Measuring Particle Acceleration in Turbulent Astrophysical Plasmas

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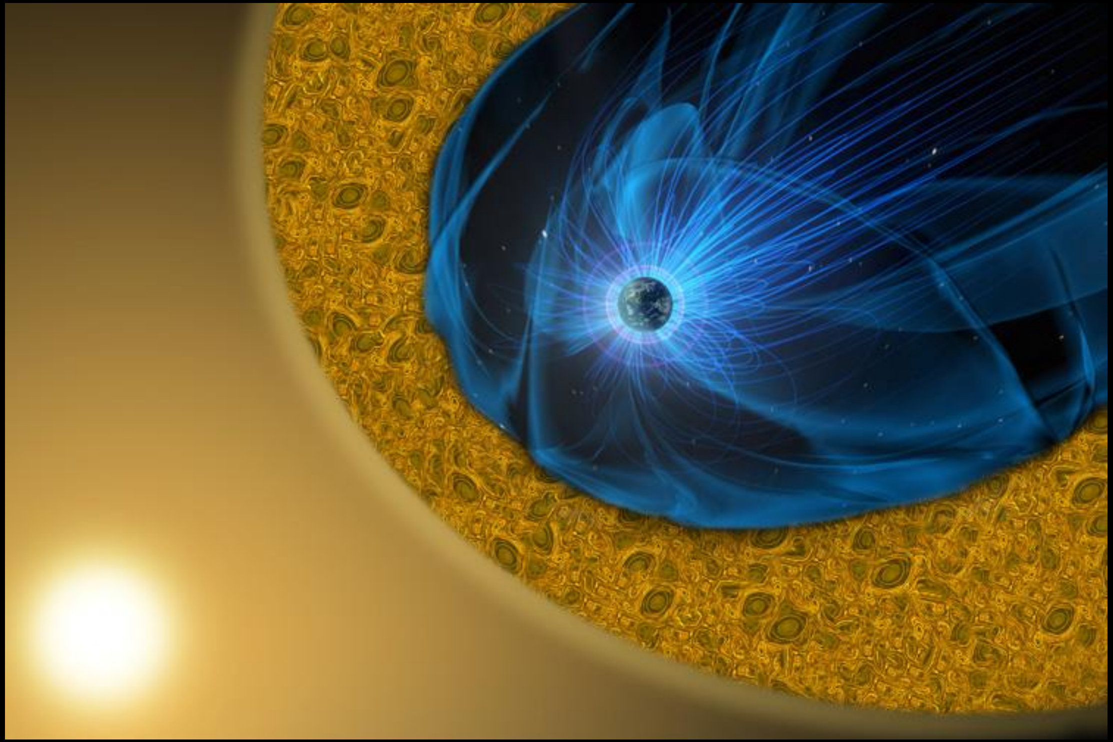
Magnetosheath Turbulence



- Region downstream of the bow shock consisting of shocked solar wind plasma
- Local laboratory accessible to spacecraft measurements
- Extensive spacecraft measurements are available here
- The magnetosheath contains shocked plasma from the bow shock, so is naturally turbulent.
- This can be due to;
  - Kinetic instabilities generated at the bow shock
  - Plasma instabilities developing within the magnetosheath
  - Solar wind fluctuations advected through the shock

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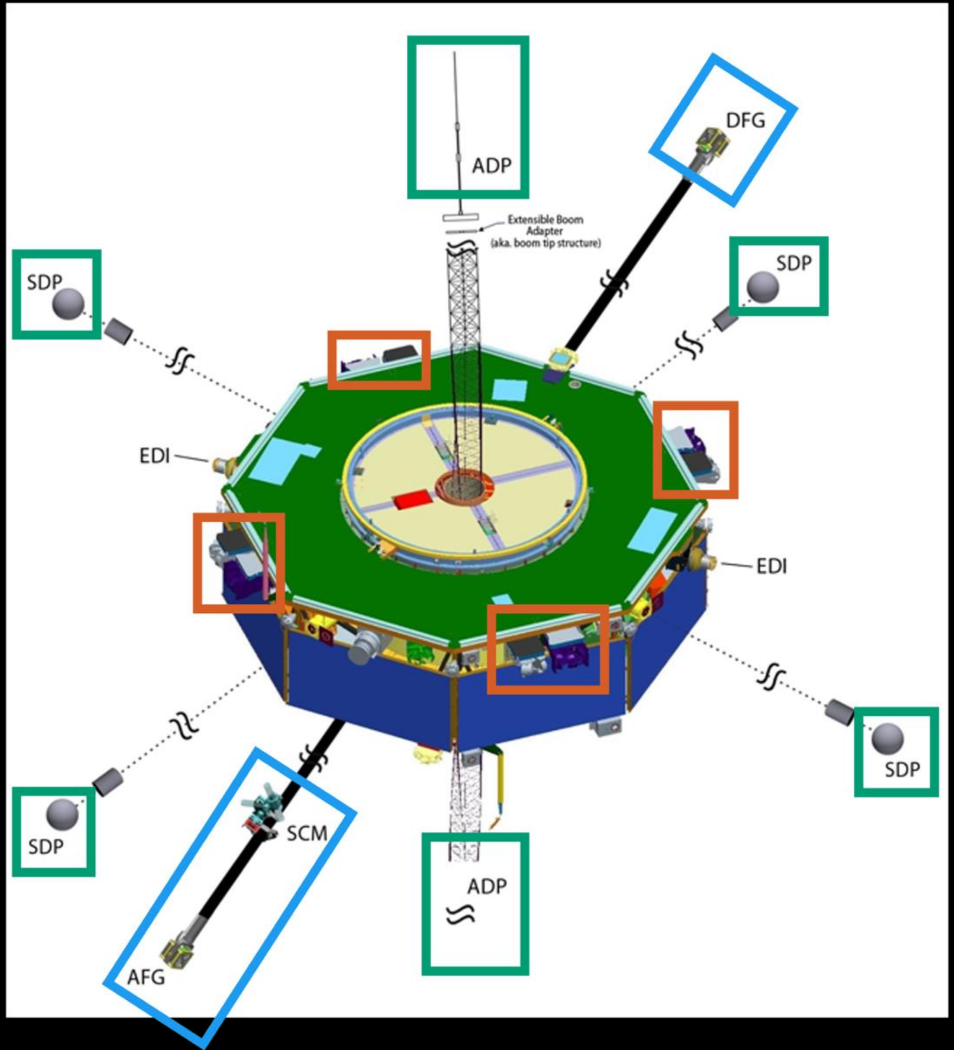
MMS



- NASA's **M**agnetospheric **M**ulti**S**cale Mission – 4 spacecraft in a tetrahedral formation
- High cadence instrumentation:
  - Fields: Up to 8192 samples/s
  - 3D Particle Distributions: 30-150ms resolution
- Measures both fields and velocity distribution functions simultaneously
- Allows for the analysis of field-particle correlations, seeing which particles gain energy from the fields

