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Understanding Space Plasmas Through Laboratory Experiments

Guru Ganguli

Plasma Physics Division, Naval Research Laboratory

Washington DC

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PLASMA PHYSICS DIVISION · NAVAL RESEARCH LABORATORY

In collaboration with

Chris Crabtree, NRL

Erik Tejero, NRL

Bill Amatucci, NRL

Challenges With In-Situ Measurements

- **Space-Time Ambiguity**
  - Makes detection and characterization of a specific space plasma phenomenon tricky
- **Unsteady Plasma**
  - When orbiting sensors return to the position of the original measurement the plasma has evolved
  - Meaningful statistical ensemble through repeated measurements not possible
- **Multiple Uncontrolled Variables**
  - Usually there are many variables and multiple forces operating simultaneously
  - Difficult to pinpoint the causality of events and isolate a specific phenomenon for precise measurements for unambiguous characterization
- **Mitigation: Scaled Laboratory Experiments**
  - Controlled environment scaled to the appropriate space conditions
    - Anchor theory using laboratory experiments and then apply the validated model to space conditions
    - Compare laboratory experiments to space data

Space Plasma Processes Optimal for Laboratory Experiments

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- **Turbulence**
  - Understand turbulence properties in the meso and micro scales
  - Kinetic effects
  - Turbulence pervades most plasma domains
    - Astrophysics, hemisphere, magnetosphere, ionosphere, tokamaks, etc.
    - Fundamental yet practical

- **Spatial Variability**
  - Understand the cause and effects of spatial variability in the background parameters
  - Many space plasma phenomena associated with strong spatial inhomogeneities

- **Multi-Ion-Species Effects**
  - Most space plasmas are multispecies

- **Astrophysical Plasma Processes**

Small Scale Turbulence Properties: Electrostatic or Electromagnetic?

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Electrostatic ⇄ Electromagnetic: Dispersive Properties of Whistler Branch Waves

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- Cold plasma dispersion relation for the whistler branch waves in $(\Omega_i < \omega < \Omega_e)$ frequency range

$$\omega^2 = \left(\frac{\bar{k}_z^2}{(1+\bar{k}_y^2)} + \mu \right) \frac{\bar{k}^2 \Omega_e^2}{1+\bar{k}^2}$$

$$\mu = m_e / m_i$$

$$\bar{k} = kc/\omega_{pe}$$

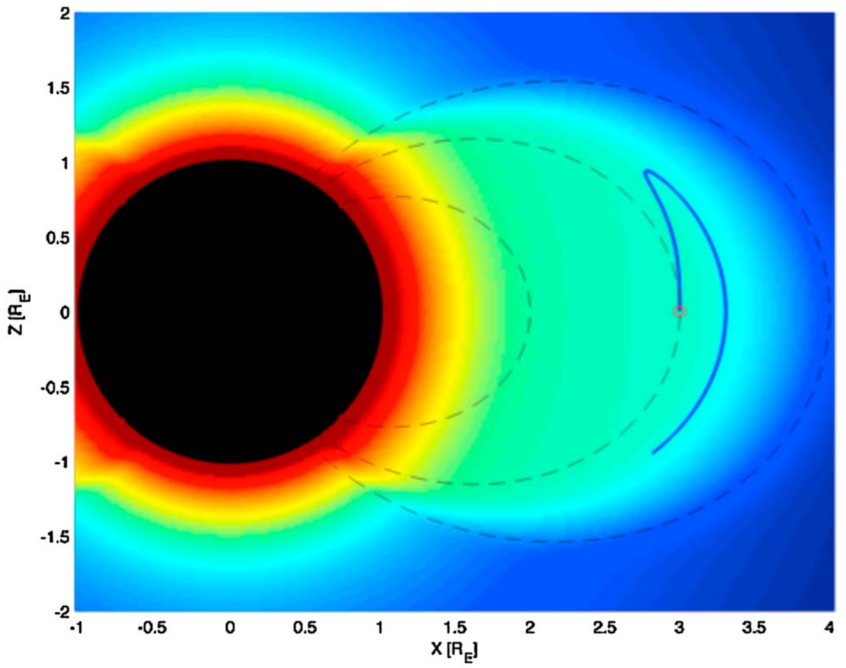
O(1) 0 O(1)

$$E_x = -ik_x\phi \left(1 + \frac{\bar{k}_z^2}{\bar{k}_\perp^2} \right) \quad E_y = E_x \frac{i\omega}{\Omega_e \bar{k}^2} \quad E_z = -ik_z\phi \left(\frac{\bar{k}^2}{1+\bar{k}^2} \right)$$

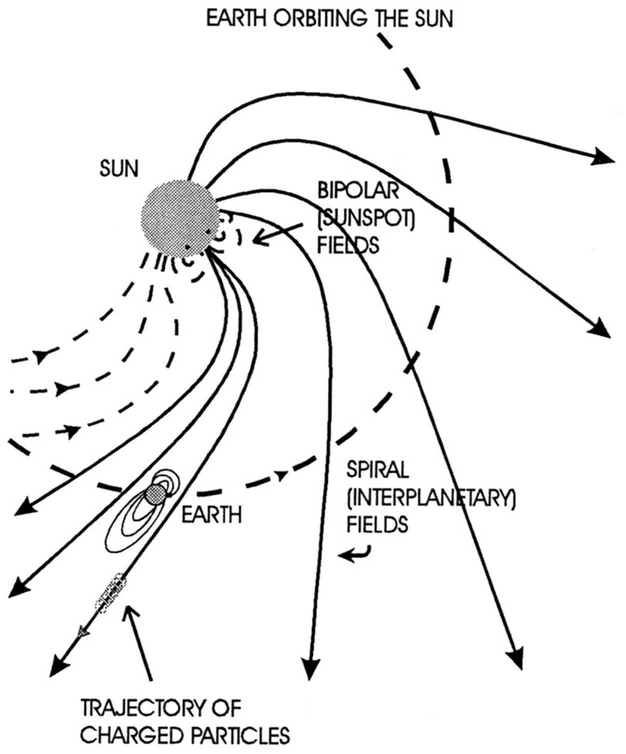
  – Electrostatic if $\bar{k} >> 1 \quad and \quad \bar{k}_\perp >> \bar{k}_z$

    - EM Whistlers $\bar{k}_y^2 < 1 \quad \bar{k}_z^2 > \mu$
    - ES Whistlers $\bar{k}_y^2 > 1 \quad 1 > k_z^2 / k_y^2 > \mu$
    - ES Lower Hybrid $\bar{k}_y^2 > 1 \quad k_z^2 / k_y^2 < \mu$
    - EM Magnetosonic $\bar{k}_y^2 < 1 \quad \bar{k}_z^2 < \mu$

Magnetosphere



Heliosphere



$$D(\omega, k, n(r), B(r)) = 0$$

[Ganguli et al., ***PoP***, 2010]

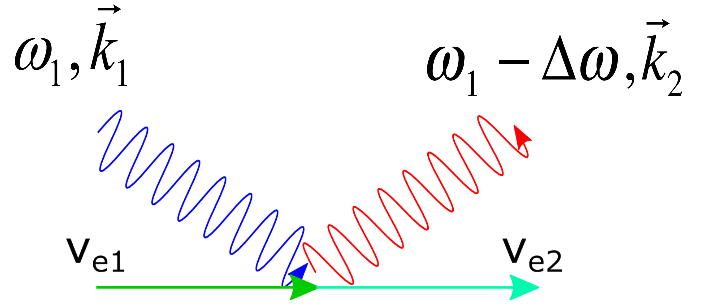
Laboratory Validation of Nonlinear Conversion

- Scattering rate by thermal electrons in EM limit
  - Generalize Hasegawa and Chen 1976

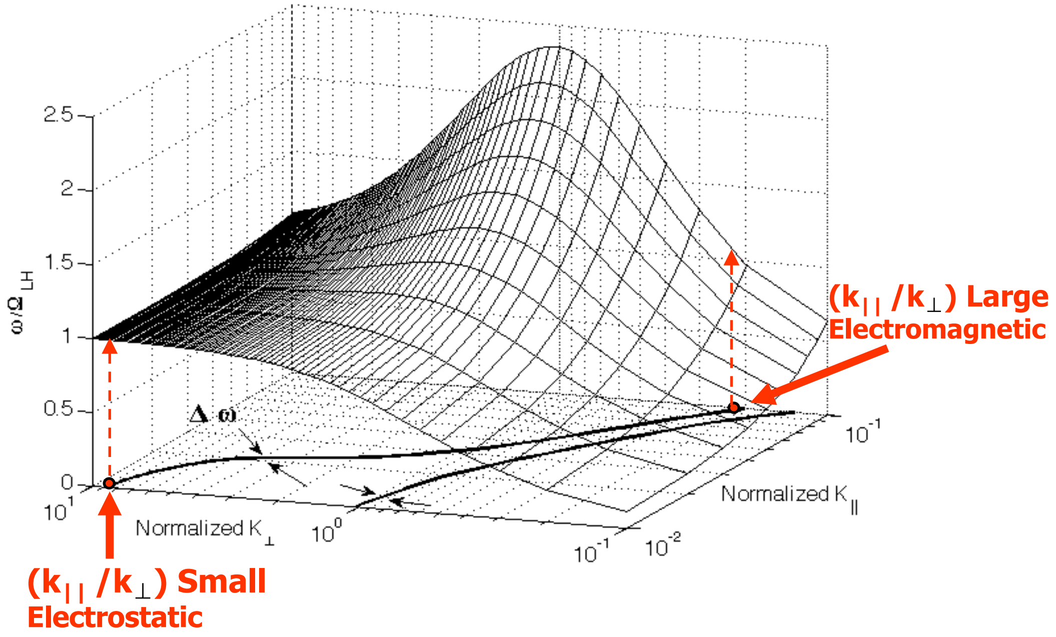
$$\gamma_{NL} \sim \frac{\Omega_e^2}{\omega_{k2}} \frac{\bar{k}_{2\perp}^2}{1+\bar{k}_{2\perp}^2} \sum_{k1} \frac{(\vec{k}_1 \times \vec{k}_2)_z^2}{k_{1\perp}^2 k_{2\perp}^2} \frac{1}{1+\left(\Delta\omega / \Delta\vec{k}_\perp c_s\right)^2} \frac{\bar{k}_{1\perp}^2}{1+\bar{k}_{1\perp}^2} \zeta \,\mathrm{Im}\, Z(\zeta) \frac{W_{k1}}{n_0 T_e}$$

$$\zeta = (\omega_1 - \omega_2)/(k_{1||} - k_{2||}) v_{te}$$

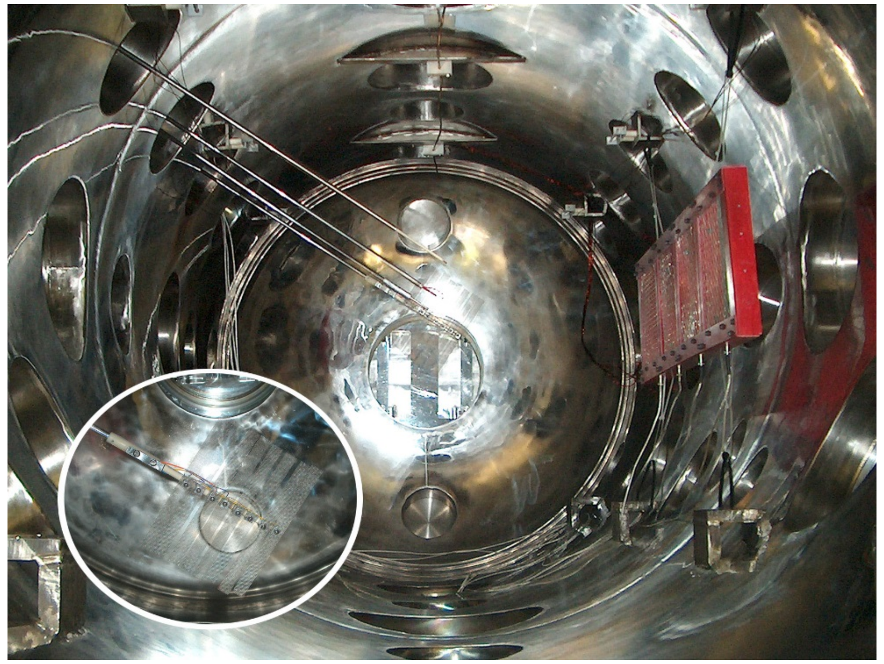
$$\omega^2 = \left(\frac{\bar{k}_z^2}{(1+\bar{k}_y^2)} + \mu \right) \frac{\bar{k}^2 \Omega_e^2}{1+\bar{k}^2}$$

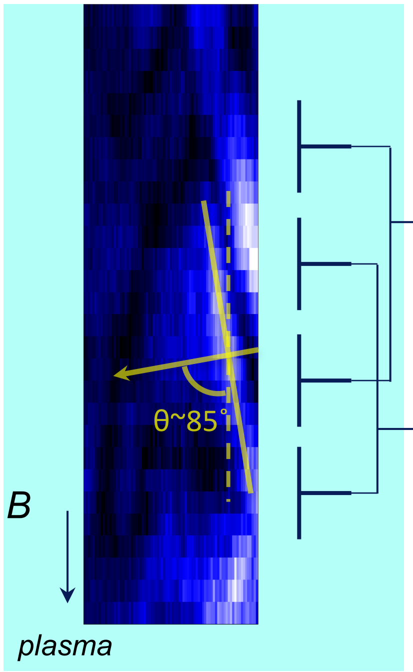


Nonlinear Landau Damping

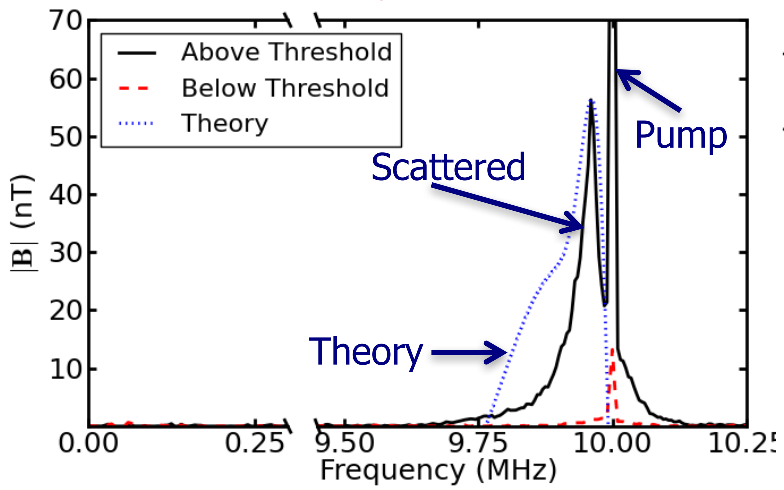


NRL Space Chamber Validation

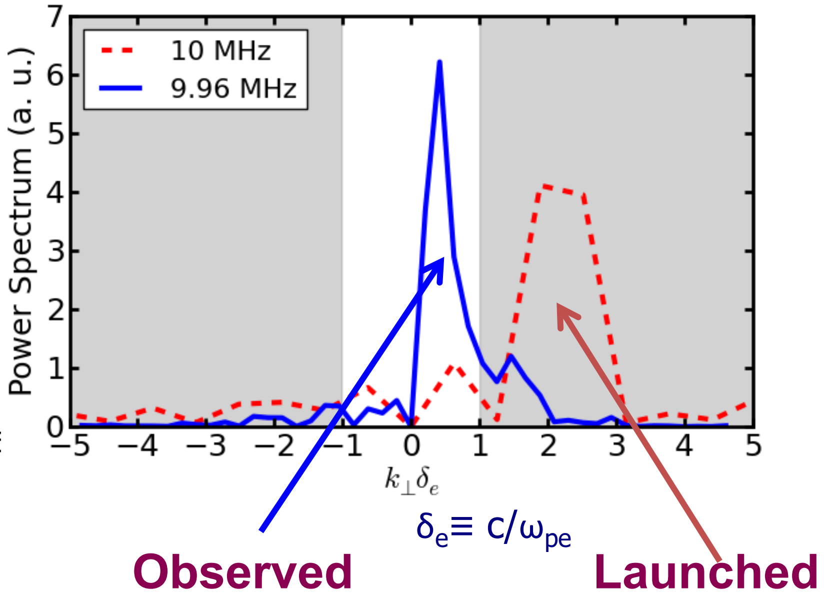




Frequency Spectrum



Wave Vector Spectrum



- Wave-particle resonance can be easily met for any combinations of ($k_{||}$, $k_\perp$) with ω ~ constant

