Unveiling the physics of feedback in galaxy formation

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in collaboration with

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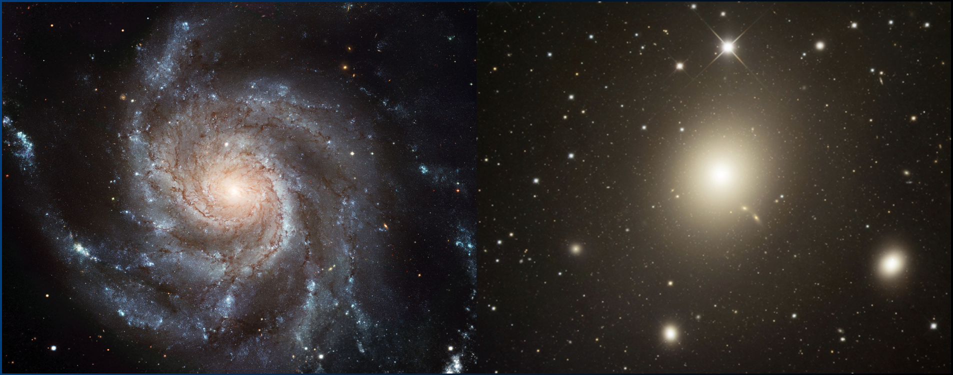
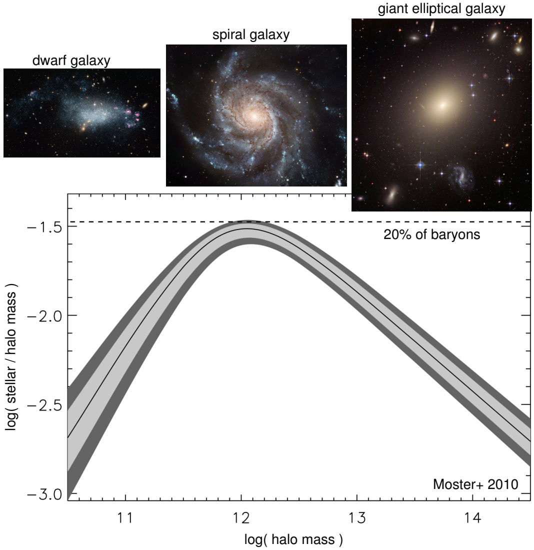
Outline

1. Introduction and Motivation
   - Puzzles in galaxy formation
   - Galactic winds
   - Cosmic rays
2. Cosmic ray simulations
   - Sedov explosions
   - Galaxy simulations
   - Cosmological simulations
3. AGN feedback
   - Heating the cooling gas in M87
   - Diversity of cool core clusters
   - Conclusions

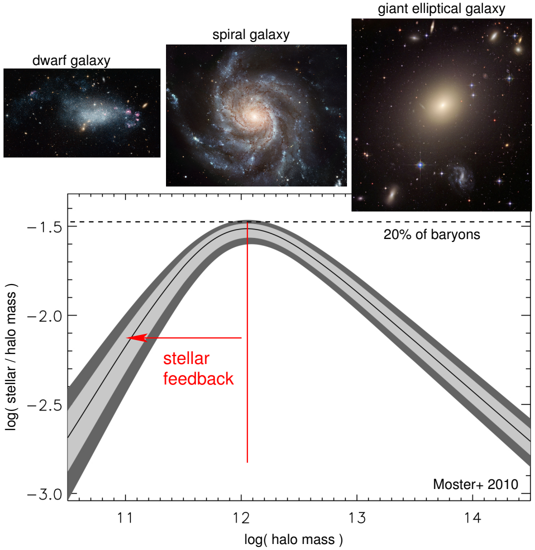
Puzzles in galaxy formation



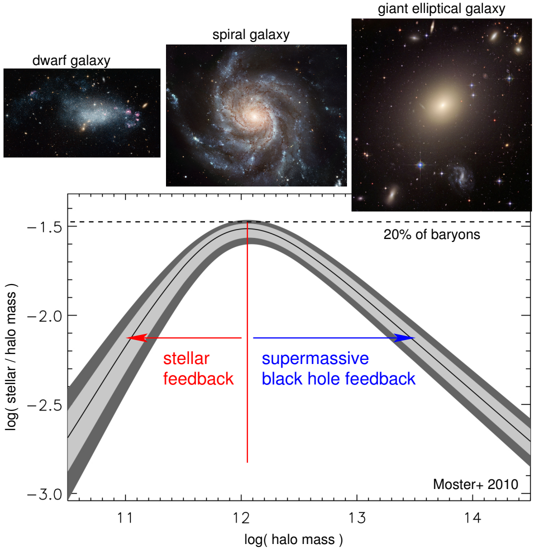
Puzzles in galaxy formation



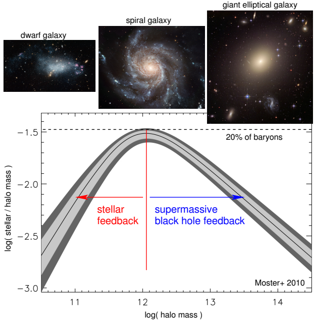
Puzzles in galaxy formation



Puzzles in galaxy formation



Puzzles in galaxy formation



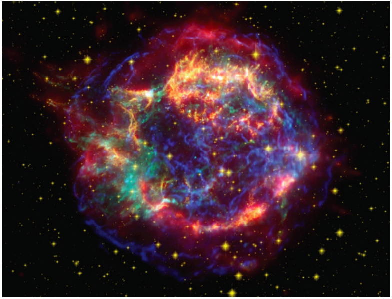
Bright-end of luminosity function:

- 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**

Galactic winds



supernova Cassiopeia A

X-ray: NASA/CXC/SAO; Optical: NASA/STScI;
Infrared: NASA/JPL-Caltech/Steward/O.Krause et al.

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

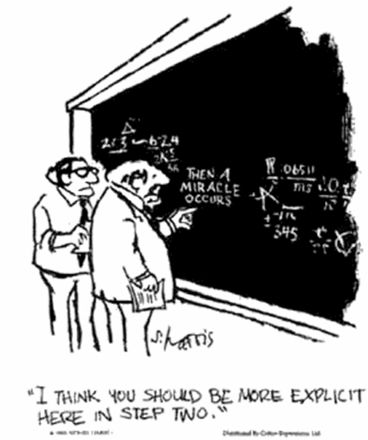
Galactic winds

super wind in M82

NASA/JPL-Caltech/STScI/CXC/UofA

- galactic supernova remnants drive shock waves, turbulence, accelerate electrons + protons, amplify magnetic fields
- star formation and supernovae drive gas out of galaxies by galactic super winds
- critical for understanding the physics of galaxy formation $\rightarrow$ may explain puzzle of low star conversion efficiency in dwarf galaxies

Galactic winds



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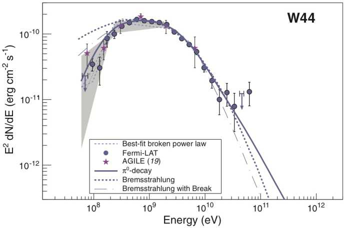
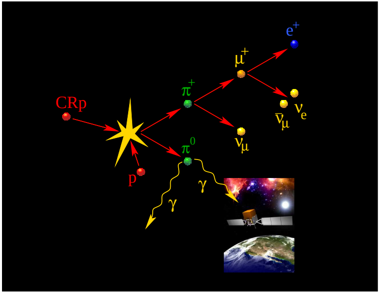
The role of supernova remnants

- supernova remnant shocks amplify magnetic fields and accelerate CR electrons up to $\sim$ 100 TeV (narrow X-ray synchrotron filaments observed by *Chandra*)
- pion bump provides evidence for CR proton acceleration (*Fermi*/AGILE γ-ray spectra)

Fermi observations of W44:



Ackermann+ (2013)



The role of supernova remnants

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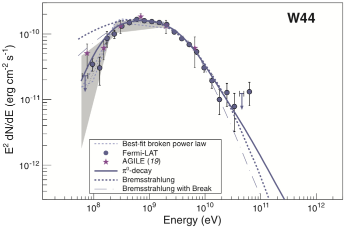
- pion bump provides evidence for CR proton acceleration (*Fermi*/AGILE γ-ray spectra)
- shell-type SNRs show evidence for efficient shock acceleration beyond $\sim$ 100 TeV (HESS TeV γ-ray observations)

Fermi observations of W44:



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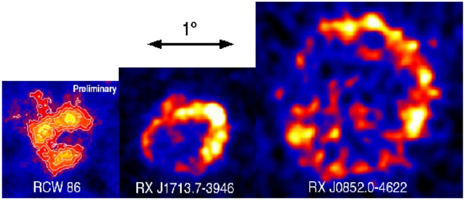
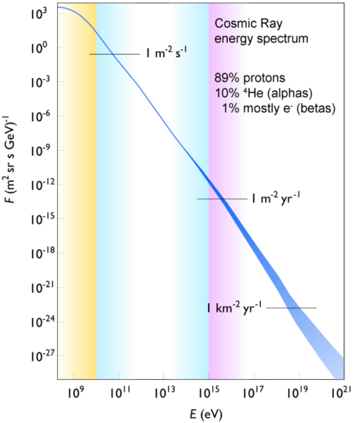
HESS observations of shell-type SNRs:



Hinton (2009)

Galactic cosmic ray spectrum

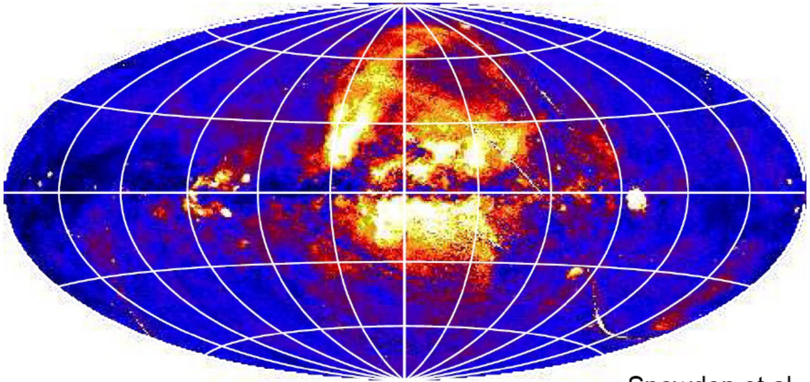


data compiled by Swordy

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

Galactic wind in the Milky Way?

