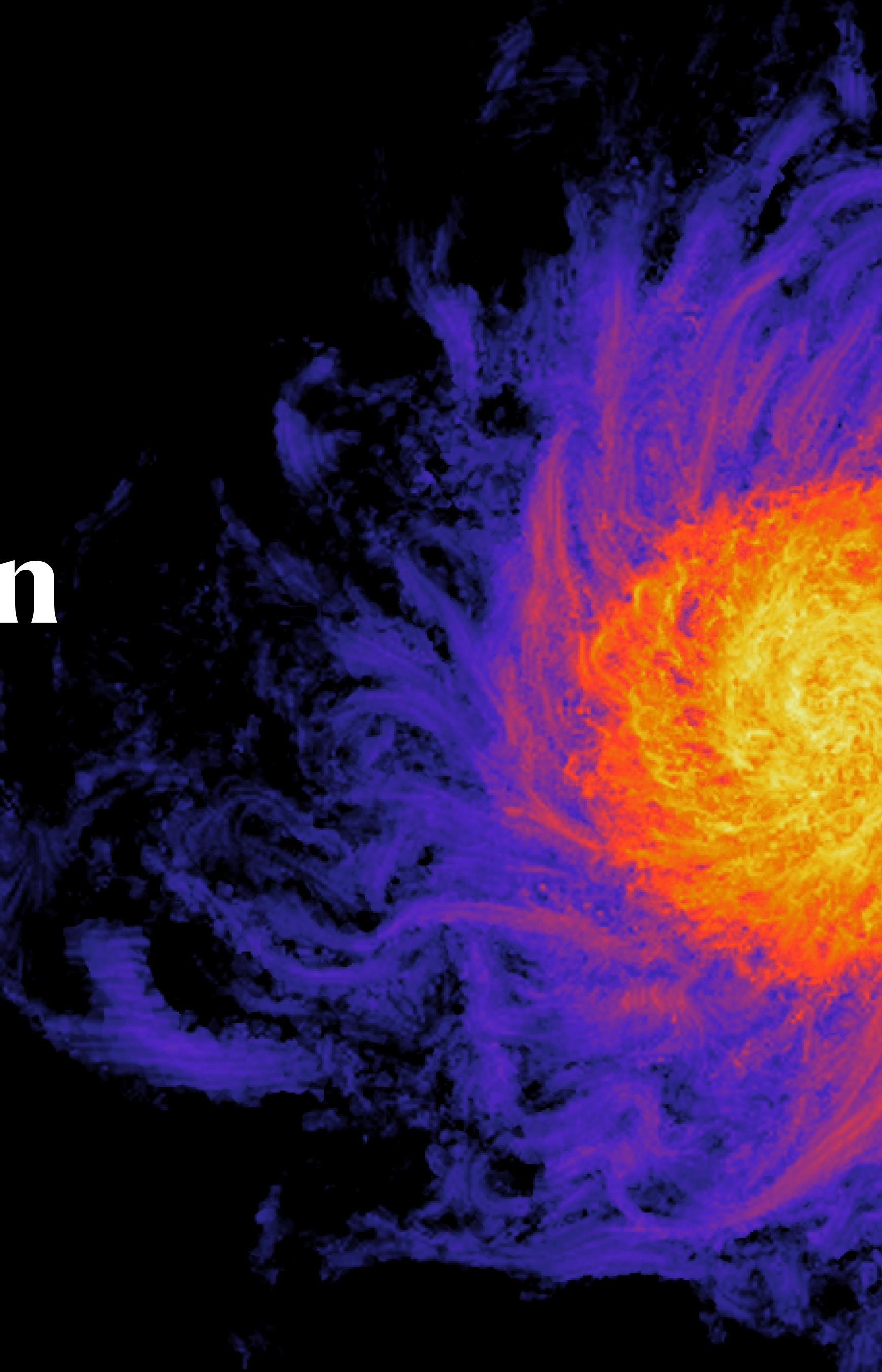


# Constraining Cosmic Ray Feedback in Galaxy Evolution

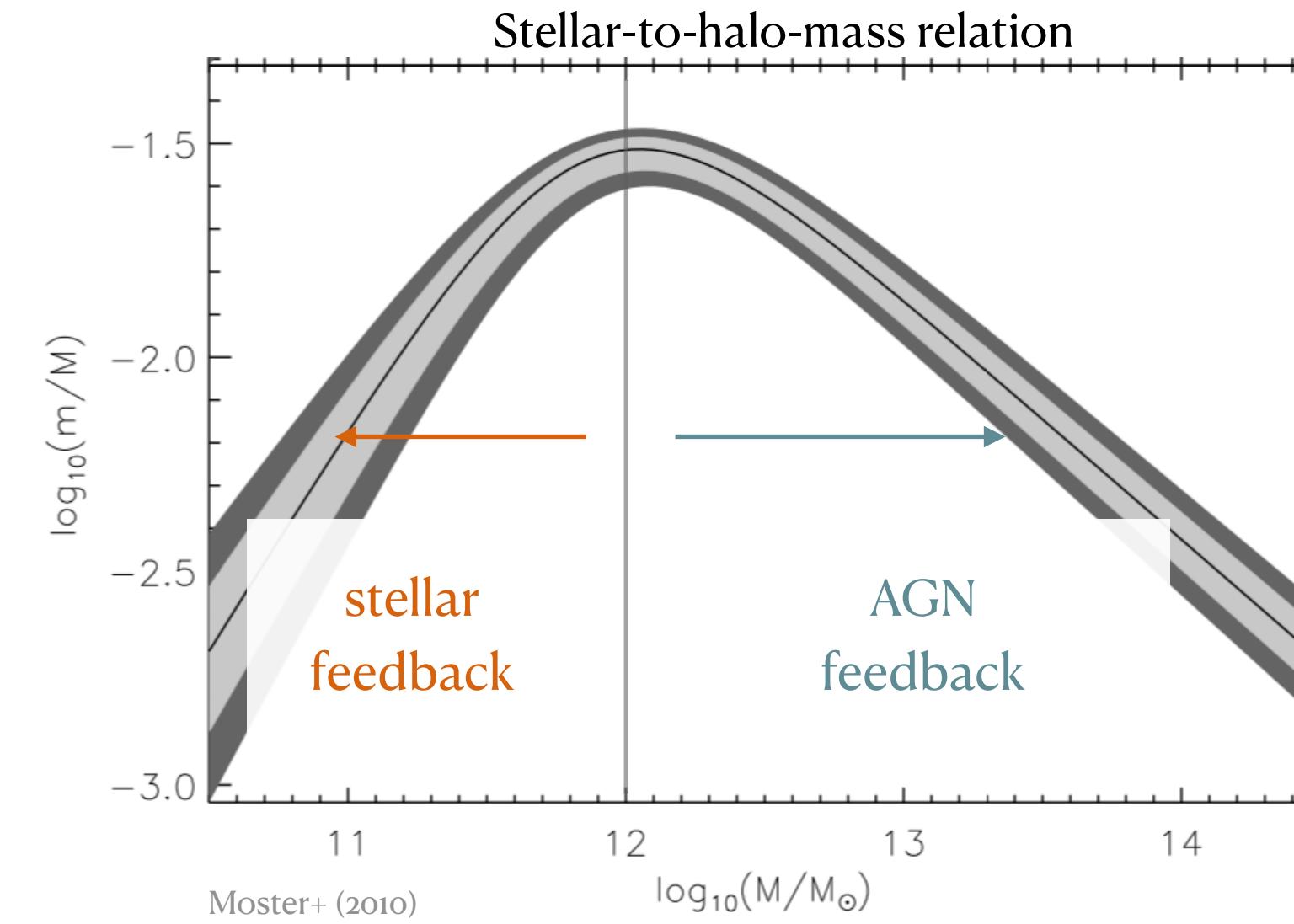
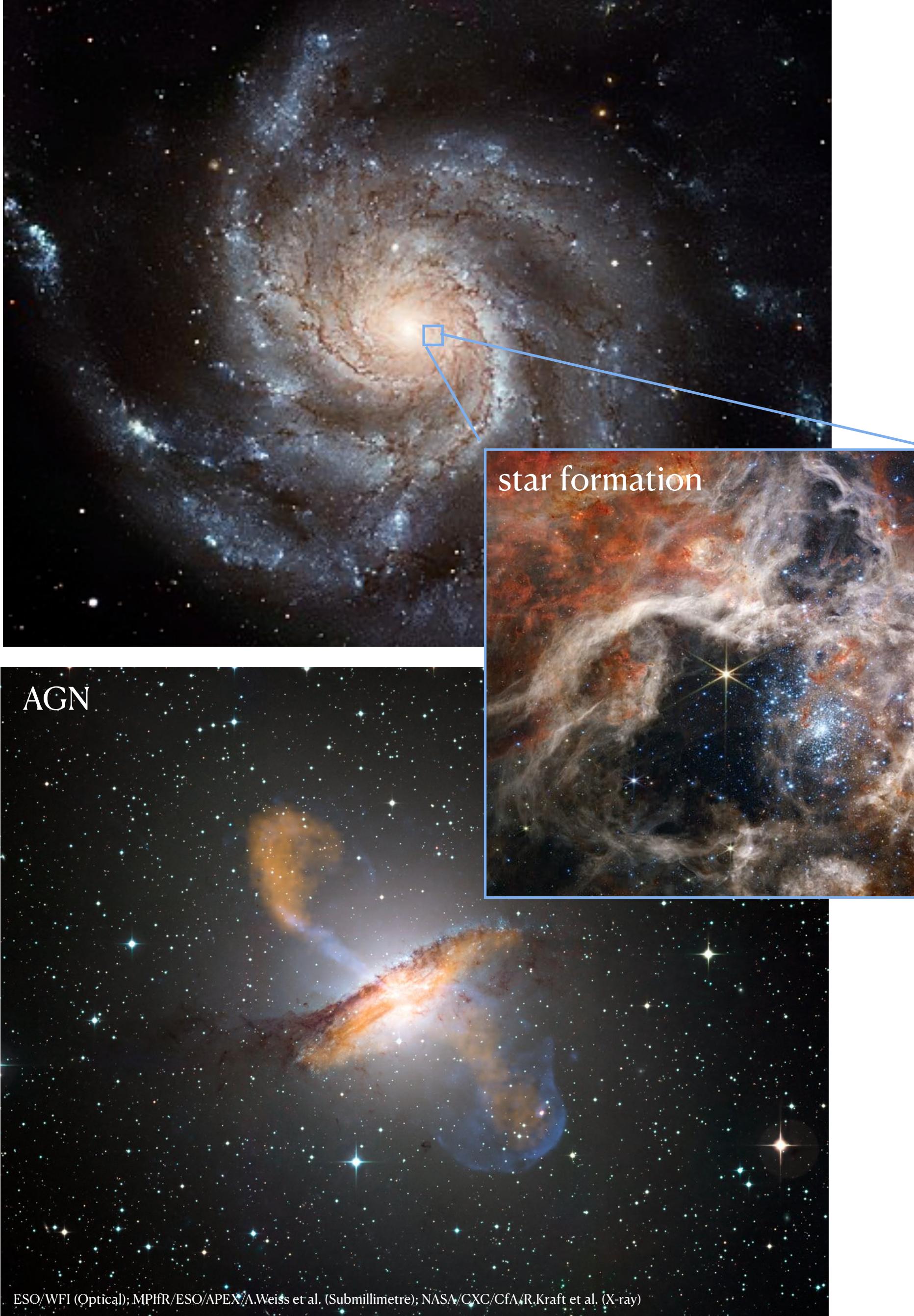
Maria Werhahn

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

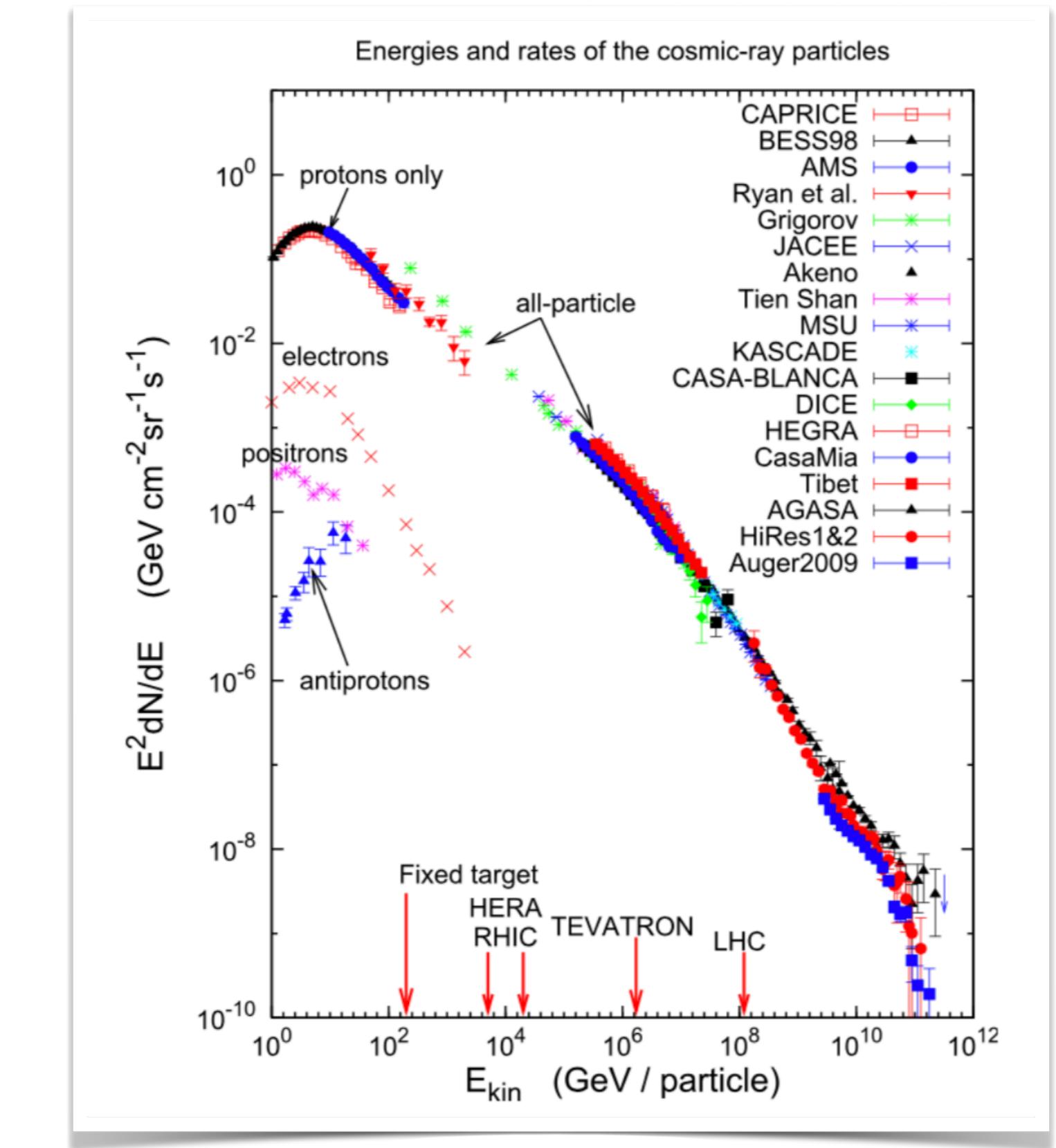
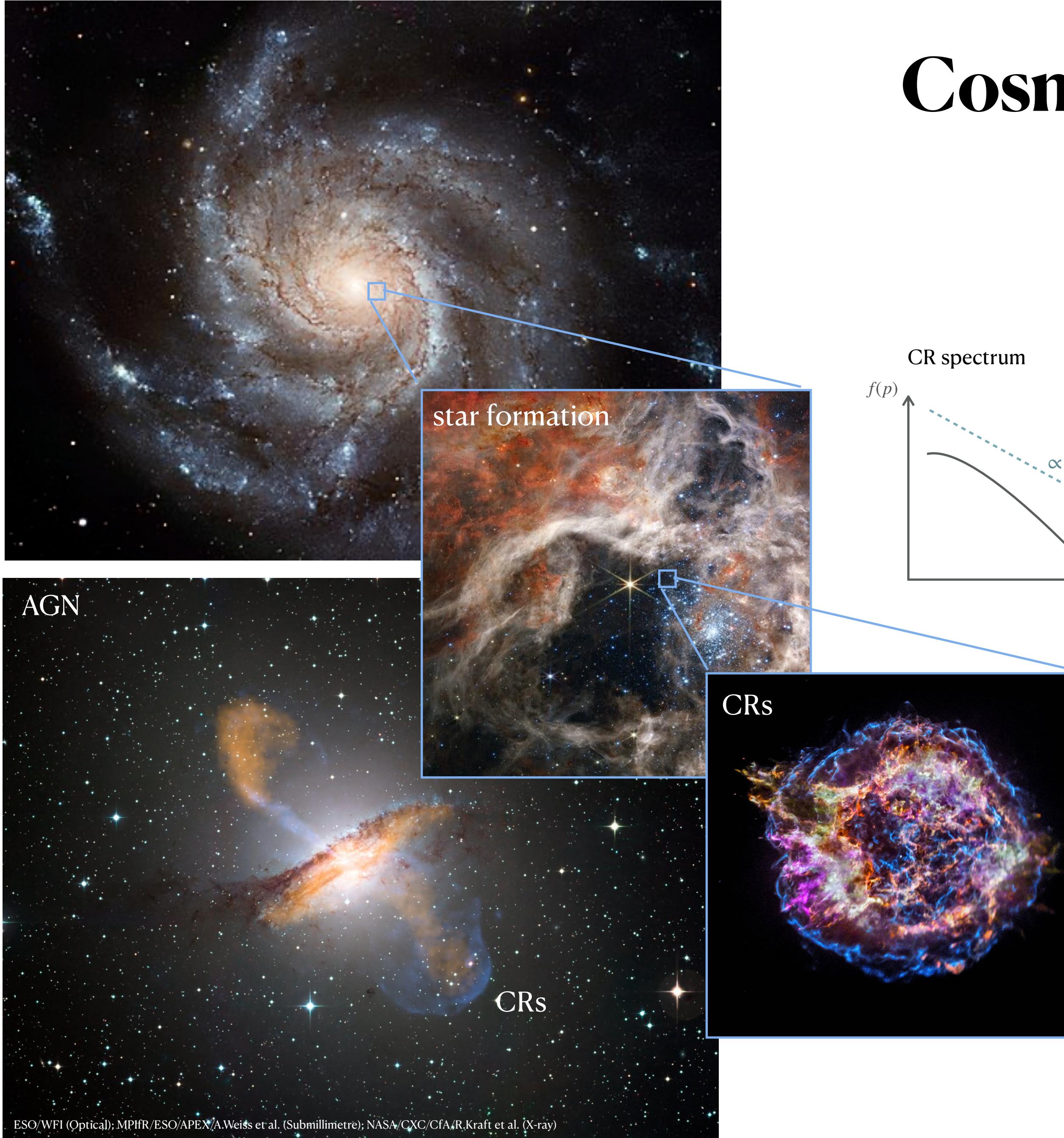
*18th Potsdam Thinkshop, July 16 2025*



# Cosmic Rays in Galaxy Formation



# Cosmic Rays in Galaxy Formation



$\varepsilon_{\text{CR}} \sim \varepsilon_B \sim \varepsilon_{\text{th}} \sim \varepsilon_{\text{kin}} \rightarrow$  feedback agent?

multi-scale problem:

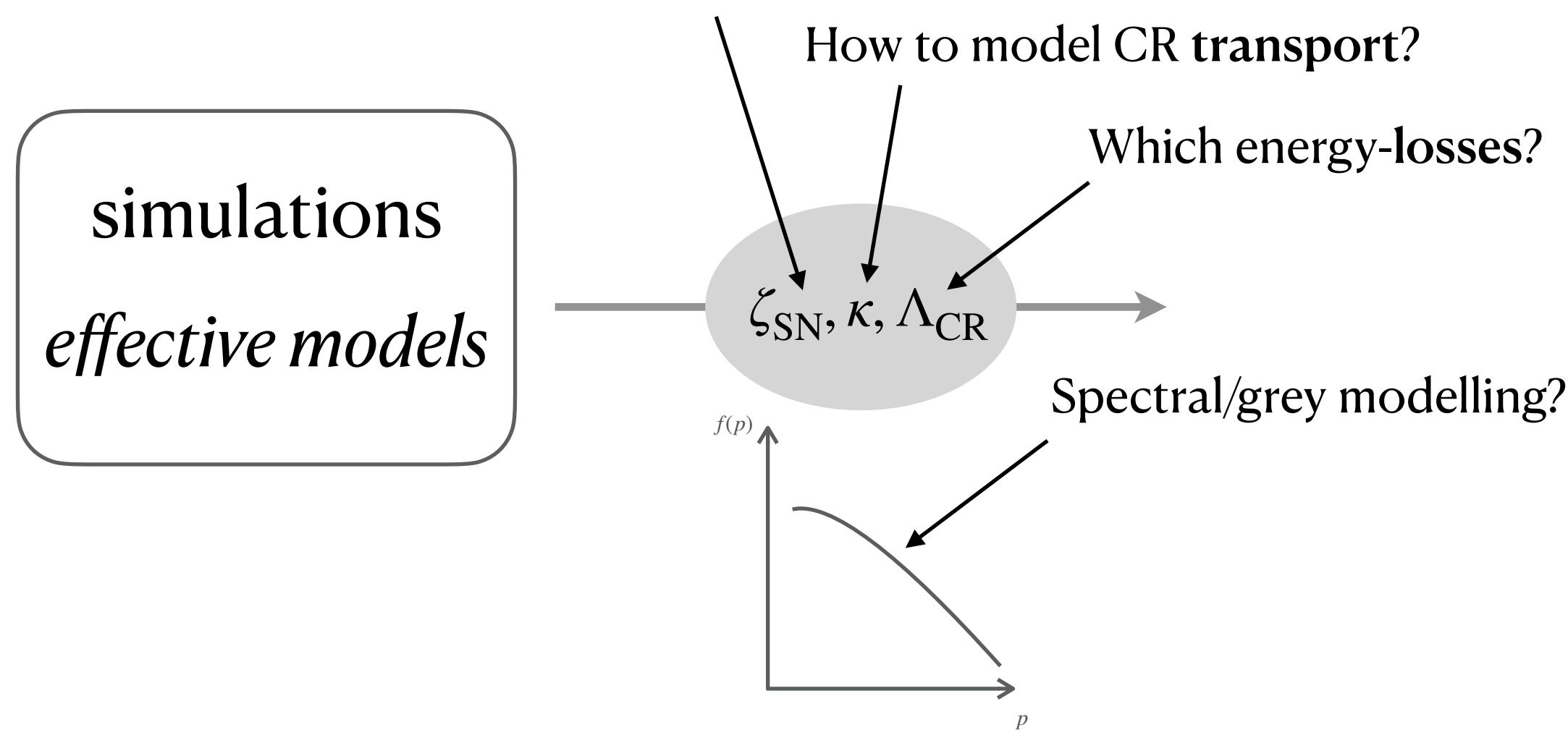
gyro-orbit:  $\sim 10^{-6} \text{ pc} \ll$  galactic scales ( $\sim \text{kpc}$ )

$\rightarrow$  very challenging to model in galaxy simulations

# Modelling Cosmic Rays in Galaxies

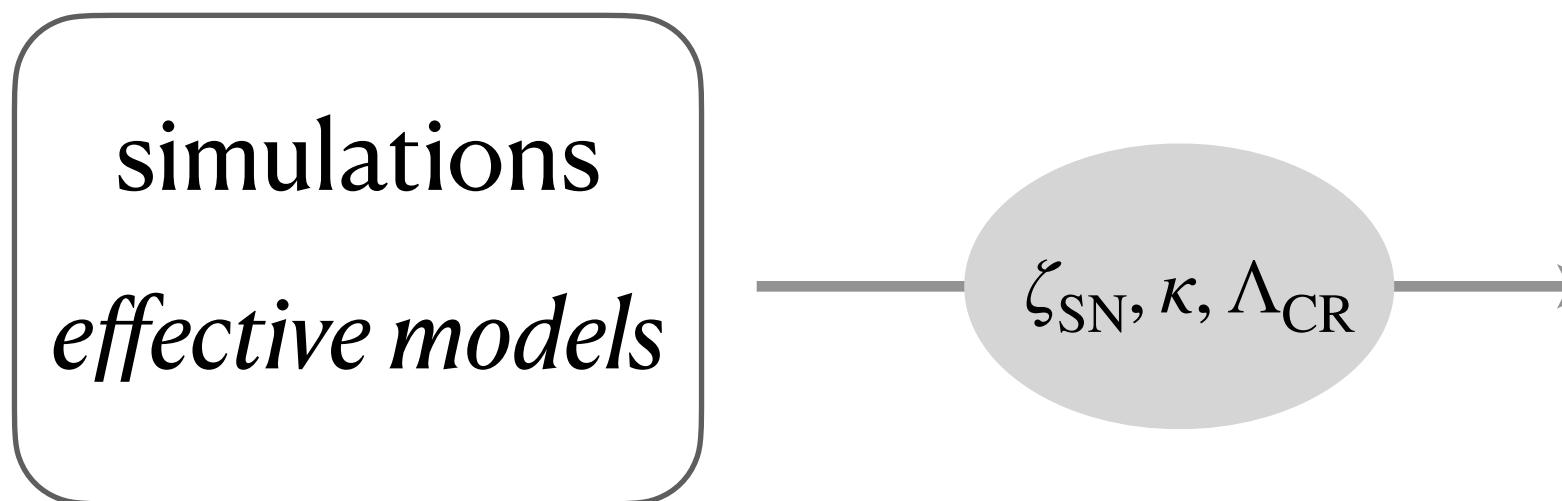
How can we constrain CR feedback?

