Cosmic ray feedback in galaxies and AGN

Christoph Pfrommer

in collaboration with

R. Pakmor, K. Schaal, C. Simpson, R. Weinberger, V. Springel
Heidelberg Institute for Theoretical Studies, Germany

Gamma 2016, Heidelberg, July 2016

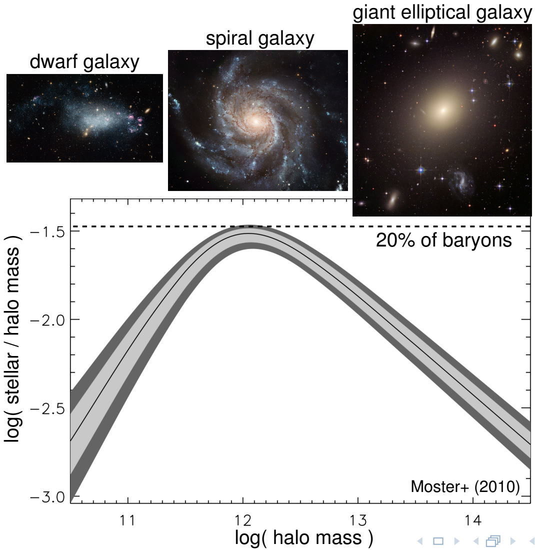
Outline

Outline

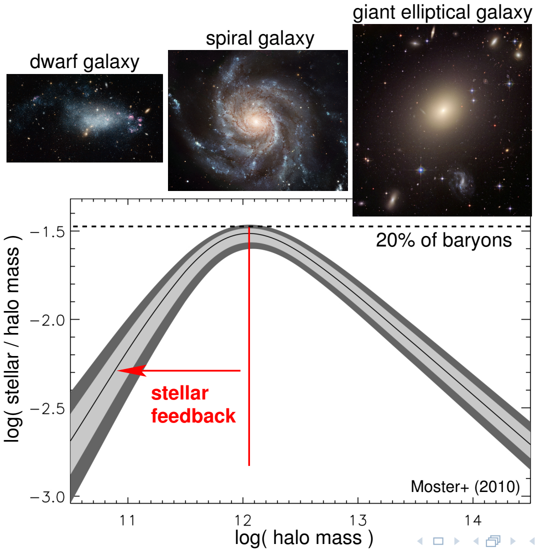
1. Introduction and Motivation
   - Puzzles in galaxy formation
   - Galactic winds
   - Cosmic rays
2. Galaxy formation
   - Sedov explosions
   - Galaxy simulations
   - Gamma-ray emission
3. AGN feedback
   - Radio and γ-ray emission
   - Cosmic-ray heating
   - Simulations

Galaxy formation and gamma-ray astrophysics

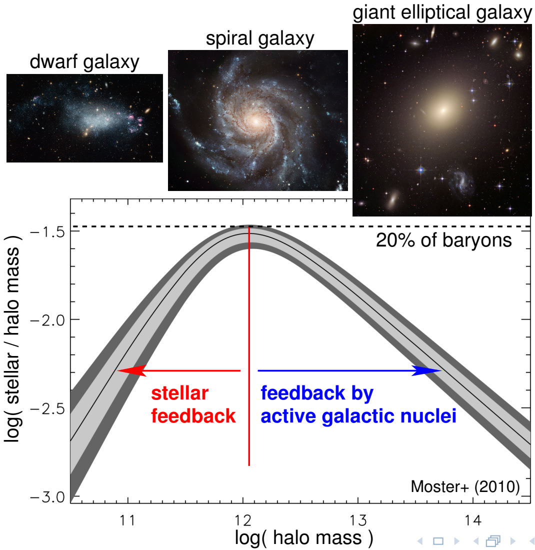
Puzzles in galaxy formation



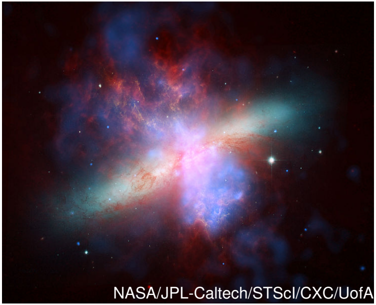
Puzzles in galaxy formation



Puzzles in galaxy formation



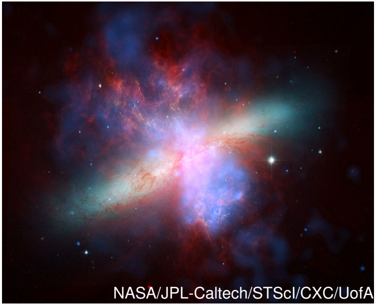
How are galactic winds driven?



super wind in M82

- thermal pressure provided by supernovae or AGNs?
- radiation pressure and photoionization by massive stars and QSOs?
- cosmic-ray (CR) pressure and Alfvén wave heating of CRs accelerated at supernova shocks?

How are galactic winds driven?



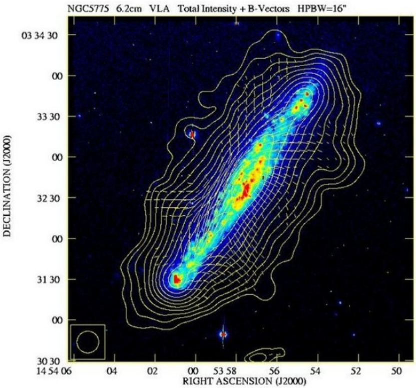
super wind in M82

- thermal pressure provided by supernovae or AGNs?
- radiation pressure and photoionization by massive stars and QSOs?
- cosmic-ray (CR) pressure and Alfvén wave heating of CRs accelerated at supernova shocks?

observed energy equipartition between cosmic rays, thermal gas and magnetic fields
→ suggests self-regulated feedback loop with CR driven winds

Why are CRs important for wind formation?

