AIP

Cosmic rays and non-thermal emission in simulated galaxies

Maria Werhahn, Christoph Pfrommer, Philipp Girichidis,
Rüdiger Pakmor, Ewald Puchwein, Georg Winner

Cosmic rays in galaxy formation

Importance of CRs in galaxy formation:

- 1D flux tube models (e.g. Breitschwerdt+1991; Zirakashvili+1996; Ptuskin+ 1997; Everett+ 2008; Samui+ 2010;…)
- 3D simulations of ISM (e.g. Hanasz+ 2013; Girichidis+ 2016; Simpson+ 2016; Farber+ 2018;…)
- CR-hydrodynamic simulations of galaxies (isolated, cosmological)

  (e.g. Jubelgas+ 2008; Uhlig+ 2012; Booth+ 2013; Salem & Bryan 2014; Pakmor + 2016; 2017; Jacob+ 2018; Dashyan & Dubois 2020,Salem+ 2014; Buck+ 2020; Hopkins+ 2020;…)

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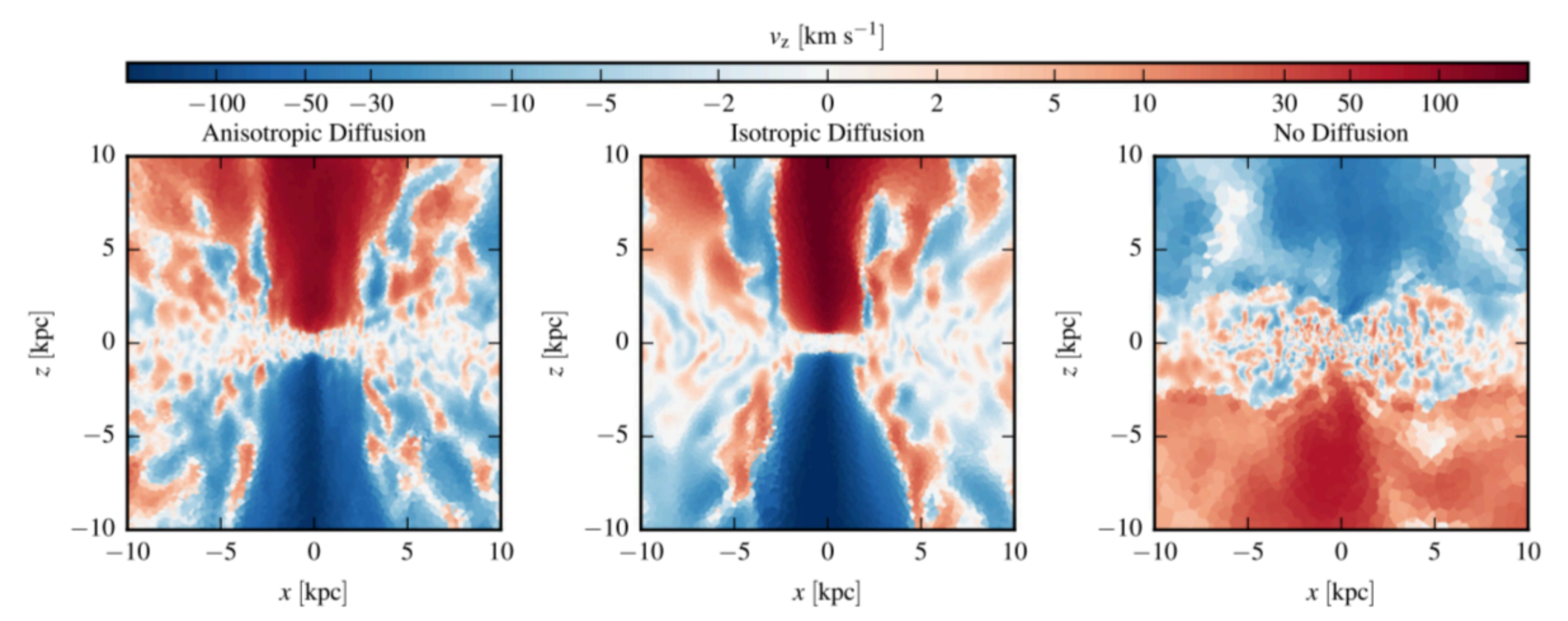
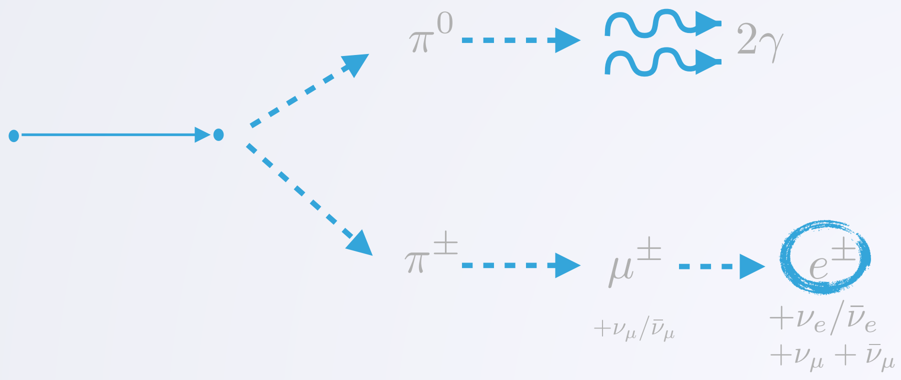
→ **CRs regulate SF, launch winds**



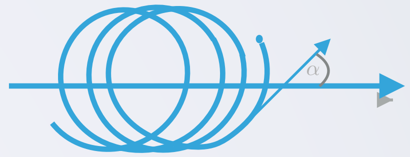
Pakmor+ (2016)

Non-thermal emission from CRs

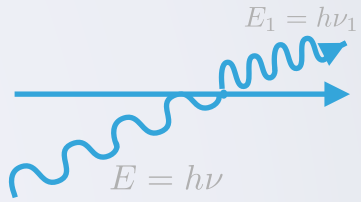
- CR **protons**:
  - pion decay



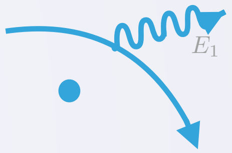
- CR **electrons**:
  - Synchrotron-emission

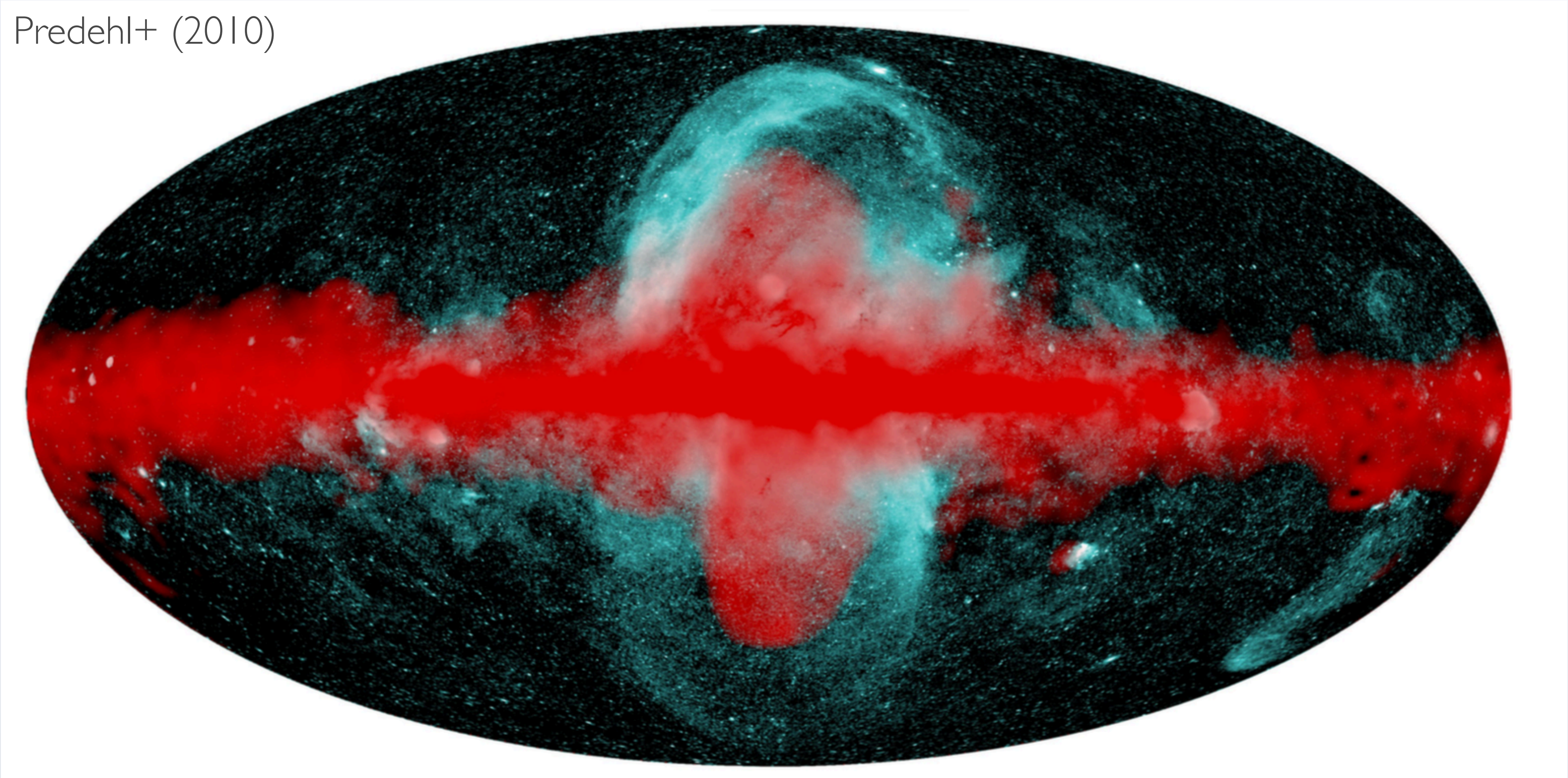


  - Inverse Compton emission



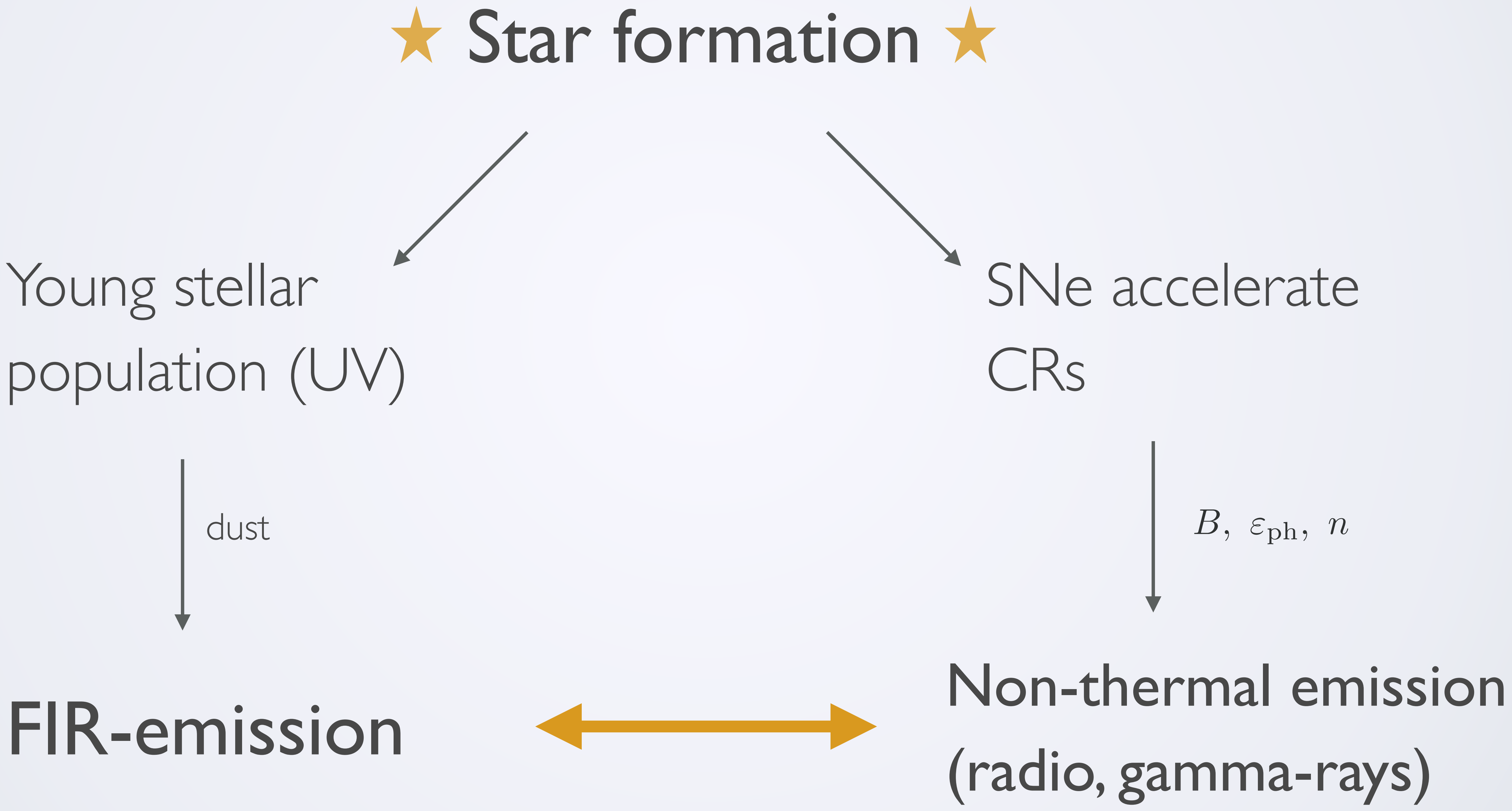
  - Bremsstrahlung




Predehl+ (2010)

cyan: eROSITA 0.6–1-keV band, **red**: GeV emission (Fermi bubbles)

CRs and non-thermal emission in galaxies



★ **Star formation** ★

Young stellar population (UV)

SNe accelerate CRs

dust

$B, \ \varepsilon_{\mathrm{ph}}, \ n$

FIR-emission

Non-thermal emission (radio, gamma-rays)

Non-thermal emission in star-forming galaxies

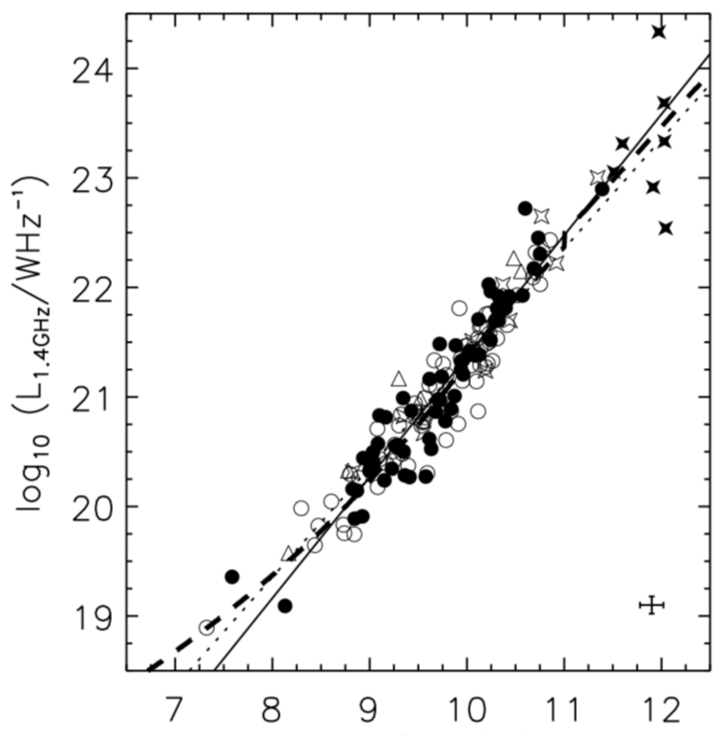
Observations:

- **FIR-Radio Relation**

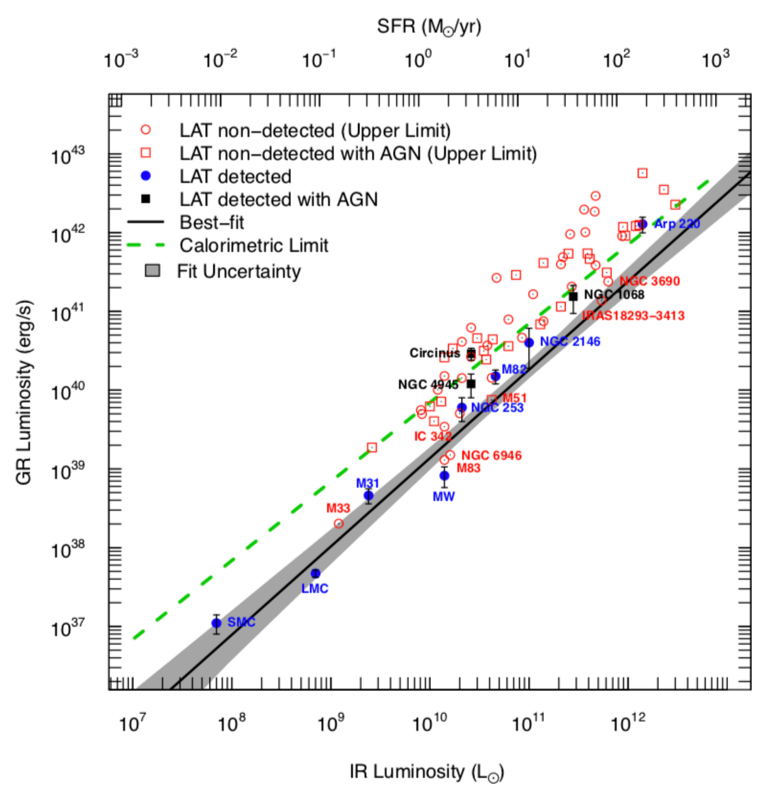
  (van der Kruit 1971; Condon 1992; Yun+2001; Bell 2003)

- **FIR-γ-Ray Relation**

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



Bell (2003)



Rojas-Bravo & Araya (2016)

suggest calorimetry

too steep radio spectra?

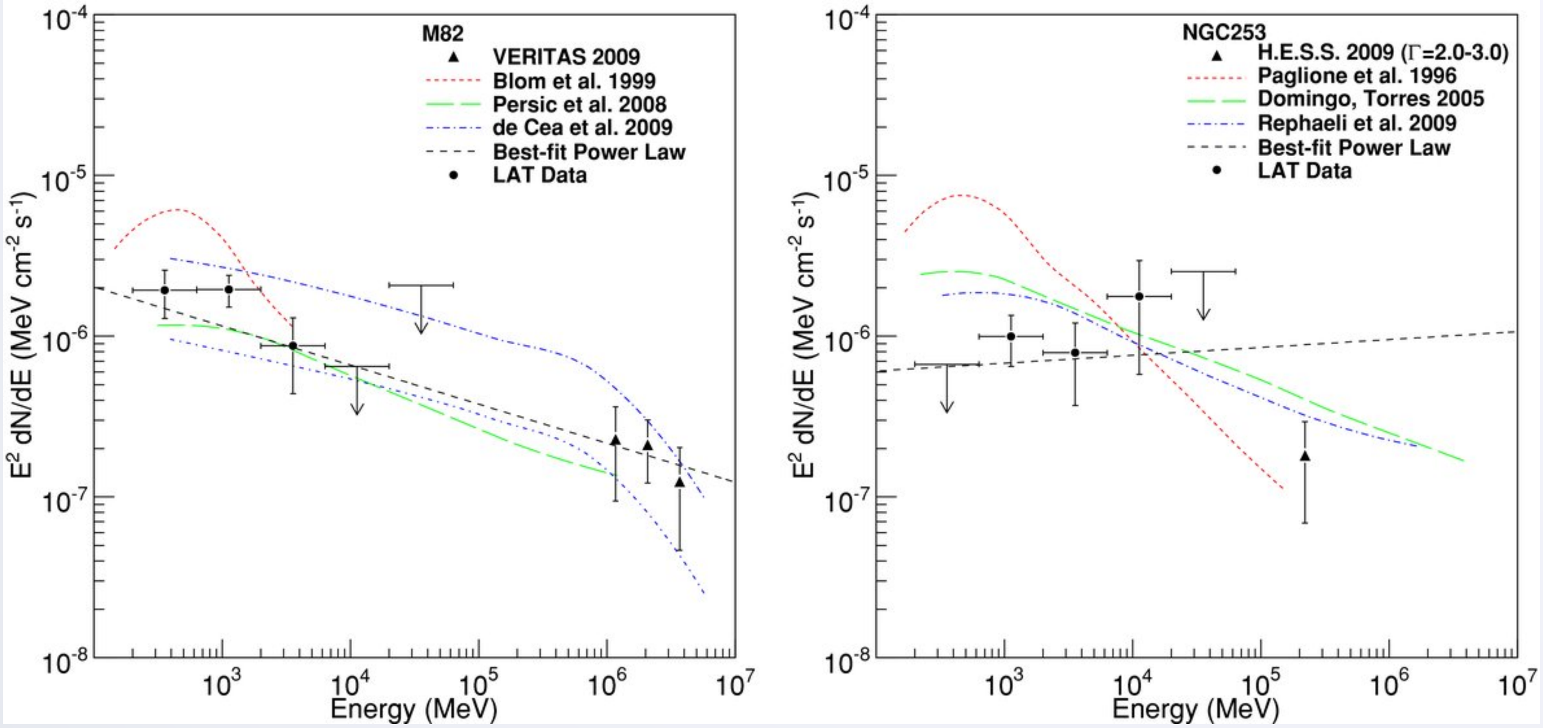
What about other proton losses (e.g. diffusion)?
What about IC emission?

Any energy left for feedback?

