How cosmic rays shape galaxies and clusters

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in collaboration with

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Outline

1. Introduction
   - Puzzles in galaxy formation
   - Particle acceleration
   - Cosmic rays
2. Small galactic scales
   - Modelling physics in galaxies
   - Supernova explosions
   - Interstellar medium
3. Simulating galaxies and clusters
   - Global galaxy models
   - Radio and gamma-rays
   - AGN jets in galaxy clusters

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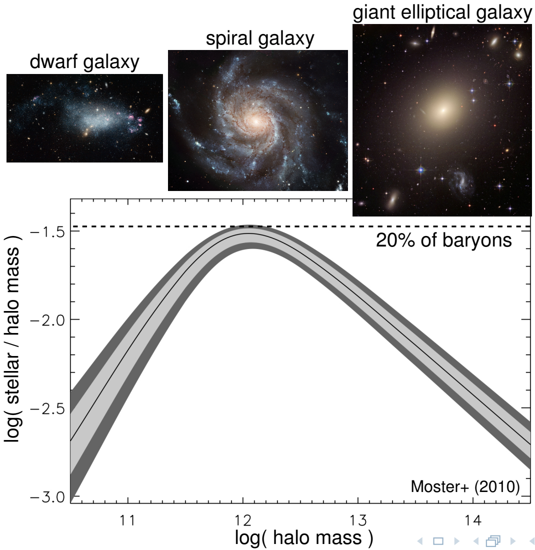
Puzzles in galaxy formation

Puzzles in galaxy formation



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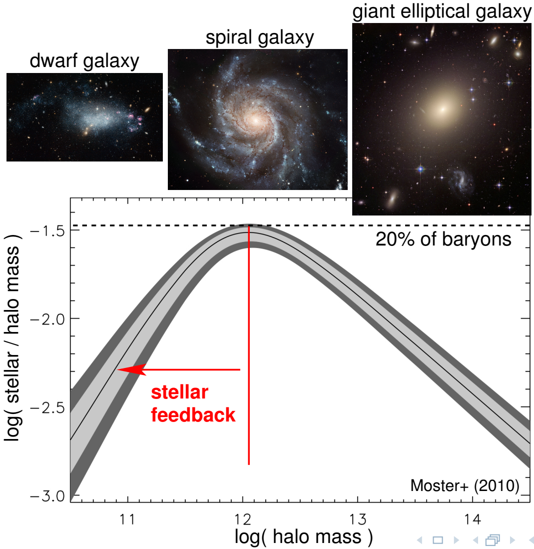
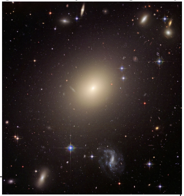


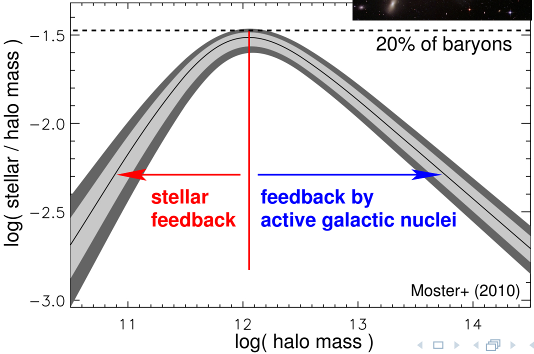
Puzzles in galaxy formation

dwarf galaxy

spiral galaxy

giant elliptical galaxy





Feedback

feedback n -s often attrib:

1. the return to the input of a part of the output of a machine, system, or process
2. the partial reversion of the effects of a given process to its source or to a preceding stage so as to reinforce or modify this process

AIP

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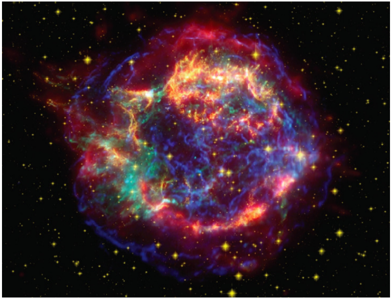
1. the return to the input of a part of the output of a machine, system, or process
2. the partial reversion of the effects of a given process to its source or to a preceding stage so as to reinforce or modify this process
3. the solution of all problems in galaxy formation

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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Feedback by galactic winds

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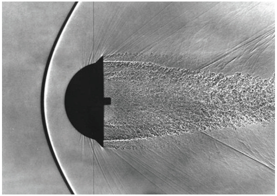
NASA/JPL-Caltech/STScI/CXC/UofA

- 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

Shock waves



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

thickness $\sim$ mean free path λ_{mfp}

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

slide concept Spitkovsky

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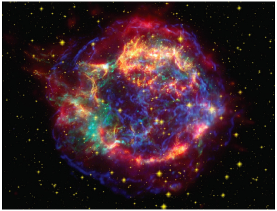

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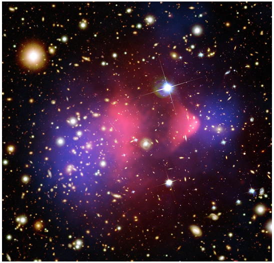


clusters/galaxies, Coulomb collisions set λ_{mfp}:

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

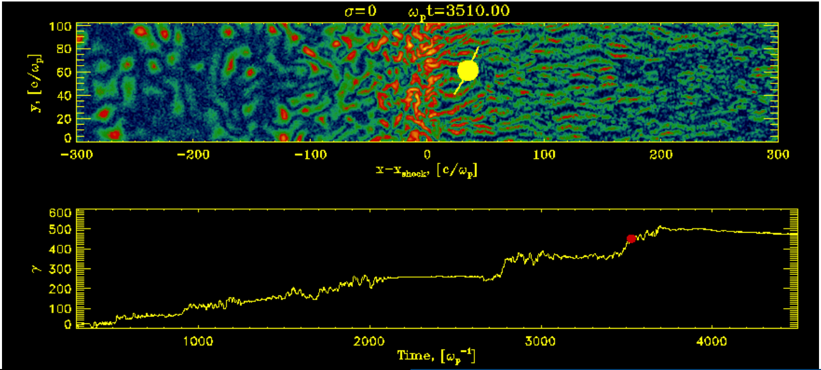
Mean free path $\gg$ observed shock width!

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

slide concept Spitkovsky

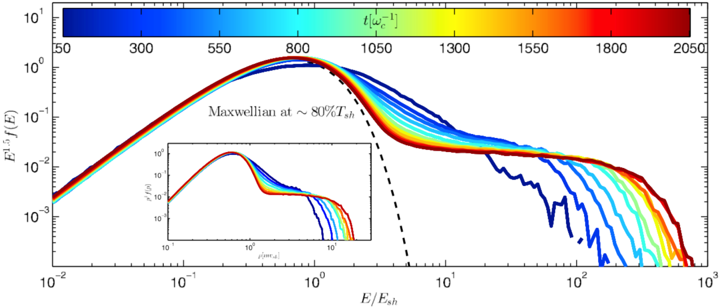
Particle acceleration at relativistic shock, $B_0 = 0$

- self-generated magnetic turbulence scatters particles across the shock
- each crossing results in energy gain – Fermi process
- movie below shows magnetic filaments in the shock frame (top), particle energy is measured the downstream frame (bottom): particle gains energy upon scattering in the upstream (Spitkovsky 2008)



Ion spectrum

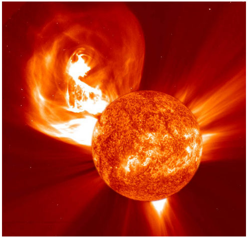
Non-relativistic parallel shock in long-term hybrid simulation



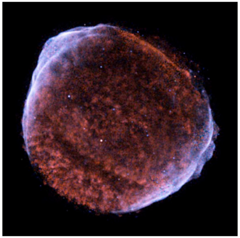
Caprioli & Spitkovsky (2014)

- quasi-parallel shocks accelerate ions
- particles gain energy in each crossing and have probability of leaving the Fermi cycle by being swept downstream → power-law spectrum
- maximum energy increases with time

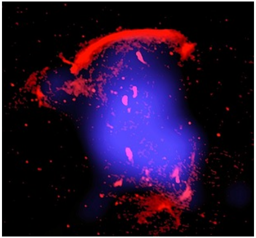
Astrophysical shocks



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



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

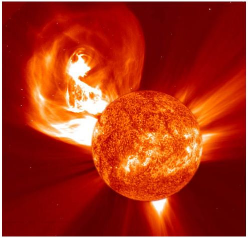


cluster shocks $\sim$ 2 Mpc
giant radio relic (van Weeren)

Astrophysical shocks

astrophysical collisionless shocks can:

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



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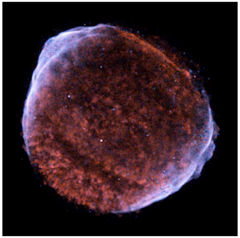

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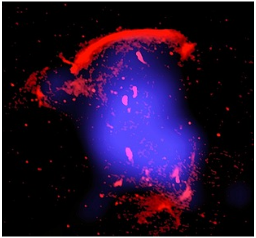

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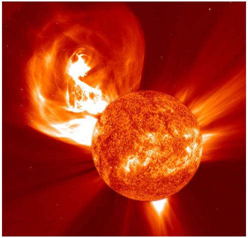
collisionless shocks $\Longleftrightarrow$ energetic particles $\Longleftrightarrow$ electro-magnetic waves



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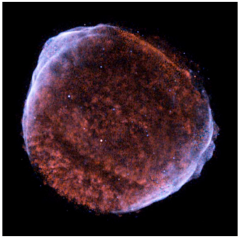

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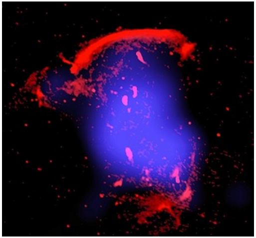

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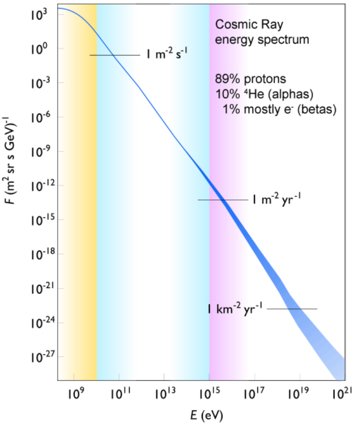
Galactic cosmic ray spectrum



data compiled by Swordy

- spans more than 33 decades in flux and 12 decades in energy
- "knee" indicates characteristic maximum energy of galactic accelerators
- CRs beyond the "ankle" have extra-galactic origin

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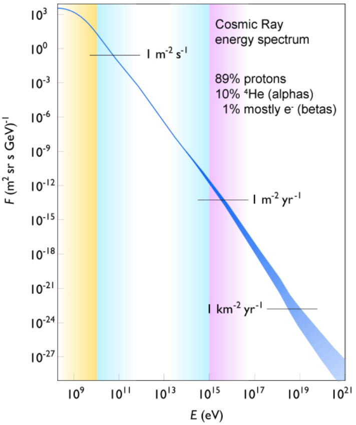

