



# *How cosmic rays shape galaxies*

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in collaboration with

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Astroparticle seminar at DESY/Zeuthen – June 2017

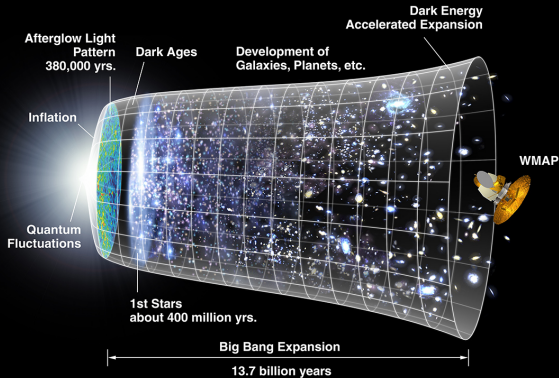
# Outline

- 1 Introduction
  - Cosmology
  - Puzzles in galaxy formation
  - Particle acceleration and cosmic rays
- 2 Physical processes
  - Modelling physics in galaxies
  - Supernova explosions
  - Interstellar medium
- 3 Simulating galaxies
  - Global galaxy models
  - Gamma-ray emission
  - Radio emission

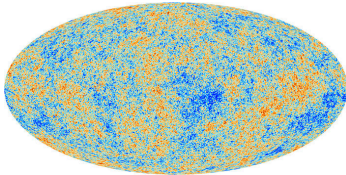
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# Time line of our Universe



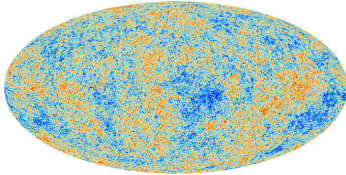
# Cosmological structure formation



ESA/Planck Collaboration (2013)

- small fluctuations in cosmic microwave background are initial conditions for structure formation

# Cosmological structure formation



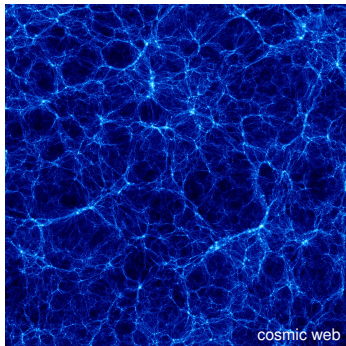
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- **small fluctuations in cosmic microwave background are initial conditions for structure formation**
- **galaxies and clusters form at sites of constructive interference of those primordial waves**



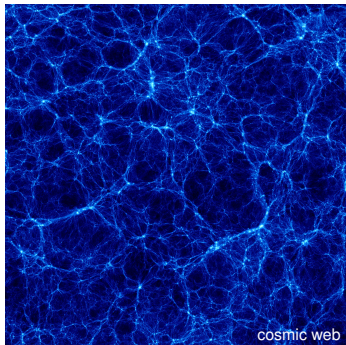
dropping pebbles into the pond generates expanding waves that interfere with each other

# Cosmological structure formation



- small fluctuations in cosmic microwave background are initial conditions for structure formation
- galaxies and clusters form at sites of constructive interference of those primordial waves
- **cosmic matter assembles in the “cosmic web”** through gravitational instability
- **galaxies form as “beats on a string”** along the cosmic filaments
- **galaxy clusters form at the knots of the cosmic web** by mergers of galaxies and galaxy groups

# Cosmological structure formation



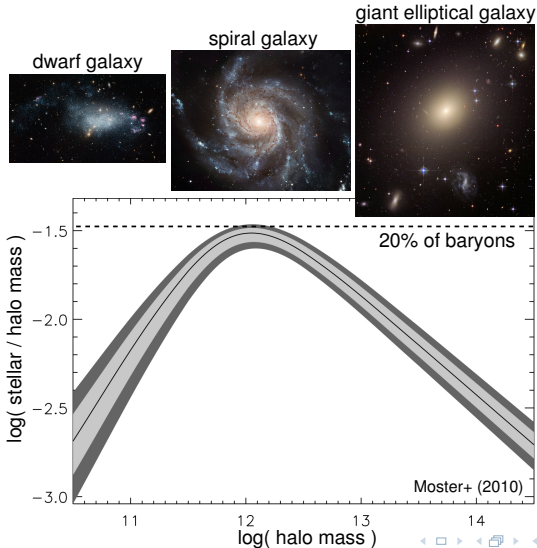
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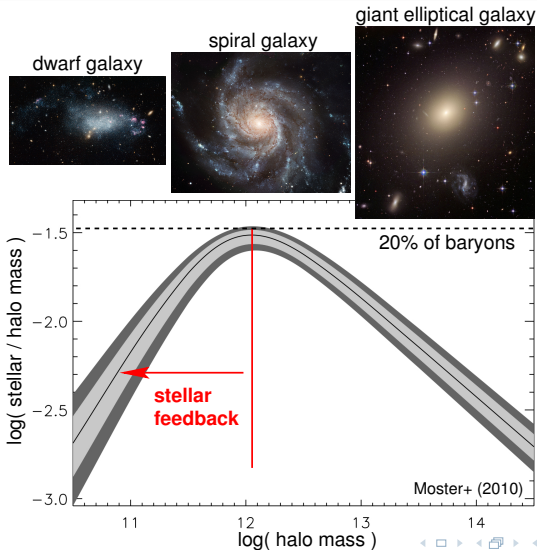
# Puzzles in galaxy formation



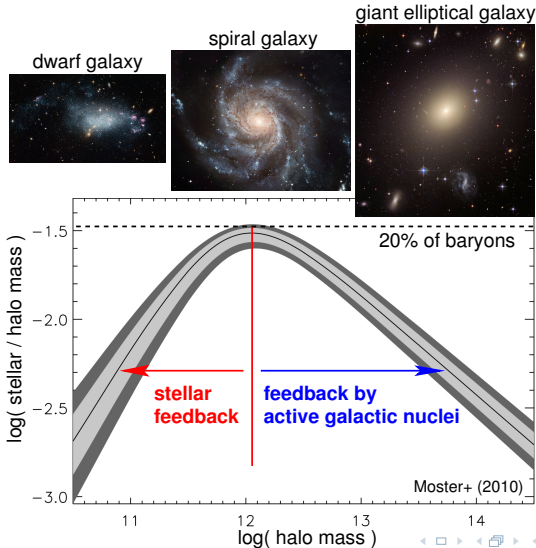
# Puzzles in galaxy formation



# Puzzles in galaxy formation



# Puzzles in galaxy formation



# Feedback

**feedback** n -s often attrib:

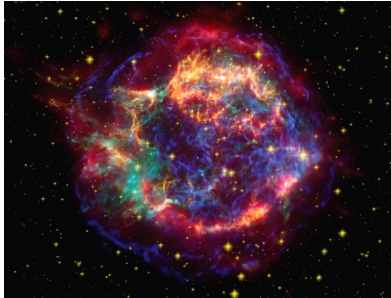
- 1 the return to the input of a part of the output of a machine, system, or process
- 2 the partial reversion of the effects of a given process to its source or to a preceding stage so as to reinforce or modify this process

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

# Feedback by galactic winds



supernova Cassiopeia A

X-ray: NASA/CXC/SAO; Optical: NASA/STScI;  
Infrared: NASA/JPL-Caltech/Steward/O.Krause et al.

- galactic supernova remnants drive shock waves, turbulence, accelerate electrons + protons, amplify magnetic fields

# Feedback by galactic winds



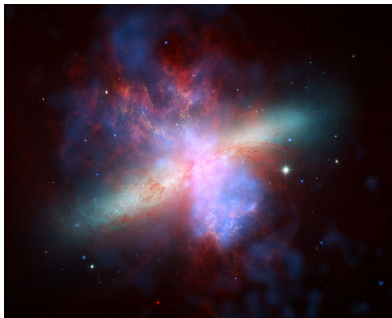
super wind in M82

NASA/JPL-Caltech/STScI/CXC/UofA

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



# Feedback by galactic winds

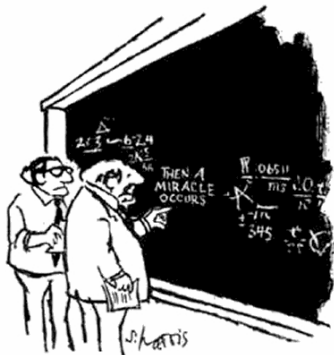


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# Feedback by galactic winds



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

A 1964 NY TIMES CARTOON

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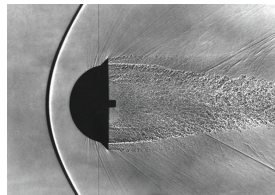
# Shock waves

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

thickness  $\sim$  mean free path  $\lambda_{\text{mfp}}$

in air,  $\lambda_{\text{mfp}} \sim \mu\text{m}$ ,

on Earth, most shocks are mediated by collisions.



