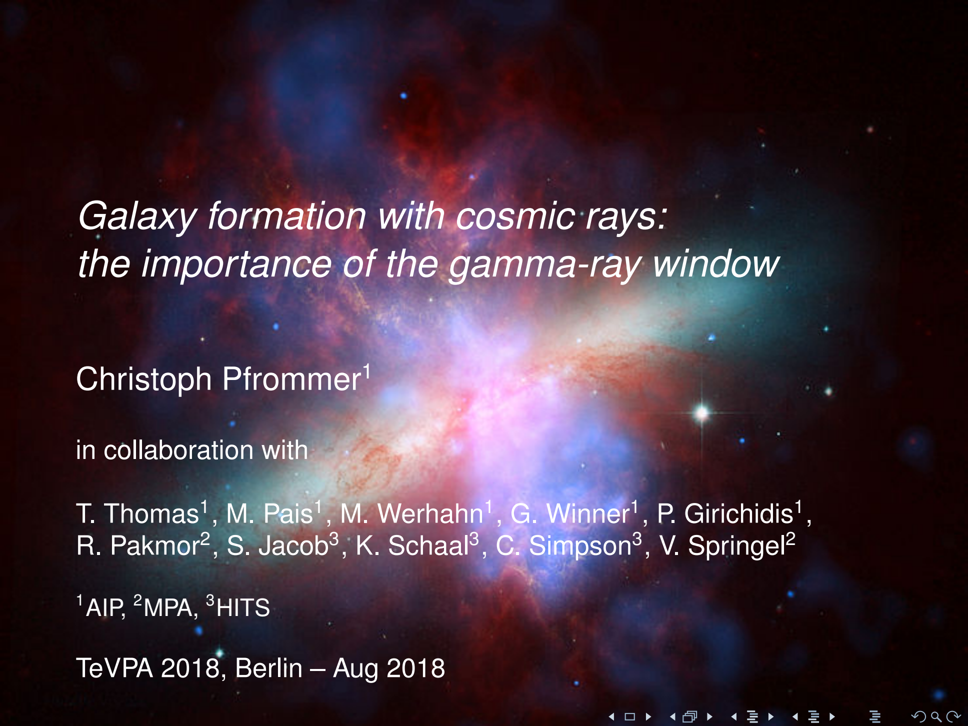


Galaxy formation with cosmic rays: the importance of the gamma-ray window

Christoph Pfrommer[1]

in collaboration with

T. Thomas[1], M. Pais[1], M. Werhahn[1], G. Winner[1], P. Girichidis[1], R. Pakmor[2], S. Jacob[3], K. Schaal[3], C. Simpson[3], V. Springel[2]

[1]AIP, [2]MPA, [3]HITS

TeVPA 2018, Berlin – Aug 2018

Outline

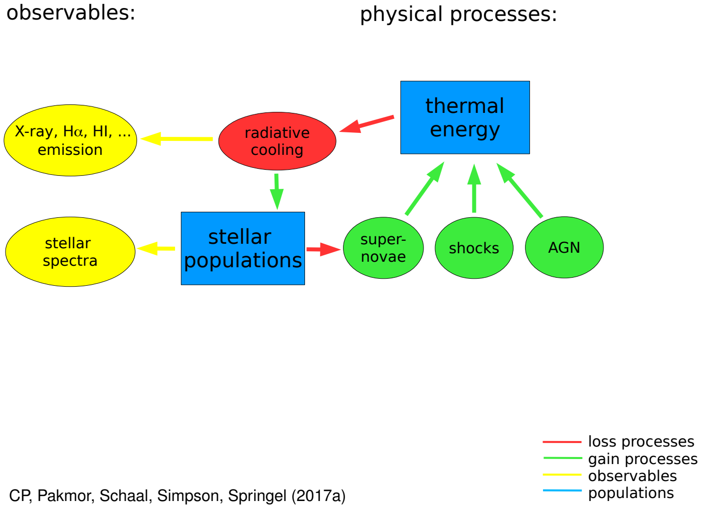
1. Small galactic scales
   - Modelling physics in galaxies
   - Supernova explosions
   - Particle acceleration
2. Galaxy formation
   - Cosmic ray advection
   - Cosmic ray diffusion
   - γ-ray emission

Outline

1. Small galactic scales
   - Modelling physics in galaxies
   - Supernova explosions
   - Particle acceleration
2. Galaxy formation
   - Cosmic ray advection
   - Cosmic ray diffusion
   - γ-ray emission

AIP

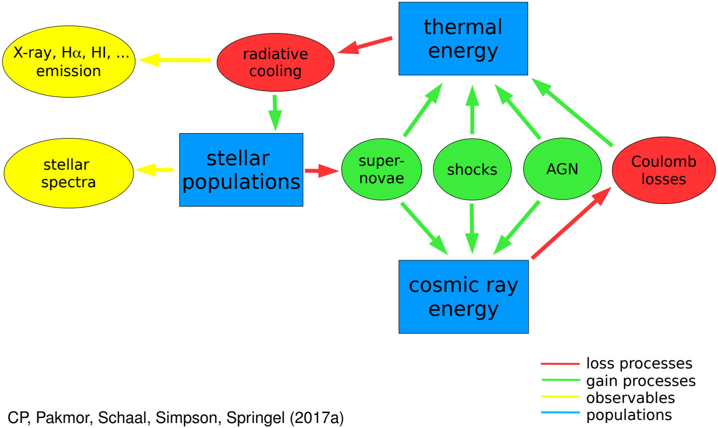
Simulations – flowchart



CP, Pakmor, Schaal, Simpson, Springel (2017a)

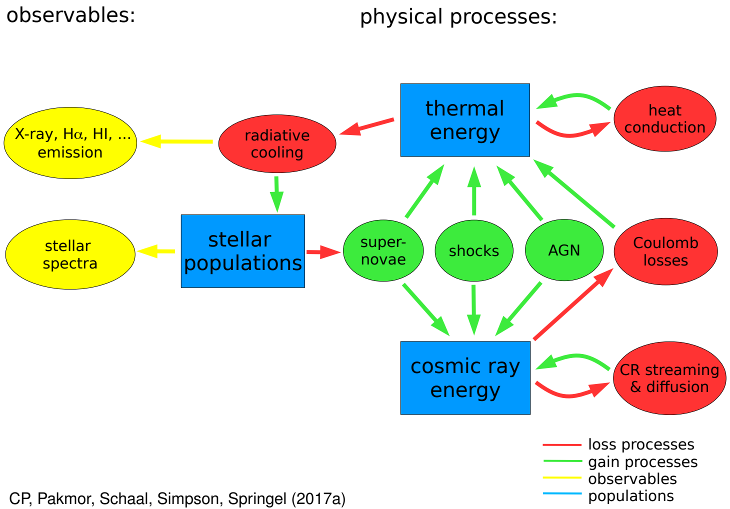
Simulations with cosmic ray physics

observables: physical processes:



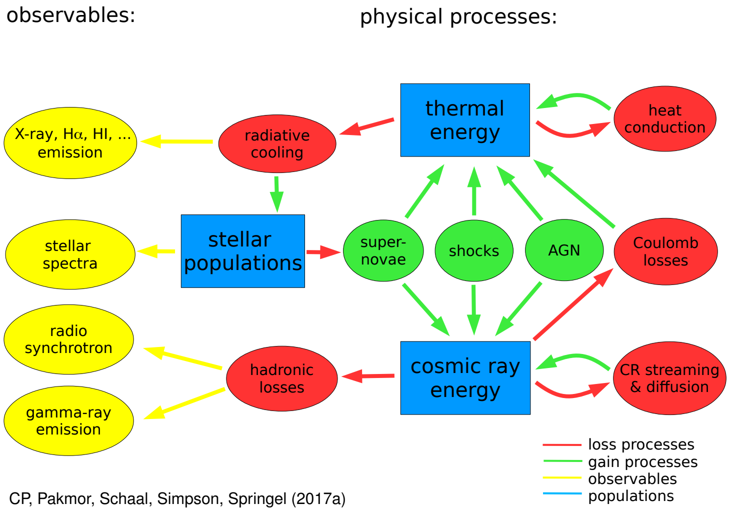
CP, Pakmor, Schaal, Simpson, Springel (2017a)

Simulations with cosmic ray physics



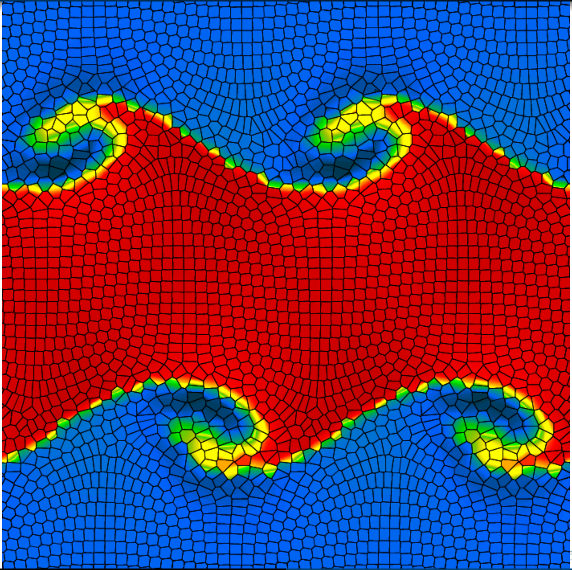
CP, Pakmor, Schaal, Simpson, Springel (2017a)

Simulations with cosmic ray physics



CP, Pakmor, Schaal, Simpson, Springel (2017a)

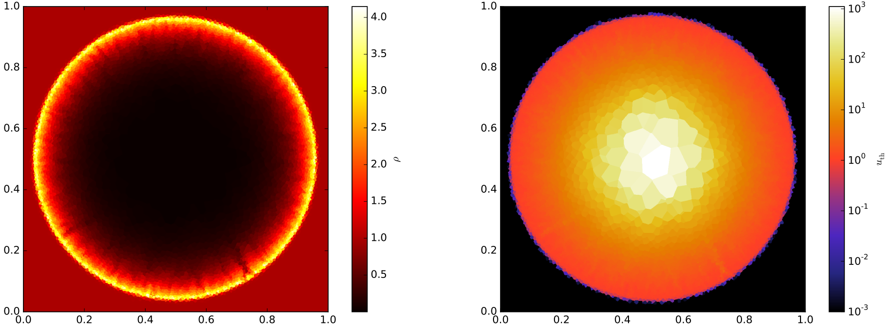
Cosmological moving-mesh code AREPO (Springel 2010)



Sedov explosion

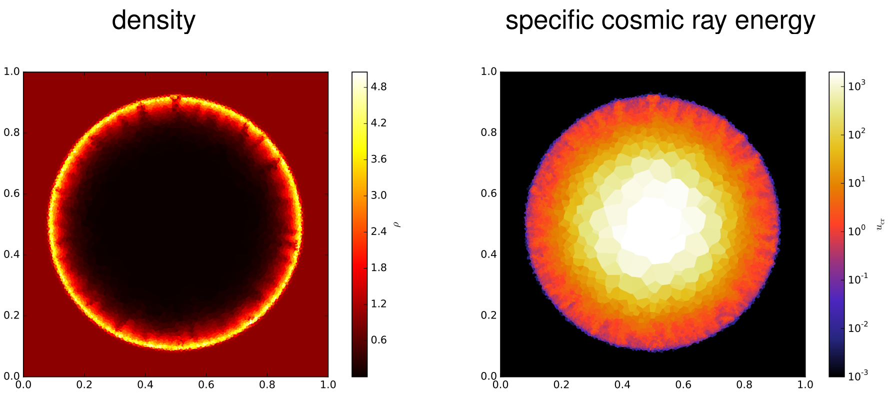
density

specific thermal energy



CP, Pakmor, Schaal, Simpson, Springel (2017a)

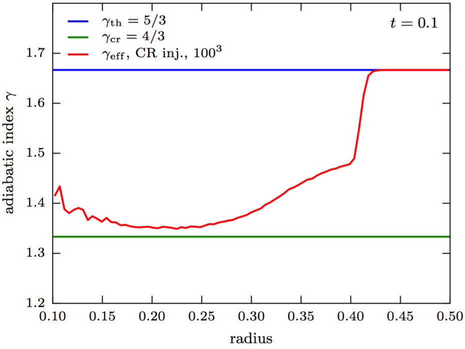
Sedov explosion with CR acceleration



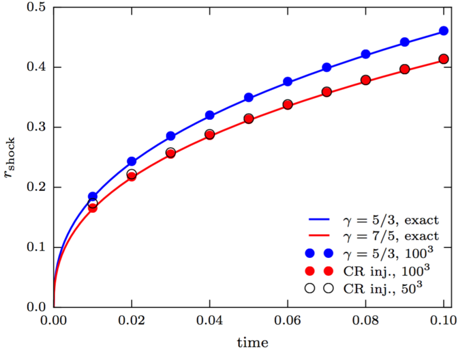
CP, Pakmor, Schaal, Simpson, Springel (2017a)

