Cosmic ray physics in galaxy formation

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in collaboration with

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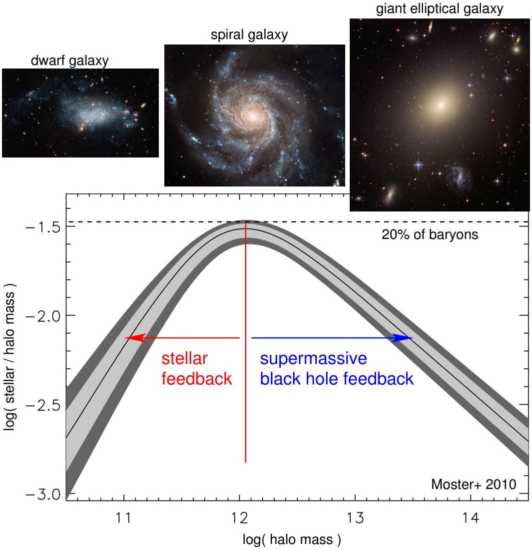
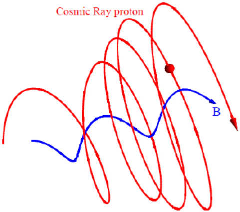
Computational Galaxy Formation, Ringberg 2016

Puzzles in galaxy formation: cosmic-ray feedback?



Interactions of CRs and magnetic fields

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



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

CR transport

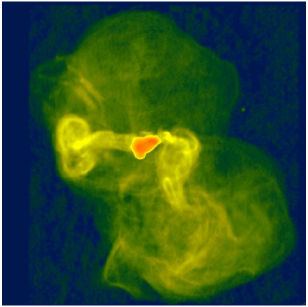
- total CR velocity $\boldsymbol{v}_{\rm cr} = \boldsymbol{v} + \boldsymbol{v}_{\rm st} + \boldsymbol{v}_{\rm di}$ (where $\boldsymbol{v} \equiv \boldsymbol{v}_{\rm gas}$)
- CRs stream down their own pressure gradient relative to the gas, CRs diffuse in the wave frame due to pitch angle scattering by MHD waves (both transports are along the local direction of $\boldsymbol{B}$):

$$\boldsymbol{v}_{\rm st} = -\frac{\boldsymbol{B}}{\sqrt{4\pi\rho}} \frac{\boldsymbol{b}\cdot\nabla P_{\rm cr}}{|\boldsymbol{b}\cdot\nabla P_{\rm cr}|}, \qquad \boldsymbol{v}_{\rm di} = -\kappa_{\rm di}\boldsymbol{b}\,\frac{\boldsymbol{b}\cdot\nabla\varepsilon_{\rm cr}}{\varepsilon_{\rm cr}},$$

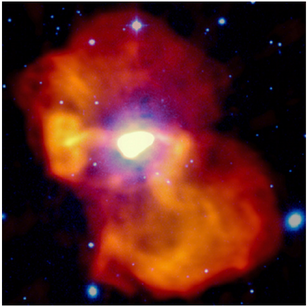
- energy equations with $\varepsilon = \varepsilon_{\rm th} + \rho v^2/2$:

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

Messier 87 at radio wavelengths



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



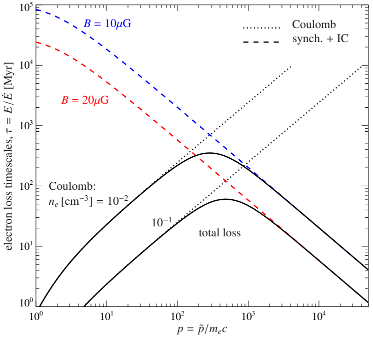
$\nu = 140$ MHz (LOFAR/de Gasperin+ 2012)

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

Solutions to the "missing fossil electrons" problem

solutions:

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



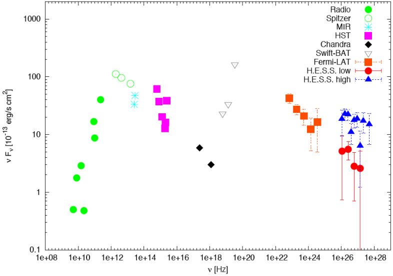
C.P. (2013)

The gamma-ray picture of M87

- high state is time variable
  $\rightarrow$ jet emission
- low state:
  (1) steady flux

  (2) γ-ray spectral index (2.2)
  $=$ CRp index
  $=$ CRe injection index as probed by LOFAR

  (3) spatial extension is under investigation (?)



