Electron Heating by Parallel Electric Fields in Magnetotail Reconnection

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Parallel Electric Fields in Reconnection

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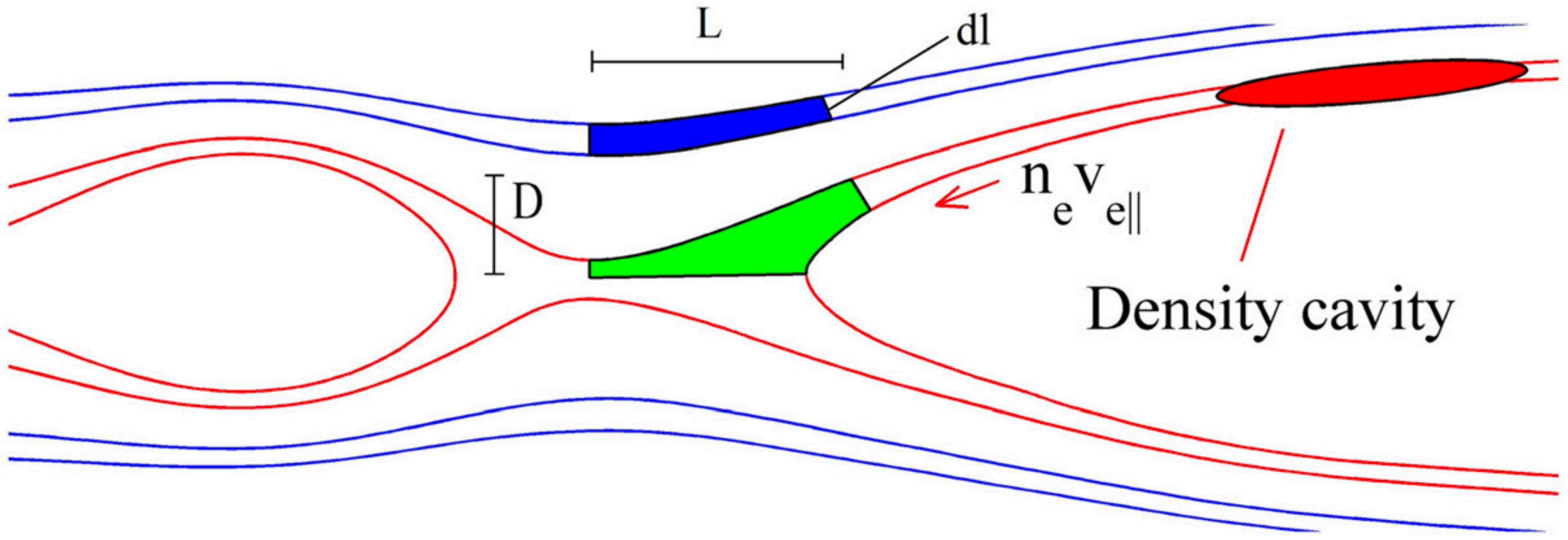
- As **magnetic flux tubes expand**, electron density should drops, while density of demagnetized ions stays constant **resulting in positive charge density.**

[Egedal+2015, PoP]



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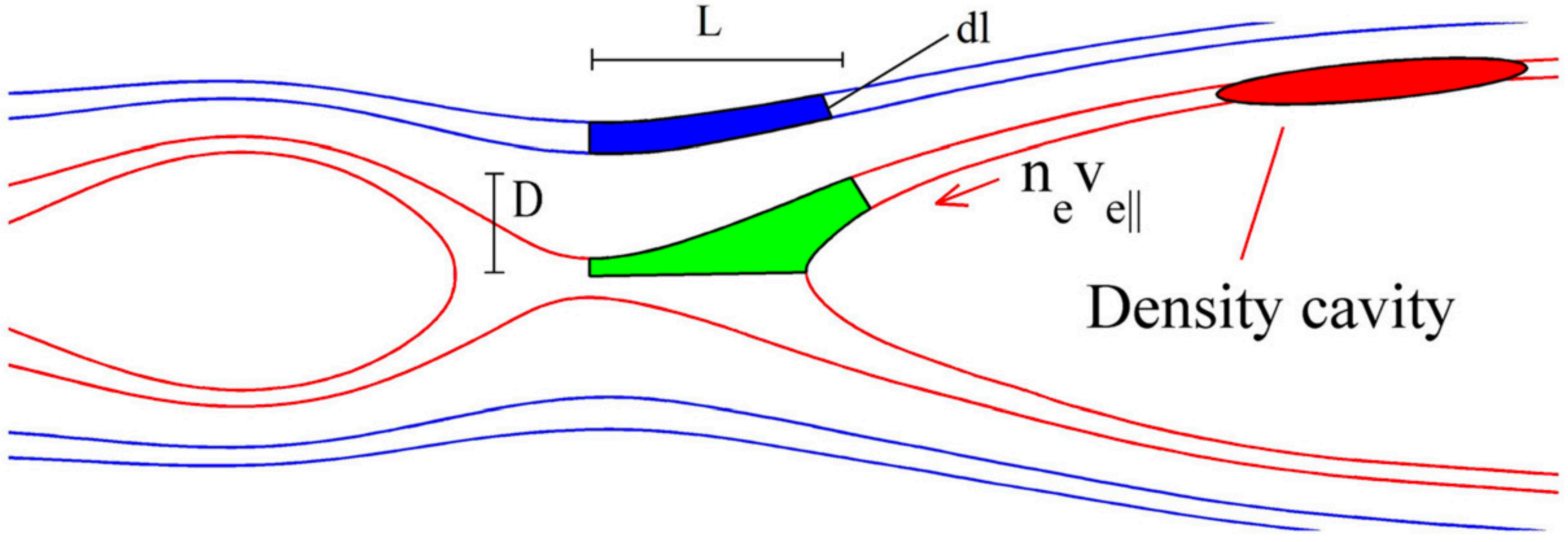

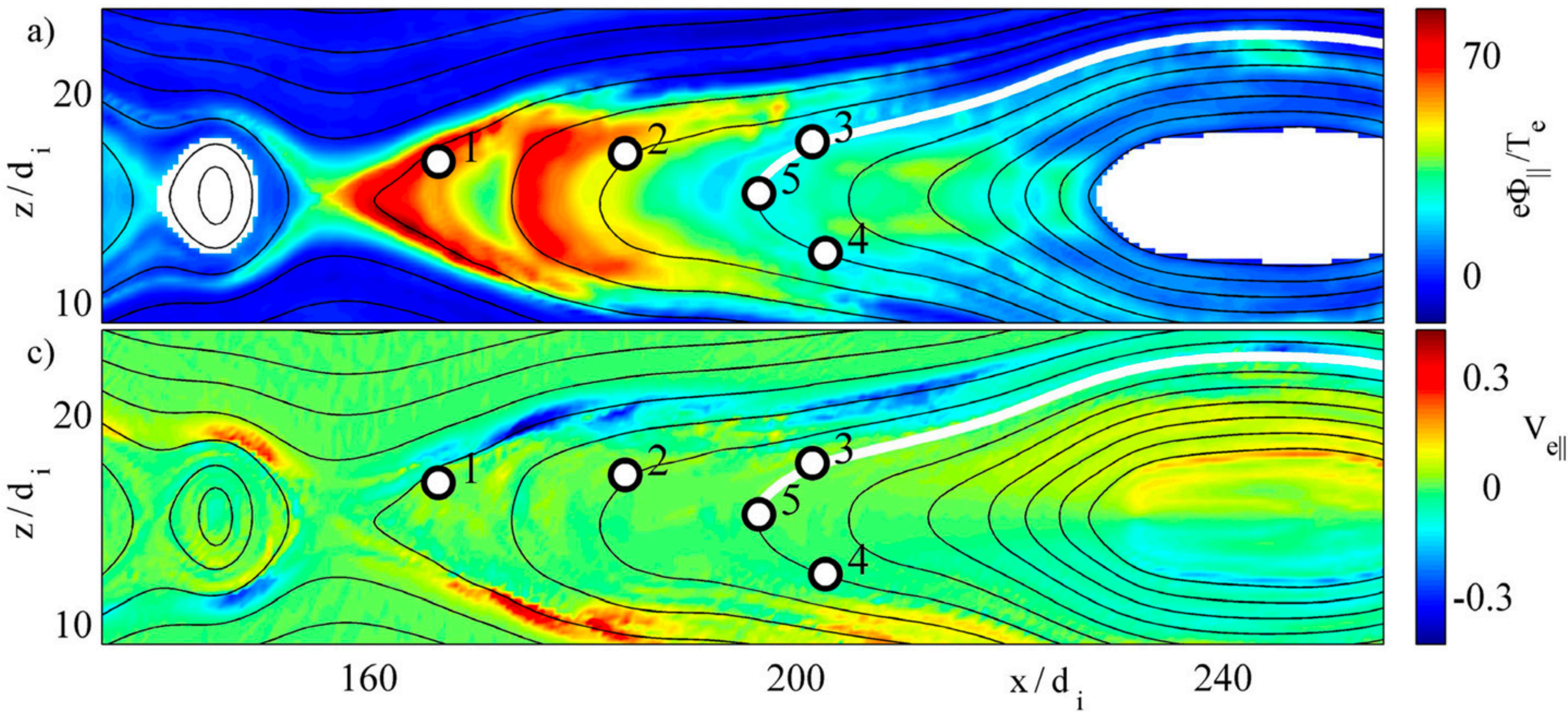

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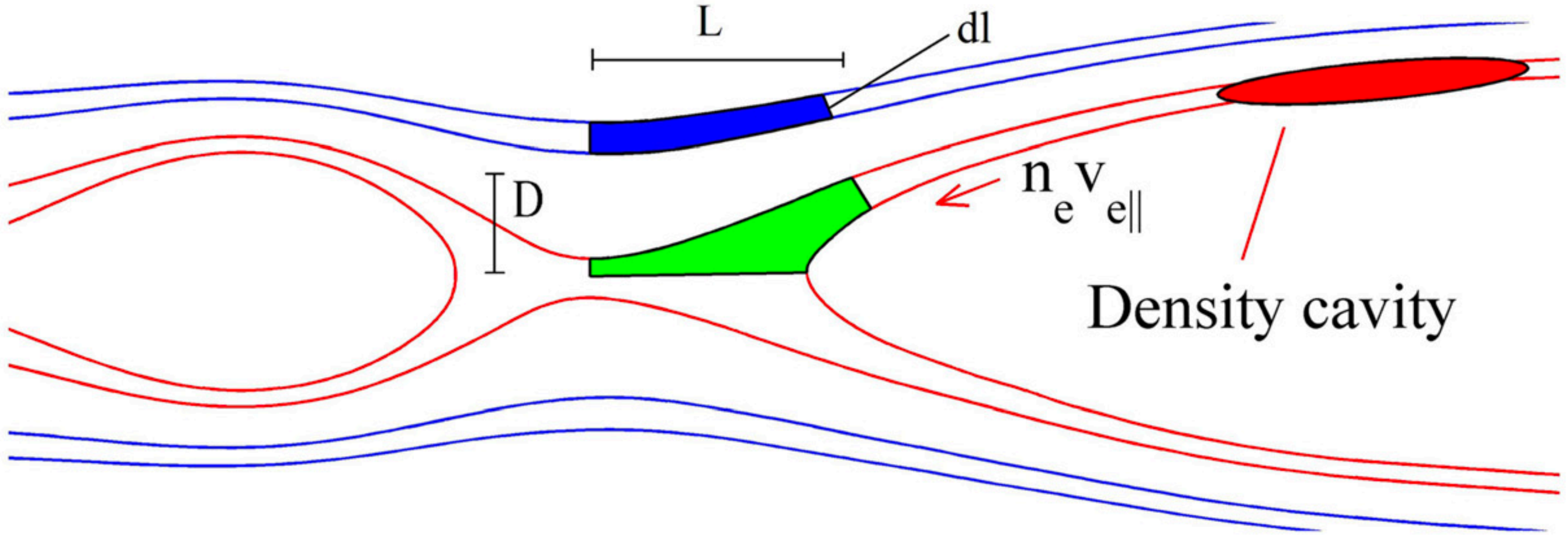
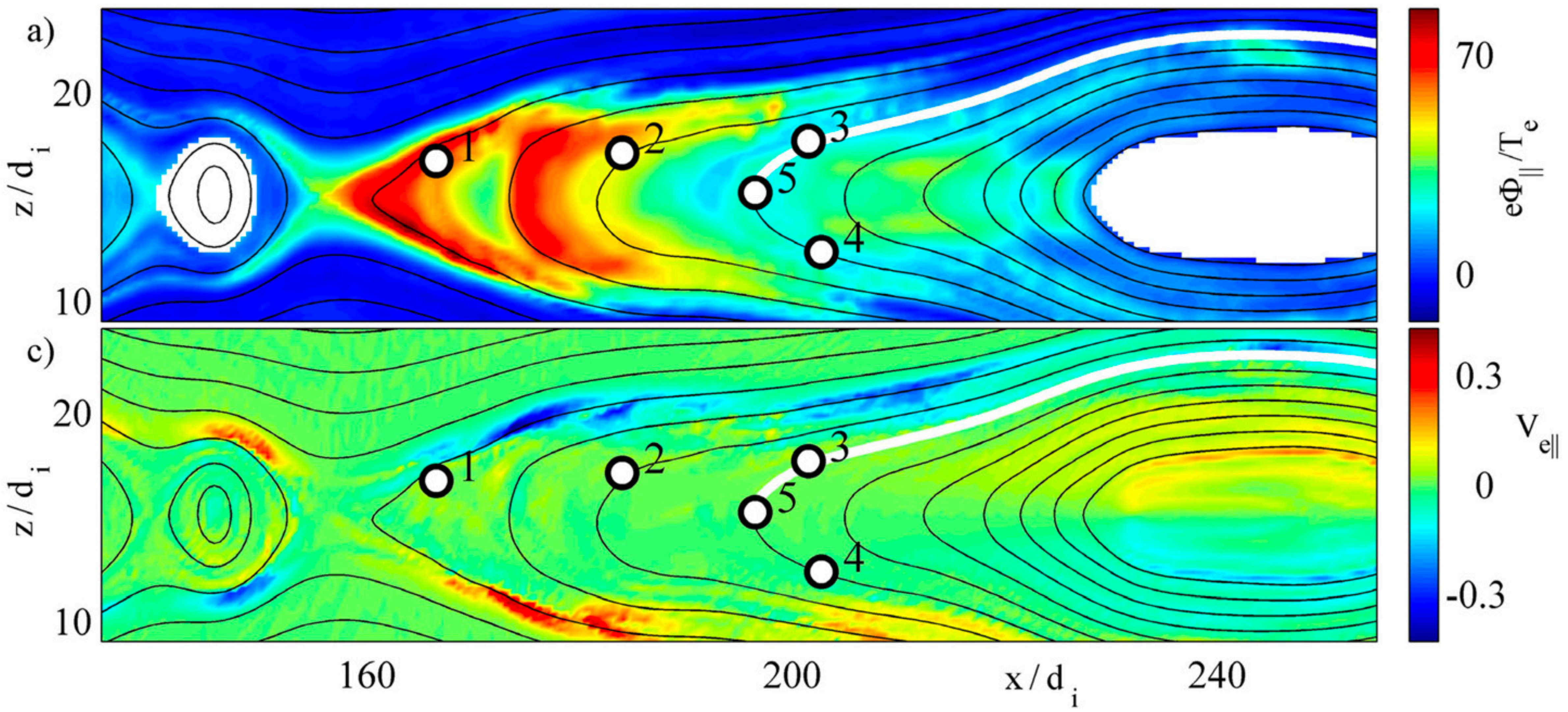
- **Parallel electric fields** $E_{||}$ form in the reconnection region to **maintain quasi-neutrality**.
- $E_{||}$ **trap electrons** locally to balance charge and maintain quasi-neutrality.

[Egedal+2015, PoP]





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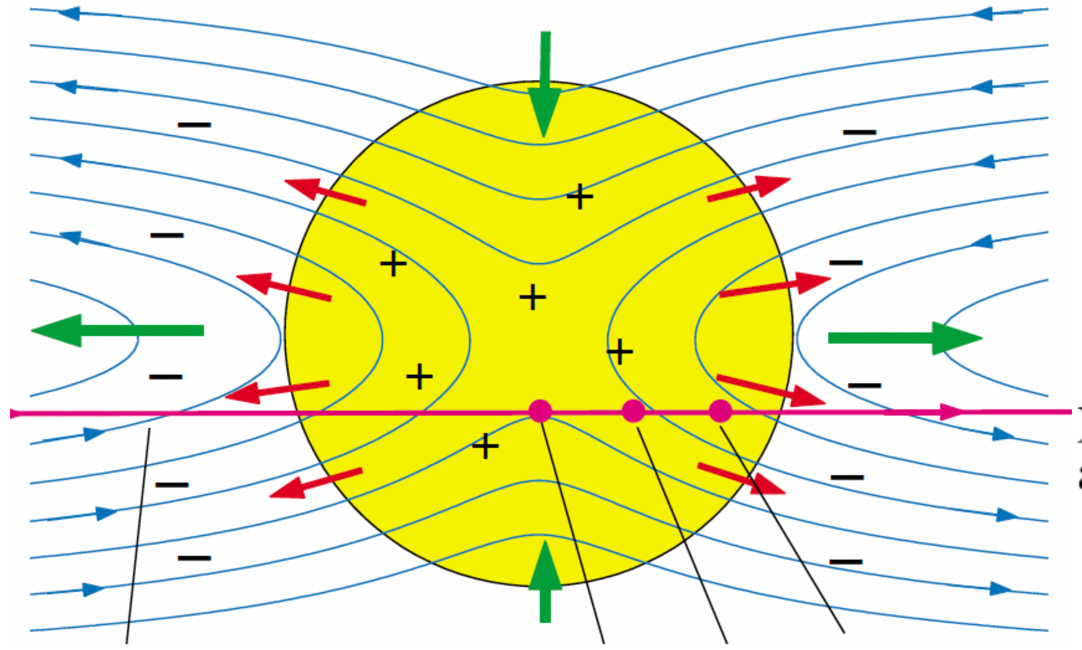

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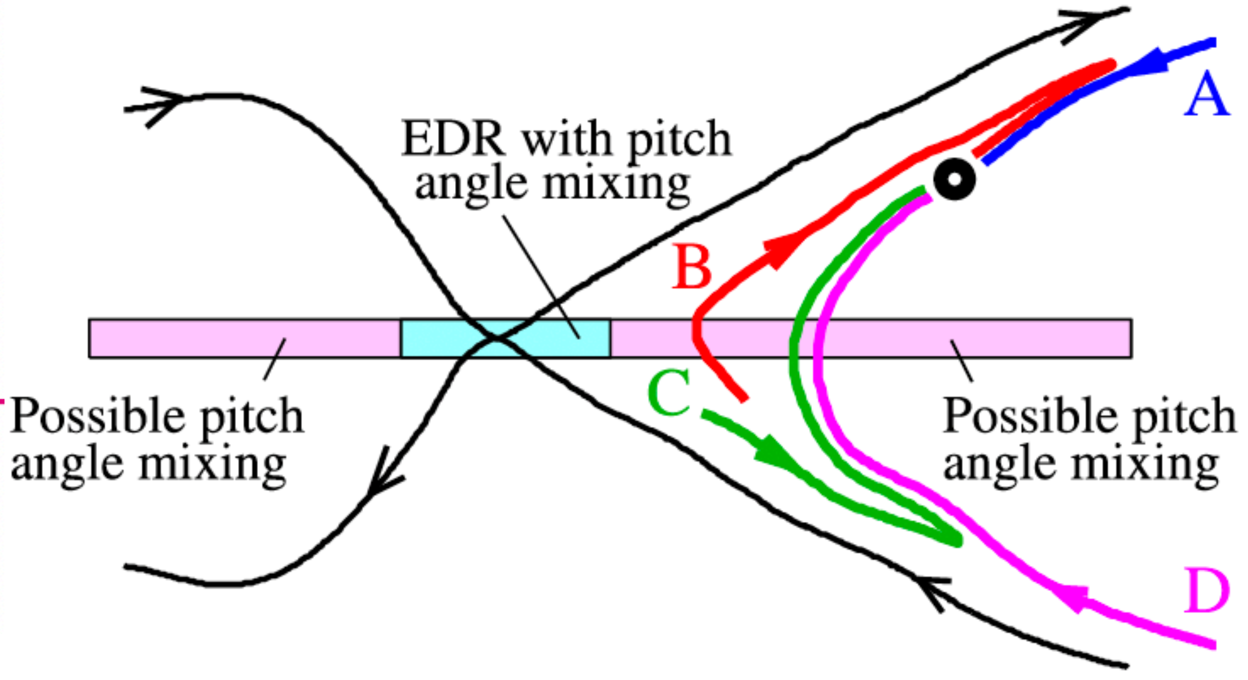

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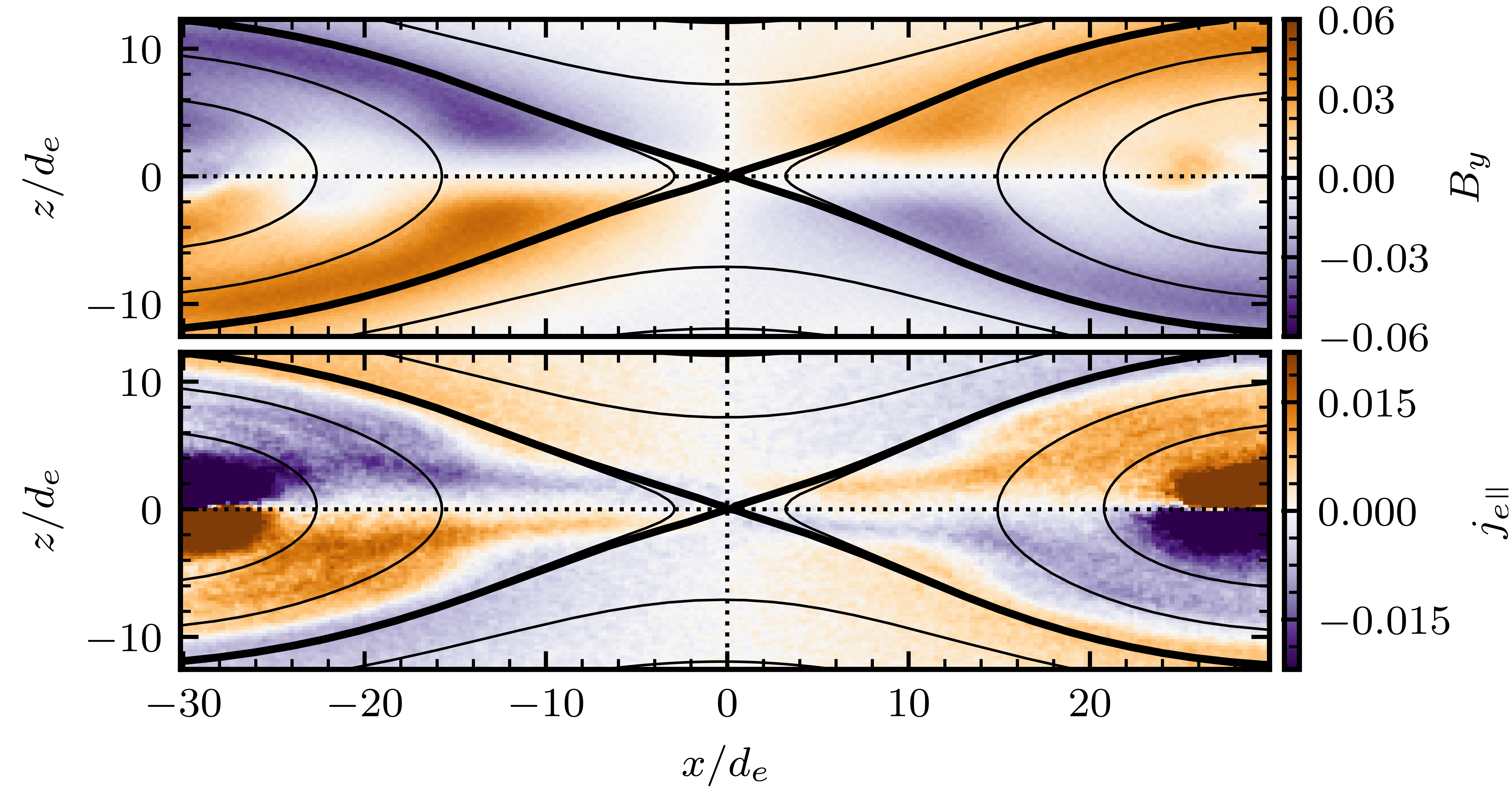