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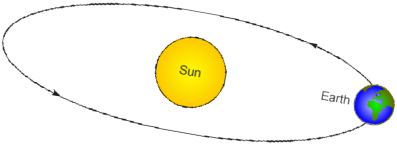
- spans more than 33 decades in flux and 12 decades in energy
- "knee" indicates characteristic maximum energy of galactic accelerators
- CRs beyond the "ankle" have extra-galactic origin
- energy density of cosmic rays, magnetic fields, and turbulence in the interstellar gas all similar

Cosmic ray feedback: an extreme multi-scale problem



Milky Way-like galaxy:

$$r_{\text{gal}} \sim 10^4 \text{ pc}$$

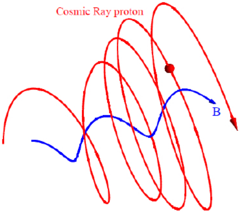
gyro-orbit of GeV cosmic ray:

$$r_{\text{cr}} = \frac{p_\perp}{e\,B_{\mu\text{G}}} \sim 10^{-6} \text{ pc} \sim \frac{1}{4} \text{ AU}$$

$\Rightarrow$ need to develop a **fluid theory for a collisionless, non-Maxwellian component!**

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



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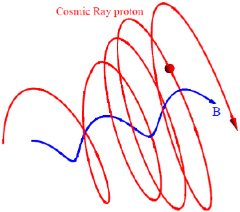

→ **CRs exert a pressure on the thermal gas by means of scattering off of Alfvén waves**

CR transport

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

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

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

$$\frac{\partial \varepsilon}{\partial t} + \nabla \cdot [(\varepsilon + P_{\rm th} \qquad) \boldsymbol{v}] = 0$$

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

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AIP

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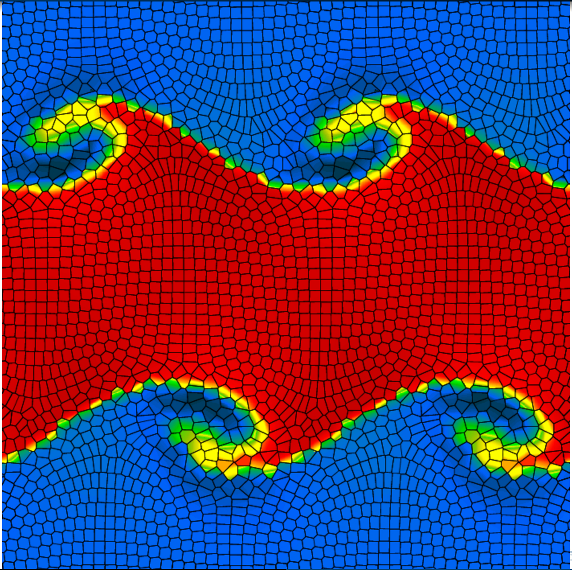
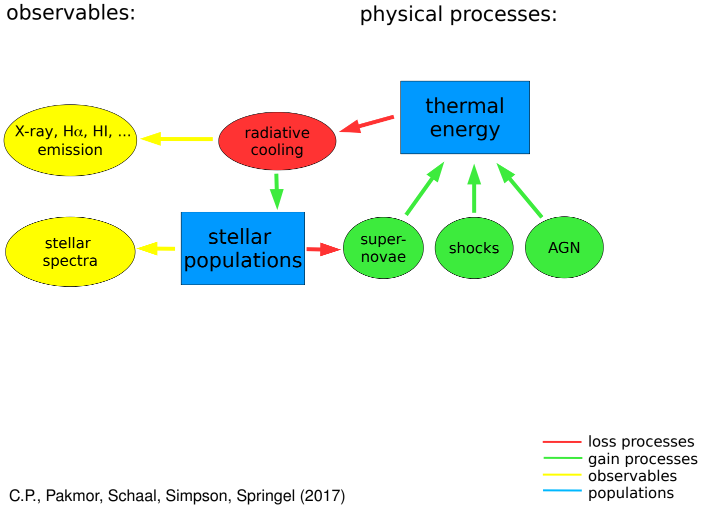
Cosmological moving-mesh code AREPO (Springel 2010)

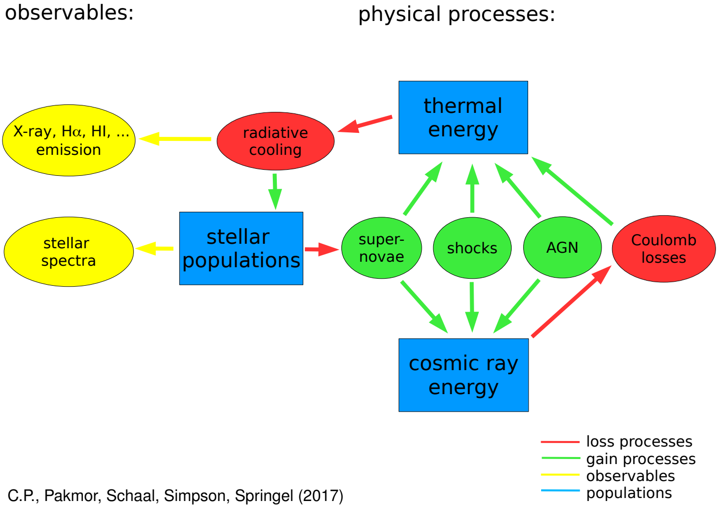


Simulations – flowchart



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

Simulations with cosmic ray physics



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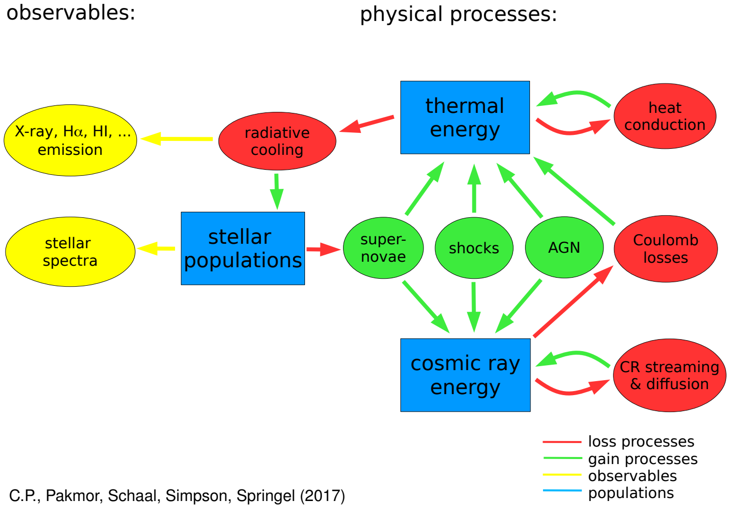

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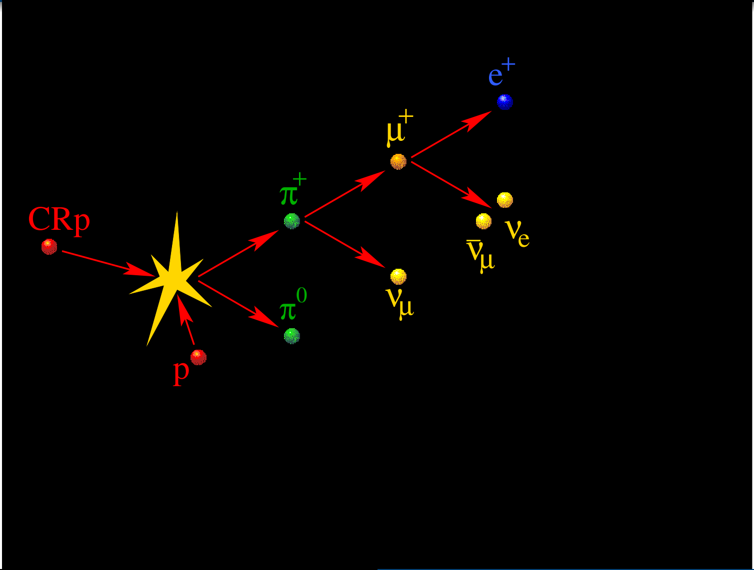
Hadronic cosmic ray proton interaction



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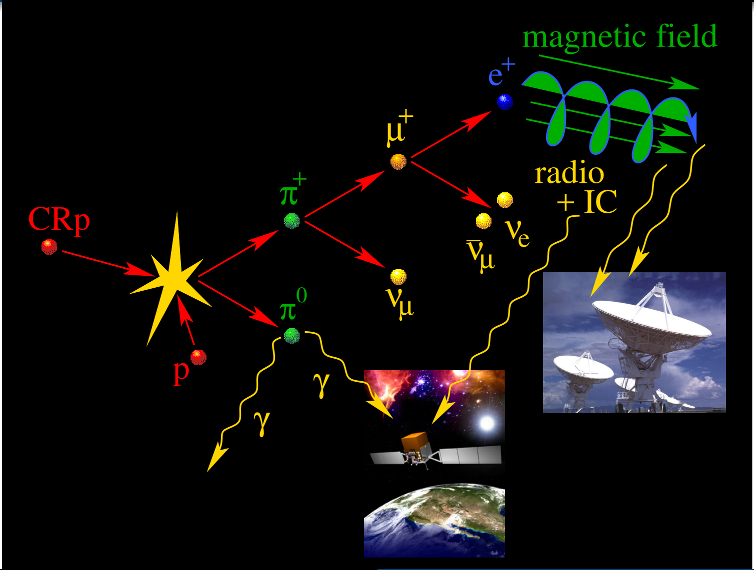

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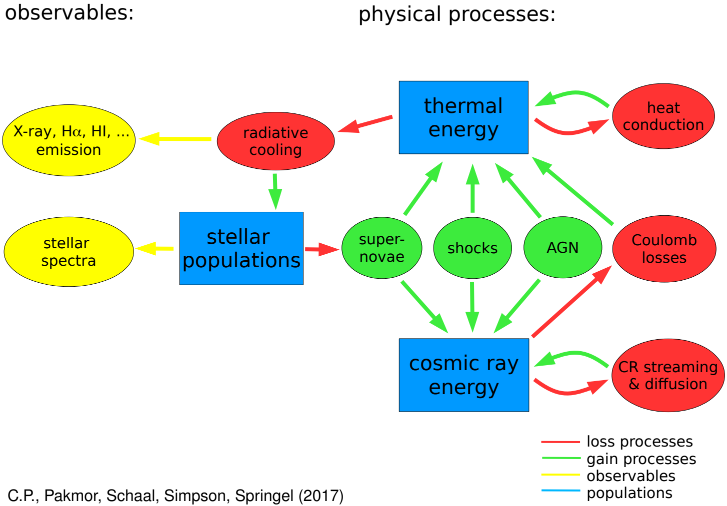

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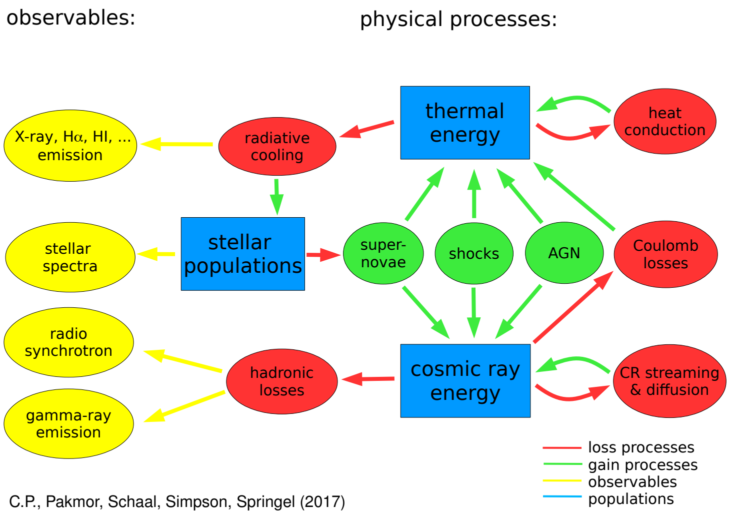

