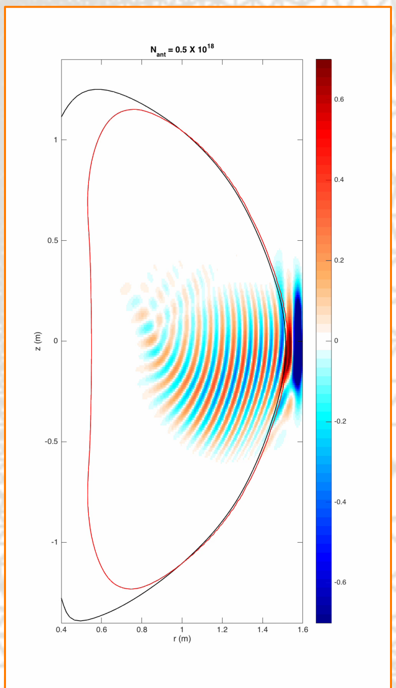
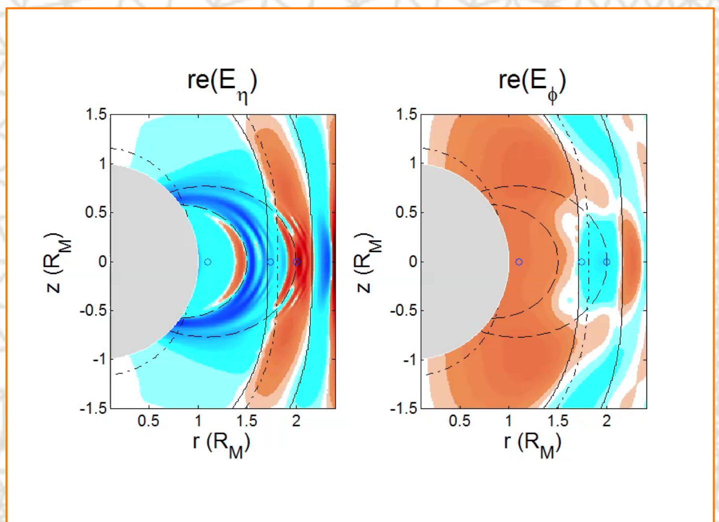
FULL-WAVE SIMULATIONS OF PLASMA WAVE IN SPACE AND TOKAMAK

Eun-Hwa Kim

Princeton Center for Heliophysics & Princeton Plasma Physics Laboratory

Princeton University





in collaboration with

J. Johnson

E. Valeo

N. Bertelli

J. Hosea

S. Keller

PRINCETON PLASMA PHYSICS LABORATORY

Motivation: Existing wave models in space cannot fully describe waves in multi-ion space plasmas

Ray tracing

e.g., Rauch and Raux, 1982

can show wave propagation path in cold and hot plasma

can not describe wave tunneling and mode conversion effects

Full-wave model

Hybrid

e.g., Omidi et al., 2011, 2013; Denton et al., 2014

can examine wave generation by temperature instability

expensive and cumbersome to run

Multi-fluid waves in slab coordinate

Kim and Lee, 2003,

1D Full waves

Johnson & Cheng 1999

can describe mode coupling and wave tunneling in multi-ion plasmas

does not include magnetic curvature effect

2D Full-wave model (FW2D) has been developed

- Wave equations : frequency domain

$$\nabla \times (\nabla \times \vec{E}) - \left(\frac{\omega}{c}\right)^2 \epsilon \cdot \vec{E} = 4\pi \frac{i\omega}{c^2} \vec{j}_{ext}$$

output ($\vec{E}$)

ϵ: dielectric tensor in *cold* plasma

$\vec{j}_{ext}$: External source i.e., antenna

$$\vec{E}(r, z) = (E_\eta, E_\mu, E_b) \exp(im\phi)$$

(E_η, E_μ): $\perp$; E_b: $\parallel \vec{B}_0$

m: Azimuthal (toroidal) wave number

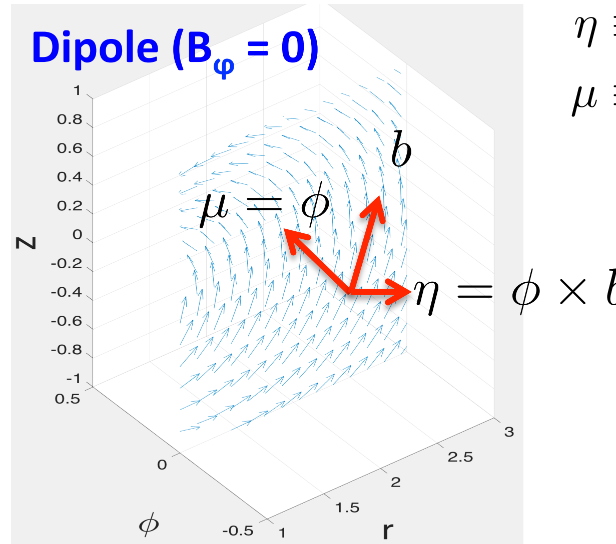
- Wave solution using **finite element method** and **unstructured triangle mesh**

✓ ***Fast***
✓ ***Easily adopted to various geometries & boundaries***
✓ ***Flexibility to extend to kinetic description***
✓ ***Easily adapted to 3D***

Kim et al. (2015) *Geophys. Res. Lett.*

2D Full-wave model (FW2D) has been developed

1. **Background Parameters**
   : $|B|$, b_r, b_z, b_ϕ, N_e, N_{ion}/N_e, ν (collision)
   - Space : Dipole,
     (or MAG2D [Cheng, 1995]…)
     Empirical density model
     (i.e., GCPM, IRI …) ....
   - Tokamak : from experiment data



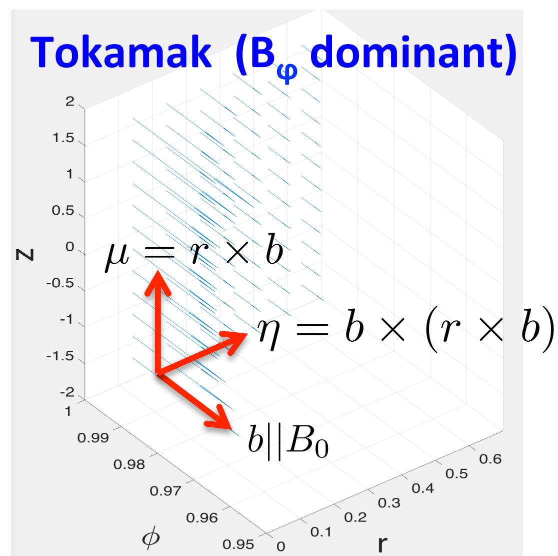
$\eta \equiv \phi \times b$

$\mu \equiv \phi$

2. **Mesh Generation** : Distmesh [Persson and Strang, 2004]
   - Based on dispersion relation of target frequency

