



How cosmic rays shape galaxies

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in collaboration with

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Outline

1 Introduction

- Puzzles in galaxy formation
- Particle acceleration
- Cosmic rays

2 Physical processes

- Modelling physics in galaxies
- Supernova explosions
- Interstellar medium

3 Simulating galaxies

- Global galaxy models
- Gamma-ray emission
- Radio emission

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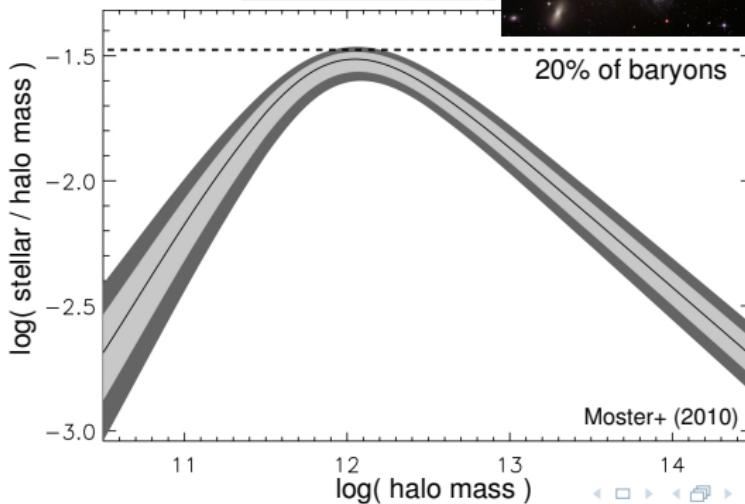
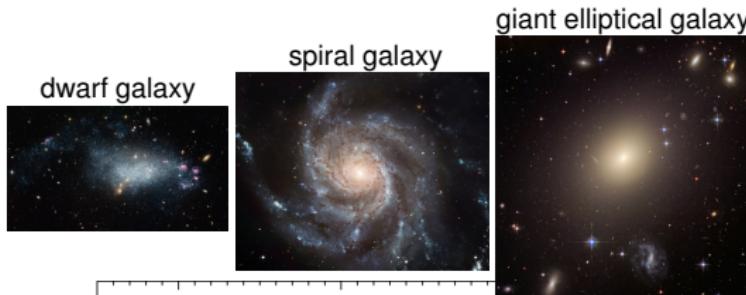
Introduction
Physical processes
Simulating galaxies

Puzzles in galaxy formation
Particle acceleration
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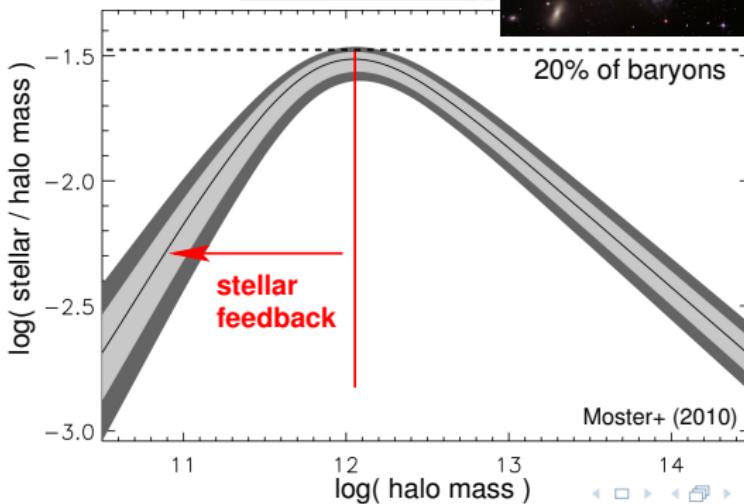
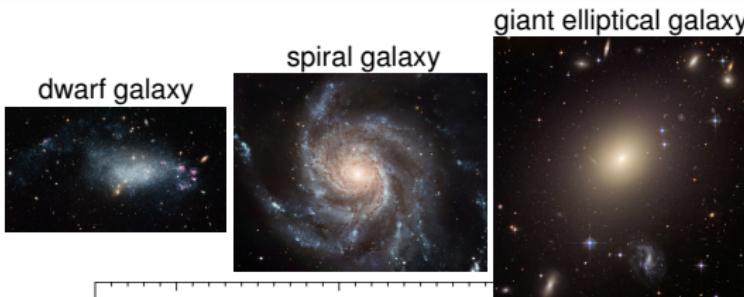
Puzzles in galaxy formation



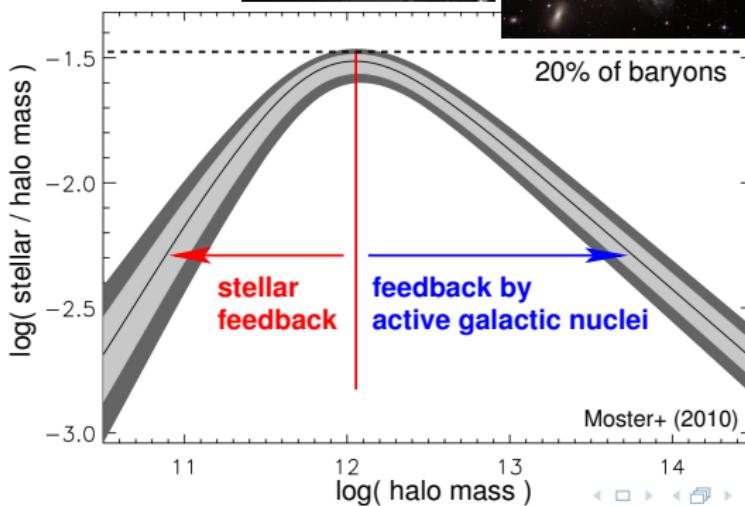
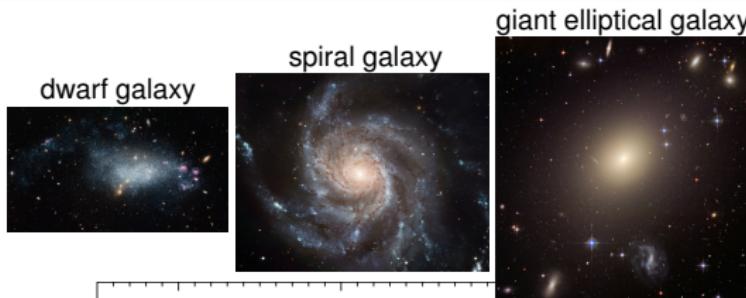
Puzzles in galaxy formation



Puzzles in galaxy formation



Puzzles in galaxy formation



Feedback

feedback n -s often attrib:

- ➊ the return to the input of a part of the output of a machine, system, or process
- ➋ 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



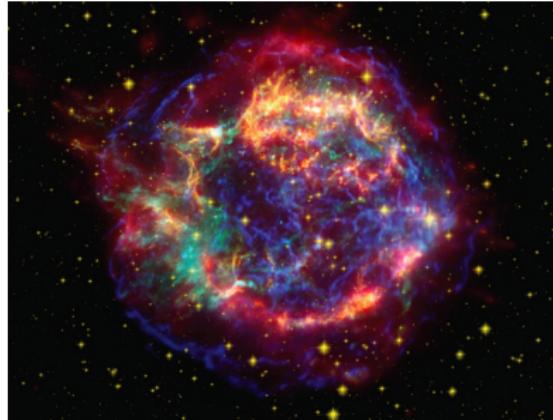
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- ③ the solution of all problems in galaxy formation



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

- **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

Feedback by galactic winds



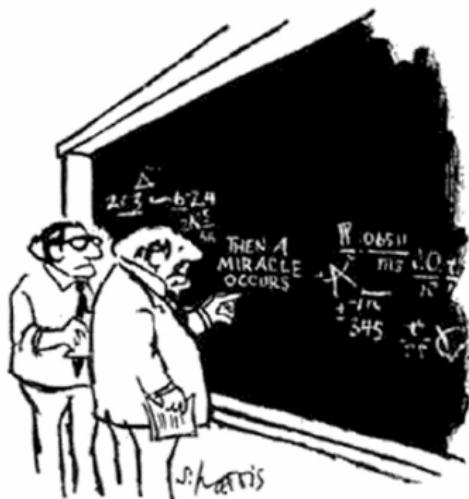
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- critical for understanding the
physics of galaxy formation
→ may explain puzzle of low
star conversion efficiency in
dwarf galaxies



Feedback by galactic winds



"I THINK YOU SHOULD BE MORE EXPLICIT
HERE IN STEP TWO."

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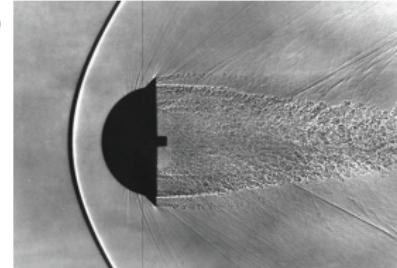
Shock waves

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.



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slide concept Spitkovsky

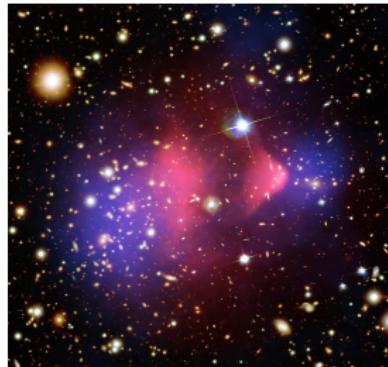
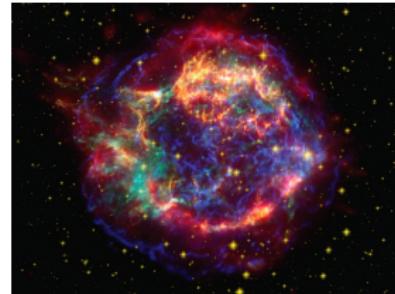
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clusters/galaxies, Coulomb collisions set λ_{mfp} :

$$\lambda_{\text{mfp}} \sim L_{\text{cluster}}/10, \quad \lambda_{\text{mfp}} \sim L_{\text{SNR}}$$

Mean free path \gg observed shock width!

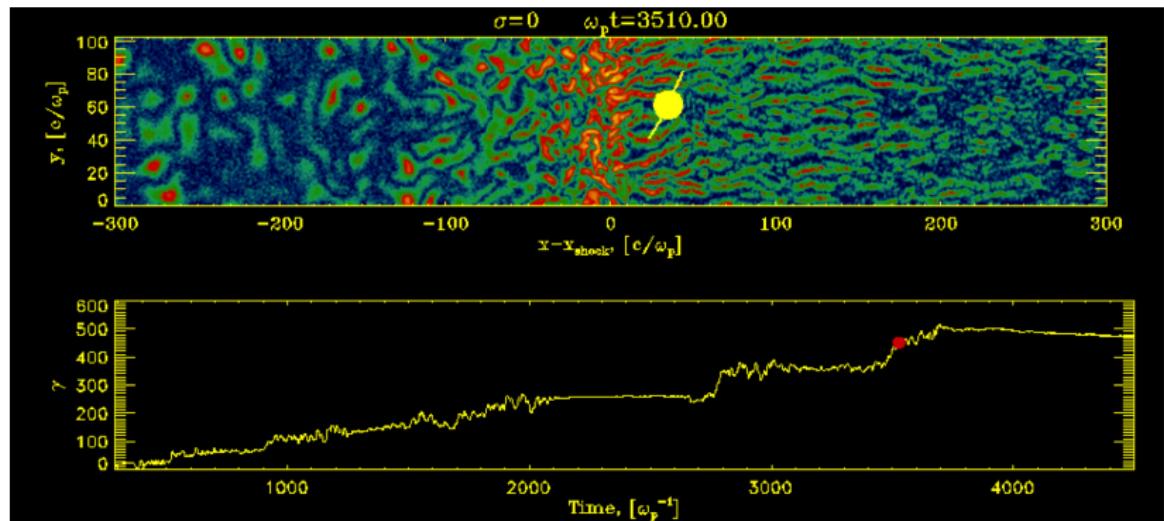
→ shocks must be mediated without collisions,
but through interactions with collective fields

→ collisionless shocks



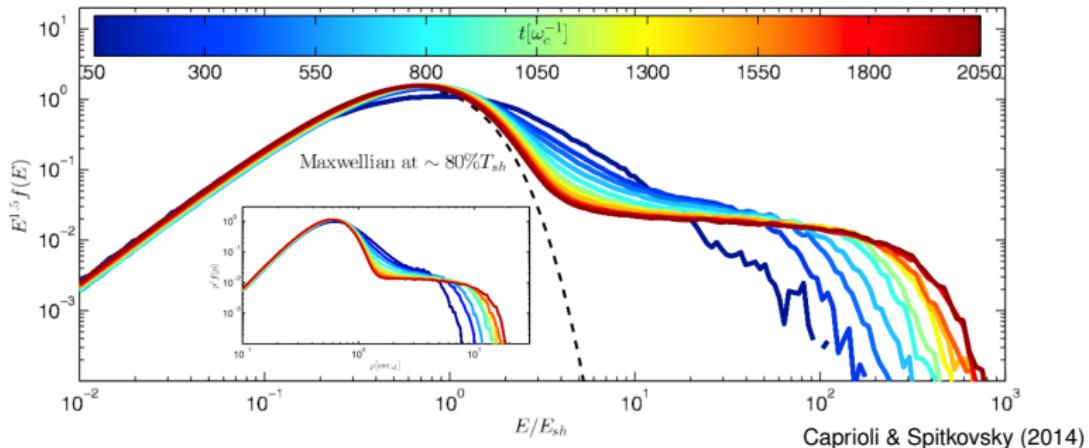
Particle acceleration at relativistic shock, $B_0 = 0$

- 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)



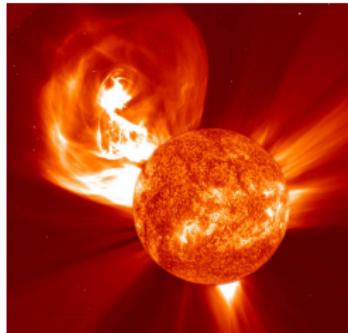
Ion spectrum

Non-relativistic parallel shock in long-term hybrid simulation



- quasi-parallel shocks accelerate ions and produce self-generated waves in the upstream
- particles gain energy in each crossing and have probability of leaving the Fermi cycle by being swept downstream → power-law spectrum
- cosmic ray backreaction is affecting downstream temperature

