Modeling Cosmic Ray Electrons in the Multiphase ISM

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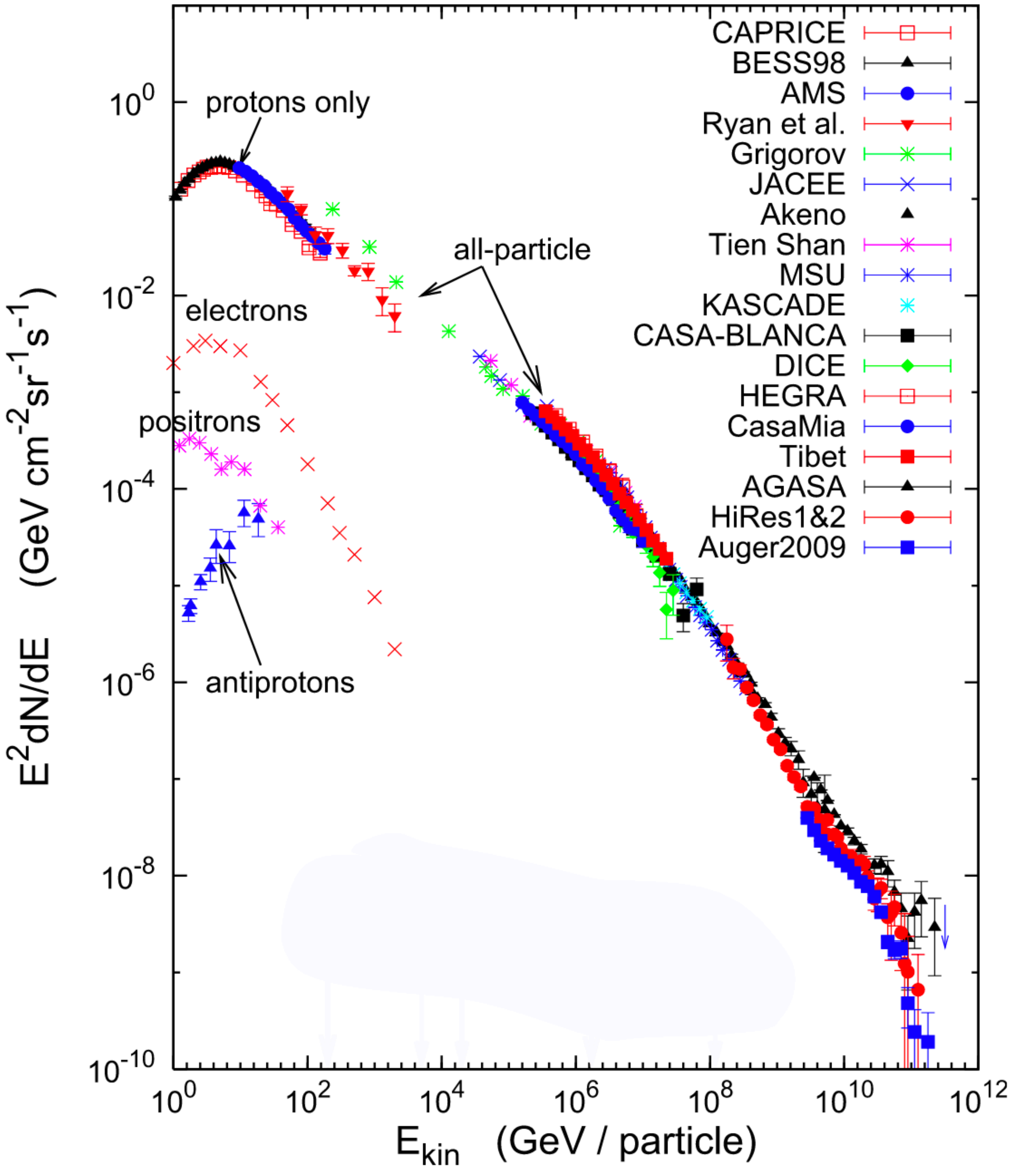
Image: Ruszkowski and Pfrommer, 2023

Why model electrons?