3. **Source**
   - Frequency, amplitude, location, and polarization

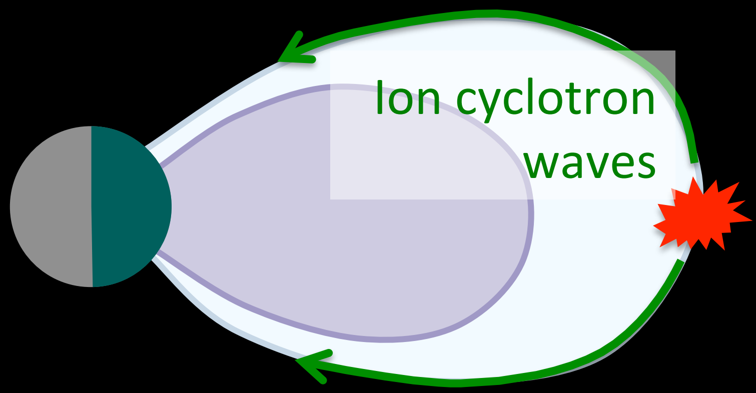
4. **Output**



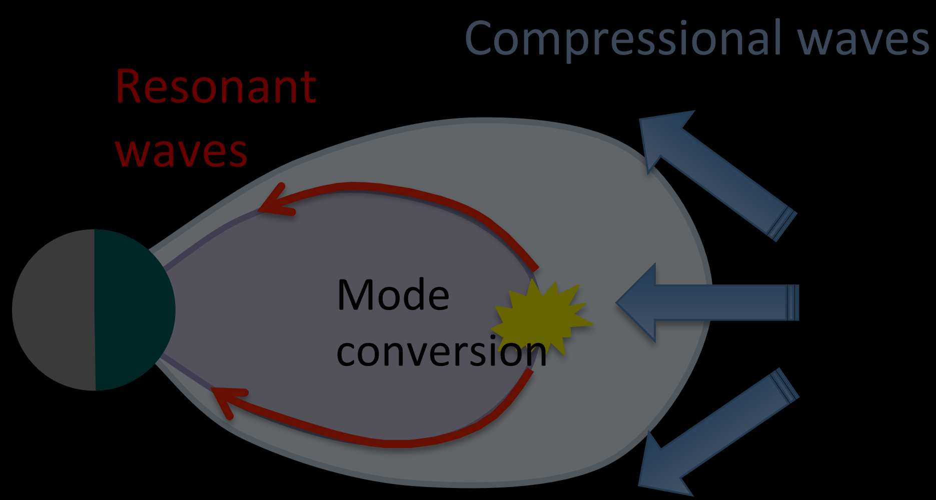
$\eta \equiv b \times (r \times b)$

$\mu \equiv r \times b$

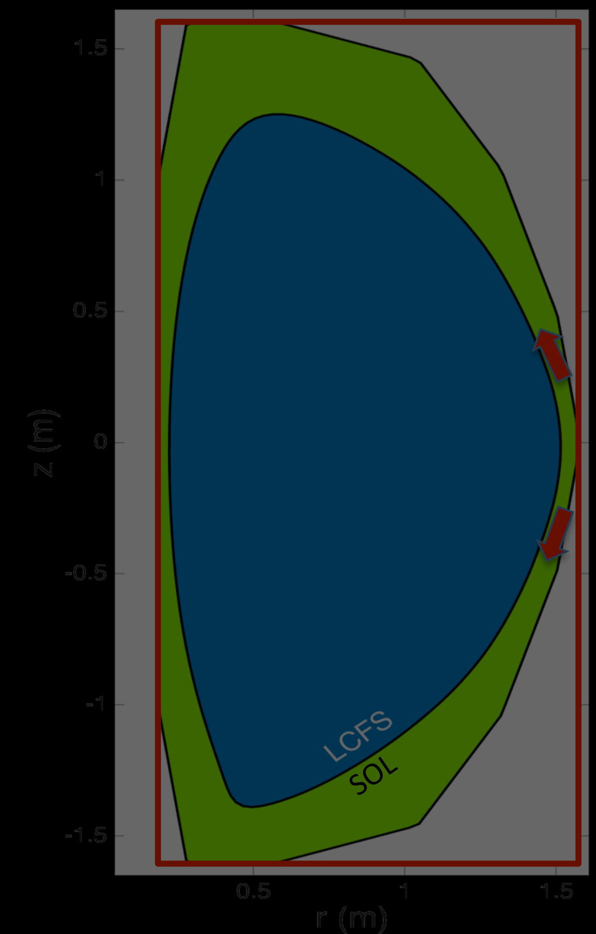
Internally generated waves in space



Externally driven waves in space

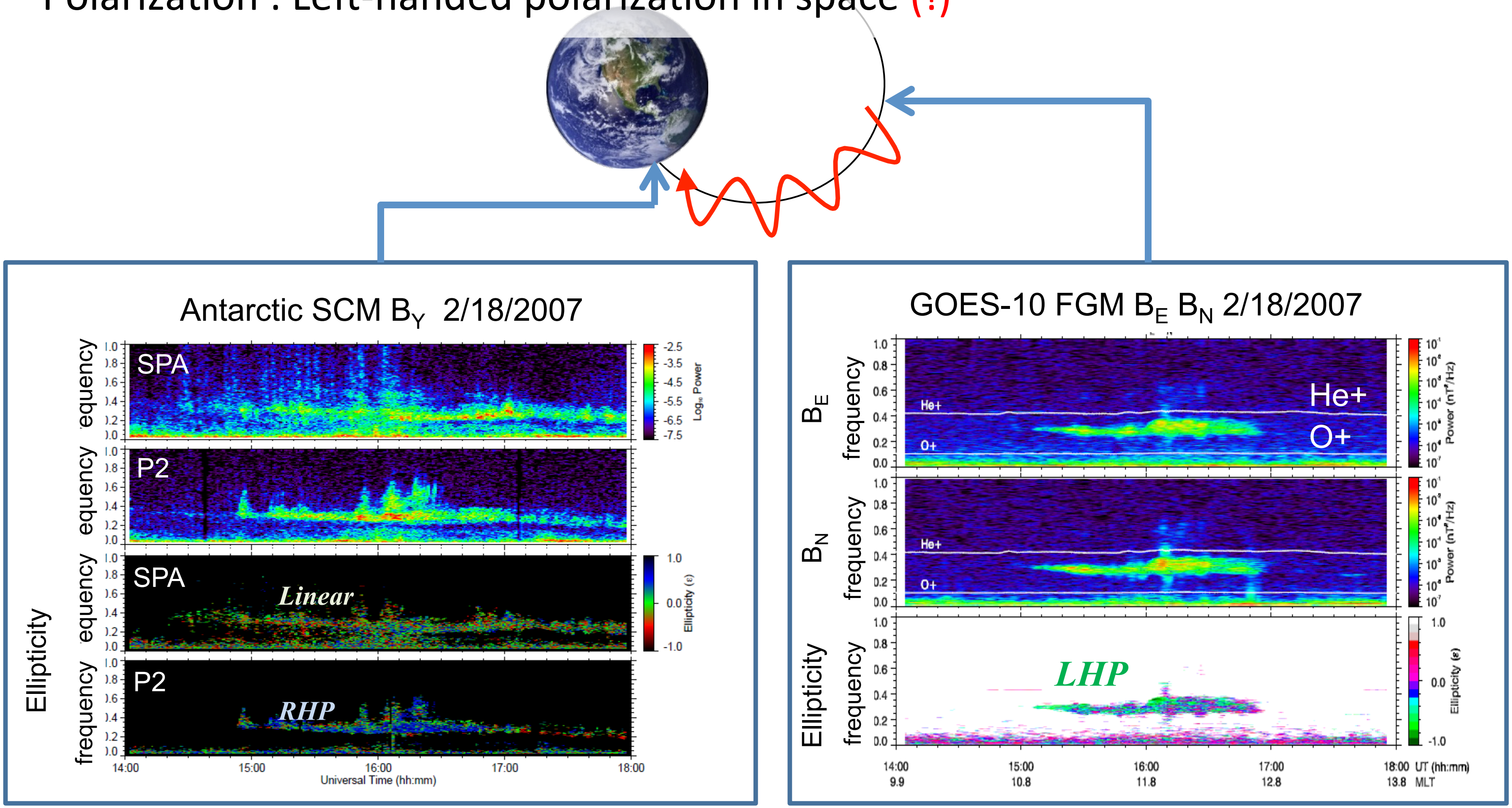


Fast waves in the SOL



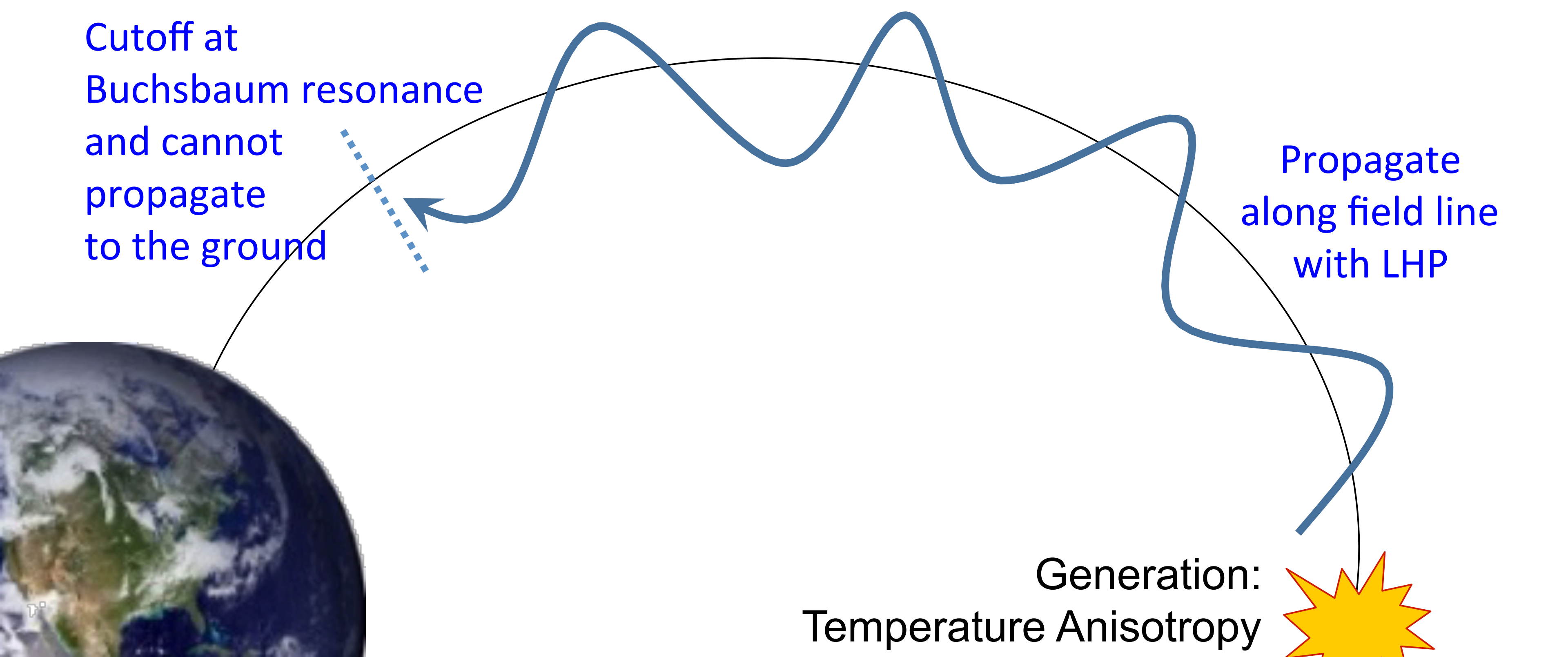
What are electromagnetic ion cyclotron waves?

- Frequency : 0.2 ~ 5 Hz (Pc 1-2) ~ ion cyclotron frequency
- Observation : both space & ground
- Generation : Temperature Anisotropy ($T_{\perp} > T_{||}$) near magnetic equator (!)
- Polarization : Left-handed polarization in space (!)



Existing theories predict LHP EMIC waves generated near equator

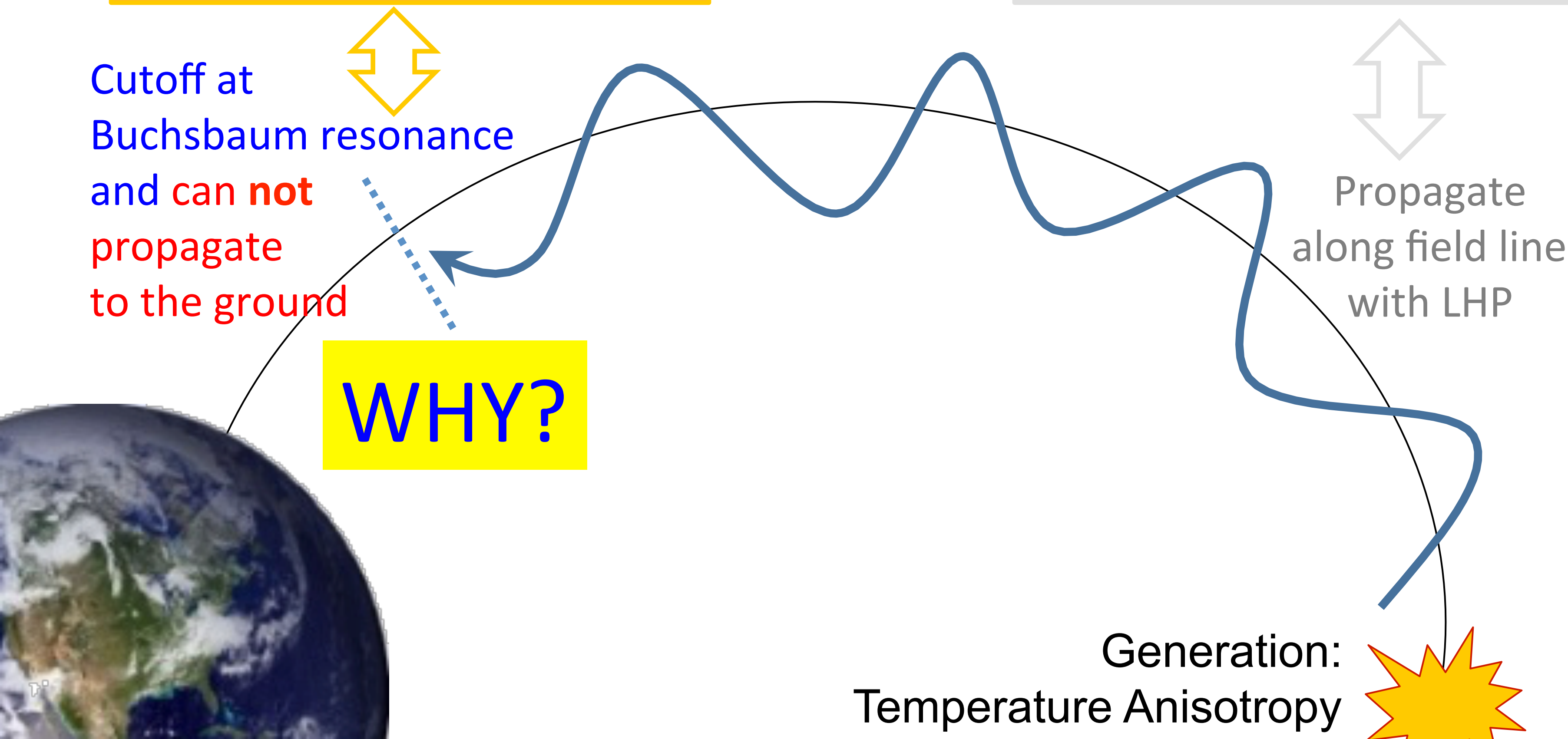
- The existing instability theories and ray tracing predicted that left-handed EMIC waves are generated near the magnetic equator, propagate along the field line, and reflect at the Buchsbaum resonance in the higher magnetic field region [e.g., *Rauch and Roux*, 1982; *Horne and Thorne*, 1994].



Existing theories predict LHP EMIC waves generated near equator

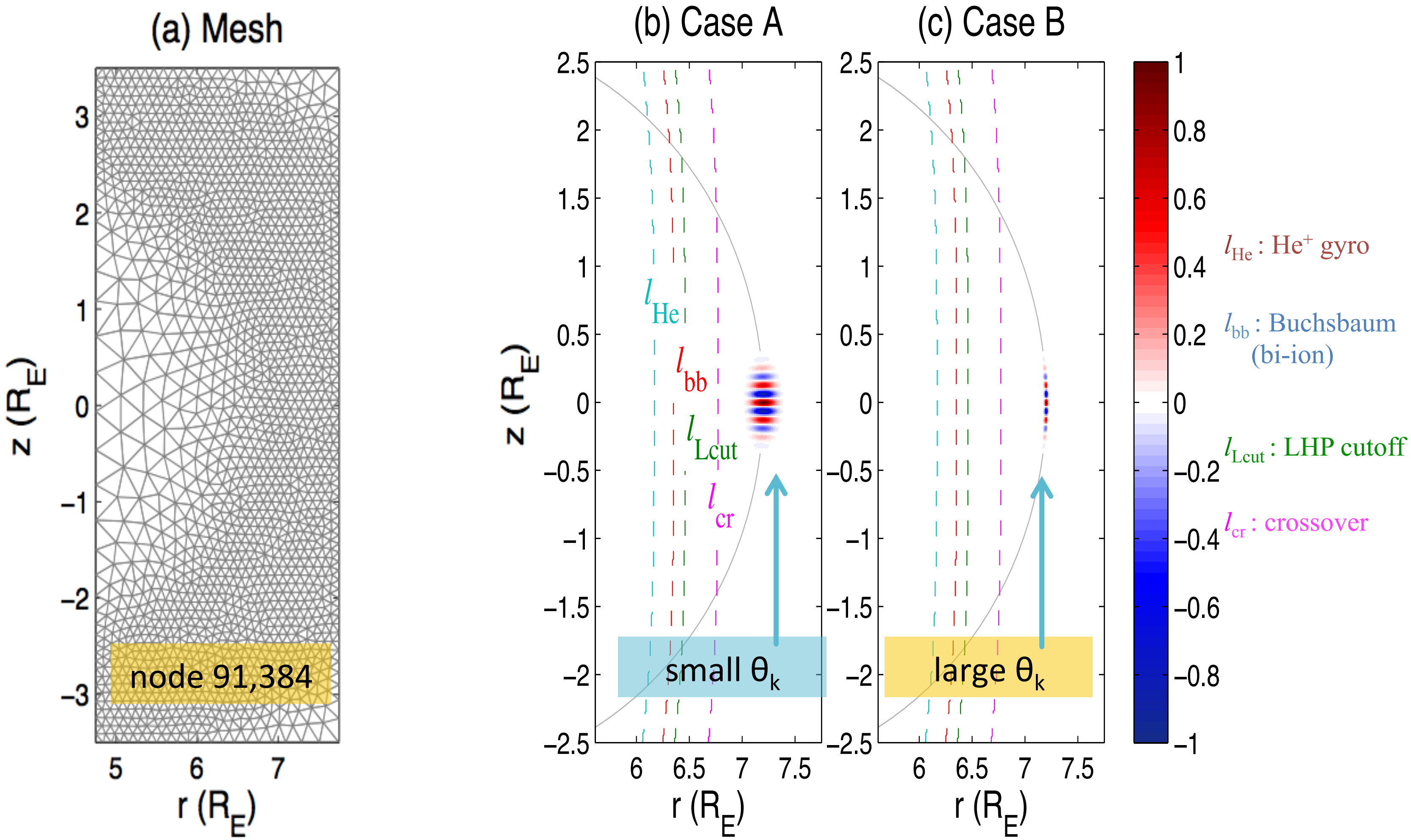
At least 50% of **EMIC waves can propagate** to the ground
[e.g., Anderson et al., 1996]

EMIC waves have **various polarizations**
[e.g., Fraser et al., 1982, Anderson et al., 1992, Min et al., 2012]



Full-wave simulation has been performed

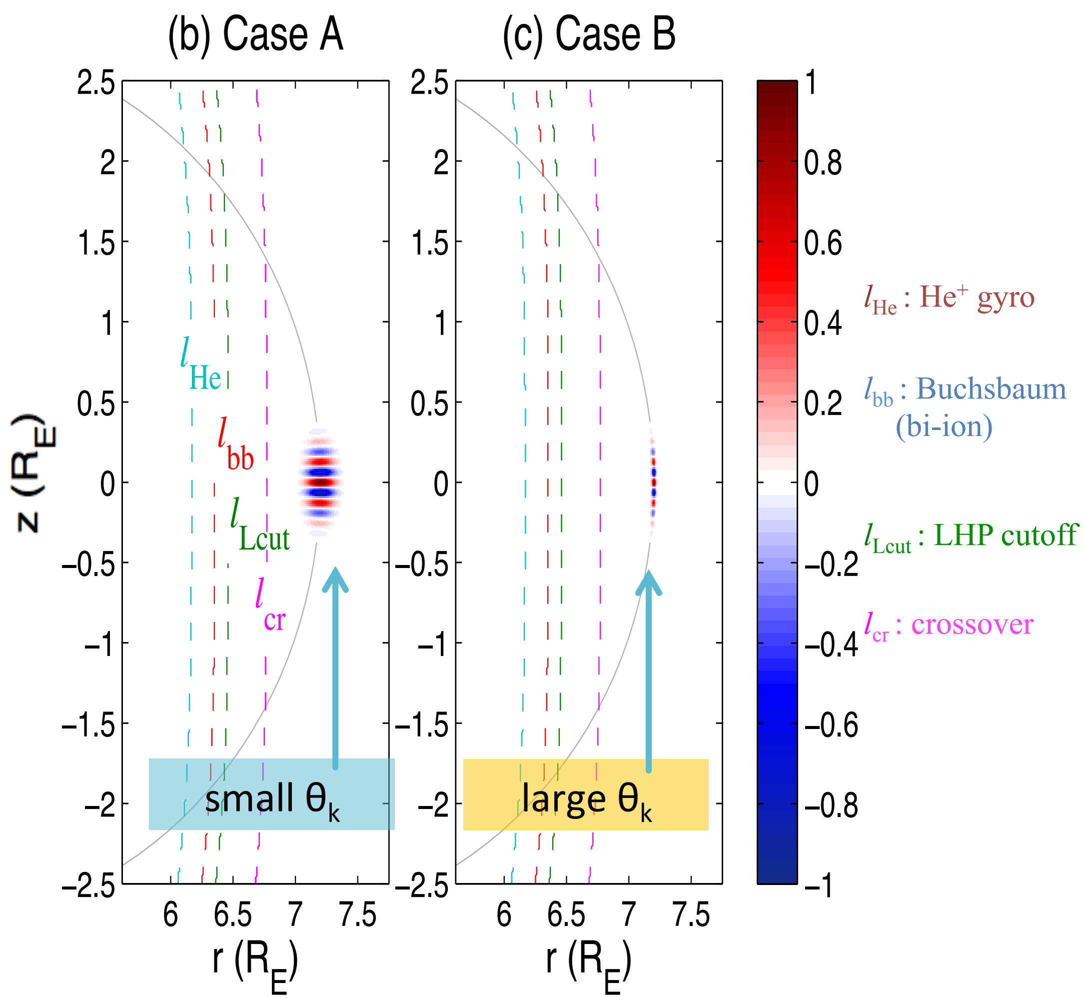
Fine mesh long the field line / **LHP waves launched near the equator**



