Cosmic ray acceleration at shocks

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in collaboration with

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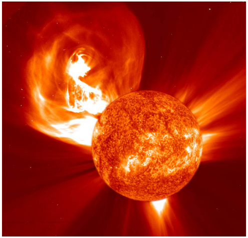
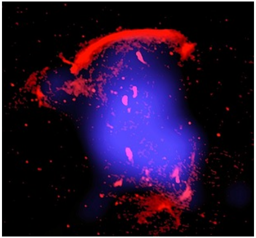
Astrophysical shocks, AIP, Mar 2018

Astrophysical shocks



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

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

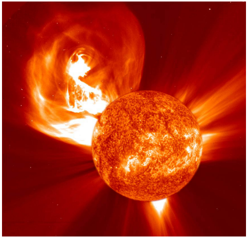


cluster shocks $\sim$ 2 Mpc
giant radio relic (van Weeren)

Astrophysical shocks

Astrophysical collisionless shocks can:

- accelerate particles (electrons and ions) $\rightarrow$ cosmic rays (CRs)
- amplify magnetic fields (or generate them from scratch)



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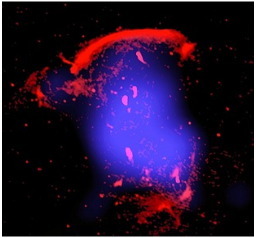

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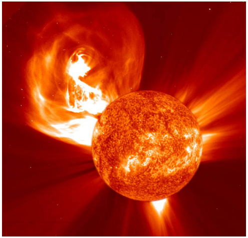
$\Rightarrow$ non-thermal emission (radio to gamma rays)

$\Rightarrow$ cosmic ray feedback in galaxies and galaxy clusters



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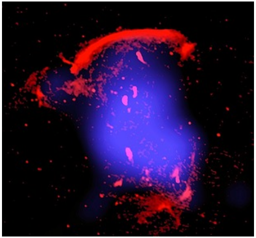

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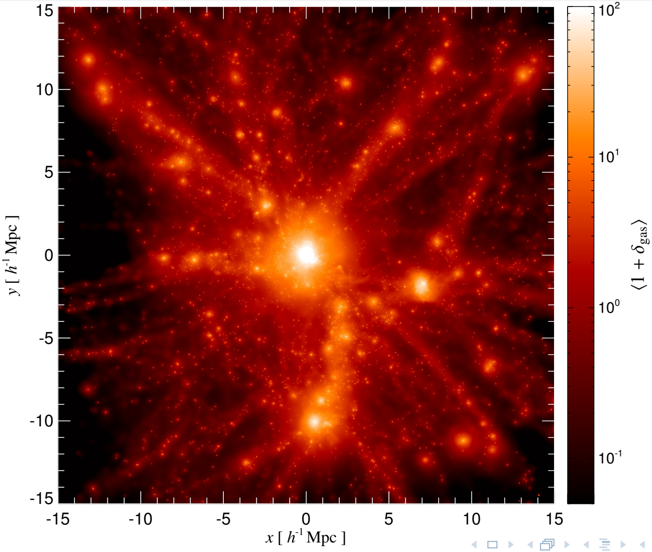
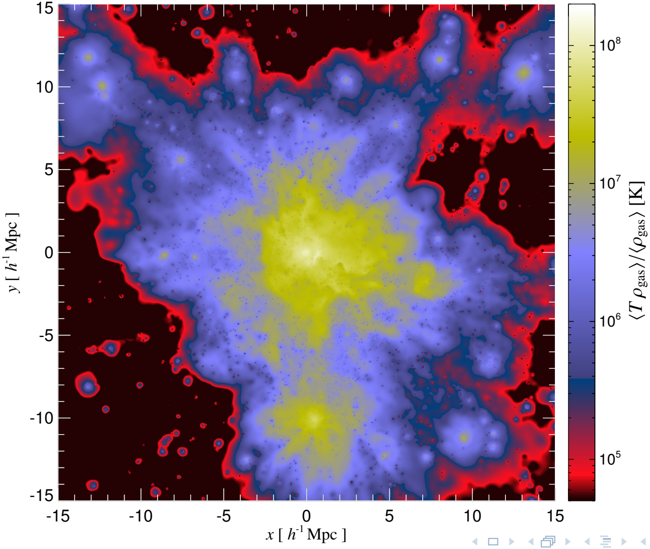
Cosmological cluster simulation: gas density



Mass weighted temperature



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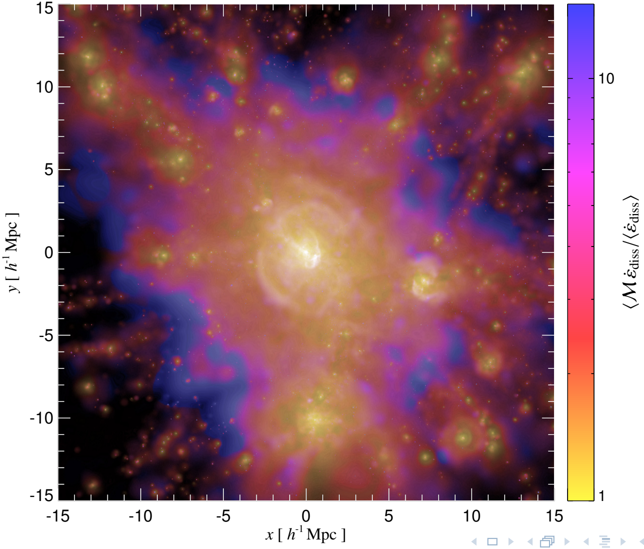
Shock strengths weighted by dissipated energy



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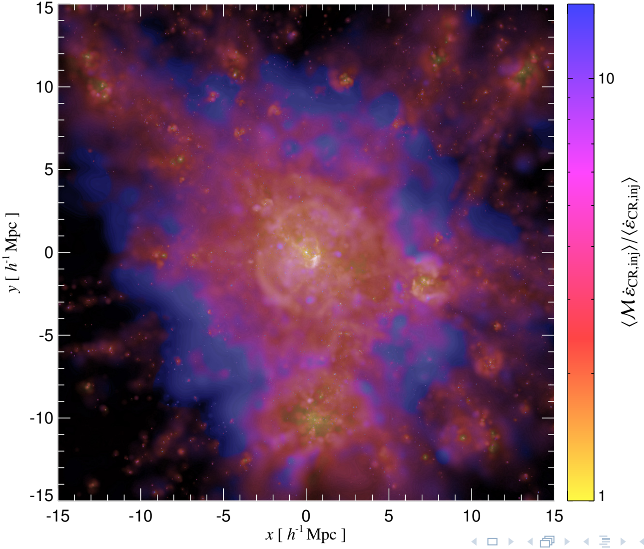
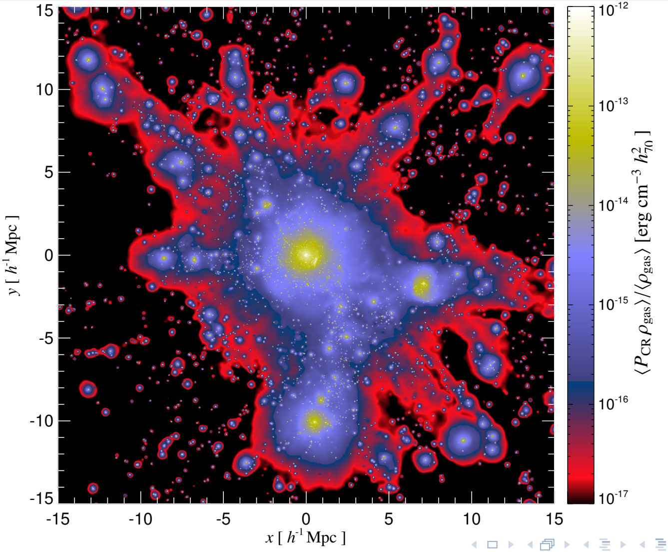
Shock strengths weighted by injected CR energy