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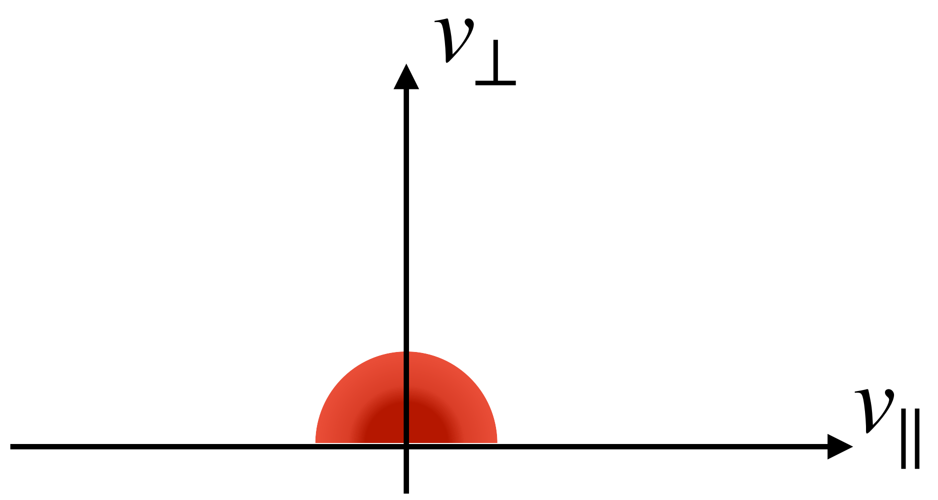
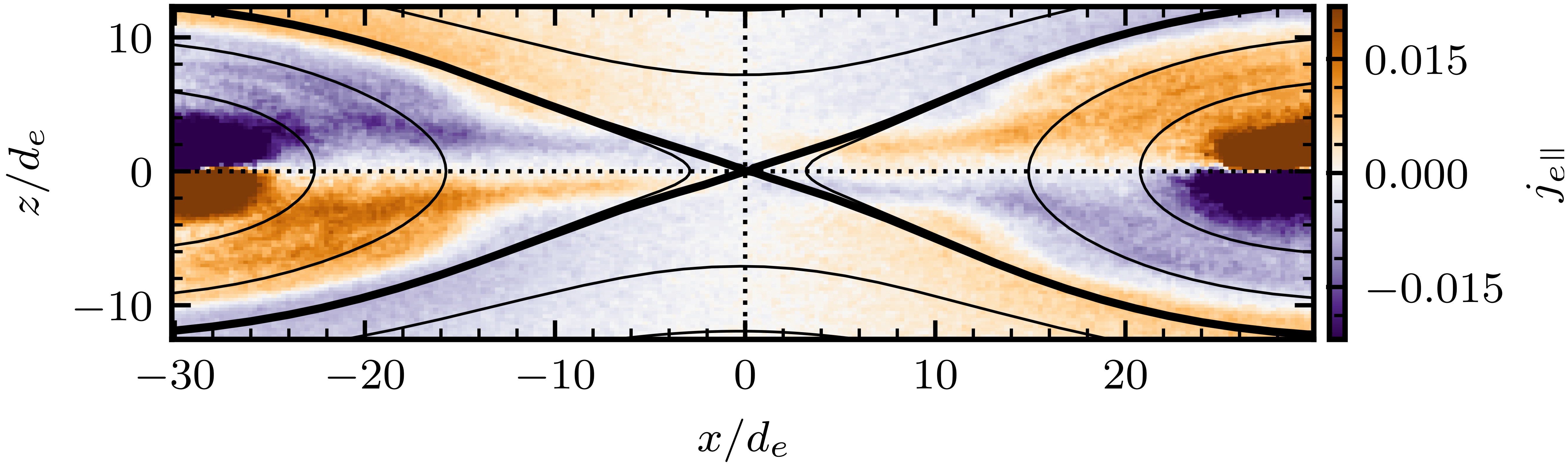
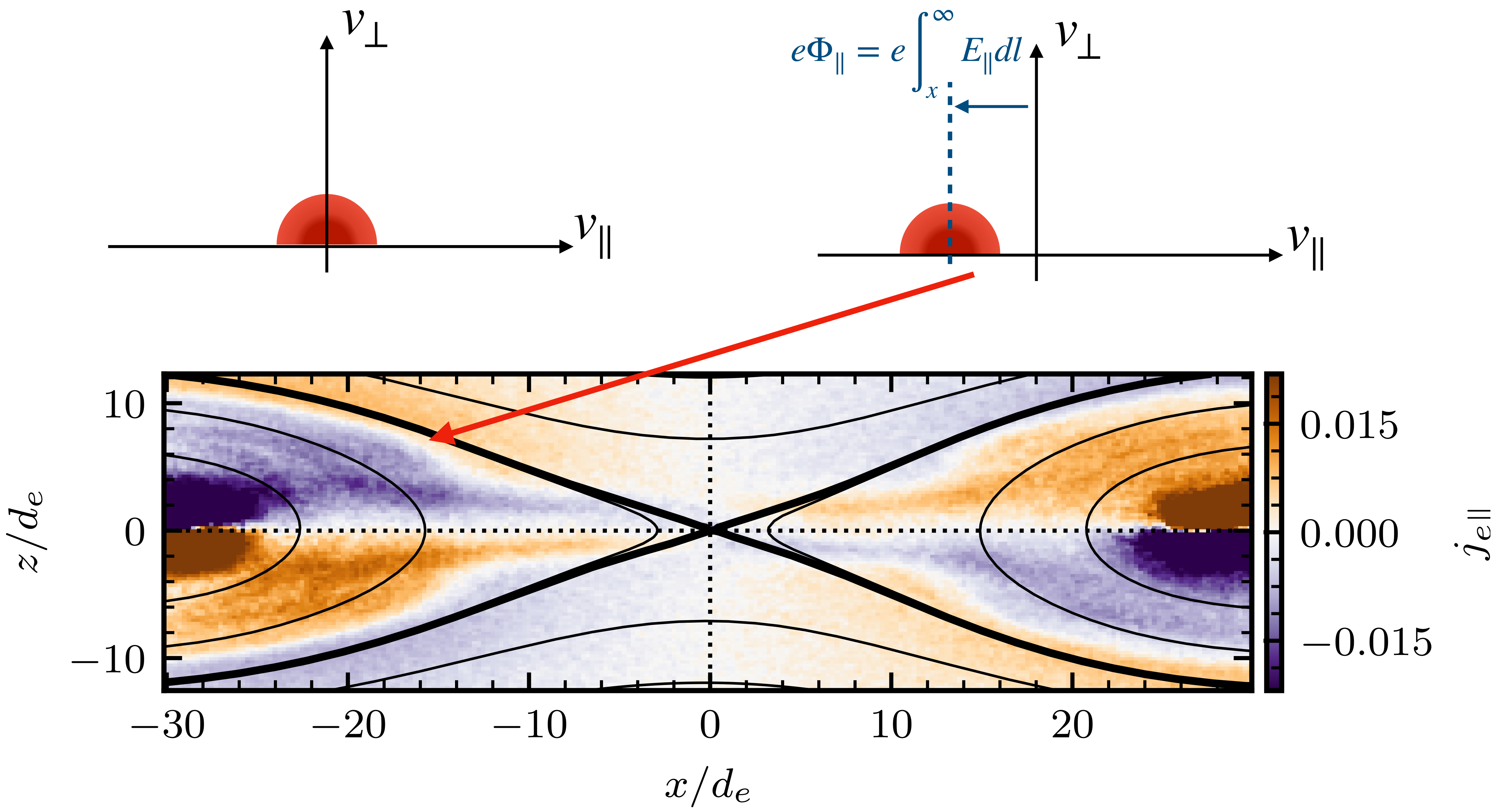




Electron Heating by Parallel Electric Fields

- Parallel electric fields accelerate electrons toward the X-line, forming **beam-type electron VDFs**.



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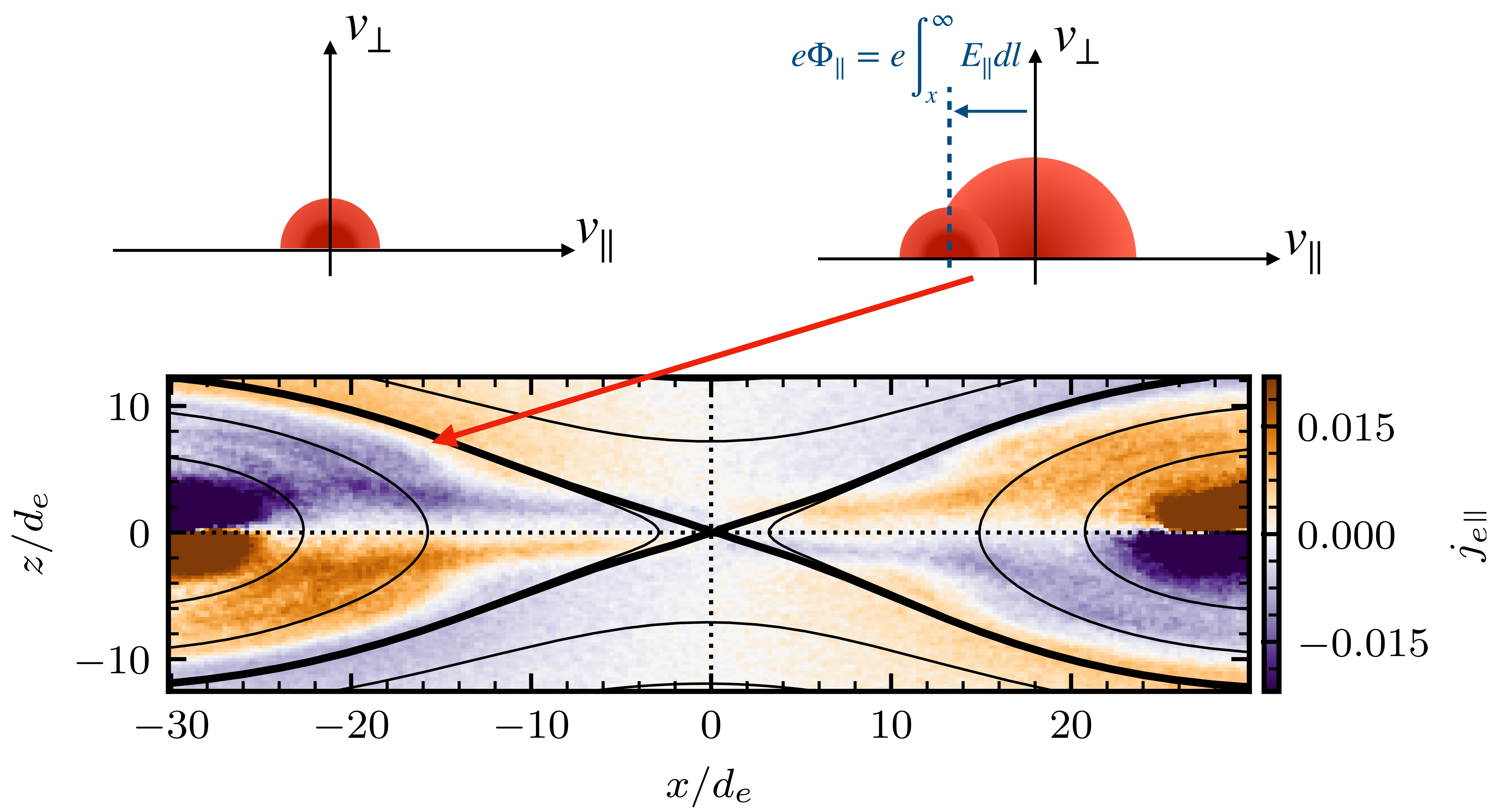

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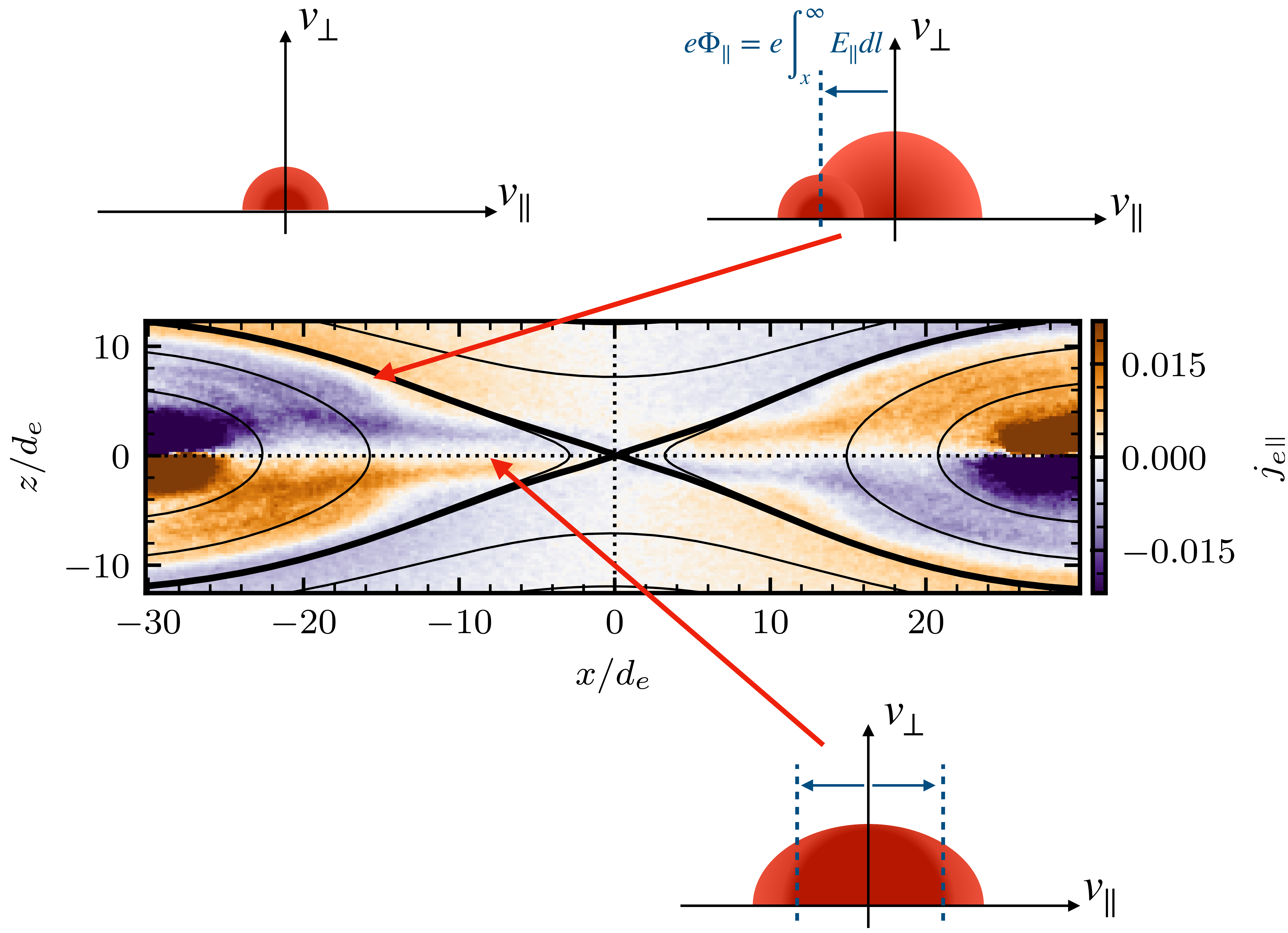
- Unstable beam + thermalized hot electron excites **electrostatic waves** and forming **flat-top VDFs** [Fujimoto, 2014, GRL].



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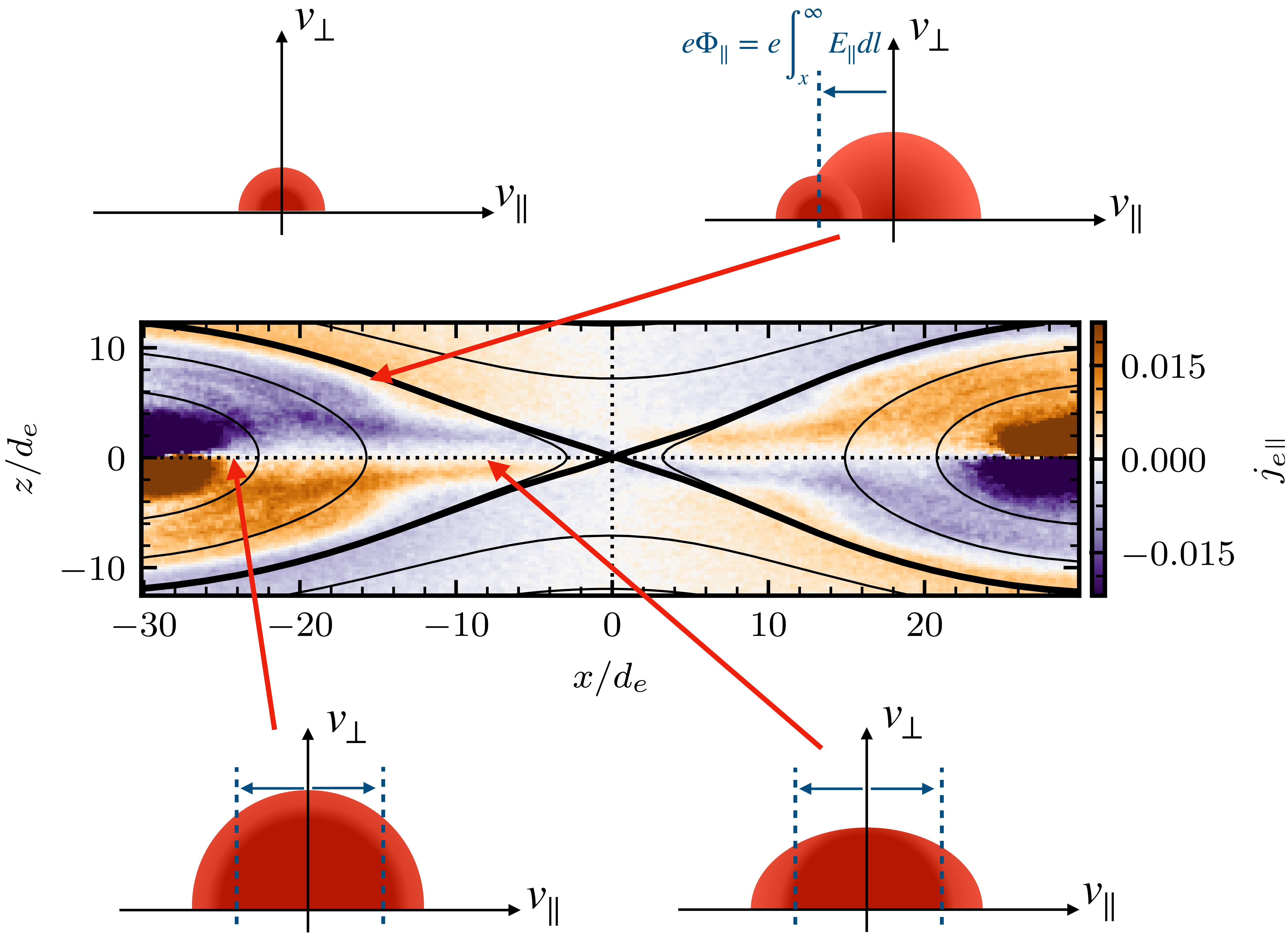

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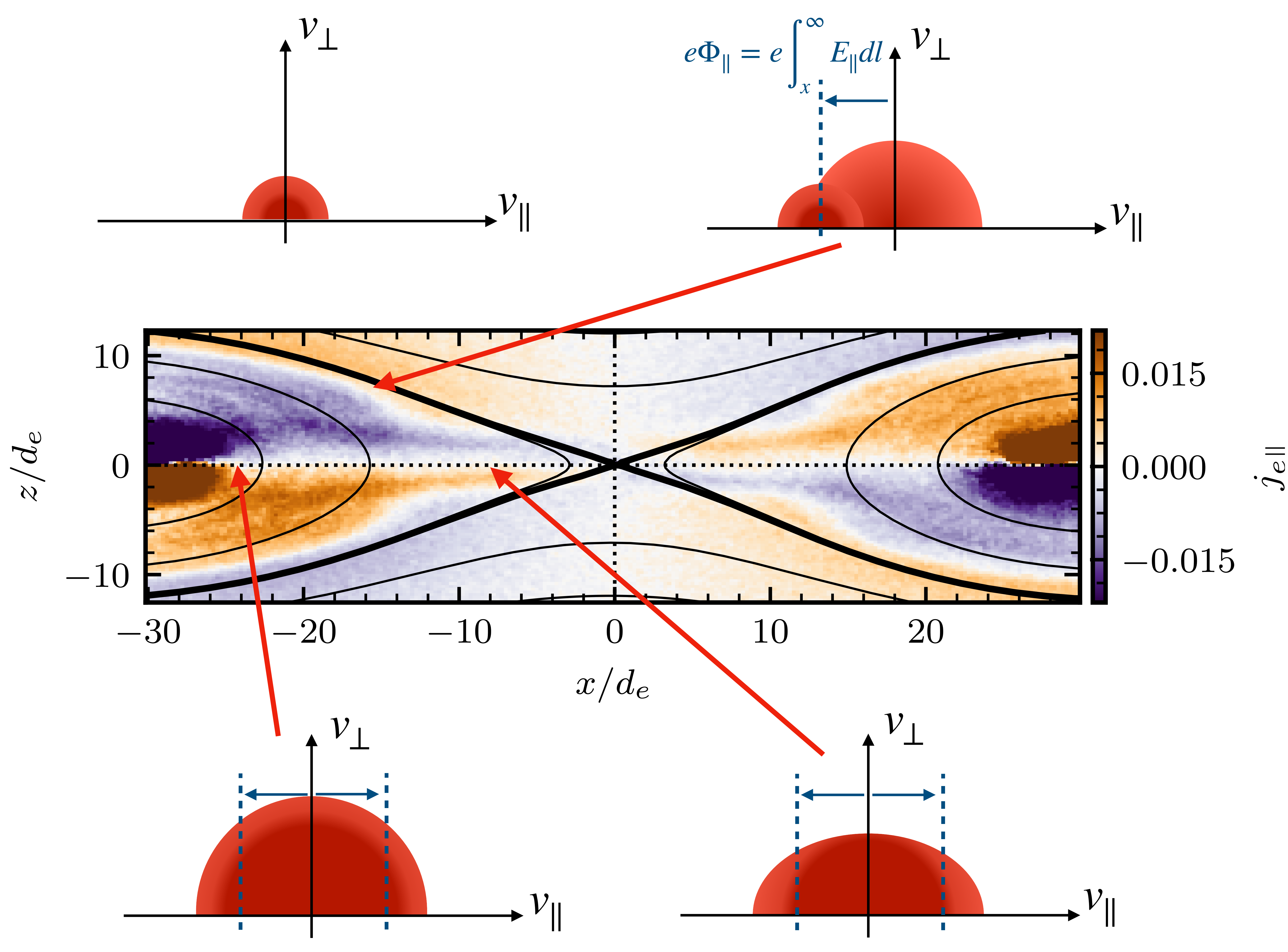
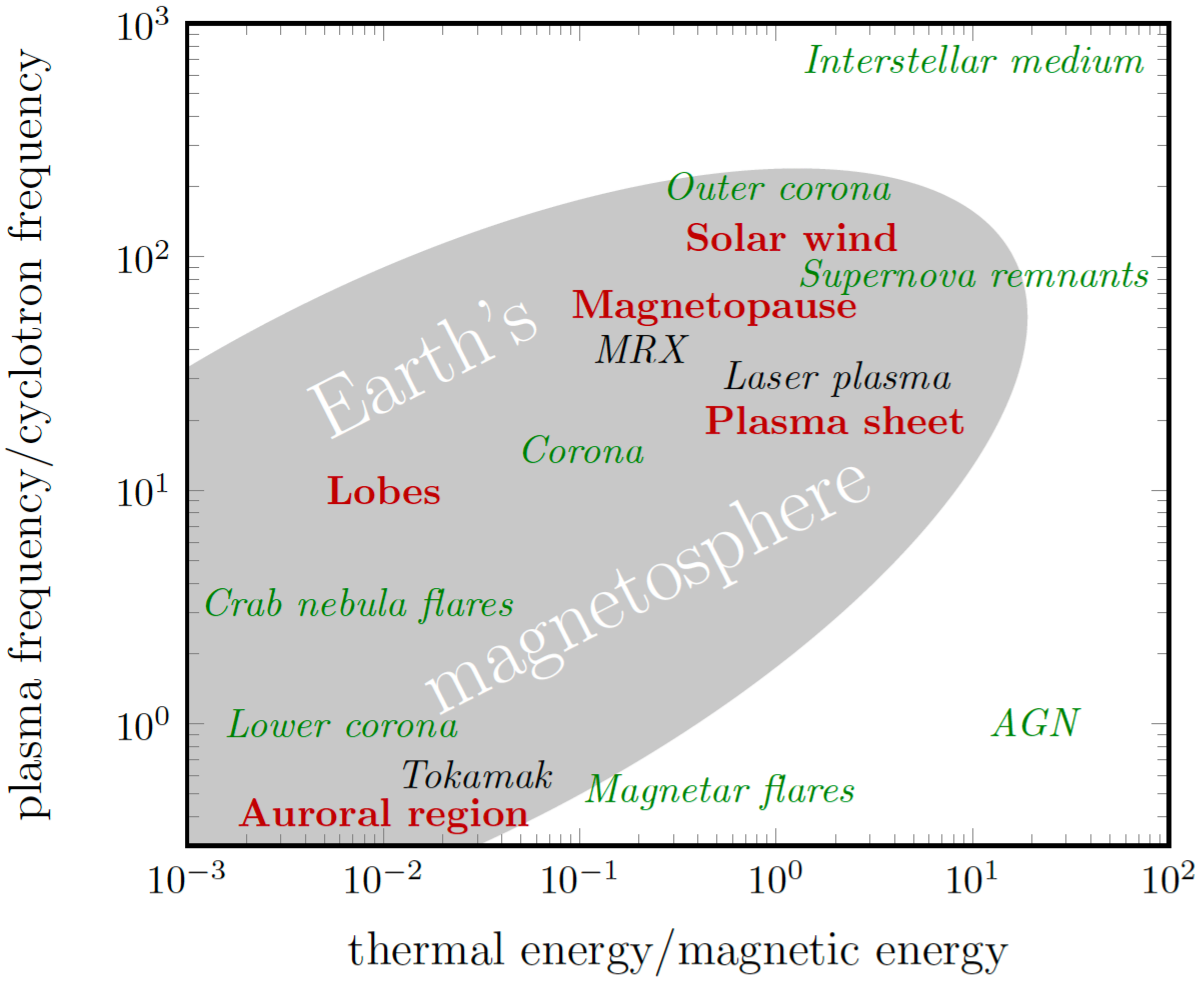
What is the nature and the role of parallel electric fields in magnetic reconnection?



