Plasma Turbulence in Nature and Laboratory

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Turbulence: Fundamental Yet Practical

- Fundamental to understanding the natural plasma environments
  - Astrophysical
  - Heliospheric
  - Magnetospheric
  - Ionsopheric

- Practical importance in controlling the plasma environments in
  - Laboratory devices
    - Tokamaks heating and confinement, etc.
  - Near-earth space
    - Satellite lifetime
    - Space weather

Turbulence Pervades Most Plasma Domains

State-of-the-Art

- Dimensional analysis (Kolmogorov)
- Limiting cases of turbulence
  - Strong coherent processes
    - NLS equation, solitons, etc.
    - Trapping, frequency chirping, triggered emission
  - Weak Incoherent processes
    - Ensemble of waves with random phase
    - Hydrodynamic (Wave-wave interactions)
      - Maxwellian distribution assumption
    - Kinetic (Wave-particle interactions)
      - Nonlinear Landau damping
      - Quasilinear diffusion

- Low ($\lceil < \wedge_i$) or intermediate ($\wedge_i < \rceil < \wedge_e$) frequencies
  - Cross over in inhomogeneous environments
    - Boundary layers

The Frontier

- The challenges are in understanding the overlap regions
  - Strong to weak
  - MHD to kinetic (meso-scale)
  - Electrostatic to electromagnetic
  - Homogeneous to inhomogeneous
  - Low ($\lceil < \wedge_i$) to intermediate ($\wedge_i < \lceil < \wedge_e$) frequencies
  - Laboratory to natural

- Need coordinated approach
  - Analytical
  - Numerical
  - Experimental
    - Laboratory
    - Space

Turbulence Characteristics in Hybrid Domains Least Known

Strong to Weak: Multi-Species Plasmas

- **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 Frequency

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

$$w^2 = k_z^2(k_z^2 + k_x^2)V_A^4 / W_r^2$$

Ion Whistler Wave

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

Alfven-Magnetosonic Hybrid Wave
Similar to Langmuir waves

$$w^2 = w_{pe}^2 + k^2 V_{th}^2$$

Langmuir wave

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

Strong Turbulence for Long Wavelength

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 $\wedge_r$ (≡ ω_{pe})
- Slow time-scale is dust kV_A (≡ kc_s)

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

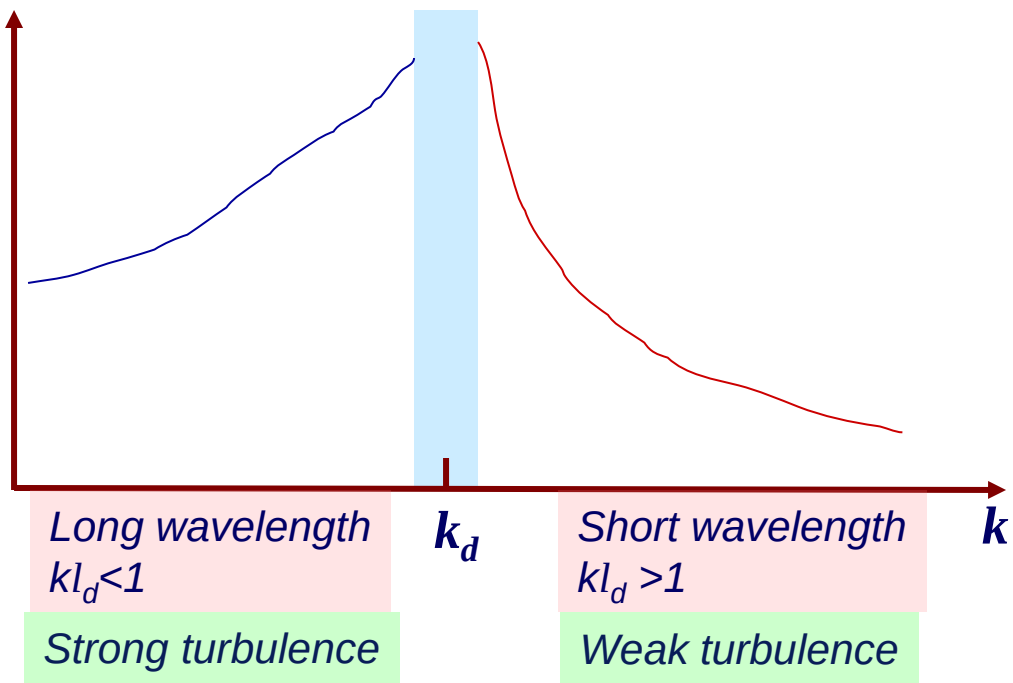
- Long time average: t >> 1/ $\wedge_r$,1/ $\wedge_d$
- Nonlinear frequency shift, ™ω , due to ponderomotive force

