A New Regime of Plasma Wave Modes in Jupiter's Polar Cap

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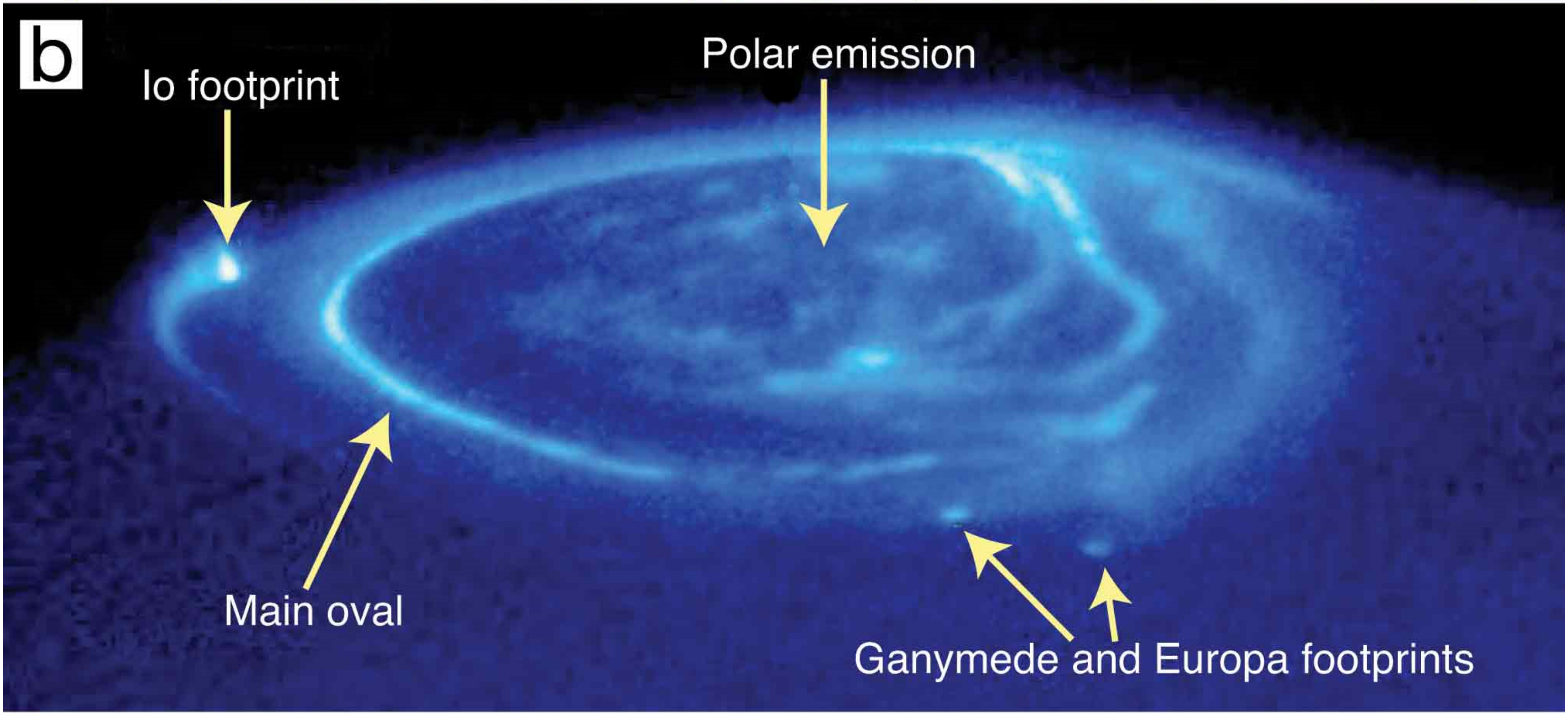
:

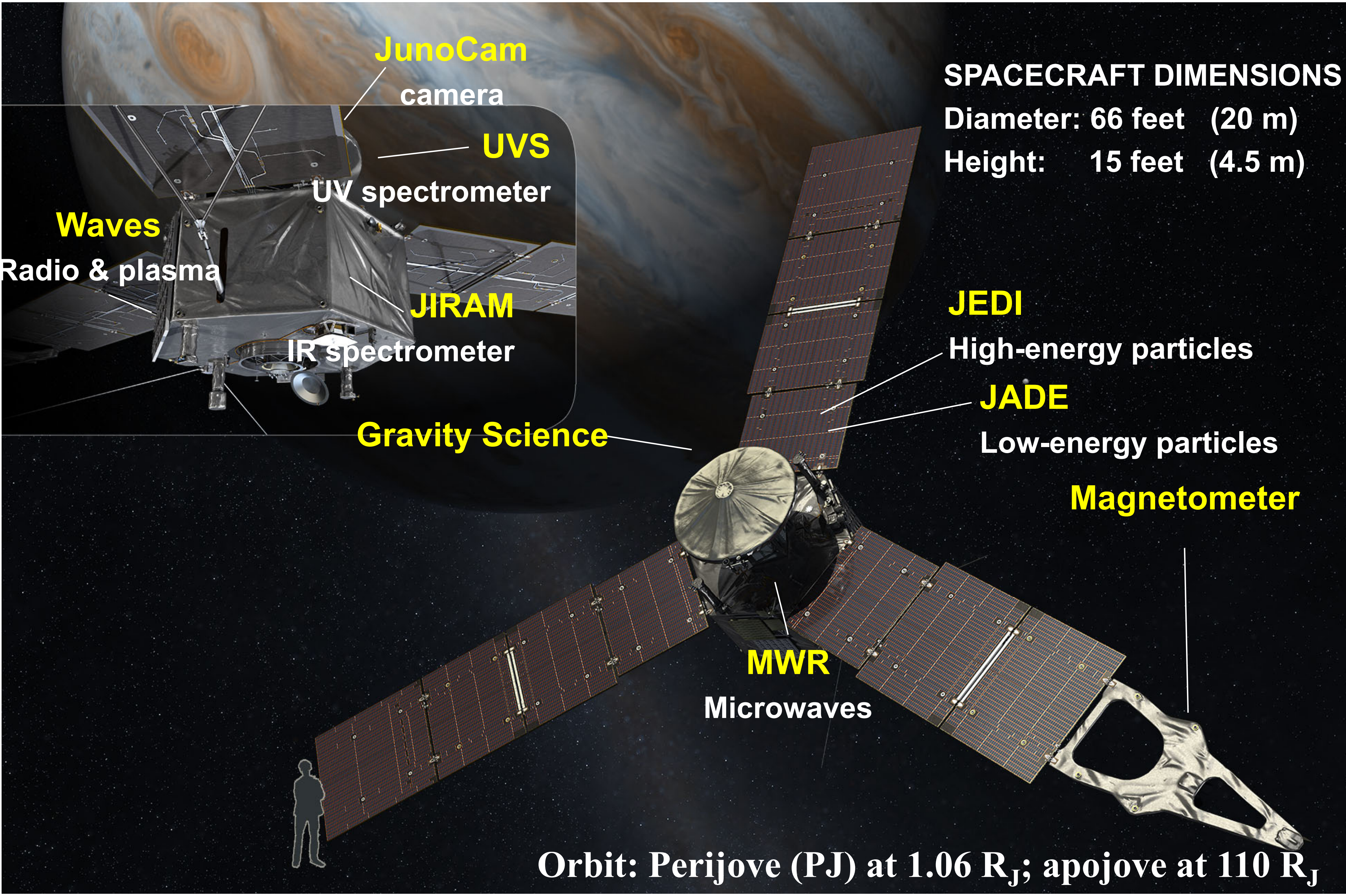
- Jupiter's polar regions have been sampled for the first time by the Juno satellite
- Jupiter's aurora largely driven by co-rotation rather than solar wind-magnetosphere interaction
- Auroral emissions not just in upward current regions; bi-directional electron acceleration gives aurora in downward current and polar cap
- Focus on polar cap: overall downward current, but Juno observations show plasma densities < 1 cm^{-3} and magnetic field strengths > 1 G (=10^{-4} T)
- These parameters lead to the unusual condition that $\omega_{pe} < \Omega_{ci}$, leading to a new mode structure for Alfvén waves in this region.