The Earth's Magnetotail as a Plasma Lab



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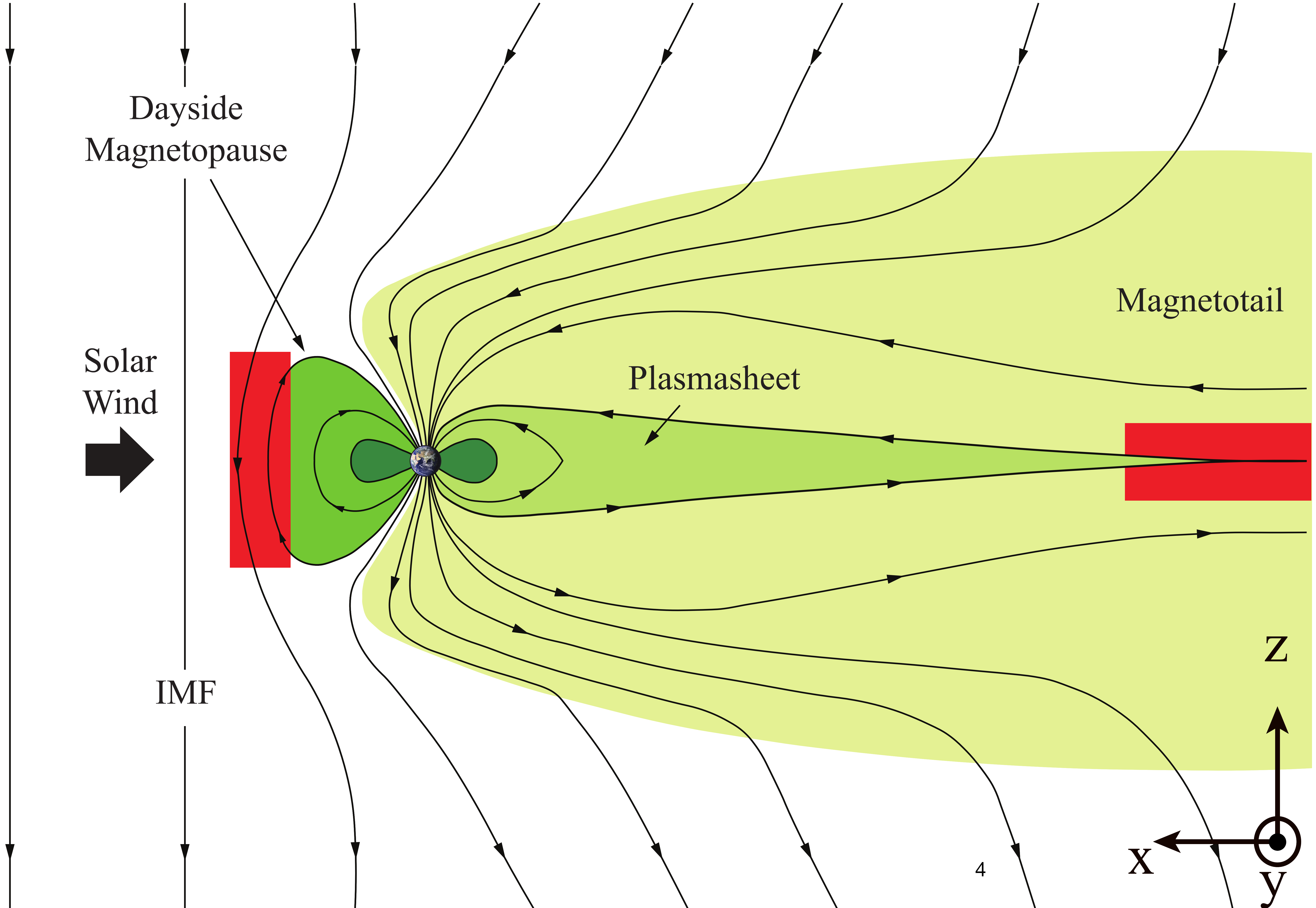
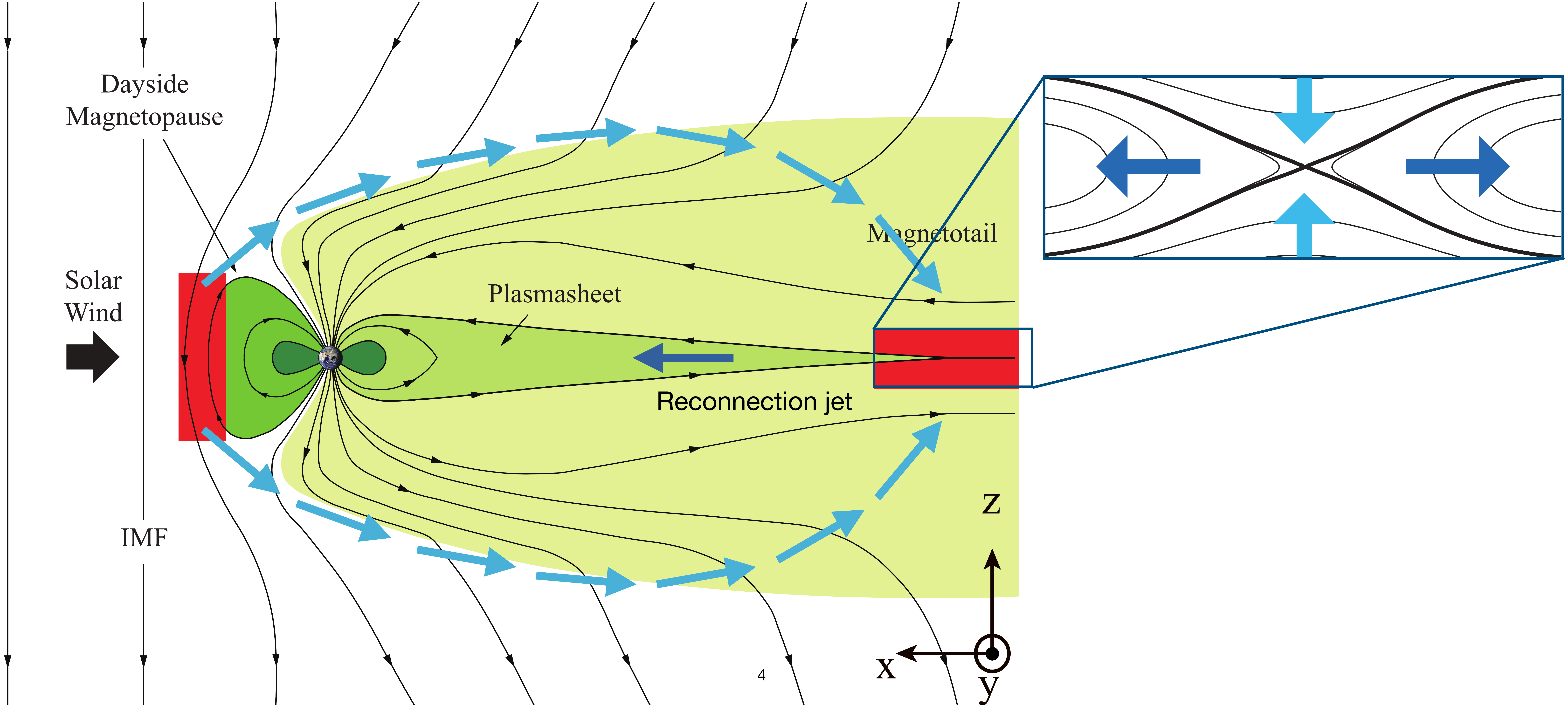


The Earth's Magnetotail as a Plasma Lab



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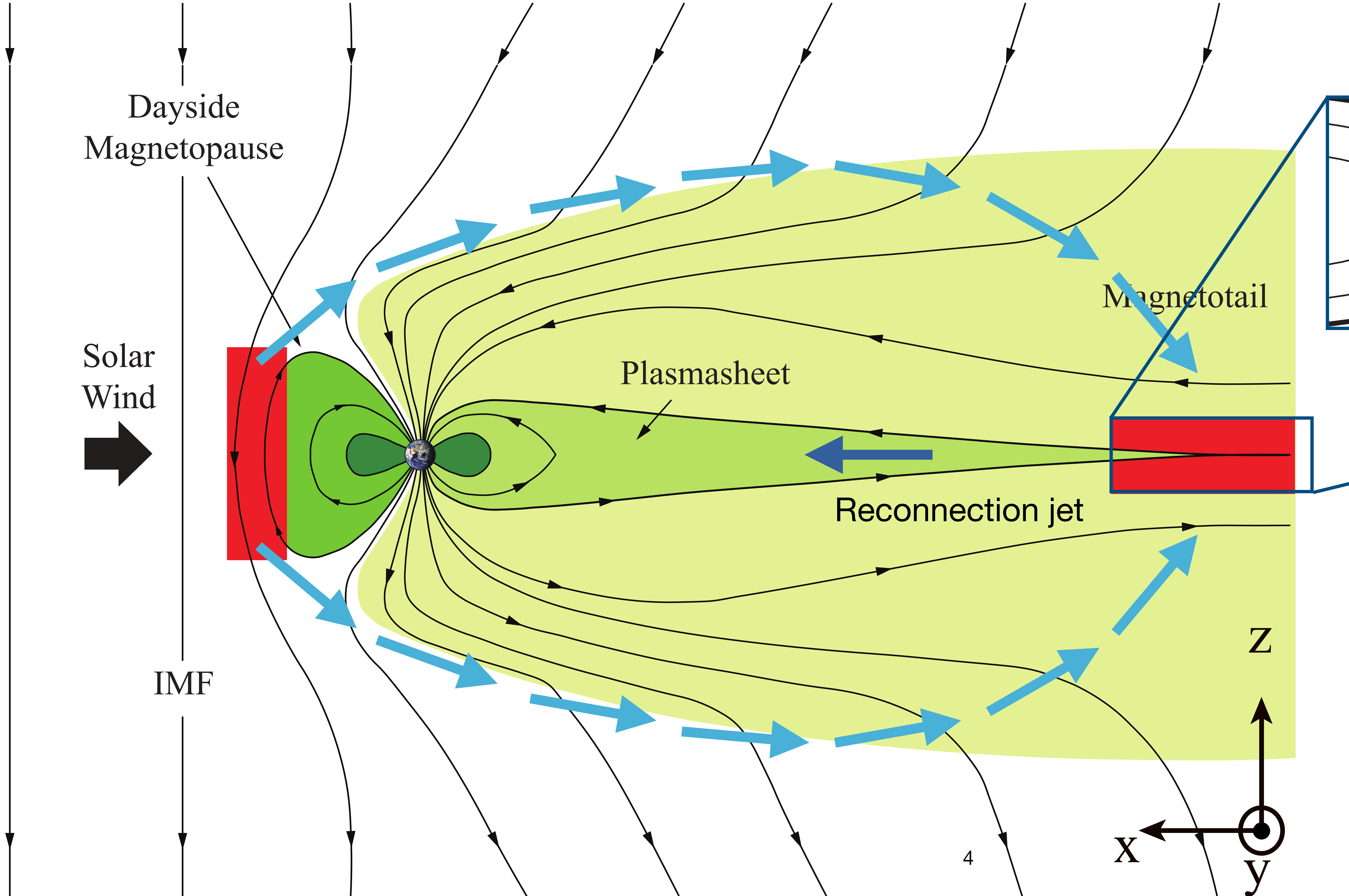
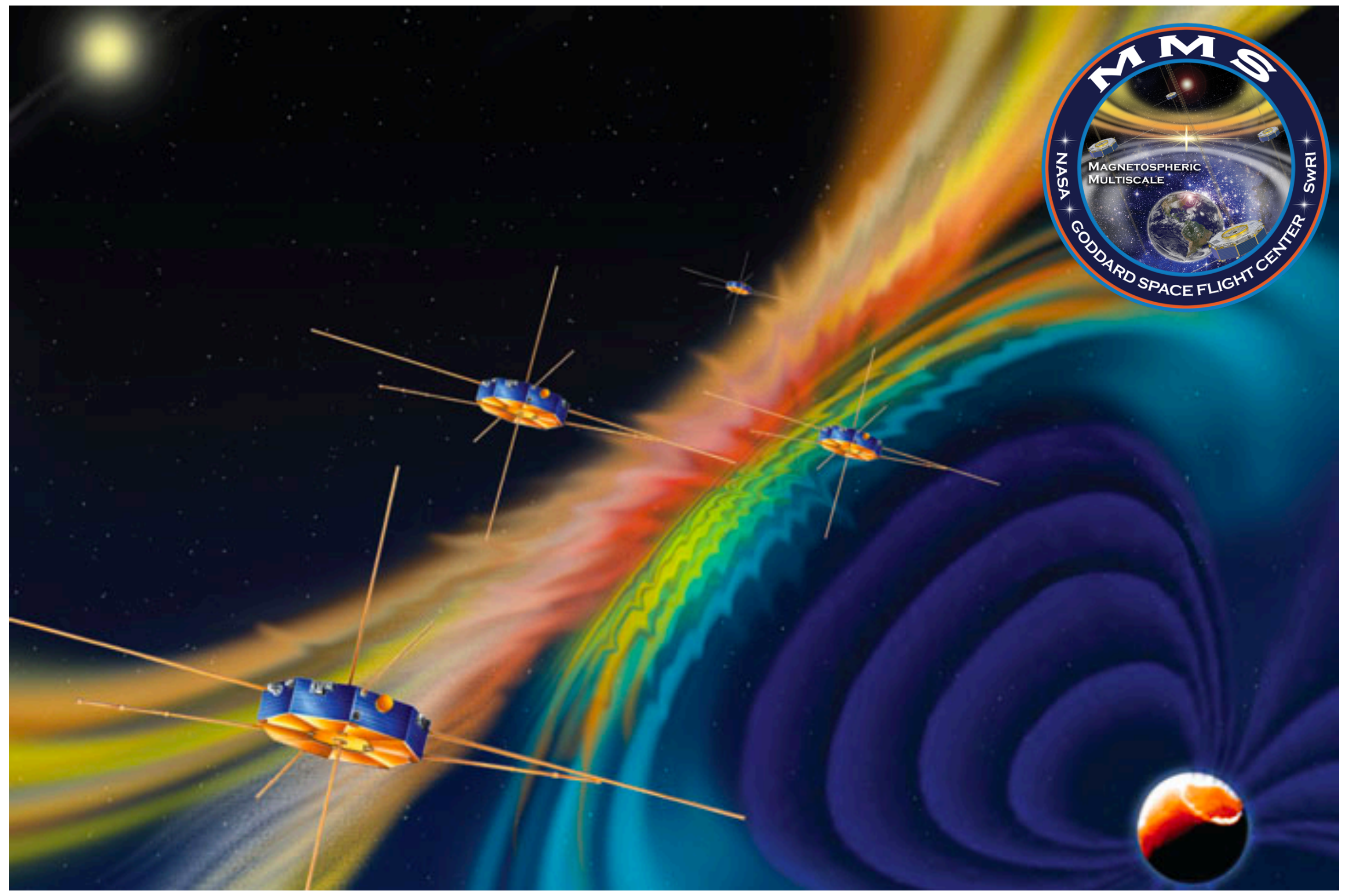
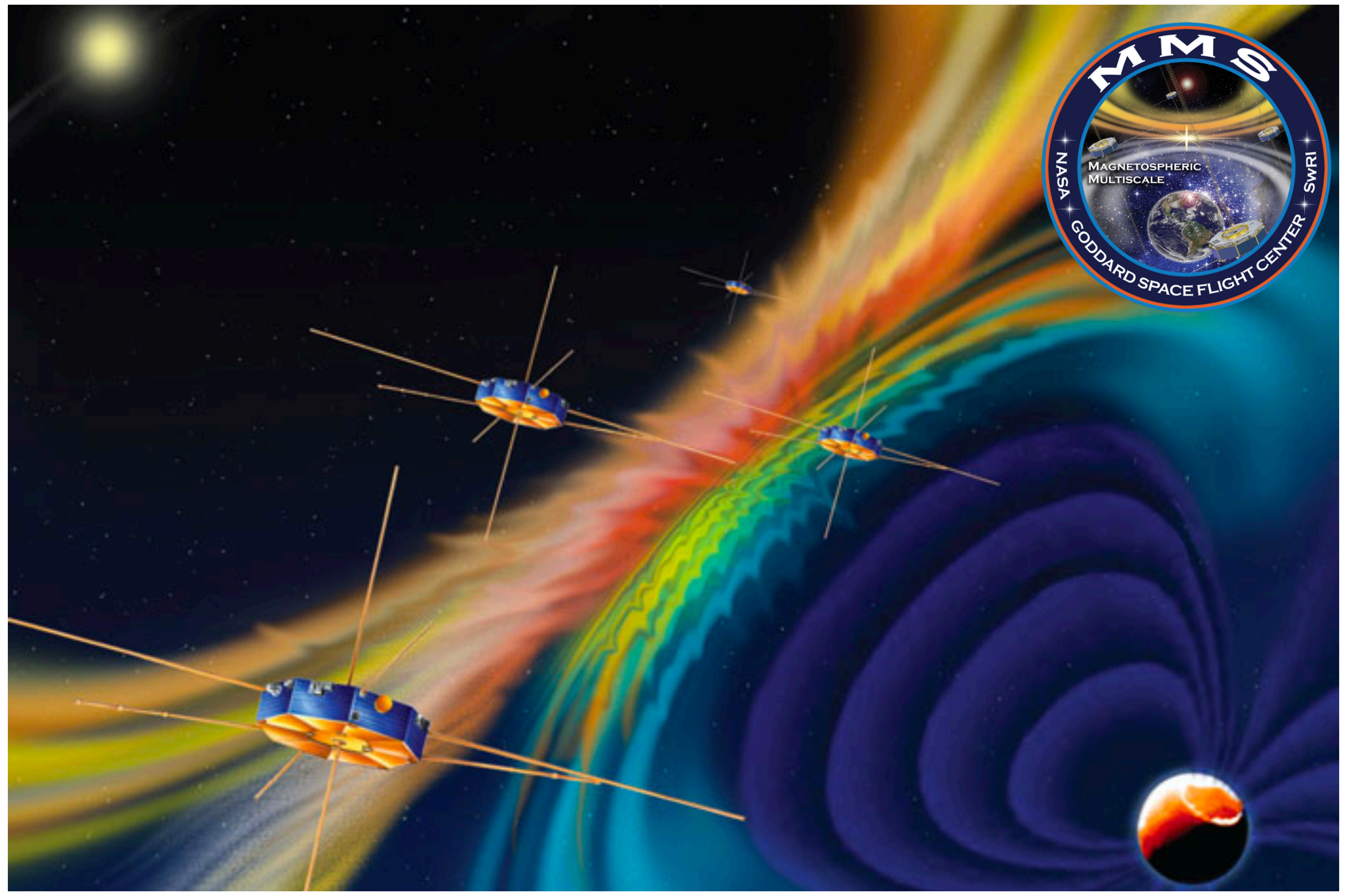




The Magnetospheric Multiscale (MMS) mission†



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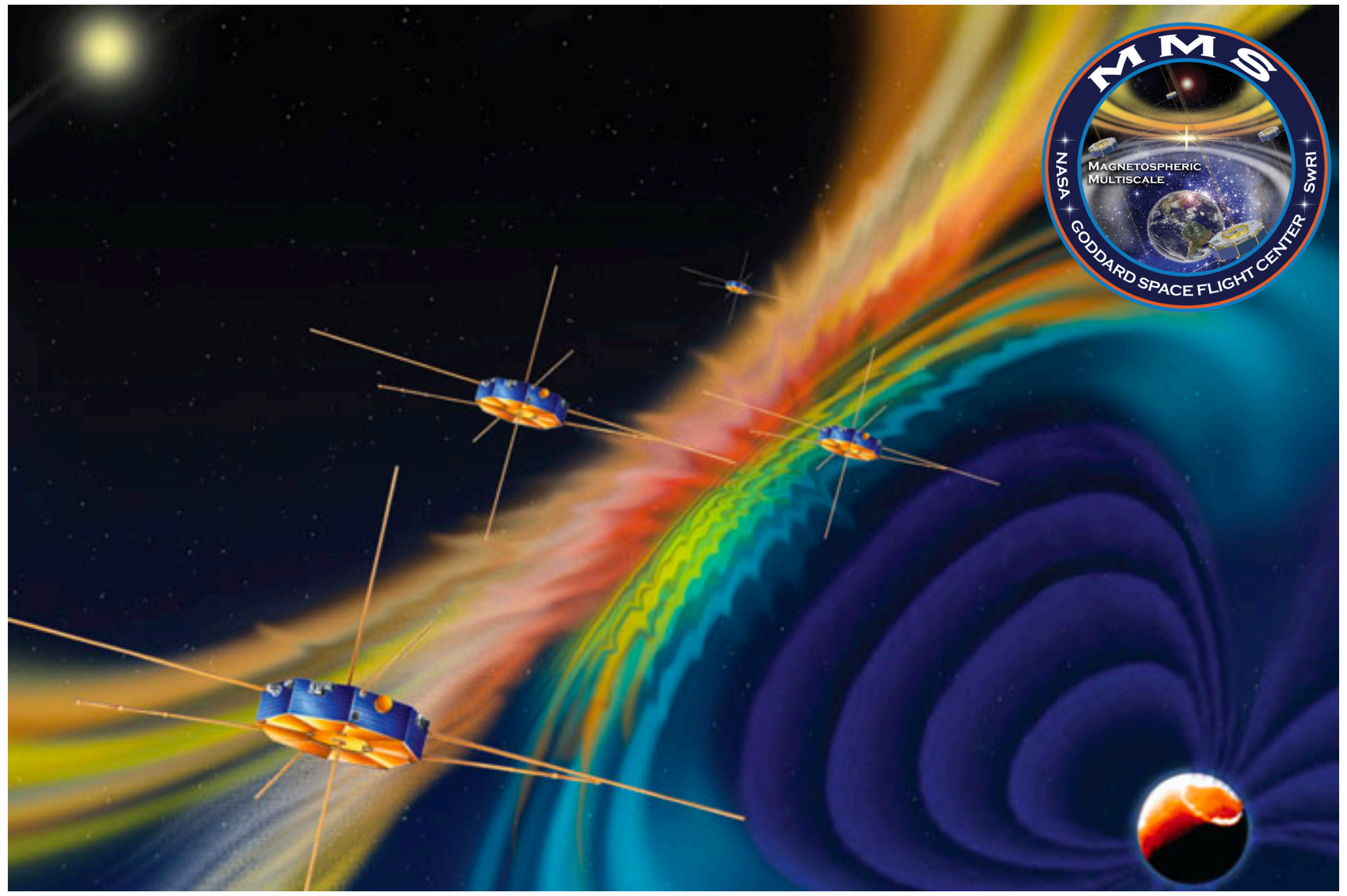
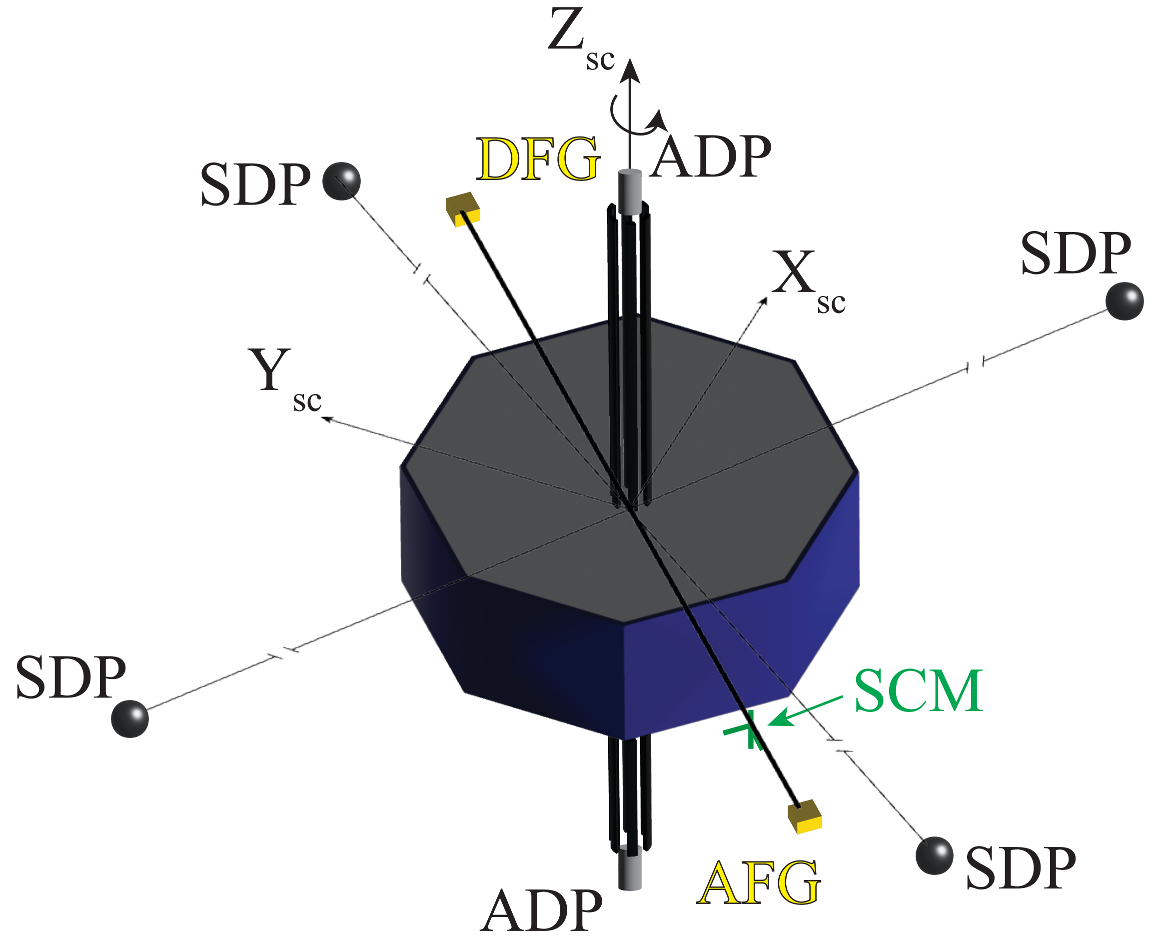
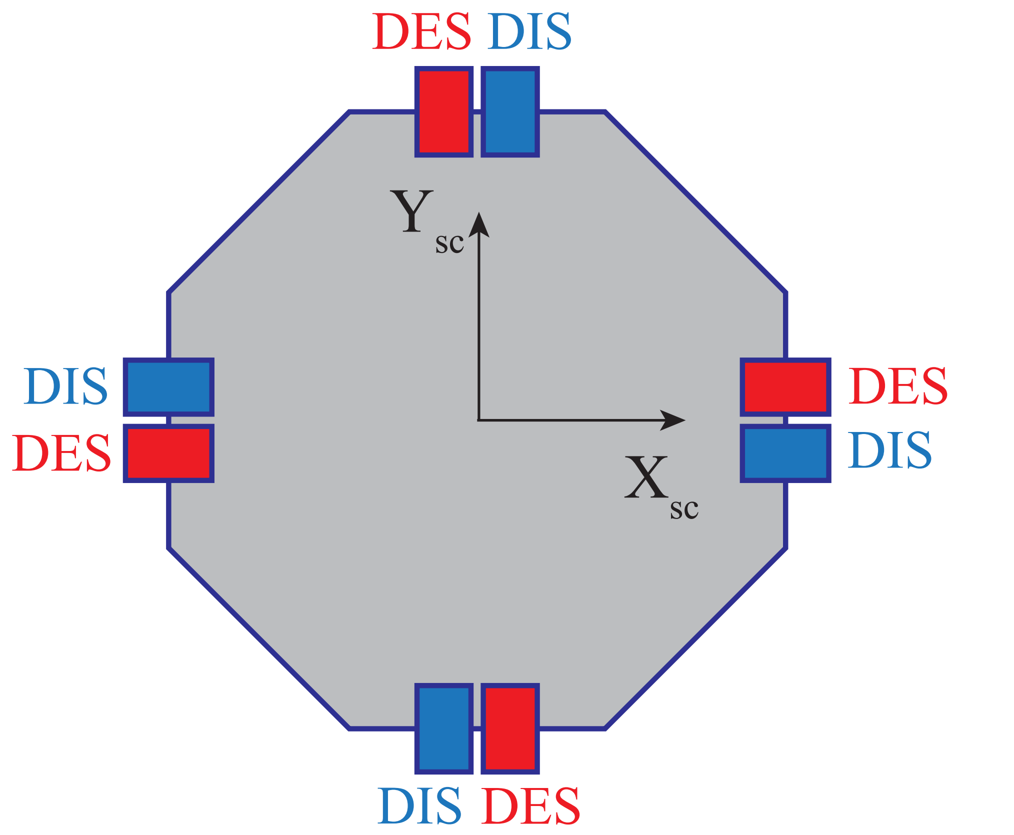


- NASA mission launched in 2015, designed to study magnetic reconnection in Earth's magnetosphere.
- Four spacecraft flying in a tetrahedral formation with ~10 km separation, enabling 3D measurements.
- Fields instruments provide high-cadence measurements of electromagnetic fields:
  - Electric and magnetic field data at up to 64 kHz (electric) and 8 kHz (magnetic).
- Particle instruments deliver high-resolution plasma measurements:
  - Thermal protons sampled every 150 ms and electrons every 30 ms.
  - Spin-resolution measurements (20 s cadence) of mass-resolved ions.
  - Suprathermal particles: ions at 10 s / 30 s and electrons at 30 s cadence.





