Puzzles in galaxy formation
Driving galactic winds
AGN feedback

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

Feb 26, 2015 / U of Wisconsin, Madison: *Colloquium*

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Puzzles in galaxy formation
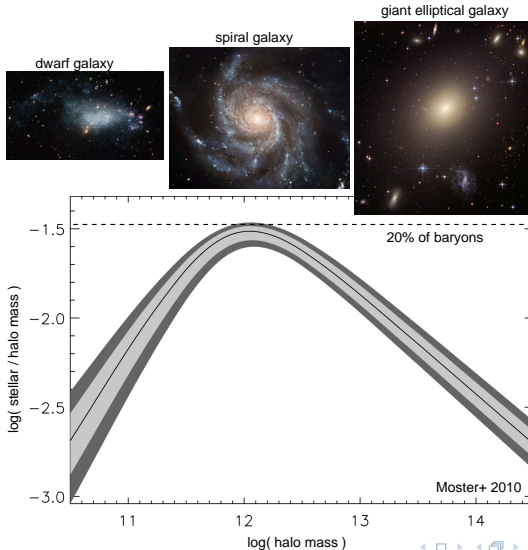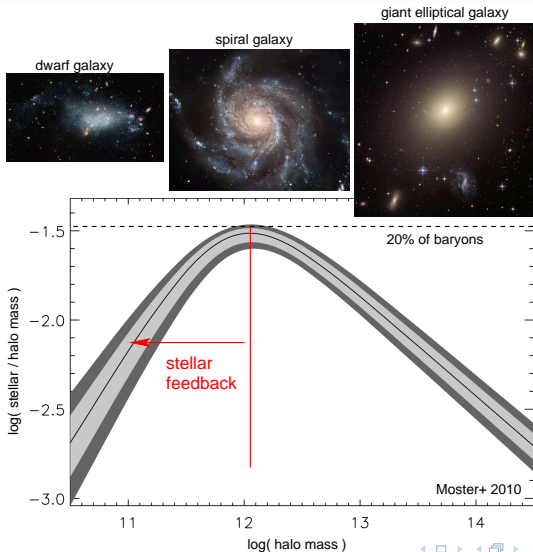Driving galactic winds
AGN feedback

Outline

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
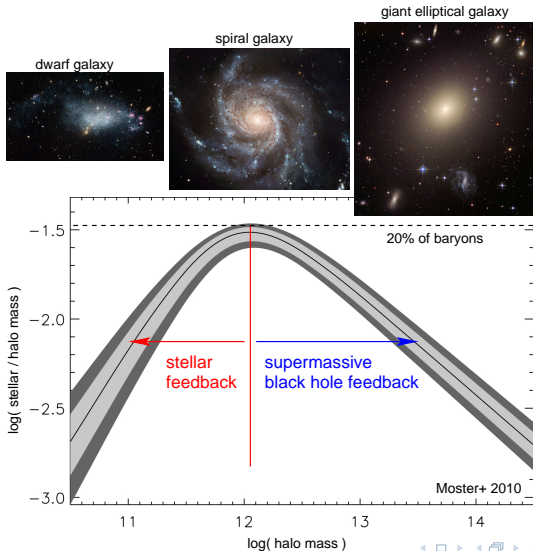   - Observations of M87
   - Cosmic-ray heating
   - Conclusions

Puzzles in galaxy formation
Driving galactic winds
AGN feedback

Puzzles in galaxy formation

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AGN feedback

Puzzles in galaxy formation

Puzzles in galaxy formation
Driving galactic winds
AGN feedback

Puzzles in galaxy formation

dwarf galaxy

spiral galaxy

giant elliptical galaxy

20% of baryons

stellar feedback

supermassive black hole feedback

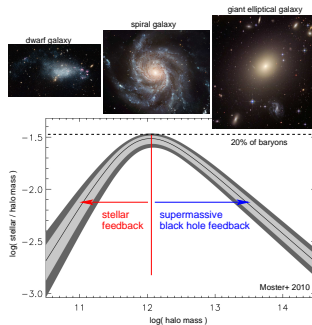Moster+ 2010

Puzzles in galaxy formation
Driving galactic winds
AGN feedback

Puzzles in galaxy formation

Bright-end of luminosity function:

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

Puzzles in galaxy formation
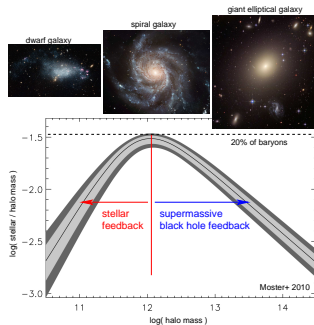Driving galactic winds
AGN feedback

Puzzles in galaxy formation

Bright-end of luminosity function:

- astrophysical solutions:
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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
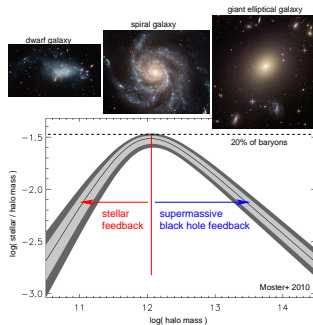Driving galactic winds
AGN feedback

Puzzles in galaxy formation
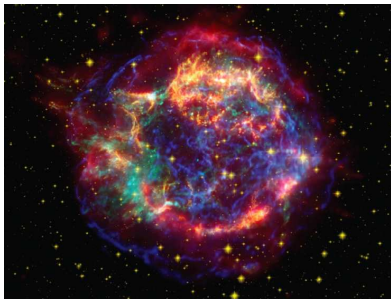
Bright-end of luminosity function:

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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 → **galactic winds**

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AGN feedback

Galactic winds and cosmic rays
Mass loss and star formation
Cosmic-ray heating

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

Puzzles in galaxy formation
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super wind in M82

NASA/JPL-Caltech/STScI/CXC/UofA

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- star formation and supernovae drive gas out of galaxies by galactic super winds

Puzzles in galaxy formation
Driving galactic winds
AGN feedback

Galactic winds and cosmic rays
Mass loss and star formation
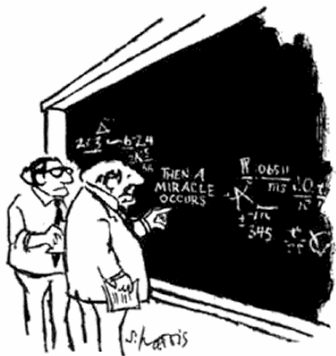Cosmic-ray heating

