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. Galaxy formation
   - Modelling physics in galaxies
   - Supernova explosions
   - Galaxy simulations
3. Galaxy cluster evolution
   - Steady state models
   - AGN jet simulations
   - Conclusions

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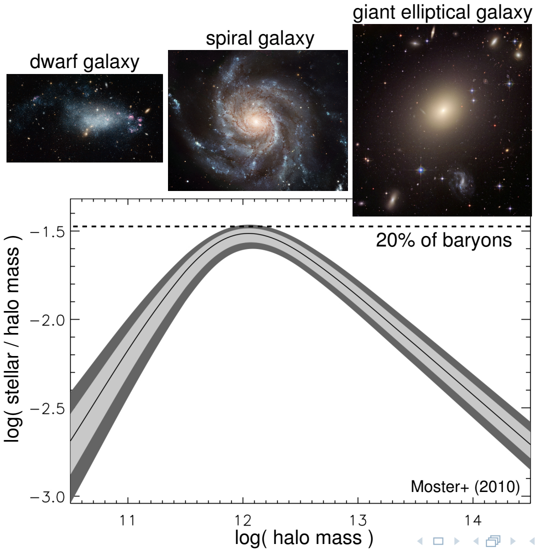
Puzzles in galaxy formation

Puzzles in galaxy formation



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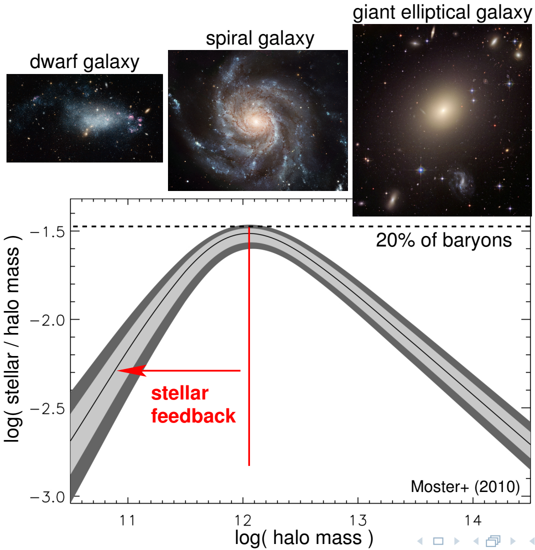

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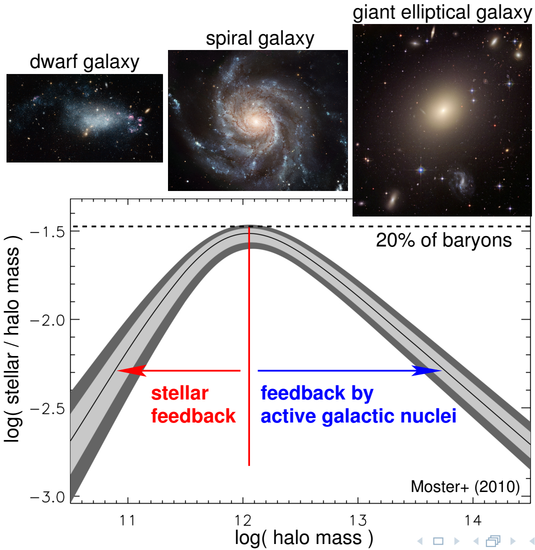

Feedback

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

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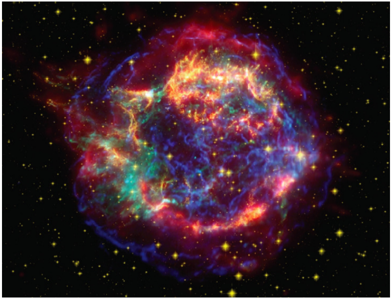
2. the partial reversion of the effects of a given process to its source or to a preceding stage so as to reinforce or modify this process
3. the solution of all problems in galaxy formation

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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- star formation and supernovae drive gas out of galaxies by galactic super winds

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Feedback by galactic winds

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NASA/JPL-Caltech/STScI/CXC/UofA

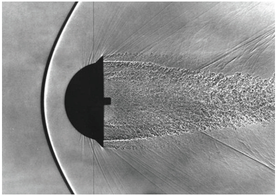
- galactic supernova remnants drive shock waves, turbulence, accelerate electrons + protons, amplify magnetic fields
- star formation and supernovae drive gas out of galaxies by galactic super winds
- critical for understanding the physics of galaxy formation $\rightarrow$ may explain puzzle of low star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

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



slide concept Spitkovsky

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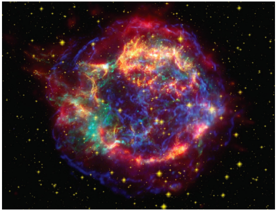

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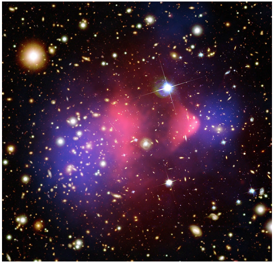

clusters/galaxies, Coulomb collisions set $\lambda_{\rm mfp}$:
$\lambda_{\rm mfp} \sim L_{\rm cluster}/10, \qquad \lambda_{\rm mfp} \sim L_{\rm SNR}$

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

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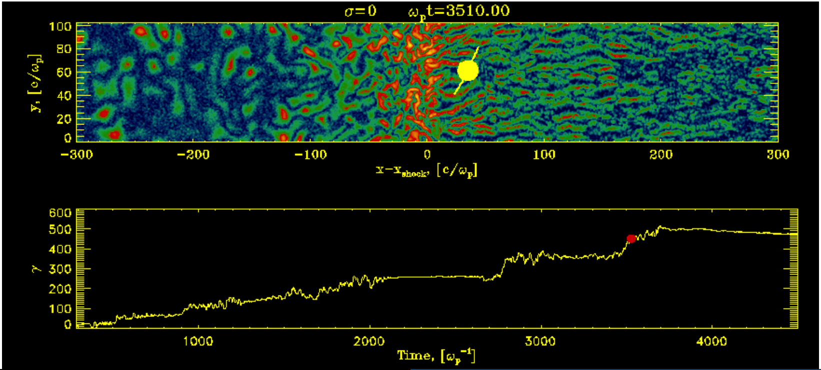
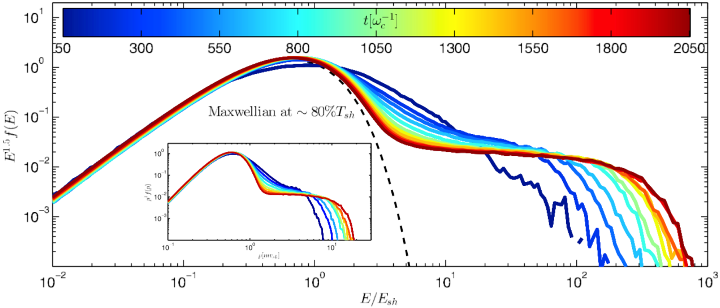
Particle acceleration at relativistic shock, $B_0 = 0$

- 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

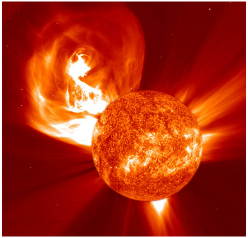
Non-relativistic parallel shock in long-term hybrid simulation



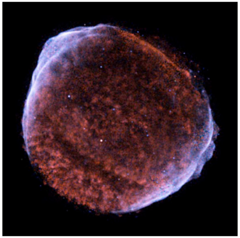
Caprioli & Spitkovsky (2014)

- 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

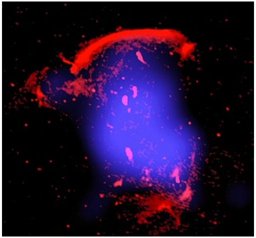
Astrophysical shocks



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



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

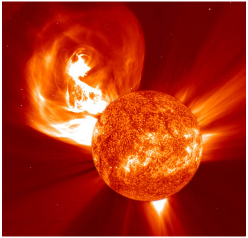


cluster shocks $\sim$ 2 Mpc
giant radio relic (van Weeren)

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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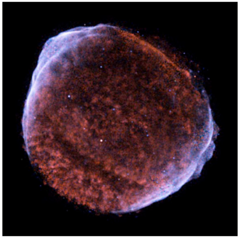

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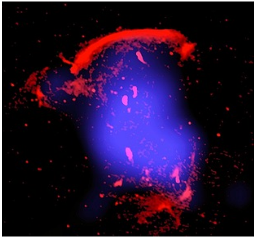

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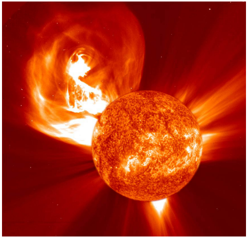
collisionless shocks $\Longleftrightarrow$ energetic particles $\Longleftrightarrow$ electro-magnetic waves



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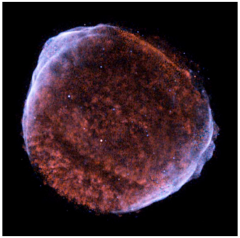

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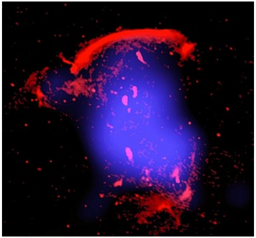

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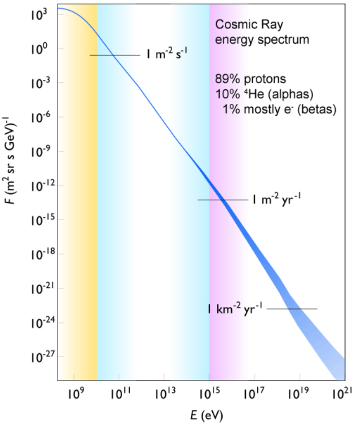
Galactic cosmic ray spectrum



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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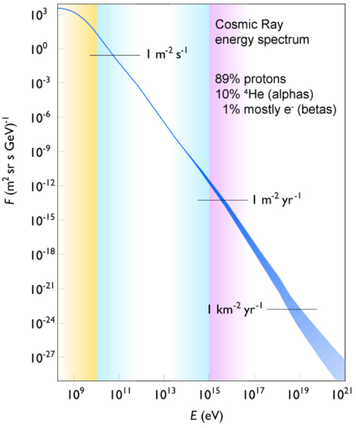

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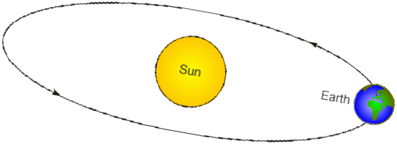
- spans more than 33 decades in flux and 12 decades in energy
- "knee" indicates characteristic maximum energy of galactic accelerators
- CRs beyond the "ankle" have extra-galactic origin
- energy density of cosmic rays, magnetic fields, and turbulence in the interstellar gas all similar

Cosmic ray feedback: an extreme multi-scale problem



Milky Way-like galaxy:

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

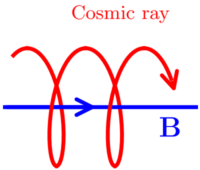
gyro-orbit of GeV cosmic ray:

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

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

Zweibel (2017), Jiang & Oh (2018), Thomas & CP (2018)

Interactions of CRs and magnetic fields



sketch: Jacob

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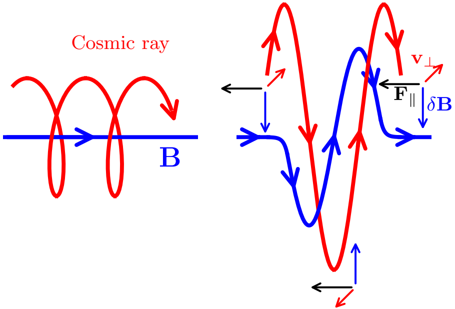

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  Doppler-shifted MHD frequency is a multiple of the CR gyrofrequency