Jupiter's Aurora



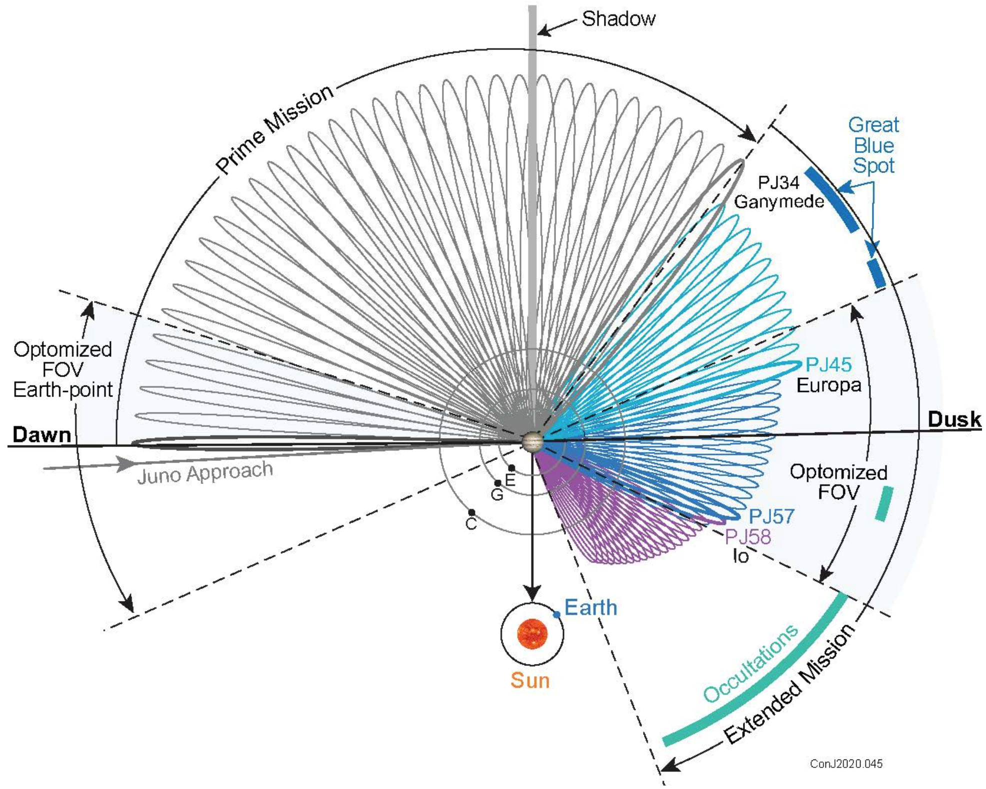
- At Jupiter, 3 different drivers for aurora:
  - Main auroral oval driven by co-rotation
  - Inner moons Io, Ganymede, Europa drive current systems to produce auroral footprints and (especially for Io) extended tail
  - Polar "swirl" emission: origin not clear, solar wind or plasma sheet

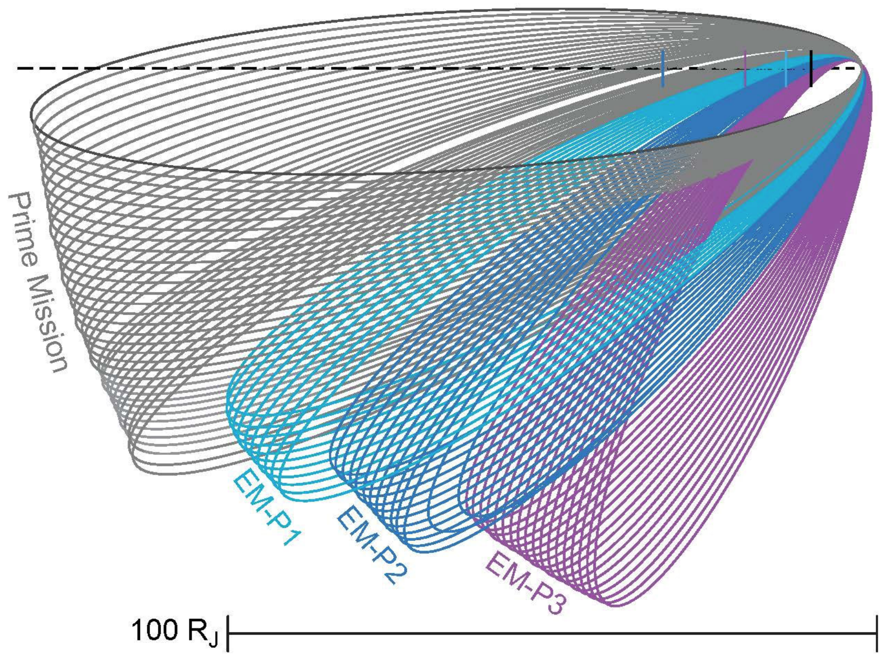
Juno: Spacecraft and Instrumentation



Orbit: Perijove (PJ) at 1.06 R_J; apojove at 110 R_J

Juno Orbit

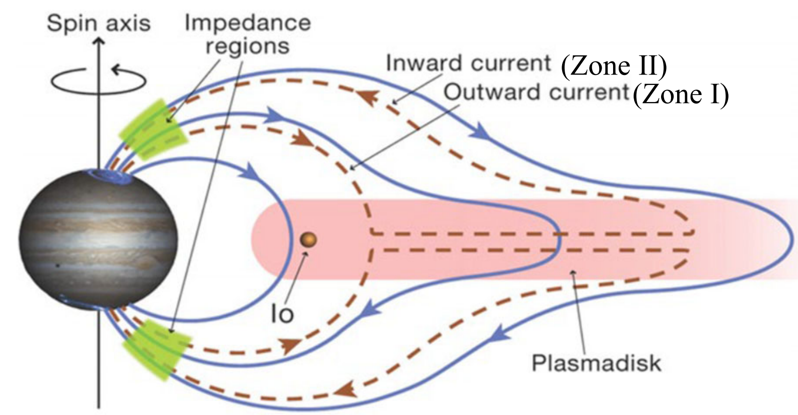




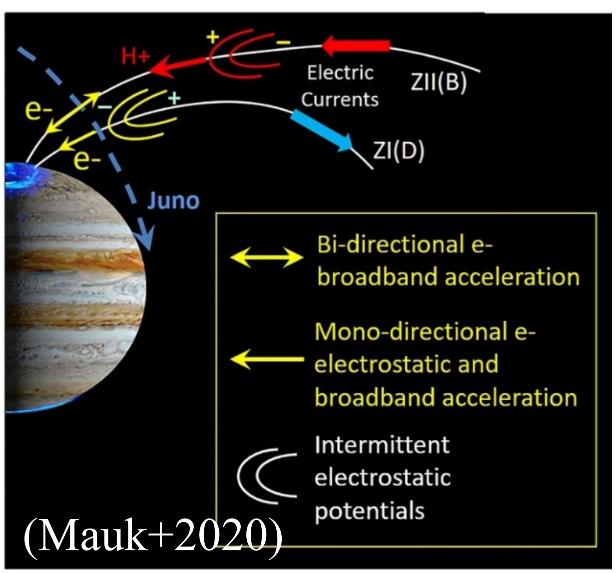
- Highly elliptical orbit: Perijove, 1.06 R_J; Apojove, 110 R_J
- Extended mission: Flybys of Ganymede (8 June 2021), Europa (29 Sept 2022) and Io (30 Dec 2023; 3 Feb 2024) lower apojove
- Precession allows for low altitude passes over Jupiter's north pole

Currents and Aurora at Jupiter

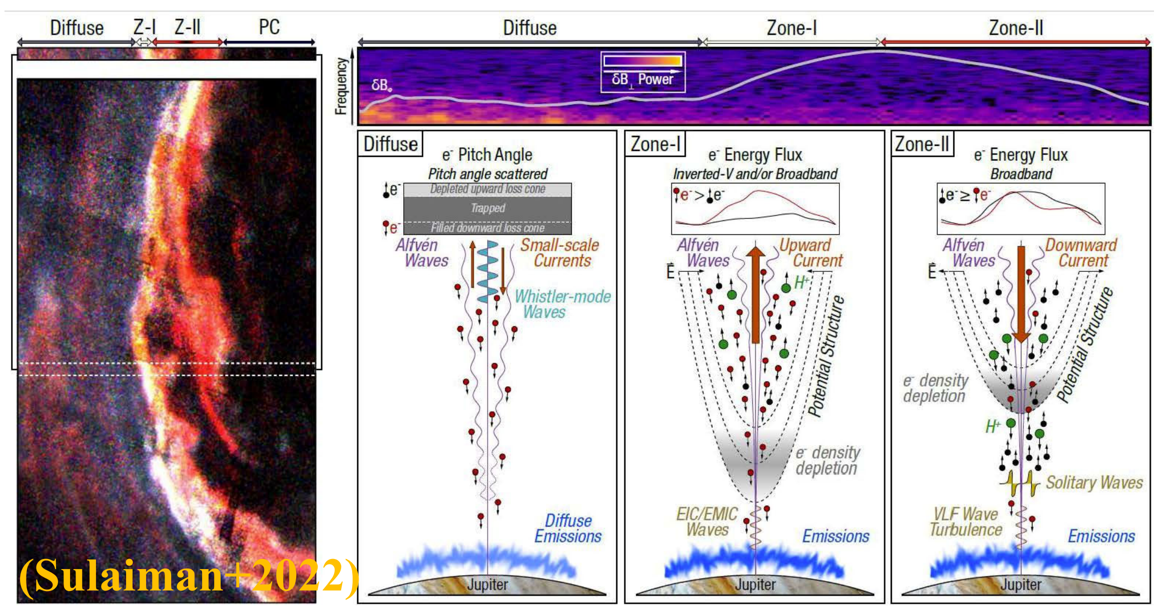
- Main current system driven by co-rotation
  - Tail current **j**×**B** enforces co-rotation
  - Upward current on equatorward side
  - Downward current on poleward side
- But true current structure filamented:
  - Zone I: upward current, monoenergetic beams plus broadband acceleration
  - Zone II: downward current, bidirectional electron fluxes; net electron flux upward but significant downward fluxes to produce aurora



