Constraining Cosmic Ray Feedback in Galaxy Evolution

Maria Werhahn

Rüdiger Pakmor, Volker Springel,
Freeke van de Voort, Rebekka Bieri, Rosie Talbot,
Christoph Pfrommer, Philipp Girichidis,
Joseph Whittingham, Léna Jlassi, H.-H. Sandy Chiu

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MAX PLANCK INSTITUTE
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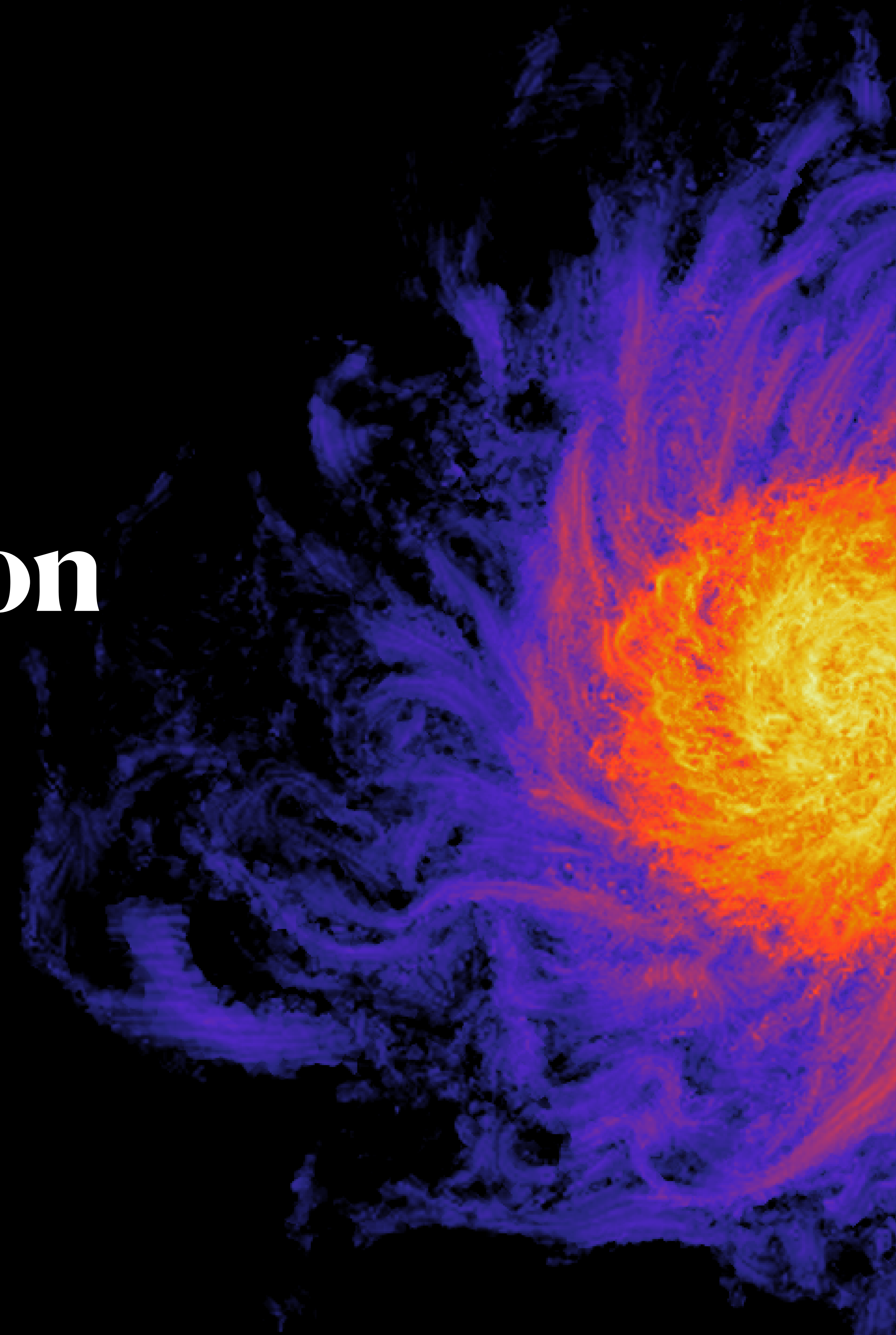
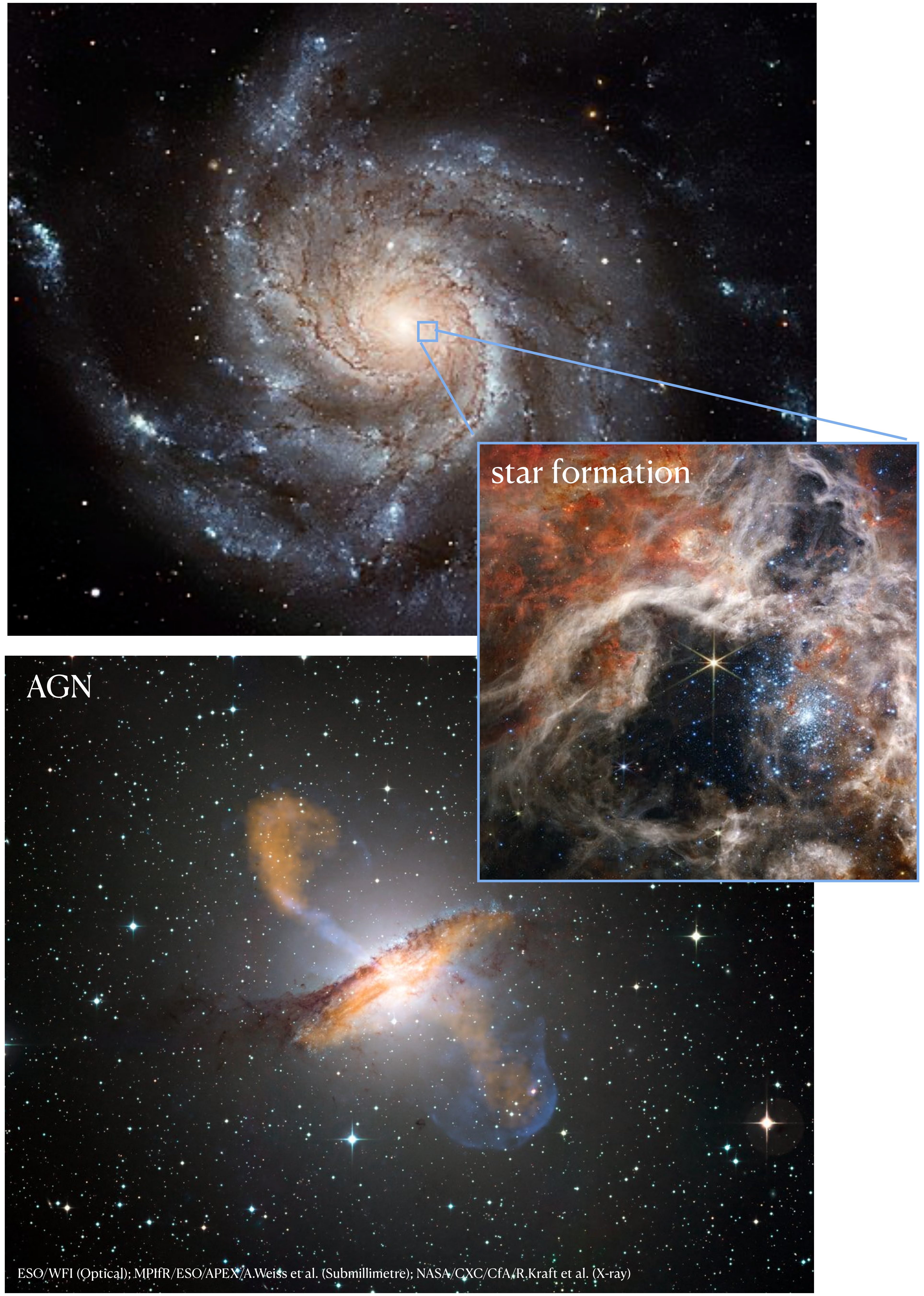
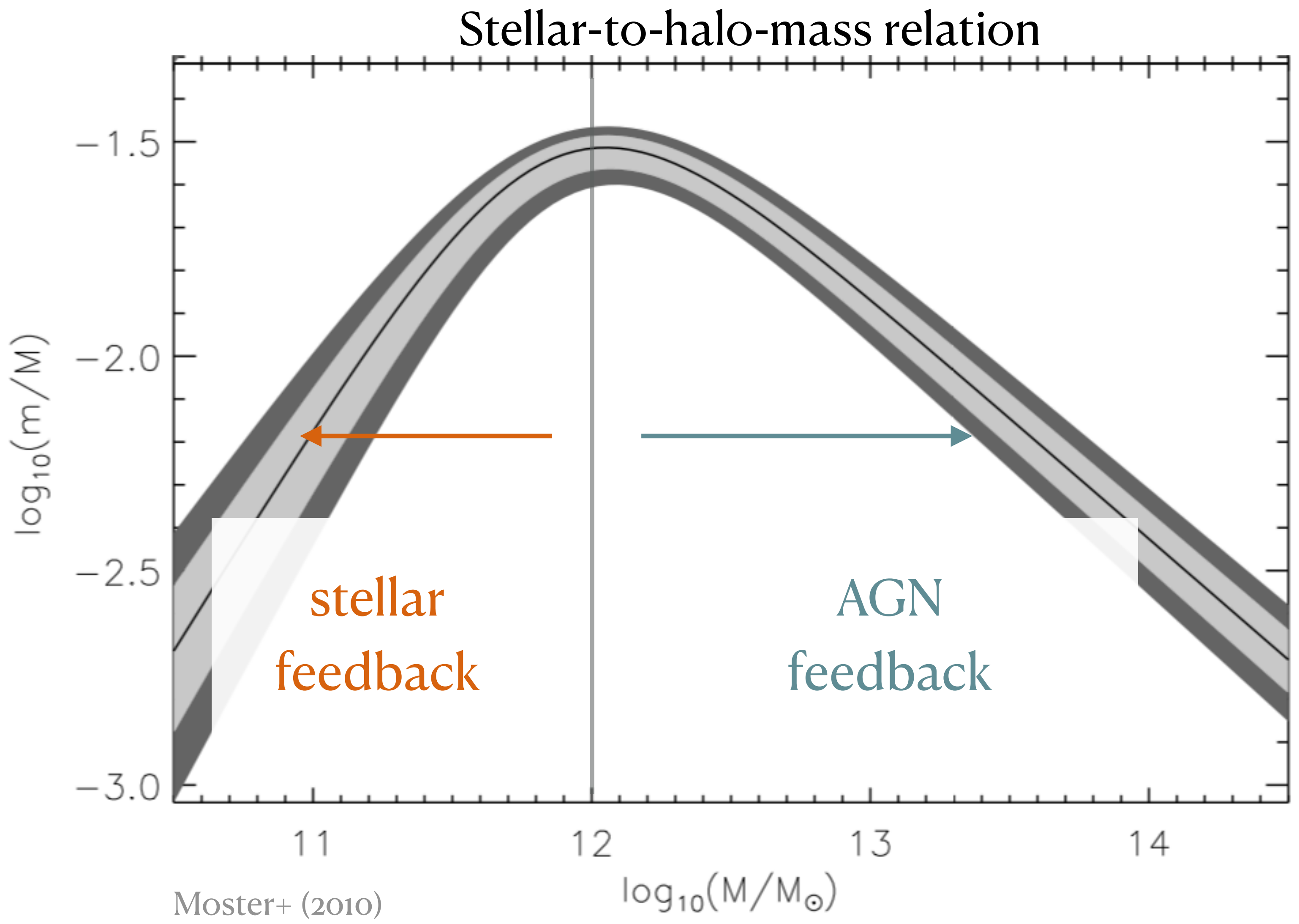


Cosmic Rays in Galaxy Formation





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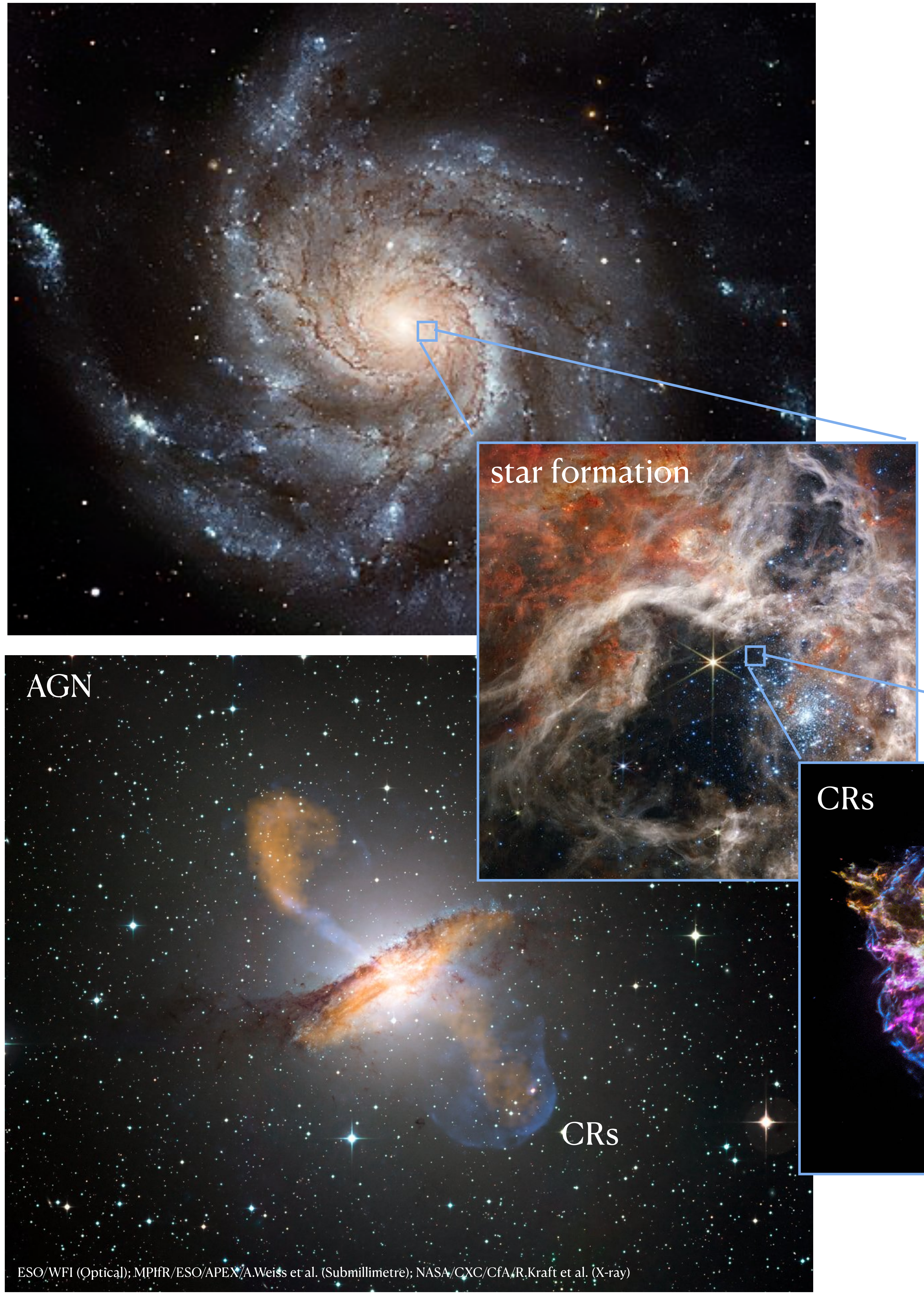

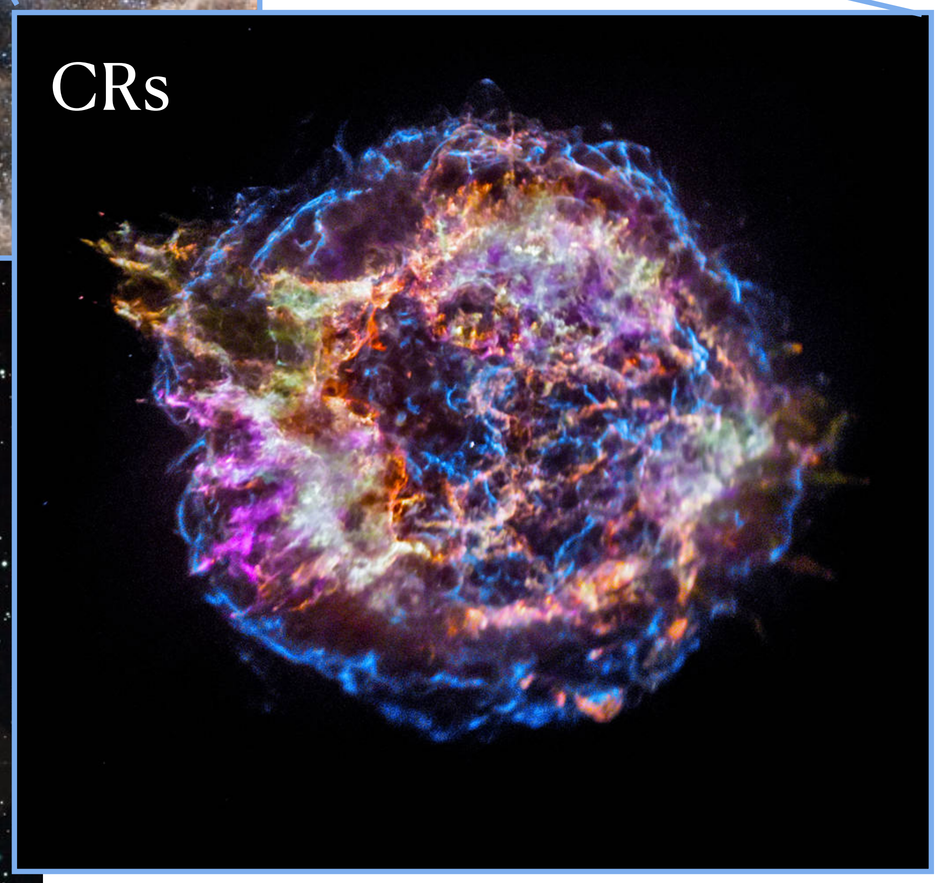

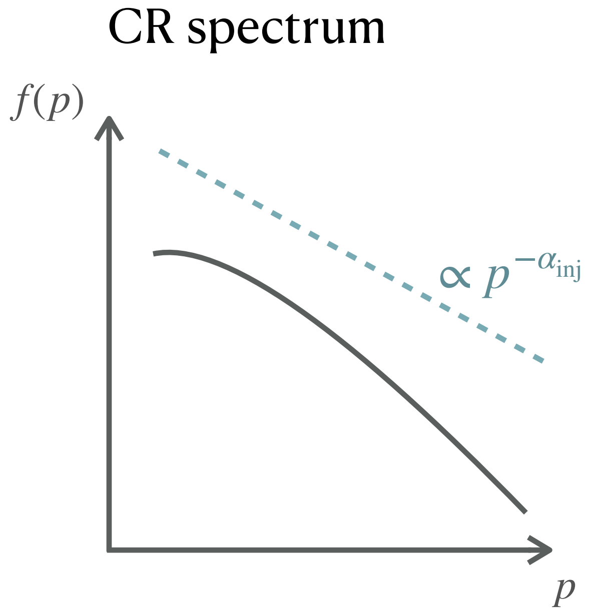

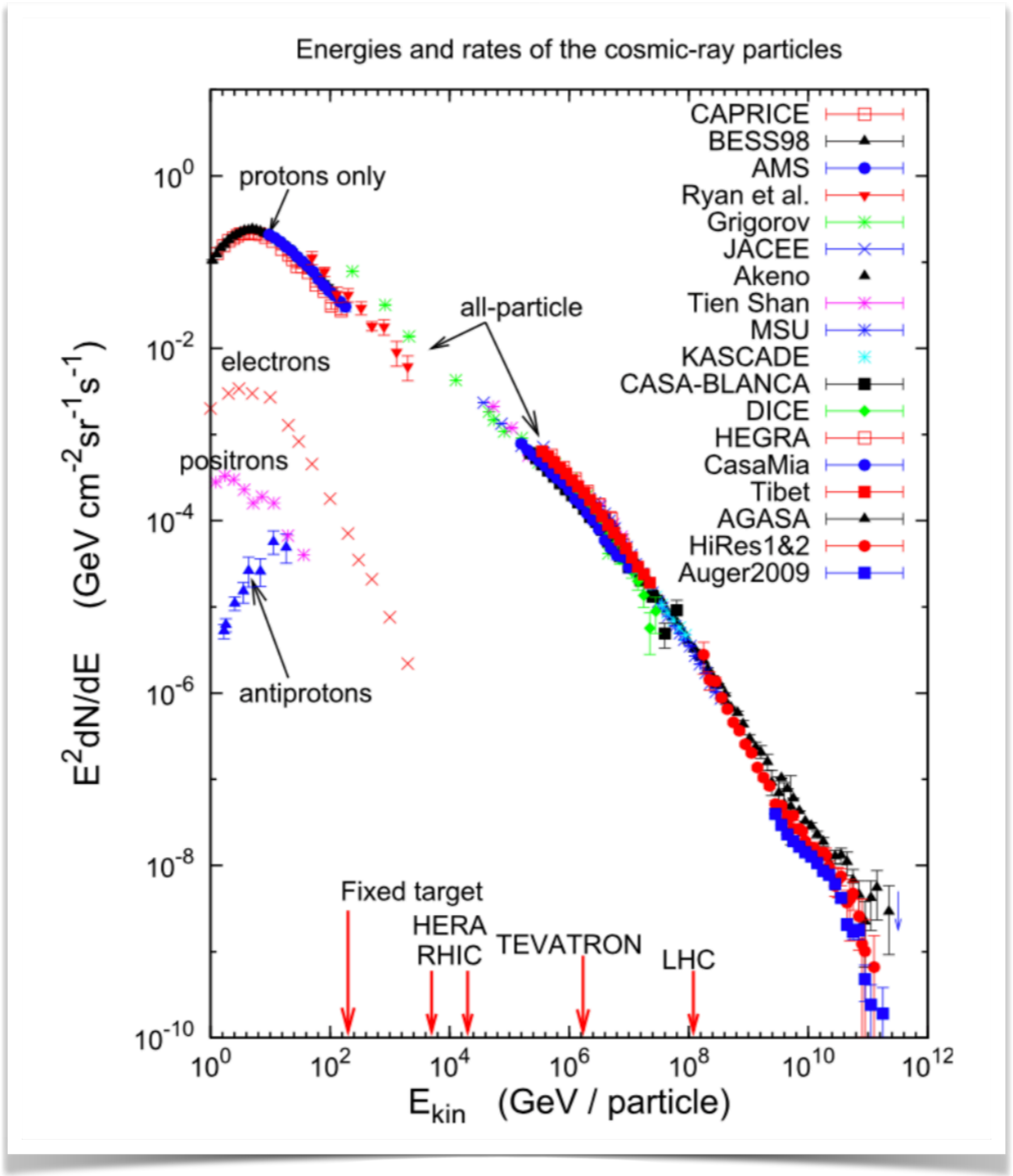

$\varepsilon_{\rm CR} \sim \varepsilon_B \sim \varepsilon_{\rm th} \sim \varepsilon_{\rm kin}$—> feedback agent?

multi-scale problem:

gyro-orbit: $\sim 10^{-6}$ pc << galactic scales (~kpc)

—> *very challenging to model in galaxy simulations*

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Modelling Cosmic Rays in Galaxies

How can we constrain CR feedback?

How much **energy** —> CRs?

How to model CR **transport**?

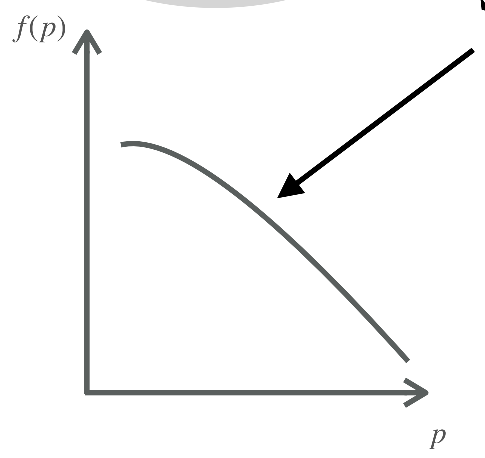
Which energy-**losses**?

simulations

effective models

$\zeta_{\mathrm{SN}}, \kappa, \Lambda_{\mathrm{CR}}$

Spectral/grey modelling?