Galactic winds

super wind in M82

NASA/JPL-Caltech/STScI/CXC/UofA

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

Puzzles in galaxy formation
Driving galactic winds
AGN feedback

Galactic winds and cosmic rays
Mass loss and star formation
Cosmic-ray heating

Galactic winds

© Sydney Harris

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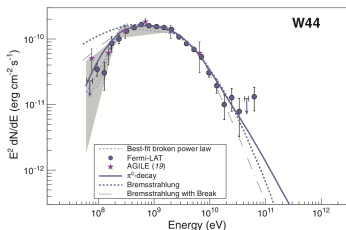
The role of supernova remnants

- supernova remnant shocks amplify magnetic fields and accelerate CR electrons up to ~ 100 TeV (narrow X-ray synchrotron filaments observed by *Chandra*)

Puzzles in galaxy formation
Driving galactic winds
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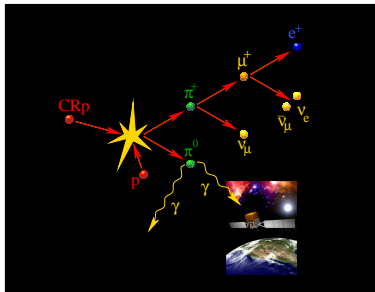Cosmic-ray heating

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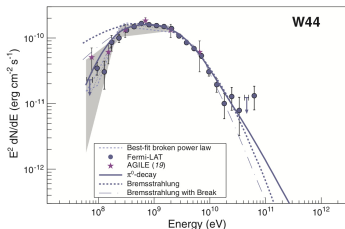
Fermi observations of W44:

Ackermann+ (2013)

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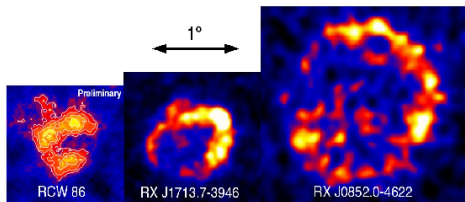
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- shell-type SNRs show evidence for efficient shock acceleration beyond ~ 100 TeV (HESS TeV γ-ray observations)

Fermi observations of W44:   *HESS observations of shell-type SNRs:*
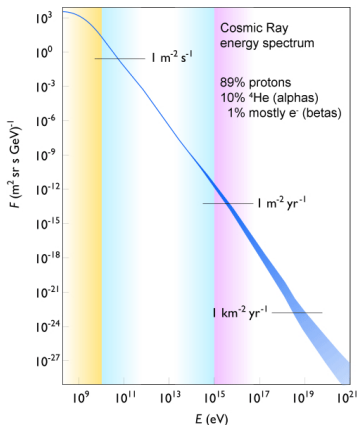
Ackermann+ (2013)

Hinton (2009)

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Galactic winds and cosmic rays
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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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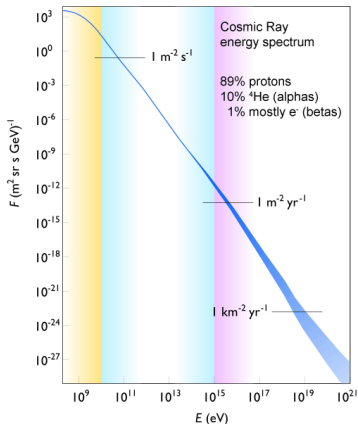
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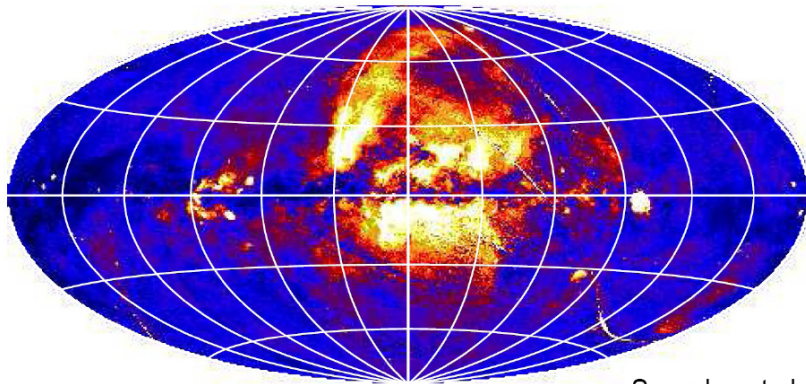data compiled by Swordy

- 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
- energy density of cosmic rays, magnetic fields, and turbulence in the interstellar gas all similar:

  → CRs and magnetic fields appear to be necessary for understanding galactic winds!

Puzzles in galaxy formation
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Galactic winds and cosmic rays
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Cosmic-ray heating

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)

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Fermi gamma-ray bubbles
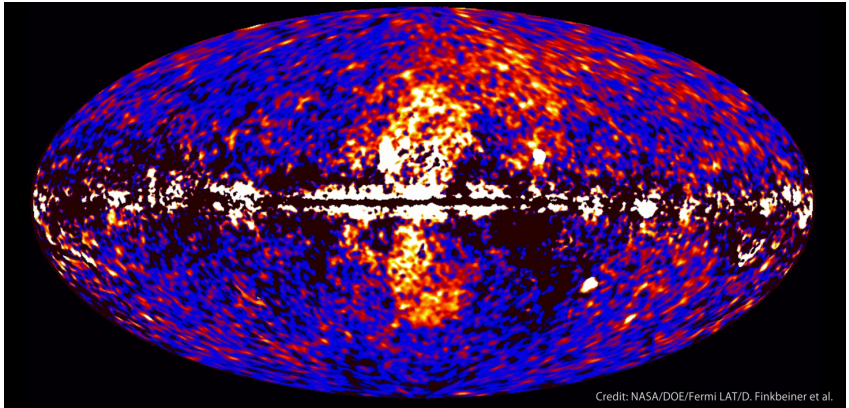
Credit: NASA/DOE/Fermi LAT/D. Finkbeiner et al.

Puzzles in galaxy formation
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How to drive a wind?

- standard picture: wind driven by thermal pressure

- energy sources for winds: supernovae, AGN

- problem with the standard picture: fast radiative cooling

- alternative channels:
  - radiation pressure on atomic lines and dust grains?
  - cosmic rays (CRs, relativistic protons with $\gamma_{ad} = 4/3$):
    promising idea since observationally $\varepsilon_{CR} \simeq \varepsilon_{turb} \simeq \varepsilon_B$

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Radio halos in edge-on disk galaxies
CRs and magnetic fields exist at the disk-halo interface → wind launching site?

