The role of cosmic rays in galaxy formation

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in collaboration with

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Max-Planck-Princeton Research Center for Plasma Physics – 2017

Outline

1. Introduction
    - Galactic winds
    - Cosmic ray physics
    - Simulated physical processes
2. Simuating galaxies
    - Supernova explosions
    - Interstellar medium
    - Galaxy formation

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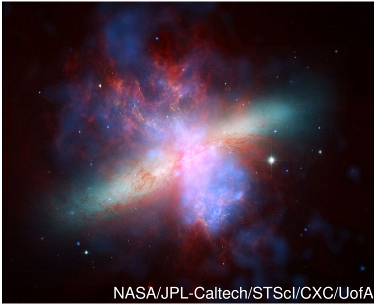
How are galactic winds driven?


NASA/JPL-Caltech/STScI/CXC/UofA

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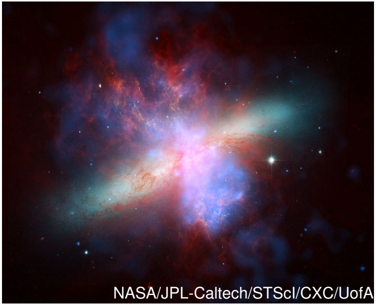
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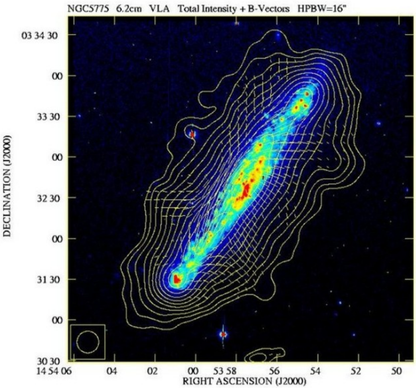
observed energy equipartition between cosmic rays, thermal gas and magnetic fields
→ suggests self-regulated feedback loop with CR driven winds

Why are CRs important for wind formation?

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

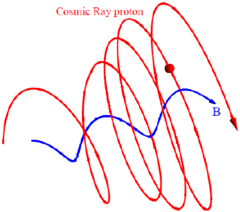


Tüllmann+ (2000)

- 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

Interactions of CRs and magnetic fields

- CRs scatter on magnetic fields → isotropization of CR momenta
- **CR streaming instability:** Kulsrud & Pearce 1969
  - if $v_{\rm cr} > v_{\rm A}$, CR current provides steady driving force, which amplifies an Alfvén wave field in resonance with the gyroradii of CRs
  - scattering off of this wave field limits the (GeV) CRs' bulk speed $\sim v_{\rm A}$
  - wave damping: transfer of CR energy and momentum to the thermal gas



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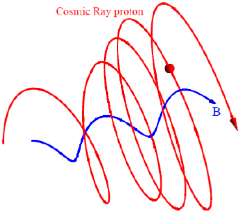

→ CRs exert a pressure on the thermal gas by means of scattering off of Alfvén waves

CR transport

- total CR velocity $\boldsymbol{v}_{\rm cr} = \boldsymbol{v} + \boldsymbol{v}_{\rm st} + \boldsymbol{v}_{\rm di}$ (where $\boldsymbol{v} \equiv \boldsymbol{v}_{\rm gas}$)
- 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 $\boldsymbol{B}$):

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

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

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

CR transport

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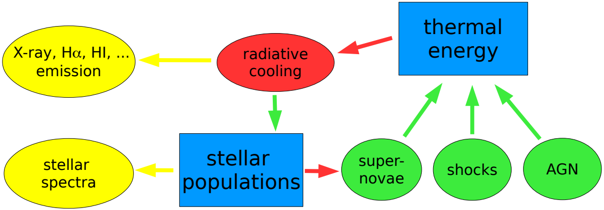
\Longleftrightarrow \quad \frac{\partial\varepsilon_{\rm cr}}{\partial t} + \nabla\cdot\left[\varepsilon_{\rm cr}(\boldsymbol{v} + \boldsymbol{v}_{\rm st} + \boldsymbol{v}_{\rm di})\right] &= -P_{\rm cr}\nabla\cdot(\boldsymbol{v} + \boldsymbol{v}_{\rm st})
\end{aligned}$$

Simulations – flowchart

observables:

physical processes:



thermal energy

X-ray, Hα, HI, ... emission

radiative cooling

stellar spectra

stellar populations

super-novae

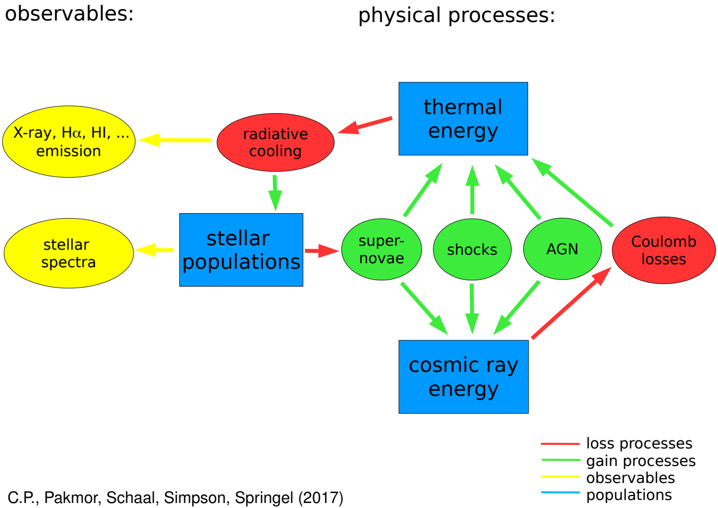
shocks

AGN

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

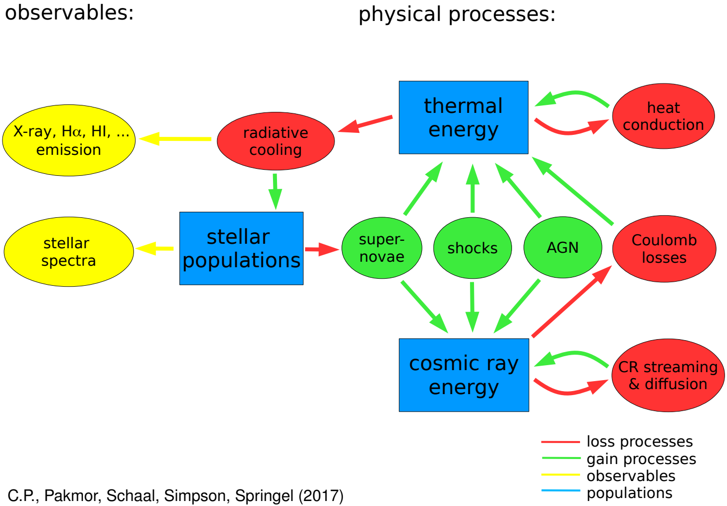
- 🟥 loss processes
- 🟩 gain processes
- 🟨 observables
- 🟦 populations