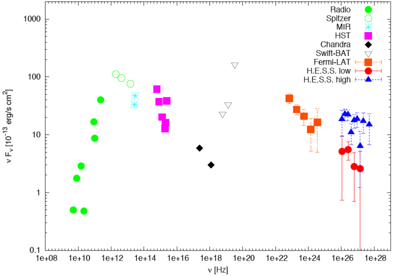
Rieger & Aharonian (2012)

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

Estimating the CR pressure in M87

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

- X-ray data $\rightarrow$ n and T profiles
- assume $X_{\rm cr} = P_{\rm cr}/P_{\rm th}$ (heating due to streaming CRs in steady state)
- $F_\gamma \propto \int \mathrm{d}V\, P_{\rm cr}\, n$ enables to estimate $P_{\rm cr}/P_{\rm th} = 0.3$ (allowing for Coulomb cooling with $\tau_{\rm Coul} = 40\,\mathrm{Myr}$)



Rieger & Aharonian (2012)

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

Cosmic-ray heating vs. radiative cooling (1)

CR Alfvén-wave heating:

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

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

- 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 $\mathcal{M} \simeq 1.1$)

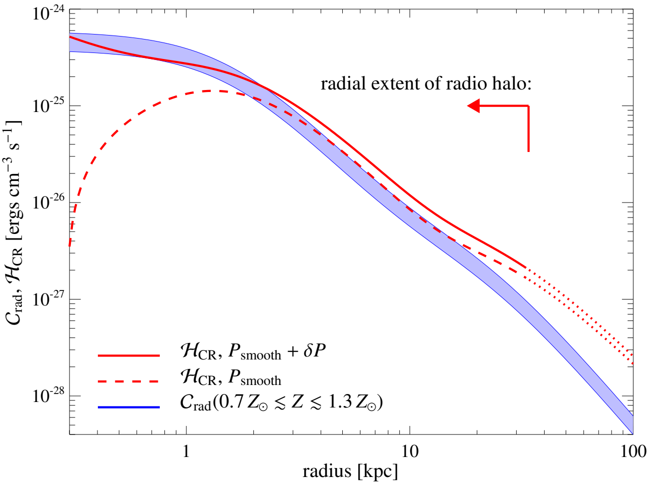
radiative cooling:

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

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

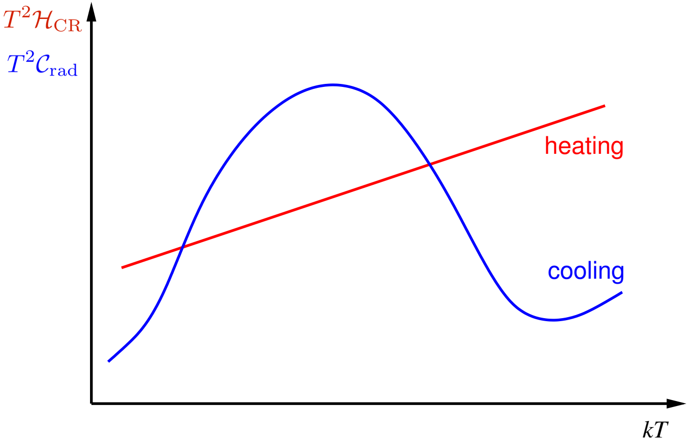
Cosmic-ray heating vs. radiative cooling (2)

Global thermal equilibrium on all scales in M87



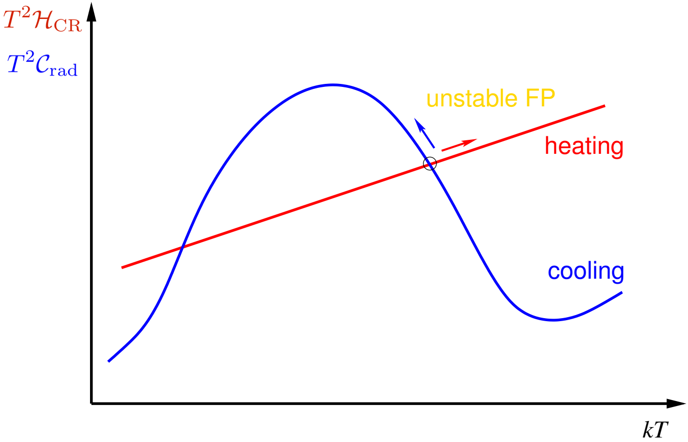
C.P. (2013)

Local stability analysis (1)



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

Local stability analysis (1)



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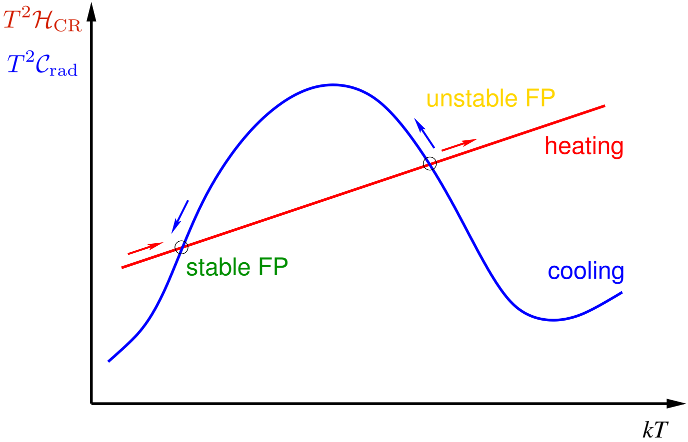

