2024 IPELS (Garching, Germany)

Recent Observations of Waves in Laboratory Reconnection Experiments

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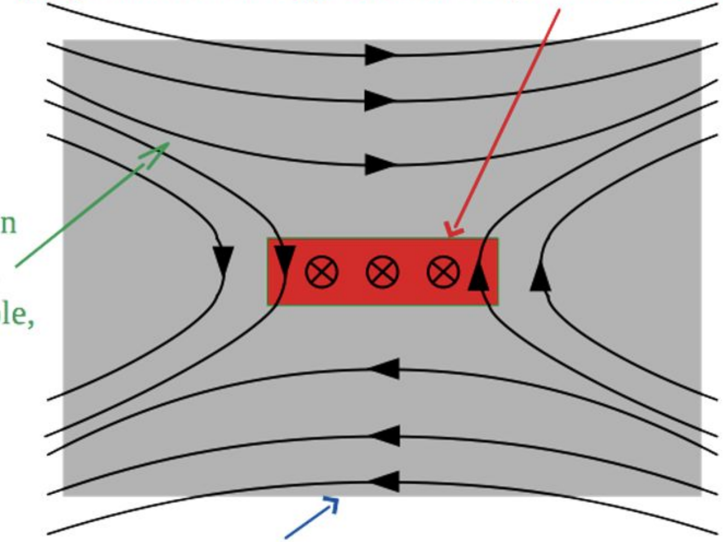
Work supported by NASA-ECIP

Magnetic Reconnection Produces Various Free Energy Sources for Waves and Instabilities



Electron Diffusion Region – Large electron flow velocity (large current density), electron temperature anisotropy

Near Separatrix – electron temperature anisotropy, electron beam, electron hole, pressure gradient

Ion Diffusion Region – Fast ion outflow, ion temperature anisotropy

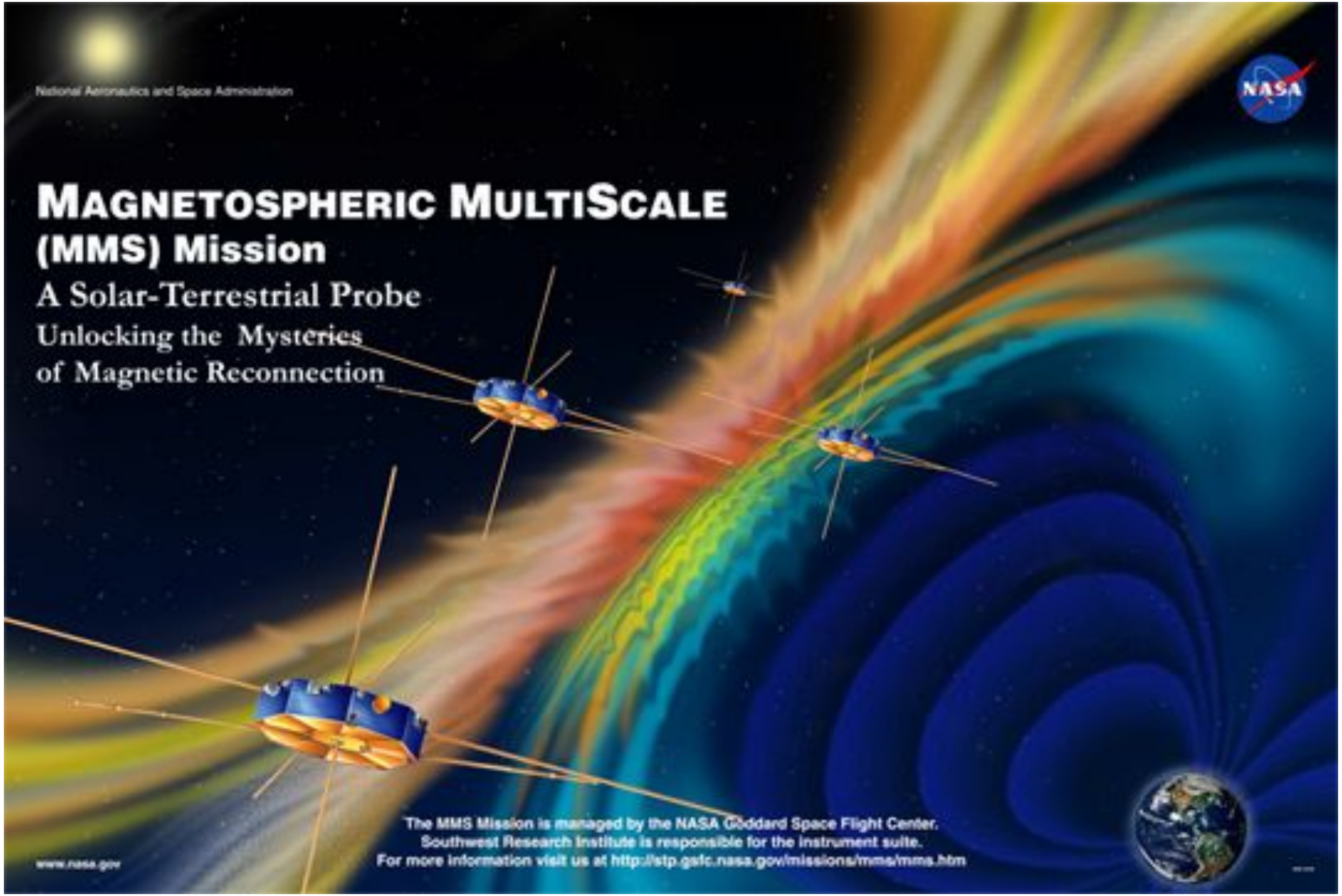
Waves interact with the plasma to reduce the free energy source

