Cosmic rays in galaxy formation: a solution to the faint and bright-end of the population?

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in collaboration with

Max Uhlig, Mahavir Sharma, Biman Nath, Torsten Enßlin, Volker Springel
(cosmic ray-driven winds)

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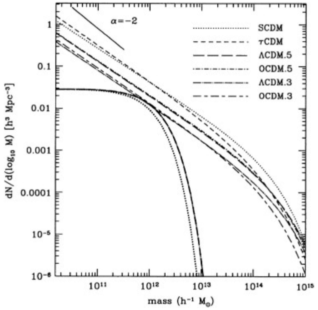
Outline

Puzzles in galaxy formation

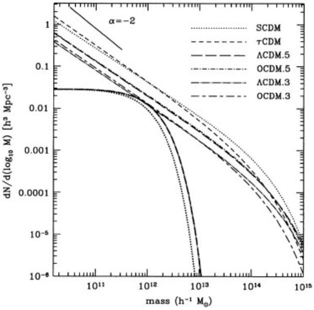


Somerville+1999

Puzzles in galaxy formation

Bright-end of luminosity function:

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



Somerville+1999

Puzzles in galaxy formation

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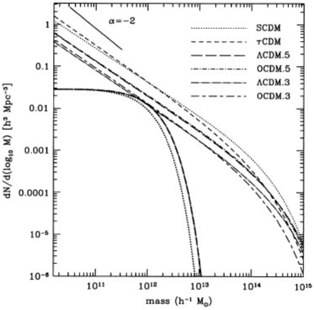
Faint-end of luminosity function:

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



Somerville+1999

Puzzles in galaxy formation

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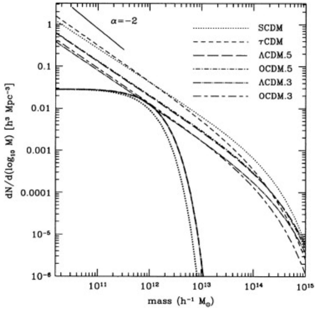
- astrophysical solutions:
  AGN/quasar feedback, . . .

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 → **galactic winds**

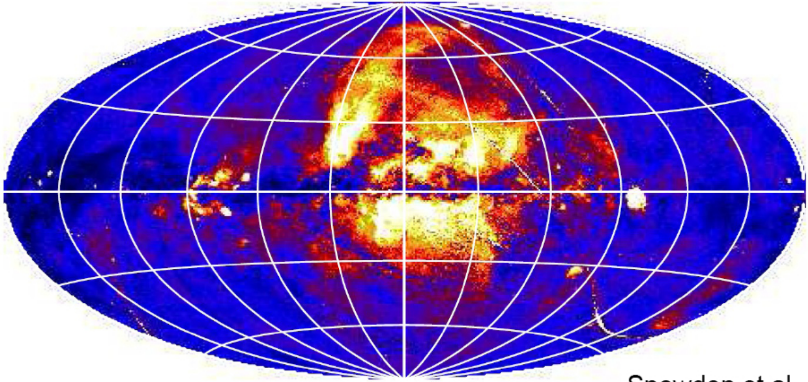


Somerville+1999

Galactic super wind in M82

Galactic wind in the Milky Way?

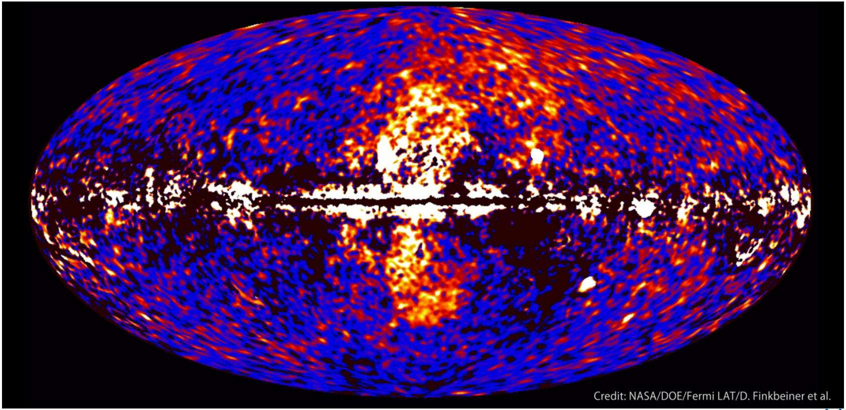
Diffuse X-ray emission in our galaxy



Snowden et al., 2007

Galactic wind in the Milky Way?

Fermi gamma-ray bubbles

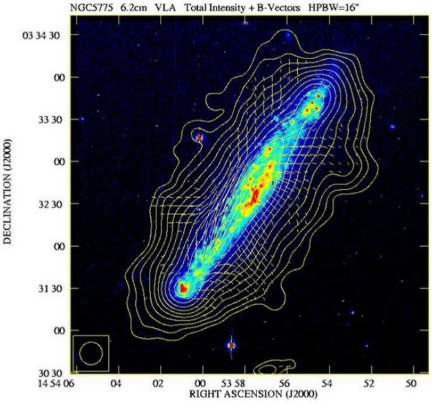


How to drive a wind?

- 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 dust grains
  - cosmic rays (CRs, relativistic protons with $\gamma_{\text{ad}} = 4/3$): promising idea since observationally $\varepsilon_{\text{CR}} \simeq \varepsilon_{\text{th}} \simeq \varepsilon_B$

Radio halos in edge-on disk galaxies

CRs and magnetic fields exist at the disk-halo interface → wind launching site?