[Tejero et al., ***Nature Scientific Reports***, 2015]

Evidence of Nonlinear Conversion by Scattering in Lightning Generated Whistlers

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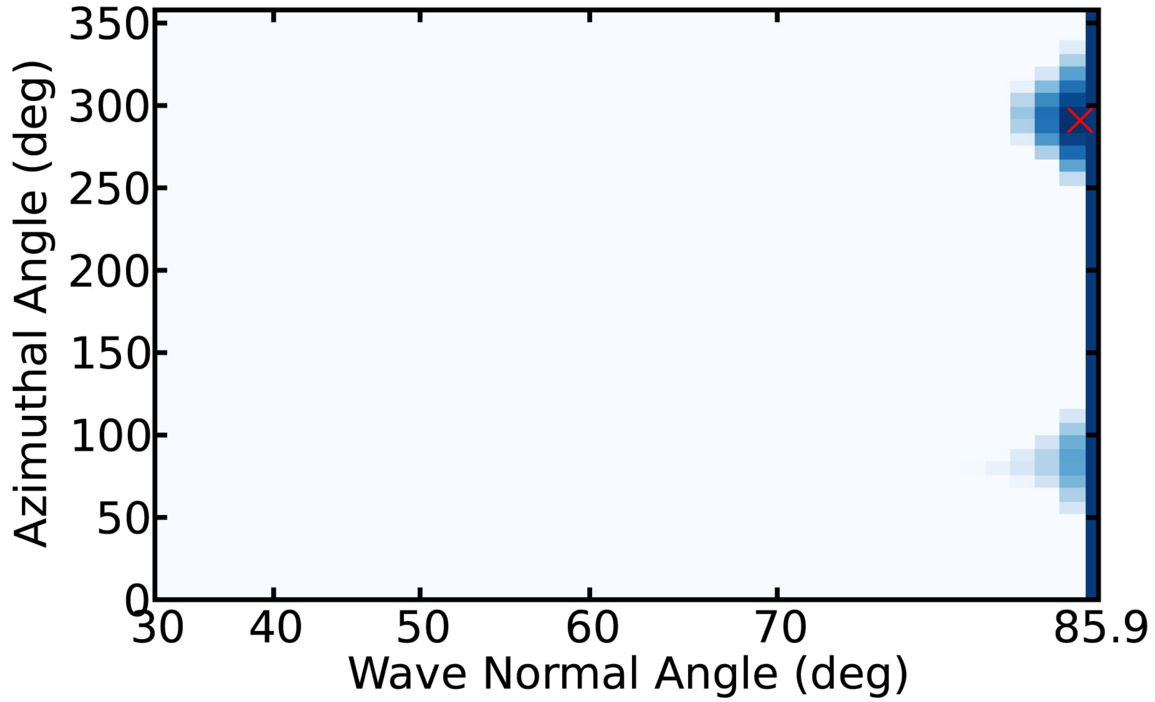
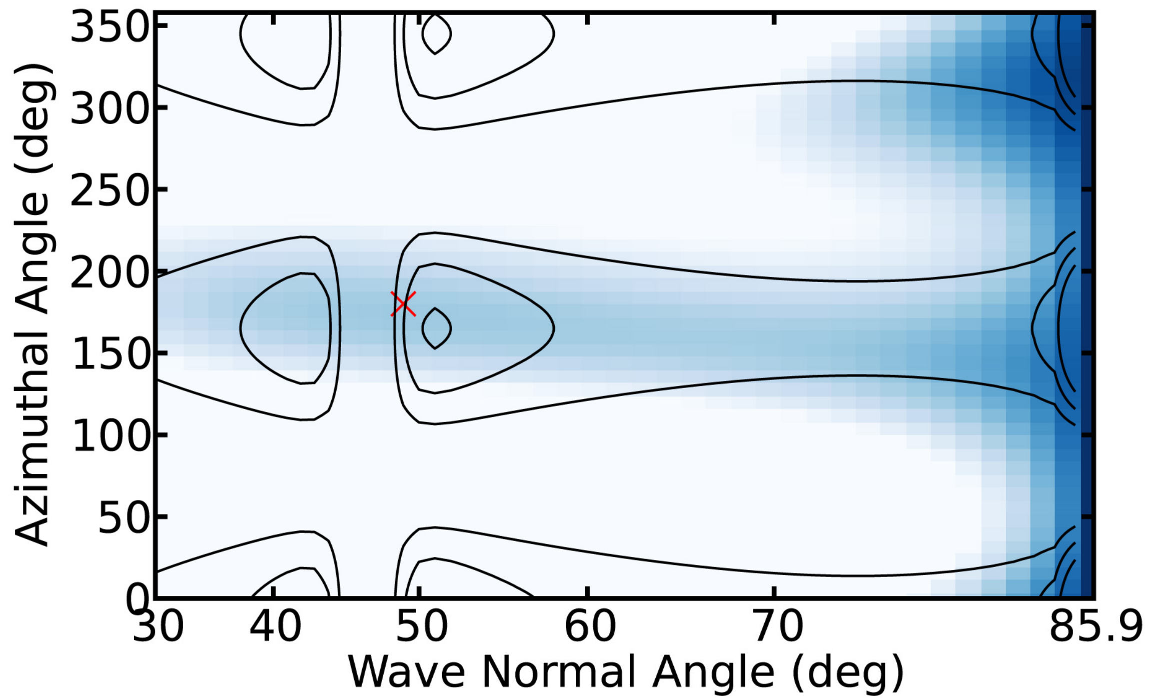
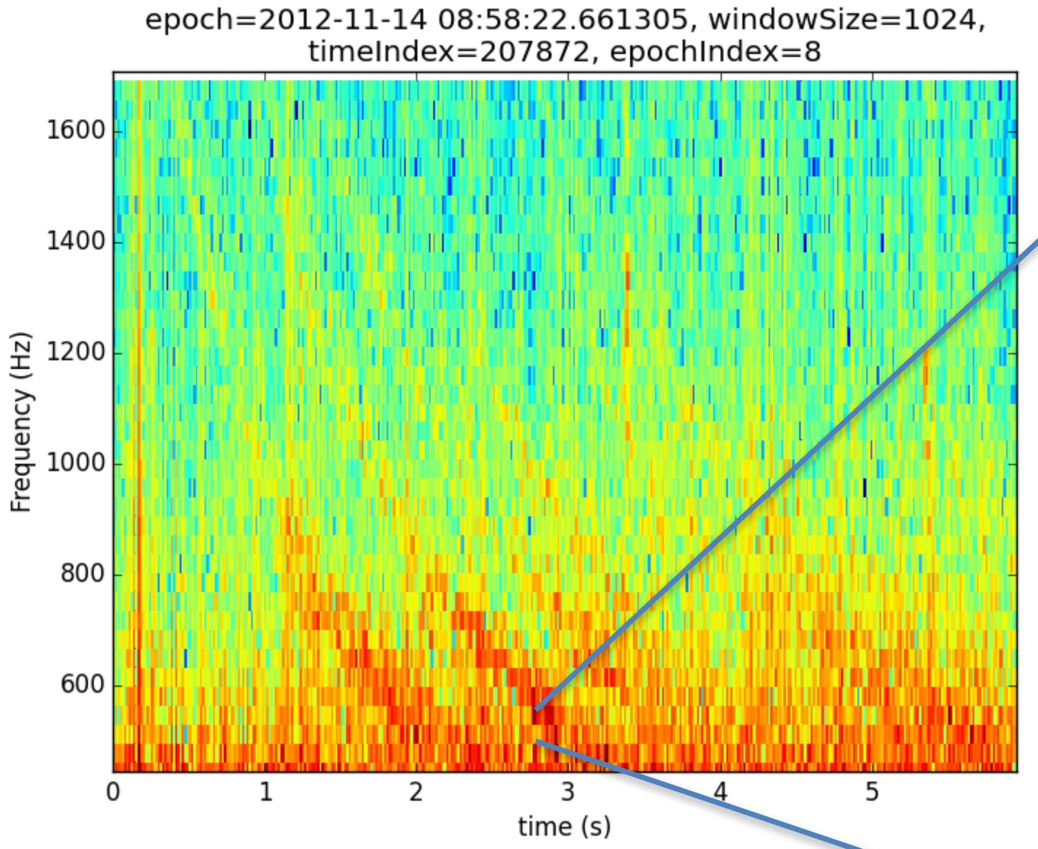
10 MHz – Lab Pump Wave



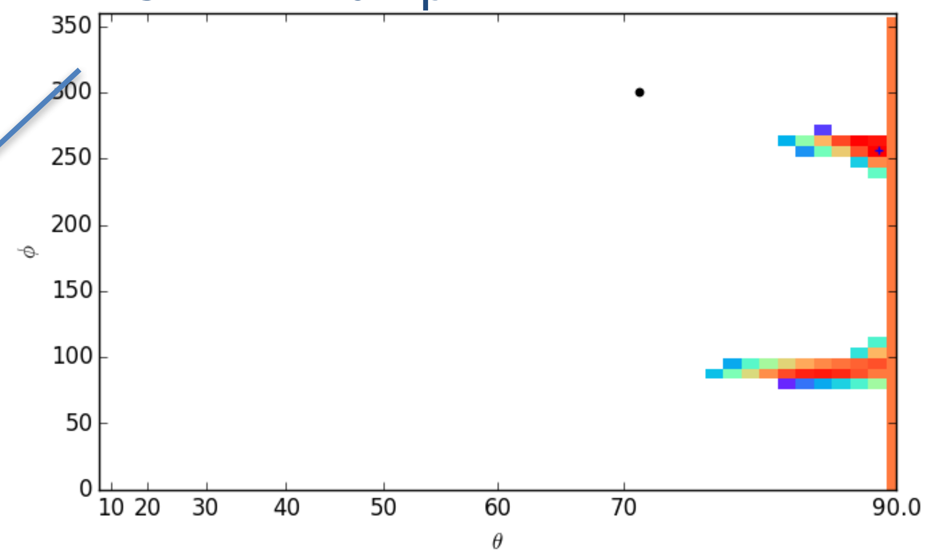
9.96 MHz – Lab Scattered Wave



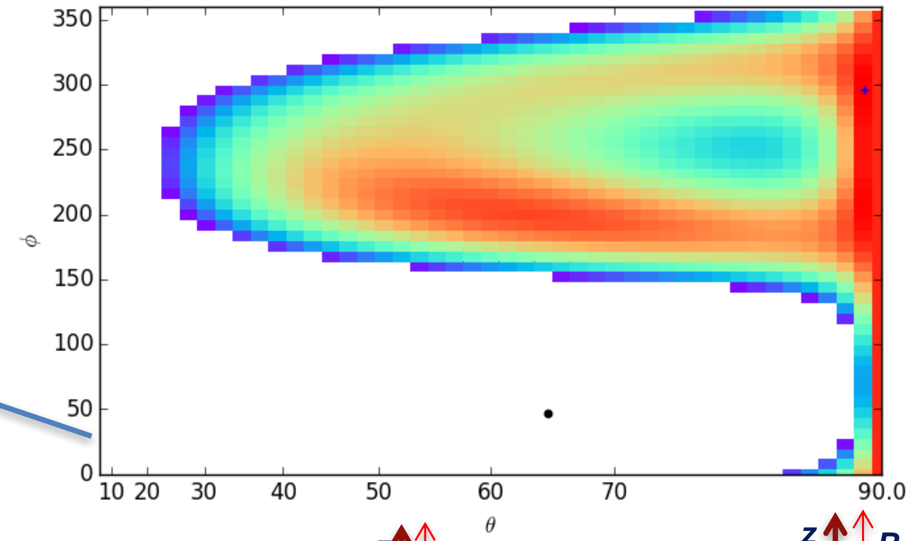
Van Allen Probe Data

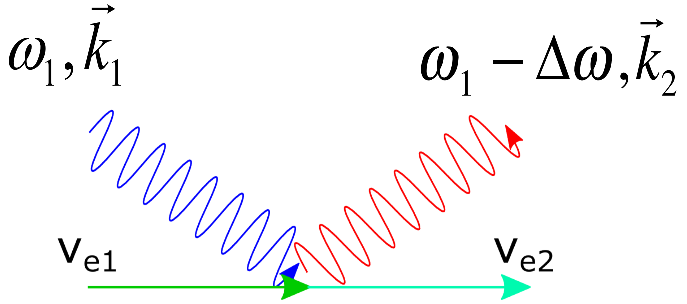


547 Hz-Pump

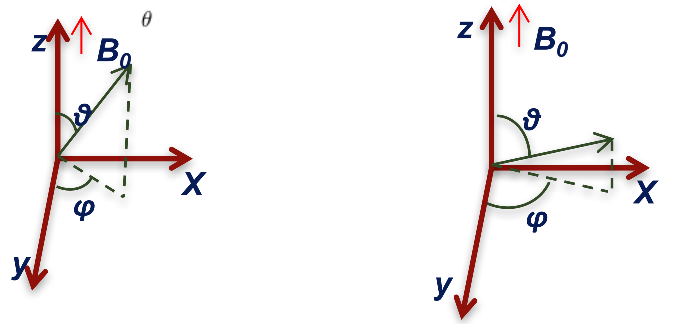


512 Hz-Scattered





Nonlinear Landau Damping



Changing Turbulence Character Critical in the Radiation Belt

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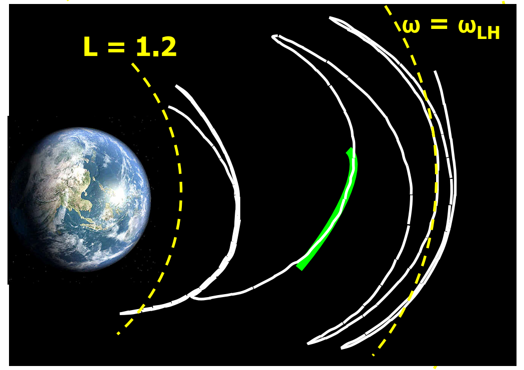
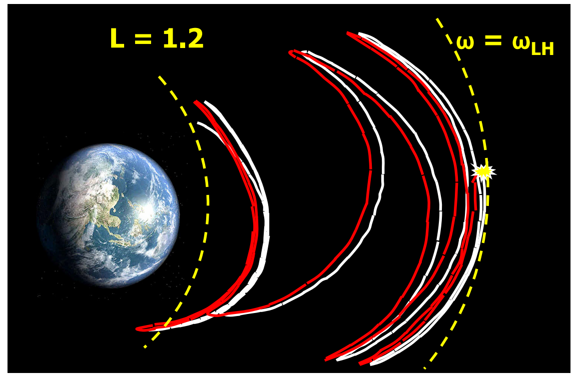
Fate of lightning generated whistlers in the ionosphere