Full-wave simulation has been performed

- Dipole magnetic field
- Empirical Density Model [Sheeley et al 2001; Denton et al 2006]
- 5% He+

- ω = 3.2Hz (between H+ and He+ gyrofrequencies)



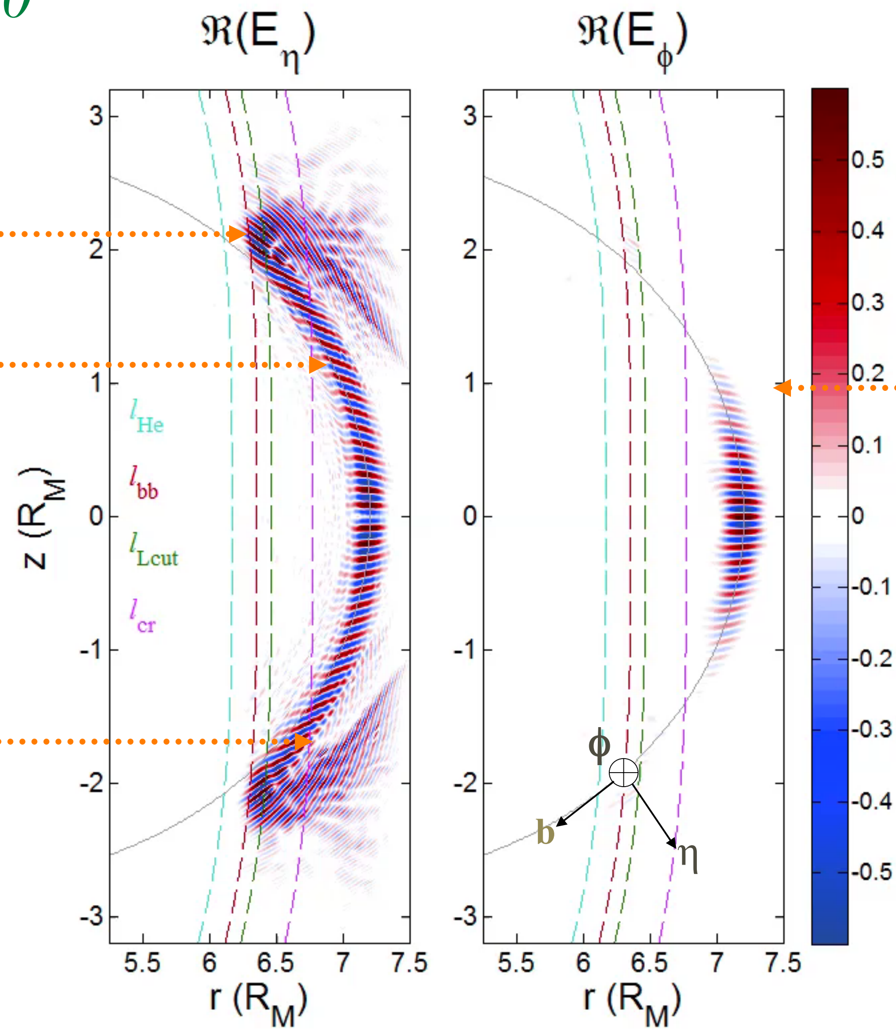
Wave normal angle is important on EMIC wave propagation

SMALL normal angle ~ 0

Reflect at Buchsbaum Resonance (bi-ion freq)

Propagate slightly to the outer L-shell

Linear polarization due to wave refraction / reflection



LHP wave launched

Kim and Johnson (2016) Geophys. Res. Lett.

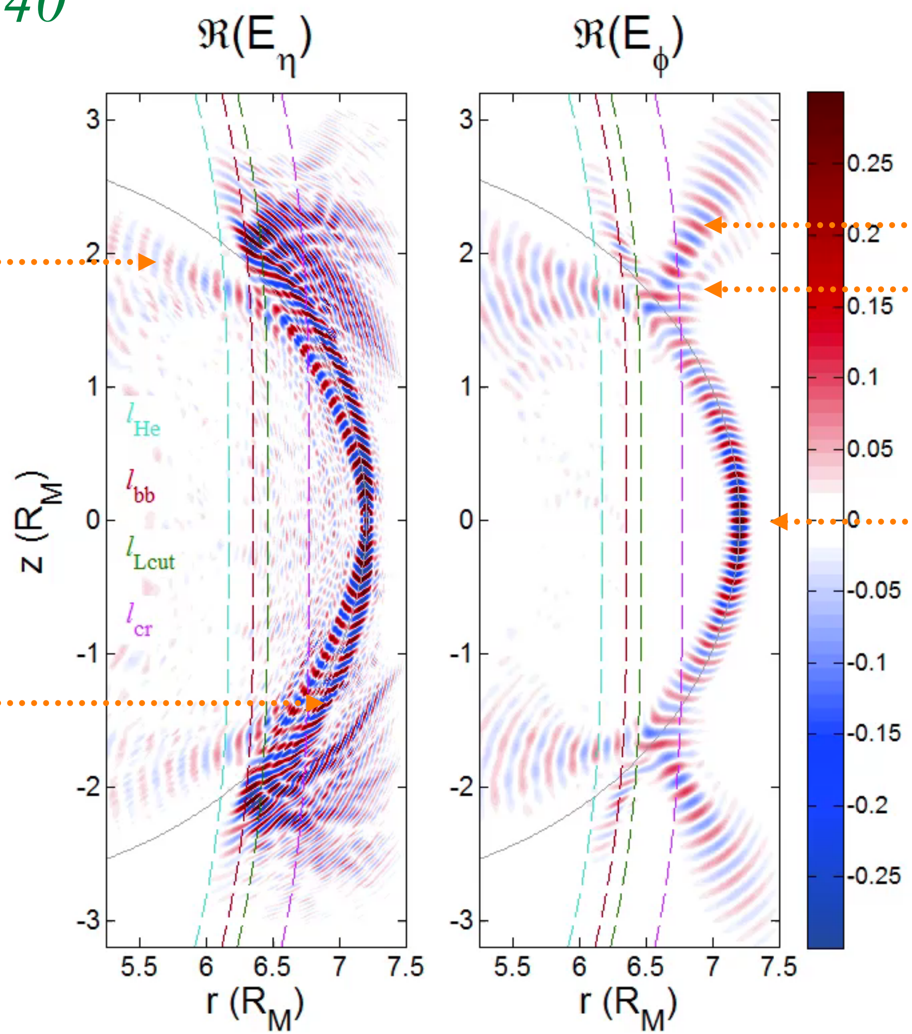
Wave normal angle is important on EMIC wave propagation

LARGE normal angle ~ 40

Unguided Class II (RHP)

Polarization reversal at the crossover

Outer ray
Similar to the case of "small" normal angle



Mode coupling at the crossover

Class I (RHP)

Class I (RHP)

LHP wave launched

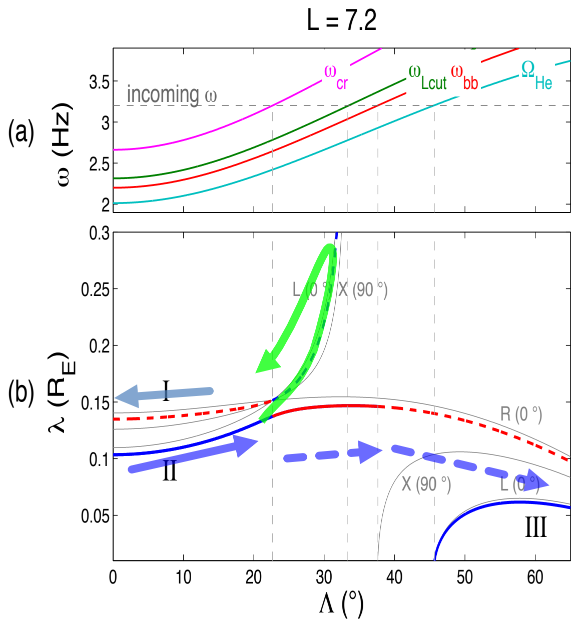
Wave normal angle is important on EMIC wave propagation

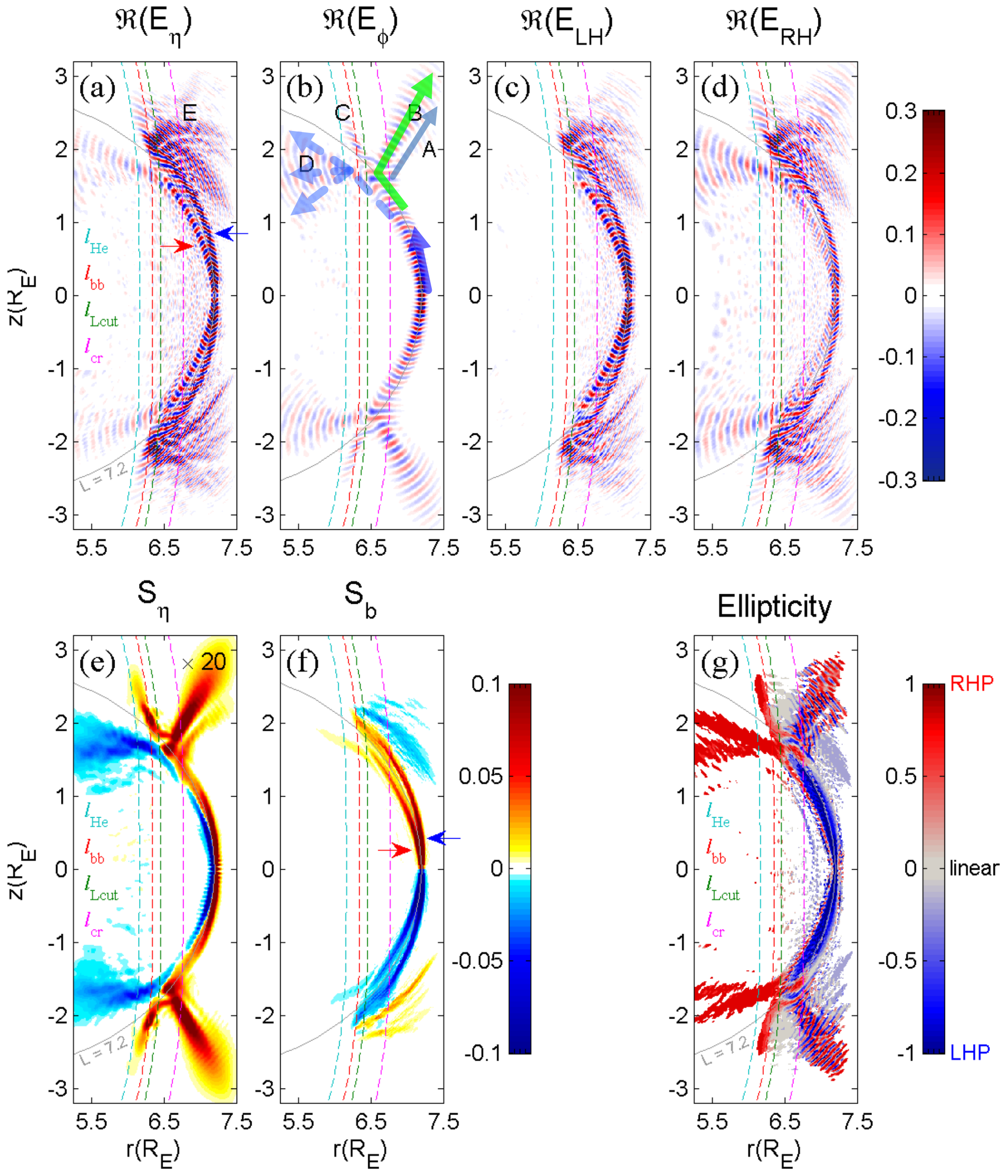
- Outer Ray

: Similar to the small normal angle

- Inner Ray

: Much more complex!





Full-wave calculation shows good agreement with previous theories

Ray tracing

Waves reflected at the Buchsbaum resonance and cannot reach the ground!

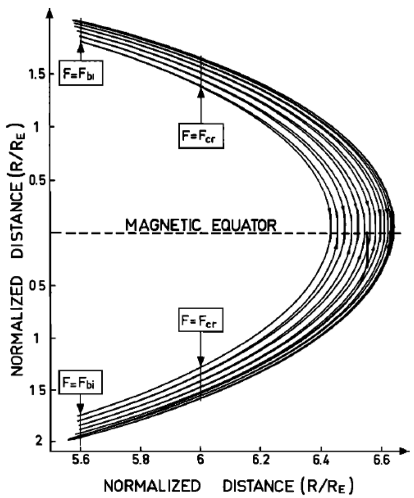
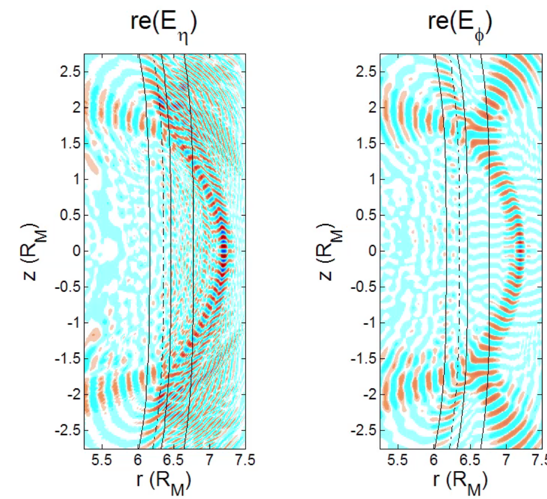


Fig. 8. Ray path of class III wave starting with $X = 0.55$ at the equator with $(\mathbf{k}, \mathbf{B}_0) = 0$ and $N_e = 40\ \mathrm{cm}^{-3}$. Note the different scales used for the horizontal and vertical axes. The wave is left handed for $F > F_{cr}$ in the equatorial vicinity; it becomes right handed away from the equator where $F < F_{cr}$.

Rauch and Raux, 1982

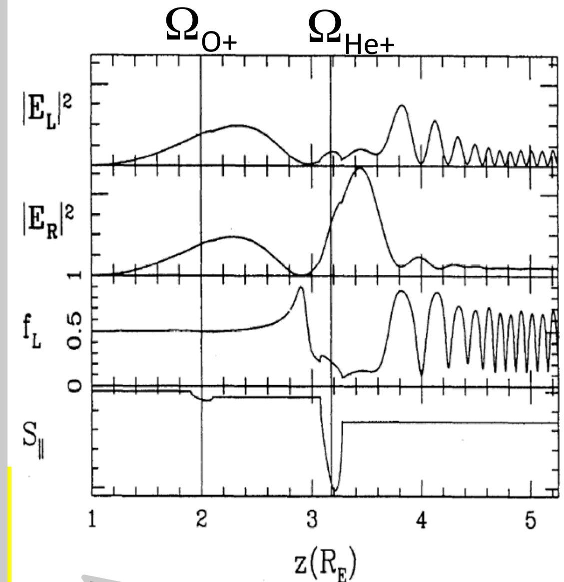


** Mode coupling occurs near the crossover frequency between several propagating mode*

** Waves propagate to the inner magnetosphere*

Consistent !

