How cosmic rays shape galaxies and clusters

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in collaboration with

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Outline

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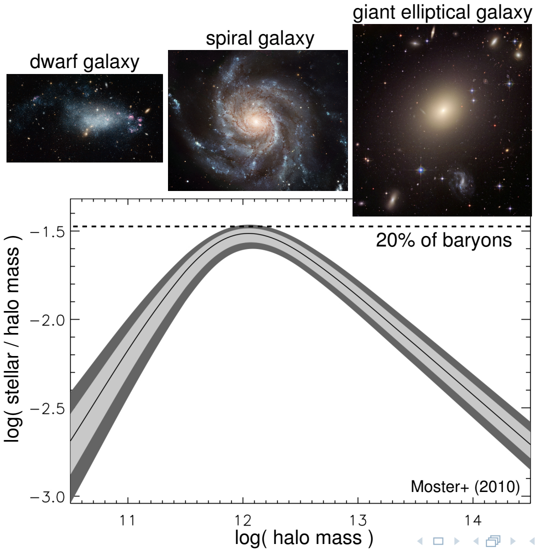
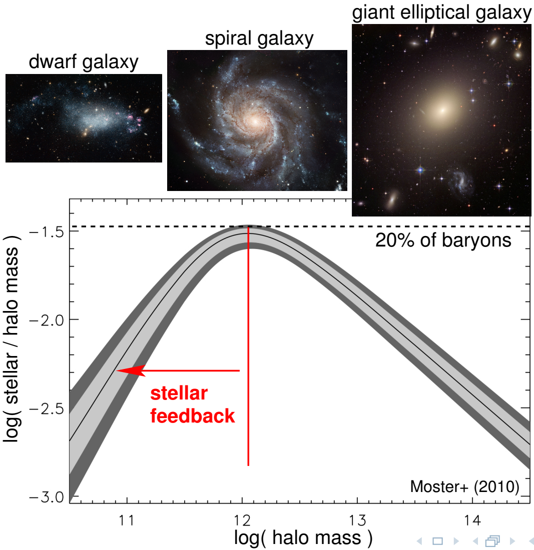
1. Introduction
   - Puzzles in galaxy formation
   - Particle acceleration
   - Cosmic rays
2. Small galactic scales
   - Modelling physics in galaxies
   - Supernova explosions
   - Gamma-ray maps
3. Simulating galaxies and clusters
   - Global galaxy models
   - Radio and gamma-rays
   - AGN jets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

Puzzles in galaxy formation

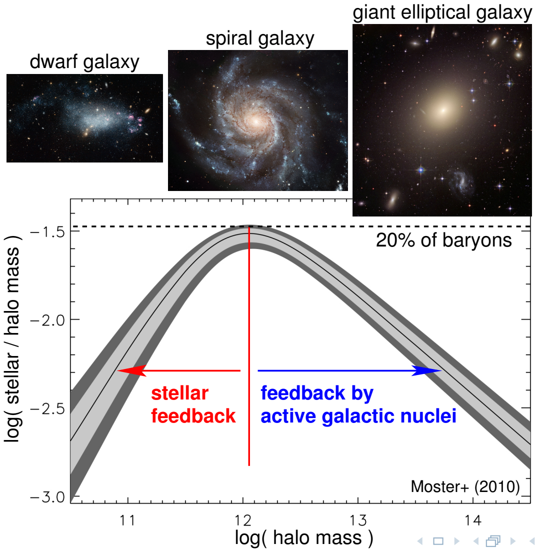
Puzzles in galaxy formation



Puzzles in galaxy formation



Puzzles in galaxy formation



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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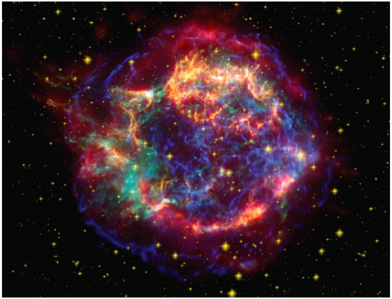
3. the solution of all problems in galaxy formation

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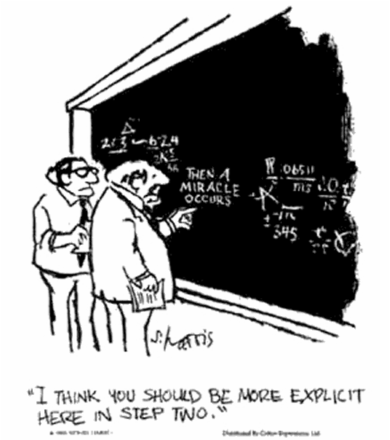
- critical for understanding the physics of galaxy formation $\rightarrow$ may explain puzzle of low star conversion efficiency in dwarf galaxies

Feedback by galactic winds



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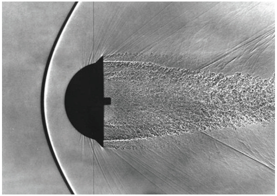
Shock waves

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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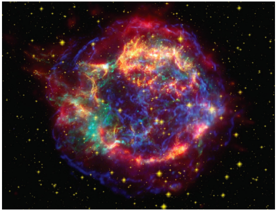

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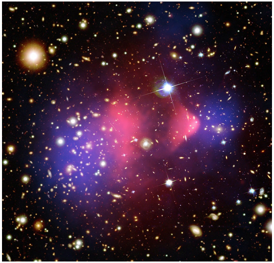


clusters/galaxies, Coulomb collisions set $\lambda_{\rm mfp}$:
$\lambda_{\rm mfp} \sim L_{\rm cluster}/10, \qquad \lambda_{\rm mfp} \sim L_{\rm SNR}$

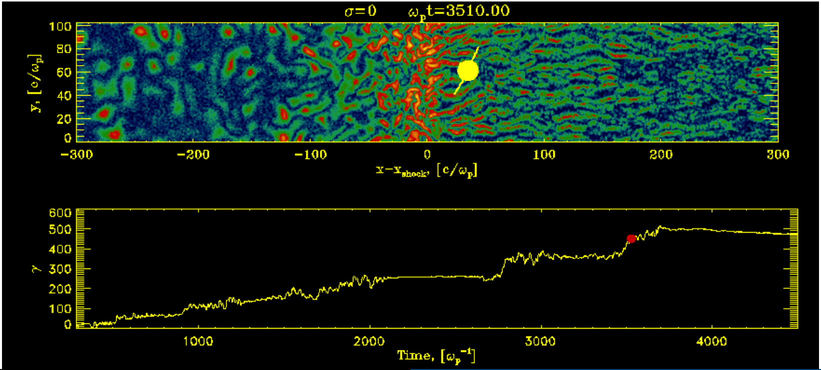
Mean free path $\gg$ observed shock width!

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

slide concept Spitkovsky

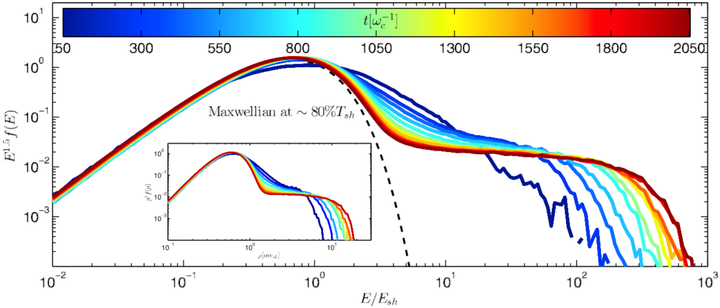
Particle acceleration at relativistic shock, $\boldsymbol{B_0 = 0}$

- 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

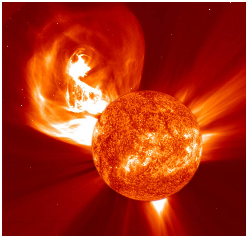
Non-relativistic parallel shock in long-term hybrid simulation



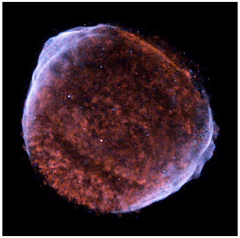
Caprioli & Spitkovsky (2014)

- 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

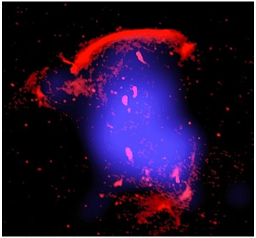
Astrophysical shocks



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



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

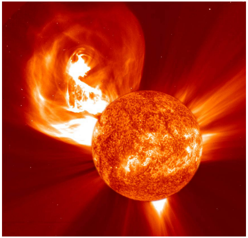


cluster shocks $\sim$ 2 Mpc
giant radio relic (van Weeren)

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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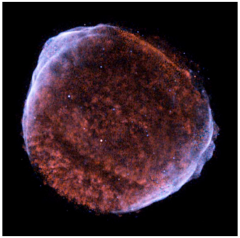

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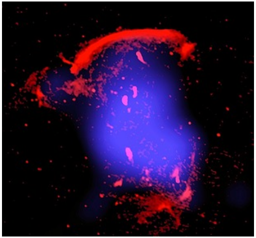

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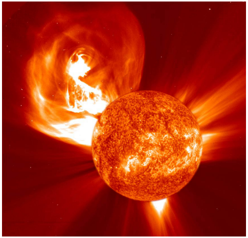
collisionless shocks $\Longleftrightarrow$ energetic particles $\Longleftrightarrow$ electro-magnetic waves



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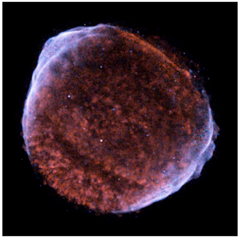

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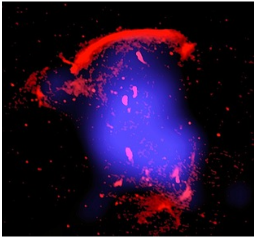

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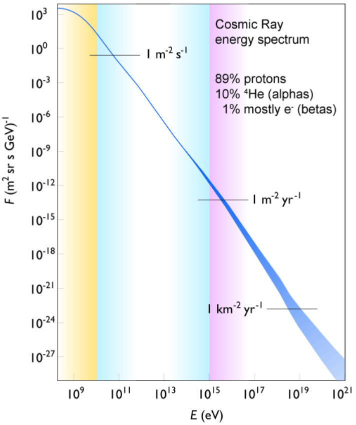
Galactic cosmic ray spectrum



