Simulating cosmic rays, radio synchrotron and gamma-ray emission in star-forming galaxies

Christoph Pfrommer[1]

in collaboration with

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Postdocs: Berlok[1], Buck[1], Shalaby[1], Girichidis[2], Sparre[3,1], Simpson[4]
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Breakthroughs in Galaxy Formation, Schloss Ringberg, April 2022

Non-thermal emission processes

Probing cosmic ray physics and quantifying feedback energy

hadronic processes:

- pion decay:

$$\mathrm{p+ion} \rightarrow \begin{cases} \pi^0 & \rightarrow \quad \gamma\gamma \\ \pi^\pm & \rightarrow \quad \mathrm{e}^\pm + 3\nu \end{cases}$$

- photo-meson production:

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- Bethe-Heitler pair production:

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leptonic processes:

- inverse Compton:

$$\mathrm{e}^* + \gamma \rightarrow \mathrm{e} + \gamma^*$$

- synchrotron radiation:

$$\mathrm{e}^* + B \rightarrow \mathrm{e} + B + \gamma^*$$

- bremsstrahlung:

$$\mathrm{e}^* + \mathrm{ion} \rightarrow \mathrm{e} + \mathrm{ion} + \gamma^*$$

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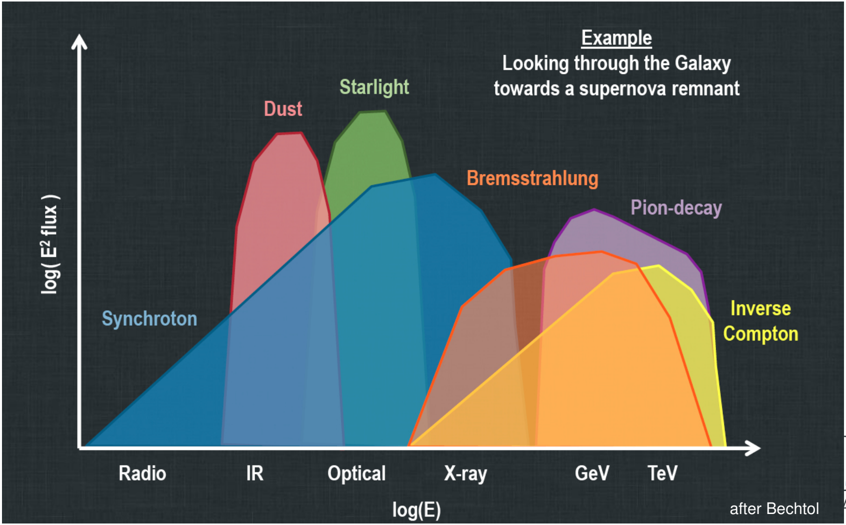
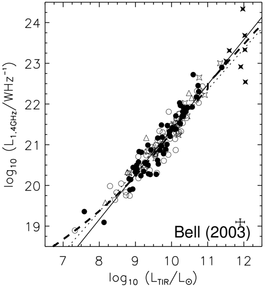
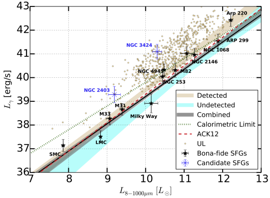
A sketch of the non-thermal emission



Non-thermal emission in star-forming galaxies

- ***previous theoretical modeling:***
  - one-zone steady-state models
    (Lacki+ 2010, 2011, Yoast-Hull+ 2013)
  - 1D transport models (Heesen+ 2016)
  - static Milky Way models
    (Strong & Moskalenko 1998, Evoli+ 2008, Kissmann 2014)





Ajello+ (2020)

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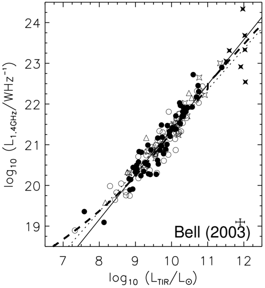
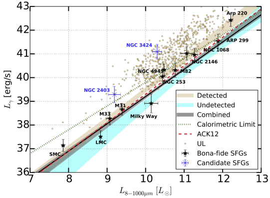
  - run MHD simulations of galaxies at different halos masses and SFRs
  - model cosmic rays (CRs): protons, primary and secondary electrons
  - model all radiative processes from radio to gamma rays





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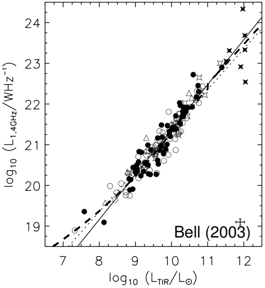
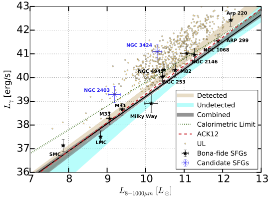
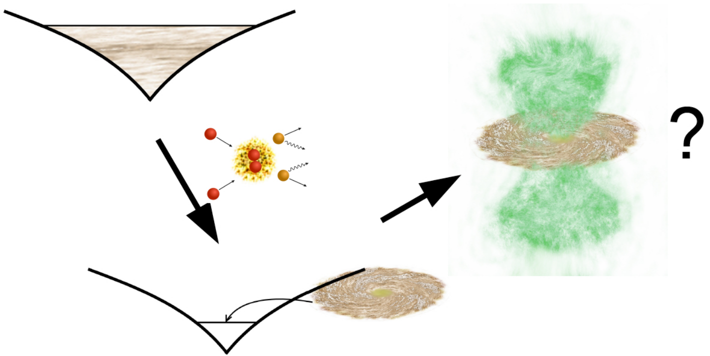
  - model all radiative processes from radio to gamma rays
  - gamma rays: understand hadronic vs. leptonic gamma rays $\Rightarrow$ calorimetric fraction + cosmic ray feedback
  - radio: understand magnetic dynamo, primary and secondary electrons





