How cosmic rays shape the faint- and bright-end of the galaxy 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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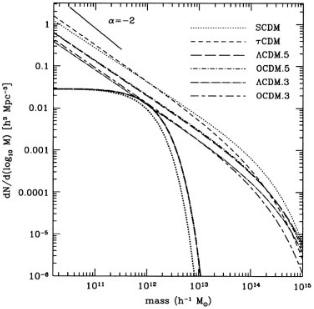
Outline

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

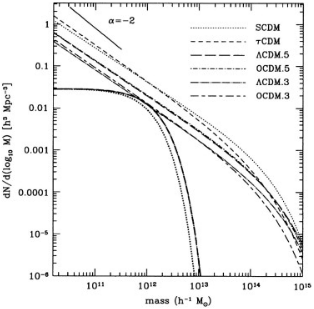


Somerville+1999

Puzzles in galaxy formation

Bright-end of luminosity function:

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



Somerville+1999

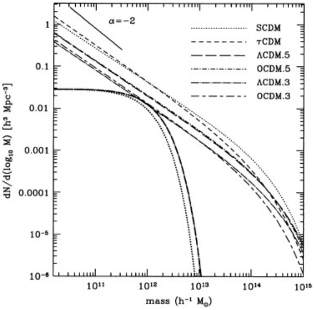
Puzzles in galaxy formation

Bright-end of luminosity function:

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

Faint-end of luminosity function:

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



Somerville+1999

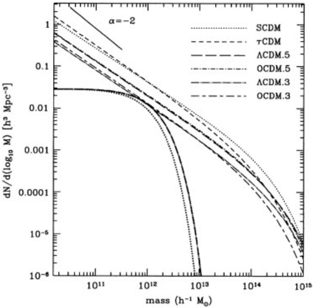
Puzzles in galaxy formation

Bright-end of luminosity function:

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

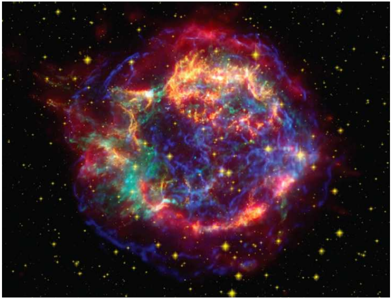
Faint-end of luminosity function:

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



Somerville+1999

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, amplify magnetic fields

Galactic winds

super wind in M82

NASA/JPL-Caltech/STScI/CXC/UofA

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

Galactic winds

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NASA/JPL-Caltech/STScI/CXC/UofA

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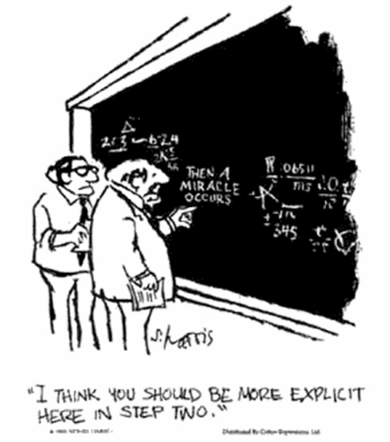
- star formation and supernovae drive gas out of galaxies by galactic super winds
- critical for understanding the physics of galaxy formation $\rightarrow$ explains puzzle of low star conversion efficiency in dwarf galaxies

Galactic winds



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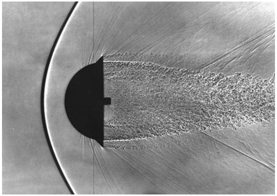
Shock waves

shock waves: sudden change in density, temperature, and pressure that decelerates supersonic flow.



thickness $\sim$ mean free path $\lambda_{\rm mfp}$

in air, $\lambda_{\rm mfp} \sim \mu$m,
on Earth, most shocks are mediated by collisions.

slide concept Spitkovsky

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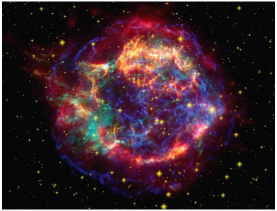
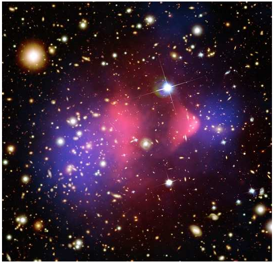




clusters/galaxies, Coulomb collisions set $\lambda_{\rm mfp}$:

$\lambda_{\rm mfp} \sim L_{\rm cluster}/10, \qquad \lambda_{\rm mfp} \sim L_{\rm SNR}$

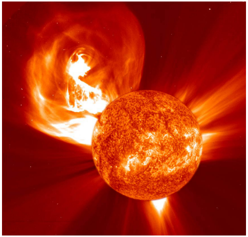
Mean free path $\gg$ observed shock width!

$\rightarrow$ shocks must be mediated without collisions, but through interactions with collective fields

$\rightarrow$ collisionless shocks

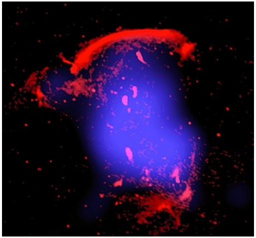
slide concept Spitkovsky

Astrophysical shocks



solar system shocks $\sim R_\odot$
coronal mass ejection (SOHO)

interstellar shocks $\sim$ 20 pc
supernova 1006 (CXC/Hughes)

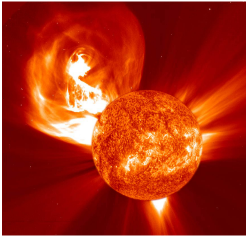


cluster shocks $\sim$ 2 Mpc
giant radio relic (van Weeren)

Astrophysical shocks

astrophysical collisionless shocks can:

- accelerate particles (electrons and ions) $\rightarrow$ cosmic rays (CRs)
- amplify magnetic fields (or generate them from scratch)
- exchange energy between electrons and ions