How much energy  $\rightarrow$  CRs?



# Modelling Cosmic Rays in Galaxies

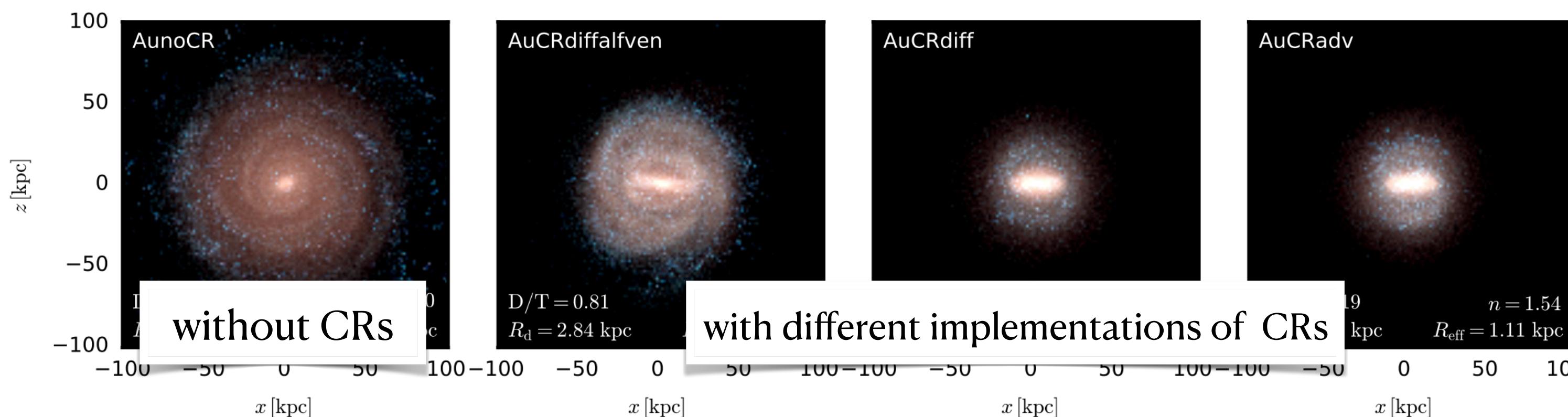
## How can we constrain CR feedback?



### *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)



# Modelling Cosmic Rays in Galaxies

## How can we constrain CR feedback?

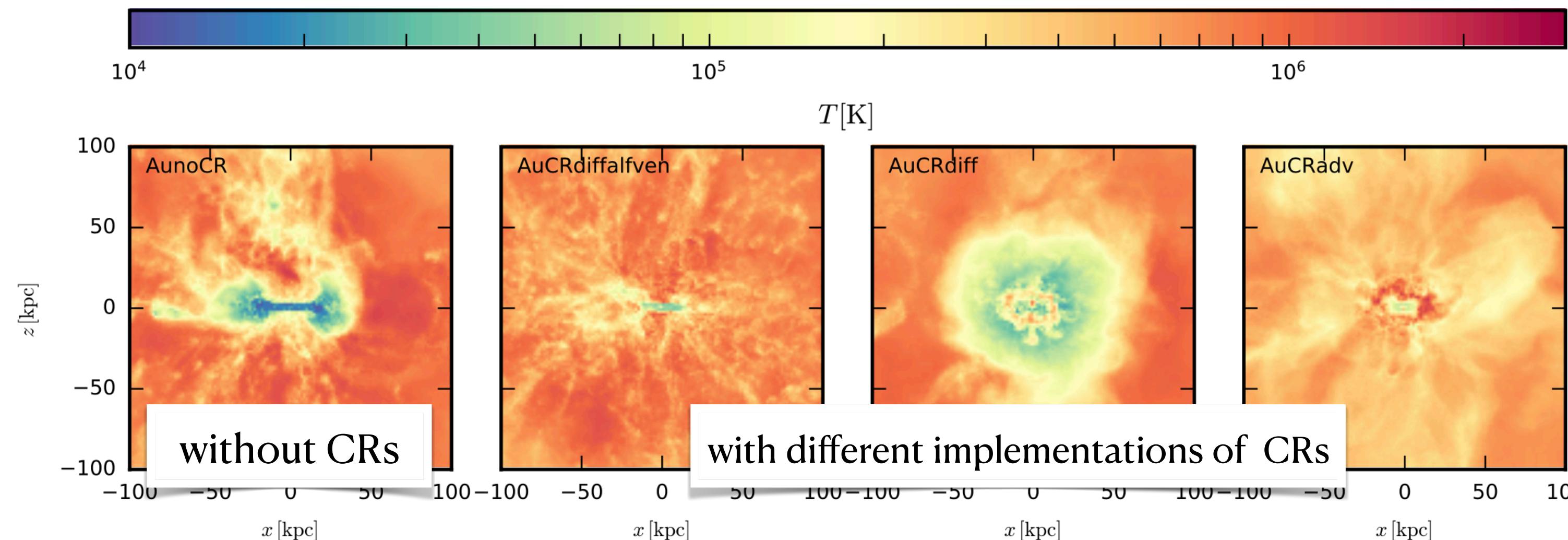
simulations  
*effective models*

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

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Buck+2020

# Modelling Cosmic Rays in Galaxies

## How can we constrain CR feedback?

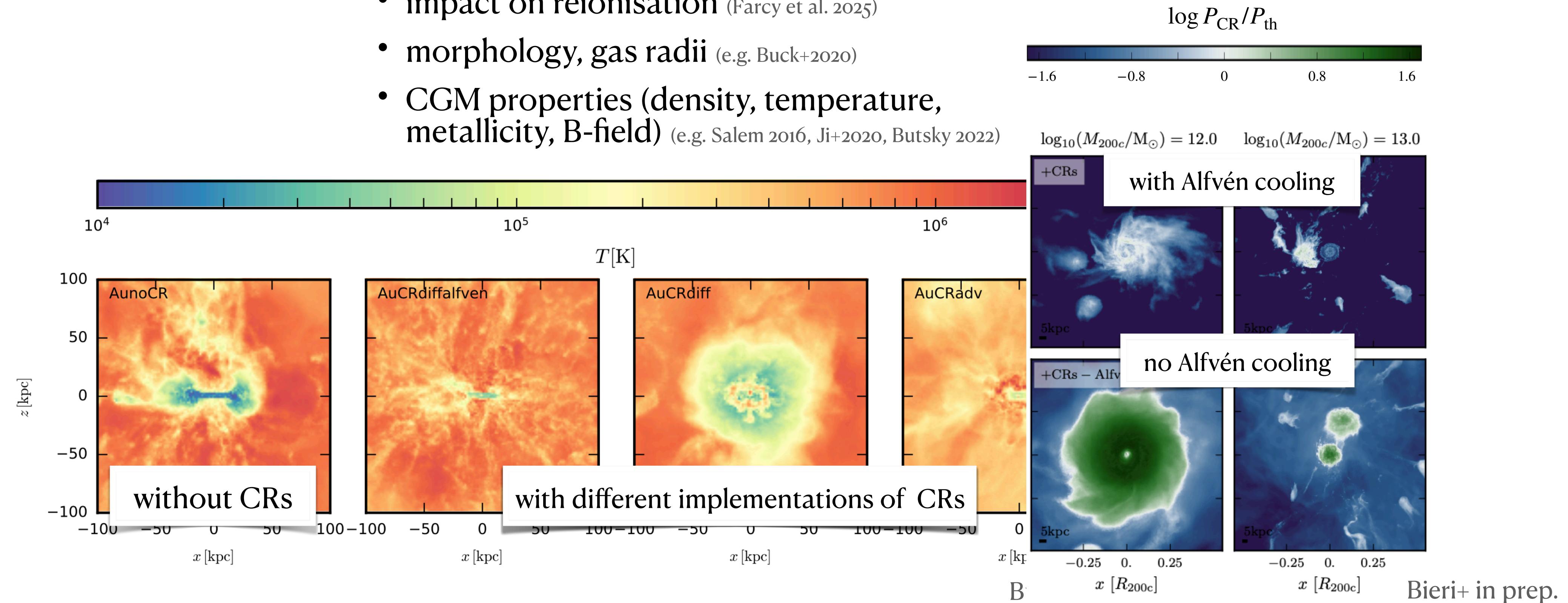
simulations  
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# Modelling Cosmic Rays in Galaxies

How can we constrain CR feedback?

simulations  
*effective models*

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

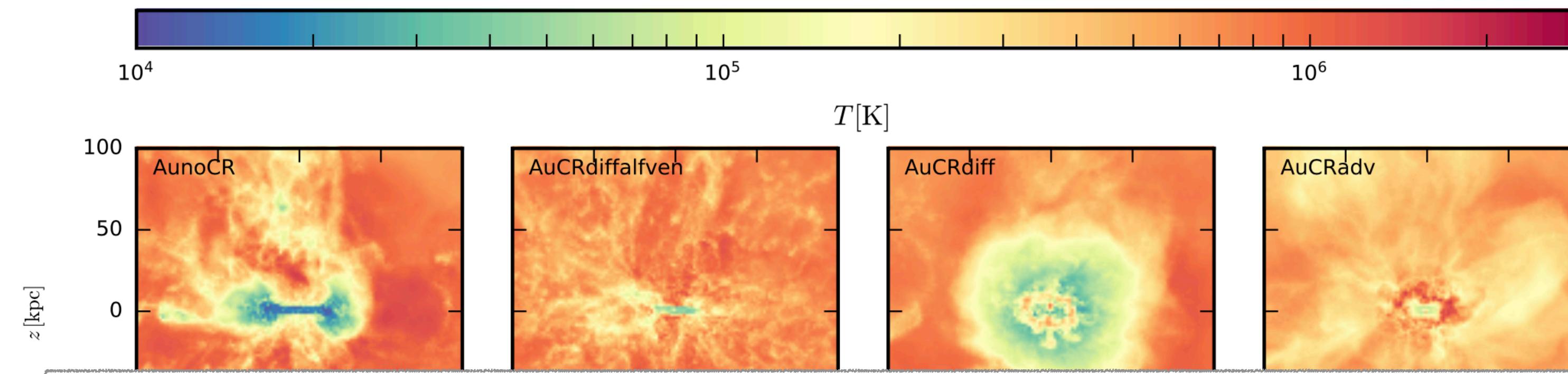
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?

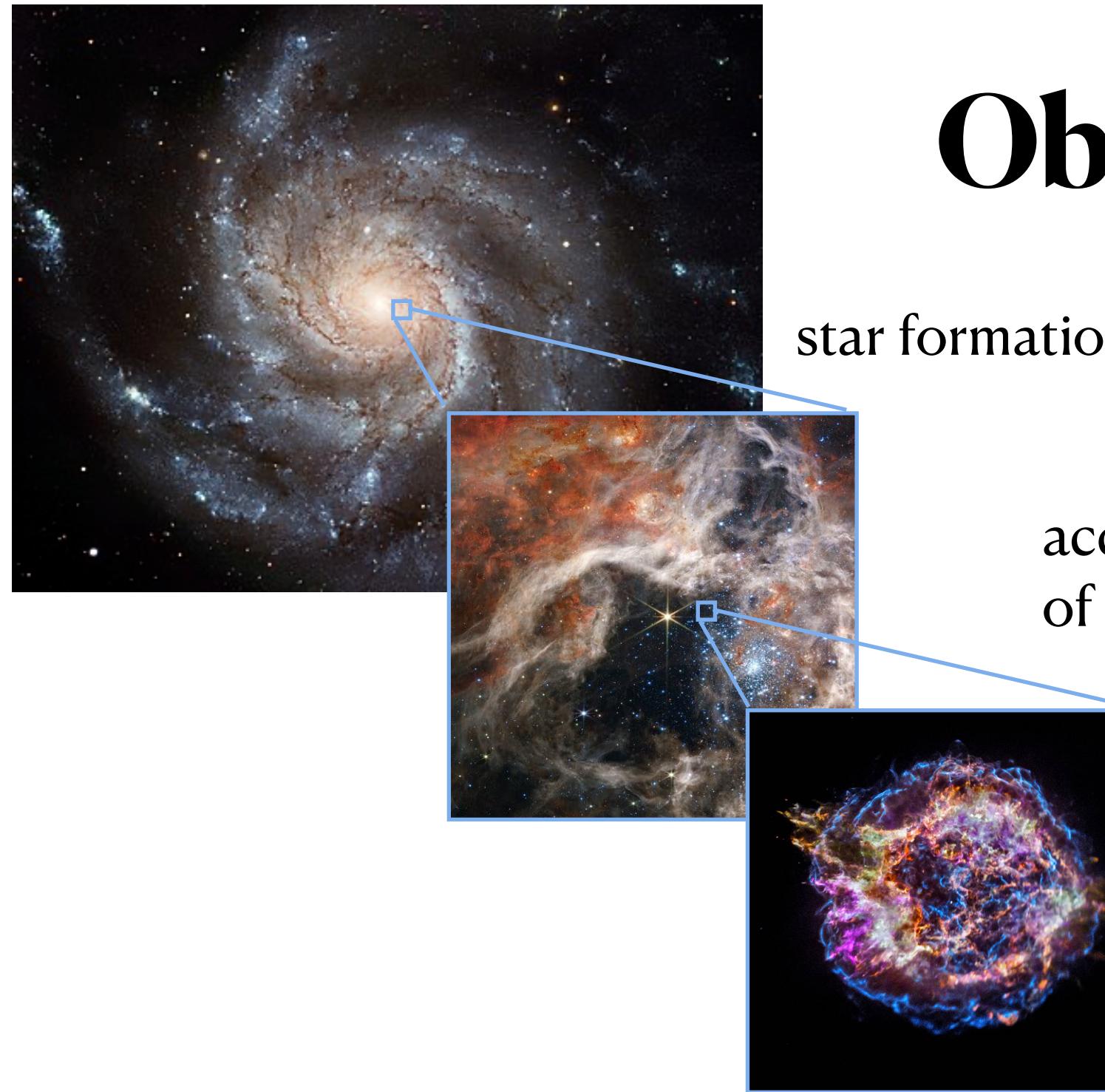
observables



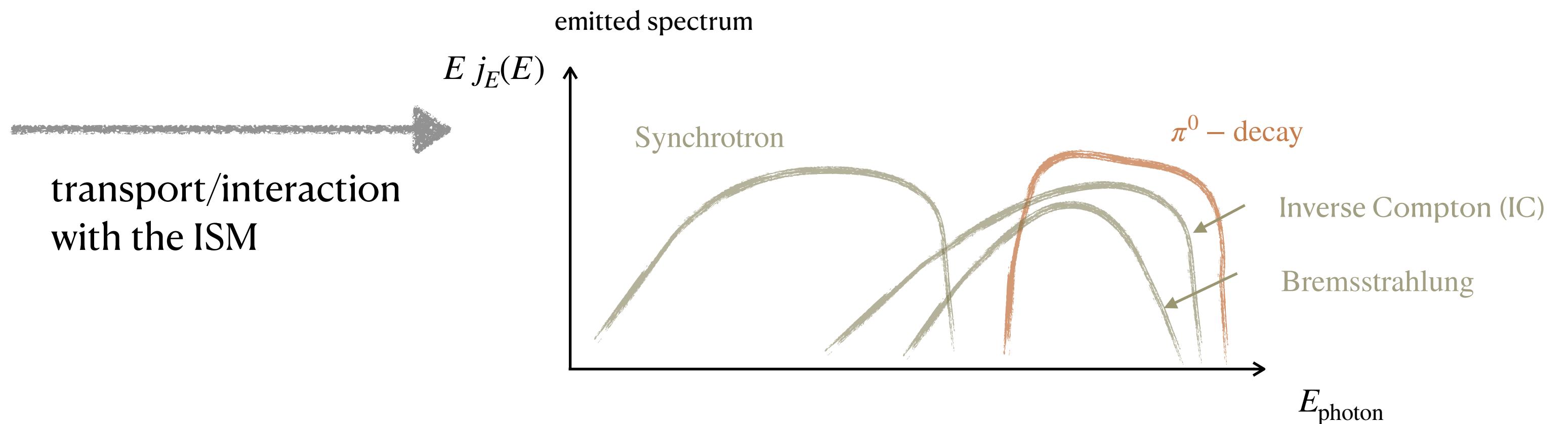
need to forward model CR-related observables

to clarify role of CRs in galaxy evolution

# Observational Constraints of CRs

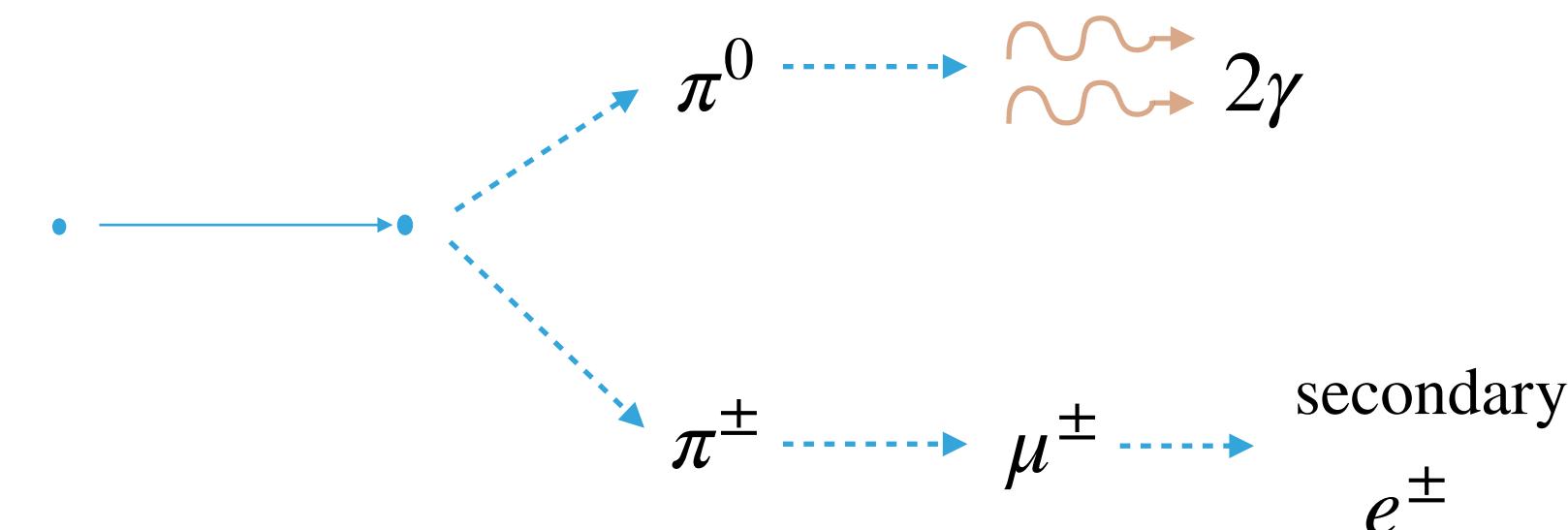


## Non-thermal emission



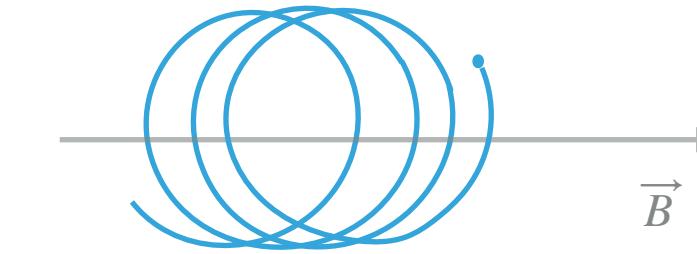
CR protons:

- pion decay

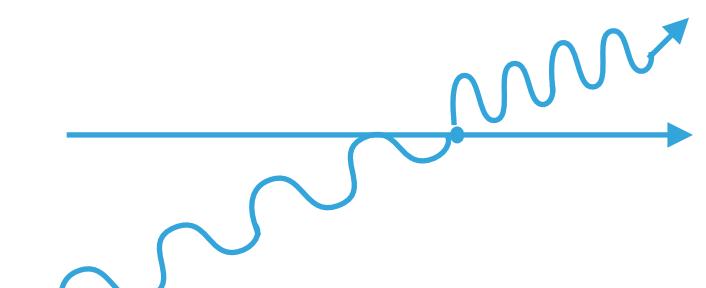


CR electrons (primary + secondary):