Evolved CR pressure



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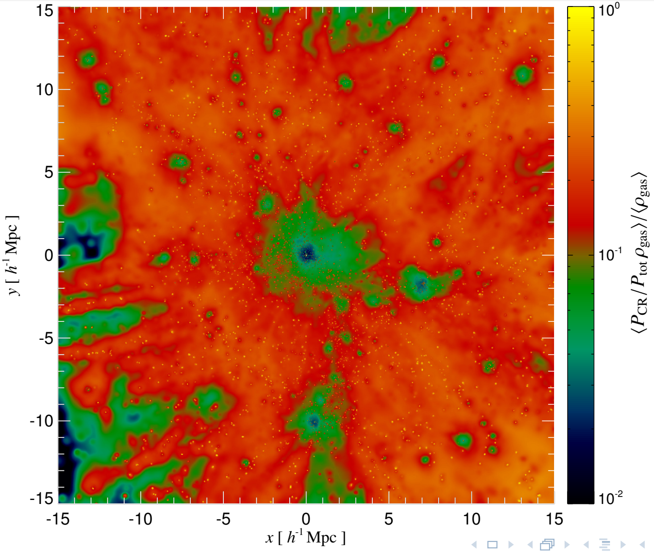
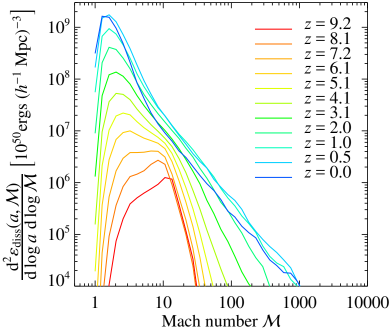
Relative CR pressure $P_{\rm CR}/P_{\rm total}$

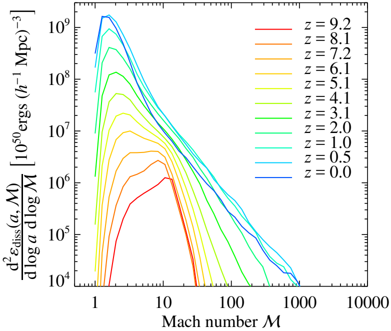


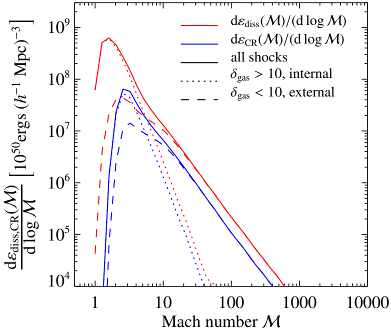
Cosmological shock statistics



- more energy is dissipated at later times
- mean Mach number decreases with time

Cosmological shock statistics: CR acceleration

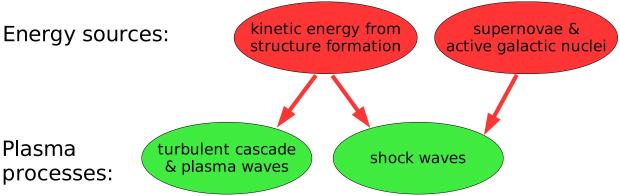




- more energy is dissipated in weak shocks internal to collapsed structures than in external strong shocks
- injected CR energy within clusters only makes up a small fraction of the total dissipated energy

Multi messenger approach for non-thermal processes

Relativistic populations and radiative processes in clusters:



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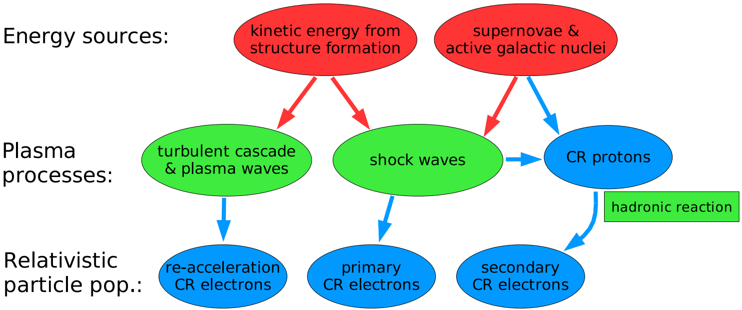

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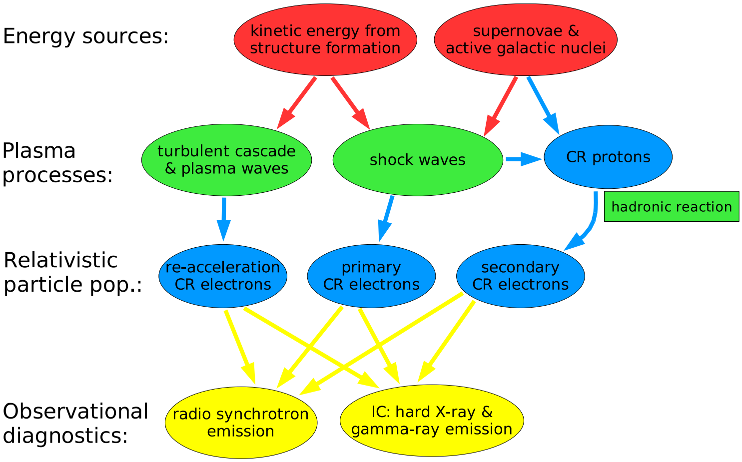

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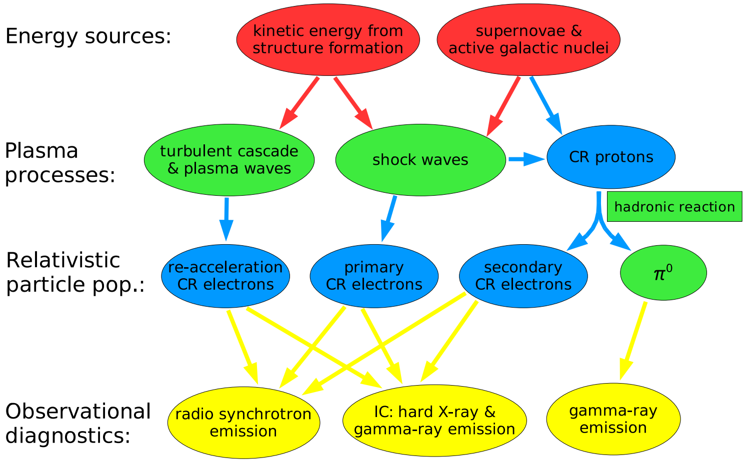
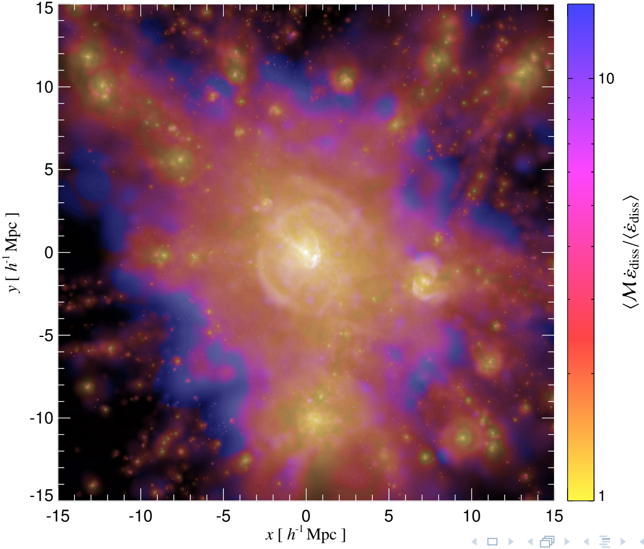
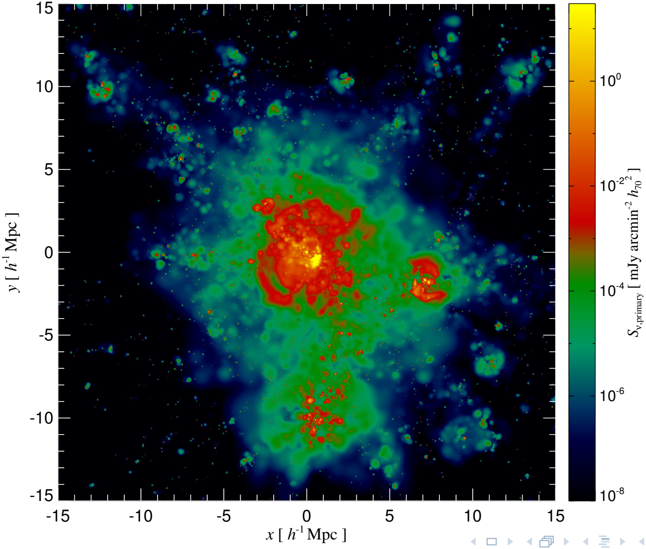


