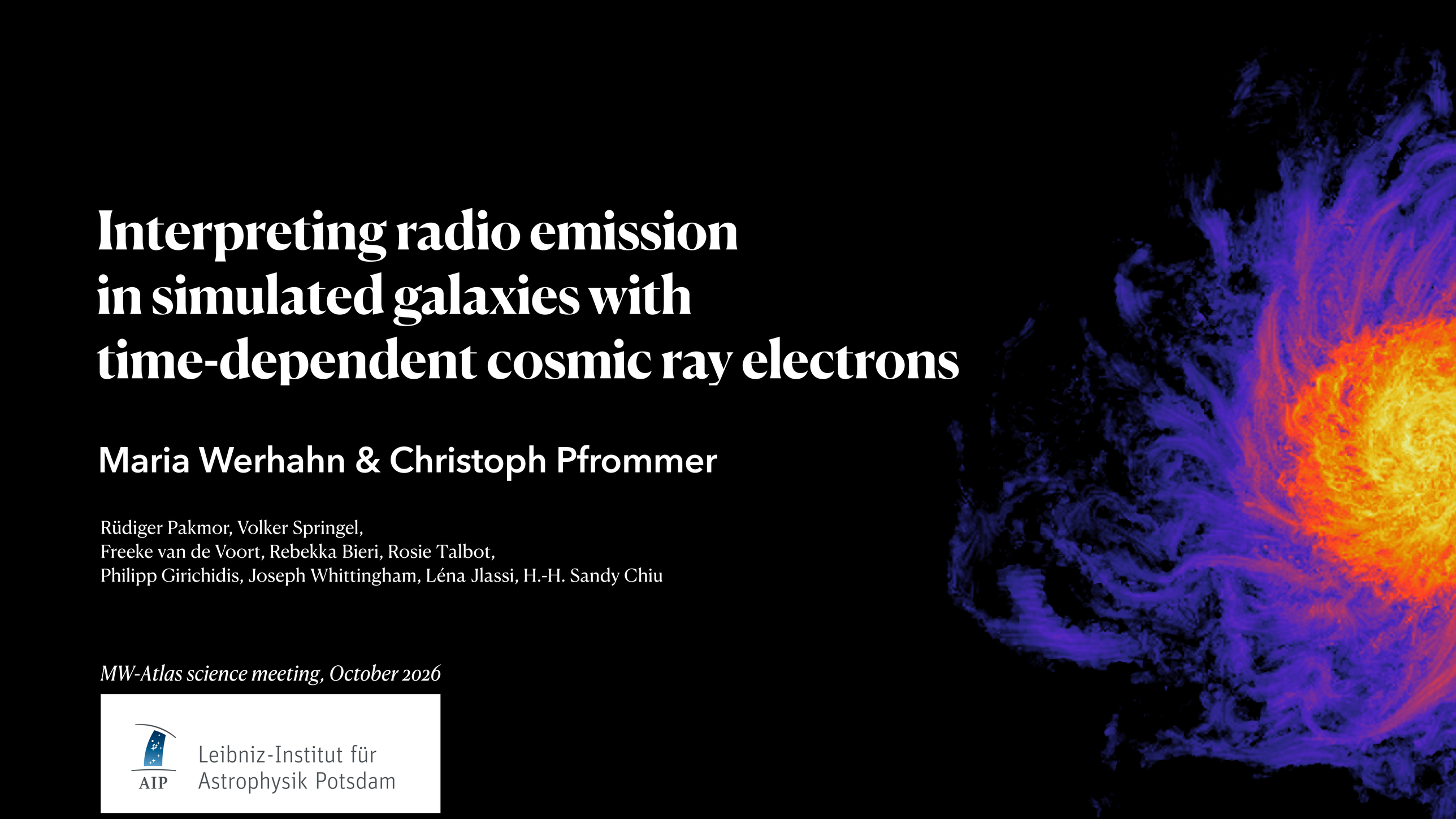
Interpreting radio emission in simulated galaxies with time-dependent cosmic ray electrons

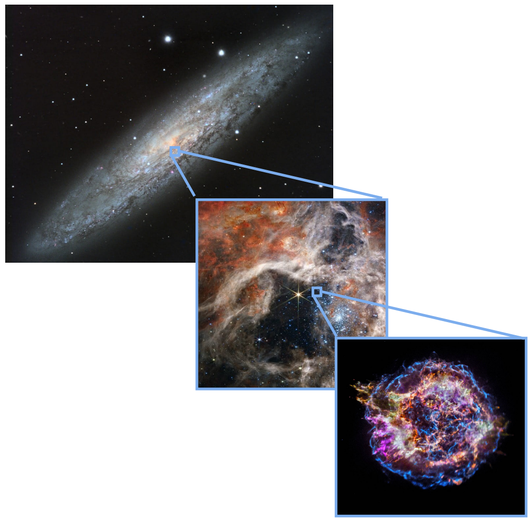
Maria Werhahn & Christoph Pfrommer

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

MW-Atlas science meeting, October 2026



AIP Leibniz-Institut für Astrophysik Potsdam

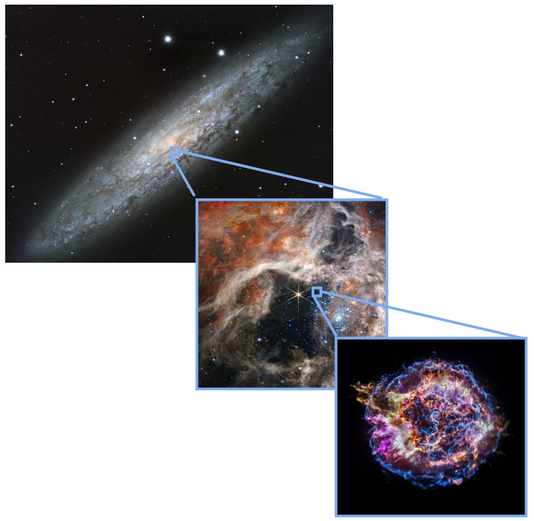


Cosmic Rays in Galaxy Formation

an uncertain ingredient

- $\varepsilon_{\rm CR} \sim \varepsilon_B \sim \varepsilon_{\rm th} \sim \varepsilon_{\rm kin}$
- Transport physics unresolved —> macroscopic transport models (advection, diffusion, streaming)

Credit: Paul Luckas, ICRAR

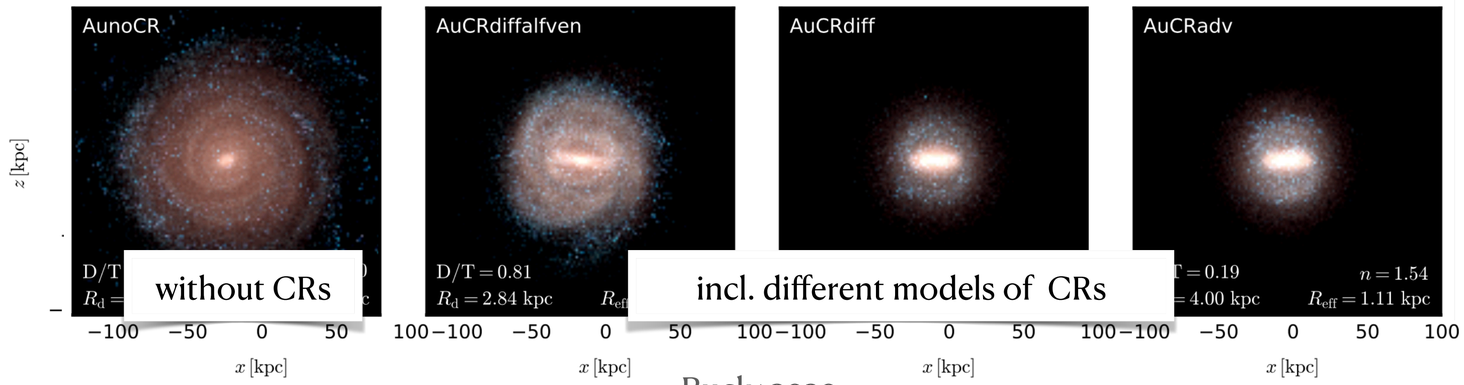


Cosmic Rays in Galaxy Formation

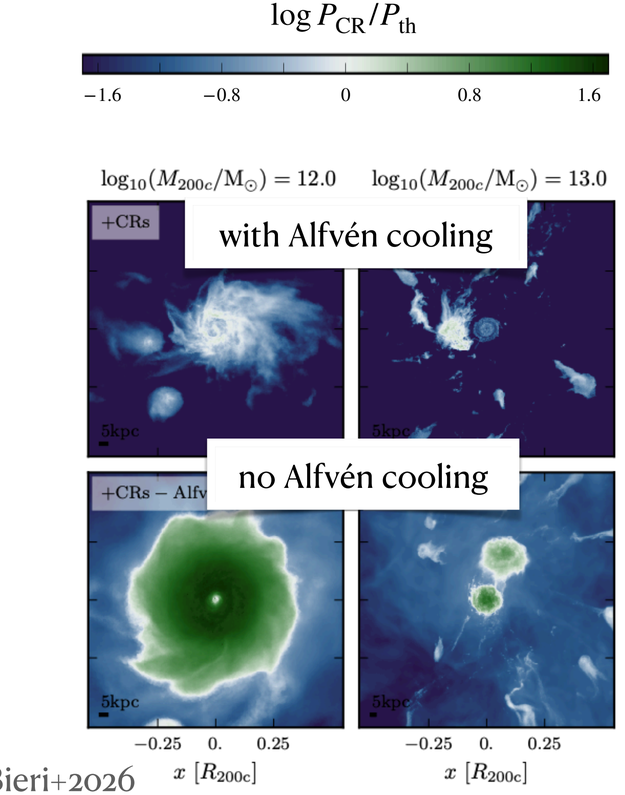
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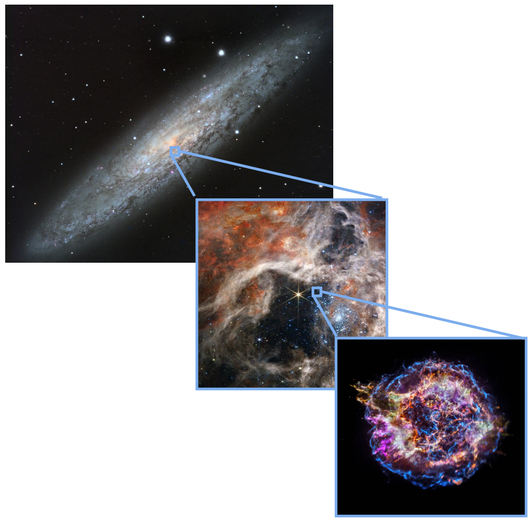
Credit: Paul Luckas, ICRAR



Buck+2020



Bieri+2026

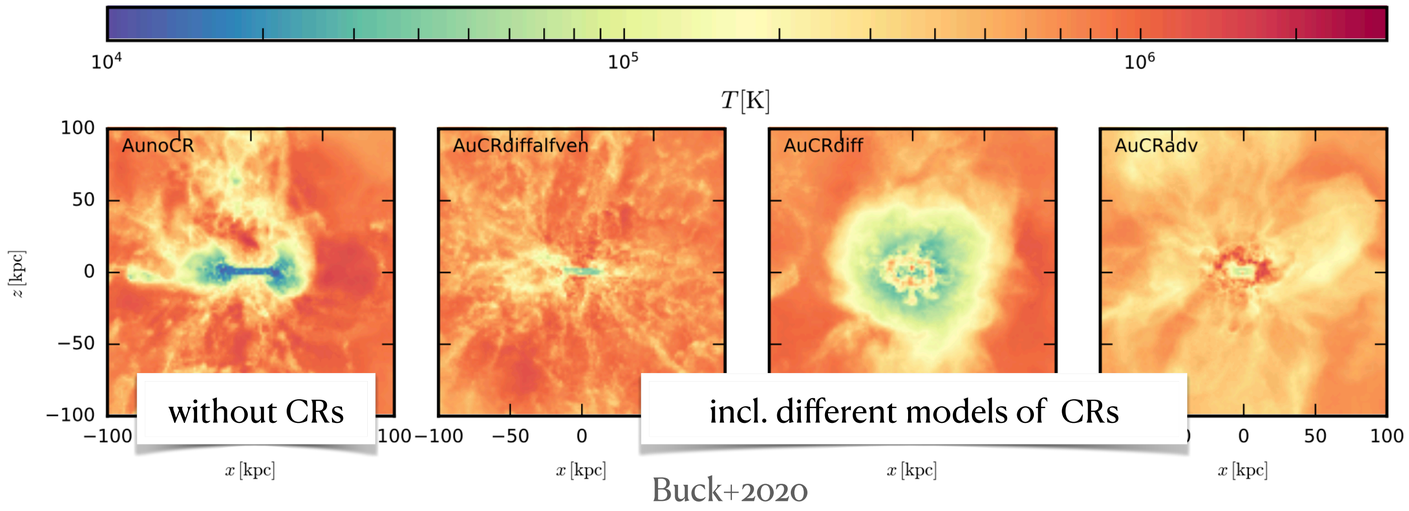


Cosmic Rays in Galaxy Formation

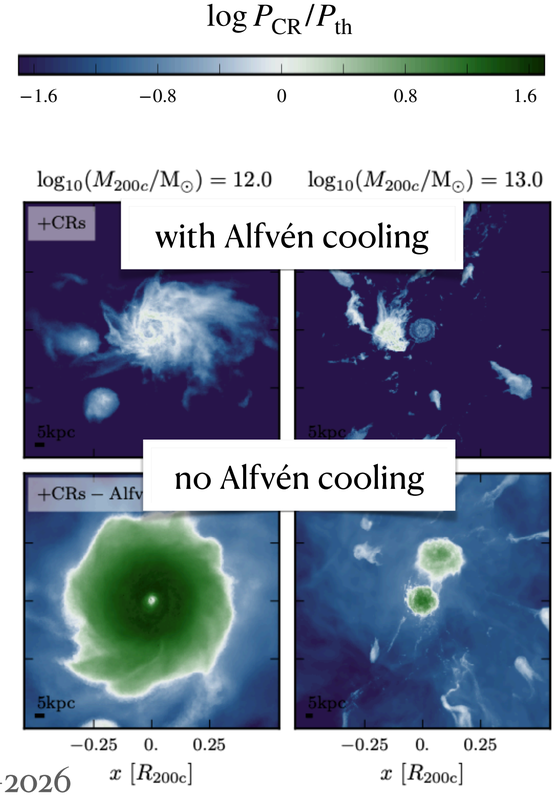
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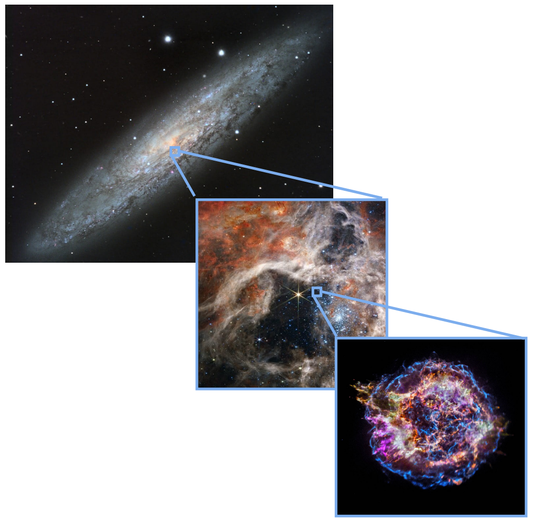
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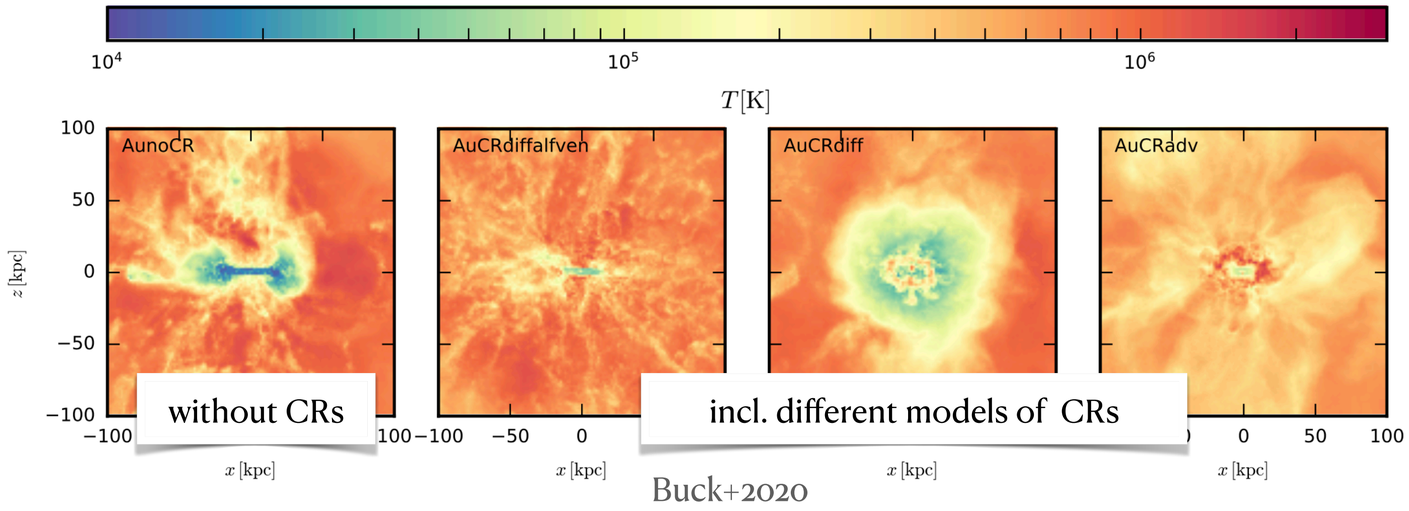
Cosmic Rays in Galaxy Formation

an uncertain ingredient

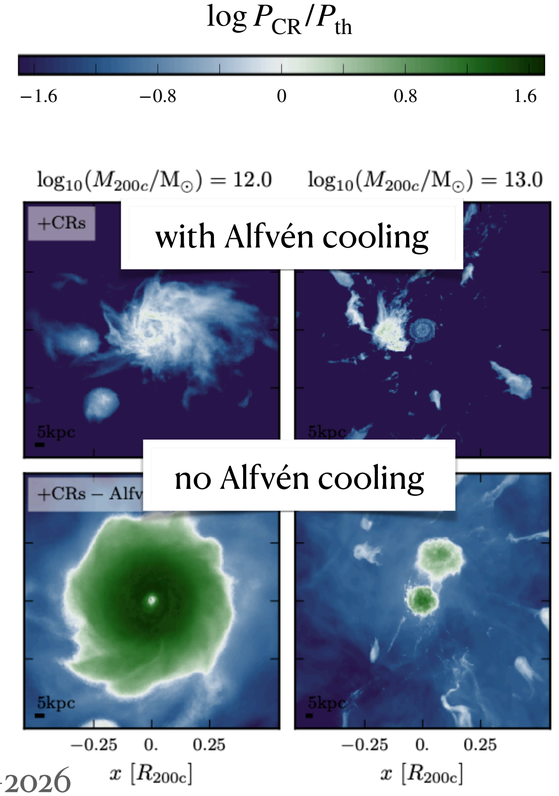
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- Different transport —> different impact on galaxies

Credit: Paul Luckas, ICRAR

How can we constrain CR transport?



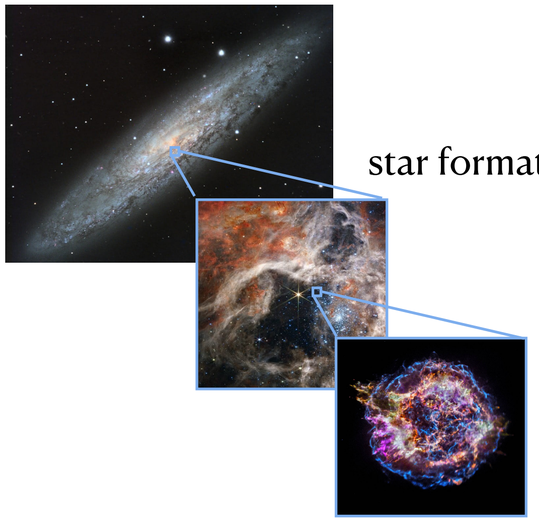
Buck+2020



Bieri+2026

Cosmic Rays in Galaxy Formation

From CRs to observables



star formation

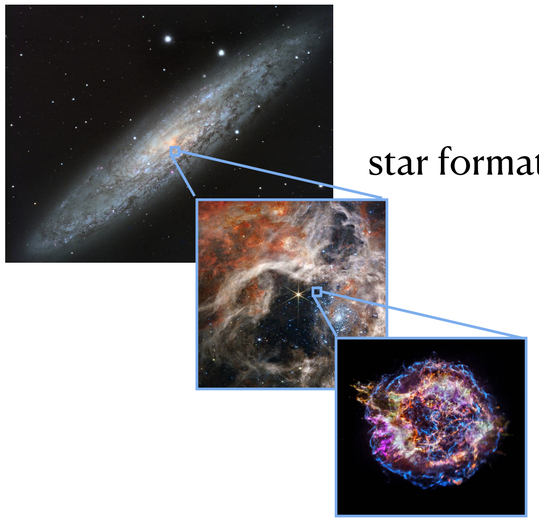
acceleration of
CR protons and
CR electrons

Direct observational constraints

Credit: Paul Luckas, ICRAR

Cosmic Rays in Galaxy Formation

From CRs to observables



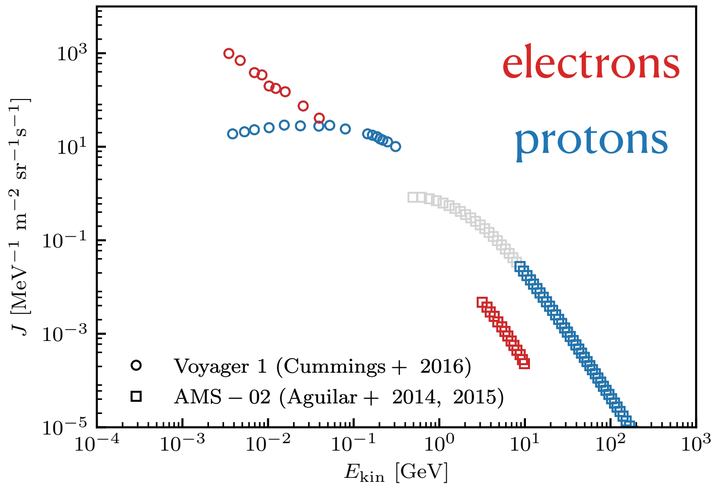
star formation

acceleration of
CR protons and
CR electrons

Credit: Paul Luckas, ICRAR

Direct observational constraints

measured CR spectrum — *only locally accessible*

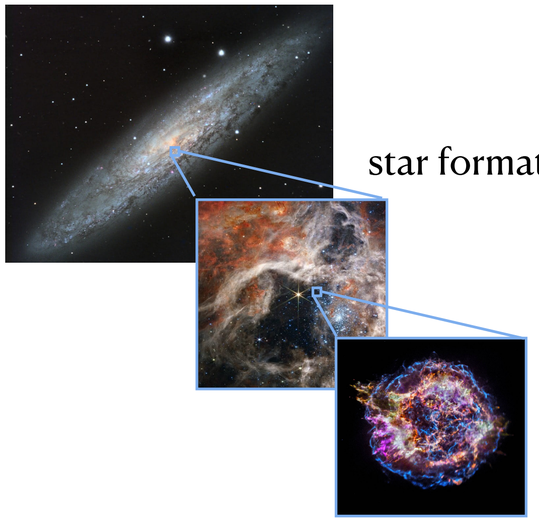


AMS-02 (ISS)



Cosmic Rays in Galaxy Formation

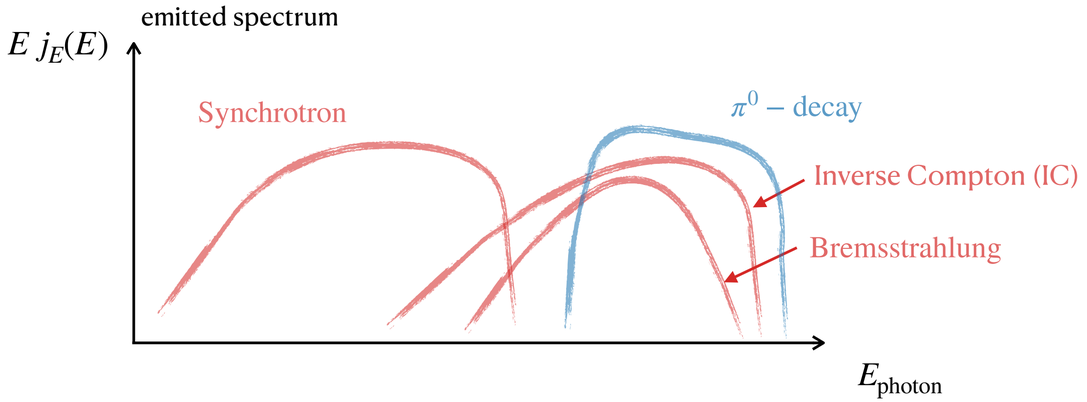
From CRs to observables



star formation

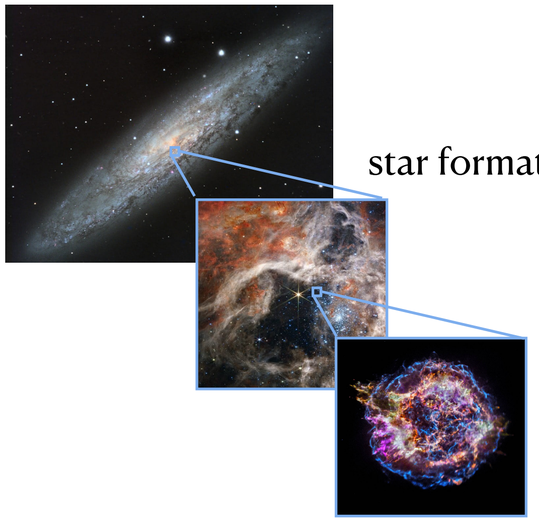
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Indirect observational constraints



Cosmic Rays in Galaxy Formation

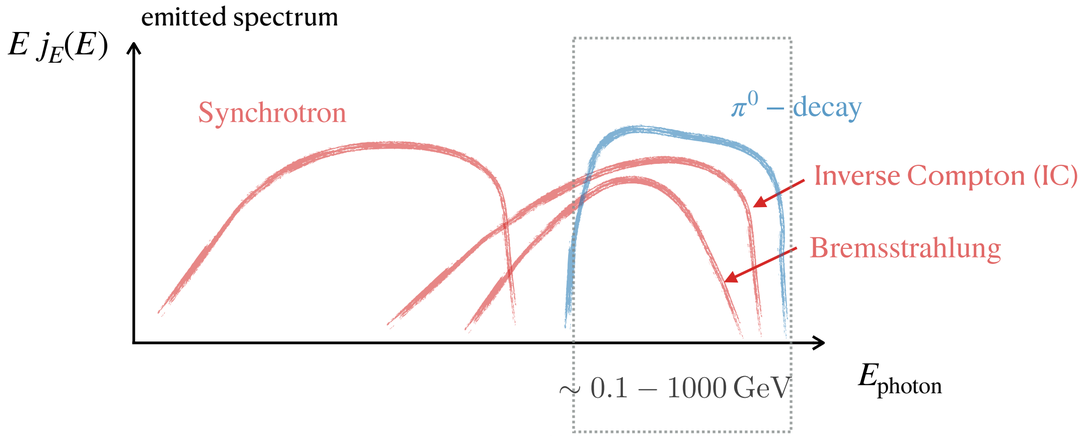
From CRs to observables



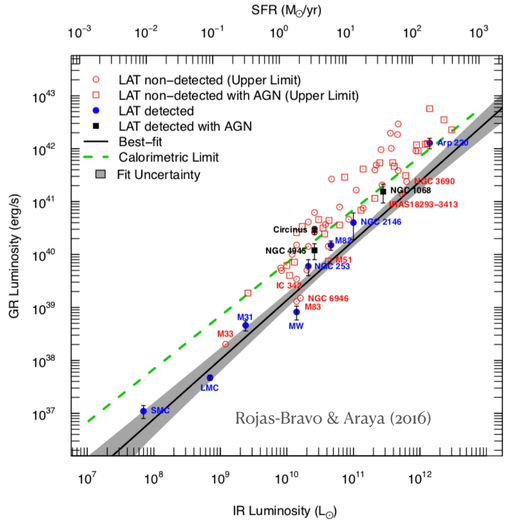
star formation

acceleration of CR protons and CR electrons

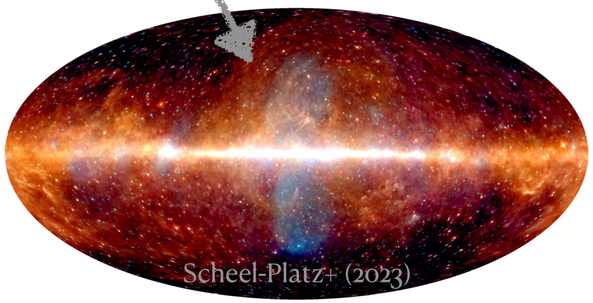
Indirect observational constraints



FIR-gamma-ray relation



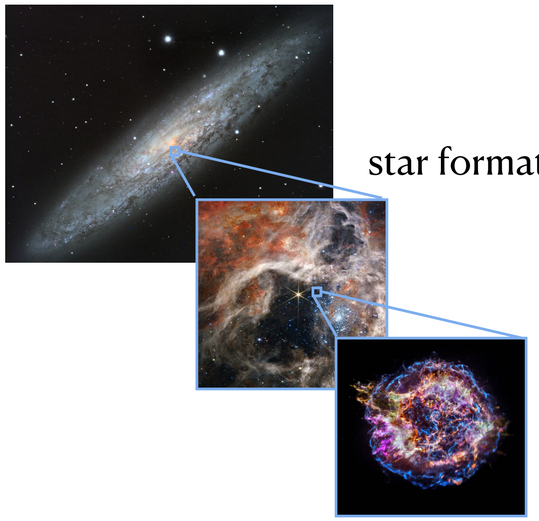
gamma-ray



only for MW and nearby star-forming galaxies ...

Cosmic Rays in Galaxy Formation

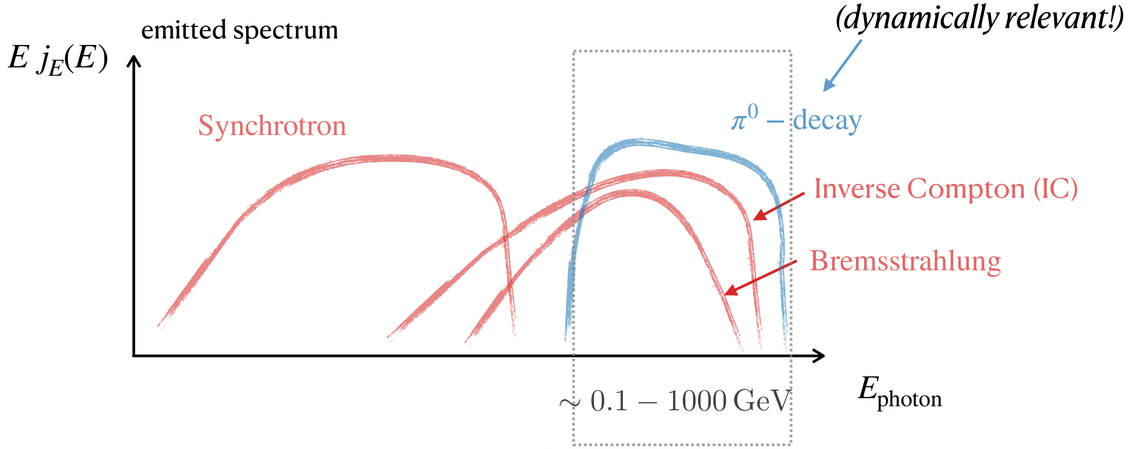
From CRs to observables



star formation

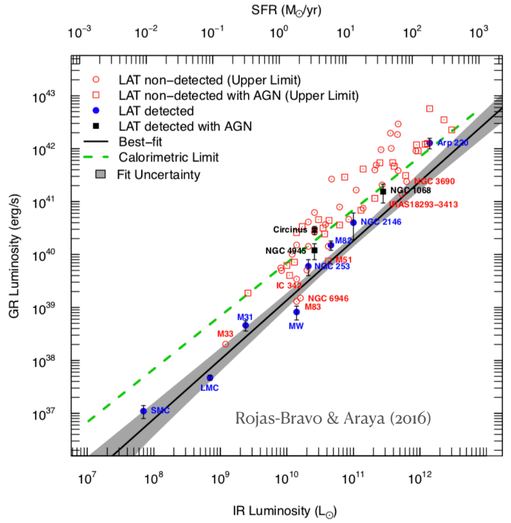
acceleration of CR protons and CR electrons

Indirect observational constraints

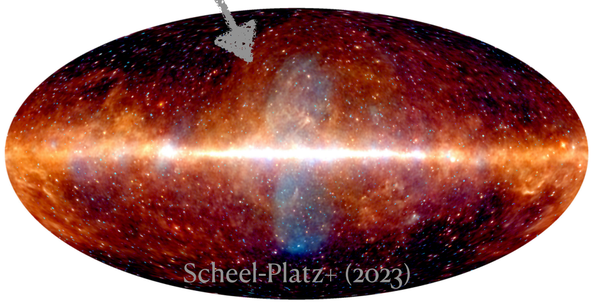


traces CR protons (dynamically relevant!)

FIR-gamma-ray relation



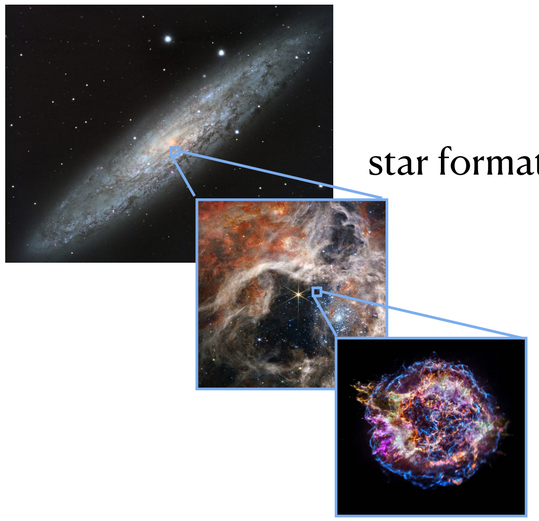
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only for MW and nearby star-forming galaxies ...

Cosmic Rays in Galaxy Formation

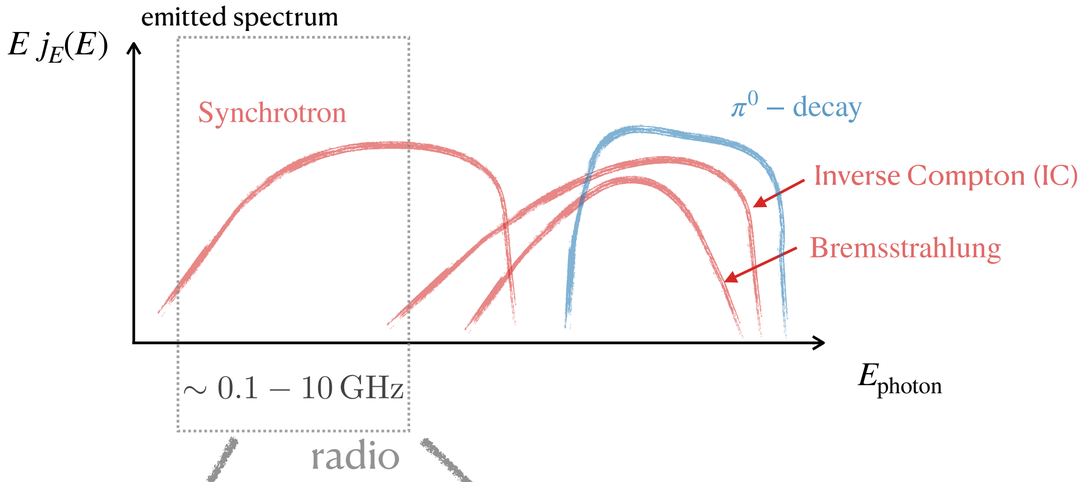
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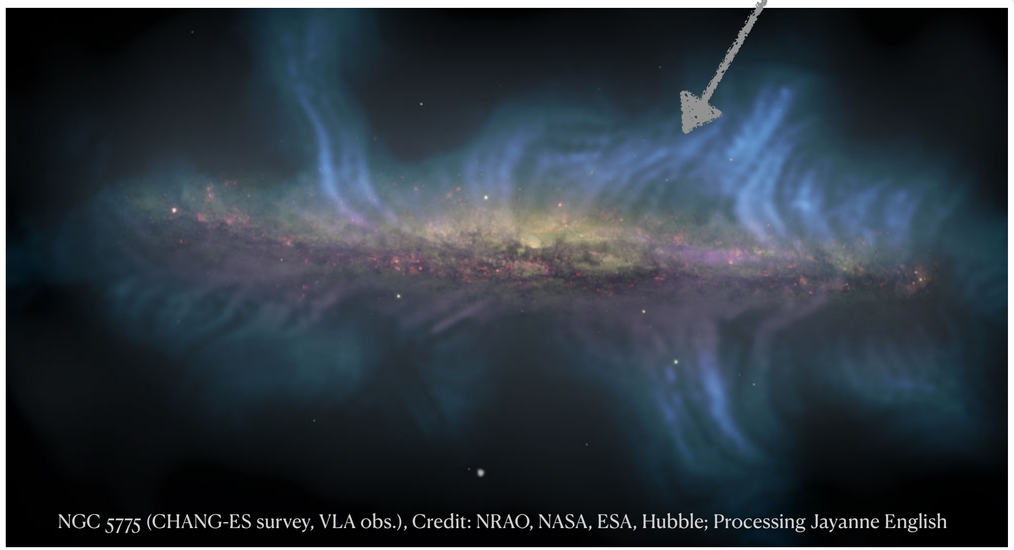


star formation

acceleration of
CR protons and
CR electrons

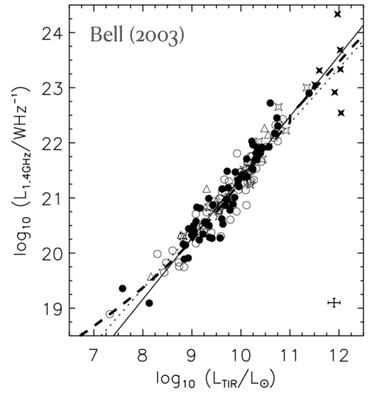
Indirect observational constraints





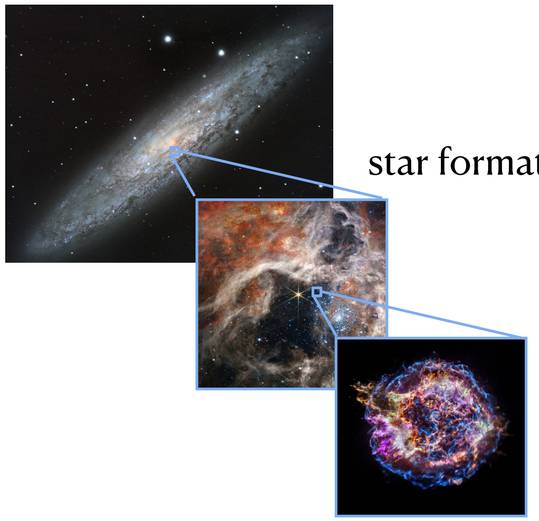
NGC 5775 (CHANG-ES survey, VLA obs.), Credit: NRAO, NASA, ESA, Hubble; Processing Jayanne English

FIR-Radio relation



Cosmic Rays in Galaxy Formation

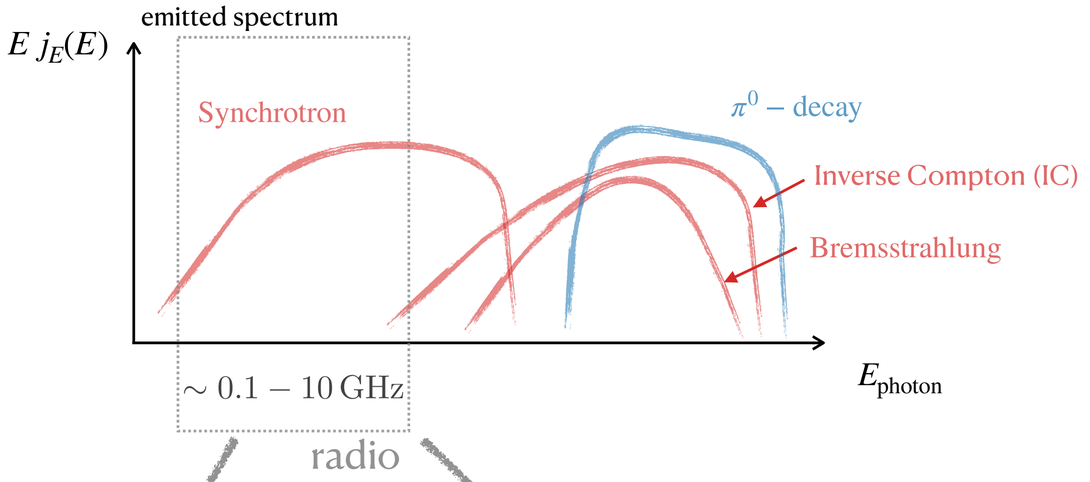
From CRs to observables



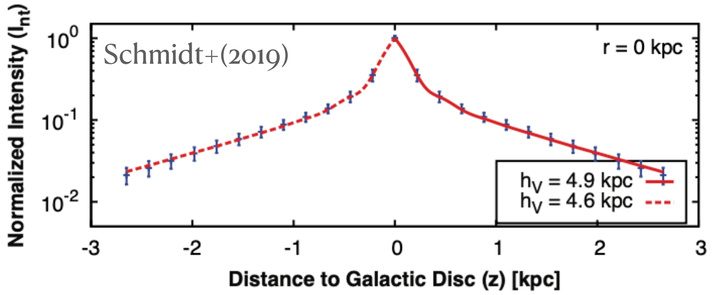
star formation

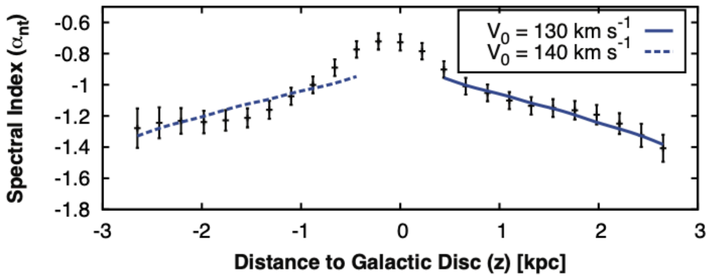
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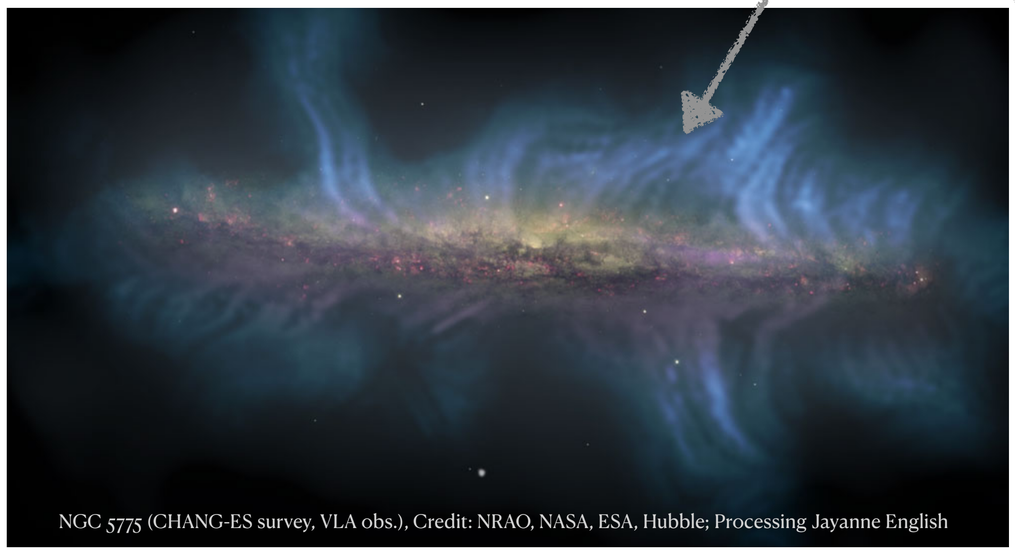
Indirect observational constraints



Vertical radio profiles

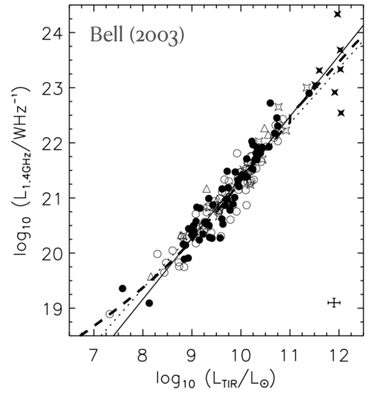






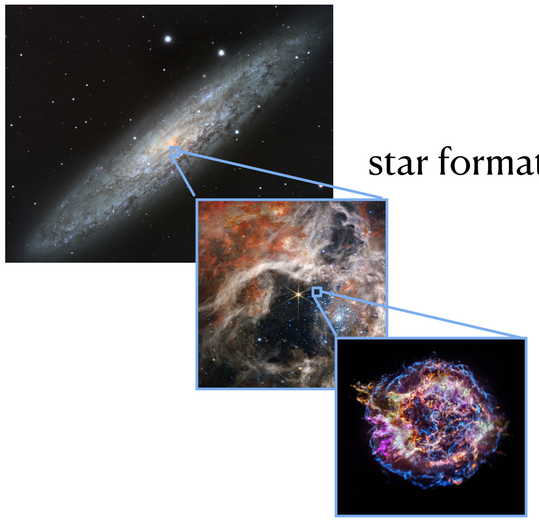
NGC 5775 (CHANG-ES survey, VLA obs.), Credit: NRAO, NASA, ESA, Hubble; Processing Jayanne English

FIR-Radio relation



Cosmic Rays in Galaxy Formation

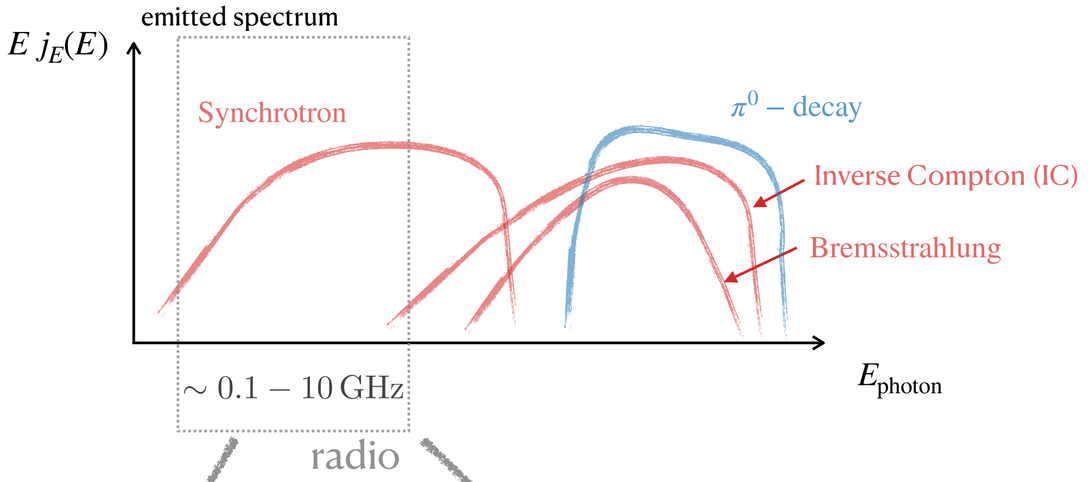
From CRs to observables



star formation

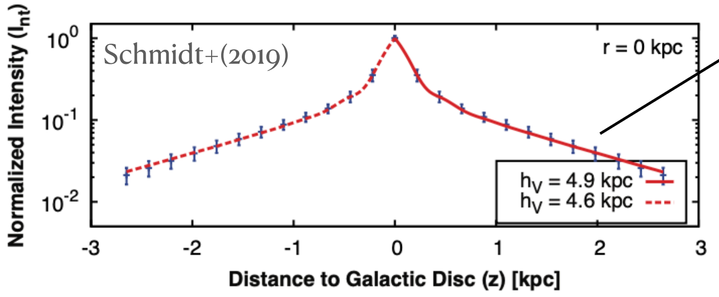
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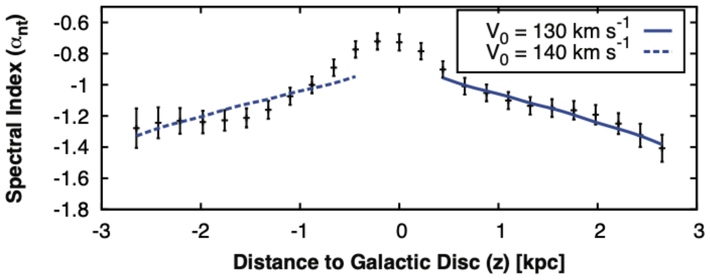
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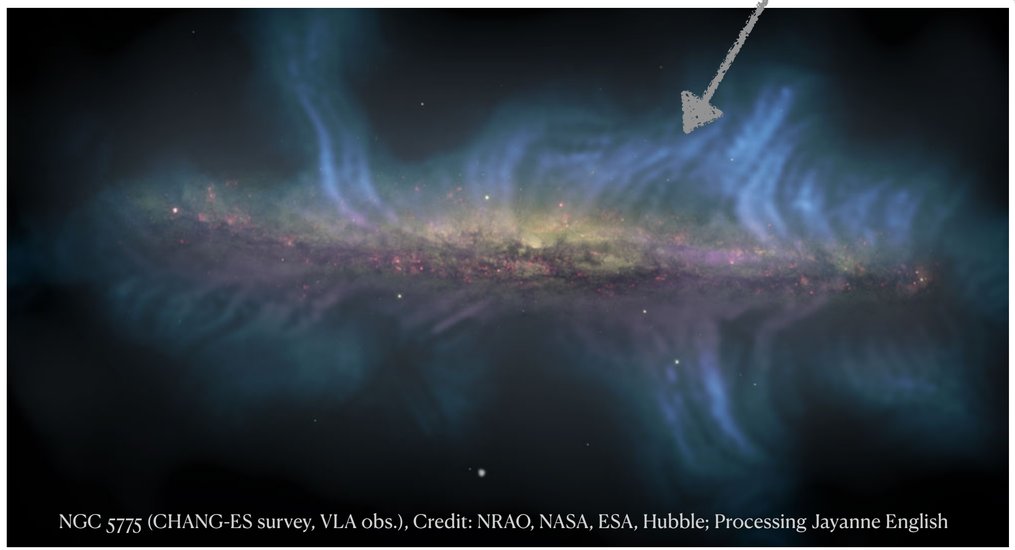


Vertical radio profiles

fitted with 1D transport models

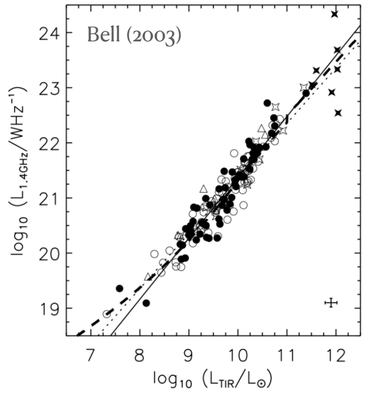






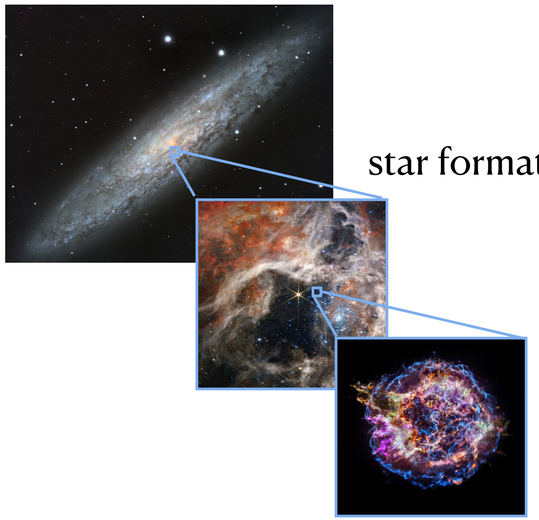
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FIR-Radio relation



Cosmic Rays in Galaxy Formation

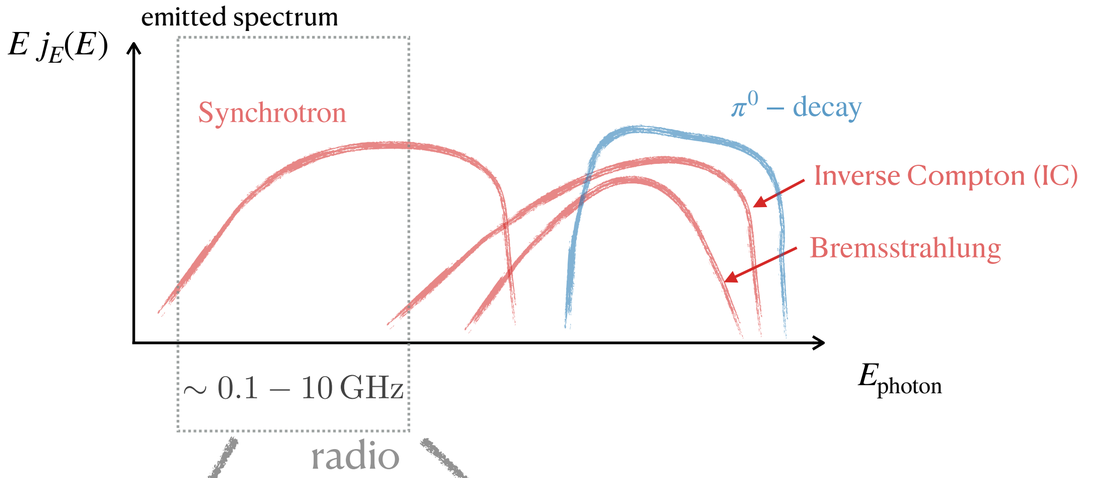
From CRs to observables



star formation

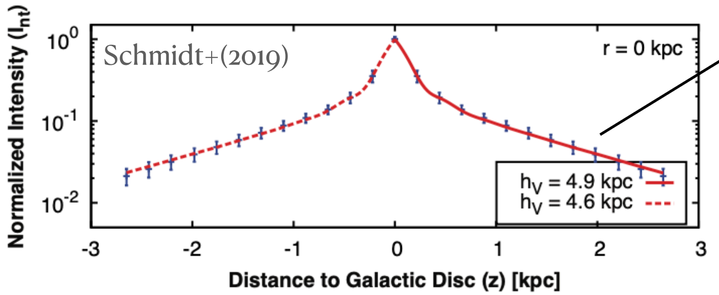
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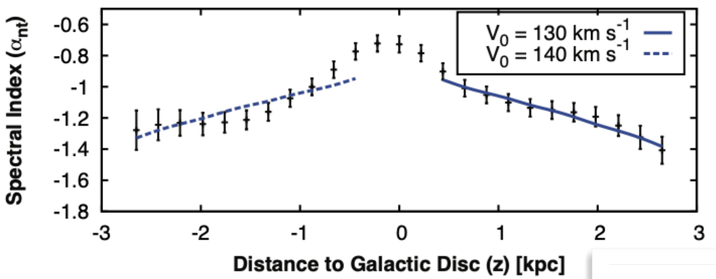
Indirect observational constraints

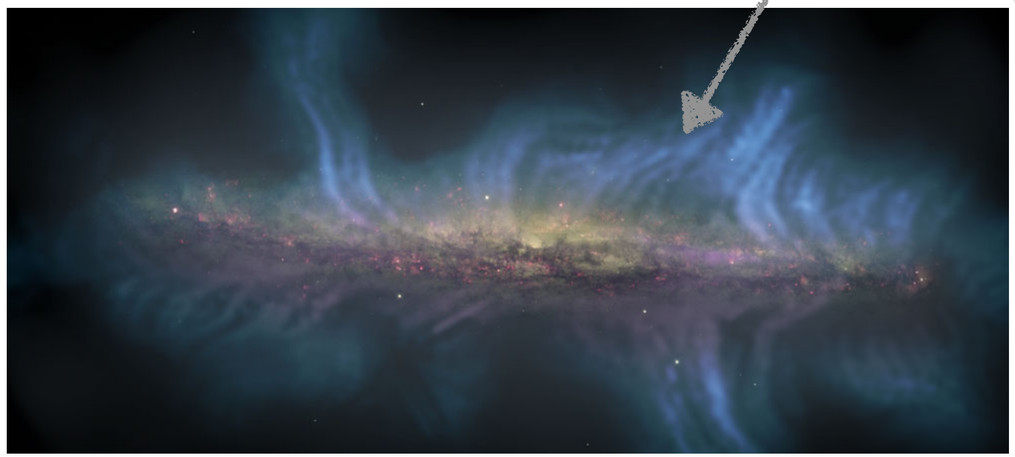


Vertical radio profiles

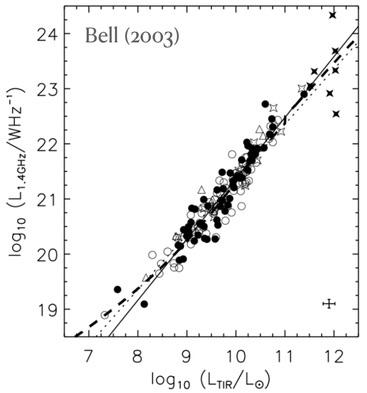
fitted with 1D transport models







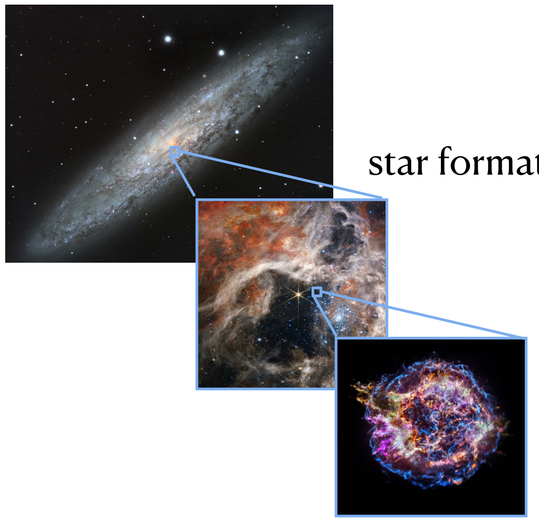
FIR-Radio relation



Can we use these observations to constrain CR transport?

Cosmic Rays in Galaxy Formation

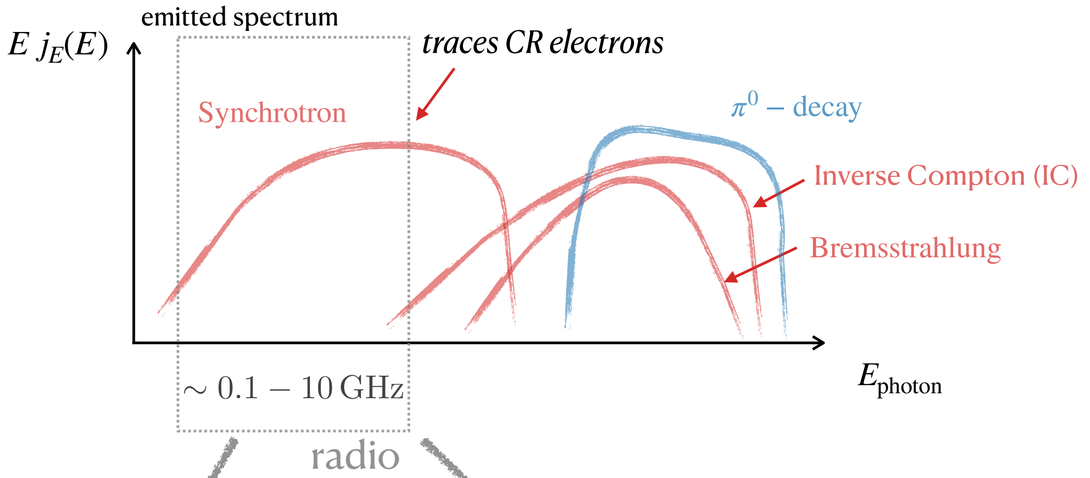
From CRs to observables



star formation

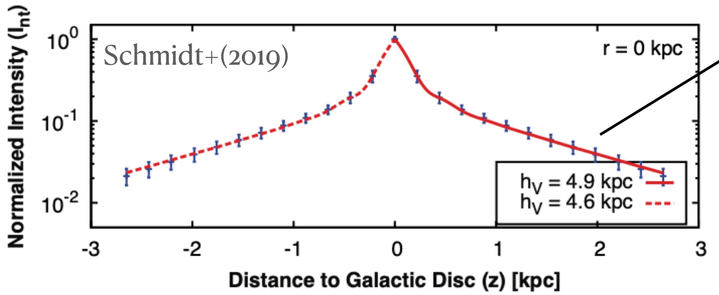
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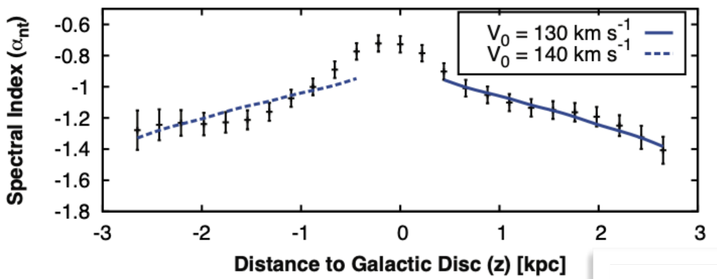
Indirect observational constraints

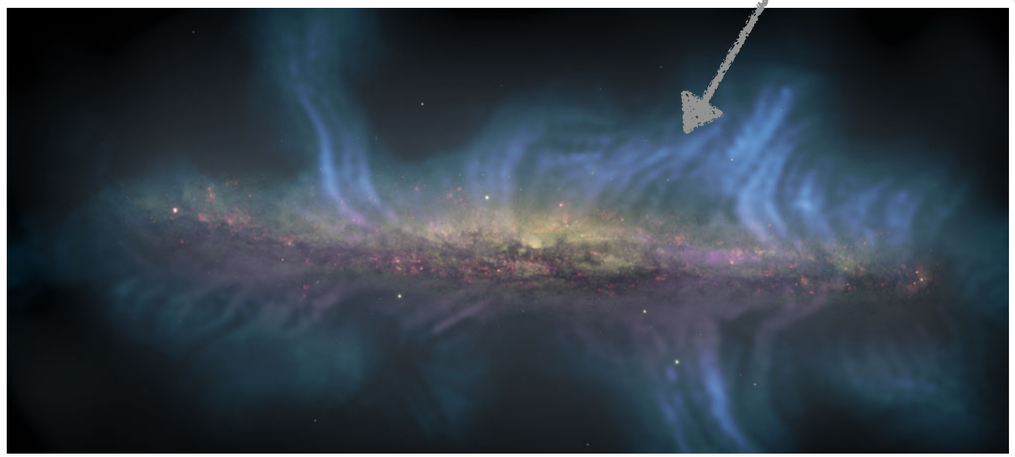


Vertical radio profiles

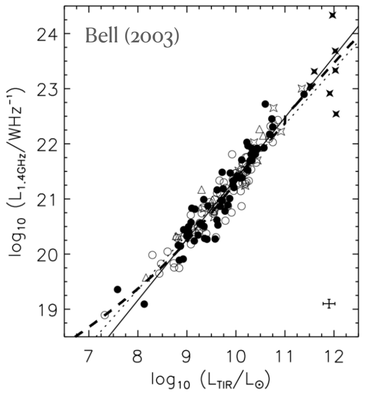
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FIR-Radio relation

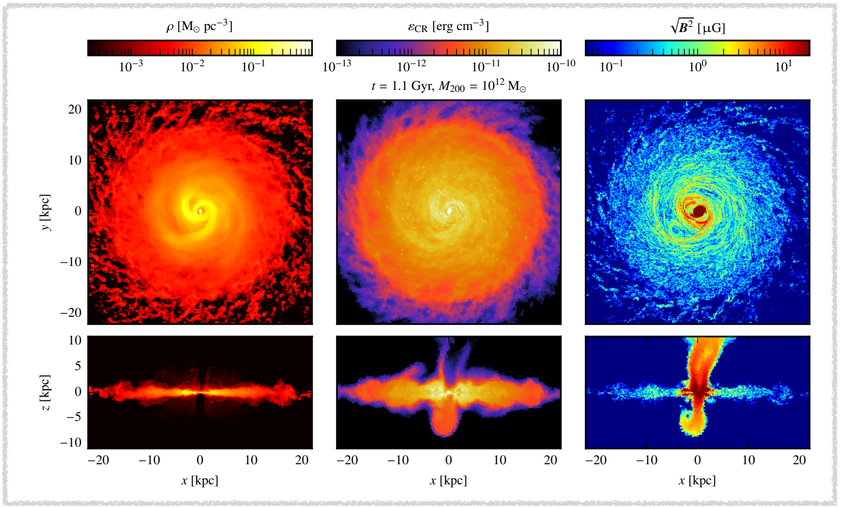


Can we use these observations to constrain CR transport?