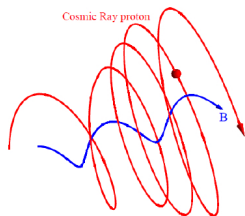NGC5775 6.2cm VLA Total Intensity + B-Vectors HPBW=16"
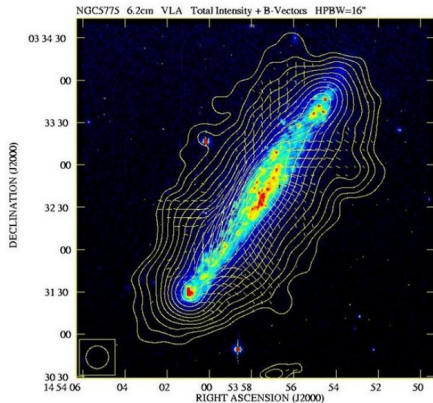
Tüllmann+ (2000)

why are CRs important for wind formation?

- CR pressure drops less quickly than thermal pressure ($P \propto \rho^{\gamma}$)

- CRs cool less efficiently than thermal gas

- most CR energy loss goes into thermal pressure

Puzzles in galaxy formation
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Galactic winds and cosmic rays
Mass loss and star formation
Cosmic-ray heating

Interactions of CRs and magnetic fields

- CRs scatter on magnetic fields $\rightarrow$ 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

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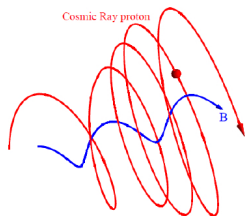Cosmic-ray heating

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Cosmic Ray proton

B

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

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

CR transport

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

- 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 $\boldsymbol{B}$):

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

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

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

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

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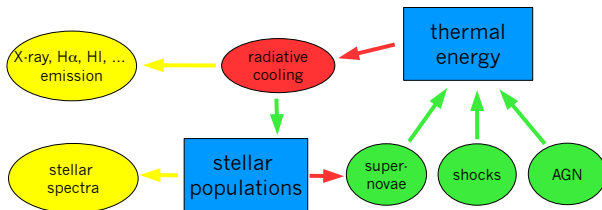- energy equations with $\varepsilon = \varepsilon_{th} + \rho v^2/2$ (neglecting CR diffusion):

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

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

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AGN feedback

Galactic winds and cosmic rays
Mass loss and star formation
Cosmic-ray heating

Simulations – flowchart

ISM observables:

Physical processes in the ISM:

C.P., Enßlin, Springel (2008)

loss processes
gain processes
observables
populations

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Simulations with cosmic ray physics
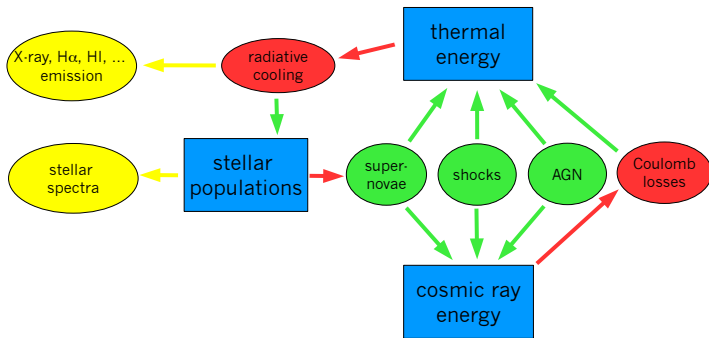
ISM observables:

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loss processes
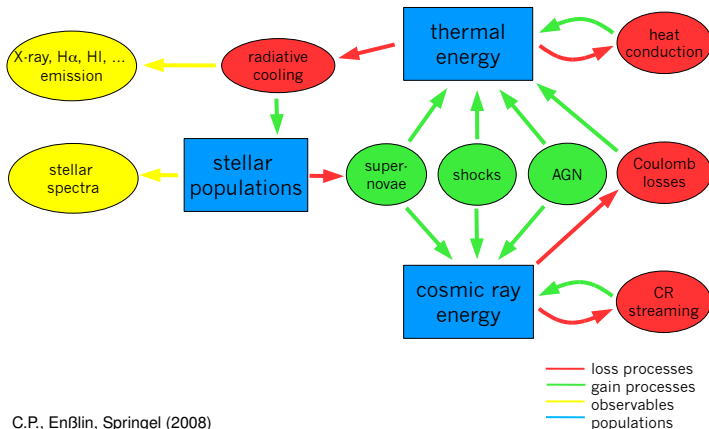gain processes
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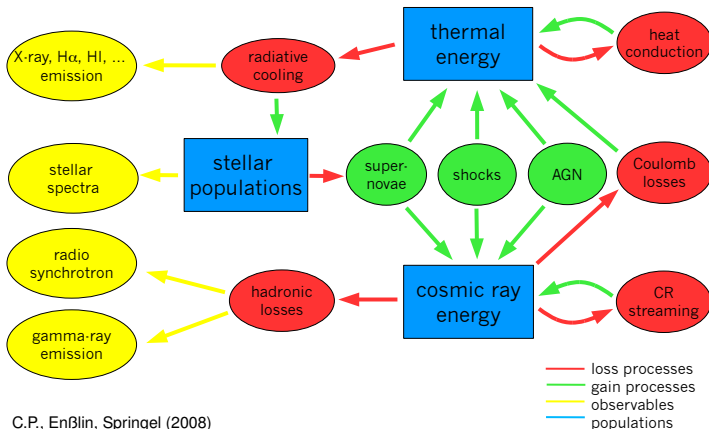
Simulations with extended cosmic ray physics

ISM observables:

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AGN feedback

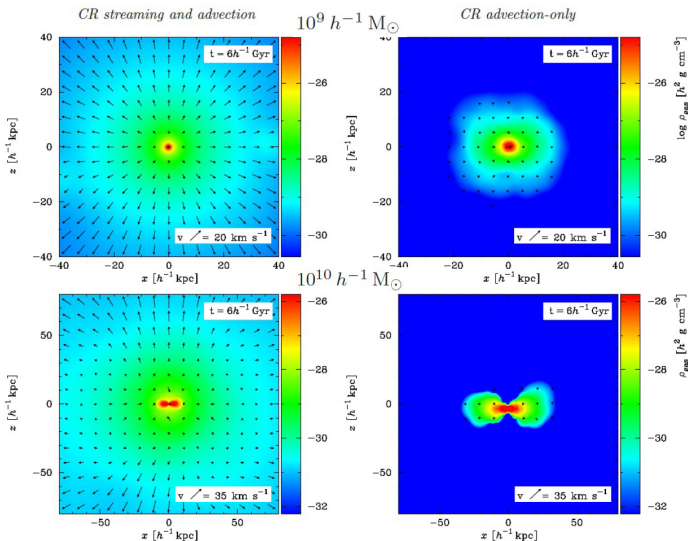Galactic winds and cosmic rays
Mass loss and star formation
Cosmic-ray heating

Simulation setup
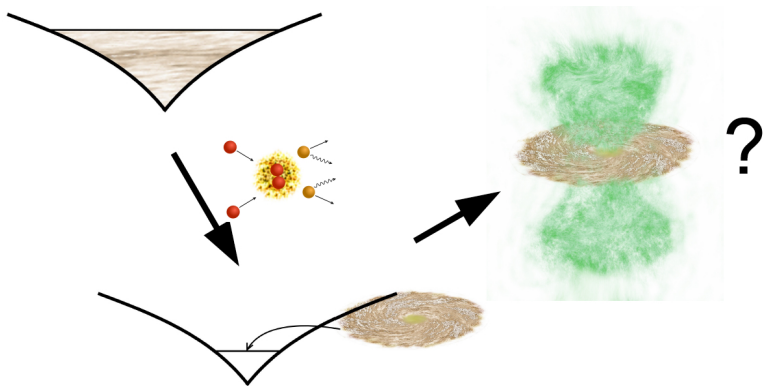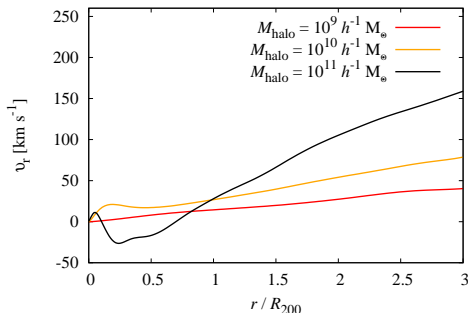

Uhlig, C.P., Sharma, Nath, Enßlin, Springel, *MNRAS* **423**, 2374 (2012)
Galactic winds driven by cosmic-ray streaming

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AGN feedback

Galactic winds and cosmic rays
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CR streaming drives winds

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

Wind velocity profile along the symmetry axis

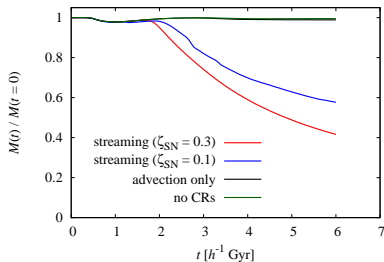- $10^9 - 10^{10}\,\mathrm{M_\odot}$: accelerating wind due to a continuous CR momentum and energy deposition during the ascent of the wind in the gravitational potential
  $\rightarrow$ different from traditional energy- or momentum-driven winds!

- $10^{11}\,\mathrm{M_\odot}$: wind stalls in halo and falls back onto the disk
  $\rightarrow$ fountain flow

Puzzles in galaxy formation
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Galactic winds and cosmic rays
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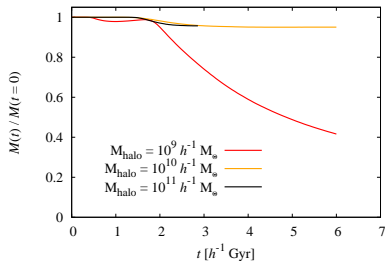Cosmic-ray heating

Gas mass loss within the virial radius
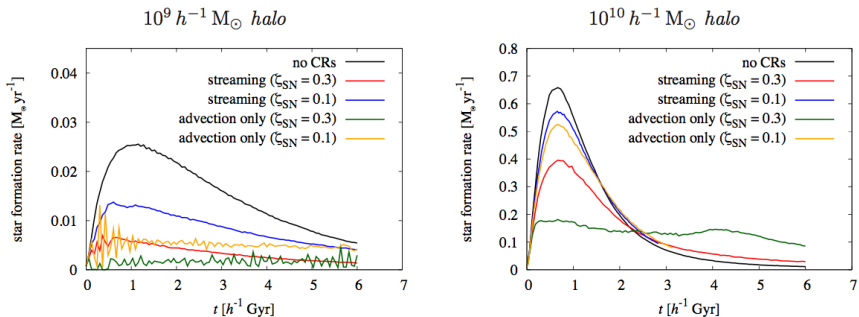
different scenarios:

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 ζ_{SN} *(left)* and toward smaller galaxy masses *(right)*

Puzzles in galaxy formation
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Galactic winds and cosmic rays
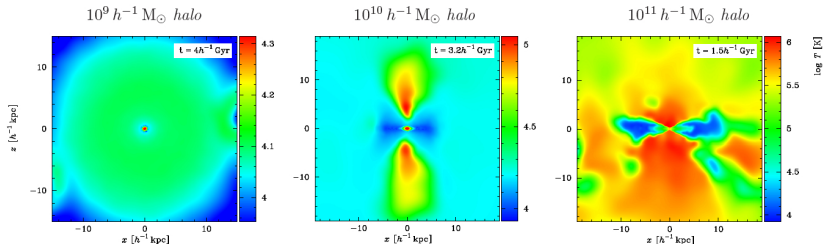**Mass loss and star formation**
Cosmic-ray heating

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

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Temperature structure due to CR heating

$10^9 \, h^{-1} \, \mathrm{M}_\odot \, halo$ $10^{10} \, h^{-1} \, \mathrm{M}_\odot \, halo$ $10^{11} \, h^{-1} \, \mathrm{M}_\odot \, halo$

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

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

- $10^{10} \to 10^{11} \, \mathrm{M}_\odot$: 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
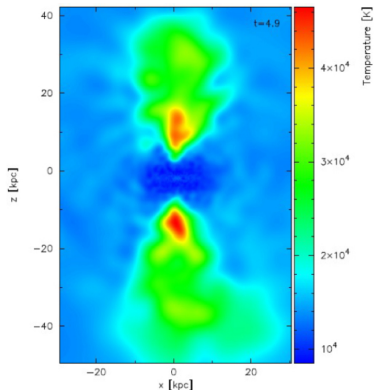
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Gas temperature: observation vs. simulation

