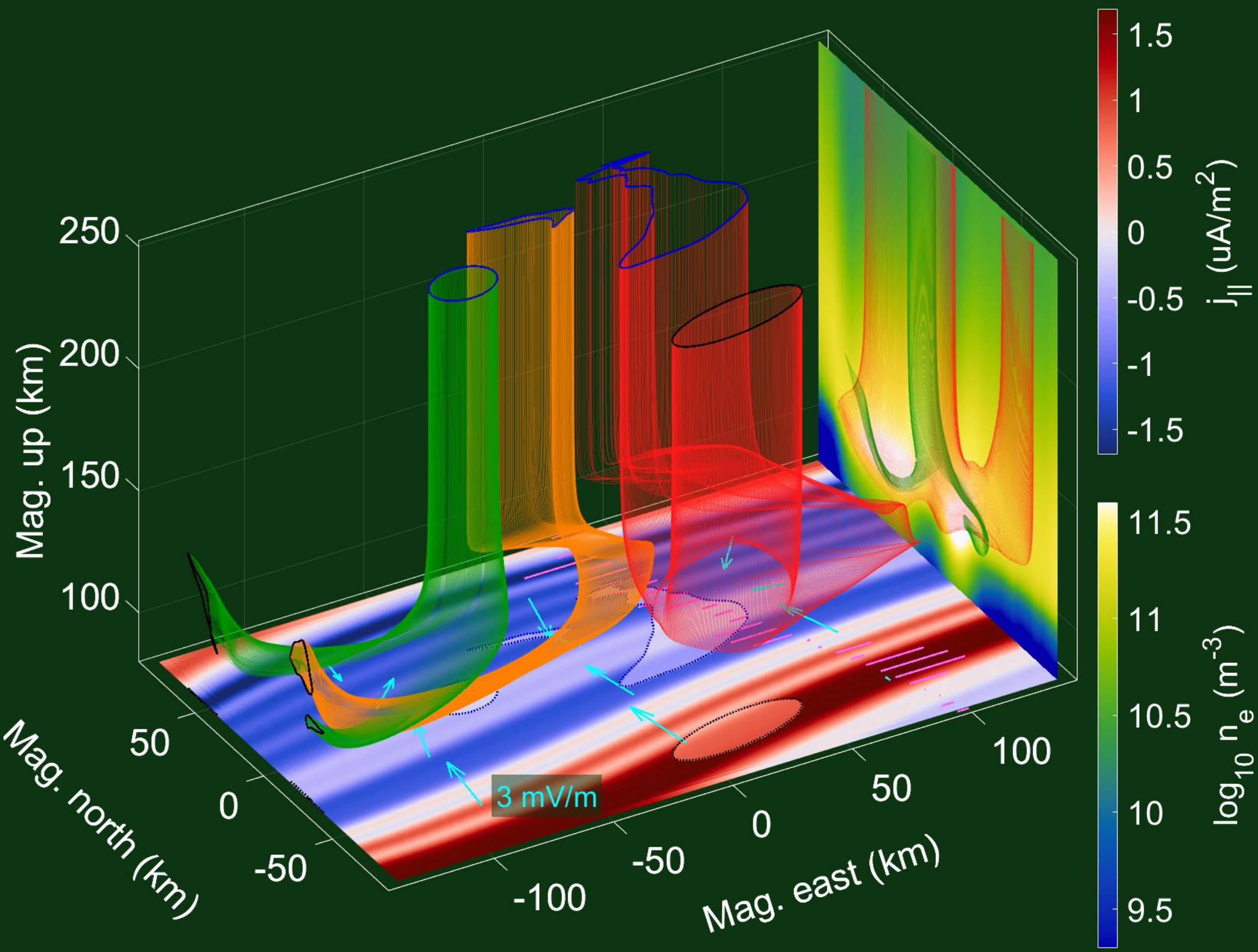
Current Continuity in Auroral System Science:
Data-Driven Auroral GEMINI 3D Simulations



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Overview

I. Motivation & Methodology
II. Top-boundary drivers
III. Simulation results
IV. Comments & Conclusions

I. Motivation & Methodology

Why the need for 3D?

- Integrating over ionospheric altitudes can hide significant information about polar ionospheric systems (Yano and Ebihara, 2021, *JGR*).
  - E.g., altitude profiles of impact ionization balance with finite recombination times and low-altitude plasma transport.
- We want to study to which parameters 3D simulations are sensitive.
- Two examples of such sensitivities are:
  A. The choice of electron precipitation energy spectra; unaccelerated vs. accelerated Maxwellians can significantly alter Hall/Pedersen conductance ratios.
  B. The choice of an initial background electric field, $\mathbf{E}_{\mathrm{bg}}$; the non-uniqueness* of solutions, $\mathbf{E} + a\mathbf{E}_0$, to current continuity with $a \in \mathbb{R}$ and where $\mathbf{E}$, $\mathbf{E}_0$ are such that

$$j_{\parallel}(x, y) = \Sigma_{\mathrm{P}} \nabla \cdot \mathbf{E} + \mathbf{E} \cdot \nabla \Sigma_{\mathrm{P}} + (\mathbf{E} \times \mathbf{b}) \cdot \nabla \Sigma_{\mathrm{H}}$$

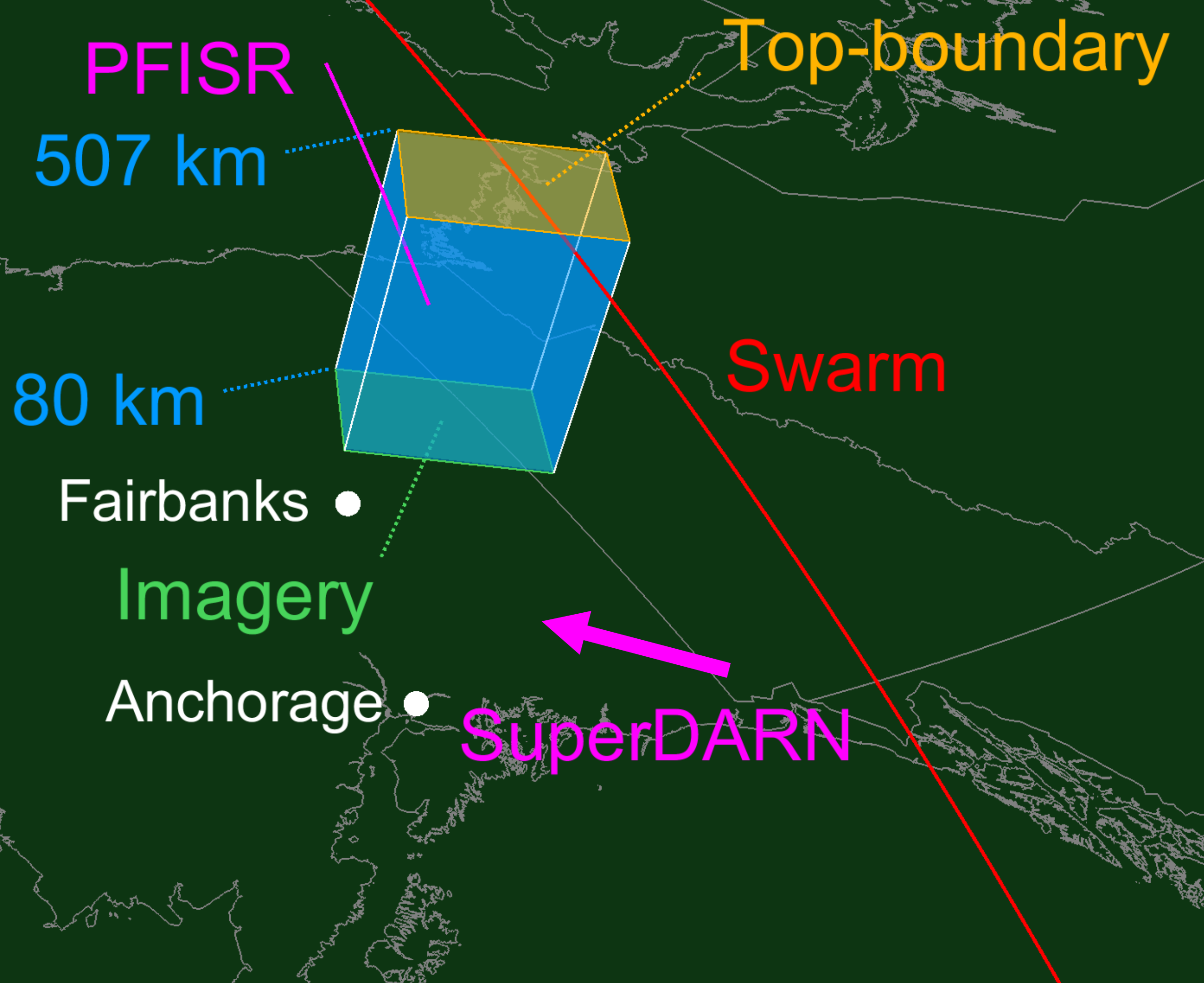
$$0 = \Sigma_{\mathrm{P}} \nabla \cdot \mathbf{E}_0 + \mathbf{E}_0 \cdot \nabla \Sigma_{\mathrm{P}} + (\mathbf{E}_0 \times \mathbf{b}) \cdot \nabla \Sigma_{\mathrm{H}}$$

**Pers. Comm. A. Mule (Feb. 2025)*

What’s needed to simulate auroral arcs in 3D?