Role of Waves in Magnetic Reconnection

$$m_e\left\langle n_e\frac{\partial \boldsymbol{V}_e}{\partial t}\right\rangle-\frac{m_e}{e}\langle\boldsymbol{J}_e\rangle\cdot\nabla\langle\boldsymbol{V}_e\rangle+e\langle n_e\rangle\langle\boldsymbol{E}\rangle-\langle\boldsymbol{J}_e\rangle\times\langle\boldsymbol{B}\rangle$$
$$=-\nabla\cdot\langle\boldsymbol{P}_e\rangle-e\langle\delta n_e\delta\boldsymbol{E}\rangle+\langle\delta\boldsymbol{J}_e\times\delta\boldsymbol{B}\rangle+\frac{m_e}{e}\langle\delta\boldsymbol{J}_e\cdot\nabla\delta\boldsymbol{V}_e\rangle.$$

- Waves may impact both reconnection and electron dynamics by producing fluctuations in fields and plasma parameters.
- The effects of fluctuations on the reconnection dynamics can be quantified through the last three terms.
  - $\langle\delta n_e\,\delta\boldsymbol{E}\rangle$ is the anomalous resistivity (drag) term.
  - Other terms can be classified as anomalous viscosity and Reynold's stress.
- Waves can also affect heating, transport, and relaxation processes in plasma via wave-particle interactions.