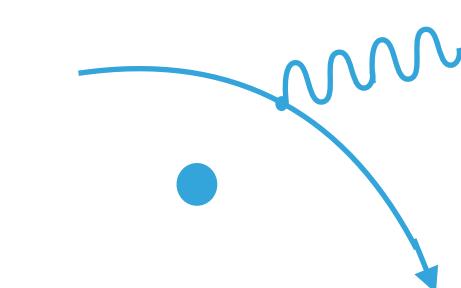
- Synchrotron emission



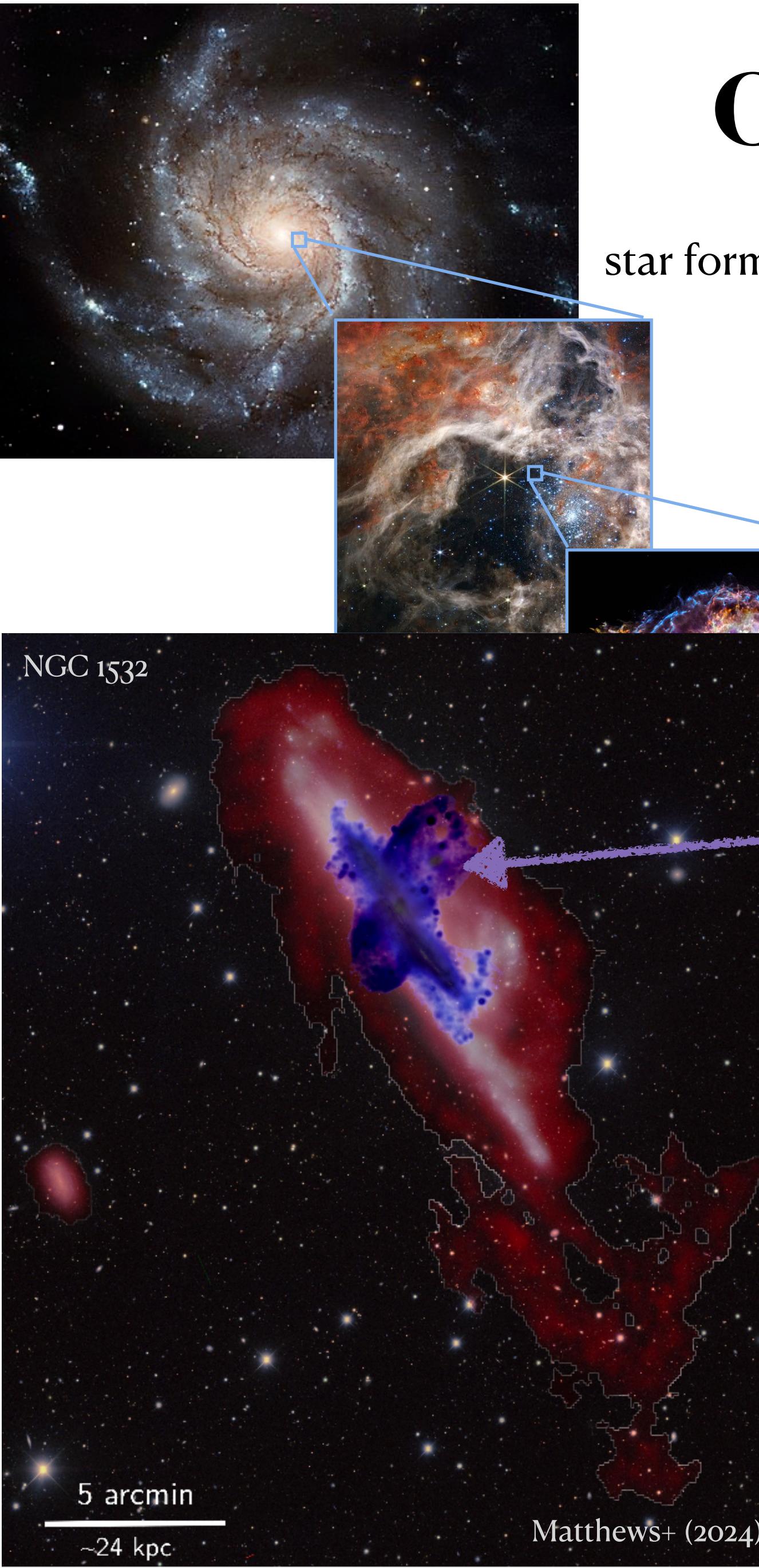
- Inverse Compton (IC) emission



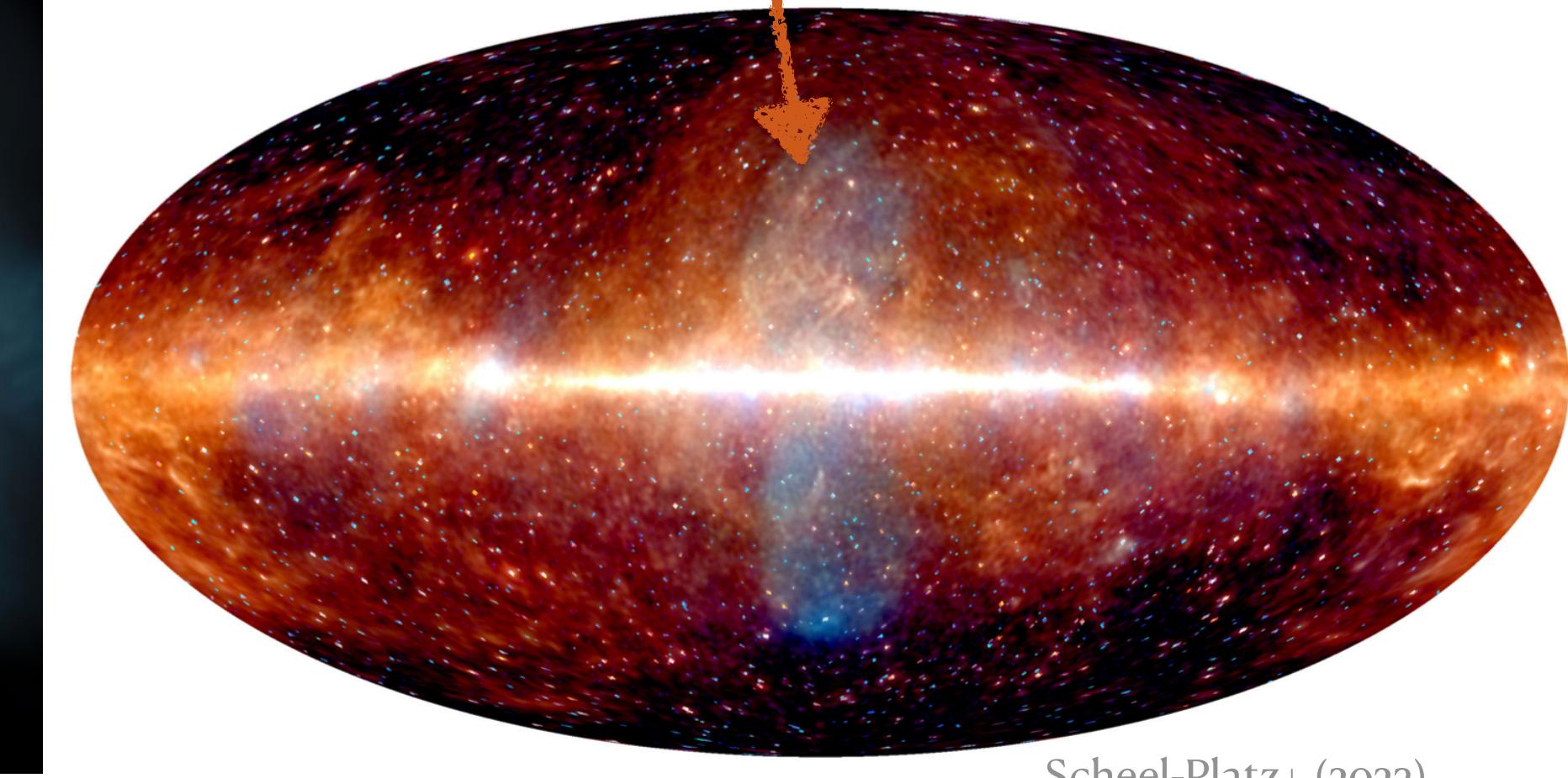
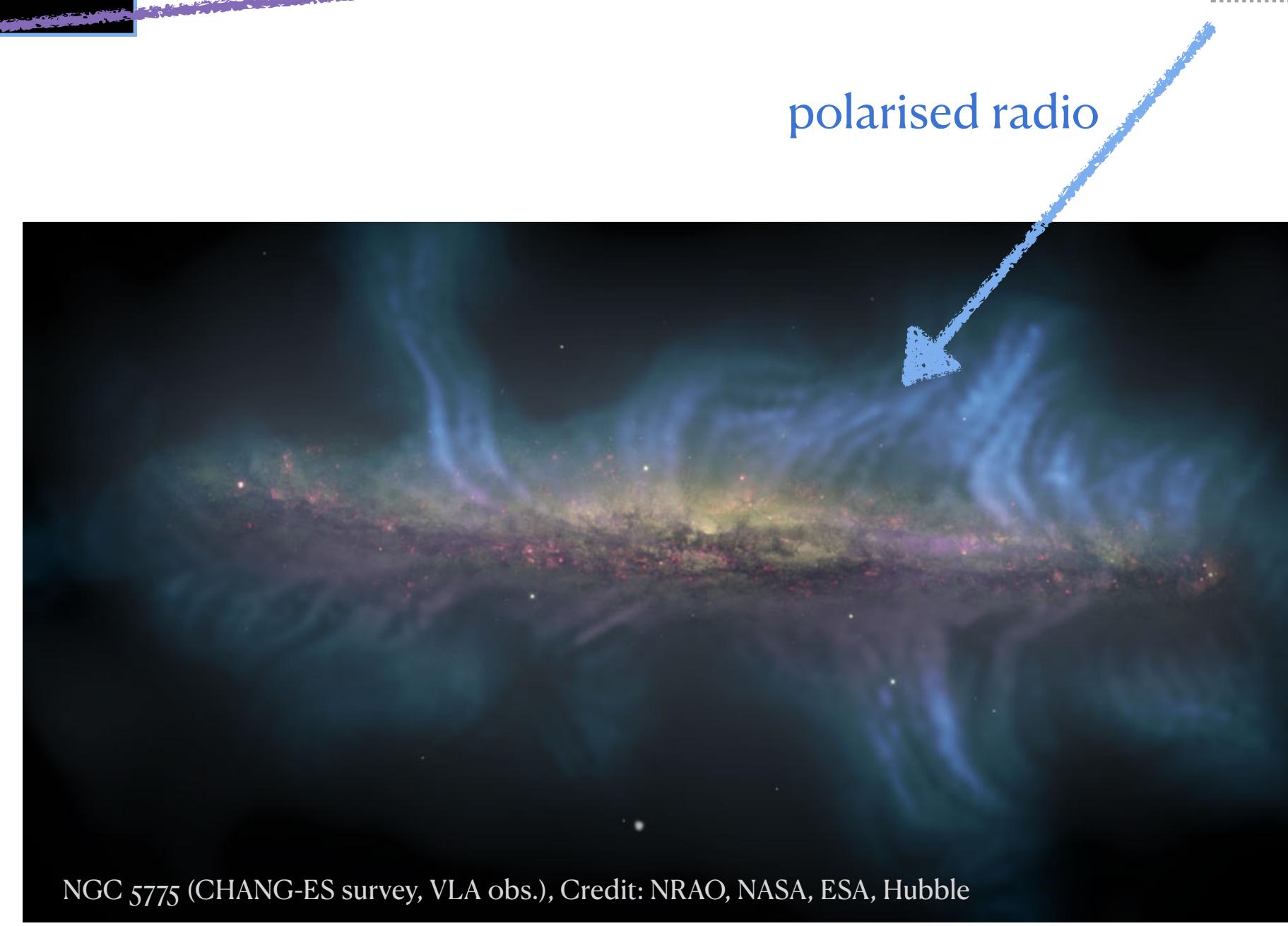
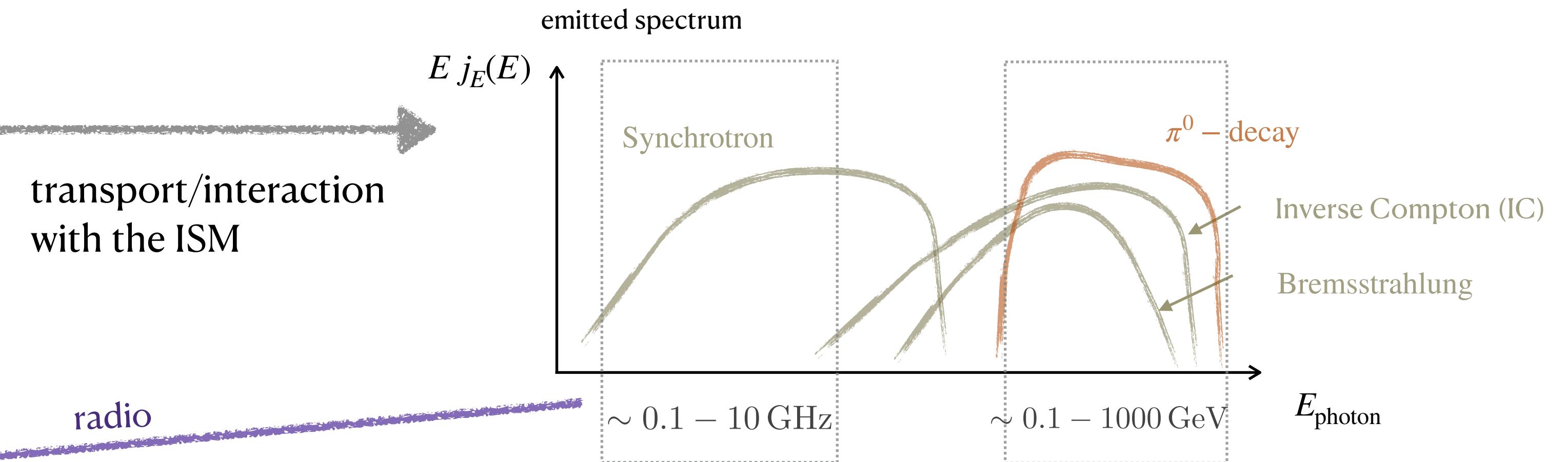
- Bremsstrahlung



# Observational Constraints of CRs



## Non-thermal emission



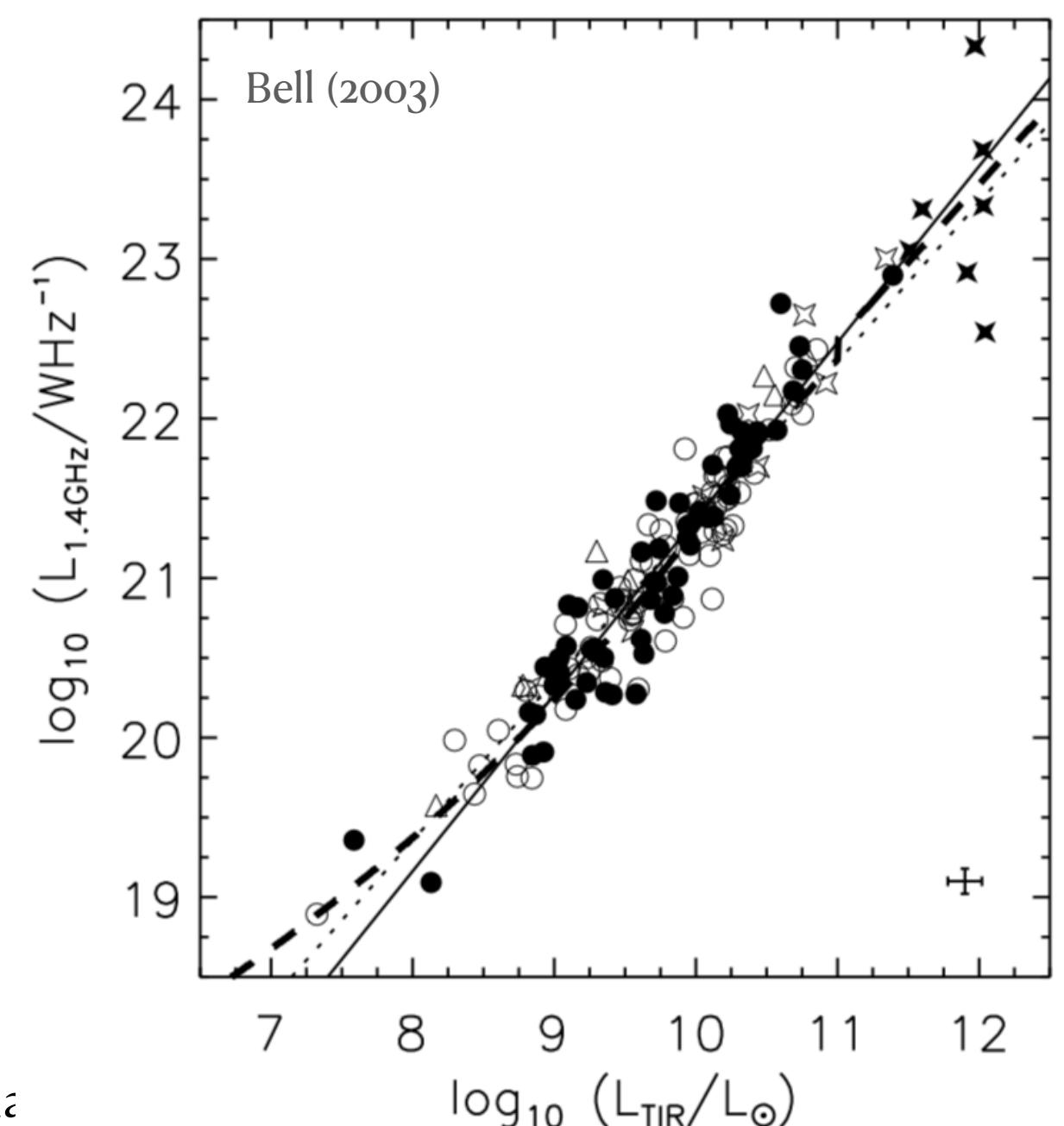
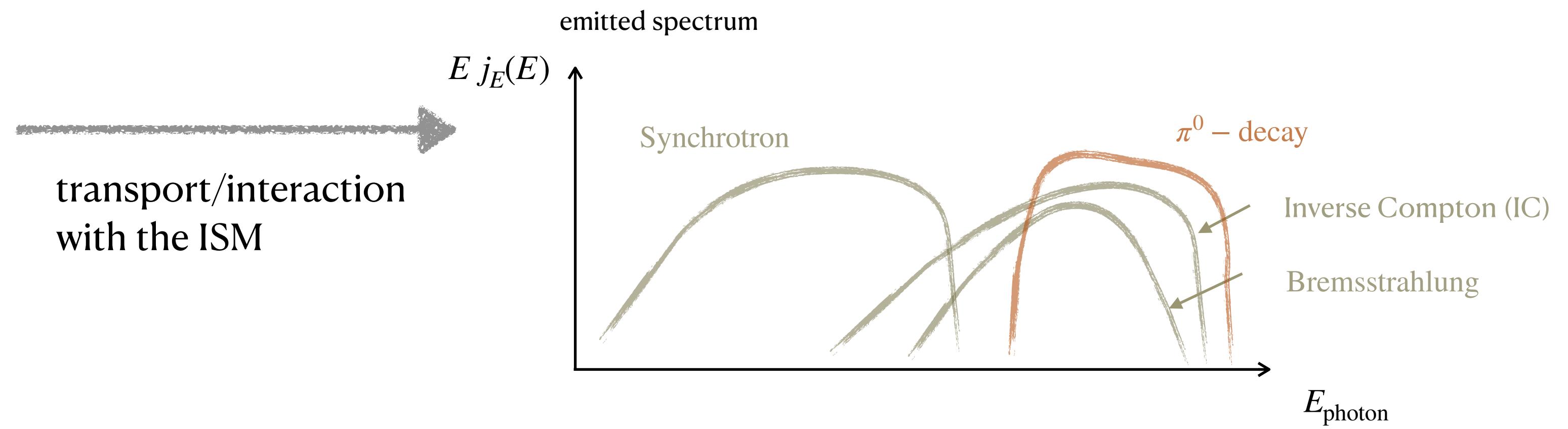
# Observational Constraints of CRs



acceleration  
of CRs



## Non-thermal emission

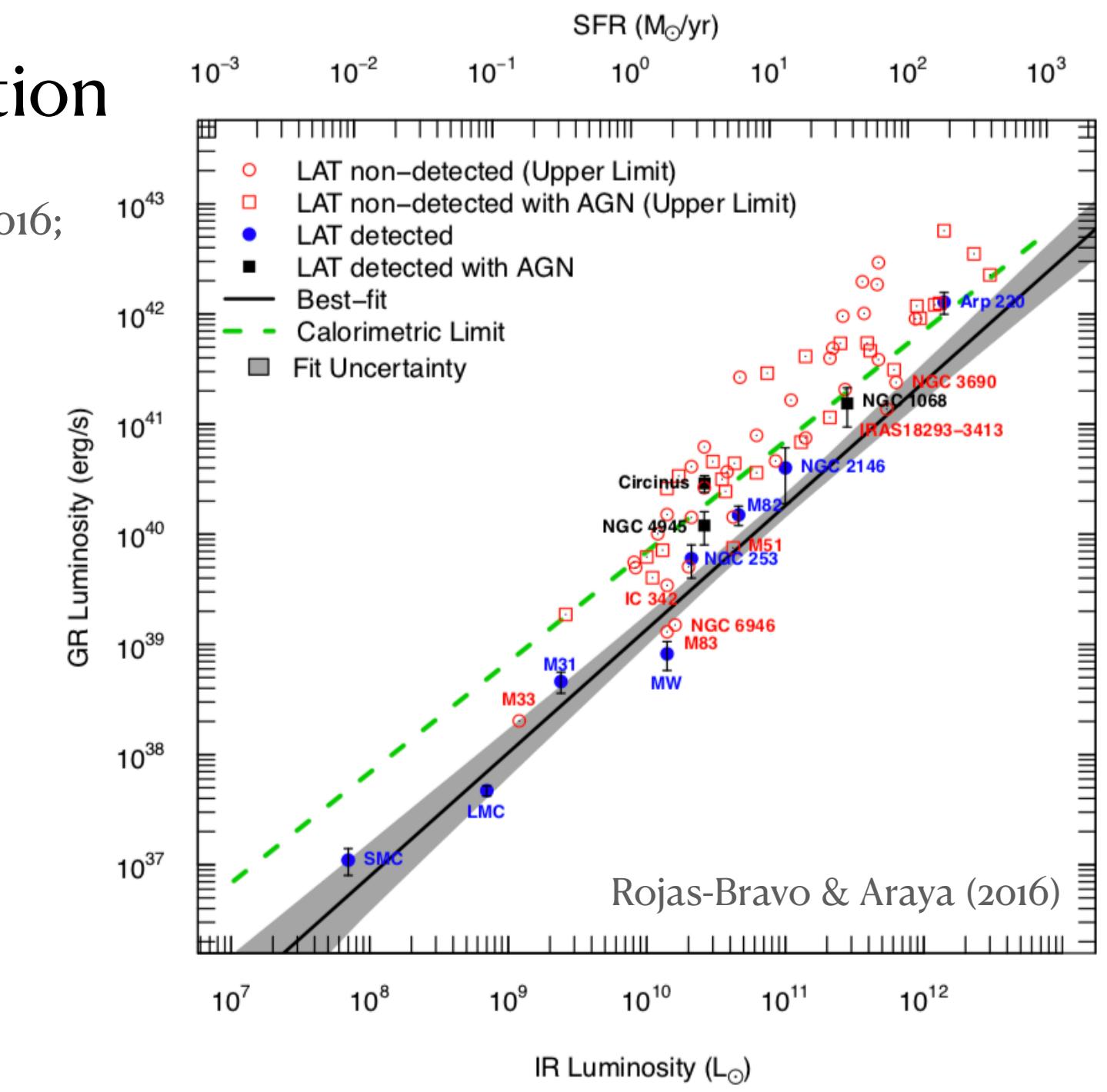


## FIR-radio relation

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

## FIR- $\gamma$ -ray relation

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



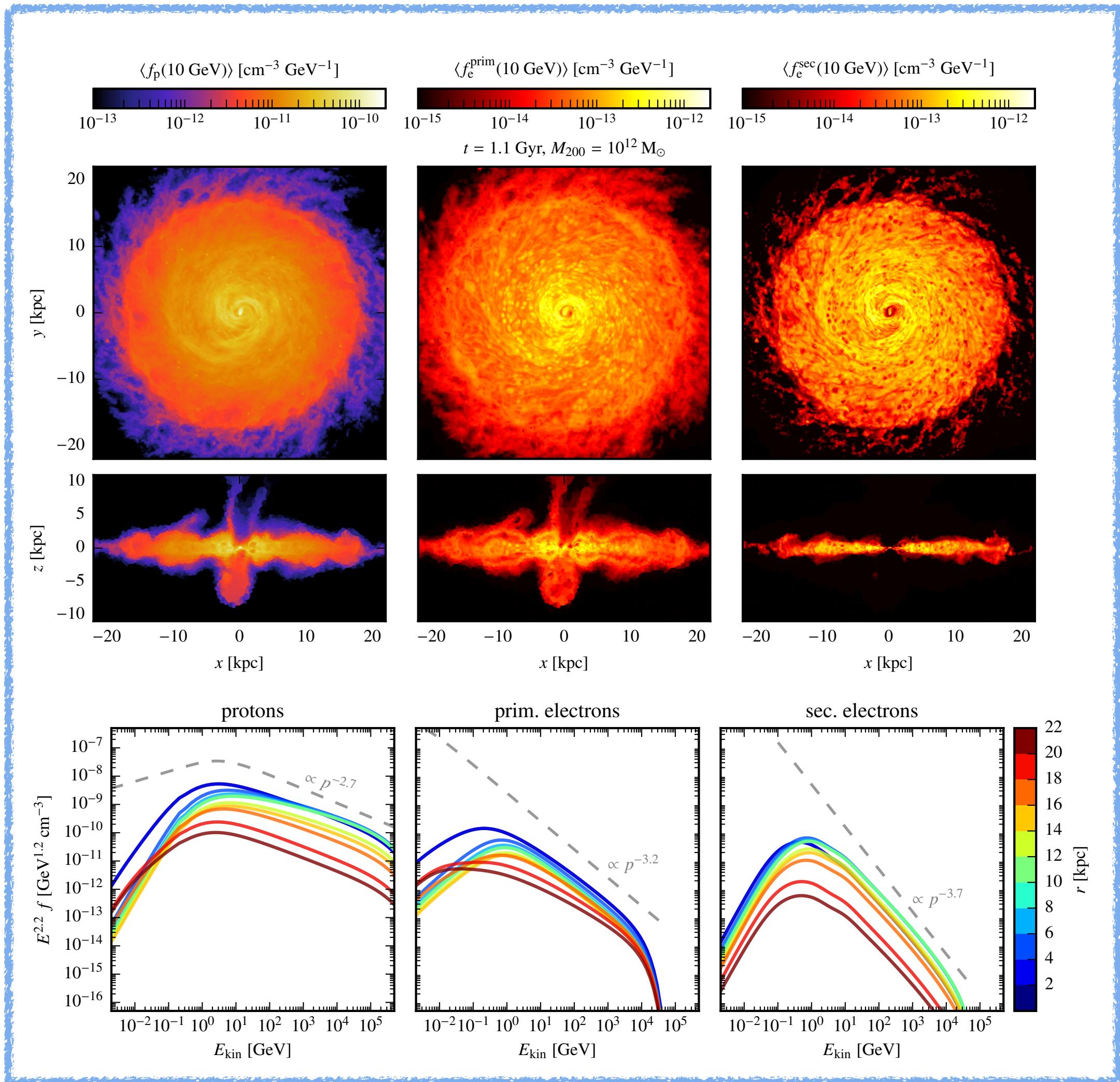
Can we constrain CR transport using these relations?