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simulations

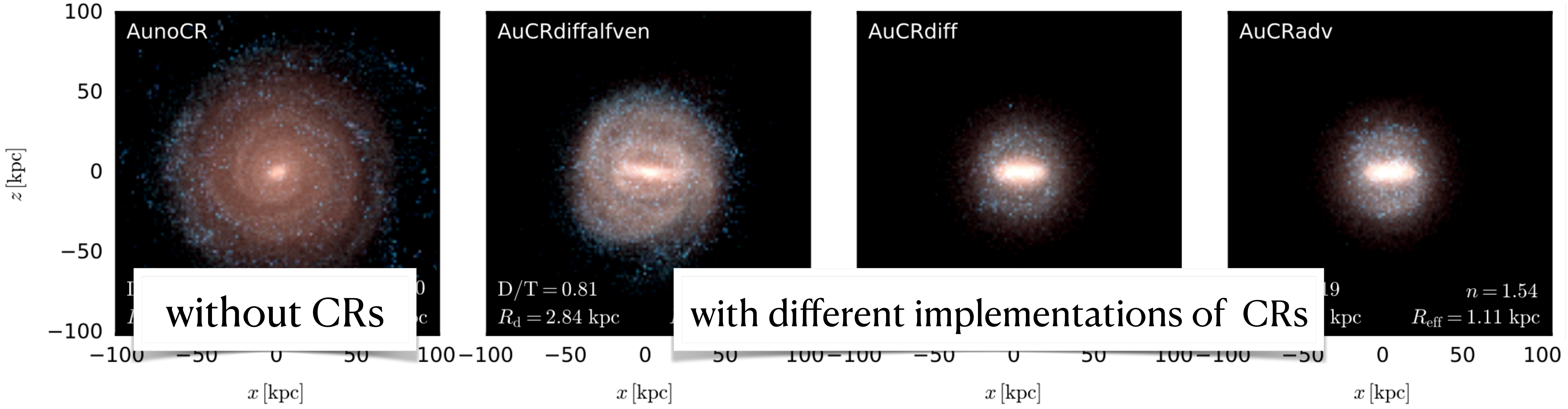
effective models

$\zeta_{SN}, \kappa, \Lambda_{CR}$ →

varying impact on galaxy formation

(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; , Armillotta+ 2021; Hopkins+ 2020,2022; Peschken+ 2021; Girichidis+ 2022, 2024; Thomas+ 2023;2024;Rodríguez Montero+ 2024,...)

- outflows, regulating star formation
- impact on reionisation (Farcy et al. 2025)
- morphology, gas radii (e.g. Buck+2020)
- CGM properties (density, temperature, metallicity, B-field) (e.g. Salem 2016, Ji+2020, Butsky 2022)



Buck+2020

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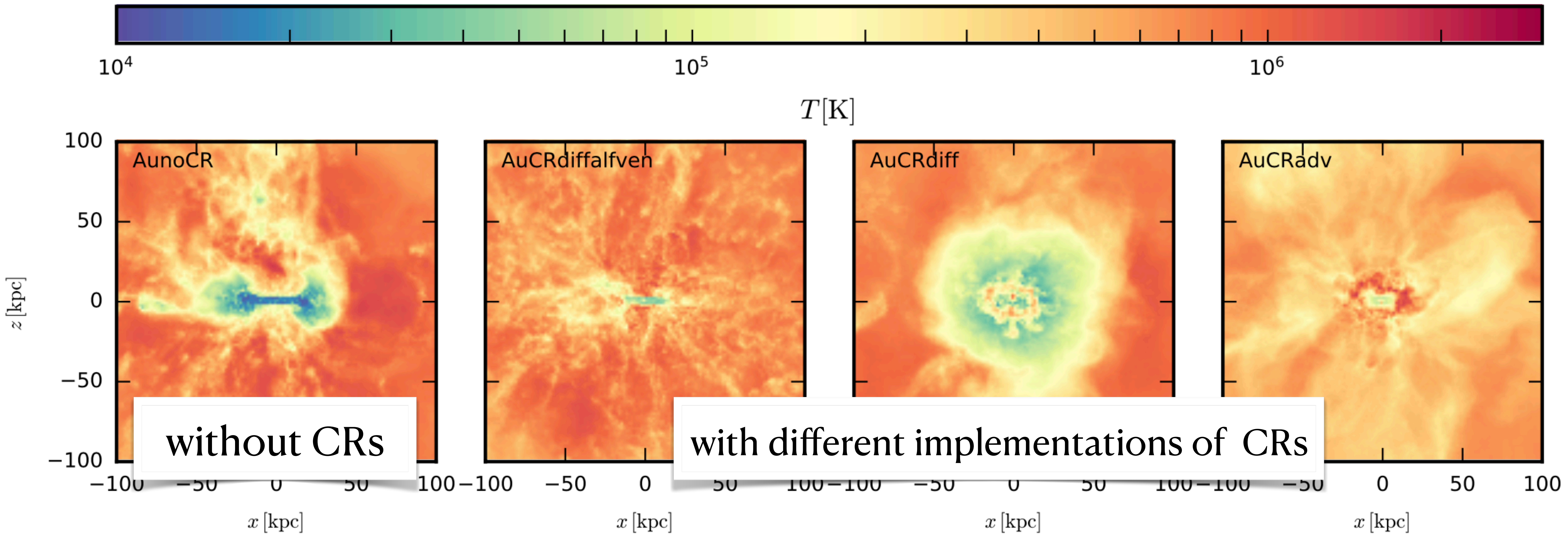

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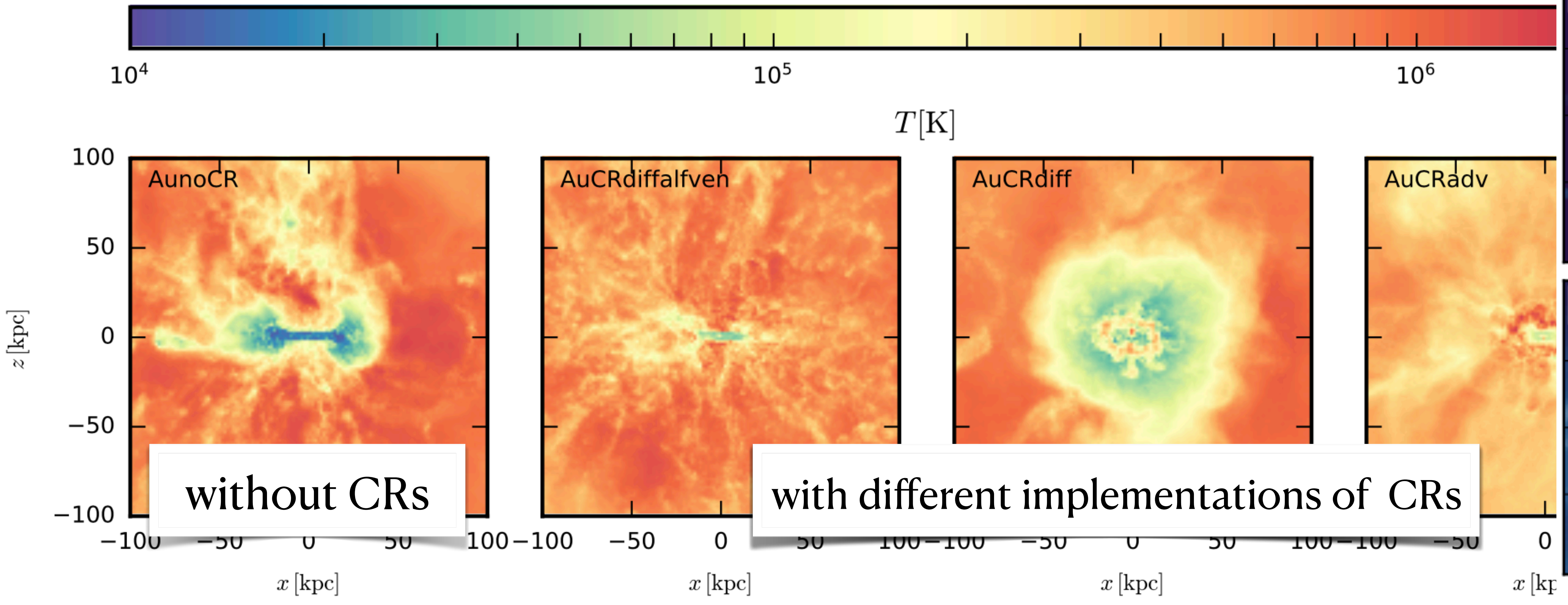

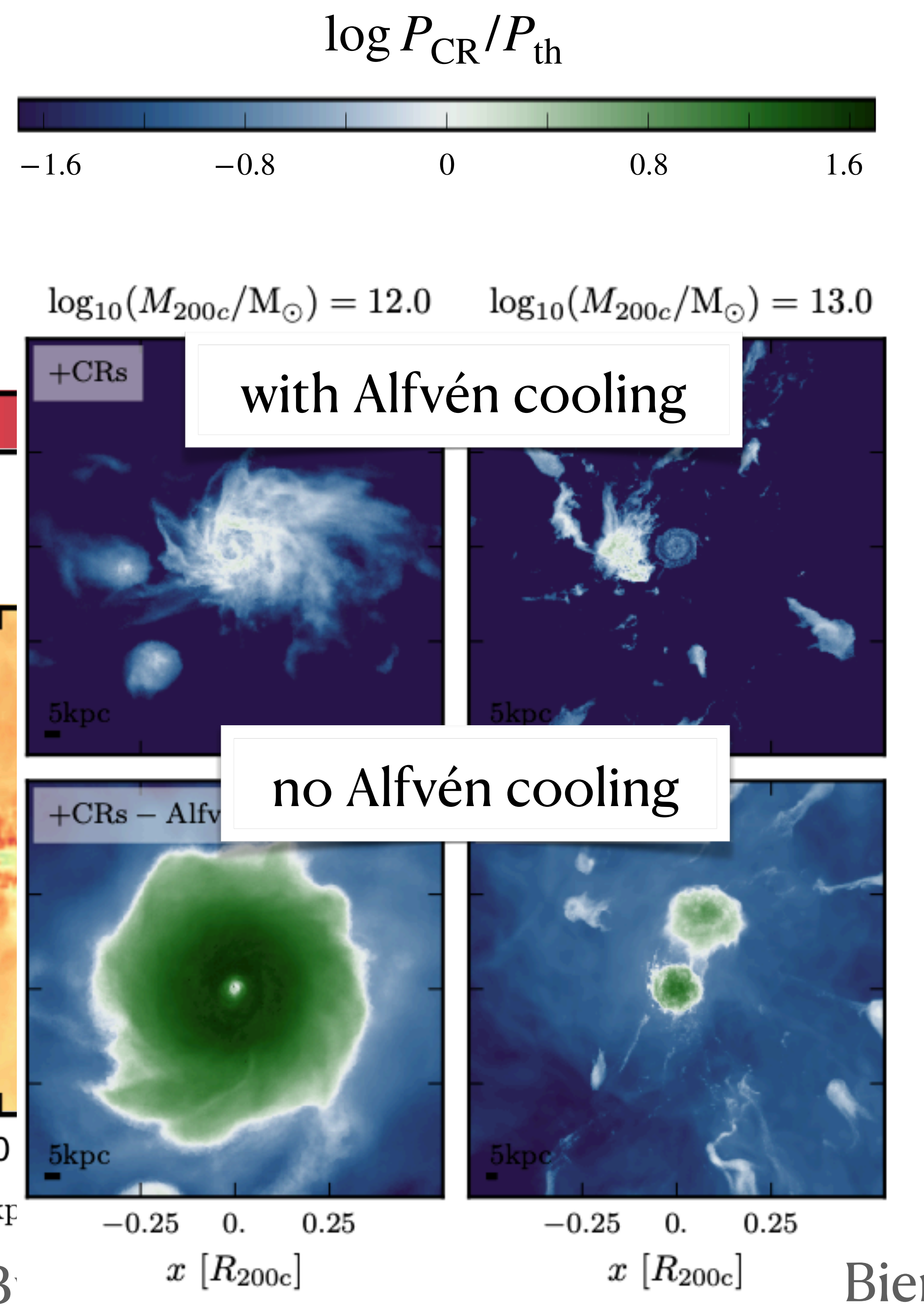

Bieri+ in prep.

Modelling Cosmic Rays in Galaxies

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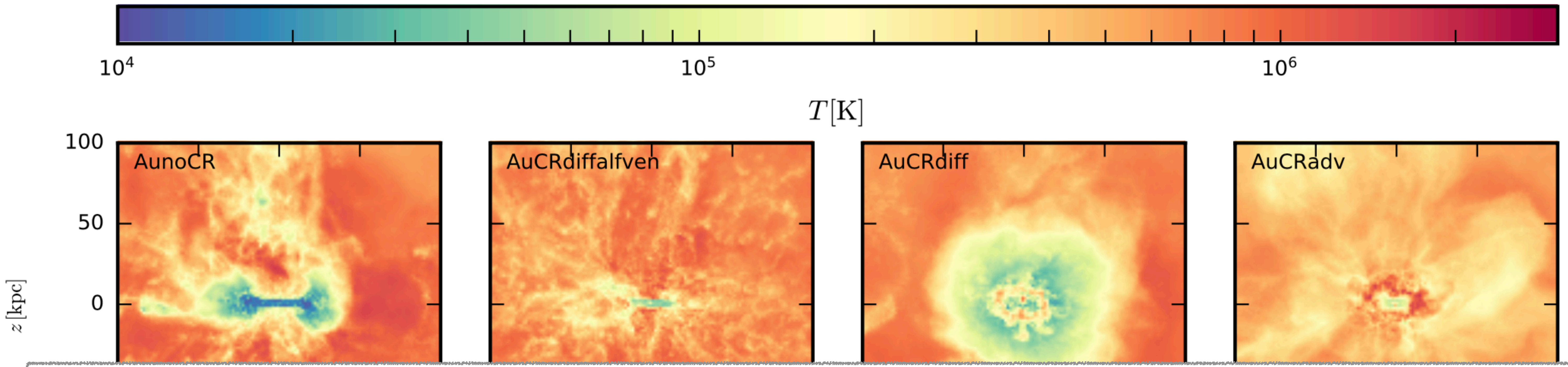
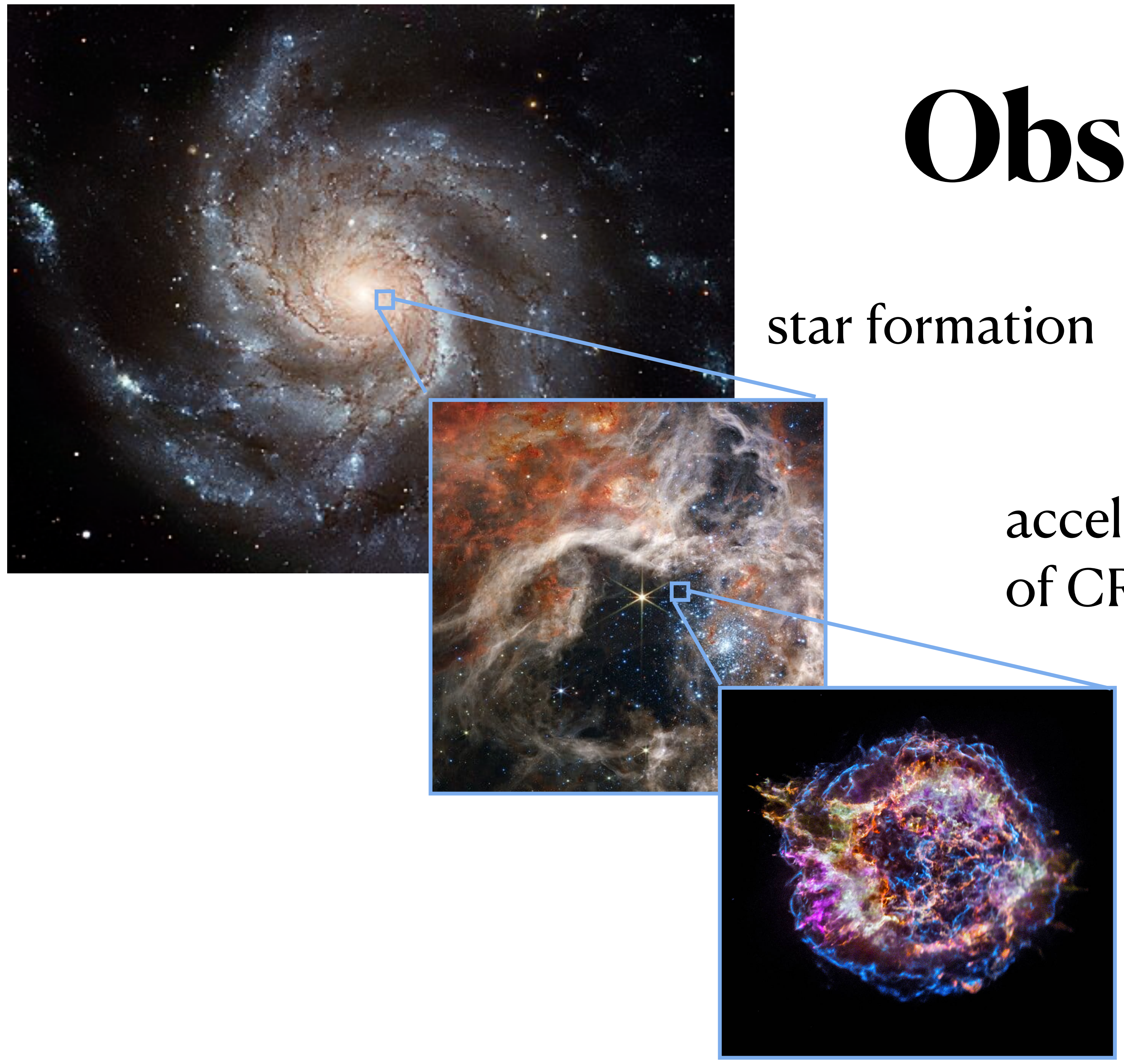
→ ? → observables



need to **forward model CR-related observables**

to clarify **role of CRs in galaxy evolution**

Observational Constraints of CRs

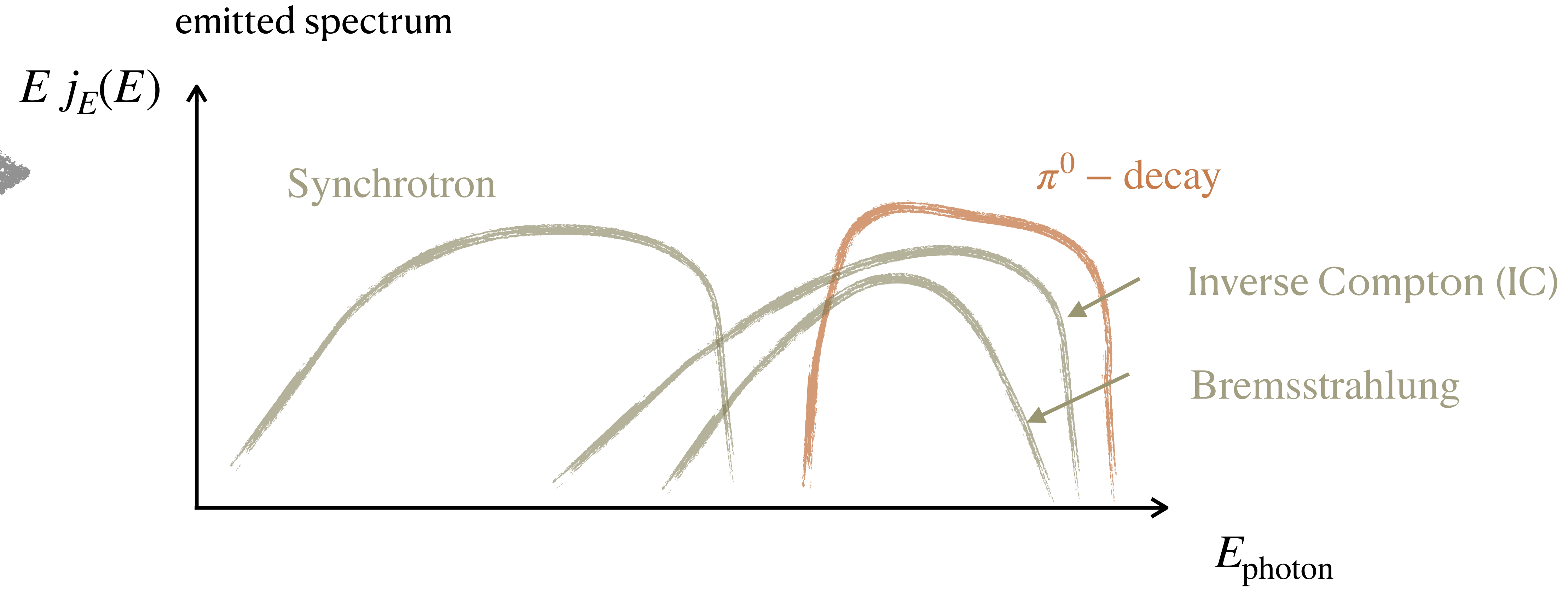


star formation

acceleration of CRs

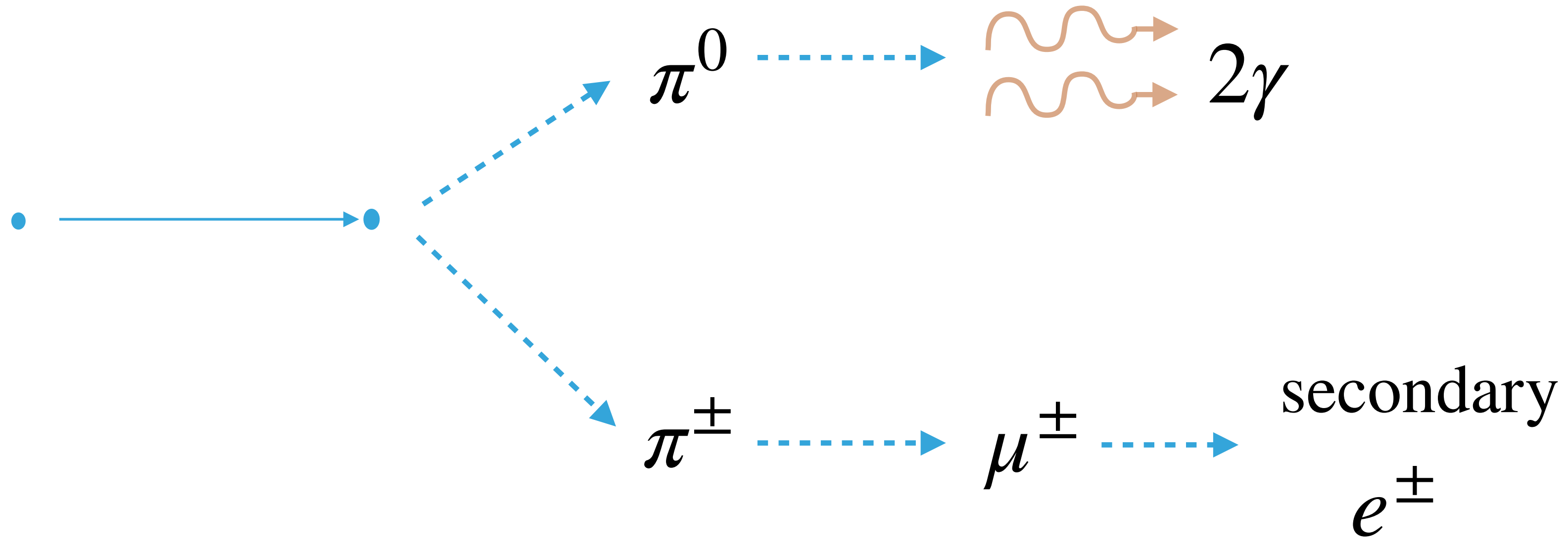
Non-thermal emission

transport/interaction with the ISM



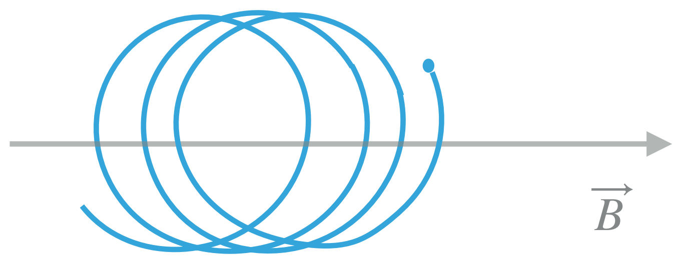
CR protons:

- pion decay

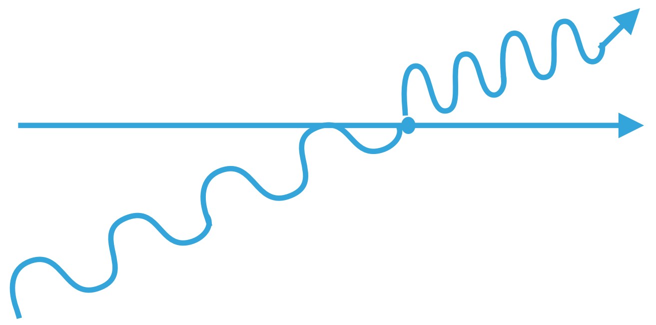


CR electrons (primary + secondary):

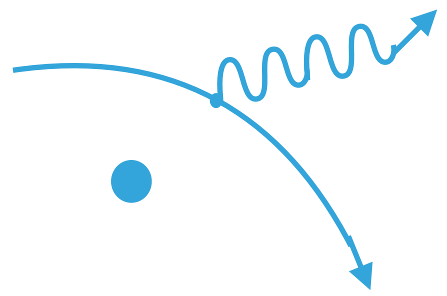
- Synchrotron emission



- Inverse Compton (IC) emission



- Bremsstrahlung



Observational Constraints of CRs

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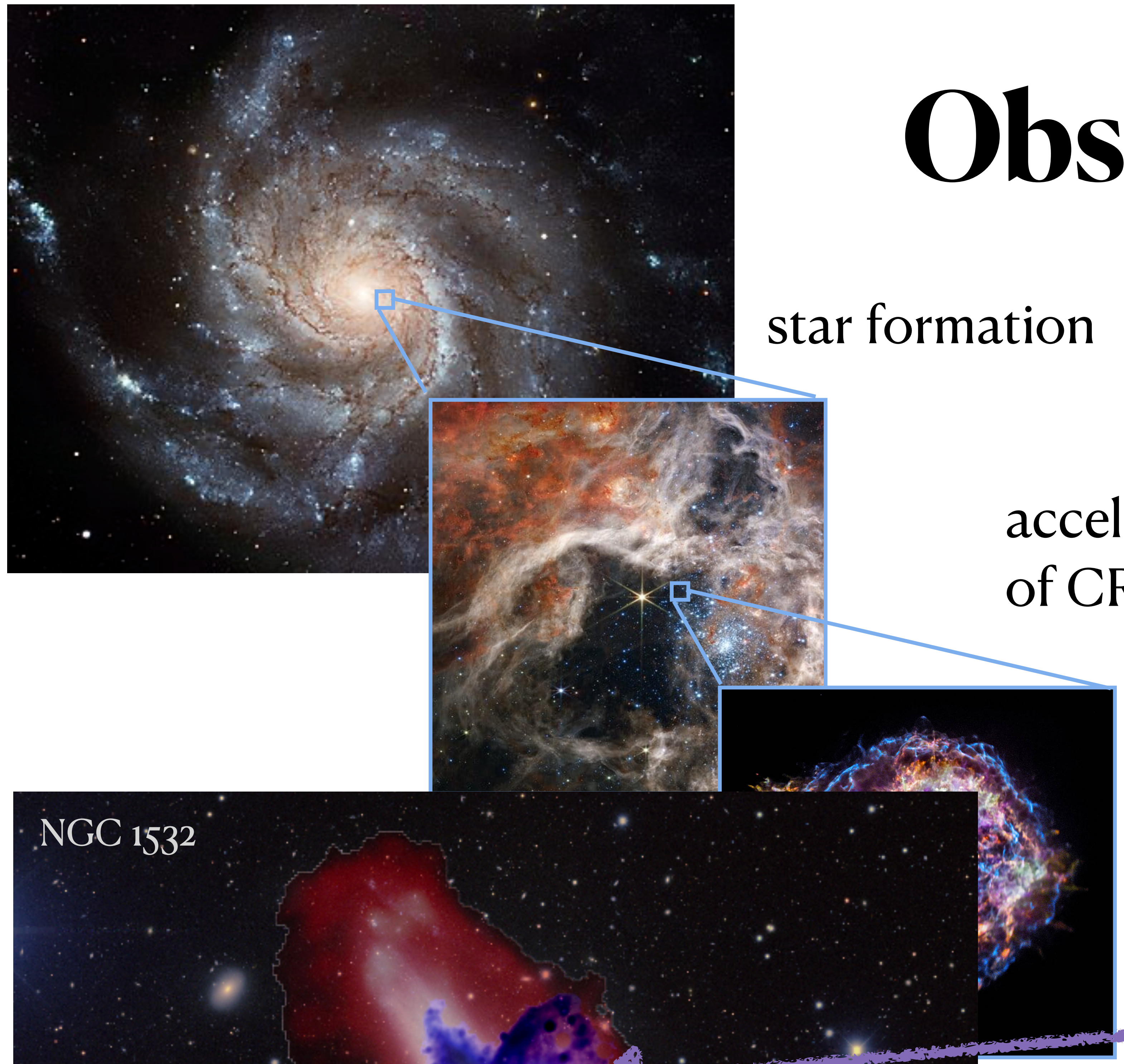

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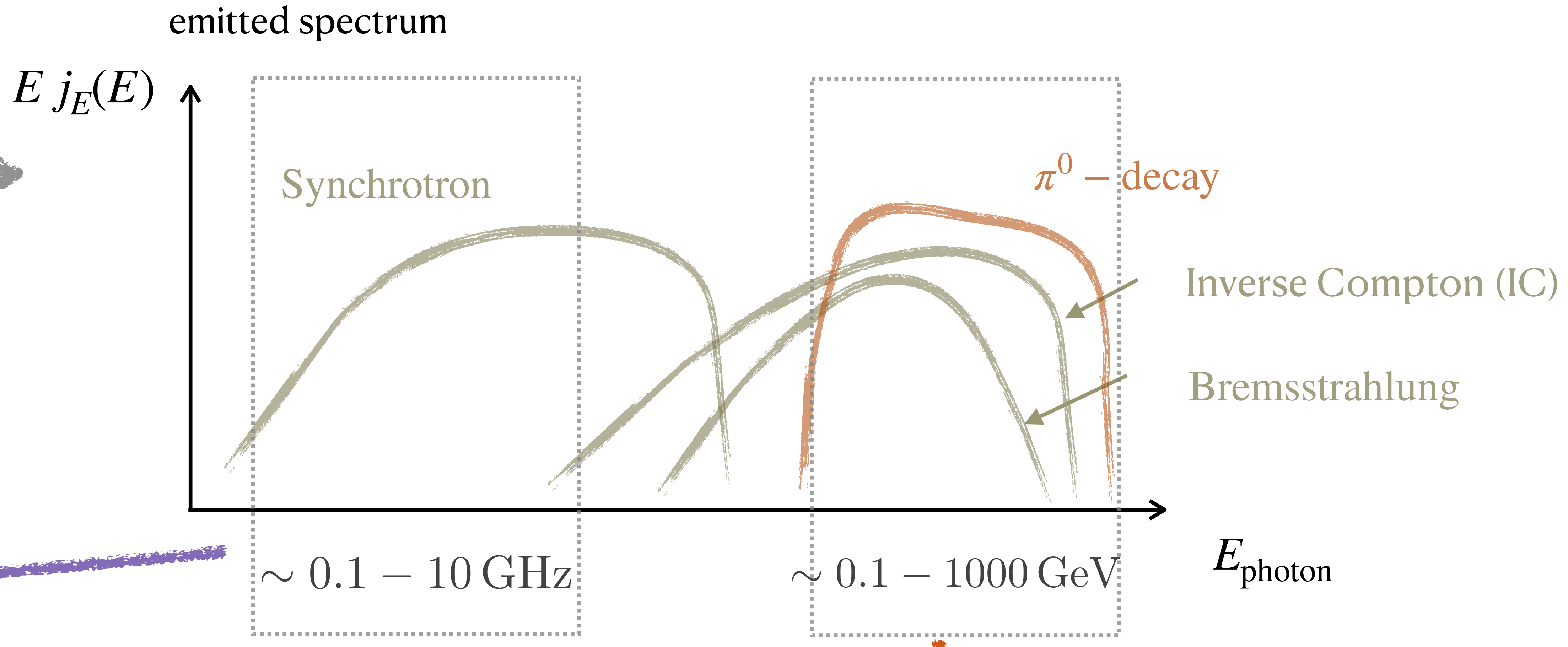
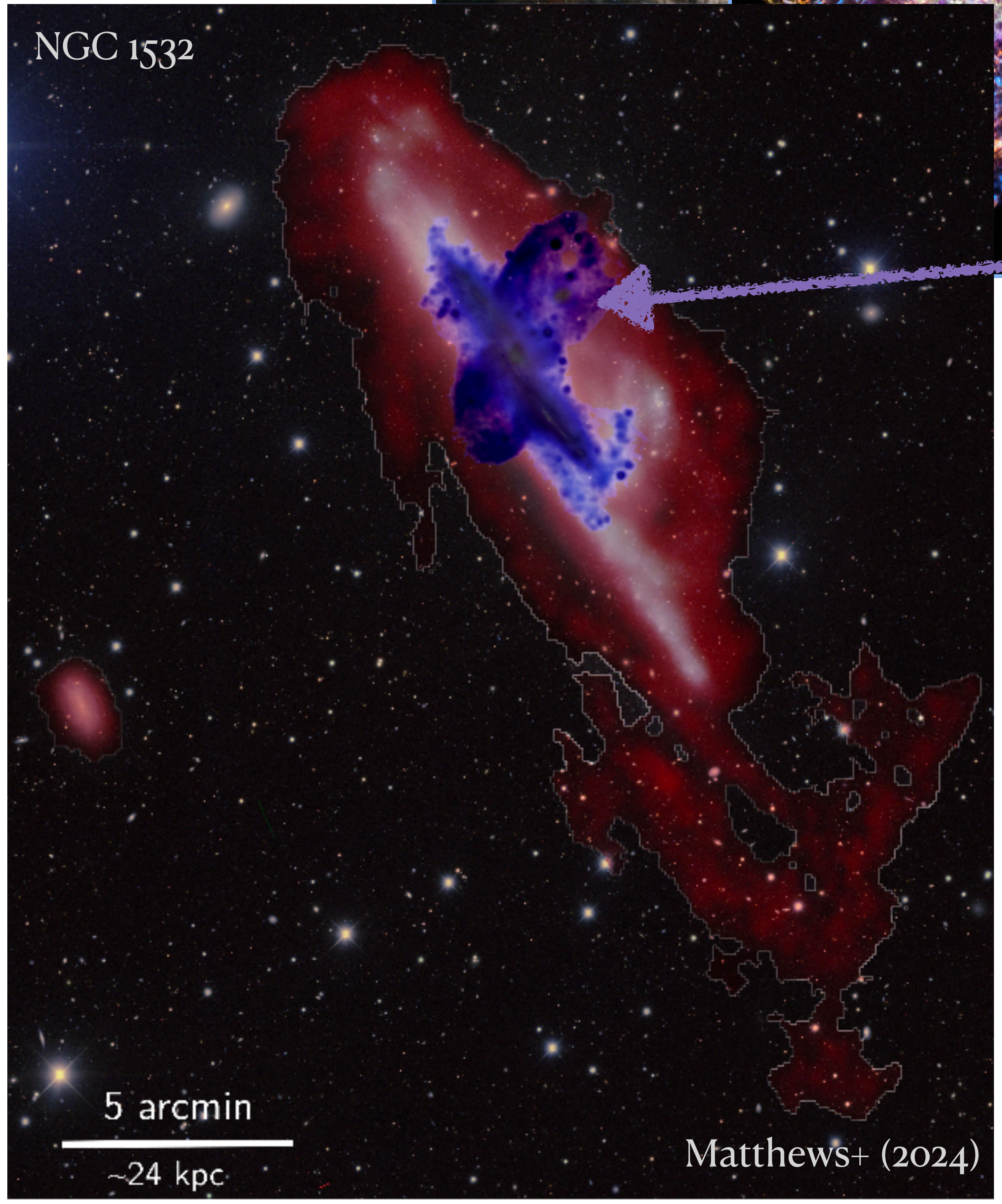
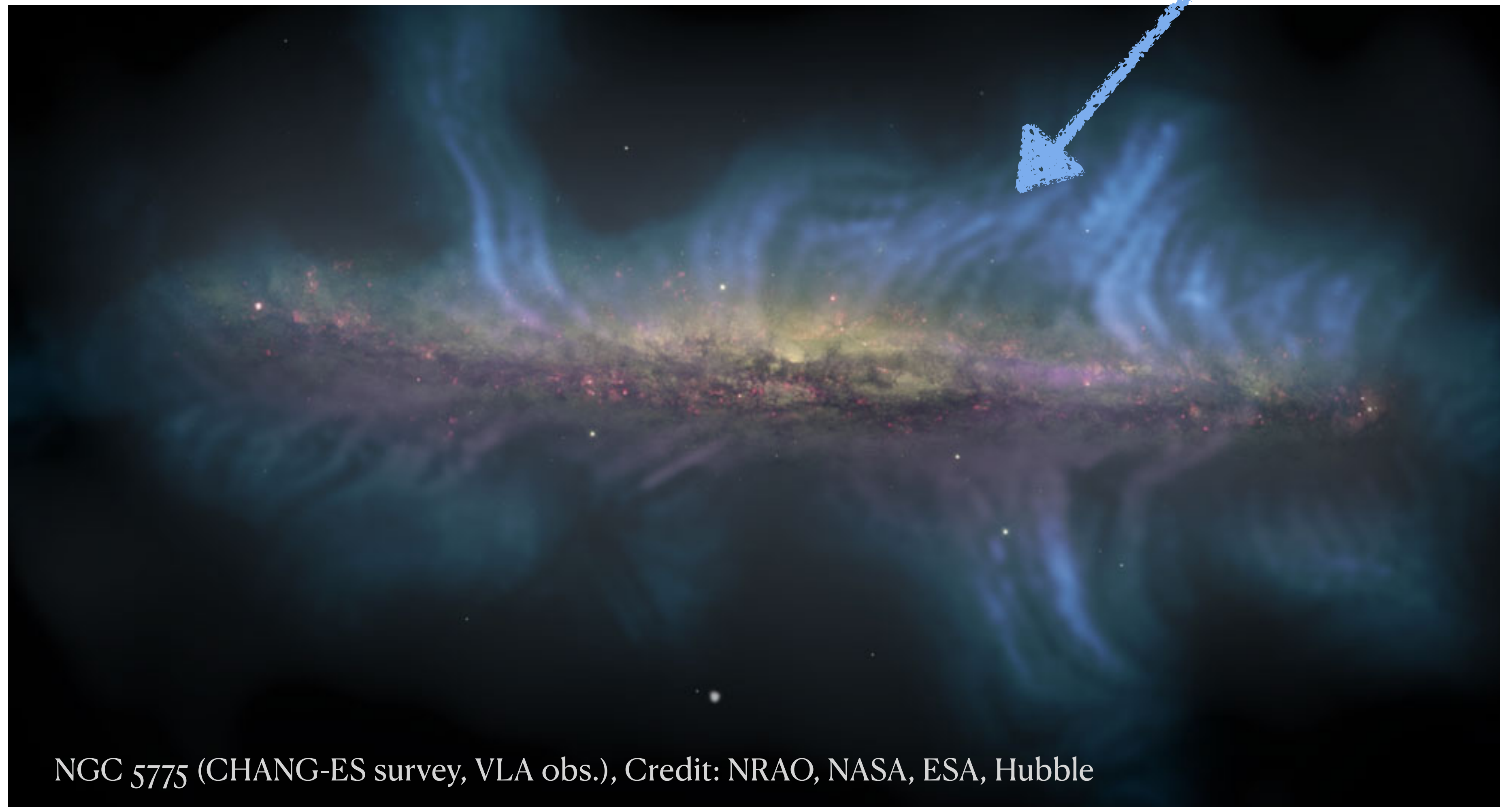


radio

polarised radio

gamma-ray





Scheel-Platz+ (2023)

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Observational Constraints of CRs

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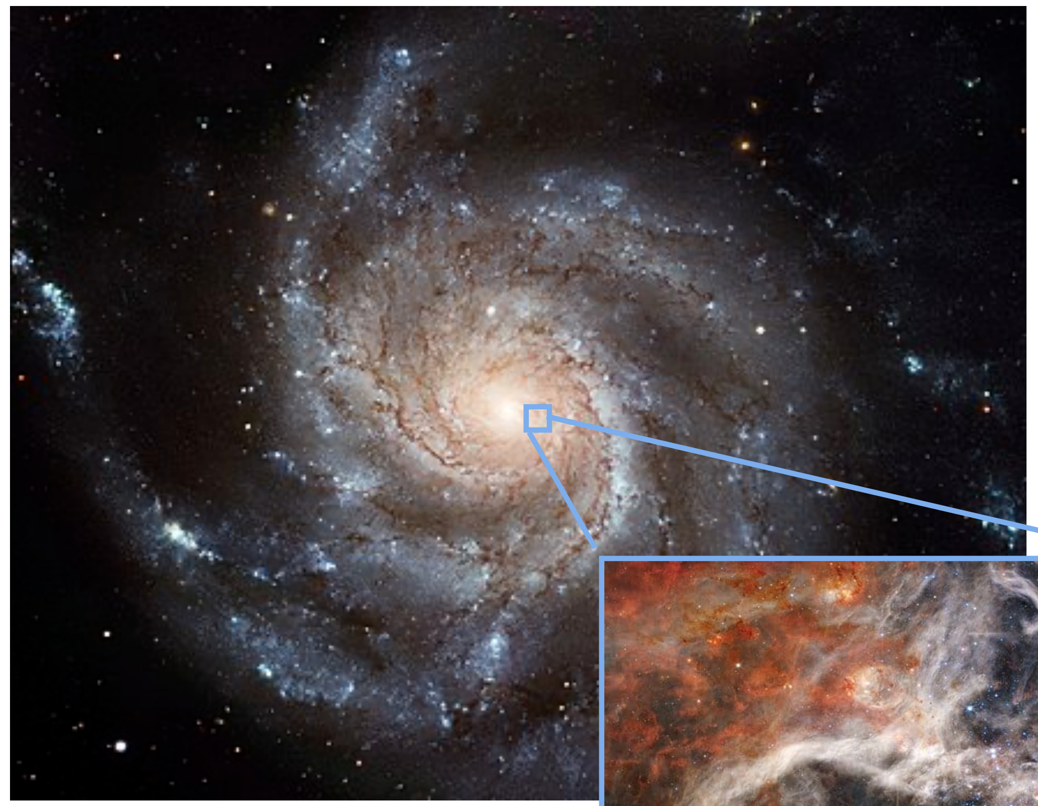
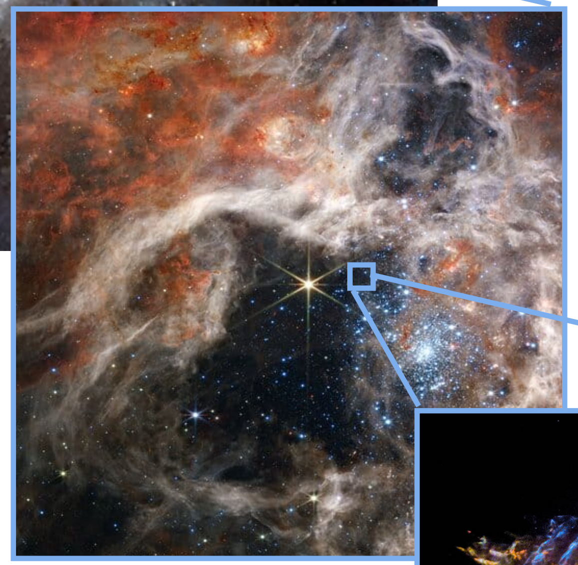
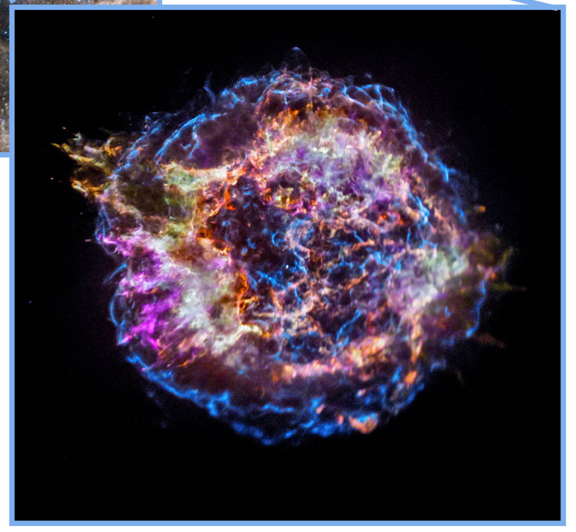

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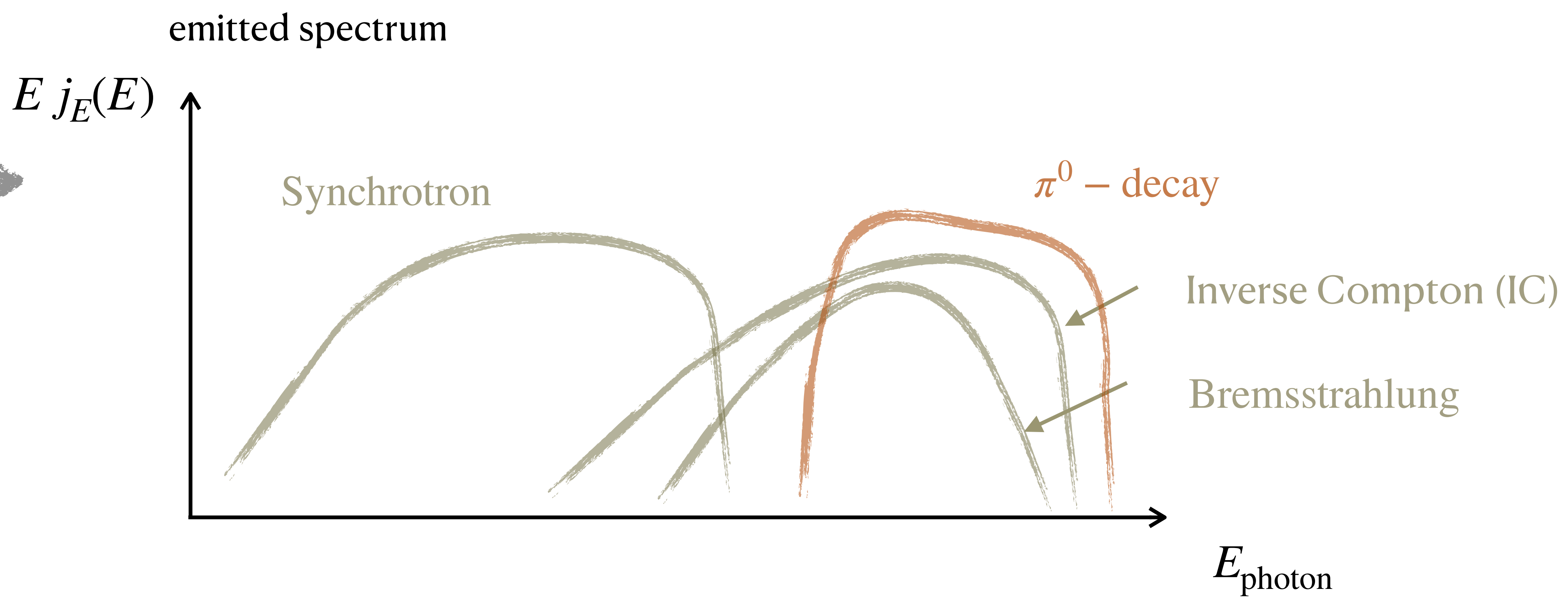
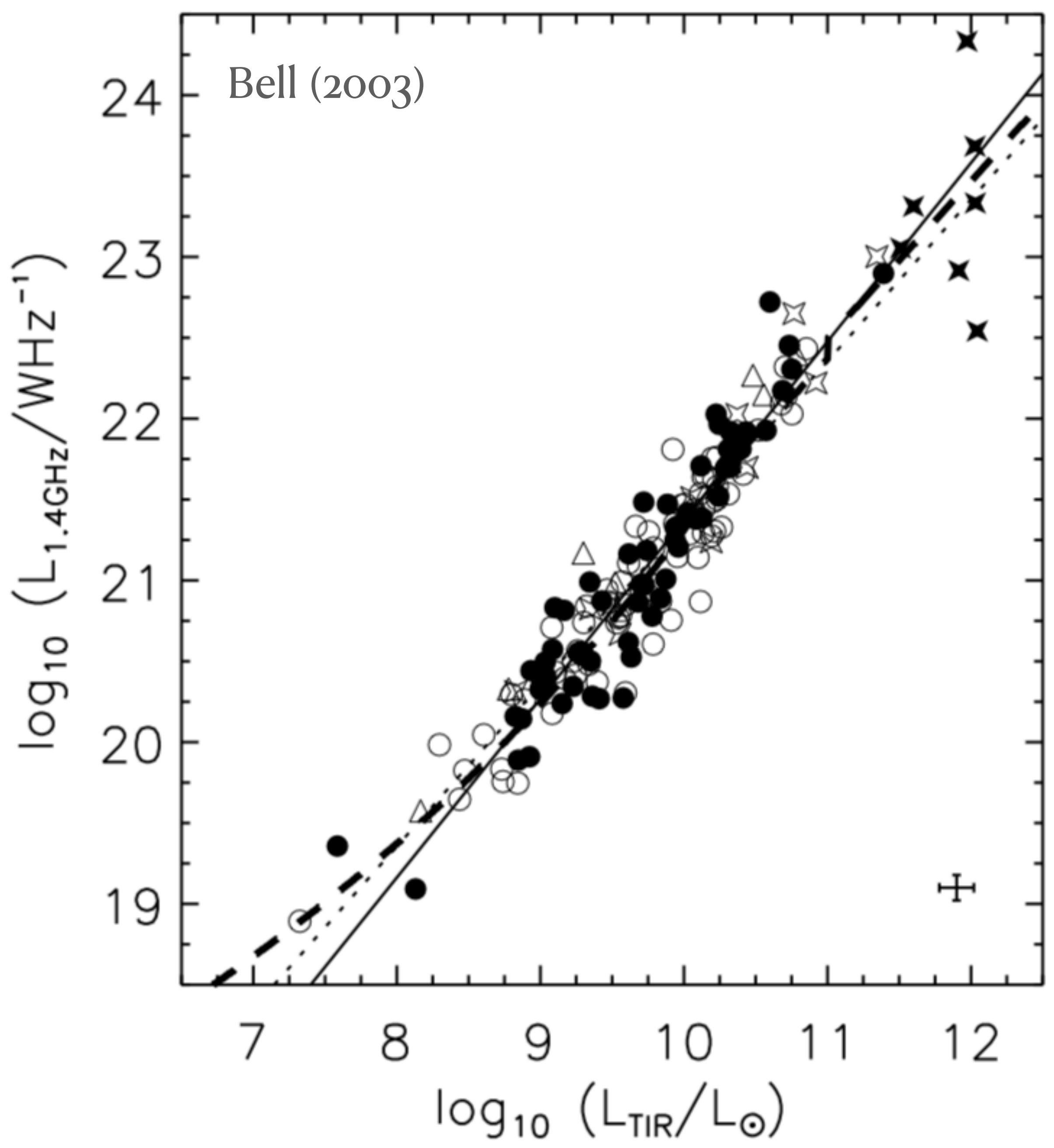


