Ionospheric **Plasma Physics**

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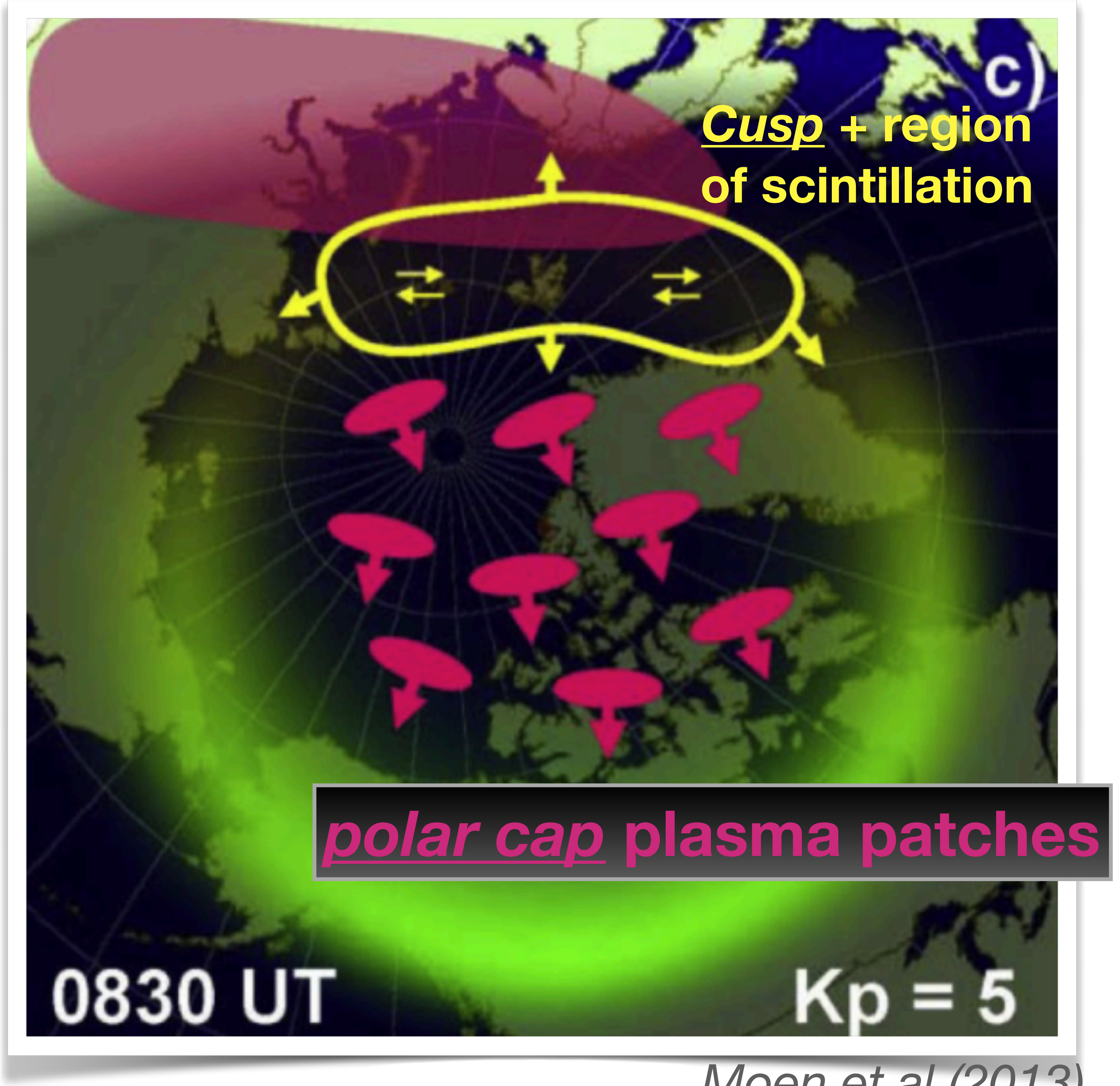
Ionospheric Plasma Physics: Spatial Inhomogeneities and Instability

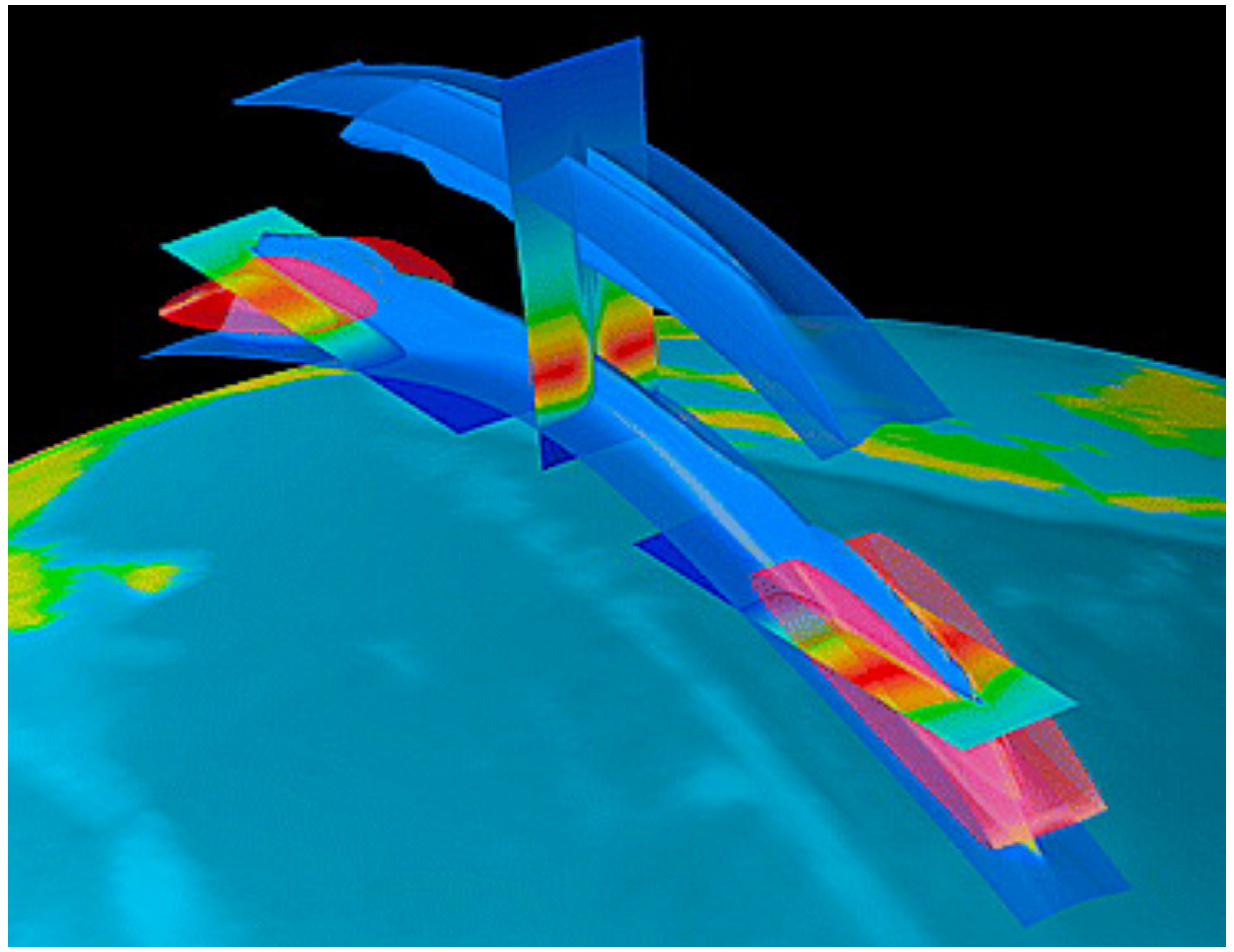
Large scale, dense regions of plasma form in cusp region, break up into ~100 km structures (patches) due to transient reconnection, and undergo unstable cascade,

dense dayside plasma



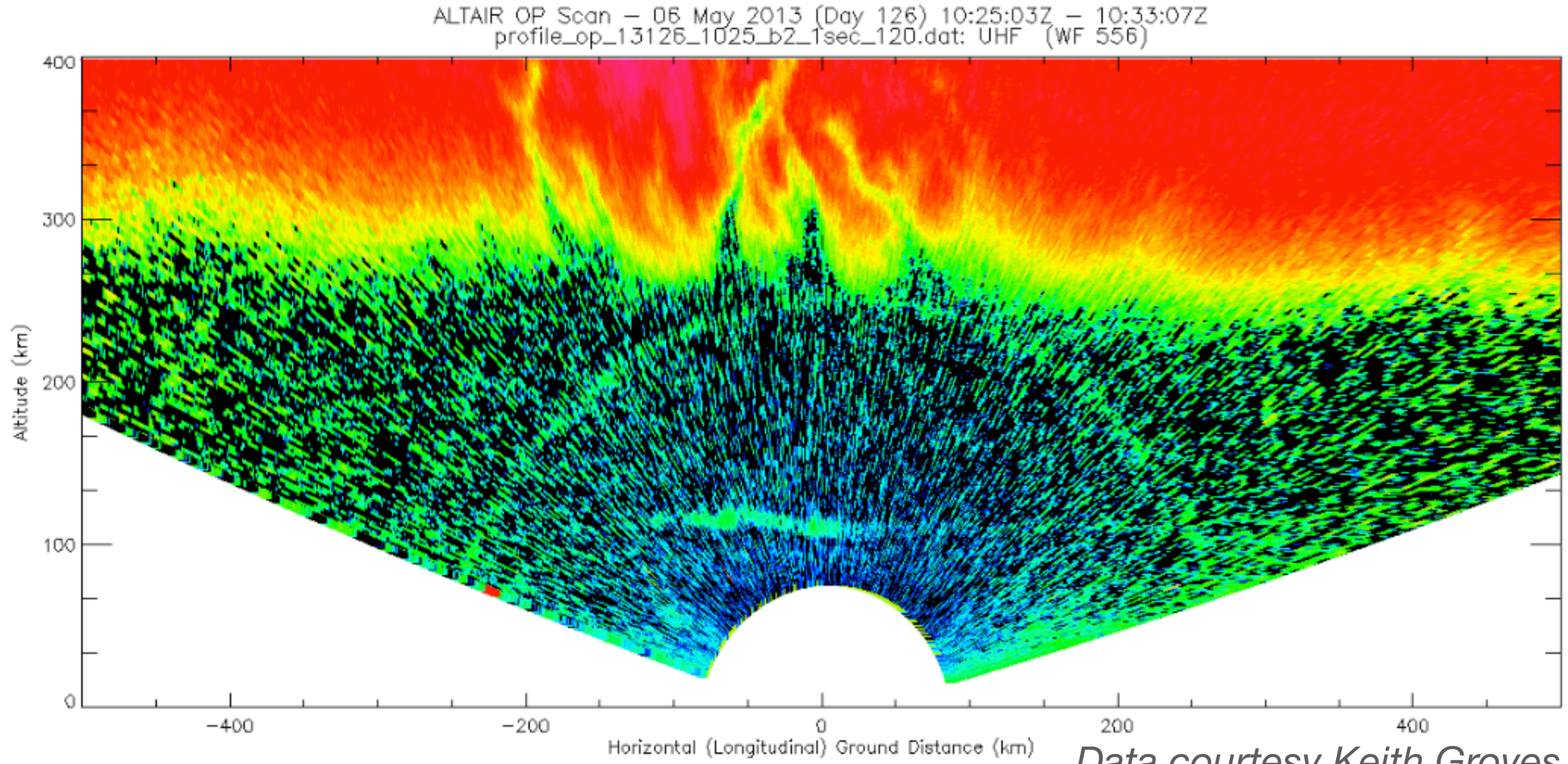
Moen et al (2013)

