Cosmic rays, particle acceleration, and γ-ray constraints on star and galaxy formation

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in collaboration with

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International Fermi Symposium, Garmisch-Partenkirchen – 2017

Outline

1. Introduction
   - Galaxy formation
   - Cosmic ray physics
   - Simulated physical processes

2. Galaxy simulations
   - Supernova explosions
   - Interstellar medium
   - Galaxy formation

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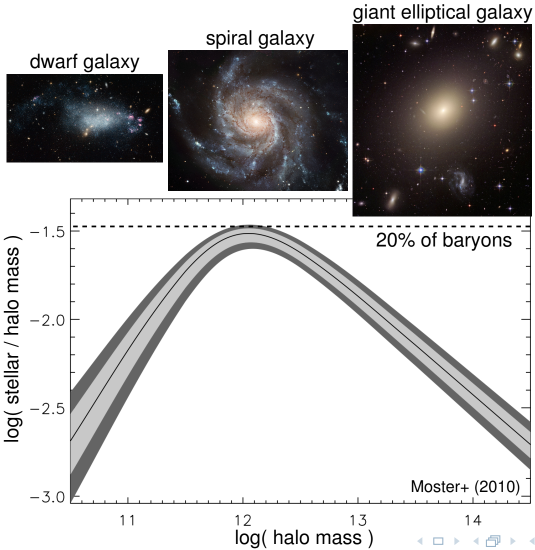
Puzzles in galaxy formation

Puzzles in galaxy formation

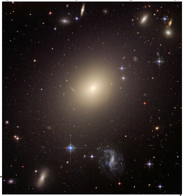


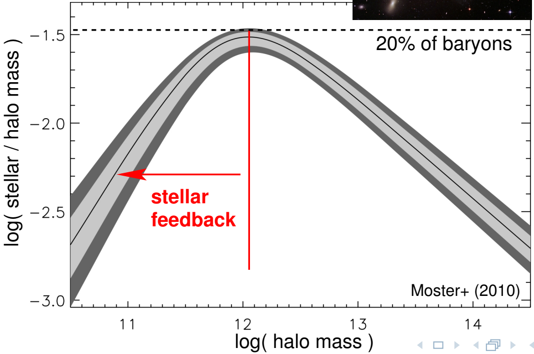
Puzzles in galaxy formation

dwarf galaxy

spiral galaxy

giant elliptical galaxy





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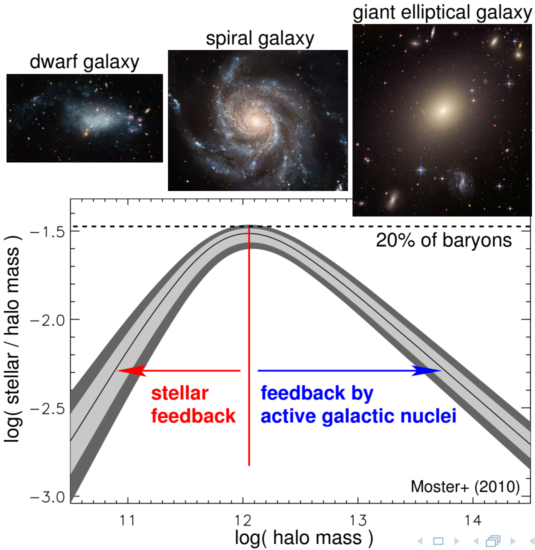
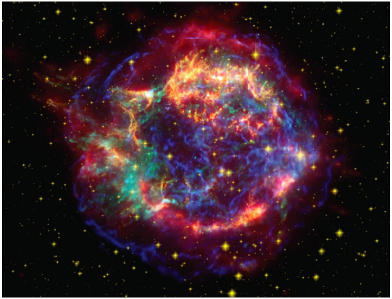


Feedback by galactic winds



supernova Cassiopeia A

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

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

Feedback by galactic winds

super wind in M82

NASA/JPL-Caltech/STScI/CXC/UofA

- galactic supernova remnants drive shock waves, turbulence, accelerate electrons + protons, amplify magnetic fields
- star formation and supernovae drive gas out of galaxies by galactic super winds

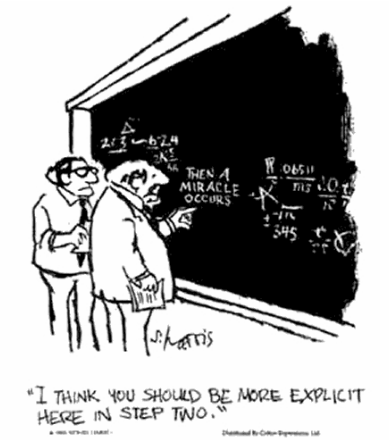
Feedback by galactic winds

super wind in M82

NASA/JPL-Caltech/STScI/CXC/UofA

- galactic supernova remnants drive shock waves, turbulence, accelerate electrons + protons, amplify magnetic fields
- star formation and supernovae drive gas out of galaxies by galactic super winds
- critical for understanding the physics of galaxy formation $\rightarrow$ may explain puzzle of low star conversion efficiency in dwarf galaxies

Feedback by galactic winds



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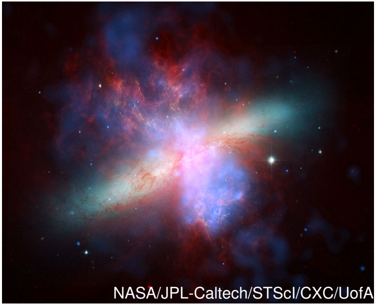
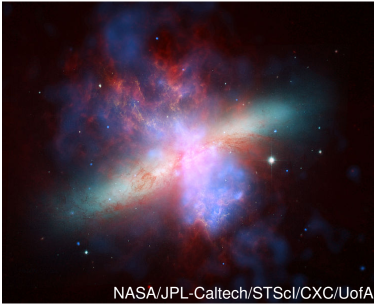
How are galactic winds driven?



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?

How are galactic winds driven?



super wind in M82

- thermal pressure provided by supernovae or AGNs?
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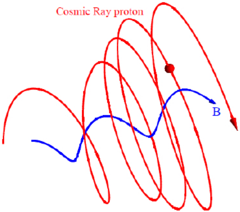
- cosmic-ray (CR) pressure and Alfvén wave heating of CRs accelerated at supernova shocks?