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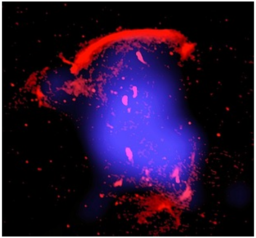

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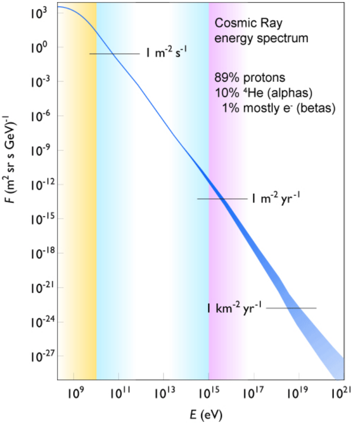
Galactic cosmic ray spectrum



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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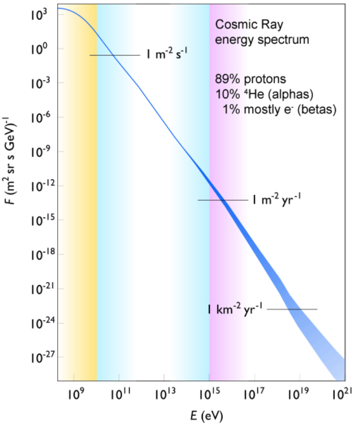

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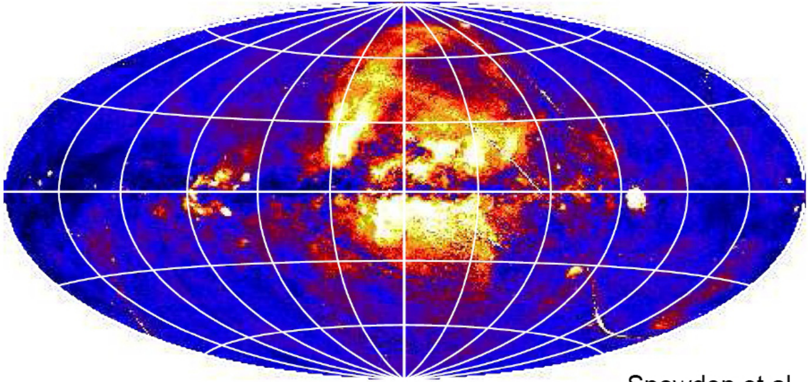
- spans more than 33 decades in flux and 12 decades in energy
- "knee" indicates characteristic maximum energy of galactic accelerators
- CRs beyond the "ankle" have extra-galactic origin
- energy density of cosmic rays, magnetic fields, and turbulence in the interstellar gas all similar:

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

Galactic wind in the Milky Way?

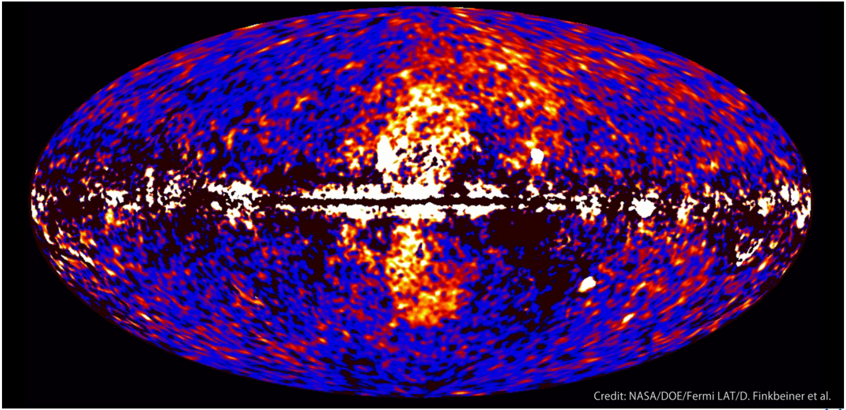
Diffuse X-ray emission in our galaxy



Snowden et al., 2007

Galactic wind in the Milky Way?

Fermi gamma-ray bubbles

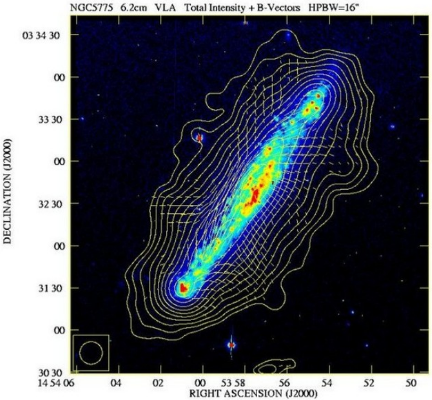


How to drive a wind?

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

Radio halos in edge-on disk galaxies

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



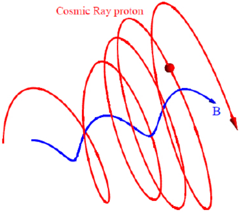
Tüllmann+ (2000)

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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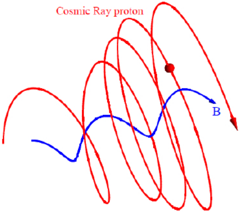

$\rightarrow$ **CRs exert a pressure on the thermal gas by means of scattering off Alfvén waves**

CR transport (1)

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

$$\boldsymbol{v}_{\rm st} = -v_{\rm A}\,\frac{\nabla P_{\rm cr}}{|\nabla P_{\rm cr}|}, \qquad \boldsymbol{v}_{\rm di} = -\kappa_{\rm di}\,\frac{\nabla P_{\rm cr}}{P_{\rm cr}},$$

$\rightarrow$ neglect CR diffusion (small for a plasma with $P_B \sim P_{\rm th}$)

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- CR transport equation $\rightarrow$ 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 transport (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:

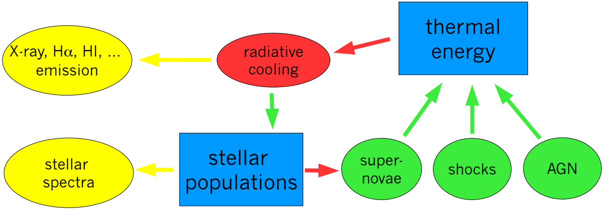
$$\rho\frac{\mathrm{d}\tilde{n}_{\mathrm{cr}}}{\mathrm{d}t} = -\nabla \cdot [\boldsymbol{v}_{\mathrm{st}}\,\rho\,\tilde{n}_{\mathrm{cr}}]$$

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

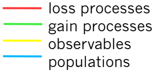
Interstellar medium (ISM) simulations – flowchart

ISM observables:

Physical processes in the ISM:



C.P., Enßlin, Springel (2008)



ISM simulations with cosmic ray physics

ISM observables:

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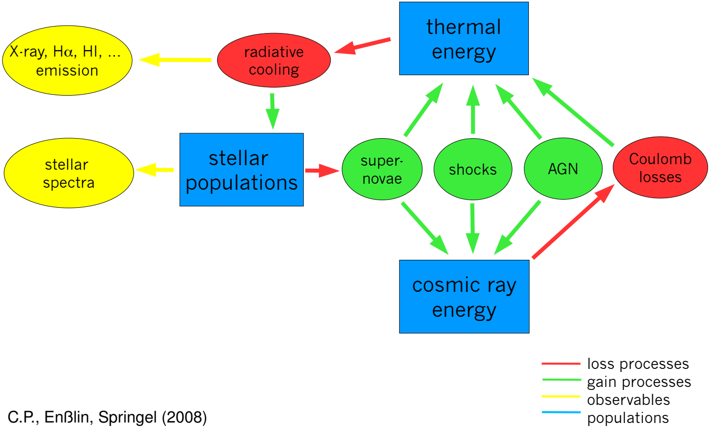
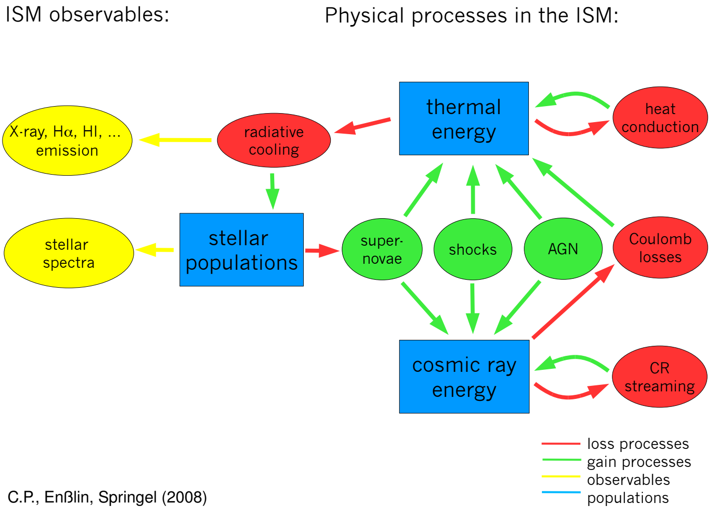


C.P., Enßlin, Springel (2008)

ISM simulations with extended cosmic ray physics



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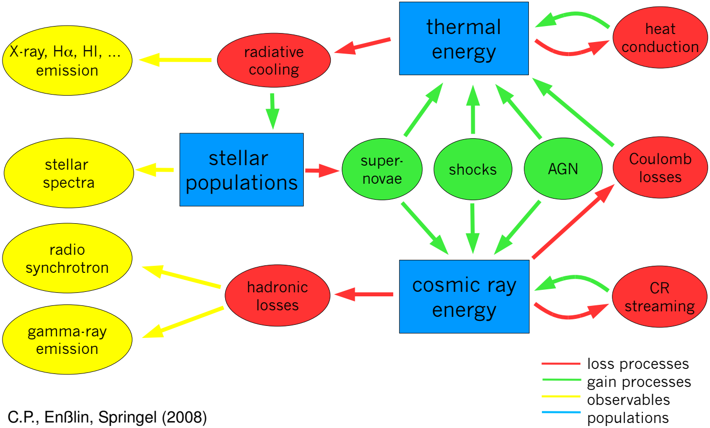
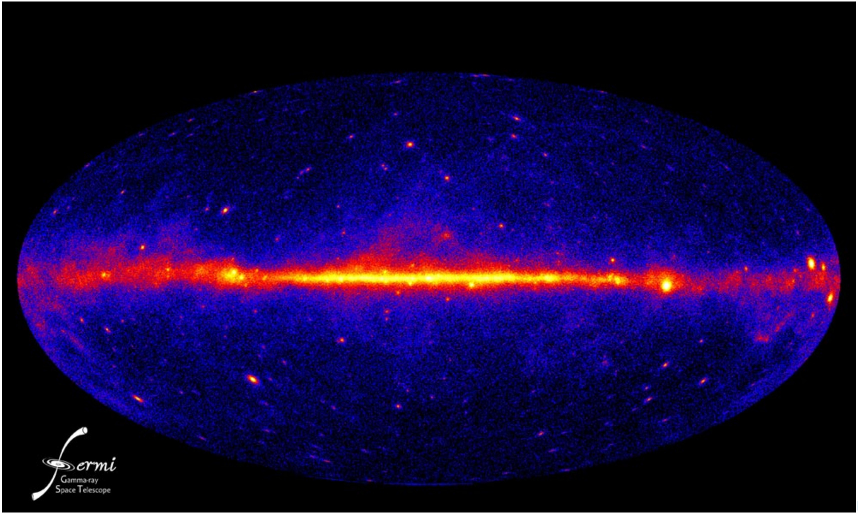
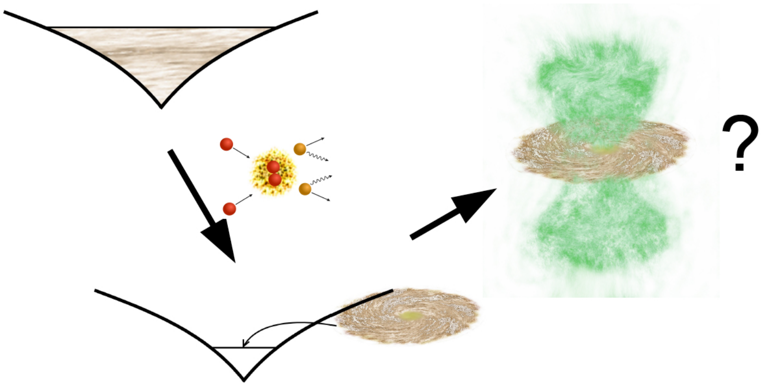