Non-thermal emission in star-forming galaxies

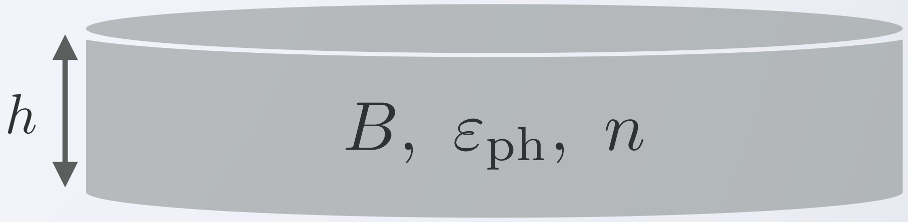
Theoretical models to explain observations:

- static MW models (GALPROP, Strong & Moskalenko 1998; DRAGON, Evoli+. 2008; PICARD, Kissmann 2014)
- 1D transport models (Heesen+ 2016; Miskolczi+ 2019)
- one-zone steady-state models (Lacki+ 2010,2011; Yoast-Hull+ 2013)



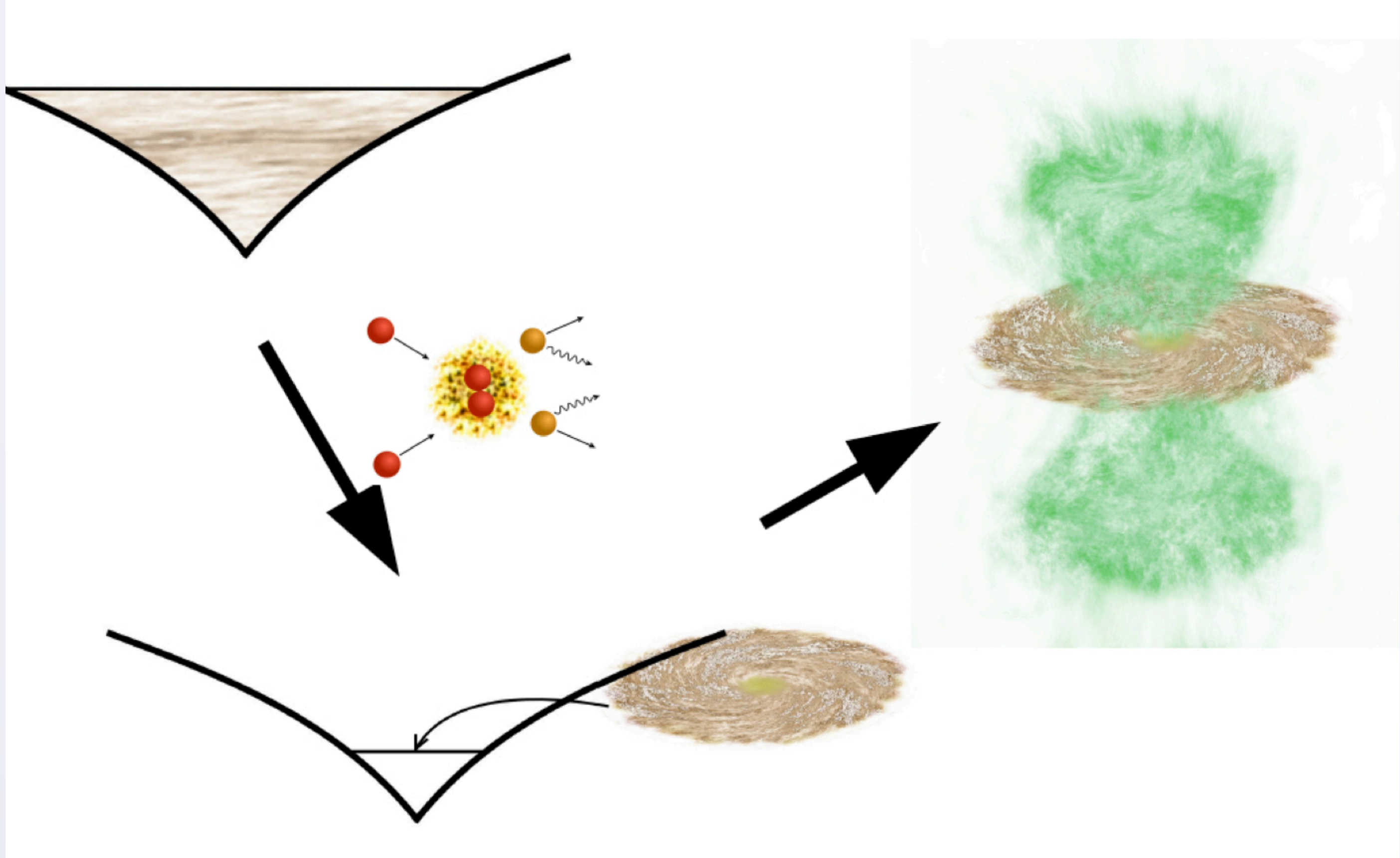
Fermi-LAT (Abdo+ 2009)

One-zone models:



3D MHD Simulations

- **AREPO simulations** of isolated galactic disks, with different:
  - halo masses $(10^{10} - 10^{12})\mathrm{M}_{\odot}$
  - concentration parameters
  - initial magnetic field $B_0 = \{10^{-10}, 10^{-12}\}\,\mathrm{G}$



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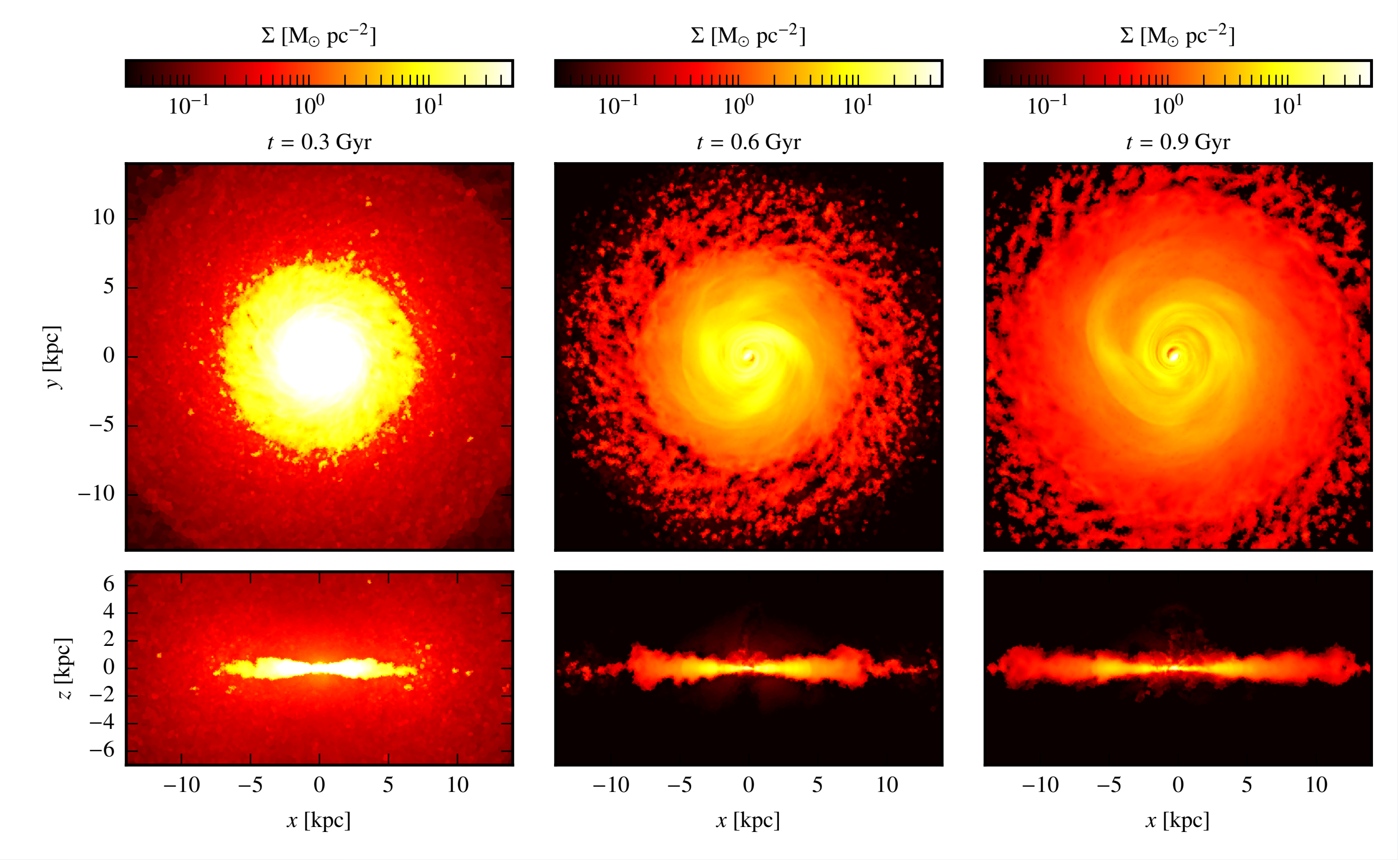

Werhahn et al. (2021a)

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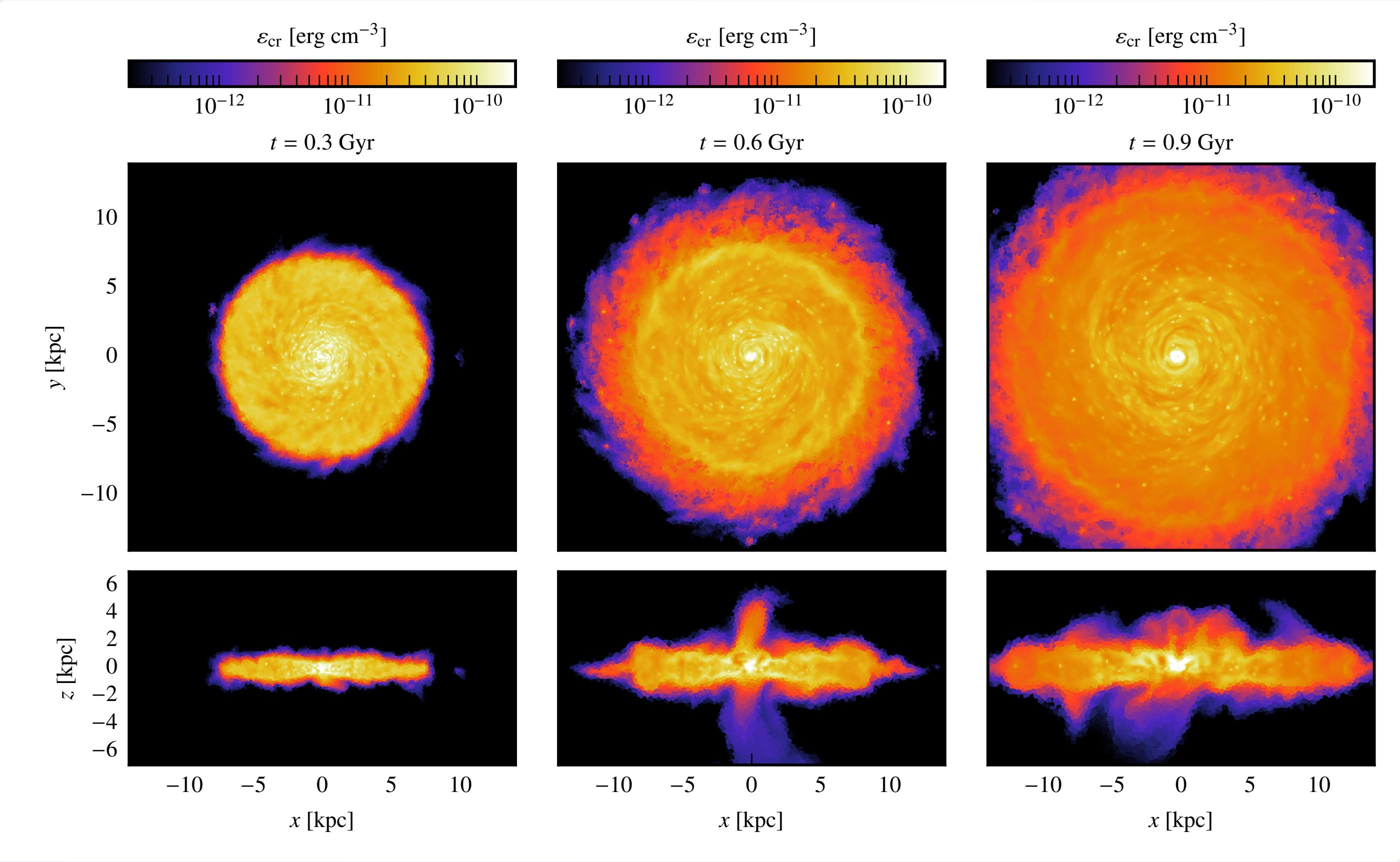
  - initial magnetic field $B_0 = \{10^{-10}, 10^{-12}\}\,\mathrm{G}$
  - injection efficiency of CRs $\zeta_\mathrm{SN} = 5 - 10\%$
  - CR transport (advection, advection + diffusion)



Werhahn et al. (2021a)

CR modeling

$$\frac{f(E)}{\tau_{\mathrm{esc}}} - \frac{\mathrm{d}}{\mathrm{d}E}\left[f(E)b(E)\right] = q(E)$$

- **CR steady-state spectra** in each cell (post-processing)
  - **Protons:** $\tau_{\mathrm{Coul,p}} \propto \frac{E_{\mathrm{p}}}{n_{\mathrm{e}}}$

    $\tau_{\pi} \propto \frac{1}{n_{\mathrm{N}}}$
  - **Electrons:** $\tau_{\mathrm{Coul,e}} \propto \frac{E_{\mathrm{e}}}{n_{\mathrm{p}}}$

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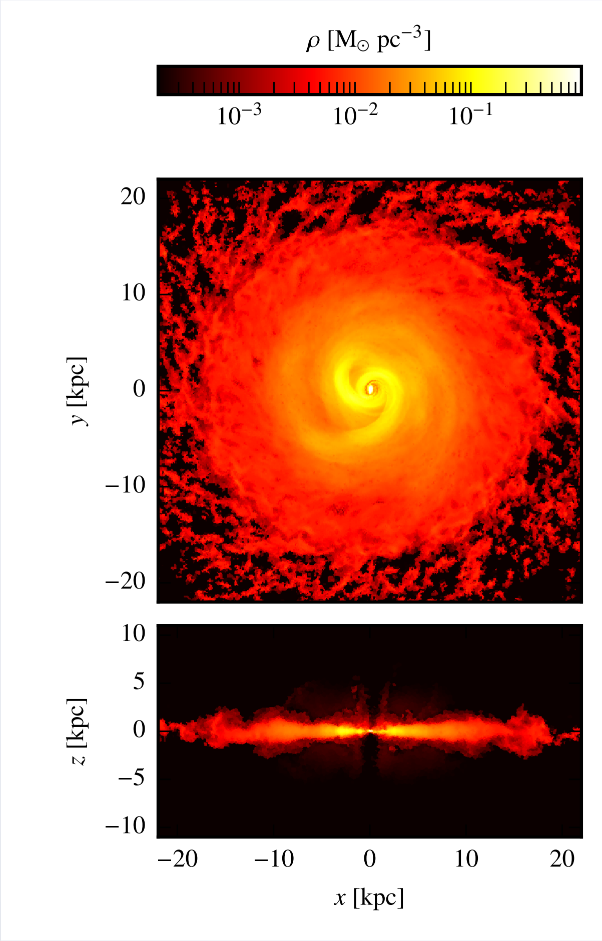

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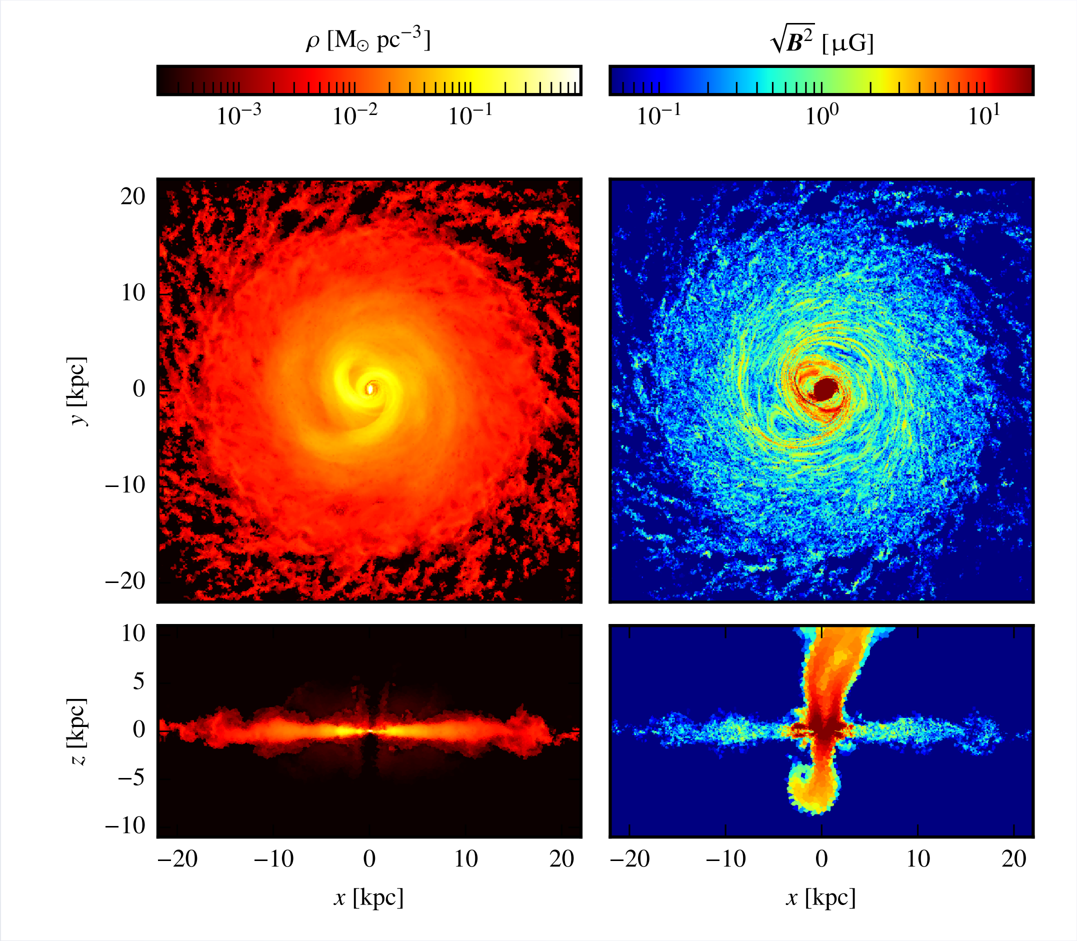

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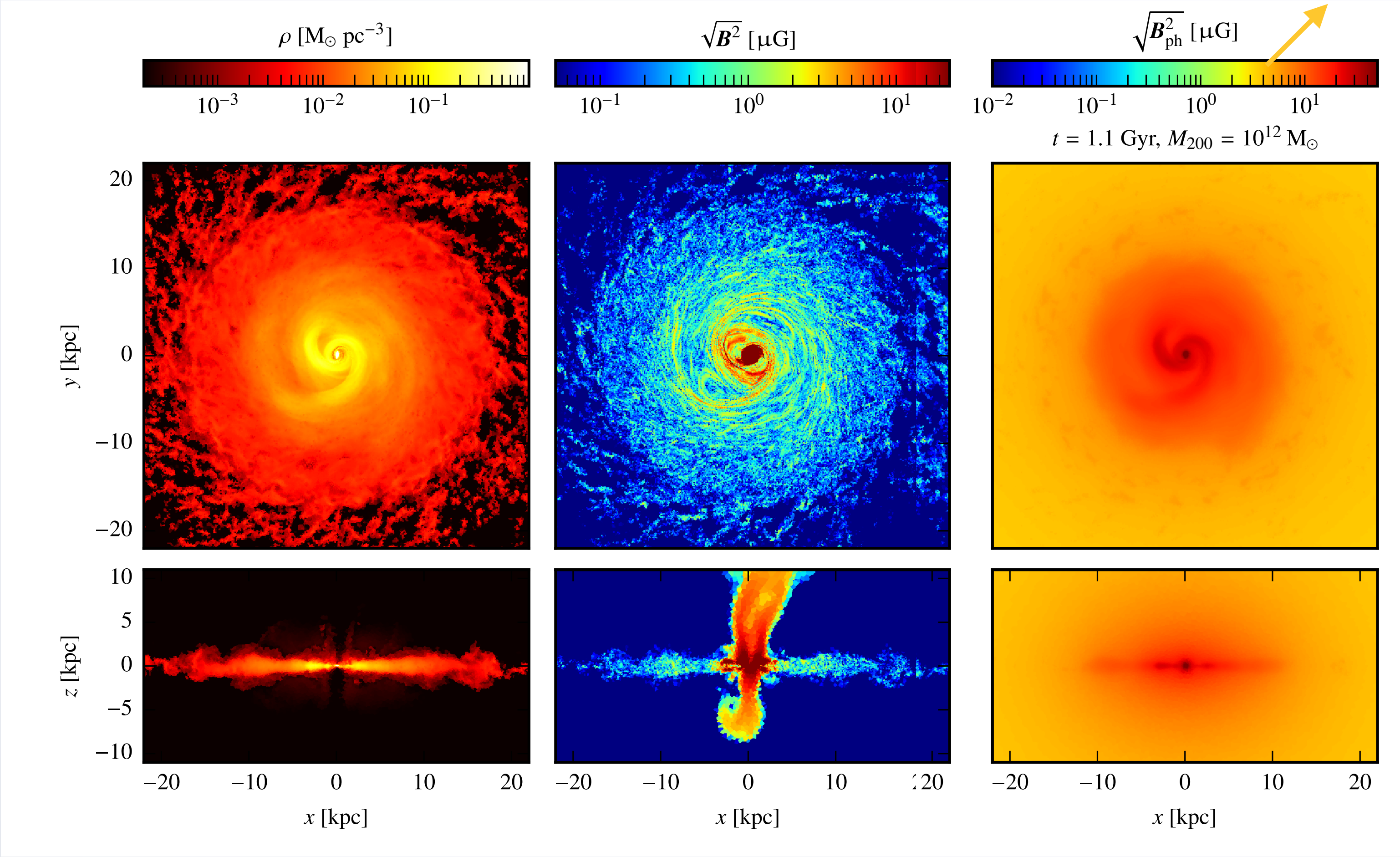
$$\frac{B_{\mathrm{ph}}^2}{8\pi} = \varepsilon_{\mathrm{ph}} = \varepsilon_* + \varepsilon_{\mathrm{CMB}}$$