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

Interactions of CRs and magnetic fields

- CRs scatter on magnetic fields $\rightarrow$ isotropization of CR momenta
- **CR streaming instability:** Kulsrud & Pearce 1969
  - if $v_{\mathrm{cr}} > v_{\mathrm{A}}$, 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 $\sim v_{\mathrm{A}}$
  - wave damping: transfer of CR energy and momentum to the thermal gas



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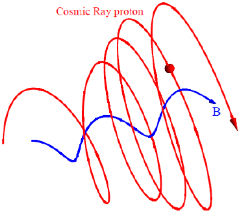

→ **CRs exert a pressure on the thermal gas by means of scattering off of Alfvén waves**

Cosmic-ray transport: streaming vs. diffusion

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

$$\boldsymbol{v}_{\text{st}} = -\boldsymbol{v}_{\text{A}} \frac{\boldsymbol{b} \cdot \nabla P_{\text{cr}}}{|\boldsymbol{b} \cdot \nabla P_{\text{cr}}|}, \qquad \boldsymbol{v}_{\text{di}} = -\kappa_{\text{di}} \boldsymbol{b} \frac{\boldsymbol{b} \cdot \nabla \varepsilon_{\text{cr}}}{\varepsilon_{\text{cr}}},$$

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- CR streaming adiabatically transports CR energy with $\sim v_{\rm A}$
  CR diffusion irreversibly disperses the CR energy

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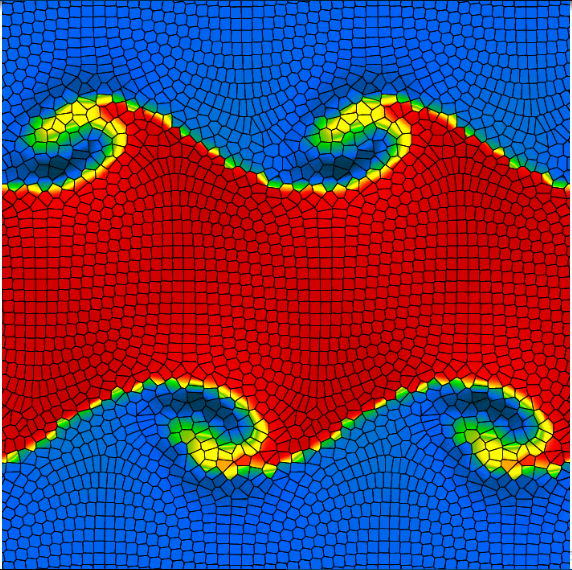
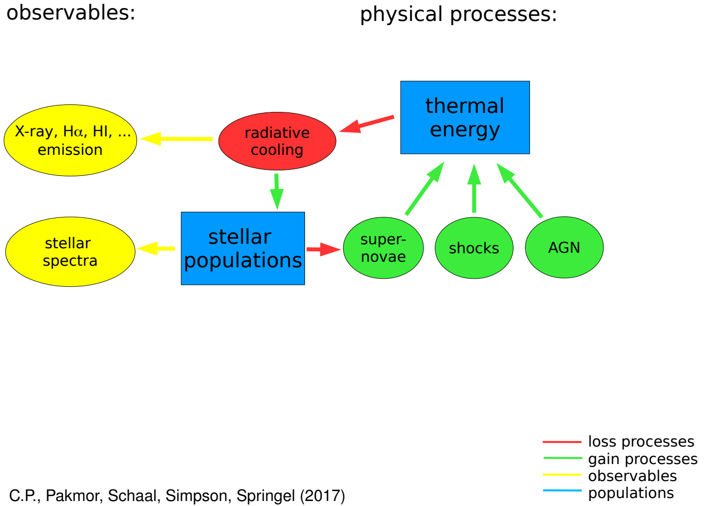
Cosmological moving-mesh code AREPO (Springel 2010)



Simulations – flowchart

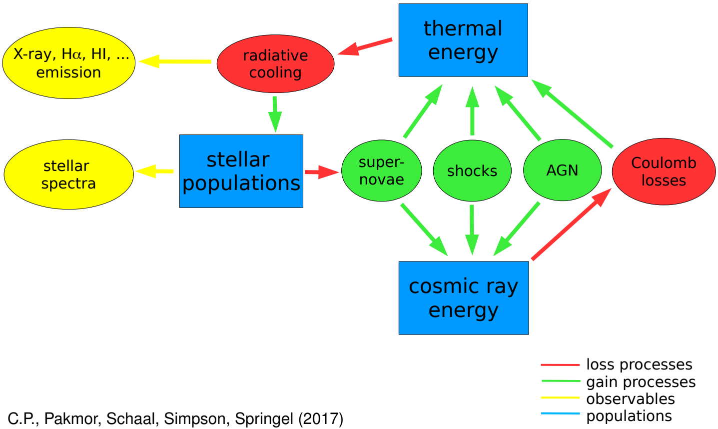


C.P., Pakmor, Schaal, Simpson, Springel (2017)

Simulations with cosmic ray physics

observables:

physical processes:



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

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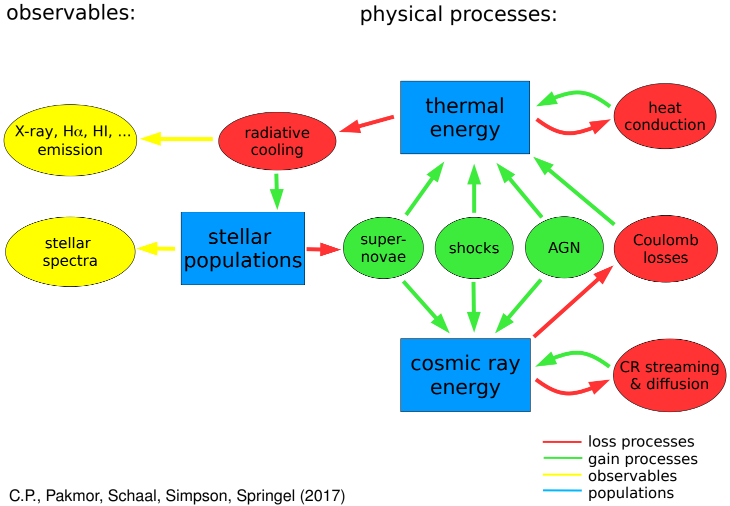
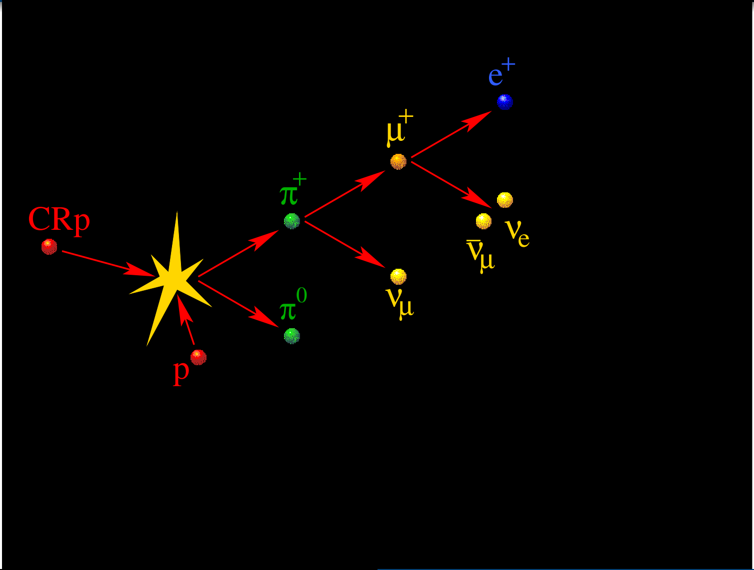