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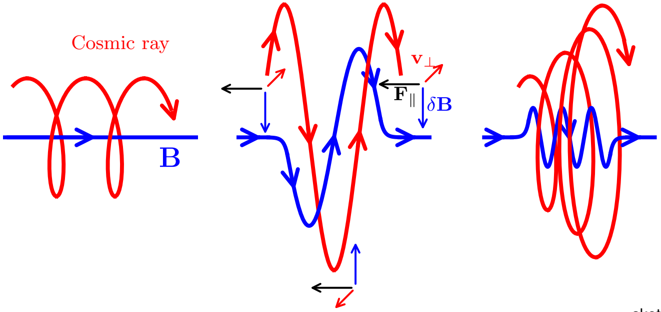

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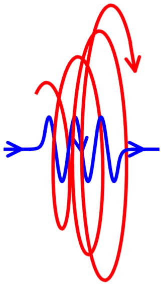
- **gyro resonance:** $\omega - k_{||} v_{||} = n\Omega$
  Doppler-shifted MHD frequency is a multiple of the CR gyrofrequency
- CRs scatter on magnetic fields → isotropization of CR momenta

CR streaming and diffusion

- **CR streaming instability:** Kulsrud & Pearce 1969
  - if $v_{cr} > v_A$, CR flux excites and amplifies an Alfvén wave field in resonance with the gyroradii of CRs
  - scattering off of this wave field limits the (GeV) CRs' bulk speed $\sim v_A$
  - wave damping: transfer of CR energy and momentum to the thermal gas



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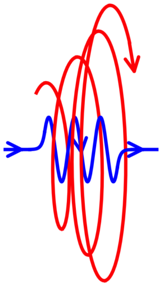

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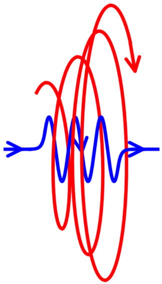

$\rightarrow$ *CRs exert pressure on thermal gas via scattering on Alfvén waves*

weak wave damping: strong coupling $\rightarrow$ CR stream with waves
strong wave damping: less waves to scatter $\rightarrow$ CR diffusion prevails

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CR transport (steady-state flux)

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

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$$\boldsymbol{v}_{\mathrm{st}} = \boldsymbol{v}_{\mathrm{A}} \frac{\bar{\nu}_{+} - \bar{\nu}_{-}}{\bar{\nu}_{+} + \bar{\nu}_{-}},$$

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

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

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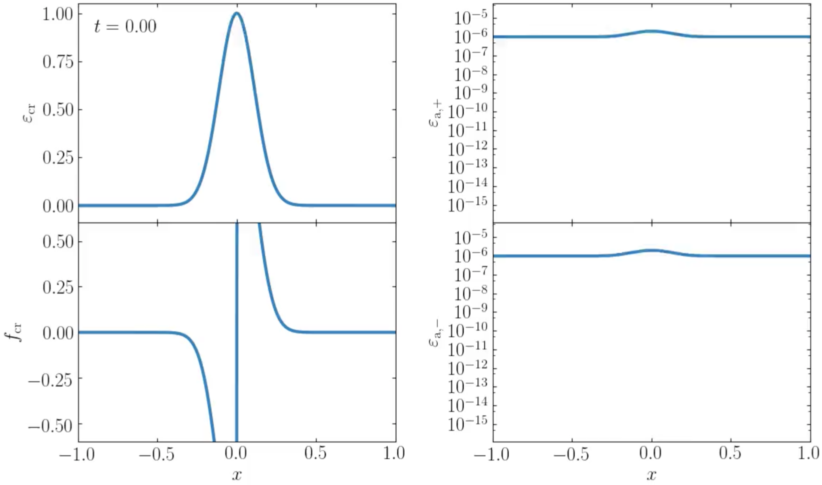
Non-equilibrium CR streaming and diffusion

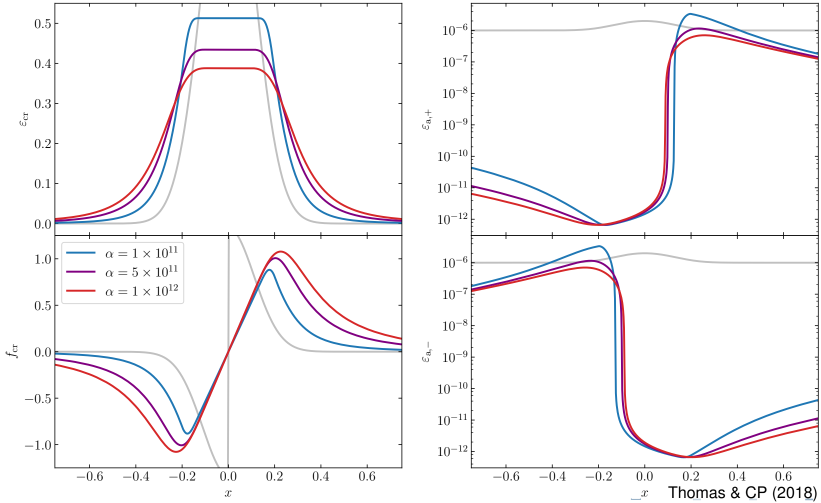
Coupling the evolution of CR and Alfvén wave energy densities



Thomas & CP (2018)

Non-equilibrium CR streaming and diffusion

Varying damping rate of Alfvén waves modulates the diffusivity of solution

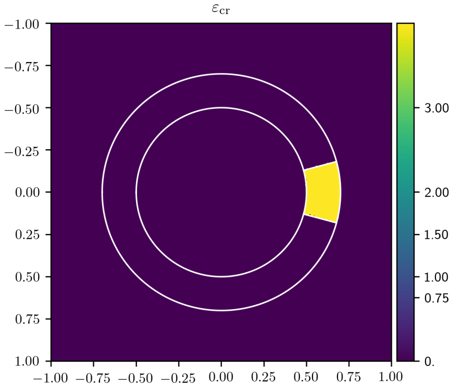


Thomas & CP (2018)

Anisotropic CR streaming and diffusion – AREPO

CR transport mediated by Alfvén waves and coupled to magneto-hydrodynamics

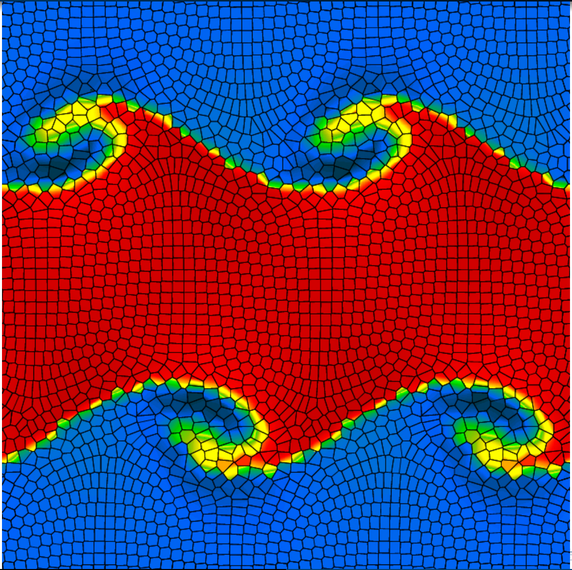
- CR streaming and diffusion along magnetic field lines in the self-confinement picture
- moment expansion similar to radiation hydrodynamics
- accounts for kinetic physics: non-linear Landau damping, gyro-resonant instability, ...
- Galilean invariant and causal transport
- energy and momentum conserving



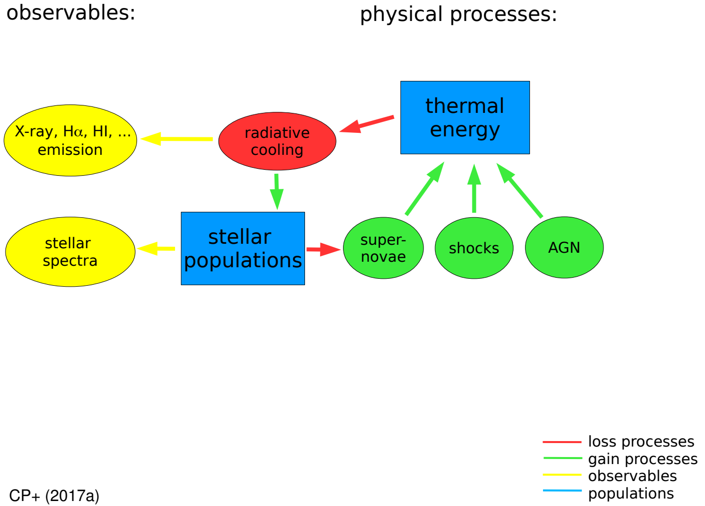
Thomas, Pakmor, CP (in prep.)

Outline

Cosmological moving-mesh code AREPO (Springel 2010)

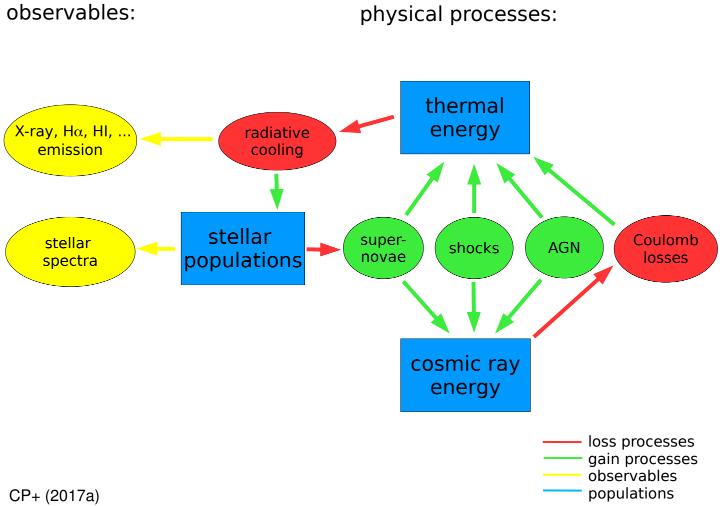


Simulations – flowchart



CP+ (2017a)

Simulations with cosmic ray physics



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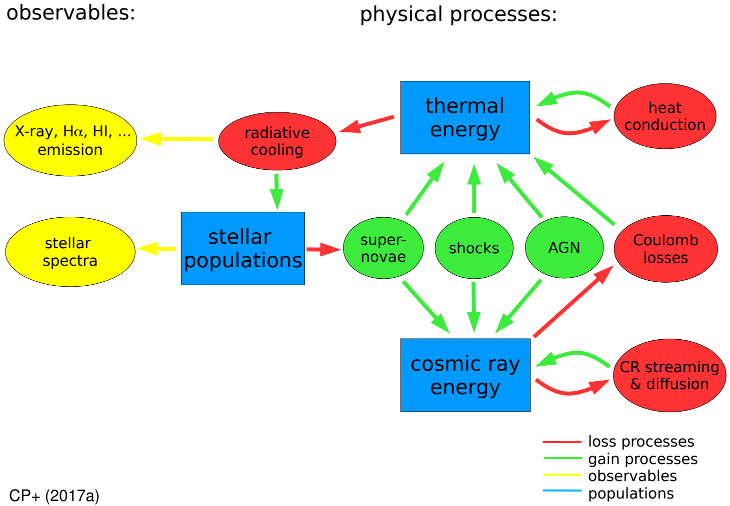
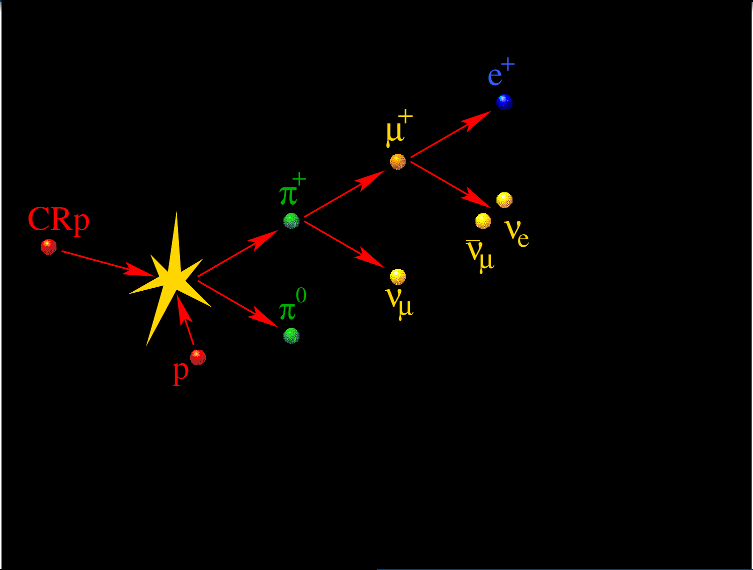