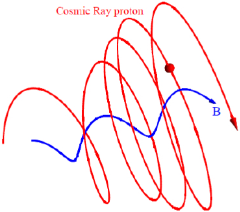
Tüllmann+ (2000)

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

Interactions of CRs and magnetic fields

- CRs scatter on magnetic fields → isotropization of CR momenta
- **CR streaming instability:** Kulsrud & Pearce 1969
  - if $v_{\rm cr} > v_{\rm waves}$ with respect to the gas, CR excite Alfvén waves
  - scattering off this wave field limits the CRs' bulk speed $\ll c$
  - wave damping: transfer of CR energy and momentum to the thermal gas



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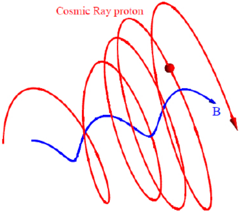
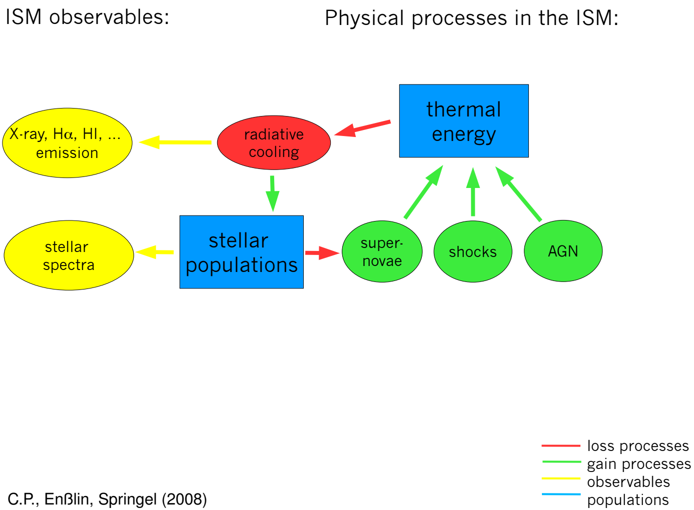


$\rightarrow$ **CRs exert a pressure on the thermal gas by means of scattering off Alfvén waves**

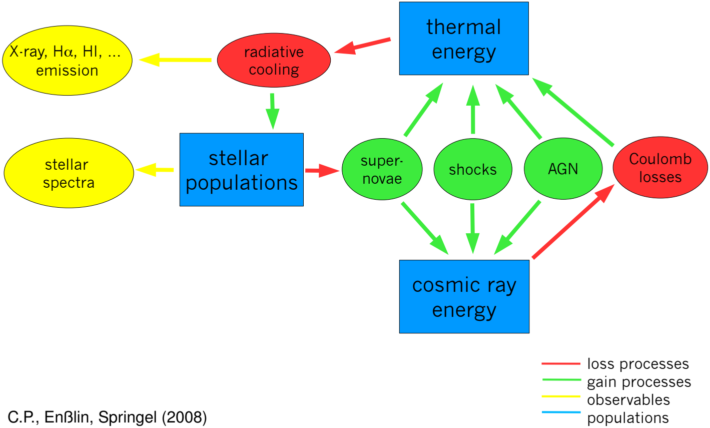
Interstellar medium (ISM) simulations – flowchart



C.P., Enßlin, Springel (2008)

ISM simulations with cosmic ray physics

ISM observables: Physical processes in the ISM:



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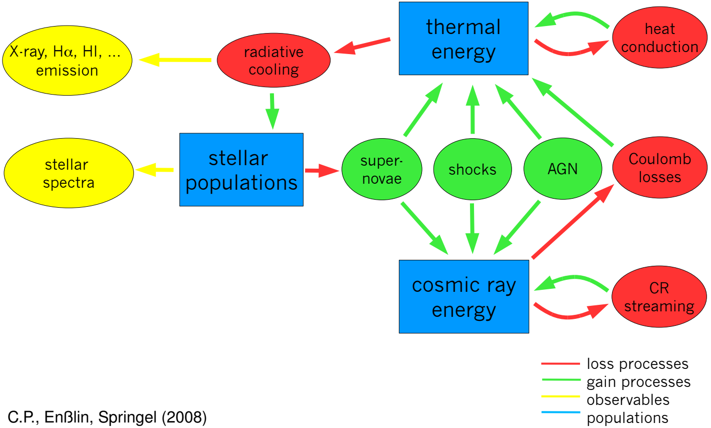