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Field-Particle Correlations

The phase-space energy density, $\mathrm{w}_s = \frac{1}{2}\mathrm{m}_s \mathrm{v}^2 \mathrm{f}_s$ evolves as:

$$\frac{\partial w_s}{\partial t} = -\mathbf{v} \cdot \nabla w_s - \frac{q_s \mathrm{v}^2}{2} \boldsymbol{E} \cdot \frac{\partial f_s}{\partial \mathbf{v}} - \frac{q_s \mathrm{v}^2}{2} (\mathbf{v} \times \boldsymbol{B}) \cdot \frac{\partial f_s}{\partial \mathbf{v}}$$

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Term 1: Transport of w_s in and out of a physical volume

Term 2: Exchange of energy with the EM fields (integrates to $\boldsymbol{j_s} \cdot \boldsymbol{E}$)

Term 3: Integrates to zero

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Knowing that $\mathrm{f_s} = 2\mathrm{w_s}/\mathrm{m_s v^2}$, we can obtain:

$$\frac{\partial w_s}{\partial t} + \mathbf{v}\cdot\nabla w_s + \frac{q_s}{\mathrm{m_s}}(\boldsymbol{E} + \mathbf{v}\times\boldsymbol{B})\cdot\frac{\partial \mathrm{w_s}}{\partial \mathbf{v}} = \mathrm{q_s}\mathbf{v}\cdot\mathbf{E}\mathrm{f_s}$$

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Lagrangian Derivative, Dw_s/Dt, along phase-space trajectory

Energy increase or decrease along phase-space trajectory (integrates to $\boldsymbol{j_s} \cdot \boldsymbol{E}$)

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Field-Particle Correlations

If we are interested in the secular energy exchange, we can average over time and/or space and isolate individual terms, giving the Field Particle Correlation (FPC) technique (Klein et al 2016)

$$C_j(\mathbf{v}) = \left\langle -\frac{q_s \mathrm{v}^2}{2} E_j \frac{\partial f_s}{\partial \mathrm{v}_j} \right\rangle$$

$$C_j'(\mathbf{v}) = \langle q_s \mathrm{v}_j \cdot E_j f_s \rangle$$

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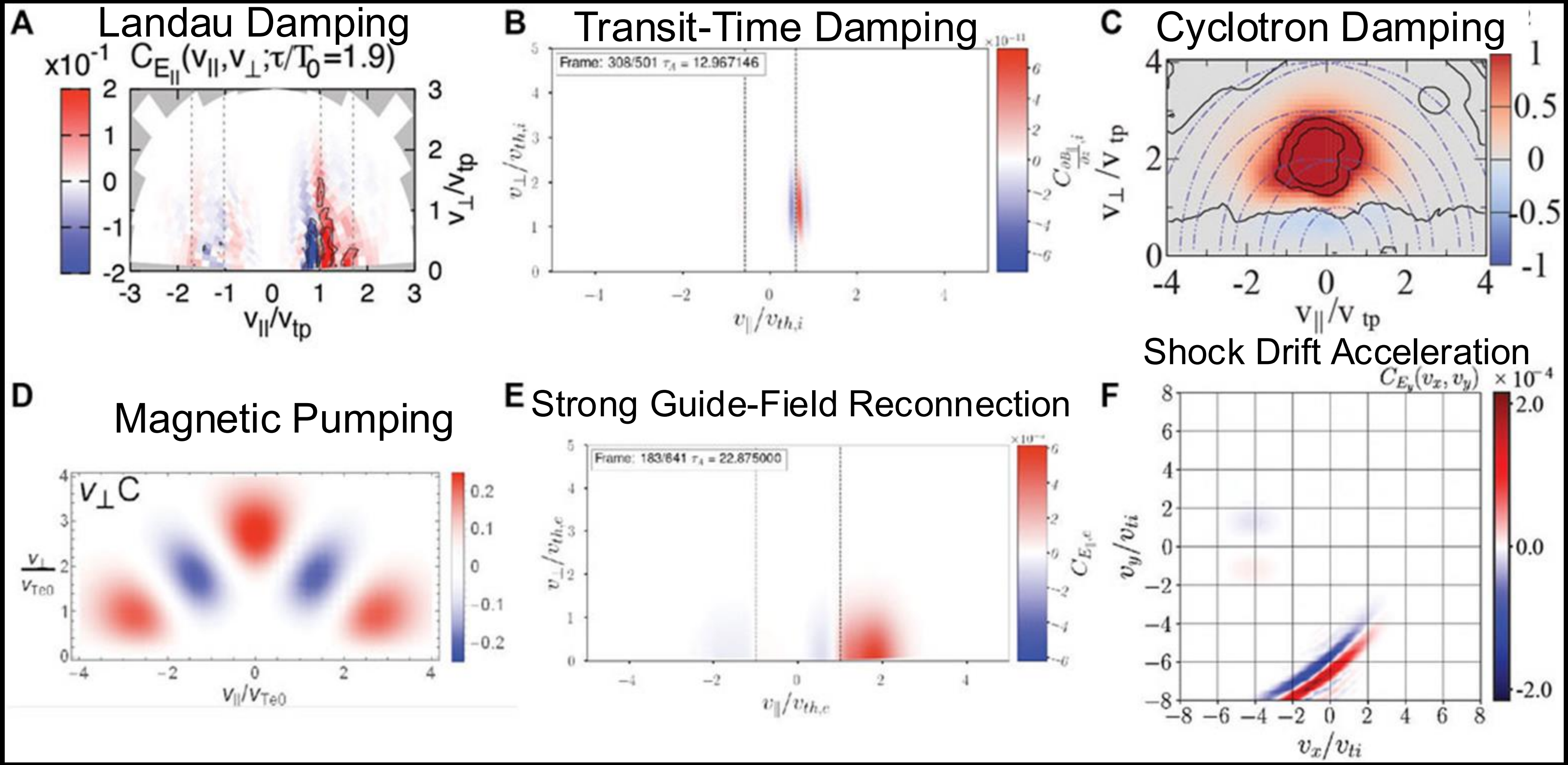
Field-Particle Correlations

Applications of the FPC technique in simulations (Howes et al 2022) show unique ‘fingerprints’ for energy dissipation mechanisms during turbulence:



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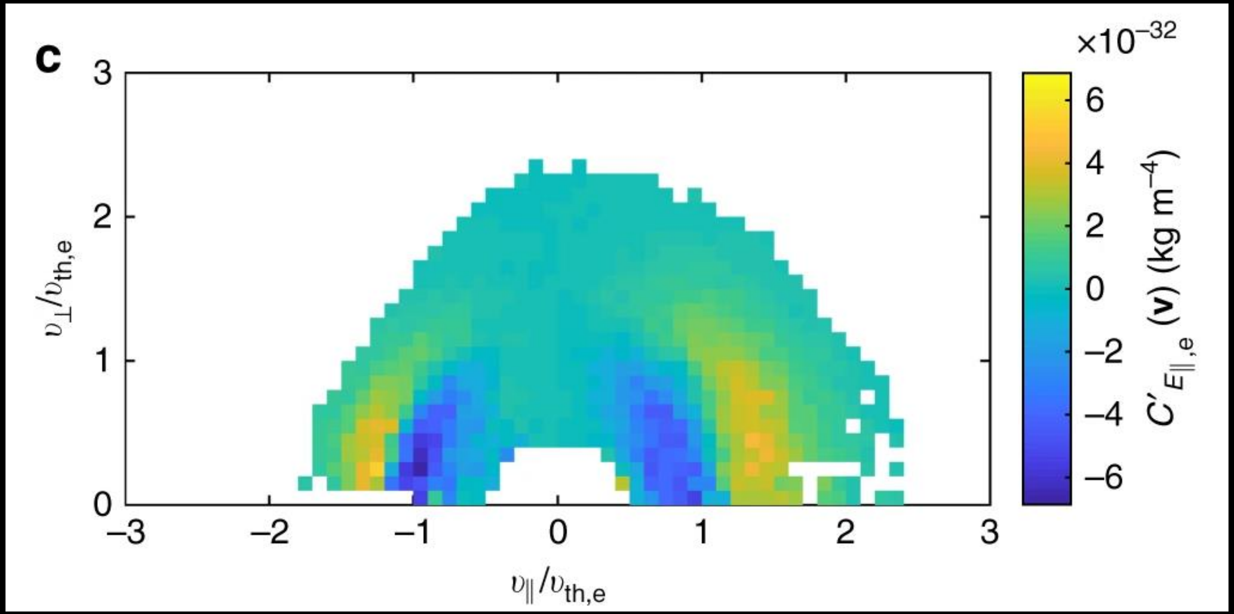
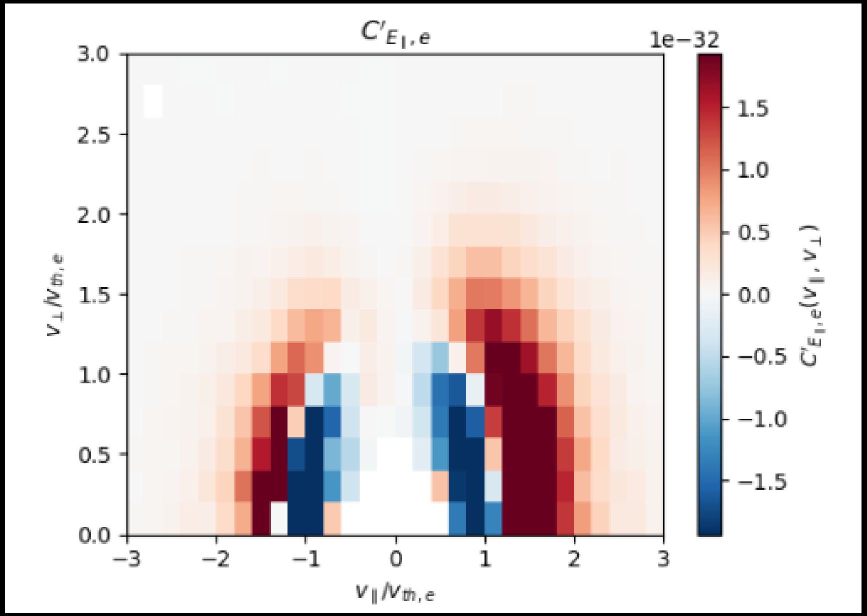
Electron Landau Damping



Field-particle alternative energy transfer rate using δf_e and high-pass-filtered (at 1 Hz) $E_{||}$ from Chen et al 2019



Recreation of the left panel using current code

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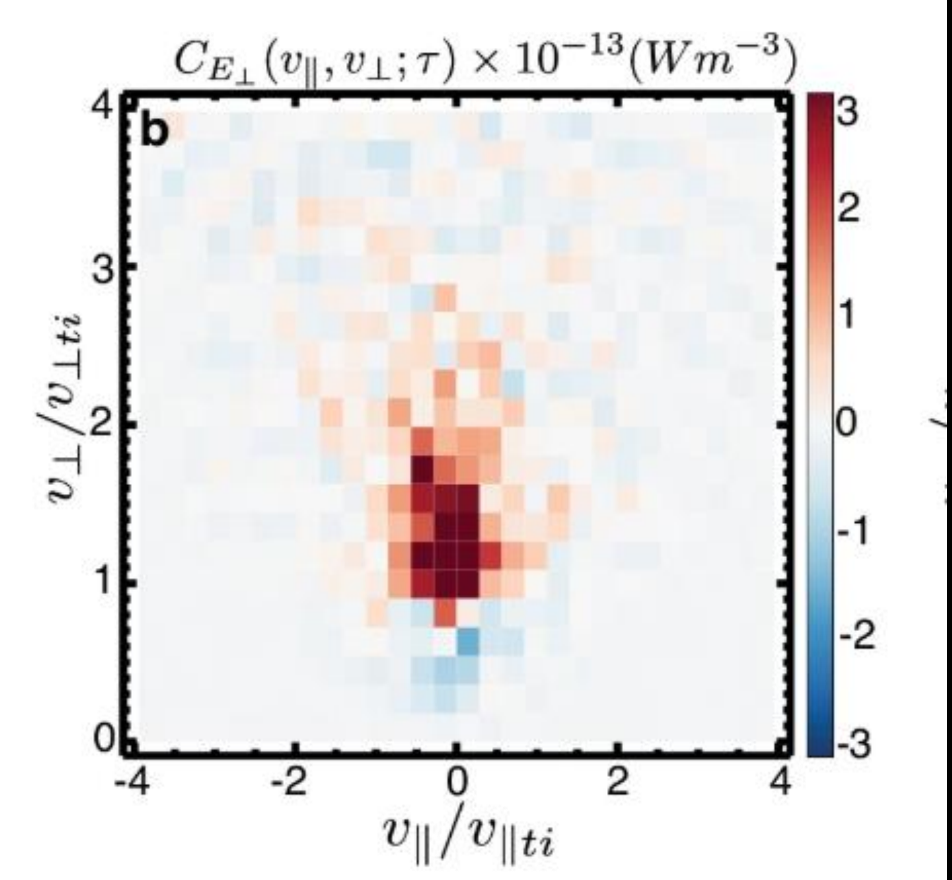
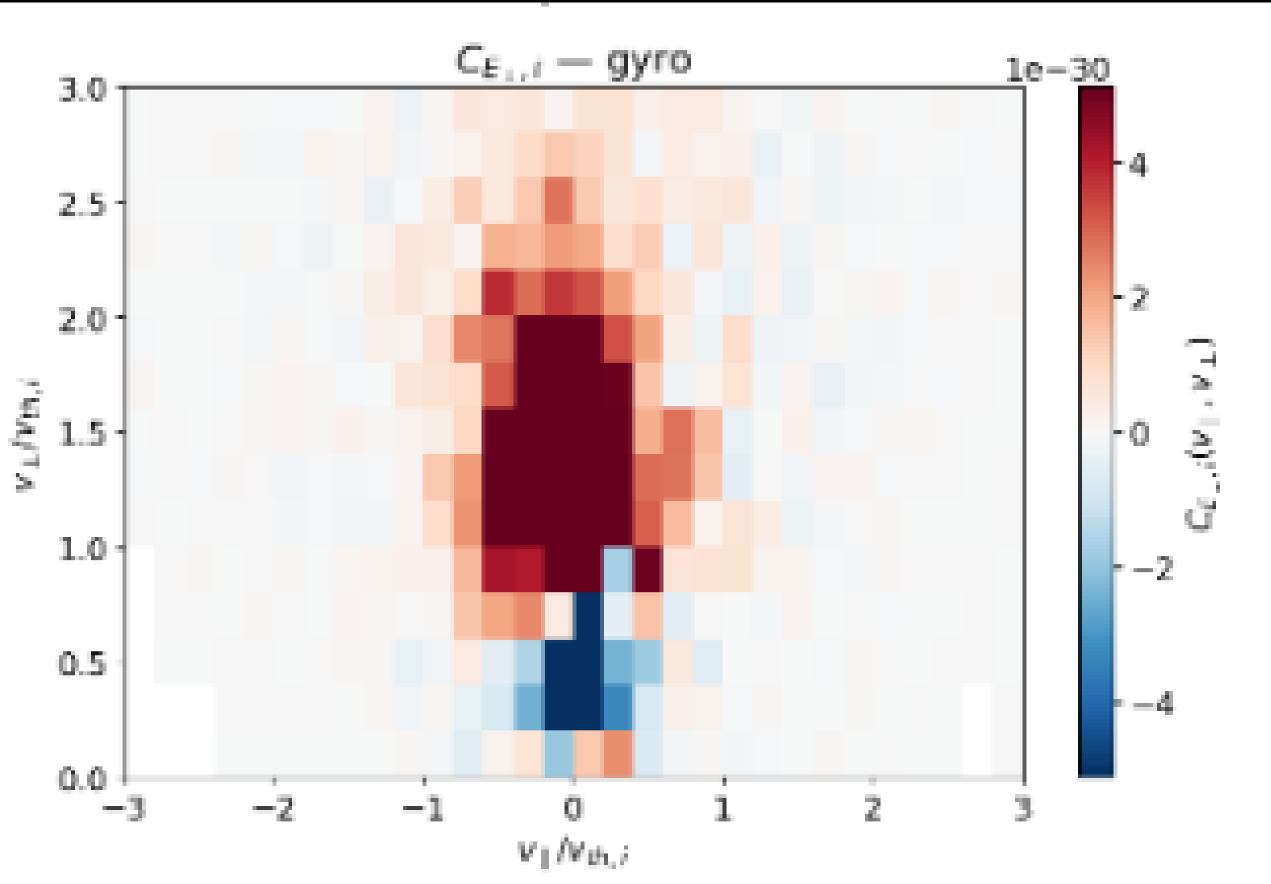
Ion Cyclotron Damping