C.P., Pakmor, Schaal, Simpson, Springel (2017)

Hadronic cosmic ray proton interaction



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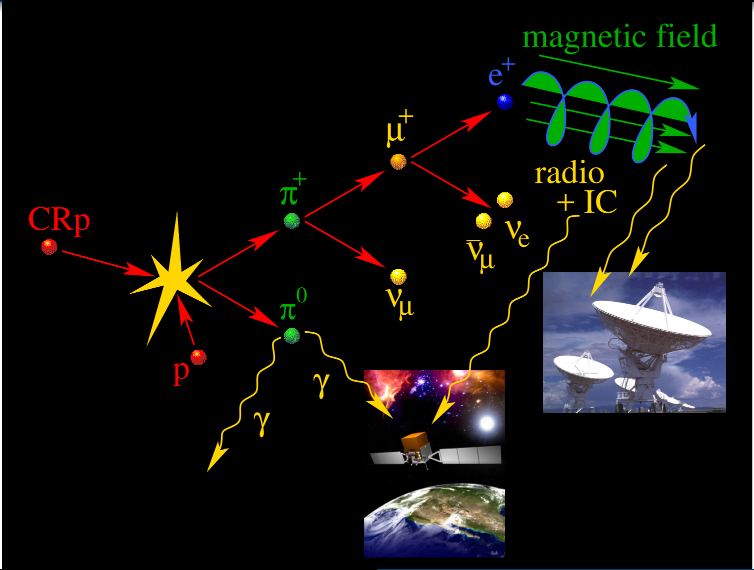
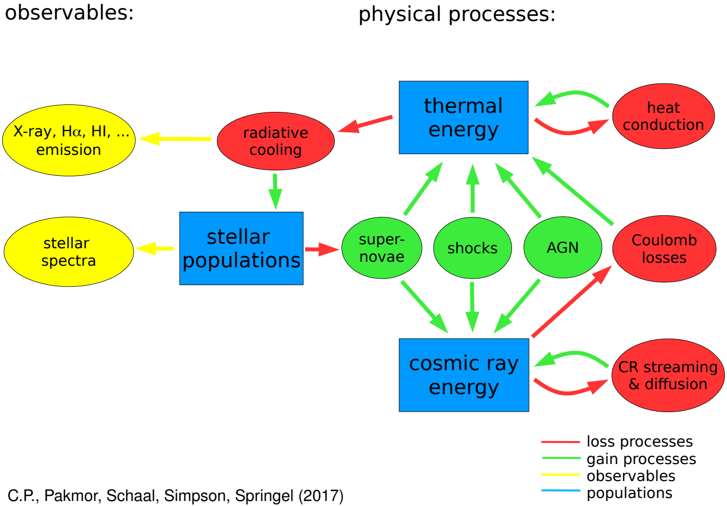
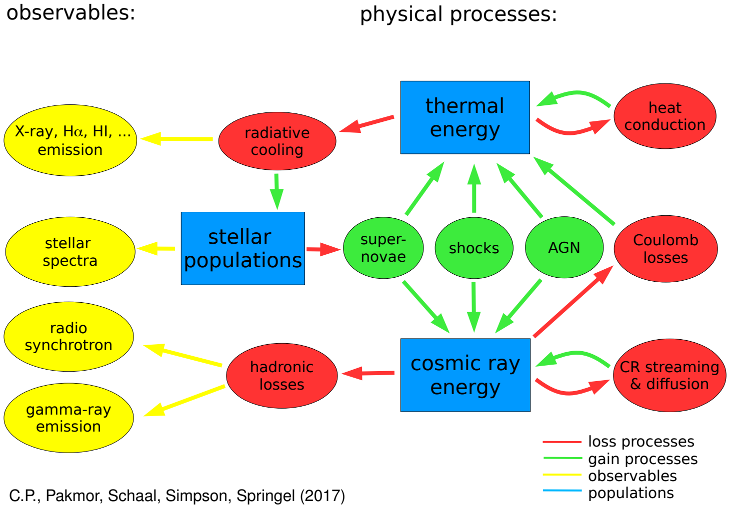


Simulations with cosmic ray physics



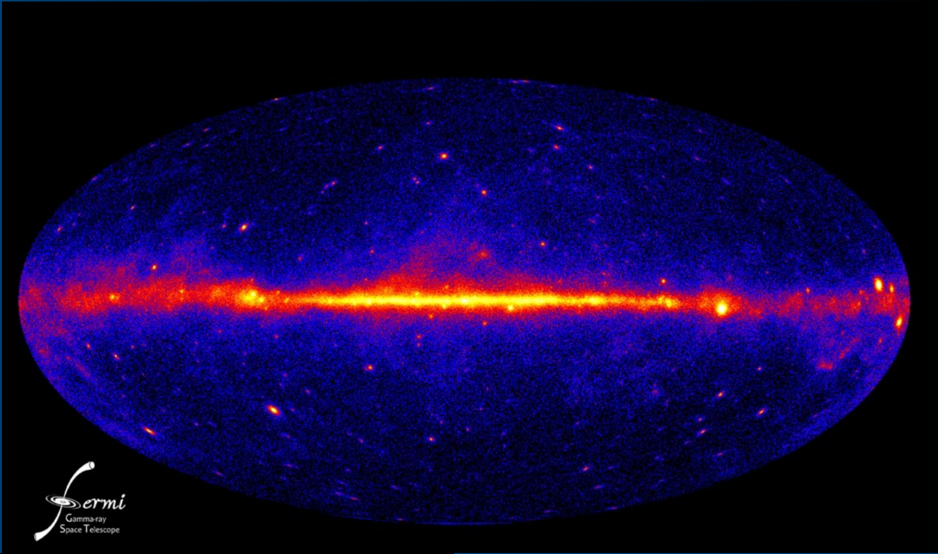
C.P., Pakmor, Schaal, Simpson, Springel (2017)