$B_{\mathrm{CMB}} \approx 3\,\mu\mathrm{G}$



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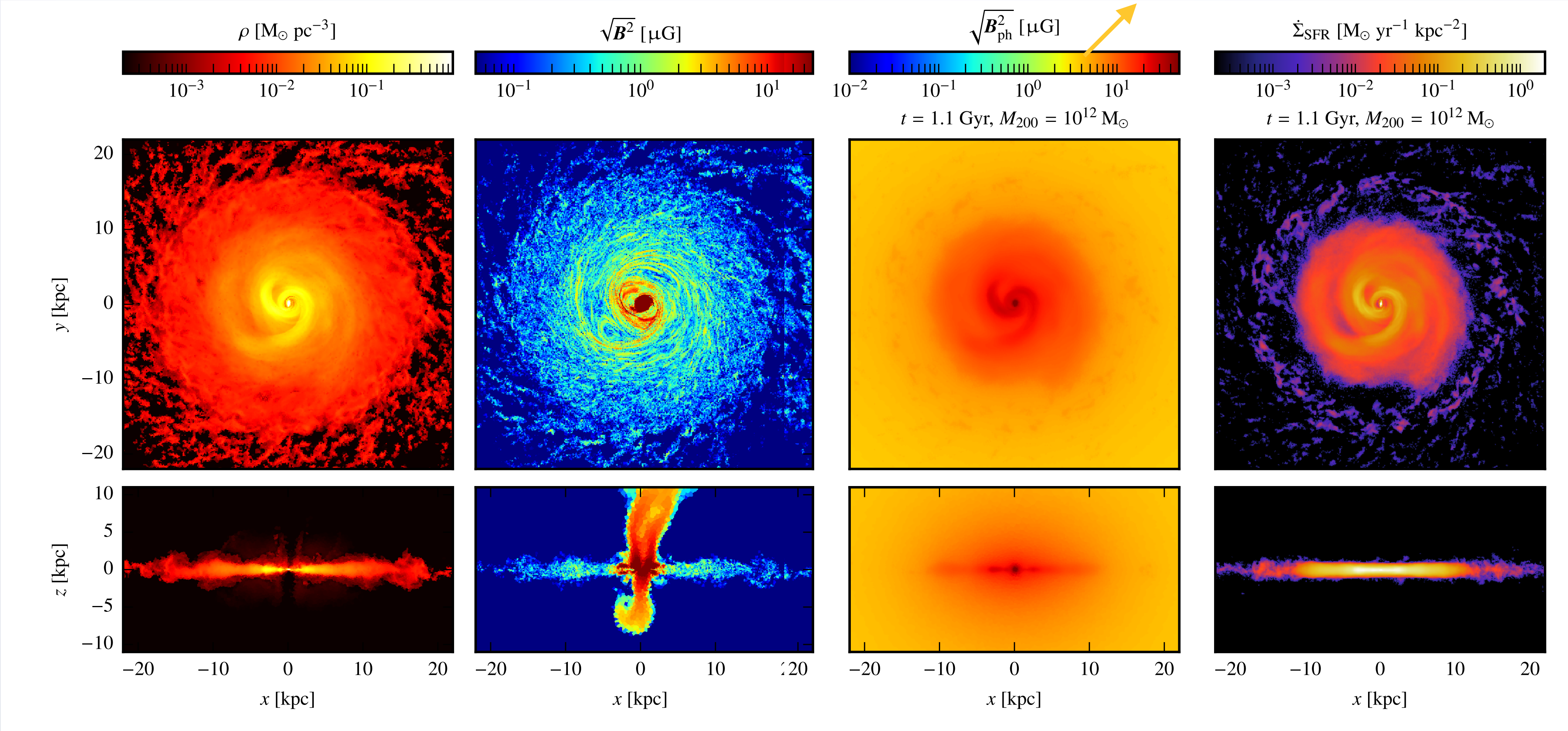

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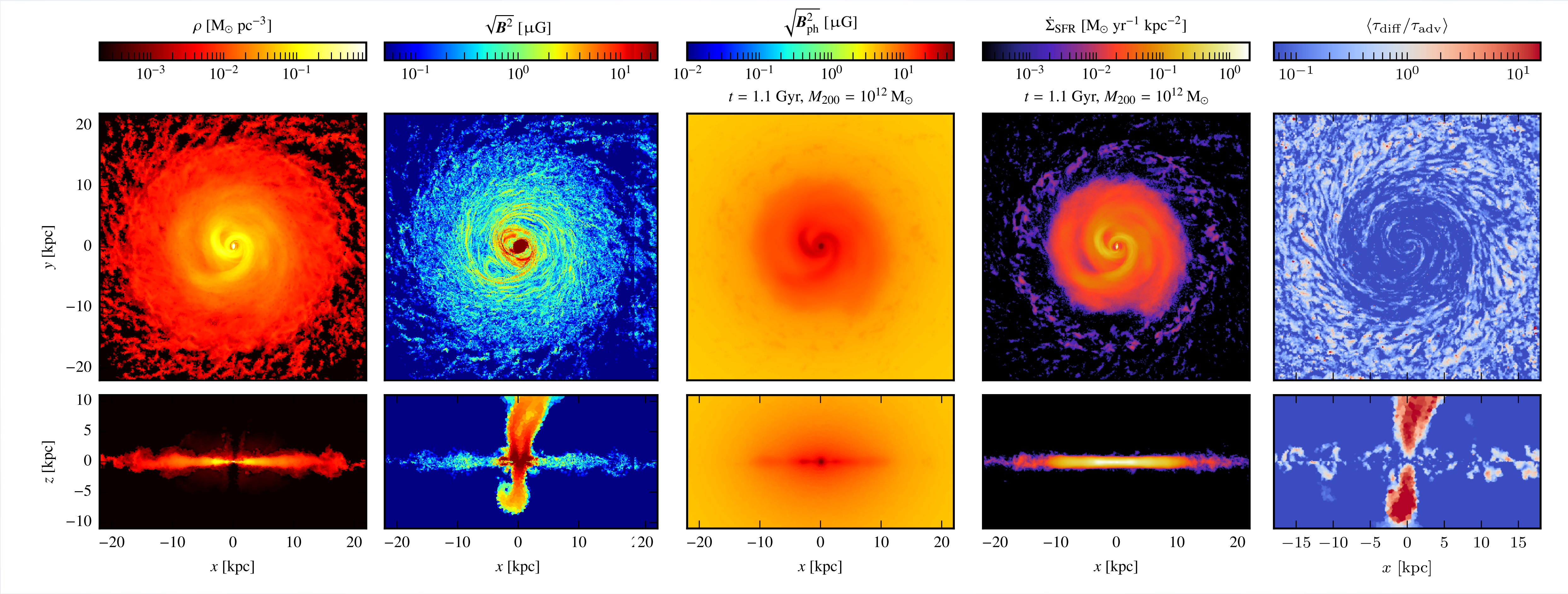

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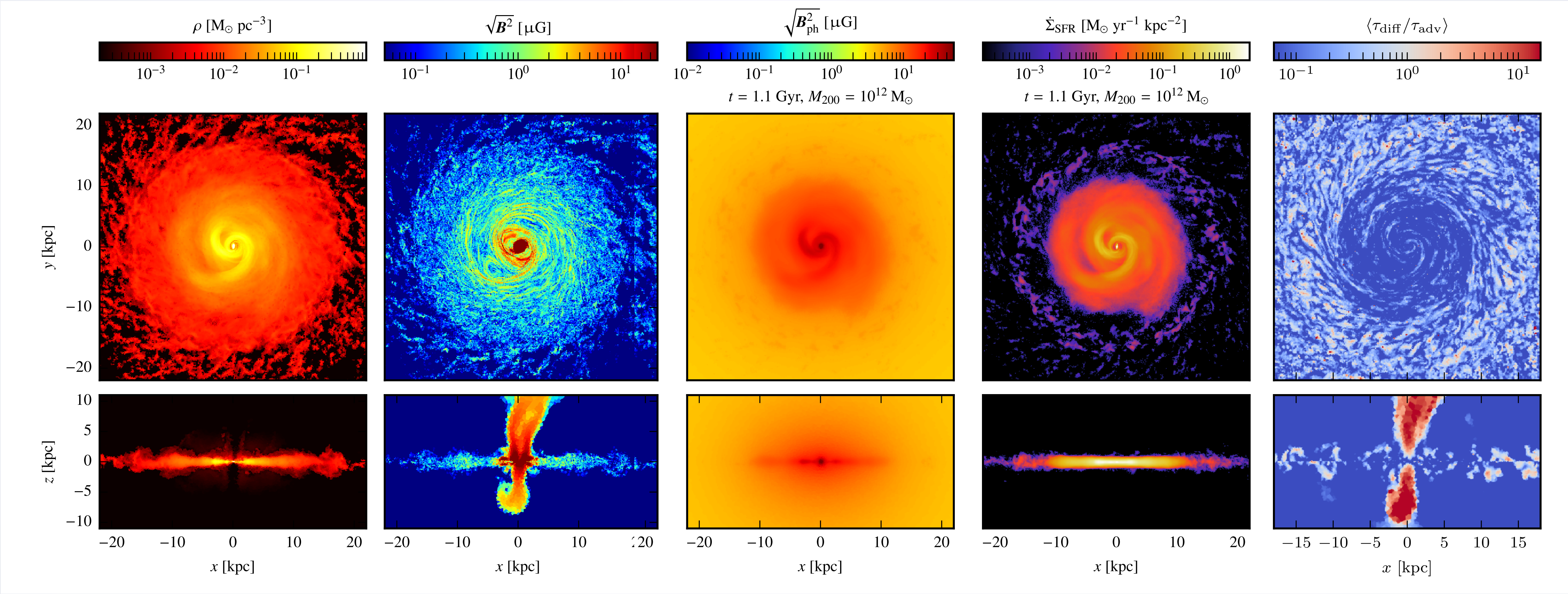
$$D \propto E^{\delta}$$



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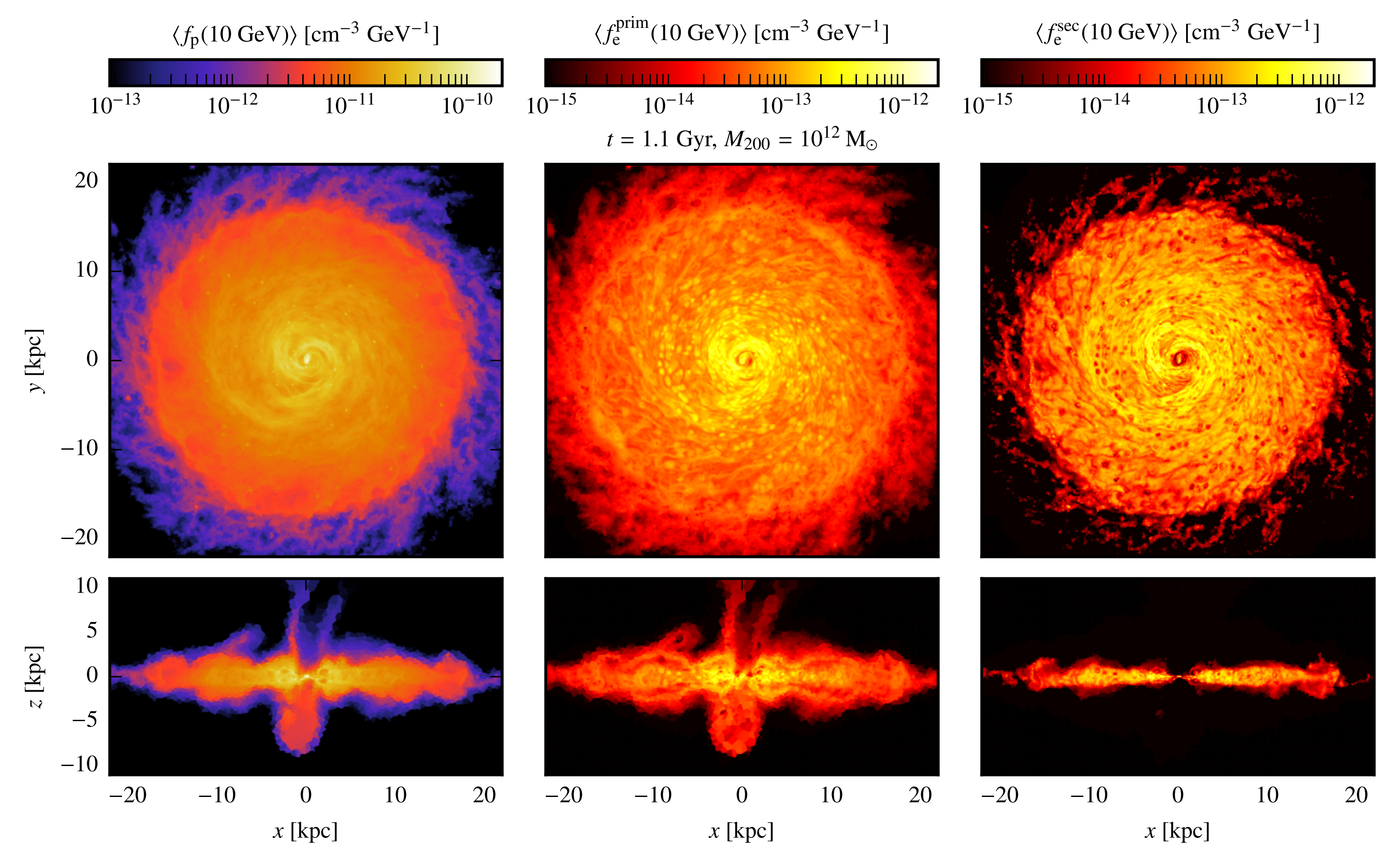
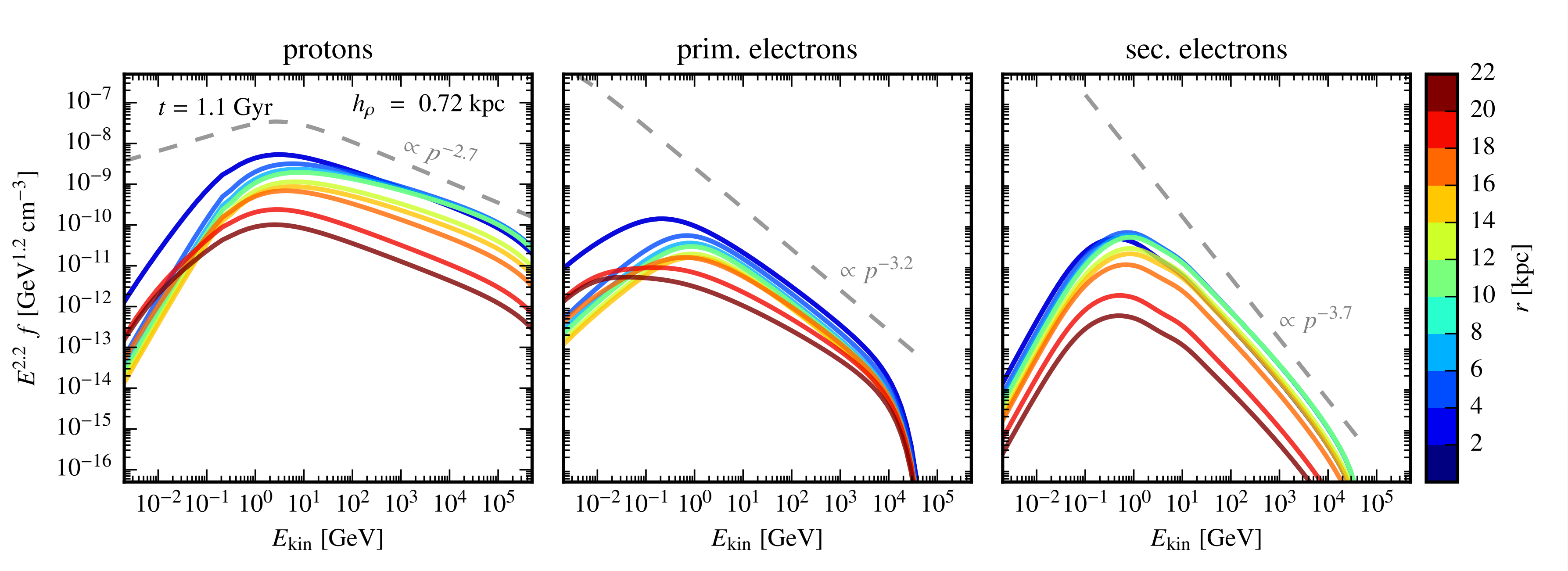
CR spectra & maps





$\alpha_{\mathrm{inj}} = 2.2$

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Werhahn et al. (2021a)

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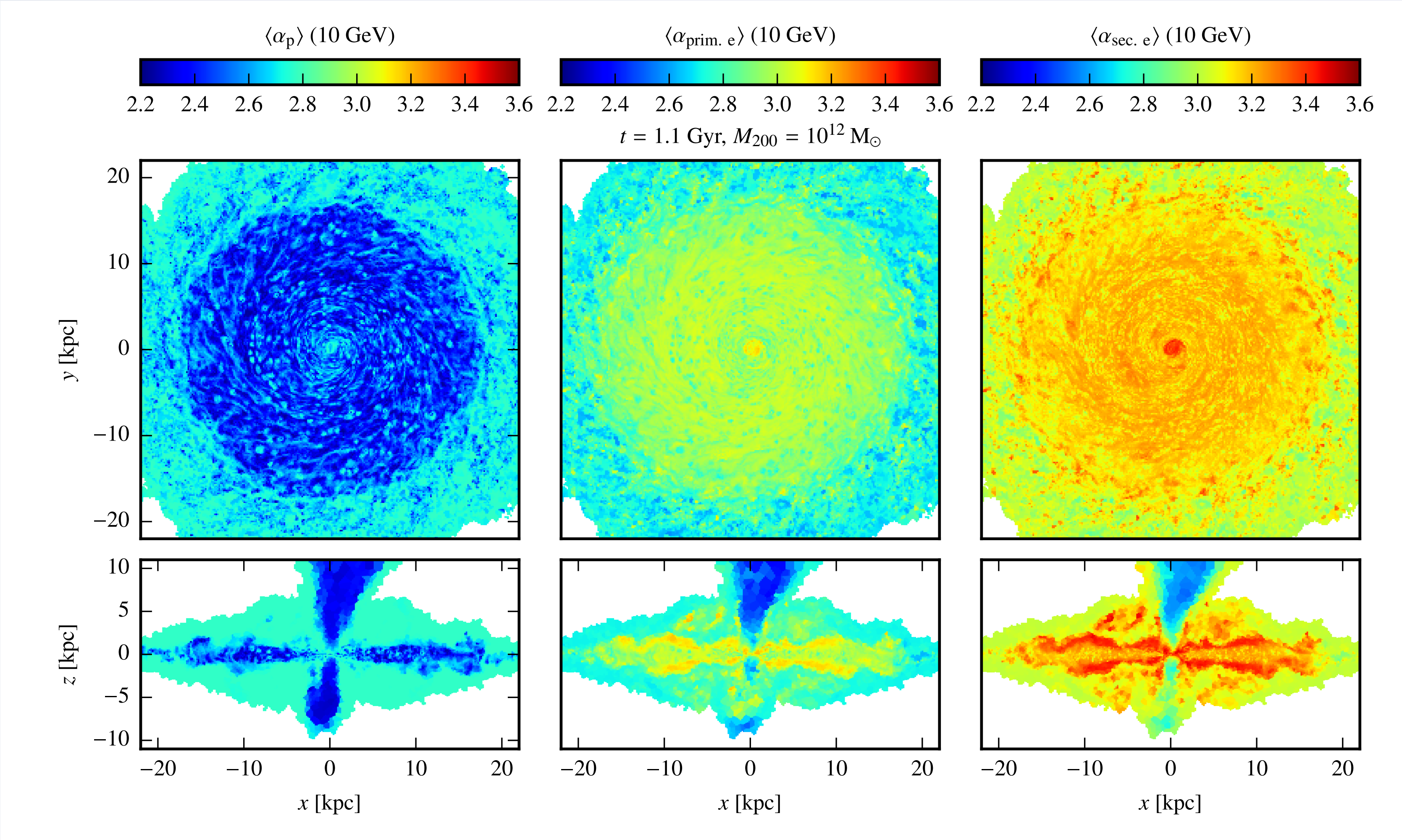