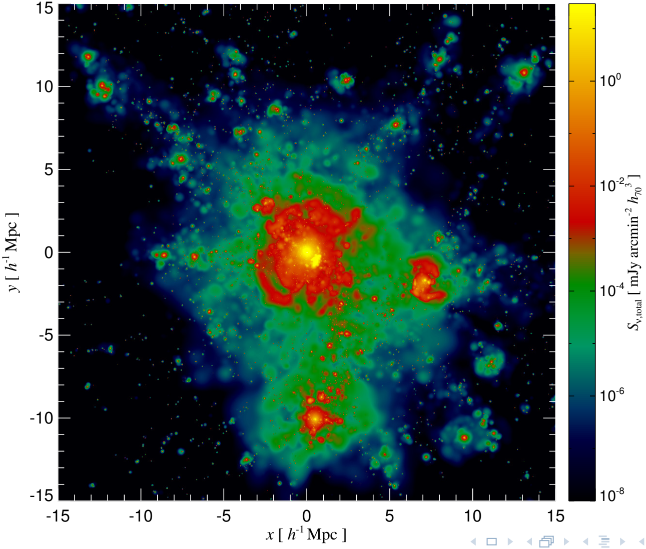
Structure formation shocks



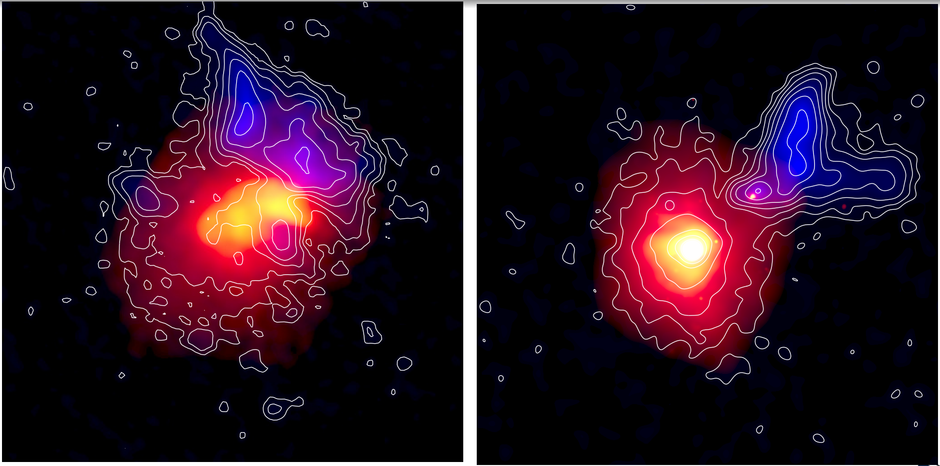
Radio gischt: shock-accelerated CRe



Radio gischt + central hadronic halo = giant radio halo

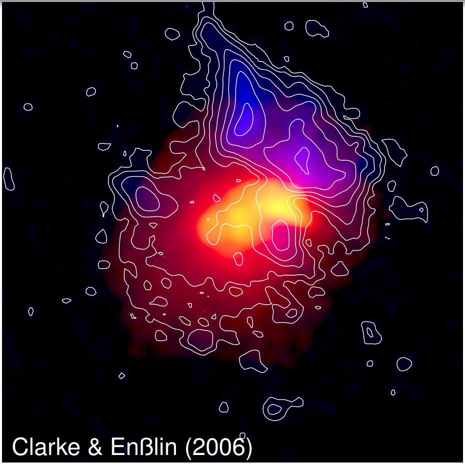


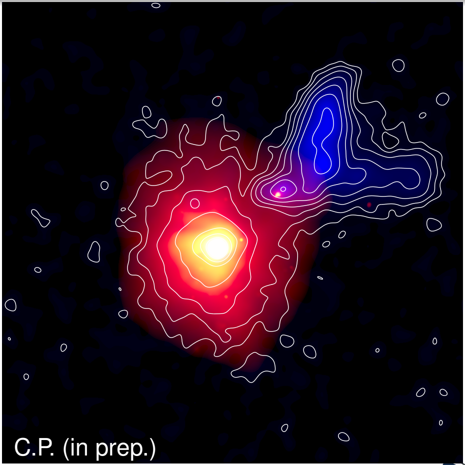
Which one is the simulation/observation of A2256?



red/yellow: thermal X-ray emission,
blue/contours: 1.4 GHz radio emission with giant radio halo and relic

Observation – simulation of A2256





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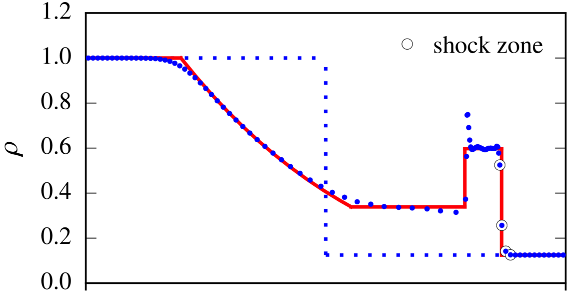
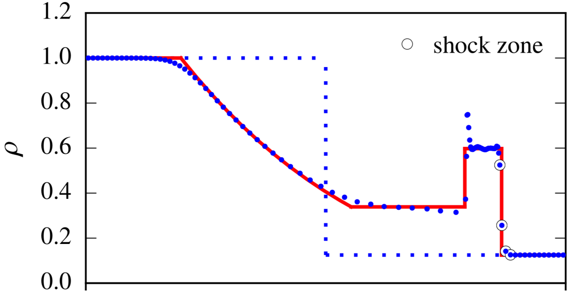
Shock finder



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

Shock finder

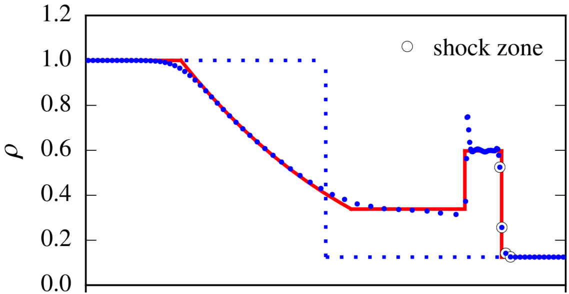


C.P., Pakmor, Schaal, Simpson, Springel (2017)

Voronoi cells belong to **shock zone** if

- $\nabla \cdot \boldsymbol{v} < 0$ (converging flow)
- $\nabla T \cdot \nabla \rho > 0$ (filtering out tangential discontinuities)
- $\mathcal{M}_1 > \mathcal{M}_{\mathrm{min}}$ (safeguard against numerical noise)