Simulations with cosmic ray physics



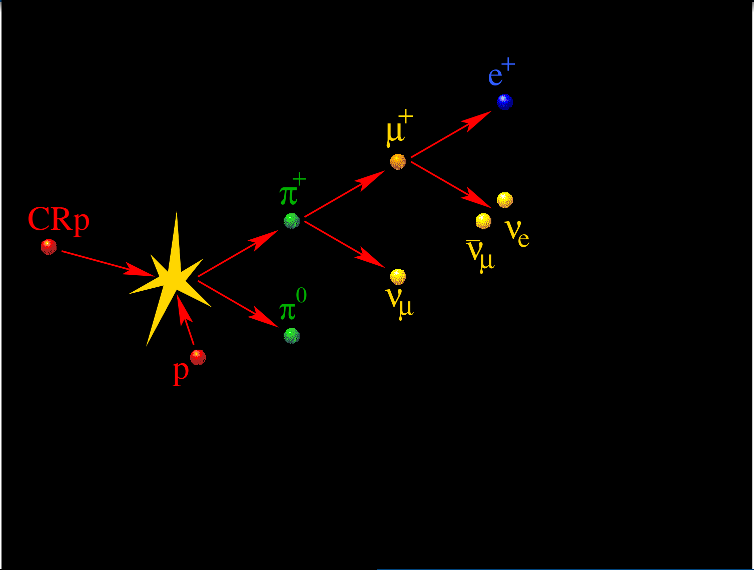
C.P., Pakmor, Schaal, Simpson, Springel (2017)

Simulations with cosmic ray physics



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

Hadronic cosmic ray proton interaction



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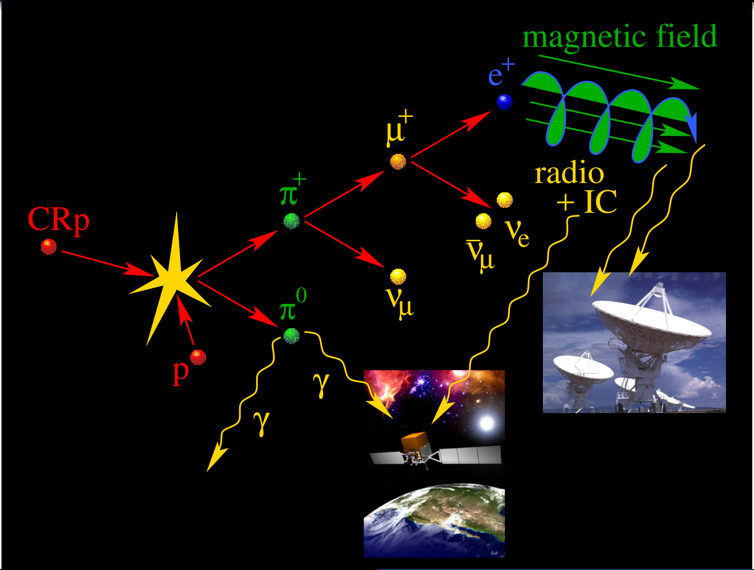
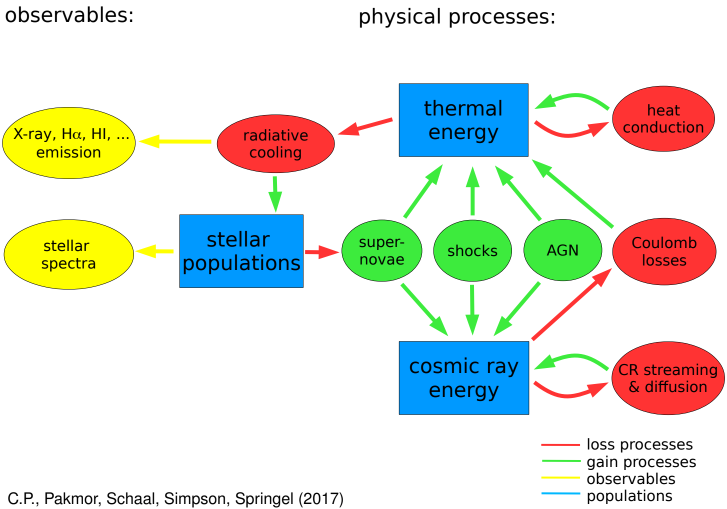


Simulations with cosmic ray physics



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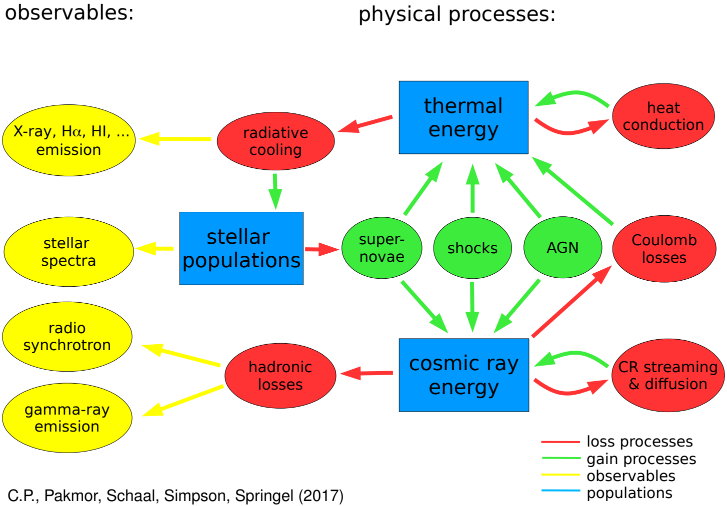
Simulations with cosmic ray physics



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

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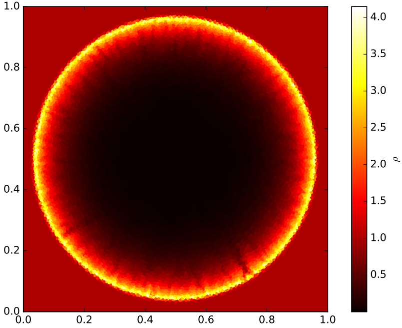
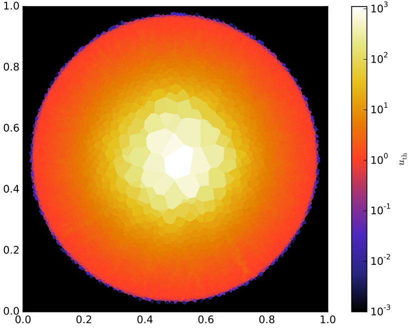
Sedov explosion