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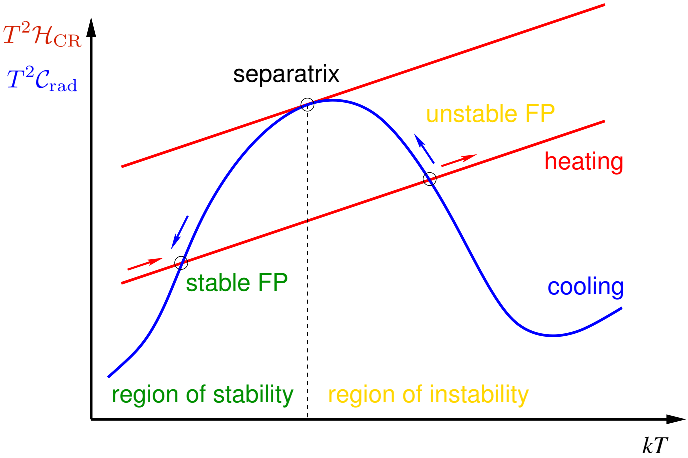
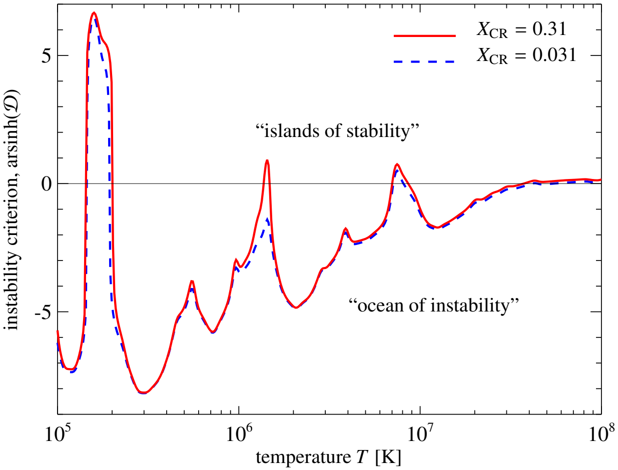


- isobaric perturbations to global thermal equilibrium
- CRs are adiabatically trapped by perturbations

Local stability analysis (2)

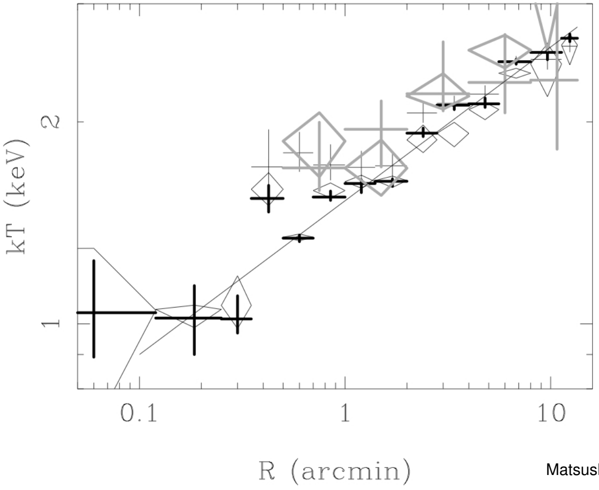
Theory predicts observed temperature floor at $kT \simeq 1$ keV



C.P. (2013)

Virgo cluster cooling flow: temperature profile

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



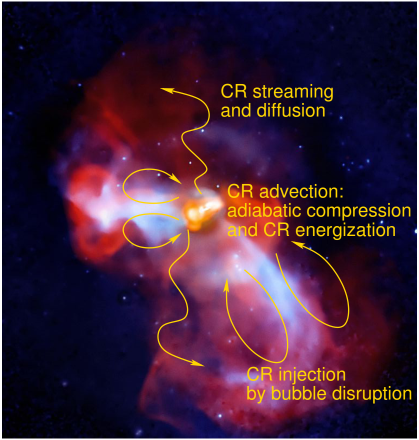
Matsushita+ (2002)

Emerging picture of CR feedback by AGNs

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

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

(3) CR escape and outward streaming $\rightarrow$ CR Alfvén-wave heating



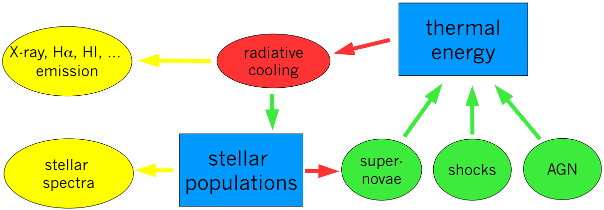
Conclusions on cosmic-ray heating in M87

- LOFAR puzzle of "missing fossil electrons" in M87 solved by mixing with dense cluster gas and Coulomb cooling
- predicted γ rays identified with low state of M87
  $\rightarrow$ estimate CR-to-thermal pressure of $X_{\rm cr} = 0.3$
- CR Alfvén wave heating balances radiative cooling on all scales within the central radio halo ($r < 35$ kpc)
- local thermal stability analysis predicts observed temperature floor at $kT \simeq 1$ keV

AREPO simulations – flowchart

ISM observables:

Physical processes in the ISM:



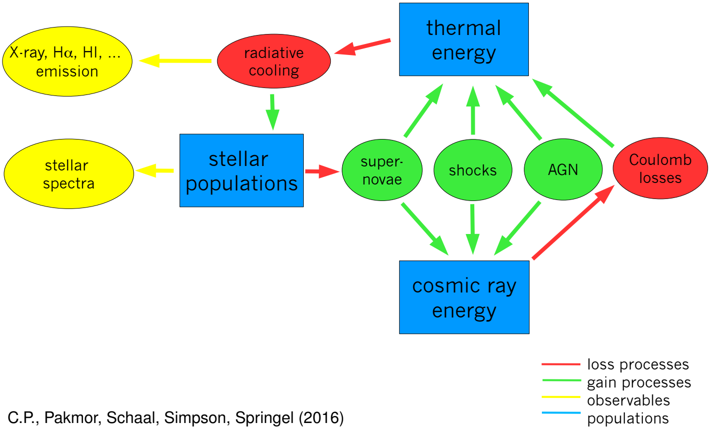
loss processes
gain processes
observables
populations

C.P., Pakmor, Schaal, Simpson, Springel (2016)

AREPO simulations with cosmic ray physics

ISM observables:

Physical processes in the ISM:



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AREPO simulations with cosmic ray physics

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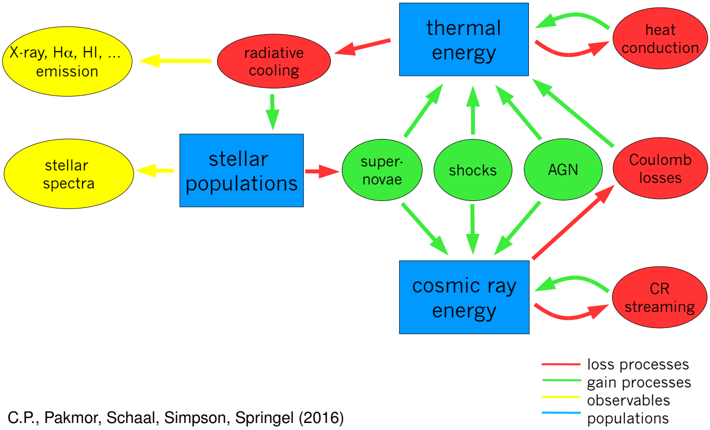

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AREPO simulations with cosmic ray physics

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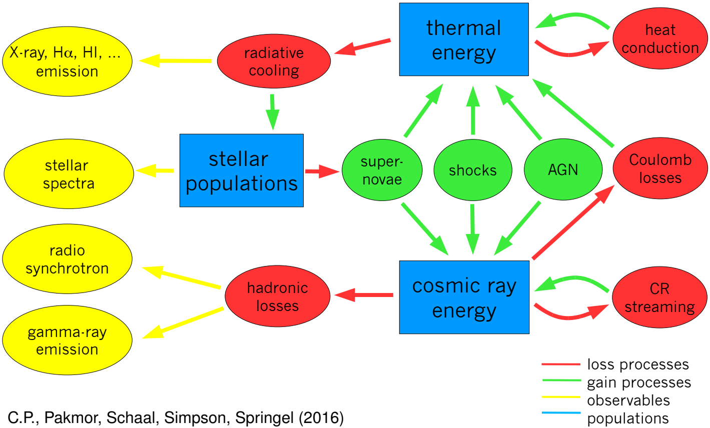

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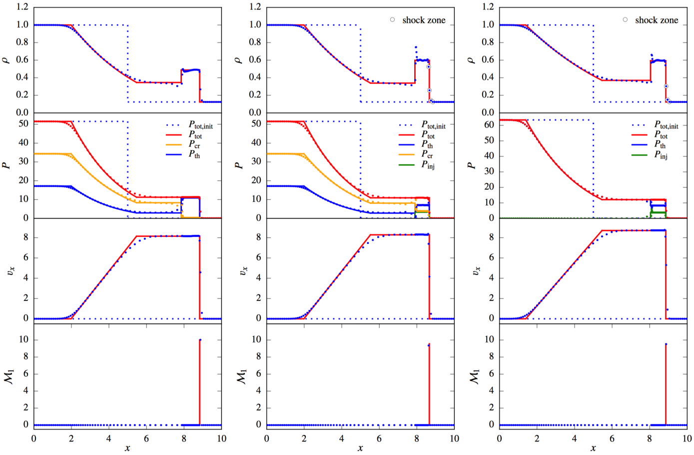
CR shock acceleration