# Modelling CR spectra & emission with crayon+

from MHD simulation

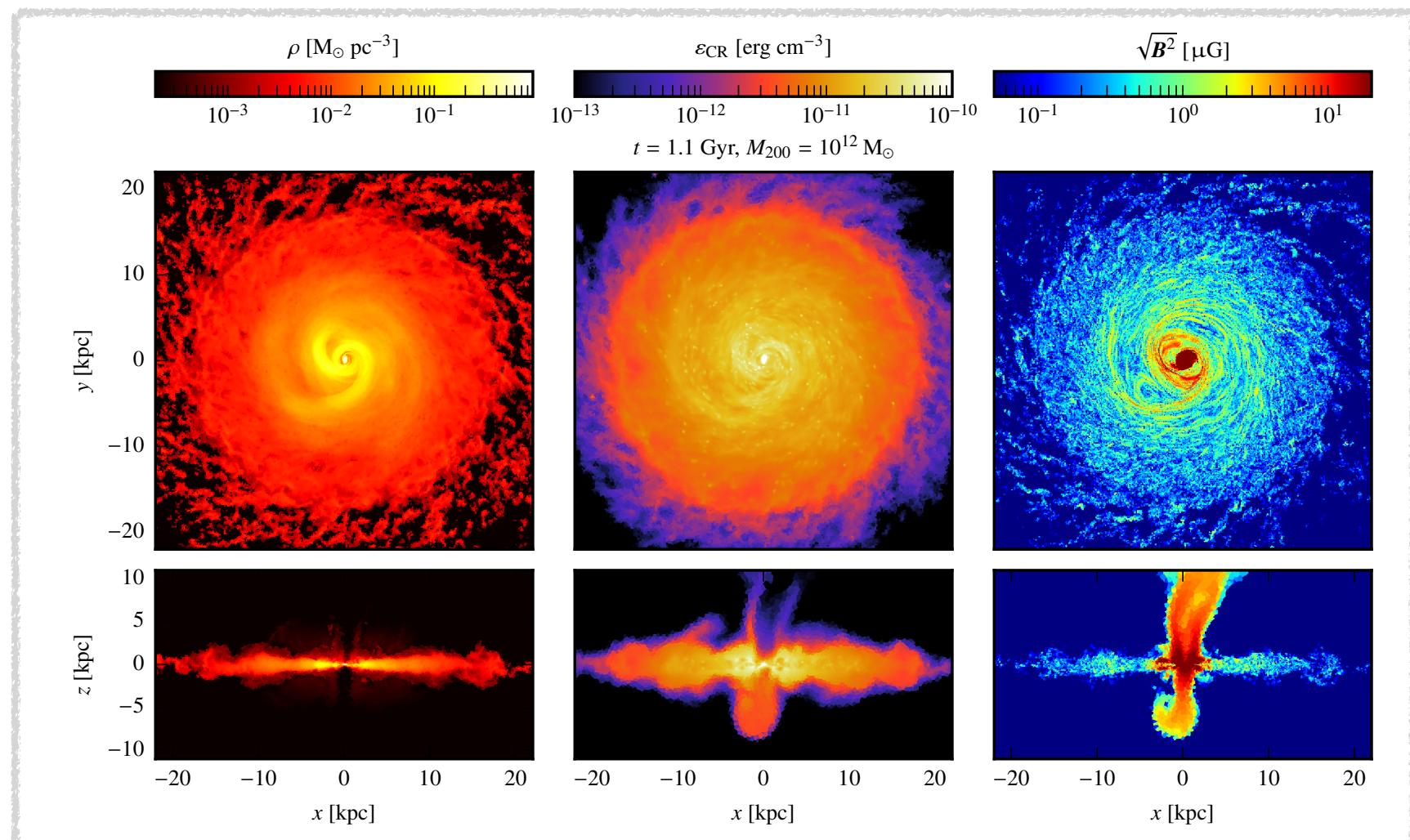
Cosmic RAY emissiON + more:)

modelling of CR proton, primary and secondary electron spectra

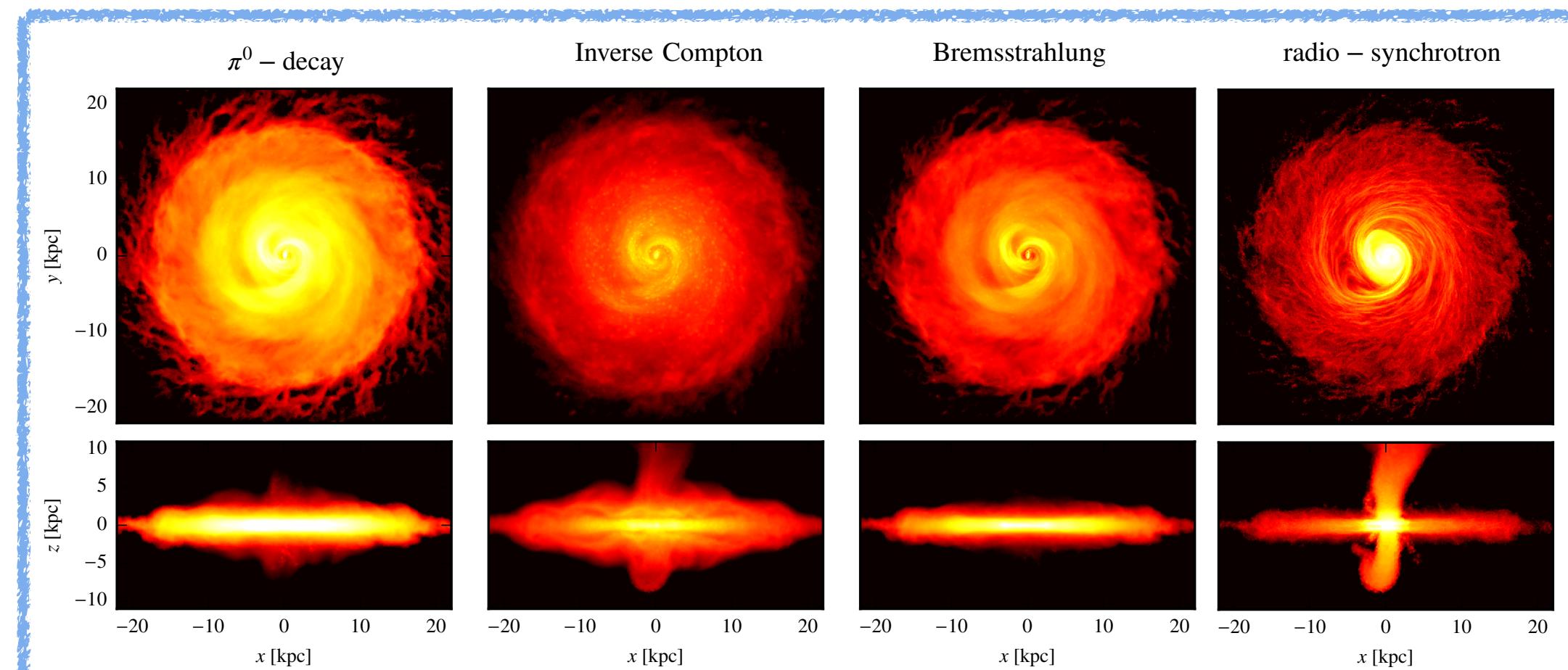


crayon+

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

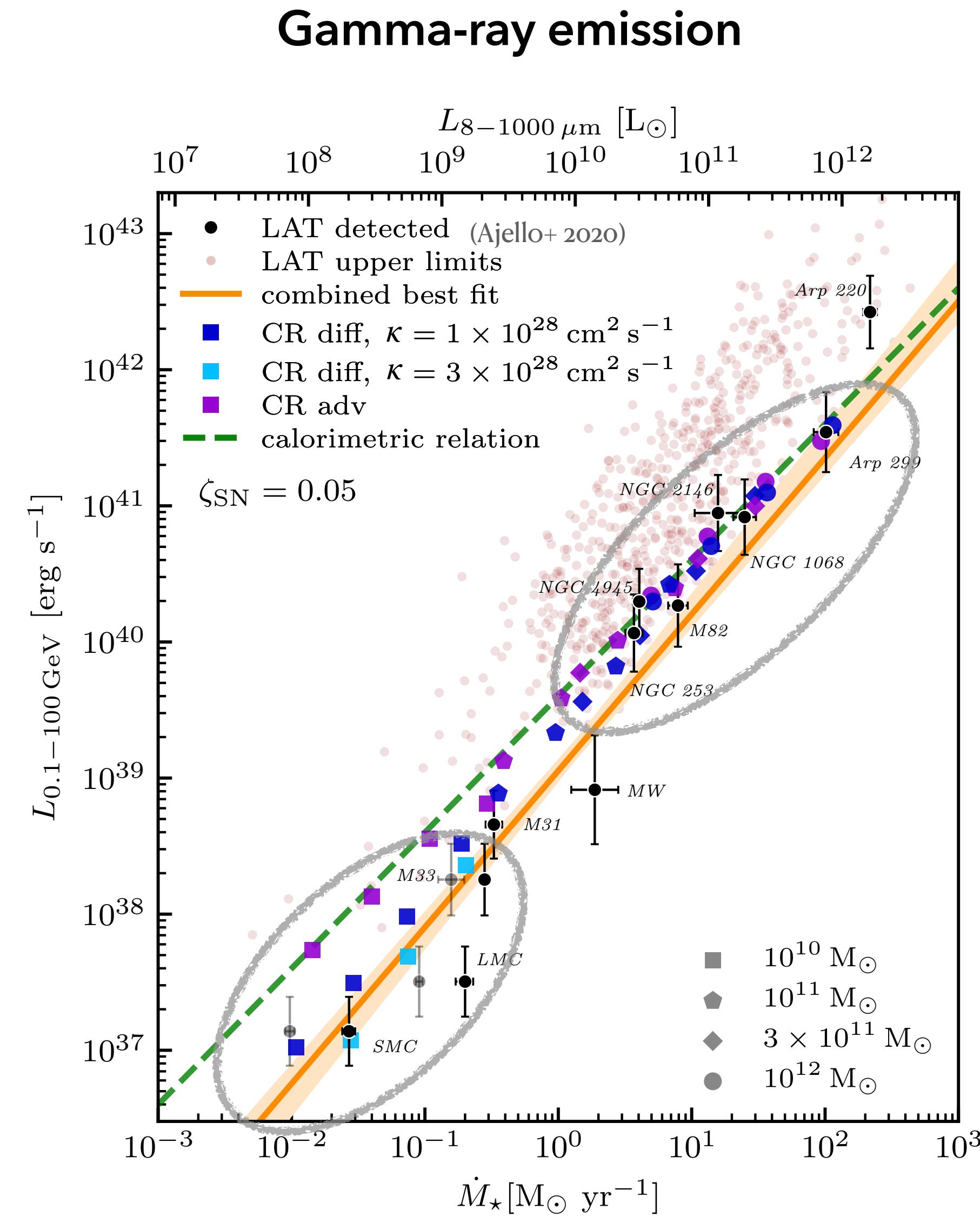


calculation of radiation processes

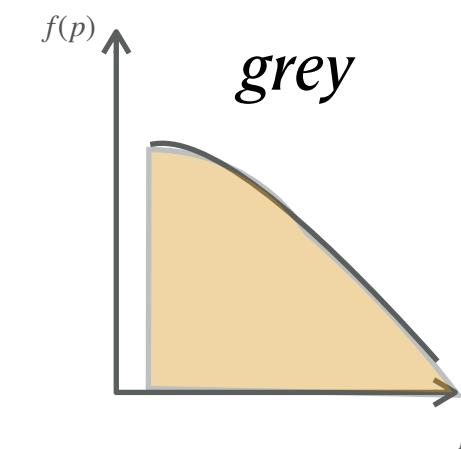


# Lessons learned from isolated setups

*low SFR: sensitive  
to CR transport  
→ constrain  $\kappa$*



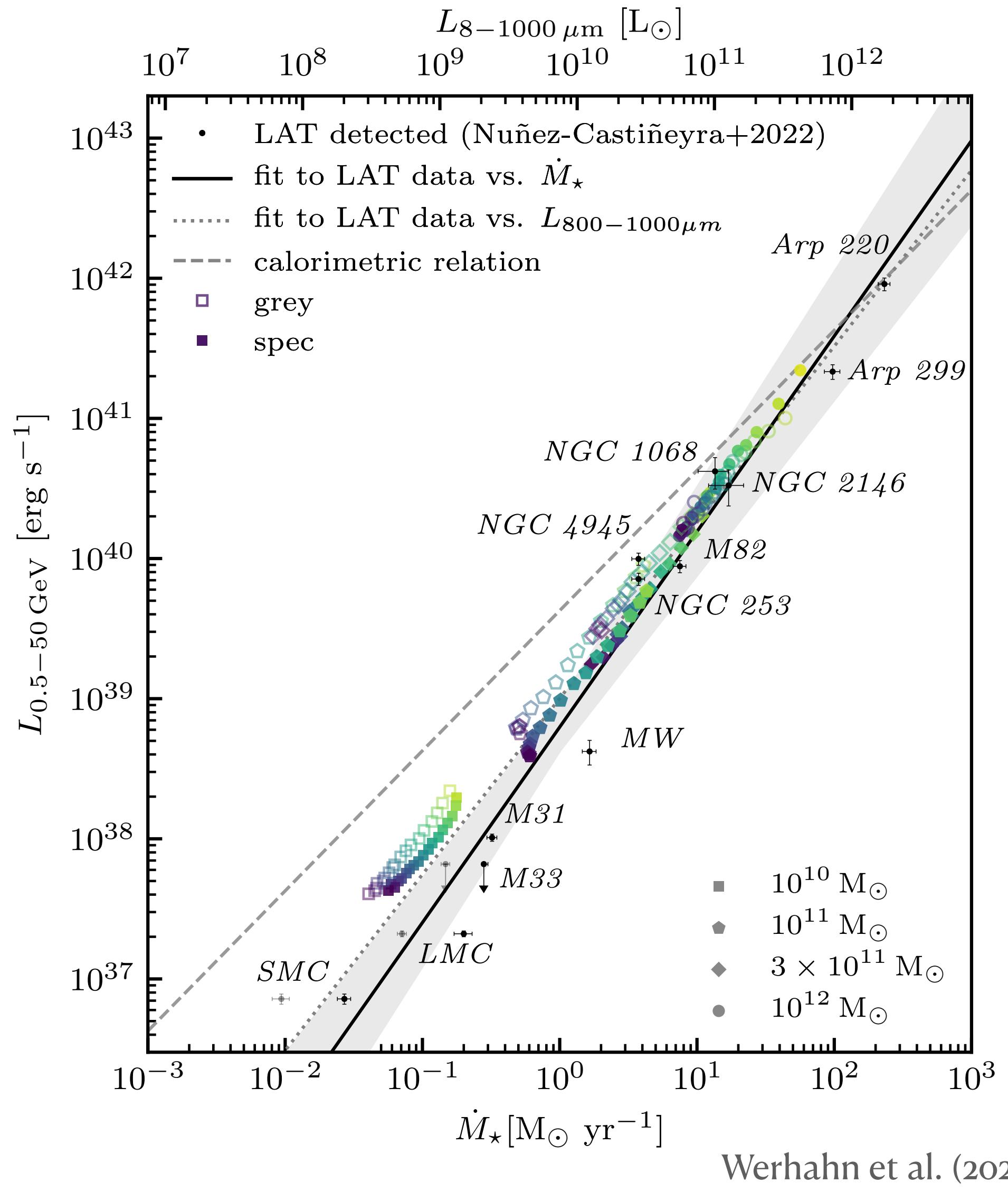
Werhahn et al. (2021b)



*high SFR: close to calorimetric limit  
(complete conversion to  $\gamma$ -rays)  
→ constrain  $\zeta_{\text{SN}}$*

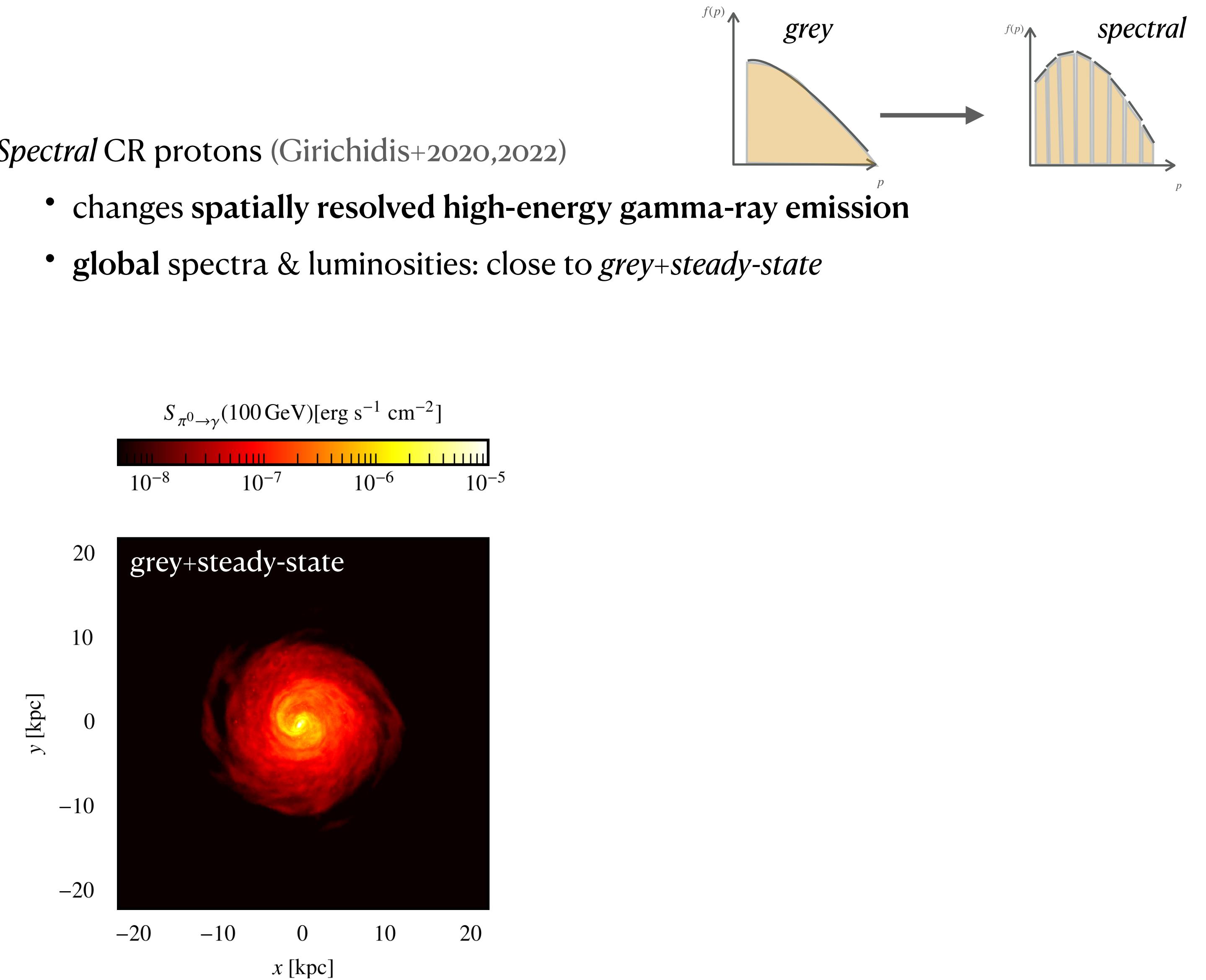
# Lessons learned from isolated setups

## Gamma-ray emission



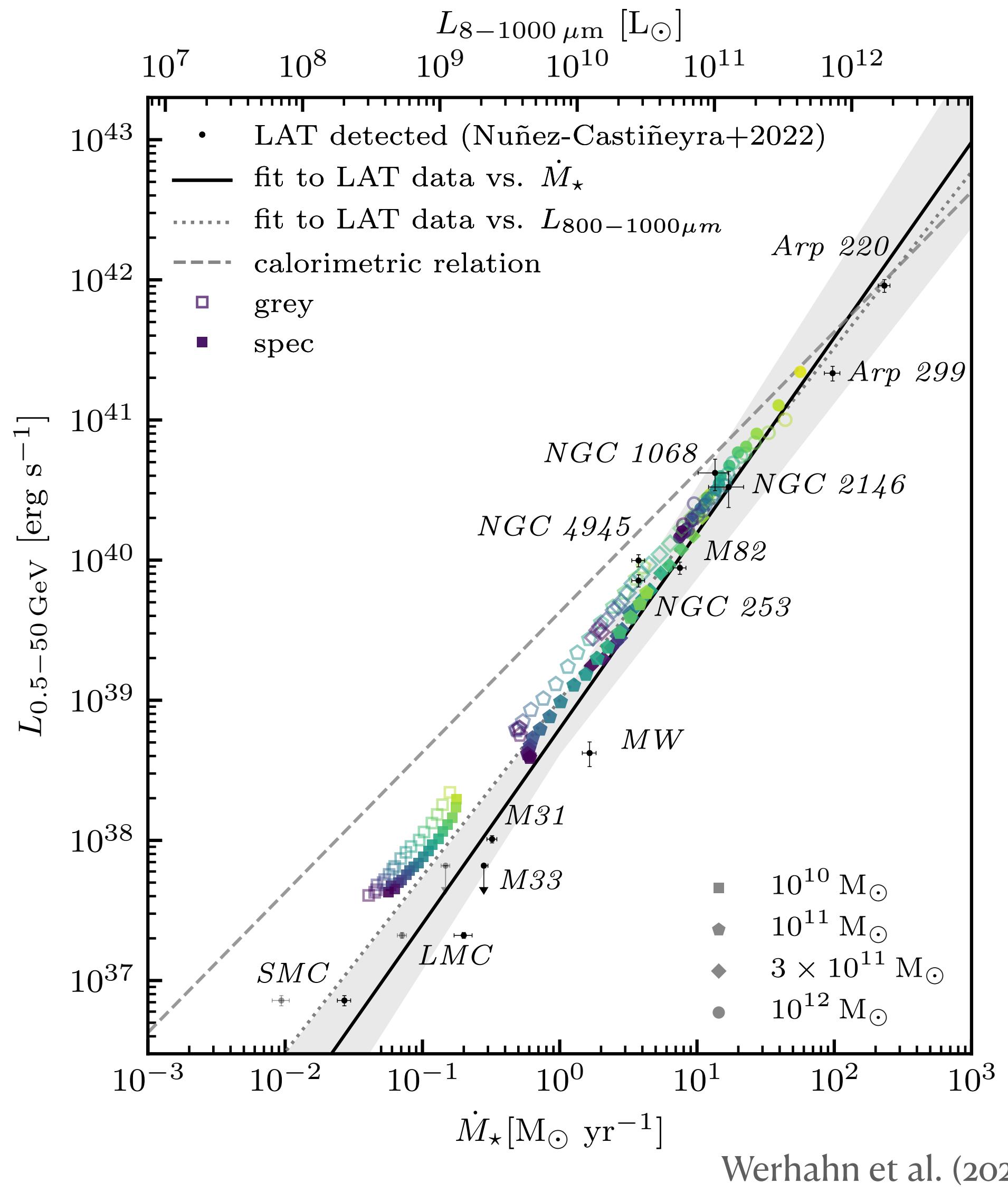
*Spectral CR protons (Girichidis+2020,2022)*

