# Foreshock electron beams and electrostatic waves observed by Cluster

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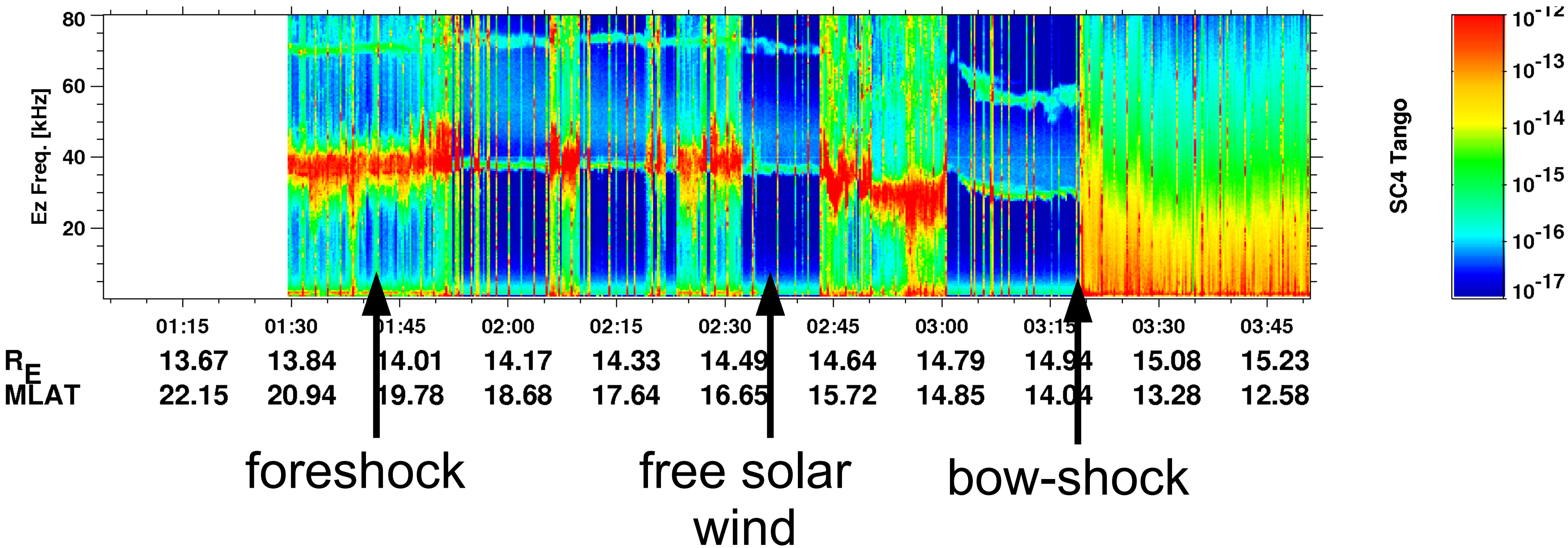
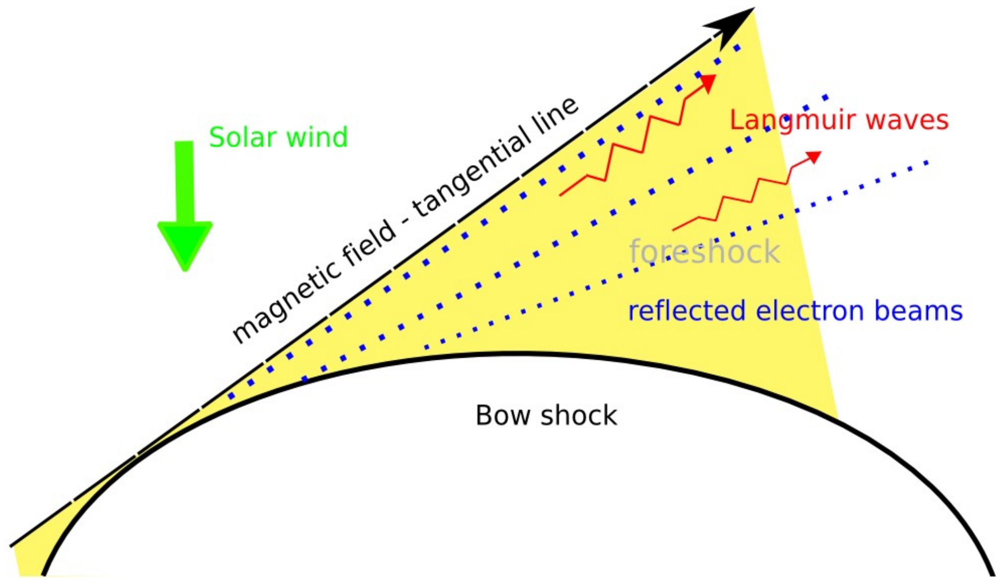
# Electron foreshock



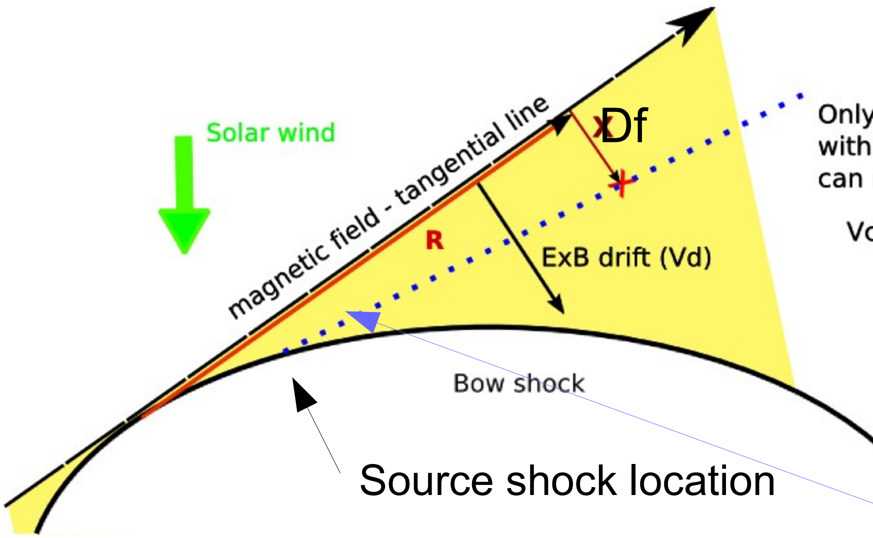

- Foreshock: a region of solar wind magnetically connected to the bow shock
- Populated by beams of back-streaming electrons (and further downstream ions), reflected and accelerated by the shock.
- Characteristic observable signature – intense electrostatic wave activity around the electron plasma frequency.
- Foreshock electron beams are a universal feature shocks: observed at at planets, interplanetary shock, termination shock ...