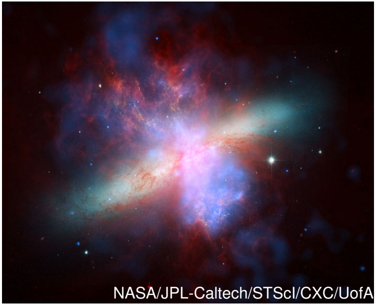
Diffuse X-ray emission in our galaxy



Snowden et al., 2007

. . . as suggested by Everett+ (2008) and Everett, Schiller, Zweibel (2010)

How are galactic winds driven?



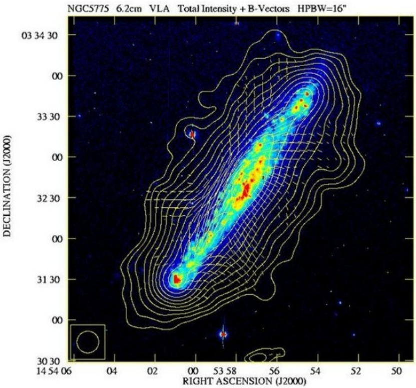
super wind in M82

- 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

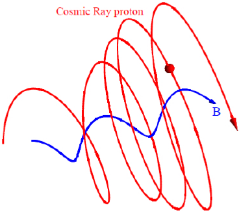


Tüllmann+ (2000)

- 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 → 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**

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 $\boldsymbol{B}$):

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

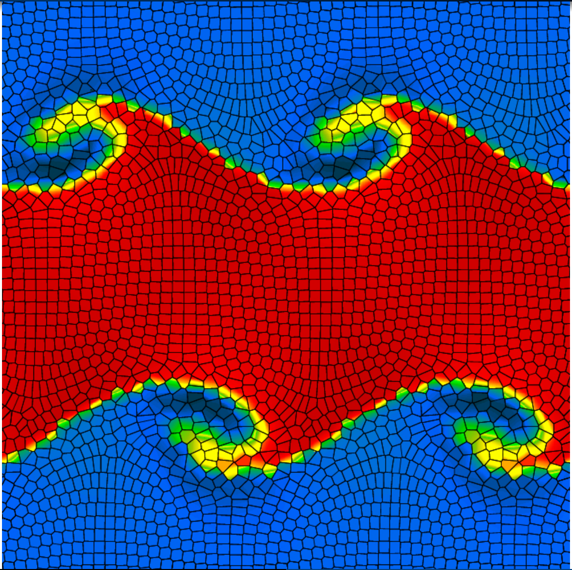
- energy equations with $\varepsilon = \varepsilon_{\rm th} + \rho v^2/2$:

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

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

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

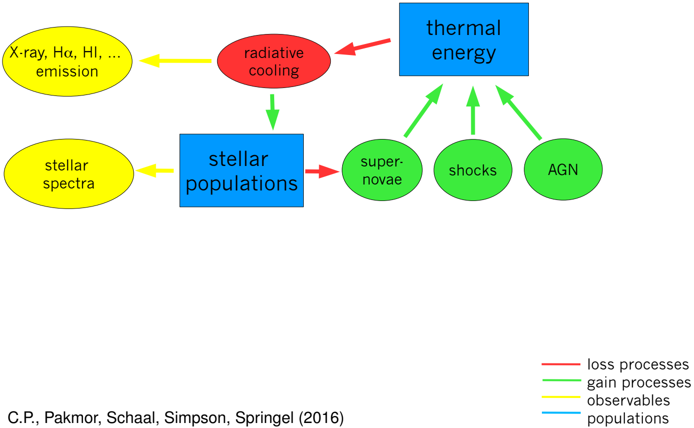
Cosmological moving-mesh code AREPO (Springel 2010)



Simulations – flowchart

ISM observables:

Physical processes in the ISM:



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

Simulations with cosmic ray physics

ISM observables:

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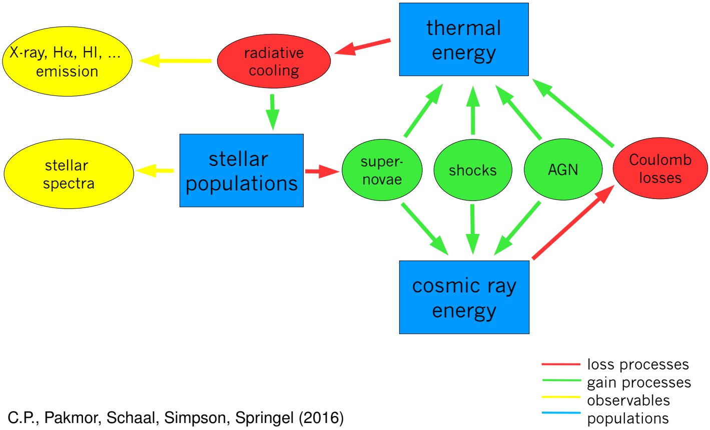

C.P., Pakmor, Schaal, Simpson, Springel (2016)

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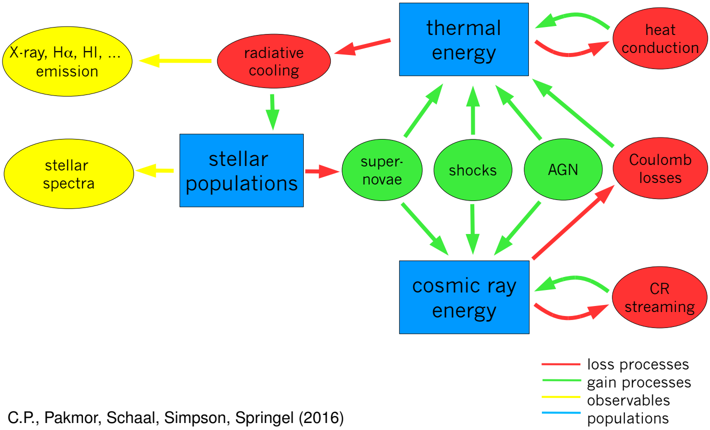

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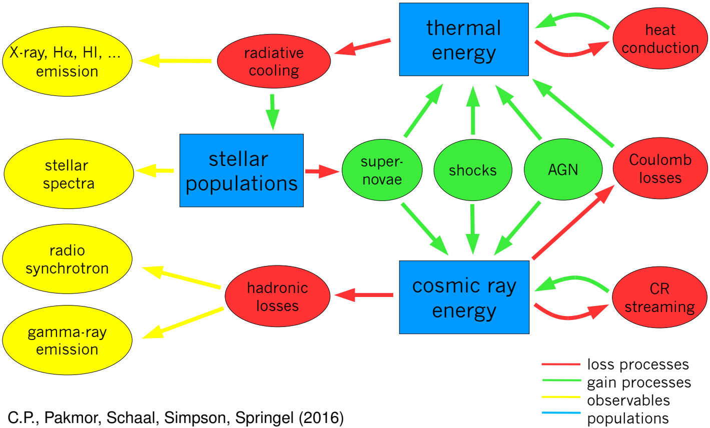
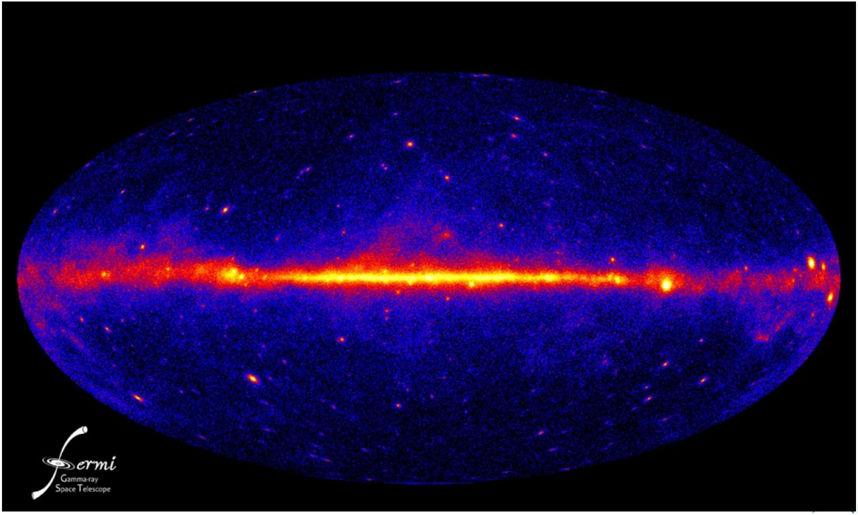