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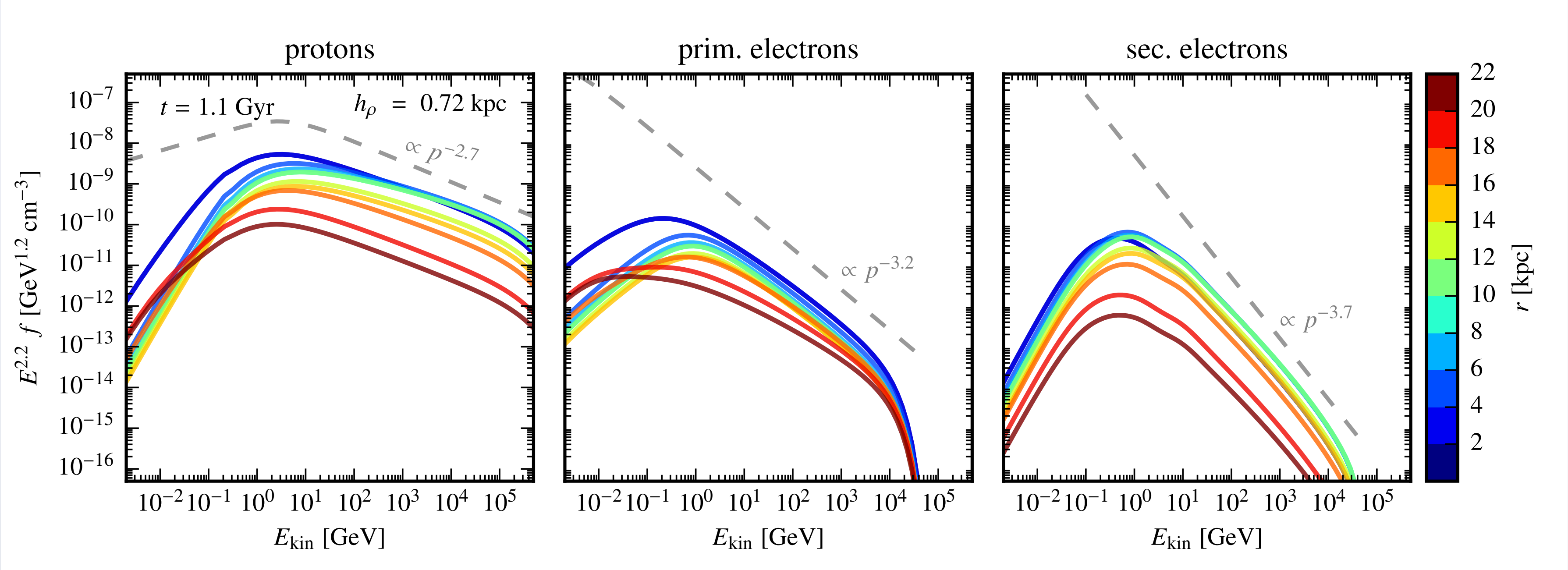
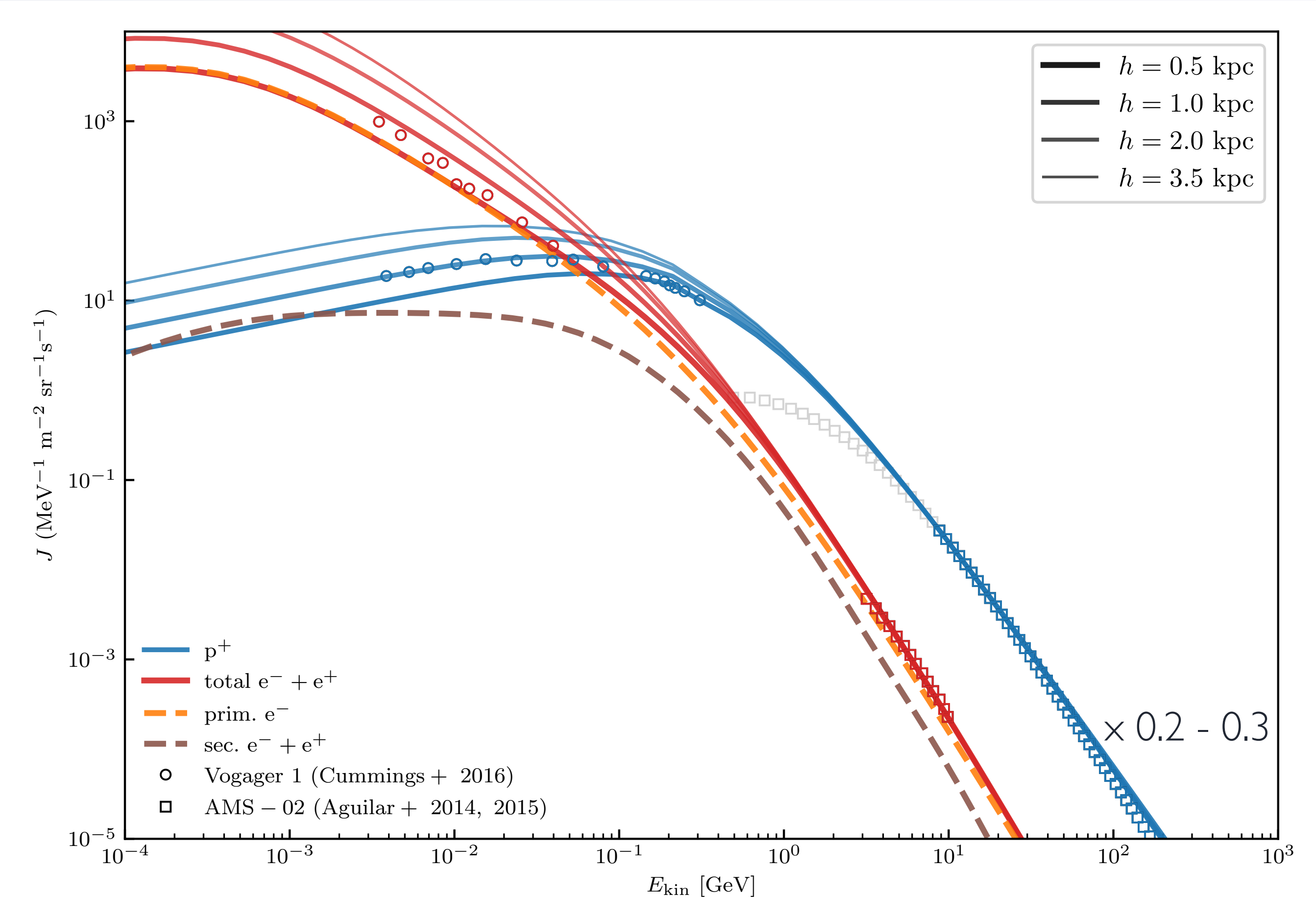


Werhahn et al. (2021a)

I) CR spectra - Voyager and AMS-02



At low energies (< 1GeV):

Coulomb cooling dominates

$$b_{\rm Coul,p} = \frac{3\sigma_{\rm T} n_{\rm e} m_{\rm e} c^3}{\boxed{2\beta}} \left[\ln\left(\frac{2\gamma m_{\rm e} c^2 \beta^2}{\hbar\omega_{\rm pl}}\right) - \frac{\beta^2}{2} \right]$$

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Werhahn et al. (2021a)

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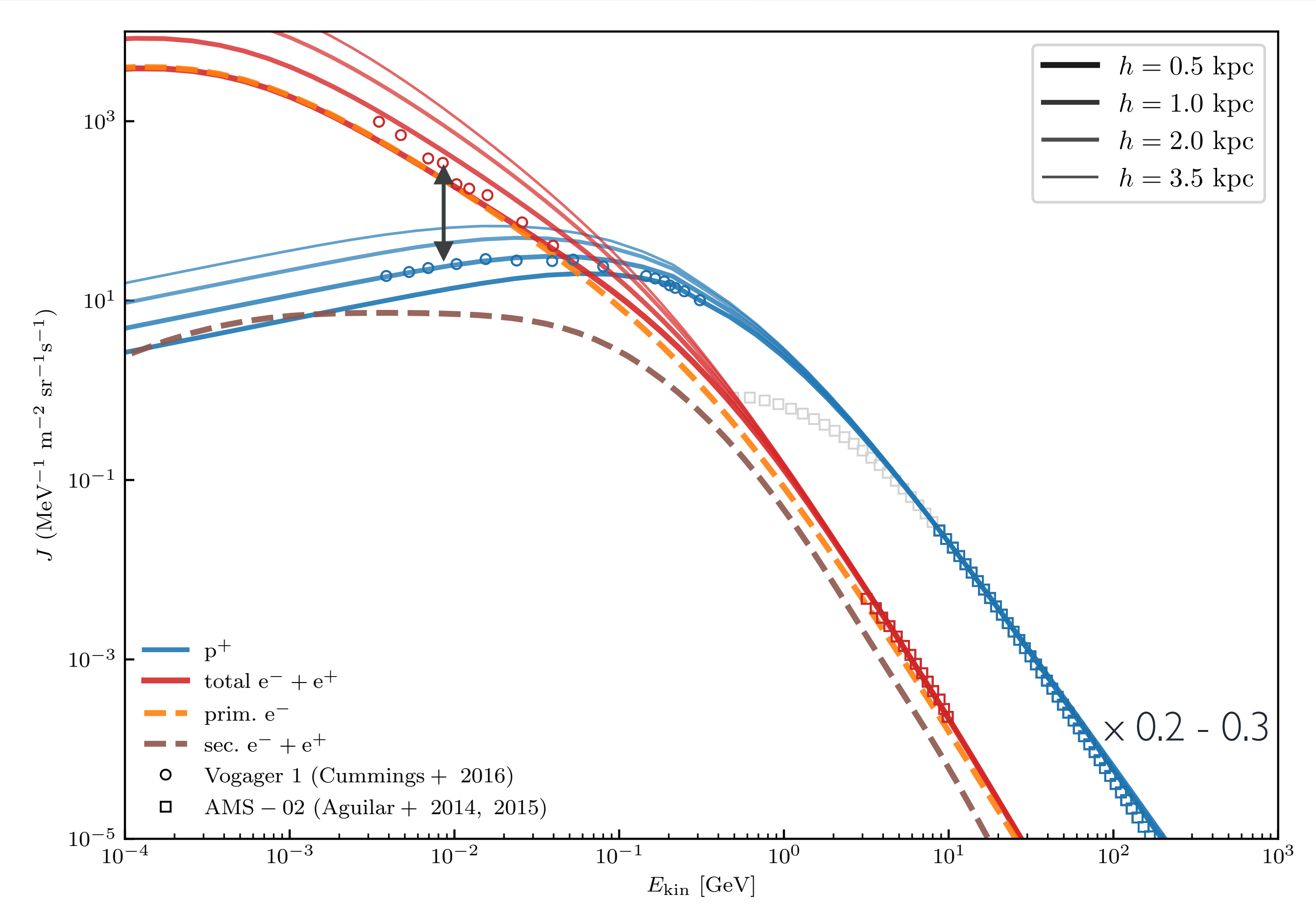

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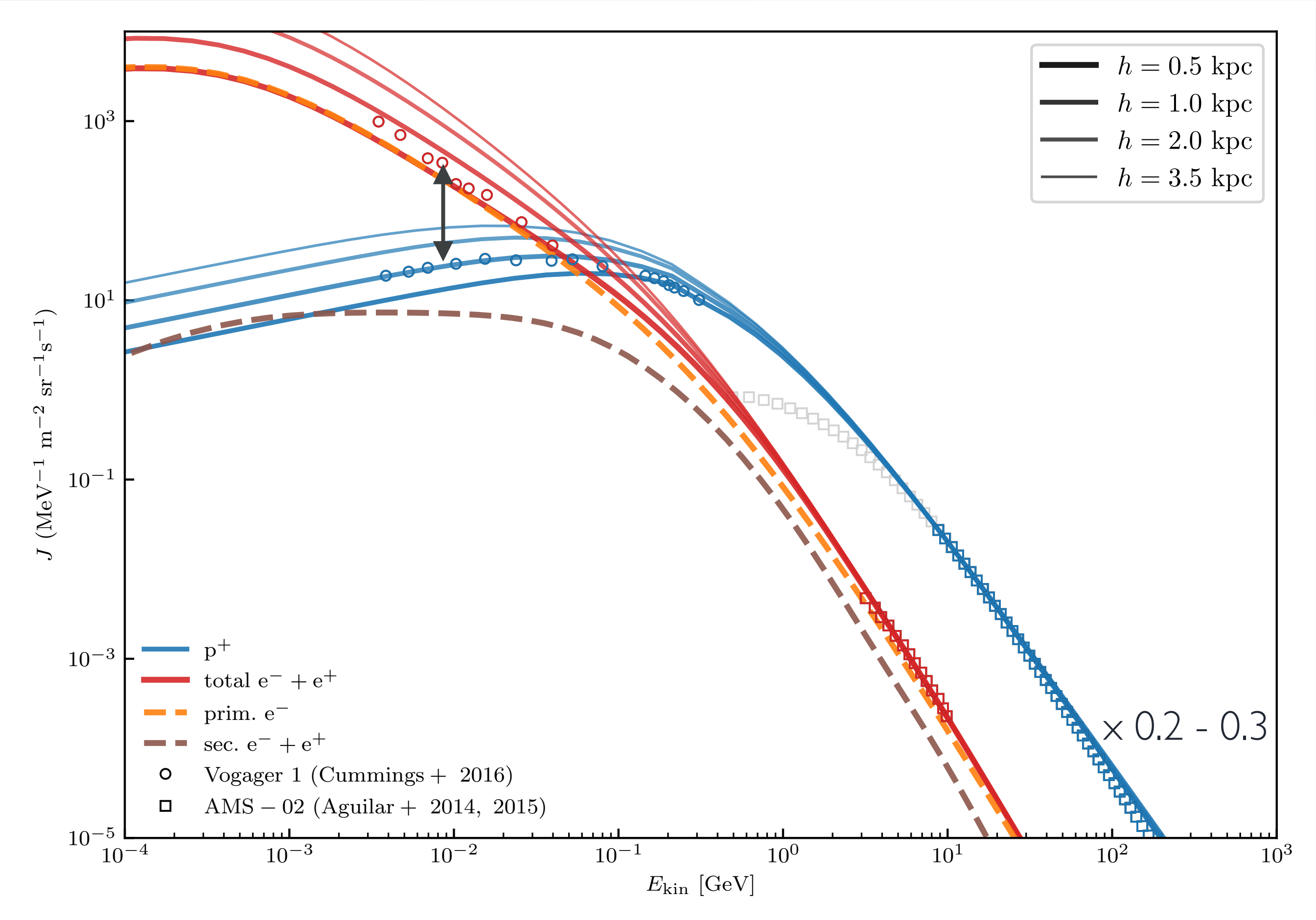

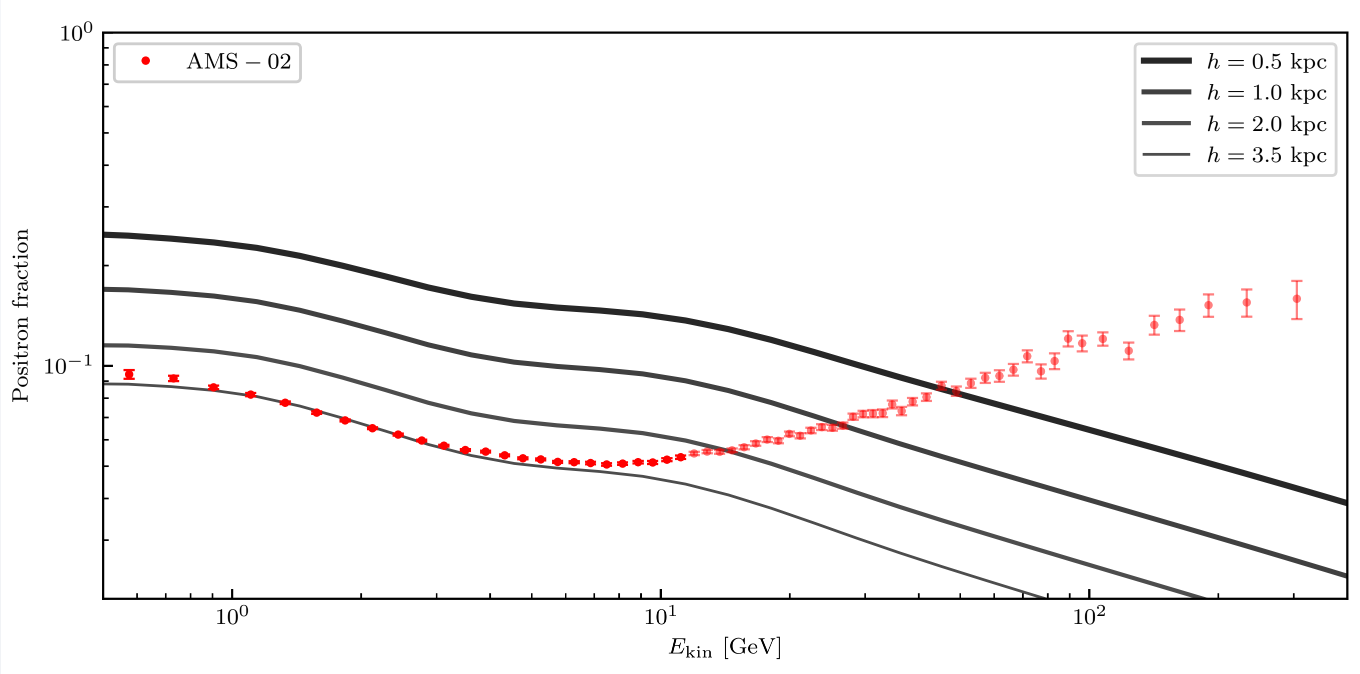

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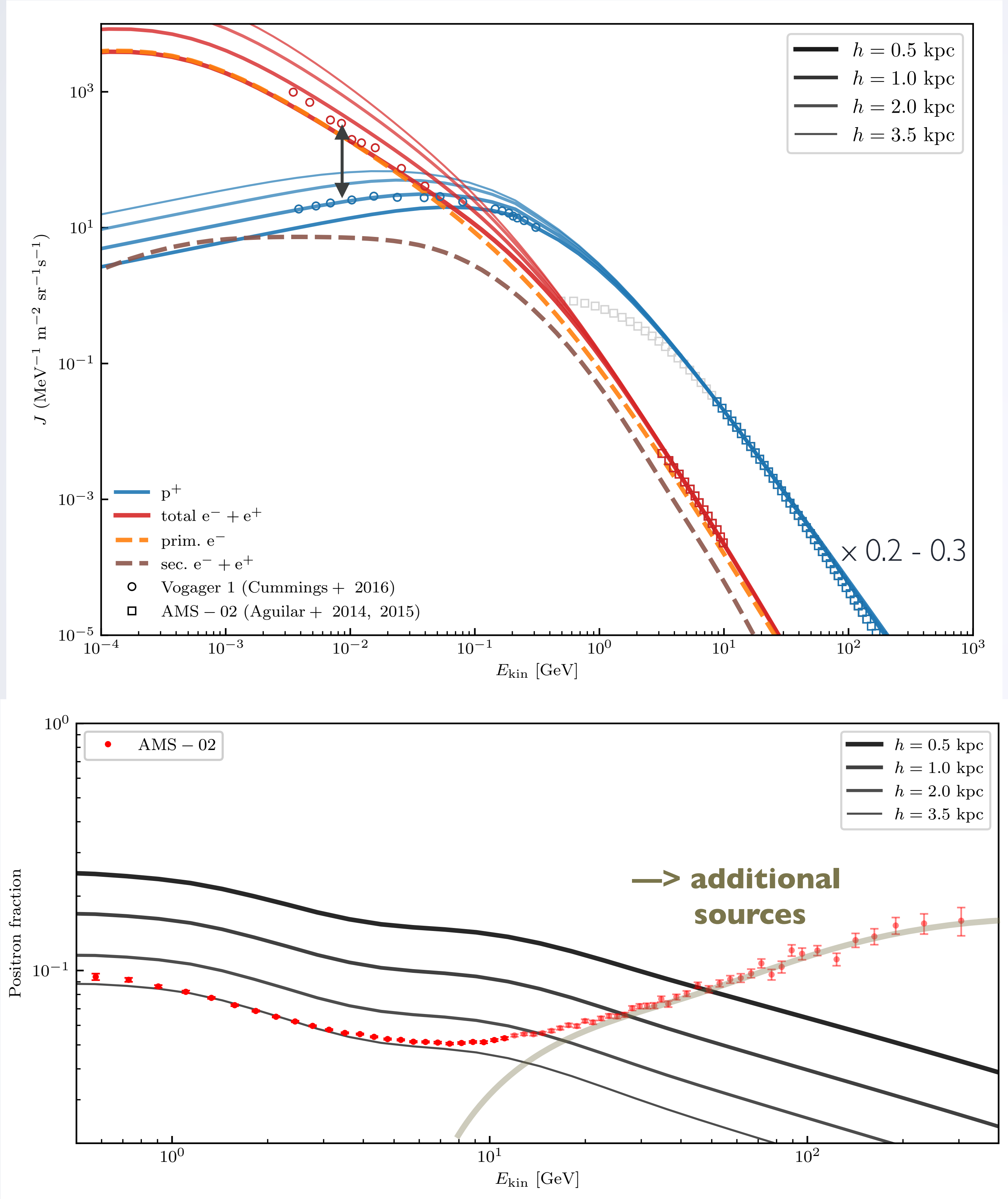

—> additional sources

Werhahn et al. (2021a)

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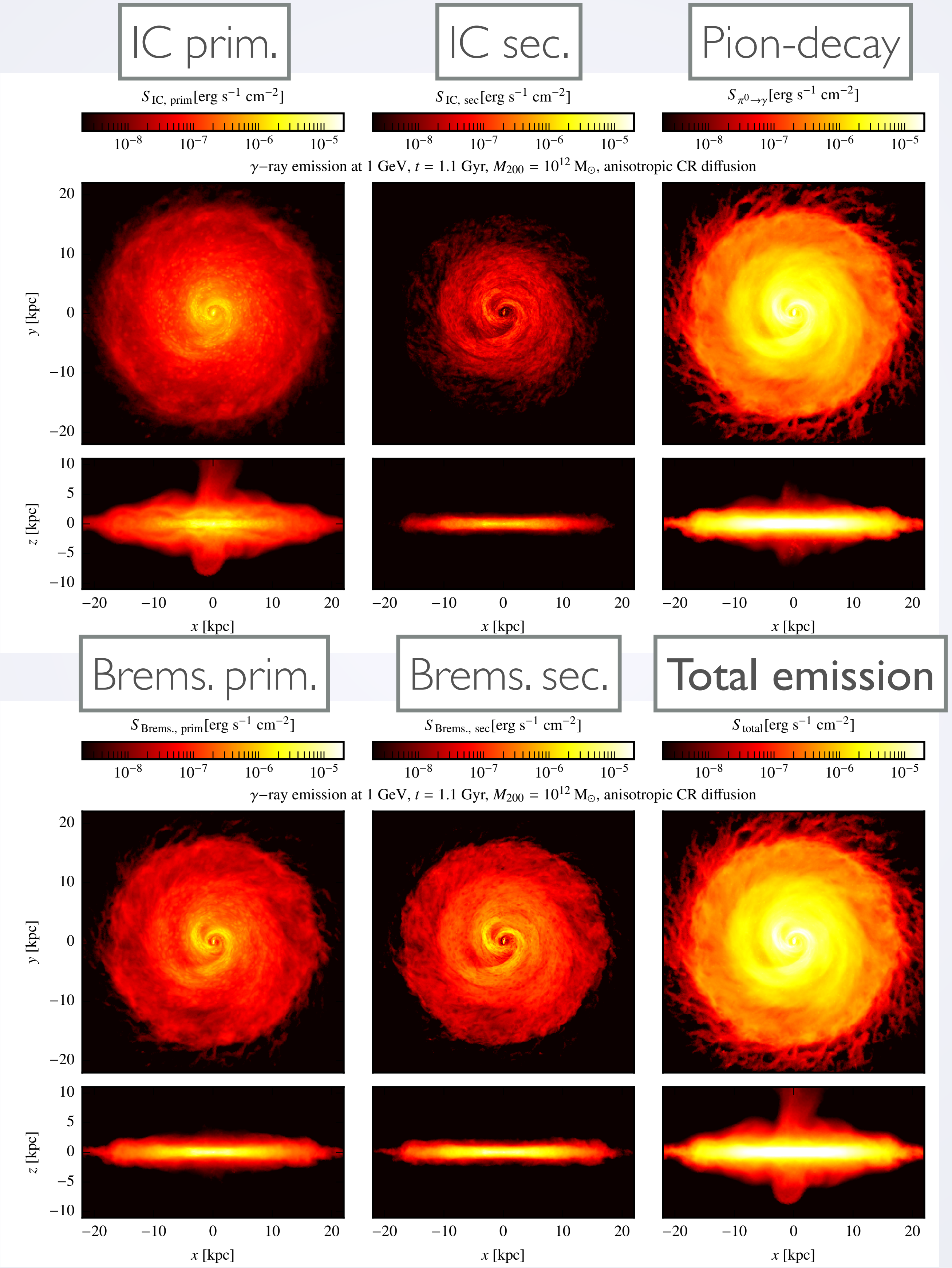
- Astrophysical sources (pulsars, SNe)