(Bagenal et al., 2017)



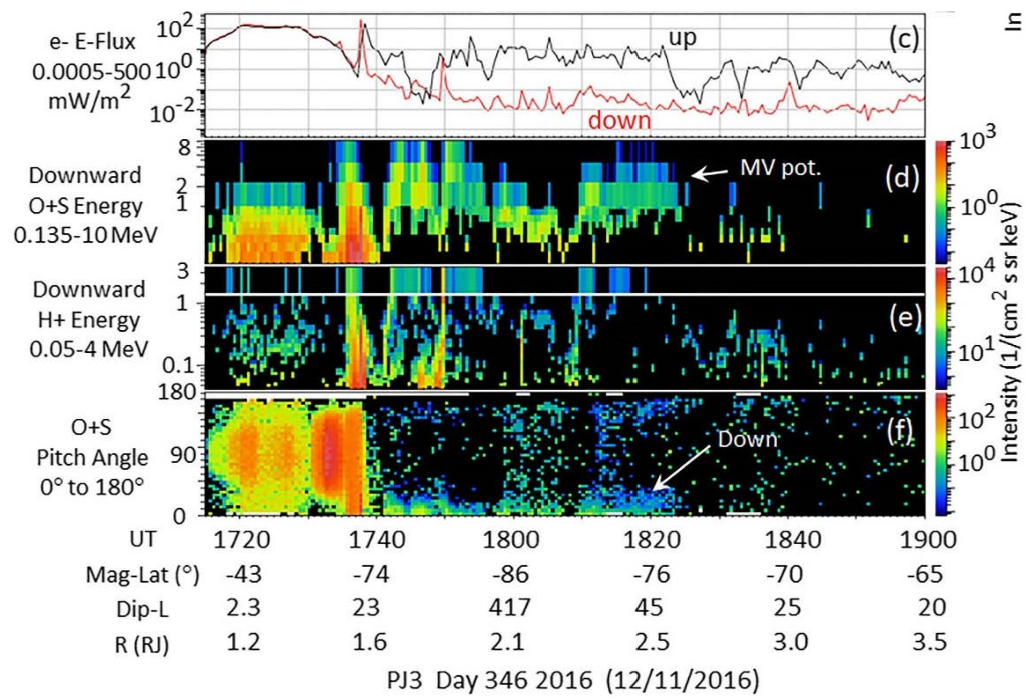
(Mauk+2020)



(Sulaiman+2022)

Focus: Jupiter's Polar Cap

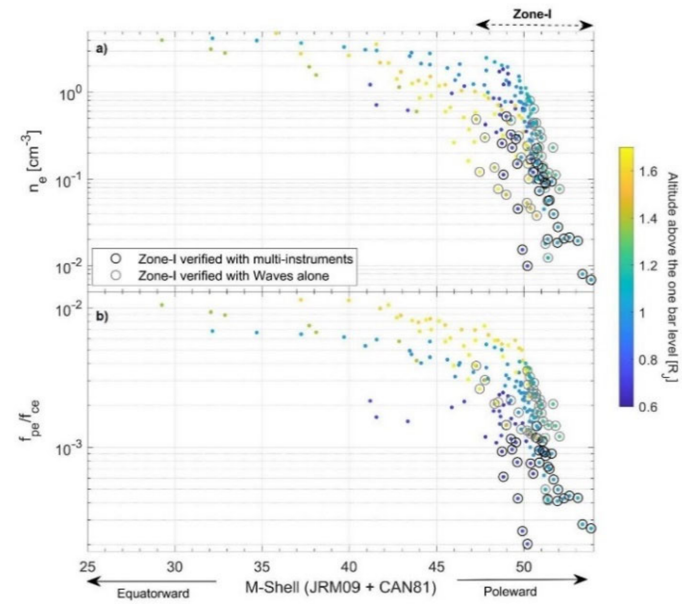
- Juno observations indicate strong potentials > 1 MV on polar cap potentials, accelerating heavy ions (O^{n+}, S^{n+}) downward (Clark+2017; Mauk+2020) and upward electrons (Elliott+2017, Mauk+2020).
- Polar caps are downward current regions (extension of Zone II?)
  - Upward energy flux > downward
- Plasma densities very low (perhaps as low as 10^{-3} cm^{-3})
- Presence of heavy ions indicates connection to plasma sheet
- Inverted-V ion distributions suggest an ion Knight relation operative.

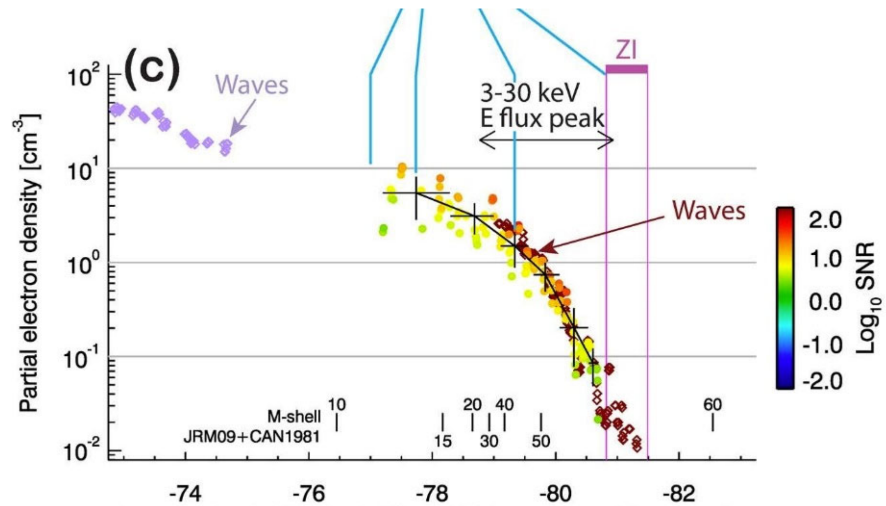


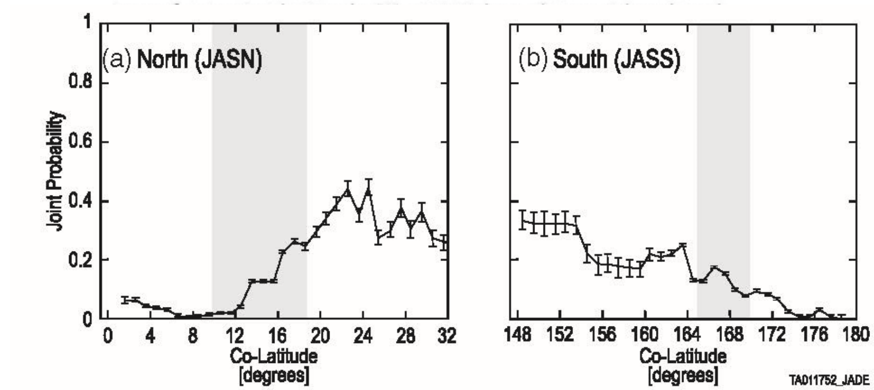
Evidence for Low Densities

- Juno often observed depletion of density at high latitude from Waves measurement (top: Sulaiman+2022) and JADE (middle: Allegrini+2021)
  - ➢ Observations in Zone I, but trend toward lower densities at higher latitude
  - ➢ Densities down to 0.01 cm^{-3} observed

- Pollock+2020 (bottom) computed probability of ion fluxes above threshold in count rate and sweep-to-sweep correlation from JADE as function of co-latitude centered on center of auroral ring.
  - ➢ Lowest probabilities within 10 degrees of pole