Simulations with cosmic ray physics

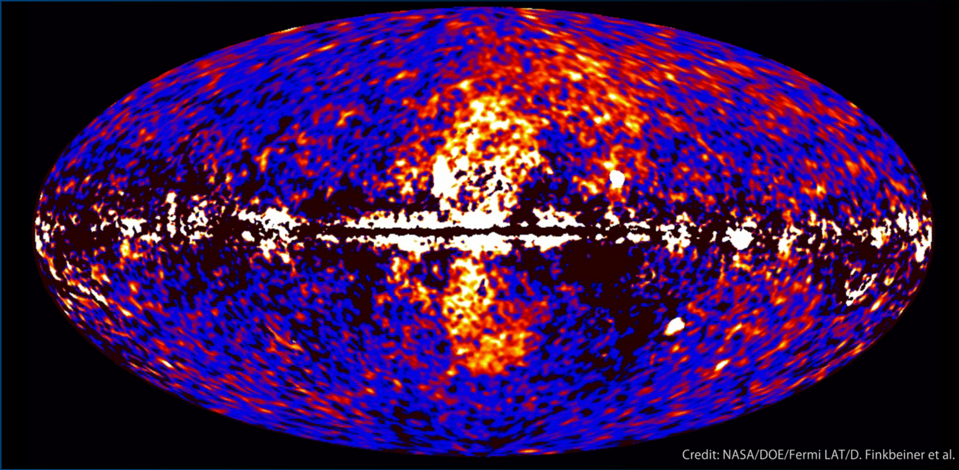


C.P., Pakmor, Schaal, Simpson, Springel (2017)

Gamma-ray emission of the Milky Way



Galactic wind in the Milky Way?
Fermi gamma-ray bubbles



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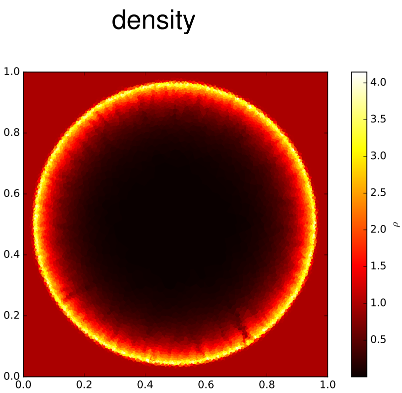
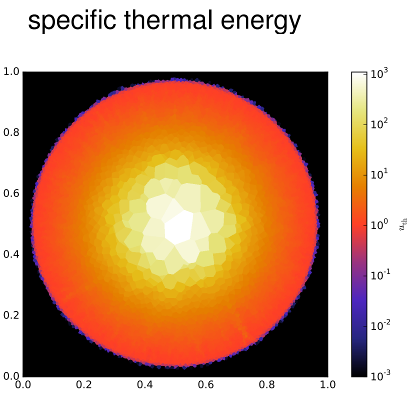
Sedov explosion

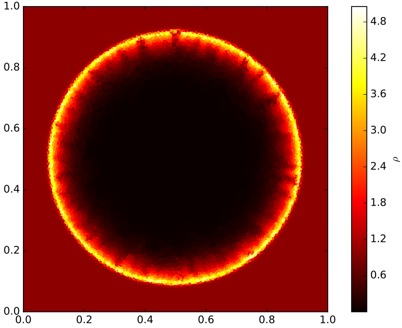




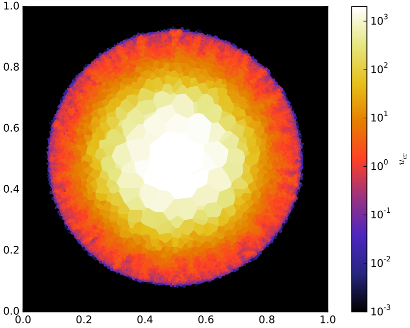
C.P., Pakmor, Schaal, Simpson, Springel (2017)

Sedov explosion with CR acceleration

density



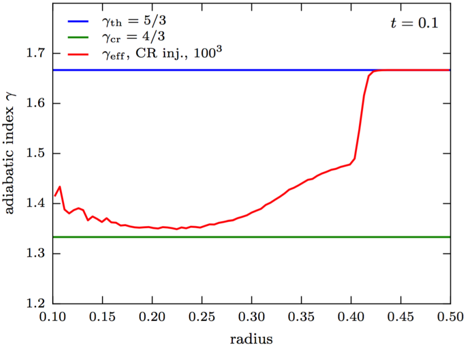
specific cosmic ray energy



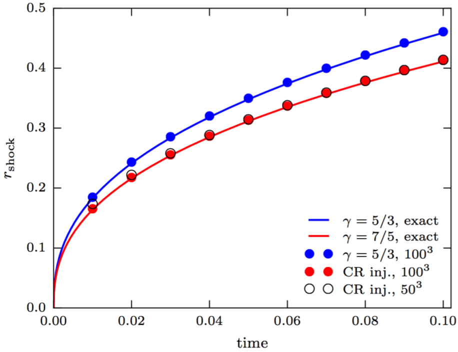
C.P., Pakmor, Schaal, Simpson, Springel (2017)

