Ion non-Maxwellianity and its relation to turbulence and electrostatic waves

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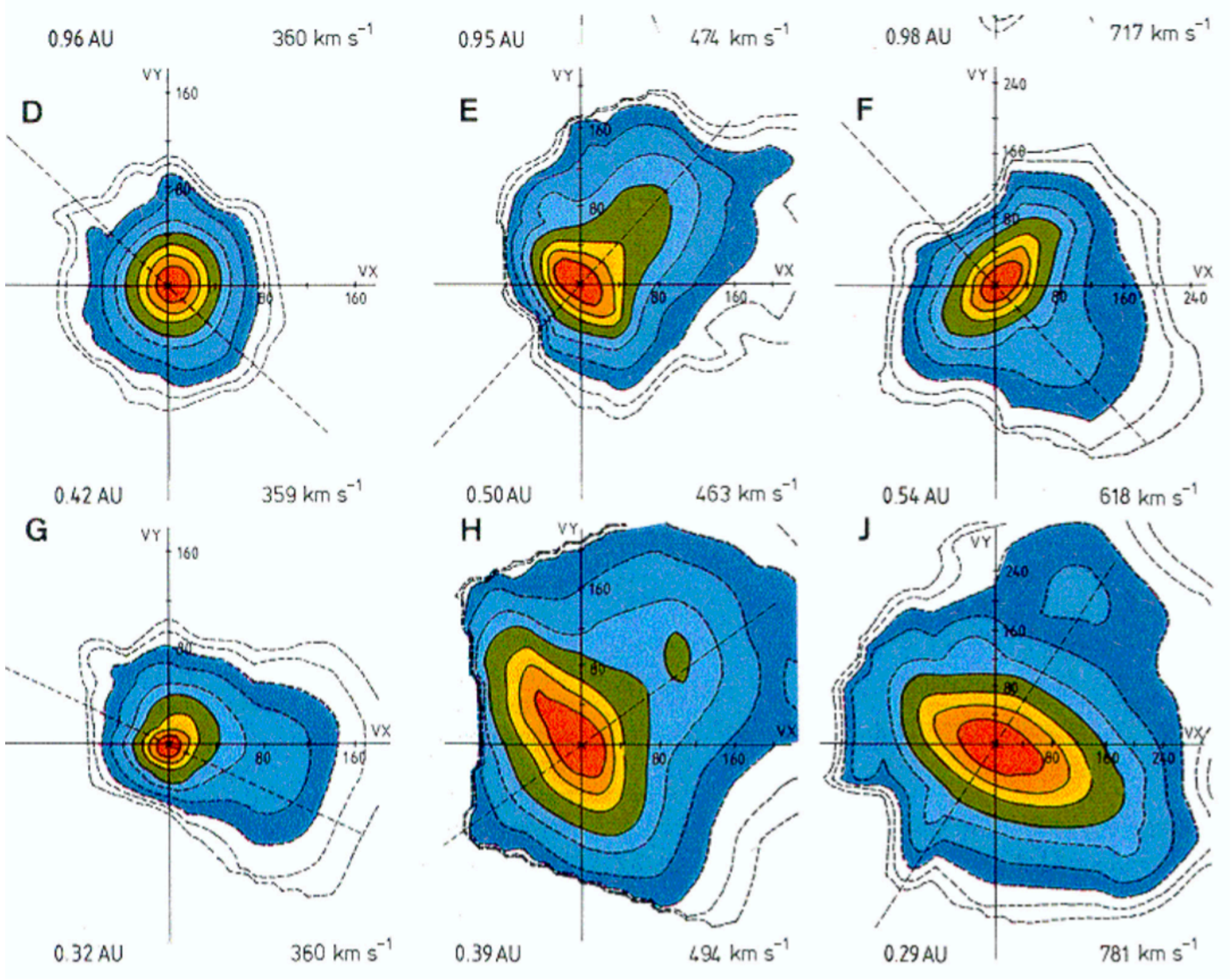
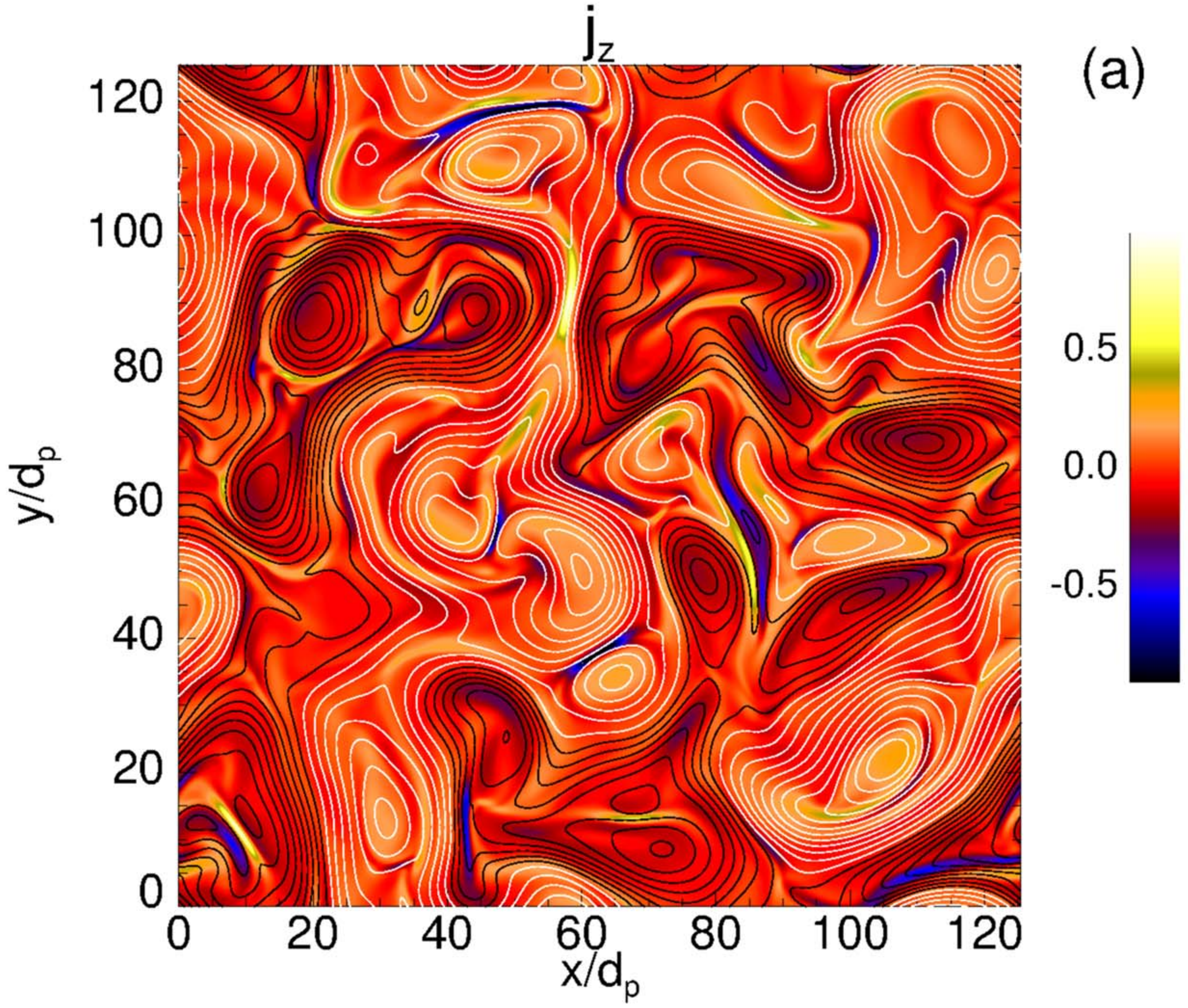
Background



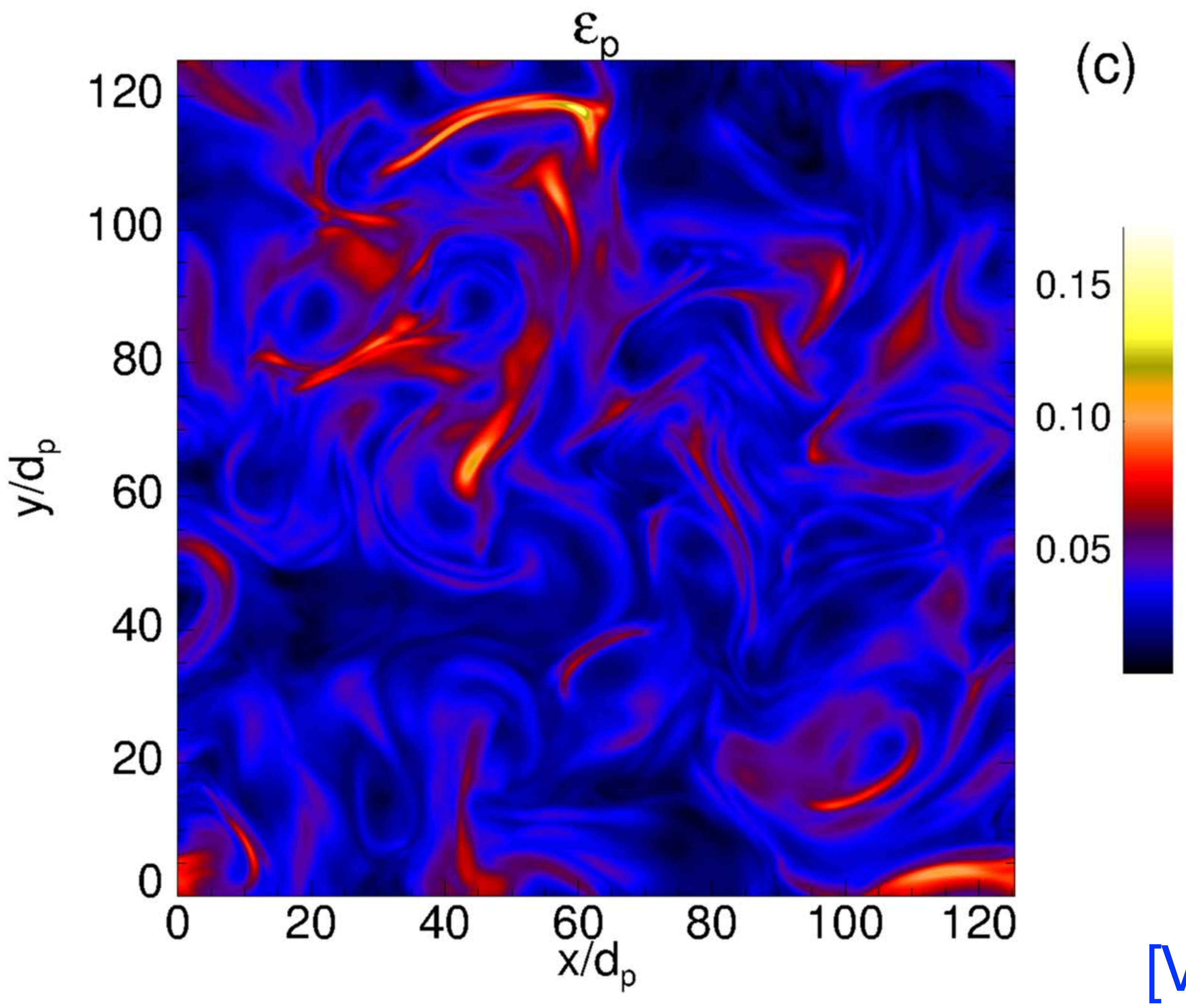
[Marsch et al., 1982; 2018]

