# Electromagnetic Ion Cyclotron Waves for RBR Applications

## Thesis Proposal

Maria de Soria-Santacruz

Committee:
Prof. Kerri Cahoy
Prof. David Miller
Dr. Gregory Ginet
Prof. Jeffrey Hoffman
Prof. Manuel Martinez-Sanchez

Space Propulsion Laboratory
Department of Aeronautics and Astronautics

9 April 2012

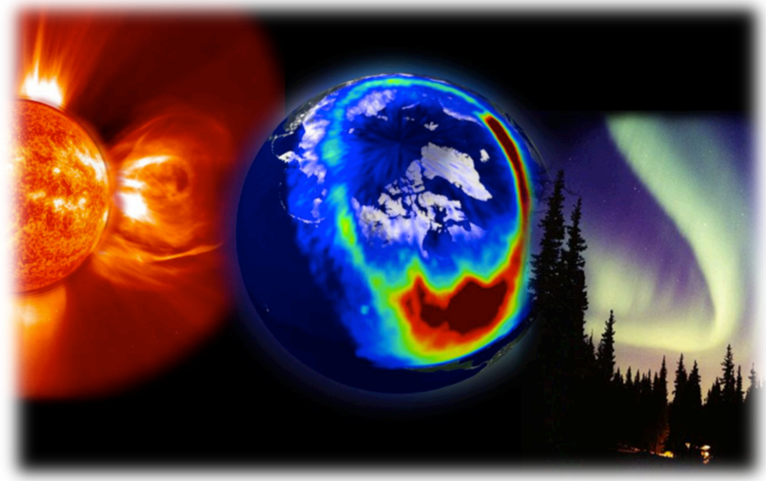
# Outline

# Outline

1. **Introduction**
2. Research Objectives and Contributions
3. Literature Review
4. Approach
5. Results
6. Schedule and Future Work
7. Minor

# 1. Introduction – Motivation

The high-energy particles of the Van Allen belts coming from cosmic rays, solar storms, High Altitude Nuclear Explosions (HANEs) and other processes represent an obstacle to exploration and development of space technologies. The emission of ULF and VLF waves from orbiting antennae is a problem of growing interest to the scientific, engineering and defense community. These emissions will create a pitch-angle scattering of the energetic particles, causing a portion of them to precipitate into the atmosphere.



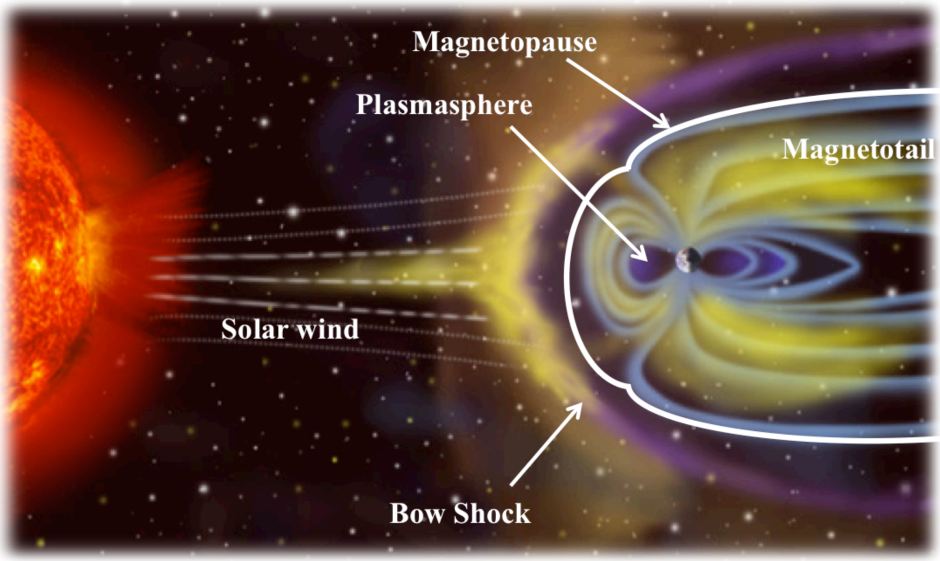
Recent studies [1] have concluded that wave-particle interactions may dominate the losses of these energetic particles, suggesting man-made control of the Van Allen belts, which contain energetic electrons and ions (protons mainly), with similar deleterious effects:

HANES → Electron injection [11,44,45] → Whistler waves → DSX

Cosmic rays, Solar wind } → Electron/proton injection → **EMIC waves** → **??**

**Radiation Belt Remediation (RBR):** Some approaches use spaceborne antennas that inject ULF/VLF waves in the belts to scatter and precipitate the very energetic particles of the radiation belts.

# 1. Introduction – The Magnetosphere and Trapped Particles




This work focuses on the **inner magnetosphere** (L<7): dipole magnetic field model and cold and collisionless bulk plasma in diffusive equilibrium.

The **Van Allen belts** are concentrations of high-energy particles trapped in the plasmasphere. Two belts of very low (<1 el/$cm^3$) density:

- Inner belt (L≈1-2): $E_{proton} \leq 400$ MeV, $E_{ele} \leq 1$ MeV
- Outer belt (L≈3-5): $E_{ele}$ = 0.1-10 MeV

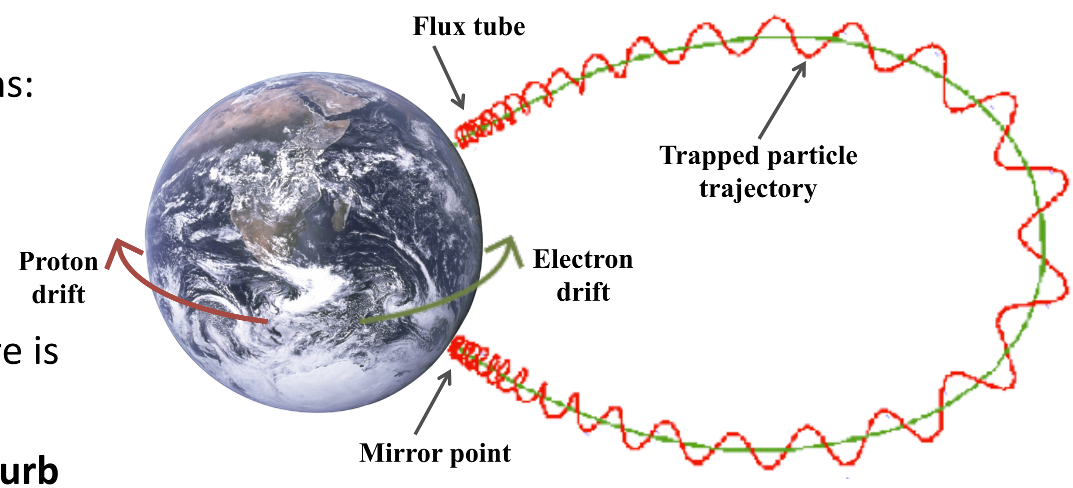
In addition, low-energy background plasma. Much higher density but lower energy.

Trapped particles perform three basic motions:

- Gyro-motion around magnetic lines
- Bouncing motion along magnetic lines
- Drift motion around the Earth

When the variation B is sufficiently slow, there is and adiabatic invariant for each motion.

But… **wave-particle interactions can perturb the adiabatic motions!**



# 1. Introduction – EMIC Waves (I)

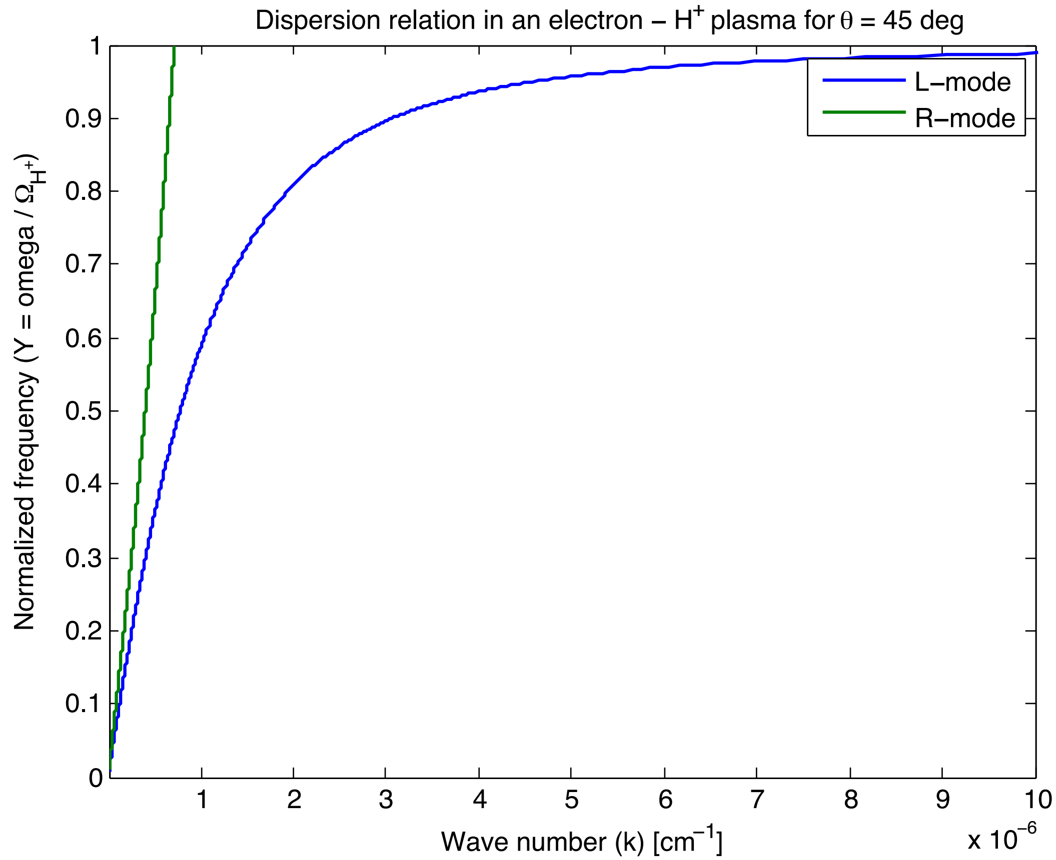
Electromagnetic Ion Cyclotron (EMIC) waves are plasma waves that propagate below the proton gyrofrequency:

$$\omega < \Omega_p = eB_0 / m_p$$

where e is the electron charge, $B_0$ is the external magnetic field and $m_p$ is the proton mass. In this study we use the theory of cold plasma wave propagation as a first approximation.

The dispersion relation has two branches with left and the right polarizations.

