EGU General Assembly 2022, 23/05

UCL

Local Emission of Whistler Waves by Landau Resonance As a Signature of a Converging Magnetic Hole

Joe Wence Jiang (蒋文策)[1,2,3], Daniel Verscharen[3], Hui Li (李晖)[1,2], Chi Wang (王赤)[1,2] and Kristopher G. Klein[4]

1. State Key Laboratory of Space Weather, National Space Science Center, Beijing , China
2. University of Chinese Academy of Sciences, Beijing, China
3. Mullard Space Science Laboratory, University College London, UK
4. Department of Planetary Sciences, University of Arizona, USA

@JoeWChiang

Email: joe.jiang@ucl.ac.uk

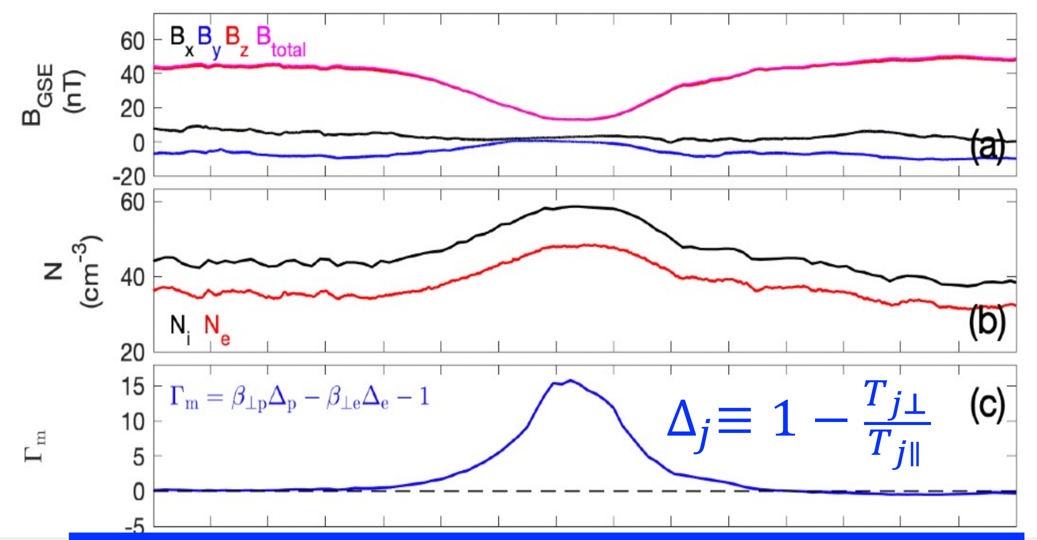
Acknowledgment: Dr. Wenya Li, Dr. Yong Ren, Dr. Seong-Yeop Jeong and Xingyu Zhu

What is the origin of magnetic holes?

- Candidates: **mirror-mode instability,** nonlinear Alfvén waves, solitons, decaying turbulence …
- In Earth's magnetosheath: **high-Mach** and **quasi-perpendicular** shock favors the growth (e.g., Soucek et al. 2015)

Baumgärtel [1999]; Li et al. [2016]; Tsurutani et al. [2002]; Haynes et al. [2015]

Mirror-mode instability



$$\Delta_j \equiv 1 - \frac{T_{j\perp}}{T_{j\parallel}}$$

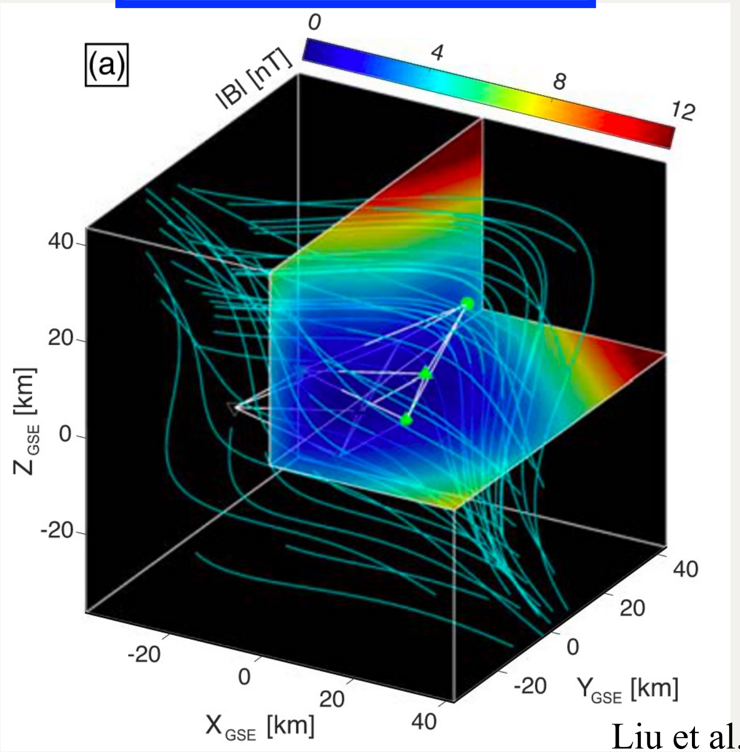
$$\gamma \simeq -\frac{|k_\parallel| v_A}{R_p^2 \sqrt{\pi \beta_{\parallel p}}}(1 - \beta_{\perp p}\Delta_p - \beta_{\perp e}\Delta_e)$$

$$\Gamma_m = \beta_{\perp p}\Delta_p - \beta_{\perp e}\Delta_e - 1 \begin{cases} \Gamma_m > 0: \text{growing} \\ \Gamma_m < 0: \text{damping} \end{cases}$$

