Simulating cosmic ray feedback and radio synchrotron emission in star-forming galaxies

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in collaboration with

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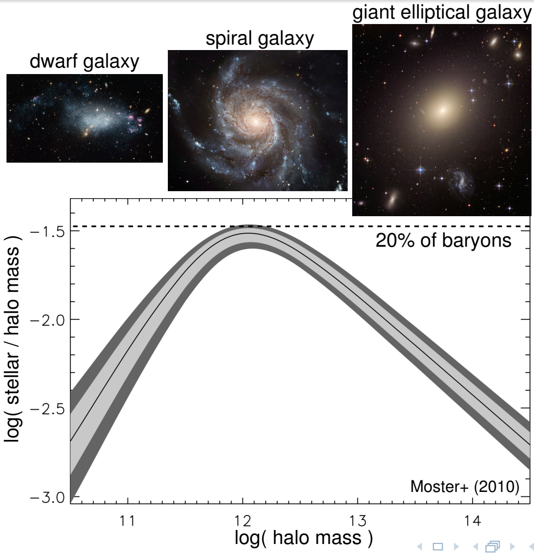
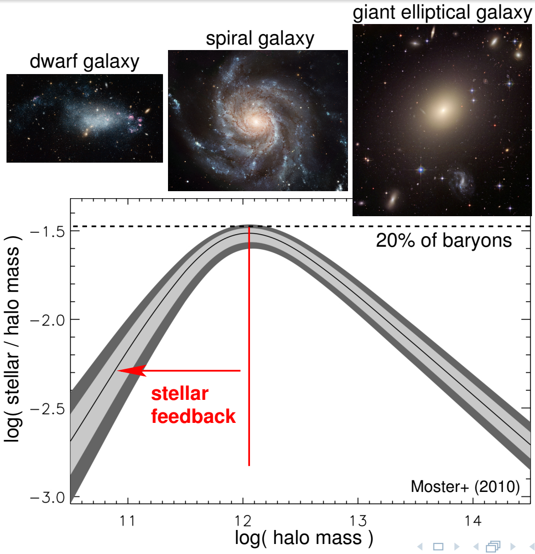
Radio emission from galaxies, clusters and the cosmic web, Mar 2021

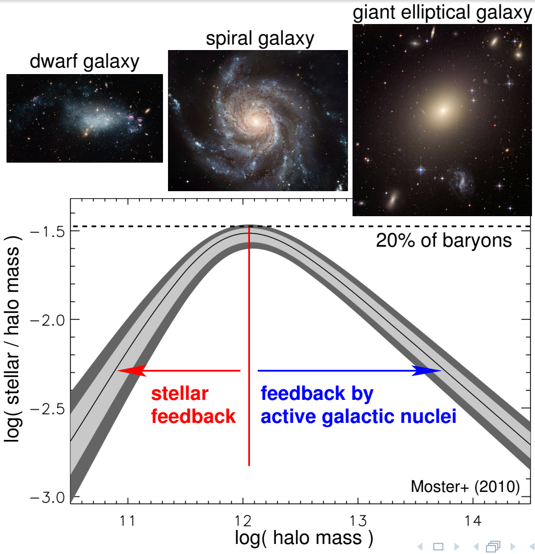
Puzzles in galaxy formation



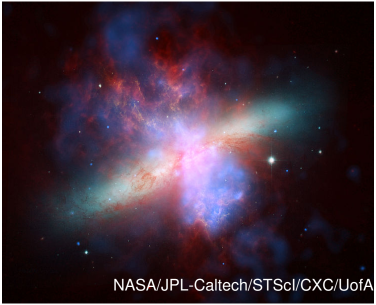
Puzzles in galaxy formation



Puzzles in galaxy formation



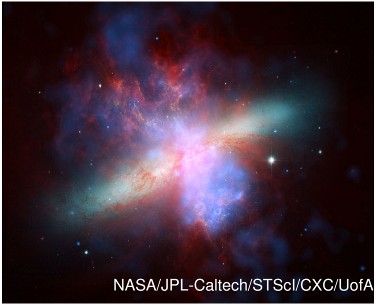
How are galactic winds driven?



super wind in M82

- thermal pressure provided by supernovae or AGNs?
- radiation pressure and photo-ionization 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

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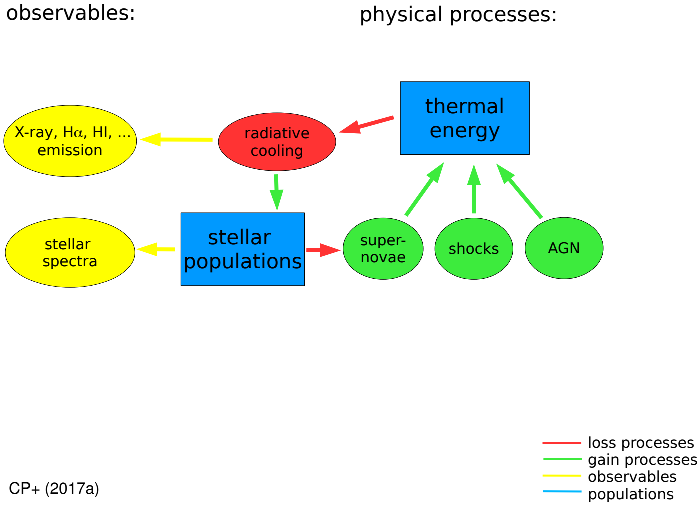
- cosmic-ray (CR) pressure and Alfvén wave heating of CRs accelerated at supernova shocks?

observed energy equipartition between CRs, thermal gas and magnetic fields in the Milky Way
$\Rightarrow$ suggests self-regulated feedback loop with CR driven winds