Radio halos in disks: CRs and magnetic fields exist at the disk-halo interface

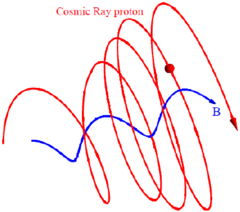


Tüllmann+ (2000)

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

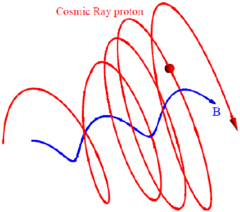
Interactions of CRs and magnetic fields

- CRs scatter on magnetic fields $\rightarrow$ isotropization of CR momenta
- **CR streaming instability:** Kulsrud & Pearce 1969
  - if $v_{\rm cr} > v_{\rm A}$, CR current provides steady driving force, which amplifies an Alfvén wave field in resonance with the gyroradii of CRs
  - scattering off of this wave field limits the (GeV) CRs' bulk speed $\sim v_{\rm A}$
  - wave damping: transfer of CR energy and momentum to the thermal gas



Interactions of CRs and magnetic fields

- CRs scatter on magnetic fields → isotropization of CR momenta
- **CR streaming instability:** Kulsrud & Pearce 1969
  - if $v_{\rm cr} > v_{\rm A}$, CR current provides steady driving force, which amplifies an Alfvén wave field in resonance with the gyroradii of CRs
  - scattering off of this wave field limits the (GeV) CRs' bulk speed $\sim v_{\rm A}$
  - wave damping: transfer of CR energy and momentum to the thermal gas

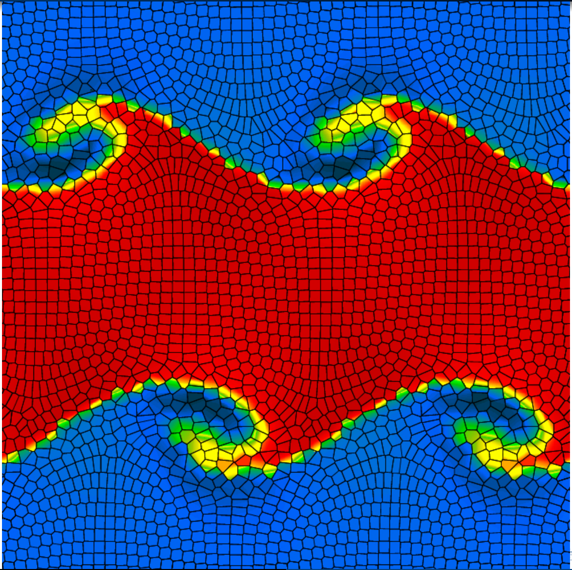


→ **CRs exert a pressure on the thermal gas by means of scattering off of Alfvén waves**

Outline

1. Introduction and Motivation
   - Puzzles in galaxy formation
   - Galactic winds
   - Cosmic rays
2. Galaxy formation
   - Sedov explosions
   - Galaxy simulations
   - Gamma-ray emission
3. AGN feedback
   - Radio and γ-ray emission
   - Cosmic-ray heating
   - Simulations

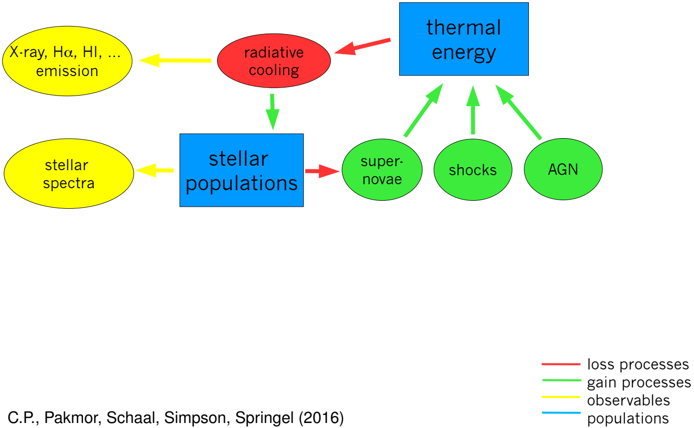
Cosmological moving-mesh code AREPO (Springel 2010)



Simulations – flowchart

ISM observables:

Physical processes in the ISM:

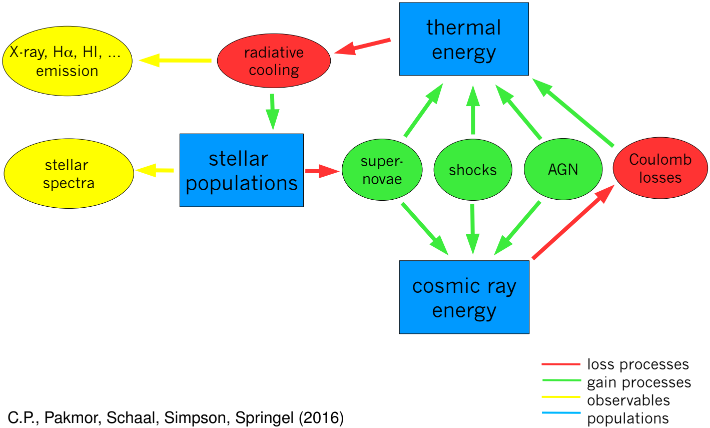


C.P., Pakmor, Schaal, Simpson, Springel (2016)

Simulations with cosmic ray physics

ISM observables:

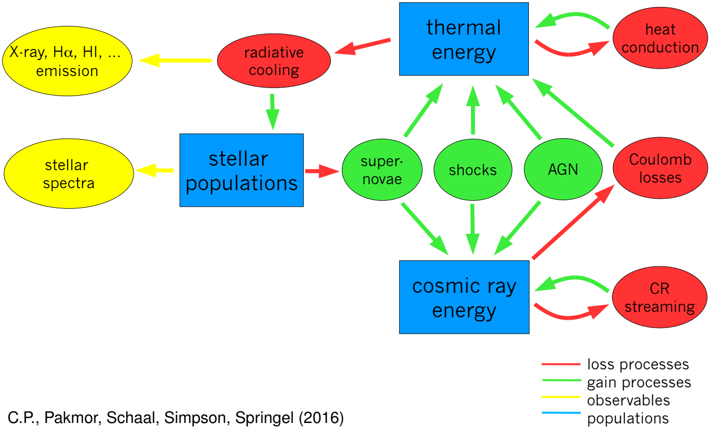
Physical processes in the ISM:



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

Simulations with cosmic ray physics

ISM observables: Physical processes in the ISM:

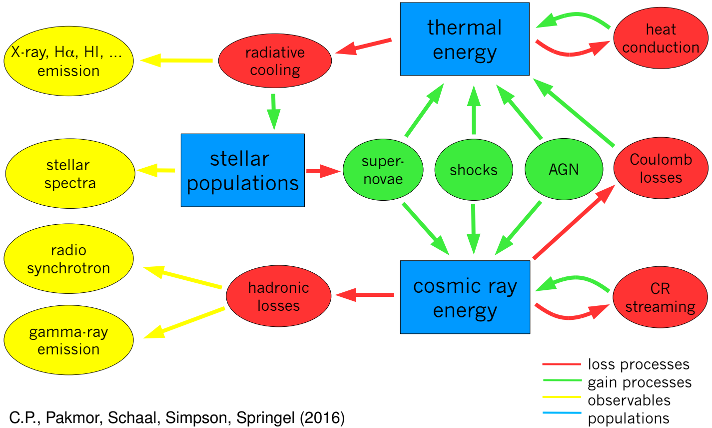


C.P., Pakmor, Schaal, Simpson, Springel (2016)