Shock finder and CR acceleration

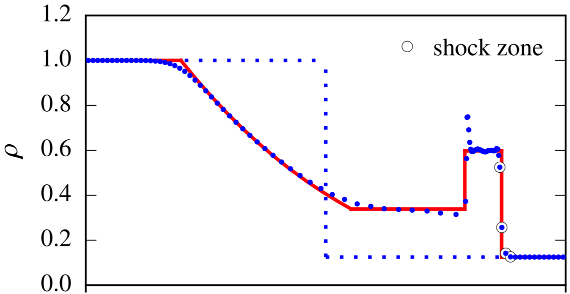


C.P., Pakmor, Schaal, Simpson, Springel (2017)

CR acceleration:

- **shock surface:** cell with most converging flow

Shock finder and CR acceleration



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

CR acceleration:

- **shock surface:** cell with most converging flow
- collect pre- and post-shock energy at shock surface $\Rightarrow E_{\text{diss}}$
- inject $\Delta E_{\text{cr}} = \zeta(\mathcal{M}_1, \theta)\, E_{\text{diss}}$ to shock and 1[st] post-shock cell

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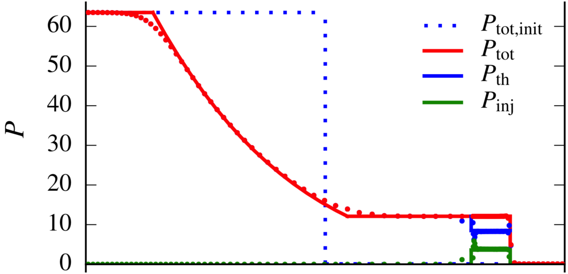
Shock finder and CR acceleration



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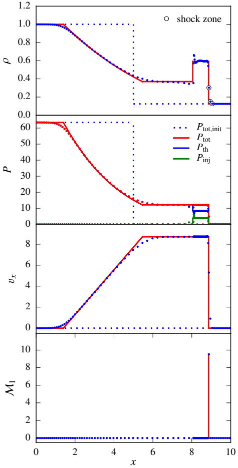
Shock finder and CR acceleration

Comparing simulations to novel exact solutions that include CR acceleration



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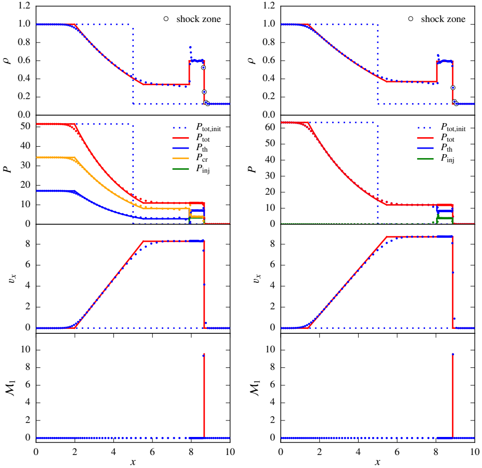

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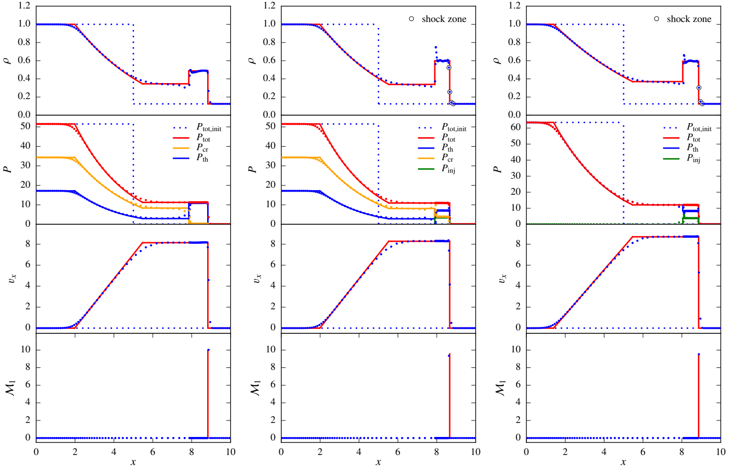

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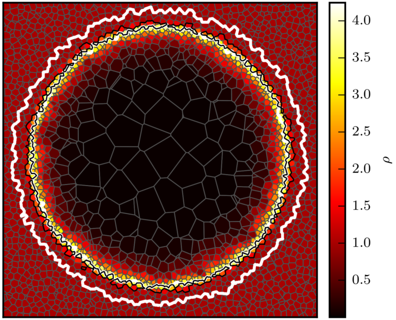

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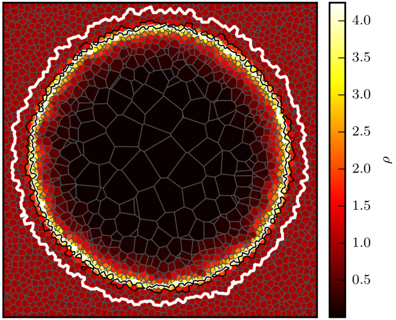
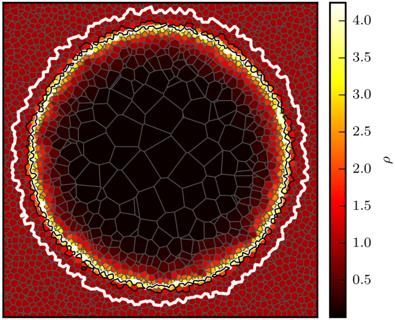


C.P., Pakmor, Schaal, Simpson, Springel (2017)

CR acceleration:

- **shock surface:** cell with most converging flow along ∇T

Shock finder and CR acceleration



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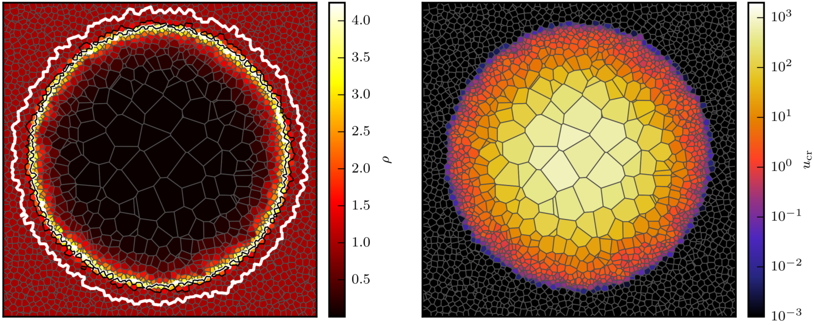
Shock finder and CR acceleration



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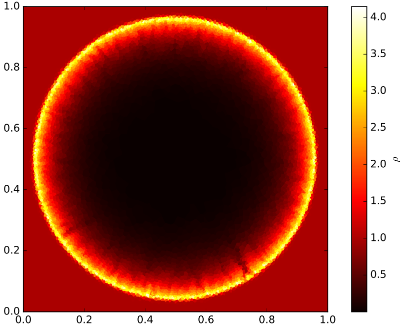
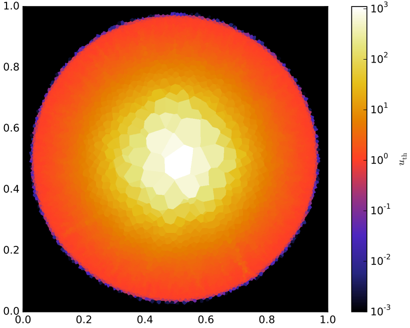
Sedov explosion

density



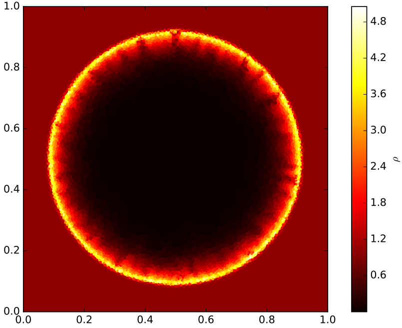
specific thermal energy



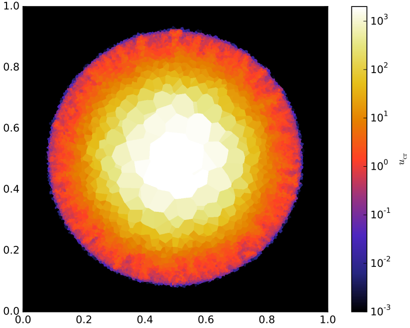
C.P., Pakmor, Schaal, Simpson, Springel (2017)