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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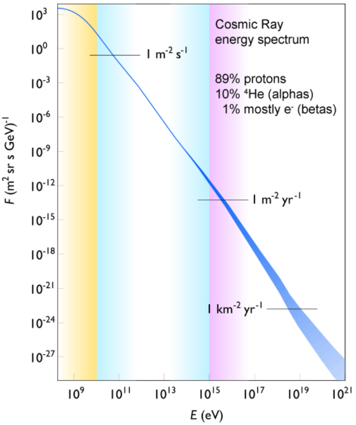

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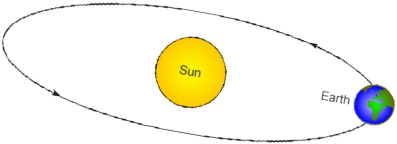
- spans more than 33 decades in flux and 12 decades in energy
- "knee" indicates characteristic maximum energy of galactic accelerators
- CRs beyond the "ankle" have extra-galactic origin
- energy density of cosmic rays, magnetic fields, and turbulence in the interstellar gas all similar

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!**

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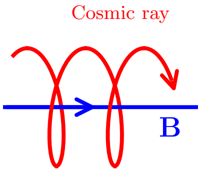
Interactions of CRs and magnetic fields



sketch: Jacob

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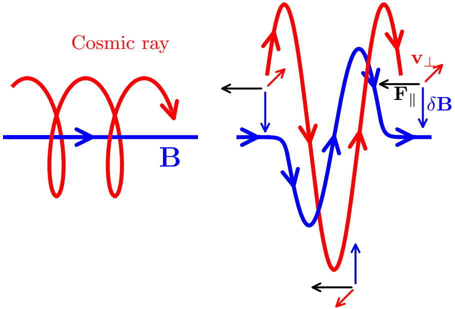

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- **gyro resonance:** $\omega - k_{\parallel} v_{\parallel} = n\Omega$

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

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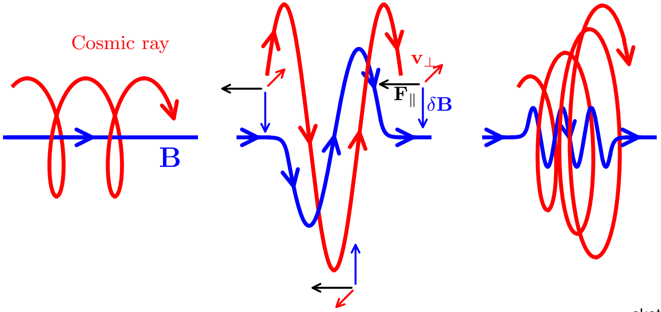

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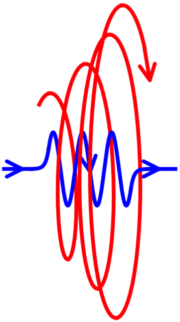
- **gyro resonance:** $\omega - k_{\|} v_{\|} = n\Omega$
  Doppler-shifted MHD frequency is a multiple of the CR gyrofrequency
- CRs scatter on magnetic fields $\rightarrow$ isotropization of CR momenta

CR streaming

- **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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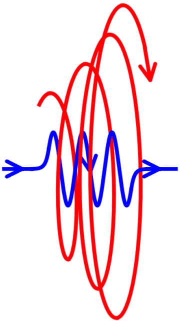

$\rightarrow$ **CRs exert a pressure on the thermal gas by means of scattering off of Alfvén waves**

CR transport in steady state

- 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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$$\boldsymbol{v}_{\mathrm{st}} = \boldsymbol{v}_{\mathrm{A}} \frac{\bar{\nu}_+ - \bar{\nu}_-}{\bar{\nu}_+ + \bar{\nu}_-}, \quad \boldsymbol{v}_{\mathrm{di}} = -\kappa_{\mathrm{di}} \boldsymbol{b} \frac{\boldsymbol{b} \cdot \nabla \varepsilon_{\mathrm{cr}}}{\varepsilon_{\mathrm{cr}}}, \quad \kappa_{\mathrm{di}} = \frac{c^2}{3(\bar{\nu}_+ + \bar{\nu}_-)}$$

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

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

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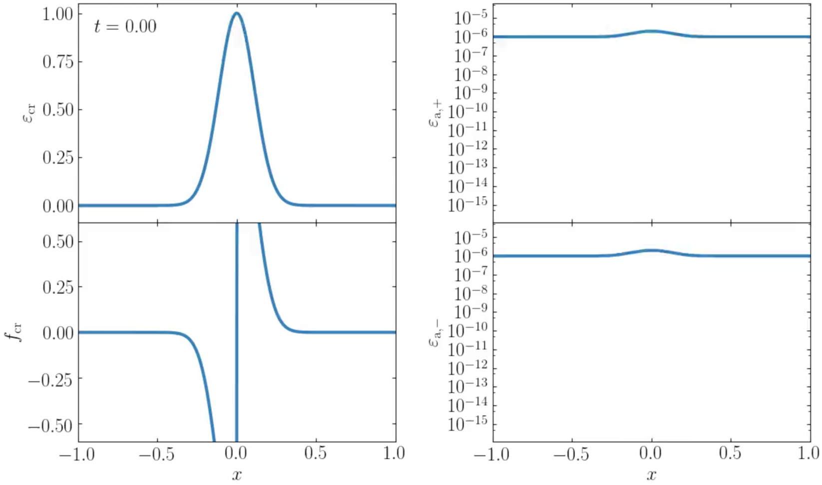
$$\frac{\partial \varepsilon_{\rm cr}}{\partial t} + \boldsymbol{\nabla}\cdot\left[P_{\rm cr}\boldsymbol{v}_{\rm st} + \varepsilon_{\rm cr}(\boldsymbol{v} + \boldsymbol{v}_{\rm st} + \boldsymbol{v}_{\rm di})\right] = -P_{\rm cr}\boldsymbol{\nabla}\cdot\boldsymbol{v} + \boldsymbol{v}_{\rm st}\cdot\boldsymbol{\nabla}P_{\rm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

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

Non-equilibrium CR streaming and diffusion

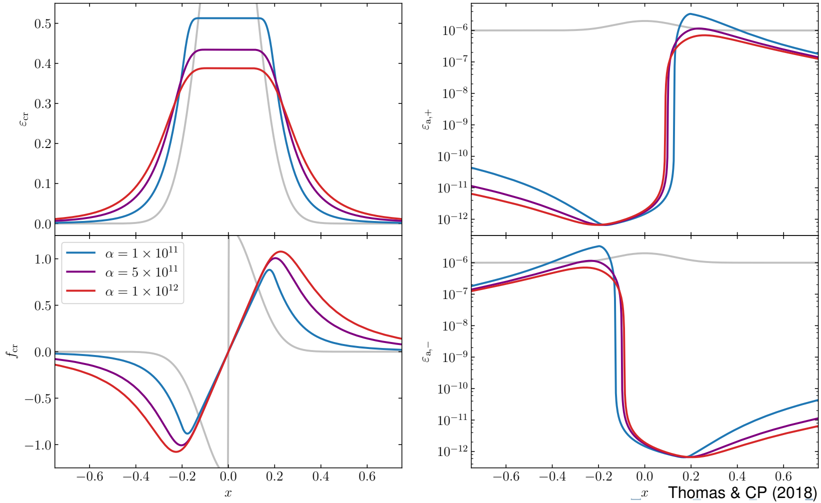
Coupling the evolution of CR and Alfvén wave energy densities



Thomas & CP (2018)

Non-equilibrium CR streaming and diffusion

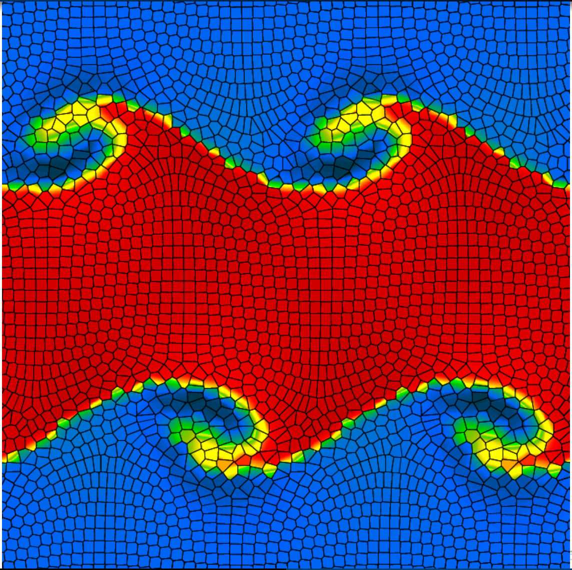
Varying damping rate of Alfvén waves modulates the diffusivity of solution



Thomas & CP (2018)

Outline

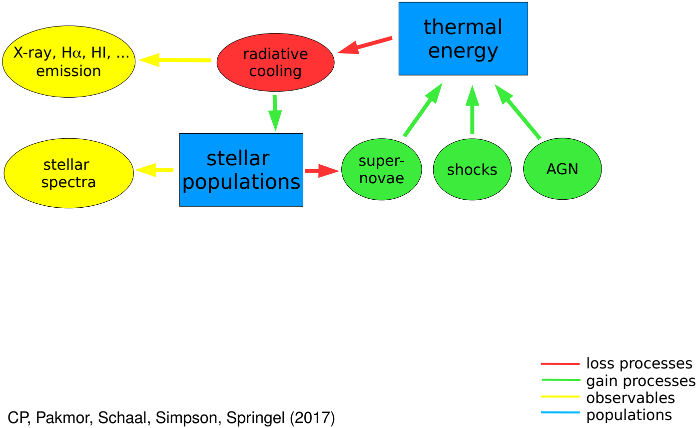
Cosmological moving-mesh code AREPO (Springel 2010)



