How cosmic rays shape the interstellar medium and galaxies

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in collaboration with

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Bochum University, 2016

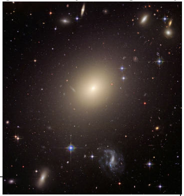
Outline

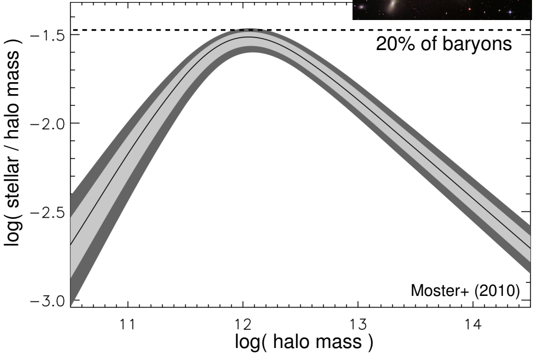
Puzzles in galaxy formation

dwarf galaxy

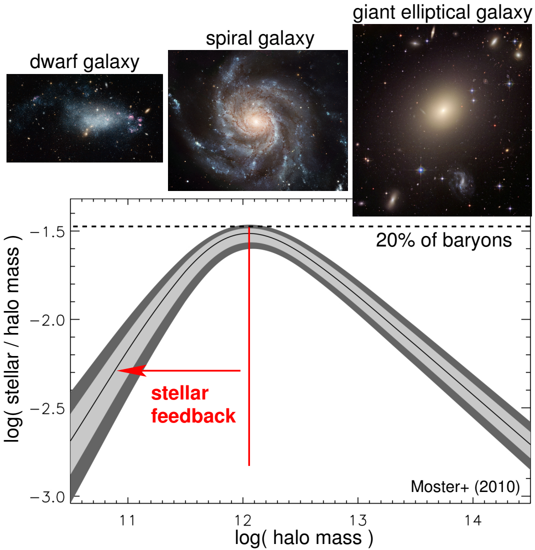
spiral galaxy

giant elliptical galaxy

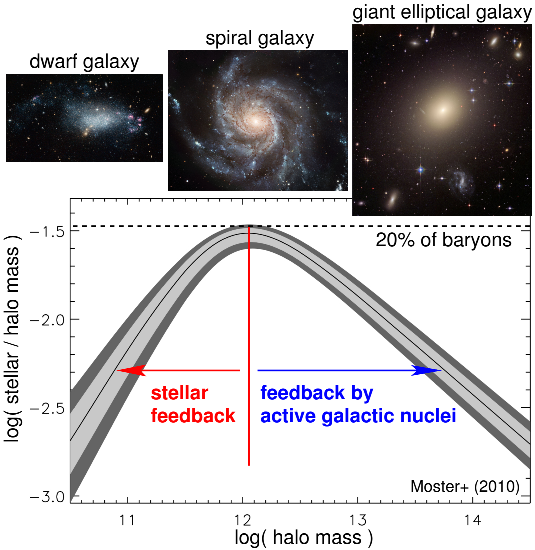




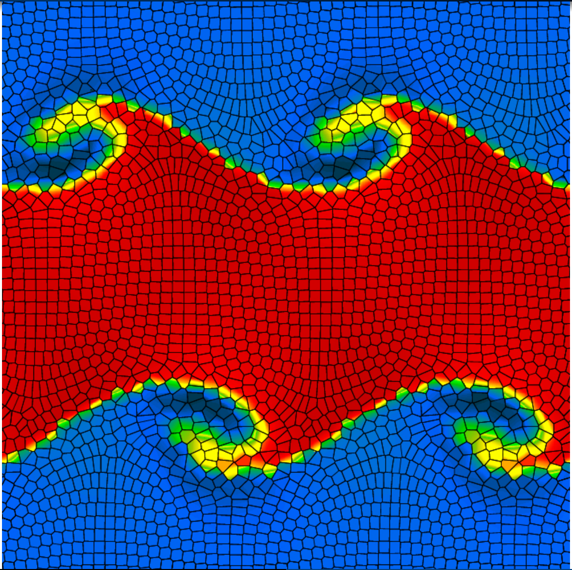
Puzzles in galaxy formation



Puzzles in galaxy formation



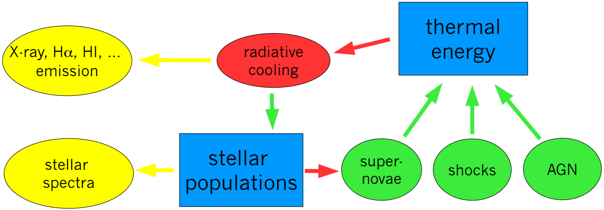
Cosmological moving-mesh code AREPO (Springel 2010)