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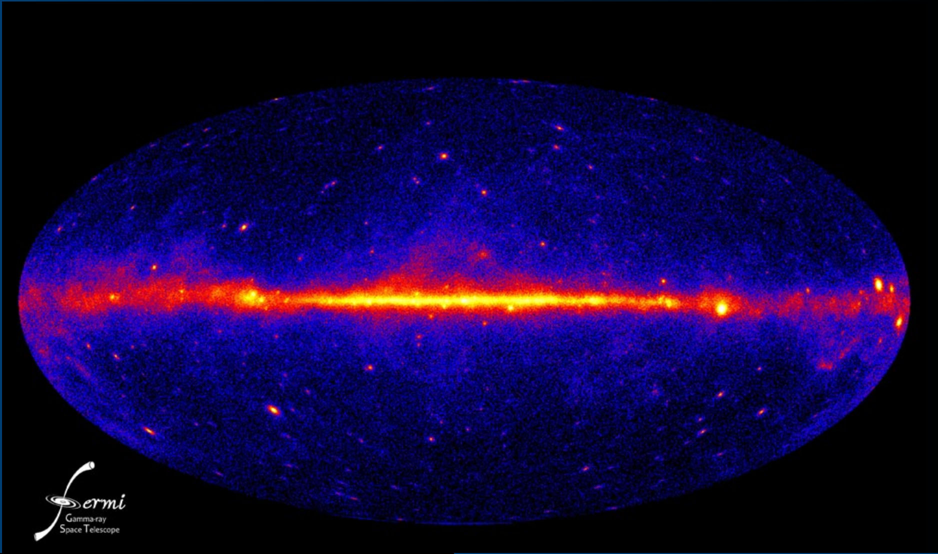
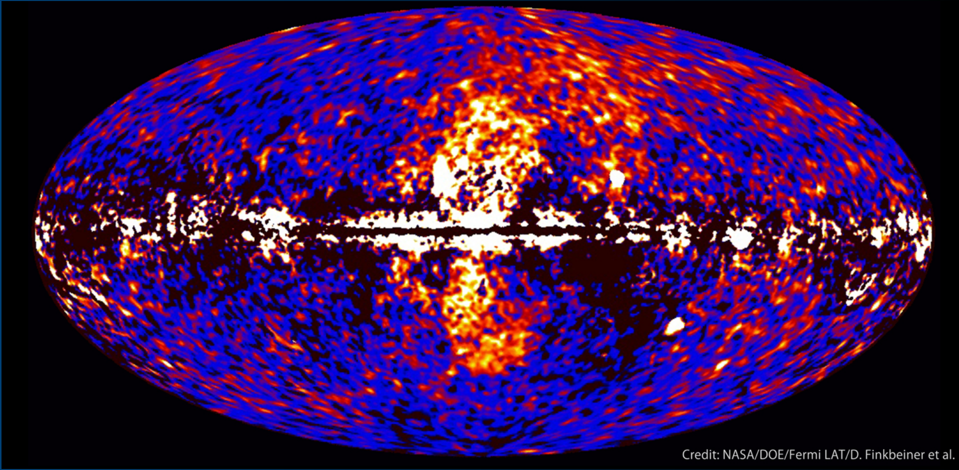
Gamma-ray emission of the Milky Way



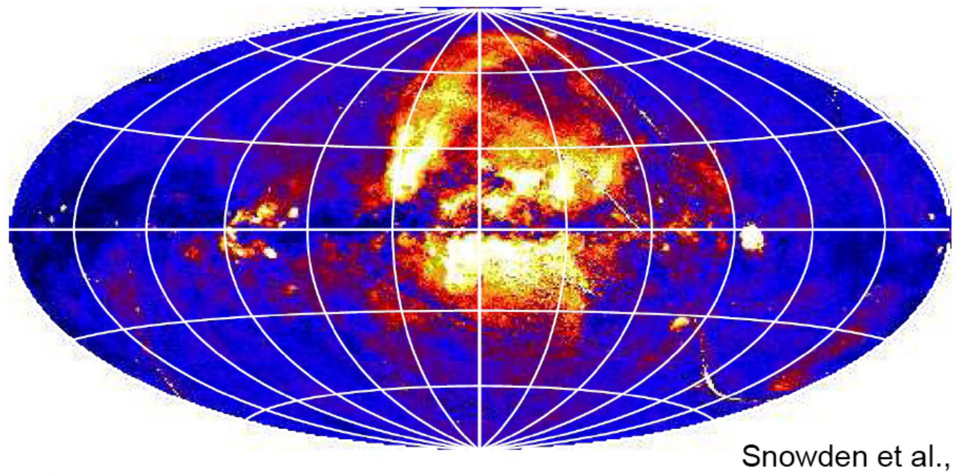
Galactic wind in the Milky Way?

Fermi gamma-ray bubbles

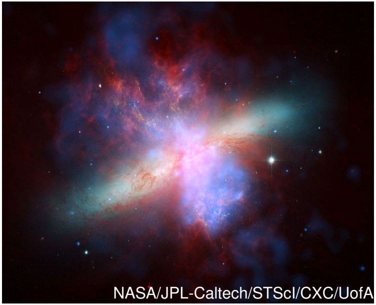


Galactic wind in the Milky Way?

Diffuse X-ray emission in our Galaxy



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 pressure and Alfvén wave heating of CRs accelerated at supernova shocks?

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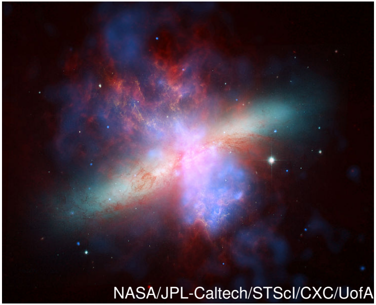

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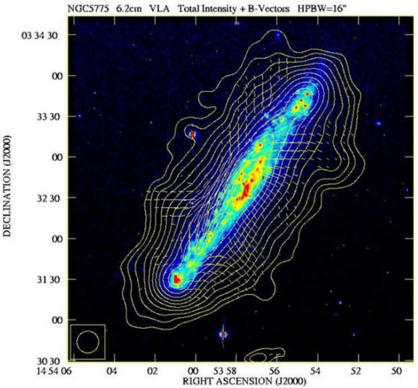
observed energy equipartition between cosmic rays, thermal gas and magnetic fields
→ suggests self-regulated feedback loop with CR driven winds

Why are CRs important for wind formation?

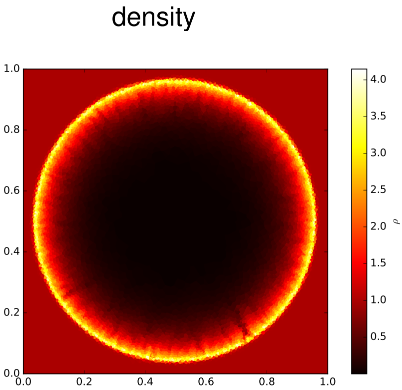
Radio halos in disks: CRs and magnetic fields exist at the disk-halo interface

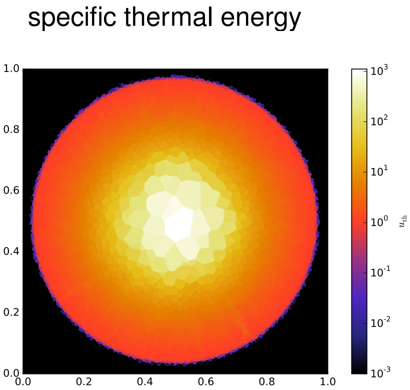


Tüllmann+ (2000)

- 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

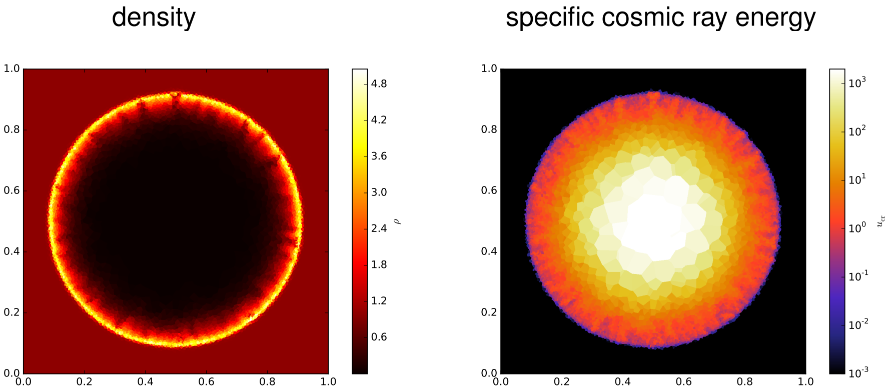
Sedov explosion





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

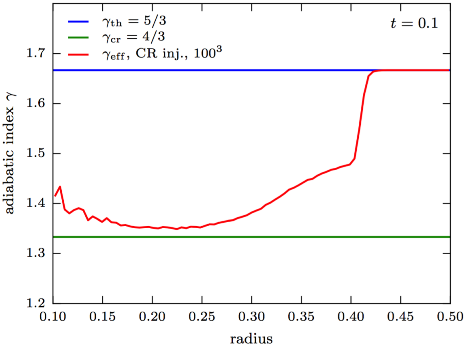
Sedov explosion with CR acceleration



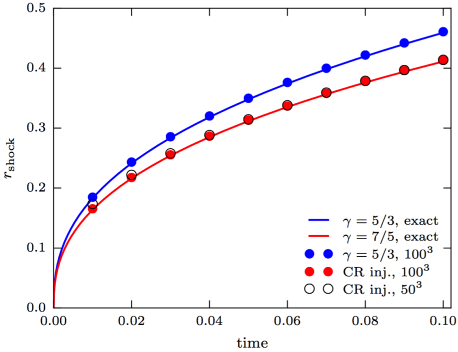
C.P., Pakmor, Schaal, Simpson, Springel (2017)

Sedov explosion with CR acceleration

adiabatic index



shock evolution

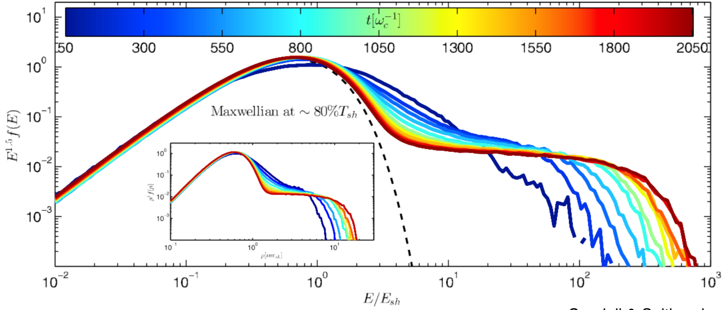


C.P., Pakmor, Schaal, Simpson, Springel (2017)