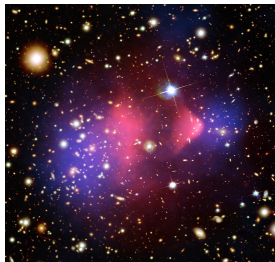
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**clusters/galaxies,** Coulomb collisions set  $\lambda_{\text{mfp}}$ :

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

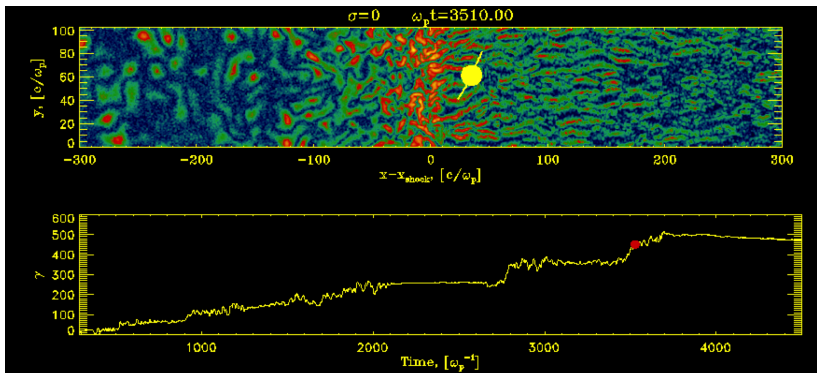
Mean free path  $\gg$  observed shock width!

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

→ **collisionless shocks**

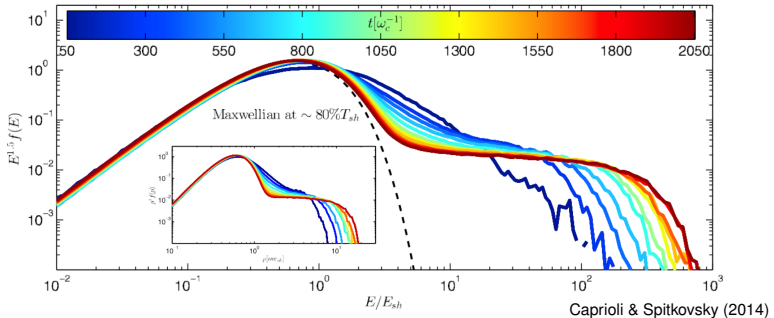
# Particle acceleration at relativistic shock, $B_0 = 0$

- 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)



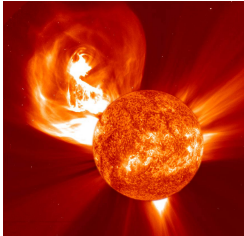
# Ion spectrum

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**

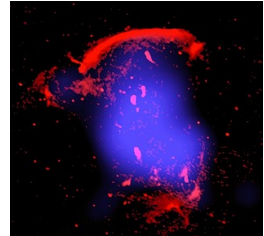
# Astrophysical shocks



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



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

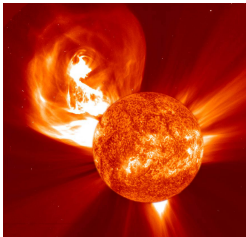


cluster shocks  $\sim 2$  Mpc  
giant radio relic (van Weeren)

# Astrophysical shocks

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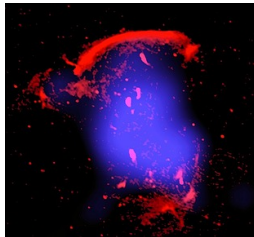
- **accelerate particles** (electrons and ions) → cosmic rays (CRs)
- **amplify magnetic fields** (or generate them from scratch)
- **exchange energy** between electrons and ions



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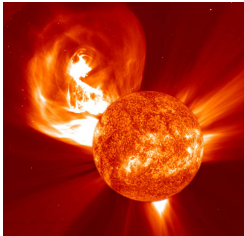


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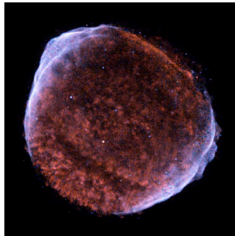
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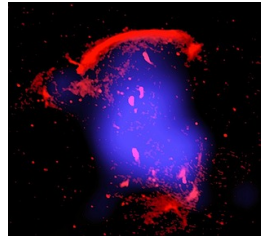
collisionless shocks  $\iff$  energetic particles  $\iff$  electro-magnetic waves



solar system shocks  $\sim R_{\odot}$   
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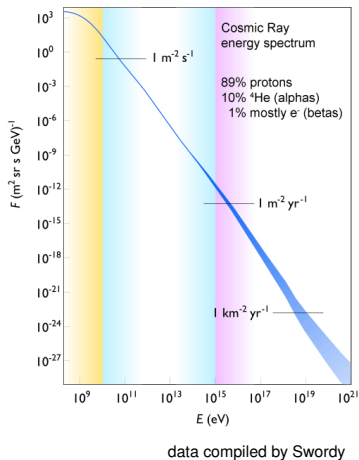


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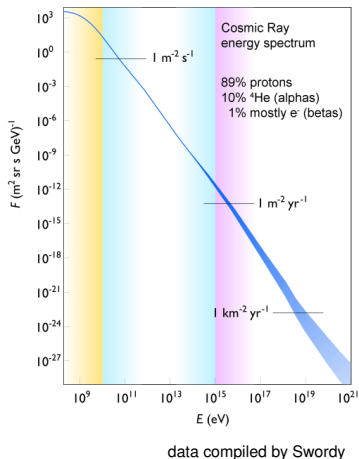
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# Galactic cosmic ray spectrum



- 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

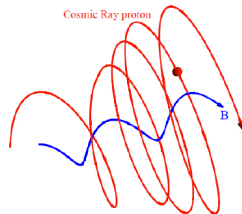
# Galactic cosmic ray spectrum



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

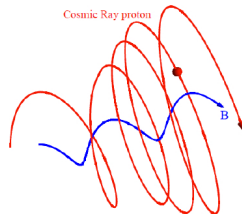
# Interactions of CRs and magnetic fields

- 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  $\mathbf{B}$ ):

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

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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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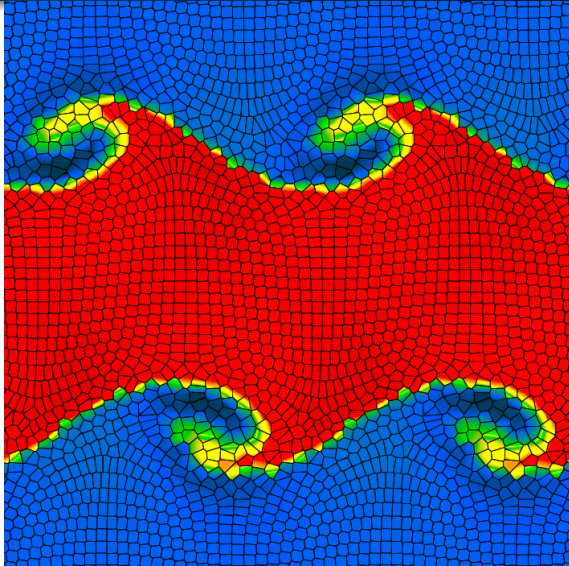




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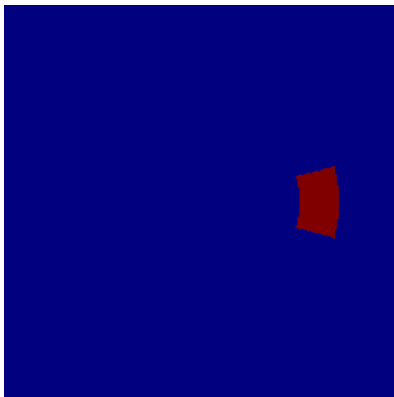
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# Cosmological moving-mesh code AREPO (Springel 2010)



# 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  $\Delta S \geq 0$ )

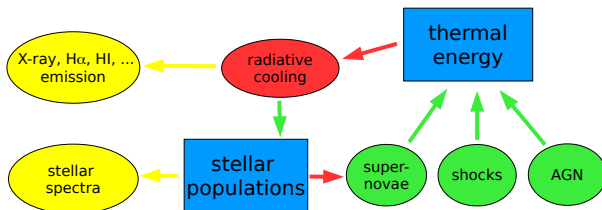


Pakmor, C.P., Simpson, Kannan, Springel (2016)

# Simulations – flowchart

observables:

physical processes:



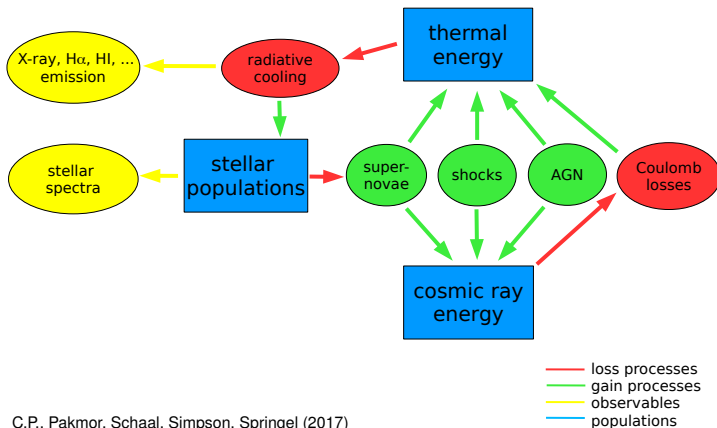
C.P., Pakmor, Schaal, Simpson, Springel (2017)

— loss processes  
— gain processes  
— observables  
— populations

# Simulations with cosmic ray physics

observables:

physical processes:

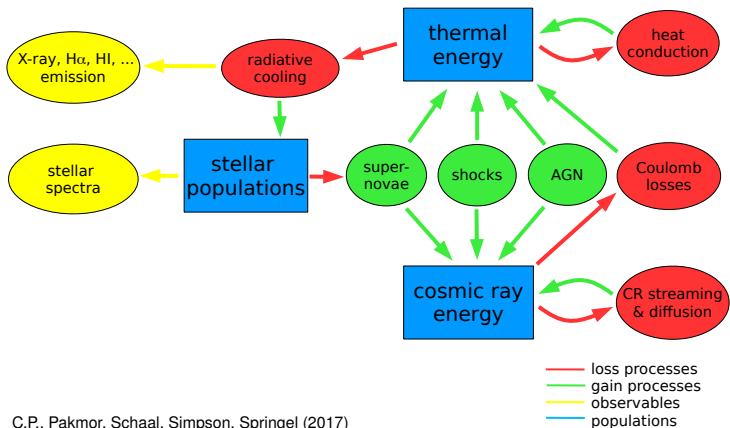


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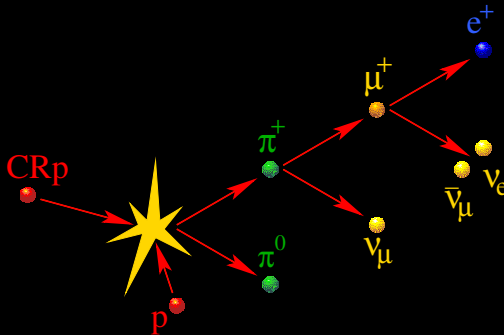
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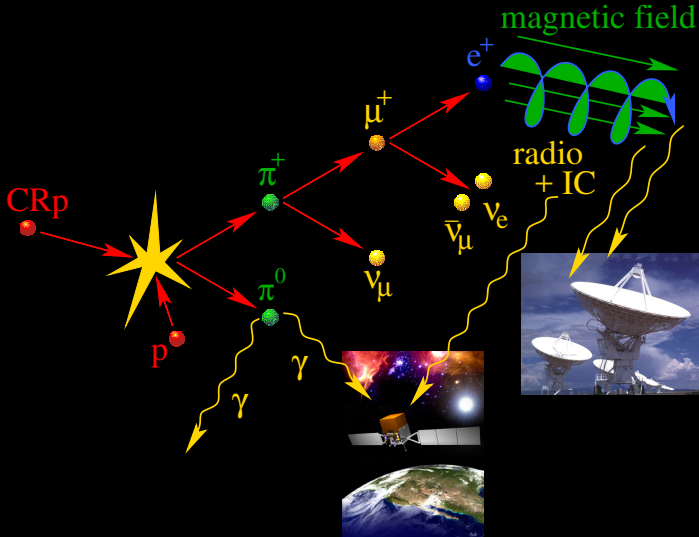


C.P., Pakmor, Schaal, Simpson, Springel (2017)

# Hadronic cosmic ray proton interaction



# Hadronic cosmic ray proton interaction

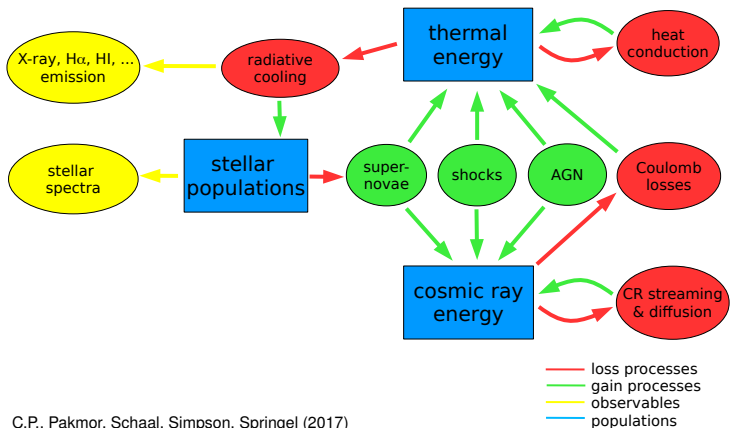




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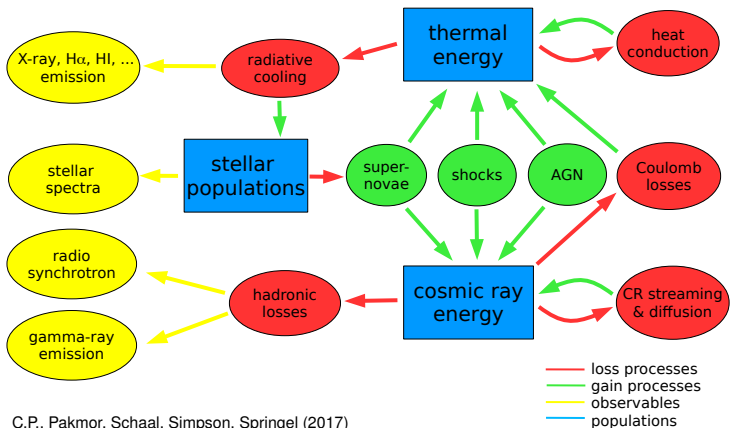


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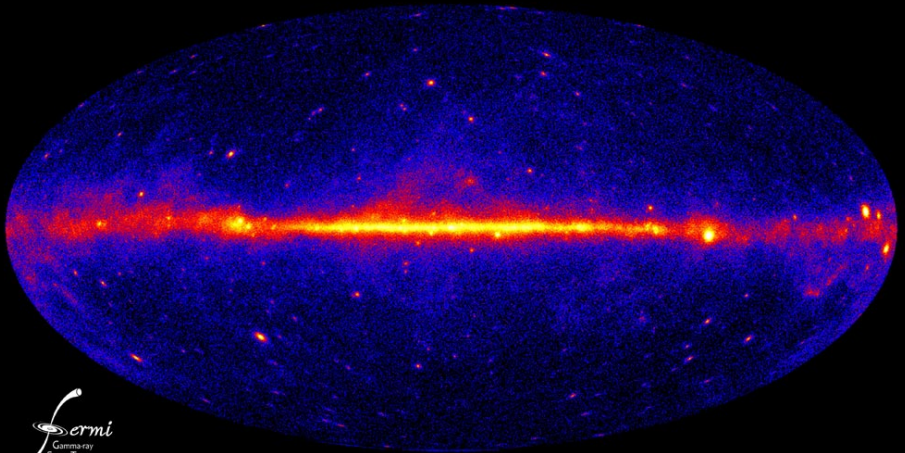


C.P., Pakmor, Schaal, Simpson, Springel (2017)

Introduction  
Physical processes  
Simulating galaxies

Modelling physics in galaxies  
Supernova explosions  
Interstellar medium

# Gamma-ray emission of the Milky Way

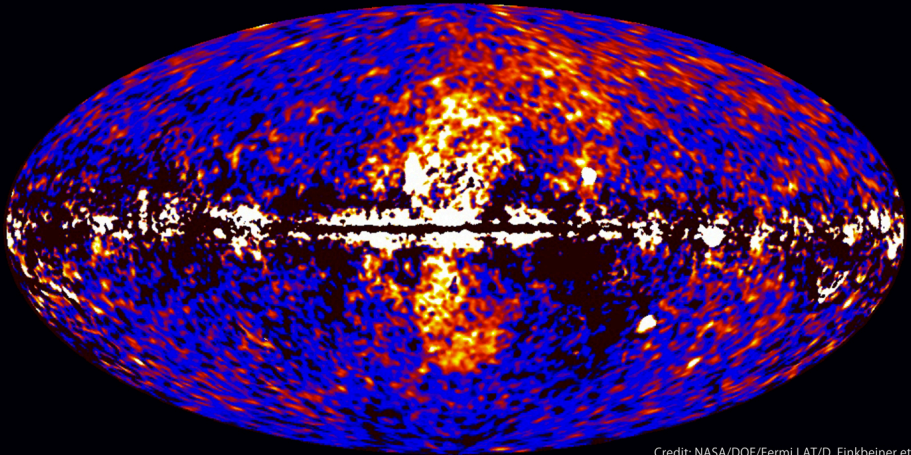


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# Galactic wind in the Milky Way?

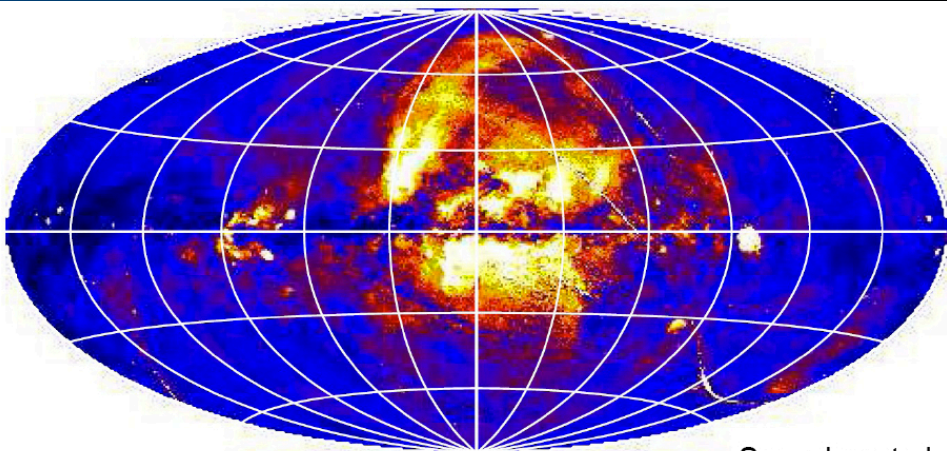
Fermi gamma-ray bubbles



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

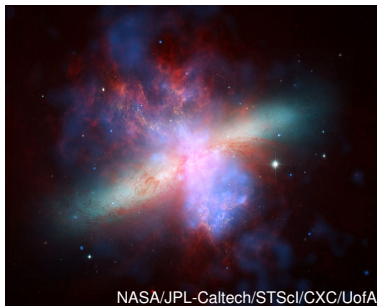
# Galactic wind in the Milky Way?