Modelling CR spectra & emission with CRAYON+ Cosmic RAY emissiON + more :)

from MHD simulation

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



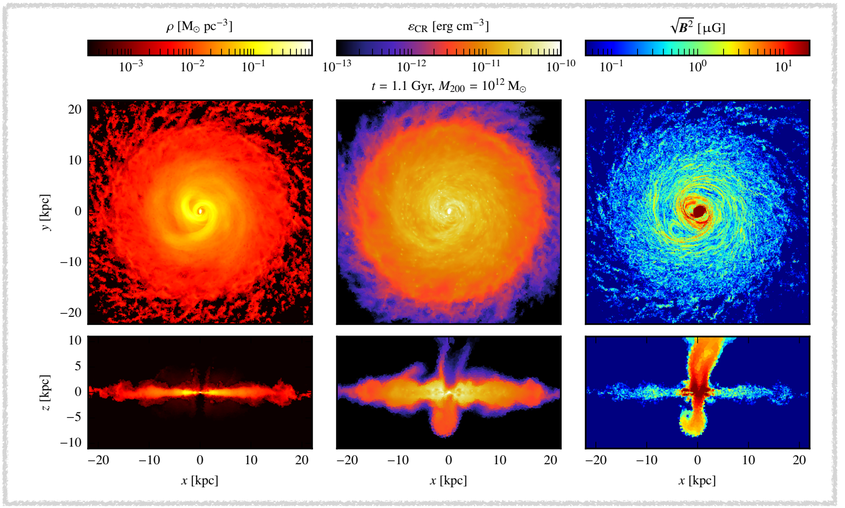
Christoph Pfrommer

Werhahn et al. (2021 a)

Modelling CR spectra & emission with CRAYON+ Cosmic RAY emissiON + more :)

from MHD simulation

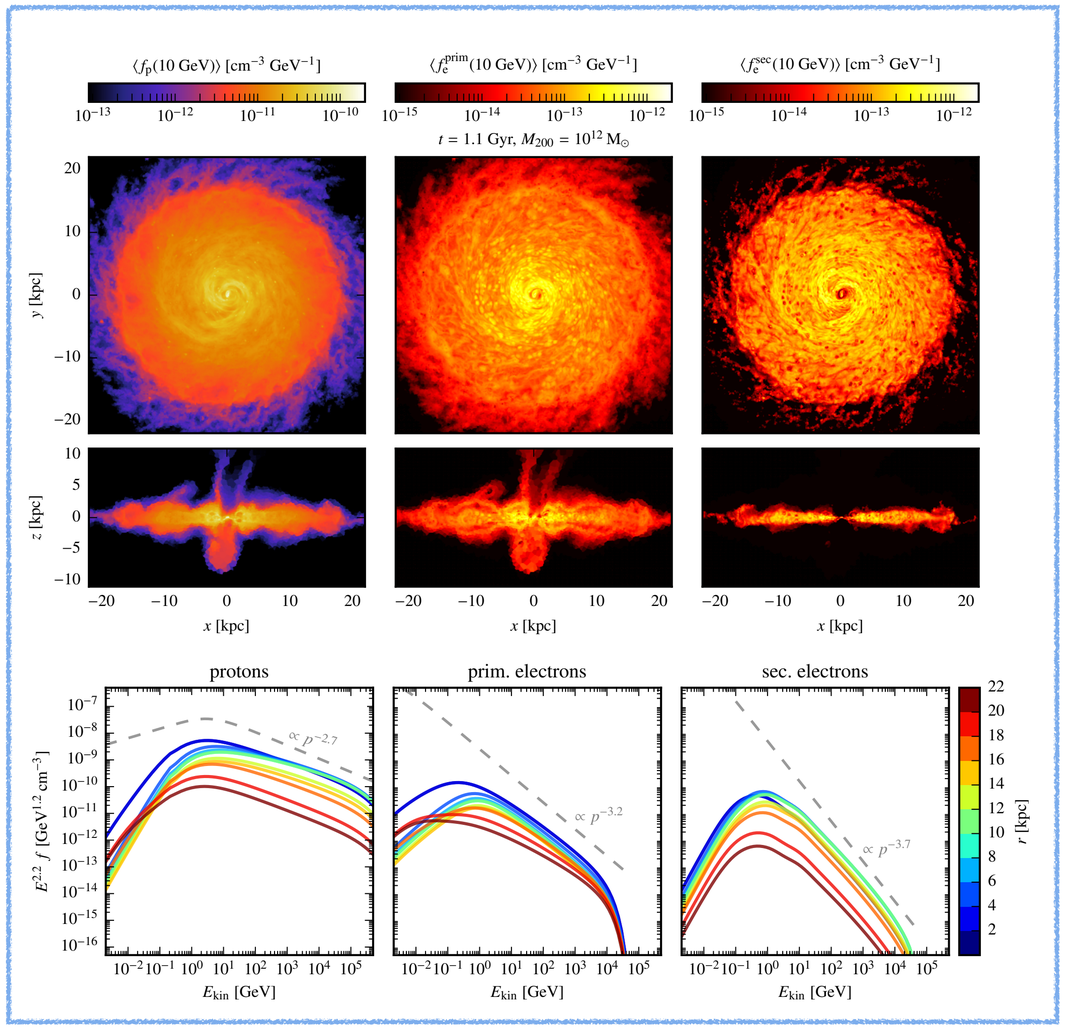
MHD simulations of isolated galaxies ($10^{10} - 10^{12}\,M_\odot$)



CRAYON+

steady-state spectra
(injection ≈ cooling)

CR proton, primary and secondary electron spectra



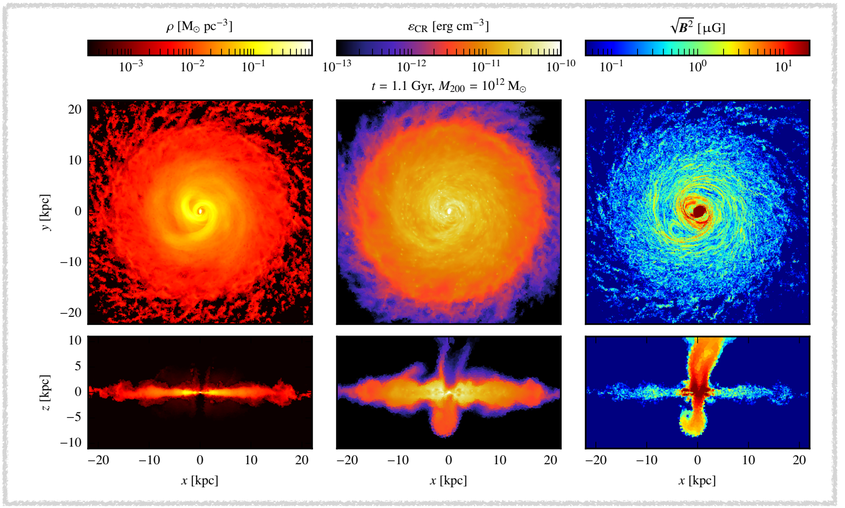
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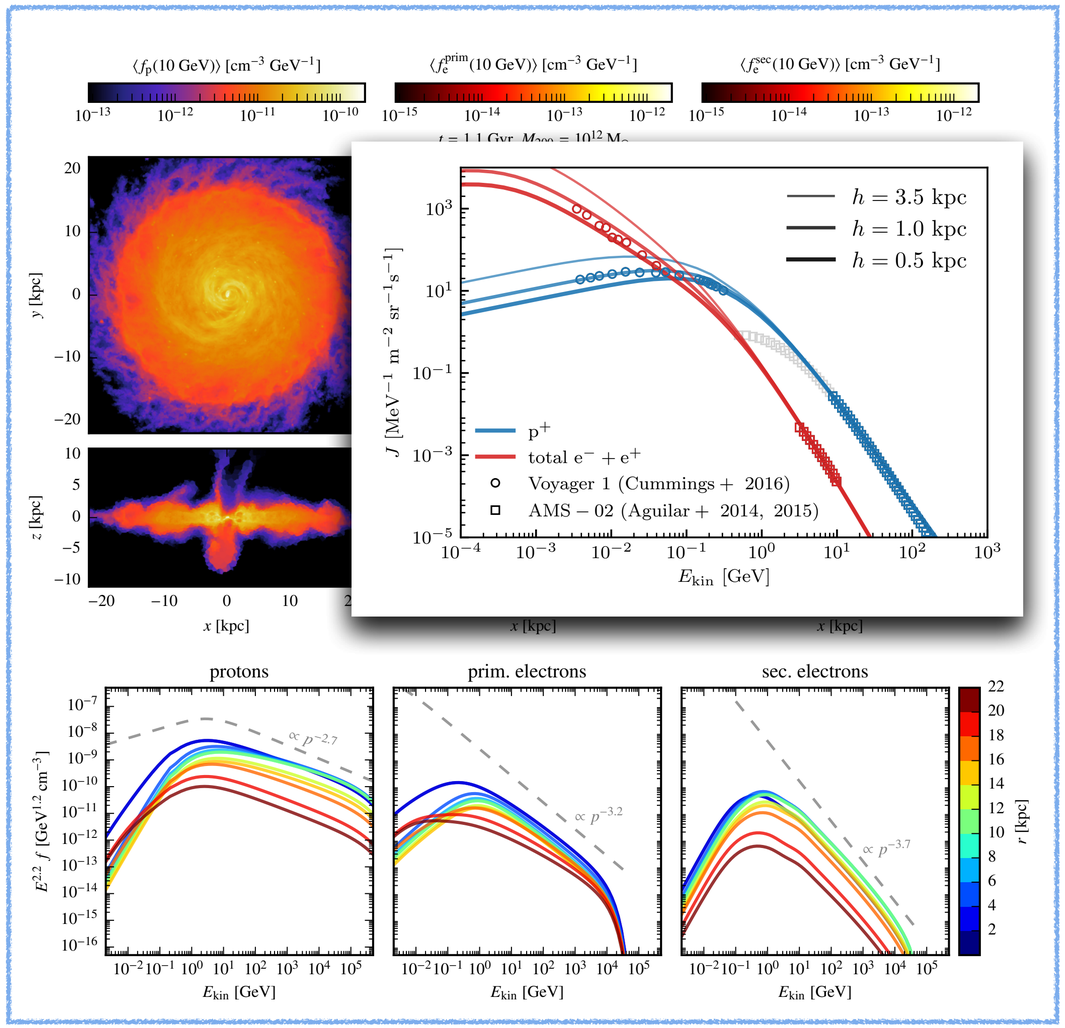
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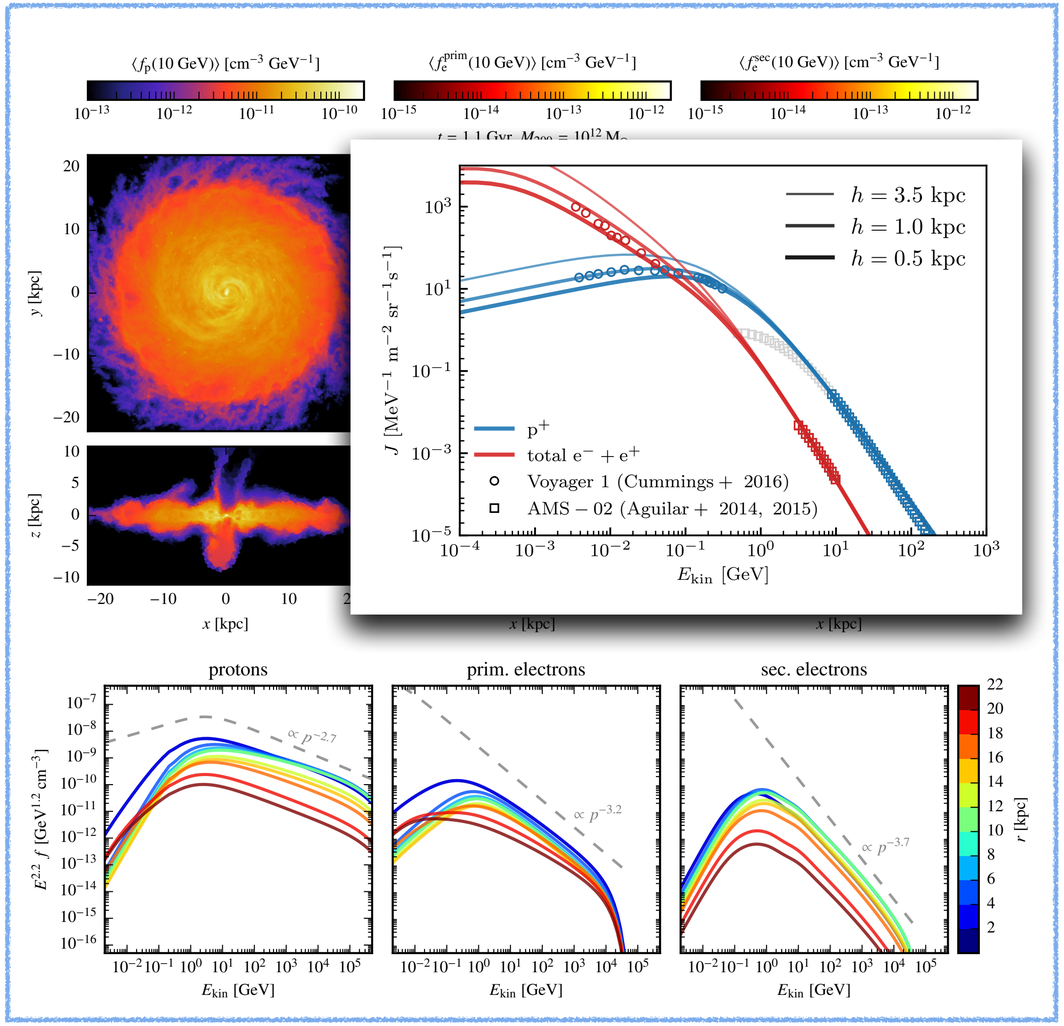


Werhahn et al. (2021 a)

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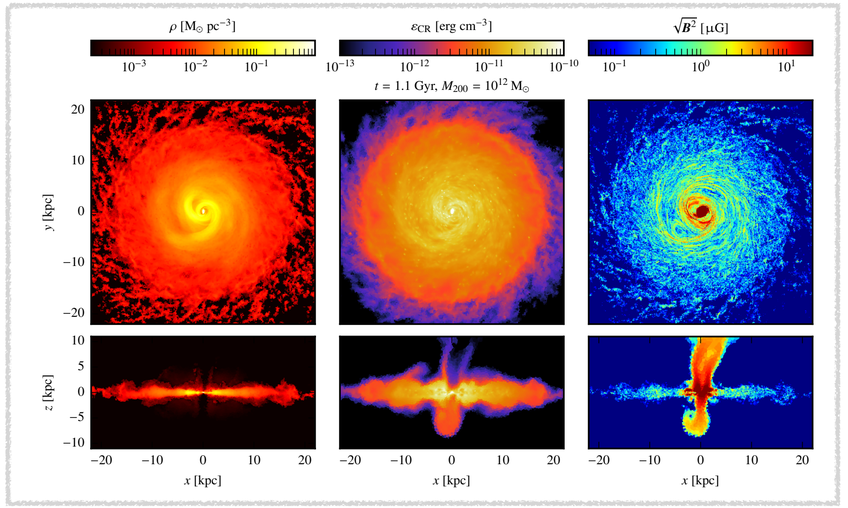
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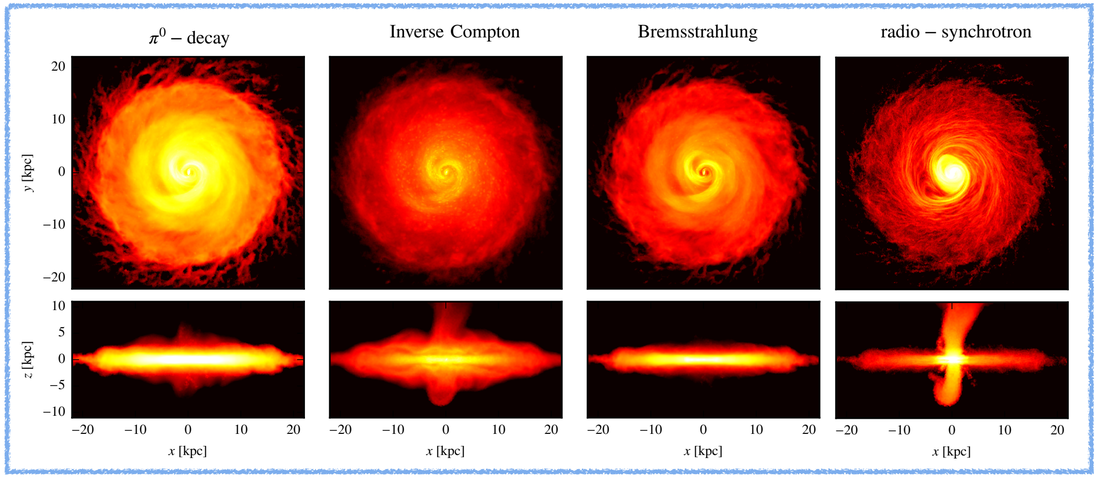
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CRAYON+

emission spectra



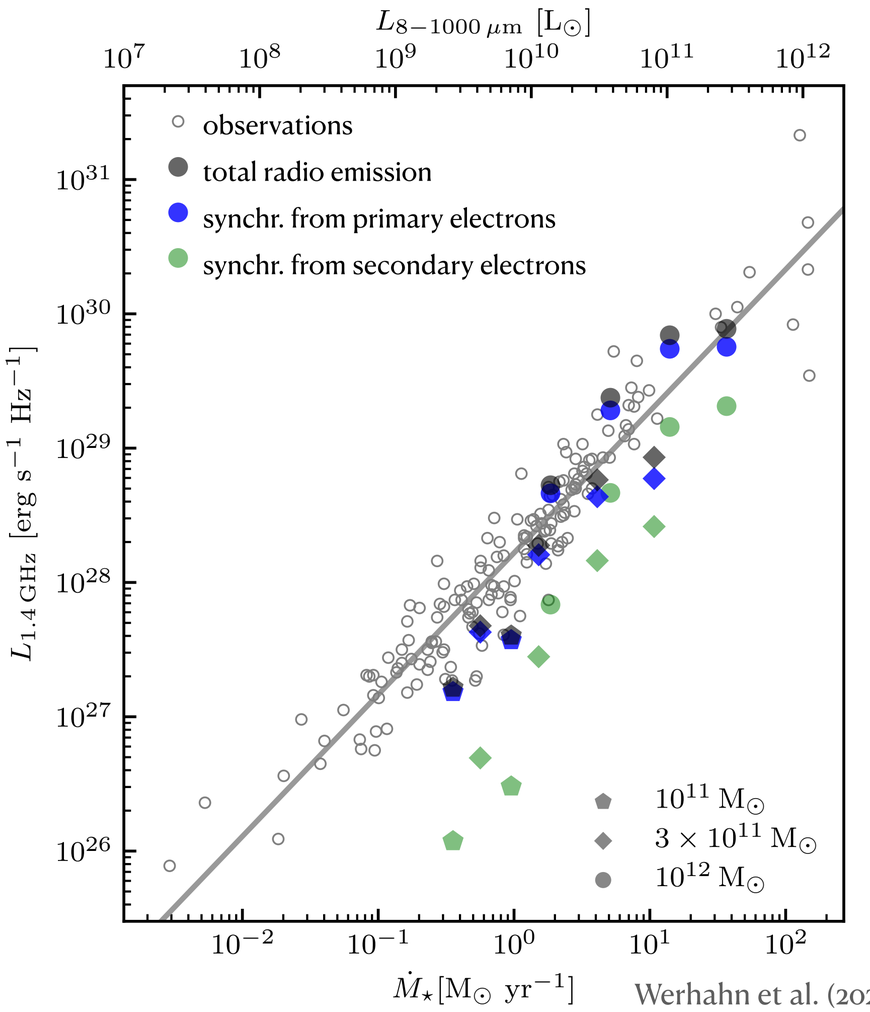
Christoph Pfrommer

Werhahn et al. (2021 a)

Non-thermal emission from isolated galaxies

with CRAYON+

FIR-Radio relation

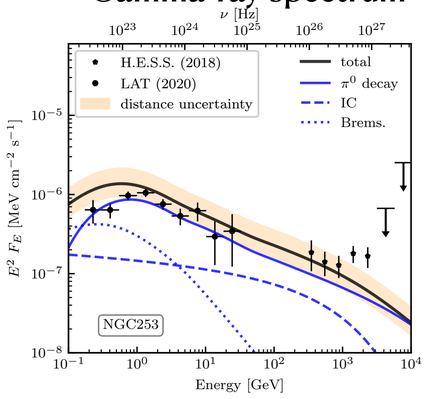


Werhahn et al. (2021c)

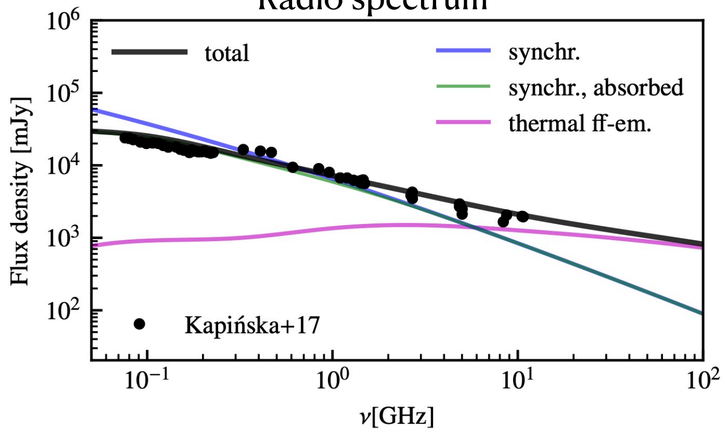
NGC 253



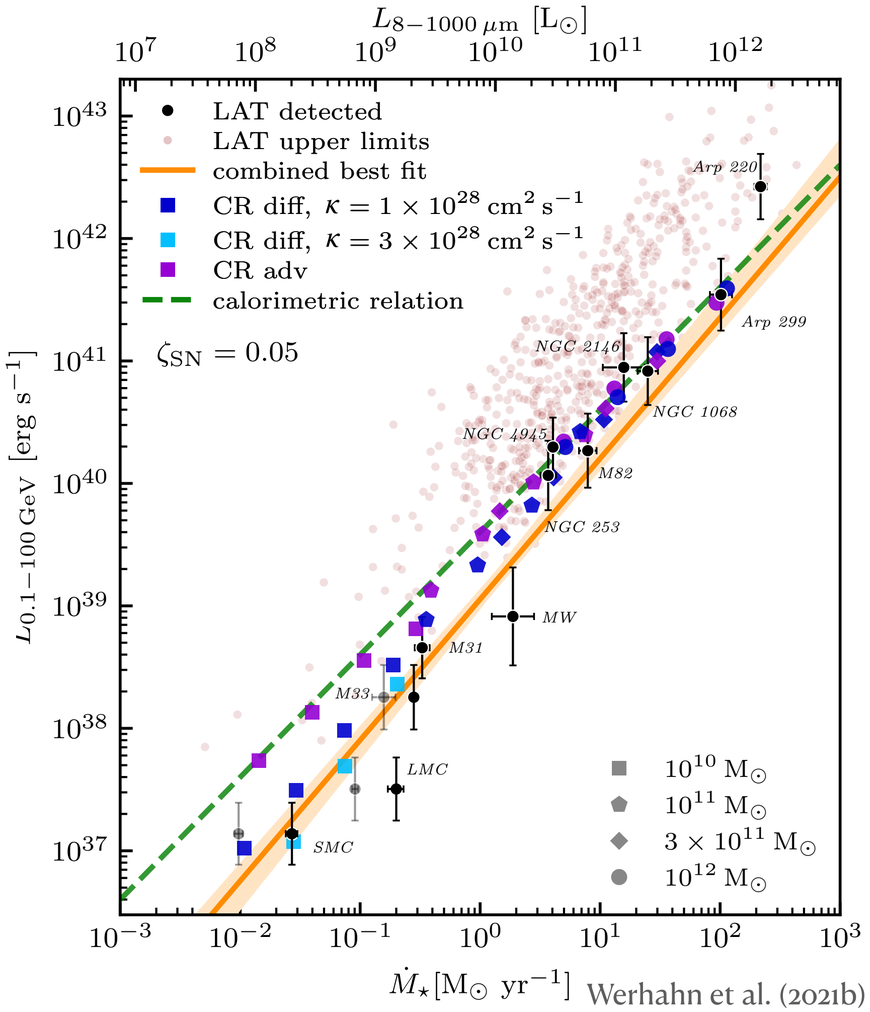
Gamma-ray spectrum



Radio spectrum



FIR-gamma-ray relation

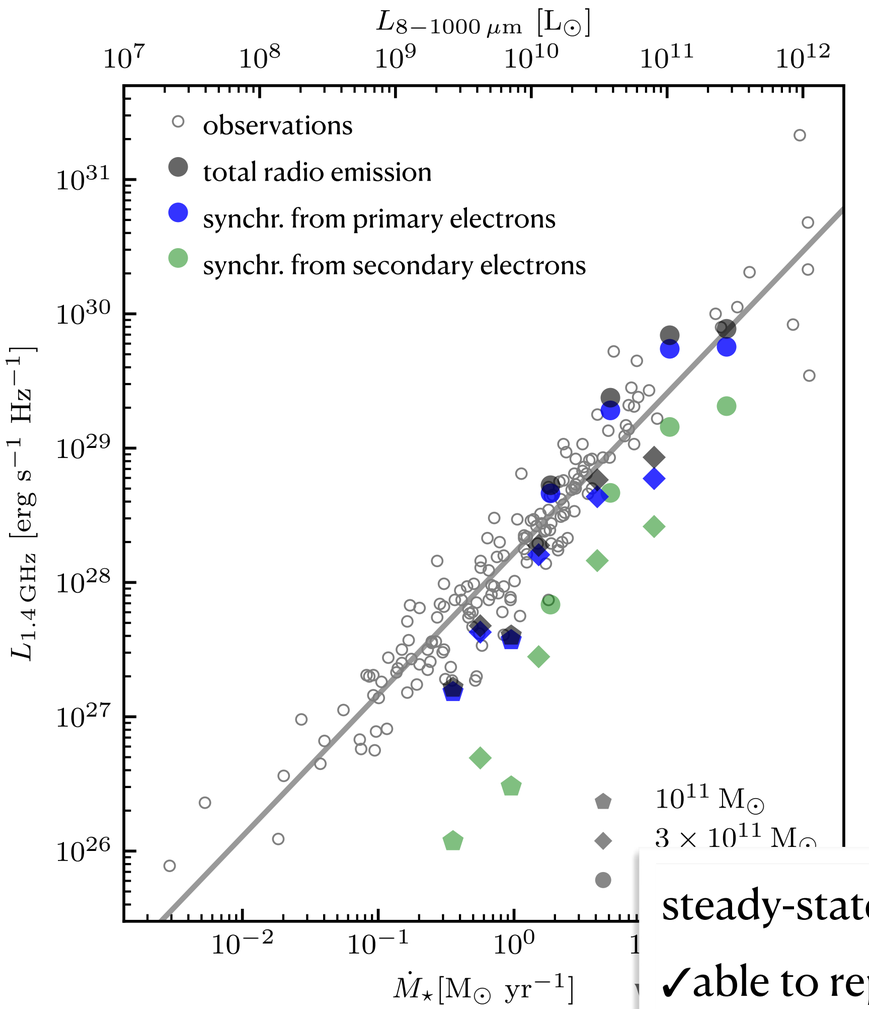


Werhahn et al. (2021b)

Non-thermal emission from isolated galaxies

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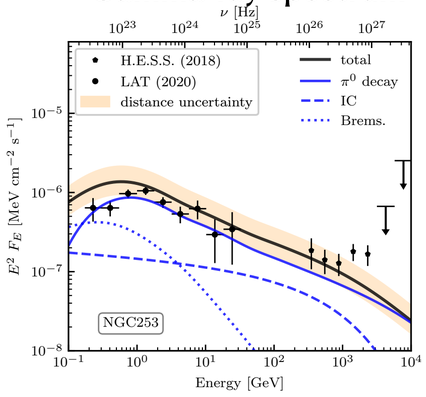
FIR-Radio relation



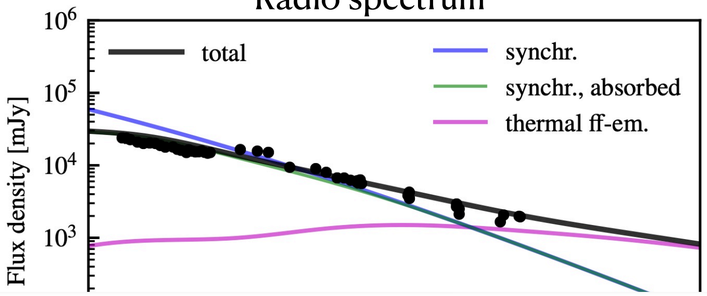
NGC 253



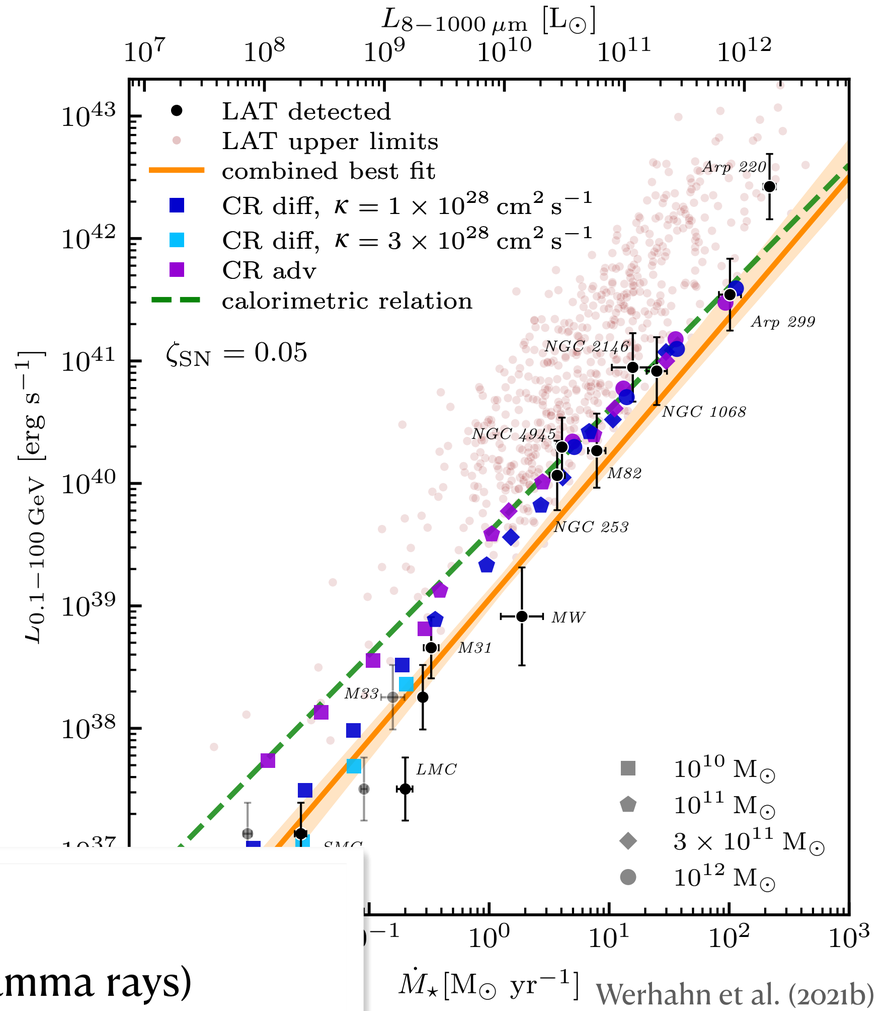
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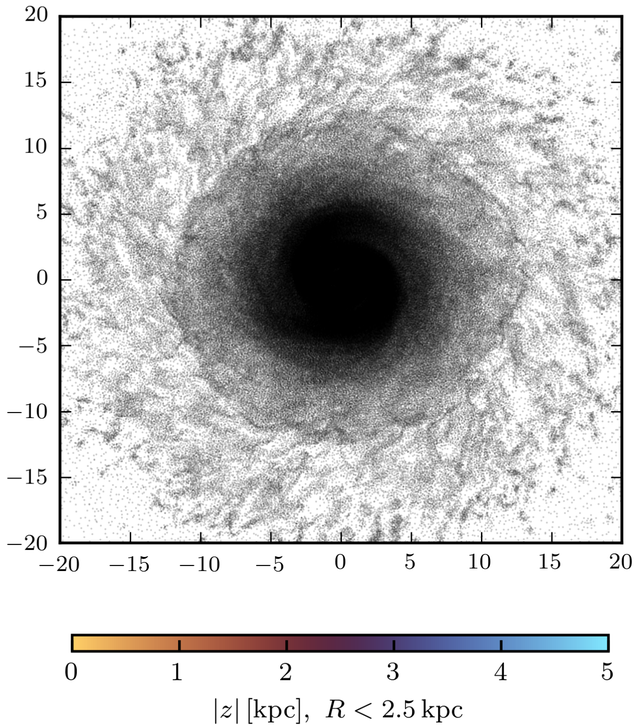
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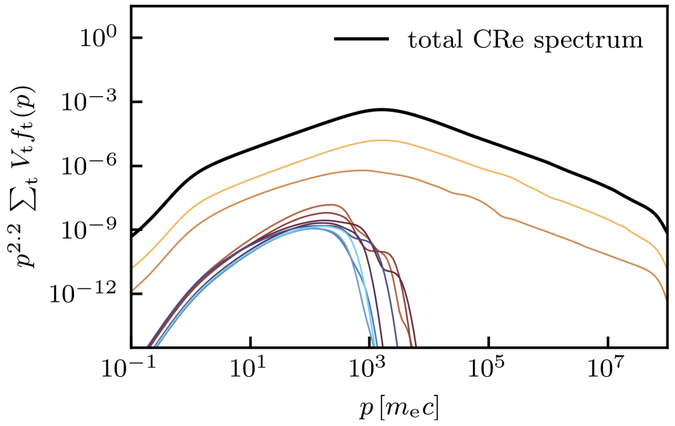
steady-state CRs with CRAYON+ :

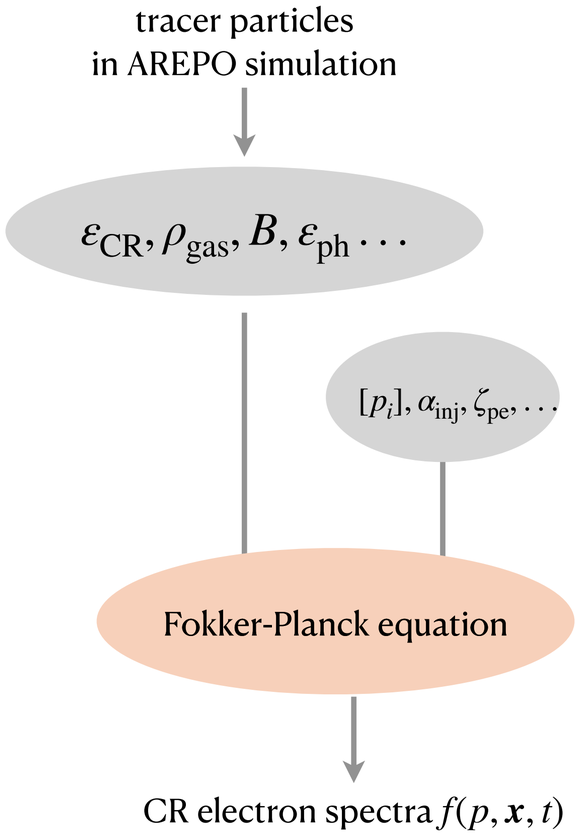
✓able to reproduce several key observables (radio & gamma rays)

○ where does steady-state break down?

Live modelling of CR electrons (CREST)





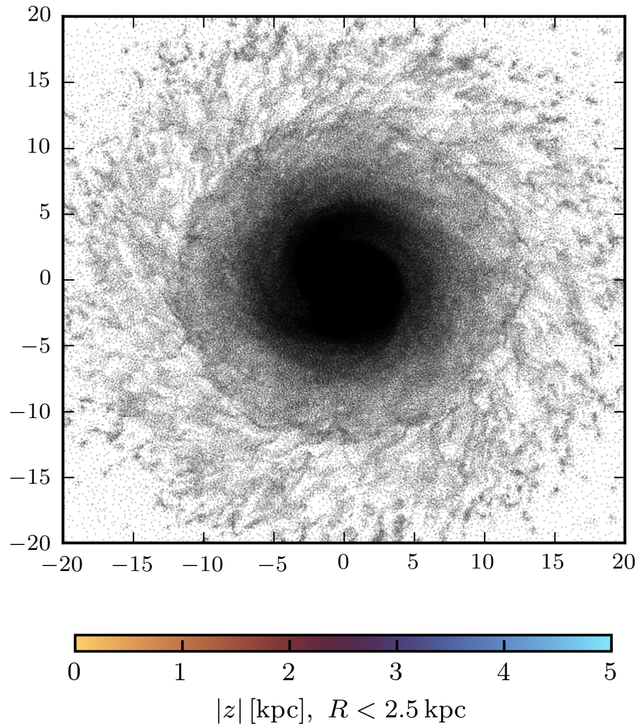


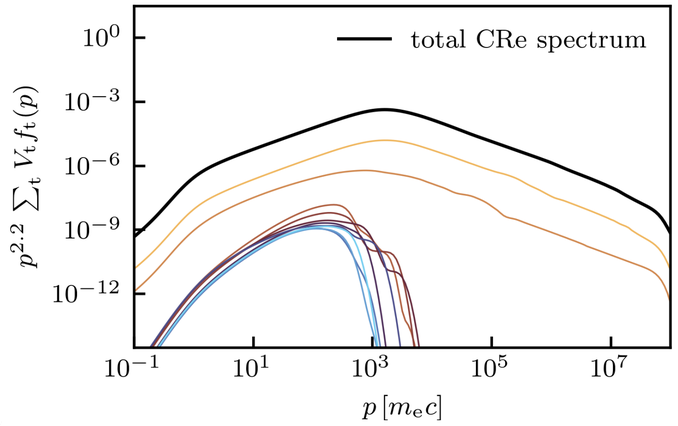
CREST (Cosmic Ray Electron Spectra evolved in Time)

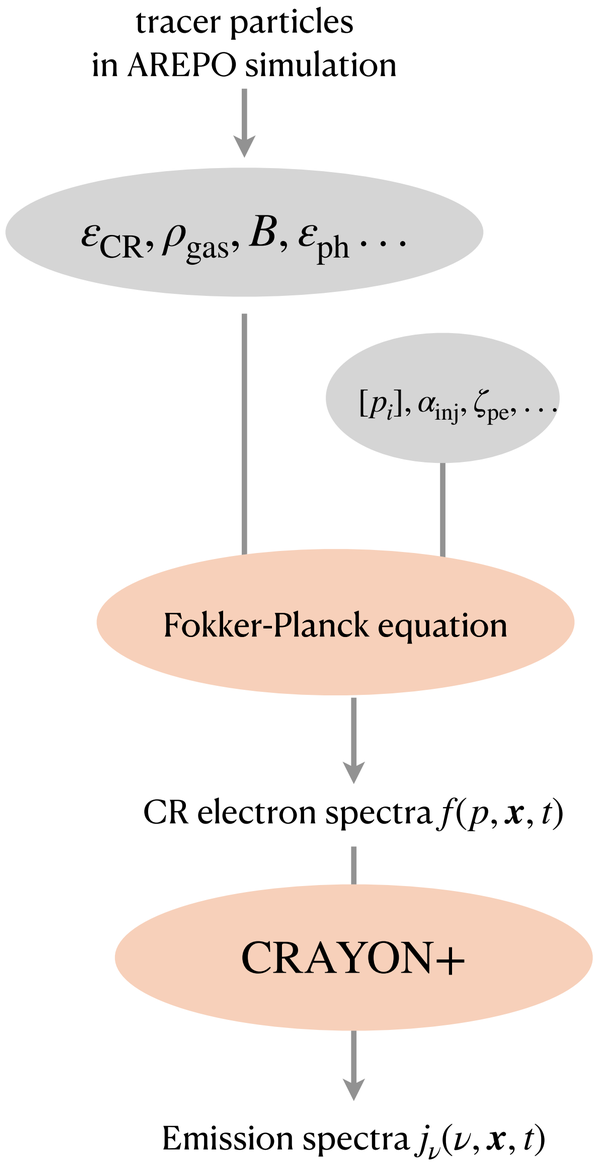
Winner, CP+2019, *further development by Whittingham, Jlassi (AIP) and Werhahn (MPA)*

- solve Fokker-Planck equation on Lagrangian tracer particles
- accurate calculation of CR electron spectra as function of time and space
- including injection, cooling, adiabatic changes and **advective transport** with gas

Live modelling of CR electrons (CREST)





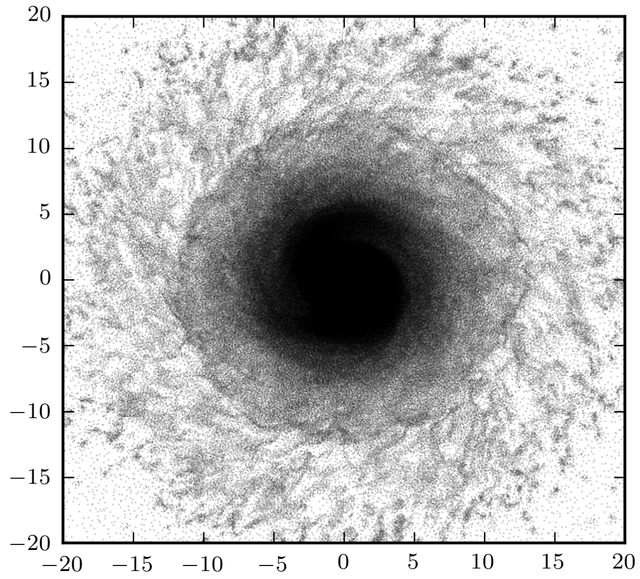


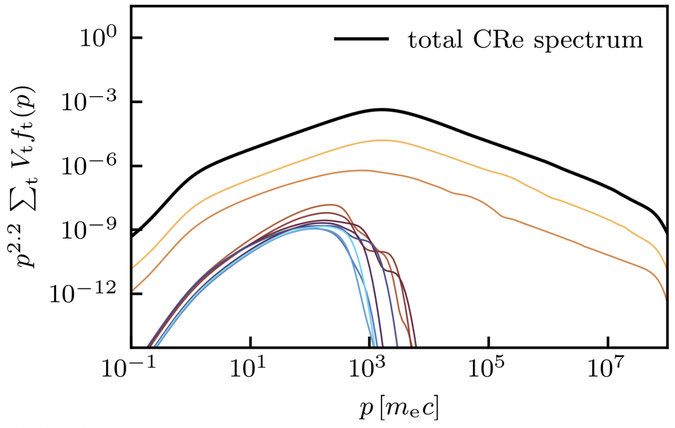
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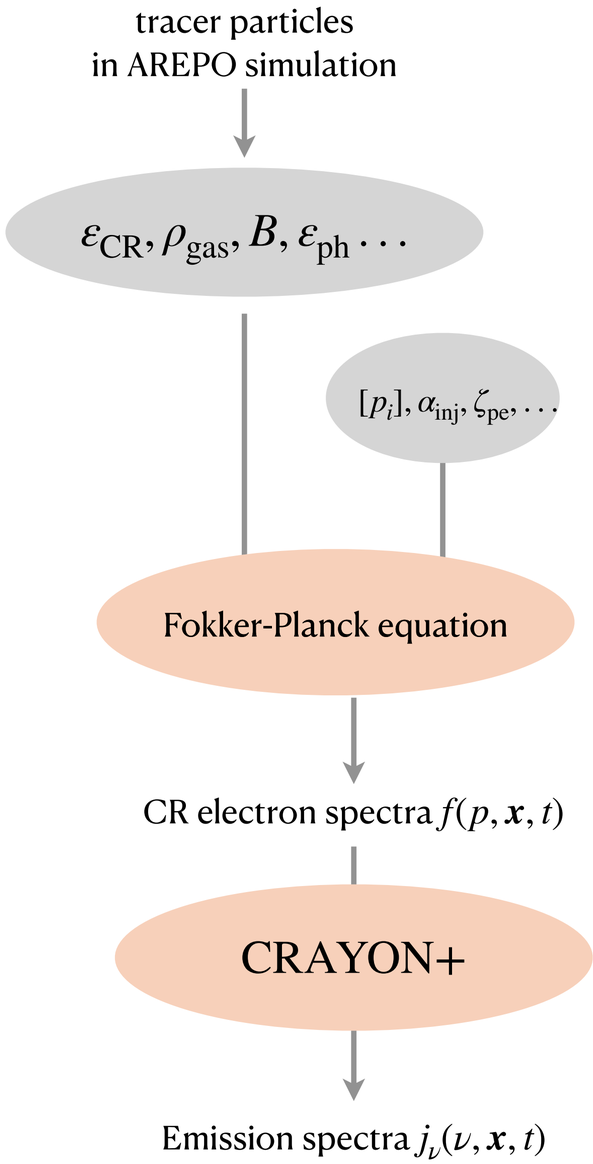
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- including injection, cooling, adiabatic changes and **advective transport** with gas
- coupled to **CRAYON**+ for radiation processes

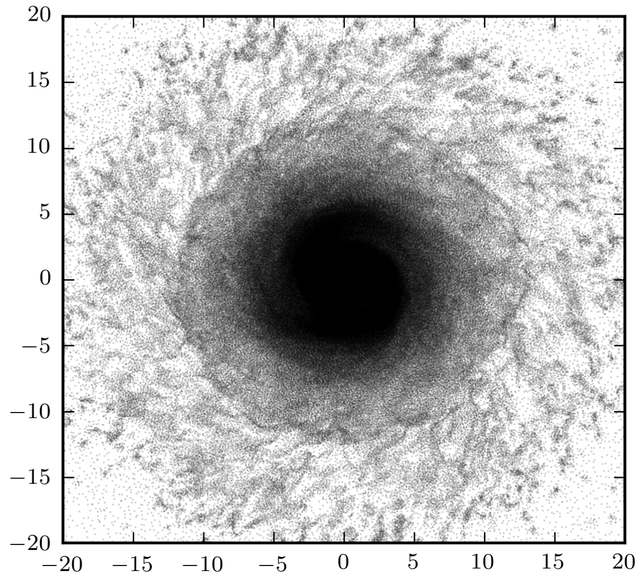
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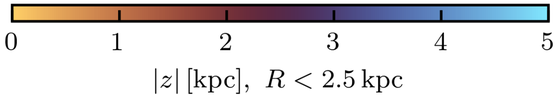


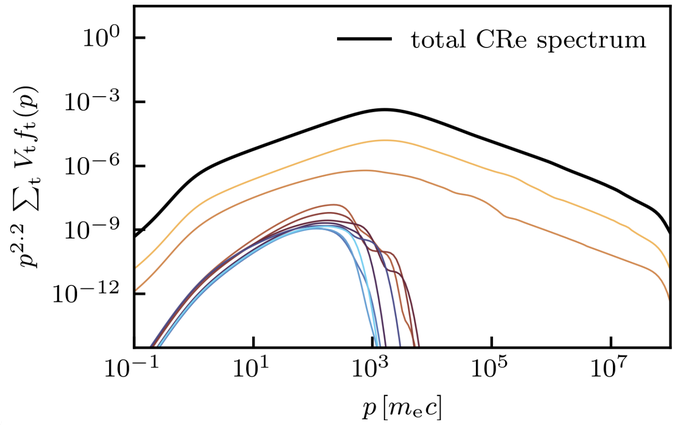


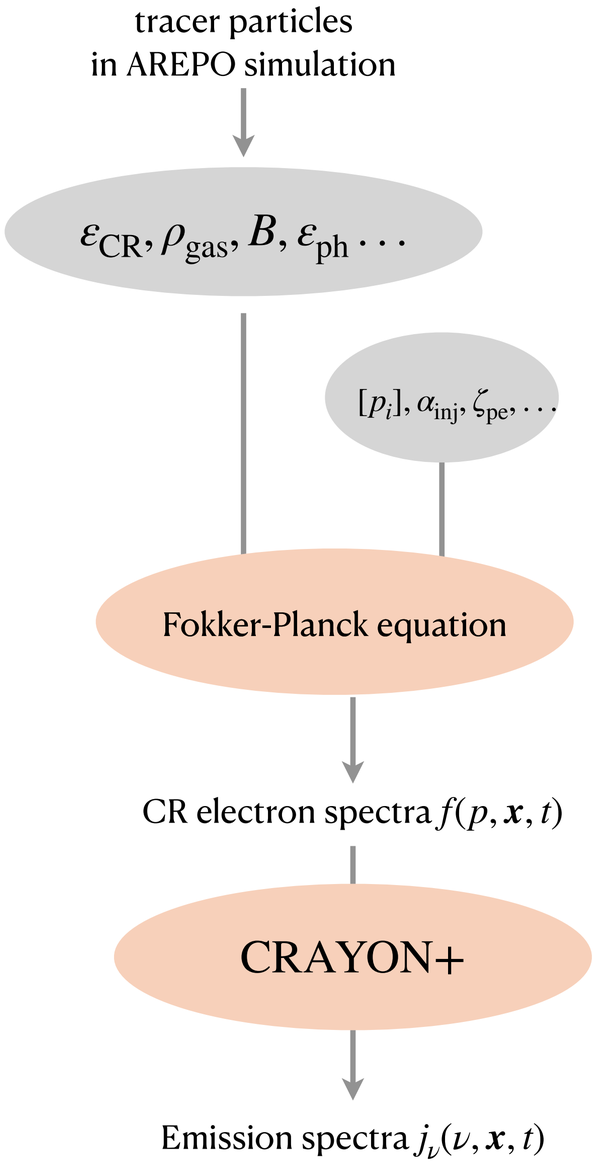


Live modelling of CR electrons (CREST)

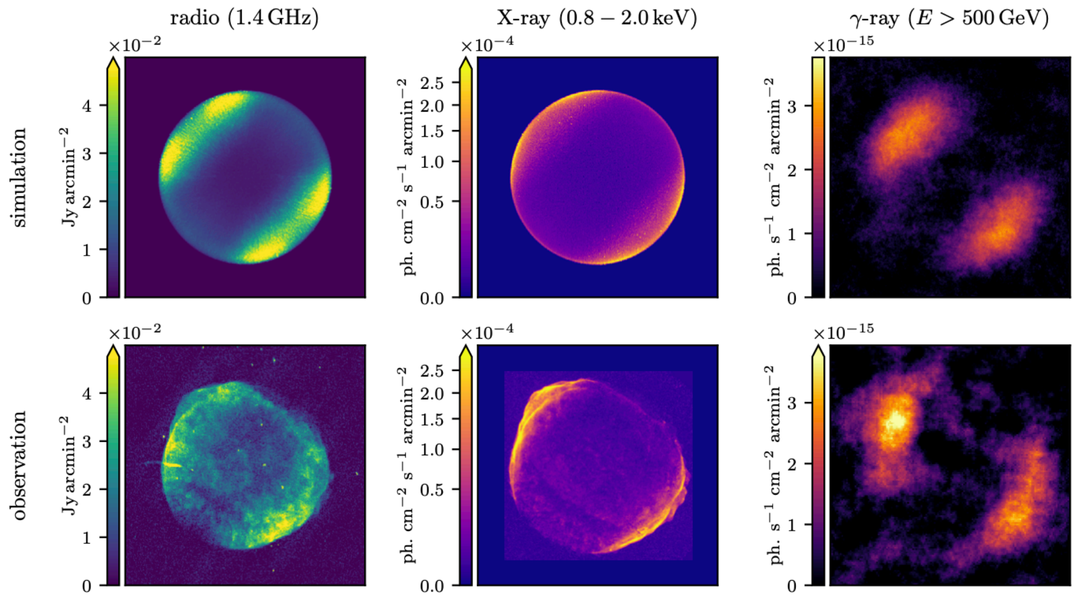


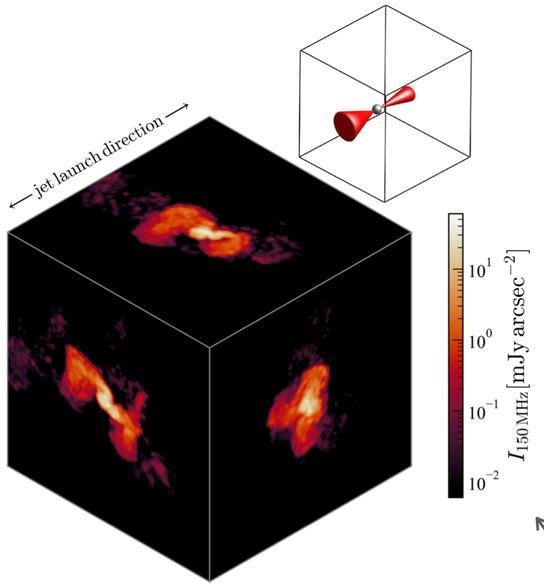


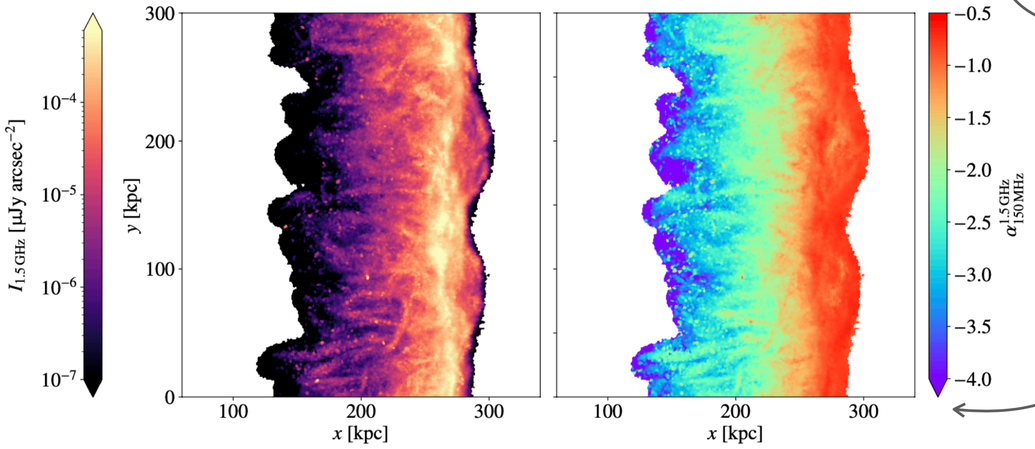




Live modelling of CR electrons (CREST)







- ✓ Supernova remnants (SN 1006) (Winner, CP+ 2020)
- ✓ AGN jets (Jlassi, Weinberger, CP+ 2026a,2026b)
- ✓ Radio relics (Whittingham, CP+ 2026a, 2026b)
- ✓ Galaxies (Werhahn, CP+2026a, 2026b)

tracer particles in AREPO simulation

$\varepsilon_{\mathrm{CR}}, \rho_{\mathrm{gas}}, B, \varepsilon_{\mathrm{ph}} \ldots$

$[p_i], \alpha_{\mathrm{inj}}, \zeta_{\mathrm{pe}}, \ldots$

Fokker-Planck equation

CR electron spectra $f(p, \boldsymbol{x}, t)$

CRAYON+

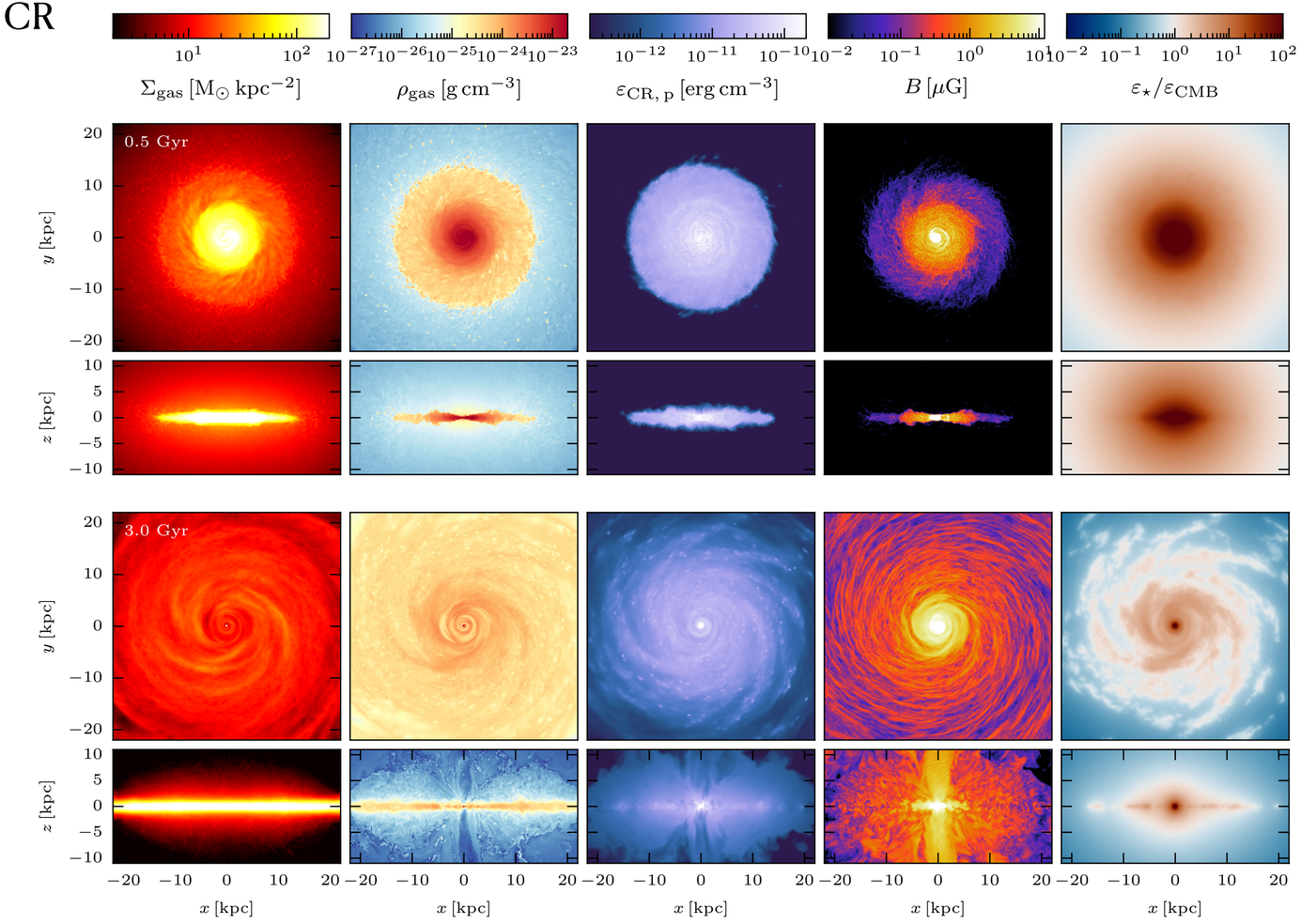
Emission spectra $j_\nu(\nu, \boldsymbol{x}, t)$

CREST in galaxies

Simulation setup (Werhahn+ 2026a)

Isolated galaxy simulation with AREPO
(Springel 2010; Pakmor et al. 2016; Weinberger et al. 2020)

- $10^{12}\,M_\odot$ halo, collapsing gas cloud, star-formation, MHD + CR protons with anisotropic diffusion (Pakmor et al. 2016; CP et al. 2017)
- Lagrangian tracer particles, for ~500 Myrs
  —> recovers full history (Werhahn et al. 2026a)
- 3 approaches for **CR electron spectra**:



CREST in galaxies

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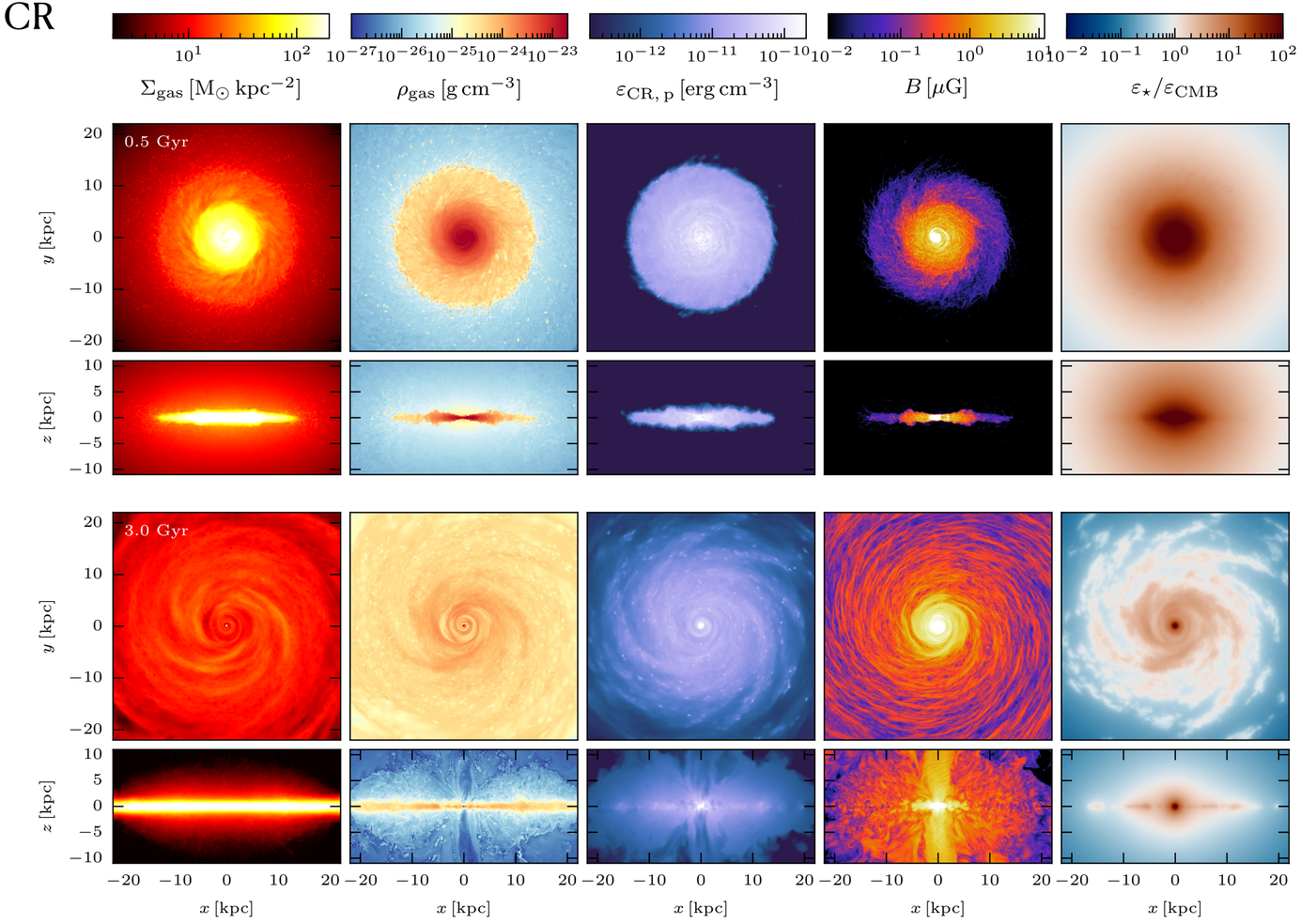
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CREST

$f(p, \boldsymbol{x}, t)$

CRAYON+
radio emission



CREST in galaxies

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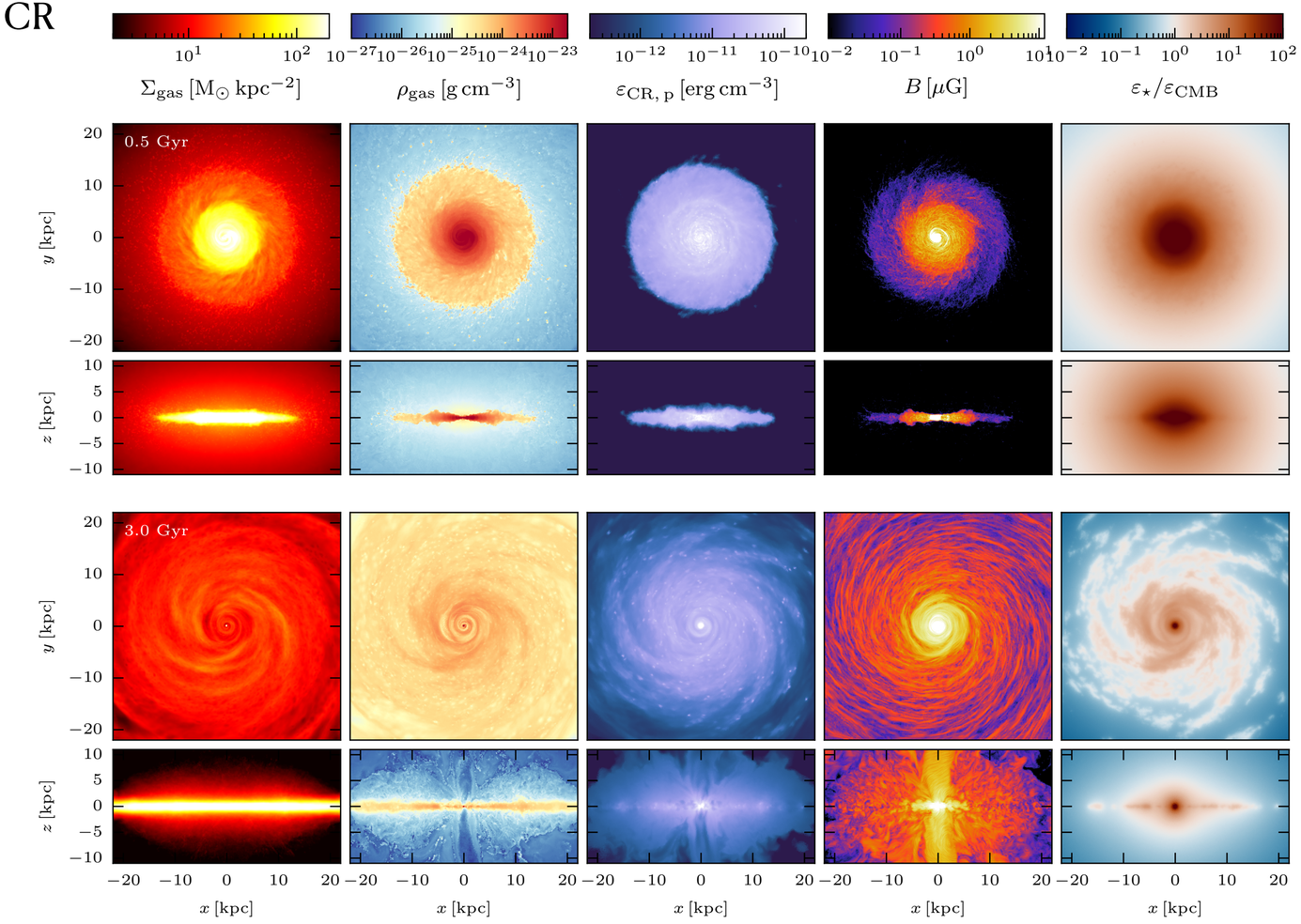
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CREST
$f(p, \boldsymbol{x}, t)$

CRAYON+
cell-based steady-state
$f(p, \boldsymbol{x})$

CRAYON+
radio emission

CRAYON+
radio emission



CREST in galaxies

Simulation setup (Werhahn+ 2026a)

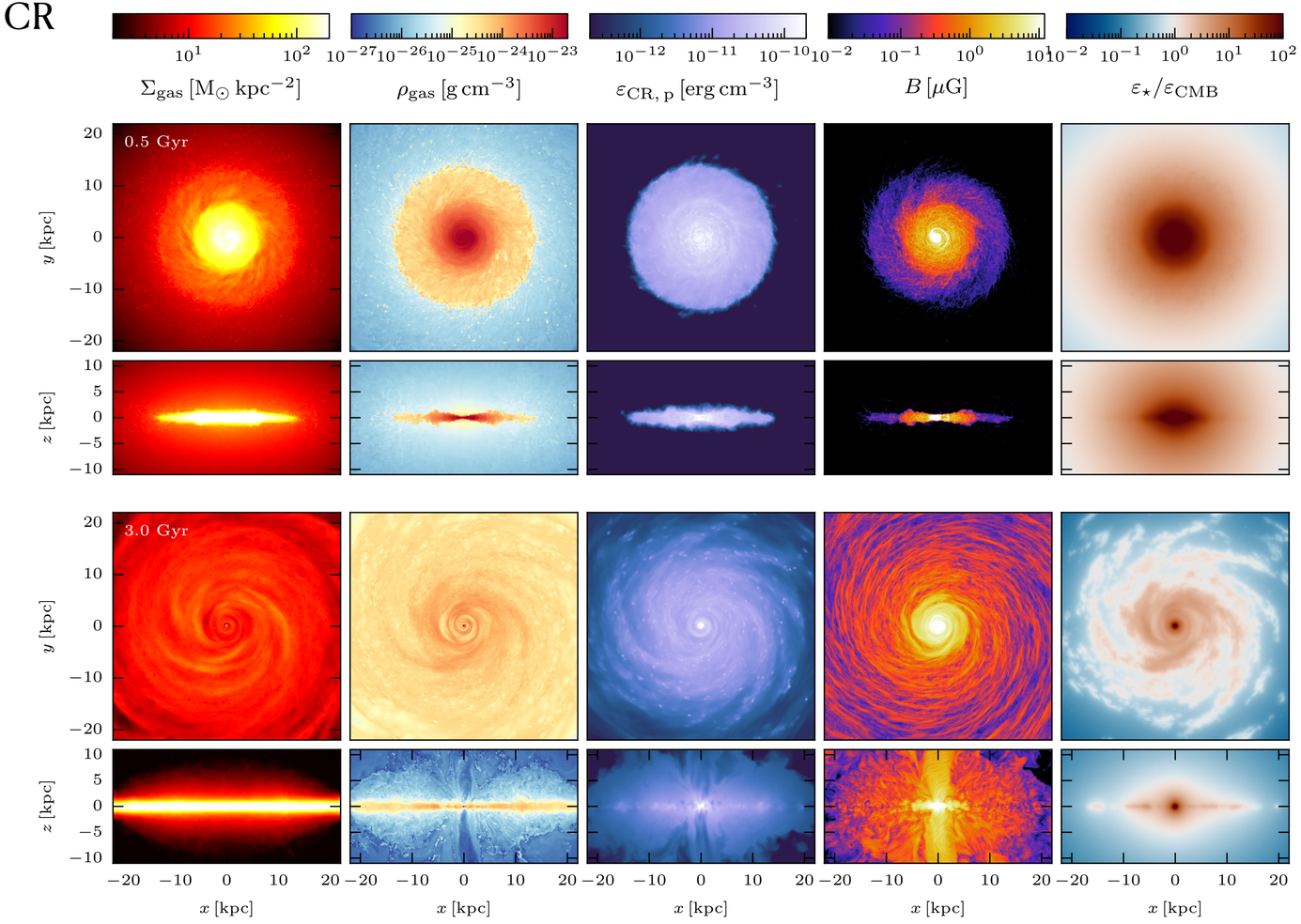
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CREST
$f(p, \boldsymbol{x}, t)$
→ CRAYON+ radio emission

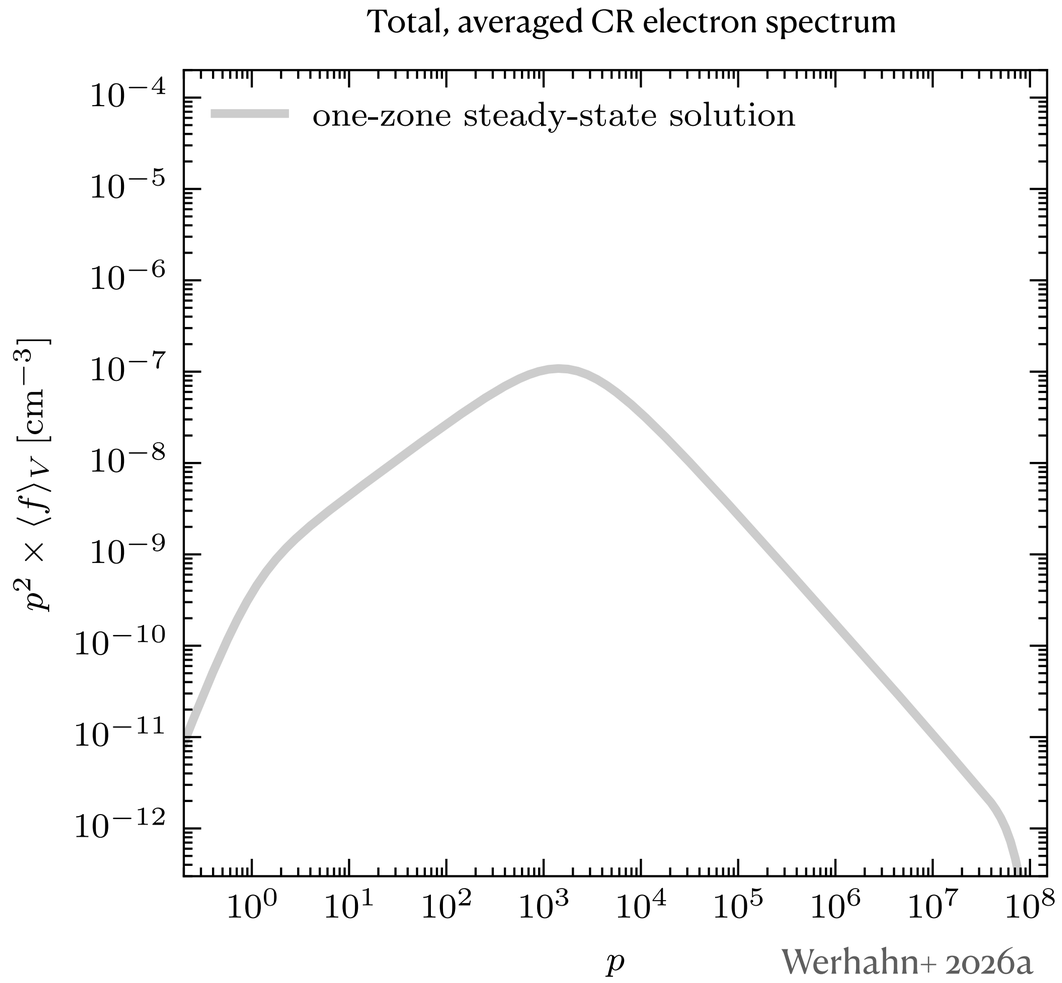
CRAYON+
cell-based steady-state
$f(p, \boldsymbol{x})$
→ CRAYON+ radio emission

one-zone
steady-state with
averaged quantities
$\langle f(p) \rangle$
→ CRAYON+ radio emission



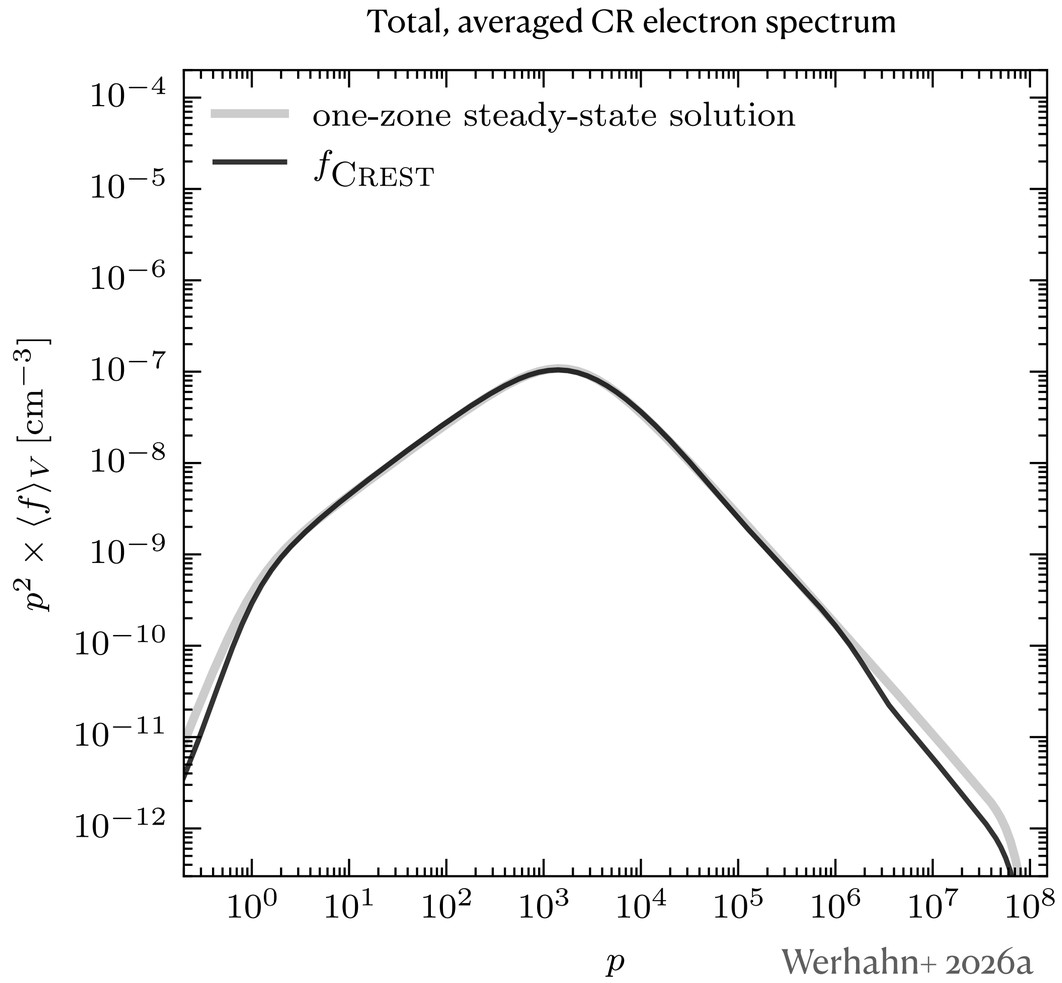
CREST in galaxies

Are galaxies in a steady-state?



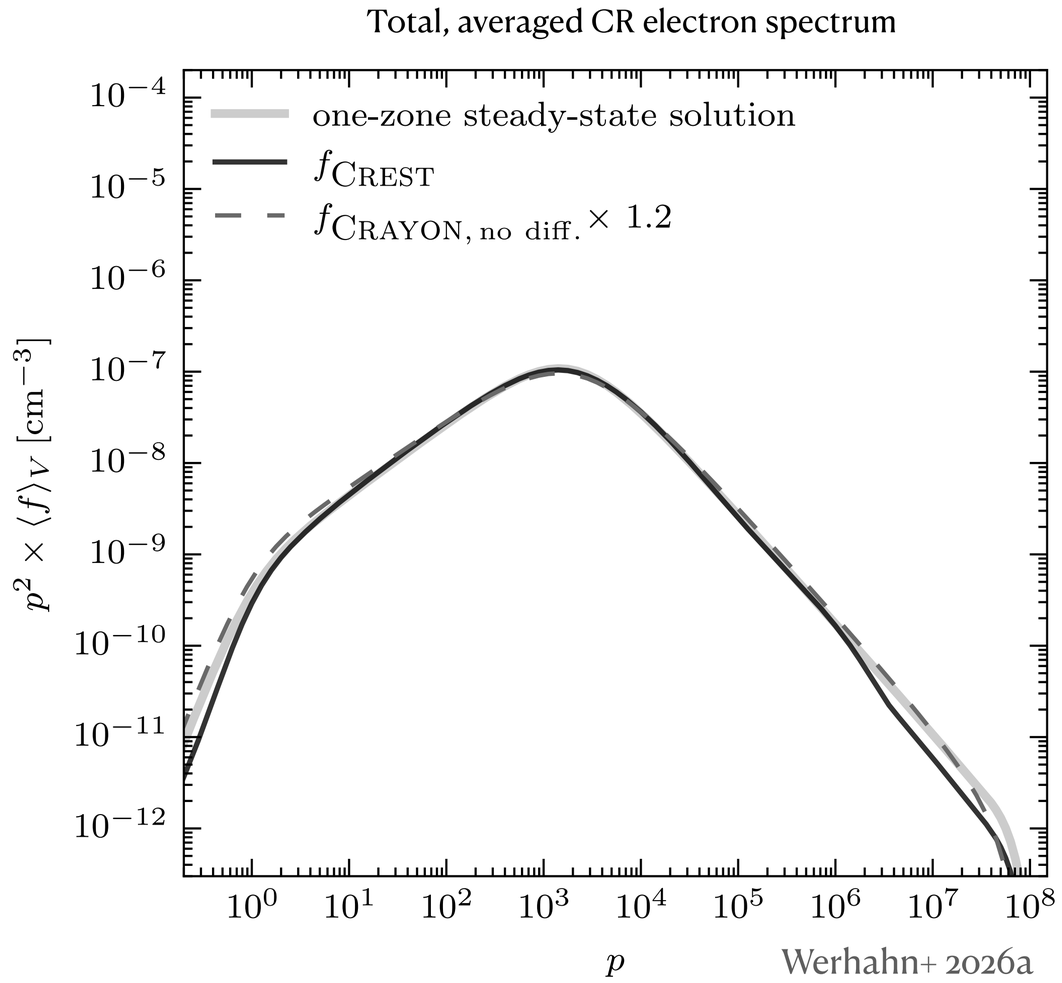
CREST in galaxies

Are galaxies in a steady-state?



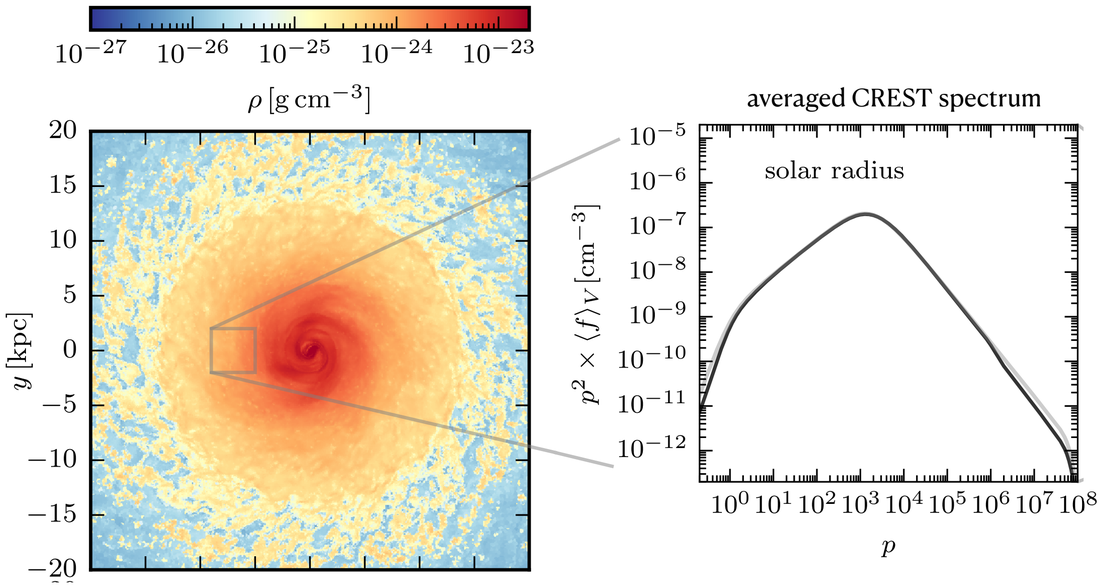
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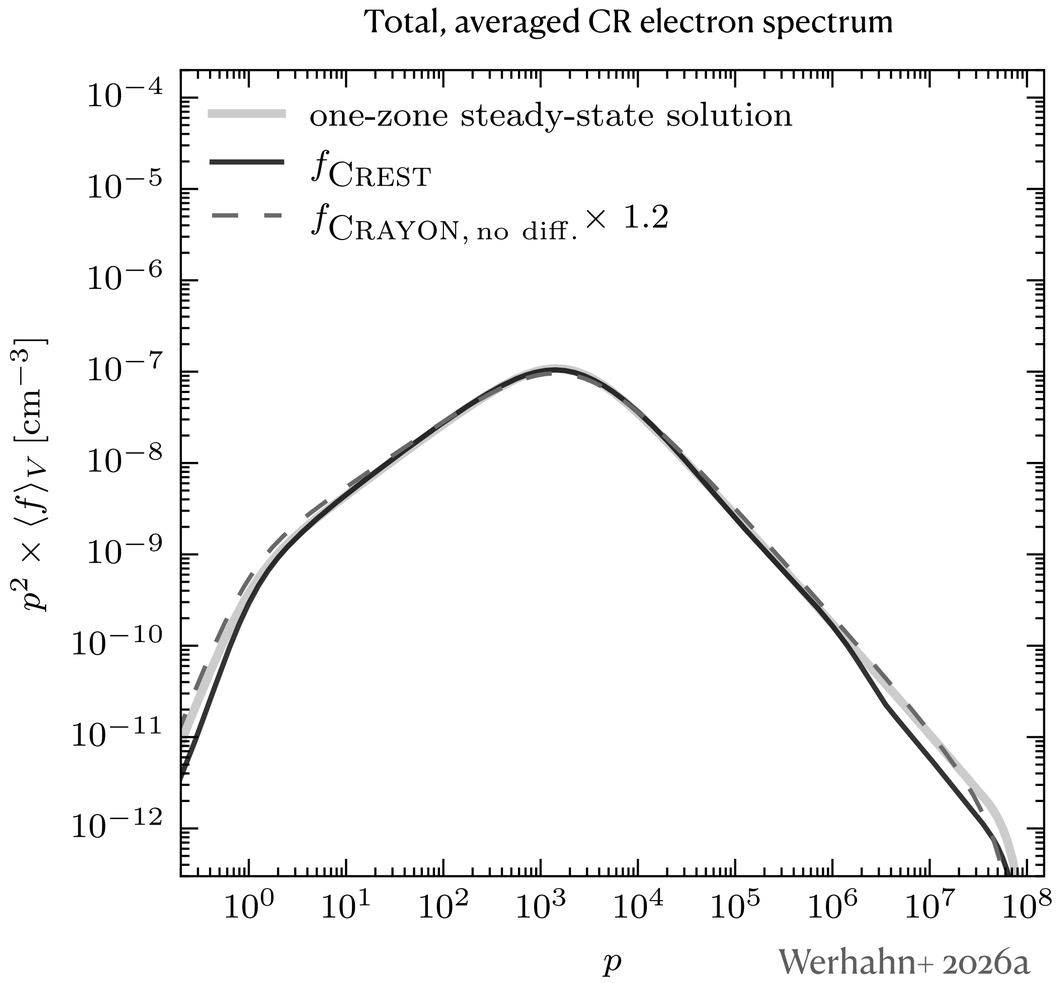
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CREST in galaxies

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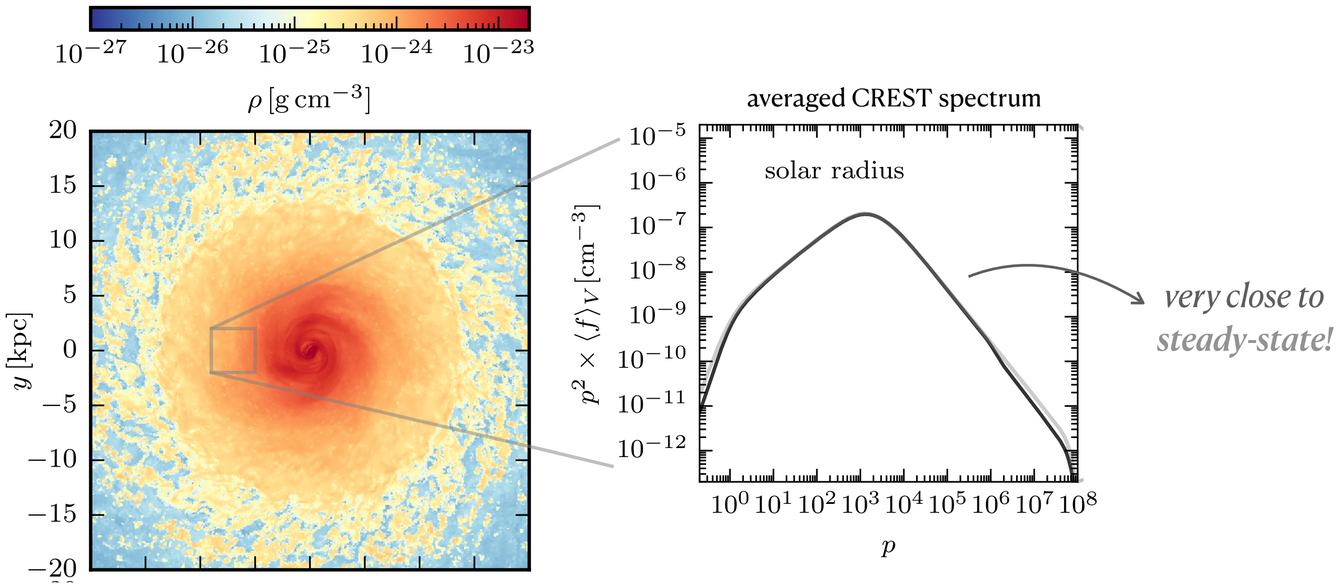


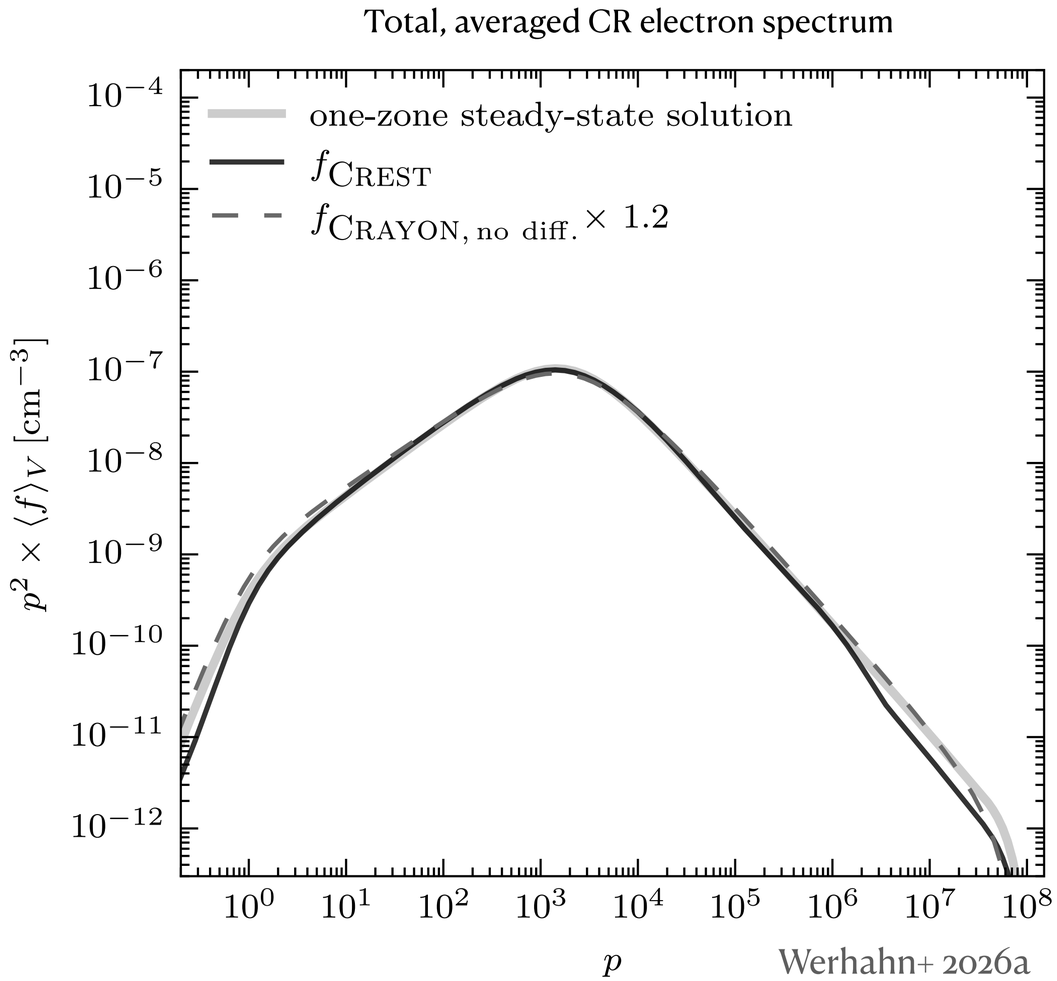


Werhahn+ 2026a

CREST in galaxies

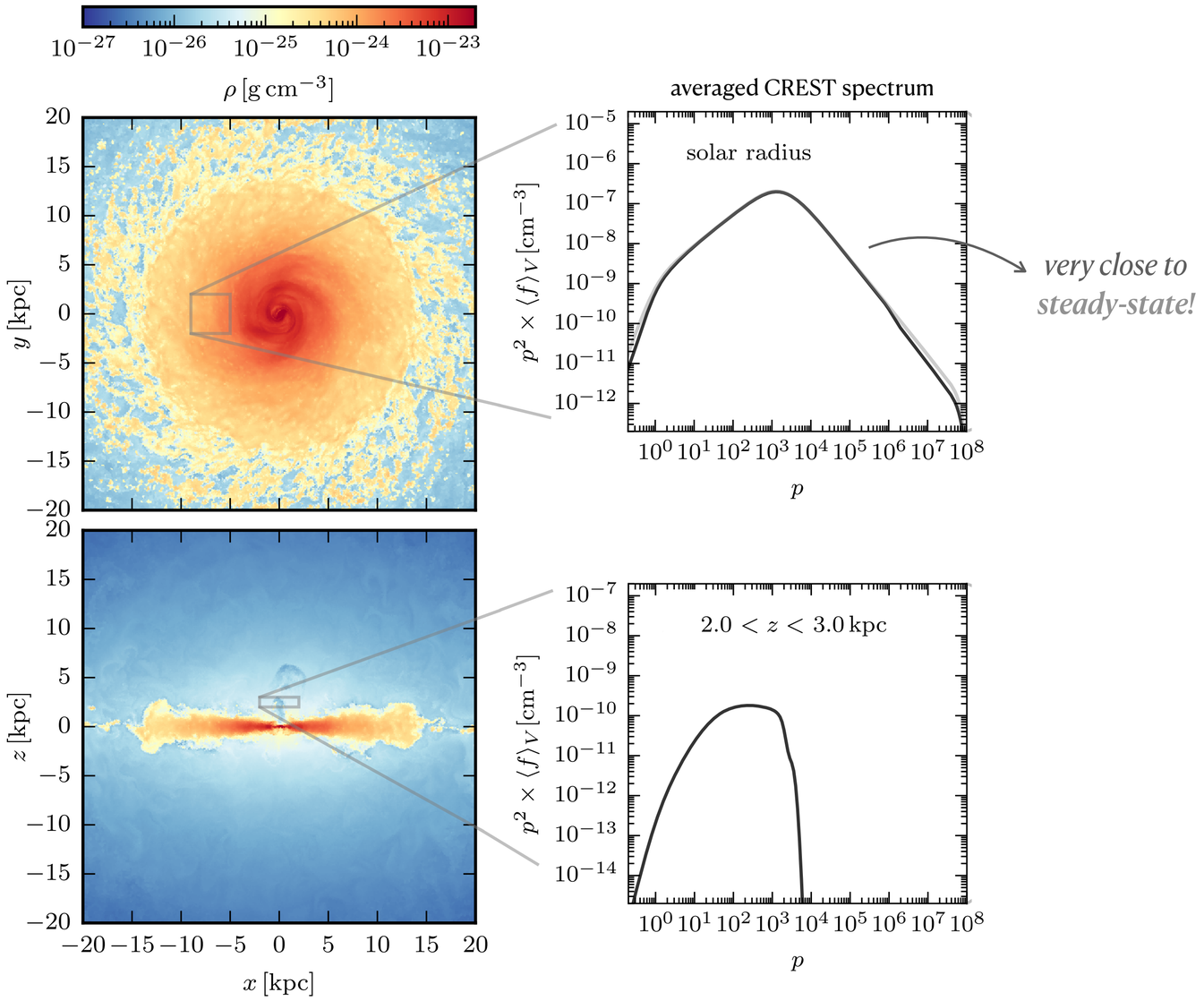
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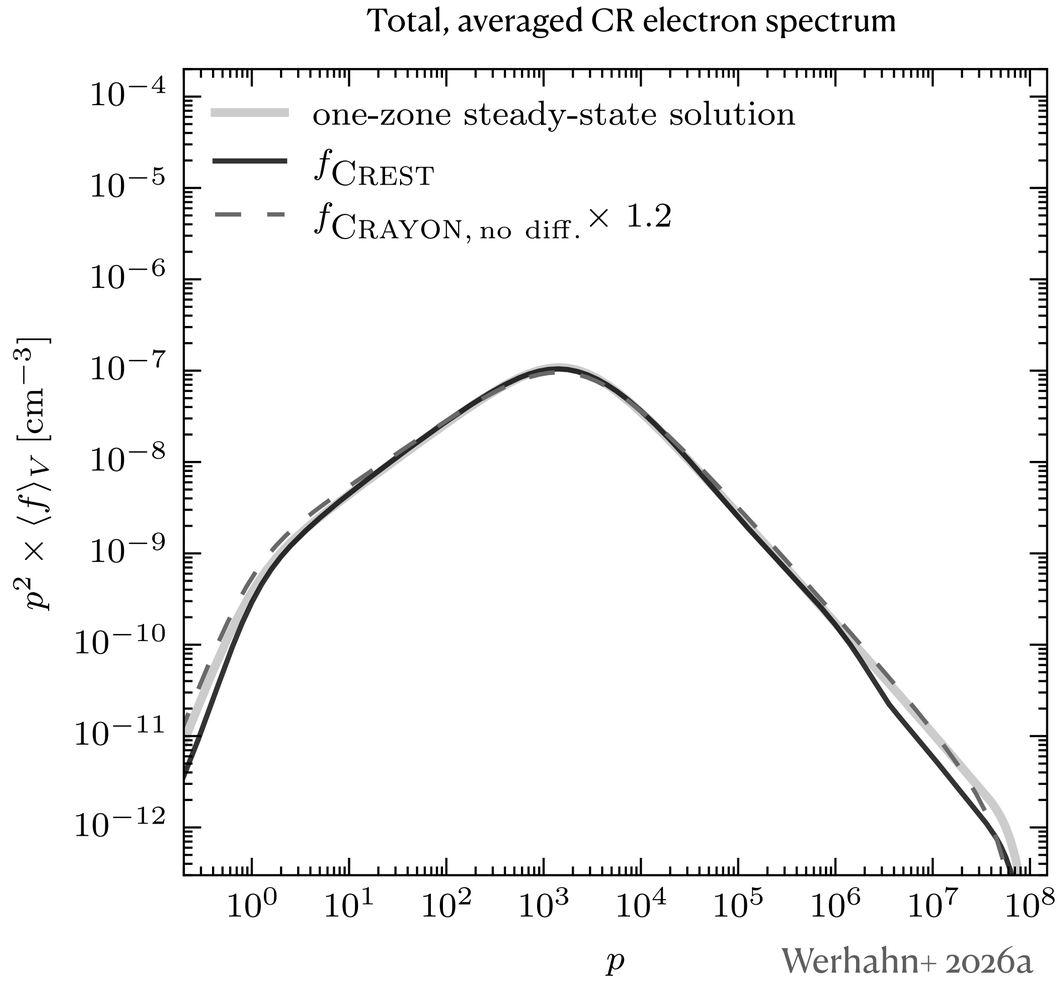


CREST in galaxies

Are galaxies in a steady-state?

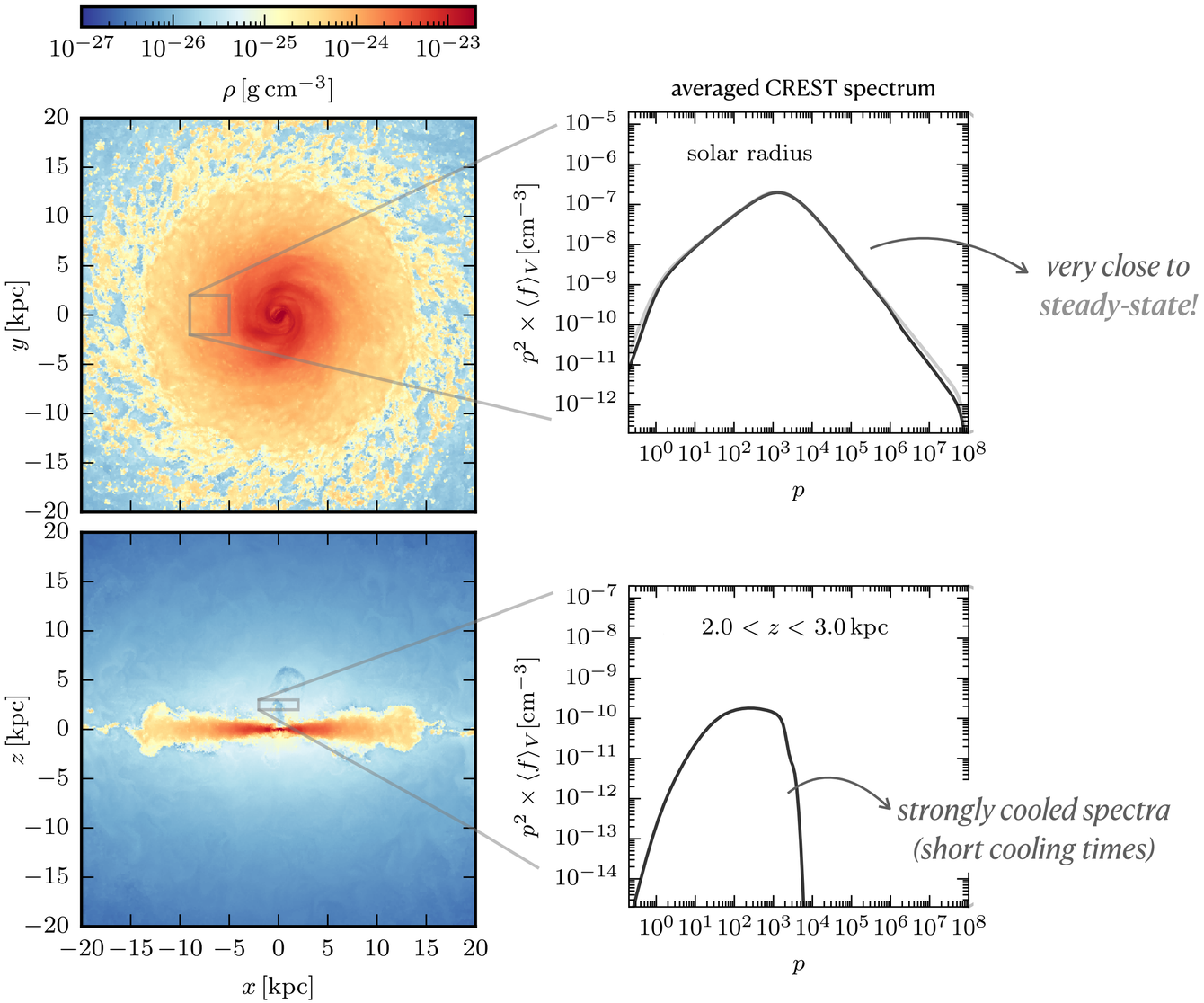


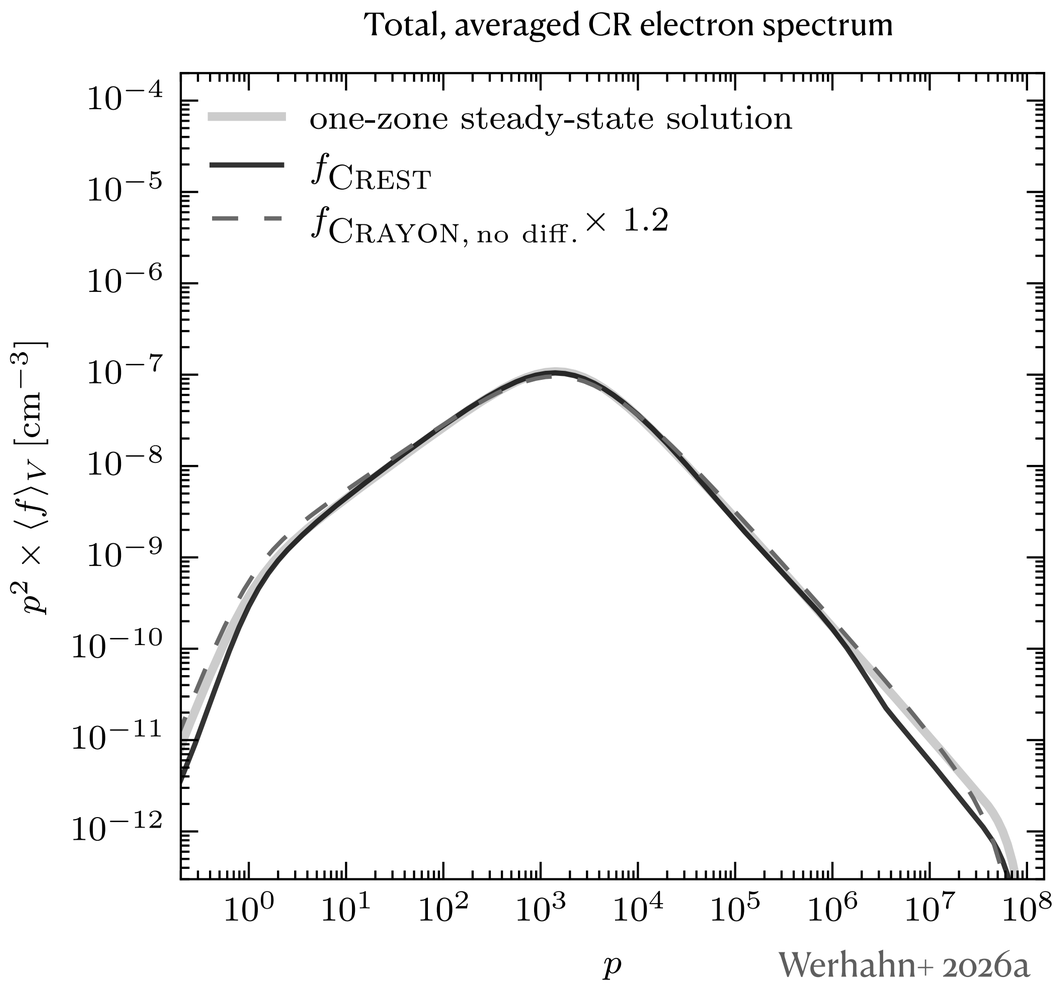
very close to steady-state!



CREST in galaxies

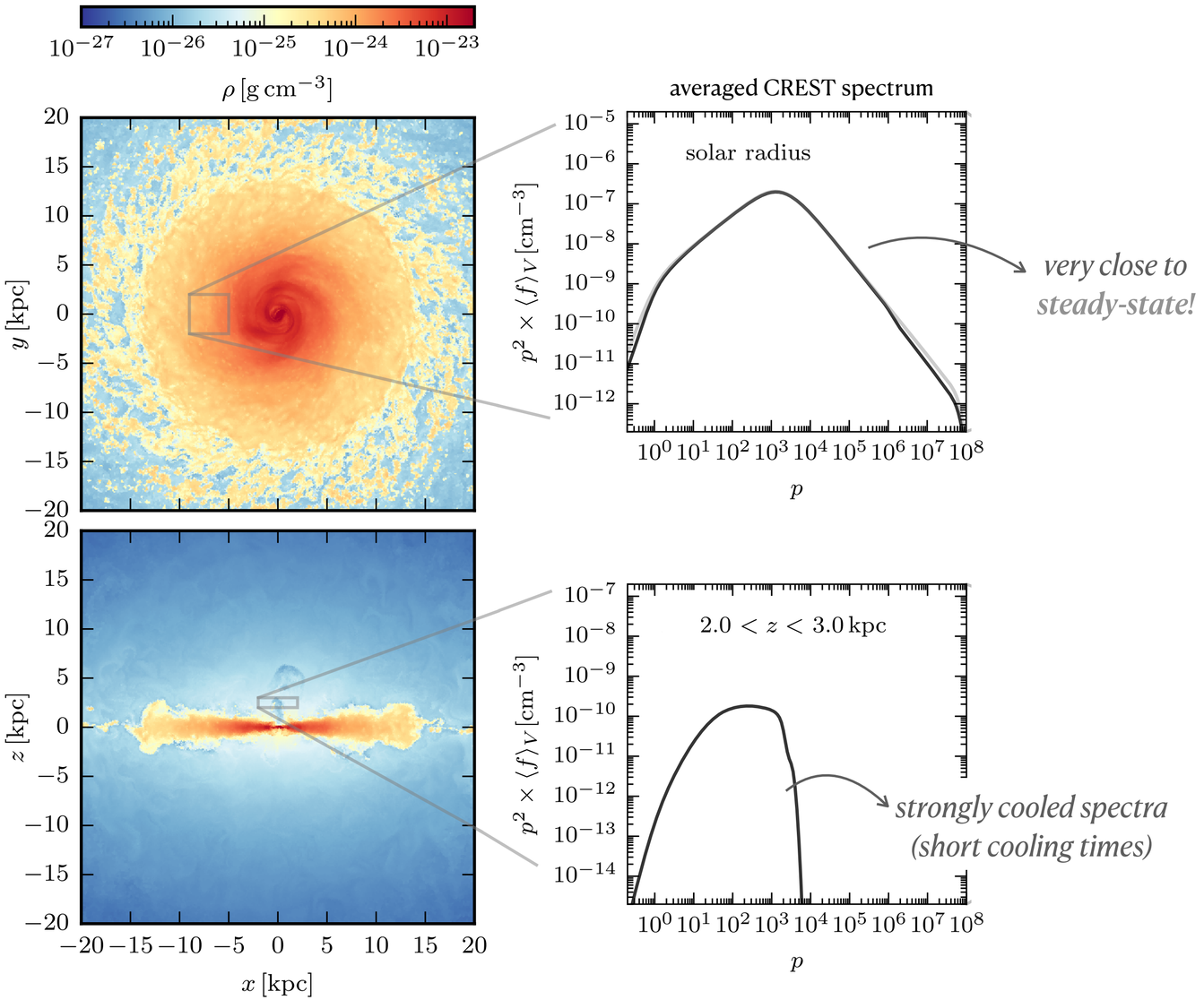
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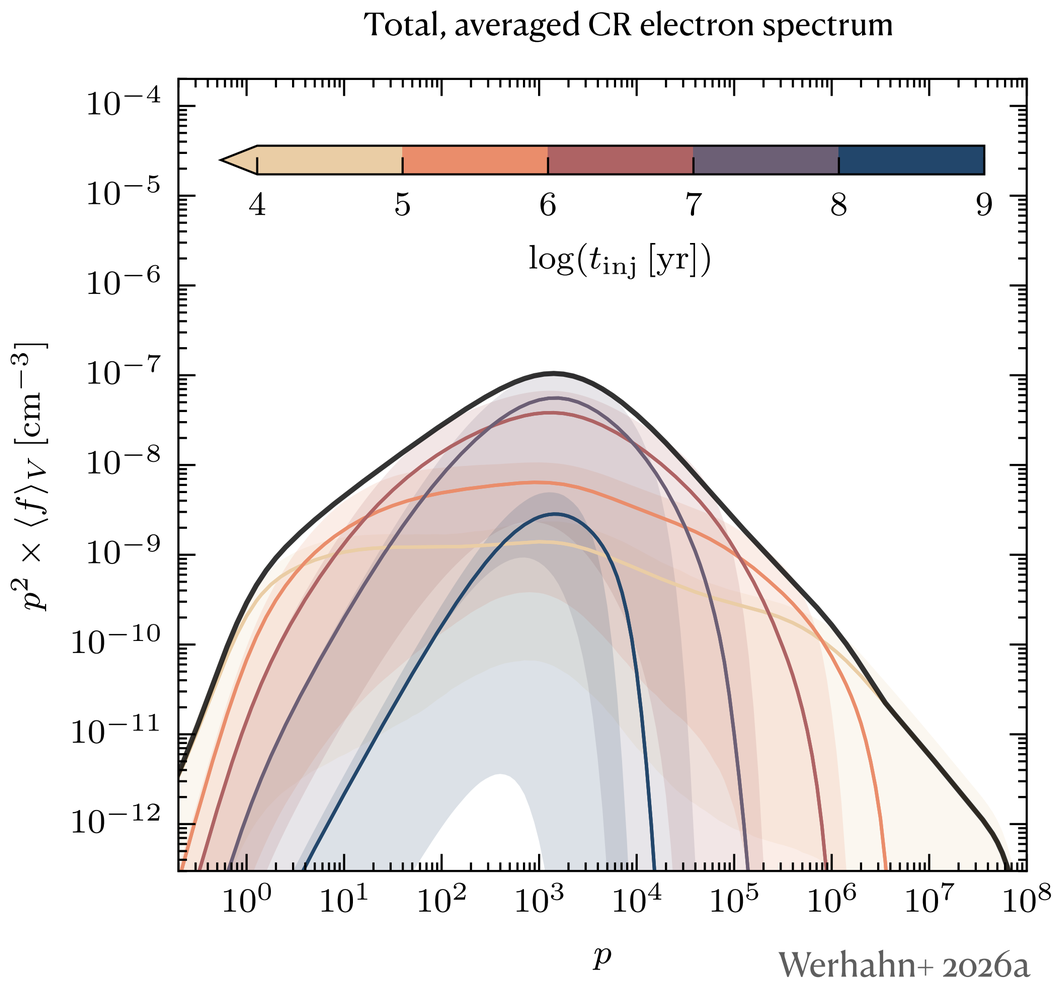




CREST in galaxies

Are galaxies in a steady-state?