The gyrotropic velocity-space signature of ion cyclotron damping from MMS data in Afshari et al 2024.



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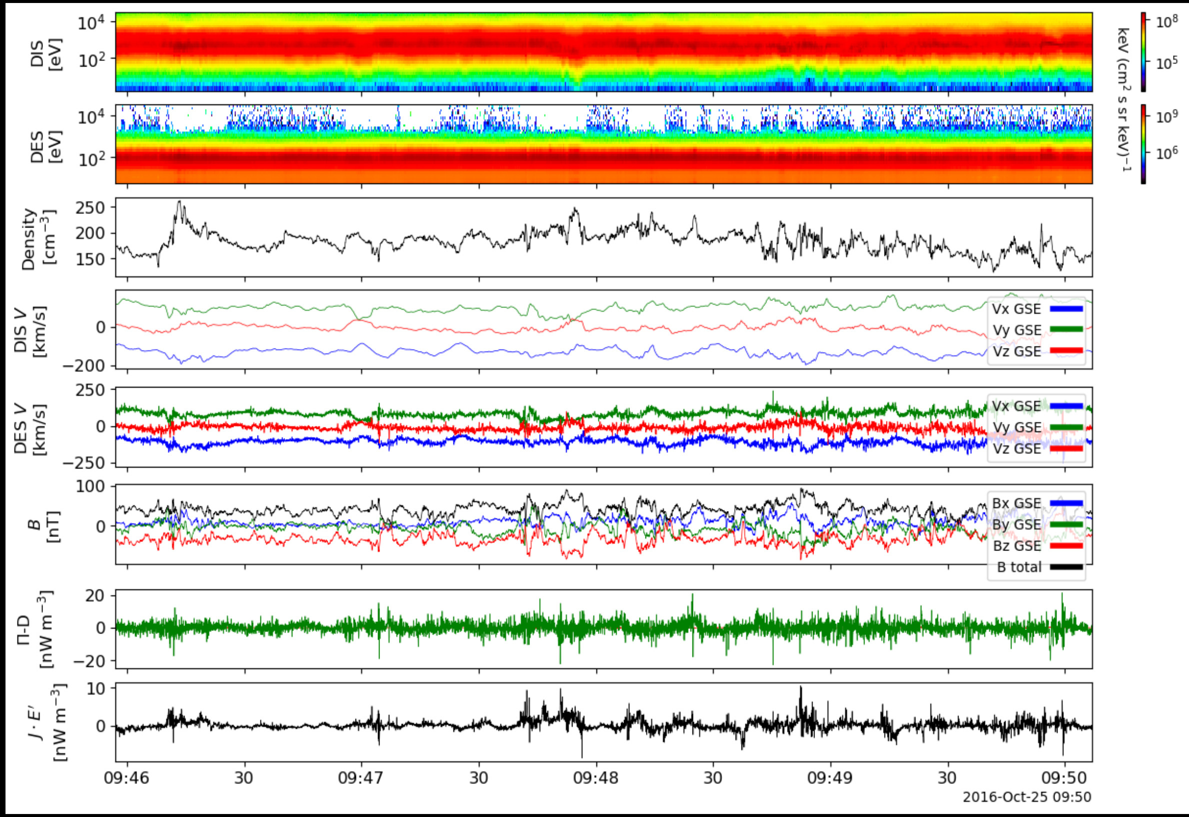
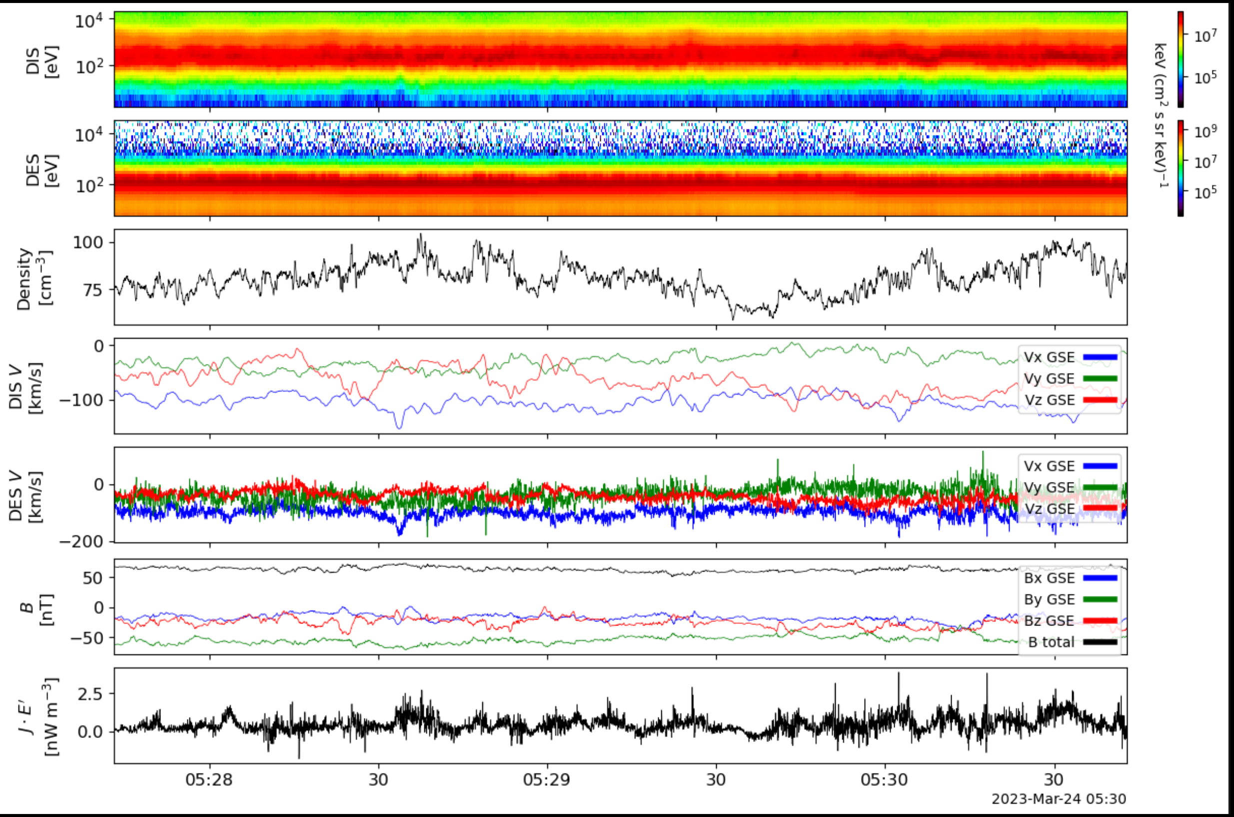
High Density Intervals