Sedov explosion with CR acceleration

adiabatic index



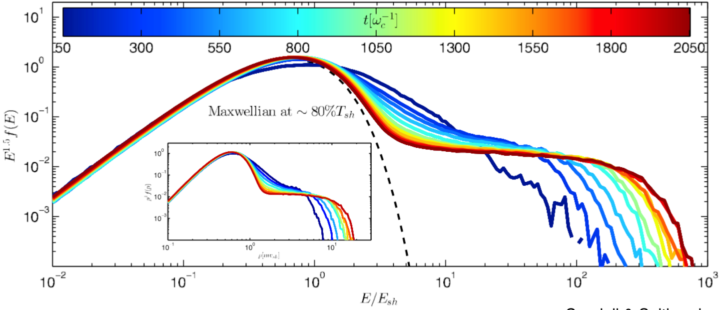
shock evolution



CP, Pakmor, Schaal, Simpson, Springel (2017a)

Ion spectrum

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



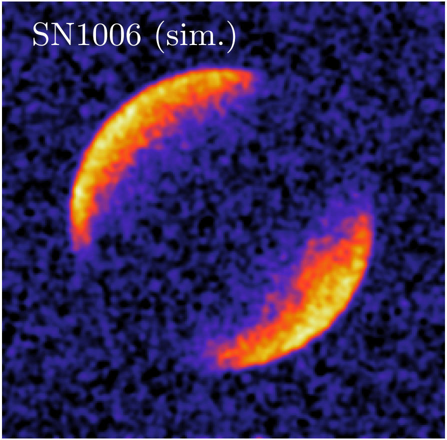
Caprioli & Spitkovsky (2014)

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

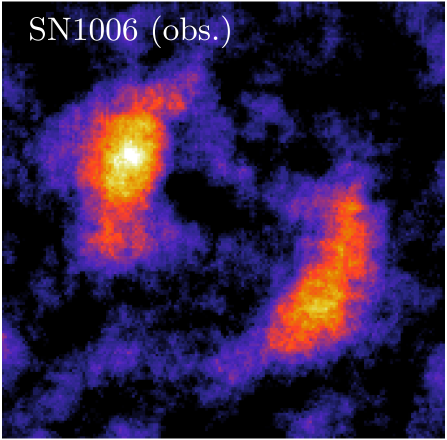
AIP

TeV γ rays from shell-type SNRs: SNR 1006

AREPO simulation



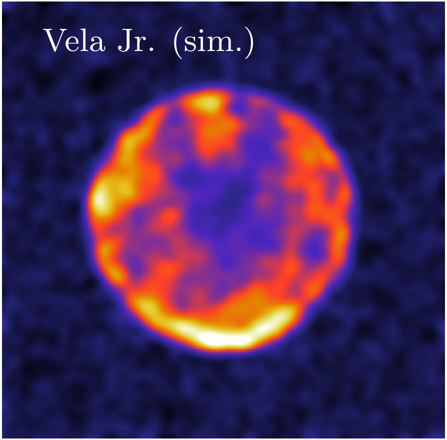
H.E.S.S. observation



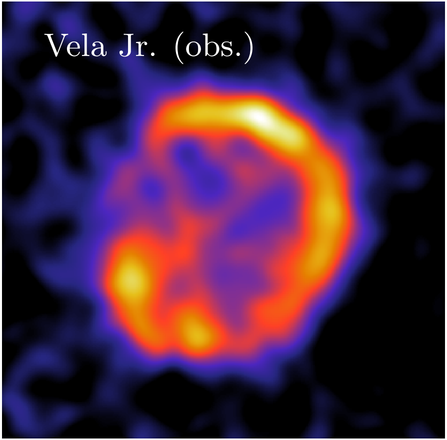
Pais, CP, Ehlert (2018)

TeV γ rays from shell-type SNRs: Vela Junior

AREPO simulation



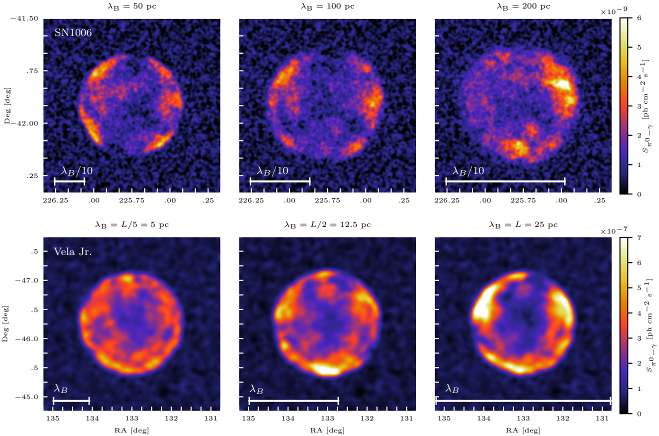
H.E.S.S. observation



Pais, CP, Ehlert (2018)

TeV γ rays from shell-type supernova remnants

Varying magnetic coherence scale in simulations of SN1006 and Vela Junior

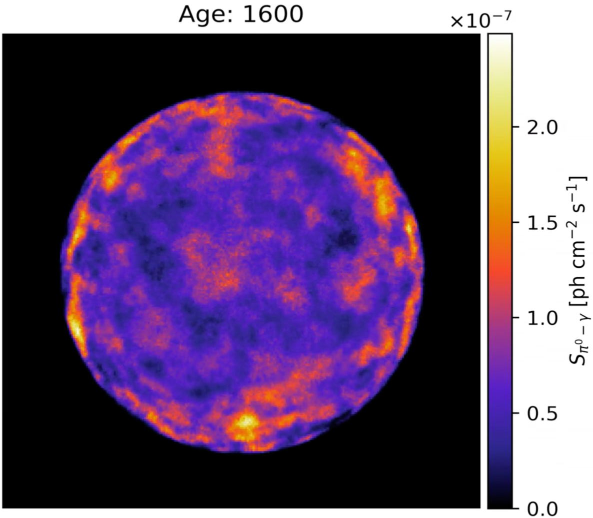


Pais, CP, Ehlert (2018)