J



Out-of plane current

ε



Ion non-Maxwellianity

[Valentini et al., 2016]

Theory

- We define the deviation from bi-Maxwellianity as:

$$\epsilon = \frac{1}{2n_i}\int_{v,\theta,\phi} |f_i(v,\theta,\phi) - f_{\mathrm{model}}(v,\theta,\phi)| v^2 \sin\theta dv d\theta d\phi,$$

[Graham, et al., 2021b]

where

$$f_{\mathrm{model}}(\mathbf{v}) = \frac{n_e}{\pi^{3/2} v_{i,\|}^3}\frac{T_{i,\|}}{T_{i,\perp}} \exp\left(-\frac{(v_\| - V_\|)^2}{v_{i,\|}^2} - \frac{(v_{\perp,1} - V_\perp)^2 + v_{\perp,2}^2}{v_{i,\|}^2 (T_{i,\perp}/T_{i,\|})}\right),$$

- We use ion moments to determine f$_{\mathrm{model}}$:

$$n = \int f(\mathbf{v}) d^3v$$

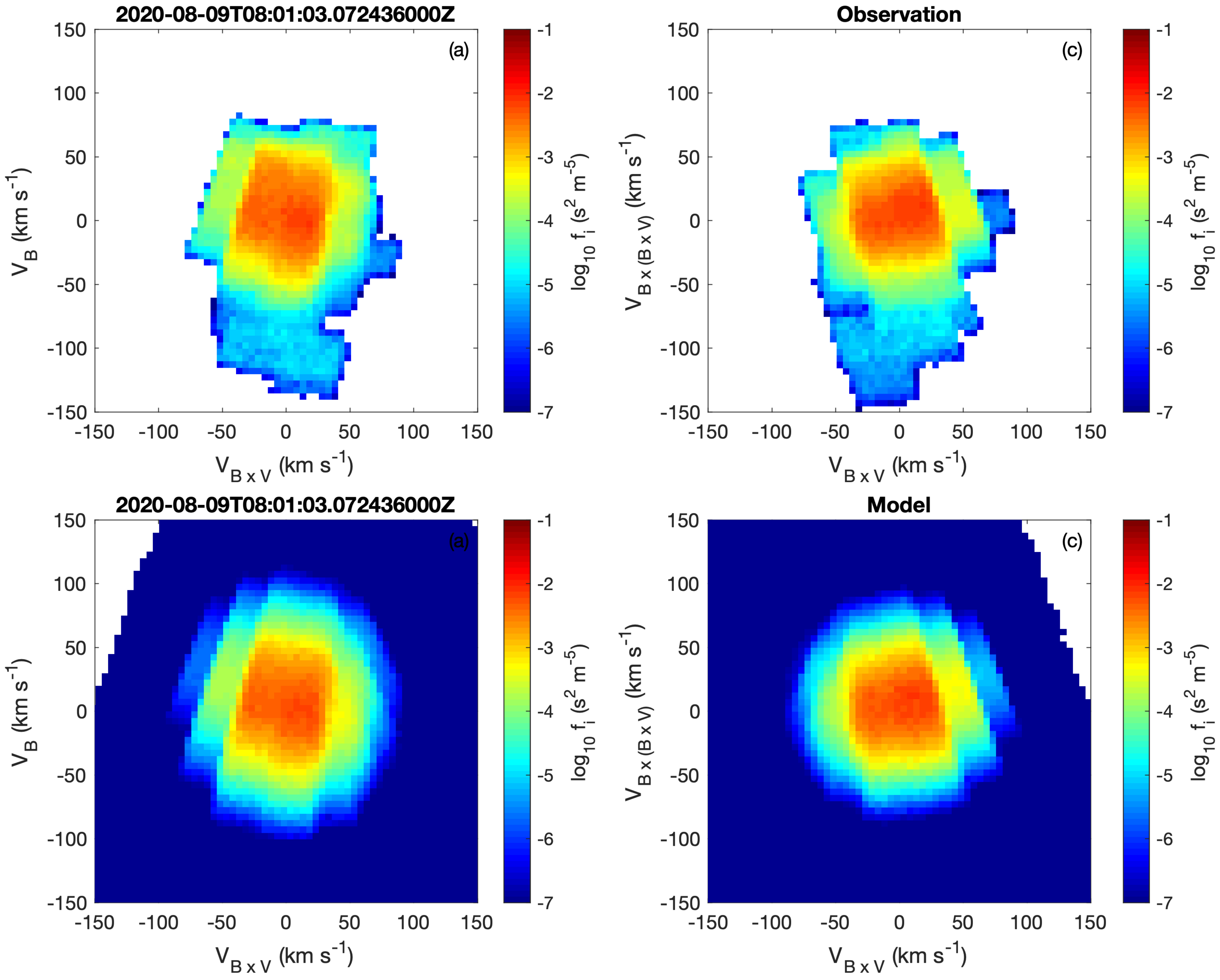
$$\mathbf{V} = \frac{1}{n}\int \mathbf{v} f(\mathbf{v}) d^3v \qquad \mathbf{T} = \mathbf{P}/nk_B$$

$$\mathbf{P} = m\int (\mathbf{v} - \mathbf{V})(\mathbf{v} - \mathbf{V}) f(\mathbf{v}) d^3v$$

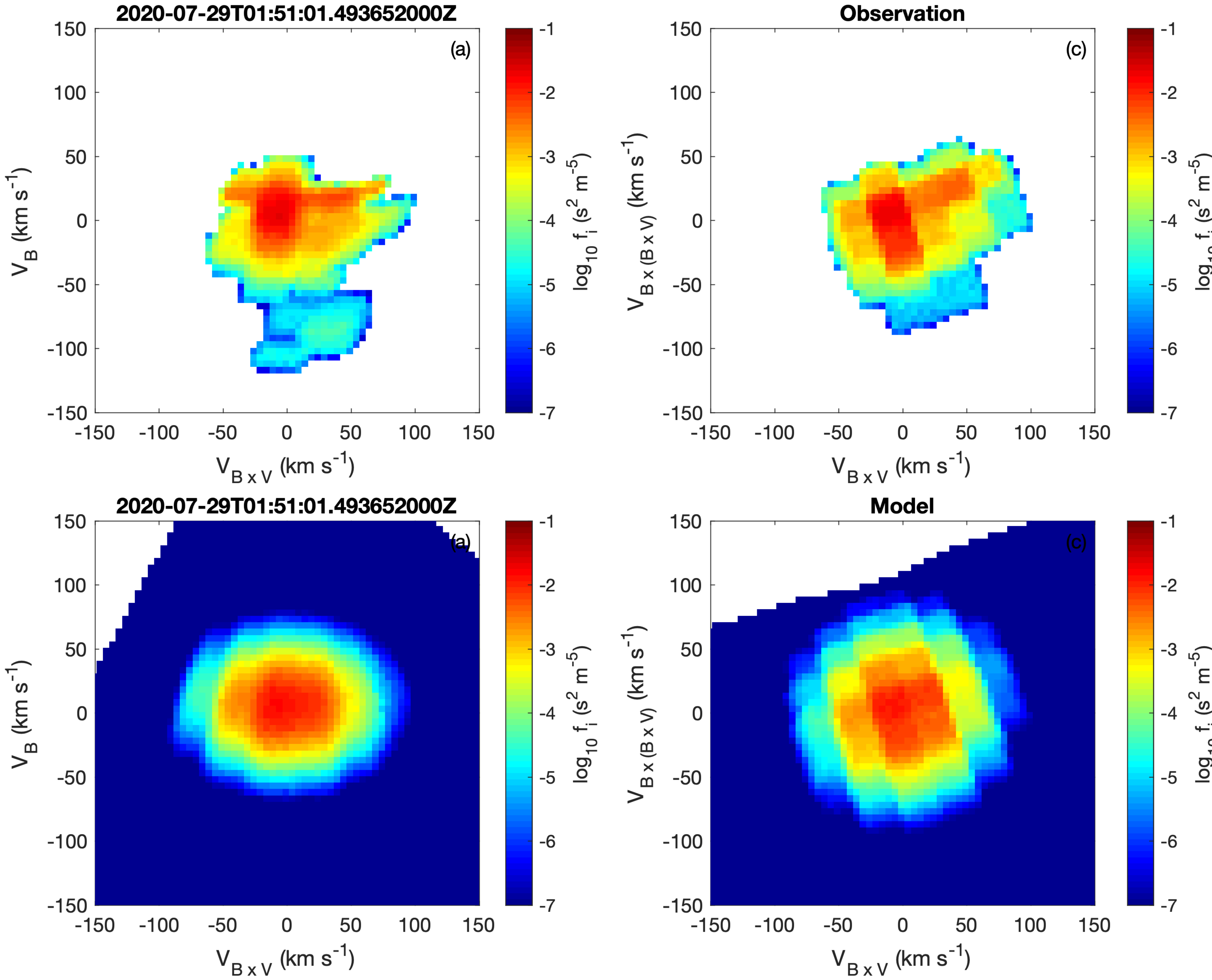
We use a bi-Maxwellian because we do not want a quantity that scales with T$_\|$/T$_\perp$.