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

- The nonlinear Schrodinger Equation
- Solutions: Solitons

Unlike Langmuir Waves no Dissipation as Wavelength Approaches l_d

Weak Turbulence for Short Wavelength



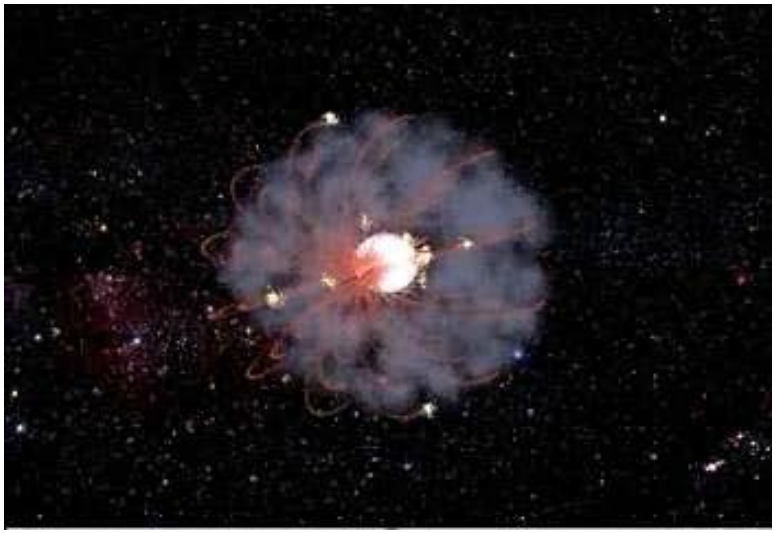
- **Strong turbulence dominates for $k \ll k_d$ but breaks down for $k \simeq k_d$**
- **Collapse towards k_d pumps weak turbulence for $k \gg k_d$**
- **Peak in energy density at k_d**
- **Typical structure scale size ~ l_d**

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

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

Astrophysical Relevance

Molecular Clouds



Artist Rendition Based on Observations

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

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

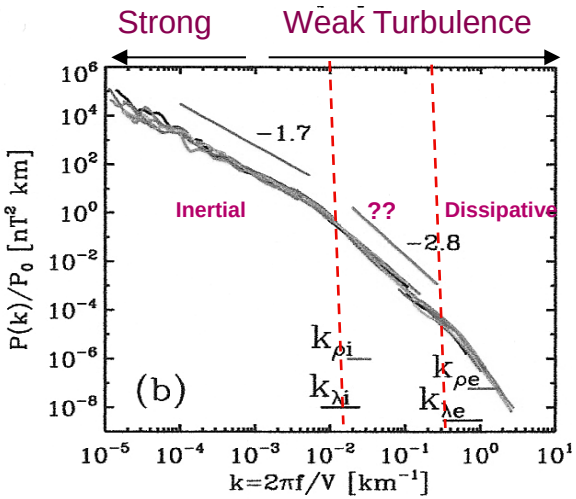
MHD to Kinetic: Heliospheric Plasmas

- **Observation in solar wind**
  - **Turbulence energy spectrum non-Kolmogorov**
  - **Appearance of spectral steepening at $k\rangle_i \sim 1$**

- **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 $k\rangle_i \geq 1$ in collisionless SW if Landau damping is negligible compared to NL rates**