Verscharen et al. [2017]

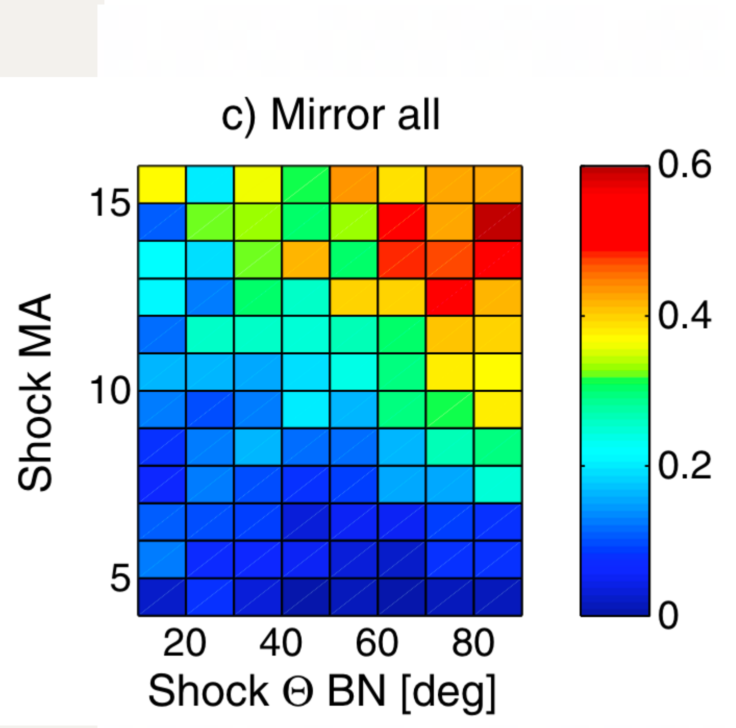
Quasi-steady structure

$$t_{trap} \ll {}^{1}/_{\gamma_m}$$



Liu et al. [2020]

Magnetosheath



Soucek et al. [2015]

What is the evolution of magnetic holes?

- **In velocity space, particles response to the field and structure variations differently:**

a) Betatron effect with slow temporal variation of field:

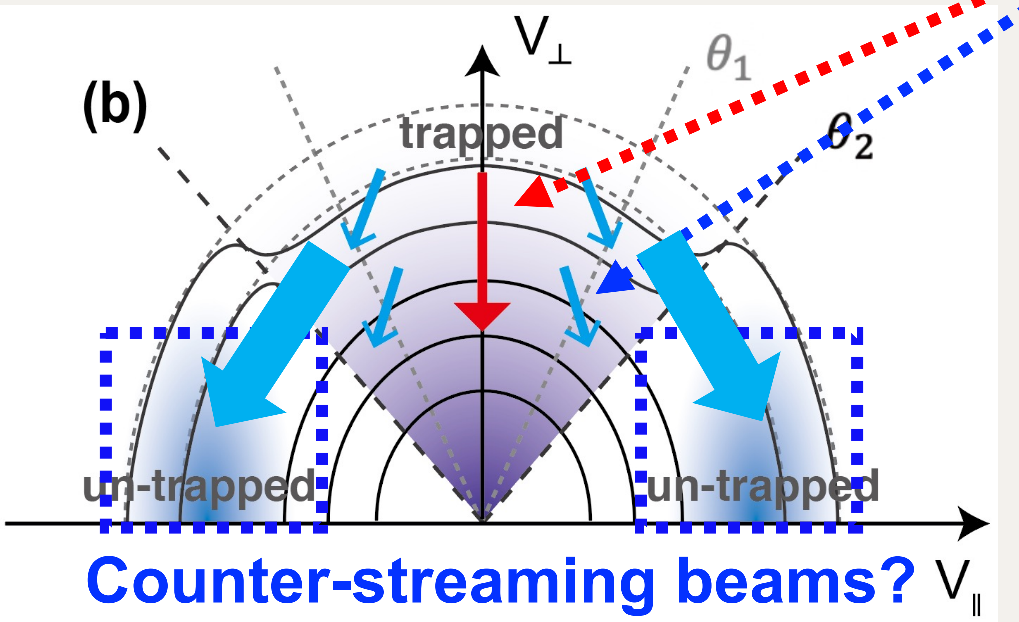
$$\frac{d\mu}{dt} \equiv 0 \rightarrow \frac{dv_\perp}{dt} = \frac{v_\perp}{2B}\frac{dB}{dt} < 0 \rightarrow v_\perp \textbf{ decreases}$$