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



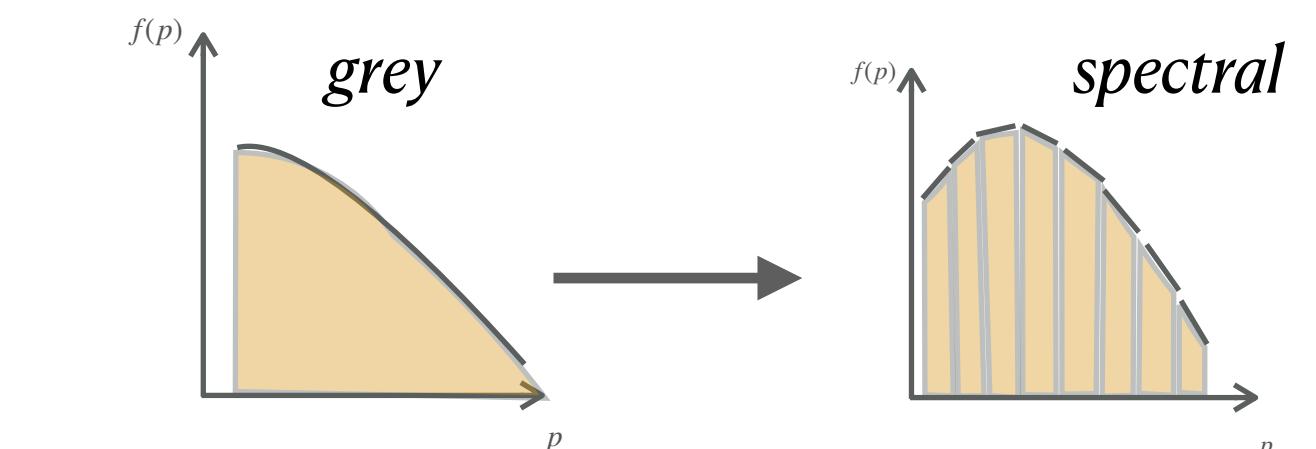
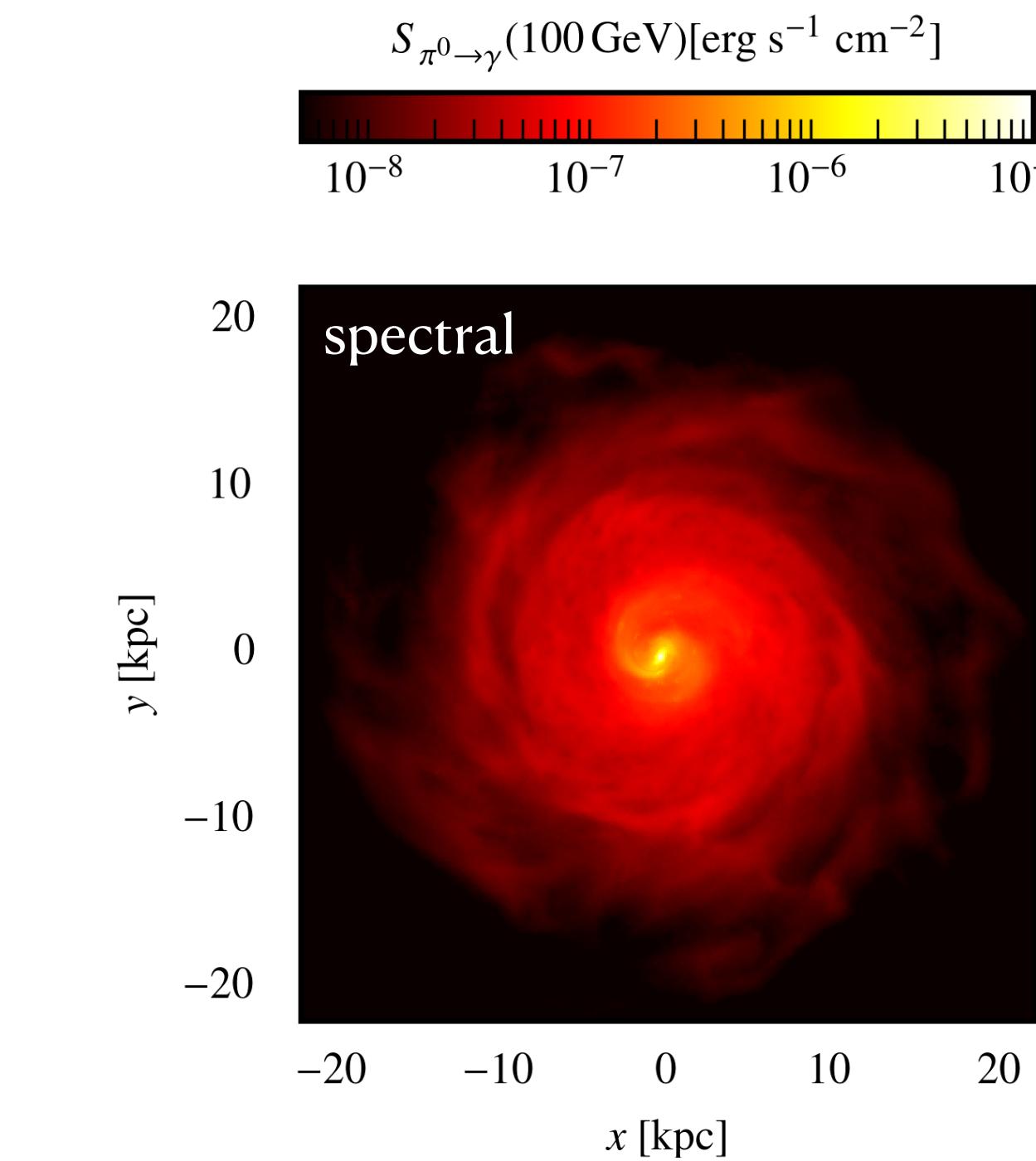
# Lessons learned from isolated setups

## Gamma-ray emission

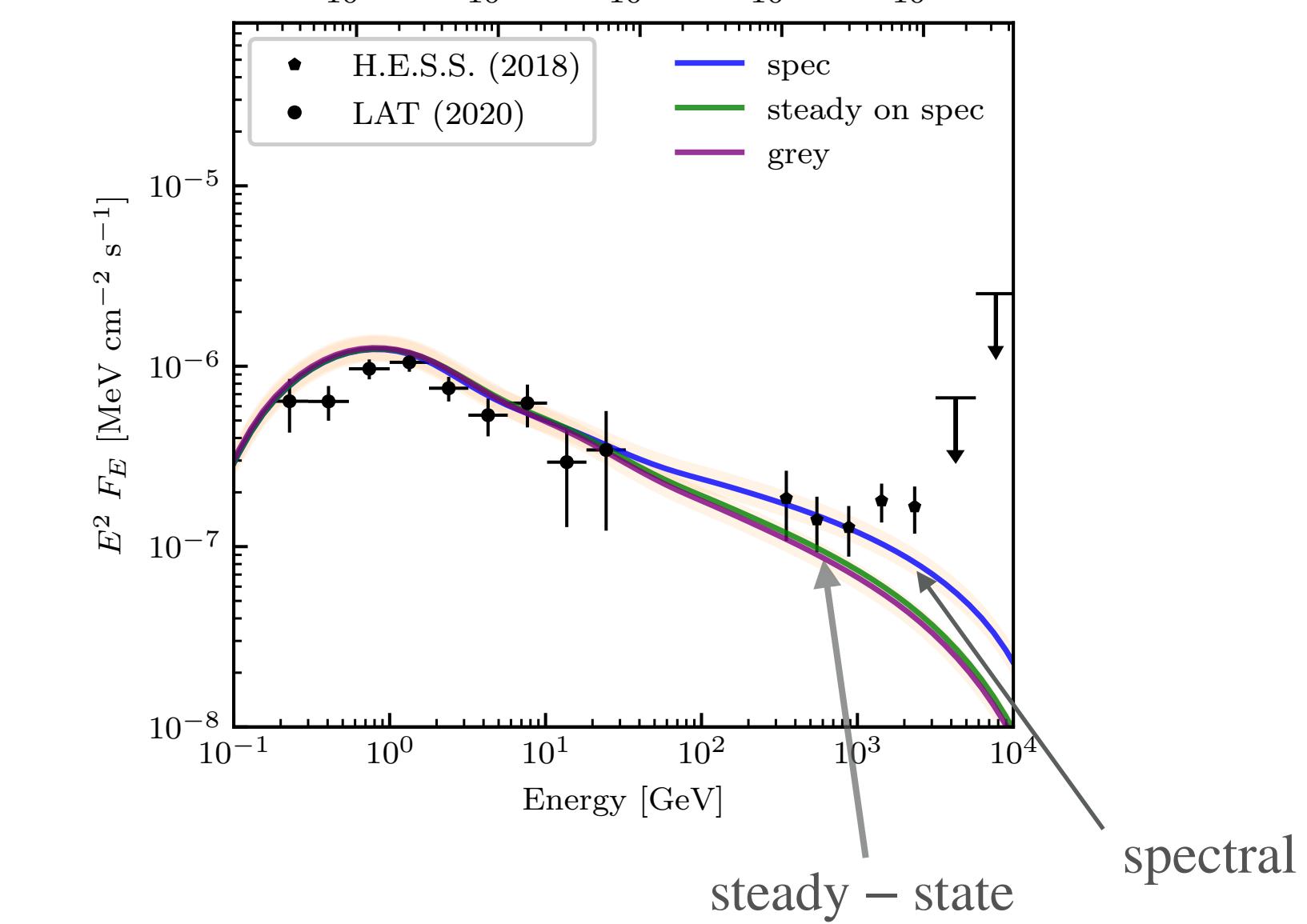


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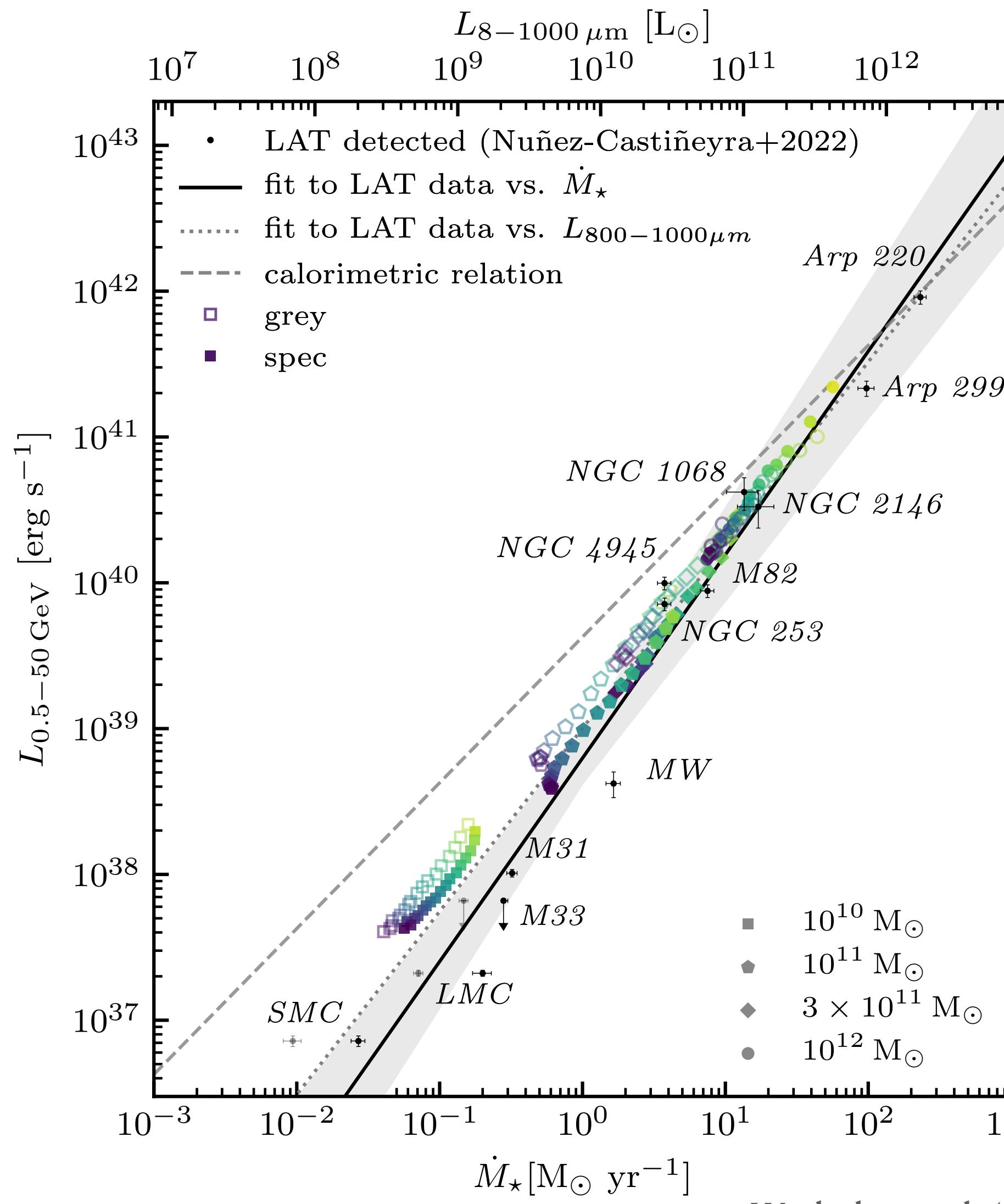


gamma-ray spectrum of NGC253

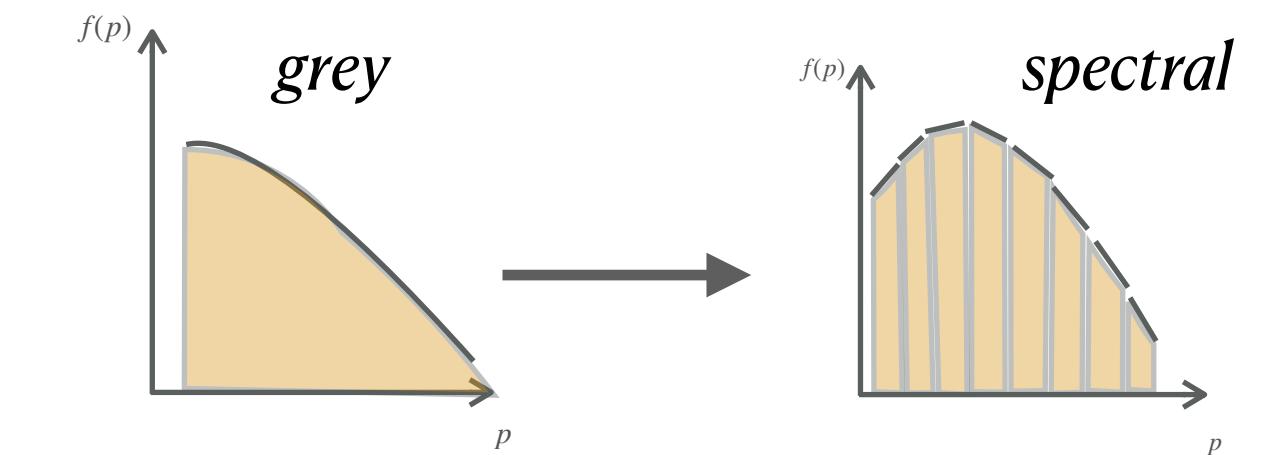


# Lessons learned from isolated setups

## Gamma-ray emission

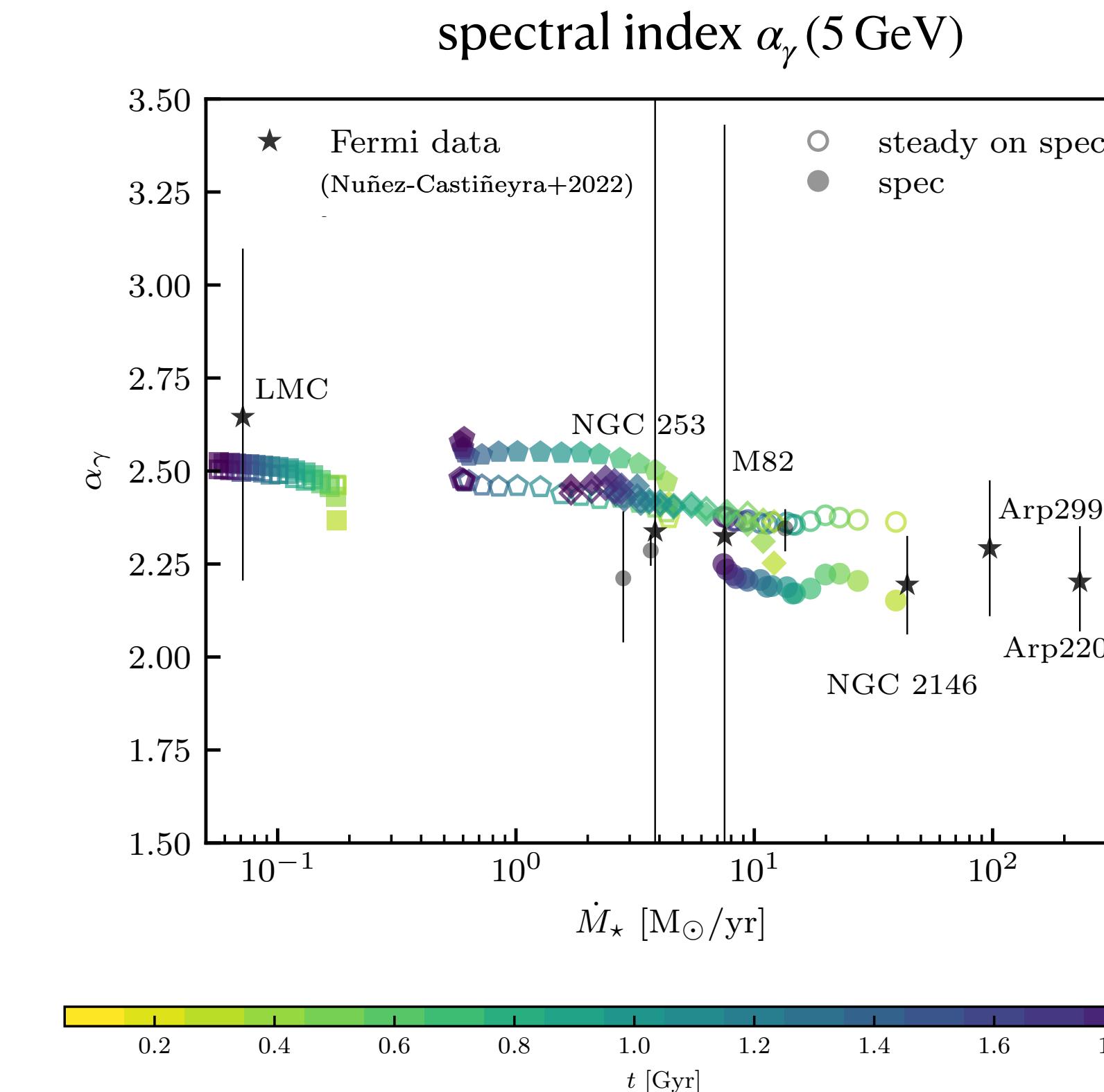


Werhahn et al. (2023)



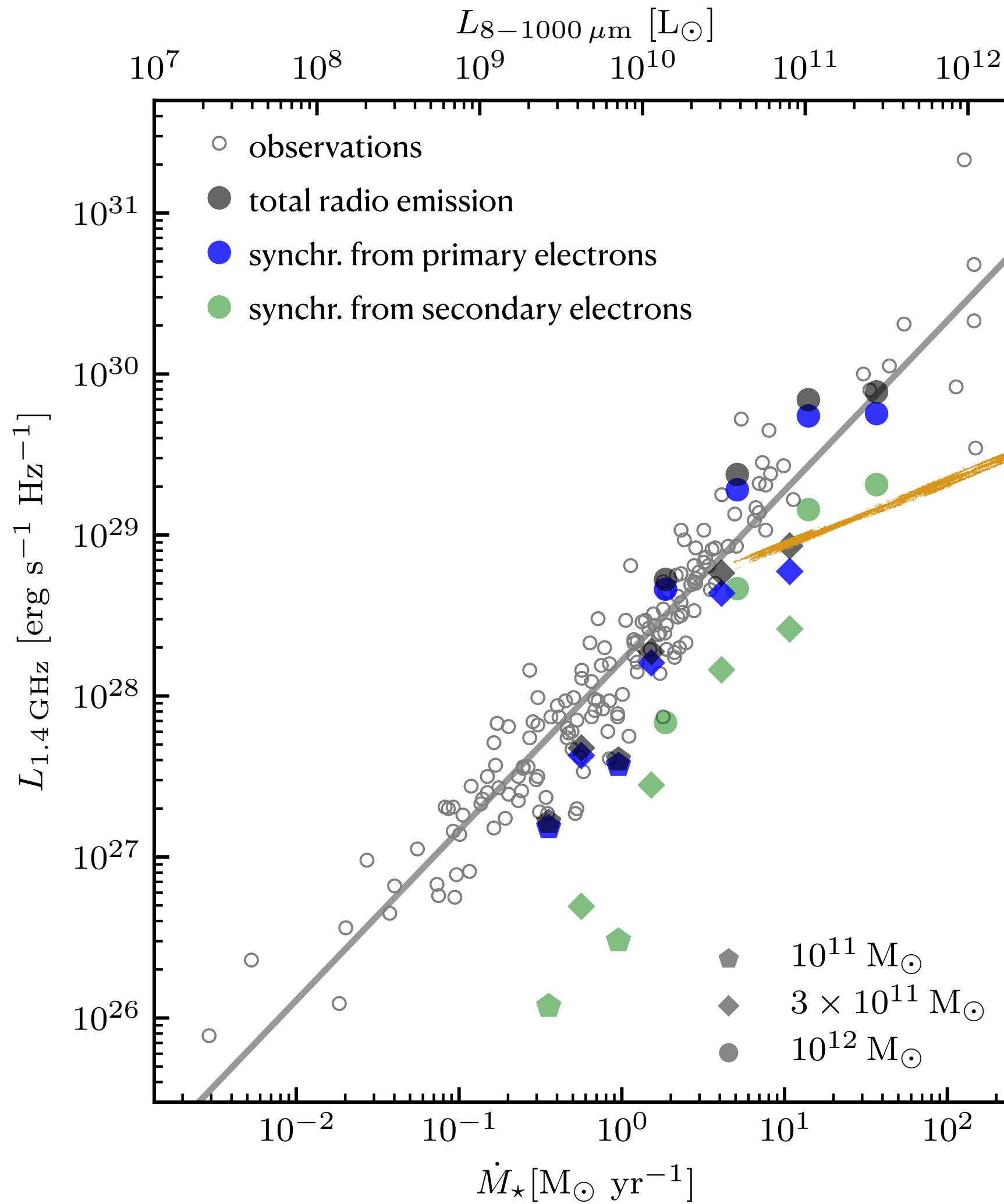
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# Lessons learned from isolated setups