Sedov explosion with CR acceleration

density



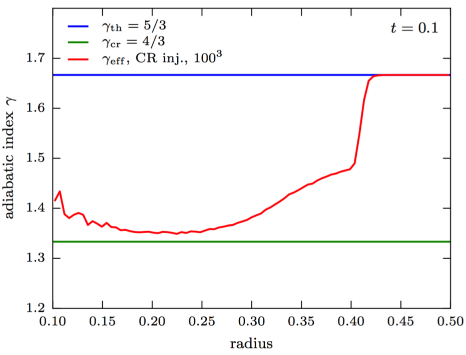
specific cosmic ray energy



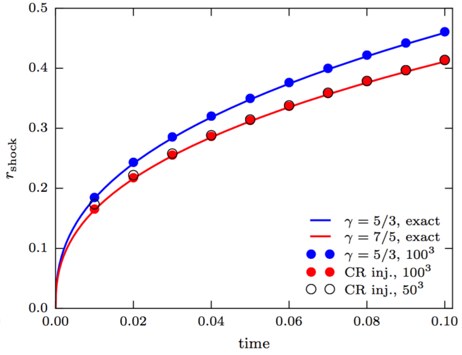
C.P., Pakmor, Schaal, Simpson, Springel (2017)

Sedov explosion with CR acceleration

adiabatic index



shock evolution



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

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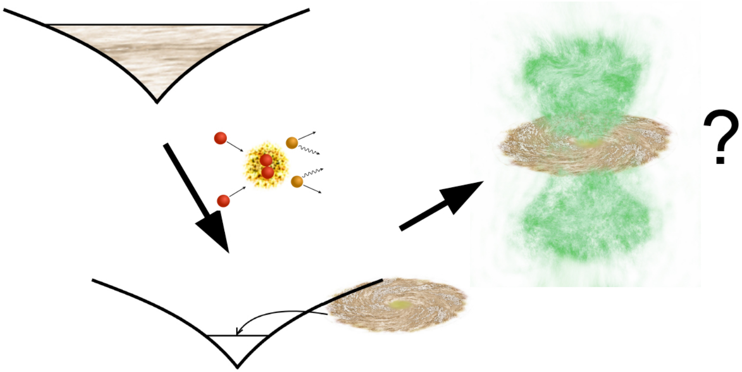
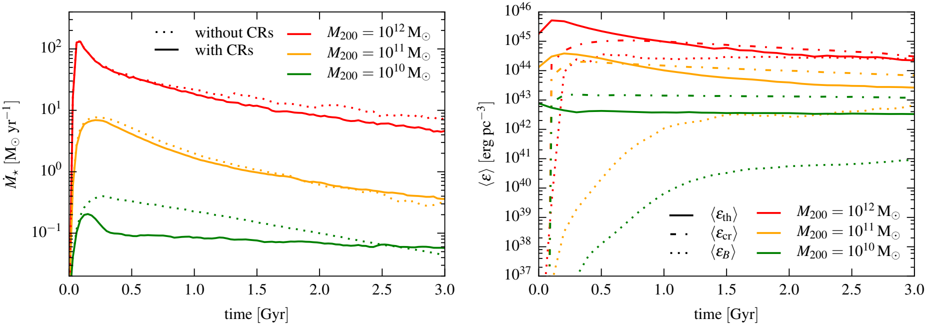
Galaxy simulation setup: 1. cosmic ray advection



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

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

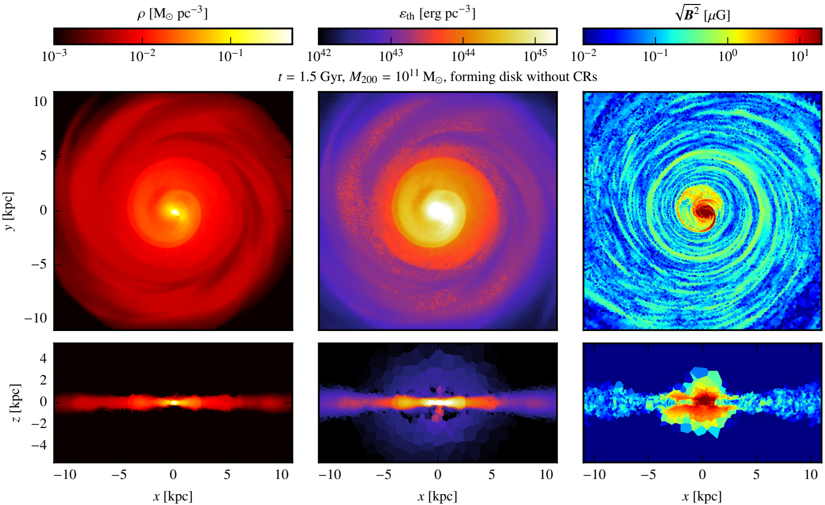
Time evolution of SFR and energy densities



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

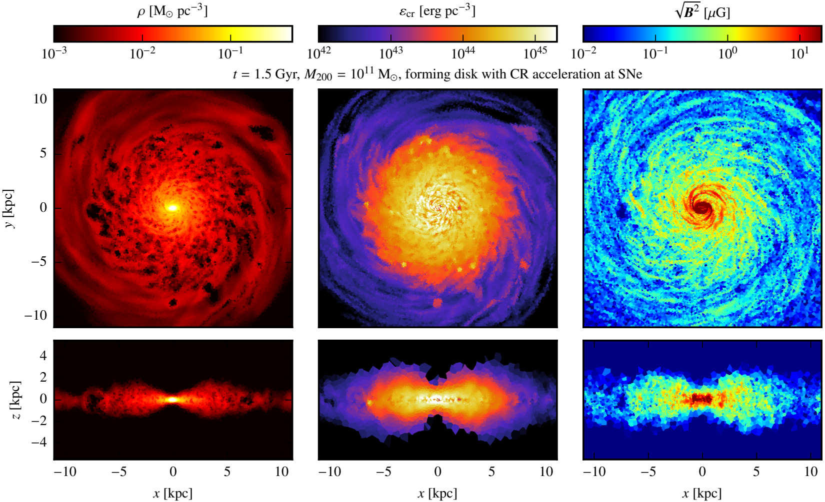
- CR pressure feedback suppresses SFR more in smaller galaxies
- energy budget in disks is dominated by CR pressure
- magnetic dynamo faster in Milky Way galaxies than in dwarfs

MHD galaxy simulation without CRs



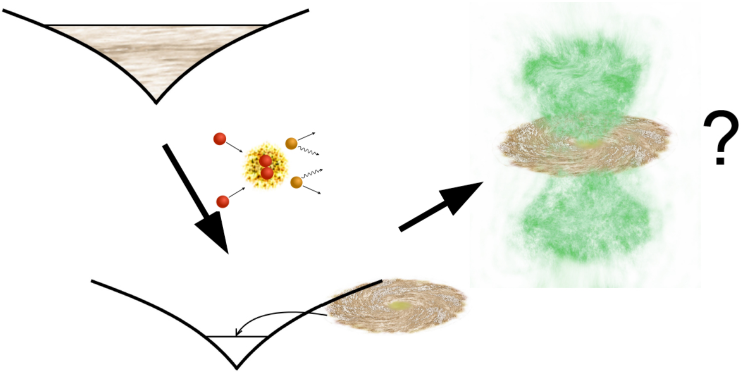
C.P., Pakmor, Schaal, Simpson, Springel (2017)