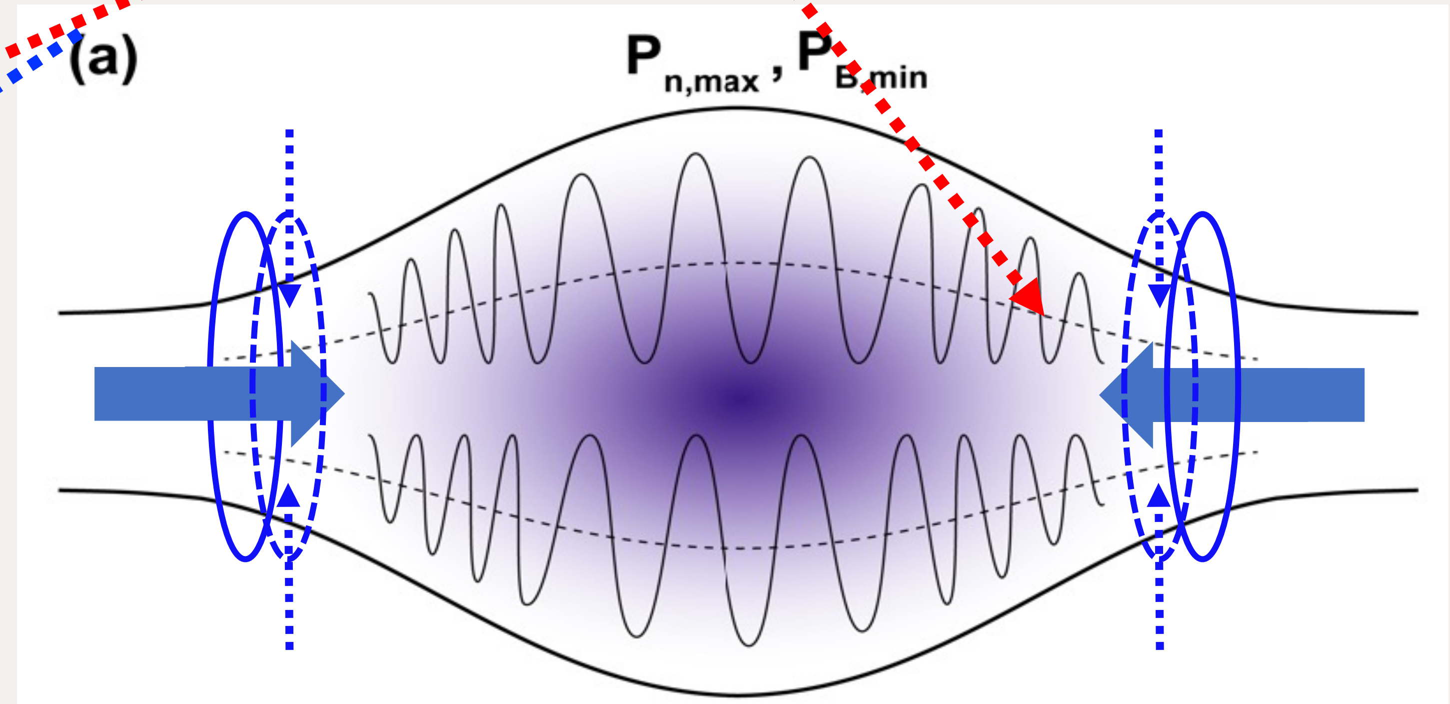
Southwood&Kivelson [1993]
Kilvelson&Southwood [1996]

b) Fermi effects possibly due to structural convergence:

✓ Mirror points moving apart → $v_\parallel$ decreases

✓ Mirror points moving together → $v_\parallel$ **increases**



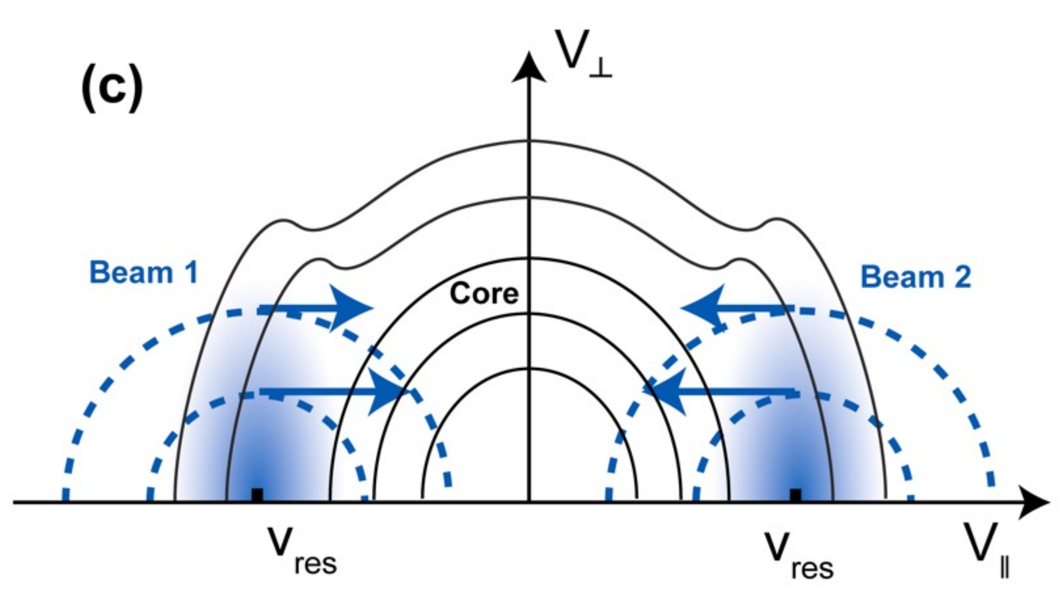


What is the evolution of magnetic holes?