Sedov explosion with CR acceleration

adiabatic index



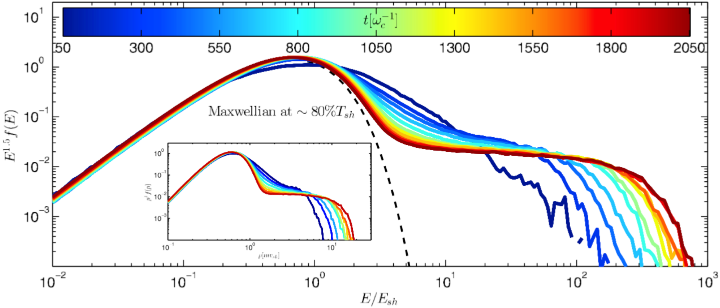
shock evolution



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

Ion spectrum

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



Caprioli & Spitkovsky (2014)

- quasi-parallel shocks ($\boldsymbol{B} \parallel \boldsymbol{n}_\mathrm{s}$) accelerate ions
- quasi-perpendicular shocks ($\boldsymbol{B} \perp \boldsymbol{n}_\mathrm{s}$) cannot
- model magnetic obliquity in AREPO simulations

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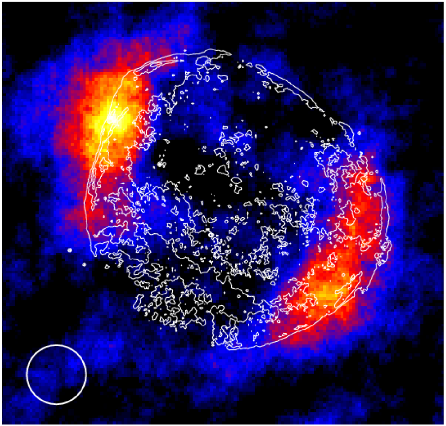
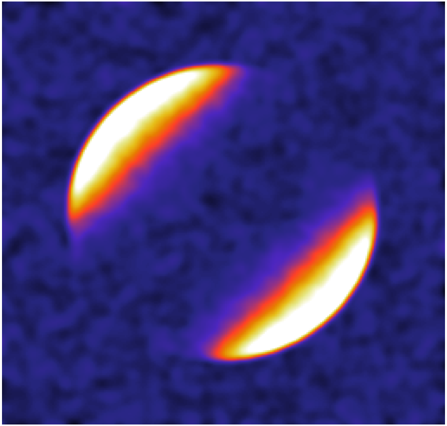
TeV γ rays from shell-type SNRs: SNR 1006

H.E.S.S. observation



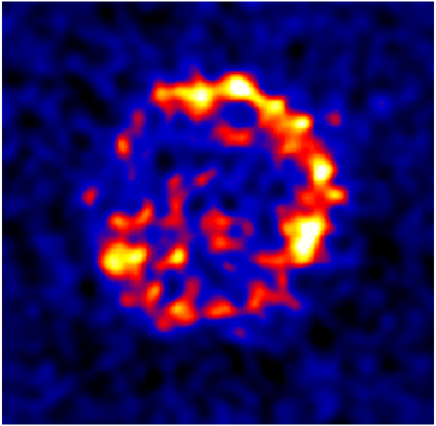
AREPO simulation



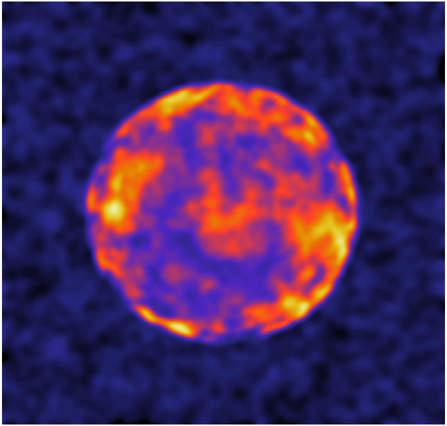
Pais, C.P., Ehlert (in prep.)

TeV γ rays from shell-type SNRs: Vela Junior

H.E.S.S. observation



AREPO simulation



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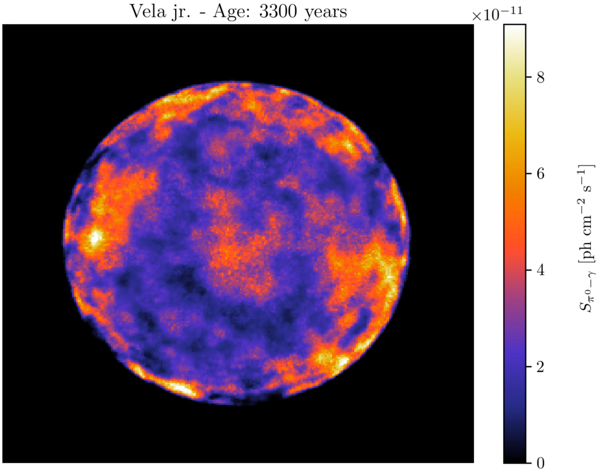
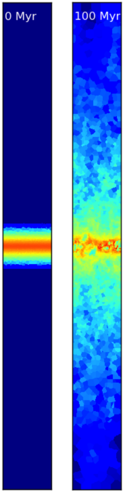


A model for the multi-phase interstellar medium

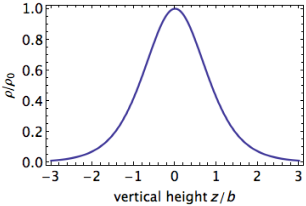
Explore supernovae-driven outflows at high resolution – stratified box simulations



Simpson+ (2016)

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

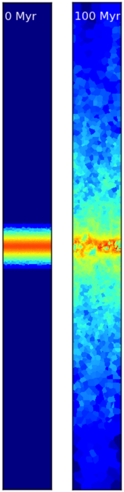
$$f_g \nabla^2 \Phi = 4\pi G \rho$$



- 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



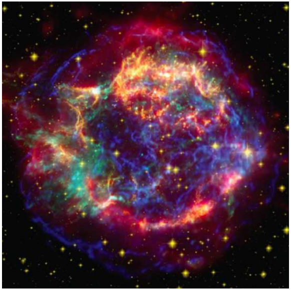
Simpson+ (2016)

- star formation rate:

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

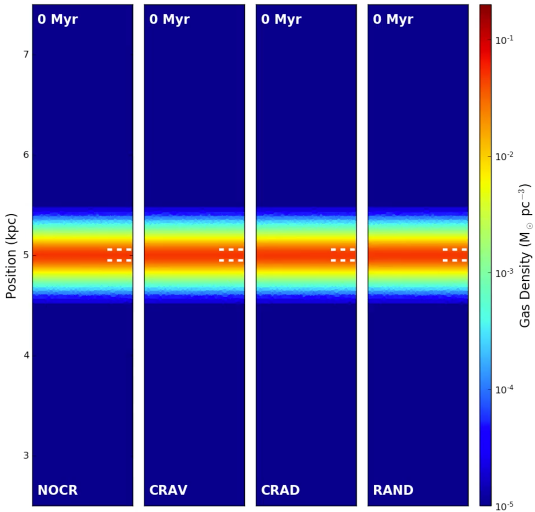
- supernova rate:

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



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

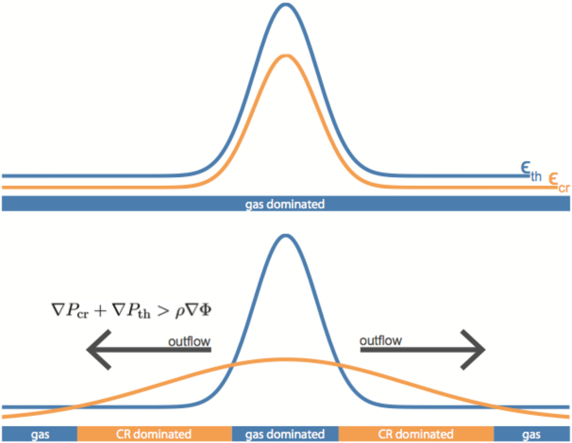
Interstellar medium – turbulence and outflows



Simpson+ (2016)

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

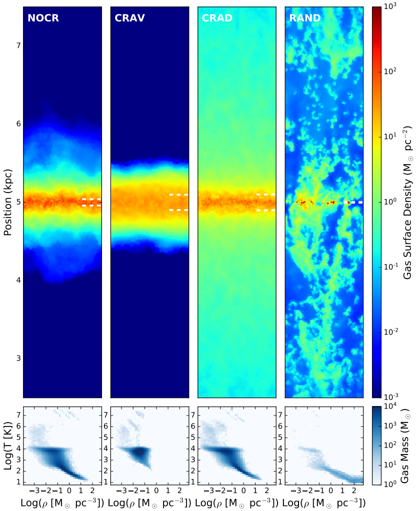
Cosmic ray driven wind: mechanism



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

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

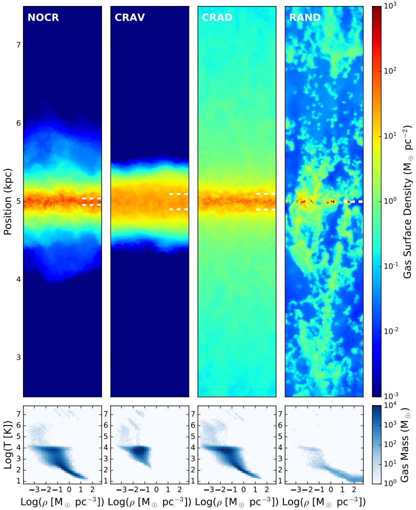
Interstellar medium – turbulence and outflows



Simpson+ (2016)

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

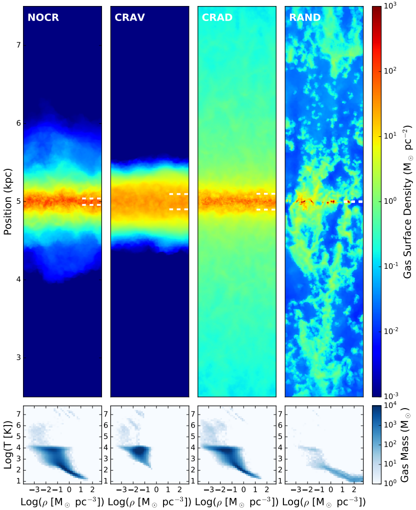
Interstellar medium – turbulence and outflows



Simpson+ (2016)

- 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

Interstellar medium – turbulence and outflows

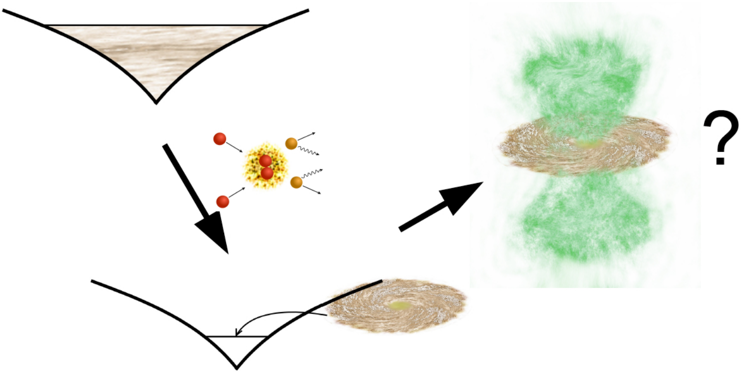


Simpson+ (2016)

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

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

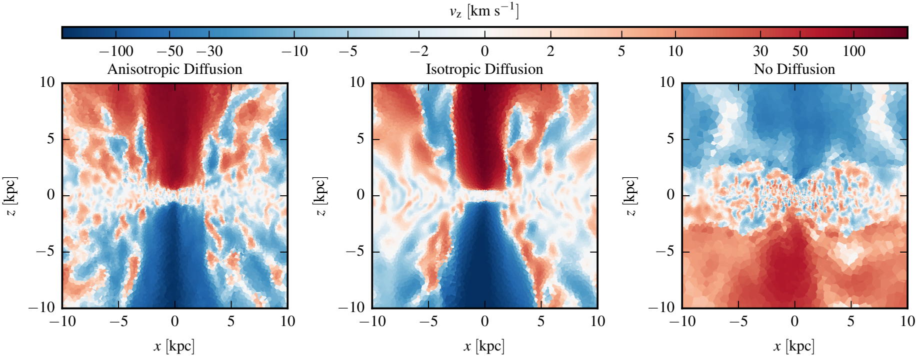
Galaxy simulation setup: 1. cosmic ray-driven winds