MHD galaxy simulation with CRs



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

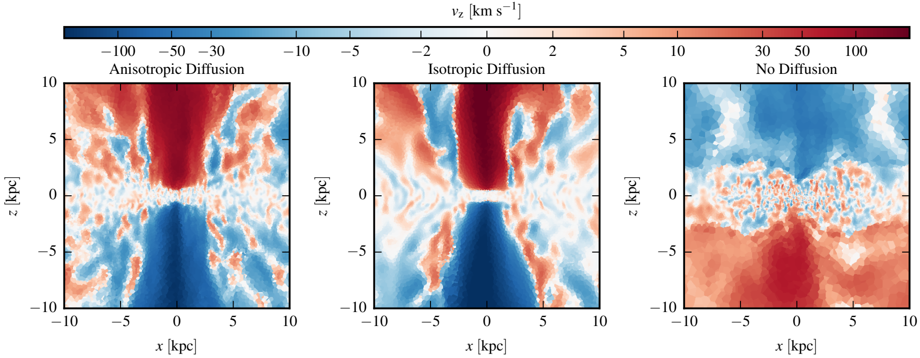
Galaxy simulation setup: 2. cosmic ray diffusion



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

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

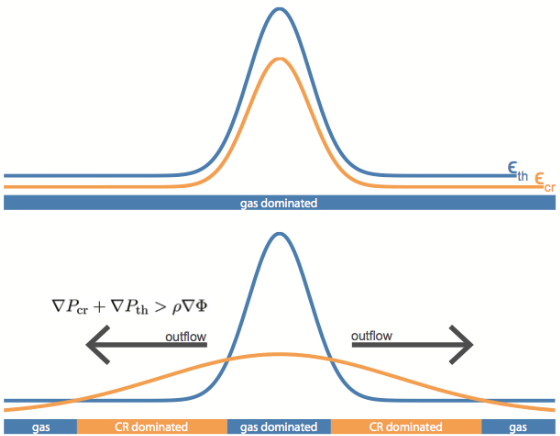
MHD galaxy simulation with CR diffusion



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

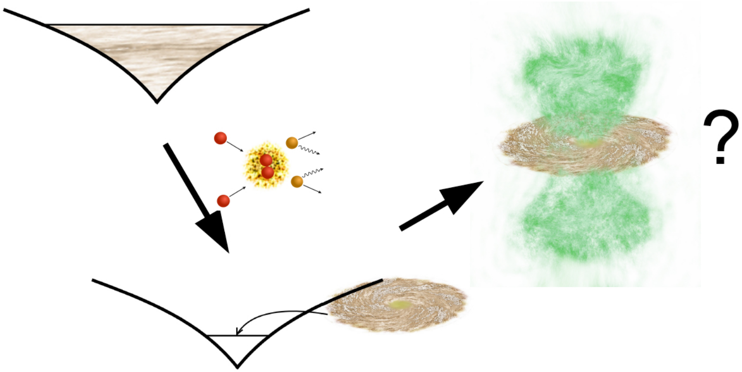
- CR diffusion launches powerful winds
- simulation without CR diffusion exhibits only weak fountain flows

Cosmic ray driven wind: mechanism



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

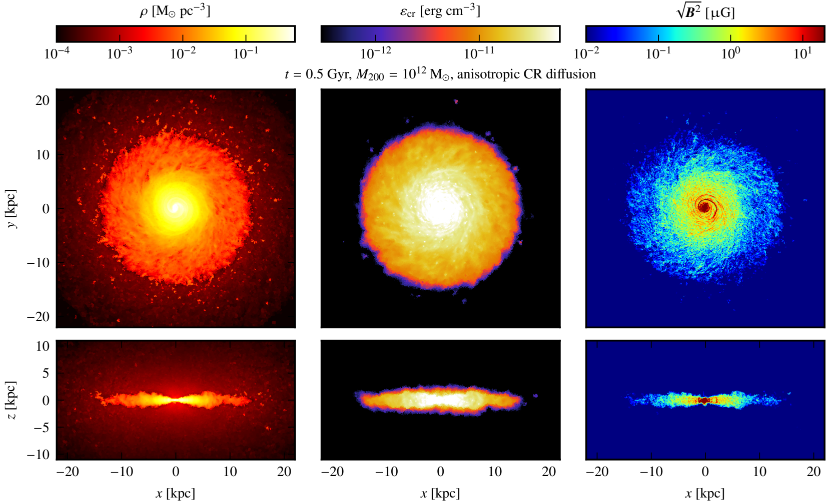
Galaxy simulation setup: 3. non-thermal emission



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

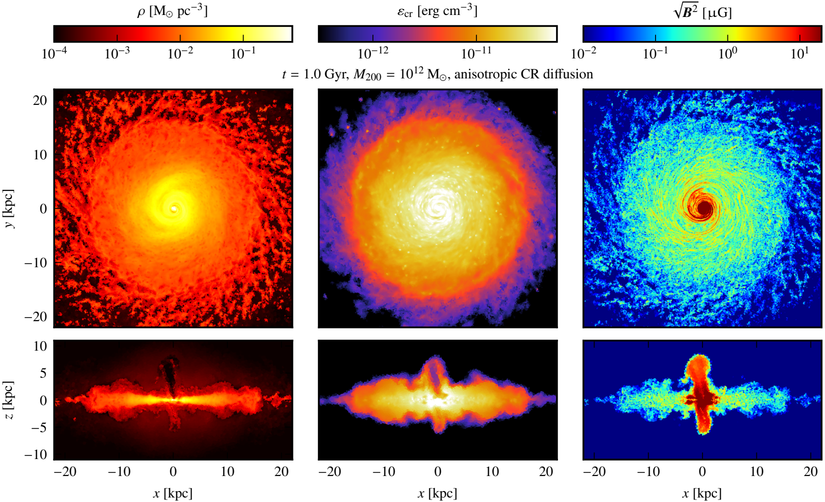
MHD + CR advection + diffusion: $\{10^{10}, 10^{11}, 10^{12}\}$ $M_\odot$

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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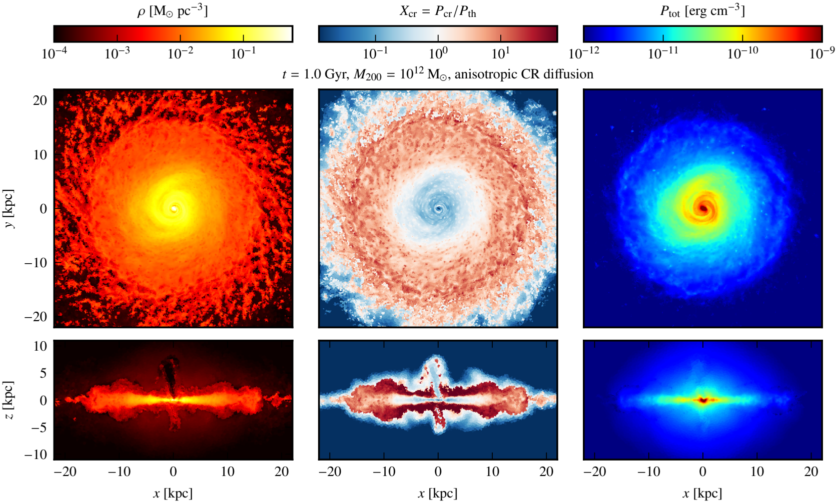
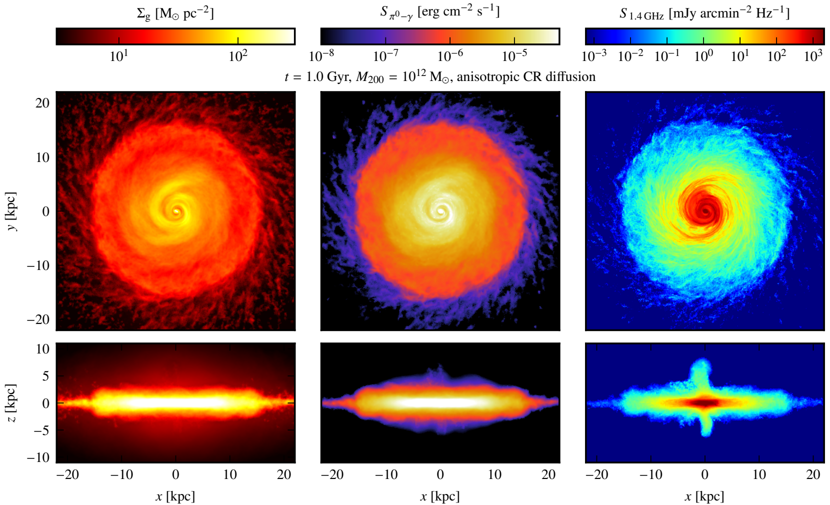