Simulations – flowchart

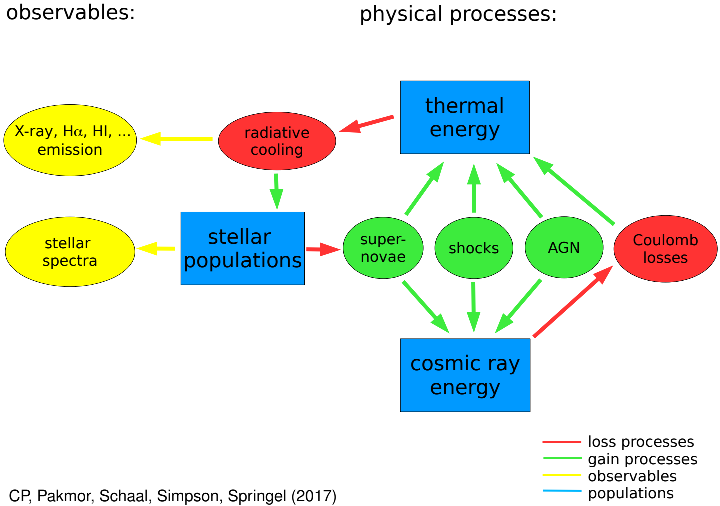
observables:

physical processes:



CP, Pakmor, Schaal, Simpson, Springel (2017)

Simulations with cosmic ray physics



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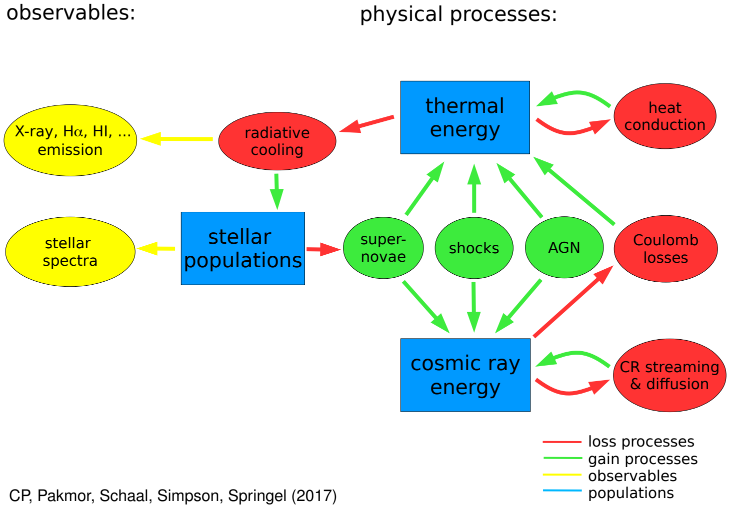

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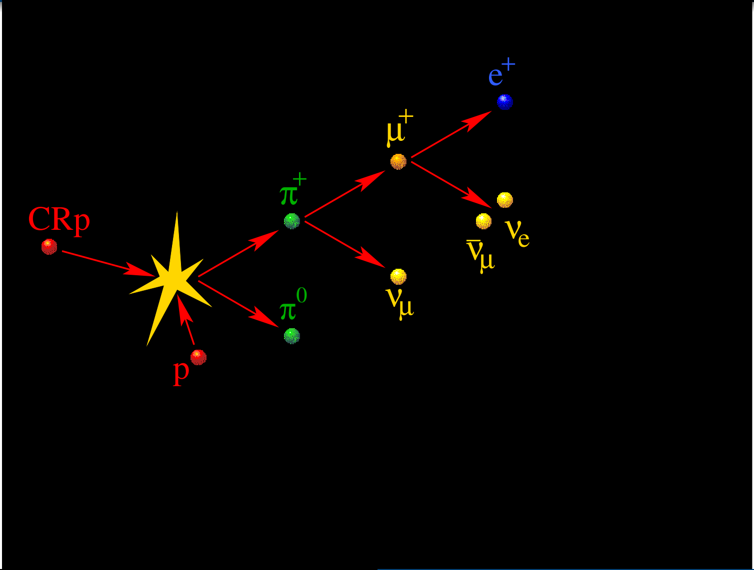
Hadronic cosmic ray proton interaction



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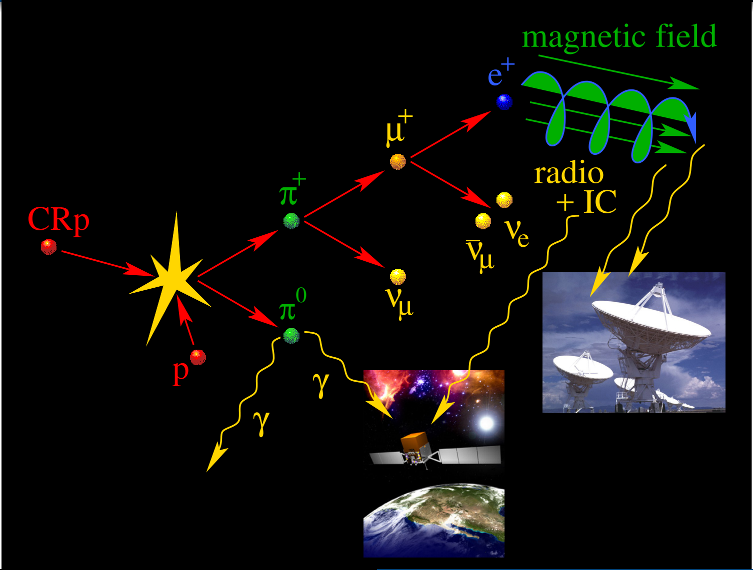
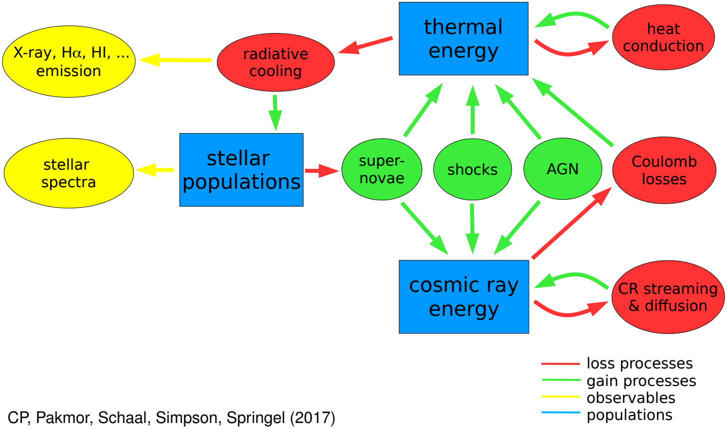


Simulations with cosmic ray physics

observables: physical processes:



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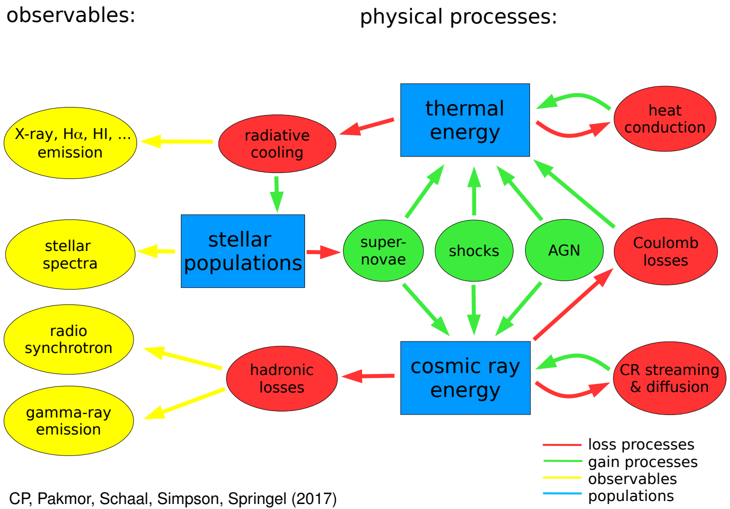
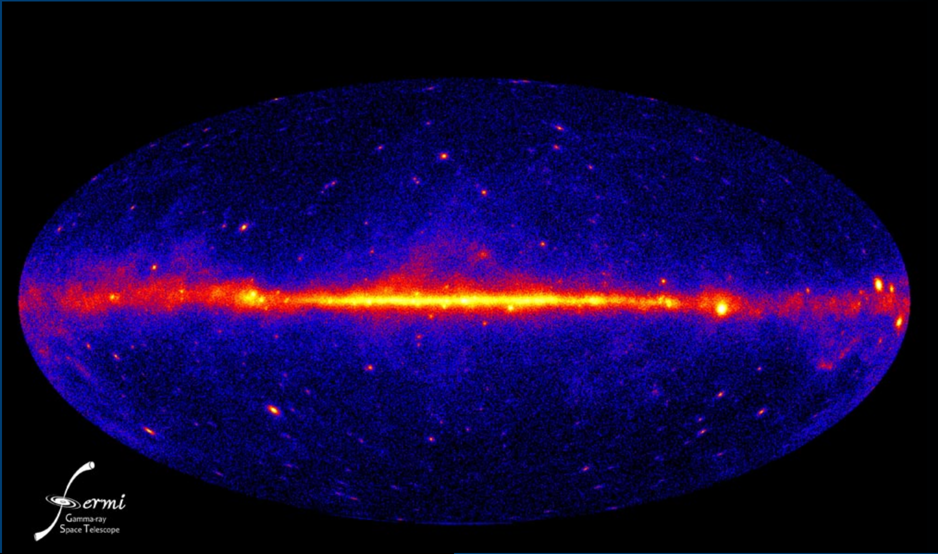


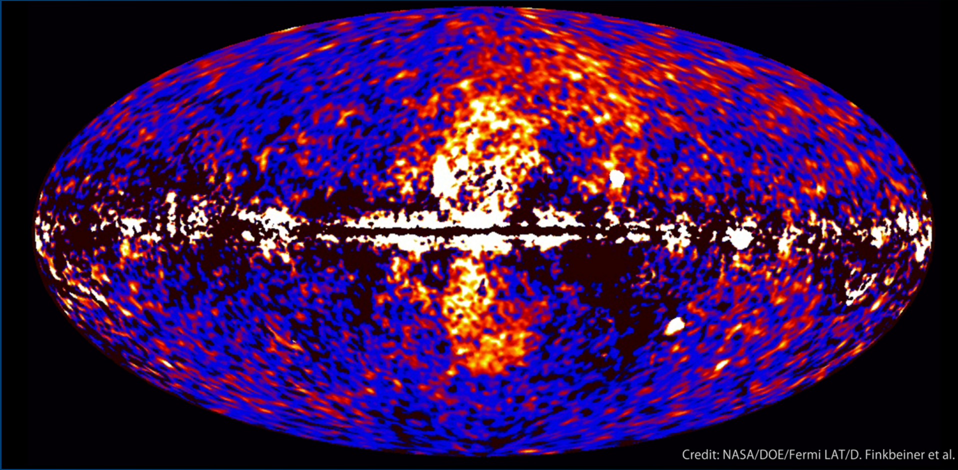
CP, Pakmor, Schaal, Simpson, Springel (2017)

Gamma-ray emission of the Milky Way



Galactic wind in the Milky Way?

