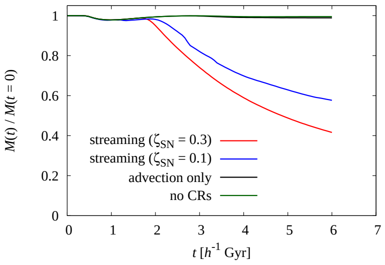
Wind velocity profile along the symmetry axis



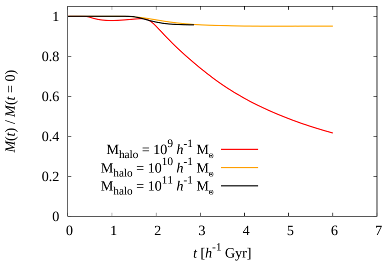
- $10^9 - 10^{10}\ M_\odot$: accelerating wind due to a continuous CR momentum and energy deposition during the ascent of the wind in the gravitational potential
  → different from traditional energy- or momentum-driven winds!
- $10^{11}\ M_\odot$: wind stalls in halo and falls back onto the disk
  → fountain flow

Gas mass loss within the virial radius

different scenarios:



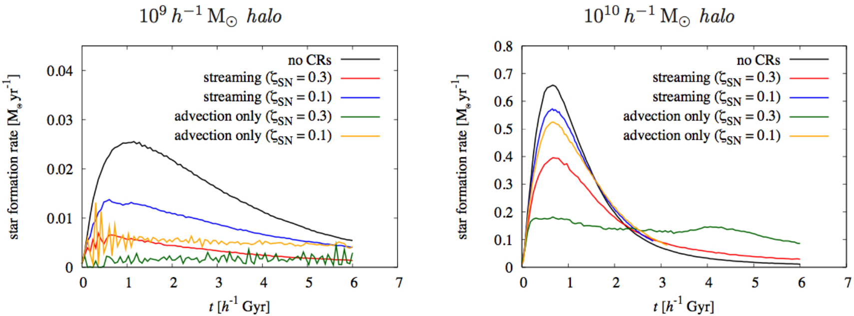
different galaxy masses:



- after initial phase ($\sim$ 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 $\zeta_{\rm SN}$ *(left)* and toward smaller galaxy masses *(right)*

HITS

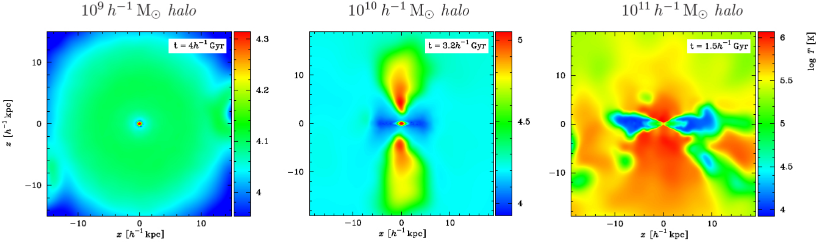
Star formation histories (SFHs)



- 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

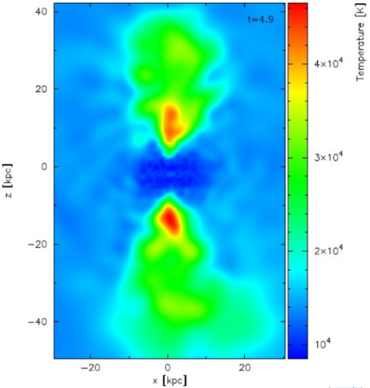


- halo temperatures scale as $kT \propto v_{\mathrm{wind}}^2 \sim v_{\mathrm{esc}}^2$
- $10^9 \rightarrow 10^{10}\ \mathrm{M}_\odot$: transition of isotropic to bi-conical wind; in these cones, CR wave heating overcomes radiative cooling
- $10^{10} \rightarrow 10^{11}\ \mathrm{M}_\odot$: broadening of 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