C.P.+ (2017a,b)

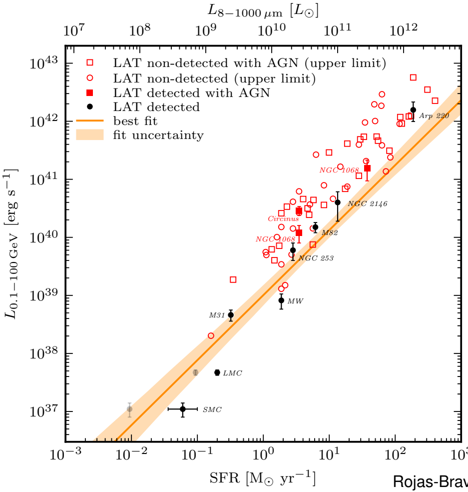
γ-ray and radio emission of Milky Way-like galaxy



C.P.+ (2017a,b)

Far infra-red – gamma-ray correlation

Universal conversion: star formation → cosmic rays → gamma rays

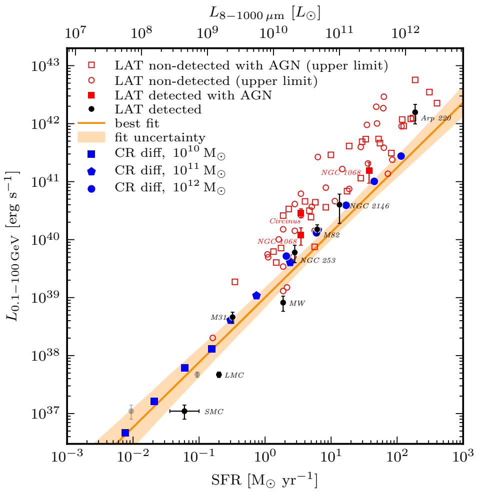


Rojas-Bravo & Araya (2016)

AIP

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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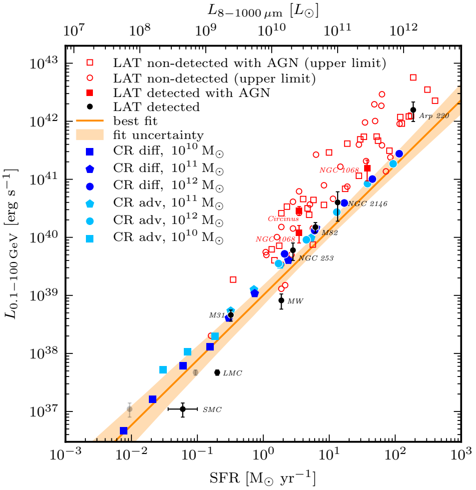

C.P.+ (2017a)

Far infra-red – gamma-ray correlation

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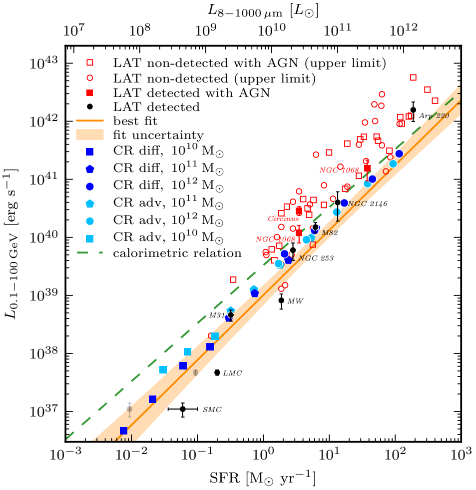


C.P.+ (2017a)

Conclusions

Cosmic ray shock acceleration in galaxies and clusters is critical for

- cosmic ray feedback in galaxies (and galaxy clusters)
- non-thermal emission (radio to gamma rays)

AIP

Conclusions

Cosmic ray shock acceleration in galaxies and clusters is critical for

- cosmic ray feedback in galaxies (and galaxy clusters)
- non-thermal emission (radio to gamma rays)
    - messengers to understand physics of shock-acceleration
    - key to understanding galaxy and cluster formation
    - characterizing galactic magnetism & cluster properties

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

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

Literature for the talk

Cosmological formation shocks and cluster simulations:

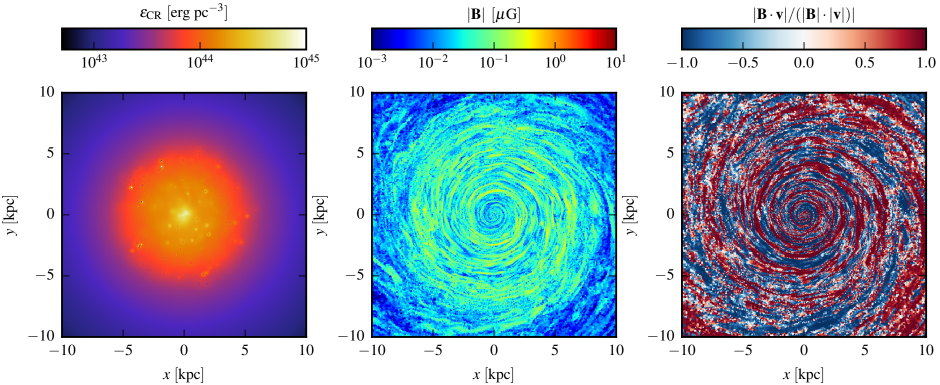
- Pfrommer, Springel, Enßlin, Jubelgas, *Detecting shock waves in cosmological smoothed particle hydrodynamics simulations,* 2006, MNRAS.
- Pfrommer, Springel, Enßlin, Jubelgas, Dolag, *Simulating cosmic rays in clusters of galaxies - I. Effects on the Sunyaev-Zel'dovich effect and the X-ray emission,* 2007, MNRAS.
- Pfrommer, Springel, Enßlin, *Simulating cosmic rays in clusters of galaxies - II. A unified scenario for radio halos and relics with predictions of the gamma-ray emission,* 2008, MNRAS.
- Pfrommer, *Simulating cosmic rays in clusters of galaxies - III. Non-thermal scaling relations and comparison to observations,* 2008, MNRAS.

Cosmic ray feedback in galaxies:

- Pfrommer, Pakmor, Schaal, Simpson, Springel, *Simulating cosmic ray physics on a moving mesh,* 2017, MNRAS.
- Pfrommer, Pakmor, Simpson, Springel, *Simulating Gamma-ray Emission in Star-forming Galaxies,* 2017, ApJL.
- Pakmor, Pfrommer, Simpson, Springel, *Galactic winds driven by isotropic and anisotropic cosmic ray diffusion in isolated disk galaxies,* 2016, ApJL.