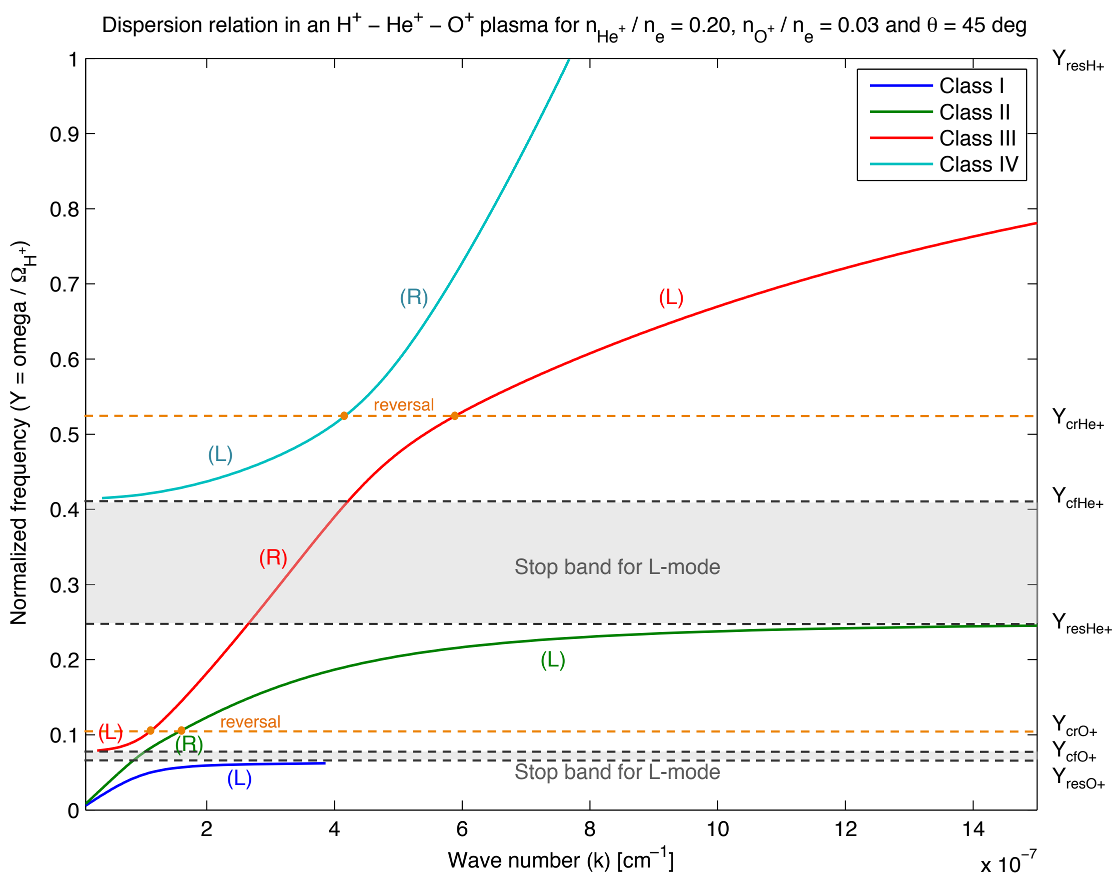
In an **electron-proton plasma**, the left-branch is guided and has a resonance at $Y = \omega/\Omega_p = 1$. The unguided right-hand mode remains unaffected by the proton gyrofrequency.



# 1. Introduction – EMIC Waves (II)

The propagation of EMIC waves is strongly affected by the heavy ions' concentration ($H^+$-$He^+$-$O^+$ plasma) [3,36]. Heavy ions give rise to polarization reversals and spectral slots.

- **Resonances:** For θ=90° resonances happen at the bi-ion frequencies. For oblique propagation, resonances happen at the resonance frequencies ($Y_{res}$), which is close to the cyclotron frequencies.
- **Cutoffs ($Y_{cf}$):** Reflection of the L-mode occurs and it does not propagate between the cutoff and the resonance frequencies.
- **Crossovers ($Y_{cr}$):** A particular branch changes from R to L modes through linear polarization. Left and right polarizations of obliquely propagating EMIC waves in a multi-ion plasma are coupled, while they are decoupled for parallel propagation.



# 1. Introduction – Wave-Particle Interactions

The equations of motion of the energetic particles in the presence of the wave are

$$\dot{\vec{p}} = q\left[\vec{E}^{w} + \frac{\vec{p}}{\gamma m}\times\left(\vec{B}^{w} + \vec{B}_0\right)\right]$$

Cumulative change of energy or momentum between EMIC-particle

↓

The wave vectors as seen by the particle must be stationary/periodic for a significant length of time

↓

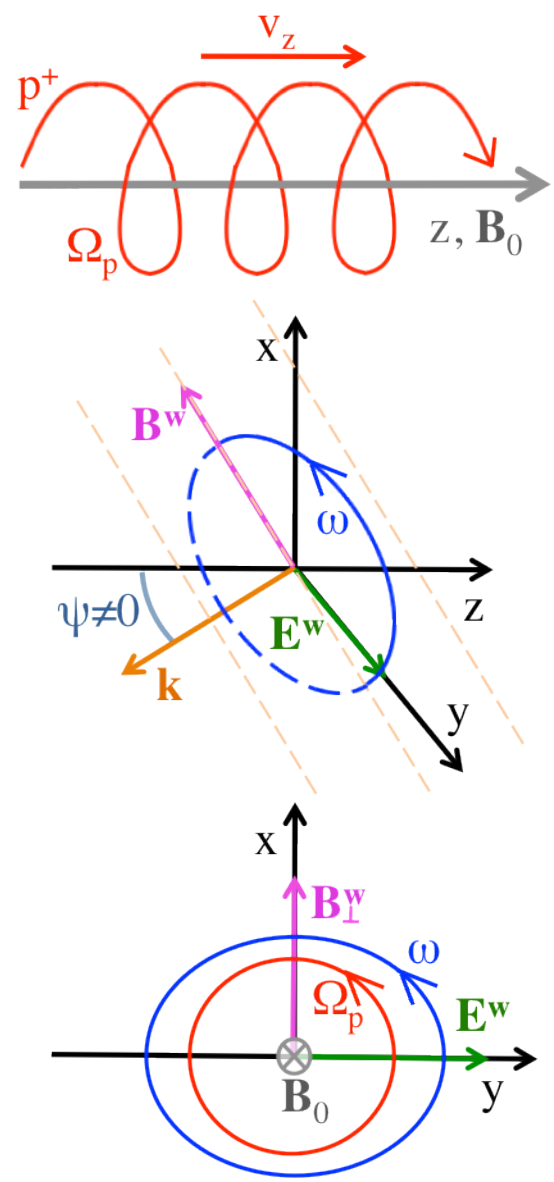
Doppler-shifted frequency as seen by the particle must equal its cyclotron frequency (multiple)

$$\omega - \vec{k}\cdot\vec{v} = l\frac{\Omega}{\gamma}$$

where ω is the frequency, *γ* is the relativistic factor, *l* is the harmonic number , **k** is the wavenumber vector and **v** is the particle's velocity.

L-mode with protons → $\vec{k}\cdot\vec{v} < 0$ → Opposite directions

L-mode with electrons → $\vec{k}\cdot\vec{v} > 0$ → Same direction



# Outline

1. Introduction
2. **Research Objectives and Contributions**
3. Literature Review
4. Approach
5. Results
6. Schedule and Future Work
7. Minor

## 2. Research Objectives and Contributions

This study aims at characterizing the ability of Electromagnetic Ion Cyclotron (EMIC) waves to precipitate the energetic particles trapped in the Van Allen belts, and to translate these findings into engineering specifications of a spaceborne RBR system able to significantly reduce this energetic radiation.

The following objectives have been defined:

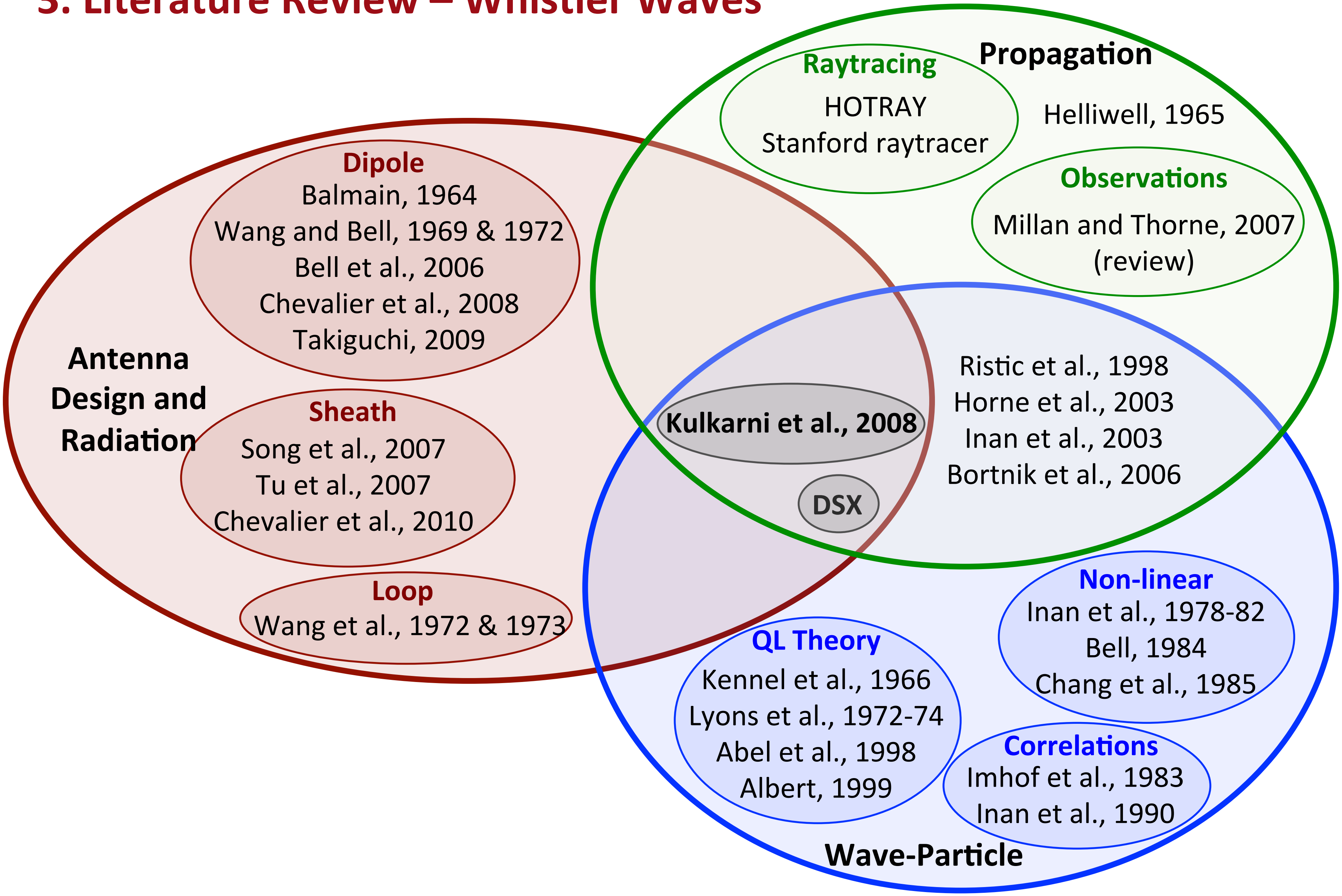
- Determine the type of antenna able to radiate EMIC waves in the magnetosphere, which is a largely unexplored territory.
- Characterize its radiation impedance in the far-field region.
- Study EMIC cold plasma wave-propagation using ray-tracing.
- Characterize the interaction of EMIC waves with the energetic population of particles in the belts. Similar studies have been previously developed for Whistlers interacting with electrons, but no attention has been paid to the lower frequency and its interaction with high-energy protons.
- Characterize the feasibility in terms of power levels, frequencies, voltages, currents and mass of a potential spaceborne RBR antennae capable of significantly reduce the energetic radiation in the belts.