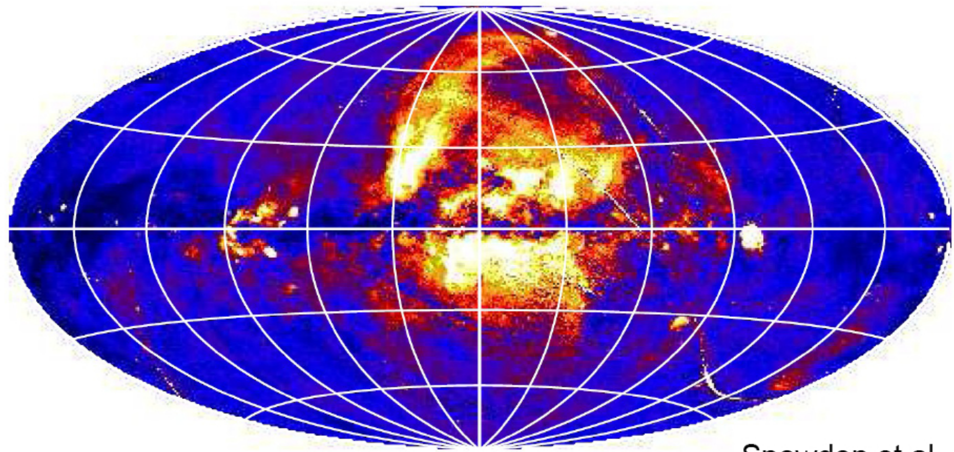
Fermi gamma-ray bubbles



Credit: NASA/DOE/Fermi LAT/D. Finkbeiner et al.

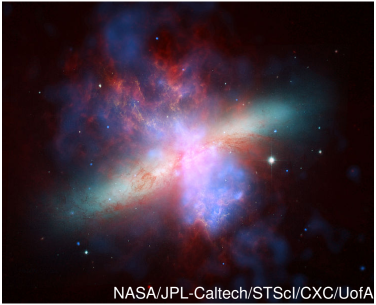
Galactic wind in the Milky Way?

Diffuse X-ray emission in our Galaxy



Snowden et al.,

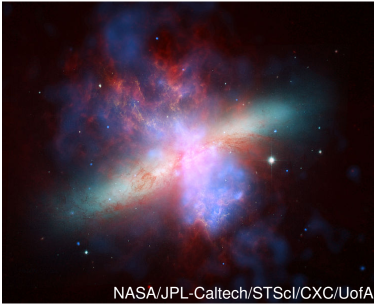
How are galactic winds driven?



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?



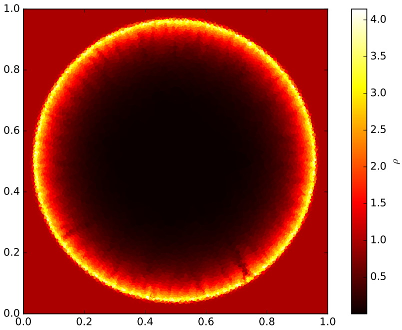
super wind in M82

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

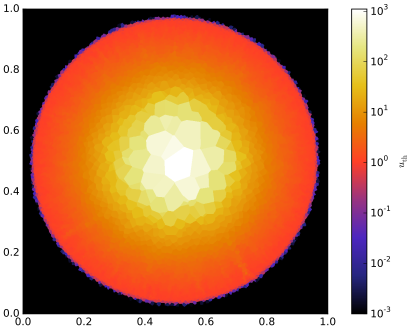
observed energy equipartition between cosmic rays, thermal gas and magnetic fields
$\rightarrow$ suggests self-regulated feedback loop with CR driven winds

Sedov explosion

density



specific thermal energy

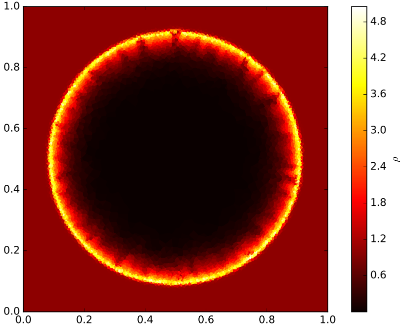


CP, Pakmor, Schaal, Simpson, Springel (2017)

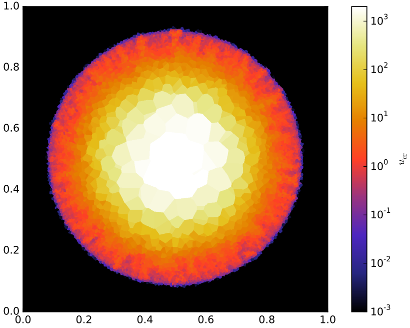
AIP

Sedov explosion with CR acceleration

density



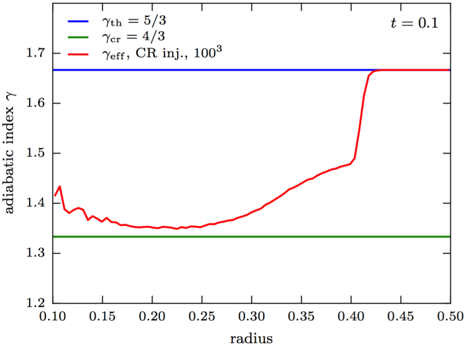
specific cosmic ray energy



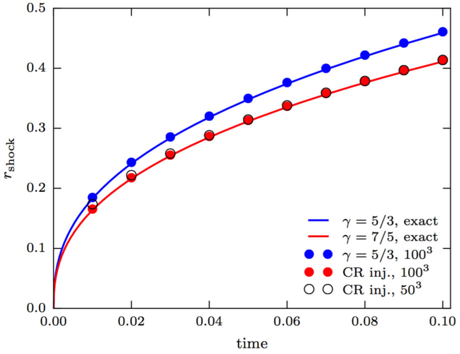
CP, Pakmor, Schaal, Simpson, Springel (2017)

Sedov explosion with CR acceleration

adiabatic index



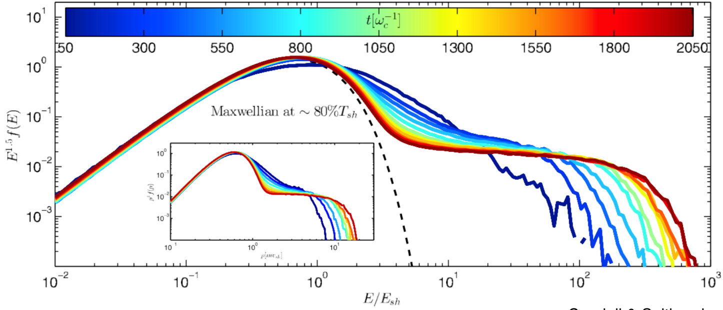
shock evolution



CP, Pakmor, Schaal, Simpson, Springel (2017)

Ion spectrum

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

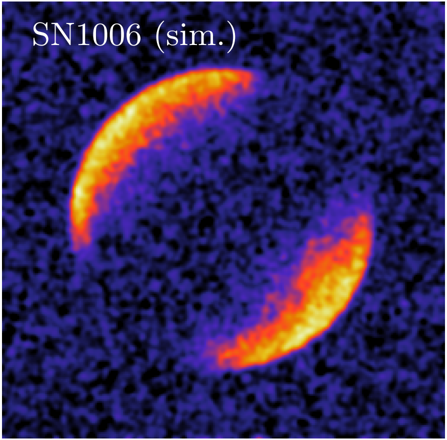


Caprioli & Spitkovsky (2014)

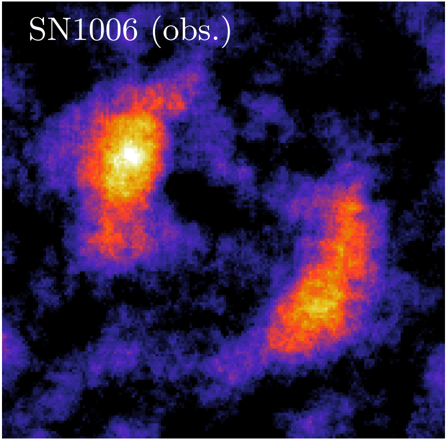
- quasi-parallel shocks ($\boldsymbol{B} \parallel \boldsymbol{n}_\mathrm{s}$) accelerate ions
- quasi-perpendicular shocks ($\boldsymbol{B} \perp \boldsymbol{n}_\mathrm{s}$) cannot
- model magnetic obliquity in AREPO simulations

TeV γ rays from shell-type SNRs: SNR 1006

AREPO simulation



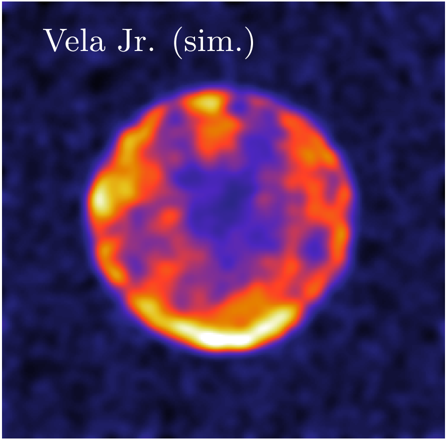
H.E.S.S. observation



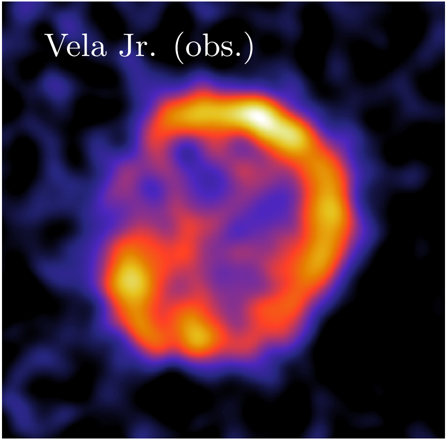
Pais, CP, Ehlert (2018)