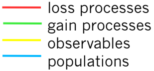
Simulations – flowchart

ISM observables:

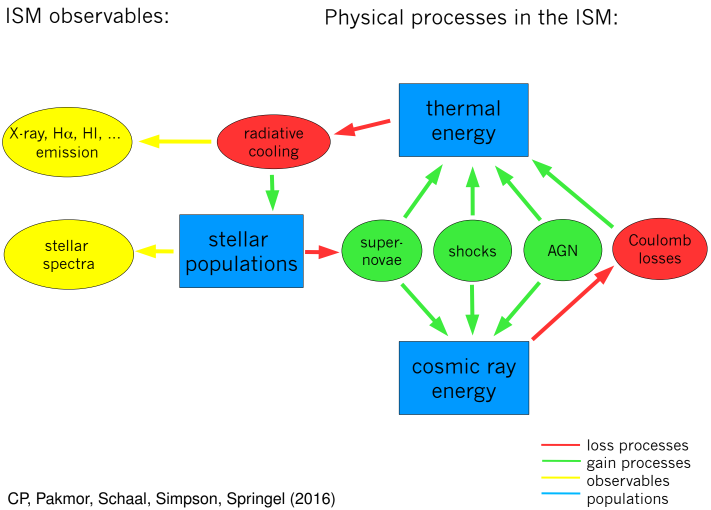
Physical processes in the ISM:



CP, Pakmor, Schaal, Simpson, Springel (2016)



Simulations with cosmic ray physics



CP, Pakmor, Schaal, Simpson, Springel (2016)

Simulations with cosmic ray physics

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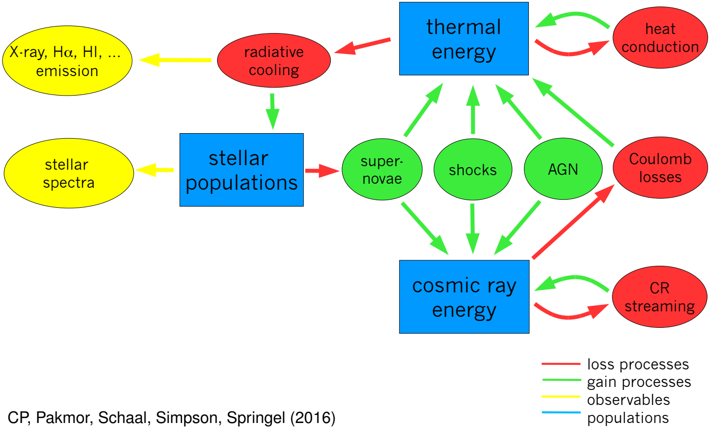
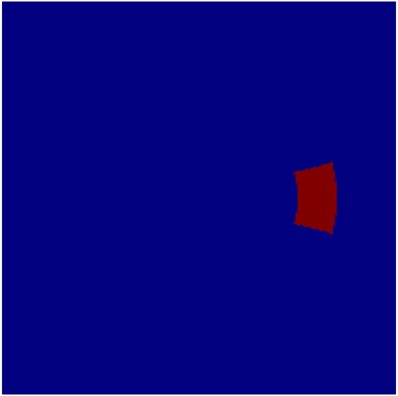


CP, Pakmor, Schaal, Simpson, Springel (2016)

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 $\Delta S \geq 0$)

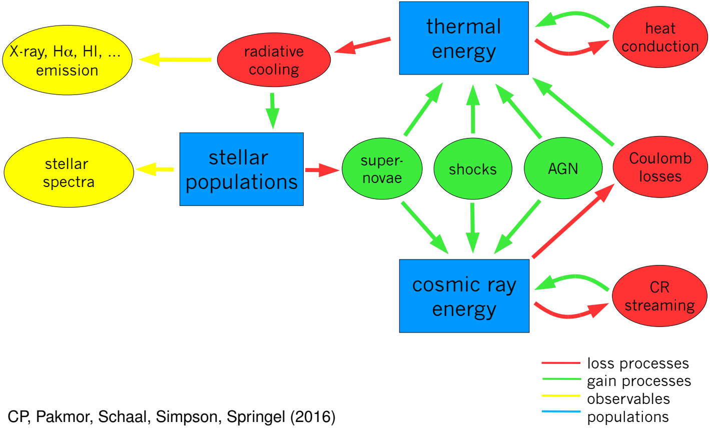


Pakmor, CP, Simpson, Kannan, Springel (2016)

Simulations with cosmic ray physics

ISM observables:

Physical processes in the ISM:

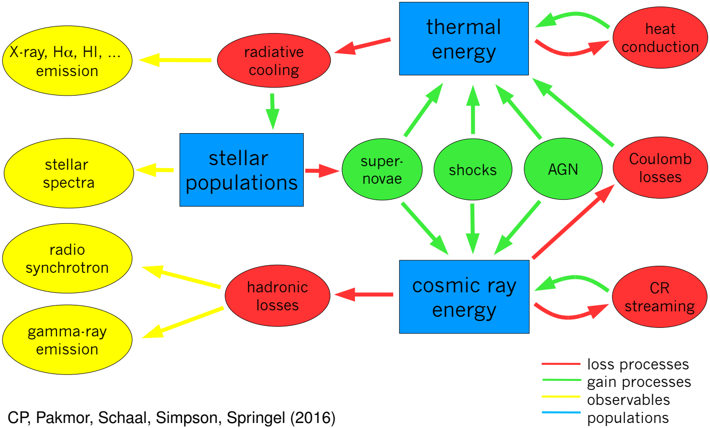


CP, Pakmor, Schaal, Simpson, Springel (2016)

Simulations with cosmic ray physics

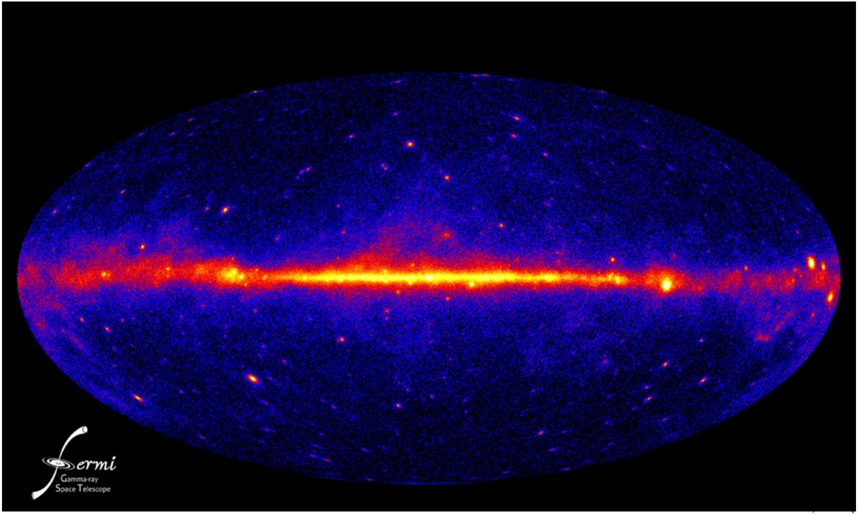
ISM observables:

Physical processes in the ISM:



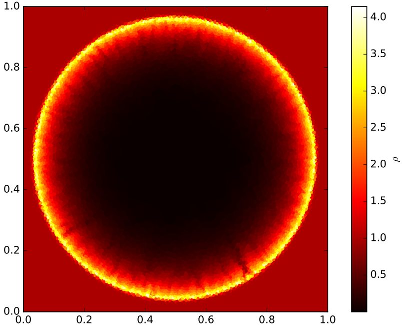
CP, Pakmor, Schaal, Simpson, Springel (2016)

Gamma-ray emission of the Milky Way

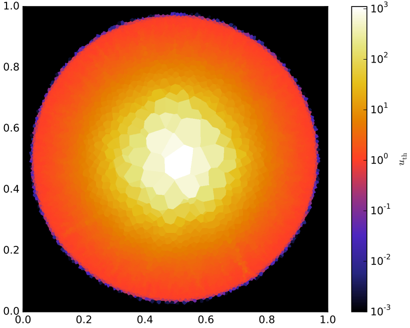


Sedov explosion

density



specific thermal energy



CP, Pakmor, Schaal, Simpson, Springel (2016)

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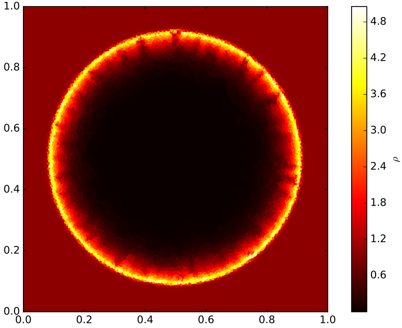
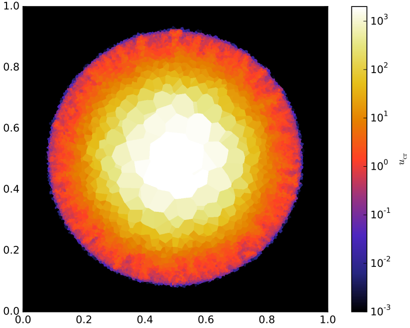
Sedov explosion with CR acceleration