*Intercosmos 24 Satellite*

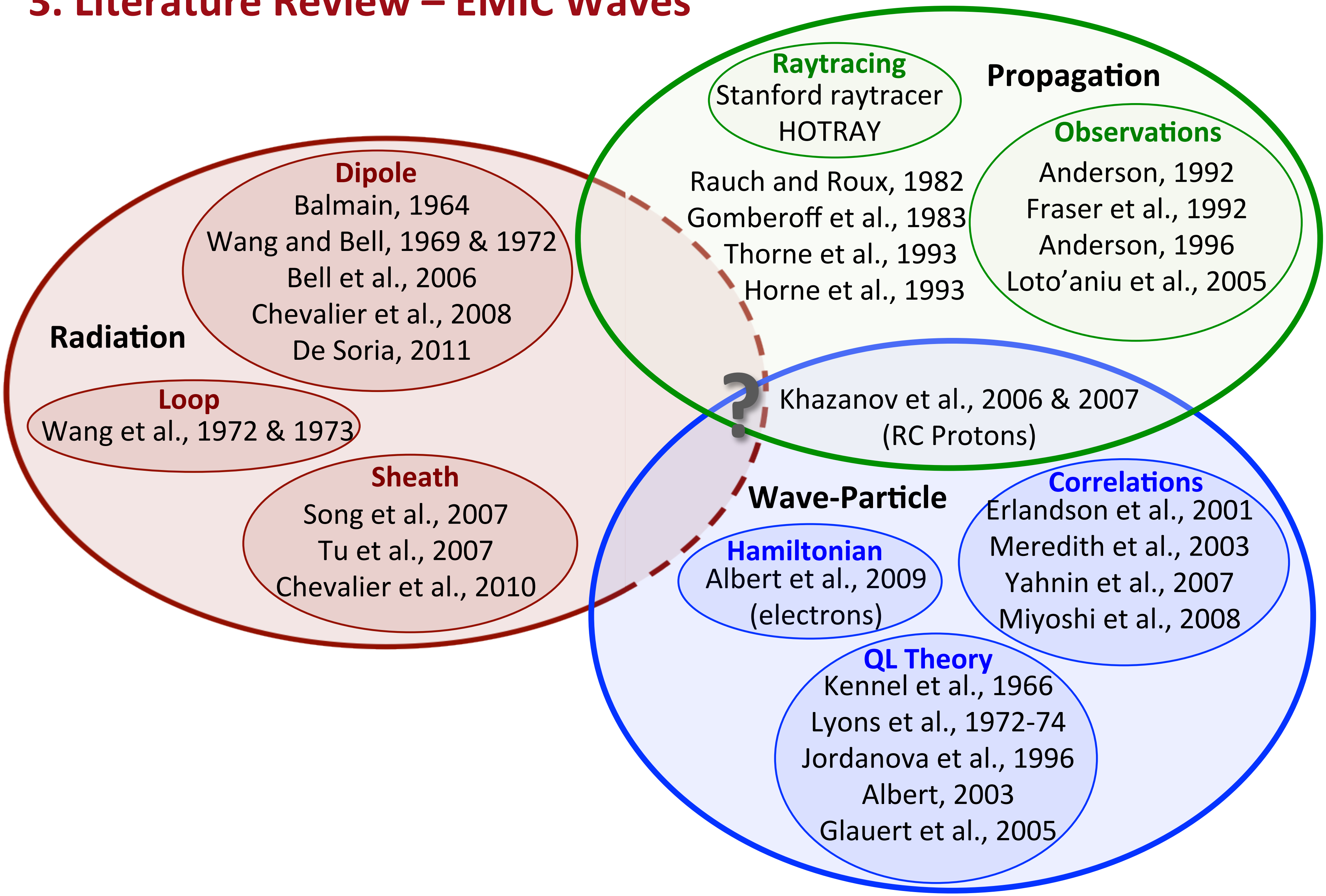
# Outline

1. Introduction
2. Research Objectives and Contributions
3. **Literature Review**
4. Approach
5. Results
6. Schedule and Future Work
7. Minor

# 3. Literature Review – Whistler Waves



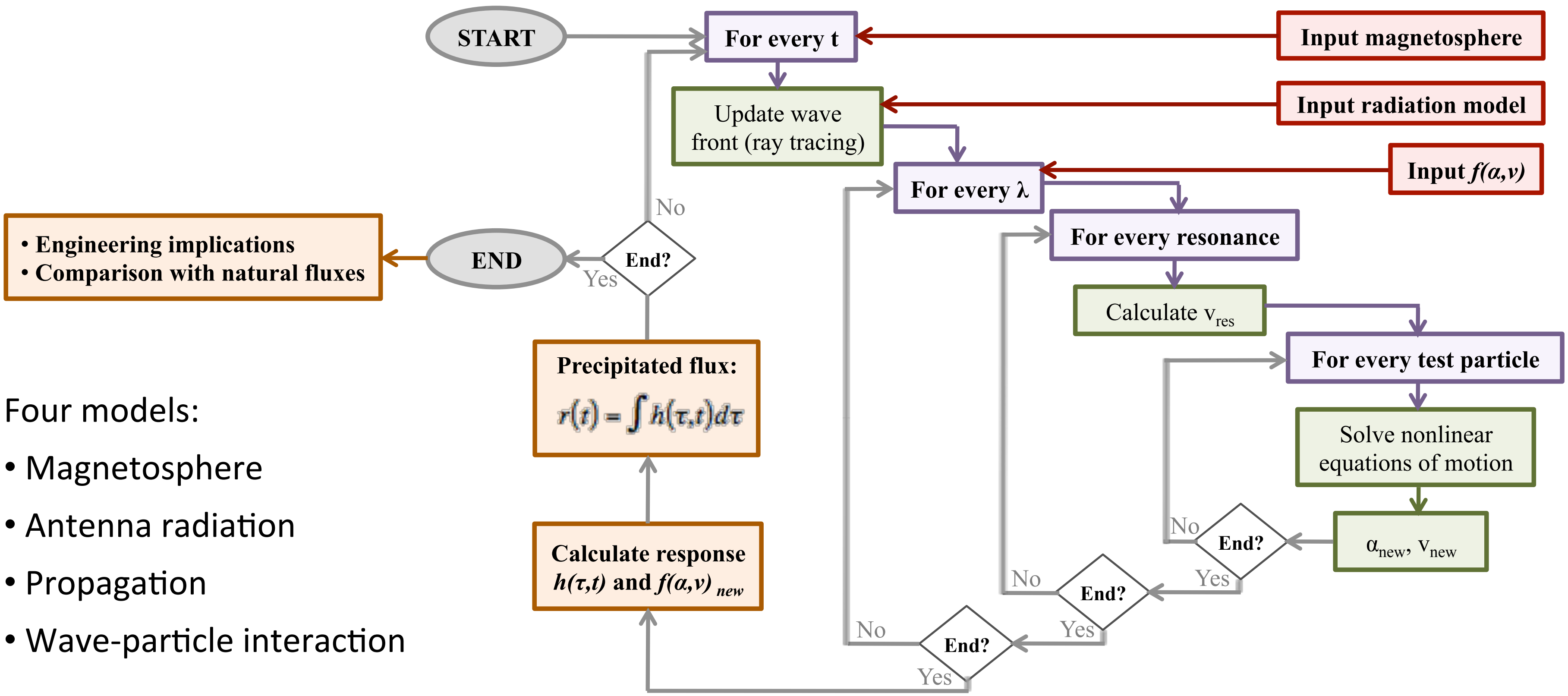
# 3. Literature Review – EMIC Waves



# Outline

1. Introduction
2. Research Objectives and Contributions
3. Literature Review
4. **Approach**
5. Results
6. Schedule and Future Work
7. Minor

# 4. Approach – The Algorithm




Four models:

- Magnetosphere
- Antenna radiation
- Propagation
- Wave-particle interaction

Magnetic lines are discretized in latitude. For every time and latitude step the properties of the wave are updated using ray-tracing.

We solve the non-linear equations of motion of test energetic particles from a given distribution. The process is repeated for every time step and every latitude and the precipitated flux is calculated as a result of this iteration (for every ray).

# 4. Approach – The Radiation Model

**Electric dipole in the EMIC band:**

$L_a \downarrow, \omega \downarrow \quad \Rightarrow \quad R_{rad} \uparrow$ → Favors short dipole

$\Rightarrow \quad X_{antenna} \approx X_{vac} \uparrow\uparrow$ → Favors very long dipole

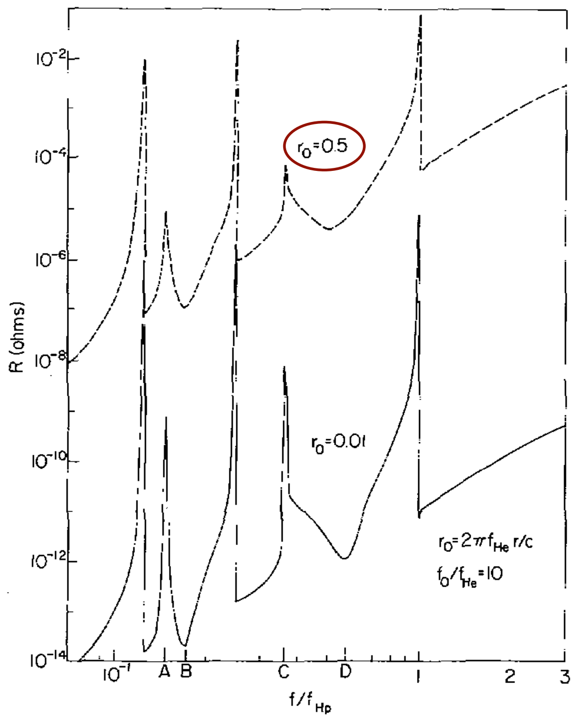
$Q = X_{antenna} / R_{rad} \approx 5 \cdot 10^5$!!

Electric dipole **NOT** possible

**Possible solutions:**

1. Plasma contactors → Avoids oscillatory charge accumulation
2. Magnetic dipoles (loop antenna) → Investigate different configurations

   Importance of near-field phenomena




Require $R_{rad} = 10^{-5}\,\Omega$, $L = 2$, $P_{rad} = 100\ W$ → $r_{loop} \approx 220\ m$, $I_{loop} \approx 4.5\ kA$!!