TeV γ rays from shell-type SNRs: Vela Junior

AREPO simulation



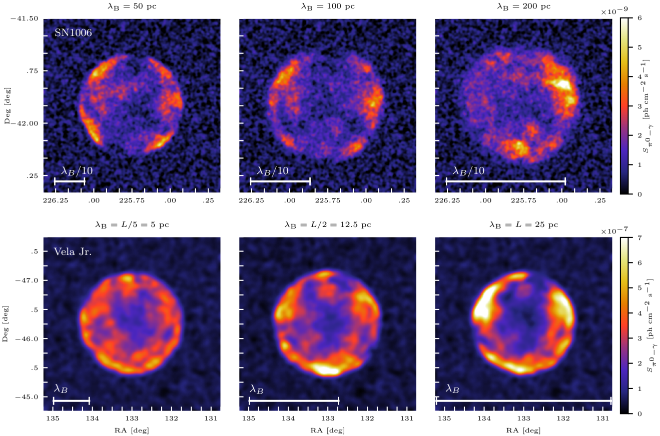
H.E.S.S. observation



Pais, CP, Ehlert (2018)

TeV γ rays from shell-type supernova remnants

Varying magnetic coherence scale in simulations of SN1006 and Vela Junior

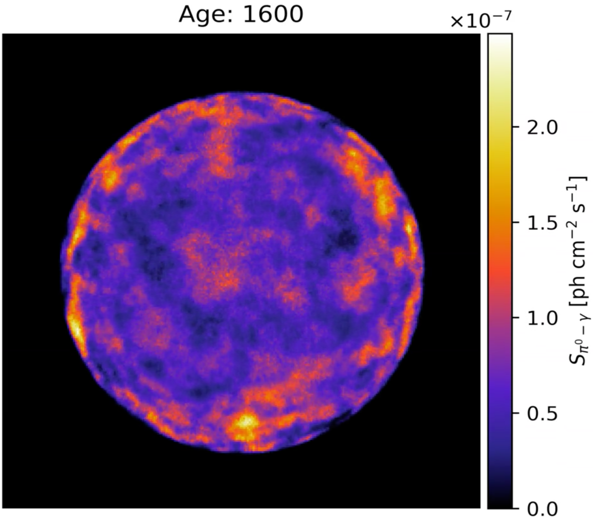


Pais, CP, Ehlert (2018)

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

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

TeV γ rays from shell-type SNRs: Vela Junior

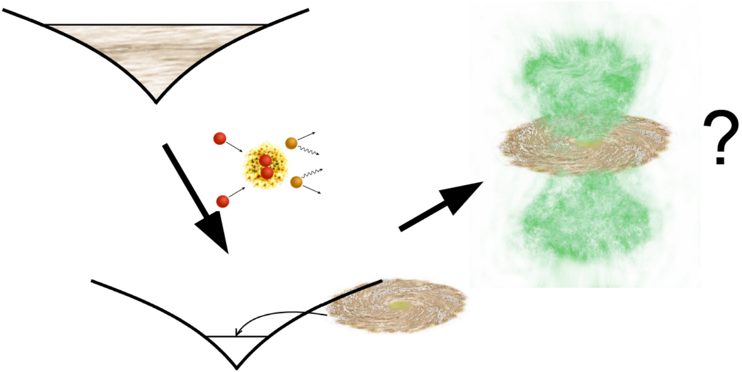


Pais, CP, Ehlert (2018)

Outline

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

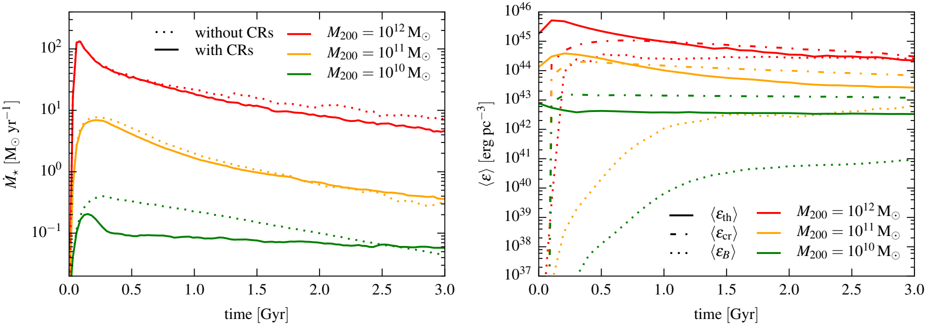
Galaxy simulation setup: 1. cosmic ray advection



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

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

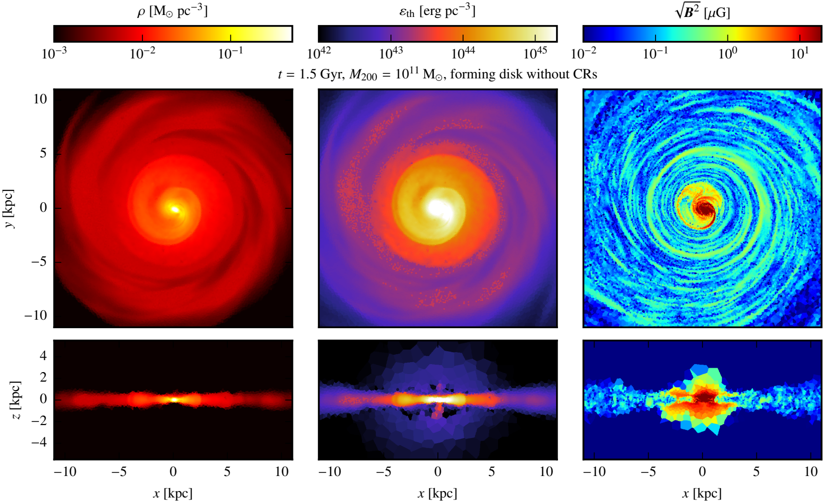
Time evolution of SFR and energy densities



CP, Pakmor, Schaal, Simpson, Springel (2017)

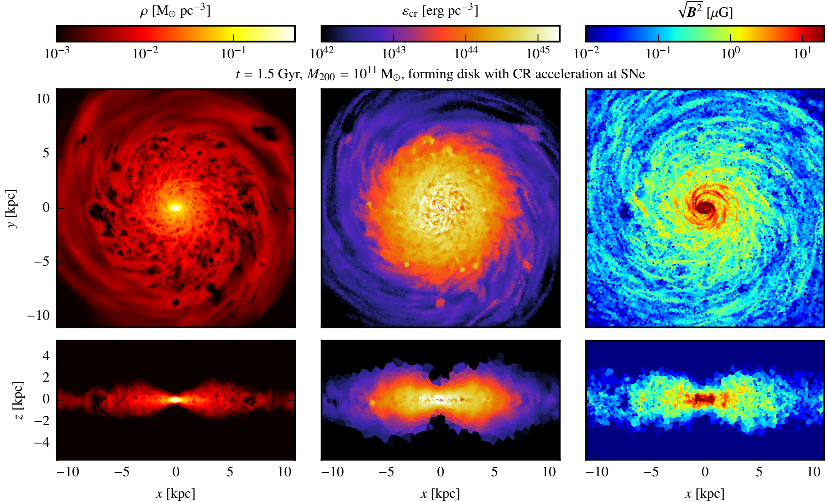
- CR pressure feedback suppresses SFR more in smaller galaxies
- energy budget in disks is dominated by CR pressure
- magnetic dynamo faster in Milky Way galaxies than in dwarfs

MHD galaxy simulation without CRs



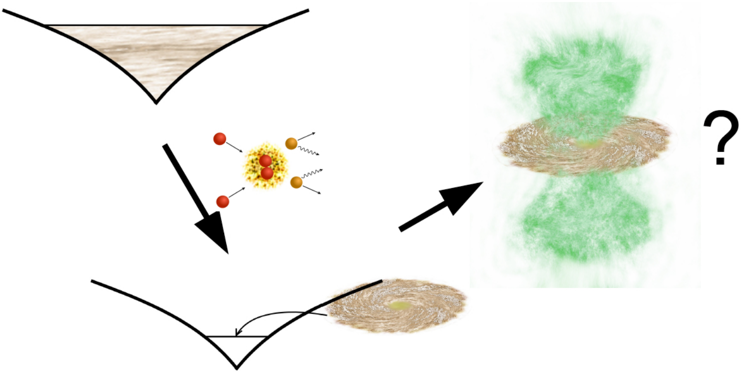
CP, Pakmor, Schaal, Simpson, Springel (2017)

MHD galaxy simulation with CRs



CP, Pakmor, Schaal, Simpson, Springel (2017)

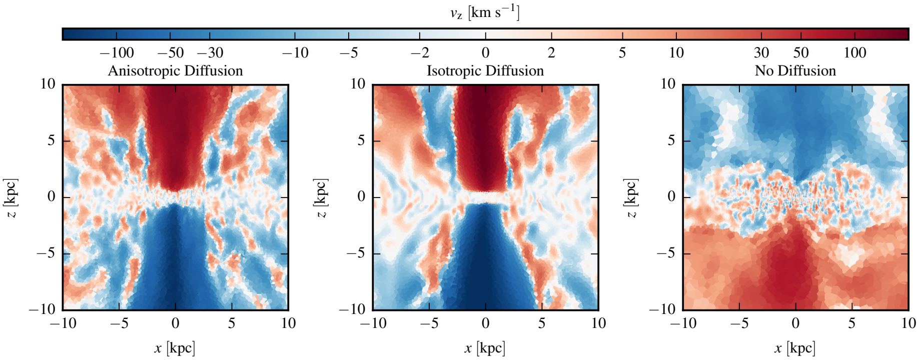
Galaxy simulation setup: 2. cosmic ray diffusion