1D Full wave calculation



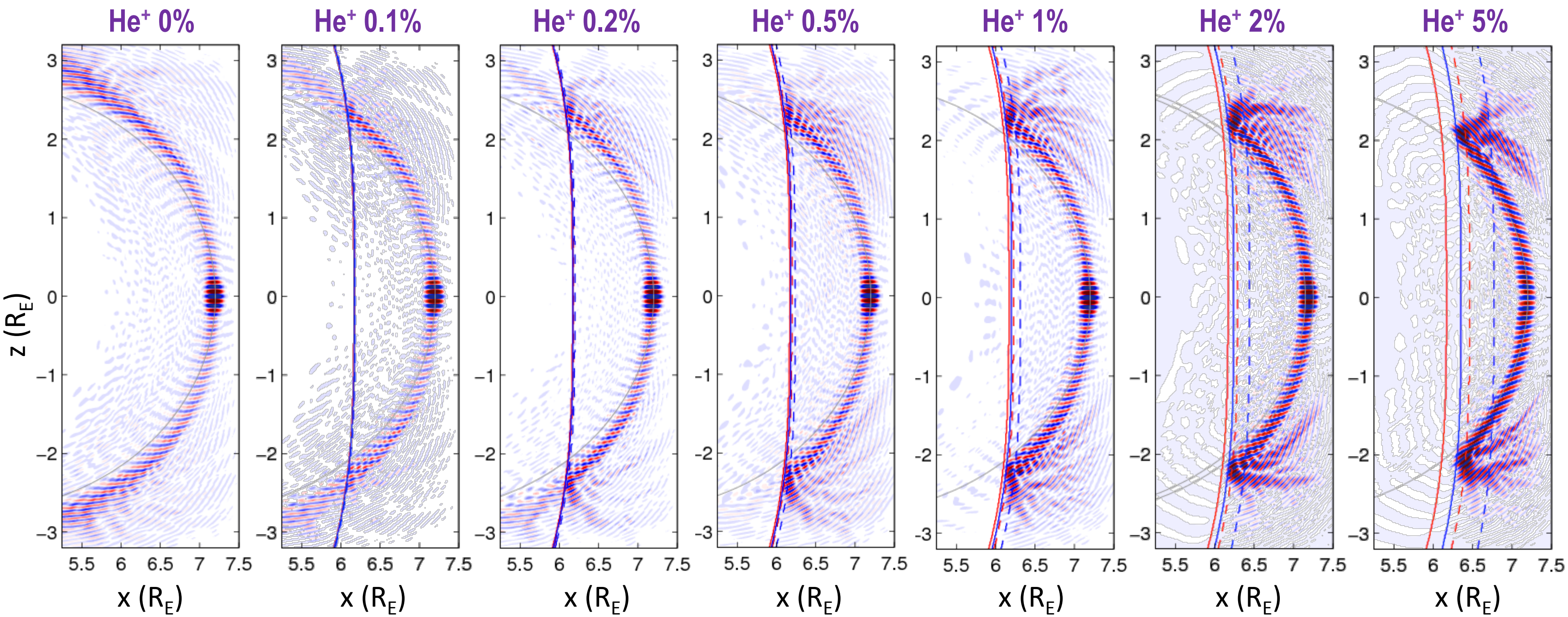
Johnson and Cheng, 1999

1D Full wave calculation

Substantial coupling occurs between the four propagating mode near the crossover frequency

Johnson et al., 1995

Wave tunneling cannot occur even for small amount of heavy ions



He (%)	0.2	0.4	0.7	1.0
Transmission Coefficient	0.53 ± 0.10	0.29 ± 0.09	0.11 ± 0.04	0.04 ± 0.01

Keller et al. (2016) Influence of Heavy Ions on Electromagnetic Ion Cyclotron Wave Propagation in the Earth's Magnetosphere, *in preparation*

Wave normal angle and ion densities are critical for EMIC wave propagation!

At least 50% of **EMIC waves can propagate** to the ground
[e.g., Anderson et al., 1996]

Cutoff at Buchsbaum resonance and can **not** propagate to the ground

WHY?

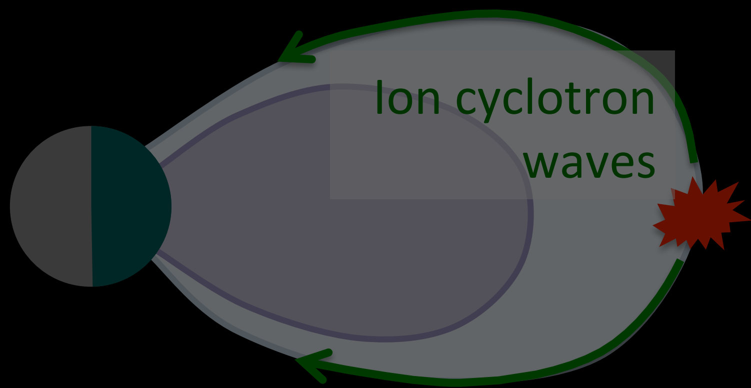
Wave normal angle
→Mode coupling, polarization reversal…

Heavy ion density ratio
→Wave tunneling…

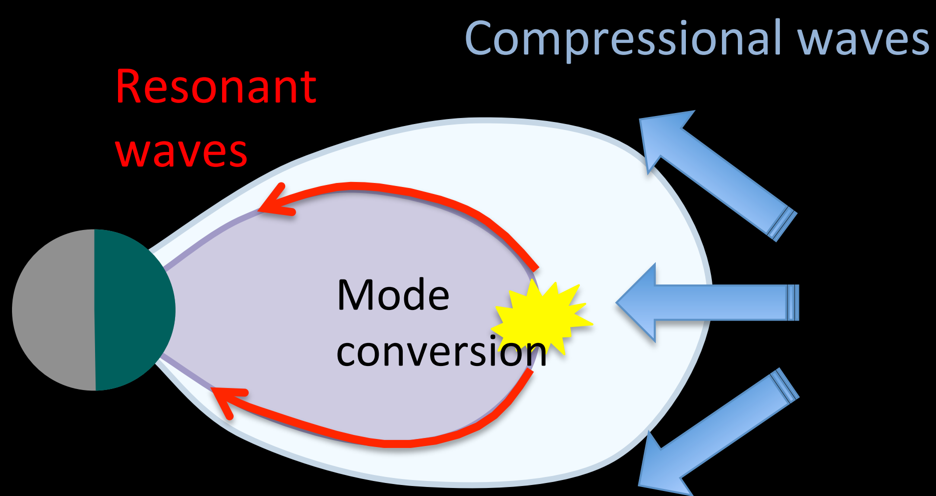
Further research is necessary !

Kim and Johnson, 2016, GRL
Keller et al., 2016 (in preparation)

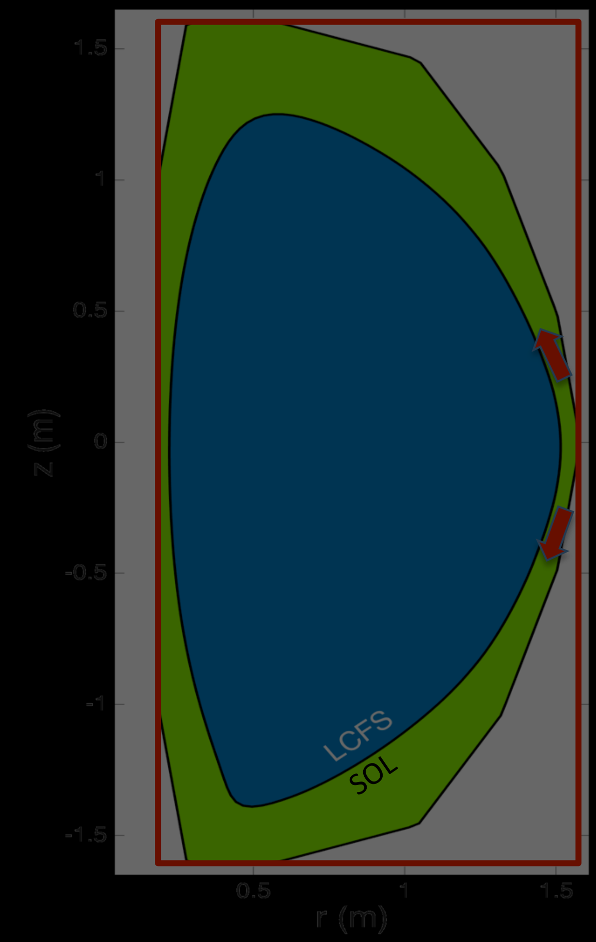
Internally generated waves in space



Externally driven waves in space



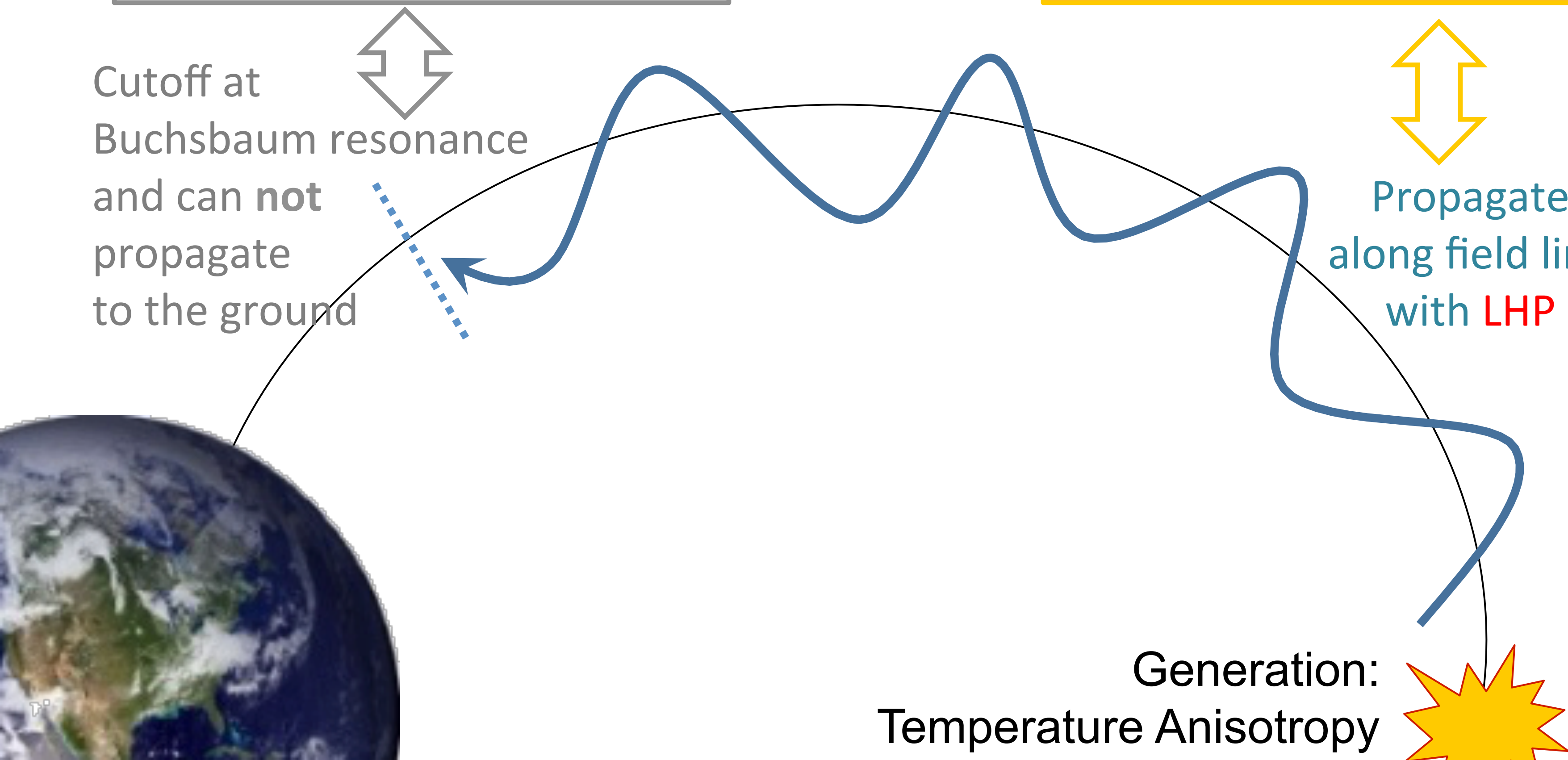
Fast waves in the SOL



Existing theories predict LHP EMIC waves generated near equator

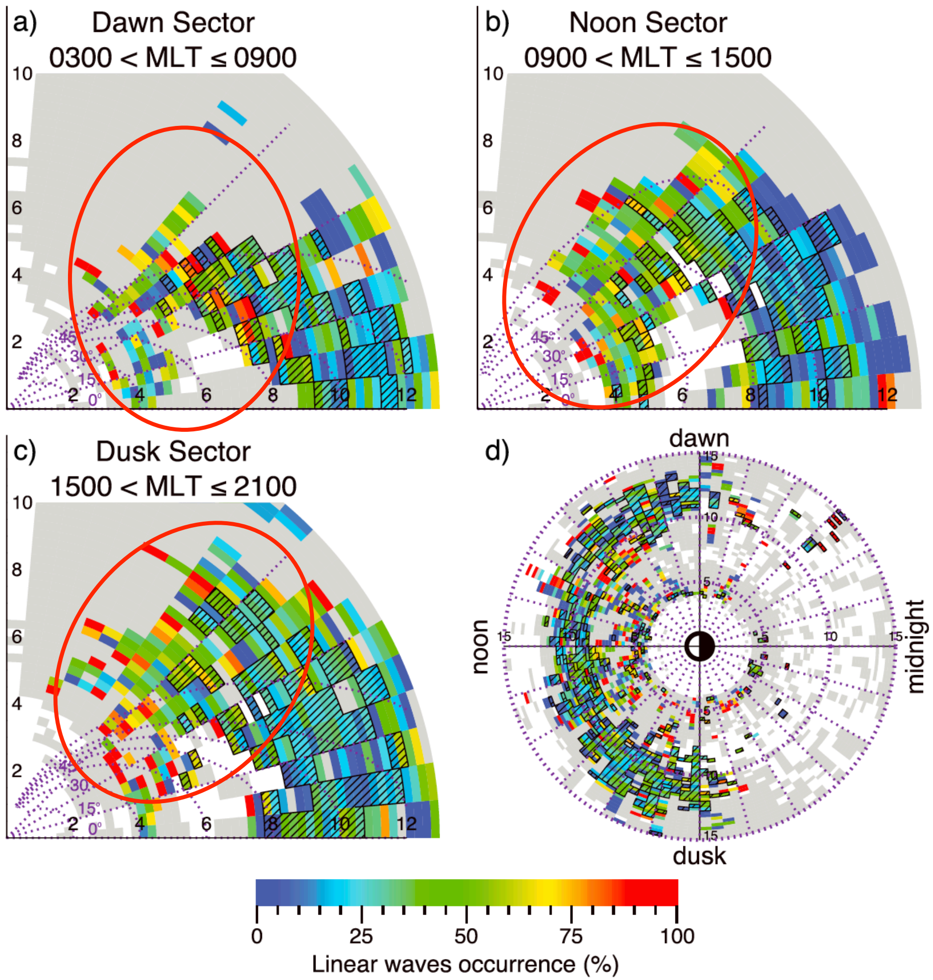
At least 50% of **EMIC waves can propagate** to the ground
[e.g., Anderson et al., 1996]

EMIC waves have **a wide range of polarization**
[e.g., Fraser et al., 1982, Anderson et al., 1992, Min et al., 2012]



Linearly polarized EMIC waves at Earth are dominant !