Post-sunset low density plasma bubbles form from a due to Rayleigh-Taylor type instability



Huba et al (2008)

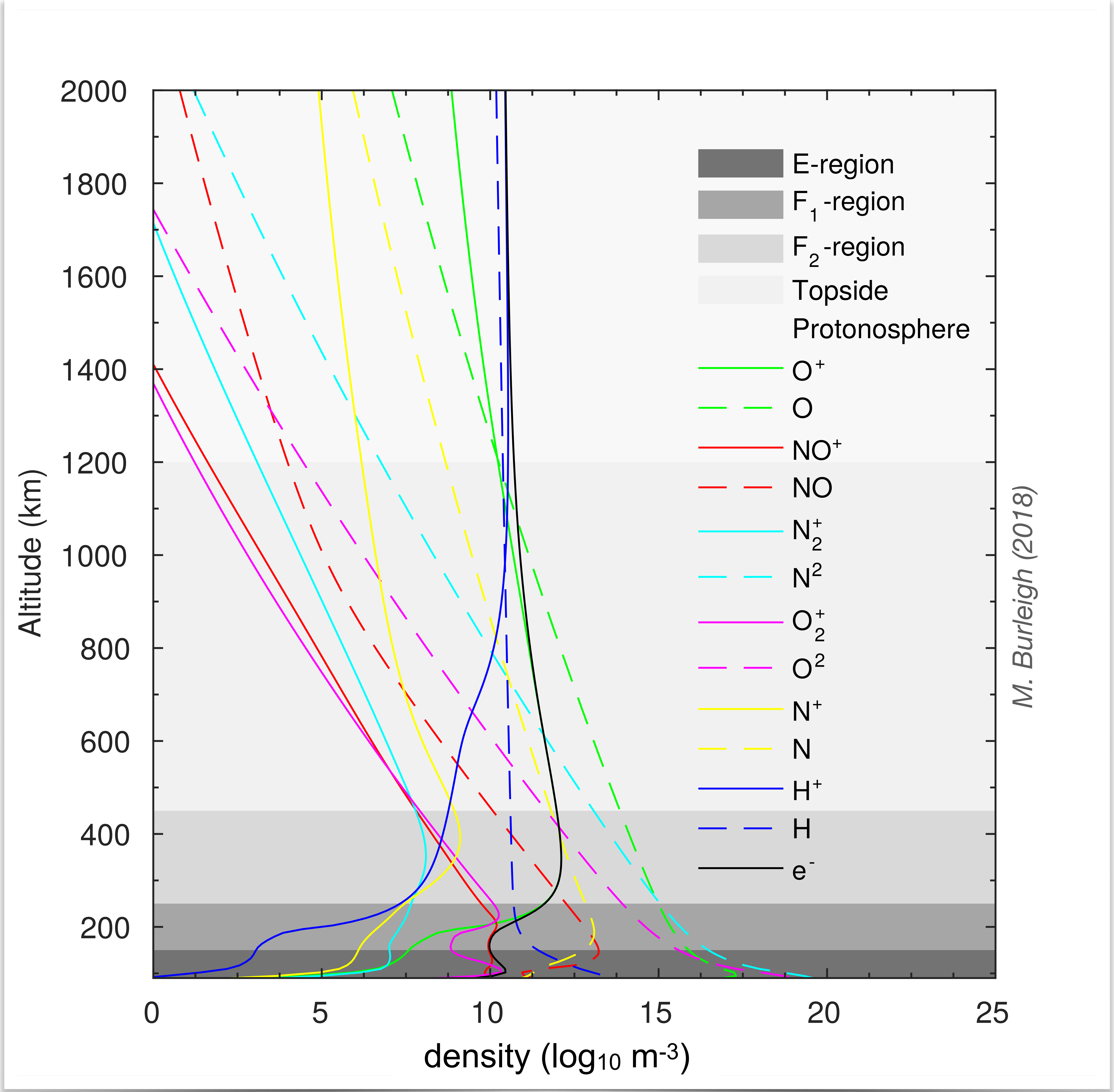
Equatorial plasma bubbles



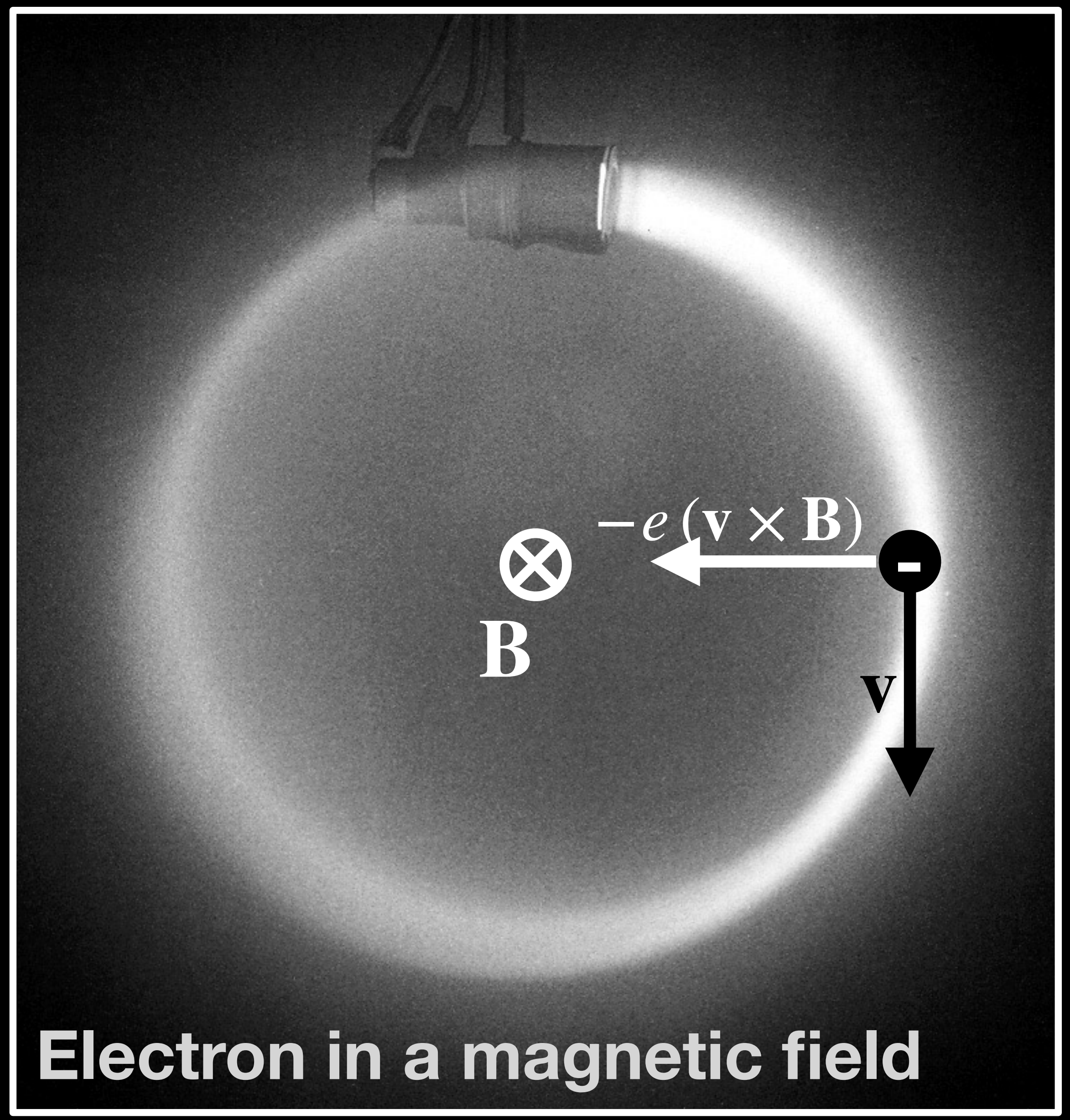
Data courtesy Keith Groves

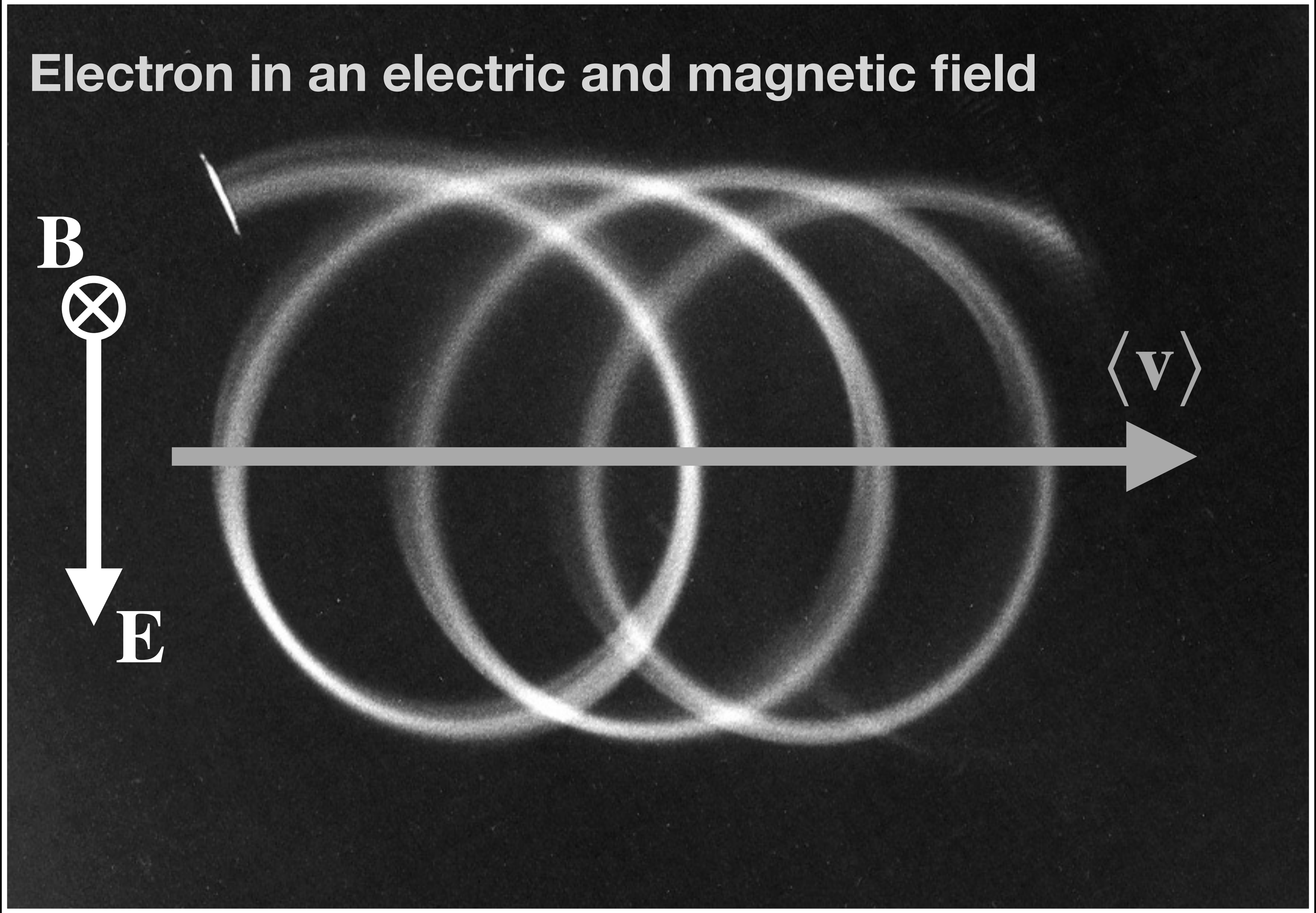
Earth's Ionosphere

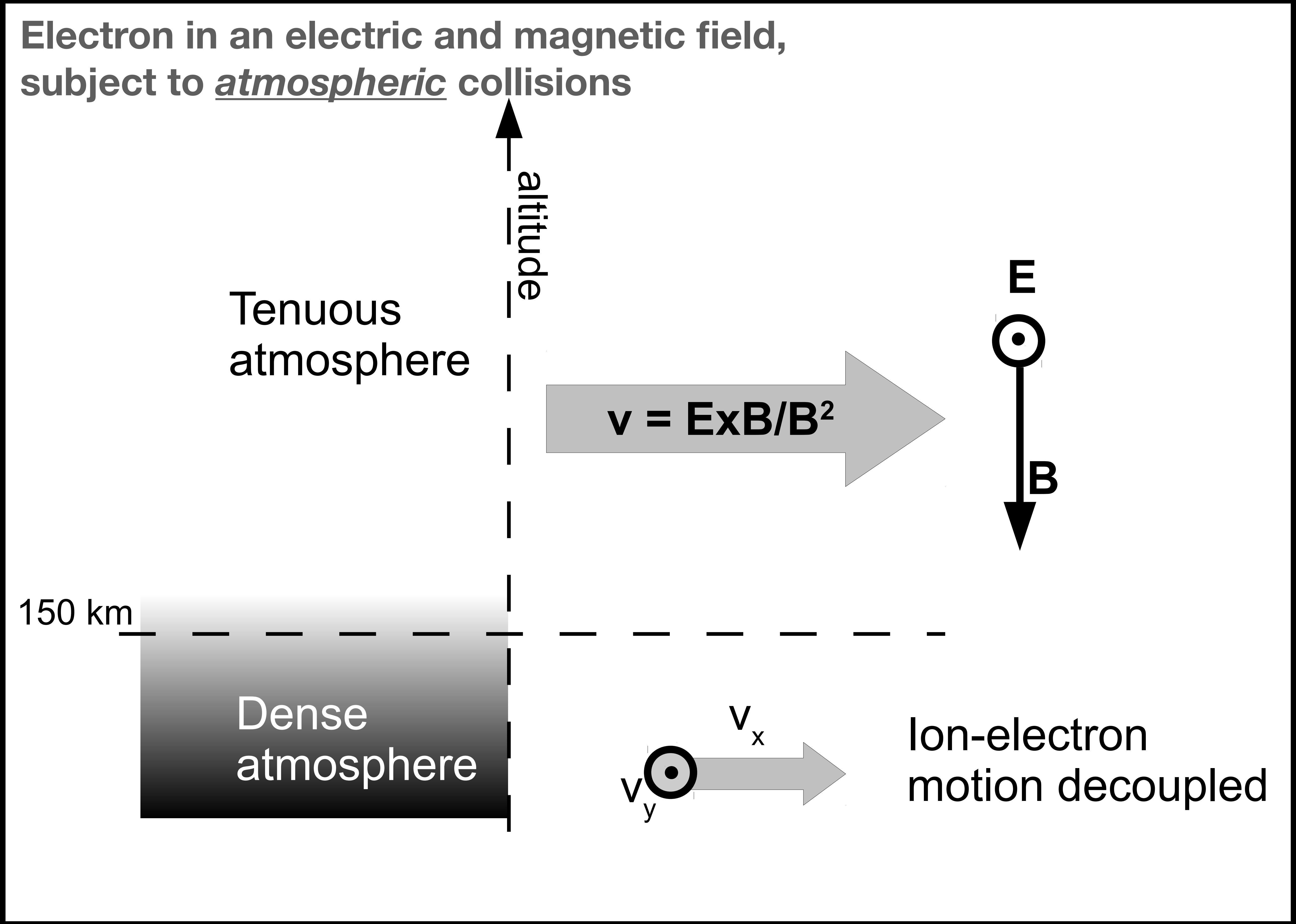
- Ionosphere - ionized portion of the upper atmosphere ~100-300 km altitude