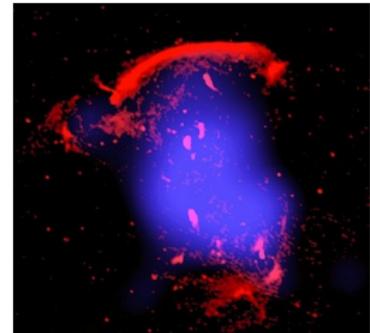
Astrophysical shocks



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



interstellar shocks ~ 20 pc
supernova 1006 (CXC/Hughes)

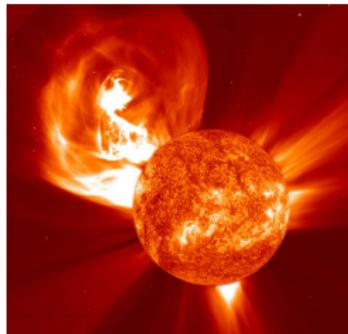


cluster shocks ~ 2 Mpc
giant radio relic (van Weeren)

Astrophysical shocks

astrophysical **collisionless shocks** can:

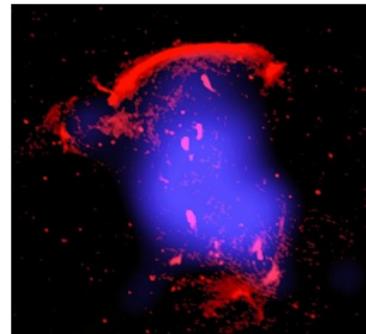
- **accelerate particles** (electrons and ions) → cosmic rays (CRs)
- **amplify magnetic fields** (or generate them from scratch)
- **exchange energy** between electrons and ions



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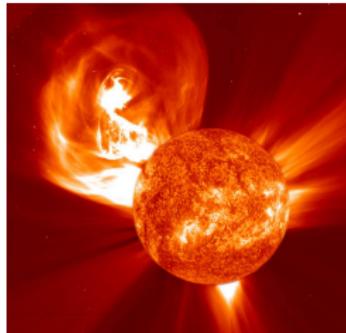
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Astrophysical shocks

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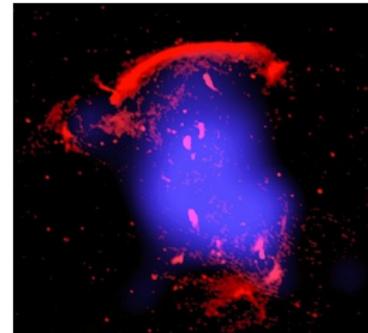
collisionless shocks \iff energetic particles \iff electro-magnetic waves



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

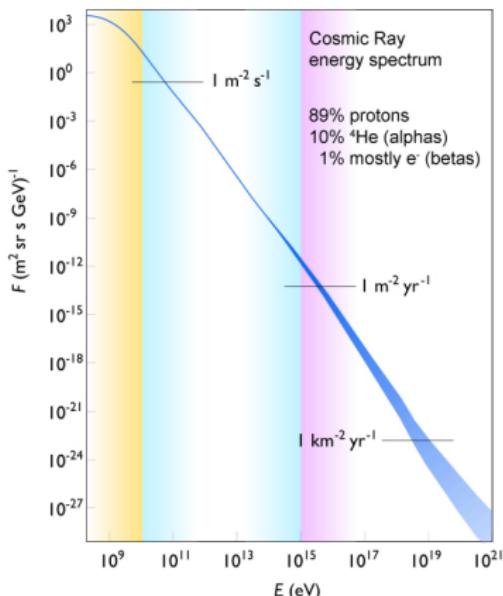


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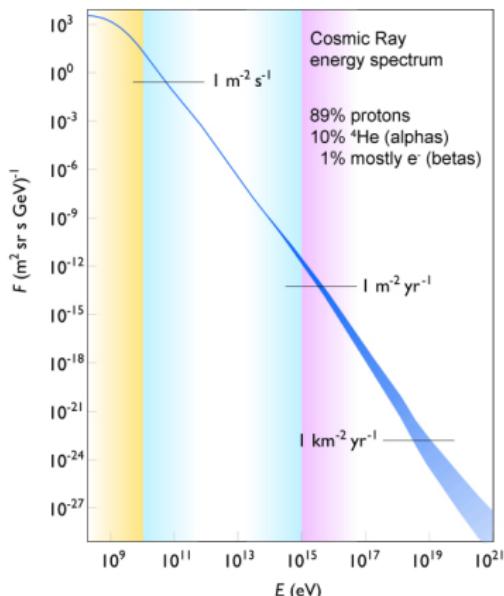
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Galactic cosmic ray spectrum



- 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

Galactic cosmic ray spectrum

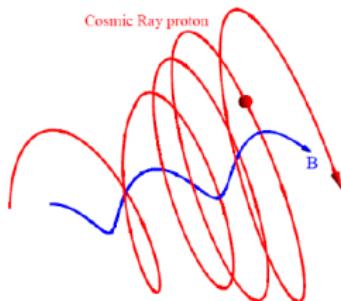


- spans more than 33 decades in flux and 12 decades in energy
- “knee” indicates characteristic maximum energy of galactic accelerators
- CRs beyond the “ankle” have extra-galactic origin
- **energy density of cosmic rays, magnetic fields, and turbulence in the interstellar gas all similar**



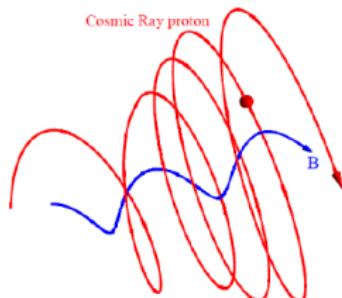
Interactions of CRs and magnetic fields

- CRs scatter on magnetic fields → isotropization of CR momenta
- **CR streaming instability:** Kulsrud & Pearce 1969
 - if $v_{\text{cr}} > v_A$, 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 $\sim v_A$
 - 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 $\mathbf{v}_{\text{cr}} = \mathbf{v} + \mathbf{v}_{\text{st}} + \mathbf{v}_{\text{di}}$ (where $\mathbf{v} \equiv \mathbf{v}_{\text{gas}}$)
- CRs stream** down their own pressure gradient relative to the gas,
CRs diffuse in the wave frame due to pitch angle scattering by
MHD waves (both transports are along the local direction of \mathbf{B}):

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

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

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

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



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



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- Puzzles in galaxy formation
- Particle acceleration
- Cosmic rays

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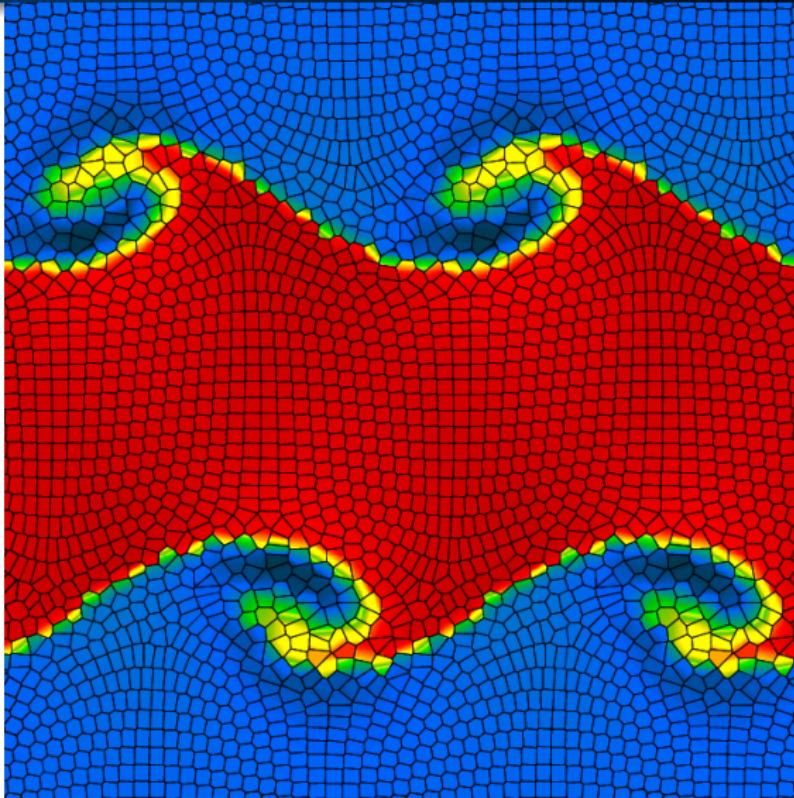
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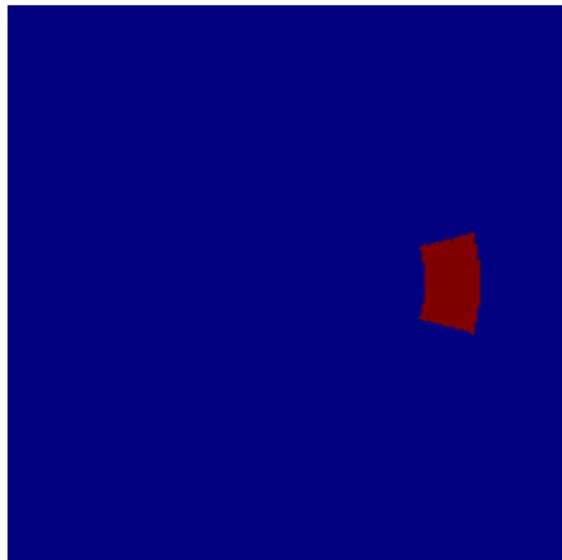


Cosmological moving-mesh code AREPO (Springel 2010)



Anisotropic CR diffusion

- diffusion of CR energy density along magnetic field lines
- implemented on unstructured mesh in AREPO
- implicit solver with local time stepping
- obeys 1. and 2. law of thermodynamics (energy conserving and $\Delta S \geq 0$)



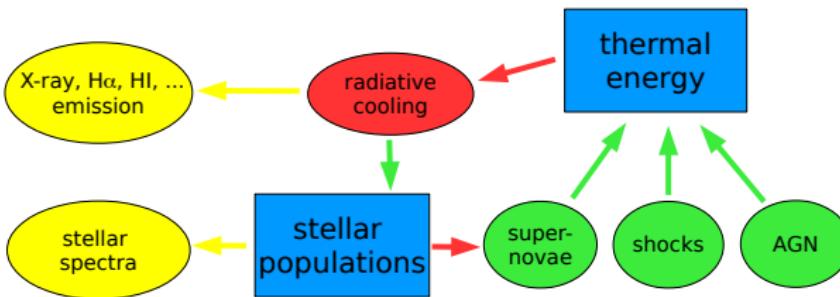
Pakmor, C.P., Simpson, Kannan, Springel (2016)



Simulations – flowchart

observables:

physical processes:



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

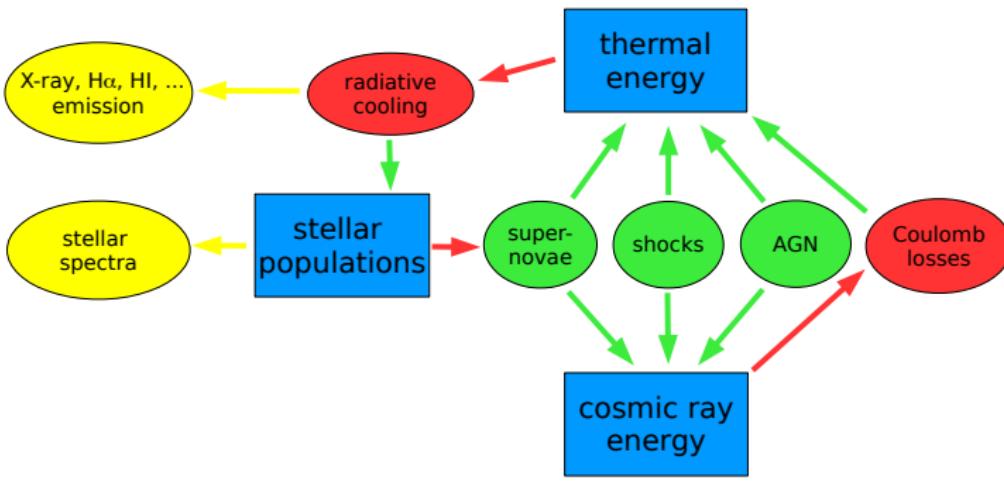
- loss processes
- gain processes
- observables
- populations



Simulations with cosmic ray physics

observables:

physical processes:



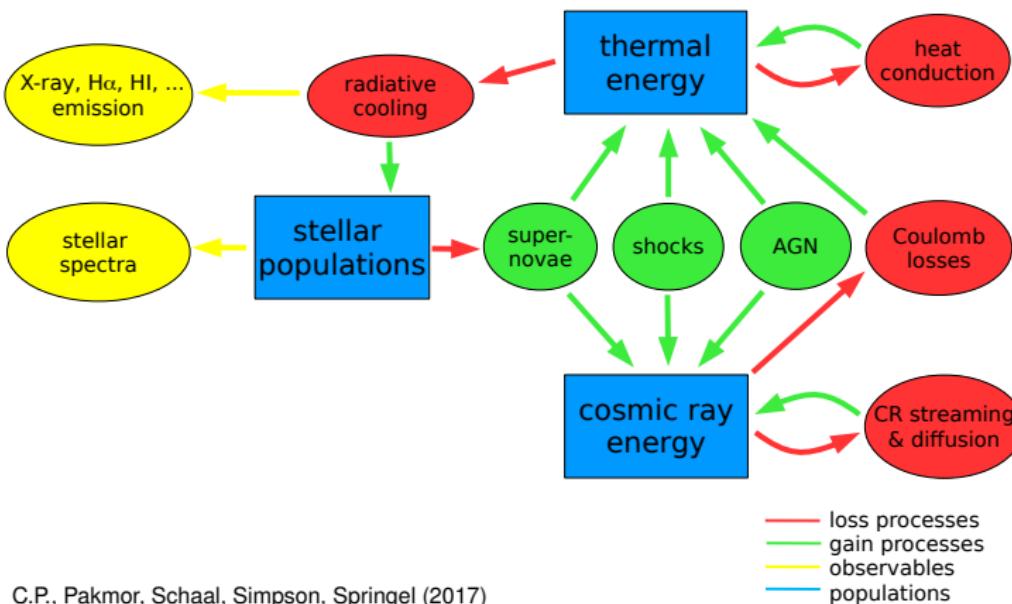
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Simulations with cosmic ray physics