Single loop **NOT** possible

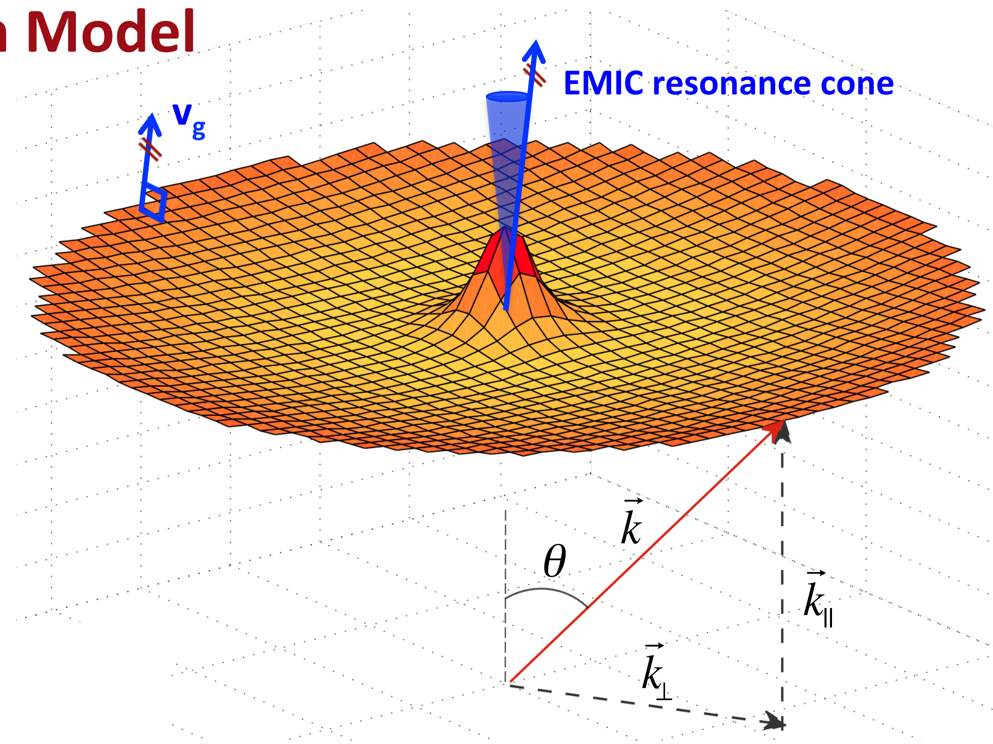
*Loop radiation resistance as function of frequency in multi-ion plasma [7]*

# 4. Approach – The Propagation Model

**Ray path** → trajectory of the wave energy ($v_g$), always perpendicular to the refractive index surface (**k**).

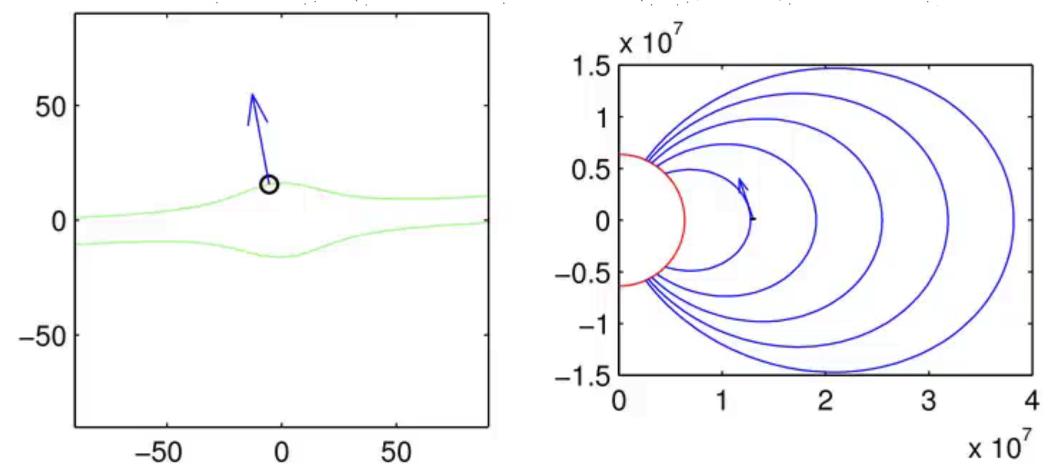
**Geometric optics approx.** → medium slowly varying within one wavelength.

**Ray-tracing** → follow the ray path along the belts assuming the geometric optics approximation holds.




Updates on ray-tracing:

- Got the code from Stanford
  - 2D
  - Written in Fortran, Matlab interface
  - Dipole geomagnetic field, diffusive equilibrium plasma
  - For whistlers
  - No Landau or cyclotron damping
- Modified the code for EMIC
  - Takes into account heavy-ion species: cutoffs, crossovers and resonances




*Stanford VLF raytracer. Video by F. Foust.*

# 4. Approach – The Wave-Particle Interaction Model (I)

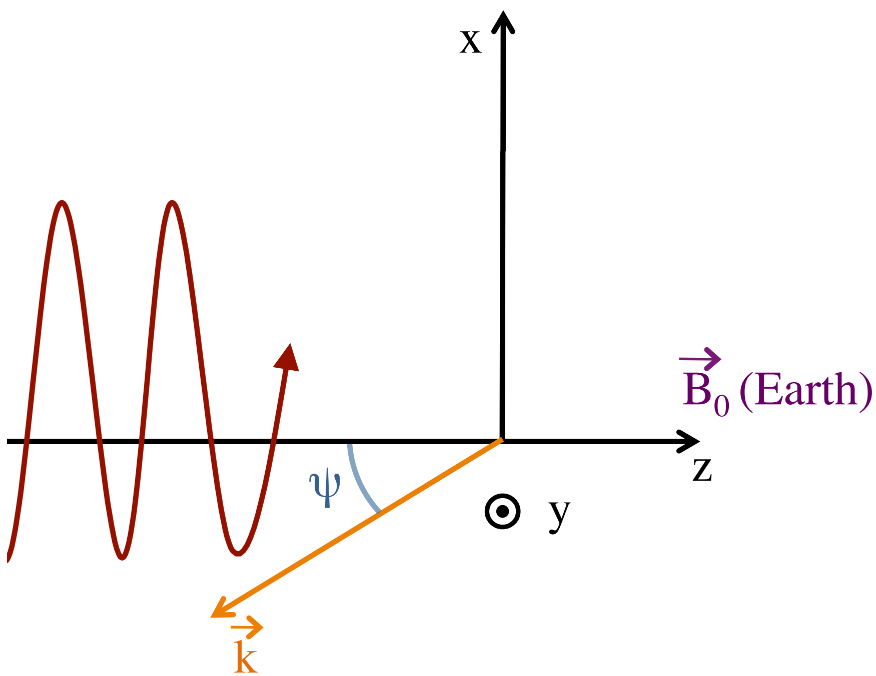
**Solve the Non-Linear Equations of Motion:**

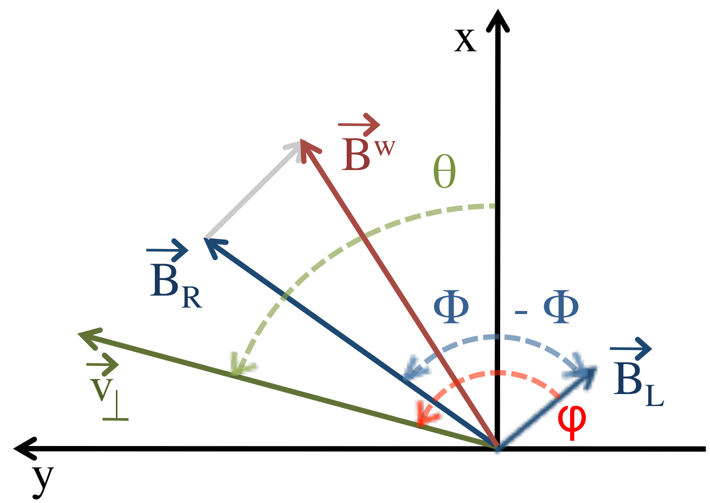
$$\dot{p}_x = -eE_x^w \sin\Phi + \frac{e}{m_p\gamma}\left[p_y\left(-B_z^w \cos\Phi + B_{0z}\right) - p_z\left(B_y^w \sin\Phi + B_{0\perp y}\right)\right]$$

$$\dot{p}_y = eE_y^w \cos\Phi + \frac{e}{m_p\gamma}\left[-p_x\left(-B_z^w \cos\Phi + B_{0z}\right) + p_z\left(B_x^w \cos\Phi + B_{0\perp x}\right)\right]$$

$$\dot{p}_y = -eE_z^w \sin\Phi + \frac{e}{m_p\gamma}\left[p_x\left(-B_y^w \sin\Phi + B_{0\perp y}\right) - p_y\left(B_x^w \cos\Phi + B_{0\perp x}\right)\right]$$

1. Express in $\left(p_z, p_\perp, \varphi\right)$ coordinates
1. Gyroaverage over one gyroperiod
2. Apply to test particles from a distribution
3. Integrate



# Outline

# 5. Results – Preliminary Whistlers' Study (I)

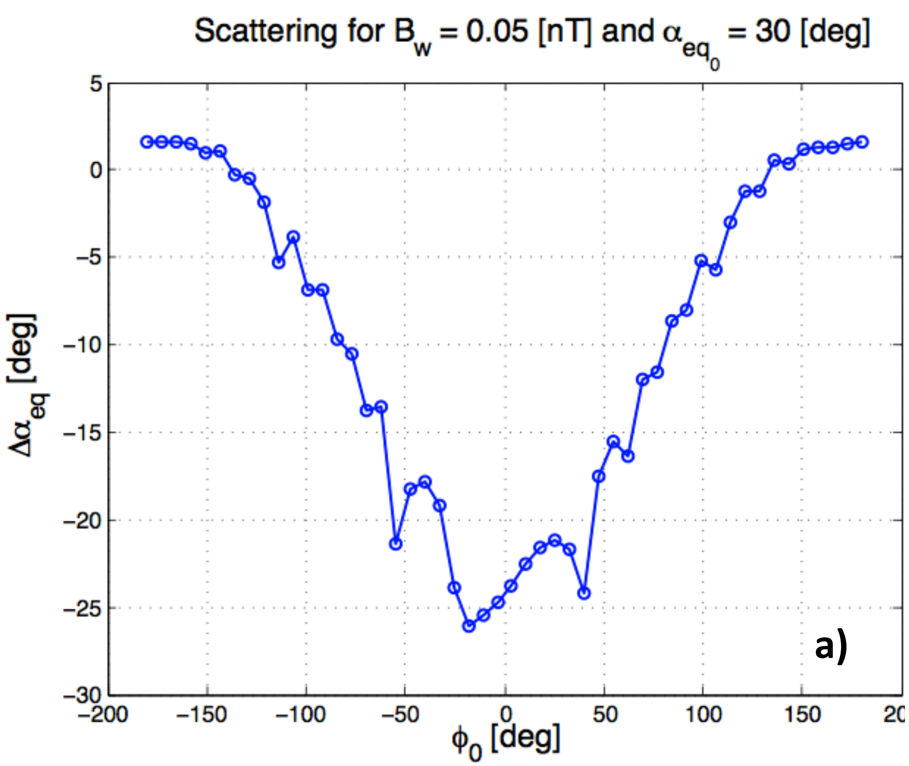
**First step:**

**Inan et al., 1978** [28]*:* Non-linear, non-relativistic cyclotron resonant interaction between electrons with coherent and ducted whistler waves in steady state.

