The role of cosmic rays in galaxies and galaxy clusters

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in collaboration with

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IceCube Collaboration Meeting in Berlin – 2017

Outline

1. Introduction and Motivation
   - Puzzles in galaxy formation
   - Cosmic ray physics
   - Simulated physics
2. Simulating galaxies
   - Supernova explosions
   - Galaxy formation
   - Gamma rays
3. Galaxy clusters
   - Feedback
   - Cosmic ray heating
   - 3D MHD simulations

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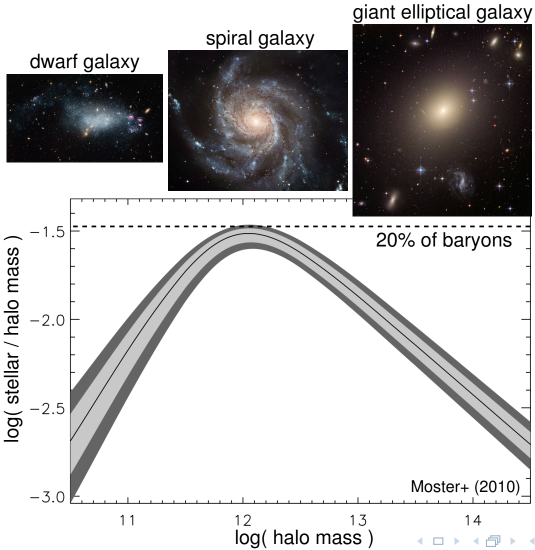
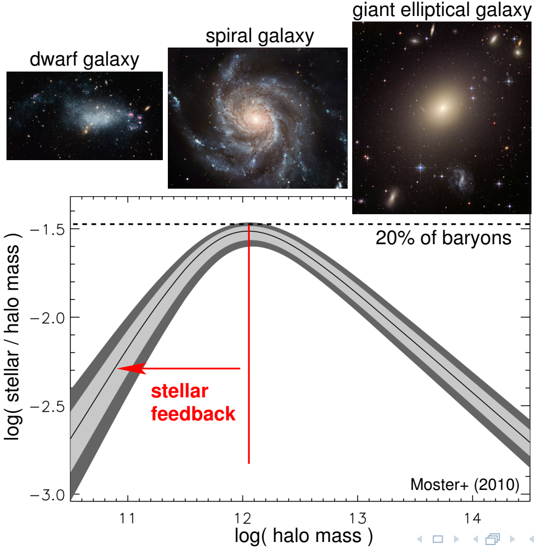
Puzzles in galaxy formation

Puzzles in galaxy formation



Puzzles in galaxy formation



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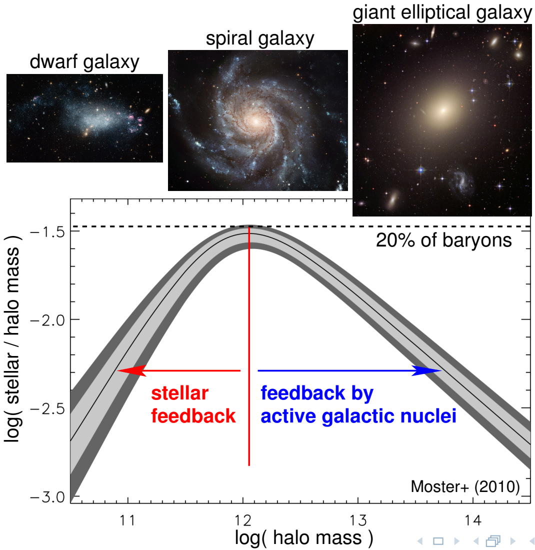
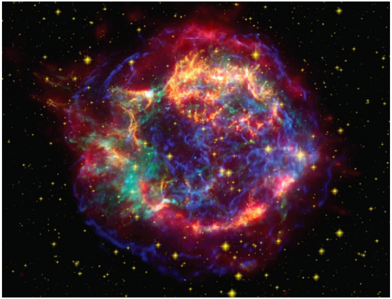


Feedback by galactic winds



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

Feedback by galactic winds

super wind in M82

NASA/JPL-Caltech/STScI/CXC/UofA

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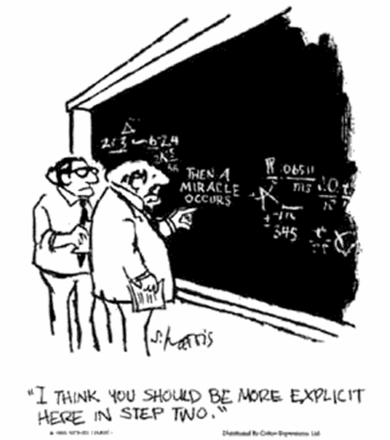
- critical for understanding the physics of galaxy formation $\rightarrow$ may explain puzzle of low star conversion efficiency in dwarf galaxies

Feedback by galactic winds



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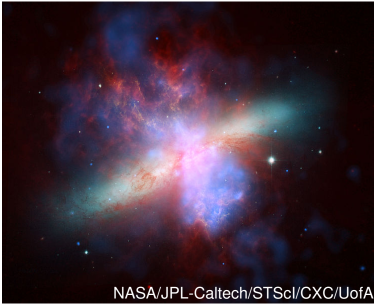
How are galactic winds driven?



super wind in M82

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

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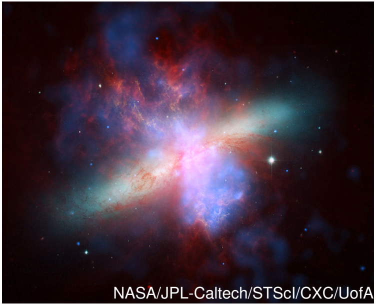

super wind in M82

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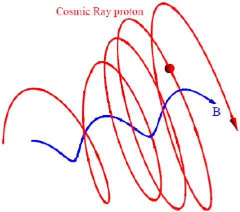
observed energy equipartition between cosmic rays, thermal gas and magnetic fields
$\rightarrow$ suggests self-regulated feedback loop with CR driven winds

AIP

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



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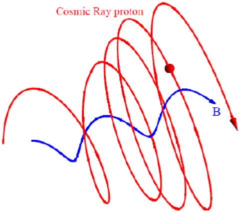

$\rightarrow$ **CRs exert a pressure on the thermal gas by means of scattering off of Alfvén waves**

CR transport

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

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

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

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

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

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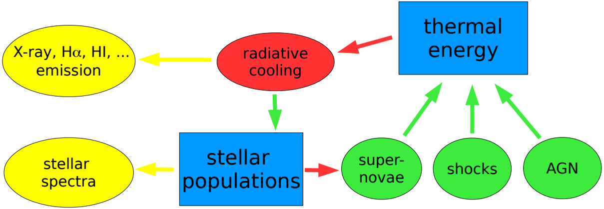
Simulations – flowchart

observables:

physical processes:

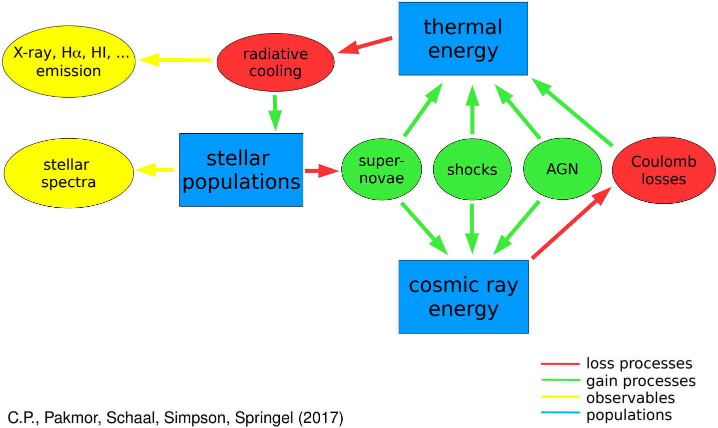


C.P., Pakmor, Schaal, Simpson, Springel (2017)

loss processes
gain processes
observables
populations

Simulations with cosmic ray physics

observables: physical processes:



C.P., Pakmor, Schaal, Simpson, Springel (2017)

Simulations with cosmic ray physics

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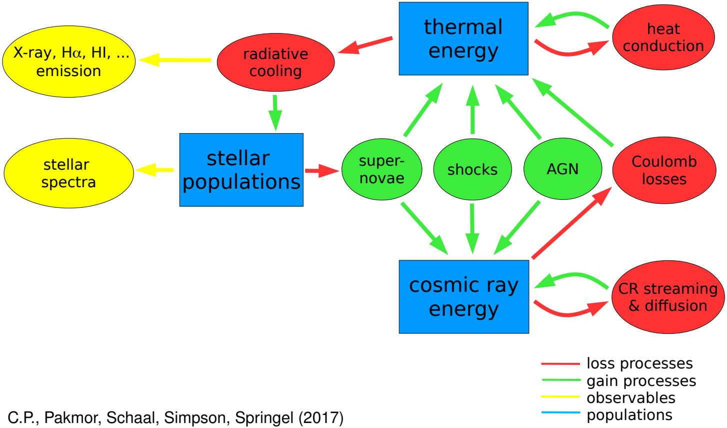
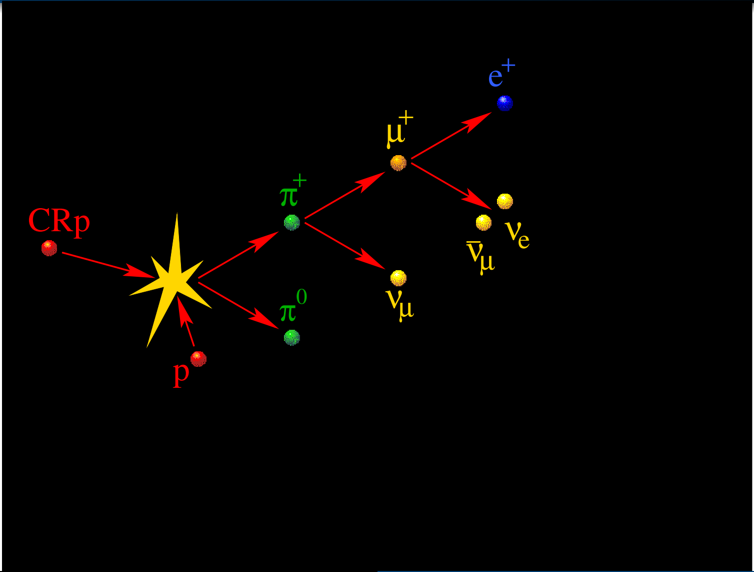


C.P., Pakmor, Schaal, Simpson, Springel (2017)

Hadronic cosmic ray proton interaction



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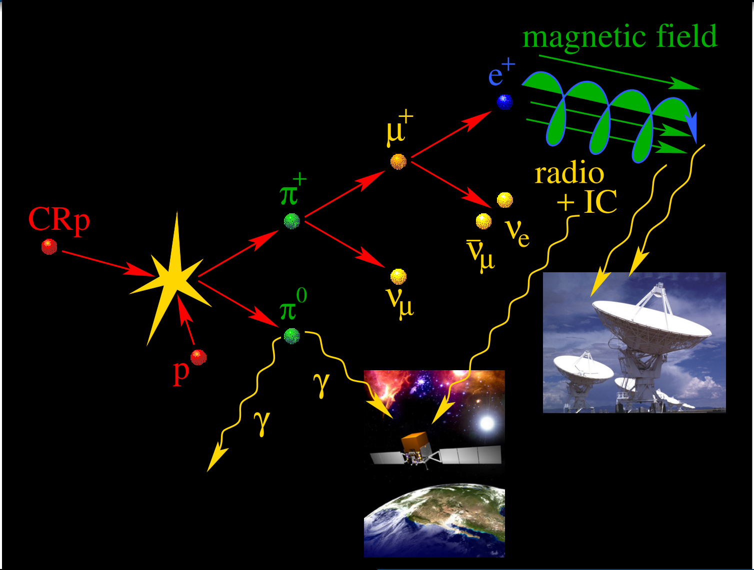
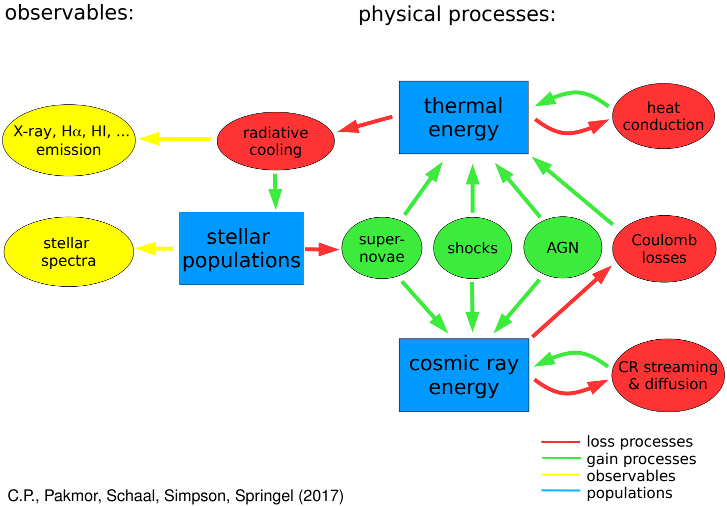
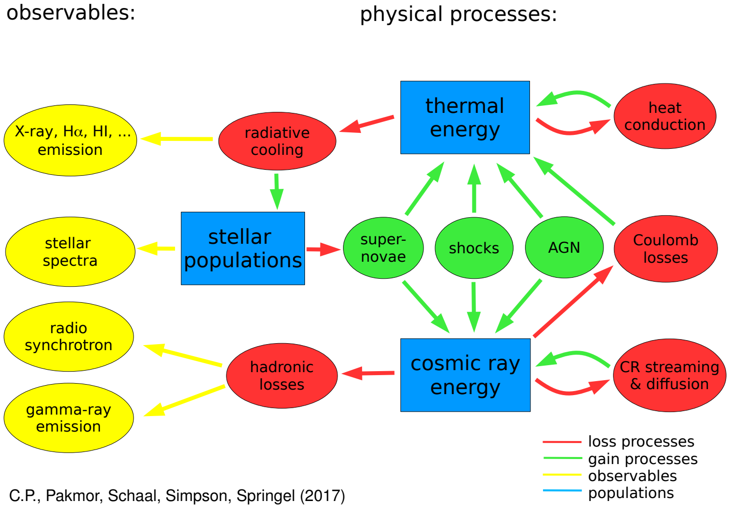