A. 2D, top-boundary maps of
   - Electron precipitation energetics
     - Determines 3D conductivity volume
     - Requires imagery, choice of energy spectra, and a transport model
   - Field-aligned current
     - Forces the simulation
     - Requires 1D track data + replication
   - A background electric field

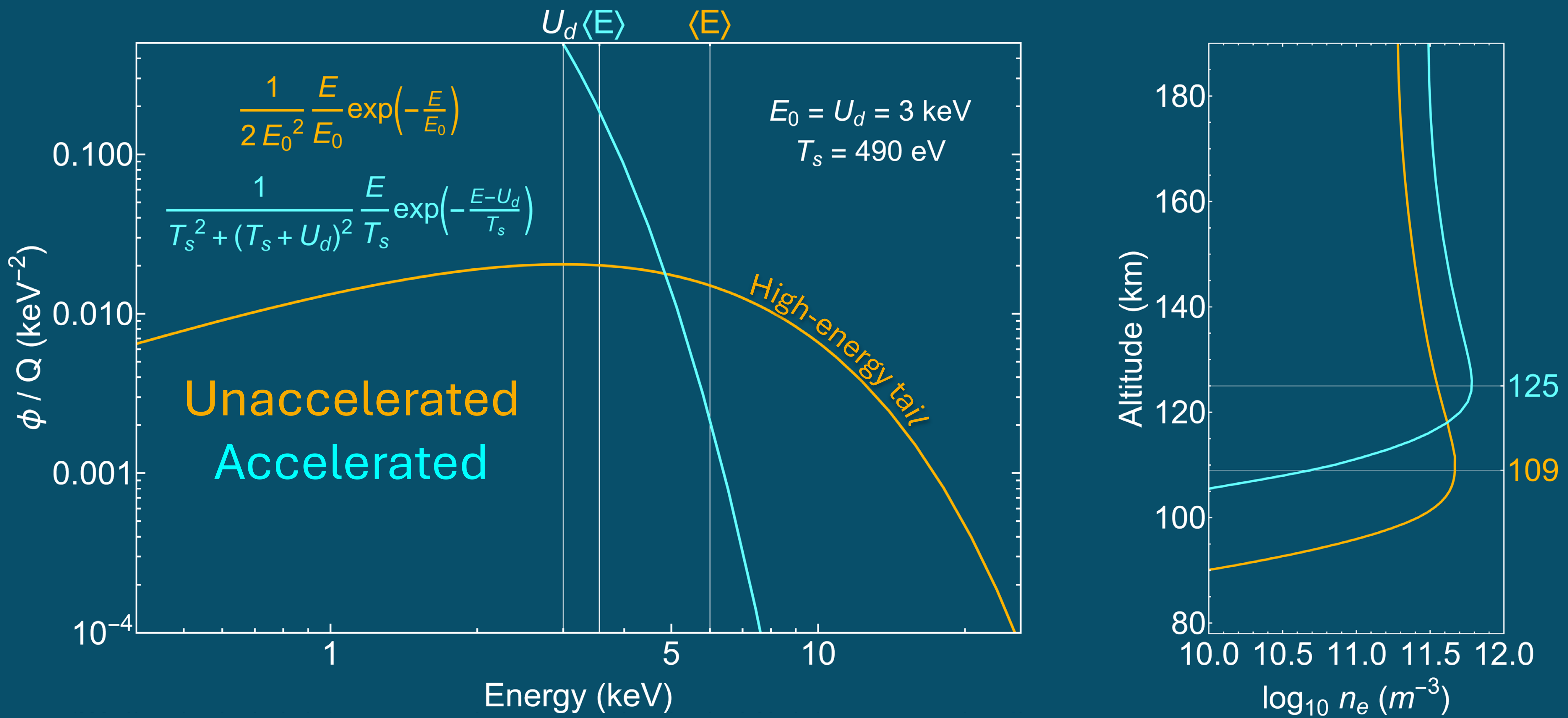
B. A 3D Model: GEMINI
   - Provides state-of-the-art, 3D ionospheric, multi-fluid simulations
   - Github.com/gemini3d



GEMINI model: Zetergren & Semeter, 2012, *JGR*; Zettergren & Snively, 2019, *GRL*
Swarm data: swarmhandbook.earth.esa.int – PFISR data: data.amisr.com

II. Top-Boundary Drivers

Choosing Electron Precipitation Energy Spectra



Transport model: Solomon et al., 1988, *JGR* (GLOW)
Ionization rate parameterization: Fang et al., 2010, *GRL*

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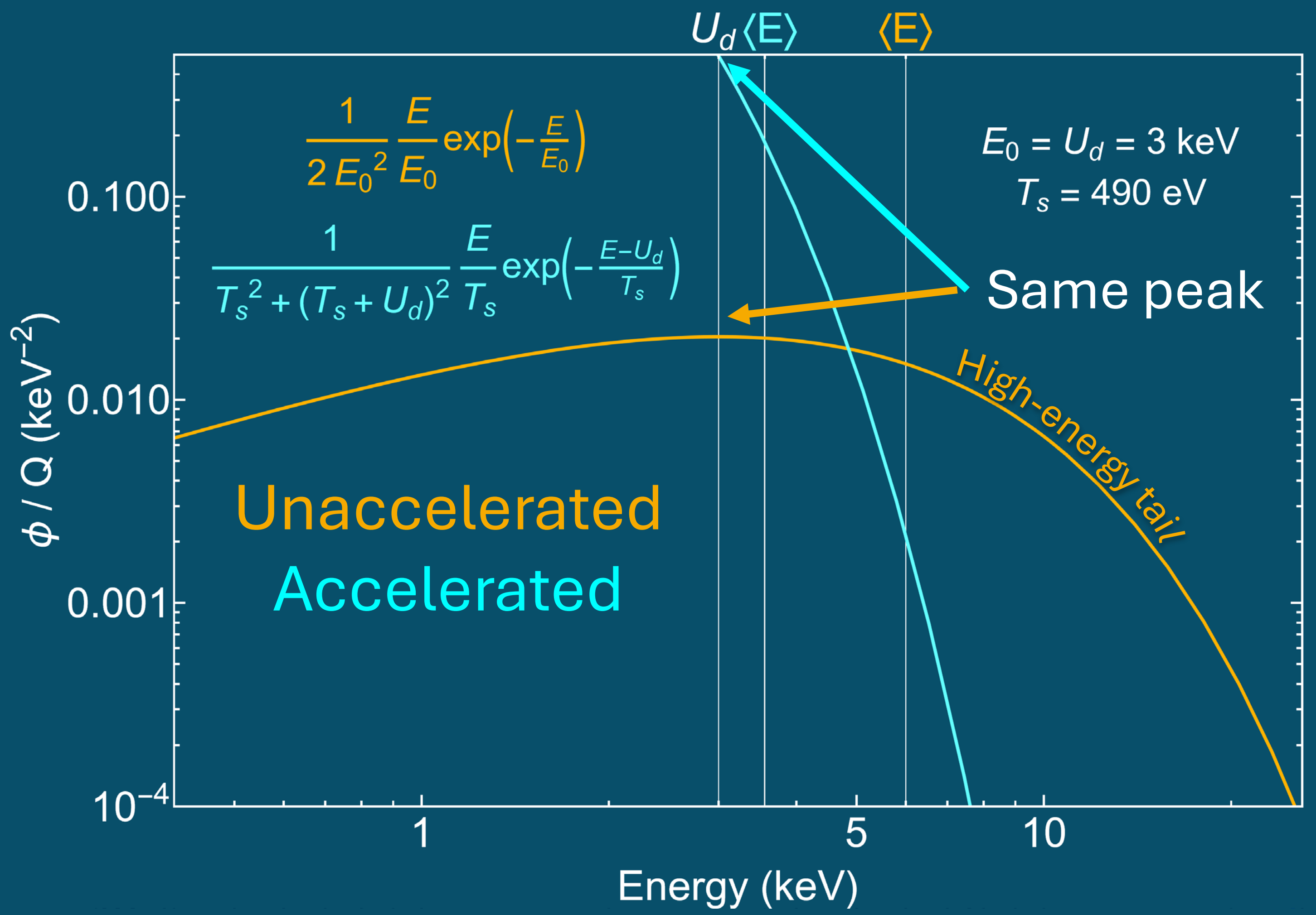