Ajello+ (2020)

1. Cosmic rays and gamma rays



Werhahn, CP, Girichidis+ (2021a,b)
Cosmic rays and non-thermal emission in simulated galaxies: I & II
MHD + CR advection + anisotropic diffusion: $\{10^{10}, 10^{11}, 10^{12}\}$ $M_\odot$
steady-state spectra of CR protons, primary & secondary electrons

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

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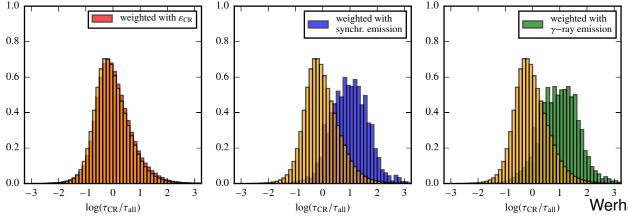
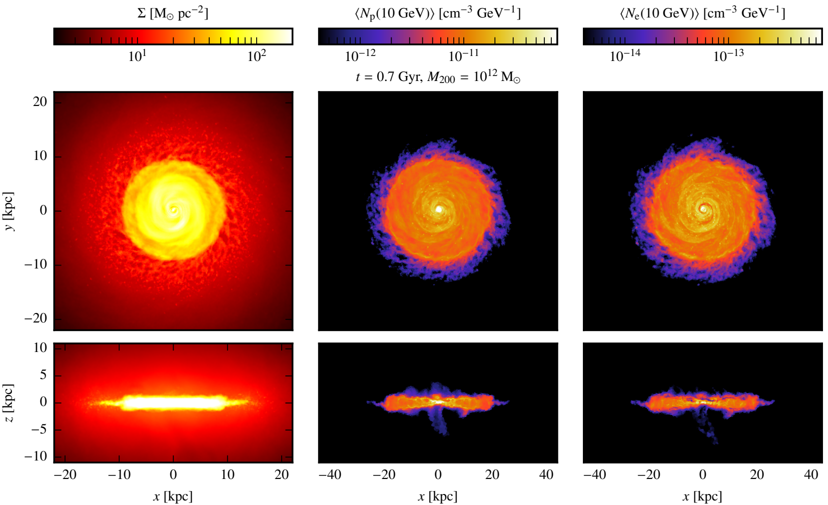
- electrons: Coulomb, bremsstr., IC, synchrotron and escape losses
  - primaries (re-normalized using $K_{\rm ep} = 0.02$)
  - secondaries
- steady state assumption is fulfilled in disk and in regions dominating the non-thermal emission but not at low densities, at SNRs and in outflows



Werhahn+ (2021a)

From a starburst galaxy to a Milky Way analogy



Werhahn, CP+ (2021a,b)

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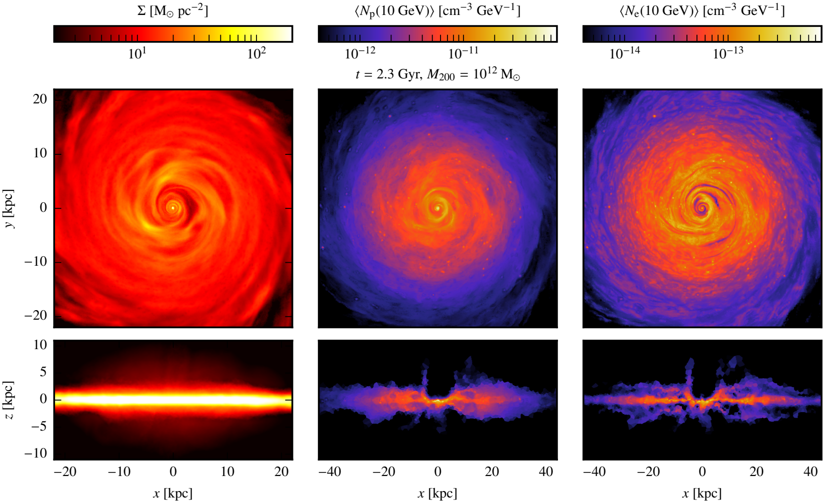

Werhahn, CP+ (2021a,b)