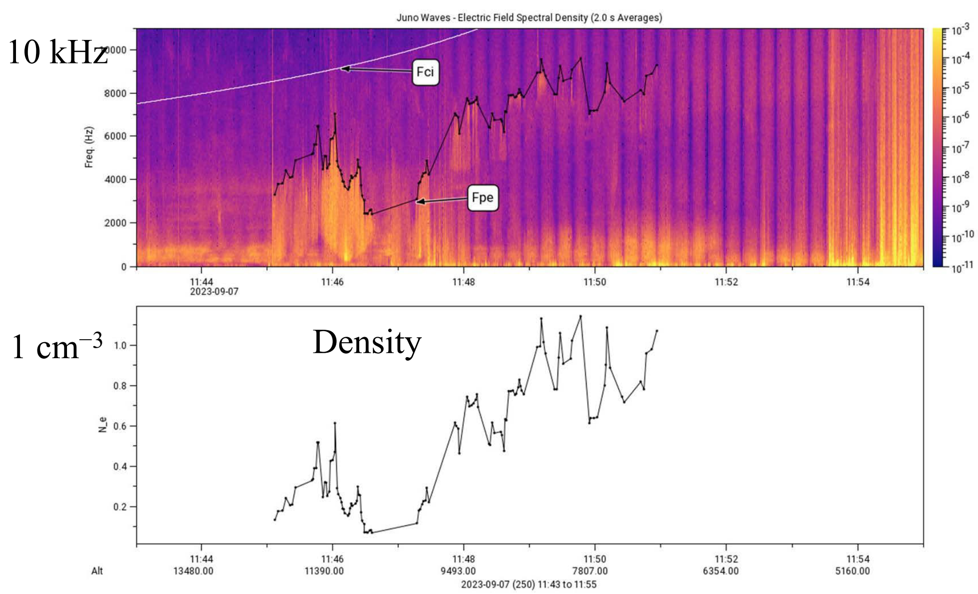






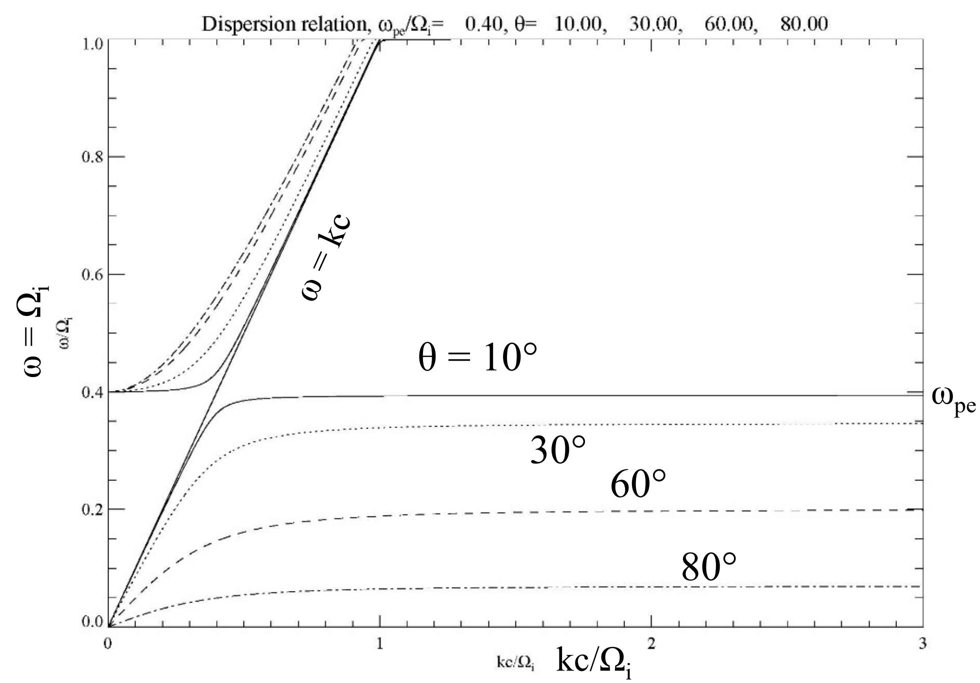
A new plasma regime in Jupiter's polar cap: $\omega_{pe} < \Omega_i$

- Juno Waves observation over polar cap, shows cutoff at plasma frequency less than ion gyrofrequency
  - Requires $n < 0.03\ \text{cm}^{-3}\ B^2$, where B is in Gauss ($1\ \text{G} = 10^{-4}\ \text{T}$)
  - Or $n < 1\ \text{cm}^{-3}$ at 5.9 G



- Sulaiman et al. (2023)

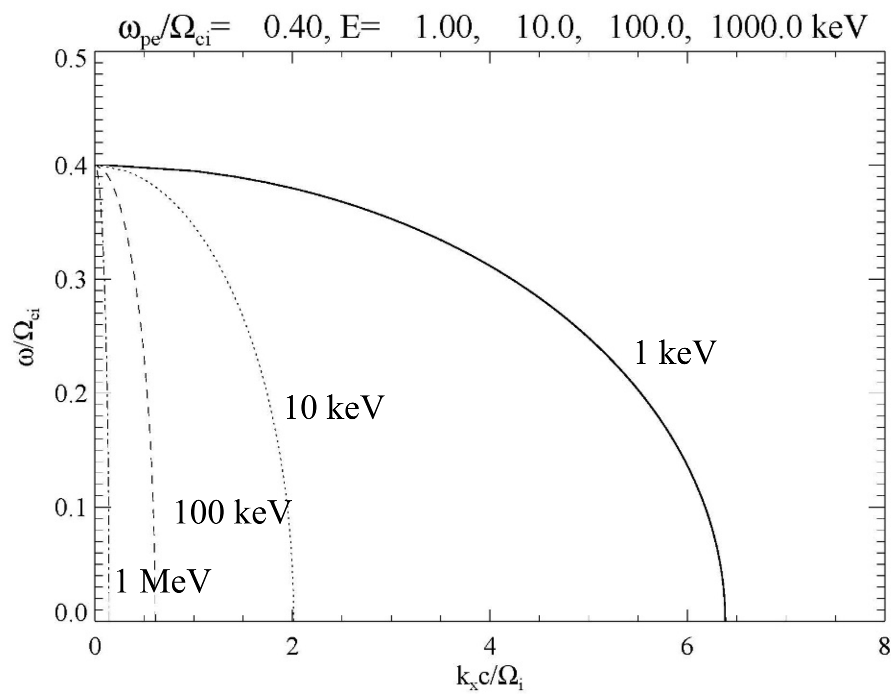
- Cold plasma dispersion relation, $\omega_{pe}/\Omega_i = 0.4$
- Alfvén speed is c



- Alfvén wave branch extends to plasma frequency
- Resonance cone develops with frequency a function of θ
- O-mode with $\omega > \omega_{pe}$ has $v_{ph} > c$

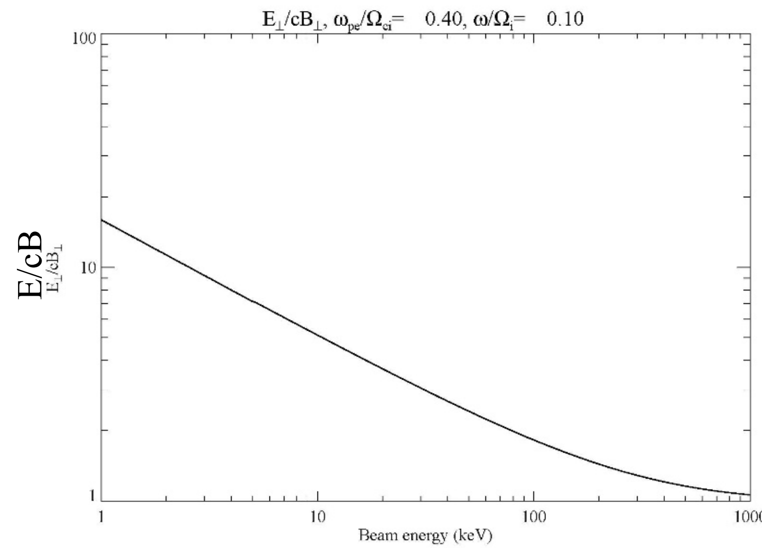
Wave Landau Resonances

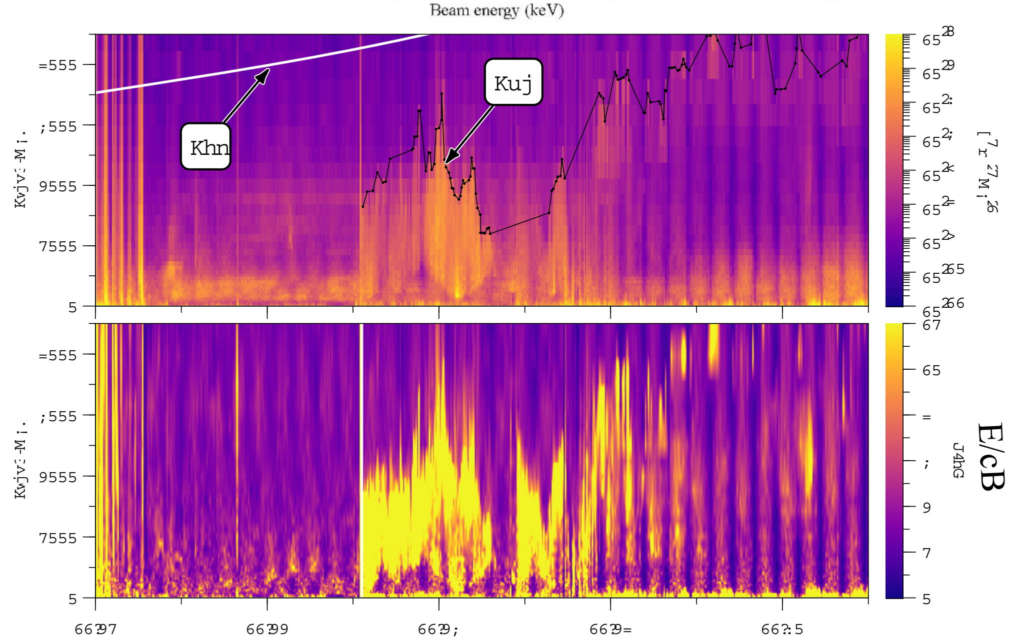
- Plots as a function of parallel phase velocity for electrons at 1, 10, 100 and 1000 keV



- Note no resonances above ω_{pe}
- More energetic particles excite waves near parallel propagation, shorter perp wavelengths for low energy particles