Allen et al. [2015]

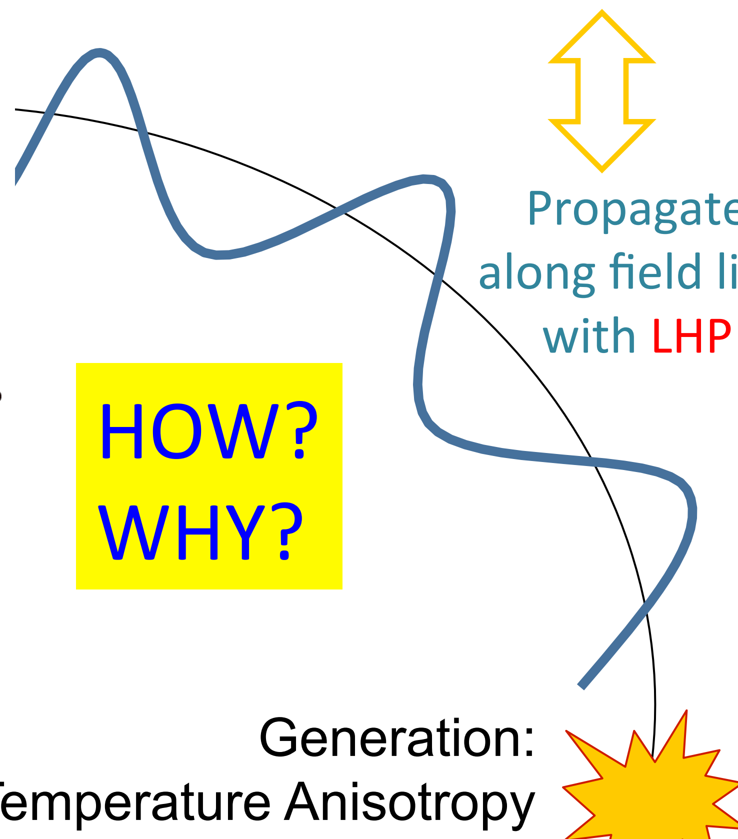


EMIC waves have **a wide range of polarization**

[e.g., Fraser et al., 1982, Anderson et al., 1992, Min et al., 2012]

Propagate along field line with LHP

HOW?
WHY?

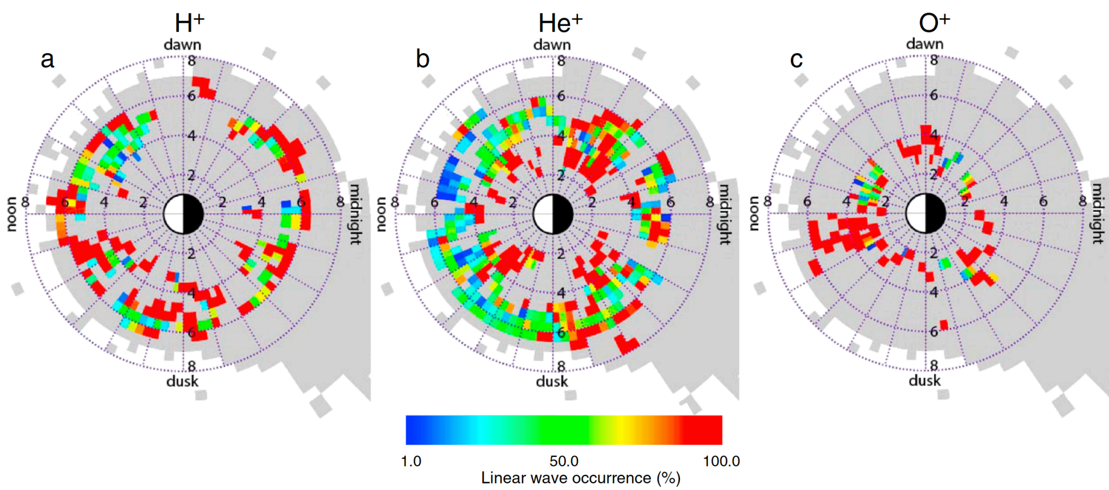


Generation:
Temperature Anisotropy

Linearly polarized EMIC waves at Earth is dominant !

Saikin et al. [2015]

Inner magnetosphere / near the equator (e.g., source)

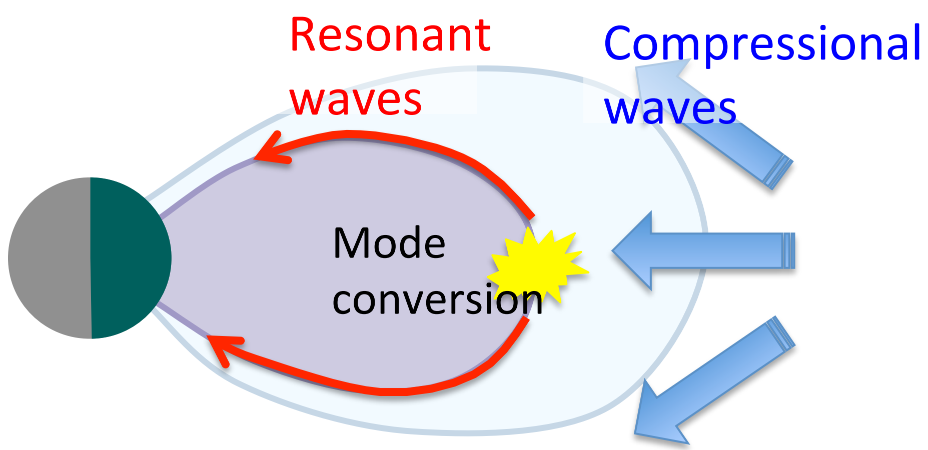


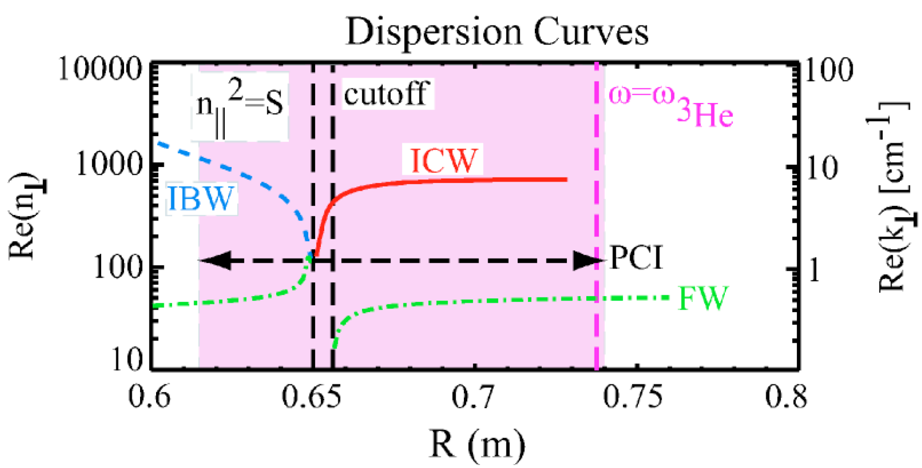
EMIC waves have **a wide range of polarization**

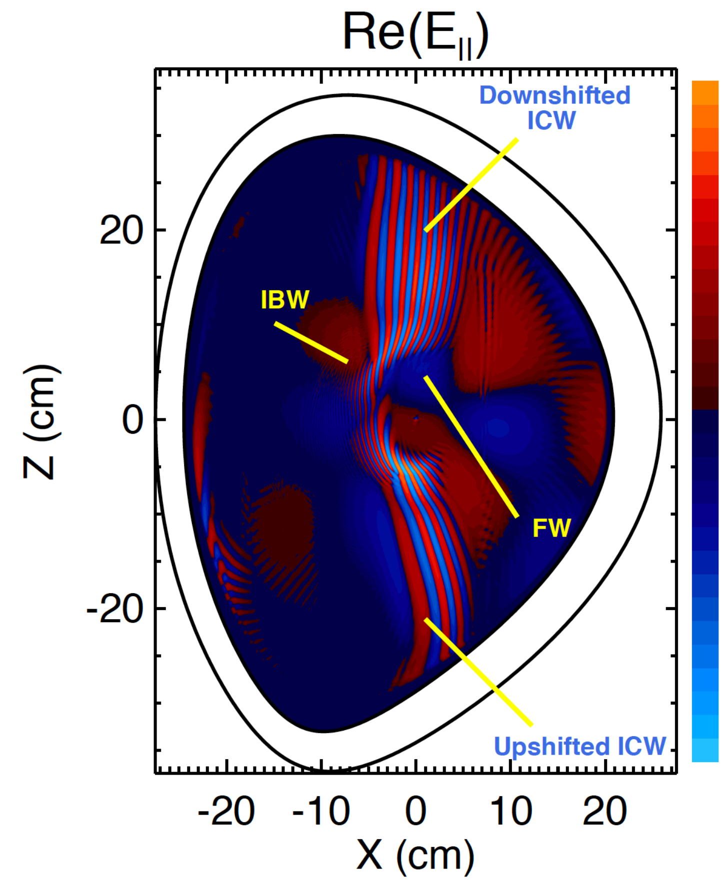
[e.g., Fraser et al., 1982, Anderson et al., 1992, Min et al., 2012]

Ion-ion hybrid resonance can explain linearly polarized waves near the ion cyclotron frequencies in space

Externally driven waves in space



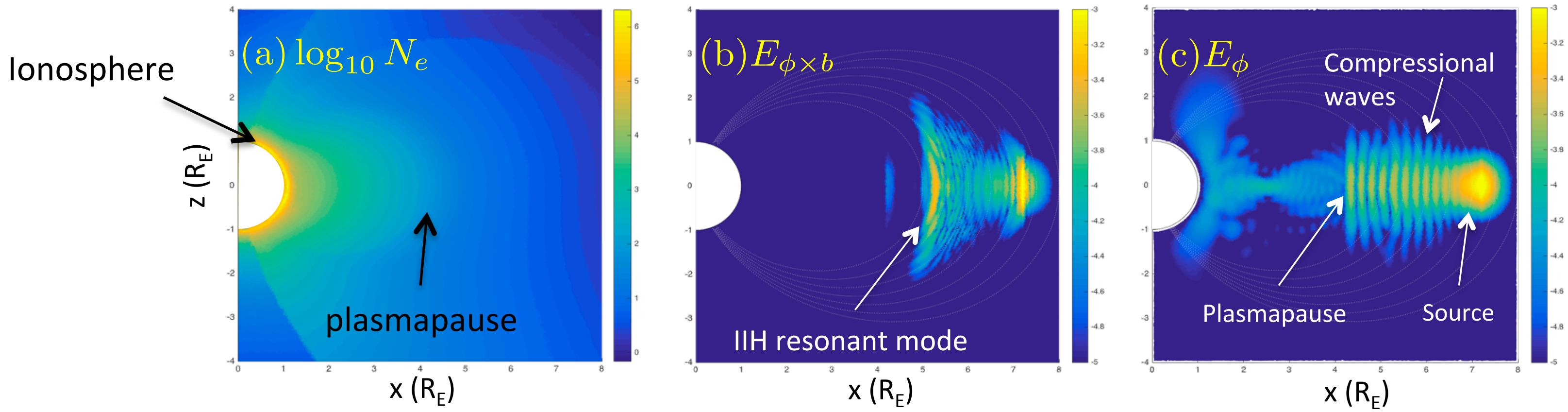




MC in the tokamak

Wukitch et al. [2005]