”Stawarz” Interval



”Svenningsson” Interval



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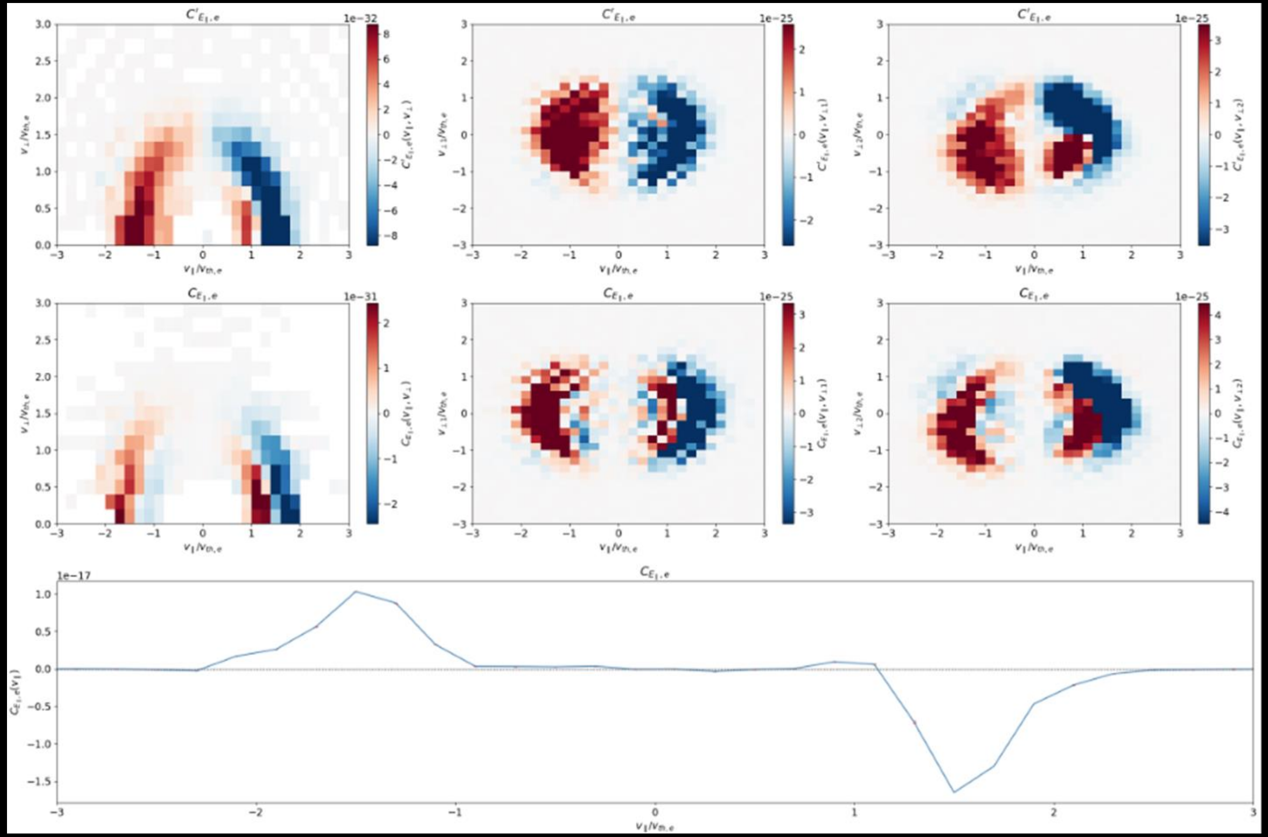
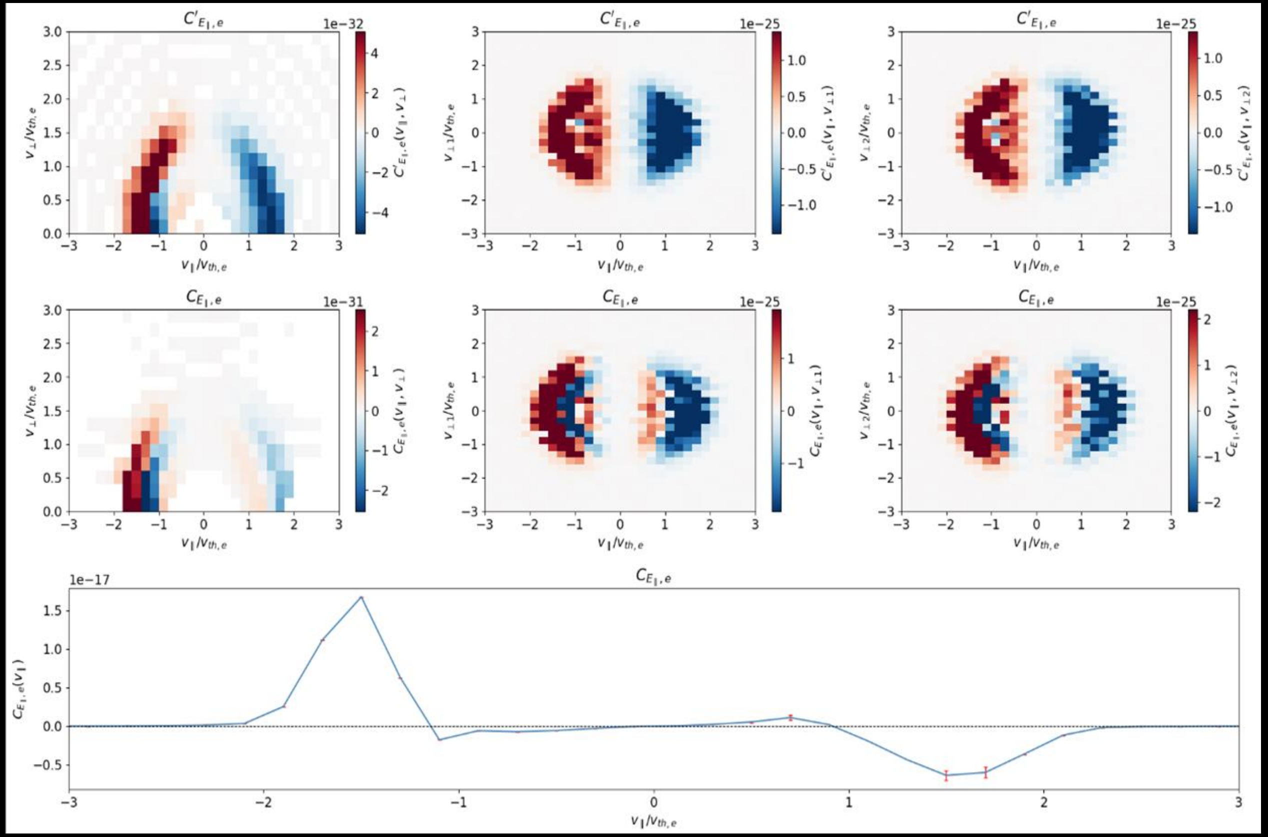
High Density Intervals