Simulations with cosmic ray physics

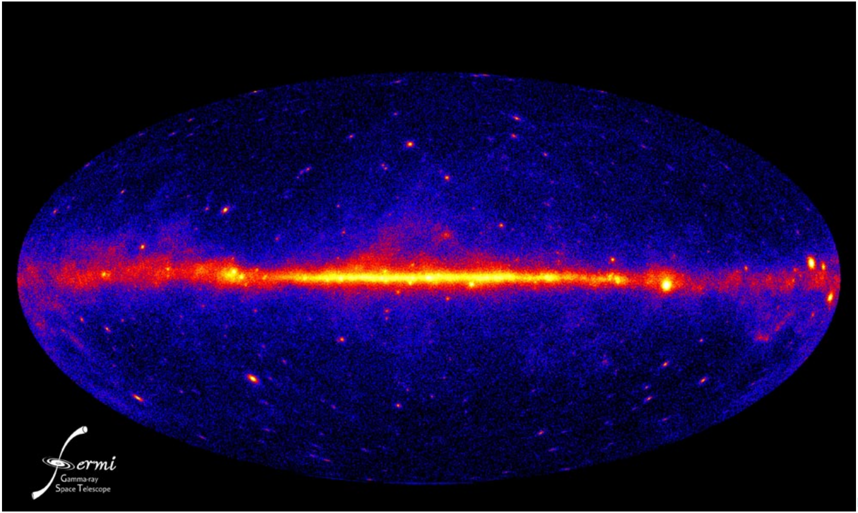
ISM observables:

Physical processes in the ISM:



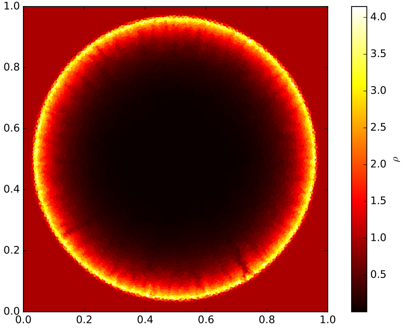
C.P., Pakmor, Schaal, Simpson, Springel (2016)

Gamma-ray emission of the Milky Way

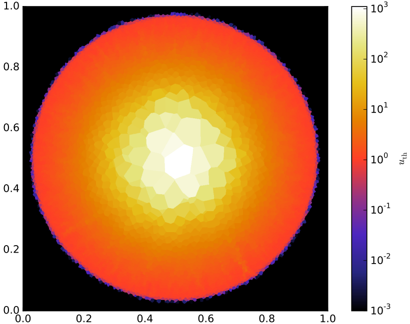


Sedov explosion

density

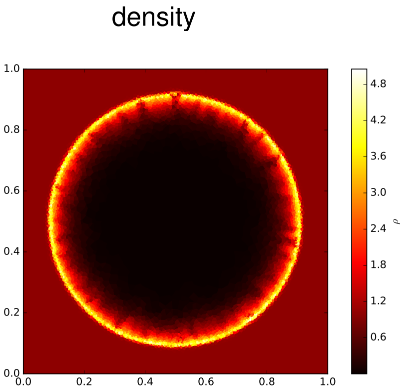


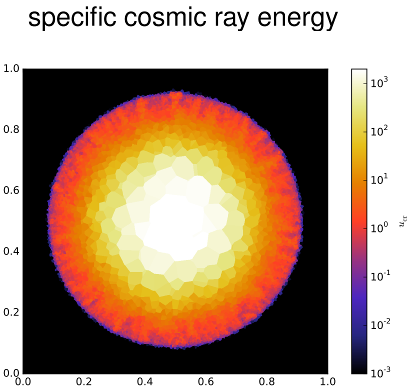
specific thermal energy



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

Sedov explosion with CR acceleration



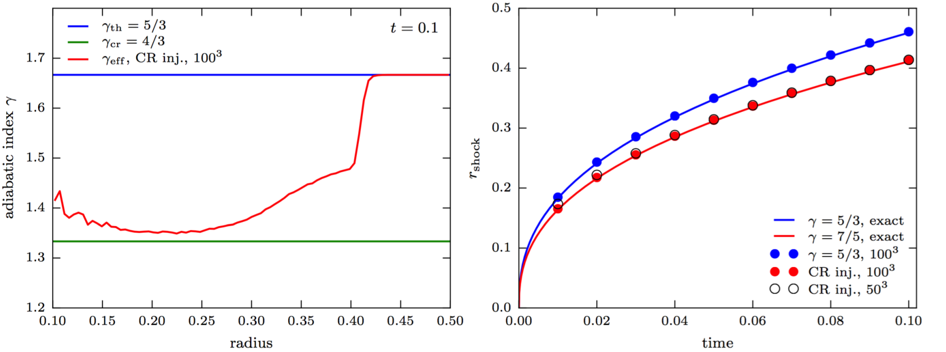


C.P., Pakmor, Schaal, Simpson, Springel (2016)

Sedov explosion with CR acceleration

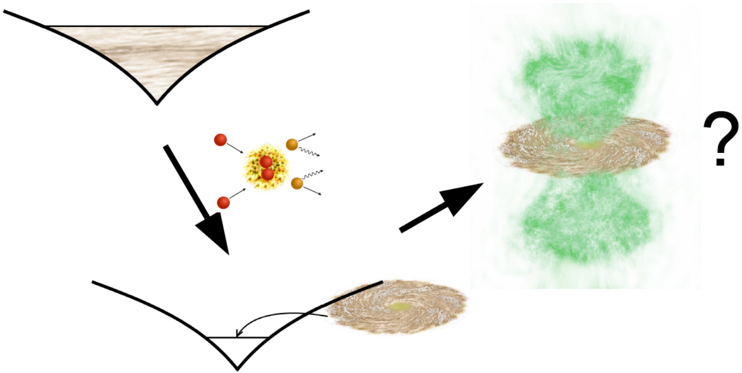
adiabatic index

shock evolution



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

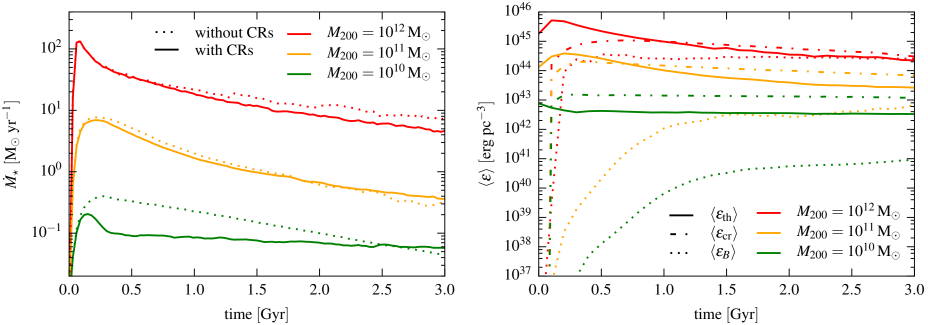
Galaxy simulation setup: 1. cosmic ray advection