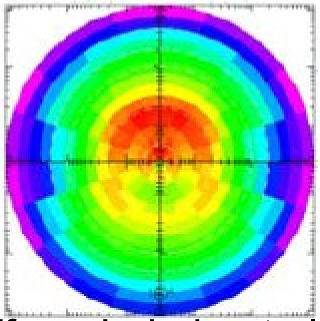
# Foreshock electron beams



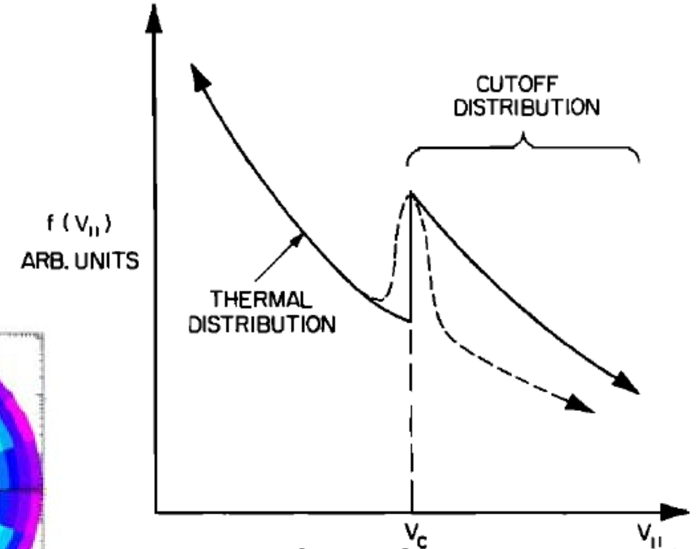

- A fraction of incident solar wind electrons is reflected and accelerated by the bow shock *[Leroy & Mangeney, 1984, Wu, 1984*].
- These electrons (10 eV – 10's of keV) are responsible for the generation of the Langmuir waves via beam plasma instability.
- ExB drift in the foreshock acts as a velocity filter on the reflected electrons, forming the beams [Fitzenreiter et al., 1990].

# Origin of the beams



[from Lobzin et al., 2005]




[from Cairns et al., 1987]

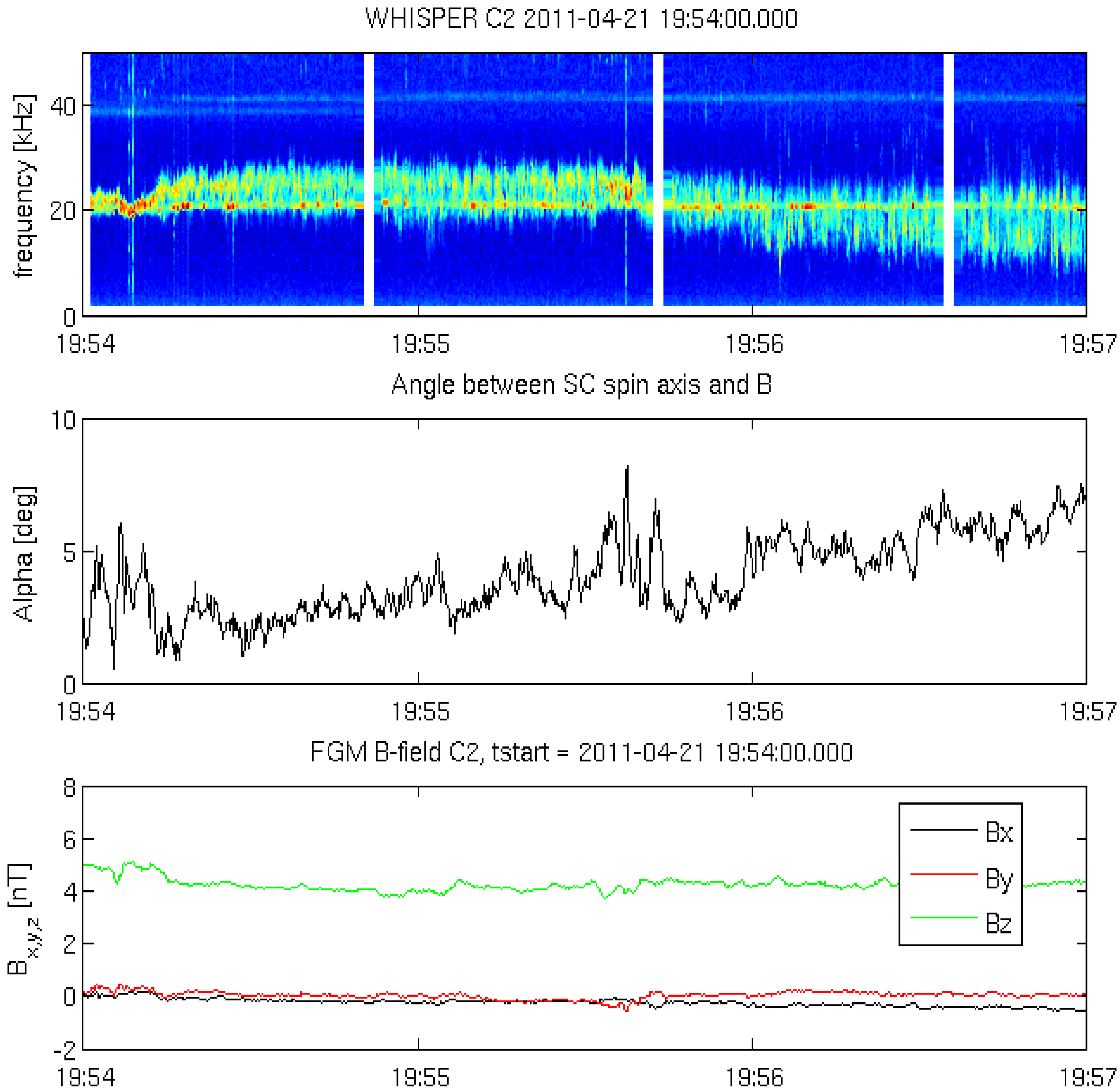
**Foreshock beam formation:**

- Cutoff distribution [Filbert & Kellogg, 1979, Fitzenreiter et al., 1990]:
  - For each point (R,Df) cutoff velocity is defined Vc = VE x B R / Df
  - "Bump on tail" required for the beam-plasma instability is formed at Vc
- Bump formed by reflection process [Leroy & Mangeney, 1984, Wu, 1984].
  - Beam with loss-cone ("rabbit ears")
  - Model allows to calculate beam energy from parameters of source shock ($\theta_{Bn}$, $B_{down}/B_{up}$ etc.)

# Observation of foreshock electron beams

- Foreshock beams are typically faint ($n_b/n_e = 10^{-2} – 10^{-4}$) and non-stationary.
- Beams are present consistently, but not many direct observations were published [Fitzenreiter et al., 1996, Kasaba et al., 2000].
- Under favorable conditions, PEACE electron spectromenter on Cluster can be used to observe and characterize these beams - at least the slower ones.
  - Large geometrical factor needed (HEEA)
  - Good energy resolution (BM preferred)