(e.g. Serpico 2012; Di Mauro et al. 2017; Hooper et al. 2009; Mertsch et al. 2020)

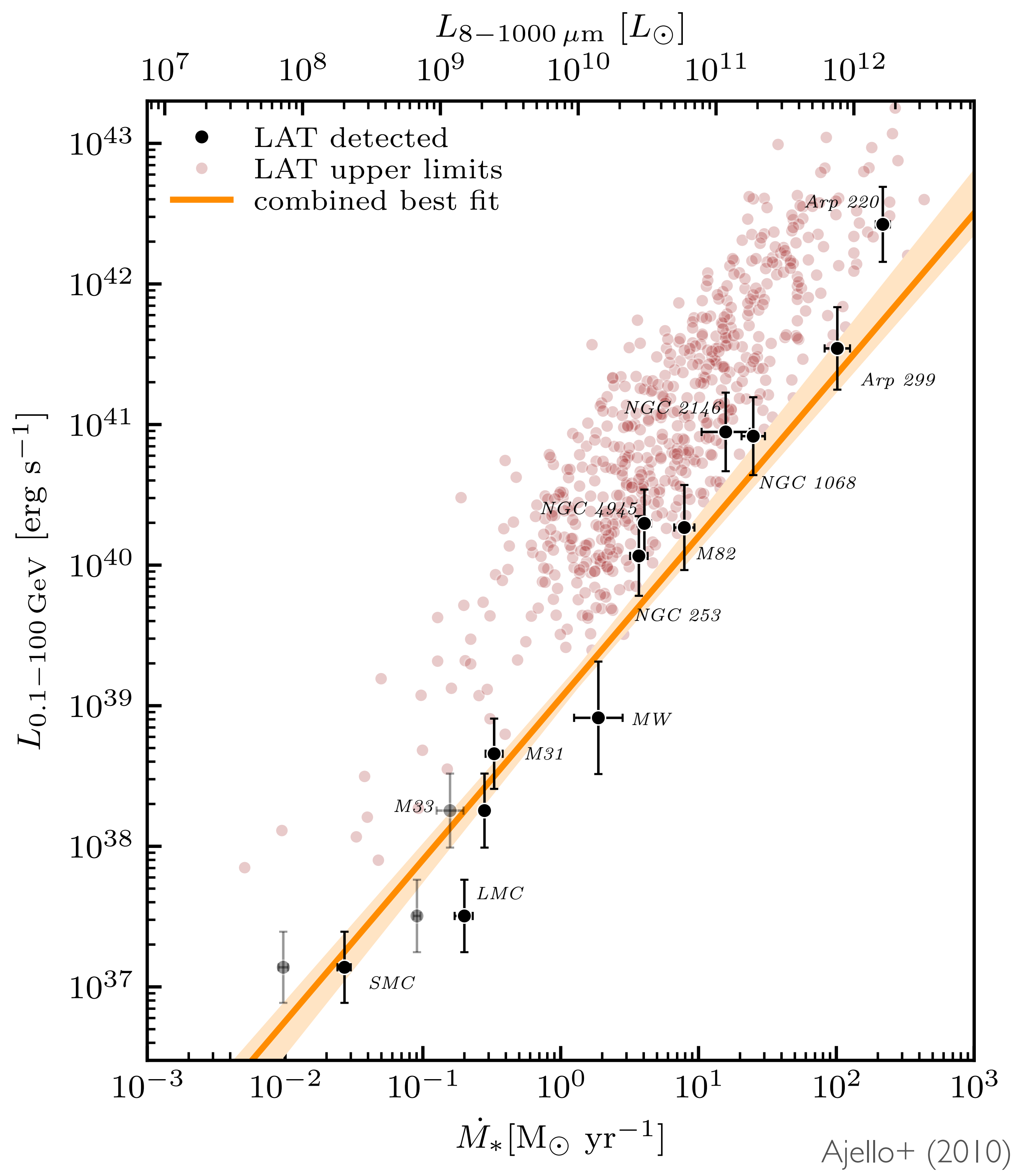
II) γ-ray emission

maps at 1GeV:



Werhahn et al. (2021b)

II) FIR - γ-ray Relation



Ajello+ (2010)

Werhahn et al. (2021b)

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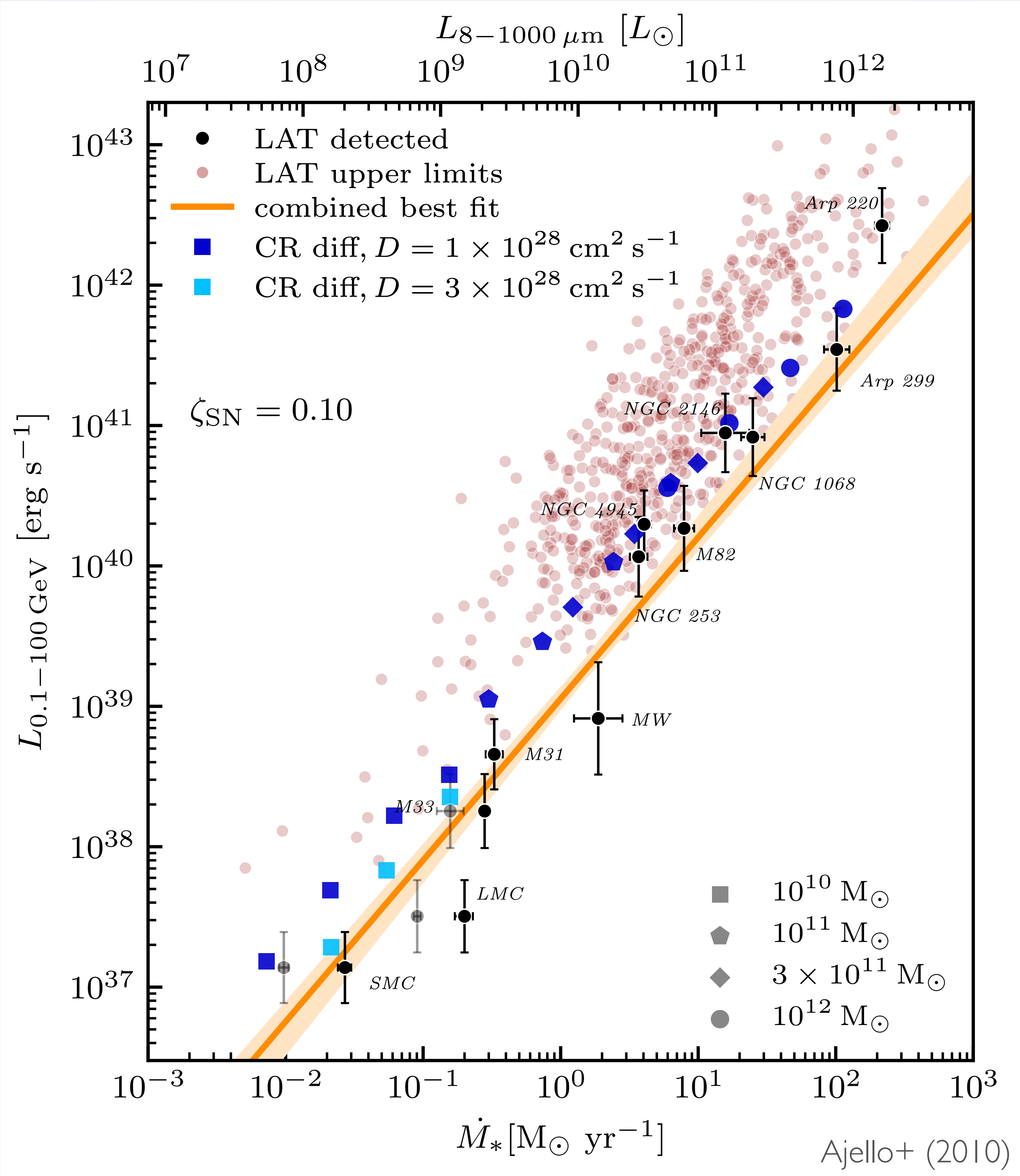

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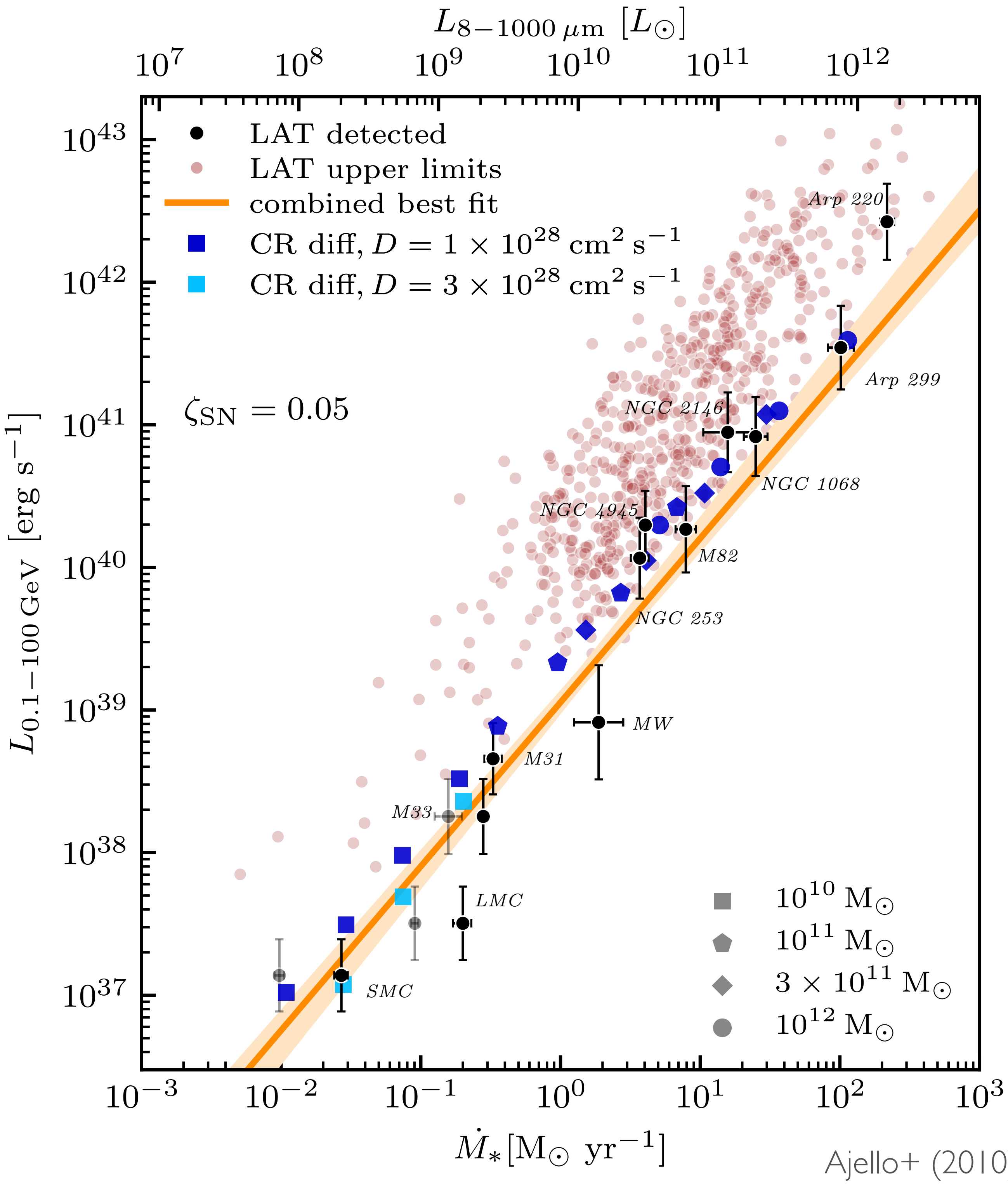

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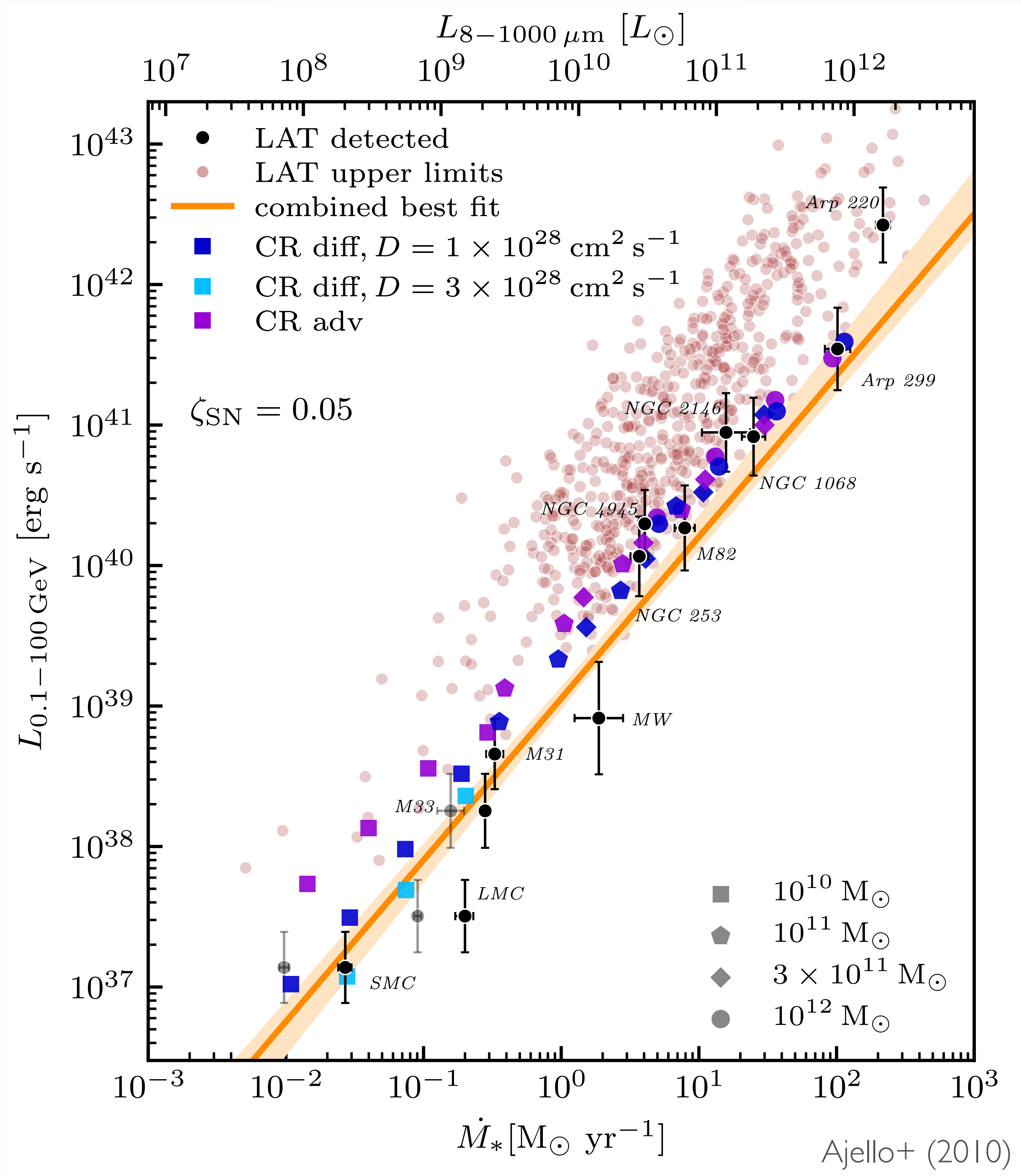

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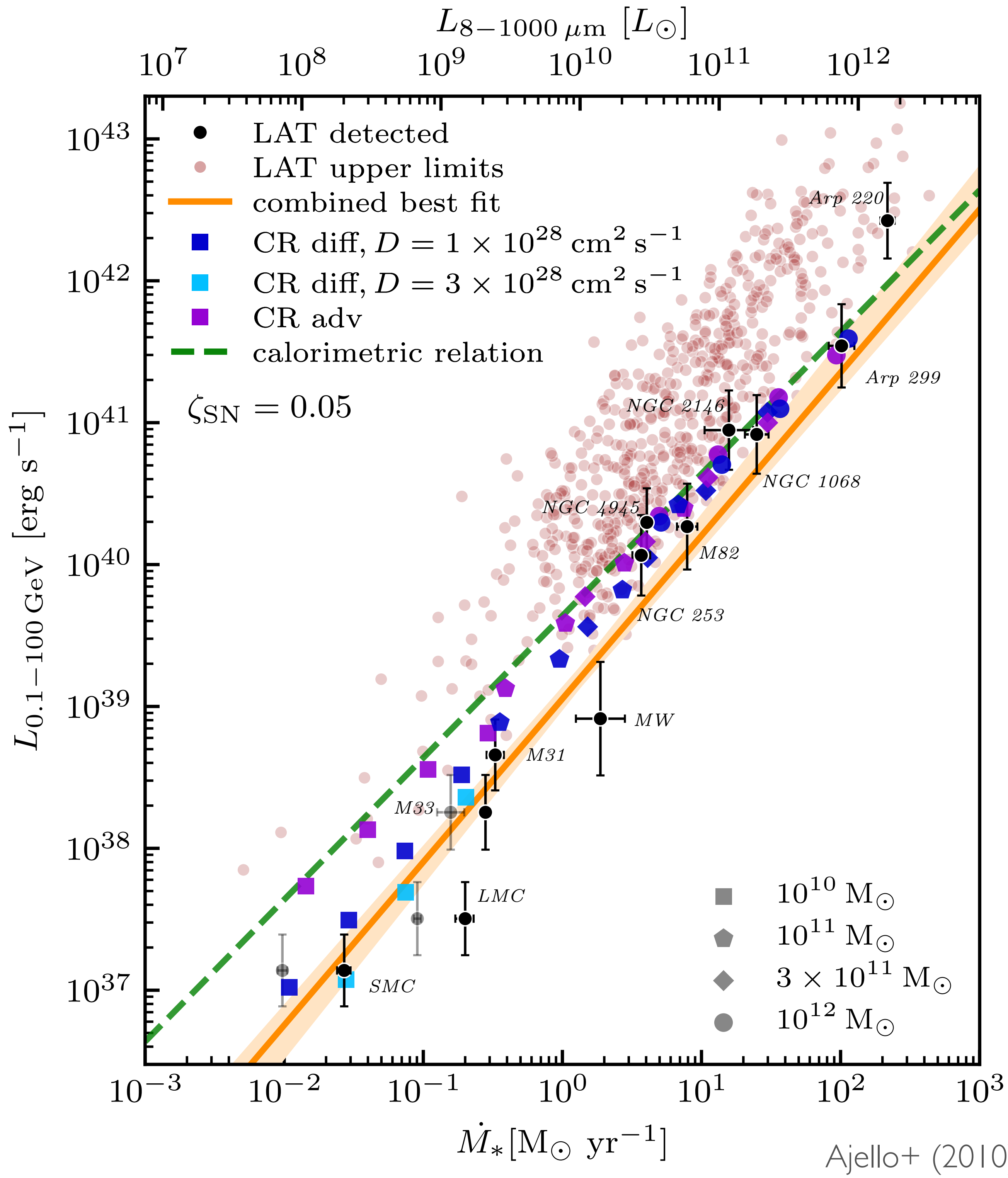

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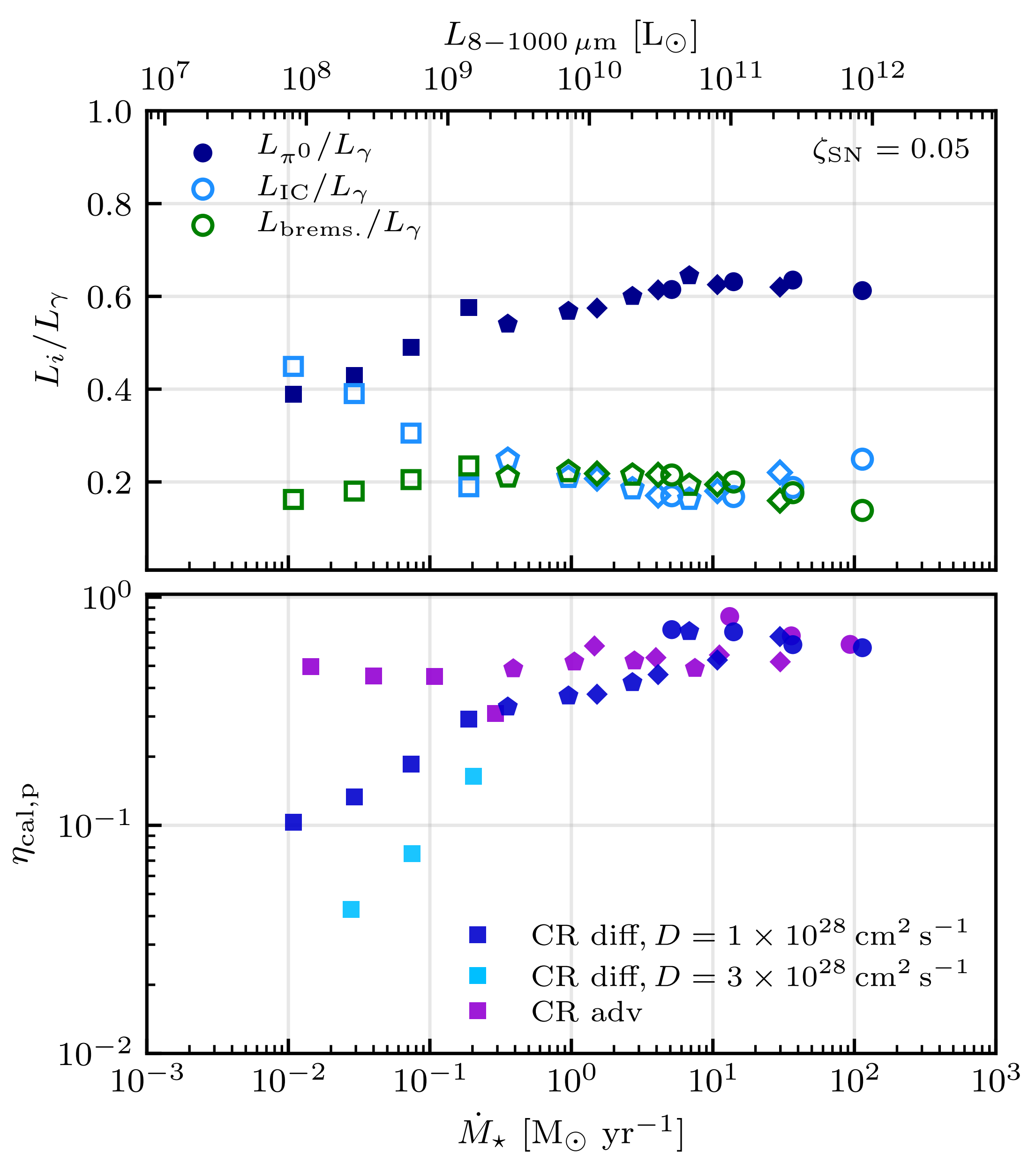