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} $M_\odot$

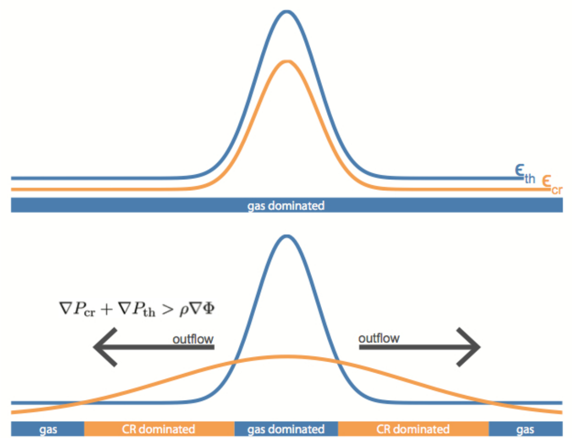
MHD galaxy simulation with CR diffusion



Pakmor, CP, Simpson, Springel (2016)

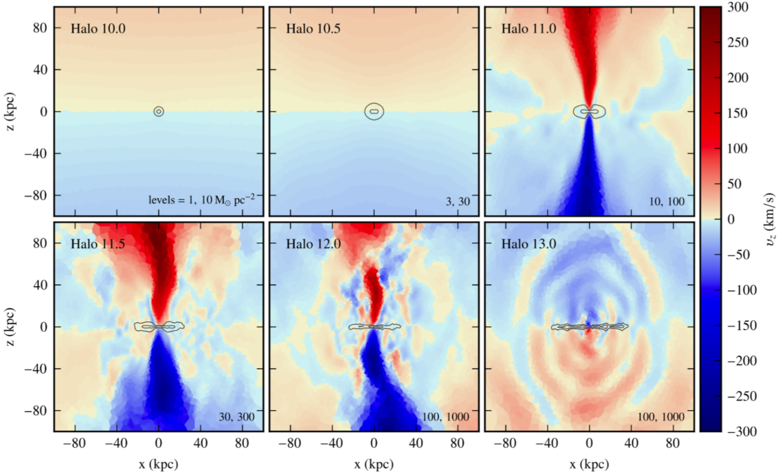
- CR diffusion launches powerful winds
- simulation without CR diffusion exhibits only weak fountain flows

Cosmic ray driven wind: mechanism



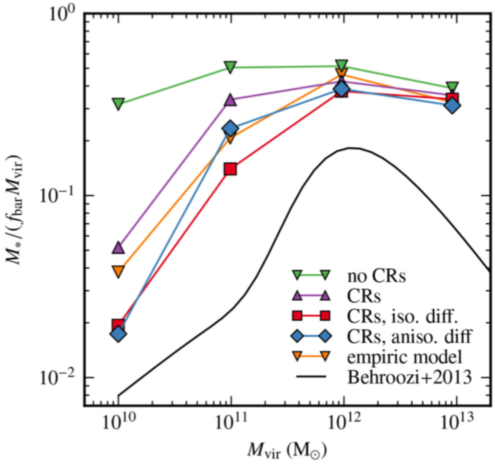
CR streaming in 3D simulations: Uhlig, CP+ (2012), Ruszkowski+ (2017)
CR diffusion in 3D simulations: Jubelgas+ (2008), Booth+ (2013), Hanasz+ (2013), Salem & Bryan (2014), Pakmor, CP+ (2016), Simpson+ (2016), Girichidis+ (2016), Dubois+ (2016), CP+ (2017), Jacob+ (2018)

CR-driven winds: dependence on halo mass



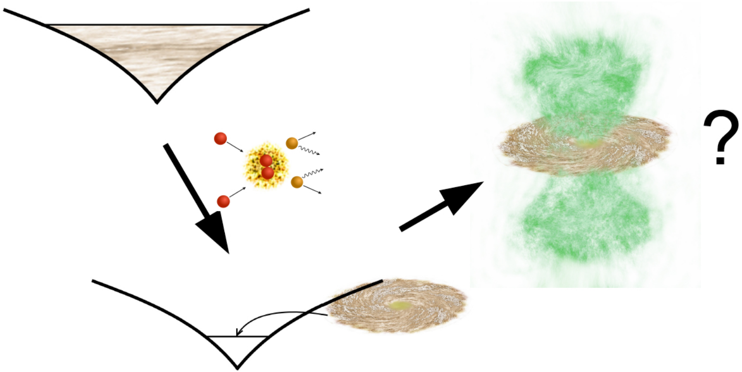
Jacob+ (2018)

CR-driven winds: suppression of star formation



Jacob+ (2018)

Galaxy simulation setup: 3. non-thermal emission

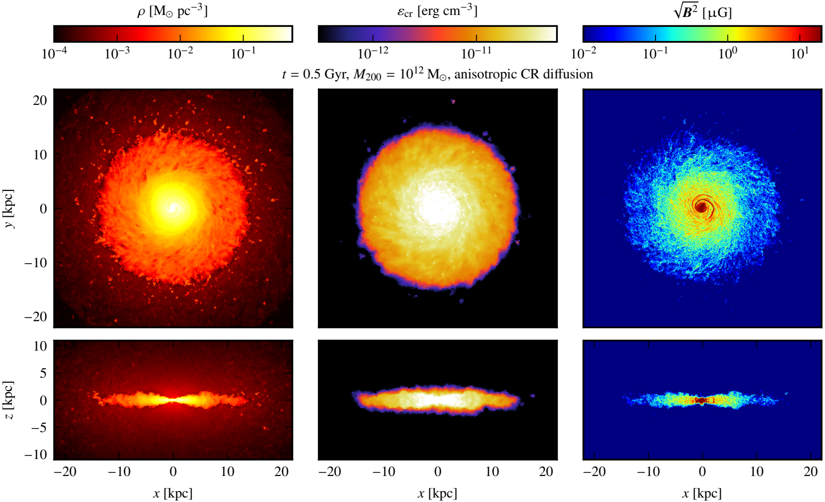


CP, Pakmor, Simpson, Springel (2017a,b)

Simulating radio synchrotron and gamma-ray emission in galaxies

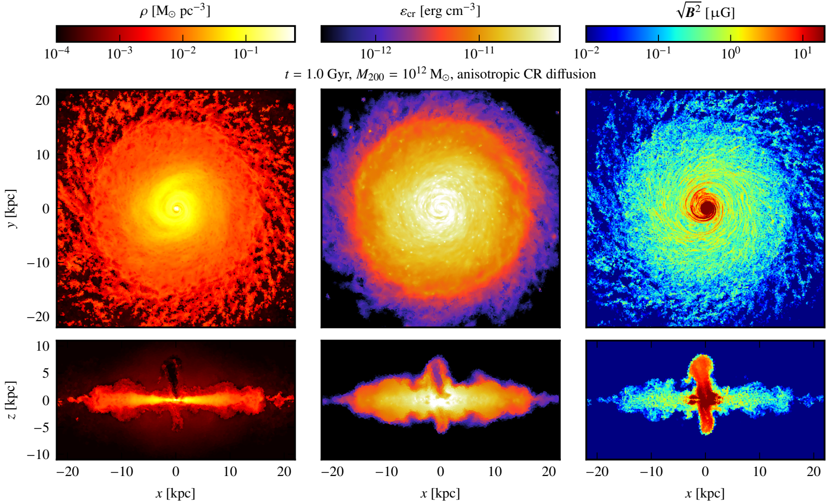
MHD + CR advection + diffusion: $\{10^{10}, 10^{11}, 10^{12}\}$ $M_\odot$

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



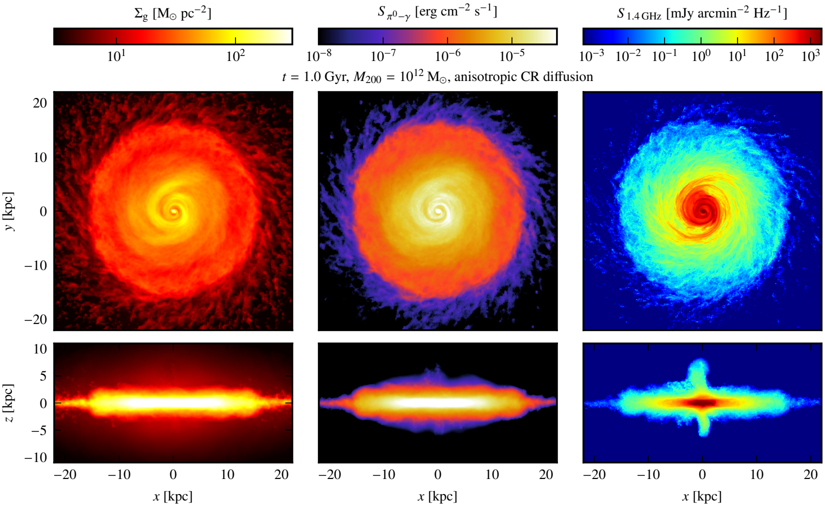
CP+ (2017a,b)

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



CP+ (2017a,b)

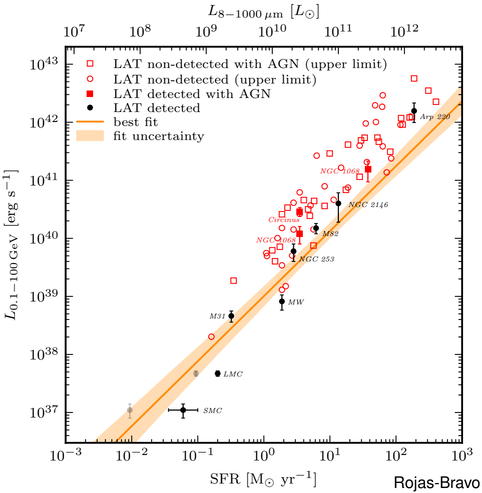
γ-ray and radio emission of Milky Way-like galaxy



CP+ (2017a,b)