- Produced by solar EUV and soft X-ray radiation (~80-200 km altitude)
- Vertical structure controlled by diffusion (through atmosphere) along field line
- Horizontal structure often due to neutral motions and electromagnetic forces
- *Ionosphere is a weakly ionized plasma*, i.e. it in embedded in a relatively dense atmosphere!



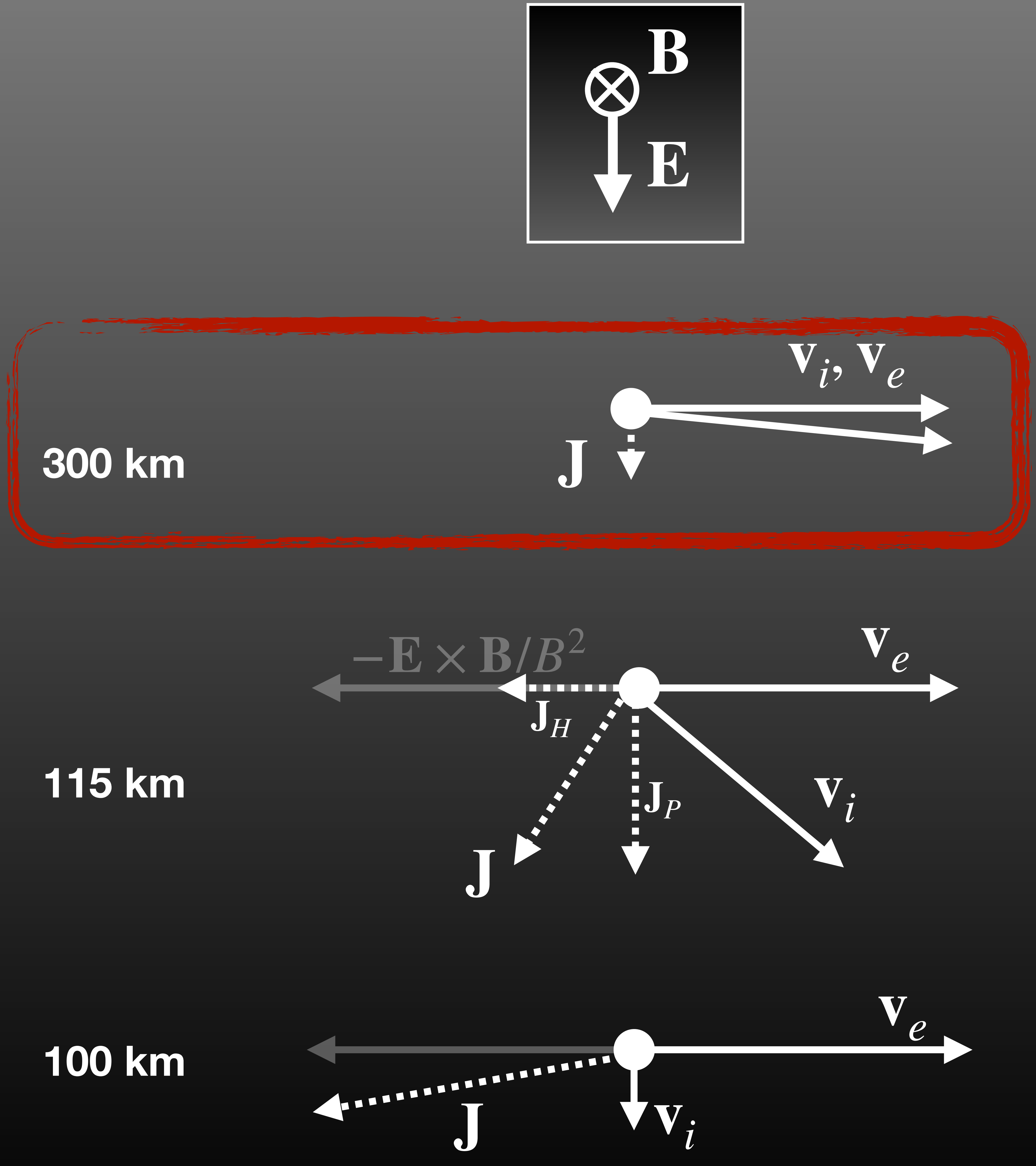
Ionospheric Motions Perpendicular to *B*