Simulations – flowchart

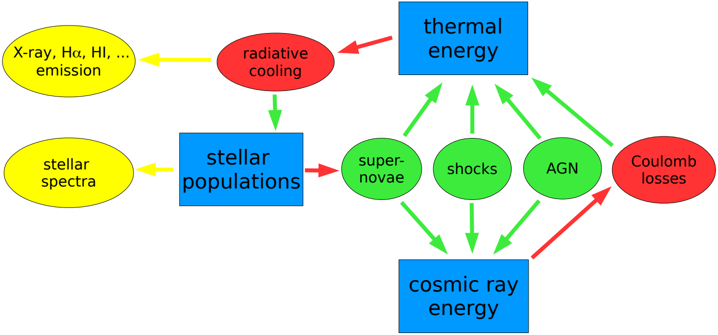


CP+ (2017a)

Simulations with cosmic ray physics

observables:

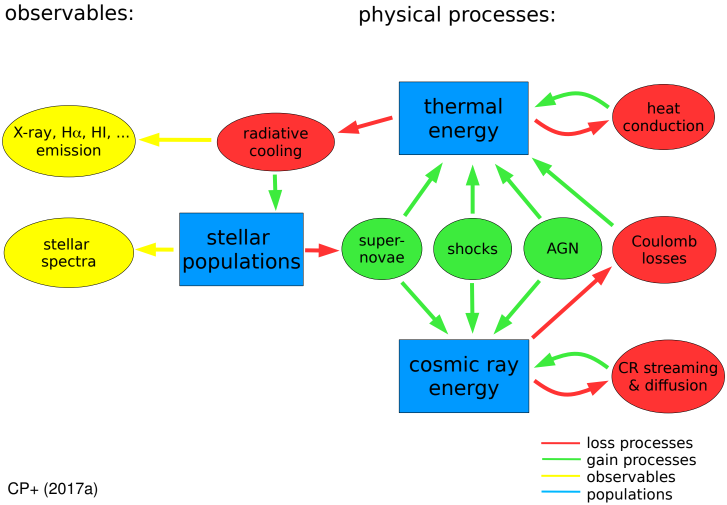
physical processes:



loss processes
gain processes
observables
populations

CP+ (2017a)

Simulations with cosmic ray physics



CP+ (2017a)

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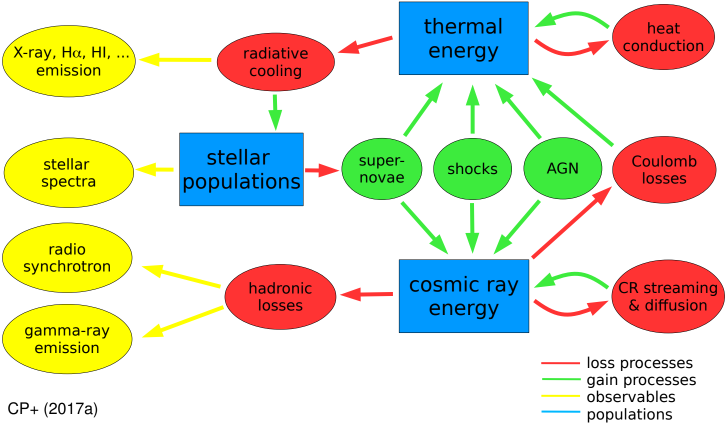
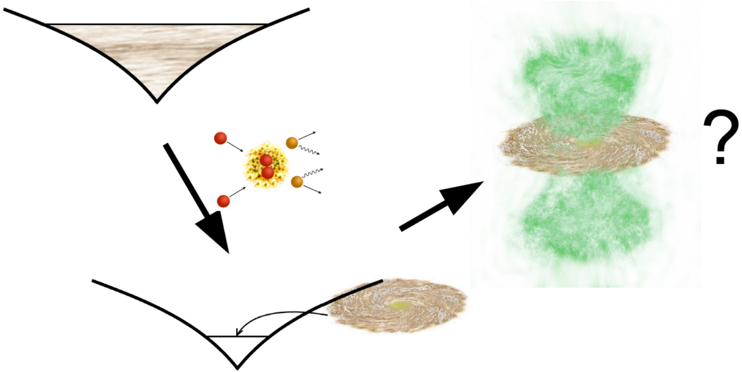


CP+ (2017a)

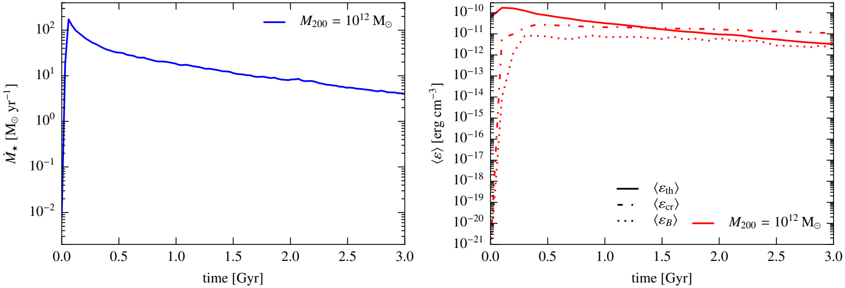
Galaxy simulations: 1. CR-driven winds



CP, Pakmor, Simpson, Springel (2017b)
Simulating gamma-ray emission in star-forming galaxies

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

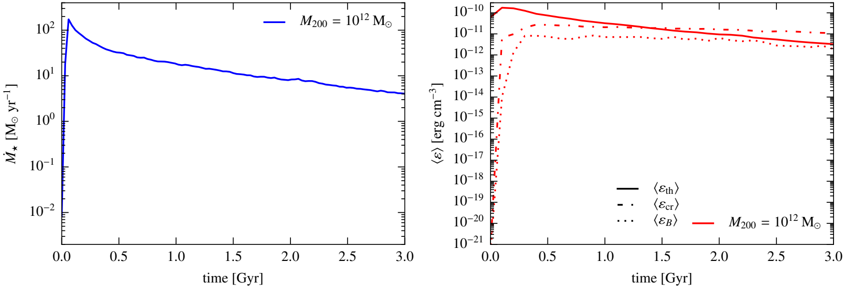
Time evolution of SFR and energy densities