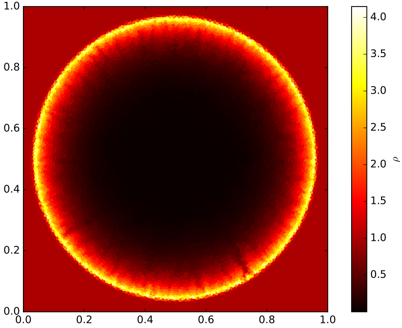
C.P., Pakmor, Schaal, Simpson, Springel (2016)

Gamma-ray emission of the Milky Way

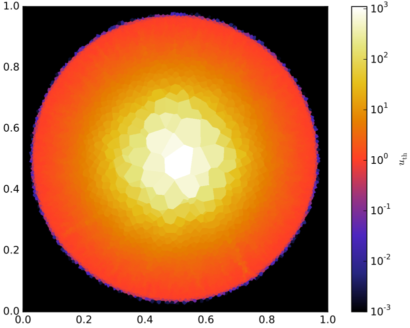


Sedov explosion

density

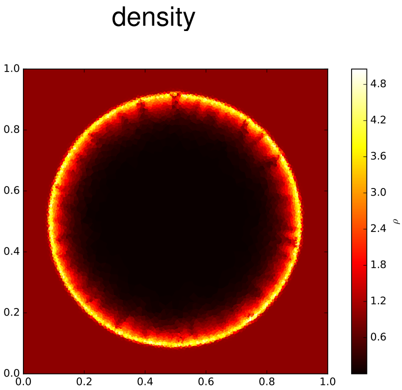


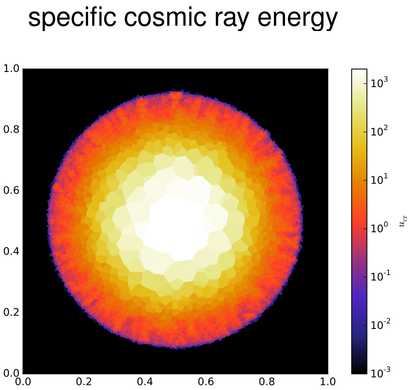
specific thermal energy



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

Sedov explosion with CR acceleration

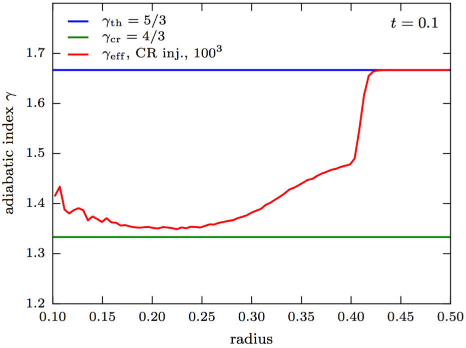




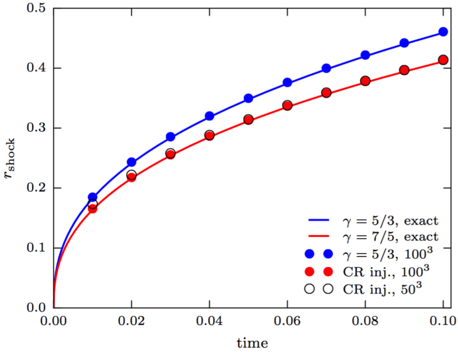
C.P., Pakmor, Schaal, Simpson, Springel (2016)

Sedov explosion with CR acceleration

adiabatic index



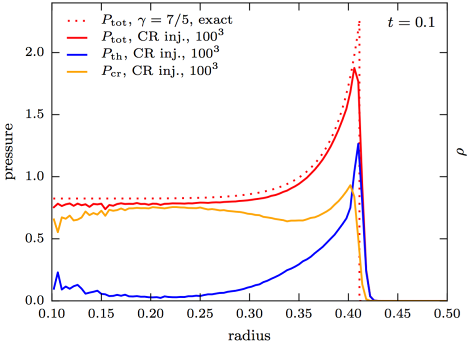
shock evolution



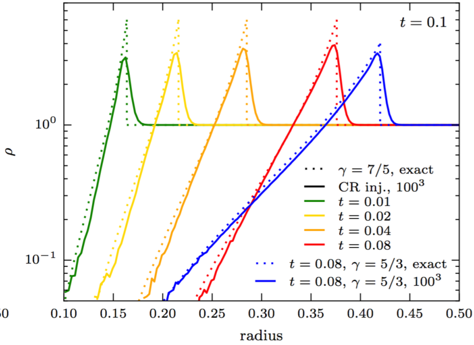
C.P., Pakmor, Schaal, Simpson, Springel (2016)

Sedov explosion with CR acceleration

pressure

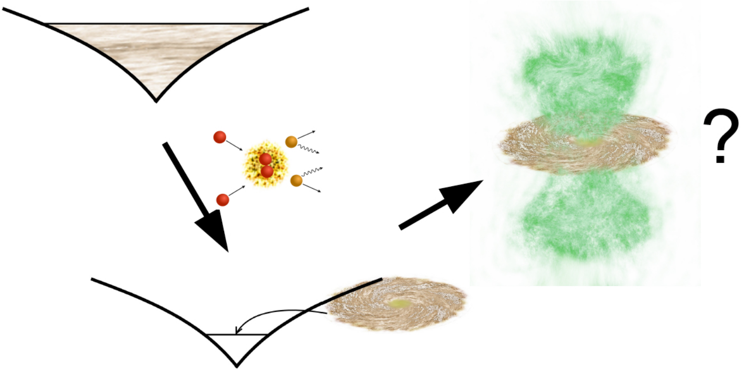


density



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

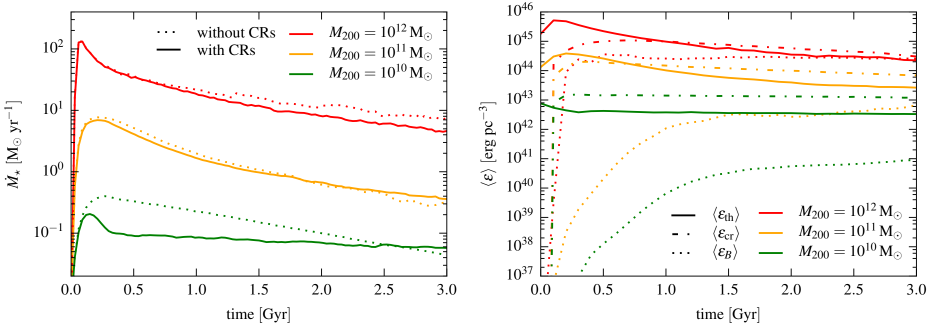
Galaxy simulation setup: 1. cosmic ray advection



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

MHD + cosmic ray advection

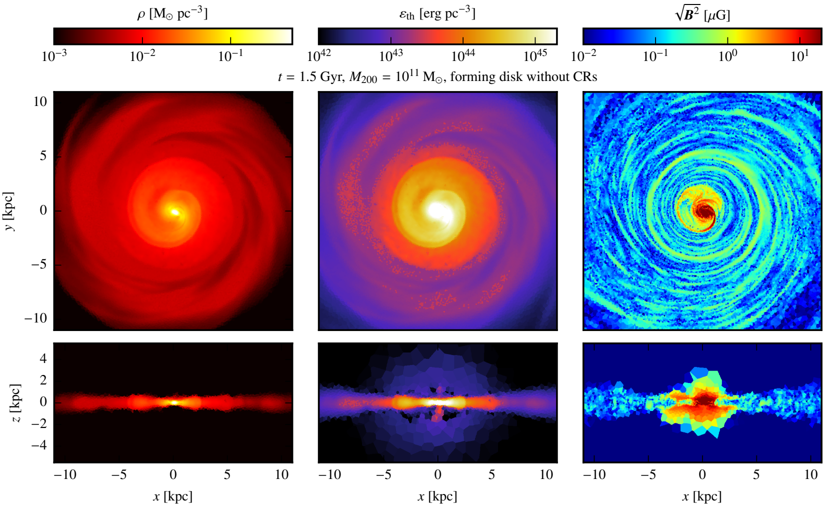
Time evolution of SFR and energy densities



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

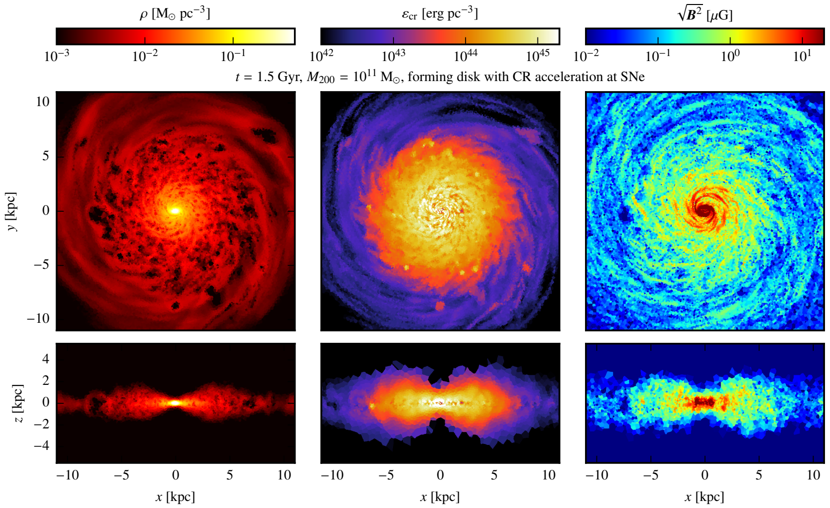
- CR pressure feedback suppresses SFR more in smaller galaxies
- energy budget in disks is dominated by CR pressure
- magnetic dynamo faster in Milky Way galaxies than in dwarfs