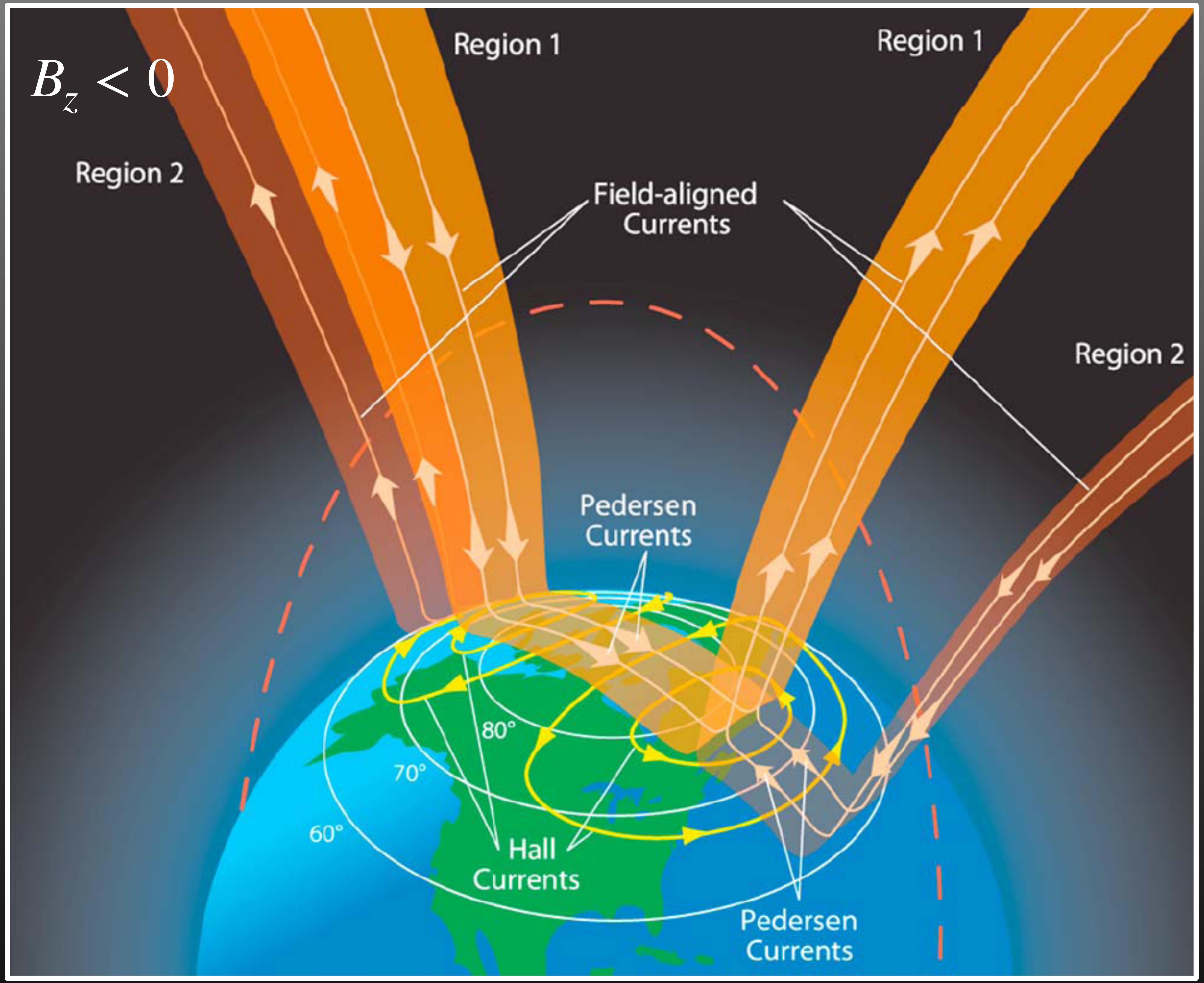






Ionospheric *Collisional* Electric Currents





https://en.wikipedia.org/wiki/Birkeland_current

$$\mathbf{J} = \mathbf{J}_P + \mathbf{J}_H + \mathbf{J}_{\parallel} = \sigma_P \mathbf{E}_{\perp} - \sigma_H \left(\mathbf{E}_{\perp} \times \mathbf{B}/B\right) + \sigma_{\parallel} \mathbf{E}_{\parallel}$$

(Some) Structures and Instabilities: Conceptual Approach + Linear Theory

Governing Equations

$$\frac{\partial n}{\partial t} + \nabla \cdot (n\mathbf{v}) = 0$$

$$\nabla \cdot \mathbf{J} = 0$$

$$\mathbf{v} \approx \frac{\mathbf{E} \times \mathbf{B}}{B^2}$$

$$\mathbf{E} = -\nabla\Phi$$

"Constitutive" relation specifying *J*

Zero-order (background) conditions

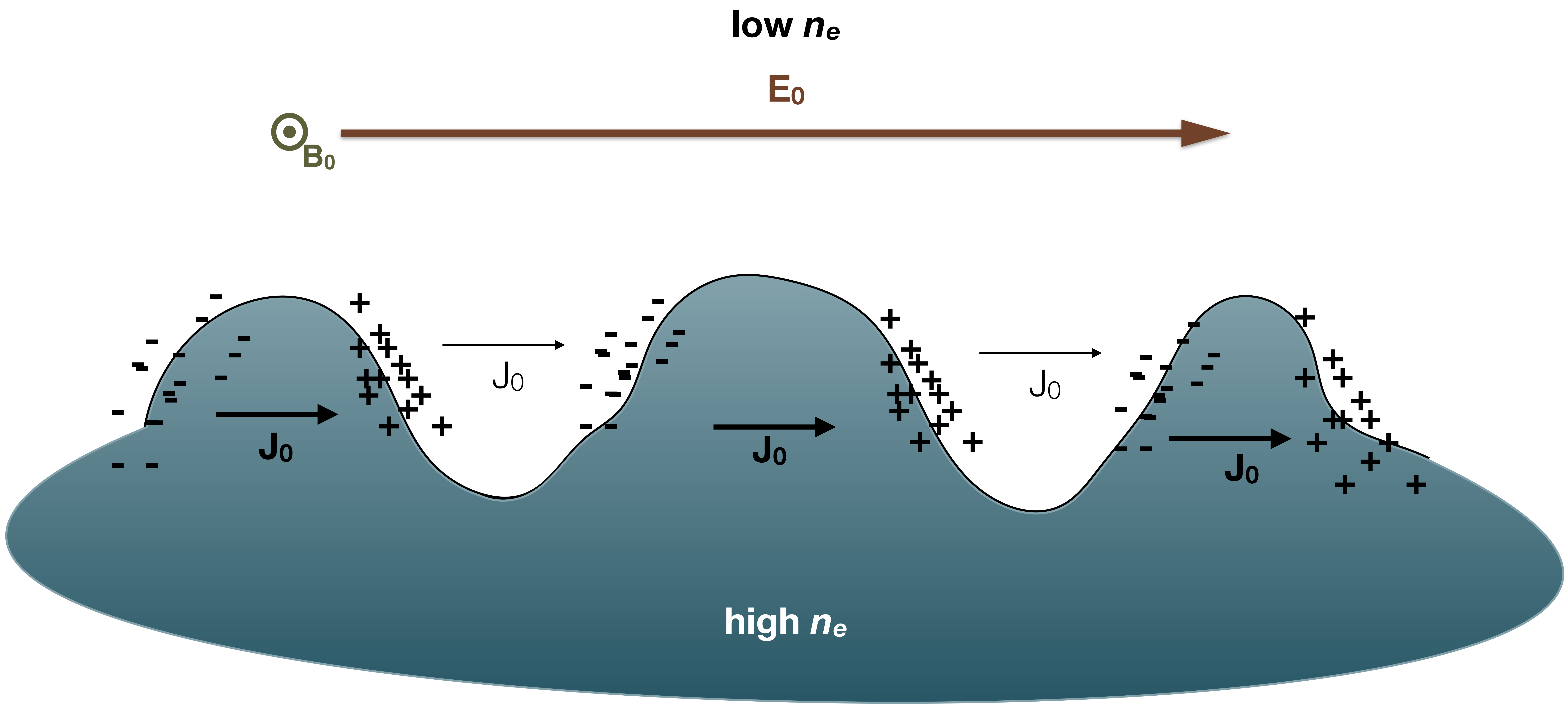
Dispersion relation: complex freq. —> growth/decay

Linearization

Fourier Decomposition of first-order variations

Drift Instabilities Due to Conductance Variations

gradient drift instability (GDI)