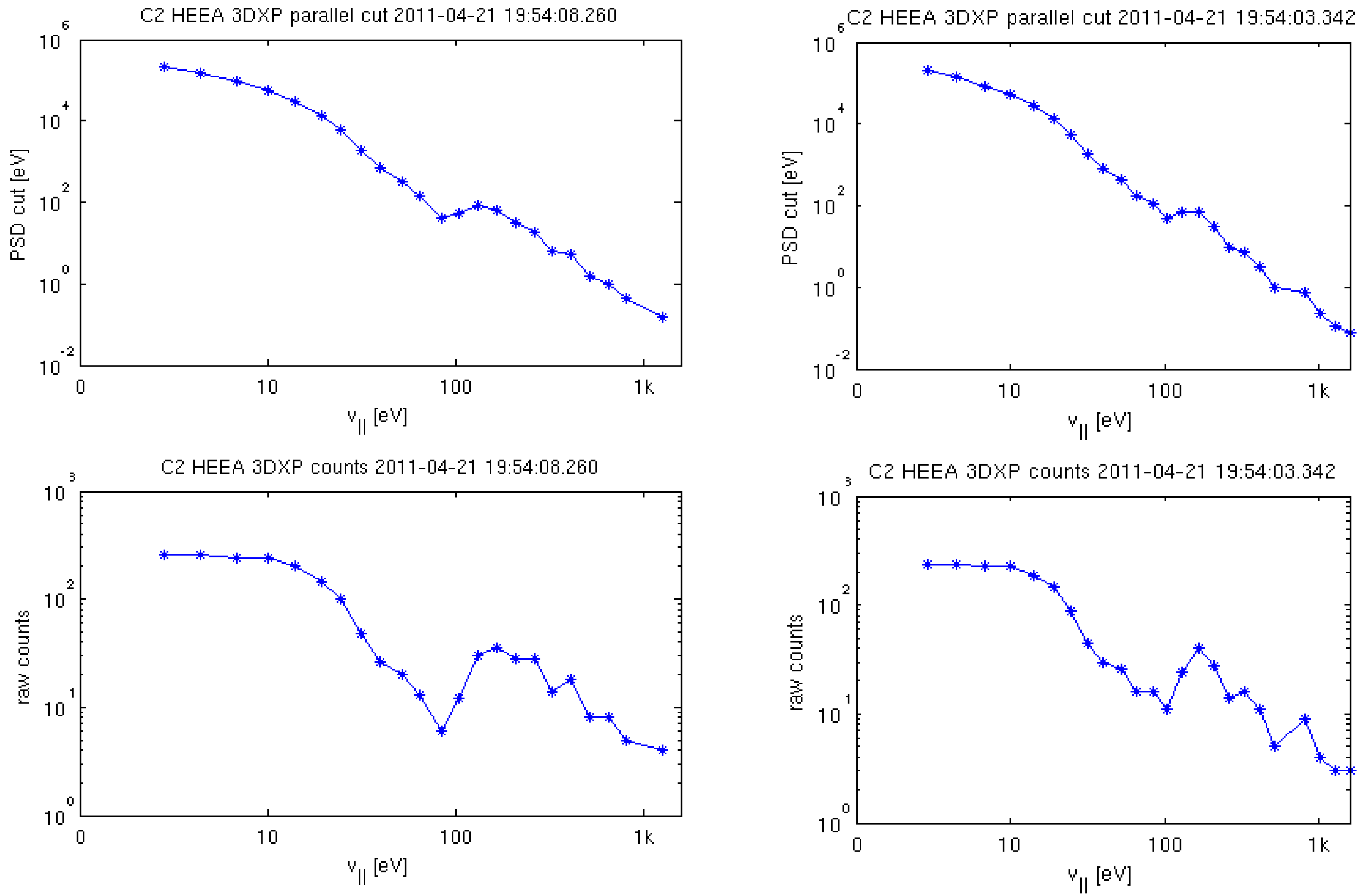
# Foreshock event C2 2011-04-21




Suitable event:

- Cluster in BM
  - PEACE HEEA on
- B field in GSE Z direction (near parallel to spin axis)
  - pitch angle distribution available every PEACE sweep (8 per second).
- FS waves waves above and below $\omega_p$ observed

# PEACE observed beams

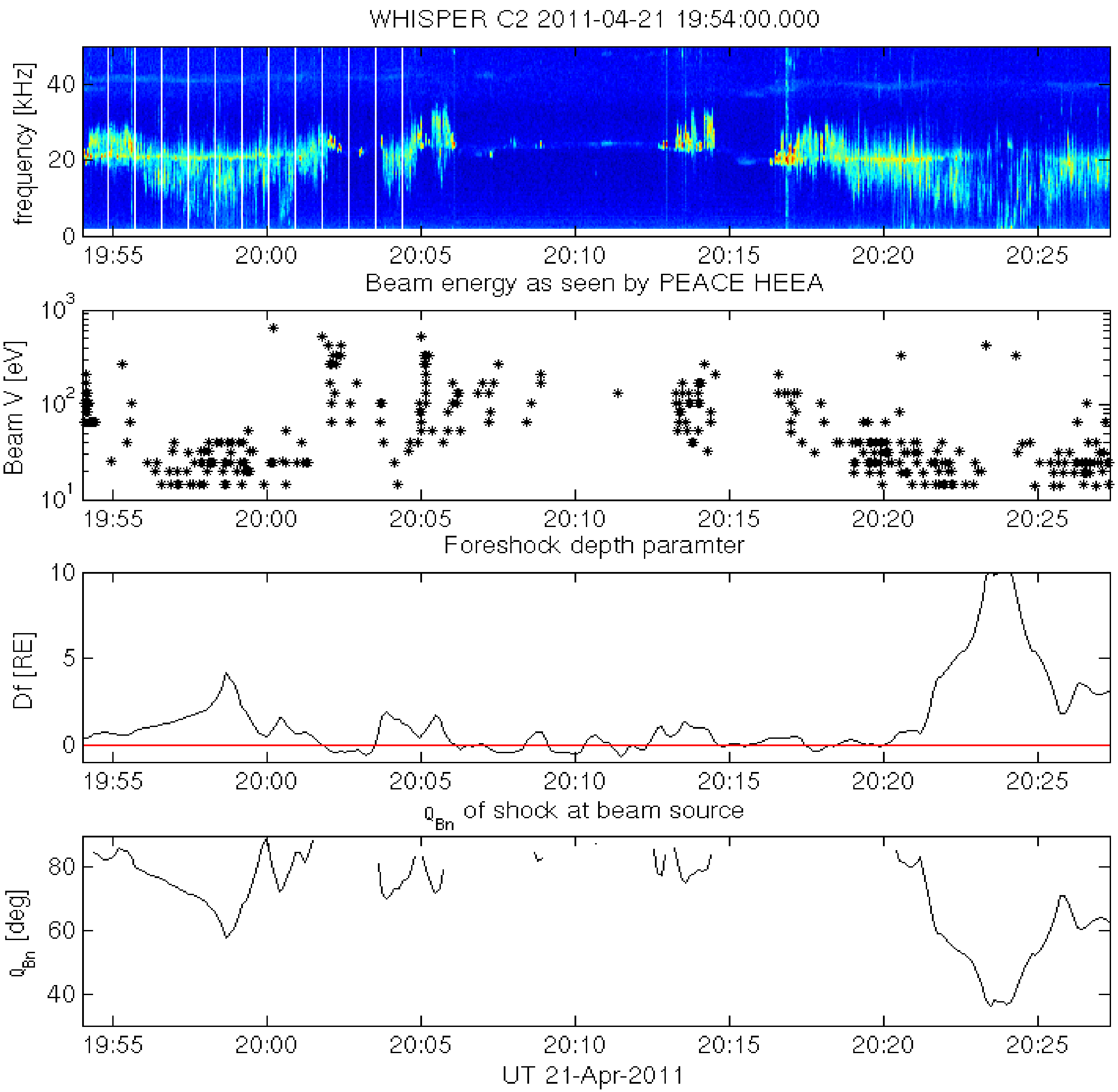



B-parallel PSD cut (30 deg. bin)

Raw counts

- Beam-like bumps between 20 eV and 1 keV observed in the B-parallel bin
- Higher energies not available due to low count rates
  - In the ~100 eV range, the counting statistics is typically good.