CP+ (in prep)

- initial gravitational collapse causes peak in SFR
- SFR declines exponentially with decreasing accretion rate

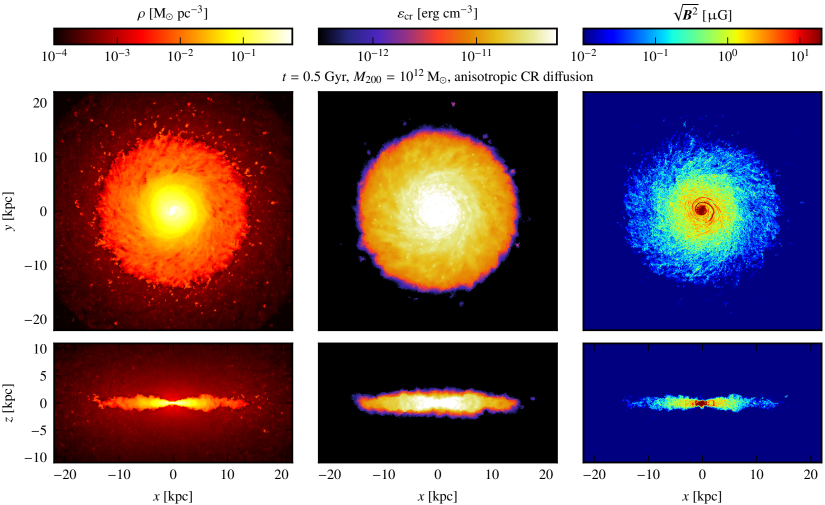
Time evolution of SFR and energy densities



CP+ (in prep)

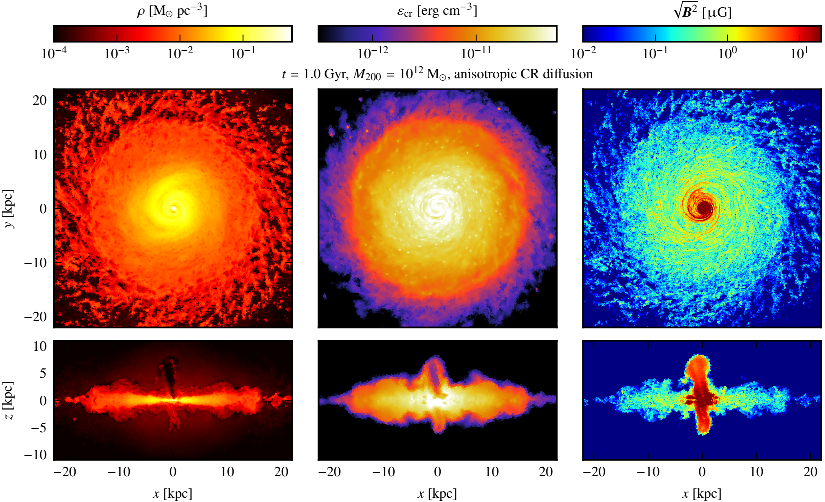
- initial gravitational collapse causes peak in SFR
- SFR declines exponentially with decreasing accretion rate
- magnetic field grows exponentially from $B_{init} = 10^{-10}$ G
- CR and magnetic energies saturate at equipartition with thermal energy in Milky Way-mass galaxy

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



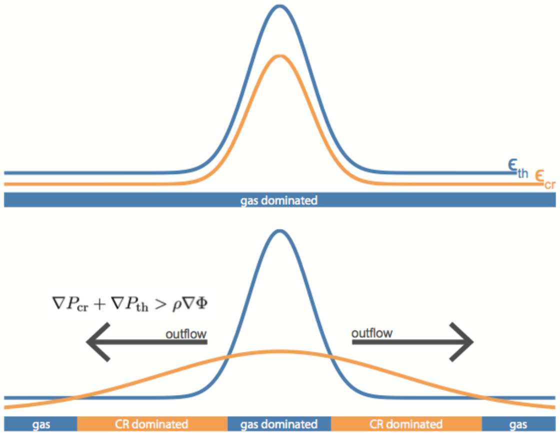
CP+ (2017b, in prep.)

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



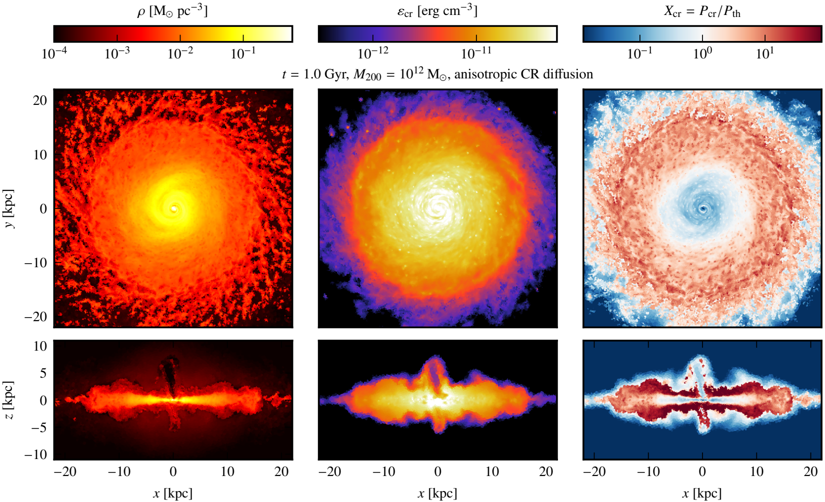
CP+ (2017b, in prep.)