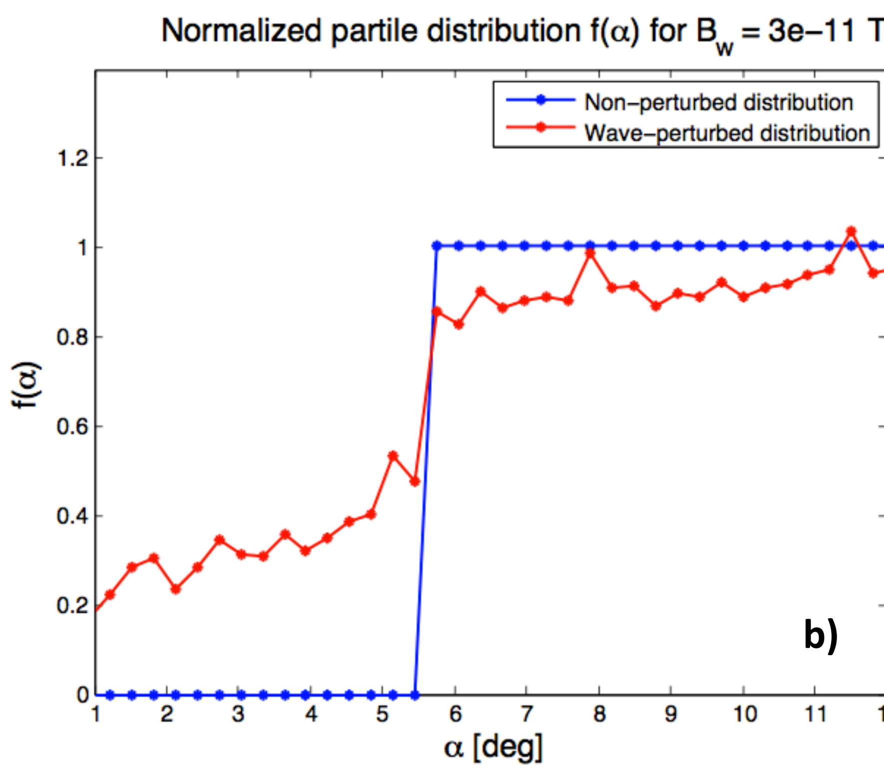
Parameters: $L = 4$, $n_{eq} = 400\ el/cm^3$, $f = 5\ kHz$

Energy flux of precipitated particles (Figure b)): $Q = 0.2\ J/(m^2s)$

Single particle's scattering




Distribution's scattering

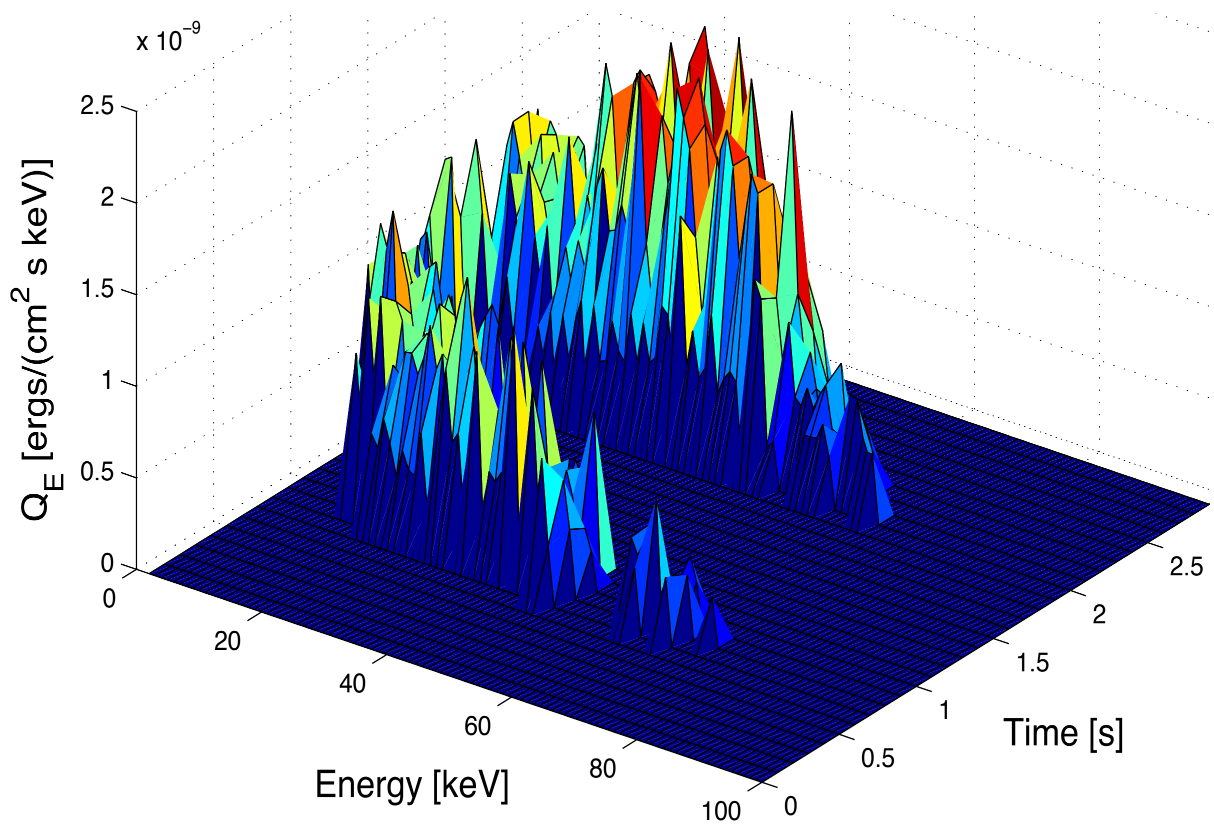


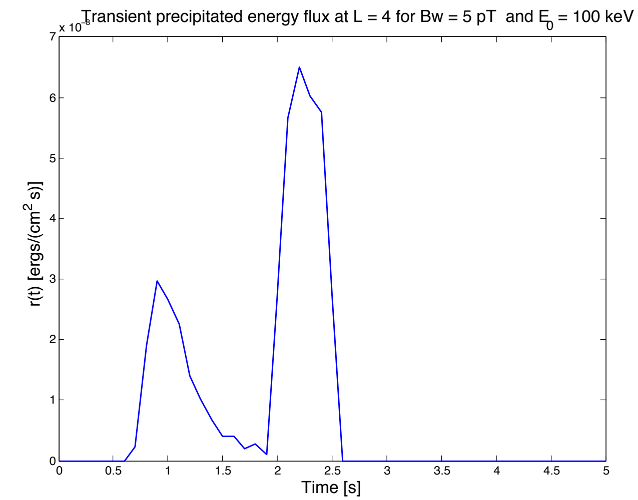
# 5. Results – Preliminary Whistlers' Study (II)

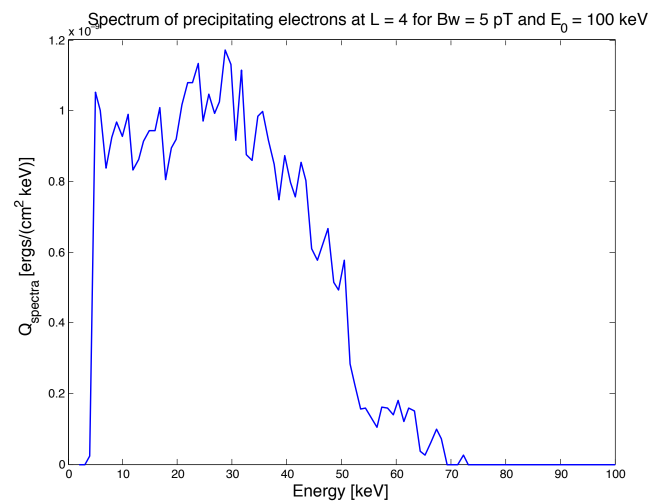
**Chang and Inan, 1985** [13]*:* Transient, non-linear, relativistic cyclotron resonant interaction between electrons with coherent and ducted whistler waves.

Parameters: $L = 4$, $n_{eq} = 400\ el/cm^3$, $f = 2.5\ kHz$, $B_{weq} = 5\ pT$.

Whistler pulse of 0.5 seconds injected at 1000 km



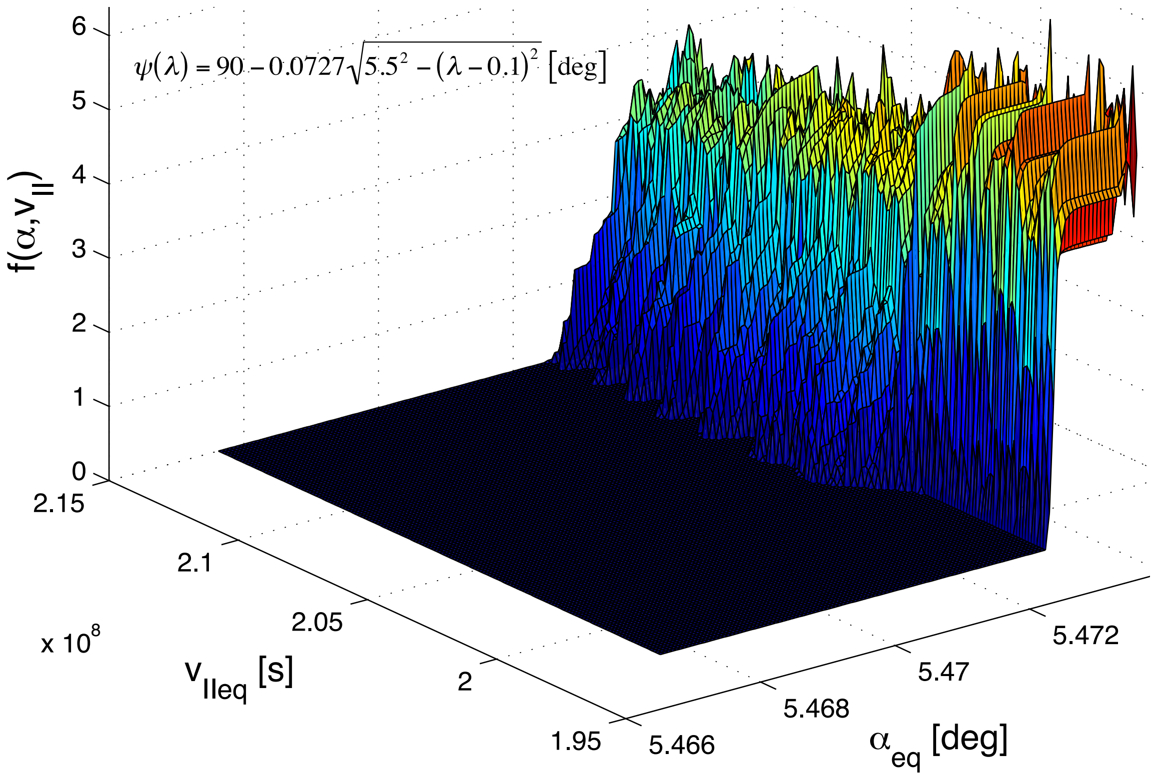



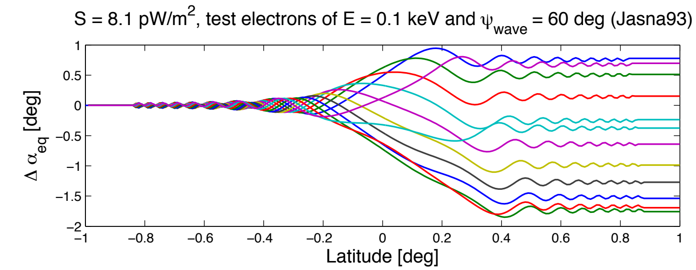
# 5. Results – Preliminary Whistlers' Study (III)

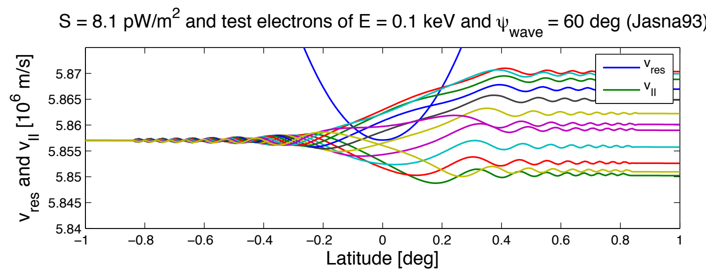
**Ristic-Djurovic, 1992 and 1998** [48, 49]*:* Non-linear, relativistic cyclotron resonant interaction between electrons with oblique whistler waves in steady state.