# Beam identification

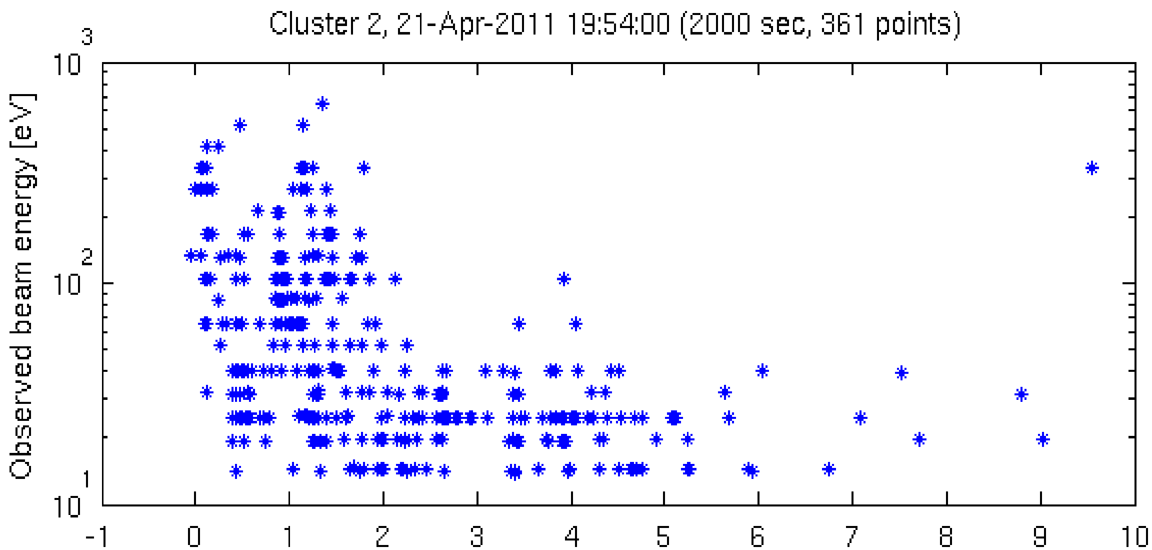



- Beams identified automatically
  - Statistically significant (> 2σ) increase in PSD.
- 361 beams between 13 eV and 850 eV identified (Te ~ 5 eV).
- Beam energy correlates with foreshock waves
  - Higher energy –> narrow-band
  - Low energy –> broad-band

Consistent with [Lacombe et al.,1985, Cairns & Fung,1988].

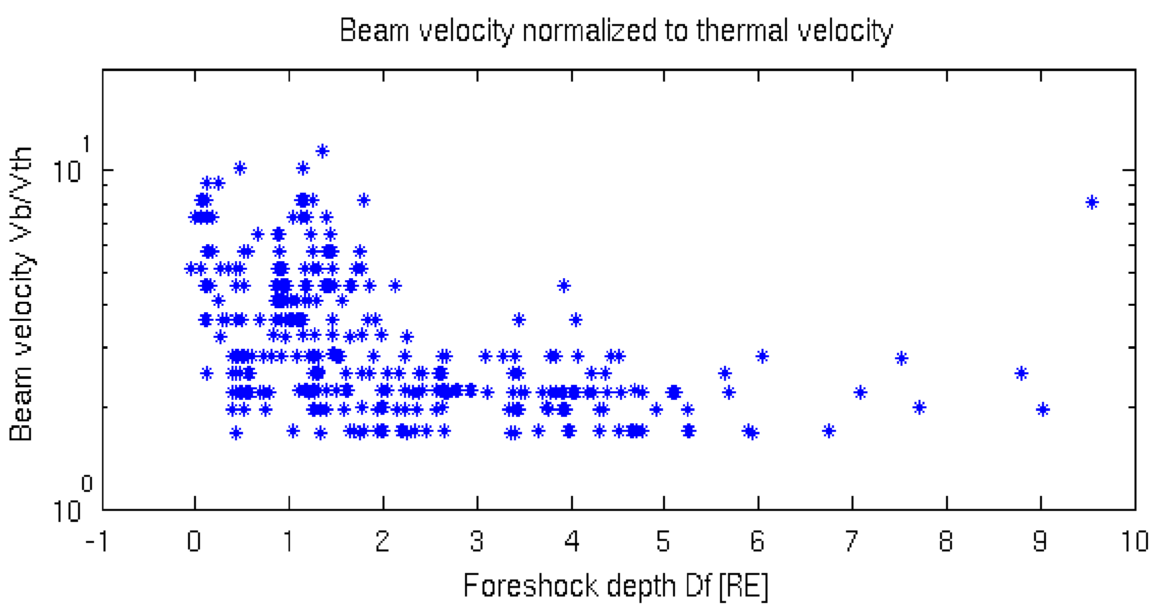
- Df and $\Theta_{Bn}$ parameters calculated.

# Comparison to model - statistics




Strong dependence of beam energy on foreshock depth parameter [Fitzenreiter et al., 1990].

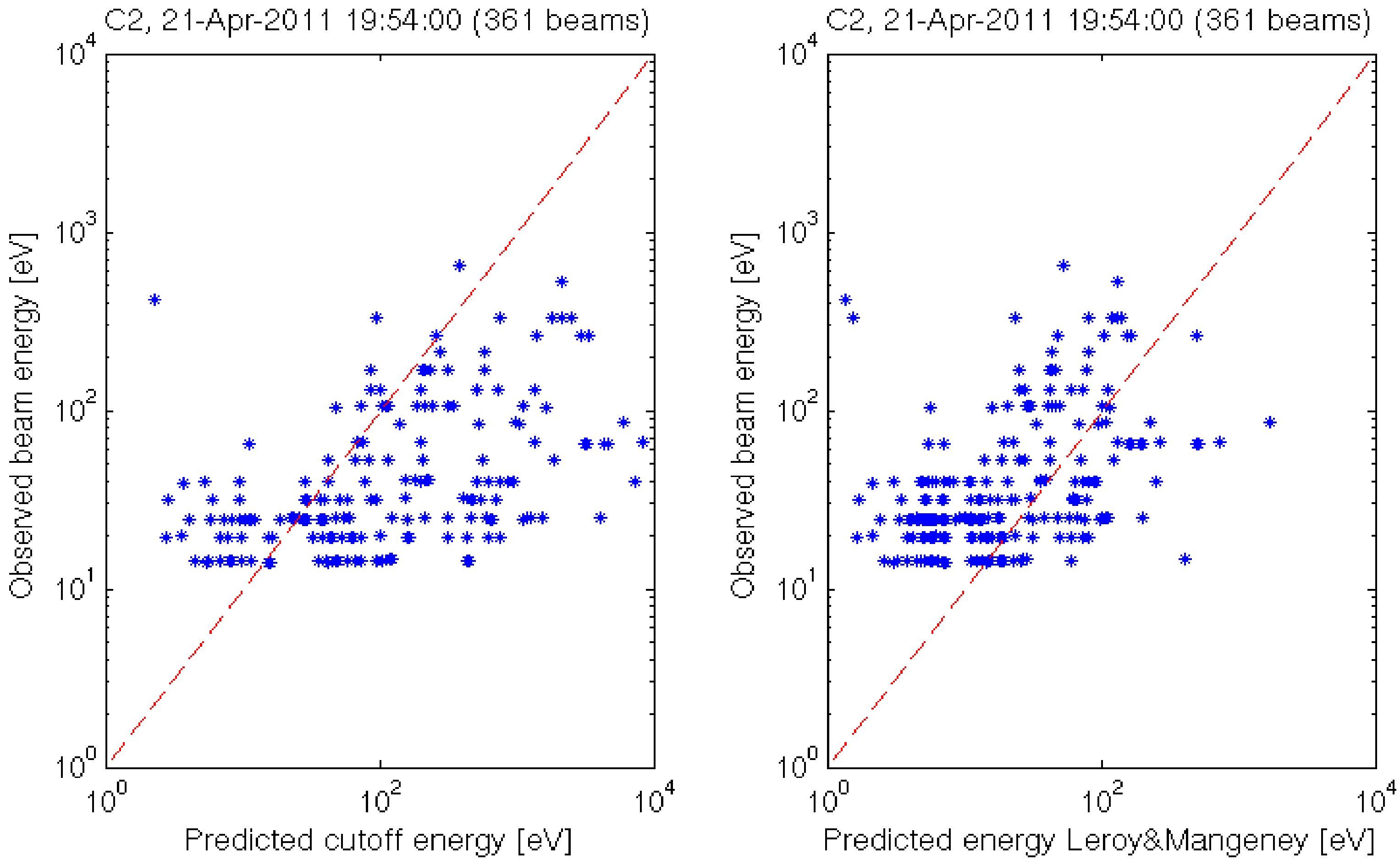
- Energetic beams E > 100 eV found for Df < 2 RE.