CP+ (2017a)

Hadronic cosmic ray proton interaction



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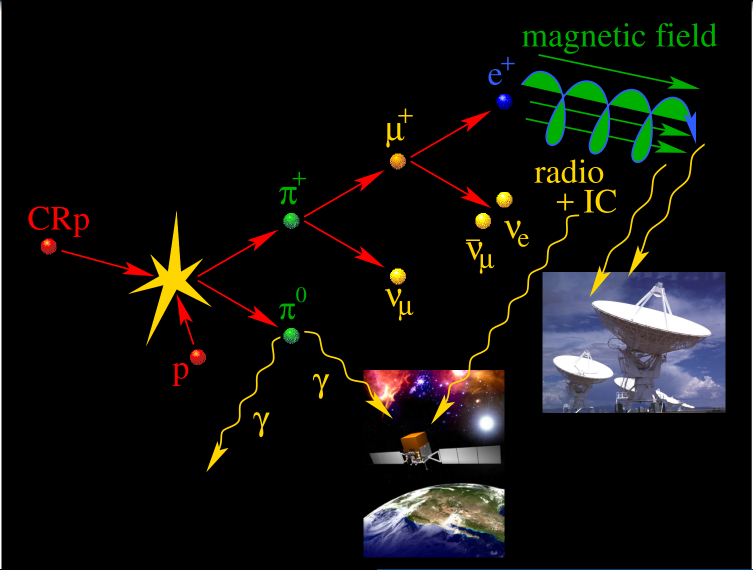

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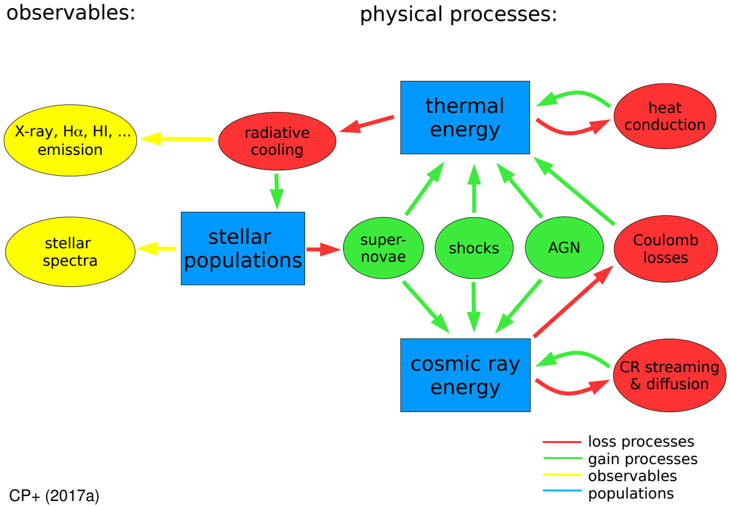
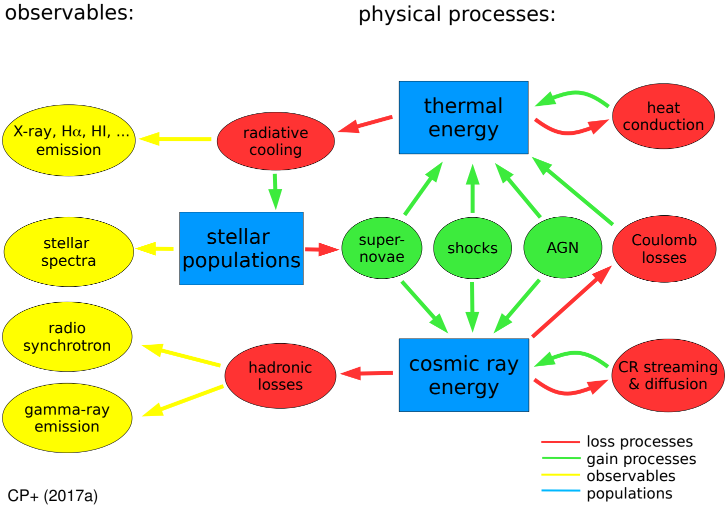


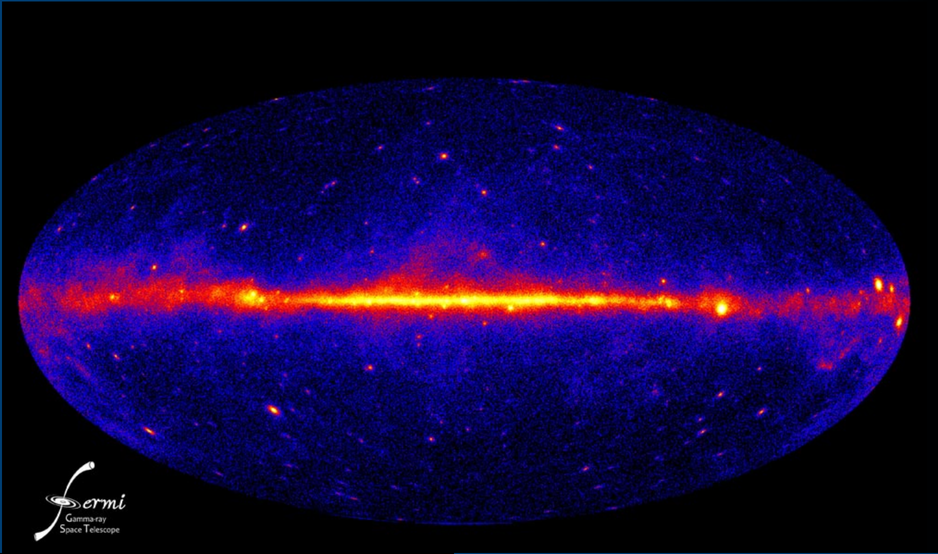
CP+ (2017a)

Simulations with cosmic ray physics



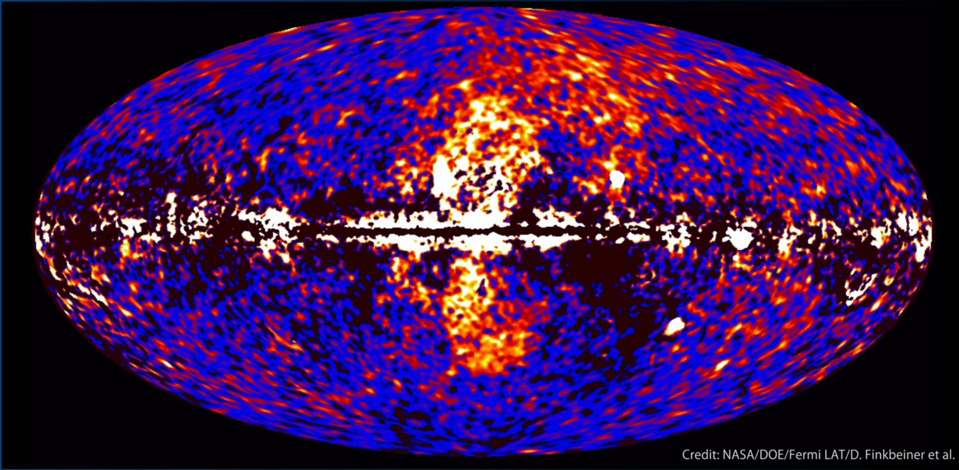
CP+ (2017a)

Gamma-ray emission of the Milky Way



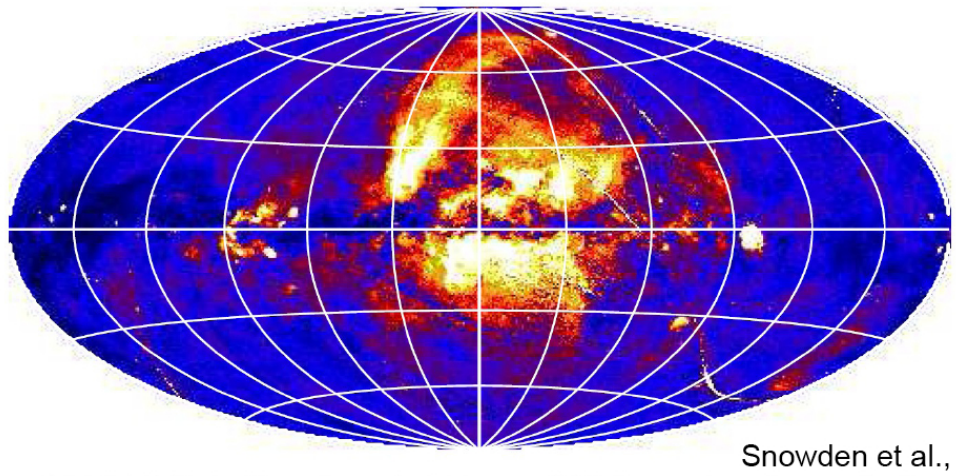
Galactic wind in the Milky Way?

Fermi gamma-ray bubbles

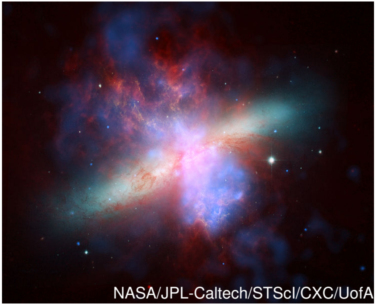


Galactic wind in the Milky Way?

Diffuse X-ray emission in our Galaxy



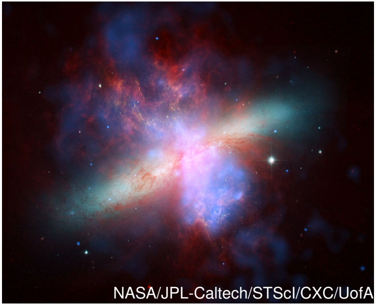
How are galactic winds driven?



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?