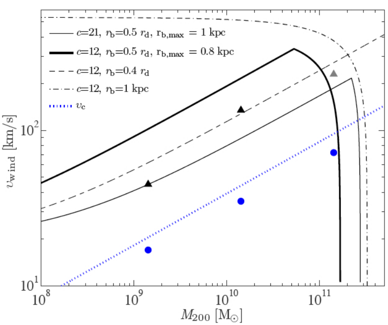
M82 observation

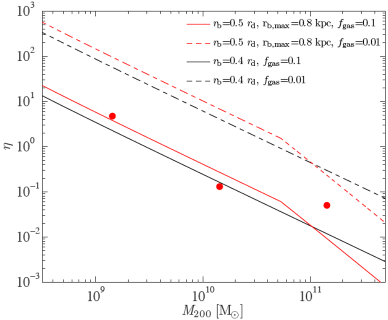
CR streaming (10^{10} M$_\odot$)



CR-driven winds: analytics versus simulations

Bernoulli theorem along streamlines: wind speeds and mass loading factors





- winds speeds increase with galaxy mass as $v_\mathrm{wind} \propto v_\mathrm{circ} \propto M_{200}^{1/3}$ until they cutoff around 10^{11} M$_\odot$ due to a fixed wind base height (set by radiative physics)
- mass loading factor $\eta = \dot{M}/\mathrm{SFR}$ decreases with galaxy mass

Conclusions on cosmic-ray driven winds in galaxies

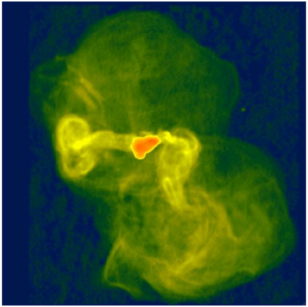
- galactic winds are naturally explained by CR streaming (known energy source and plasma physics)
- CR streaming heating can explain observed hot wind regions above disks
- substantial mass losses of low mass galaxies
  $\rightarrow$ opportunity for understanding the physics at the faint end of galaxy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

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

$\rightarrow$ recent work: Booth+ (2013), Hanasz+ (2013), Salem & Bryan (2014)

“Radio-mode” AGN feedback

Messier 87 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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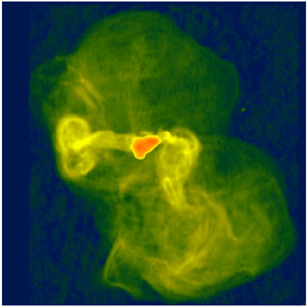

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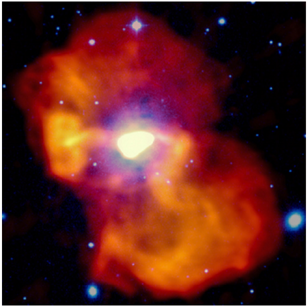

$\nu = 140$ MHz (LOFAR/de Gasperin+ 2012)

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

Solutions to the “missing fossil electrons” problem

solutions:

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

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- special time: M87 turned on $\sim$ 40 Myr ago after long silence
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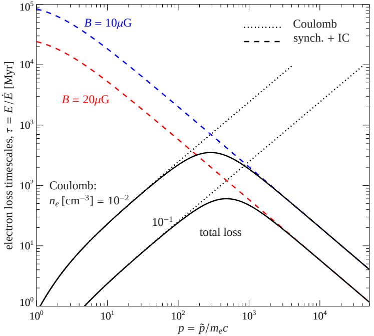
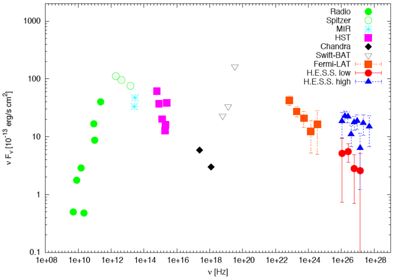
- Coulomb cooling removes fossil electrons
  $\rightarrow$ efficient mixing of CR electrons and protons with dense cluster gas
  $\rightarrow$ predicts γ rays from CRp-p interactions:
  $p + p \rightarrow \pi^0 + \ldots \rightarrow 2\gamma + \ldots$



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 (?)