Normalized to thermal velocity Vt

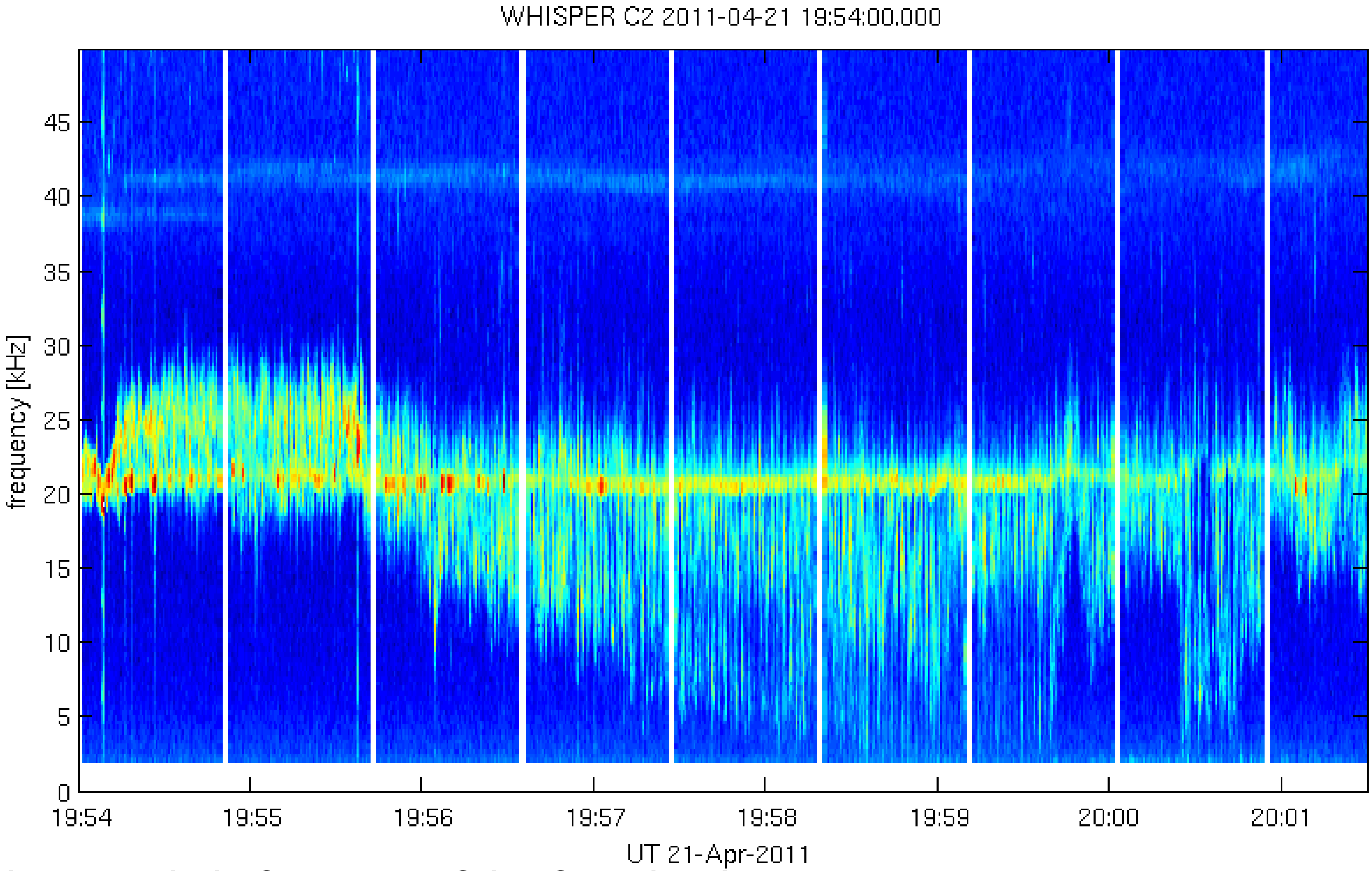
- Df < 2 RE → Vb up to 10 Vt
- Df > 2 RE → Vb ~ 2-4 Vt