Example distributions

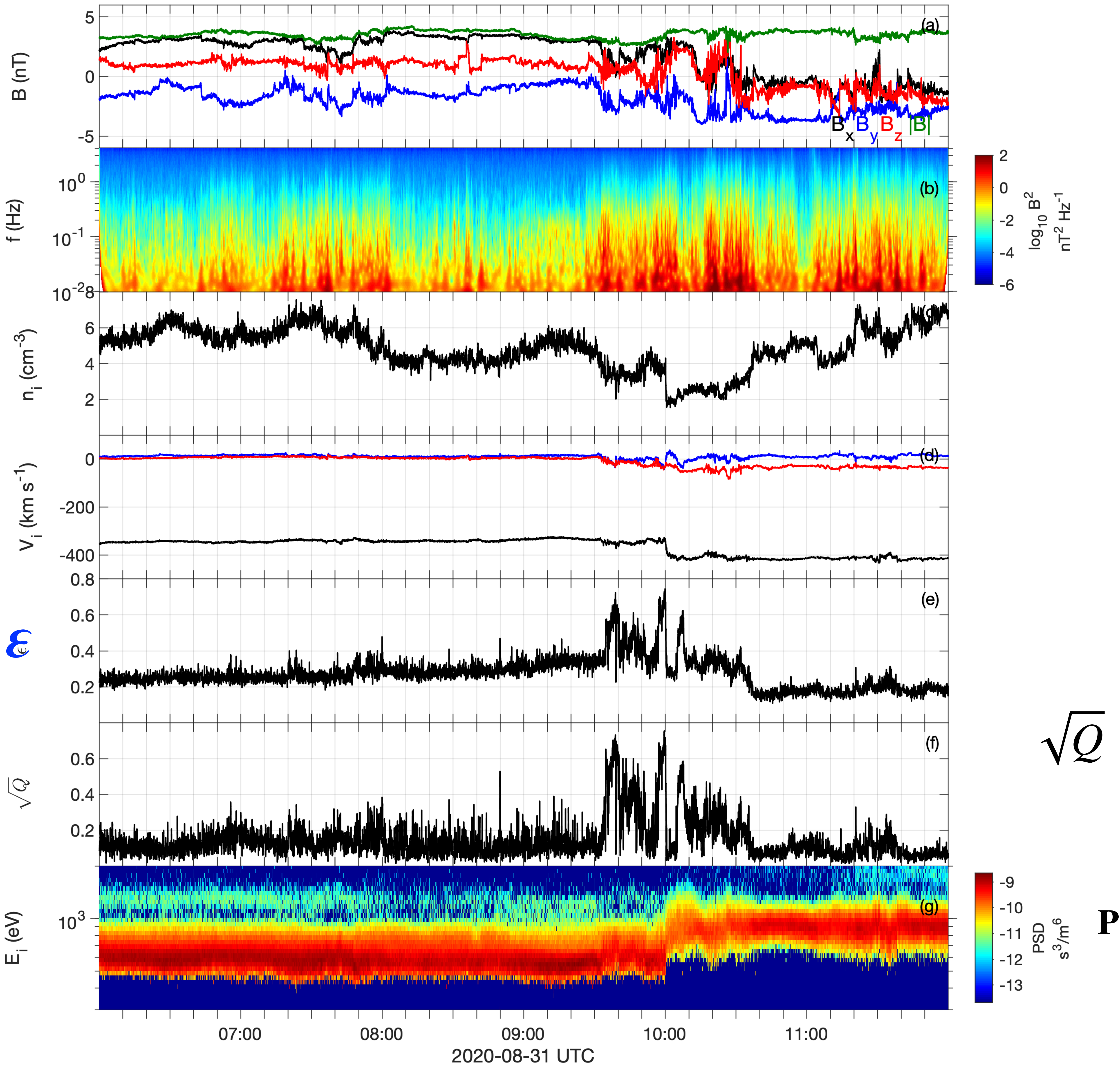
$n = 20\ \mathrm{cm}^{-3}$
$T = 4\ \mathrm{eV}$
$T_\perp / T_\parallel = 0.7$
$\varepsilon = 0.12$



$n = 9\ \mathrm{cm}^{-3}$
$T = 5\ \mathrm{eV}$
$T_\perp / T_\parallel = 1.7$
$\varepsilon = 0.56$



Solar wind example



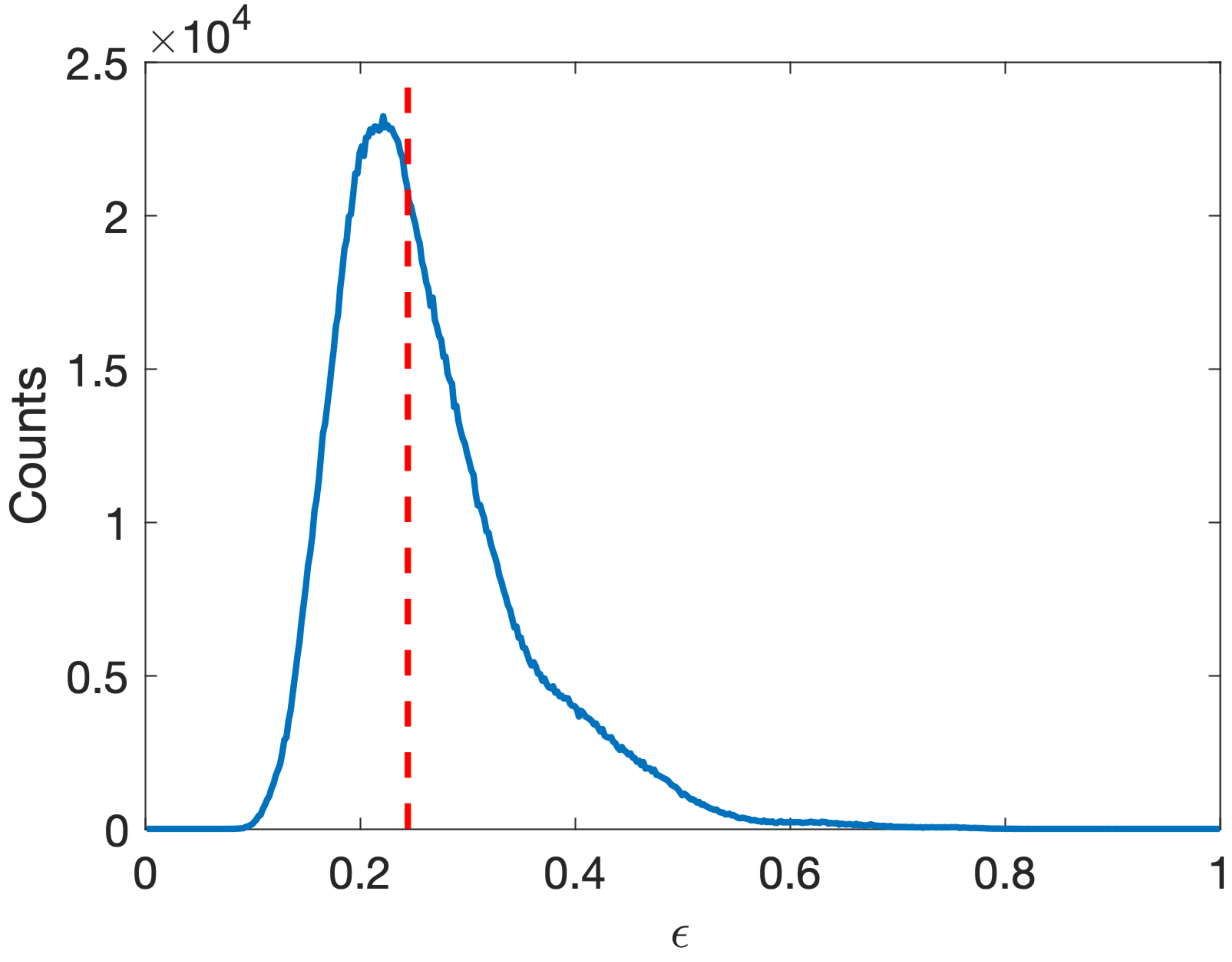
$$\sqrt{Q} = \left(\frac{P_{12}^2 + P_{13}^2 + P_{23}^2}{P_\perp^2 + 2P_\perp P_\parallel} \right)^{1/2}$$

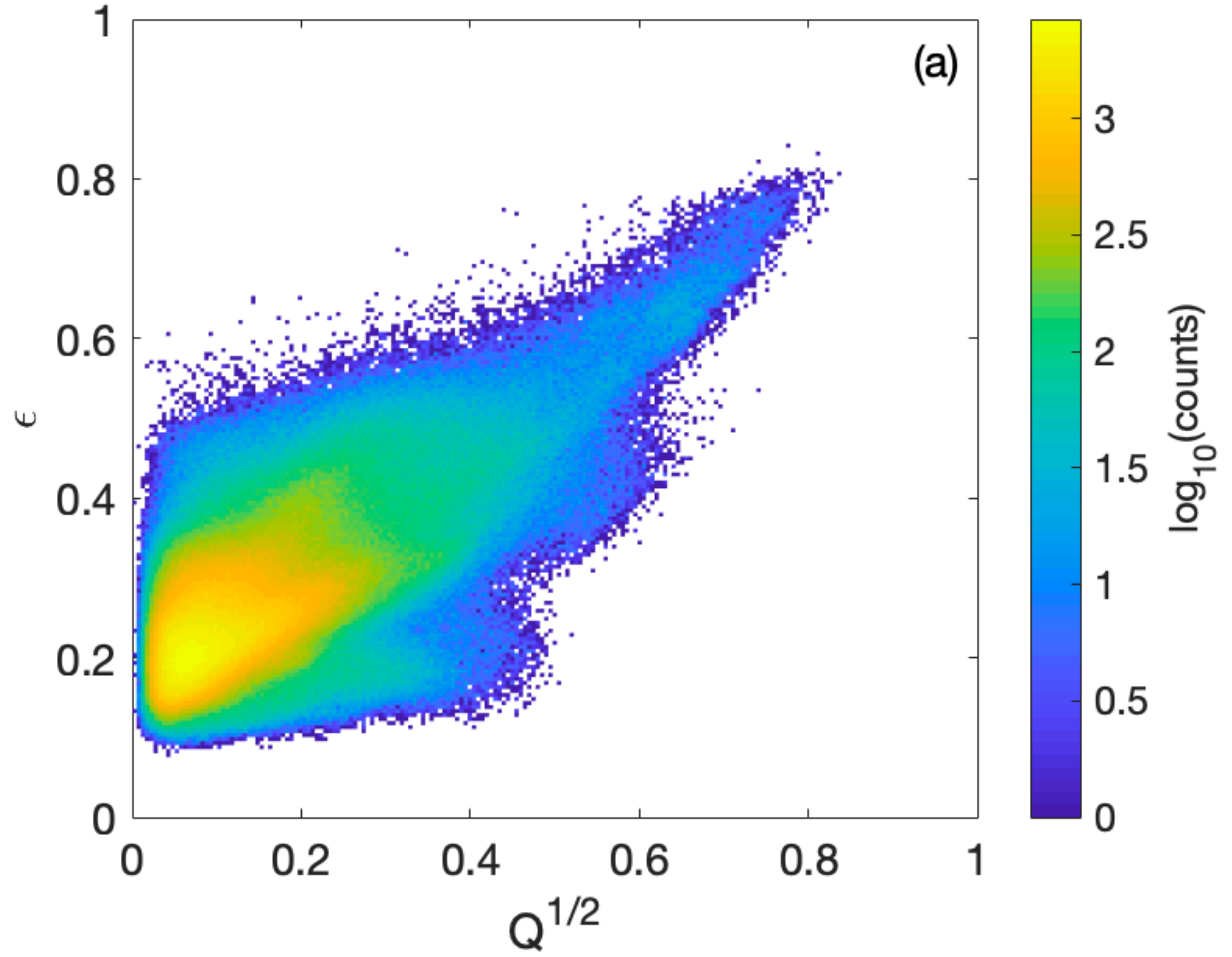
$$\mathbf{P}_i = \begin{pmatrix} P_\parallel & P_{12} & P_{13} \\ P_{12} & P_\perp & P_{23} \\ P_{13} & P_{23} & P_\perp \end{pmatrix}$$