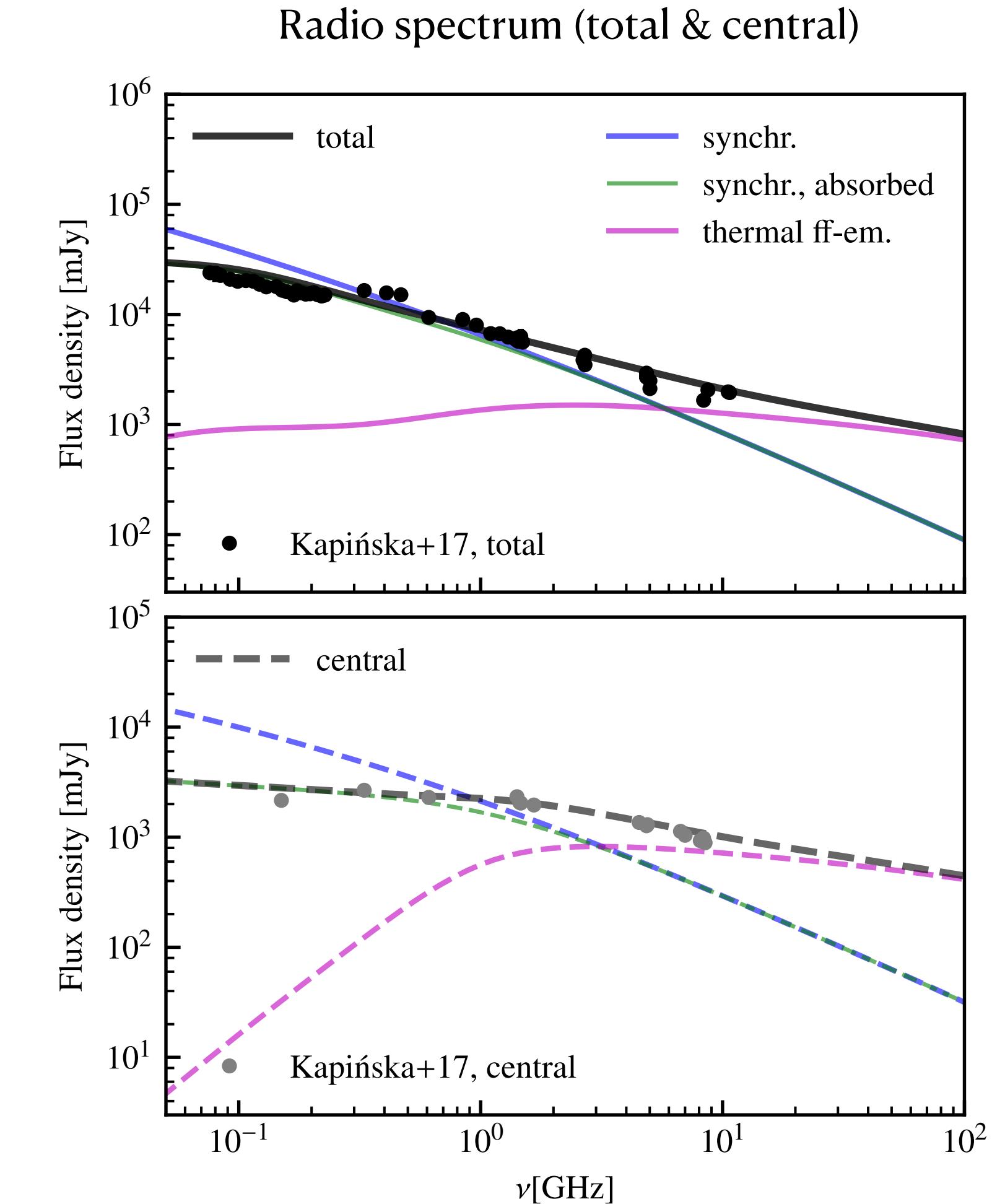
## Radio emission



NGC 253



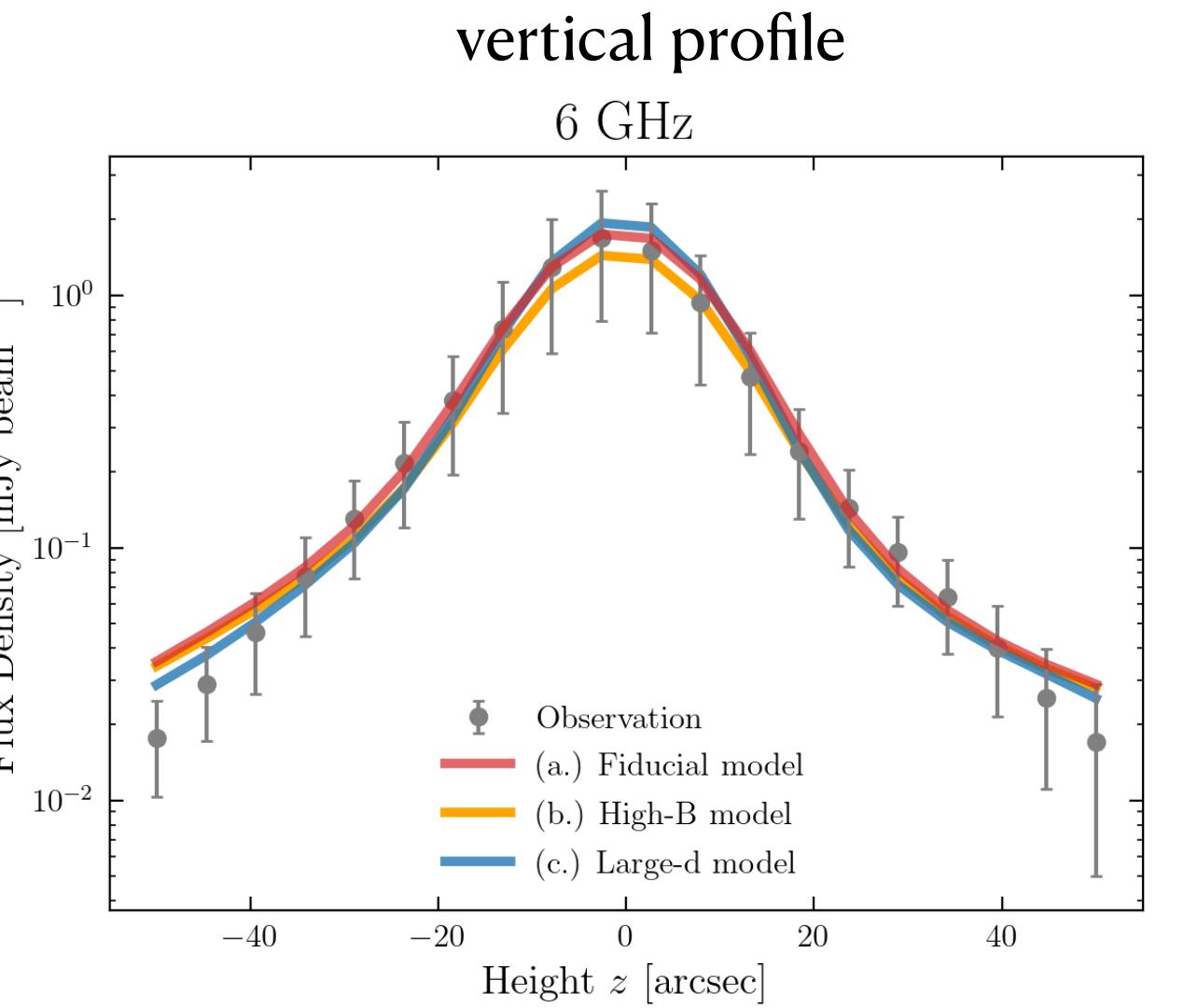
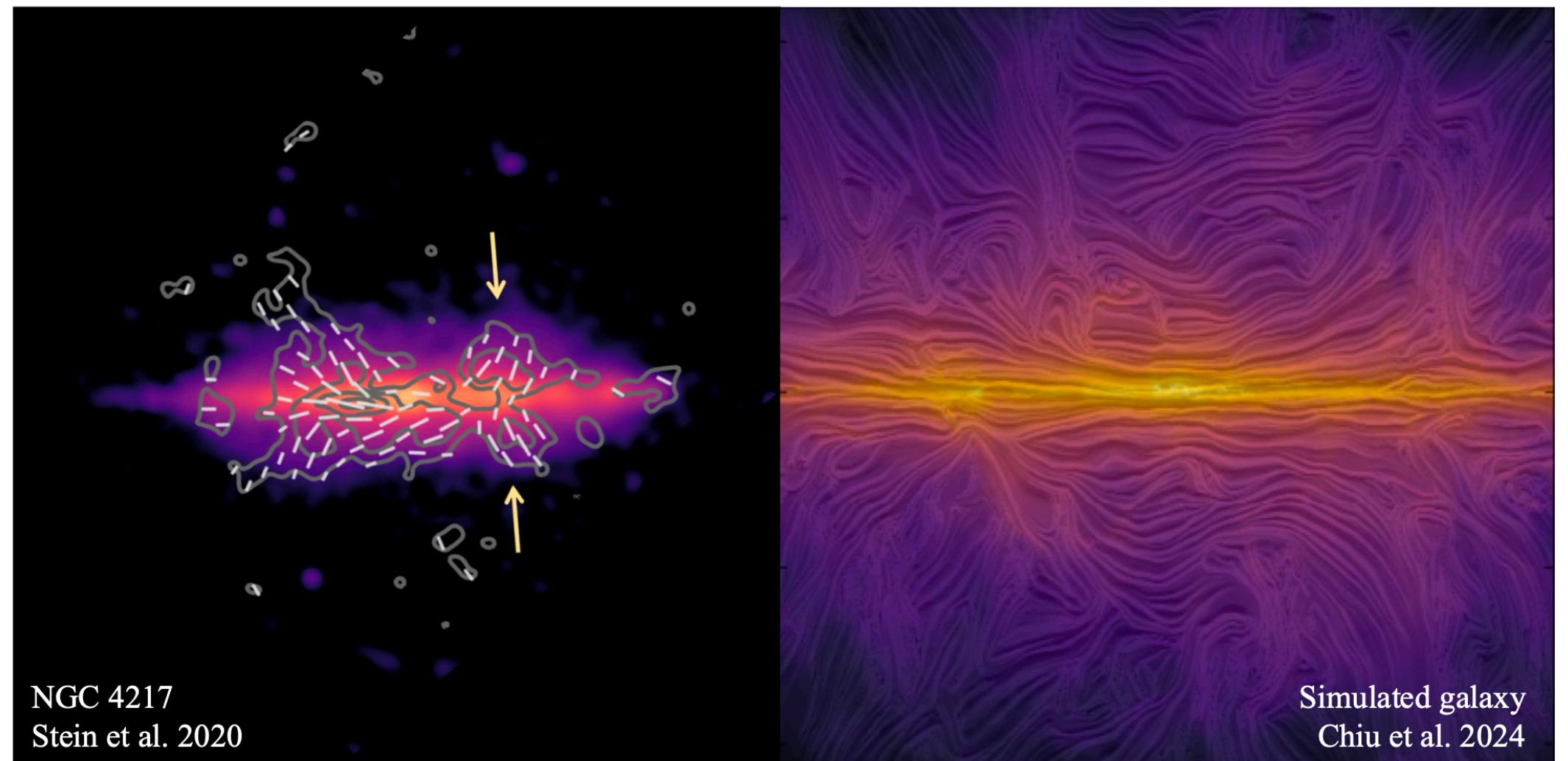
- primary electrons dominate
- high frequencies: steep radio synchr. spectra (IC & synchr. cooling)
- thermal free-free emission & absorption needed for flat spectra



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)

**Tracing the Wind: How Cosmic Rays Paint Galaxies in Radio Light**  
Radio Synchrotron Morphology, Spectra, and Polarization of Cosmic Ray Driven Galactic Winds  
H.-H. Sandy Chiu, Mateusz Ruszkowski, Timon Thomas, Maria Werhahn, and Christoph Pfrommer

**Introduction**  
Theoretical models of galactic winds powered by supernovae or radiation pressure face key challenges, including the overcooling problem and inefficient coupling between stellar radiation and gas. Cosmic rays (CRs) offer a promising alternative, as they cool more slowly than thermal energy and couple more effectively to the gas than radiation. Magnetohydrodynamic simulations using simplified CR transport, such as constant diffusion coefficients or fixed streaming speeds—have shown that CR pressure can successfully drive galactic winds. However, realistic CR transport likely involves spatially varying scattering frequencies, motivating the need for more advanced computational approaches. The two-moment method offers one such approach and has been validated on small scales. In this project, we test whether this method can be extended to galactic scales and evaluate if the resulting wind properties align with observations.

**Method**

**CR-MHD simulation**  
Thomas et al. (2024)  
Two-moment CR transport  
CRISPy physic model  
Adaptive mesh refinement  
Include CR advection, diffusion, streaming and other cooling mechanisms

**CR spectrum calculation**  
Werhahn et al. (2020)  
Adaptive mesh refinement  
Include CR advection, diffusion, streaming and other cooling mechanisms

**Calculate emission map & Compare with observation**  
Chiu et al. (2024; this work)  
Flux density [mJy beam<sup>-1</sup>]

**Result**

**Conclusion 1:** Our simulated emission maps match observations provided that the difference of SFR between the observed and simulated galaxy is considered. The shapes of intensity profiles are insensitive to the normalization of the CR electron spectrum, magnetic field and the assumed distance of the simulated galaxy.

Model	B Field Boost	Assumed Distance	$K_{\text{em}}^{(0)}$	$\zeta_{\text{sim}}$
Fiducial	$1.5^{+0.1}_{-0.1}$	15.85 Mpc	0.092	0.15
High-B	$1.5^{+0.2}_{-0.2}$	14.88 Mpc	0.093	0.14
Larged	$1.5^{+0.2}_{-0.2}$	18.88 Mpc	0.12	0.2

**Conclusion 3:** The simulated spectrum above 0.1 GHz agrees well with observations. Slightly increasing the magnetic field steepens the spectrum but still keeps it consistent with the data.

**Conclusion 2:** The simulated radio polarization images exhibit X-shaped morphology, which is consistent with a presence of galactic-scale outflow.

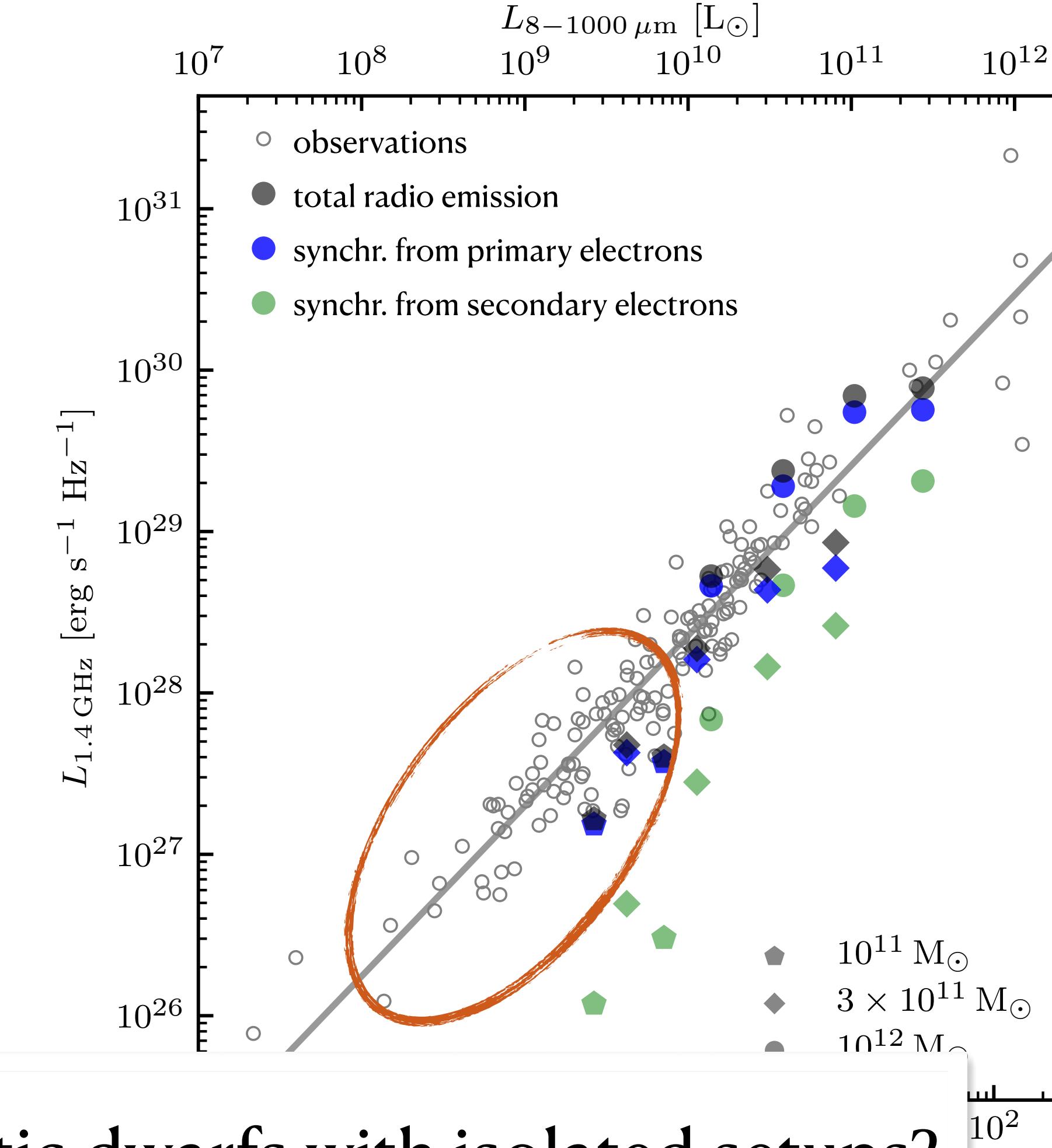
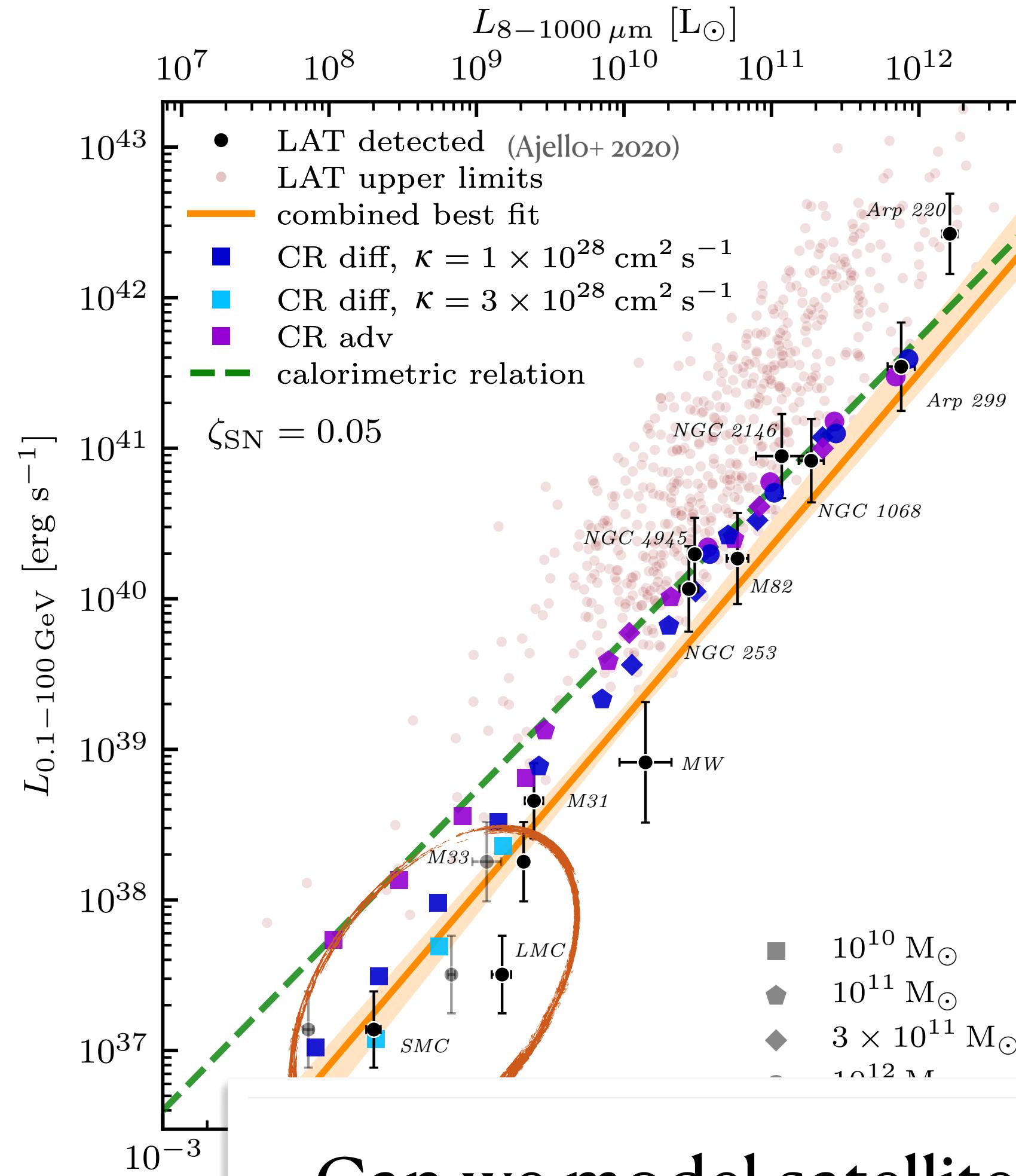
**NGC 4217 Stein et al. 2020**      **Simulated galaxy Chiu et al. 2024**

**LSA ASTRONOMY** **Leibniz-Institut für Astrophysik Potsdam**

see poster  
by H.-H. Sandy Chiu!

# Lessons learned from isolated setups

## Open questions



Can we model satellites/realistic dwarfs with isolated setups?