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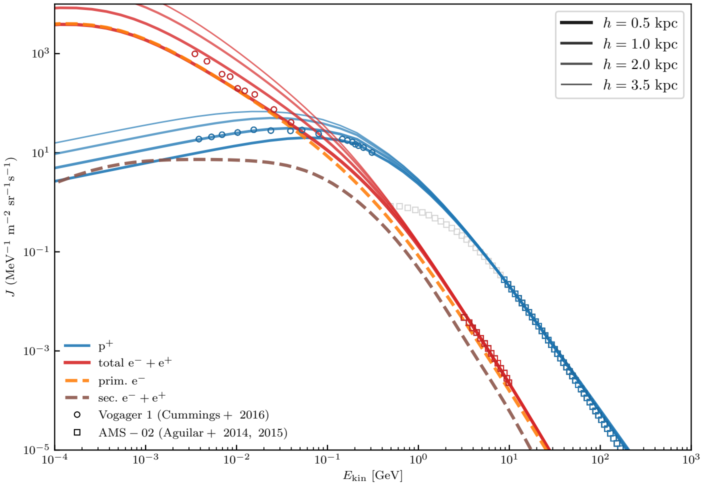
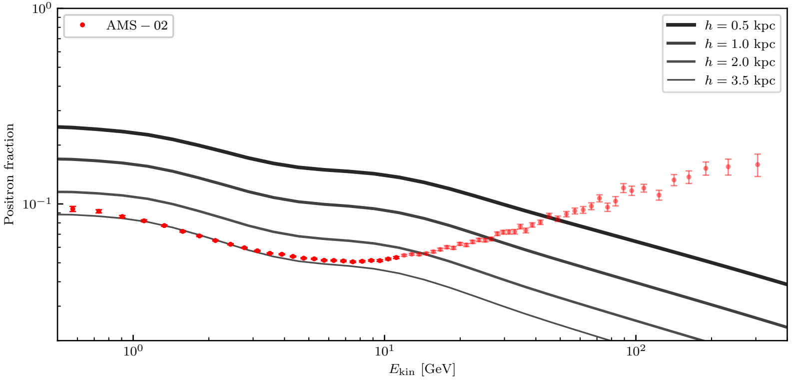
Comparing CR spectra to Voyager and AMS-02 data



Werhahn, CP+ (2021a)

Comparing the positron fraction to AMS-02 data



Werhahn, CP+ (2021a)

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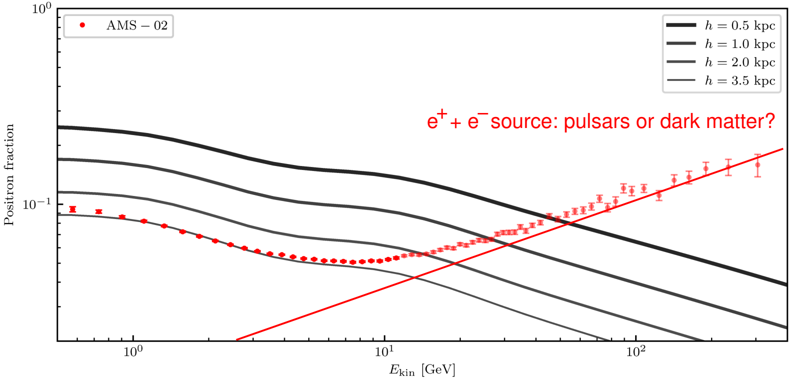
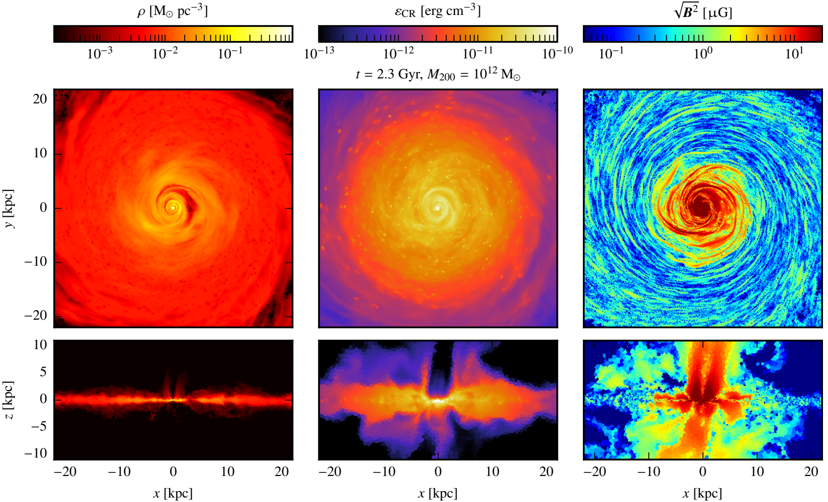


Werhahn, CP+ (2021a)

Simulation of a starburst galaxy



Werhahn, CP+ (2021b,c)

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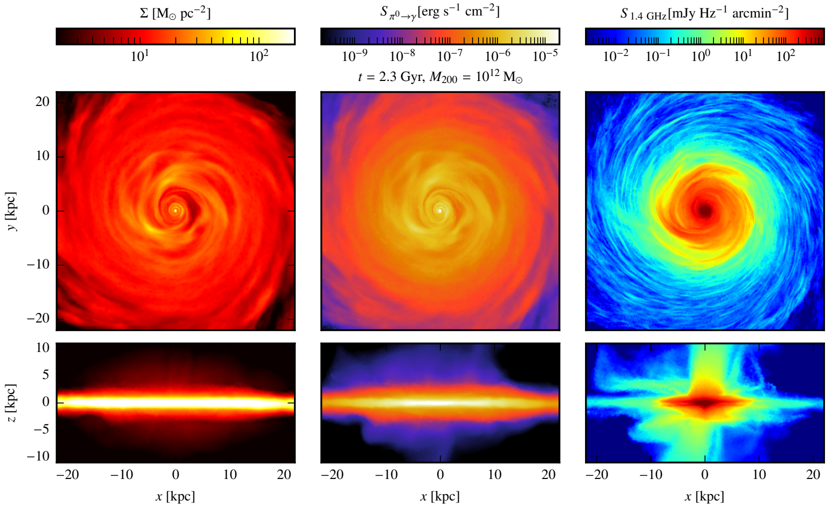
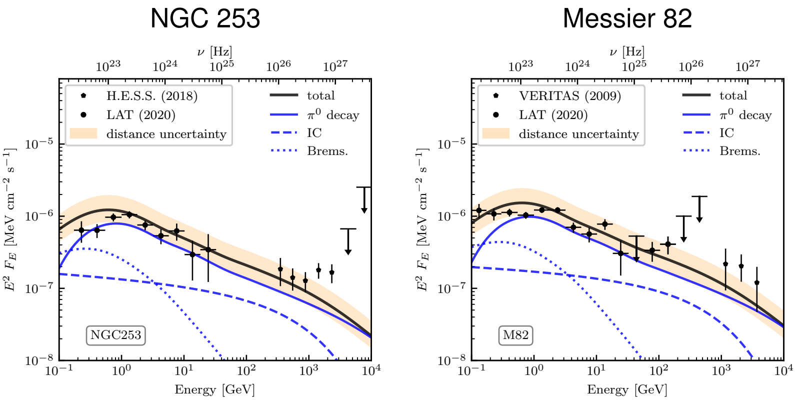


