How cosmic rays shape galaxies

Christoph Pfrommer[1]

in collaboration with

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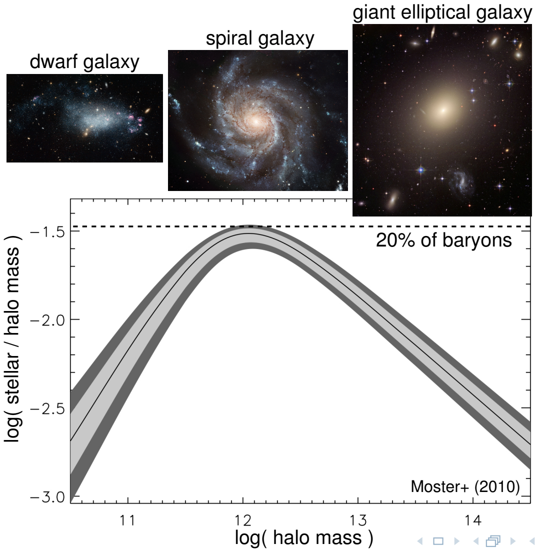
Outline

1. Introduction
   - Puzzles
   - Galactic winds
   - Cosmic ray transport
2. Small galactic scales
   - Modelling physics in galaxies
   - Supernova explosions
   - Particle acceleration
3. Simulating galaxy formation
   - Cosmic ray advection
   - Cosmic ray diffusion
   - Radio and γ rays

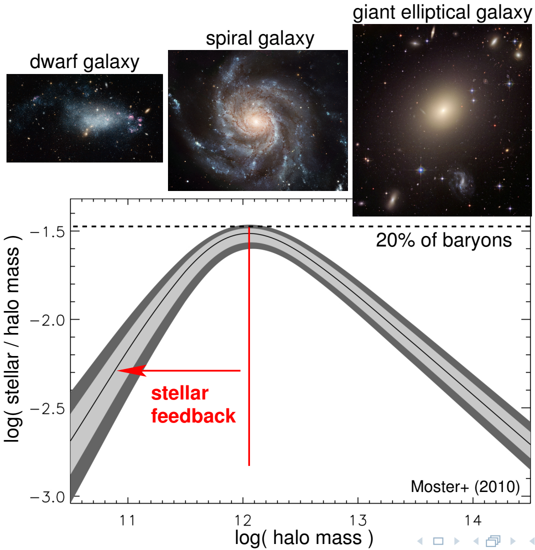
Outline

Puzzles in galaxy formation

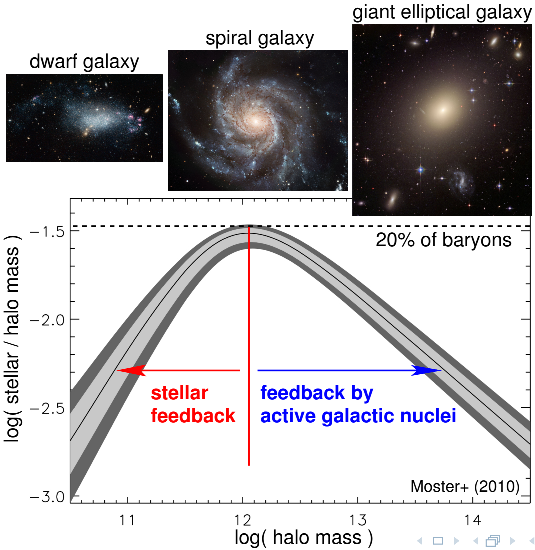

Puzzles in galaxy formation



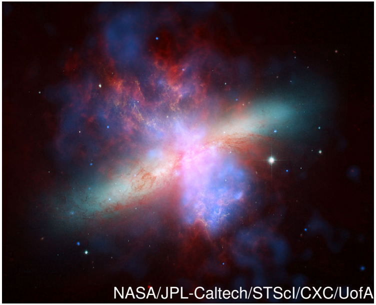
Puzzles in galaxy formation



Puzzles in galaxy formation



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 pressure and Alfvén wave heating of CRs accelerated at supernova shocks?

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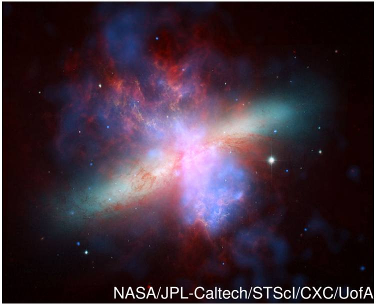

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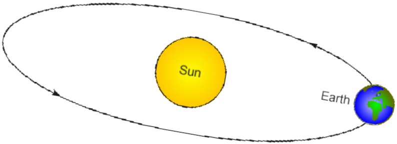
observed energy equipartition between cosmic rays, thermal gas and magnetic fields

$\rightarrow$ suggests self-regulated feedback loop with CR driven winds

AIP

Cosmic ray feedback: an extreme multi-scale problem



Milky Way-like galaxy:

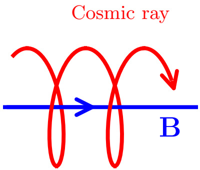
$$r_{\rm gal} \sim 10^4 \text{ pc}$$

gyro-orbit of GeV cosmic ray:

$$r_{\rm cr} = \frac{p_\perp}{e\,B_{\mu\rm G}} \sim 10^{-6} \text{ pc} \sim \frac{1}{4} \text{ AU}$$

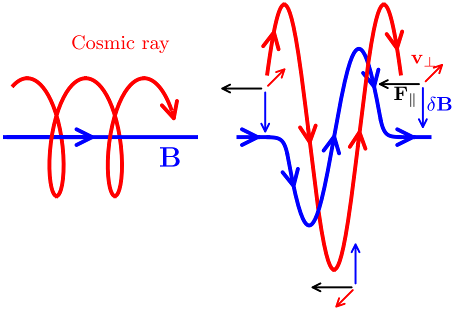
$\Rightarrow$ need to develop a **fluid theory for a collisionless, non-Maxwellian component!**

Interactions of CRs and magnetic fields



sketch: Jacob

Interactions of CRs and magnetic fields



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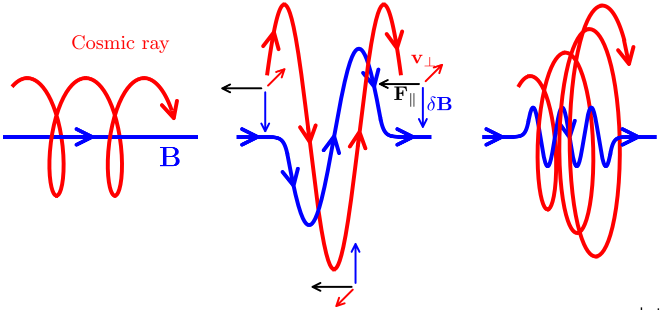
- **gyro resonance:** $\omega - k_{\|} v_{\|} = n\Omega$

  Doppler-shifted MHD frequency is a multiple of the CR gyrofrequency

Interactions of CRs and magnetic fields

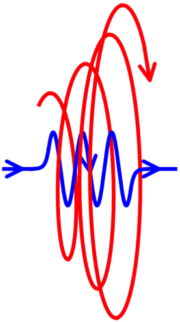


sketch: Jacob

- **gyro resonance:** $\omega - k_{||} v_{||} = n\Omega$
  Doppler-shifted MHD frequency is a multiple of the CR gyrofrequency
- CRs scatter on magnetic fields $\rightarrow$ isotropization of CR momenta

CR streaming

- **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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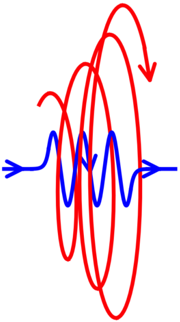

$\rightarrow$ **CRs exert a pressure on the thermal gas by means of scattering off of Alfvén waves**

CR transport in steady state

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

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- 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 $\boldsymbol{B}$):

$$\boldsymbol{v}_{\mathrm{st}} = \boldsymbol{v}_{\mathrm{A}} \frac{\bar{\nu}_{+} - \bar{\nu}_{-}}{\bar{\nu}_{+} + \bar{\nu}_{-}}, \quad \boldsymbol{v}_{\mathrm{di}} = -\kappa_{\mathrm{di}} \boldsymbol{b} \frac{\boldsymbol{b} \cdot \nabla \varepsilon_{\mathrm{cr}}}{\varepsilon_{\mathrm{cr}}}, \quad \kappa_{\mathrm{di}} = \frac{c^2}{3(\bar{\nu}_{+} + \bar{\nu}_{-})}$$