SNR 1006: $\lambda_B > 200^{+10}_{-60}$ pc

Vela Junior: $\lambda_B = 8^{+15}_{-6}$ pc

TeV γ rays from shell-type SNRs: Vela Junior



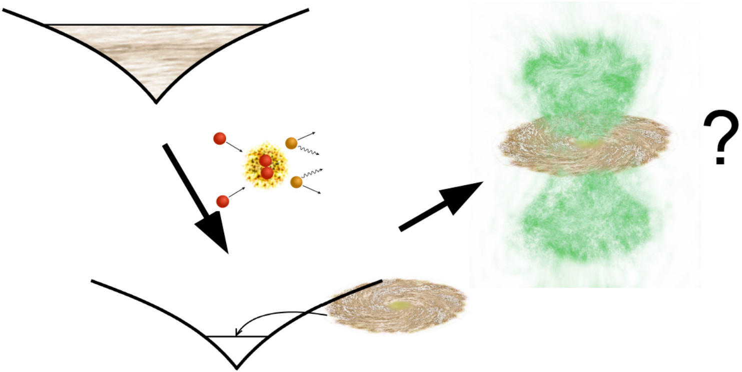
Pais, CP, Ehlert (2018)

Outline

1. Small galactic scales
   - Modelling physics in galaxies
   - Supernova explosions
   - Particle acceleration

2. Galaxy formation
   - Cosmic ray advection
   - Cosmic ray diffusion
   - γ-ray emission

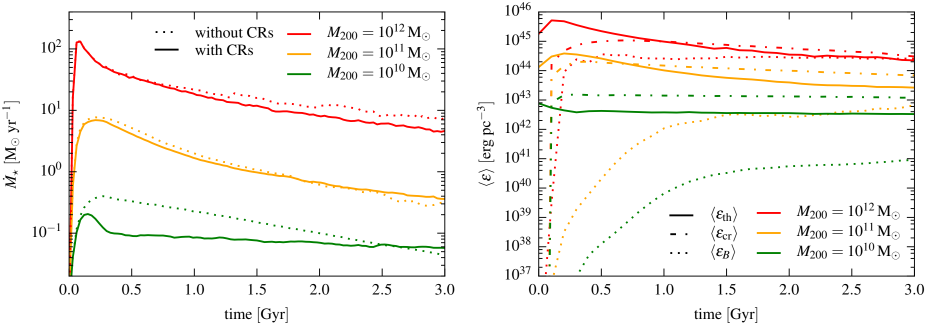
Galaxy simulation setup: 1. cosmic ray advection



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

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

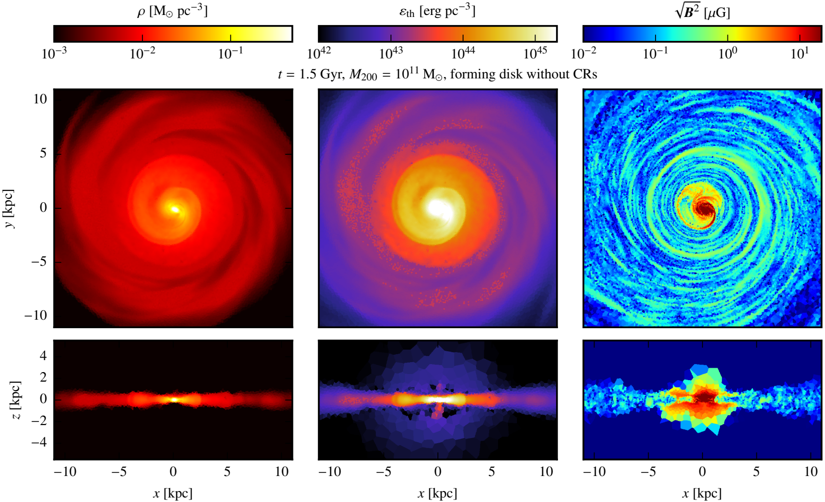
Time evolution of SFR and energy densities



CP, Pakmor, Schaal, Simpson, Springel (2017a)

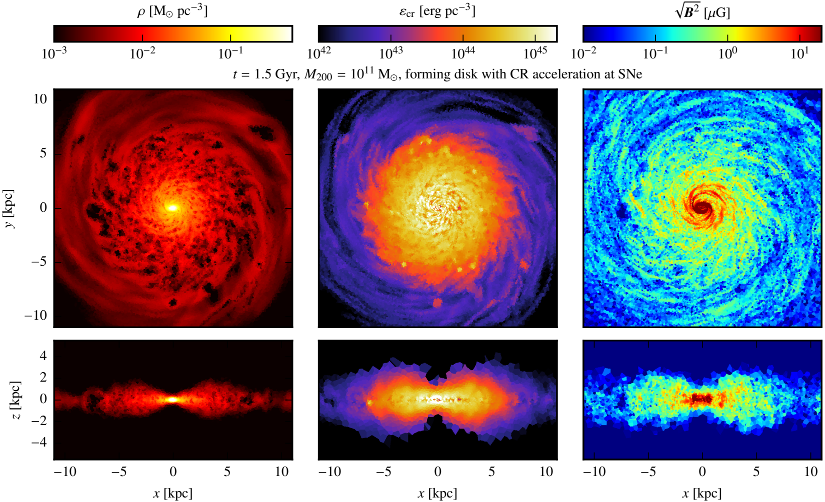
- CR pressure feedback suppresses SFR more in smaller galaxies
- energy budget in disks is dominated by CR pressure
- magnetic dynamo faster in Milky Way galaxies than in dwarfs