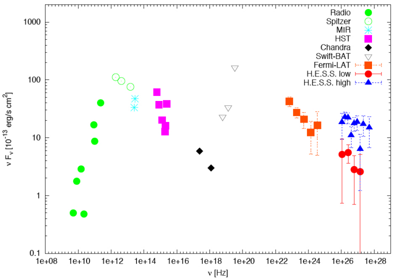
Rieger & Aharonian (2012)

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

Estimating the CR pressure in M87

hypothesis: low state of γ-ray emission traces π^0 decay in ICM:

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



Rieger & Aharonian (2012)

$\rightarrow$ 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)

$$\mathcal{H}_{\rm cr} = -\boldsymbol{v}_A \cdot \boldsymbol{\nabla} P_{\rm cr} = -v_A \left(X_{\rm cr} \nabla_r \langle P_{\rm th} \rangle_\Omega + \frac{\delta P_{\rm cr}}{\delta l} \right)$$

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

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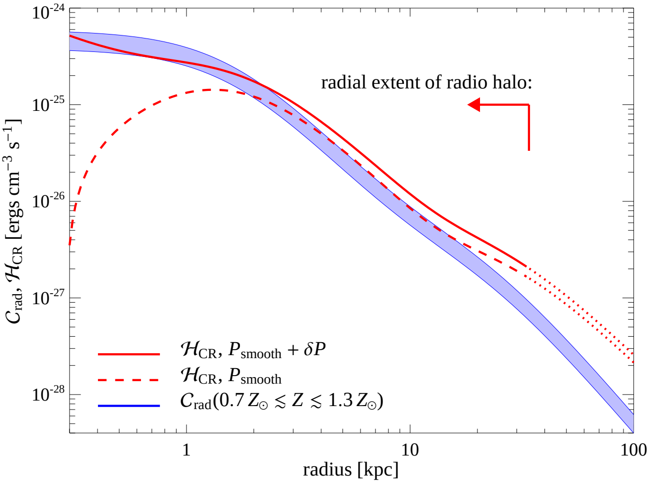
radiative cooling:

$$\mathcal{C}_{\rm rad} = n_e n_i \Lambda_{\rm cool}(T, Z)$$

- cooling function $\Lambda_{\rm cool}$ with $Z \simeq Z_\odot$, all quantities determined from X-ray data

Cosmic-ray heating vs. radiative cooling (2)

Global thermal equilibrium on all scales in M87



C.P. (2013)

Cosmic-ray heating vs. radiative cooling (3)

is this global thermal equilibrium a coincidence in Virgo?

Cosmic-ray heating vs. radiative cooling (3)

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- 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 $v_A =$ const. and steady-state CR streaming, $P_{\rm cr} \propto \rho^{\gamma_{\rm cr}/2} \propto P_{\rm th}$ (also required for self-consistency):

$$
\begin{aligned}
\mathcal{H}_{\rm cr} &\propto \frac{\partial}{\partial r} P_{\rm th} \propto \frac{\partial}{\partial r} r^{\alpha-1} \propto r^{\alpha-2} \\
\mathcal{C}_{\rm rad} &\propto n^2 \propto r^{-2}
\end{aligned}
$$

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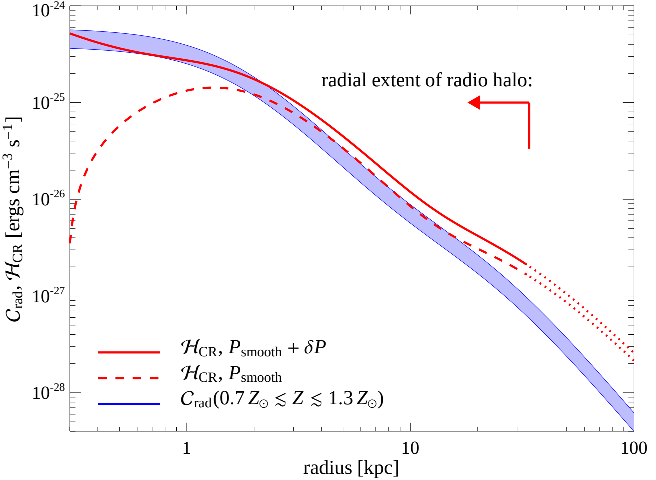
(1) identical radial profiles expected for $T \simeq$ const. ($\alpha \simeq 0$)