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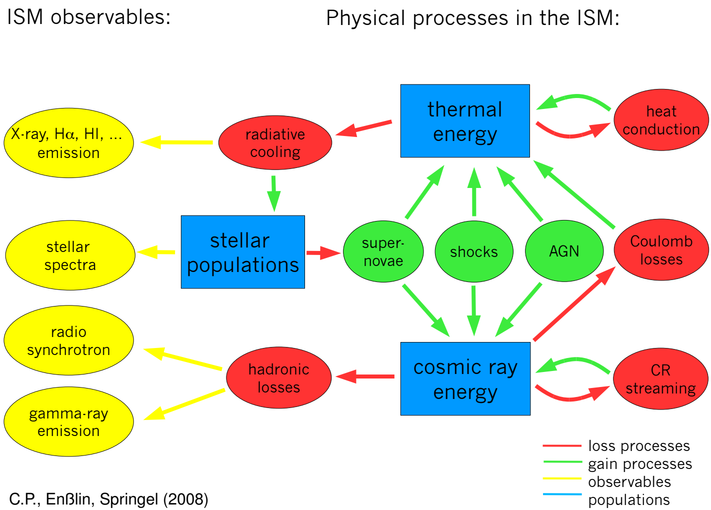
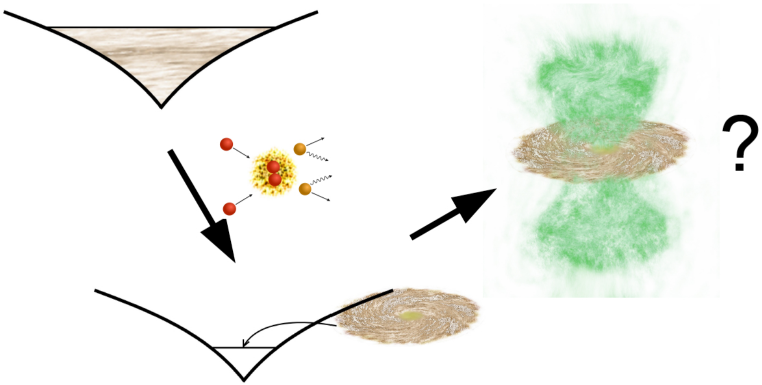


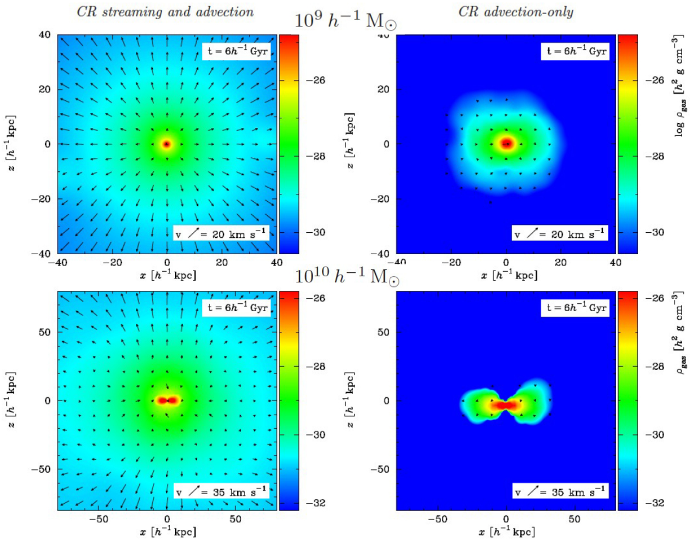
C.P., Enßlin, Springel (2008)

Simulation setup

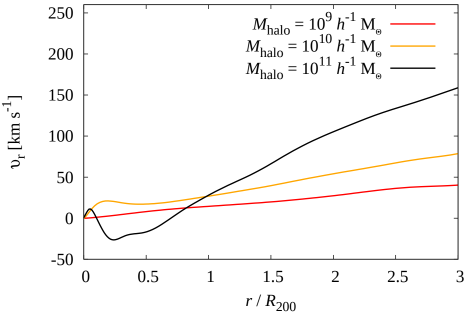


Uhlig, C.P., Sharma, Nath, Enßlin, Springel, *MNRAS* **423**, 2374 (2012)
Galactic winds driven by cosmic-ray streaming

CR streaming drives winds

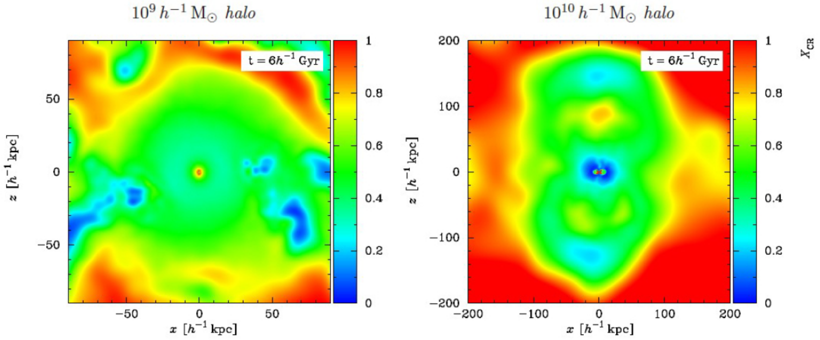


Wind velocity profile along the symmetry axis



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

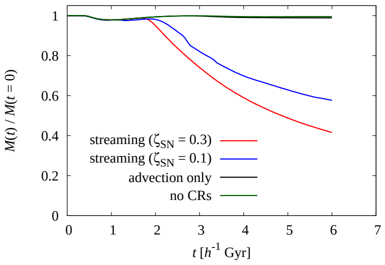
CR-to-thermal pressure in edge-on slice



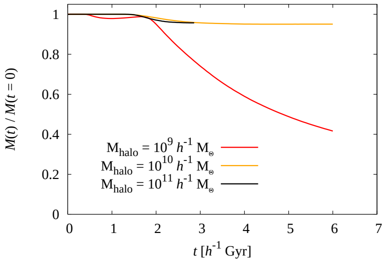
- $X_{cr} = P_{cr}/P_{th} < 50\%$ in vicinity of center because of loss processes that effectively transfer CR into thermal energy
- X_{cr} becomes dominant at larger heights due to the softer adiabatic index of CRs