NASA’s Magnetospheric Multiscale (MMS) Mission



National Aeronautics and Space Administration

MAGNETOSPHERIC MULTISCALE (MMS) Mission

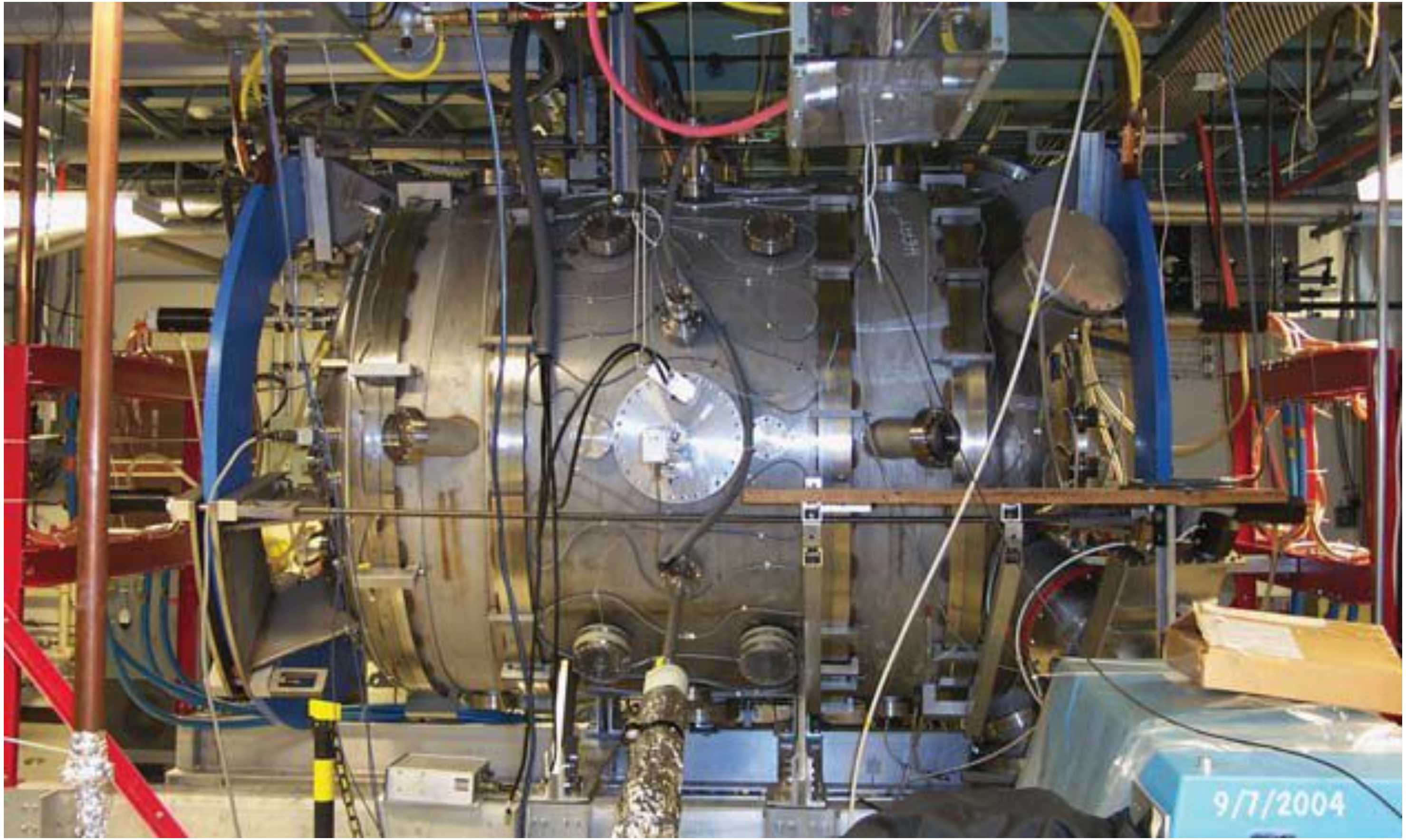
A Solar-Terrestrial Probe

Unlocking the Mysteries of Magnetic Reconnection

The MMS Mission is managed by the NASA Goddard Space Flight Center.
Southwest Research Institute is responsible for the instrument suite.
For more information visit us at http://stp.gsfc.nasa.gov/missions/mms/mms.htm

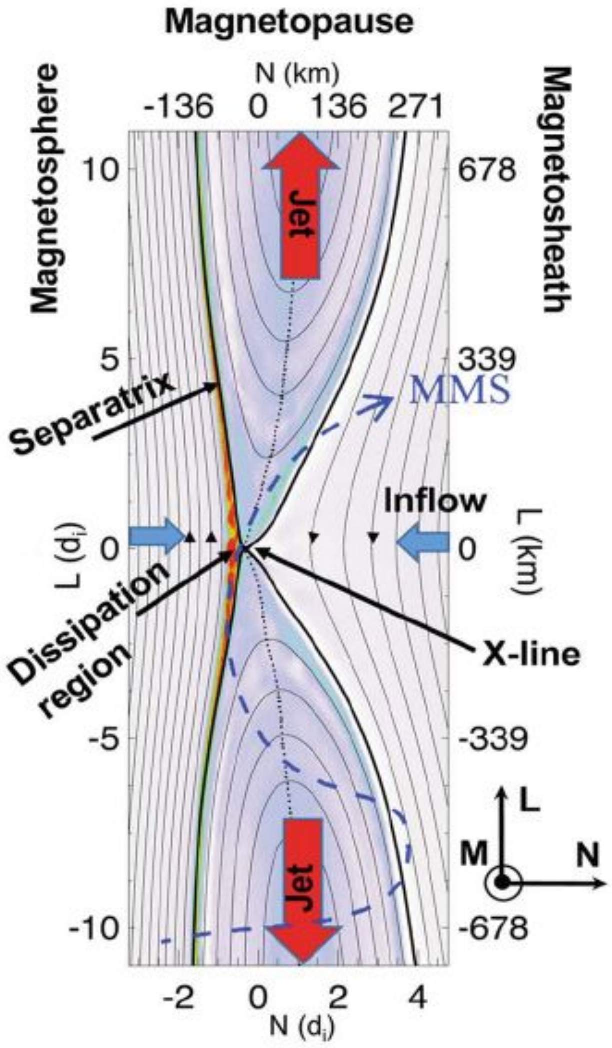
www.nasa.gov

Magnetic Reconnection Experiment (MRX)