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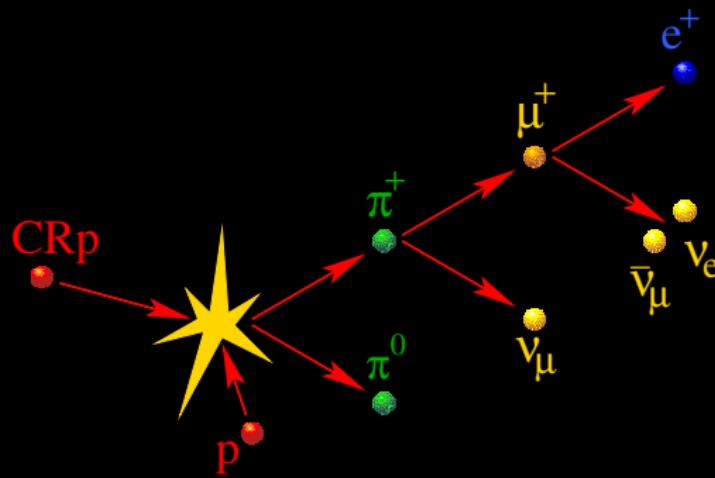
physical processes:



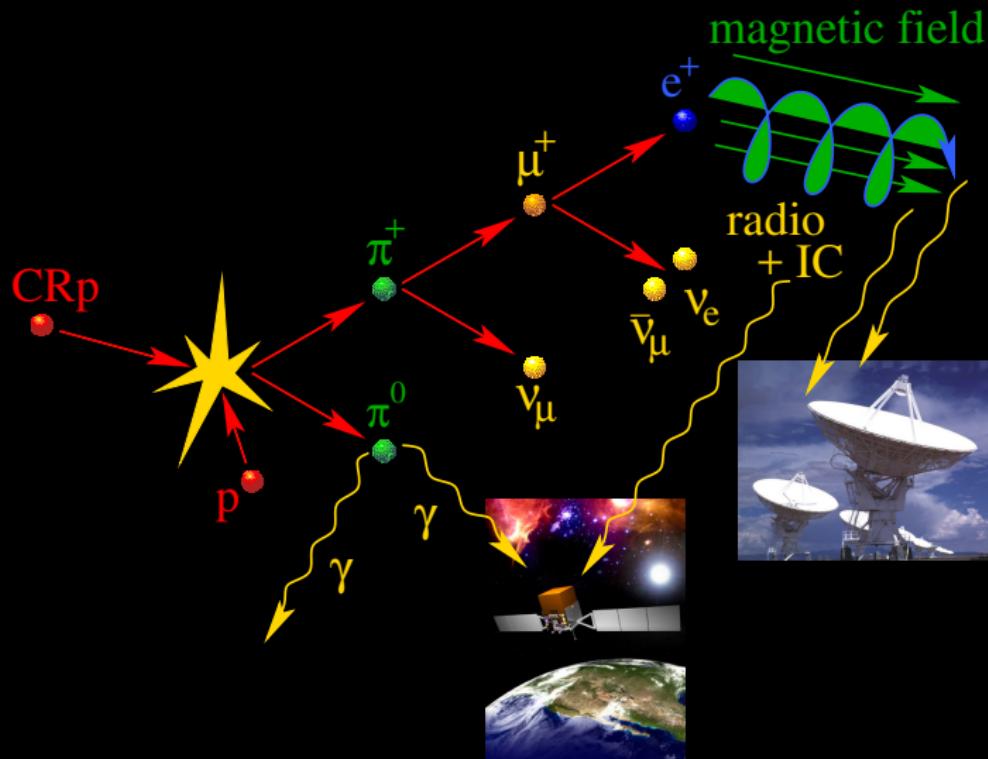
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Hadronic cosmic ray proton interaction



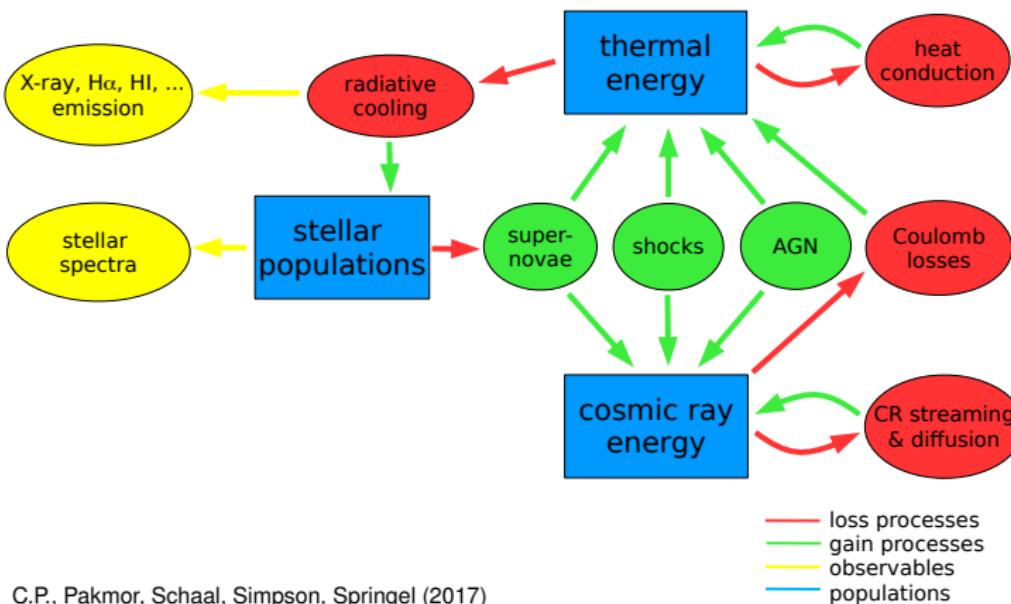
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Simulations with cosmic ray physics

observables:

physical processes:

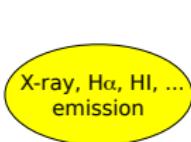


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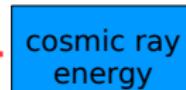
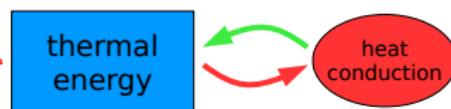


Simulations with cosmic ray physics

observables:



physical processes:



radiative cooling

thermal energy

stellar populations

supernovae

shocks

AGN

heat conduction

Coulomb losses

hadronic losses

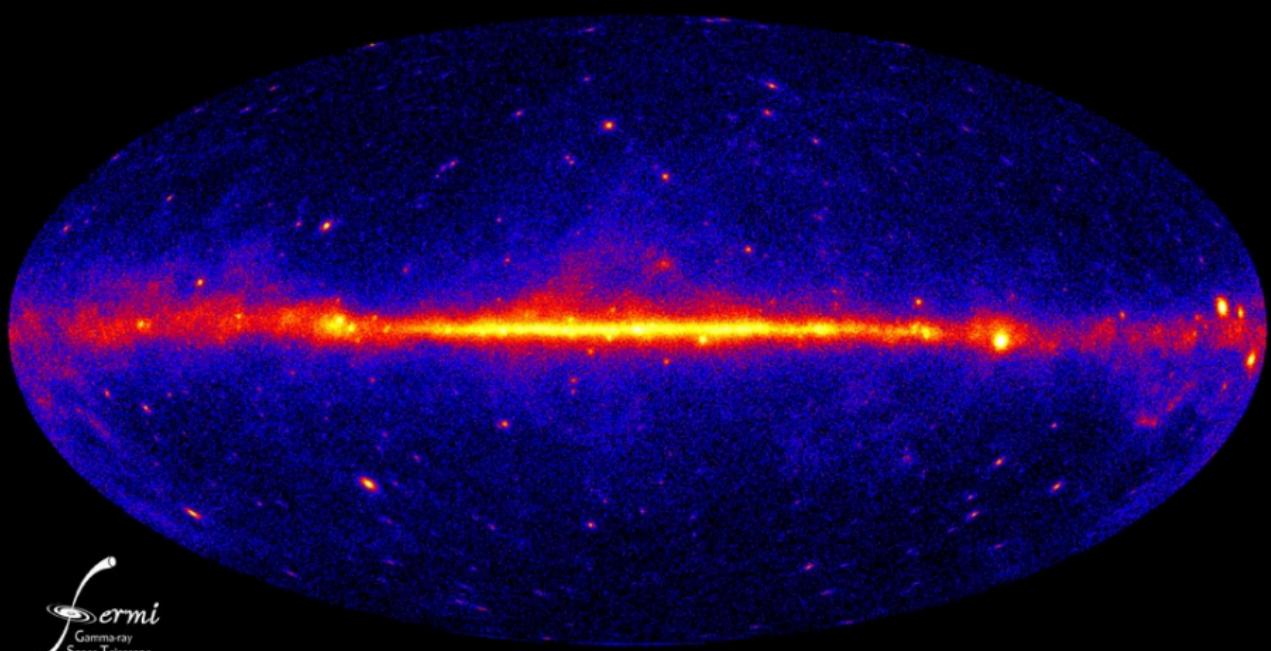
CR streaming & diffusion

- loss processes
- gain processes
- observables
- populations

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

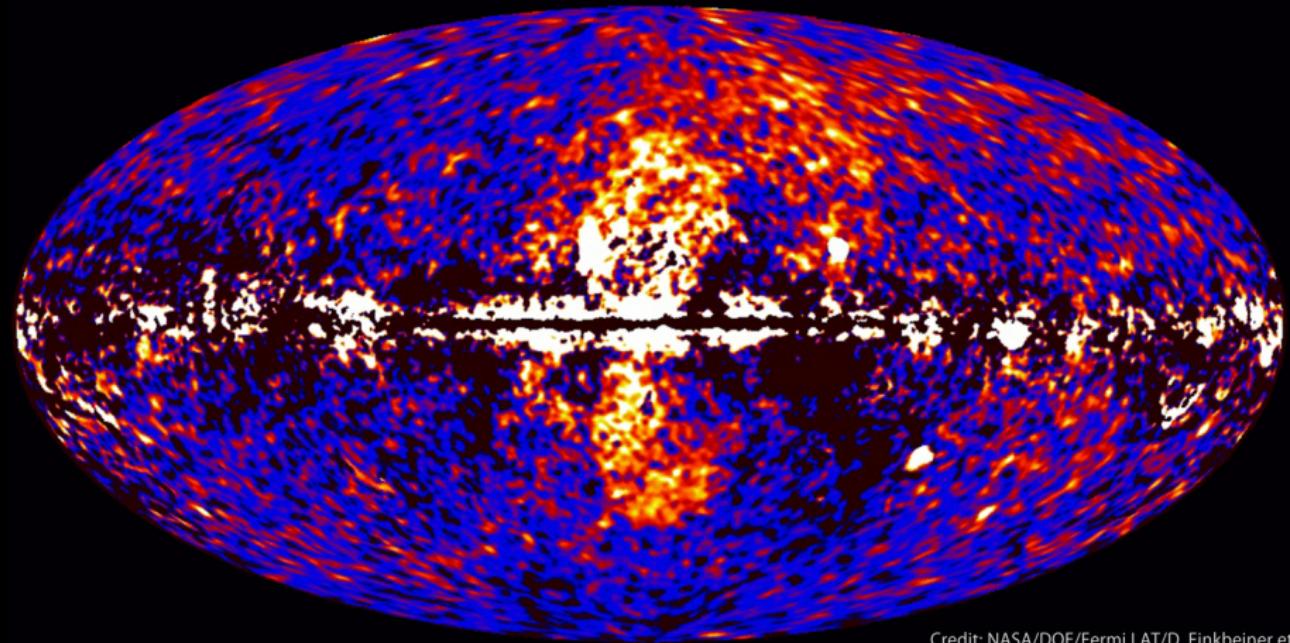


Gamma-ray emission of the Milky Way



Galactic wind in the Milky Way?

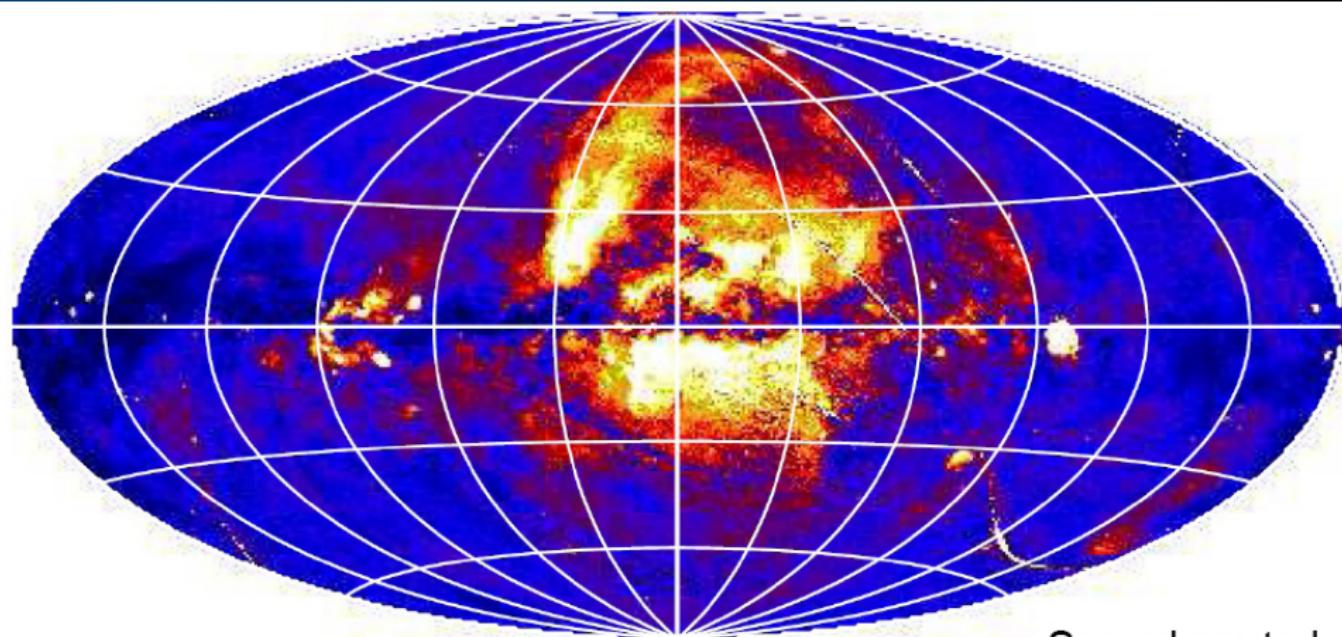
Fermi gamma-ray bubbles



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



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How are galactic winds driven?