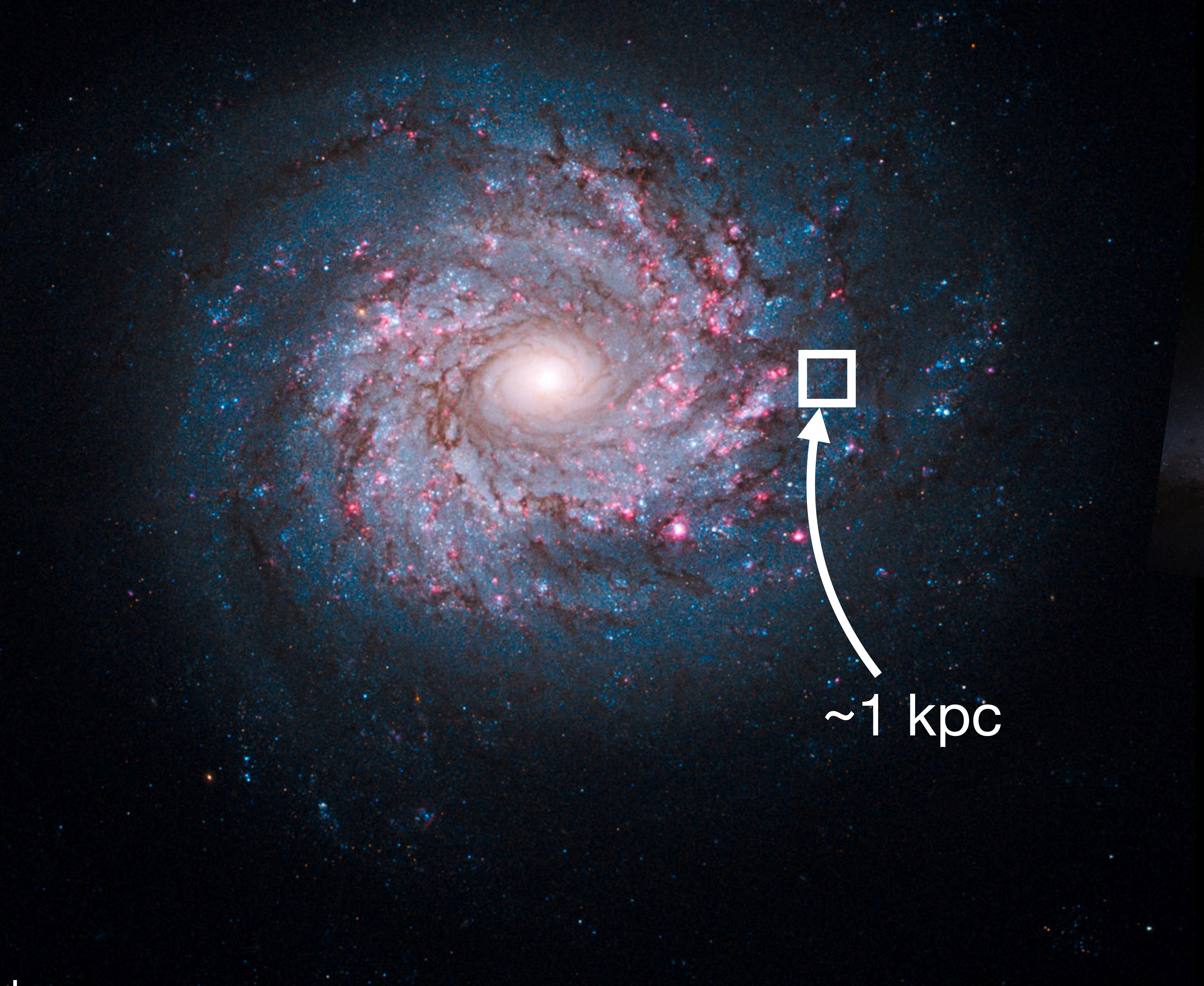
- Unlike protons, do not impact the gas dynamically
- Visible in **synchrotron radiation** → key tracer of the CR population where protons are not detectable
- From radio observations, learn about:
    - CR electron spectrum
    - CR proton spectrum
    - Magnetic field

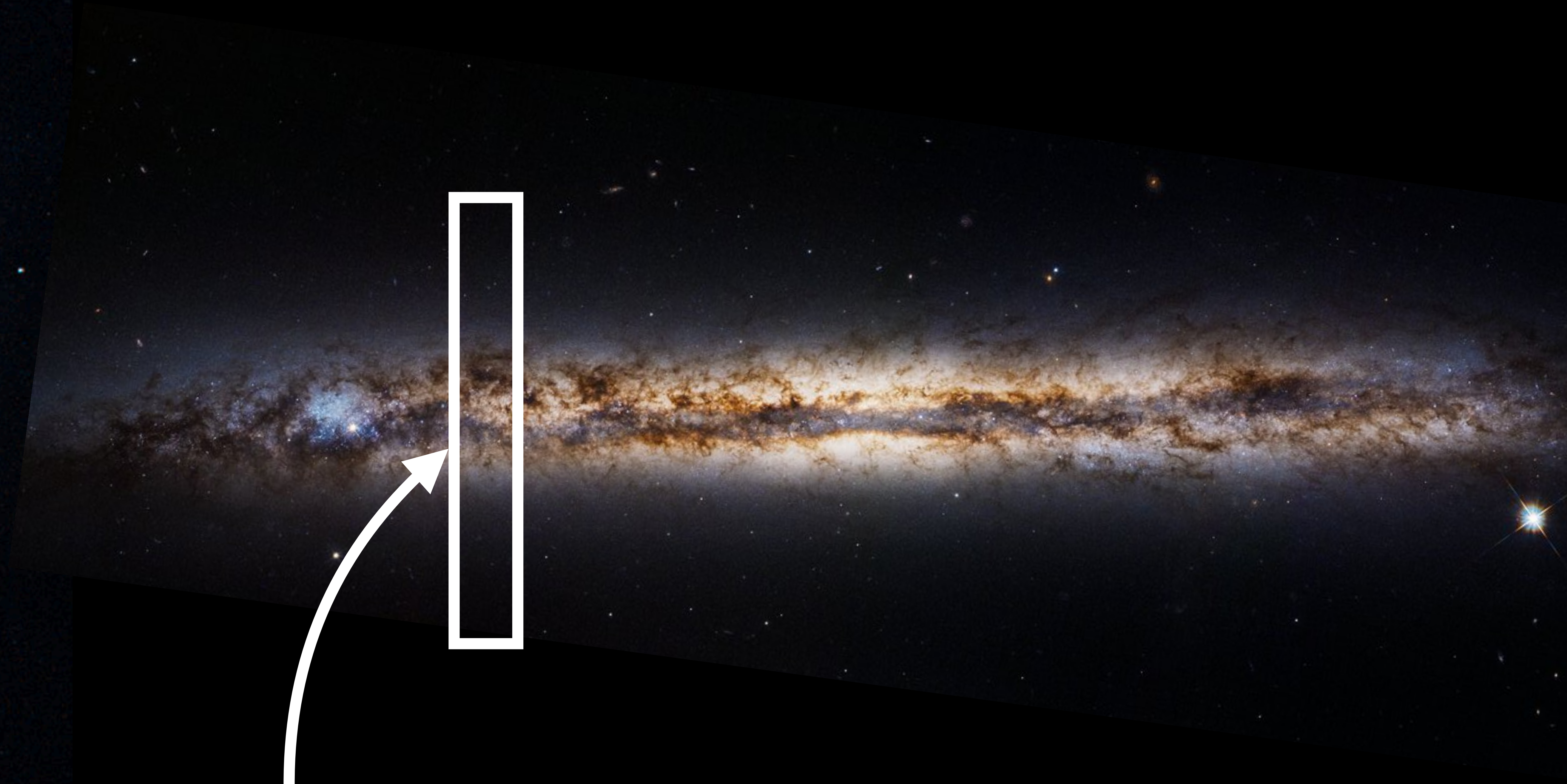
Zweibel (2013)