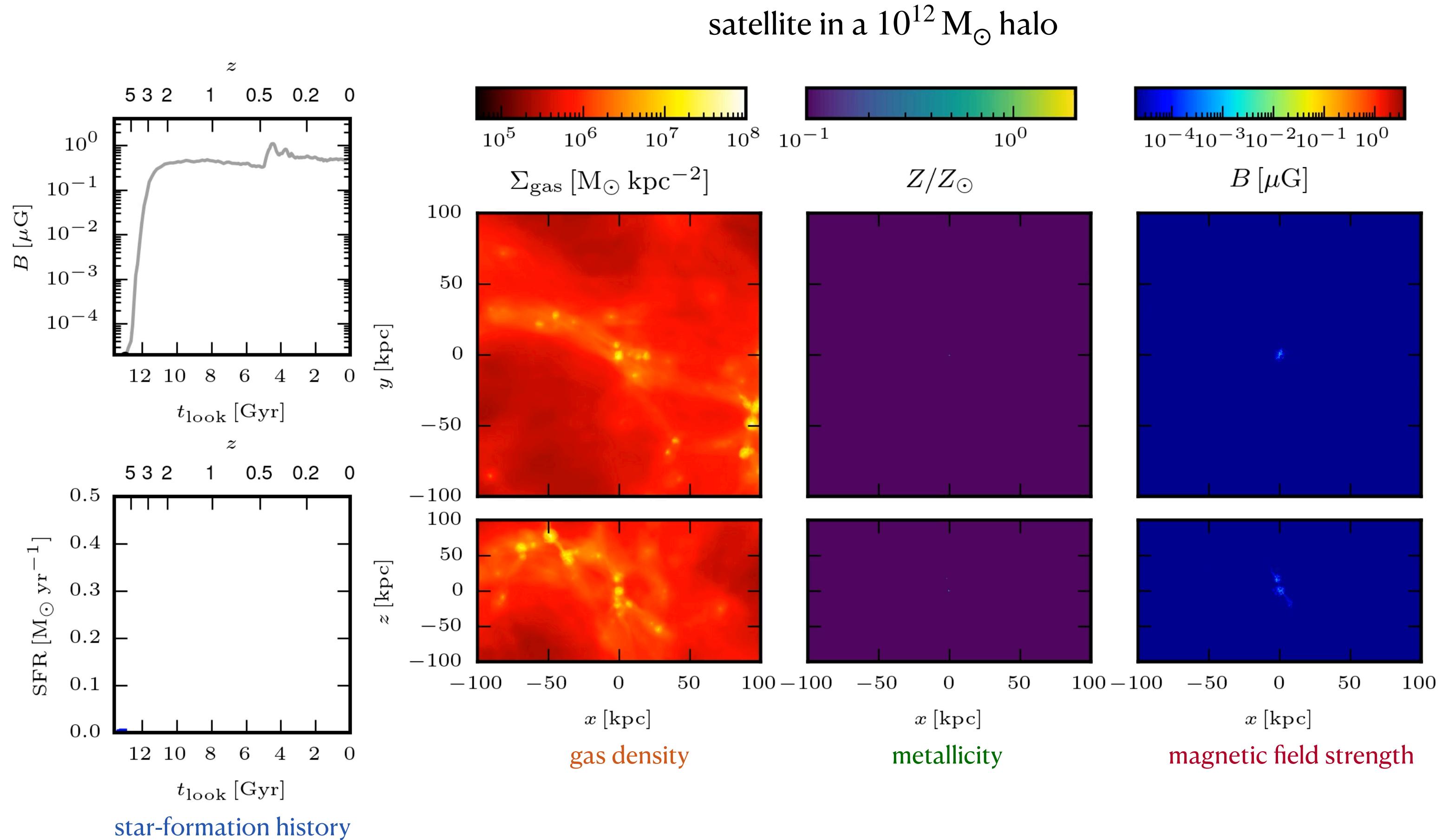
# Cosmological zoom simulations

with CRs

## Auriga zoom simulations with CRs

(Bieri, [...], Werhahn+ in prep)

- $M_{200} = 10^{10} - 10^{13} M_\odot$
  - with grey CRs (Alfvén cooling, anisotropic diffusion)
  - **crayon+**: CR spectra & emission
- ✓ more realistic environment and star-formation history
- ✓ study isolated dwarfs vs. satellites

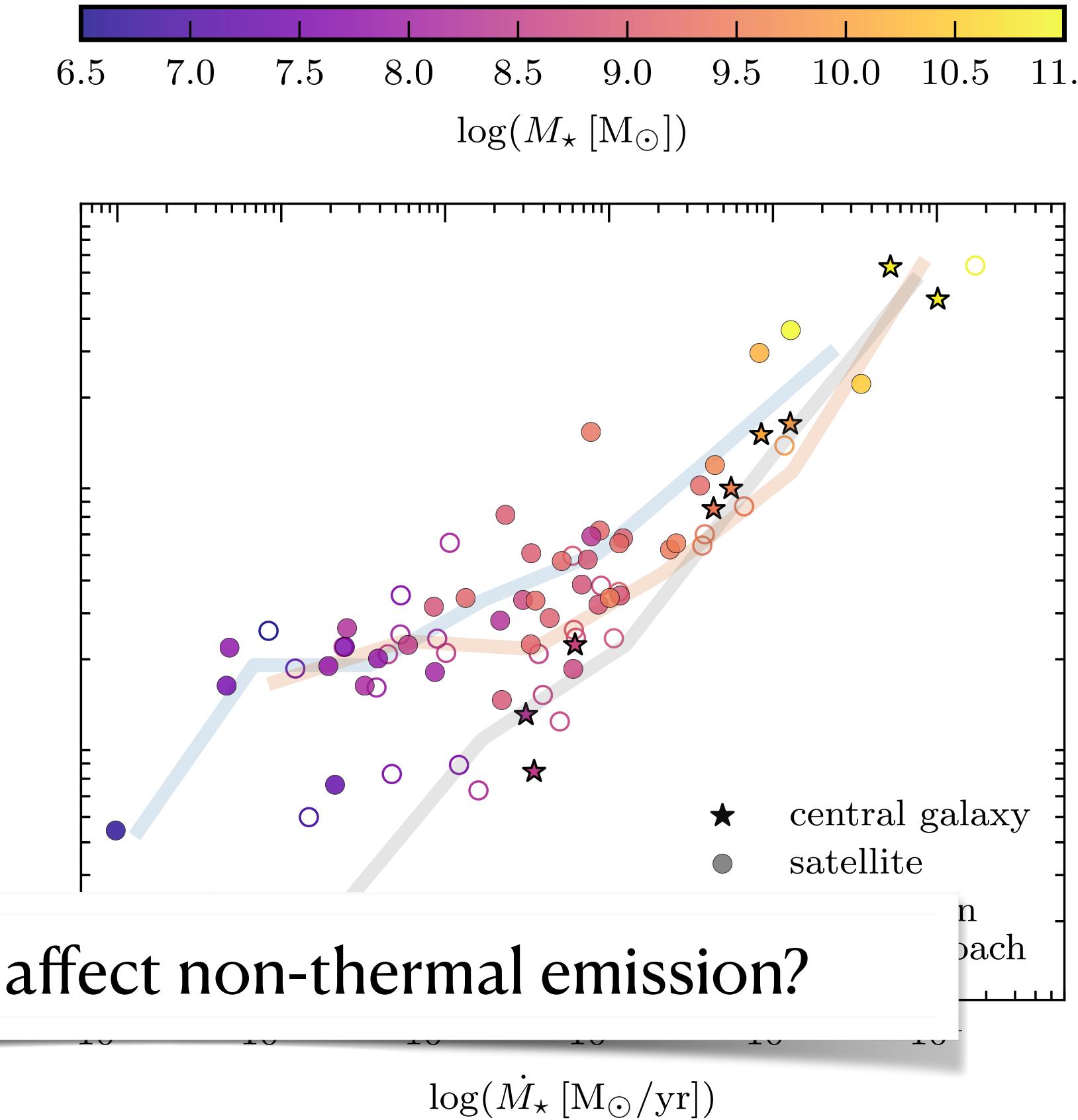
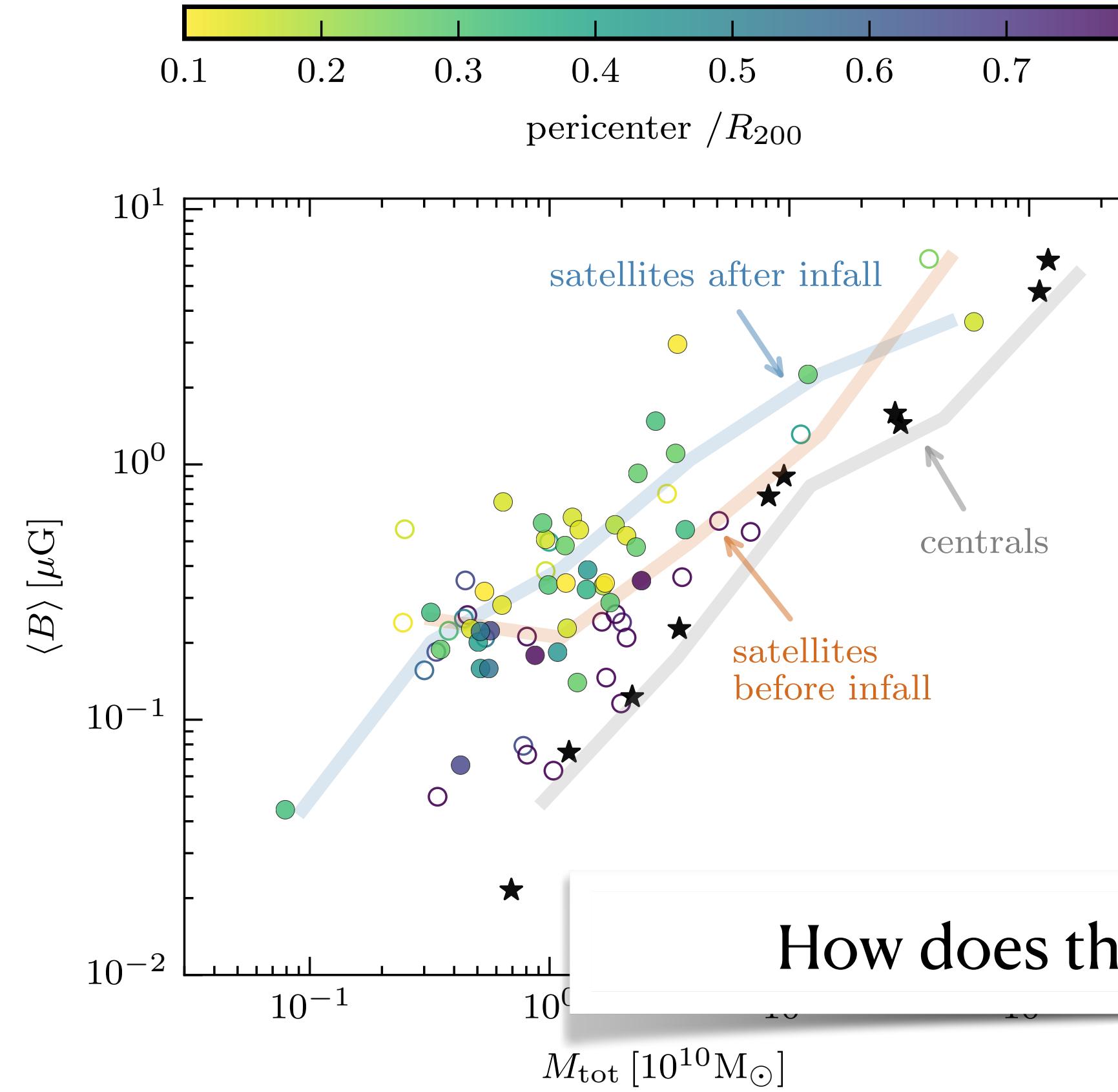


# Cosmological zoom simulations

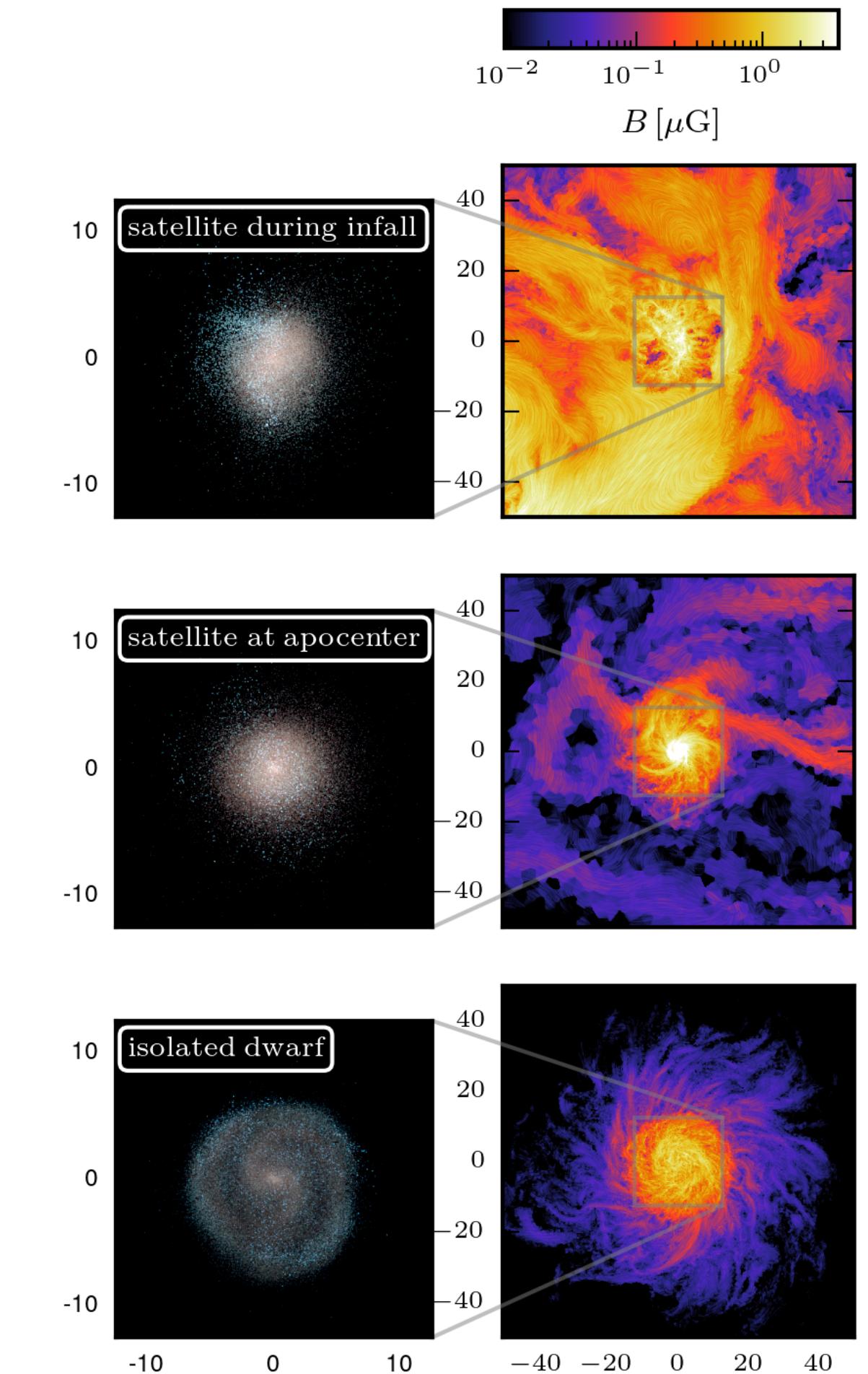
with CRs

## B-field amplification

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



How does this affect non-thermal emission?

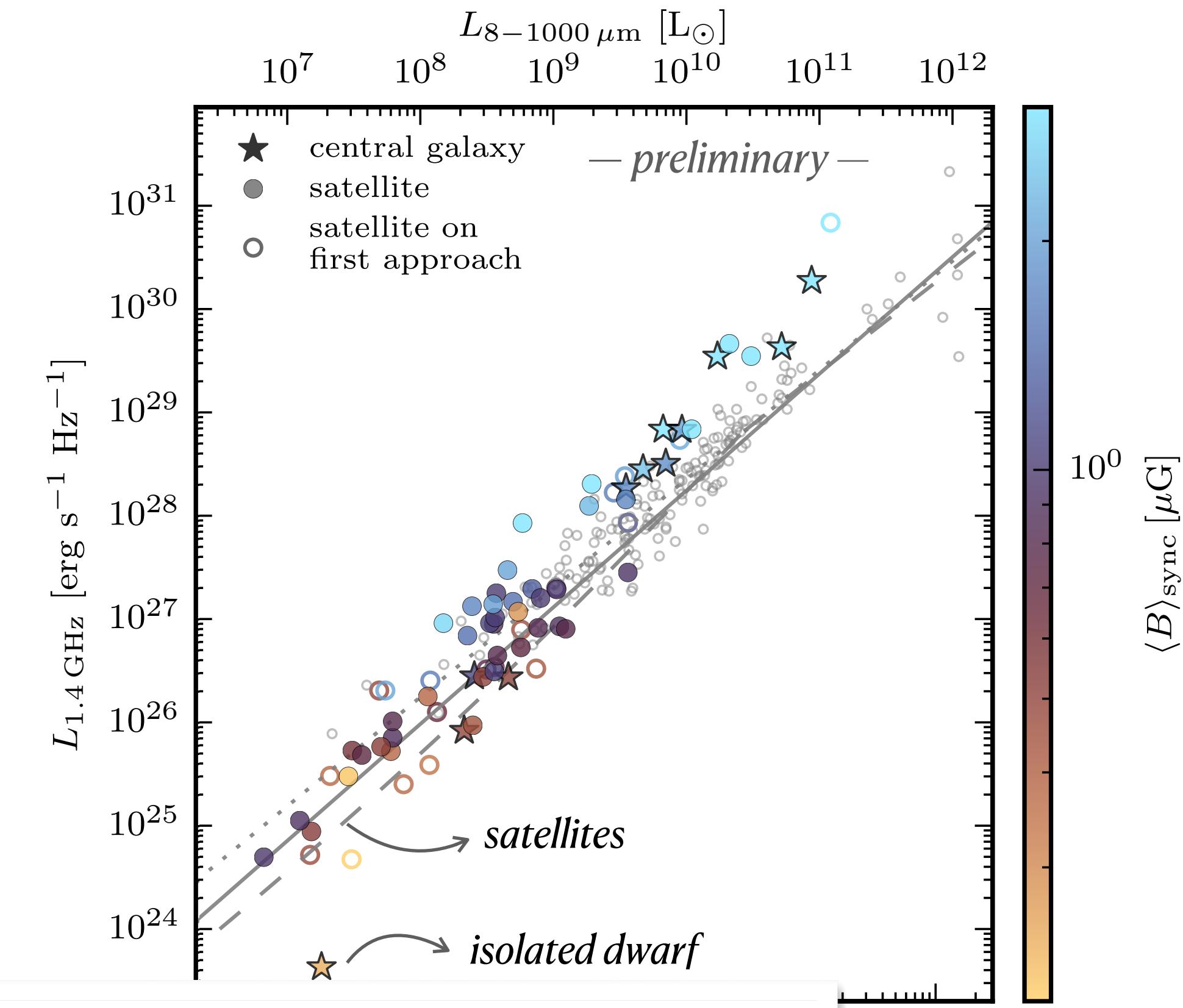
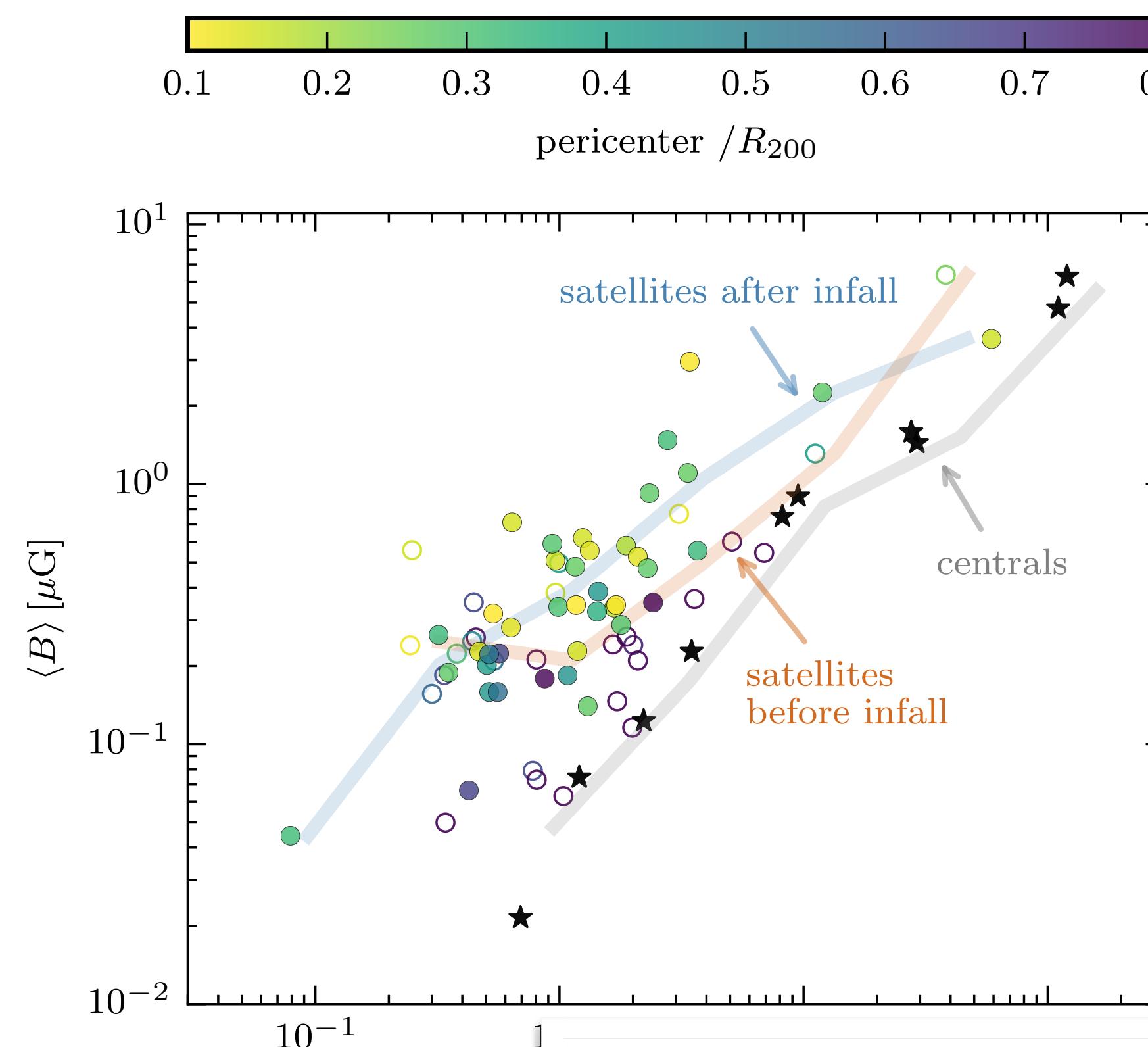