Simulations with cosmic ray physics



C.P., Pakmor, Schaal, Simpson, Springel (2017)

Simulations with cosmic ray physics



C.P., Pakmor, Schaal, Simpson, Springel (2017)

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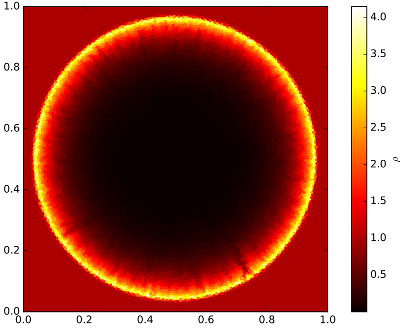
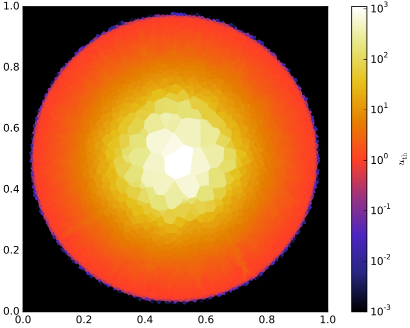
Sedov explosion

density

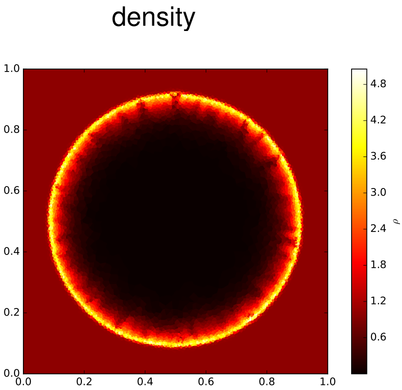


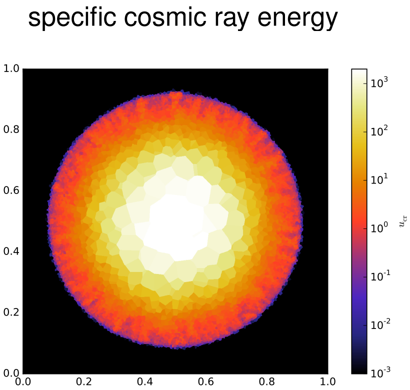
specific thermal energy



C.P., Pakmor, Schaal, Simpson, Springel (2017)

Sedov explosion with CR acceleration

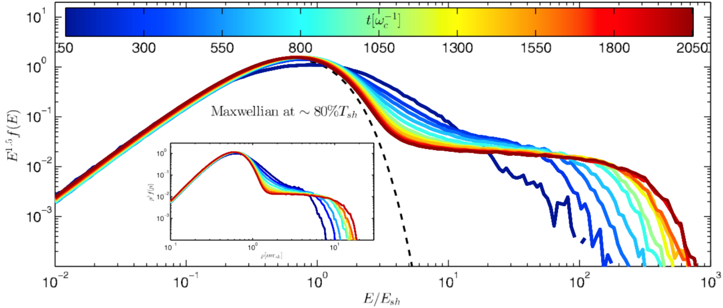




C.P., Pakmor, Schaal, Simpson, Springel (2017)

Ion spectrum

Non-relativistic *parallel shock* in long-term hybrid simulation

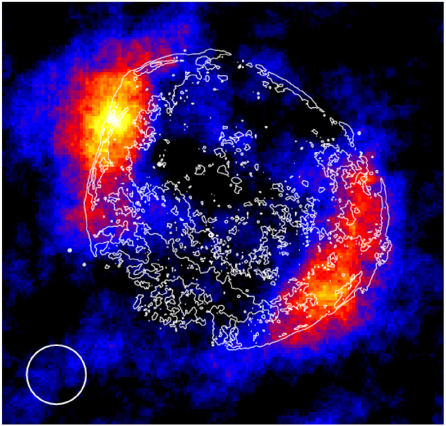


Caprioli & Spitkovsky (2014)

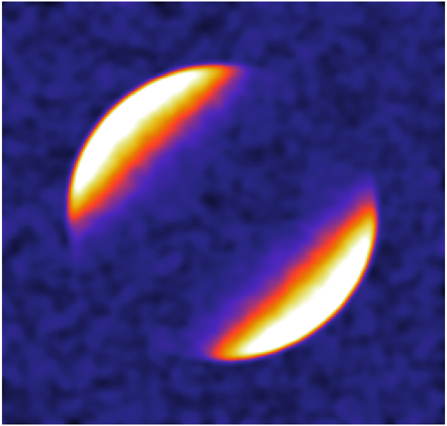
- quasi-parallel shocks ($\boldsymbol{B} \parallel \boldsymbol{n}_s$) accelerate ions
- quasi-perpendicular shocks ($\boldsymbol{B} \perp \boldsymbol{n}_s$) cannot
- model magnetic obliquity in AREPO simulations

TeV γ rays from shell-type SNRs: SNR 1006

H.E.S.S. observation



AREPO simulation



Pais, C.P., Ehlert (in prep.)

TeV γ rays from shell-type SNRs: Vela Junior

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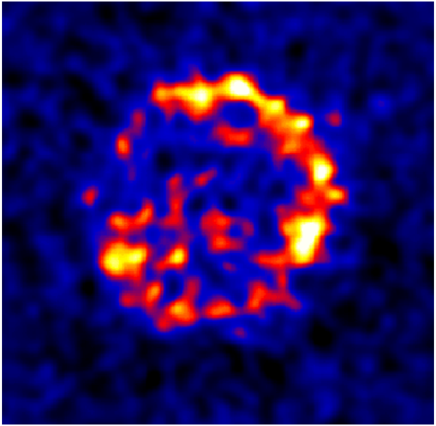
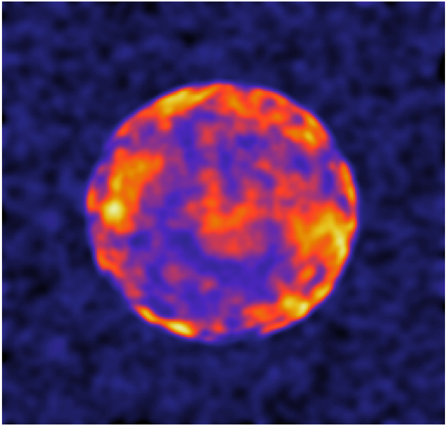