C.P., Enßlin, Springel (2008)

Gamma-ray emission of the Milky Way



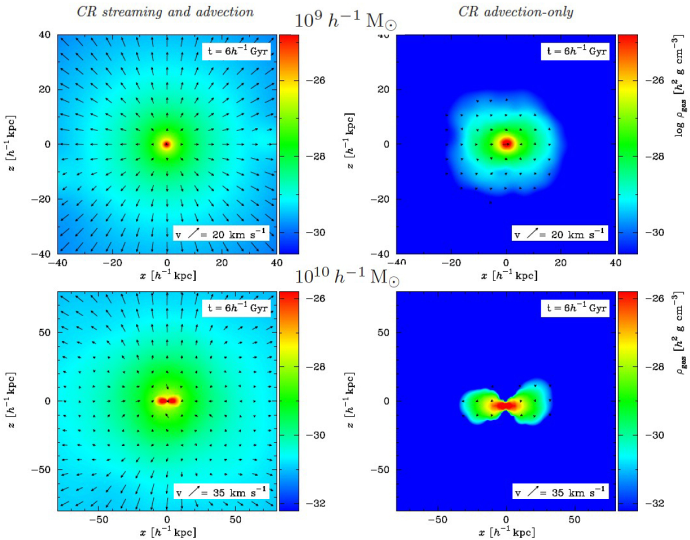
Simulation setup



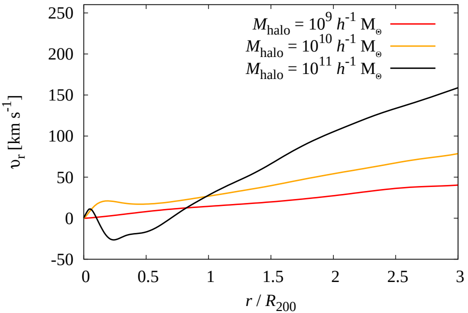
Uhlig, C.P., Sharma, Nath, Enßlin, Springel, *MNRAS* **423**, 2374 (2012)
Galactic winds driven by cosmic-ray streaming

HITS

CR streaming drives winds

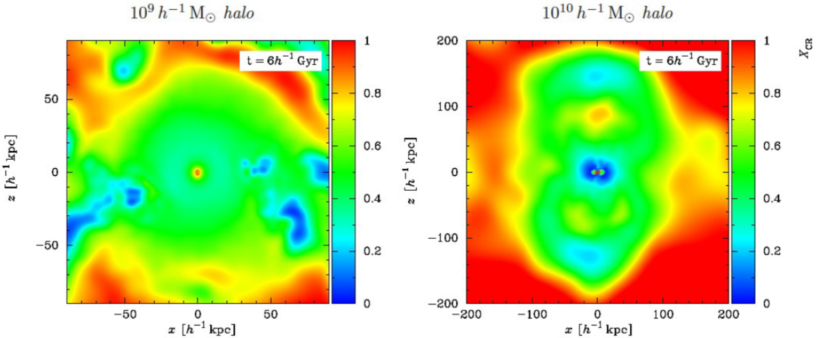


Wind velocity profile along the symmetry axis



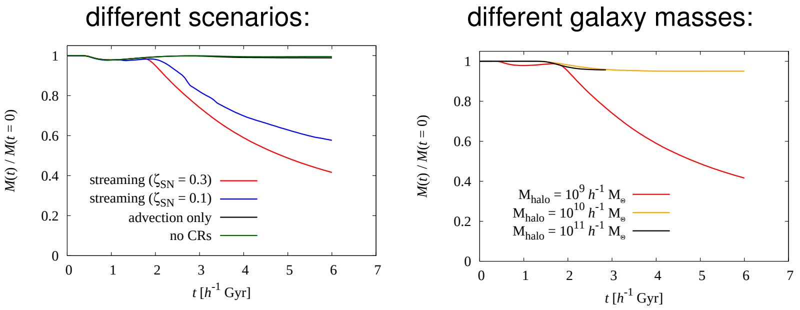
- $10^9 - 10^{10}\,M_\odot$: accelerating wind due to a continuous CR momentum and energy deposition during the ascent of the wind in the gravitational potential
  $\rightarrow$ different from traditional energy- or momentum-driven winds!
- $10^{11}\,M_\odot$: wind stalls in halo and falls back onto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

CR-to-thermal pressure in edge-on slice



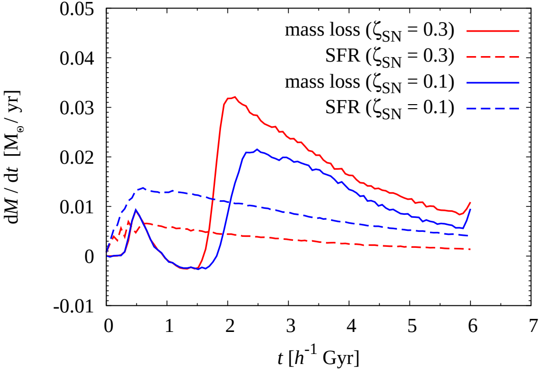
- $X_{\mathrm{cr}} = P_{\mathrm{cr}}/P_{\mathrm{th}} < 50\%$ in vicinity of center because of loss processes that effectively transfer CR into thermal energy
- X_{cr} becomes dominant at larger heights due to the softer adiabatic index of CRs

