A multi-frequency view on simulating galaxy evolution with cosmic rays

Maria Werhahn

Christoph Pfrommer, Philipp Girichidis, Joseph Whittingham,
Rüdiger Pakmor, Volker Springel, Freeke van de Voort, Rebekka Bieri

MAX PLANCK INSTITUTE
FOR ASTROPHYSICS

Building Galaxies from Scratch, 19. February 2024, Vienna

CRs in galaxy formation

Motivation & simulations

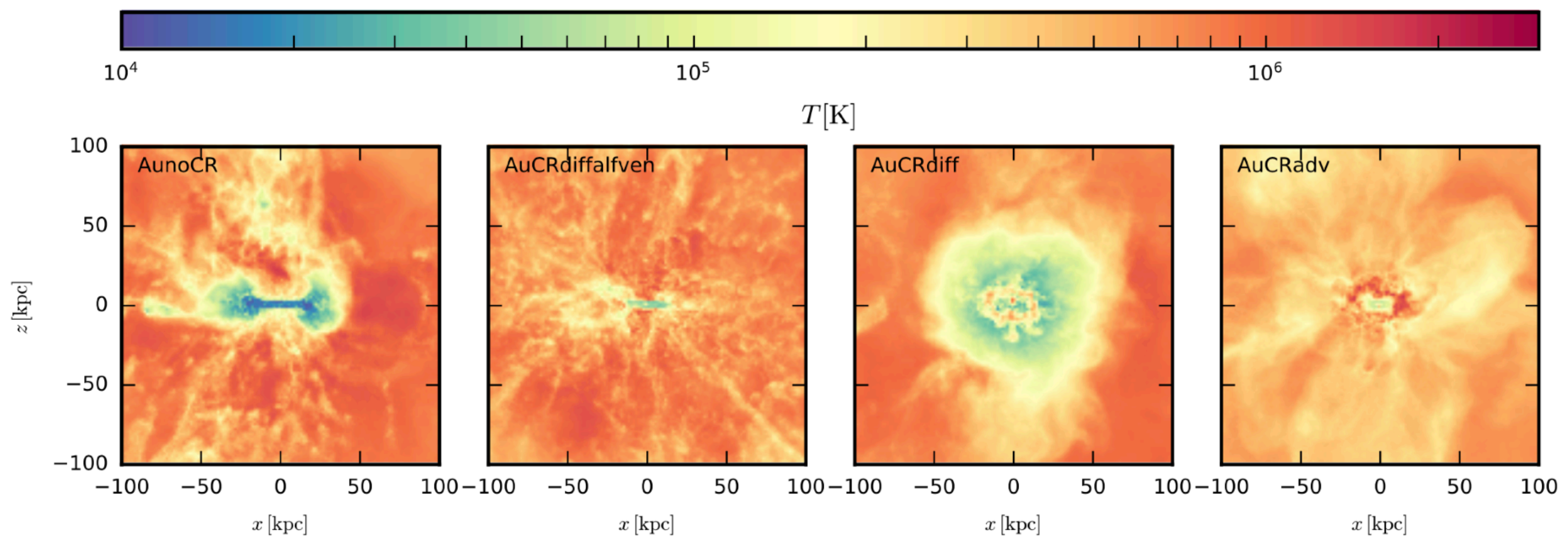
Simulations of galaxies (isolated & cosmological)

(e.g. Jubelgas+ 2008; Uhlig+ 2012; Booth+ 2013; Hanasz+2013; Salem & Bryan 2014; Pakmor + 2016; 2017; Jacob+ 2018; Dashyan & Dubois 2020; Salem+ 2014; Buck+ 2020; Hopkins+ 2020; Peschken+ 2021; Thomas+2021;Rodríguez Montero+2023...)

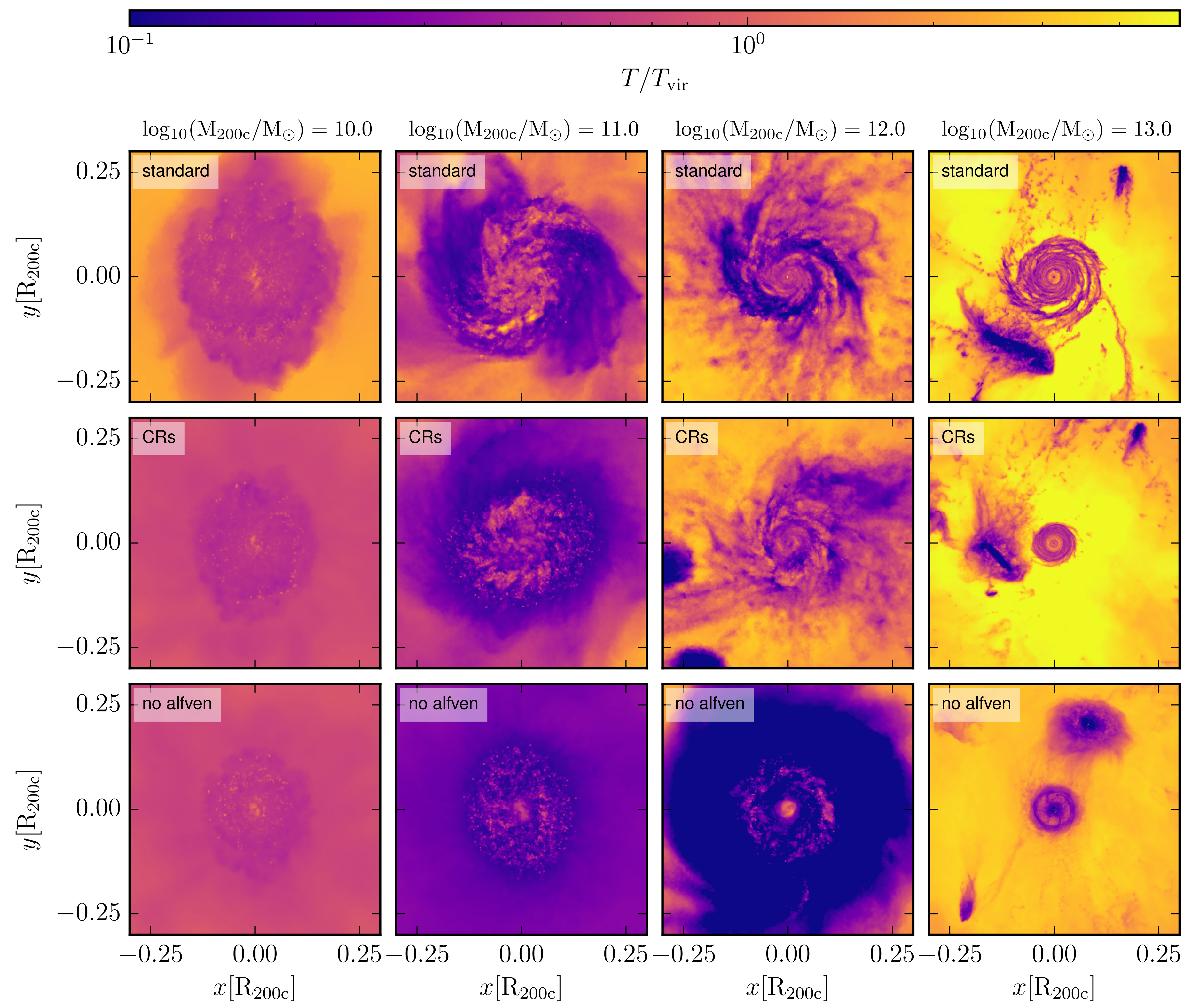
- CRs drive outflows, regulate star formation
- constitute significant fraction of total pressure in CGM
- strongly affect morphology and CGM properties

—> effect depends on CR modelling

—> need to **model observables to constrain this**



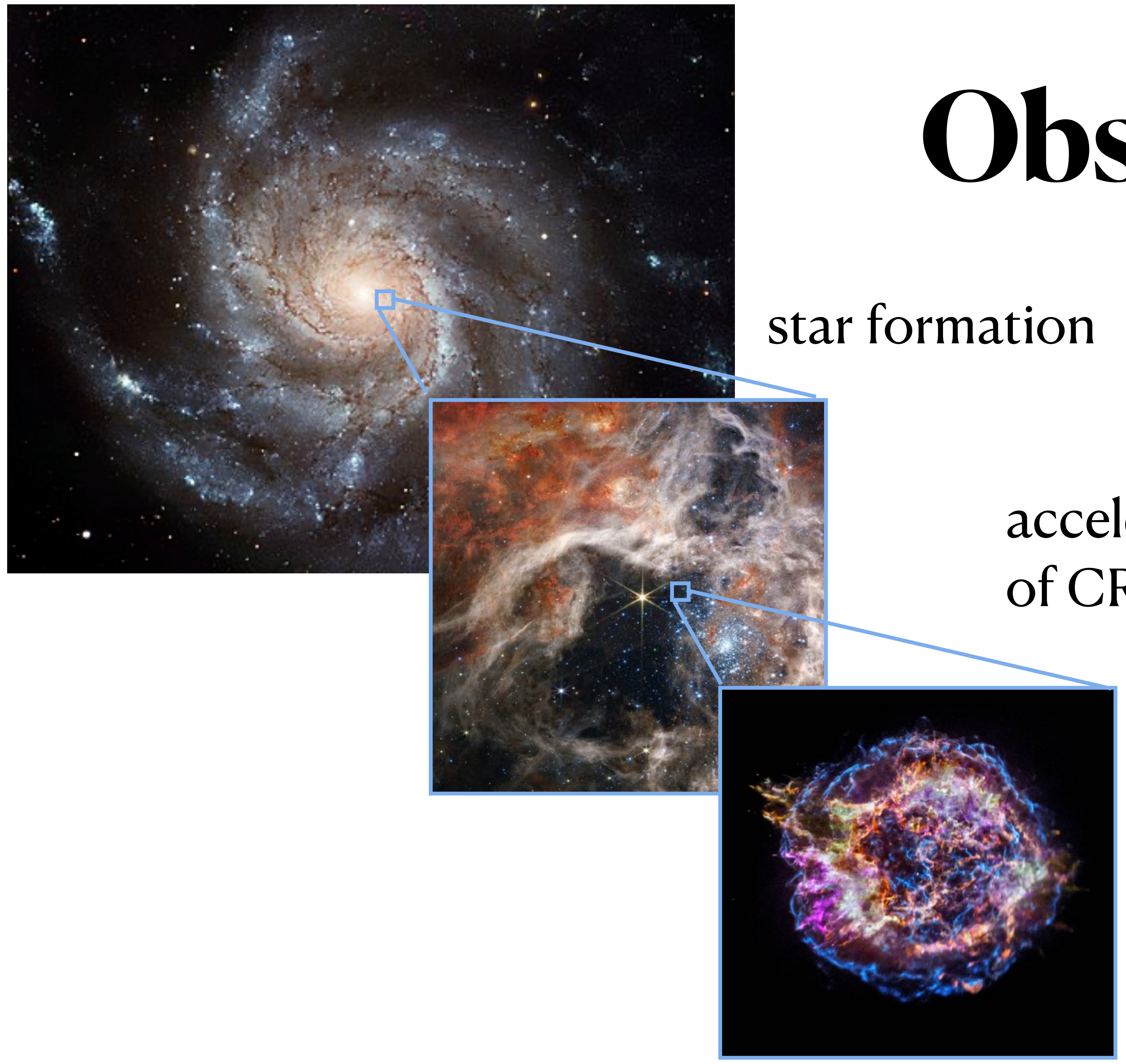
Buck+2020



Bieri+in prep.

Observational constraints of CRs

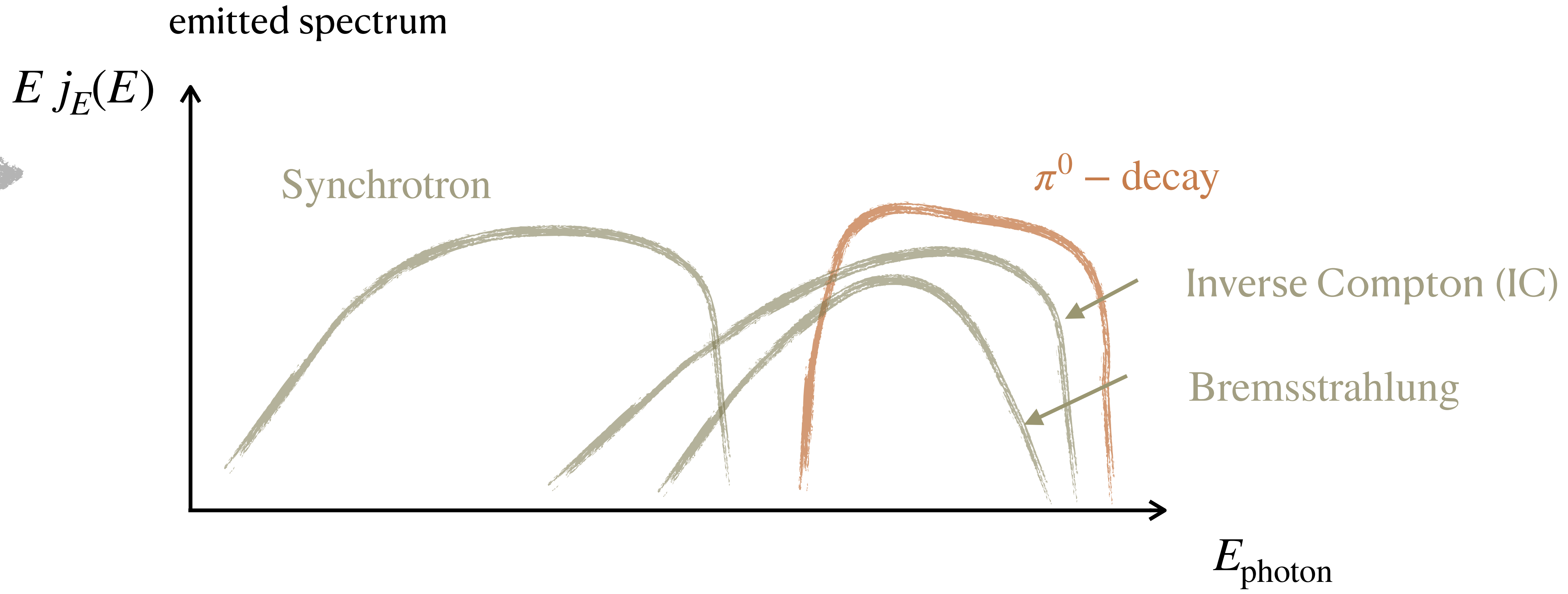
Non-thermal emission



star formation

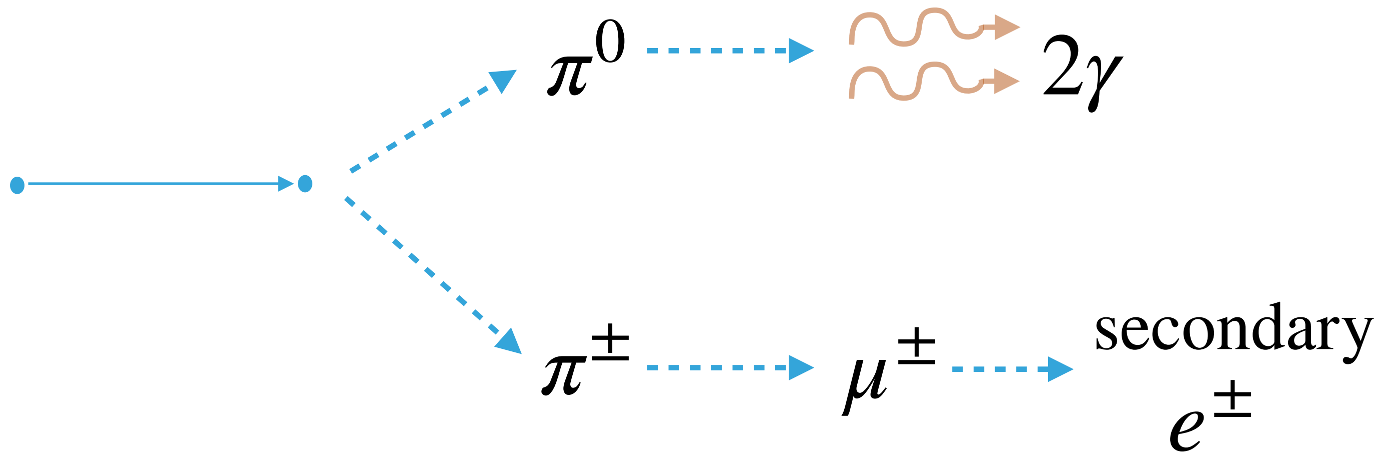
acceleration
of CRs

transport/
interaction
with the ISM



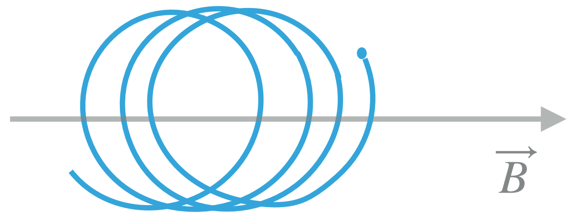
CR protons:

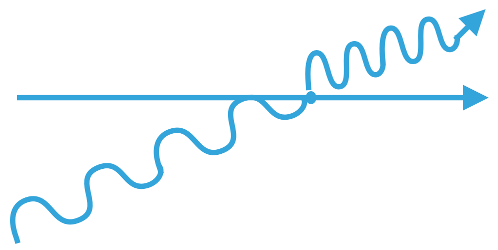
- pion decay

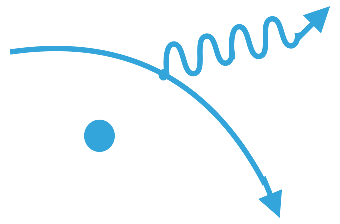


CR electrons (primary + secondary):