NASA/JPL-Caltech/STScI/CXC/UofA

super wind in M82

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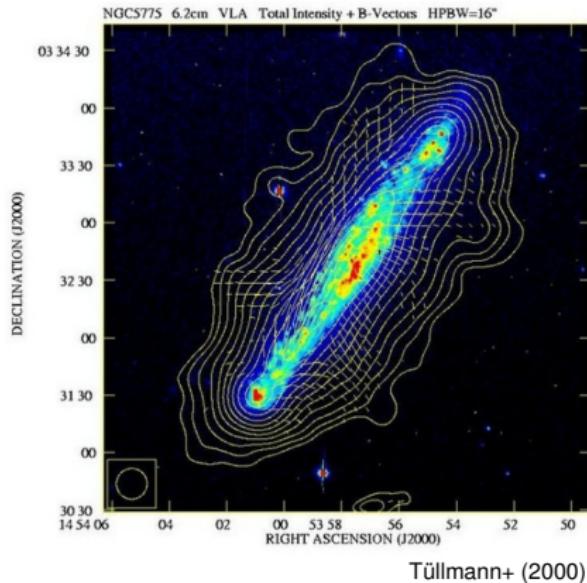
observed energy equipartition between cosmic rays, thermal gas and magnetic fields

→ 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

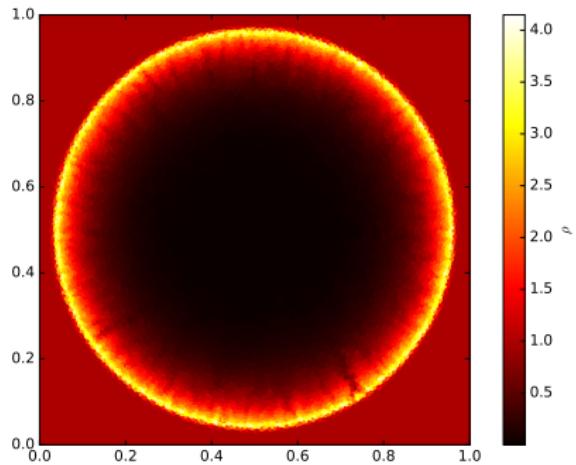


- CR pressure drops less quickly than thermal pressure ($P \propto \rho^\gamma$)
- CRs cool less efficiently than thermal gas
- CR pressure energizes the wind → “CR battery”
- poloidal (“open”) field lines at wind launching site
→ CR-driven Parker instability

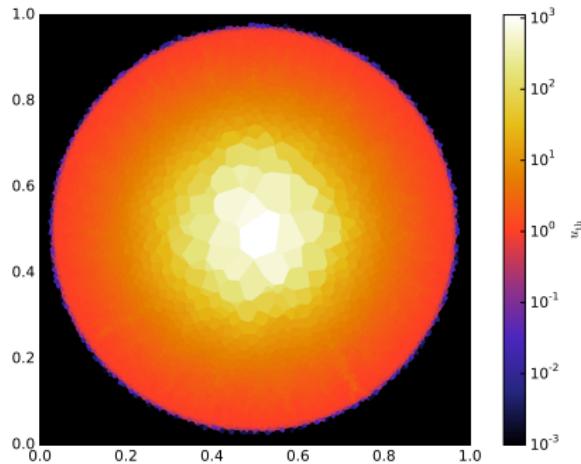


Sedov explosion

density



specific thermal energy



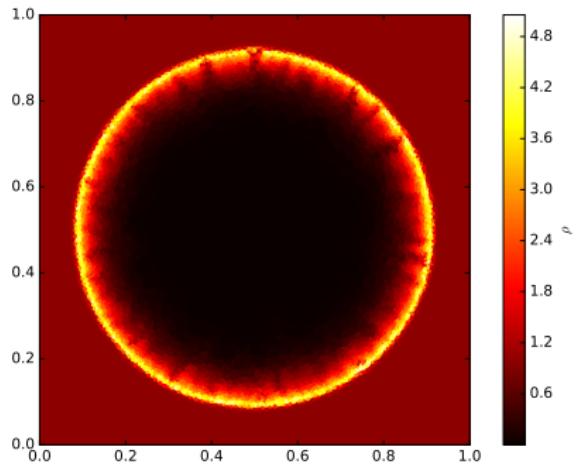
C.P., Pakmor, Schaal, Simpson, Springel (2017)



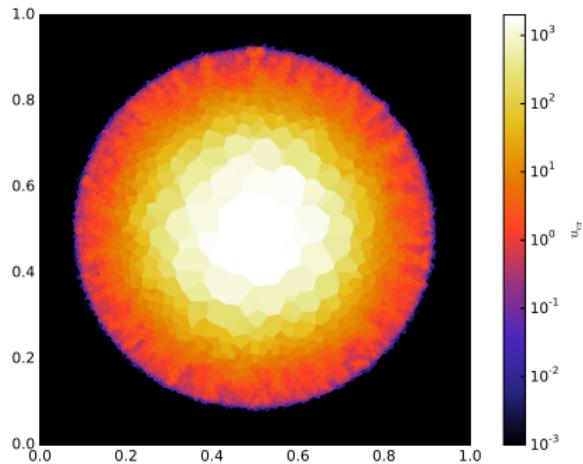
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Sedov explosion with CR acceleration

density



specific cosmic ray energy



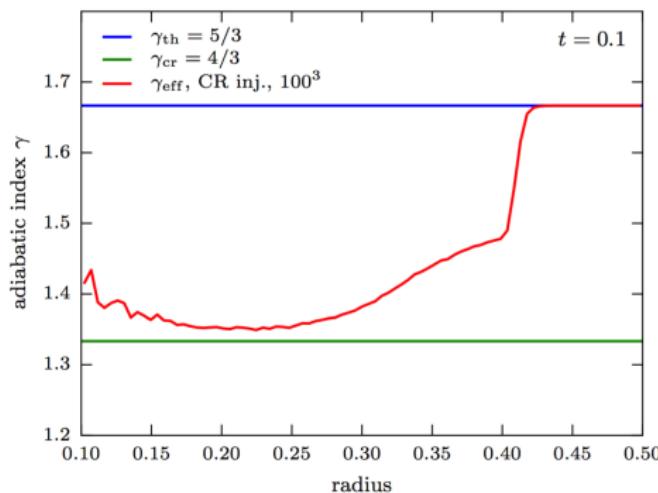
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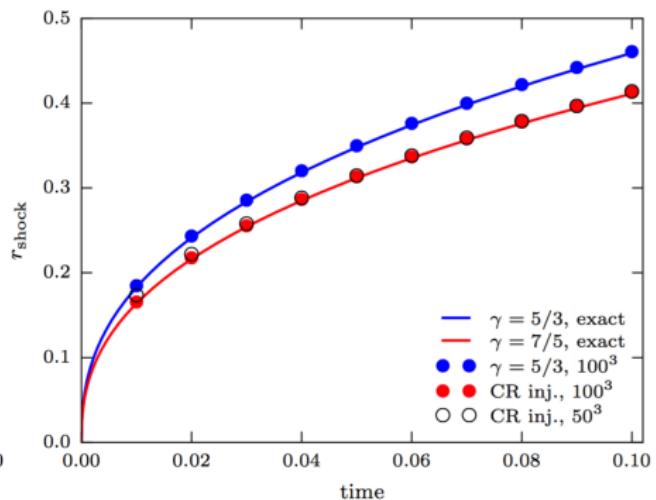
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Sedov explosion with CR acceleration

adiabatic index



shock evolution

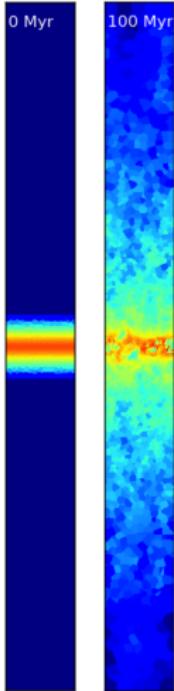


C.P., Pakmor, Schaal, Simpson, Springel (2017)



A model for the multi-phase interstellar medium

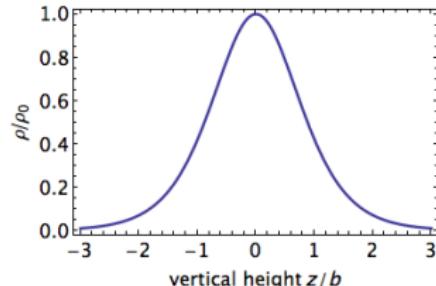
Explore supernovae-driven outflows at high resolution – stratified box simulations



Simpson+ (2016)

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

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



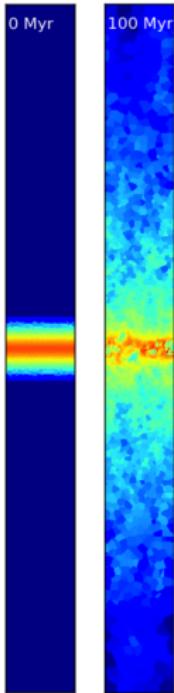
- self-gravity
- atomic & molecular cooling network, self-shielding (Glover & Clark 2012, Smith+ 2014)
- MHD with small magnetic seed field (Pakmor+ 2011)
- cosmic ray physics (C.P.+ 2017, Pakmor+ 2016)



AIP

Supernova feedback

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



- star formation rate:

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

- supernova rate:

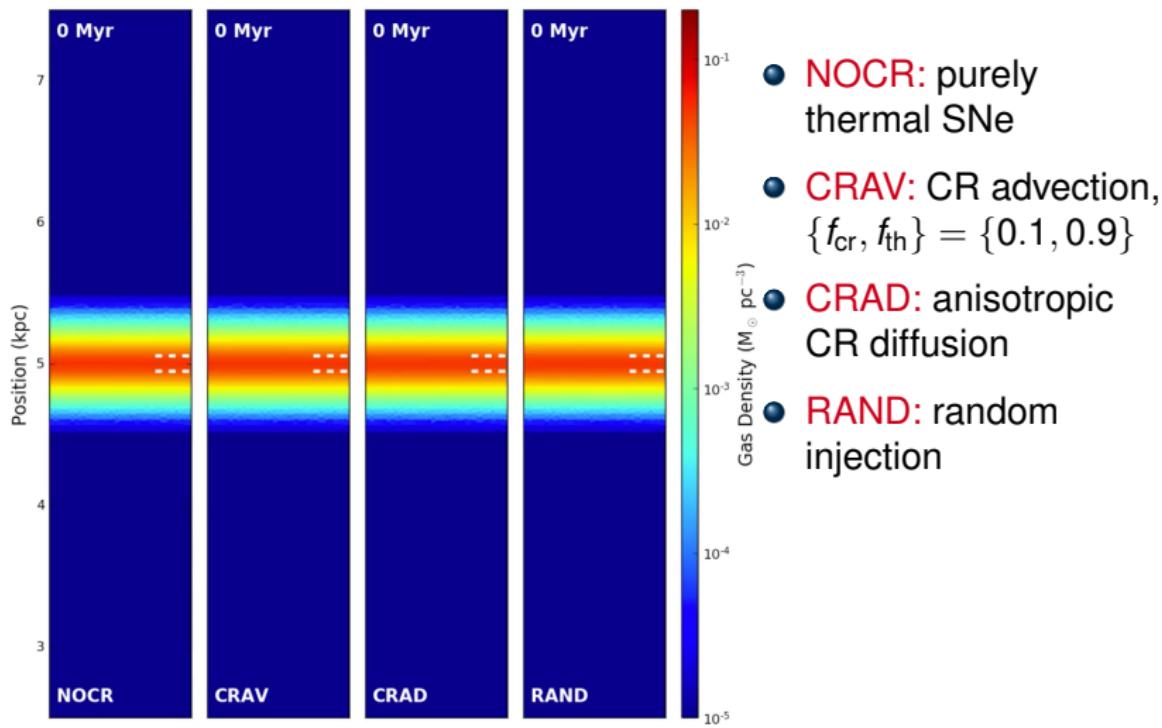
$$\dot{M}_{\text{SN},i} = \dot{M}_{*,i} \frac{1.8 \text{ events}}{100 M_{\odot}}$$



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

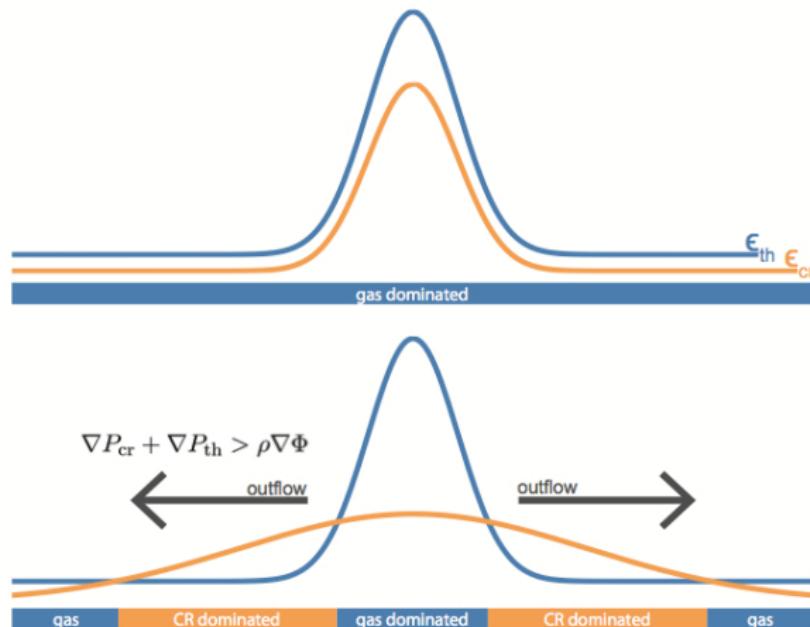
Simpson+ (2016)

Interstellar medium – turbulence and outflows



Simpson+ (2016)