MHD galaxy simulation without CRs



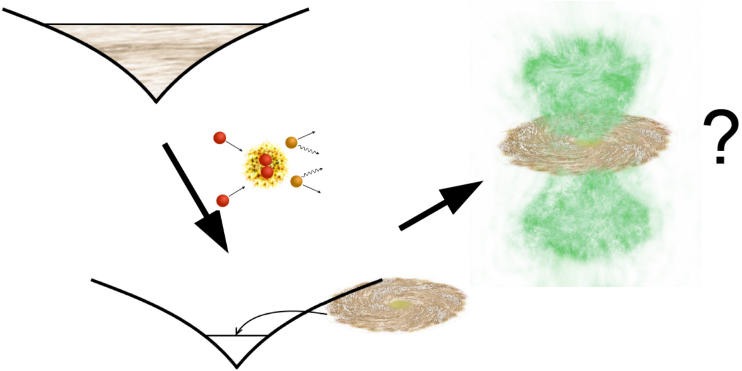
CP, Pakmor, Schaal, Simpson, Springel (2017a)

MHD galaxy simulation with CRs



CP, Pakmor, Schaal, Simpson, Springel (2017a)

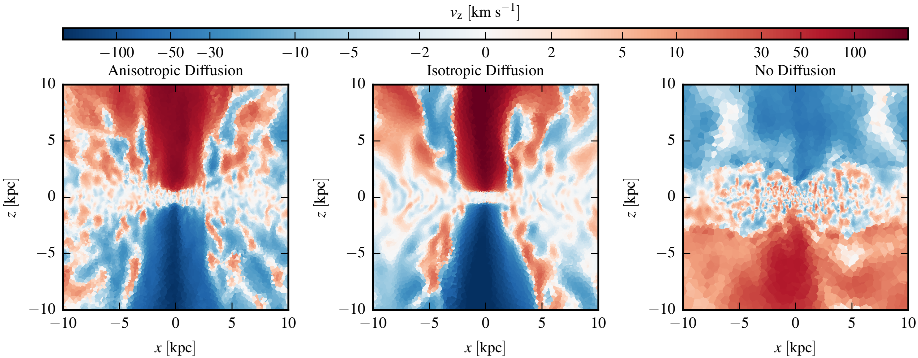
Galaxy simulation setup: 2. cosmic ray diffusion



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

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

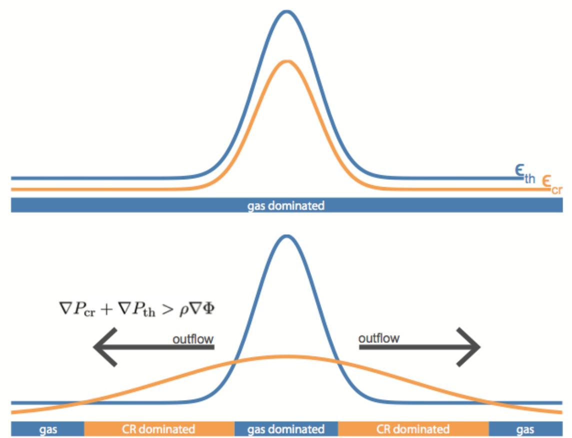
MHD galaxy simulation with CR diffusion



Pakmor, CP, Simpson, Springel (2016)

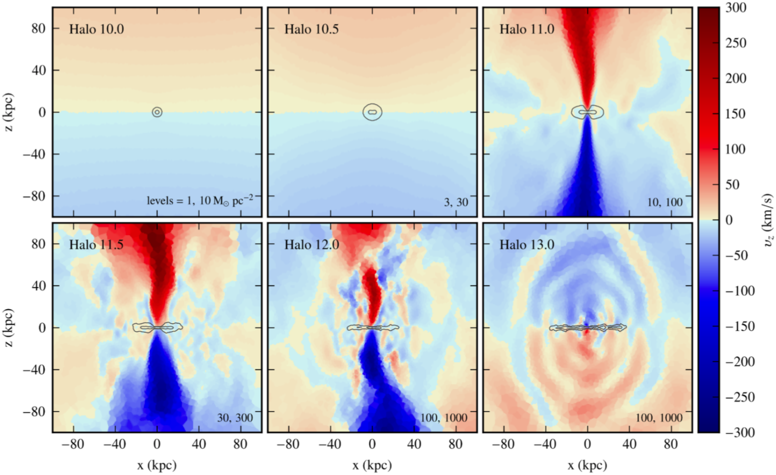
- CR diffusion launches powerful winds
- simulation without CR diffusion exhibits only weak fountain flows

Cosmic ray driven wind: mechanism



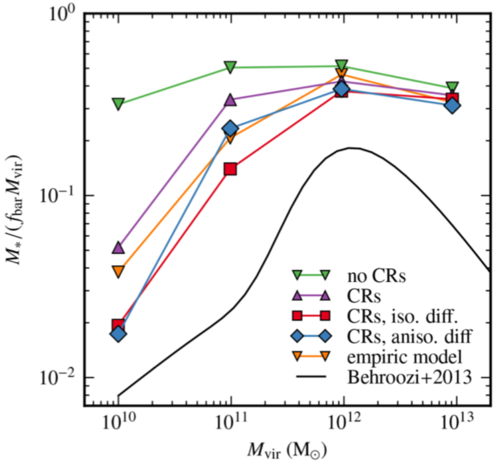
CR streaming in 3D simulations: Uhlig, CP+ (2012), Ruszkowski+ (2017)
CR diffusion in 3D simulations: Jubelgas+ (2008), Booth+ (2013), Hanasz+ (2013), Salem & Bryan (2014), Pakmor, CP+ (2016), Simpson+ (2016), Girichidis+ (2016), Dubois+ (2016), CP+ (2017b), Jacob+ (2018)

CR-driven winds: dependence on halo mass



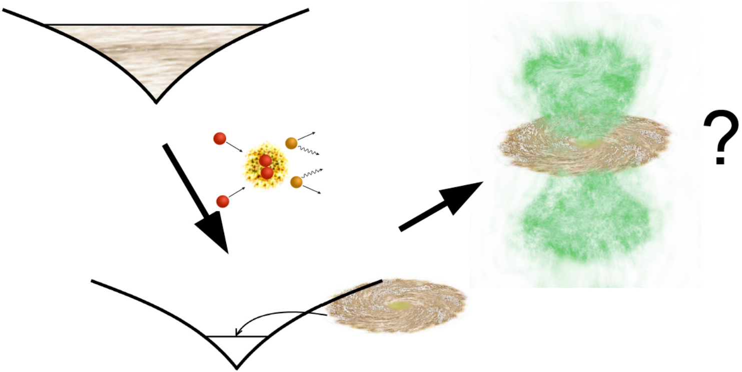
Jacob+ (2018)