Electron Parallel

"Stawarz" Interval



"Svenningsson" Interval



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High Density Intervals

Electron Parallel

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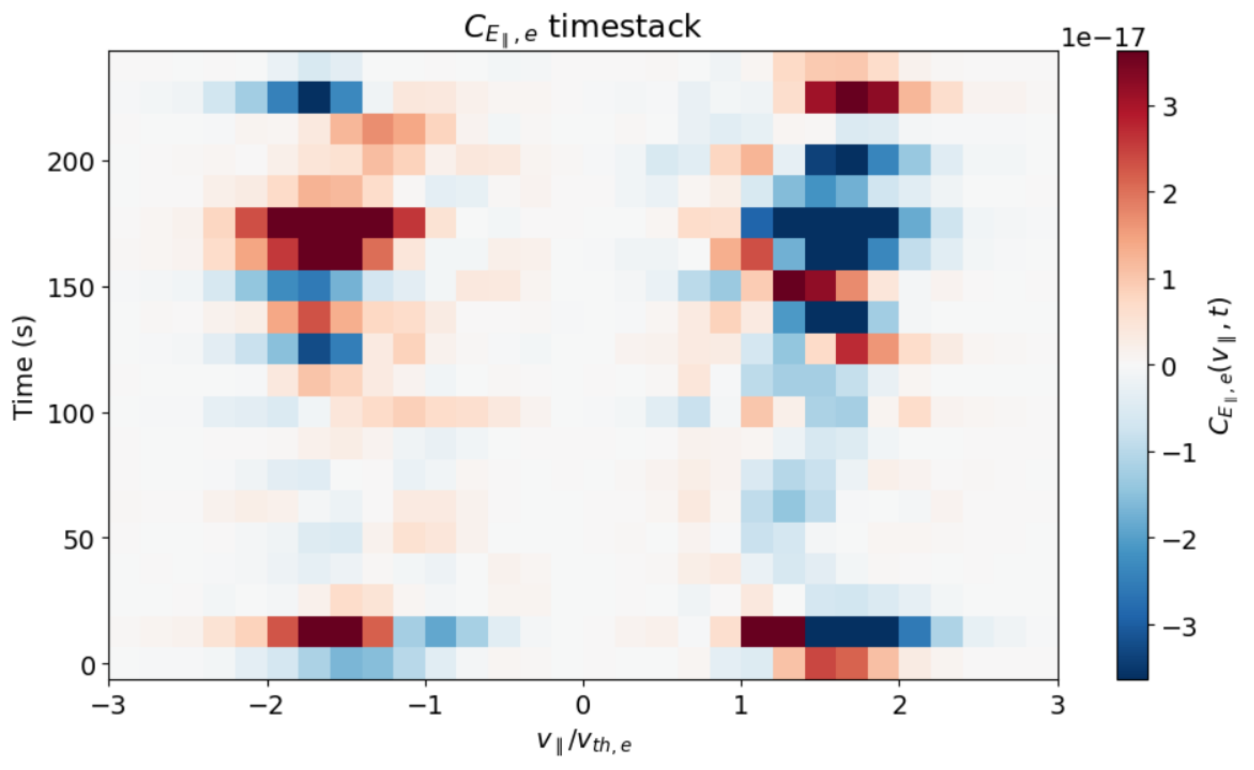

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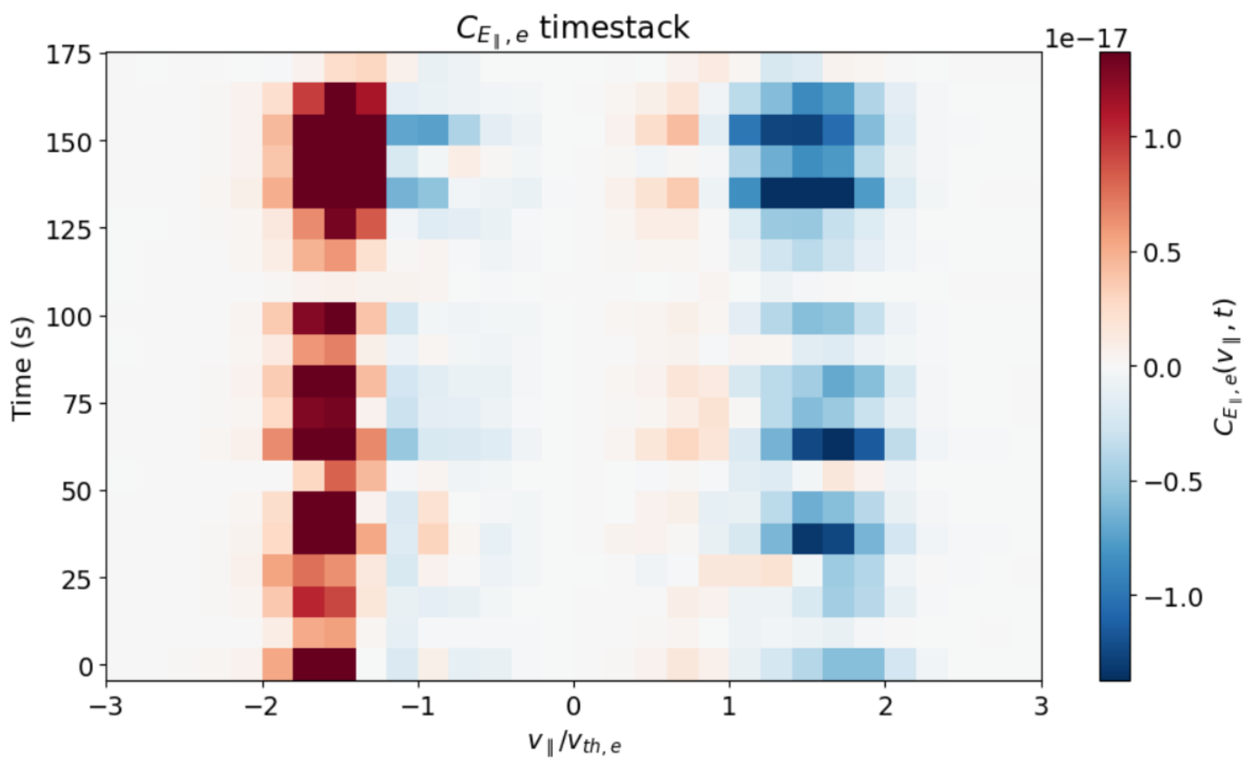