# Comparison to models - statistics



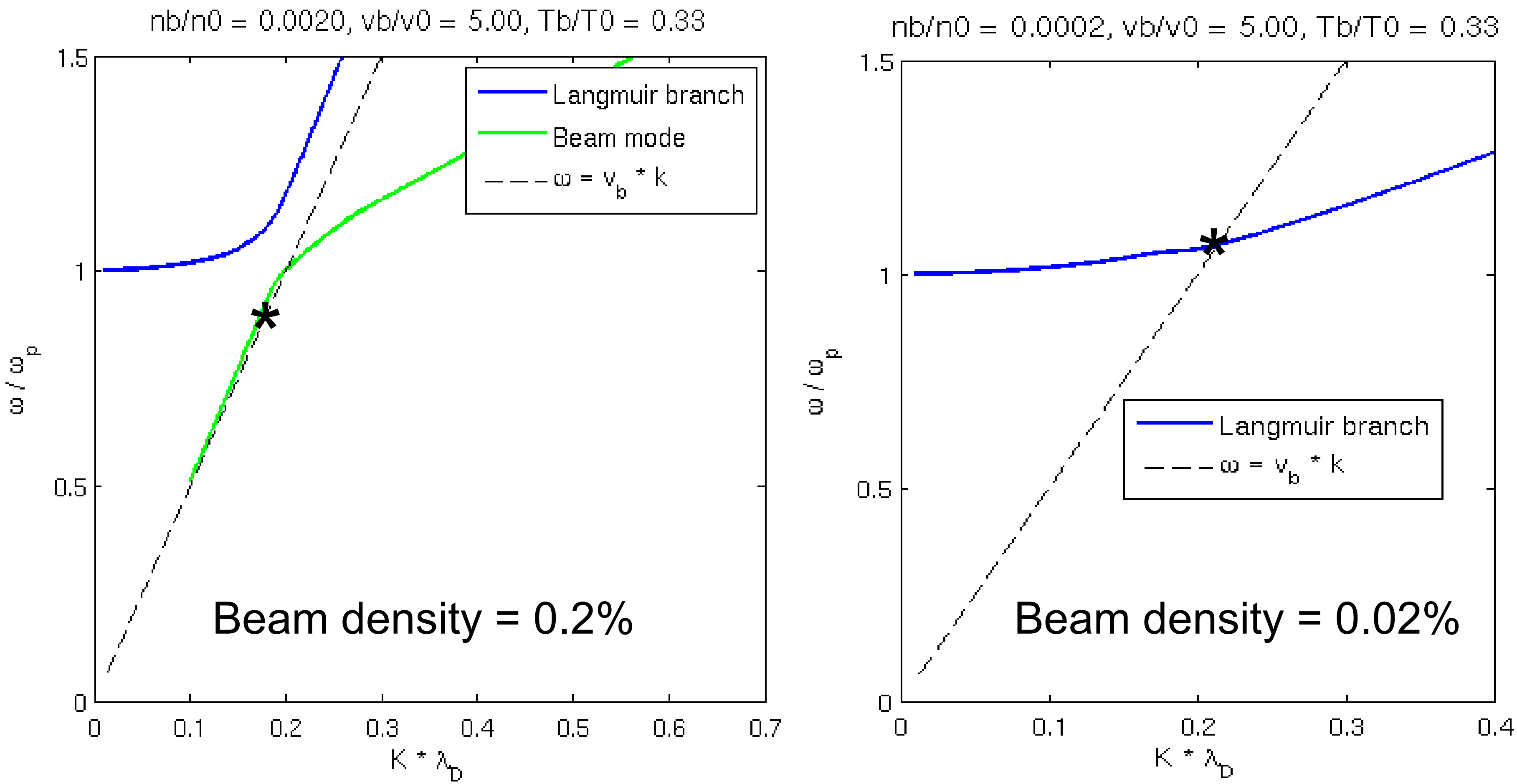

- Comparison of measured and model beam speeds for moderate beam speeds.
  - Fitzenreiter et al., 1990 cutoff distribution model.
  - Leroy and Mangeney, 1984 energy.
- The measured and predicted value are comparable, but correlation is weak.

# Foreshock wave structure



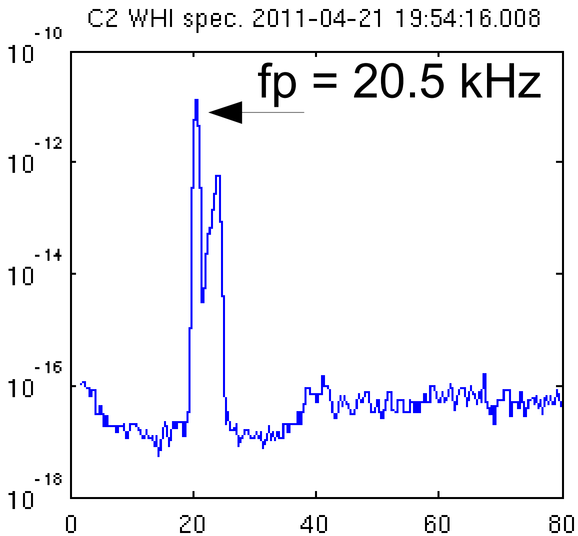

- Characteristic features of the foreshock spectrum:
  - Wave activity at plasma frequency.
  - Waves far above and below the plasma frequency (Δf/f up to 80%)

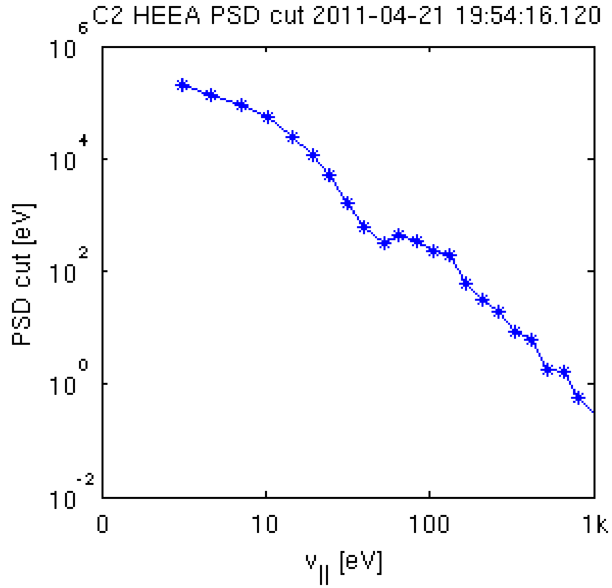
# Plasma dispersion relation

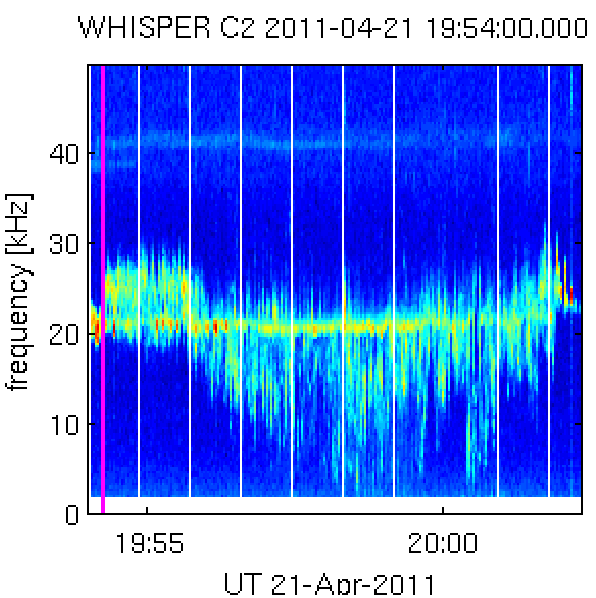


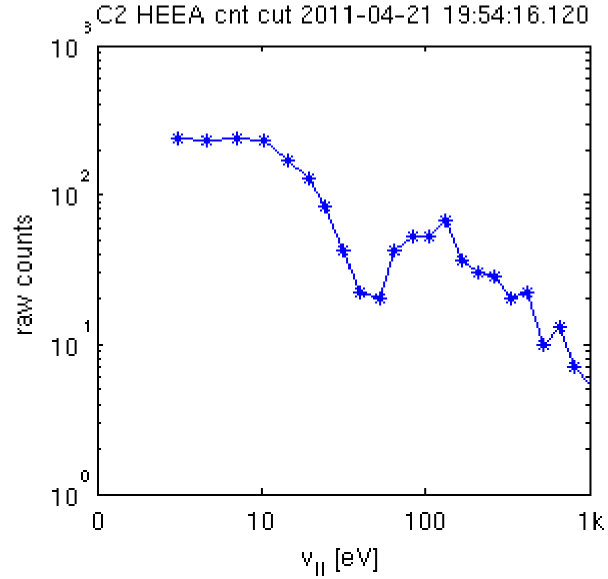

- Electrostatic dispersion relation for beam-plasma instability (Gary 1983)
  - Second solution – beam mode.
  - Langmuir wave branch modified
- Growth often on the beam mode
  - “Real” Langmuir waves only grow for fast and tenuous beams