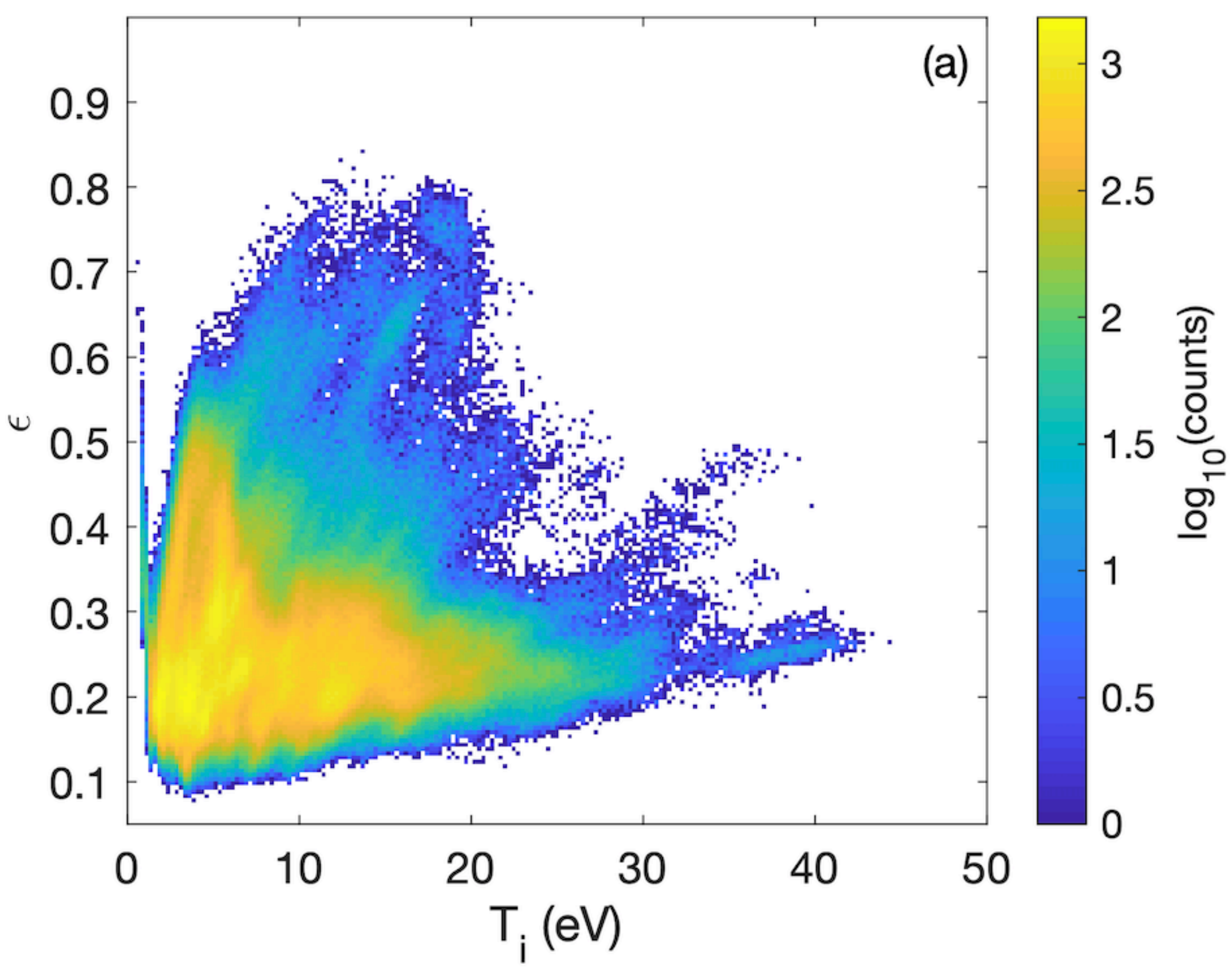
[Swisdak, 2016]

- Example of ion Non-Maxwellianity in the solar wind.
- Large ε occurs in turbulent regions in this example.

Statistics







- Distribution of ε for all available data.

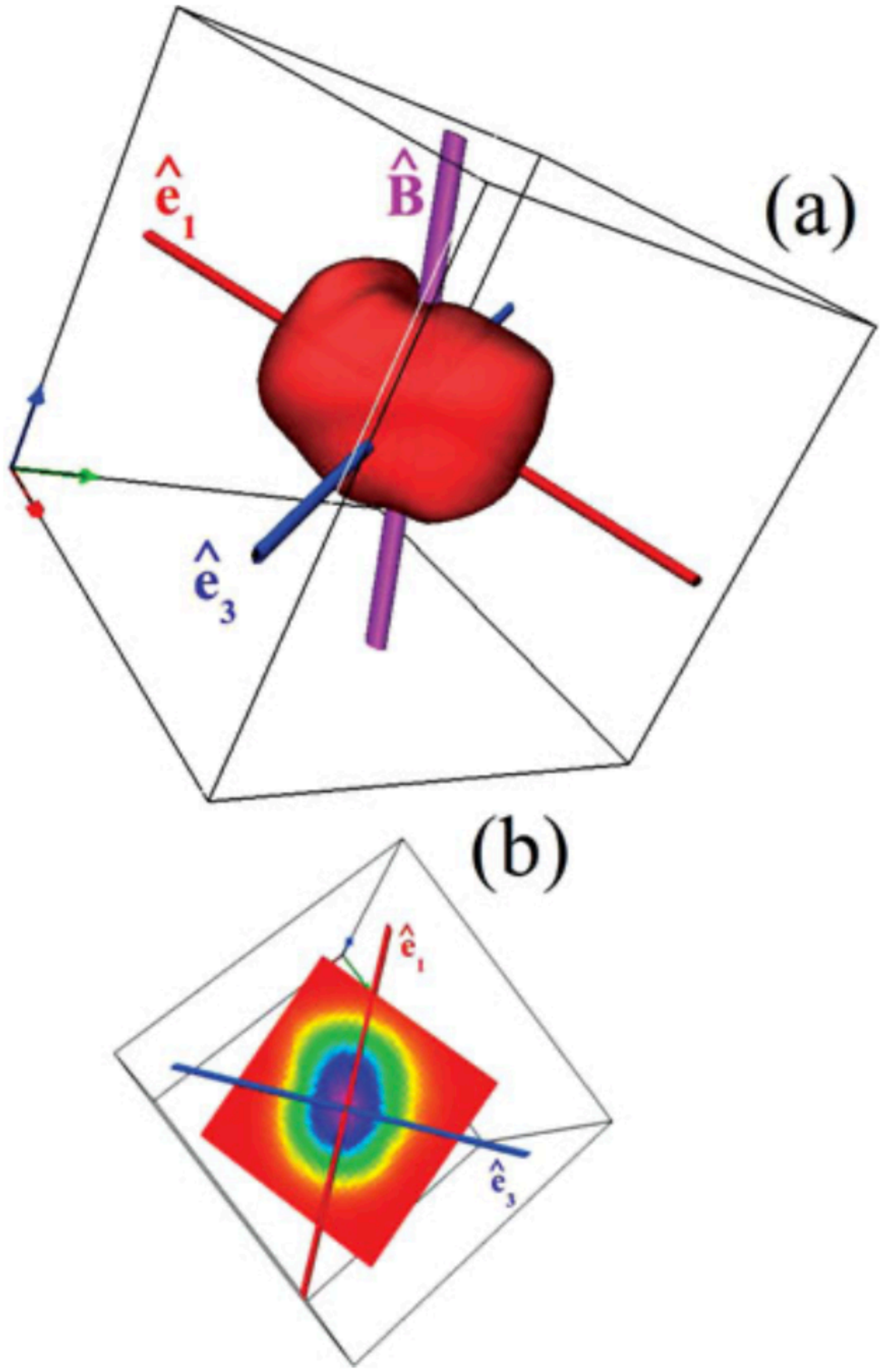
$$\epsilon = \frac{1}{2n_i} \int_{v,\theta,\phi} |f_i(v,\theta,\phi) - f_{\text{model}}(v,\theta,\phi)| v^2 \sin\theta \, dv \, d\theta \, d\phi,$$

$$\sqrt{Q} = \left(\frac{P_{12}^2 + P_{13}^2 + P_{23}^2}{P_\perp^2 + 2P_\perp P_\parallel} \right)^{1/2}$$