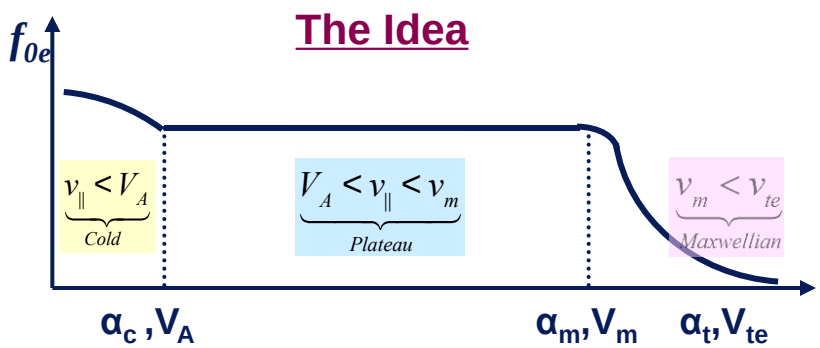


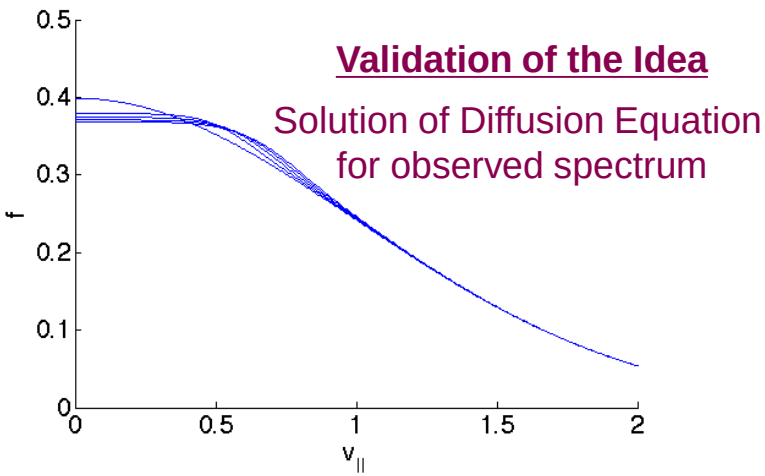
From Alexandrova et al. PRL (2009), Cluster data.

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

Evolution of f_{0e} 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





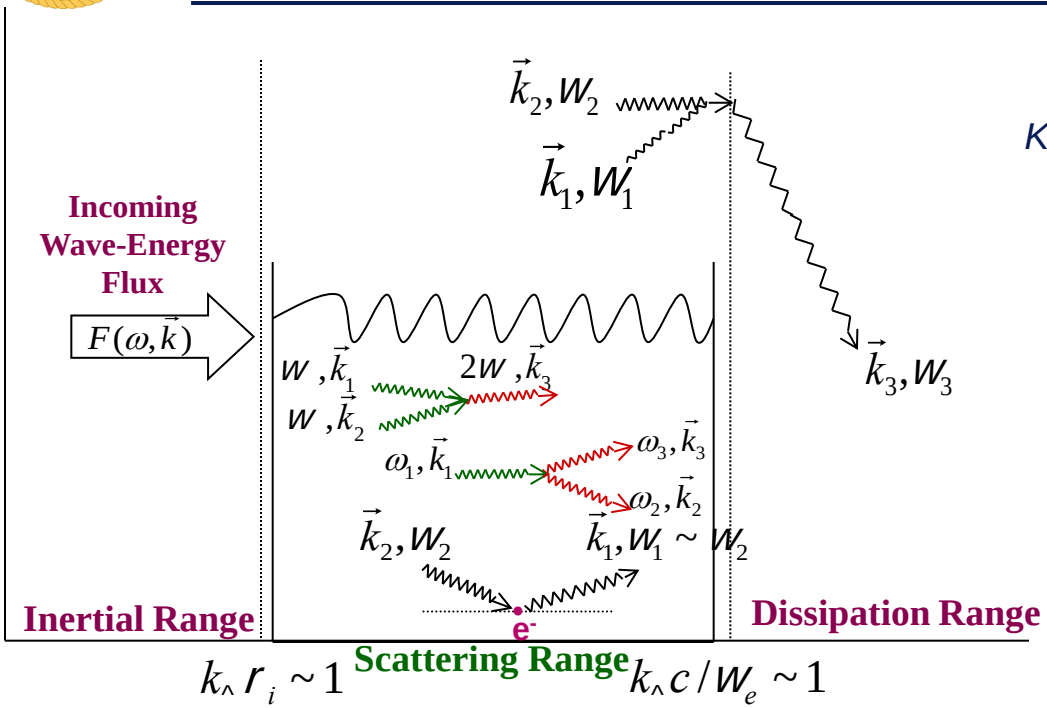
- Electron density redistributed in 3 components:

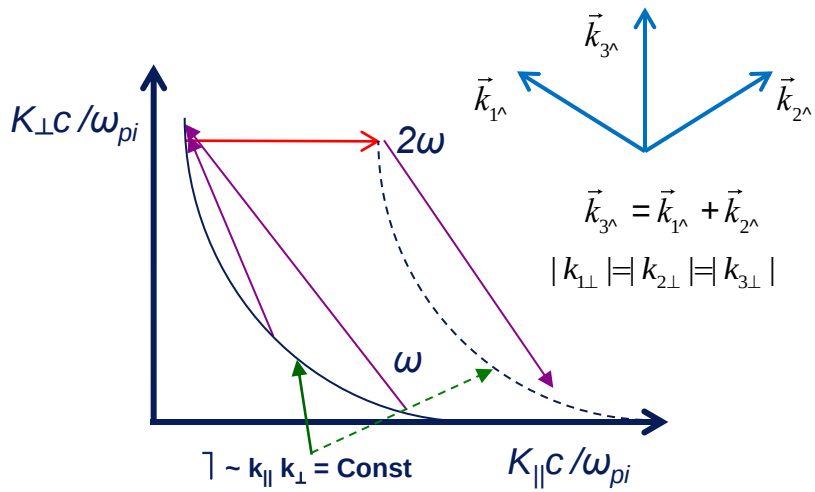
  Cold, Plateau and Maxwellian; in fractions $\langle_c, \langle_m, \langle_t$