Gas mass loss within the virial radius



- 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)*

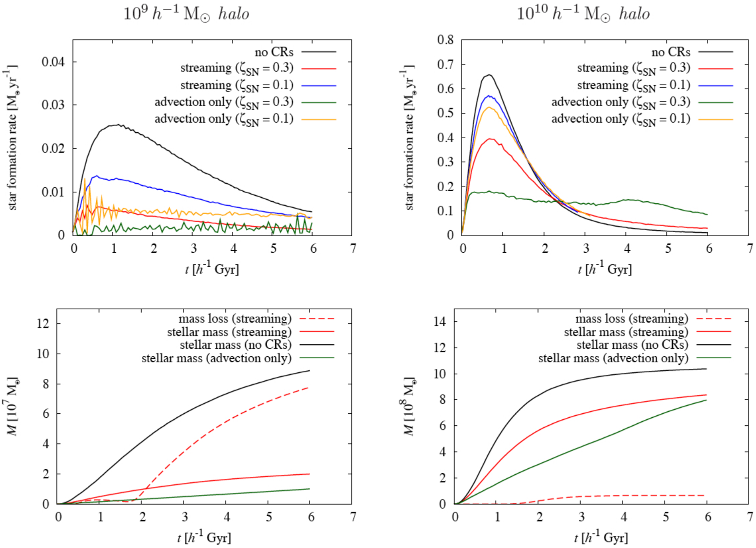
Mass loss and star formation rates



- time lag between onset of star formation and associated supernovae (that inject CRs) and mass loss rate (from R_{200})

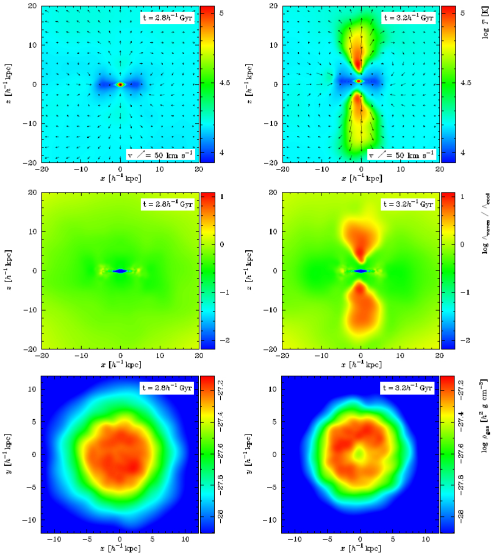
$$10^9\,h^{-1}\mathrm{M}_\odot: \qquad \tau_{\mathrm{lag}} = \frac{R_{200}}{v_{\mathrm{esc}}} \simeq \frac{20\,\mathrm{kpc}}{20\,\mathrm{km\,s}^{-1}} \simeq 1\,\mathrm{Gyr}$$

Mass loss and star formation histories

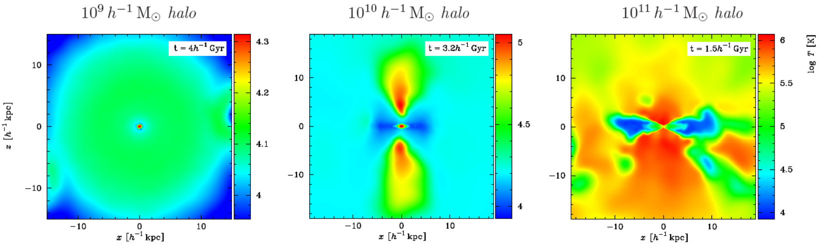


Heating of the halo gas by wave damping

$10^{10}\ h^{-1}\mathrm{M}_{\odot}$:



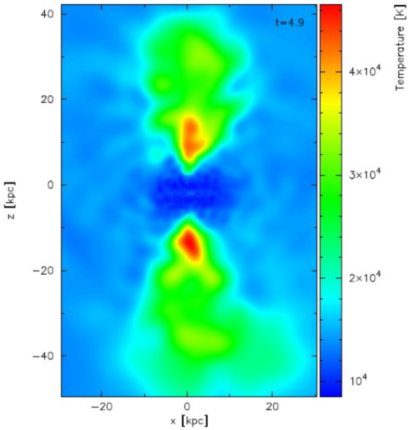
Temperature structure



- halo temperatures scale as $kT \propto v_\mathrm{wind}^2 \sim v_\mathrm{esc}^2$
- $10^9 \rightarrow 10^{10}\,M_\odot$: transition of isotropic to bi-conical wind; in these cones, CR wave heating overcomes radiative cooling
- $10^{10} \rightarrow 10^{11}\,M_\odot$: broadening of hot temperature structure due to inability of CR streaming to drive a sustained wind; instead, fountain flows drive turbulence, thereby heating larger regions

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

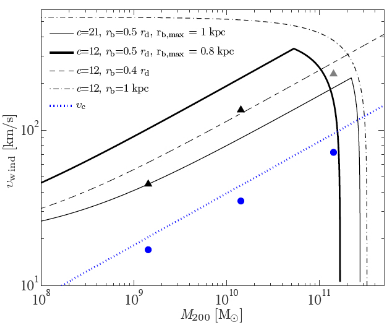
t = 4.9 Gyr, streaming

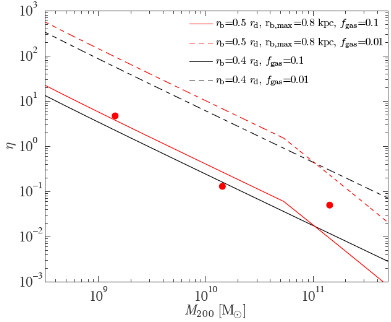


M82

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

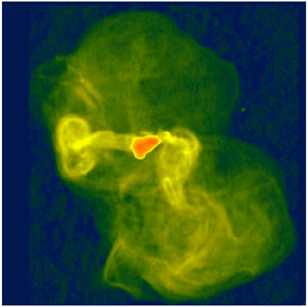
- galactic winds are naturally explained by CR streaming (known energy source and plasma physics)
- CR streaming heating can explain observed hot wind regions above disks
- substantial mass losses of low mass galaxies
  → opportunity for understanding the physics at the faint end of galaxy luminosity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