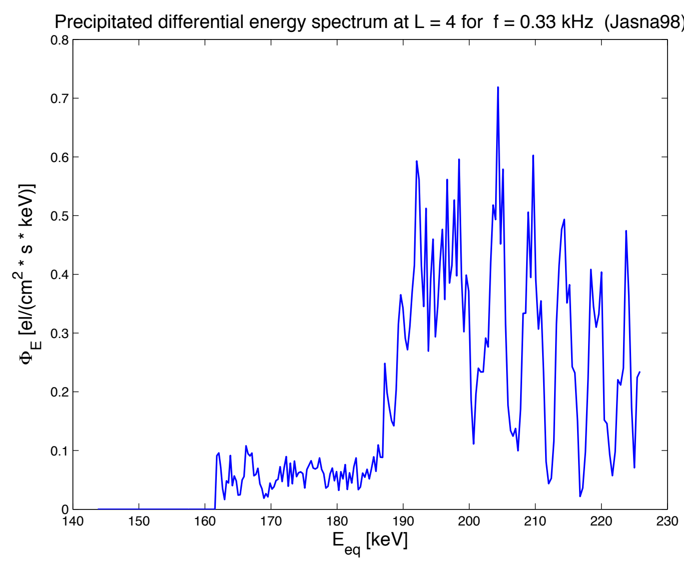
Parameters: $L = 4$, $n_{eq} = 400\ el/cm^3$, $f = 0.33\ kHz$, $S = 133\ pW/m^2$.

Energy flux of precipitated particles: $Q = 3.87\ nJ/(m^2 s)$



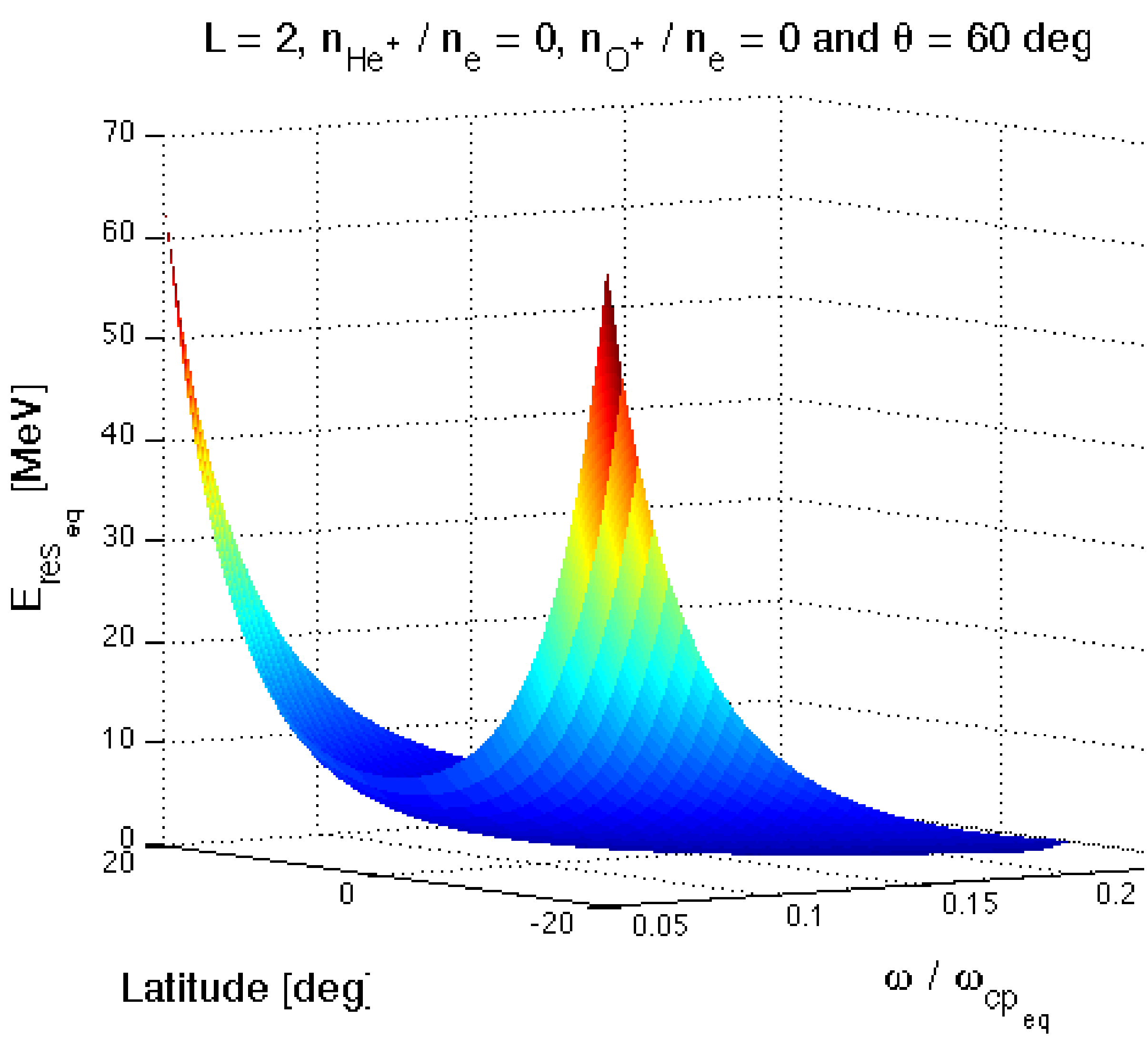




Local maxima and minima in electron scattering occur due to constructive and destructive interference between the two resonant encounters.

# 5. Results – EMIC (I)

**Resonant proton energy:**




Cumulative change of momentum with the particle → solution to the cyclotron resonance condition:

$$\Omega + k_{\parallel} \cdot v_{\parallel} = \Omega_p / \gamma$$

Where ω is the frequency, γ is the relativistic factor and $k_{\parallel}$ and $v_{\parallel}$ are the wavenumber and velocity parallel to $B_0$, respectively.

The Figure shows the resonant energy required for cyclotron interaction with MeV protons vs resonant latitude and frequency at L = 2. The wave-normal angle has been taken equal to ψ = 60°.

# 5. Results – EMIC (II)

**Proton sheet – Equatorial interaction with E = 14.4 MeV:**

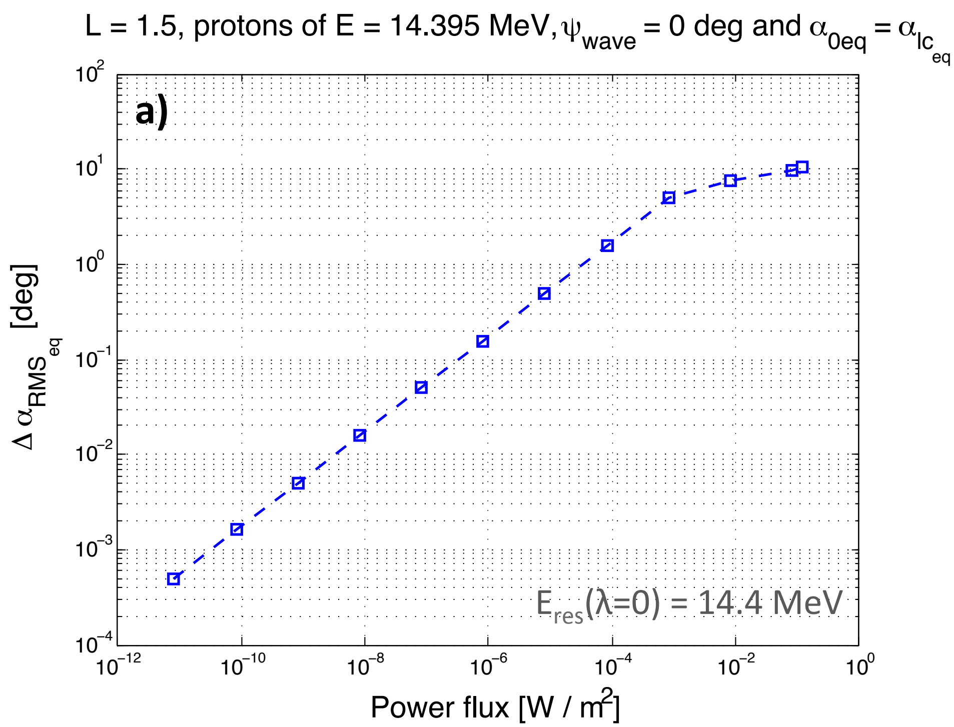
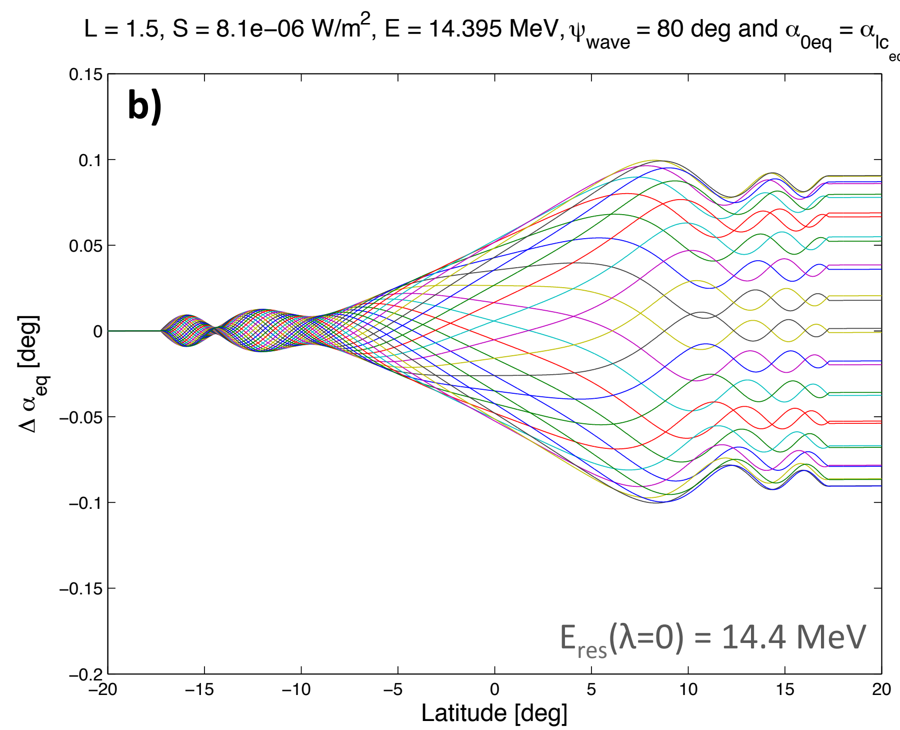