Gas mass loss within the virial radius

different scenarios:

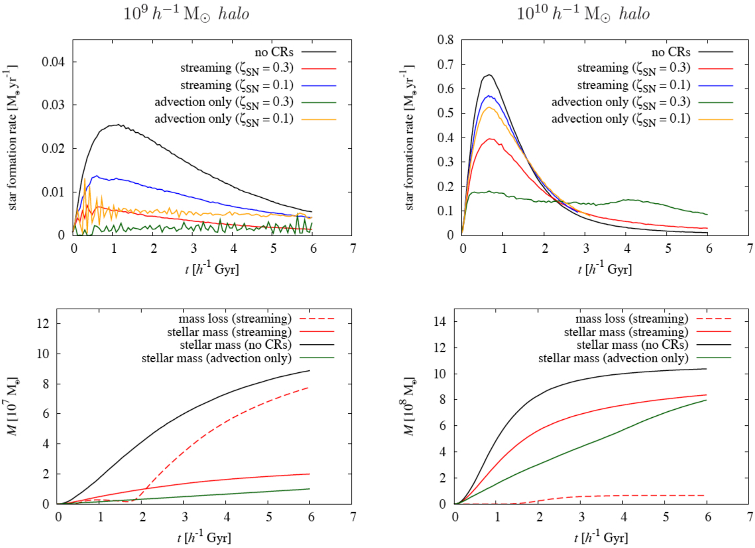


different galaxy masses:



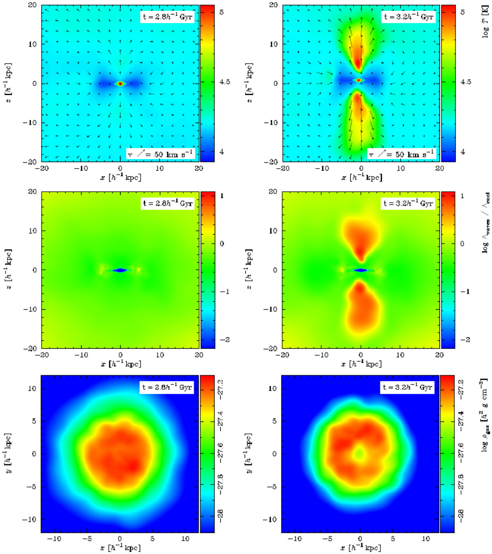
- after initial phase ($\sim$ 2.5 Gyr), only winds driven by CR streaming overcome the ram pressure of infalling gas and expel gas from the halo
- mass loss rate increases with CR injection efficiency ζ_{SN} *(left)* and toward smaller galaxy masses *(right)*

Mass loss and star formation histories

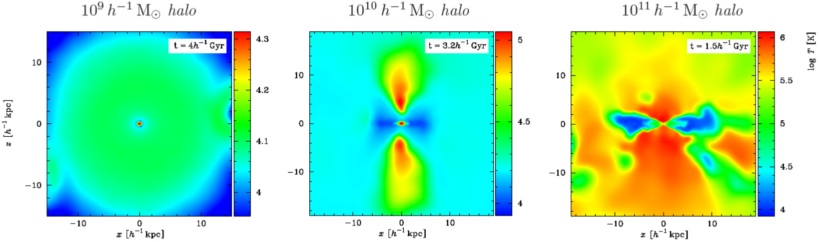


Heating of the halo gas by wave damping

$10^{10}\, h^{-1} M_\odot$:



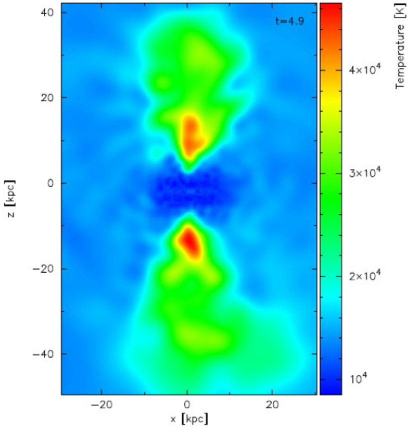
Temperature structure



- 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: simulation ($10^{10}\,M_\odot$) vs. observation

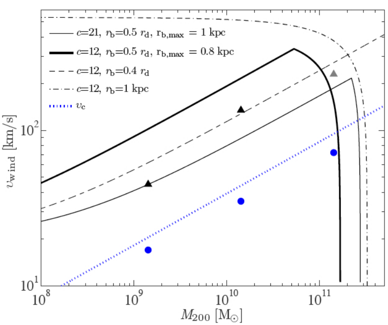
t = 4.9 Gyr, streaming

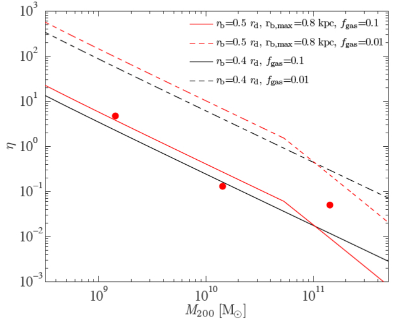


M82

CR-driven winds: analytics versus simulations

Wind speeds and mass loading factors





- winds speeds increase with galaxy mass as $v_{\rm wind} \propto v_{\rm circ} \propto M_{200}^{1/3}$ 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

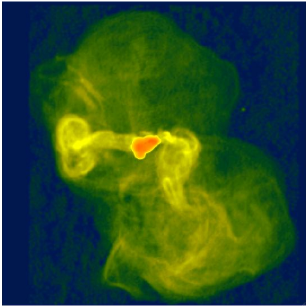
- galactic winds are naturally explained by CR streaming (energy source, known plasma physics, observed scaling relations)
- CR streaming heating can explain observed hot wind regions above disks
- substantial mass losses of low mass galaxies
  $\rightarrow$ opportunity for understanding the physics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

outlook: MHD simulations, better understanding of plasma physics, cosmological settings, ...