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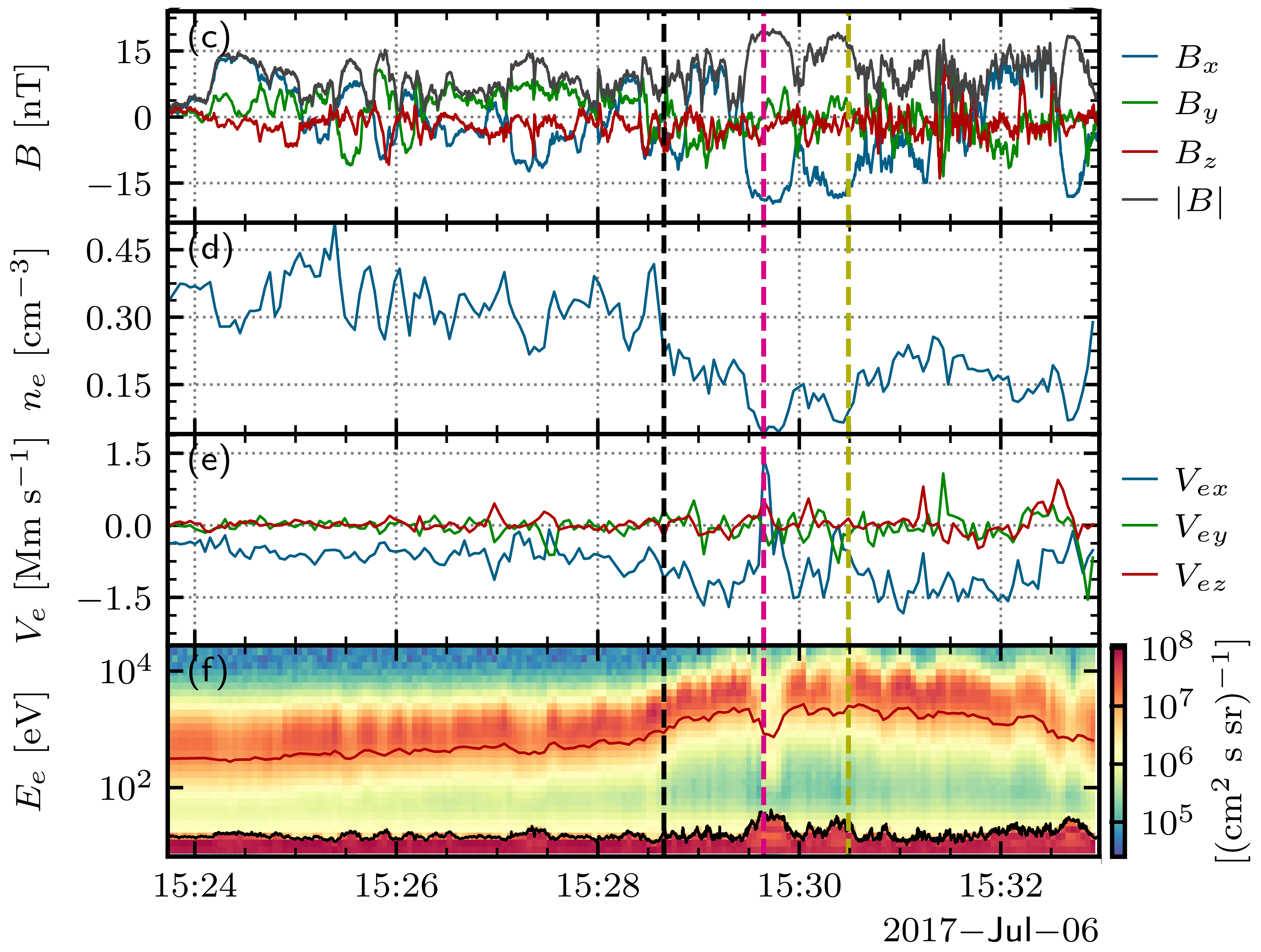
Electron VDFs in the Outflow

[Richard+2025, PRL]

Example



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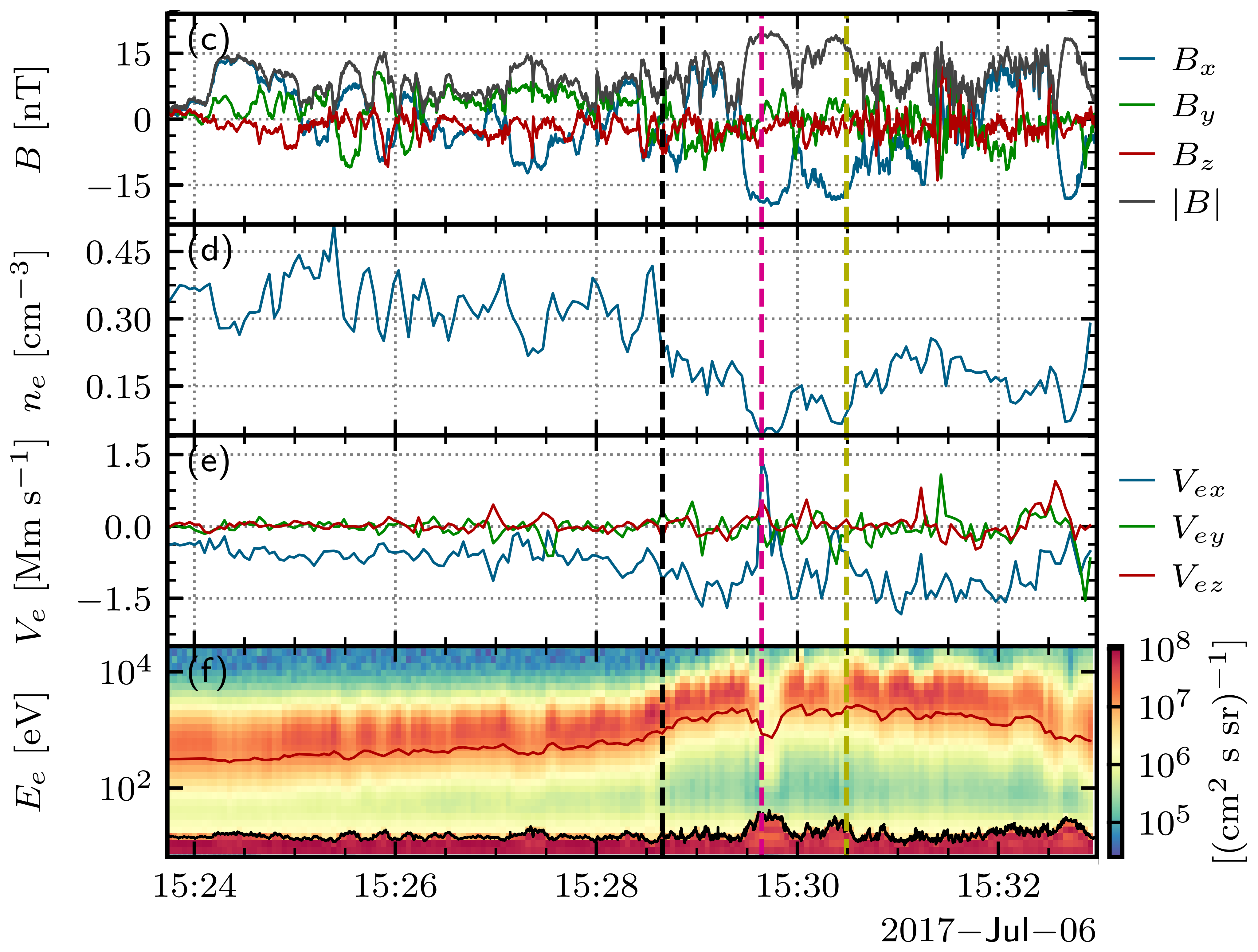

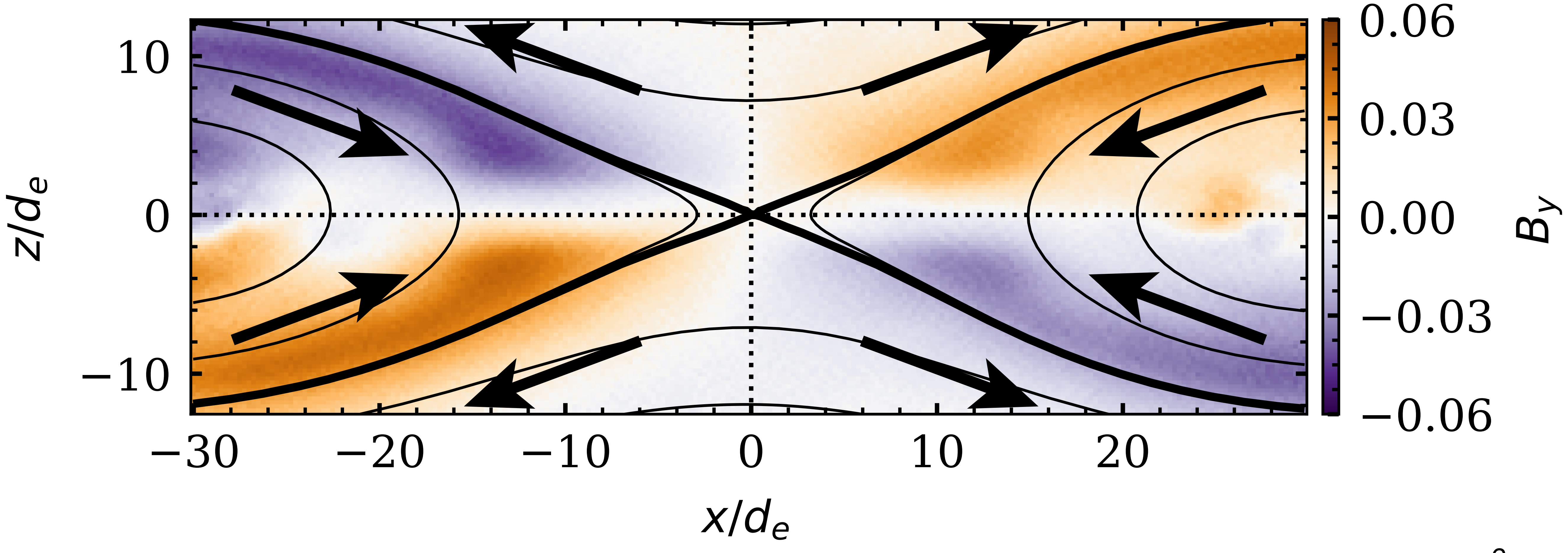

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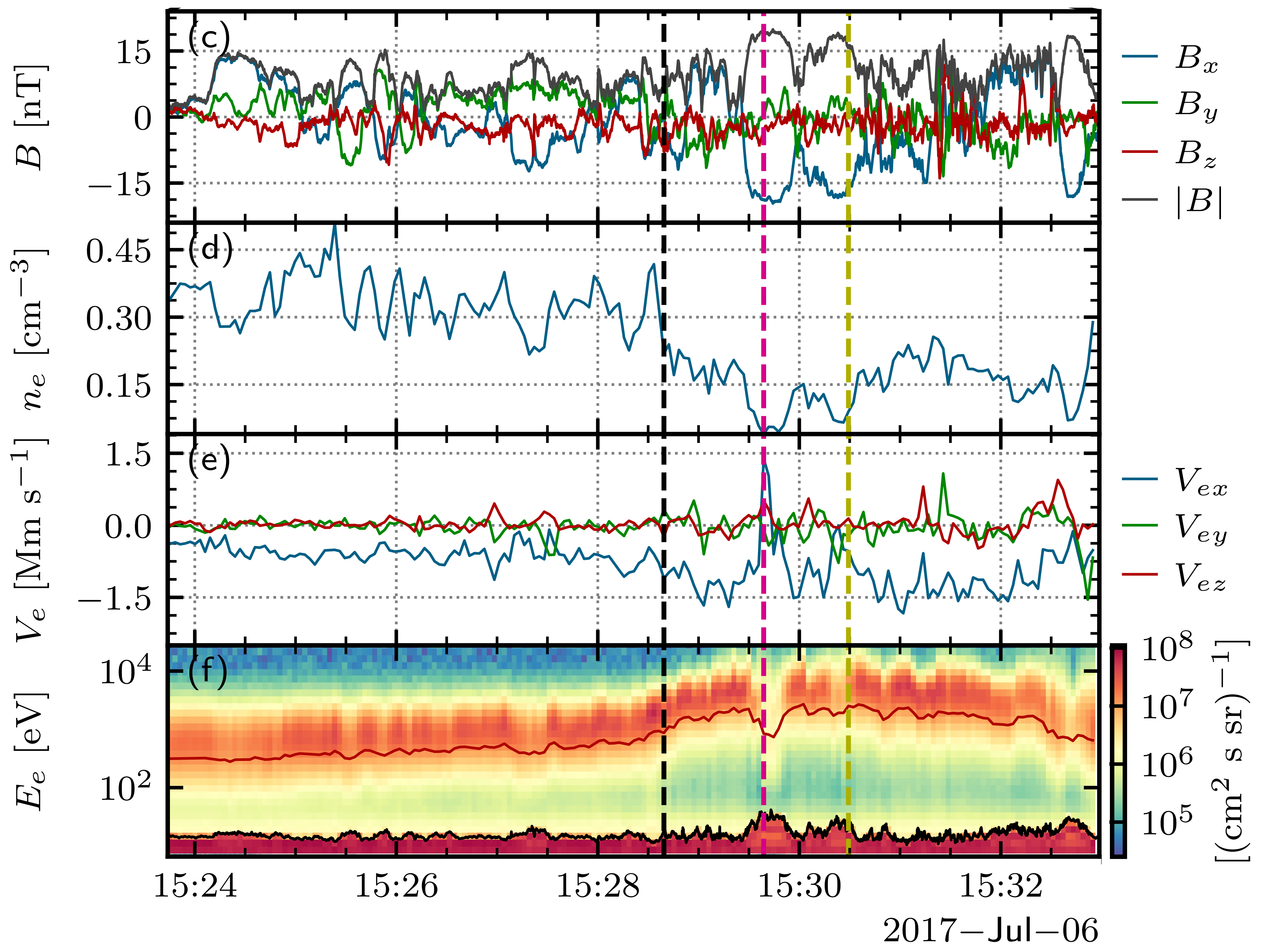

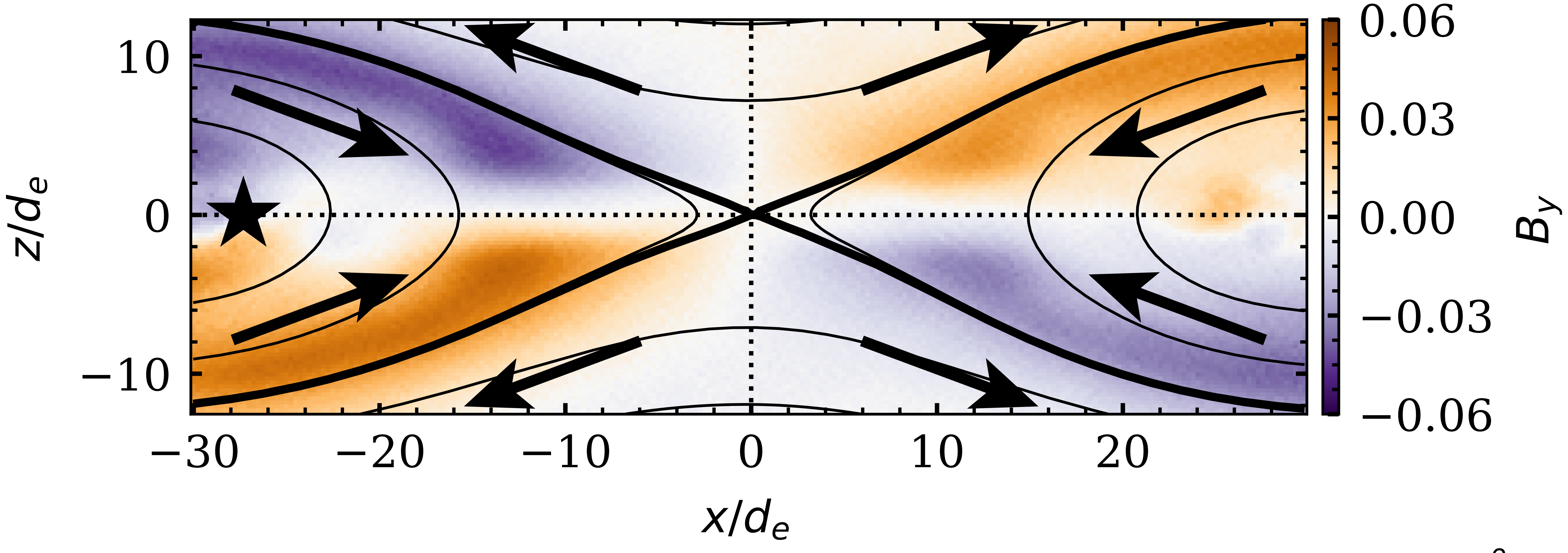

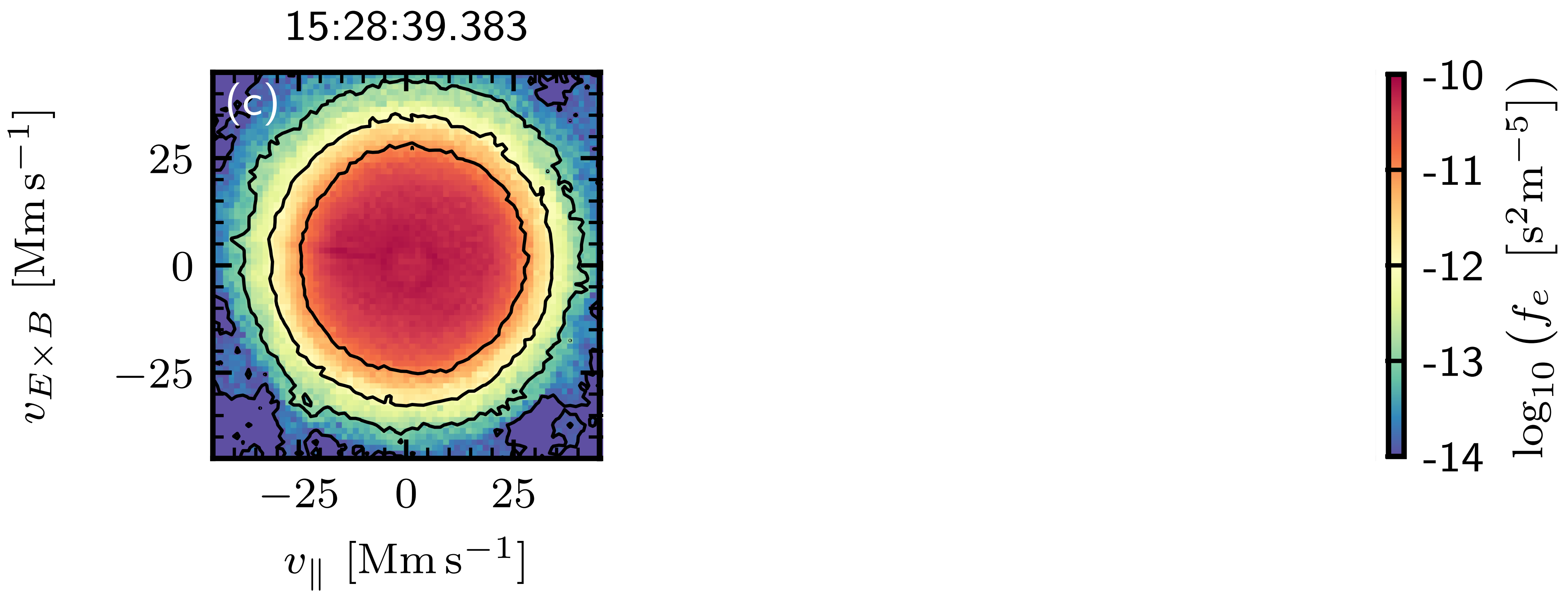

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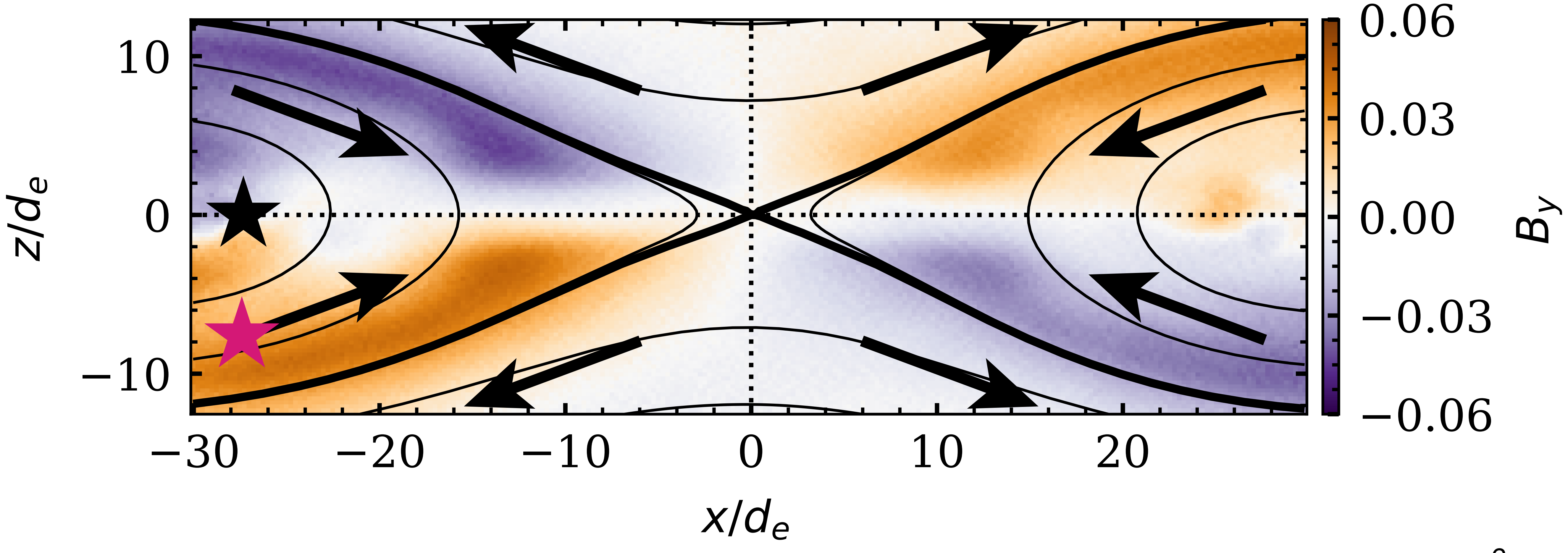