density



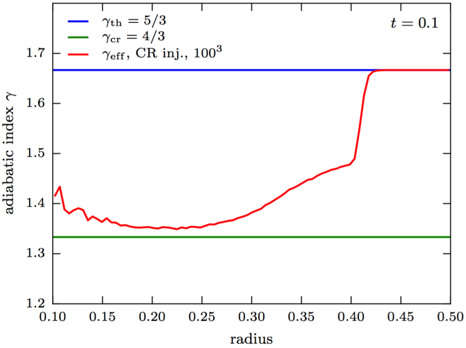
specific cosmic ray energy



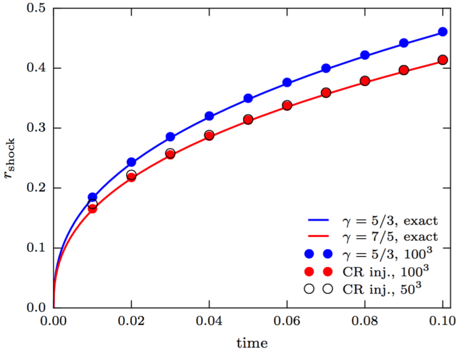
CP, Pakmor, Schaal, Simpson, Springel (2016)

Sedov explosion with CR acceleration

adiabatic index



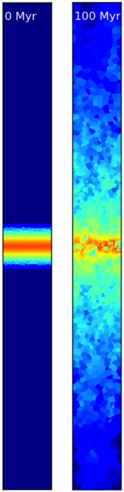
shock evolution



CP, Pakmor, Schaal, Simpson, Springel (2016)

A model for the multi-phase interstellar medium

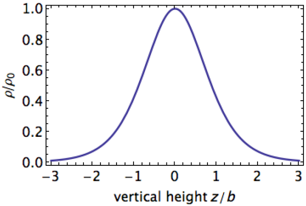
Explore supernovae-driven outflows at high resolution – stratified box simulations



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 (CP+ 2016, Pakmor+ 2016)

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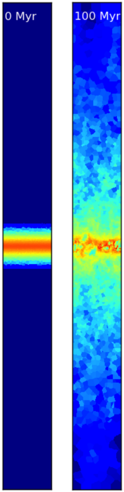
Supernova feedback

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



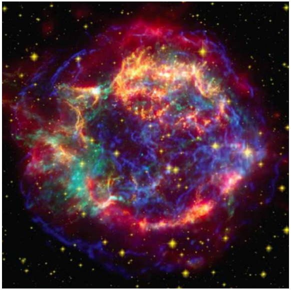
Simpson+ (2016)

- star formation rate:

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

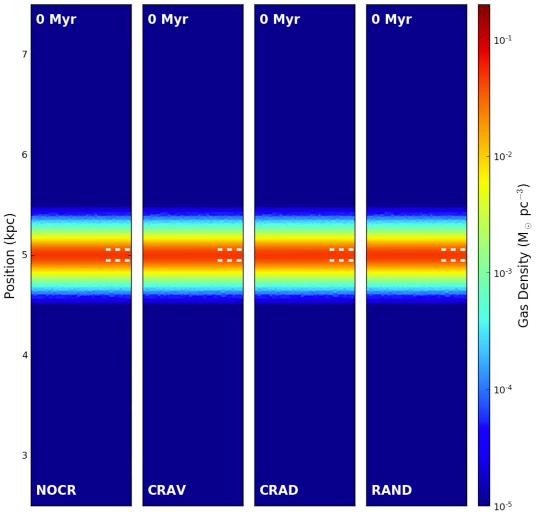
- supernova rate:

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



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

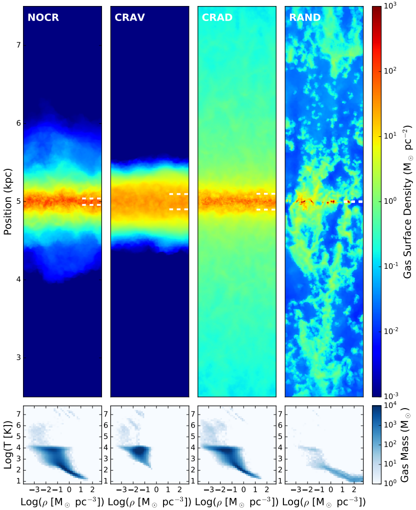
Interstellar medium – turbulence and outflows



Simpson+ (2016)