Diffuse X-ray emission in our Galaxy



Snowden et al.,

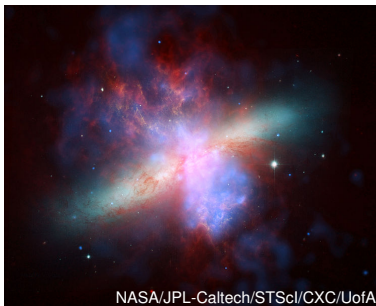
# How are galactic winds driven?



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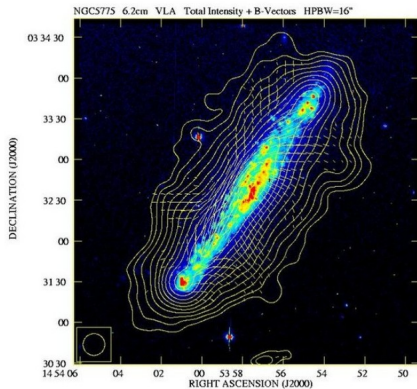
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observed energy equipartition between **cosmic rays, thermal gas and magnetic fields**

→ suggests **self-regulated feedback loop with CR driven winds**

# Why are CRs important for wind formation?

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



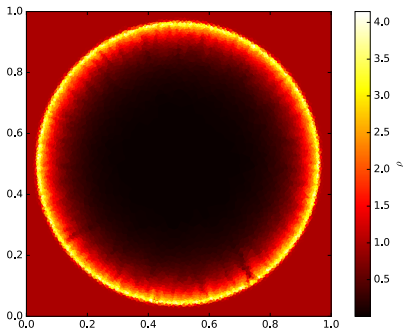
Tüllmann+ (2000)

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

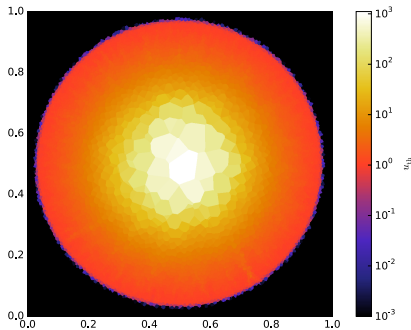


# Sedov explosion

density



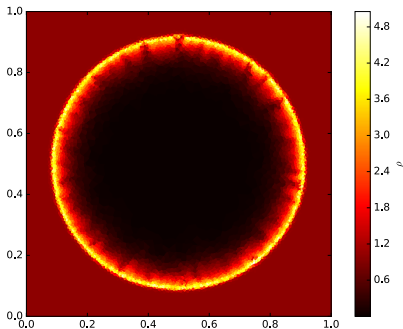
specific thermal energy



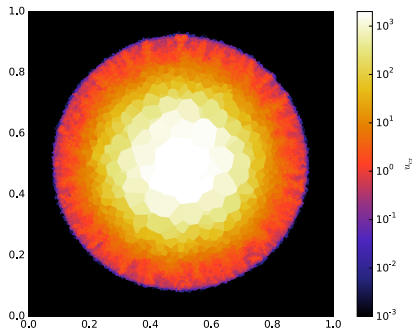
C.P., Pakmor, Schaal, Simpson, Springel (2017)

# Sedov explosion with CR acceleration

density



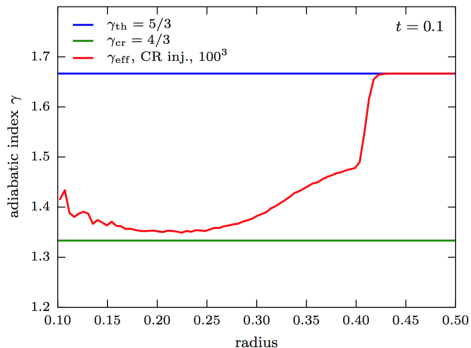
specific cosmic ray energy



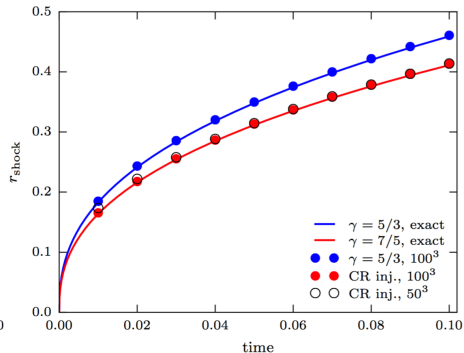
C.P., Pakmor, Schaal, Simpson, Springel (2017)

# Sedov explosion with CR acceleration

adiabatic index



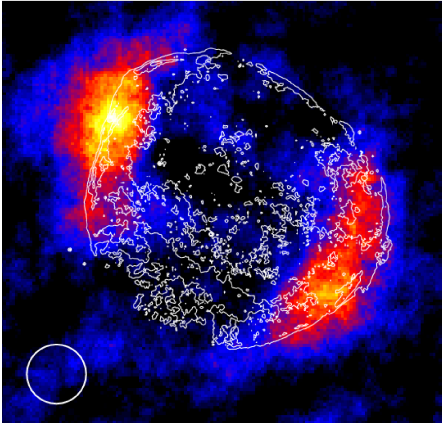
shock evolution



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

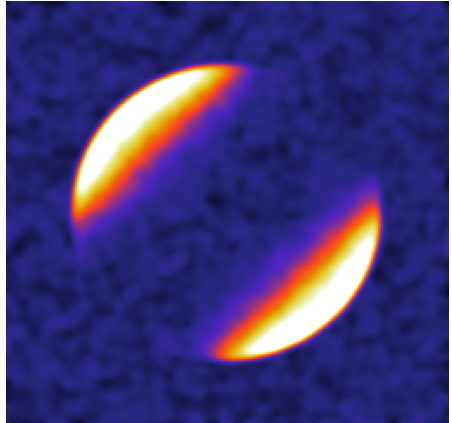
# TeV $\gamma$ rays from shell-type SNRs: SNR 1006

H.E.S.S. observation



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

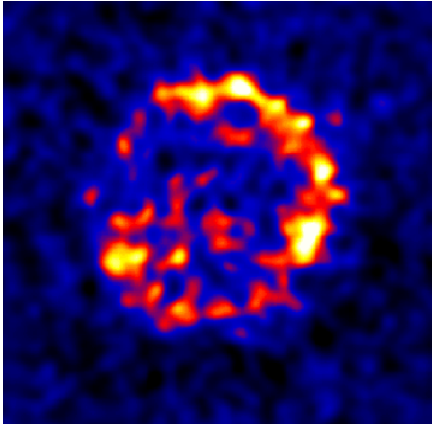
AREPO simulation



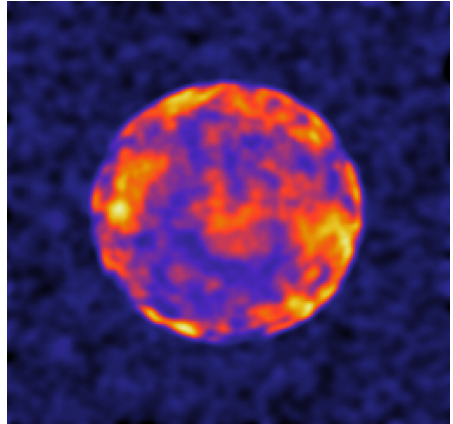
AIP

# TeV $\gamma$ rays from shell-type SNRs: Vela Junior

H.E.S.S. observation



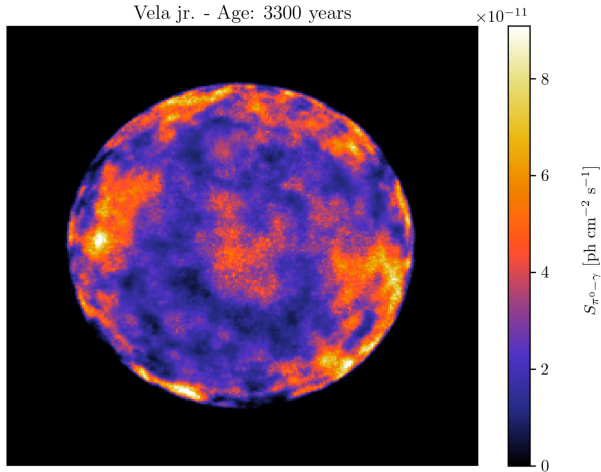
AREPO simulation



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

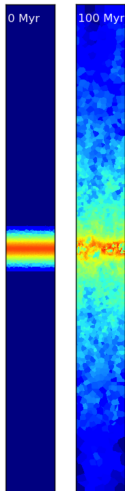
AIP

# TeV $\gamma$ rays from shell-type SNRs: Vela Junior



# A model for the multi-phase interstellar medium

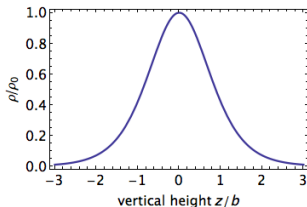
Explore supernovae-driven outflows at high resolution – stratified box simulations