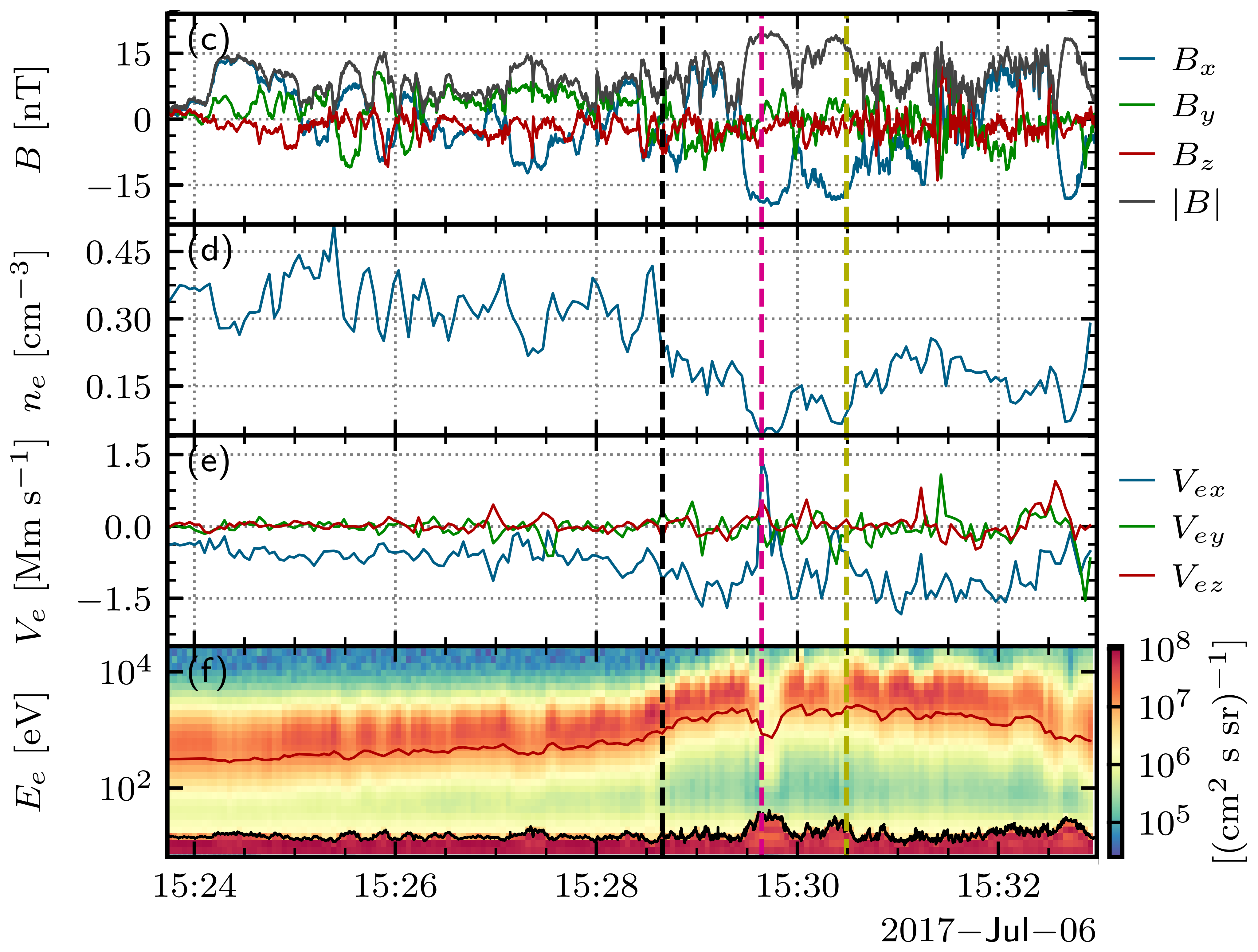

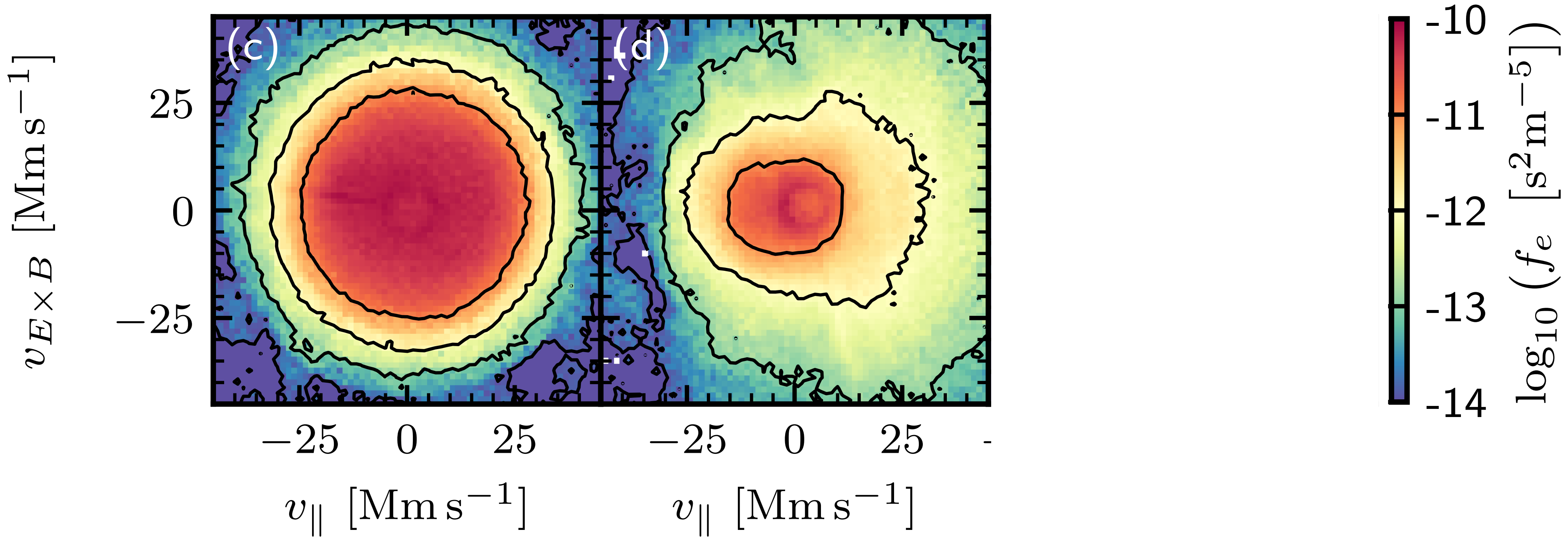

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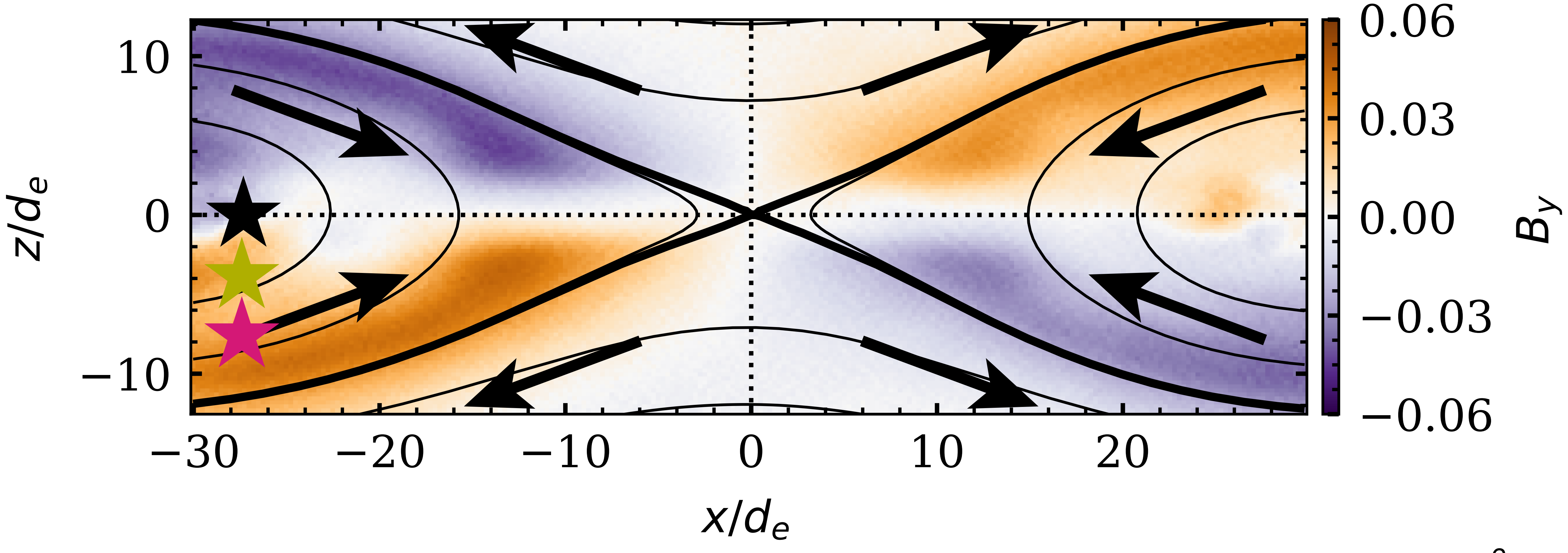
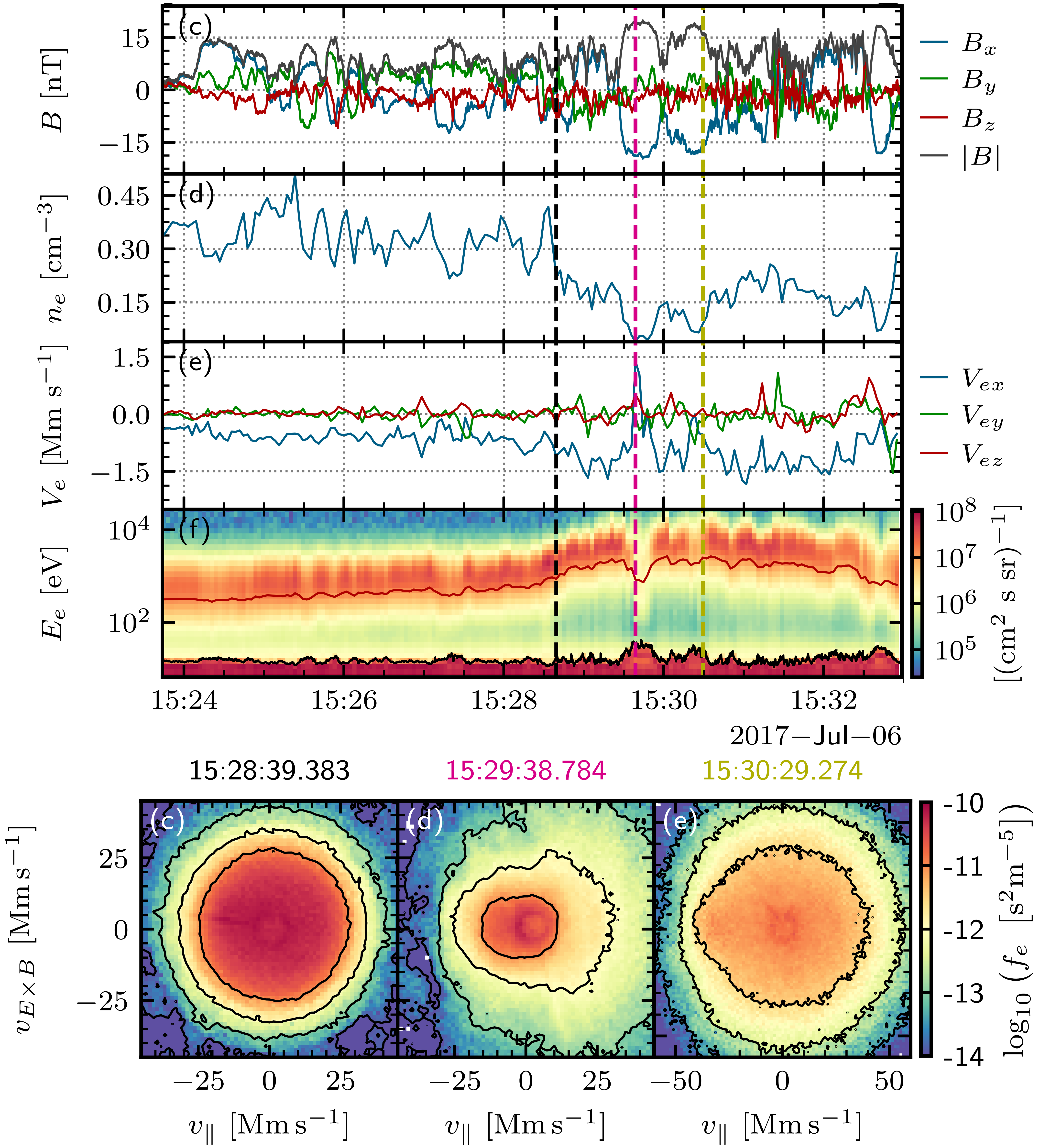
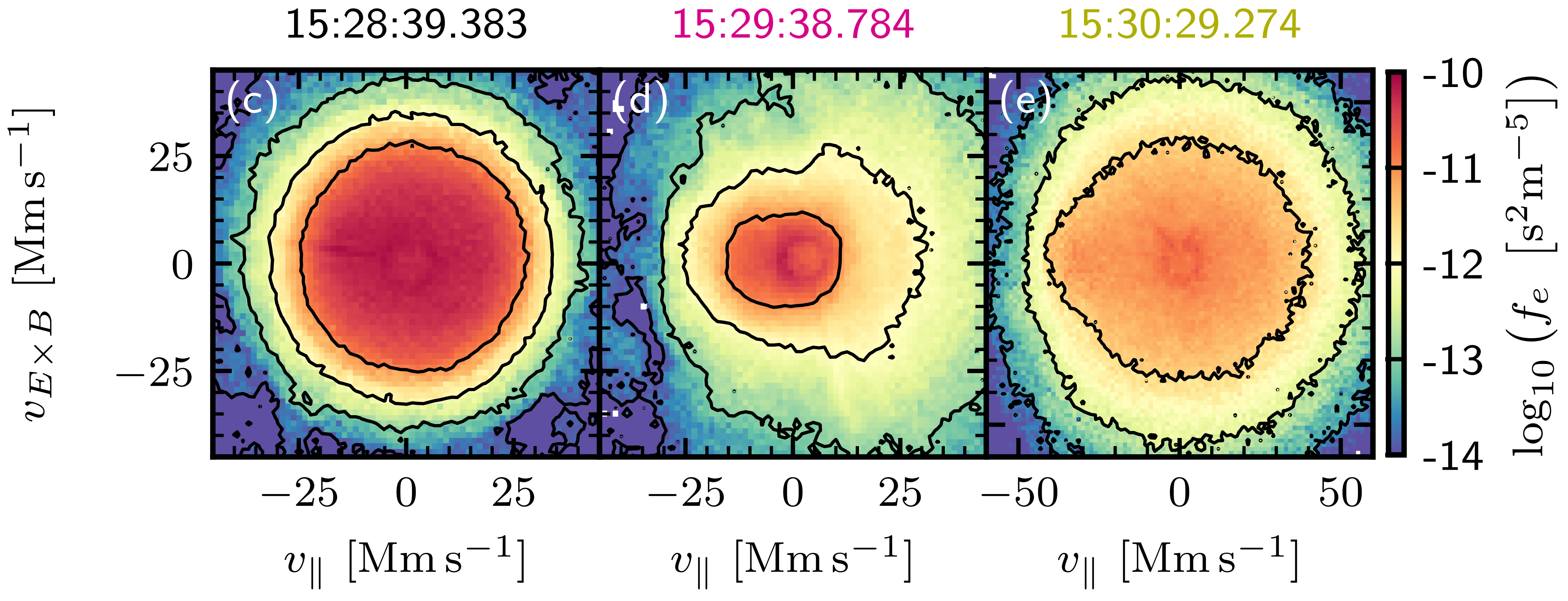




Electron VDFs in the Outflow

[Richard+2025, PRL]

Modeling the electron VDFs



Electron VDFs in the Outflow

[Richard+2025, PRL]

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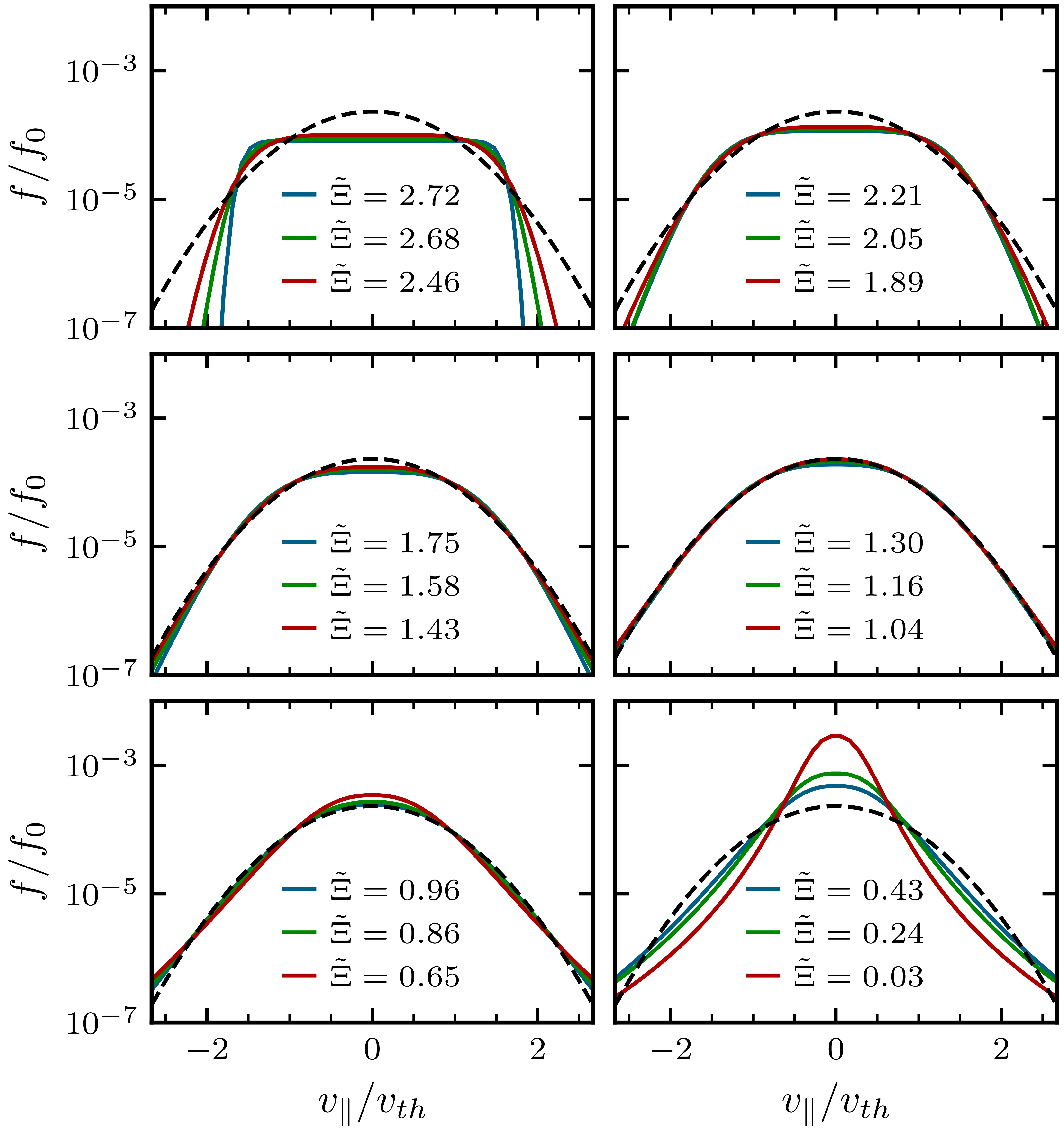
- Model electron VDF (r,q) [Qureshi+2004, PoP] for $v_\perp \simeq 0$

$$f_{(r,q)} = f_0 \left[1 + \left(\frac{v_\parallel^2}{\xi(r,q) v_{te,\parallel}^2} \right)^{r+1} \right]^{-q}$$



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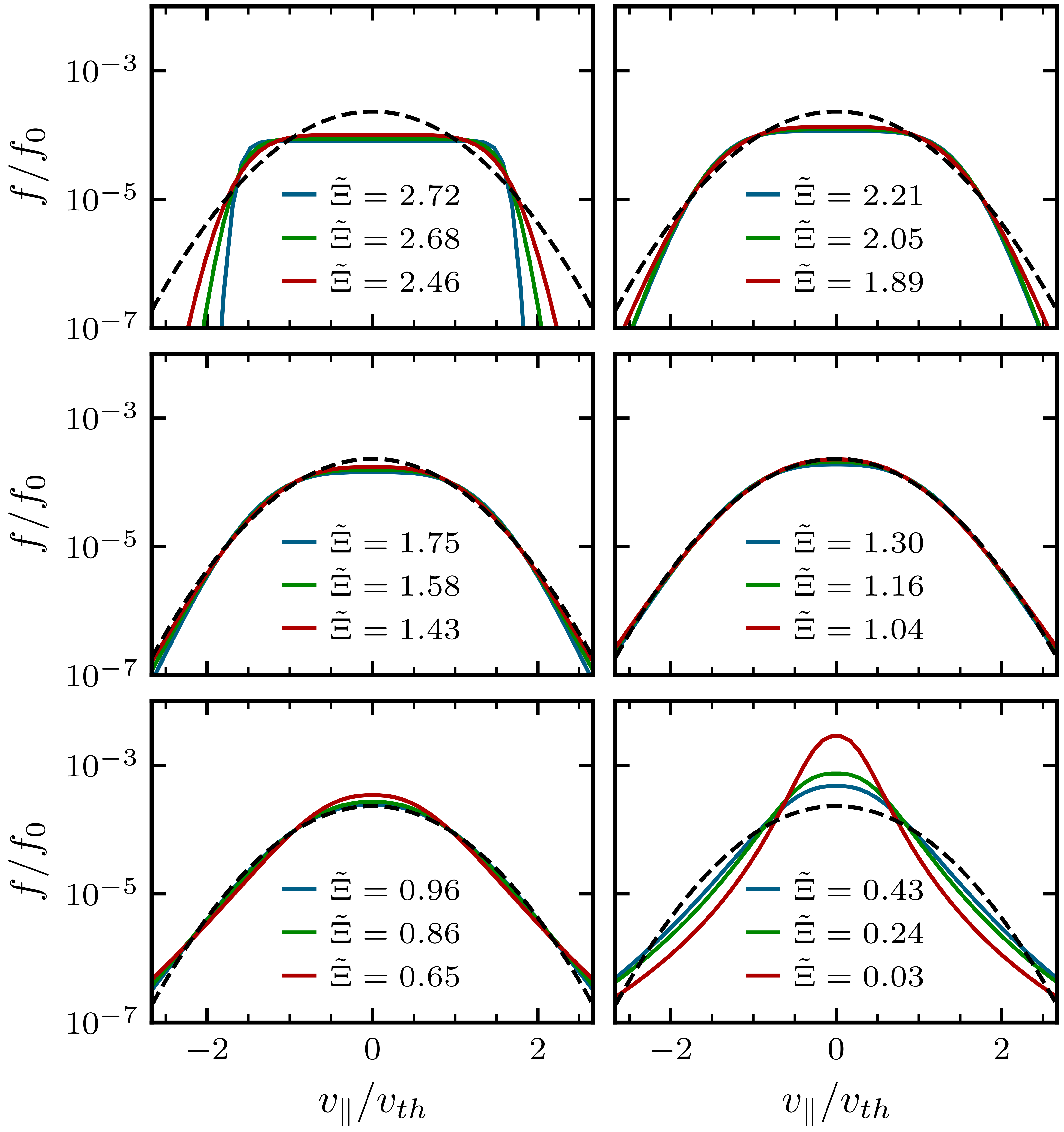

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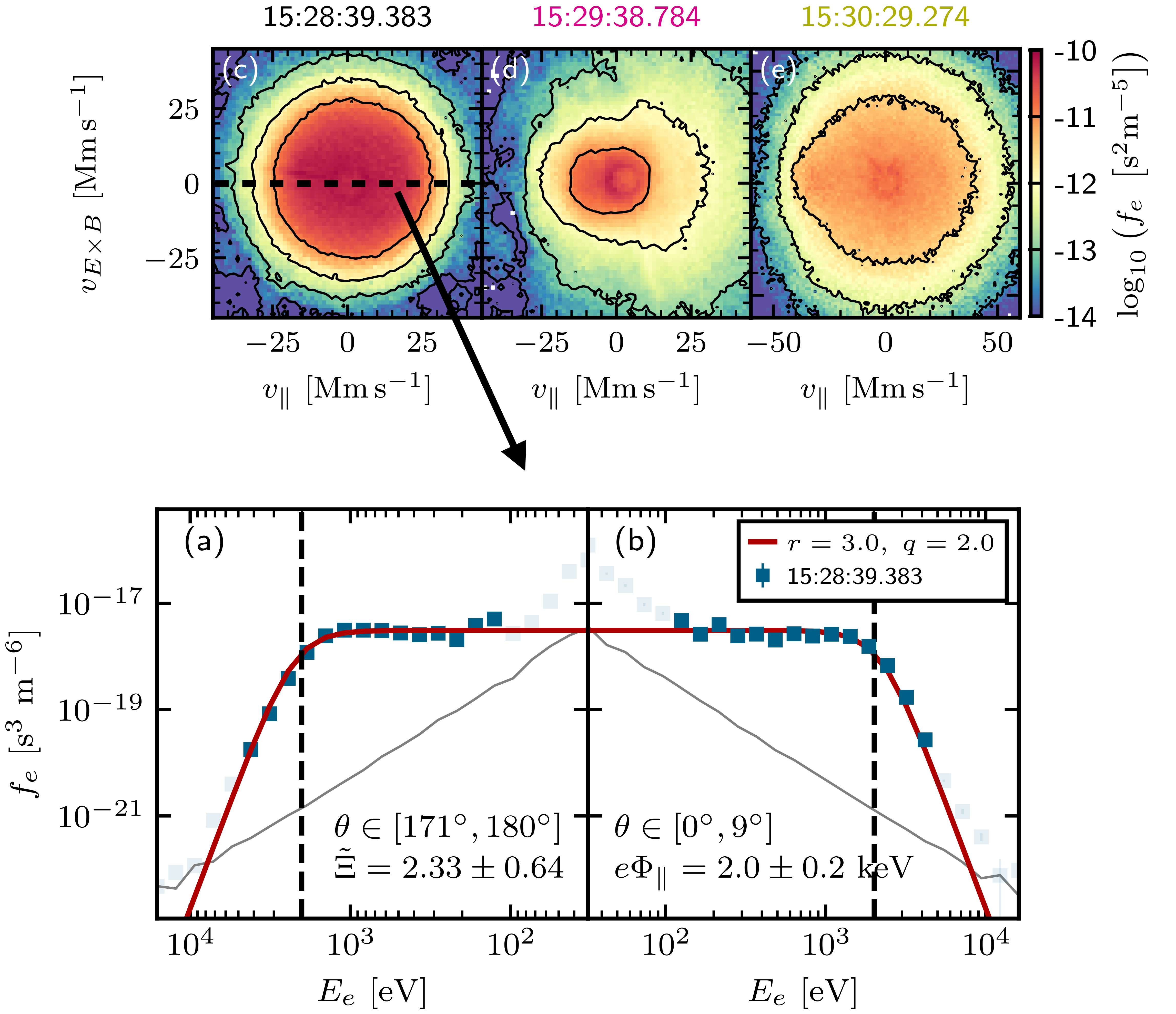
- Knee velocity v_Φ corresponding to the acceleration potential $f(v_\Phi)/f_0 = \varepsilon$

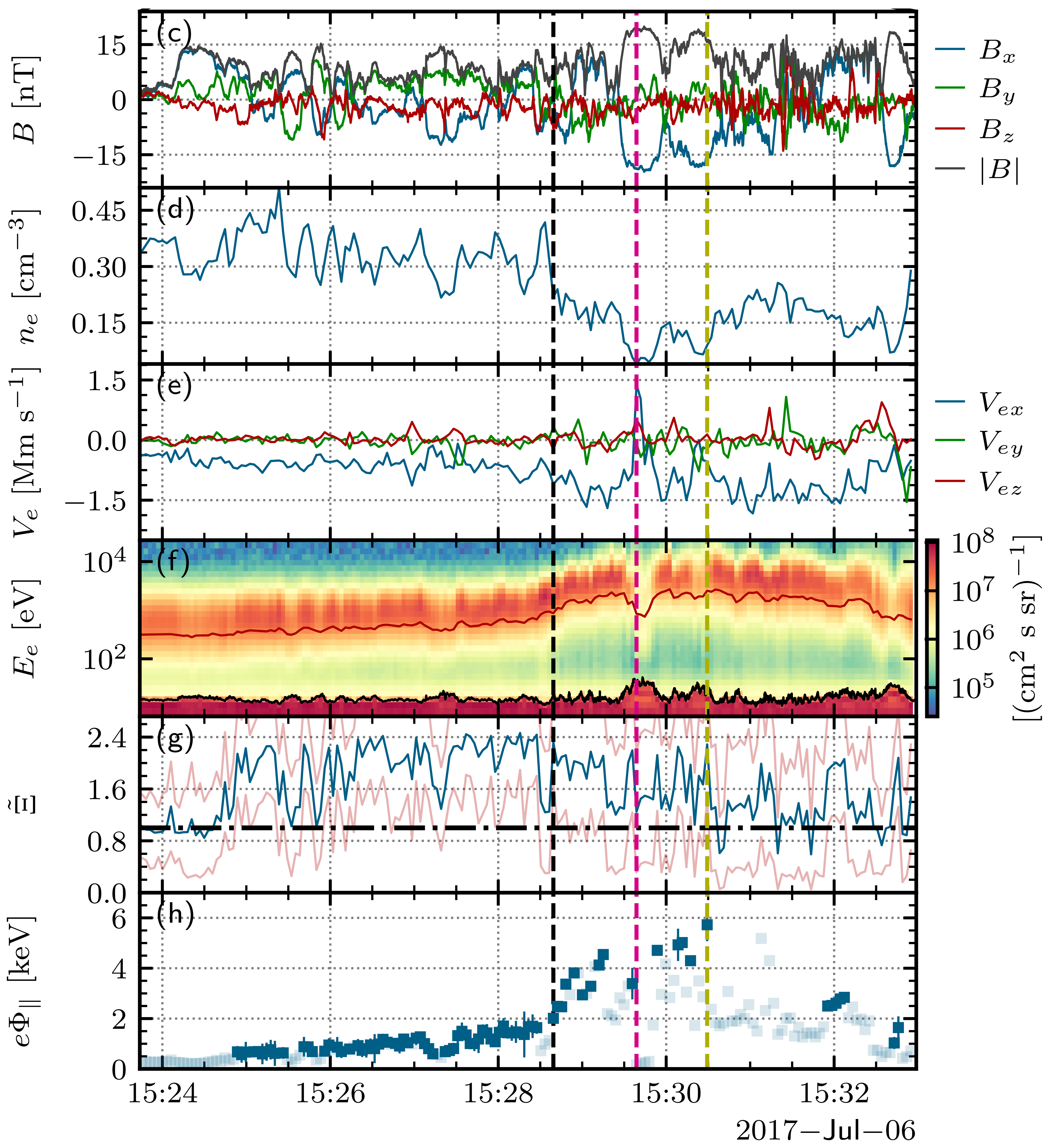
$$v_\Phi = \left(\varepsilon^{-1/q} - 1 \right)^{1/2(r+1)} \xi^{1/2} v_{te,\parallel}$$



Results

[Richard+2025, PRL]