AIP

Ion spectrum

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



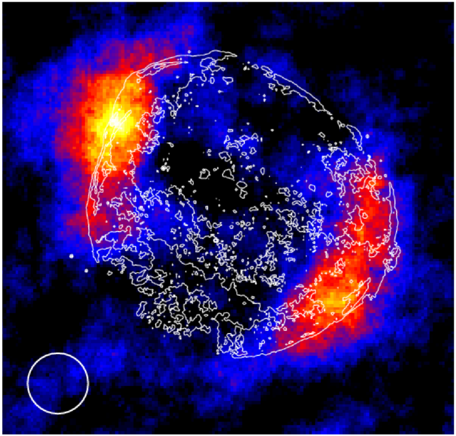
Caprioli & Spitkovsky (2014)

- 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

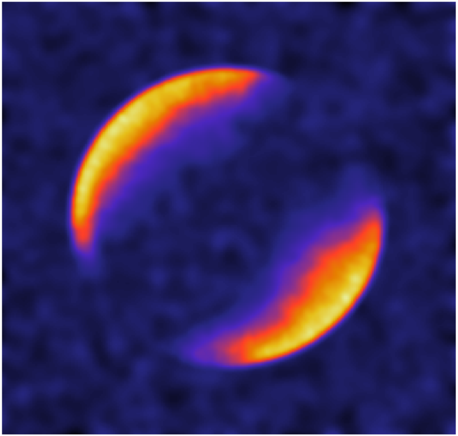
AIP

TeV γ rays from shell-type SNRs: SNR 1006

H.E.S.S. observation



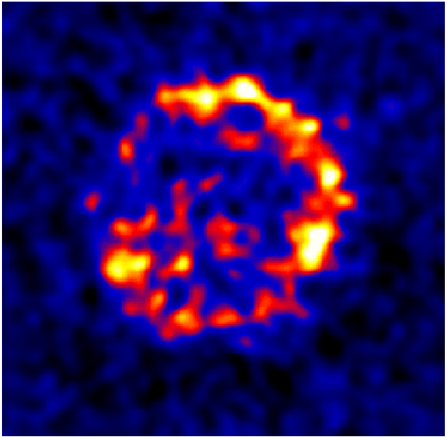
AREPO simulation



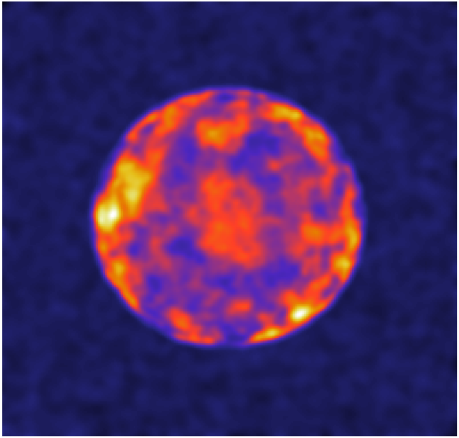
Pais, C.P., Ehlert (in prep.)

TeV γ rays from shell-type SNRs: Vela Junior

H.E.S.S. observation



AREPO simulation



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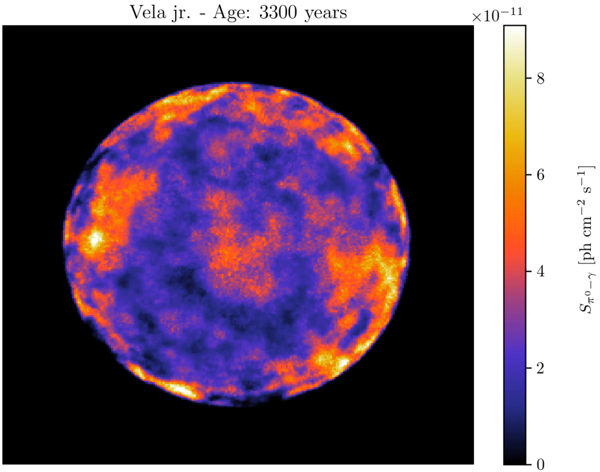
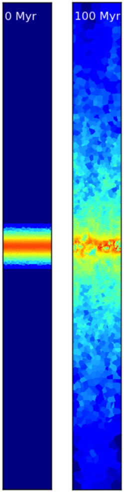
TeV γ rays from shell-type SNRs: Vela Junior



A model for the multi-phase interstellar medium

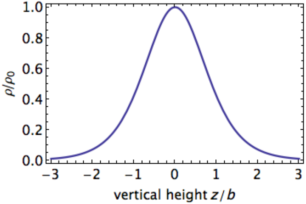
Explore supernovae-driven outflows at high resolution – stratified box simulations



Simpson+ (2016)

- isothermal disk with $T_0 = 10^4$ K
- hydrostatic equilibrium:

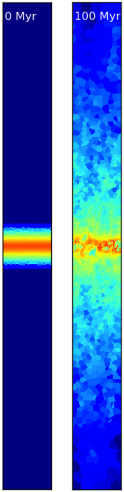
$$f_g \nabla^2 \Phi = 4\pi G \rho$$



- self-gravity
- atomic & molecular cooling network, self-shielding (Glover & Clark 2012, Smith+ 2014)
- MHD with small magnetic seed field (Pakmor+ 2011)
- cosmic ray physics (C.P.+ 2017, Pakmor+ 2016)

Supernova feedback

Explore supernovae-driven outflows at high resolution – stratified box simulations



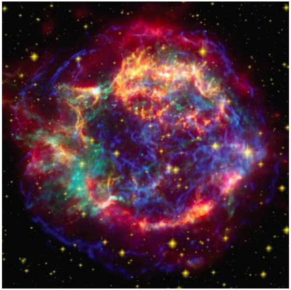
Simpson+ (2016)

- star formation rate:

$$\dot{M}_{*,i} = \epsilon \frac{M_i}{t_{\mathrm{dyn},i}}$$

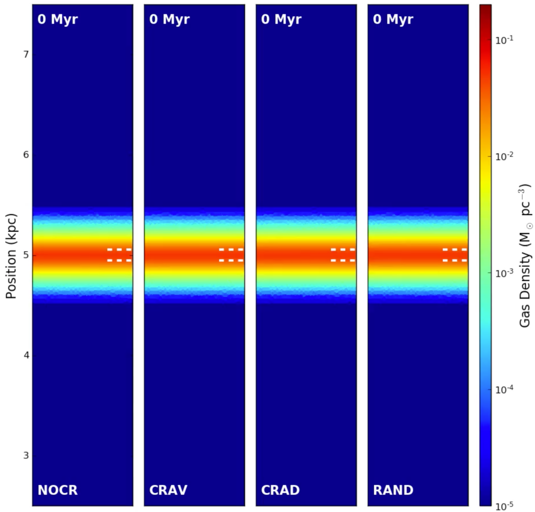
- supernova rate:

$$\dot{M}_{\mathrm{SN},i} = \dot{M}_{*,i} \frac{1.8 \text{ events}}{100 \text{ M}_\odot}$$



- supernova energy $E_{\mathrm{SN}} = 10^{51}$ erg distributed over 32 nearest neighbors
- input in form of thermal, kinetic, or cosmic ray energy

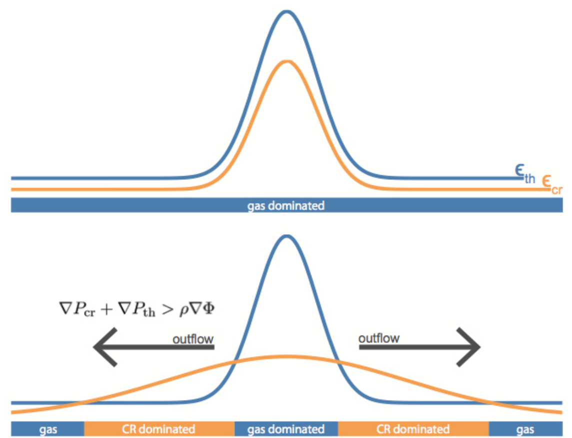
Interstellar medium – turbulence and outflows



Simpson+ (2016)

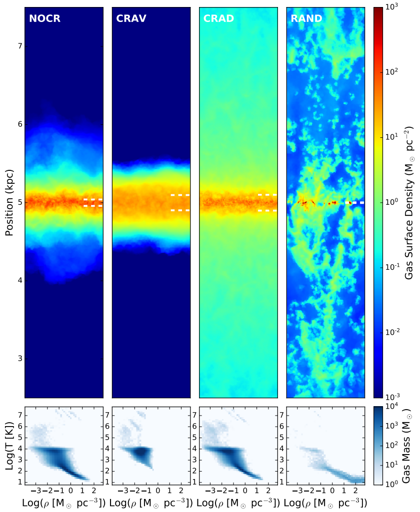
- NOCR: purely thermal SNe
- CRAV: CR advection, $\{f_{\rm cr}, f_{\rm th}\} = \{0.1, 0.9\}$
- CRAD: anisotropic CR diffusion
- RAND: random injection

Cosmic ray driven wind: mechanism



CR streaming in 3D simulations: Uhlig, C.P.+ (2012), Ruszkowski+ (2017)
CR diffusion in 3D simulations: Jubelgas+ (2008), Booth+ (2013), Hanasz+ (2013), Salem & Bryan (2014), Pakmor, C.P.+ (2016), Simpson+ (2016), Girichidis+ (2016), Dubois+ (2016), C.P.+ (2017), Jacob+ (2018)

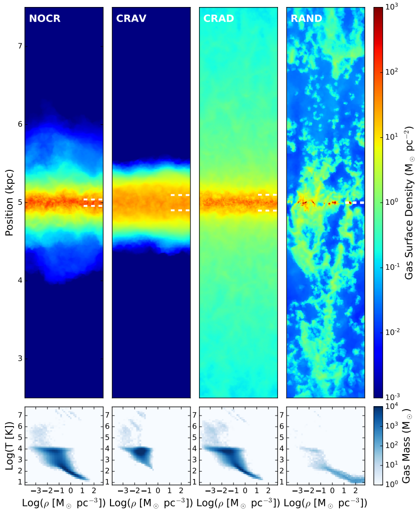
Interstellar medium – turbulence and outflows



Simpson+ (2016)

- diffusing CRs (CRAD) launch outflows with similar mass loadings as randomly placed feedback models (RAND)

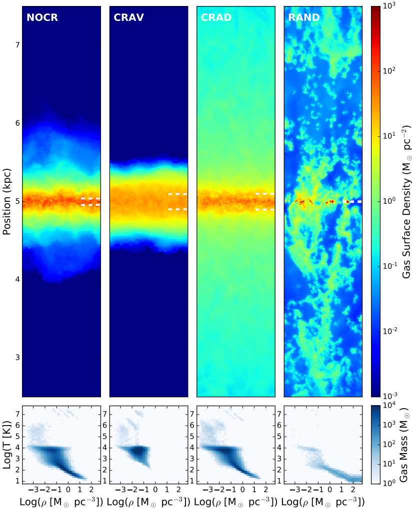
Interstellar medium – turbulence and outflows



Simpson+ (2016)

- diffusing CRs (CRAD) launch outflows with similar mass loadings as randomly placed feedback models (RAND)
- different forcing: CR pressure gradient (CRAD) vs. kinetic pressure gradients propelling a ballistic outflow (RAND)
  $\rightarrow$ velocity and clumpiness differ