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

$$\frac{\partial \varepsilon}{\partial t} + \boldsymbol{\nabla} \cdot [(\varepsilon + P_{\mathrm{th}} \qquad) \boldsymbol{v}] = 0$$

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$$\frac{\partial \varepsilon_{\mathrm{cr}}}{\partial t} + \boldsymbol{\nabla} \cdot [P_{\mathrm{cr}} \boldsymbol{v}_{\mathrm{st}} + \varepsilon_{\mathrm{cr}}(\boldsymbol{v} + \boldsymbol{v}_{\mathrm{st}} + \boldsymbol{v}_{\mathrm{di}})] = -P_{\mathrm{cr}} \boldsymbol{\nabla} \cdot \boldsymbol{v} + \boldsymbol{v}_{\mathrm{st}} \cdot \boldsymbol{\nabla} P_{\mathrm{cr}}$$

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$$\Longleftrightarrow \quad \frac{\partial \varepsilon_{\text{cr}}}{\partial t} + \nabla \cdot [\varepsilon_{\text{cr}}(\boldsymbol{v} + \boldsymbol{v}_{\text{st}} + \boldsymbol{v}_{\text{di}})] = -P_{\text{cr}} \nabla \cdot (\boldsymbol{v} + \boldsymbol{v}_{\text{st}})$$

Alfvén-wave regulated CR transport

- coupled equations for CR energy and flux density, $\varepsilon_{\rm cr}$ and $f_{\rm cr}$ and Alfvén-wave energy density $\varepsilon_{{\rm a},\pm}$ (Thomas & CP 2018):

$$\frac{\partial \varepsilon_{\rm cr}}{\partial t} + \boldsymbol{\nabla} \cdot [\boldsymbol{u}(\varepsilon_{\rm cr} + P_{\rm cr}) + \boldsymbol{b} f_{\rm cr}] = \boldsymbol{u} \cdot \boldsymbol{\nabla} P_{\rm cr} - \frac{v_{\rm a}}{3\kappa_+}[f_{\rm cr} - v_{\rm a}(\varepsilon_{\rm cr} + P_{\rm cr})] + \frac{v_{\rm a}}{3\kappa_-}[f_{\rm cr} + v_{\rm a}(\varepsilon_{\rm cr} + P_{\rm cr})] \quad (1)$$

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$$\frac{\partial f_\mathrm{cr}}{\partial t} + \boldsymbol{\nabla} \cdot (\boldsymbol{u} f_\mathrm{cr}) + \frac{c^2}{3} \boldsymbol{b} \cdot \boldsymbol{\nabla} \varepsilon_\mathrm{cr} = -(\boldsymbol{b} \cdot \boldsymbol{\nabla} \boldsymbol{u}) \cdot (\boldsymbol{b} f_\mathrm{cr}) - \frac{c^2}{3\kappa_+}[f_\mathrm{cr} - v_\mathrm{a}(\varepsilon_\mathrm{cr} + P_\mathrm{cr})] - \frac{c^2}{3\kappa_-}[f_\mathrm{cr} + v_\mathrm{a}(\varepsilon_\mathrm{cr} + P_\mathrm{cr})] \quad (2)$$

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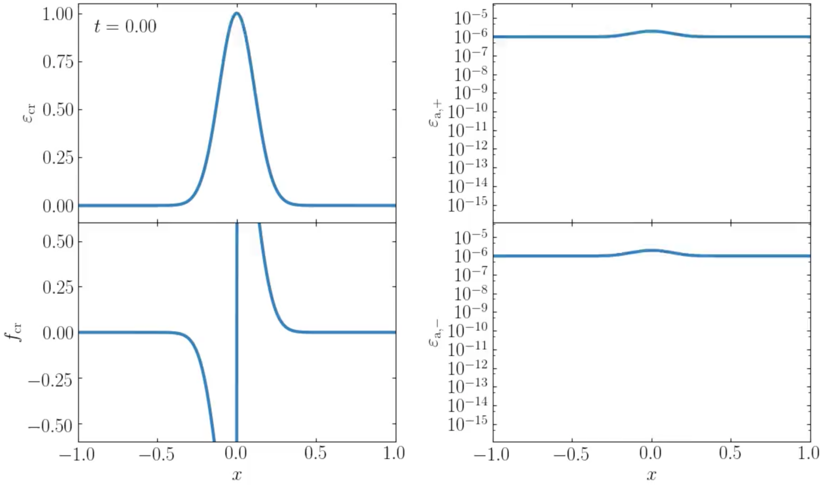
$$\frac{\partial \varepsilon_{\mathrm{a},\pm}}{\partial t} + \boldsymbol{\nabla} \cdot [\boldsymbol{u}(\varepsilon_{\mathrm{a},\pm} + P_{\mathrm{a},\pm}) \pm v_{\mathrm{a}} \boldsymbol{b} \varepsilon_{\mathrm{a},\pm}] = \boldsymbol{u} \cdot \boldsymbol{\nabla} P_{\mathrm{a},\pm} \pm \frac{v_{\mathrm{a}}}{3\kappa_\pm}[f_{\mathrm{cr}} \mp v_{\mathrm{a}}(\varepsilon_{\mathrm{cr}} + P_{\mathrm{cr}})] - S_{\mathrm{a},\pm} \quad (3)$$

Non-equilibrium CR streaming and diffusion

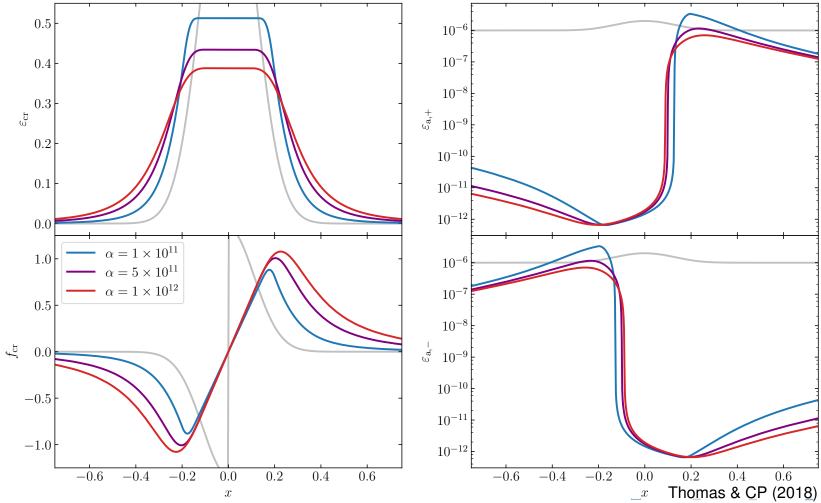
Coupling the evolution of CR and Alfvén wave energy densities



Thomas & CP (2018)

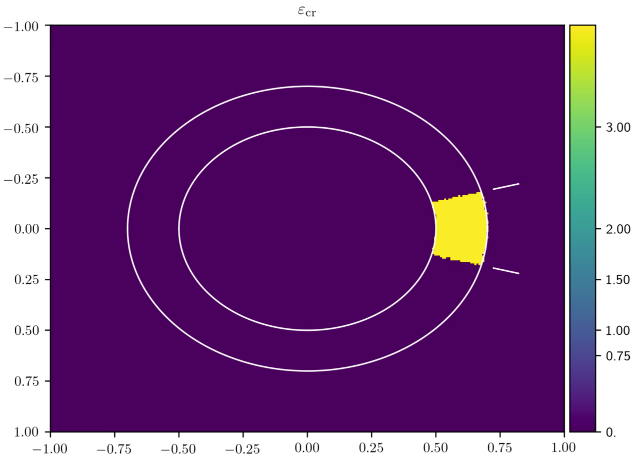
Non-equilibrium CR streaming and diffusion

Varying damping rate of Alfvén waves modulates the diffusivity of solution



Thomas & CP (2018)

Non-equilibrium CR streaming and diffusion – AREPO



Thomas, CP & Pakmor (2018)