(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

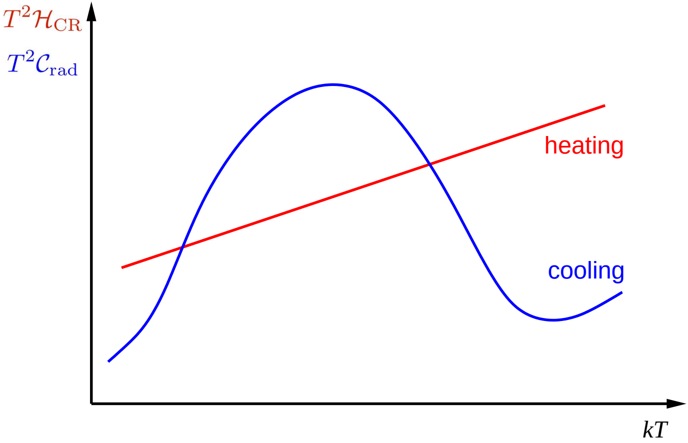
Cosmic-ray heating vs. radiative cooling

Global thermal equilibrium on all scales in M87



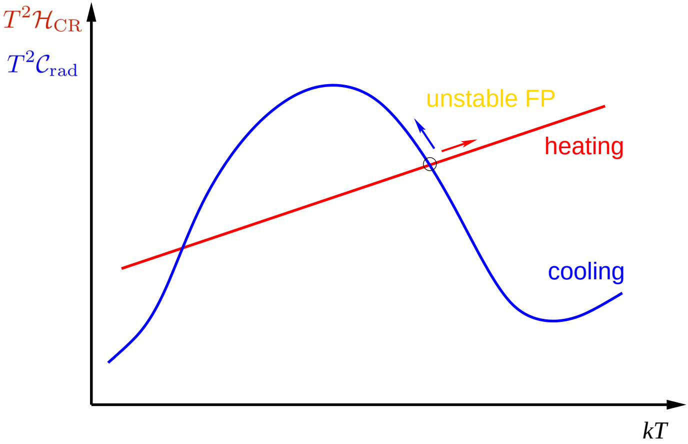
C.P. (2013)

Local stability analysis (1)



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

Local stability analysis (1)



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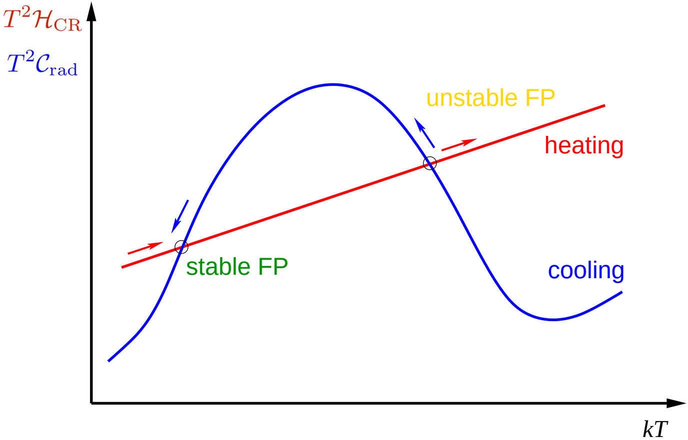