Interstellar medium – turbulence and outflows



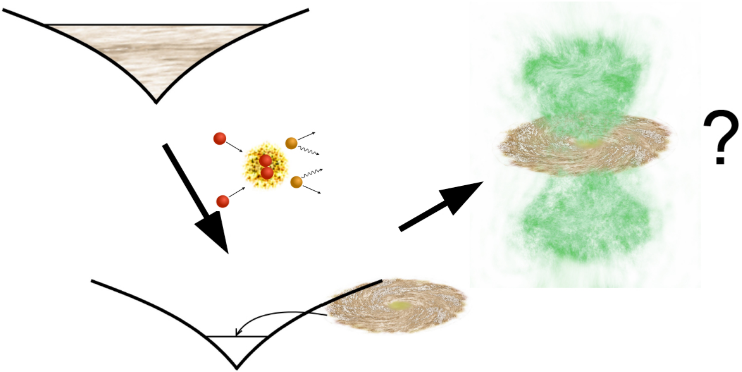
Simpson+ (2016)

- diffusing CRs (CRAD) launch outflows with similar mass loadings as randomly placed feedback models (RAND)
- different forcing: CR pressure gradient (CRAD) vs. kinetic pressure gradients propelling a ballistic outflow (RAND)
  $\rightarrow$ velocity and clumpiness differ
- CR + turbulent pressure self-regulate ISM $\rightarrow$ scale height $h_{1/2} \approx 100$ pc; ISM in RAND collapses to dense phase

$\Rightarrow$ **CR physics is essential for correctly modeling the ISM!**

Outline

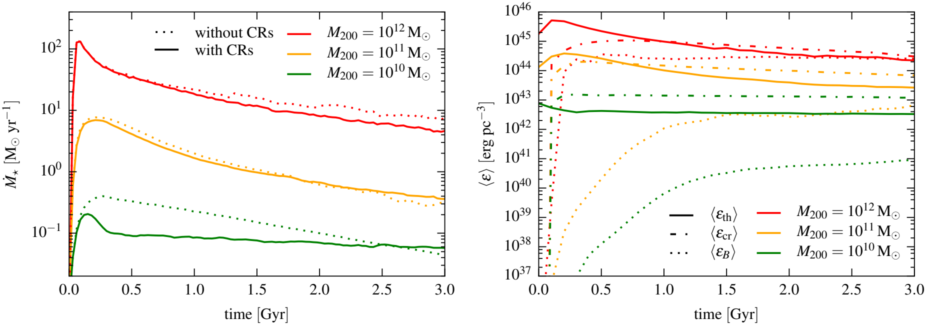
Galaxy simulation setup: 1. cosmic ray advection



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

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

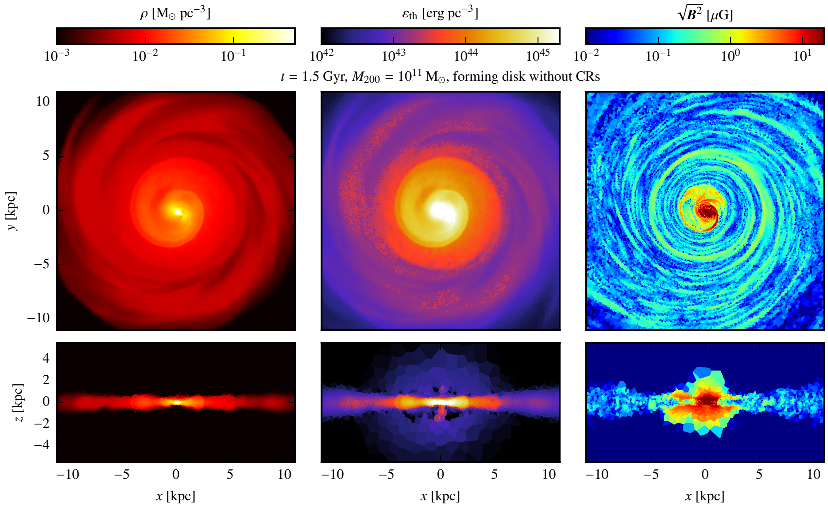
Time evolution of SFR and energy densities



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

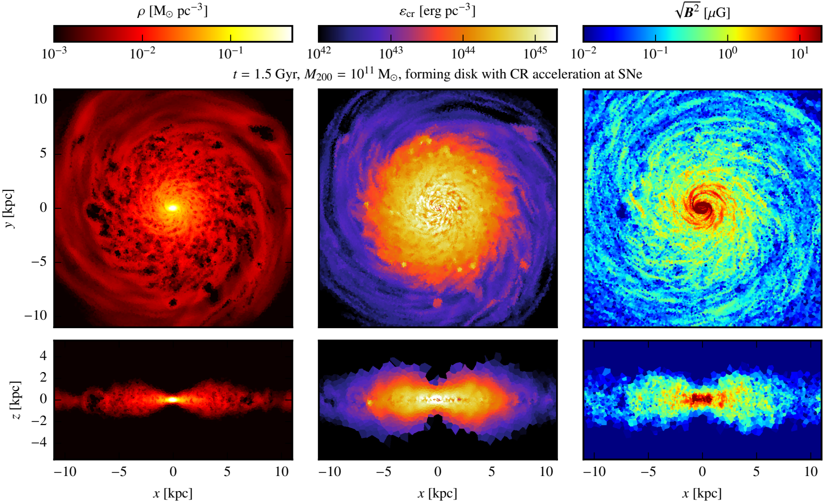
- CR pressure feedback suppresses SFR more in smaller galaxies
- energy budget in disks is dominated by CR pressure
- magnetic dynamo faster in Milky Way galaxies than in dwarfs

MHD galaxy simulation without CRs



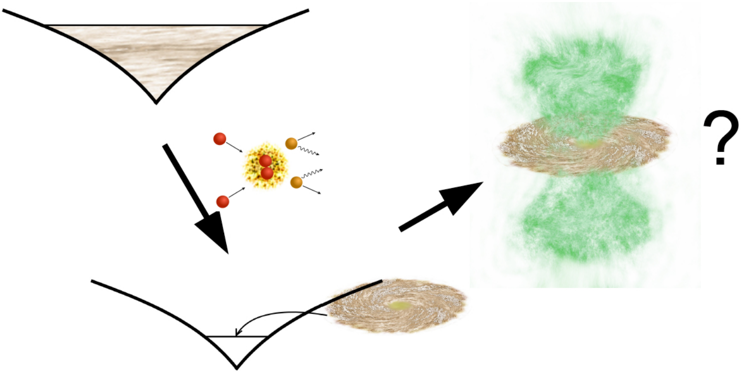
C.P., Pakmor, Schaal, Simpson, Springel (2017)

MHD galaxy simulation with CRs



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

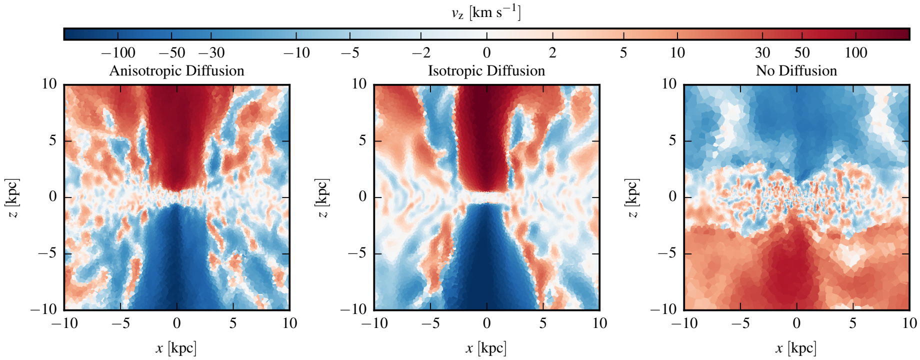
Galaxy simulation setup: 2. cosmic ray diffusion



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

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

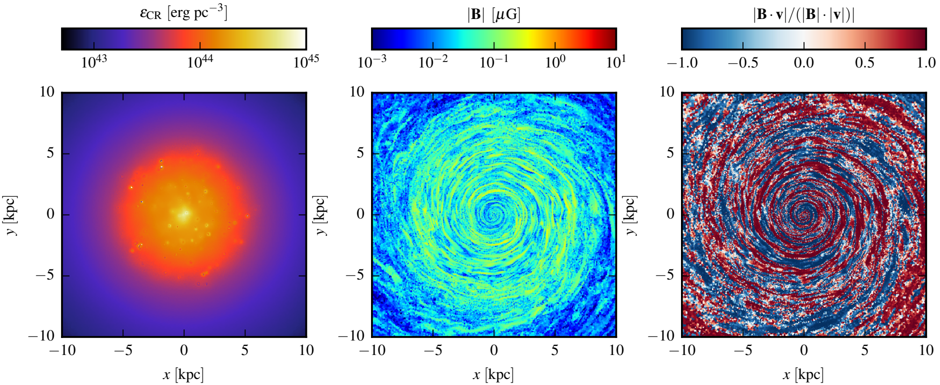
MHD galaxy simulation with CR diffusion



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

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

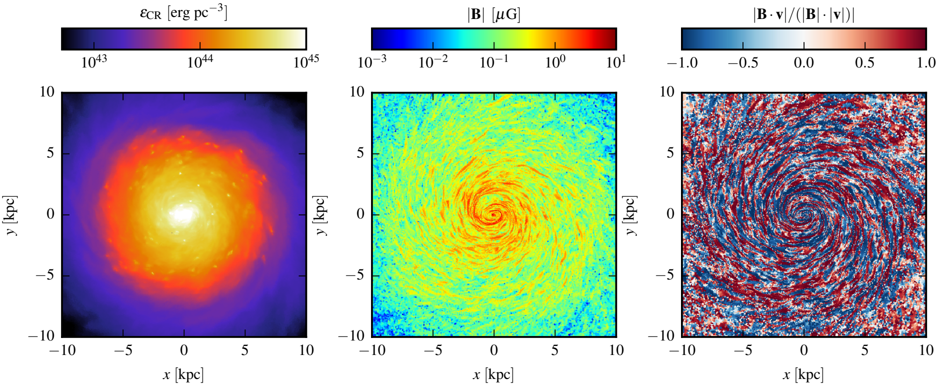
MHD galaxy simulation with CR isotropic diffusion



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

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

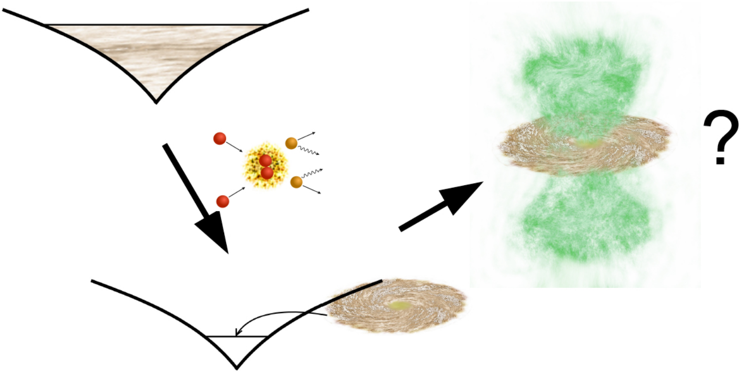
MHD galaxy simulation with CR anisotropic diffusion