C.P., Pakmor, Schaal, Simpson, Springel (2016)
Simulating cosmic ray physics on a moving mesh

MHD + cosmic ray advection

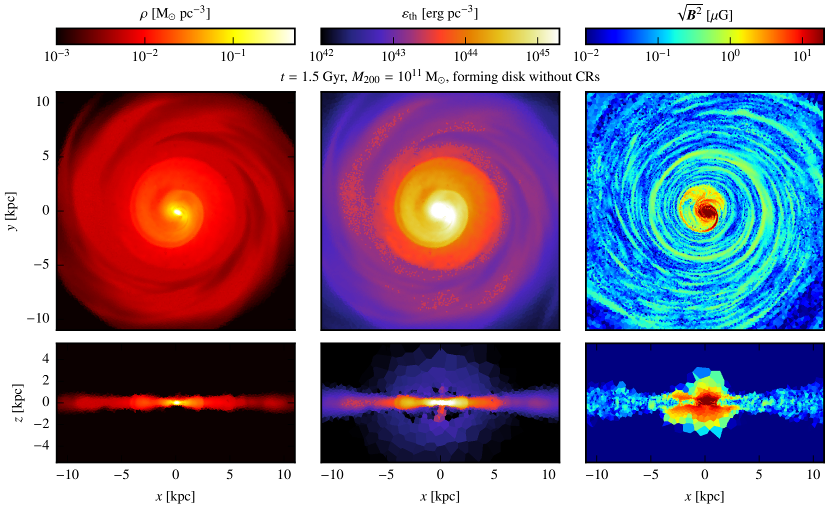
Time evolution of SFR and energy densities



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

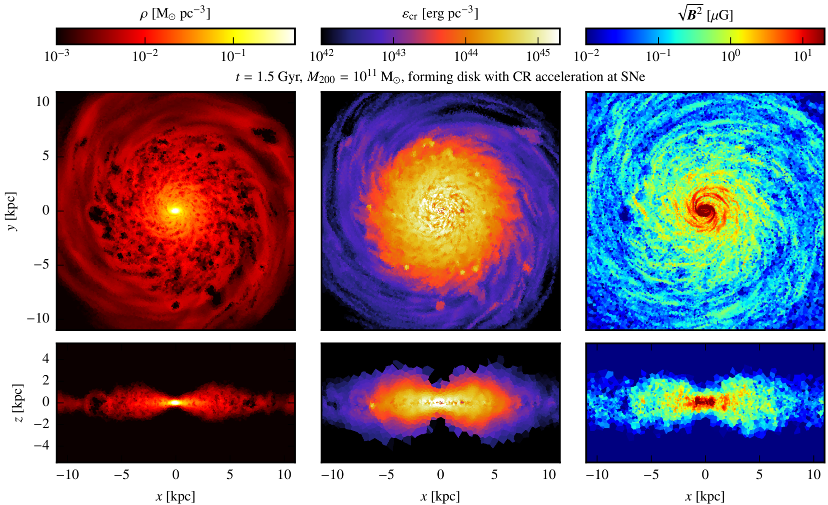
- CR pressure feedback suppresses SFR more in smaller galaxies
- energy budget in disks is dominated by CR pressure
- magnetic dynamo faster in Milky Way galaxies than in dwarfs

MHD galaxy simulation without CRs



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

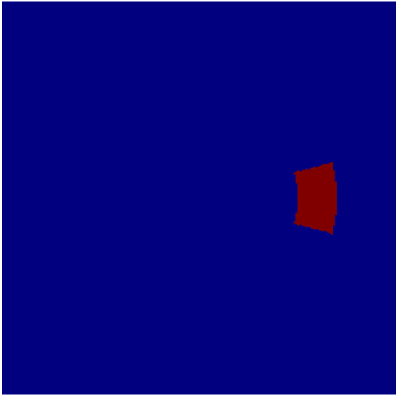
MHD galaxy simulation with CRs



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

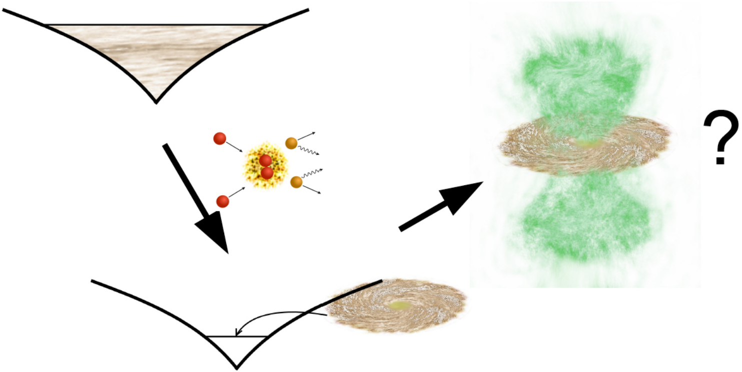
Anisotropic CR diffusion

- diffusion of CR energy density along magnetic field lines
- implemented on unstructured mesh in AREPO
- implicit solver with local time stepping
- obeys 1. and 2. law of thermodynamics (energy and entropy flux conserving)



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

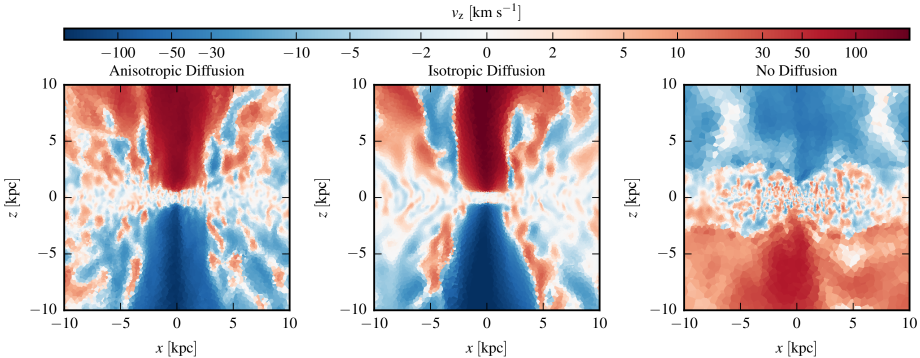
Galaxy simulation setup: 2. cosmic ray diffusion



Pakmor, C.P., Simpson, Springel (2016)
Galactic winds driven by isotropic and anisotropic cosmic ray diffusion in isolated disk galaxies