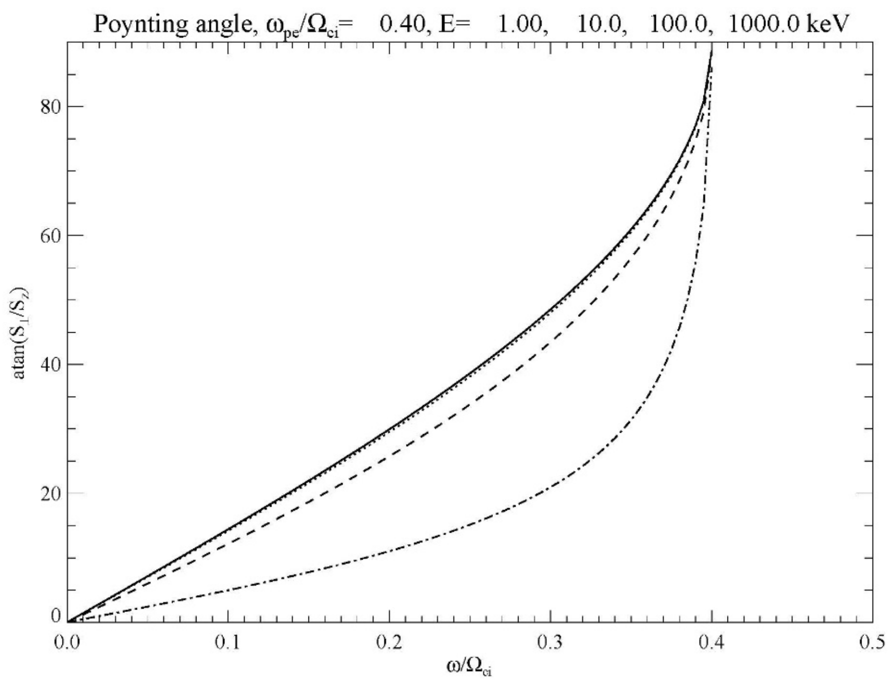
- $E_\perp/B_\perp$ ratio: observable by satellite



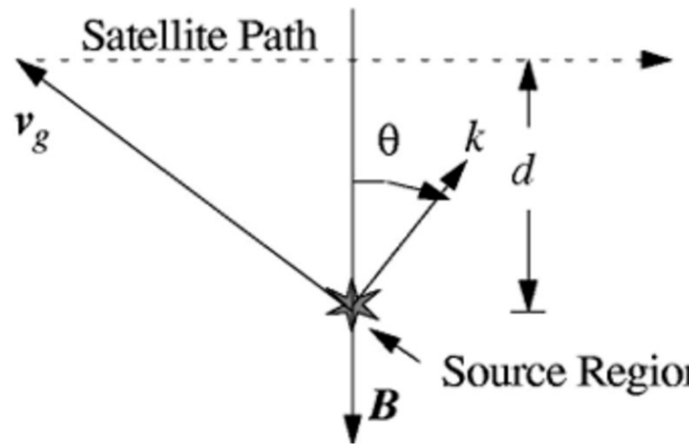


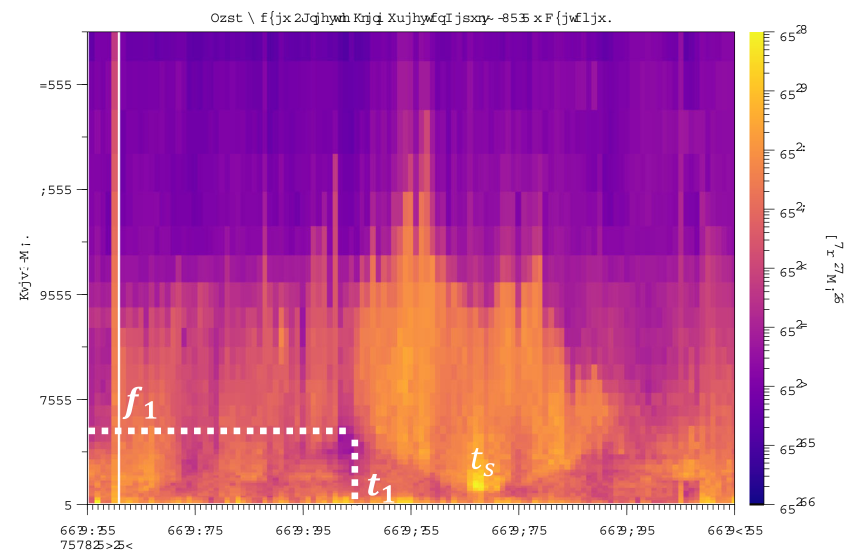
Wave Propagation

- Wave group velocity (i.e., Poynting flux) angle: low energies resonate at resonance cone



- Low frequency waves propagate parallel to field; higher frequency across field

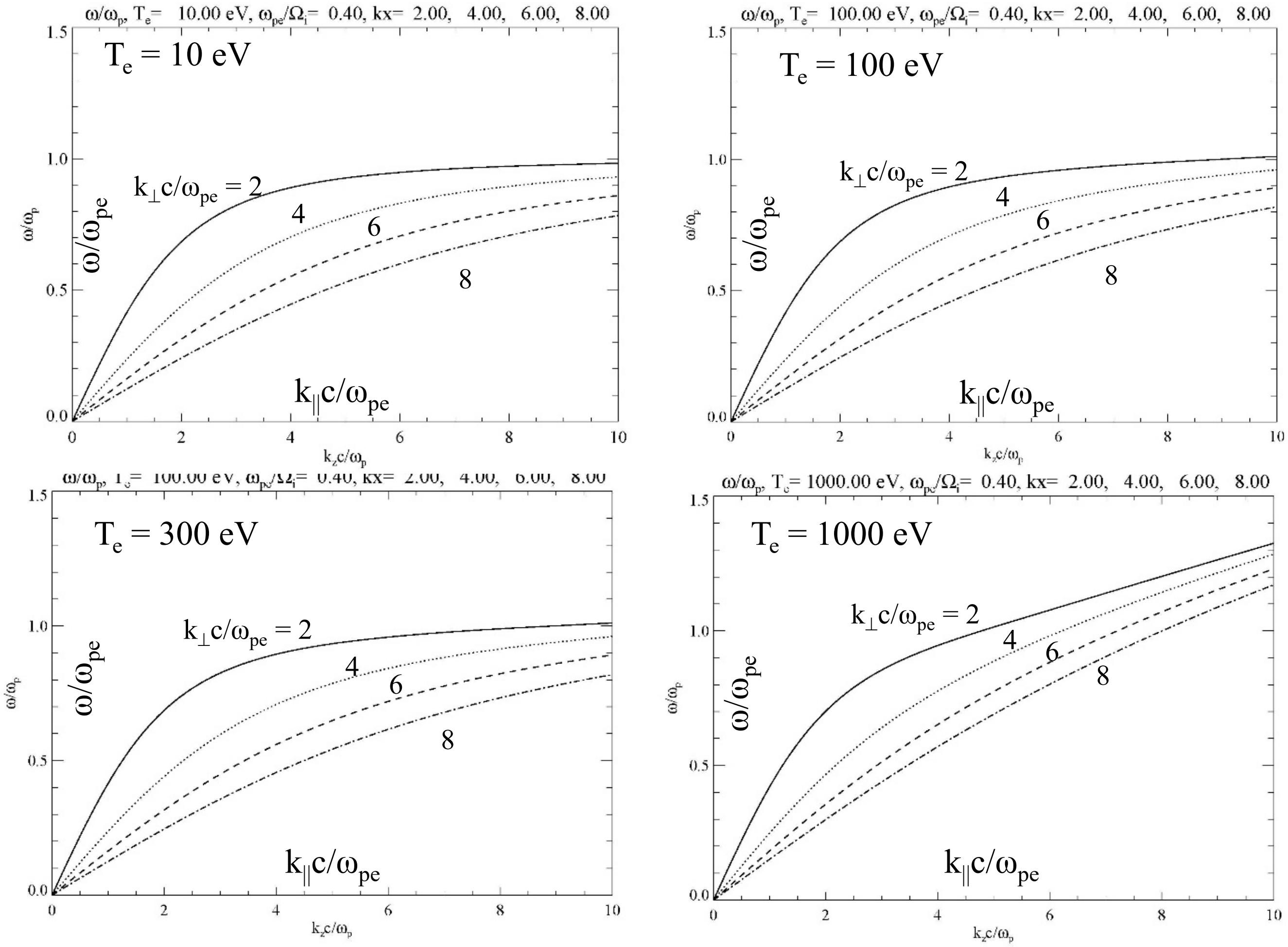




- Saucer shaped emission from Juno (courtesy S. Elliott). Apex of saucer indicates source field line