Werhahn, CP+ (2021b,c)

Gamma-ray spectra of starburst galaxies



Werhahn, CP+ (2021b)

- gamma-ray spectra in starbursts dominated by pion decay
- CR protons propagate in Kolmogorov turbulence: $\kappa \propto E^{0.3}$

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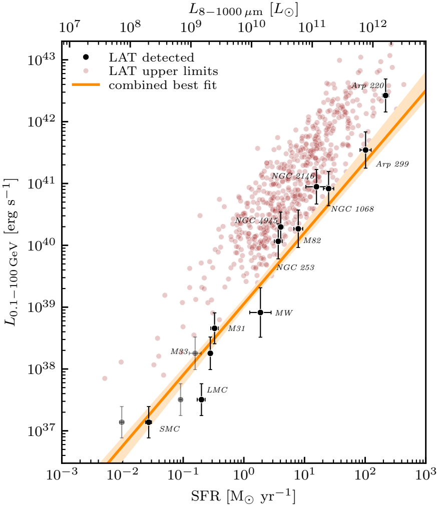
Far infra-red – gamma-ray correlation

Universal conversion: star formation → cosmic rays → gamma rays



Ajello+ (2020)

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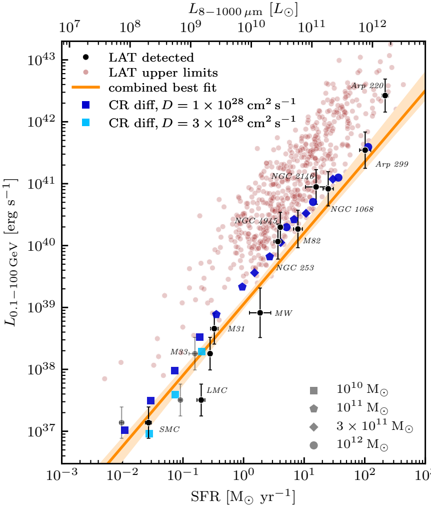

Werhahn, CP+ (2021b)

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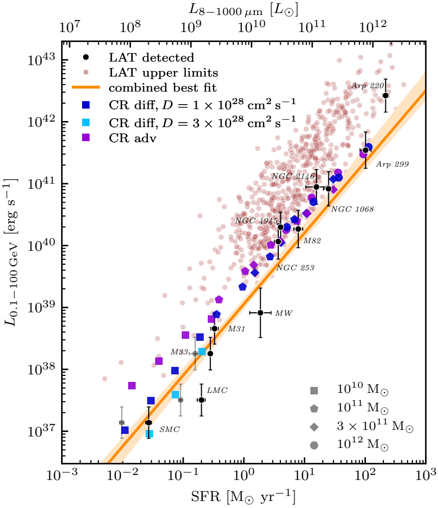

Werhahn, CP+ (2021b)

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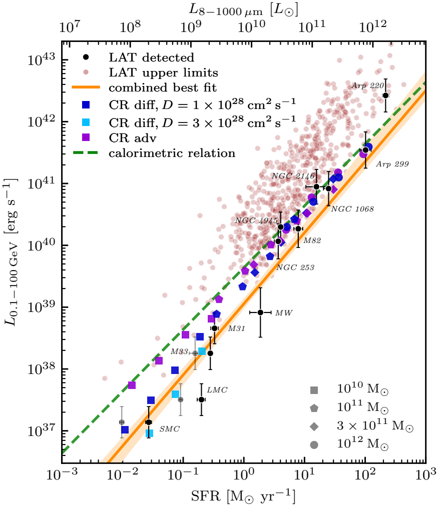
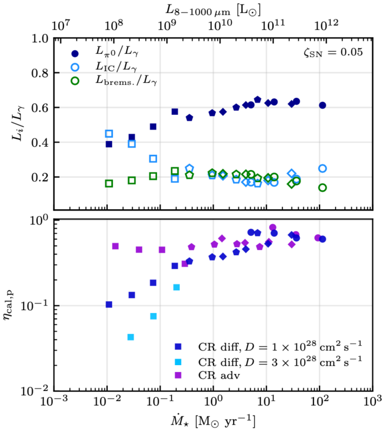


Werhahn, CP+ (2021b)

Far infra-red – gamma-ray correlation

Hadronic vs. leptonic emission and calorimetric fraction across galaxy scales



Werhahn, CP+ (2021b)