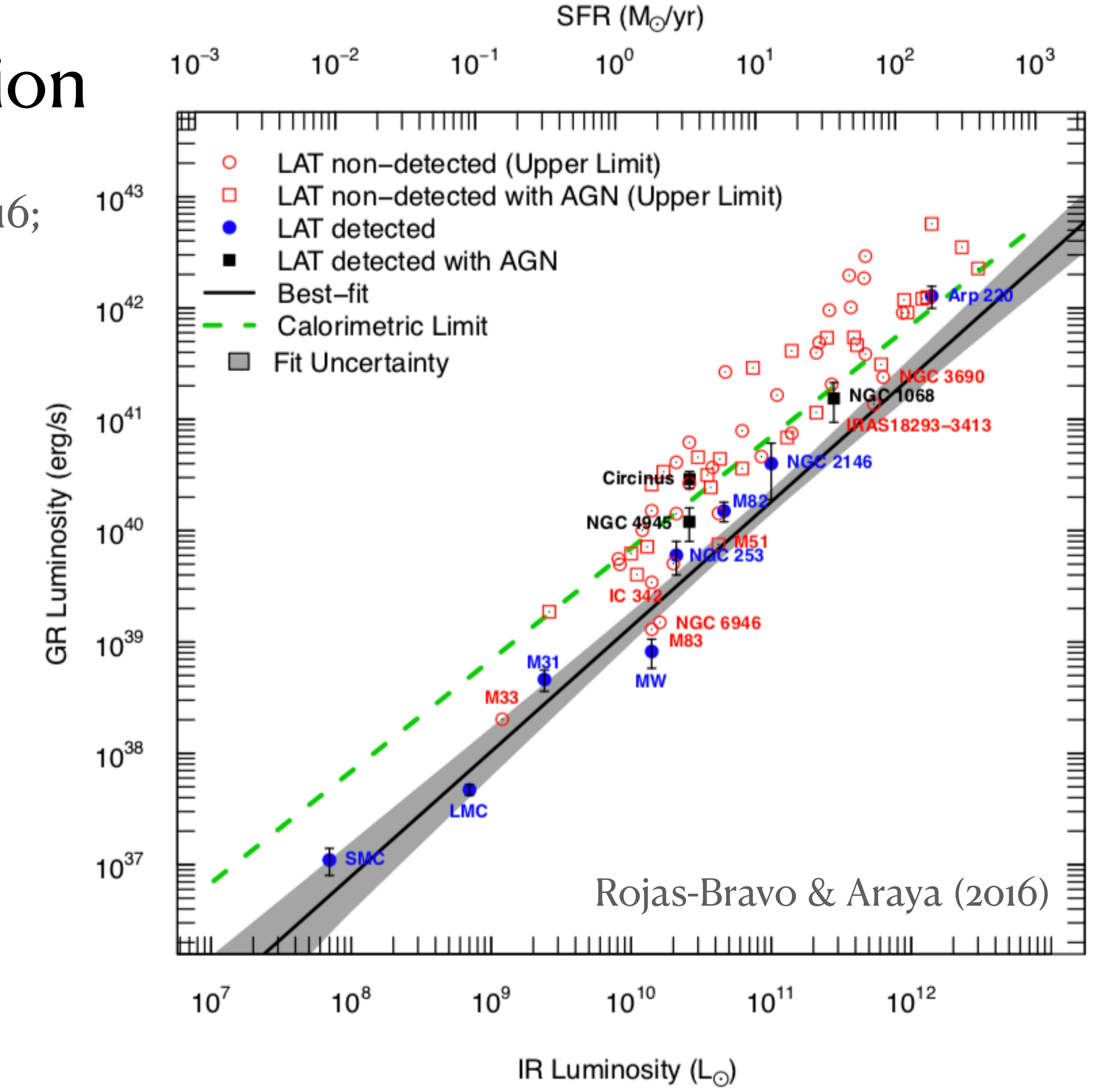


FIR-radio relation

(van der Kruit 1971; Condon 1992; Yun+2001; Bell 2003,Molnár 2021, Heesen+2022, Jin+2025)

FIR-γ-ray relation

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



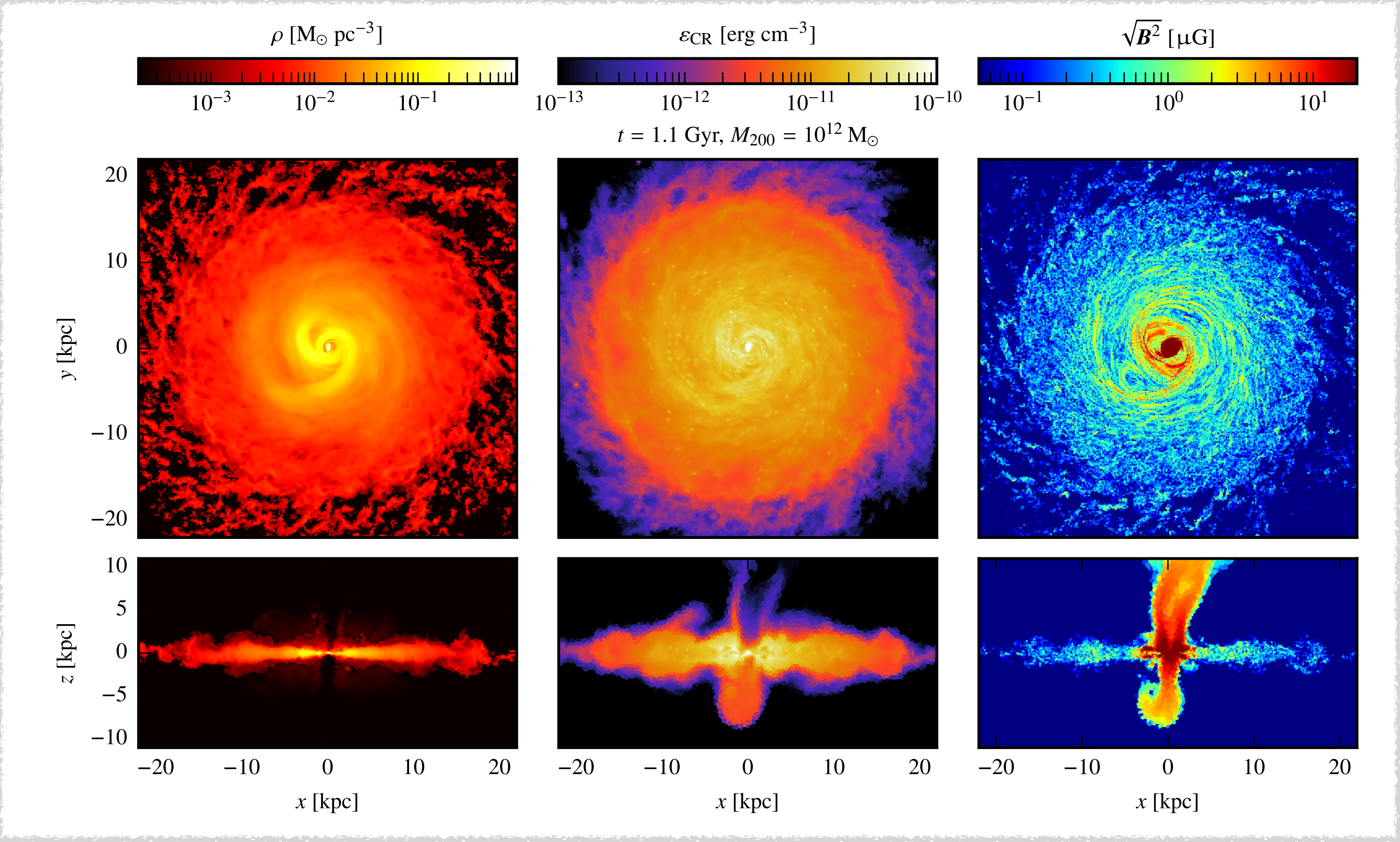
Can we constrain CR transport using these relations?

Modelling CR spectra & emission with crayon+

Cosmic **RAY** emissi**ON** + more :)

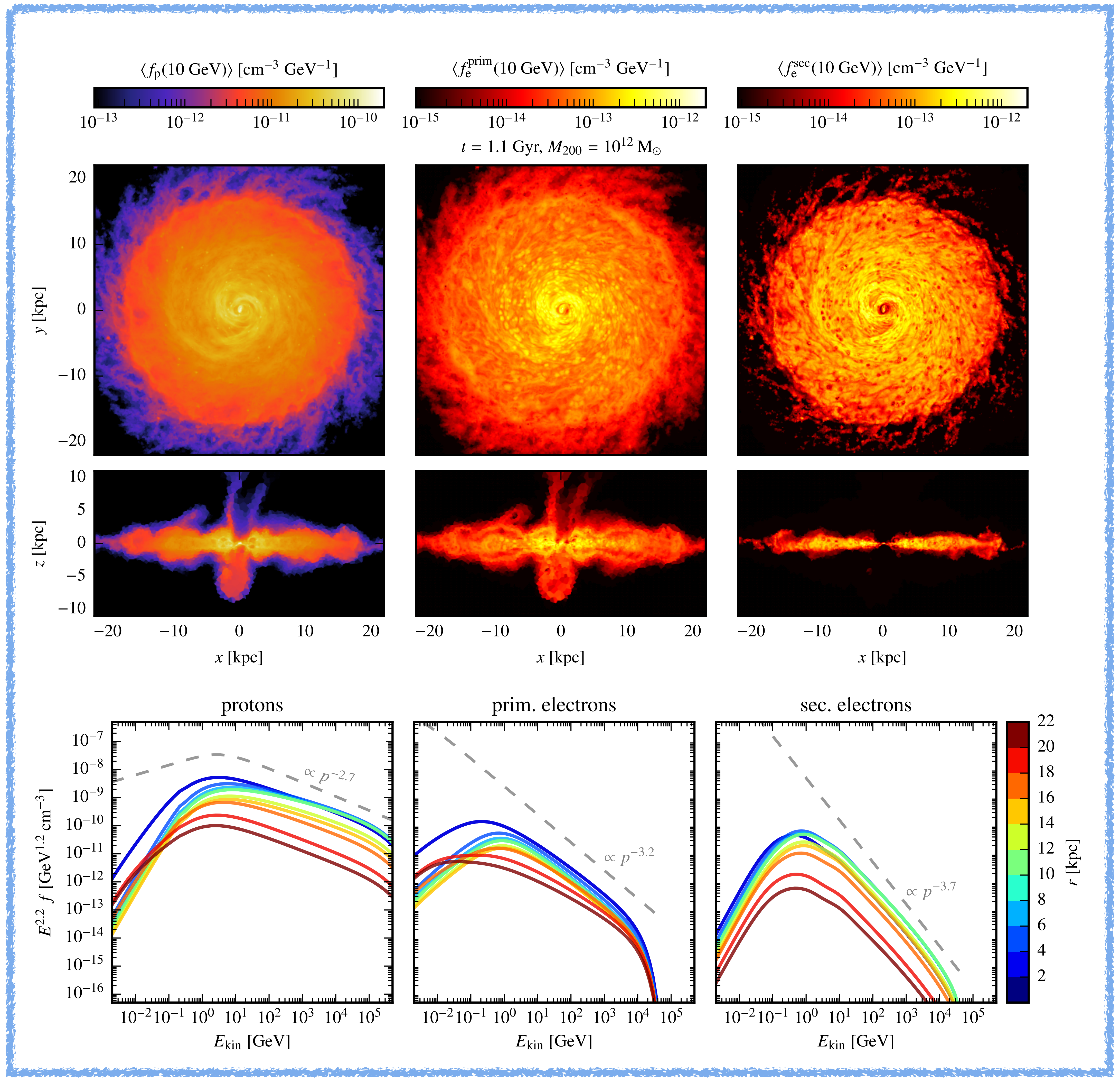
from MHD simulation

MHD simulations of isolated galaxies ($10^{10} - 10^{12}\,M_\odot$)



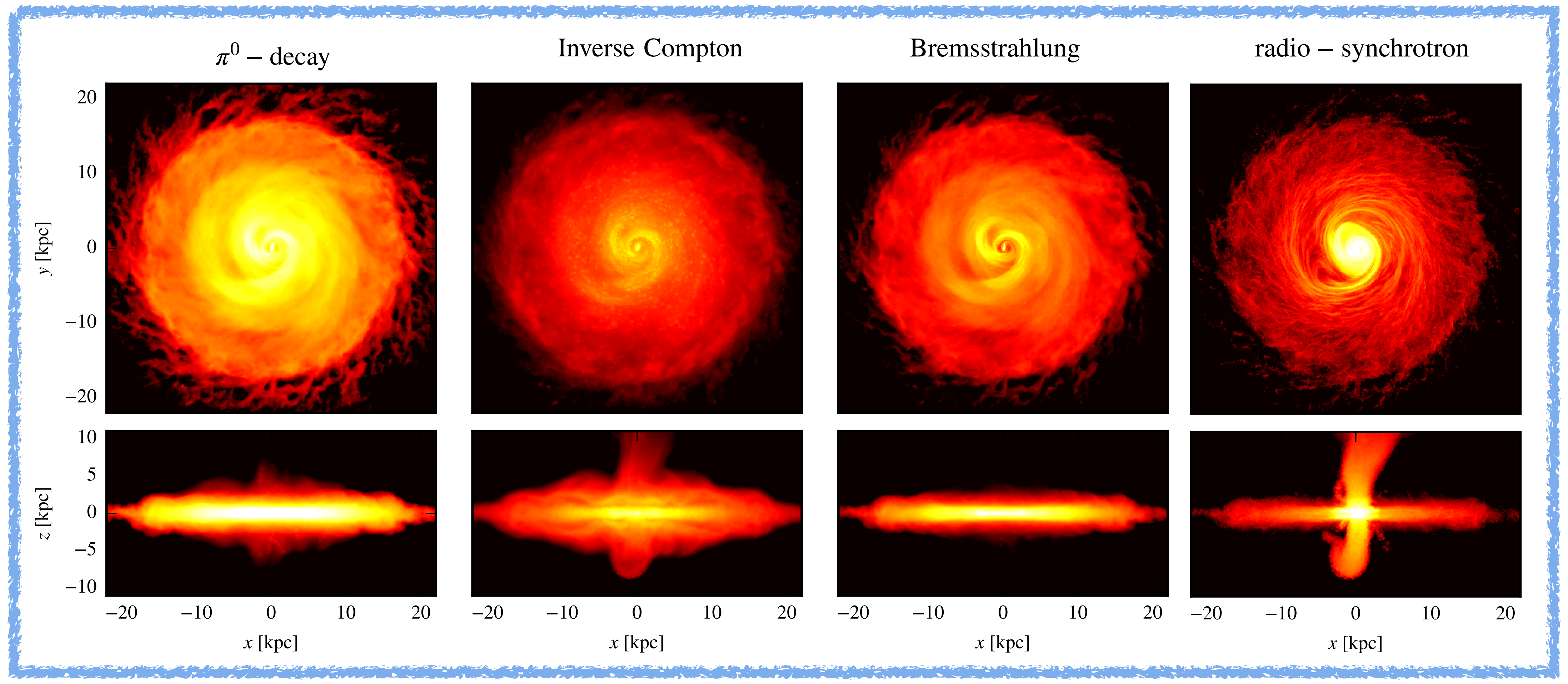
crayon+

modelling of CR proton, primary and secondary electron spectra



crayon+

calculation of radiation processes



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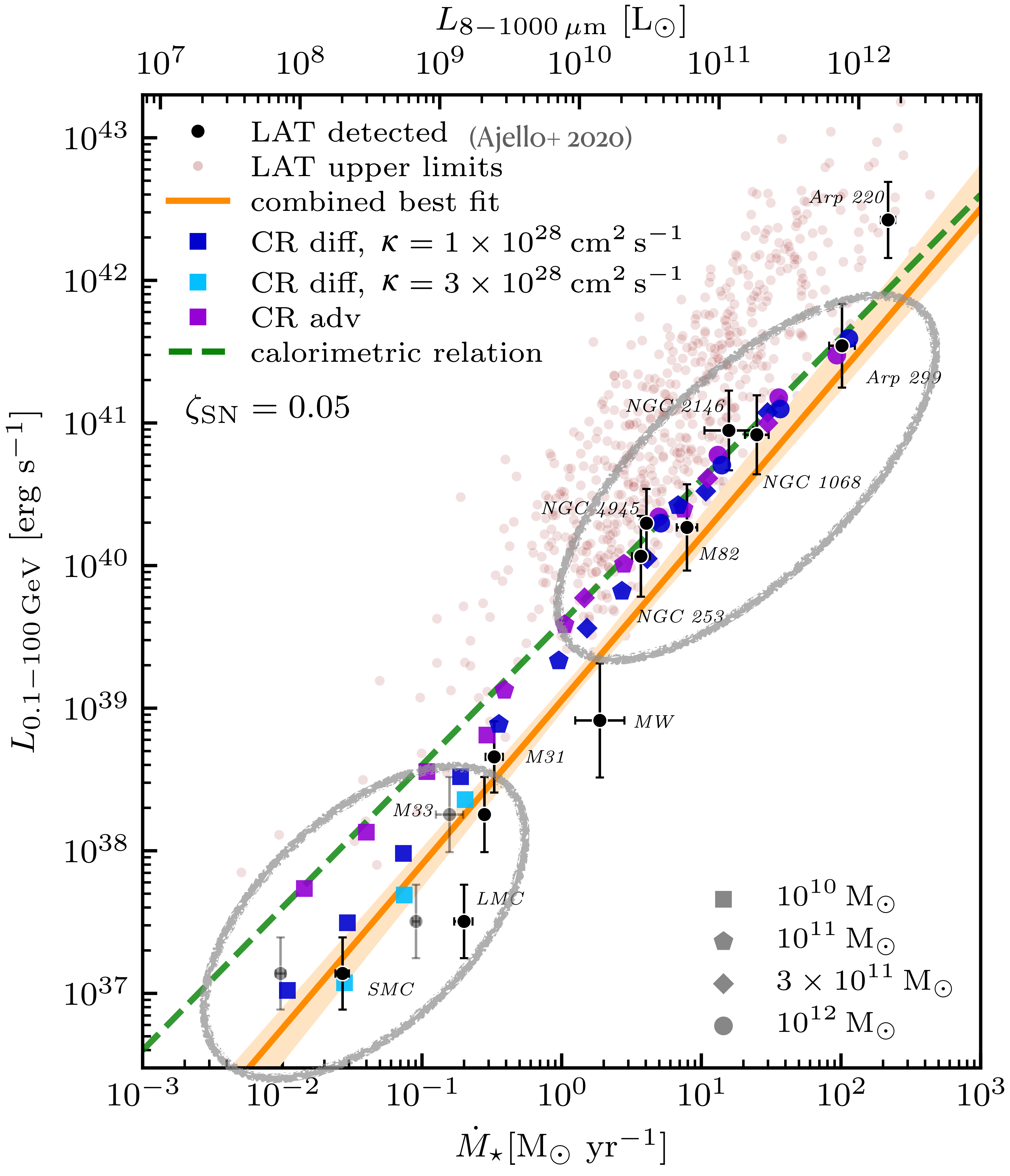
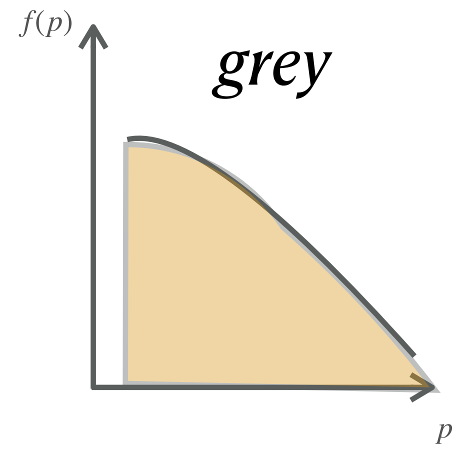
Werhahn et al. (2021 a)