AREPO simulation



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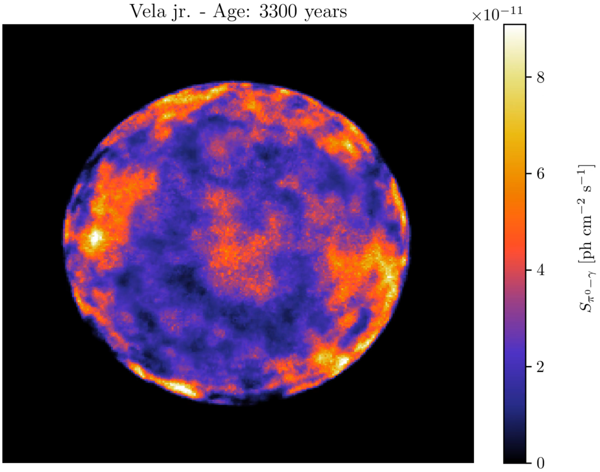
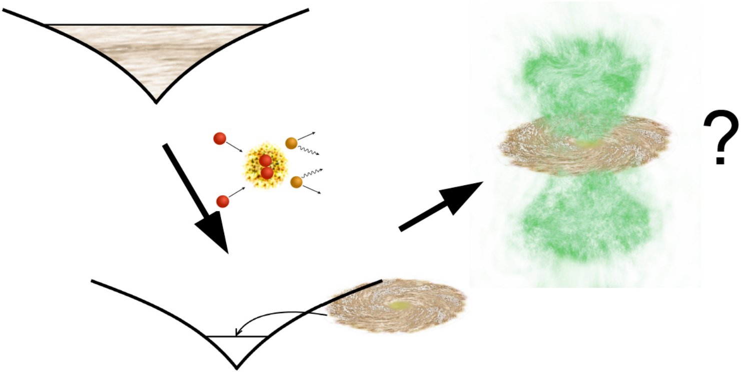


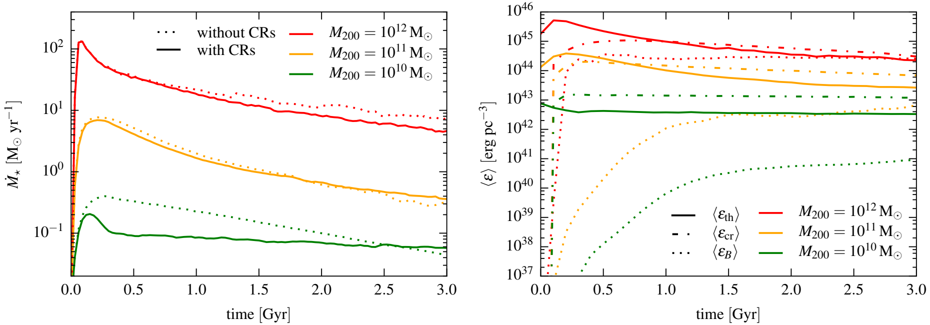
Galaxy simulation setup: 1. cosmic ray advection



C.P., Pakmor, Schaal, Simpson, Springel (2017)
Simulating cosmic ray physics on a moving mesh

MHD + cosmic ray advection: $\{10^{10}, 10^{11}, 10^{12}\}\ M_\odot$

Time evolution of SFR and energy densities

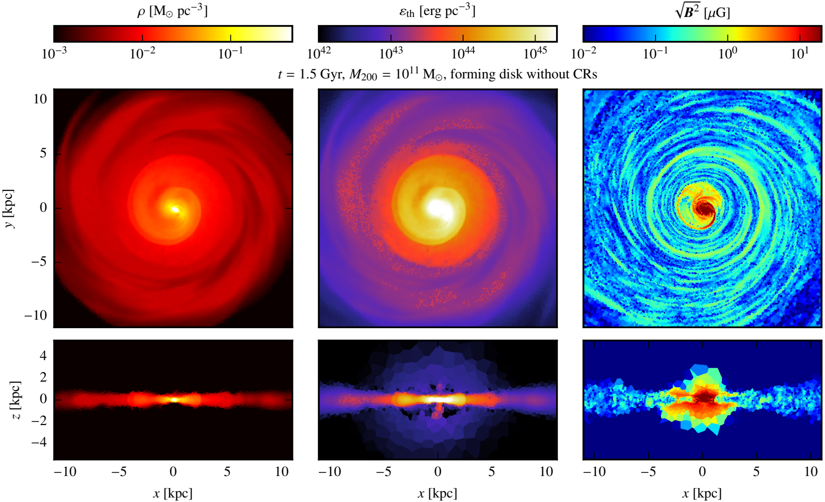


C.P., Pakmor, Schaal, Simpson, Springel (2017)

- 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

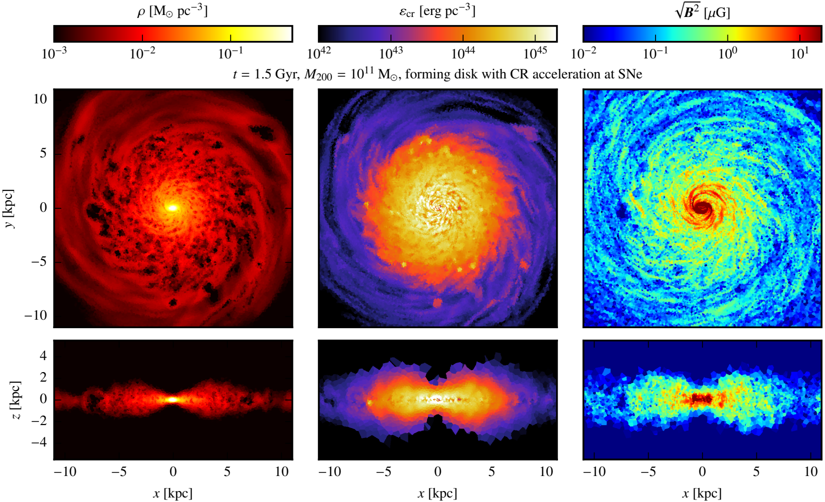
AIP

MHD galaxy simulation without CRs



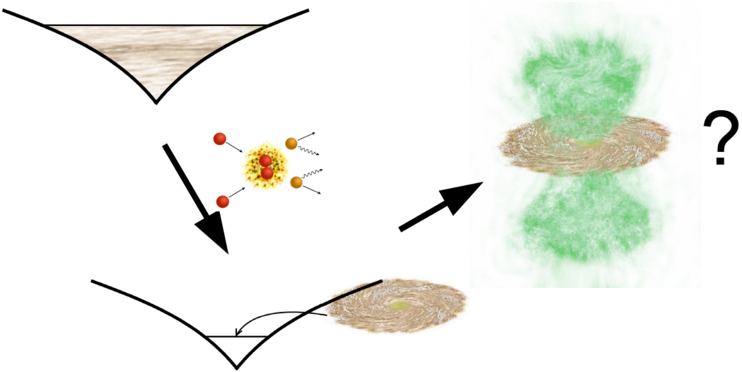
C.P., Pakmor, Schaal, Simpson, Springel (2017)