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

Plateau in Electron Distribution Can be Established on SW Transit Time Scale

Solar Wind Turbulence: Schematic Model





(a) W-P Scattering create a wave with same ⌉, larger $|k_\perp|$ and smaller $k_{||}$

(b) W-W Coalescence creates waves with 2⌉, same $|k_\perp|$ and $2k_{||}$

(c) W-P scattering once again creates a Wave with 2⌉, smaller $k_\perp$ and larger $k_{||}$

(d) The cycle repeats to create waves with 4⌉ and 4 $k_{||}$ and so on

(e) For short enough wavelengths W-W coalescence can eject waves into the dissipation range

Strong Turbulence

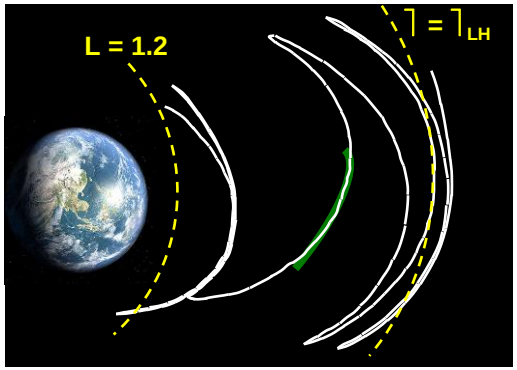
Formation of Plateau Weak Turbulence

[Rudakov et al., PoP, 2011]

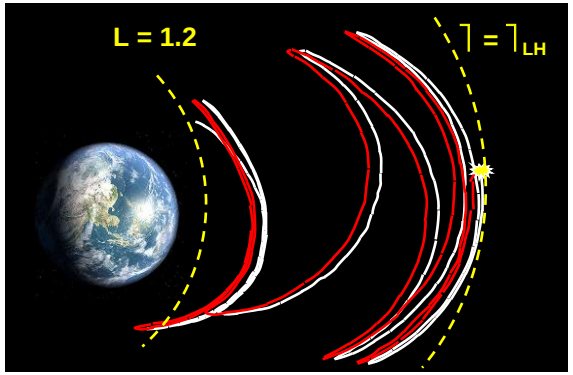
Does the MHD Turbulence Morph into Weak Turbulence? Or Do They Coexist?

Electrostatic to Electromagnetic

Fate of lightning generated whistlers in the ionosphere



Without Nonlinear Scattering



With Nonlinear Scattering

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

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

Cyclotron resonance time ($\lfloor_{int}$) given by ($\rceil - k_{||}V_{||} - n\wedge_e(r)) \simeq 0$

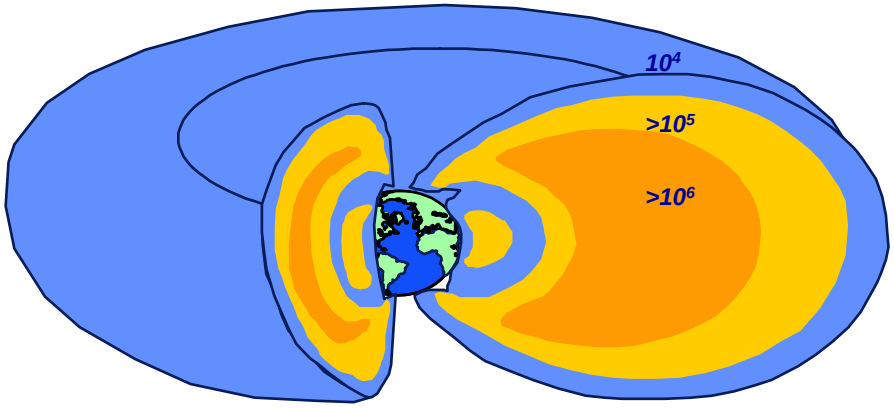
Satellite Lifetime Inversely Proportional to Trapped Electron Population

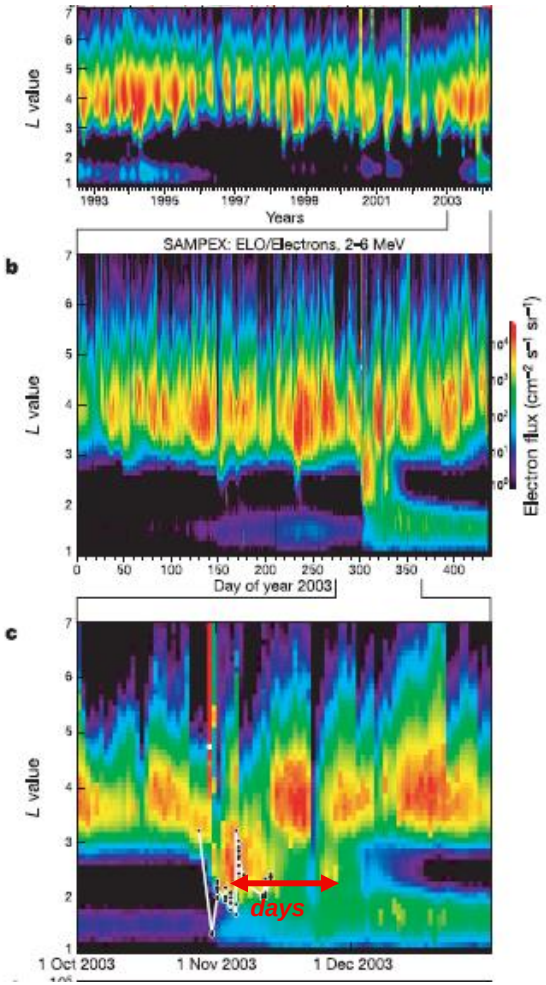
[Ganguli et al., PoP, 2010; Crabtree et al., PoP, 2012]