Comparing simulations to novel exact solutions that include CR acceleration



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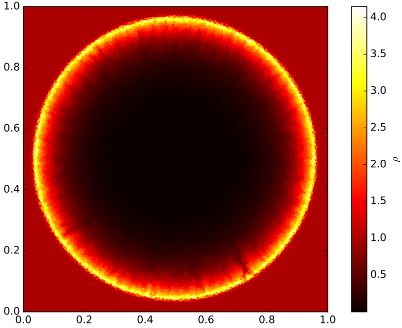
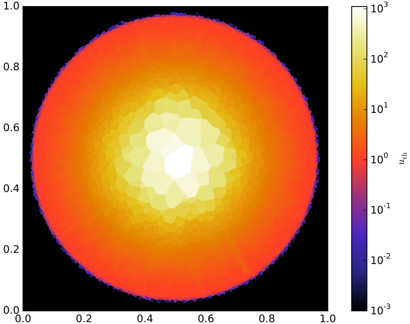
Sedov explosion

density



specific thermal energy



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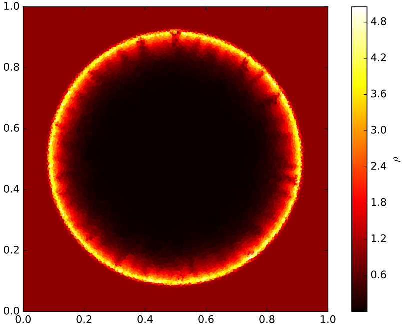
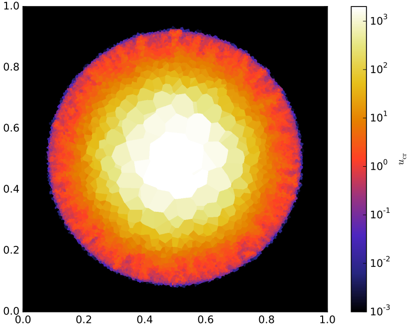
Sedov explosion with CR acceleration

density



specific cosmic ray energy



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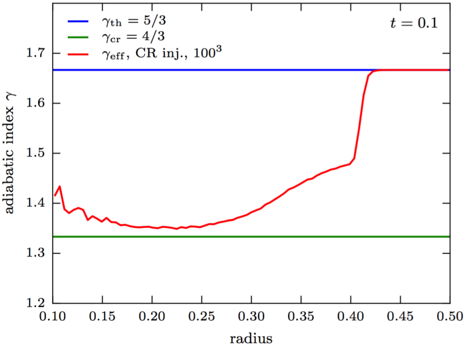
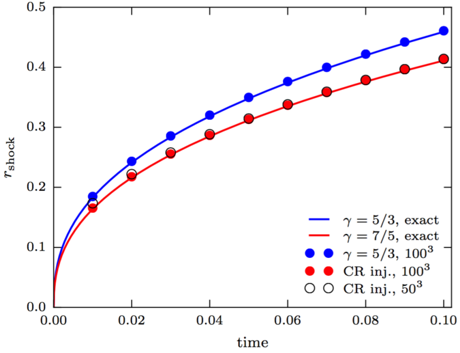
Sedov explosion with CR acceleration

adiabatic index



shock evolution



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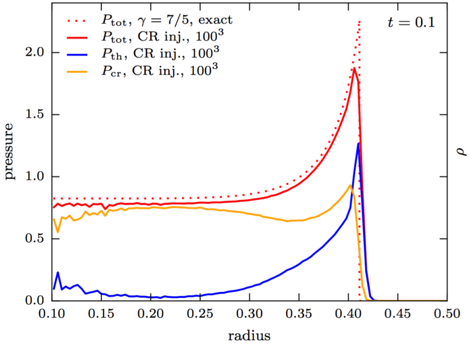
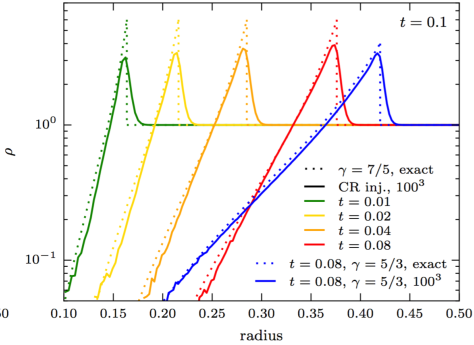
Sedov explosion with CR acceleration

pressure



density



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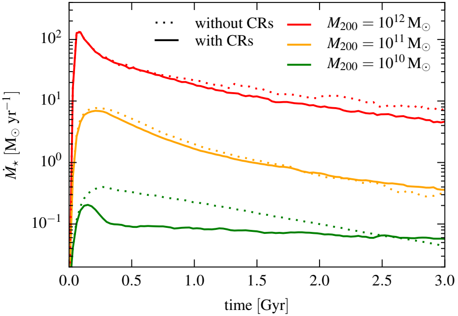
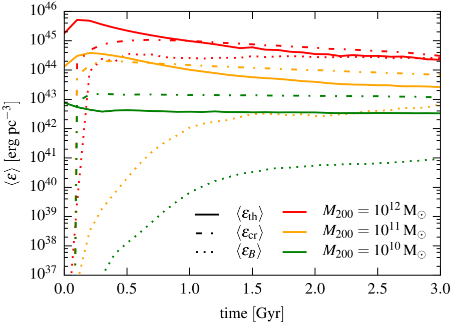
Time evolution of SFR and energy densities