MHD galaxy simulation with CRs



C.P., Pakmor, Schaal, Simpson, Springel (2017)

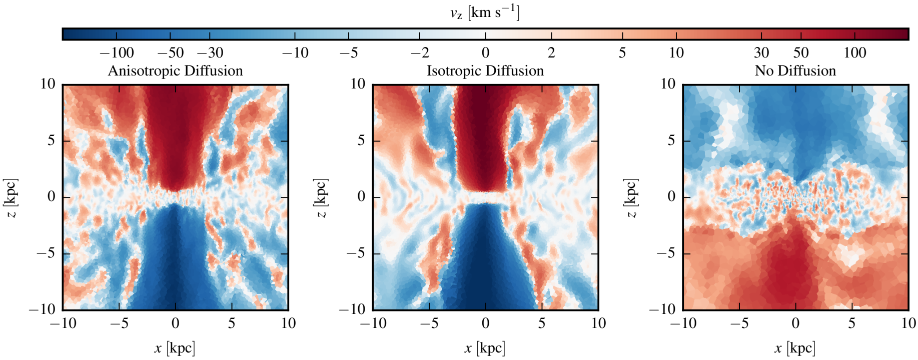
Galaxy simulation setup: 2. cosmic ray diffusion



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

MHD + CR advection + diffusion: $10^{11}\ M_\odot$

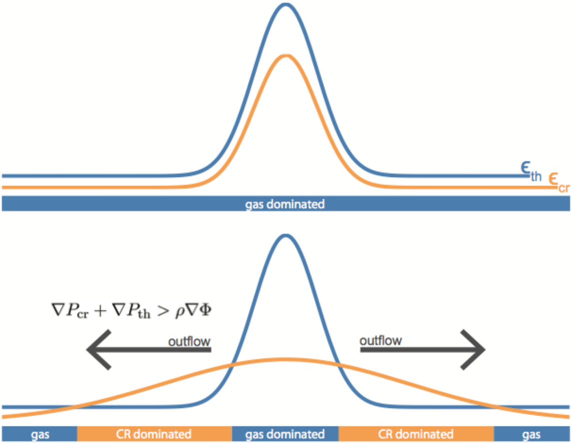
MHD galaxy simulation with CR diffusion



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

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

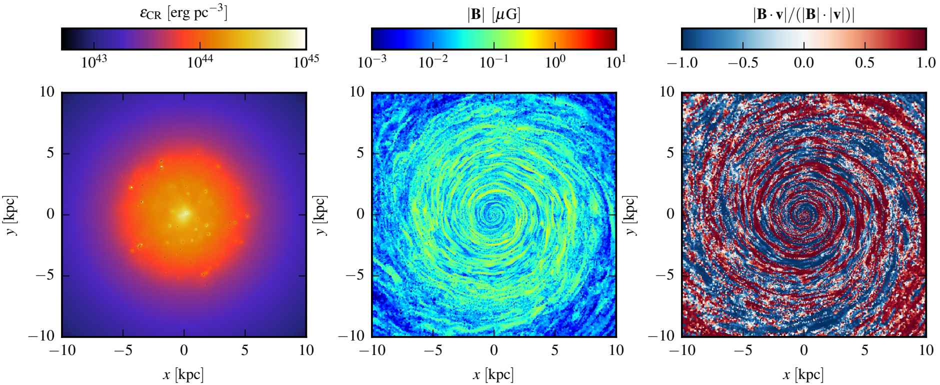
Cosmic ray driven wind: mechanism



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

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

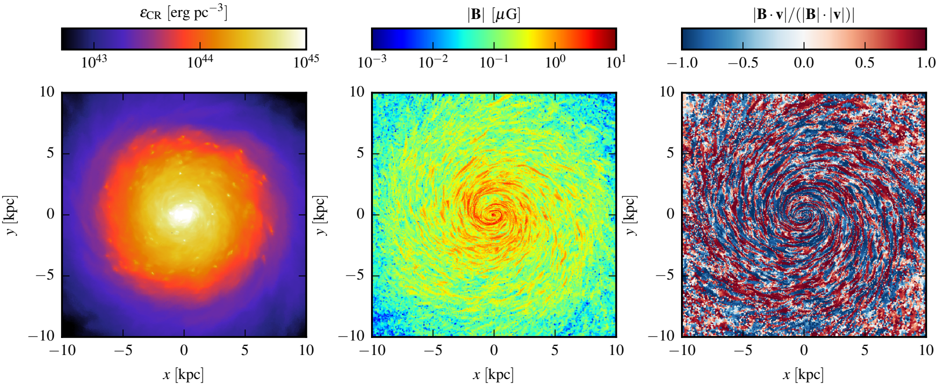
MHD galaxy simulation with CR isotropic diffusion



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

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

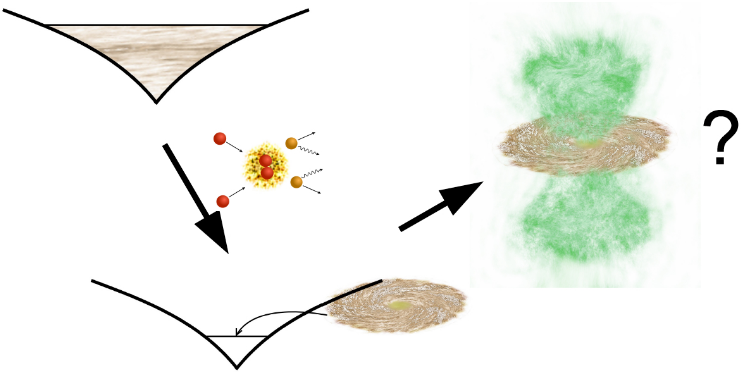
MHD galaxy simulation with CR anisotropic diffusion



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

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

Galaxy simulation setup: 3. non-thermal emission

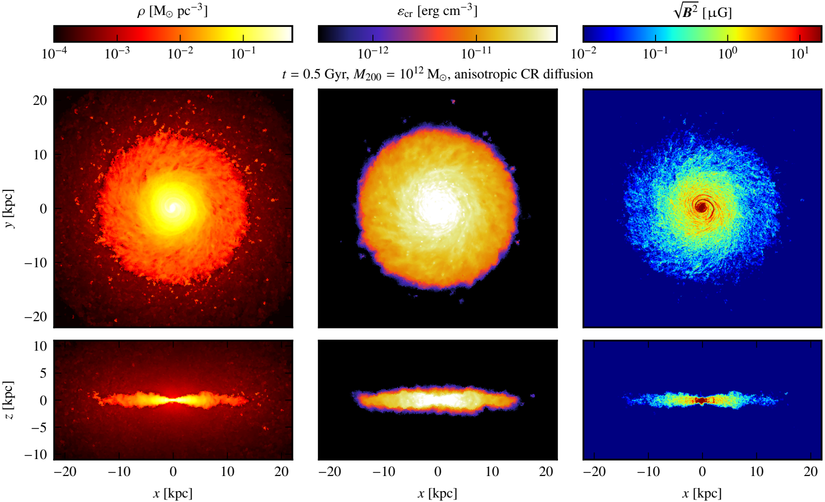


C.P., Pakmor, Simpson, Springel (2017a,b)