Cosmic ray driven wind: mechanism



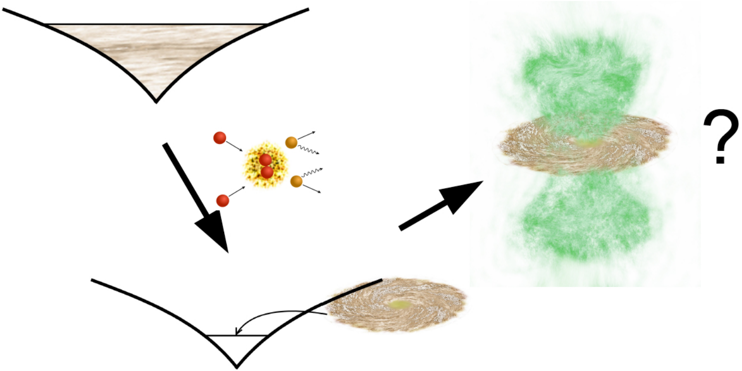
CR streaming in 3D simulations: Uhlig, CP+ (2012), Ruszkowski+ (2017), . . .
CR diffusion in 3D simulations: Jubelgas+ (2008), Booth+ (2013), Hanasz+ (2013), Salem & Bryan (2014), Pakmor, CP+ (2016), Simpson+ (2016), Girichidis+ (2016), Dubois+ (2016), CP+ (2017b), Jacob+ (2018), . . .

Simulation of Milky Way galaxy: CR pressure support



CP+ (2017b)

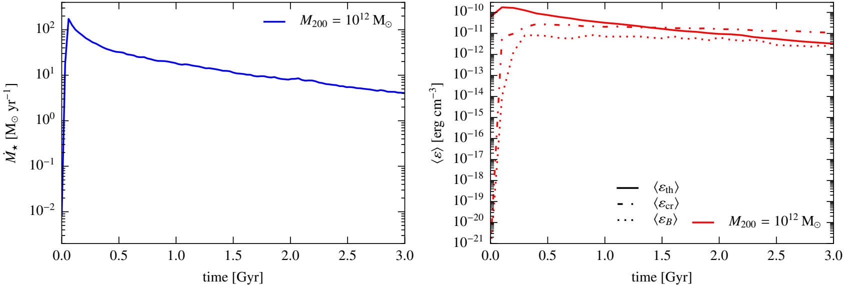
Galaxy simulations: 2. magnetic dynamo



CP, Werhahn, Pakmor, Girichidis, Simpson, Springel (in prep.)
Simulating radio synchrotron emission in star-forming galaxies: magnetic dynamo and the origin of the FIR–radio correlation

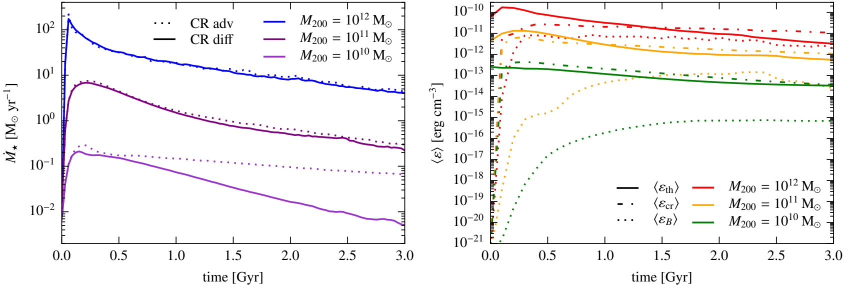
MHD + CR advection + diffusion: 10^{10}, 10^{11}, 10^{12} $M_\odot$

Time evolution of SFR and energy densities



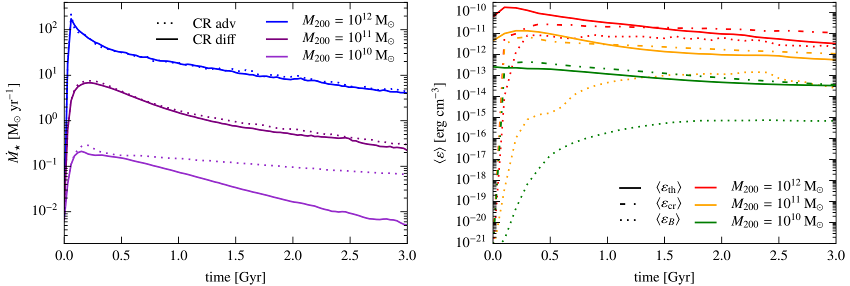
CP+ (in prep)

Time evolution of SFR and energy densities



CP+ (in prep)

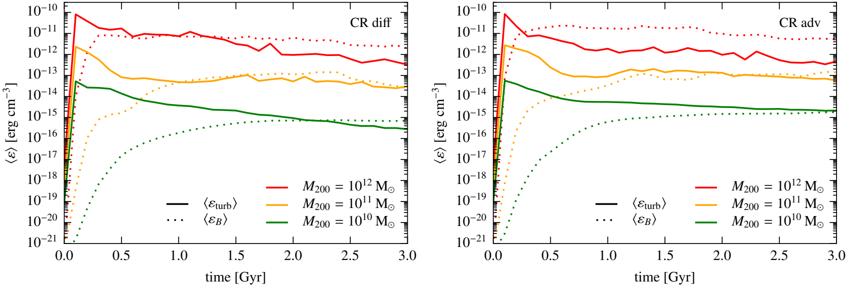
Time evolution of SFR and energy densities



CP+ (in prep)

- CR diffusion suppresses SFR in small (dwarf) galaxies
- equipartition of CR and thermal energy density
- magnetic dynamo faster in Milky Way galaxies than in dwarfs
- magnetic field reaches saturation after initial growth at / below equipartition in Milky Way /dwarf galaxies – why?