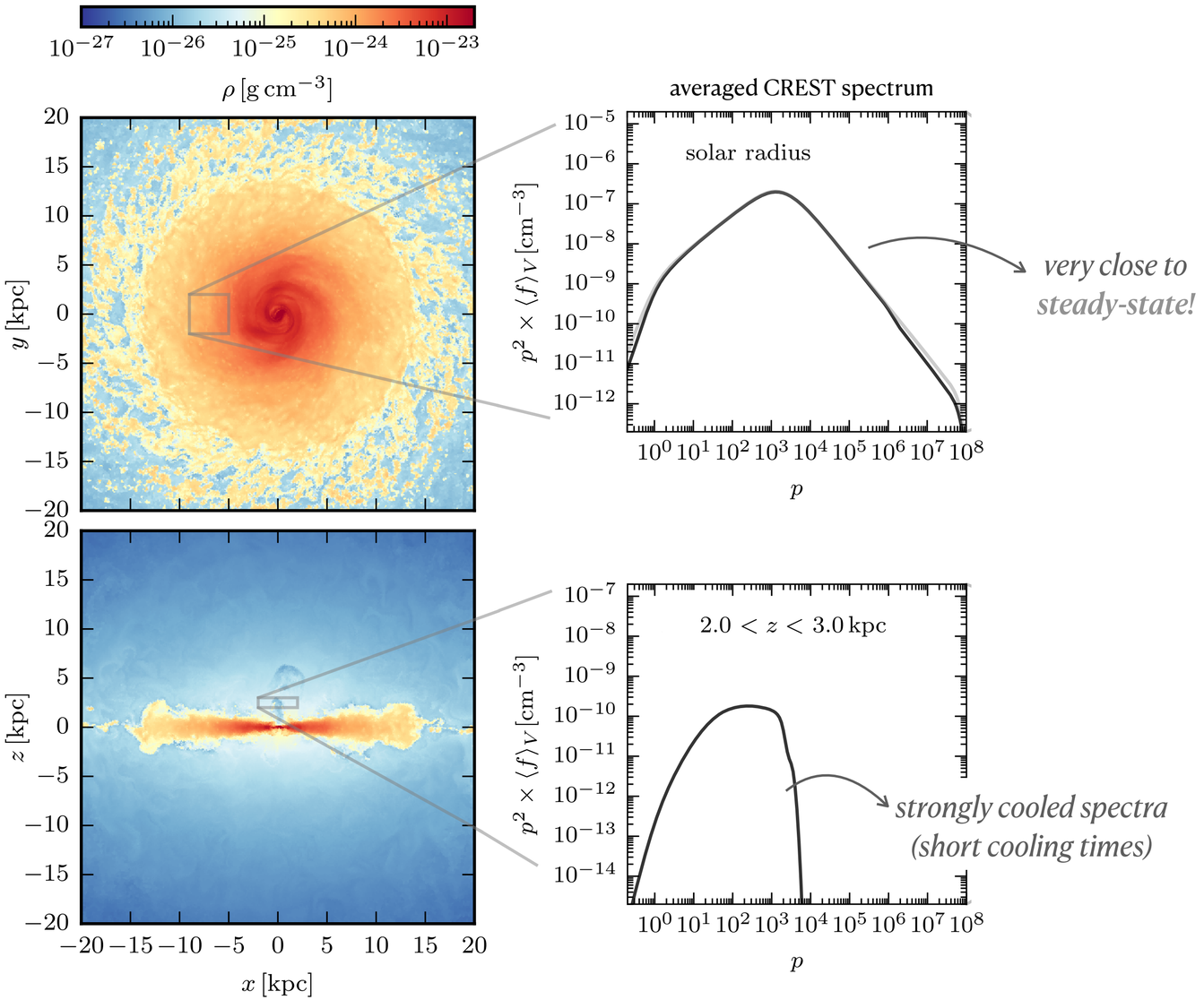


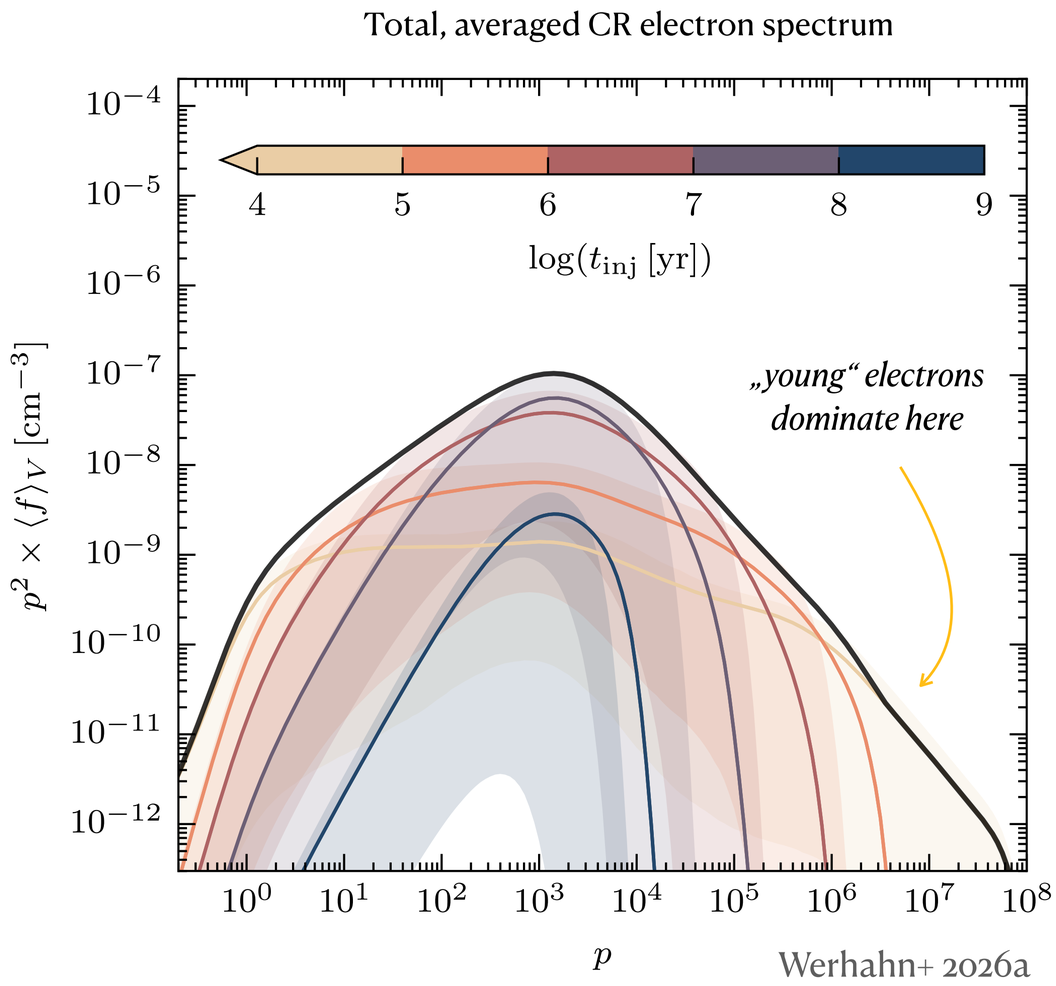


Werhahn+ 2026a

CREST in galaxies

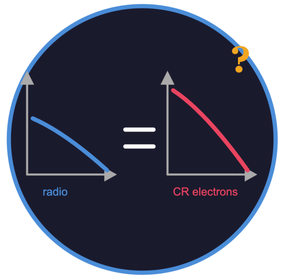
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Revisiting radio diagnostics with CREST

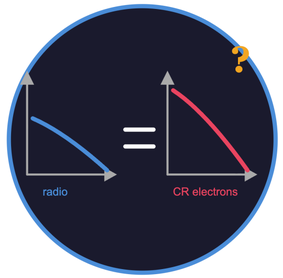
3 Questions



1. Does the radio spectrum trace the underlying, galaxy-wide CR electron spectrum?

Revisiting radio diagnostics with CREST

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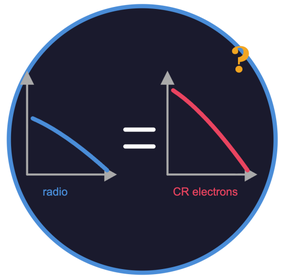
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Revisiting radio diagnostics with CREST

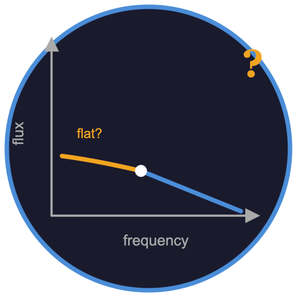
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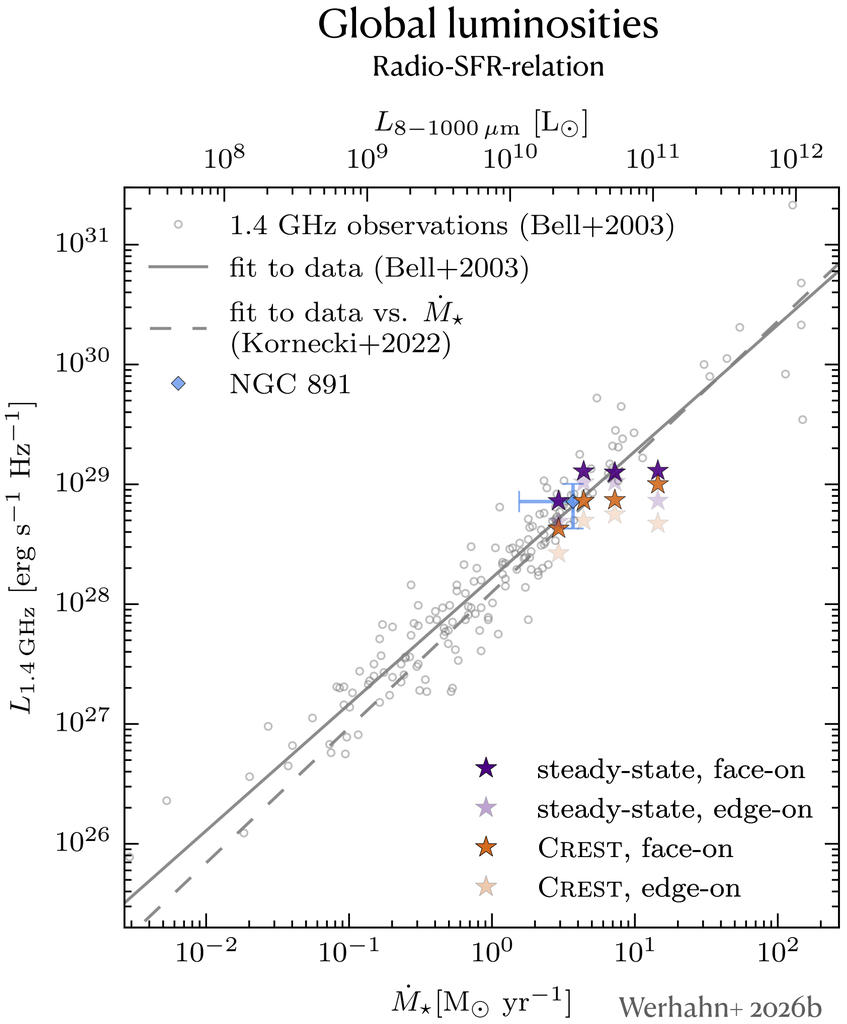


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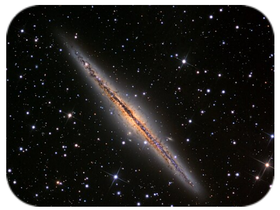
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Revisiting radio diagnostics with CREST



Werhahn+ 2026b

Global properties compared to NGC 891



CREST

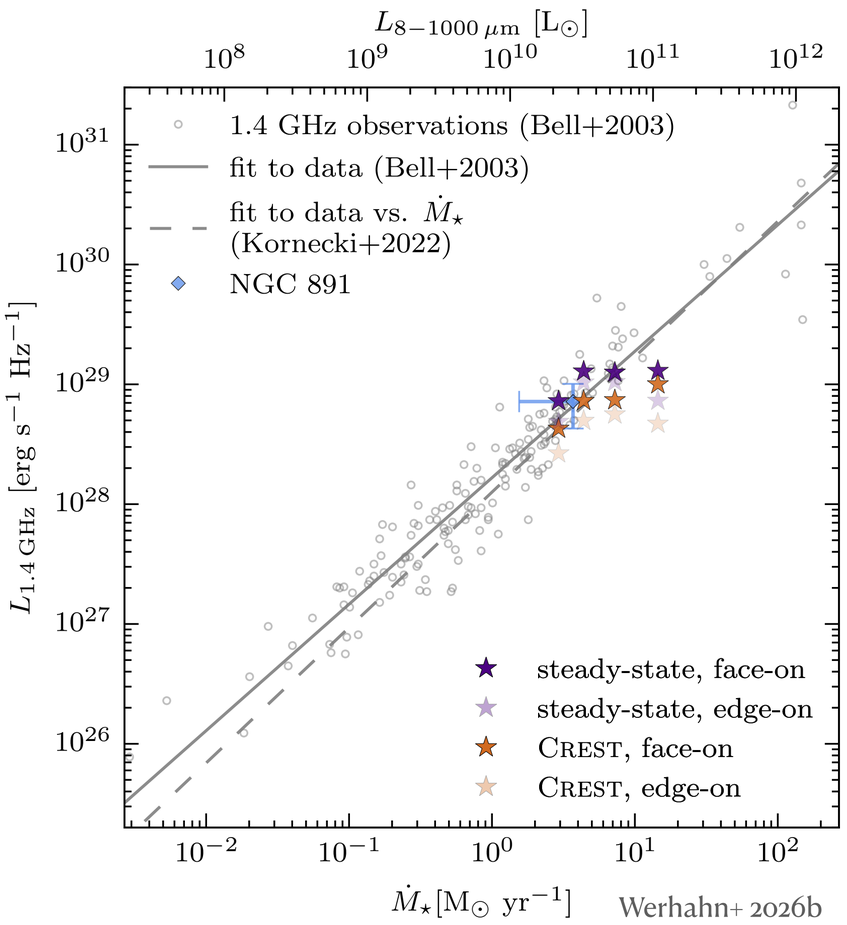
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Revisiting radio diagnostics with CREST

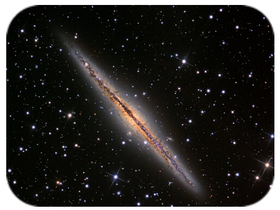
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Global luminosities

Radio-SFR-relation



Werhahn+ 2026b

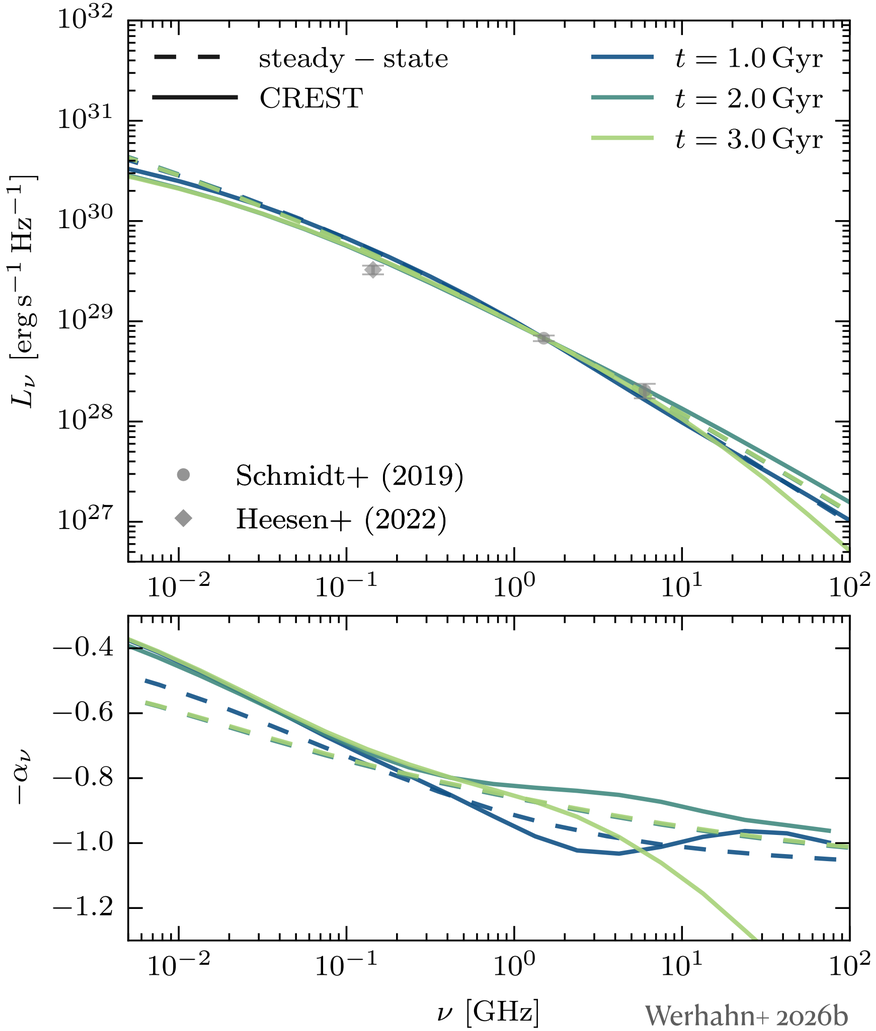


CREST

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Global radio spectra

(re-normalised by factors < 1.5)



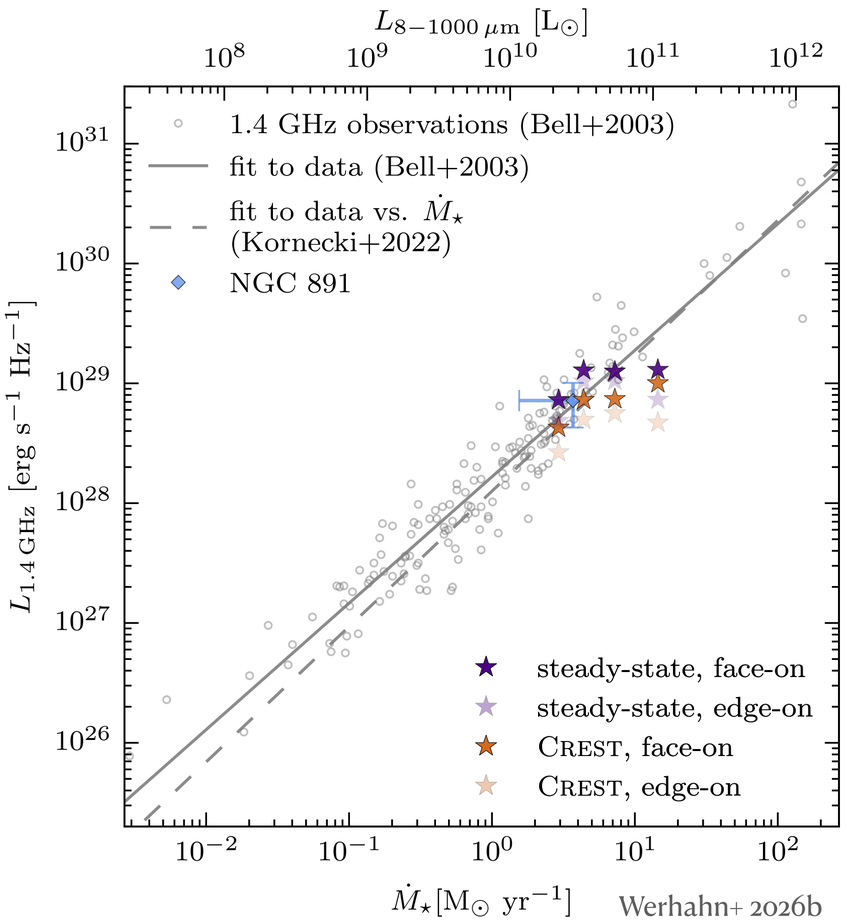
Werhahn+ 2026b

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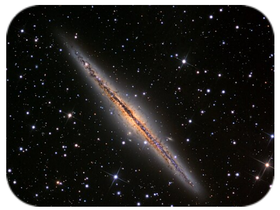
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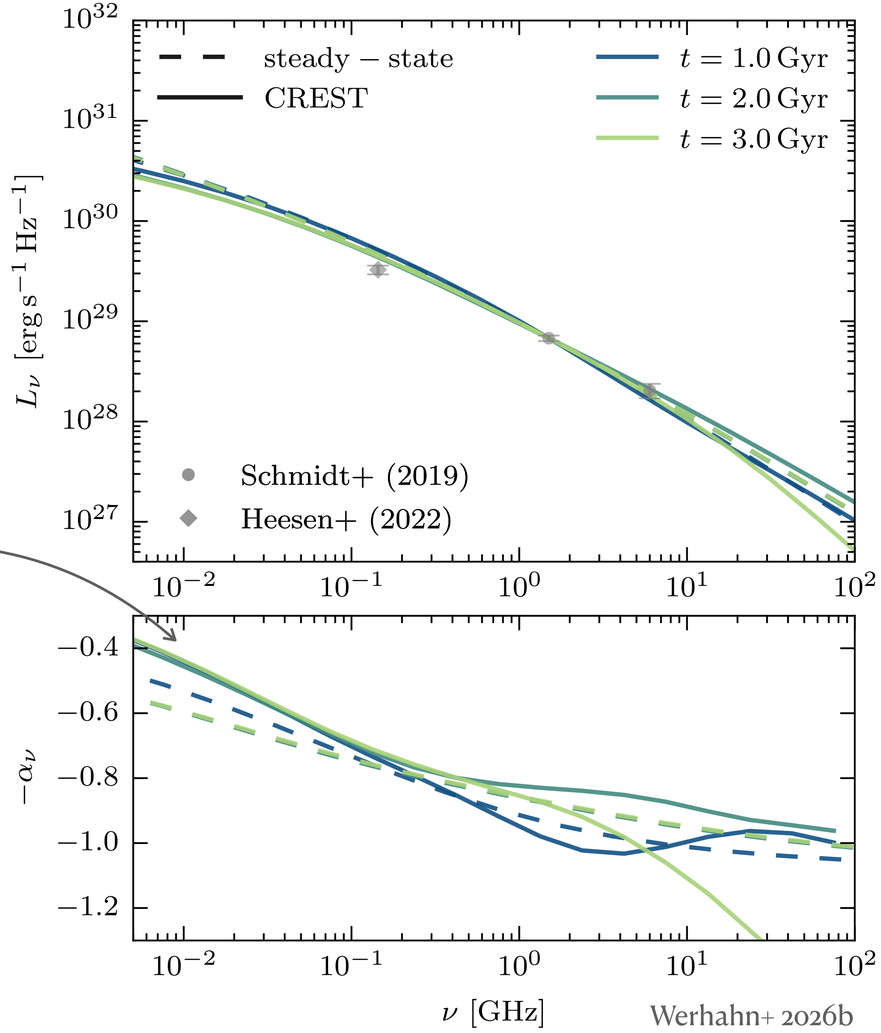


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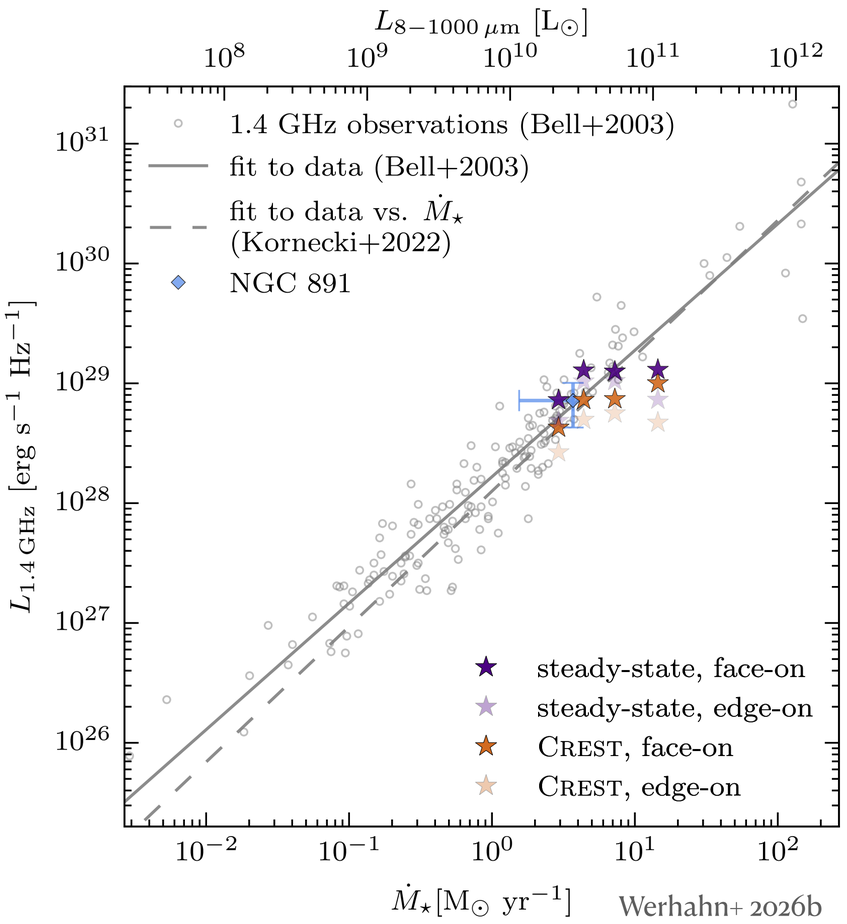
Werhahn+ 2026b

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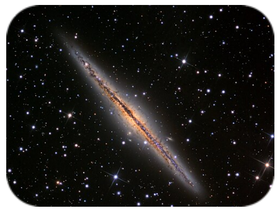
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Werhahn+ 2026b

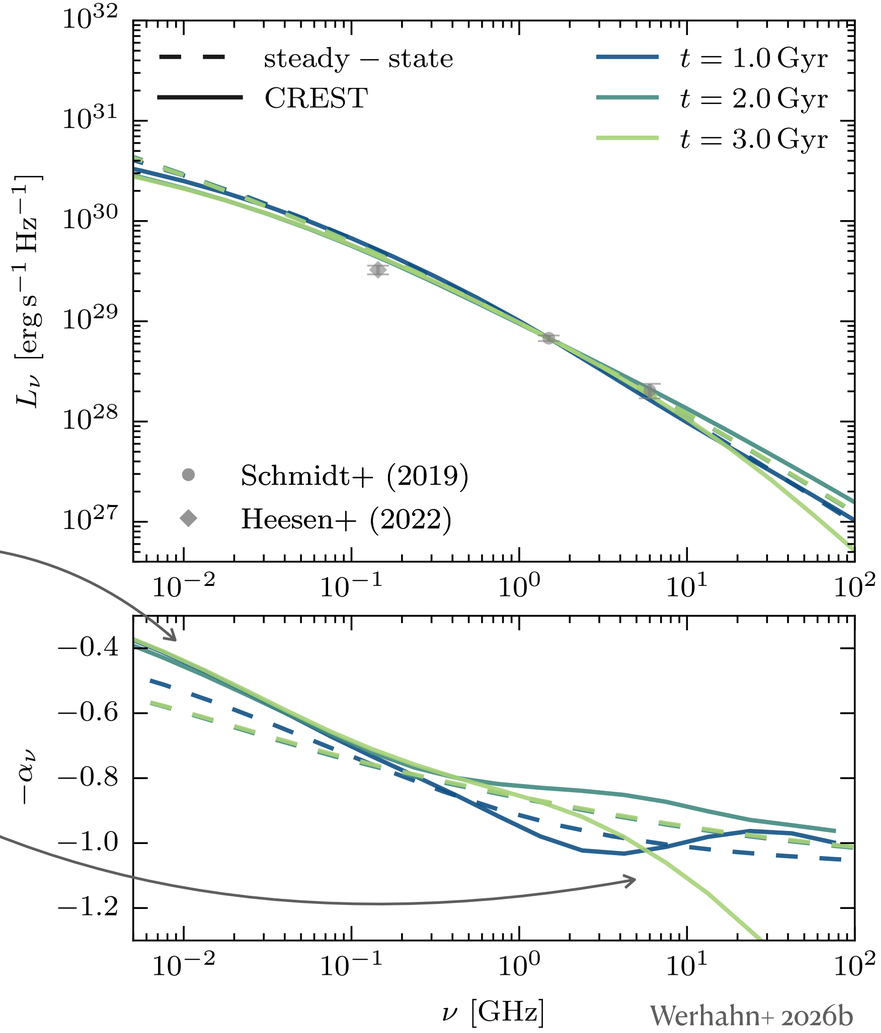


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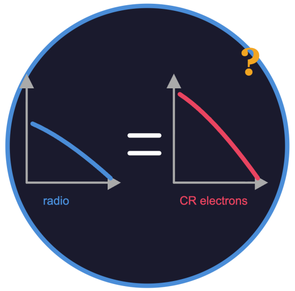
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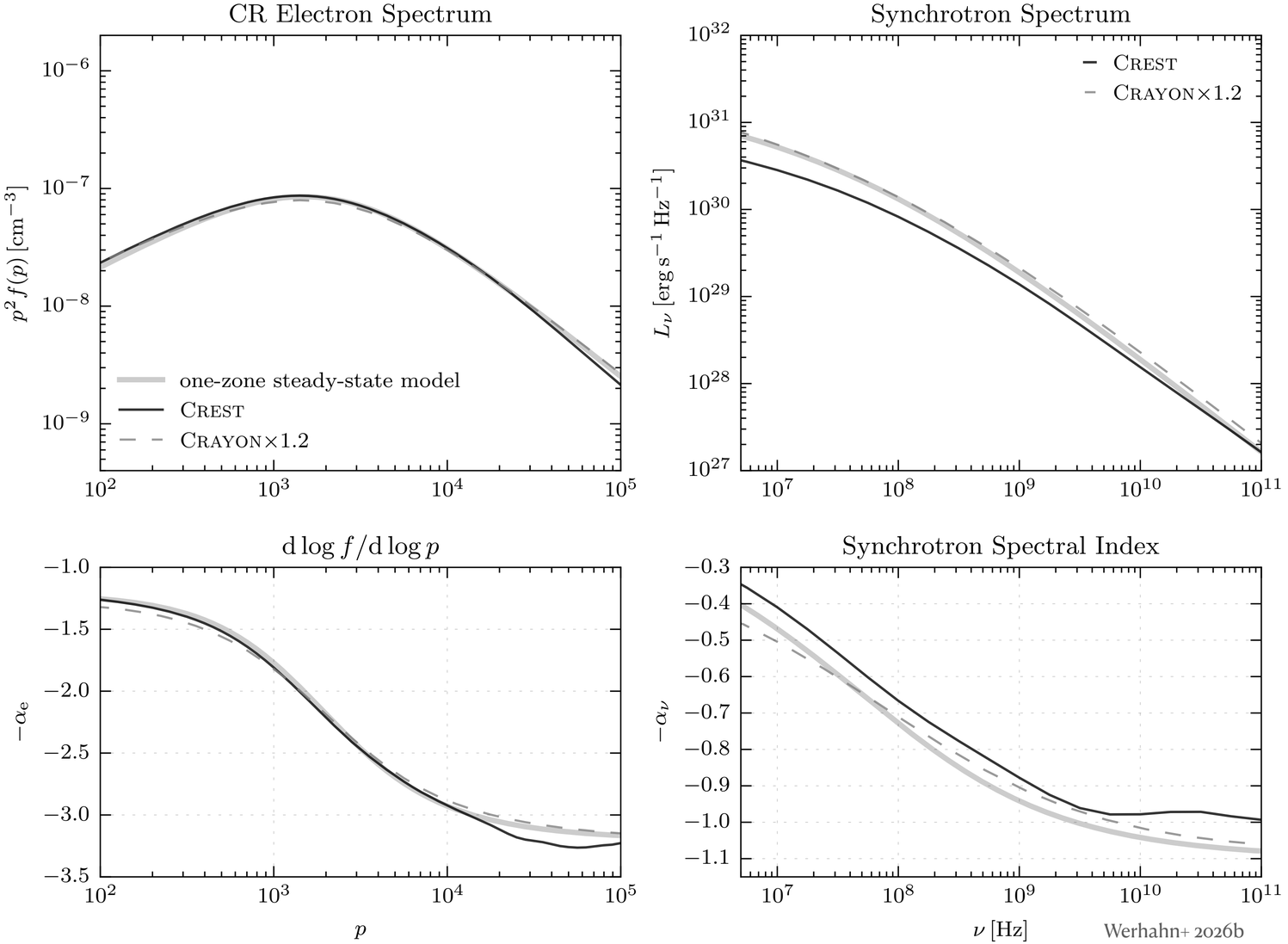
Revisiting radio diagnostics with CREST

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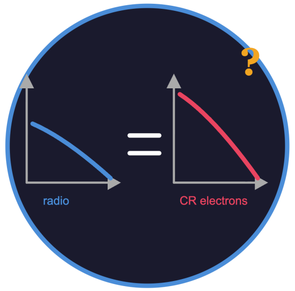
one-zone steady-state:
using galaxy-averaged properties + steady-state

CRAYON+
cell-based steady-state

CREST
full time-evolution of spectra



Werhahn+ 2026b



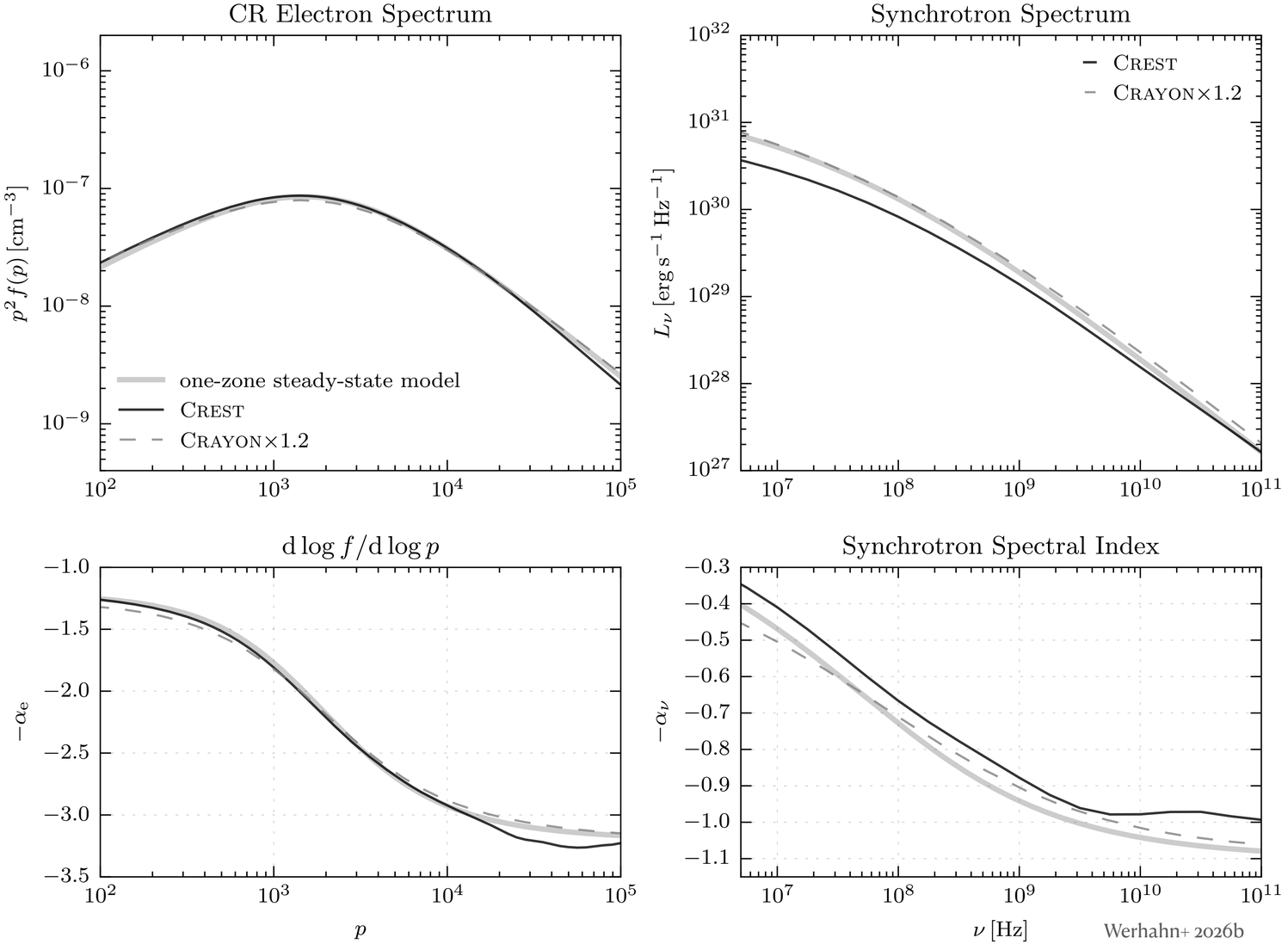
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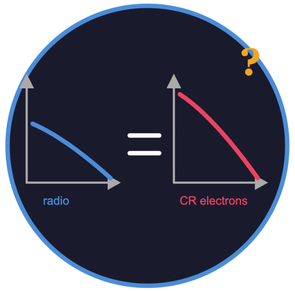
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CREST spectra:

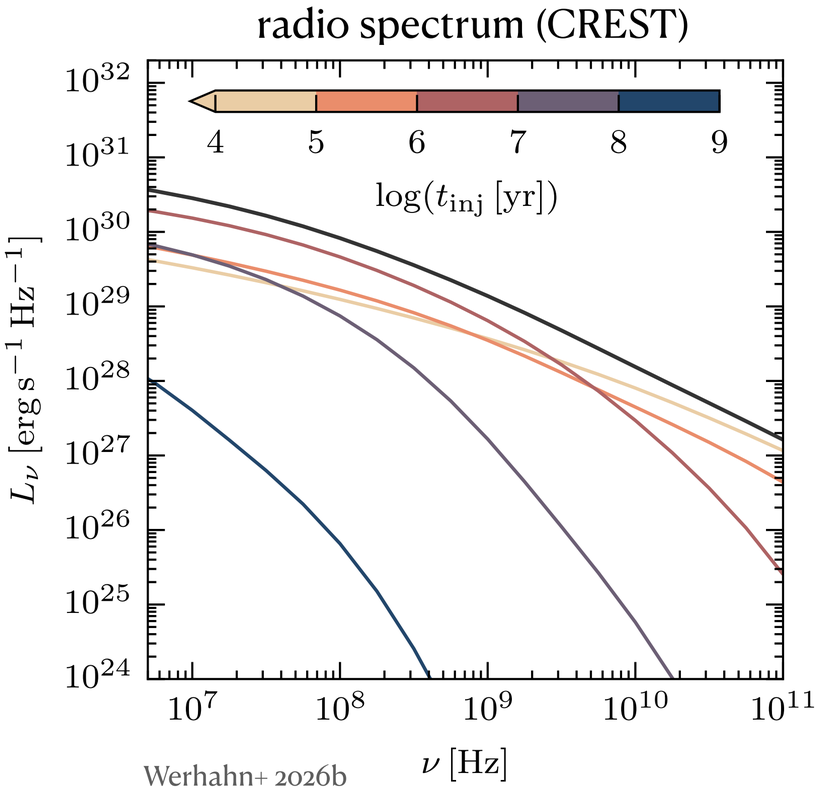
→ **flatter** radio spectra despite almost **identical** global CR electron spectra!

Werhahn+ 2026b

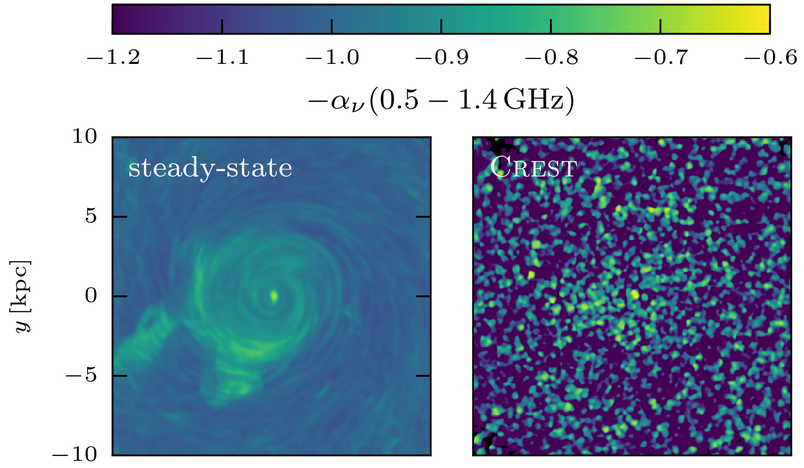


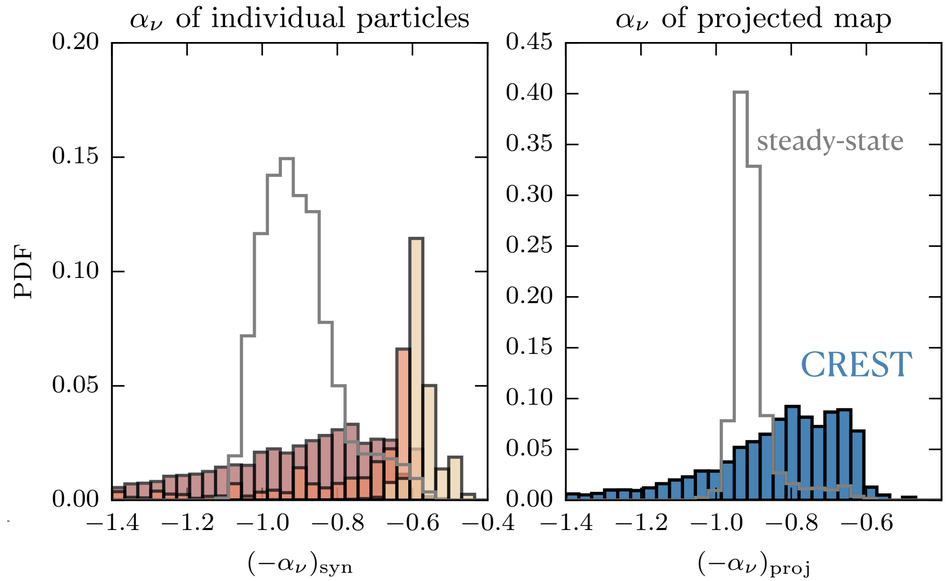
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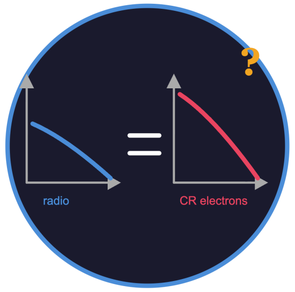
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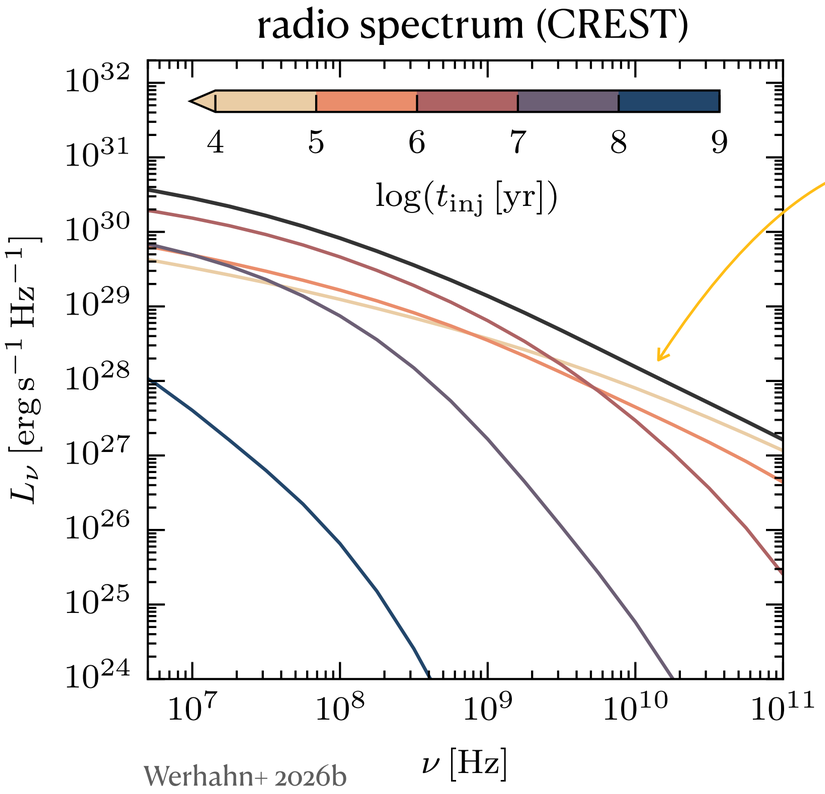




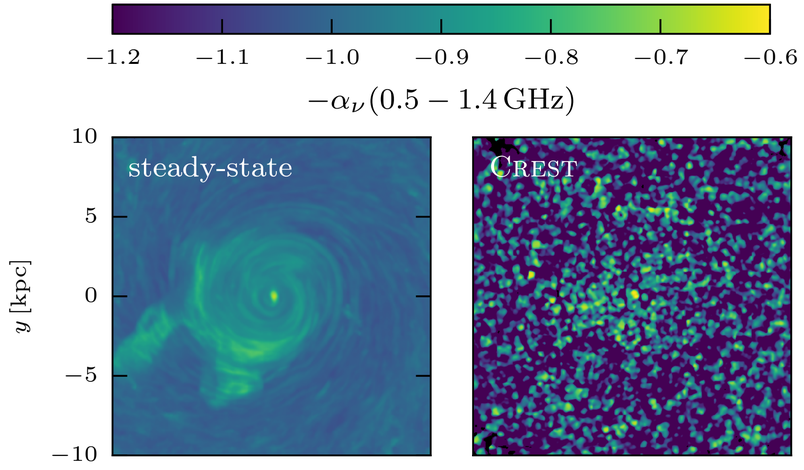


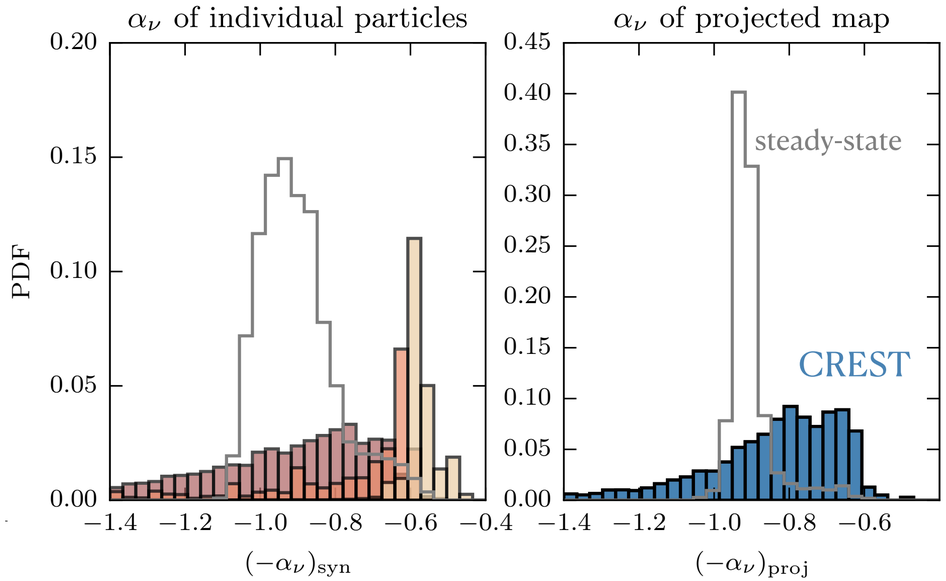
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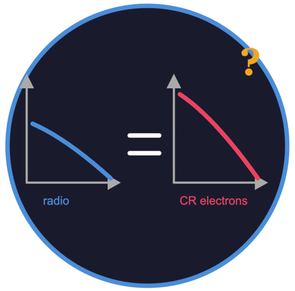
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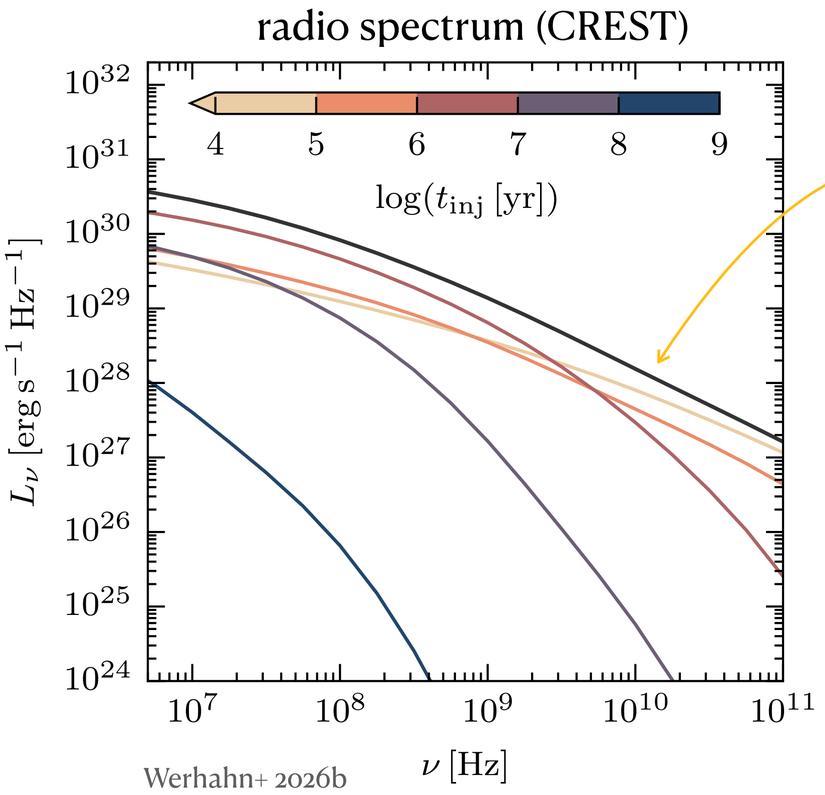




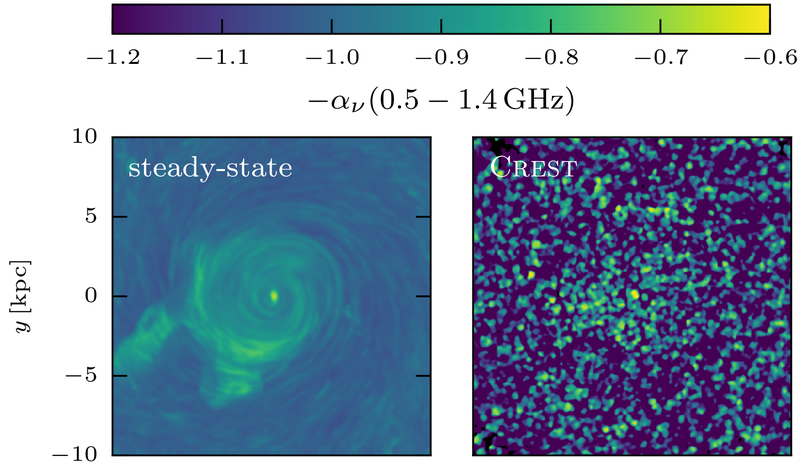


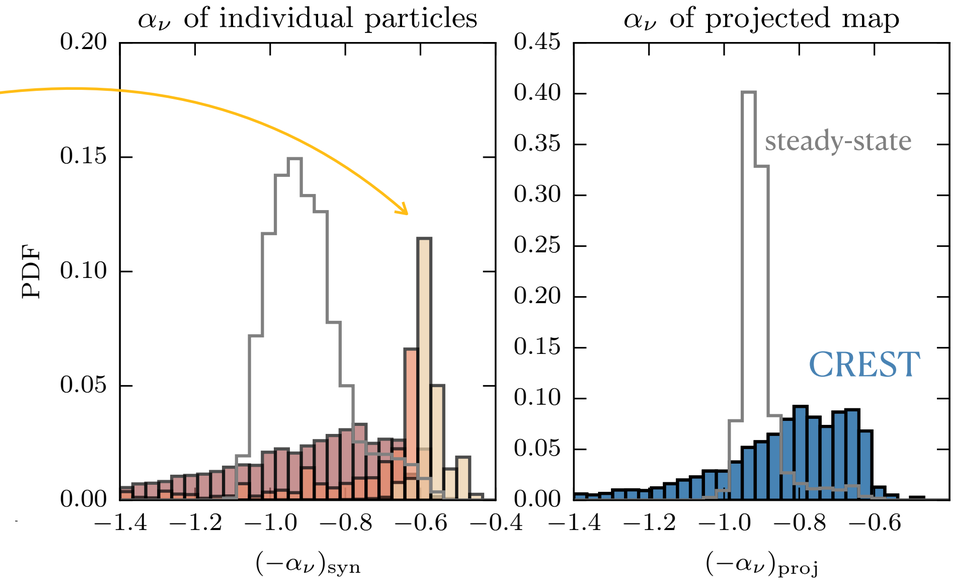
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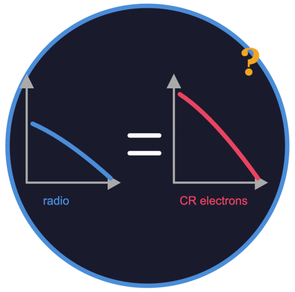
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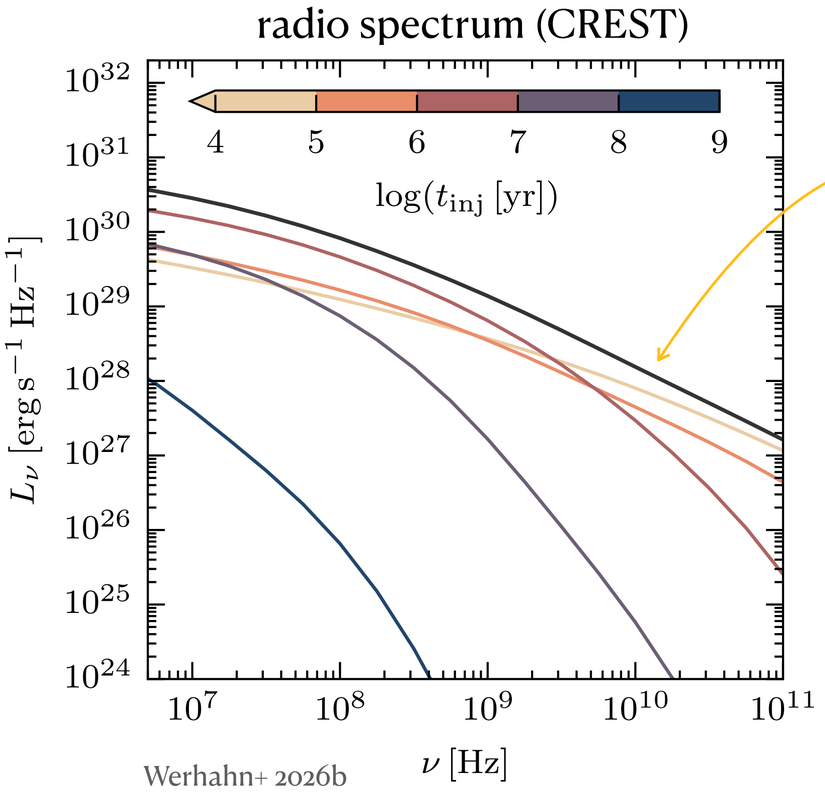






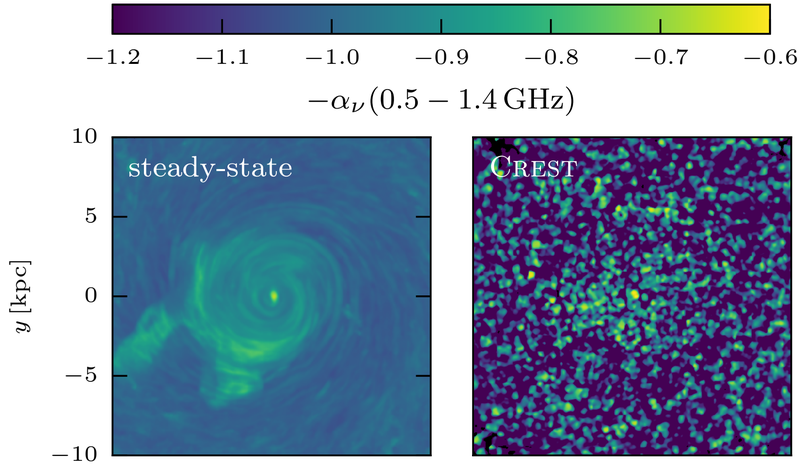
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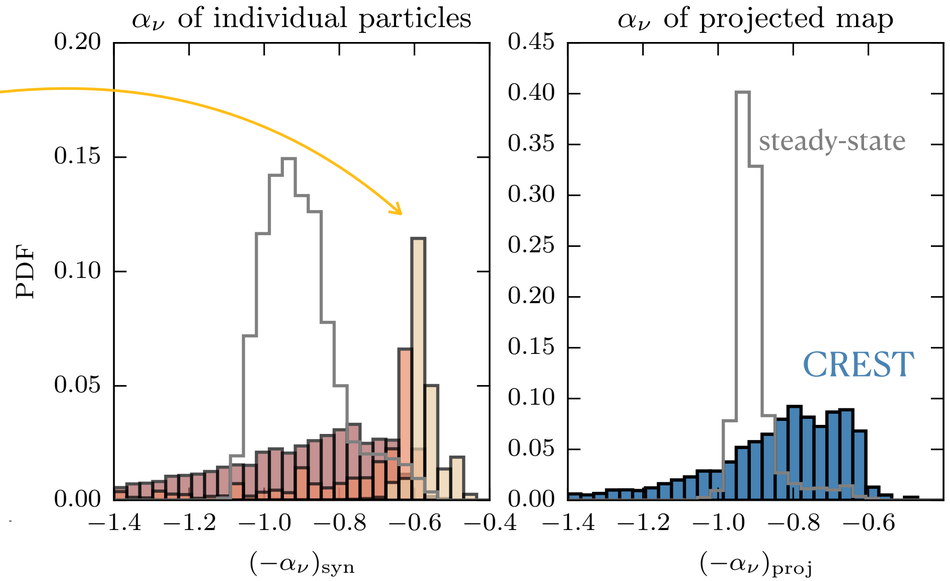
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→ radio spectra are not a direct probe of the full CR electron population







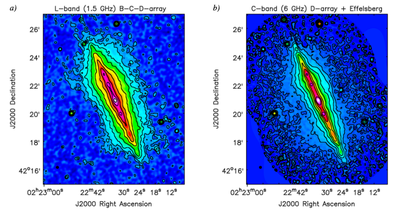
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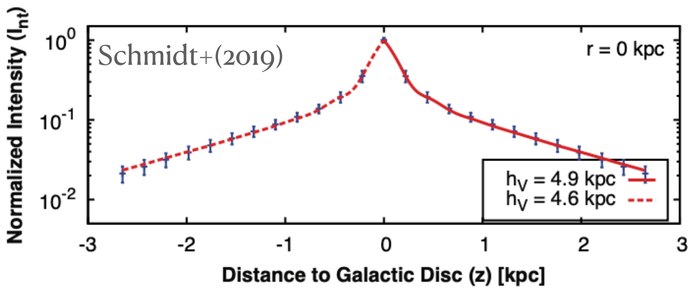
2. Can radio halos be explained by purely advective CRs?

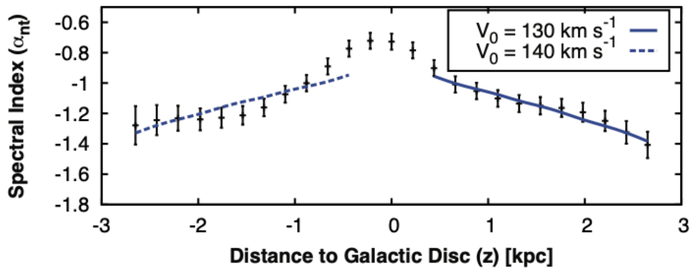
Observations + 1D model (SPINNAKER)

(Heesen et al. 2016; Schmidt+2019)



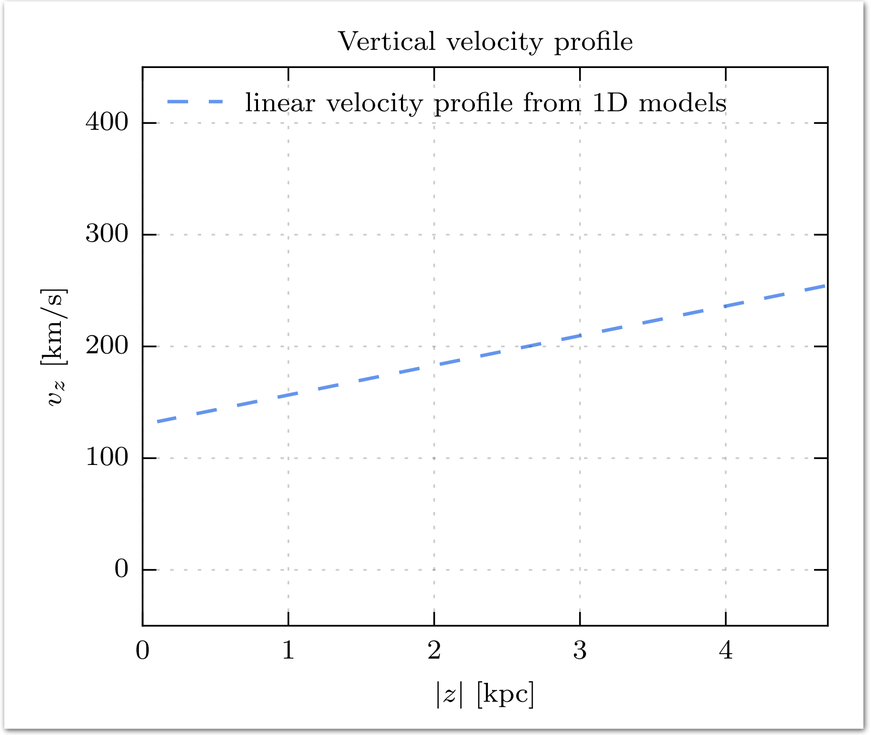






1D Model with advection only (Schmidt+2019):

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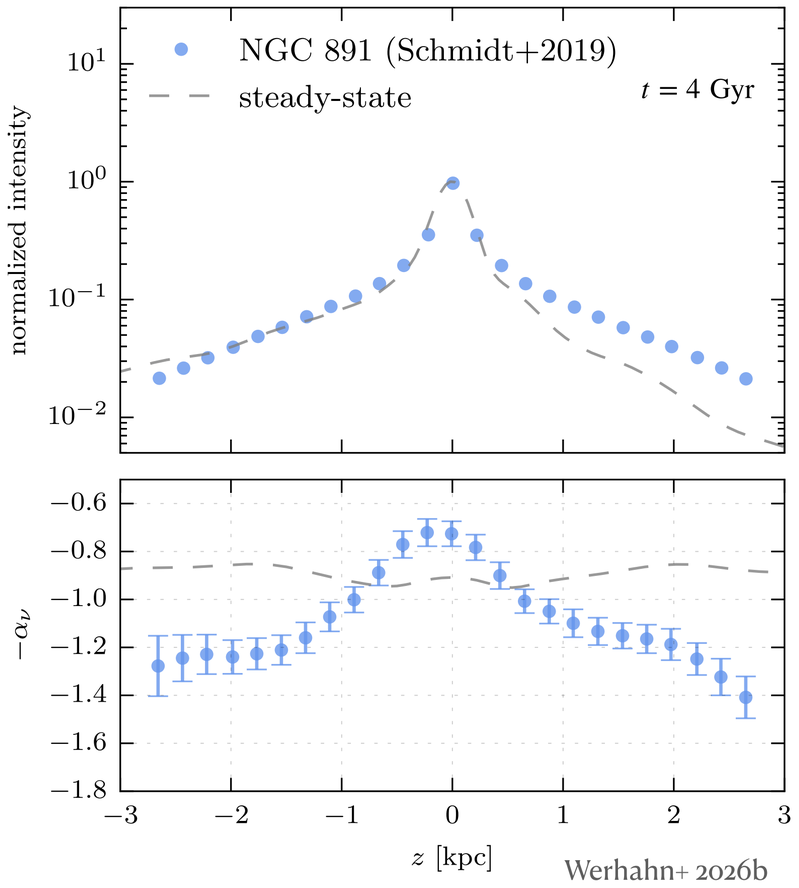




Revisiting radio diagnostics with CREST

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Simulations + steady-state/CREST



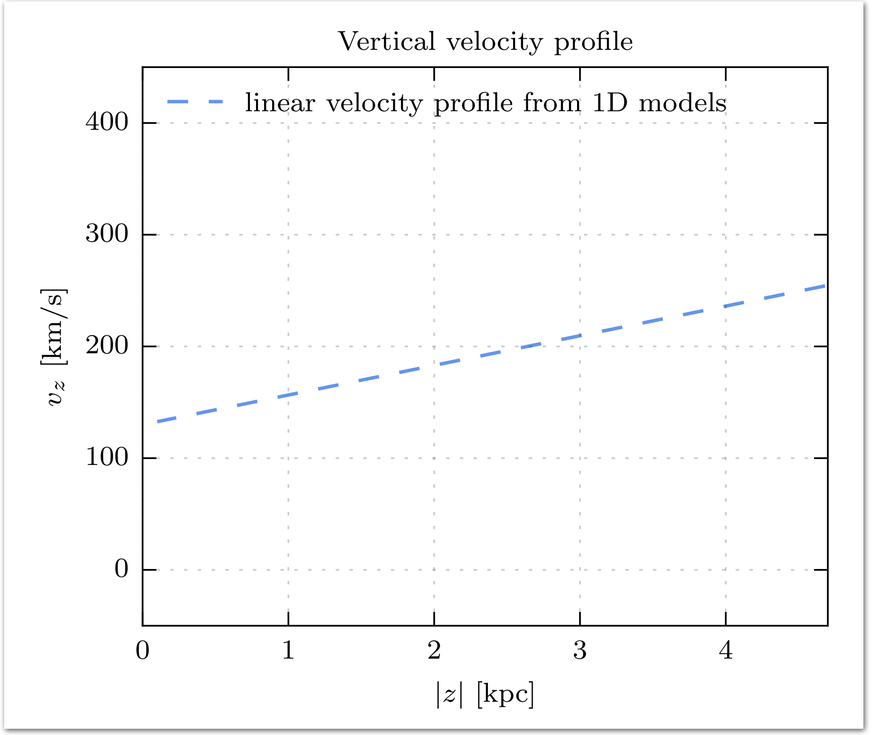
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- ✓ somewhat extended intensity profiles
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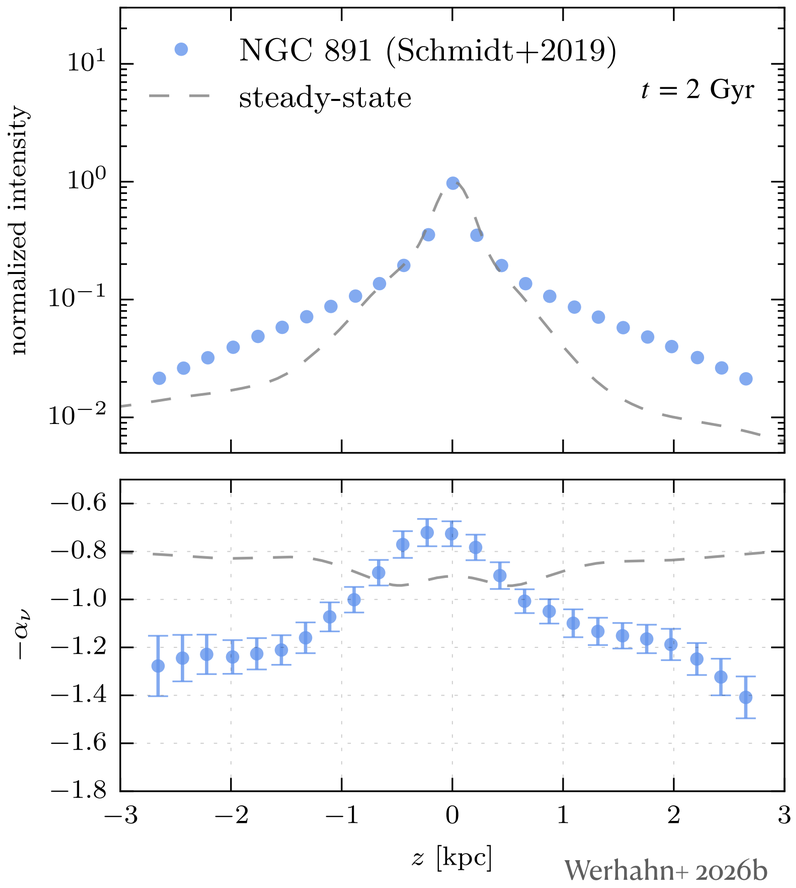




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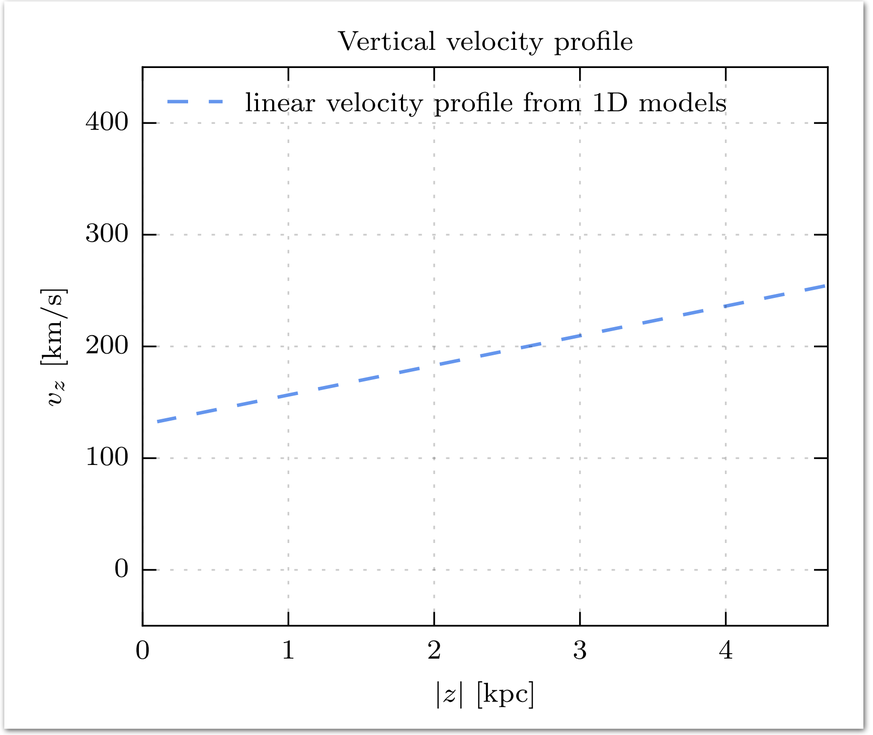
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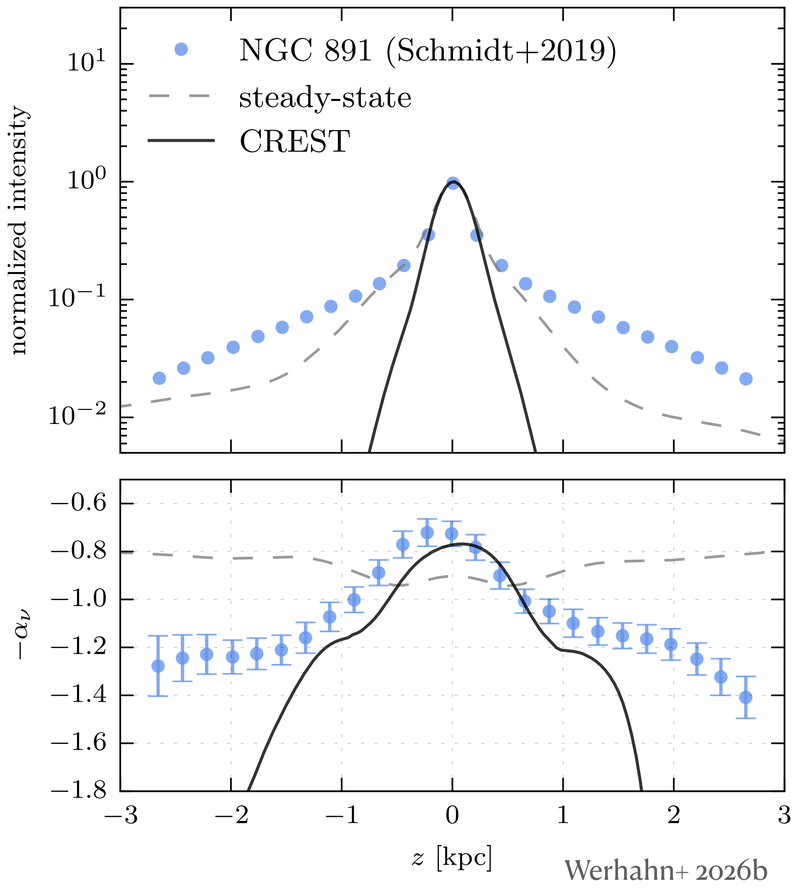




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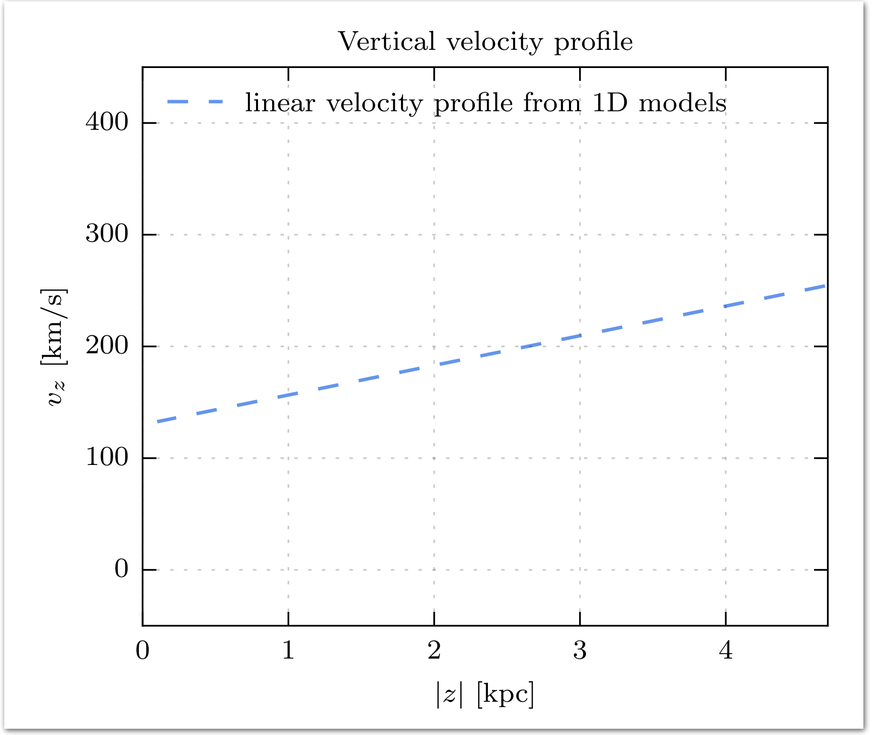
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Simulation with CREST:

- ✓ steepening of radio spectra with height
- *x* intensity profile too compact ...