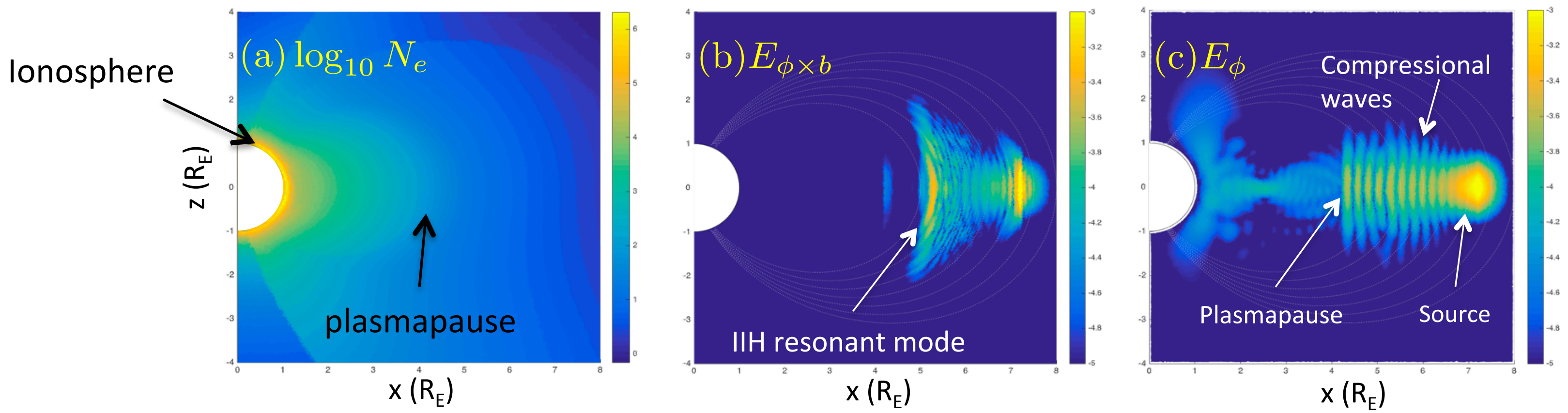
IIH resonance can occur at Earth

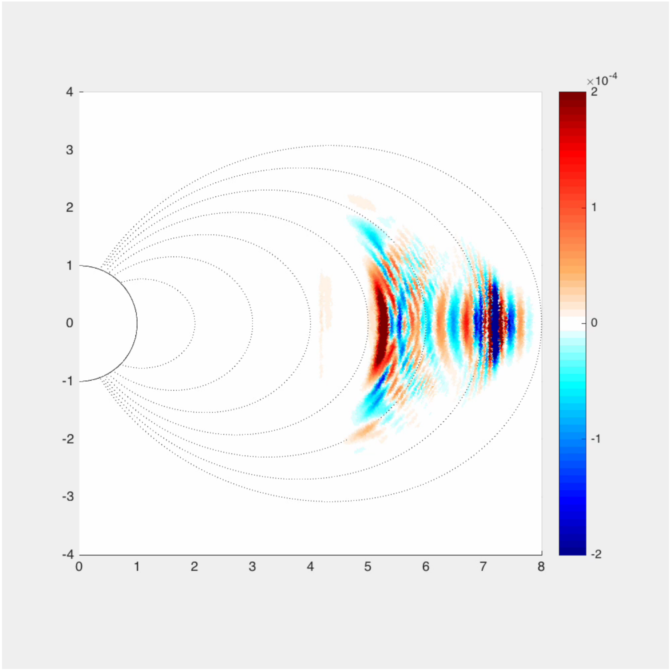


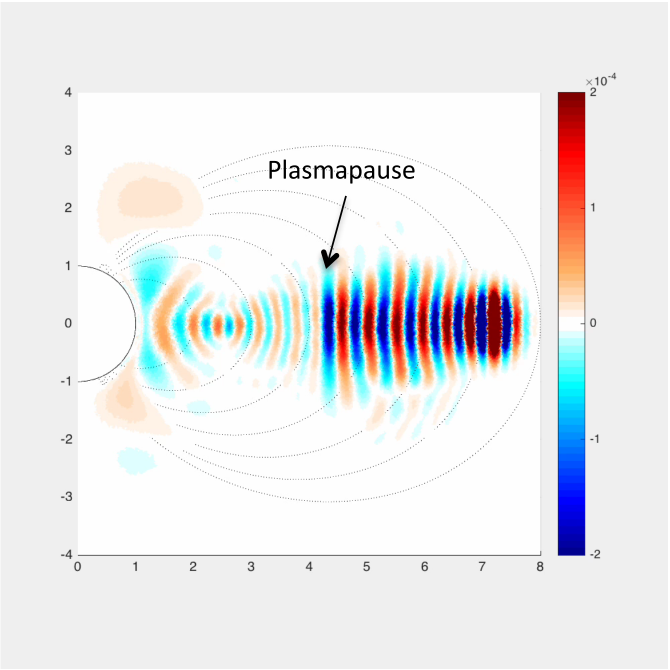
- Dipole magnetic field
- Empirical density model (GCPM)
    - 01/01/2000 UT00:00 MLT 12:00 (noon)
    - Quiet geomagnetic condition (Kp=1)
- Node: 79,722
- Source : L ~ 7 R_E

Kim et al. (2016b) Generation of linearly polarized EMIC waves at Earth: Full-wave simulation, *in preparation*

IIH resonance can occur at Earth

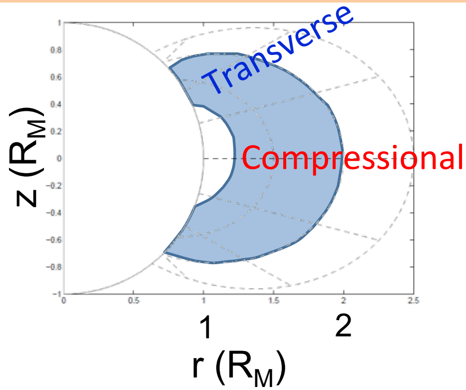




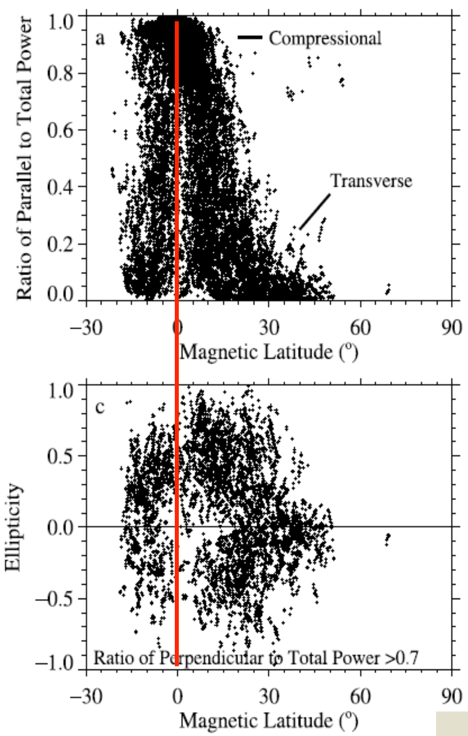


Kim et al. (2016b) Generation of linearly polarized EMIC waves at Earth: Full-wave simulation, *in preparation*

IIH resonant waves globally oscillate at Mercury

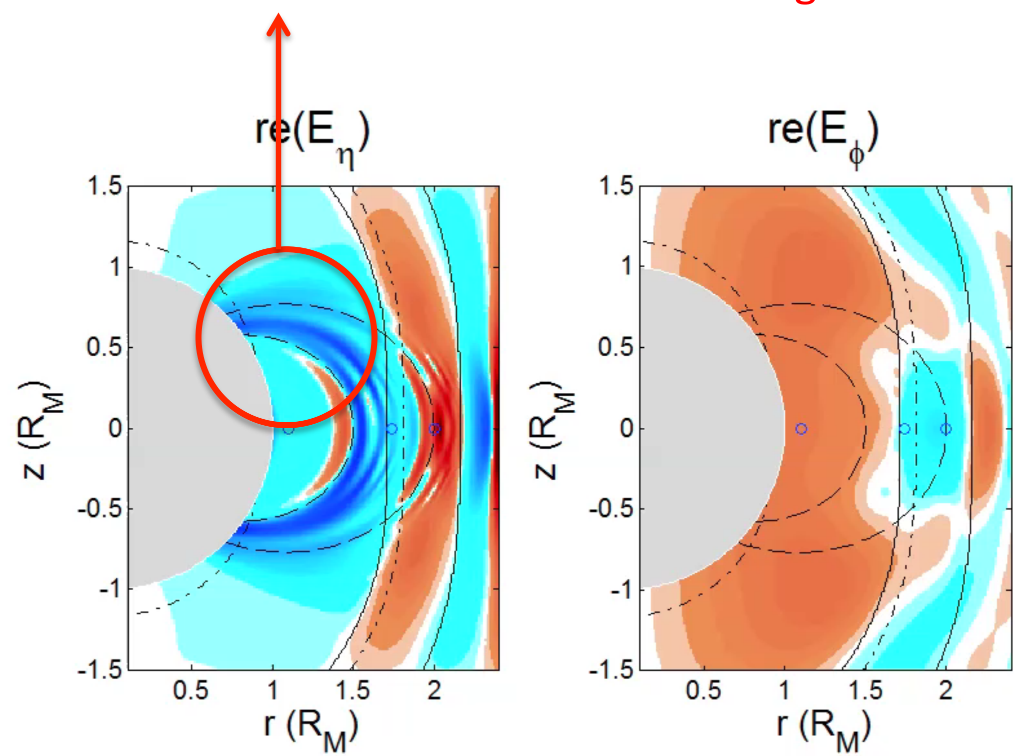


$B_{Compressional}$ is dominant near the equator
$B_{transverse}$ is dominant around high latitude – linear!



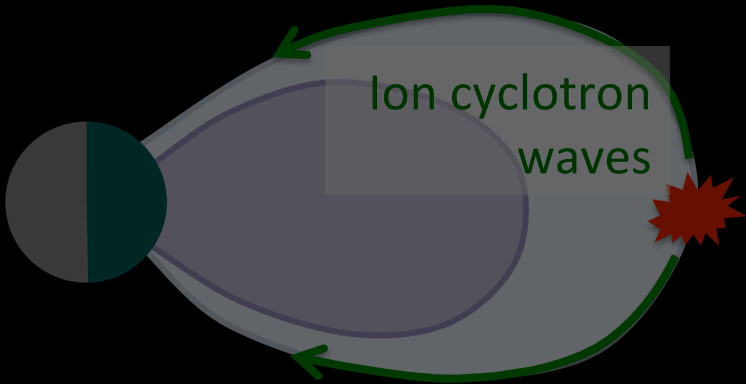
[Boardsen et. al, 2012]

Linear & transverse waves at high latitudes

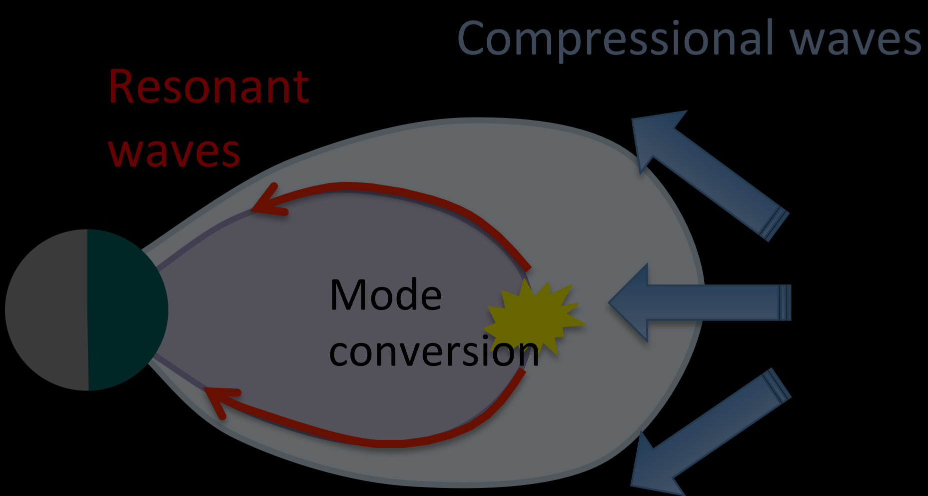


Kim et al. (2015) *Geophys. Res. Lett.*
Kim et al. (2016c) ULF waves at Mercury, in *Low-Frequency Waves in Space Plasmas*, AGU Monograph

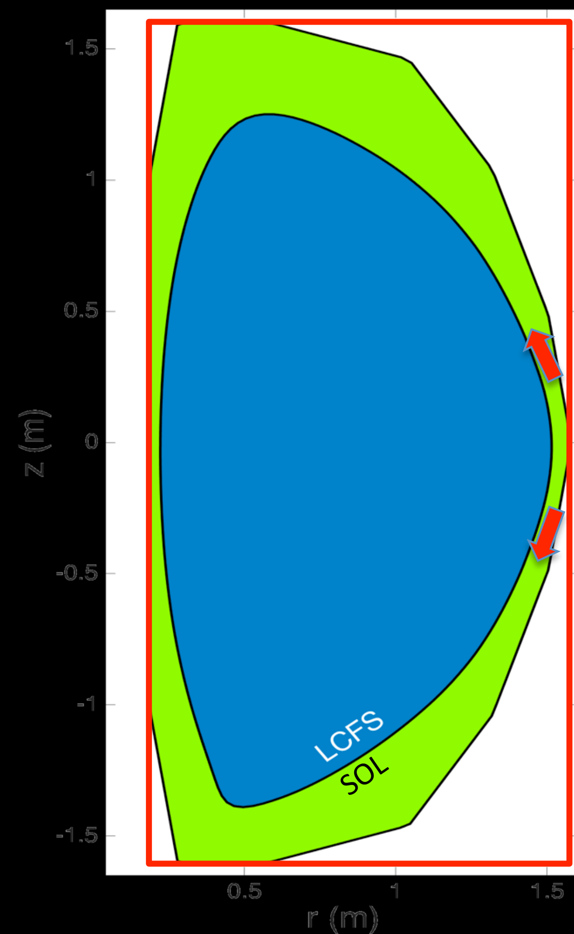
Internally generated waves in space



Externally driven waves in space

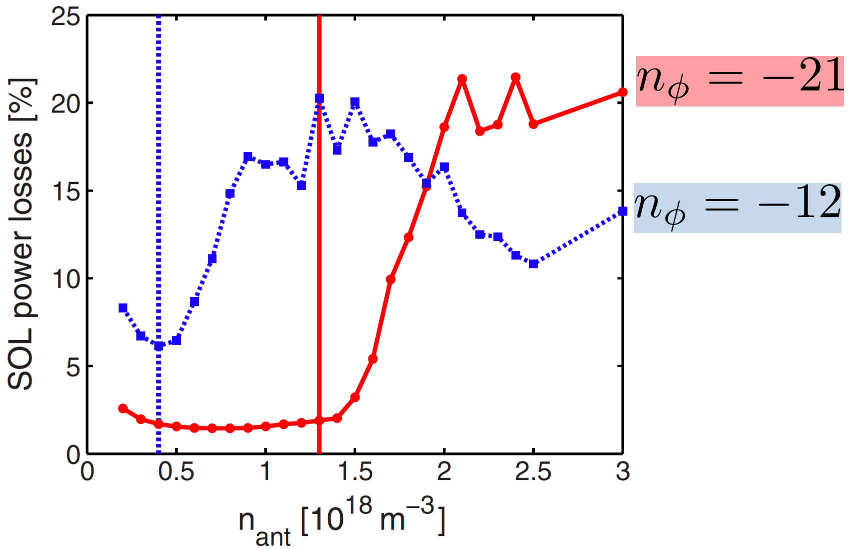


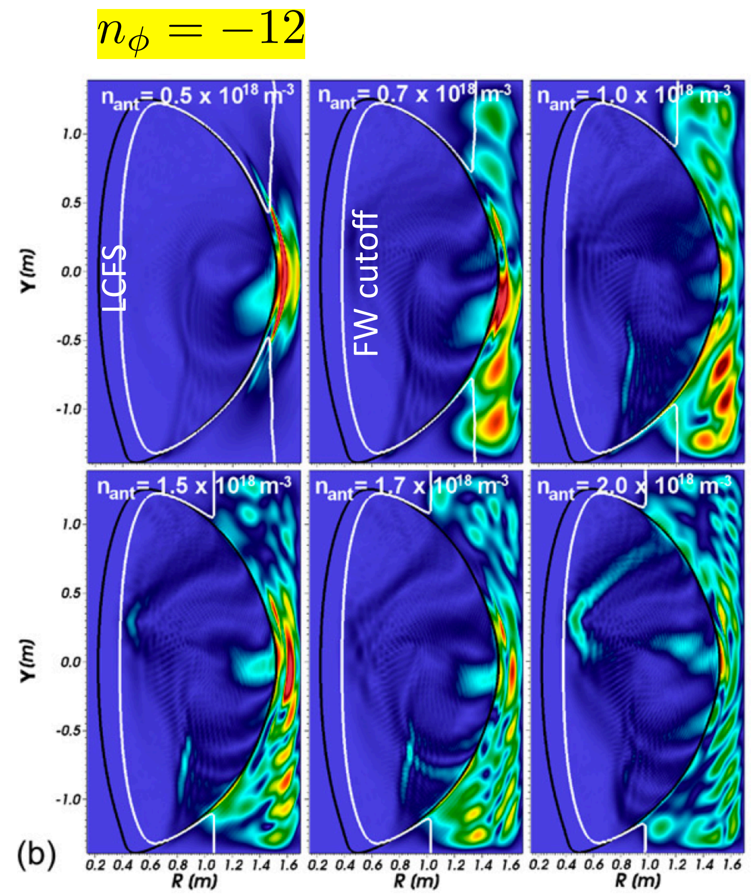
Fast waves in the SOL



Significant wave power loss can occur in the scrape-off region

- The scrape-off layer (SOL) region is important for RF wave heating of tokamaks because significant wave power loss can occur in this region. For instance, up to 60% of the coupled higher harmonic fast wave power can be lost in the SOL of NSTX [e.g., *Ono et al.*, 2000, *Hosea et al.*, 2008, *Phillips et al.*, 2009, *Perkins et al.*, 2012, 2013].