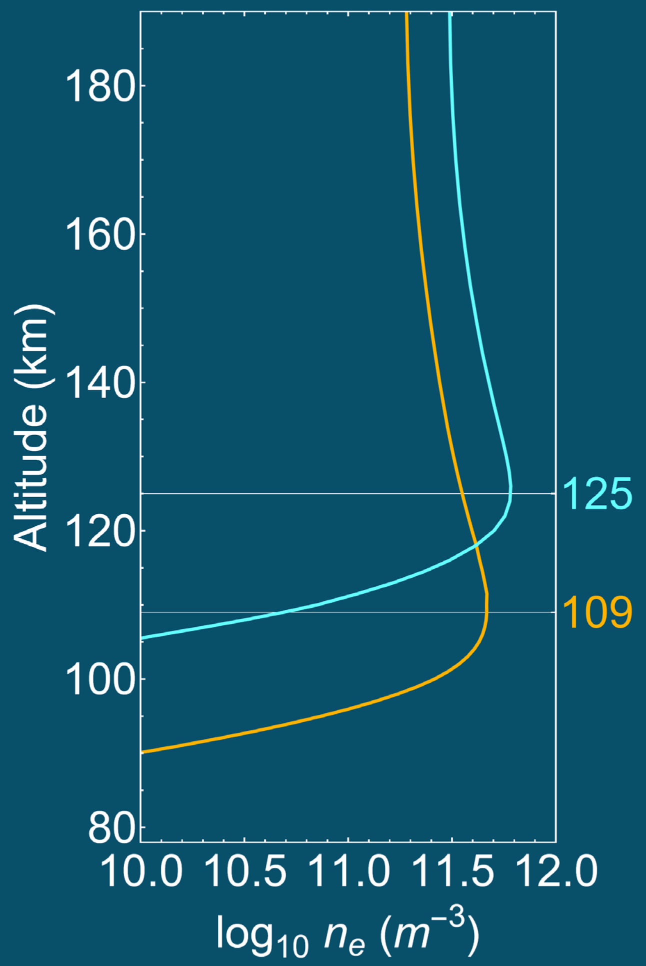

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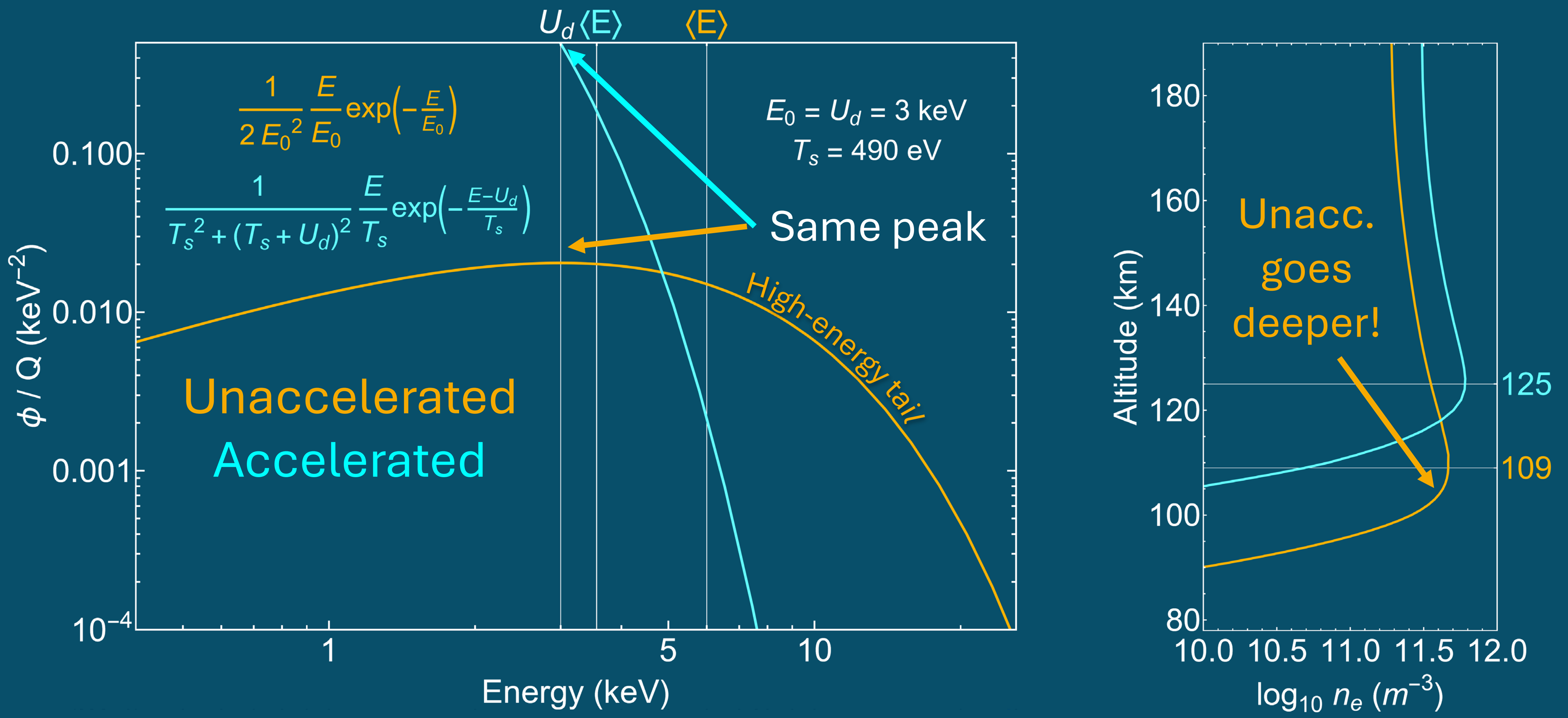

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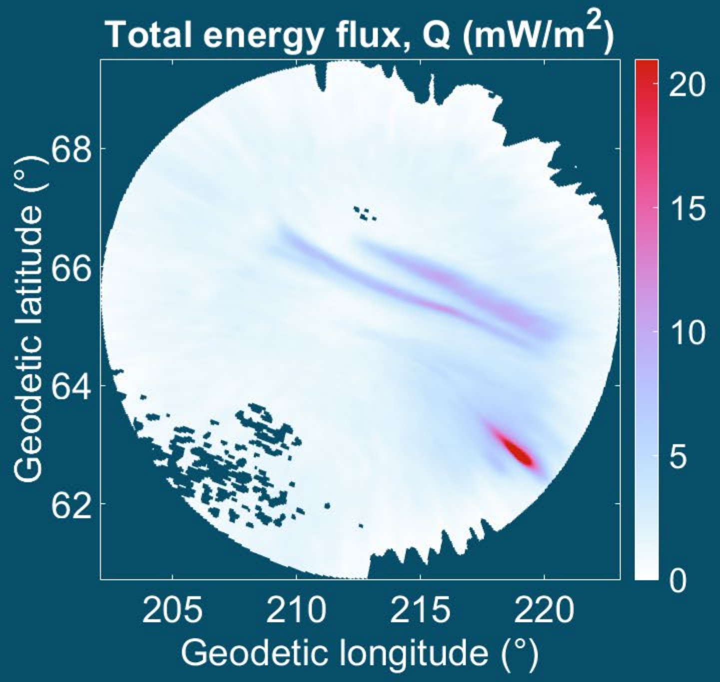
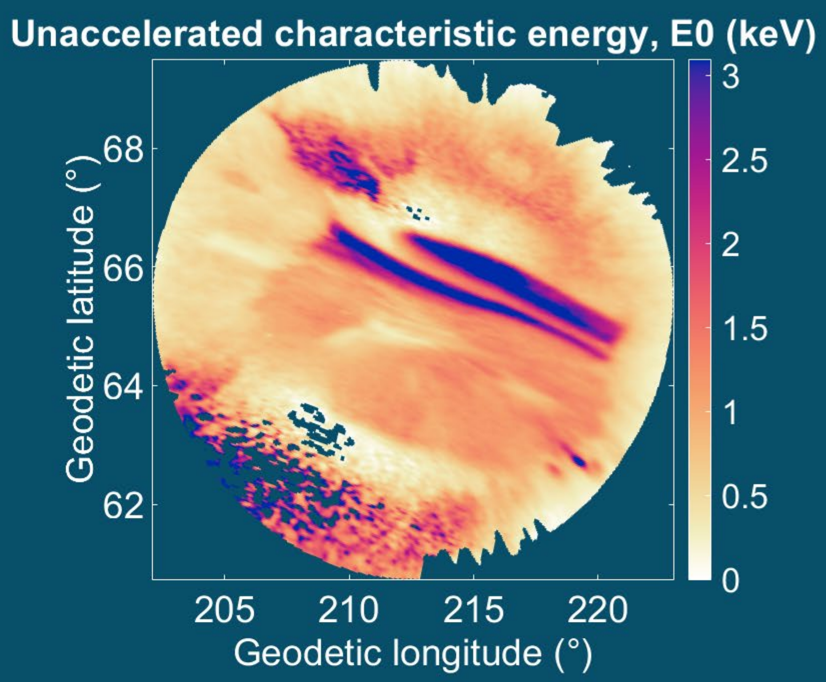
Determining Source Region Thermal Energy, T_s

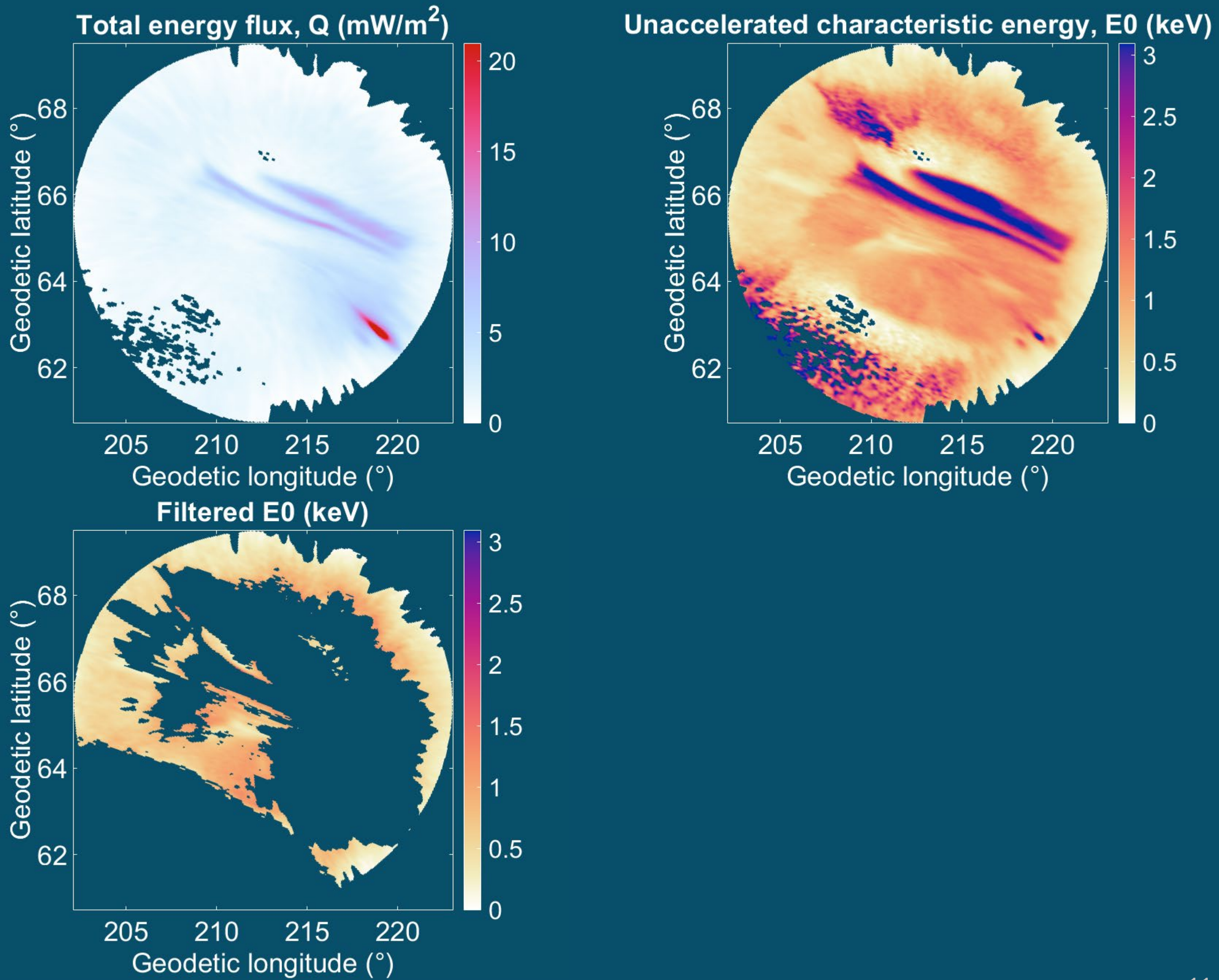
1) Invert multi-spectral imagery assuming unaccelerated Maxwellian spectra.





Determining Source Region Thermal Energy, T_s

1) Invert multi-spectral imagery assuming unaccelerated Maxwellian spectra.
2) Filter for low energy fluxes (where we assume $U_d \approx 0$) and low 630 nm light.