Kinetic Dispersion

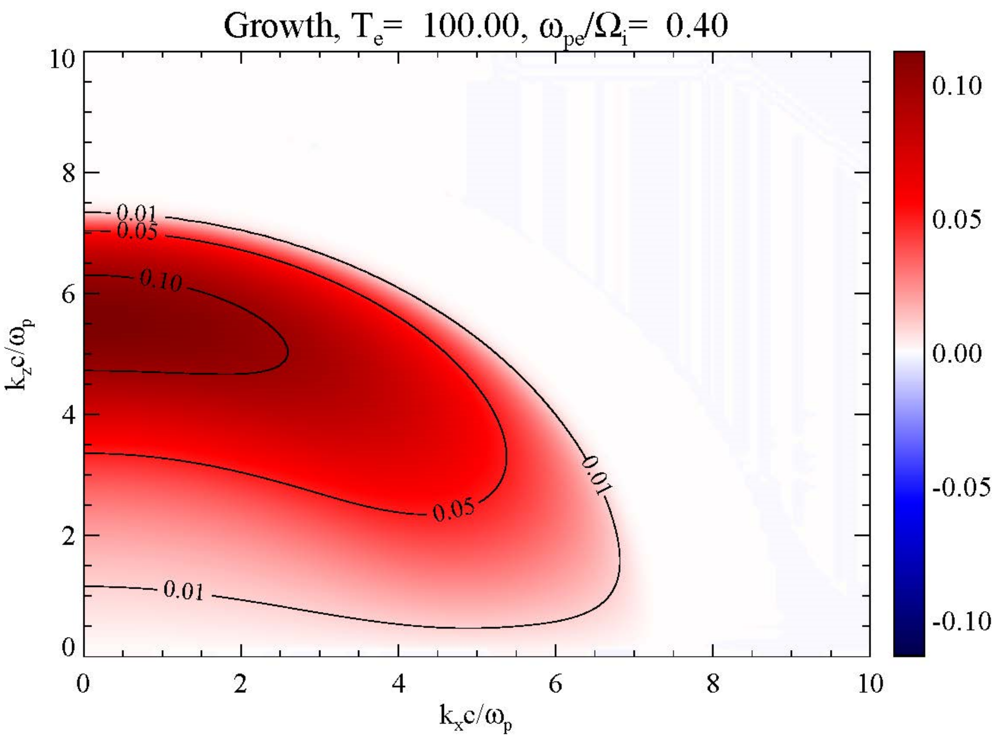
- Kinetic low-frequency dispersion relation (Lysak and Lotko, 1996; Lysak, 2008) solved including hot plasma effects

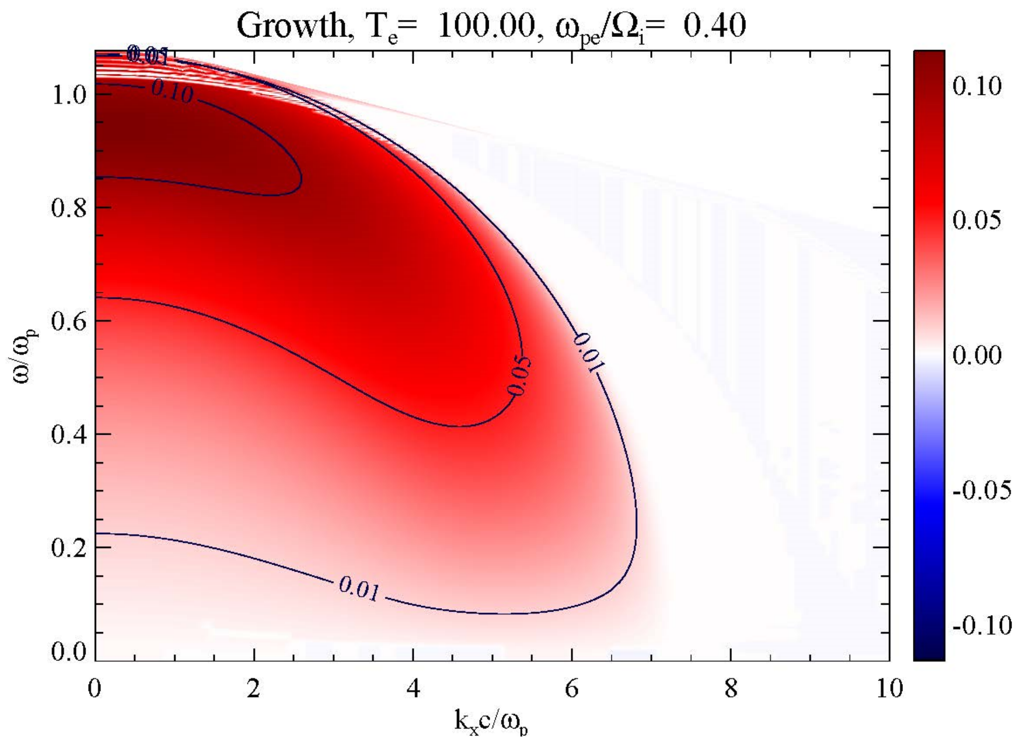


- Plots for $T_e = 10, 100, 300, 1000$ eV with curves for $k_\perp c/\omega_{pe} = 0, 2, 4, 6, 8$
- For large T_e and large $k_\perp$, waves extend above plasma frequency with slopes scaling with electron thermal speed: *Alfvén-Langmuir waves*

Beam Plasma Instability

- 100 eV plasma with 10 keV beam
- Plot in k-space (left); Plot vs. k_x-ω (right)