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- CR pressure feedback suppresses SFR more in smaller galaxies
- energy budget in disks is dominated by CR pressure
- magnetic dynamo faster in Milky Way galaxies than in dwarfs

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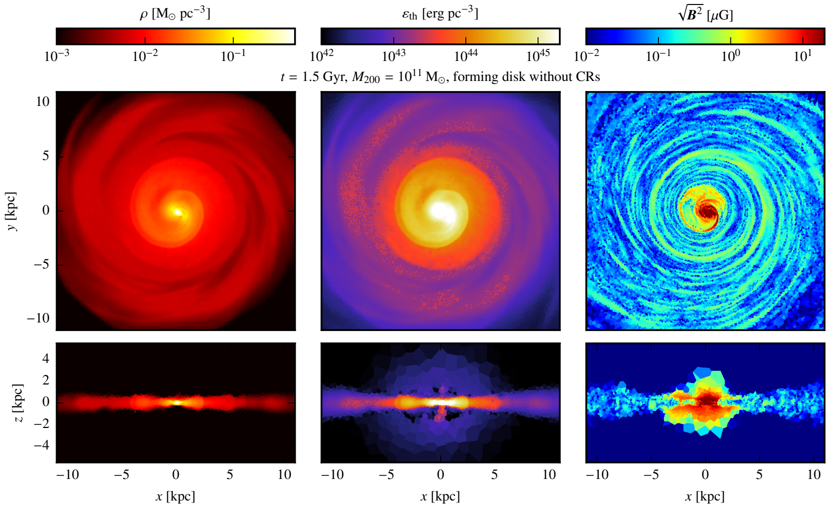
MHD galaxy simulation without CRs



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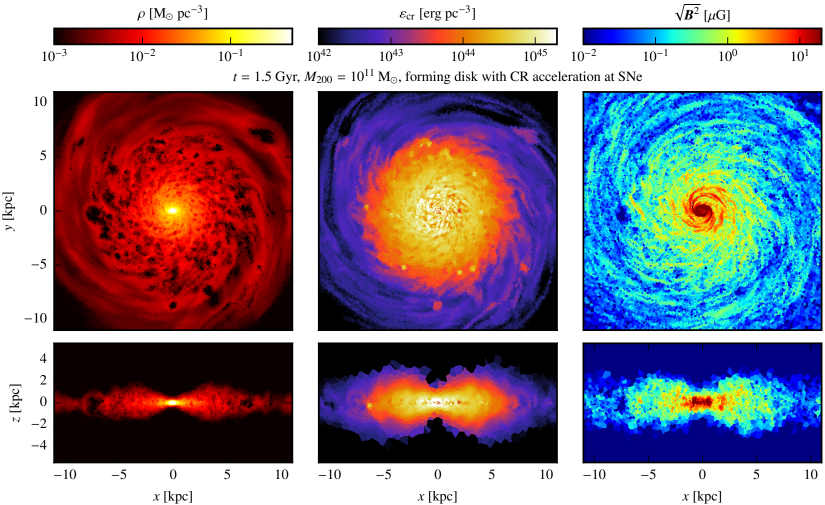
MHD galaxy simulation with CRs



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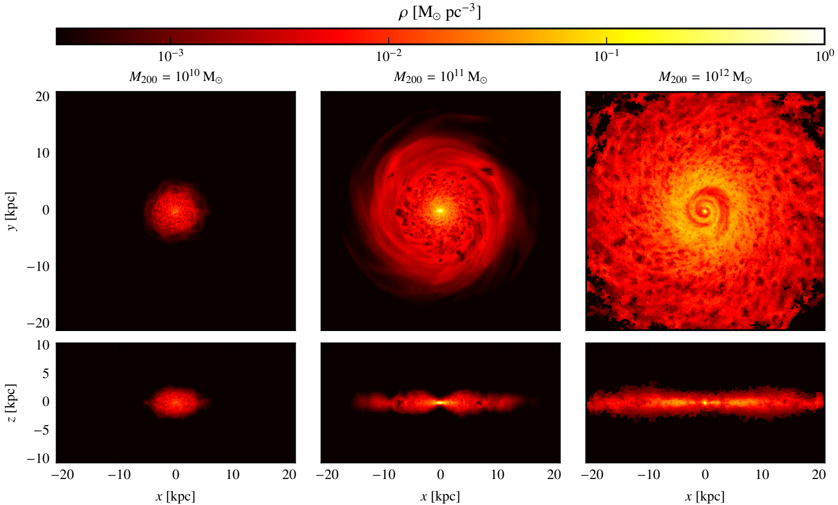
Gas density in galaxies from 10^{10} to $10^{12}\,\mathrm{M}_\odot$