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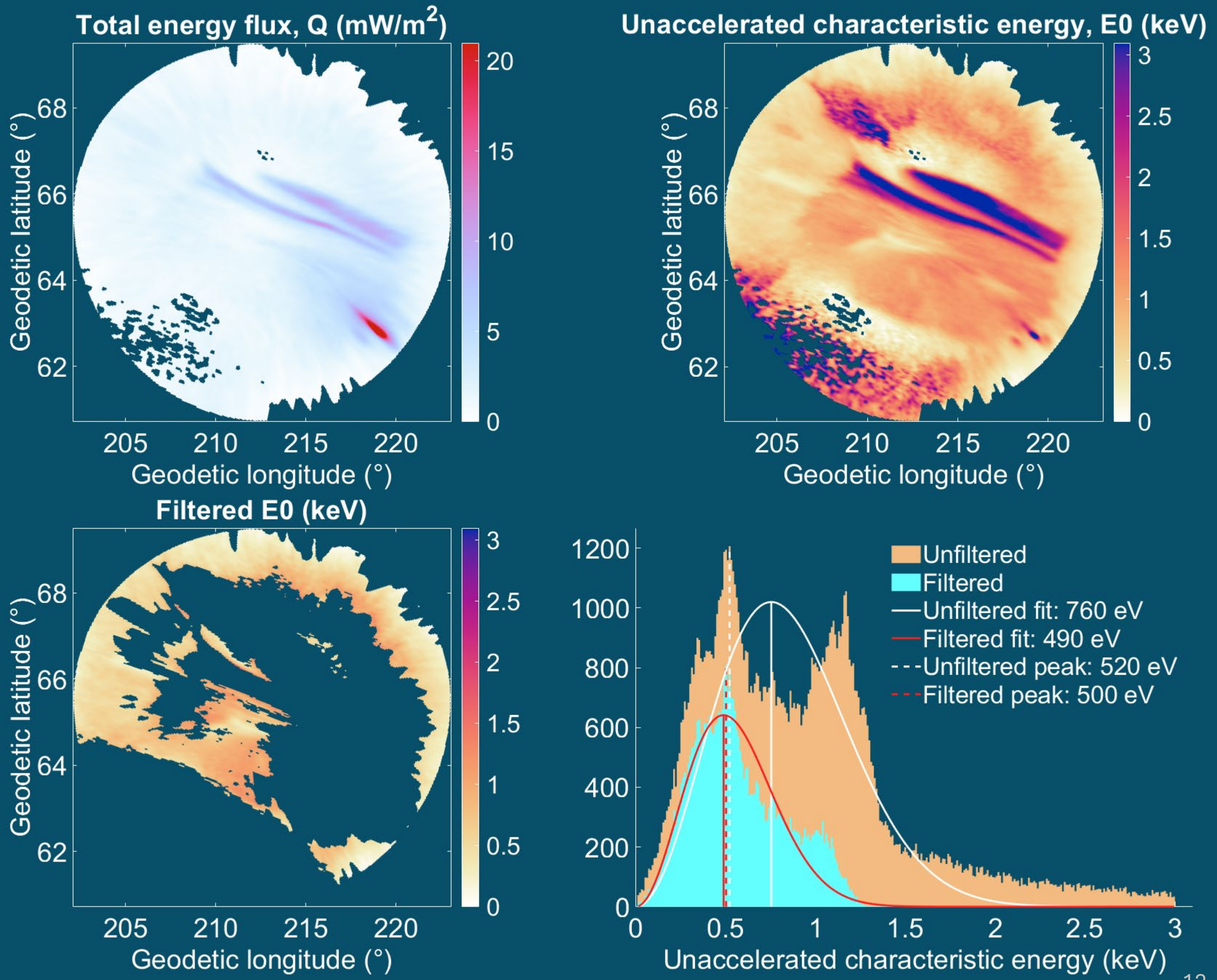
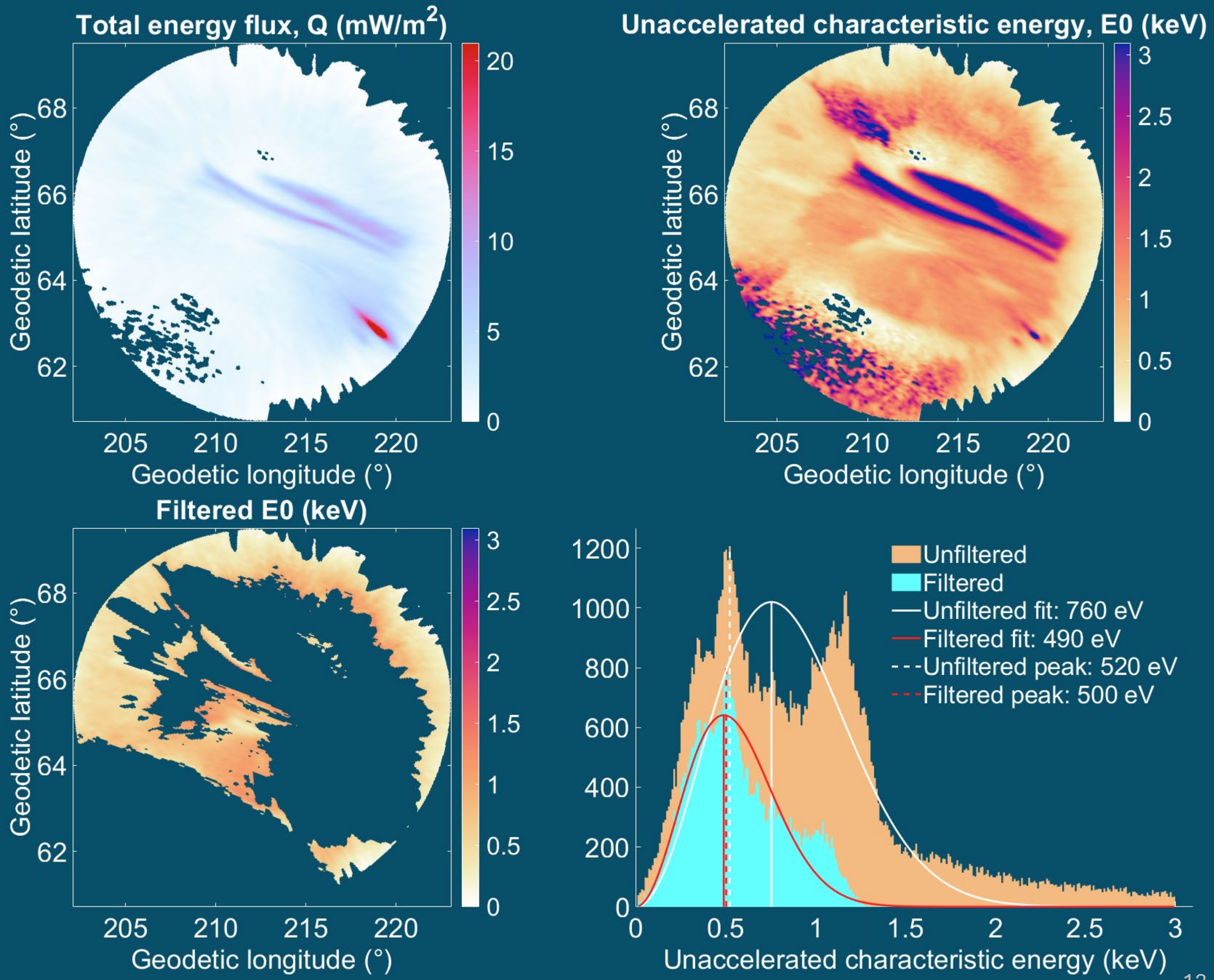
3) Find T_s, the peak energy of filtered E_0.



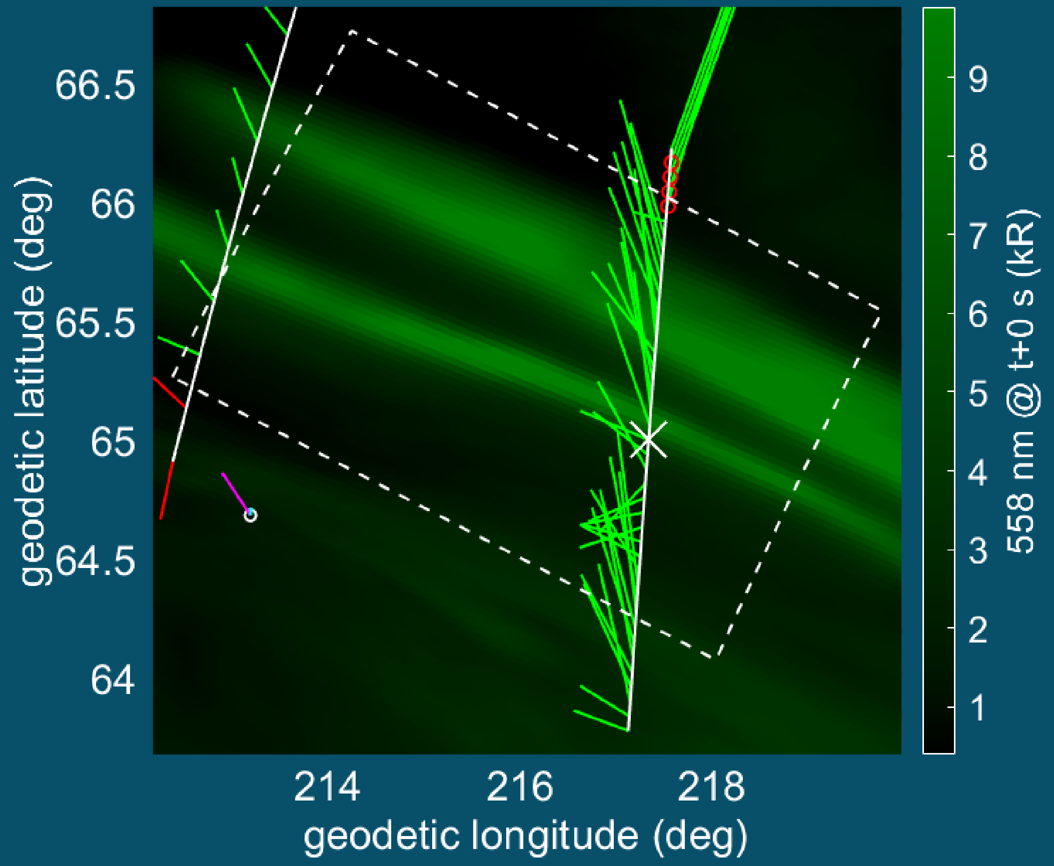
Determining Source Region Thermal Energy, T_s

1) Invert multi-spectral imagery assuming unaccelerated Maxwellian spectra.
2) Filter for low energy fluxes (where we assume $U_d \approx 0$) and low 630 nm light.
3) Find T_s, the peak energy of filtered E_0.
4) Invert imagery using accelerated spectra.