# Cosmological zoom simulations

with CRs

## B-field amplification

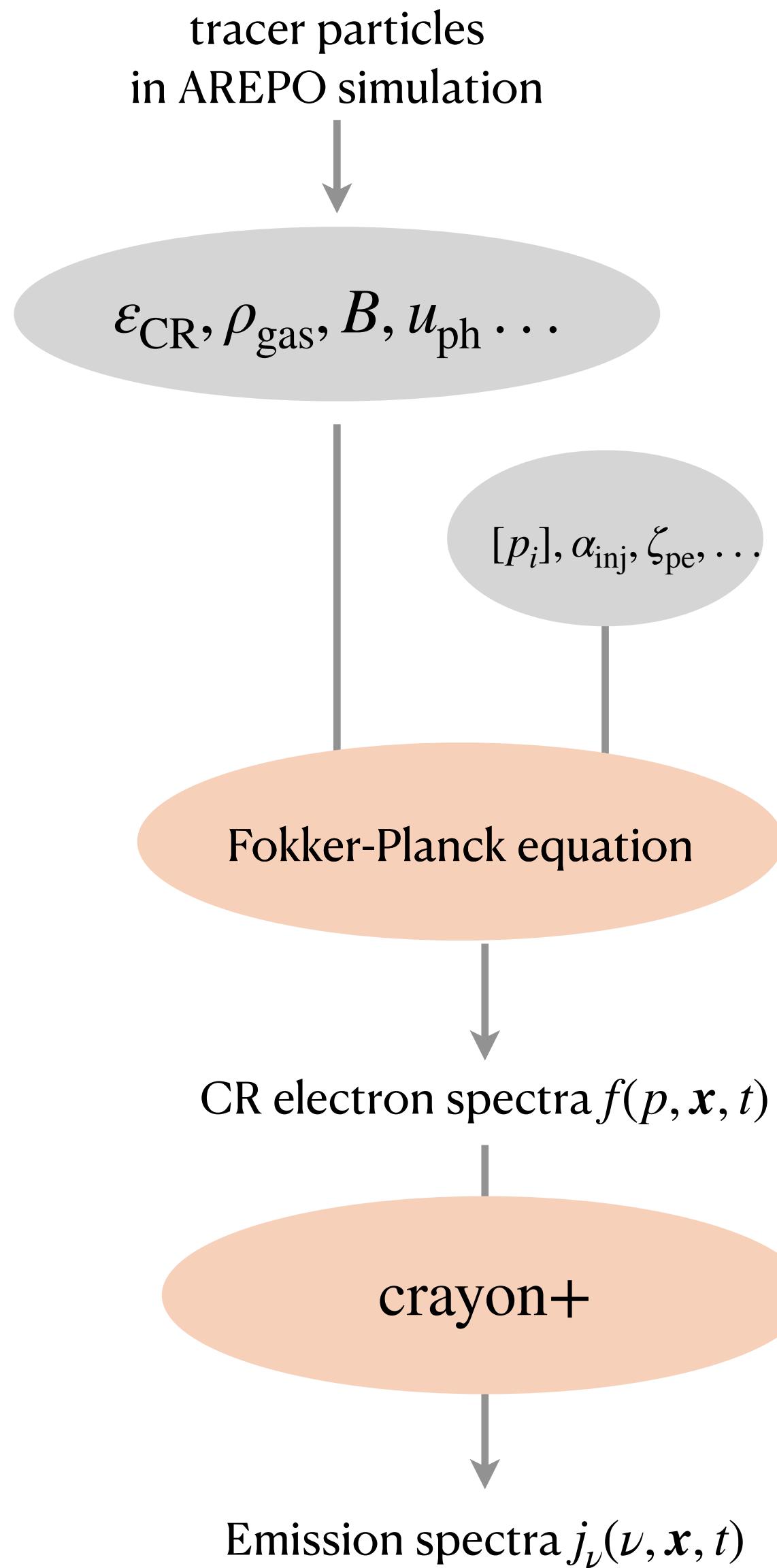
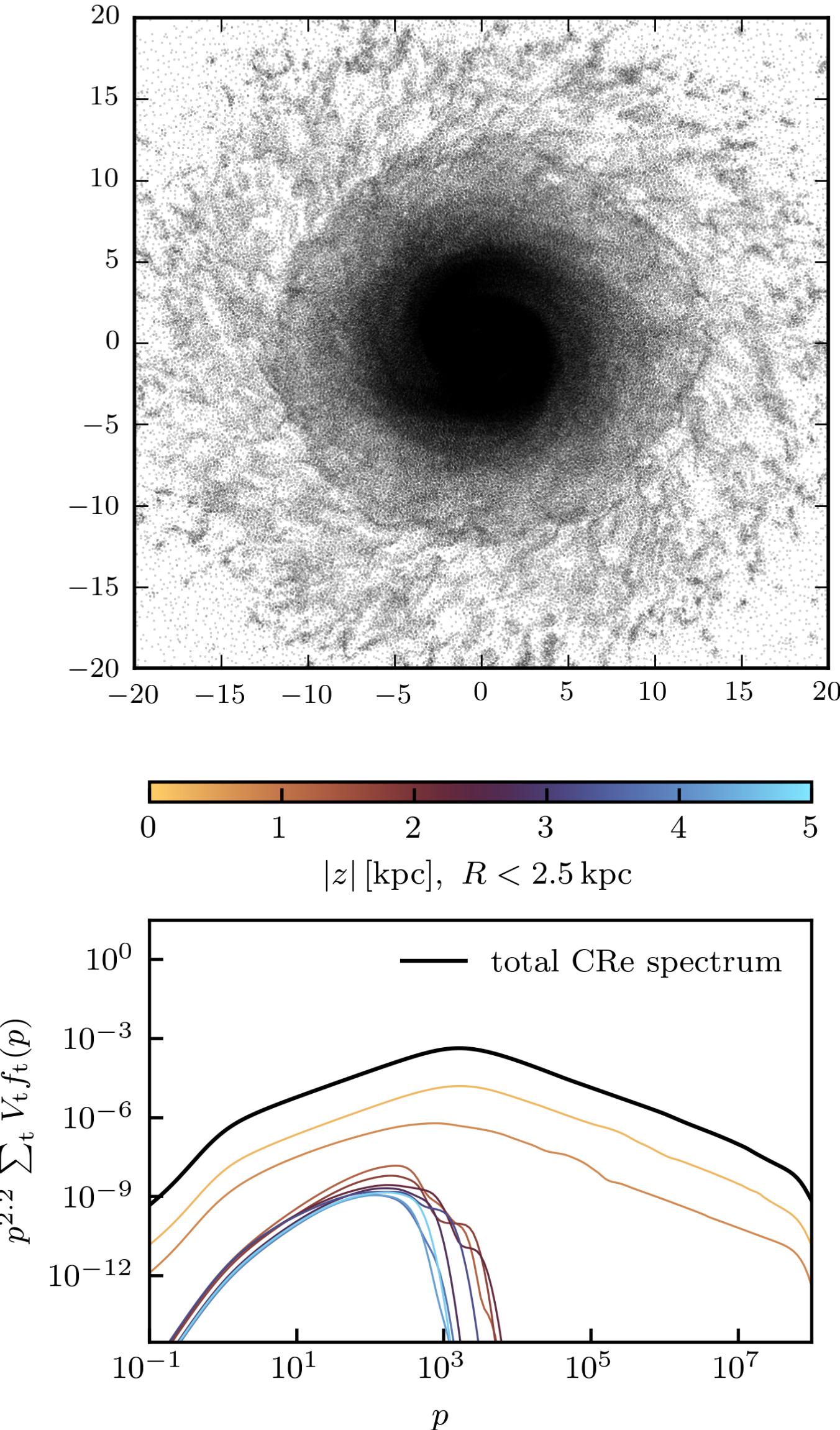
stronger B-fields in satellites, particularly after close encounter with host



How good is the steady-state modelling for electrons?

Werhahn et al. (in prep)

# CREST - CR electron spectra evolved in time



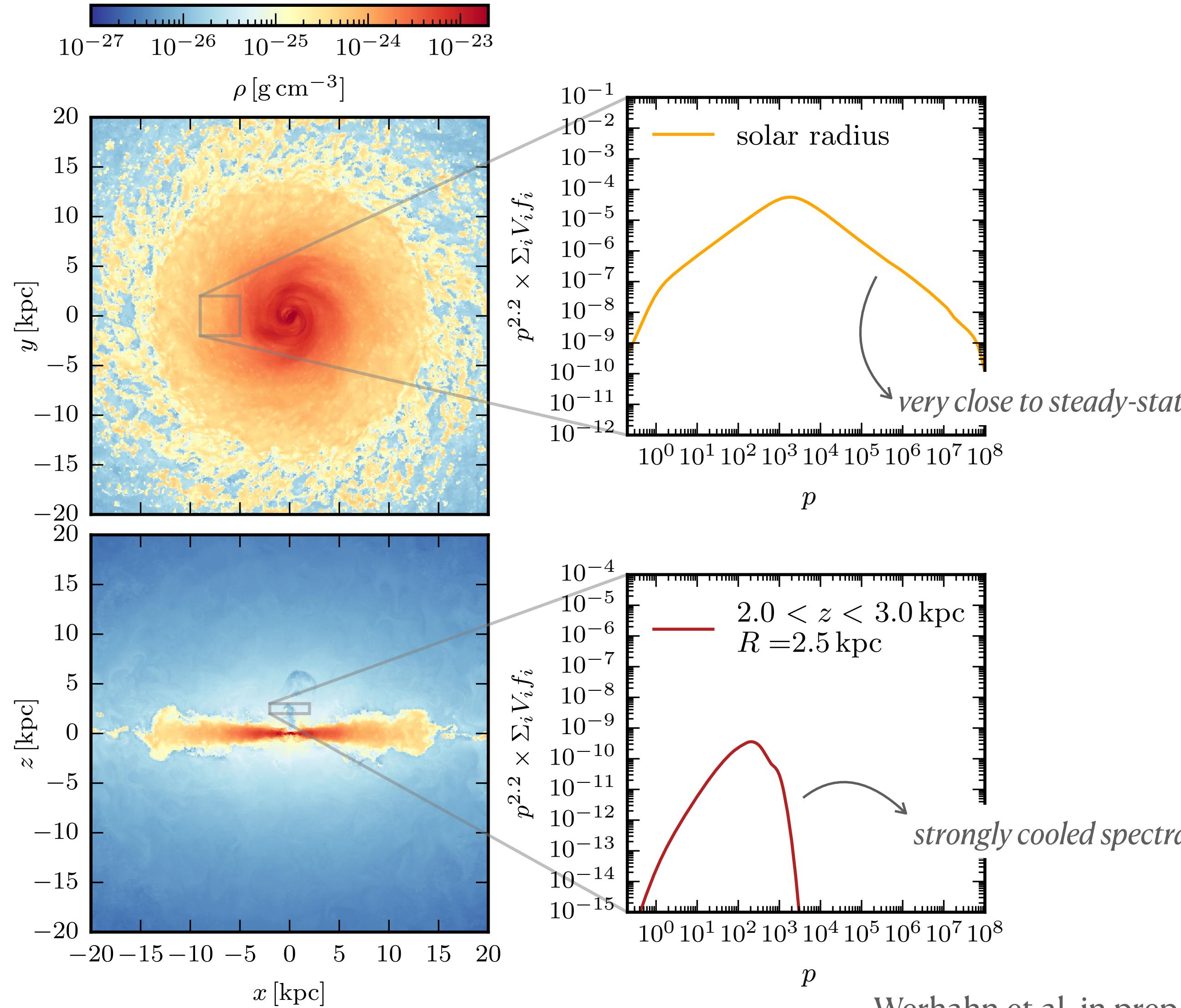
**CREST** (Winner+2019)

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?



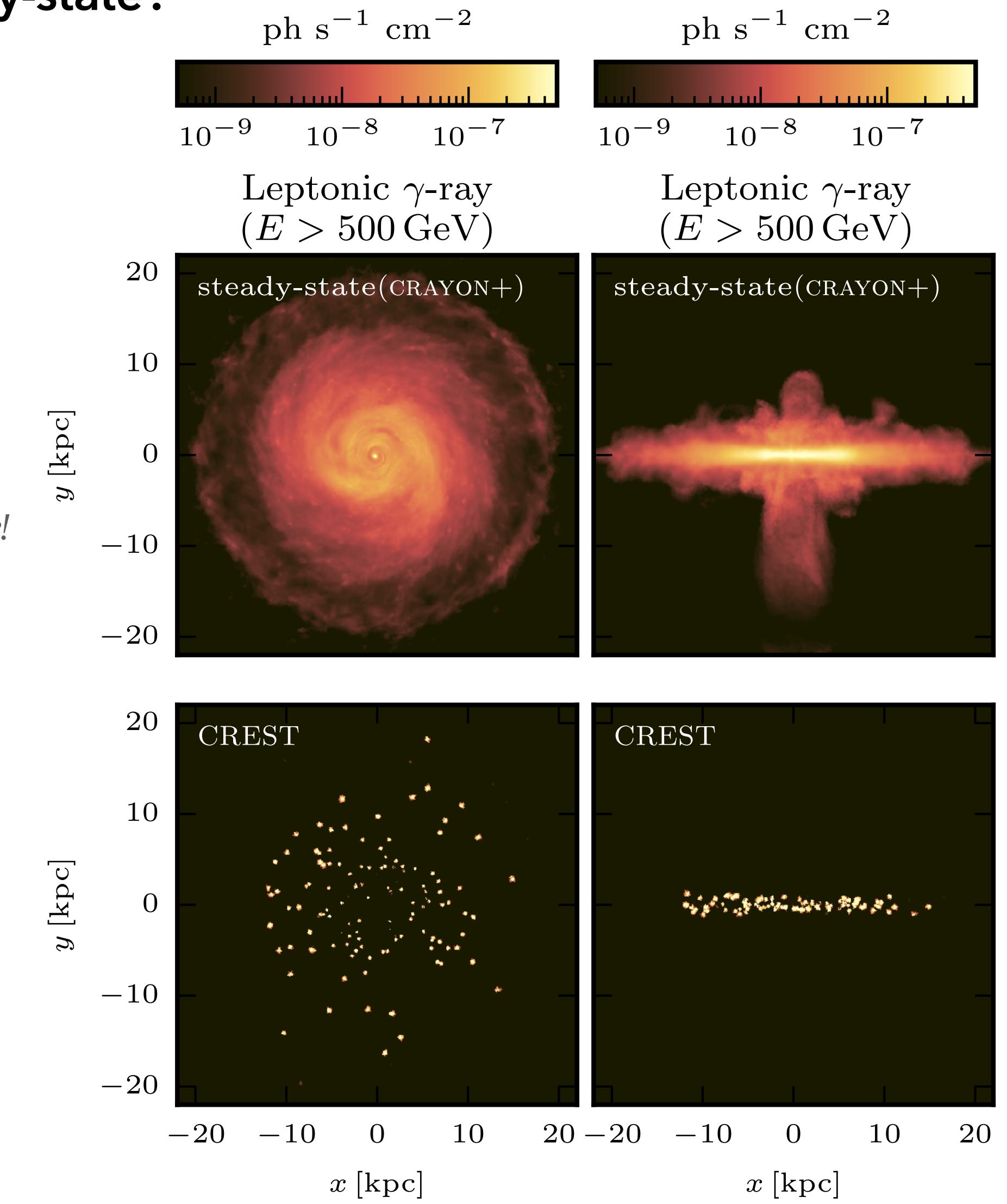
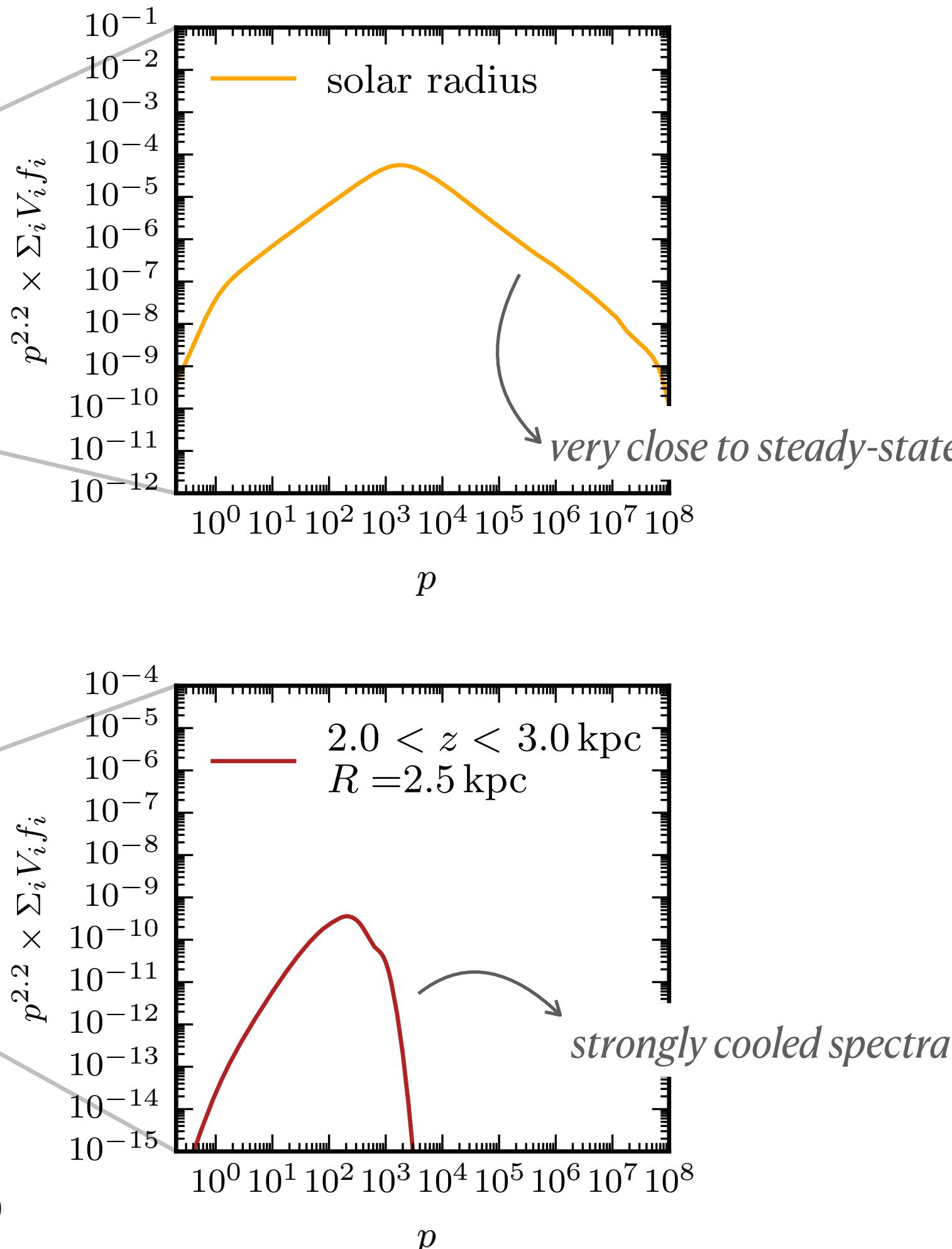
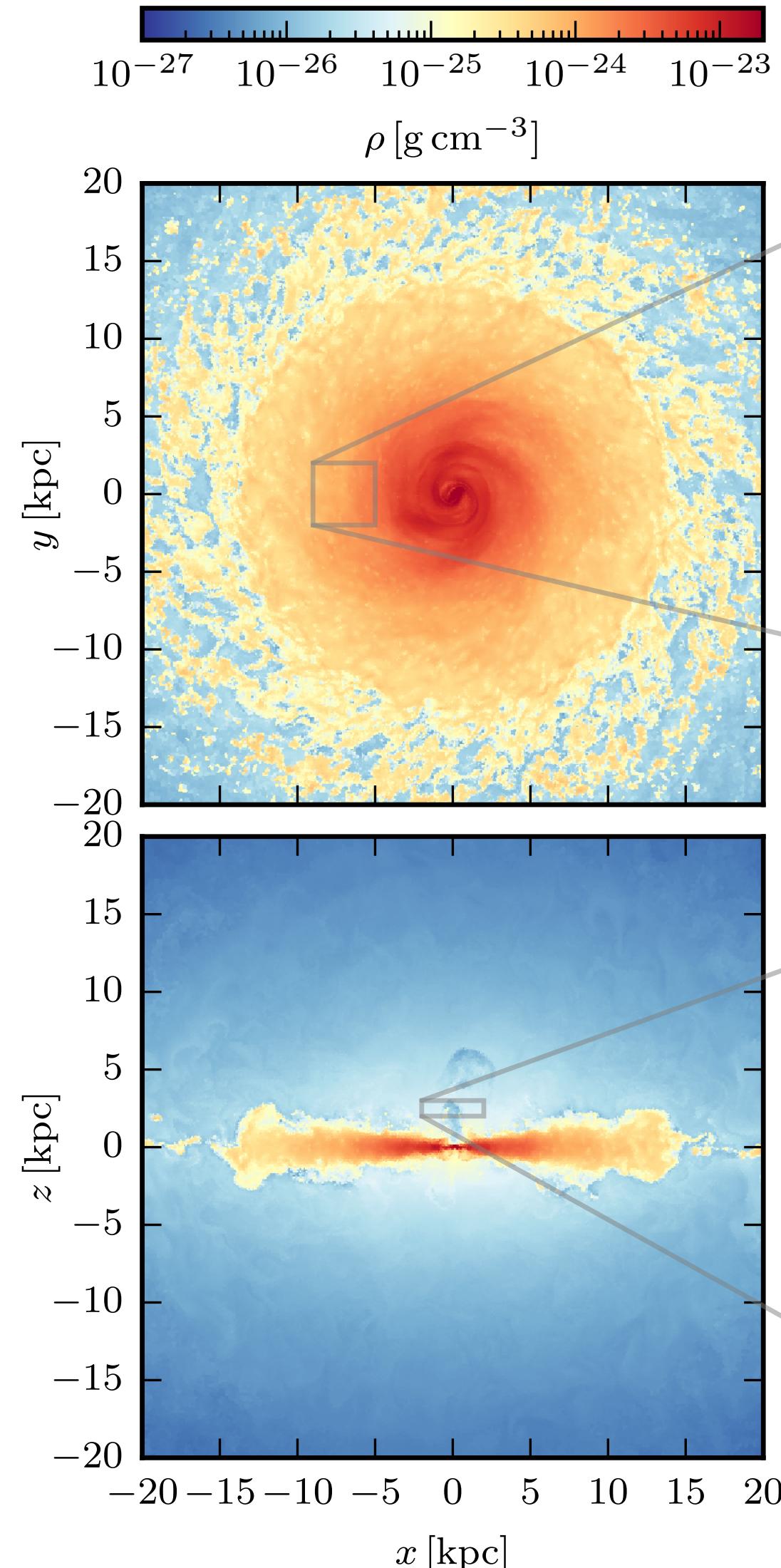
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- post-processing MHD simulations: solve Fokker-Planck equation on Lagrangian tracer particles
- accurate calculation of CR electron spectra as function of time and space
- coupled to **crayon+** for calculation of radiation processes
- *global* spectrum: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

# CREST - CR electron spectra evolved in time

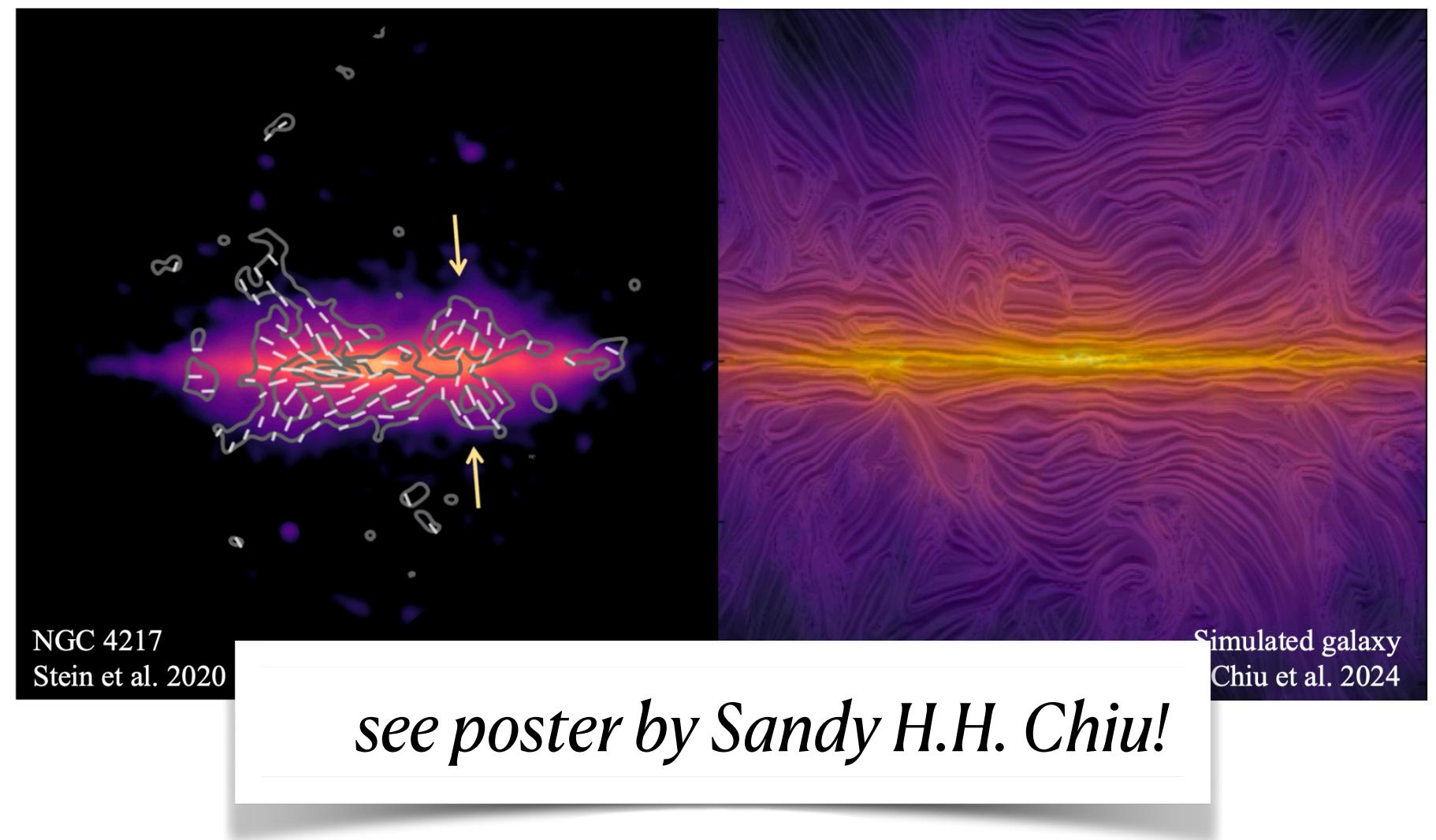
Are galaxies in a steady-state?



# 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



## 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