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

→ recent work: Salem & Bryan (2013), Booth et al. (2013), Hanasz et al. (2013)

"Radio-mode" AGN feedback

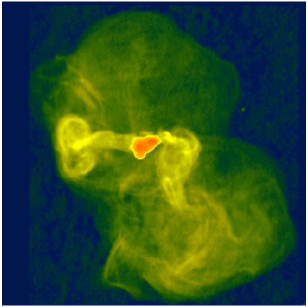
Messier 87 at radio wavelengths



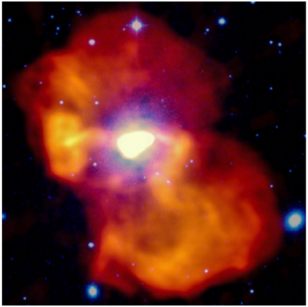
$\nu = 1.4$ GHz (Owen+ 2000)

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

Messier 87 at radio wavelengths



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



$\nu = 140$ 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)

Solutions to the “missing fossil electrons” problem

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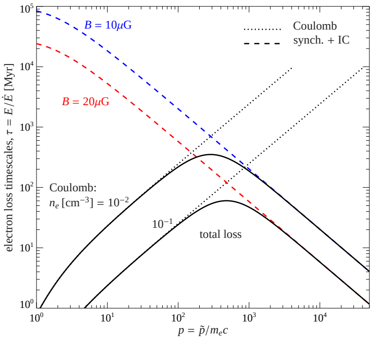
- special time: M87 turned on $\sim$ 40 Myr ago after long silence
  $\Leftrightarrow$ conflicts order unity duty cycle inferred from stat. AGN feedback studies (Birzan+ 2012)
- Coulomb cooling removes fossil electrons
  $\rightarrow$ efficient mixing of CR electrons and protons with dense cluster gas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



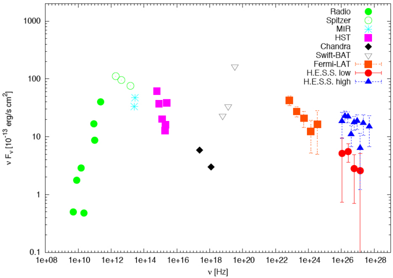
C.P. (2013)

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 (?)

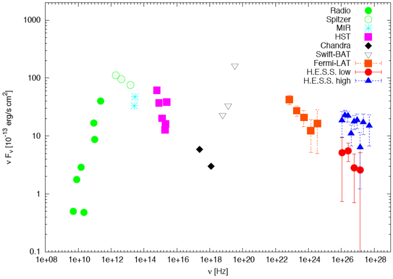


Rieger & Aharonian (2012)

$\rightarrow$ **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
  $X_{\rm cr} = P_{\rm cr}/P_{\rm th} = \text{const.}$
  (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:

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

- 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} calibrated to γ rays
- P_{th} from X-ray data
- pressure fluctuations $\delta P_{\mathrm{cr}}/\delta l$ (e.g., due to weak shocks of $\mathcal{M} \simeq 1.1$)

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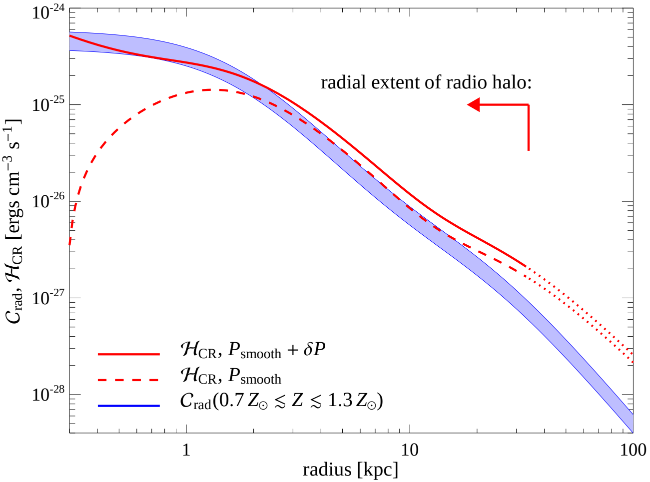
radiative cooling:

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

- 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



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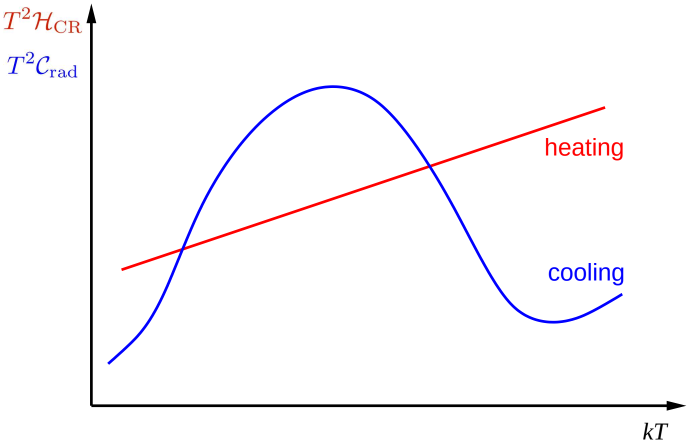
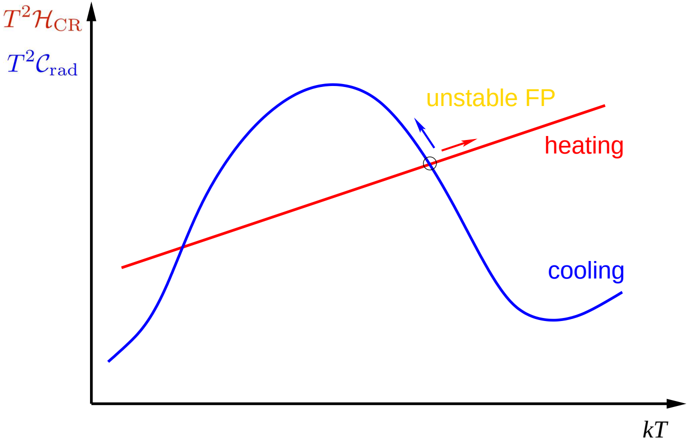
Local stability analysis (1)