density

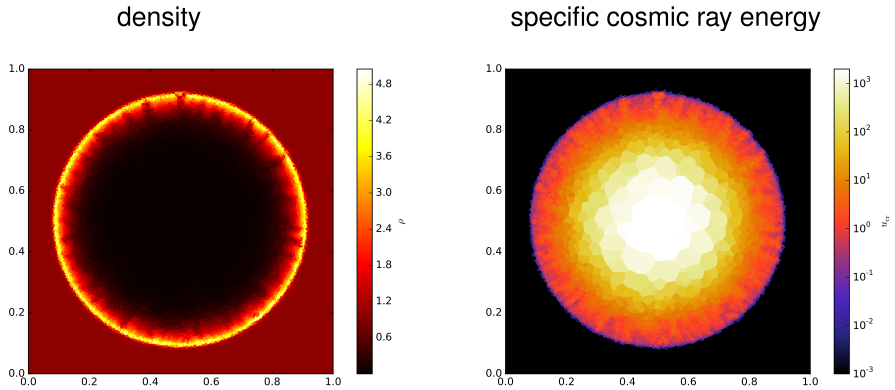


specific thermal energy



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

Sedov explosion with CR acceleration



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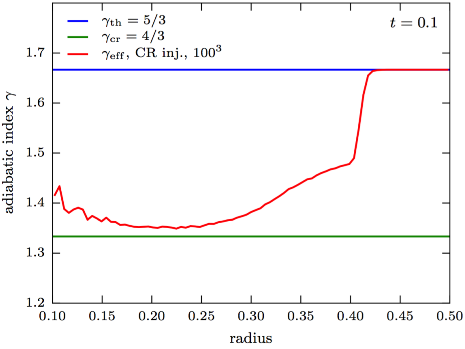
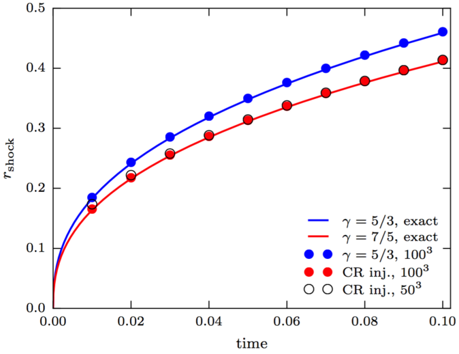
Sedov explosion with CR acceleration

adiabatic index



shock evolution



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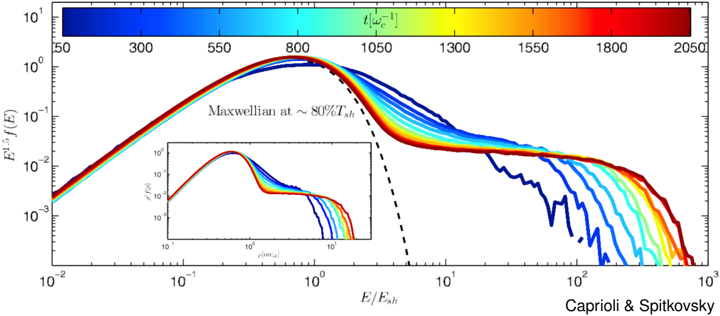
Ion spectrum

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

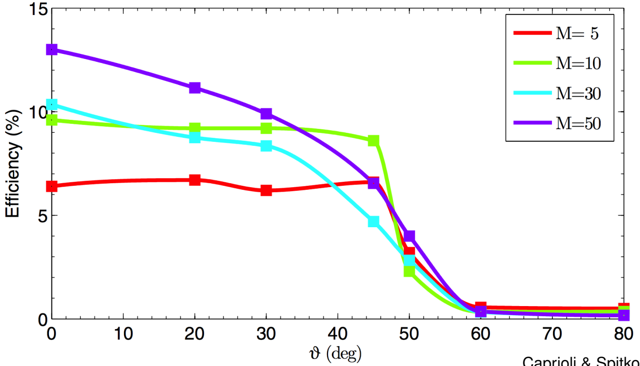


Caprioli & Spitkovsky (2014)

- 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

Ion acceleration efficiencies

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

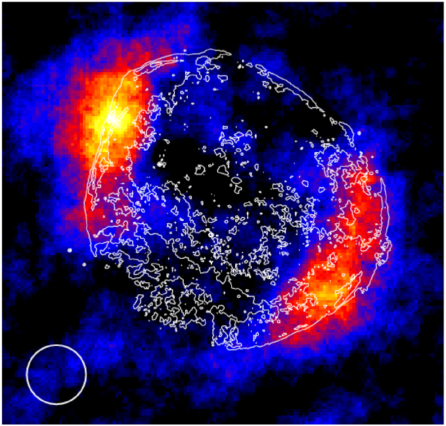


Caprioli & Spitkovsky (2014)

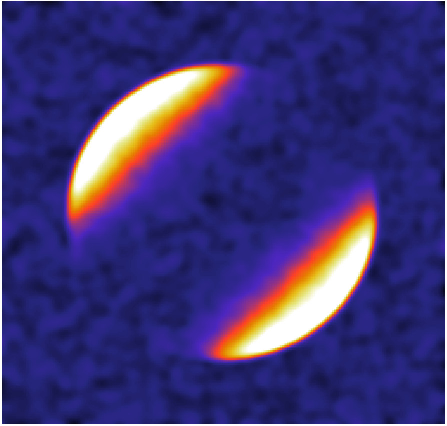
- quasi-parallel shocks accelerate ions
- quasi-perpendicular shocks cannot
- transition occurs at obliquity of $\vartheta \sim 45^\circ$

TeV γ rays from shell-type SNRs: SNR 1006

H.E.S.S. observation



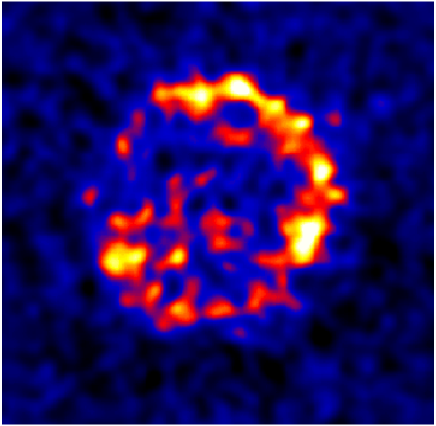
AREPO simulation



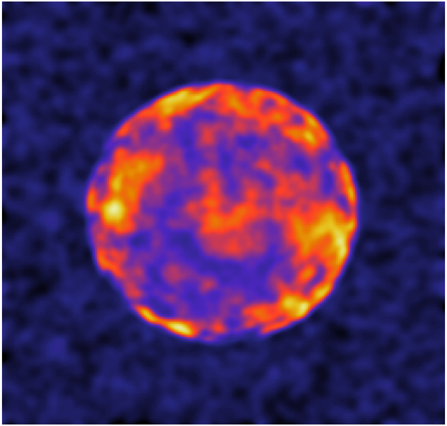
Pais, C.P., Ehlert (in prep.)