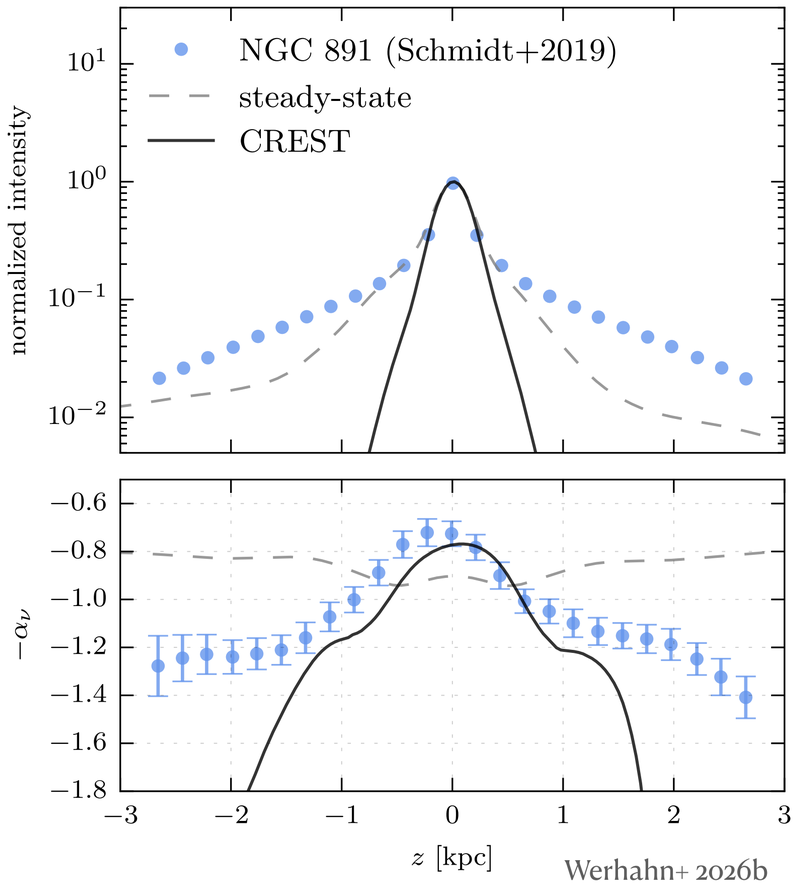




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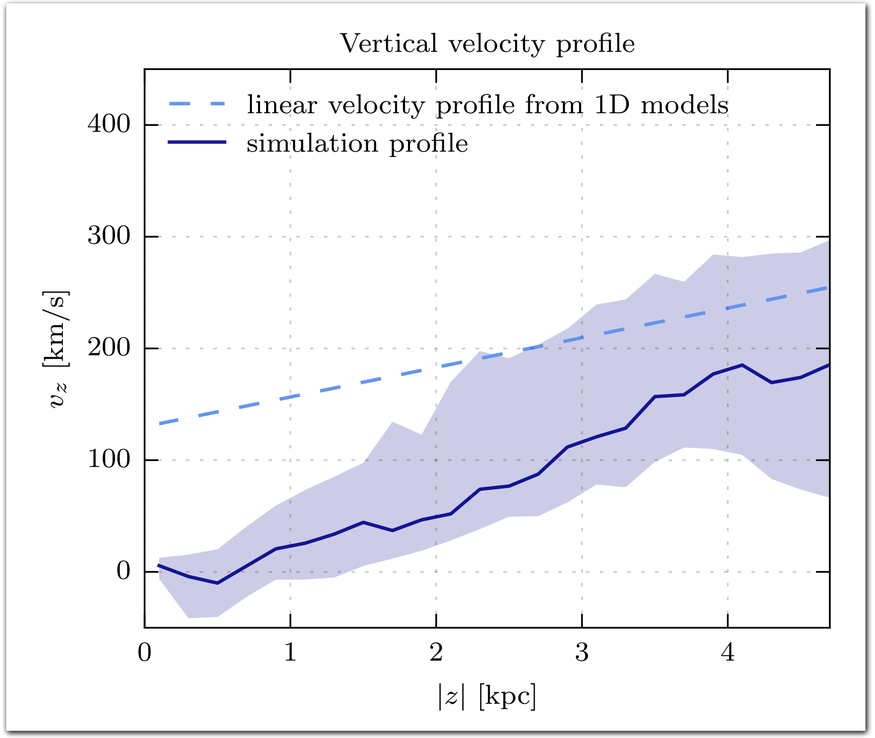
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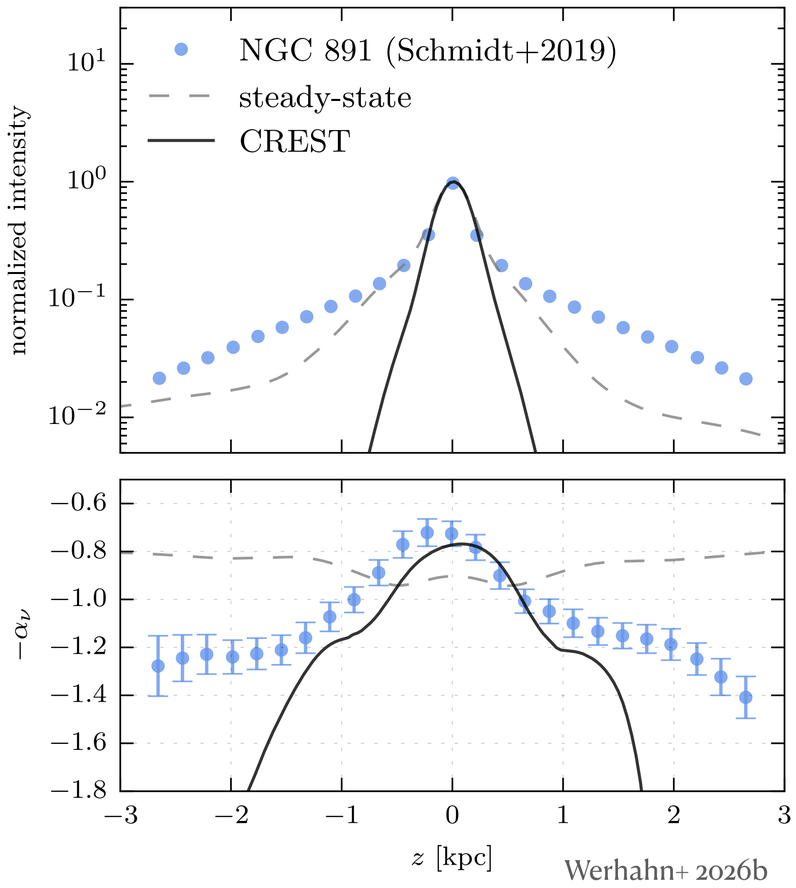




Revisiting radio diagnostics with CREST

2. Can radio halos be explained by purely advective CRs?

Simulations + steady-state/CREST



Werhahn+ 2026b

1D Model with advection only (Schmidt+2019):

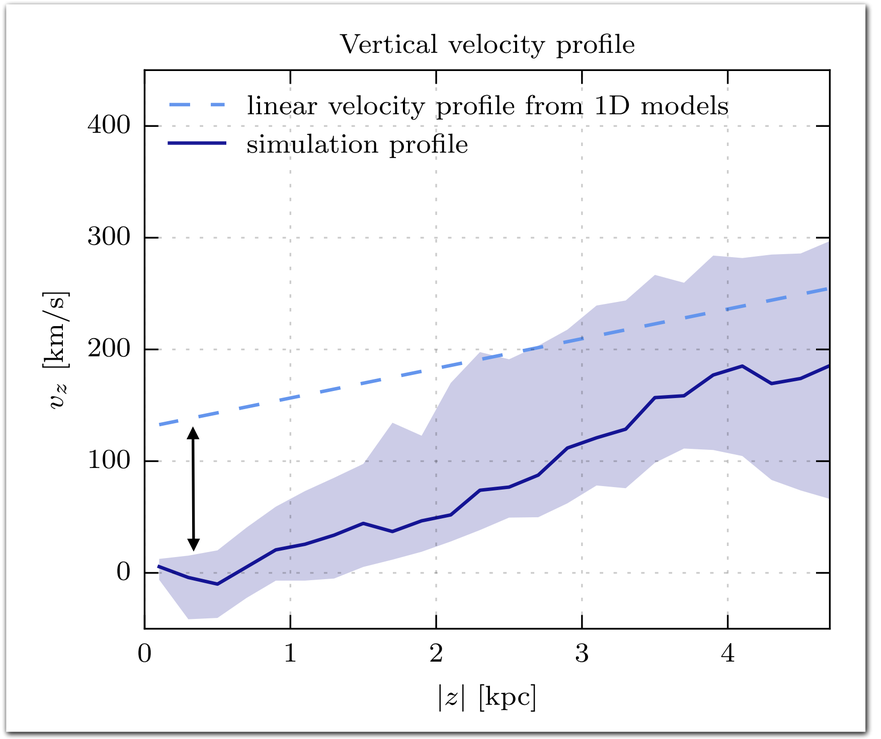
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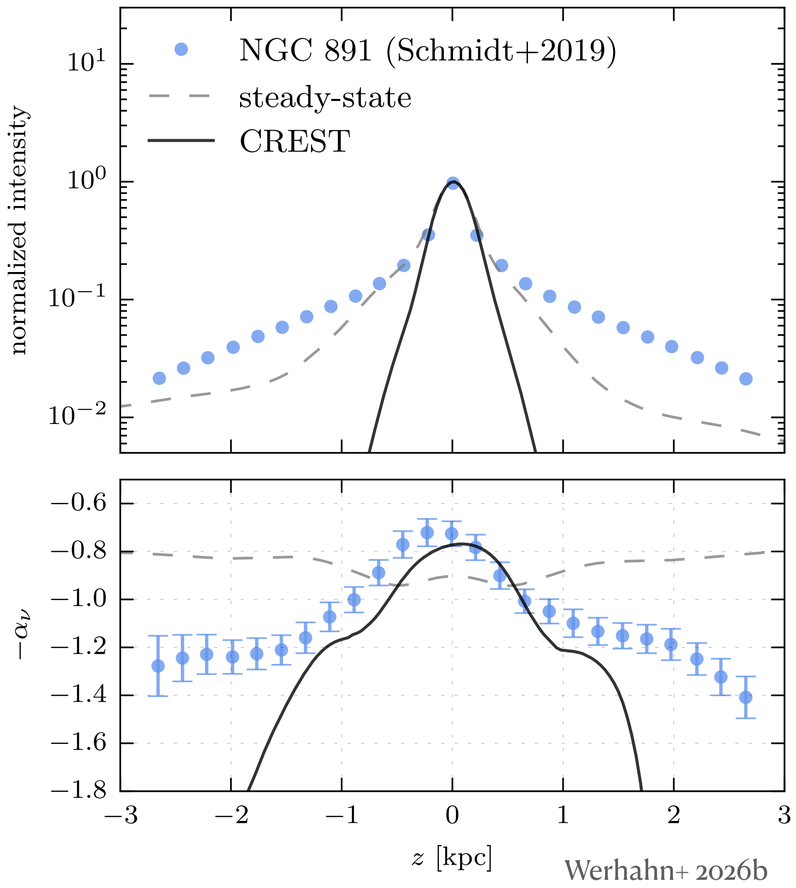




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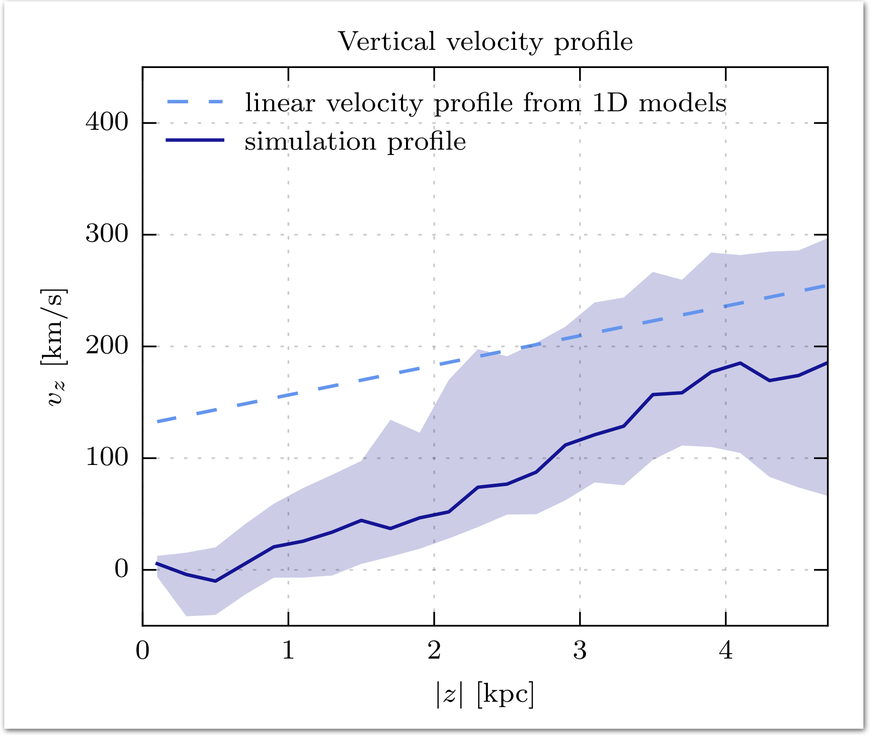
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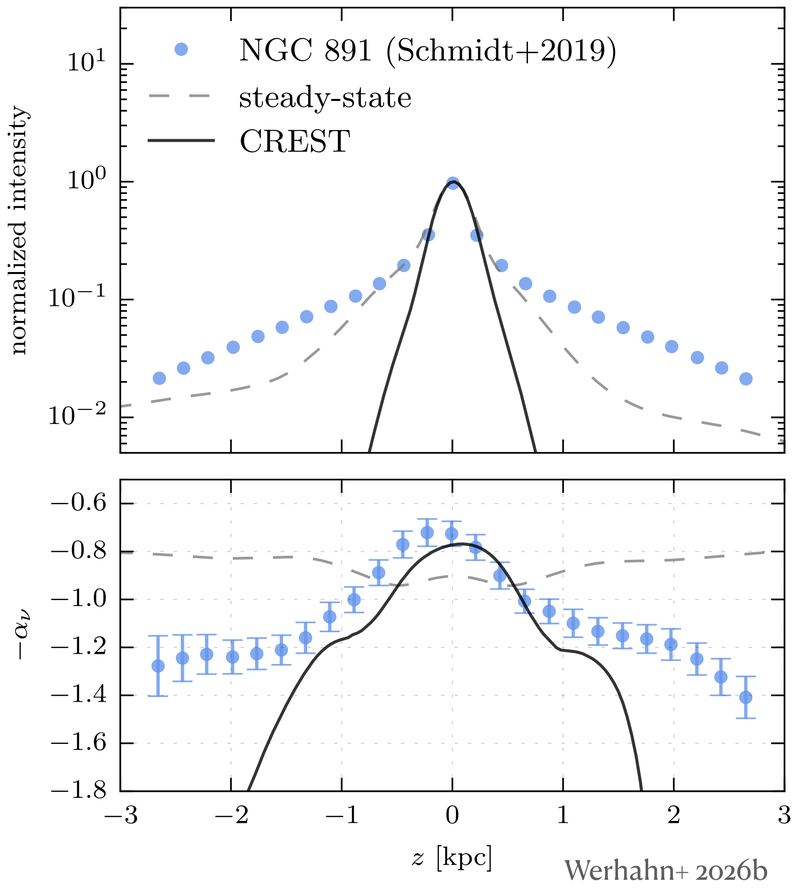




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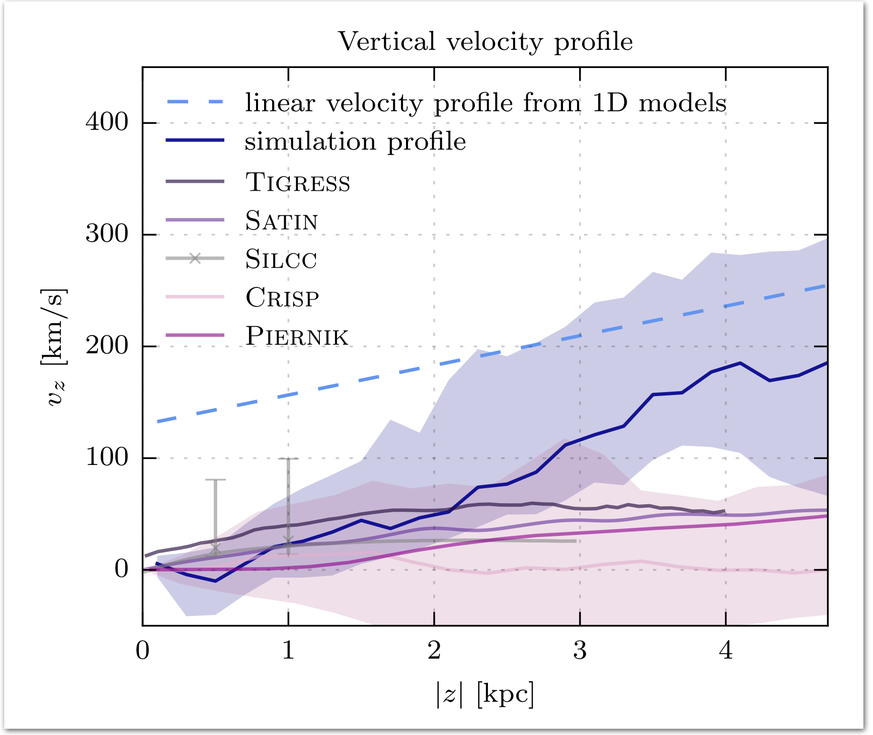
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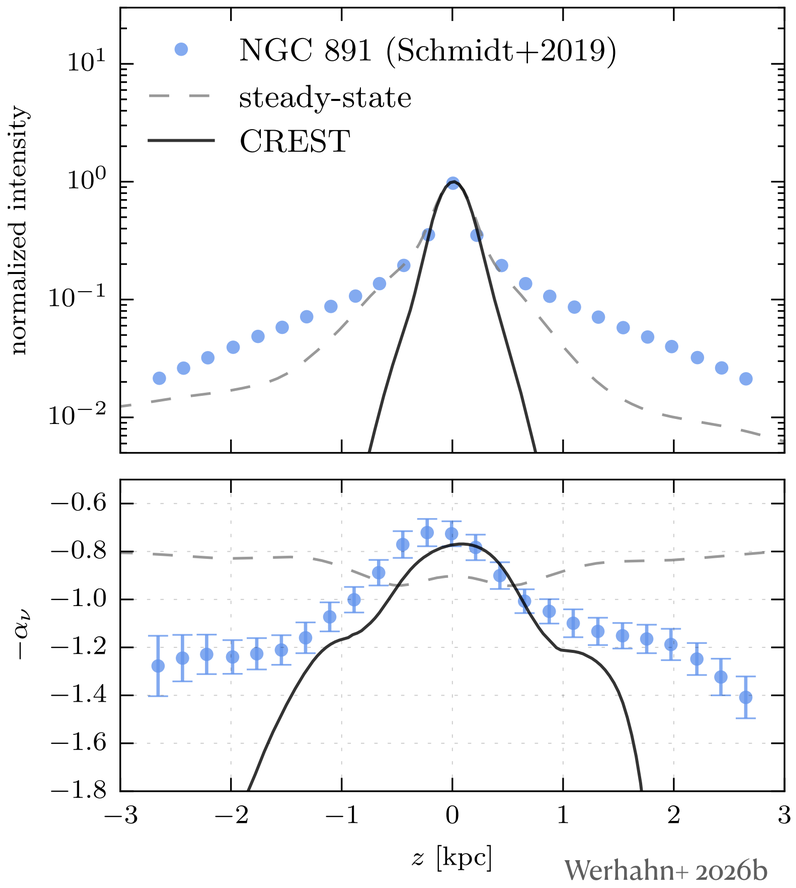




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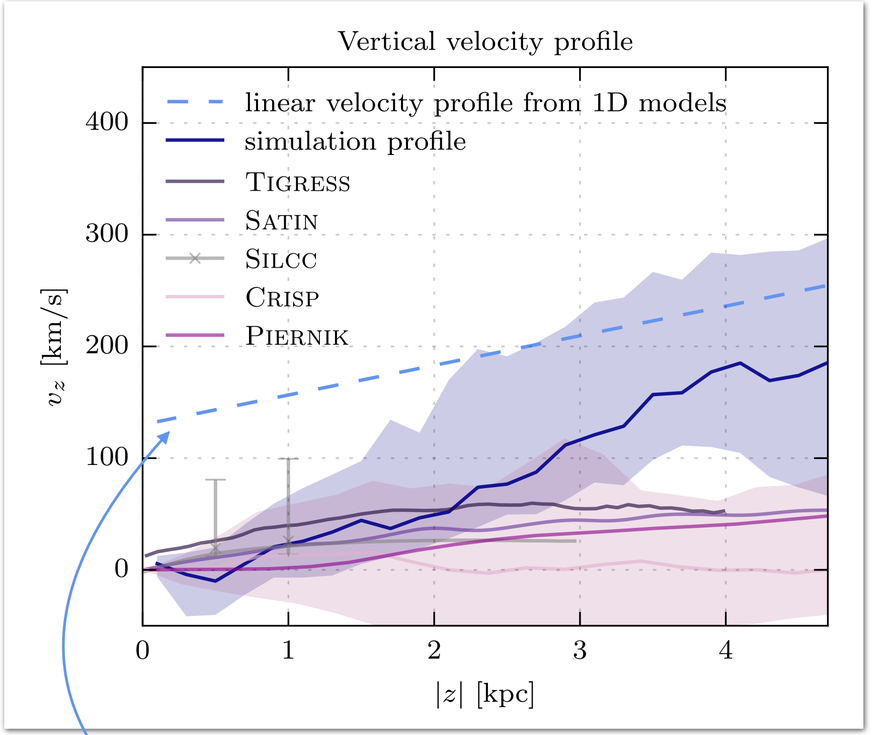
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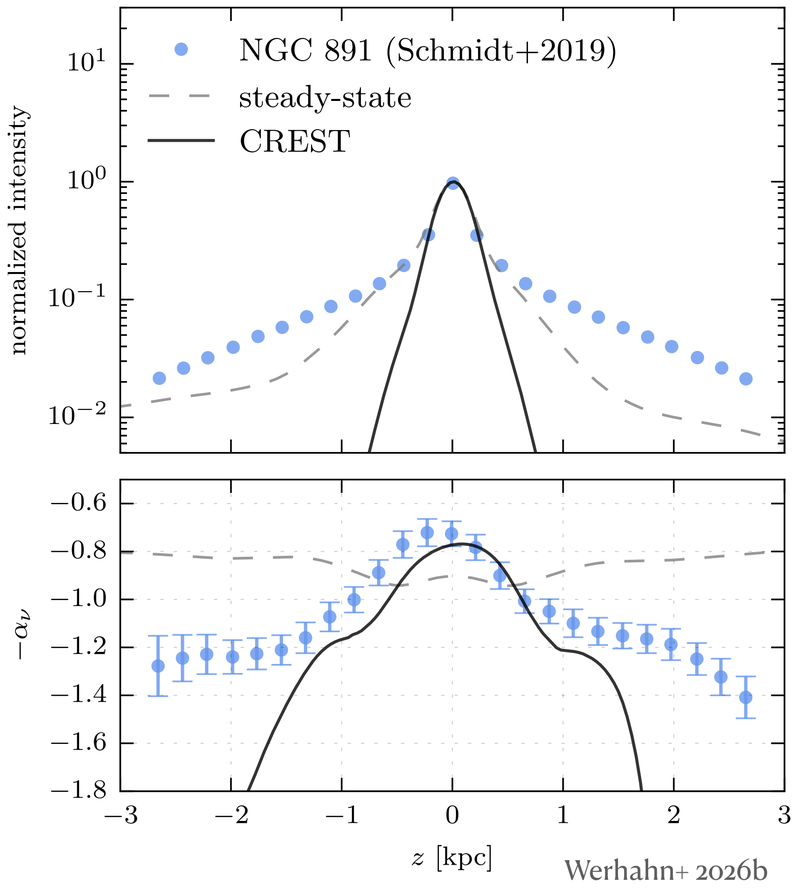
matching observations with advection-only requires large mid-plane wind velocities!



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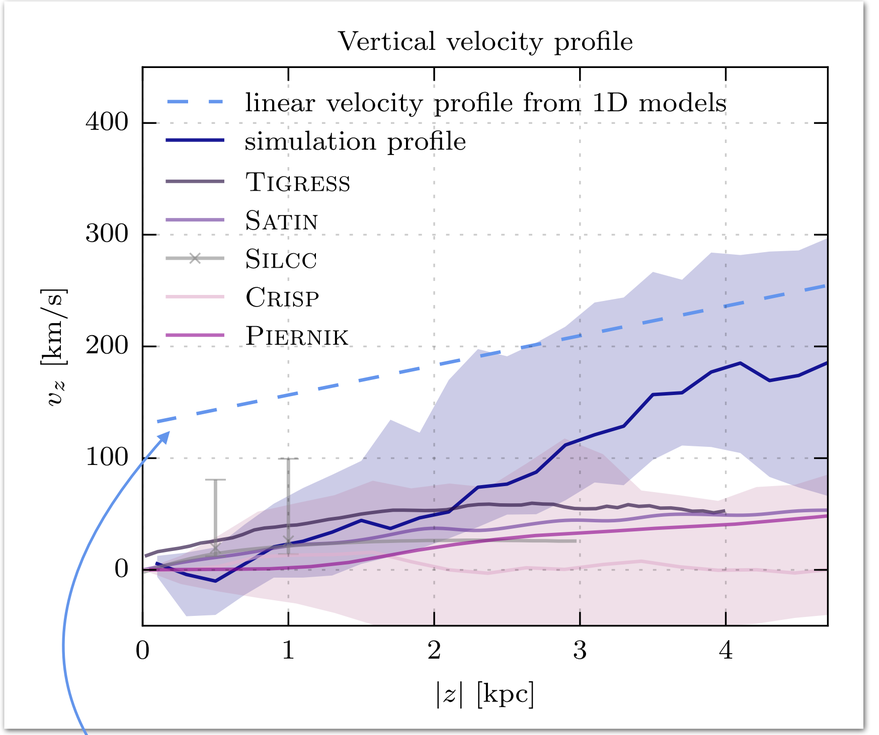
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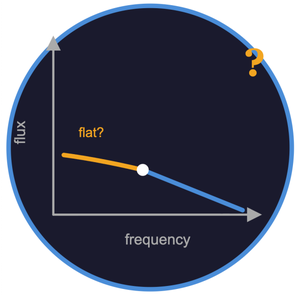
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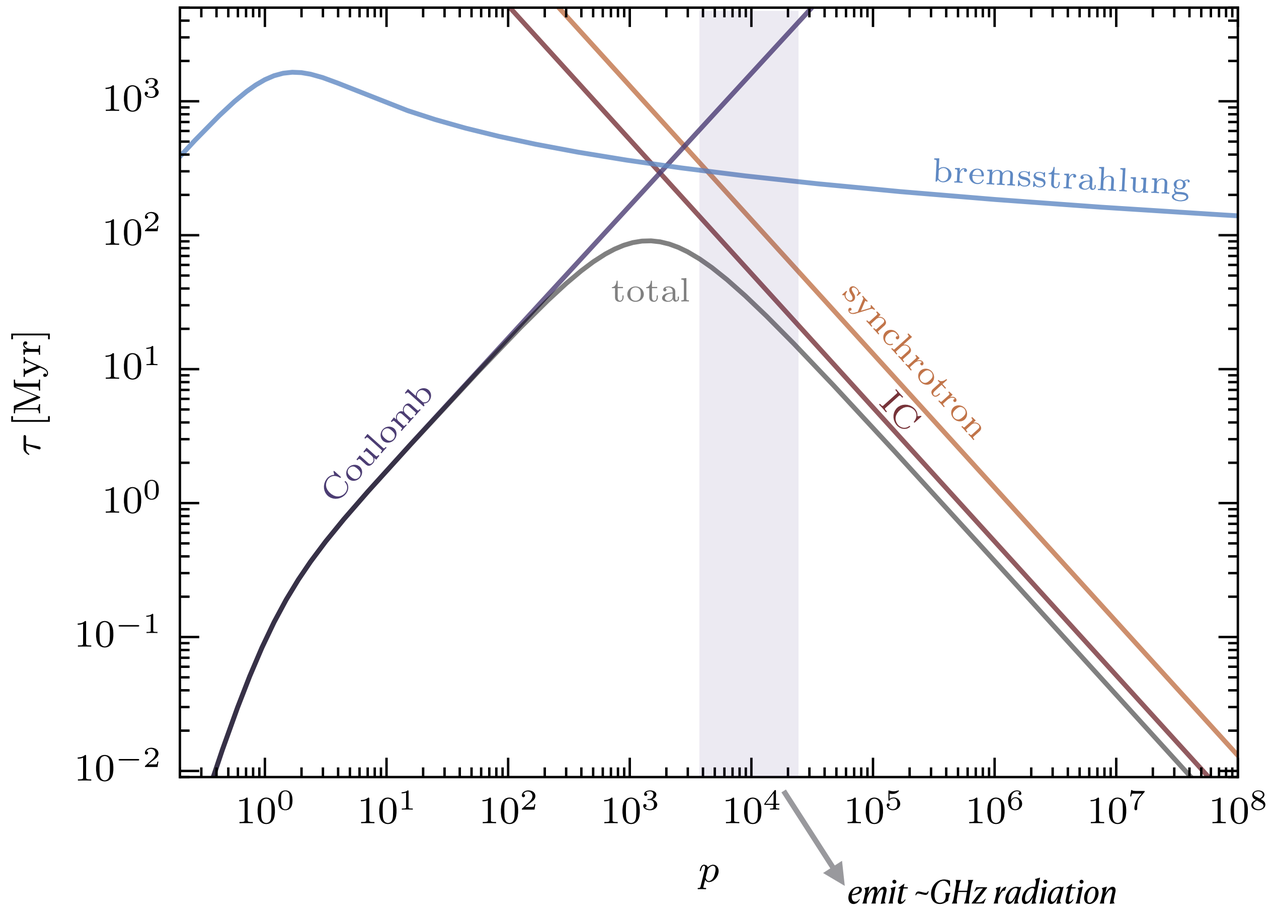
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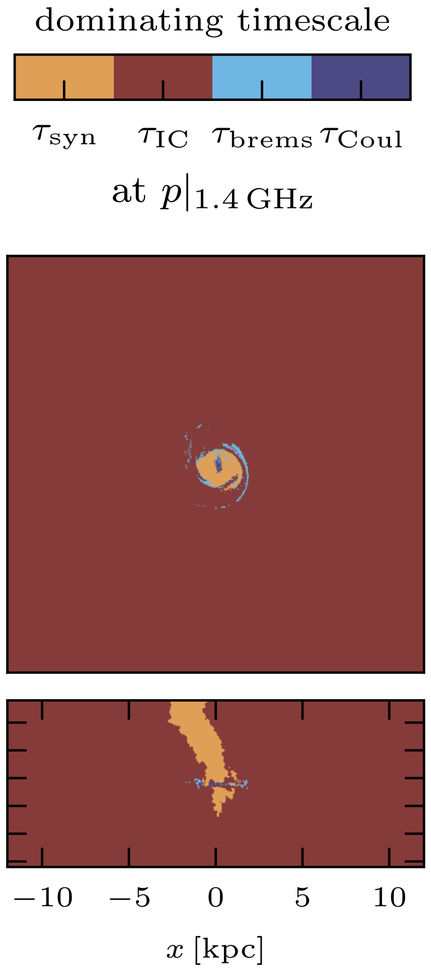
→ additional processes required (diffusion, streaming, re-acceleration)

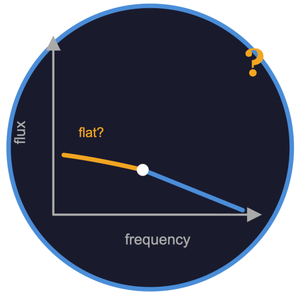


Revisiting radio diagnostics with CREST

3. Are bremsstrahlung and Coulomb losses negligible for radio-emitting electrons?

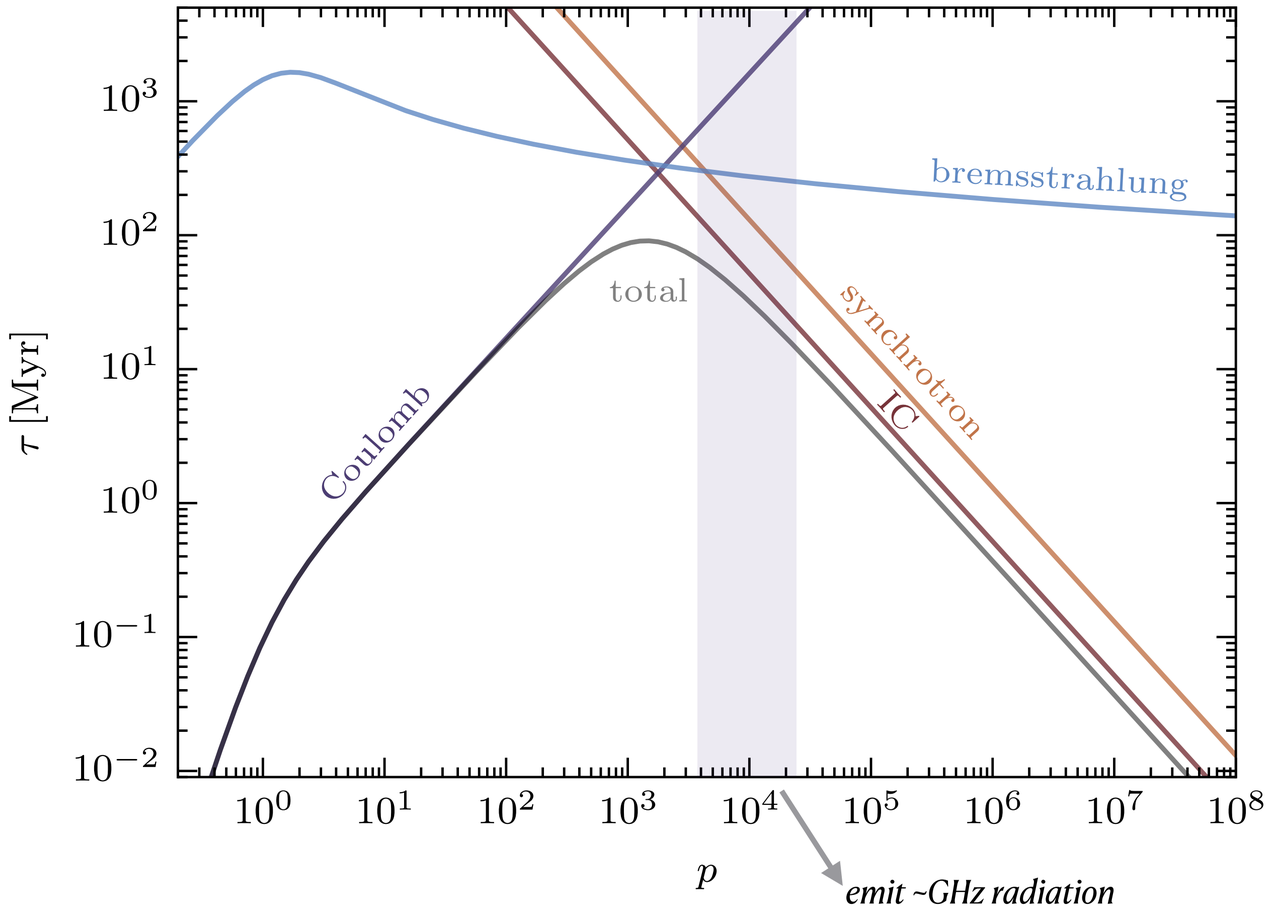


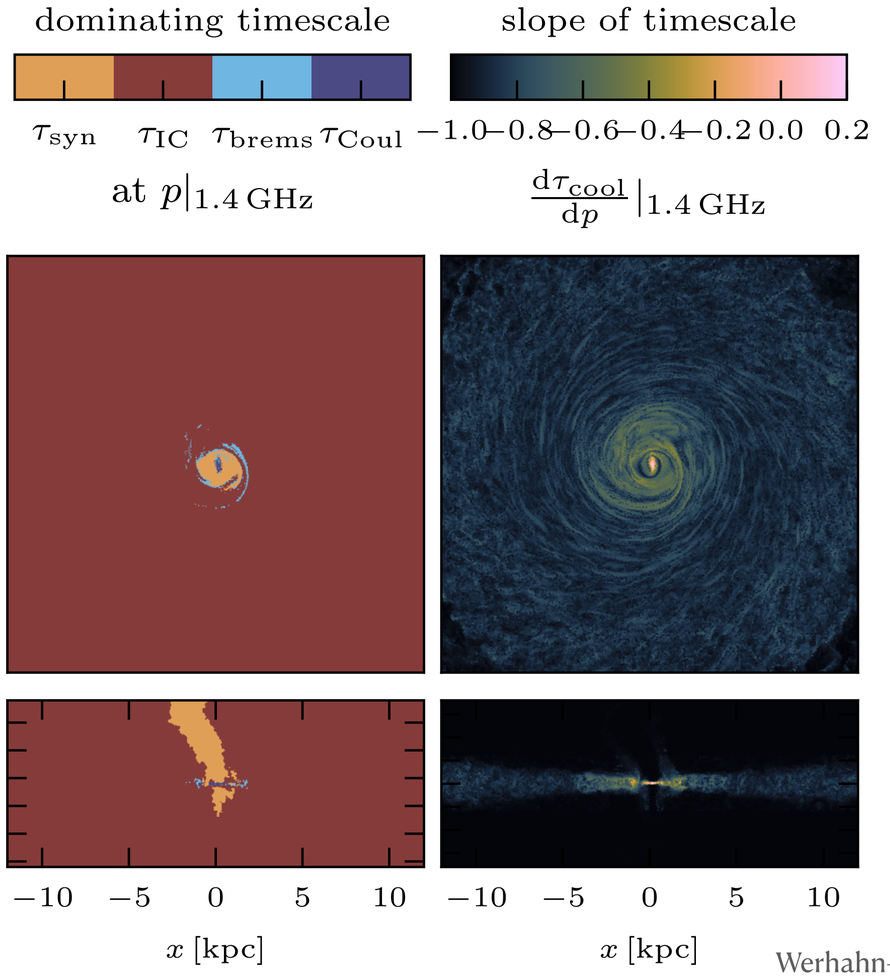




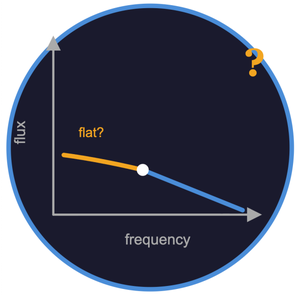
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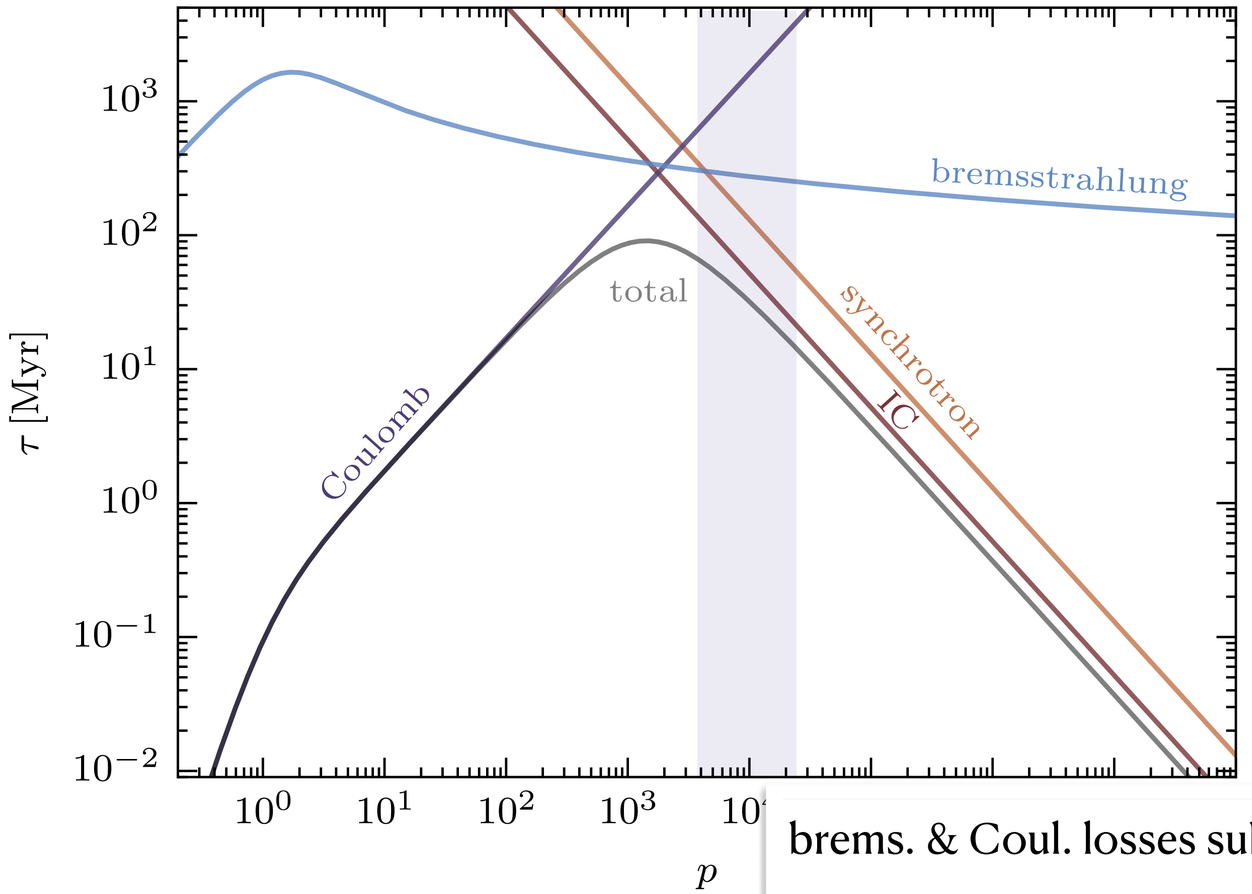


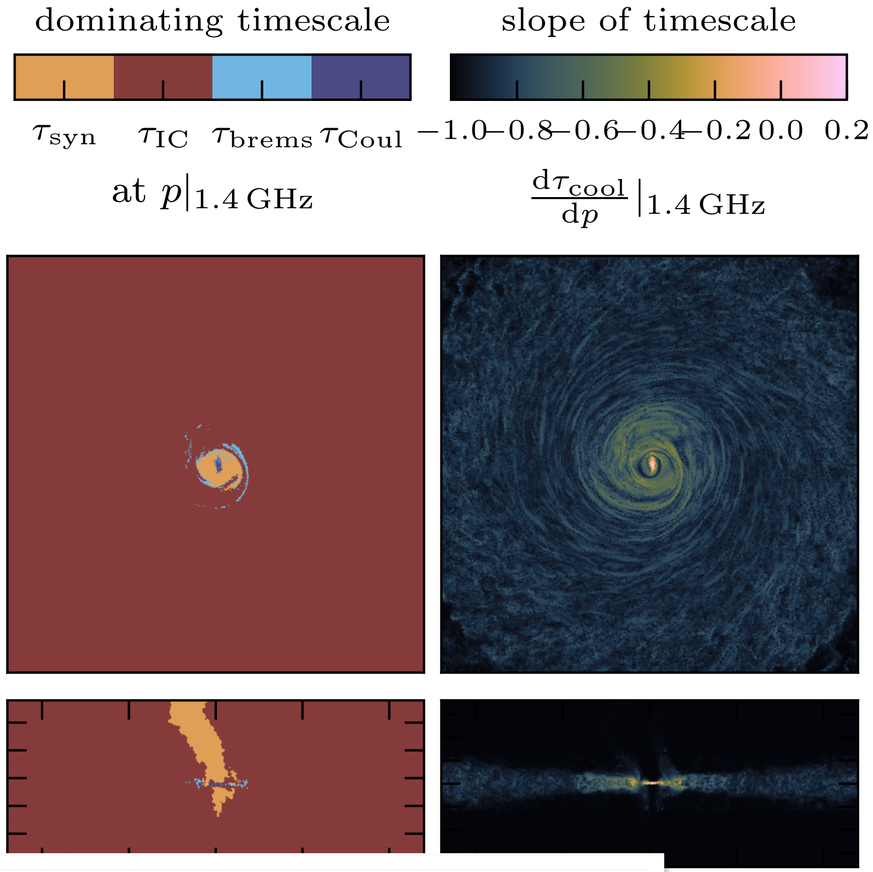
Werhahn+ 2026b



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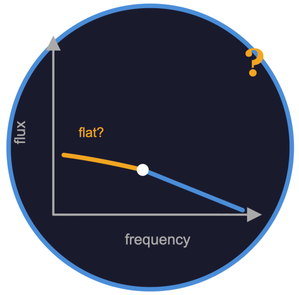




brems. & Coul. losses subdominant for radio-emitting electrons

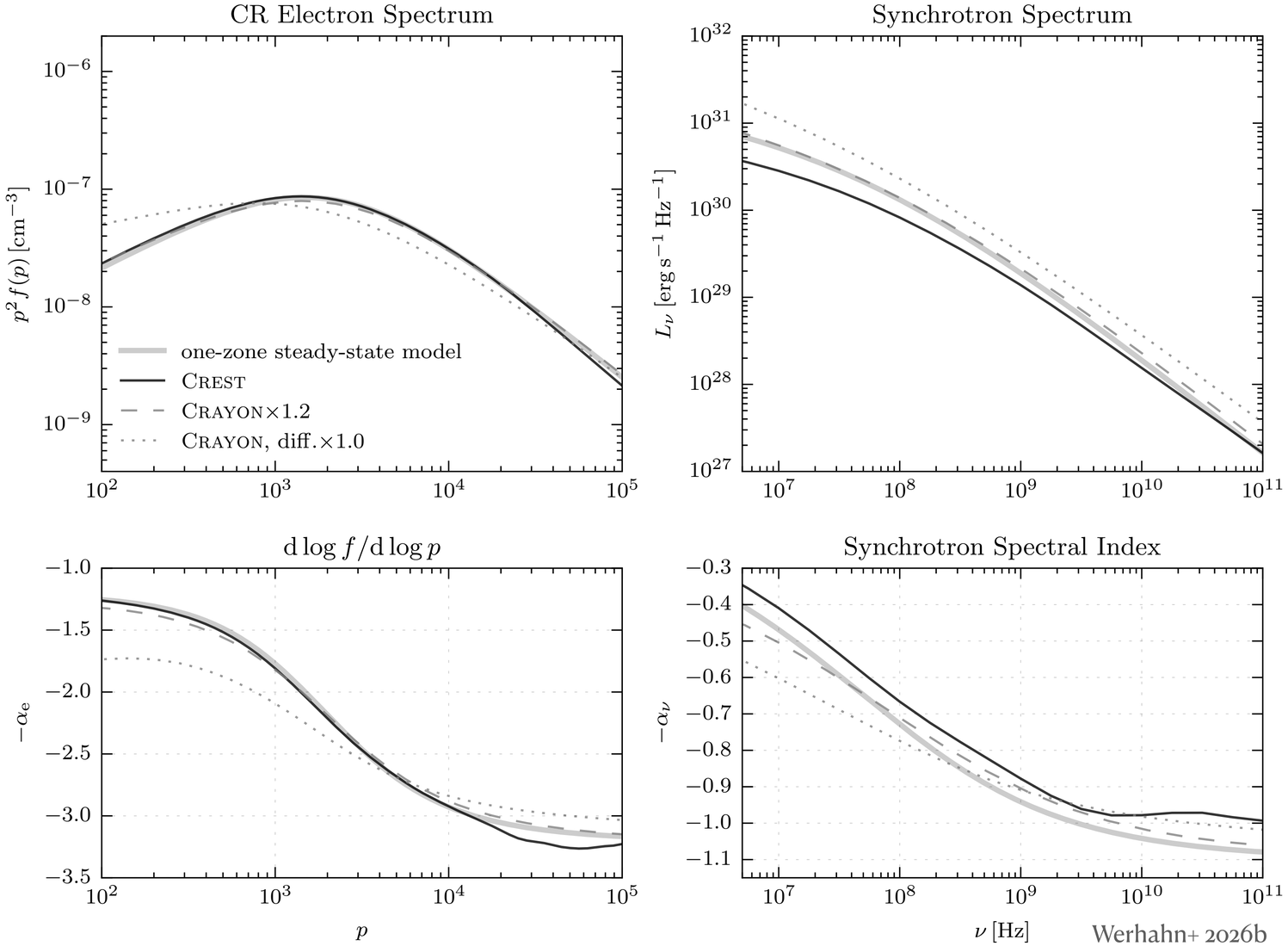
→ **but can still affect slope!**

Werhahn+ 2026b

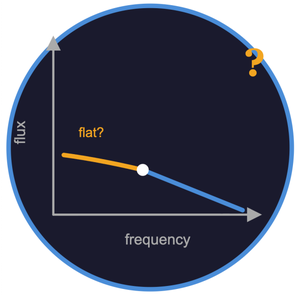


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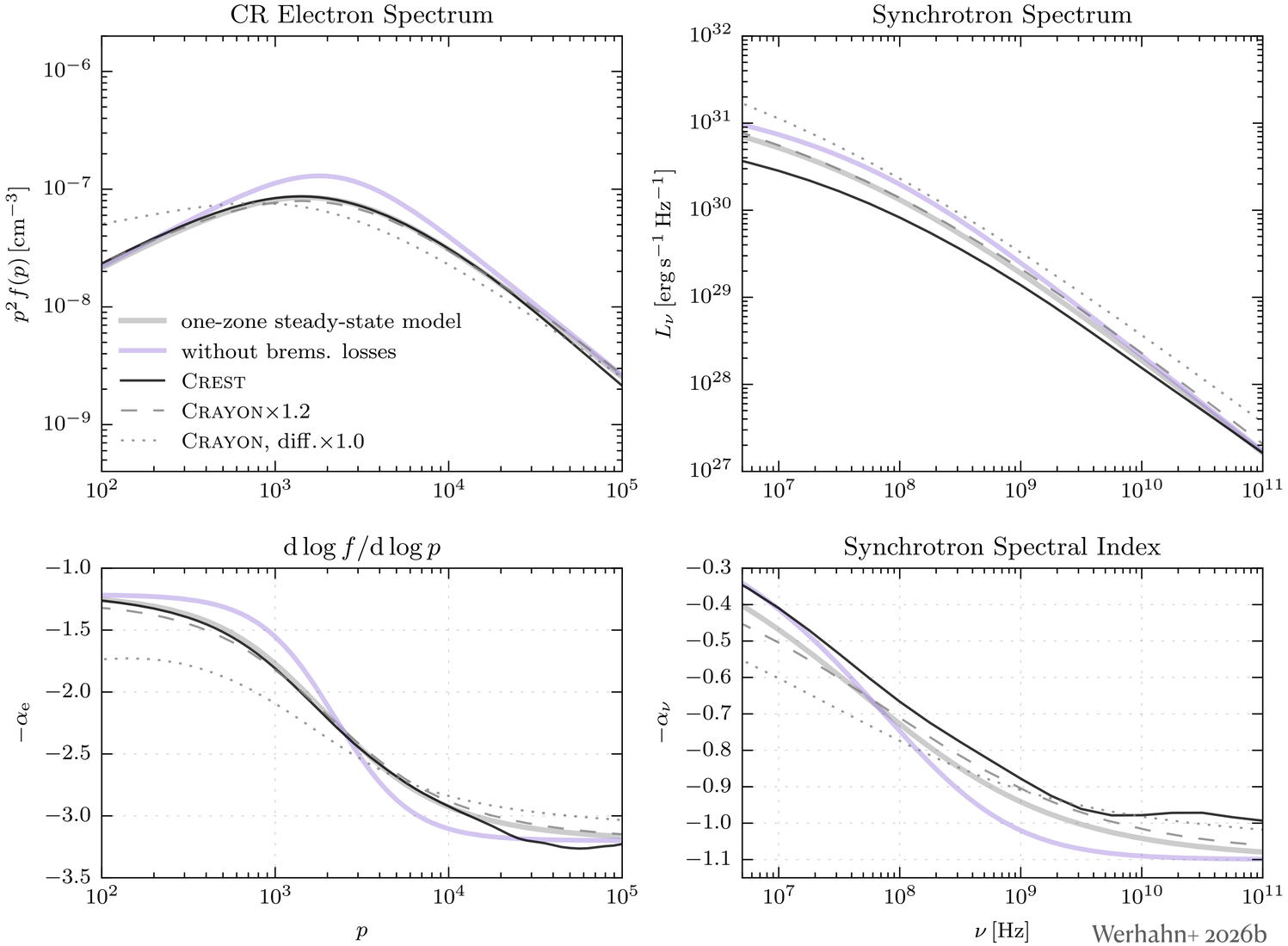


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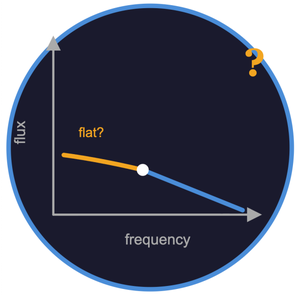
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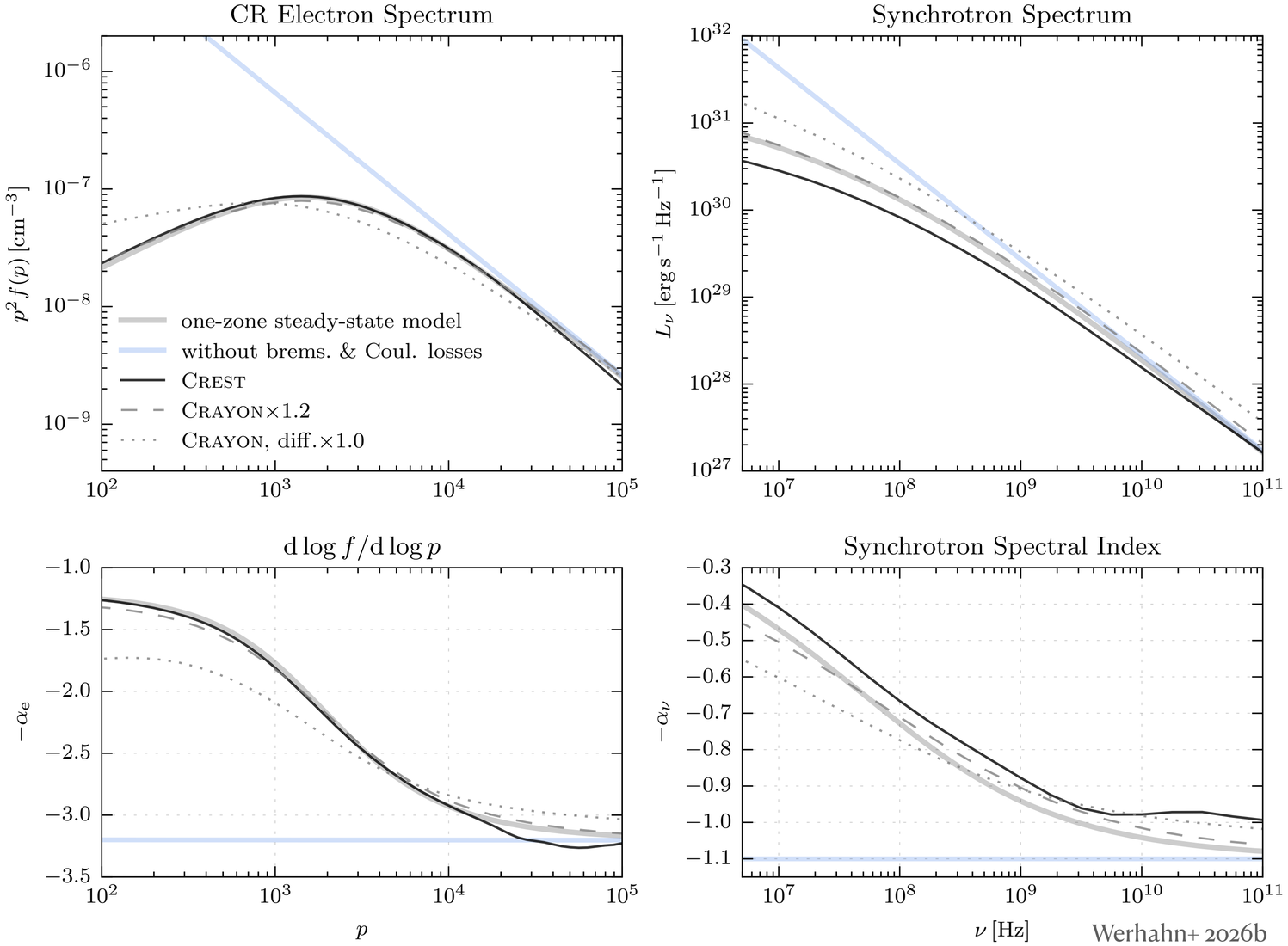
bremsstrahlung losses flatten radio spectra at $\nu \gtrsim 100\,\mathrm{MHz}$