Consequences On Radiation Belts: Control of Trapped Population

- **Storm-enhanced radiation belts can return to ambient values sometimes**
  - **Not always. Why?**
- **Quasi-linear theory cannot explain this behavior**

Natural Electron Flux ($e^-/cm^2/s$)





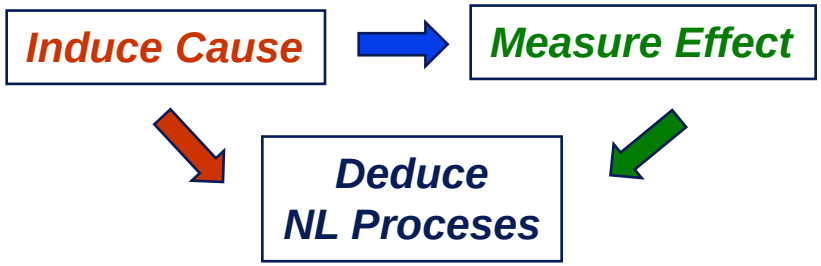
Haloween 2003 Storm, SAMPEX
Baker et al, Nature, 2004

Laboratory to Space

- **Bounded laboratory devices cannot exactly reproduce development of turbulence in unbounded natural systems**
  - **But critical physics can be examined in controlled laboratory conditions**
  - **Lab experiments are repeatable and initial conditions are known**

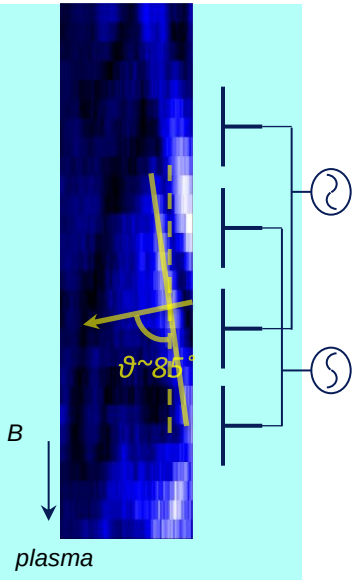
- **Natural observations of turbulence are generally in a developed state**
  - **Initial conditions are unknown**

- **Active experiments in space provide knowledge of both initial and final states in turbulence evolution for a unbounded system**
  - **Both cause and effect is necessary to validate the physical process**



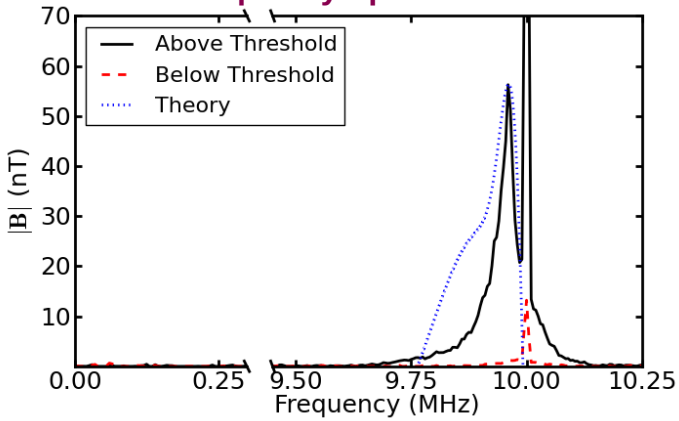
Example 1:
Electrostatic to Electromagnetic Conversion