MHD galaxy simulation without CRs



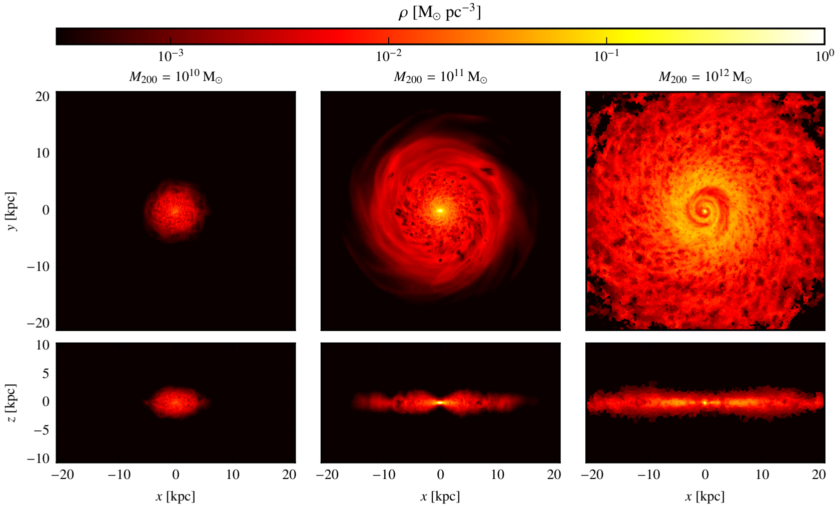
C.P., Pakmor, Schaal, Simpson, Springel (2016)

MHD galaxy simulation with CRs



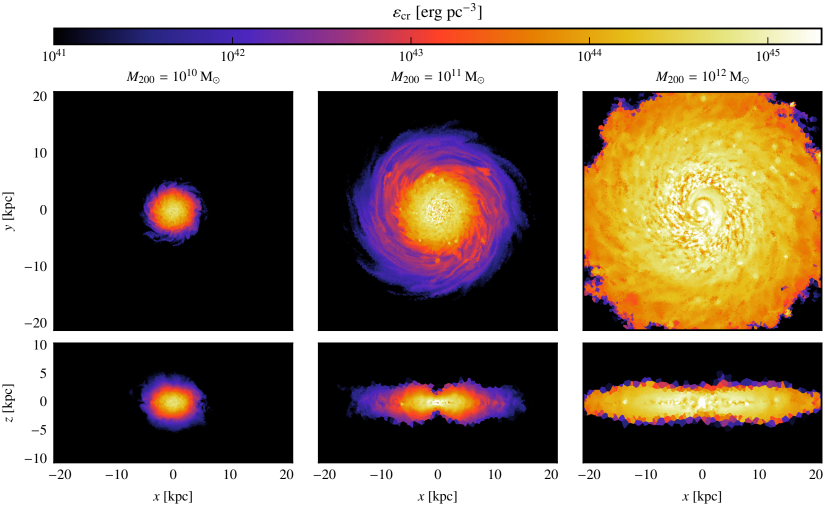
C.P., Pakmor, Schaal, Simpson, Springel (2016)

Gas density in galaxies from 10^{10} to $10^{12}\,M_\odot$



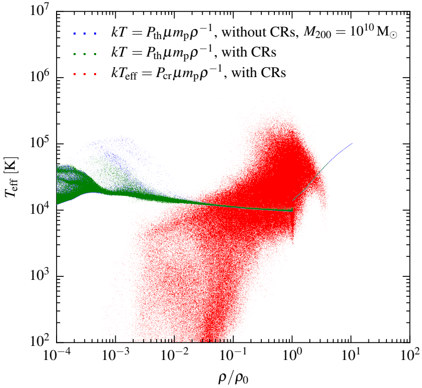
C.P., Pakmor, Schaal, Simpson, Springel (2016)

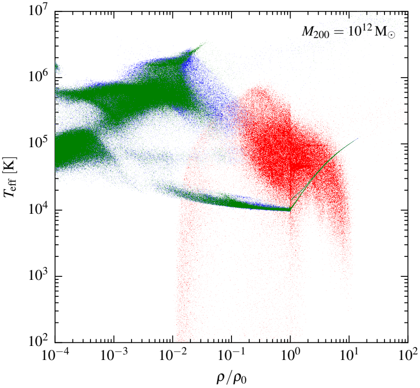
CR energy density in galaxies from 10^{10} to 10^{12} $M_\odot$



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

Temperature-density plane: CR pressure feedback

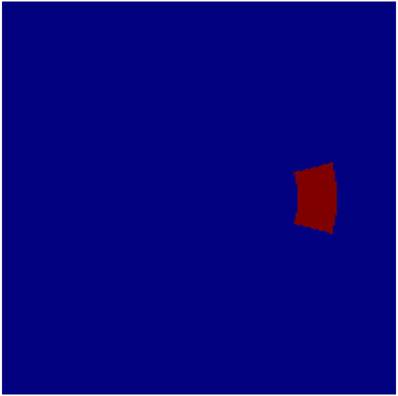




C.P., Pakmor, Schaal, Simpson, Springel (2016)

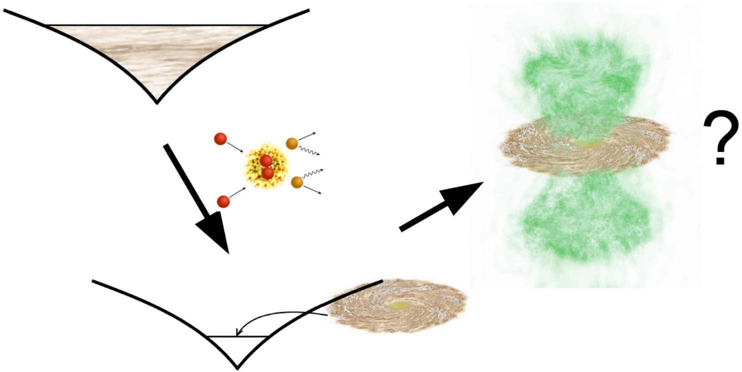
Anisotropic CR diffusion

- 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)

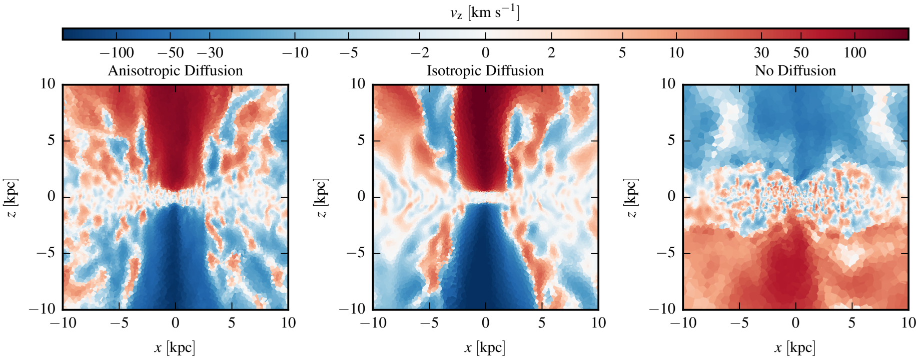
Galaxy simulation setup: 2. cosmic ray diffusion



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

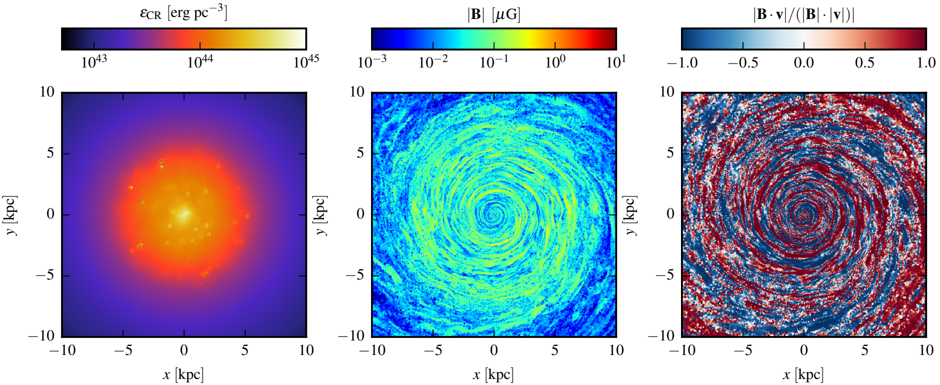
MHD galaxy simulation with CR diffusion



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

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

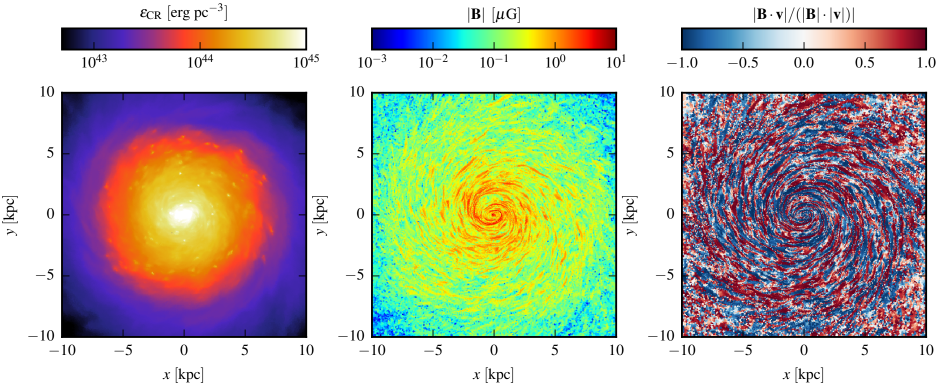
MHD galaxy simulation with CR isotropic diffusion