- Synchrotron emission
- Inverse Compton (IC) emission
- Bremsstrahlung

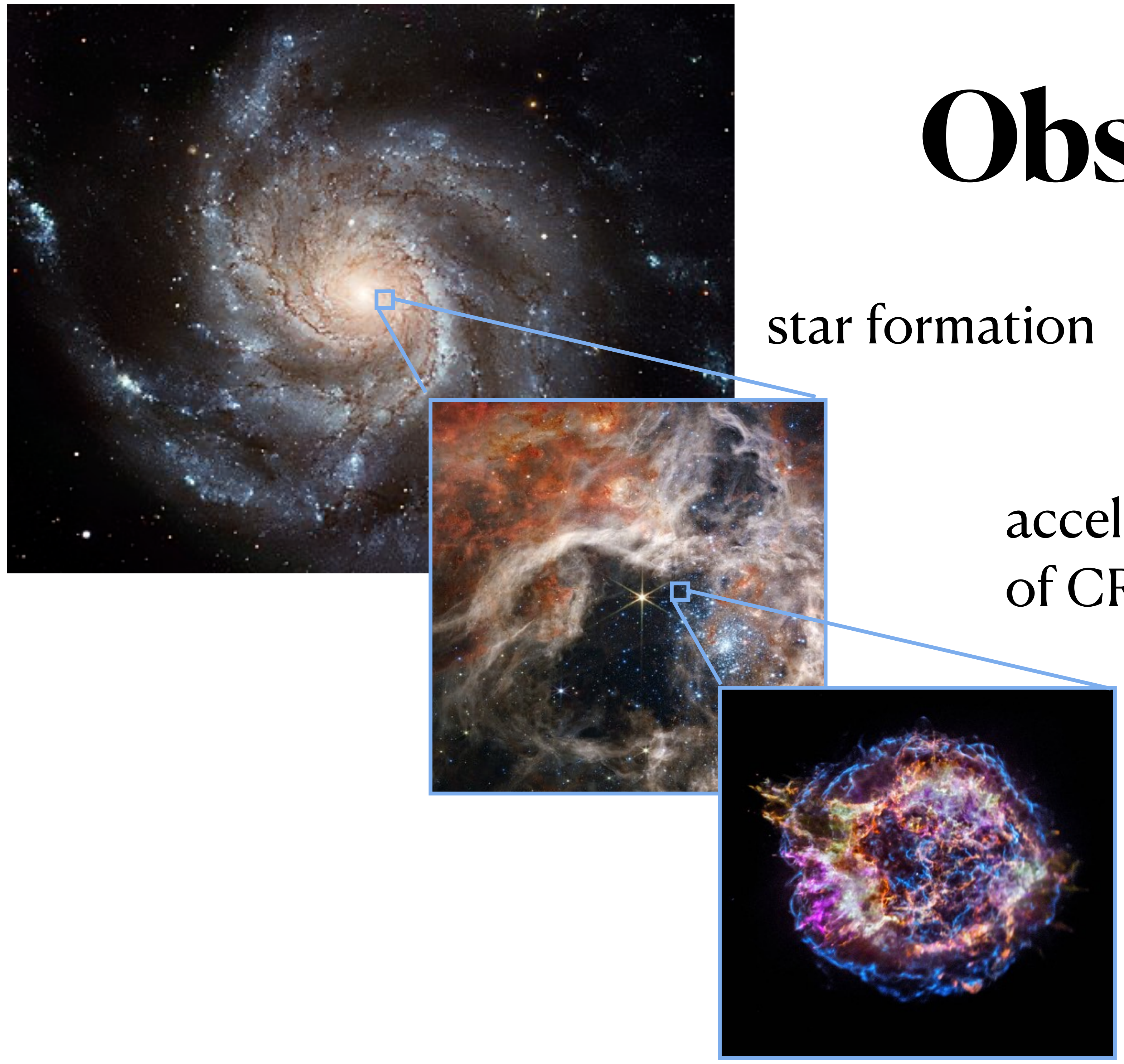






Observational constraints of CRs

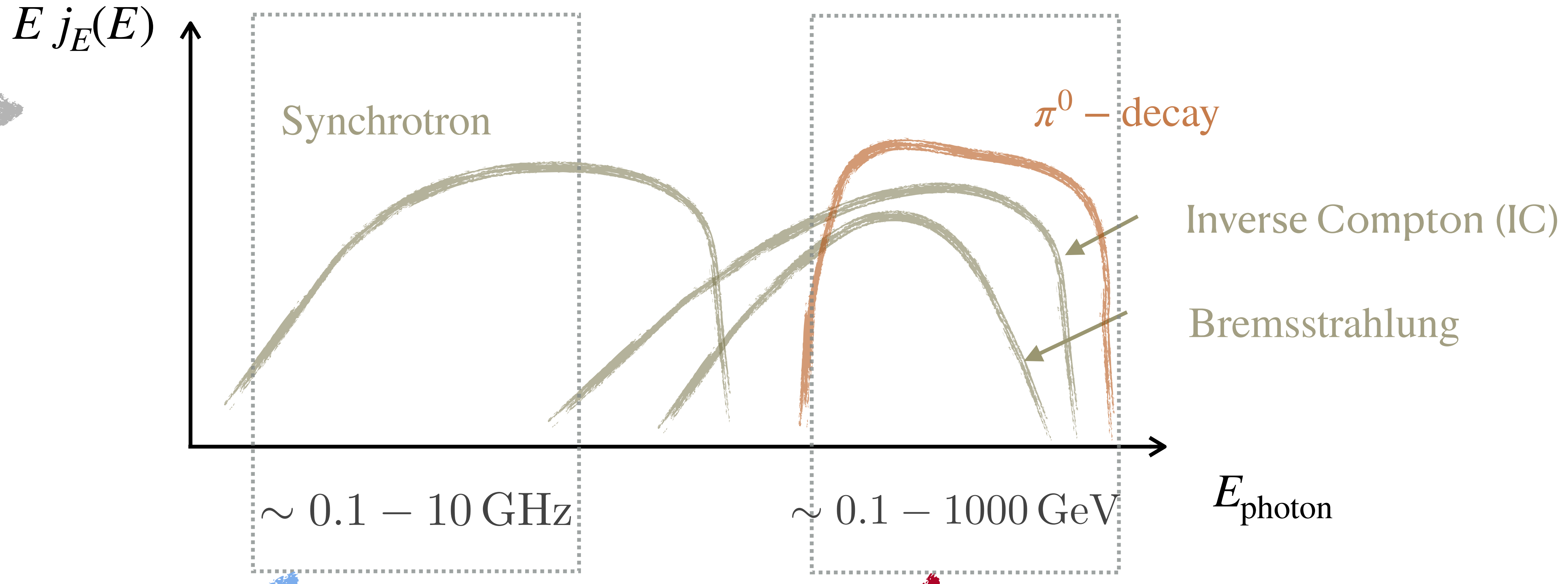
Non-thermal emission

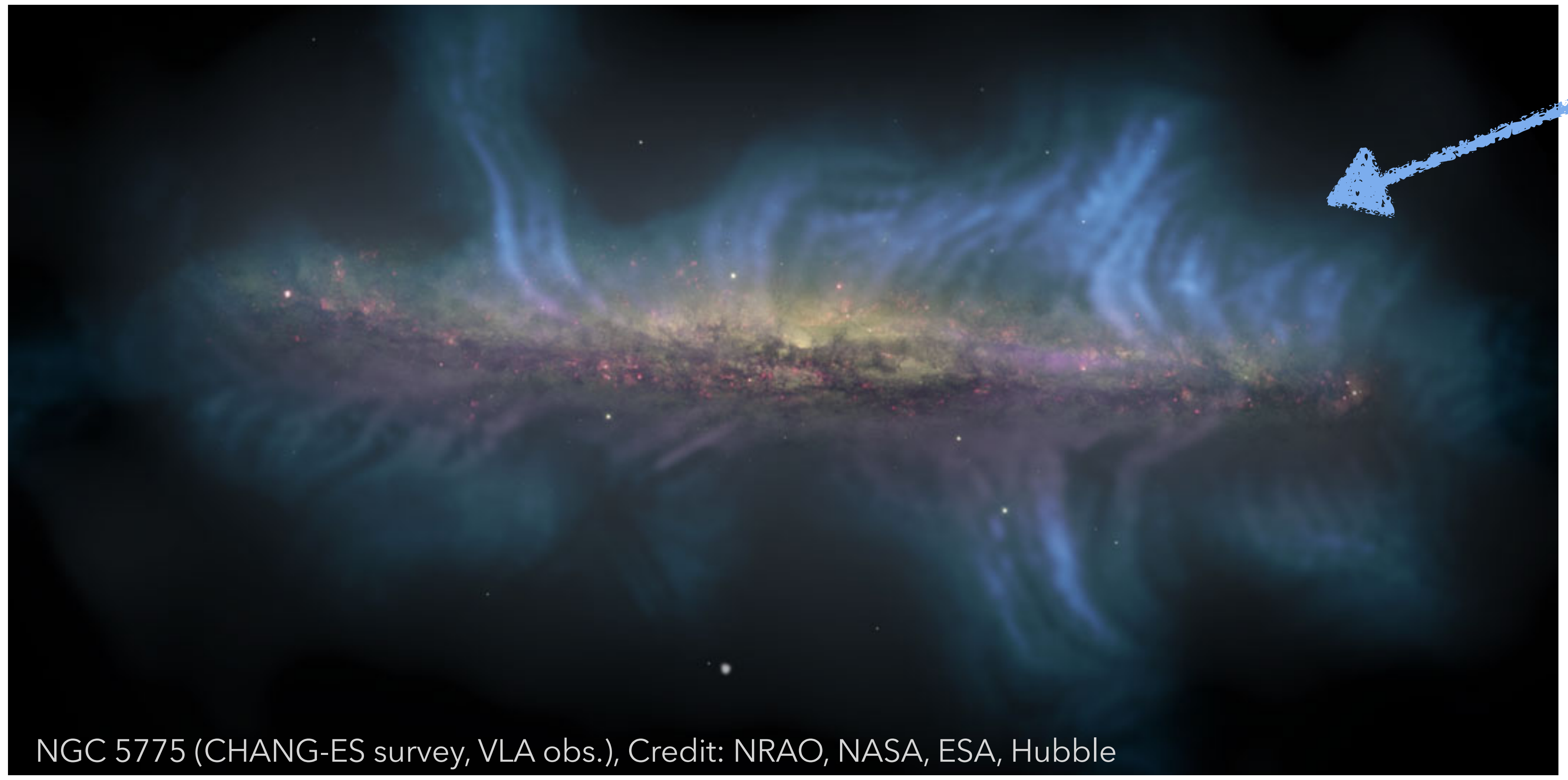


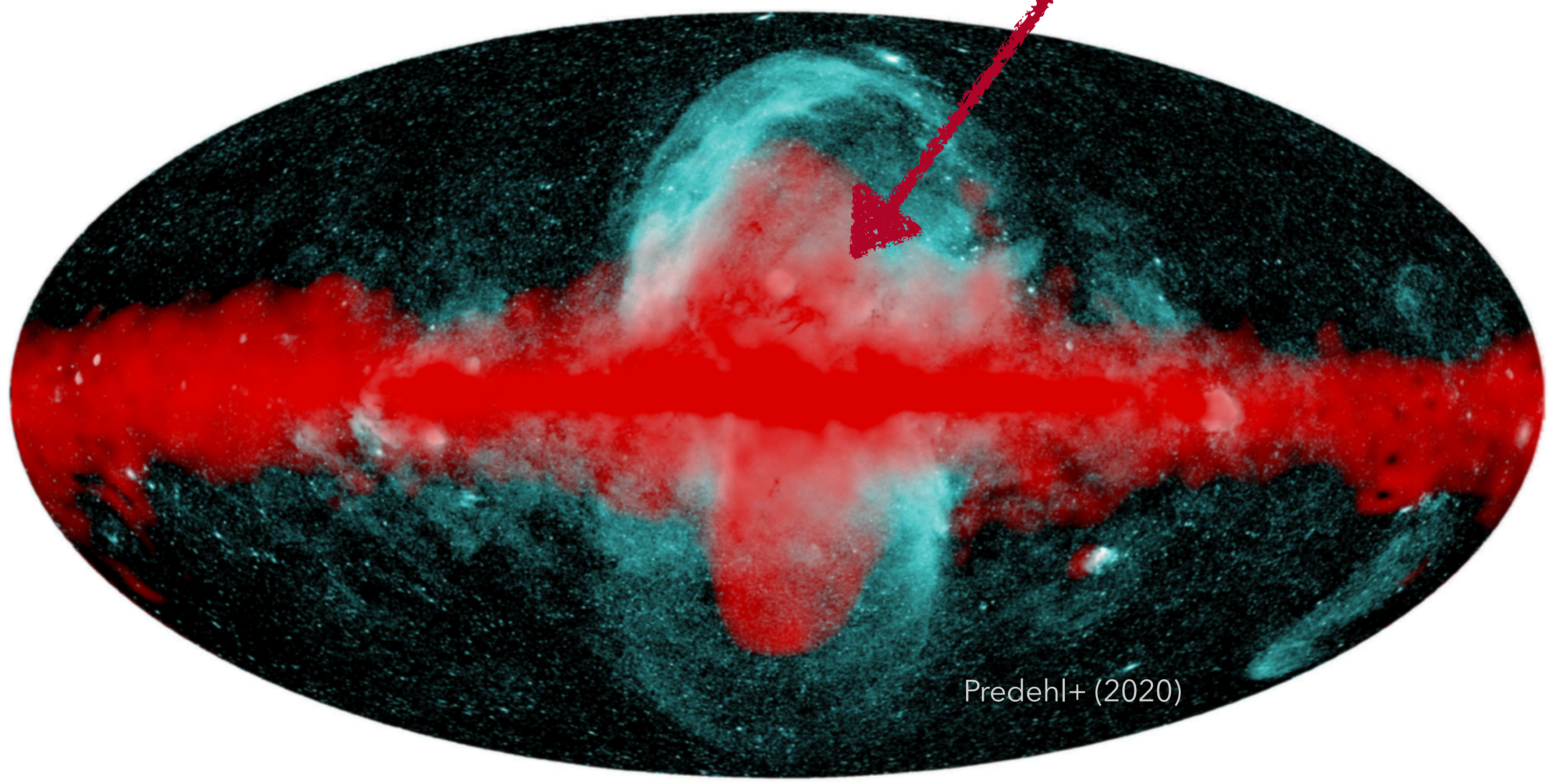
star formation

acceleration
of CRs

transport/
interaction
with the ISM



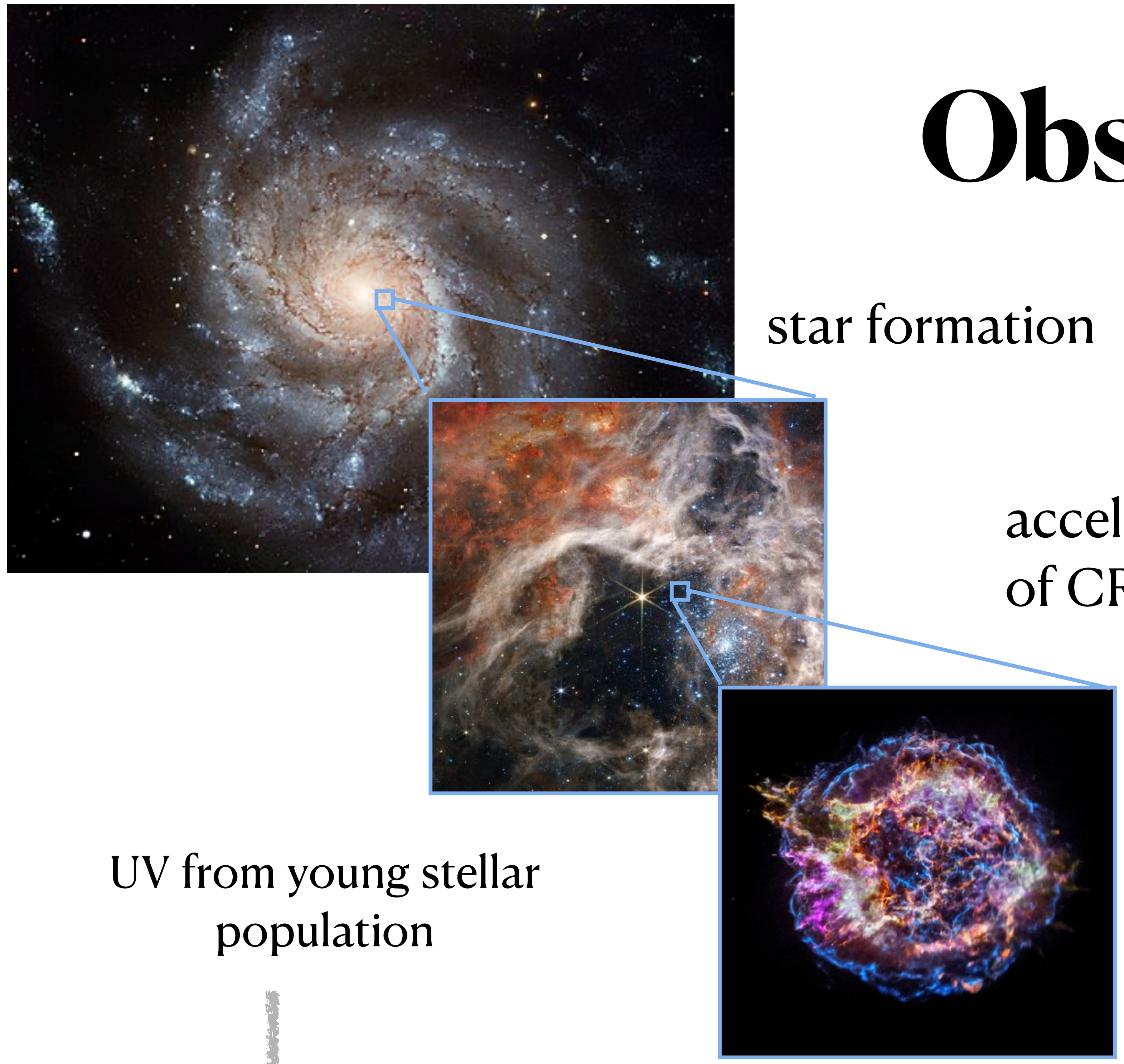

NGC 5775 (CHANG-ES survey, VLA obs.), Credit: NRAO, NASA, ESA, Hubble



cyan: eROSITA 0.6–1-keV band, red: GeV emission

Observational constraints of CRs

Non-thermal emission



star formation

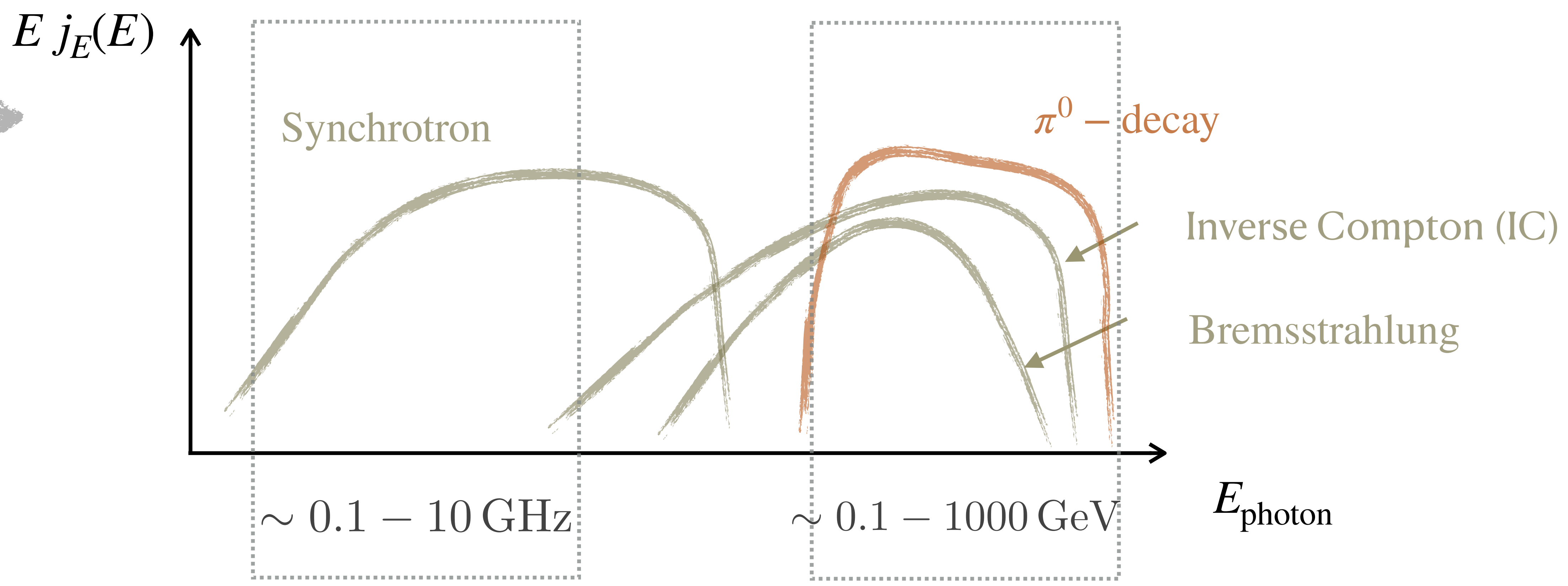
acceleration of CRs

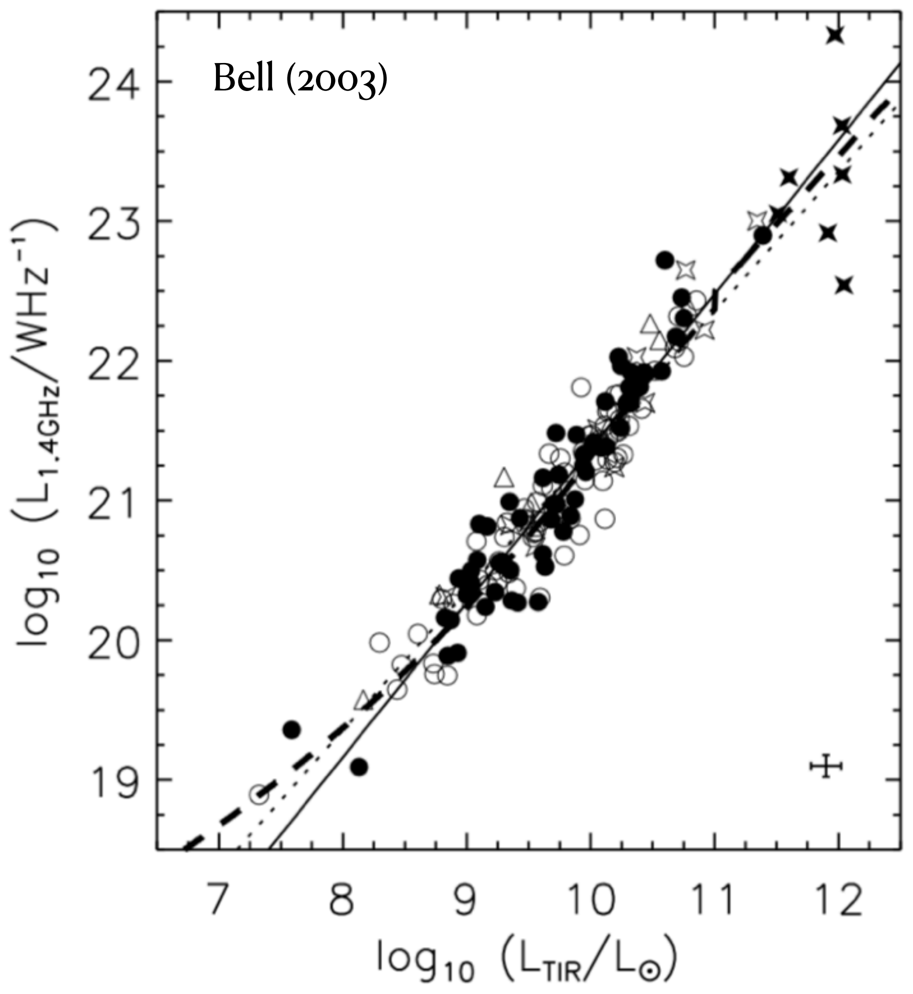
transport/
interaction
with the ISM

UV from young stellar population

dust

FIR-emission



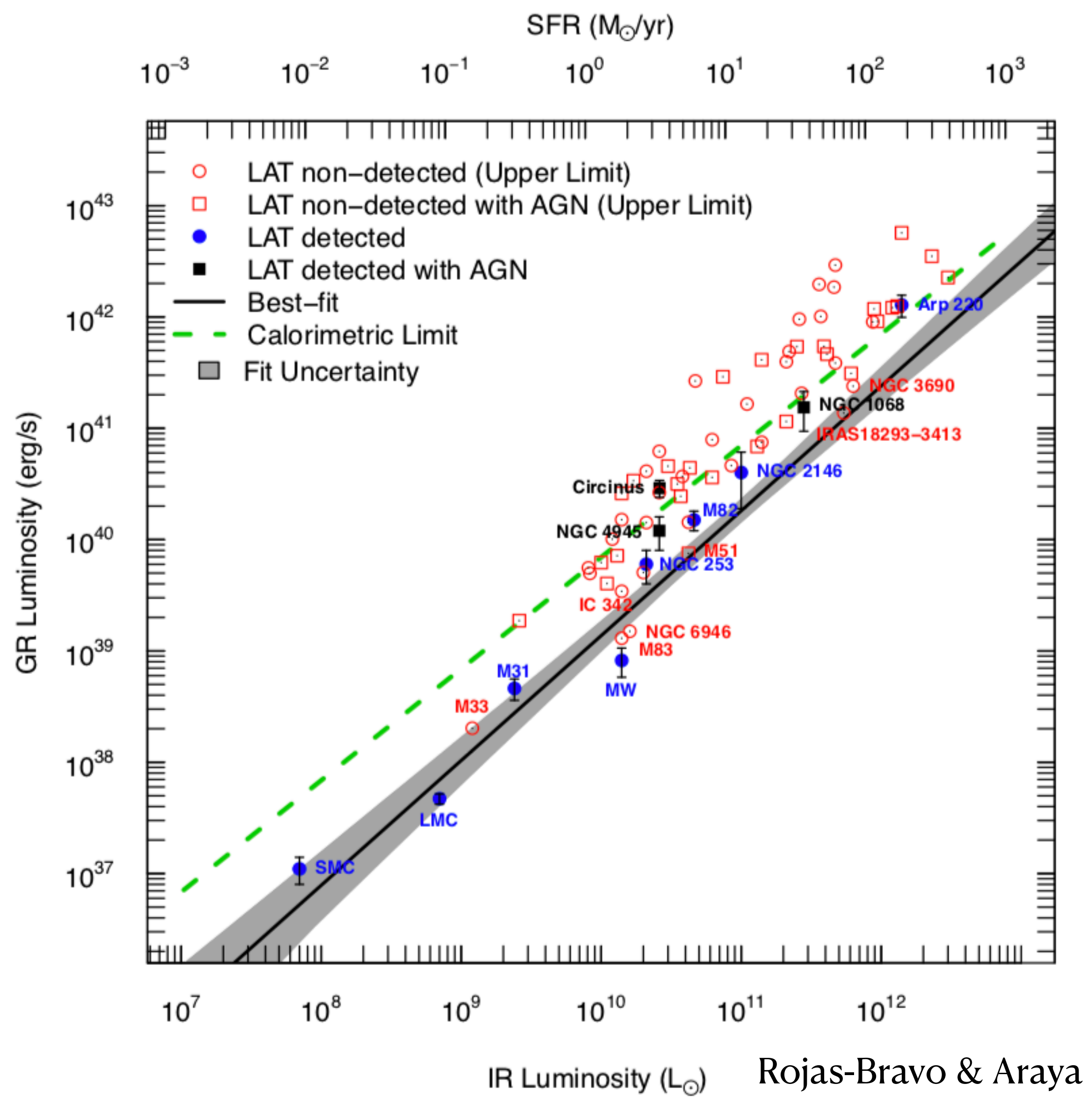


FIR-radio relation

(van der Kruit 1971; Condon 1992; Yun+2001; Bell 2003,Molnár 2021)