TeV γ rays from shell-type SNRs: Vela Junior

H.E.S.S. observation



AREPO simulation



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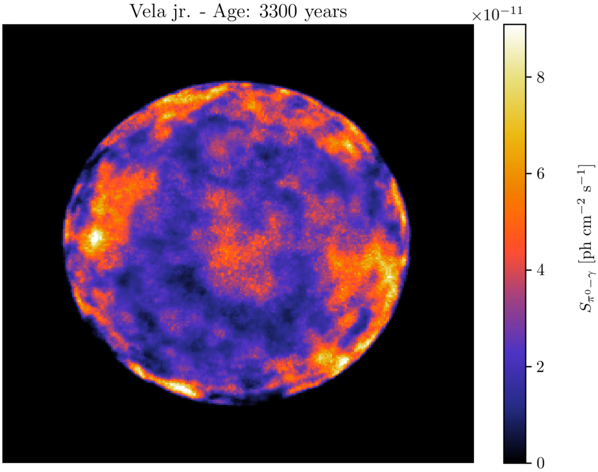
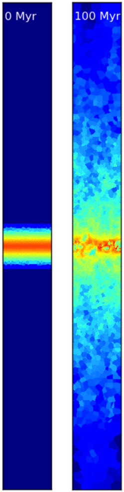
TeV γ rays from shell-type SNRs: Vela Junior



A model for the multi-phase interstellar medium

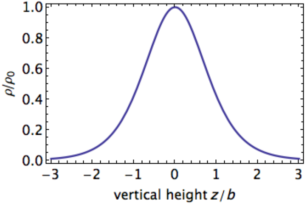
Explore supernovae-driven outflows at high resolution – stratified box simulations



Simpson+ (2016)

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

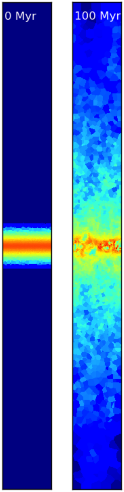
$$f_g \nabla^2 \Phi = 4\pi G \rho$$



- 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



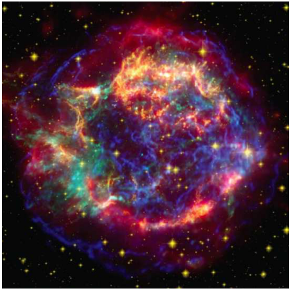
Simpson+ (2016)

- star formation rate:

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

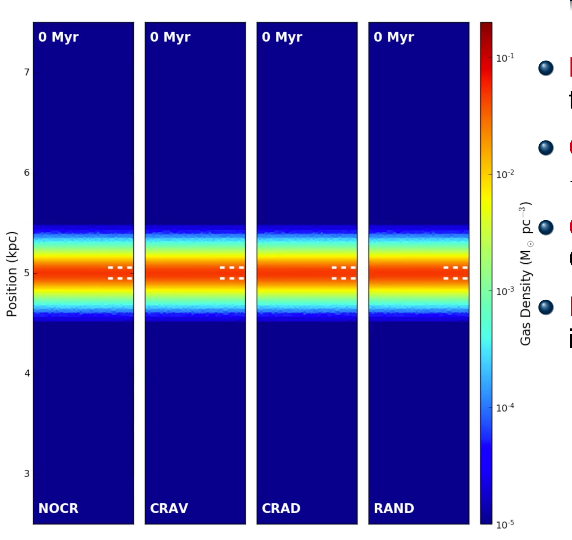
- supernova rate:

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



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

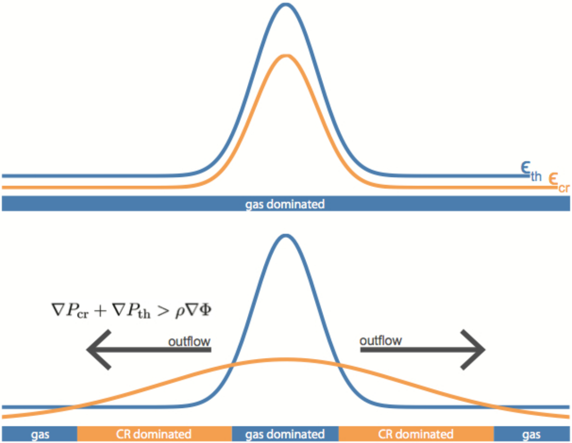
Interstellar medium – turbulence and outflows



Simpson+ (2016)

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

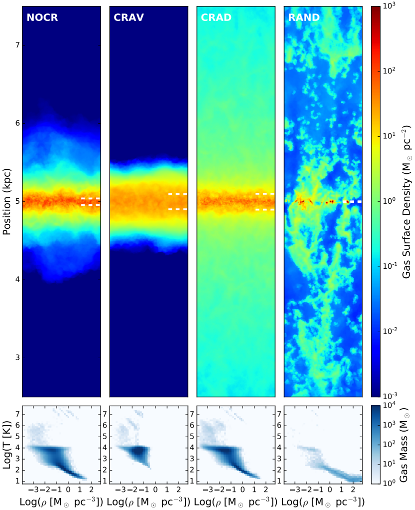
Cosmic ray driven wind: mechanism



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

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

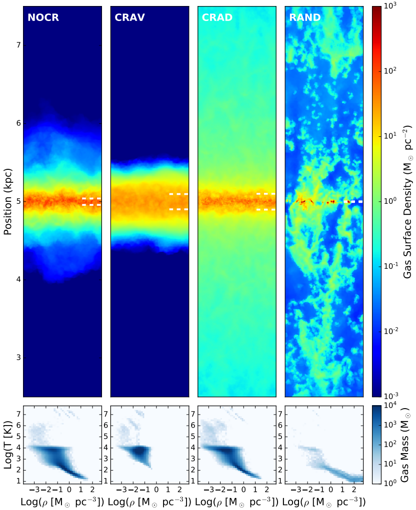
Interstellar medium – turbulence and outflows



Simpson+ (2016)

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

Interstellar medium – turbulence and outflows



Simpson+ (2016)

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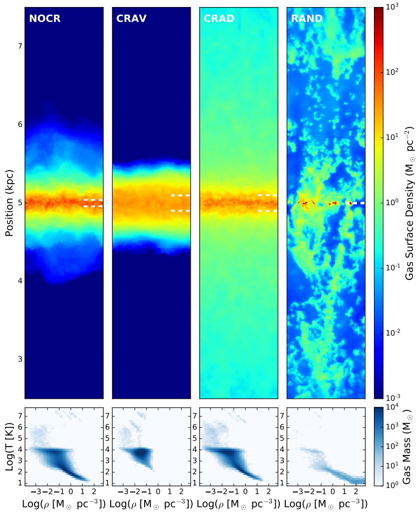
- different forcing: CR pressure gradient (CRAD) vs. kinetic pressure gradients propelling a ballistic outflow (RAND)
→ velocity and clumpiness differ