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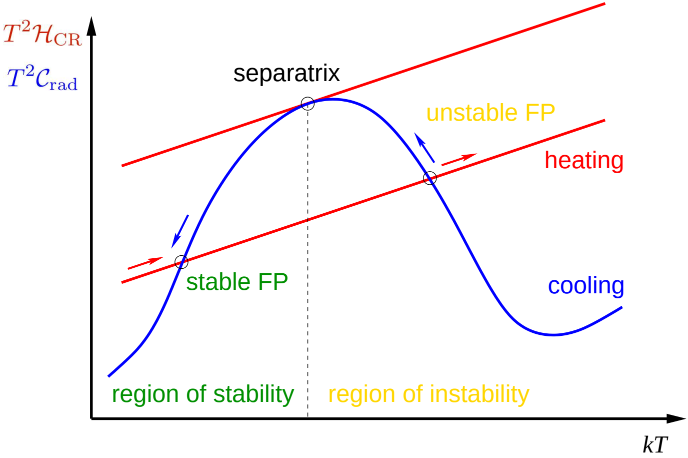
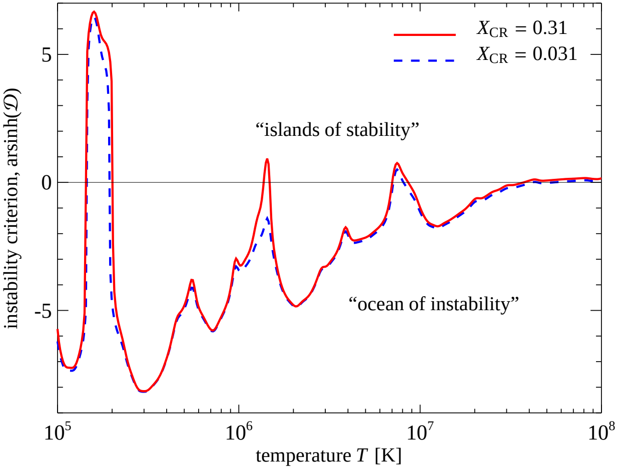


- isobaric perturbations to global thermal equilibrium
- CRs are adiabatically trapped by perturbations

Local stability analysis (2)

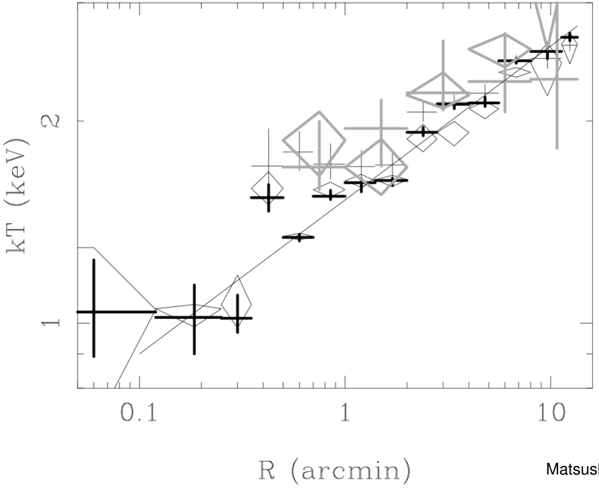
Theory predicts observed temperature floor at $kT \simeq 1$ keV



C.P. (2013)

Virgo cluster cooling flow: temperature profile

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



Matsushita+ (2002)

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

- CR streaming transfers energy to a gas parcel with the rate

$$\mathcal{H}_{\rm cr} = -\boldsymbol{v}_A \cdot \boldsymbol{\nabla} P_{\rm cr} \sim f_s v_A |\nabla P_{\rm cr}|,$$

where f_s is the magnetic suppression factor

- line and bremsstrahlung emission radiate energy with a rate $\mathcal{C}_{\rm rad}$

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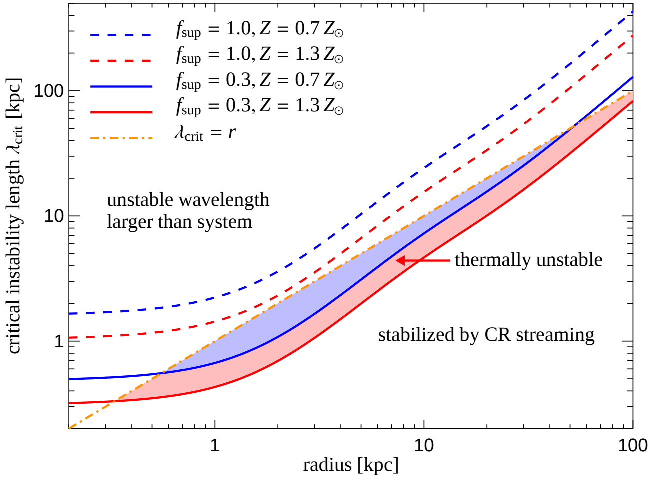
- line and bremsstrahlung emission radiate energy with a rate $\mathcal{C}_{\rm rad}$
- limiting size of unstable gas parcel since CR Alfvén-wave heating smoothes out temperature inhomogeneities on small scales:

$$\lambda_{\rm crit} = \frac{f_s v_A P_{\rm cr}}{\mathcal{C}_{\rm rad}}$$

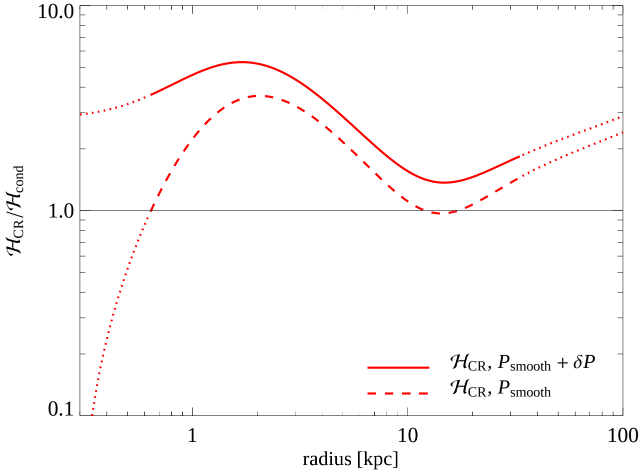
- however: unstable wavelength must be supported by the system $\rightarrow$ constraint on magnetic suppression factor f_s

Critical length scale of the instability (∼ Fields length)



C.P. (2013)

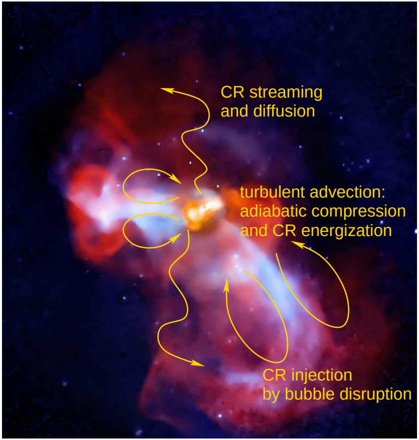
CR heating dominates over thermal conduction



C.P. (2013)

Emerging picture of CR feedback by AGNs

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

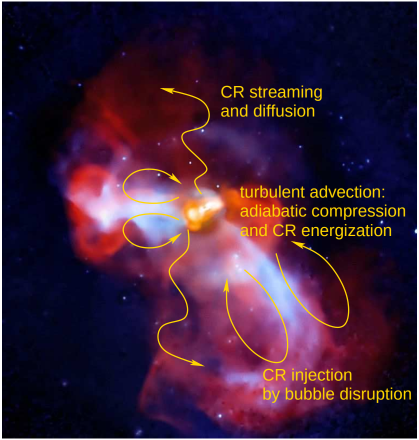


Emerging picture of CR feedback by AGNs

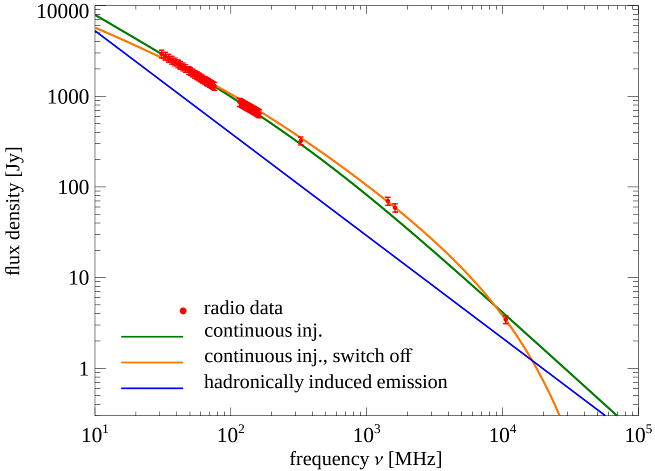
(1) during buoyant rise of bubbles: CRs diffuse and stream outward
$\rightarrow$ CR Alfvén-wave heating

(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: $P_{\mathrm{cr}}/P_{\mathrm{cr},0} = \delta^{4/3} \sim 20$ 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 $X_{\rm cr} = 0.31$
- 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 . . .