Werhahn+ 2026b



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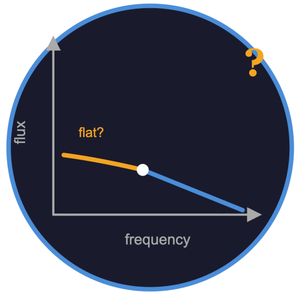
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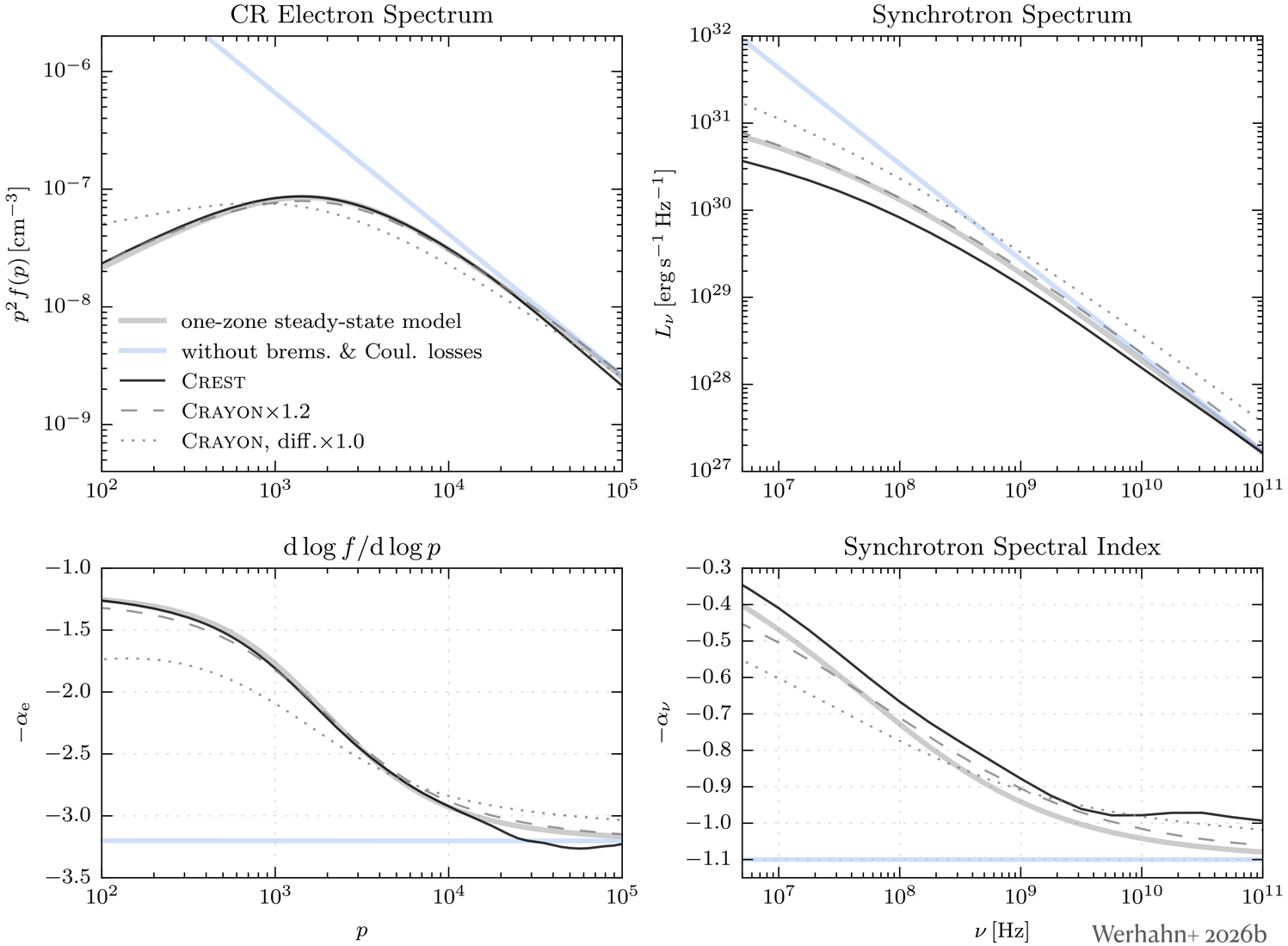
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Coulomb losses flatten radio spectra at $\nu \lesssim 10\,\mathrm{GHz}$



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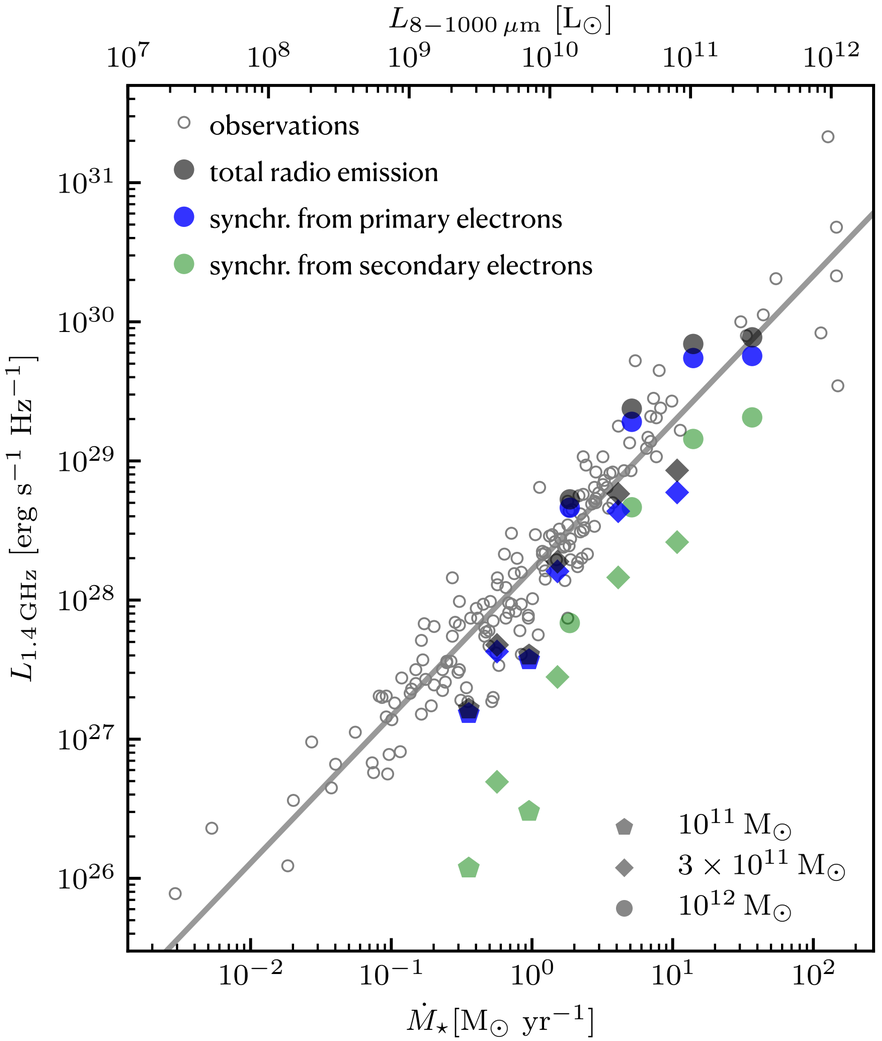
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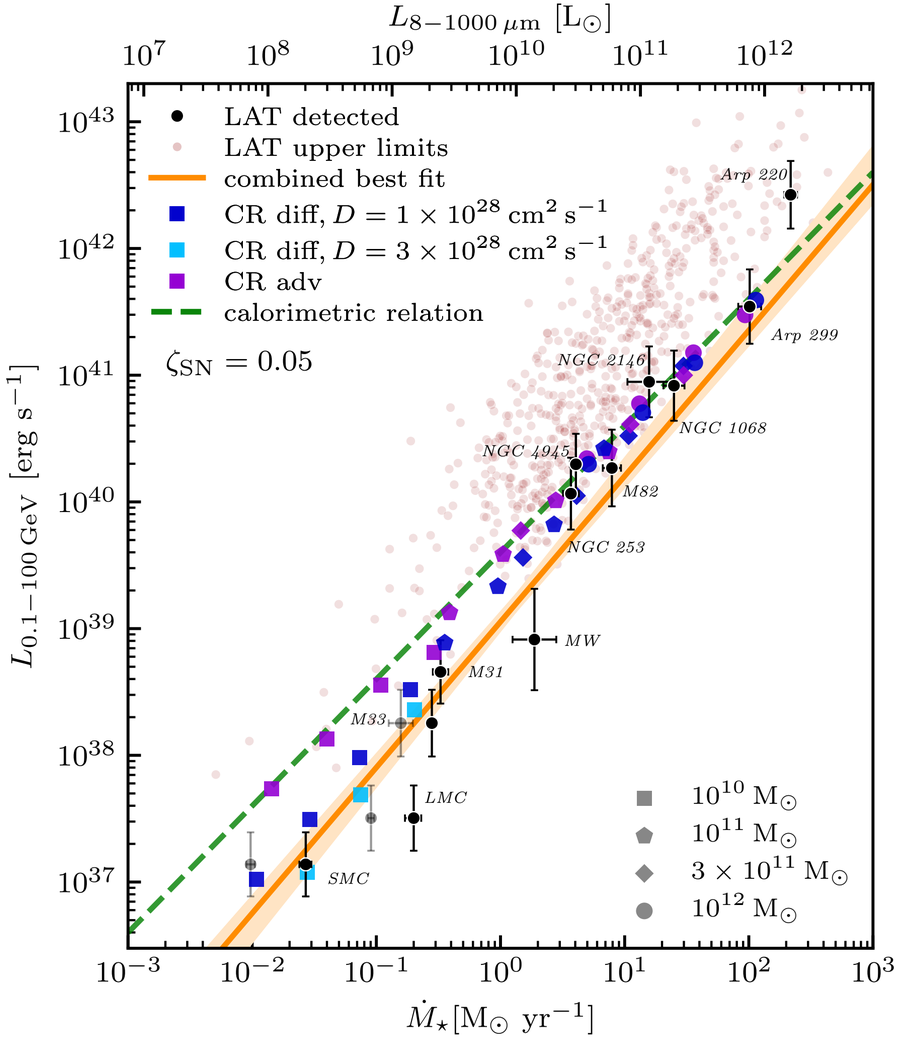
Coulomb losses flatten radio spectra at $\nu \lesssim 10\,\mathrm{GHz}$

→ *important for interpreting detailed shapes of radio spectra!*

Non-thermal emission from isolated galaxies

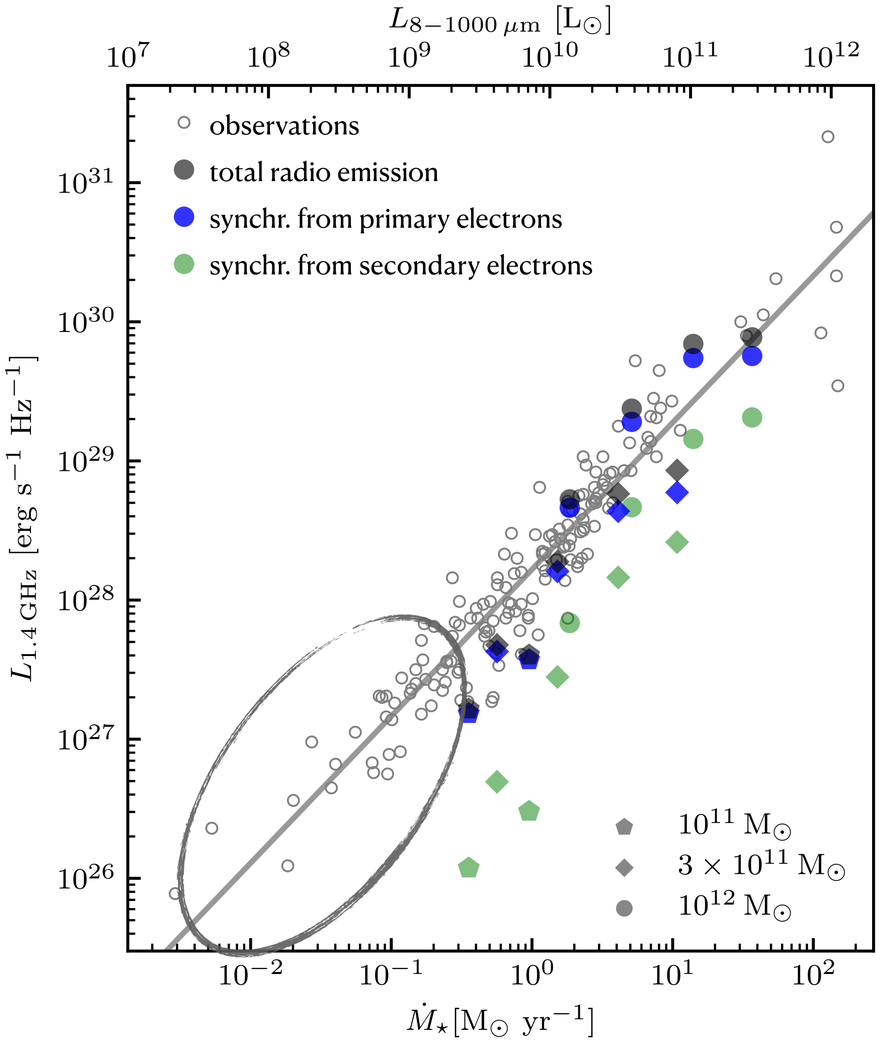
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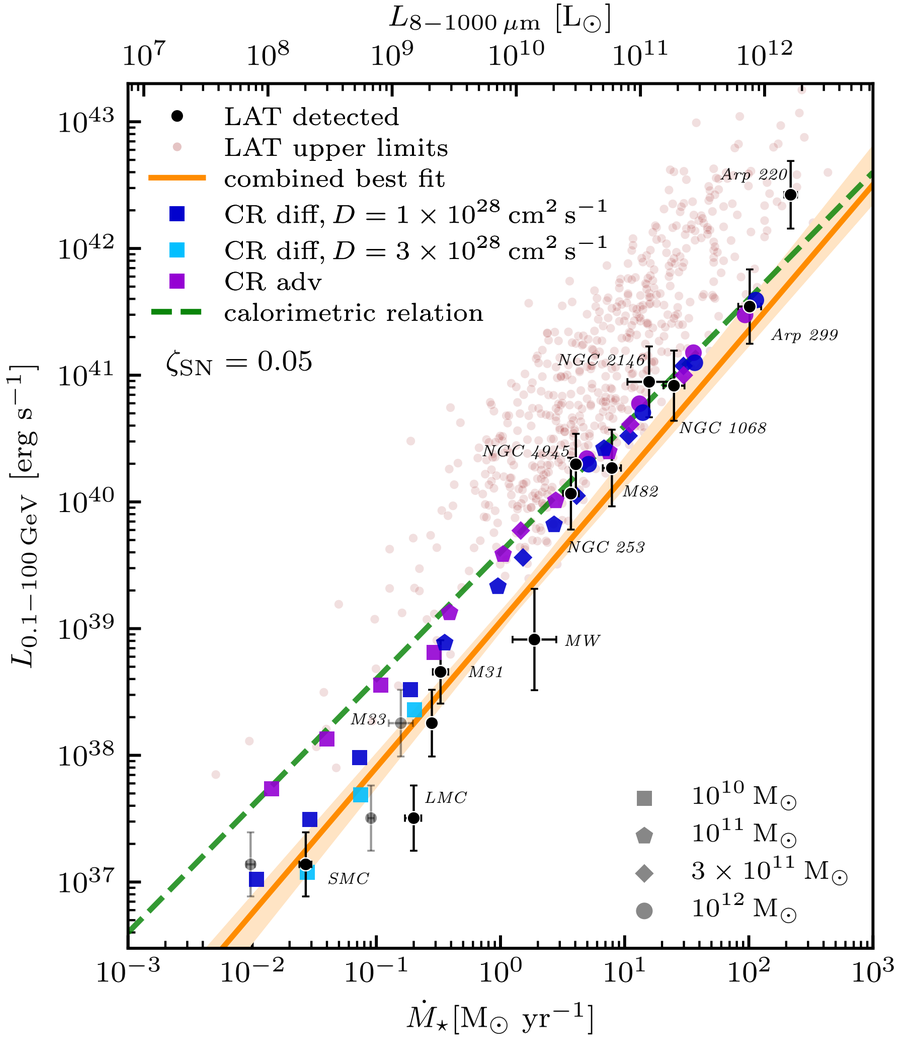




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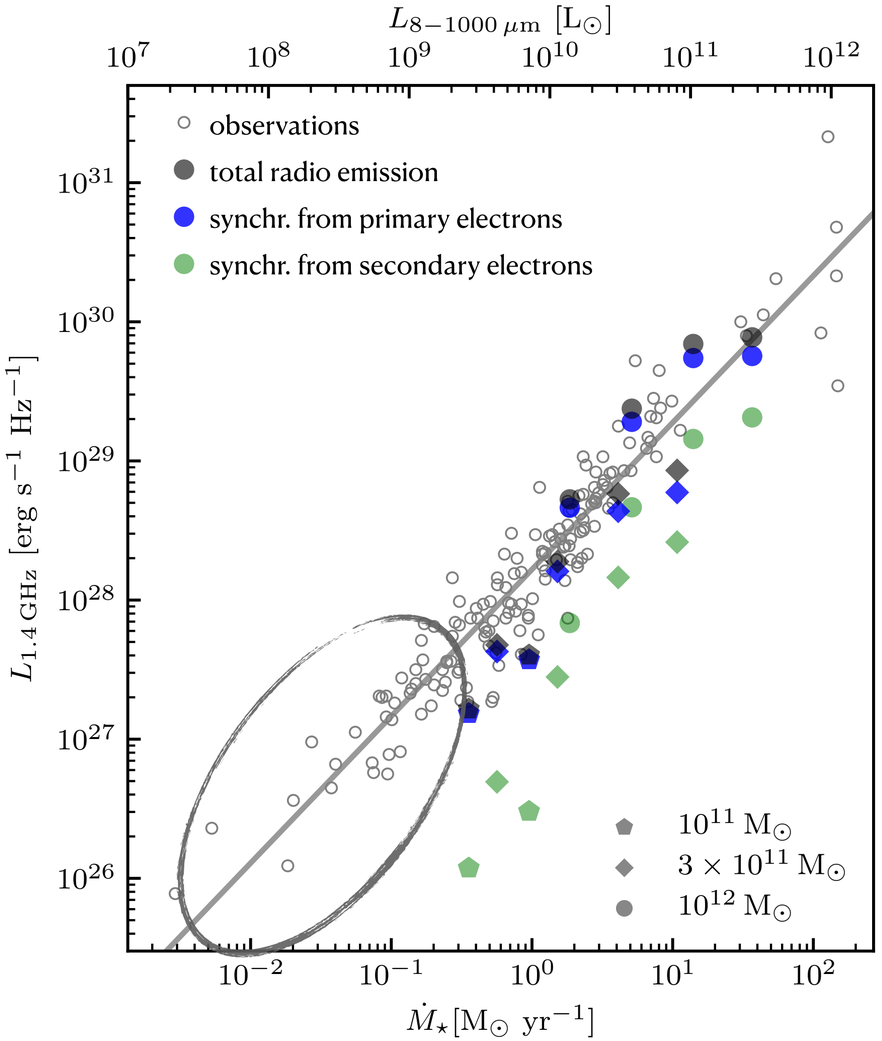
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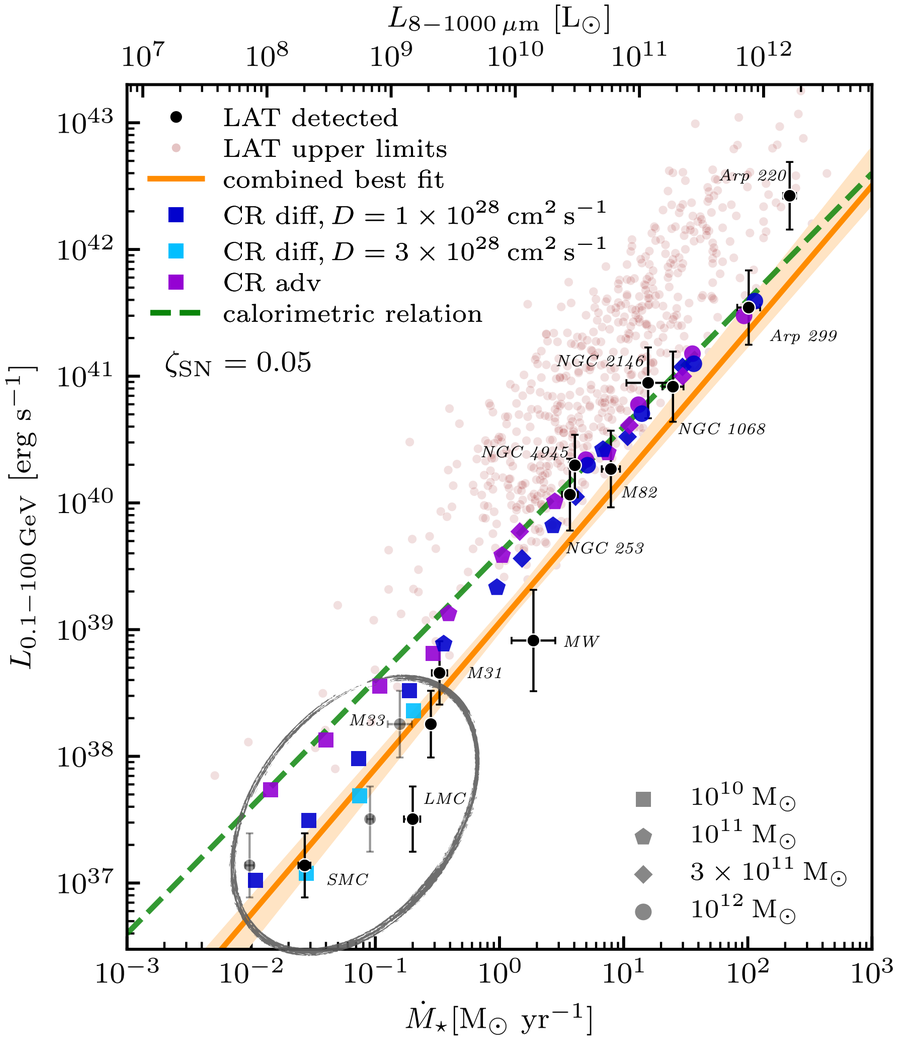




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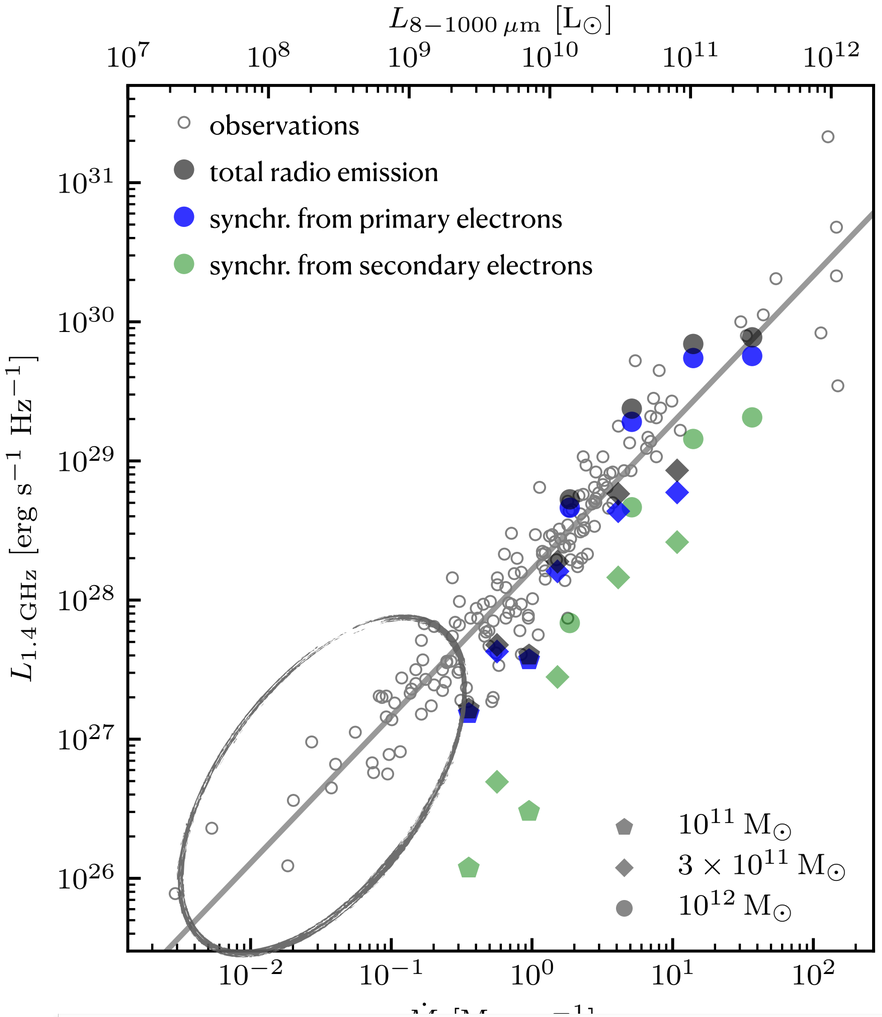
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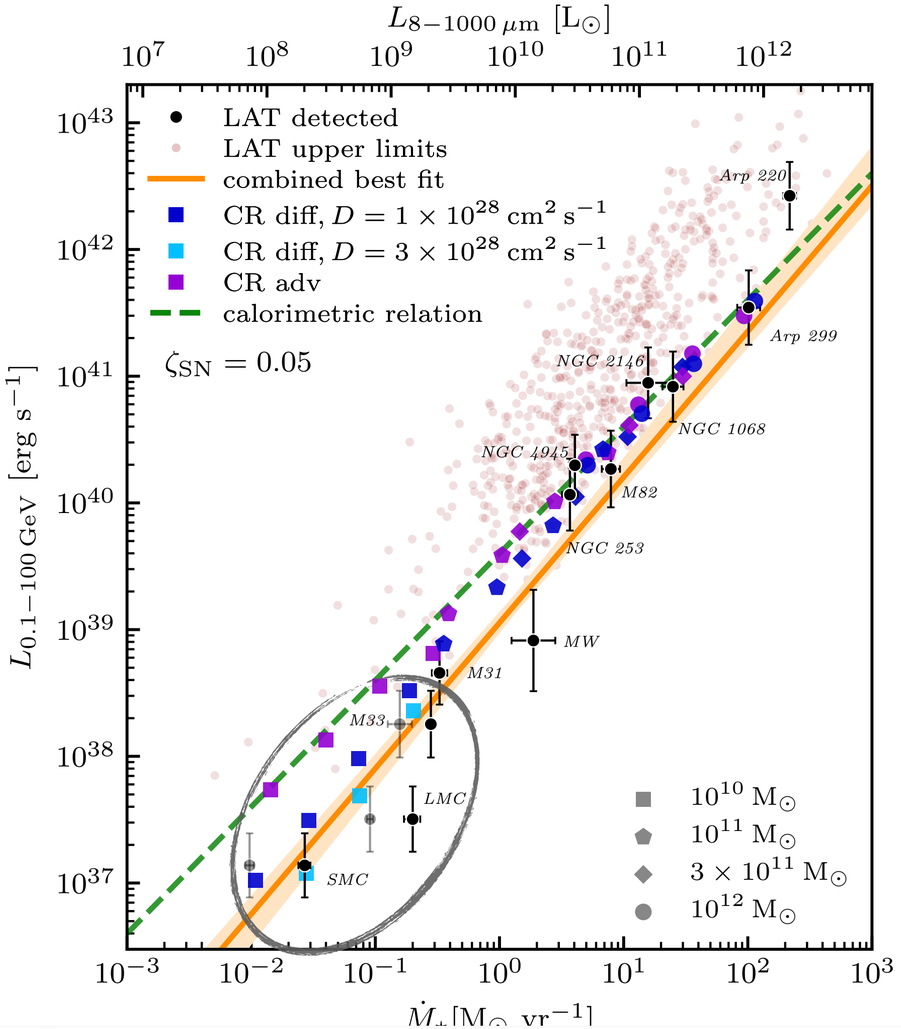




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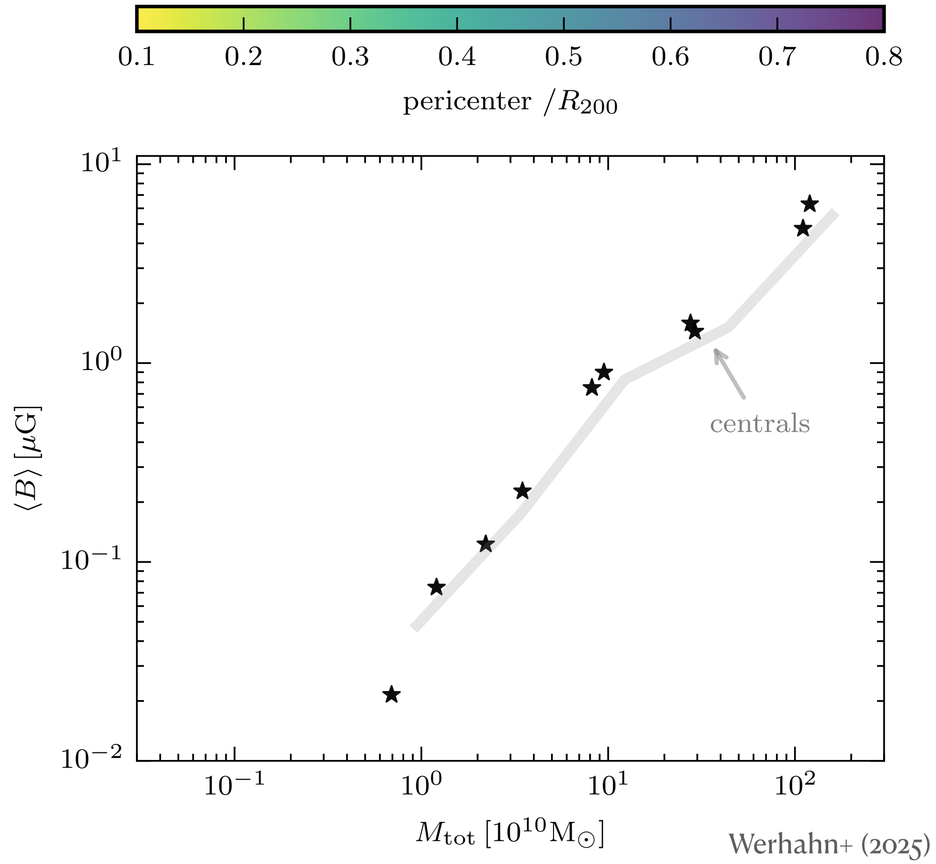




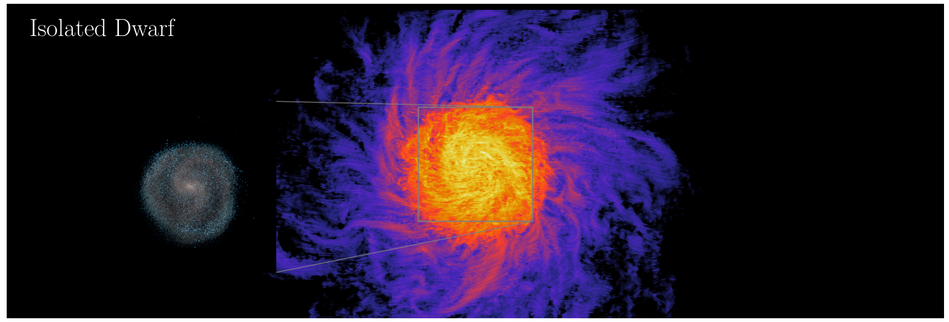
Can we model realistic dwarfs / satellites without including their environment?

Cosmological zoom simulations

- Auriga zoom simulations with CRs (Bieri+ 2026)

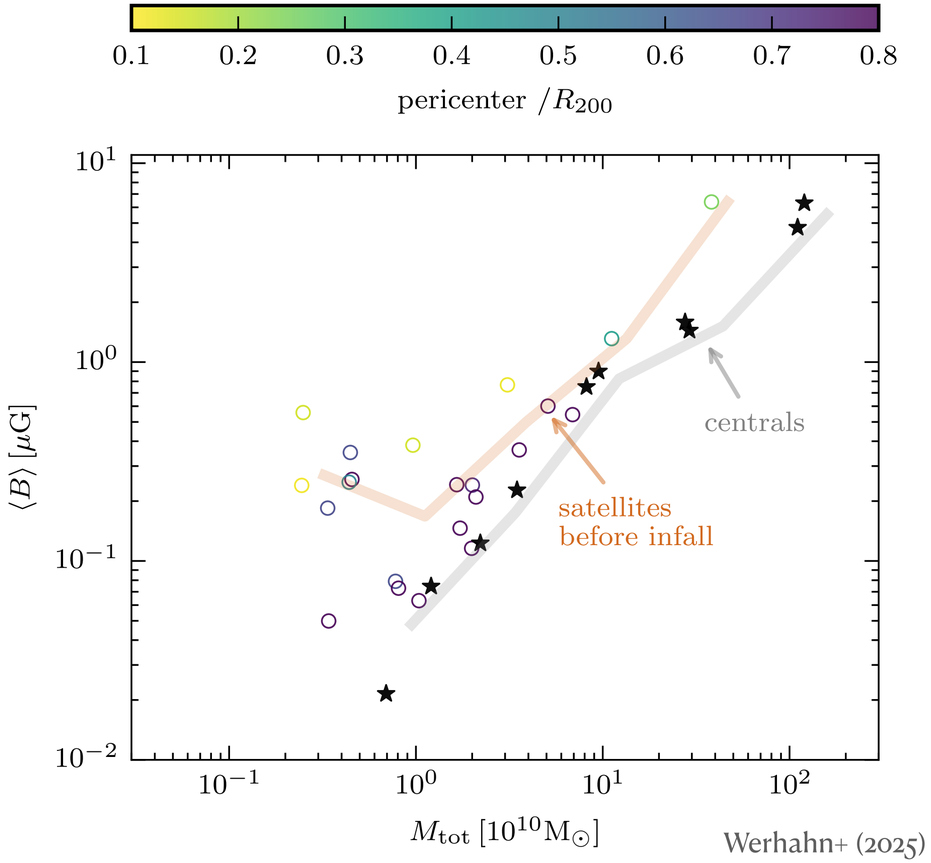


Werhahn+ (2025)

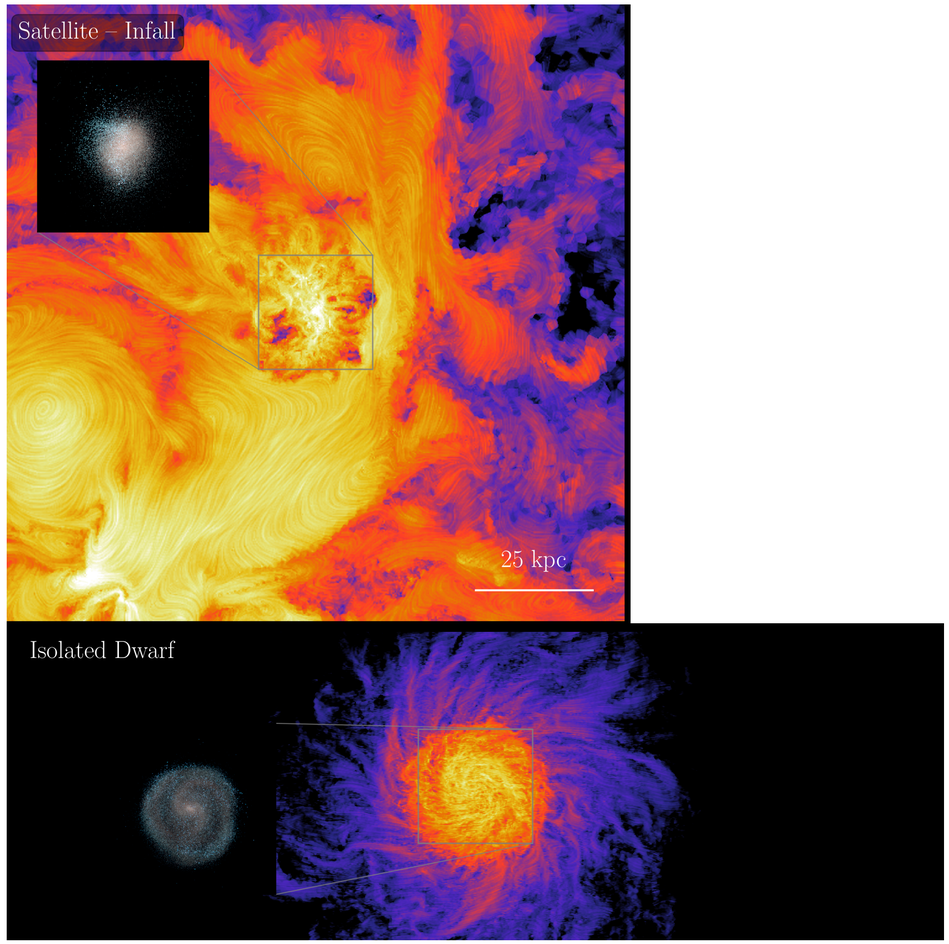


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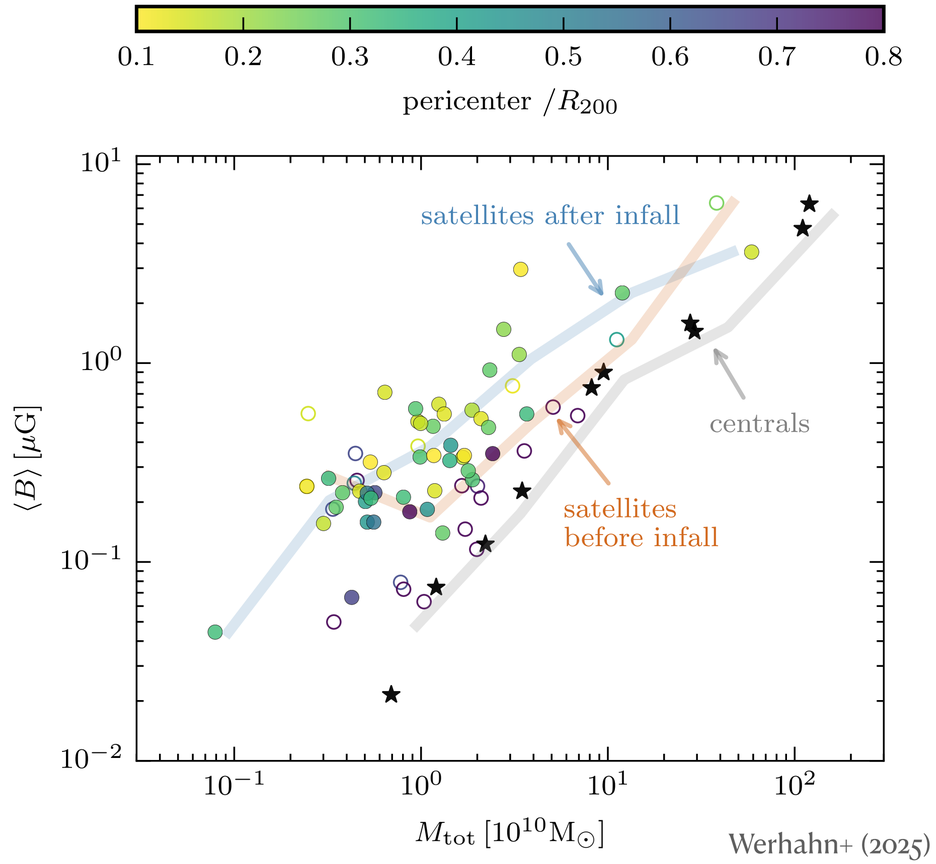


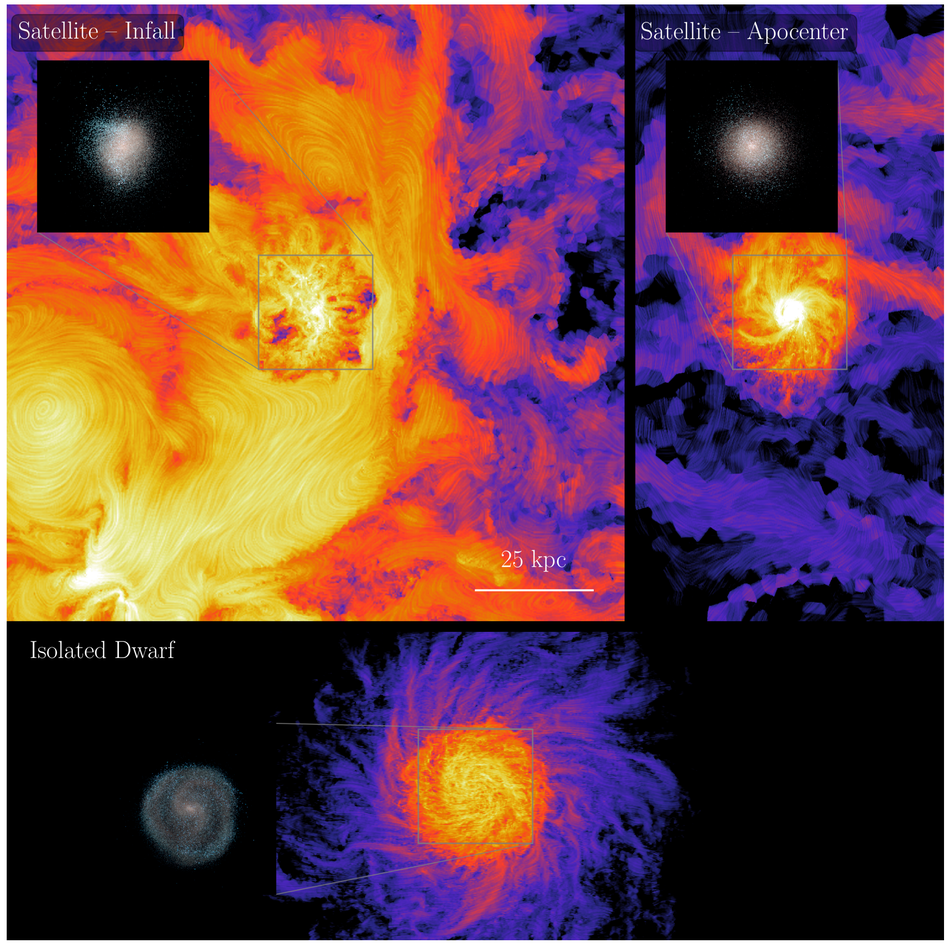
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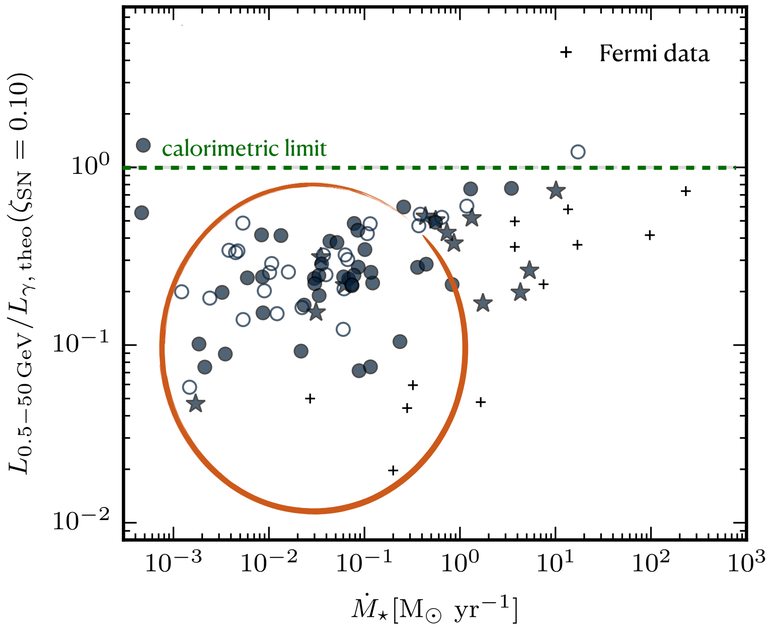




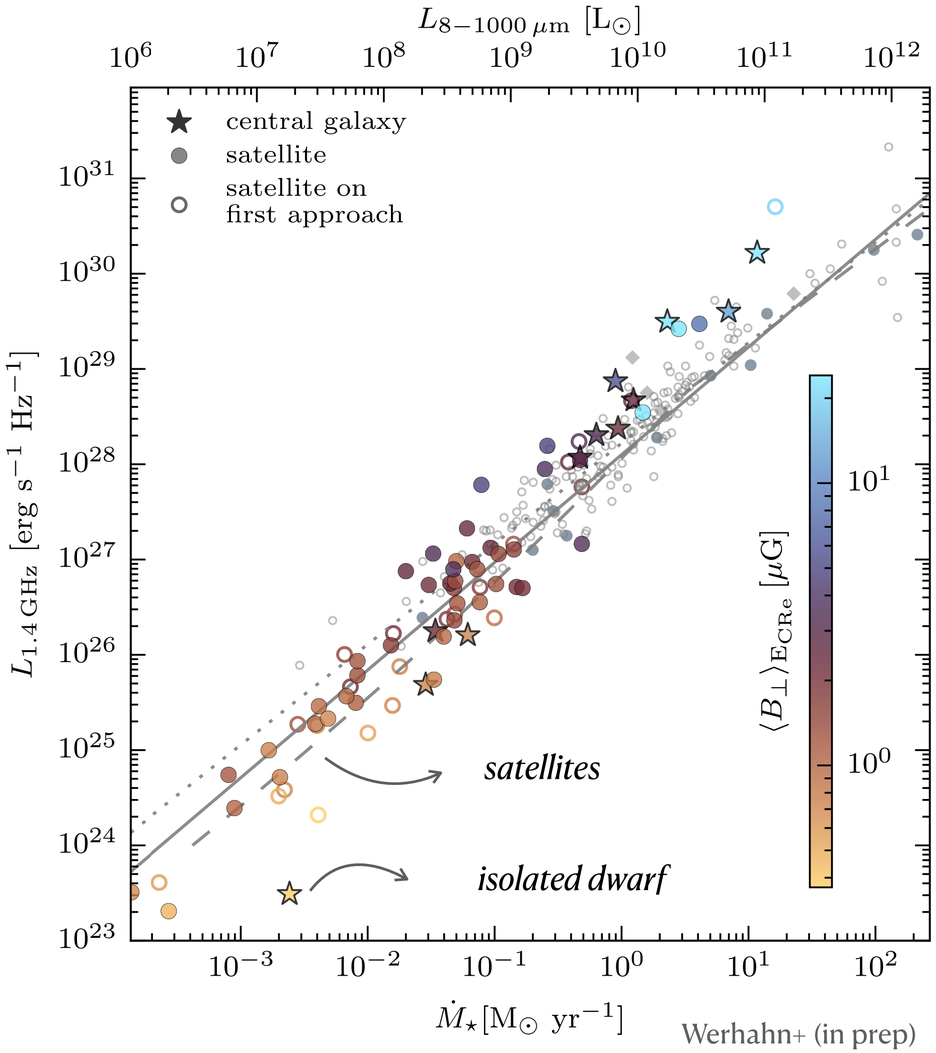
Cosmological zoom simulations

- Auriga zoom simulations with CRs (Bieri+ 2026)
- **stronger B-fields in satellites**, particularly after close encounter with host (Werhahn+ 2025)
  - increased radio emission in satellites
  - large scatter in FIR-gamma-ray relation

(normalised to calorimetric limit)

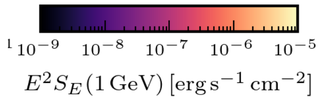


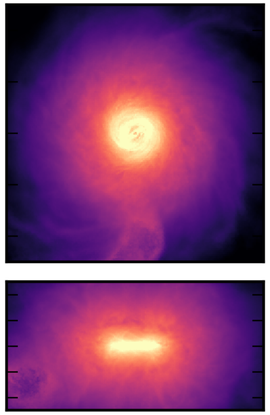
Radio-SFR correlation



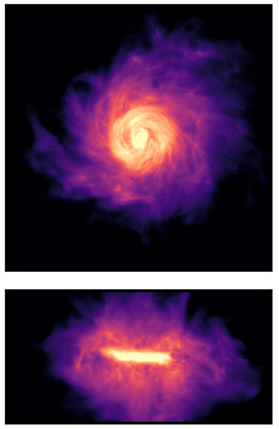
Werhahn+ (in prep)

Cosmological zoom simulations



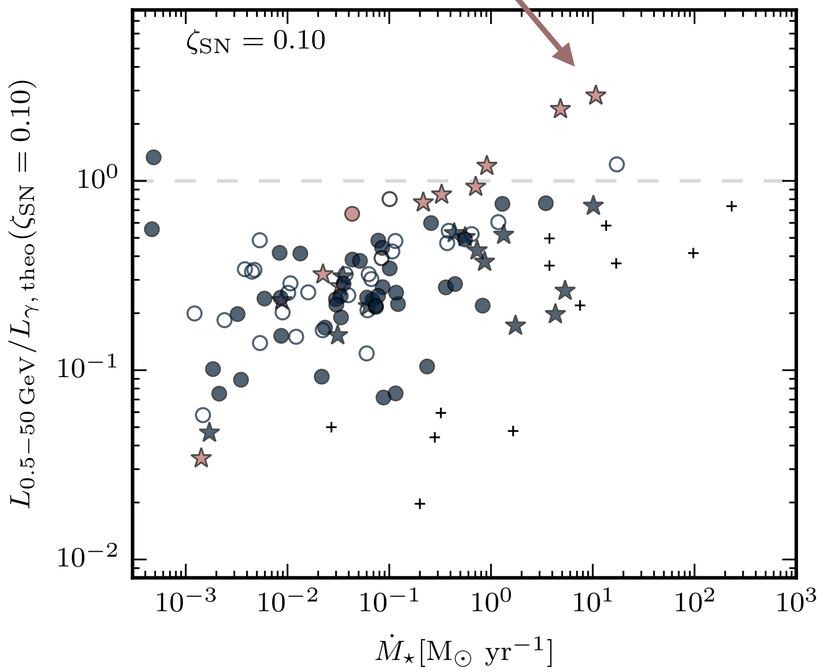


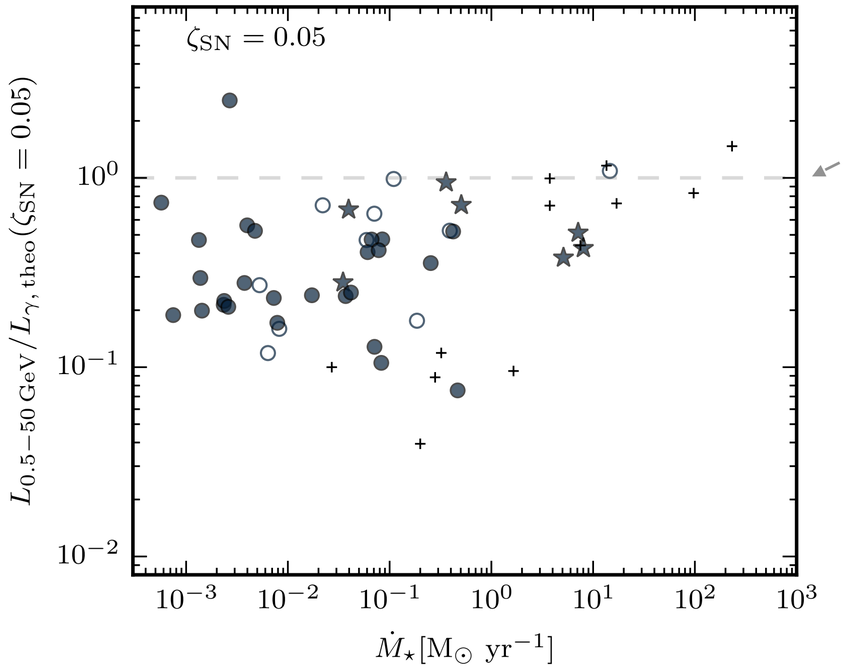
with Alfvén cooling



FIR-gamma-ray relation

without Alfvén cooling





theoretical limit for instantaneous conversion to γ-rays

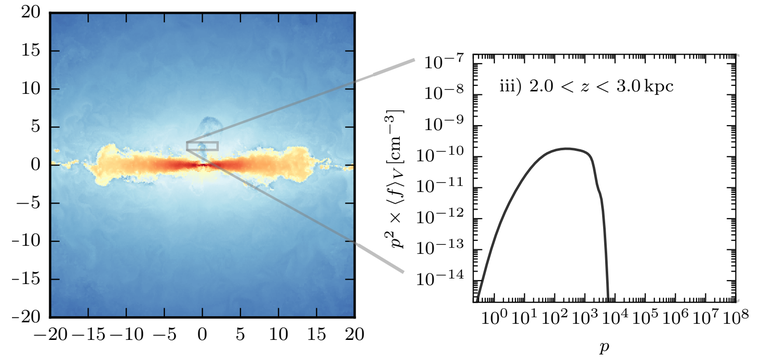
\+ Fermi data

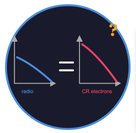
★ central galaxy
● satellite
○ satellite on first approach

— preliminary —

Summary & Outlook

- **CRs can regulate galaxy evolution** through their pressure, transport, and interaction with the ISM and CGM
- **Non-thermal emission links simulations and observations**, providing constraints on CR physics & can probe additional galaxy physics (e.g. environmental magnetic field amplification)
- **Detailed CR electron modelling** enables interpretation of radio signatures in star-forming galaxies

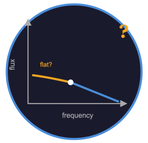




1. Radio emission can be biased!



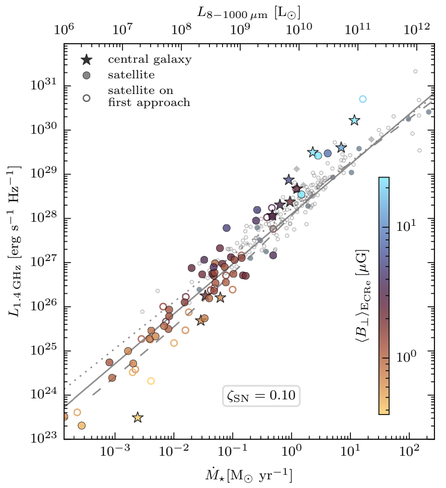
2. Advection-only does not work with self-consistently driven, slowly accelerating winds!

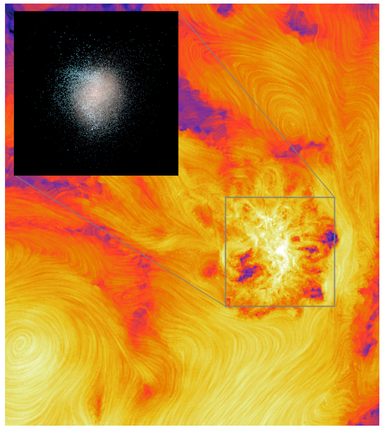


3. Brems. & Coulomb-losses and free-free absorption are important!

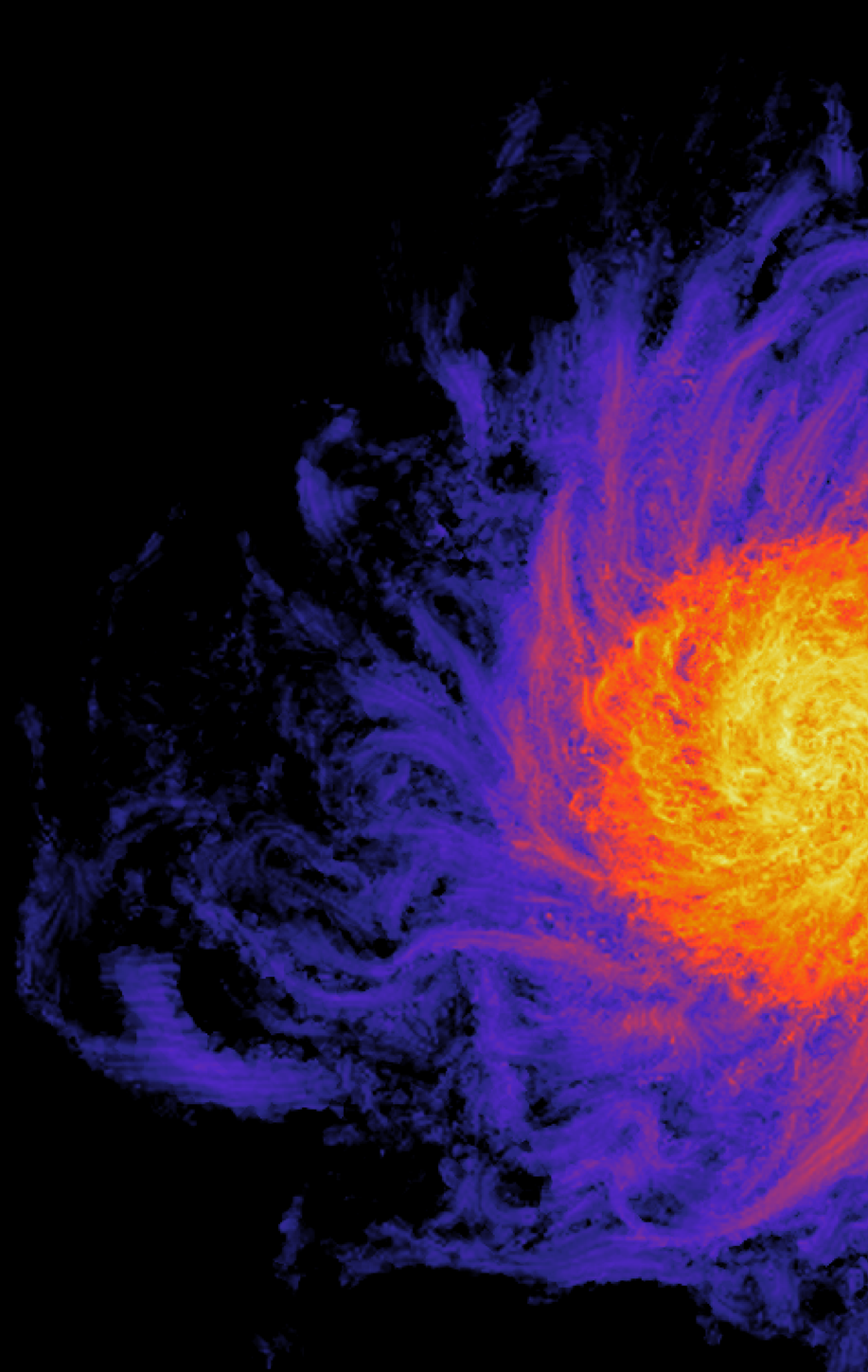
Outlook

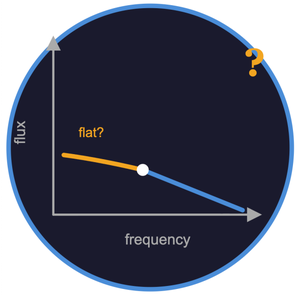
- **Combine cosmological simulations with detailed CR modelling** to predict multi-wavelength non-thermal emission across cosmic time
- **Forward modelling will be essential** to interpret upcoming observations, e.g. from SKA & CTA





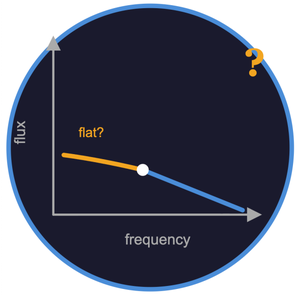
Additional slides





Revisiting radio diagnostics with CREST

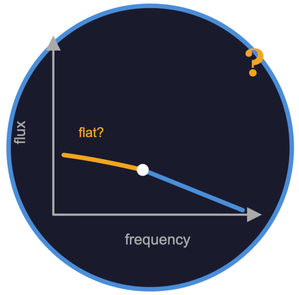
3. Are bremsstrahlung and Coulomb losses negligible for radio-emitting electrons?



Revisiting radio diagnostics with CREST

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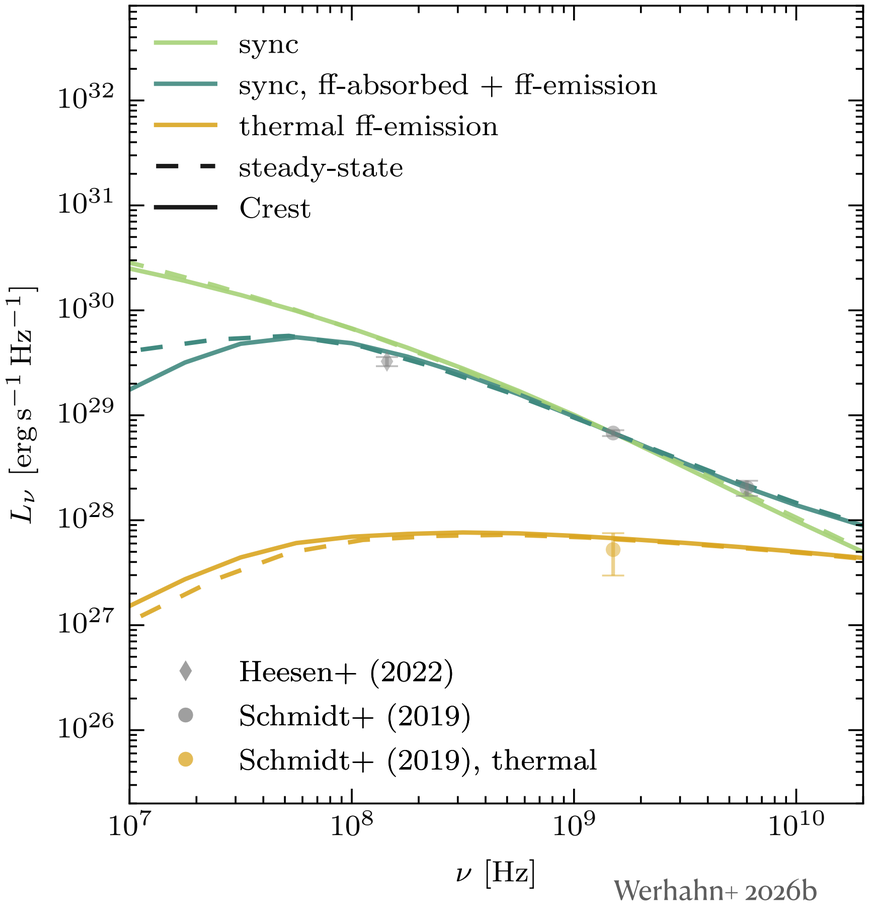
Bonus: What about free-free absorption?



Revisiting radio diagnostics with CREST

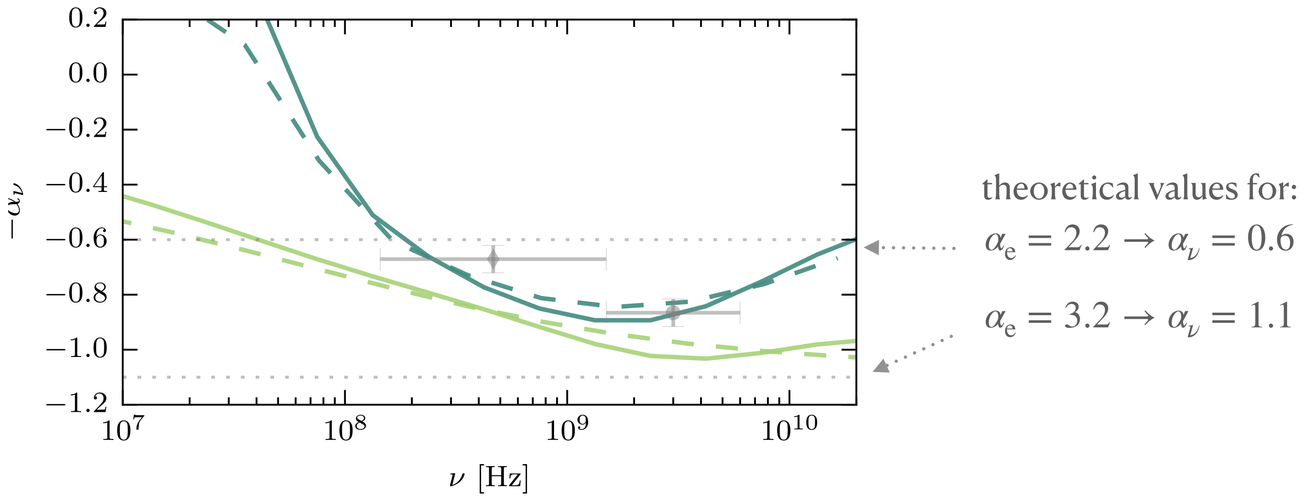
3. Are bremsstrahlung and Coulomb losses negligible for radio-emitting electrons?