Simpson+ (2016)

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

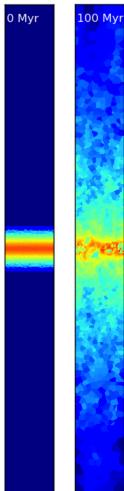
$$f_g \nabla^2 \Phi = 4\pi G \rho$$



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

# Supernova feedback

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



Simpson+ (2016)

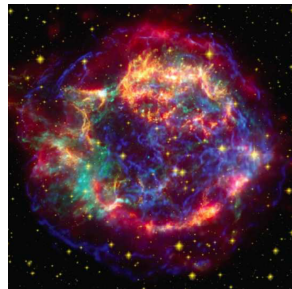
- star formation rate:

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

- supernova rate:

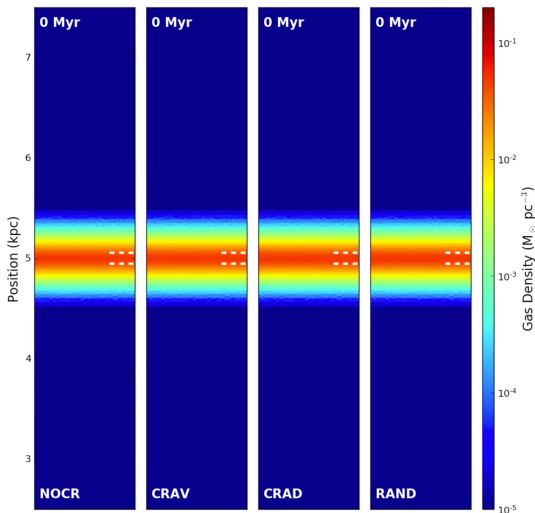
$$\dot{M}_{\text{SN},i} = \dot{M}_{*,i} \frac{1.8 \text{ events}}{100 M_{\odot}}$$

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





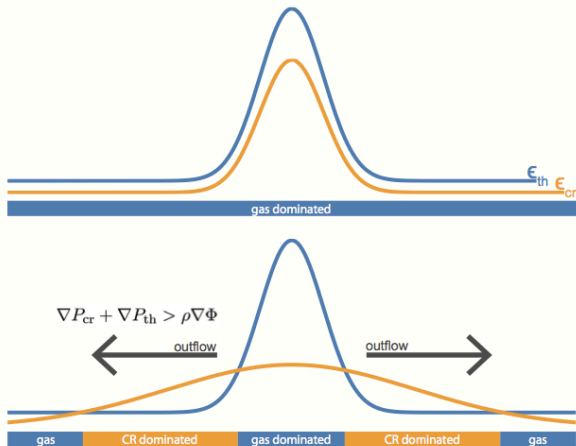
# Interstellar medium – turbulence and outflows



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

Simpson+ (2016)

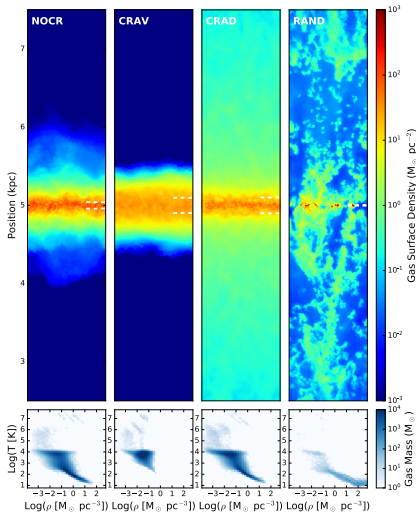
# Cosmic ray driven wind: mechanism



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

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

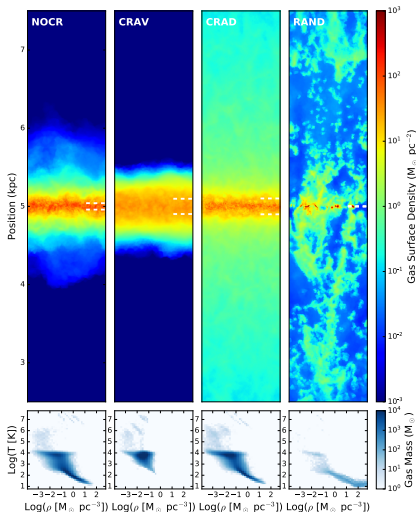
# Interstellar medium – turbulence and outflows



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

Simpson+ (2016)

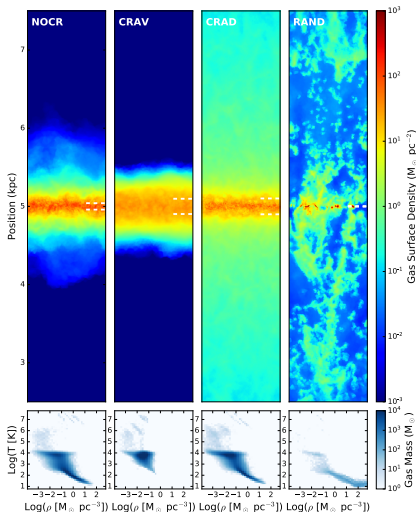
# Interstellar medium – turbulence and outflows



Simpson+ (2016)

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

# Interstellar medium – turbulence and outflows



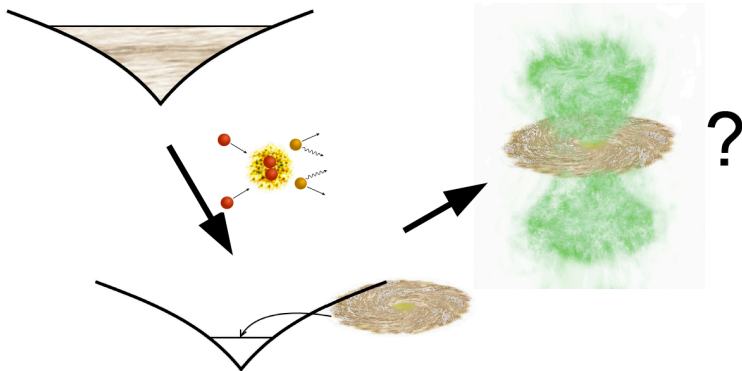
Simpson+ (2016)

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

# Outline

- 1 Introduction
  - Cosmology
  - Puzzles in galaxy formation
  - Particle acceleration and cosmic rays
- 2 Physical processes
  - Modelling physics in galaxies
  - Supernova explosions
  - Interstellar medium
- 3 Simulating galaxies
  - Global galaxy models
  - Gamma-ray emission
  - Radio emission

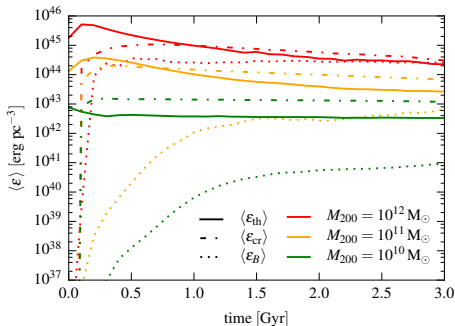
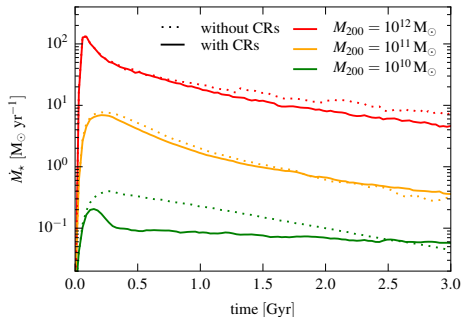
# Galaxy simulation setup: 1. cosmic ray advection



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



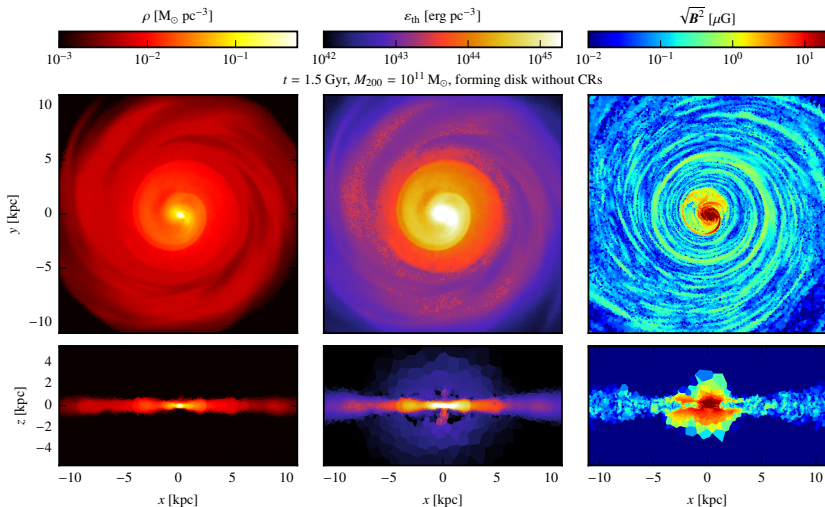
C.P., Pakmor, Schaal, Simpson, Springel (2017)