Kim & Ostriker (2017)

TIGRESS



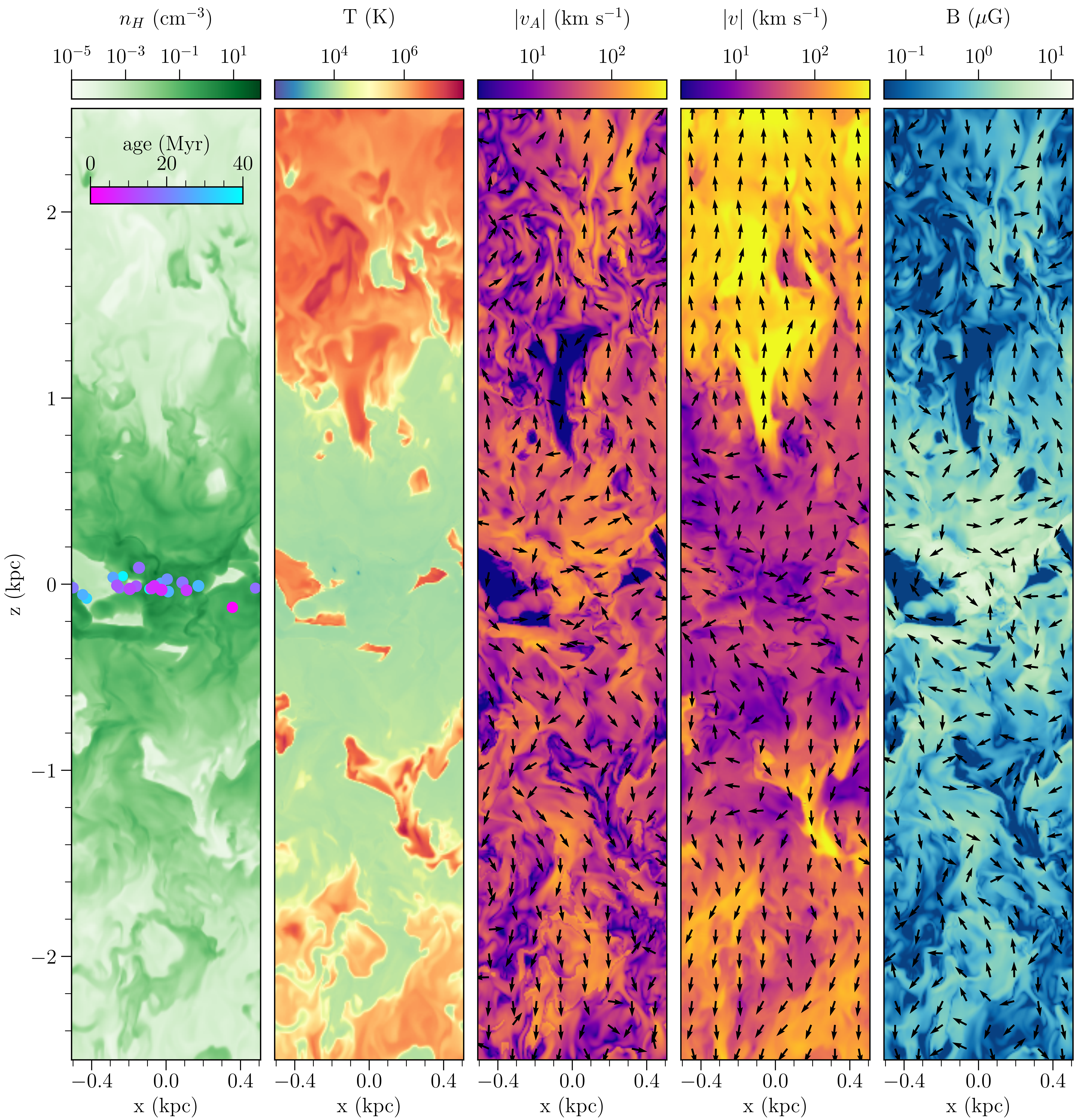


Images:
NASA, ESA, and the Hubble Heritage Team (STScI/AURA
NASA, ESA, and M. Mutchler (STScI)

Modeling CRs in TIGRESS

See Jiang & Oh (2018) + Armillotta et al. (2021)

1. **Injection** around star particles
2. **Transport** including:
    1. **Advection** with the gas
    2. **Streaming** along magnetic fields
    3. **Diffusion** relative to the magnetic fields
3. Energetic **losses** through interactions with the local ISM



More details: Armillotta et al. (2021)

Streaming Coefficient

CRs scatter off of Alfvén waves generated by the streaming instability — the **self-confinement** model

$$\Gamma_{\text{stream}} = \Gamma_{\text{damp}}$$

Depends on local CR properties

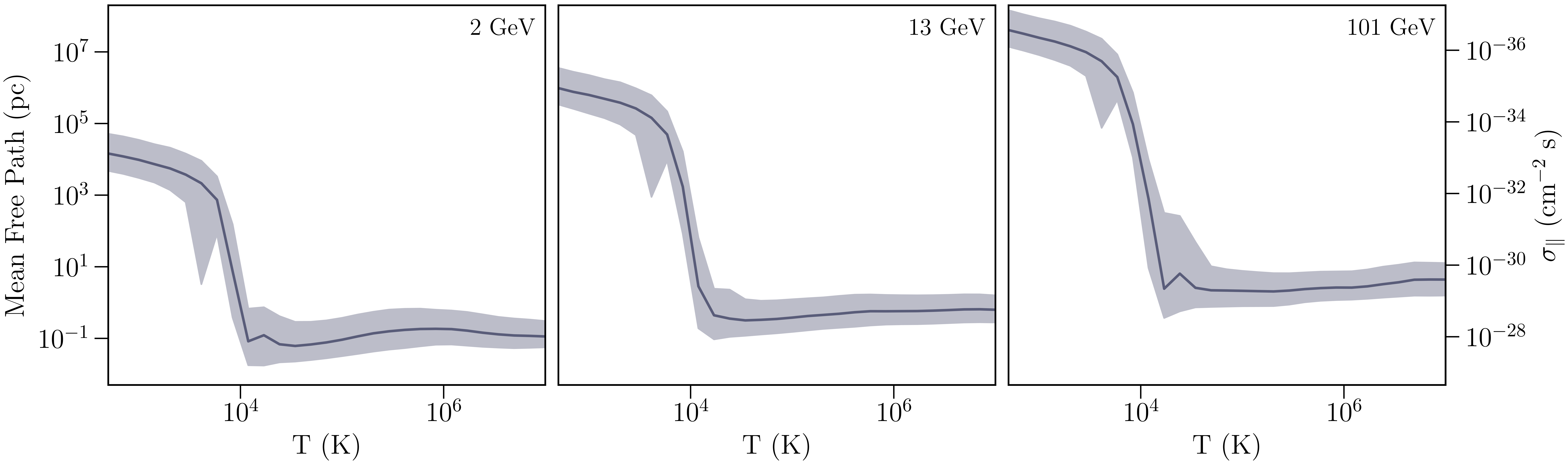
Either ion-neutral or non-linear Landau damping, value depends on local gas properties

More details: Armillotta et al. (2021)