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

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

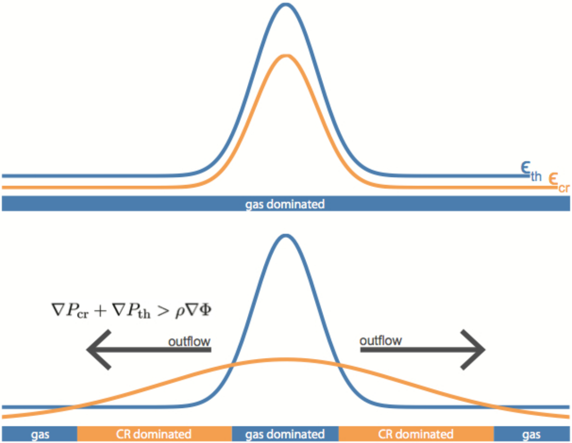
MHD galaxy simulation with CR anisotropic diffusion



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

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

Cosmic ray driven wind: mechanism



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

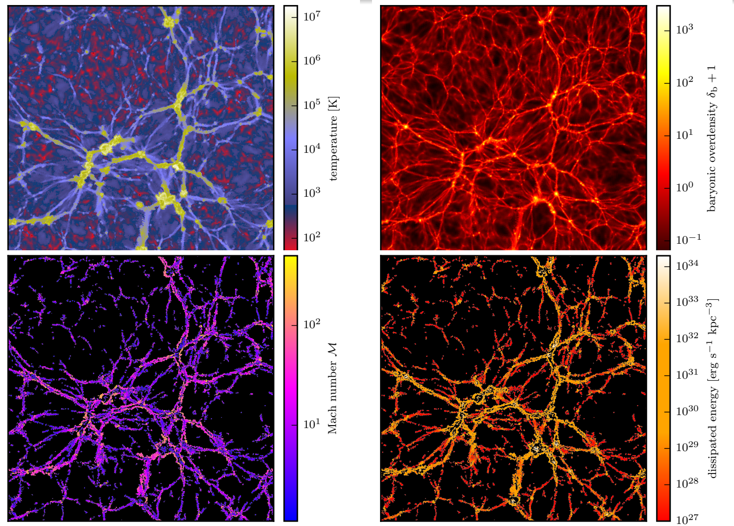
CR diffusion: Booth+ (2013), Hanasz+ (2013), Salem & Bryan (2014)

Conclusions on cosmic-ray feedback in galaxies

- CR pressure feedback slows down star formation and provides additional stability to galactic disks
- 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

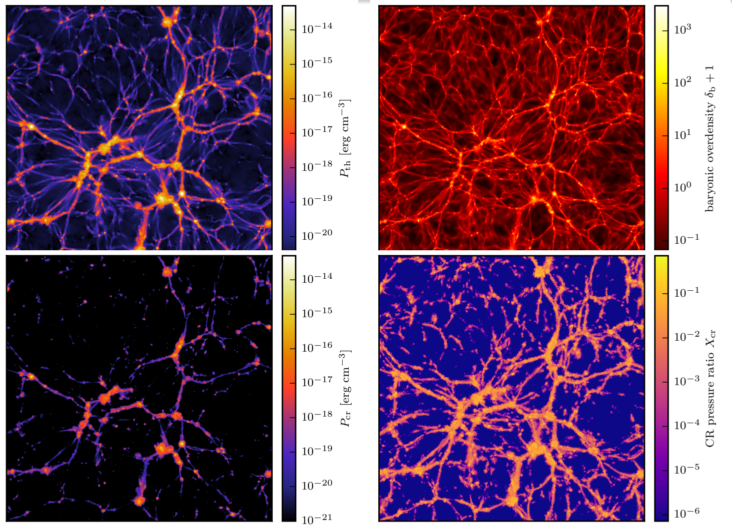
$\rightarrow$ versatile CR-MHD code to explore the physics of galaxy formation!
outlook: improved modeling of plasma physics, cosmological settings

Cosmological simulations with cosmic rays



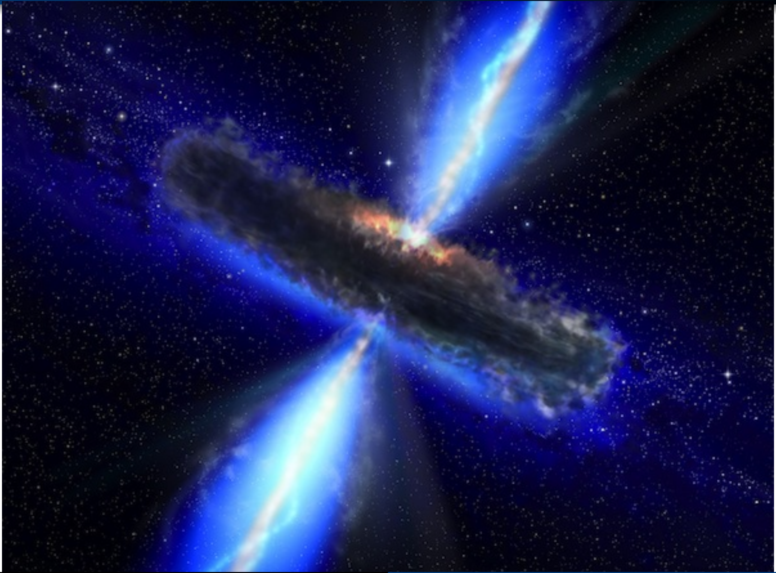
C.P., Pakmor, Schaal, Simpson, Springel (2016)

Cosmological simulations with cosmic rays



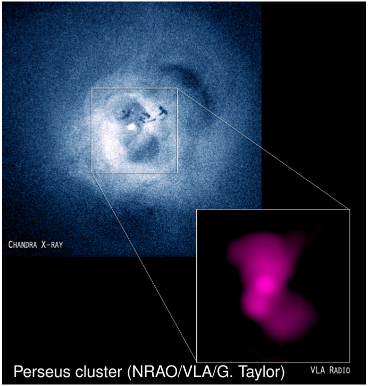
C.P., Pakmor, Schaal, Simpson, Springel (2016)

"Radio-mode" AGN feedback



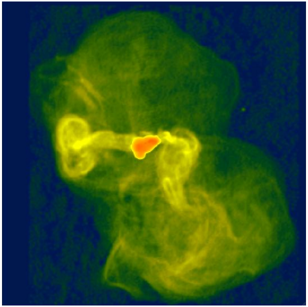
Radio mode feedback by AGN: open questions

- energy source:
  release of non-gravitational accretion energy of a black hole
- jet-ICM interaction and rising bubbles:
  1.) magnetic draping → amplification
  2.) CR confinement vs. release
  3.) excitation of turbulence
- heating mechanism:
  1.) self-regulated to avoid overcooling
  2.) thermally stable to explain T floor
  3.) low energy coupling efficiency
- cosmic ray heating:
  1.) are CRs efficiently mixed into the ICM?
  2.) is the CR heating rate sufficient to balance cooling?
  3.) how universal is this heating mechanism in cool cores?

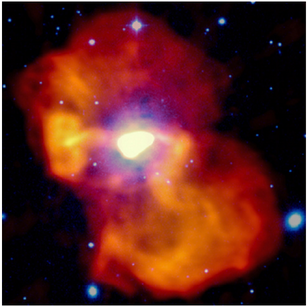


Perseus cluster (NRAO/VLA/G. Taylor)

Messier 87 at radio wavelengths



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



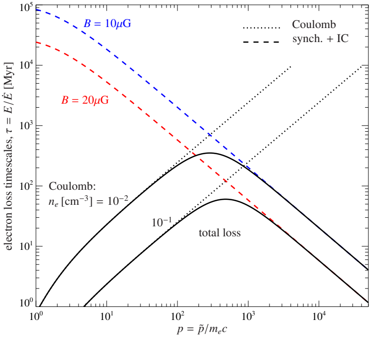
$\nu = 140$ MHz (LOFAR/de Gasperin+ 2012)

- 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:

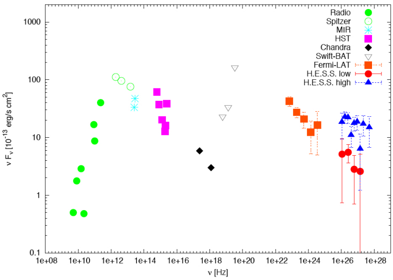
- special time: M87 turned on $\sim$ 40 Myr ago after long silence
  $\Leftrightarrow$ conflicts order unity duty cycle inferred from stat. AGN feedback studies (Birzan+ 2012)
- Coulomb cooling removes fossil electrons
  $\rightarrow$ efficient mixing of CR electrons and protons with dense cluster gas
  $\rightarrow$ 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 (?)