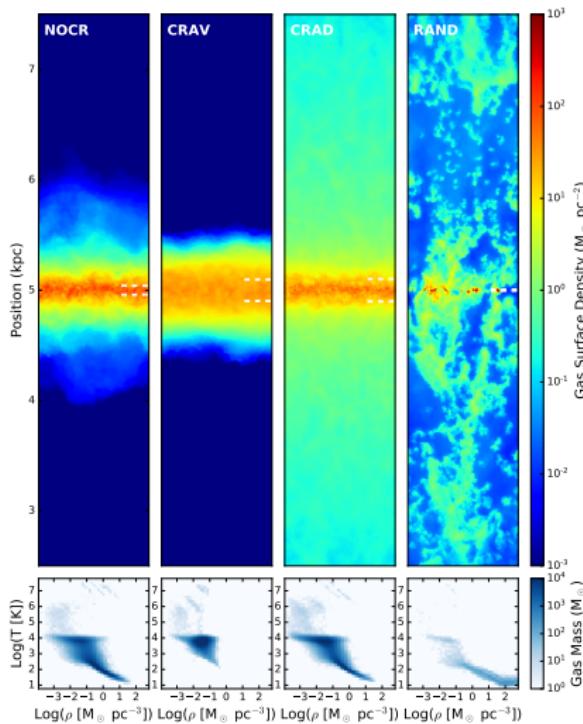
Cosmic ray driven wind: mechanism



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

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

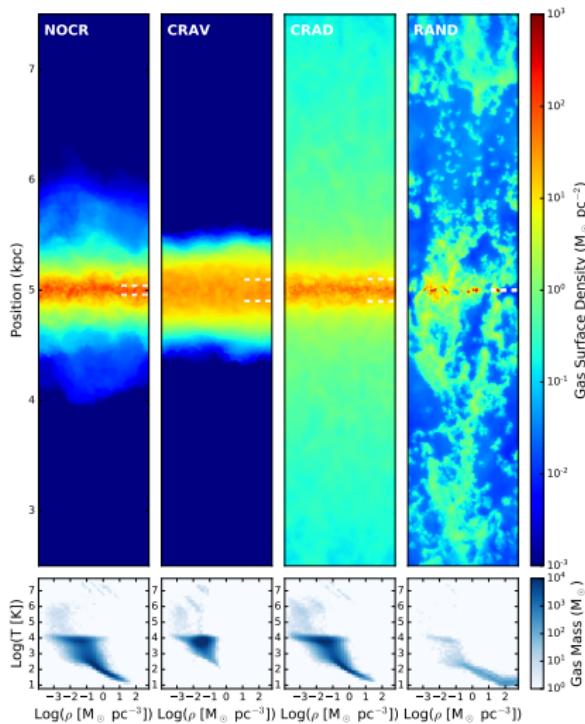
Interstellar medium – turbulence and outflows



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

Simpson+ (2016)

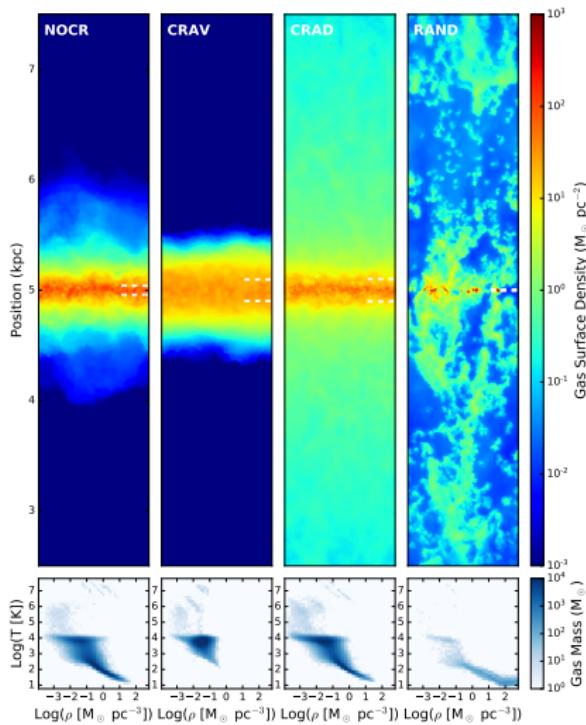
Interstellar medium – turbulence and outflows



- 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)
→ velocity and clumpiness differ

Simpson+ (2016)

Interstellar medium – turbulence and outflows



- 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)
→ velocity and clumpiness differ
 - CR + turbulent pressure self-regulate ISM → scale height $h_{1/2} \approx 100$ pc; ISM in RAND collapses to dense phase
- ⇒ CR physics is essential for correctly modeling the ISM!

Simpson+ (2016)

Outline

1 Introduction

- Puzzles in galaxy formation
- Particle acceleration
- Cosmic rays

2 Physical processes

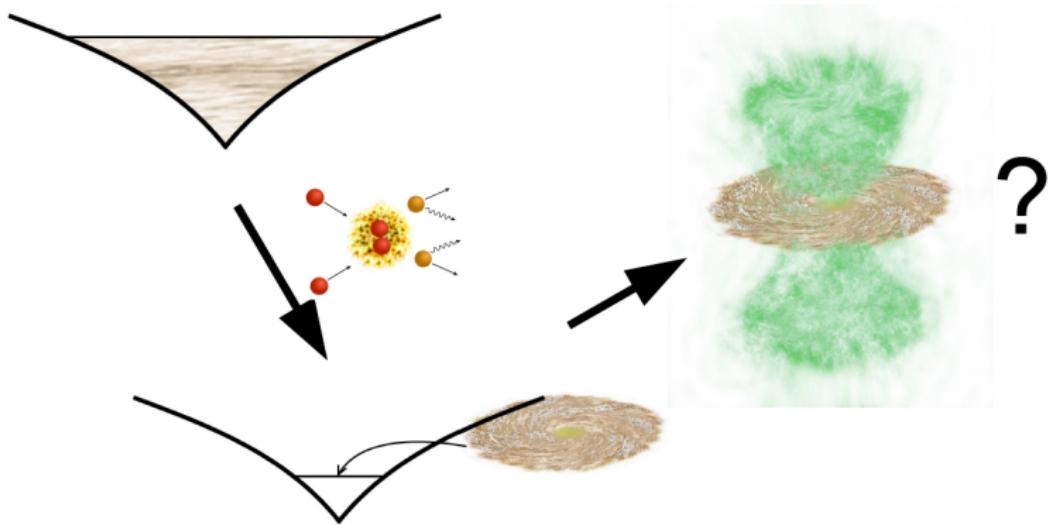
- Modelling physics in galaxies
- Supernova explosions
- Interstellar medium

3 Simulating galaxies

- Global galaxy models
- Gamma-ray emission
- Radio emission



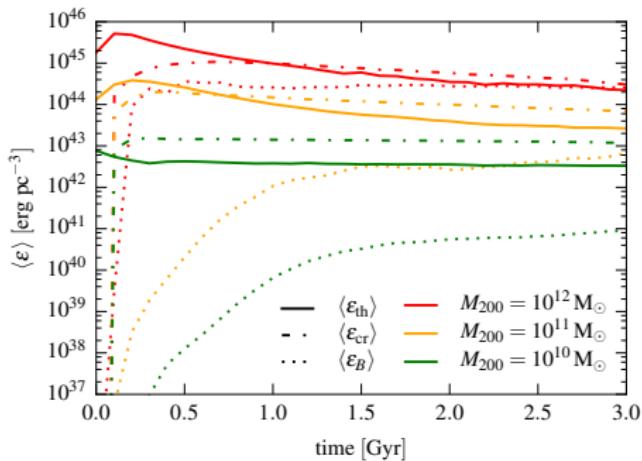
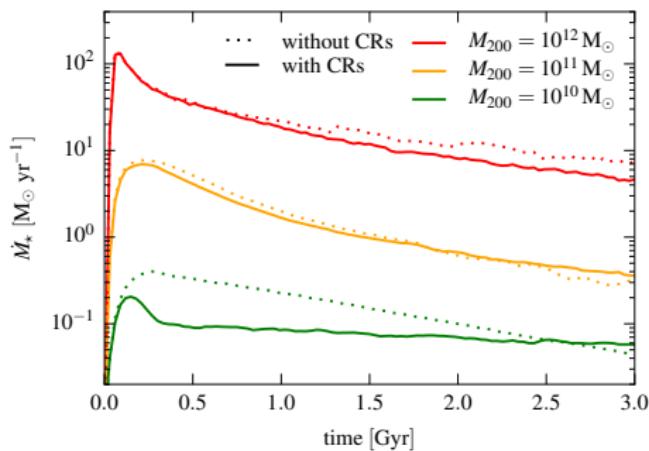
Galaxy simulation setup: 1. cosmic ray advection



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

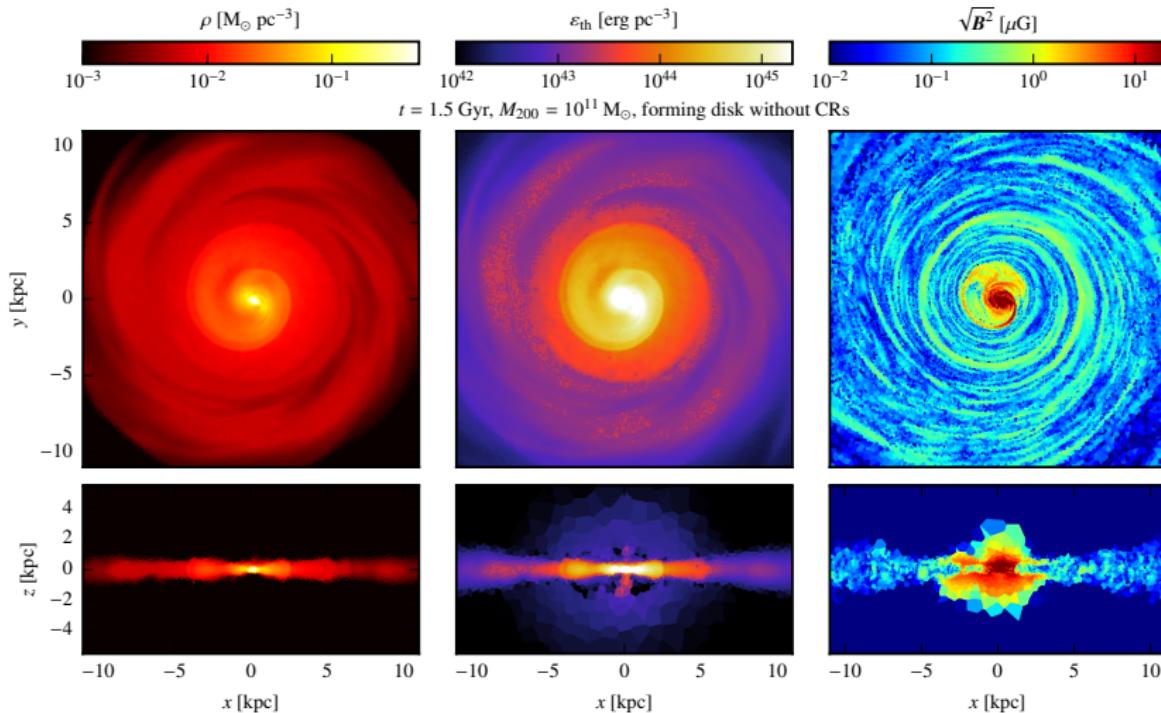


C.P., Pakmor, Schaal, Simpson, Springel (2017)

- 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

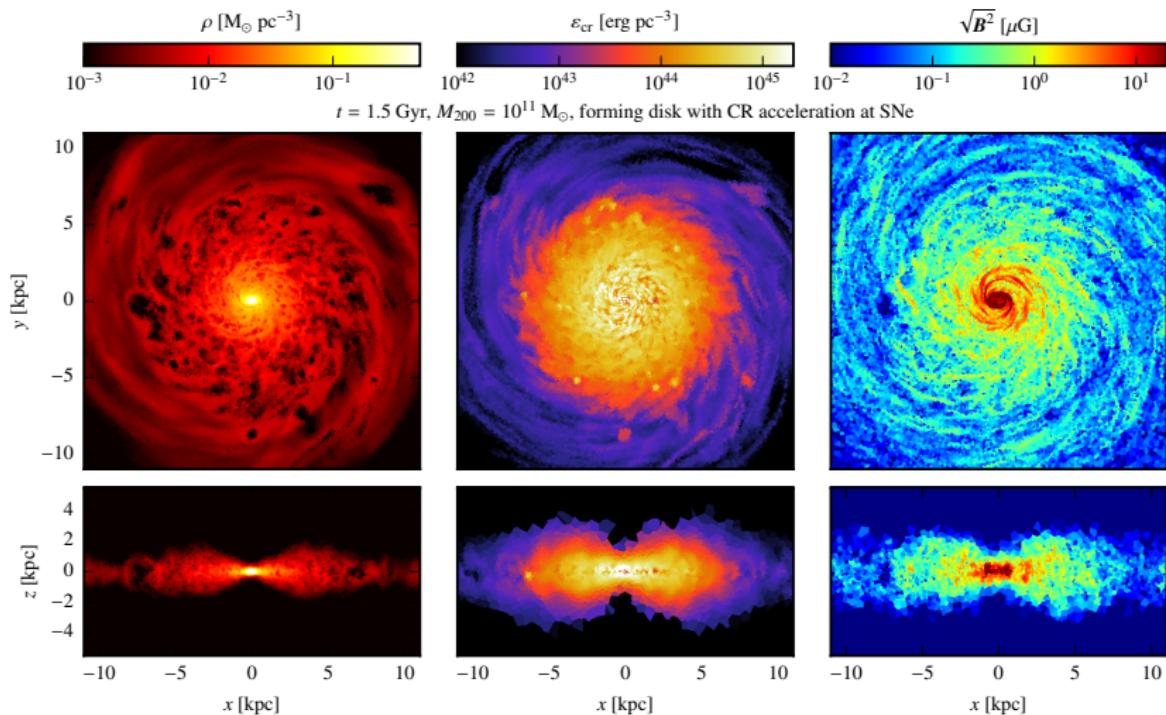


MHD galaxy simulation without CRs



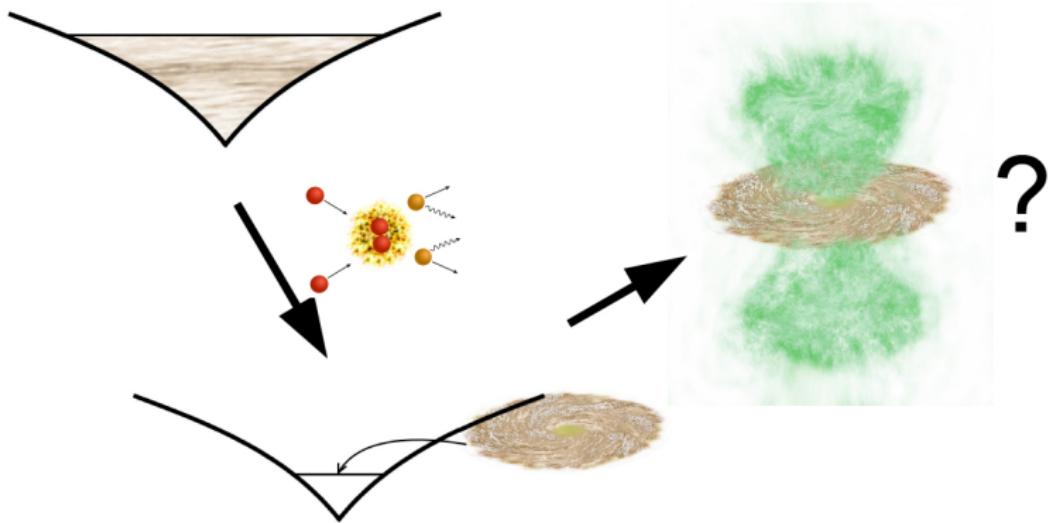
C.P., Pakmor, Schaal, Simpson, Springel (2017)