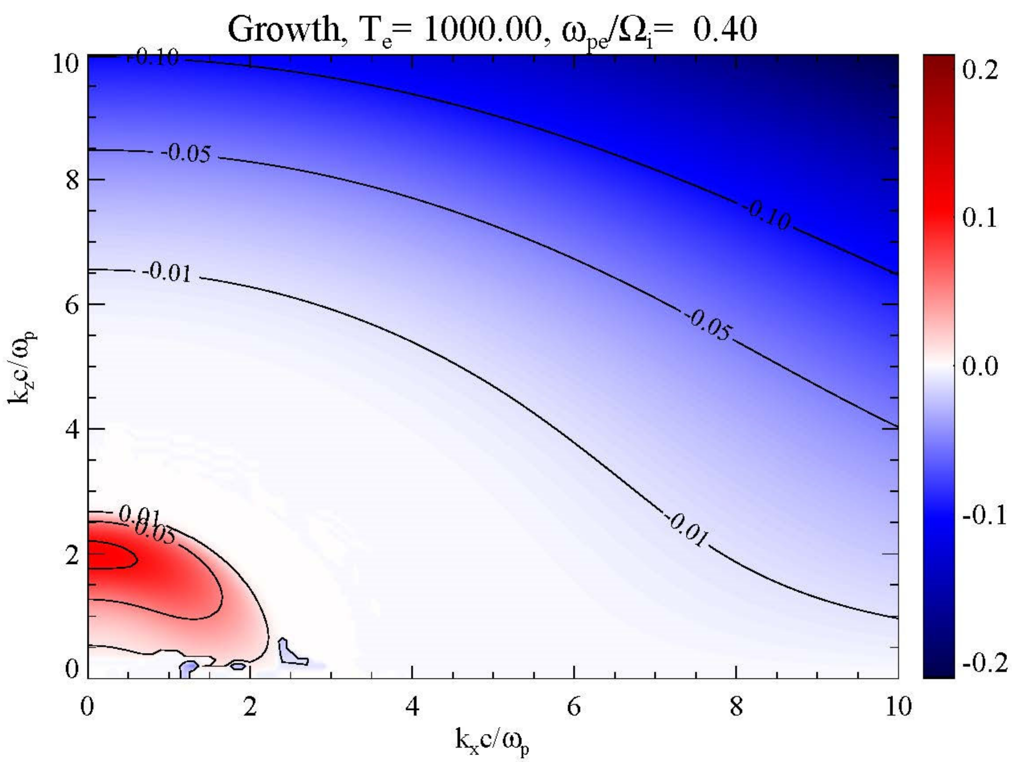


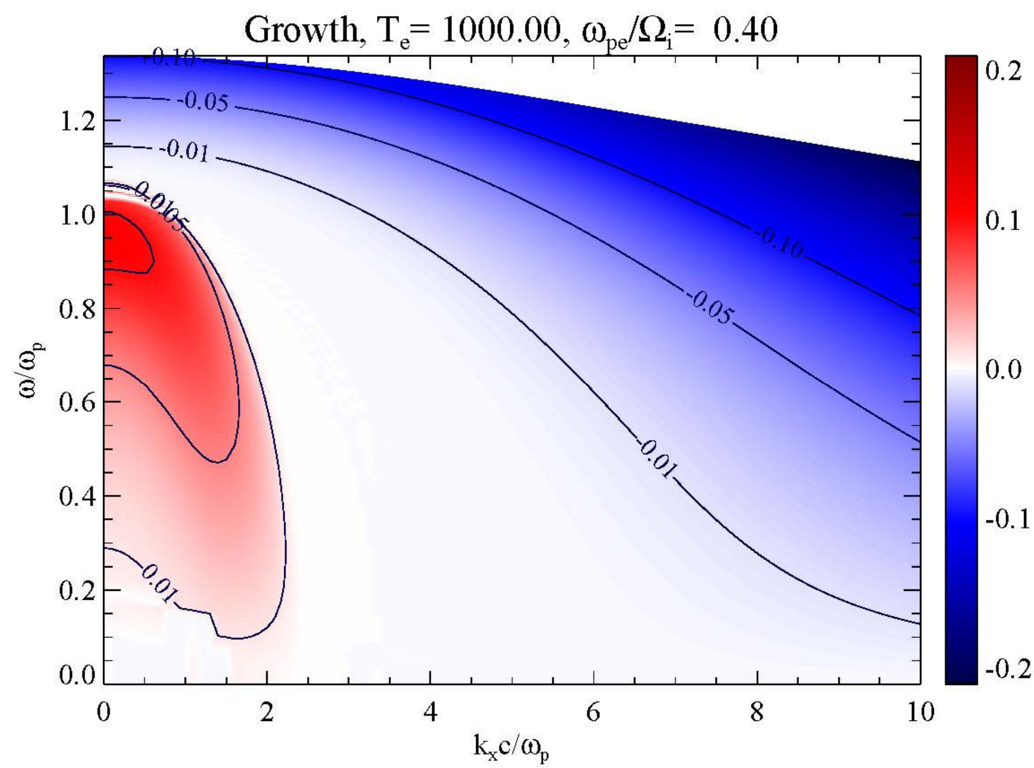


- Most unstable waves just below plasma frequency

Beam Plasma Instability

- 1000 eV plasma with 100 keV beam
- Plot in k-space (left); Plot vs. k_x-ω (right)

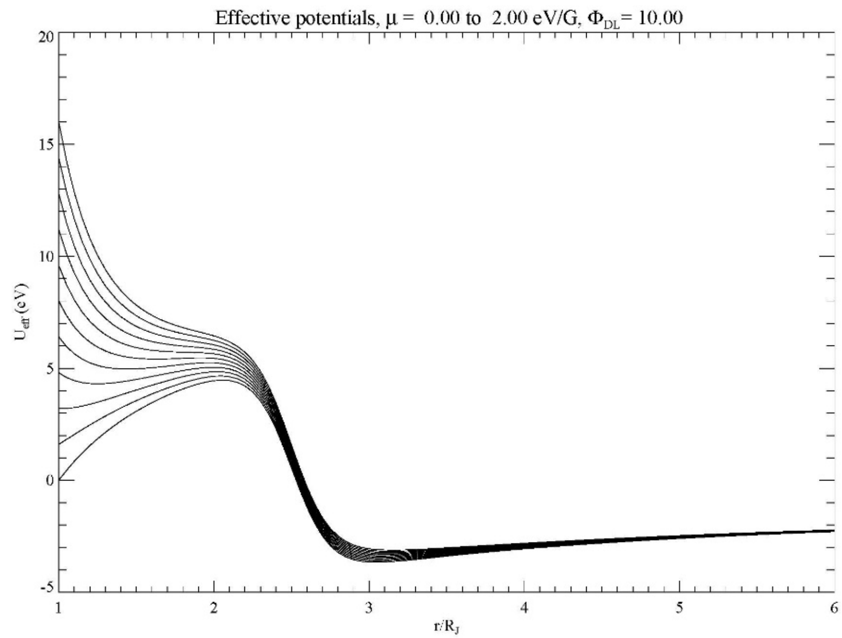


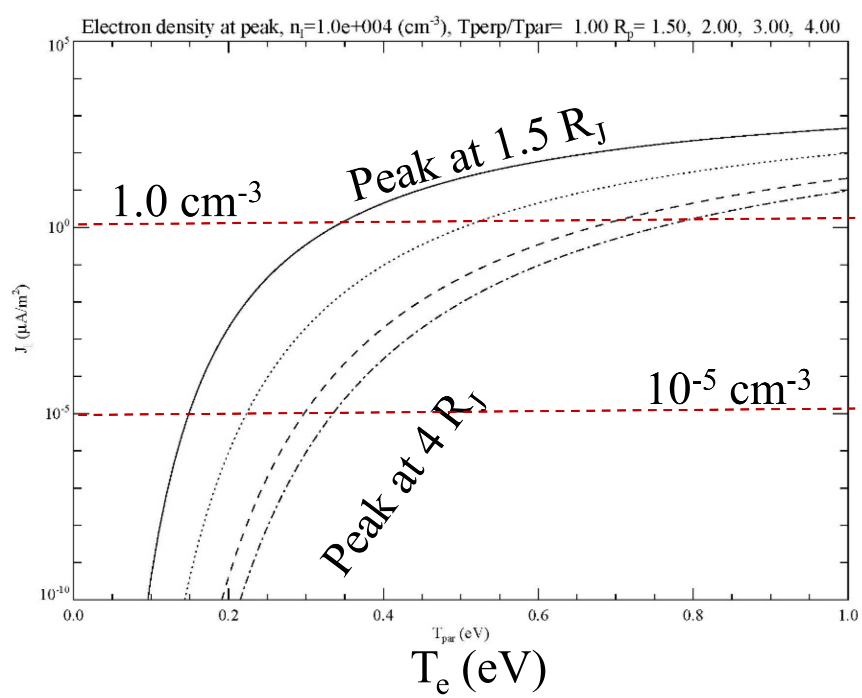


- Note that unstable region at smaller $k_\perp$, consistent with cold plasma result

Why are densities so low?

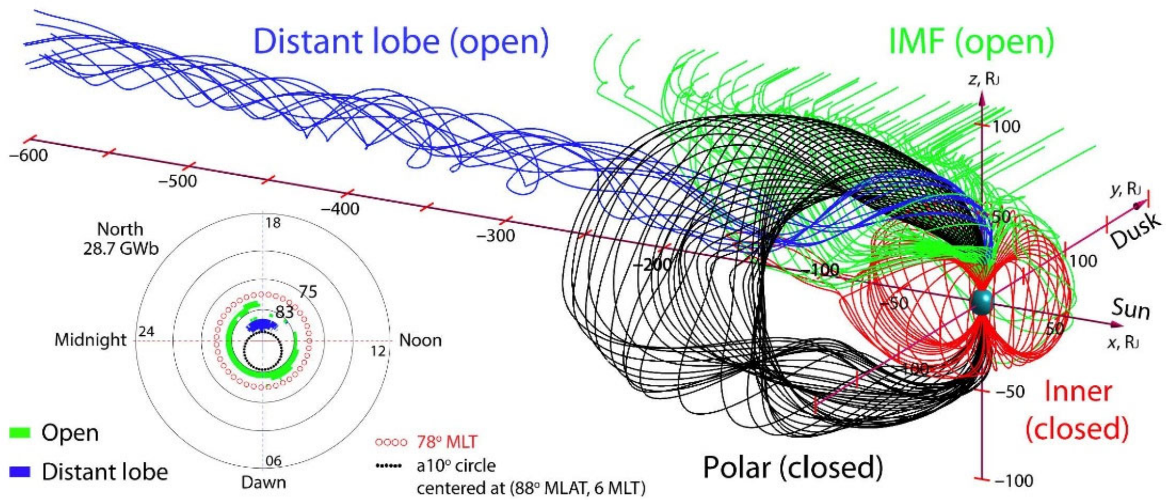
- Strong ambipolar potentials (~10 eV) suppresses outflow of ionospheric plasma
  - Ions gravitationally bound, upward electric field holds back electrons to maintain quasi-neutrality
  - Ambipolar potential 9.25 eV at Jupiter (0.326 eV at Earth)
  - Precipitation of ions indicates downward electric field, so effective potential has a low-altitude peak (top)
  - Observations indicate ionosphere has temperature < 1 eV.
  - Bottom figure gives density of escaping electrons as function of ionospheric temp and altitude of effective potential peak.





Are polar cap field lines open?

- Zhang et al. (2021) performed simulations with the GAMERA code and mapped field lines:



- Blue "lobe" field lines map to dusk side of polar cap
- Black field lines are closed and connect both hemispheres
- Presence of heavy ions indicates mapping to plasma sheet, populated by heavy ions from Io
- Open question: how to overcome mirror force from distant source?