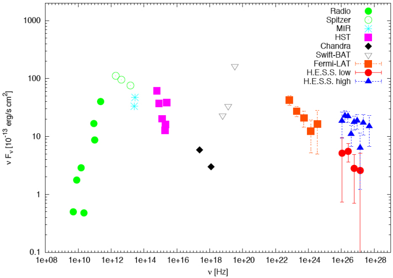
Rieger & Aharonian (2012)

$\rightarrow$ 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 $X_{cr} = P_{cr}/P_{th}$ (heating due to streaming CRs in steady state)
- $F_\gamma \propto \int \mathrm{d}V\, P_{cr}\, n$ enables to estimate $P_{cr}/P_{th} = 0.31$ (allowing for Coulomb cooling with $\tau_{Coul} = 40\,\mathrm{Myr}$)



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)

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

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

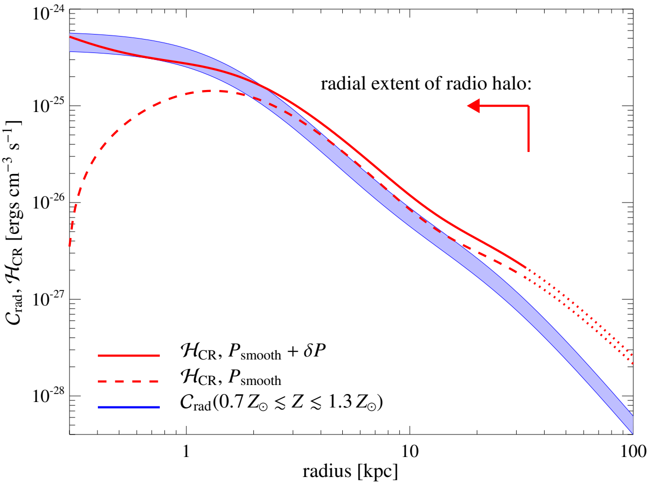
radiative cooling:

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

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

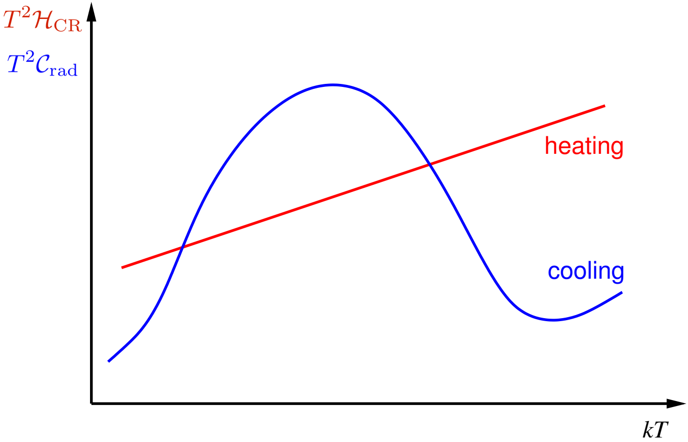
Cosmic-ray heating vs. radiative cooling (2)

Global thermal equilibrium on all scales in M87



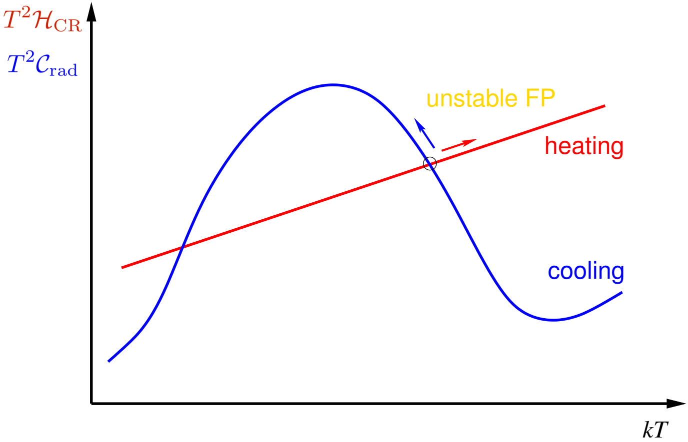
C.P. (2013)

Local stability analysis (1)



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

Local stability analysis (1)



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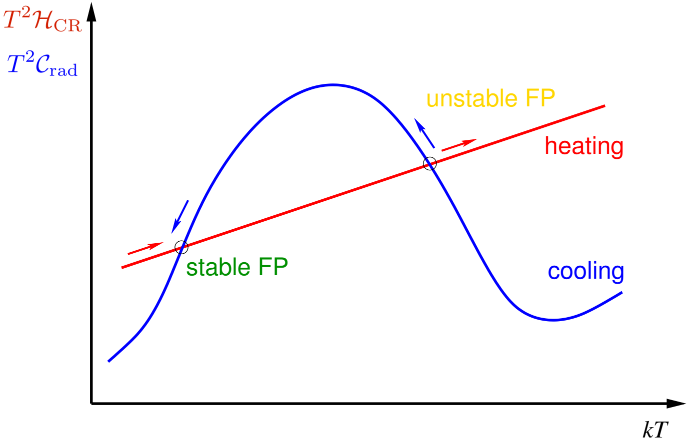

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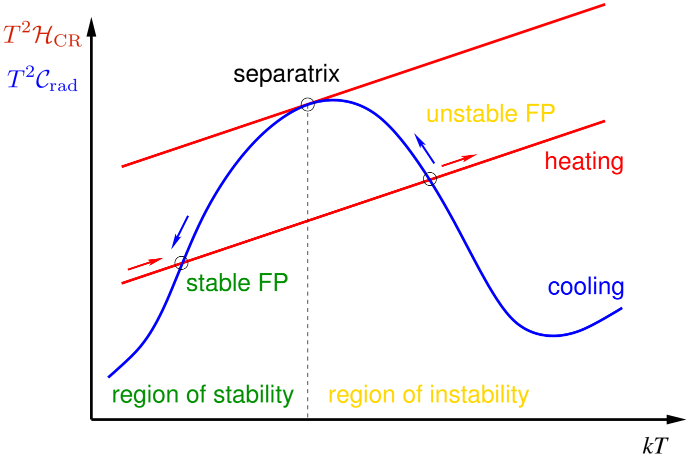
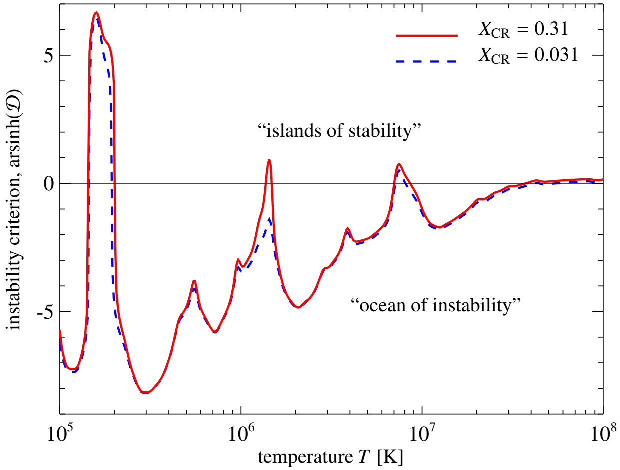
Local stability analysis (1)



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

Local stability analysis (2)

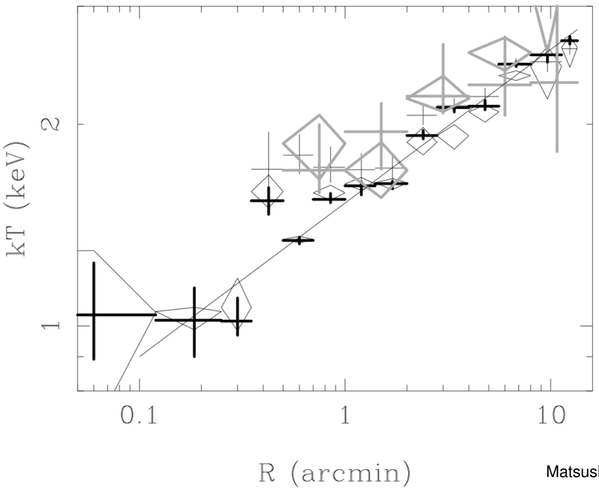
Theory predicts observed temperature floor at $kT \simeq 1$ keV



C.P. (2013)

Virgo cluster cooling flow: temperature profile

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



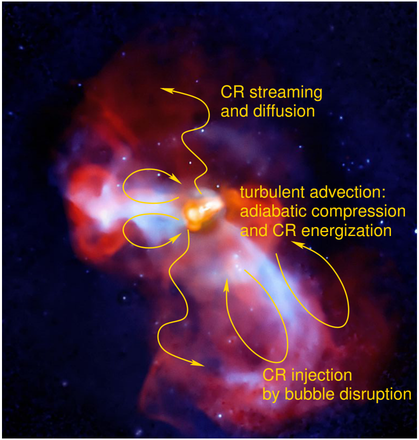
Matsushita+ (2002)