MHD galaxy simulation with CRs



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

Galaxy simulation setup: 2. cosmic ray diffusion

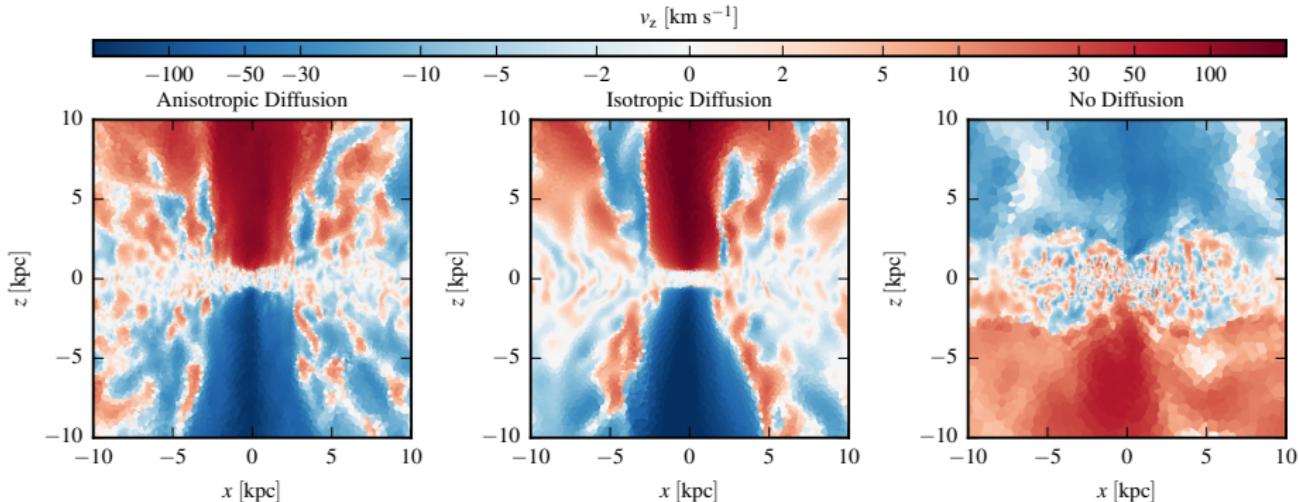


Pakmor, C.P., Simpson, Springel (2016)

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

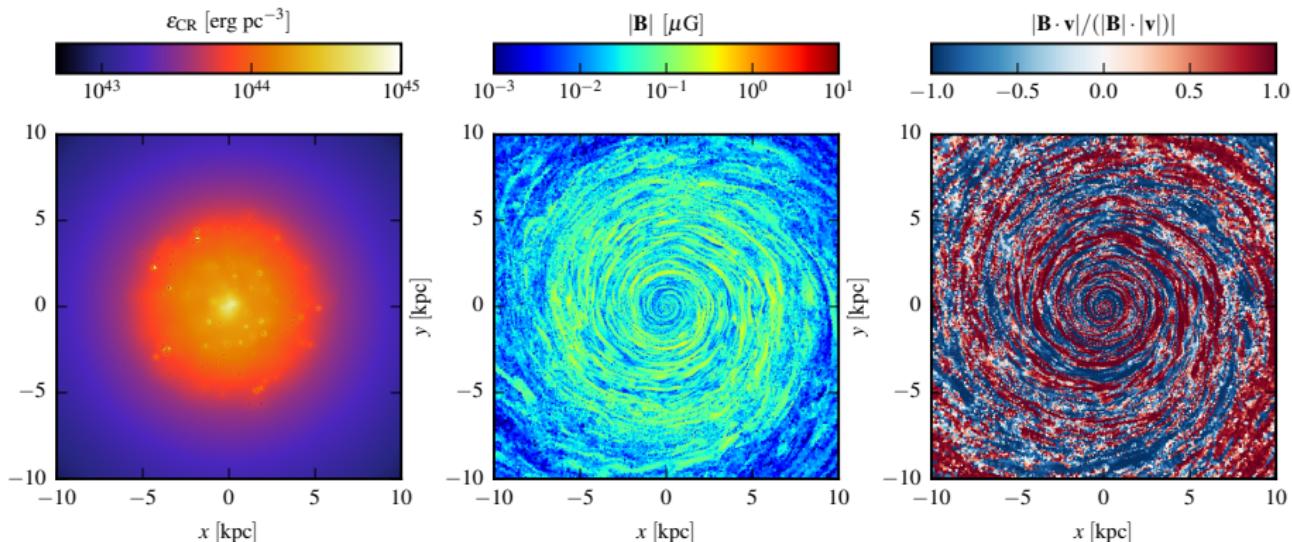


Pakmor, C.P., Simpson, Springel (2016)

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



MHD galaxy simulation with CR isotropic diffusion

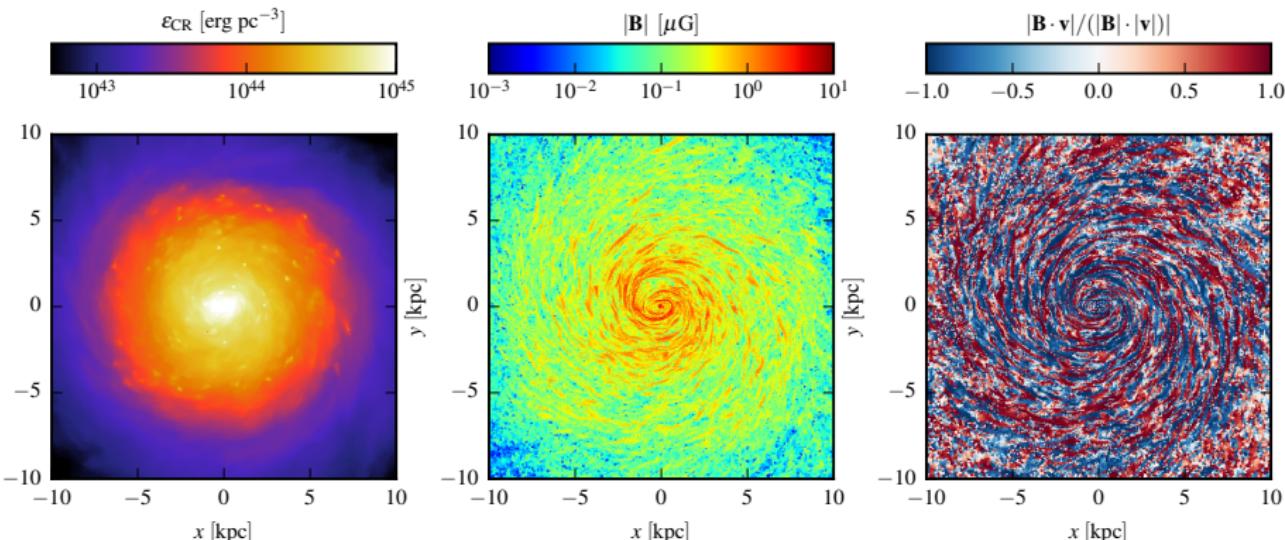


Pakmor, C.P., Simpson, Springel (2016)

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



MHD galaxy simulation with CR anisotropic diffusion

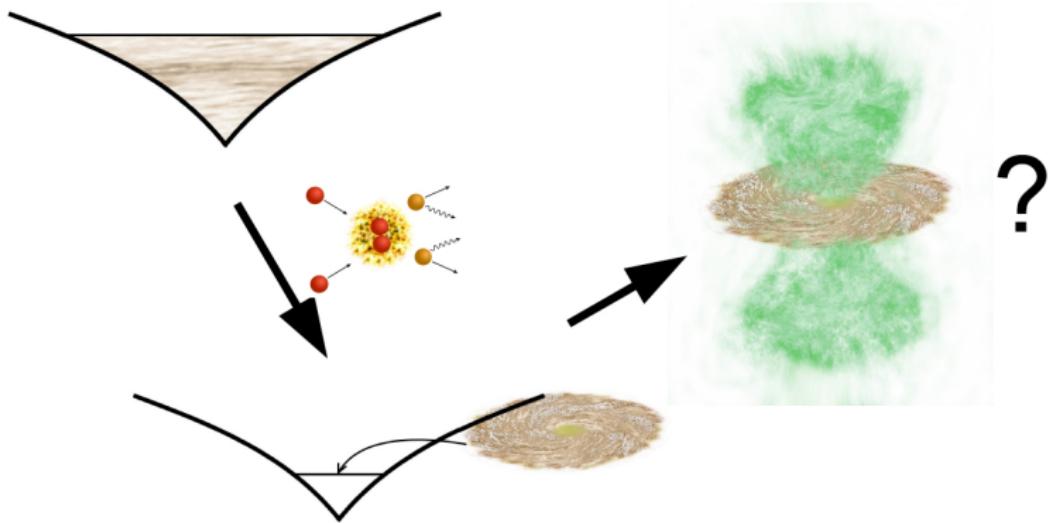


Pakmor, C.P., Simpson, Springel (2016)

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



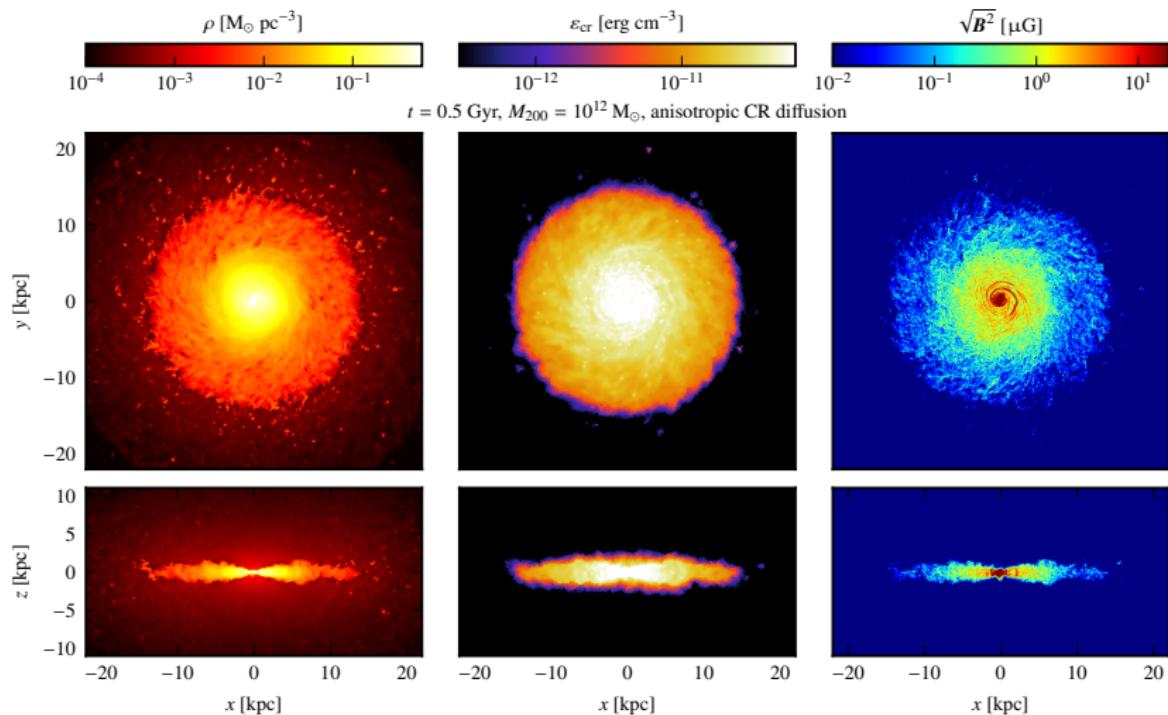
Galaxy simulation setup: 3. non-thermal emission



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

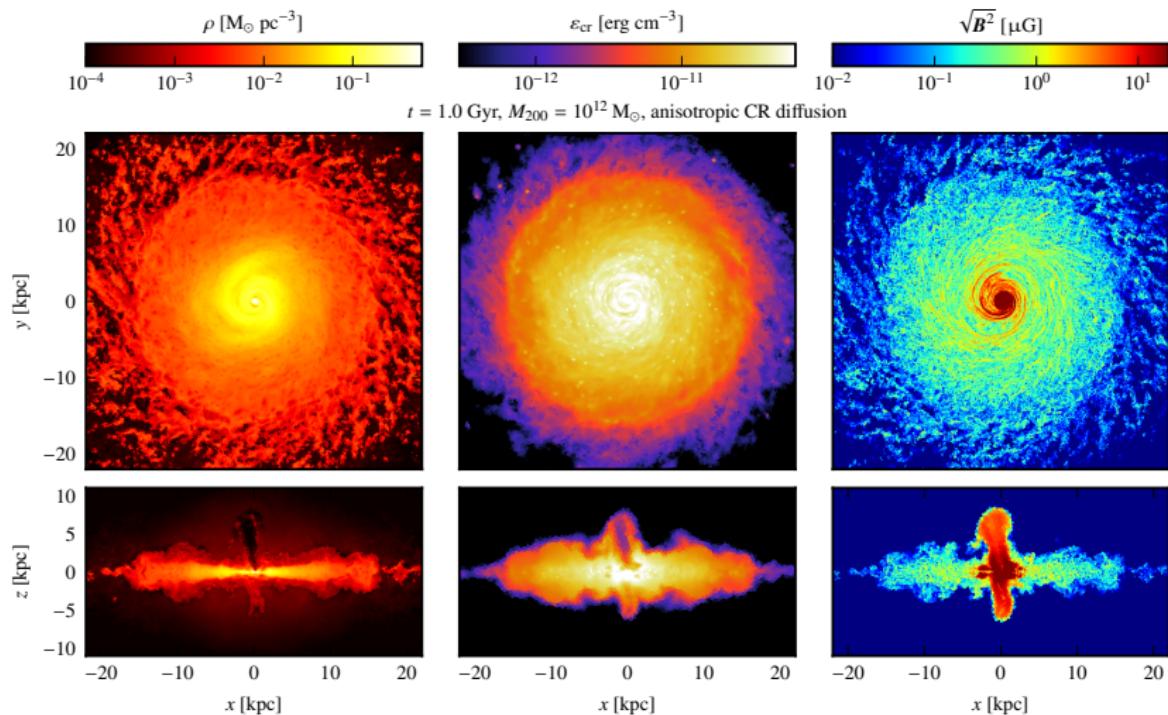
MHD + CR advection + diffusion: $\{10^{10}, 10^{11}, 10^{12}\} M_{\odot}$