- In velocity space, the energy of electrons changes due to betatron and fermi effects → **electron kinetic instabilities to grow?**
- Final stage of magnetic holes? **Kinetic evolution?**

Counter-streaming beams?

After betatron cooling + Fermi acceleration



Quasi-linear diffusion via Landau resonant wave-particle

$$\frac{\partial f_e}{\partial t} = \frac{q_e^2}{8\pi^2 m_e^2 V}\int \left(\frac{k_\parallel}{\omega_w}\right)^2 \tilde{G}\frac{1}{|v_\parallel|}\delta(\omega_w - k_\parallel v_\parallel)|\psi^*|^2 \tilde{G} f_e d^3k,$$

$$\frac{\partial f_e}{\partial t} \sim v_\parallel \frac{\partial}{\partial v_\parallel}\left(\nu_d v_\parallel \frac{\partial f}{\partial v_\parallel}\right)$$

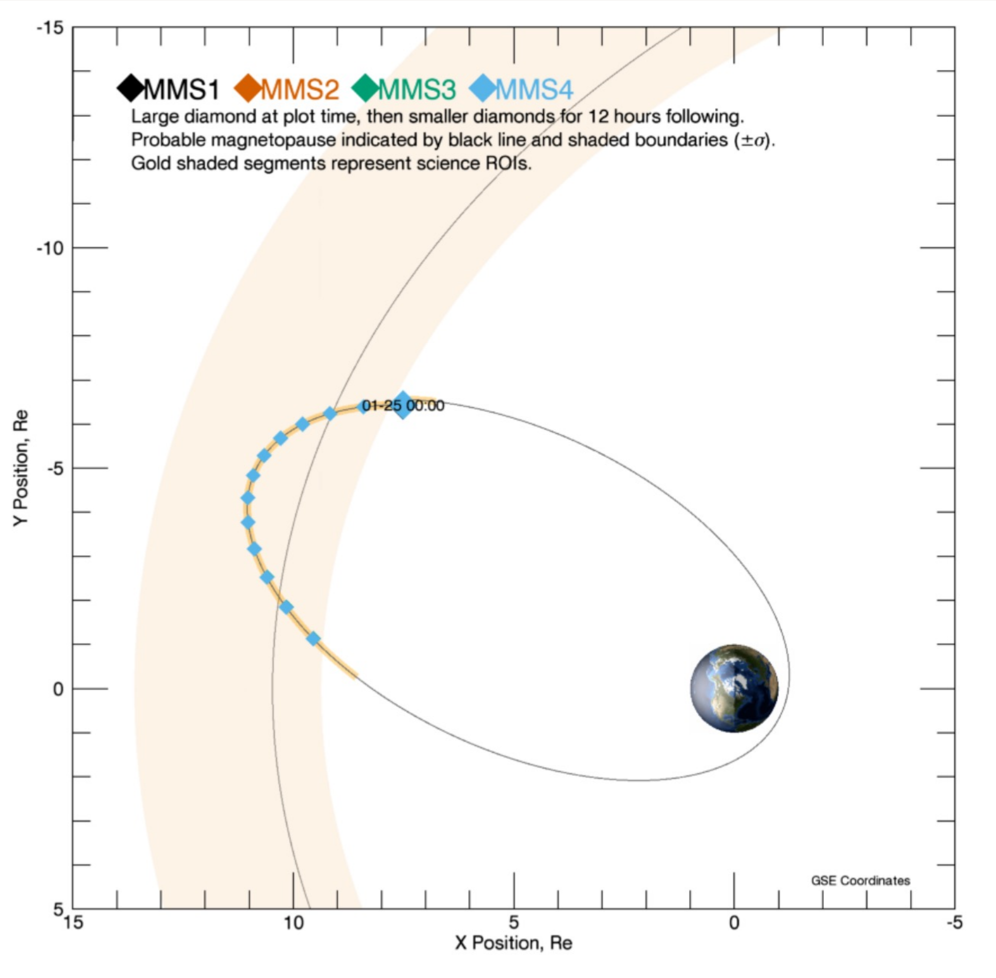
Multi-scale process?