M82 observation

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

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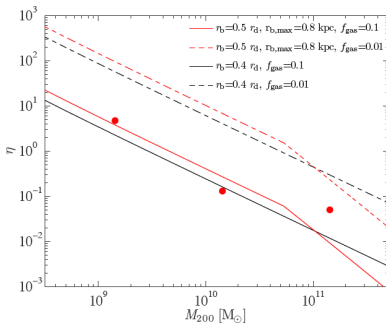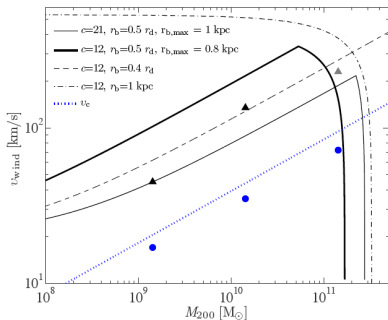
CR-driven winds: analytics versus simulations
Bernoulli theorem along streamlines: wind speeds and mass loading factors

- 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 $\eta = \dot{M}/$SFR decreases with galaxy mass

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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,
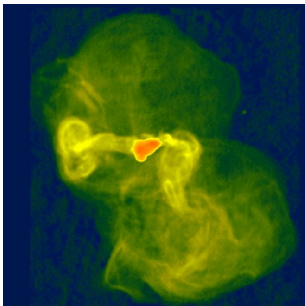cosmological settings, . . .

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

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Observations of M87
Cosmic-ray heating
Conclusions

"Radio-mode" AGN feedback

Puzzles in galaxy formation
Driving galactic winds
AGN feedback

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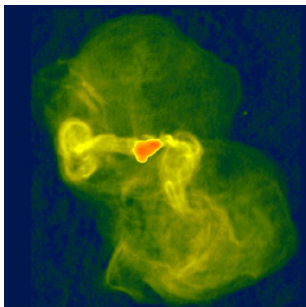
Messier 87 at radio wavelengths

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

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

Puzzles in galaxy formation
Driving galactic winds
AGN feedback

Observations of M87
Cosmic-ray heating
Conclusions

Messier 87 at radio wavelengths

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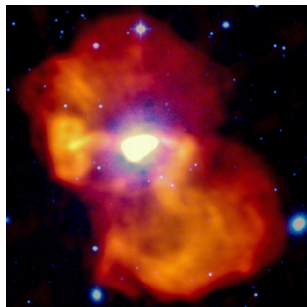
$\nu = 140$ MHz (LOFAR/de Gasperin+ 2012)

- 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"

Puzzles in galaxy formation
Driving galactic winds
AGN feedback

Observations of M87
Cosmic-ray heating
Conclusions

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)

Puzzles in galaxy formation
Driving galactic winds
AGN feedback

Observations of M87
Cosmic-ray heating
Conclusions

Solutions to the "missing fossil electrons" problem

solutions:

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

- 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:
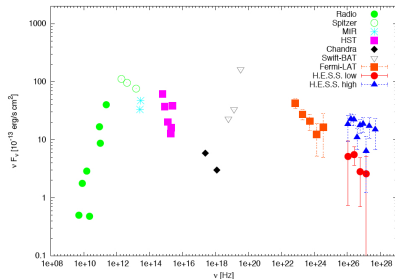 $p + p \rightarrow \pi^0 + \ldots \rightarrow 2\gamma + \ldots$

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Puzzles in galaxy formation
Driving galactic winds
AGN feedback

Observations of M87
Cosmic-ray heating
Conclusions
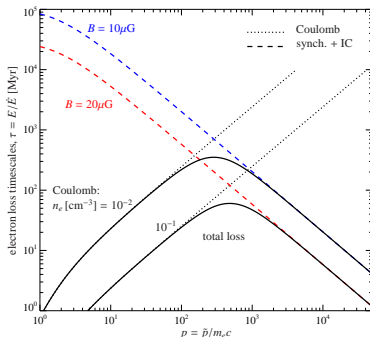
The gamma-ray picture of M87

- **high state** is time variable
  → 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)

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

Puzzles in galaxy formation
Driving galactic winds
AGN feedback

Observations of M87
Cosmic-ray heating
Conclusions

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: $P_{cr} \propto \rho^{\gamma_{cr}/2} \propto P_{th}$

- $F_\gamma \propto \int dV\, P_{cr} n$ enables to estimate $X_{cr} = P_{cr}/P_{th} = 0.31$ (allowing for Coulomb cooling with $\tau_{Coul} = 40\,\text{Myr}$)
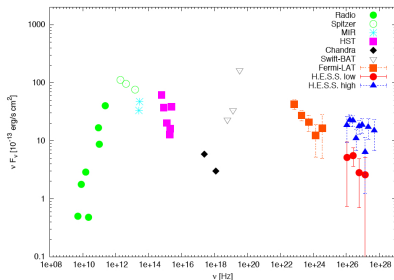
Rieger & Aharonian (2012)

$\rightarrow$ in agreement with non-thermal pressure constraints from dynamical potential estimates (Churazov+ 2010)

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Driving galactic winds
AGN feedback

Observations of M87
Cosmic-ray heating
Conclusions

Cosmic-ray heating vs. radiative cooling (1)

CR Alfvén-wave heating:

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

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

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

Puzzles in galaxy formation
Driving galactic winds
AGN feedback

Observations of M87
Cosmic-ray heating
Conclusions

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radiative cooling:

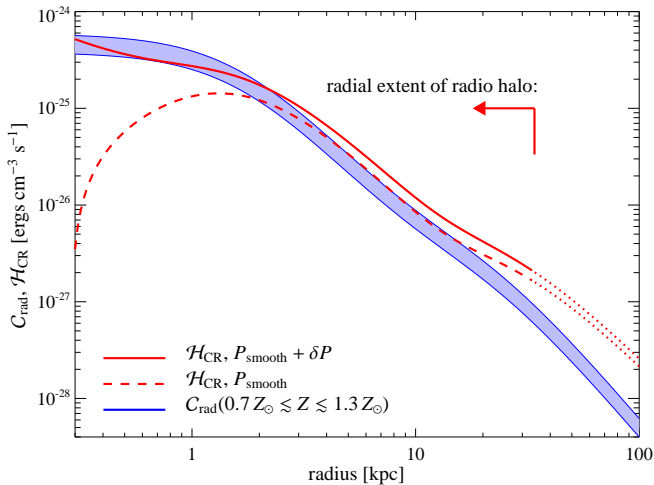$$\mathcal{C}_{rad} = n_e n_i \Lambda_{cool}(T, Z)$$

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

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Driving galactic winds
AGN feedback

Observations of M87
Cosmic-ray heating
Conclusions

Cosmic-ray heating vs. radiative cooling (2)
Global thermal equilibrium on all scales in M87

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

Cosmic-ray heating vs. radiative cooling (3)

is this global thermal equilibrium a coincidence in Virgo?