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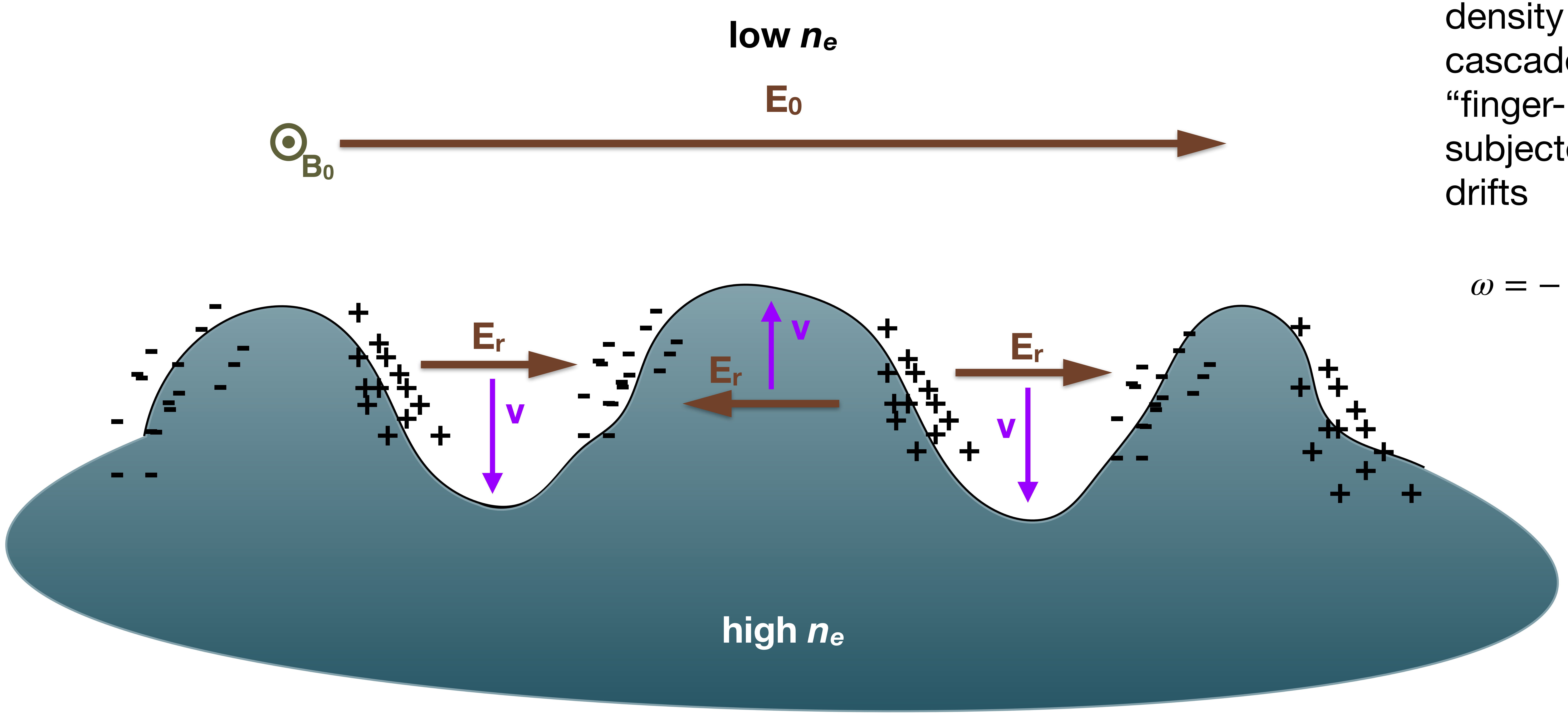


Strong F-region ionospheric density gradients can cascade into smaller-scale “finger-like” structures when subjected to background drifts

$$\omega = -\frac{1}{2}i\tilde{\nu} \pm \frac{1}{2}i\sqrt{\tilde{\nu}^2 + 4\tilde{\nu}\frac{E_0}{\ell B}};$$

$$\tilde{\nu} \equiv \frac{\Sigma_P}{C_M}$$

Rayleigh-Taylor Instability: Plasma Bubbles

Non-local Rayleigh-Taylor growth rate from Sultan (1996)

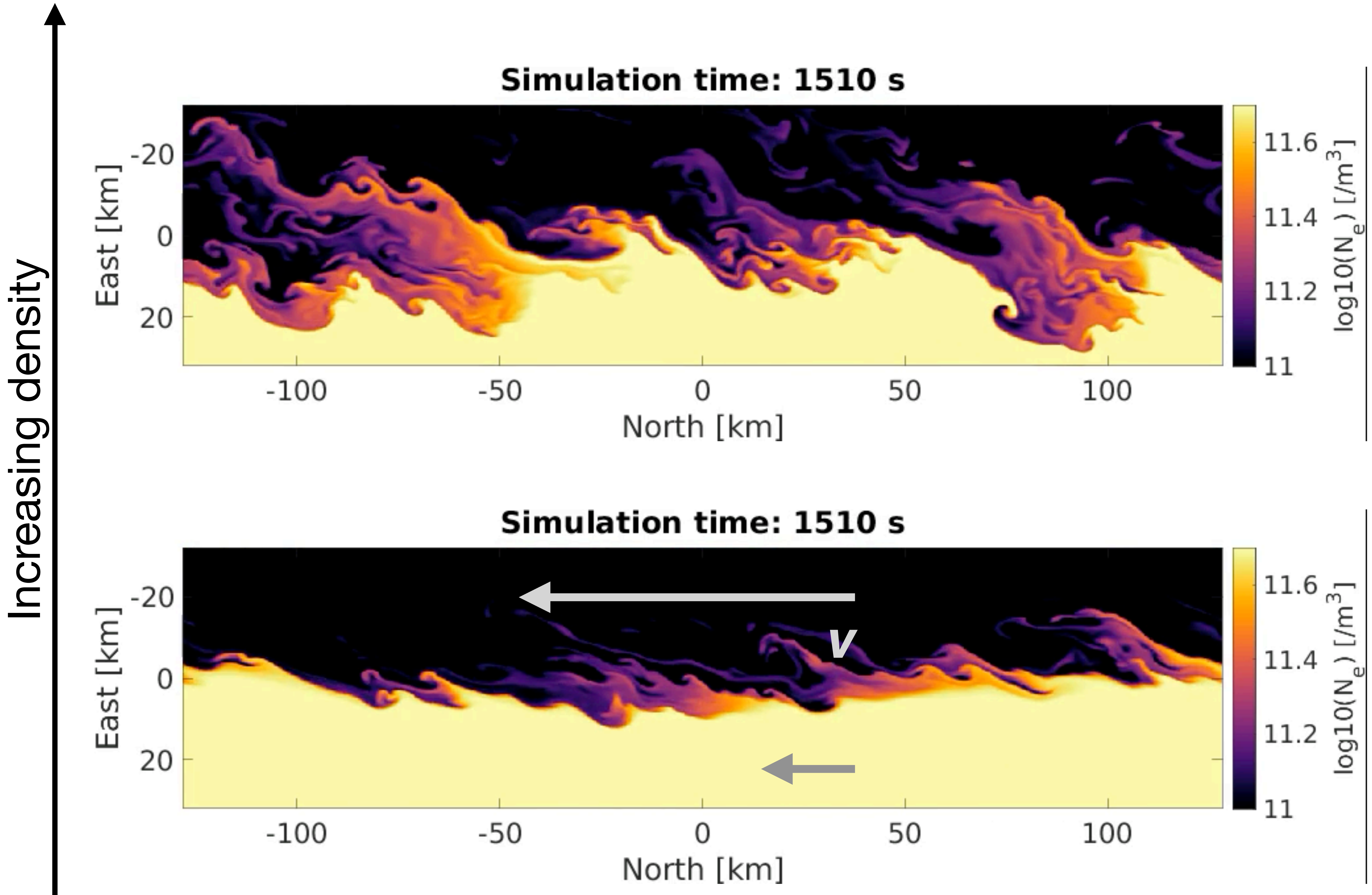
$$\gamma_{RT} = \frac{\tilde{\Sigma}^F_{P,0}}{\tilde{\Sigma}^E_{P,0} + \tilde{\Sigma}^F_{P,0}} \left(V_p - U^P_L - \frac{g_e}{\nu^F_{eff}} \right) K^F - R_T$$

Shear (inertial) Instabilities

Kelvin Helmholtz (KHI)

Fluid inertia plays a central role in destabilizing perturbations in an ordinary fluid

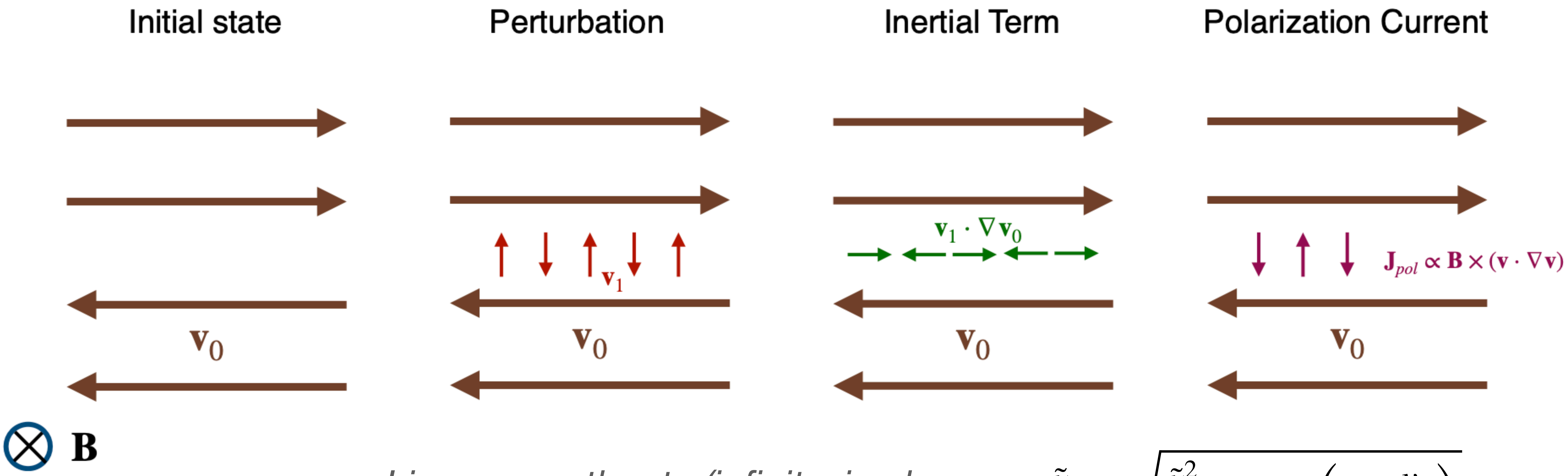
In the ionospheric F-region inertia is provided by the ions through polarization drifts *(cf. Kintner and Seyler, 1985).* In the ionospheric case finite conductivity tends to break up vortices in the nonlinear stage and finite inertia implies finite conductivity.