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



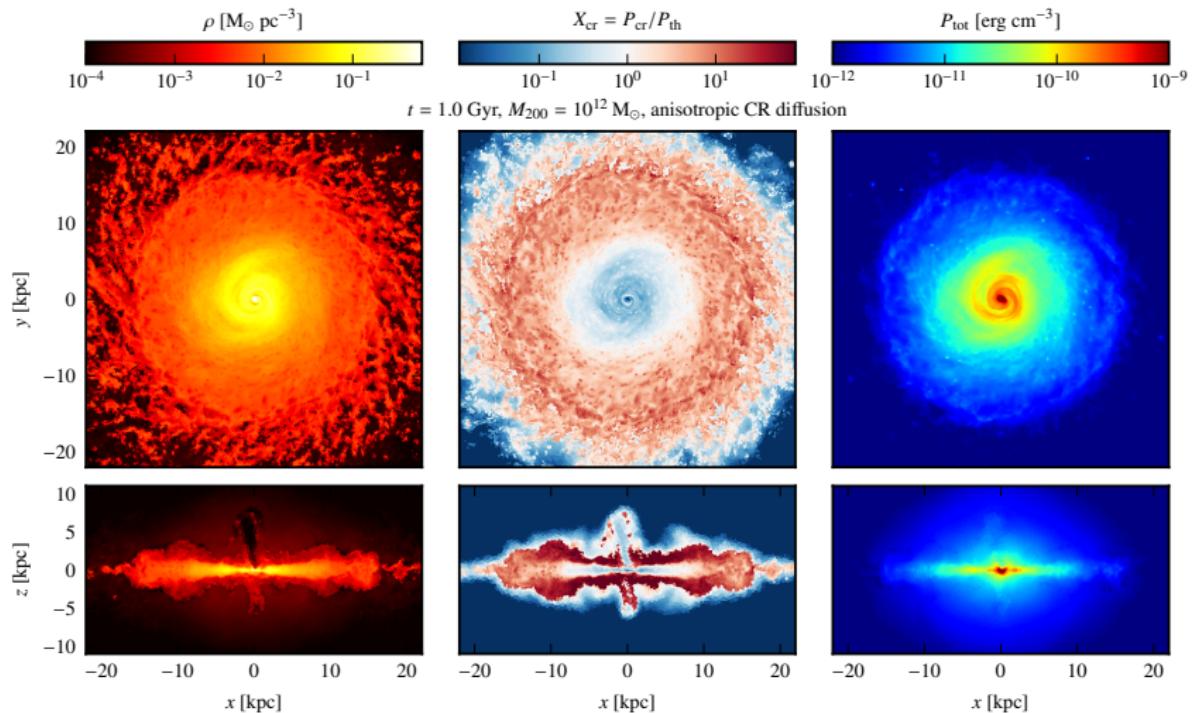
C.P.+ (2017a,b)

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



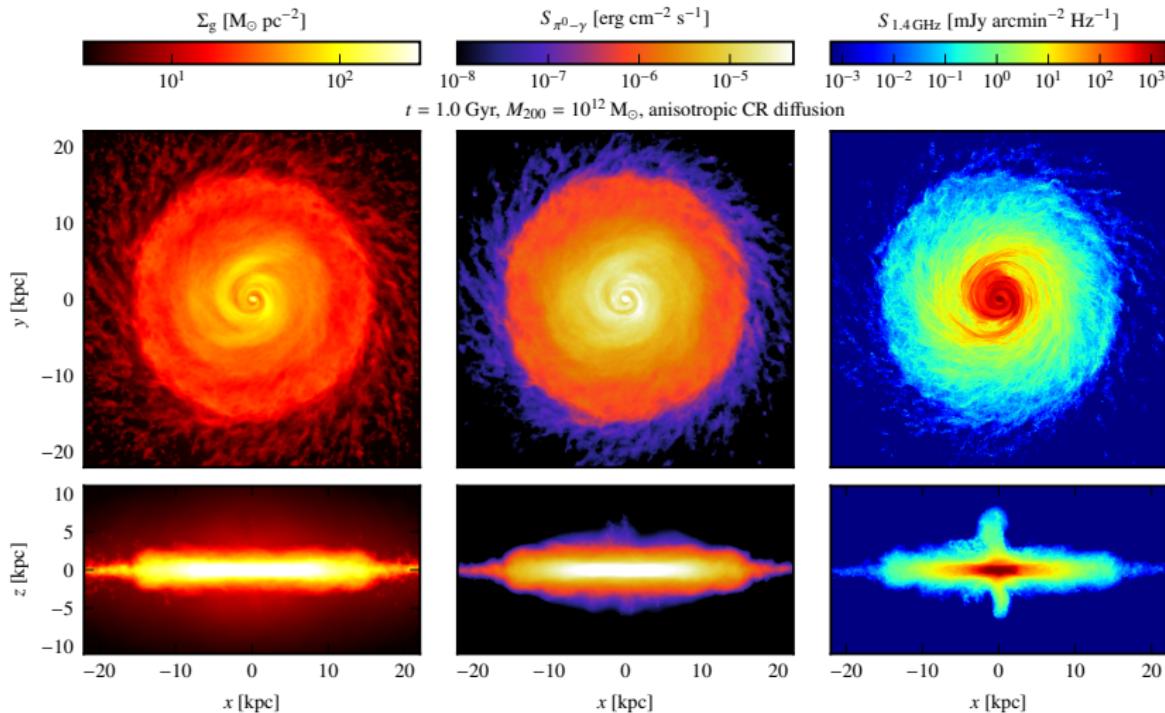
C.P.+ (2017a,b)

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



C.P.+ (2017a,b)

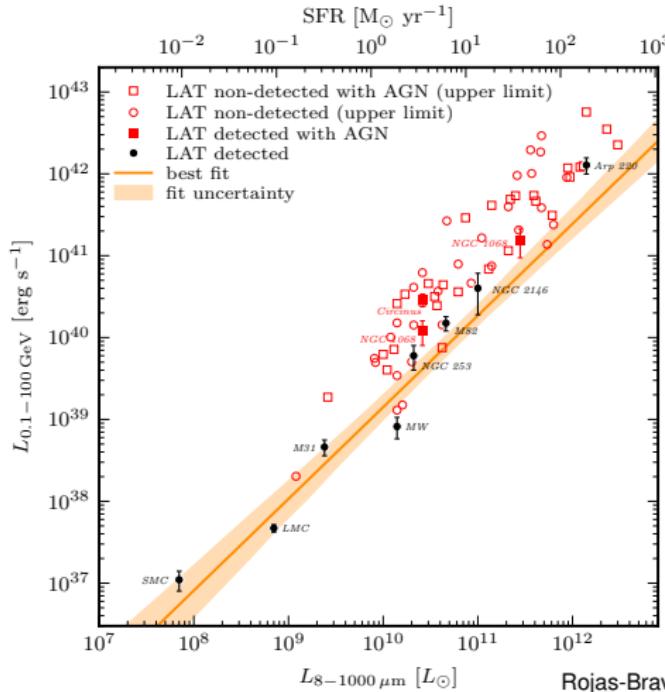
γ -ray and radio emission of Milky Way-like galaxy



C.P.+ (2017a,b)

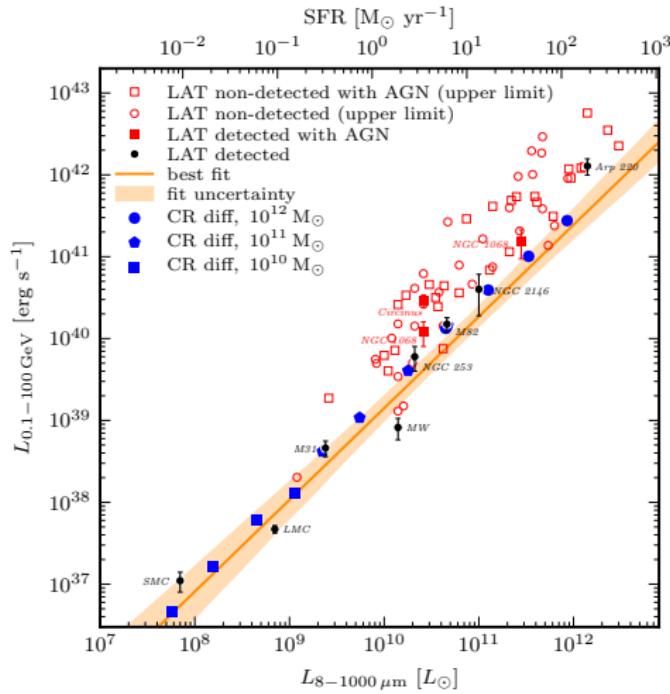
Far infra-red – gamma-ray correlation

Universal conversion: star formation → cosmic rays → gamma rays



Far infra-red – gamma-ray correlation

Universal conversion: star formation → cosmic rays → gamma rays

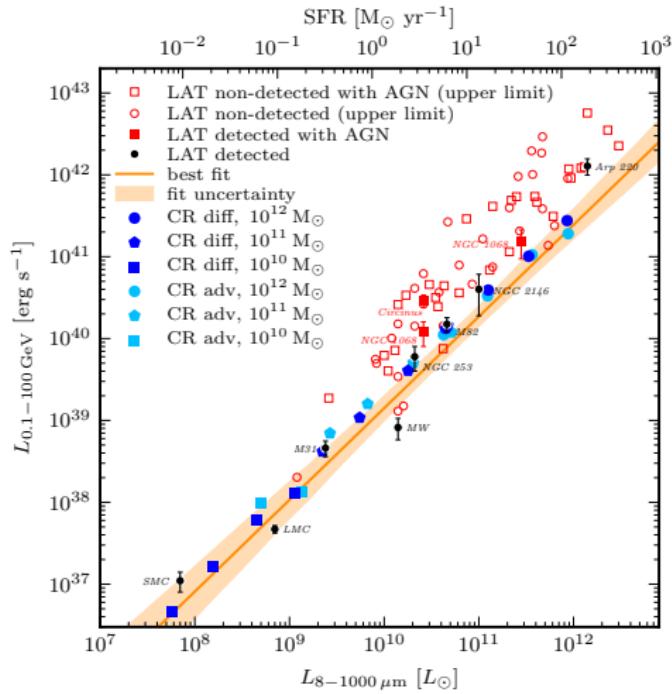


C.P.+ (2017a)



Far infra-red – gamma-ray correlation

Universal conversion: star formation → cosmic rays → gamma rays

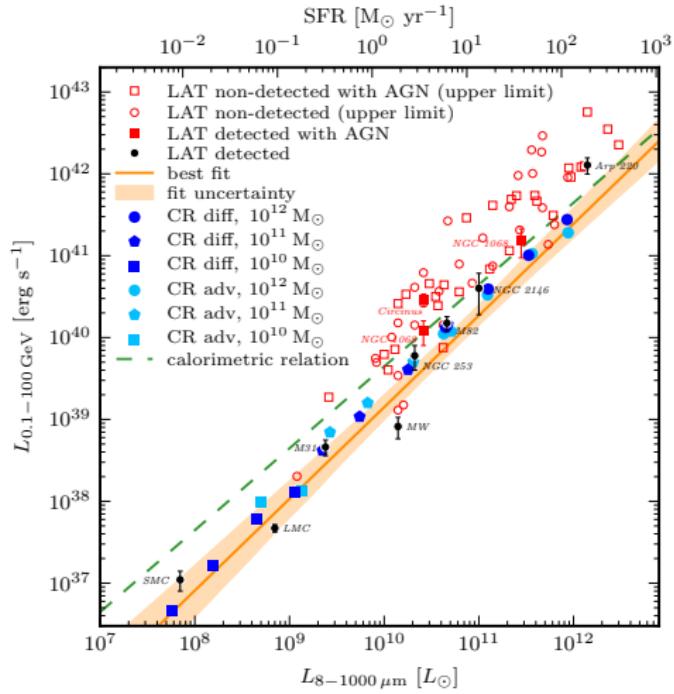


C.P.+ (2017a)