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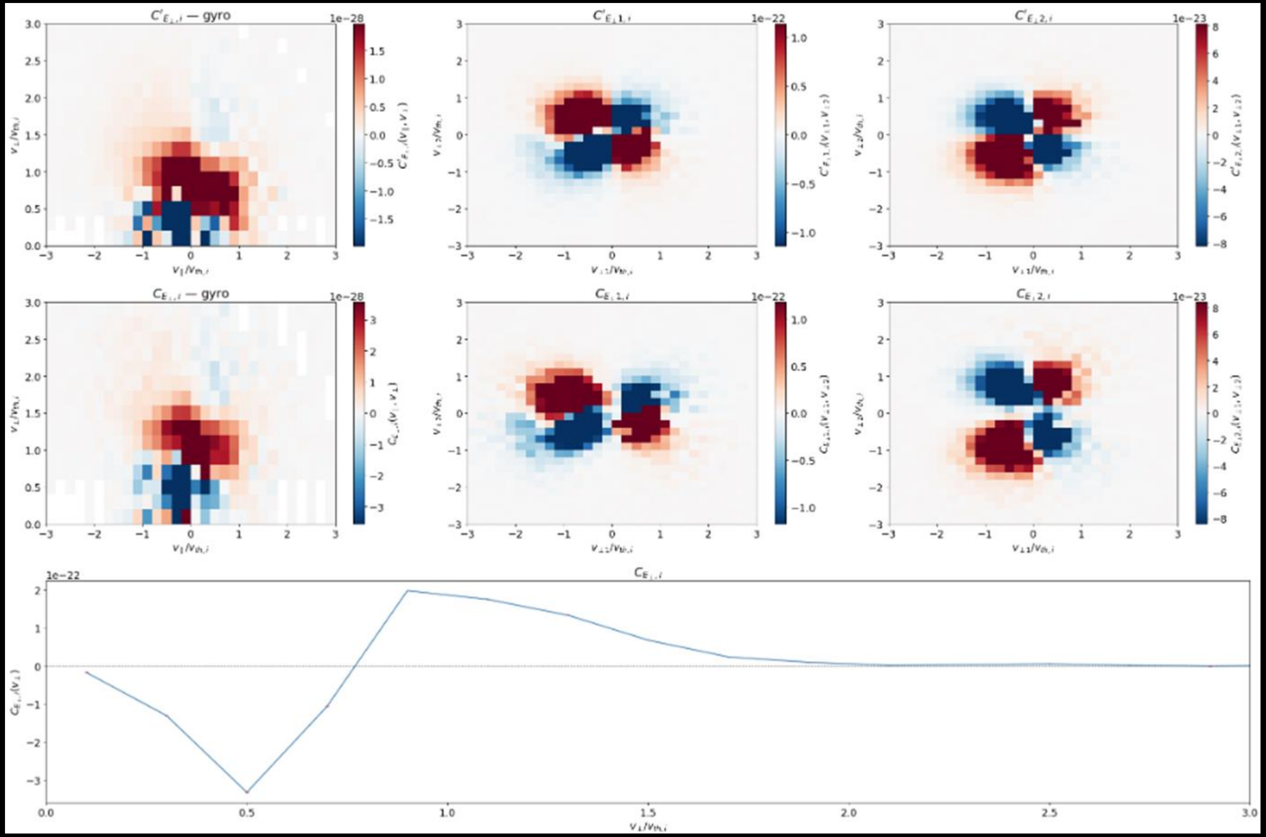
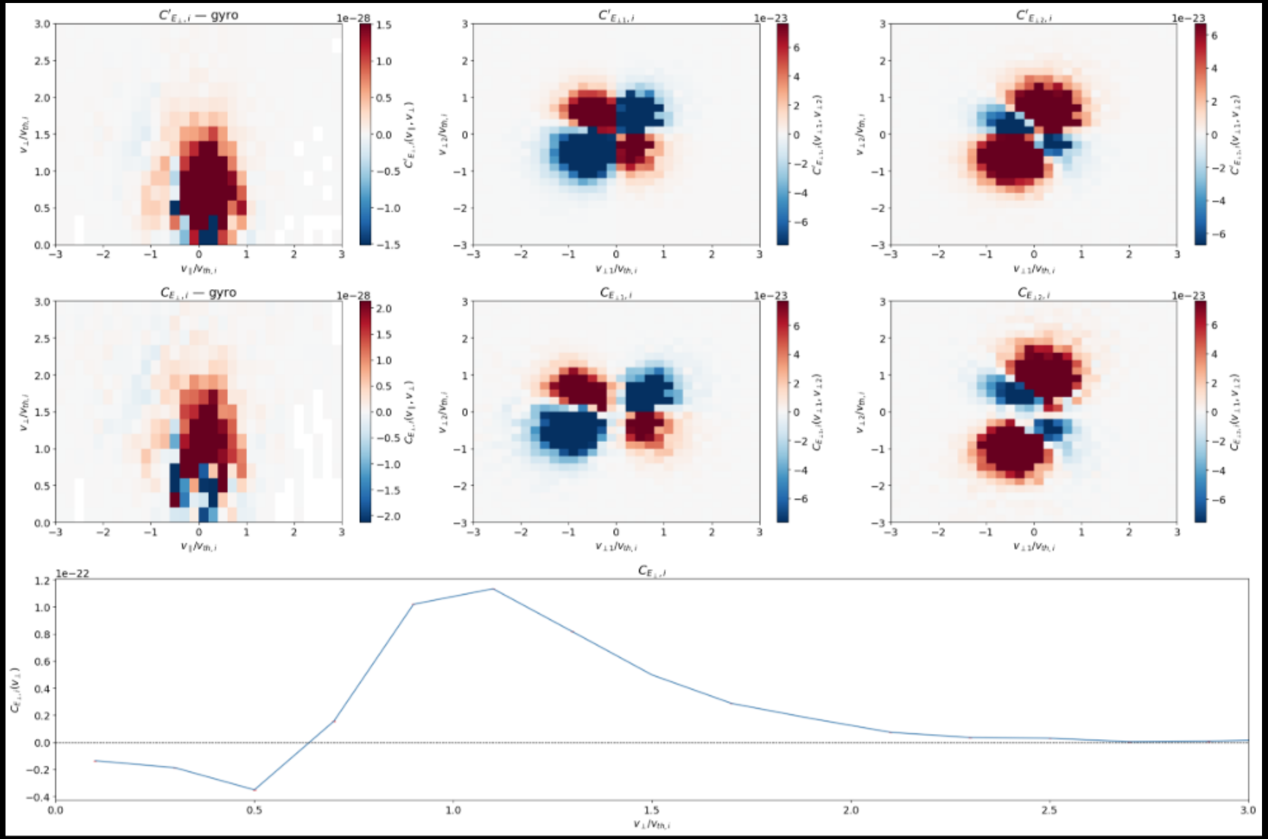
High Density Intervals