Movies courtesy Andreas Kvammen

Inertial Connections to Electrostatic Destabilization

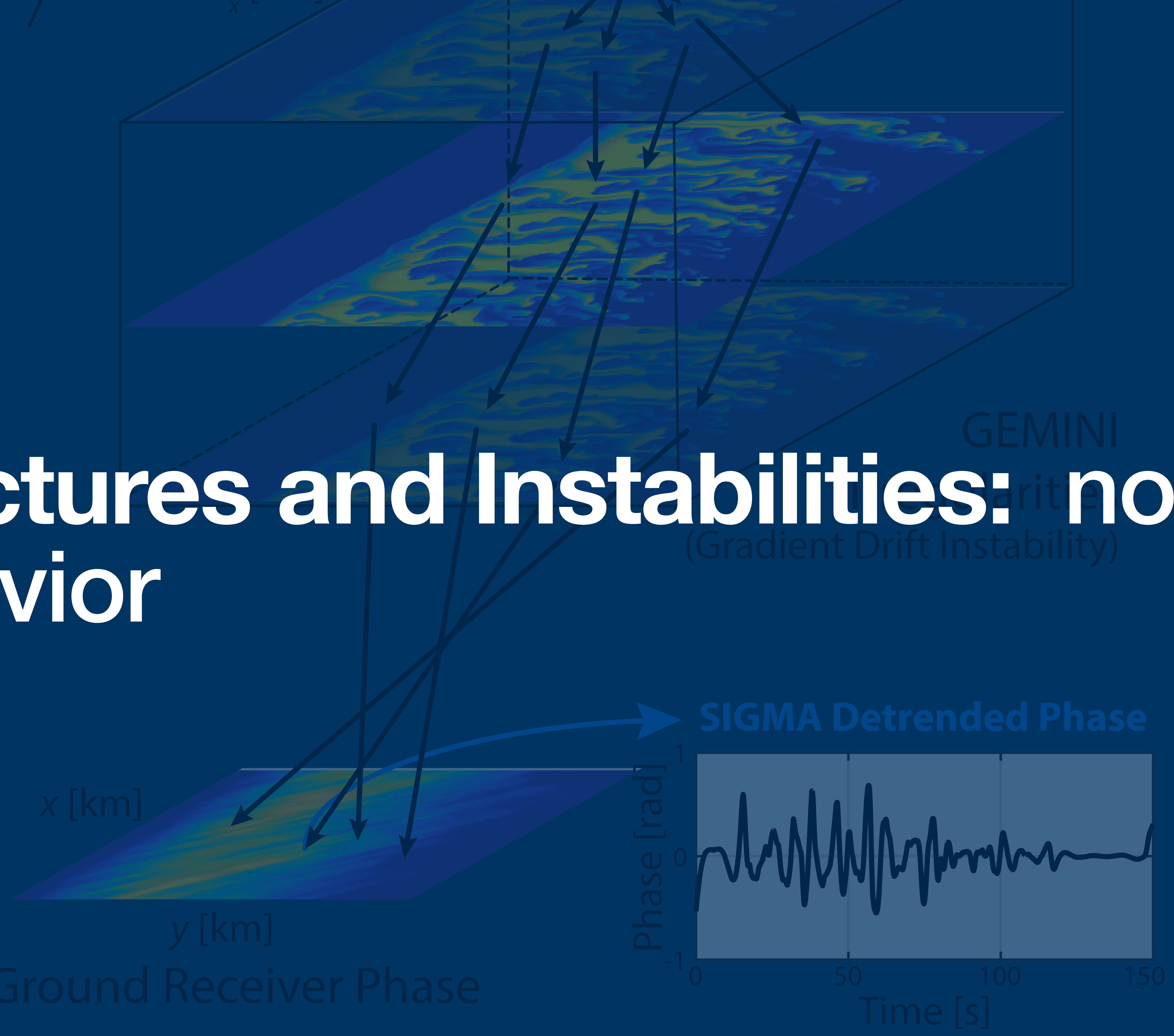
$$\mathbf{J}_{pol} = c_m \left(\frac{\partial}{\partial t} + \mathbf{v} \cdot \nabla \right) \mathbf{E} = (c_m \mathbf{B}) \times \left(\frac{\partial \mathbf{v}}{\partial t} + \mathbf{v} \cdot \nabla \mathbf{v} \right)$$



Linear growth rate (infinitesimal boundary layer width):

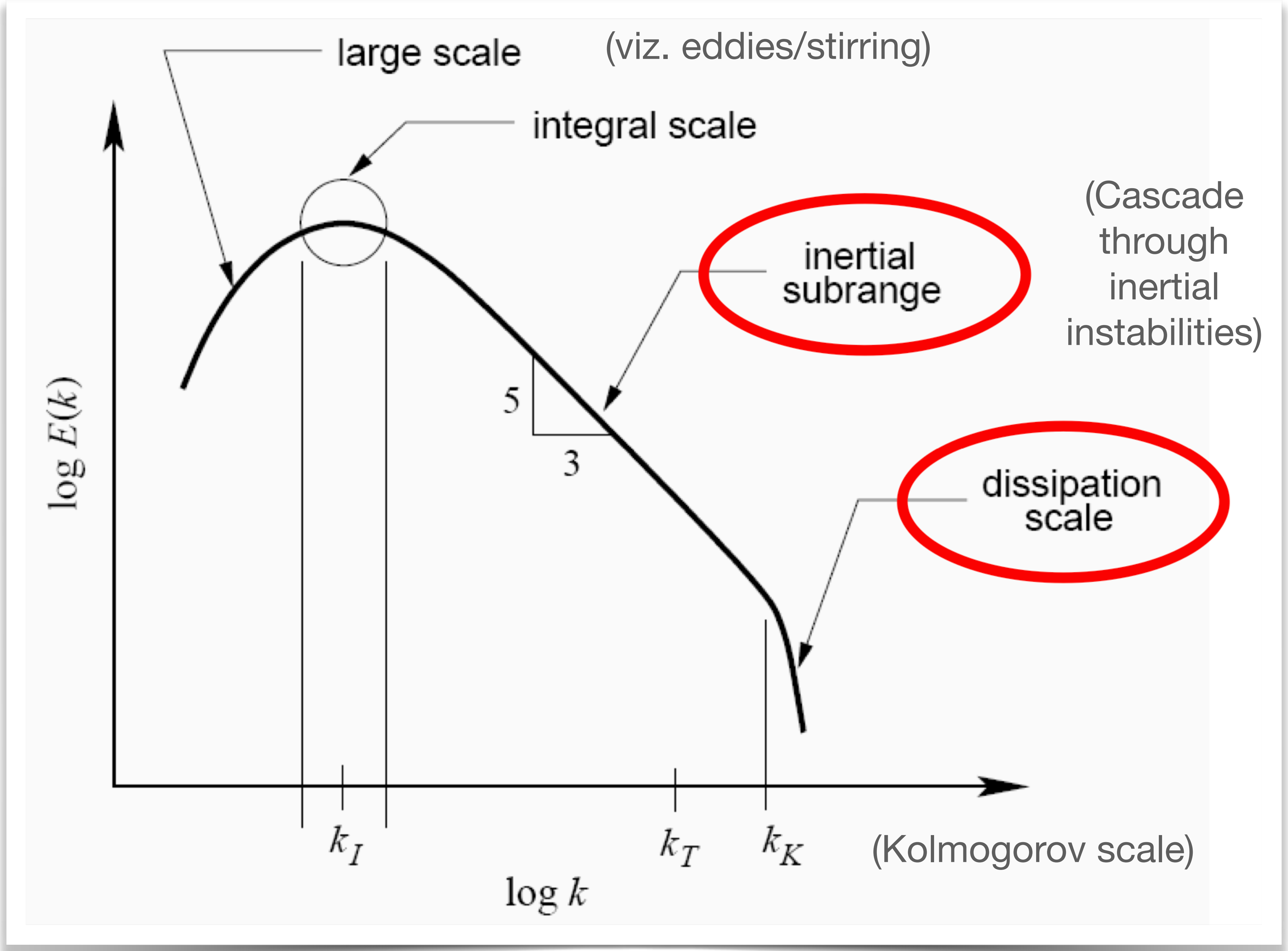
$$\omega = i\frac{\tilde{\nu}}{2} \pm i\sqrt{\frac{\tilde{\nu}^2}{4} + k^2 v_0^2 \left(1 - \frac{v_0}{v_n}\right)}$$

Structures and Instabilities: nonlinear behavior



Spectra and "Turbulence"

- *Kintner and Seyler, (1985)* present analogues between plasma and neutral fluid *turbulence* - steady exchange of energy between unstable modes resulting in a well-defined spectrum of fluctuations.
- Breaks in the spectral slope may be attributable to physical processes, e.g. standard Kolmogorov picture.
- Having turbulent spectrum is only part of the information necessary to understand density structuring - **transients matter**
- Nonlinear codes are extremely useful ways to study the transition between linear behavior and turbulence; however, they can be time-consuming due to resolution requirements



(GDI growth) — (diffusive decay)