Emerging picture of CR feedback by AGNs

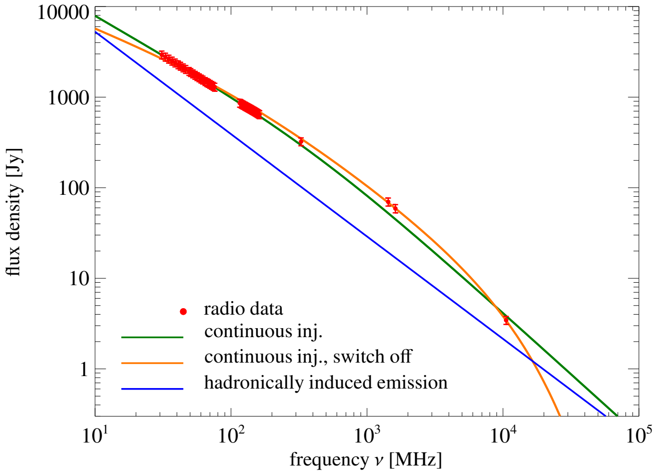
(1) during buoyant rise of bubbles: CRs diffuse and stream outward
$\rightarrow$ CR Alfvén-wave heating

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

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



Prediction: flattening of high-ν radio spectrum

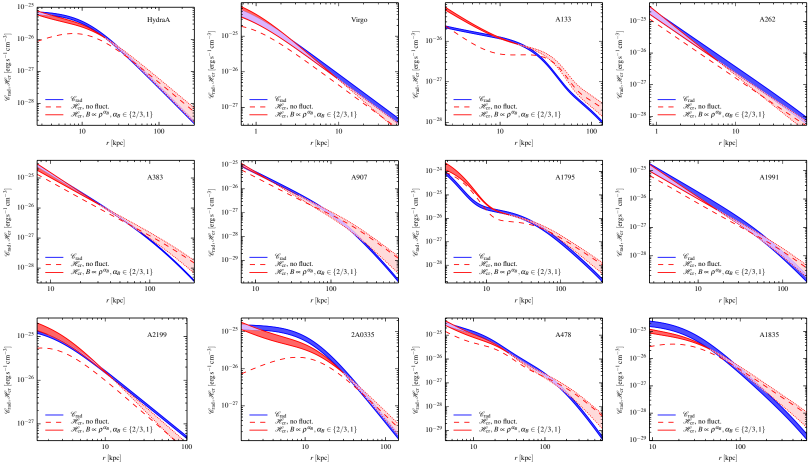


C.P. (2013)

How universal is CR heating in cool core clusters?

- no γ rays observed from other clusters $\rightarrow P_{\mathrm{cr}}$ unconstrained
- **strategy:** construct sample of 24 cool cores
  (1) assume $\mathcal{H}_{\mathrm{cr}} = \mathcal{C}_{\mathrm{rad}}$ at $r = r_{\mathrm{cool,\,1\,Gyr}}$
  (2) assume steady-state CR streaming: $P_{\mathrm{cr}} \propto P_{\mathrm{th}}$
  (3) adopt B model from Faraday rotation studies:
  $B = 40\,\mu\mathrm{G} \times \left(n/0.1\,\mathrm{cm}^{-3}\right)^{\alpha_B}$ where $\alpha_B \in \{2/3, 1\}$
  (4) calculate hadronic radio and γ-ray emission and compare to observations
- **consequences:**
  $\Rightarrow$ if $\mathcal{H}_{\mathrm{cr}} = \mathcal{C}_{\mathrm{rad}}\ \forall\ r$ and hadr. emission below observational limits:
  successful CR heating model that is locally stabilized at ~ 1 keV
  $\Rightarrow$ otherwise CR heating ruled out as dominant heating source

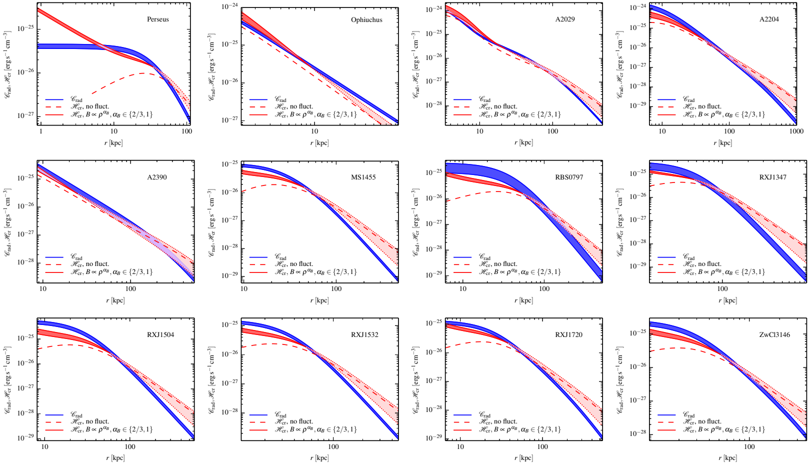
Cosmic-ray heating in cool core clusters (1)



Jacob & C.P. (2016)

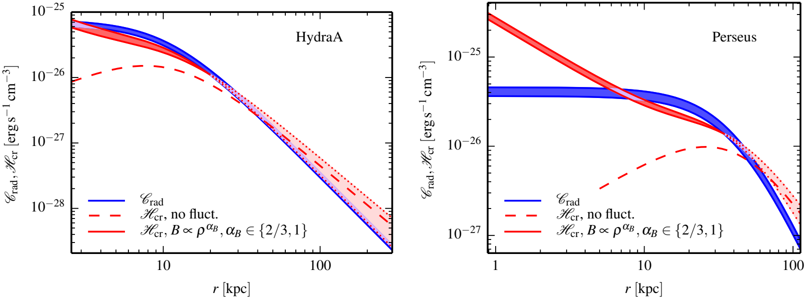
HITS

Cosmic-ray heating in cool core clusters (2)



Jacob & C.P. (2016)

Cosmic-ray heating in Hydra A vs. Perseus

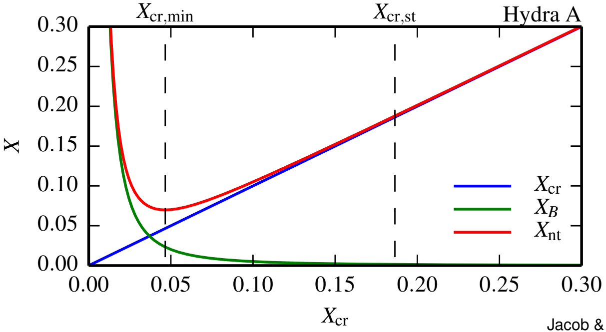


Jacob & C.P. (2016)

2 populations of cool cores emerging:

- pop 1 (Hydra A, Virgo, . . .): $\mathcal{H}_{\rm cr} = \mathcal{C}_{\rm rad} \rightarrow$ CR heated?
- pop 2 (Perseus, Ophiuchus, . . .): $\mathcal{H}_{\rm cr} \neq \mathcal{C}_{\rm rad}$: host radio-mini halos!

Non-thermal pressure balance

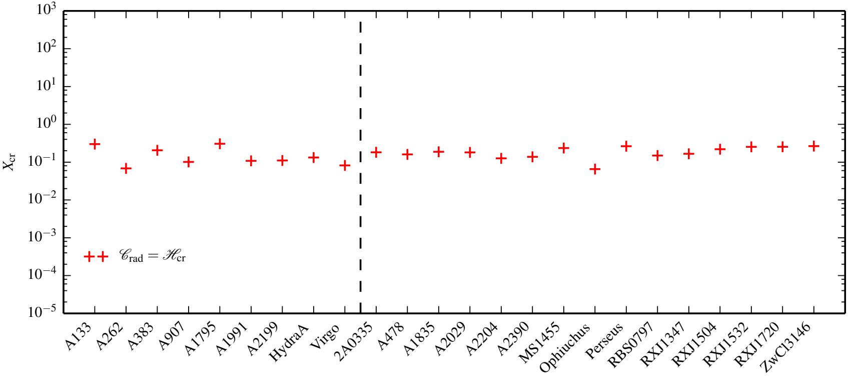


Jacob & C.P. (2016)

- define $X_{\rm cr} = P_{\rm cr}/P_{\rm th}$ and $X_B = P_B/P_{\rm th}$
- CR heating rate: $\mathcal{H}_{\rm cr} = -\boldsymbol{v}_A \cdot \nabla P_{\rm cr} \propto X_B^{0.5} X_{\rm cr}$
- non-thermal pressure at fixed heating rate:

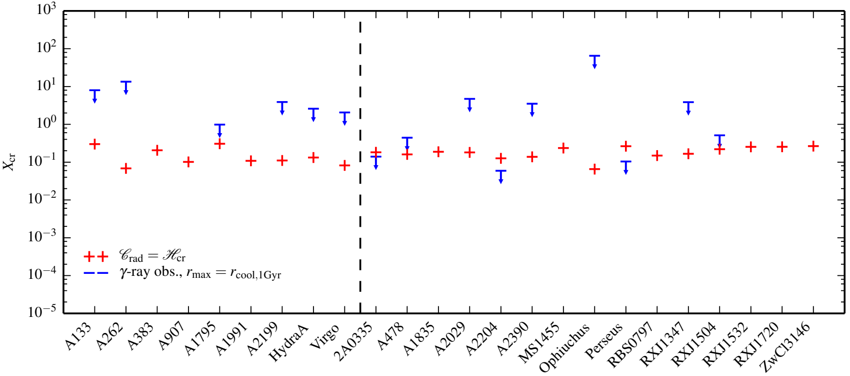
$$X_{\rm nt} \equiv (X_B + X_{\rm cr})_{\mathcal{H}_{\rm cr}} = A X_{\rm cr}^{-2} + X_{\rm cr} \quad \rightarrow \quad X_{\rm cr,min} = (2A)^{1/3}$$