MHD + cosmic ray advection + diffusion, $M_{200} = 10^{11}\,\mathrm{M}_\odot$

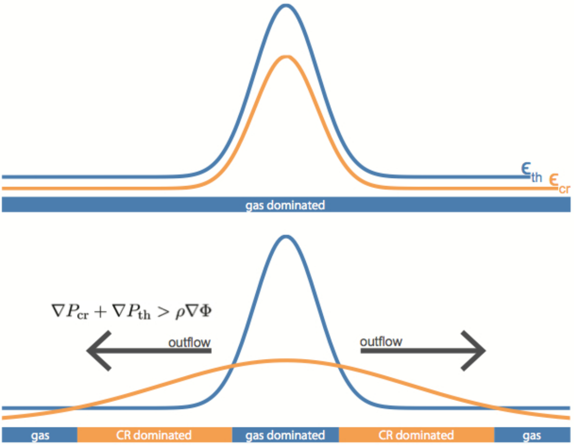
MHD galaxy simulation with CR diffusion



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

- CR diffusion launches powerful winds
- simulation without CR diffusion exhibits only weak fountain flows

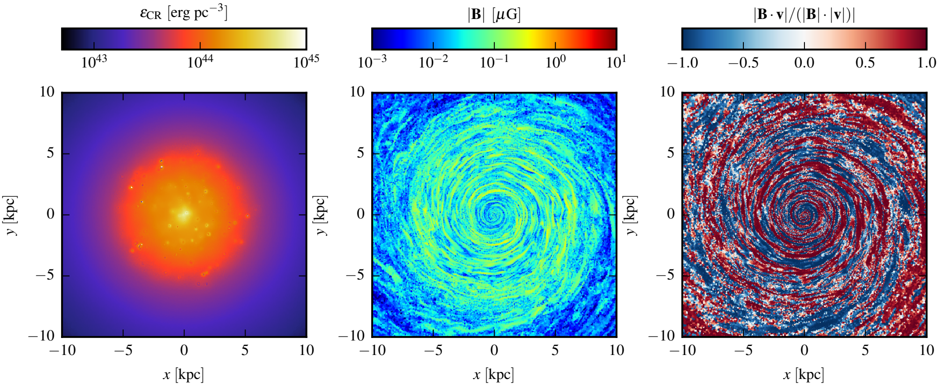
Cosmic ray driven wind: mechanism



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

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

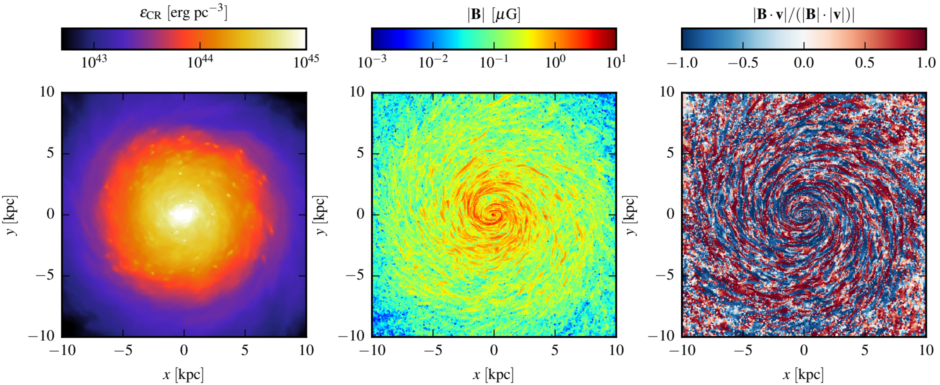
MHD galaxy simulation with CR isotropic diffusion



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

- CR diffusion strongly suppresses SFR
- strong outflow quenches magnetic dynamo to yield $B \sim 0.1\ \mu\mathrm{G}$

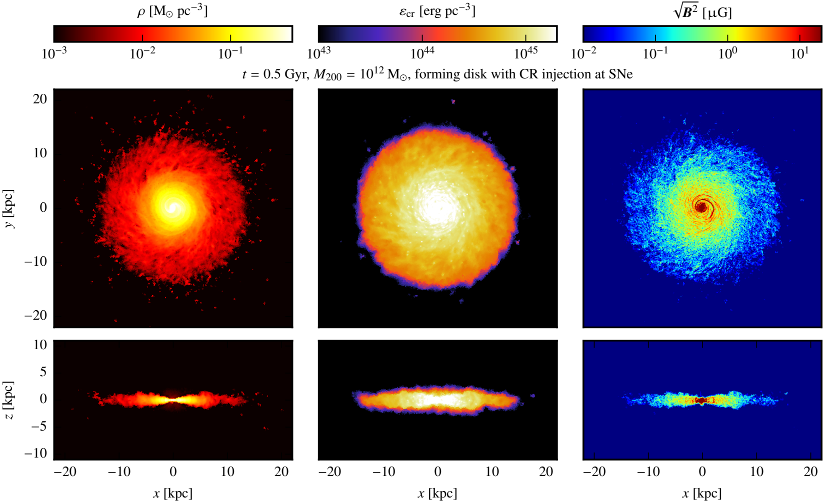
MHD galaxy simulation with CR anisotropic diffusion



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

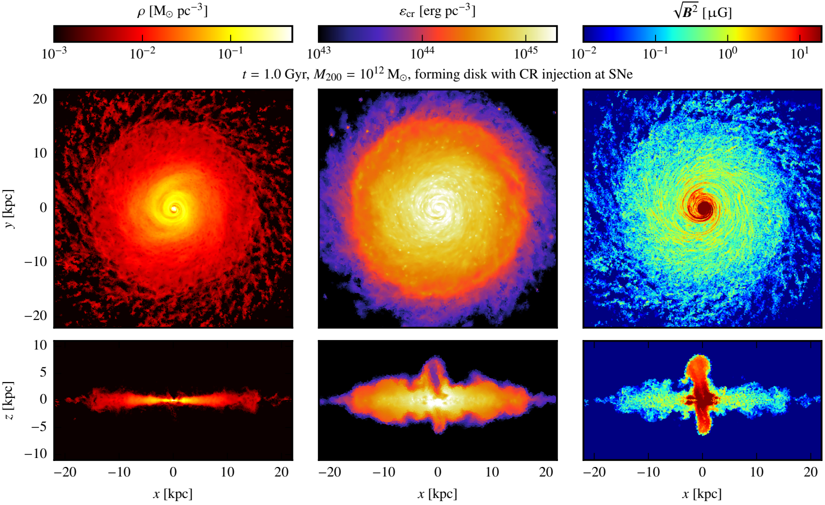
- anisotropic CR diffusion also suppresses SFR
- reactivation of magnetic dynamo: growth to observed strengths