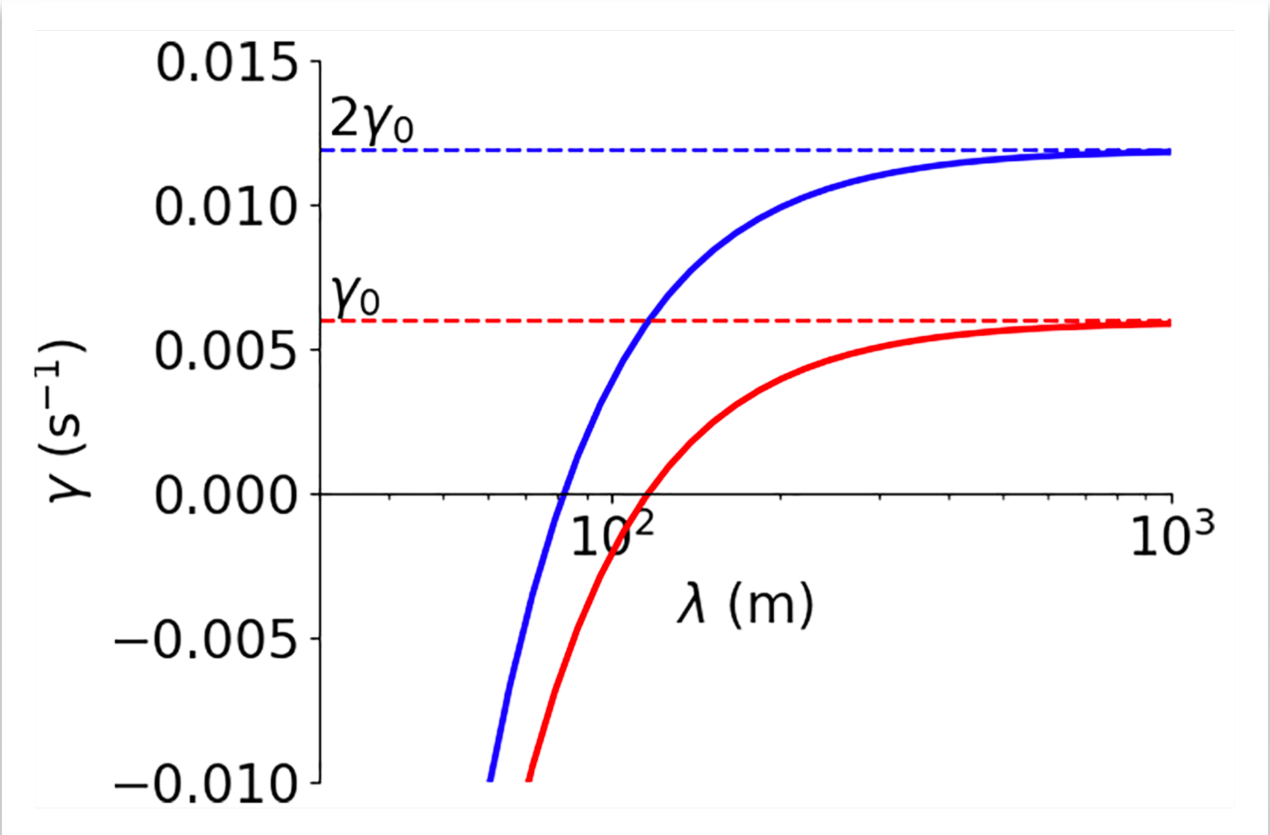


Illustration based on Lamarche et al (2020)

Physical Processes at Small Scales

Scales based on basic dimensional analyses, E.g.

$$\frac{J_{displacement}}{J_{conduct}} \approx \left(\frac{\sigma}{\epsilon_0 \omega}\right)^{-1}$$

Pedersen drifts (scale independent)

Inertial effects (~1-4 km)

Potential mapping (~100-1000 m)

Diffusive drifts (~100-300 m)

Diamagnetic drifts (~50-300 m)

Scale sizes perp-to-B for physics to start to matter (e.g. Farley, 1959; Kintner and Seyler, 1985)

Time variability effects on polarization charge

$$\frac{J_{pol}}{J_{conduct}} \approx \frac{\omega}{\tilde{\nu}} = 1 \quad \text{when} \quad \tau \approx \frac{2\pi}{\tilde{\nu}} \approx 15 \text{ s}$$

Shearing effects on polarization current

$$\frac{J_{pol}}{J_{conduct}} \approx \frac{kv}{\tilde{\nu}} = 1 \quad \text{when} \quad \lambda = \frac{2\pi v}{\tilde{\nu}} \approx 3.5 \text{ km}$$

Pressure effects (diamagnetic/diffusive)

$$\frac{J_{pressure}}{J_{conduct}} \approx k\frac{k_B}{q}\frac{T}{E} = 1 \quad \text{when} \quad \lambda = 2\pi\frac{k_B}{q}\frac{T}{E} \approx 100 \text{ m}$$

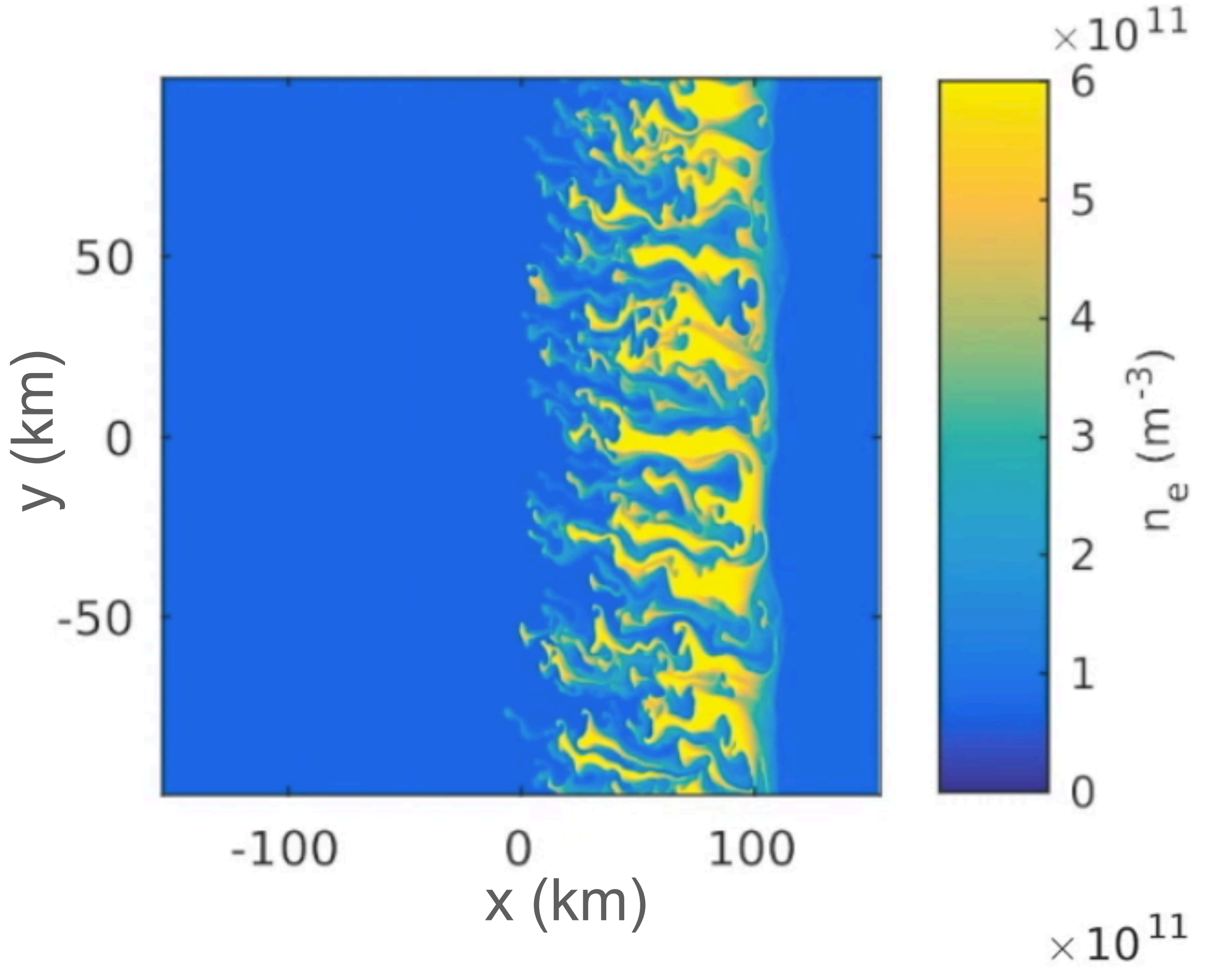
Electric field mapping

$$\frac{\lambda_{\parallel}}{\lambda_{\perp}} \approx \sqrt{\frac{\sigma_{\parallel}}{\sigma_{\perp}}} = 1 \quad (\text{alt. dep.})$$