How are galactic winds driven?



super wind in M82

- thermal pressure provided by supernovae or AGNs?
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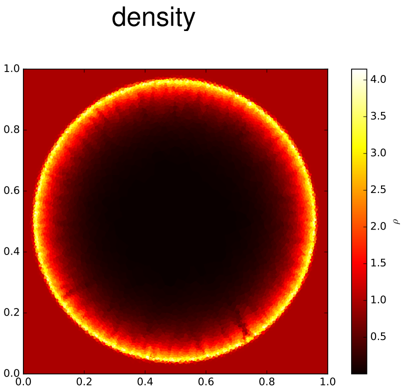
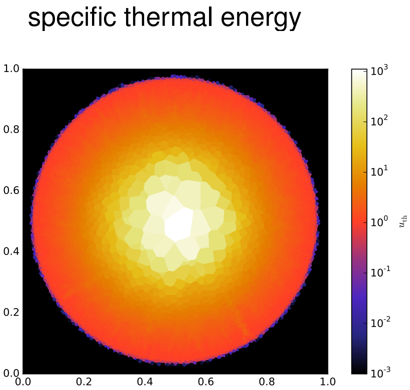
observed energy equipartition between cosmic rays, thermal gas and magnetic fields
$\rightarrow$ suggests self-regulated feedback loop with CR driven winds

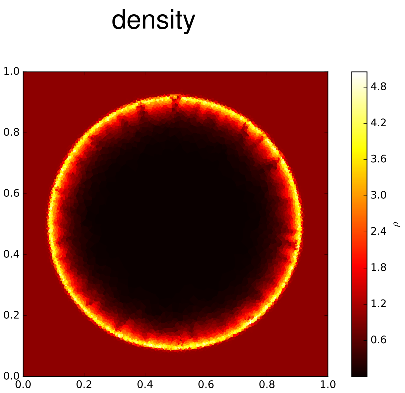
Sedov explosion

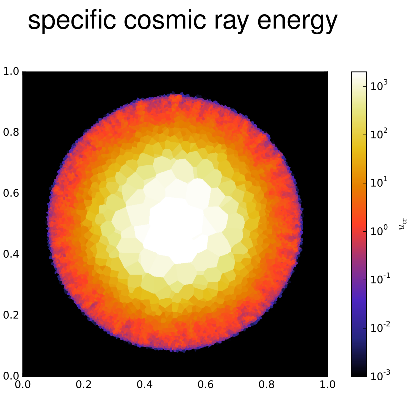




CP+ (2017a)

Sedov explosion with CR acceleration

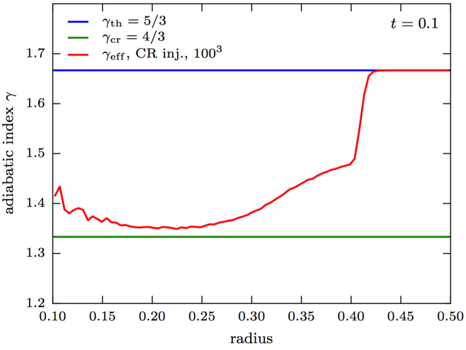




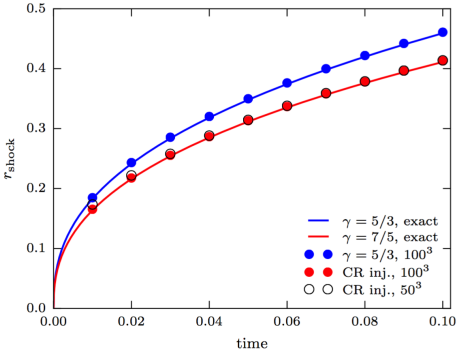
CP+ (2017a)

Sedov explosion with CR acceleration

adiabatic index



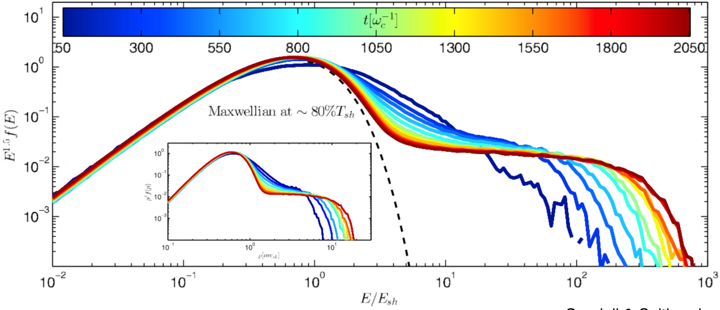
shock evolution



CP+ (2017a)

Ion spectrum

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

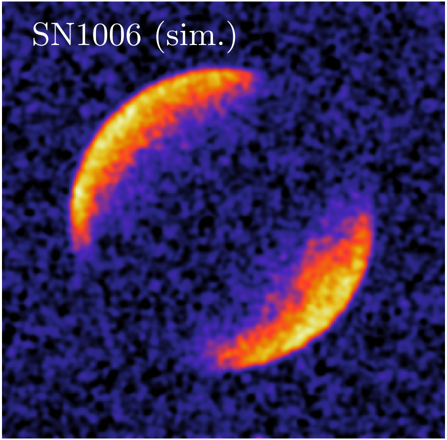


Caprioli & Spitkovsky (2014)

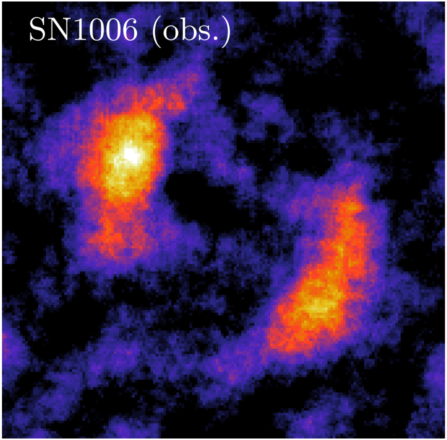
- quasi-parallel shocks ($\boldsymbol{B} \parallel \boldsymbol{n}_s$) accelerate ions
- quasi-perpendicular shocks ($\boldsymbol{B} \perp \boldsymbol{n}_s$) cannot
- model magnetic obliquity in AREPO simulations

TeV γ rays from shell-type SNRs: SNR 1006

AREPO simulation



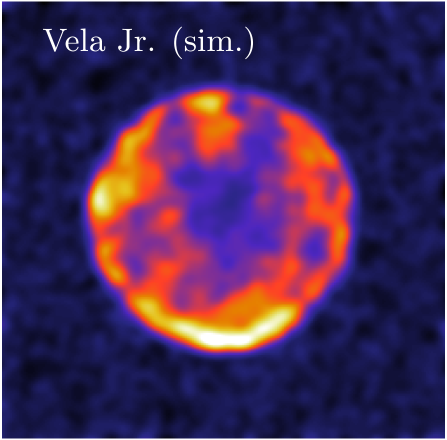
H.E.S.S. observation



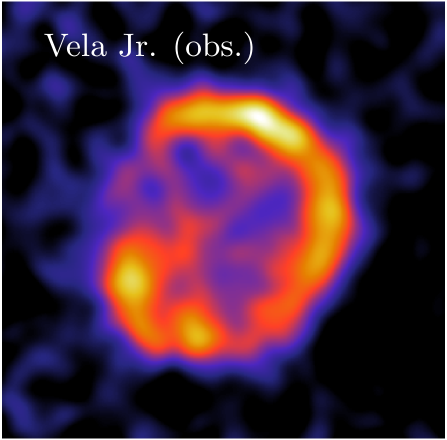
Pais, CP, Ehlert (2018)

TeV γ rays from shell-type SNRs: Vela Junior

AREPO simulation



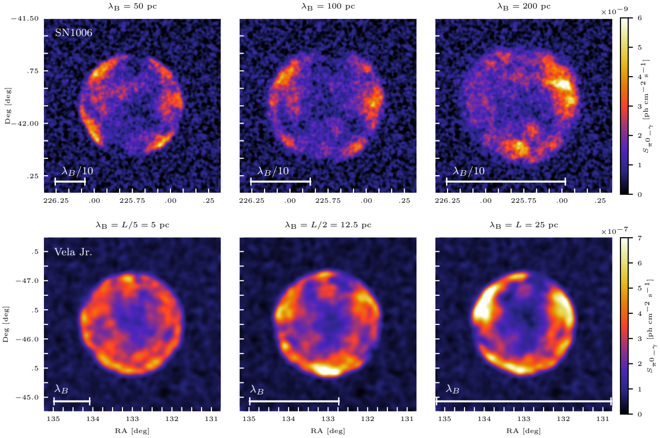
H.E.S.S. observation



Pais, CP, Ehlert (2018)

TeV γ rays from shell-type supernova remnants

Varying magnetic coherence scale in simulations of SN1006 and Vela Junior

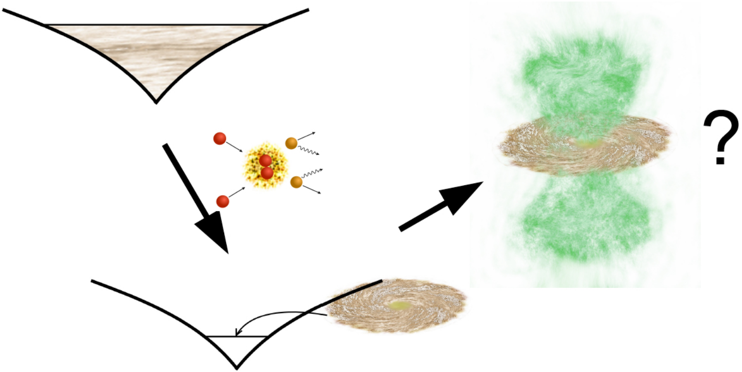


Pais, CP, Ehlert (2018)

SNR 1006: $\lambda_B > 200^{+10}_{-60}$ pc

Vela Junior: $\lambda_B = 8^{+15}_{-6}$ pc

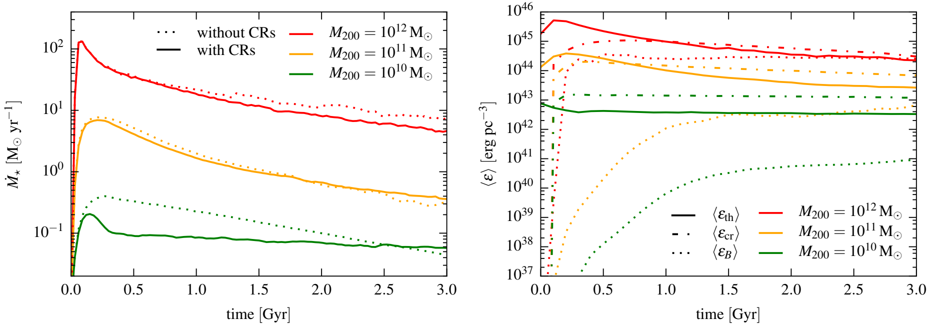
Galaxy simulation setup: 1. cosmic ray advection



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

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

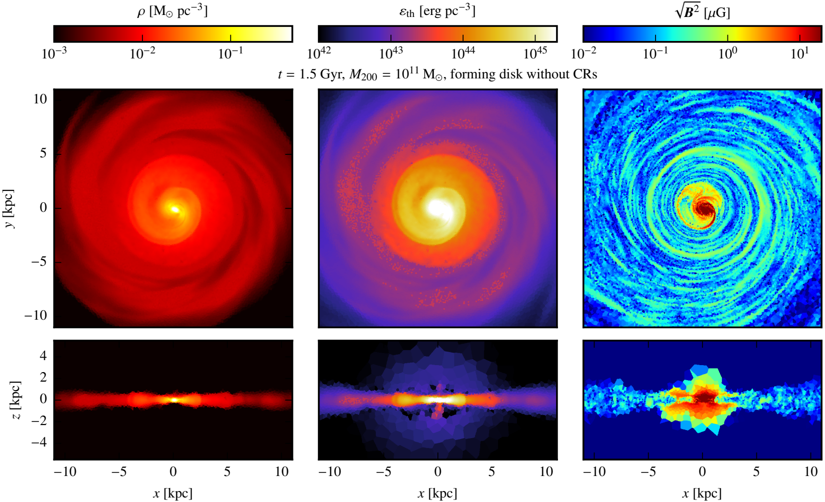
Time evolution of SFR and energy densities



CP+ (2017a)

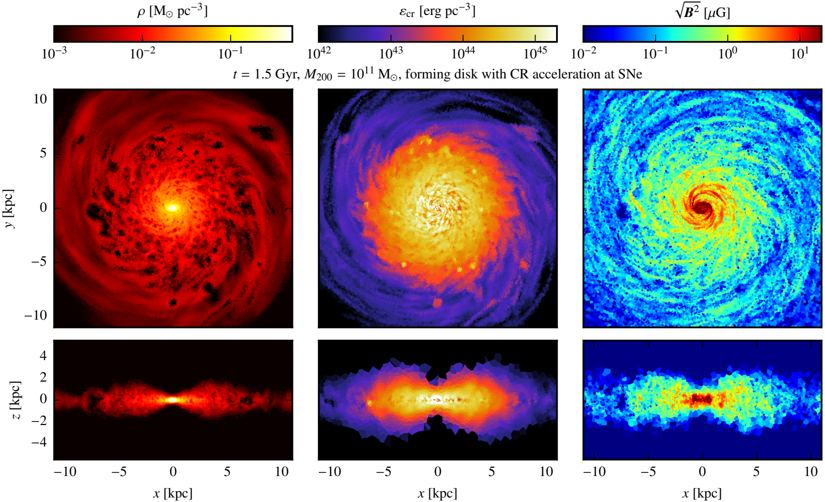
- CR pressure feedback suppresses SFR more in smaller galaxies
- energy budget in disks is dominated by CR pressure
- magnetic dynamo faster in Milky Way galaxies than in dwarfs