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

Local stability analysis (1)



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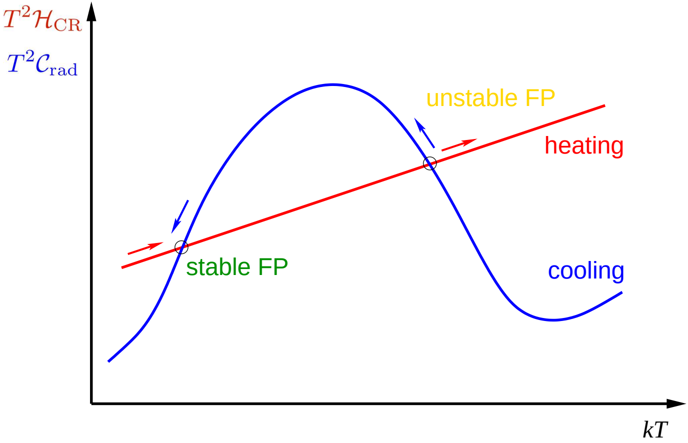
Local stability analysis (1)



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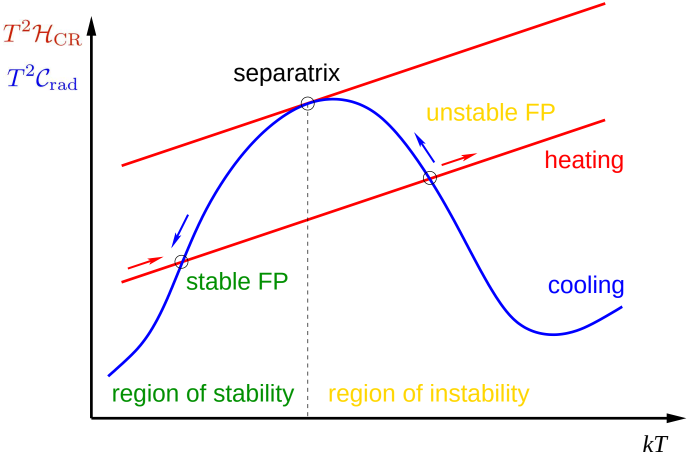
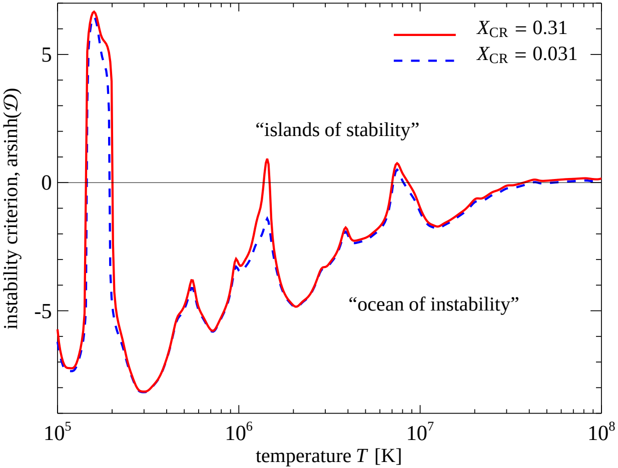


- isobaric perturbations to global thermal equilibrium
- CRs are adiabatically trapped by perturbations

Local stability analysis (2)

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



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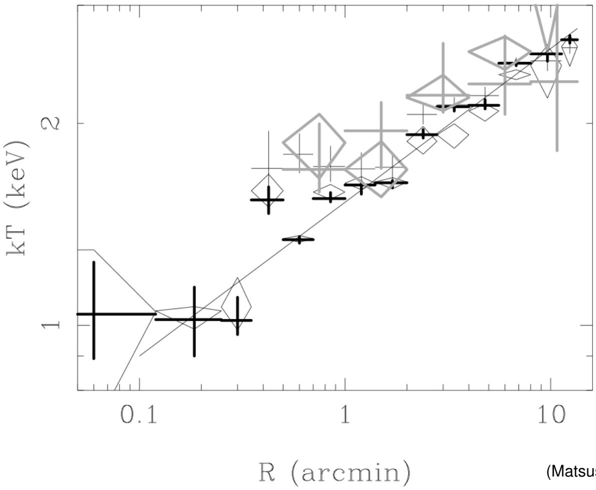
Virgo cluster cooling flow: temperature profile

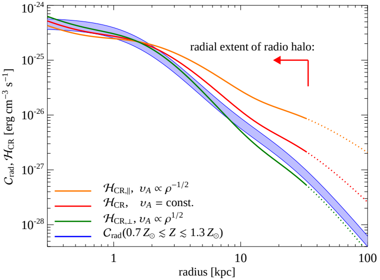
X-ray observations confirm temperature floor at $kT \simeq 1$ keV



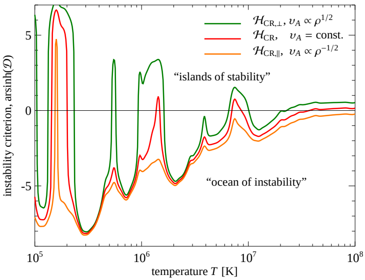
(Matsushita+ 2002)

Impact of varying Alfvén speed on CR heating

global thermal equilibrium:



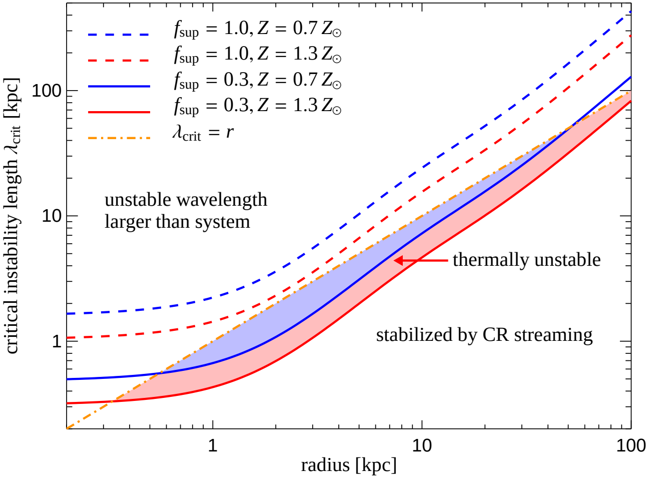
local stability criterion:



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 $v_A = \mathrm{const.}$
- $\alpha_B = 0$ for collapse along ***B***, implying $v_{A,\parallel} \propto \rho^{-1/2}$
- $\alpha_B = 1$ for collapse perpendicular to ***B***, implying $v_{A,\perp} \propto \rho^{1/2}$

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



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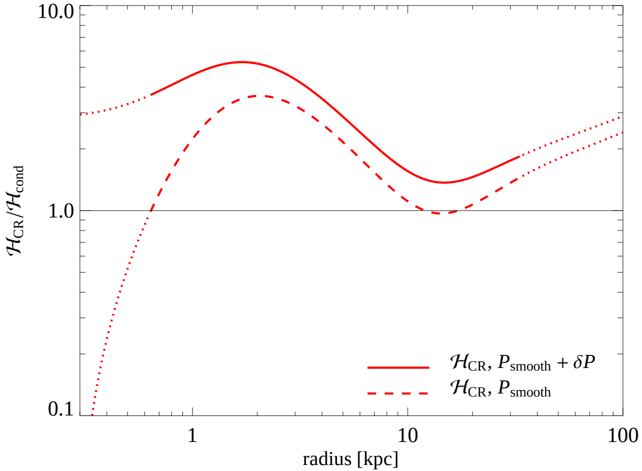
CR heating dominates over thermal conduction



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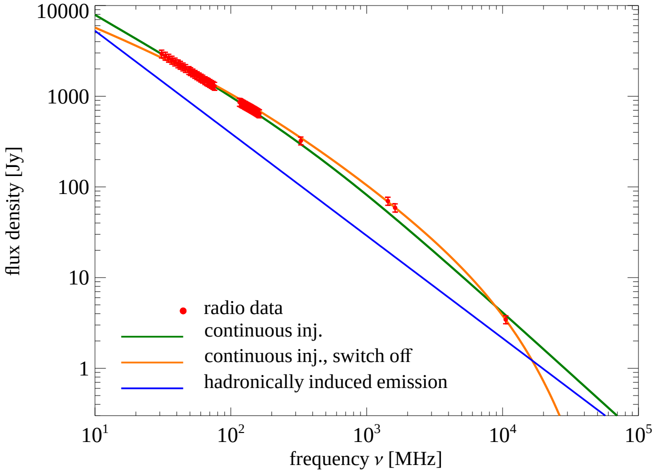
Prediction: flattening of high-ν radio spectrum



C.P. (2013)

Conclusions on AGN feedback by cosmic-ray heating

- LOFAR puzzle of “missing fossil electrons” solved by mixing with dense cluster gas and Coulomb cooling
- predicted γ rays identified with low state of M87
  $\rightarrow$ estimate CR-to-thermal pressure of $X_{\mathrm{cr}} = 0.31$
- CR Alfvén wave heating balances radiative cooling on all scales within the radio halo ($r < 35$ kpc)
- local thermal stability analysis predicts observed temperature floor at $kT \simeq 1$ keV

outlook: simulate steaming CRs coupled to MHD, cosmological cluster simulations, improve γ-ray and radio observations …

cf. Loewenstein et al. (1991), Guo & Oh (2008), Enßlin et al. (2011)

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.

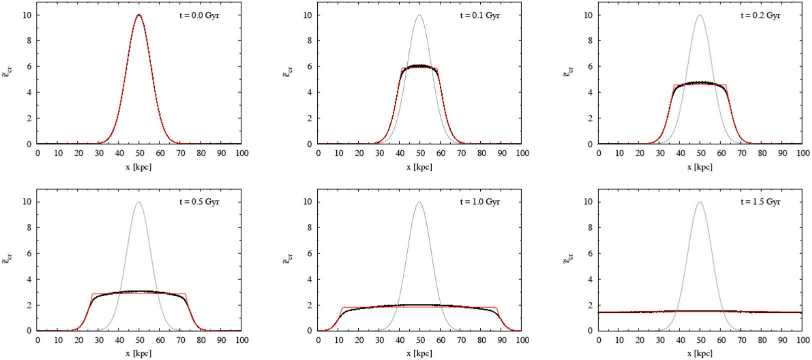
AGN feedback by cosmic rays:

- 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

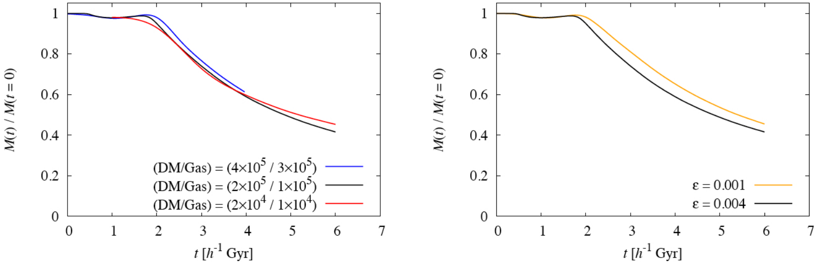
Test: Gadget-2 versus 1-d grid solver

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



Uhlig+2012

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)*