Simulation of Milky Way-like galaxy, $t = 0.5$ Gyr



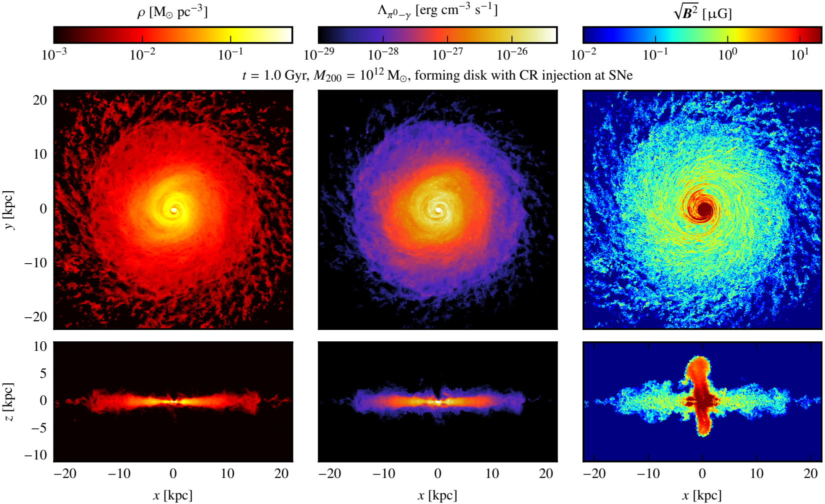
C.P.+ in prep.

Simulation of Milky Way-like galaxy, $t = 1.0$ Gyr



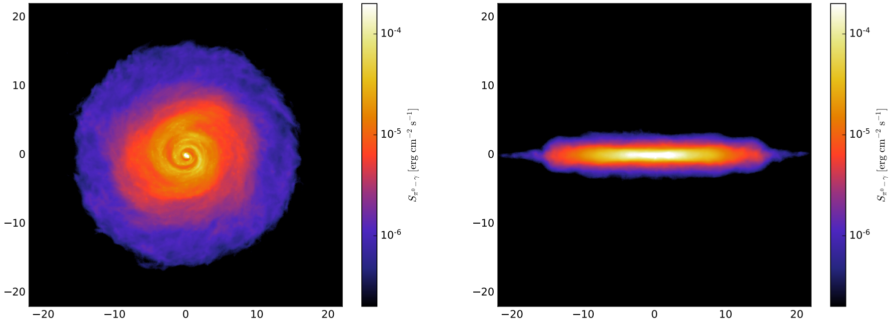
C.P.+ in prep.

Simulation of Milky Way-like galaxy: γ-ray emission



C.P.+ in prep.

Projected γ-ray emission of Milky Way-like galaxy



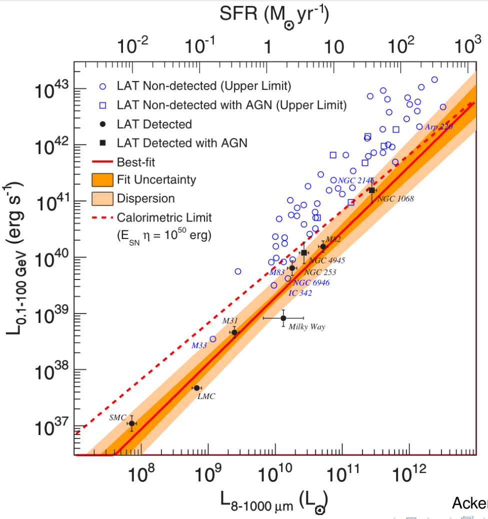
C.P.+ in prep.

- pion decay γ-ray emission shows no *Fermi*-like bubbles due to low density in wind region $\rightarrow$ leptonic emission? (Selig+ 2015)
- compute gamma-ray luminosity $\rightarrow L_{\mathrm{FIR}} - L_\gamma$

HITS

Far infra-red – gamma-ray correlation

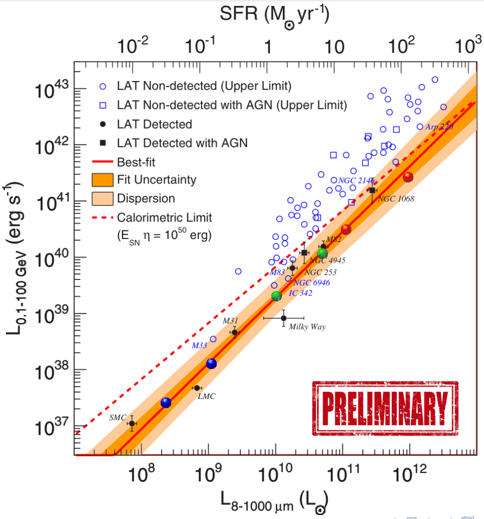
Universal conversion: star formation → cosmic rays → gamma rays



Ackermann+ (2012)

Far infra-red – gamma-ray correlation

Universal conversion: star formation → cosmic rays → gamma rays



C.P.+ in prep.

Conclusions on cosmic-ray feedback in galaxies

- CR pressure feedback slows down star formation
- galactic winds are naturally explained by CR diffusion
- anisotropic CR diffusion necessary for efficient galactic dynamo: observed field strengths of $B \sim 10\,\mu$G

Conclusions on cosmic-ray feedback in galaxies

- CR pressure feedback slows down star formation
- galactic winds are naturally explained by CR diffusion
- anisotropic CR diffusion necessary for efficient galactic dynamo: observed field strengths of $B \sim 10\,\mu$G
- no hadronic *Fermi*-like bubbles $\rightarrow$ leptonic emission?
- $L_{\mathrm{FIR}} - L_{\gamma}$ correlation allows to test calorimetric assumption

Conclusions on cosmic-ray feedback in galaxies

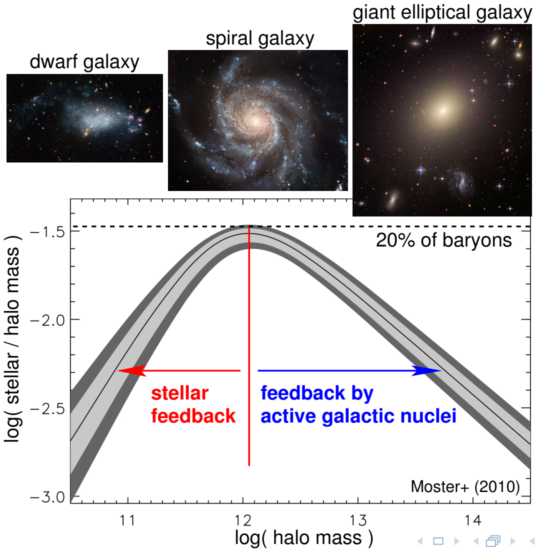
- CR pressure feedback slows down star formation
- galactic winds are naturally explained by CR diffusion
- anisotropic CR diffusion necessary for efficient galactic dynamo: observed field strengths of $B \sim 10\,\mu$G
- no hadronic *Fermi*-like bubbles $\rightarrow$ leptonic emission?
- $L_{\mathrm{FIR}} - L_\gamma$ correlation allows to test calorimetric assumption

outlook: improved modeling of plasma physics, follow CR spectra, cosmological settings