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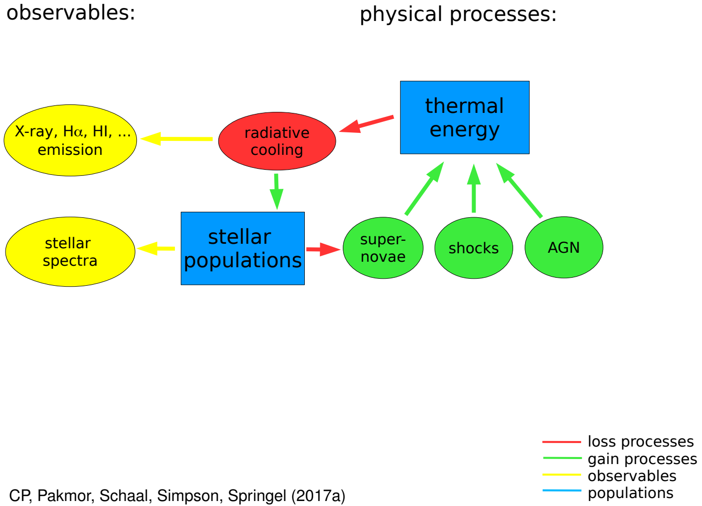
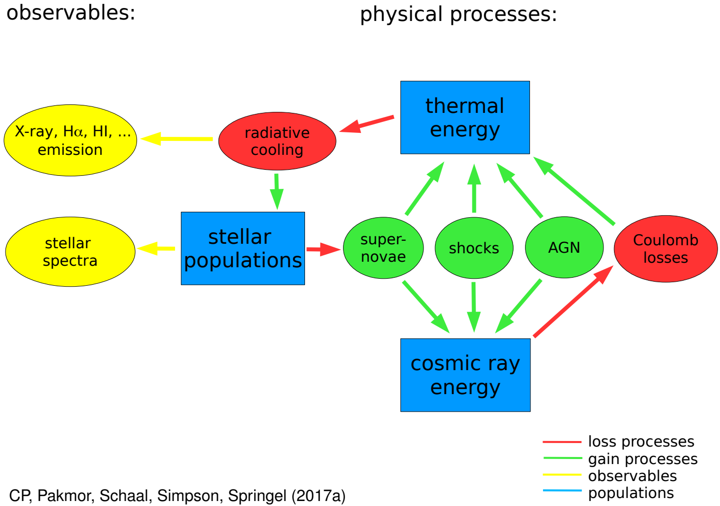
Simulations – flowchart



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

Simulations with cosmic ray physics



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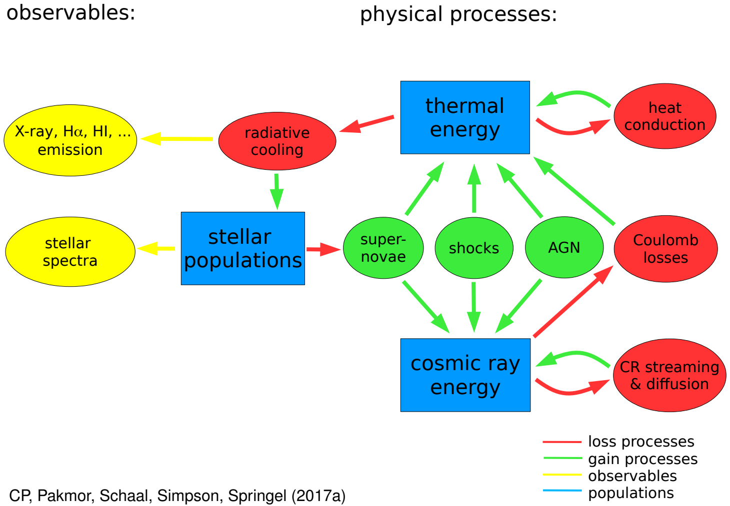

CP, Pakmor, Schaal, Simpson, Springel (2017a)

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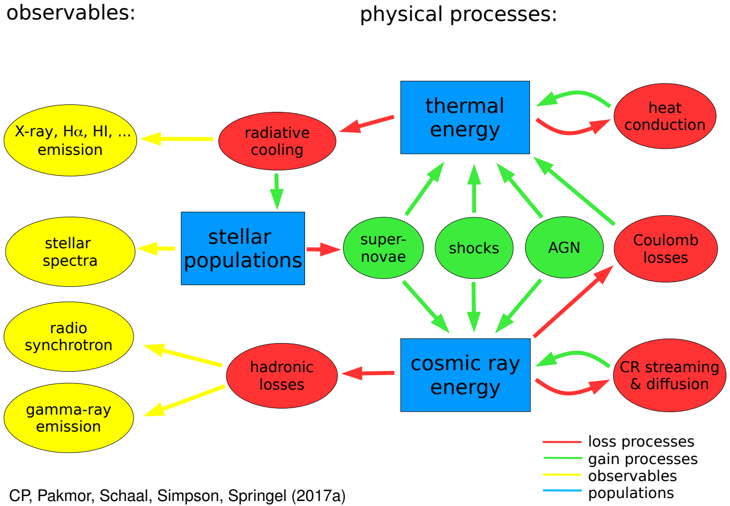
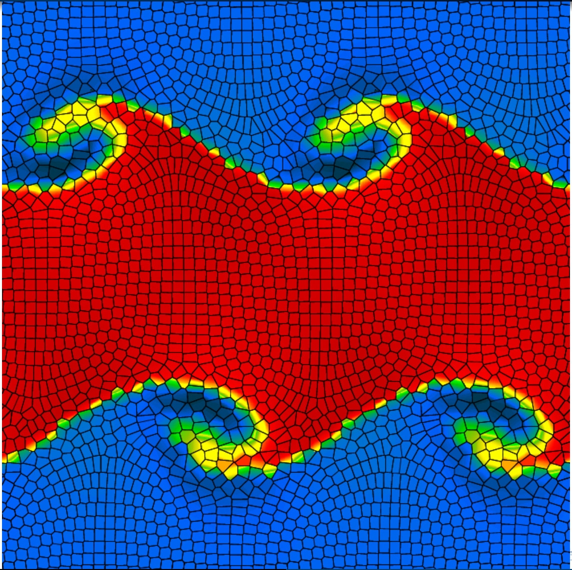


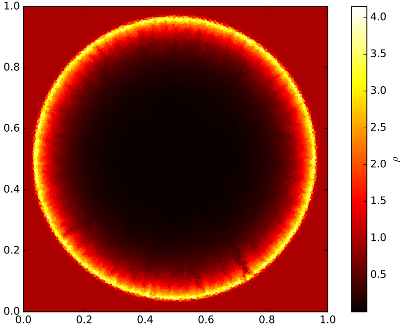
CP, Pakmor, Schaal, Simpson, Springel (2017a)

Cosmological moving-mesh code AREPO (Springel 2010)

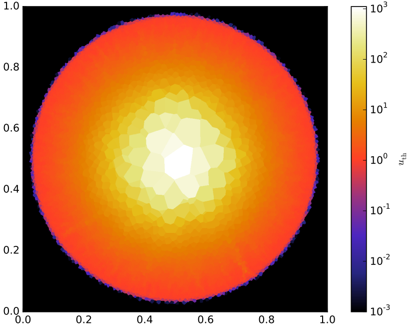


Sedov explosion

density



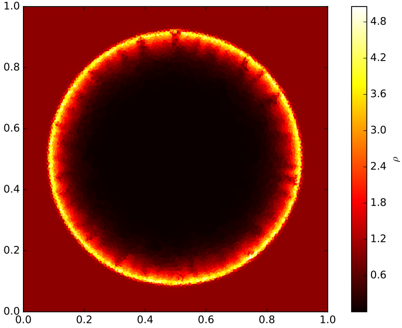
specific thermal energy



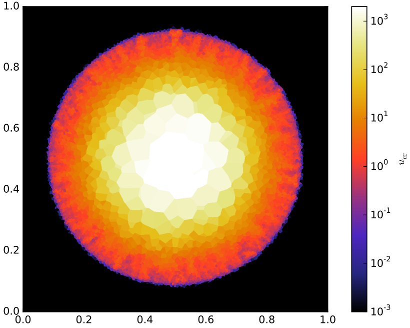
CP, Pakmor, Schaal, Simpson, Springel (2017a)