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

Interstellar medium – turbulence and outflows

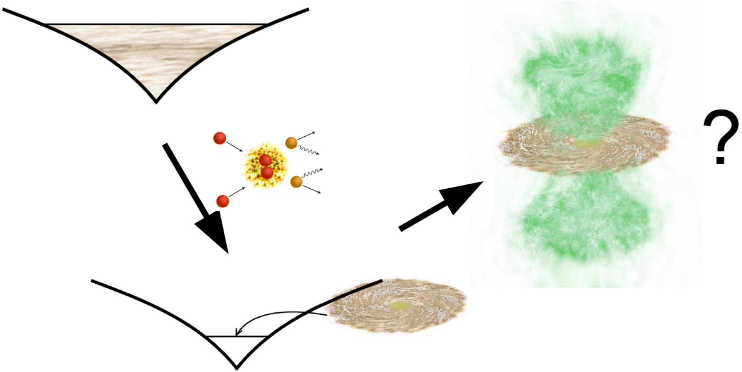


Simpson+ (2016)

- diffusing CRs (CRAD) launch outflows with similar mass loadings as randomly placed feedback models (RAND)
- different forcing: CR pressure gradient (CRAD) vs. kinetic pressure gradients propelling a ballistic outflow (RAND) $\rightarrow$ velocity and clumpiness differ
- CR + turbulent pressure self-regulate ISM $\rightarrow$ scale height $h_{1/2} \approx 80$ pc; ISM in RAND collapses to dense phase

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

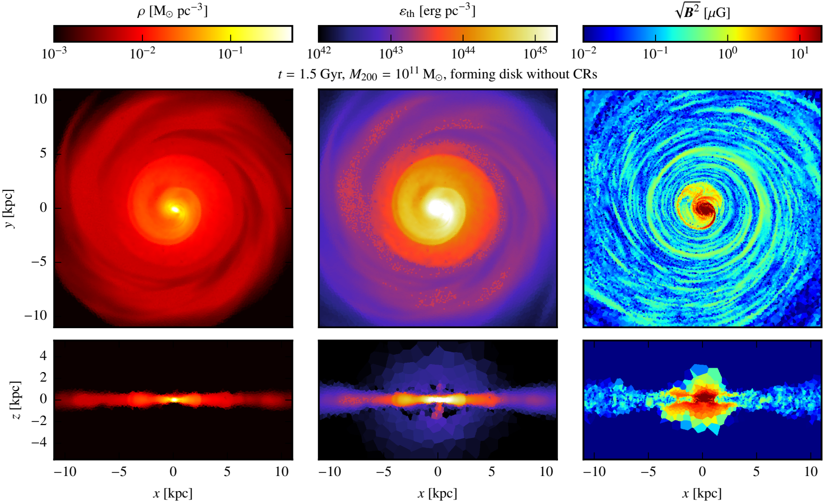
Galaxy simulation setup: 1. cosmic ray advection



CP, Pakmor, Schaal, Simpson, Springel (2016)
Simulating cosmic ray physics on a moving mesh

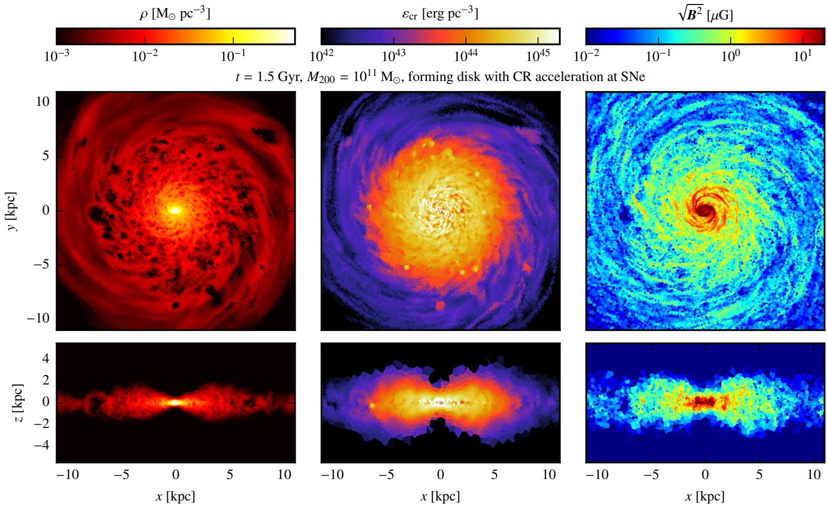
MHD + cosmic ray advection: $10^{11}\ M_\odot$

MHD galaxy simulation without CRs



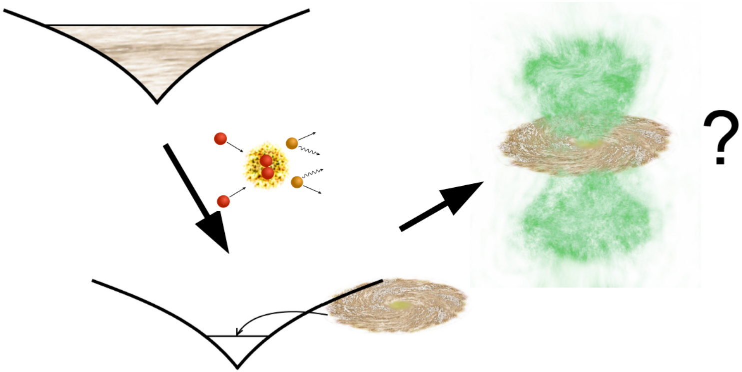
CP, Pakmor, Schaal, Simpson, Springel (2016)