Outline

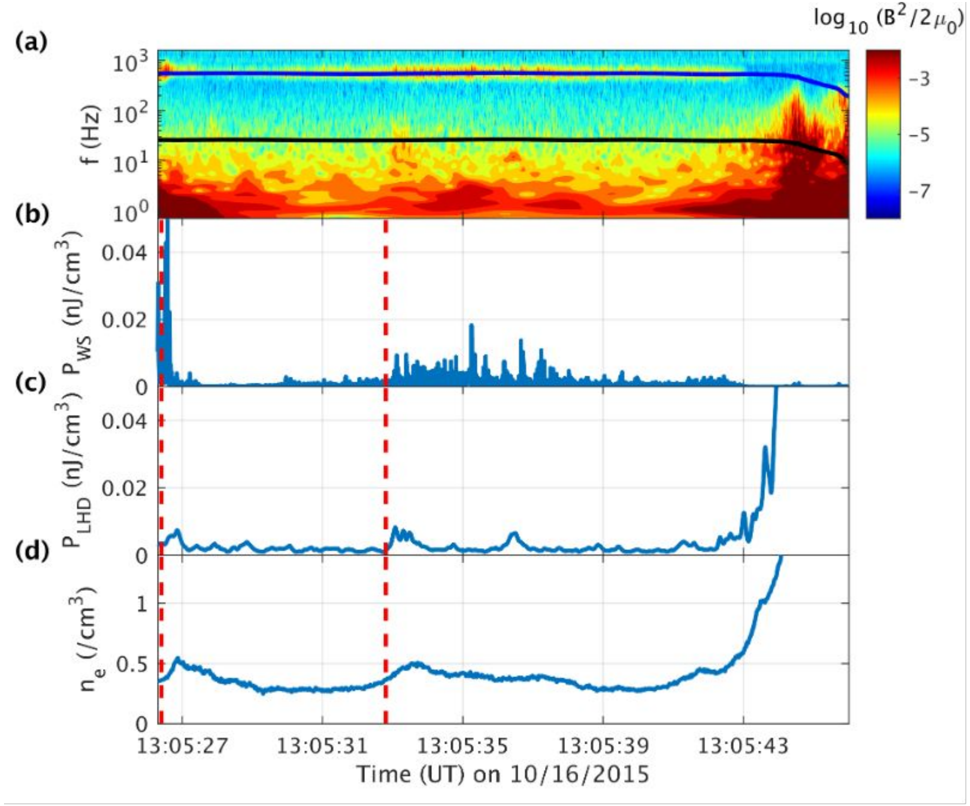
1. Anisotropy-driven whistler waves near the low-density side separatrix.
    a. MMS observations
    b. Similar observations in MRX
2. Lower hybrid drift waves in the electron diffusion region of reconnection with guide field
    a. MMS observations inside a reconnecting current sheet
    b. MRX observations inside the electron diffusion region.
3. Ion acoustic waves during laser-driven reconnection
    a. Talk by H. Ji on Monday
4. Possible wave projects in Facility for Laboratory Reconnection Experiments (FLARE)

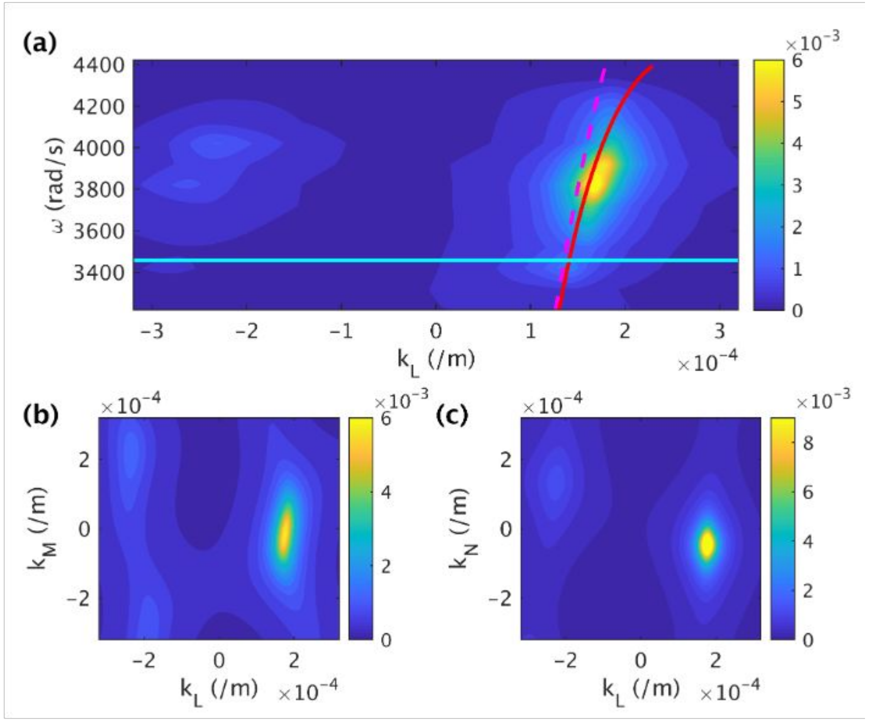


Overview of MMS Event of Burch *et al.* 2016

- The dashed line is a suggested path of MMS, based on comparison of measured plasma and field profiles with those from a 2D simulation.
- Whistler waves were observed when MMS stayed near the low-density side separatrix.
- There are many observations of whistler waves.
  - The propagation direction is case by case.