Standard Quasi-linear Picture

- Increasing $k_\perp \Rightarrow$ enhanced dissipation ($\sim k_\perp^2$)
- Wave dissipates as $k_\perp c/\omega_{pe} > 1$
- $\tau_{int} \sim \tau_{prop}$, during which $k_\perp c/\omega_{pe} < 1$



Weak Turbulence Picture

- Increasing $k_\perp \Rightarrow$ enhanced NL scattering ($\sim W k_\perp^6$)
- $k_\perp c/\omega_{pe} < 1$ maintained by NL scattering
- $\tau_{int} \sim \tau_{turb} >> \tau_{prop}$, NL scatter keeps $k_\perp c/\omega_{pe} < 1$

Cyclotron resonance time (τ_{int}) given by $(\omega - k_{||}V_{||} - n\Omega_e(r)) \simeq 0$

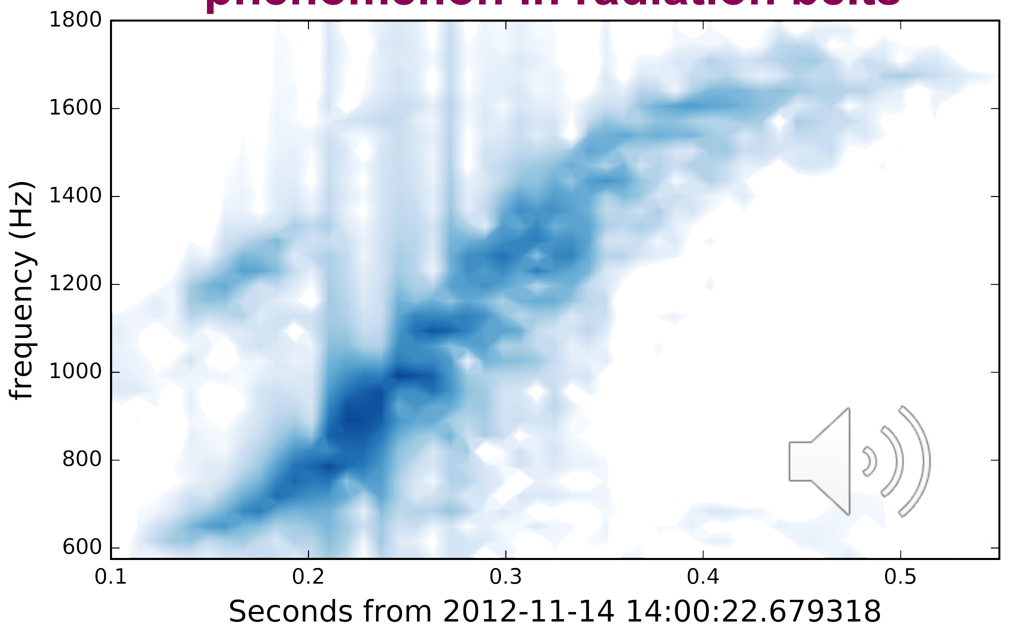
[Ganguli et al., ***GRL***, 2012; Crabtree et al., ***PoP***, 2012]

Small Scale Turbulence Properties: Coherent or Incoherent?

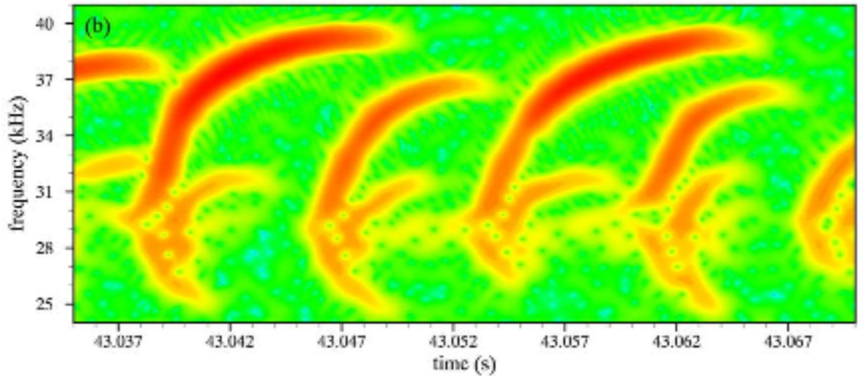
Signature of Weak Turbulence Processes in Radiation Belts

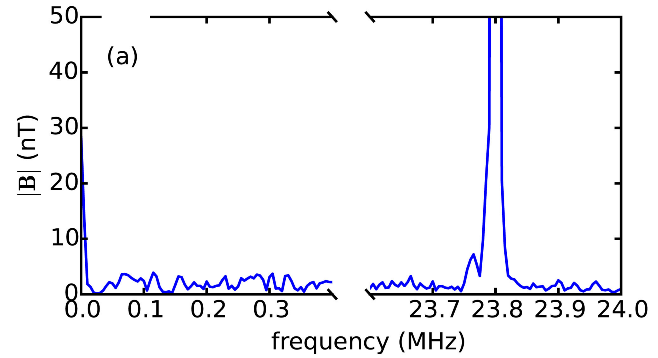
- Analysis of in-situ data from NASA/Van Allen Probes

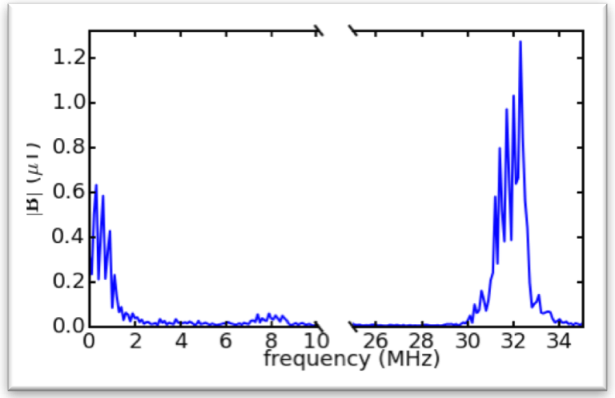
Van Allen Probe data of chorus phenomenon in radiation belts



Chirping in Joint European Tokamak (JET)

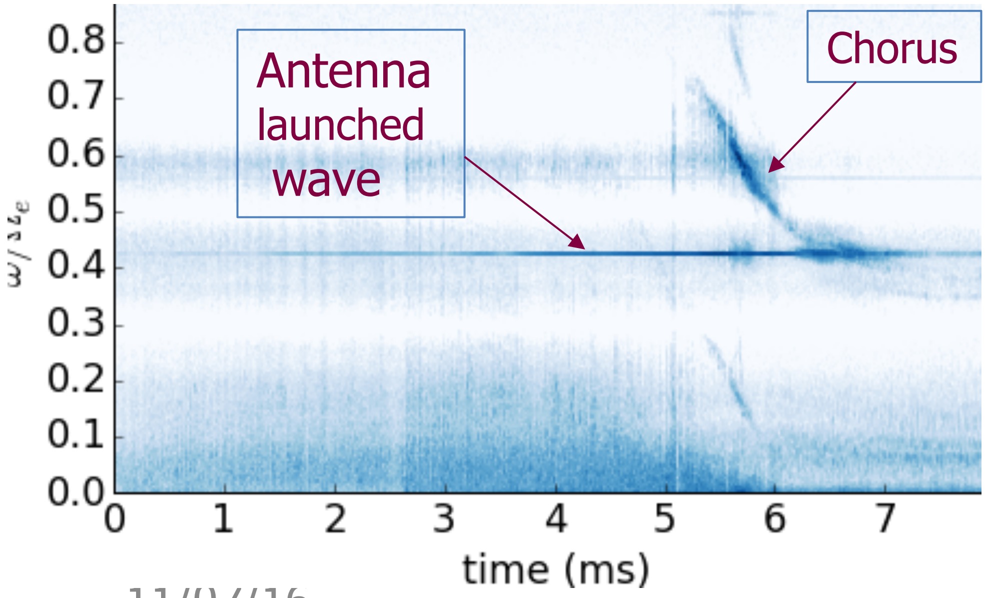




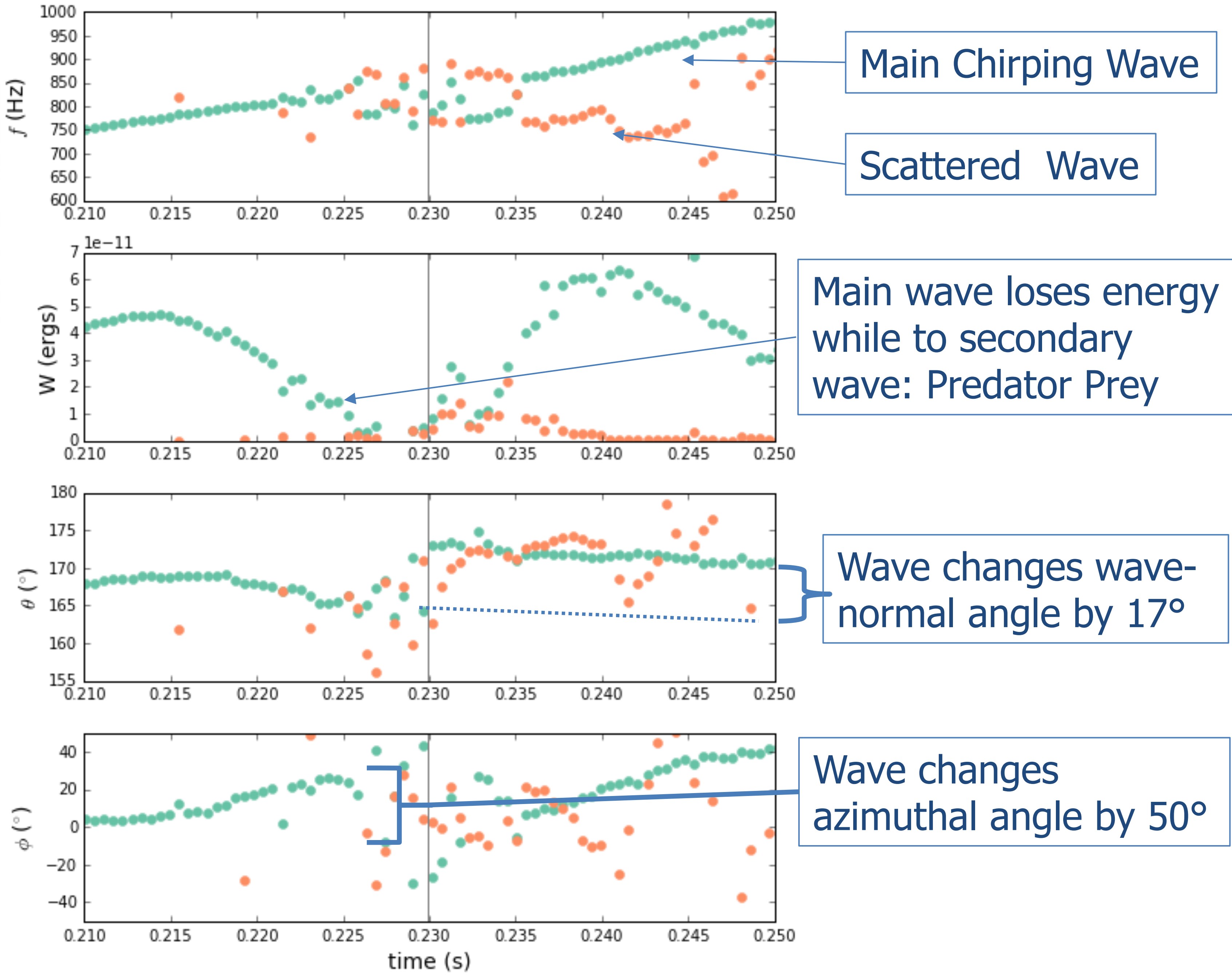


Evidence of nonlinear W-W and W-P scatterings in laboratory data

Space Chamber Recreation



Bayesian analysis of Van Allen Probe data



Crabtree et al., ***JGR***, 2017 (in press)