$$\gamma_m \ll \nu_d \lesssim {}^{1}/_{\tau_t} \ll \gamma_w \ll \omega_w$$

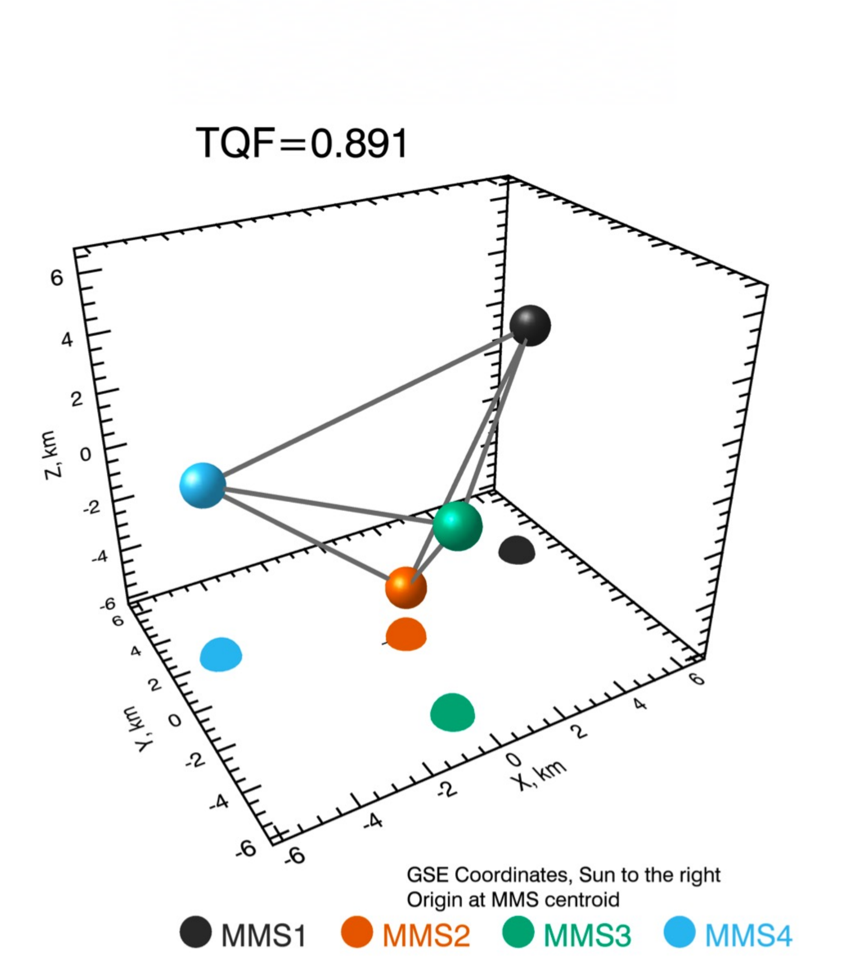
γ_m	ν_d	$1/\tau_t$	γ_w	ω_w
mirror-mode growth	Wave-particle diffusion	Electron trapping	Whistler waves growth	Freq.

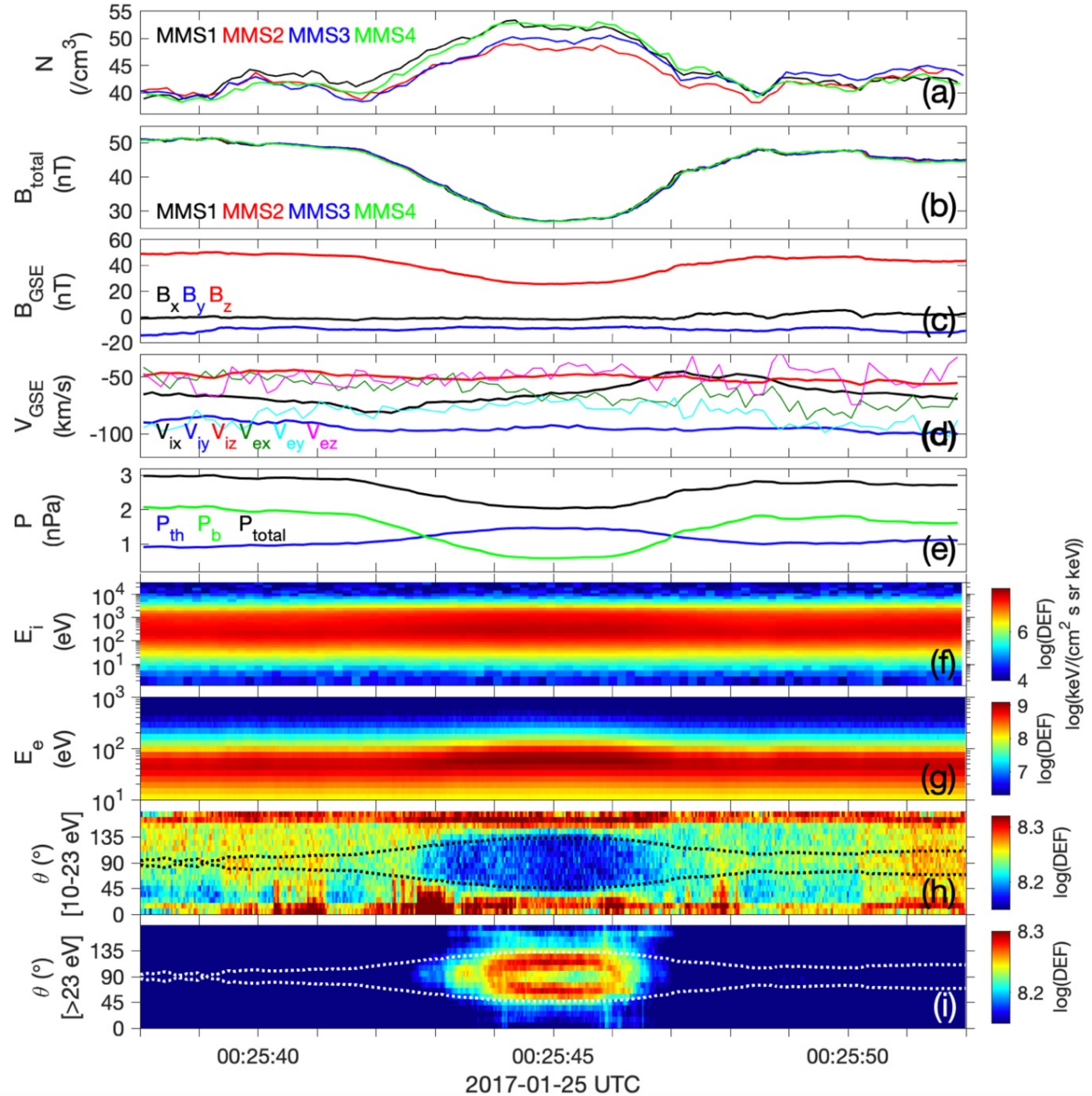
Magnetic hole case: 2017-01-25/00:25:45 ± 5 seconds