Streaming Coefficient

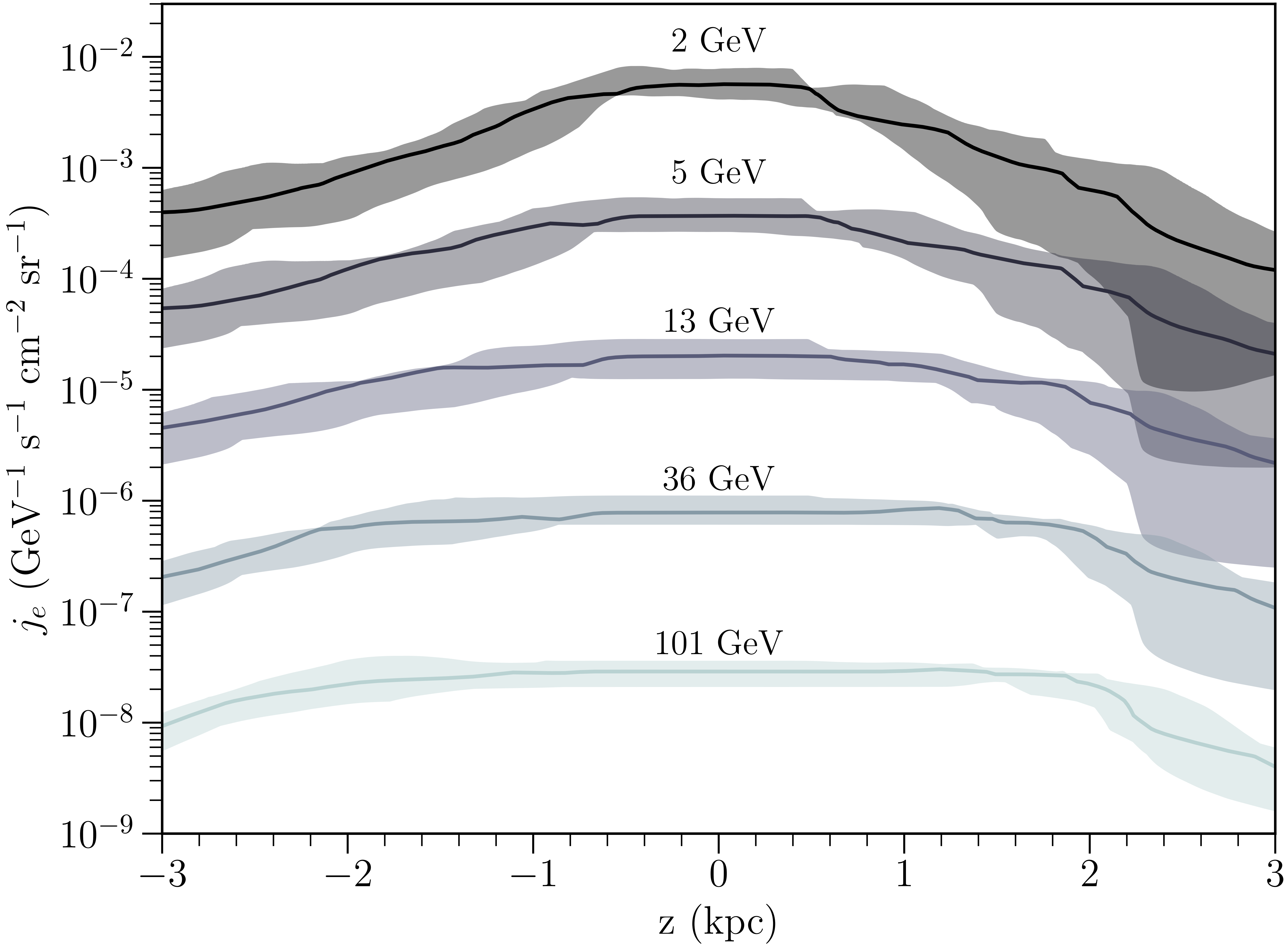
CRs scatter off of Alfvén waves generated by the streaming instability — the **self-confinement** model