- pion decay dominates gamma-ray emission in starbursts
- leptonic inverse Compton dominates at low SFRs

Far infra-red – gamma-ray correlation

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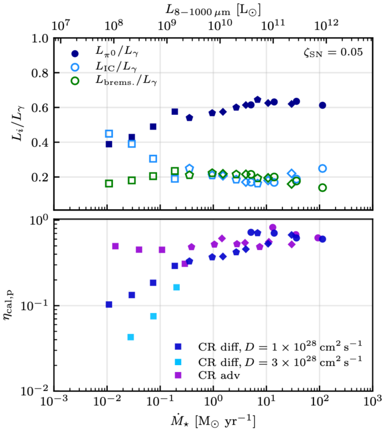
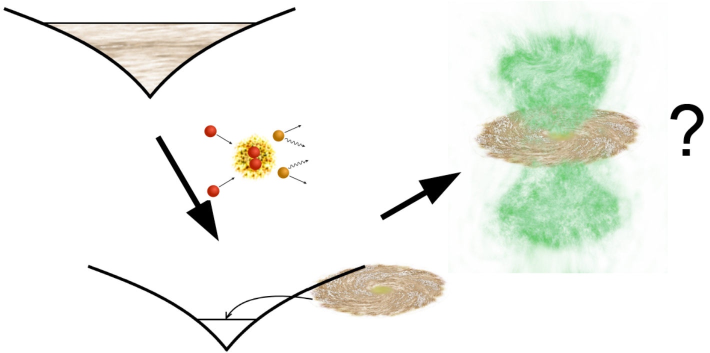


Werhahn, CP+ (2021b)

- pion decay dominates gamma-ray emission in starbursts
- leptonic inverse Compton dominates at low SFRs
- calorimetric energy fraction in starbursts $\eta_{\rm cal,p} \sim 0.5$: half of CR energy available for feedback ⇒ galactic winds
- faster CR diffusion decreases calorimetric fraction at low SFRs ⇒ more CR feedback

2. Magnetic fields and radio emission



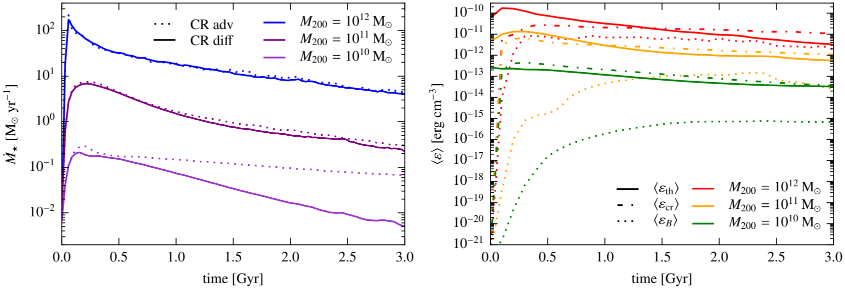
CP, Werhahn, Pakmor+ (2022), Werhahn, CP, Girichidis+ (2021c)

Simulating radio synchrotron emission in star-forming galaxies

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

steady-state spectra of CR protons, primary & secondary electrons

Time evolution of SFR and energy densities



CP+ (2022)

- 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

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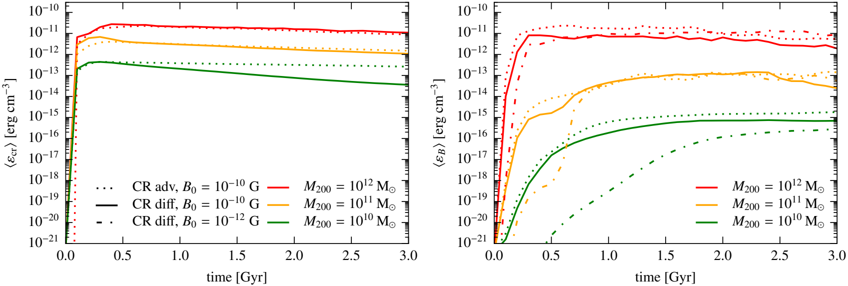
Time evolution of CR and magnetic energy densities

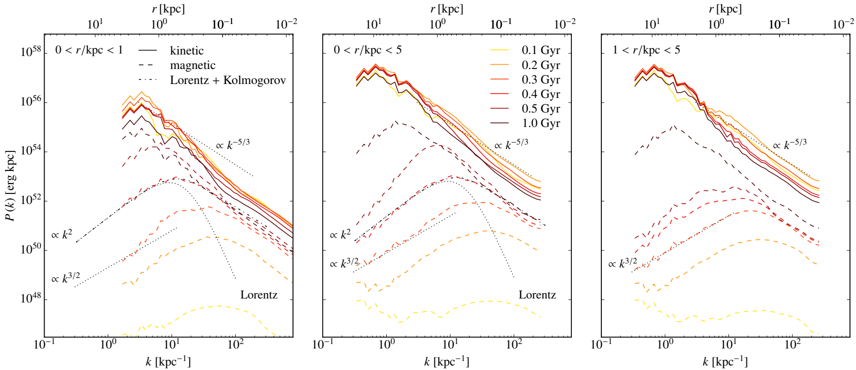


CP+ (2022)

- CRs diffuse out of galaxies $\Rightarrow$ lowers ε_{cr} in disk
- CR diffusion quenches large-scale dynamo $\Rightarrow$ lowers ε_B
- both effects decrease synchrotron emissivity
- magnetic field reaches saturation after initial growth phase: small-scale dynamo?