FIR-γ-ray relation

(Ackermann et al. 2012; Rojas-Bravo & Araya 2016; Linden 2017; Ajello+2020,Núñez-Castiñeyra+2022)



Rojas-Bravo & Araya (2016)

→ suggest calorimetry:
emission ∝ injection rate

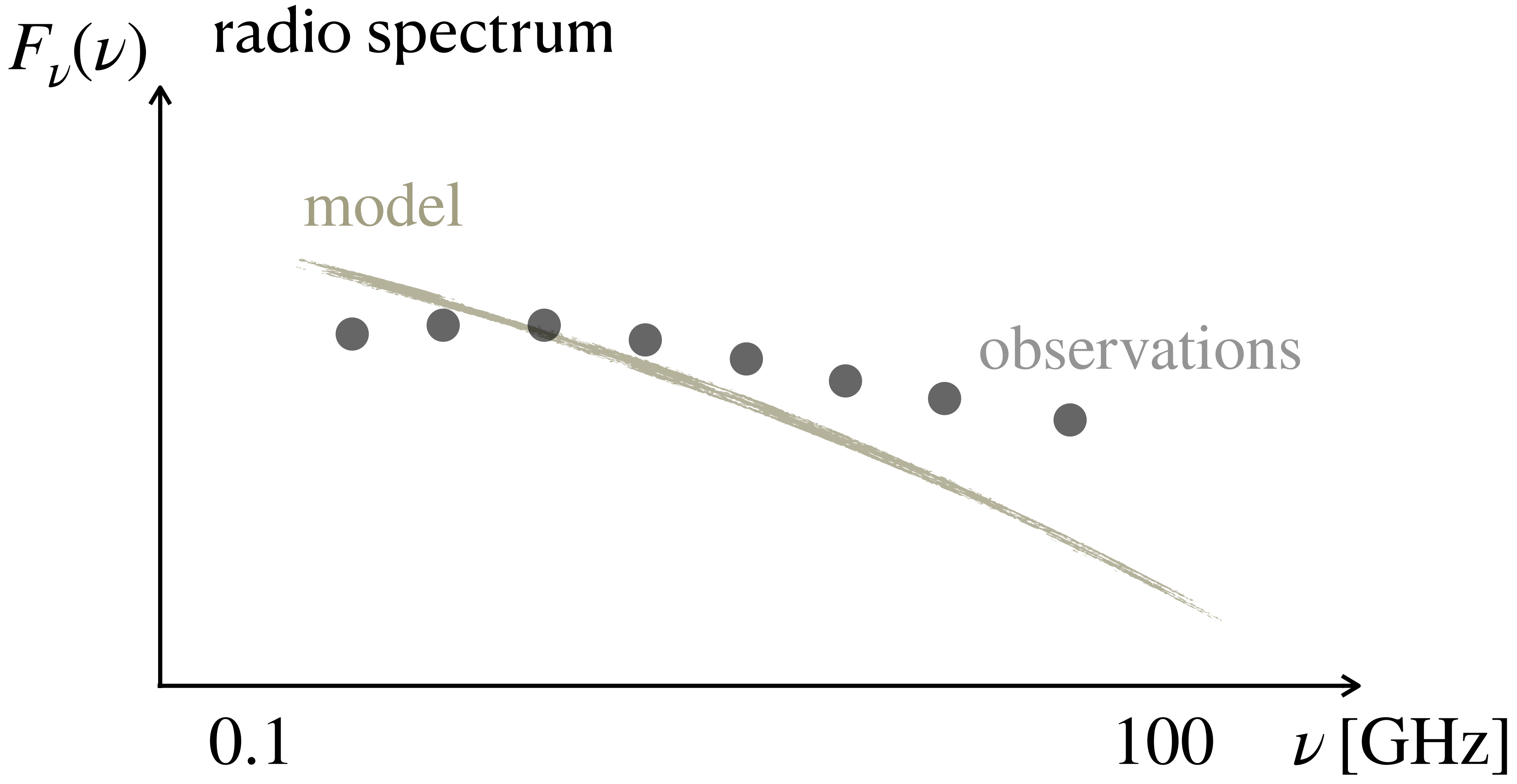
Maria Werhahn

Observational constraints of CRs

Implications

FIR-radio relation

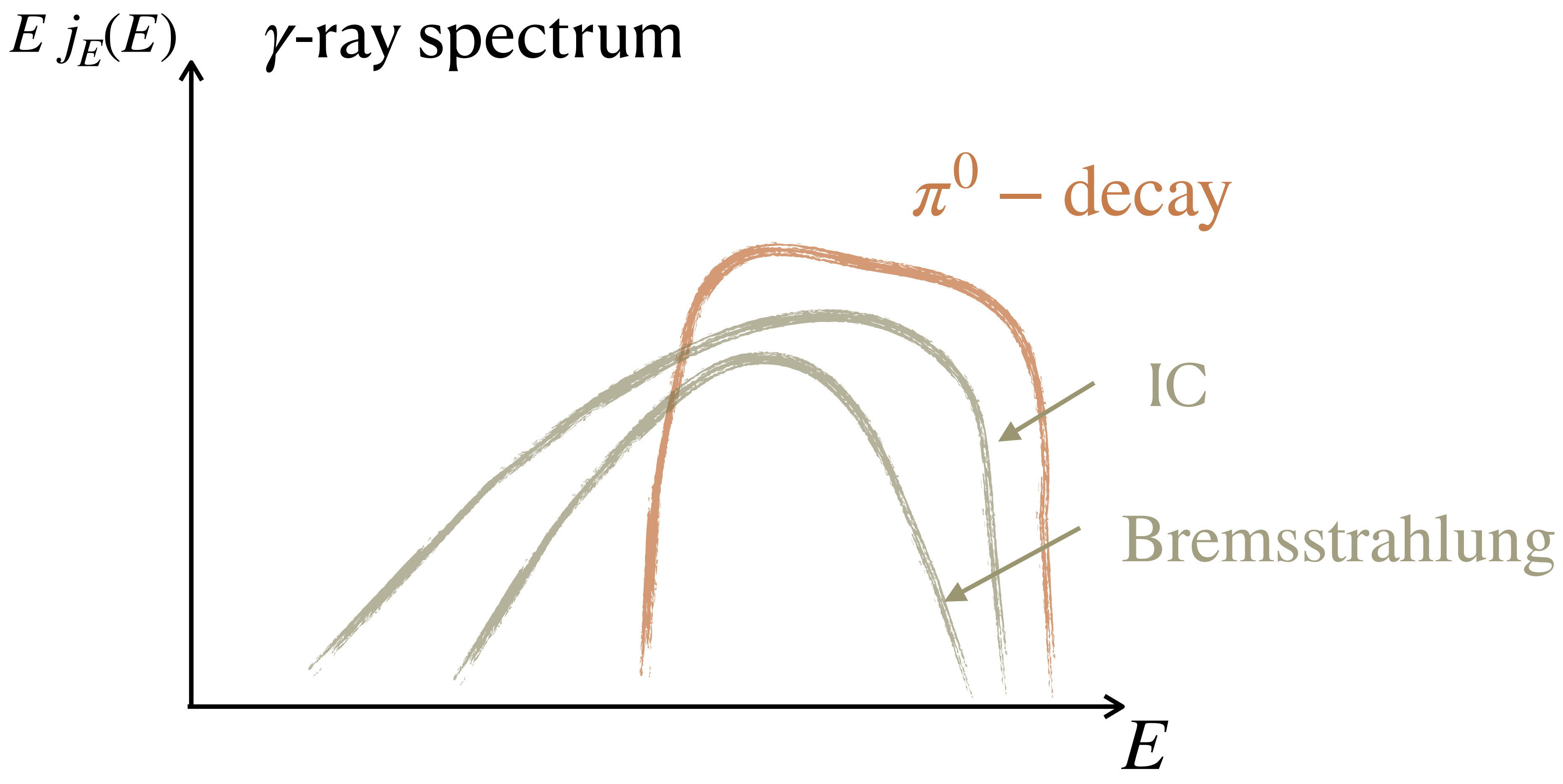
electron calorimetry



Observed flat radio spectra?

FIR-γ-ray relation

proton calorimetry



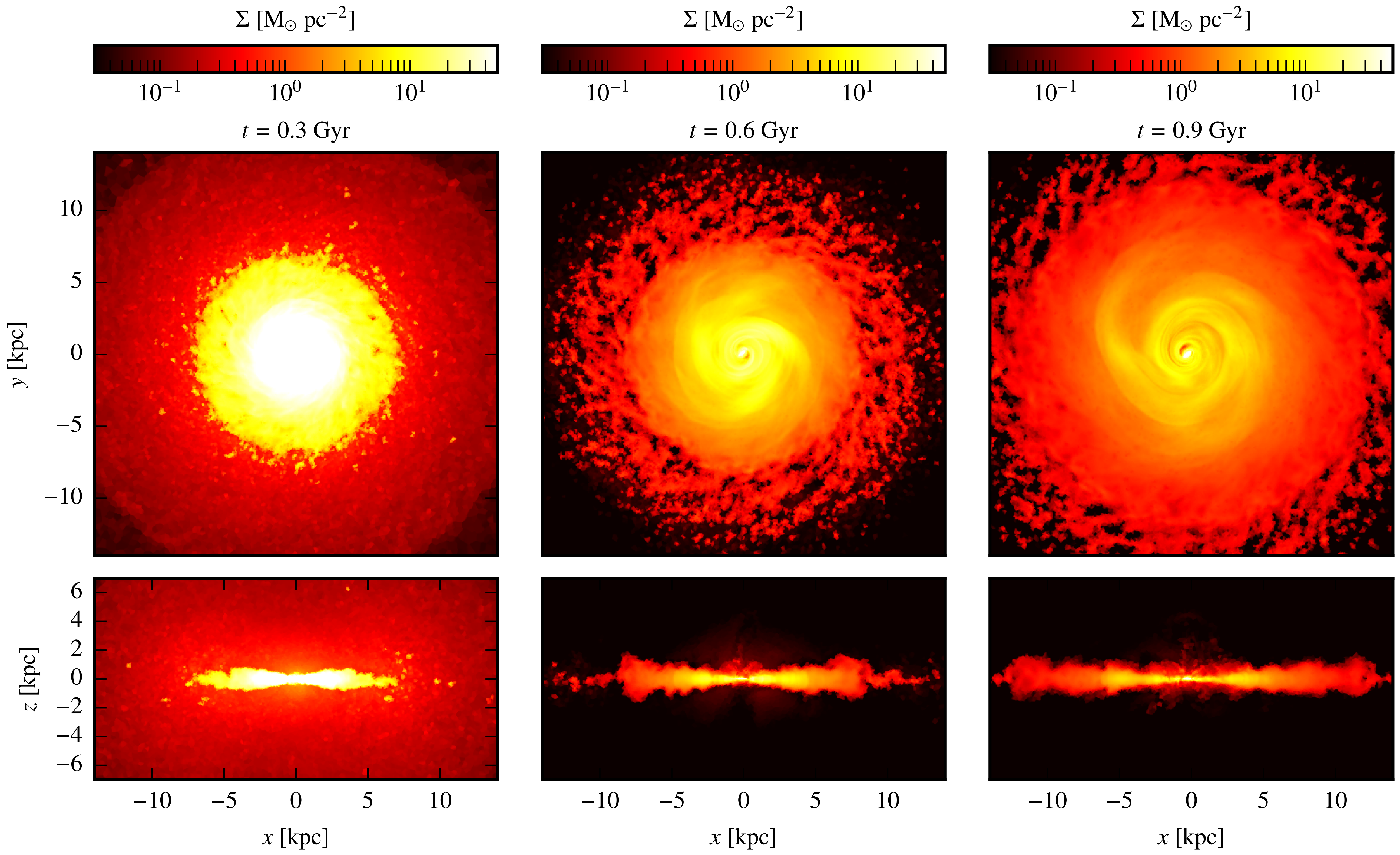
IC and bremsstrahlung ?

Other proton losses? Feedback?

CRs in MHD simulations (AREPO)

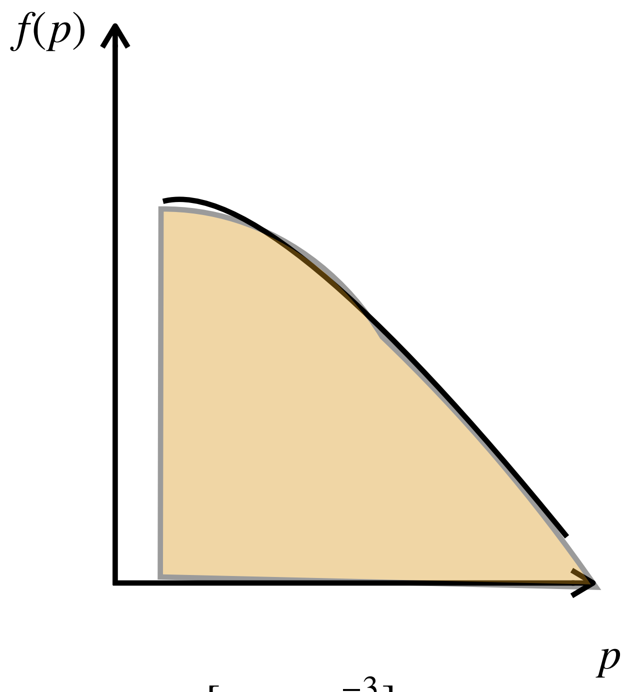
- collapsing gas cloud in dark matter halo
- star formation

gas surface density Σ

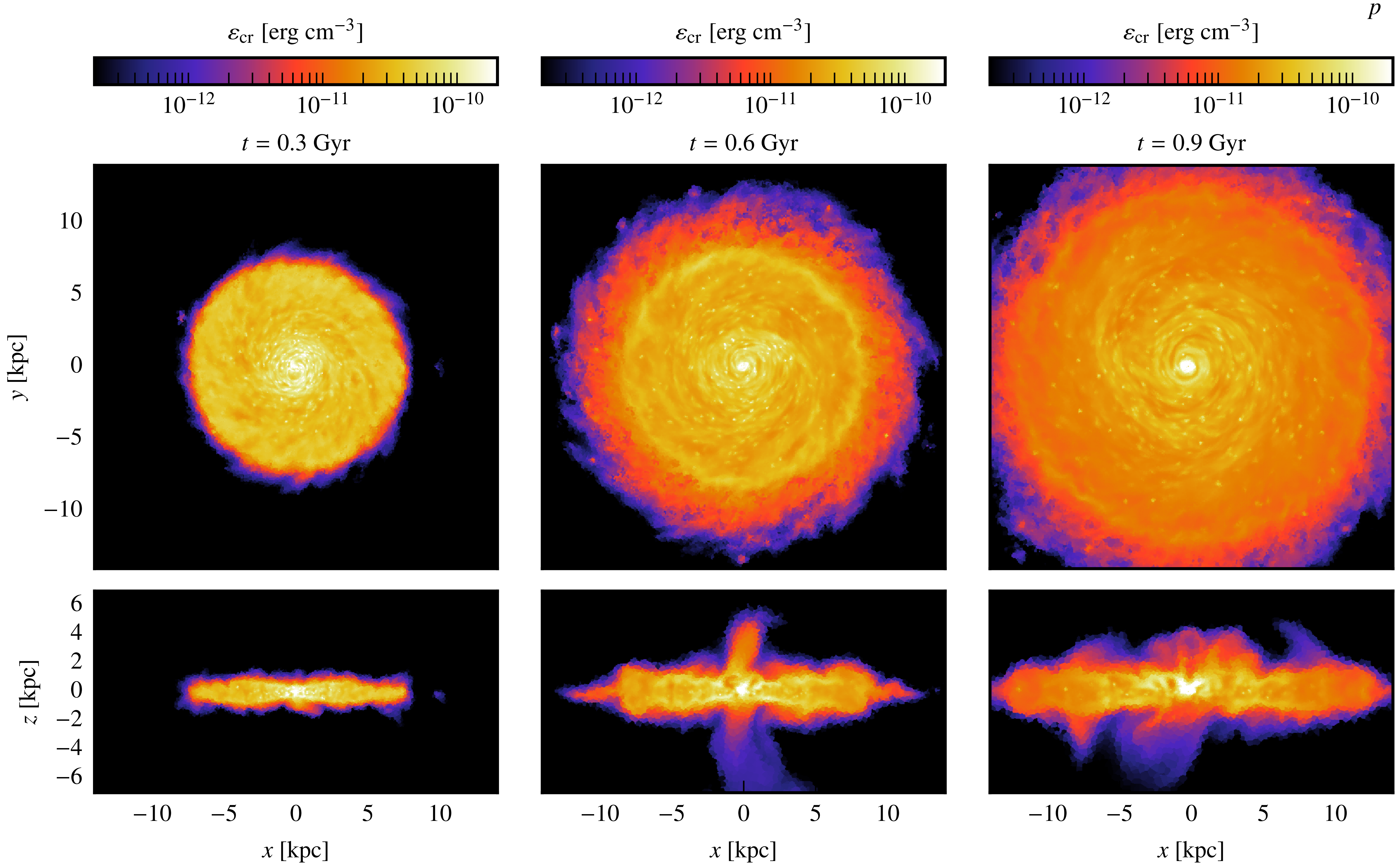


CRs in MHD simulations (AREPO)

- collapsing gas cloud in dark matter halo
- star formation —> injection of CRs
- **`grey' CR model**
  advection & anisotropic diffusion



CR energy density ε_{cr}

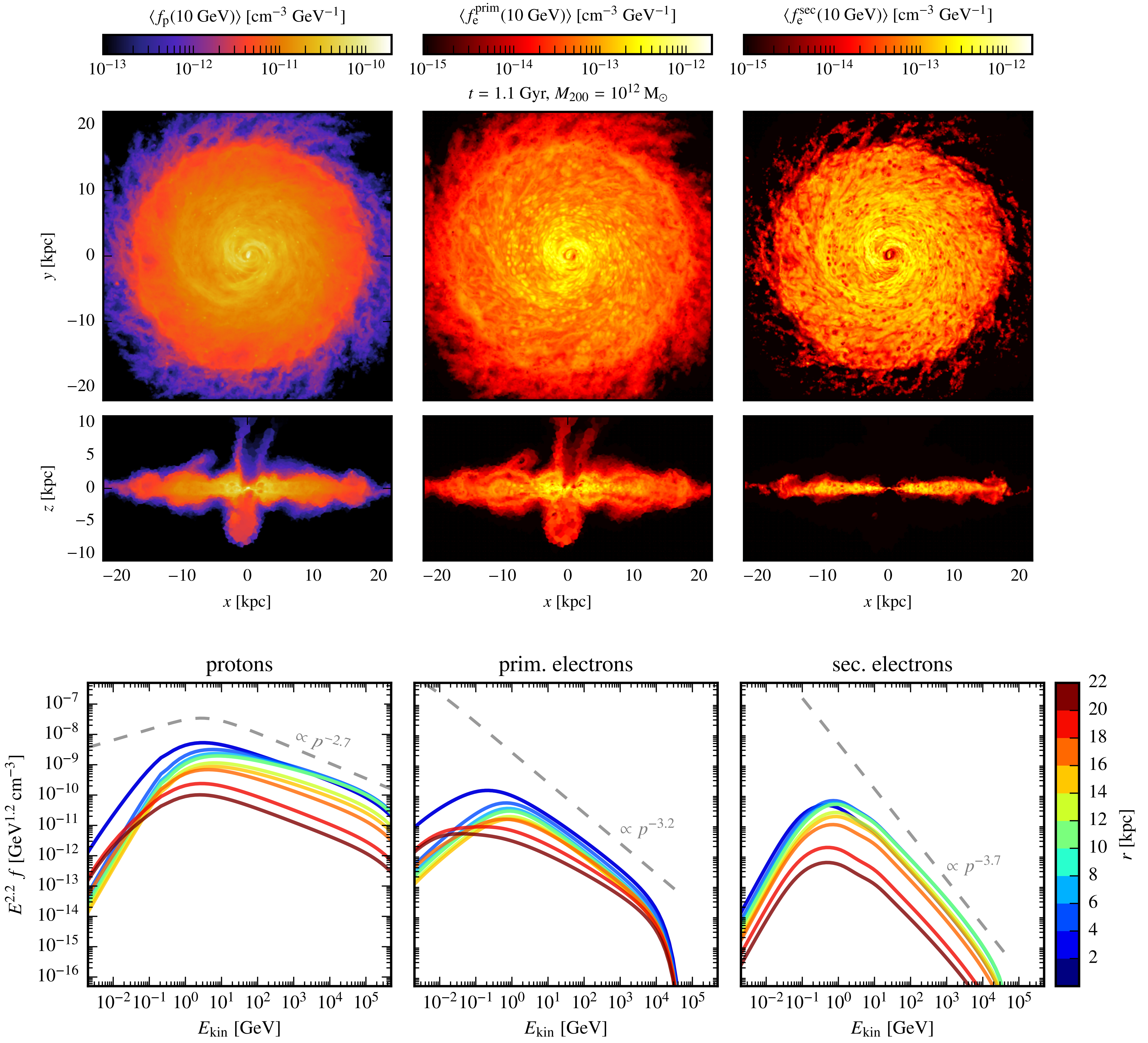


Maria Werhahn

CRs in MHD simulations (AREPO)