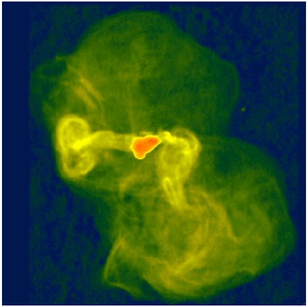
need: spatially/spectrally resolved γ-ray observations $\rightarrow$ **CTA**

Outline

Puzzles in galaxy formation



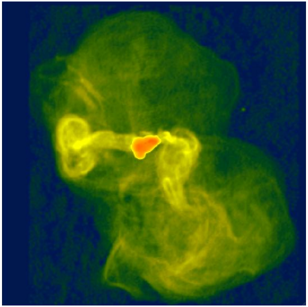
Messier 87 at radio wavelengths



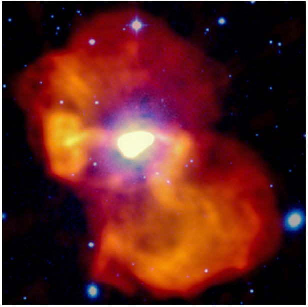
$\nu = 1.4$ GHz (Owen+ 2000)

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

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

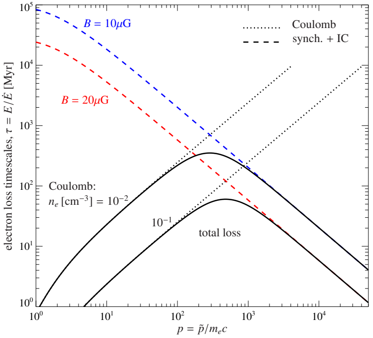
solutions:

- 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)

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



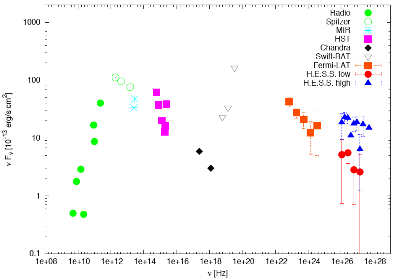
C.P. (2013)

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!**

AGN feedback = cosmic ray heating (?)

hypothesis: low state γ-ray emission traces π^0 decay within cluster

- cosmic rays excite Alfvén waves that dissipate the energy → heating rate

$$\mathcal{H}_{\rm cr} = -\boldsymbol{v}_{\rm st} \cdot \nabla P_{\rm cr}$$

(Loewenstein+ 1991, Guo & Oh 2008, Enßlin+ 2011, Wiener+ 2013, C.P. 2013)

- calibrate $P_{\rm cr}$ to γ-ray emission and $|\boldsymbol{v}_{\rm st}| = |\boldsymbol{v}_{\rm A}|$ to radio/X-ray emission → spatial heating profile

AGN feedback = cosmic ray heating (?)

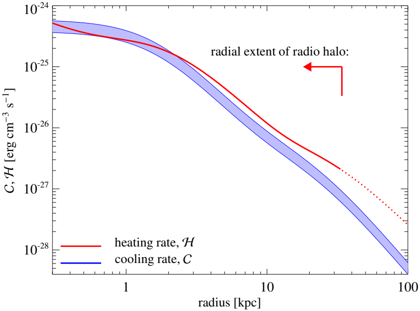
hypothesis: low state γ-ray emission traces π^0 decay within cluster

- cosmic rays excite Alfvén waves that dissipate the energy $\rightarrow$ heating rate

$$\mathcal{H}_{\rm cr} = -\boldsymbol{v}_{\rm st} \cdot \nabla P_{\rm cr}$$

(Loewenstein+ 1991, Guo & Oh 2008, Enßlin+ 2011, Wiener+ 2013, C.P. 2013)

- calibrate $P_{\rm cr}$ to γ-ray emission and $|\boldsymbol{v}_{\rm st}| = |\boldsymbol{v}_{\rm A}|$ to radio/X-ray emission $\rightarrow$ spatial heating profile

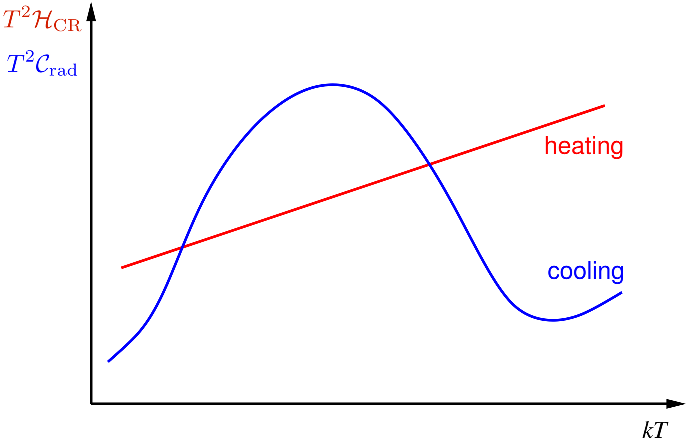


C.P. (2013)

$\rightarrow$ cosmic-ray heating matches radiative cooling (observed in X-rays) and may solve the famous "cooling flow problem" in galaxy clusters!

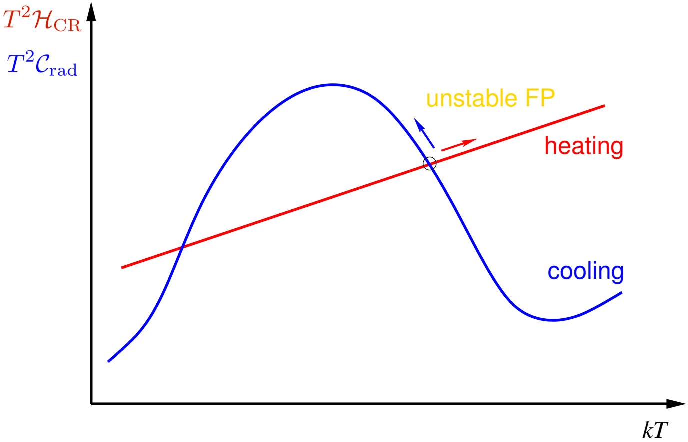
HITS

Local stability analysis (1)