Interstellar medium – turbulence and outflows

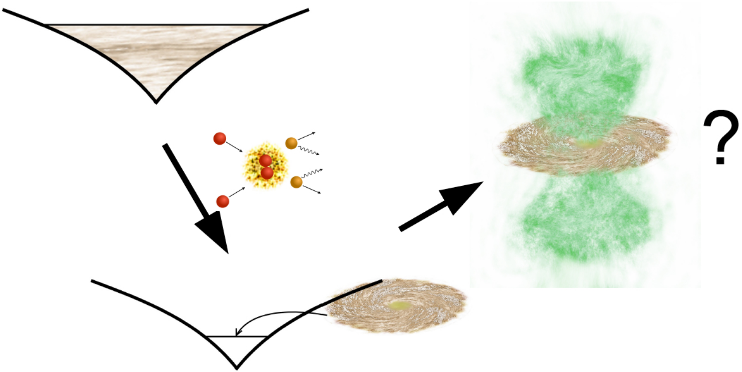


Simpson+ (2016)

- 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 $h_{1/2} \approx 100$ pc; ISM in RAND collapses to dense phase

⇒ **CR physics is essential for correctly modeling the ISM!**

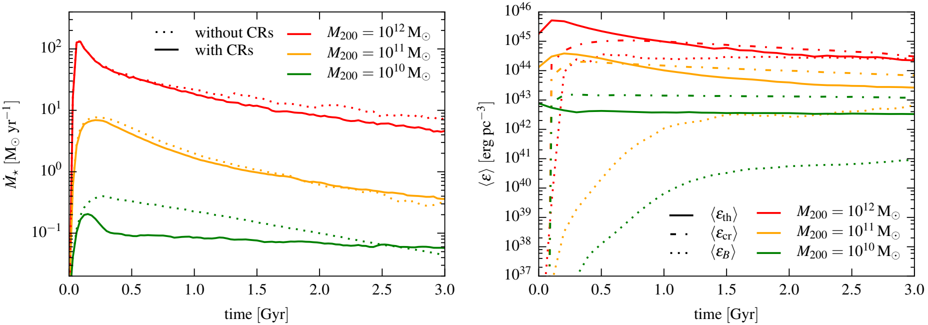
Galaxy simulation setup: 1. cosmic ray advection



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

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

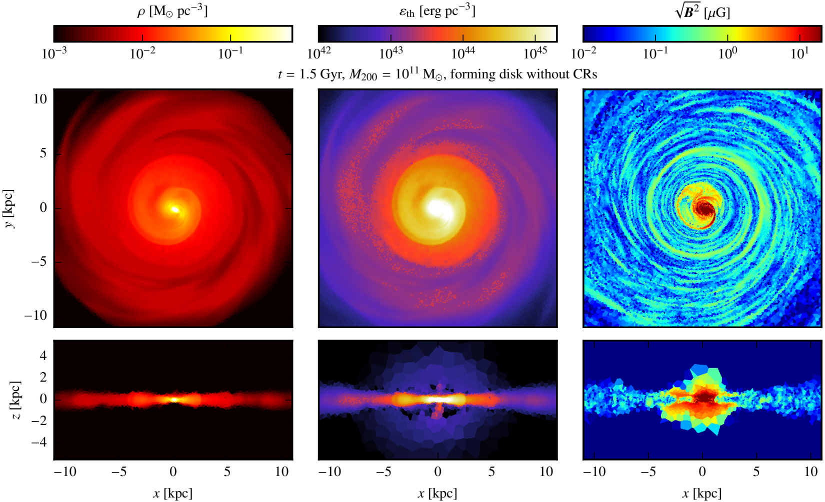
Time evolution of SFR and energy densities



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

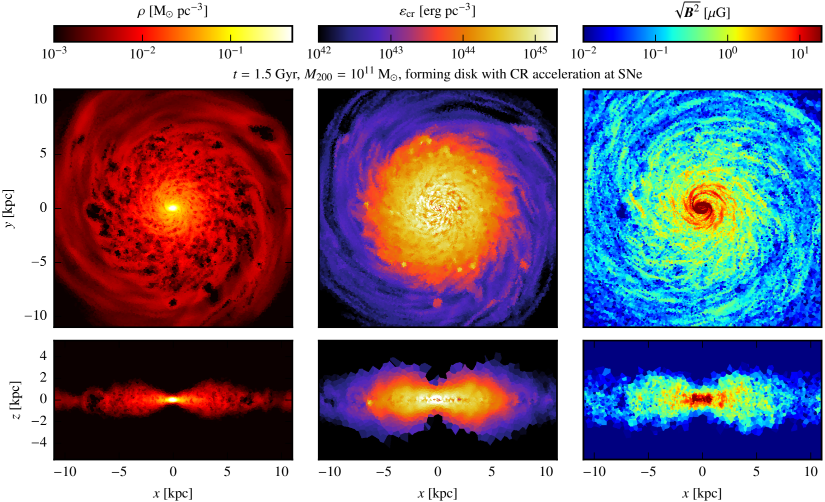
- CR pressure feedback suppresses SFR more in smaller galaxies
- energy budget in disks is dominated by CR pressure
- magnetic dynamo faster in Milky Way galaxies than in dwarfs

MHD galaxy simulation without CRs



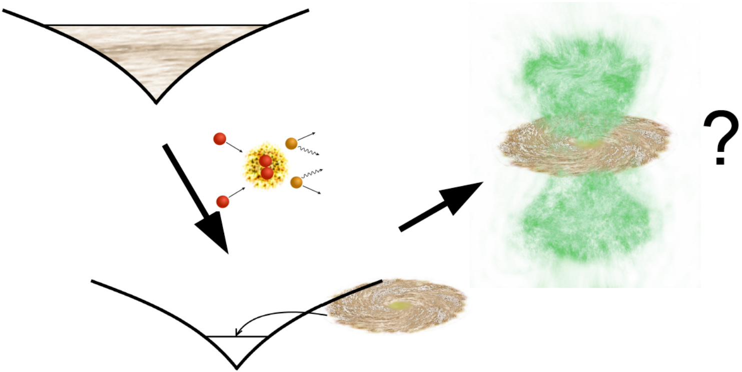
C.P., Pakmor, Schaal, Simpson, Springel (2017)