MHD galaxy simulation with CRs



CP, Pakmor, Schaal, Simpson, Springel (2016)

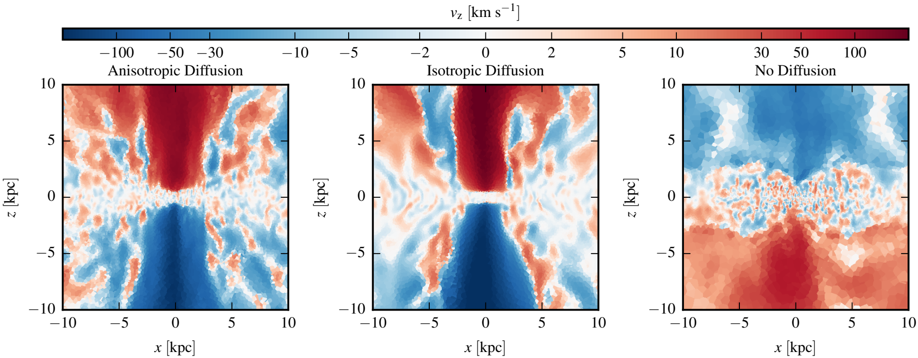
Galaxy simulation setup: 2. cosmic ray diffusion



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

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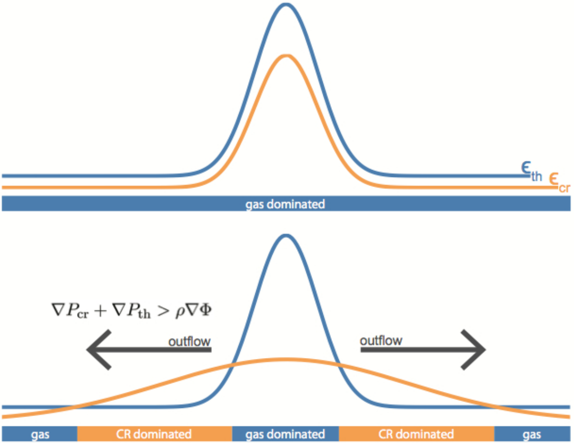
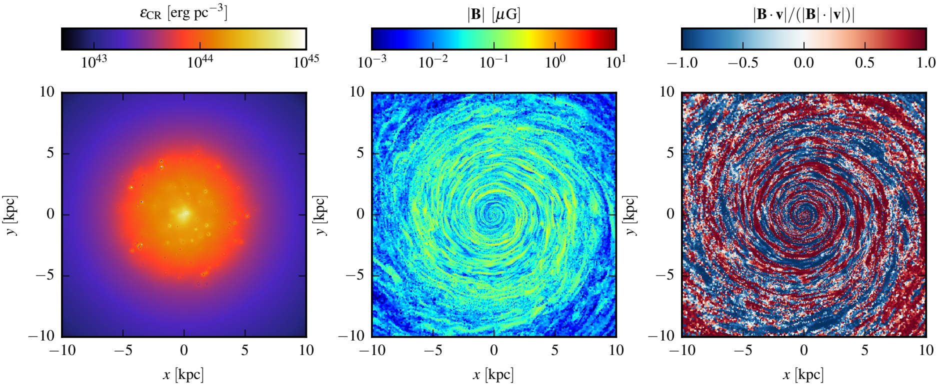
Cosmic ray driven wind: mechanism



CR streaming: Uhlig, CP+ (2012)

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

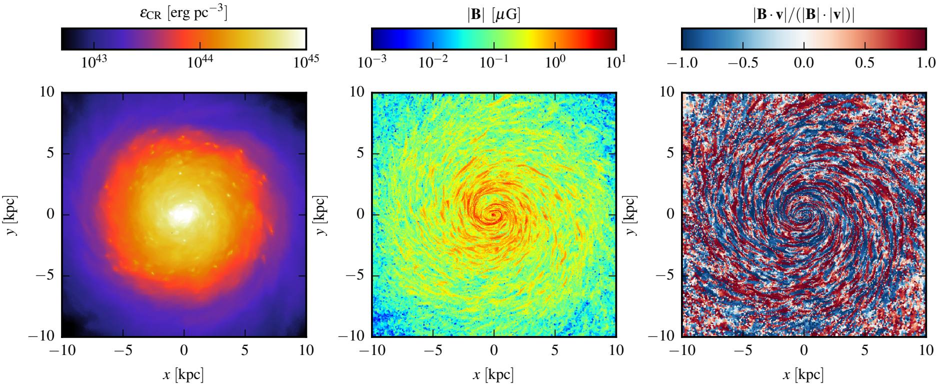
MHD galaxy simulation with CR isotropic diffusion