Acceleration potential



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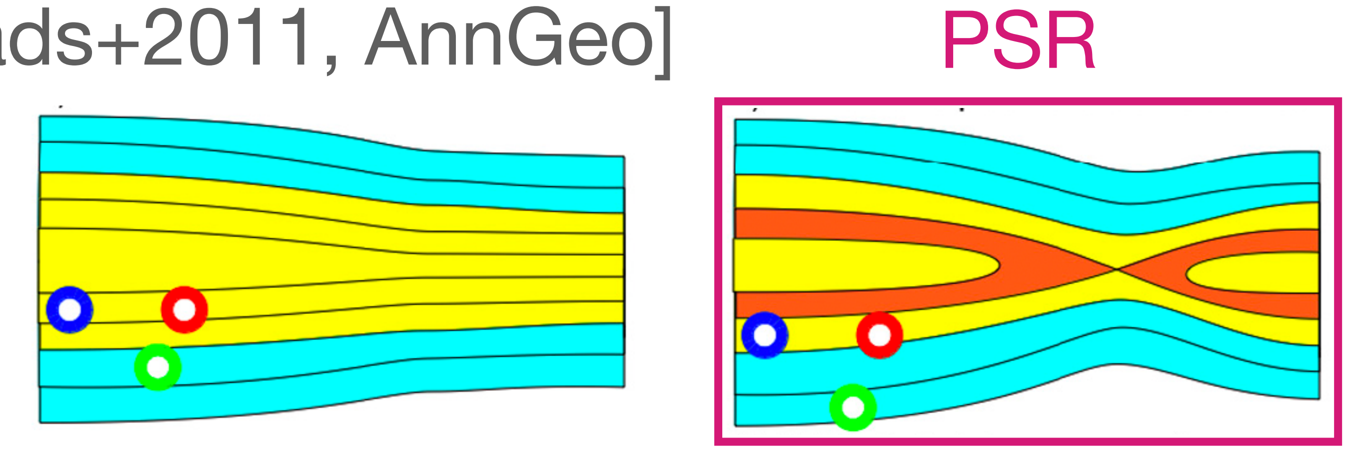
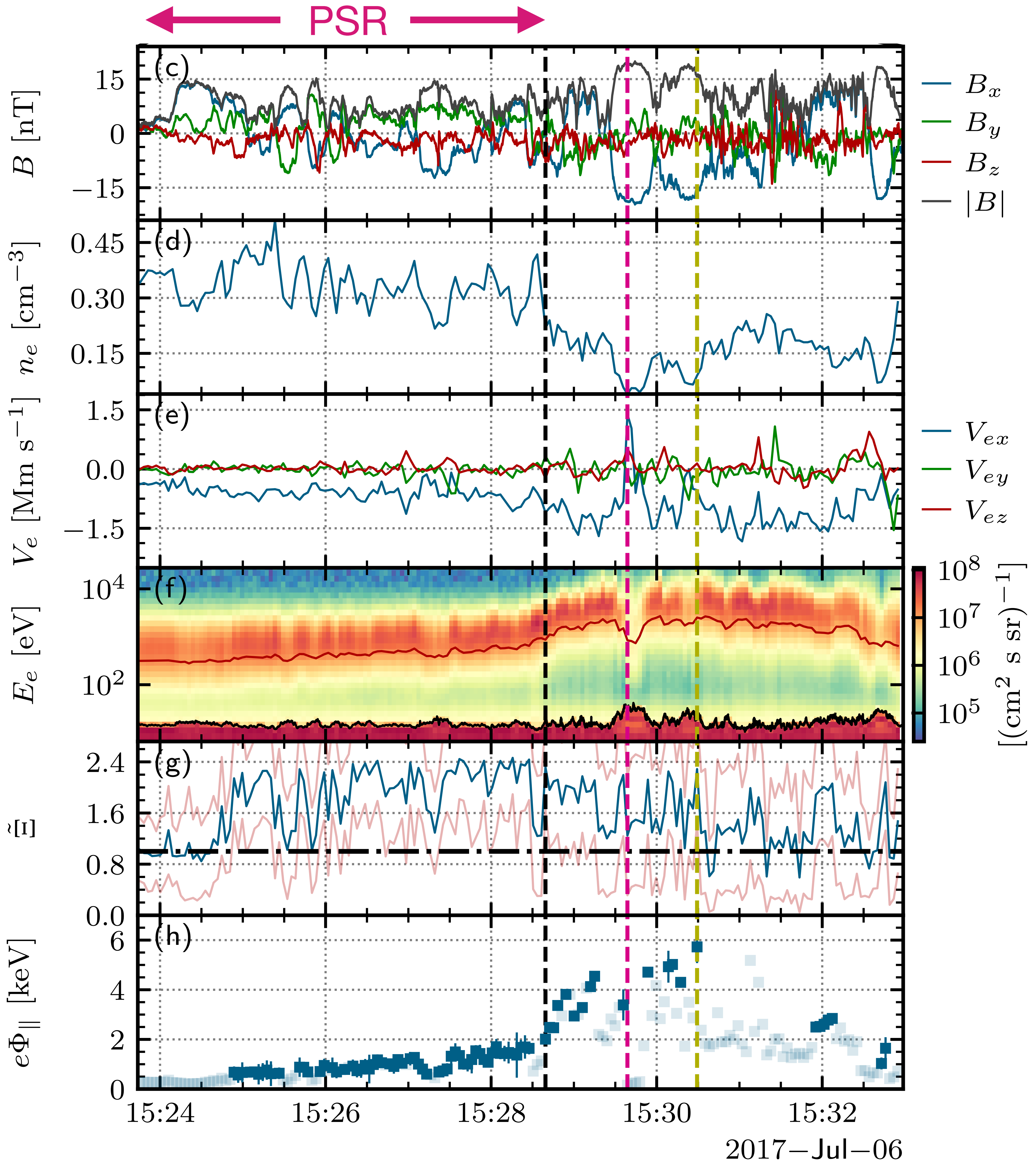
Acceleration potential

[Richard+2025, PRL]

- Plasma sheet reconnection followed by lobe reconnection

[Vaivads+2011, AnnGeo]





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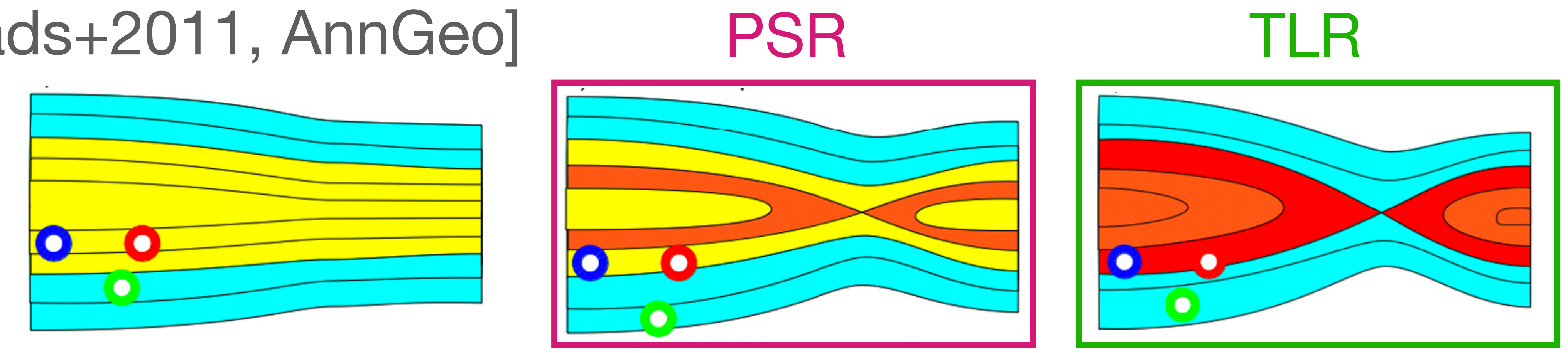

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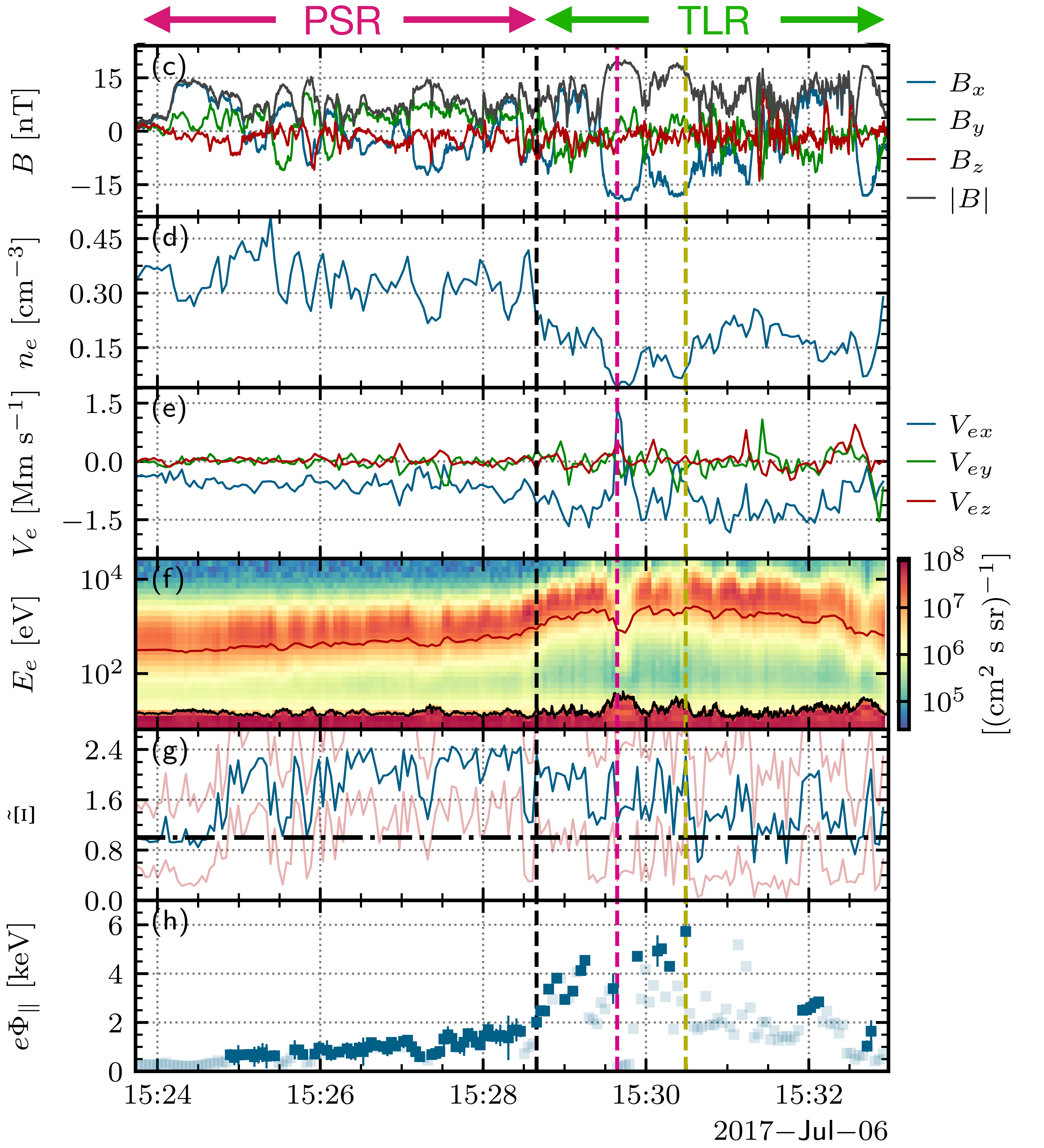

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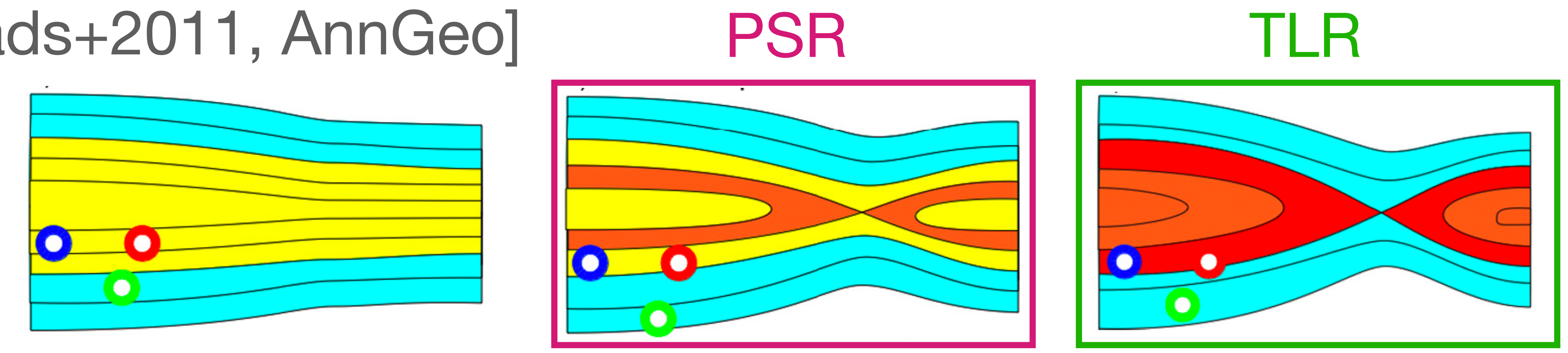
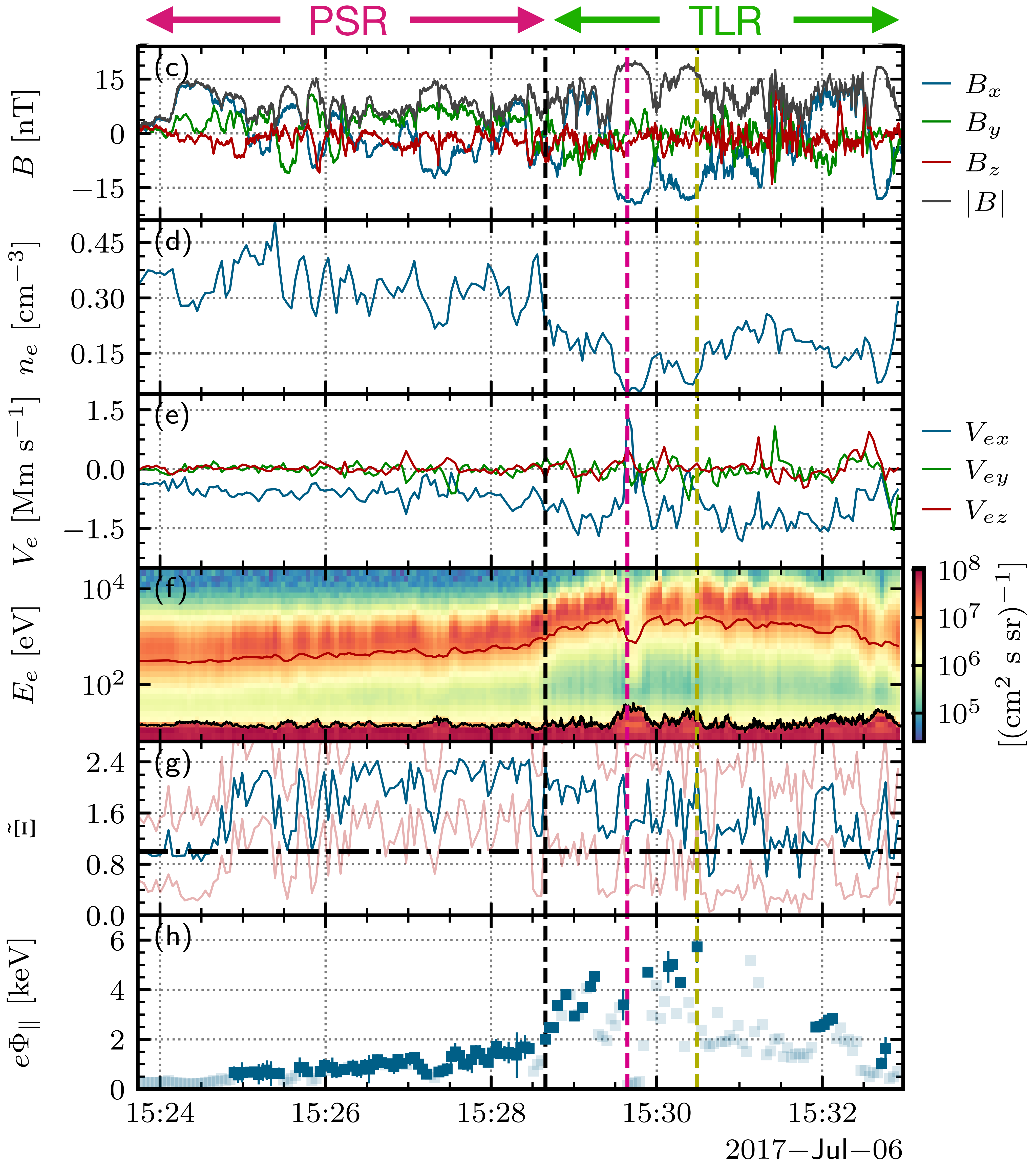


- The increase in acceleration potential is proportional to the increase in inflow Alfvén speed

$$e\Phi_{\parallel}^{TLR}/e\Phi_{\parallel}^{PSR} \sim V_{Ae\infty}^{TLR}/V_{Ae\infty}^{PSR}$$

The acceleration potential increases with the inflow Alfvén speed

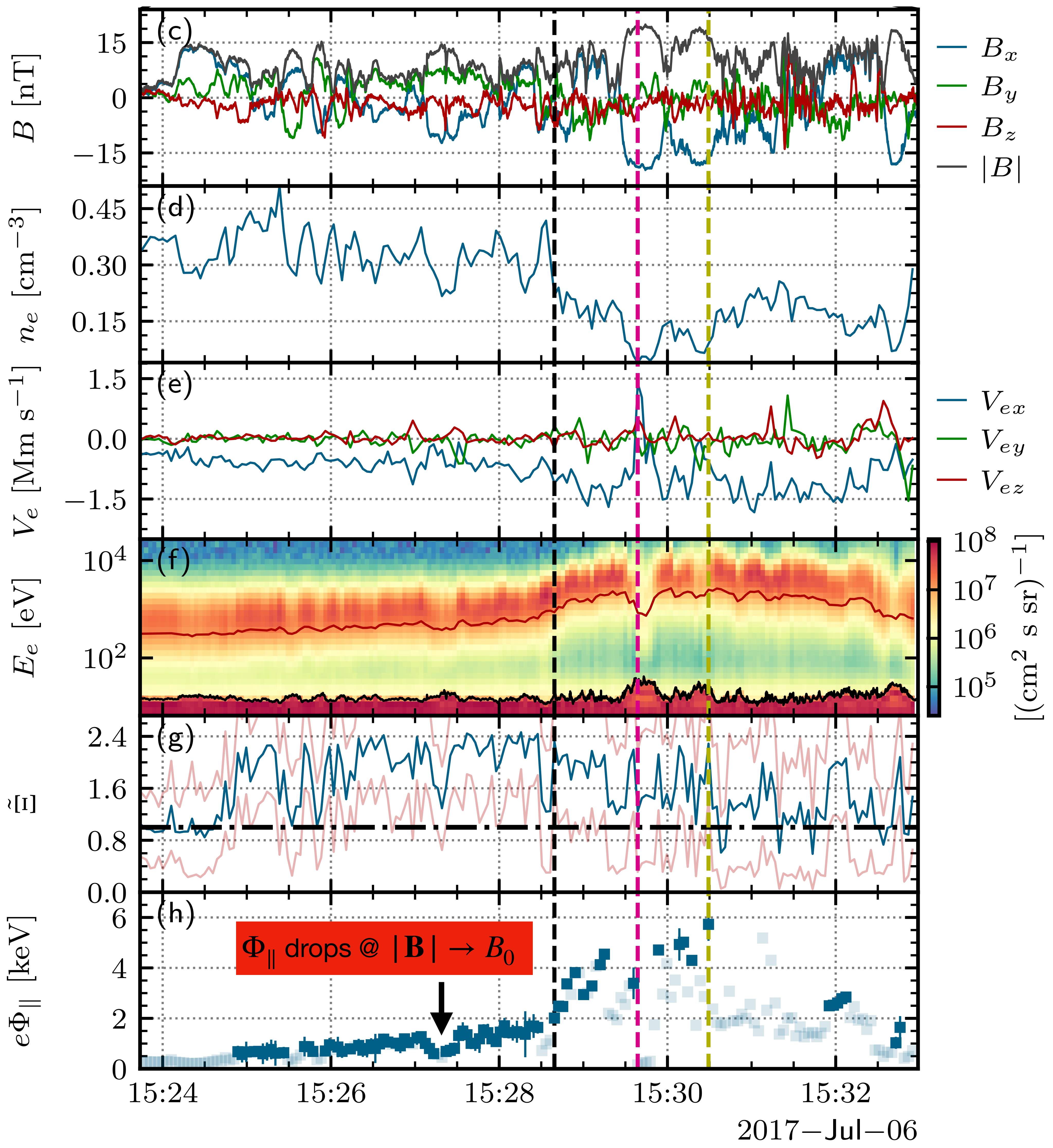
[Richard+2025, PRL]



Results

The origin of $E_{\parallel}$

[Richard+2025, PRL]



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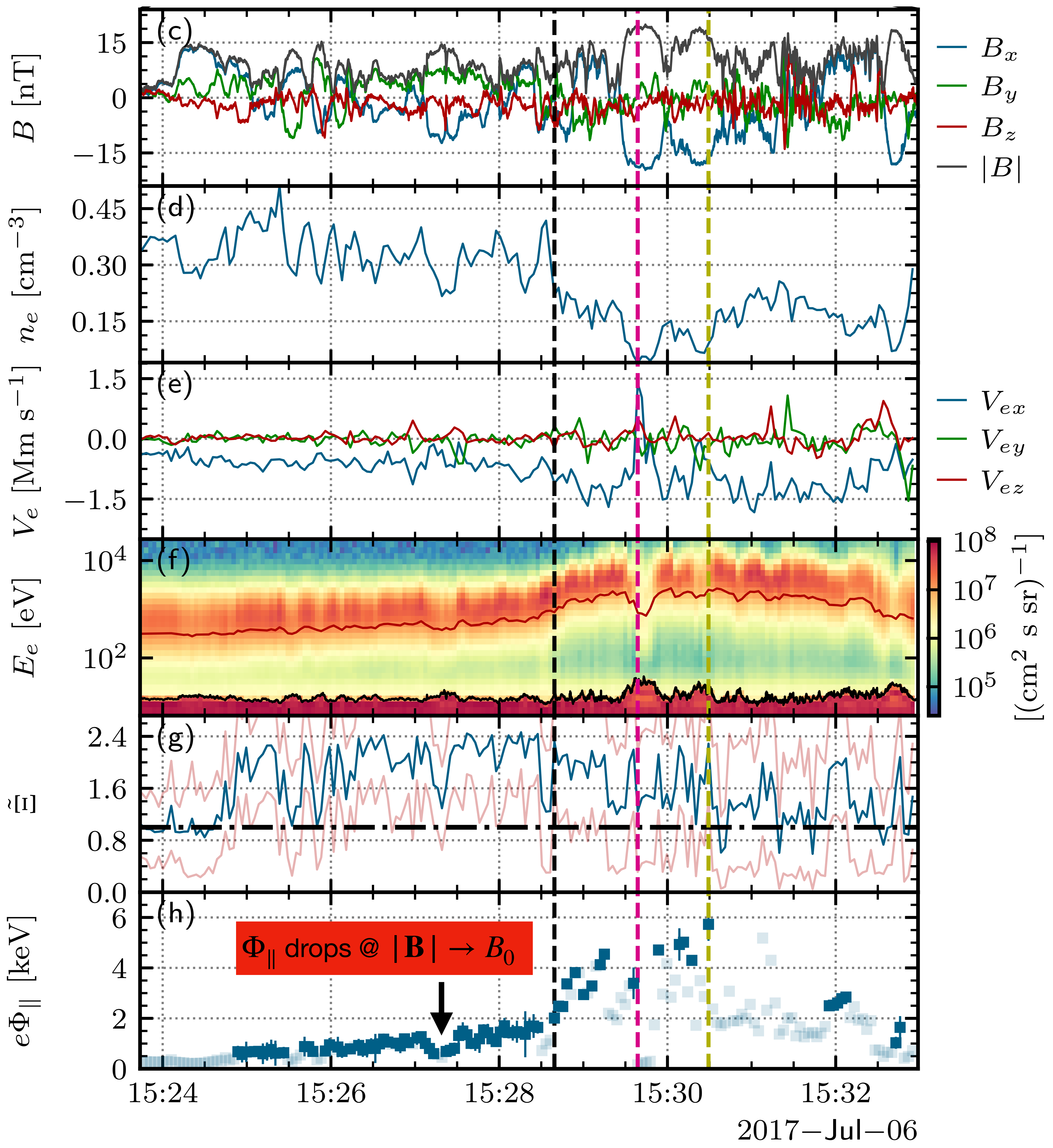
The origin of $E_{\|}$

- Steady-state local electron momentum balance along the field line

$$eE_{\|} = -\underbrace{\nabla_{\|} T_{e\|}}_{\Phi_{\|T}} - \underbrace{T_{e\|}\nabla_{\|}\ln n}_{\Phi_{\|n}} + \underbrace{(T_{e\|} - T_{e\perp})\nabla_{\|}\ln B}_{\Phi_{\|B}}$$



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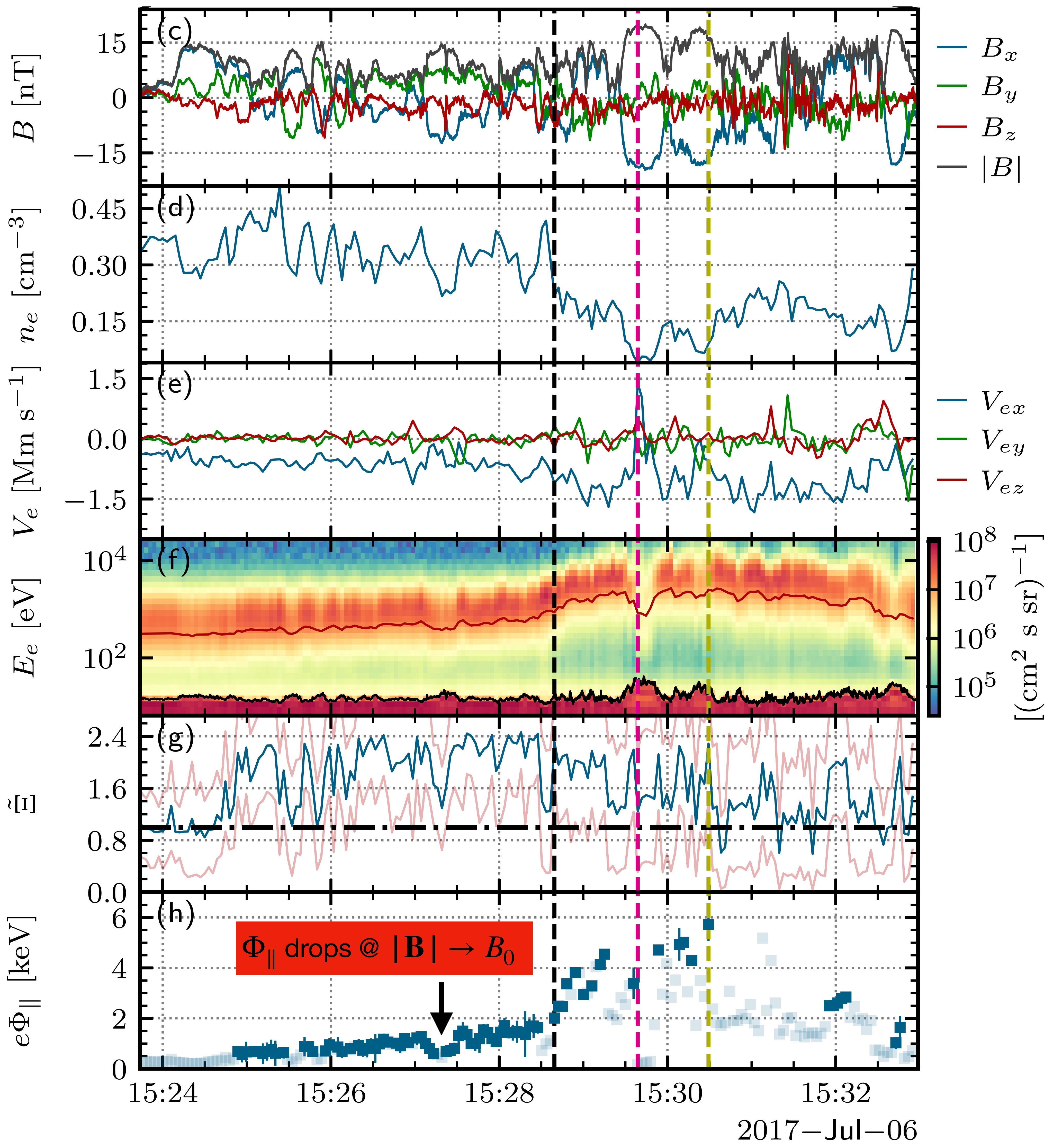
- Potential drop (incremental) across the outflow [Haggerty+2015, GRL]

$$e\Delta\Phi_\parallel = -\int_b^a E_\parallel dl \simeq \left(\frac{e\Delta\Phi_{\parallel T}}{10\ \text{eV}}\right) + \left(\frac{e\Delta\Phi_{\parallel n}}{160\ \text{eV}}\right) + \left(\frac{e\Delta\Phi_{\parallel B}}{50\ \text{eV}}\right)$$