Bayesian Spectral Analysis of Chorus Element

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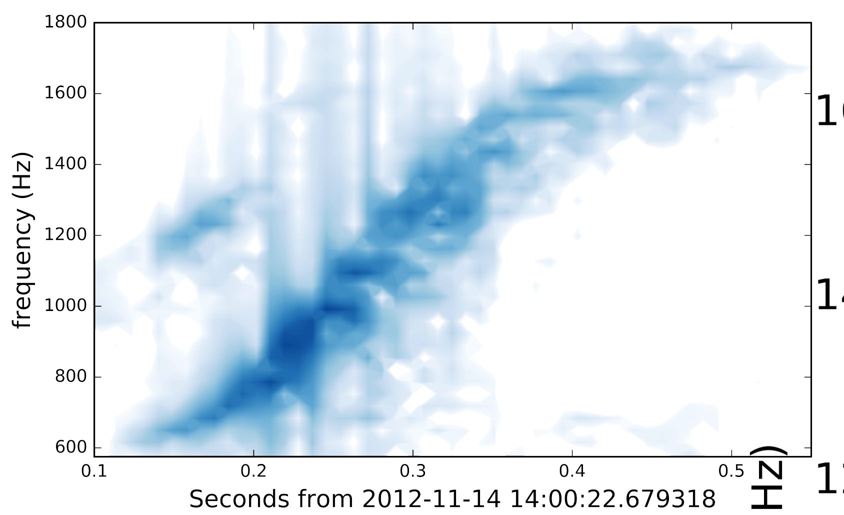
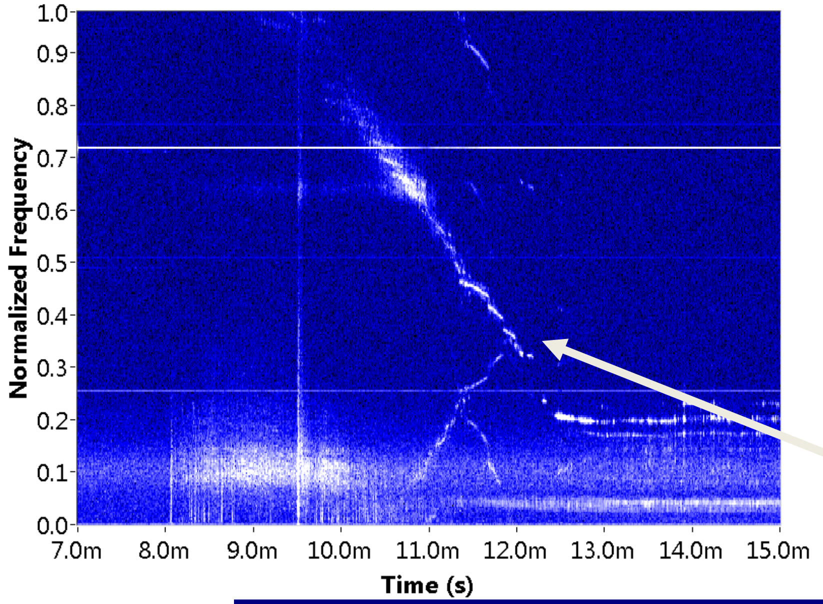
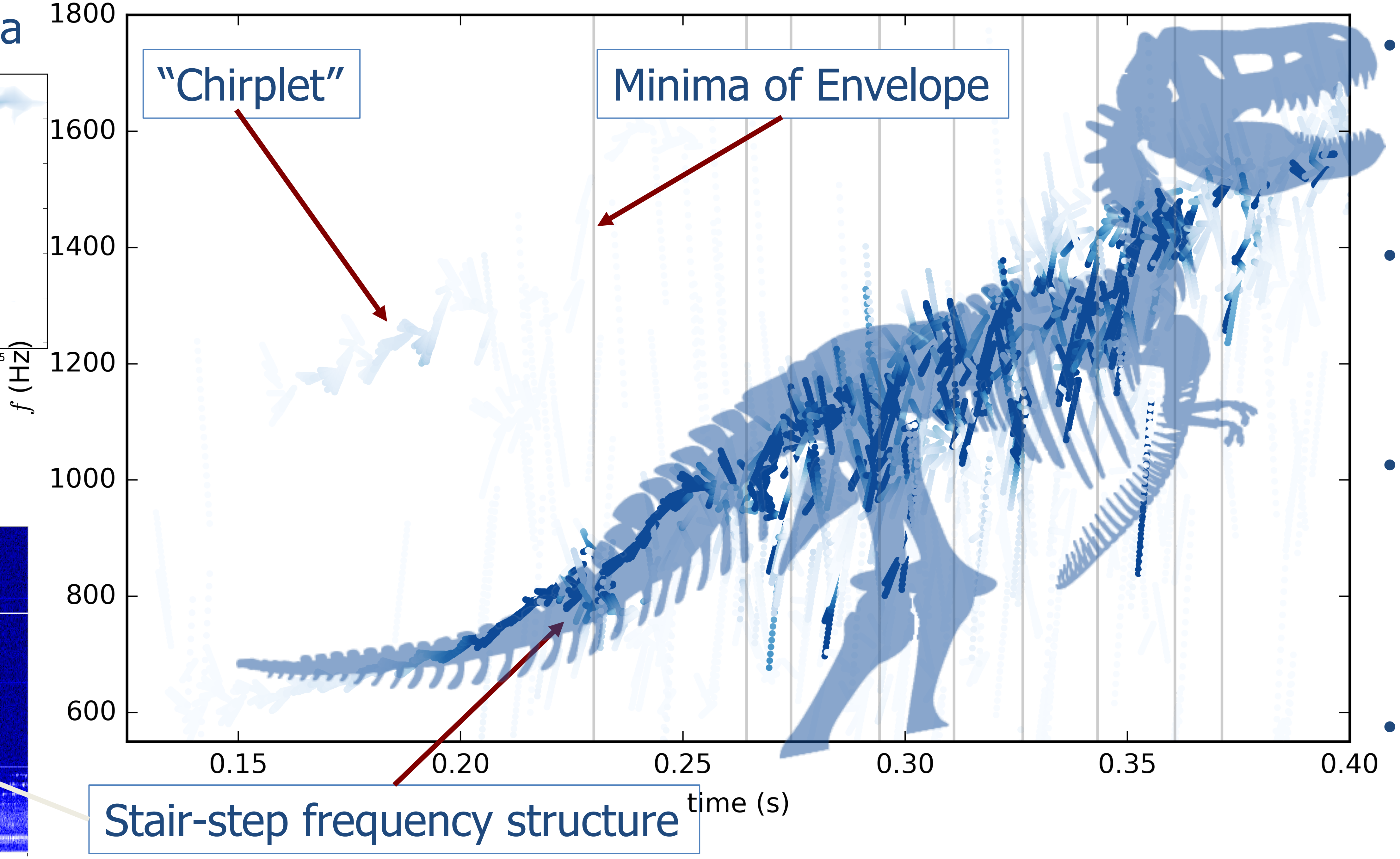
Van Allen Probe Data



NRL Experiment





- Intensity corresponds to wave energy density
- Instantaneous frequency is plotted over time window
- Growth rate is used to adjust wave energy density over time window
- Color saturates at 10^{-11} ergs

Chorus may consist of coherent & incoherent processes, multiple waves with 3D propagation

Small Scale Turbulence Properties: Strong or Weak Turbulence?

MHD (Strong) ⇄ Kinetic (Weak): Heliospheric Plasmas

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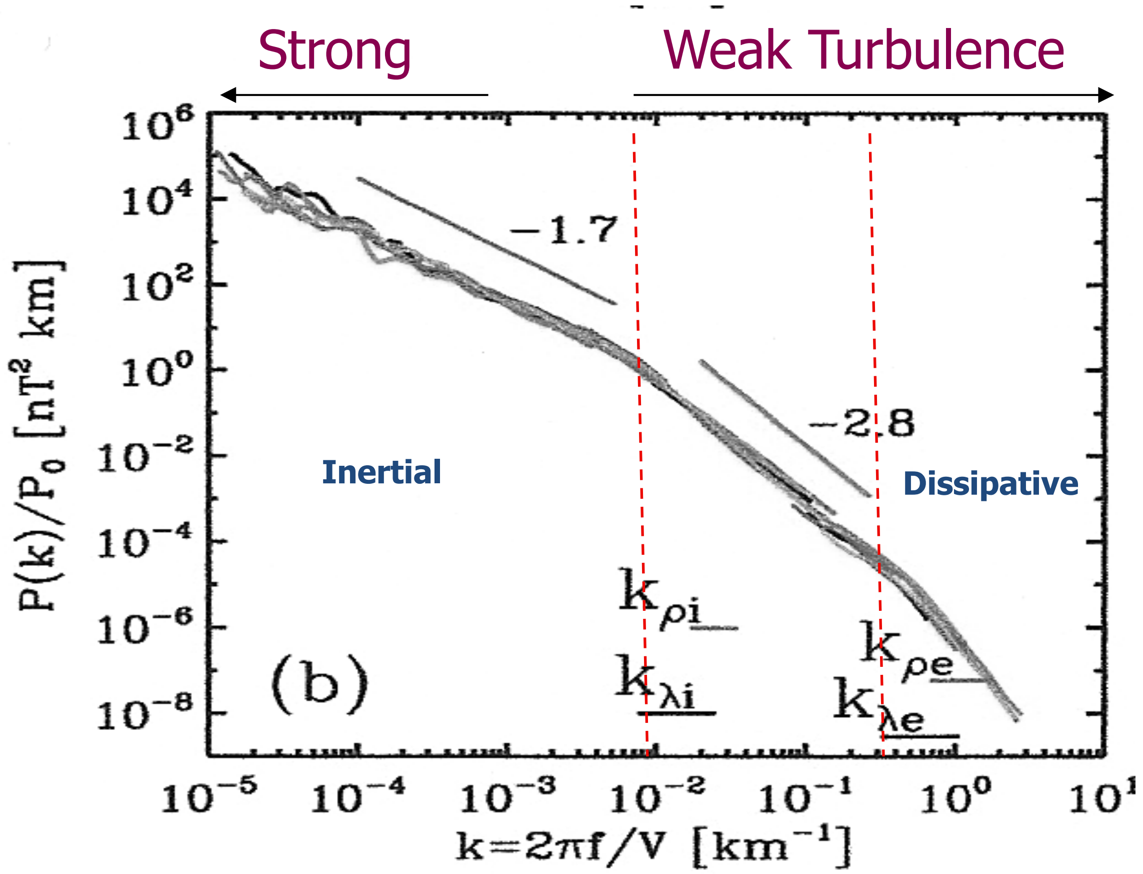
- Observation in solar wind
  - Turbulence energy spectrum non-Kolmogorov
  - Appearance of spectral steepening at $k\rho_i \sim 1$
- Ongoing debate:
  - Origin of spectral steepening for shorter wavelengths
- Common belief:
  - Spectral evolution dominated by Landau damping
  - Strong turbulence prevails at all scale sizes
- No good reason to reject weak turbulence for $k\rho_i \geq 1$ in collisionless SW if Landau damping is negligible compared to NL rates



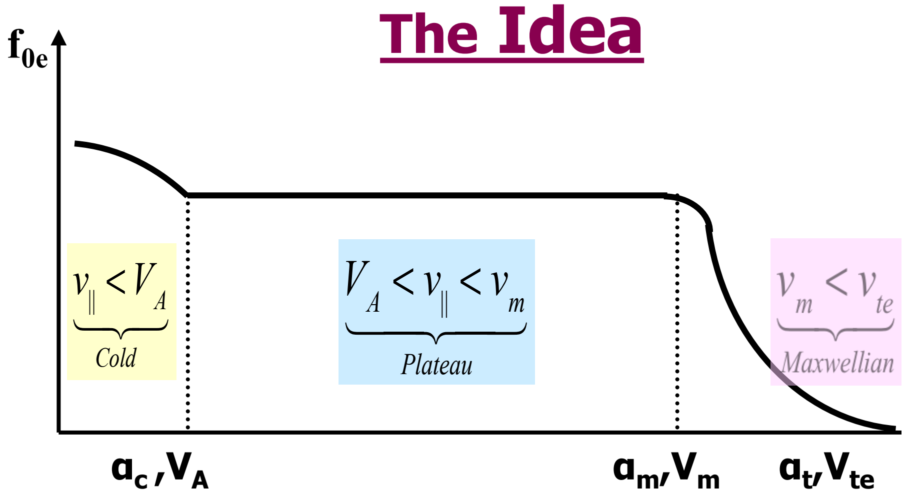
From Alexandrova et al. ***PRL***, 2009, Cluster data

- Can Solar Wind Maintain Sufficiently Small $df_{0e}/dv_{||}$ to Ignore Landau Damping?

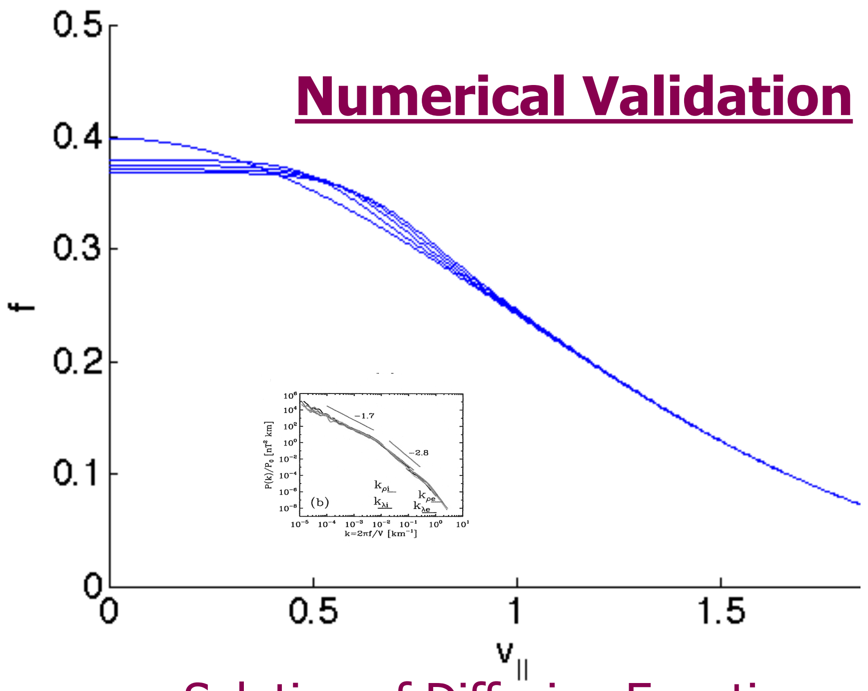
Development of Plasma Distribution in Solar Wind

- Stable distributions can Landau damp waves and create plateau
- In SW Coulomb collision time and free path are long (~10^5 sec, ~1AU)
  - Can not thermalize within SW transit time
- Evolution of distribution function given by quasi-linear equation

The Idea

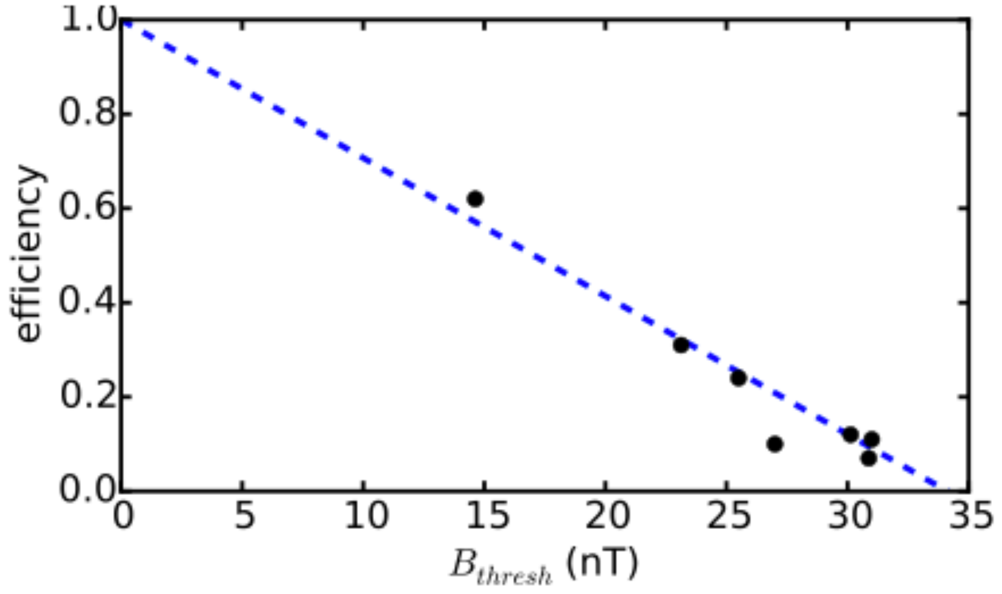


Numerical Validation



Solution of Diffusion Equation for observed spectrum

Experimental Validation



Scattering efficiency increases with decreasing linear growth rate in Space Chamber experiment