Kinetic and magnetic power spectra

Turbulent small-scale dynamo in different analysis regions



CP+ (2022)

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

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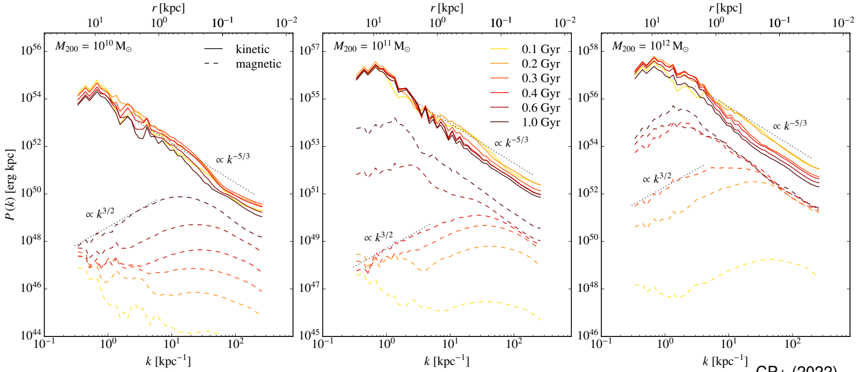
Kinetic and magnetic power spectra: different halos

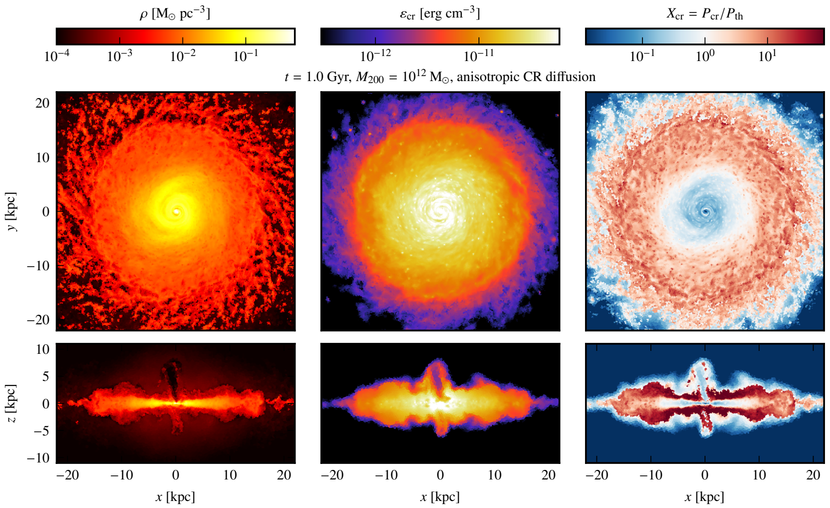
Saturation mechanisms of turbulent small-scale dynamo



CP+ (2022)

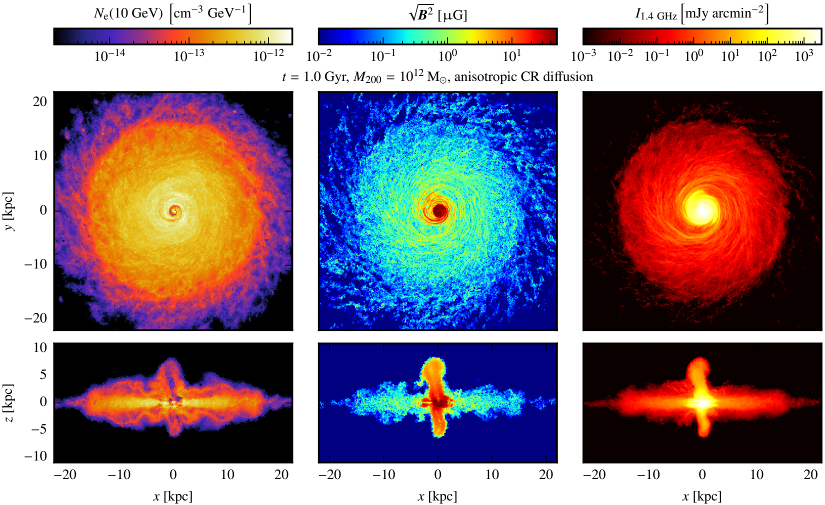
- inverse cascade saturates close to equipartition in Milky Way
- inverse cascade stalls in dwarf galaxies: equipartition not with total kinetic energy but with turbulent energy

MHD galaxy simulation with cosmic rays



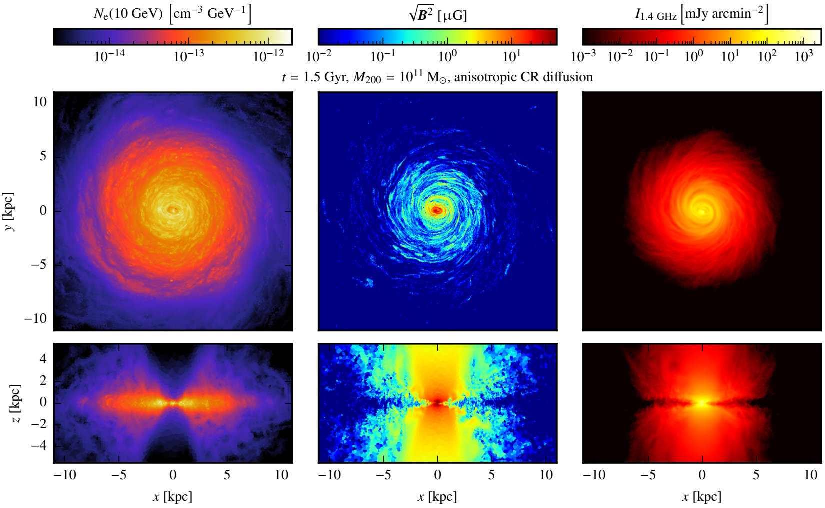
CP+ (2017)