- 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



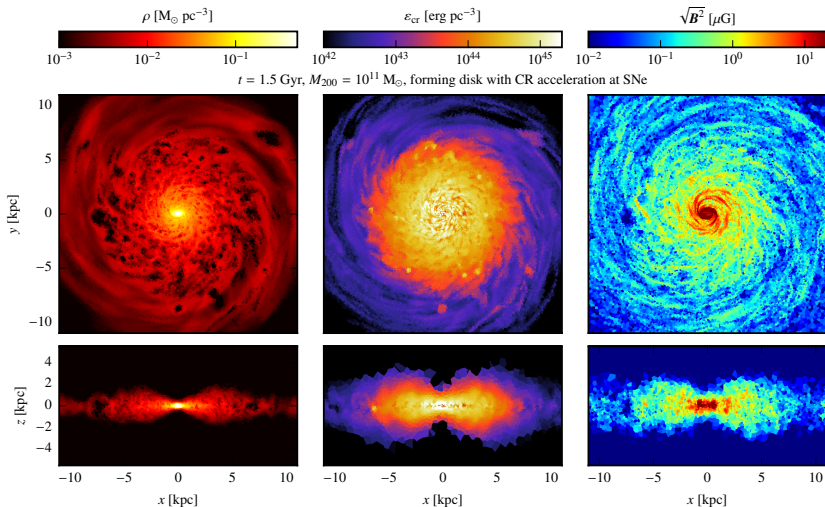


# MHD galaxy simulation without CRs



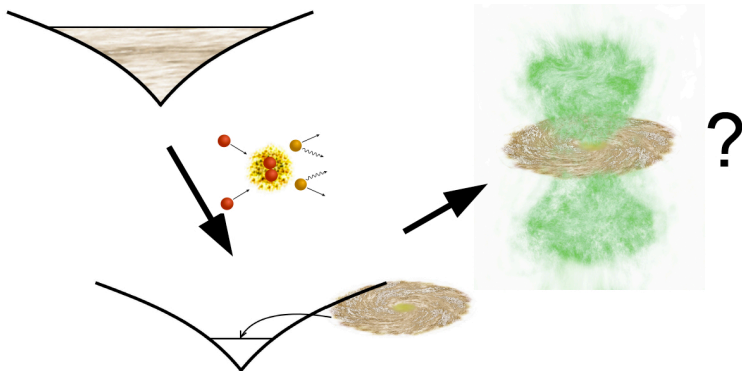
C.P., Pakmor, Schaal, Simpson, Springel (2017)

# MHD galaxy simulation with CRs



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

## Galaxy simulation setup: 2. cosmic ray diffusion

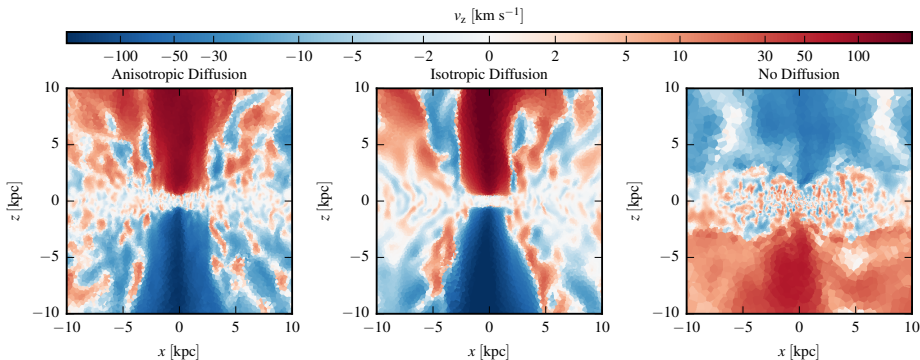


Pakmor, C.P., Simpson, Springel (2016)

*Galactic winds driven by isotropic and anisotropic cosmic ray diffusion in isolated disk galaxies*

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

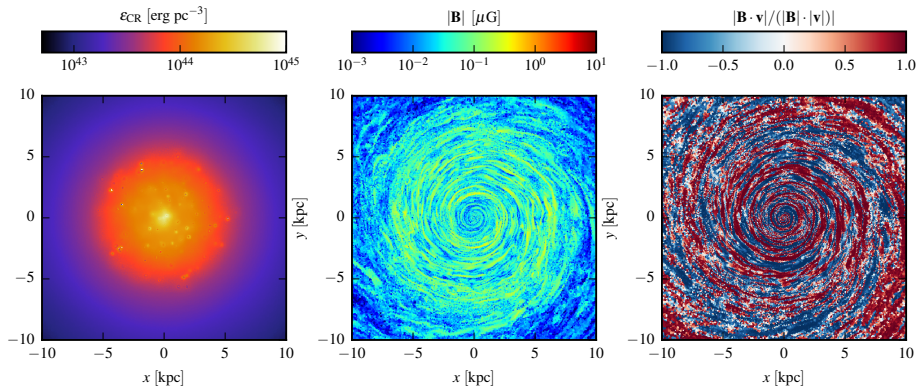
# MHD galaxy simulation with CR diffusion



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

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

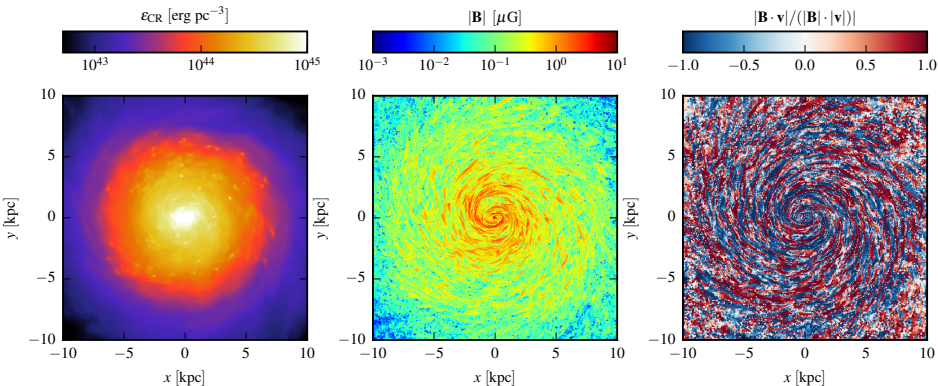
# MHD galaxy simulation with CR isotropic diffusion



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

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

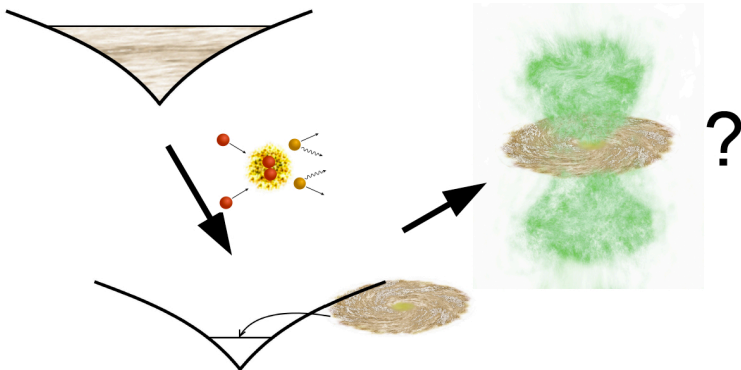
# MHD galaxy simulation with CR anisotropic diffusion



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

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

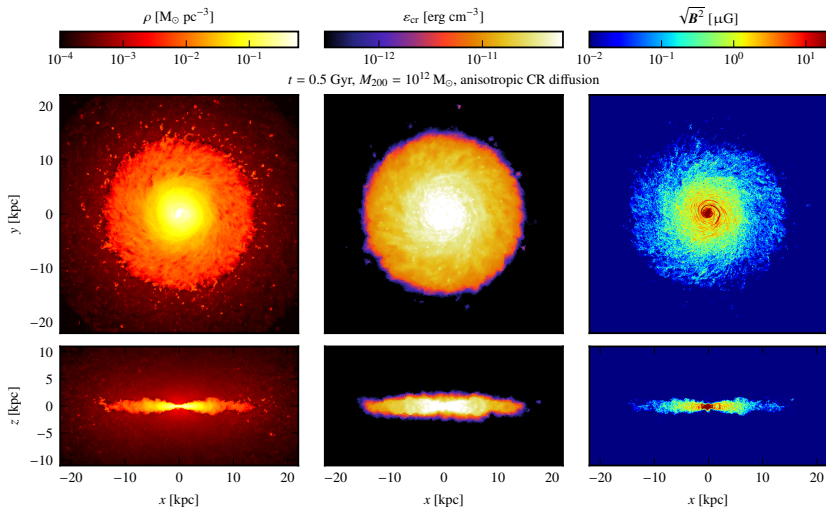
# Galaxy simulation setup: 3. non-thermal emission