Summary

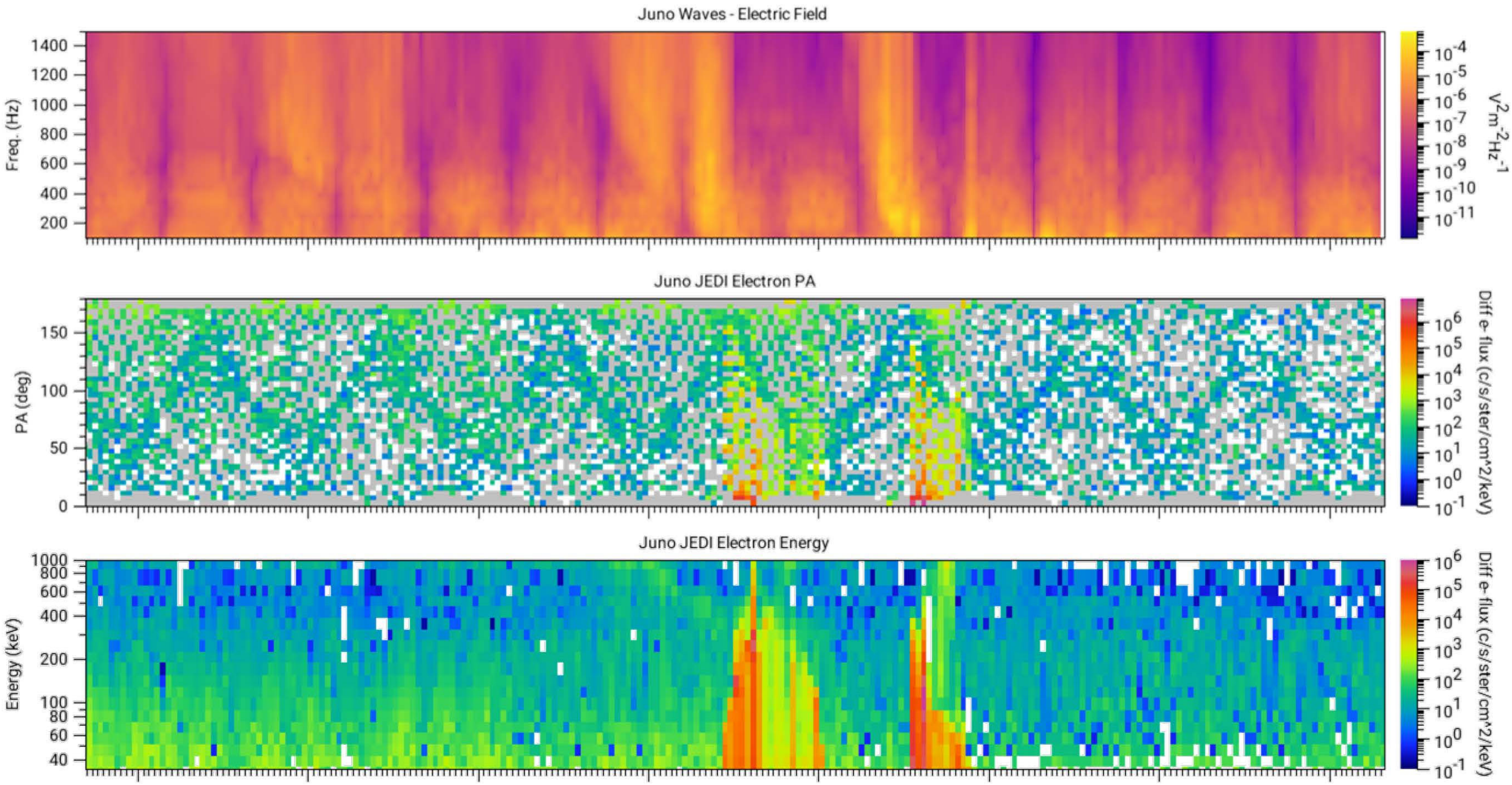
- Jupiter's polar cap characterized by very low densities, precipitating heavy ions (up to ~MeV), indicating closed field lines

- For low density, highly magnetized plasmas, electron plasma frequency can be less than the ion gyrofrequency
  - Leads to different structure for dispersion relation, with Alfvén wave only propagating to plasma frequency, not ion cyclotron frequency, so it's a modification of Alfvén-ion cyclotron branch
  - In warm plasma, plasma wave shows characteristics of Langmuir wave, so it could be called **Alfvén-Langmuir wave**, or simply a version of the inertial Alfvén wave.

- This work has been supported by NASA grant 80NSSC20K1269

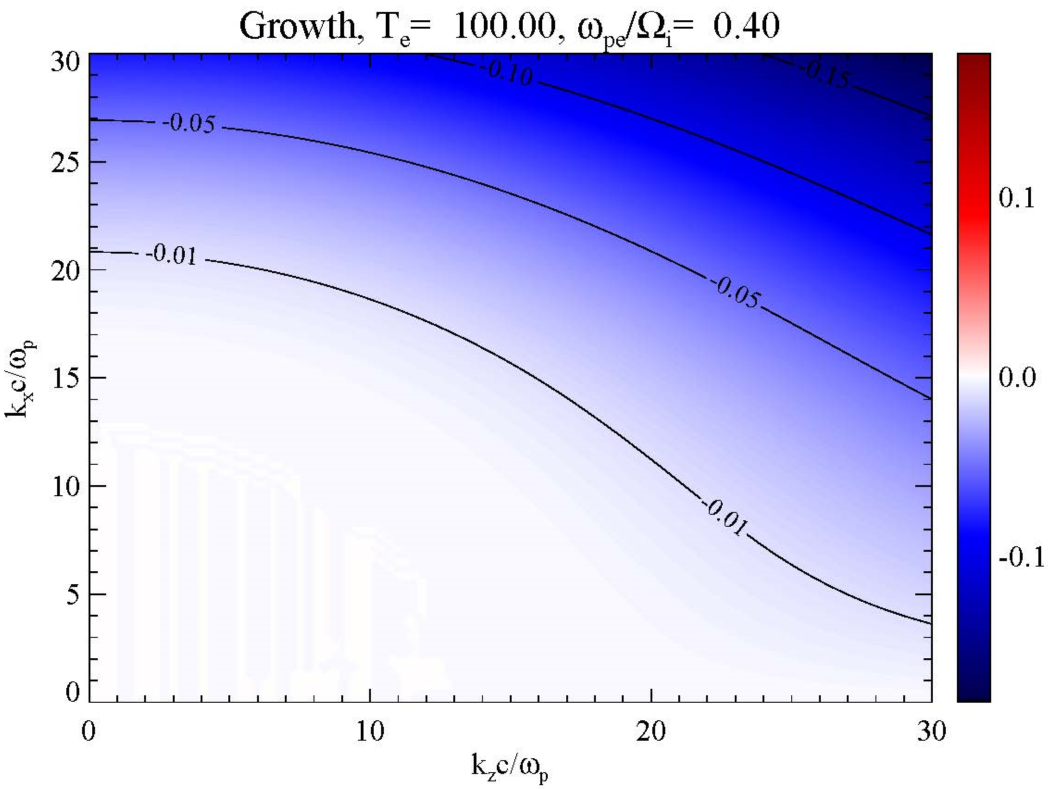
Broadband Electron Acceleration in Polar Cap

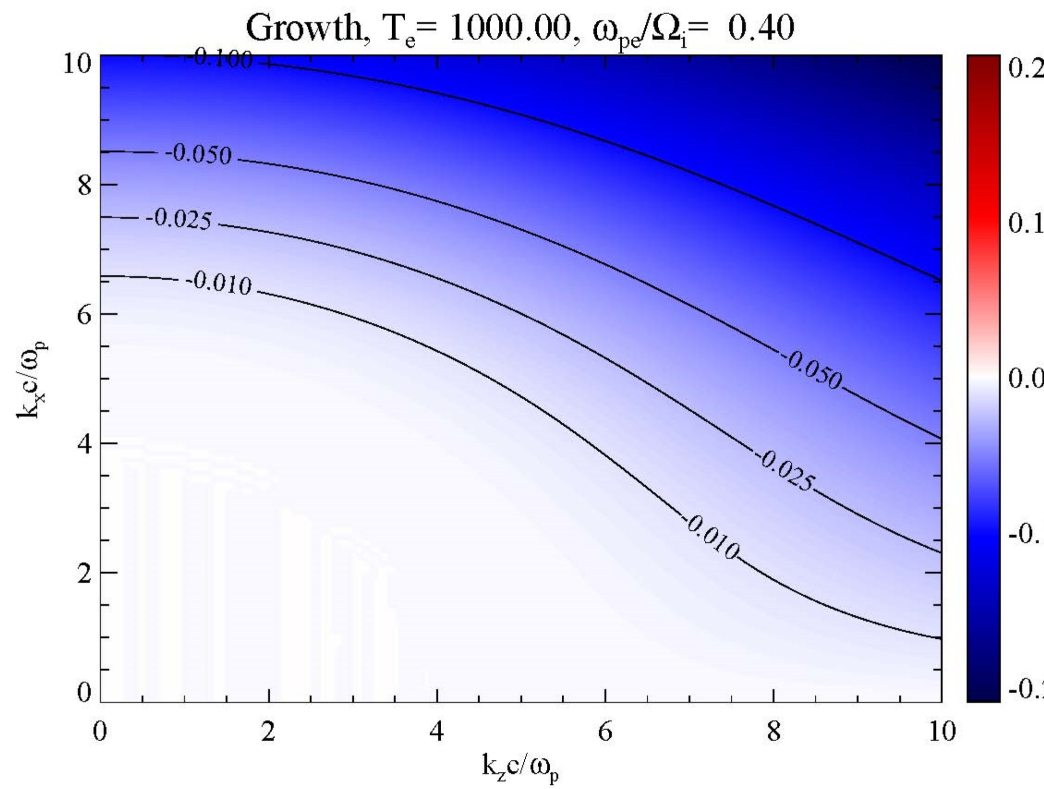
- Sulaiman+ (2023) shows broadband acceleration of electrons to 100's keV in this region



Wave Damping

- Waves damped by Landau damping at large k values





- Lower temperatures, damping sets in at shorter perpendicular wavelengths