CR-driven winds: suppression of star formation



Jacob+ (2018)

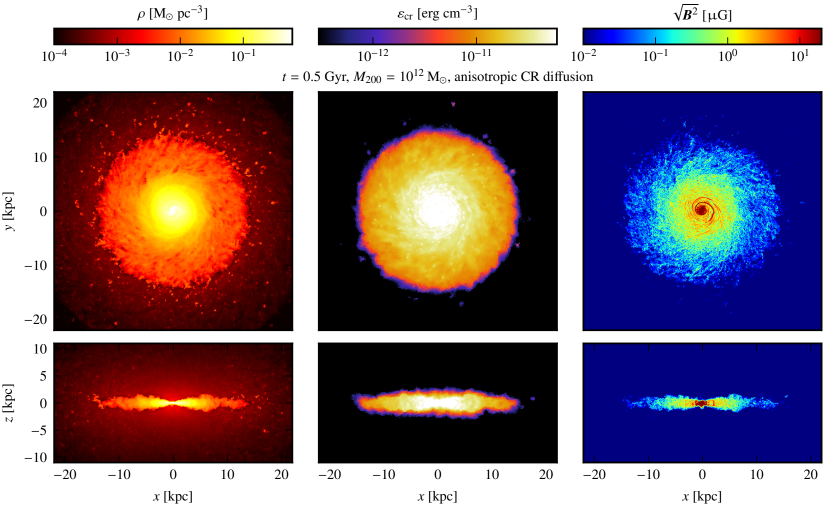
Galaxy simulation setup: 3. non-thermal emission



CP, Pakmor, Simpson, Springel (2017b, 2018)
Simulating radio synchrotron and gamma-ray emission in galaxies

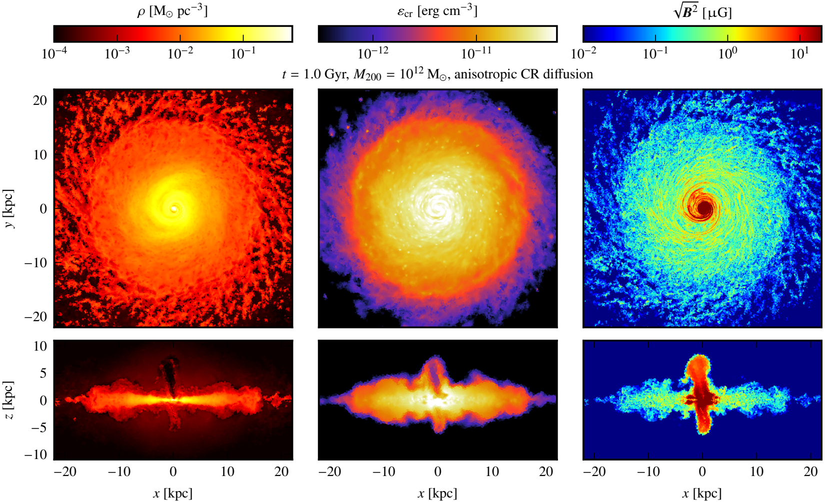
MHD + CR advection + diffusion: $\{10^{10}, 10^{11}, 10^{12}\}\ M_\odot$

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



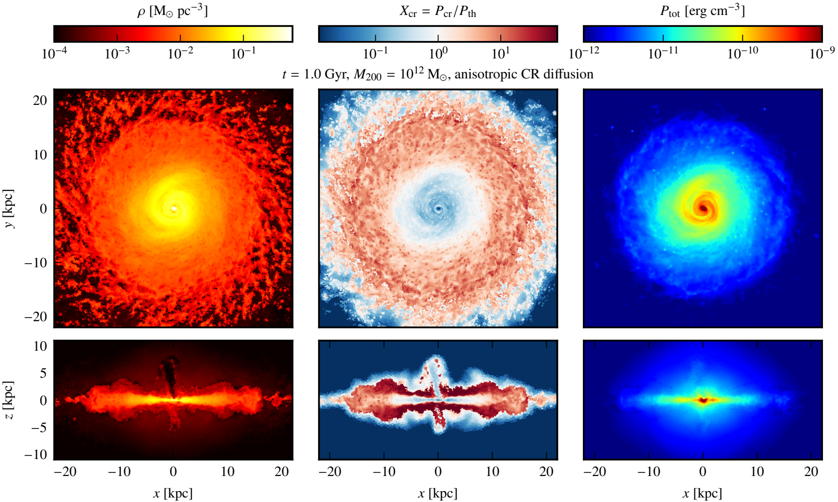
CP+ (2017b, 2018)

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



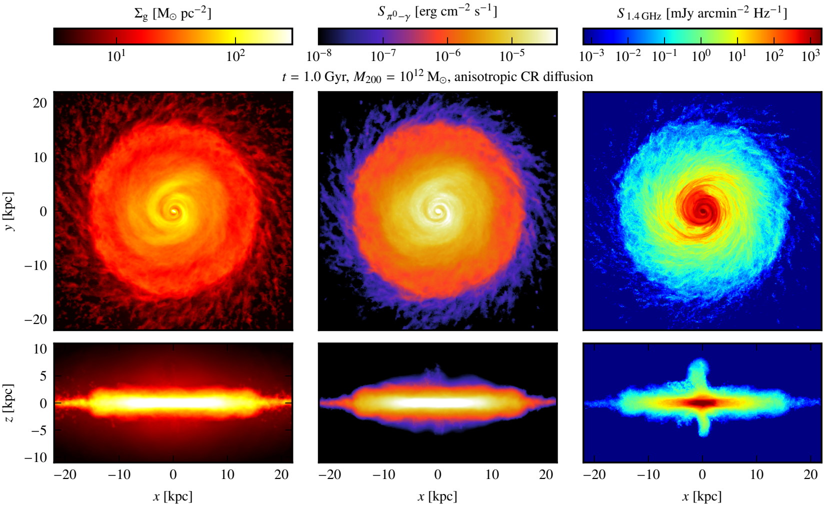
CP+ (2017b, 2018)

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



CP+ (2017b, 2018)