- collapsing gas cloud in dark matter halo
- star formation —> injection of CRs
- **`grey' CR model**
  advection & anisotropic diffusion

- **CRAYON+ (Cosmic RAY emissiON):**
  - steady-state modelling of CR spectra (protons, prim. & sec. electrons) incl. all radiative cooling losses + escape

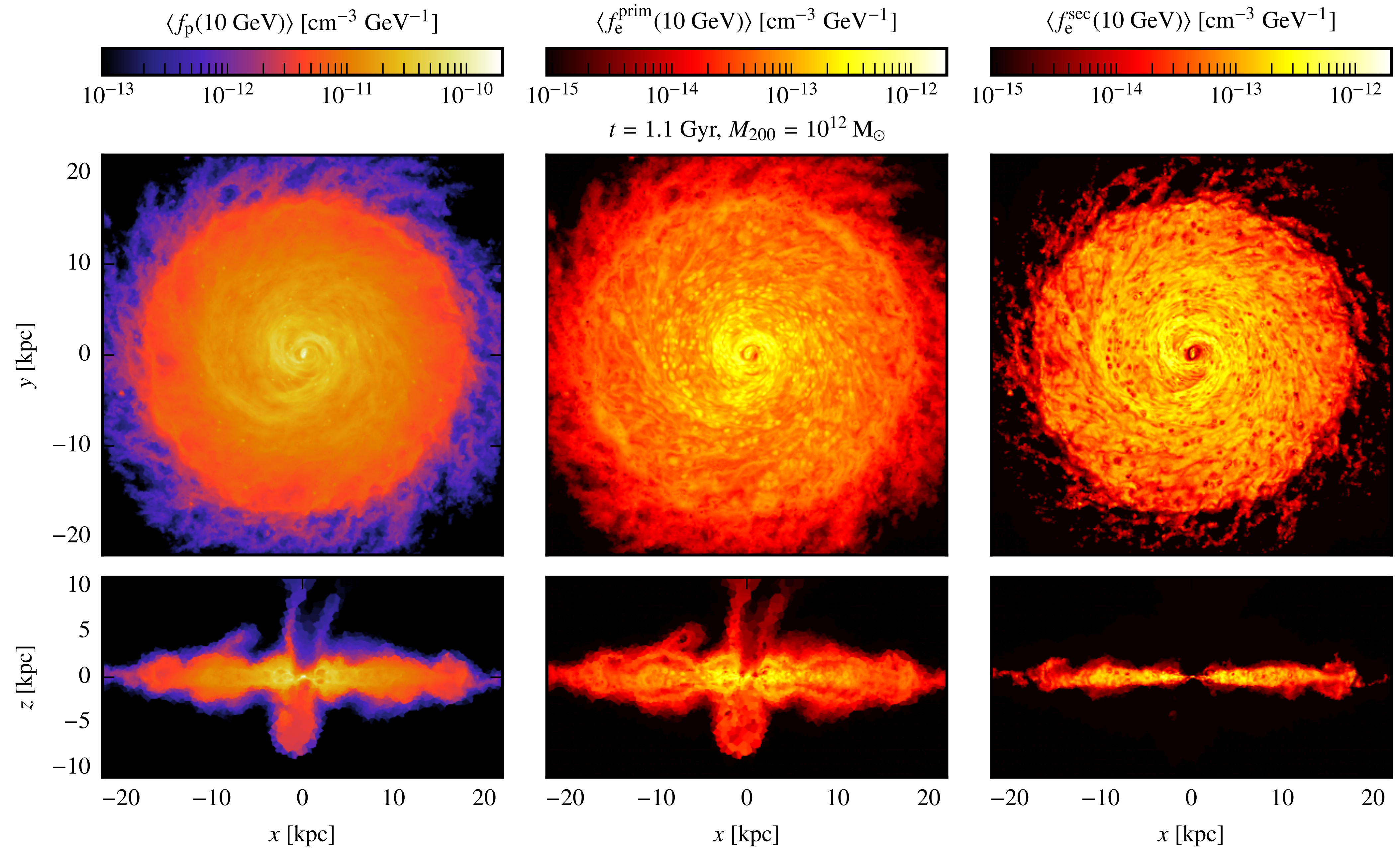


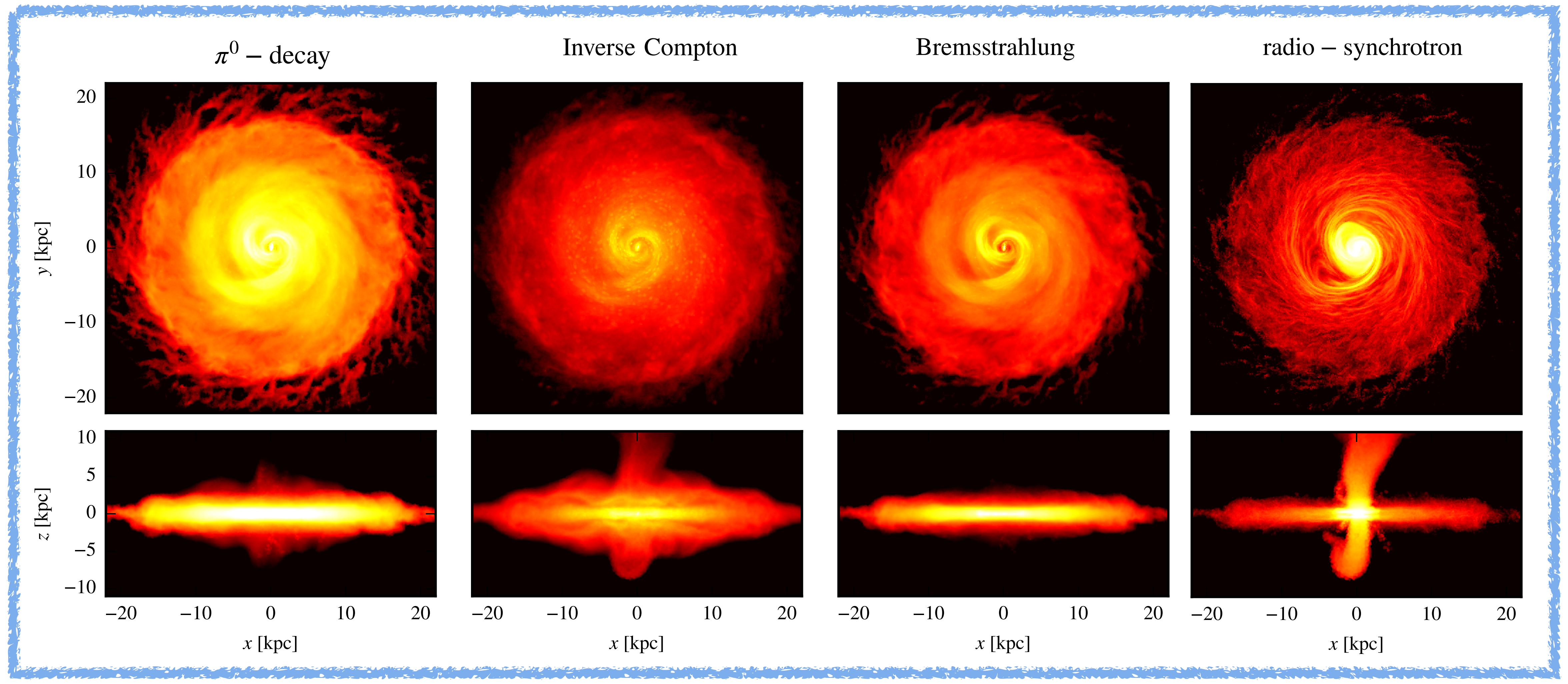
Werhahn et al. (2021a)

CRs in MHD simulations (AREPO)

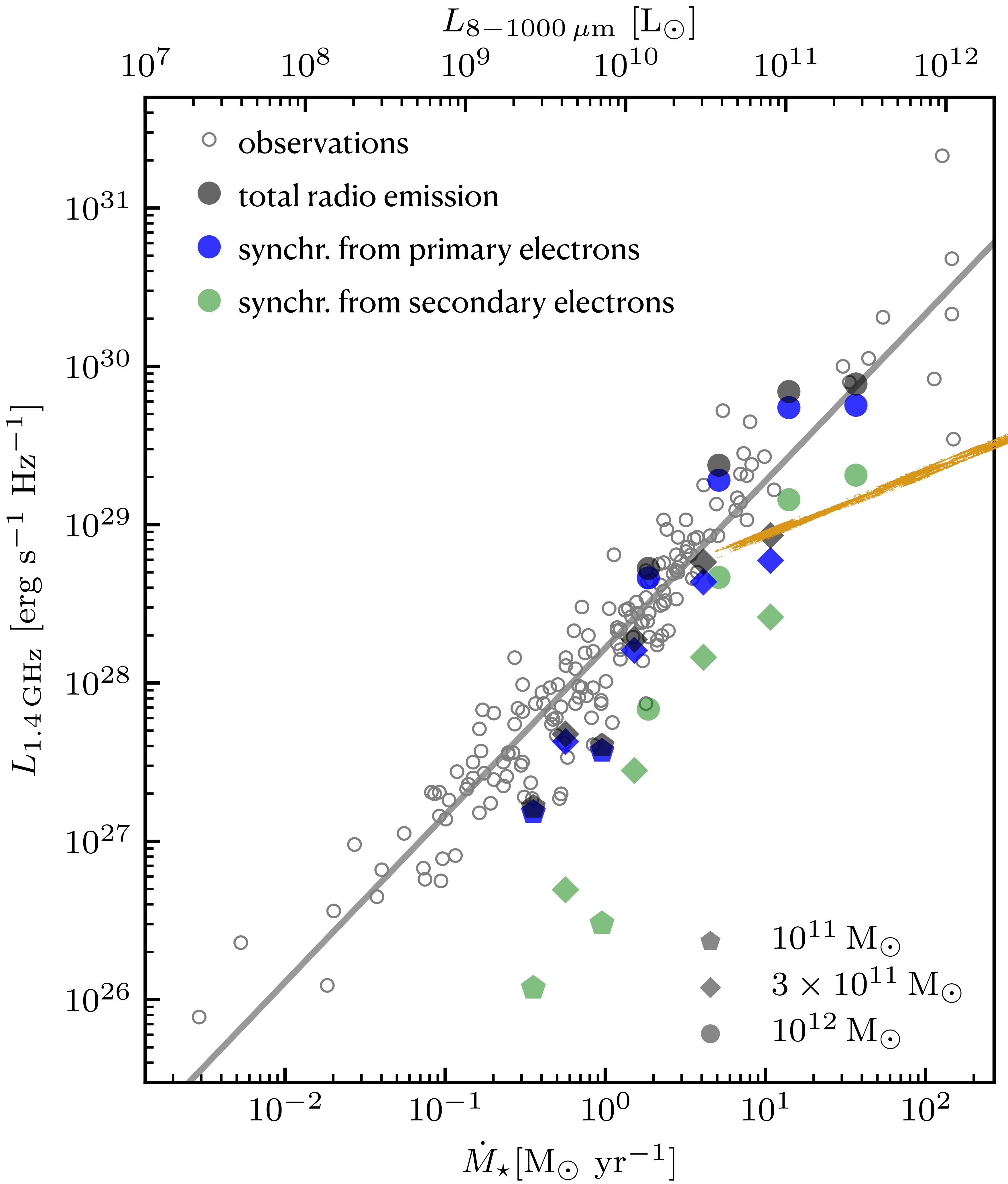
- collapsing gas cloud in dark matter halo
- star formation —> injection of CRs
- `grey' CR model
  advection & anisotropic diffusion

- **CRAYON+ (Cosmic RAY emissiON):**
  - steady-state modelling of CR spectra (protons, prim. & sec. electrons) incl. all radiative cooling losses + escape
  - + non-thermal multifrequency emission (radio to gamma-rays)

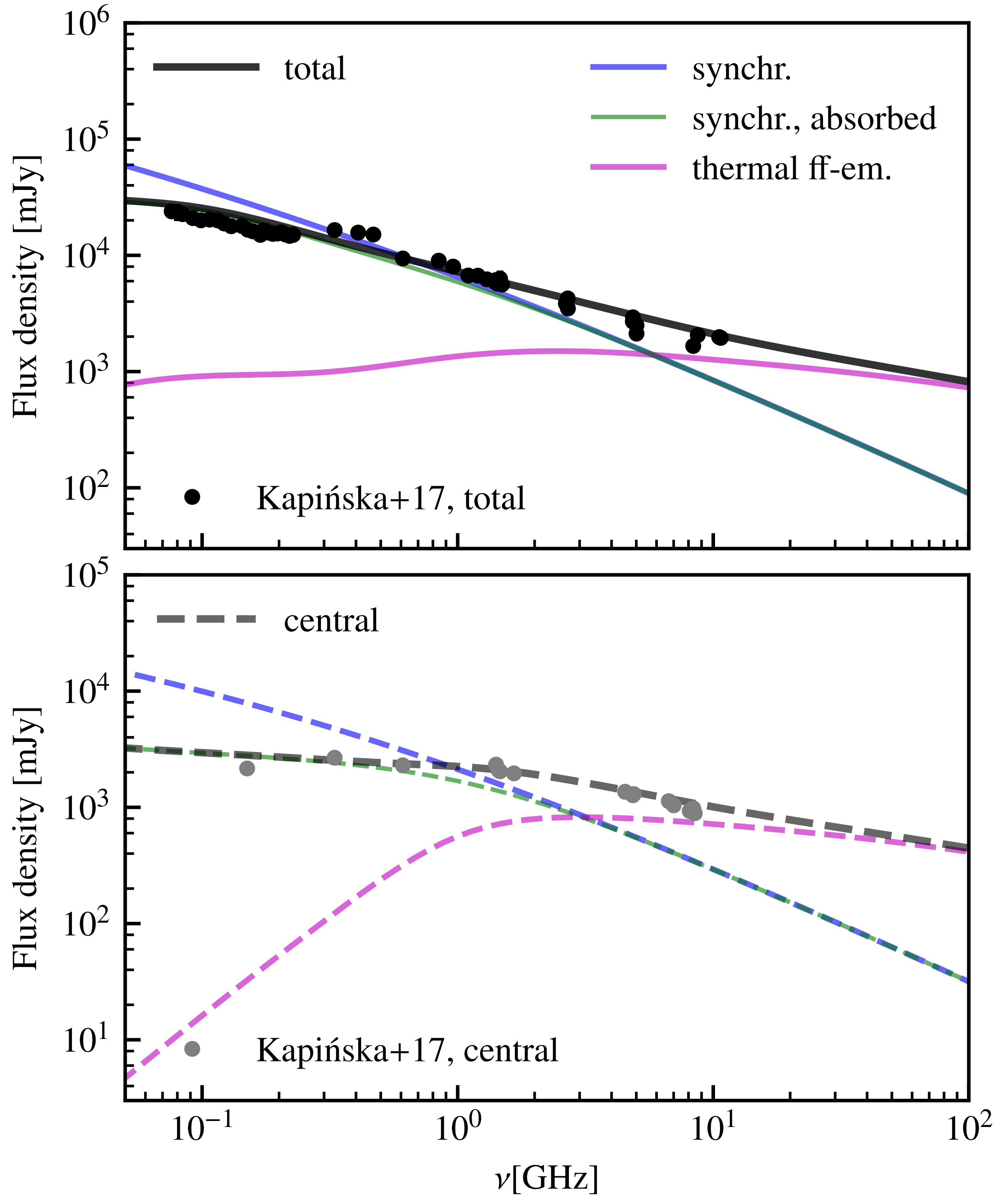




Radio emission



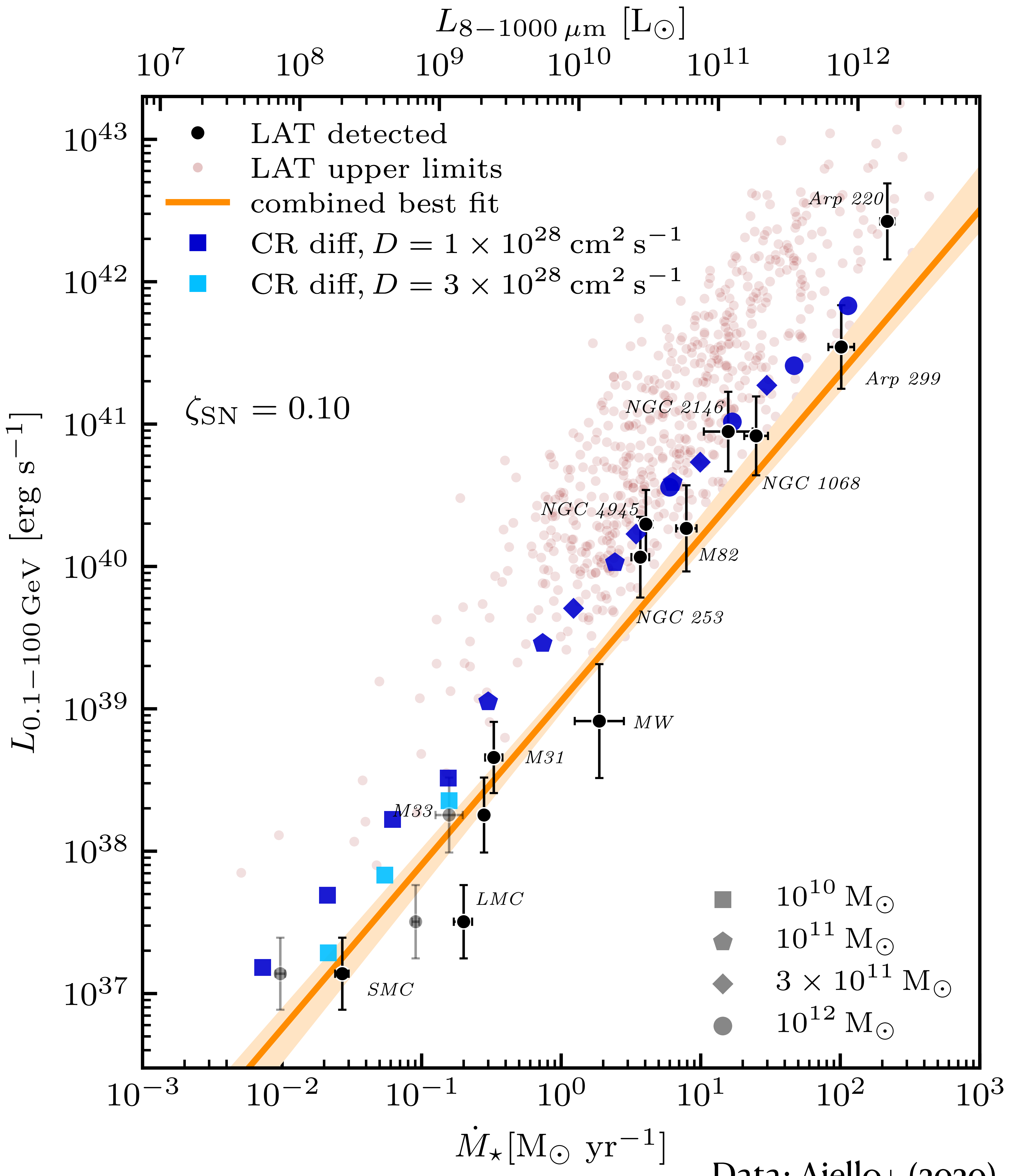
NGC 253



- IC & synchrotron losses dominate at high frequencies
—> steep radio synchr. spectra
- **Thermal free-free emission & absorption needed**
—> strong in central regions

Werhahn et al. (2021c)