Far infra-red – gamma-ray correlation

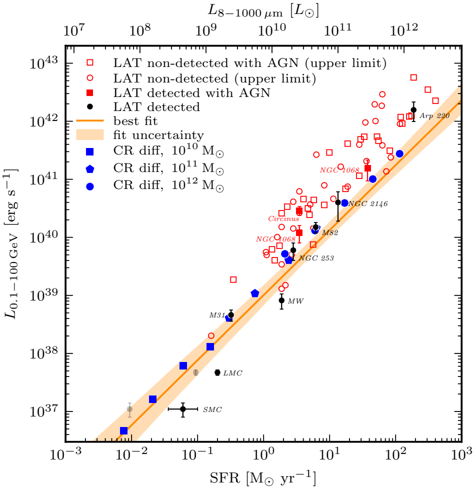
Universal conversion: star formation → cosmic rays → gamma rays



Rojas-Bravo & Araya (2016)

Far infra-red – gamma-ray correlation

Universal conversion: star formation → cosmic rays → gamma rays



CP+ (2017a)

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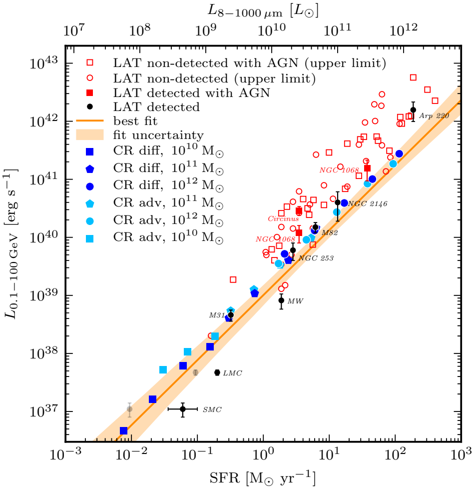
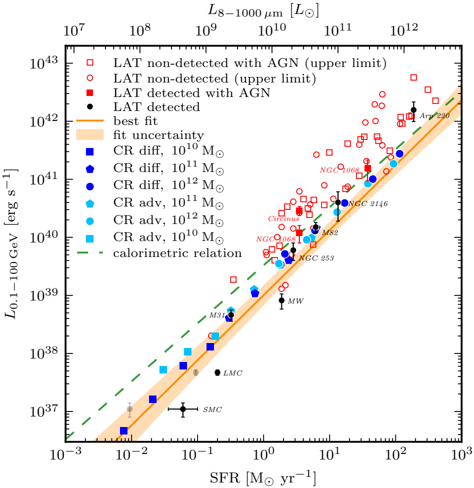


CP+ (2017a)

Far infra-red – gamma-ray correlation

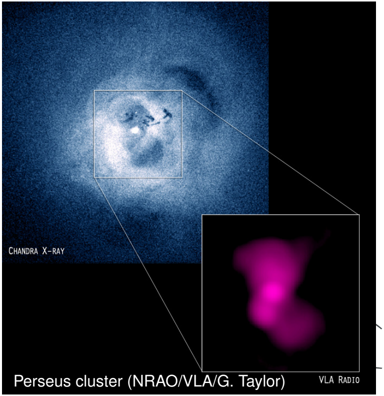
Universal conversion: star formation → cosmic rays → gamma rays



CP+ (2017a)

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?**

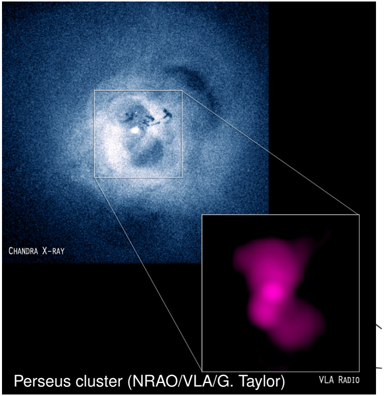


Perseus cluster (NRAO/VLA/G. Taylor)

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

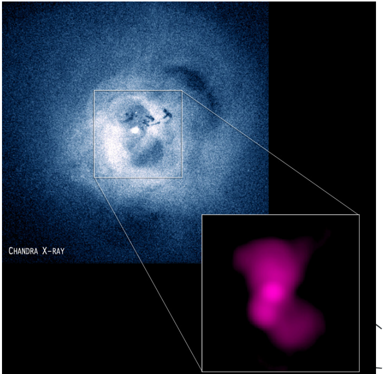


Perseus cluster (NRAO/VLA/G. Taylor)

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 $\Rightarrow$ **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 $\rightarrow$ turbulence
- jet accelerates cosmic rays $\rightarrow$ release from bubbles provides source of heat

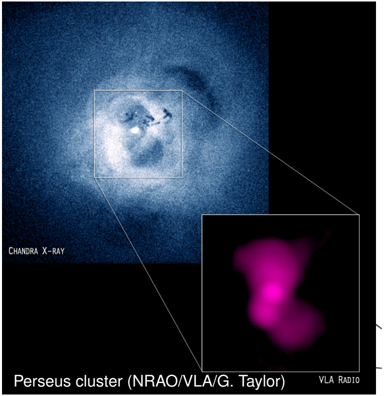


Perseus cluster (NRAO/VLA/G. Taylor)

Feedback by active galactic nuclei

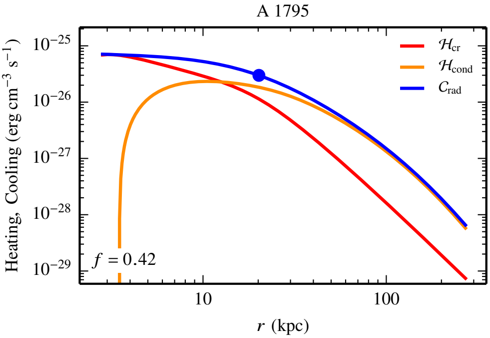
Paradigm: accreting super-massive black holes at galaxy cluster centers launch relativistic jets, which provide energetic feedback to balance cooling $\Rightarrow$ **but how?**

- 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)

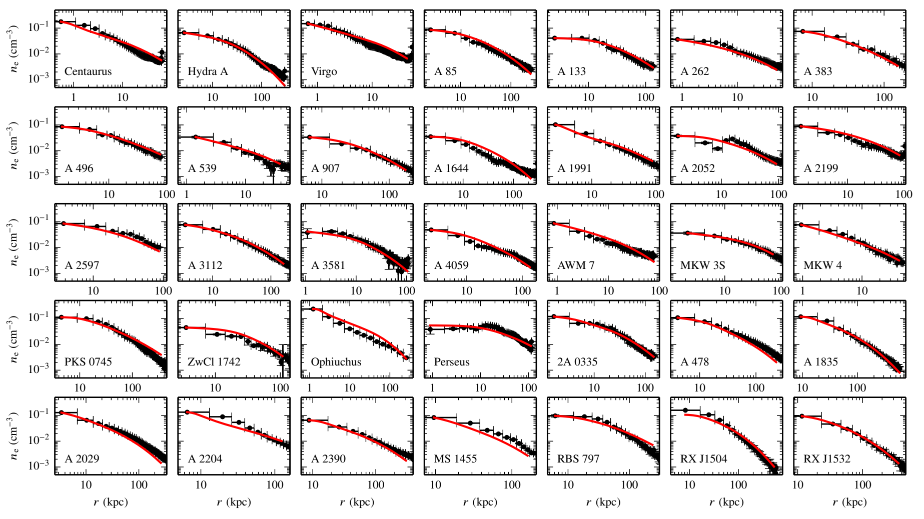
Case study A1795: heating and cooling



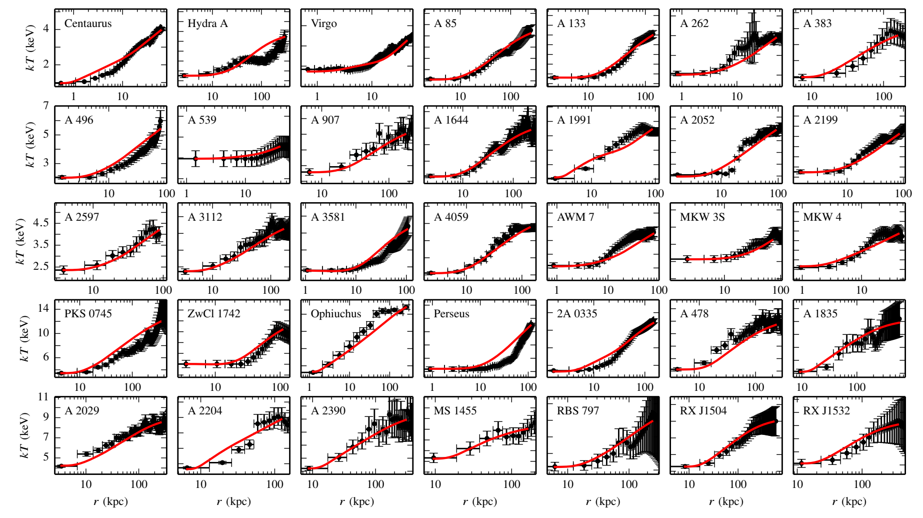
Jacob & CP (2016a)

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

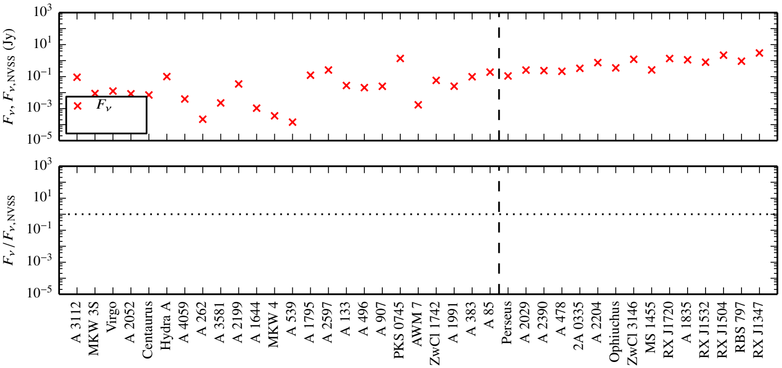
Gallery of solutions: density profiles



Gallery of solutions: temperature profiles

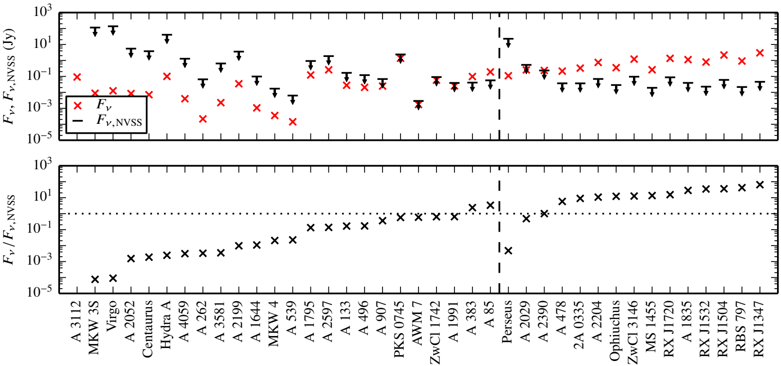


Hadronically induced radio emission



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)

AIP

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

How can we explain these results?