Simulating radio synchrotron and gamma-ray emission in galaxies

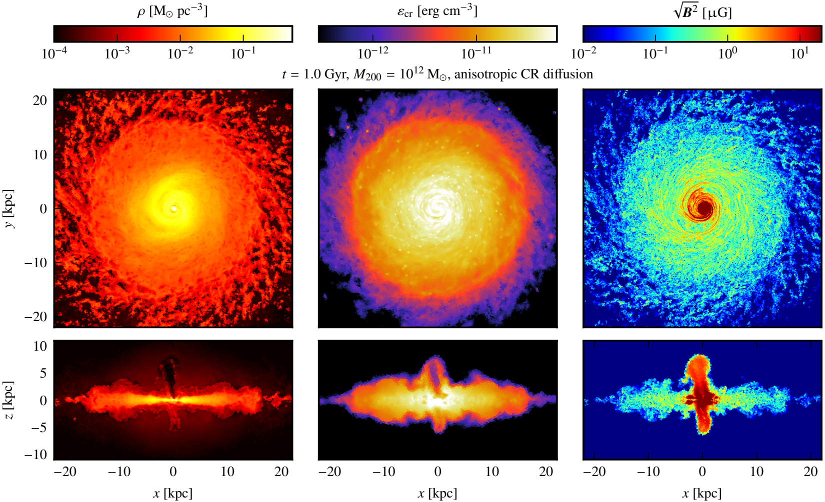
MHD + CR advection + diffusion: $\{10^{10}, 10^{11}, 10^{12}\}\ \mathrm{M}_\odot$

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



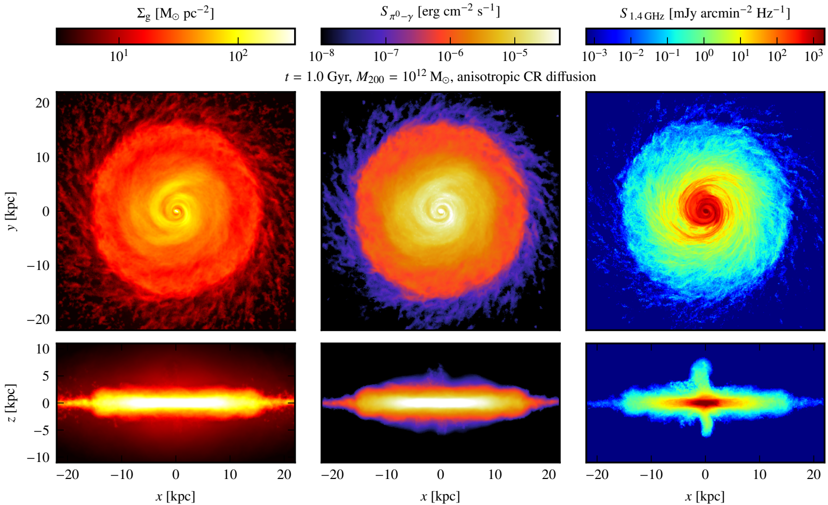
C.P.+ (2017a,b)

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



C.P.+ (2017a,b)

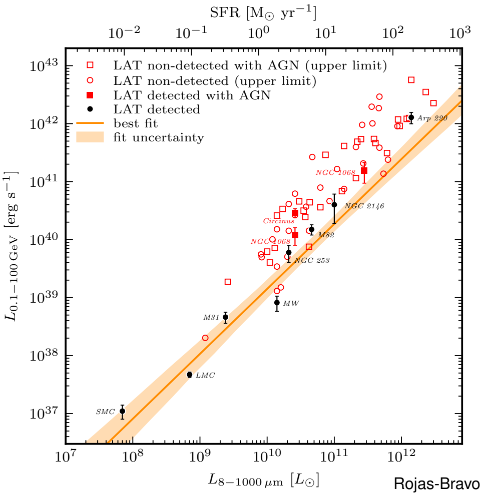
γ-ray and radio emission of Milky Way-like galaxy



C.P.+ (2017a,b)

Far infra-red – gamma-ray correlation

Universal conversion: star formation → cosmic rays → gamma rays



Rojas-Bravo & Araya (2016)

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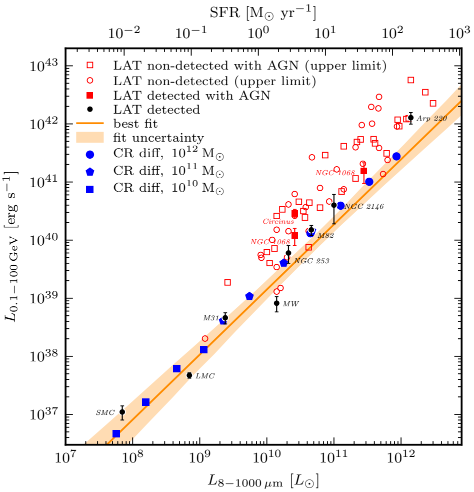

C.P.+ (2017a)

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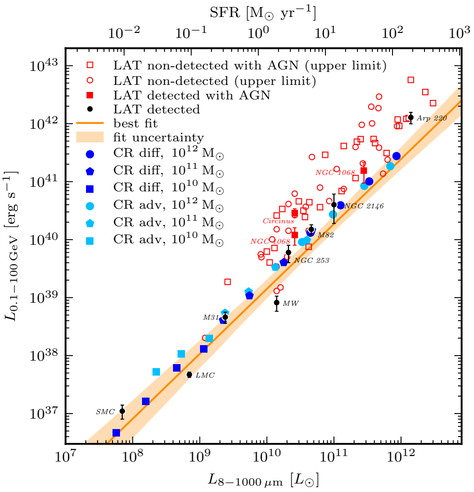

C.P.+ (2017a)

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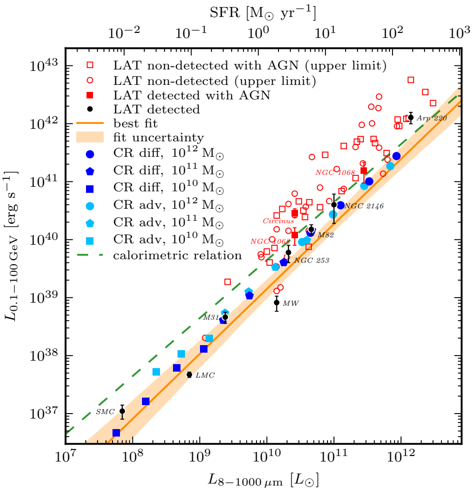