Magnetic saturation across galaxy masses



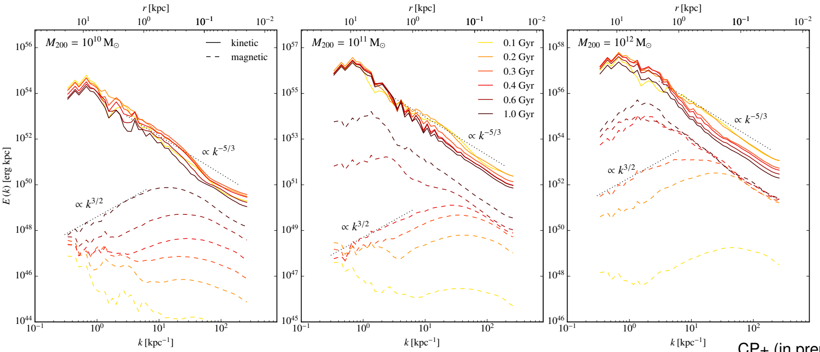
CP+ (in prep.)

- turbulence driven by gravitational collapse, decreases with time
- magnetic field saturates in equipartition with turbulent energy

$$E_B \sim E_{\mathrm{turb}} \sim \frac{\eta\, M_{200}\, v_{200}^2}{2} \propto M_{200}^{5/3}$$

- further magnetic growth in 10^{12} M$_\odot$ halo (large-scale dynamo?)

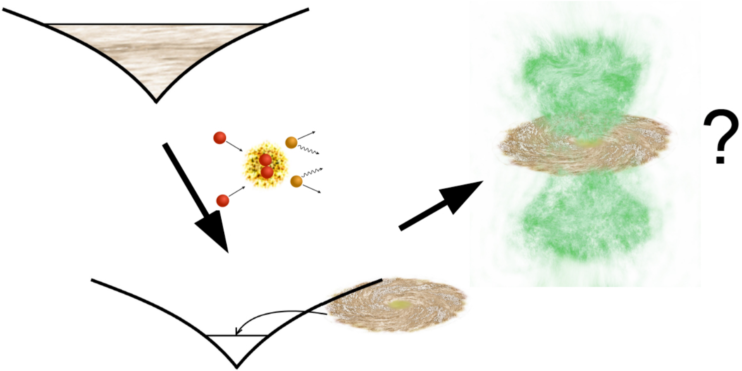
Kinetic / magnetic power spectra across halo masses



CP+ (in prep.)

- magnetic fields grow via turbulent small-scale dynamo
- kinematic regime: Kazantsev $k^{3/2}$ scaling on large scales
- saturated regime: Kolmogorov $k^{-5/3}$ scaling on small scales
- magnetic dynamo grows faster in MW galaxies than in dwarfs

Galaxy simulation: 3. FIR–radio correlation



Werhahn, CP, Girichidis (in prep.)
CRs and non-thermal emission in simulated galaxies: III. probing CR calorimetry with radio spectra and the FIR–radio correlation

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

Steady-state cosmic ray spectra

- solve the steady-state equation in every cell for each CR population:

$$\frac{f(E)}{\tau_{\mathrm{esc}}} - \frac{\mathrm{d}}{\mathrm{d}E}\left[f(E)b(E)\right] = q(E)$$

- protons: Coulomb, hadronic and escape losses (re-normalized to $\varepsilon_{\mathrm{cr}}$)
- electrons: Coulomb, bremsstr., IC, synchrotron and escape losses
  - primaries (re-normalized using $K_{\mathrm{ep}} = 0.02$)
  - secondaries

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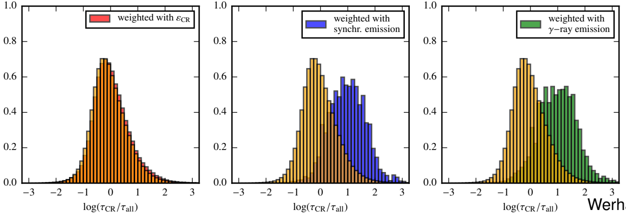
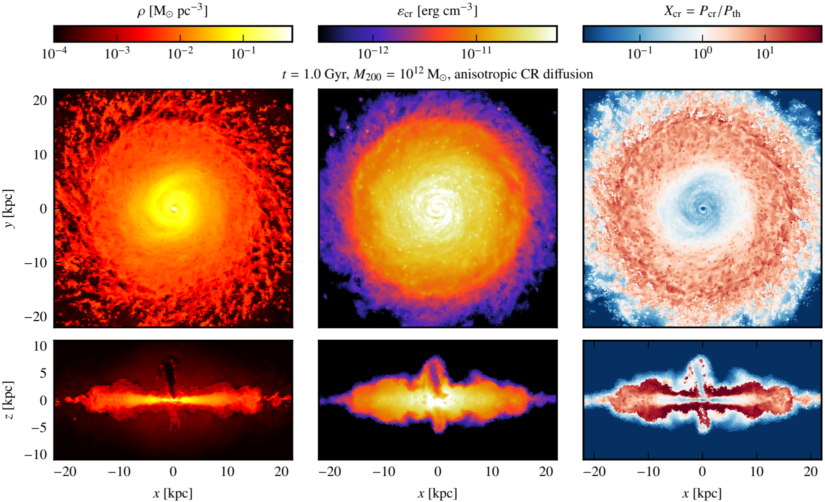
- protons: Coulomb, hadronic and escape losses (re-normalized to ε_cr)
- electrons: Coulomb, bremsstr., IC, synchrotron and escape losses
  - primaries (re-normalized using $K_\mathrm{ep} = 0.02$)
  - secondaries
- steady state assumption is fulfilled in disk and in regions dominating the non-thermal emission but not at low densities, at SNRs and in outflows