NRL Space Chamber

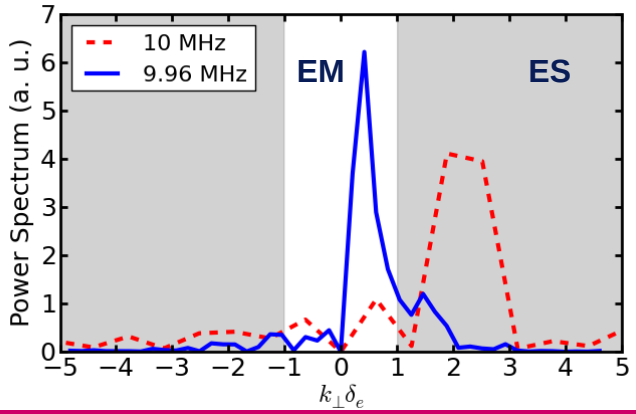


- **Laboratory test limited by band width of waves that can be generated in a laboratory device**
- **Boundary conditions may not be exactly as in space**
- **Accurate measurements and repeatability in laboratory a major benefit to understand the detailed physics**

Frequency Spectrum



Wave Vector Spectrum



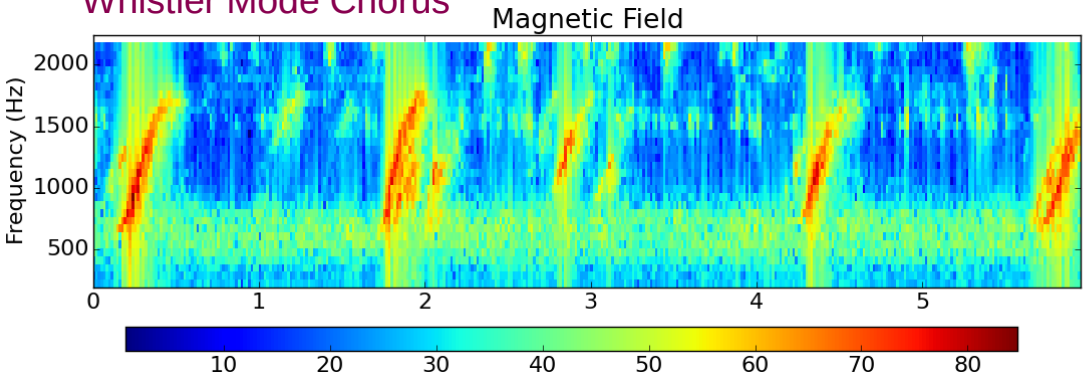
Nonlinear Conversion of ES Lower Hybrid Waves into EM Whistler Waves

[Tejero et al., PoP, 2015 (in press)]

Example 2:
Coherent Processes Embedded in Turbulence

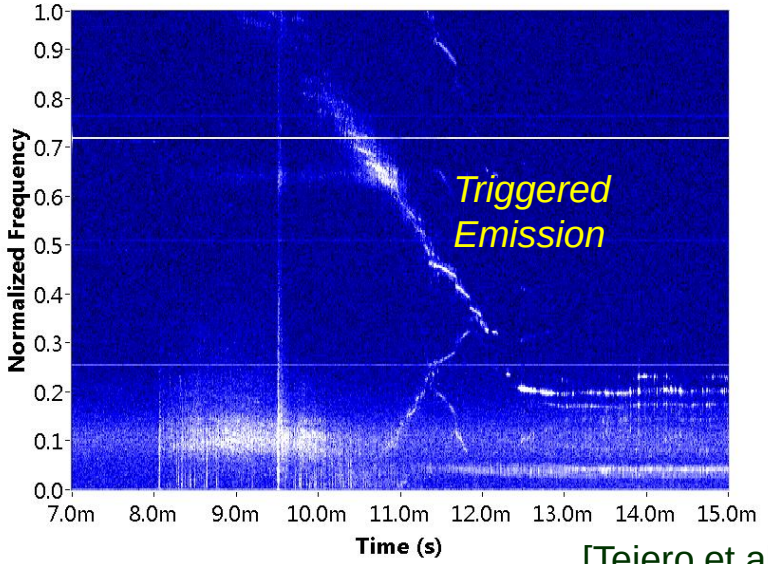
Triggered Emission in Tokamaks and Radiation Belts