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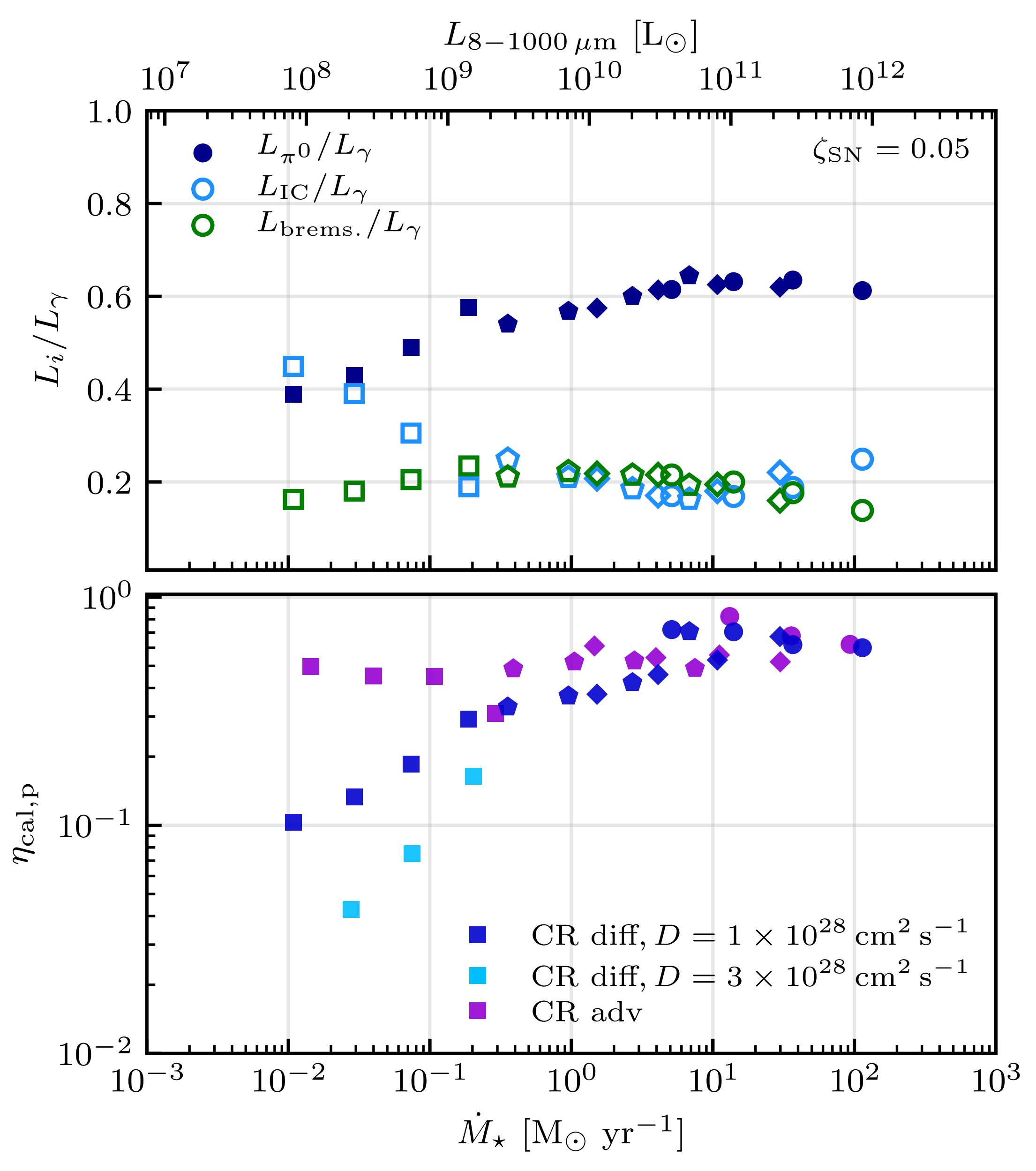

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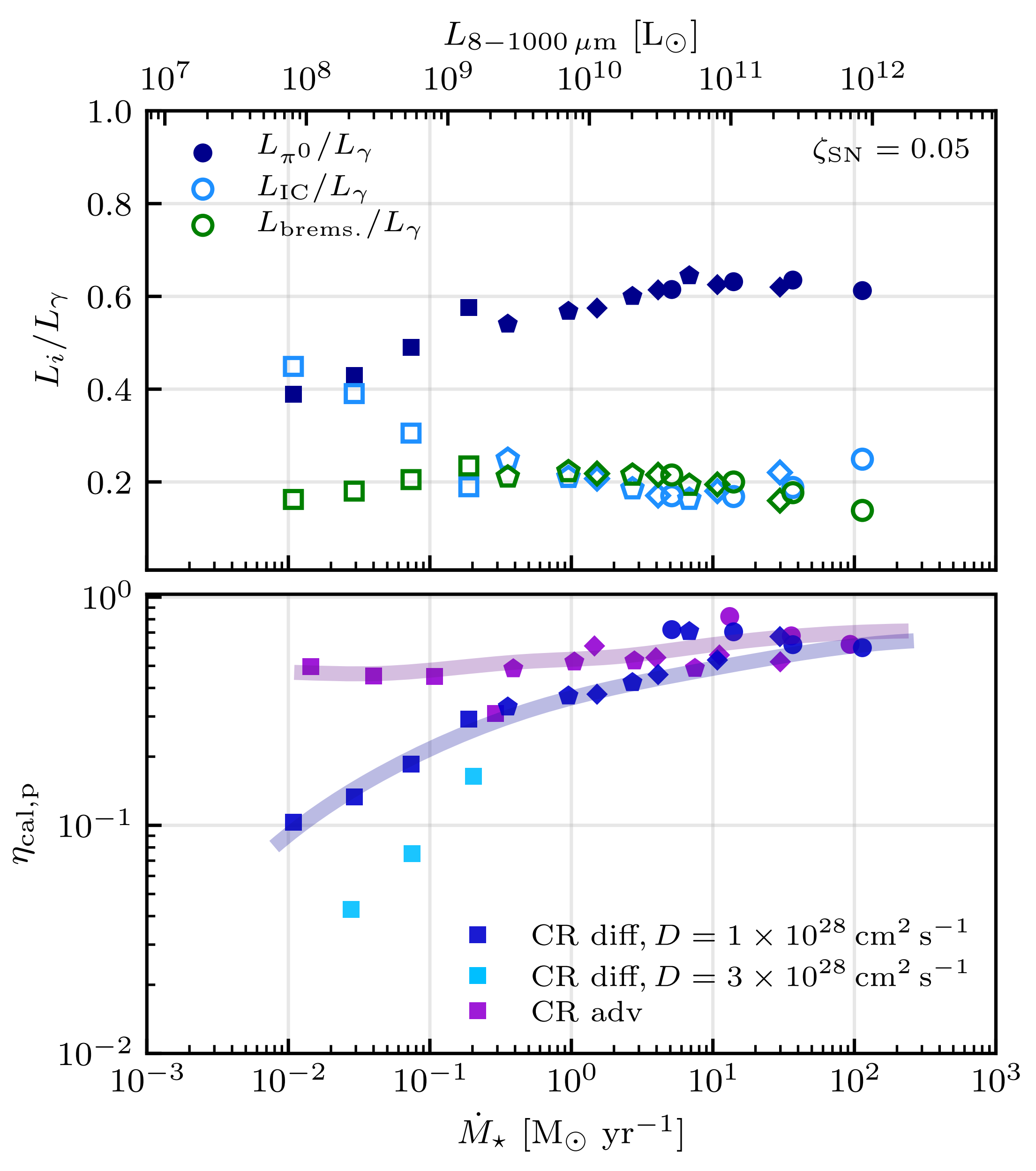

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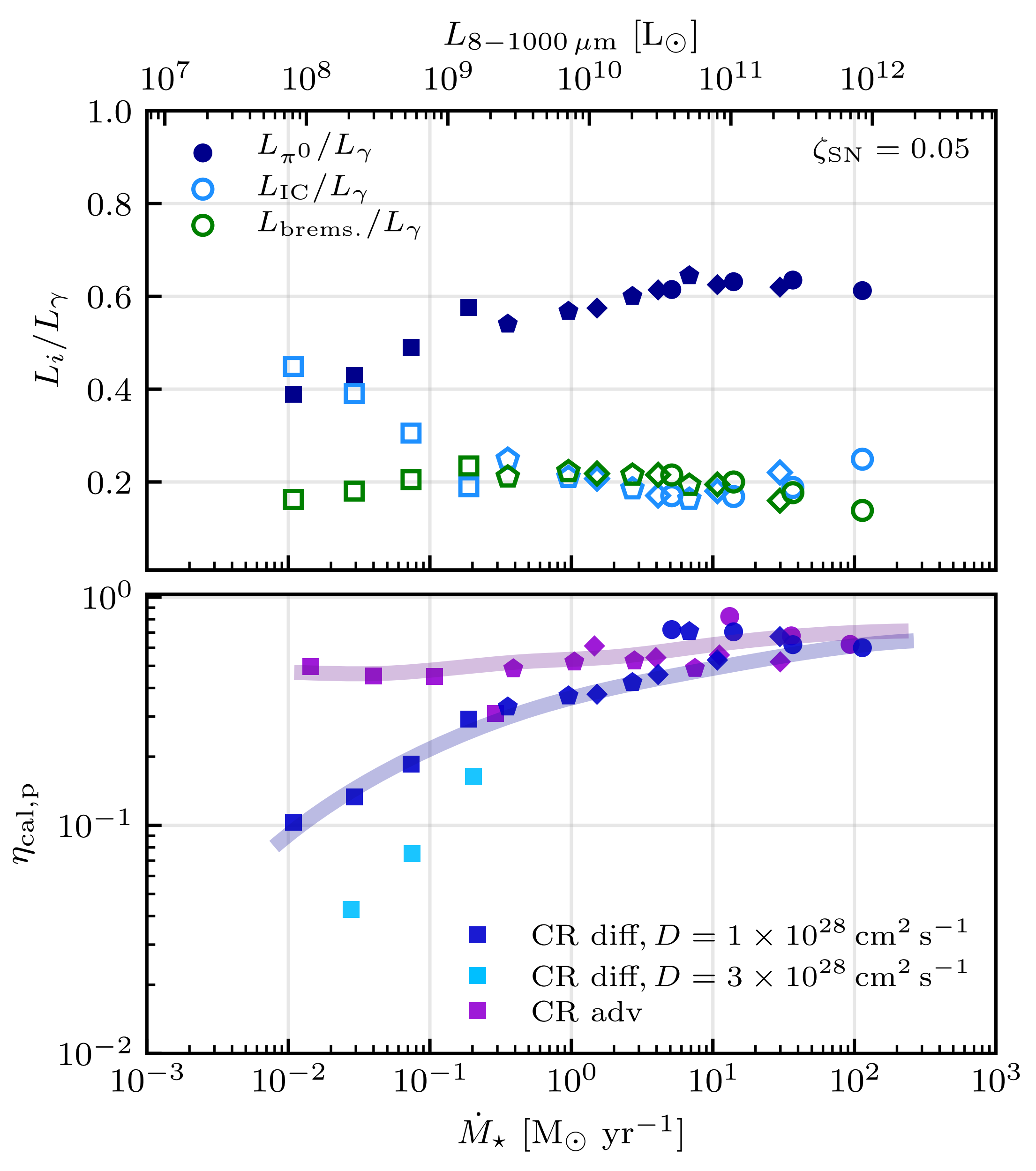

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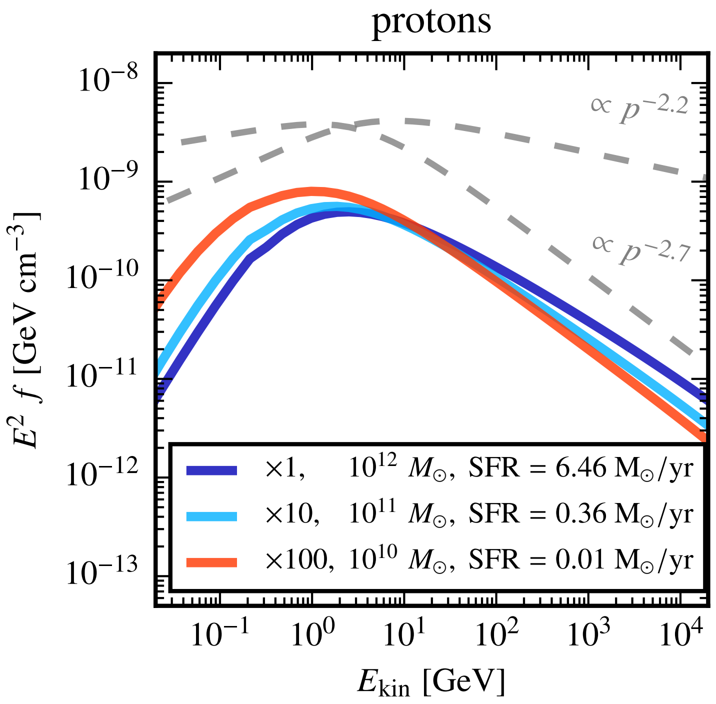

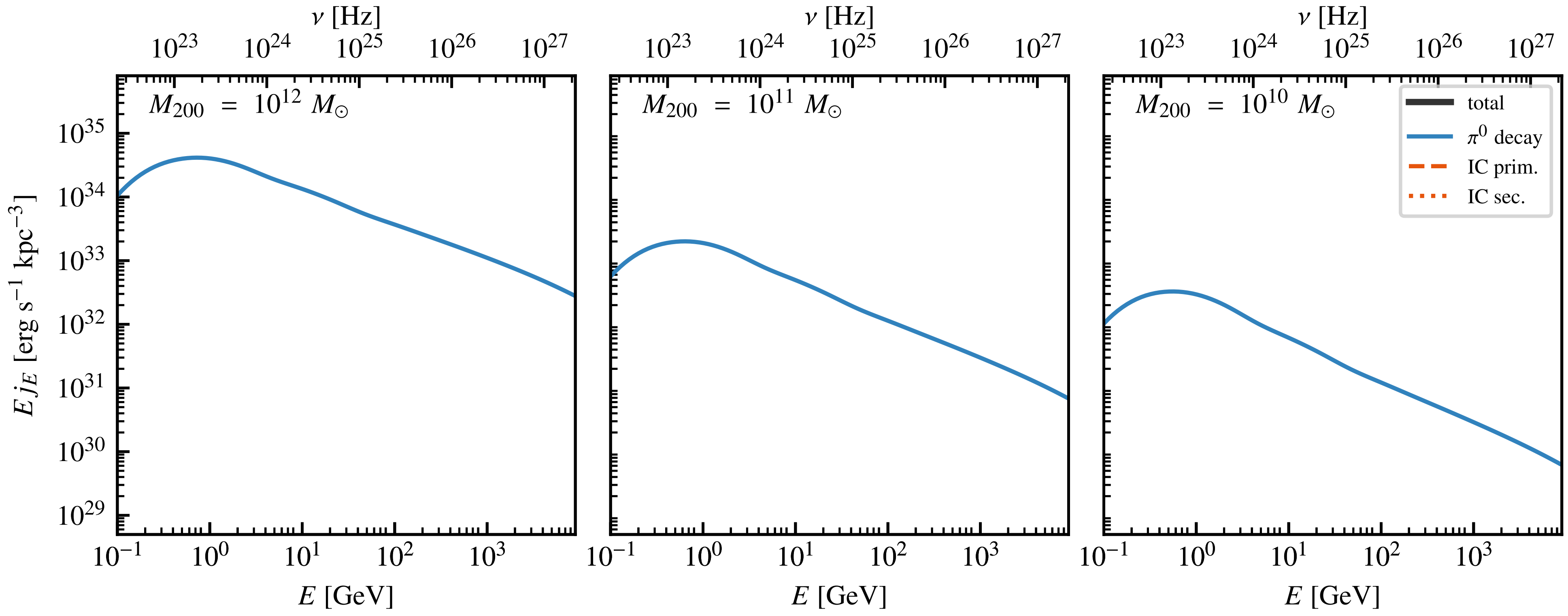

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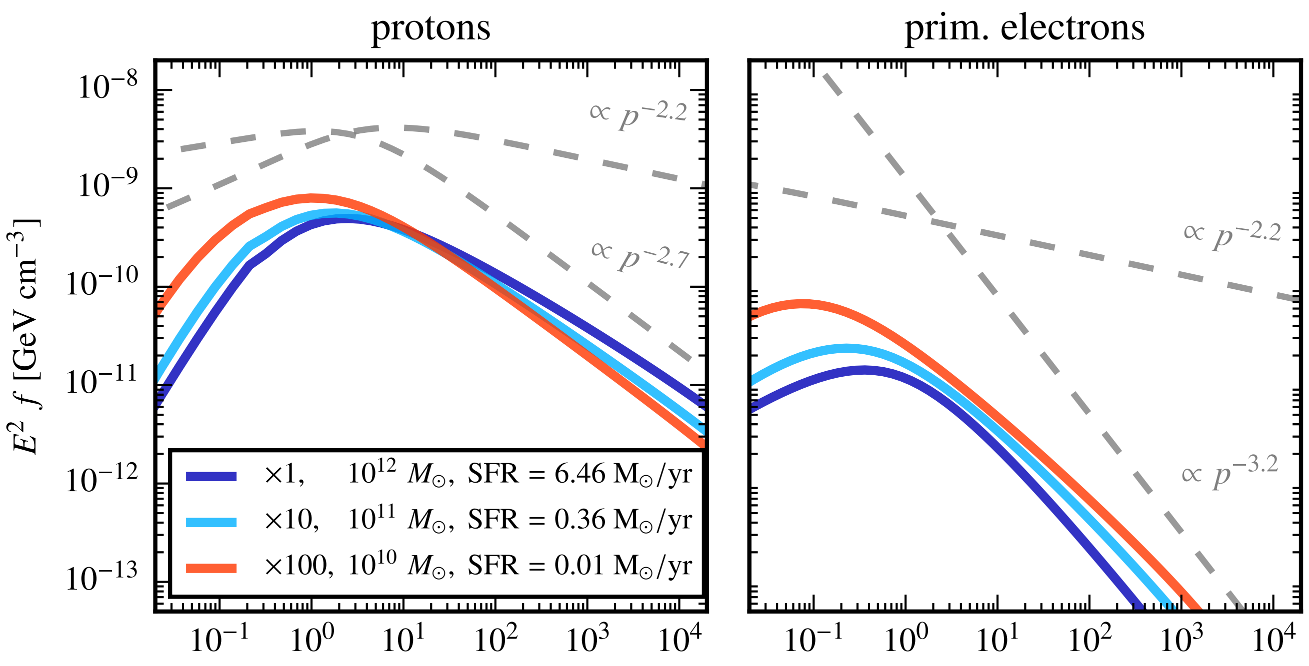