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

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

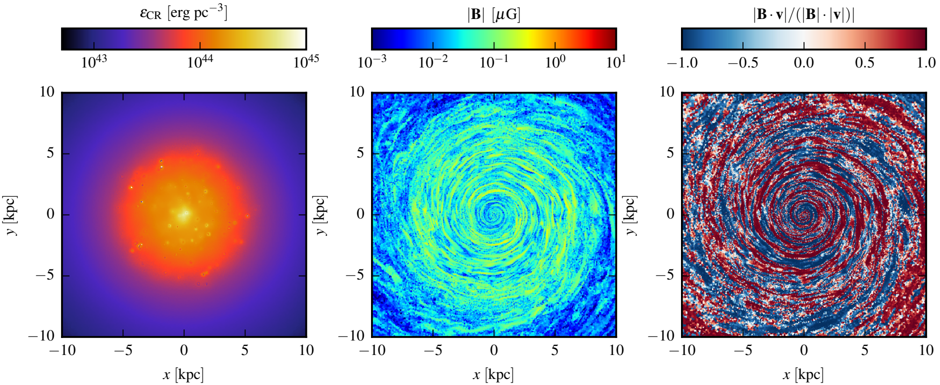
MHD galaxy simulation with CR diffusion



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

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

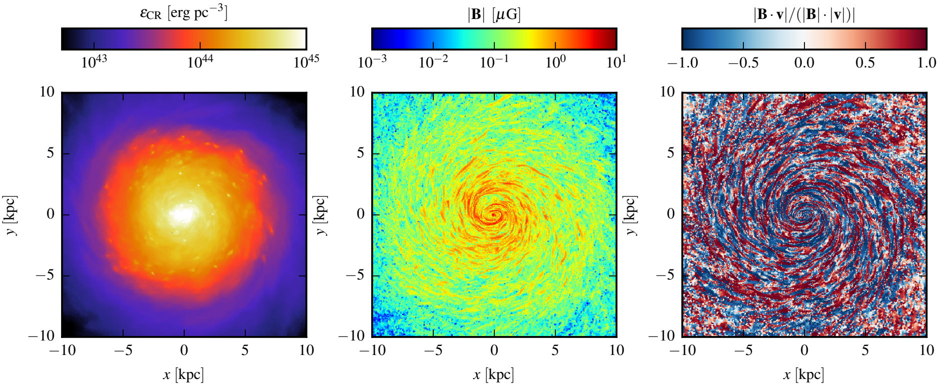
MHD galaxy simulation with CR isotropic diffusion



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

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

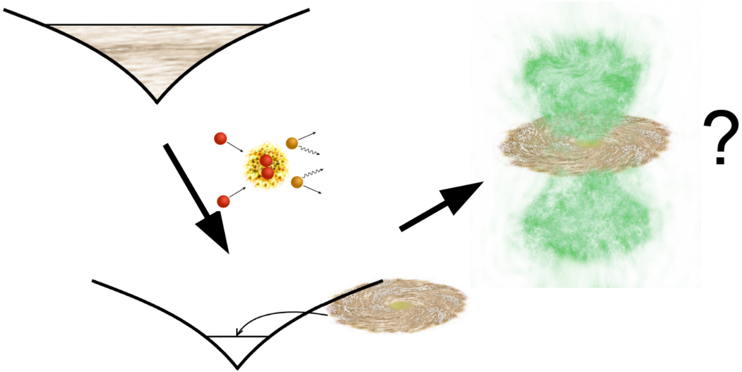
MHD galaxy simulation with CR anisotropic diffusion



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

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

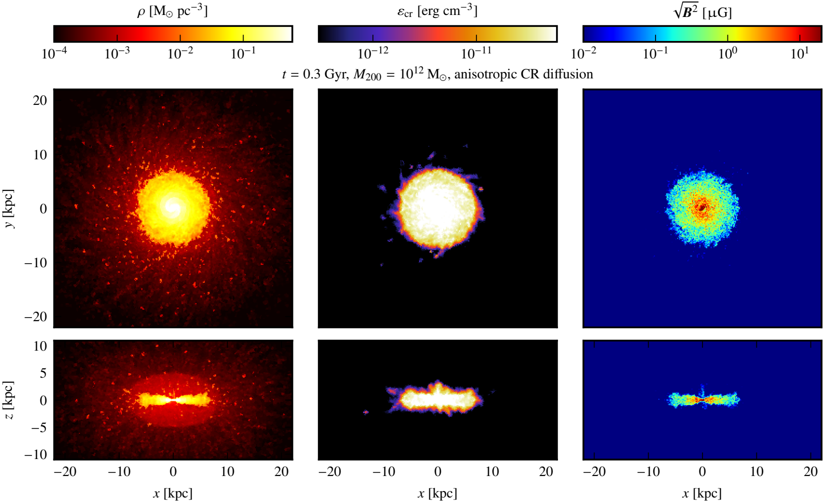
Galaxy simulation setup: 2. gamma-ray emission



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

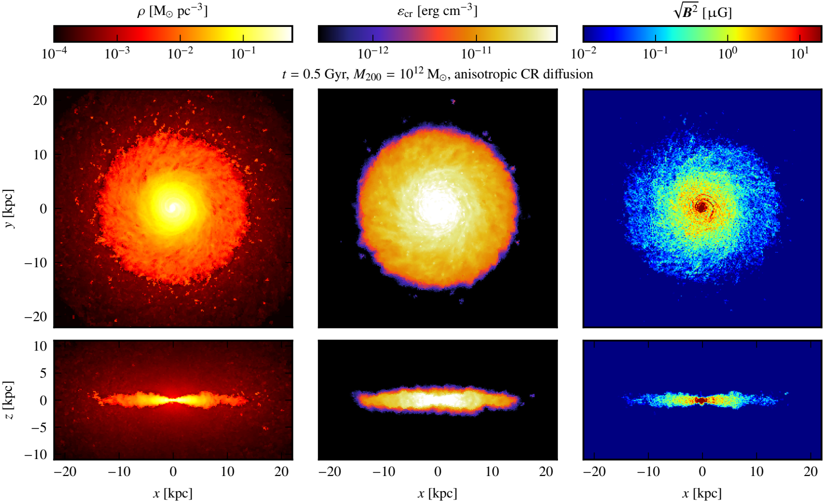
MHD + CR advection + diffusion: $\{10^{10}, 10^{11}, 10^{12}\}\ \mathrm{M}_\odot$