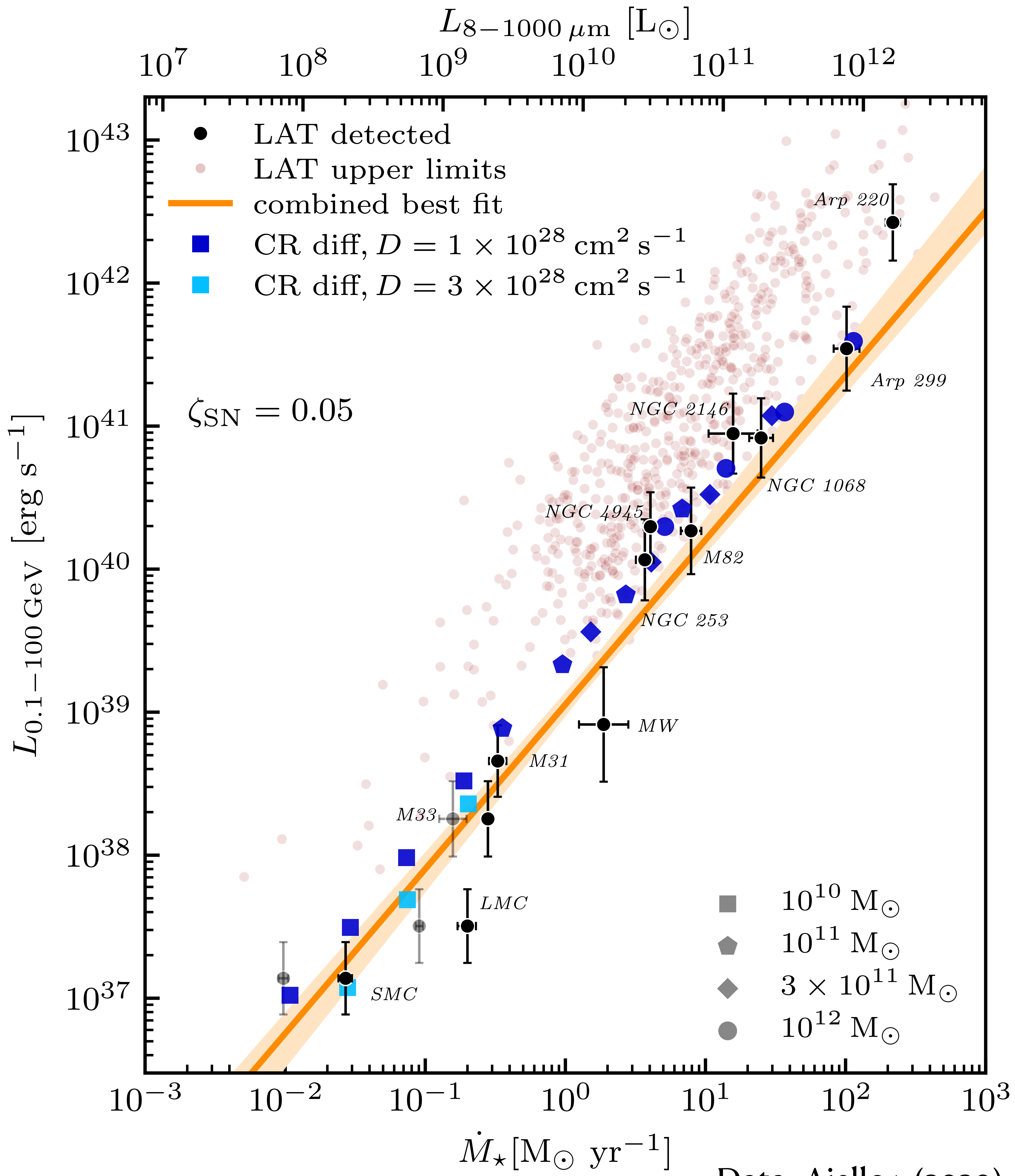
FIR - γ-ray relation



Data: Ajello+ (2020)

Werhahn et al. (2021b)

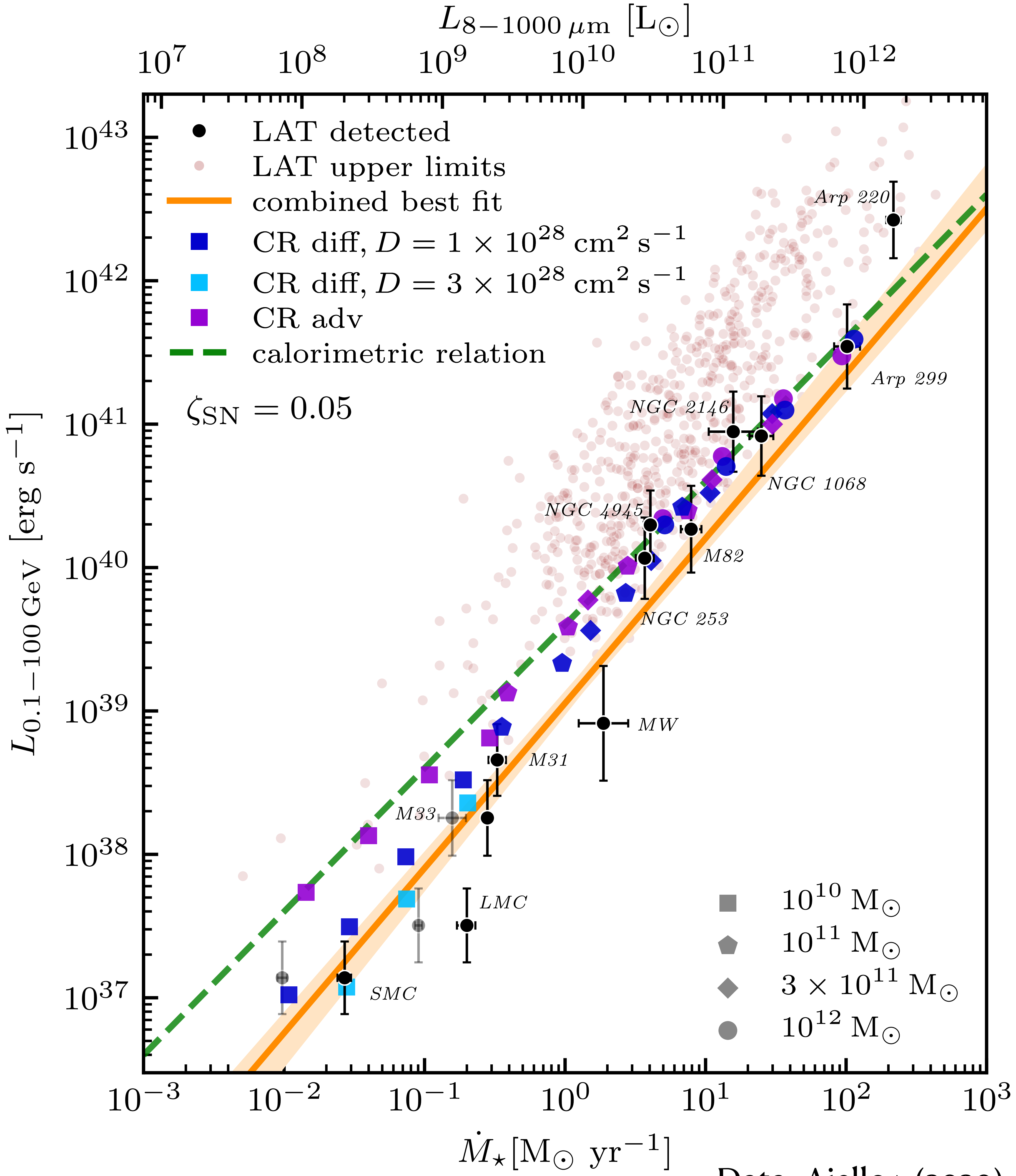
FIR - γ-ray relation



Data: Ajello+ (2020)

Werhahn et al. (2021b)

FIR - γ-ray relation



Data: Ajello+ (2020)

Werhahn et al. (2021b)

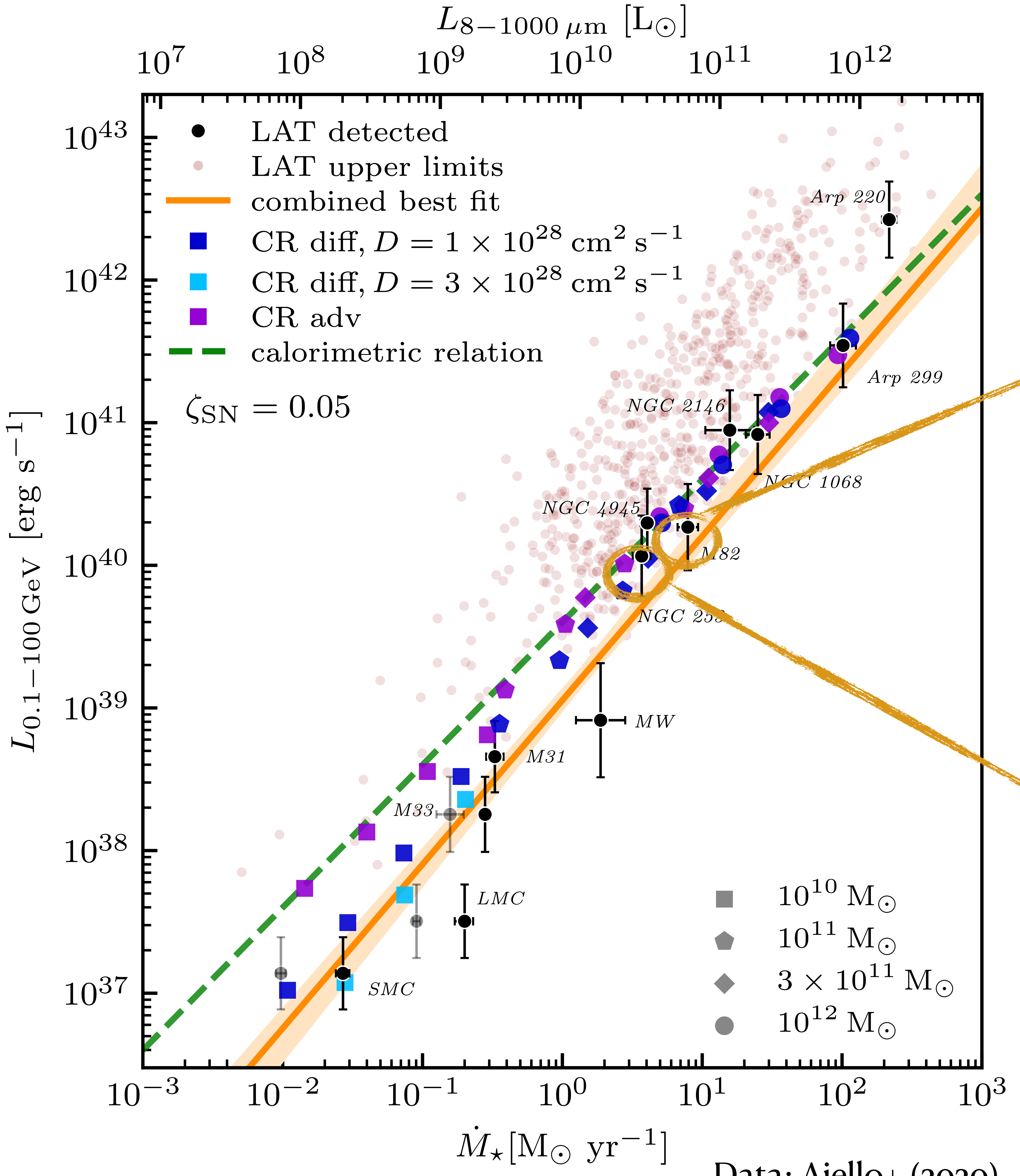
- $\dot{M}_\star < 1\,\mathrm{M}_\odot/yr$:
  many CRs diffuse out

- $\dot{M}_\star > 1\,\mathrm{M}_\odot/yr$:
  close to calorimetric limit
  (complete conversion to γ-rays)
  —> 30 - 70%

There's energy left for feedback
- we see CR driven winds!

Maria Werhahn

FIR - γ-ray relation & spectra

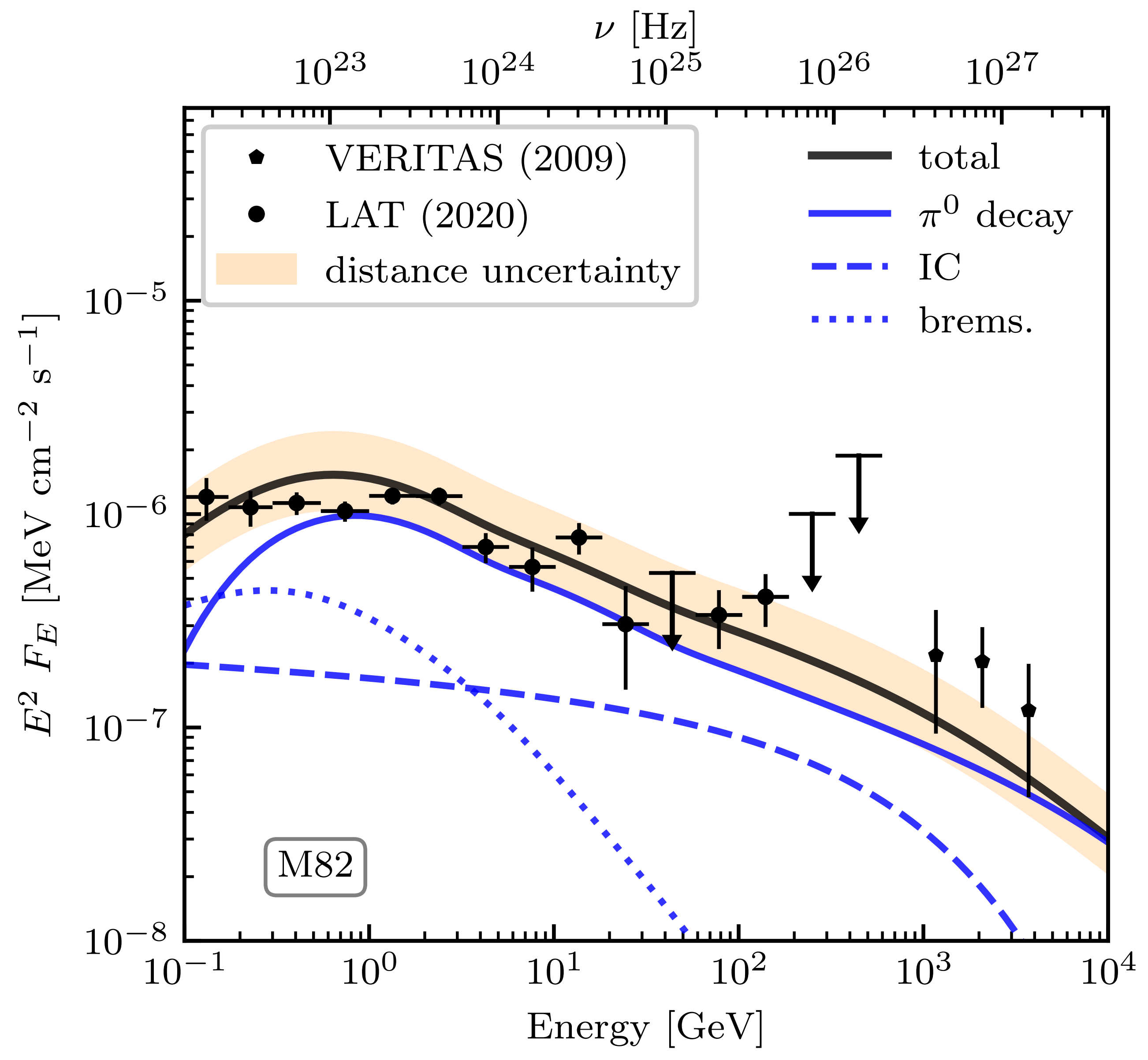


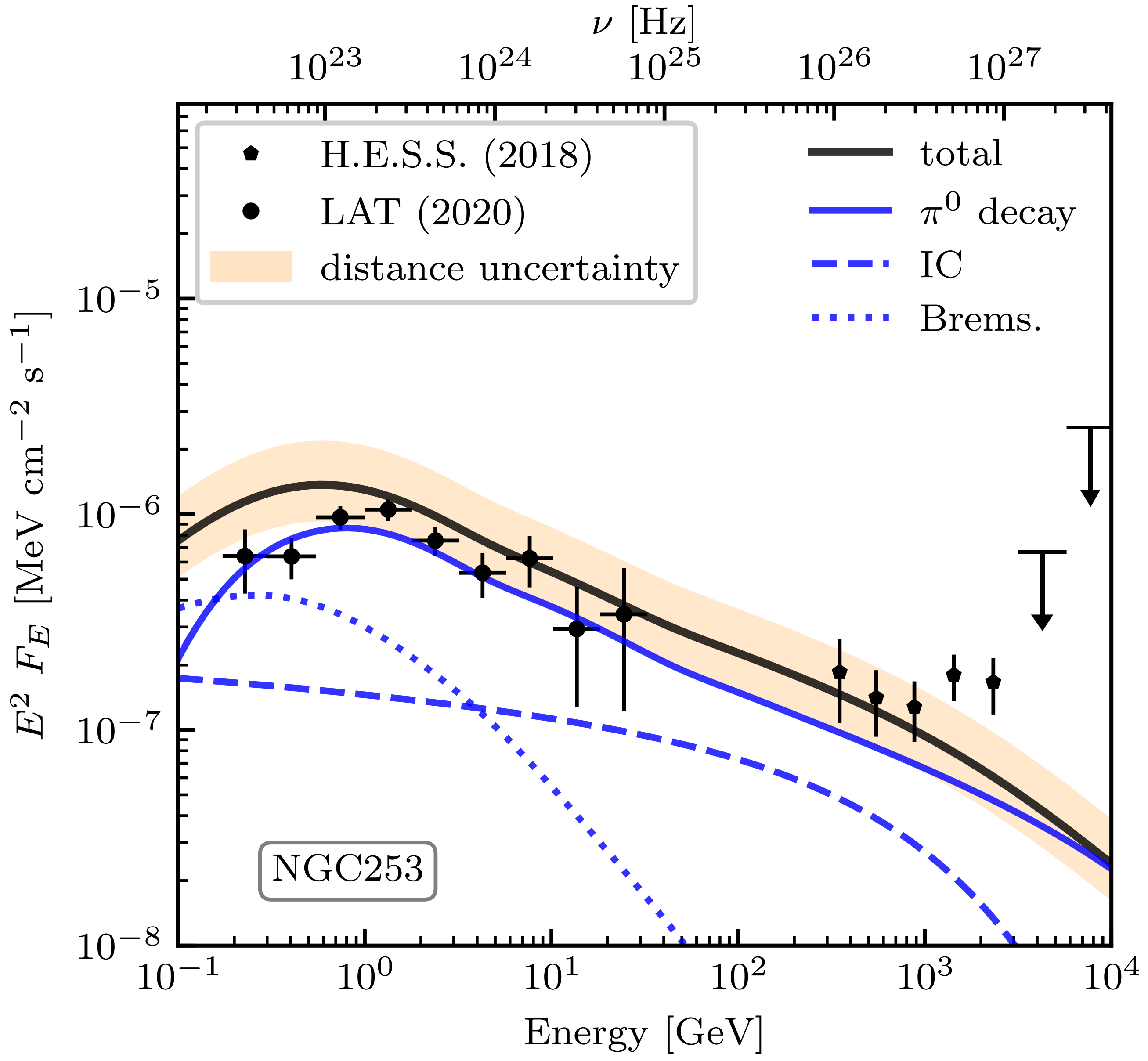
Data: Ajello+ (2020)

Werhahn et al. (2021b)

M82

NGC 253

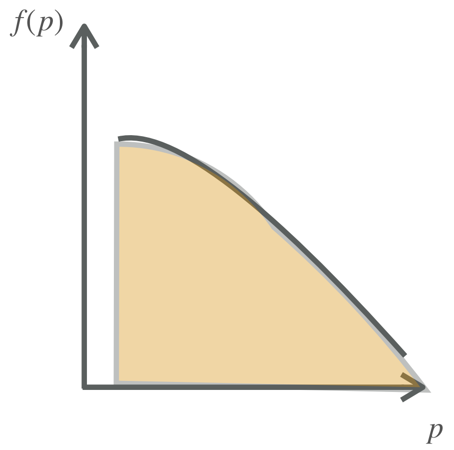




Maria Werhahn

CRs in MHD simulations (AREPO)

Grey approach:

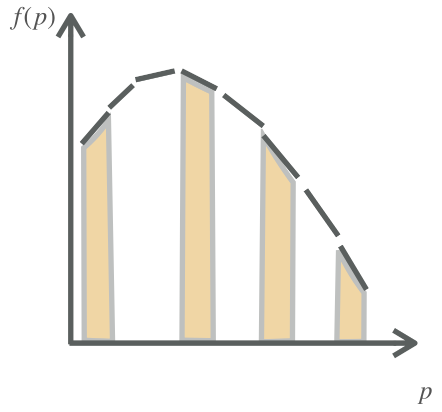


- evolves CR energy density, modelling of CR spectra in post-processing assuming steady-state

CRs in MHD simulations (AREPO)

Grey approach:

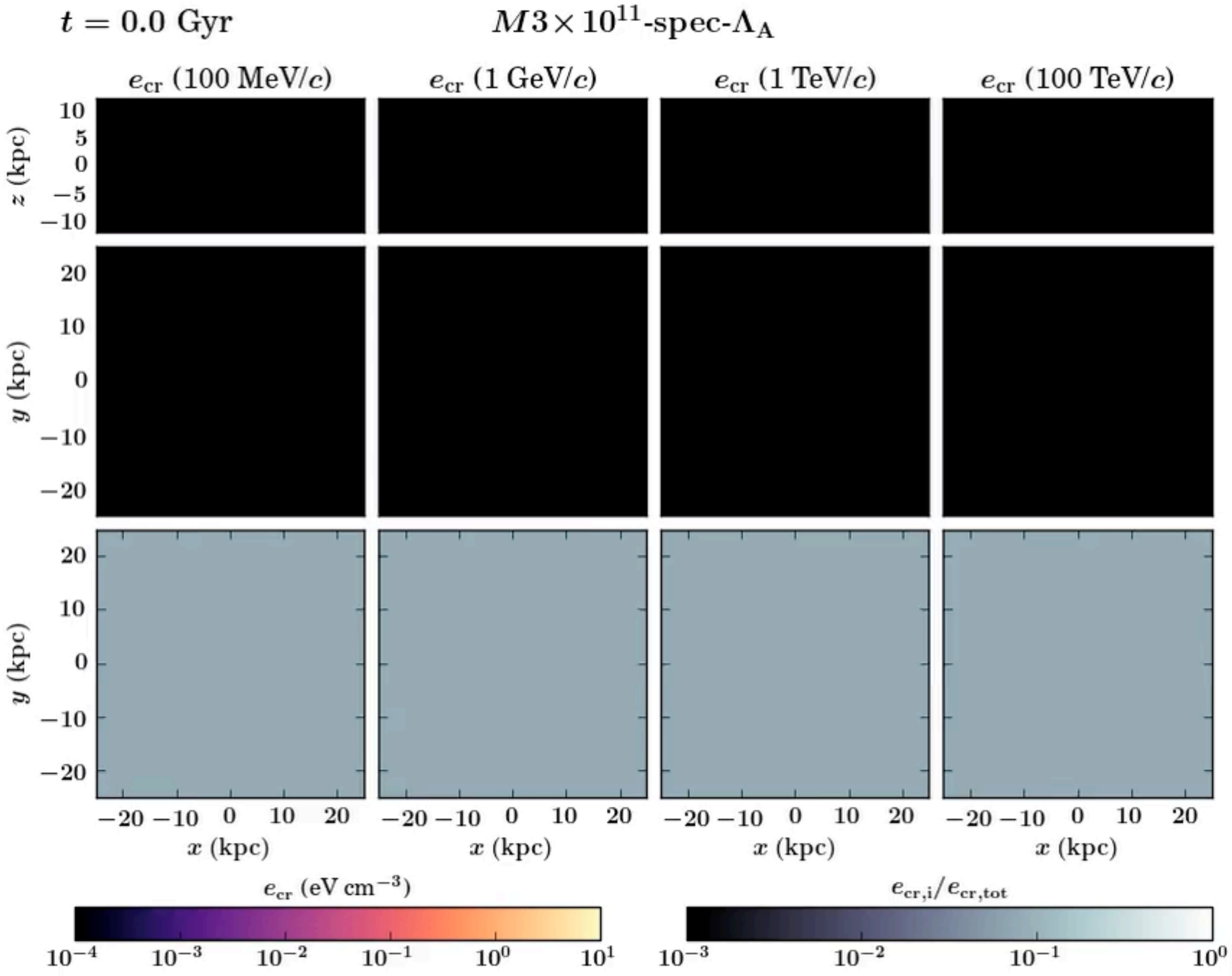
- evolves CR energy density, modelling of CR spectra in post-processing assuming steady-state



Spectral approach
(Girichidis+2022,2023)

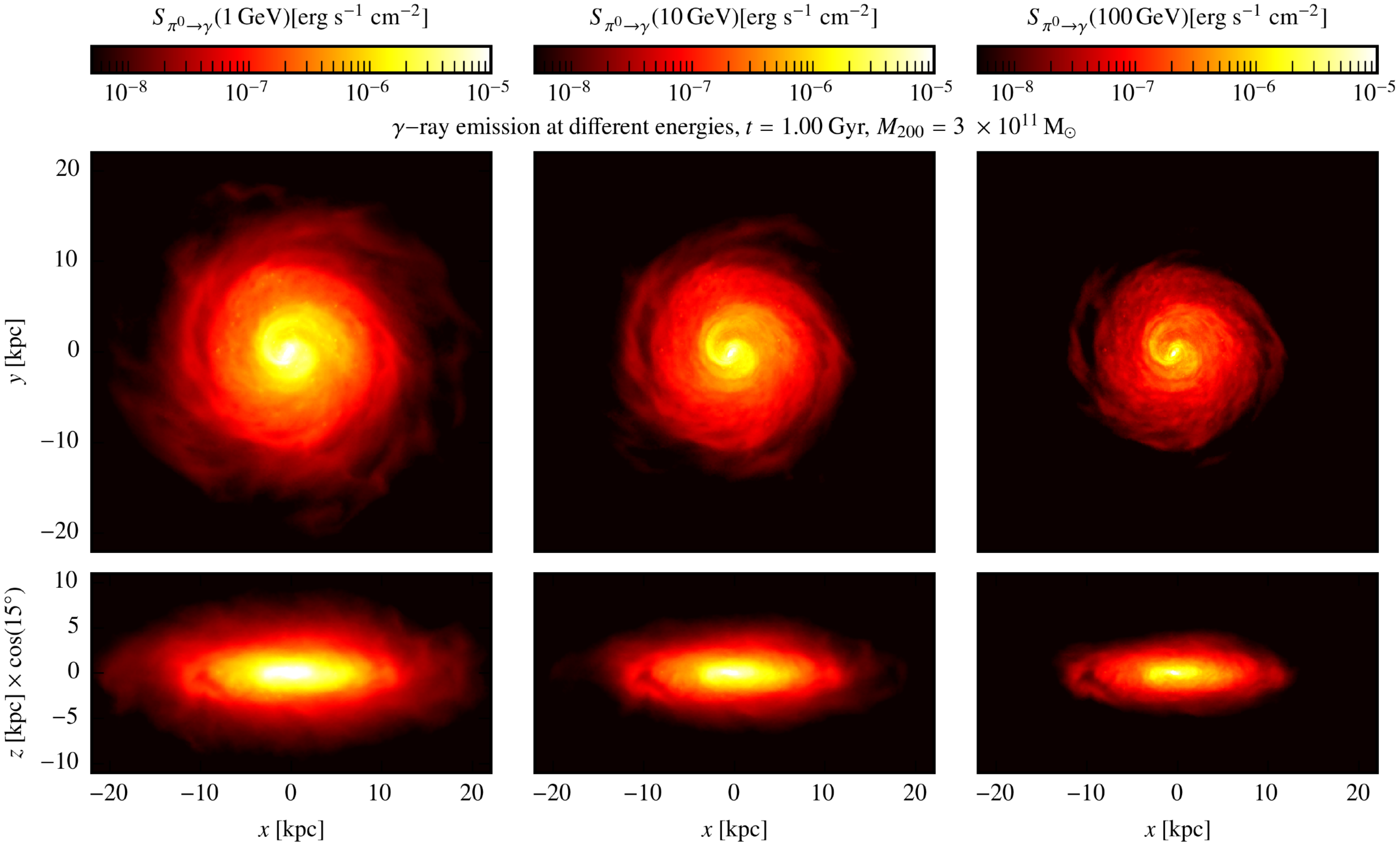
- evolves full CR proton spectra
- CR energy and number density in 12 momentum bins (100 MeV/c - 100 TeV/c)
- energy dependent diffusion

Girichidis+ 2023



Spectrally resolved CRs in galaxies

steady-state model

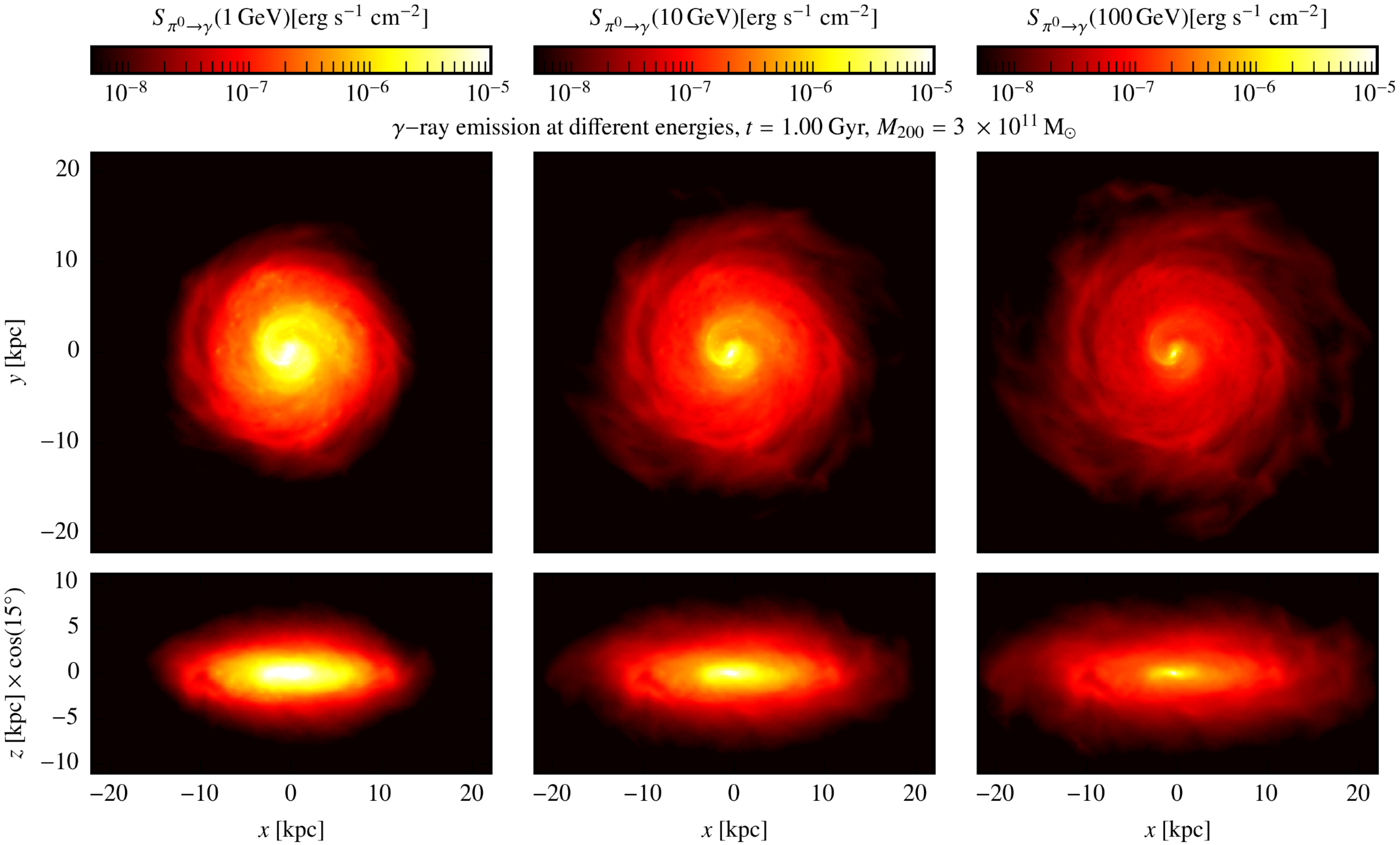


Werhahn+ (2023)

Maria Werhahn

Spectrally resolved CRs in galaxies

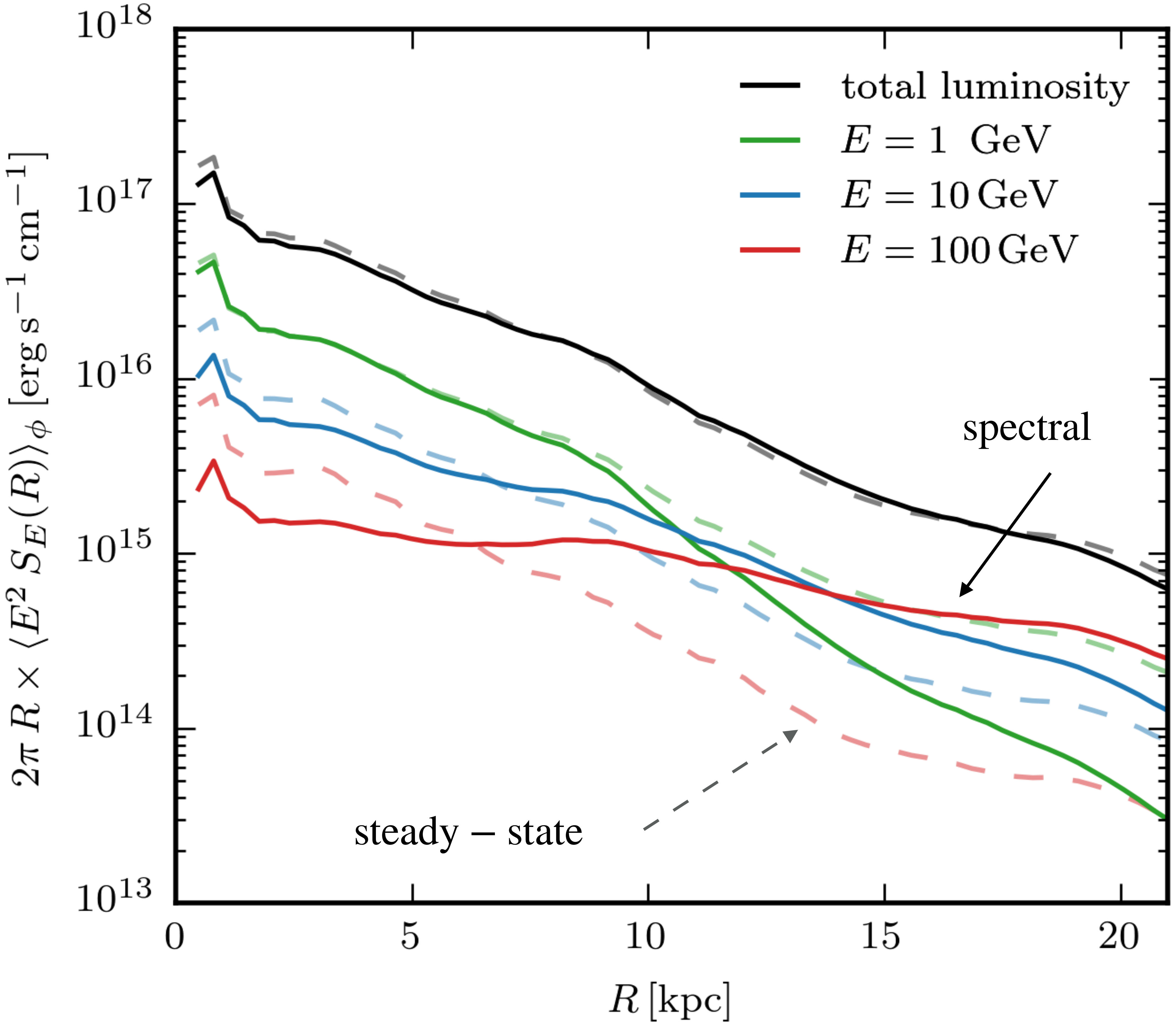
spectral CR model



Werhahn+ (2023)

Spectrally resolved CRs in galaxies

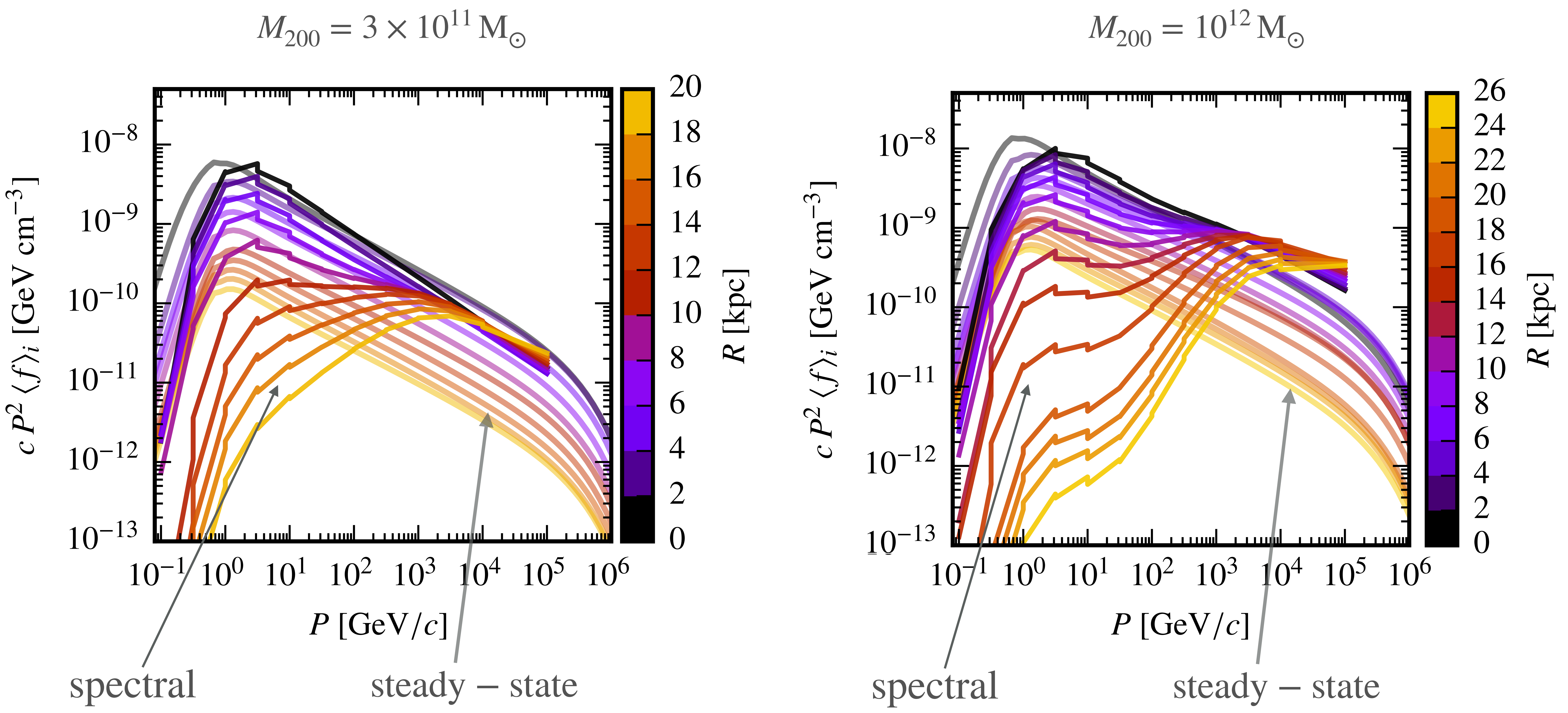
radial contribution to luminosity



Werhahn+ (2023)