$\rightarrow$ recent work: Salem & Bryan (2013), Booth et al. (2013), Hanasz et al. (2013)

"Radio-mode" AGN feedback

Messier 87 at radio wavelengths



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

- expectation: low frequencies sensitive to fossil electrons ($E \sim 100$ MeV) $\rightarrow$ time-integrated activity of AGN feedback!

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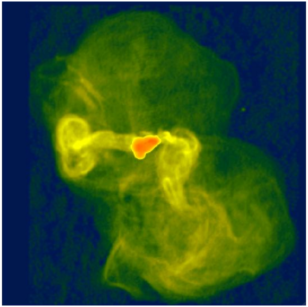

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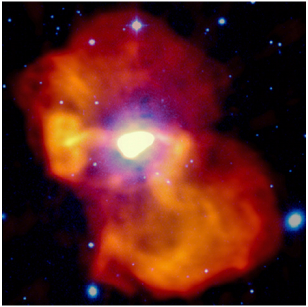

$\nu = 140$ MHz (LOFAR/de Gasperin+ 2012)

- expectation: low frequencies sensitive to fossil electrons ($E \sim 100$ MeV) $\rightarrow$ time-integrated activity of 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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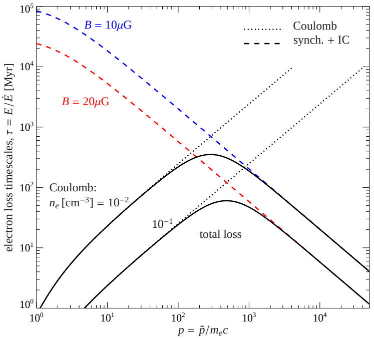
- special time: M87 turned on $\sim$ 40 Myr ago after long silence
  $\Leftrightarrow$ conflicts order unity duty cycle inferred from stat. AGN feedback studies (Birzan+ 2012)
- Coulomb cooling removes fossil electrons
  $\rightarrow$ efficient mixing of CR electrons and protons with dense cluster gas
  $\rightarrow$ predicts γ rays from CRp-p interactions:
  $p + p \rightarrow \pi^0 + \ldots \rightarrow 2\gamma + \ldots$



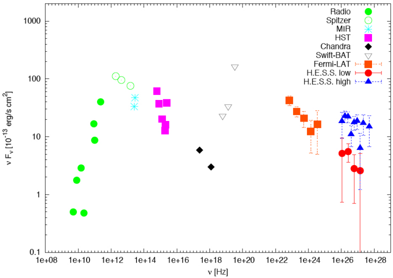
C.P. (2013)

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 (?)

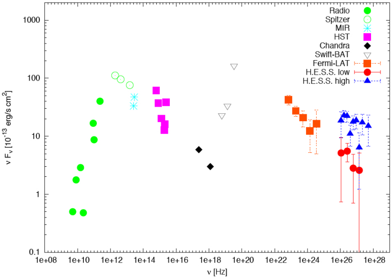


Rieger & Aharonian (2012)

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

Estimating the CR pressure in M87

- X-ray data → n and T profiles
- assume $X_{\rm cr} = P_{\rm cr}/P_{\rm th}$ (self-consistency requirement)
- $F_\gamma \propto \int \mathrm{d}V\, P_{\rm cr} n$ enables to estimate $X_{\rm cr} = 0.31$ (allowing for Coulomb cooling with $\tau_{\rm Coul} = 40\,\mathrm{Myr}$)



Rieger & Aharonian (2012)

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

Cosmic-ray heating vs. radiative cooling (1)

CR Alfvén-wave heating:

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

- Alfvén velocity $v_A = B/\sqrt{4\pi\rho}$ with $B \sim B_{\rm eq}$ from LOFAR and ρ from X-ray data
- $X_{\rm cr}$ calibrated to 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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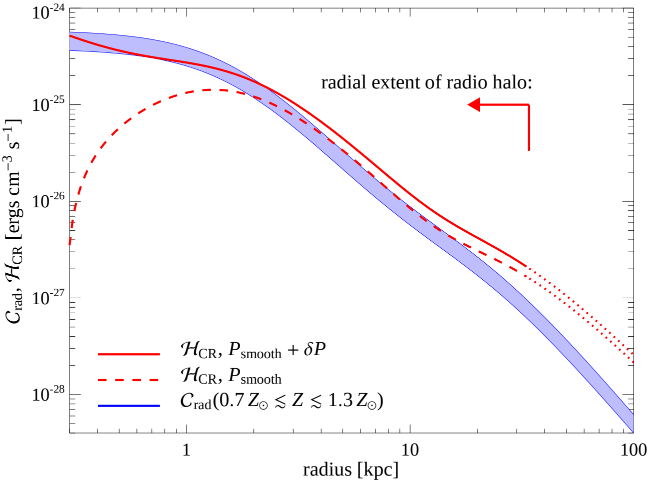
radiative cooling:

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

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

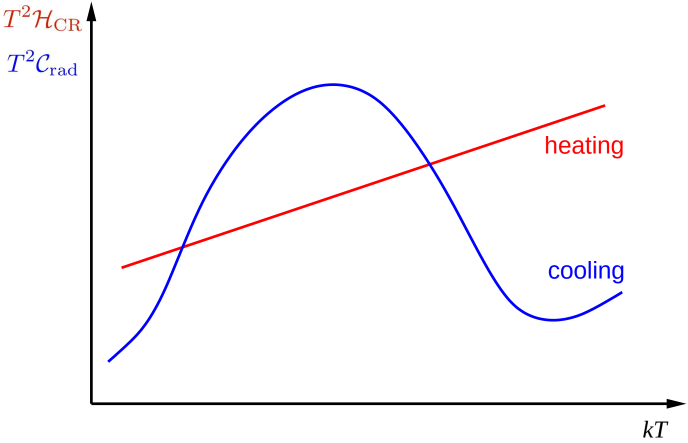
Cosmic-ray heating vs. radiative cooling (2)

Global thermal equilibrium on all scales in M87



C.P. (2013)

Local stability analysis (1)



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

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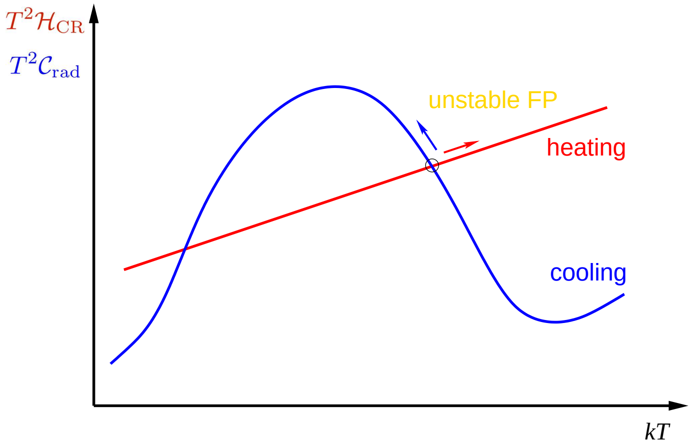

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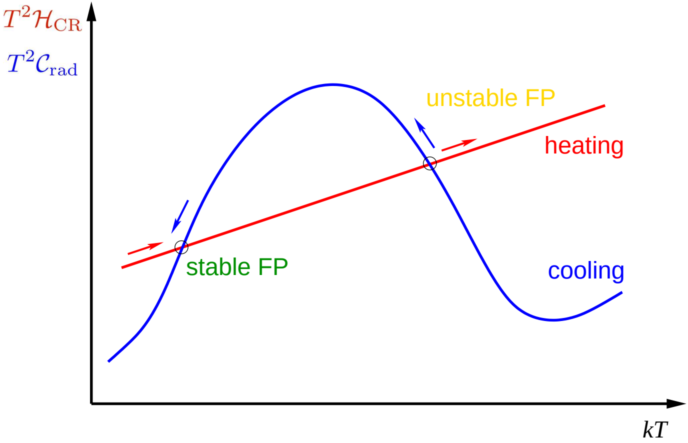

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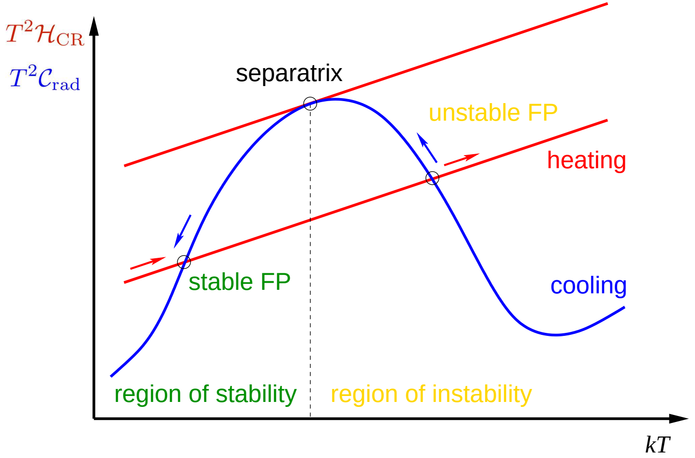

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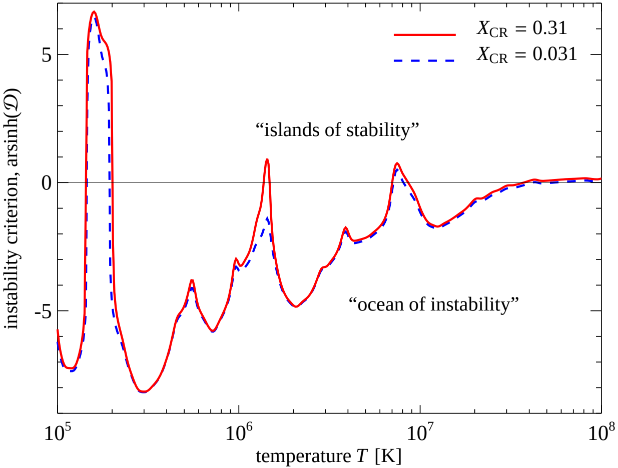
Local stability analysis (2)