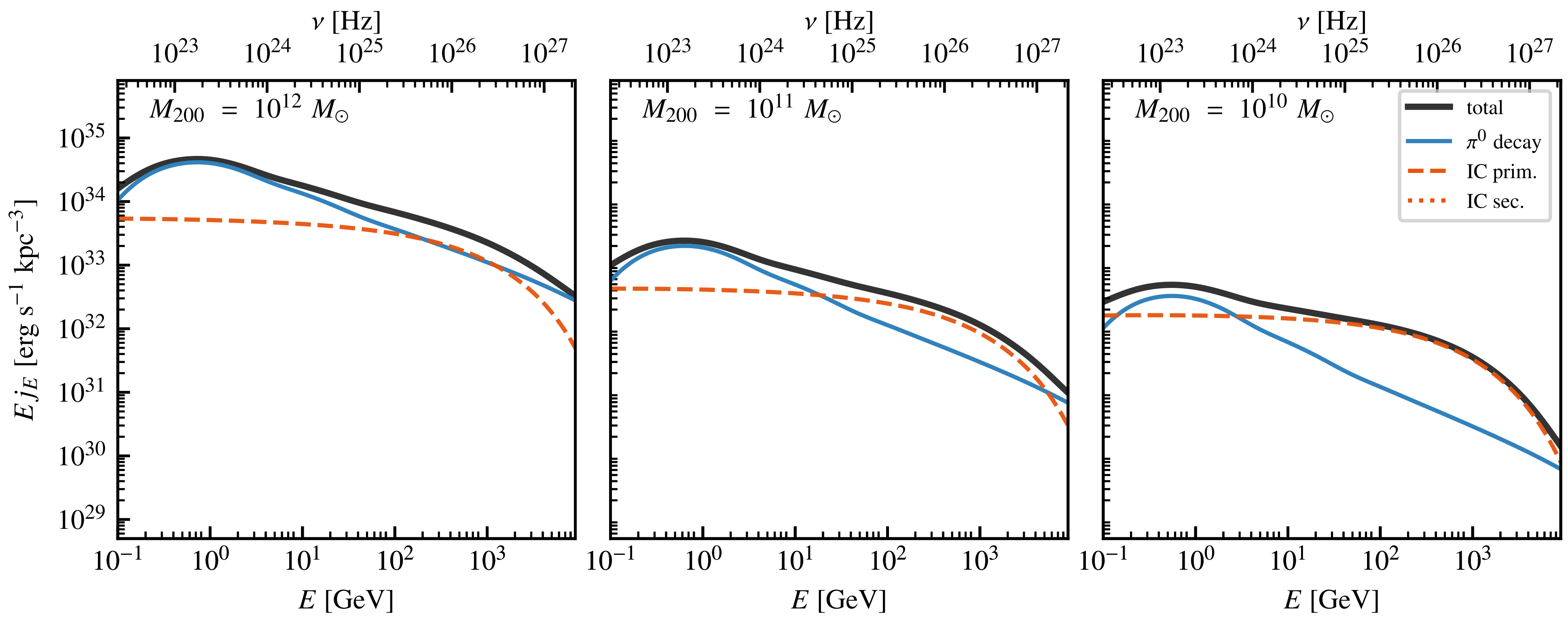

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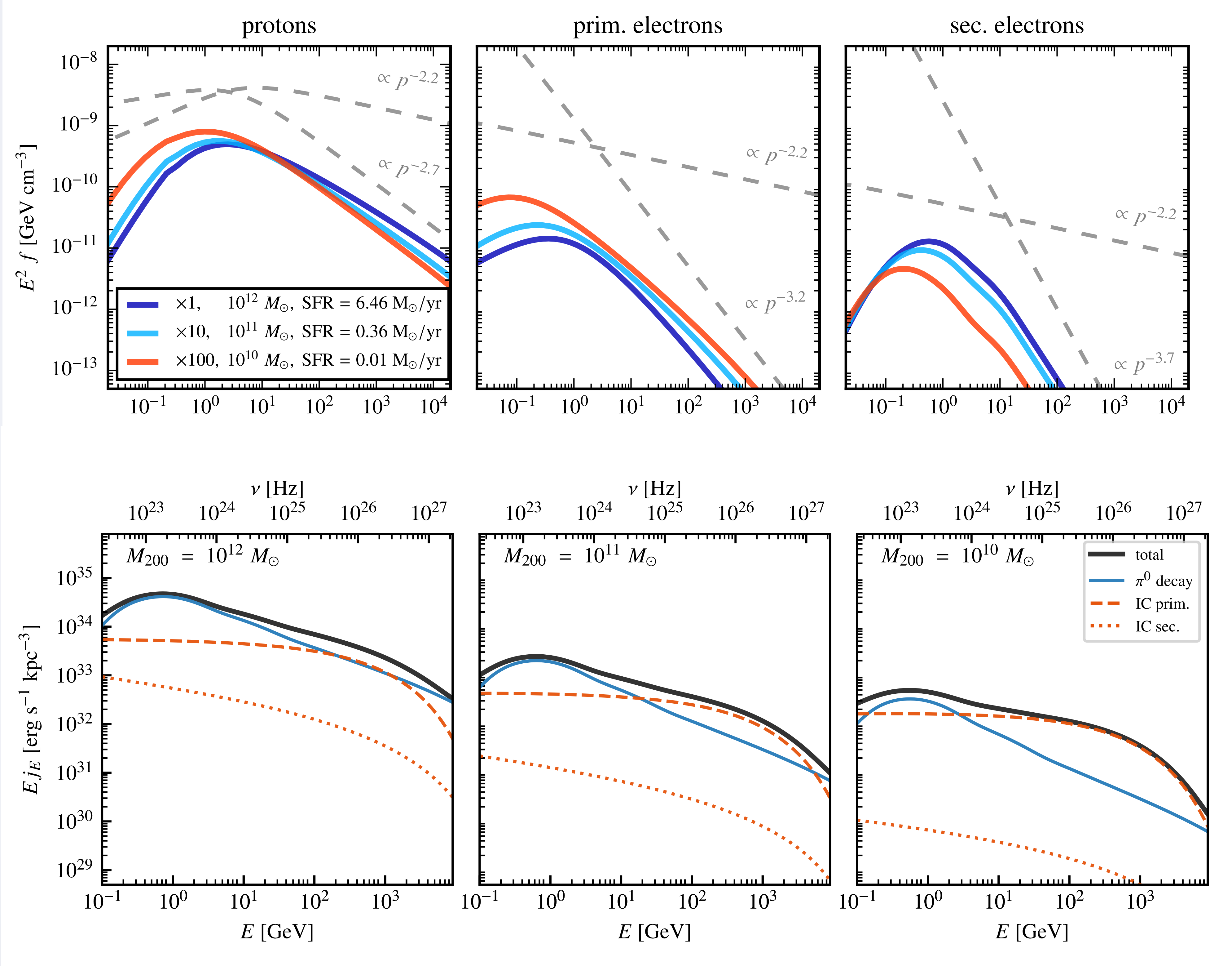

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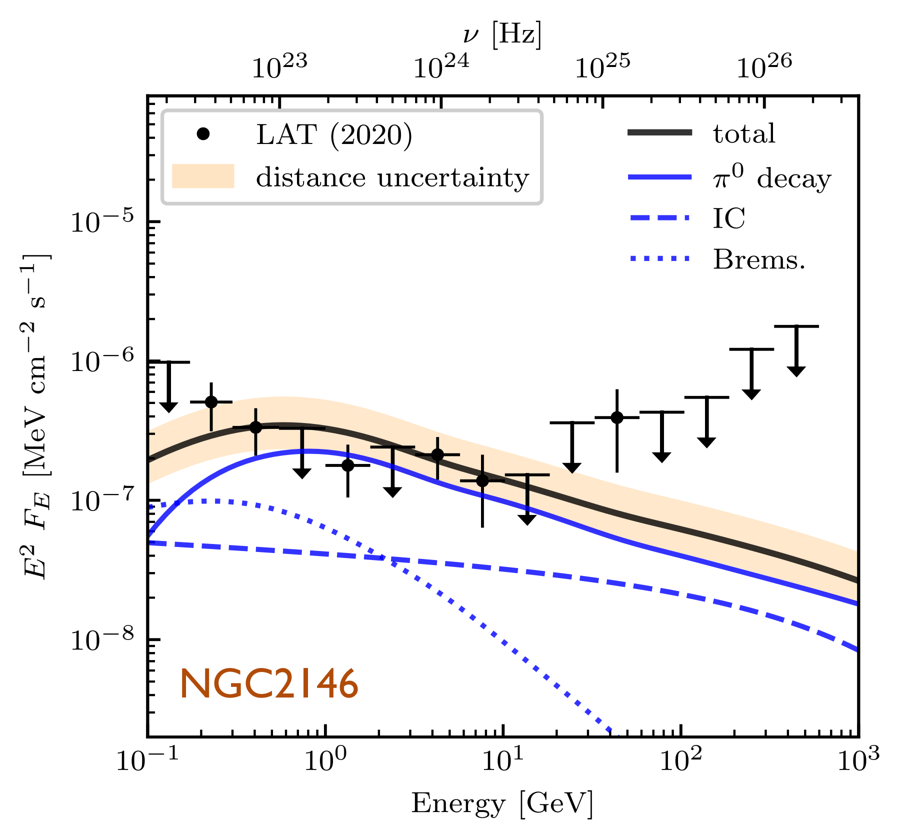

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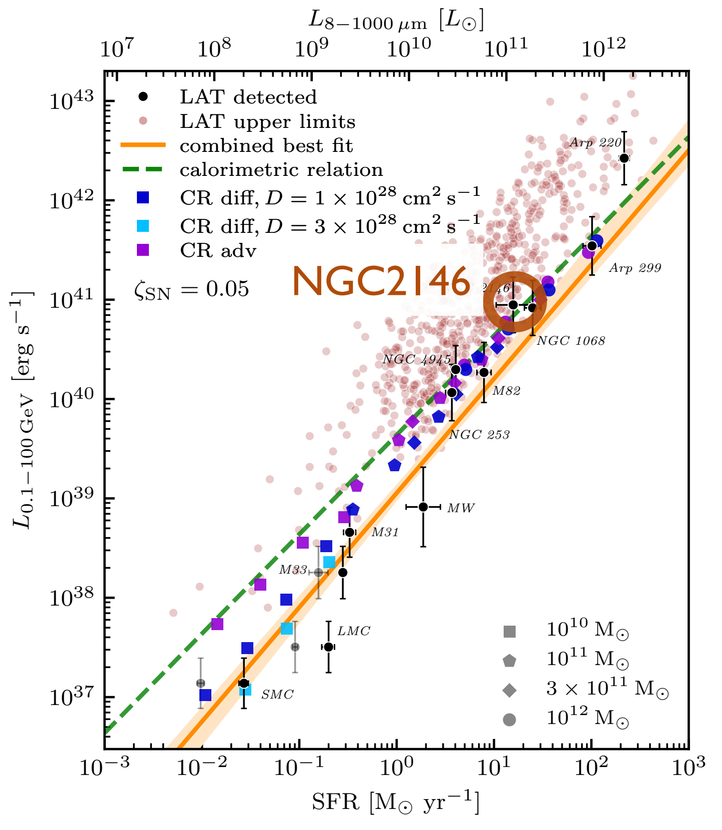

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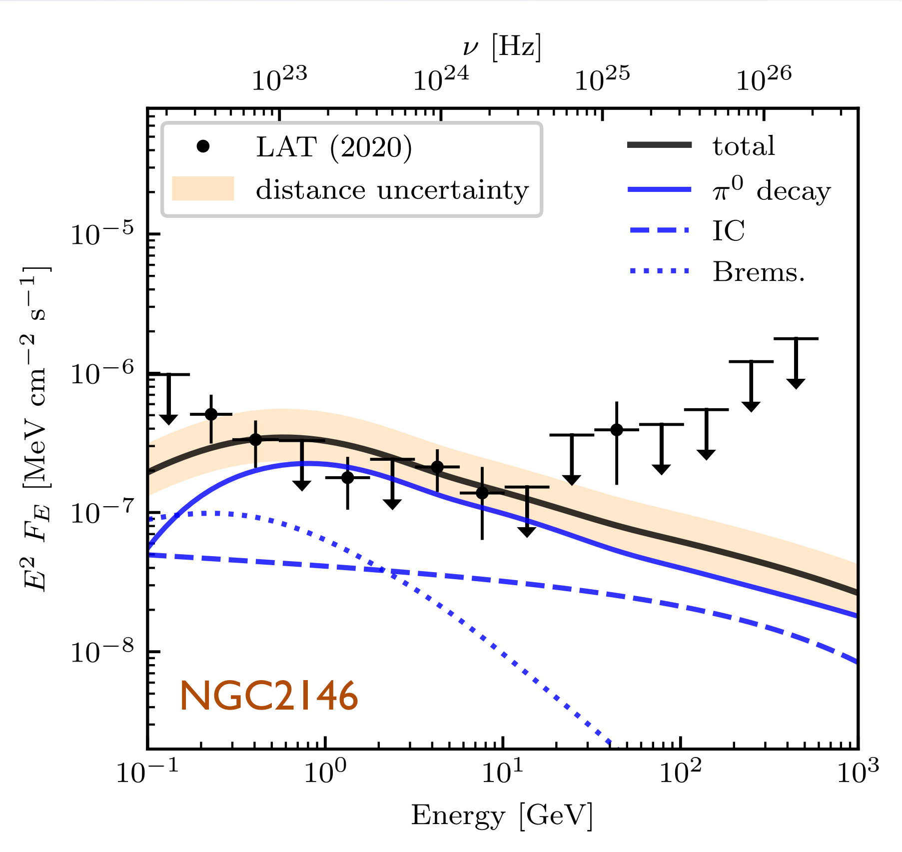

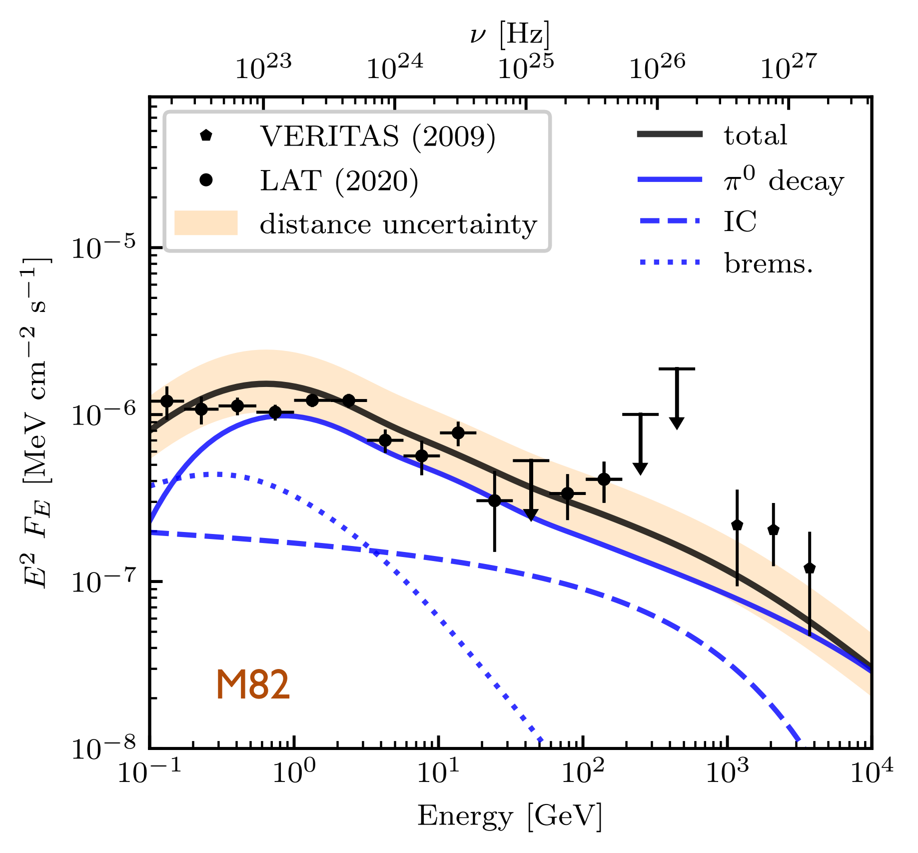

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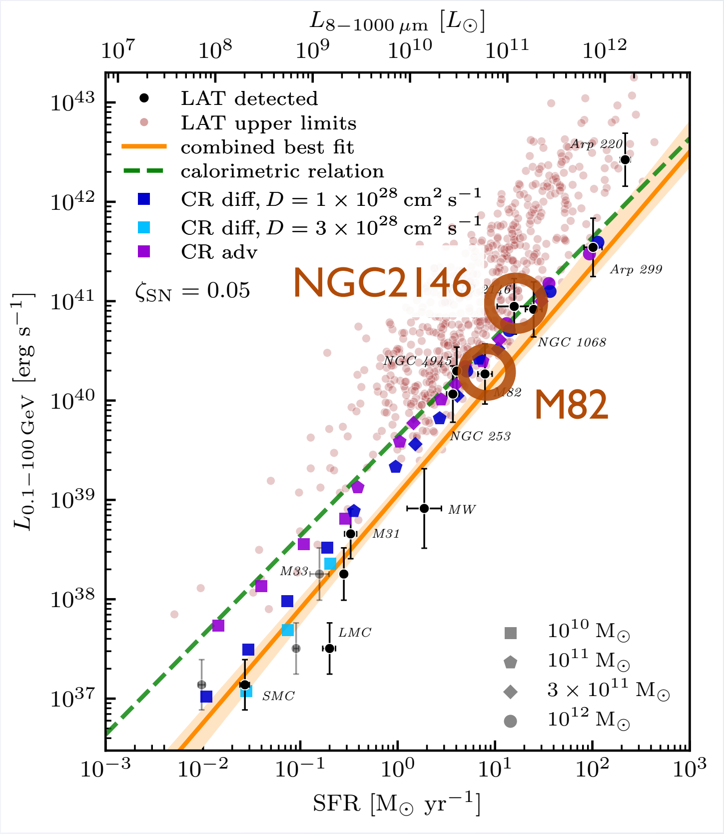

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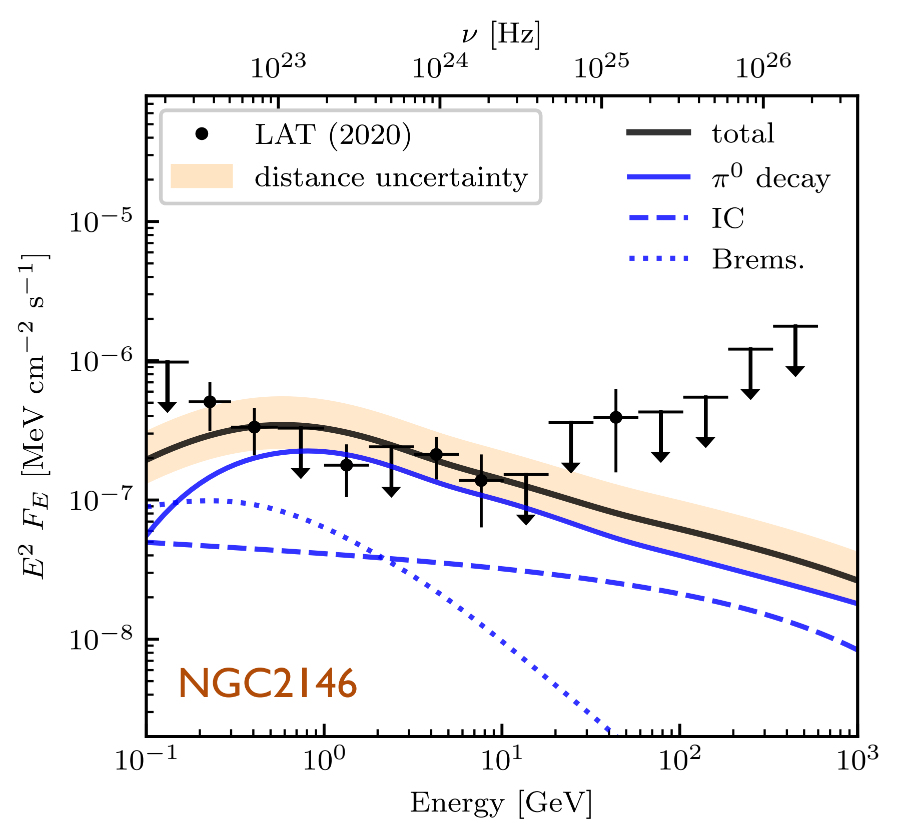

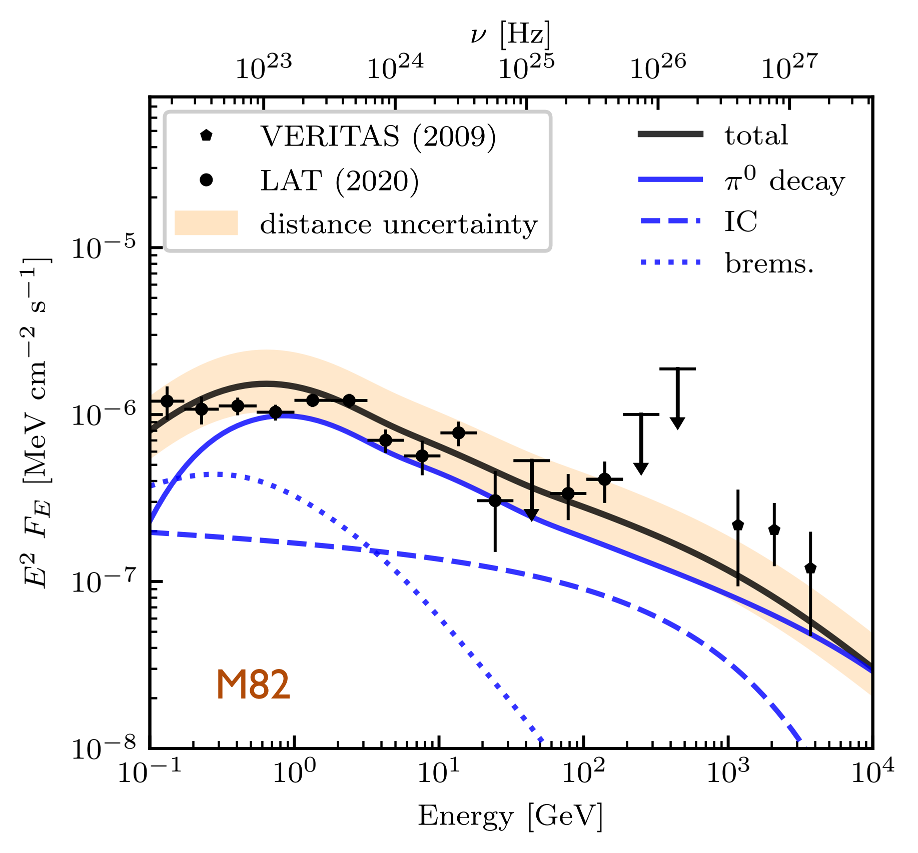

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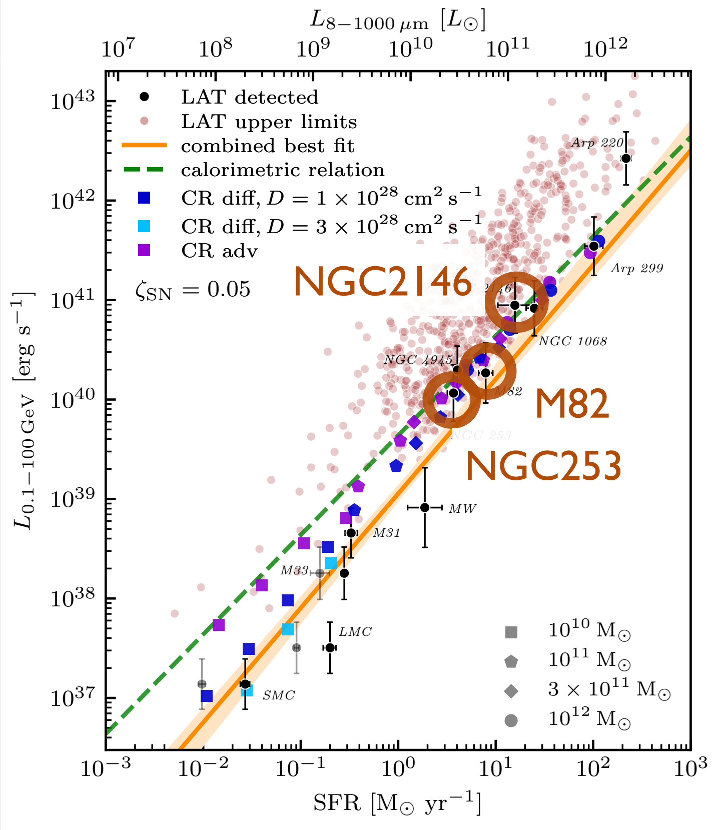