Sedov explosion with CR acceleration

density

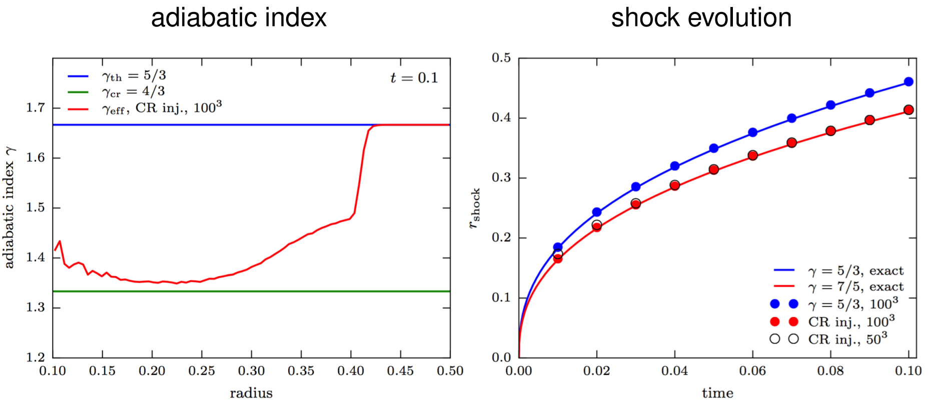


specific cosmic ray energy



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

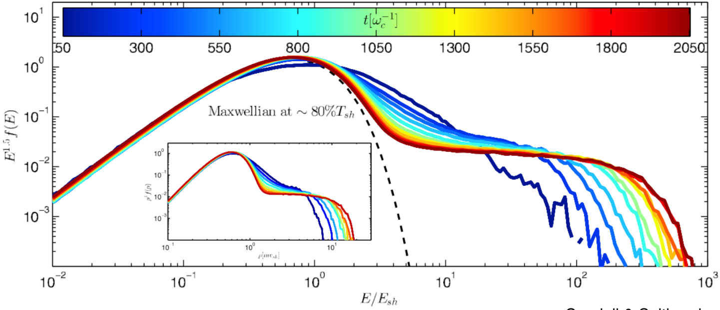
Sedov explosion with CR acceleration



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

Ion spectrum

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

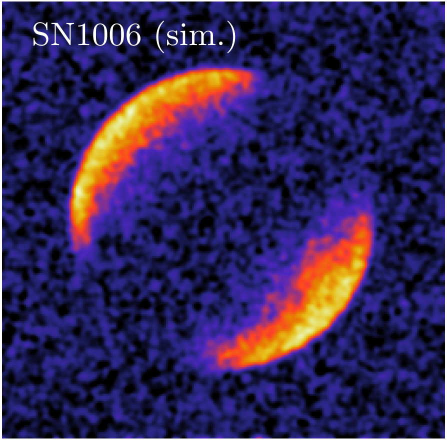


Caprioli & Spitkovsky (2014)

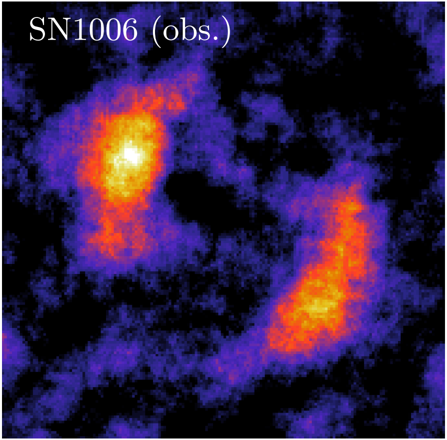
- quasi-parallel shocks ($\boldsymbol{B} \parallel \boldsymbol{n}_s$) efficiently accelerate ions
- quasi-perpendicular shocks ($\boldsymbol{B} \perp \boldsymbol{n}_s$) cannot
- model magnetic obliquity in AREPO simulations

TeV γ rays from shell-type SNRs: SNR 1006

AREPO simulation



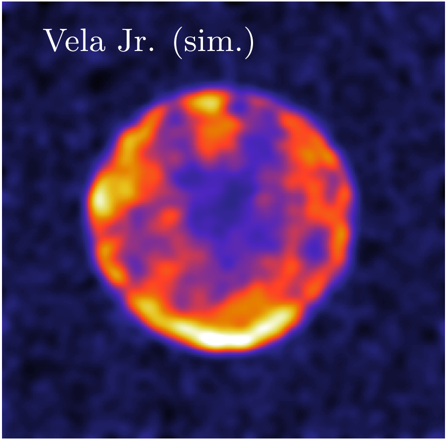
H.E.S.S. observation



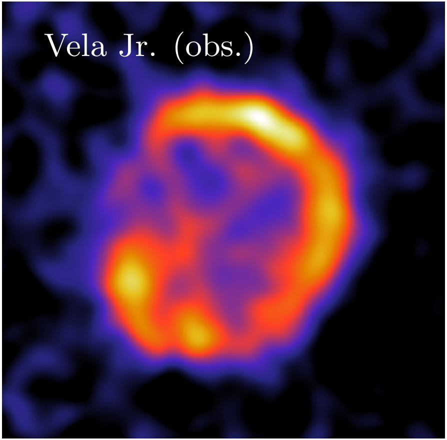
Pais, CP, Ehlert (2018)

TeV γ rays from shell-type SNRs: Vela Junior

AREPO simulation



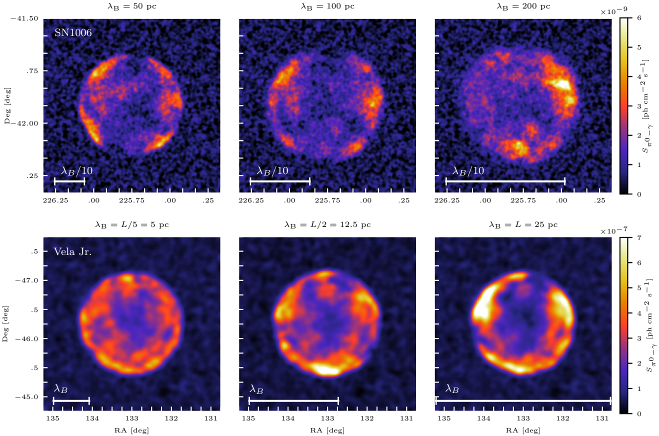
H.E.S.S. observation



Pais, CP, Ehlert (2018)

TeV γ rays from shell-type supernova remnants

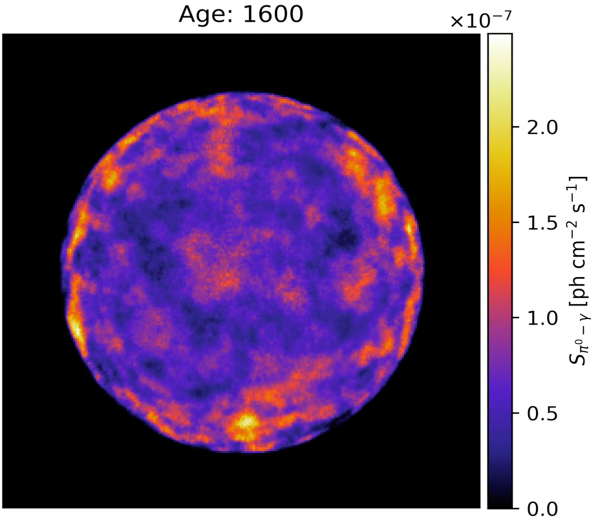
Varying magnetic coherence scale in simulations of SN1006 and Vela Junior



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)

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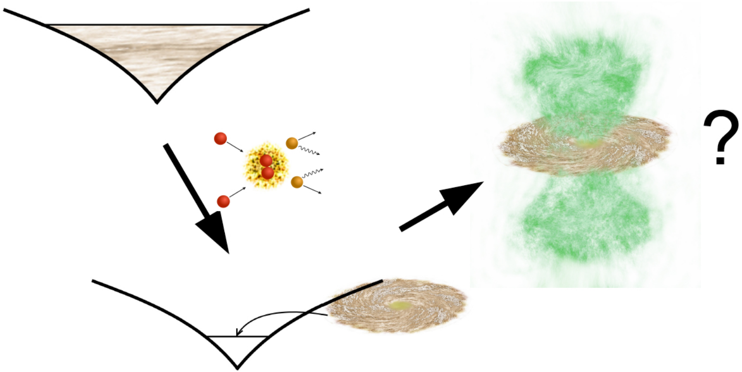
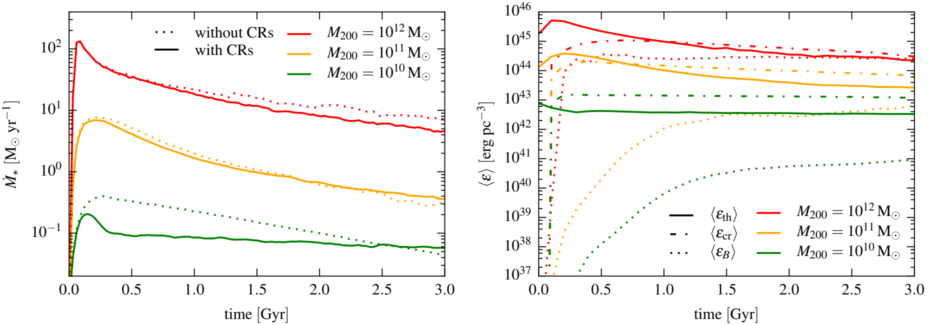
Galaxy simulation setup: 1. cosmic ray advection