Lessons learned from isolated setups

Gamma-ray emission



Werhahn et al. (2021b)



high SFR: close to calorimetric limit (complete conversion to γ-rays)
—> **constrain ζ_{SN}**

low SFR: sensitive to CR transport
—> **constrain κ**

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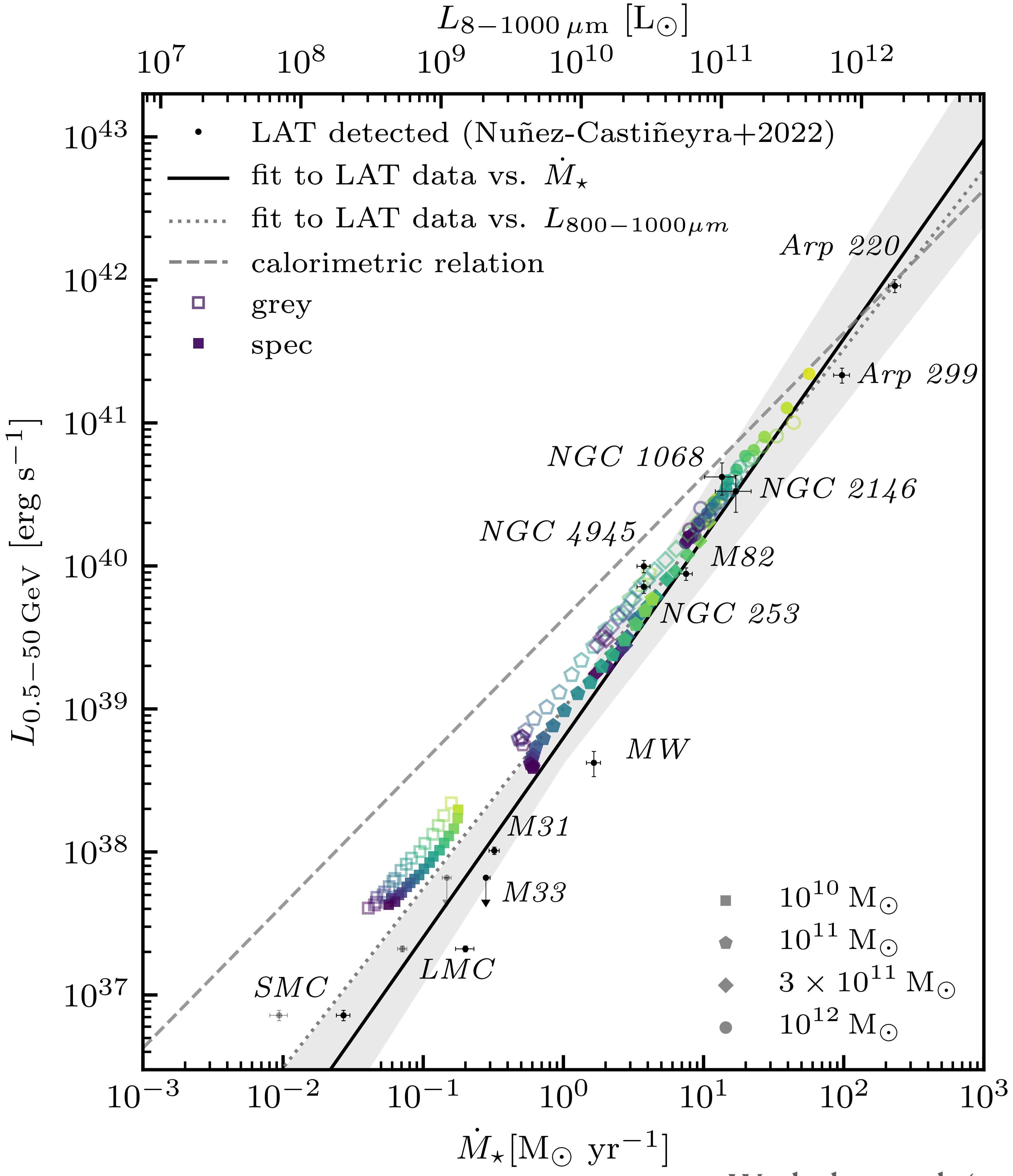
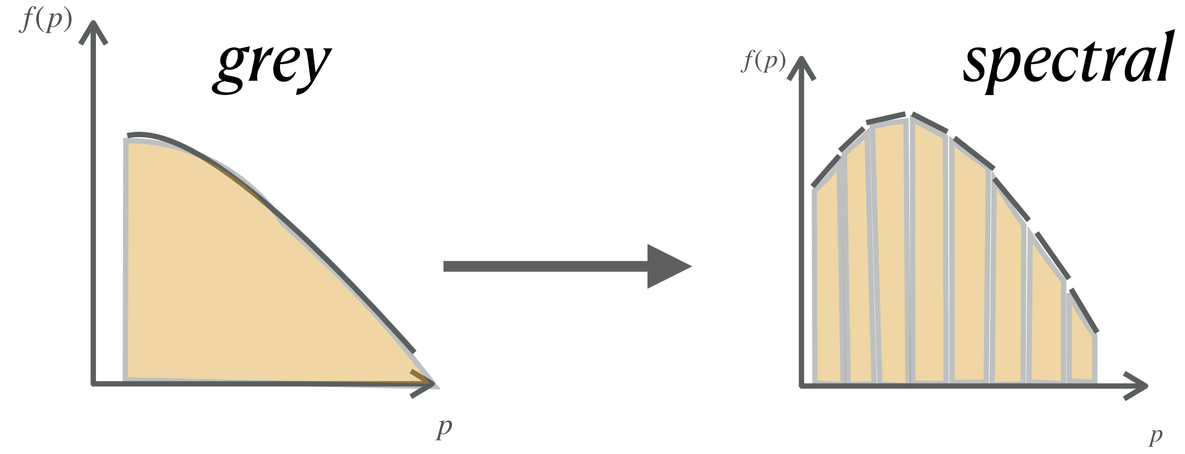
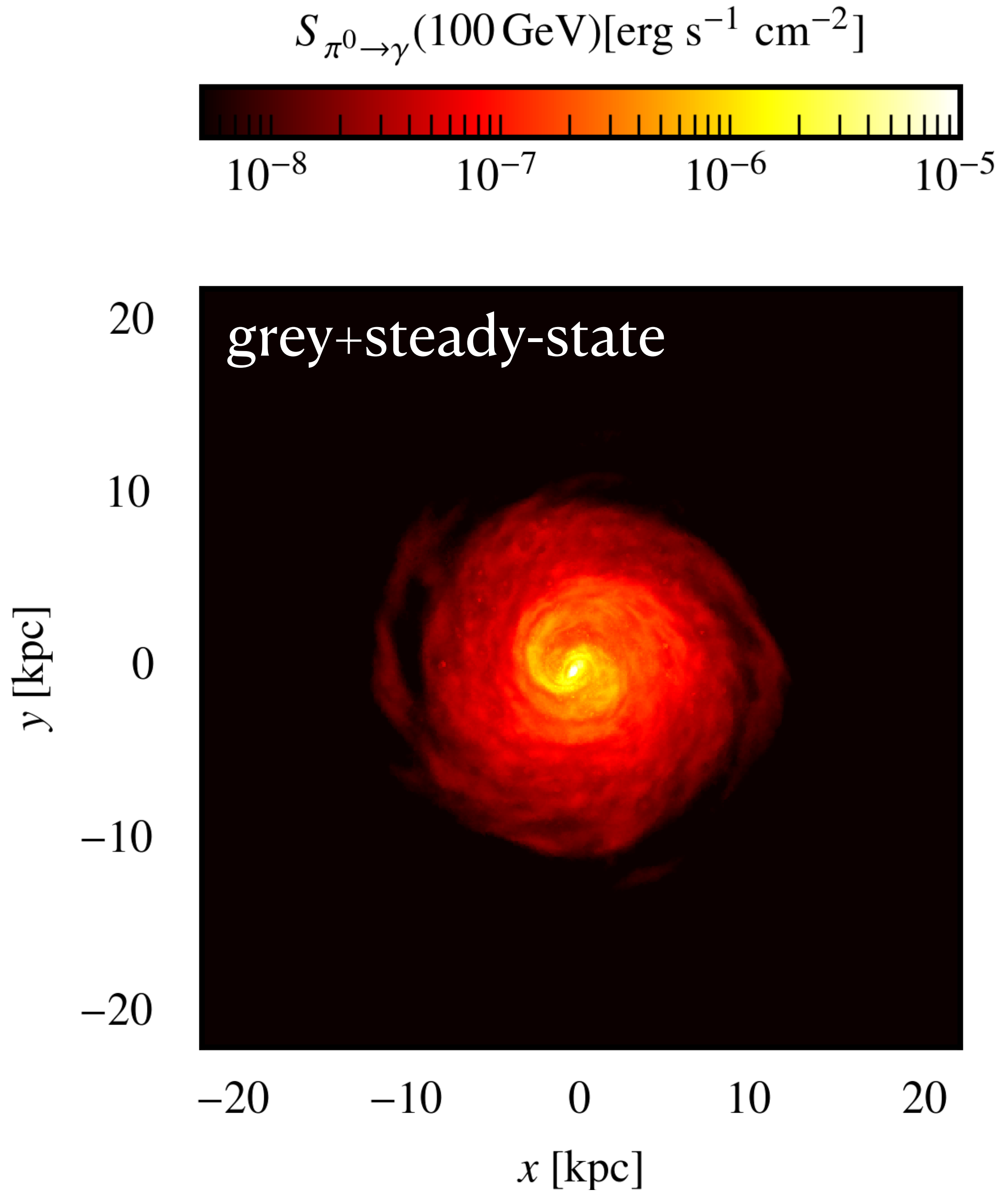


Werhahn et al. (2023)



Spectral CR protons (Girichidis+2020,2022)

- changes **spatially resolved high-energy gamma-ray emission**
- **global** spectra & luminosities: close to *grey+steady-state*



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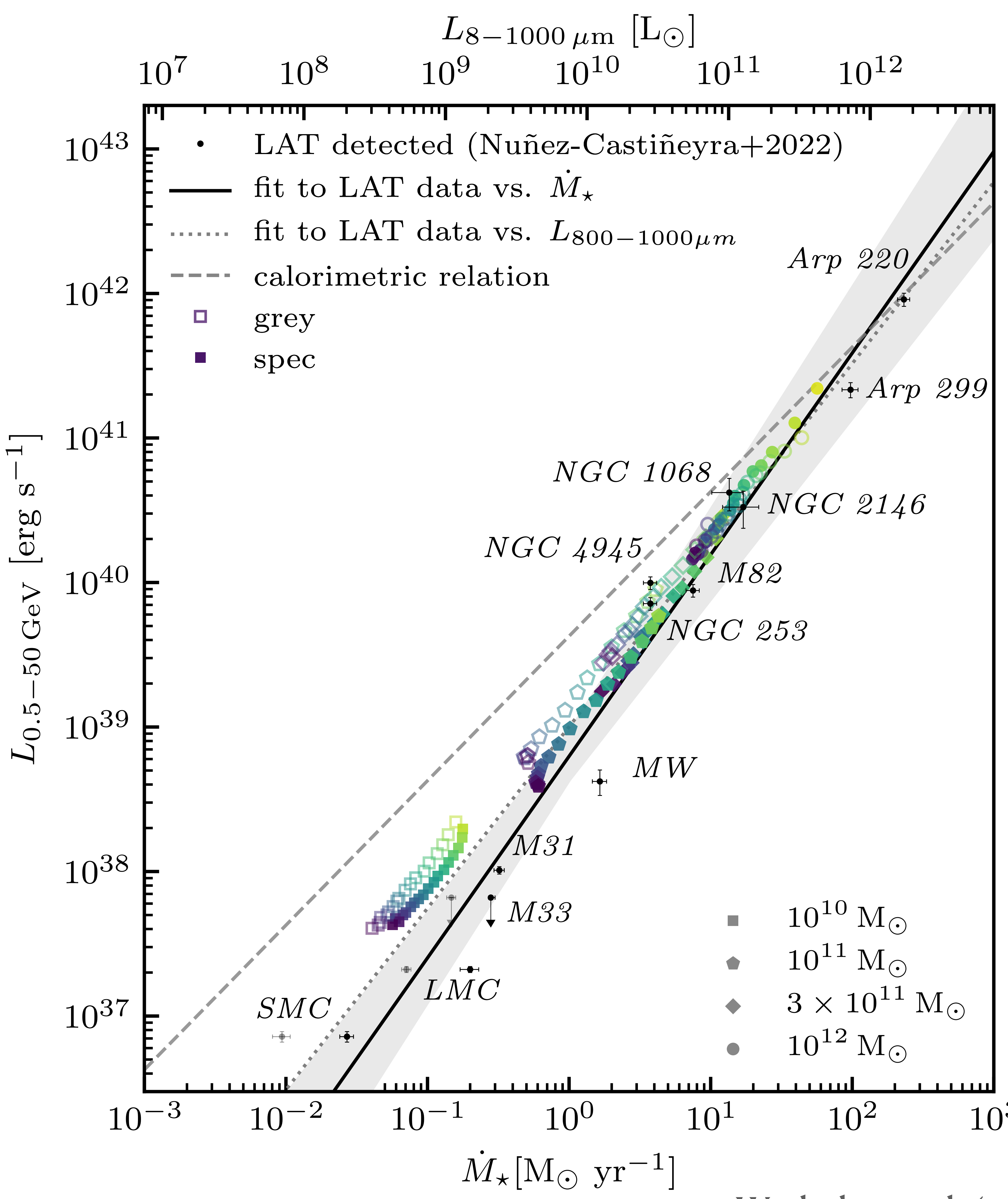
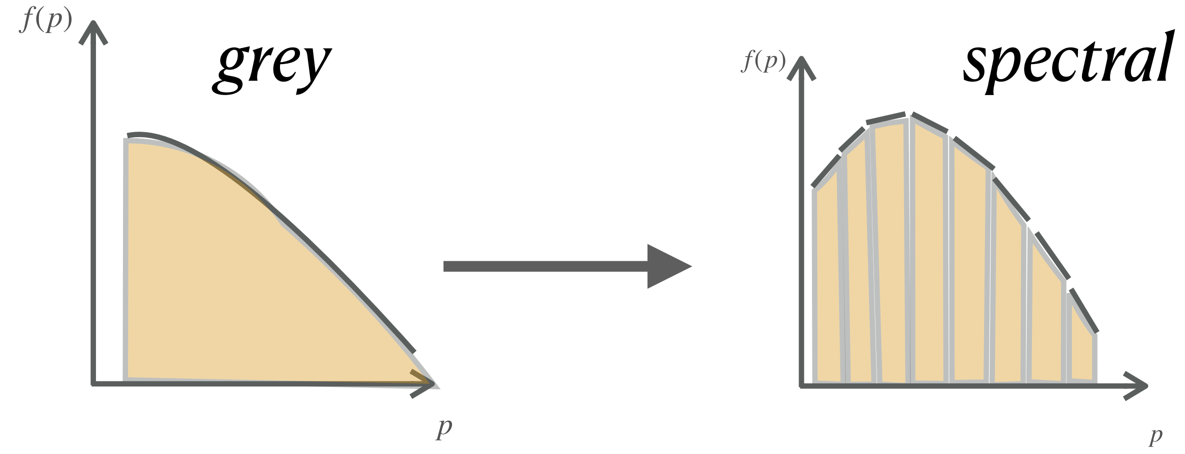


Werhahn et al. (2023)



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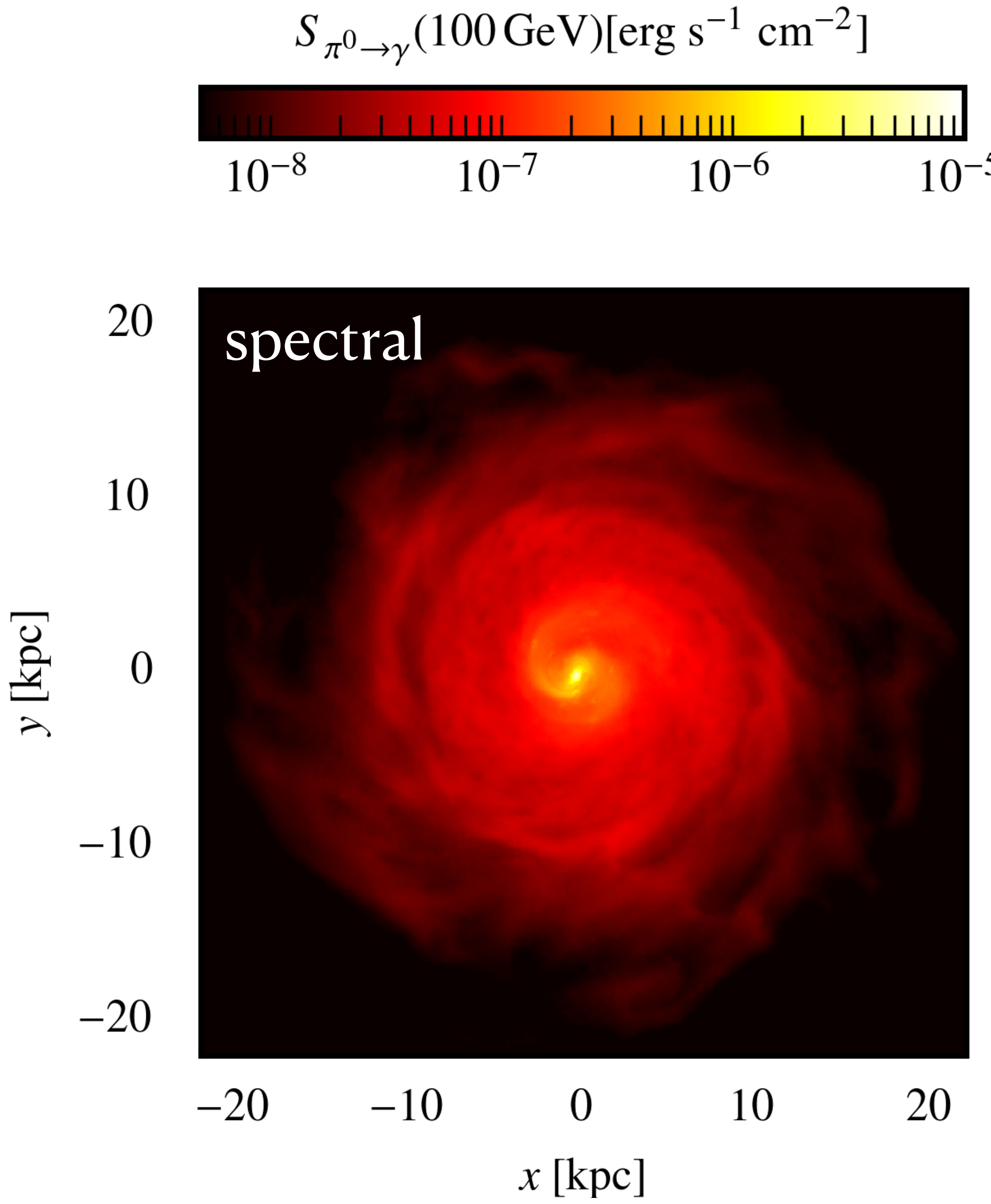
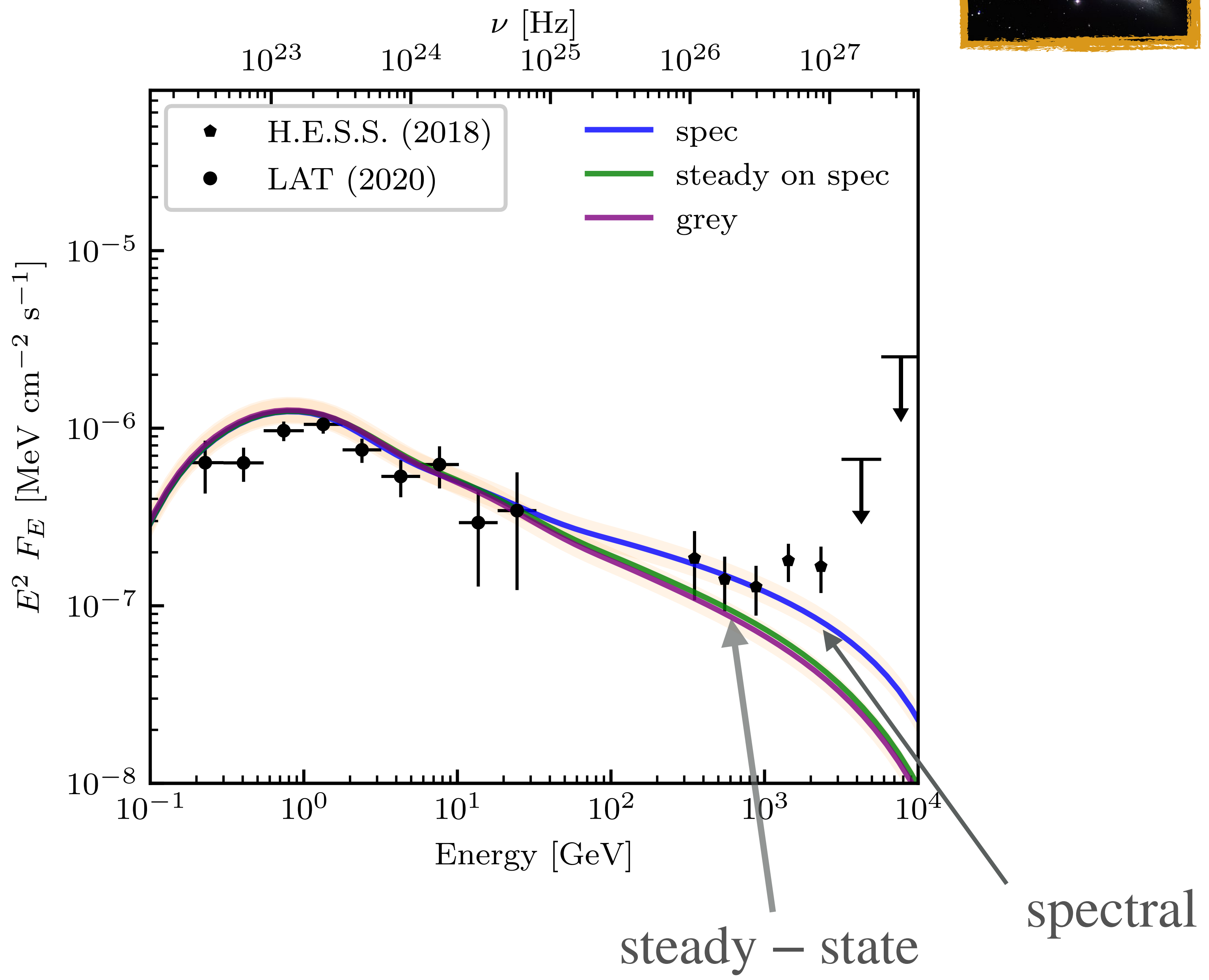


gamma-ray spectrum of NGC253



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Lessons learned from isolated setups

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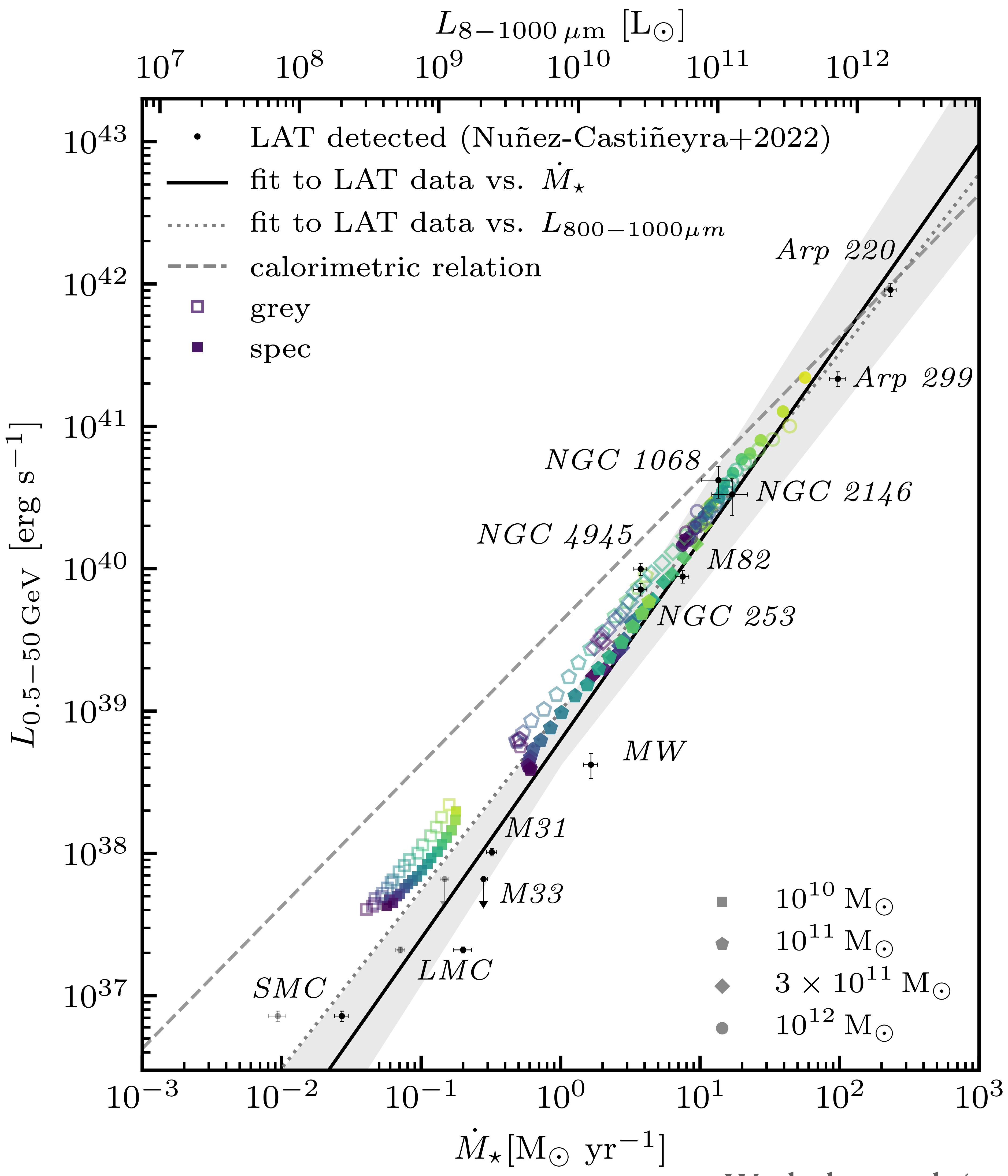
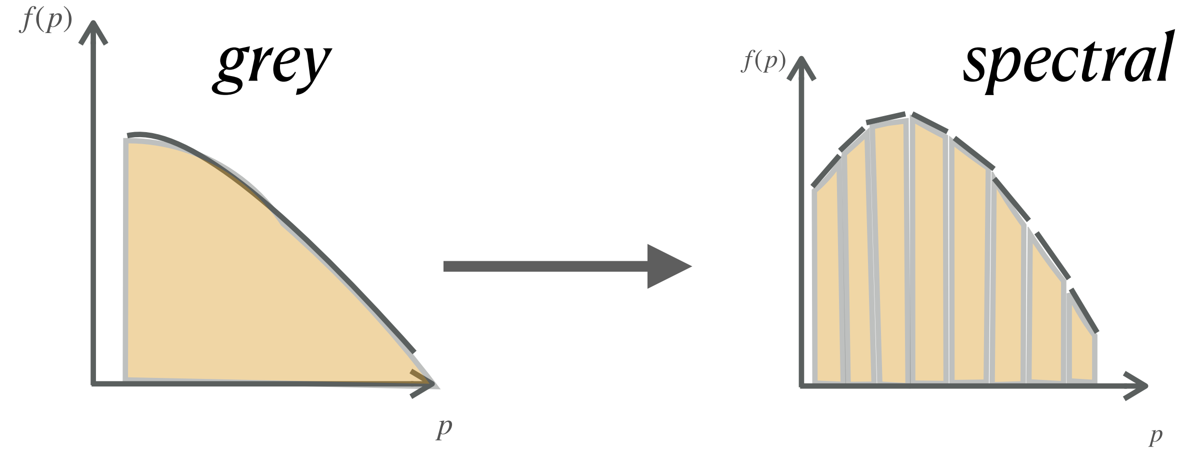