Efficiency

$$\frac{W_{scattered}}{W_{pump}} = \frac{\omega - \Delta\omega}{\omega}$$

Turbulence Onset

$$\gamma_{NL} \geq \gamma_L$$

$$\frac{\partial W_{k_1}}{\partial t} = \underbrace{2\gamma_L W_{k_1}}_{Linear\ Processes} \underbrace{- \gamma_{NL}(W_{k_1}) W_{k_2}}_{\substack{Nonlinear\ scattering \\ EM \Leftrightarrow ES\ conversion}} \underbrace{- \frac{1}{L}\frac{\partial \omega}{\partial k_1} W_{k_1}}_{Propagation}$$

[Tejero et al., ***PoP***, 2016]

- Electron density redistributed in 3 components: Cold, Plateau and Maxwellian; in fractions α_c, α_m, α_t

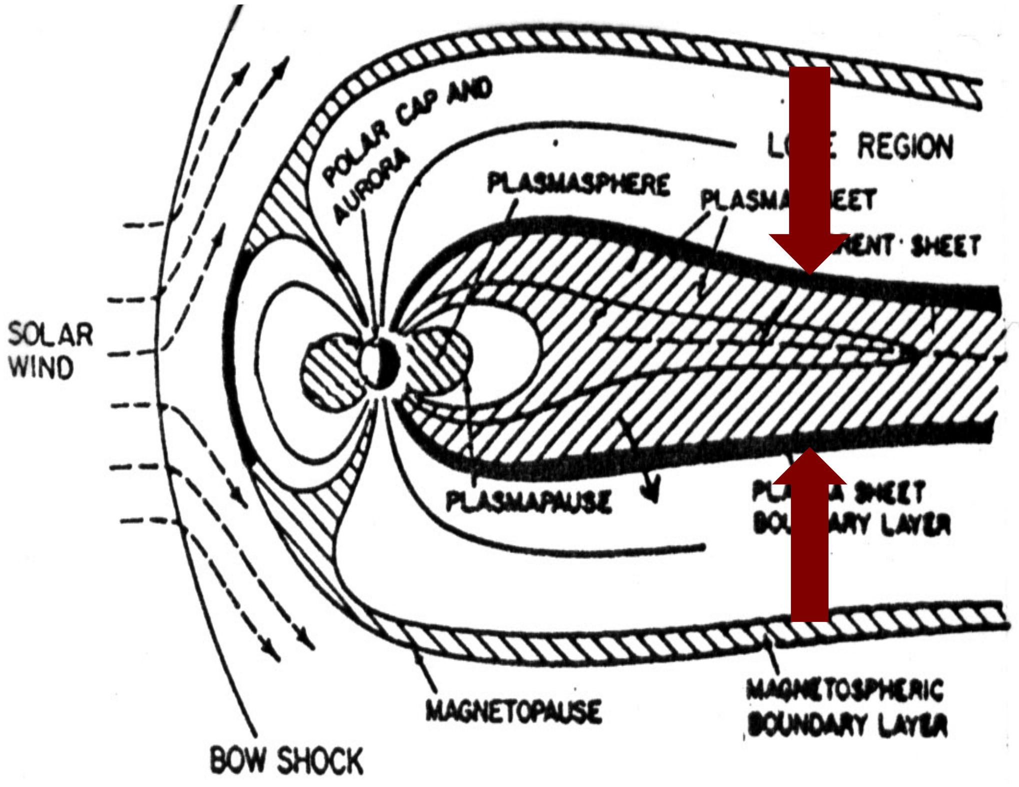
[Rudakov et al., ***PoP***, 2011, 2012]

Effects of Spatial Variability

Origin of Strong of Spatial Variability in Near-Earth Space

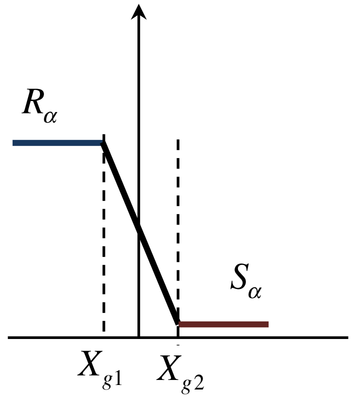
- Plasma compression leads to strong spatial gradients, e.g.,
  - Boundary layers, dipolarization fronts, reconnection region, etc.
  - Scale sizes can become comparable to an ion gyro-radius or smaller
  - Kinetic treatment becomes necessary
- Use constants of motion to construct a distribution function

$$H_\alpha = mv^2/2 + e\Phi(x), \quad X_g = x + v_y/\Omega \qquad f_{o\alpha}(X_g, H_\alpha(x)) = \frac{N_\alpha}{(\pi v_{t\alpha}^2)^2} Q_\alpha(X_g) e^{-\frac{H_\alpha(x)}{kT_\alpha}},$$



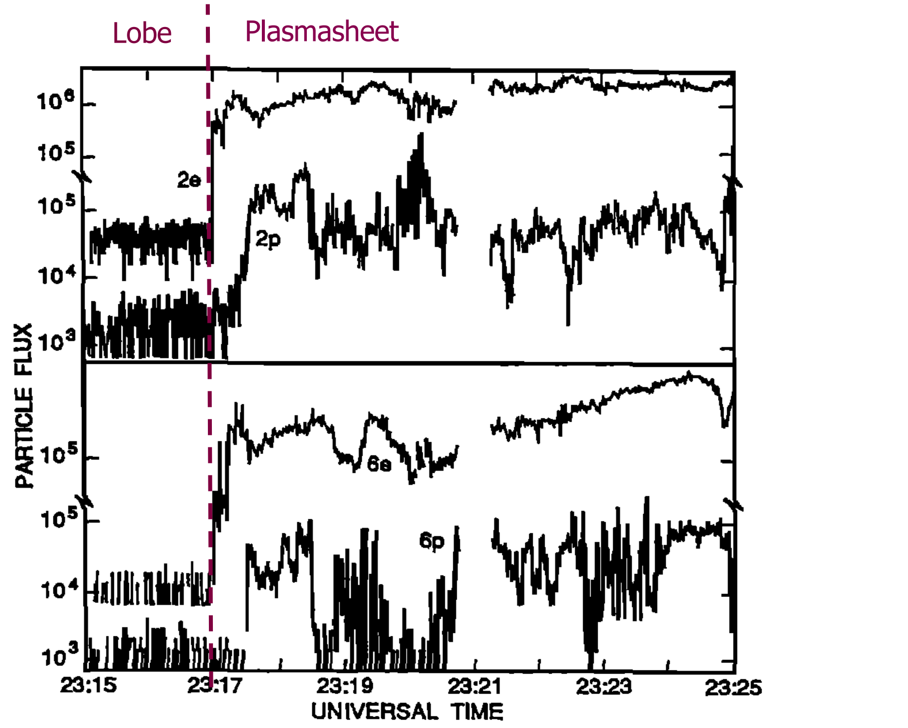
- Guiding center distribution

$$Q_\alpha(X_g) = \begin{cases} R_\alpha & , X_g < X_{g1} \\ R_\alpha + (S_\alpha - R_\alpha)\left(\dfrac{X_g - X_{g1}}{X_{g2} - X_{g1}}\right), & X_{g1} < X_g < X_{g2} \\ S_\alpha & , X_g > X_{g2} \end{cases}$$



- Obtain density

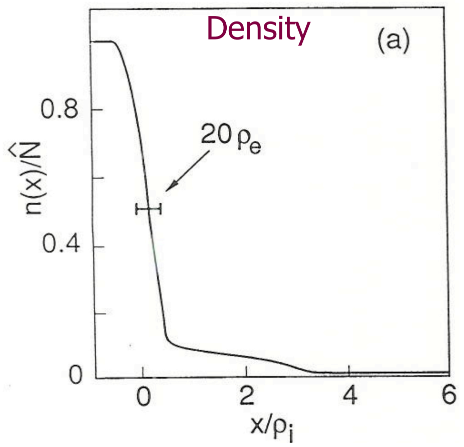
$$\int f_{0\alpha}(v, \Phi(x))\, dv = n_{0\alpha}(\Phi(x))$$

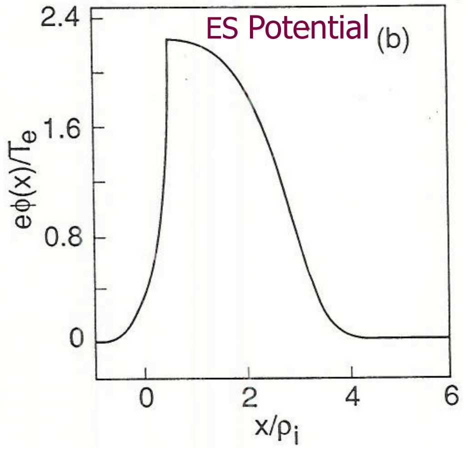


NASA/ISEE-1 data: Courtesy, George Parks

- Use quasi-neutrality to determine the electrostatic potential

$$\sum_\alpha n_{0\alpha}(\Phi(x)) = 0$$





[Romero et al., ***GRL***, 1990]

Effects of Transverse Electric Field Gradients

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- Affects zeroth-order plasma dynamics
  - Particle orbits in a magnetized plasma are affected
    - Particles can move across magnetic field lines

$$\Omega \rightarrow \underbrace{\sqrt{\eta(\xi)}\Omega}_{\text{Renormalized Gyro-frequency}}, \qquad \eta(x) = 1 + \frac{1}{\Omega}\frac{dV_E(x)}{dx}$$

  - Unique plasma distributions are created
    - Temperature anisotropy in x and y directions possible

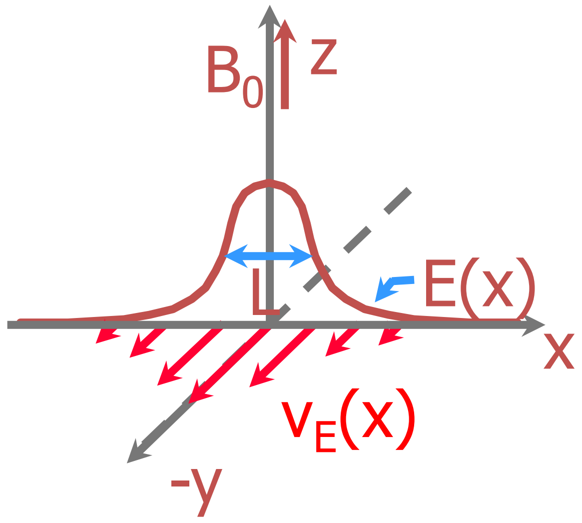
$$f_0(\xi, H) \approx \frac{n_0}{\sqrt{\eta(\xi)}}\left(\frac{\beta}{2\pi}\right)^{3/2} e^{\overbrace{-(\beta/2)(v_x^2+\eta(\xi)(v_y-<v_y>)^2)}^{Tx \neq Ty}} e^{-(\beta/2)v_z^2}$$

- where

$$\xi = x + (v_y - V_E(\xi)), \quad \beta = 1/v_{th}^2$$

$$V_E(\xi) = -cE(\xi)/B_0,$$

[Ganguli et al., ***Phys Fluids***. 1988]



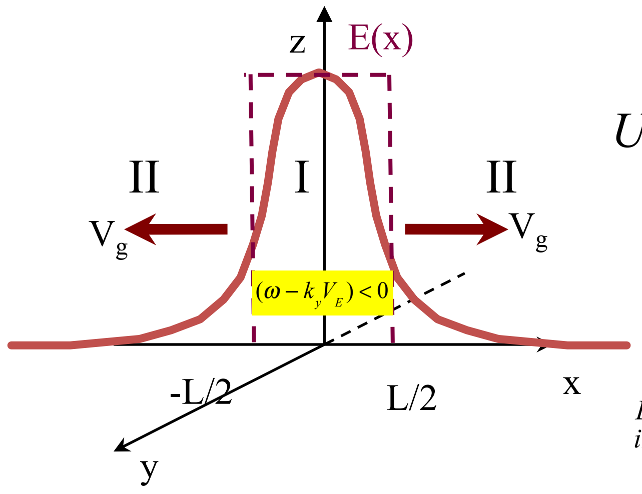
Kelvin-Helmholtz $(\omega - k_y V_E) << \Omega_i, k_y\rho_i < 1$

$$\left(\frac{d^2}{dx^2} - k_y^2 + \frac{k_y V_E''}{\omega - k_y V_E}\right)\phi_1(x) = 0$$

$$\frac{\partial}{\partial t}\int dx \left(\underbrace{\frac{|E_1|^2}{8\pi} + \frac{n_{0i}m_i}{2}\frac{|cE_1|^2}{B_0^2}}_{\text{Wave Energy}} + \underbrace{\frac{n_{0i}m_i}{2}|x_1|^2 V_E(x)V_E''(x)}_{\text{Energy Extracted Fron } E_0\times B_0 \text{ Drift}}\right) = 0$$

$$\underbrace{V_E^2(x)}_{\text{No Waves}} - \underbrace{\left\langle V_E(x+x_1)\right\rangle^2}_{\text{With Waves}} = -|x_1|^2 V_E(x)V_E''(x) + O(1/L^3)$$

IEDDI $(\omega - k_y V_E) \sim n\Omega_i, k_y\rho_i \geq 1$



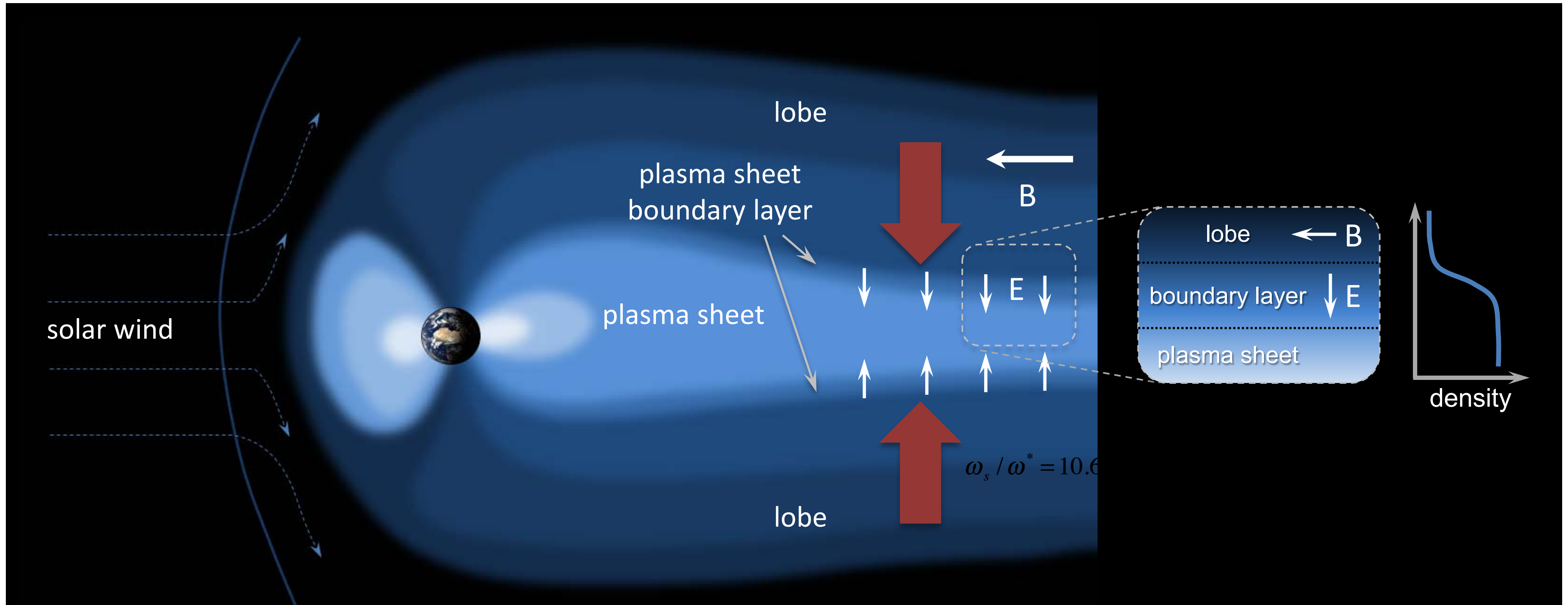
$$U \equiv \frac{\partial \omega D}{\partial \omega} \propto \omega \underbrace{(\omega - k_y V_E)}_{\text{Doppler-Shifted Frequency}}$$

$$\underbrace{\gamma U_I L A_{y,z}}_{\text{Energy Creation in Region-I}} = -\underbrace{V_g U_{II} A_{y,z}}_{\text{Energy Convection From Region-I}}$$