Simulation of Milky Way-like galaxy, $t = 0.3$ Gyr



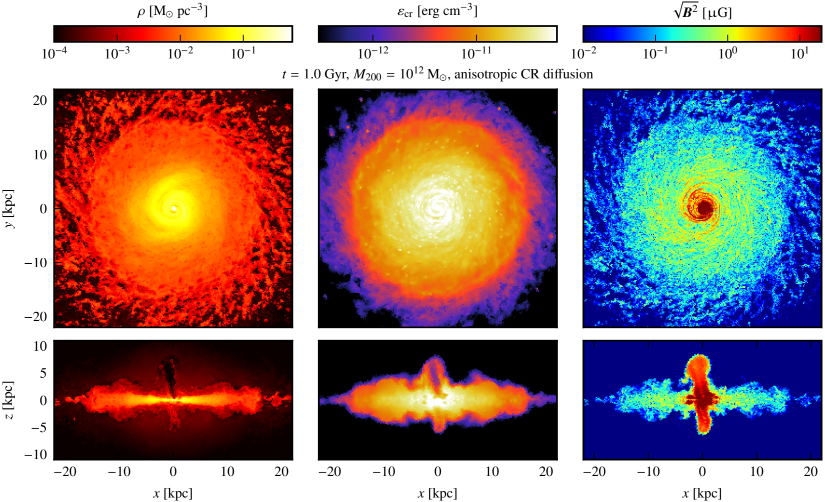
C.P.+ (2017a,b)

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



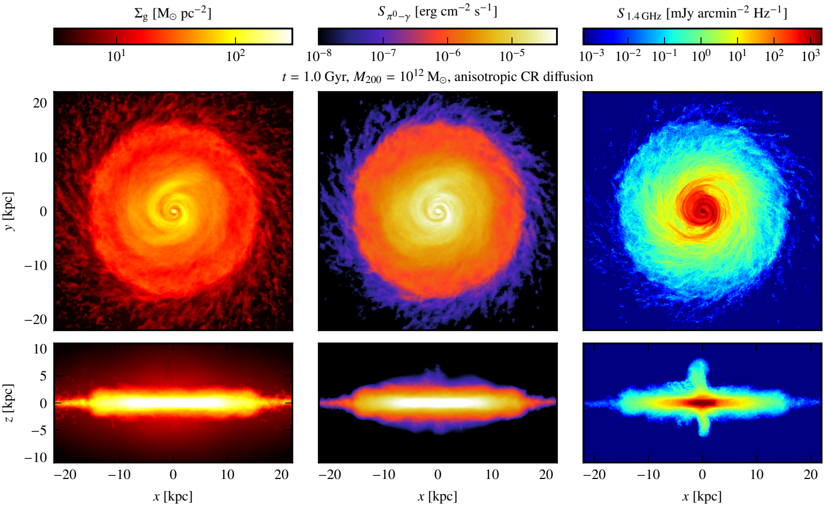
C.P.+ (2017a,b)

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



C.P.+ (2017a,b)

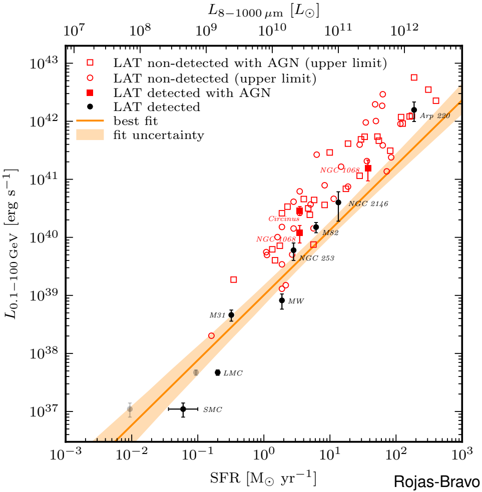
γ-ray and radio emission of Milky Way-like galaxy



C.P.+ (2017a,b)

Far infra-red – gamma-ray correlation

Universal conversion: star formation → cosmic rays → gamma rays



Rojas-Bravo & Araya (2016)

Far infra-red – gamma-ray correlation

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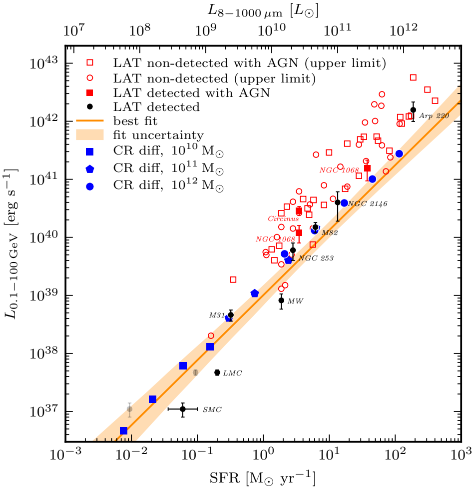

C.P.+ (2017a)

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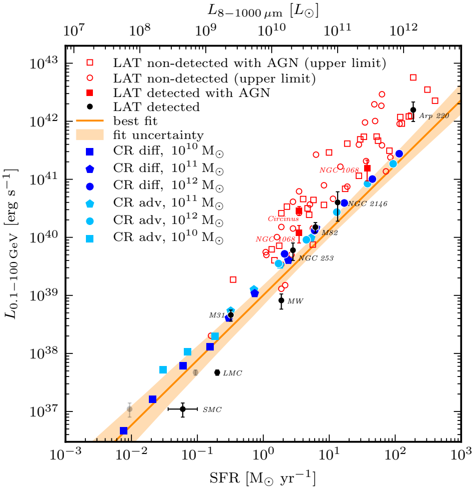

C.P.+ (2017a)

Far infra-red – gamma-ray correlation

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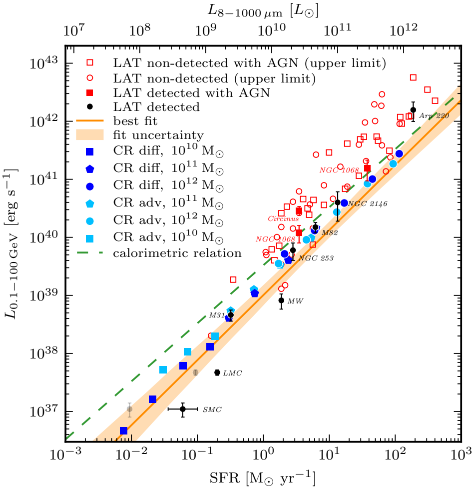

C.P.+ (2017a)

Conclusions

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AIP

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outlook: improved modeling of plasma physics, follow CR spectra, cosmological settings

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

AIP

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

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Literature for the talk

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