Werhahn et al. (2023)



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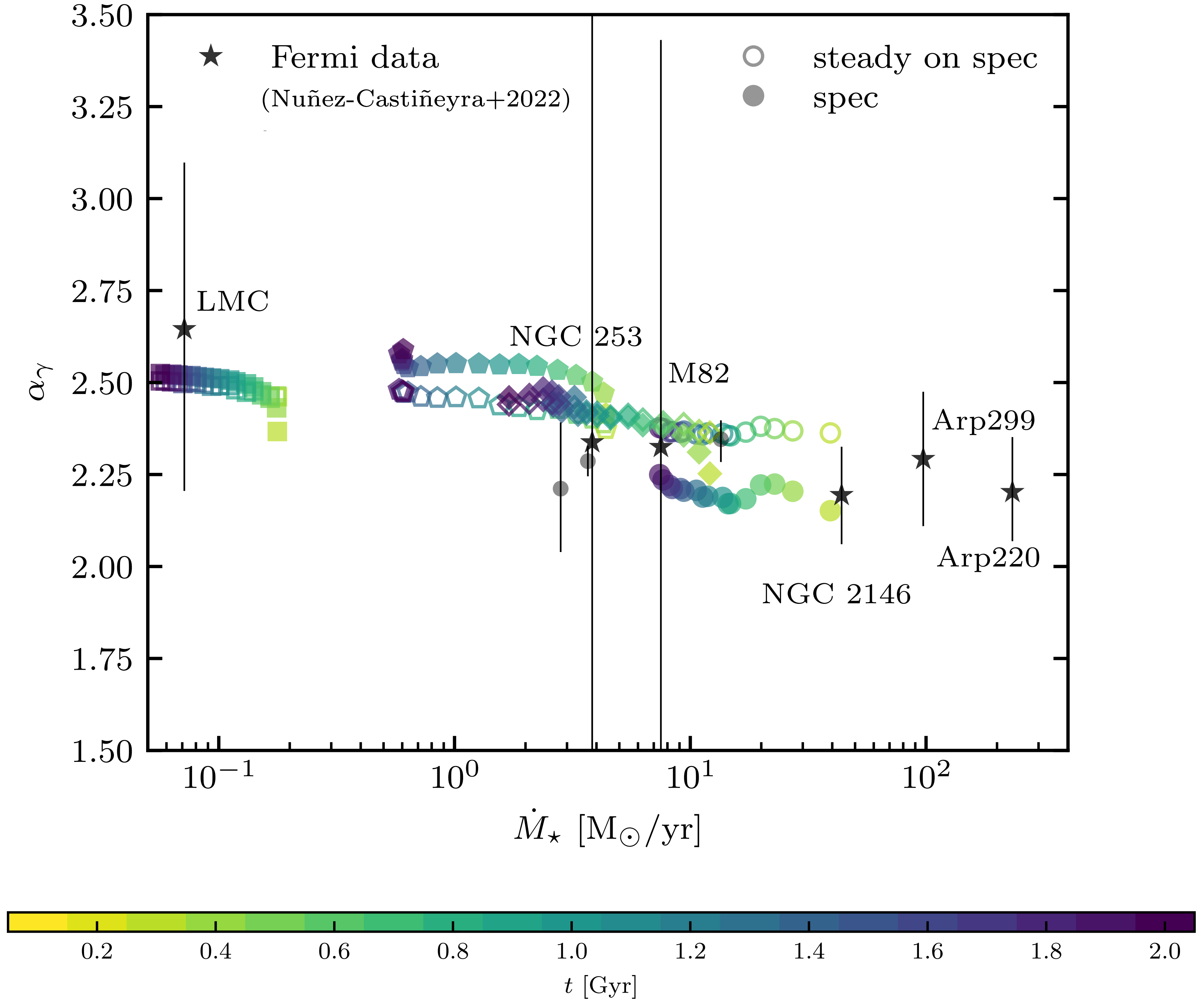

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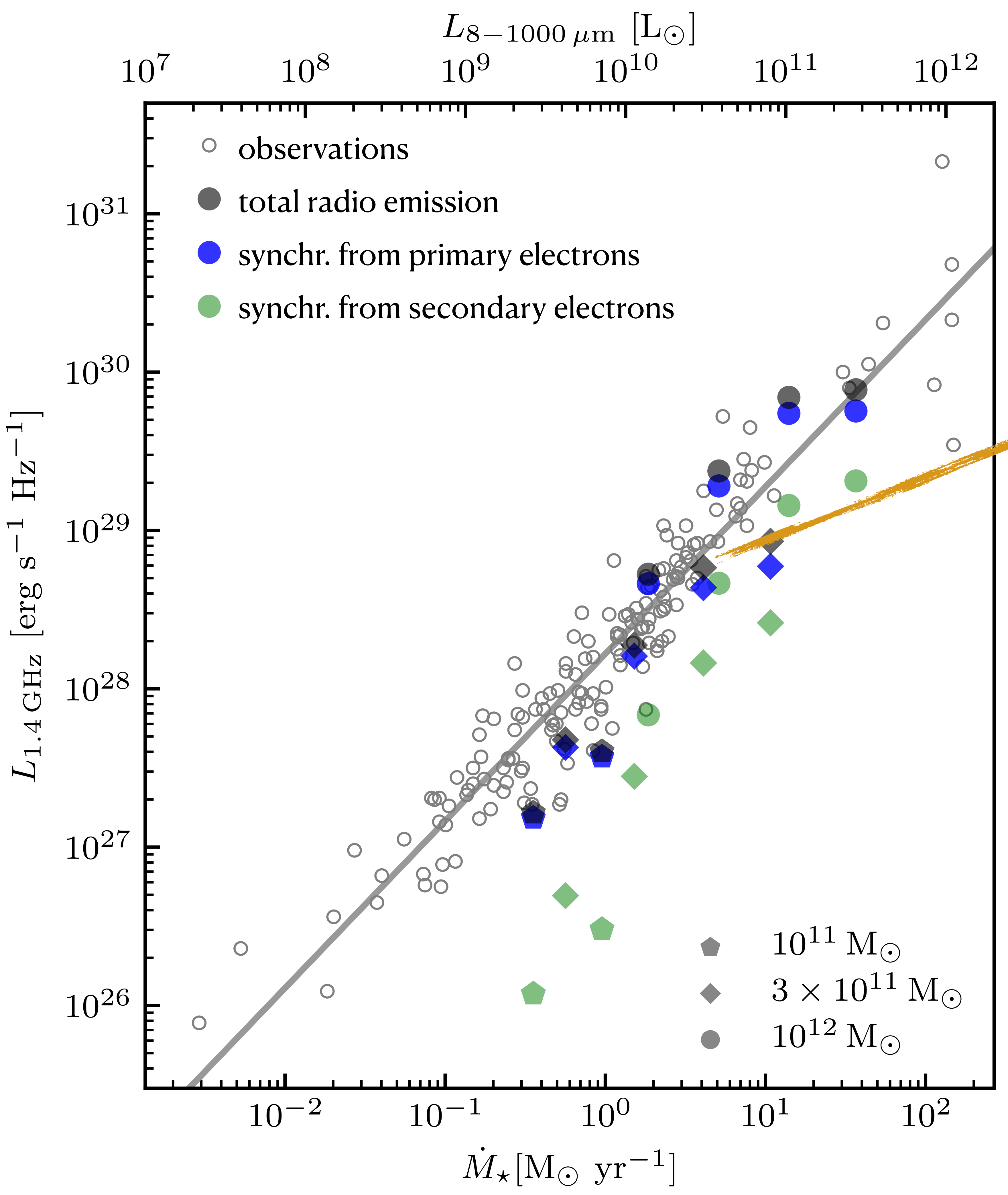
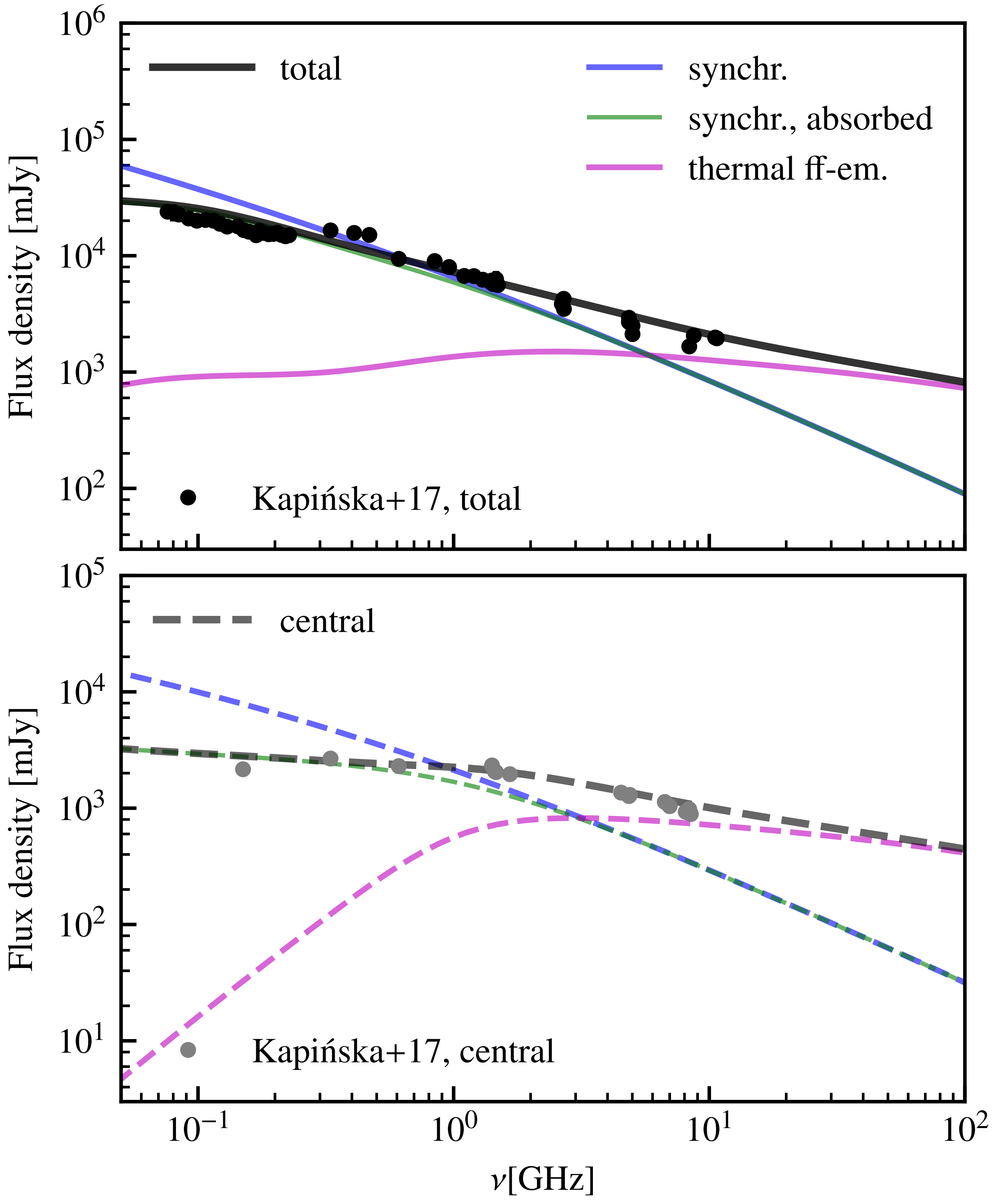
Lessons learned from isolated setups

Radio emission



NGC 253

Radio spectrum (total & central)



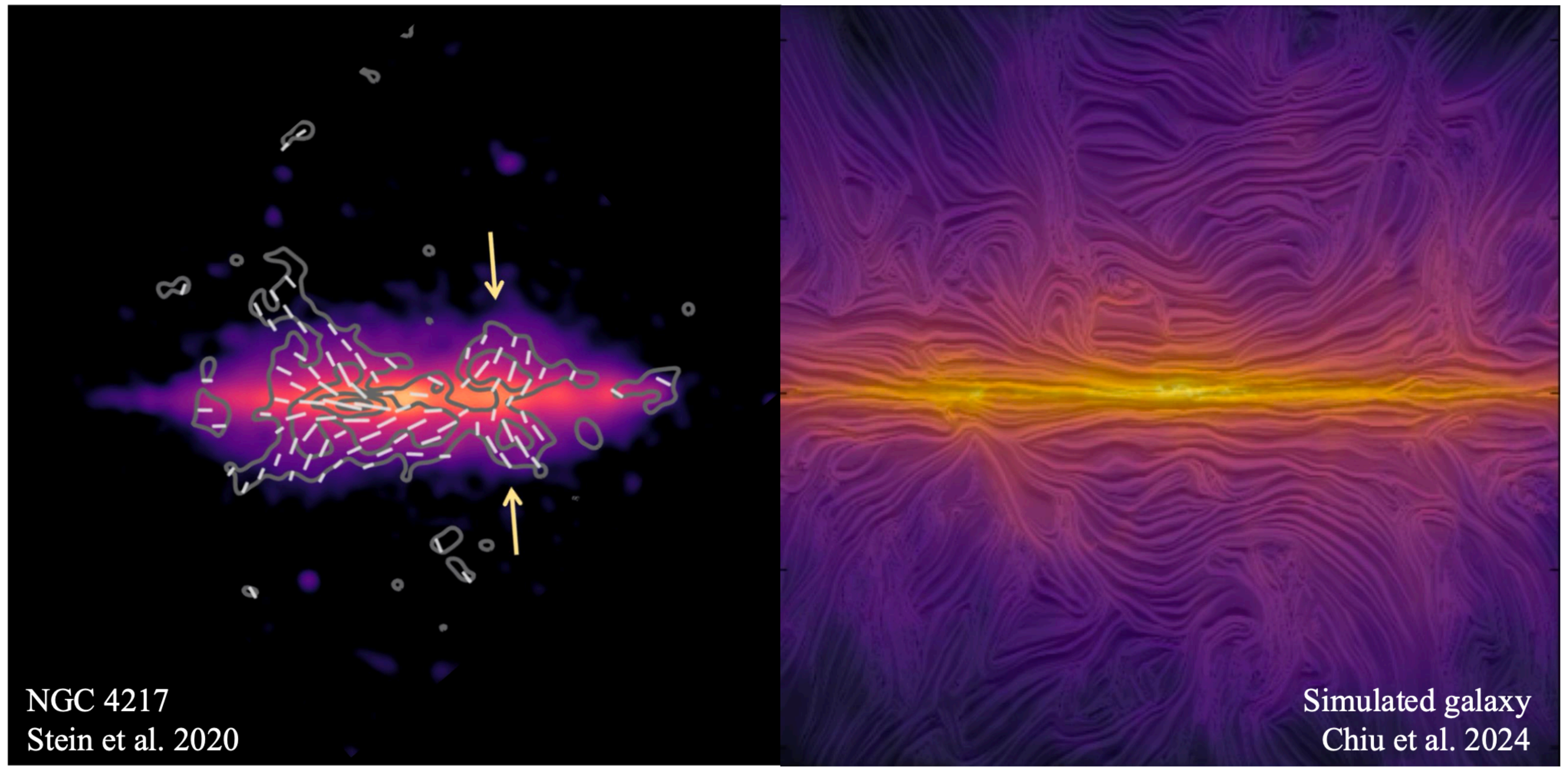
- primary electrons dominate
- high frequencies: steep radio synchr. spectra (IC & synchr. cooling)
- thermal free-free emission & absorption needed for flat spectra

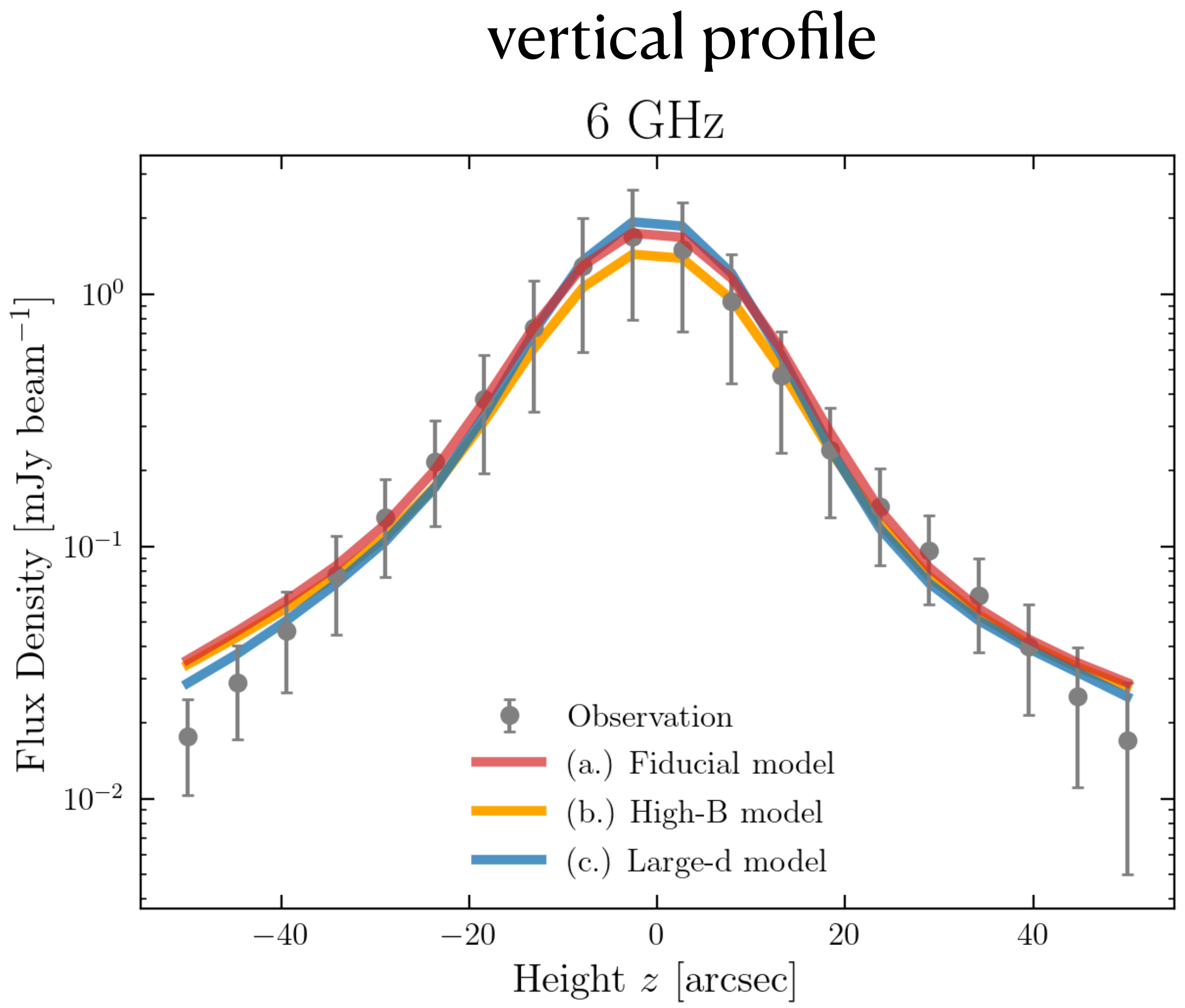
Werhahn et al. (2021c)

Polarised radio emission

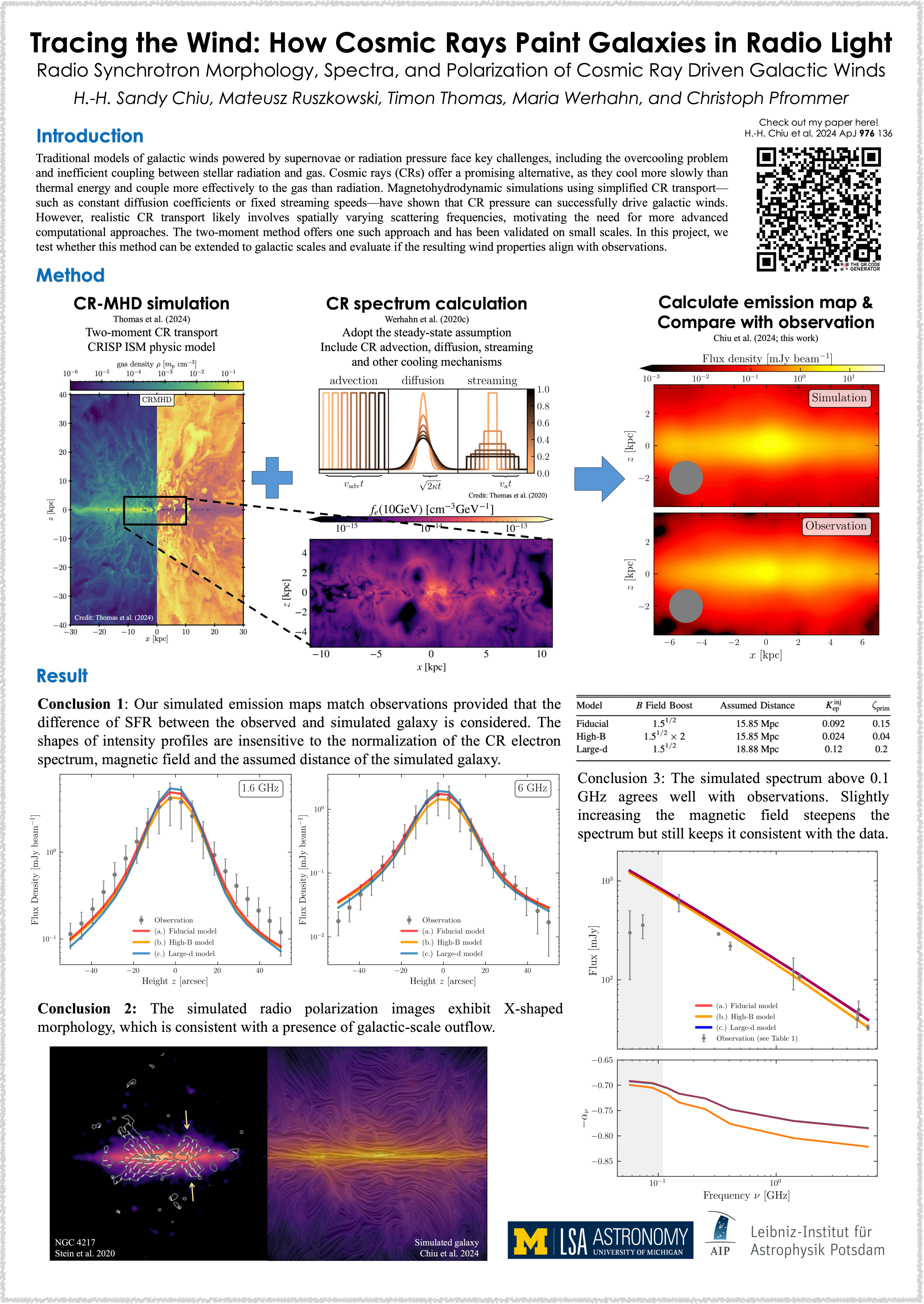
from a CRISPy galaxy

- galaxy simulation with **CRISP** (Thomas et al. 2024), including 2-moment CR transport and more detailed ISM model
- **crayon**+: model electron spectra & (polarised) radio emission
  —> compare to edge-on radio observations of NGC 4217 (Stein et al. 2020)
- X-shaped B-field morphology recovered
- shape of the vertical profile: robustly predicted