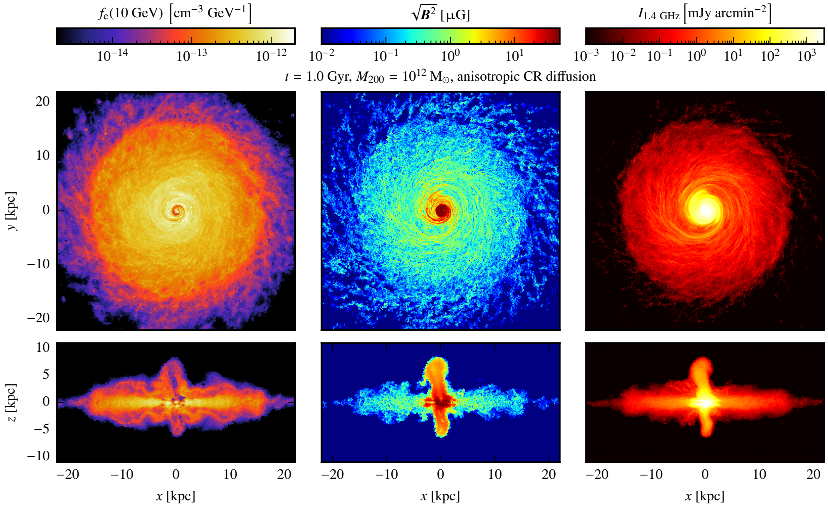
Werhahn+ (2021a)

Simulation of Milky Way galaxy: CR pressure support



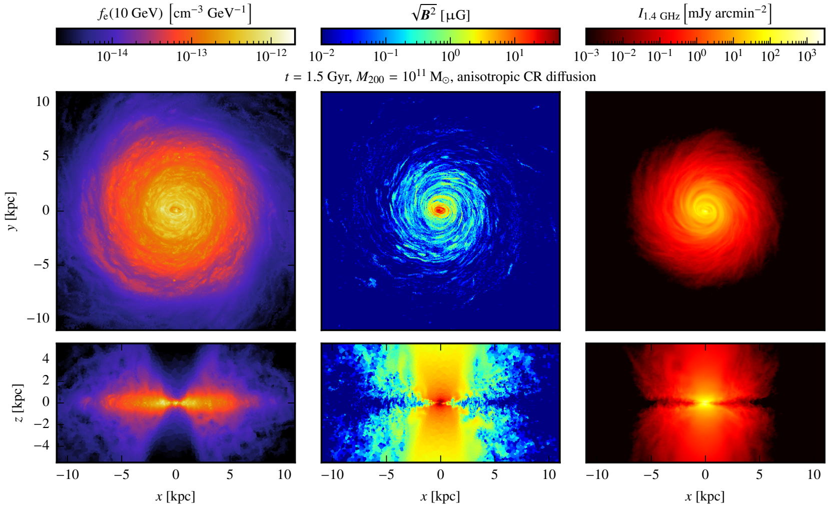
CP+ (2017b)

Simulated radio emission: $10^{12}\,M_\odot$ halo



CP+ (in prep.)

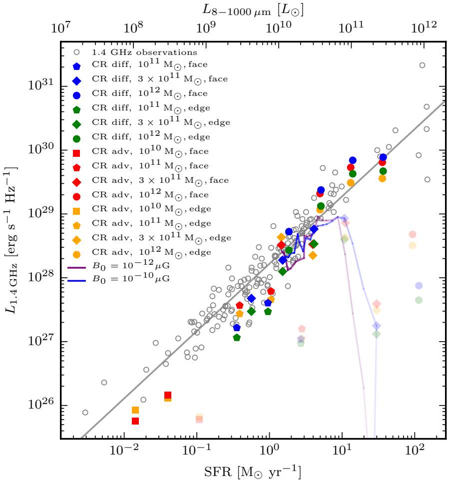
Simulated radio emission: 10^{11} $M_\odot$ halo



CP+ (in prep.)

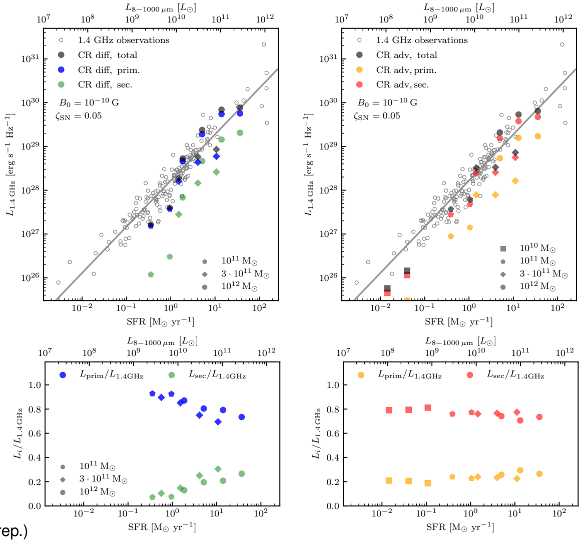
FIR–radio correlation

Universal conversion: star formation → cosmic rays → radio



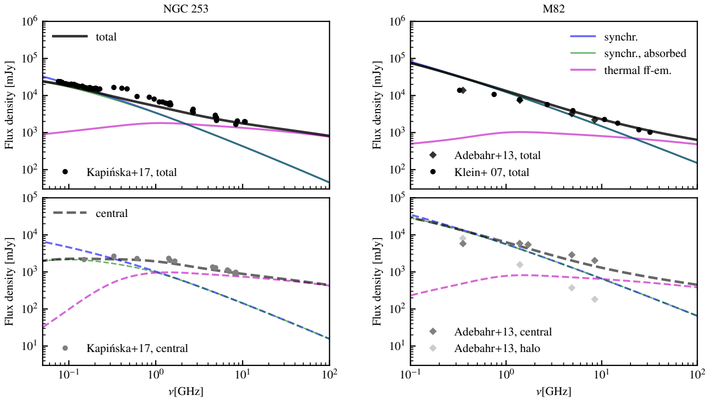
CP+ (in prep.)

FIR–radio correlation: primary vs. secondary flux



Werhahn+ (in prep.)