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

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

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

Puzzles in galaxy formation
Driving galactic winds
AGN feedback

Observations of M87
Cosmic-ray heating
Conclusions

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$$
\begin{aligned}
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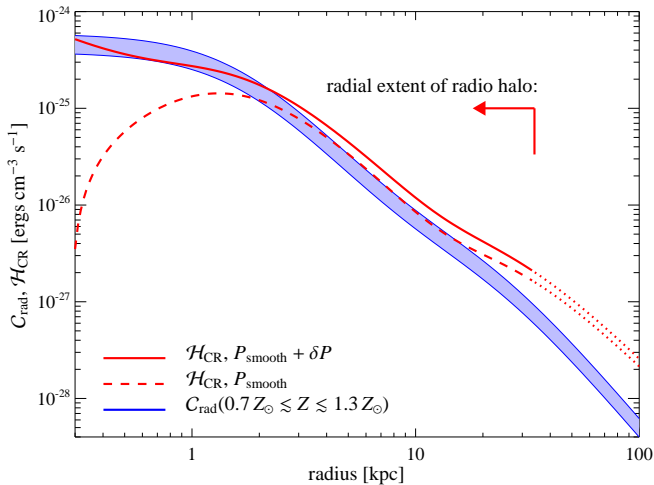\mathcal{C}_{rad} &\propto n^2 \propto r^{-2}
\end{aligned}
$$

(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

Puzzles in galaxy formation
Driving galactic winds
AGN feedback

Observations of M87
Cosmic-ray heating
Conclusions

Cosmic-ray heating vs. radiative cooling
Global thermal equilibrium on all scales in M87
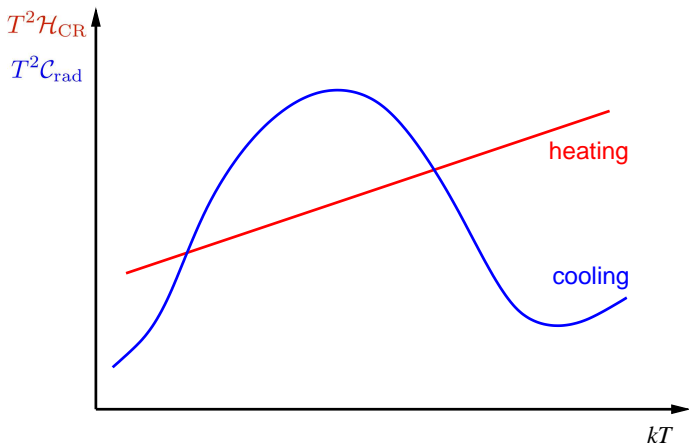
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Driving galactic winds
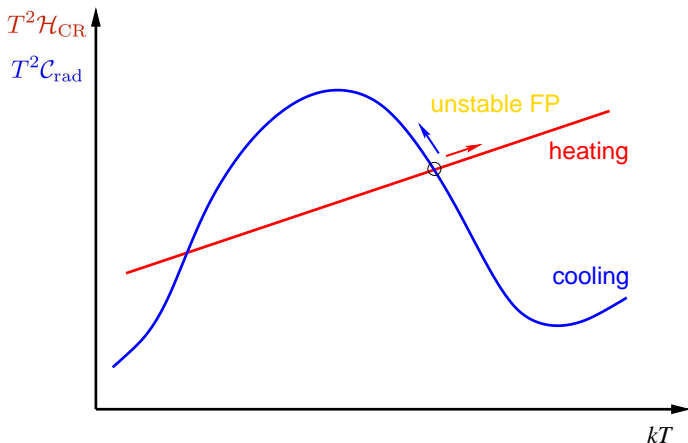AGN feedback

Observations of M87
Cosmic-ray heating
Conclusions

Local stability analysis (1)

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

Puzzles in galaxy formation
Driving galactic winds
AGN feedback

Observations of M87
Cosmic-ray heating
Conclusions

Local stability analysis (1)

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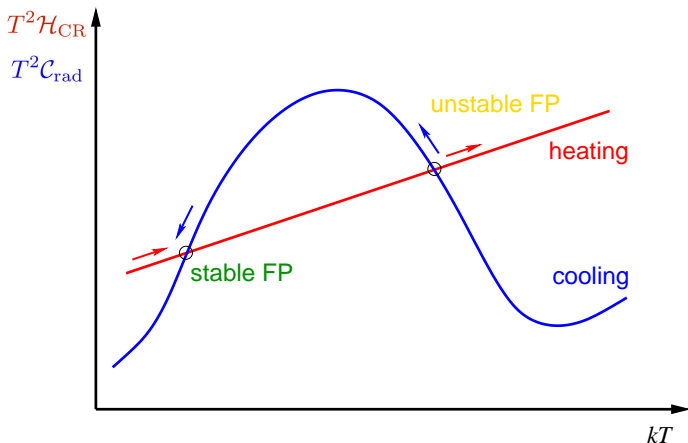Puzzles in galaxy formation
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AGN feedback

Observations of M87
Cosmic-ray heating
Conclusions

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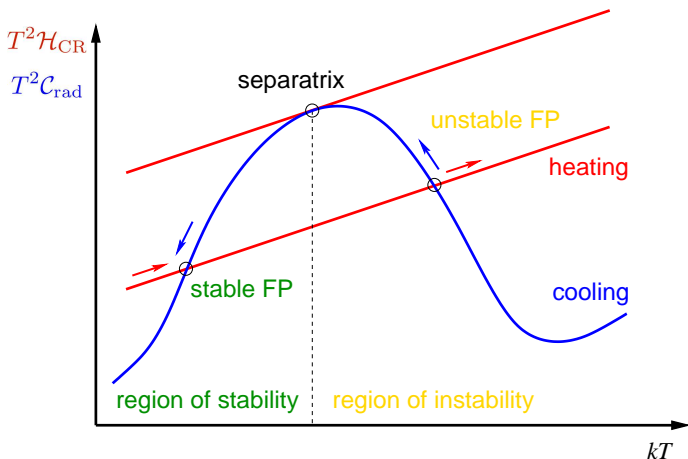Puzzles in galaxy formation
Driving galactic winds
AGN feedback