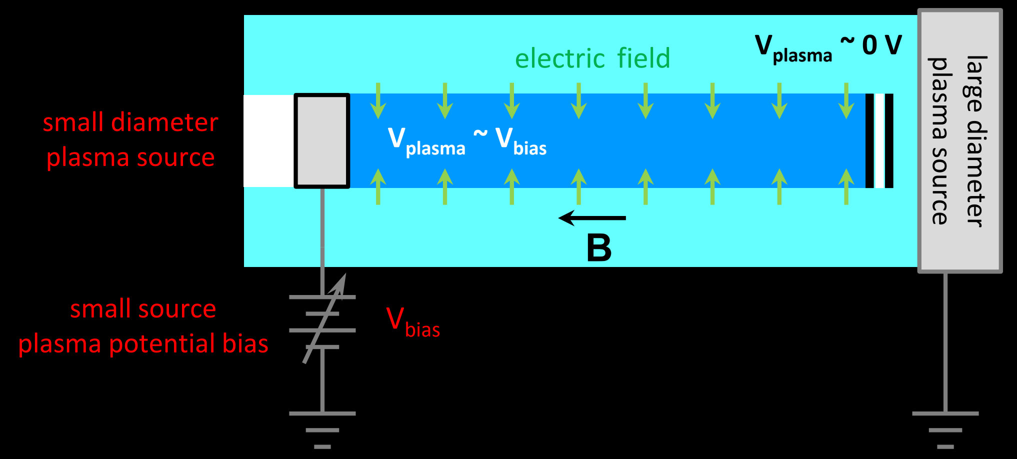
$$\gamma \propto -(U_{II}/U_I)$$

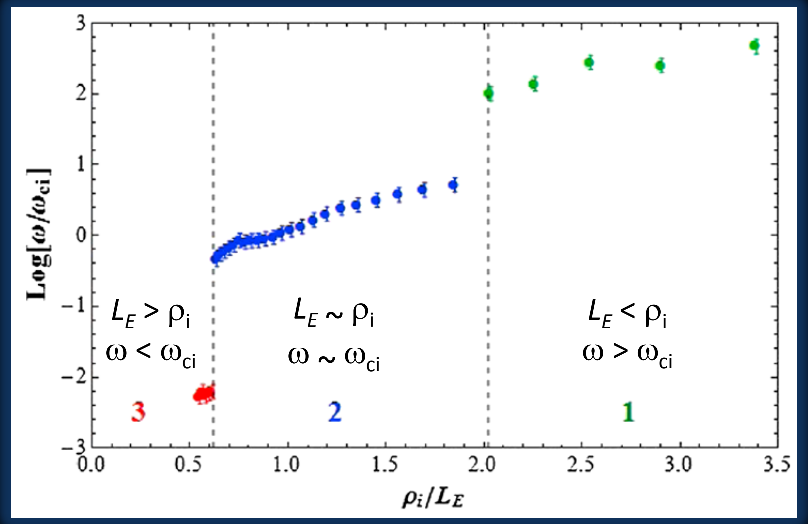
[Ganguli, ***PoP***, 1997]

Laboratory Study of Compressed Plasma Layer



Compression of the magnetosphere creates north-south dc electric field localized in the plasma sheet boundary layer





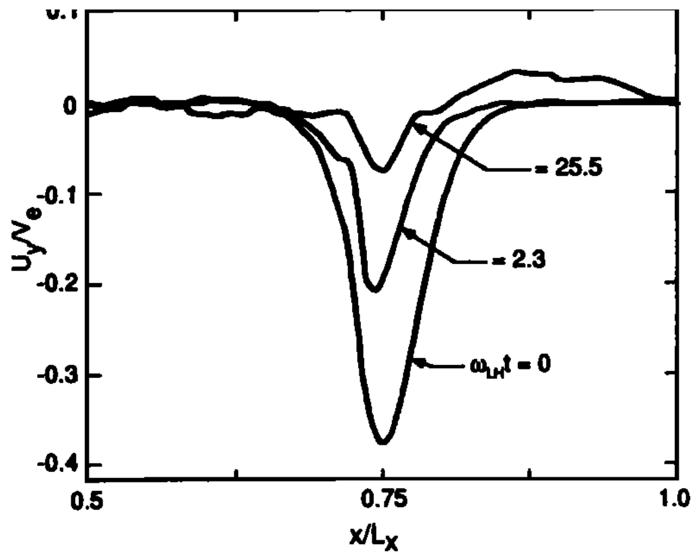
Laboratory simulation of the stressed boundary layer with localized radial electric field and axial magnetic field by inter penetrating plasma indicates emission of BEN

[Amatucci et al., ***PoP***, 2003]

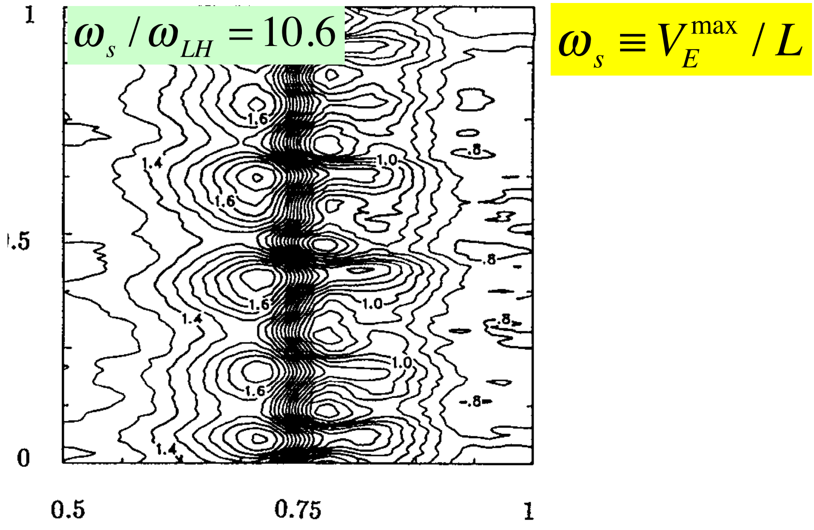
[DuBois et al, ***PRL***, 2013; ***JGR***, 2014]

21/2 D PIC simulation of EIH mode for $\rho_e < L < \rho_i$

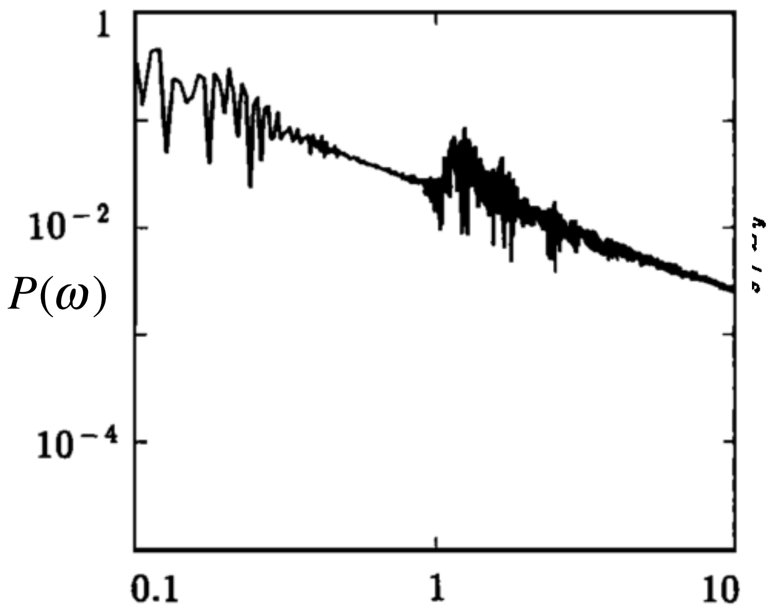
Relaxation of the initial flow

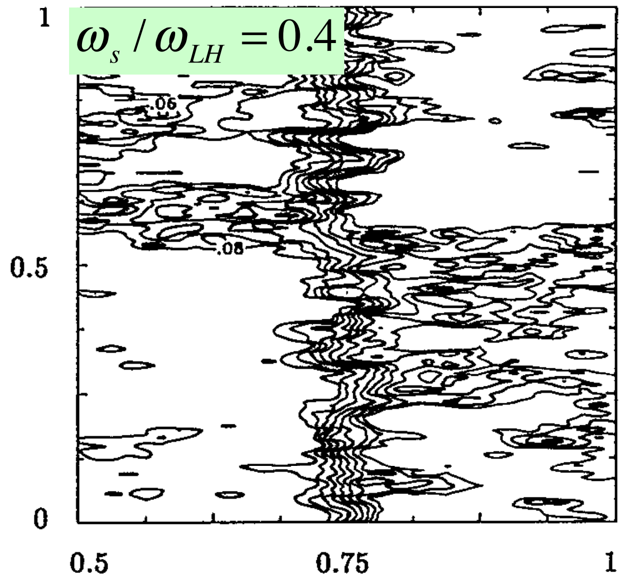


Contours of electrostatic potential



Broadband emission





[Romero and Ganguli, ***Phys. Fluids***, 1993; ***GRL***, 1994]

Laboratory Study of Dipolarization Fronts

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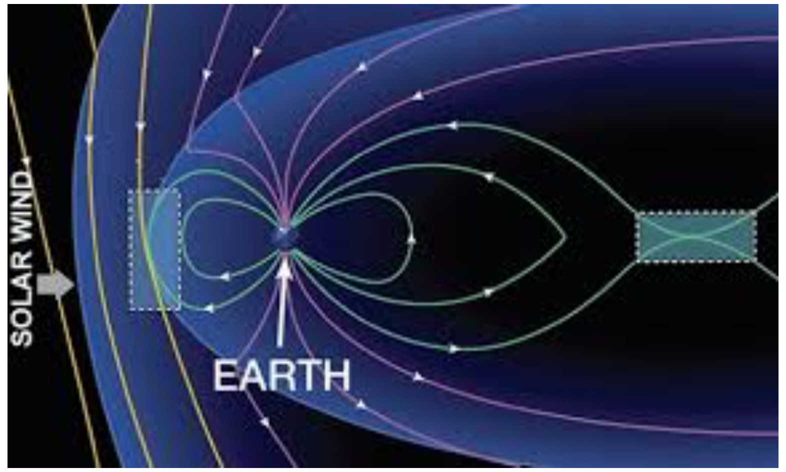
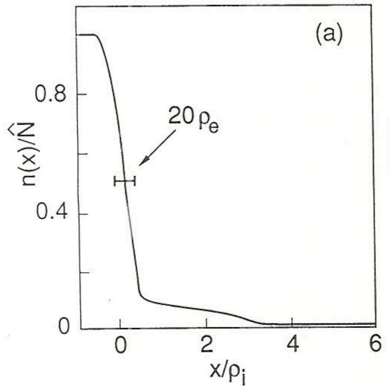
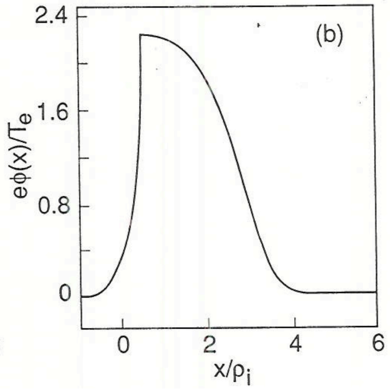
Dipolarization