Pakmor, CP, Simpson, Springel (2016)

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

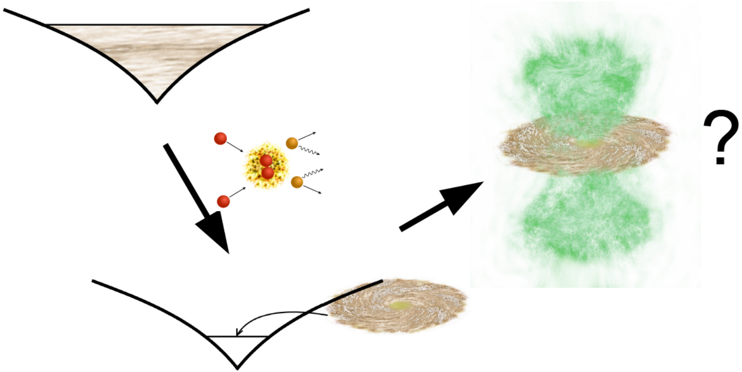
MHD galaxy simulation with CR anisotropic diffusion



Pakmor, CP, Simpson, Springel (2016)

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

Galaxy simulation setup: 3. non-thermal emission



CP, Pakmor+ (in prep)
Non-thermal radio and gamma-ray emission in isolated disk galaxies

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

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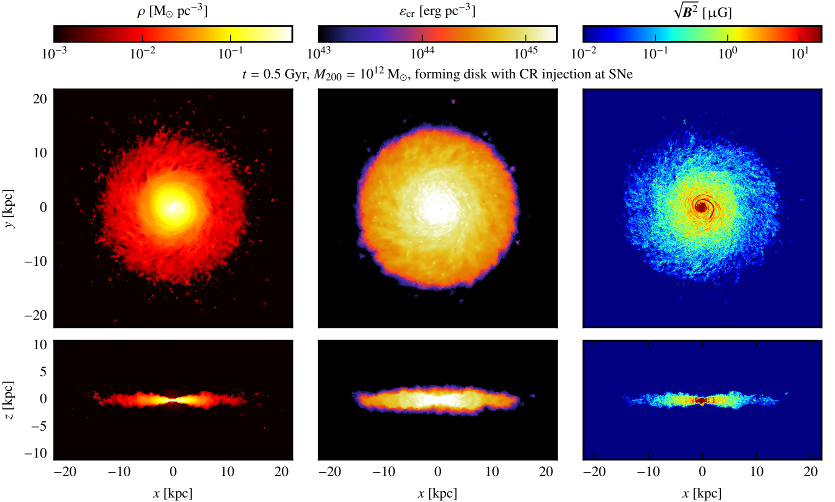
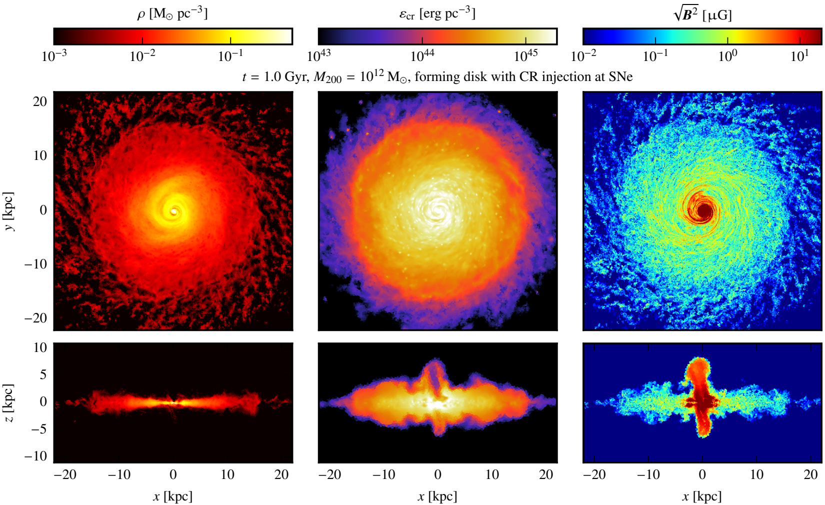
Simulation of Milky Way-like galaxy, $t = 0.5$ Gyr