Ion Perpendicular

”Stawarz” Interval



”Svenningsson” Interval



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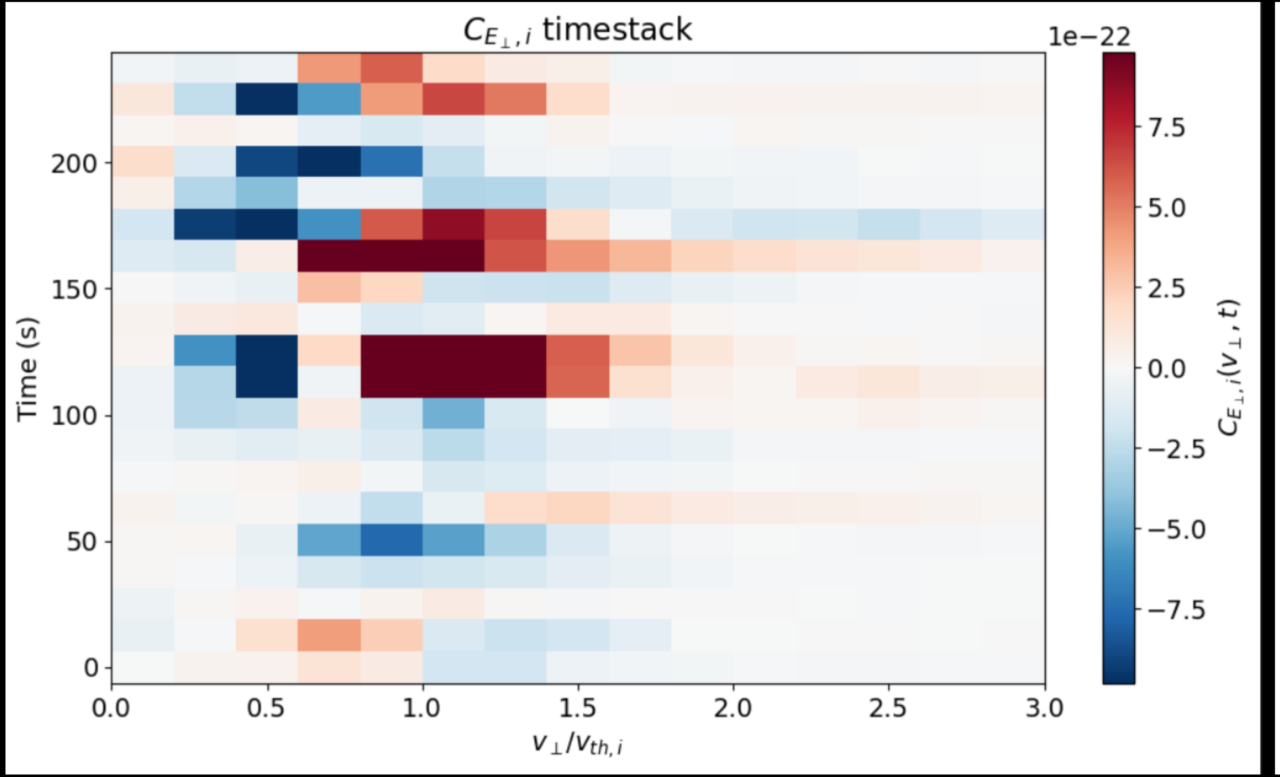
High Density Intervals

Ion Perpendicular

”Stawarz” Interval



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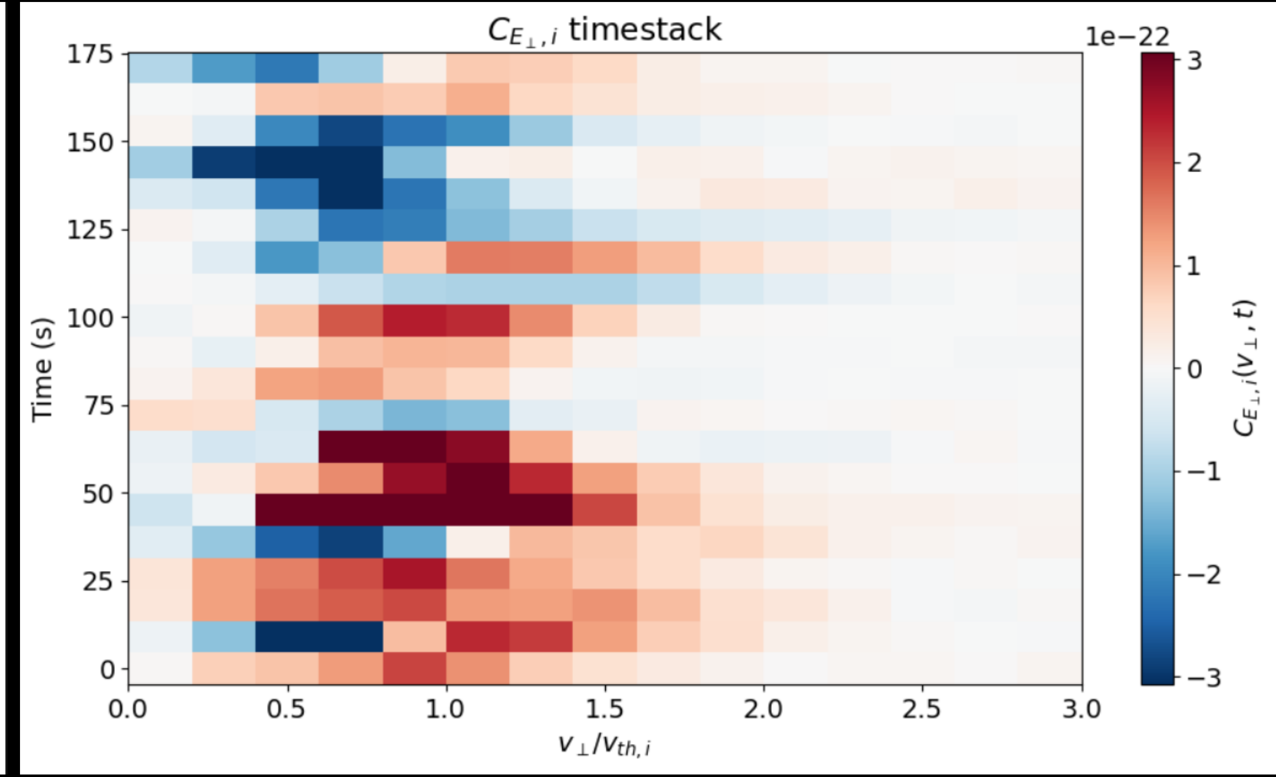

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Synergies

- Results are obtained utilising high resolution VDF and electric field measurements
- Any other ideas are welcome

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Questions/Comments?

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