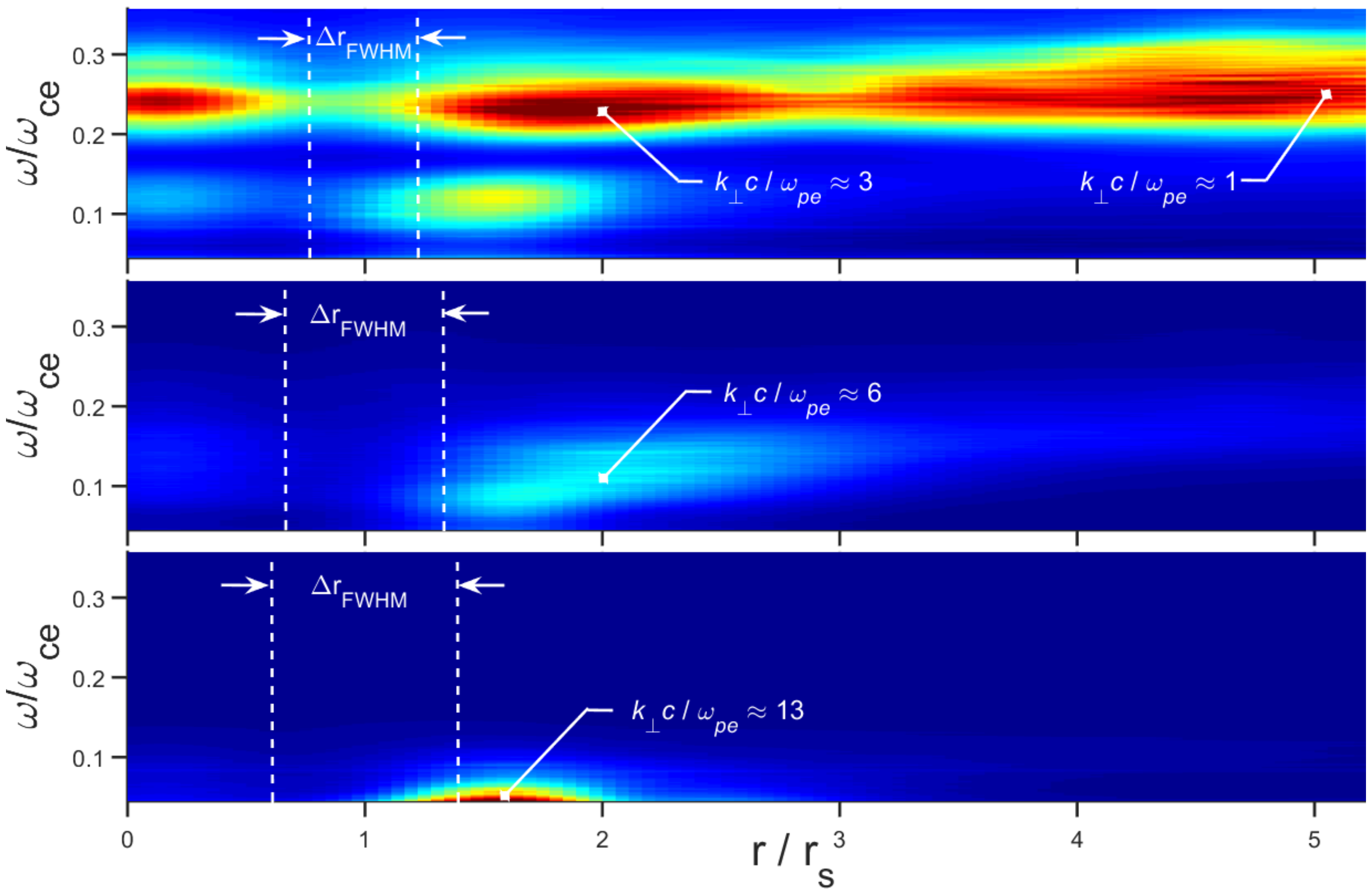
Density



Electrostatic Potential

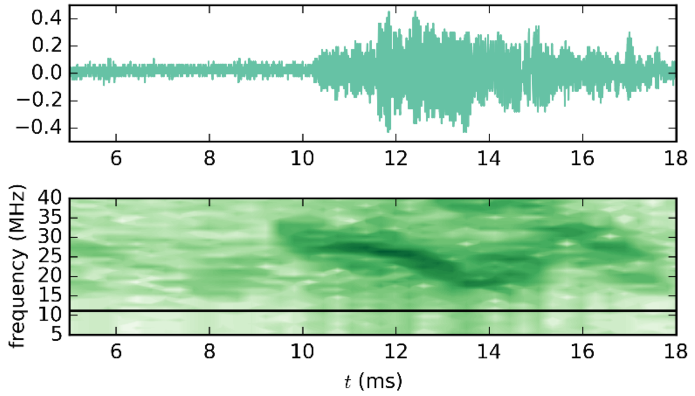


NRL Experiment on Compressed Plasma Layer

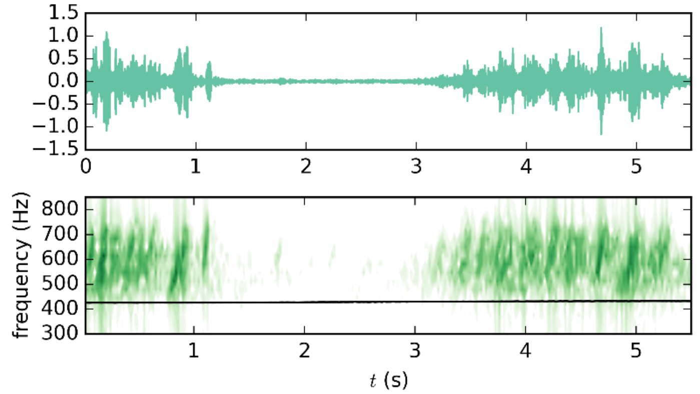


$$E_x = -ik_x\phi\left(1+\frac{\bar{k}_z^2}{\bar{k}_\perp^2}\right) \quad E_y = E_x\frac{i\omega}{\Omega_e \bar{k}^2} \quad E_z = -ik_z\phi\left(\frac{\bar{k}^2}{1+\bar{k}^2}\right)$$

Laboratory Data from NRL Experiments

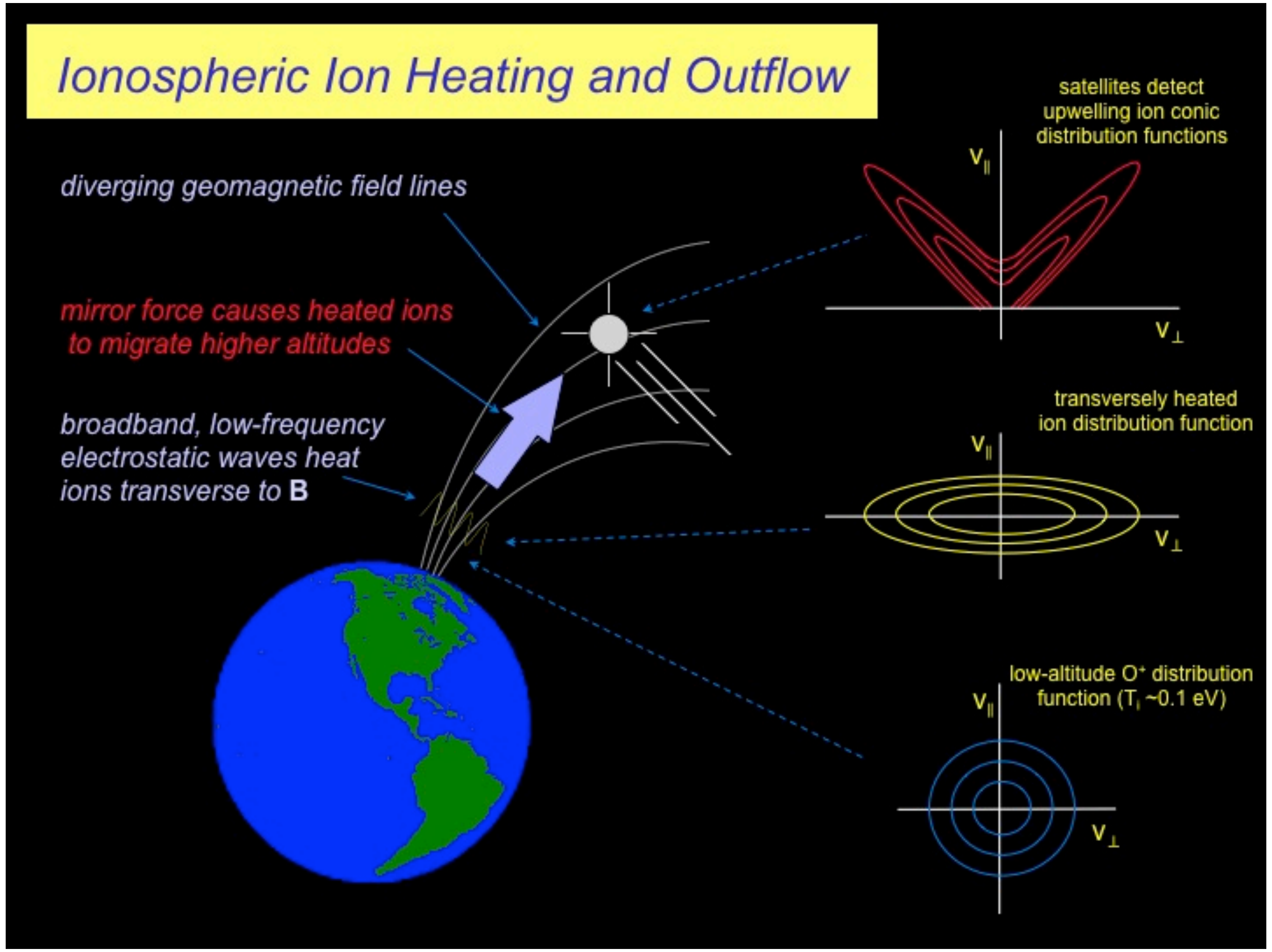


EMFISIS Burst Mode Waveform Data from Van Allen Probes

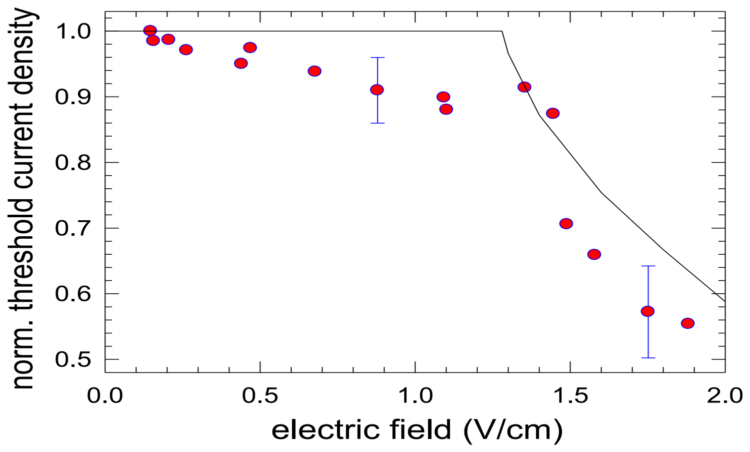


Seconds after 2012-11-14 05:40:32.437892

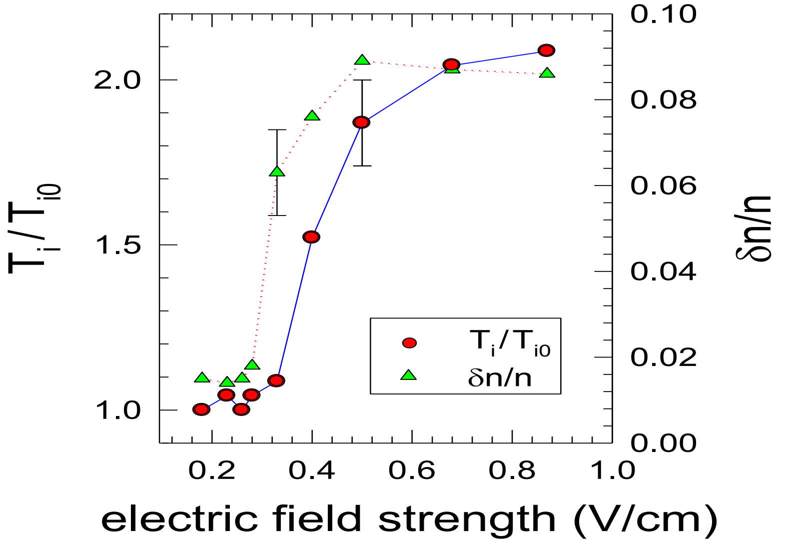
Ionospheric Plasma Phenomena: Auroral Region



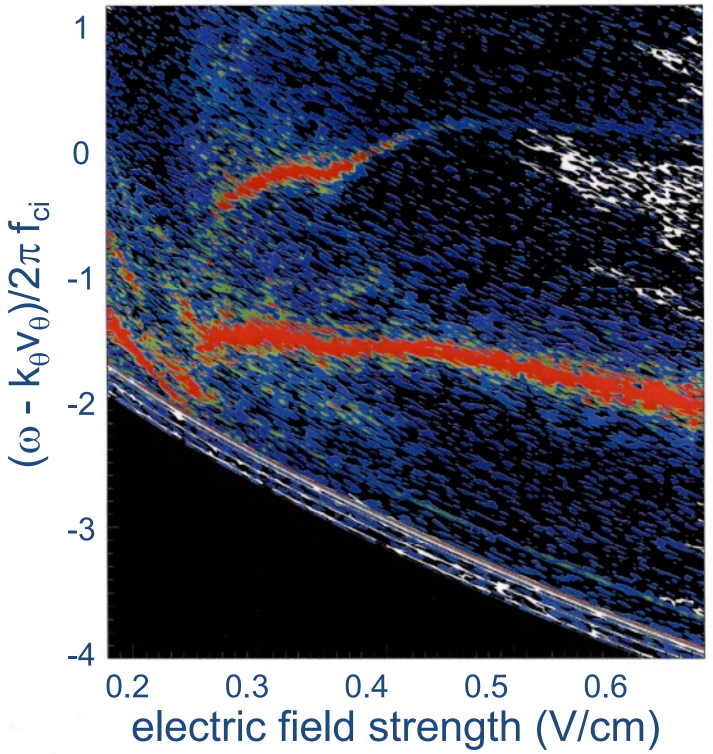
[Ganguli et al, ***JGR***, 1994]



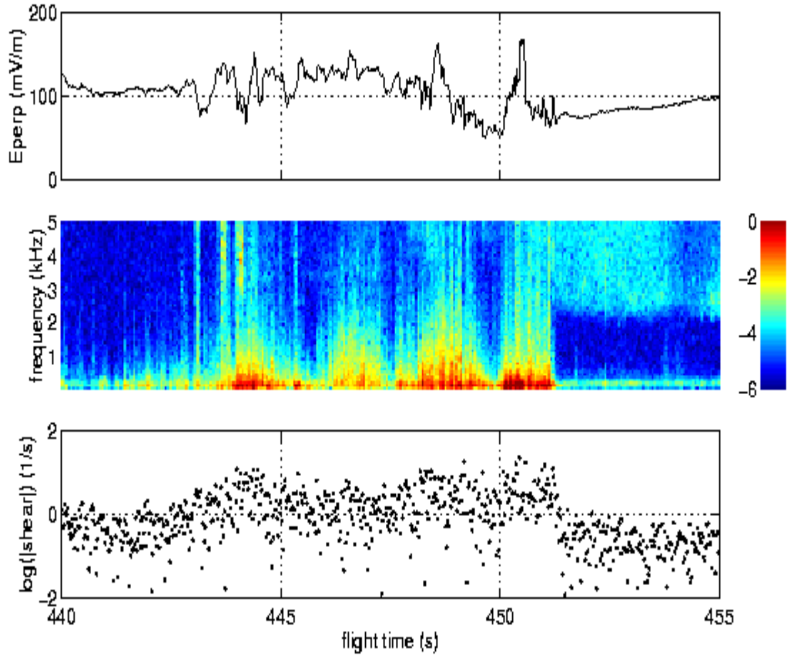
Amatucci et al., ***GRL***, 1994



Walker et al., ***GRL***, 1997,
Amatucci et al., ***JGR***, 1998



Good agreement with resonance condition



[FAST and POLAR data
J. Bonnell, Ph.D. thesis, Cornell U, 1996]

Physics of Multi-Ion Species Plasma

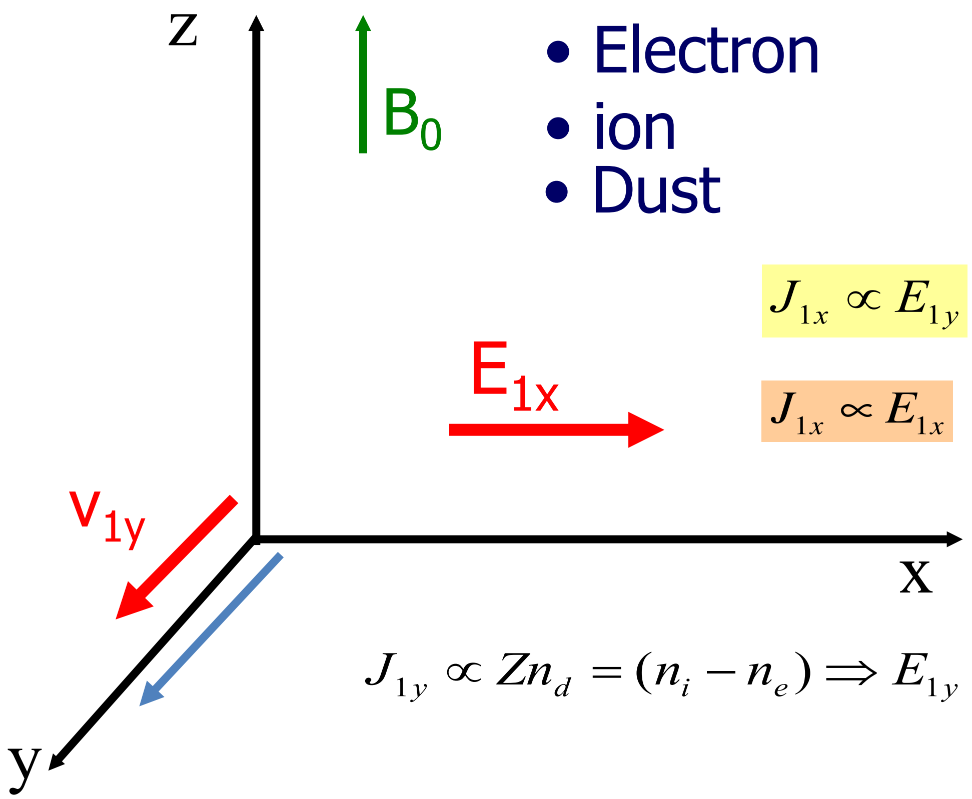
Origin of Rotation in a Dusty (Multi-Ion) Plasma