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

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

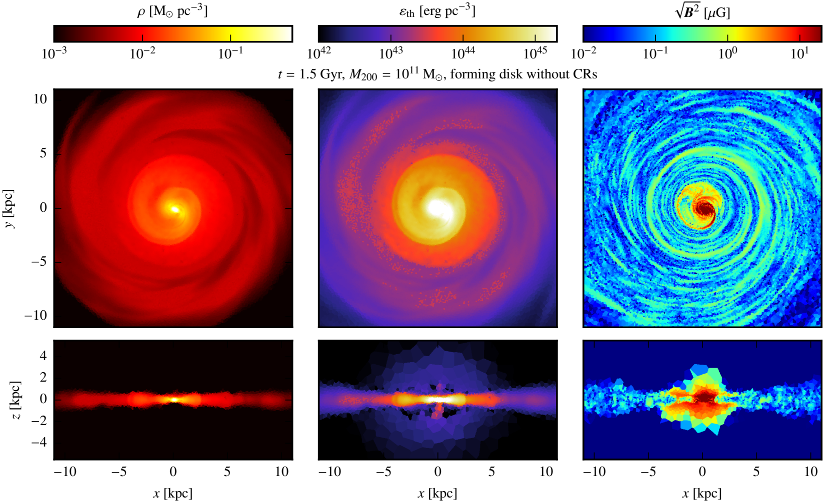
Time evolution of SFR and energy densities



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

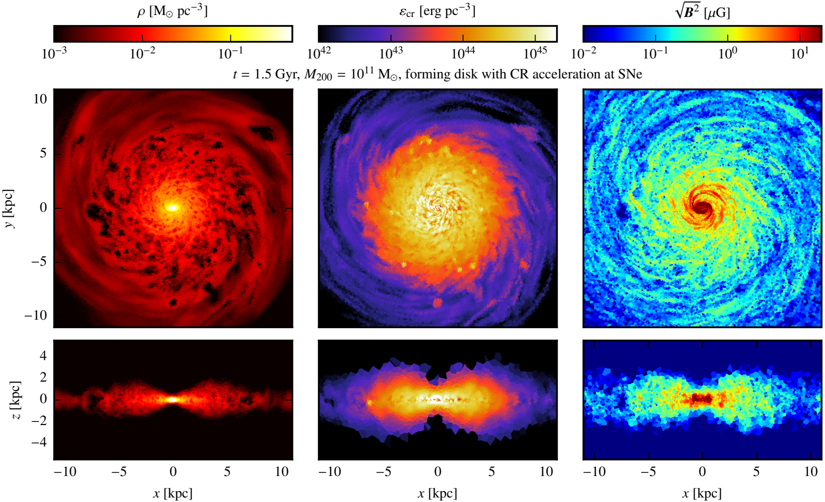
- CR pressure feedback suppresses SFR more in smaller galaxies
- energy budget in disks is dominated by CR pressure
- magnetic dynamo faster in Milky Way galaxies than in dwarfs

MHD galaxy simulation without CRs



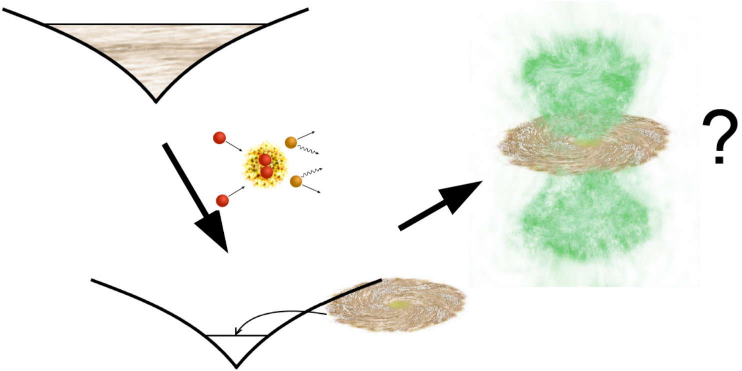
CP, Pakmor, Schaal, Simpson, Springel (2017a)

MHD galaxy simulation with CRs



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

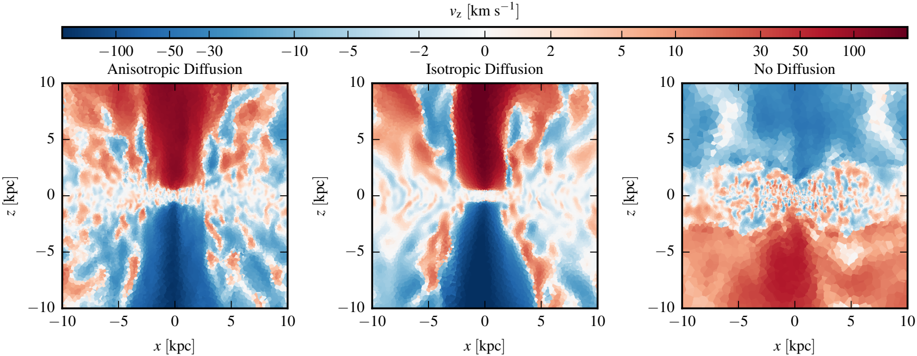
Galaxy simulation setup: 2. cosmic ray diffusion



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

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

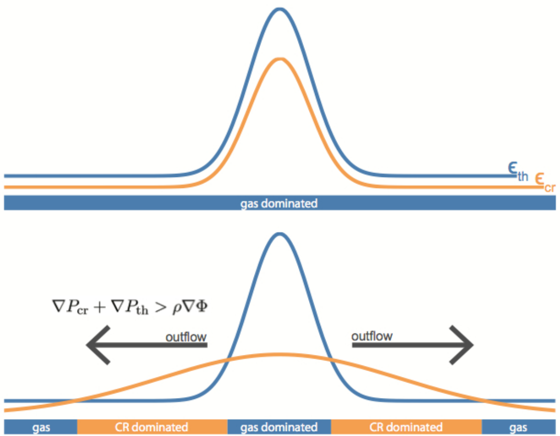
MHD galaxy simulation with CR diffusion



Pakmor, CP, Simpson, Springel (2016)

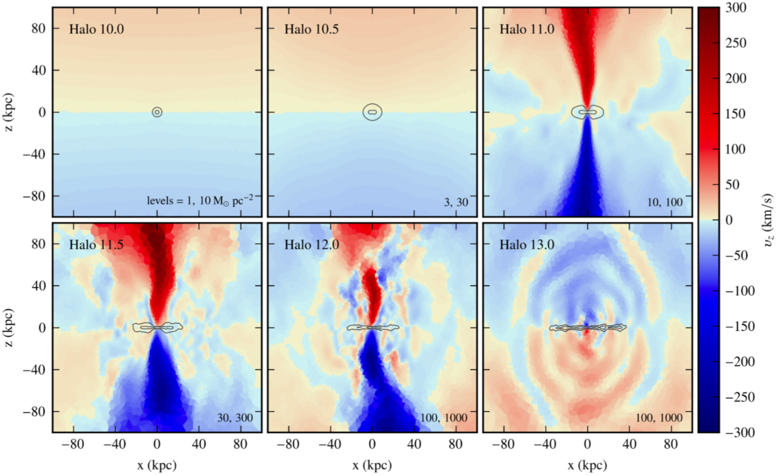
- CR diffusion launches powerful winds
- simulation without CR diffusion exhibits only weak fountain flows

Cosmic ray driven wind: mechanism



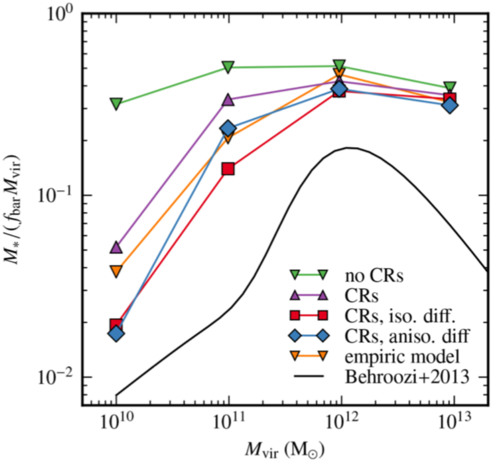
CR streaming in 3D simulations: Uhlig, CP+ (2012), Ruszkowski+ (2017)
CR diffusion in 3D simulations: Jubelgas+ (2008), Booth+ (2013), Hanasz+ (2013), Salem & Bryan (2014), Pakmor, CP+ (2016), Simpson+ (2016), Girichidis+ (2016), Dubois+ (2016), CP+ (2017b), Jacob+ (2018)