C.P.+ (2017a)

Conclusions on cosmic-ray feedback in galaxies

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- 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

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- 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 enables testing the 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 enables testing the calorimetric assumption

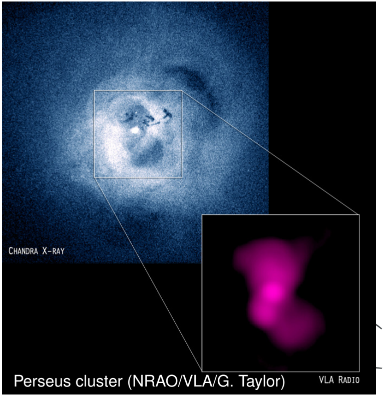
outlook: improved modeling of plasma physics, follow CR spectra, cosmological settings

need: comparison to resolved radio/γ-ray observations $\rightarrow$ **SKA/CTA**

Outline

Feedback by active galactic nuclei

Paradigm: accreting super-massive black holes at galaxy cluster centers launch relativistic jets, which provide energetic feedback to balance cooling $\Rightarrow$ **but how?**

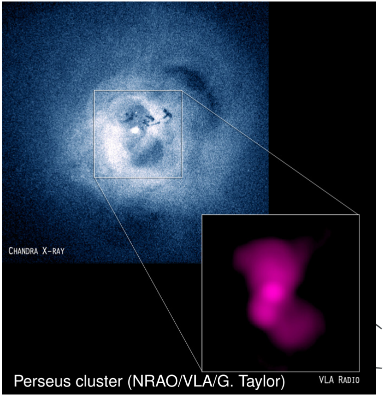


Perseus cluster (NRAO/VLA/G. Taylor)

Feedback by active galactic nuclei

Paradigm: accreting super-massive black holes at galaxy cluster centers launch relativistic jets, which provide energetic feedback to balance cooling ⇒ **but how?**

- energy source: release of non-gravitational energy due to accretion on a black hole and its spin
- self-regulated heating mechanism to avoid overcooling



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Feedback by active galactic nuclei

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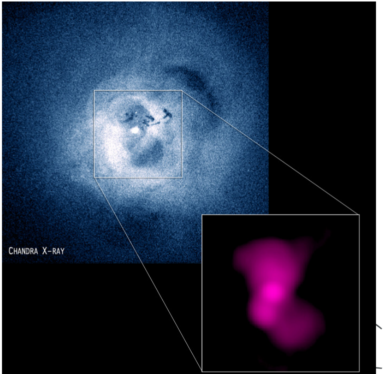
- energy source: release of non-gravitational energy due to accretion on a black hole and its spin
- self-regulated heating mechanism to avoid overcooling
- jet interaction with magnetized cluster medium → turbulence
- jet accelerates relativistic particles (cosmic rays, CRs) → release from bubbles provides source of heat

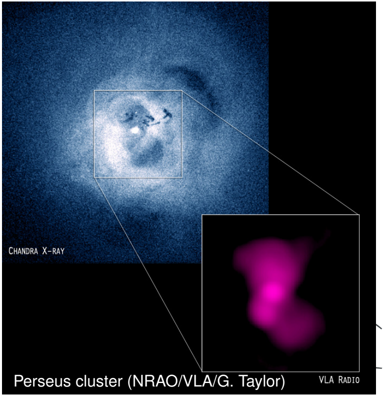


Perseus cluster (NRAO/VLA/G. Taylor)

Feedback by active galactic nuclei

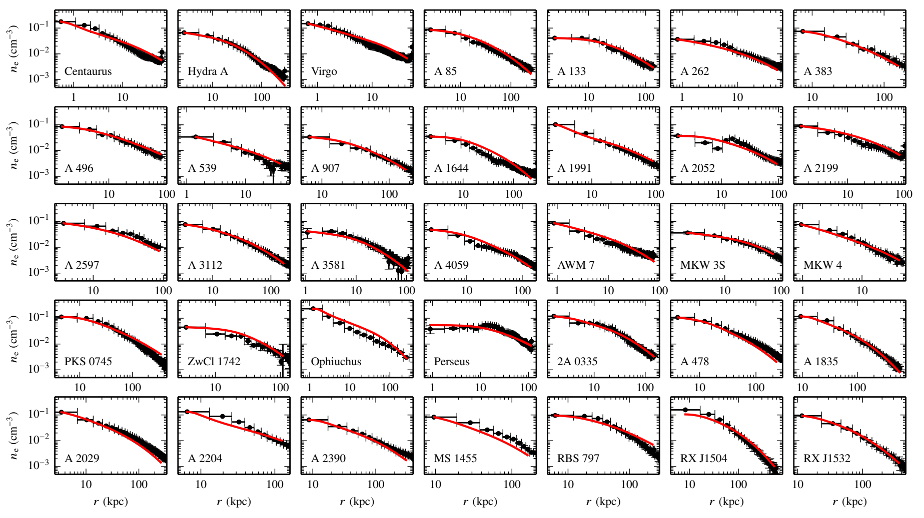
Paradigm: accreting super-massive black holes at galaxy cluster centers launch relativistic jets, which provide energetic feedback to balance cooling ⇒ **but how?**

- Jacob & C.P. (2017a,b): study large sample of 40 cool core clusters
- spherically symmetric steady-state solutions where cosmic ray heating balances radiative cooling

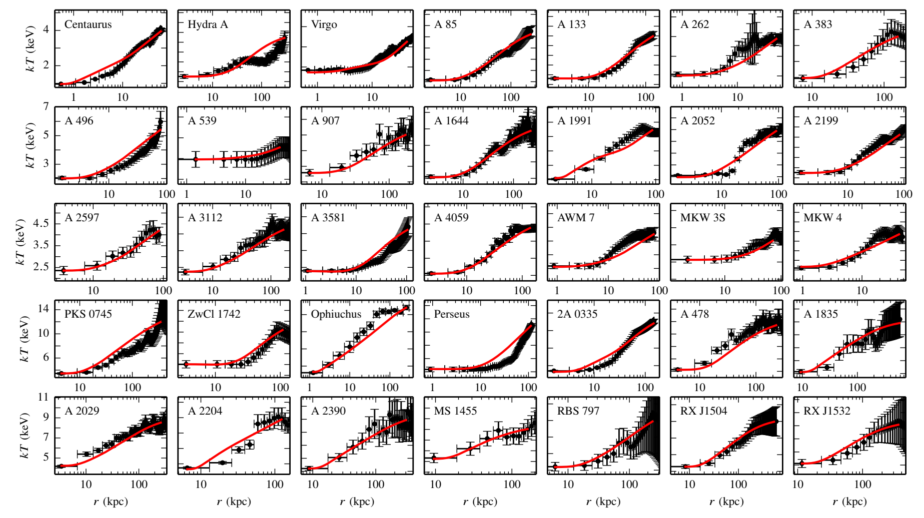


Perseus cluster (NRAO/VLA/G. Taylor)