Spectrally resolved CRs in galaxies

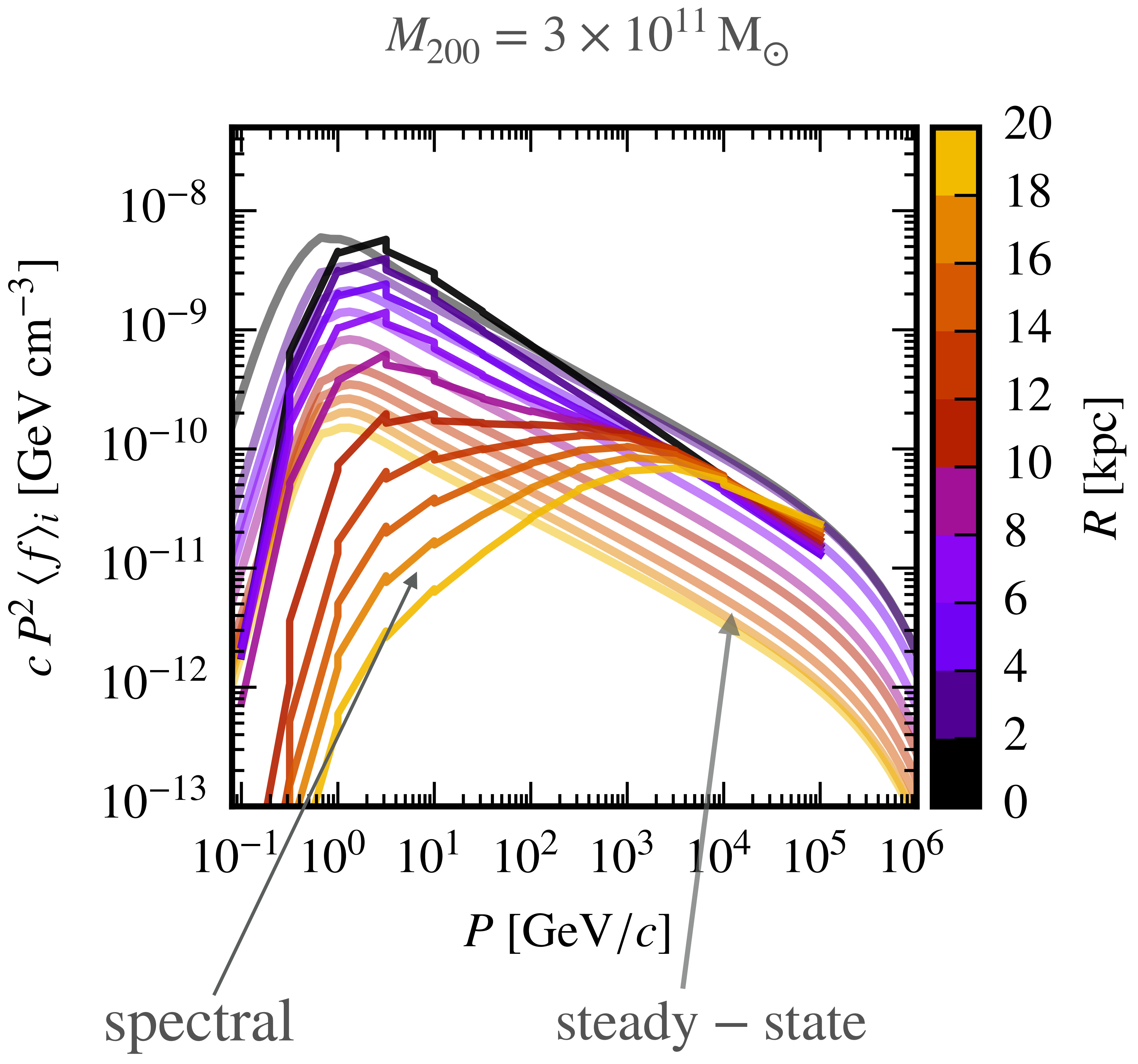
CR spectra

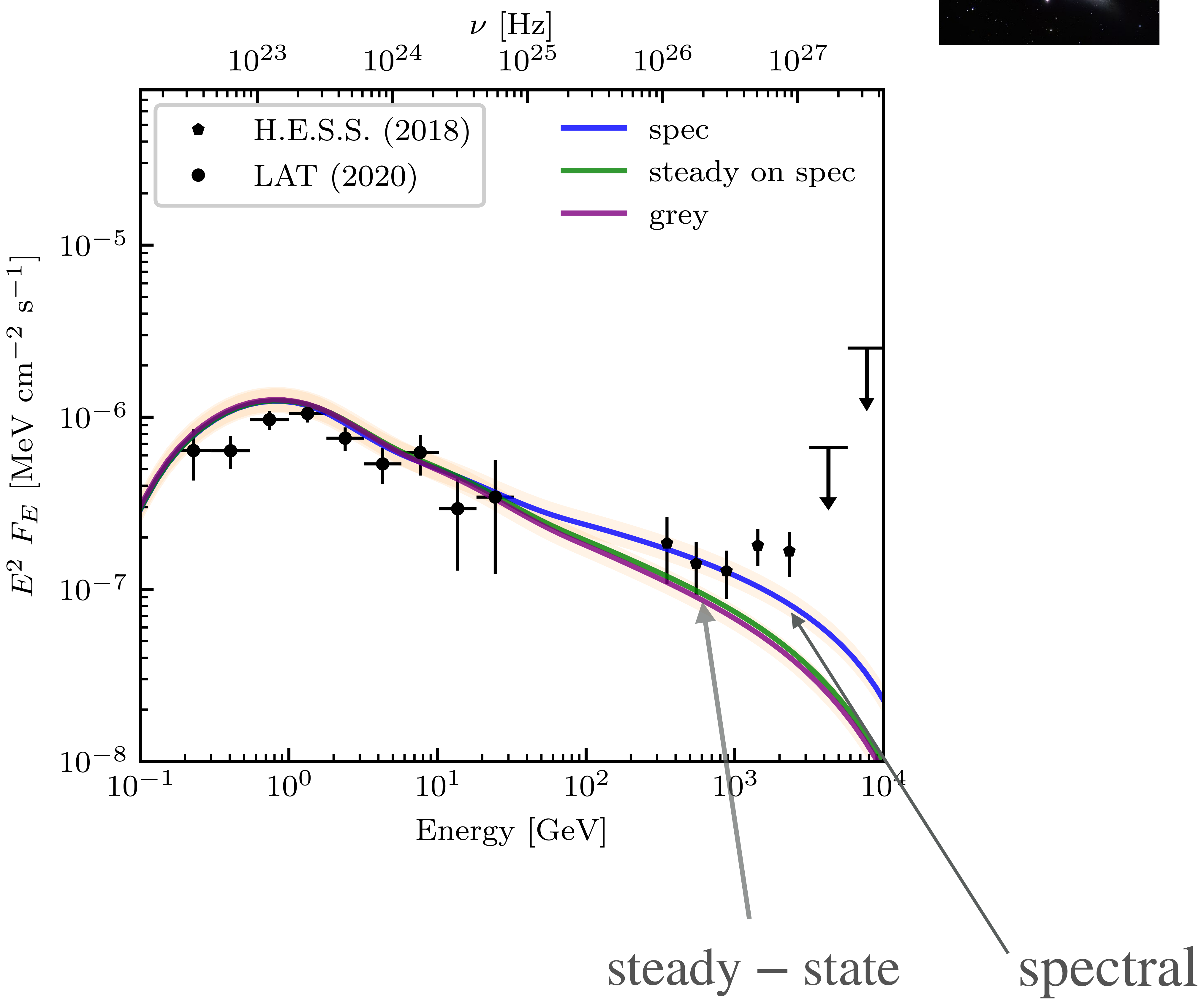


Werhahn+ (2023)

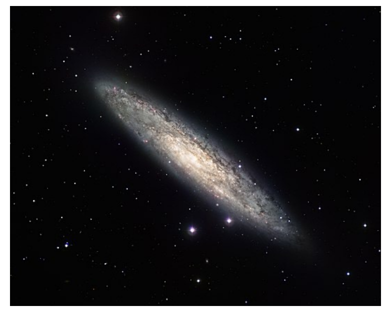
Spectrally resolved CRs in galaxies

CR spectra —> gamma-ray spectra





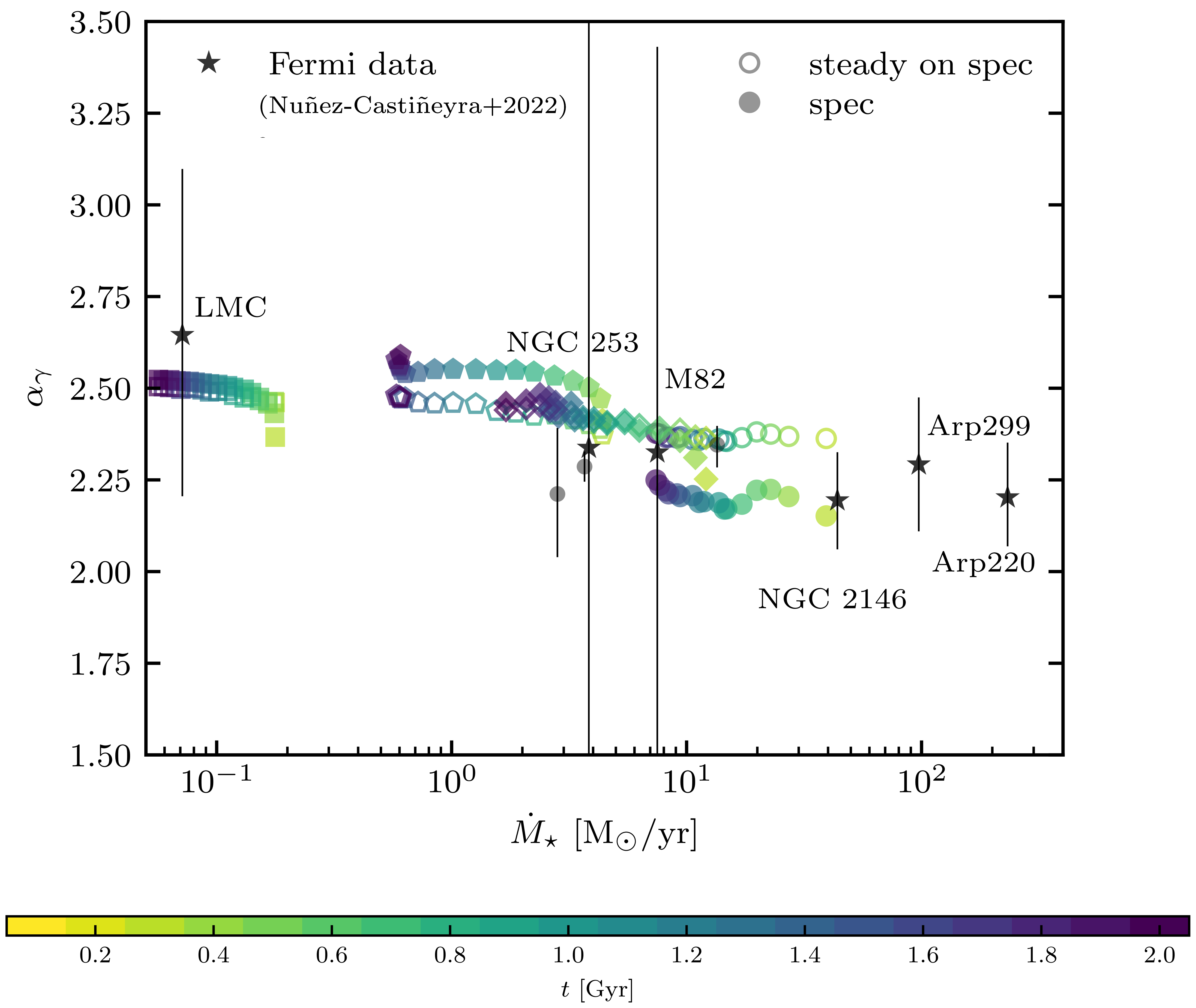
NGC 253

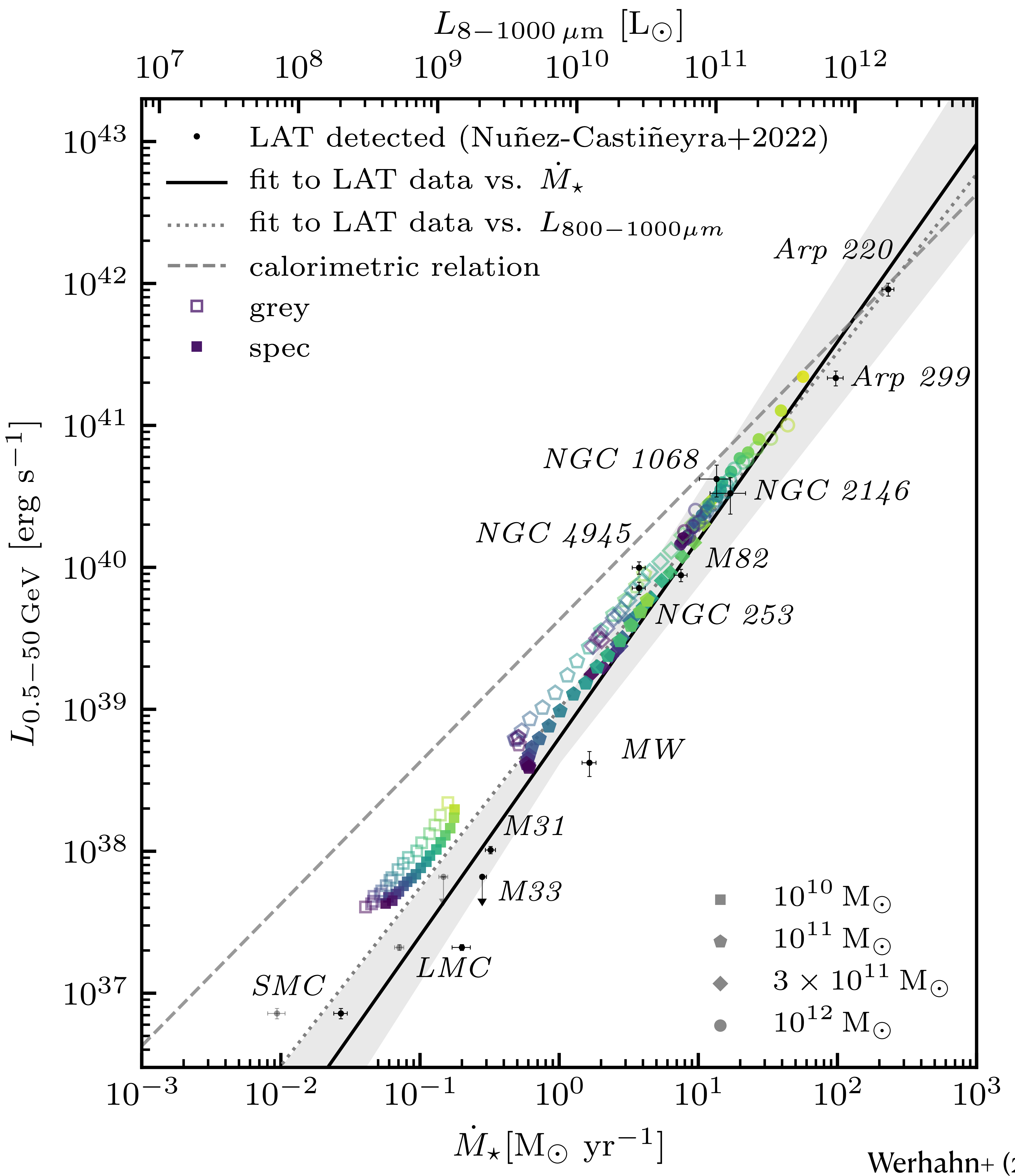


Werhahn+ (2023)

Spectrally resolved CRs in galaxies

spectral index (slope) α_γ (5 GeV)

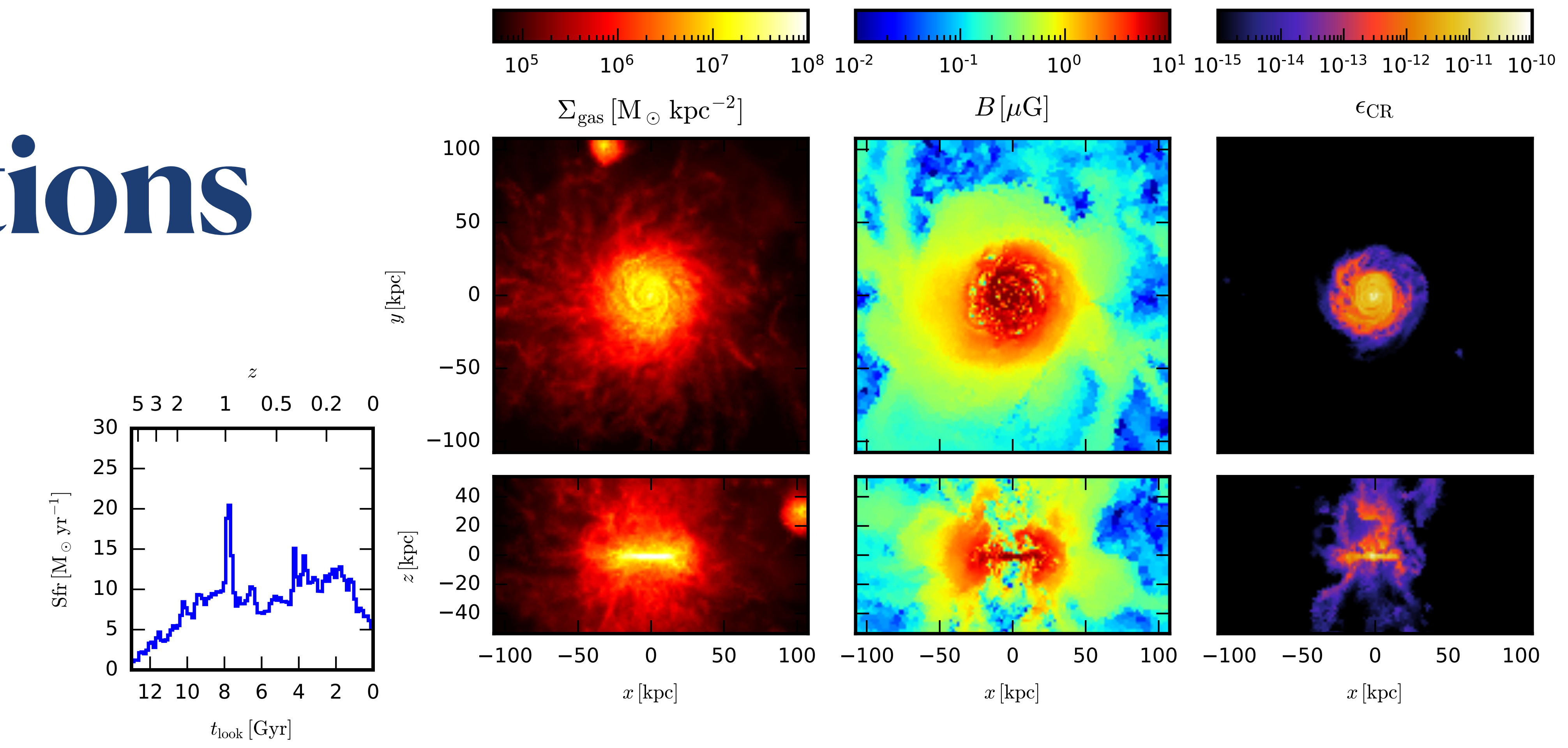




Werhahn+ (2023)

Maria Werhahn

CRs in cosmological zoom simulations



Auriga zoom simulations ($M_{200} = 10^{10}\ -\ 10^{13}\,\mathrm{M}_\odot$)
with grey CRs (Alfvén cooling, anisotropic diffusion)
—> emission from CRAYON+

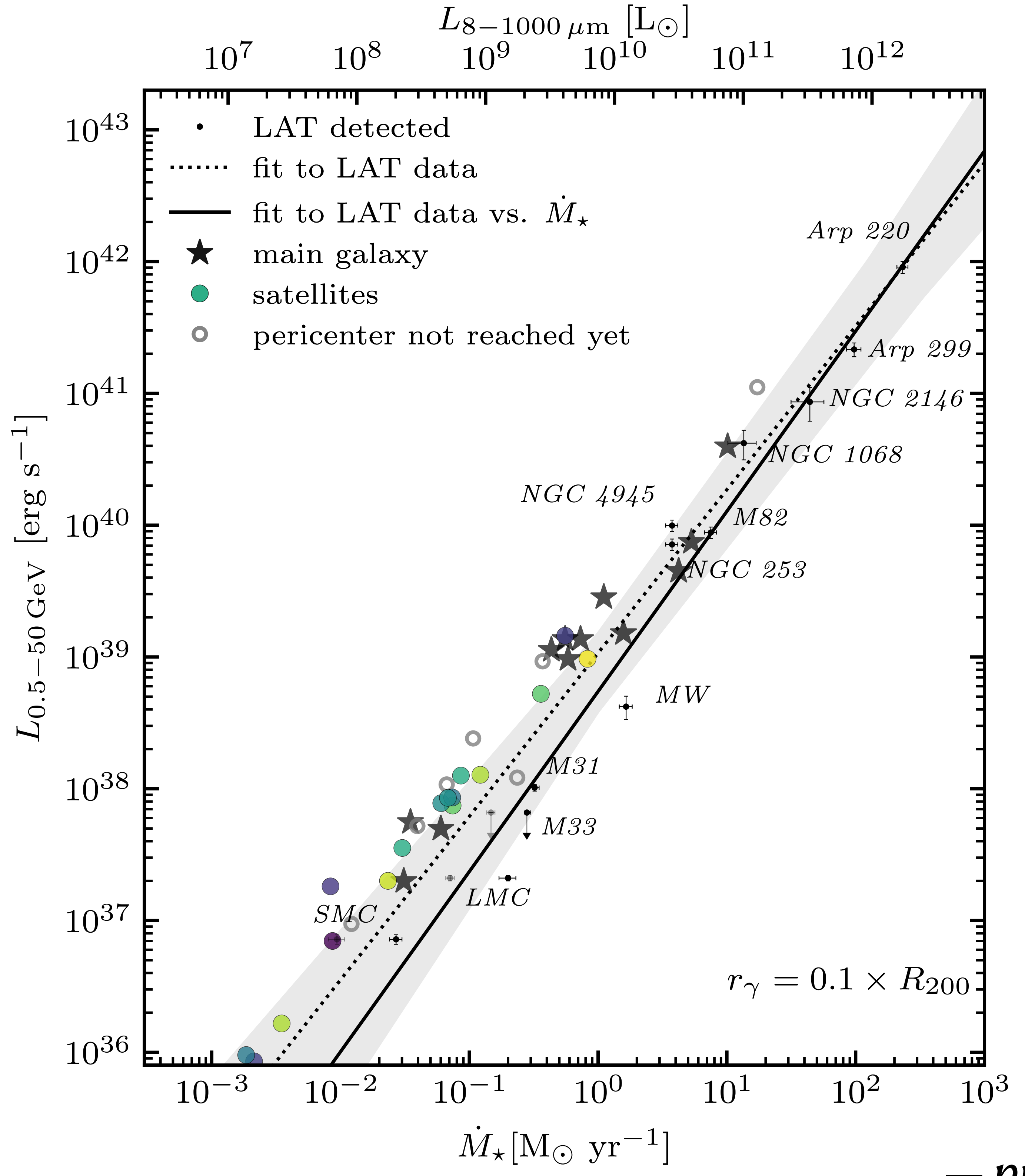
✔ more realistic environment and star-formation history

✔ study emission properties as function of redshift & environment

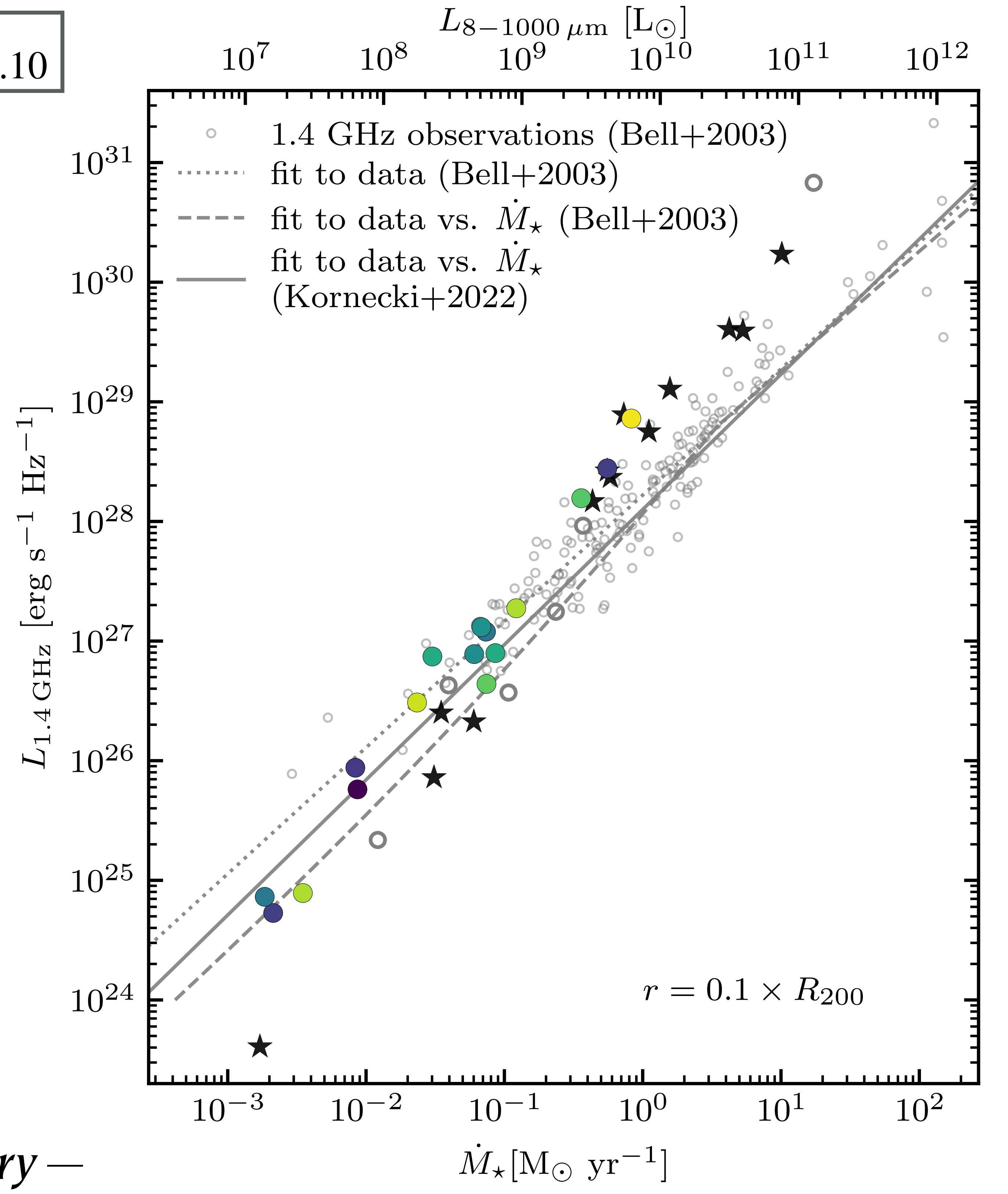
—> study isolated dwarfs vs. satellites!

but:

- resolution
- complicated environment...
  - considered radius matters?
  - satellites vs. dwarfs: does interaction with host halo matter?