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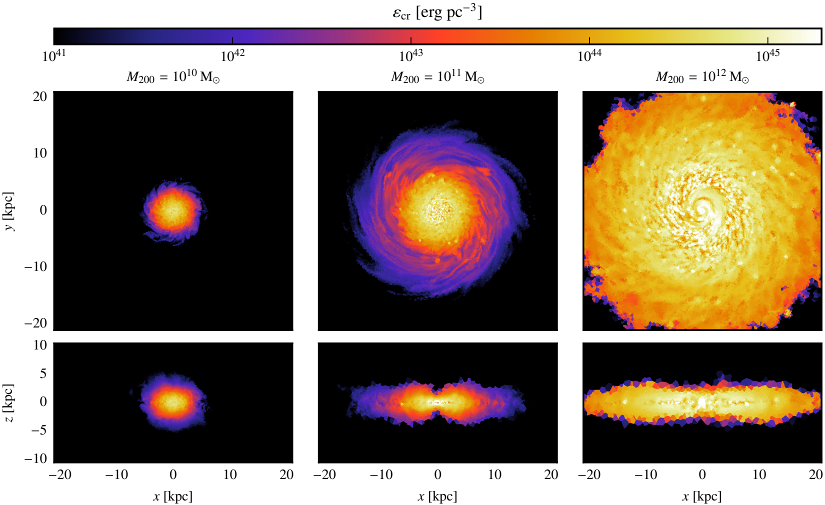
CR energy density in galaxies from 10^{10} to $10^{12}\,\mathrm{M}_\odot$



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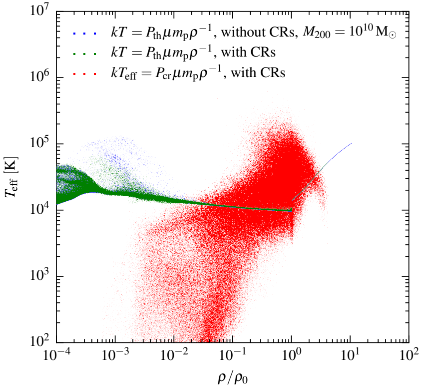
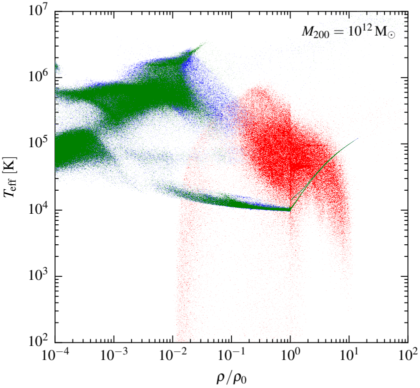
Temperature-density plane: CR pressure feedback





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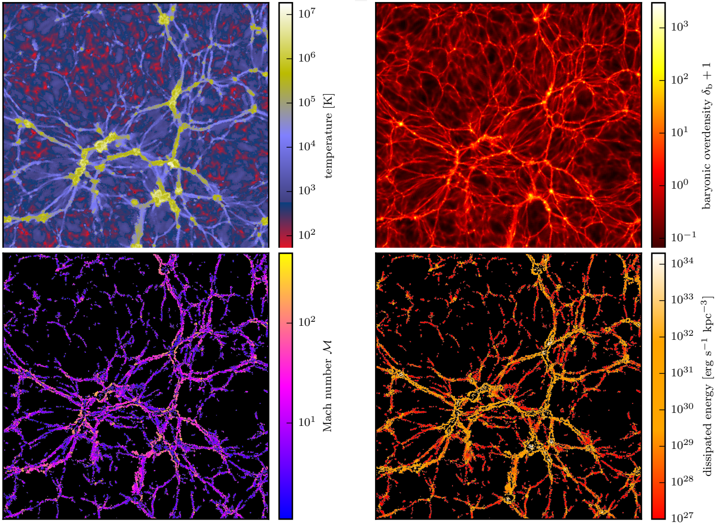
Cosmological simulations with cosmic rays



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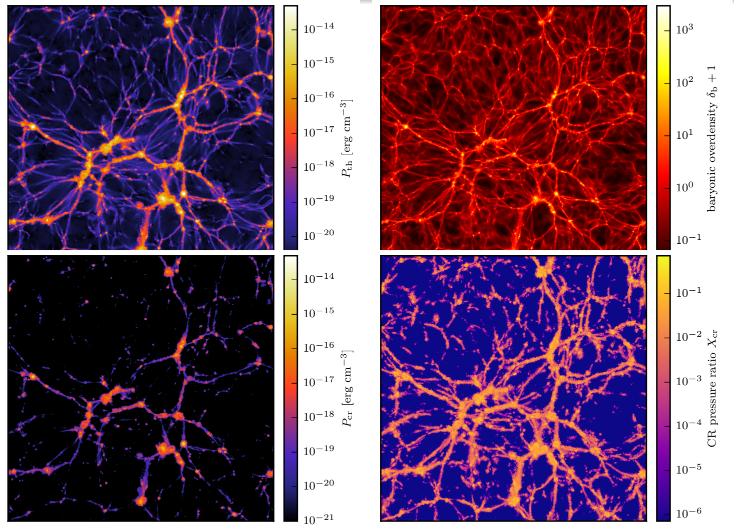
Cosmological simulations with cosmic rays