MHD galaxy simulation without CRs



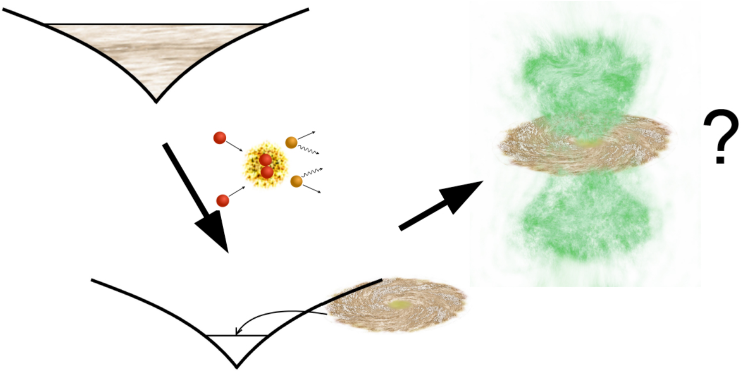
CP+ (2017a)

MHD galaxy simulation with CRs



CP+ (2017a)

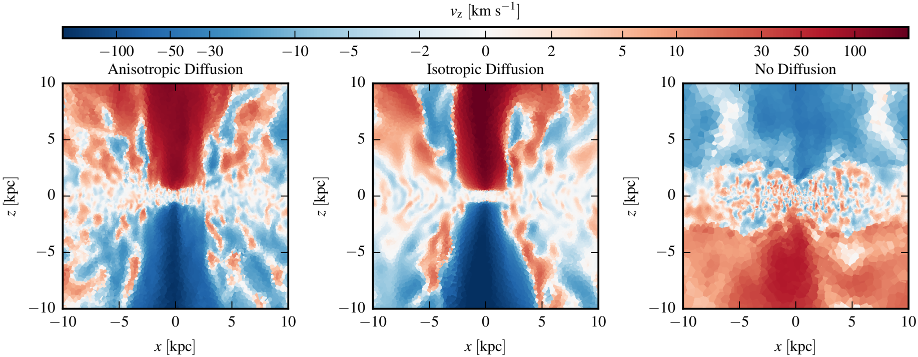
Galaxy simulation setup: 2. cosmic ray diffusion



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

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

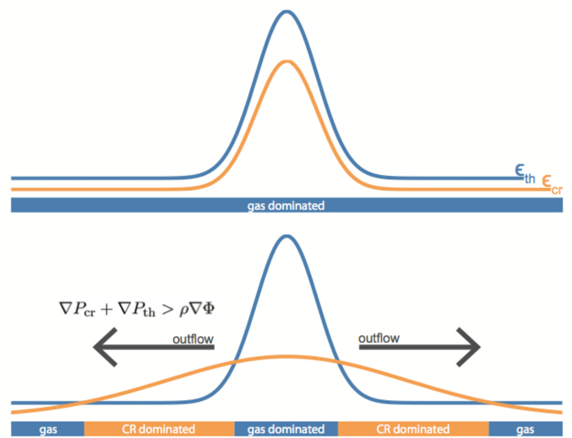
MHD galaxy simulation with CR diffusion



Pakmor, CP, Simpson, Springel (2016)

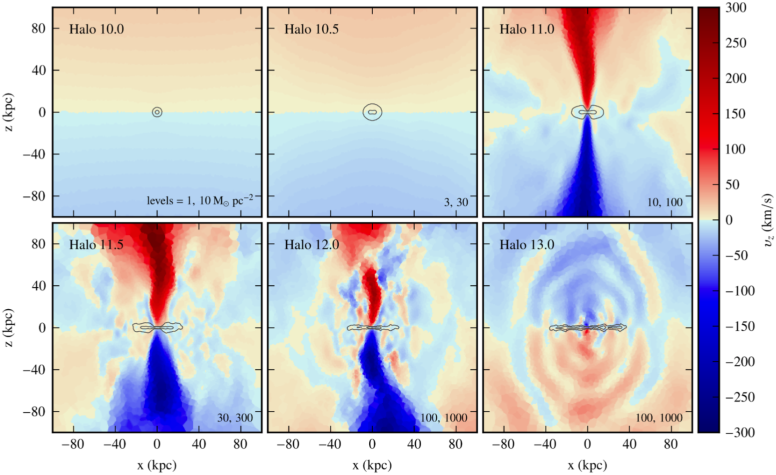
- CR diffusion launches powerful winds
- simulation without CR diffusion exhibits only weak fountain flows

Cosmic ray driven wind: mechanism



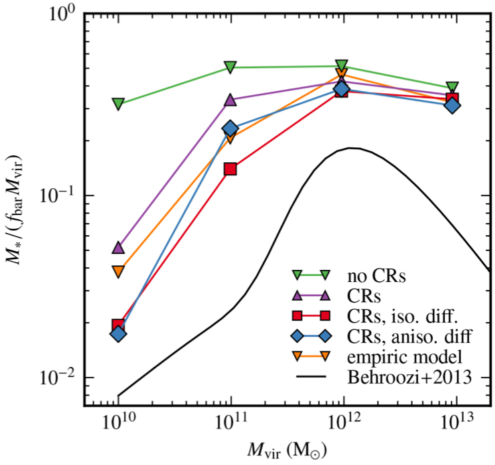
CR streaming in 3D simulations: Uhlig, CP+ (2012), Ruszkowski+ (2017)
CR diffusion in 3D simulations: Jubelgas+ (2008), Booth+ (2013), Hanasz+ (2013), Salem & Bryan (2014), Pakmor, CP+ (2016), Simpson+ (2016), Girichidis+ (2016), Dubois+ (2016), CP+ (2017b), Jacob+ (2018)

CR-driven winds: dependence on halo mass



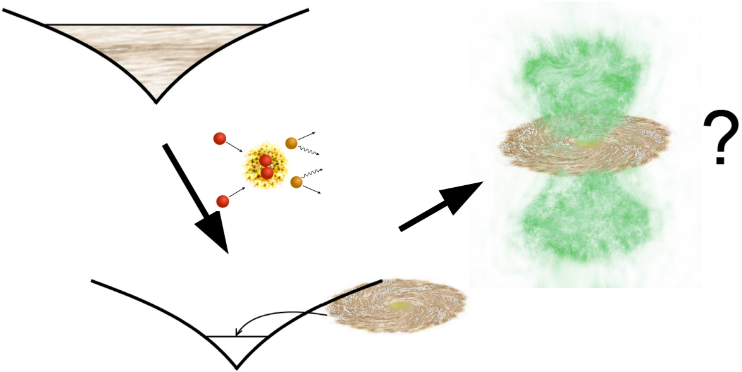
Jacob+ (2018)

CR-driven winds: suppression of star formation



Jacob+ (2018)

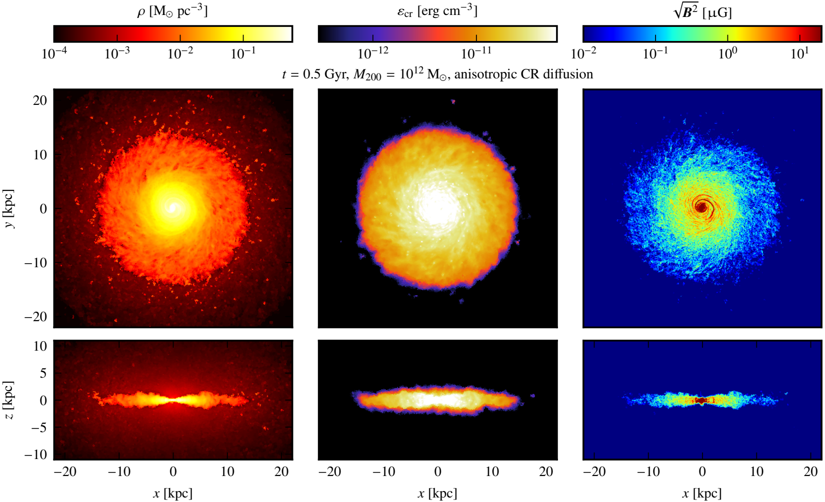
Galaxy simulation setup: 3. non-thermal emission



CP, Pakmor, Simpson, Springel (2017b, in prep.)
Simulating radio synchrotron and gamma-ray emission in galaxies

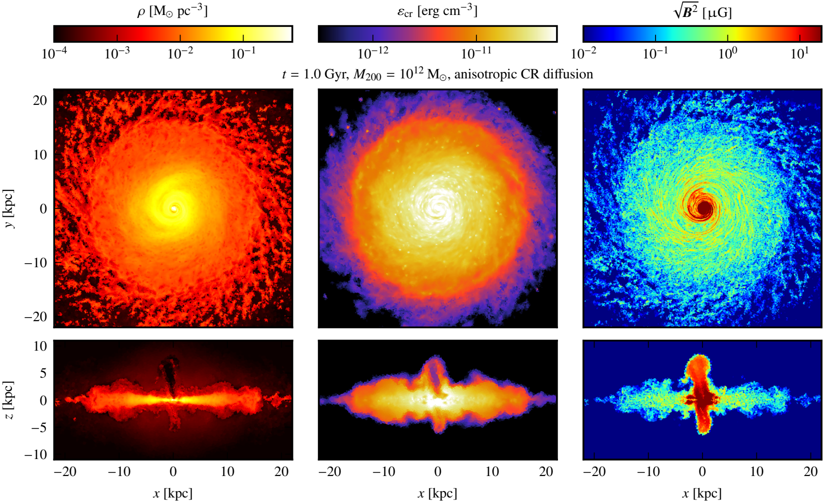
MHD + CR advection + diffusion: $\{10^{10}, 10^{11}, 10^{12}\}$ $M_\odot$

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



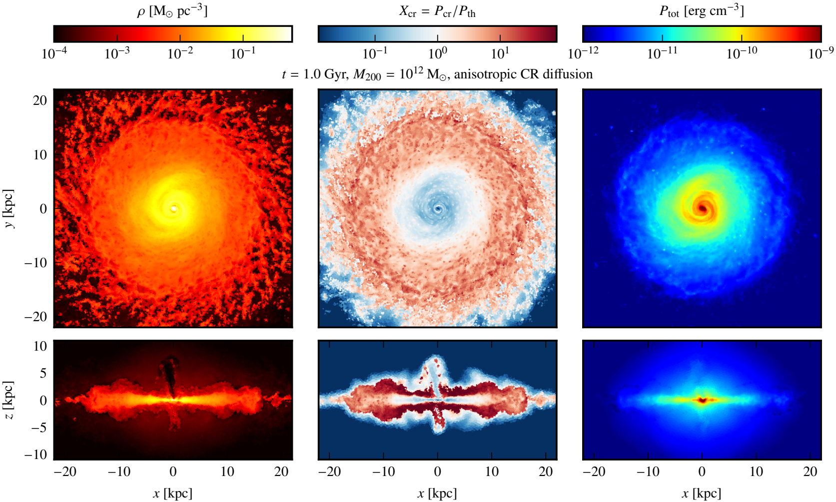
CP+ (2017b, in prep.)