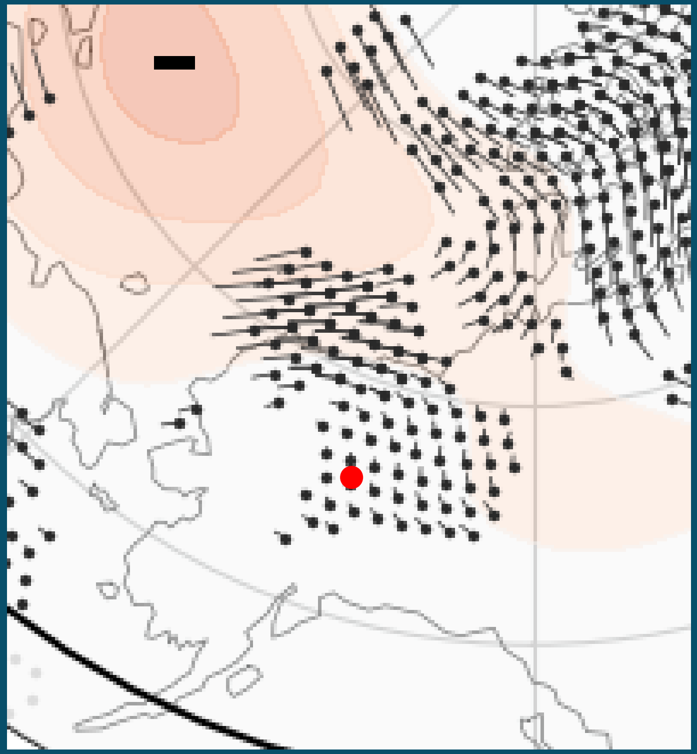


Choosing a Background Electric Field

PFISR



SuperDARN



Imagery data: optics.gi.alaska.edu/optics/archive – SuperDARN data: superdarn.ca/convection-maps

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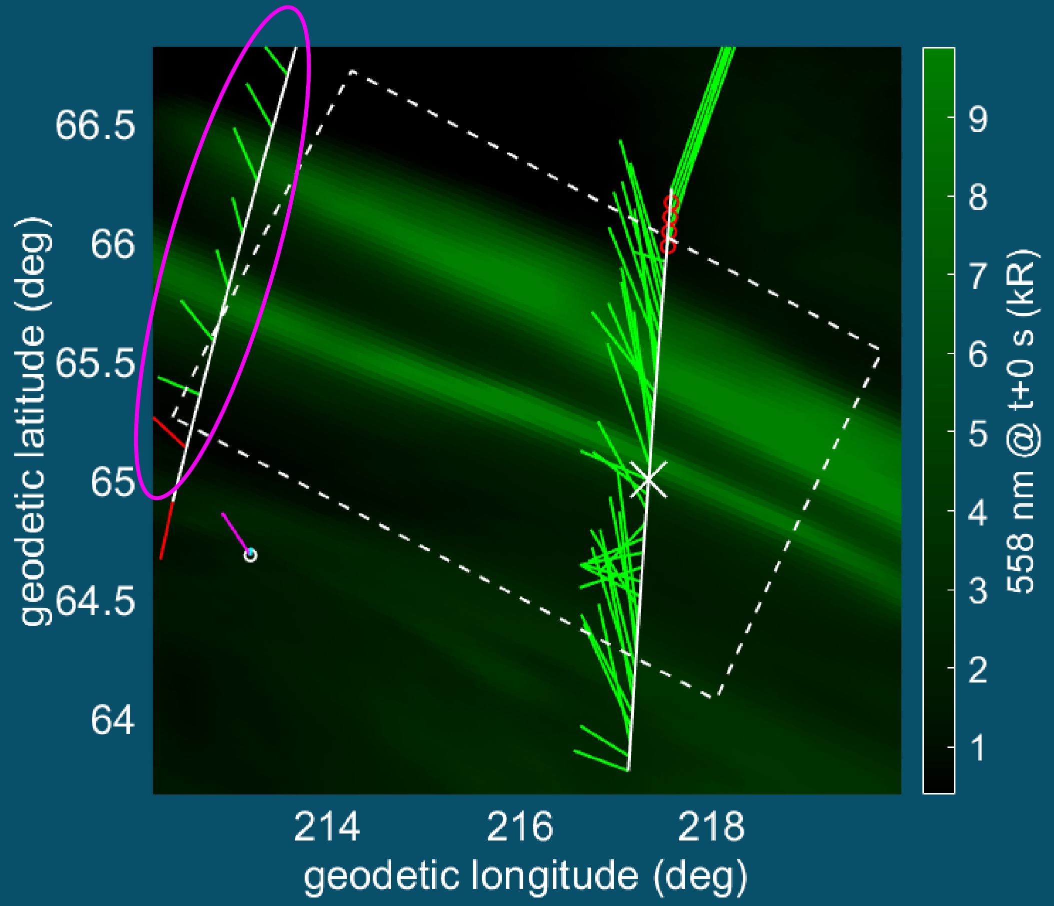

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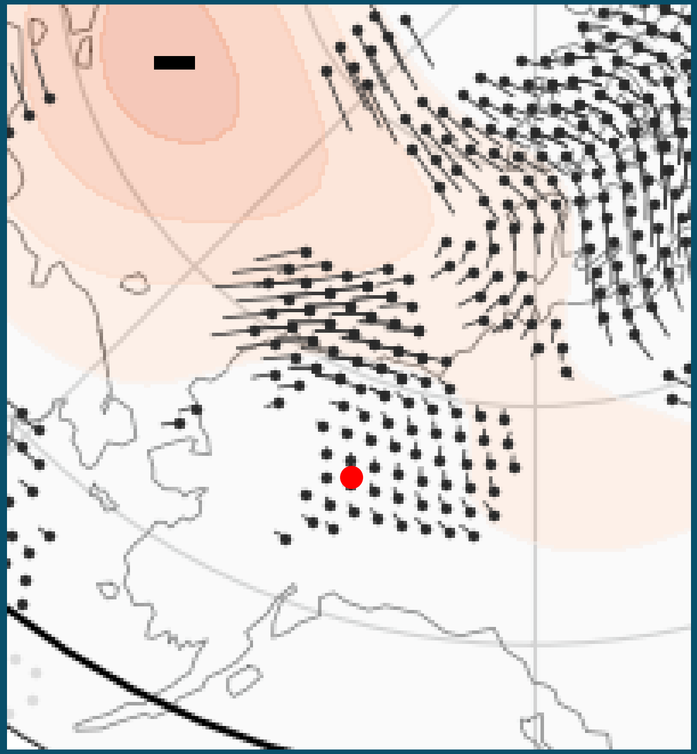

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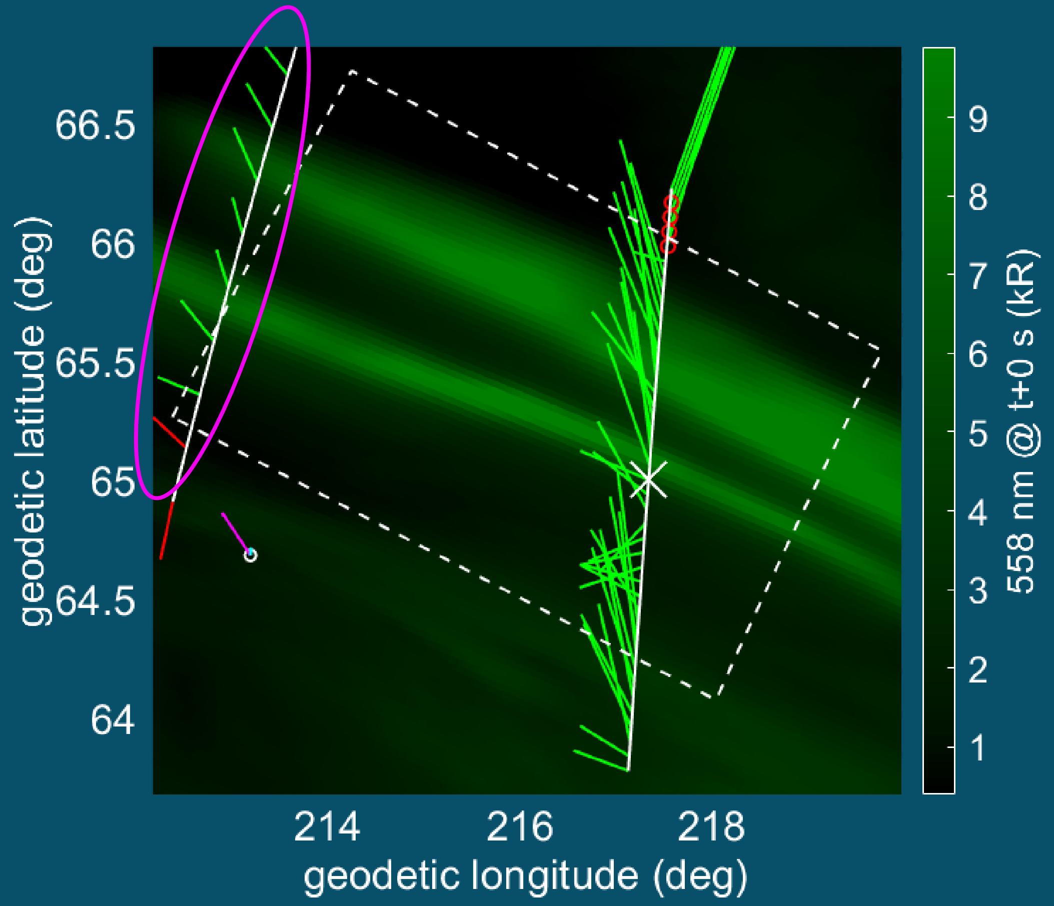