$$\Gamma_{\text{stream}} = \Gamma_{\text{damp}} \rightarrow \sigma_{\|}$$



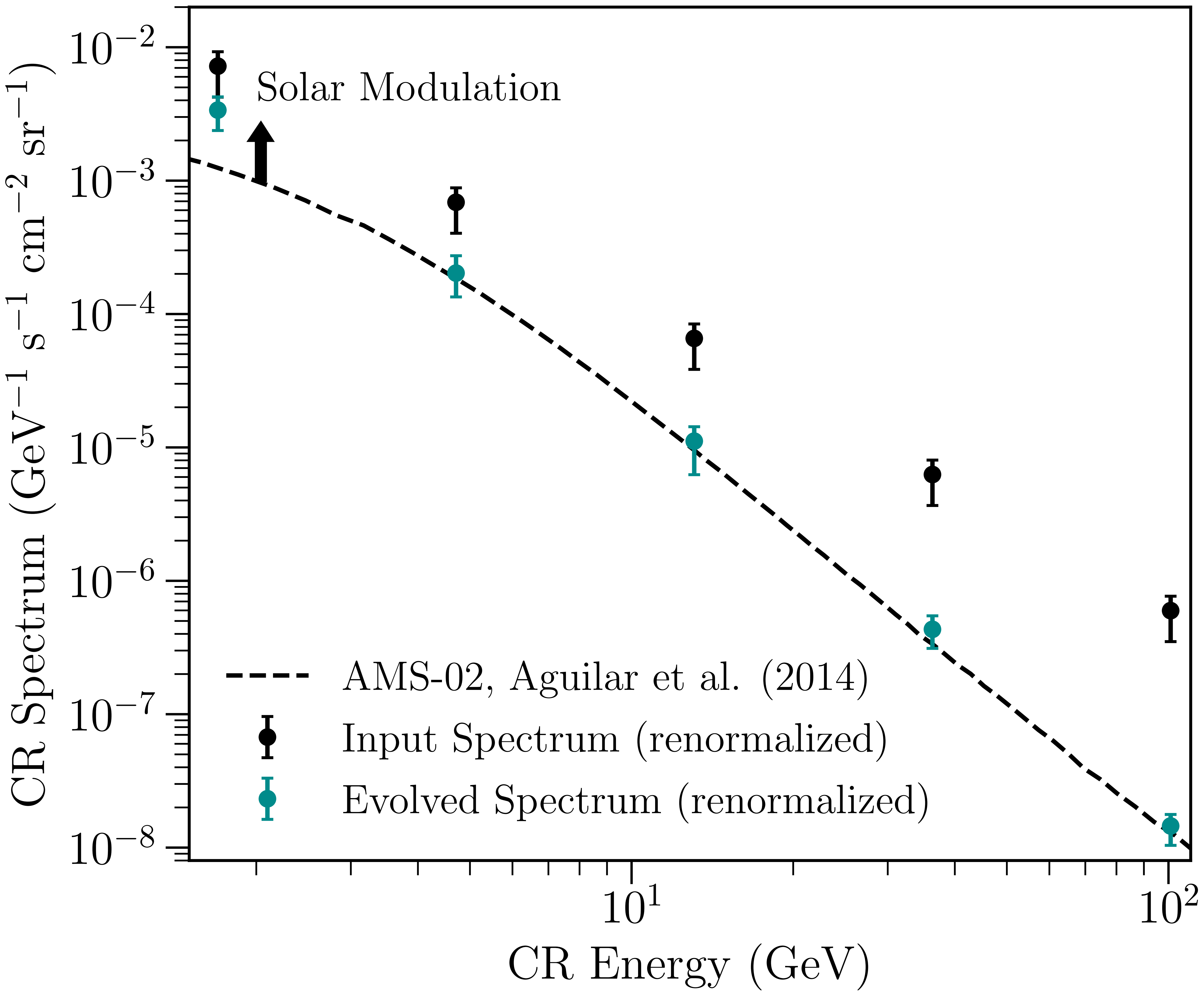
Vertical Profiles

- Horizontal average of the CRE spectrum at each energy
- The scale height of the CRs becomes larger at higher energies



CR Electron Spectrum

- We inject CR electrons with a fixed power law slope, $j_e \propto E^{-2.3}$
- Through their evolution, the electrons experience energy dependent spectral steepening due to diffusion and losses
- The final spectrum is in excellent agreement with direct observations