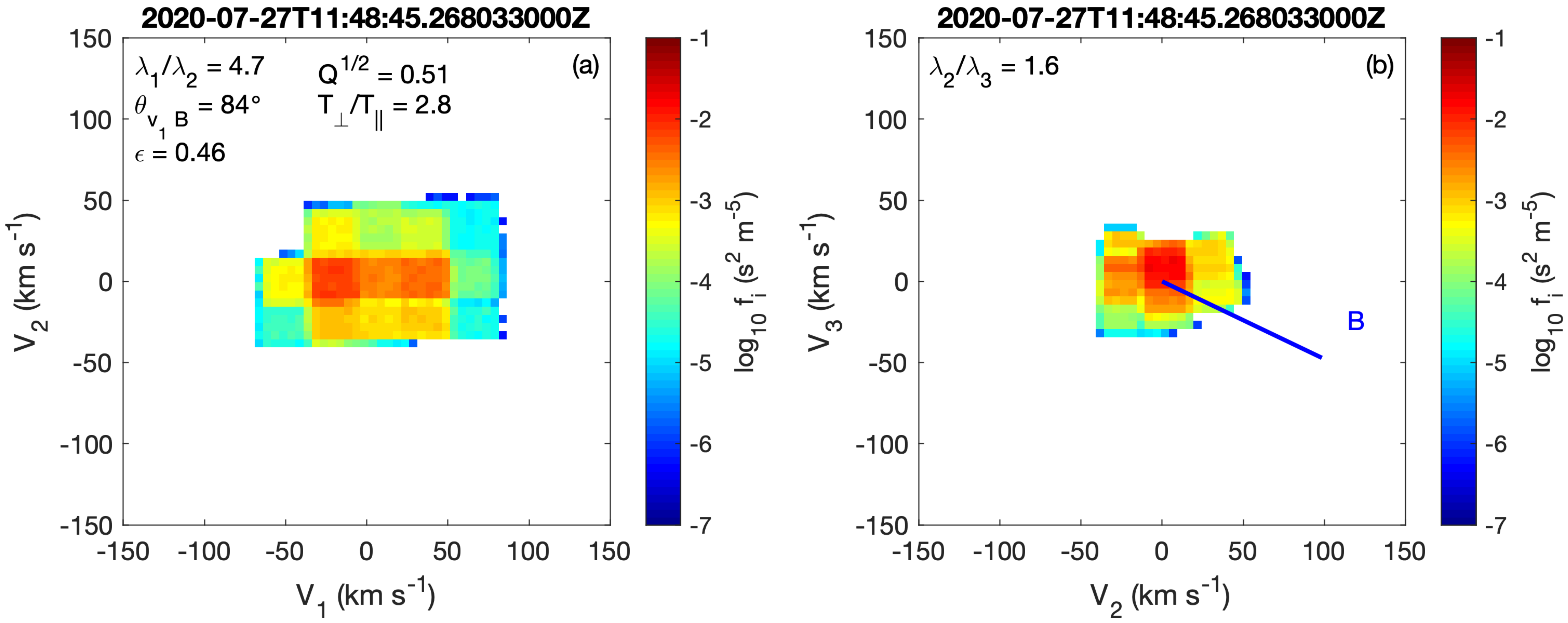
- Statistical relation between ε and sqrt(Q).

Temperature components

- To further investigate the cause of high ε, we calculate ‘proper’ temperatures of the distributions by computing the eigenvalues/vectors of the temperature tensor.

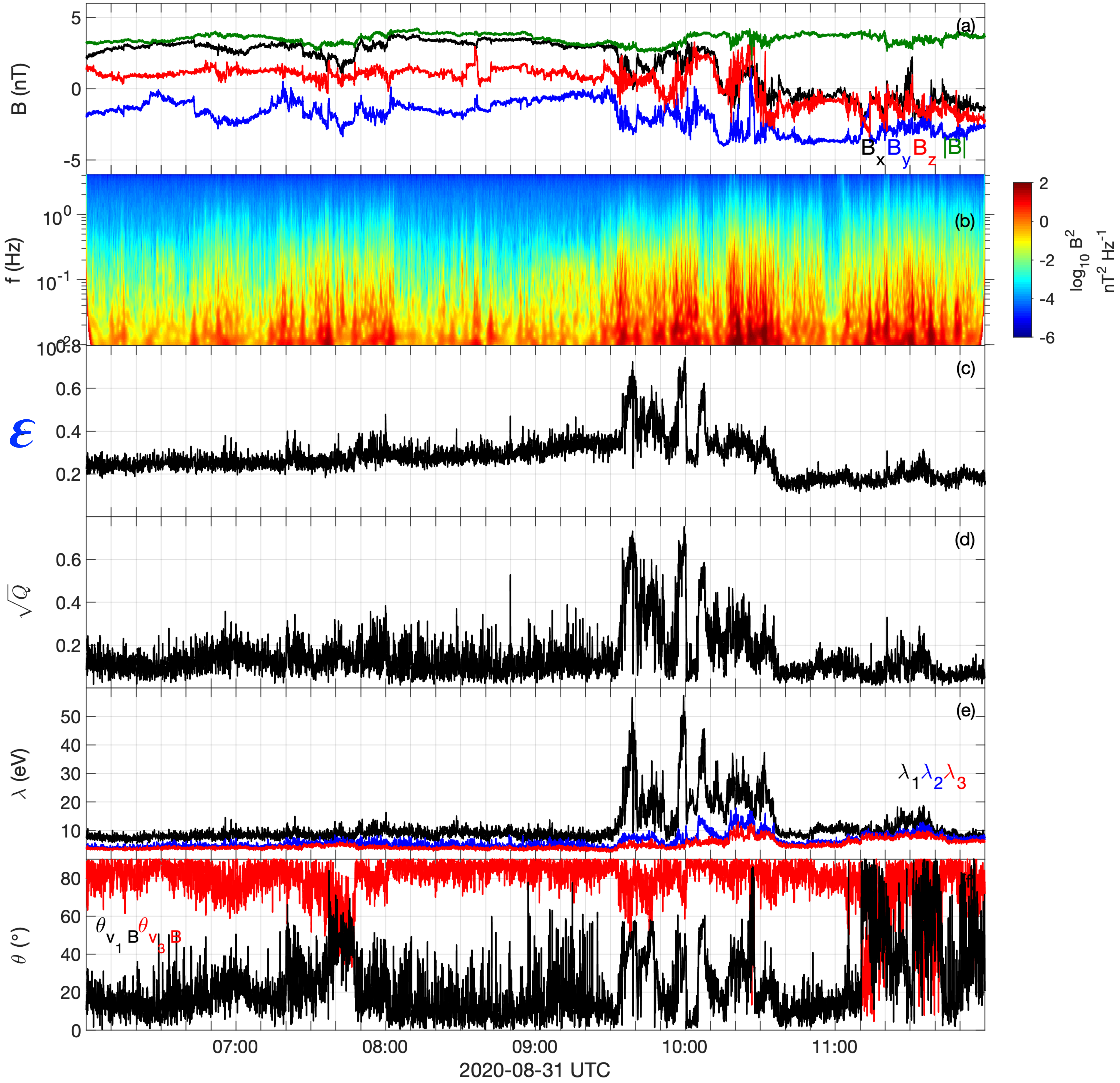


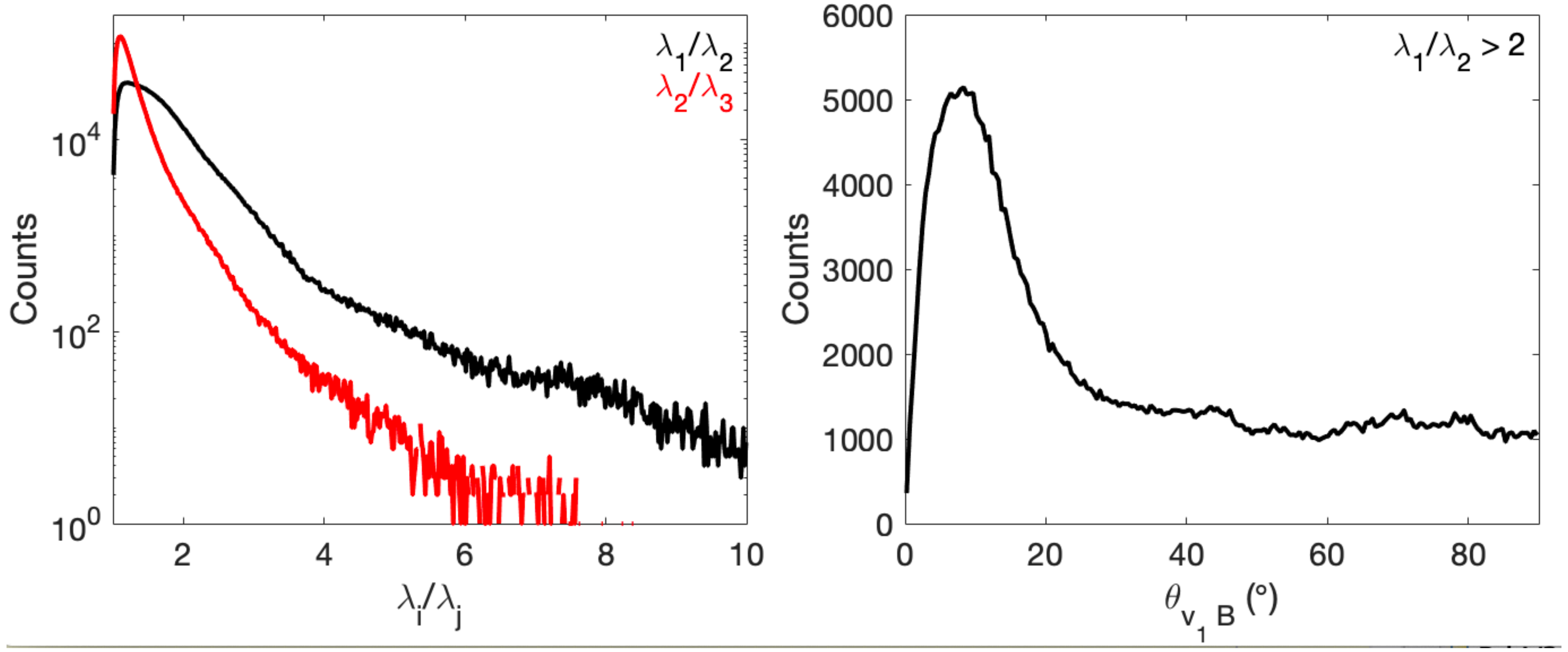
[Servidio, et al., 2016]



- Cigar-shaped distribution with major axis perpendicular to B.