Whistler Mode Chorus

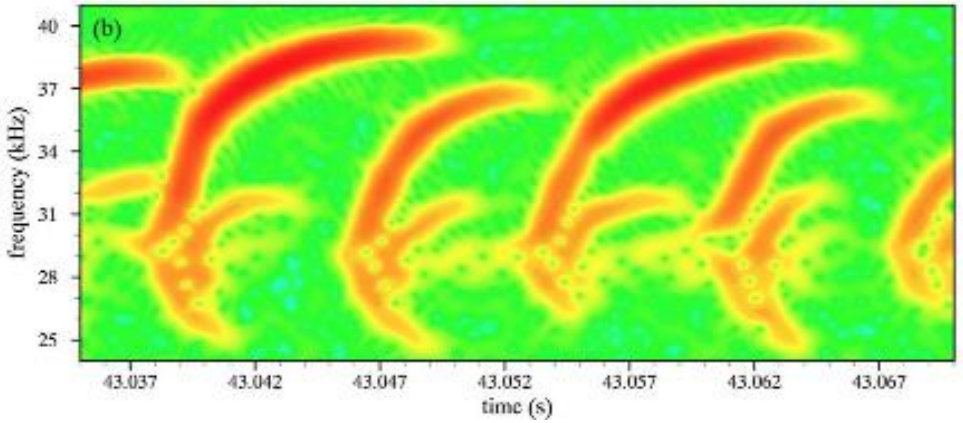


- **Frequency Chirping is a ubiquitous nonlinear plasma phenomenon, generally thought to be due to strong nonlinear wave-particle interaction.**
- **Most current models of these phenomenon have strong assumptions on locality of mode structure, coherency of mode, and adiabaticity of nonlinear particle motion.**
- **The frontier is to consider these phenomenon in more general, turbulent settings.**

Whistler Chirping in NRL Space Chamber



(n=0 Toroidal Mode Number) MHD Chirping in JET

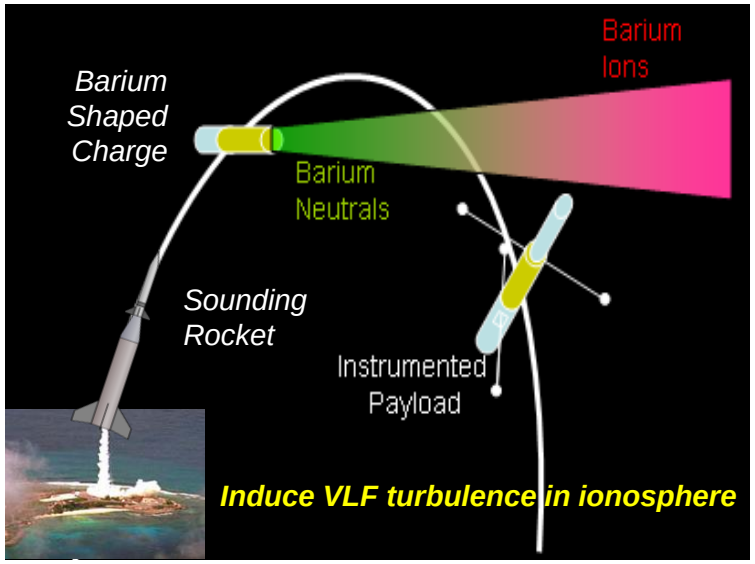


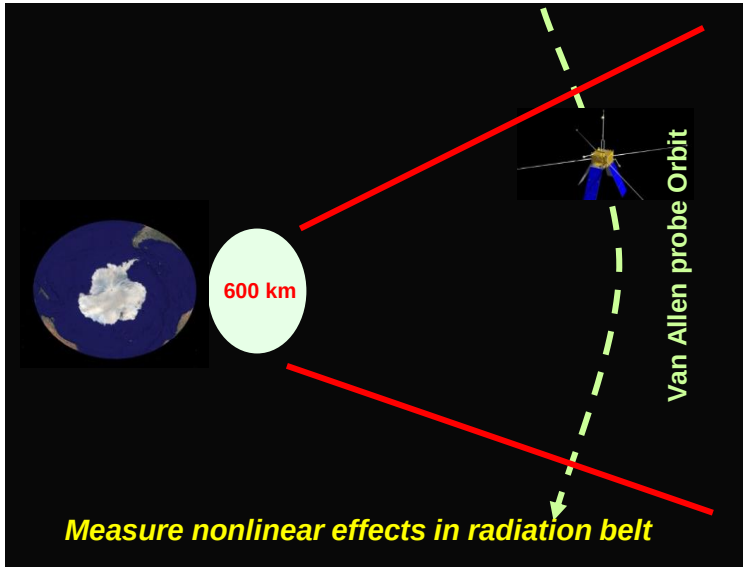
[Tejero et al., Bull APS/DPP, 2014]

Example 3:
Active Turbulence Experiment in Space

Space Measurement of a Rocket-Released Turbulence (SMART)

- **Perform rocket-based experiment to characterize nonlinear scattering in space**
  - **Seed intense lower hybrid waves by energetic ion ring beam**
  - **Enable nonlinear scattering of the LH waves into whistler/magnetosonic waves**
  - **Measure amplitudes of scattered whistler/magnetosonic waves**
- **Experiment necessary**
  - **To understand weak turbulence properties of radiation belts**