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



CP+ (2022)

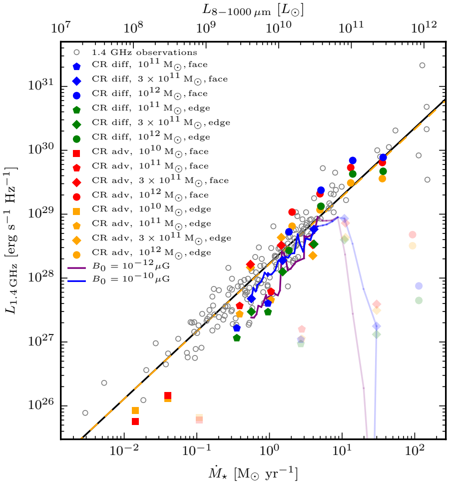
Simulated radio emission: $10^{11}\,M_\odot$ halo



CP+ (2022)

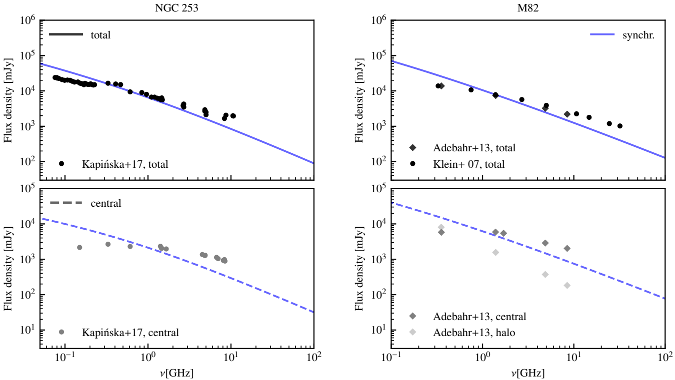
Far infra-red – radio correlation

Universal conversion: star formation → cosmic rays → radio



CP+ (2022)

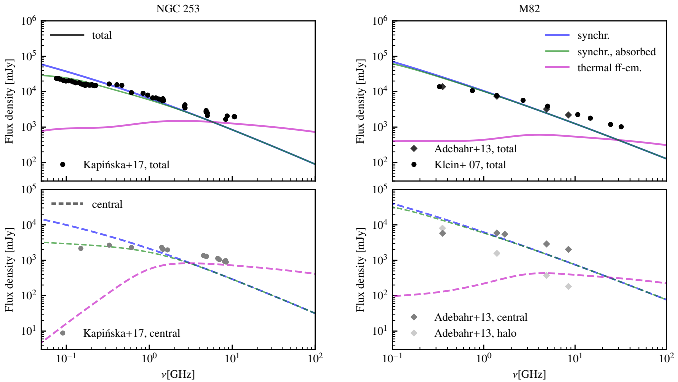
Radio-ray spectra of starburst galaxies



Werhahn, CP+ (2021c)

- synchrotron spectra too steep (cooling + diffusion losses)

Radio-ray spectra of starburst galaxies



Werhahn, CP+ (2021c)

- synchrotron spectra too steep (cooling + diffusion losses)
- synchrotron absorption (low-ν) and thermal free-free emission (high-ν)

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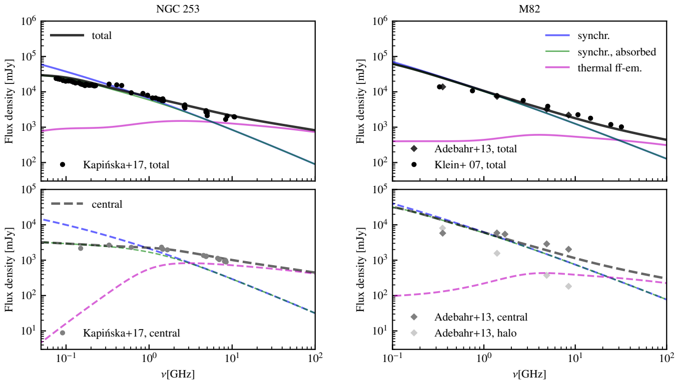
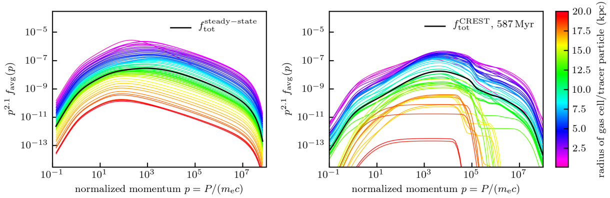
Radio-ray spectra of starburst galaxies



Werhahn, CP+ (2021c)

- synchrotron spectra too steep (cooling + diffusion losses)
- synchrotron absorption (low-ν) and thermal free-free emission (high-ν) required to match (total and central) spectra