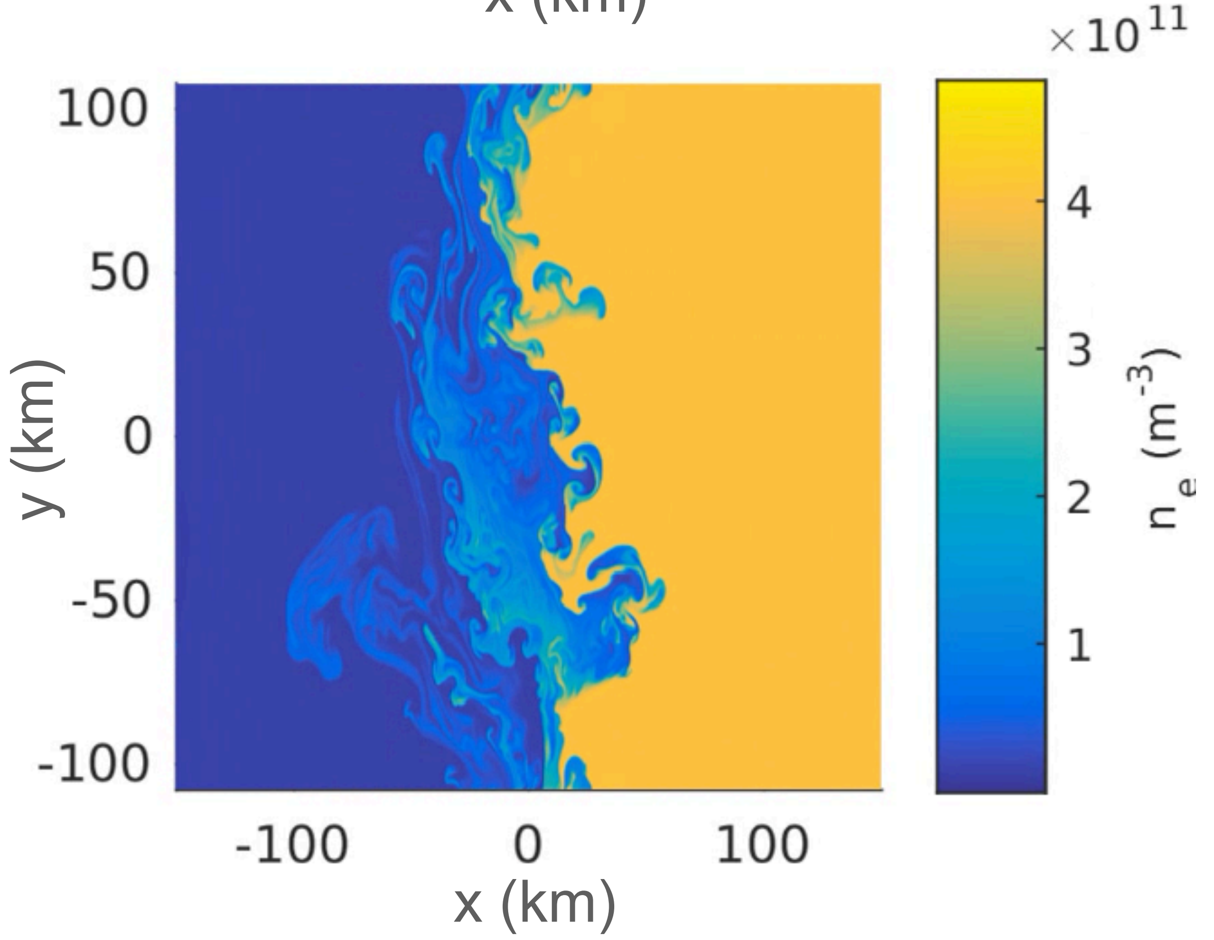
Modeling Plasma Fluid Instabilities

- Models are useful tools for capturing nonlinear behavior
  - *Polar cap patches* are interchange unstable and cascade to smaller scales
  - *Shear layers* can overturn and break
  - *Equatorial plasma bubbles* steepen, bifurcate, and merge.
- *These simulations are high simplified "wave-in-a-box" type simulations with parameters basically chosen to aggressively develop turbulence — <u>they are not really "realistic"</u>*
- GEMINI (local, nonlinear, ionospheric model) examples: https://github.com/gemini3d/gemini-examples/tree/main/init/CEDAR2024

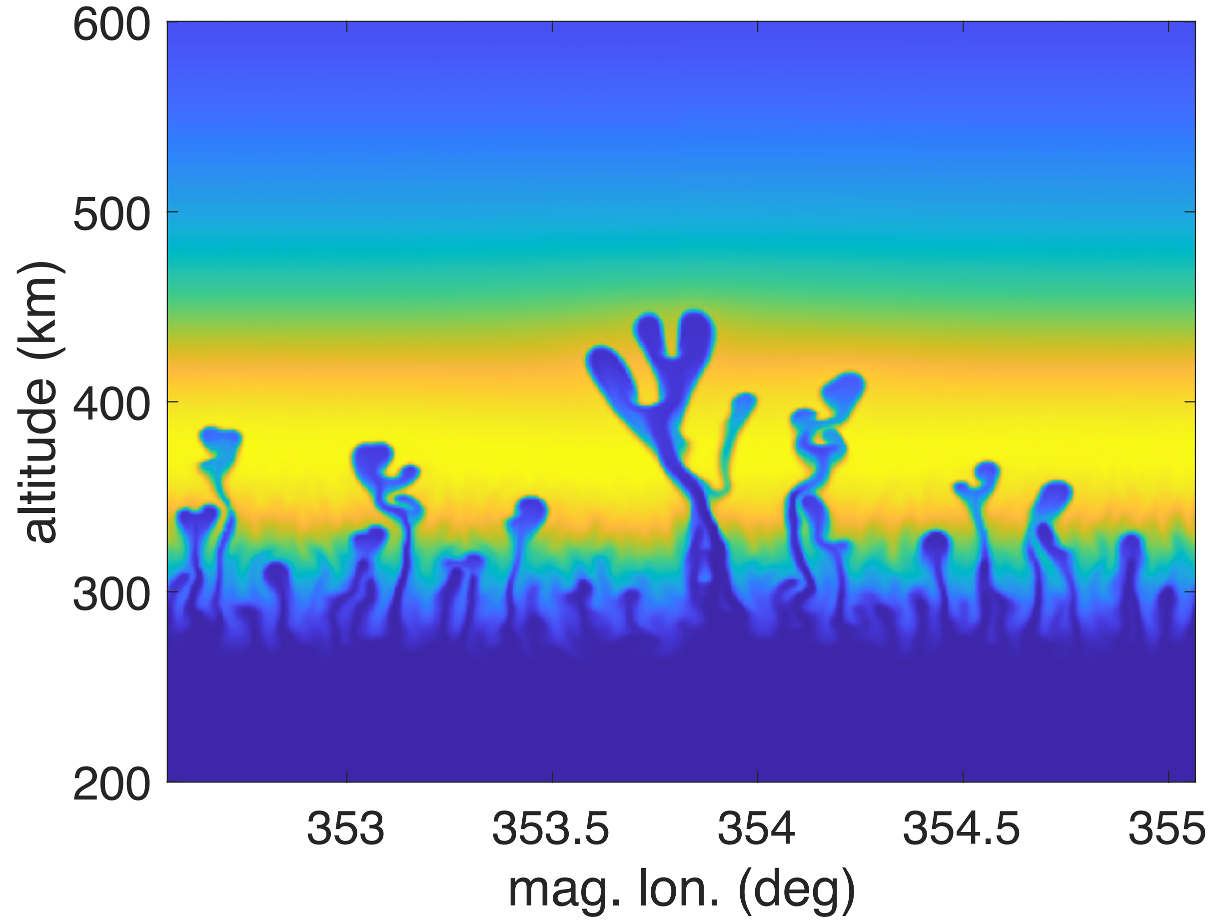
Gradient-drift instability **(GDI)**



Kelvin-Helmholtz instability **(KHI)**



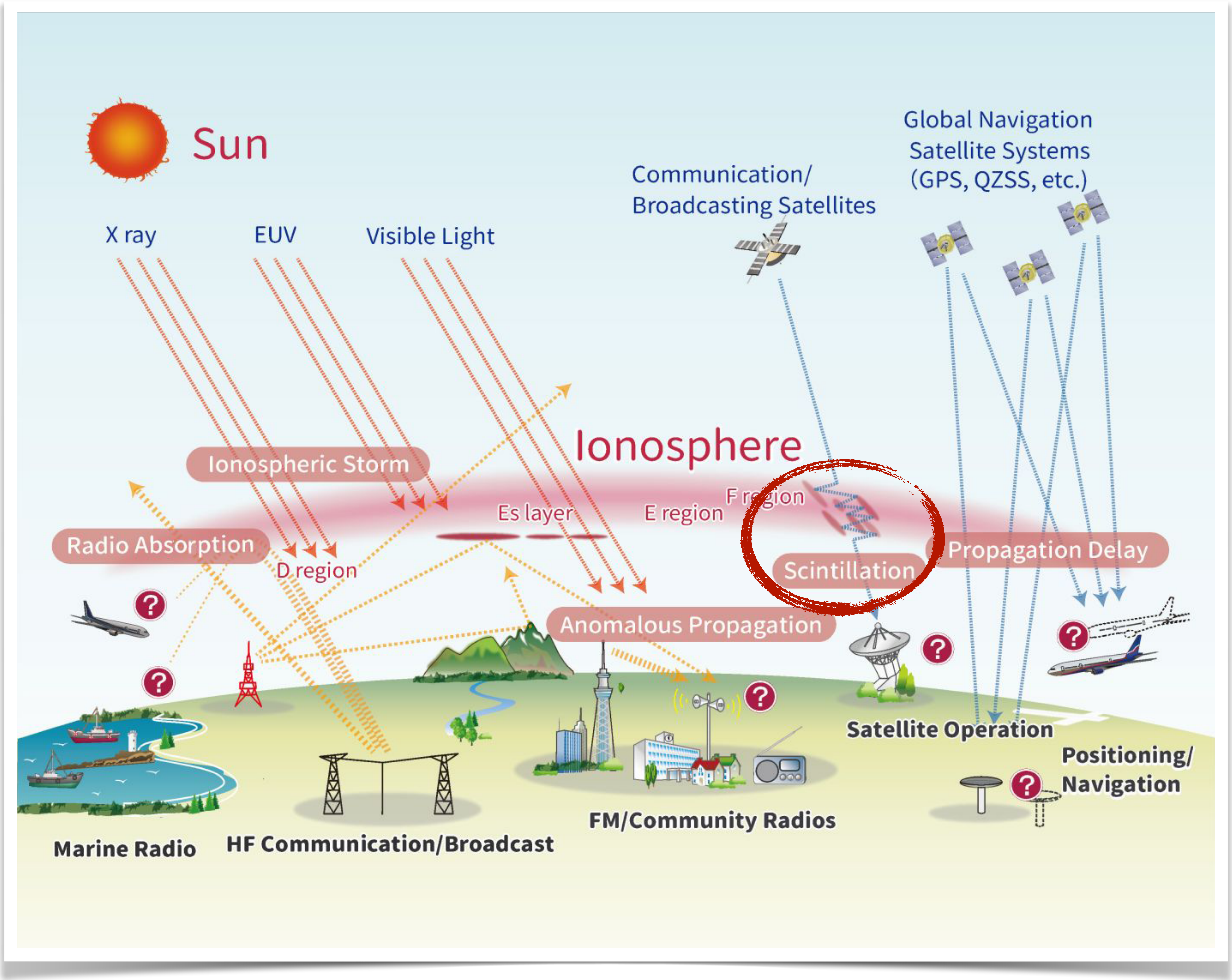
Rayleigh-Taylor instability **(RTI)**



Impact of Small-Scale Plasma Structures

- One important aspect of ionospheric dynamics is the effects on radio propagation through variations in refractive index (refraction and diffraction)
- HF (tens of MHz) refraction, scattering, and absorption
- VHF - L band (~1 GHz) scintillation and loss of lock
- Implications for positioning and navigation systems

$$r_f \approx \sqrt{\lambda h_F} \approx 800 \text{ m} \quad \text{(VHF)}$$



https://swc.nict.go.jp/en/knowledge/guide.html