- A case near the sub-solar MP

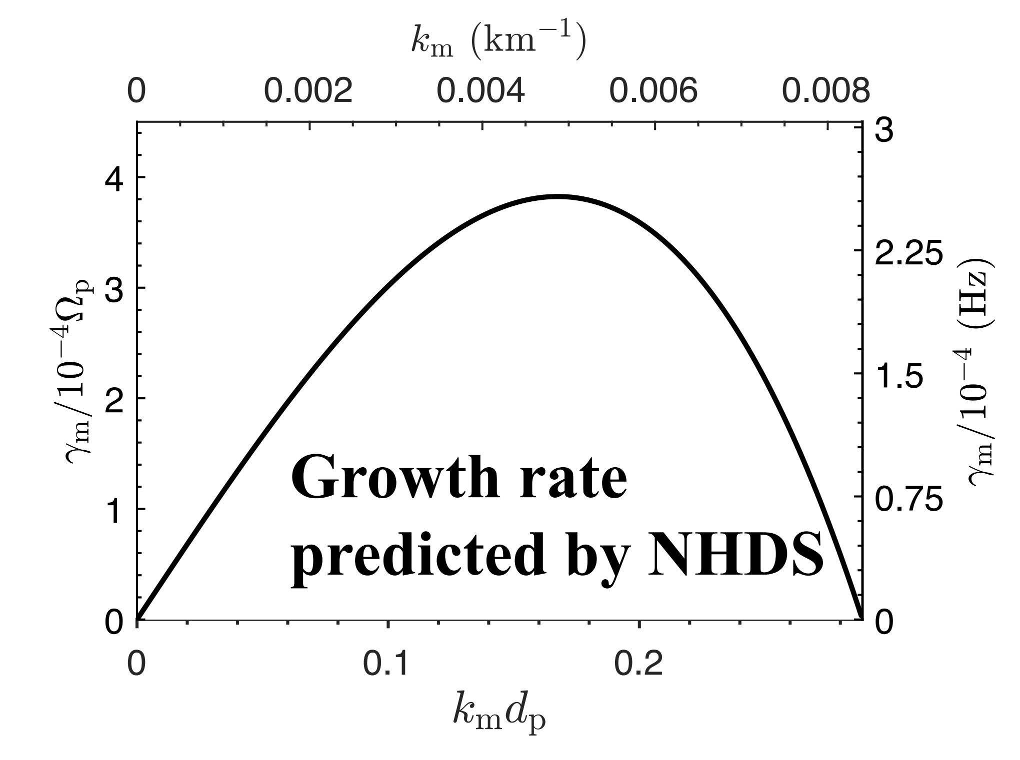


- MMS tetrahedral formation



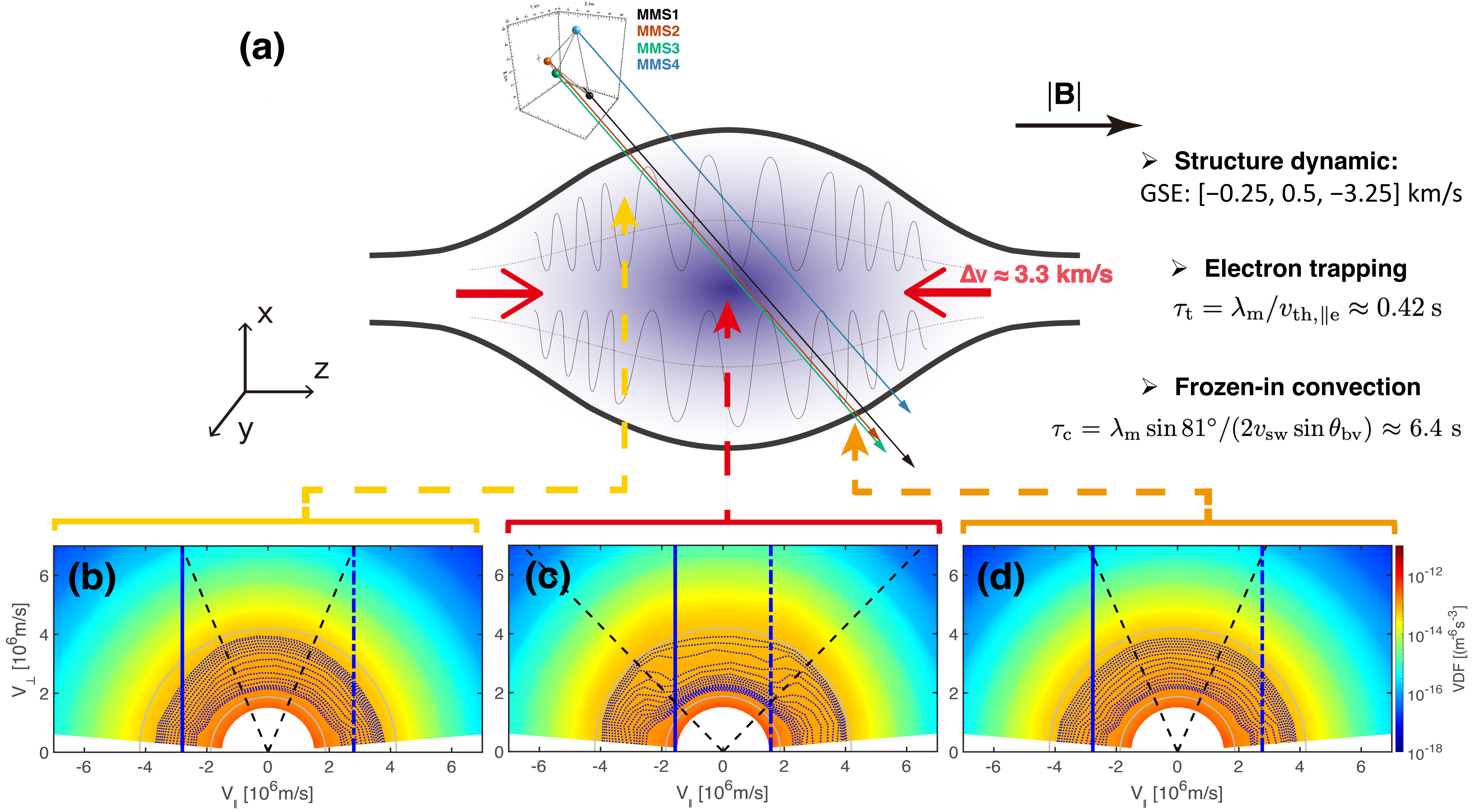


Mirror-mode unstable plasma: slowly decreasing B

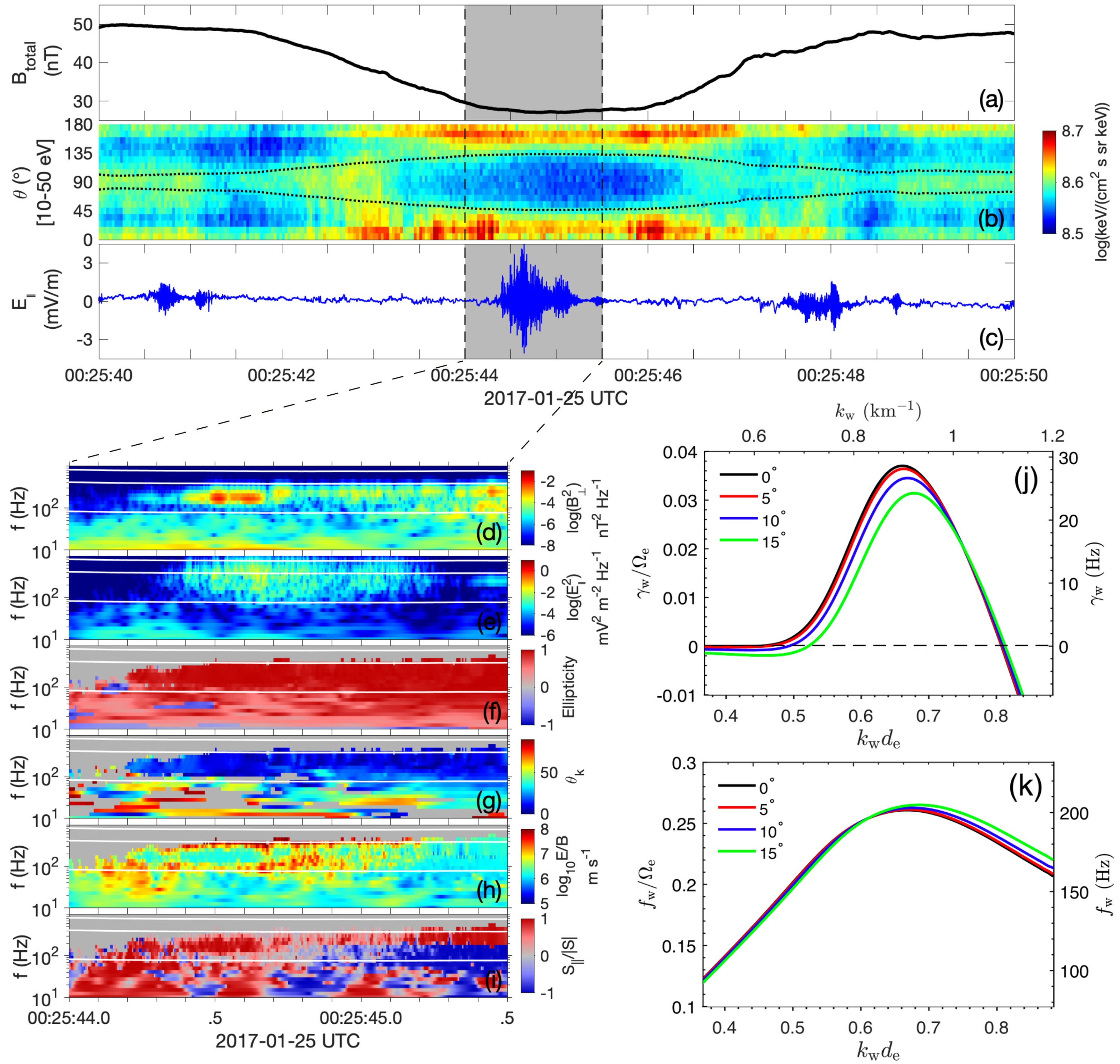


$$\theta_{critical} = \arcsin\left(\sqrt{\frac{|B|}{|B_{max}|}}\right)$$

- Maximum growth rate of 2.6×10^{-4} Hz at k=0.005 km^{-1} ($\lambda = 1257\ km$)



(a)
MMS1
MMS2
MMS3
MMS4
|B|
Structure dynamic:
GSE: [−0.25, 0.5, −3.25] km/s
Δv ≈ 3.3 km/s
Electron trapping
$\tau_t = \lambda_m / v_{th,\parallel e} \approx 0.42$ s
Frozen-in convection
$\tau_c = \lambda_m \sin 81° / (2 v_{sw} \sin\theta_{bv}) \approx 6.4$ s
x
z
y
(b)
(c)
(d)
$V_\perp$ [10^6m/s]
$V_\parallel$ [10^6m/s]
VDF [($m^{-6}s^{-3}$)]



MMS observations

- Enhanced parallel electric field fluctuations $|\delta E_{\parallel}| \sim 3\ mV/m$.