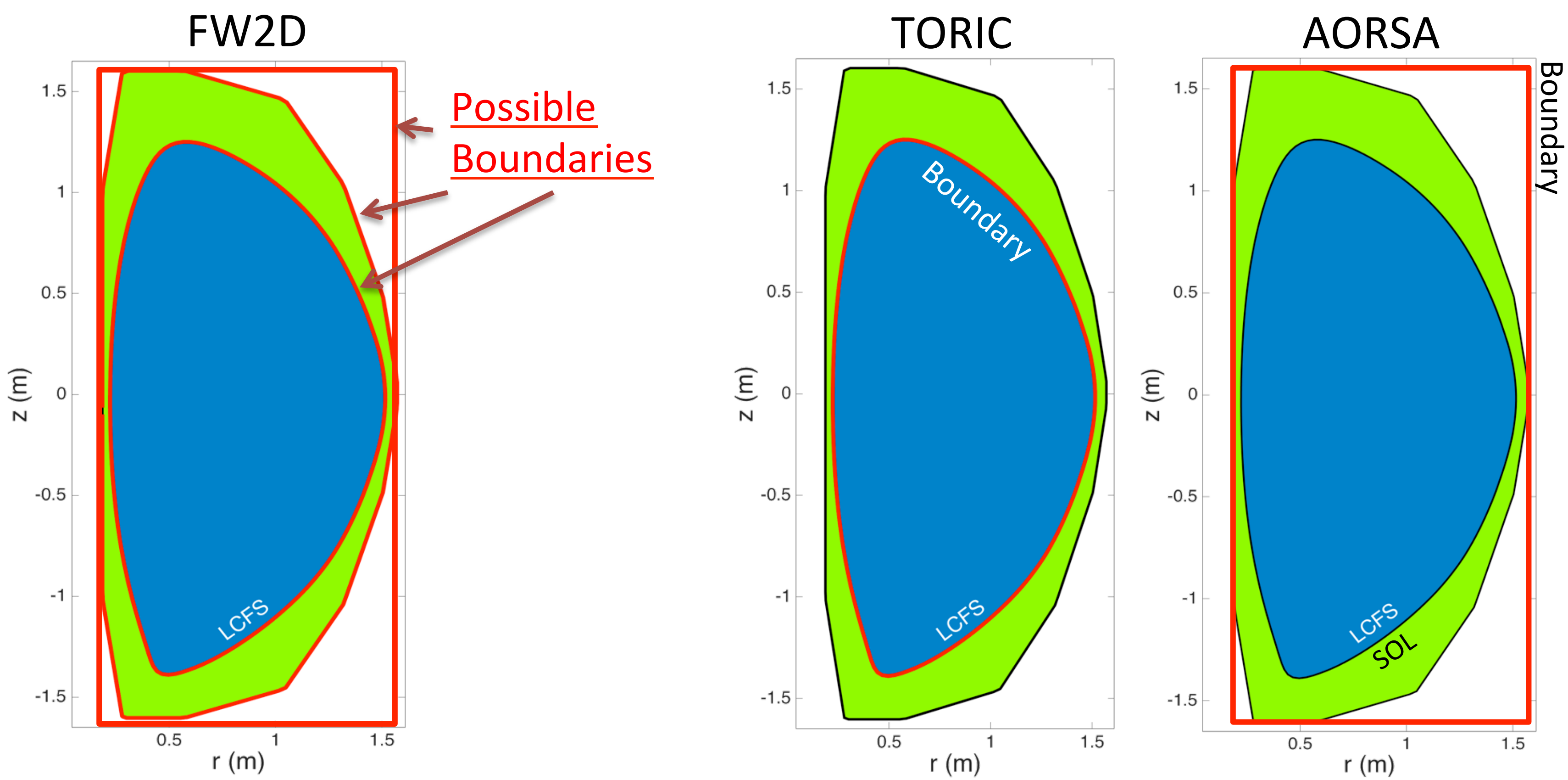


N_{ant} : Electron density in front of the antenna

Bertelli et al. [2014]

FW2D has been adopted to examine FW waves in the SOL of tokamak

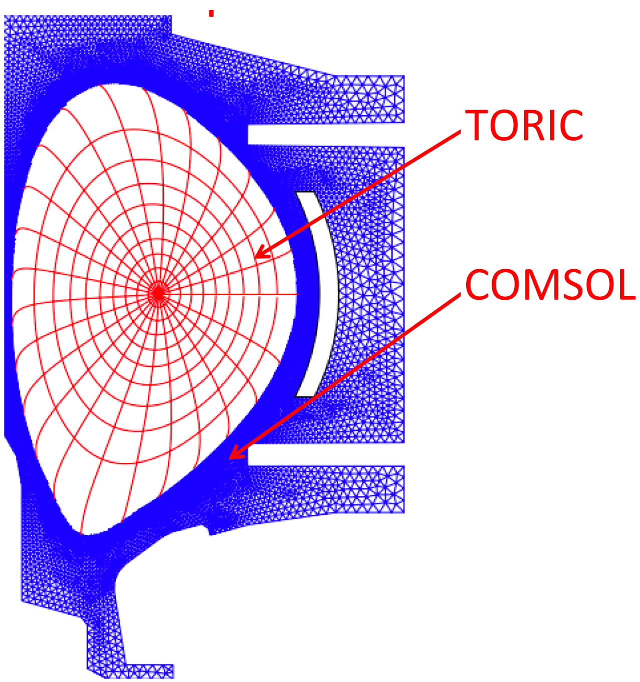
- The 2D full-wave code is also ideal to examine waves in the SOL plasma.
- The SOL plasma can be approximated as cold plasma.
- Realistic boundary shapes and arbitrary density structures can be easily adopted in the code.
- and it's *fast*!

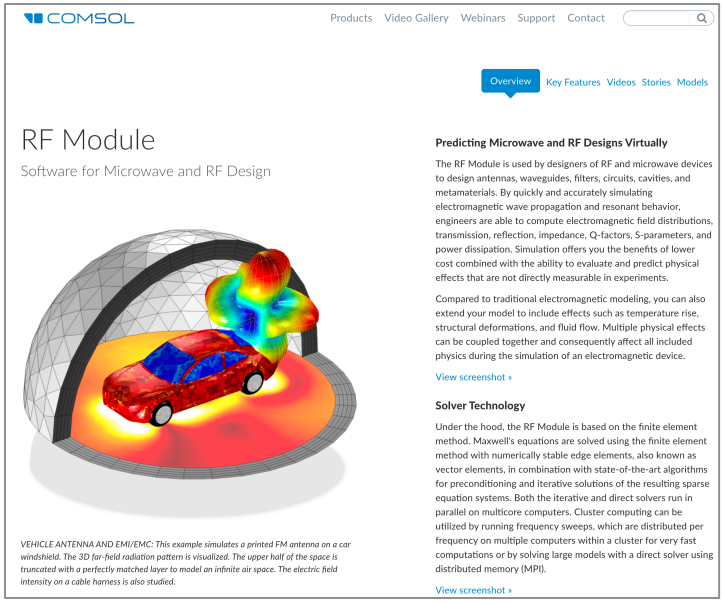


cf. other FEM codes

COMSOL – commercial code using FEM method (https://www.comsol.com)

- POND (LH)
- LHEAF (Lower Hybrid wavE Analysis based on FEM)
- TORIC – COMSOL (Connecting core ICRF solution with edge FEM solution) *in process…*





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RF Module

Software for Microwave and RF Design

VEHICLE ANTENNA AND EMI/EMC: This example simulates a printed FM antenna on a car windshield. The 3D far-field radiation pattern is visualized. The upper half of the space is truncated with a perfectly matched layer to model an infinite air space. The electric field intensity on a cable harness is also studied.

Predicting Microwave and RF Designs Virtually

The RF Module is used by designers of RF and microwave devices to design antennas, waveguides, filters, circuits, cavities, and metamaterials. By quickly and accurately simulating electromagnetic wave propagation and resonant behavior, engineers are able to compute electromagnetic field distributions, transmission, reflection, impedance, Q-factors, S-parameters, and power dissipation. Simulation offers you the benefits of lower cost combined with the ability to evaluate and predict physical effects that are not directly measurable in experiments.

Compared to traditional electromagnetic modeling, you can also extend your model to include effects such as temperature rise, structural deformations, and fluid flow. Multiple physical effects can be coupled together and consequently affect all included physics during the simulation of an electromagnetic device.

View screenshot »

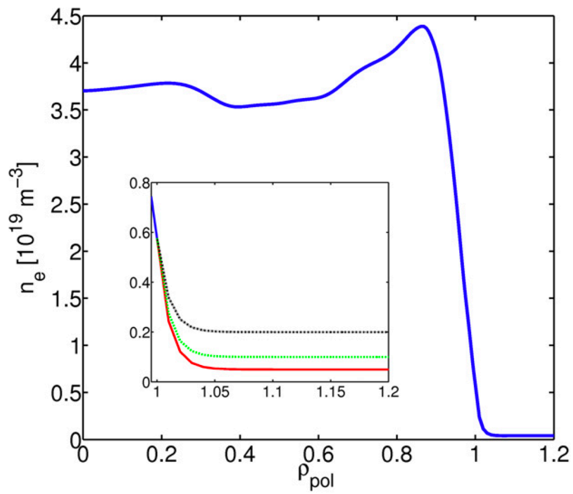
Solver Technology

Under the hood, the RF Module is based on the finite element method. Maxwell's equations are solved using the finite element method with numerically stable edge elements, also known as vector elements, in combination with state-of-the-art algorithms for preconditioning and iterative solutions of the resulting sparse equation systems. Both the iterative and direct solvers run in parallel on multicore computers. Cluster computing can be utilized by running frequency sweeps, which are distributed per frequency on multiple computers within a cluster for very fast computations or by solving large models with a direct solver using distributed memory (MPI).

View screenshot »

NSTX shot 130608 used in the test simulations

Electron Density – (normalized poloidal flux)$^{1/2}$



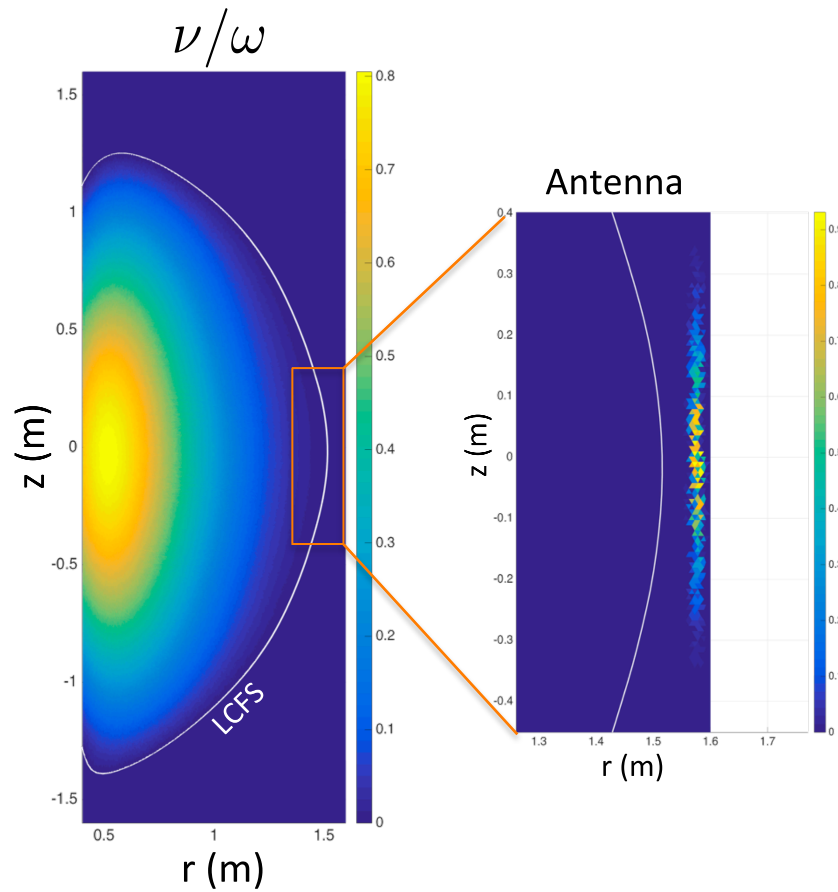
Bertelli et al. [2014]

Electron density in the SOL
→ almost constant
→ N_{ant} = 0.5, 0.7, 1.0, 1.5, 1.7, and 2.0 X 10^8