Field-aligned ambipolar electric field is primarily due to electron density gradients



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[Richard+2025, PRL]

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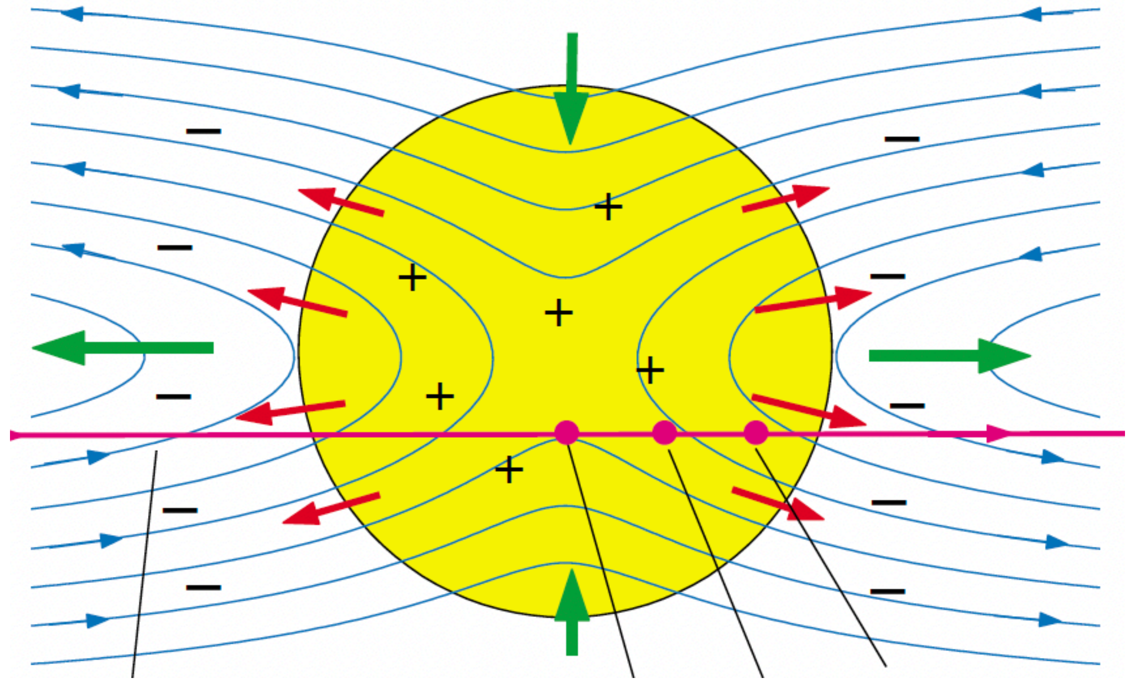
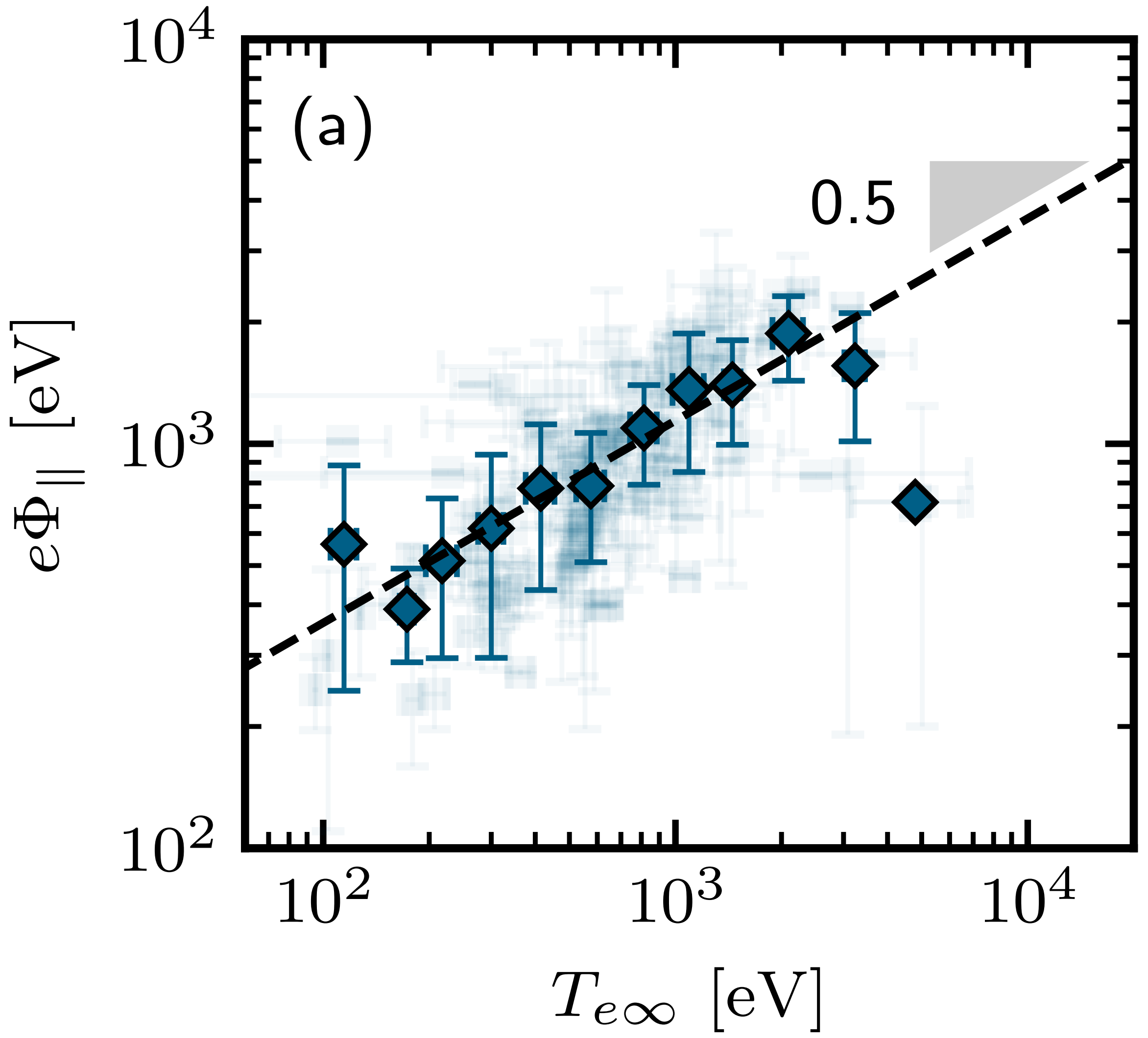
- $e\Phi_{\parallel}$ increases with $T_{e\infty}$ to keep electrons trapped.

[Egedal+2005, PRL]





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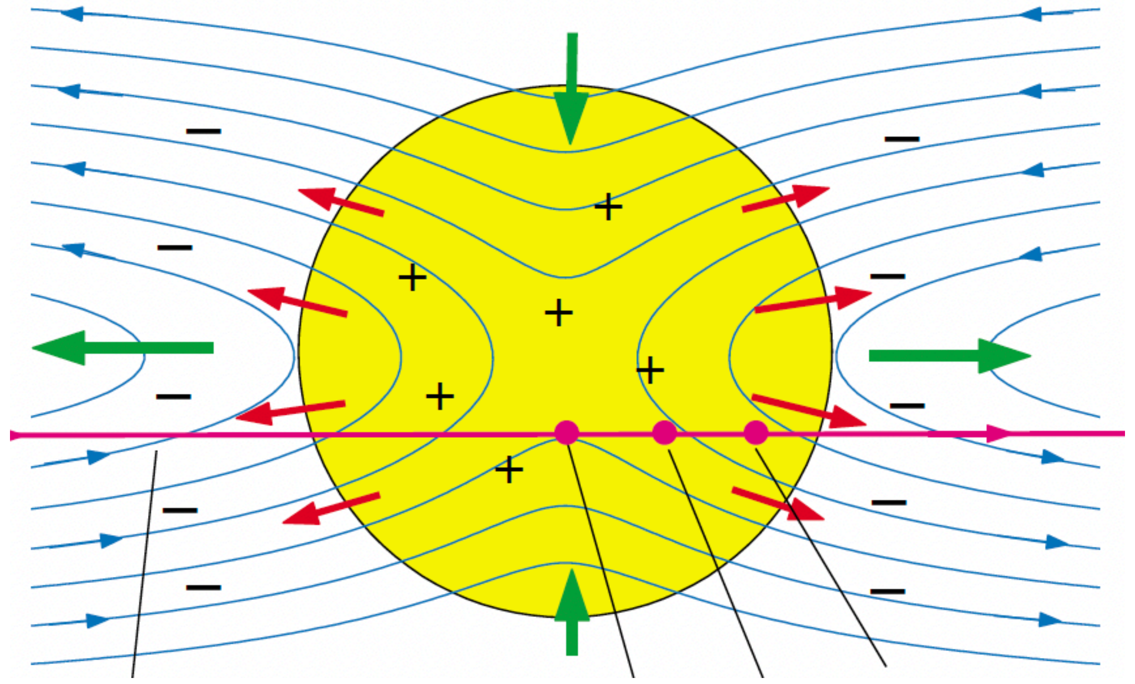
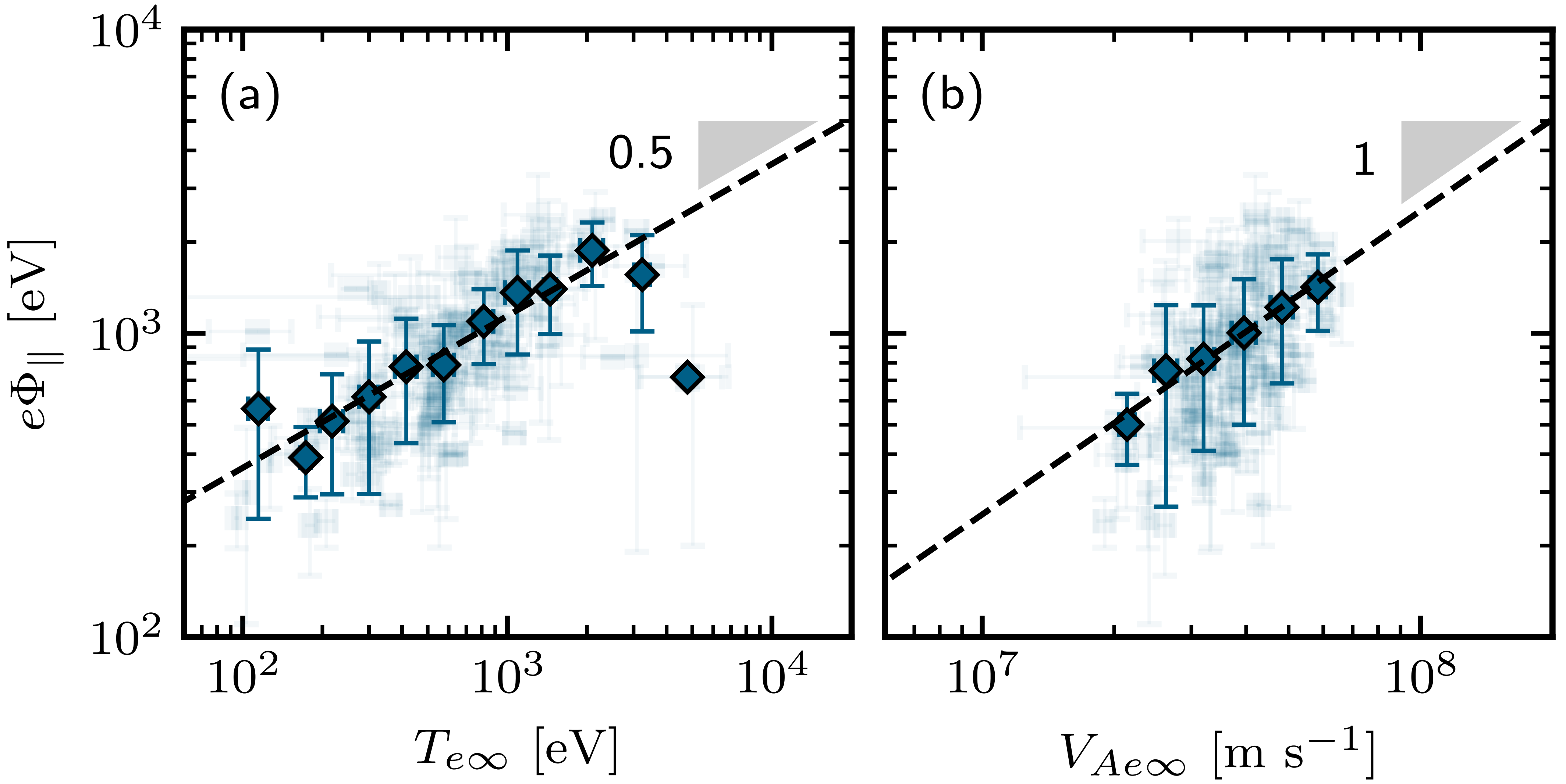
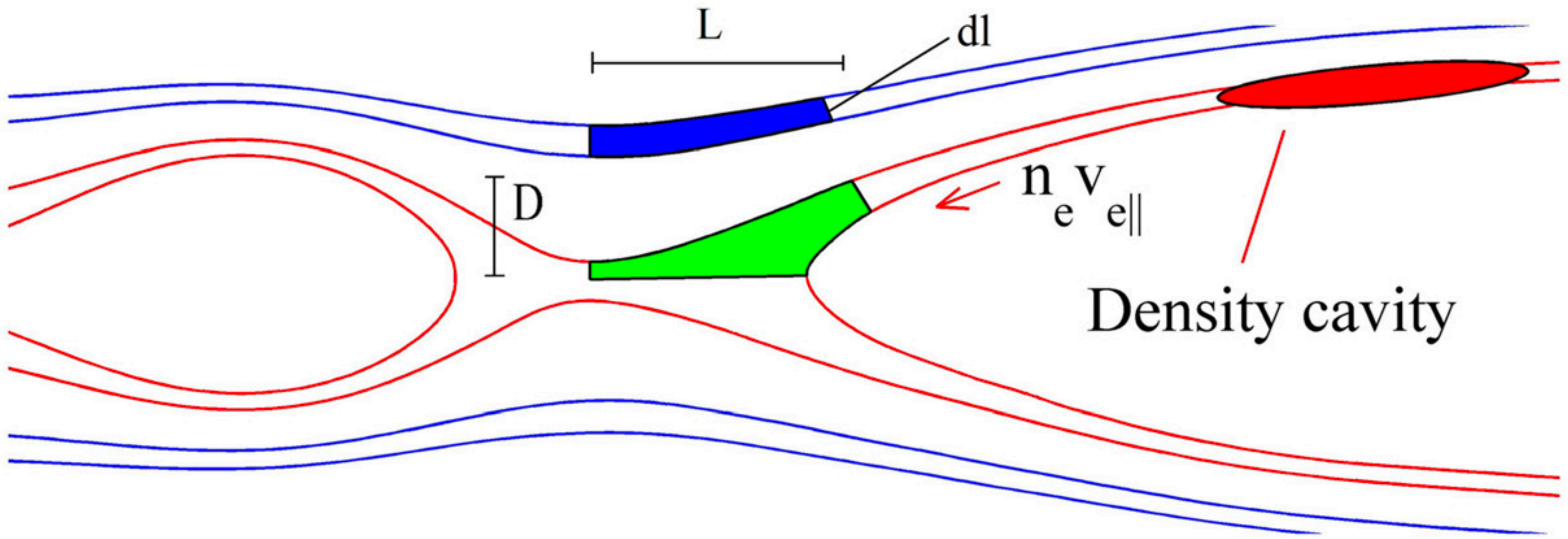


- $e\Phi_{\parallel}$ increases with $V_{Ae\infty}$ to balance the flux tube expansion



[Egedal+2015, PoP]



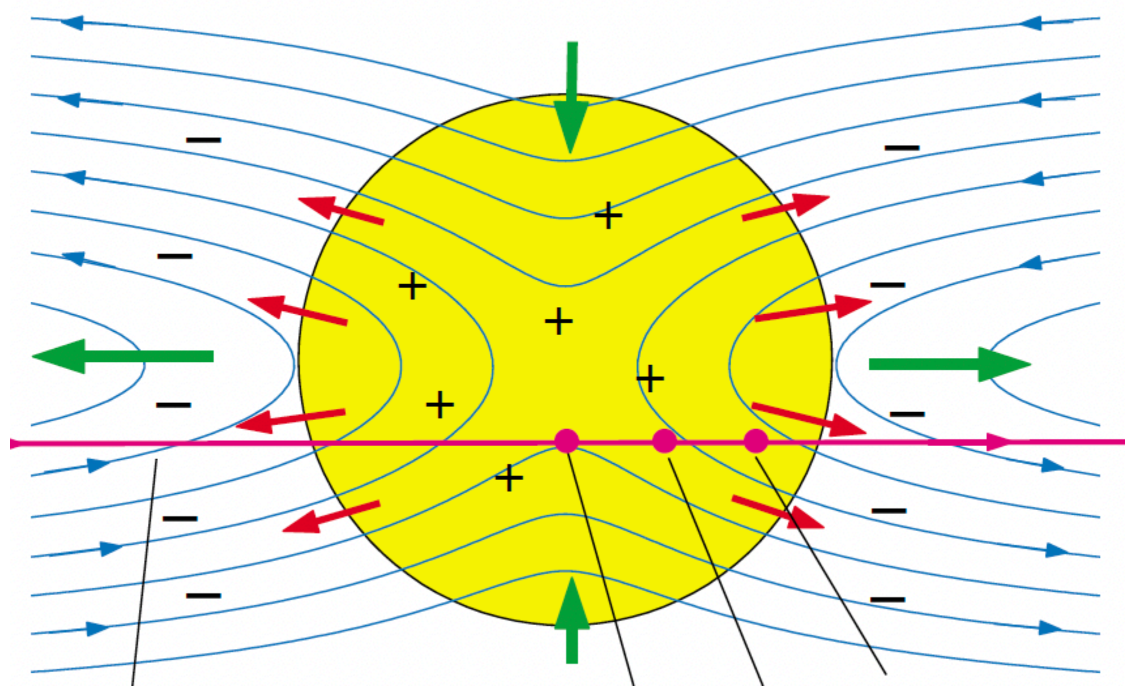
Results

Statistics

[Richard+2025, PRL]

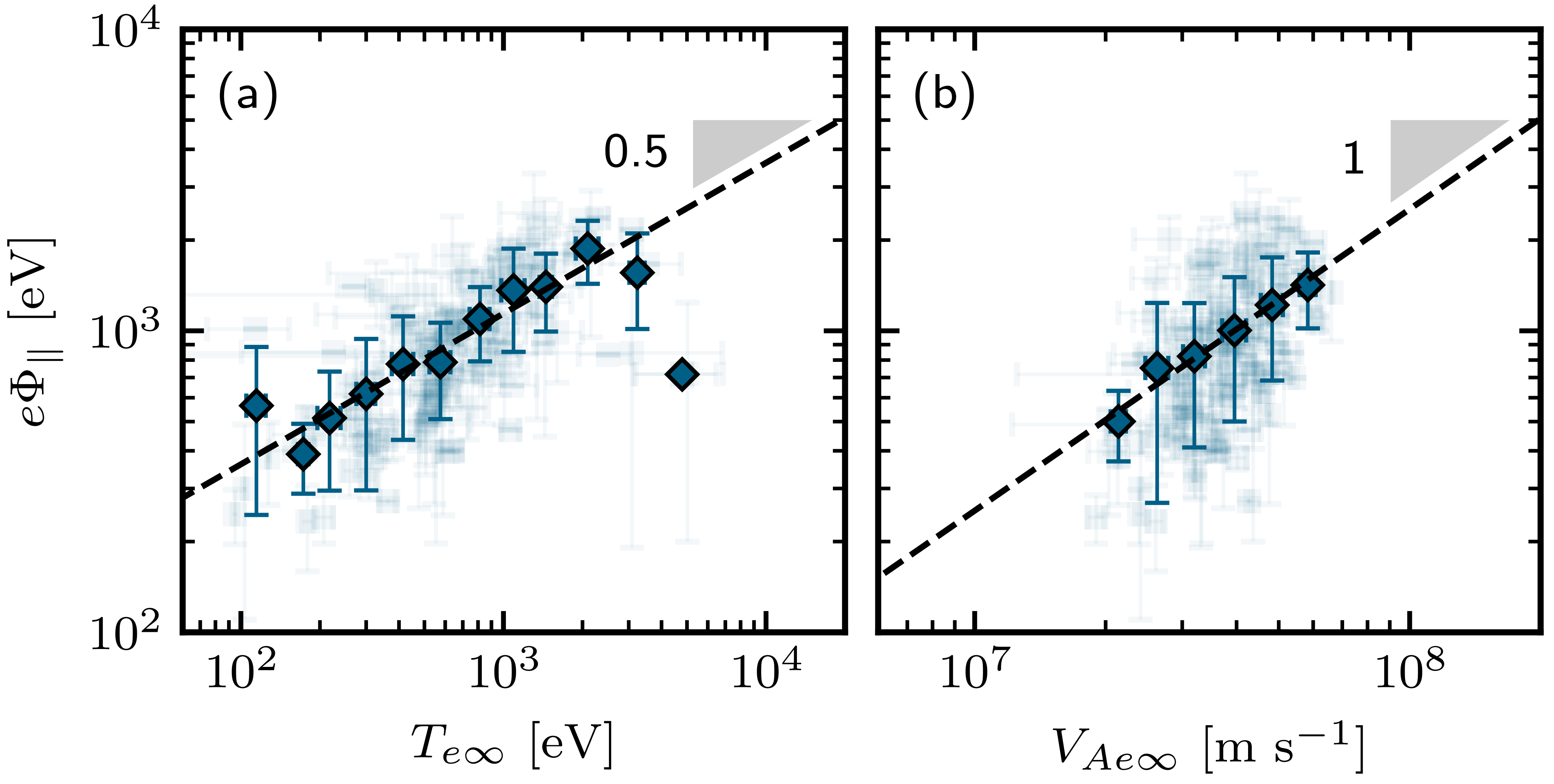
- $e\Phi_{\|}$ increases with $T_{e\infty}$ to keep electrons trapped.