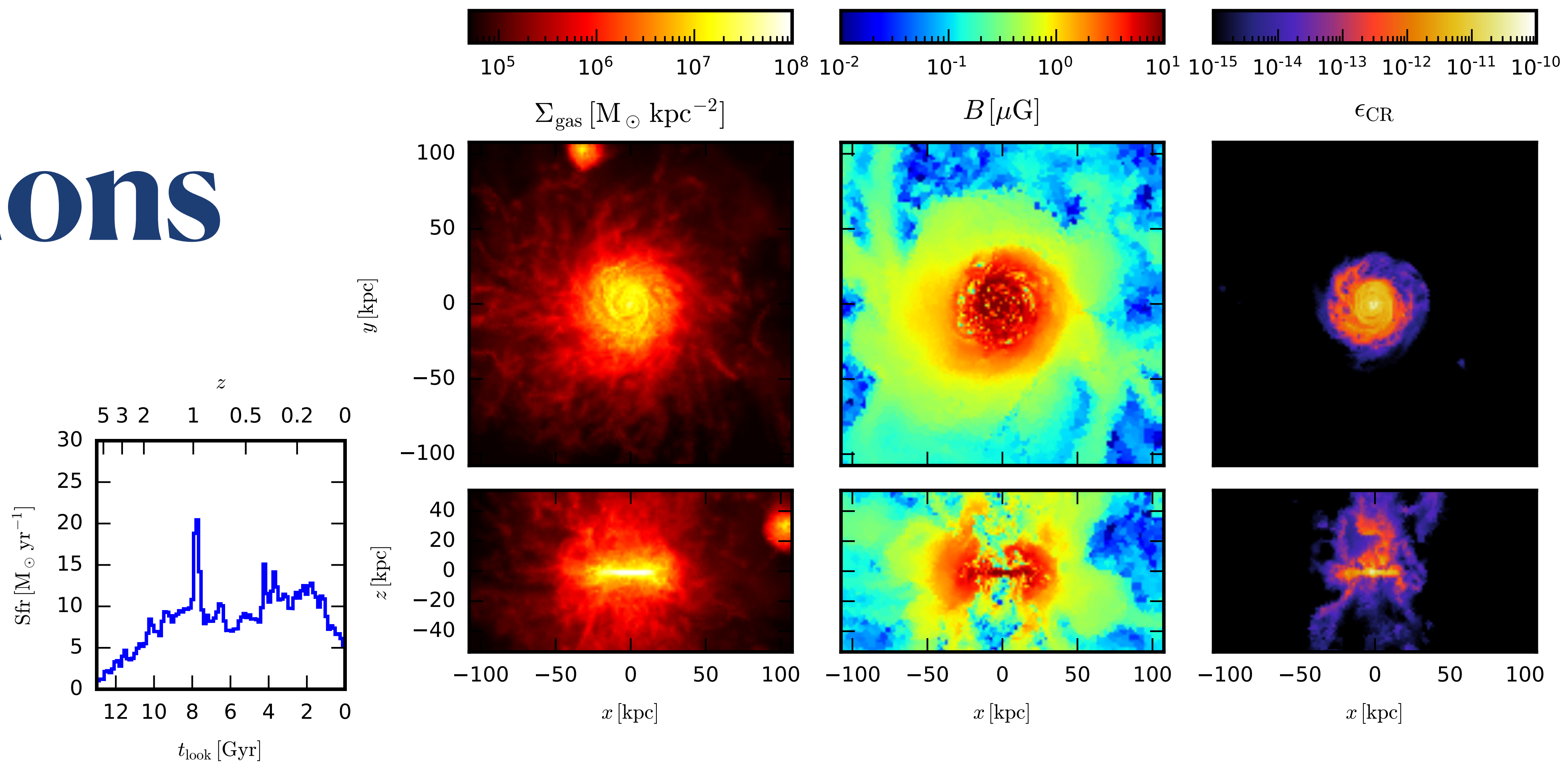
$\zeta_{\rm SN} = 0.10$



— *preliminary* —

Maria Werhahn

CRs in cosmological zoom simulations



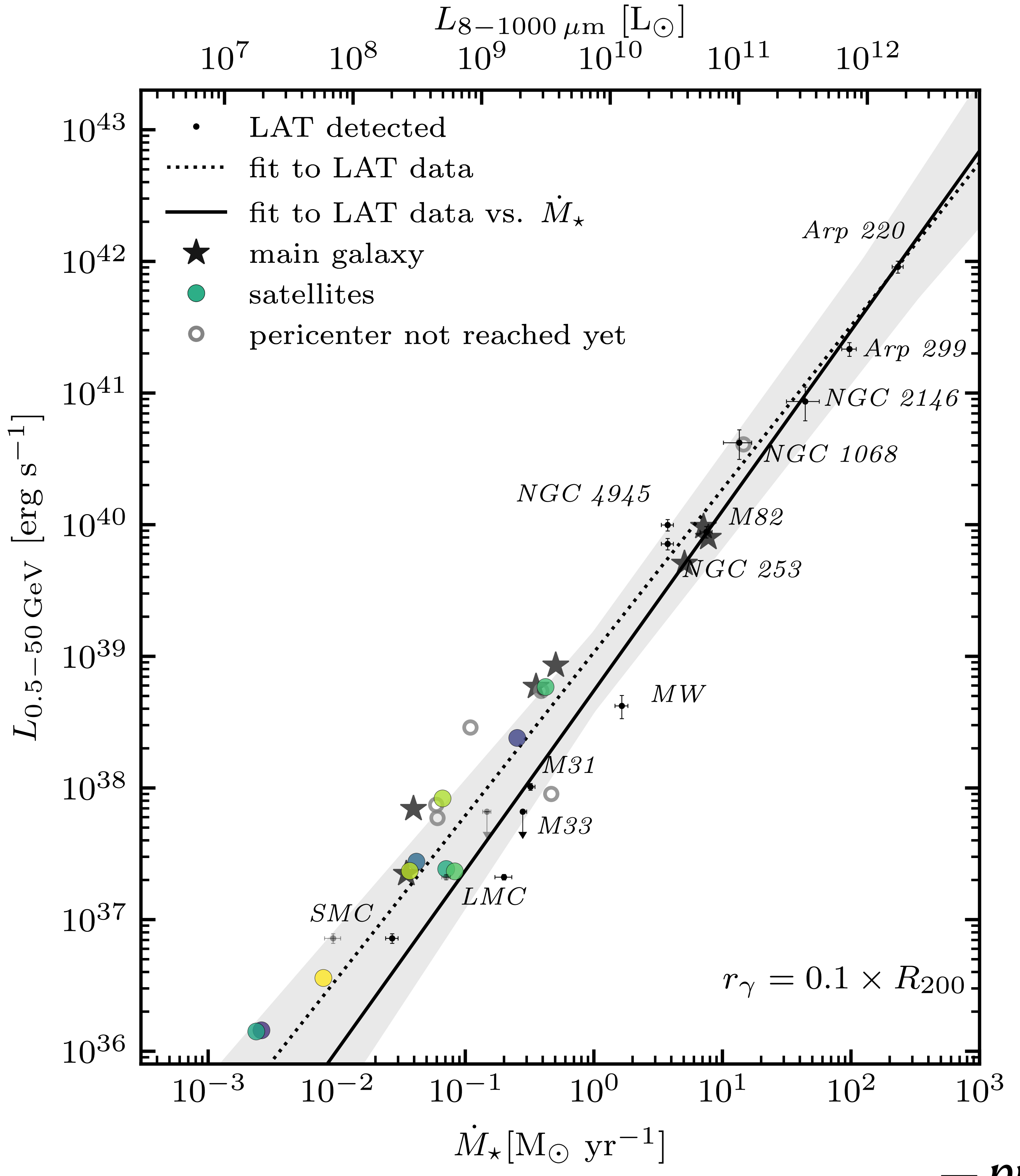
Auriga zoom simulations ($M_{200} = 10^{10}\ -\ 10^{13}\,\mathrm{M}_\odot$)
with grey CRs (Alfvén cooling, anisotropic diffusion)
—> emission from CRAYON+

- ✔ more realistic environment and star-formation history
- ✔ study emission properties as function of redshift & environment

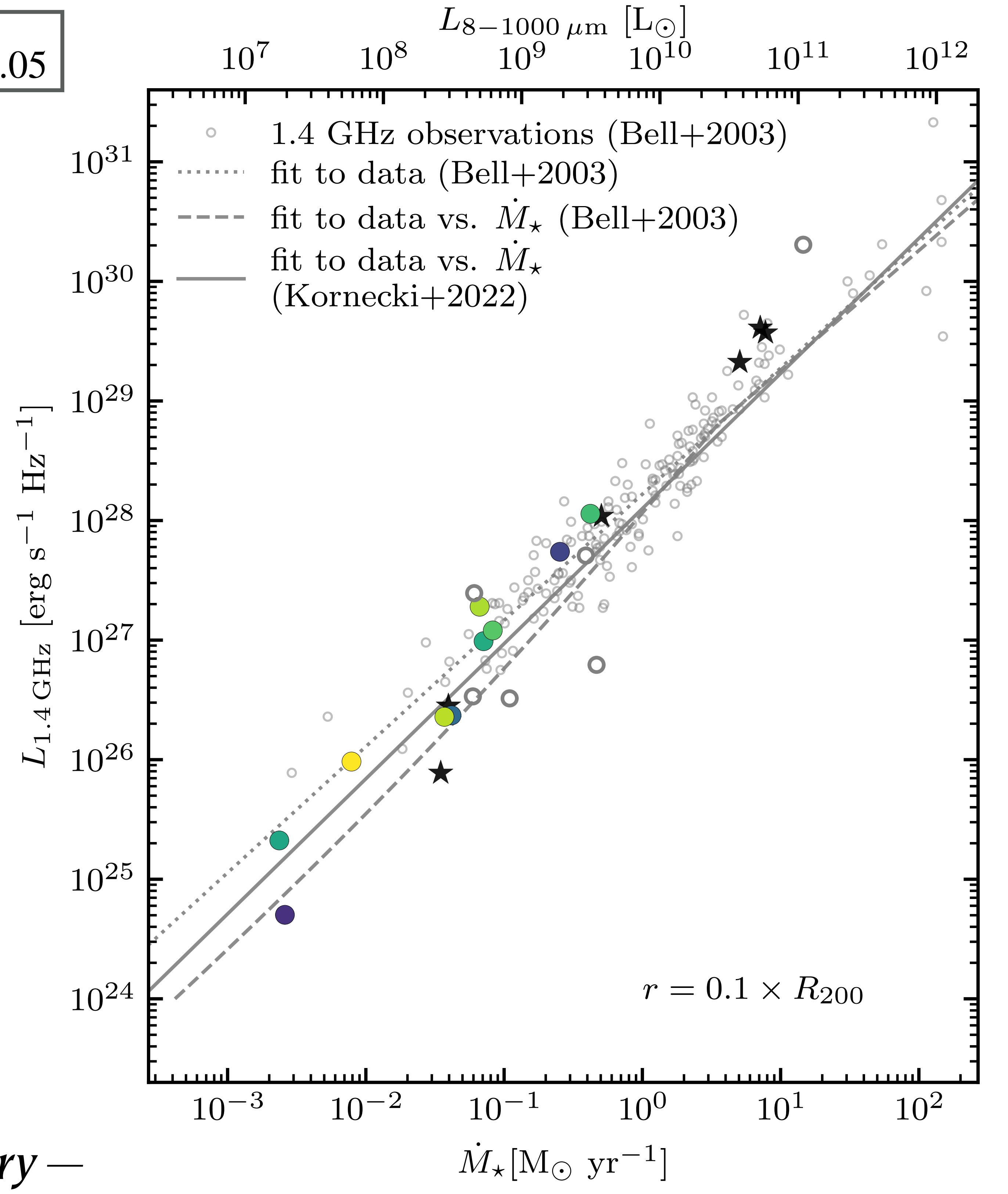
—> study isolated dwarfs vs. satellites!

but:

- resolution
- complicated environment...
  - considered radius matters?
  - satellites vs. dwarfs: does interaction with host halo matter?



$\zeta_{\rm SN} = 0.05$

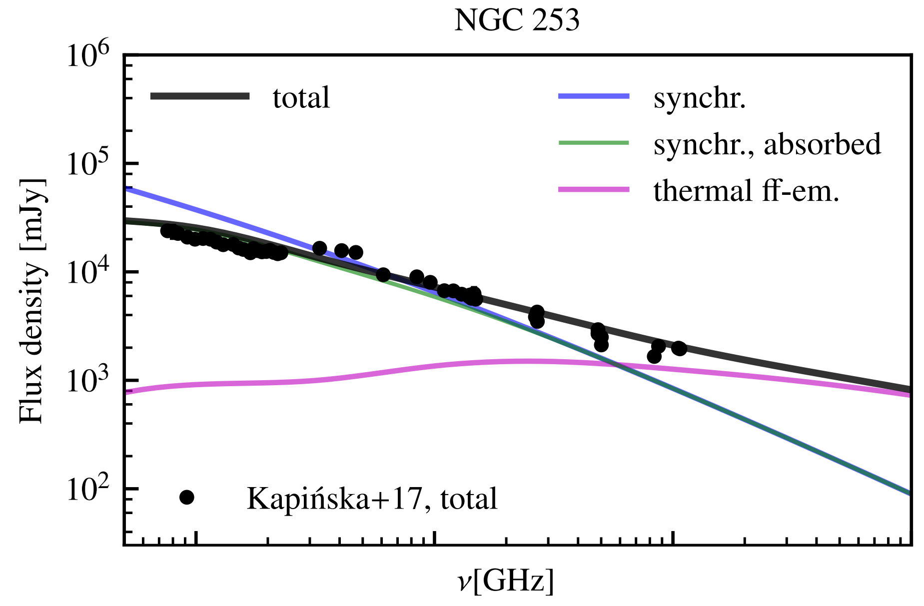


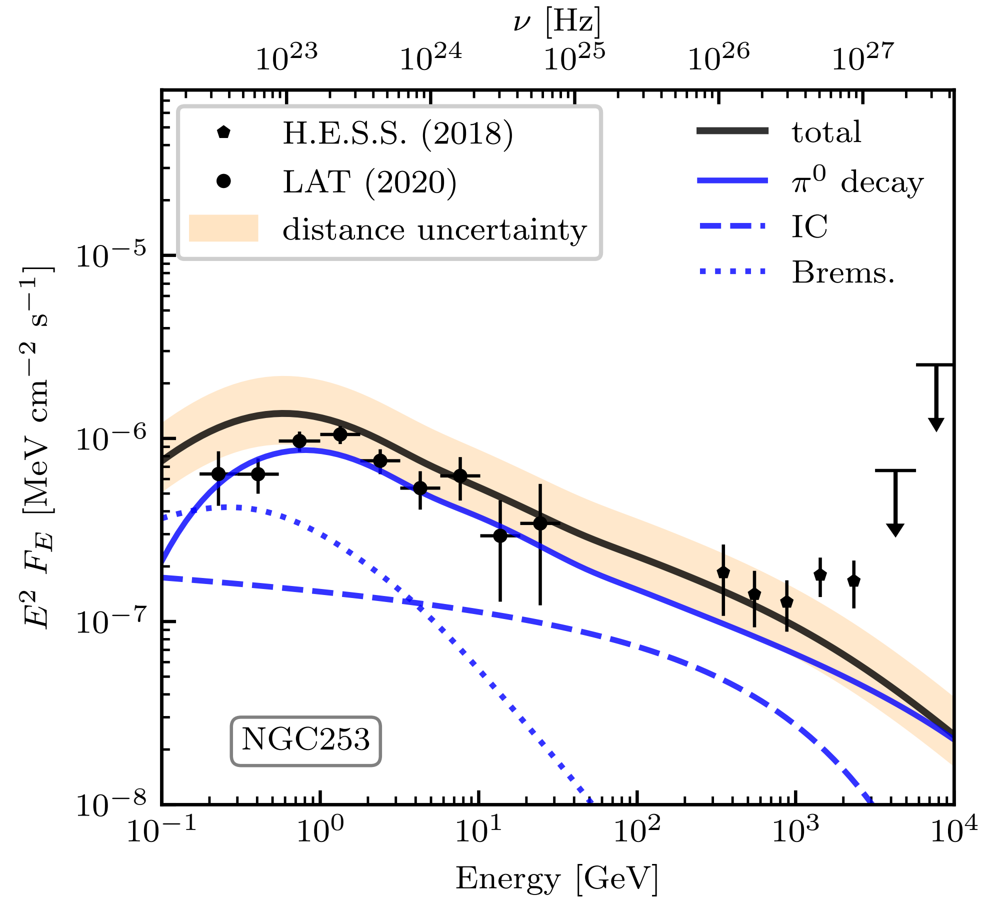
— *preliminary* —

Summary

Steady-state CR spectra in 3D MHD simulations:

- **Radio emission**:
  - reproduce FIR-radio relation (dominated by primary emission)
  - IC & sync. losses dominate (at high energies) —> flat radio spectra: thermal contribution
- **Gamma-ray emission**: match FIR-gamma-ray relation & spectra
  - low SFR: diffusion relevant
  - high SFR: close to calorimetric limit —> energy left for feedback
- **Spectral simulations of CR protons**
  —> required for modelling of spatially resolved high-energy gamma-rays

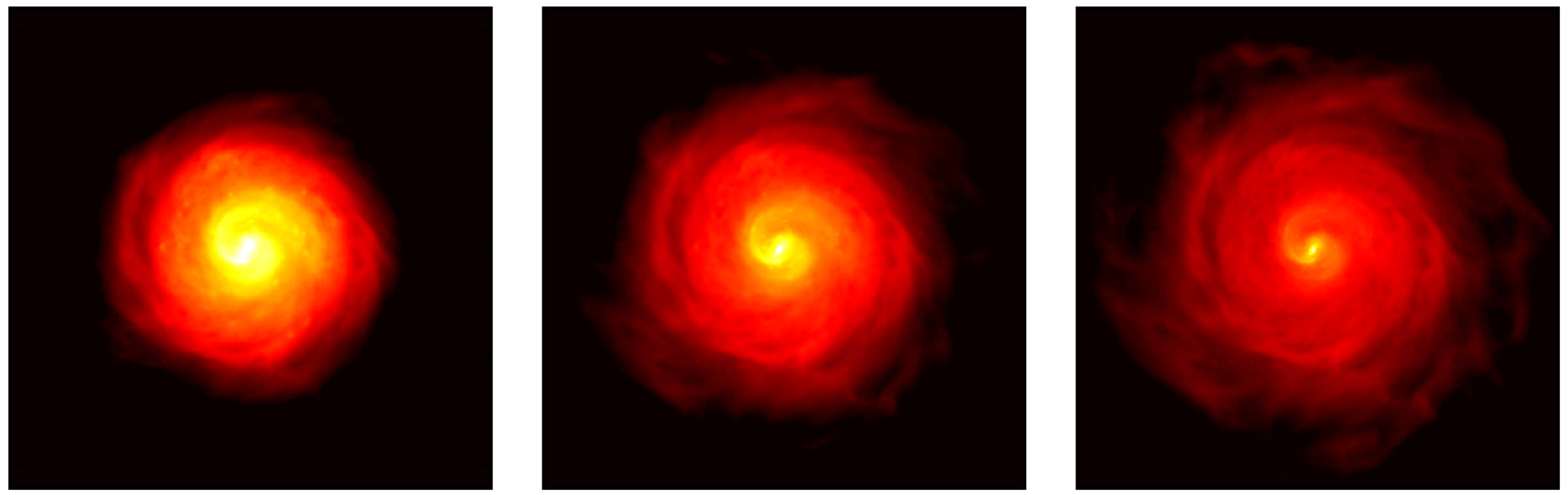




Ongoing work:

- **cosmological simulations** —> more realistic SFH
  —> study dwarfs vs. satellites
  —> radio & gamma-rays as a function of z
- live modelling of **CR electrons (CREST)**
  —> study dynamical regions (outflows)

γ−ray emission at different energies, t = 1.00 Gyr, M_{200} = 3 $\times 10^{11}$ M$_\odot$



Thanks for your attention!