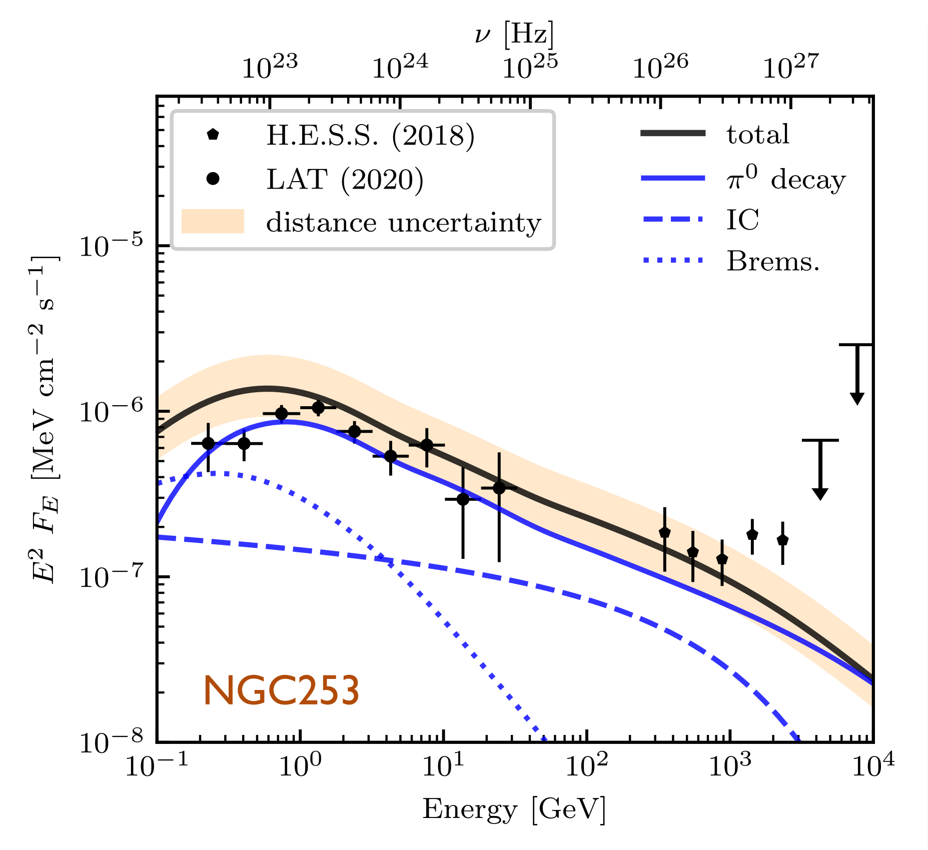

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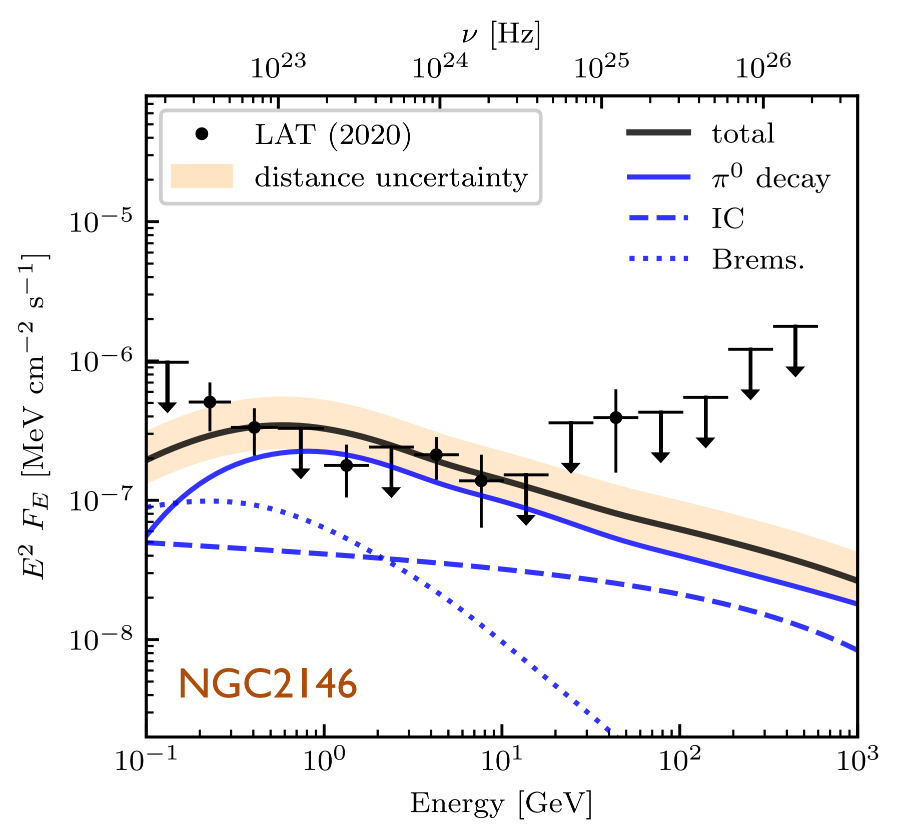

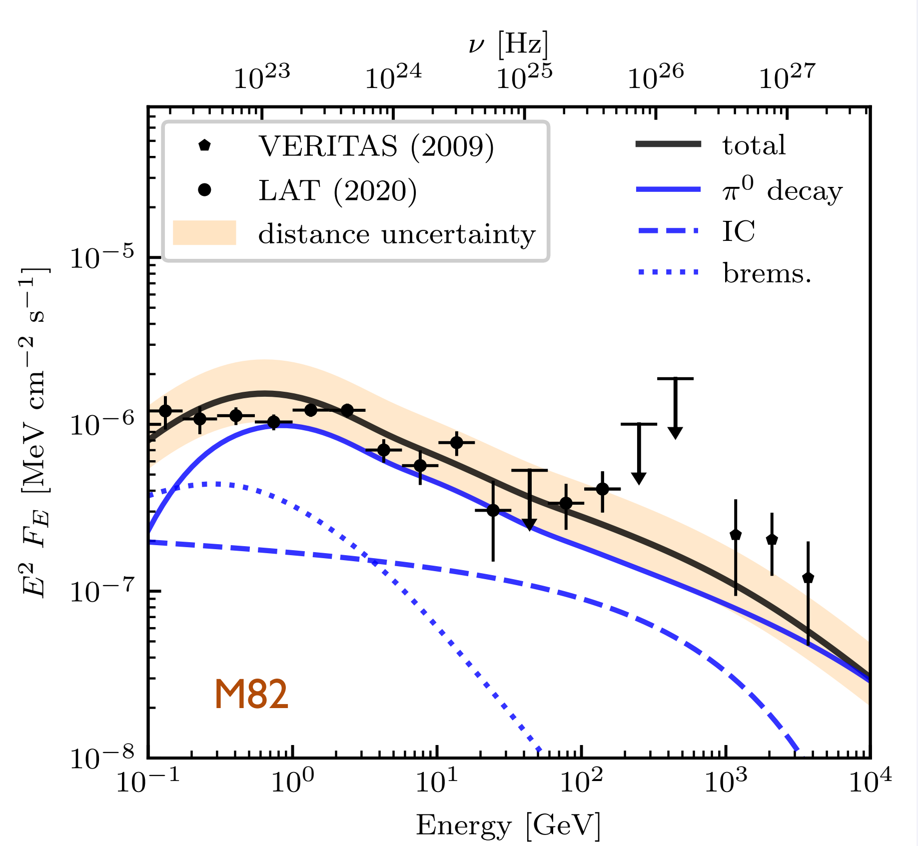

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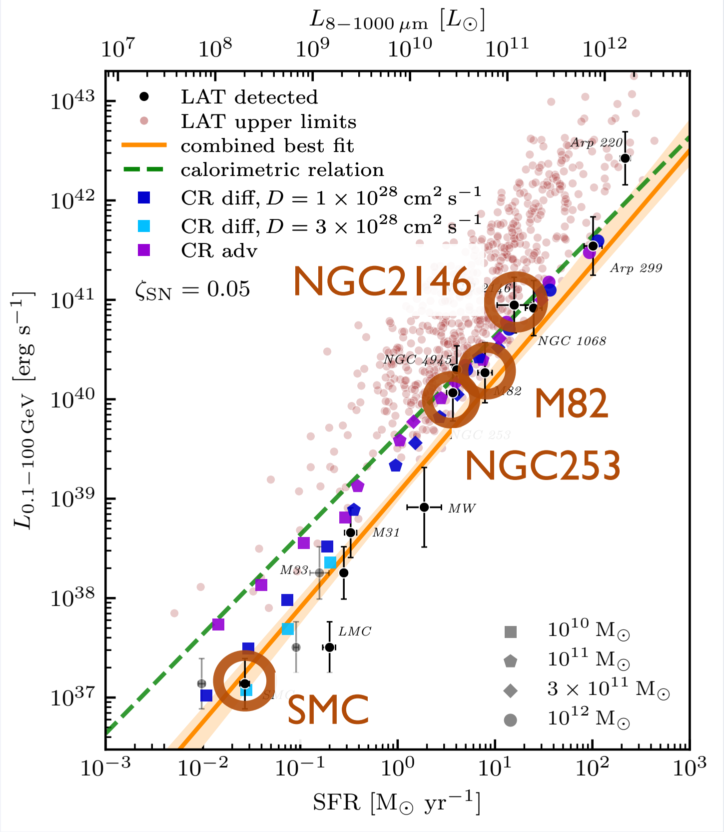

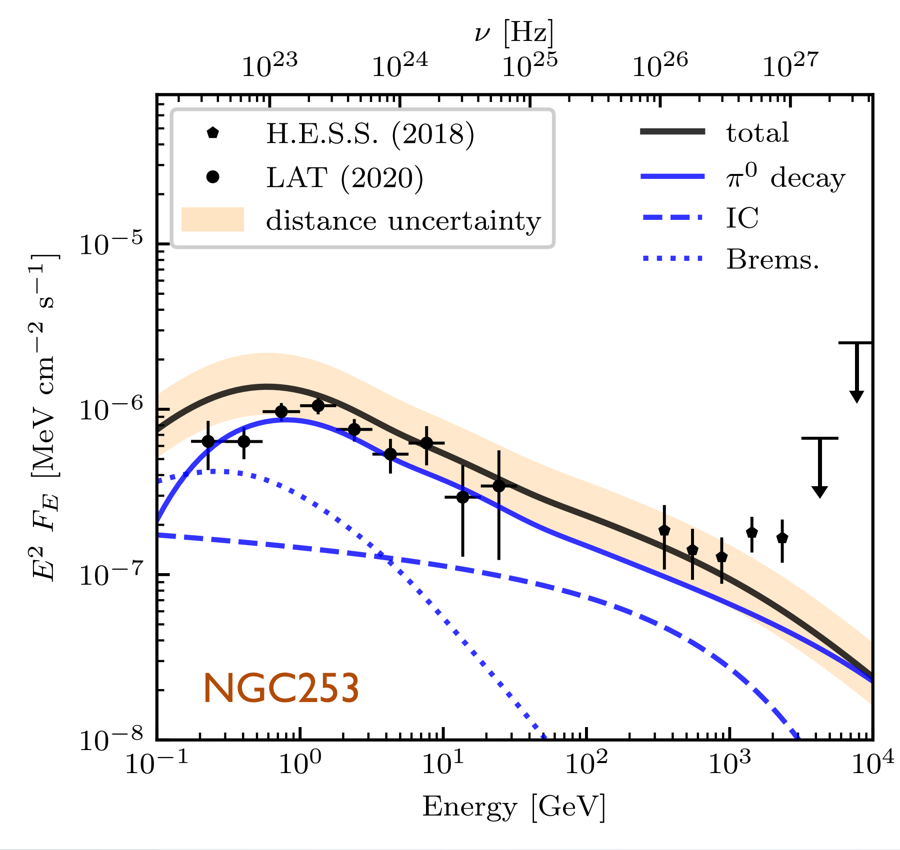

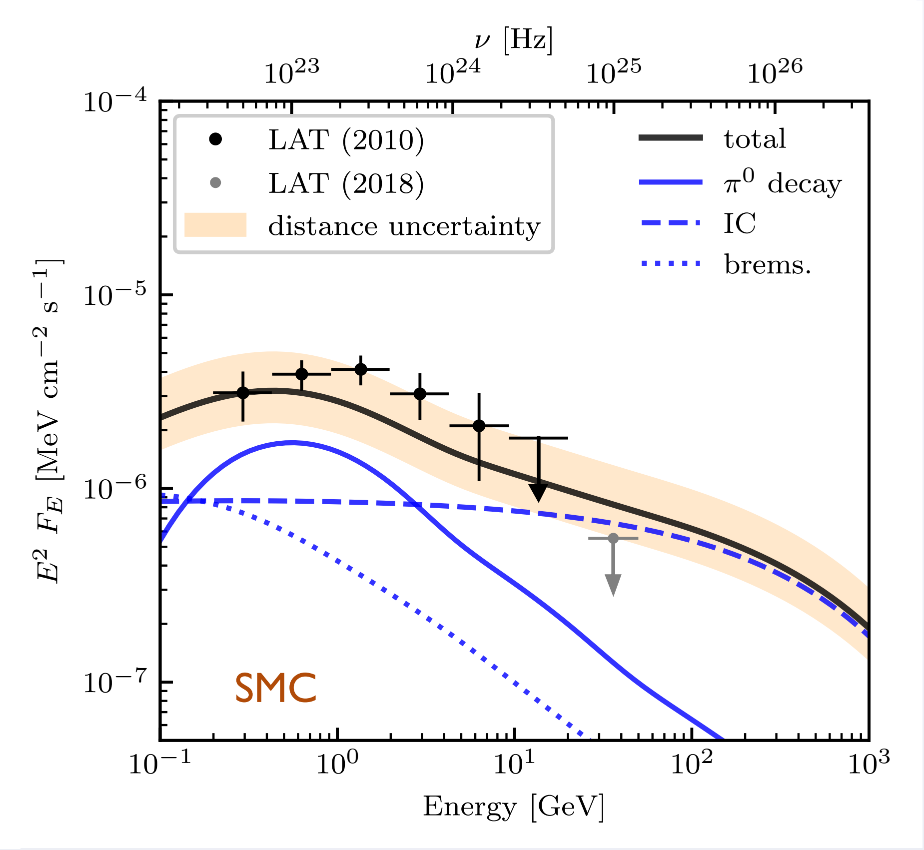

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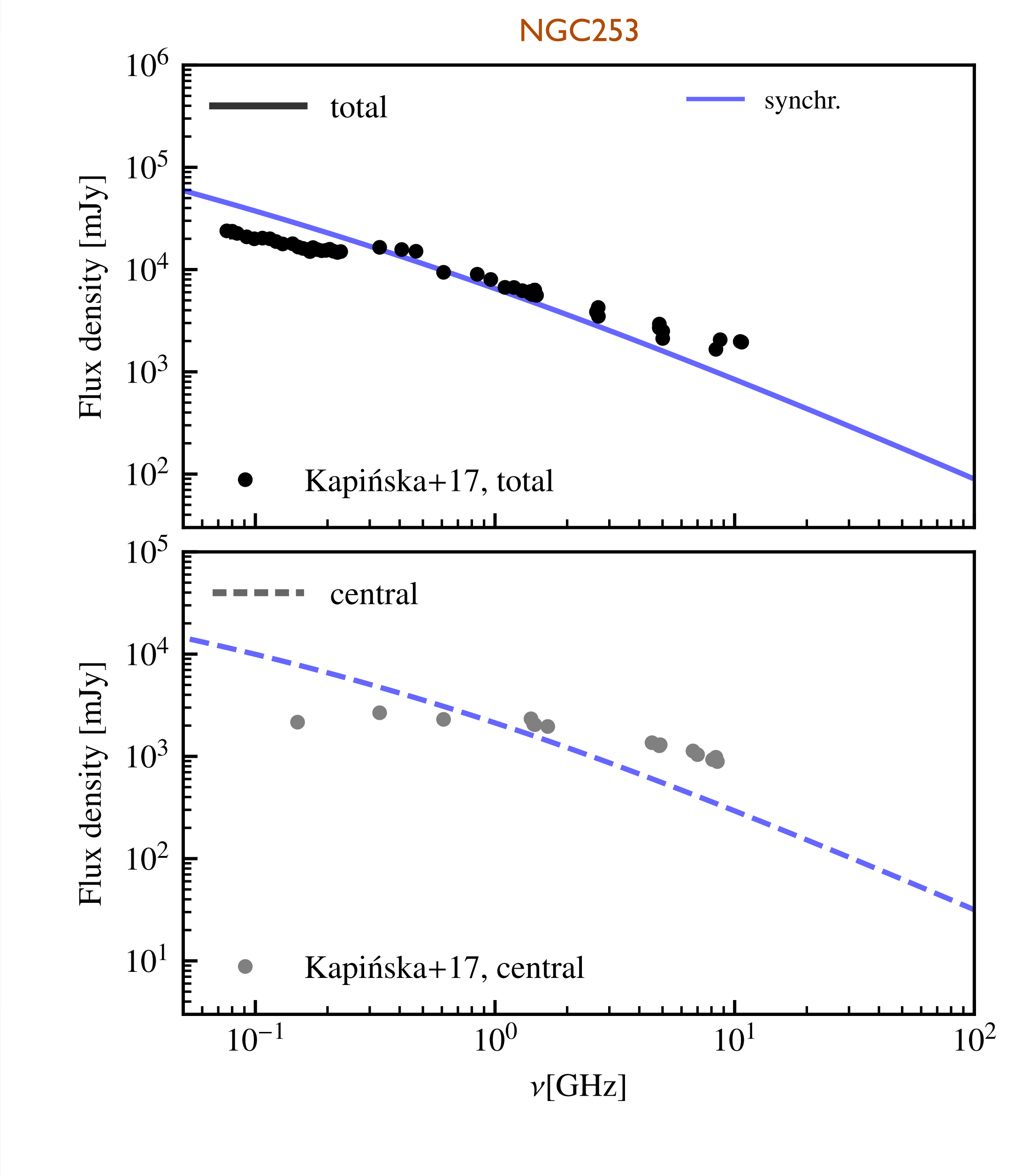
$$\text{SMC, MW} : \delta = 0.5$$

III) Radio spectra

→ *Too steep radio spectra?*



Werhahn, Pfrommer, Girichidis (2021c, subm.)

III) Radio spectra

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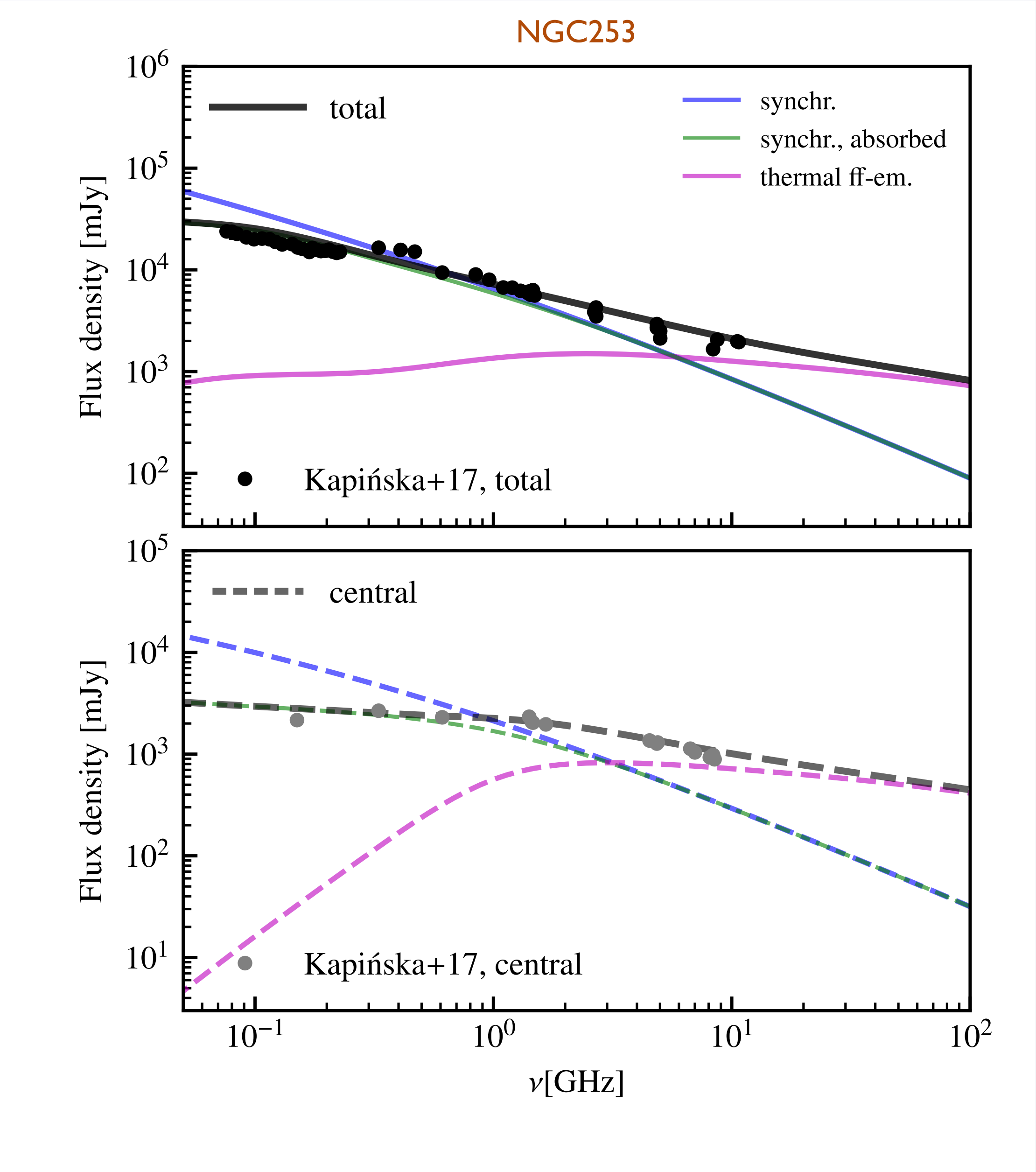
Thermal free-free emission:

- Hardens spectra at high frequencies

Thermal free-free absorption:

- flattens at low frequencies
  (stronger in central regions)



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Summary & Outlook

Steady-state CR spectra in 3D MHD simulations:

- **Reproduce observational features** of CR spectra in the MW
  - low energies: inversion of CR proton to electron spectra
  - decreasing positron fraction up to 8 GeV
- **Gamma-ray emission:** reproduce FIR-gamma-ray relation with $\zeta_{\mathrm{SN}} = 0.05$
  - **low SFR:** diffusion losses relevant, partly compensated by IC emission
  - **high SFR**: close to calorimetric limit $\eta_{\mathrm{cal,p}} = 0.3 \text{ to } 0.7$

  → energy left for feedback
- **Radio emission:** reproduce FIR-radio relation, dominated by primary emission

  → flat radio spectra due to **thermal contribution**

Caveats/improvements:

- **Full spectral-dynamical simulations of CRs** (Electrons: Winner+ 2019,2020; Protons: Girichidis+ 2020)
- **Two-moment CR hydrodynamics model** (Thomas & Pfrommer 2019,2021, Thomas+ 2021)
- **Improved ISM model:** stronger magnetic dynamo (turbulence from SF)
- **Cosmological simulations:** realistic SF history

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AIP

This project has received funding from the European Research Counsil (ERC) under the European Union's Horizon 2020 research and innovation program (grant agreement No CRAGSMAN−646955)