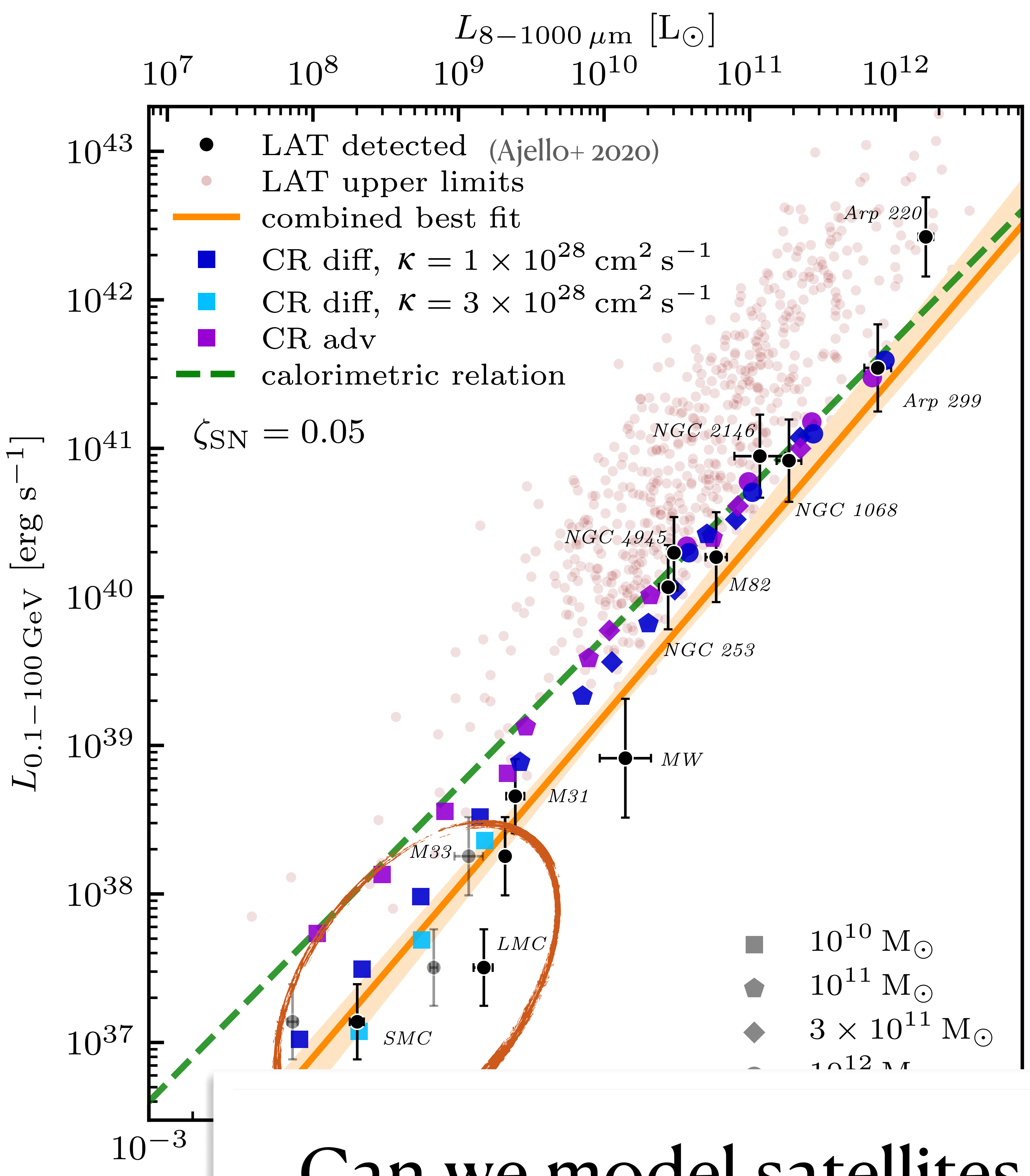
Chiu et al. (2024)



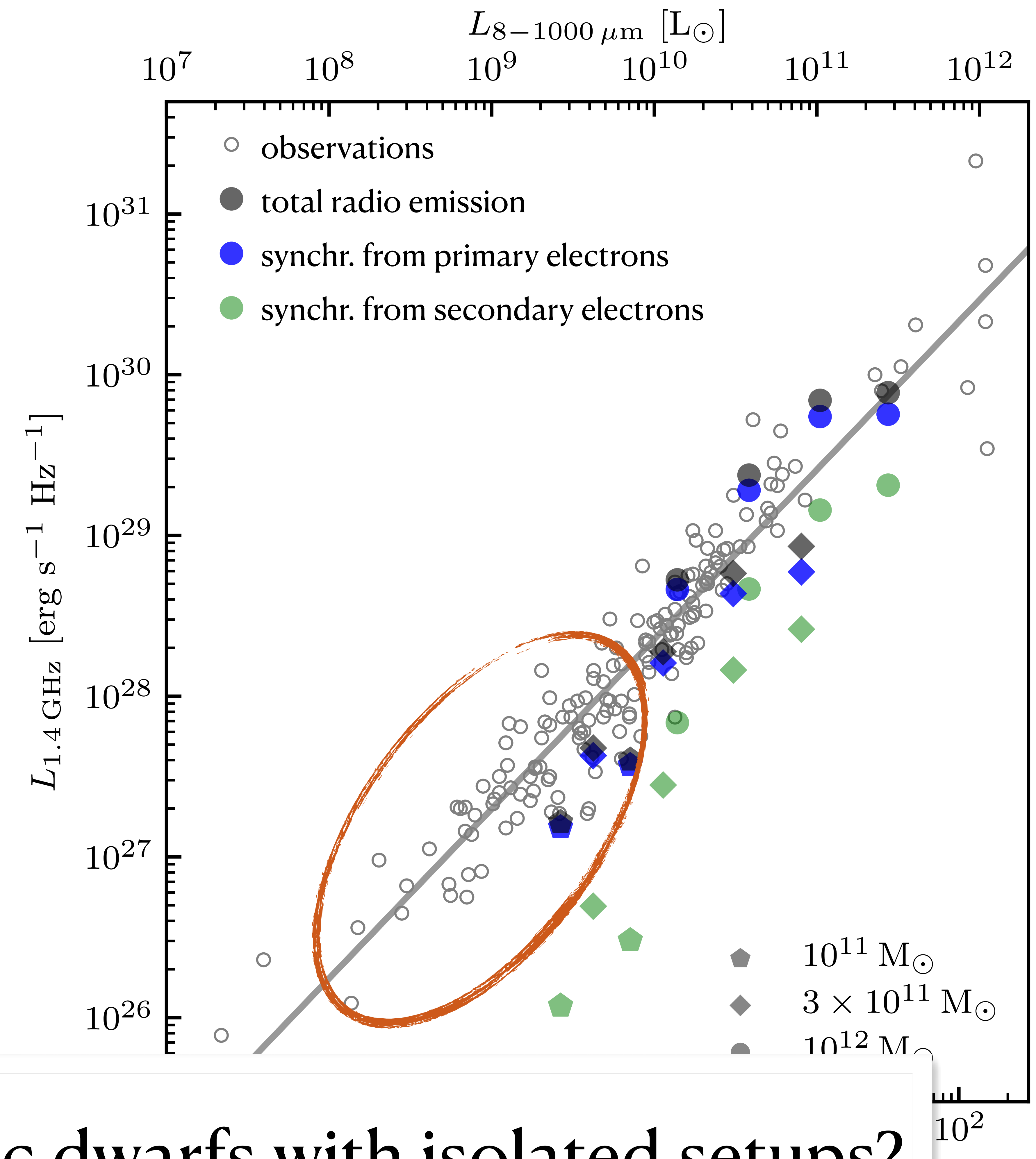
see poster by H.-H. Sandy Chiu!

Lessons learned from isolated setups

Open questions



Werhahn et al. (2021b)



Werhahn et al. (2021c)

Can we model satellites/realistic dwarfs with isolated setups?

Cosmological zoom simulations

with CRs

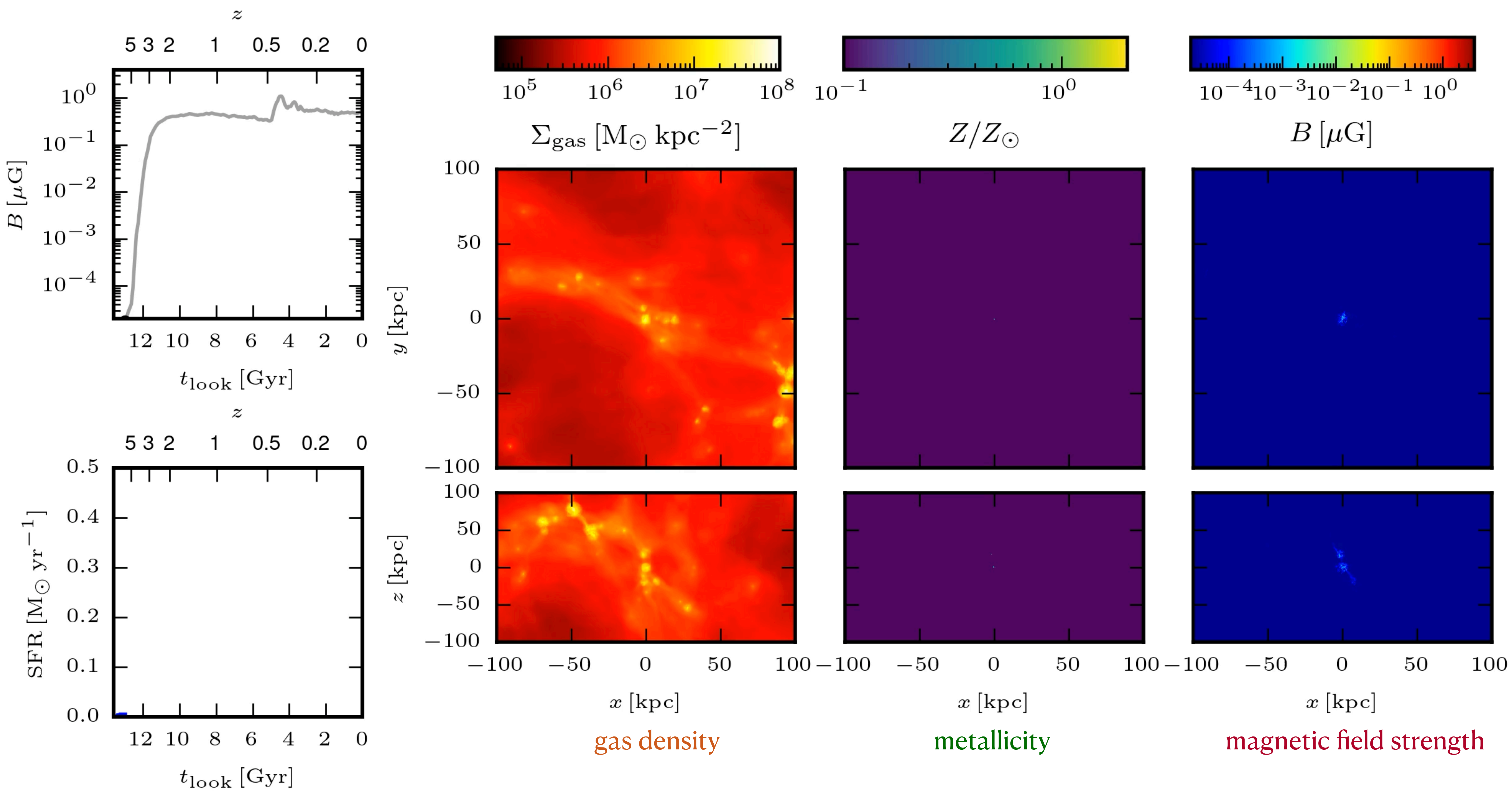
Auriga zoom simulations with CRs
(Bieri, [...], Werhahn+ in prep)

- $M_{200} = 10^{10} - 10^{13}\,\mathrm{M}_\odot$
- with grey CRs (Alfvén cooling, anisotropic diffusion)
- **crayon**+: CR spectra & emission

✓ more realistic environment and star-formation history

✓ study isolated dwarfs vs. satellites

satellite in a $10^{12}\,\mathrm{M}_\odot$ halo



star-formation history

gas density

metallicity

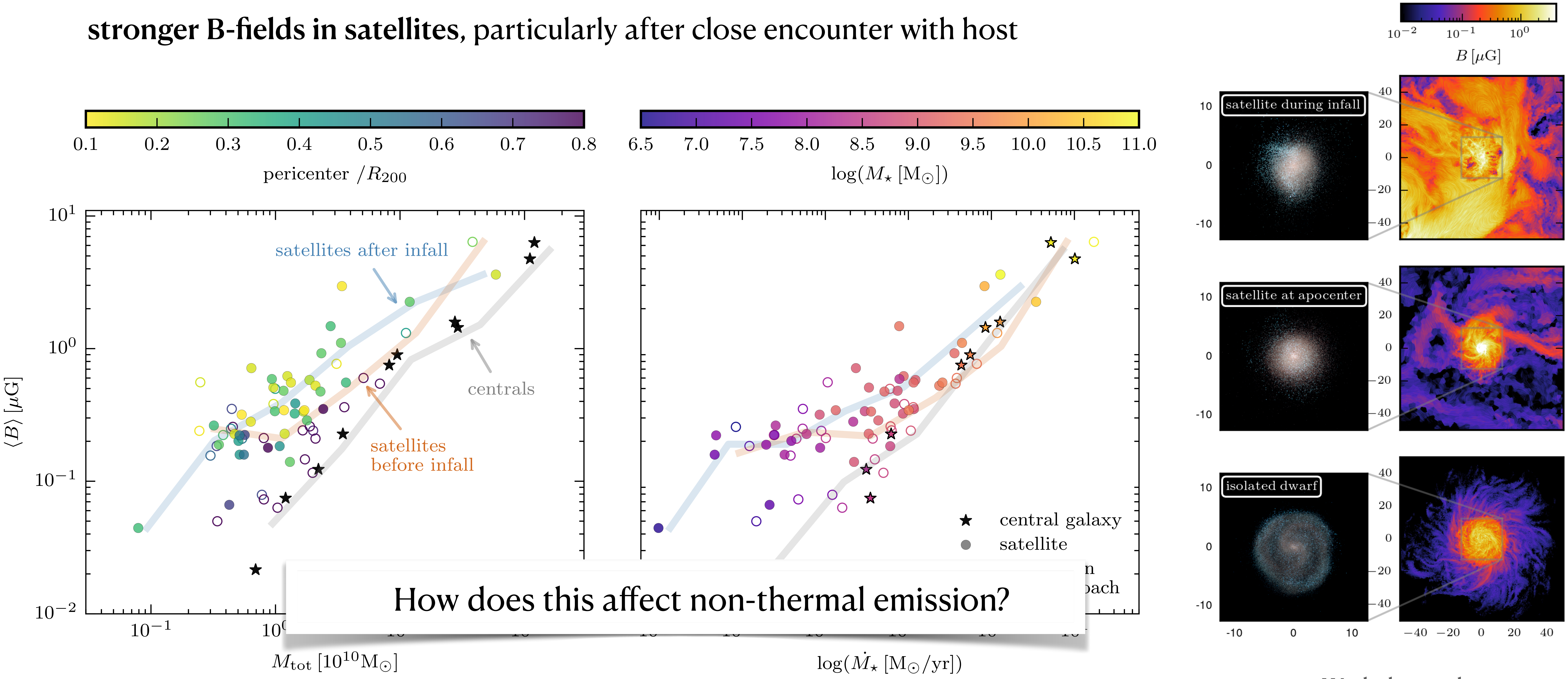
magnetic field strength

Cosmological zoom simulations

with CRs

B-field amplification

stronger B-fields in satellites, particularly after close encounter with host



How does this affect non-thermal emission?

Werhahn et al. 2025

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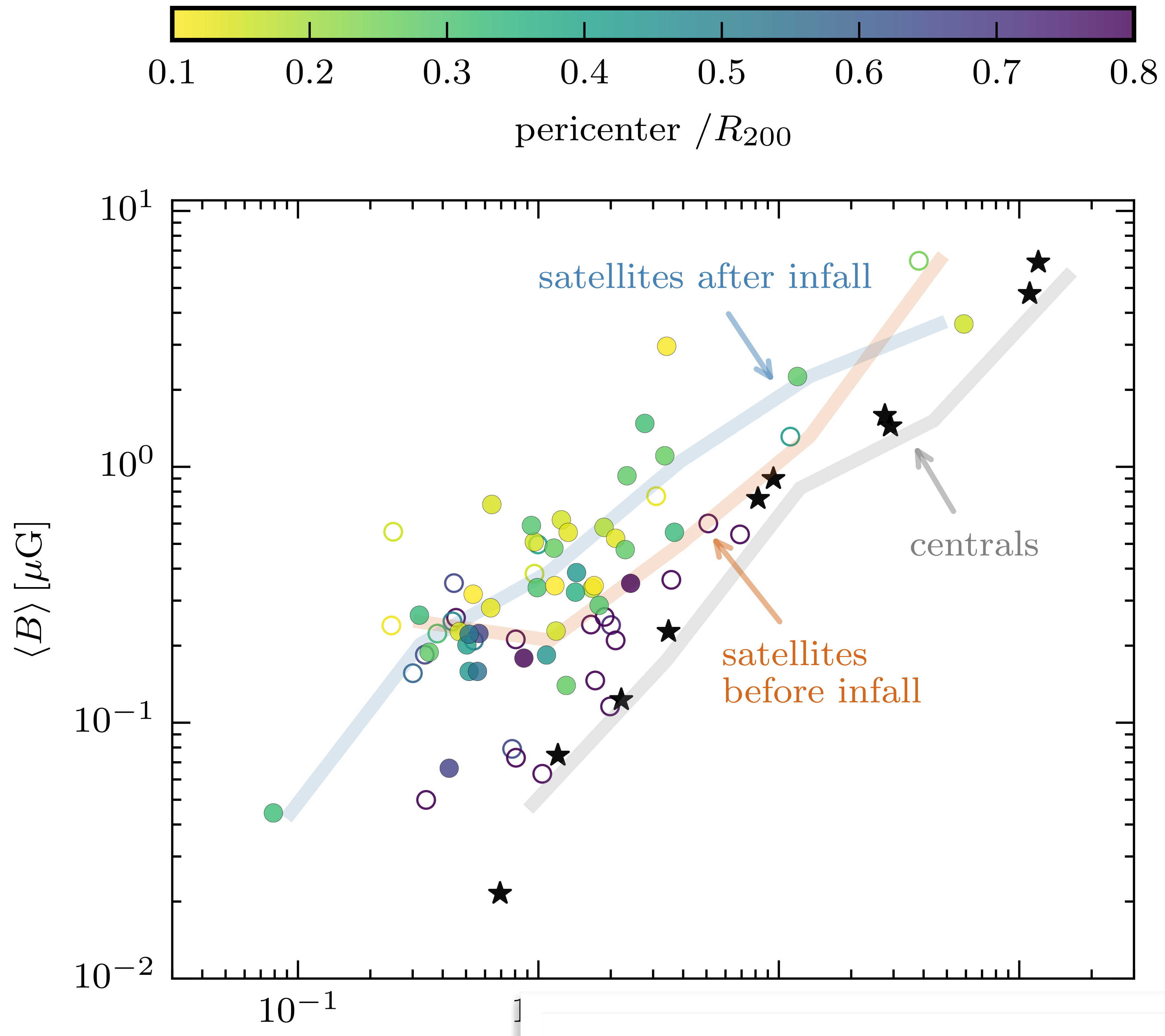
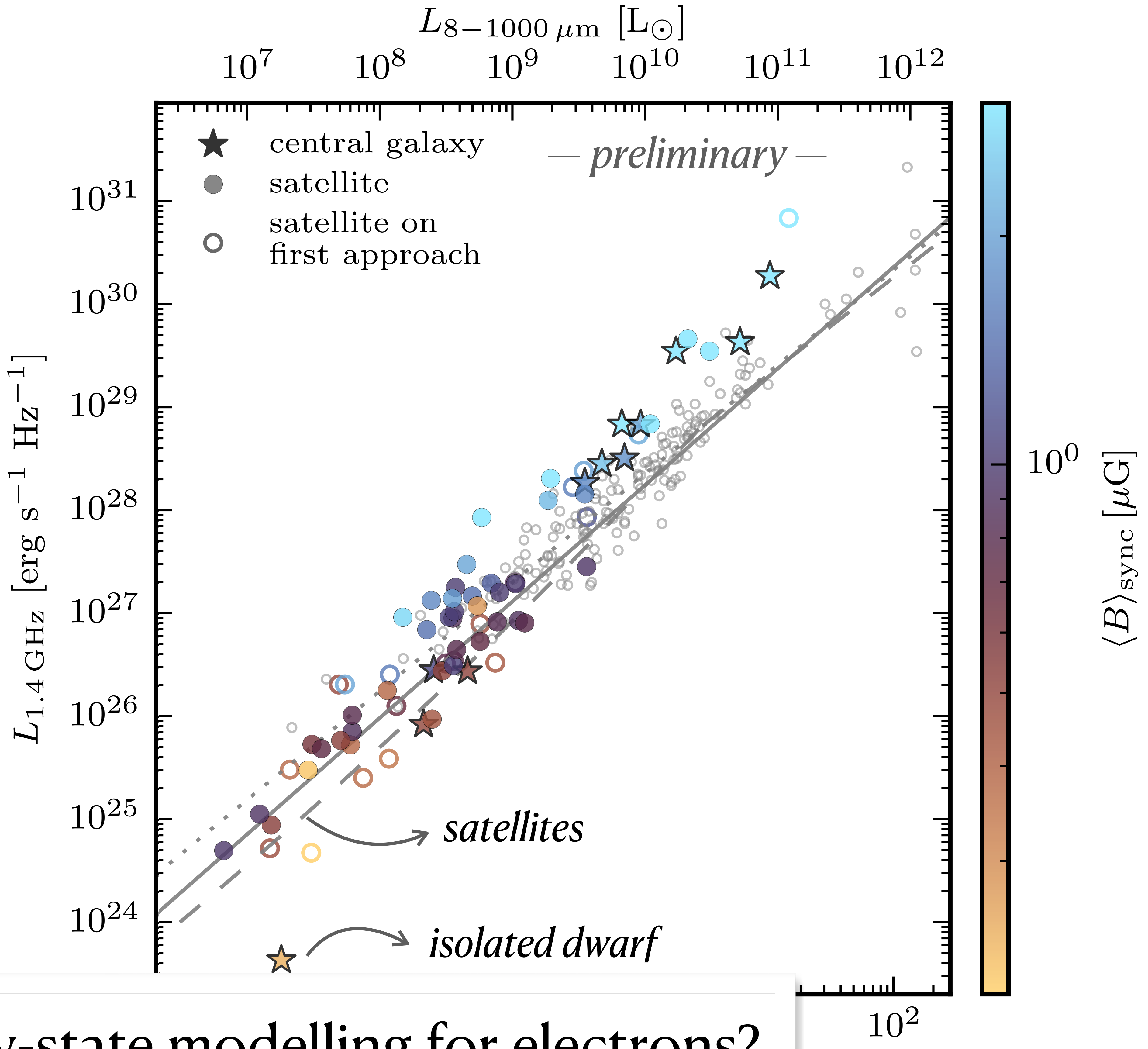
Cosmological zoom simulations