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

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

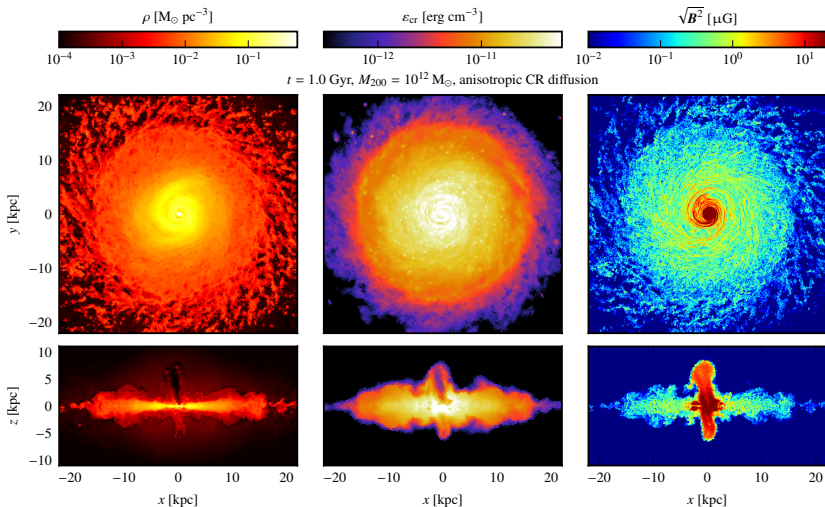
# Simulation of Milky Way-like galaxy, $t = 0.5$ Gyr



C.P.+ (2017a,b)

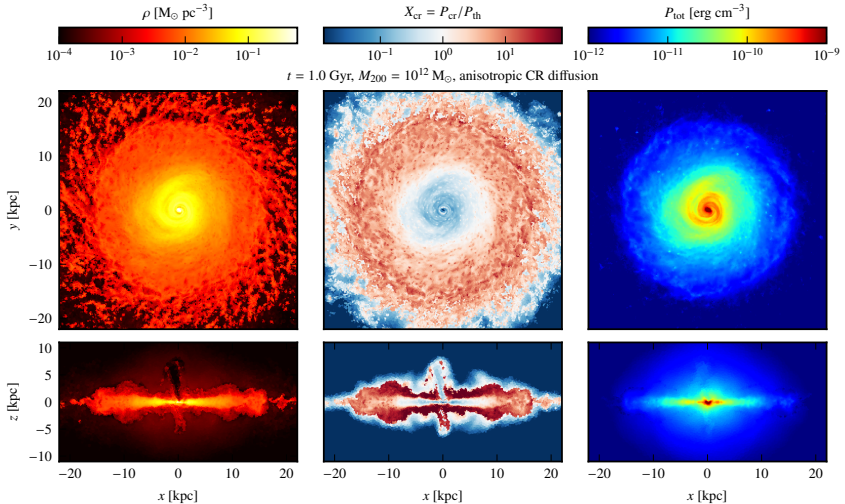


# Simulation of Milky Way-like galaxy, $t = 1.0$ Gyr



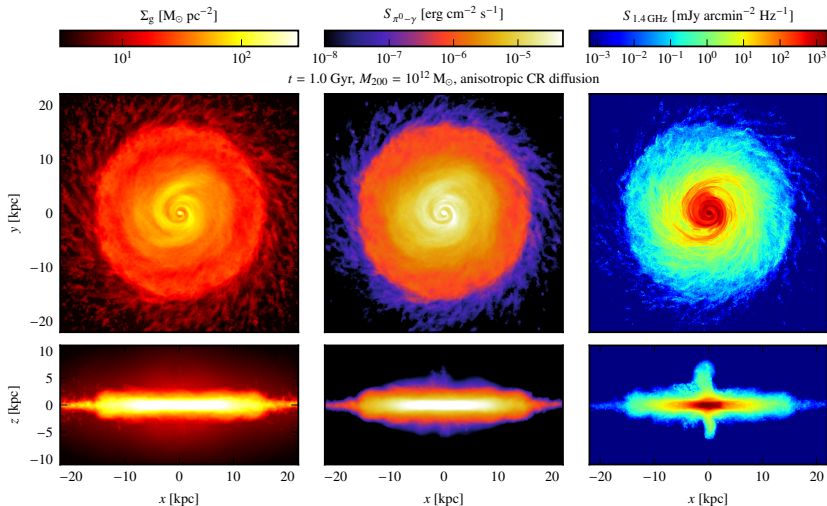
C.P.+ (2017a,b)

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C.P.+ (2017a,b)

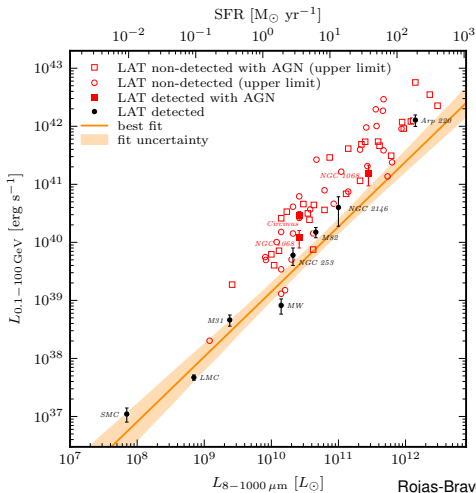
# $\gamma$ -ray and radio emission of Milky Way-like galaxy



C.P.+ (2017a,b)

# Far infra-red – gamma-ray correlation

Universal conversion: star formation  $\rightarrow$  cosmic rays  $\rightarrow$  gamma rays



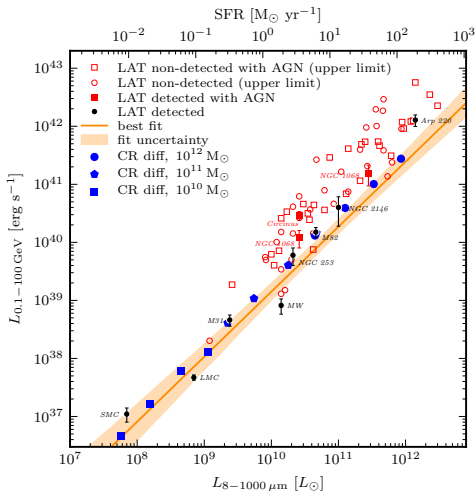
Rojas-Bravo & Araya (2016)



AIP

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Universal conversion: star formation  $\rightarrow$  cosmic rays  $\rightarrow$  gamma rays



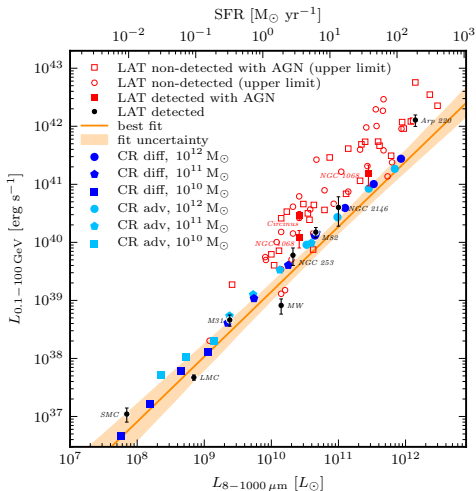
C.P.+ (2017a)



AIP

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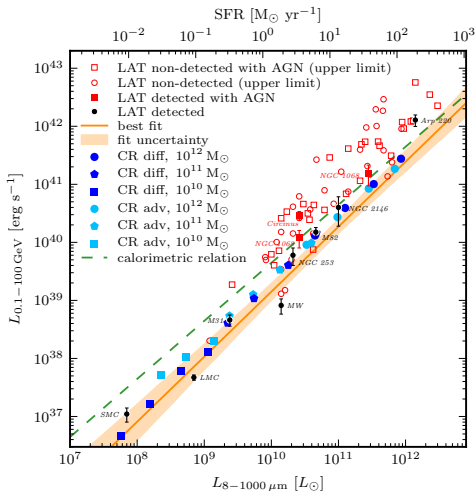


C.P.+ (2017a)



# Far infra-red – gamma-ray correlation

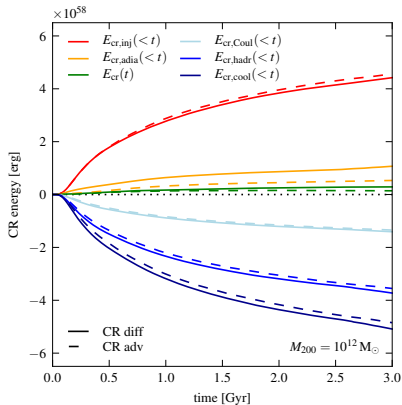
Universal conversion: star formation  $\rightarrow$  cosmic rays  $\rightarrow$  gamma rays



C.P.+ (2017a)



# Time evolution of CR energies

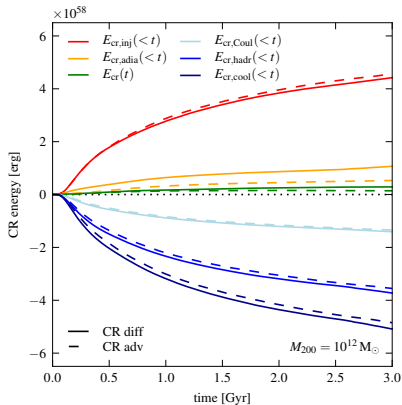
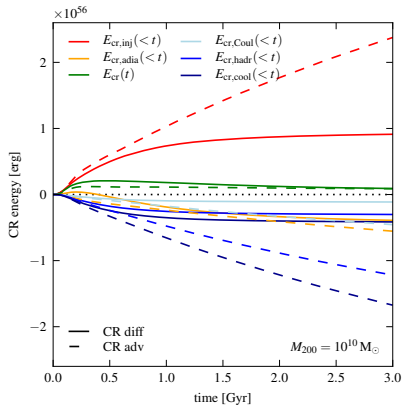