Hadronic emission: radio and γ rays



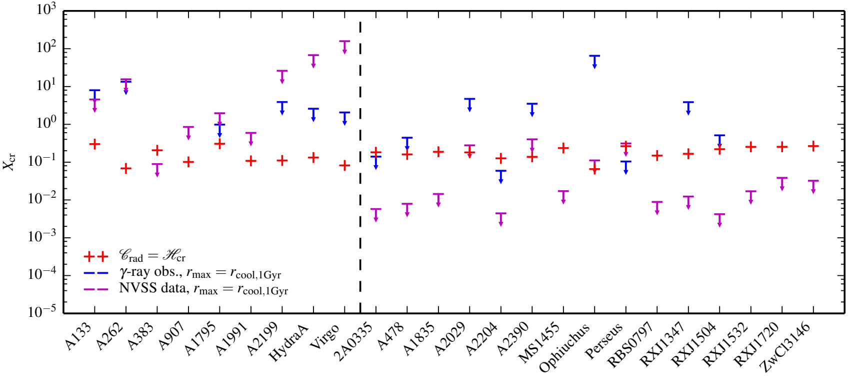
Jacob & C.P. (2016)

Hadronic emission: radio and γ rays



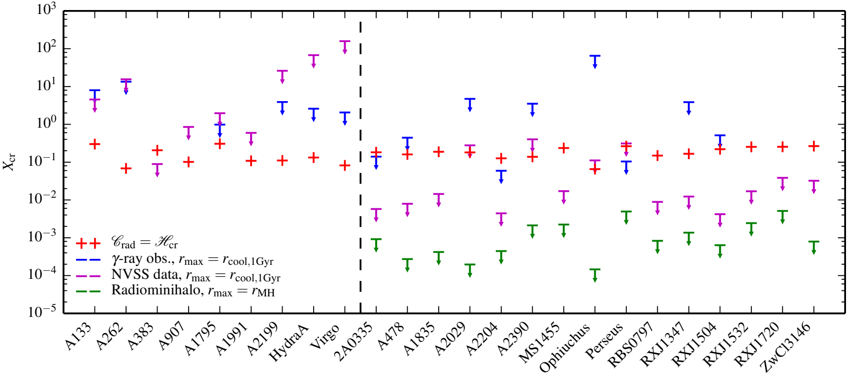
Jacob & C.P. (2016)

Hadronic emission: radio and γ rays



Jacob & C.P. (2016)

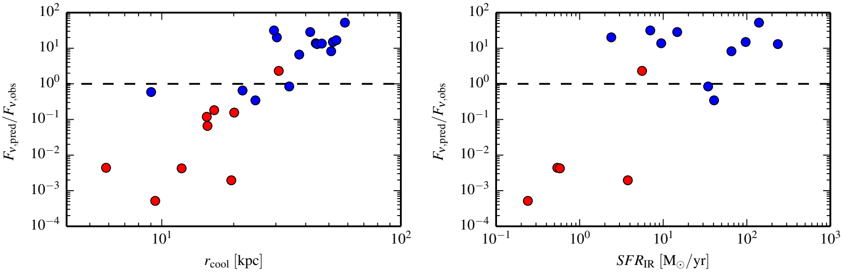
Hadronic emission: radio and γ rays



Jacob & C.P. (2016)

- CR heating solution ruled out in radio mini-halos ($\mathcal{H}_{cr} \neq \mathcal{C}_{rad}$)!

Correlations in cool cores



Jacob & C.P. (2016)

possibly cosmic ray-heated cool cores vs. radio mini halo clusters:

- $F_{\nu,\mathrm{obs}} > F_{\nu,\mathrm{pred}}$: strong radio source = abundant injection of CRs
- peaked CC profile ($r_{\mathrm{cool}} \lesssim 20$ kpc) and simmering star formation: cosmic-ray heating may effectively balance cooling
- large star formation rates: cooling wins over heating

Conclusions on AGN feedback by cosmic-ray heating

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 $X_{\rm cr} = 0.31$
- 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

diversity of cool cores:

- *peaked cool cores:* possibly stably heated by cosmic rays
- *radio mini halo clusters:* cosmic-ray heating ruled out systems are strongly cooling and form stars at large rates

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

European Research Council
Established by the European Commission

Literature for the talk

Cosmic ray feedback in galaxies:

- Pfrommer, Pakmor, Schaal, Simpson, Springel, *Simulating cosmic ray physics on a moving mesh,* 2016.
- Pakmor, Pfrommer, Simpson, Springel, *Galactic winds driven by isotropic and anisotropic cosmic ray diffusion in isolated disk galaxies,* 2016.

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.
- Jacob & Pfrommer, *Diversity in cool core clusters: implications for cosmic-ray heating*, 2016

Additional slides

Self-consistent CR pressure in steady state

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

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

  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

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

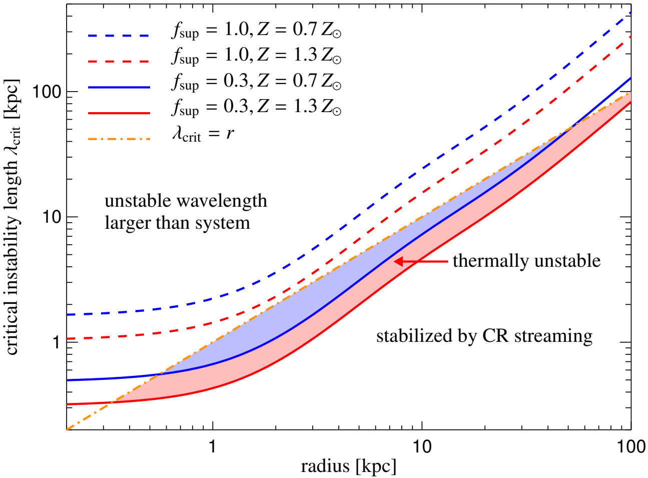
where f_s is the magnetic suppression factor

- 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:

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

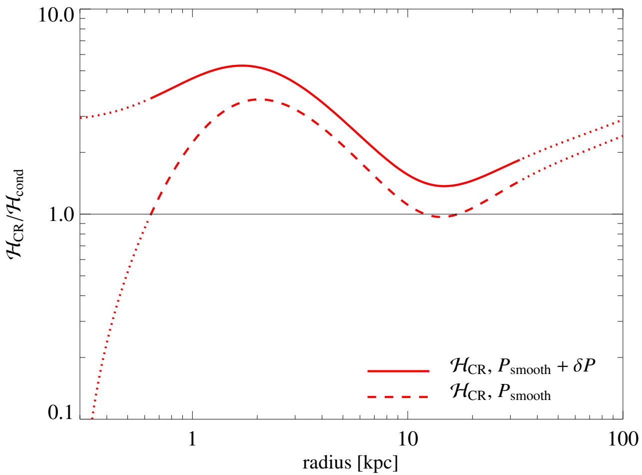
- however: unstable wavelength must be supported by the system
$\rightarrow$ constraint on magnetic suppression factor f_s

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



C.P. (2013)

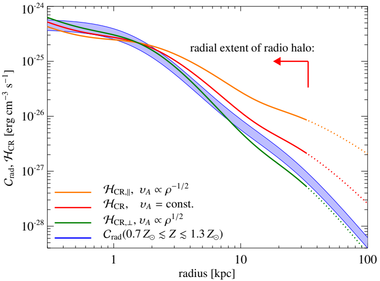
CR heating dominates over thermal conduction



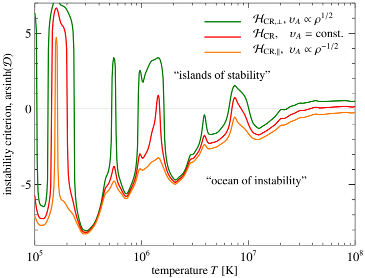
C.P. (2013)

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

Cosmic-ray heating vs. radiative cooling (3)

is this global thermal equilibrium a coincidence in Virgo?

- CCs typically show a steep central density profile: $n \propto r^{-1}$
- central temperature profile rises slowly: $T \propto r^{\alpha}$, with $\alpha \lesssim 0.3$
- assume $v_A =$ const. and steady-state CR streaming
  $\Rightarrow X_{\mathrm{cr}} = P_{\mathrm{cr}}/P_{\mathrm{th}}$ (also required for self-consistency):

$$\begin{aligned} \mathcal{H}_{\mathrm{cr}} &\propto \frac{\partial}{\partial r} P_{\mathrm{th}} \propto \frac{\partial}{\partial r} r^{\alpha-1} \propto r^{\alpha-2} \\ \mathcal{C}_{\mathrm{rad}} &\propto n^2 \propto r^{-2} \end{aligned}$$

(1) identical radial profiles expected for $T \simeq$ const. ($\alpha \simeq 0$)

(2) for a smoothly rising temperature profile, heating is slightly favored over cooling at larger radii $\rightarrow$ onset of cooling is smoothly modulated from the outside in