# Wave-particle analysis




- Fitting of two Maxwellians employed to estimate beam properties

  Vb = 86 eV = 4.1 Vt

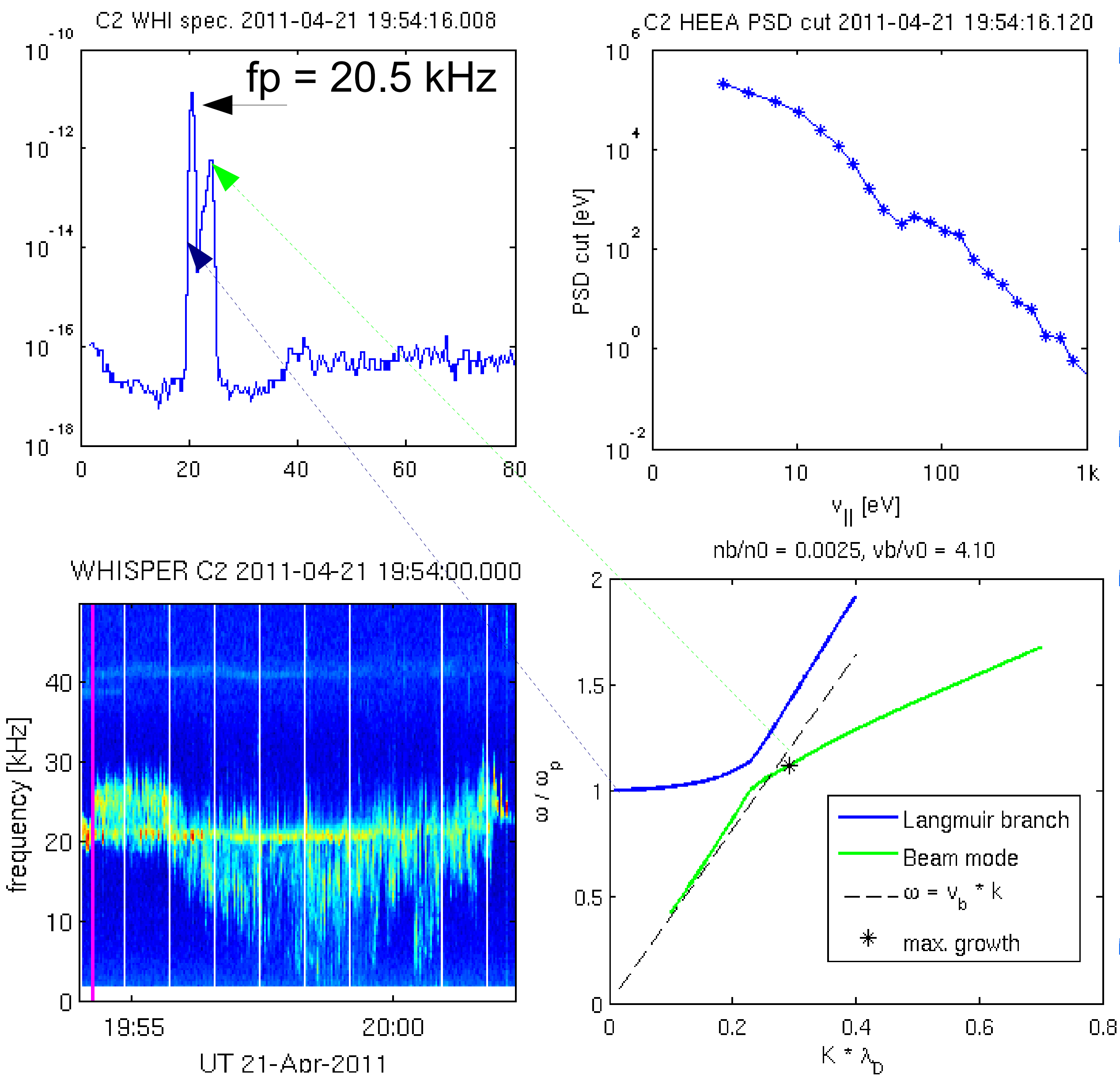
  nb/n0 = 0.25%

  Tb/T0 = 0.4

*These 3 parameters are sufficient for linear dispersion analysis.*

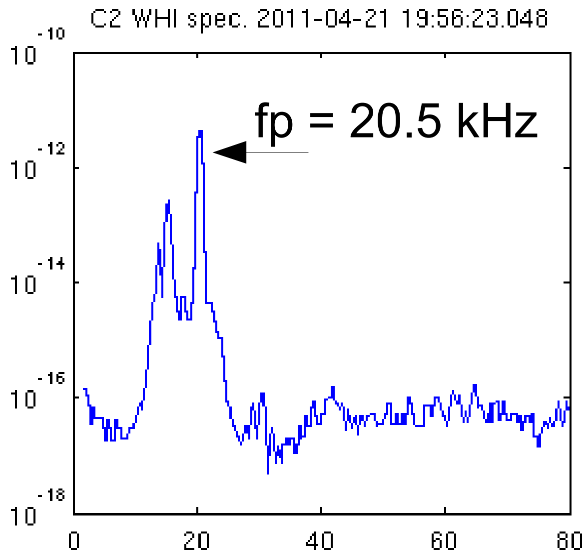
- Foreshock geometry:
  - The beam corresponds to $\Theta_{Bn}$ ~ 87º source.
  - Leroy & Mangeney model predicts ~570 ev (near 90º, model is very sensitive to $\Theta_{Bn}$ value.

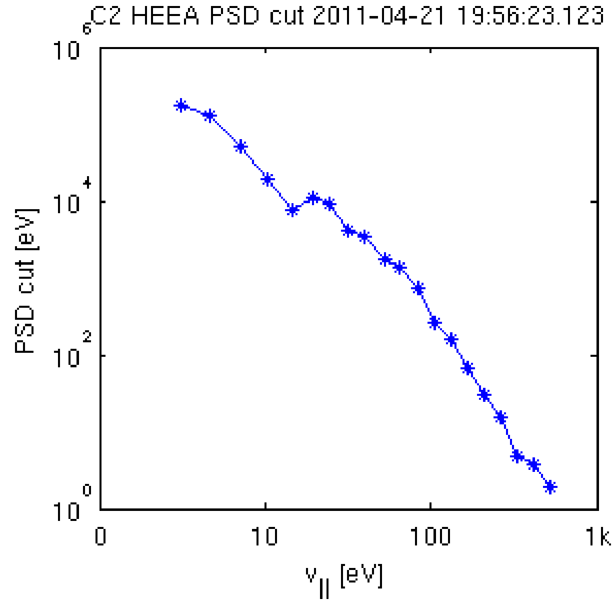
# Wave-particle analysis

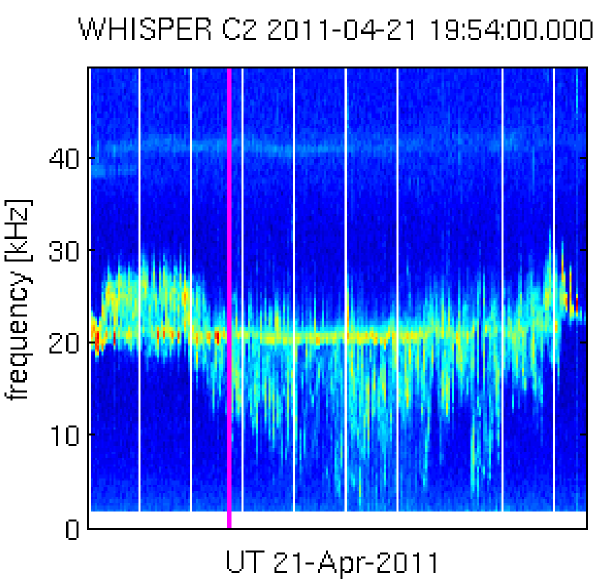


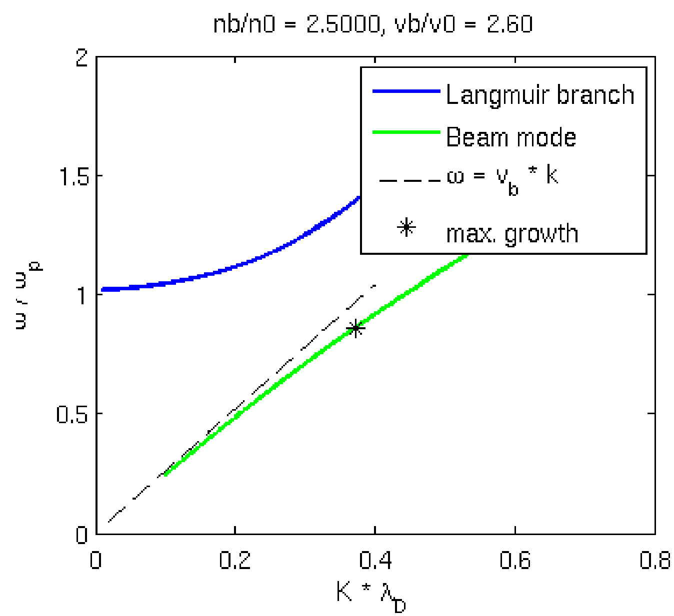

- Linear dispersion relation solved for measured parameters.
- Langmuir branch
  - No growth
  - Low damping at small k
- Beam mode
  - growth at k*λd ≈ 0.3
- Growth on the beam mode branch
  - Maximum calculated growth at 23.2 kHz
  - Peak observed at 24.3 kHz
- Oscillations near $\omega_p$ likely on Langmuir branch.