C.P.+ (2017a)



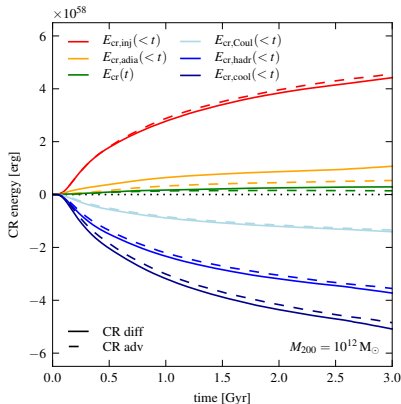
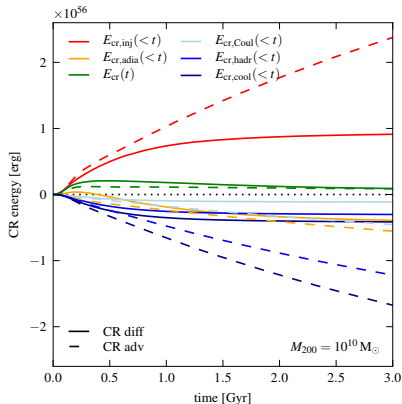


# Time evolution of CR energies



C.P.+ (2017a)

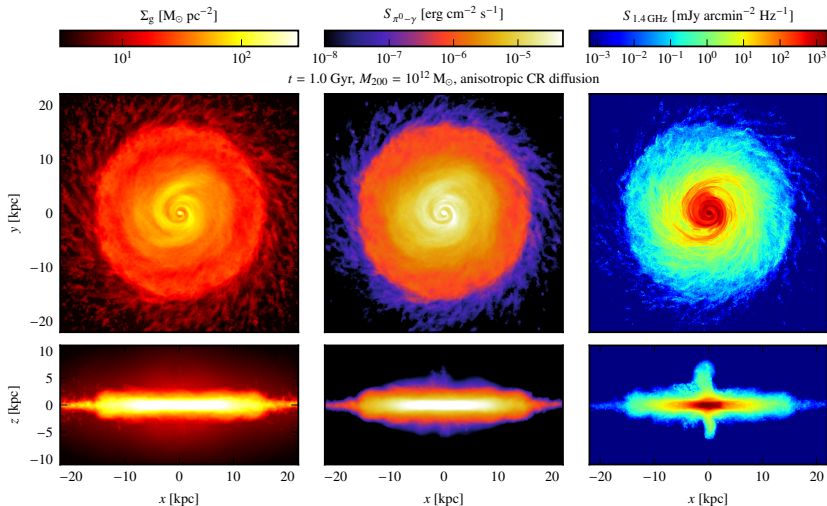
# Time evolution of CR energies



C.P.+ (2017a)

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

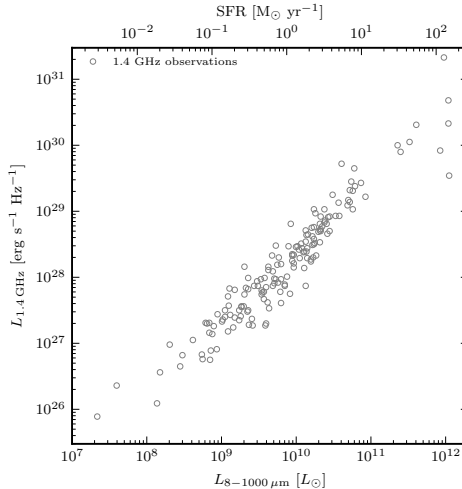
# $\gamma$ -ray and radio emission of Milky Way-like galaxy



C.P.+ (2017a,b)

# Far infra-red – radio correlation

Universal conversion: star formation  $\rightarrow$  cosmic rays  $\rightarrow$  radio



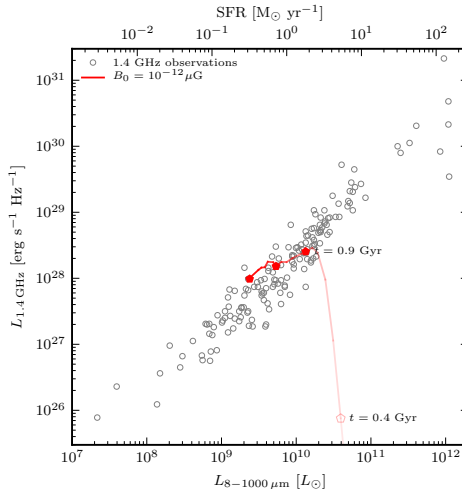
Bell (2003)



AIP

# Far infra-red – radio correlation

Universal conversion: star formation  $\rightarrow$  cosmic rays  $\rightarrow$  radio



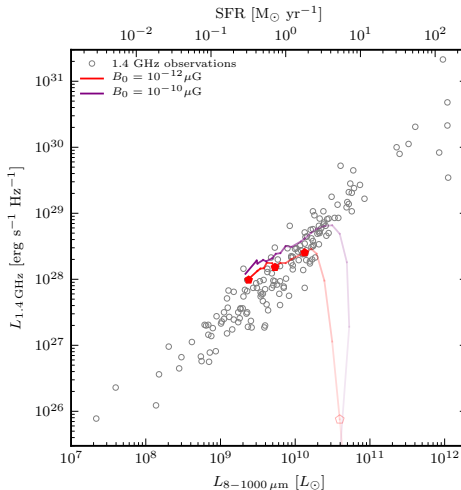
Bell (2003)



AIP

# Far infra-red – radio correlation

Universal conversion: star formation  $\rightarrow$  cosmic rays  $\rightarrow$  radio

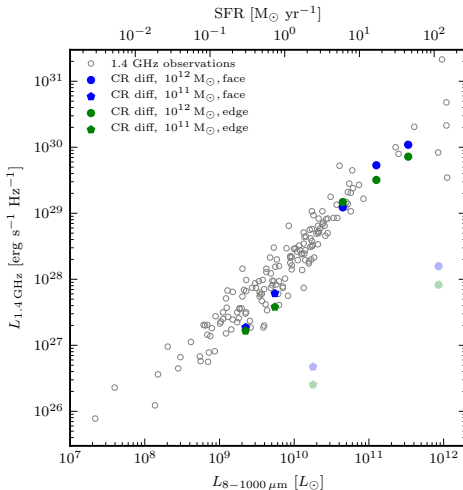


Bell (2003)



# Far infra-red – radio correlation

Universal conversion: star formation  $\rightarrow$  cosmic rays  $\rightarrow$  radio

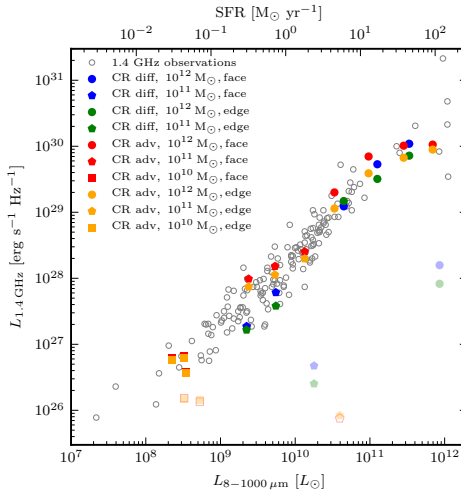


C.P.+ (2017b)



# Far infra-red – radio correlation

Universal conversion: star formation  $\rightarrow$  cosmic rays  $\rightarrow$  radio



C.P.+ (2017b)

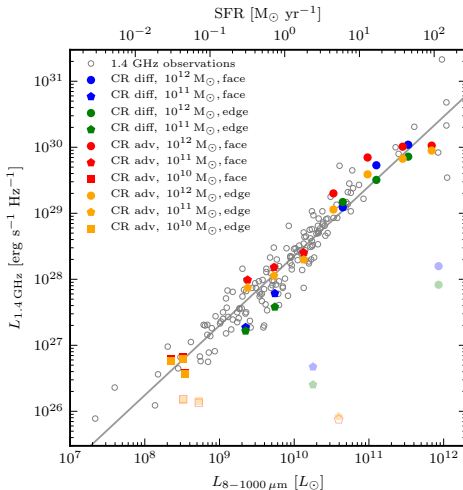


AIP



# Far infra-red – radio correlation

Universal conversion: star formation  $\rightarrow$  cosmic rays  $\rightarrow$  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  $B \sim 10 \mu\text{G}$

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- no hadronic *Fermi-like* bubbles → leptonic emission?
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**outlook:** improved modeling of plasma physics, follow CR spectra, cosmological settings

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



Introduction  
Physical processes  
Simulating galaxies

Global galaxy models  
Gamma-ray emission  
Radio emission

# CRAGSMAN: The Impact of Cosmic RAys on Galaxy and CluSter ForMationN



This project has received funding from the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation program (grant agreement No CRAGSMAN-646955).

Christoph Pfrommer

How cosmic rays shape galaxies



# 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.