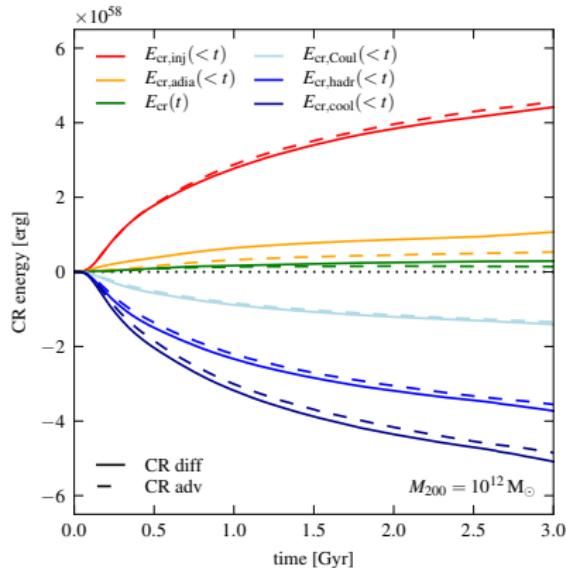


Far infra-red – gamma-ray correlation

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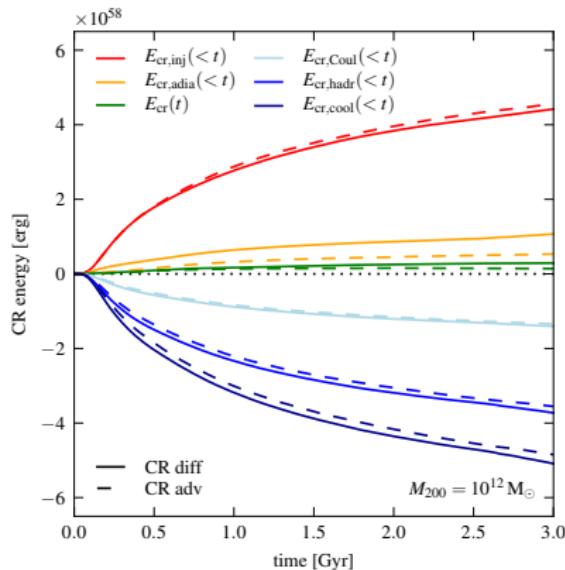
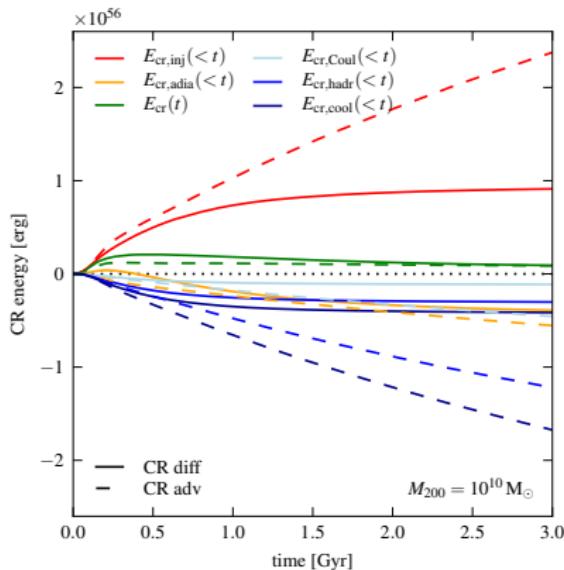
Time evolution of CR energies



C.P.+ (2017a)

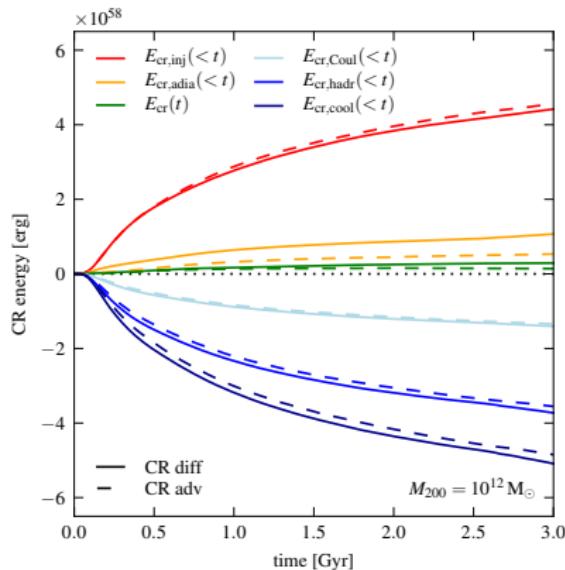
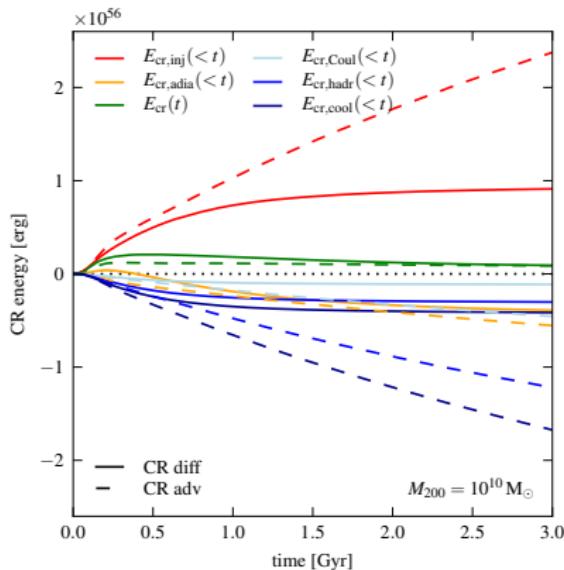


Time evolution of CR energies



C.P.+ (2017a)

Time evolution of CR energies

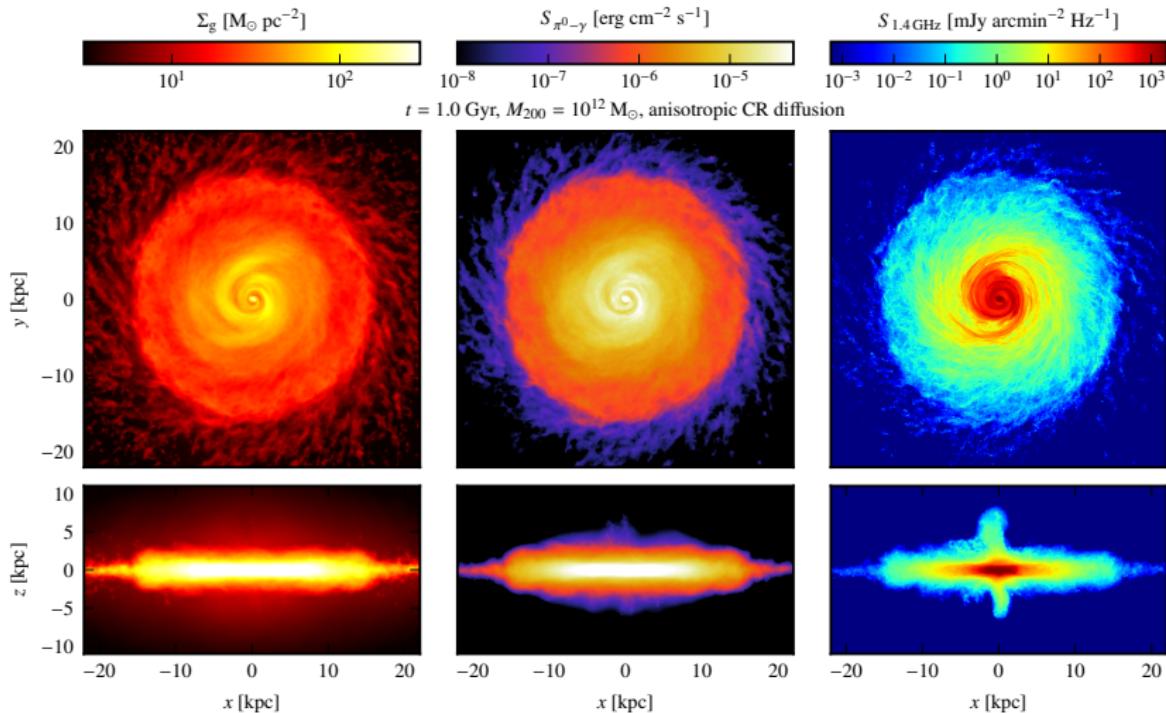


C.P.+ (2017a)

- adiabatic CR losses are significant in small galaxies
 \Rightarrow deviation from calorimetric relation at small SFRs



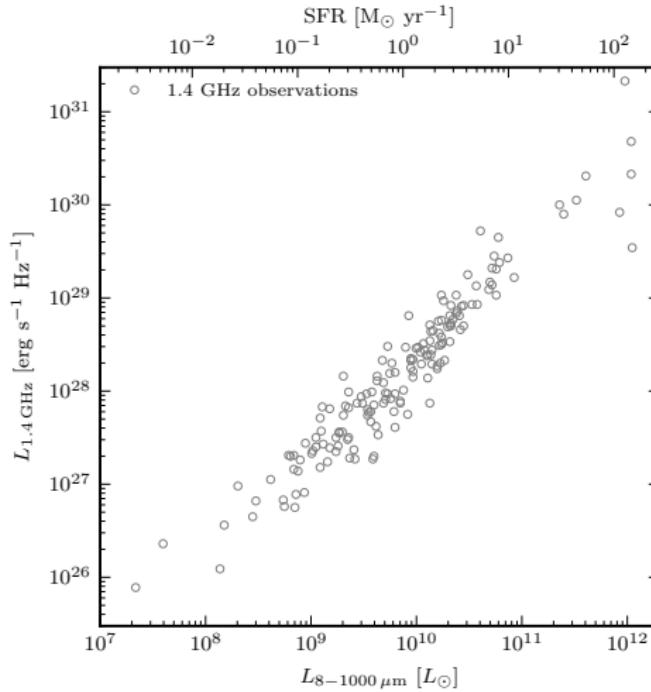
γ -ray and radio emission of Milky Way-like galaxy



C.P.+ (2017a,b)

Far infra-red – radio correlation

Universal conversion: star formation → cosmic rays → radio

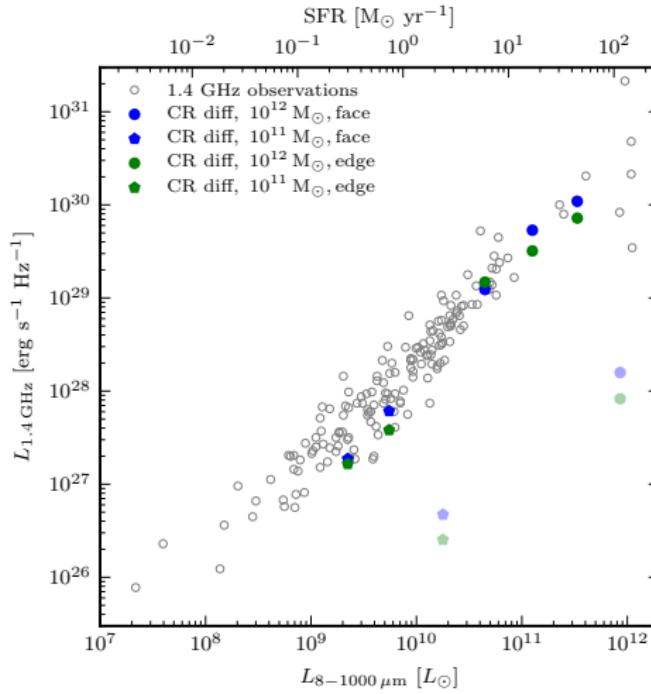


Bell (2003)



Far infra-red – radio correlation

Universal conversion: star formation → cosmic rays → radio

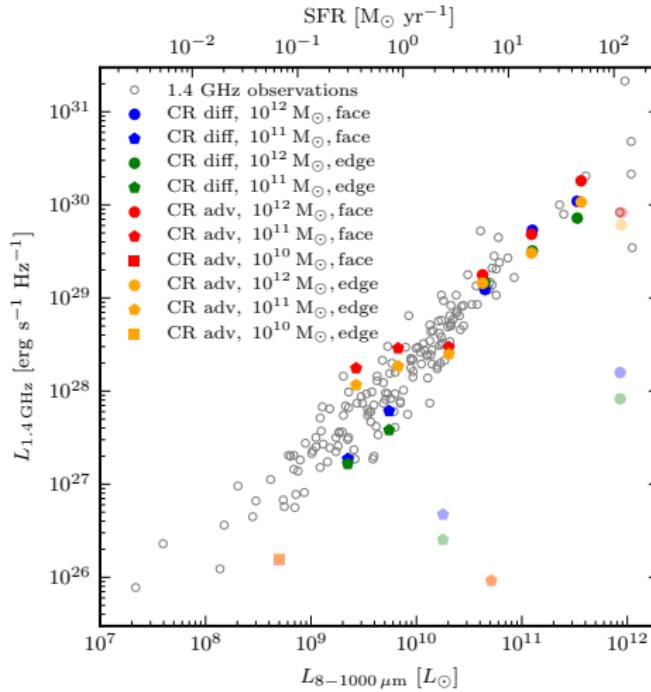


C.P.+ (2017b)



Far infra-red – radio correlation

Universal conversion: star formation → cosmic rays → radio

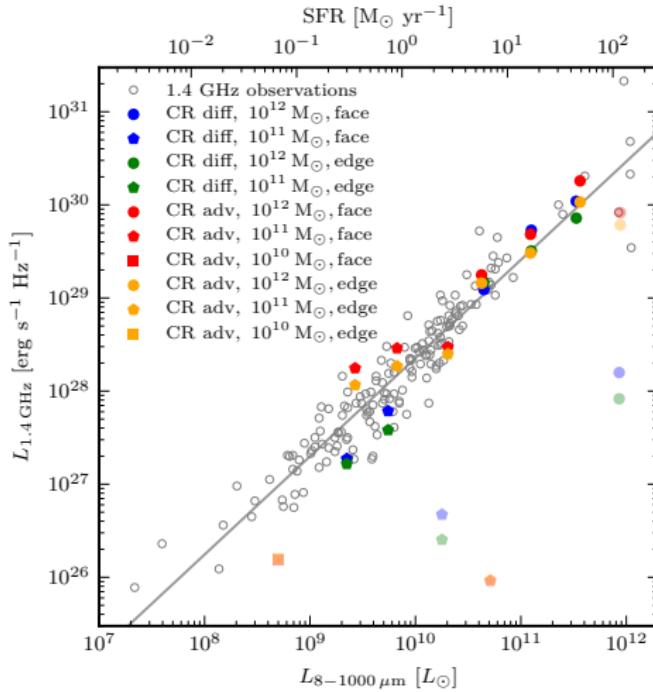


C.P.+ (2017b)



Far infra-red – radio correlation

Universal conversion: star formation → cosmic rays → radio



C.P.+ (2017b)



Conclusions on cosmic-ray feedback in galaxies

- CR pressure feedback slows down star formation
- galactic winds are naturally explained by CR diffusion
- anisotropic CR diffusion necessary for efficient galactic dynamo:
observed field strengths of $B \sim 10 \mu\text{G}$



Conclusions on cosmic-ray feedback in galaxies

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- $L_{\text{FIR}} - L_{\gamma}$ and $L_{\text{FIR}} - L_{\text{radio}}$ 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 → **SKA/CTA**



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



European Research Council
financed by the European Commission

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Literature for the talk

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

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

Cosmic ray feedback in galaxies:

- Pfrommer, Pakmor, Schaal, Simpson, Springel, *Simulating cosmic ray physics on a moving mesh*, 2017, MNRAS.
- Pakmor, Pfrommer, Simpson, Springel, *Galactic winds driven by isotropic and anisotropic cosmic ray diffusion in isolated disk galaxies*, 2016, ApJL.
- Pakmor, Pfrommer, Simpson, Kannan, Springel, *Semi-implicit anisotropic cosmic ray transport on an unstructured moving mesh*, 2016, MNRAS.

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.