Bonus: What about free-free absorption?



- free-free-emission flattens spectrum at all frequencies
- smallest effect at $\nu \sim$ GHz
- free-free absorption at low frequencies >> difference in spectral slope between the two modelling approaches

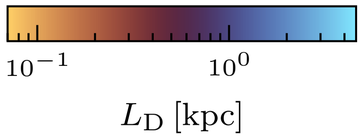
→ *thermal absorption effects important for interpreting low-frequency radio observations of star-forming galaxies*



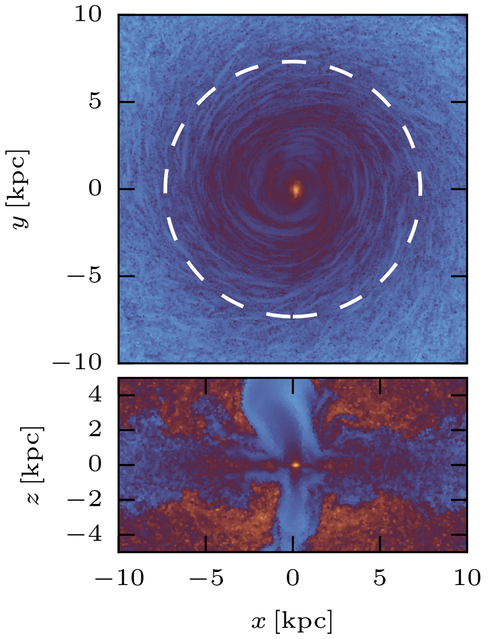
Werhahn+ 2026b

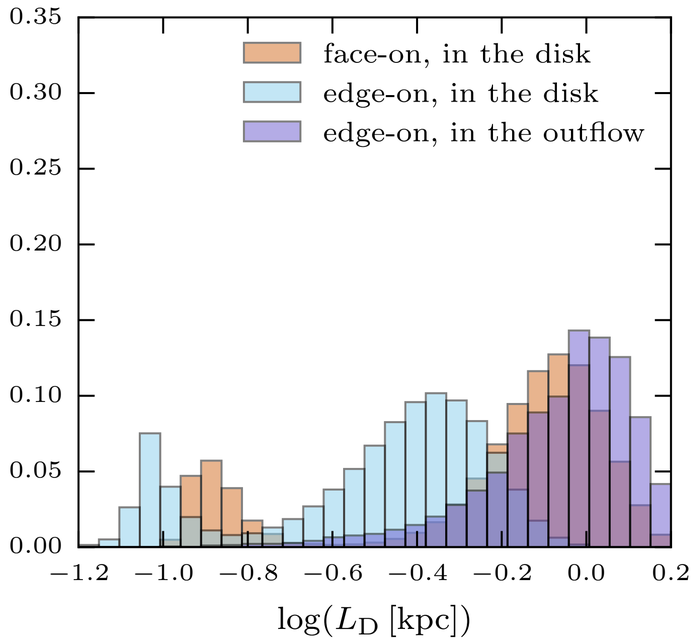
Revisiting radio diagnostics with CREST

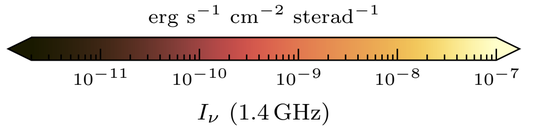
Potential effect of diffusion

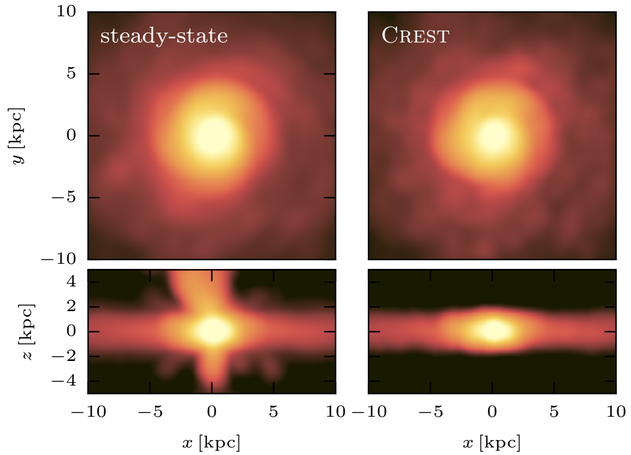


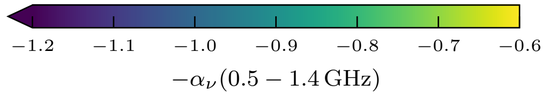
$$L_\mathrm{D} \propto \sqrt{\kappa \tau_\mathrm{cool}(p\,|_{1.4\ \mathrm{GHz}})}$$

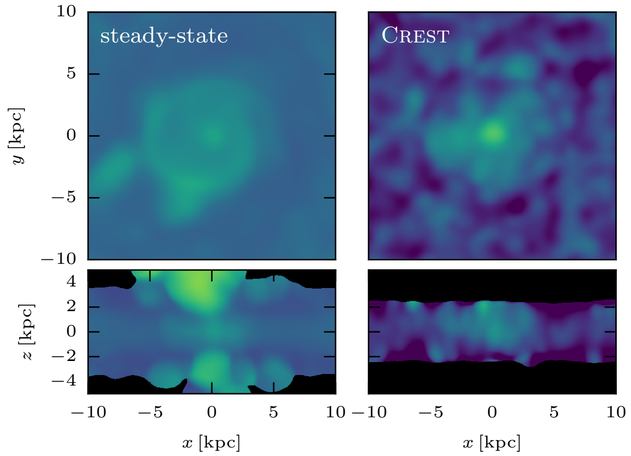






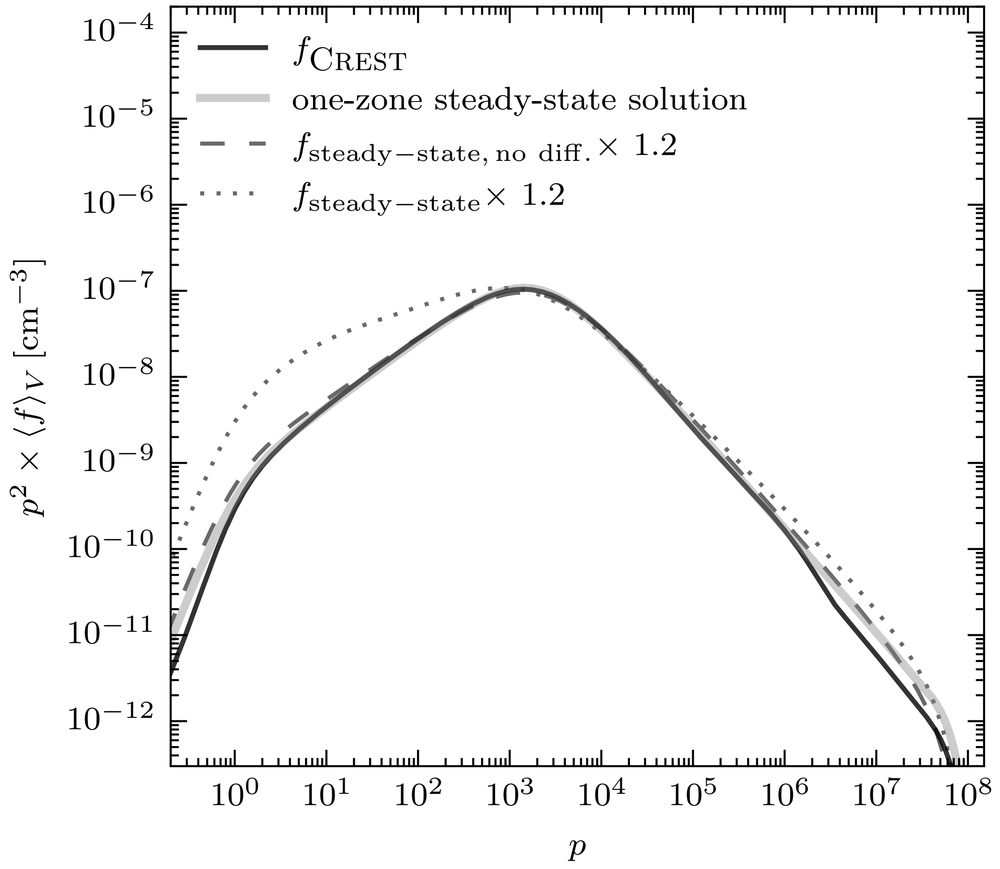


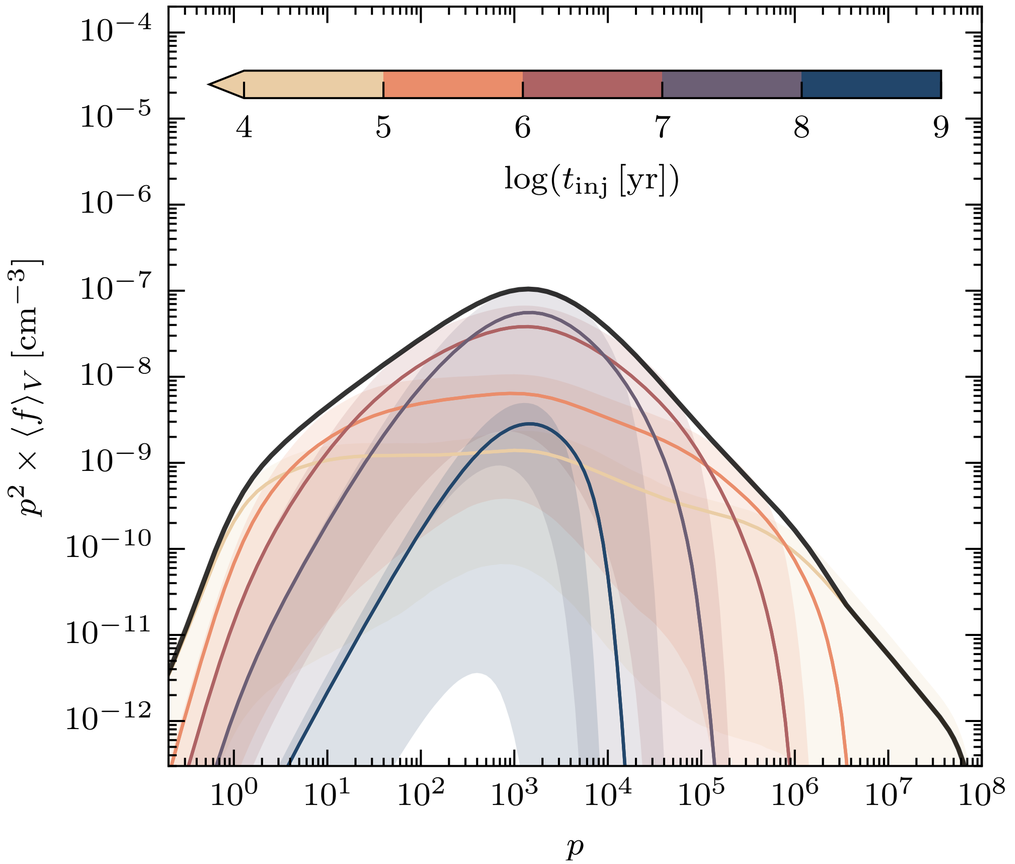




CREST - CR electron spectra evolved in time

Are galaxies in a steady-state?

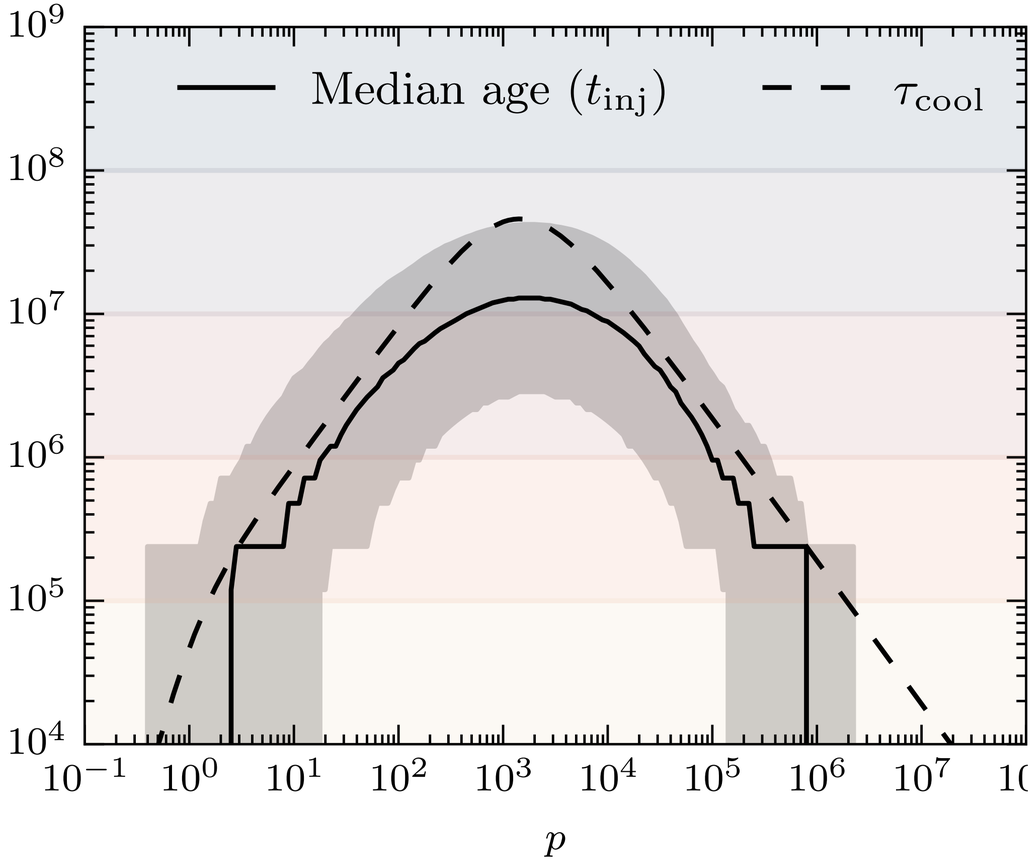


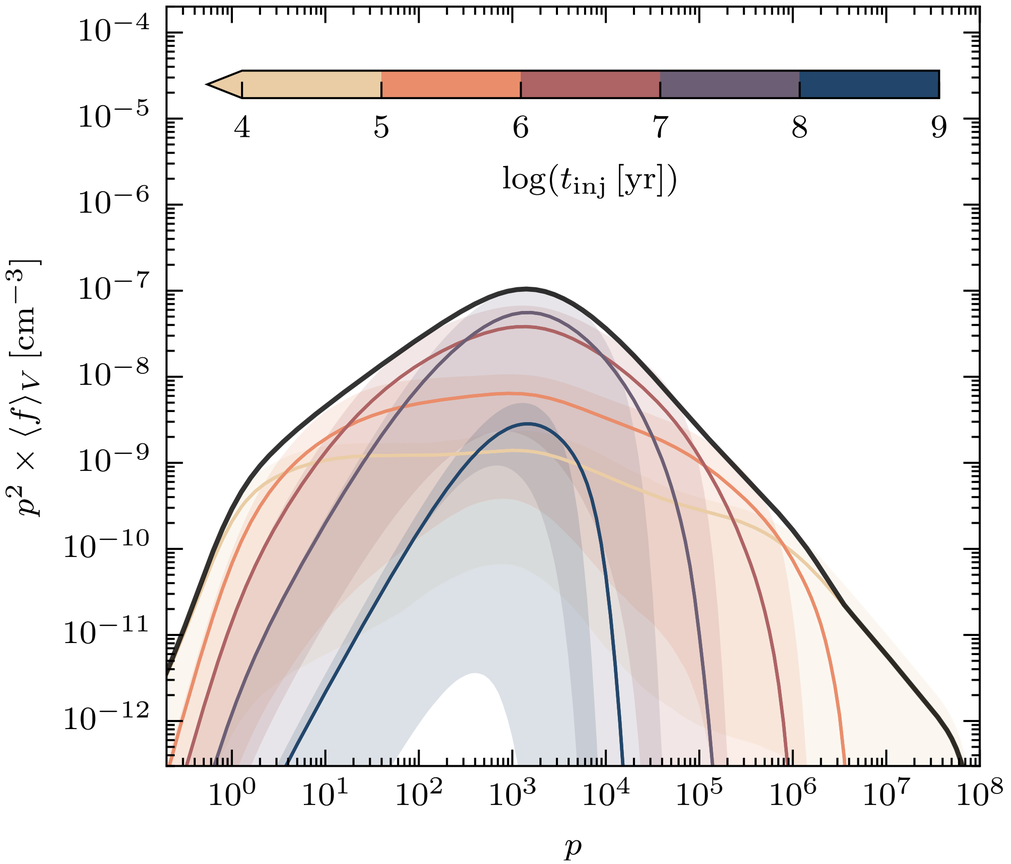


Werhahn et al. 2026a

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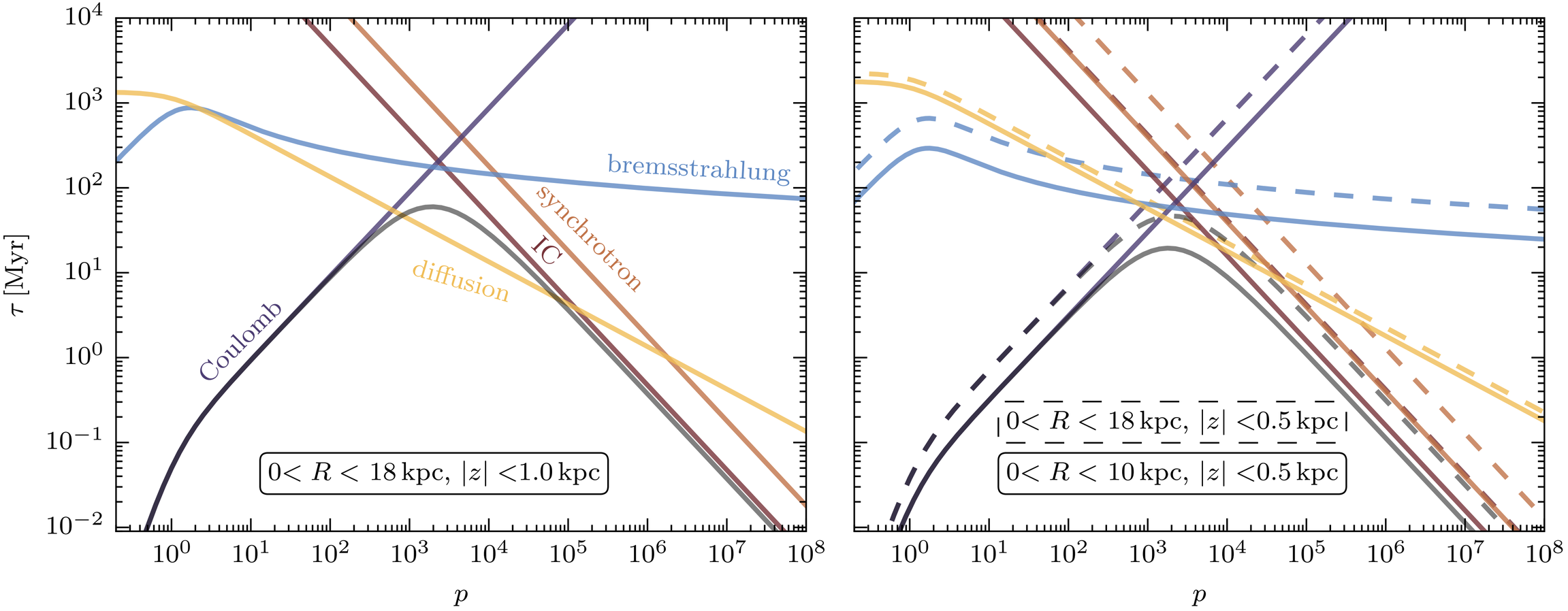




Werhahn et al. 2026a

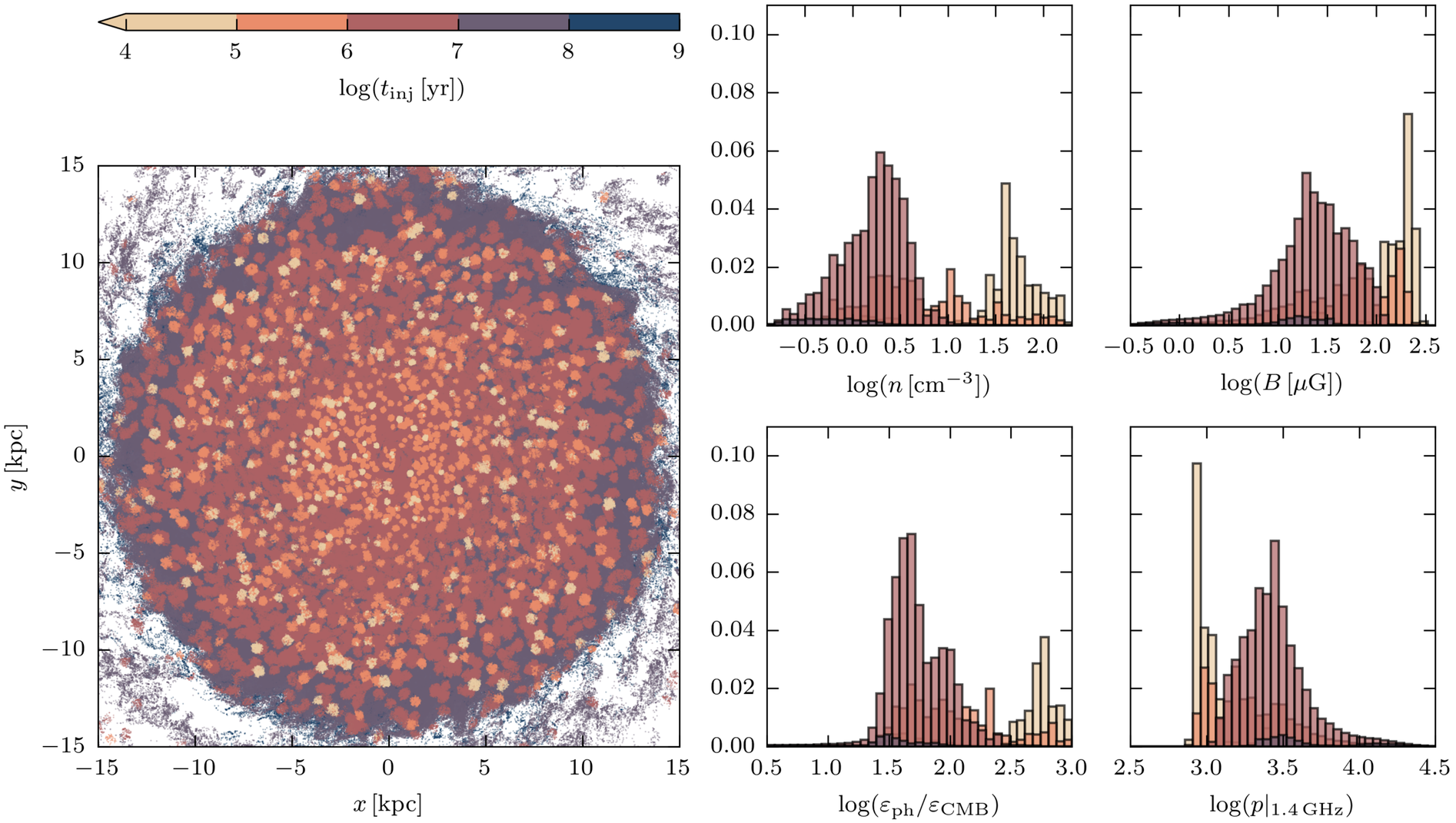
Live modelling of CR electrons (CREST)

Cooling timescales



Werhahn+ 2026a

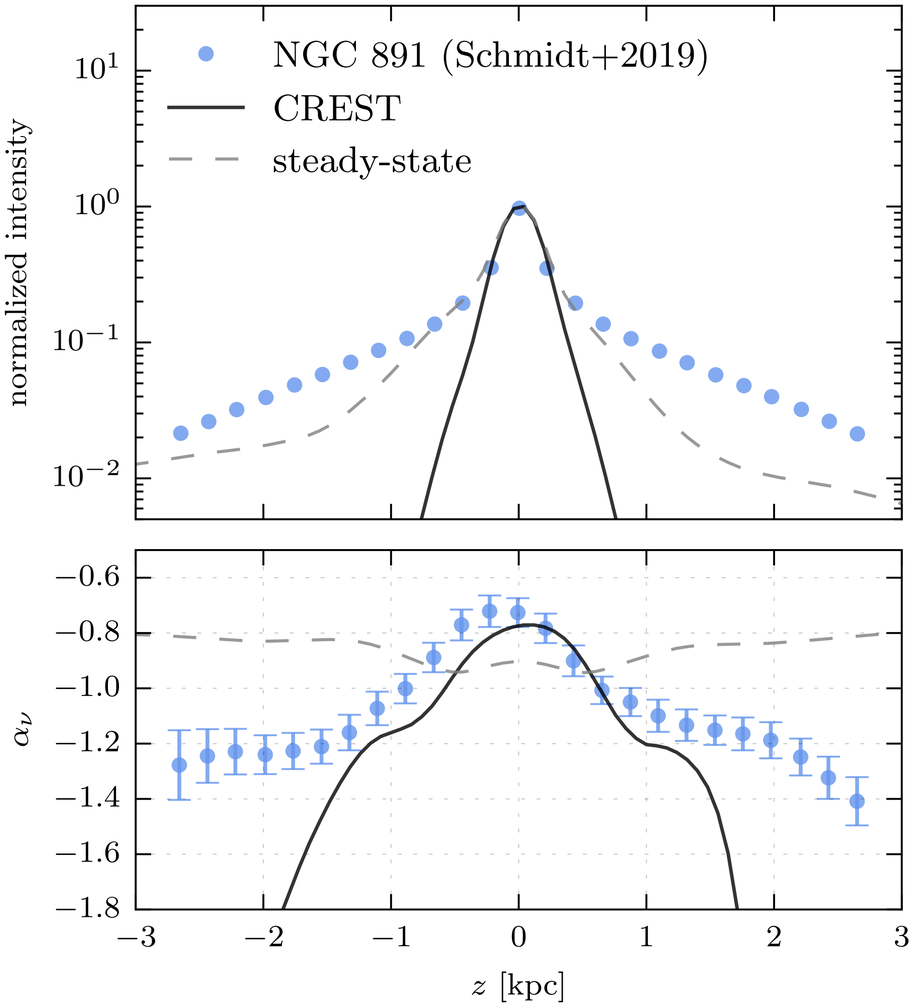
Live modelling of CR electrons (CREST)

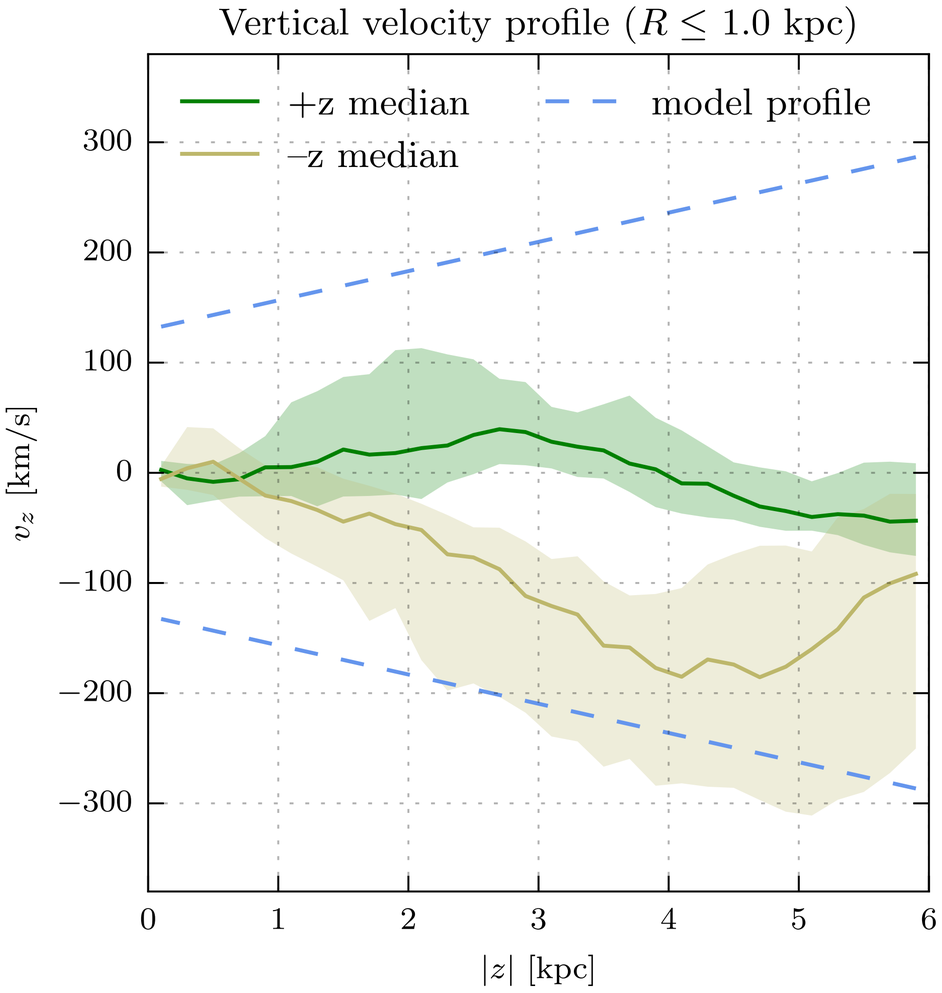


Werhahn et al. 2026a

Revisiting radio diagnostics with CREST

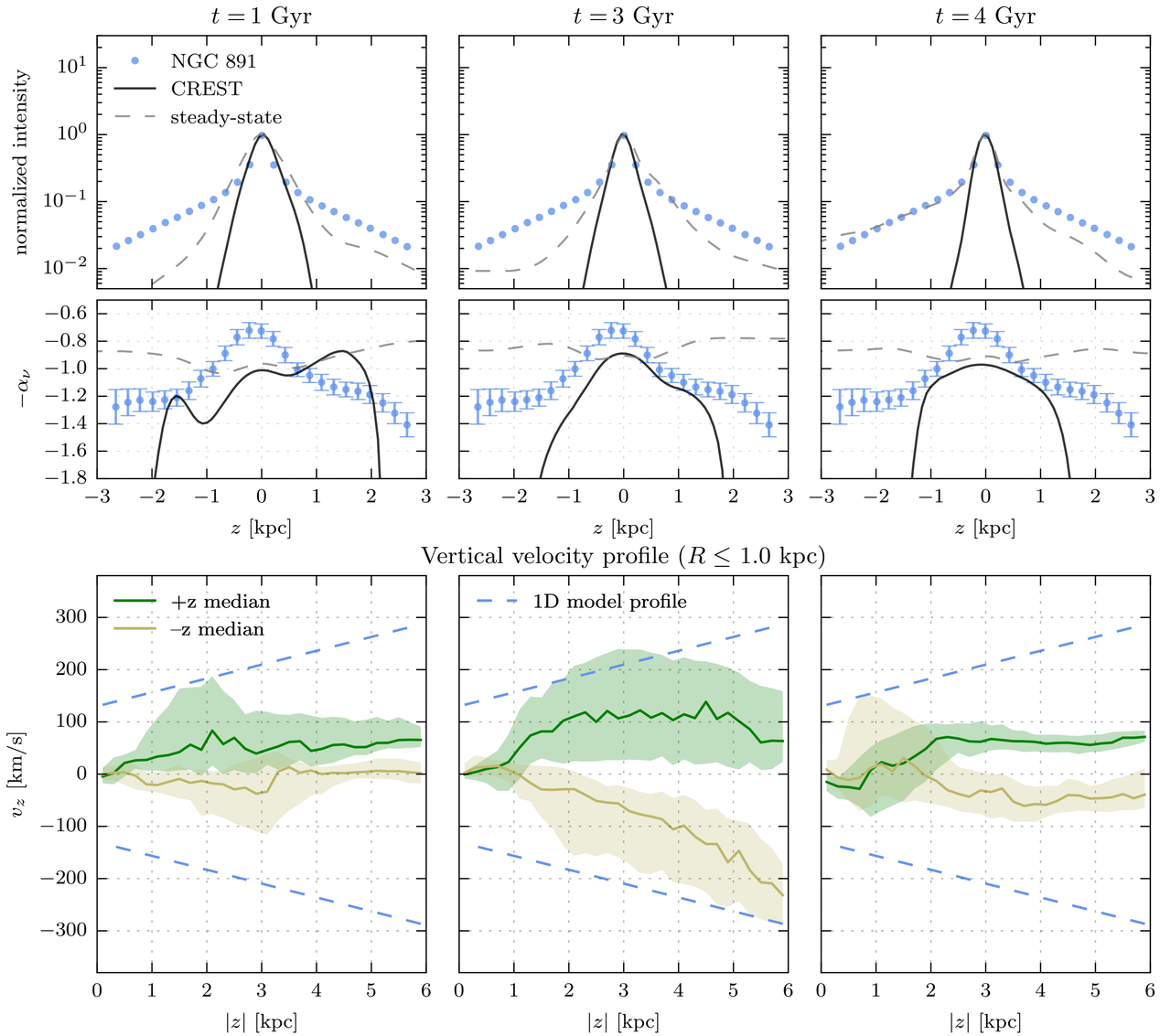
Vertical profiles





Werhahn+ 2026 b

Revisiting radio diagnostics with CREST



Werhahn+ 2026 b

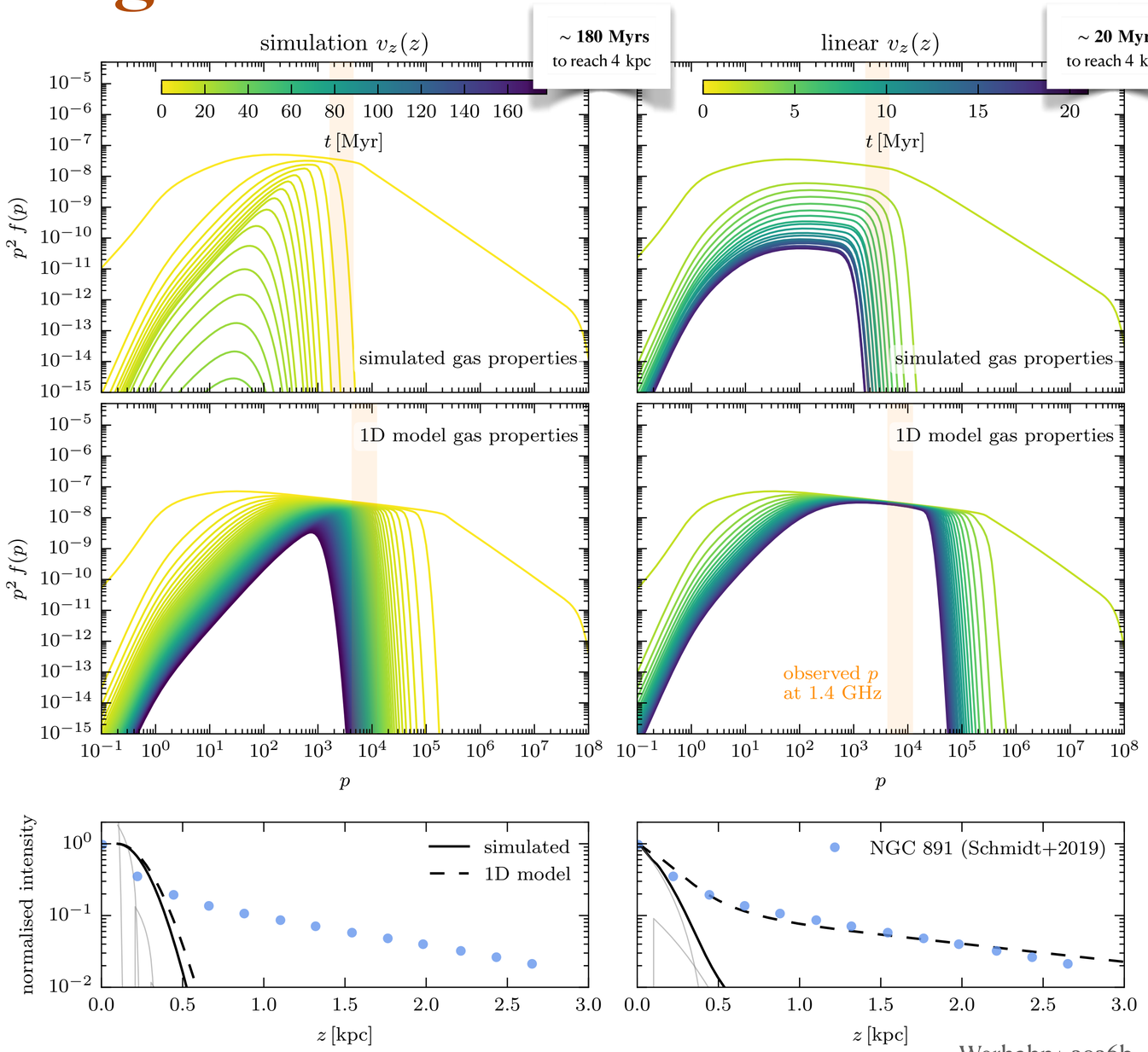


Revisiting radio diagnostics with CREST

What determines the extent of radio halos?

- Transport tracer particles through:
  - Simulation gas properties
  - 1D model gas properties (Schmidt+2019)
- Adopt either:
  - Self-consistent simulation velocity profile $v_z(z)$
  - linear velocity profile $v_z(z)$
- evolve CRe with CREST and calculate resulting vertical radio emission

- slowly accelerating winds keep CRe close to the disk where they cool efficiently → **radio halos too compact**



Werhahn+ 2026b



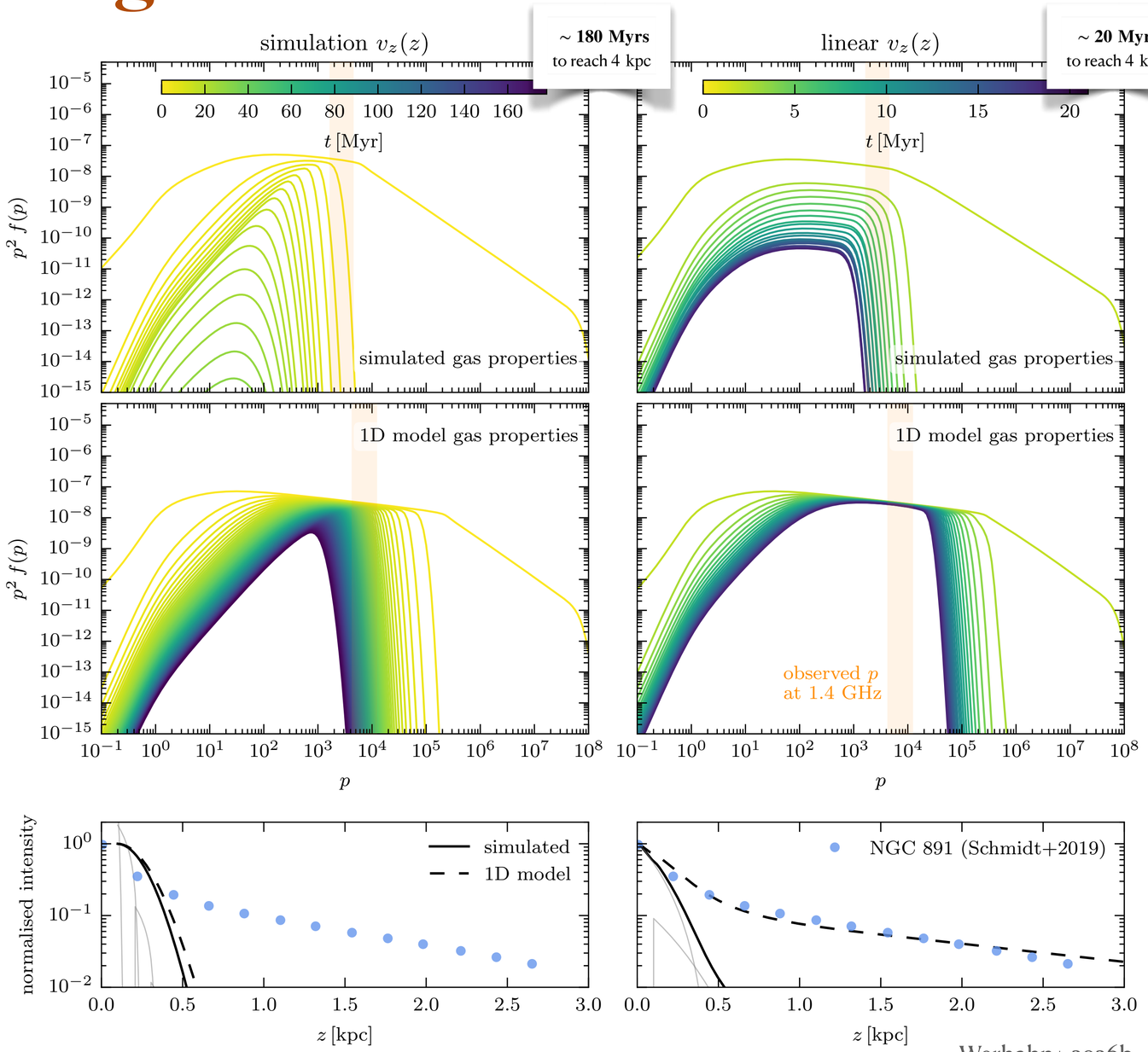
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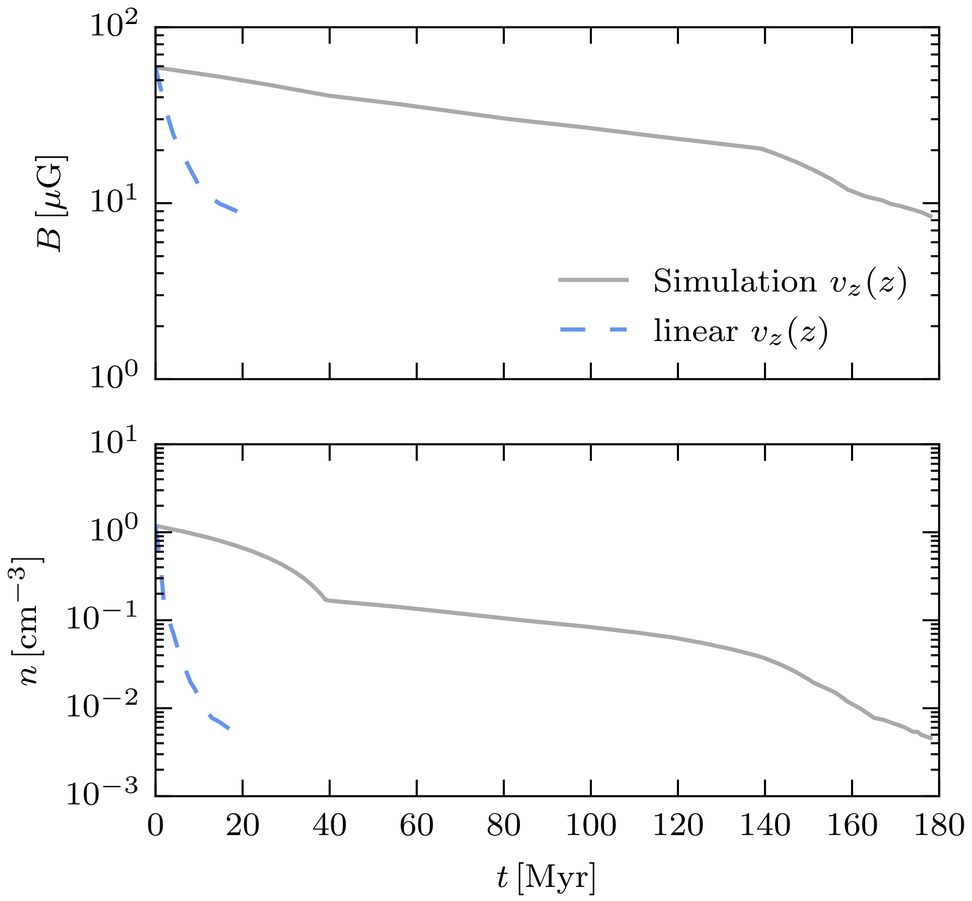
- linear velocity profile rapidly transports them into the halo → **extended radio emission**

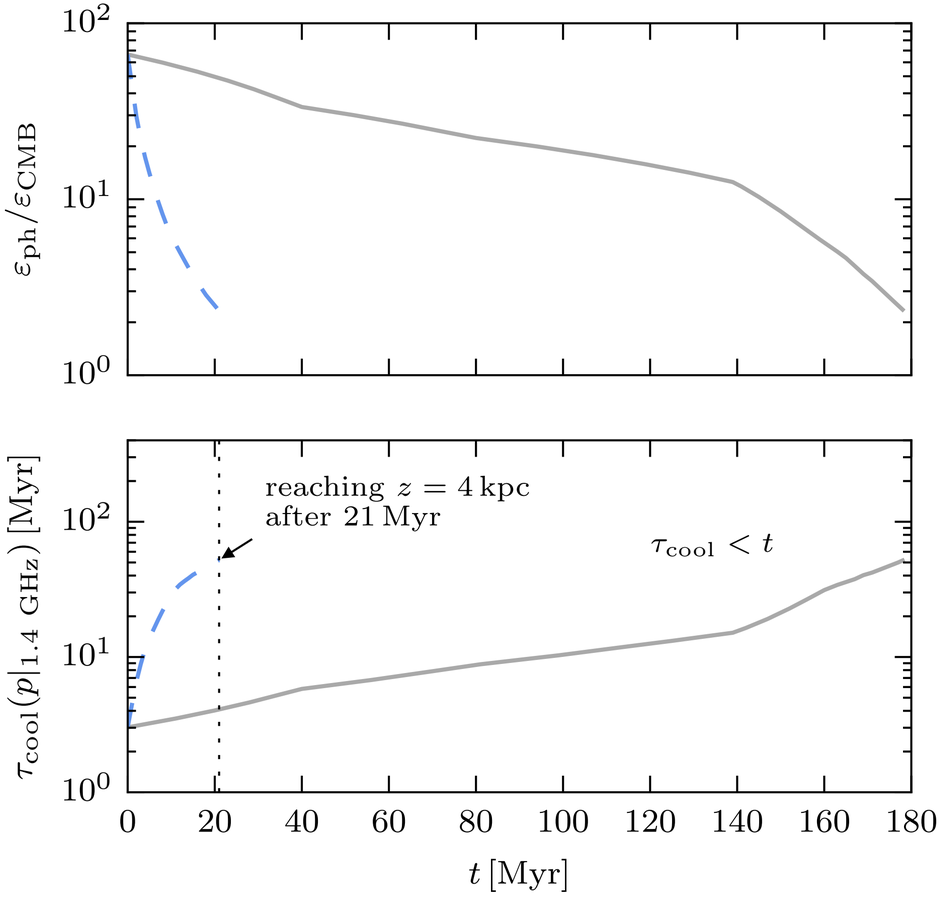


Werhahn+ 2026b

Revisiting radio diagnostics with CREST



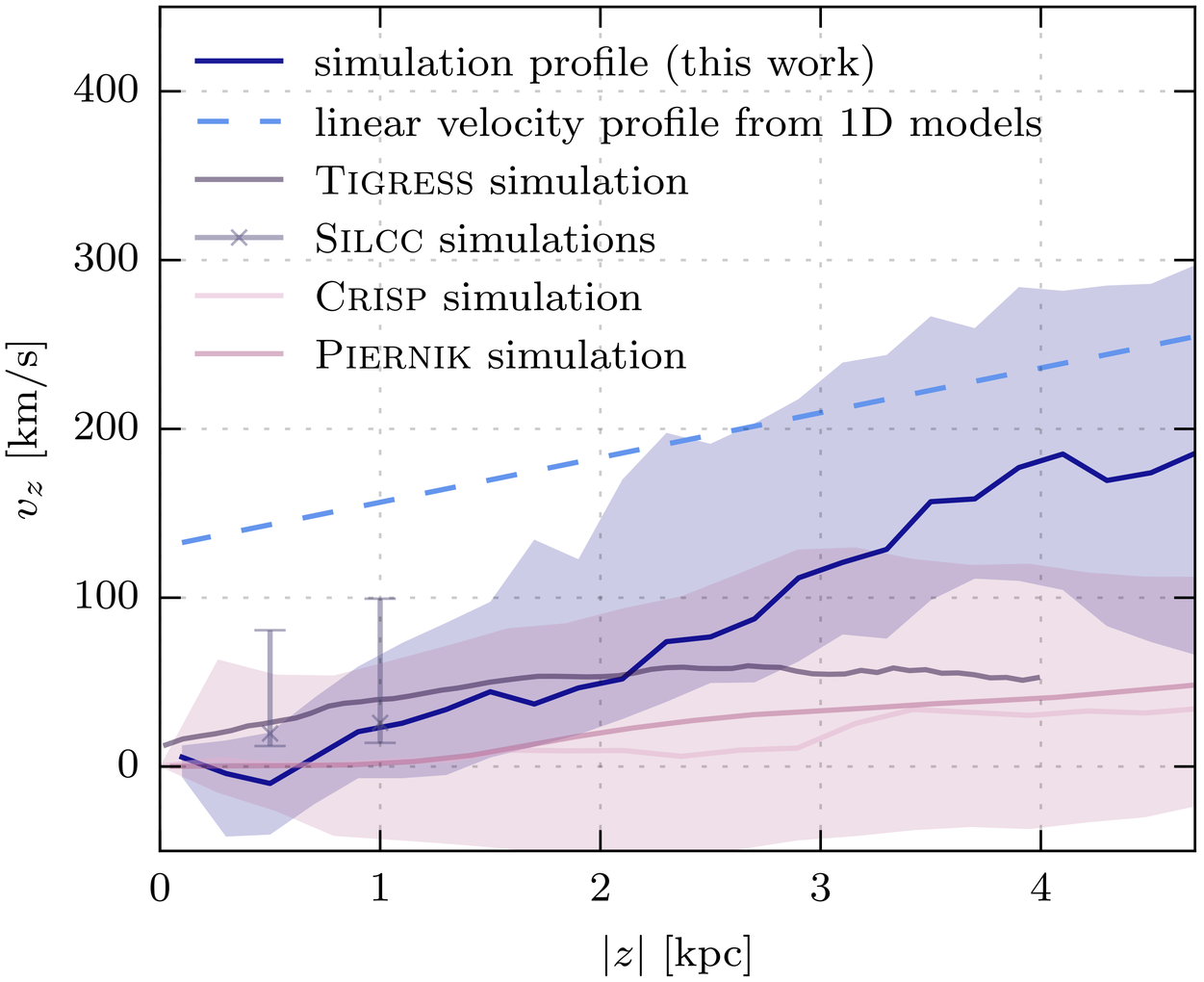


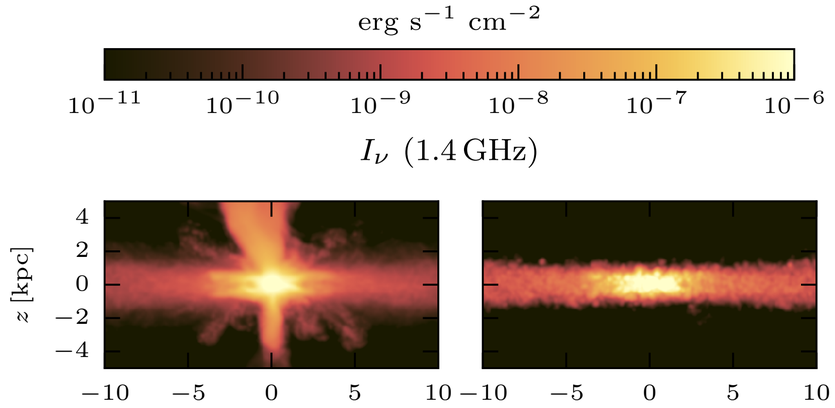


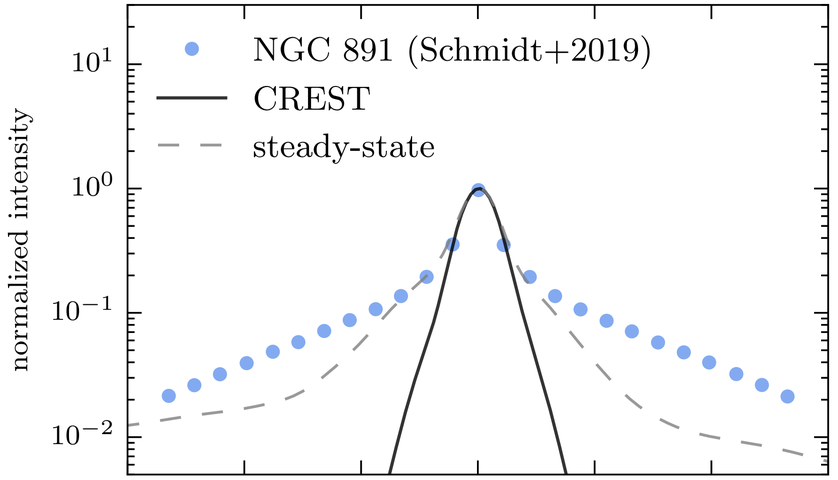
Werhahn+ 2026 b

Live modelling of CR electrons (CREST)

Radio emission

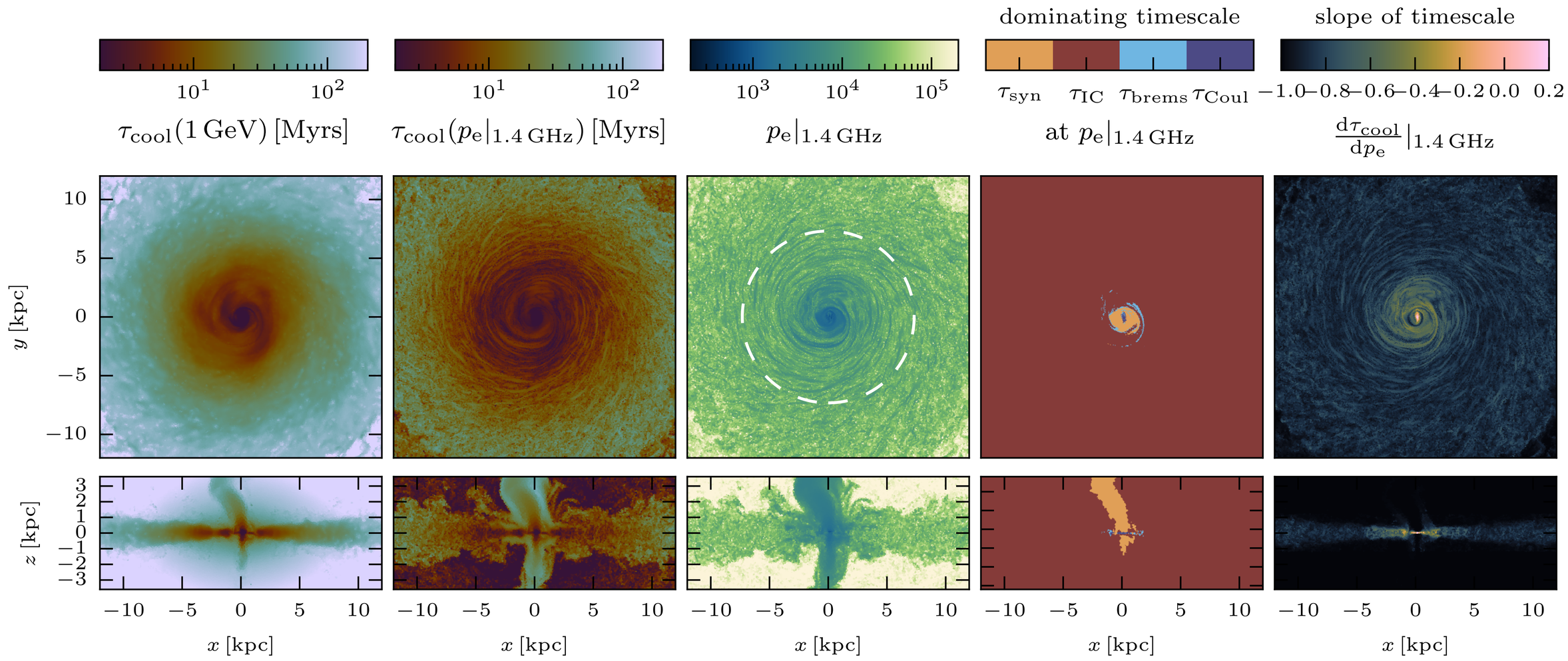






Werhahn+ 2026b

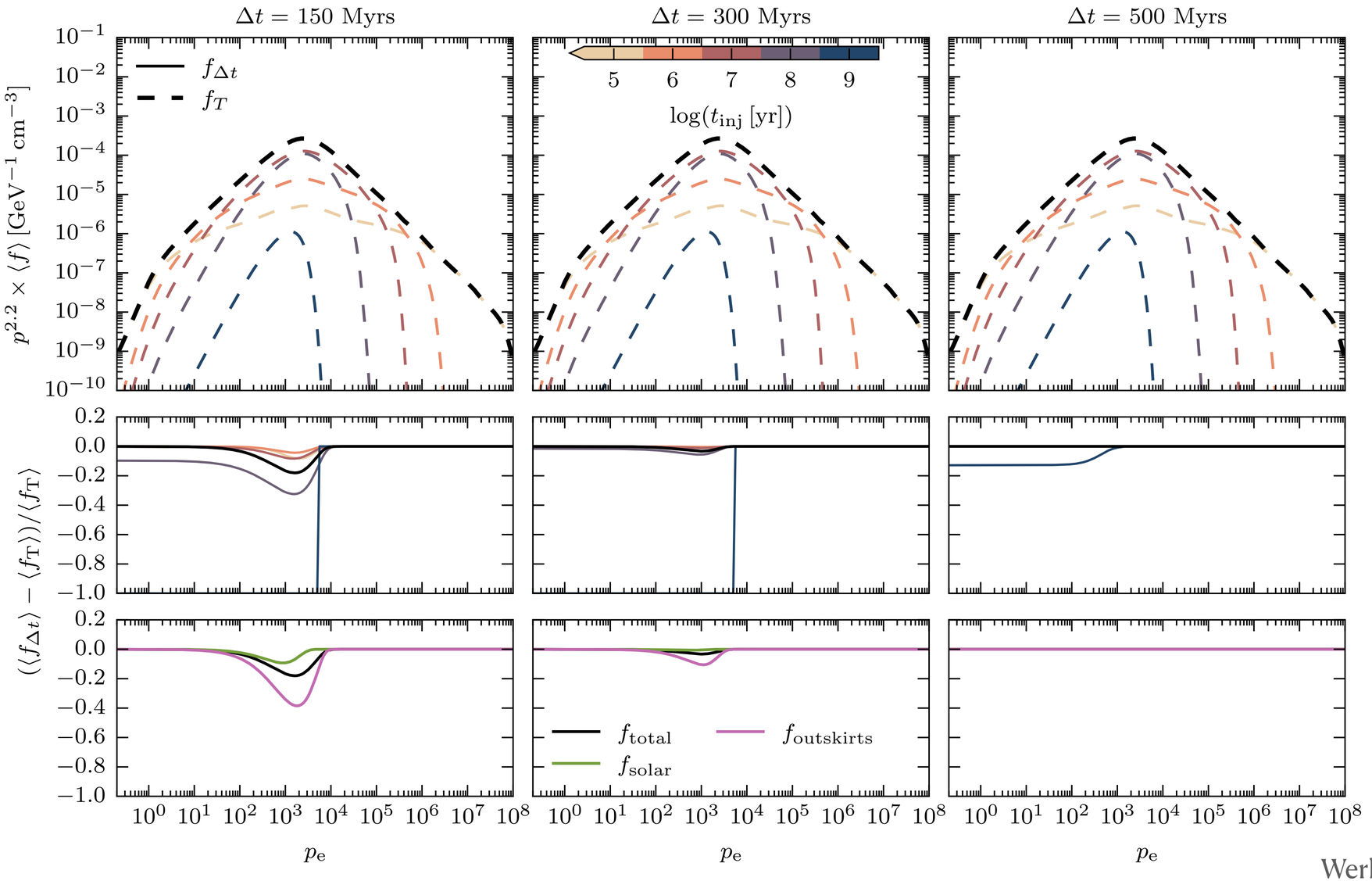
CREST - CR electron spectra evolved in time



Werhahn+ 2026 b

CREST - CR electron spectra evolved in time

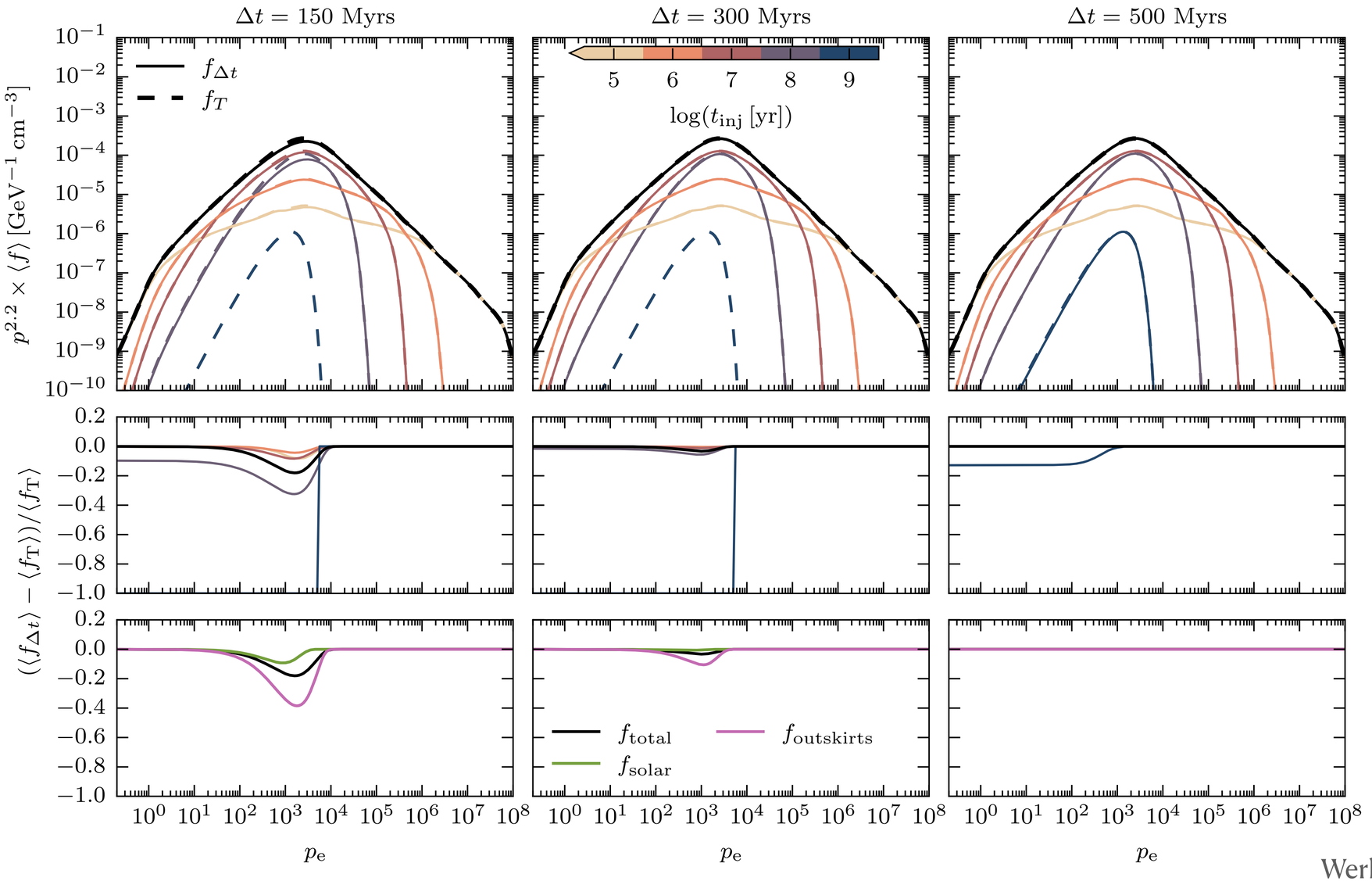
What's the memory of CR electrons?