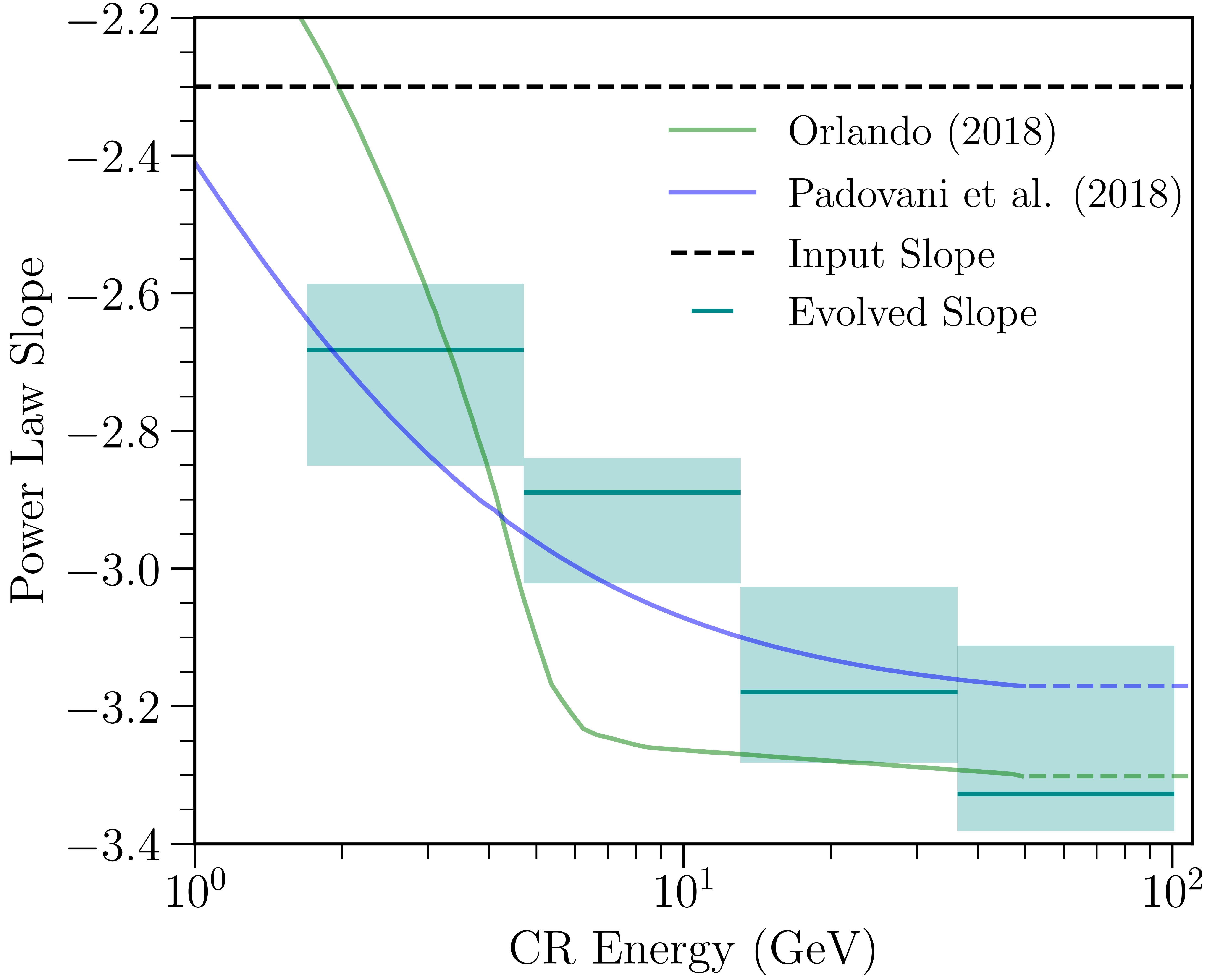


Power Law Slope

- Compare power law slope of the simulated spectrum to values based on observations

$$s = \frac{d\log j_e}{d\log E}$$

- As is observed, we find the electron spectrum not to be well represented by a single power law



Synchrotron Emission