Observations of M87
Cosmic-ray heating
Conclusions

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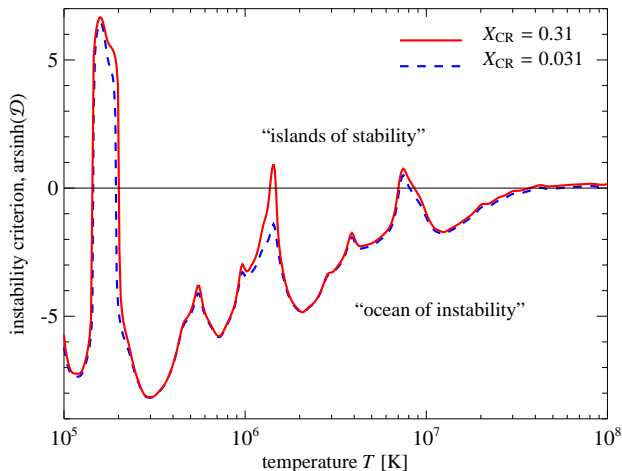- CRs are adiabatically trapped by perturbations

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Driving galactic winds
AGN feedback

Observations of M87
Cosmic-ray heating
Conclusions

Local stability analysis (2)
Theory predicts observed temperature floor at $kT \simeq 1$ keV

C.P. (2013)

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Driving galactic winds
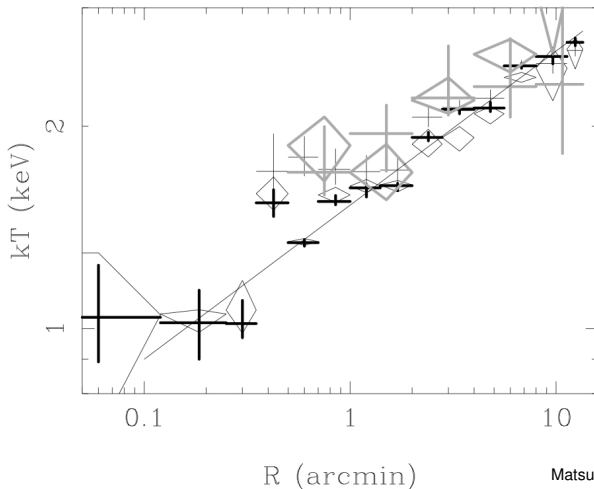**AGN feedback**

Observations of M87
Cosmic-ray heating
Conclusions

Virgo cluster cooling flow: temperature profile
X-ray observations confirm temperature floor at $kT \simeq 1$ keV

Matsushita+ (2002)

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Driving galactic winds
AGN feedback

Observations of M87
Cosmic-ray heating
Conclusions

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

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

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

where f_s is the magnetic suppression factor

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

Puzzles in galaxy formation
Driving galactic winds
AGN feedback

Observations of M87
Cosmic-ray heating
Conclusions

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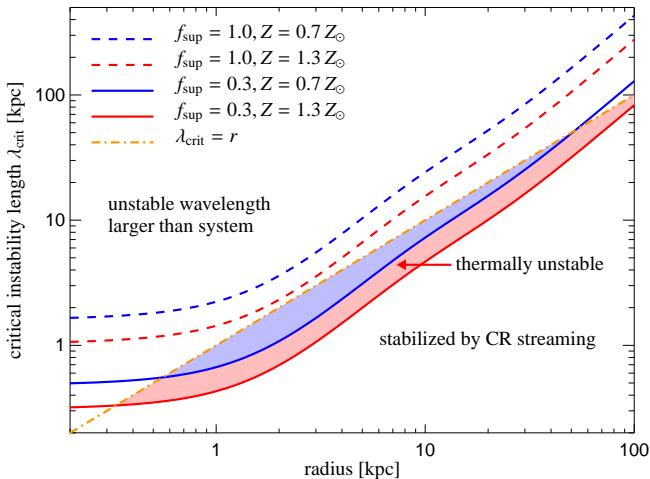 where f_s is the magnetic suppression factor

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

- limiting size of unstable gas parcel since CR Alfvén-wave heating smoothes out temperature inhomogeneities on small scales:

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

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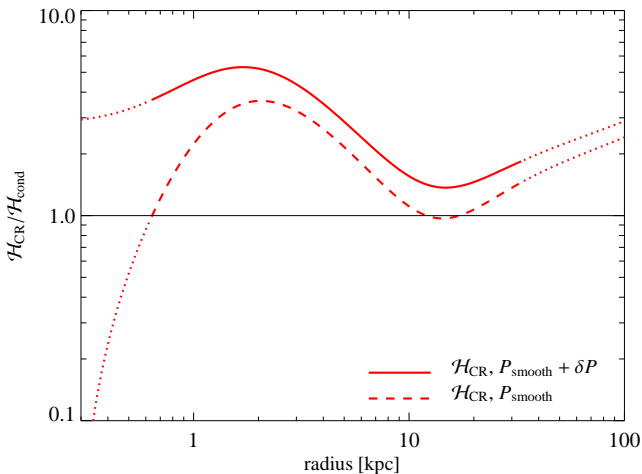 $\rightarrow$ constraint on magnetic suppression factor f_s

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Puzzles in galaxy formation
Driving galactic winds
AGN feedback

Observations of M87
Cosmic-ray heating
Conclusions

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

Puzzles in galaxy formation
Driving galactic winds
AGN feedback

Observations of M87
Cosmic-ray heating
Conclusions

CR heating dominates over thermal conduction

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Driving galactic winds
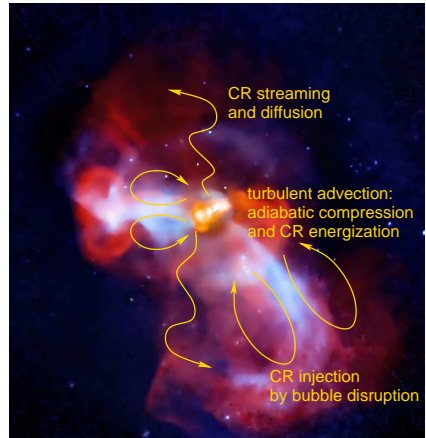AGN feedback