Steady-state vs. evolved CR electron spectra



Werhahn+ (in prep.): PRELIMINARY

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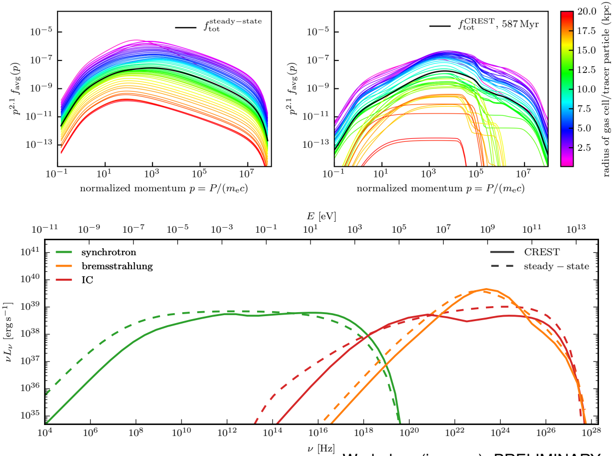
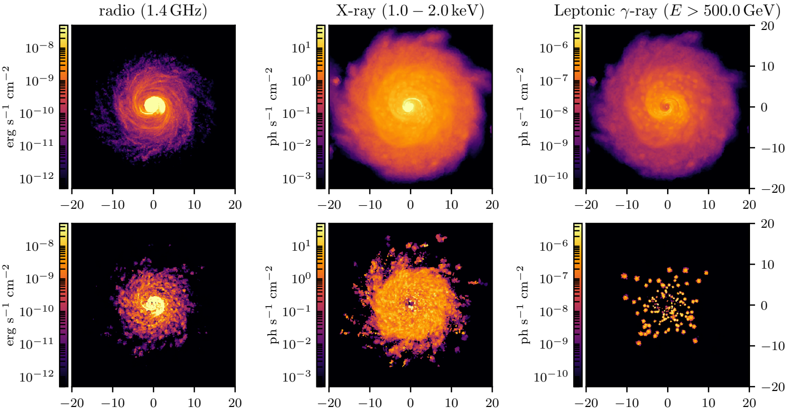
Steady-state vs. evolved CR electron spectra



Werhahn+ (in prep.): PRELIMINARY

Steady-state vs. evolved CR electrons: emission maps



Werhahn+ (in prep.): PRELIMINARY

Conclusions on non-thermal emission in galaxies

- energy budget in large galaxies is dominated by CR pressure
  $\Rightarrow$ star formation suppressed
- turbulent small-scale dynamo grows magnetic fields in isolated galaxies similar to cosmological settings
- magnetic energy saturate close to equipartition with the turbulent energy

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Conclusions on non-thermal emission in galaxies

- energy budget in large galaxies is dominated by CR pressure $\Rightarrow$ star formation suppressed
- turbulent small-scale dynamo grows magnetic fields in isolated galaxies similar to cosmological settings
- magnetic energy saturate close to equipartition with the turbulent energy
- global $L_{\mathrm{FIR}} - L_{\gamma}$ correlation enables us to test the calorimetric assumption: half of CR energy available for feedback in starbursts and more at low SFRs
- global $L_{\mathrm{FIR}} - L_{\mathrm{radio}}$ reproduced for galaxies with saturated magnetic fields, scatter due to viewing angle and CR transport
- synchrotron absorption (low-ν) and thermal free-free emission (high-ν) required to flatten cooled radio synchrotron spectra

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).

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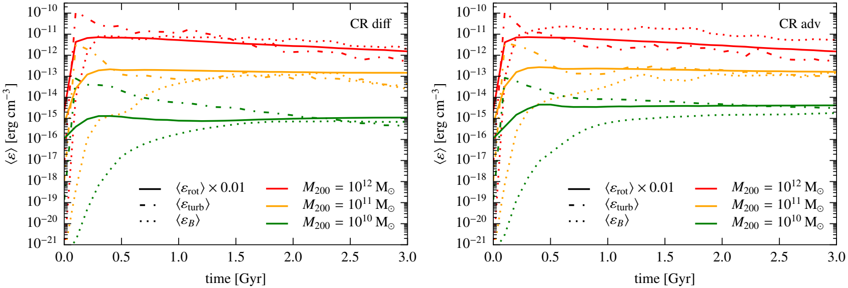
Literature for the talk

Cosmic rays and non-thermal emission in galaxies:

- Werhahn, Pfrommer, Girichidis, Puchwein, Pakmor, *Cosmic rays and non-thermal emission in simulated galaxies. I. Electron and proton spectra explain Voyager-1 data,* 2021a, MNRAS 505, 3273.
- Werhahn, Pfrommer, Girichidis, Winner, *Cosmic rays and non-thermal emission in simulated galaxies. II. γ-ray maps, spectra and the far infrared-γ-ray relation,* 2021b, MNRAS, 505, 3295.
- 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,* 2021c, MNRAS, 508, 4072.
- Pfrommer, Werhahn, Pakmor, Girichidis, Simpson, *Simulating radio synchrotron emission in star-forming galaxies: small-scale magnetic dynamo and the origin of the far infrared-radio correlation,* 2022, submitted.
- Pfrommer, Pakmor, Simpson, Springel, *Simulating gamma-ray emission in star-forming galaxies,* 2017, ApJL, 847, L13.

Additional slides

Time evolution of kinetic and magnetic and energy



CP+ (2022)

- magnetic and turbulent energy densities saturate in equipartition
- kinetic energy is dominated by rotational energy
- turbulent energy is approximately 1% of rotational energy