$$\epsilon_\nu \propto \int j_e(E) P_\nu(E, B) dE$$

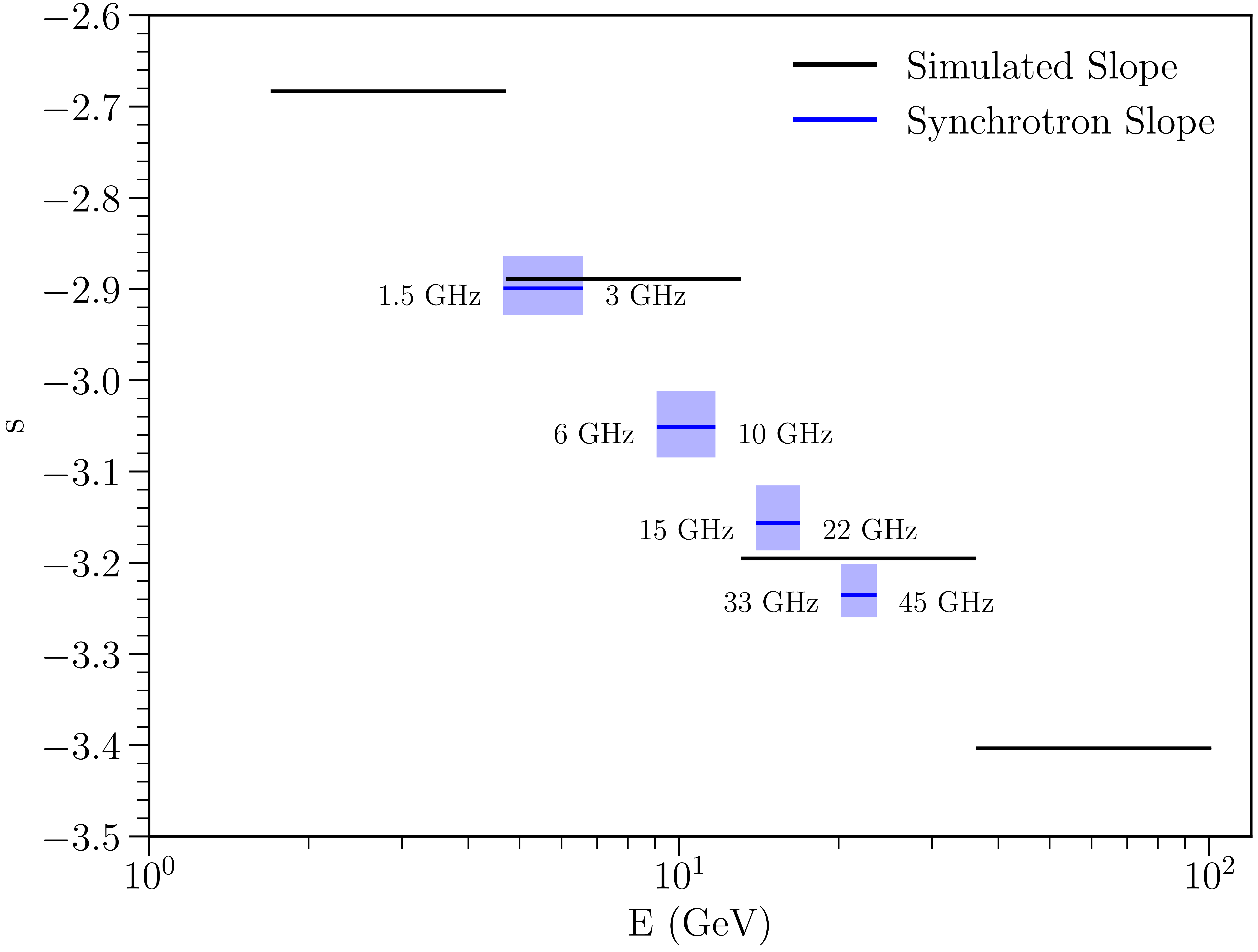
Estimated Slope

We estimate the CR spectral slope from the radio spectrum:

$$I_\nu \propto \nu^\alpha \rightarrow \alpha = \frac{\log(I_{\nu_1}/I_{\nu_2})}{\log(\nu_1/\nu_2)} = \frac{s+1}{2}$$