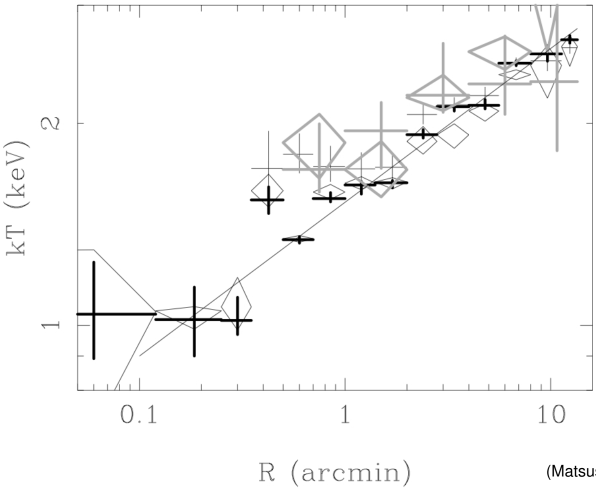
Theory predicts observed temperature floor at $kT \simeq 1$ keV



C.P. (2013)

Virgo cluster cooling flow: temperature profile

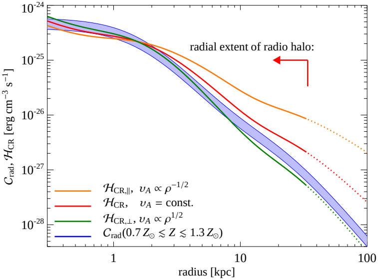
X-ray observations confirm temperature floor at $kT \simeq 1$ keV



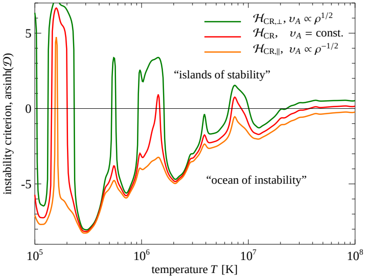
(Matsushita+ 2002)

Impact of varying Alfvén speed on CR heating

global thermal equilibrium:



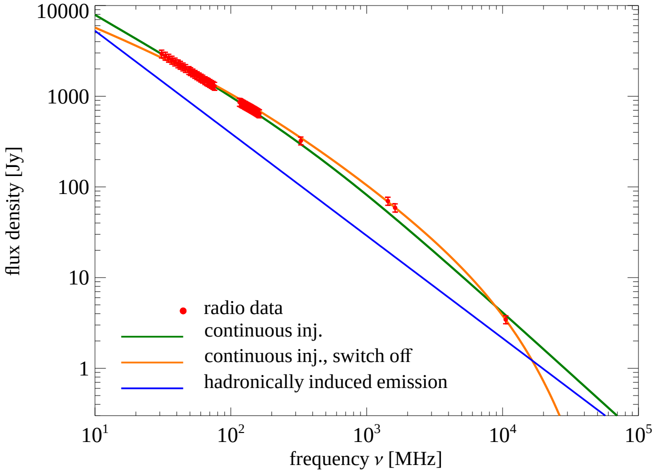
local stability criterion:



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 $\boldsymbol{B}$, implying $v_{A,\parallel} \propto \rho^{-1/2}$
- $\alpha_B = 1$ for collapse perpendicular to $\boldsymbol{B}$, implying $v_{A,\perp} \propto \rho^{1/2}$

Prediction: flattening of high-ν radio spectrum



C.P. (2013)

Conclusions on AGN feedback by cosmic-ray heating

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

outlook: simulate steaming CRs coupled to MHD, cosmological cluster simulations, ...

Literature for the talk

Cosmic ray-driven winds in galaxies:

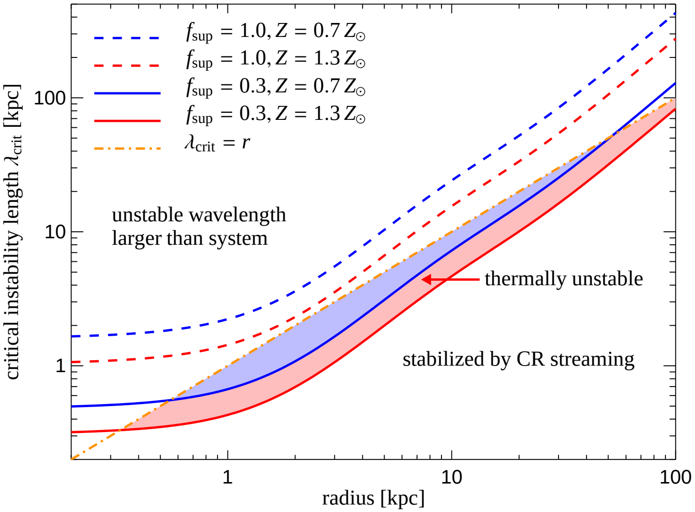
- Uhlig, Pfrommer, Sharma, Nath, Enßlin, Springel, *Galactic winds driven by cosmic-ray streaming*, 2012, MNRAS, 423, 2374.