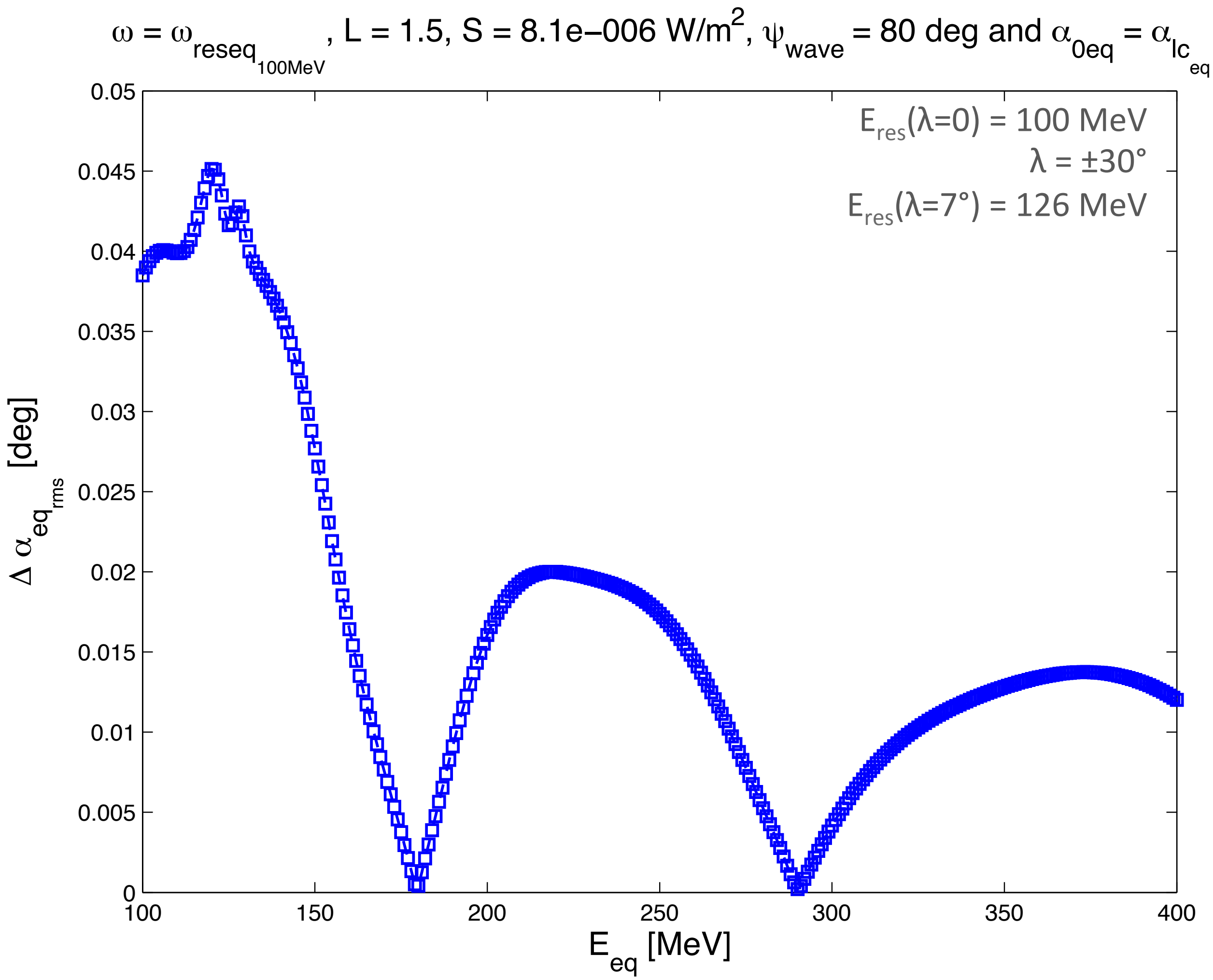

Figure a) represents the RMS scattering vs wave power flux for equatorial interaction with ducted EMIC. It shows the importance of the wave-field term compared to the basic geomagnetic field in the equation for the variation of the phase. The wave is linear with scattering for power flux S < $10^{-4}$ W/m$^2$.

Figure a) shows that the wave term in the equation for the phase can be neglected for S < $10^{-4}$ W/m$^2$. Figure b) presents the pitch-angle scattering vs latitude of an equatorially resonant sheet of protons interacting with oblique EMIC (ψ=80°) with $8.1 \cdot 10^{-6}$ W/m$^2$. $\Delta\alpha_{RMSeq}$(80°)=0.06°, one order of magnitude smaller than for $\Delta\alpha_{RMSeq}$(0°)=0.5°.



# 5. Results – EMIC (III)

**Proton sheet – Energies for maximum scattering:**



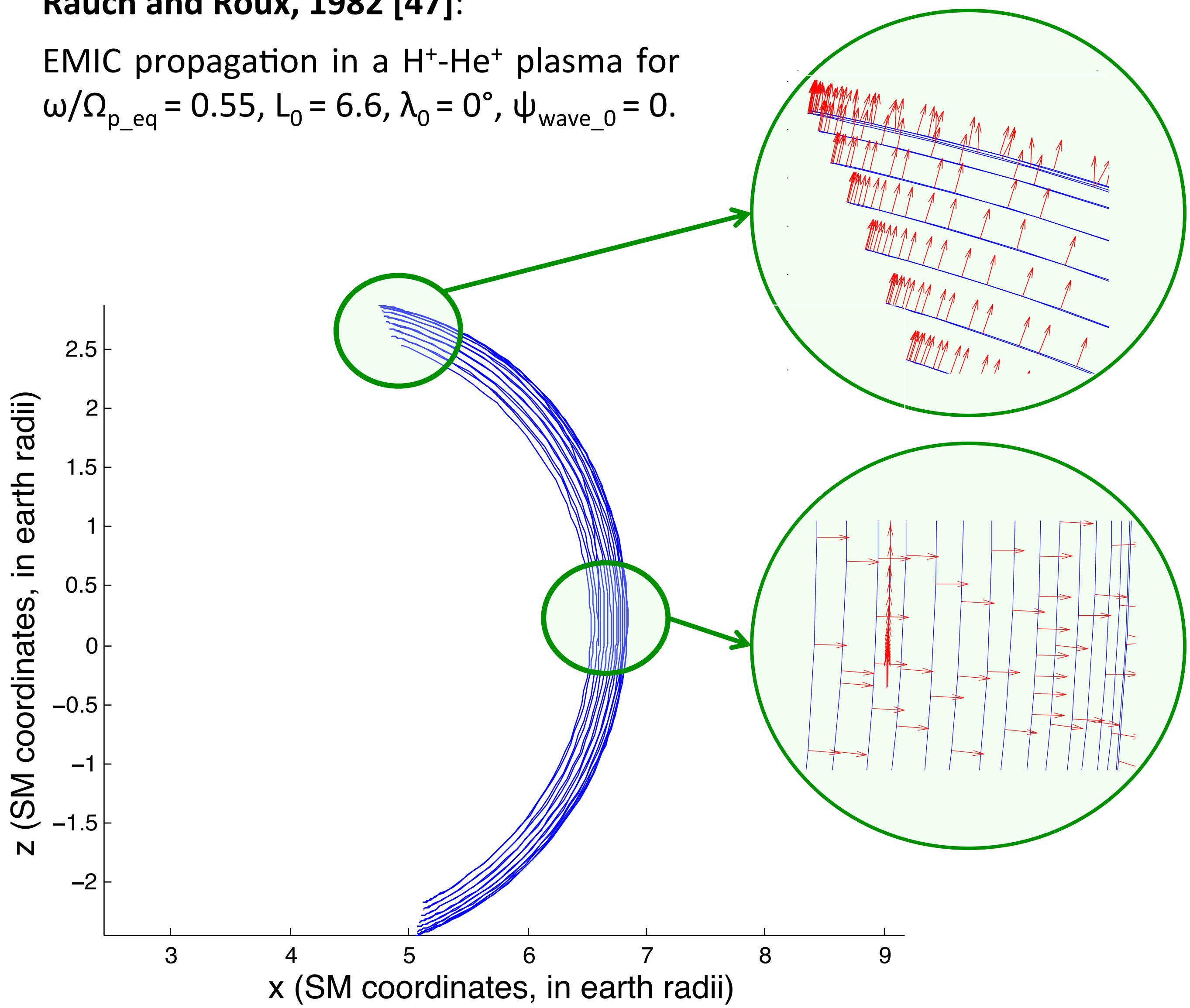

Total scattering between λ= ±30°. The interaction does not peak for equatorial resonance, but around 7° → two resonances

The quasi-periodic variation of the scattering is due to the phase coherence between resonance points.