The energy of CRs responsible for emission at frequency, v, is given by:

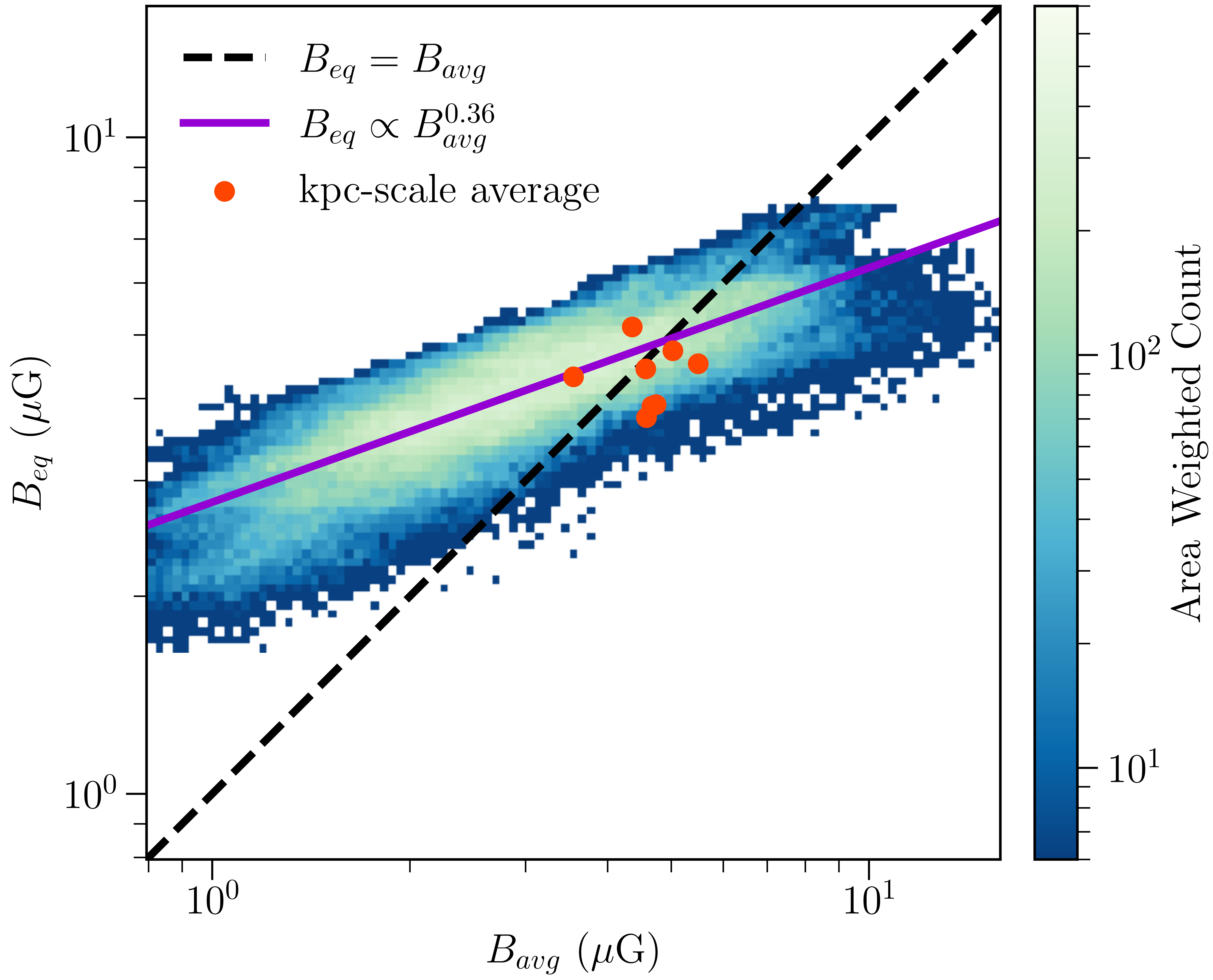
$$E \approx 8\ \mathrm{GeV}\sqrt{\left(\frac{\nu}{\mathrm{GHz}}\right)\left(\frac{\mathrm{B}_\perp}{\mu\mathrm{G}}\right)}$$



Equipartition Estimate

$$B_{\rm eq} \propto \left[\frac{(\mathbf{K_0}+1)}{Lc_4(i)} \times I_\nu\right]^{\frac{1}{\alpha+3}}$$

- The equipartition estimate of magnetic fields is a function:
  - Synchrotron intensity
  - Radio spectral index
  - Scaling factors
- Although the estimate may work well on ~kpc scales, it breaks down at smaller scales



Conclusions

- We reproduce the observed CR electron spectrum between 1-100 GeV using the self-confinement model of CR transport.
- The CR spectral slope can be recovered from synchrotron observations.
- Although the equipartition estimate of magnetic fields is a good approximation on kpc scales, it may not hold on smaller scales.