Observations of M87
Cosmic-ray heating
Conclusions

Emerging picture of CR feedback by AGNs

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

Puzzles in galaxy formation
Driving galactic winds
AGN feedback

Observations of M87
Cosmic-ray heating
Conclusions

Emerging picture of CR feedback by AGNs

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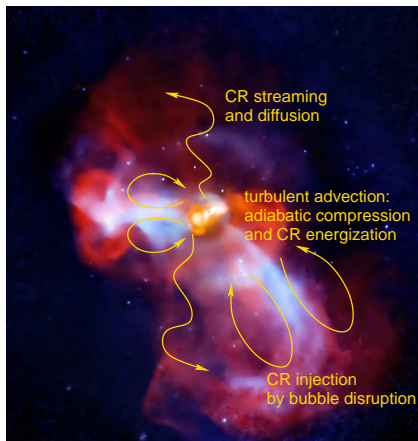→ CR Alfvén-wave heating

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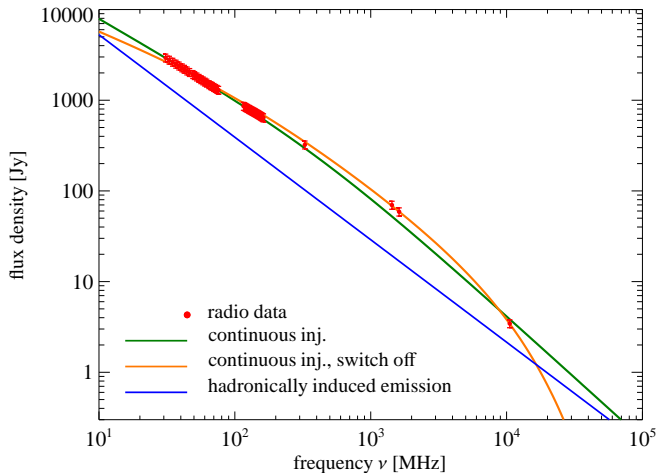→ CR advection with flux-frozen field
→ adiabatic CR compression and energizing: $P_{cr}/P_{cr,0} = \delta^{4/3} \sim 20$ for compression factor $\delta = 10$

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

CR streaming
and diffusion

turbulent advection:
adiabatic compression
and CR energization

CR injection
by bubble disruption

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Driving galactic winds
AGN feedback

Observations of M87
Cosmic-ray heating
Conclusions

Prediction: flattening of high-ν radio spectrum

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Puzzles in galaxy formation
Driving galactic winds
AGN feedback

Observations of M87
Cosmic-ray heating
Conclusions

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 $X_{cr} = 0.31$

- 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 . . .

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Driving galactic winds
AGN feedback

Observations of M87
Cosmic-ray heating
Conclusions

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.

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Driving galactic winds
AGN feedback

Observations of M87
Cosmic-ray heating
Conclusions

Additional slides

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AGN feedback

Observations of M87
Cosmic-ray heating
Conclusions

Self-consistent CR pressure in steady state

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

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

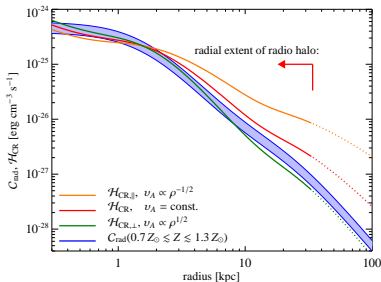where $\tau_A = \delta l / v_A$ is the Alfvén crossing time and δl the CR pressure gradient length

- 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!**

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Driving galactic winds
AGN feedback

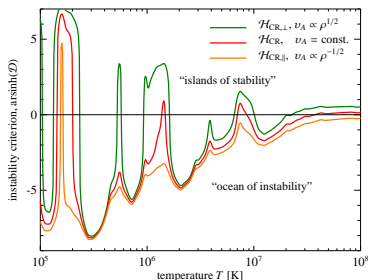Observations of M87
Cosmic-ray heating
Conclusions

Impact of varying Alfvén speed on CR heating

global thermal equilibrium:
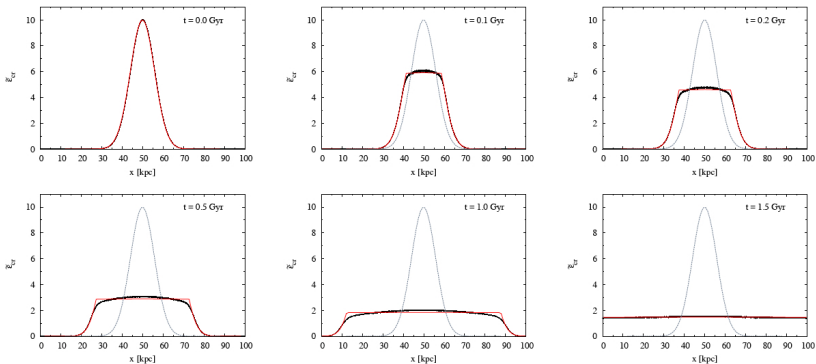

local stability criterion:

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

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Driving galactic winds | Cosmic-ray heating
AGN feedback | Conclusions

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)

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AGN feedback

Observations of M87
Cosmic-ray heating
Conclusions

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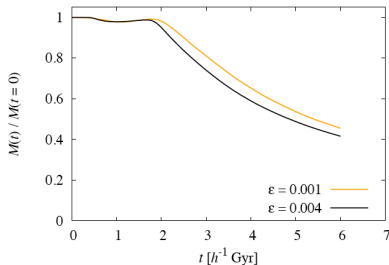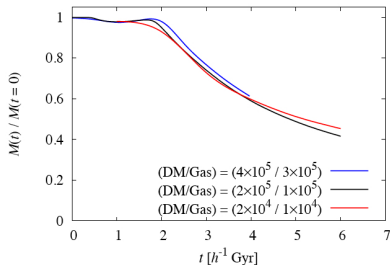
- our results winds driven by CR streaming are converged with respect to particle resolution *(left)* and time step of the explicit streaming solver *(right)*