MHD galaxy simulation with CRs



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

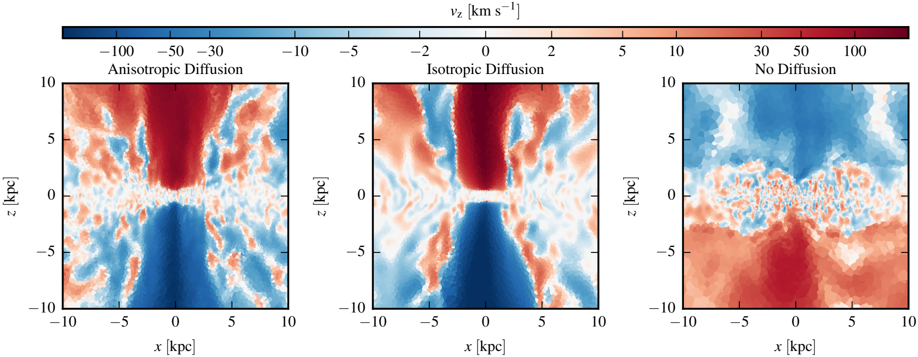
Galaxy simulation setup: 2. cosmic ray diffusion



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

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

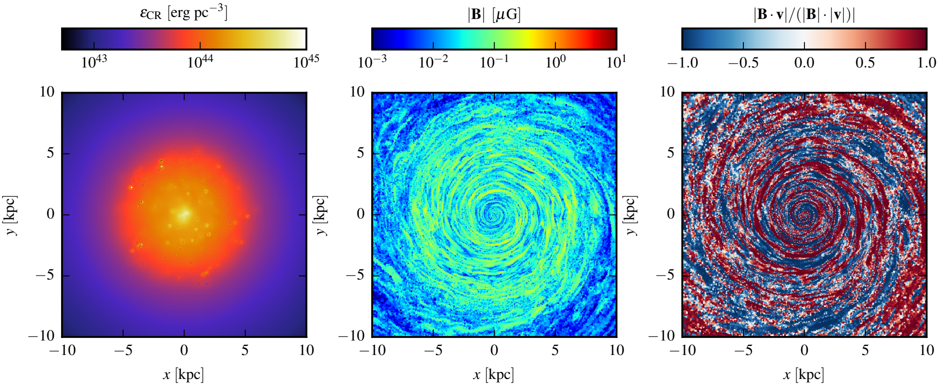
MHD galaxy simulation with CR diffusion



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

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

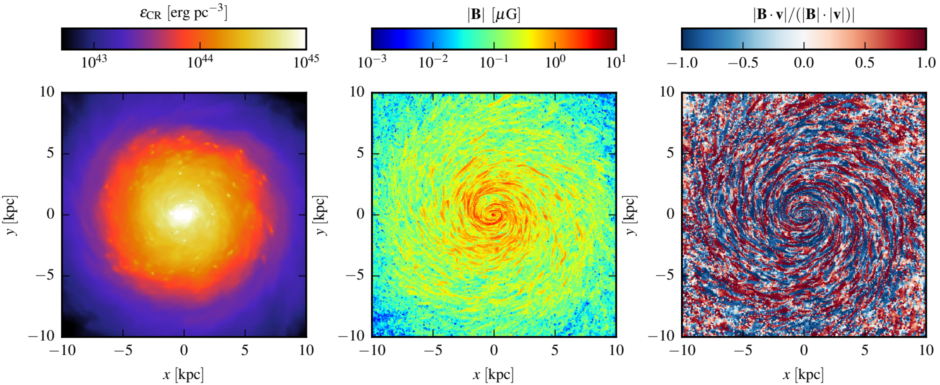
MHD galaxy simulation with CR isotropic diffusion



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

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

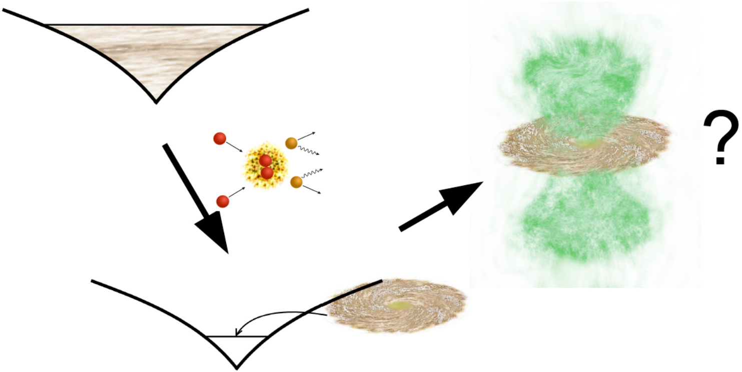
MHD galaxy simulation with CR anisotropic diffusion



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

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

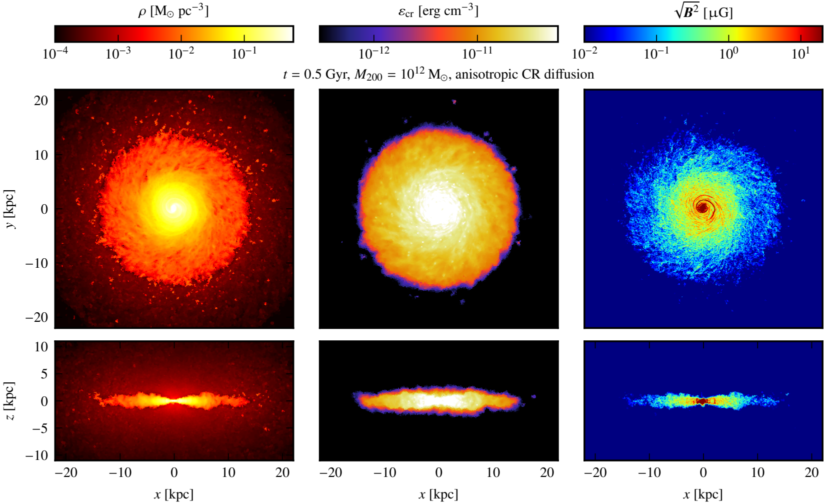
Galaxy simulation setup: 3. non-thermal emission



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

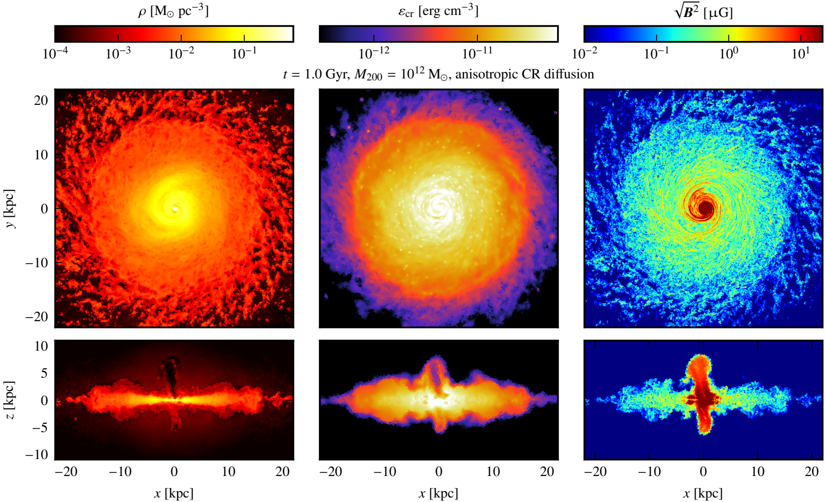
MHD + CR advection + diffusion: $\left\{10^{10}, 10^{11}, 10^{12}\right\}\ \mathrm{M}_\odot$