Mesh & Computing time

Uniform mesh : 47,371 nodes
CPU time : **65** SECONDS using a SINGLE process

Collision & Source



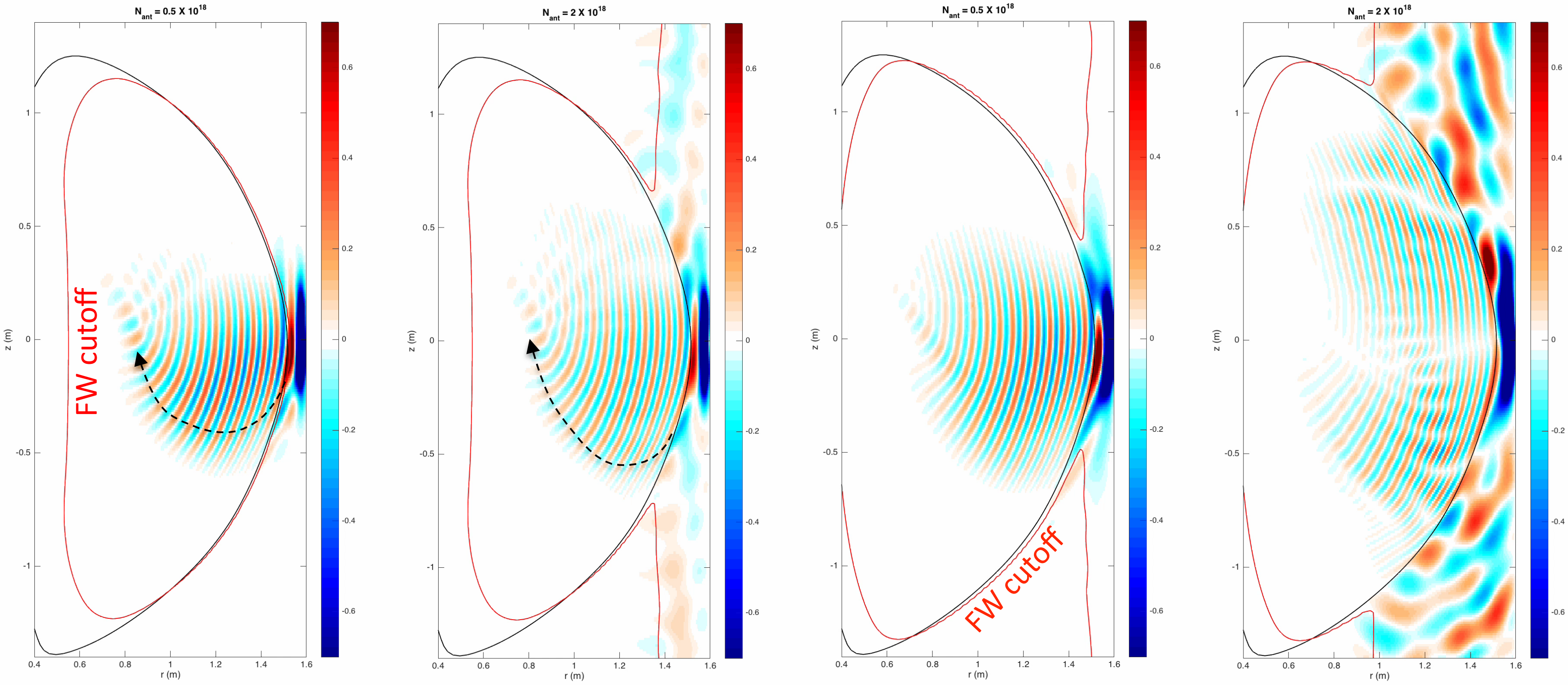
The results show good agreement with previous calculations

$n_\phi = -21$

$N_{ant} = 0.5 \text{ X } 10^{18}$ | $N_{ant} = 2.0 \text{ X } 10^{18}$

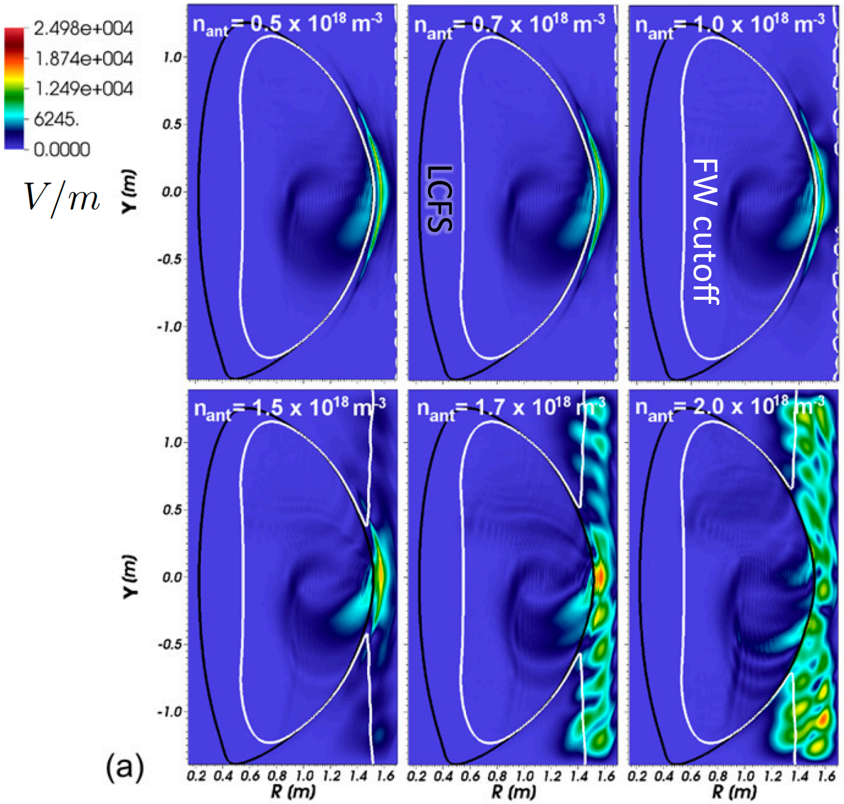
$n_\phi = -12$

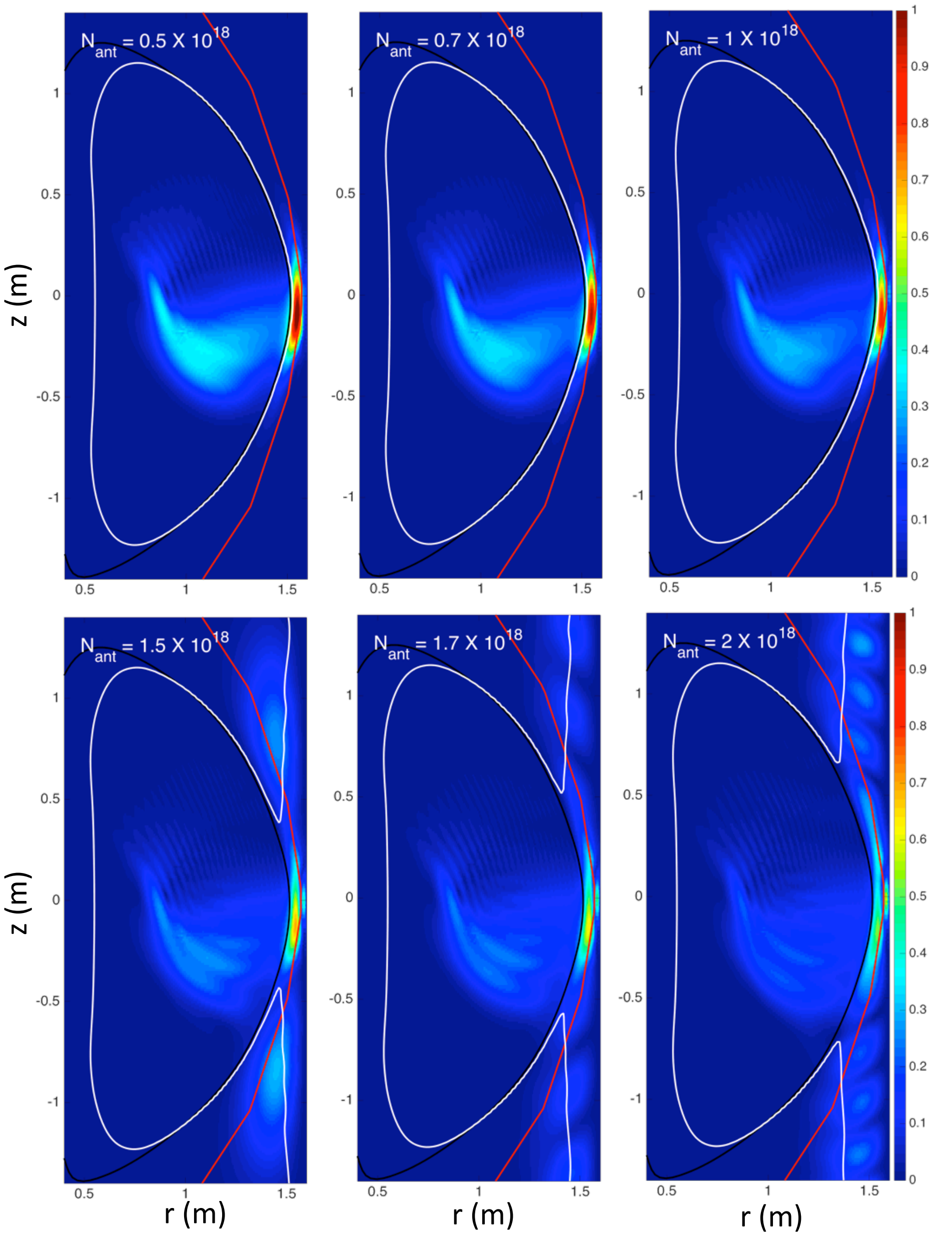
$N_{ant} = 0.5 \text{ X } 10^{18}$ | $N_{ant} = 2.0 \text{ X } 10^{18}$



AORSA vs FW2D

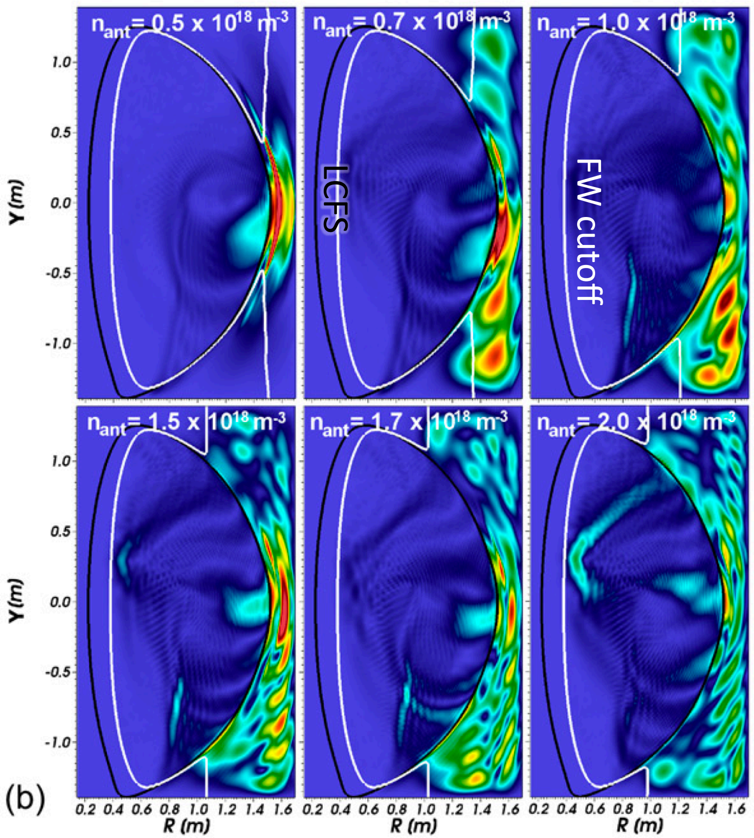
$n_\phi = -21$

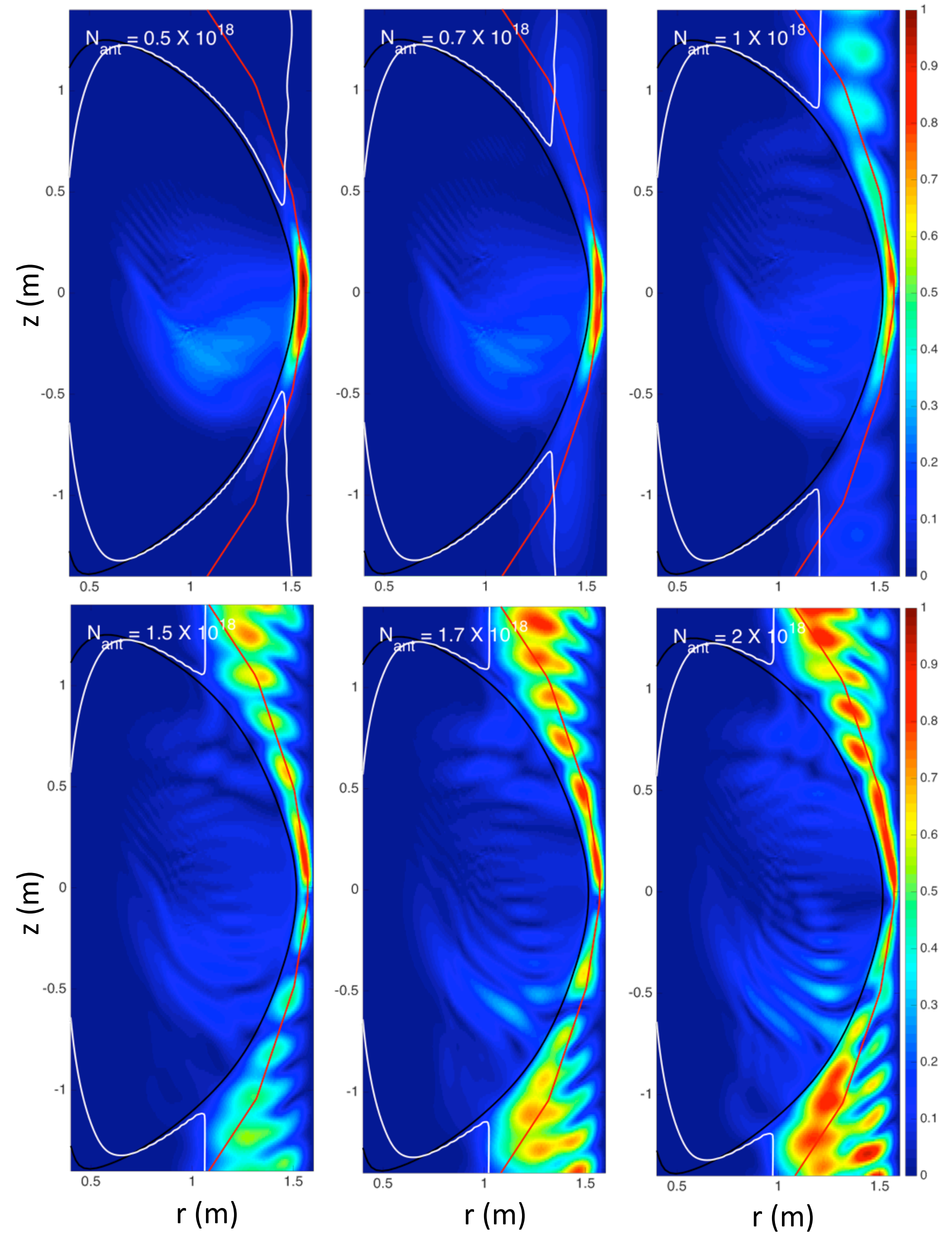




AORSA vs FW2D

$n_\phi = -12$





Including collision in the SOL ?!

Summary & Future Plans

1. 2D full-wave code has been developed to examine plasma waves in space (and tokamak)

2. The code has been successfully used to determine ULF wave properties at Earth and Mercury
   - Wave normal angle and the heavy ion density ratio are very important on ULF wave propagation along B_0.
   - Ion-ion hybrid resonance can explain linearly polarized ULF waves near the ion cyclotron frequencies.

- Examine ULF wave generation (i.e., linearly polarization) and propagation (i.e., LHP waves) under different geomagnetic conditions
- Adopt compressed/stretched magnetic field structure

1. We performed simulations of FW propagation in the SOL of NSTX. The results shows good agreement with results from AORSA

- Adopt various electron/ion densities and collision in the SOL
- Adopt *realistic* boundaries rather than “rectangular” → numerical survey!