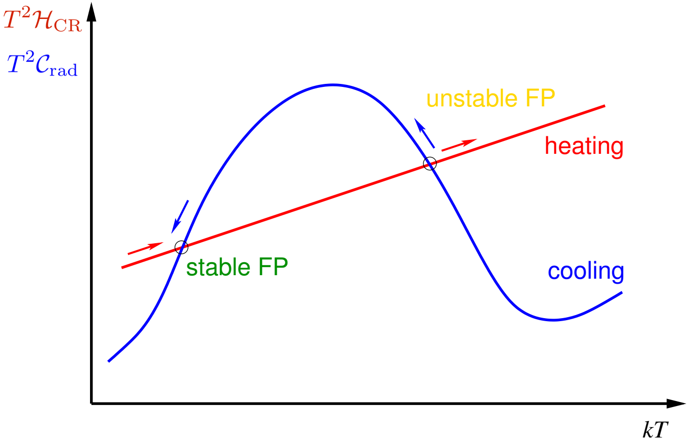
- isobaric perturbations to global thermal equilibrium
- CRs are adiabatically trapped by perturbations

Local stability analysis (1)



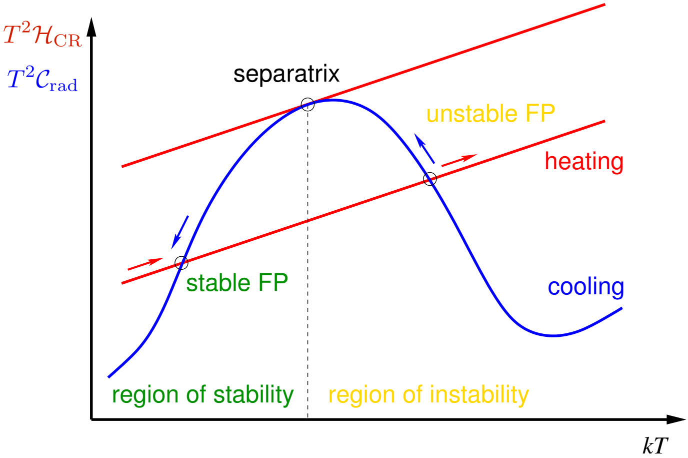
- isobaric perturbations to global thermal equilibrium
- CRs are adiabatically trapped by perturbations

Local stability analysis (1)



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

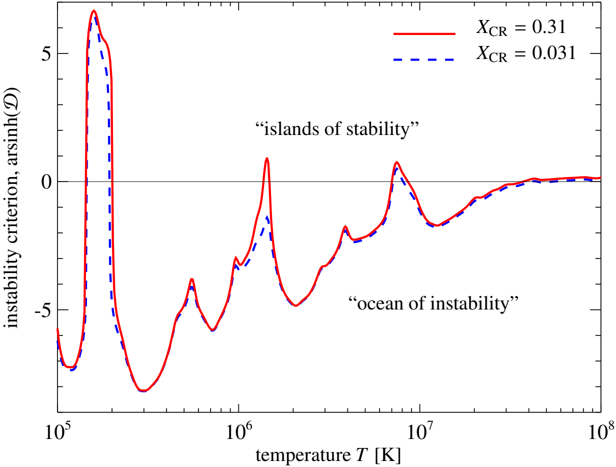
Local stability analysis (1)



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

Local stability analysis (2)

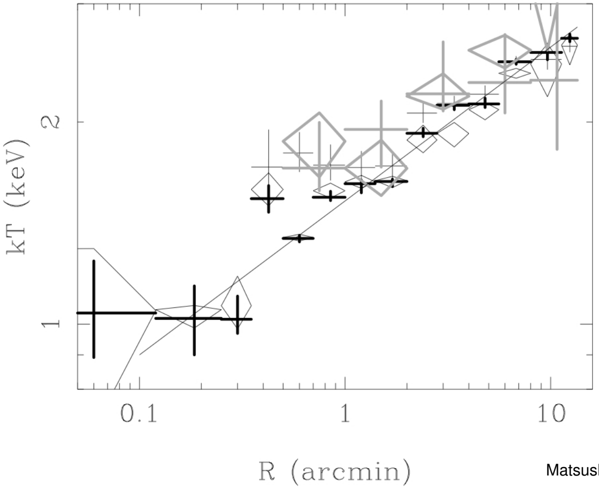
Theory predicts observed temperature floor at $kT \simeq 1$ keV



C.P. (2013)

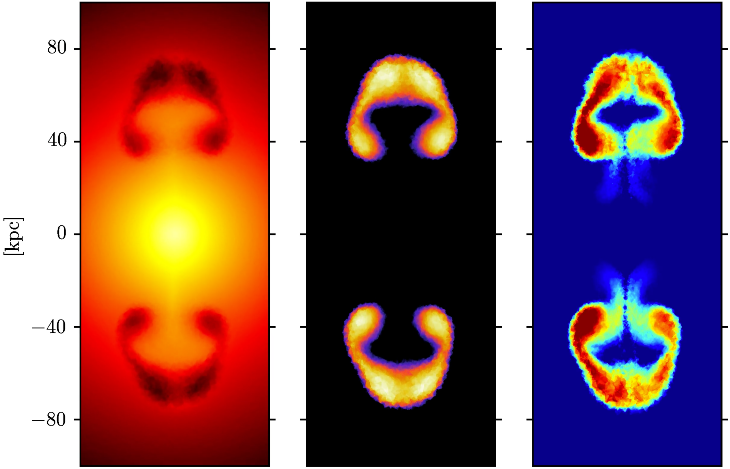
Virgo cluster cooling flow: temperature profile

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



Matsushita+ (2002)

Jet simulation: gas density, CR energy, *B* field



Weinberger+ in prep.

Conclusions on AGN feedback by cosmic-ray heating

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

Conclusions on AGN feedback by cosmic-ray heating

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

outlook: couple CRs to AGN jet model, simulate anisotropically steaming CRs, cosmological cluster simulations

need: deeper radio/γ-ray observations $\rightarrow$ **CTA**

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

This project has received funding from the European Research Counsil (ERC) under the European Union's Horizon 2020 research and innovation program (grant agreement No CRAGSMAN–646955).

Literature for the talk

Cosmic ray feedback in galaxies:

- Pfrommer, Pakmor, Schaal, Simpson, Springel, *Simulating cosmic ray physics on a moving mesh,* 2016, MNRAS.
- Pakmor, Pfrommer, Simpson, Springel, *Galactic winds driven by isotropic and anisotropic cosmic ray diffusion in isolated disk galaxies,* 2016, ApJL.
- Pakmor, Pfrommer, Simpson, Kannan, Springel, *Semi-implicit anisotropic cosmic ray transport on an unstructured moving mesh,* 2016, MNRAS.

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.