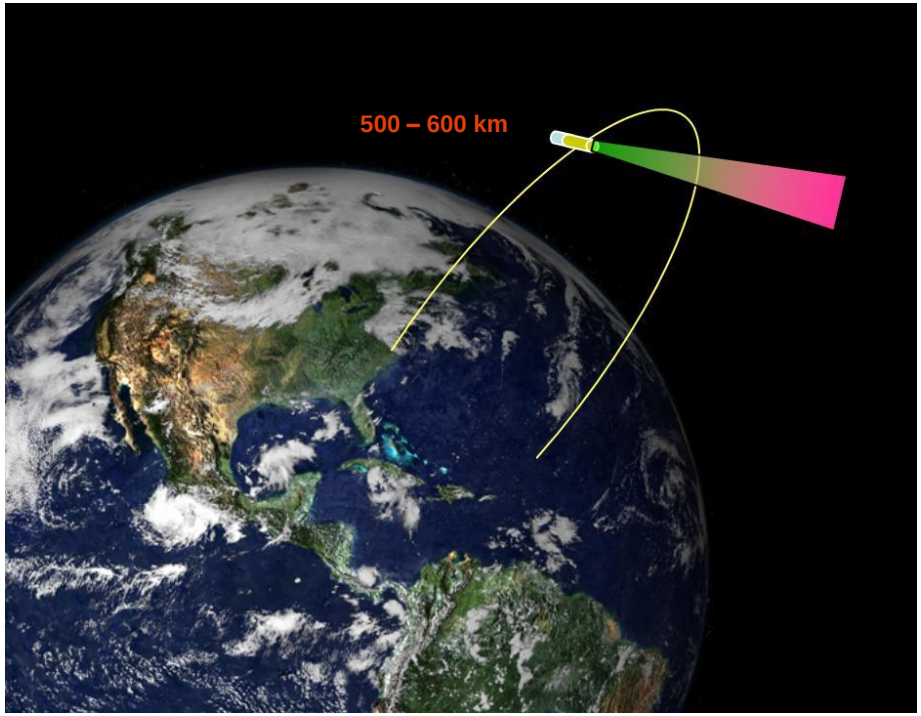




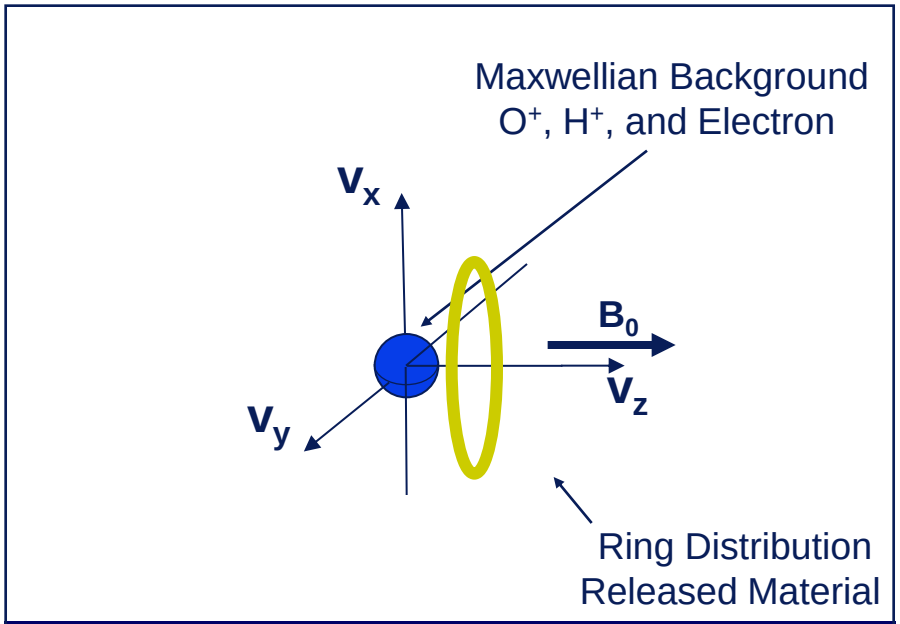
[Amatucci et al., Bull APS/DPP Meeting, 2014]

Essential Physics to be Gleaned

Release Neutral Gas Perpendicular to B_0



Ionized Neutral Atoms Form Ring Beam Distribution



Kinetic Energy of Neutrals

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Anisotropic Plasma Distribution

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Electrostatic Turbulence at LH & Ion Cyclotron Frequency

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Nonlinear Scattering by Plasma Particles

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Electromagnetic Turbulence

Generation of EM Waves Through Nonlinear Scattering by Thermal Particles

Open Questions

- **Is plasma turbulence either strong or weak? Can the two types of turbulence coexist with spatial and temporal scale separation or overlap in meso-scales?**
- **What is the criterion for seamless transition of hydrodynamic to kinetic nature of turbulence in terms of scale size of plasma fluctuations?**
- **How can nonlinear and nonlocal aspects of plasma turbulence be addressed in the same analytical framework?**
- **Can plasma turbulence be controlled, mitigated, or suppressed through active mitigation techniques?**
- **Can plasma turbulence be artificially generated and harnessed towards a specific goal?**