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



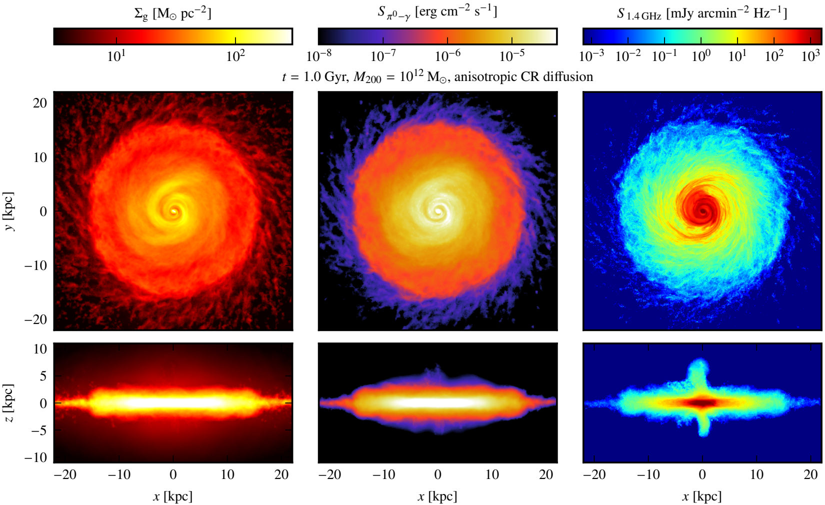
CP+ (2017b, in prep.)

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



CP+ (2017b, in prep.)

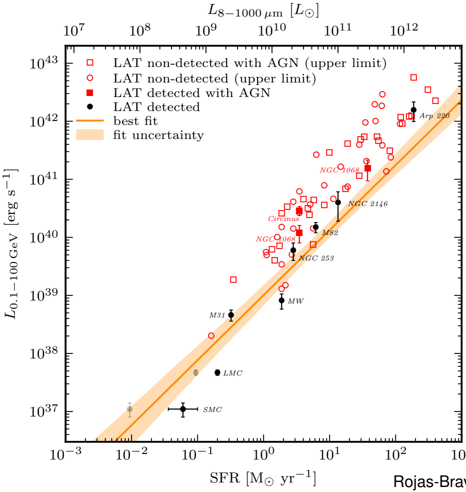
γ-ray and radio emission of Milky Way-like galaxy



CP+ (2017b, in prep.)

Far infra-red – gamma-ray correlation

Universal conversion: star formation → cosmic rays → gamma rays



Rojas-Bravo & Araya (2016)

Far infra-red – gamma-ray correlation

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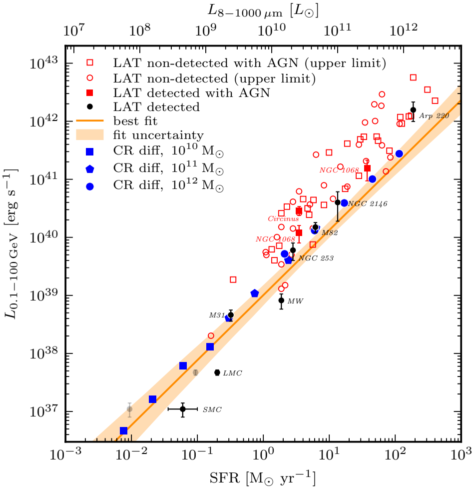

CP+ (2017b)

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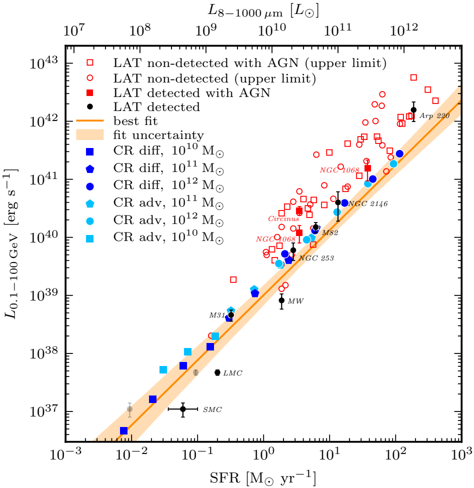

CP+ (2017b)

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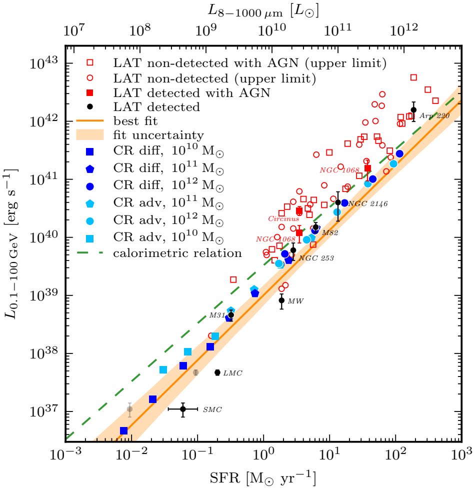
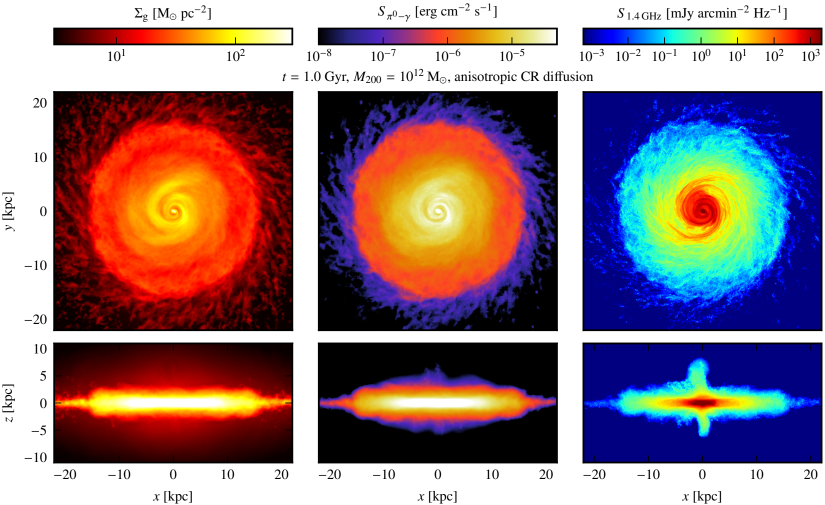


CP+ (2017b)

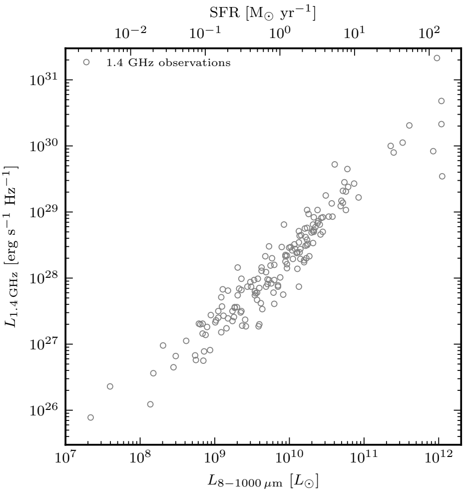
γ-ray and radio emission of Milky Way-like galaxy



CP+ (2017b, in prep.)

Far infra-red – radio correlation

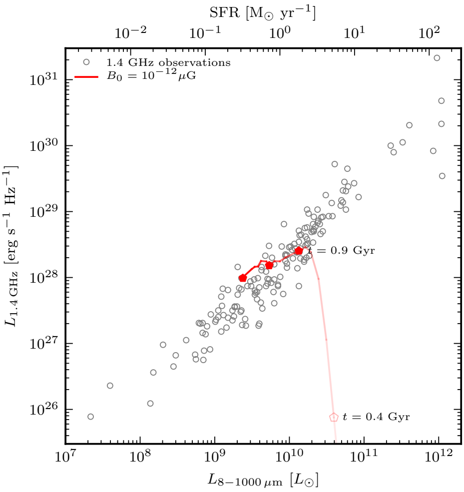
Universal conversion: star formation → cosmic rays → radio



Bell (2003)

Far infra-red – radio correlation

Universal conversion: star formation → cosmic rays → radio



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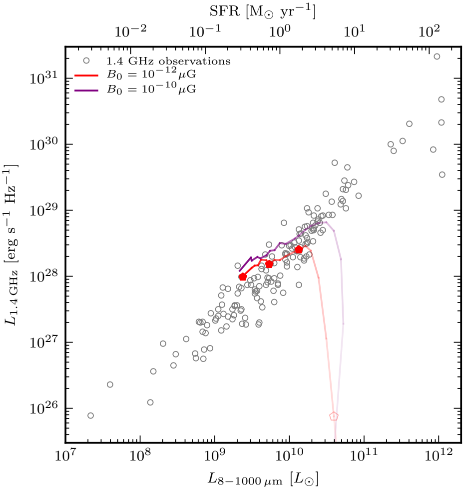

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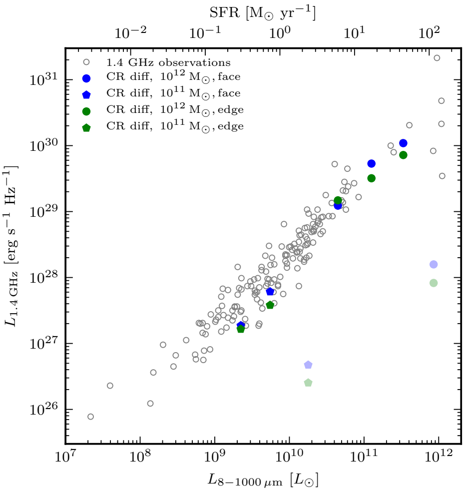

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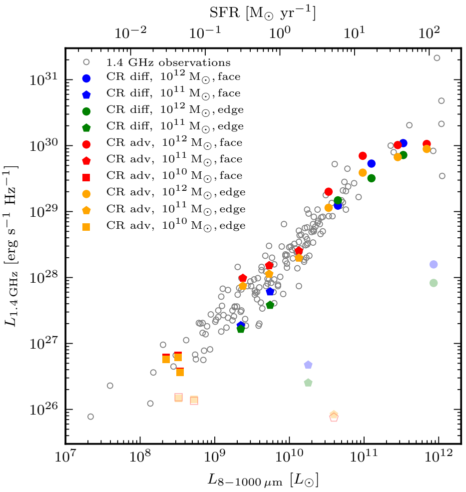

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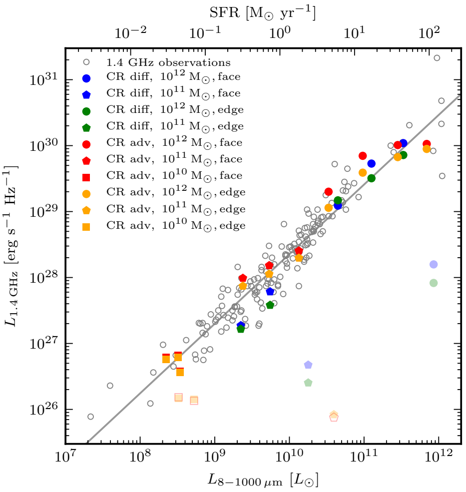


CP+ (in prep.)