Example

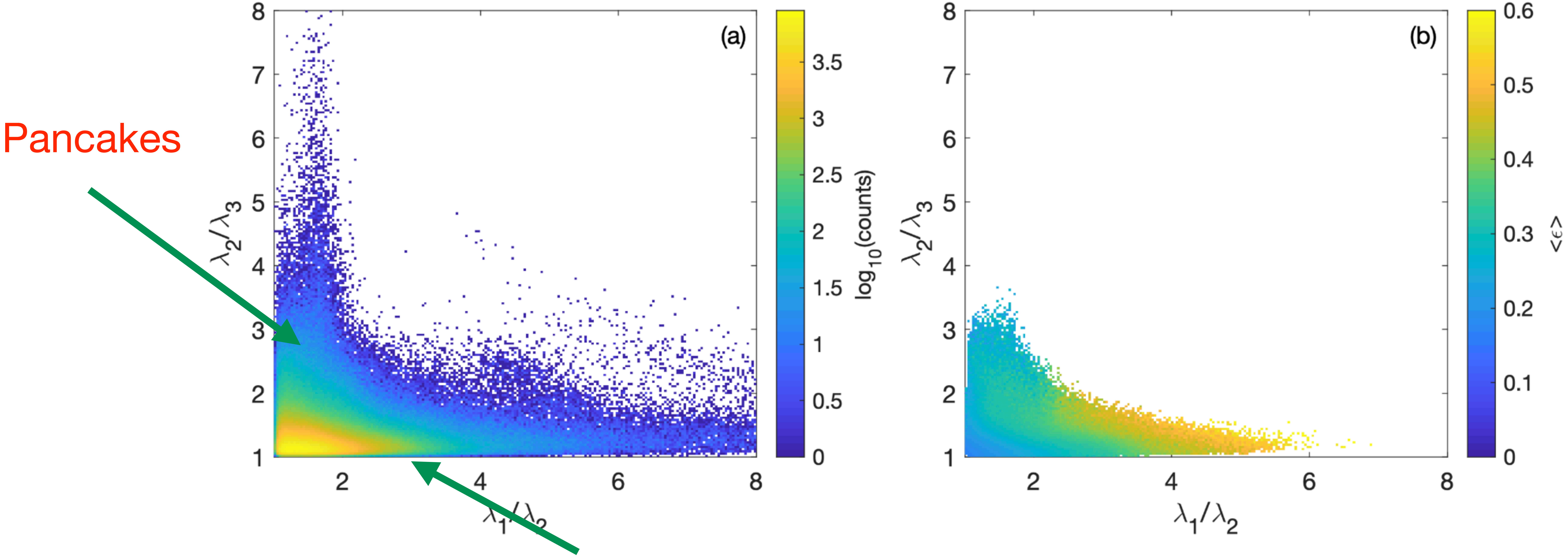




- Cigar-shaped distributions are regularly oblique to **B**.

- Non-gyrotropic and non-Maxwellianity is primarily due to cigar-shaped distributions.

Statistics

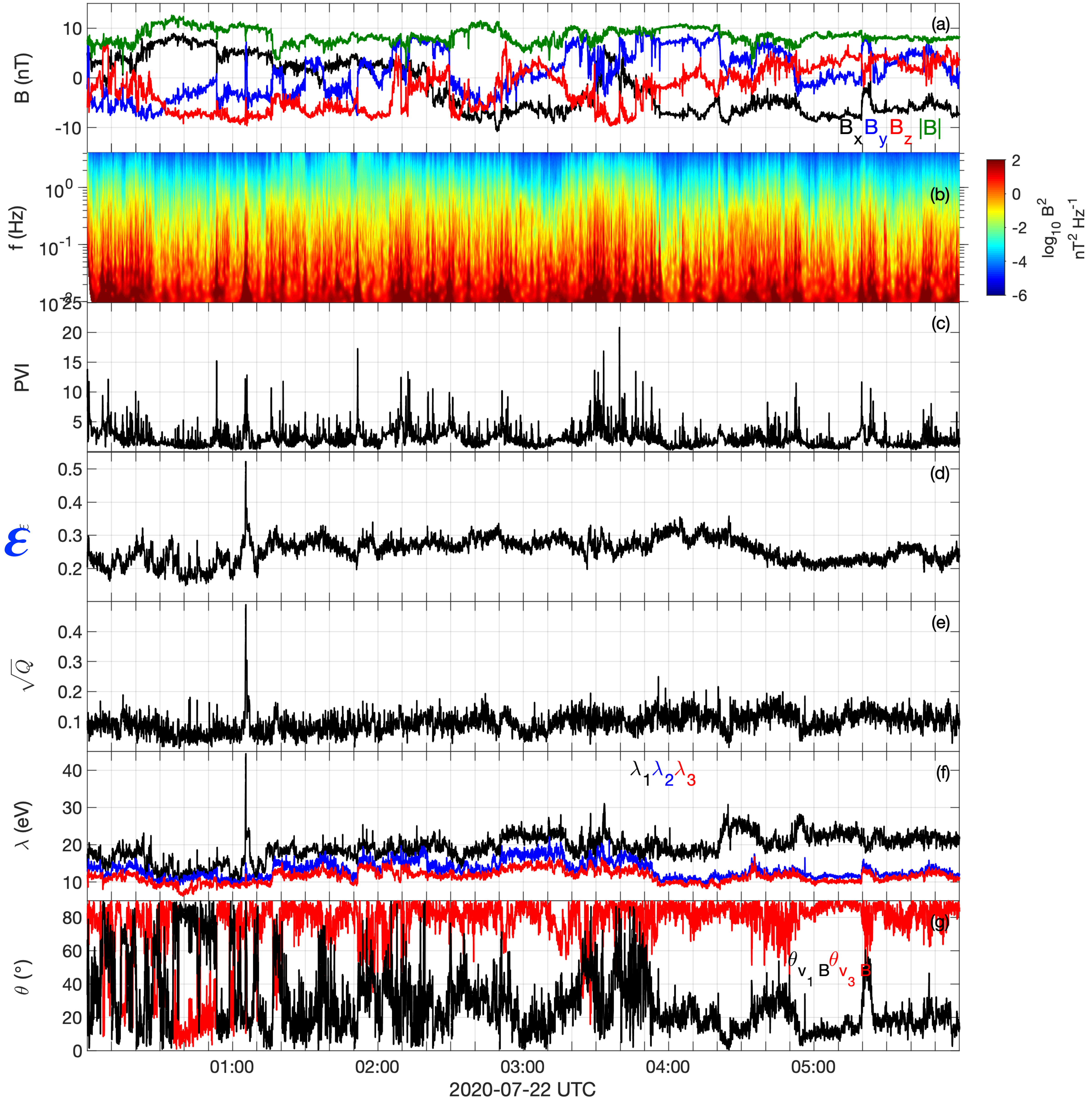


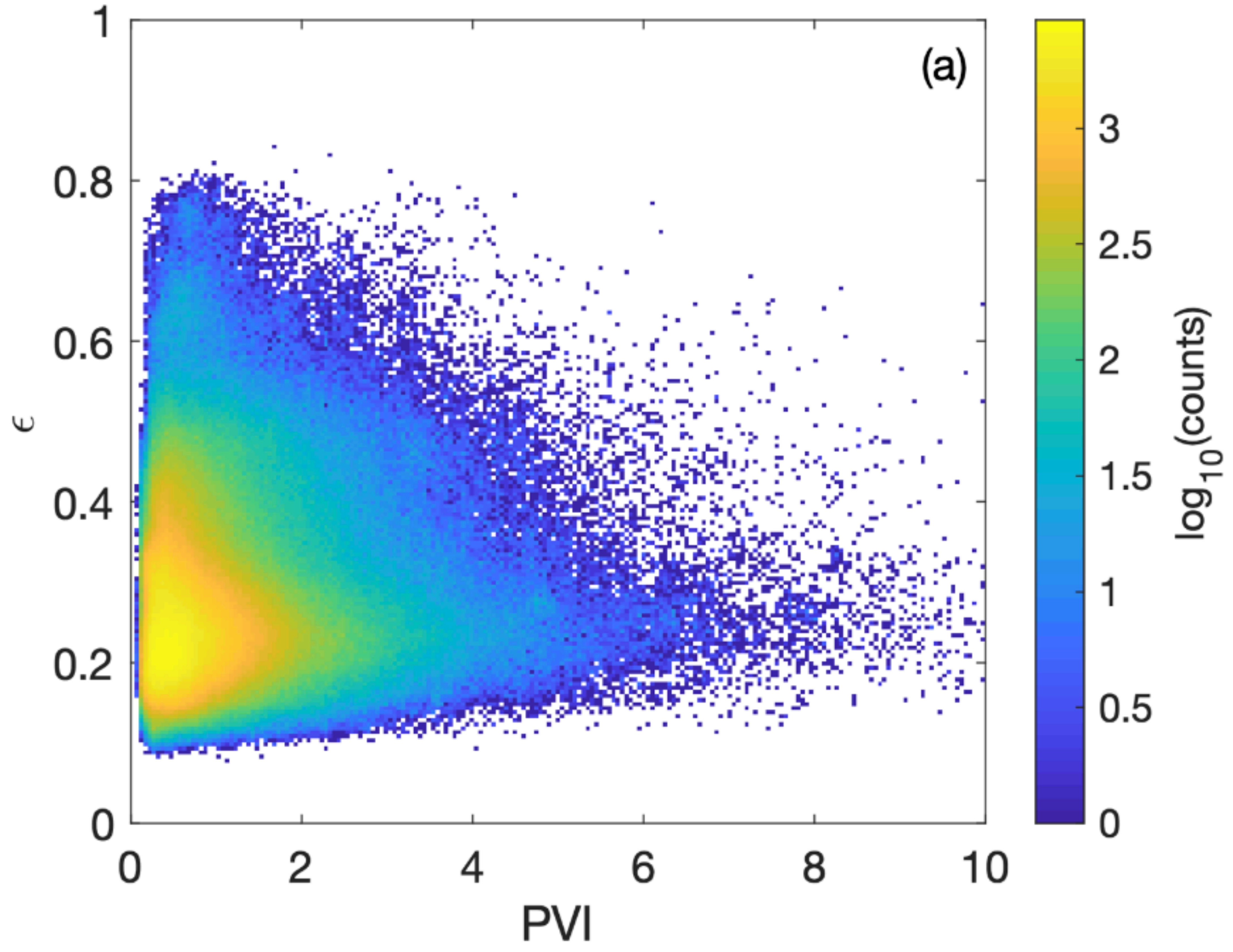
Pancakes

Cigars

- Larger mean non-Maxwellianity is associated with cigar-shaped distributions.