CR-driven winds: dependence on halo mass



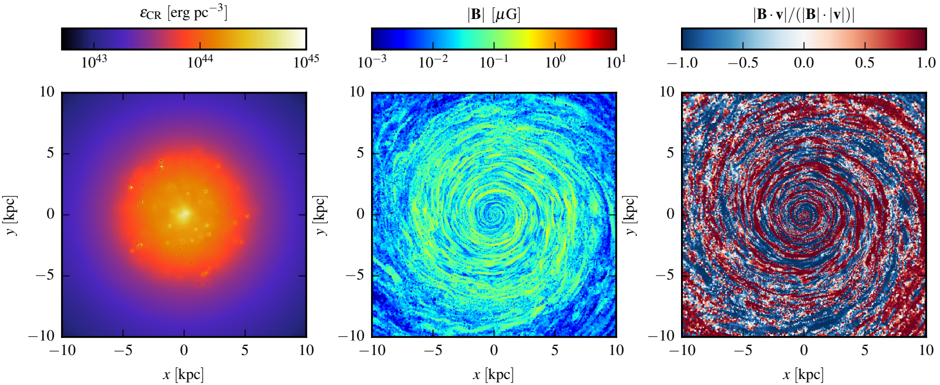
Jacob+ (2018)

CR-driven winds: suppression of star formation



Jacob+ (2018)

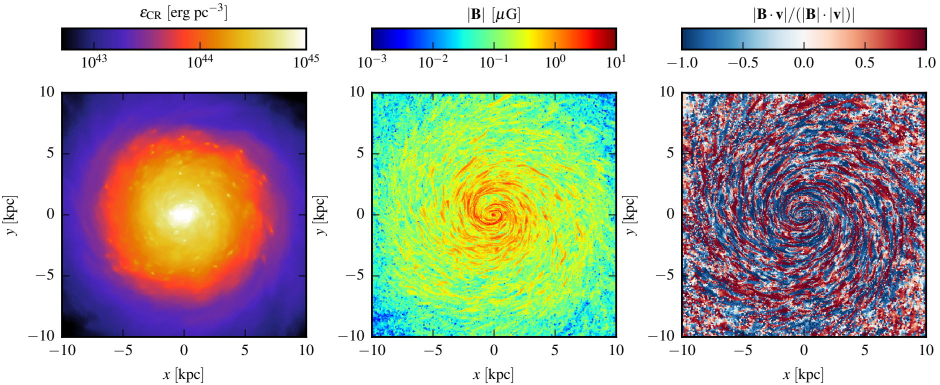
MHD galaxy simulation with CR isotropic diffusion



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

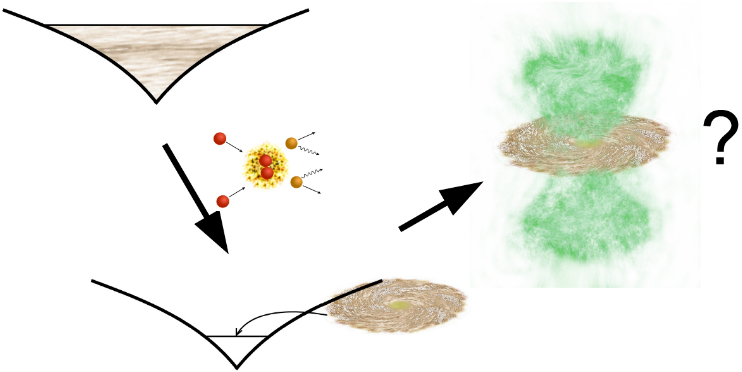


Pakmor, C.P., Simpson, Springel (2016)

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

AIP

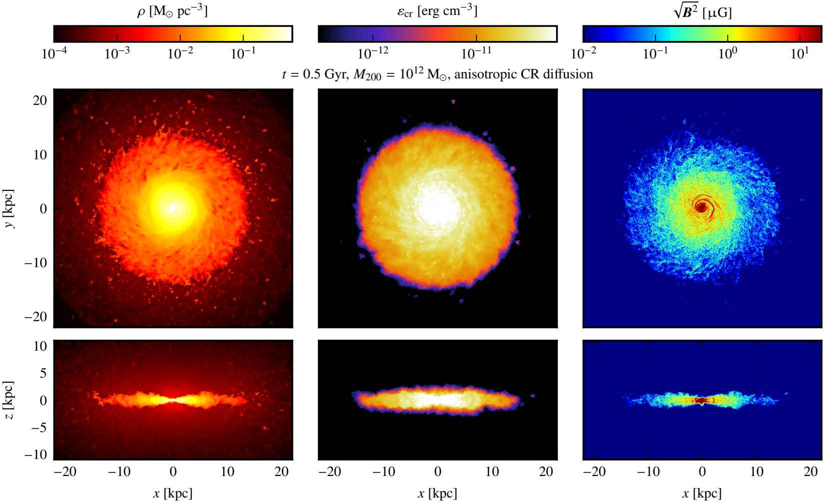
Galaxy simulation setup: 3. non-thermal emission



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

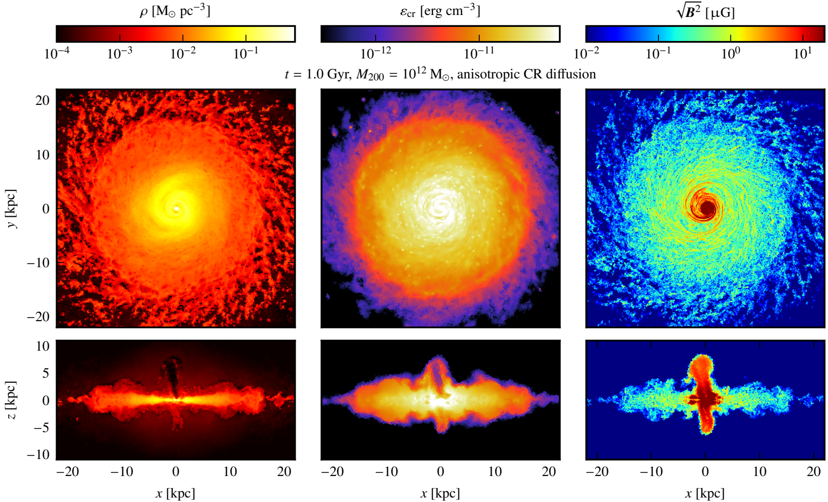
MHD + CR advection + diffusion: $\{10^{10}, 10^{11}, 10^{12}\}\ M_\odot$

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



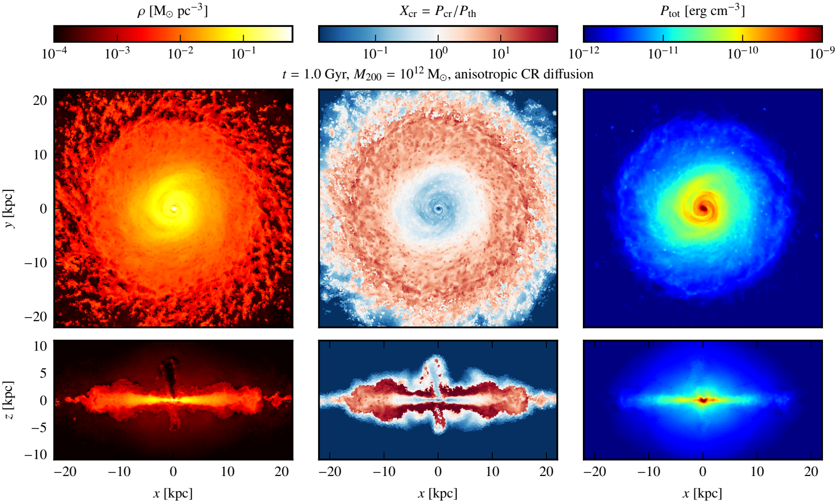
CP+ (2017b, 2018)

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



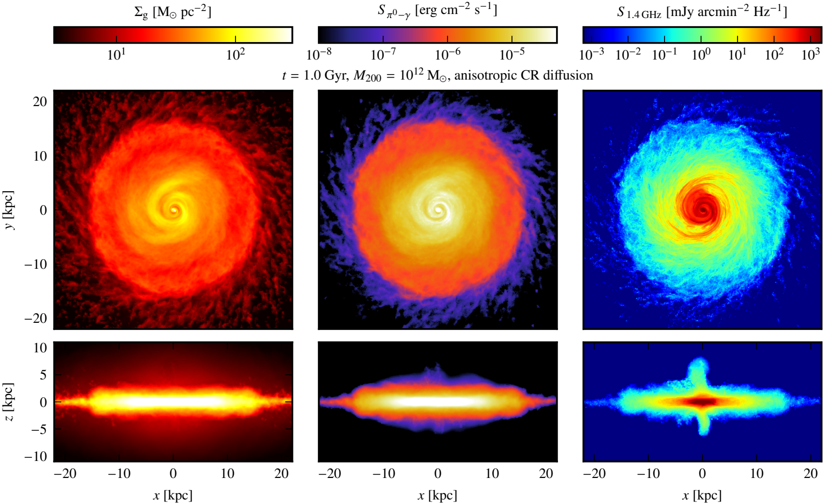
CP+ (2017b, 2018)