[Egedal+2005, PRL]

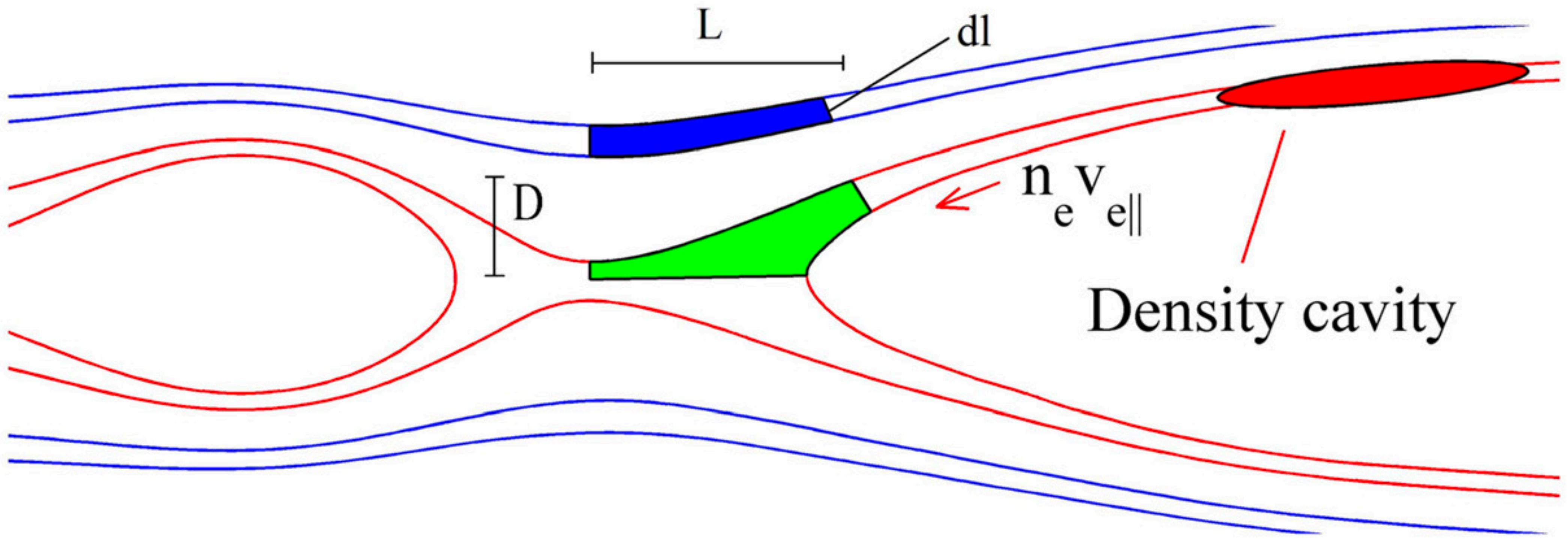


- $e\Phi_{\|}$ increases with $V_{Ae\infty}$ to balance the flux tube expansion

$e\Phi_{\|}$ increases with $T_{e\infty}$ and $V_{Ae\infty}$ to maintain quasi-neutrality



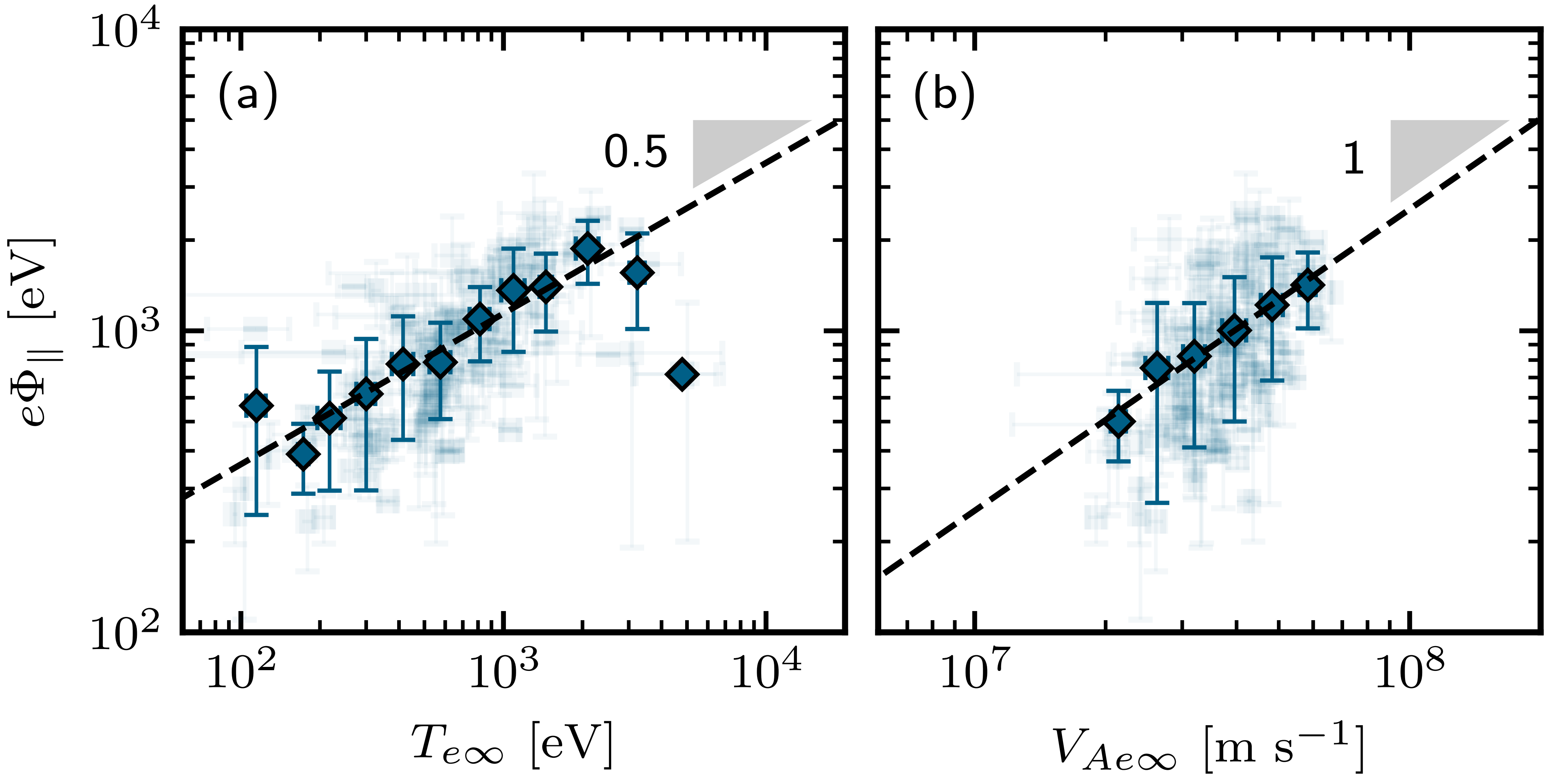
[Egedal+2015, PoP]



Results

[Richard+2025, PRL]

Role of $E_{\parallel}$ in the energy partition

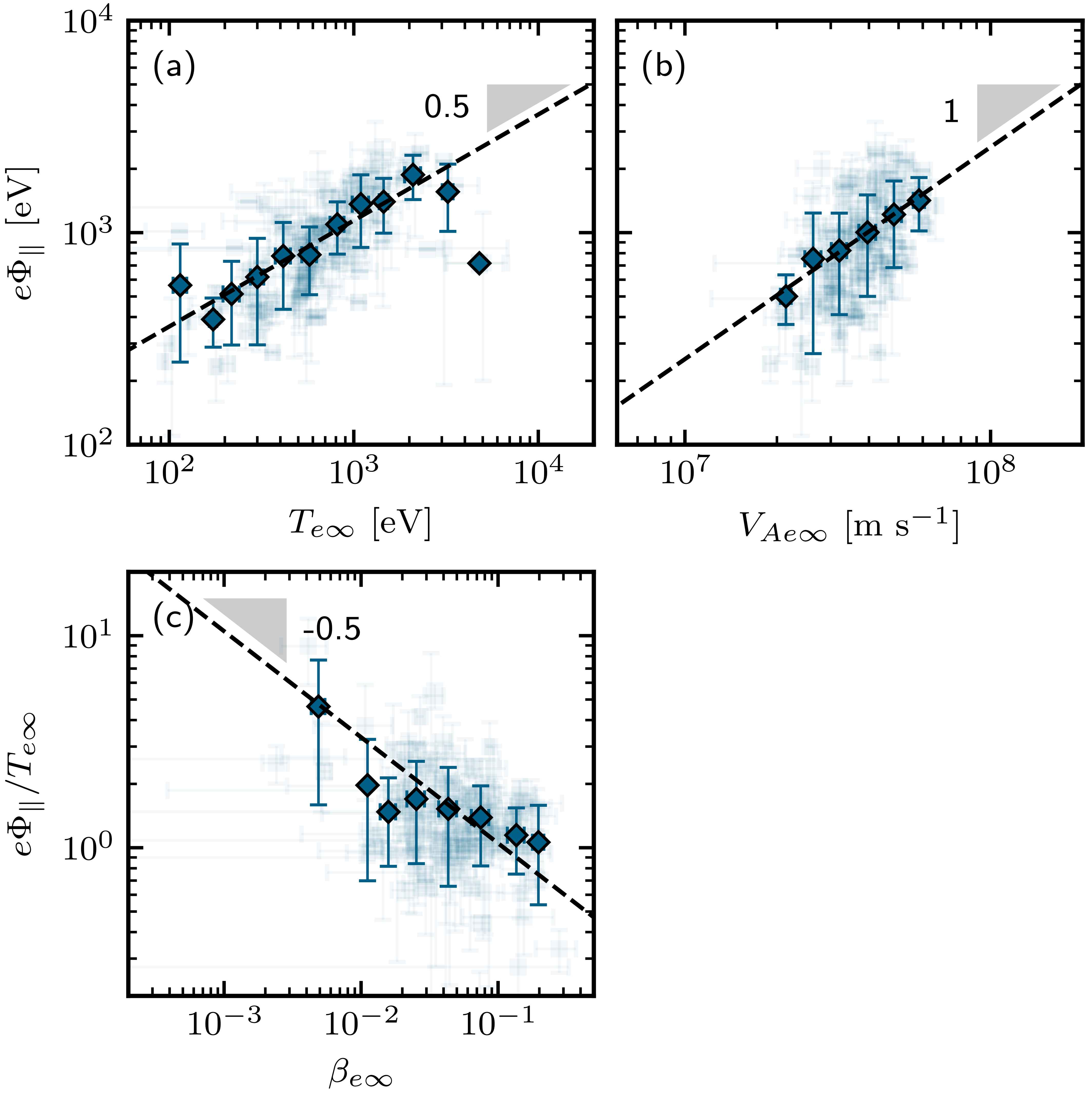


Results

[Richard+2025, PRL]

Role of $E_{\|}$ in the energy partition

- The acceleration potential scales as $e\Phi_{\|}/T_{e\infty} = \alpha_{\Phi}\beta_{e\infty}^{-1/2}$



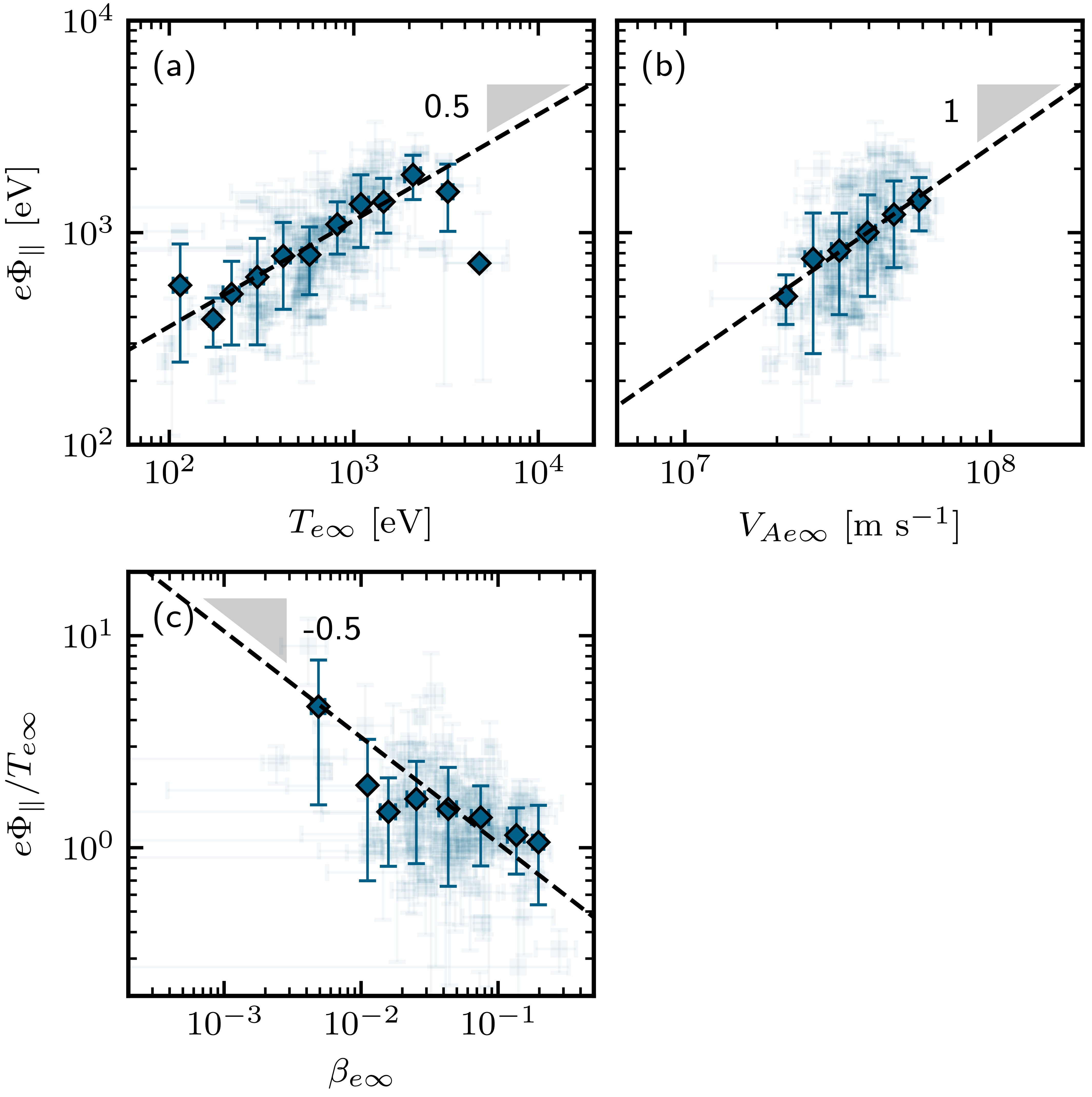
Results

[Richard+2025, PRL]

Role of $E_\parallel$ in the energy partition

- The acceleration potential scales as $e\Phi_\parallel / T_{e\infty} = \alpha_\Phi \beta_{e\infty}^{-1/2}$
- Electron heating: E_{rec} + $E_\parallel$ [Le+2016, PoP, Øieroset+2020, ApJ]

$$\Delta T_e = \alpha_e m_i V_{Ai\infty}^2$$



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[Richard+2025, PRL]

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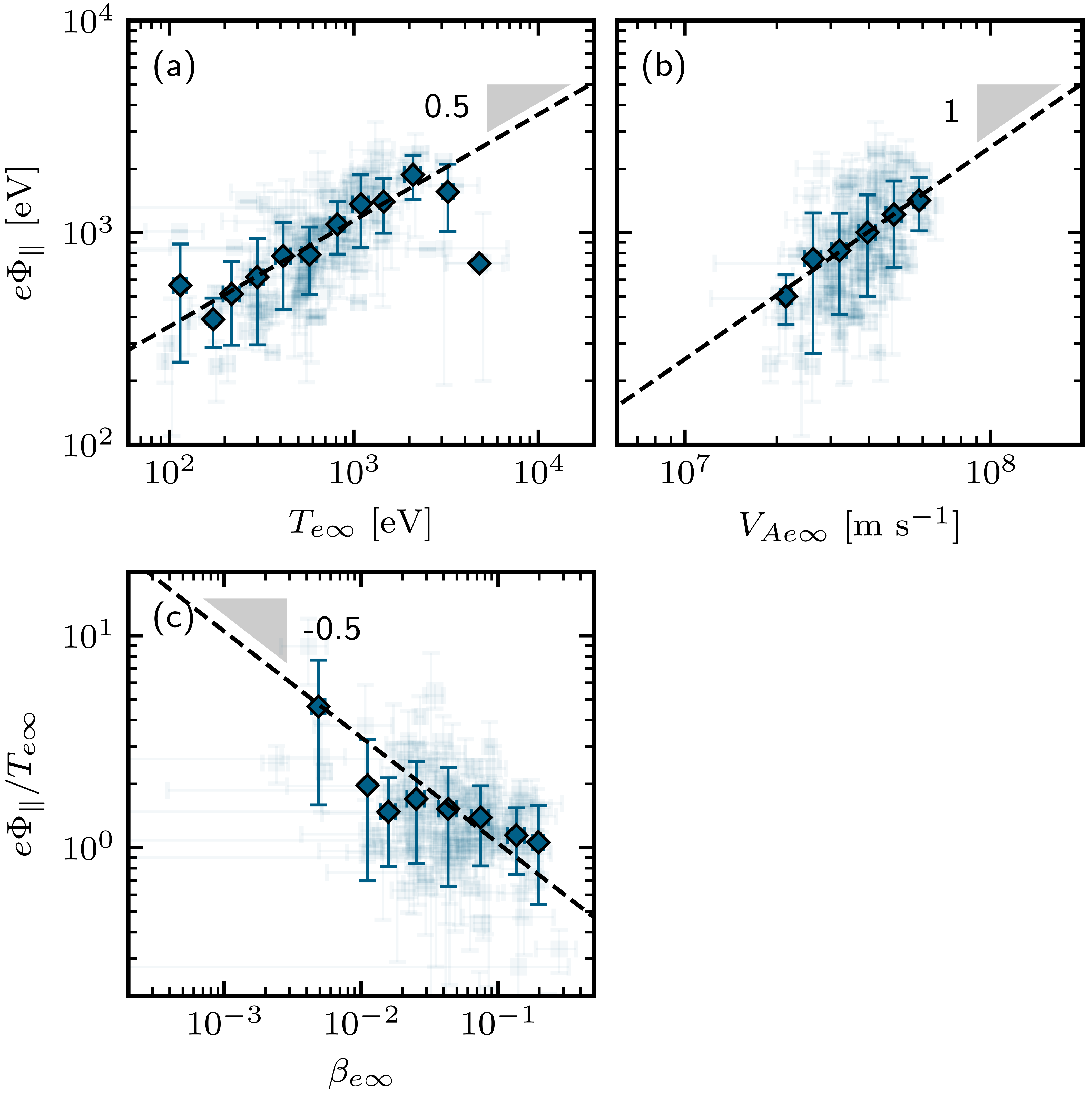
$$\Delta T_i = \alpha_{i1} m_i V_{Ai\infty}^2 - 2\alpha_{i2} e\Phi_{\parallel}$$



Results

[Richard+2025, PRL]

Role of $E_{\|}$ in the energy partition

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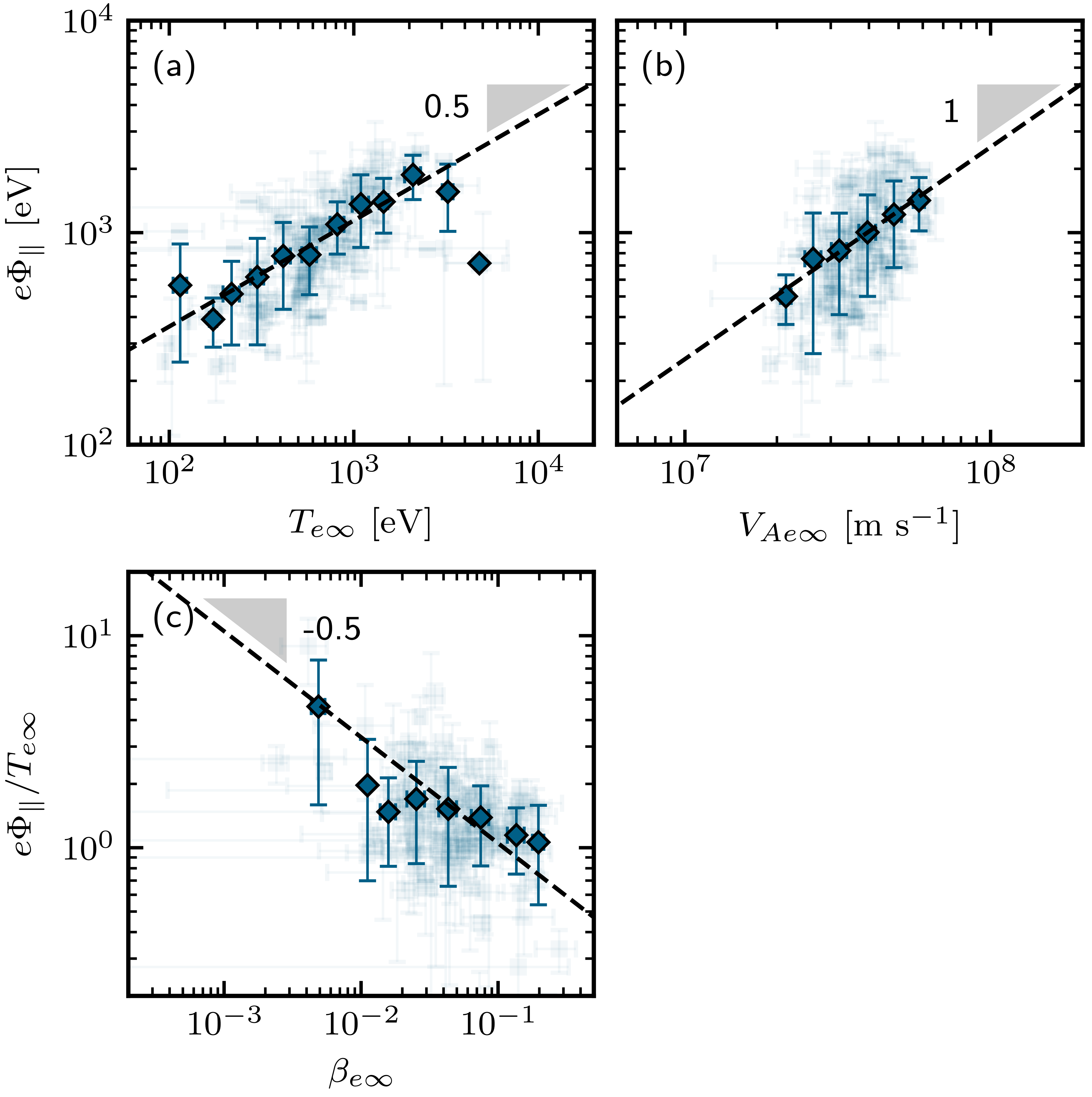
$$\Delta T_i = \alpha_{i1} m_i V_{Ai\infty}^2 - 2\alpha_{i2} e\Phi_{\|}$$

- Empirical model for the ion-to-electron energy partition

$$\frac{\Delta T_i}{\Delta T_e} = \frac{\alpha_{i1}}{\alpha_e}\left(1 - \frac{\alpha_{i2}\alpha_{\Phi}}{\alpha_{i1}}\sqrt{\beta_{e\infty}}\right)$$



Results

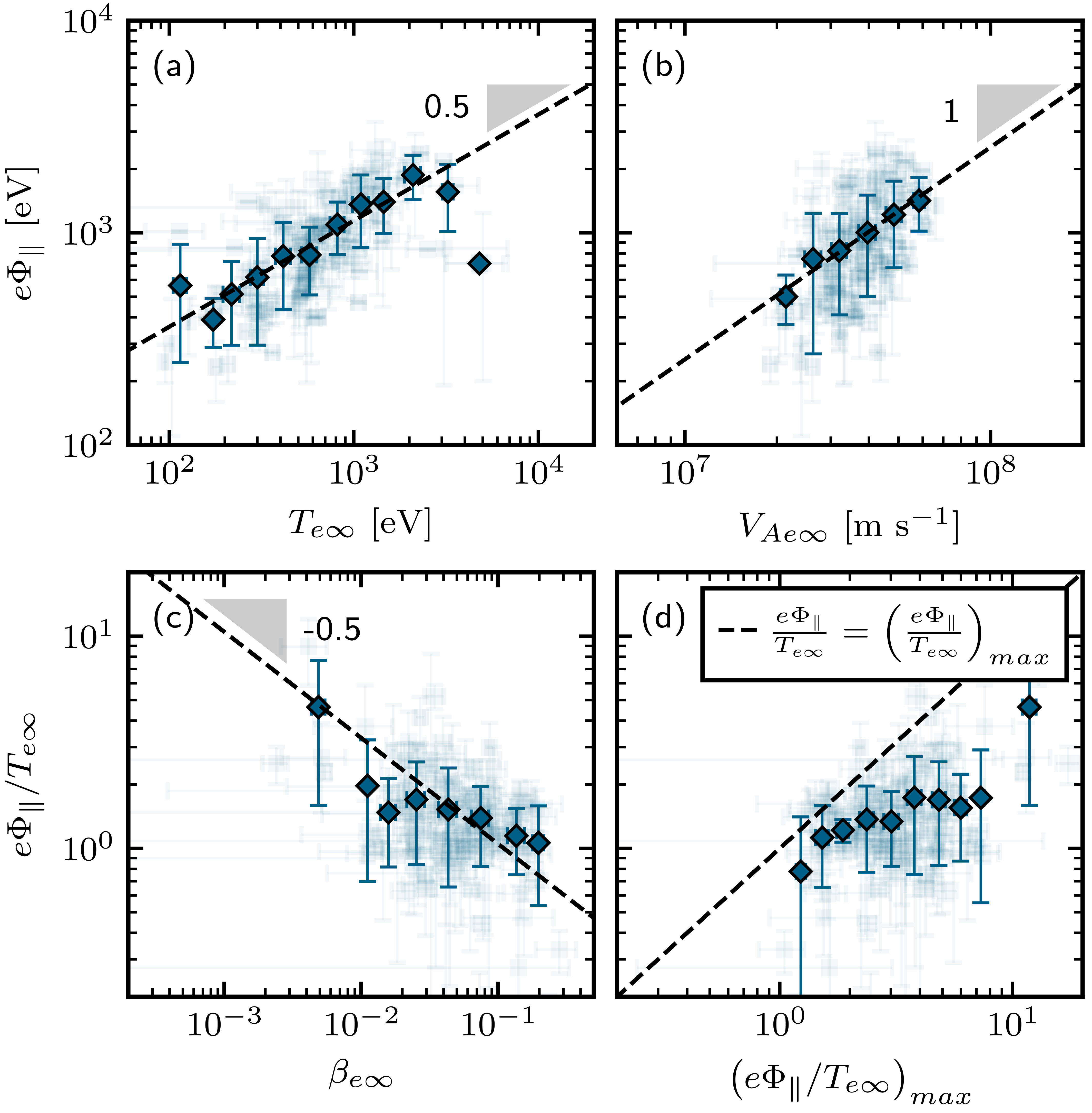
Statistics

[Richard+2025, PRL]

- Fluid firehose stability condition ($p_{\parallel} - p_{\perp} < B^2/2\mu_0$) for the entire CS requires [Le et al., 2009, 2010].

$$\left(\frac{e\Phi_{\parallel}}{T_{e\infty}}\right)_{max} \approx \frac{1}{2}\left[\left(\frac{4\tilde{n}}{\beta_{e\infty}}\right)^{1/4} - \frac{1}{2}\right]^2$$

$e\Phi_{\parallel} \ll (e\Phi_{\parallel})_{max}$ suggesting that parallel electric fields cannot produce too large electron pressure anisotropy.



Conclusions

- What is the nature of the parallel electric fields in magnetic reconnection?
  - The field-aligned ambipolar electric field is primarily due to electron density gradients.
- What is the role of the parallel electric fields in magnetic reconnection?
  - The acceleration potential scales with inflow temperature and Alfvén speed to maintain quasi-neutrality.

Conclusions

FEATURED IN PHYSICS | EDITORS' SUGGESTION

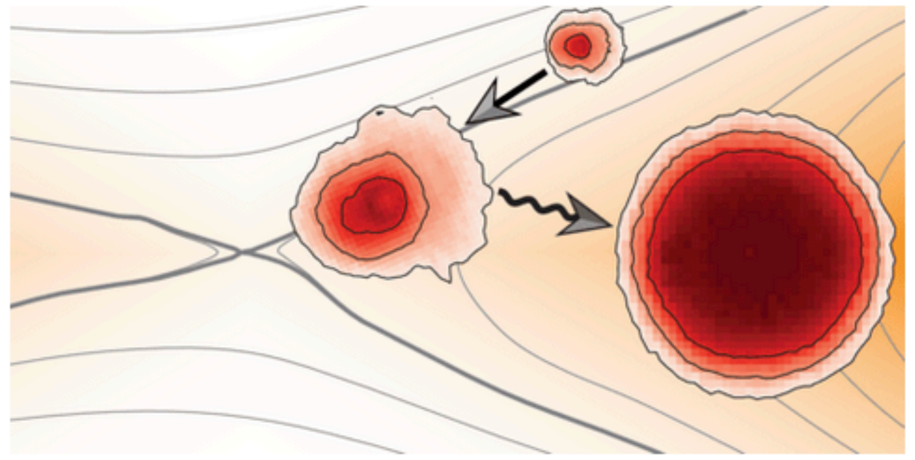
Electron Heating by Parallel Electric Fields in Magnetotail Reconnection

Louis Richard, Yuri V. Khotyaintsev, Cecilia Norgren, Konrad Steinvall, Daniel B. Graham, Jan Egedal, Andris Vaivads, and Rumi Nakamura

Phys. Rev. Lett. **134**, 215201 (2025) - Published 28 May, 2025

An analysis using unprecedented satellite observations reveals important information about how electrons get heated throughout the Universe.

Physics **VIEWPOINT**



How Magnetic Reconnection Jolts Electrons

Published 28 May, 2025

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