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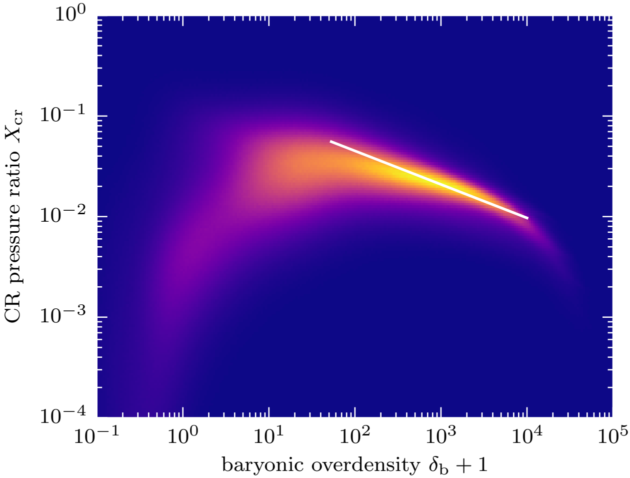
CR shock acceleration at structure formation shocks



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Cosmic ray simulations

projects:

- cosmological galaxy formation simulations:
  CR-driven galactic winds, magnetic dynamo $\rightarrow$ Rüdiger's talk
- ISM physics: CR-driven outflows $\rightarrow$ Christine Simpson
- radio mode feedback: cosmic-ray heating
- non-thermal cluster emission: radio halos and relics

$\rightarrow$ versatile CR-MHD code to explore the physics of galaxy formation

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CRAGSMAN: The Impact of Cosmic RAys on Galaxy and CluSter ForMAtioN

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Literature for the talk

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.

Simulating cosmic rays:

- Pfrommer, Pakmor, Schaal, Simpson, Springel, *Simulating cosmic ray physics on a moving mesh,* 2016.

Additional slides

Self-consistent CR pressure in steady state

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

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

  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!**

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

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

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

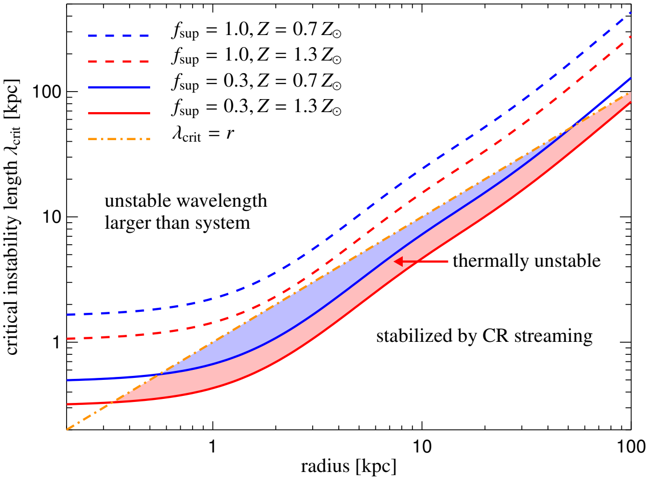
where f_s is the magnetic suppression factor

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

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

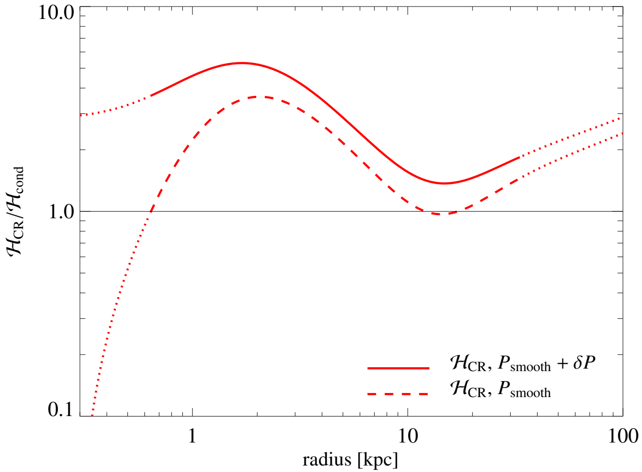
- however: unstable wavelength must be supported by the system $\rightarrow$ constraint on magnetic suppression factor f_s

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



C.P. (2013)

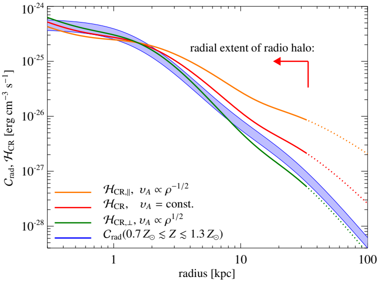
CR heating dominates over thermal conduction



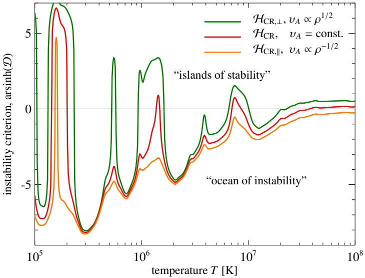
C.P. (2013)

Impact of varying Alfvén speed on CR heating

global thermal equilibrium:



local stability criterion:



parameterise $B \propto \rho^{\alpha_B}$, 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 $v_{A,\perp} \propto \rho^{1/2}$