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



CP+ (2017b, 2018)

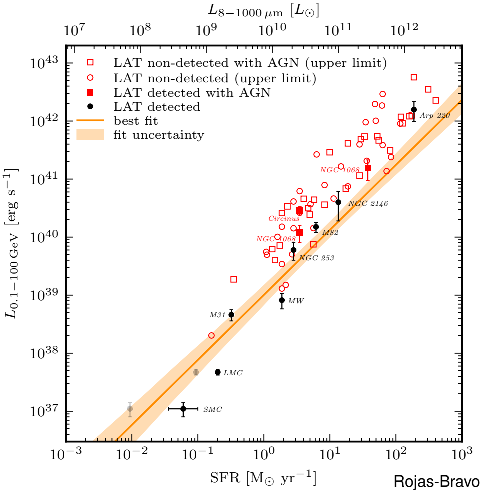
γ-ray and radio emission of Milky Way-like galaxy



CP+ (2017b, 2018)

Far infra-red – gamma-ray correlation

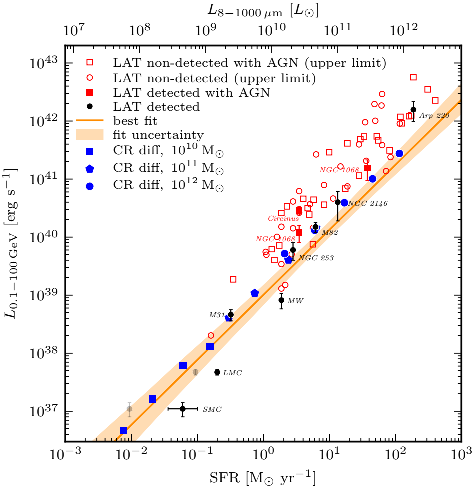
Universal conversion: star formation → cosmic rays → gamma rays



Rojas-Bravo & Araya (2016)

Far infra-red – gamma-ray correlation

Universal conversion: star formation → cosmic rays → gamma rays



CP+ (2017b)

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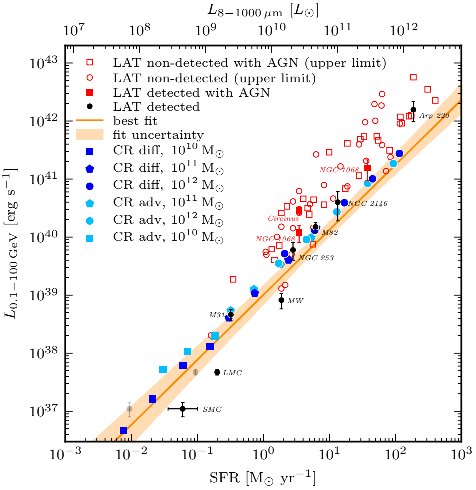

CP+ (2017b)

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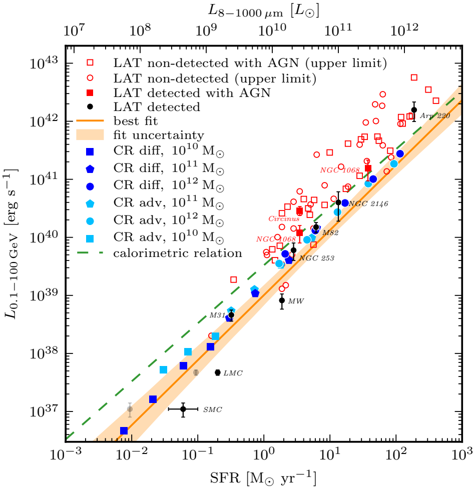
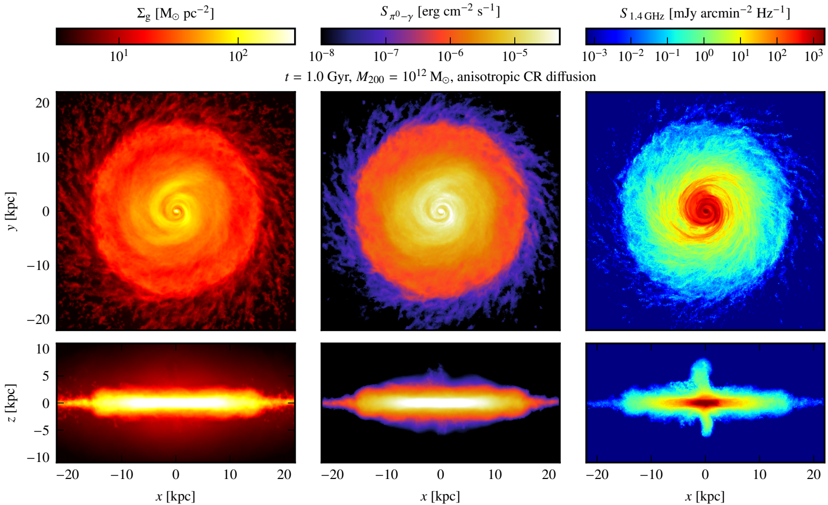


CP+ (2017b)

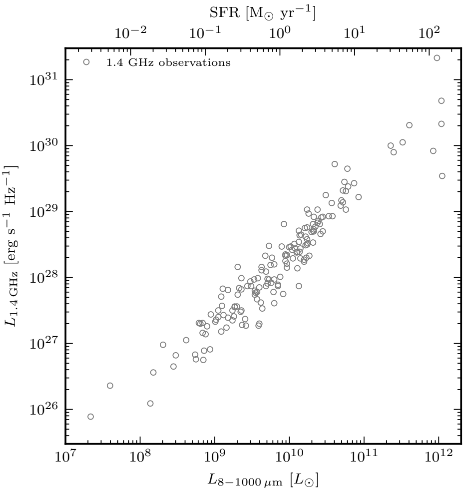
γ-ray and radio emission of Milky Way-like galaxy



CP+ (2017b, 2018)

Far infra-red – radio correlation

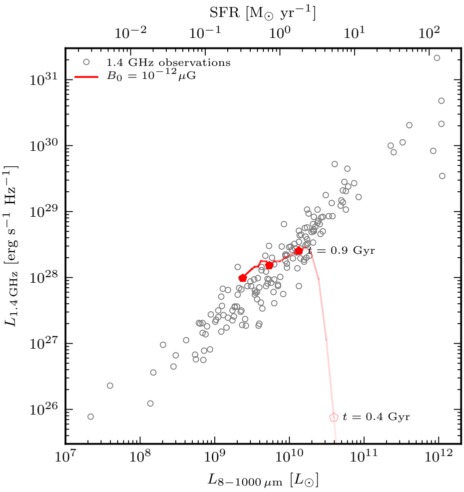
Universal conversion: star formation → cosmic rays → radio



Bell (2003)

Far infra-red – radio correlation

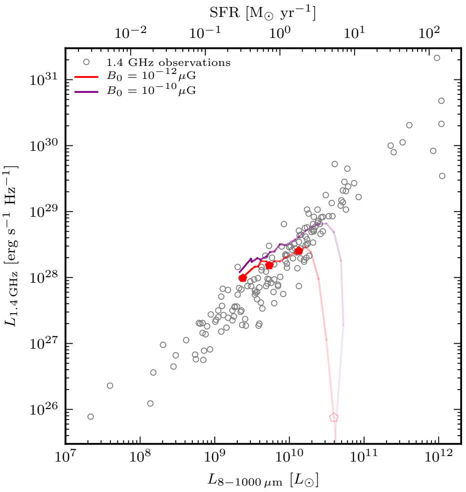
Universal conversion: star formation $\rightarrow$ cosmic rays $\rightarrow$ radio



Bell (2003)

Far infra-red – radio correlation

Universal conversion: star formation → cosmic rays → radio



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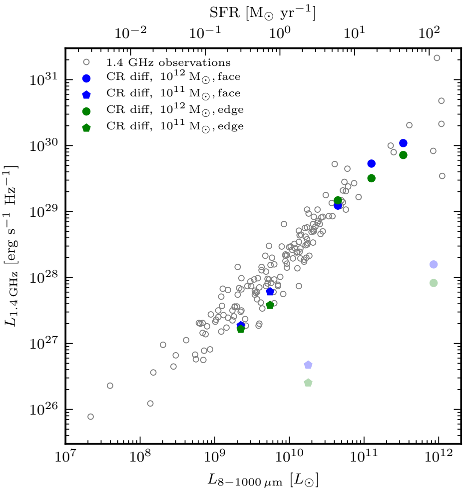