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

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

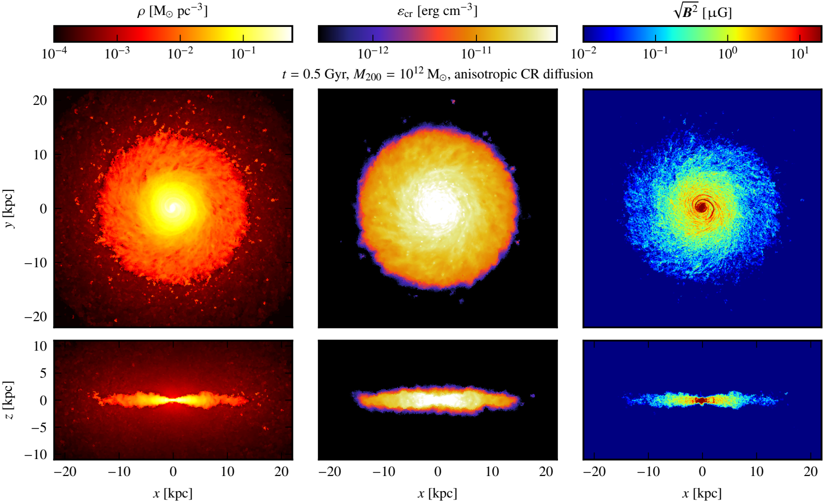
Galaxy simulation setup: 3. non-thermal emission



C.P., Pakmor, Simpson, Springel (2017a,b)
Simulating radio synchrotron and gamma-ray emission in galaxies

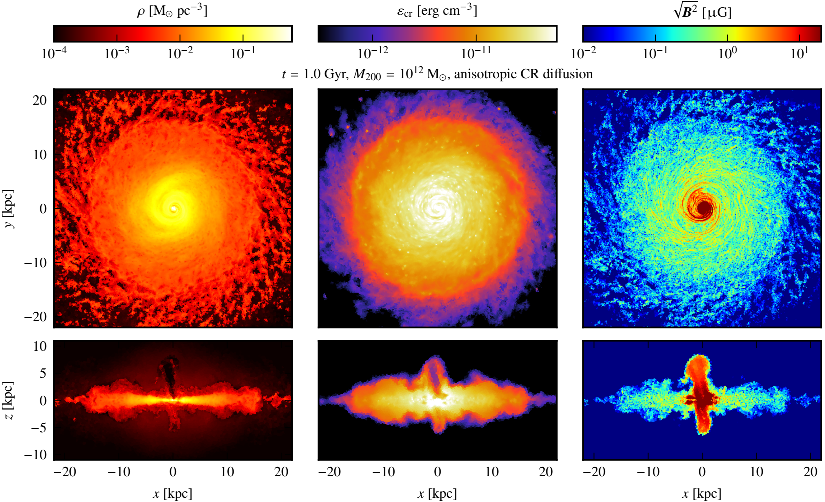
MHD + CR advection + diffusion: $\{10^{10}, 10^{11}, 10^{12}\}\ M_\odot$

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



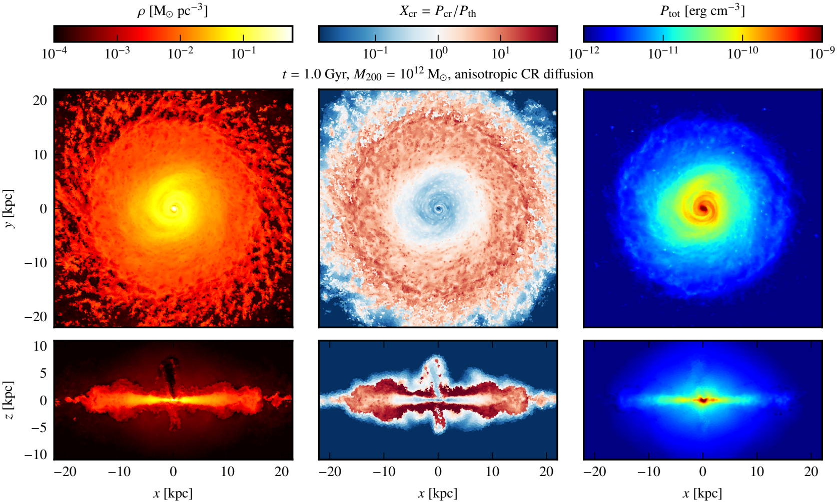
C.P.+ (2017a,b)

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



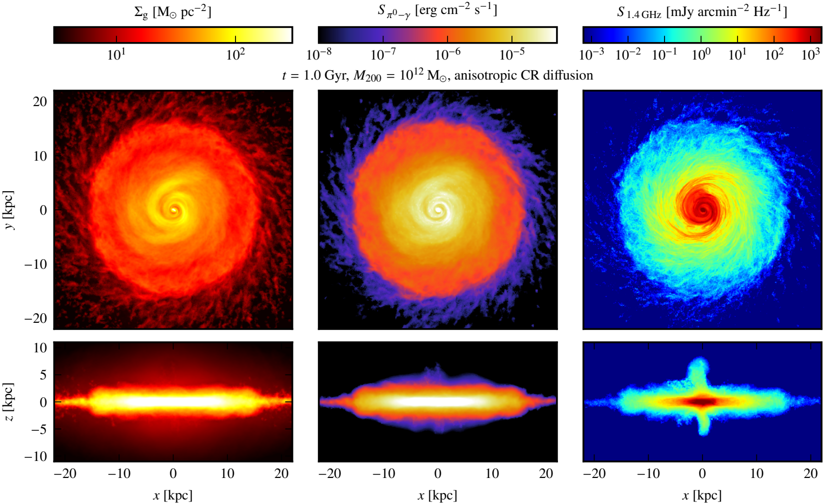
C.P.+ (2017a,b)

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



C.P.+ (2017a,b)

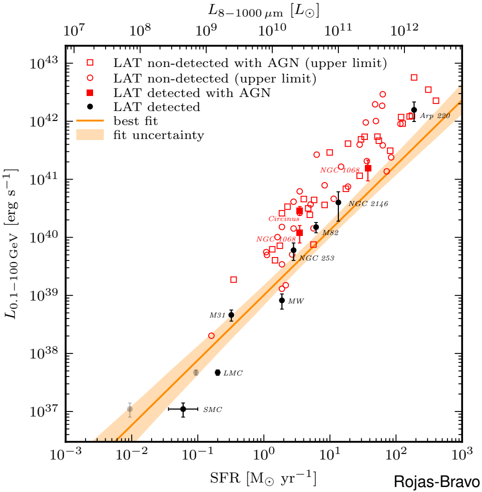
γ-ray and radio emission of Milky Way-like galaxy



C.P.+ (2017a,b)

Far infra-red – gamma-ray correlation

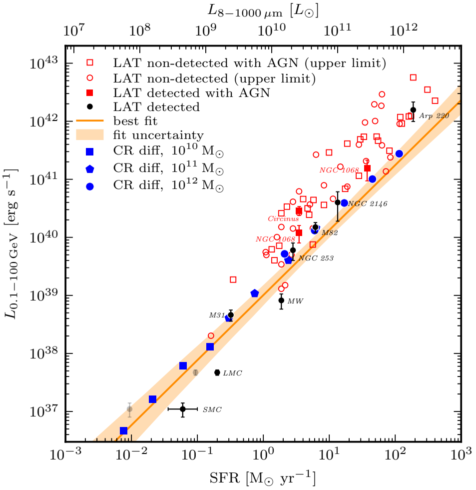
Universal conversion: star formation → cosmic rays → gamma rays



Rojas-Bravo & Araya (2016)

Far infra-red – gamma-ray correlation

Universal conversion: star formation → cosmic rays → gamma rays



C.P.+ (2017a)

Far infra-red – gamma-ray correlation

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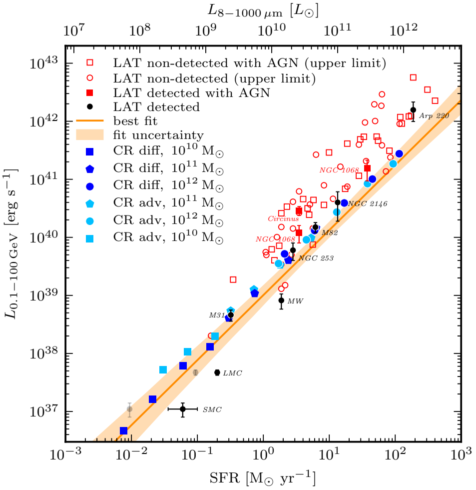
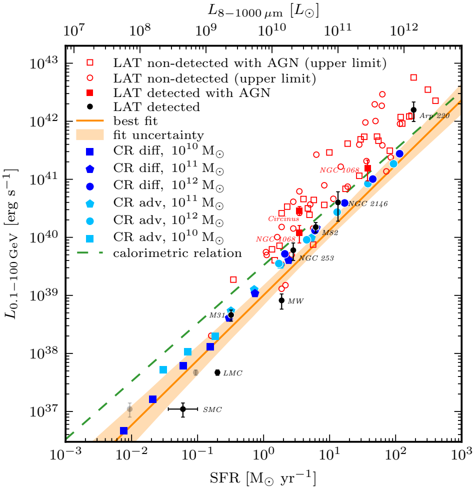


C.P.+ (2017a)

AIP

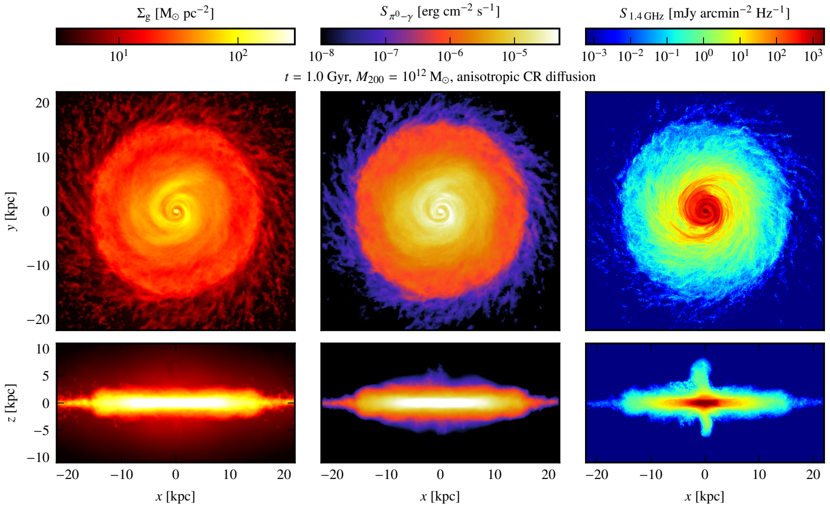
Far infra-red – gamma-ray correlation

Universal conversion: star formation → cosmic rays → gamma rays



C.P.+ (2017a)