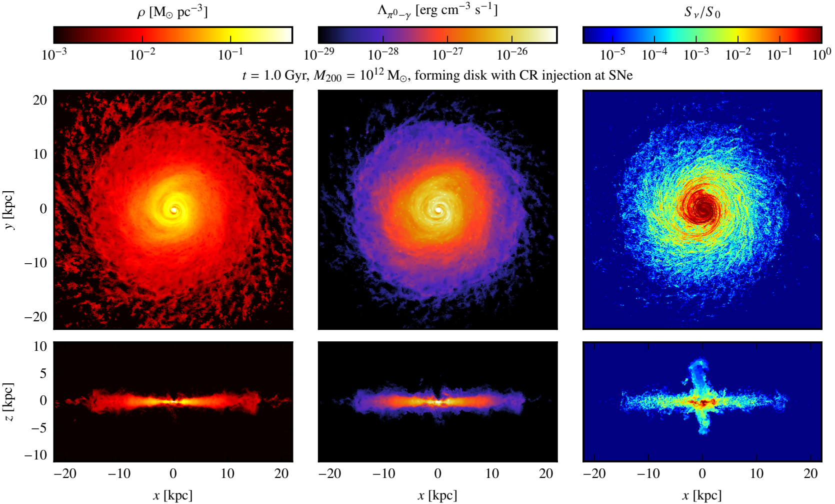
CP, Pakmor+ (in prep.)

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



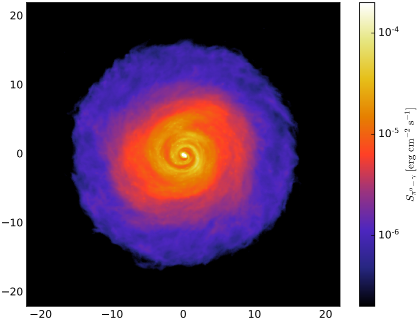
CP, Pakmor+ (in prep.)

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



CP, Pakmor+ (in prep.)

Projected γ-ray emission of Milky Way-like galaxy



CP, Pakmor+ (in prep.)

- pion decay γ-ray emission shows no *Fermi*-like bubbles due to low density in wind region $\rightarrow$ leptonic emission? (Selig+ 2015)
- compute gamma-ray luminosity $\rightarrow L_{\mathrm{FIR}} - L_\gamma$

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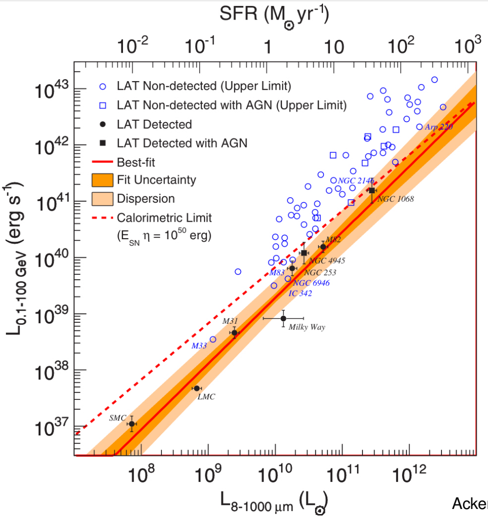
Far infra-red – gamma-ray correlation

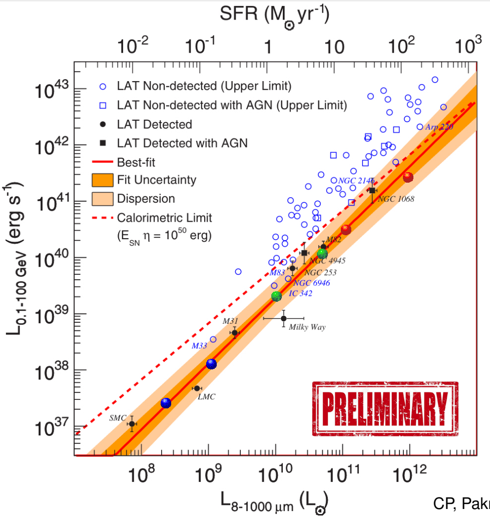
Universal conversion: star formation → cosmic rays → gamma rays



Ackermann+ (2012)

Far infra-red – gamma-ray correlation

Universal conversion: star formation → cosmic rays → gamma rays



CP, Pakmor+ (in prep.)

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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 $B \sim 10\,\mu$G
- no hadronic *Fermi*-like bubbles $\rightarrow$ leptonic emission?
- $L_{\rm FIR} - L_\gamma$ correlation allows to test calorimetric assumption

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

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.

Cosmic ray feedback in galaxies:

- Pfrommer, Pakmor, Schaal, Simpson, Springel, *Simulating cosmic ray physics on a moving mesh,* 2016, 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.