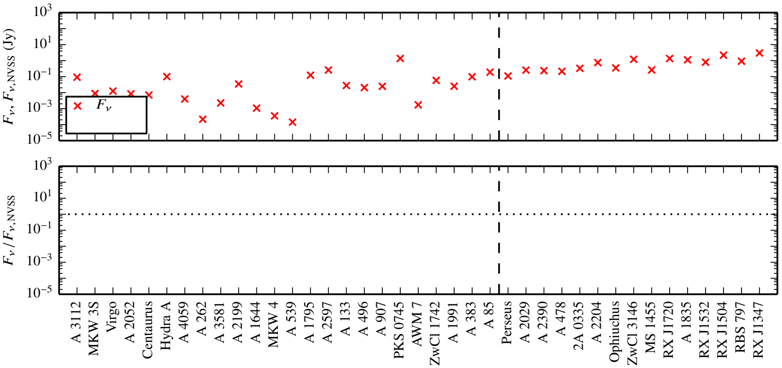
Gallery of solutions: density profiles



Gallery of solutions: temperature profiles

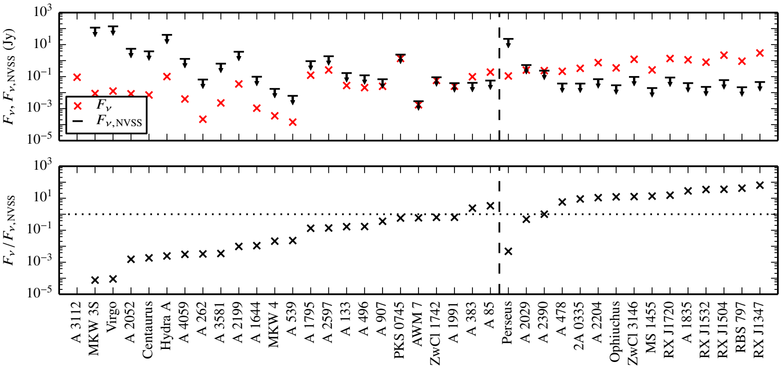


Hadronically induced radio emission



Jacob & C.P. (2017b)

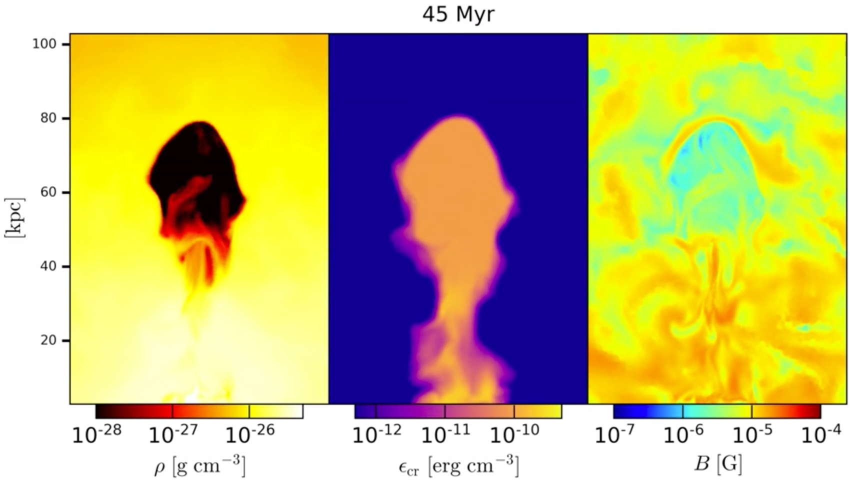
Hadronically induced radio emission: NVSS limits



Jacob & C.P. (2017b)

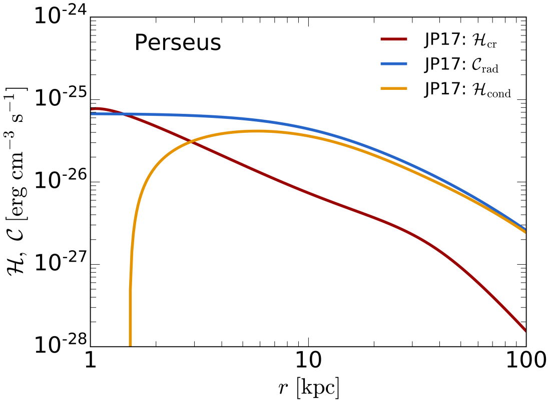
- continuous sequence in $F_{\nu,\mathrm{pred}}/F_{\nu,\mathrm{NVSS}}$
- CR heating solution ruled out in radio mini halos (RMHs)
- CR heating viable solution for non-RMH clusters

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



Ehlert+ in prep.

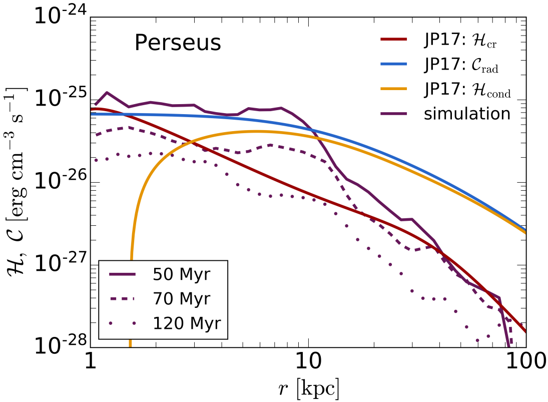
Perseus cluster – heating vs. cooling: theory



Ehlert+ in prep.

- CR and conductive heating balance radiative cooling: $\mathcal{H}_{\rm cr} + \mathcal{H}_{\rm th} \approx \mathcal{C}_{\rm rad}$: modest mass deposition rate of 1 $M_\odot$ yr^{-1}

Perseus cluster – heating vs. cooling: simulations



Ehlert+ in prep.

- CR and conductive heating balance radiative cooling: $\mathcal{H}_{\rm cr} + \mathcal{H}_{\rm th} \approx \mathcal{C}_{\rm rad}$: modest mass deposition rate of 1 $M_\odot$ yr^{-1}
- **simulated CR heating rate matches 1D steady state model**

Conclusions on AGN feedback by cosmic-ray heating

Large sample of cool cores ⇒ self-regulation cycle

- *low-density 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

Conclusions on AGN feedback by cosmic-ray heating

Large sample of cool cores ⇒ self-regulation cycle

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3D MHD simulations with cosmic rays

- isotropic cosmic-ray distribution in inner 10s of kpc
- 3D cosmic-ray heating rate matches 1D steady state models
- *towards a predictive theory of galaxy and cluster formation*

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

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Literature for the talk

Non-thermal gamma-ray emission in galaxies:

- Pfrommer, Pakmor, Simpson, Springel, *Simulating Gamma-ray Emission in Star-forming Galaxies,* 2017a, ApJL.

Cosmic ray feedback in galaxies:

- Pfrommer, Pakmor, Schaal, Simpson, Springel, *Simulating cosmic ray physics on a moving mesh,* 2017, 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.