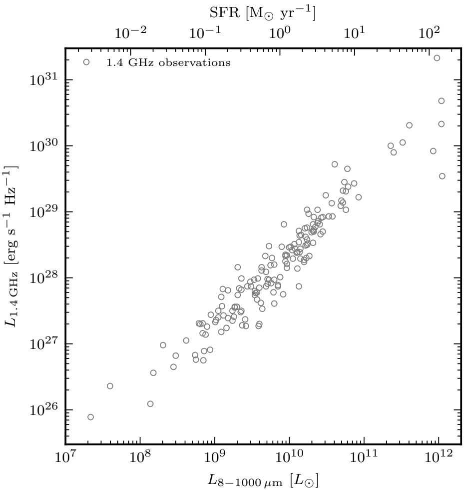
γ-ray and radio emission of Milky Way-like galaxy



C.P.+ (2017a,b)

Far infra-red – radio correlation

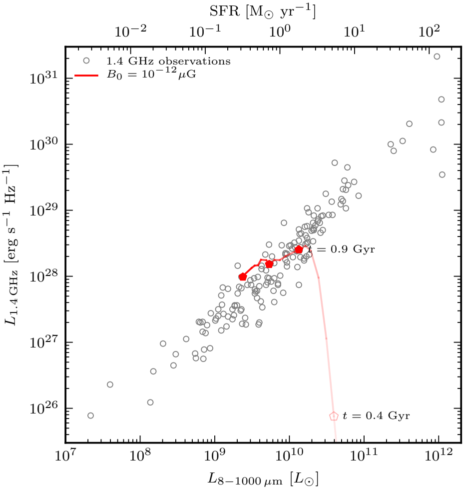
Universal conversion: star formation → cosmic rays → radio



Bell (2003)

Far infra-red – radio correlation

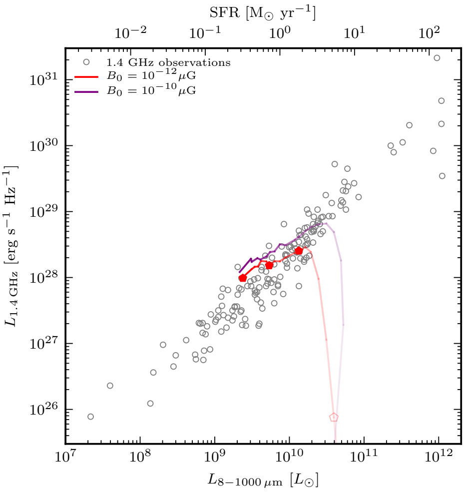
Universal conversion: star formation → cosmic rays → radio



Bell (2003)

Far infra-red – radio correlation

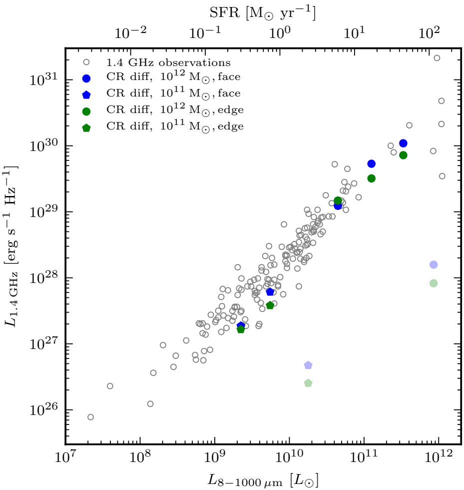
Universal conversion: star formation → cosmic rays → radio



Bell (2003)

Far infra-red – radio correlation

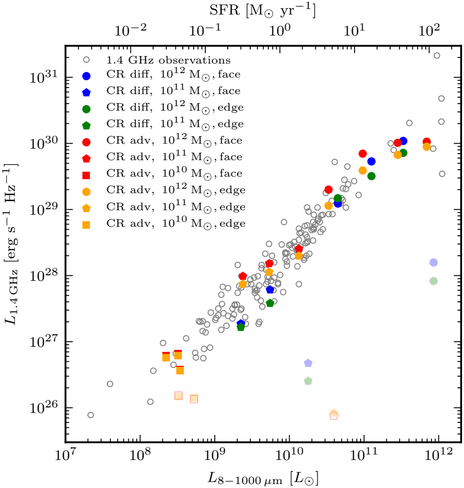
Universal conversion: star formation → cosmic rays → radio



C.P.+ (2017b)

Far infra-red – radio correlation

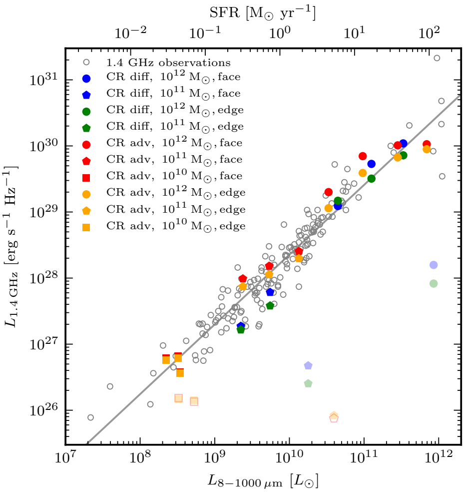
Universal conversion: star formation → cosmic rays → radio



C.P.+ (2017b)

Far infra-red – radio correlation

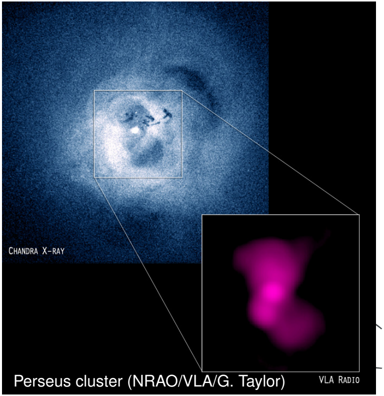
Universal conversion: star formation → cosmic rays → radio



C.P.+ (2017b)

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?**

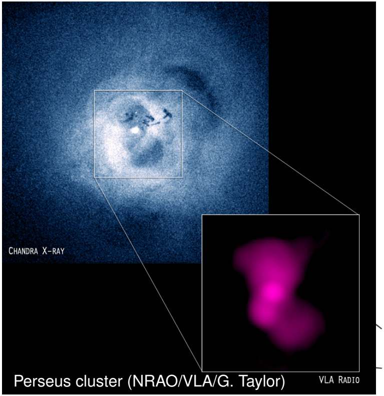


Perseus cluster (NRAO/VLA/G. Taylor)

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

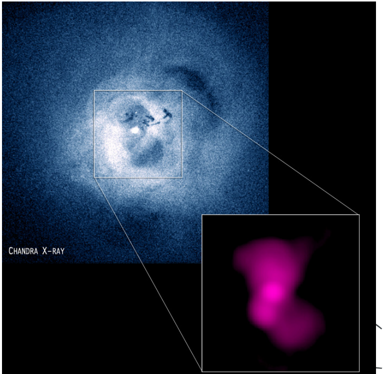


Perseus cluster (NRAO/VLA/G. Taylor)

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
- jet interaction with magnetized cluster medium → turbulence
- jet accelerates cosmic rays → release from bubbles provides source of heat

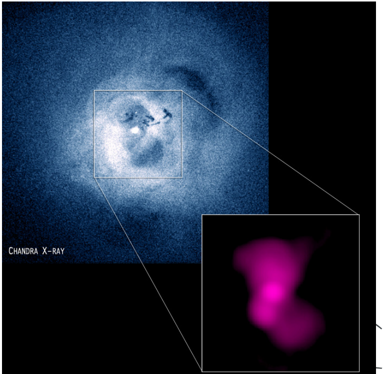


Perseus cluster (NRAO/VLA/G. Taylor)

Feedback by active galactic nuclei

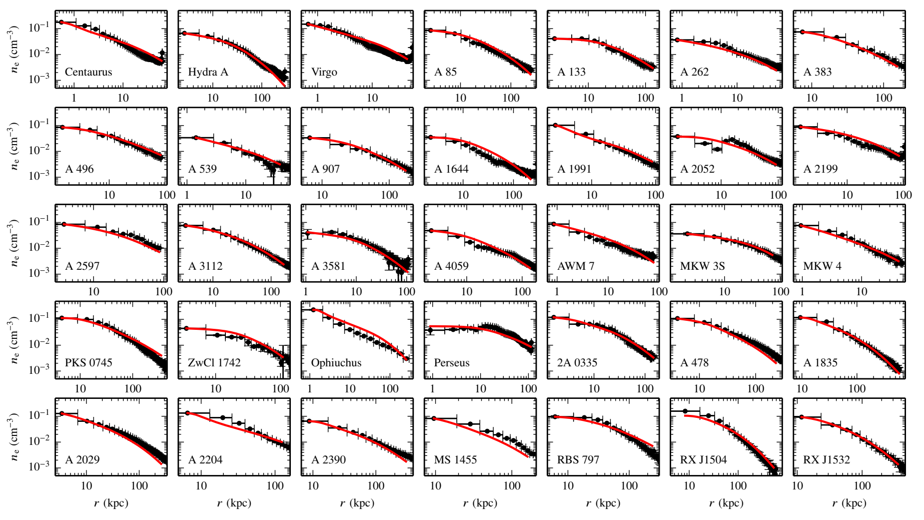
Paradigm: accreting super-massive black holes at galaxy cluster centers launch relativistic jets, which provide energetic feedback to balance cooling ⇒ **but how?**

- 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

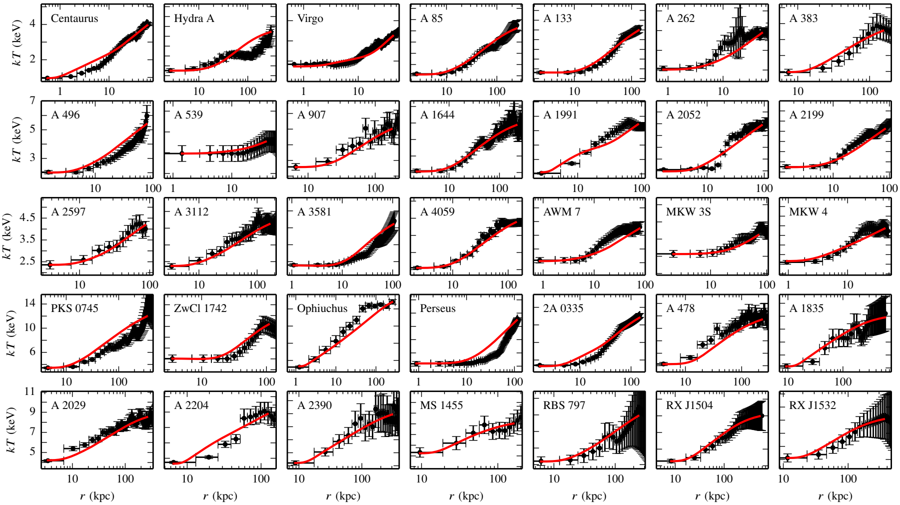


Perseus cluster (NRAO/VLA/G. Taylor)

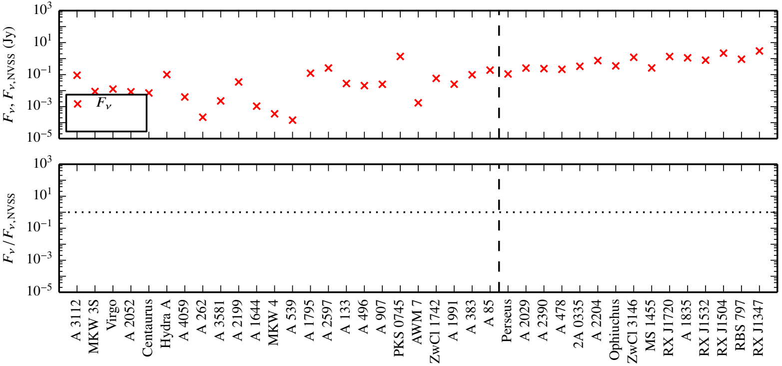
Gallery of solutions: density profiles



Gallery of solutions: temperature profiles

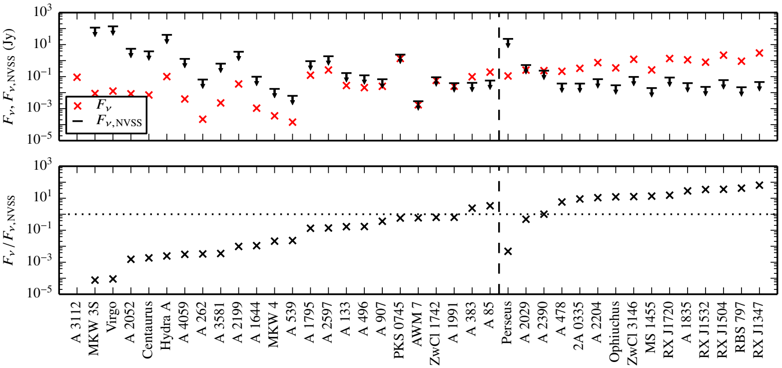


Hadronically induced radio emission



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 viable solution for non-RMH clusters
- CR heating solution ruled out in radio mini halos (RMHs)

How can we explain these results?