Additional slides

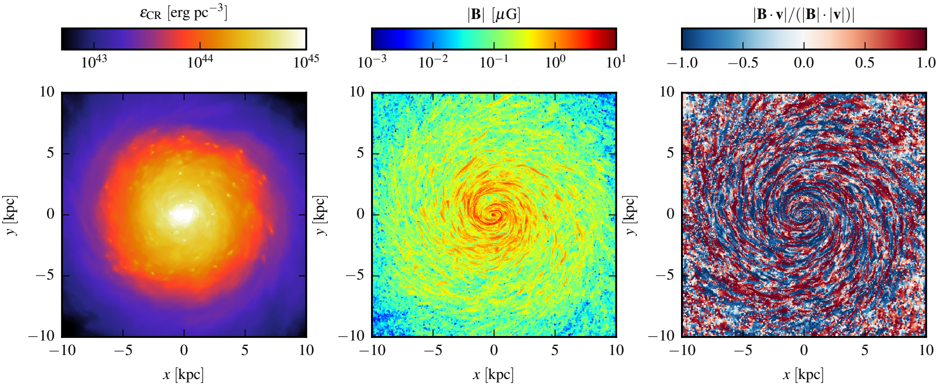
MHD galaxy simulation with CR isotropic diffusion



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

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

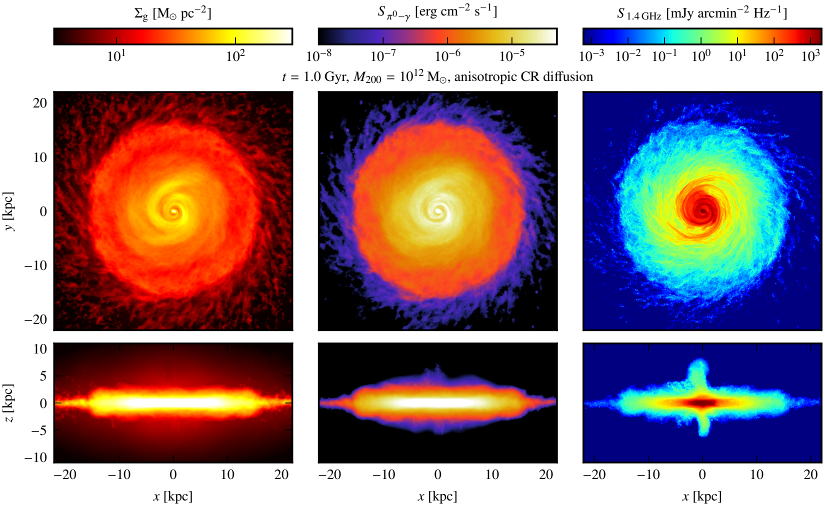
MHD galaxy simulation with CR anisotropic diffusion



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

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

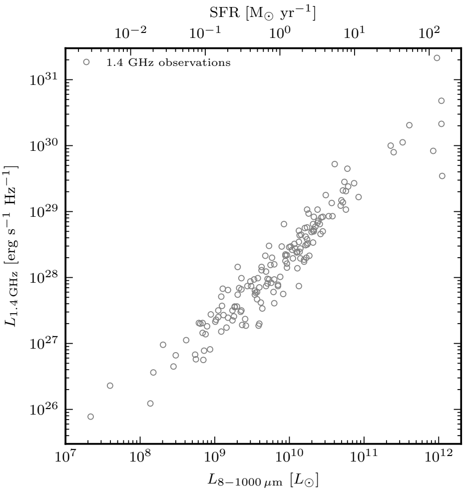
γ-ray and radio emission of Milky Way-like galaxy



C.P.+ (2017a,b)

Far infra-red – radio correlation

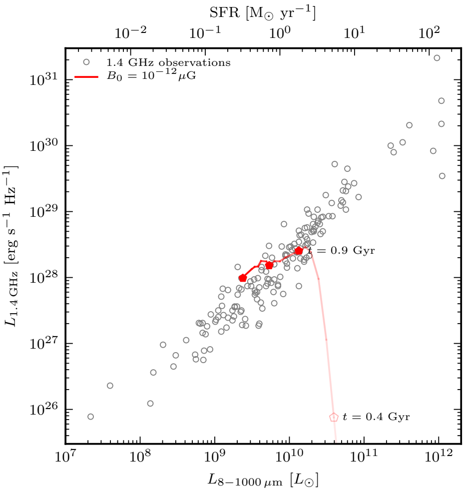
Universal conversion: star formation → cosmic rays → radio



Bell (2003)

Far infra-red – radio correlation

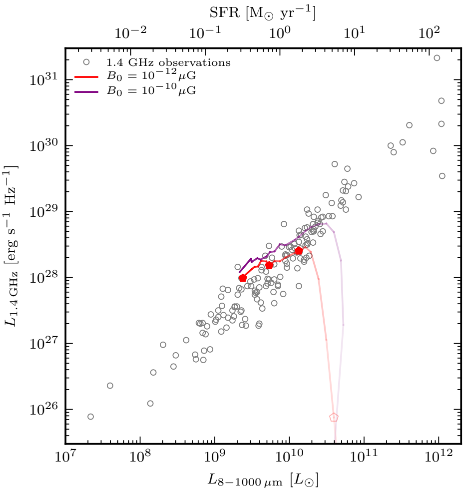
Universal conversion: star formation → cosmic rays → radio



Bell (2003)

Far infra-red – radio correlation

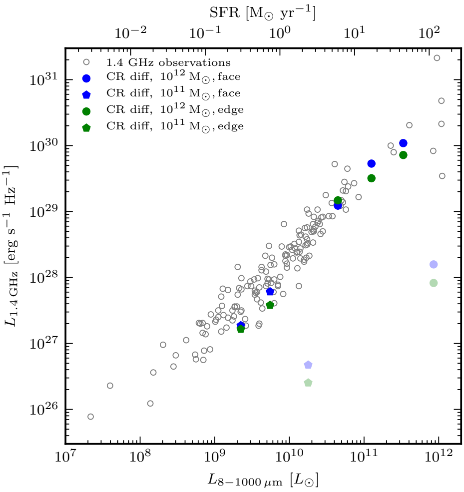
Universal conversion: star formation → cosmic rays → radio



Bell (2003)

Far infra-red – radio correlation

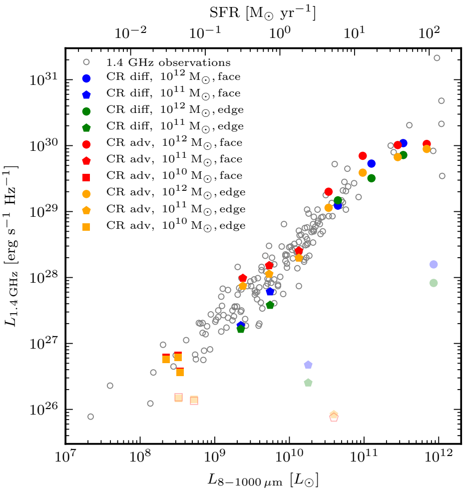
Universal conversion: star formation → cosmic rays → radio



C.P.+ (2017b)

Far infra-red – radio correlation

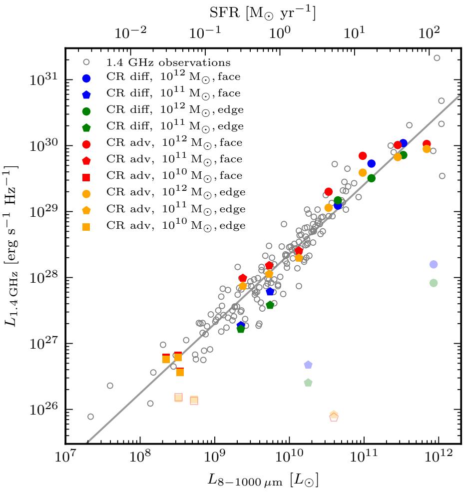
Universal conversion: star formation → cosmic rays → radio



C.P.+ (2017b)

Far infra-red – radio correlation

Universal conversion: star formation → cosmic rays → radio



C.P.+ (2017b)