Literature for the talk

Cosmic ray-driven winds in galaxies:

- Uhlig, Pfrommer, Sharma, Nath, Enßlin, Springel, *Galactic winds driven by cosmic-ray streaming*, 2012, MNRAS, 423, 2374.

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.

Additional slides

Self-consistent CR pressure in steady state

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

$$\Delta\varepsilon_{\text{th}} = -\tau_A \boldsymbol{v}_A \cdot \boldsymbol{\nabla} P_{\text{cr}} \approx P_{\text{cr}} = X_{\text{cr}} P_{\text{th}},$$

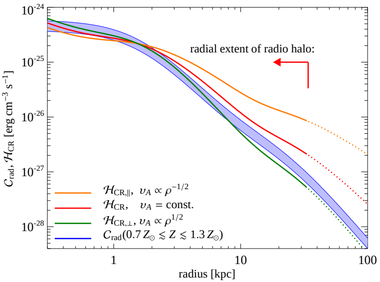
  where $\tau_A = \delta l / v_A$ is the Alfvén crossing time and δl the CR pressure gradient length

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

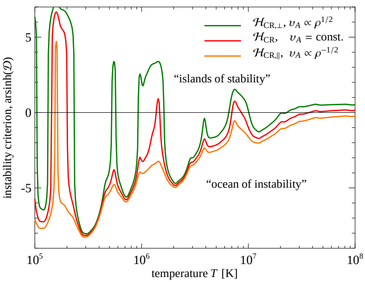
$\rightarrow$ **thermal pressure profile adjusts to that of the streaming CRs!**

Impact of varying Alfvén speed on CR heating

global thermal equilibrium:



local stability criterion:

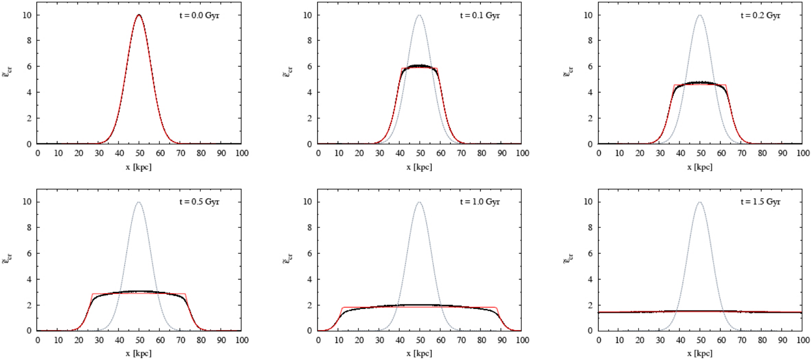


parametrize $B \propto \rho^{\alpha_B}$, which implies $v_A = B/\sqrt{4\pi\rho} \propto \rho^{\alpha_B - 1/2}$:

- $\alpha_B = 0.5$ 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 $v_{A,\perp} \propto \rho^{1/2}$

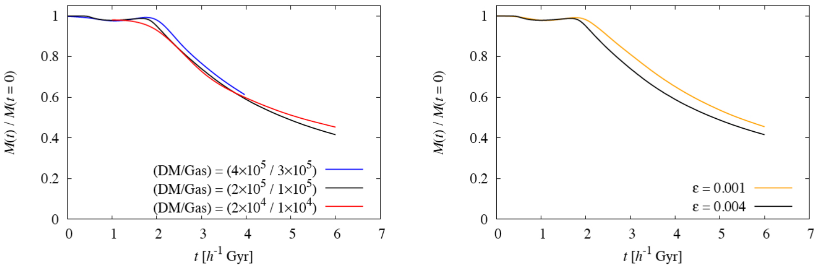
CR streaming: Gadget-2 versus 1-d grid solver

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



Uhlig+ (2012)

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)*