- Enhanced magnetic field fluctuations at $f \sim 203\ Hz$.
- Ellipticity ~1: right-handed polarization.
- Slightly-oblique whistler waves ~10°
- Phase speed: ~ 1.58×10^3 km/s.

Theory predictions

- **Non-Maxwellian VDF model**
- Frequency: ~202 Hz (~$0.26\ \omega_e$).
- Growth rate: 30 Hz
- Phase speed: ~ 1.56×10^3 km/s.
- $k = 0.9\ km^{-1} (\lambda \sim 10\rho_e \sim 0.65 d_e)$

$$\nu_\mathrm{d} \sim \frac{c^2\Omega_\mathrm{e}^2}{2B_0^2}\frac{v_\mathrm{sw}k_\mathrm{w}^3}{\omega_\mathrm{w}^3}\tilde{E}_\parallel^2(\omega_\mathrm{w})\cos\theta_\mathrm{bv} \approx 0.25\mathrm{Hz},$$

A consistent ordering of multi-scale processes in the magnetic hole

$$\gamma_m \ll \nu_d \lesssim {}^{1}/_{\tau_t} \ll \gamma_w \ll \omega_w$$

0.0003 Hz | 0.25 Hz | 2.38 Hz | 30 Hz | 203 Hz

Theory
Observations

- ✓ the maximum growth rate of the mirror-mode instability is $\gamma_m \approx 0.0003$ Hz at a wavelength of ~ 1257 km.
- ✓ the estimated quasi-linear diffusion rate for the Landau resonant wave-particle interaction of electrons is 0.25 Hz.
- ✓ the typical trapping frequency of electrons is 2.38 Hz.
- ✓ the growth rate of the unstable whistler waves is 30 Hz.
- ✓ the frequency of of the unstable whistler waves is about 203 Hz.

Conclusion: resonant wave-particle interactions transfer energy from electrons to waves, lead to isotropic electrons and possibly stabilize the magnetic holes.

More details: https://doi.org/10.21203/rs.3.rs-1485820/v1

UCL

Thank you!

Photo taken at Shoreham-by-sea, England

Any comments or suggestions are welcome: joe.jiang@ucl.ac.uk/jiangwence@swl.ac.cn