Relation to turbulence

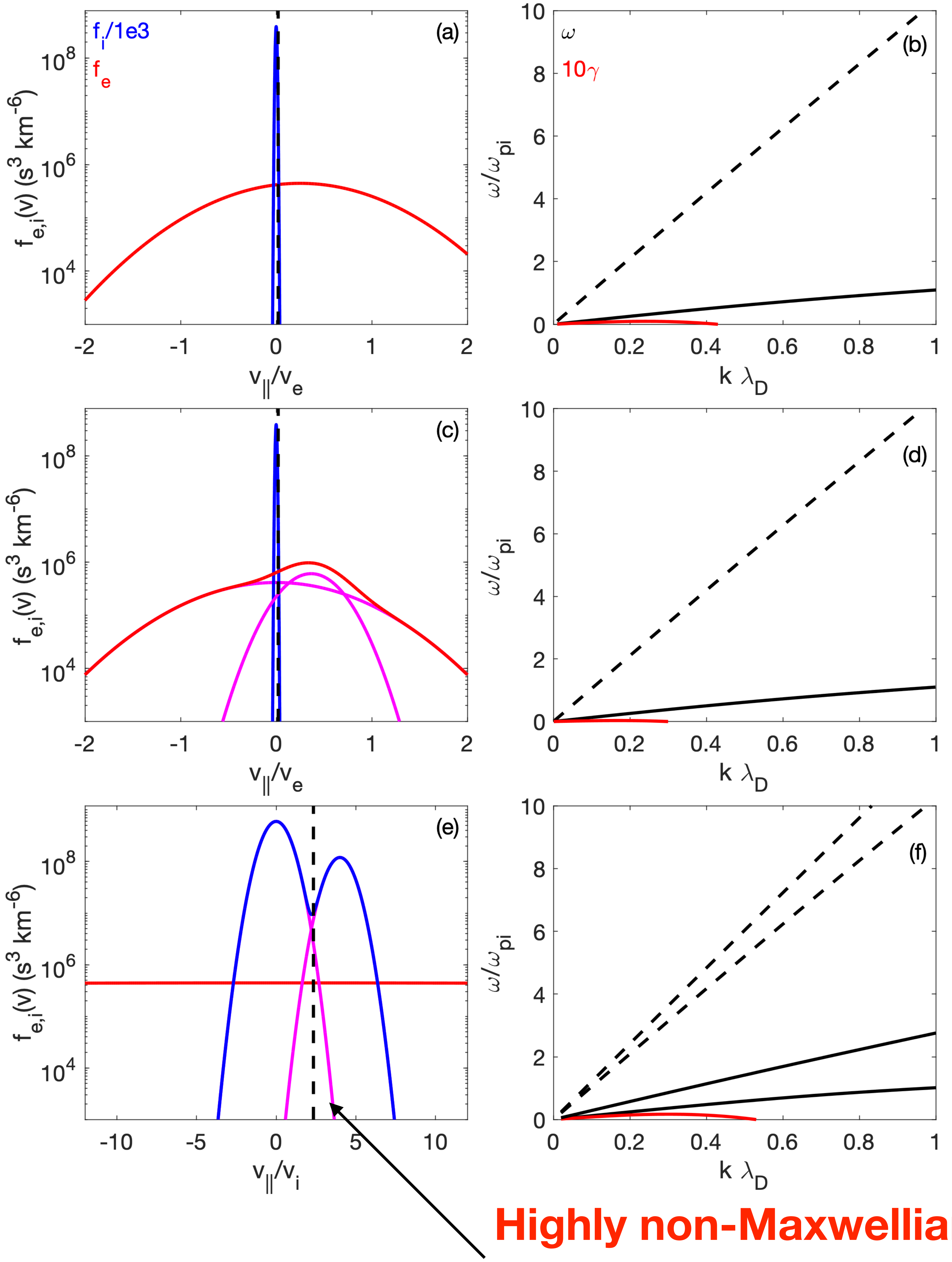




$$PVI = \frac{|\Delta \mathbf{B}(t,\tau)|}{\sqrt{\langle|\Delta \mathbf{B}(t,\tau)|^2\rangle}}, \quad \Delta \mathbf{B}(t,\tau) = \mathbf{B}(t+\tau) - \mathbf{B}(t)$$

[Greco, et al., 2008]

Ion-acoustic waves in the solar wind



Electron-ion

Electron-electron-ion

Electron-ion-ion

$$0 = 1 - \sum_j \frac{\omega_{pj}^2}{k^2 v_j^2} Z'\left(\zeta_j\right),$$

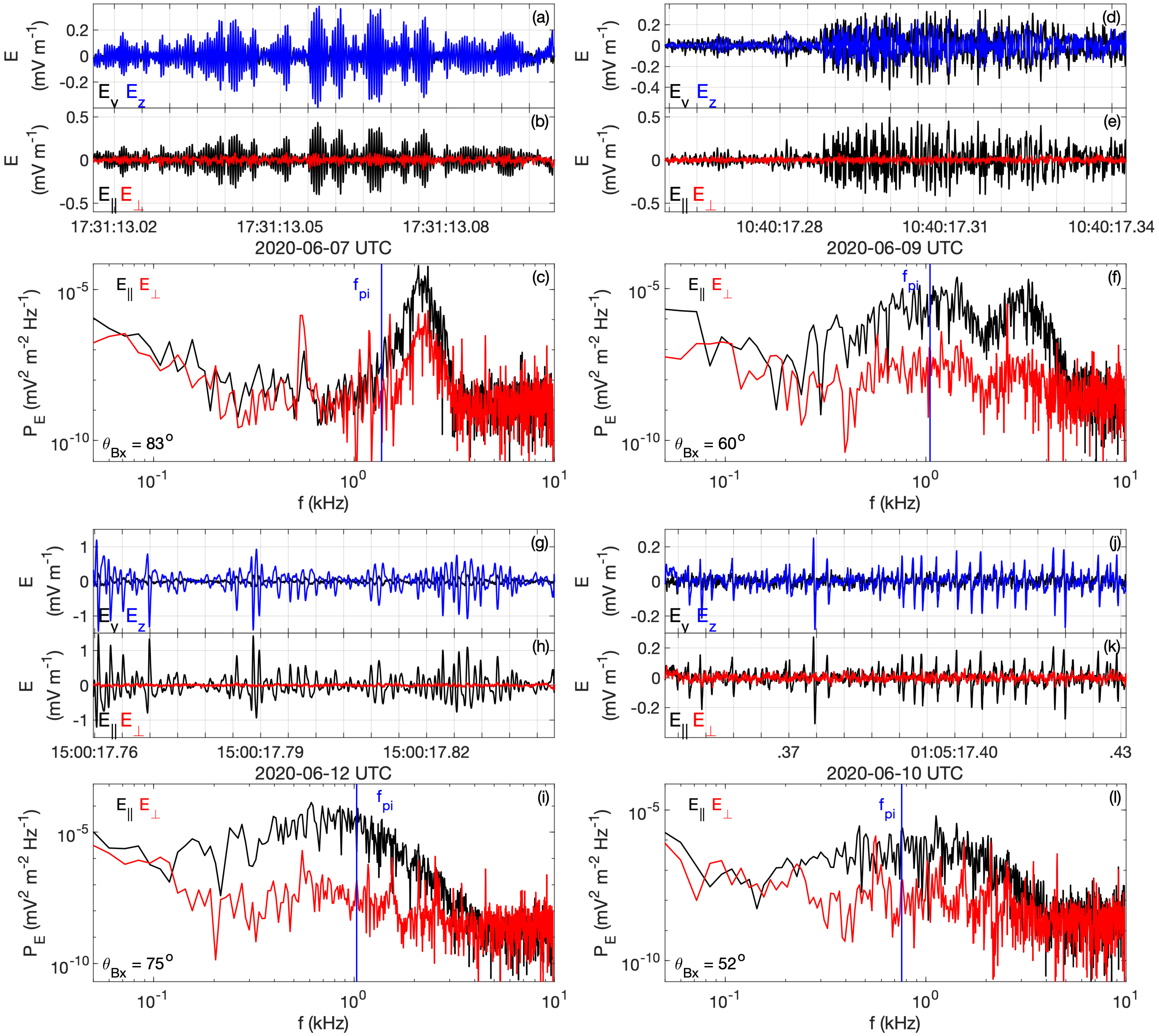
- Ion-acoustic waves can be generated by a variety of streaming instabilities.

- Based on estimated current densities, electron-ion-ion instability is most like to generate ion-acoustic waves.