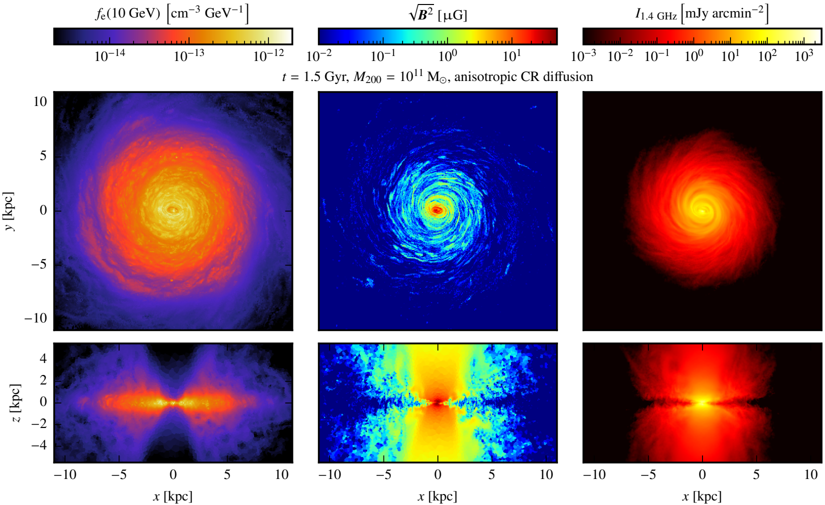
Radio spectra in starburst galaxies



Werhahn+ (in prep.)

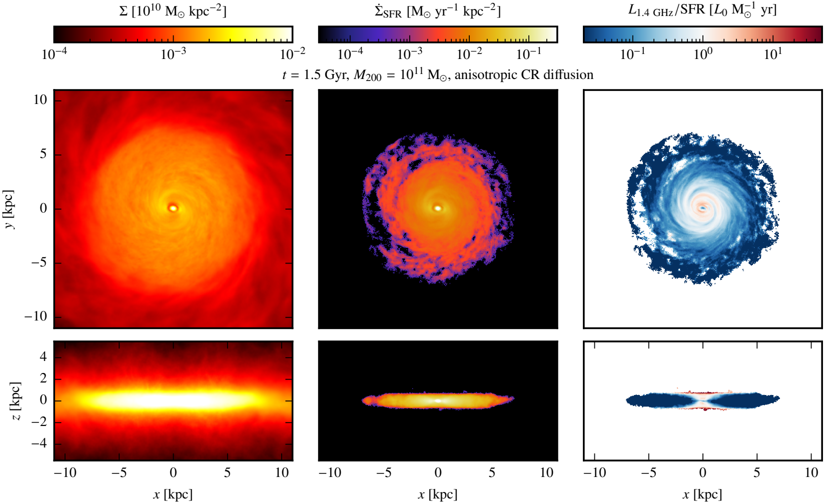
- steep radio synchrotron spectra due to fast e$^-$ cooling
- flat free-free spectra fill in high-frequency radio flux

Simulated radio emission: 10^{11} $M_\odot$ halo



CP+ (in prep.)

Local FIR–radio correlation, 10^{11} $M_\odot$ halo



CP+ (in prep.)

Conclusions on CR feedback and radio emission

- CR and thermal energy in equipartition in all galaxies
  $\Rightarrow$ CRs suppress star formation in small galaxies
- turbulent small-scale dynamo driven by gravitational infall amplifies galactic magnetic fields
- magnetic and gravo-turbulent energy in equipartition in all galaxies $\Rightarrow$ large-scale dynamo in Milky Way-mass galaxies?

Conclusions on CR feedback and radio emission

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  $\Rightarrow$ CRs suppress star formation in small galaxies
- turbulent small-scale dynamo driven by gravitational infall amplifies galactic magnetic fields
- magnetic and gravo-turbulent energy in equipartition in all galaxies $\Rightarrow$ large-scale dynamo in Milky Way-mass galaxies?
- radio emission traces bubble-like outflows in MW-sized galaxies, X-shaped magnetic fields in outflows of smaller galaxies
- global FIR–radio correlation reproduced for galaxies with saturated magnetic fields, scatter due to galaxy inclination and CR transport model
- local FIR–radio correlation reproduced for star-forming galaxies, but centers of starbursts predicted to exceed correlation

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

Cosmic ray feedback:

- Pfrommer, Pakmor, Schaal, Simpson, Springel, *Simulating cosmic ray physics on a moving mesh,* 2017a, MNRAS, 465, 4500.
- Pfrommer, Pakmor, Simpson, Springel, *Simulating gamma-ray emission in star-forming galaxies,* 2017b, ApJL, 847, L13.

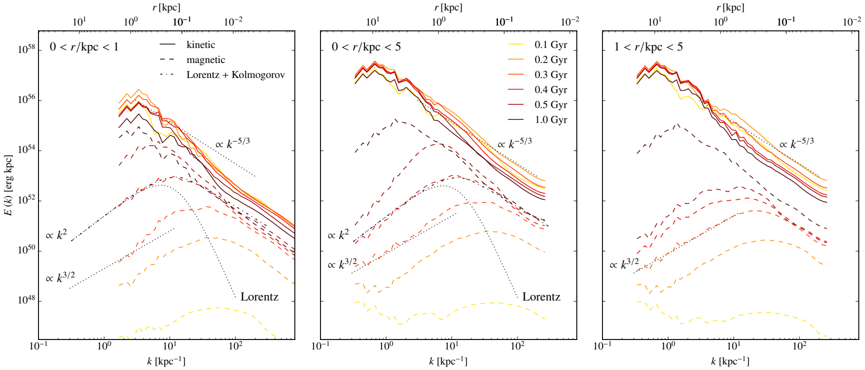
Cosmic rays and radio emission in galaxies:

- Werhahn, Pfrommer, Girichidis, Puchwein, Pakmor, *Cosmic rays and non-thermal emission in simulated galaxies. I. Electron and proton spectra compared to Voyager-1 data*, 2021, subm.
- Werhahn, Pfrommer, Girichidis, *Cosmic rays and non-thermal emission in simulated galaxies: III. probing cosmic ray calorimetry with radio spectra and the FIR-radio correlation*, in prep.
- Pfrommer, Werhahn, Pakmor, Girichidis, Simpson, Springel, *Simulating radio synchrotron emission in star-forming galaxies: small-scale magnetic dynamo and the origin of the far infrared–radio correlation*, in prep.