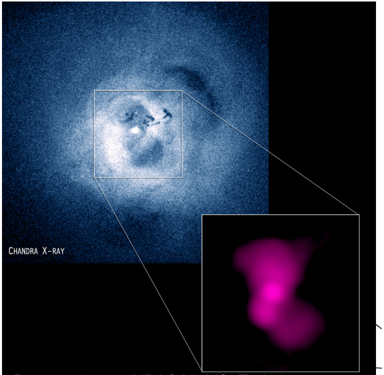
Outline

1. Introduction
   - Puzzles in galaxy formation
   - Particle acceleration
   - Cosmic rays
2. Galaxy formation
   - Modelling physics in galaxies
   - Supernova explosions
   - Galaxy simulations
3. Galaxy cluster evolution
   - Steady state models
   - AGN jet simulations
   - Conclusions

AIP

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)

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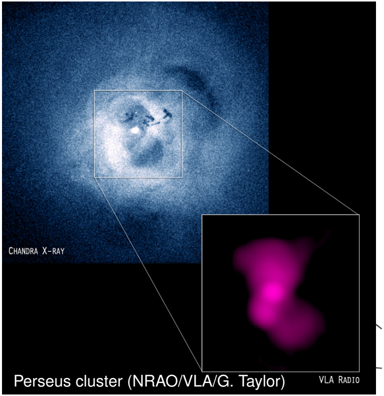
- energy source: release of non-gravitational energy due to accretion on a black hole and its spin
- self-regulated heating mechanism to avoid overcooling



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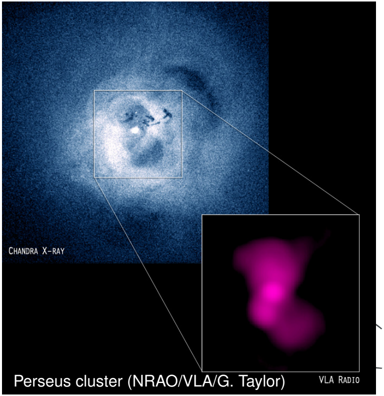
- energy source: release of non-gravitational energy due to accretion on a black hole and its spin
- self-regulated heating mechanism to avoid overcooling
- jet interaction with magnetized cluster medium → turbulence
- jet accelerates cosmic rays → release from bubbles provides source of heat



Perseus cluster (NRAO/VLA/G. Taylor)

Feedback by active galactic nuclei

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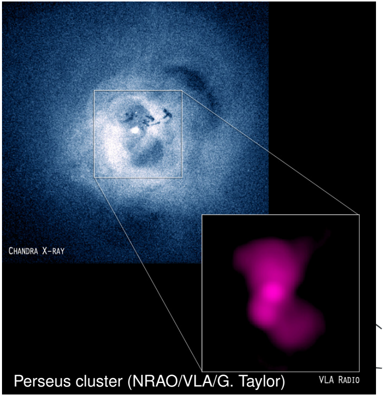
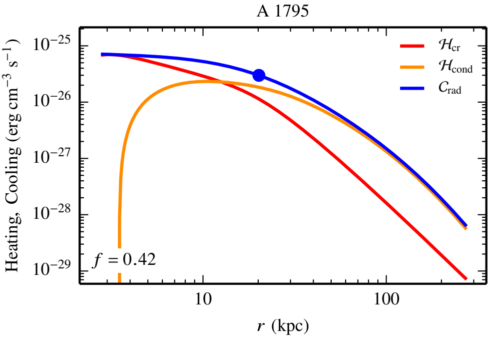
- Jacob & CP (2017a,b): study large sample of 40 cool core clusters
- spherically symmetric steady-state solutions where cosmic ray heating balances radiative cooling



Perseus cluster (NRAO/VLA/G. Taylor)

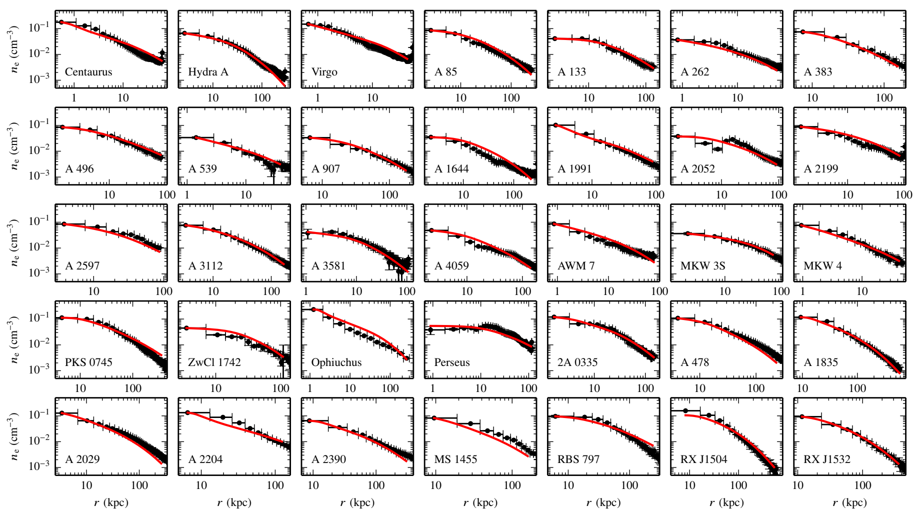
Case study A1795: heating and cooling



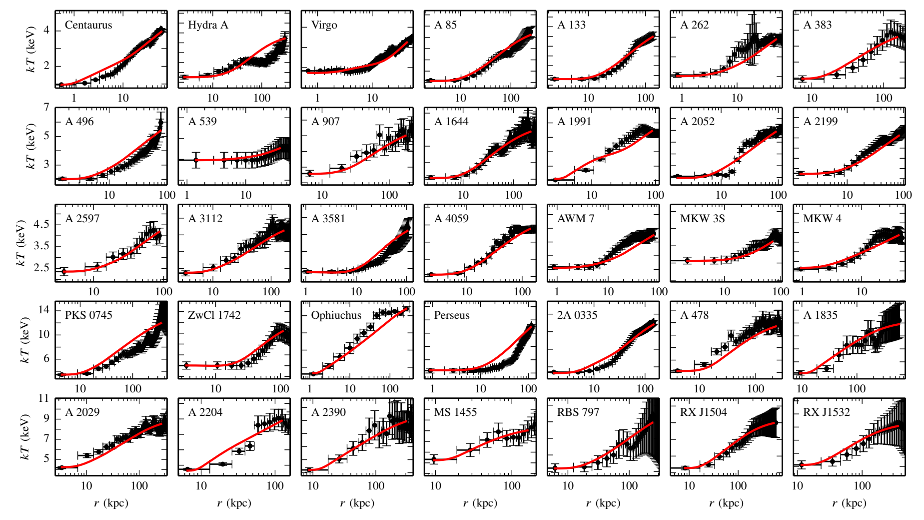
Jacob & CP (2016a)

- CR heating dominates in the center
- conductive heating takes over at larger radii, $\kappa = 0.42\kappa_{Sp}$
- $\mathcal{H}_{cr} + \mathcal{H}_{cond} \approx \mathcal{C}_{rad}$: modest mass deposition rate of 1 $M_\odot$ yr^{-1}

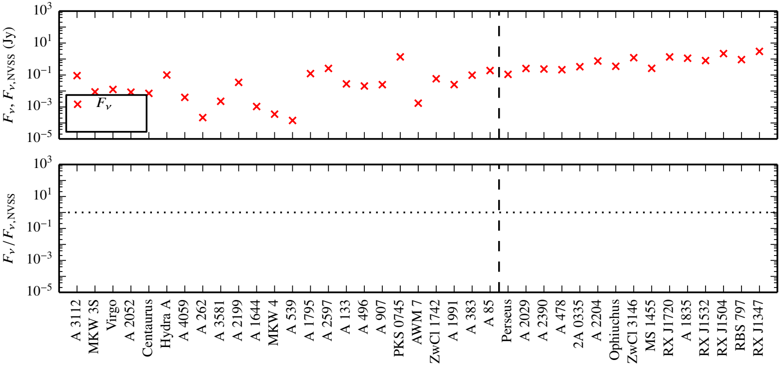
Gallery of solutions: density profiles



Gallery of solutions: temperature profiles

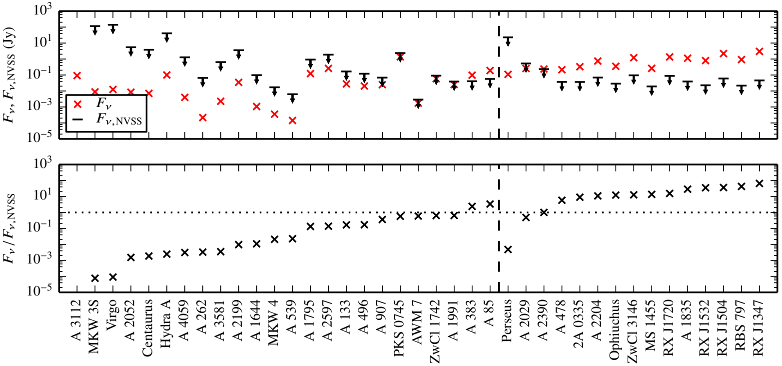


Hadronically induced radio emission



Jacob & CP (2017b)

Hadronically induced radio emission: NVSS limits



Jacob & CP (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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AGN injects CRs

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AGN injects CRs → CR heating balances cooling

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↓

CRs stream outwards and become too dilute to heat the cluster

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↘

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

How can we explain these results?

- self-regulated feedback cycle driven by CRs

AGN injects CRs → CR heating balances cooling

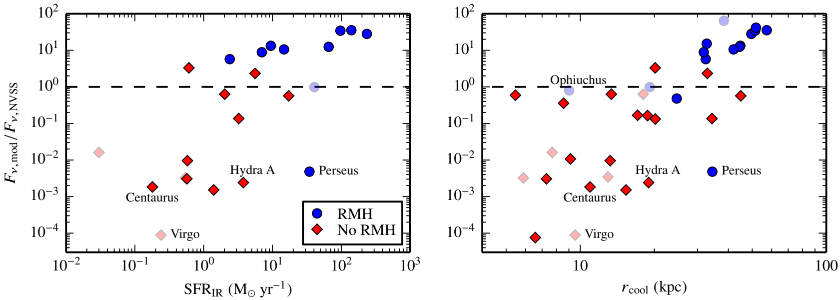
↓

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

↑

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

Self-regulated heating/cooling cycle in cool cores

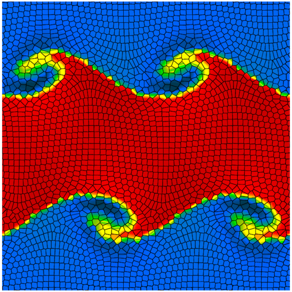


Jacob & CP (2017b)

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

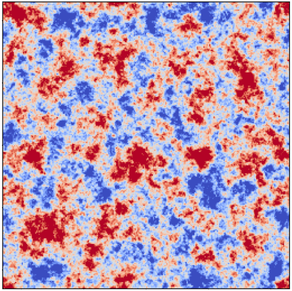
MHD jet simulations



AREPO: unstructured-mesh

- MHD moving-mesh code AREPO
- NFW cluster potential

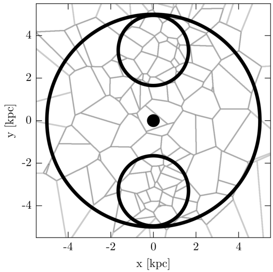
MHD jet simulations



initial magnetic field

- MHD moving-mesh code AREPO
- NFW cluster potential
- external turbulent magnetic field (Kolmogorov)

MHD jet simulations

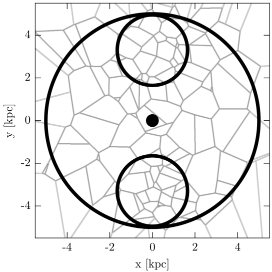


AREPO: jet injection region

(Weinberger+ 2017)

- MHD moving-mesh code AREPO
- NFW cluster potential
- external turbulent magnetic field (Kolmogorov)
- jet module
  - prepare low-density state in pressure equilibrium
  - inject kinetic energy, ***B***, and CRs
  - refine to sustain density contrast

Cosmic ray modelling

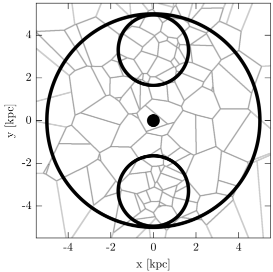


AREPO: jet injection region

(Weinberger+ 2017)

- subgrid CR acceleration:
  - reality: internal shocks
  - code: $E_{cr}/E_{th} \geq 0.5$