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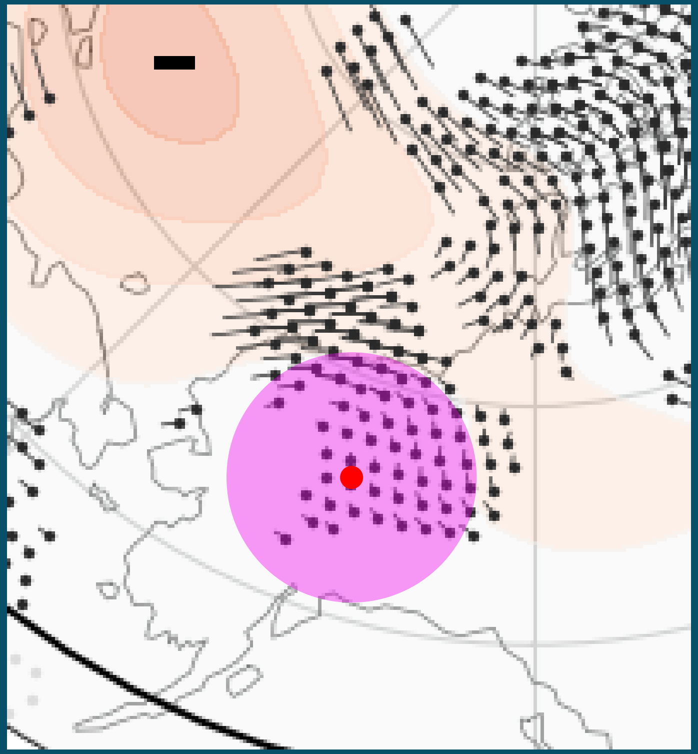

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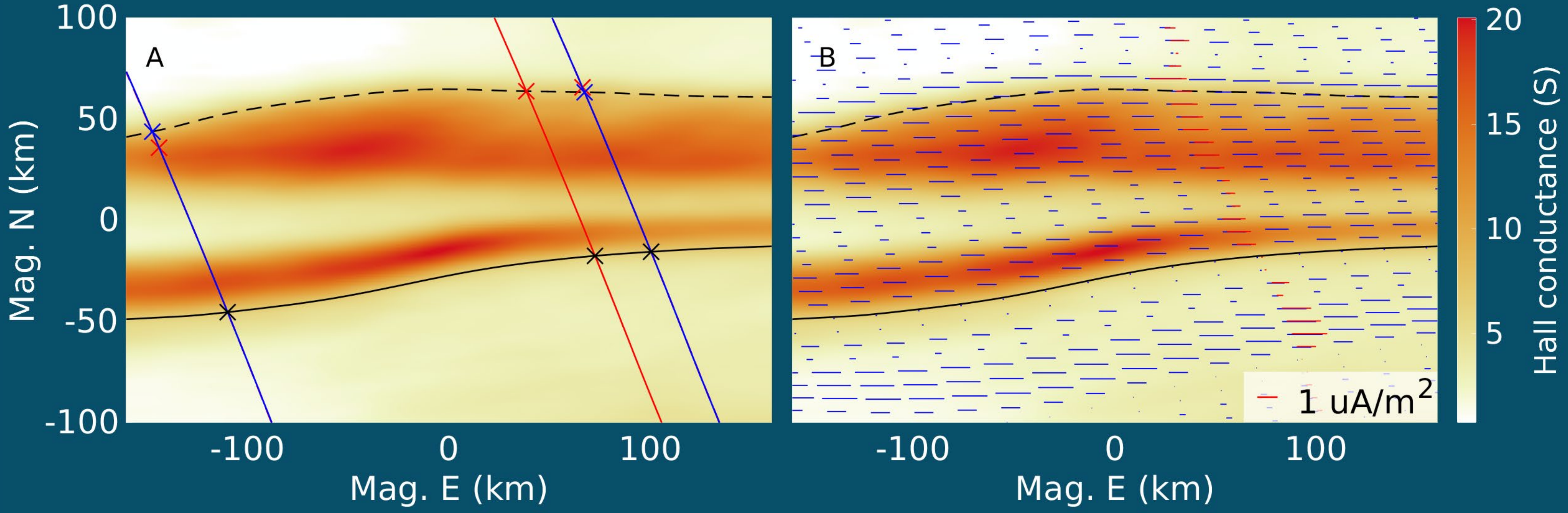
Top-Boundary Driver: Field-Aligned Current

- We convert 1D FAC data tracks into continuous 2D top-boundary drivers.
- Github.com/317Lab/aurora_gemini (van Irsel et al., 2024, *JGR*)

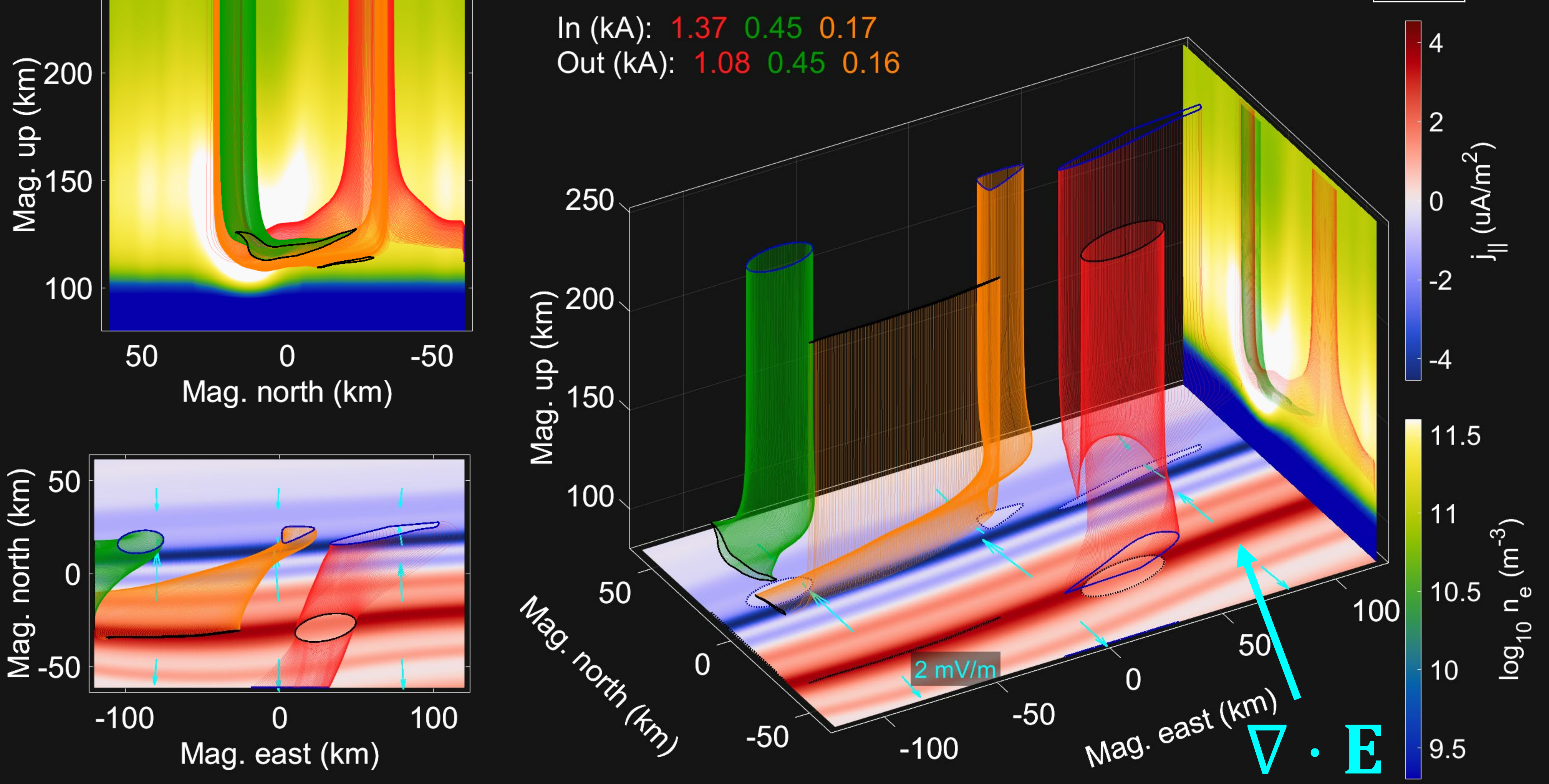


III. Simulation Results

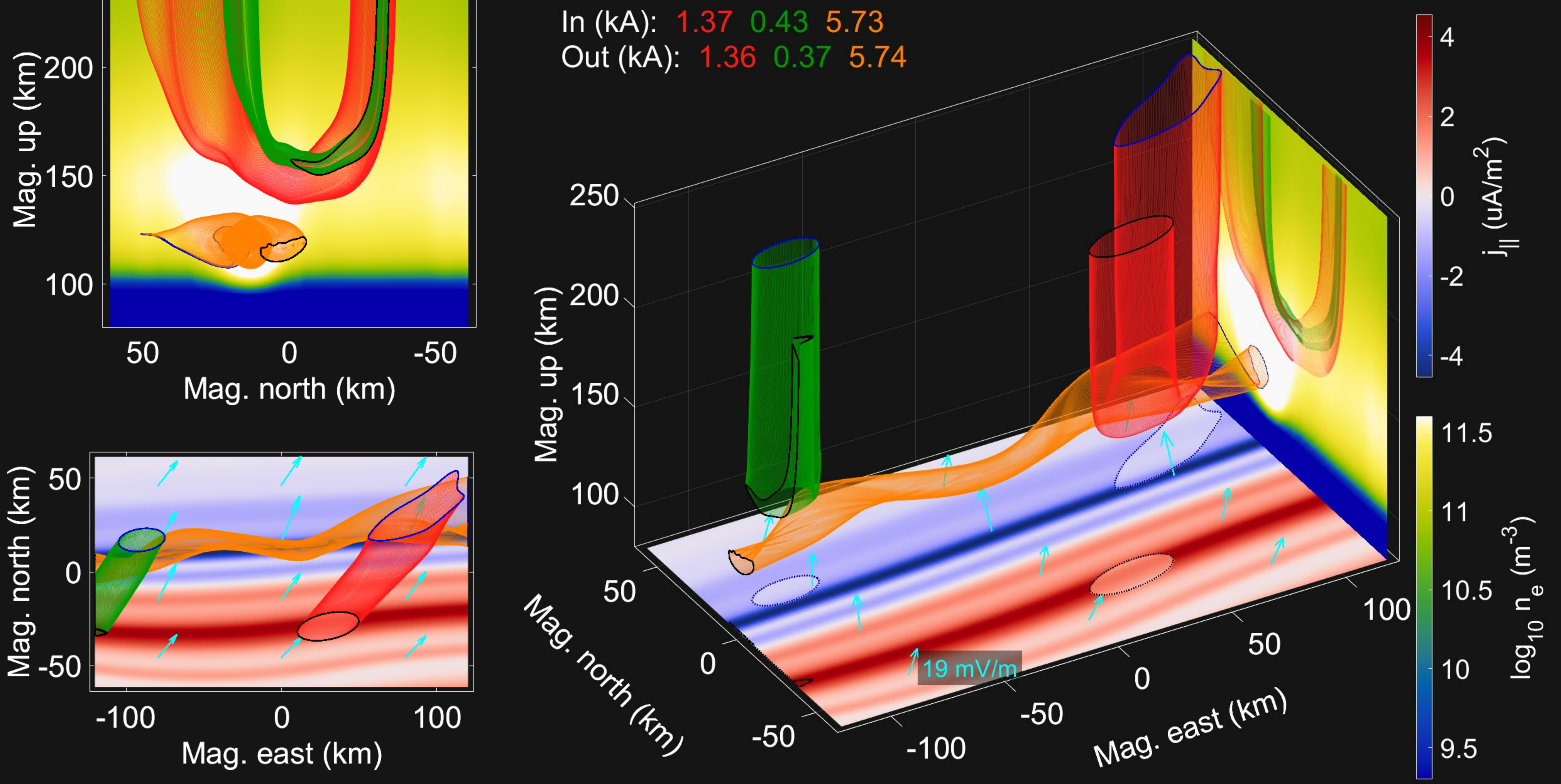
Simulation comparisons:

Mar. 4	Weak $\mathbf{E}_{bg}$ + Accelerated
	Strong $\mathbf{E}_{bg}$ + Accelerated
Feb 10.	Weak $\mathbf{E}_{bg}$ + Unaccelerated
	Weak $\mathbf{E}_{bg}$ + Accelerated

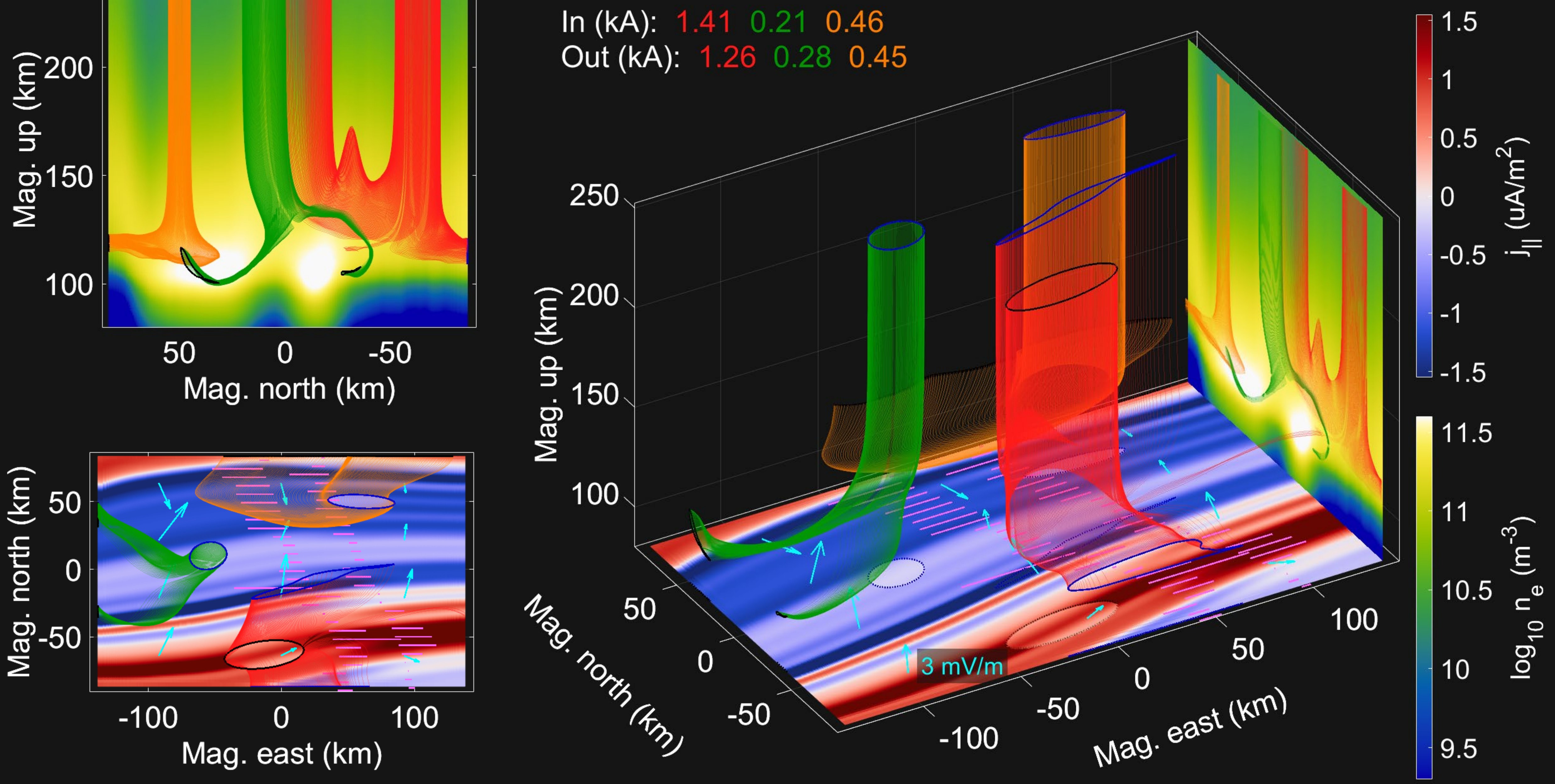
Weak $\mathbf{E}_{bg}$, Accelerated



Strong $\mathbf{E}_{bg}$, Accelerated



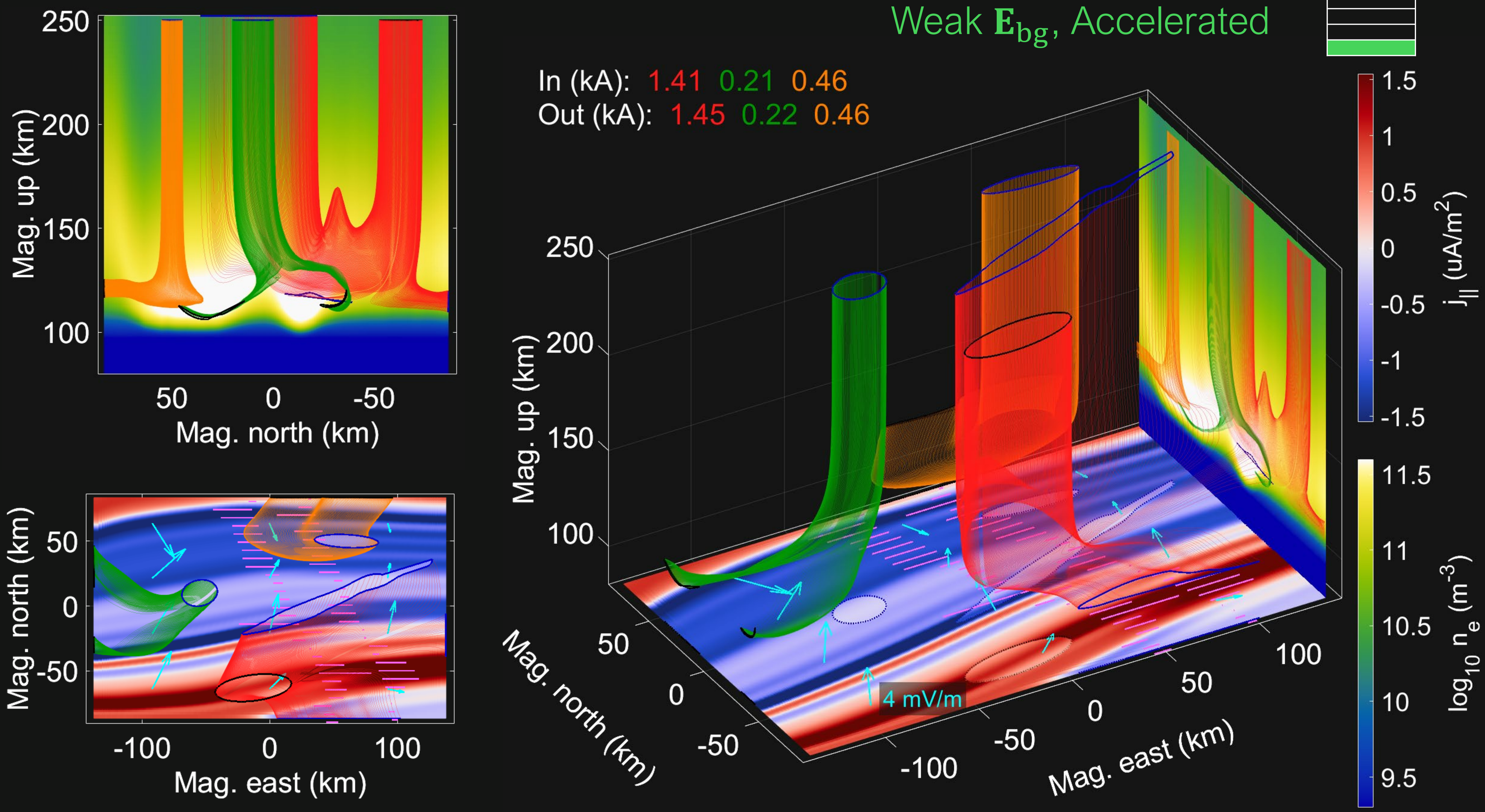
Weak $\mathbf{E}_{bg}$, Unaccelerated



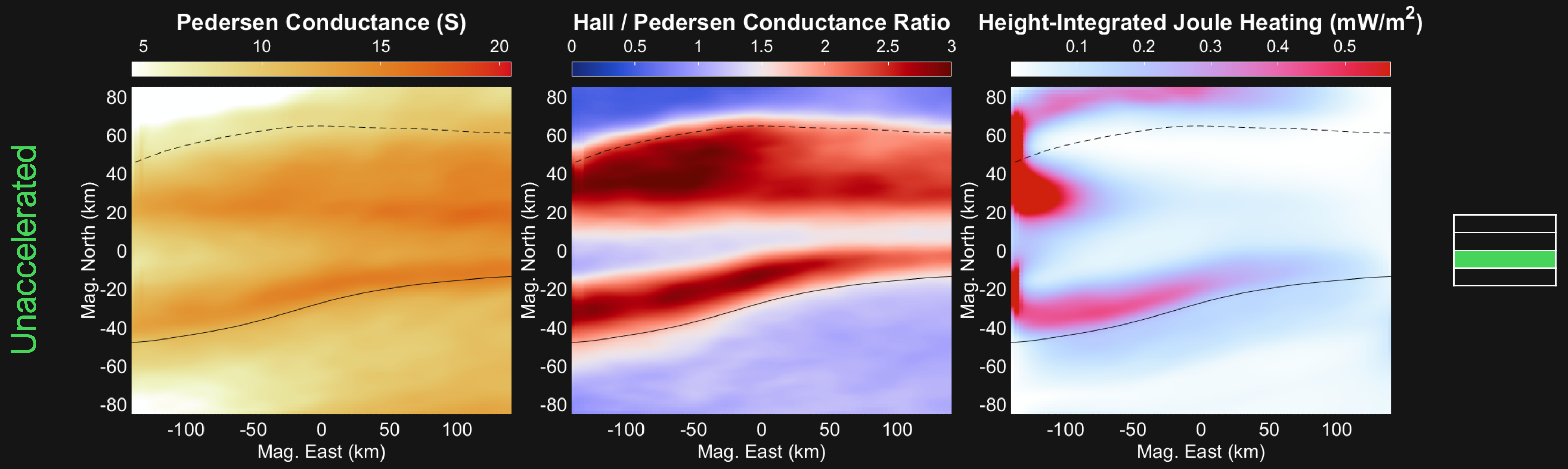
J. van Irsel

Weak $\mathbf{E}_{bg}$, Accelerated

In (kA): 1.41 0.21 0.46
Out (kA): 1.45 0.22 0.46



Height-Integrated View, Weak $\mathbf{E}_{\mathbf{bg}}$



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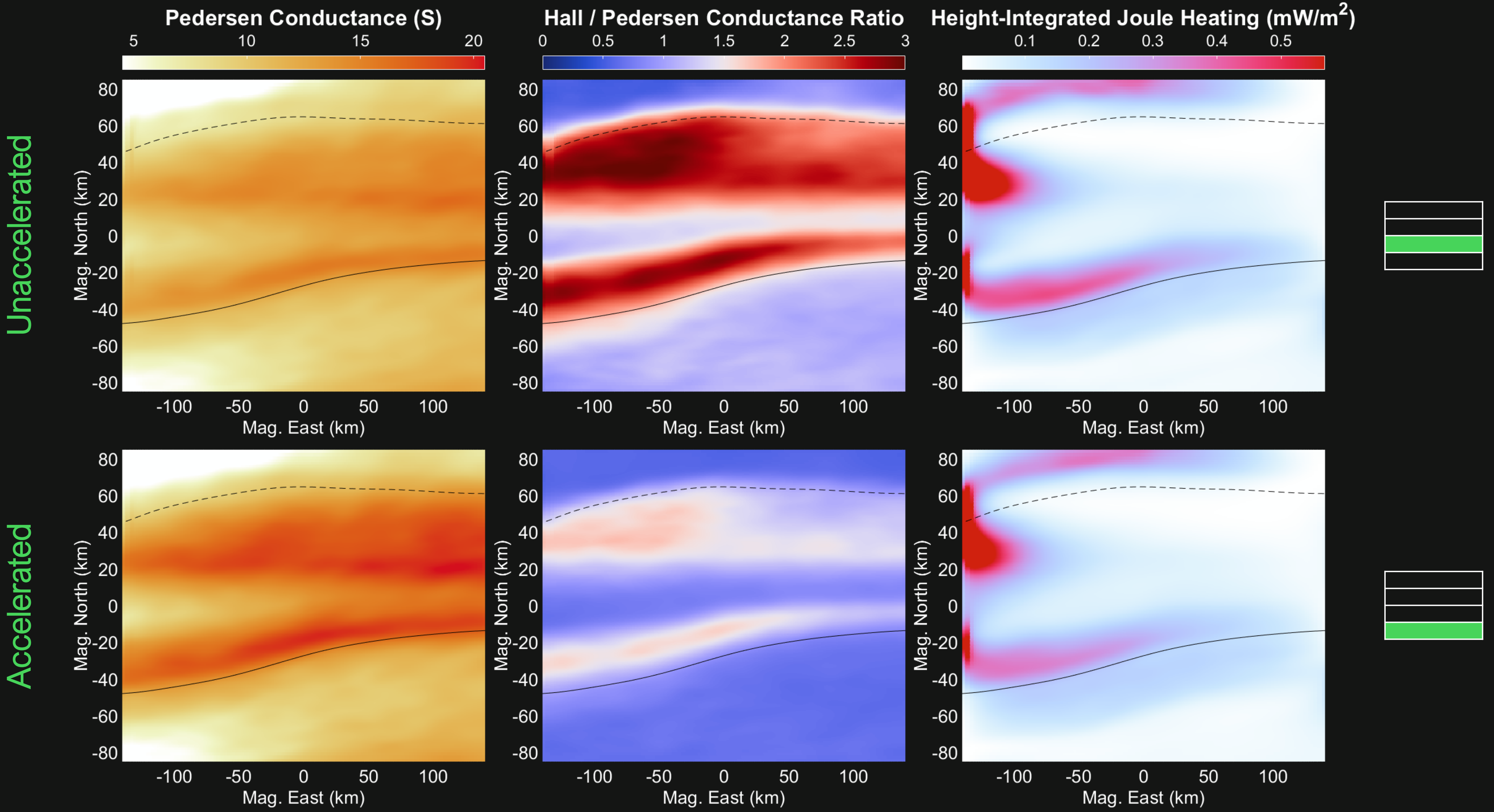
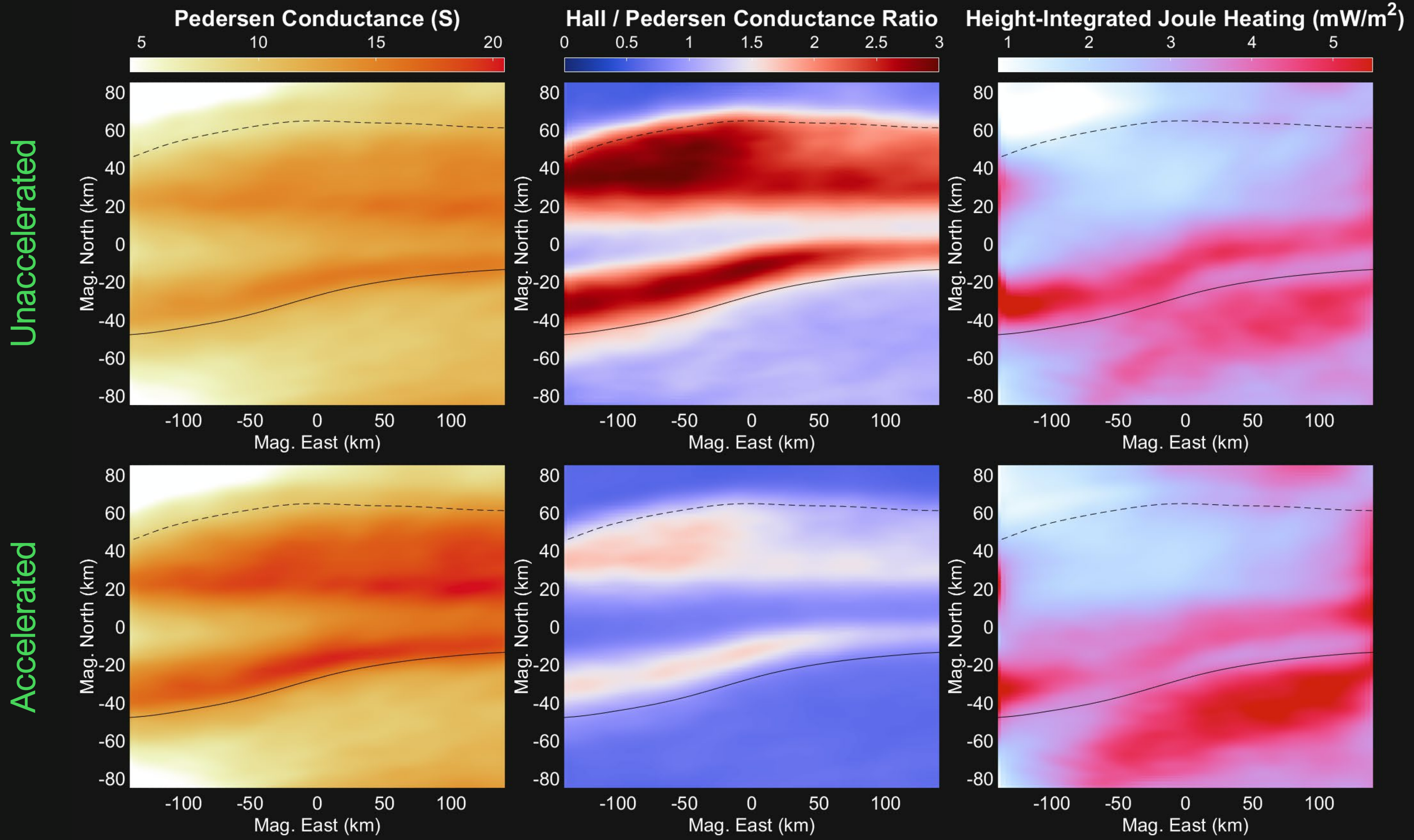


Height-Integrated View, Strong $\mathbf{E_{bg}}$



IV. Conclusions

Comments & Conclusions

- The height-integrated view of the auroral ionosphere, albeit very useful, can hide the 3D nature of current continuity.
- Simulating auroral arc systems in 3D is a sensitive undertaking:
  A. The electric potential solution is not unique mathematically:
     - An inappropriate background electric field can provide erroneous current closure morphology.
     - Sensitivity to the choice of precipitation spectra matter more with a weak background electric field.
  B. The choice of unaccelerated Maxwellian electron precipitation spectra can:
     - Overestimate the thermal spread, hence overestimate lower E-region densities.
     - Impact Hall closure and Hall-to-Pedersen conductance ratios.
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- We thank Daniel Billett for providing SuperDARN flow estimates.

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