- self-regulated feedback cycle driven by CRs

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- self-regulated feedback cycle driven by CRs

AGN injects CRs

How can we explain these results?

- self-regulated feedback cycle driven by CRs

AGN injects CRs → CR heating balances cooling

How can we explain these results?

- self-regulated feedback cycle driven by CRs

AGN injects CRs → CR heating balances cooling

↓

CRs stream outwards and become too dilute to heat the cluster

How can we explain these results?

- self-regulated feedback cycle driven by CRs

AGN injects CRs → CR heating balances cooling

↓

CRs stream outwards and become too dilute to heat the cluster

↘

radio mini halo

How can we explain these results?

- self-regulated feedback cycle driven by CRs

AGN injects CRs → CR heating balances cooling

↓

cluster cools and triggers AGN activity ← CRs stream outwards and become too dilute to heat the cluster

↘

radio mini halo

AIP

How can we explain these results?

- self-regulated feedback cycle driven by CRs

AGN injects CRs → CR heating balances cooling

↓

CRs stream outwards and become too dilute to heat the cluster

↓

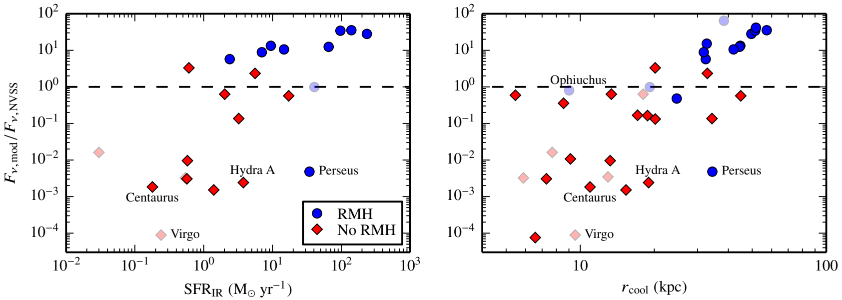
cluster cools and triggers AGN activity

↑

AGN injects CRs

CRs stream outwards and become too dilute to heat the cluster ↘ radio mini halo

Self-regulated heating/cooling cycle in cool cores

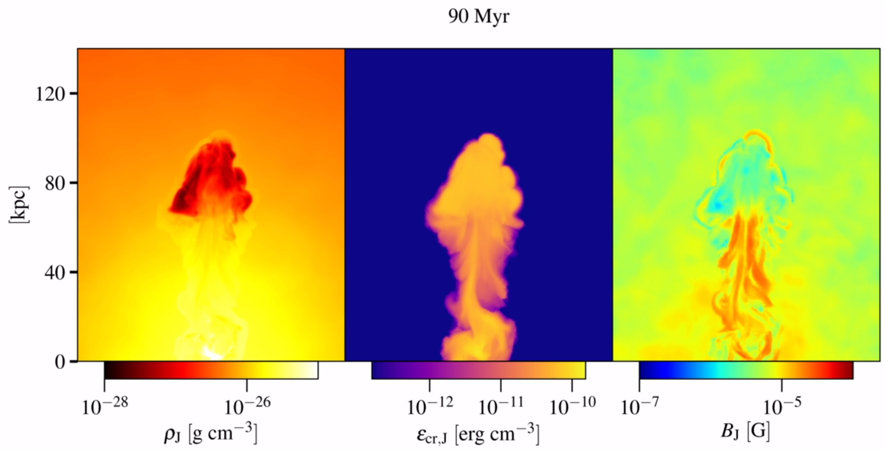


Jacob & C.P. (2017b)

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

- simmering SF: CR heating is effectively balancing cooling
- abundant SF: heating/cooling out of balance

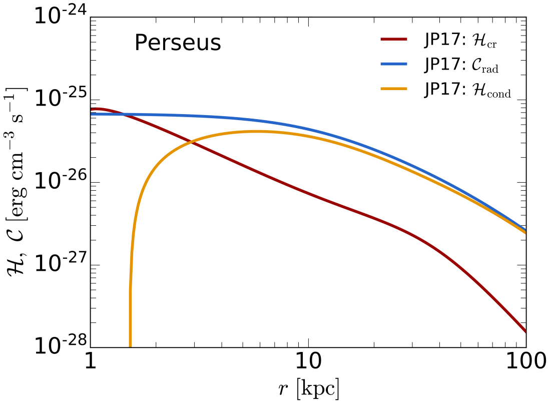
Jet simulation: gas density, CR energy density, *B* field



Ehlert+ in prep.

AIP

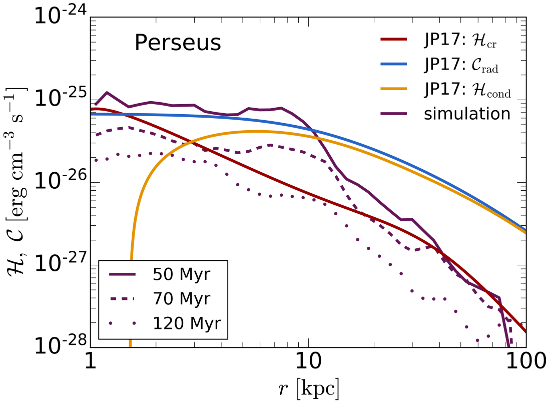
Perseus cluster – heating vs. cooling: theory



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}

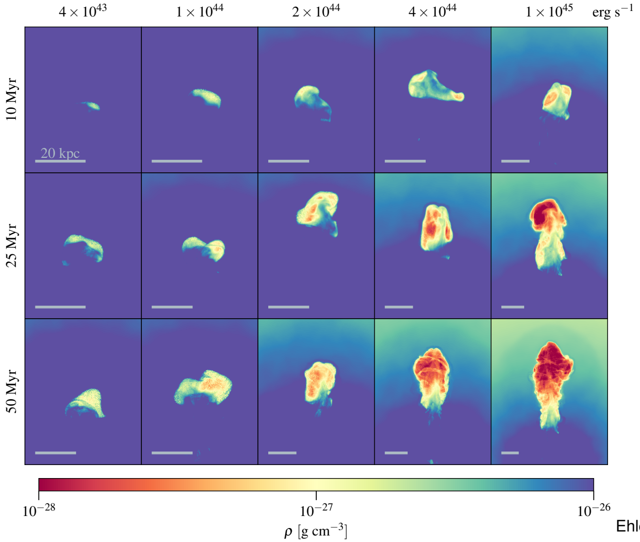
Perseus cluster – heating vs. cooling: simulations



Ehlert+ in prep.

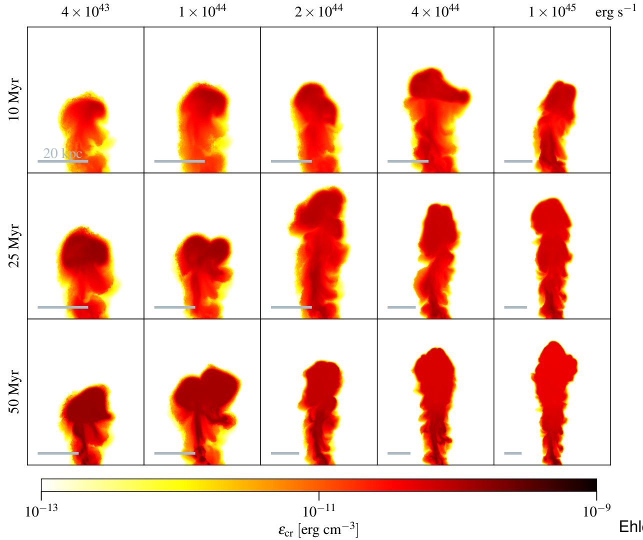
- CR and conductive heating balance radiative cooling: $\mathcal{H}_{\rm cr} + \mathcal{H}_{\rm th} \approx \mathcal{C}_{\rm rad}$: modest mass deposition rate of 1 $M_\odot$ yr^{-1}
- **simulated CR heating rate matches 1D steady state model**

Matrix of jet simulations: density at 70 Myrs



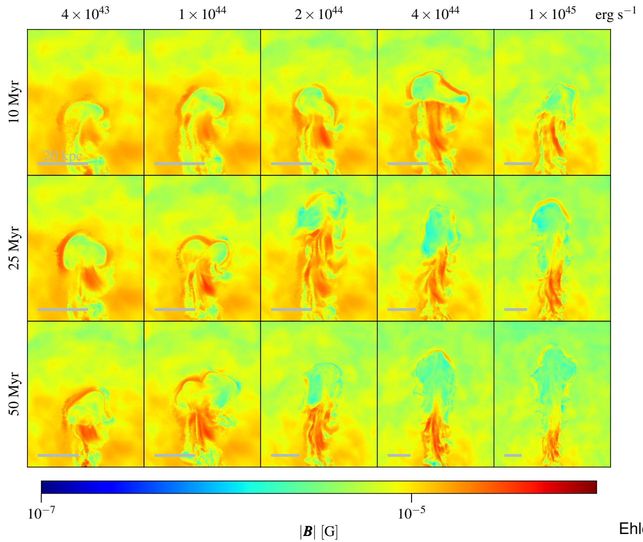
Ehlert+ in prep.

Matrix of jet simulations: CR energy density at 70 Myrs



Ehlert+ in prep.

Matrix of jet simulations: magnetic field at 70 Myrs



Ehlert+ in prep.

Conclusions on CR feedback in galaxies and clusters

- 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

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

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

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

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Literature for the talk

Non-thermal radio and gamma-ray emission in galaxies:

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- 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.

A multi-phase model of the interstellar medium:

- Simpson, Pakmor, Marinacci, Pfrommer, Springel, Glover, Clark, Smith, *The role of cosmic ray pressure in accelerating galactic outflows,* 2016, ApJL.