Cosmic ray modelling

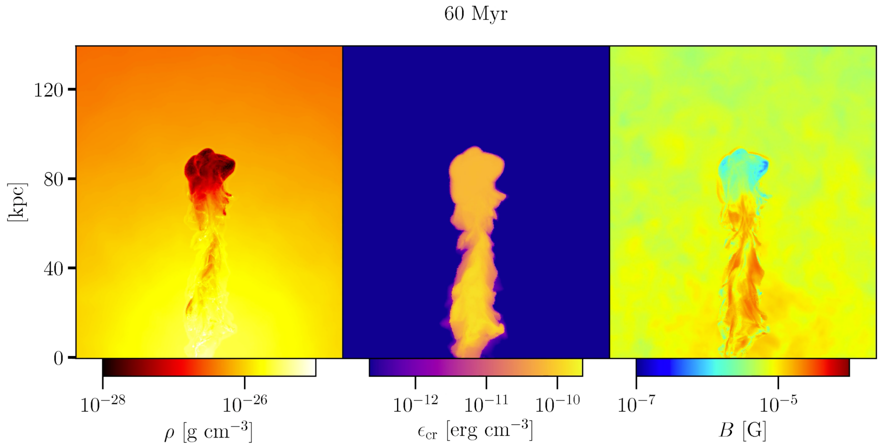


AREPO: jet injection region

(Weinberger+ 2017)

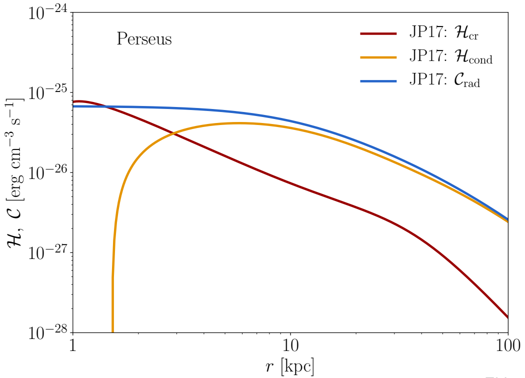
- subgrid CR acceleration:
  - reality: internal shocks
  - code: $E_{\rm cr}/E_{\rm th} \geq 0.5$
- CR transport:
  - CRs are advected
  - emulate CR streaming ≈ anisotropic CR diffusion & Alfvén cooling

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



Ehlert, Weinberger, CP+ (2018)

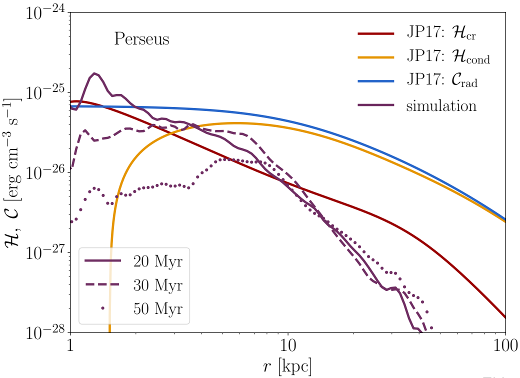
Perseus cluster – heating vs. cooling: theory



Ehlert, Weinberger, CP+ (2018)

- 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}

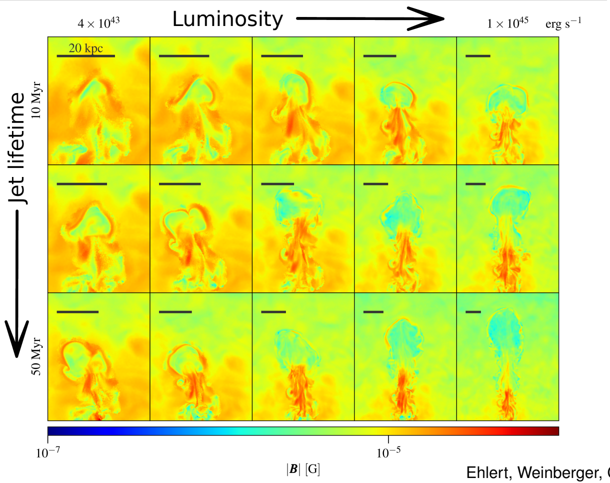
Perseus cluster – heating vs. cooling: simulations



Ehlert, Weinberger, CP+ (2018)

- 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**

Magnetic field structure



Ehlert, Weinberger, CP+ (2018)

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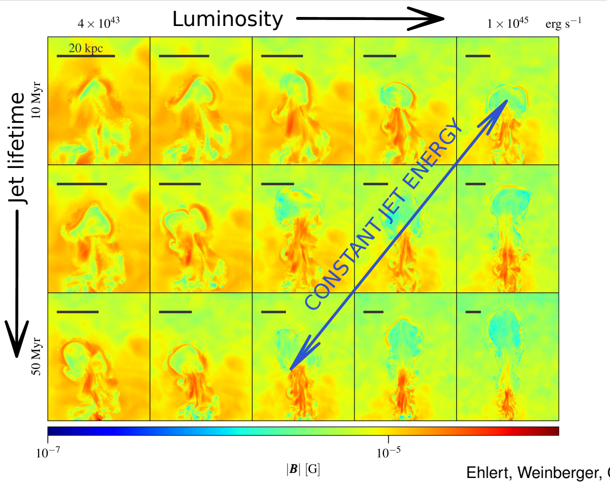

Ehlert, Weinberger, CP+ (2018)

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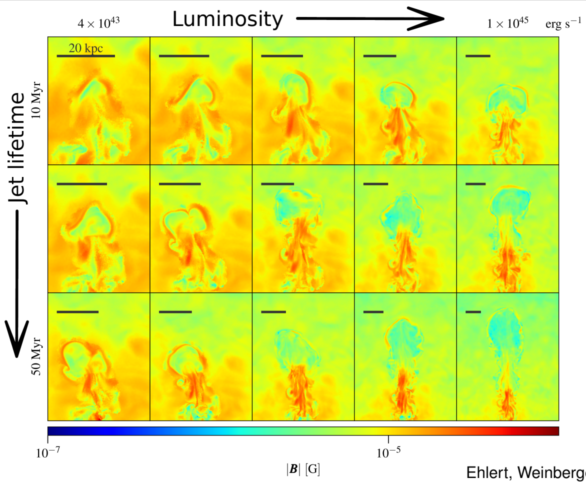
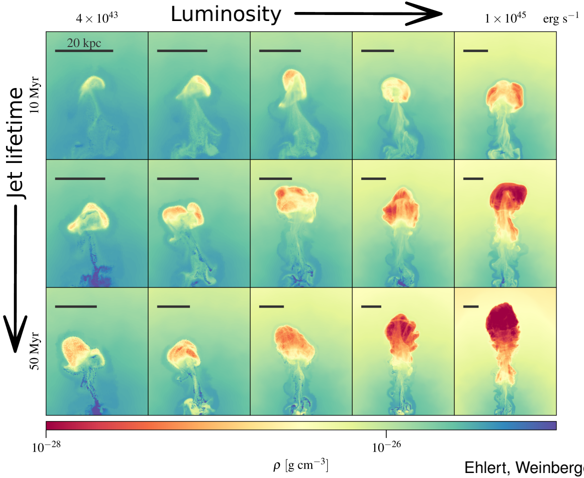


Ehlert, Weinberger, CP+ (2018)

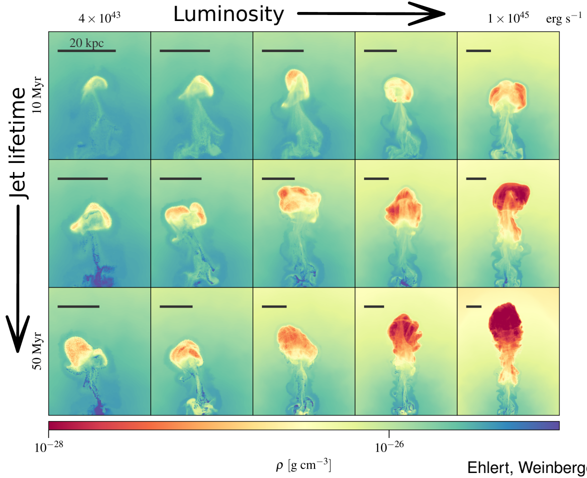
Magnetic enhancement and draping general feature

Jet morphology



Ehlert, Weinberger, CP+ (2018)

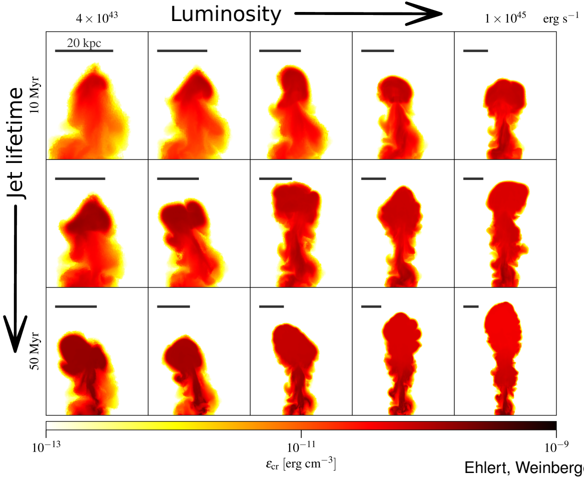
Jet morphology



Ehlert, Weinberger, CP+ (2018)

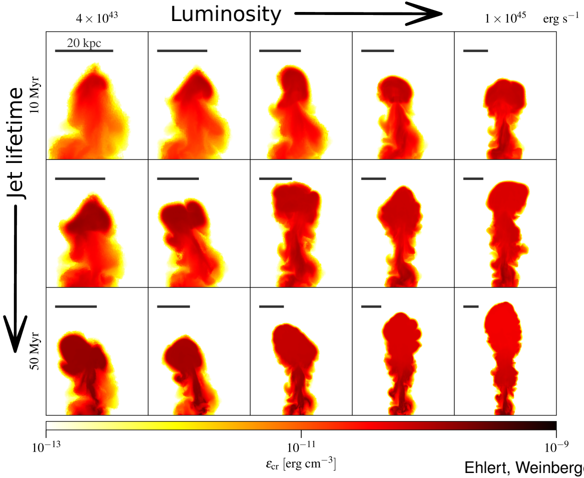
Low-energy/power jets mix more efficiently $\Rightarrow$ invisible in X-rays

CR distribution



Ehlert, Weinberger, CP+ (2018)

CR distribution



Ehlert, Weinberger, CP+ (2018)

CRs still present in low-energy/power jets

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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- $L_{\mathrm{FIR}} - L_\gamma$ and $L_{\mathrm{FIR}} - L_{\mathrm{radio}}$ correlations enable us to test the calorimetric assumption and magnetic dynamo theories
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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 – 1

Cosmic ray acceleration and transport:

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- Pais, Pfrommer, Ehlert, *Constraining the coherence scale of the interstellar magnetic field using TeV gamma-ray observations of supernova remnants,* 2018b.
- Pais, Pfrommer, Ehlert, Pakmor, *The effect of cosmic-ray acceleration on supernova blast wave dynamics,* 2018a, MNRAS.

Cosmic ray feedback 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.
- Jacob, Pakmor, Simpson, Springel, Pfrommer, *The dependence of cosmic ray driven galactic winds on halo mass,* 2018, MNRAS.

Literature for the talk – 2

Cosmic ray feedback in galaxy clusters:

- Ehlert, Weinberger, Pfrommer, Pakmor, Springel, *Simulations of the dynamics of magnetised jets and cosmic rays in galaxy clusters,* 2018.

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

- Pfrommer, Pakmor, Simpson, Springel, *Simulating Gamma-ray Emission in Star-forming Galaxies,* 2017b, ApJL.
- Pfrommer, Pakmor, Simpson, Springel, *Simulating Radio Synchrotron Emission in Galaxies: the Origin of the Far Infrared–Radio Correlation,* in prep.