- self-regulated feedback cycle driven by CRs

AGN injects CRs → CR heating balances cooling

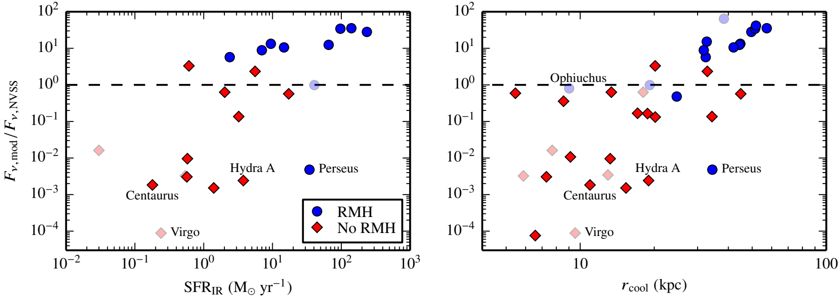
↓

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

↑ (back to AGN injects CRs)

CRs stream outwards … ↘ radio mini halo

Self-regulated heating/cooling cycle in cool cores

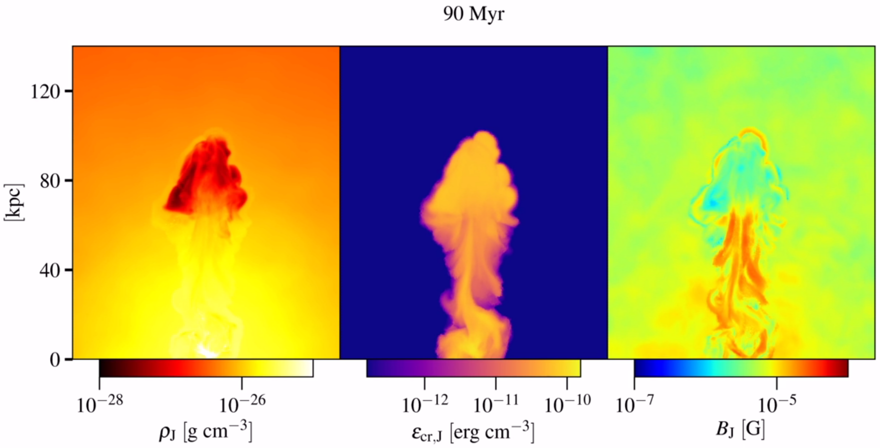


Jacob & CP (2017b)

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

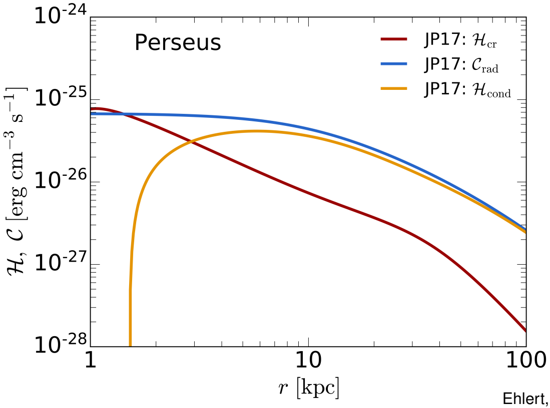
- simmering SF: CR heating is effectively balancing cooling
- abundant SF: heating/cooling out of balance

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



Ehlert, Weinberger, CP+ (2018)

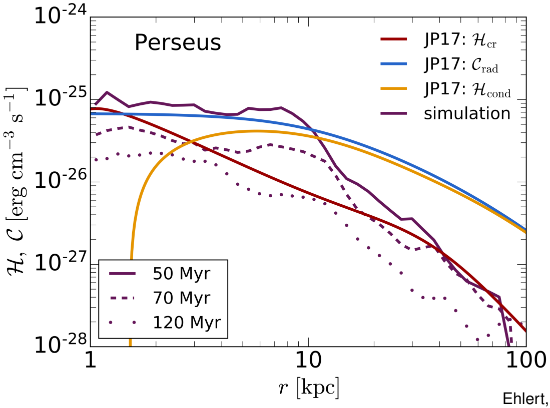
Perseus cluster – heating vs. cooling: theory



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}

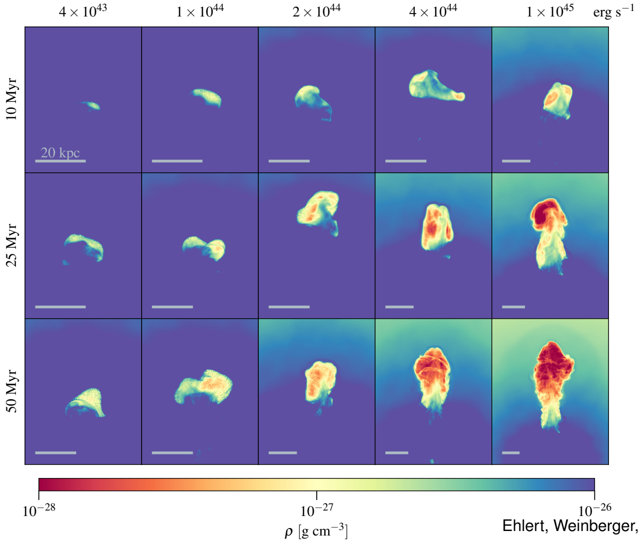
Perseus cluster – heating vs. cooling: simulations



Ehlert, Weinberger, CP+ (2018)

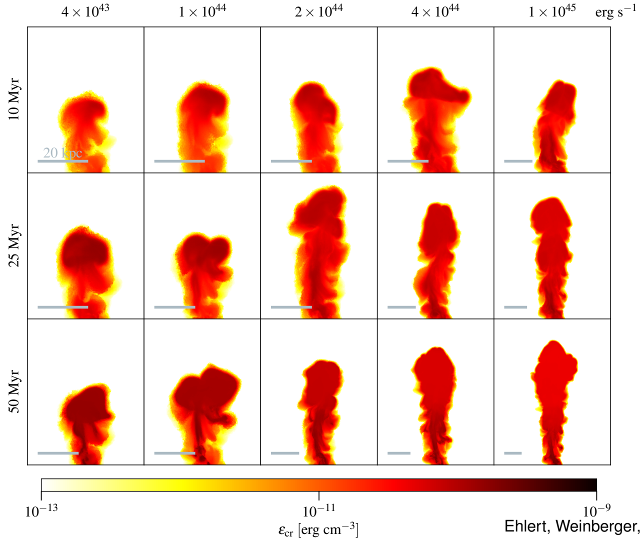
- CR and conductive heating balance radiative cooling: $\mathcal{H}_{\rm cr} + \mathcal{H}_{\rm th} \approx \mathcal{C}_{\rm rad}$: modest mass deposition rate of 1 $M_\odot$ yr^{-1}
- **simulated CR heating rate matches 1D steady state model**

Matrix of jet simulations: density at 70 Myrs



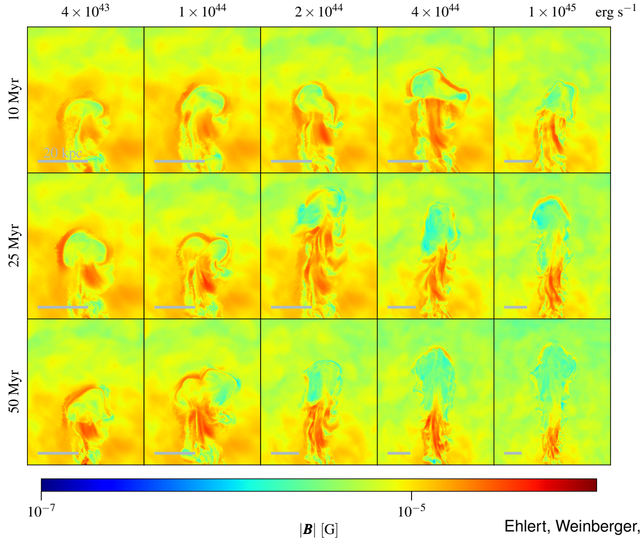
Ehlert, Weinberger, CP+ (2018)

Matrix of jet simulations: CR energy density at 70 Myrs



Ehlert, Weinberger, CP+ (2018)

Matrix of jet simulations: magnetic field at 70 Myrs



Ehlert, Weinberger, CP+ (2018)

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

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 $B \sim 10\,\mu\mathrm{G}$
- $L_{\mathrm{FIR}} - L_{\gamma}$ and $L_{\mathrm{FIR}} - L_{\mathrm{radio}}$ correlations enable us to test the calorimetric assumption and magnetic dynamo theories
- MHD simulations of AGN jets: CR heating can solve the “cooling flow problem” in galaxy clusters

AIP

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
- $L_{\mathrm{FIR}} - L_\gamma$ and $L_{\mathrm{FIR}} - L_{\mathrm{radio}}$ correlations enable us to test the calorimetric assumption and magnetic dynamo theories
- MHD simulations of AGN jets: CR heating can solve the "cooling flow problem" in galaxy clusters

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:

- Thomas, Pfrommer, *Cosmic-ray hydrodynamics: Alfvén-wave regulated transport of cosmic rays,* 2018.
- Pais, Pfrommer, Ehlert, *Constraining the coherence scale of the interstellar magnetic field using TeV gamma-ray observations of supernova remnants,* 2018.
- Pais, Pfrommer, Ehlert, Pakmor, *The effect of cosmic-ray acceleration on supernova blast wave dynamics,* 2018, MNRAS.

Cosmic ray feedback in galaxies:

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

AIP

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,* 2018.