# 5. Results – Ray-Tracing Study (I)

**Rauch and Roux, 1982 [47]**:

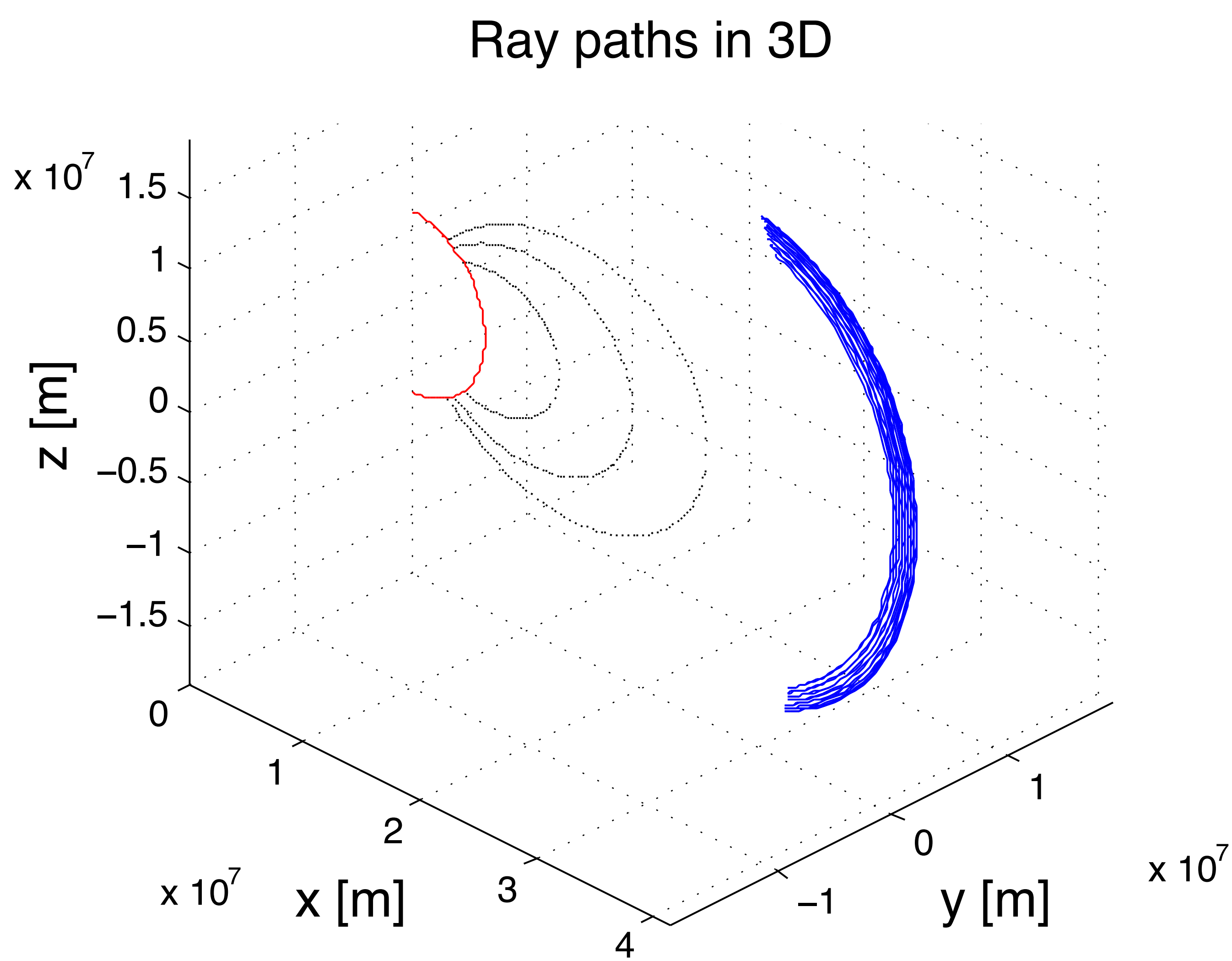
EMIC propagation in a $H^{+}$-$He^{+}$ plasma for $\omega/\Omega_{p\_eq} = 0.55$, $L_0 = 6.6$, $\lambda_0 = 0°$, $\psi_{wave\_0} = 0$.




As the wave propagates to higher latitudes it finds a crossover and changes to R-hand. It bounces back at the bi-ion frequency, where $\psi = 90°$.

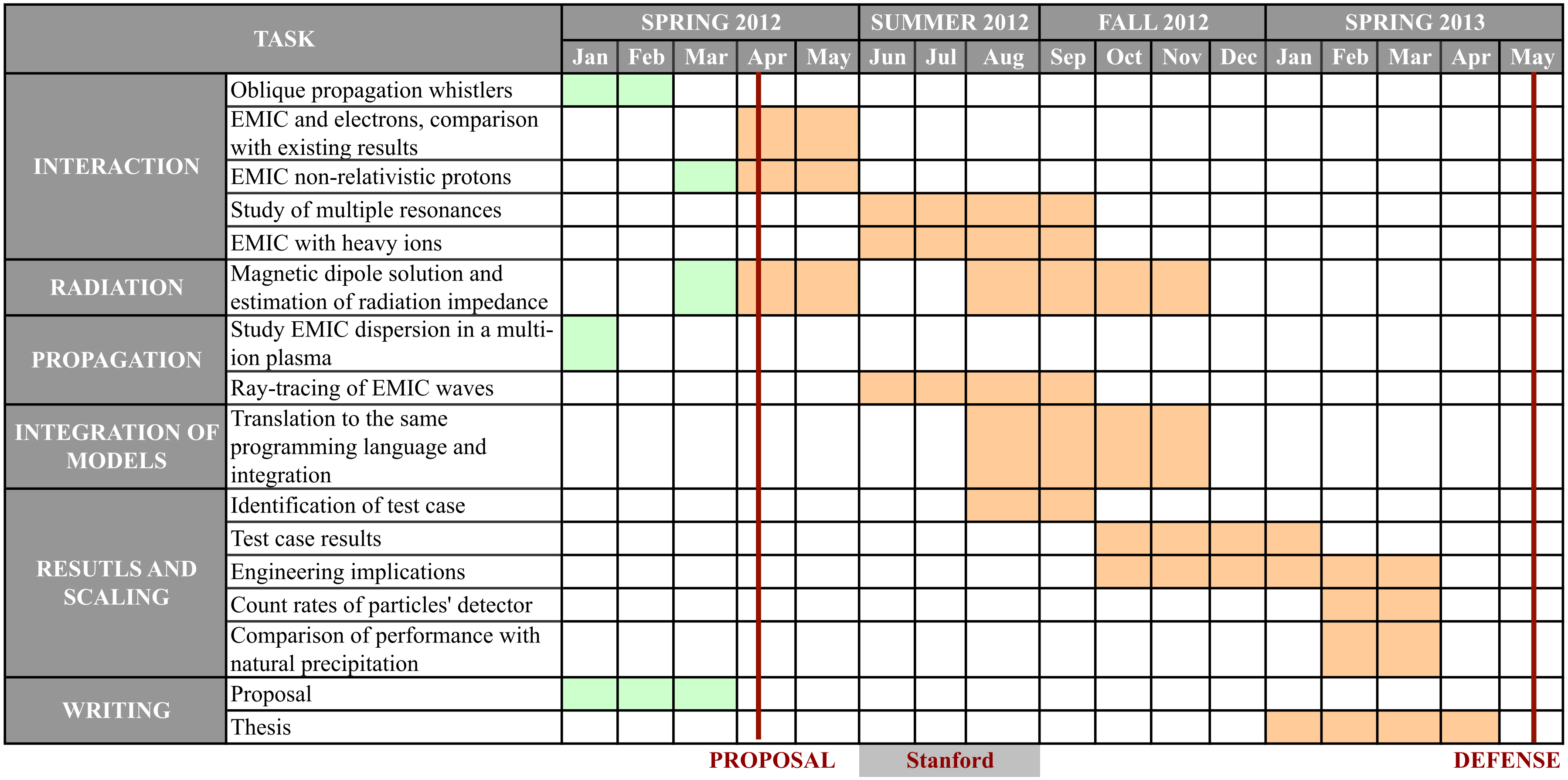
The ray starts with $\psi_0 = 0$ and as it bounces back and forth it increases its wavenormal angle to close to perpendicular.

# 5. Results – Ray-Tracing Study (II)



# Outline

# 6. Schedule and Future Work



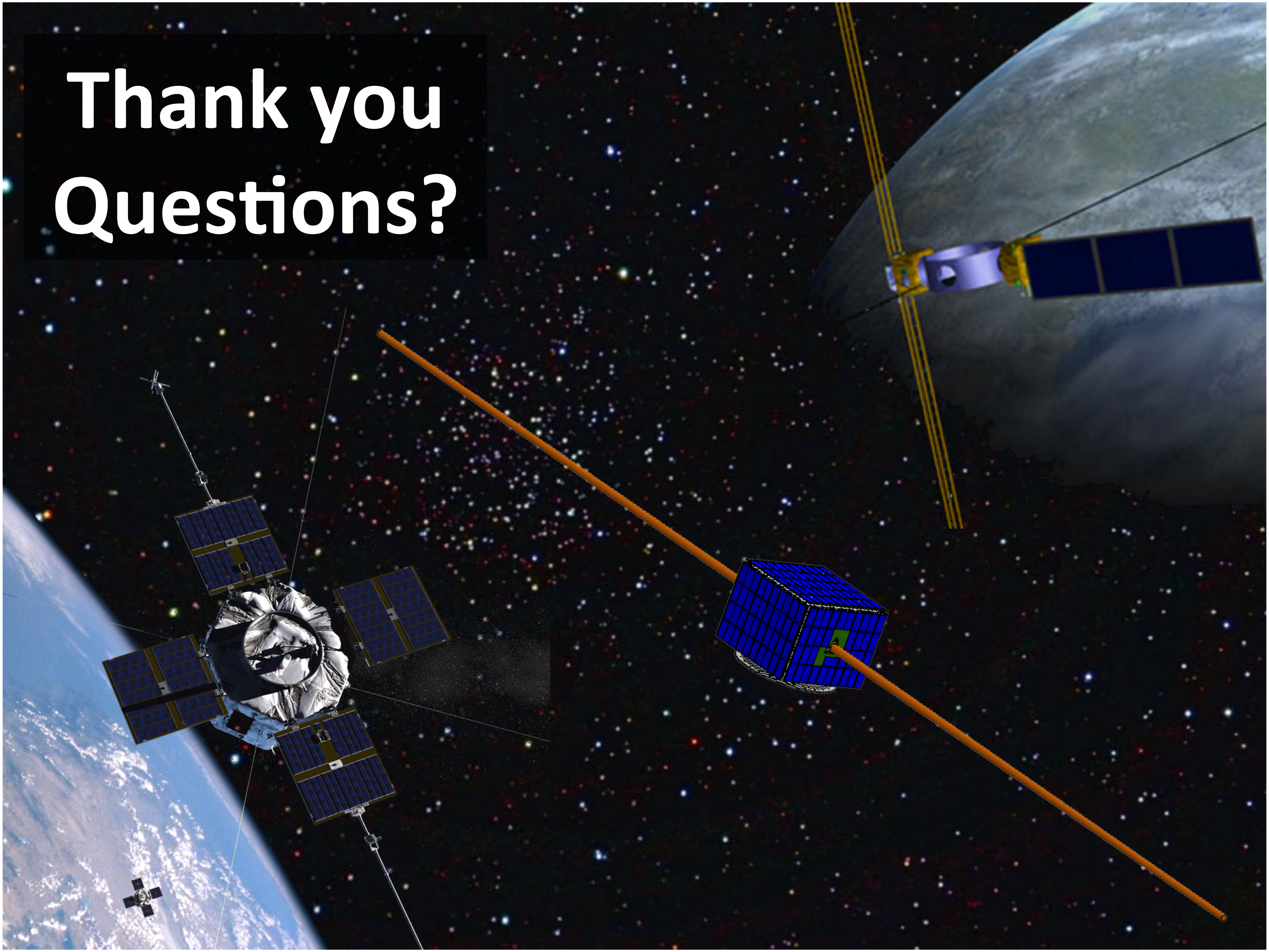

May 2012 — 12th Spacecraft Charging Technology Conference (SCTC). Kitakyushu, Japan.

June 2012 — Geospace Environment Meeting (GEM). Snowmass, CO.

# Outline

# 7. Minor – Engineering Project Leadership

- Minor Advisor: Prof. Eppinger: Management Science and Engineering Systems
- Taken classes:
  - 16.89/ESD.352J : Space Systems Engineering (Spring 2011)
  - 15.665: Power and Negotiation (Spring 2012, now)
- Next year:
  - ESD.36: System Project Management (Fall 2012)


Thank you
Questions?