# Wave-particle analysis



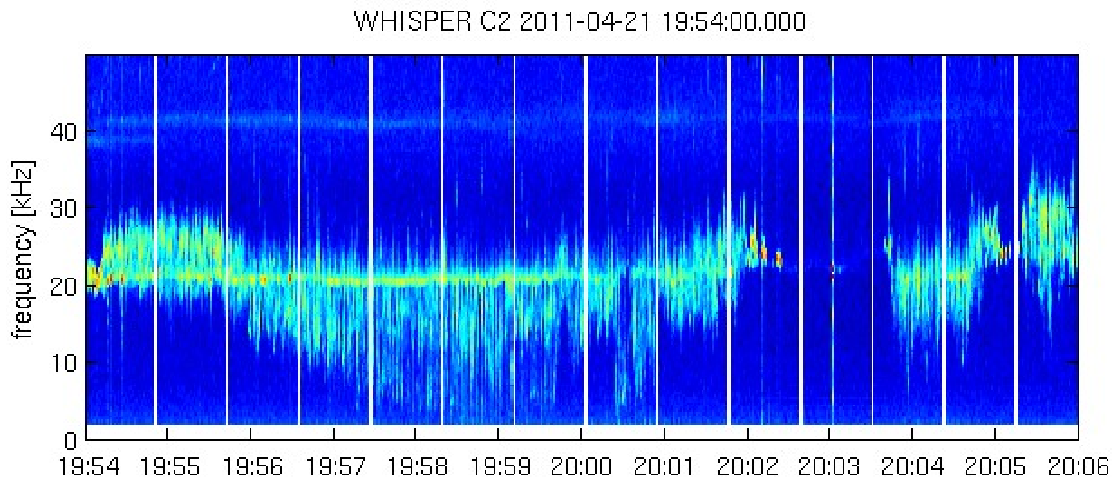



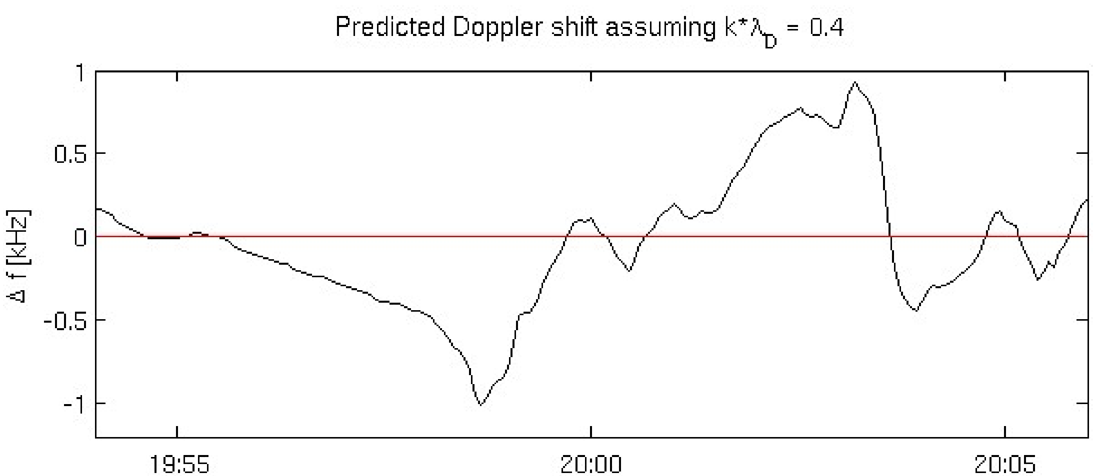



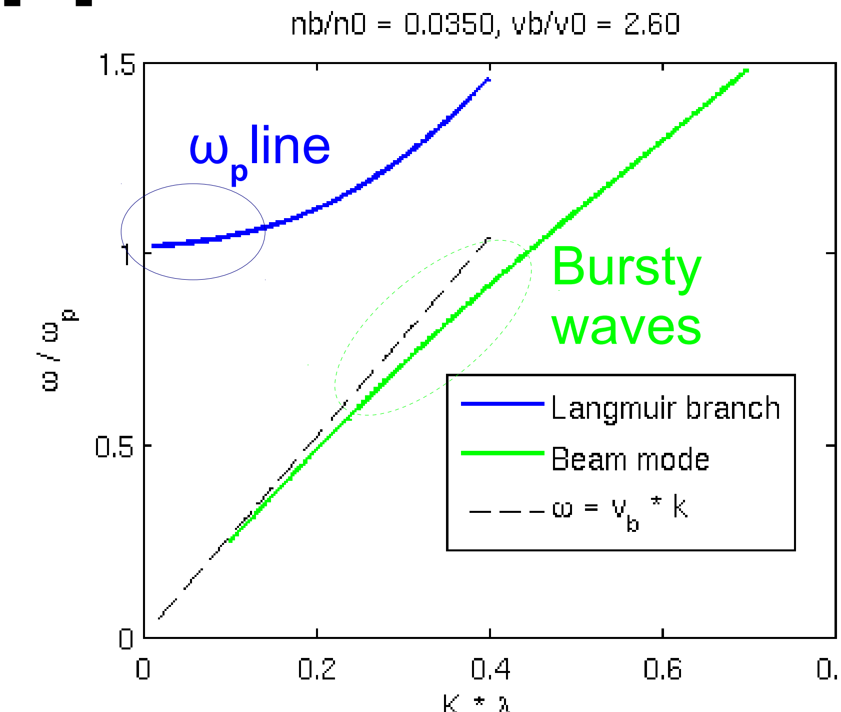

- Drifting Maxwellian fit:
  - Vb = 31 eV = 2.6 Vt
  - nb/n0 = 2.5%
  - Tb/T0 = 0.3
- Foreshock geometry:
  - The beam corresponds to $\Theta_{Bn}$ ~ 75º source.
  - Leroy & Mangeney model predicts ~33 eV
- Growth below $\omega_p$
  - Max growth at 17.6 kHz
  - Peak at 15.5 kHz
  - "Rough" agreement only. Can probably be improved by a better distribution model.

# Role of the Doppler shift




Predicted Doppler shift ($k^*\lambda_D$)




- $\omega_p$ line immune to Doppler shift
  - Very low k waves
- For beam modes, Doppler shift up to 1 kHz
  - Direction consistent
  - Cannot account for all variation

# Conclusions

- Systematic measurement of foreshock electron beam energies performed using PEACE data
  - Beams up to 1 keV observed consistently
  - Dependence on foreshock depth consistent with Leroy & Mangeney 1984 model.
- Broadband waves below $\omega_p$ correspond to slower beams [Lacombe et al., 1985, Cairns & Fung, 1988].
- Dispersion relation for electrostatic beam plasma instability solved for selected distributions.
  - Growth on the beam-mode branch at moderate k
  - Low k Langmuir oscillations at plasma frequency observed
  - Rough agreement between calculated and observed values
- Doppler shift significant, but cannot account for the variation in frequency.