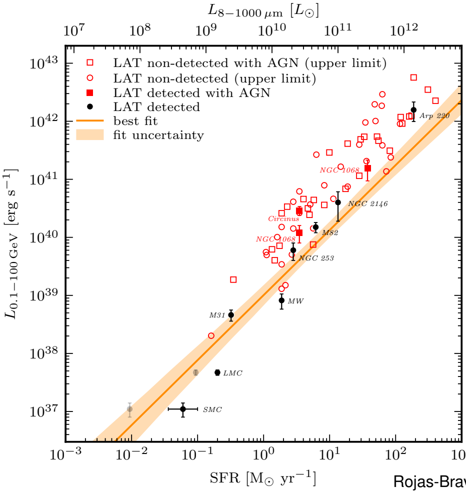
γ-ray and radio emission of Milky Way-like galaxy



CP+ (2017b, 2018)

Far infra-red – gamma-ray correlation

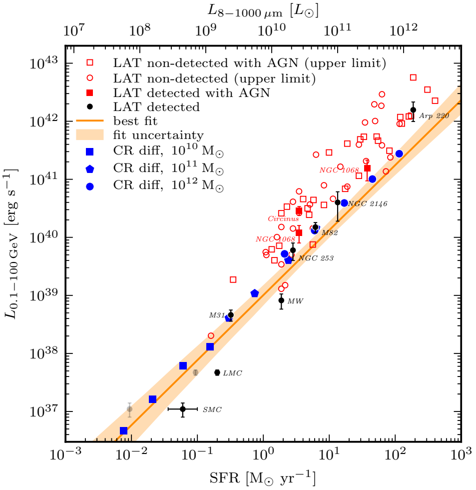
Universal conversion: star formation → cosmic rays → gamma rays



Rojas-Bravo & Araya (2016)

Far infra-red – gamma-ray correlation

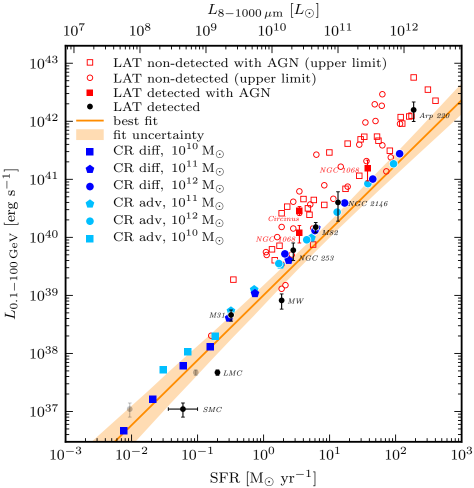
Universal conversion: star formation → cosmic rays → gamma rays



CP+ (2017b)

Far infra-red – gamma-ray correlation

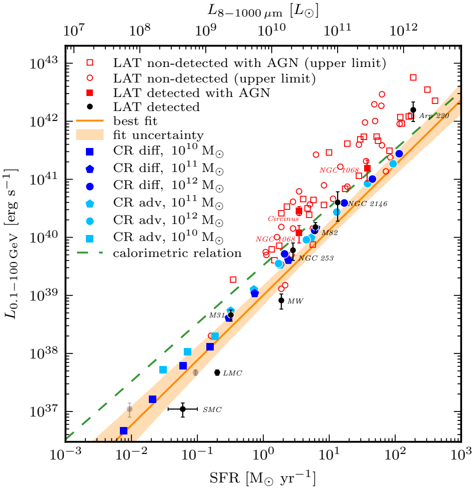
Universal conversion: star formation → cosmic rays → gamma rays



CP+ (2017b)

Far infra-red – gamma-ray correlation

Universal conversion: star formation → cosmic rays → gamma rays



CP+ (2017b)

Conclusions on CR feedback in galaxies and clusters

- CR pressure feedback slows down star formation
- galactic winds are naturally explained by CR diffusion & streaming

Conclusions on CR feedback in galaxies and clusters

- CR pressure feedback slows down star formation
- galactic winds are naturally explained by CR diffusion & streaming
- anisotropic CR diffusion necessary for efficient galactic dynamo: observed field strengths of $B \sim 10\,\mu$G
- $L_{\mathrm{FIR}} - L_\gamma$ and $L_{\mathrm{FIR}} - L_{\mathrm{radio}}$ correlations enable us to test the calorimetric assumption and magnetic dynamo theories

Conclusions on CR feedback in galaxies and clusters

- CR pressure feedback slows down star formation
- galactic winds are naturally explained by CR diffusion & streaming
- anisotropic CR diffusion necessary for efficient galactic dynamo: observed field strengths of $B \sim 10\,\mu$G
- $L_{\mathrm{FIR}} - L_\gamma$ and $L_{\mathrm{FIR}} - L_{\mathrm{radio}}$ correlations enable us to test the calorimetric assumption and magnetic dynamo theories

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

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 – 1

Cosmic ray acceleration:

- Pais, Pfrommer, Ehlert, *Constraining the coherence scale of the interstellar magnetic field using TeV gamma-ray observations of supernova remnants,* 2018.
- Pais, Pfrommer, Ehlert, Pakmor, *The effect of cosmic-ray acceleration on supernova blast wave dynamics,* 2018, MNRAS.

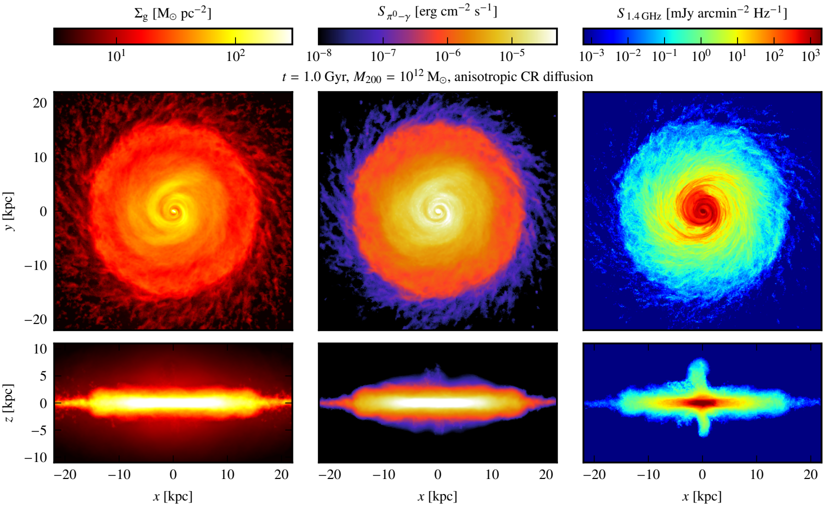
Cosmic ray feedback in galaxies:

- Pfrommer, Pakmor, Schaal, Simpson, Springel, *Simulating cosmic ray physics on a moving mesh,* 2017a, MNRAS.
- Pakmor, Pfrommer, Simpson, Springel, *Galactic winds driven by isotropic and anisotropic cosmic ray diffusion in isolated disk galaxies,* 2016, ApJL.
- Jacob, Pakmor, Simpson, Springel, Pfrommer, *The dependence of cosmic ray driven galactic winds on halo mass,* 2018, MNRAS.
- Pfrommer, Pakmor, Simpson, Springel, *Simulating Gamma-ray Emission in Star-forming Galaxies,* 2017b, ApJL.
- Pfrommer, Pakmor, Simpson, Springel, *Simulating Radio Synchrotron Emission in Galaxies: the Origin of the Far Infrared–Radio Correlation,* 2018.