with CRs

B-field amplification

stronger B-fields in satellites, particularly after close encounter with host



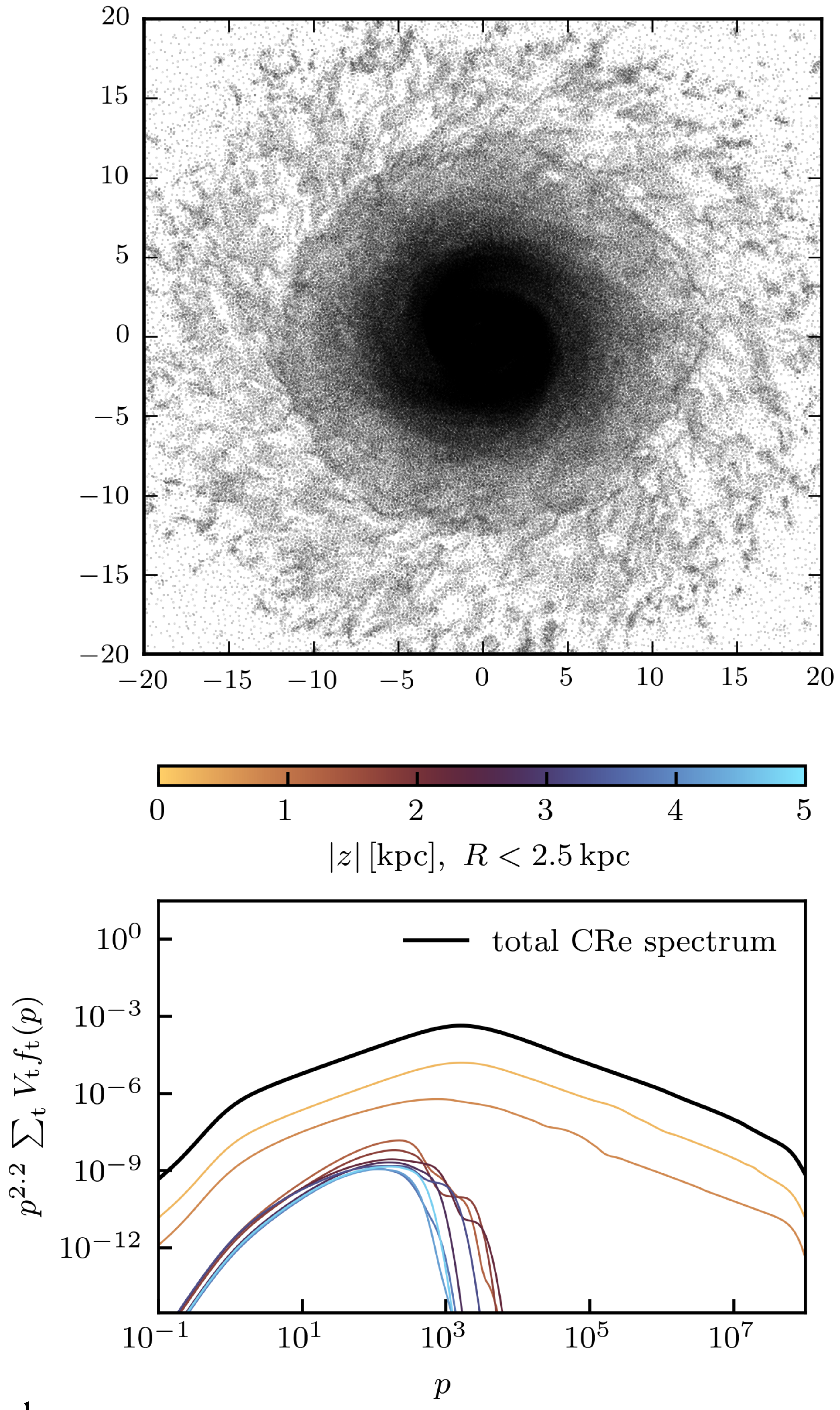


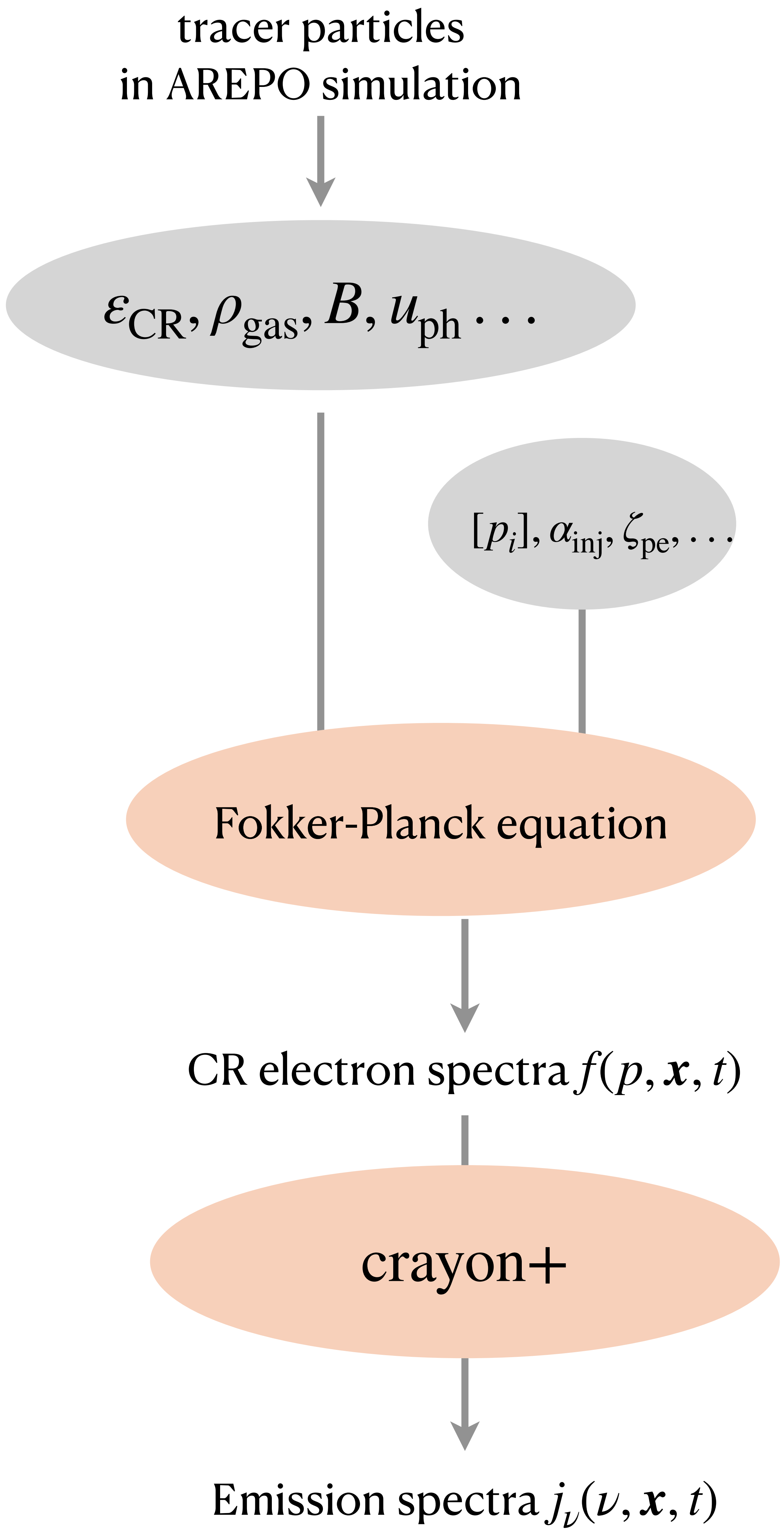
How good is the steady-state modelling for electrons?

Werhahn et al. (in prep)

Maria Werhahn

CREST - CR electron spectra evolved in time





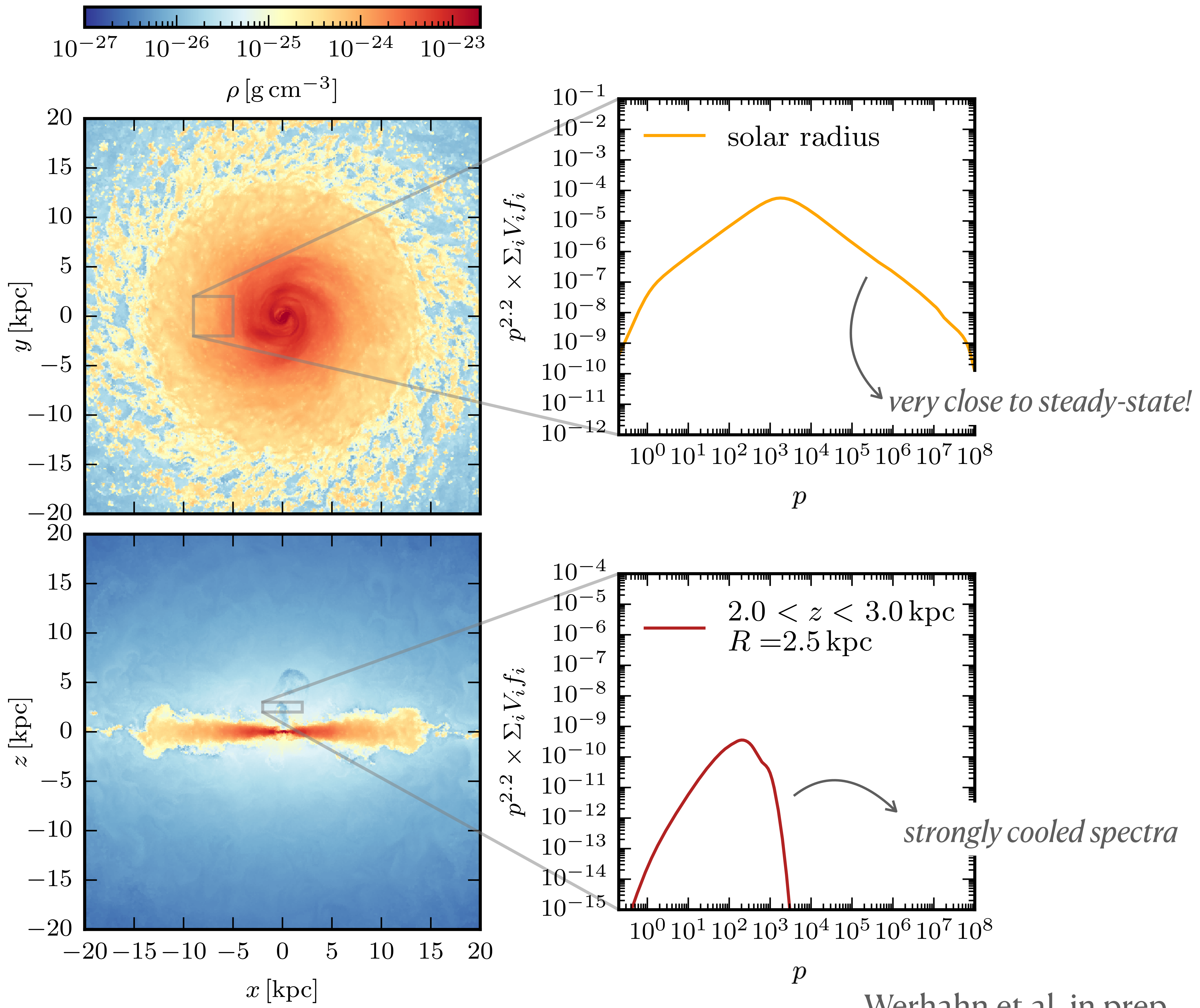
CREST (Winner+2019)

further development by Joseph Whittingham, Léna Ljassi & me

- post-processing MHD simulations: solve Fokker-Planck equation on Lagrangian tracer particles
- accurate calculation of CR electron spectra as function of time and space
- coupled to **crayon**+ for calculation of radiation processes

CREST - CR electron spectra evolved in time

Are galaxies in a steady-state?



Werhahn et al. in prep.

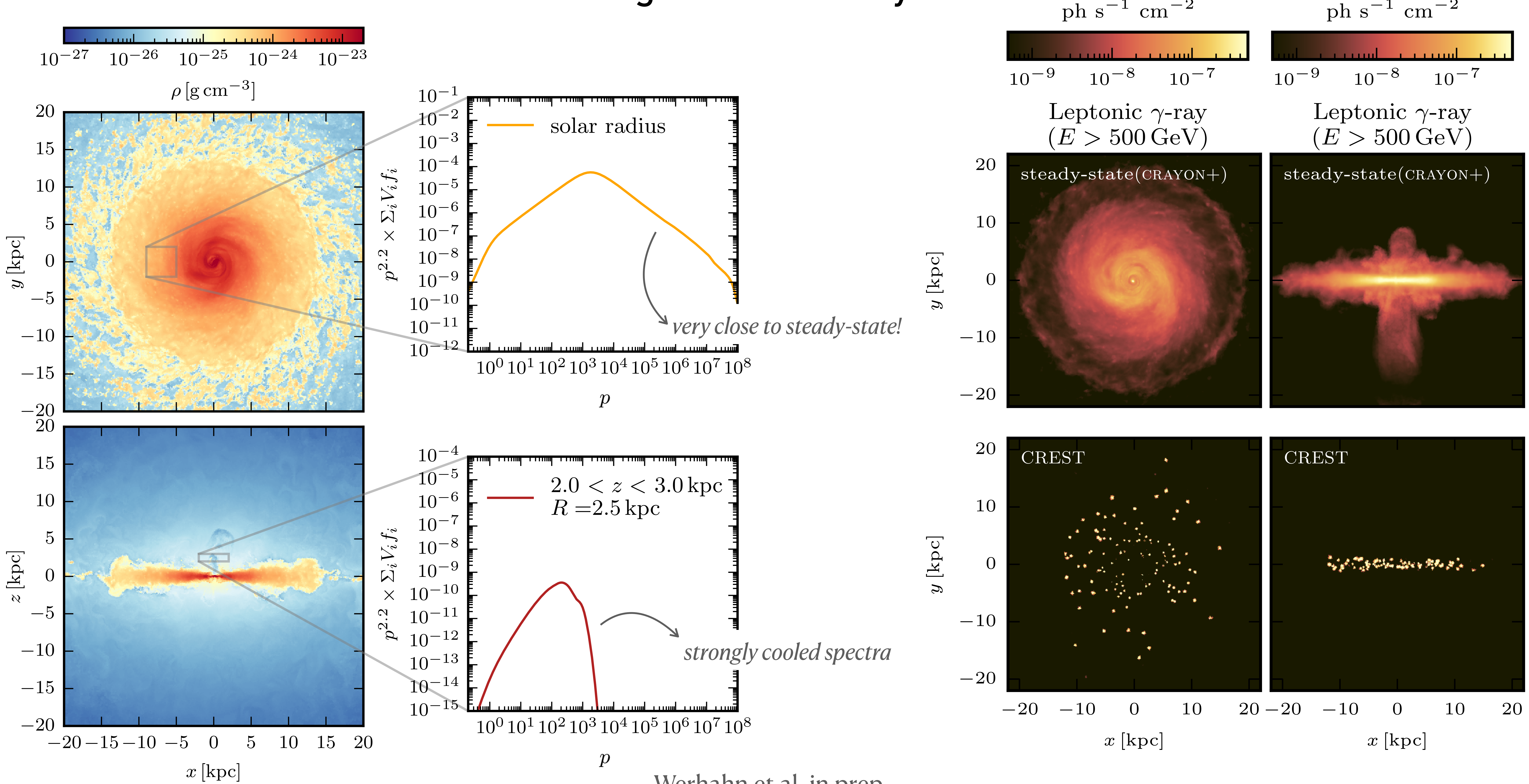
CREST (Winner+2019)

further development by Joseph Whittingham, Léna Ljassi & me

- post-processing MHD simulations: solve Fokker-Planck equation on Lagrangian tracer particles
- accurate calculation of CR electron spectra as function of time and space
- coupled to **crayon**+ for calculation of radiation processes
- *global* spectrum: very close to steady-state
- many *local* variations (outflows, regions of strong cooling/no recent injection)

CREST - CR electron spectra evolved in time

Are galaxies in a steady-state?



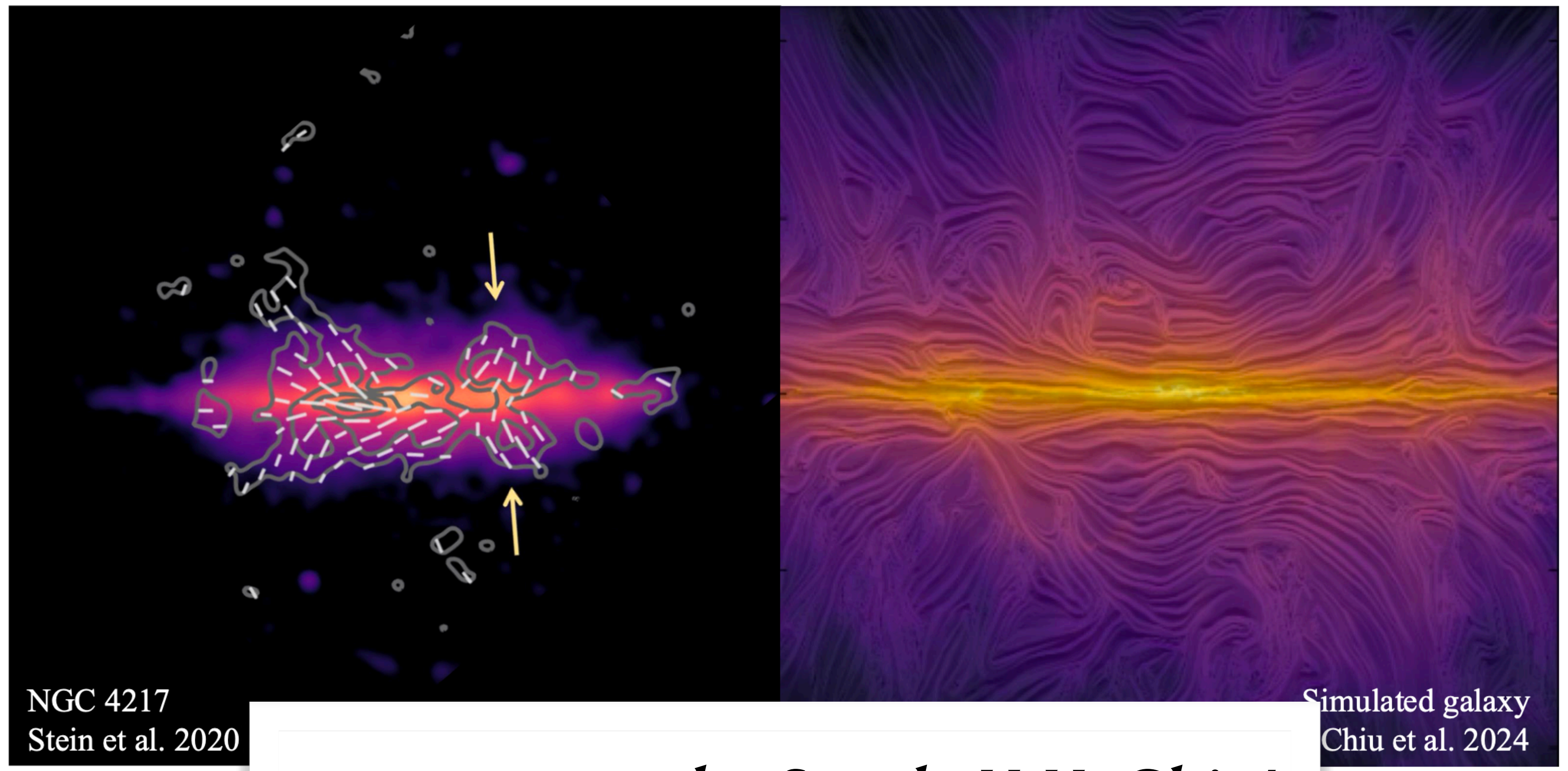
Werhahn et al. in prep.

Maria Werhahn

Summary

Steady-state CR spectra in MHD simulations:

- **Gamma-ray emission**:
  - low SFR: diffusion relevant; high SFR: close to calorimetric limit
- **Radio emission**: FIR-radio relation is dominated by primary emission
  - steep spectra due to IC & sync. losses—> flat radio spectra: thermal contribution



see poster by Sandy H.H. Chiu!

Spectral simulations of CR protons

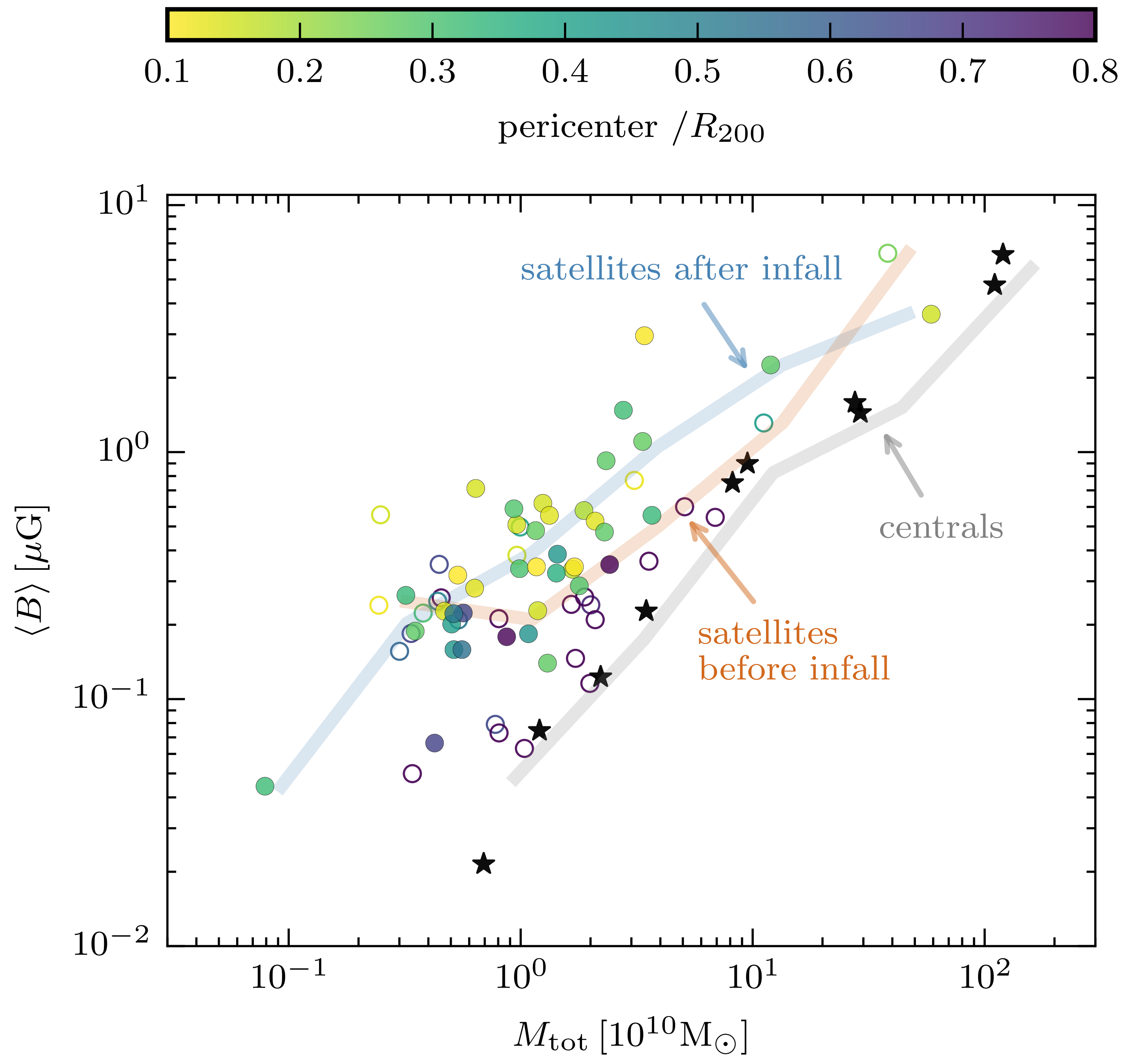
- required for modelling of spatially resolved high-energy gamma-rays

Radio emission from galaxy with two-moment CR transport (CRISP):

- X-shaped morphology in B-field direction due to galactic-scale outflows

CRs in cosmological zoom simulations

- stronger B-fields in satellites vs. isolated dwarfs
  —> affects correlations of non-thermal emission with SFR



Live electrons with CREST: global spectra close to steady-state

- strongest differences: in outflows and gamma-ray maps