AGN feedback by cosmic rays:

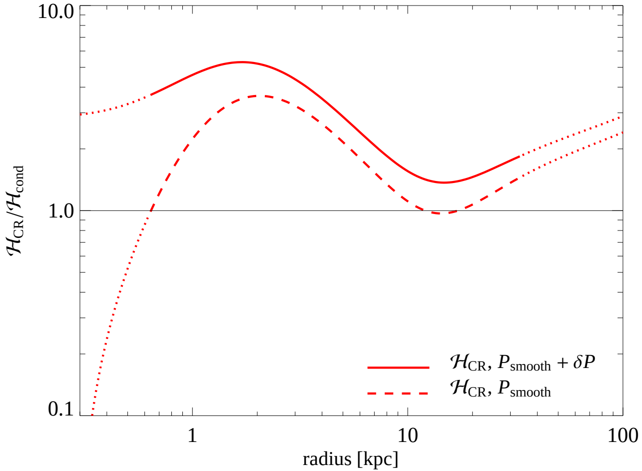
- Pfrommer, *Toward a comprehensive model for feedback by active galactic nuclei: new insights from M87 observations by LOFAR, Fermi and H.E.S.S.*, 2013, ApJ, 779, 10.

Additional slides

Critical length scale of the instability



CR heating dominates over thermal conduction



C.P. (2013)

CR streaming (1)

- total CR velocity $\boldsymbol{v}_{\rm cr} = \boldsymbol{v}_{\rm gas} + \boldsymbol{v}_{\rm st}$
- CRs stream down their own pressure gradient relative to the gas:

$$\boldsymbol{v}_{\rm st} = -\lambda\, c_{\rm s}\, \frac{\nabla P_{\rm cr}}{|\nabla P_{\rm cr}|},$$

- CR transport equation → evolution equation for CR number and energy density:

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

CR streaming (2)

- Lagrangian time derivative

$$\frac{\mathrm{d}}{\mathrm{d}t} = \frac{\partial}{\partial t} + \boldsymbol{v}_{\mathrm{gas}} \cdot \nabla$$

- specific CR energy, $\tilde{\varepsilon}_{\mathrm{cr}}$, and CR particle number, $\tilde{n}_{\mathrm{cr}}$,

$$\varepsilon_{\mathrm{cr}} = \tilde{\varepsilon}_{\mathrm{cr}}\rho \qquad \text{and} \qquad n_{\mathrm{cr}} = \tilde{n}_{\mathrm{cr}}\rho$$

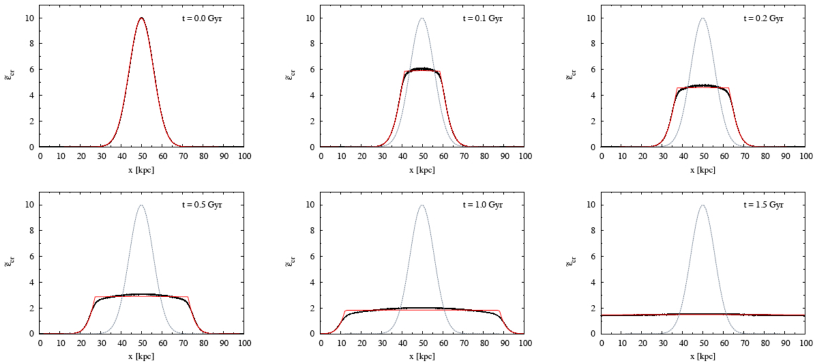
- CR evolution equations:

$$\rho\frac{\mathrm{d}\tilde{n}_{\mathrm{cr}}}{\mathrm{d}t} = -\nabla \cdot [\boldsymbol{v}_{\mathrm{st}}\,\rho\,\tilde{n}_{\mathrm{cr}}]$$

$$\rho\frac{\mathrm{d}\tilde{\varepsilon}_{\mathrm{cr}}}{\mathrm{d}t} = \underbrace{\boldsymbol{v}_{\mathrm{st}} \cdot \nabla P_{\mathrm{cr}}}_{\substack{\text{energy loss term}\\ \text{(wave damping)}}} - \underbrace{P_{\mathrm{cr}}\nabla \cdot \boldsymbol{v}_{\mathrm{gas}}}_{\substack{\text{adiabatic changes}\\ \text{due to converging/}\\ \text{diverging gas flow}}} - \underbrace{\nabla \cdot [\boldsymbol{v}_{\mathrm{st}}\,(\rho\tilde{\varepsilon}_{\mathrm{cr}} + P_{\mathrm{cr}})]}_{\substack{\text{energy change due to}\\ \text{CR streaming in/out}\\ \text{of a volume element}}}$$

Test: Gadget-2 versus 1-d grid solver

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



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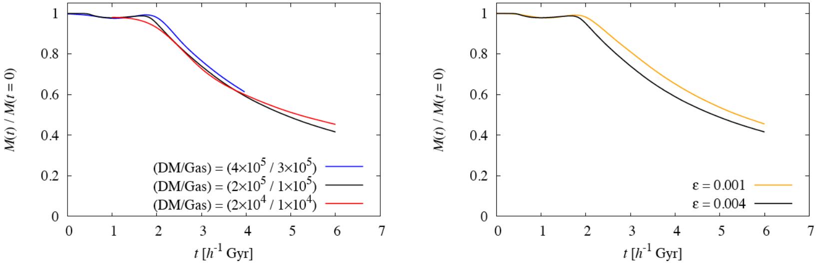
Resolution study



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