AIP

Additional slides

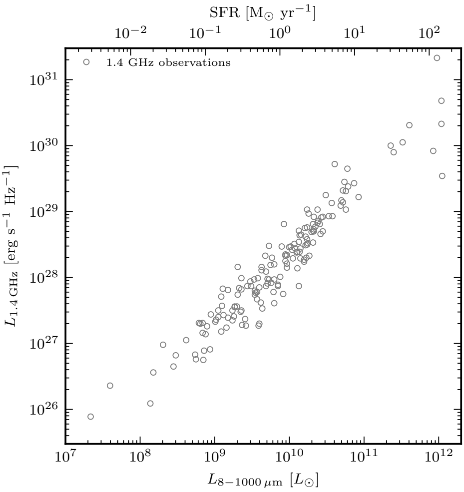
γ-ray and radio emission of Milky Way-like galaxy



CP+ (2017b, 2018)

Far infra-red – radio correlation

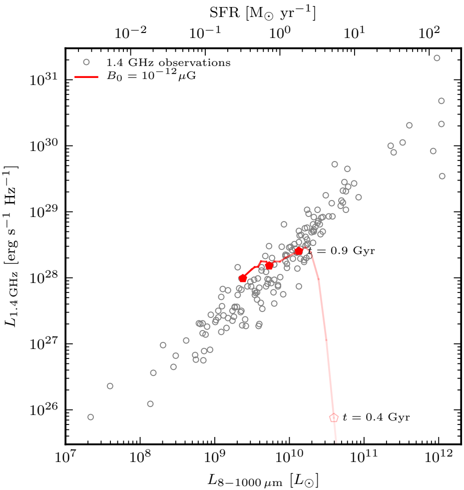
Universal conversion: star formation → cosmic rays → radio



Bell (2003)

Far infra-red – radio correlation

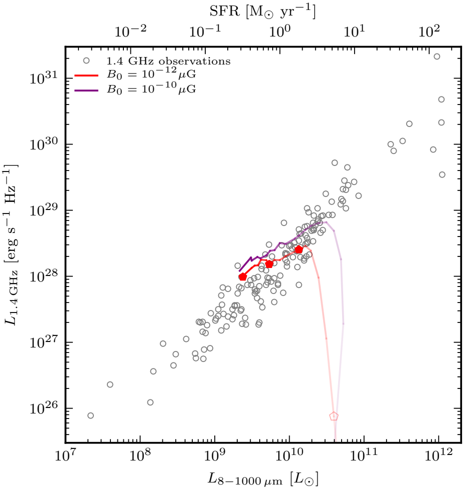
Universal conversion: star formation $\rightarrow$ cosmic rays $\rightarrow$ radio



Bell (2003)

Far infra-red – radio correlation

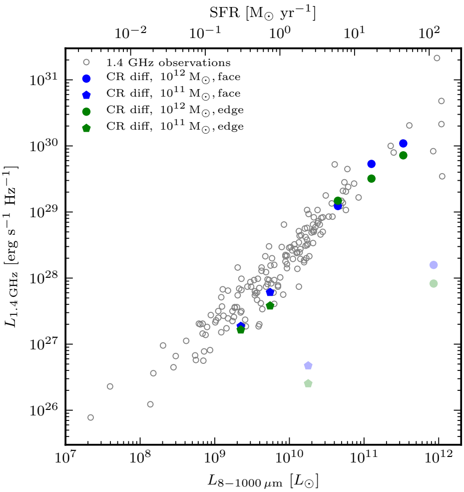
Universal conversion: star formation → cosmic rays → radio



Bell (2003)

Far infra-red – radio correlation

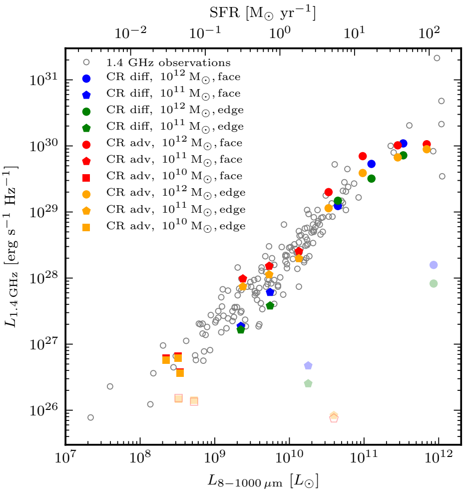
Universal conversion: star formation → cosmic rays → radio



CP+ (2018)

Far infra-red – radio correlation

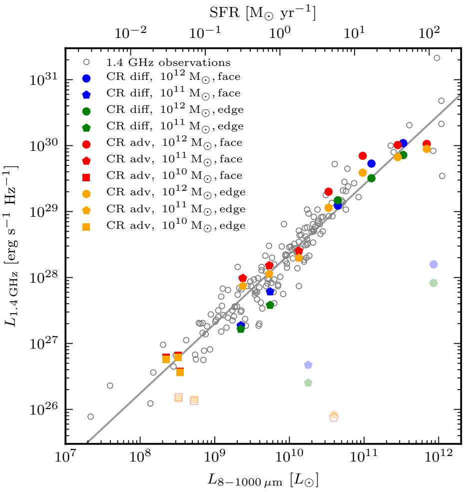
Universal conversion: star formation → cosmic rays → radio



CP+ (2018)

Far infra-red – radio correlation

Universal conversion: star formation → cosmic rays → radio



CP+ (2018)