CP+ (2018)

Far infra-red – radio correlation

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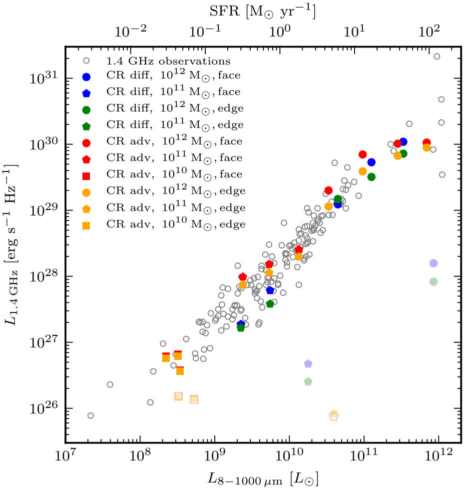

CP+ (2018)

Far infra-red – radio correlation

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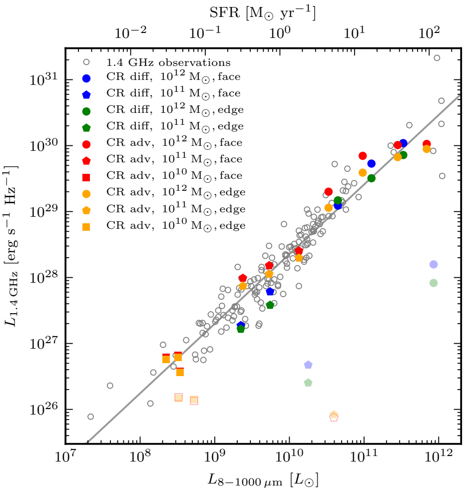

CP+ (2018)

AIP

Conclusions on CR feedback in galaxies and clusters

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

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- anisotropic CR diffusion necessary for efficient galactic dynamo: observed field strengths of $B \sim 10\,\mu$G
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Conclusions on CR feedback in galaxies and clusters

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- $L_{\mathrm{FIR}} - L_\gamma$ 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**

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 and transport:

- Thomas, Pfrommer, *Cosmic-ray hydrodynamics: Alfvén-wave regulated transport of cosmic rays,* 2018.
- 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.

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Literature for the talk – 2

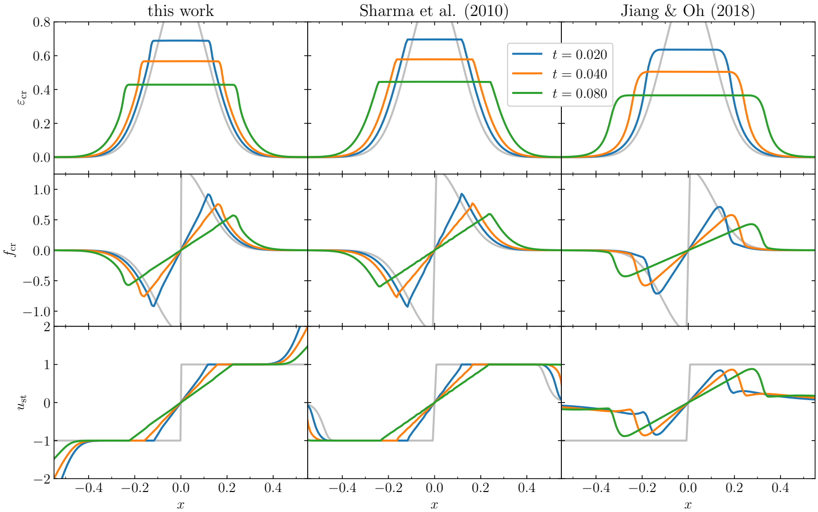
Non-thermal radio and gamma-ray emission in galaxies:

- 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

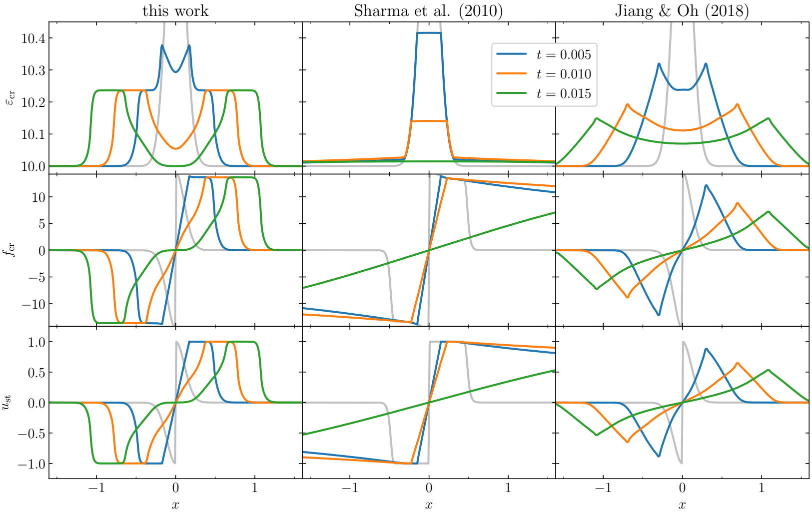
Additional slides

CR transport – evolution of isolated Gaussian



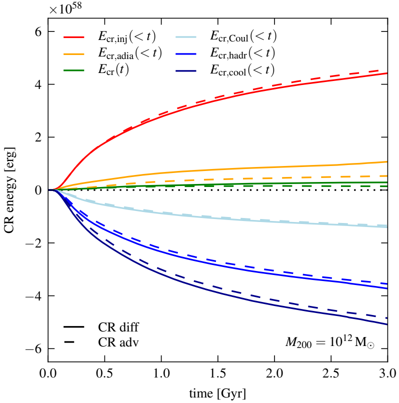
Thomas & CP (2018)

CR transport – evolution of Gaussian with background



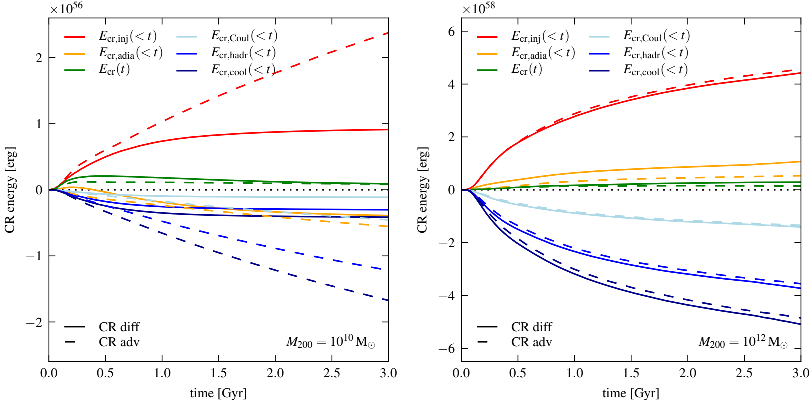
Thomas & CP (2018)

Time evolution of CR energies



CP+ (2017b)

Time evolution of CR energies



CP+ (2017b)

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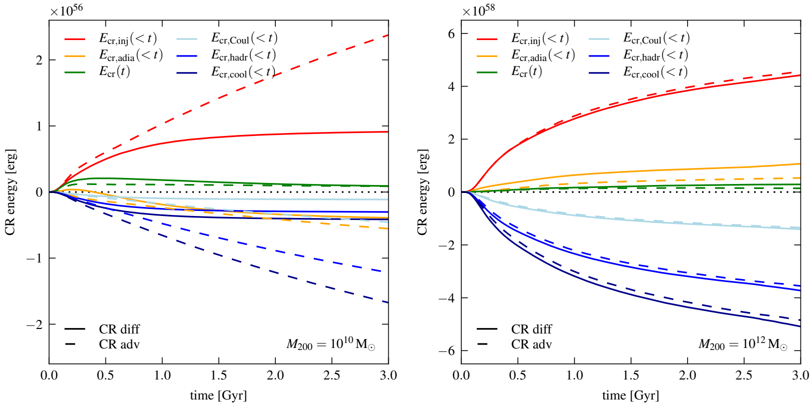

CP+ (2017b)

- adiabatic CR losses are significant in small galaxies
  $\Rightarrow$ deviation from calorimetric relation at small SFRs