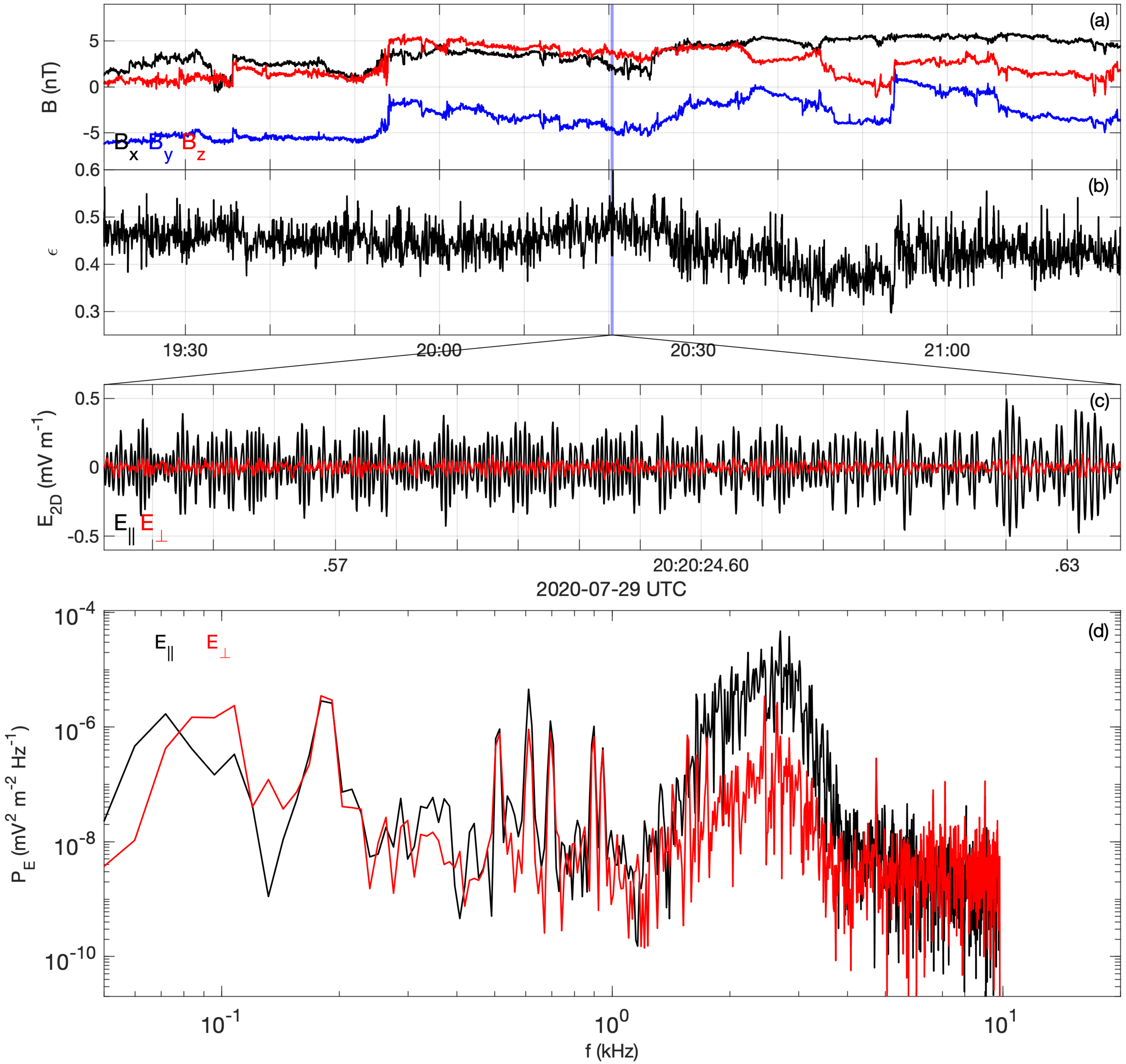
Highly non-Maxwellian ion distribution.

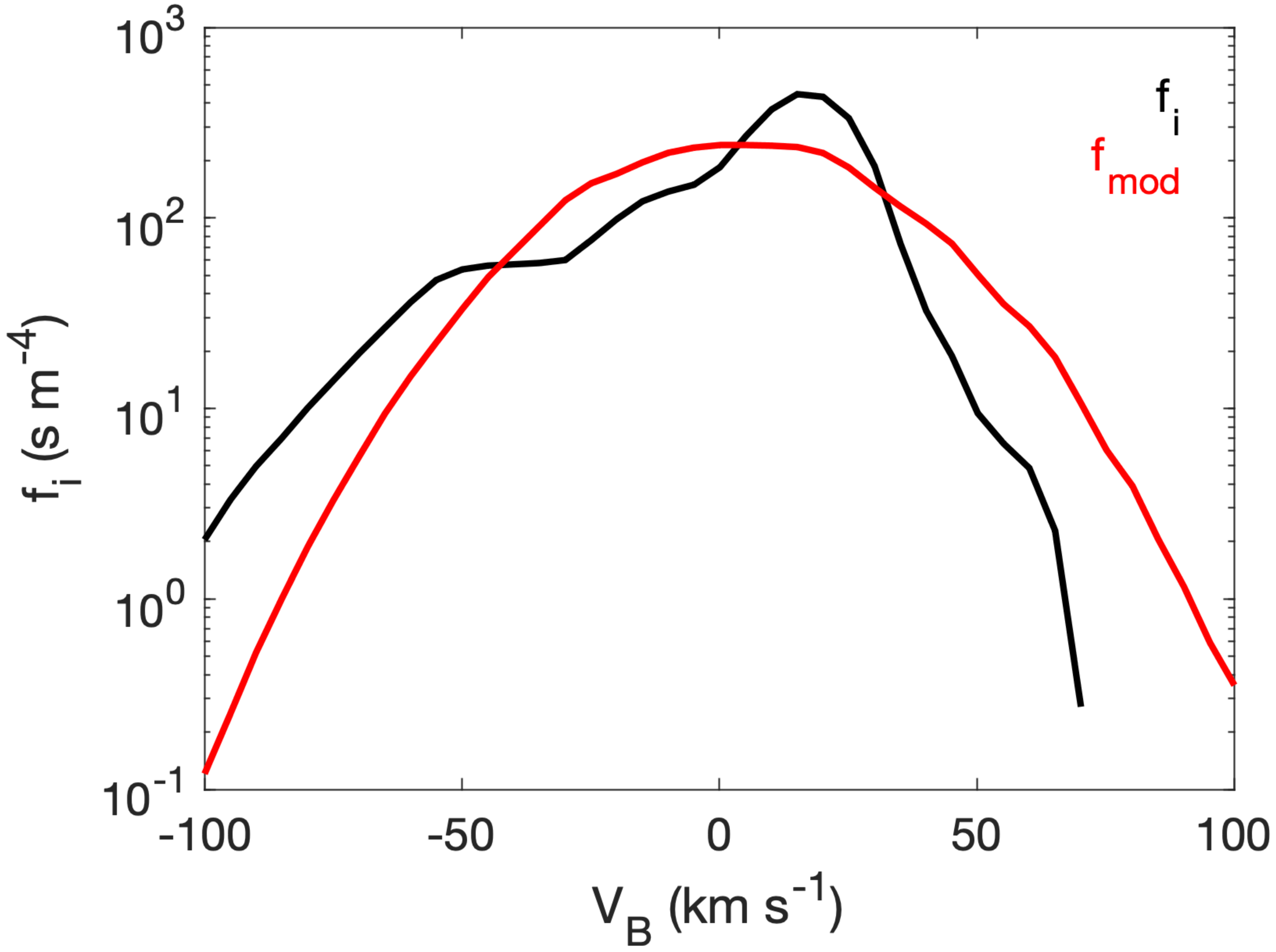
[Graham, et al., 2021a]

Ion-acoustic wave examples



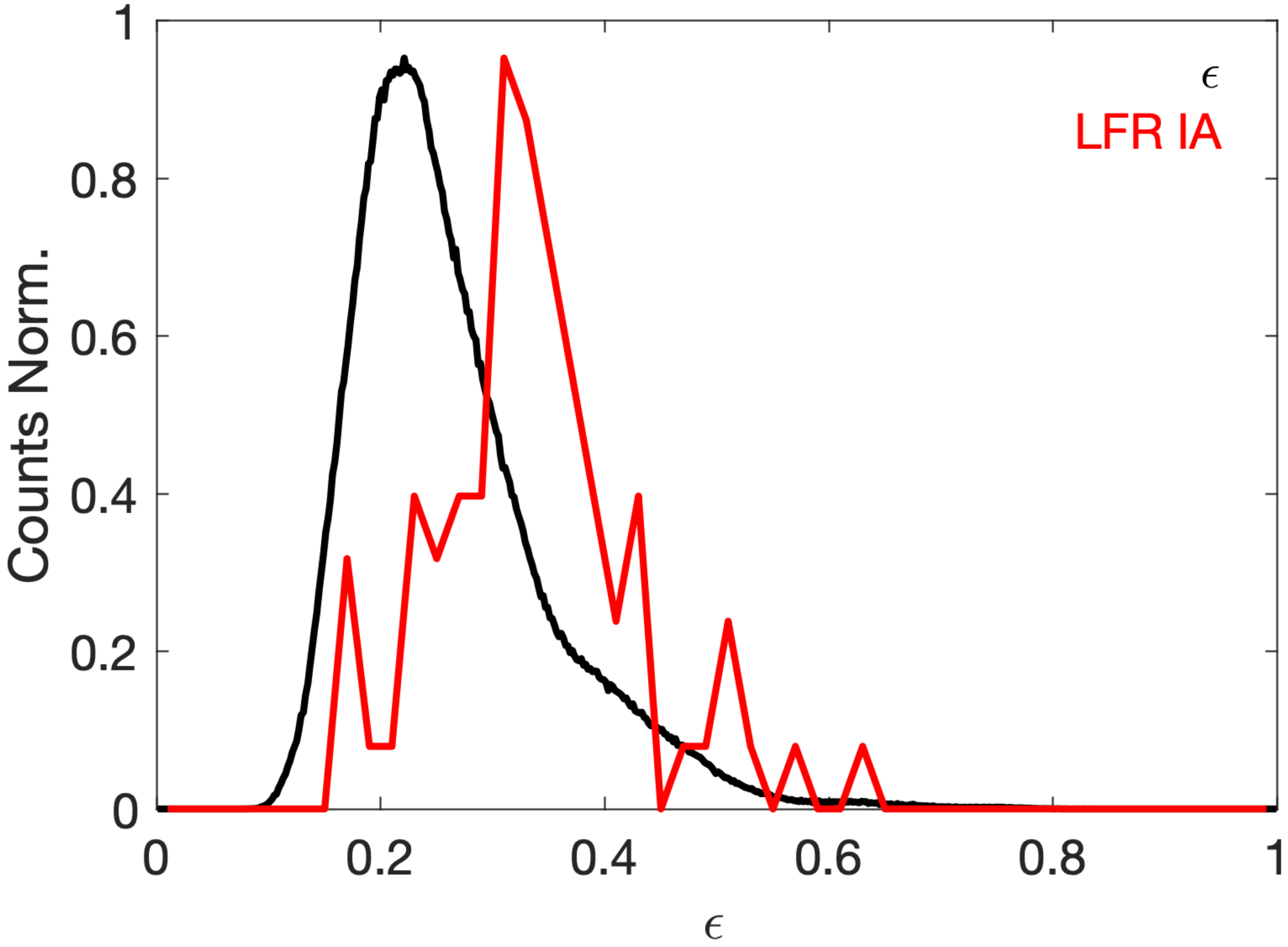
Non-Maxwellianity and ion-acoustic waves





- $\varepsilon = 0.5$

Statistics



- Slightly larger ε are observed in association with ion-acoustic waves.

Conclusions

- Ion non-Maxwellianity is routinely observed in the solar wind.
- Ion non-Maxwellianity is not strongly correlation with local turbulent structures in the solar wind.
- Slightly enhanced non-Maxwellianity is observed at the same time as ion-acoustic waves. Kinetic instability of ion distributions is a plausible source of ion-acoustic waves.