Since $E_0 = 0$, $J_0 = 0$, Quasi-neutral plasma with $k_z = k_y = 0$;

$$J_{1x} = -en_{0i}\frac{i\omega}{\Omega_i}\frac{cE_{1x}}{B_0} + Zen_{0d}\frac{cE_{1y}}{B_0}$$

$$\nabla \cdot J_1 = 0 \Rightarrow ik_x J_{1x} = 0$$

$$\frac{E_{1x}}{E_{1y}} = -i\left(\frac{Zn_{0d}}{n_{0i}}\right)\left(\frac{\Omega_i}{\omega}\right) = -i\left(\frac{n_{0e}}{n_{0i}}\right)\left(\frac{\Omega_r}{\omega}\right) \approx -i\left(\frac{\Omega_r}{\omega}\right) \qquad \Omega_r = \frac{Zn_d}{n_e}\Omega_i$$



Near resonance ($\omega \approx \Omega_\rho$): $E_{1x} = -iE_{1y}$

- Important differences:
  - only a mean fluid rotation
  - $\omega \approx \Omega_\chi$ implies a wave resonance, $k \rightarrow \infty$, wave predominantly ES
  - $\omega \approx \Omega_\rho$ implies a wave cut-off, $k \rightarrow 0$, wave predominantly EM

Effect of Rotation Wave Resonance

Energy Density of the Rotation Waves

$$\varepsilon_w = \underbrace{\frac{\langle B_1^2 \rangle}{8\pi}}_{field-energy} + \underbrace{m_i n_i \frac{\langle v_1^2 \rangle}{2}}_{kinetic-energy} = \frac{\langle B_1^2 \rangle}{8\pi}\left(1 + \frac{\omega^2}{\omega^2 - \Omega_{r0}^2}\right)$$

- Near ($\omega \approx \Omega_r$) most of the wave energy is kinetic energy of light ion rotation
- Unlike classical 2-component MHD, the ions can possess a lot of energy
- A possible source of ion energization

Ponderomotive force (for $k_y = k_z = 0$)

$$\vec{F}_p = -\frac{\partial}{\partial x}\left(\frac{|\vec{B}_1|^2}{16\pi}\frac{\Omega_{r0}^2}{(\omega^2 - \Omega_{r0}^2)}\right)\hat{x} + k_x \frac{|\vec{B}_1|^2}{8\pi}\frac{\Omega_{r0}^2}{(\omega^2 - \Omega_{r0}^2)}\hat{y}$$

- Ponderomotive force can be magnified by the rotation resonance
- Ideal for 1-dimensional force balance

Since Ω_r represents a cut-off the wave is not damped as $\omega \rightarrow \Omega_\rho$

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Electromagnetic Waves in Multi-Ion Species Plasma

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- Consider a 3-species (ion, Electron, and dust) plasma

- For short wavelength ($kl_d >> 1$) recover Alfven and magnetosonic waves with minor frequency corrections

$$\omega = kV_A\left(1+\frac{1}{2k_x^2 l_d^2}\right)$$

Magnetosonic branch

$$\omega = k_z V_A\left(1-\frac{1}{2k_x^2 l_d^2}\right)$$

Alfven branch

$$l_d = \frac{V_A}{\Omega_r}$$

Dust Hall Length

$$\Omega_r \approx \frac{Zn_d}{n_e}\Omega_i$$

New "Rotation" Frequency

- For long wavelength ($kl_d << 1$) two new branches appear

$$\omega^2 = \Omega_r^2 + (k^2 + k_z^2)V_A^2$$

Alfven-Magnetosonic Hybrid Wave
Similar to Langmuir waves

$$\omega^2 = k_z^2(k_z^2 + k_x^2)V_A^4 / \Omega_r^2$$

Ion Whistler Wave

$$k_z \approx 0 \rightarrow \omega^2 = \Omega_r^2 + k_\perp^2 V_A^2$$

$$\omega^2 = \omega_{pe}^2 + k^2 V_{th}^2$$

Langmuir wave

[Ganguli and Rudakov, ***PRL***, 2004; Ganguli and Rudakov, ***PoP,*** 2005]

Turbulence in Multi-Ion Species Plasma: Strong? Weak? Both? Composite?

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Strong turbulence? Similar to Langmuir turbulence

$$i\frac{\partial \mathrm{v}_{1s}}{\partial t} = \delta\Omega \mathrm{v}_{1s} - \frac{V_A^2}{2\Omega_r}\frac{\partial^2 \mathrm{v}_{1s}}{\partial x^2}$$

- Fast time-scale is Ω_r ($\equiv \omega_{pe}$)
- Slow time-scale is dust kV_A ($\equiv kc_s$)

$$\delta\Omega = \delta\left(\frac{ZeBn_d}{m_i c n_e}\right) = \Omega_r \frac{\delta n_d}{n_{d0}} = \Omega_r \frac{\delta B}{B_0}$$

- Long time average: $t \gg 1/\Omega_r, 1/\Omega_d$
- Nonlinear frequency shift, $\delta\omega$, due to ponderomotive force

$$i\frac{\partial \mathrm{v}_{1s}}{\partial t} = -\Omega_r \frac{|\mathrm{v}_{1s}|^2}{V_A^2}\mathrm{v}_{1s} - \frac{V_A^2}{2\Omega_r}\frac{\partial^2 \mathrm{v}_{1s}}{\partial x^2}$$

- The nonlinear Schrodinger Equation
- Solutions: Solitons

Unlike Langmuir Waves no Dissipation as Wavelength Approaches l_d

Turbulence in Multi-Ion Species Plasma: Strong? Weak? Both? Composite?

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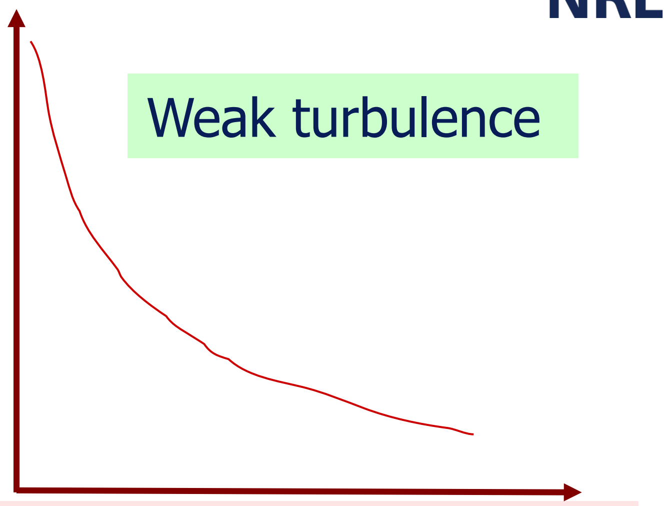
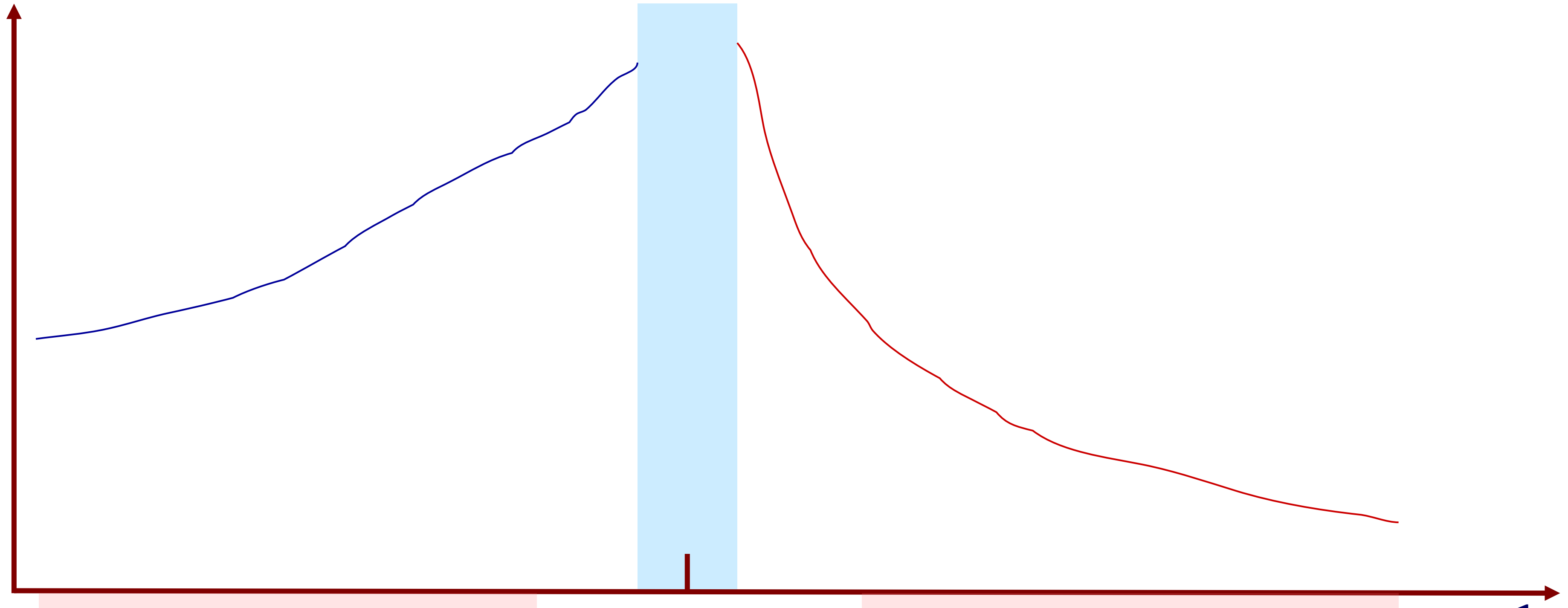
Weak turbulence? Similar to Kolmogorov Cascade of Alfven waves

$$(\omega^2 = \Omega_r^2 + k_x^2 V_A^2) \to \quad \omega = k_z V_A \left(1 - 1/2k_x^2 l_d^2\right) \quad \text{and} \quad \omega = kV_A \left(1 + 1/2k_x^2 l_d^2\right)$$



Both? Composite?



- Strong turbulence dominates for k << k_d but breaks down for k ≃ k_d
- Collapse towards k_d pumps weak turbulence for k >> k_d
- Peak in energy density at k_d
- Typical structure scale size ~ l_d

$$k_d = l_d^{-1} = \Omega_r / V_A \qquad \Omega_r \approx \frac{Zn_d}{n_e}\Omega_i$$

Astrophysical Relevance

Molecular Clouds

This cloud of gas and dust is being deleted. Likely, within a few million years, the intense light from bright stars will have boiled it away completely. The cloud has broken off of part of the Carina Nebula, a star forming region about 8000 light years away. CREDIT: Hubble Heritage Team (STScI/AURA), N. Walborn (STScI) & R. Barbß (La Plata Obs.), NASA.

Artist Rendition Based on Observations

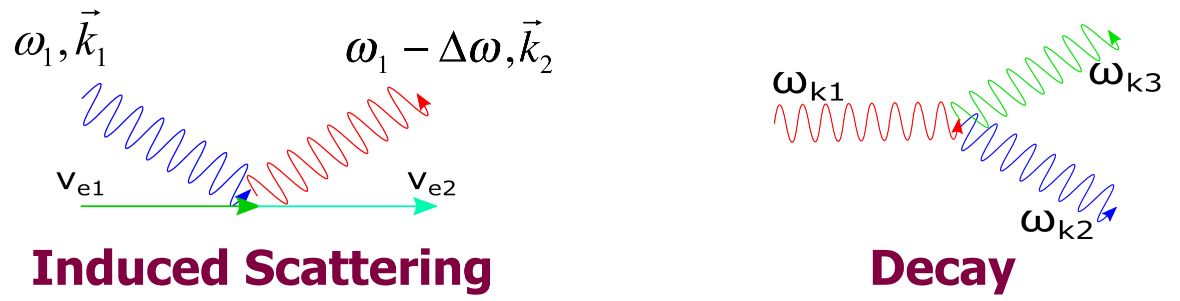
- $kV_A \sim \Omega_r$ defines structure (filament) scale size
- $l_d \sim V_A / \Omega_r \sim (c / \omega_{pi})(n_e / Zn_d)(n_i / n_e)^{1/2}$
- $n_e \sim 10^{-3}$cc, $n_d \sim 10^{-8}$ cc, $c / \omega_{pi} \sim 10^9$ cms
- $l_d \sim 10^{14}$ cms ~ 10 AU

[Ganguli and Rudakov, ***PRL***, 2004; Ganguli and Rudakov, ***PoP***, 2005]

Astrophysical Turbulence and Transport: Kolmogorov Type Cascade and/or Strong Turbulence?

Condensation

In 1D case there is no collapse



- Repeated scatterings of rotation waves leads to longer wavelengths
  - Dispersion progressively vanishes
  - Reminiscent of Bose-Einstein Condensation (BEC)
    - The rotation frequency represents the ground state

$$(\omega^2 = \Omega_r^2 + k_x^2 V_A^2) \quad \Rightarrow \quad (\omega^2 \approx \Omega_r^2)$$

- Condensates are long-lived structures
  - Condensate scale size L >> l_d

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Conclusions

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- Many inherent problems with in-situ measurements can be addressed through laboratory experiments
  - Space-time ambiguity
  - Unsteady plasma
- Provide complete characterization of a physical process
  - Repeated measurements possible in laboratory
- Laboratory experiments of triggered emission at NRL have led to a more comprehensive analysis of NASA/Van Allen Probe chorus data to show
  - Stepwise nature, presence of multiple waves, 3D wave propagation, signatures of induced scatterings, etc.
- Led to deeper understanding of the cause and effects of transverse electric fields
  - New class of broadband waves were found correlated with plasma compression which clarified unexplained auroral observations
  - This knowledge is now being used to understand the plasma dynamics of compressed layers, e.g., dipolarization fronts