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



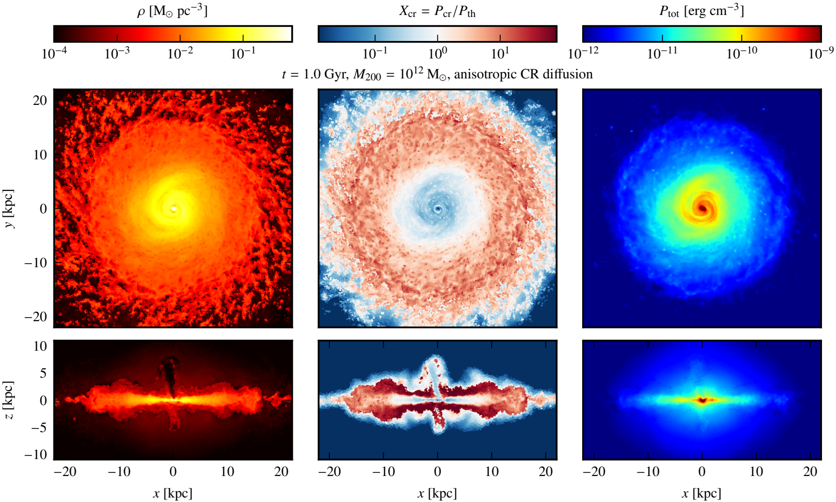
C.P.+ (2017a,b)

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



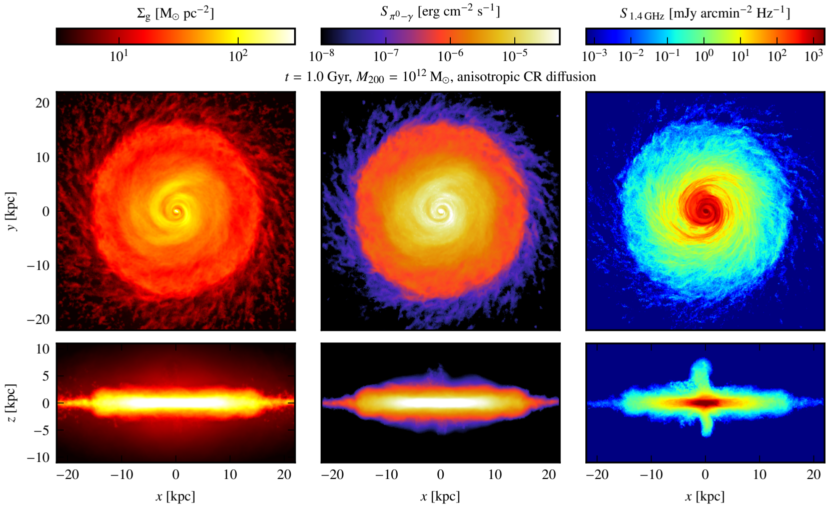
C.P.+ (2017a,b)

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



C.P.+ (2017a,b)

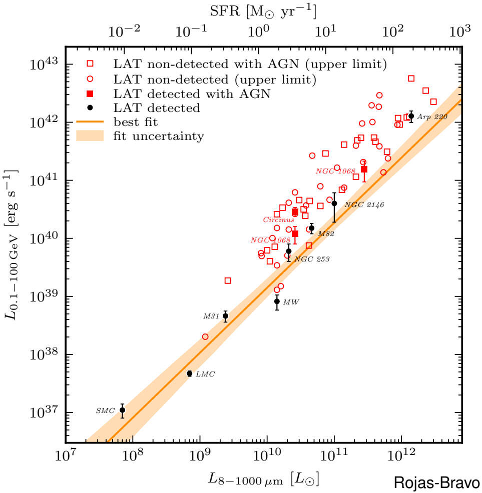
γ-ray and radio emission of Milky Way-like galaxy



C.P.+ (2017a,b)

Far infra-red – gamma-ray correlation

Universal conversion: star formation → cosmic rays → gamma rays



Rojas-Bravo & Araya (2016)

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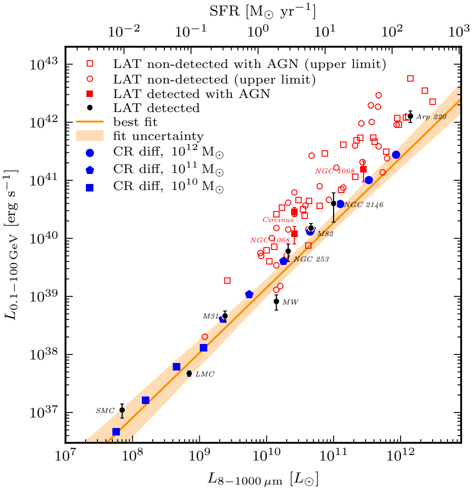

C.P.+ (2017a)

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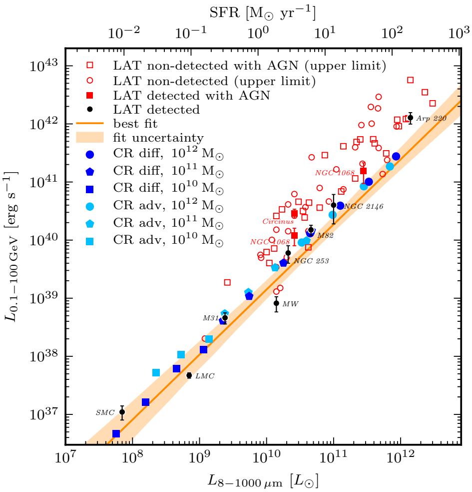

C.P.+ (2017a)