Werhahn et al. 2026a

CREST - CR electron spectra evolved in time

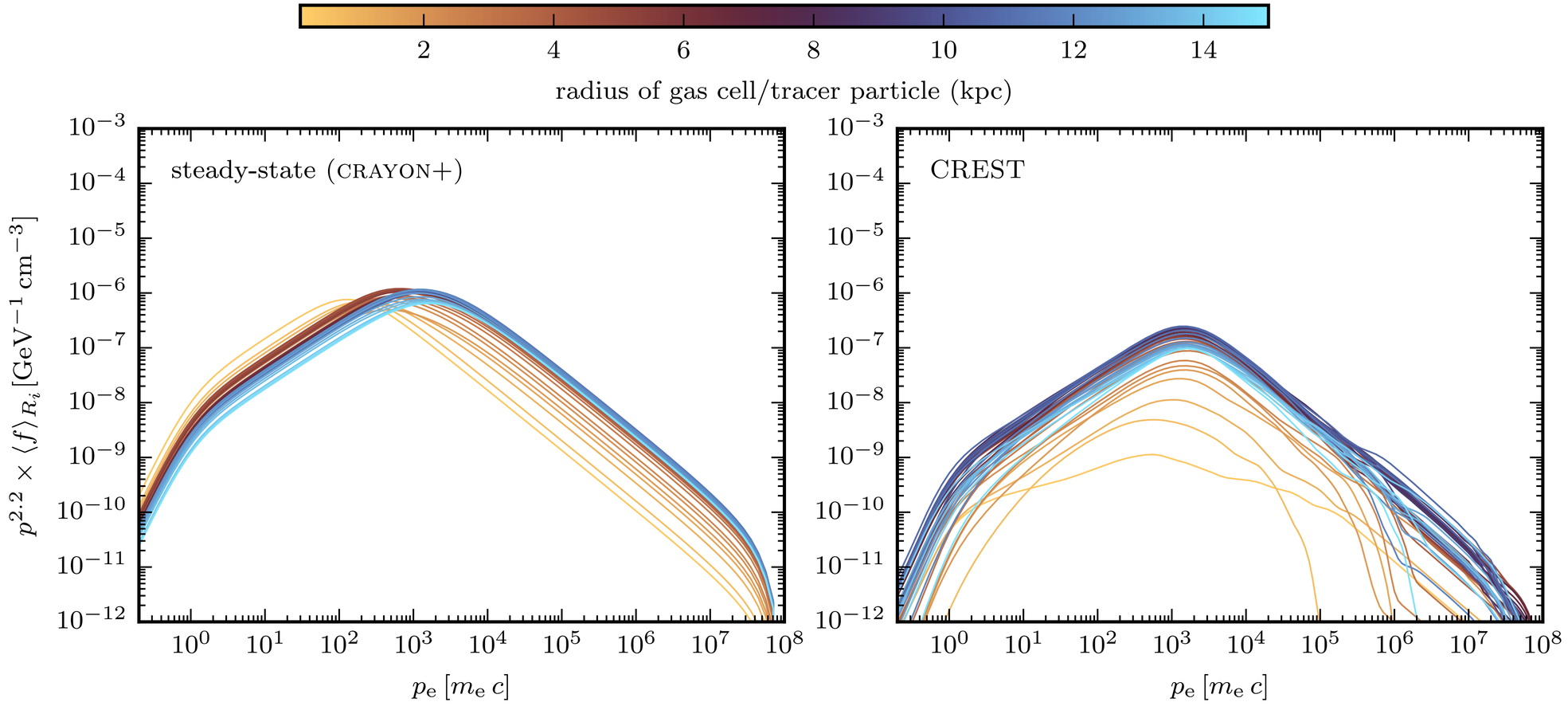
What's the memory of CR electrons?



Werhahn et al. 2026a

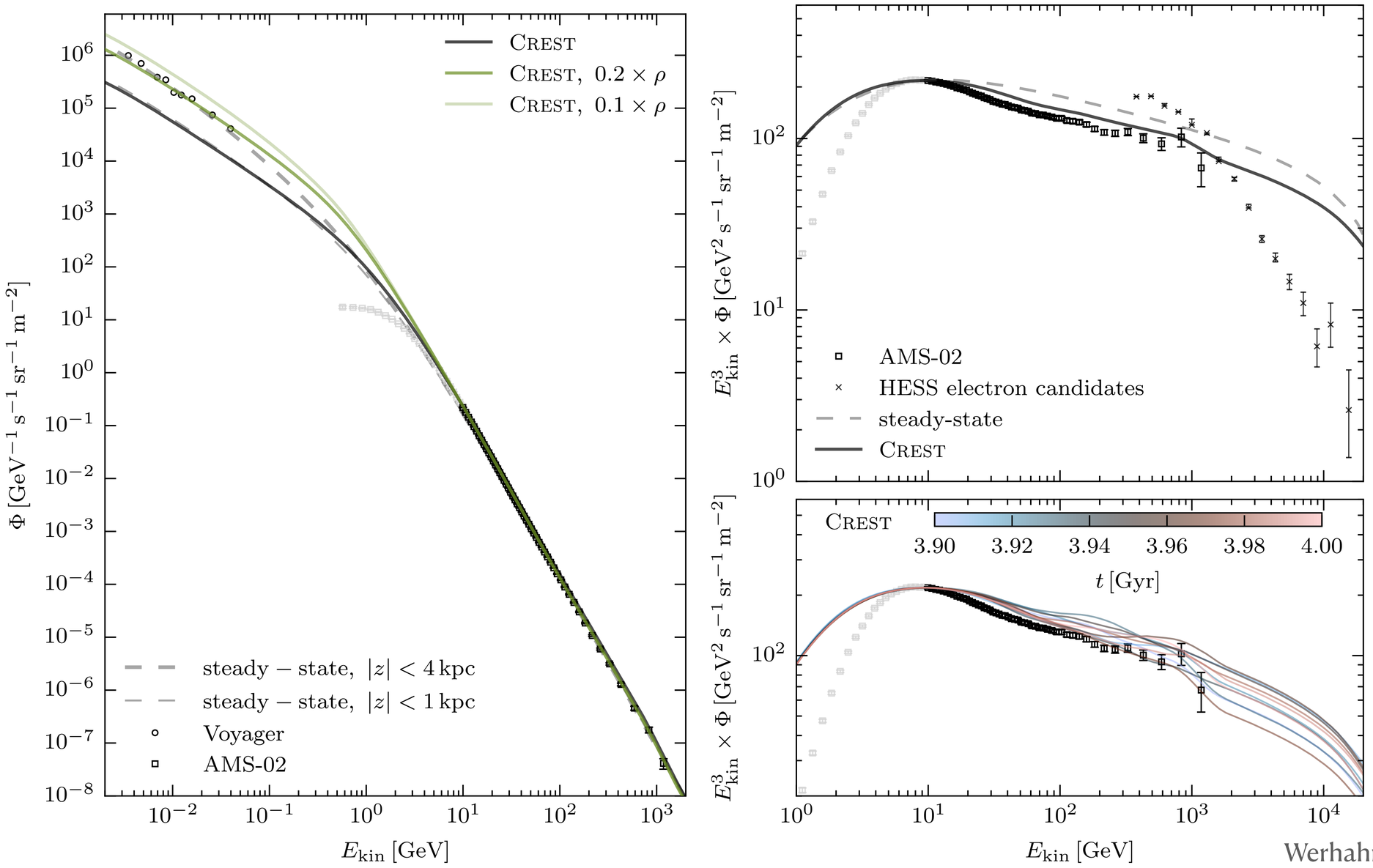
CREST - Live electrons in galaxies

Are galaxies in a steady-state?



CR electron spectra: spatial variations, globally similar

CREST - Live electrons in galaxies

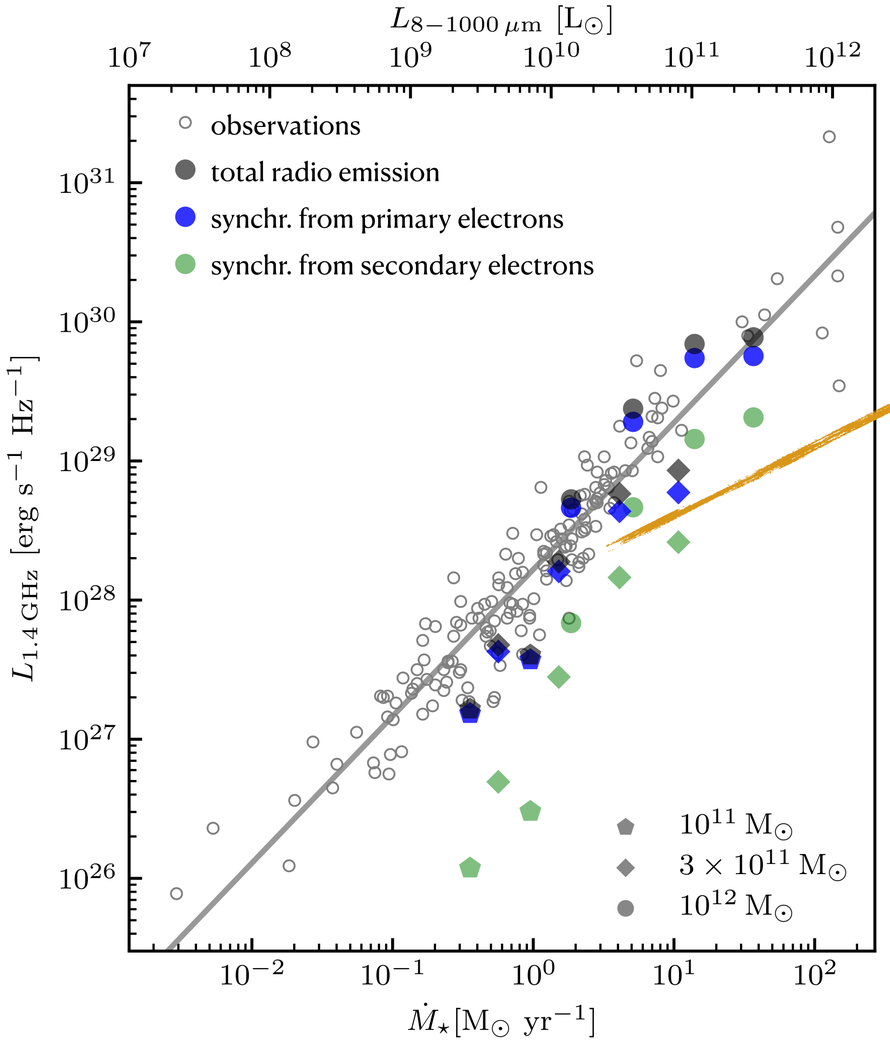


Christoph Pfrommer

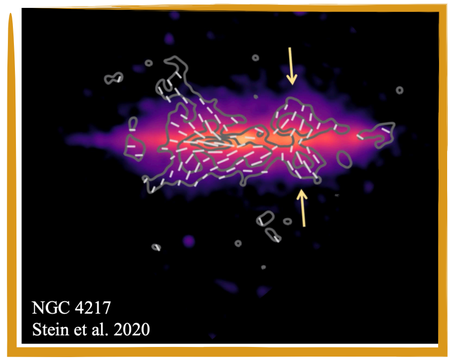
Werhahn et al. 2026a

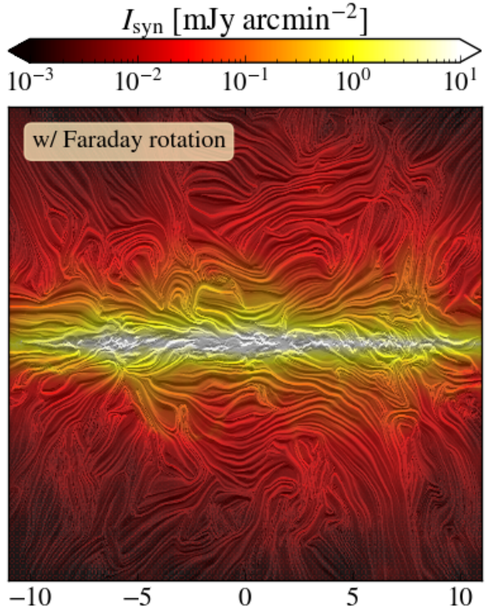
Lessons learned from isolated galaxies

Polarised radio emission



NGC 4217



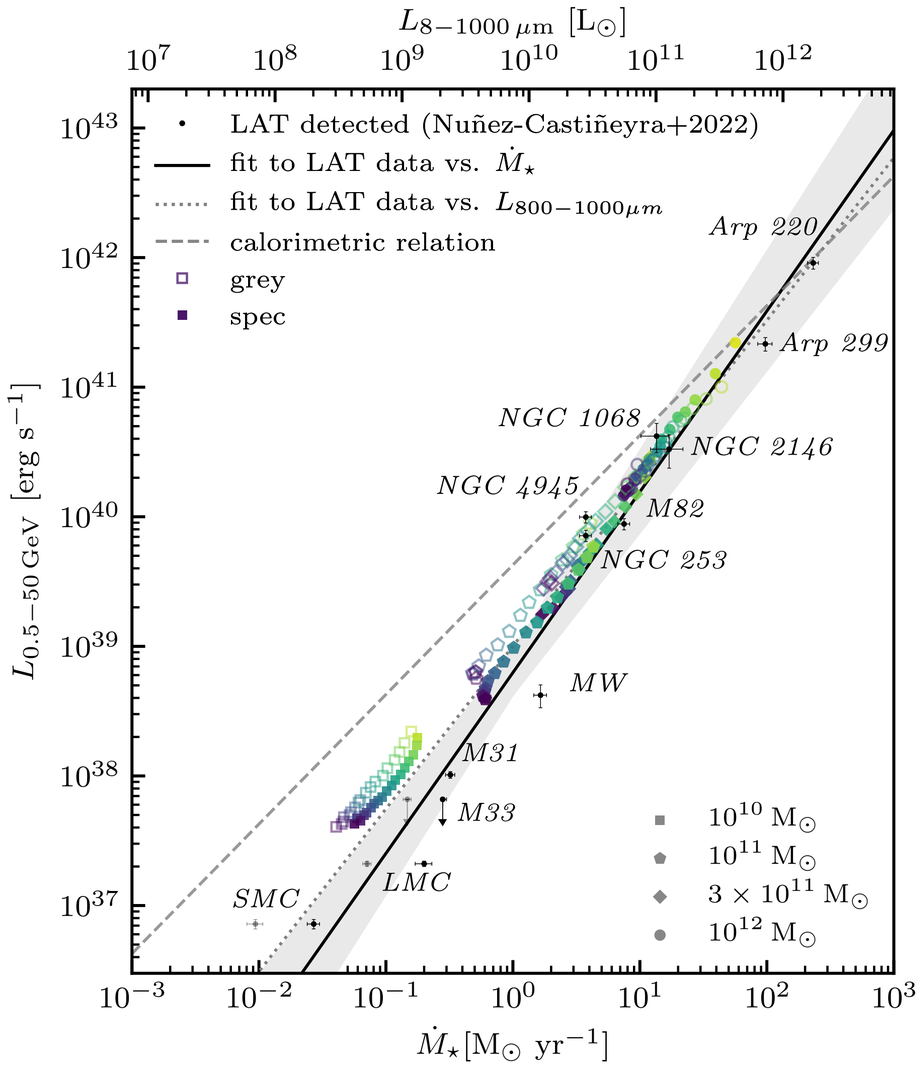


Chiu, [..], Werhahn et al. (2024)

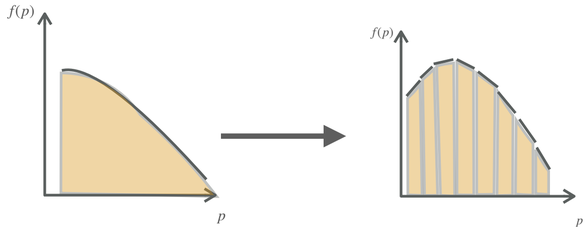
- CRAYON+ applied to galaxy simulation with 2-moment CR transport and multiphase ISM (Thomas+2024)
- X-shaped B-field morphology from galactic-scale outflows

Lessons learned from isolated setups

Gamma-ray emission



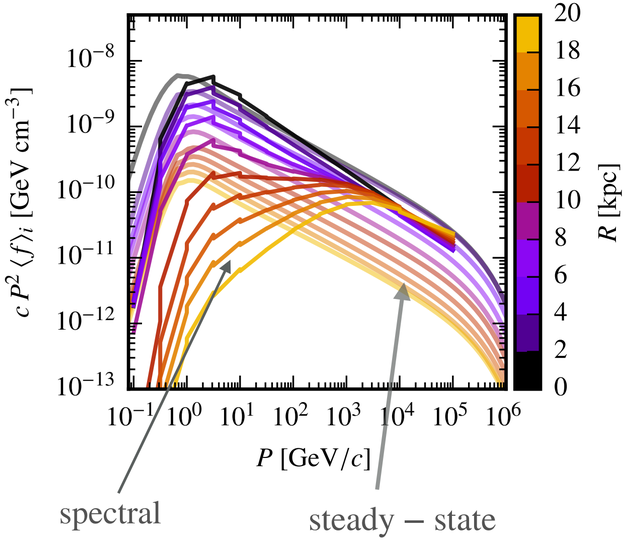
Werhahn et al. (2023)



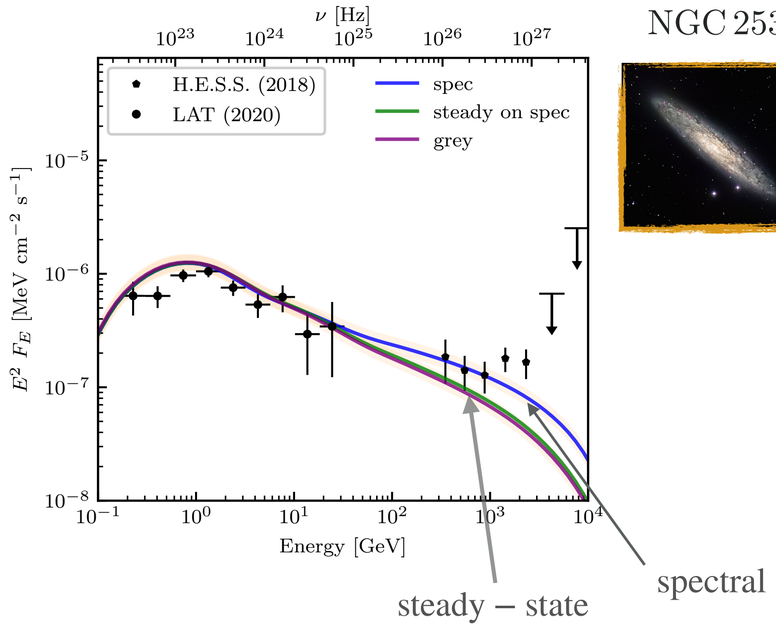
Spectral CR protons (Girichidis+2023) —> emission with **crayon**+

- required for spatially resolved high-energy gamma-rays
- **global** spectra & luminosities: close to *grey*+*steady-state*

CR proton spectra

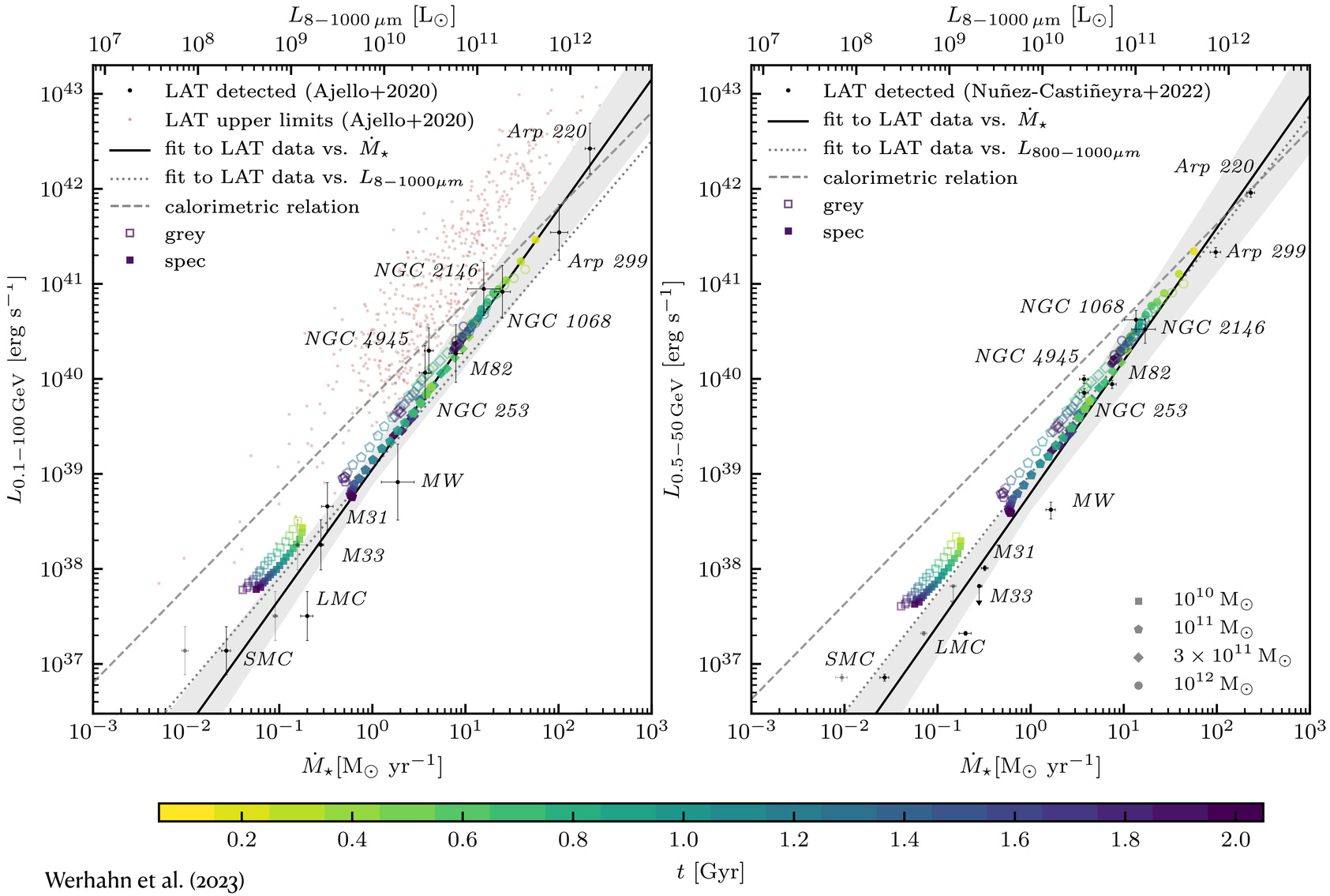


gamma-ray spectrum



NGC 253

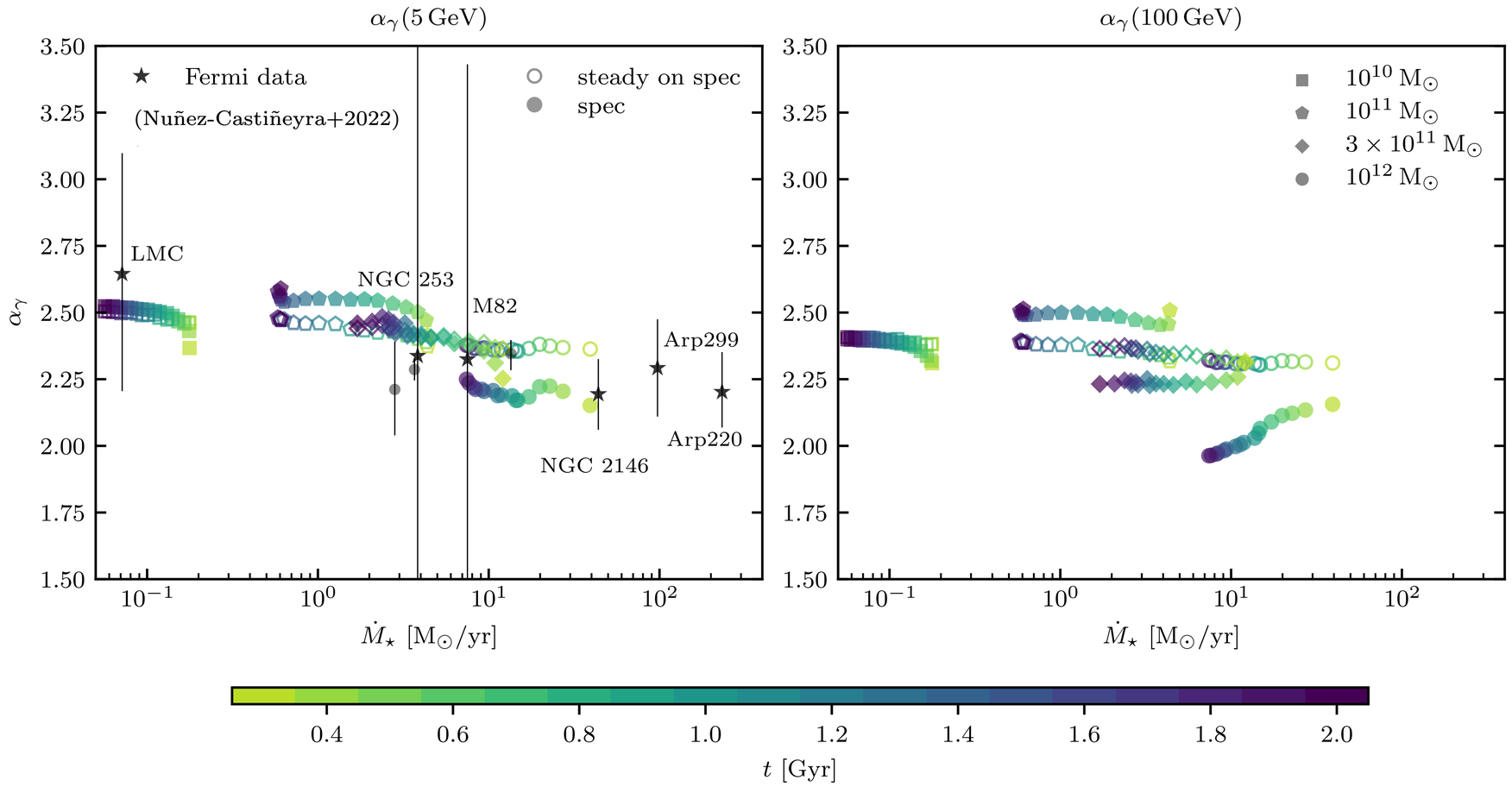
Spectrally resolved CR protons



Werhahn et al. (2023)

Spectrally resolved CRs in galaxies

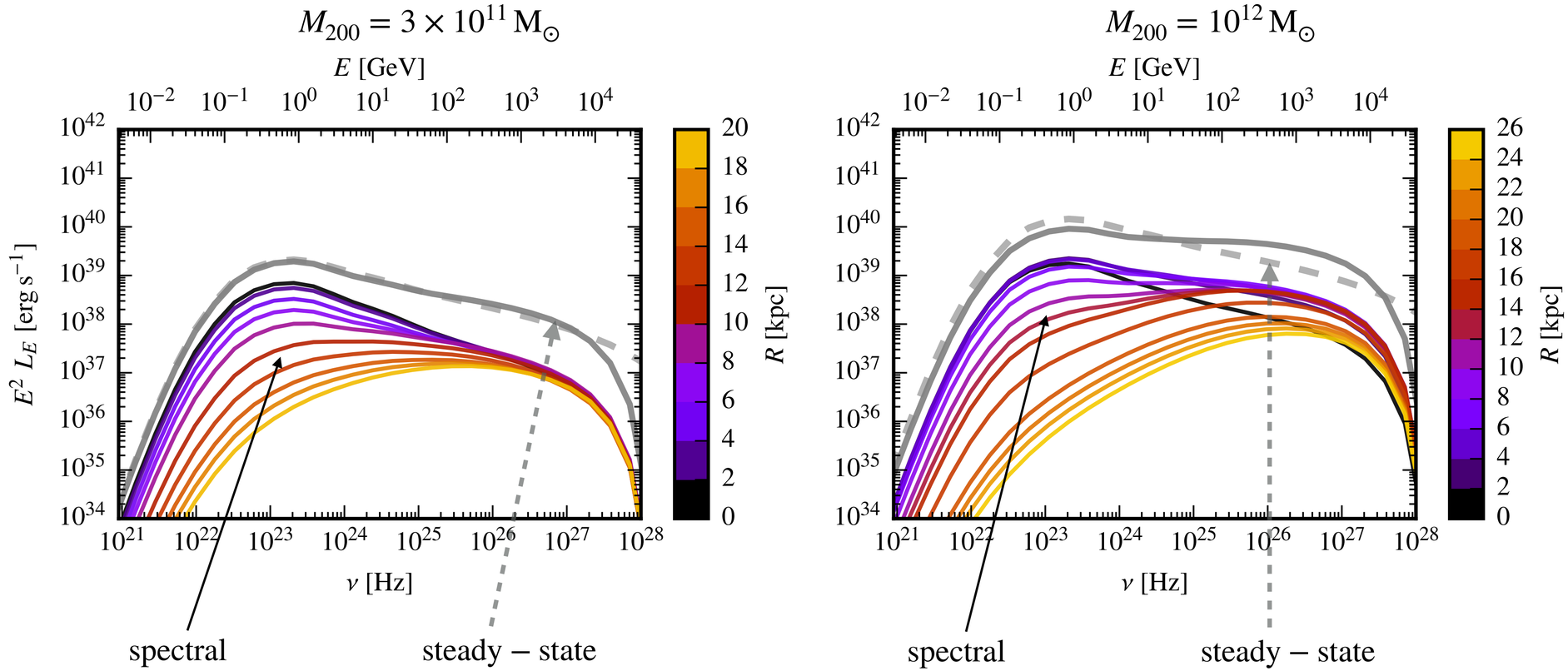
gamma-ray spectral index (slope) α_γ



Werhahn et al. (subm.)

Spectrally resolved CRs in galaxies

gamma-ray spectra



Werhahn et al. (subm.)

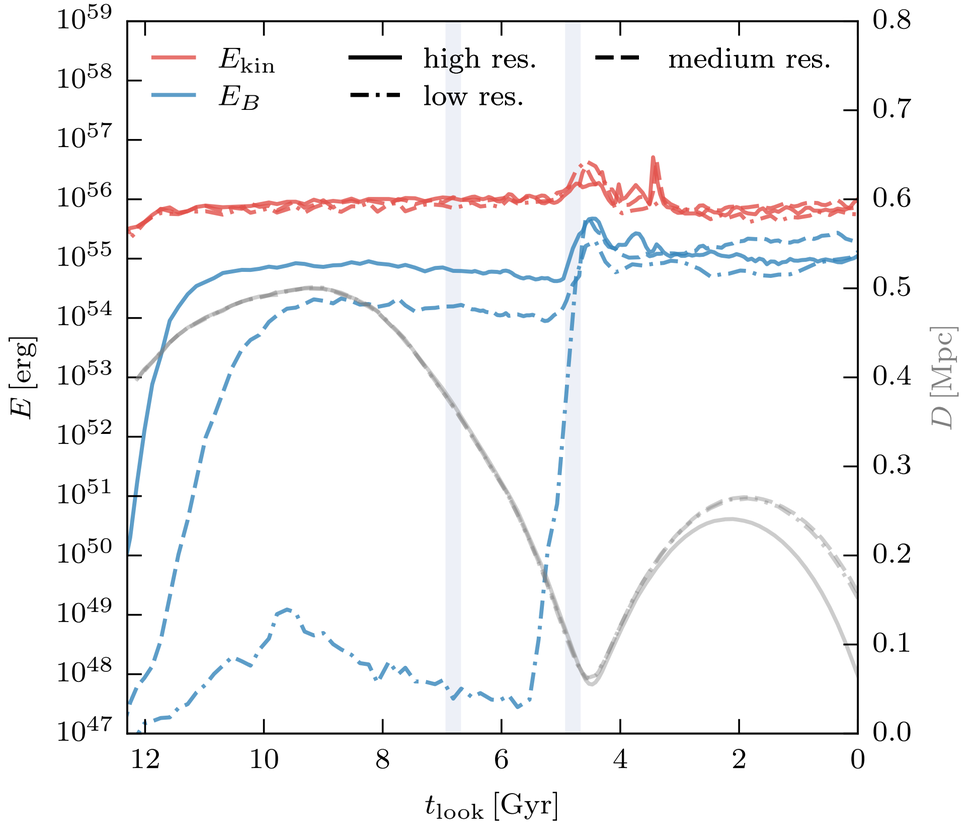
Cosmological zoom simulations

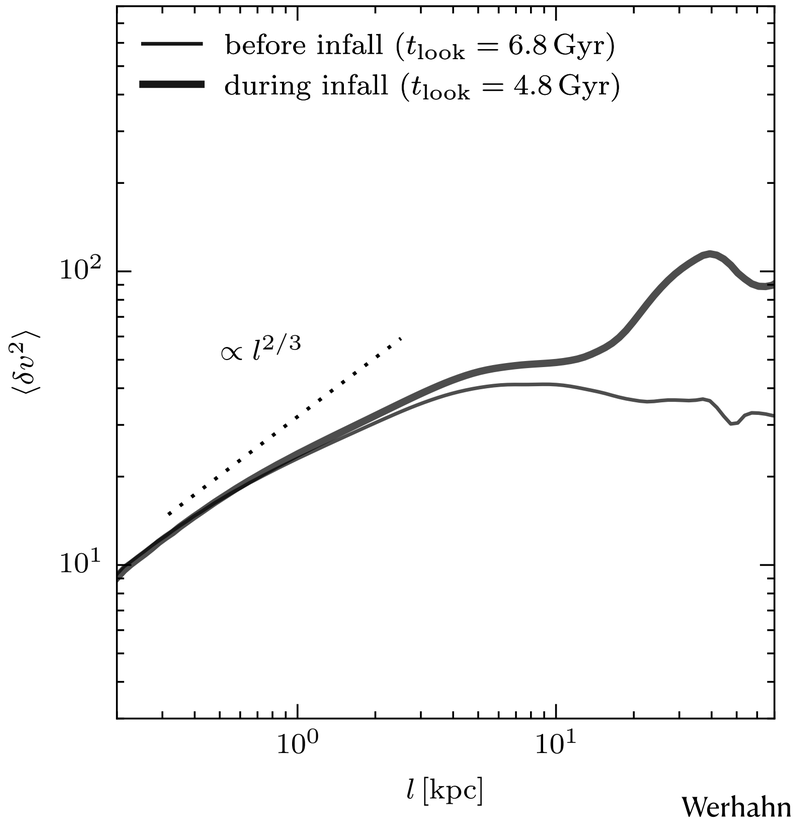
with & without CRs

B-field amplification

Auriga zoom simulations: $M_{200} = 10^{10} - 10^{13}\,\mathrm{M}_\odot$

- dwarfs: high resolution needed to get converged B-fields
- satellites: B-fields converged after infall



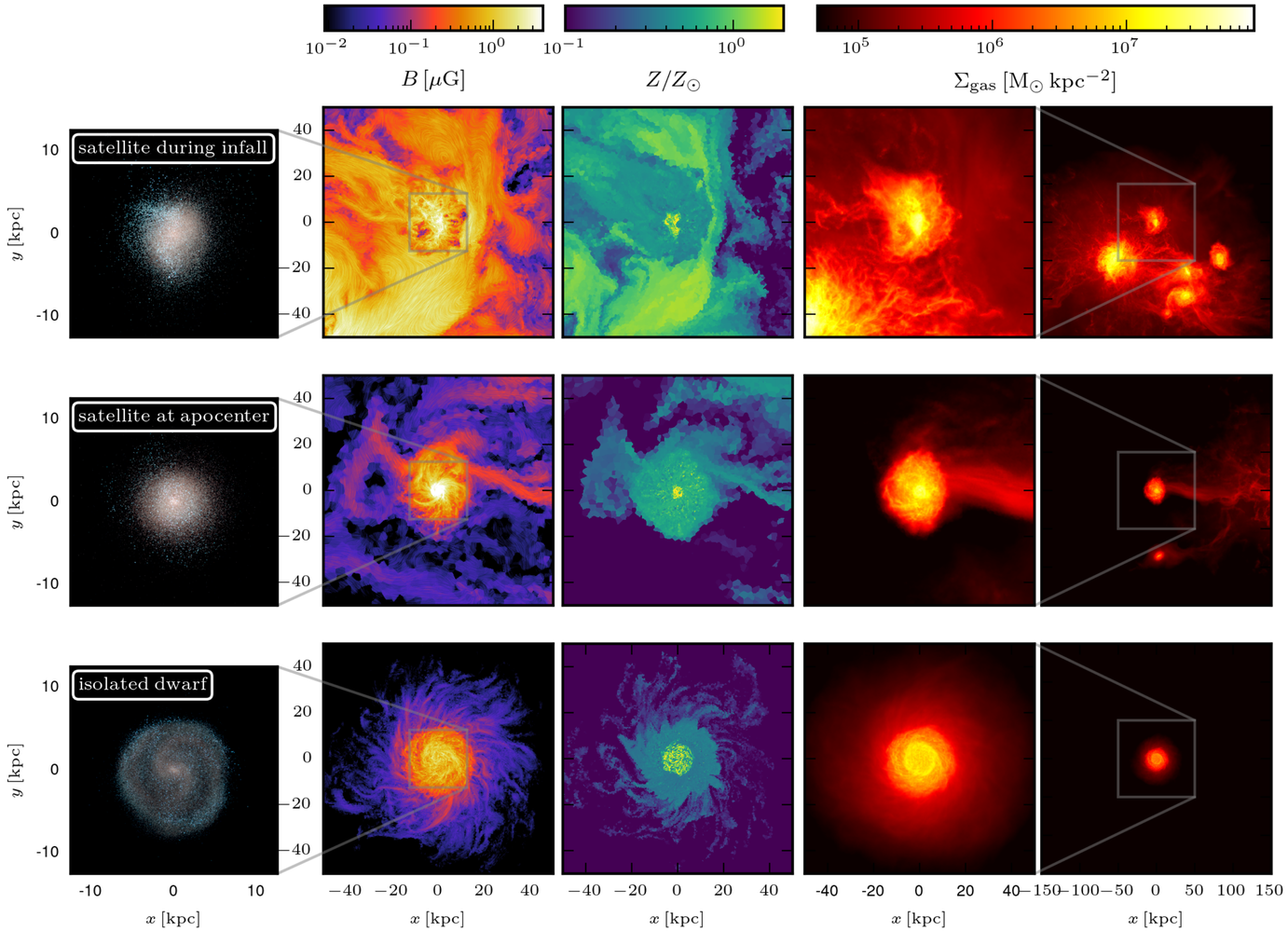


Werhahn et al. 2024 (arXiv:2409.17229)

Cosmological zoom simulations

with & without CRs

B-field amplification



Name	M_{200} [$\mathrm{M}_\odot$]	number of satellites	mass range of satellites M_{tot} [$\mathrm{M}_\odot$]
1e13-h7	$10^{13.11}$	33	$10^{9.39}$ to $10^{11.77}$
1e13-h8	$10^{12.99}$	18	$10^{9.40}$ to $10^{11.58}$
1e13-h3	$10^{12.51}$	9	$10^{9.51}$ to $10^{10.53}$
1e12-h5	$10^{12.08}$	1	$10^{10.30}$
1e12-h12	$10^{12.04}$	4	$10^{9.63}$ to $10^{10.15}$
1e11-h4	$10^{11.44}$	2	$10^{8.90}$ to $10^{9.89}$
1e11-h5	$10^{11.46}$	-	-
1e11-h11	$10^{10.98}$	1	$10^{10.30}$
1e11-h10	$10^{10.91}$	-	-
1e10-h9	$10^{10.54}$	-	-
1e10-h11	$10^{10.34}$	-	-
1e10-h8	$10^{10.08}$	-	-
1e10-h12	$10^{9.84}$	-	-

Werhahn et al. 2024 (arXiv:2409.17229)

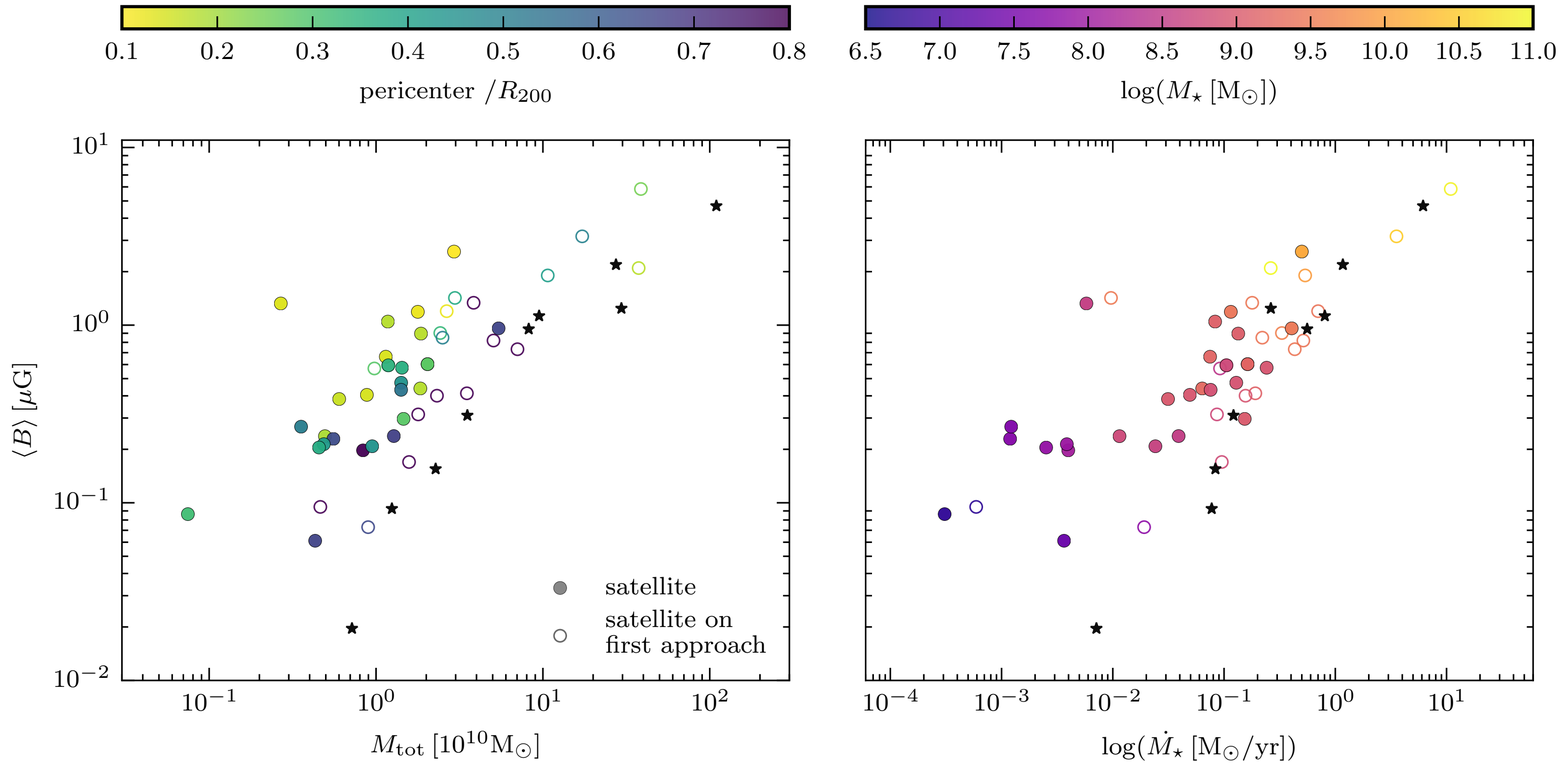
Cosmological zoom simulations

with & without CRs

B-field amplification

Auriga zoom simulations: $M_{200} = 10^{10} - 10^{13}\,\mathrm{M}_\odot$

- dwarfs: high resolution needed to get converged B-fields
- satellites: B-fields converged after infall
- higher B-fields in satellites, particularly after close encounter with host



no CRs

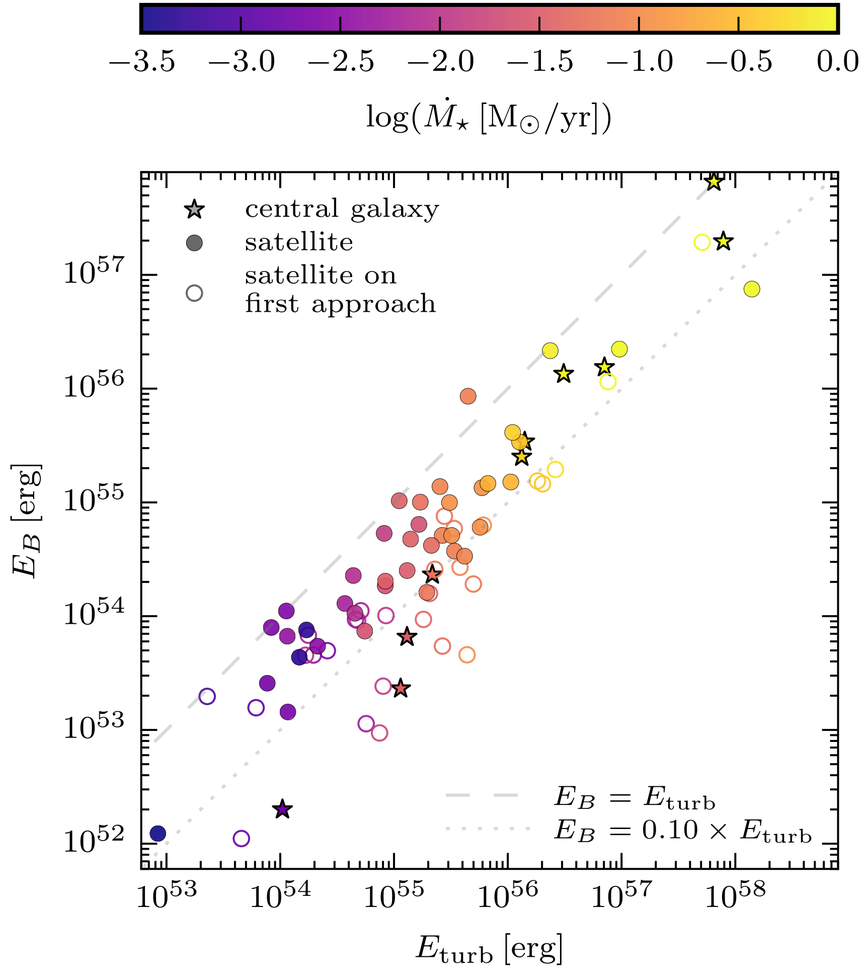
Cosmological zoom simulations

with & without CRs

B-field amplification

Auriga zoom simulations: $M_{200} = 10^{10} - 10^{13}\,\mathrm{M}_\odot$

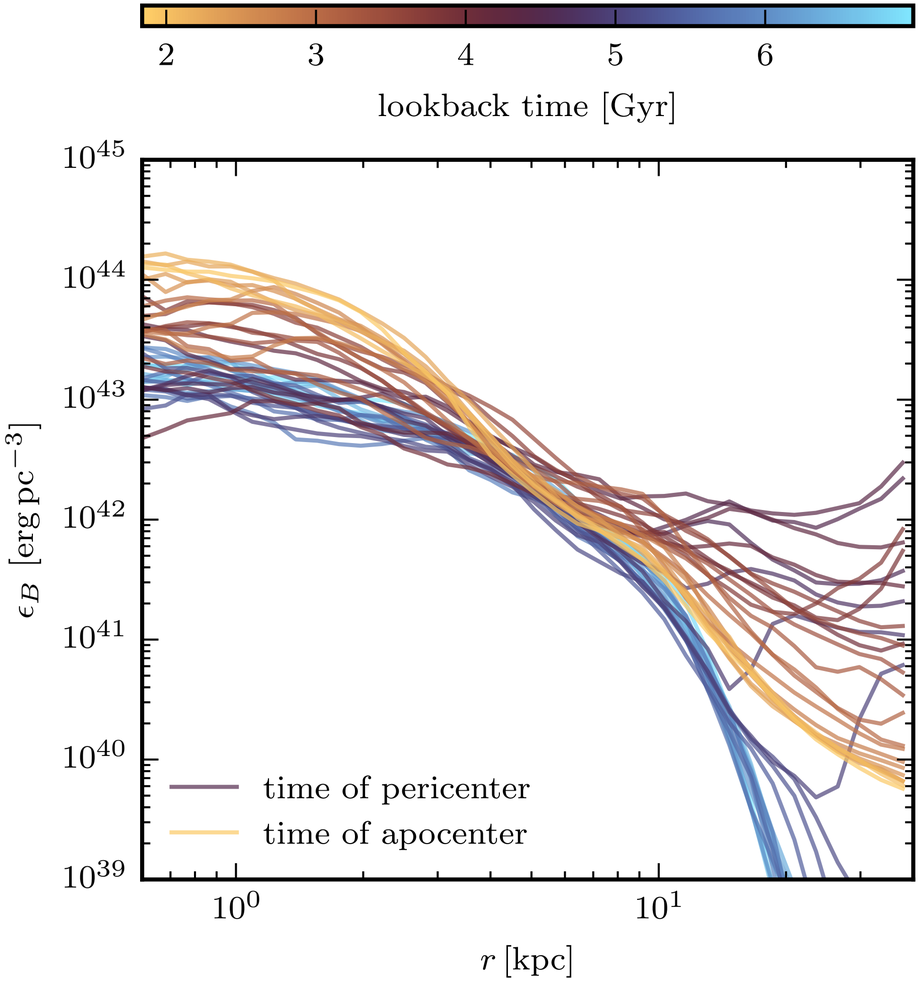
- dwarfs: high resolution needed to get converged B-fields
- satellites: B-fields converged after infall
- **stronger B-fields in satellites**, particularly after close encounter with host

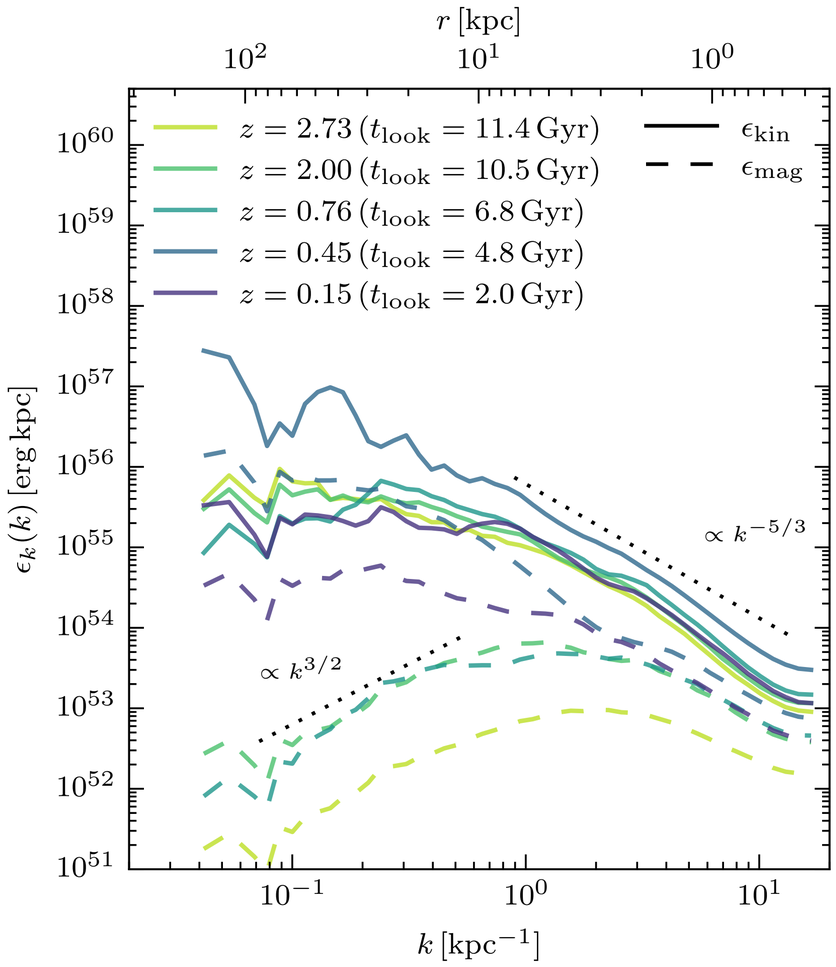


Cosmological zoom simulations

with CRs

B-field amplification

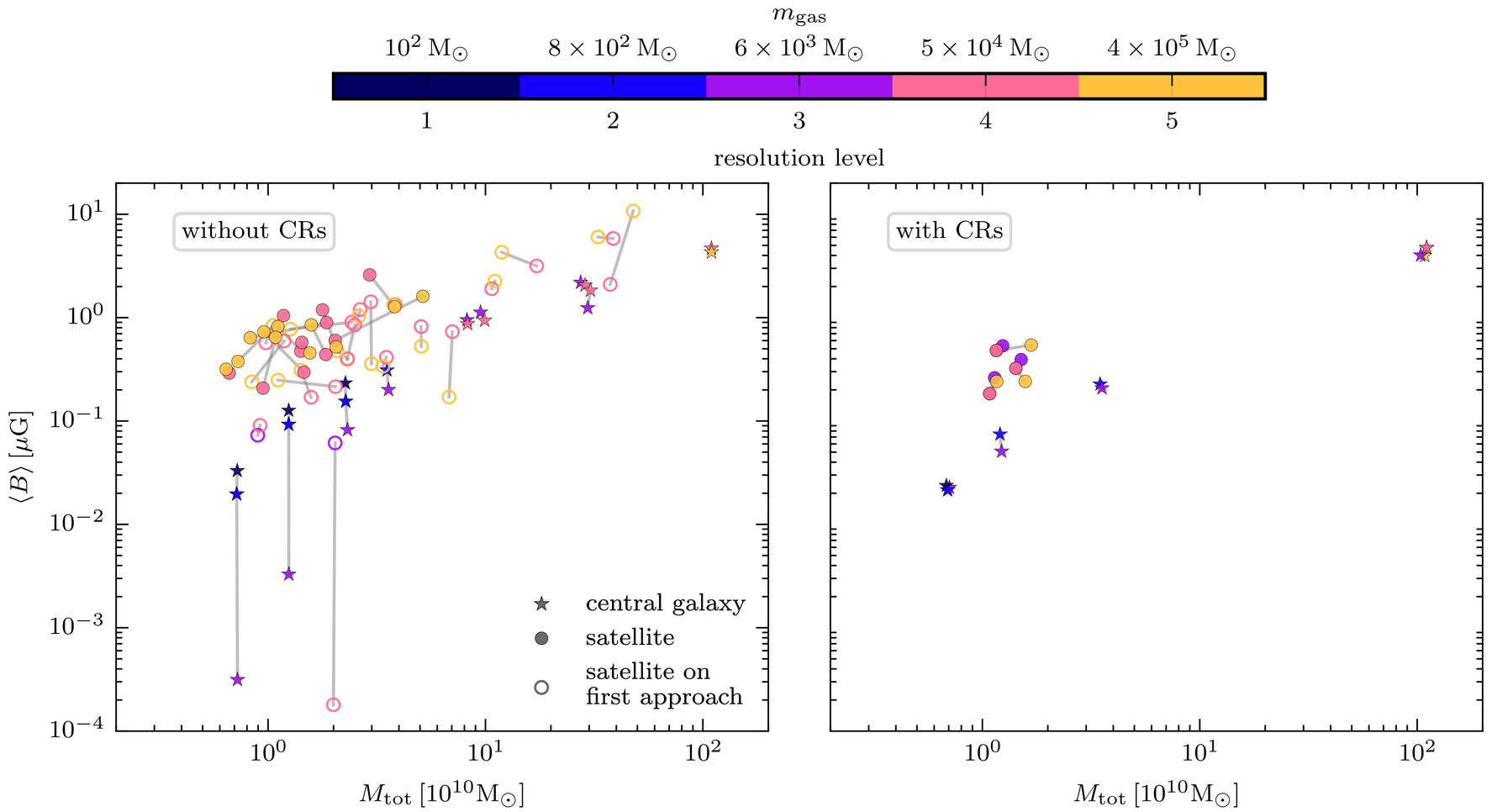




Cosmological zoom simulations

with & without CRs

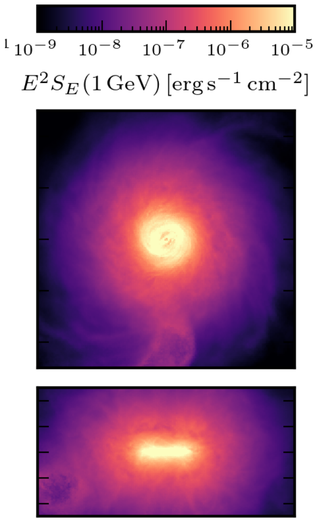
B-field amplification



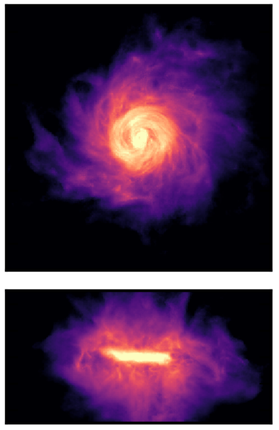
Cosmological zoom simulations

with CRs

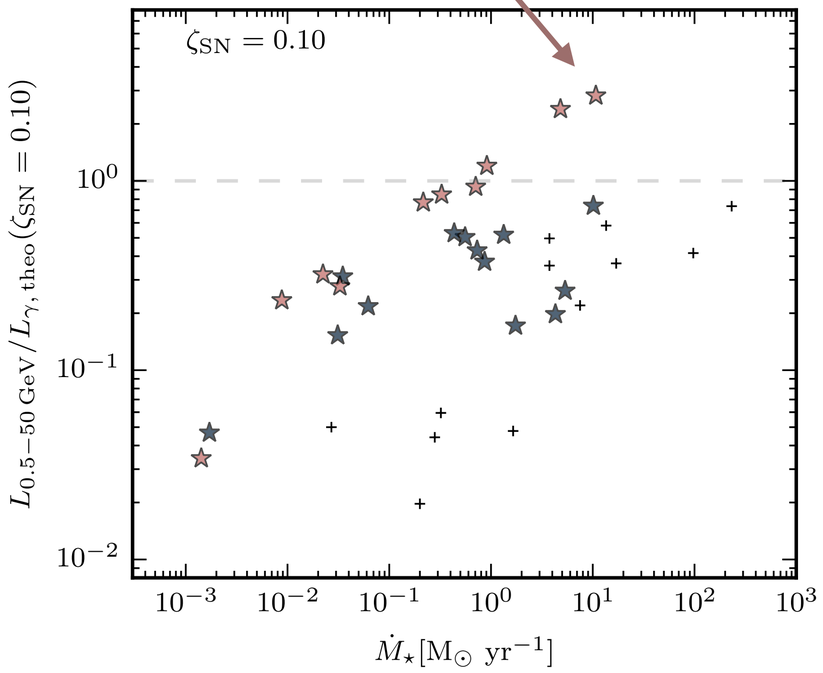
FIR-gamma-ray relation

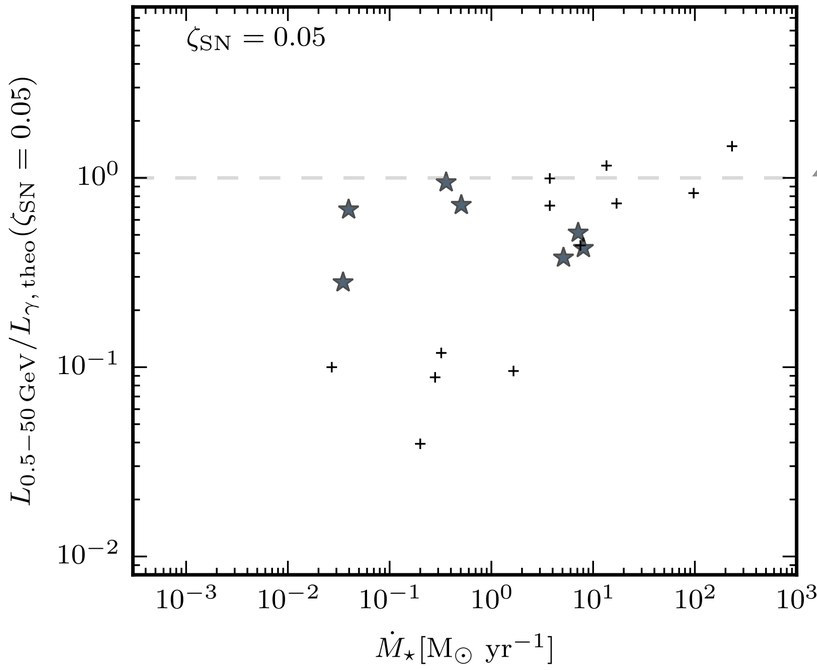


with Alfvén cooling



without Alfvén cooling





theoretical limit for instantaneous conversion to γ-rays

+ Fermi data

★ central galaxy

● satellite

○ satellite on first approach

— preliminary —