Additional slides

Kinetic and magnetic power spectra

Turbulent small-scale dynamo in different analysis regions

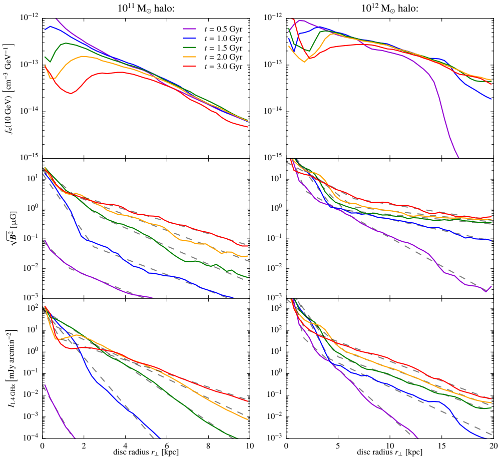


CP+ (in prep.)

- $E_B(k)$ superposition of form factor and turbulent spectrum
- pure turbulent spectrum outside steep central B profile

Electron, magnetic field and radio emission profiles

- electron profile grows in radius as galaxy assembles
- turbulent small-scale dynamo grows magnetic field in radius
- radio surface brightness follows the magnetic profile
- magnetic field obeys a double exponential:

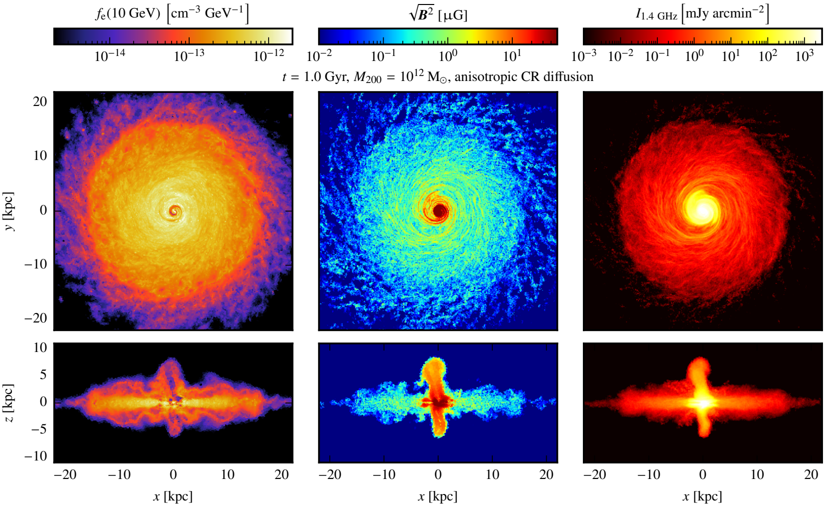


$$B(r) = \begin{cases} B_0 e^{-r/r_{\mathrm{in}}}, & \text{if } r < r_0, \\ B_0 e^{-r_0/r_{\mathrm{in}} - (r-r_0)/r_{\mathrm{out}}}, & \text{if } r \geq r_0. \end{cases}$$

CP+ (in prep.)

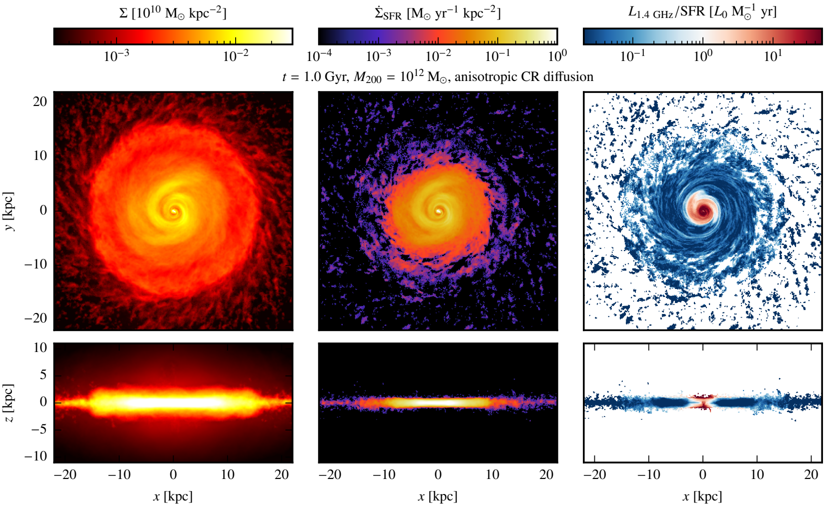
AIP

Simulated radio emission: $10^{12}\,M_\odot$ halo



CP+ (in prep.)

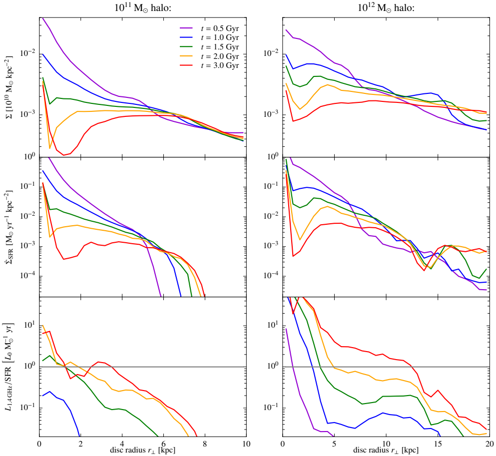
Local FIR–radio correlation, $10^{12}\,M_\odot$ halo



CP+ (in prep.)

SFR density and local FIR–radio correlation (FRC)

- gas surface mass density decreases with time as stars form and gas accretion dwindles
- SFR surface density decreases with surface mass density
- local FRC reproduced in small star-forming galaxies in the saturated dynamo stage



- centers of starbursts predicted to exceed correlation

CP+ (in prep.)