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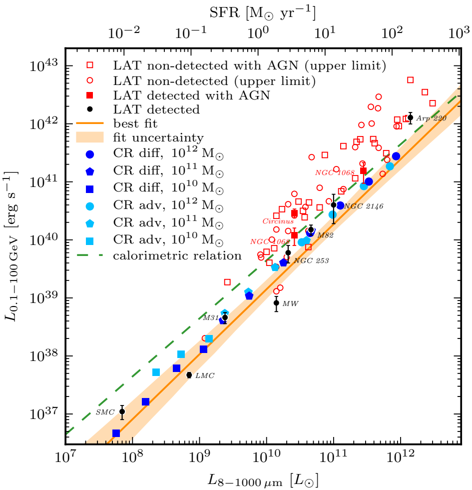
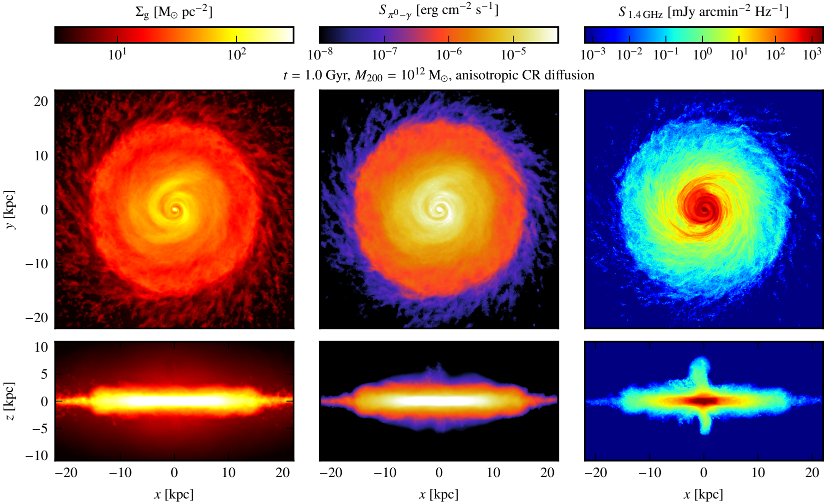


C.P.+ (2017a)

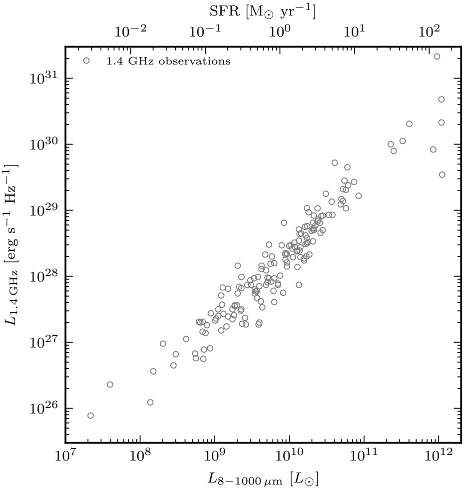
γ-ray and radio emission of Milky Way-like galaxy



C.P.+ (2017a,b)

Far infra-red – radio correlation

Universal conversion: star formation → cosmic rays → radio



Bell (2003)

Far infra-red – radio correlation

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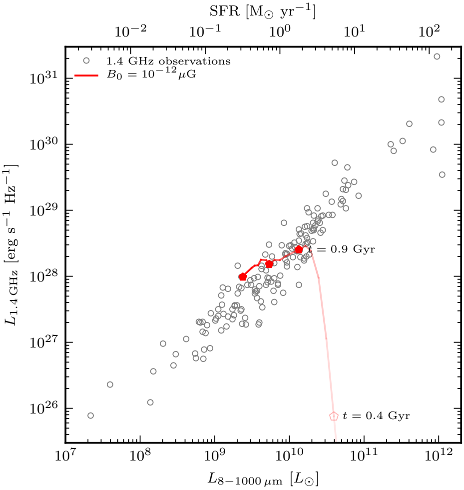
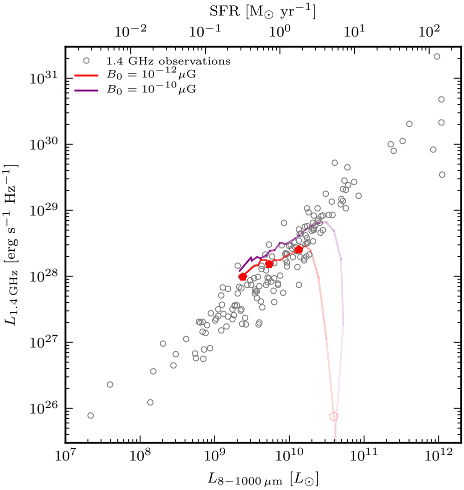


Bell (2003)

Far infra-red – radio correlation

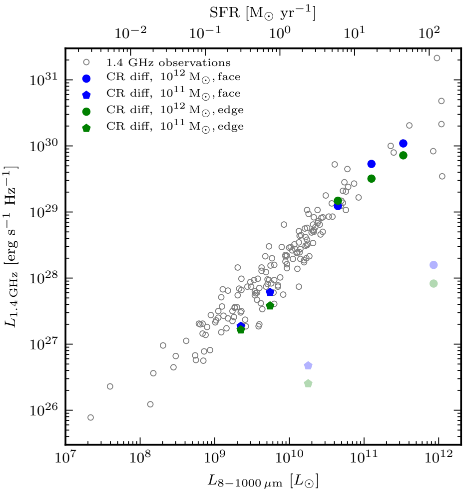
Universal conversion: star formation → cosmic rays → radio



Bell (2003)

Far infra-red – radio correlation

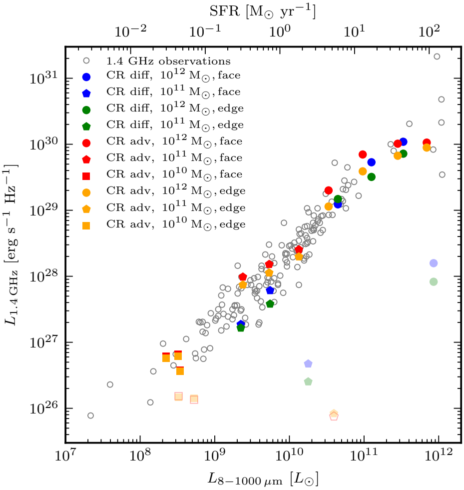
Universal conversion: star formation → cosmic rays → radio



C.P.+ (2017b)

Far infra-red – radio correlation

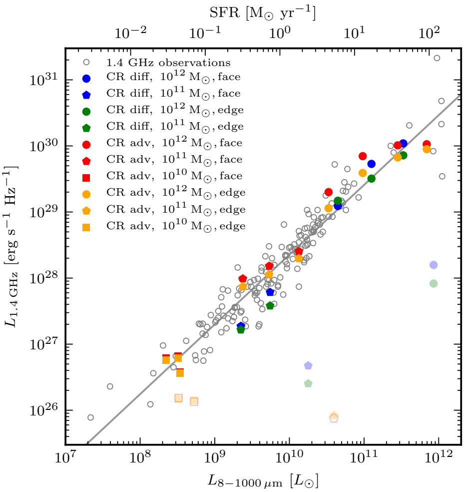
Universal conversion: star formation → cosmic rays → radio



C.P.+ (2017b)

Far infra-red – radio correlation

Universal conversion: star formation → cosmic rays → radio



C.P.+ (2017b)

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

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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

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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, ApJL.
- 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.