MMS Observation of Anisotropy-driven Whistler



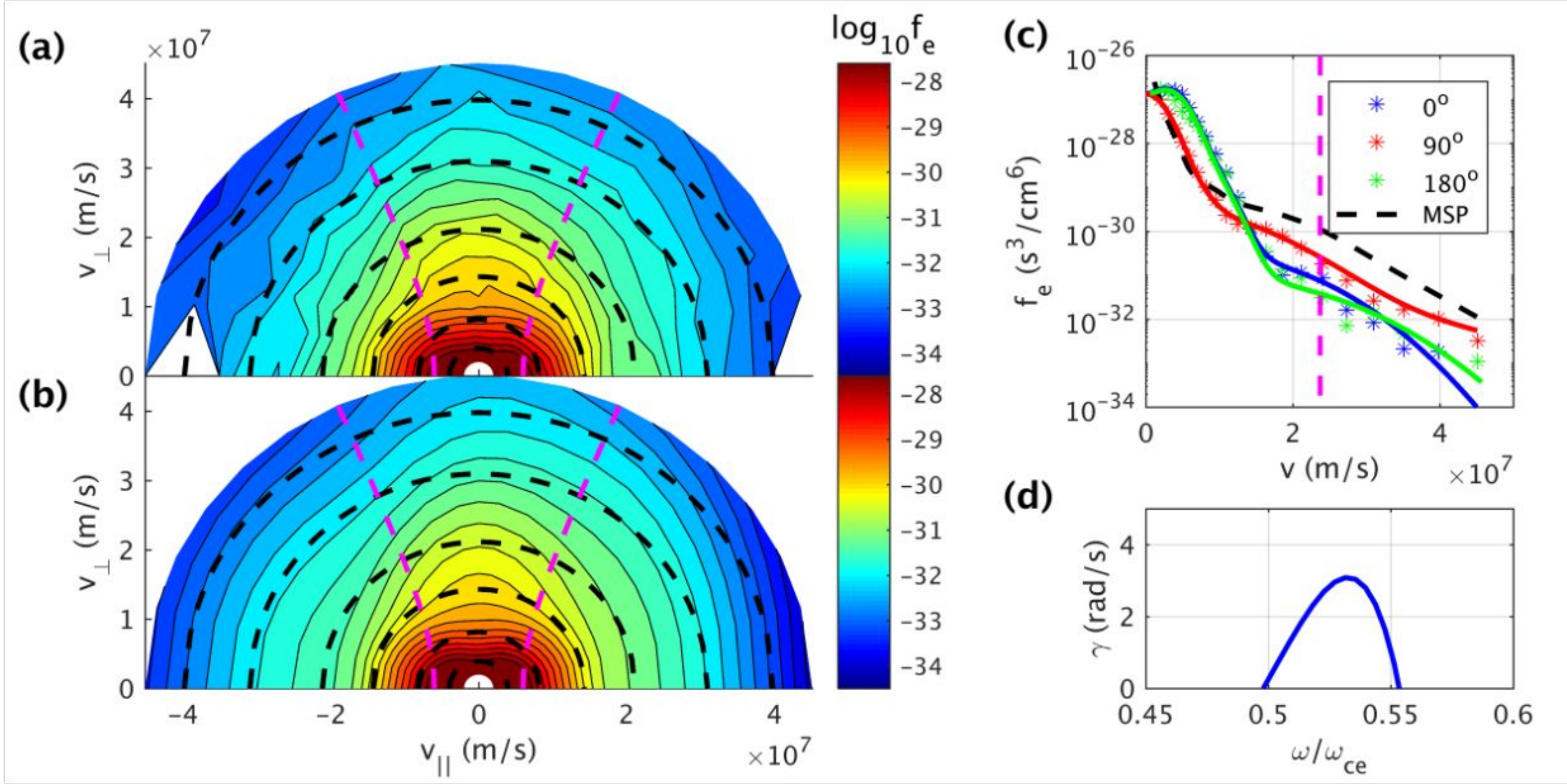


Yoo *et al.* 2018 and 2019

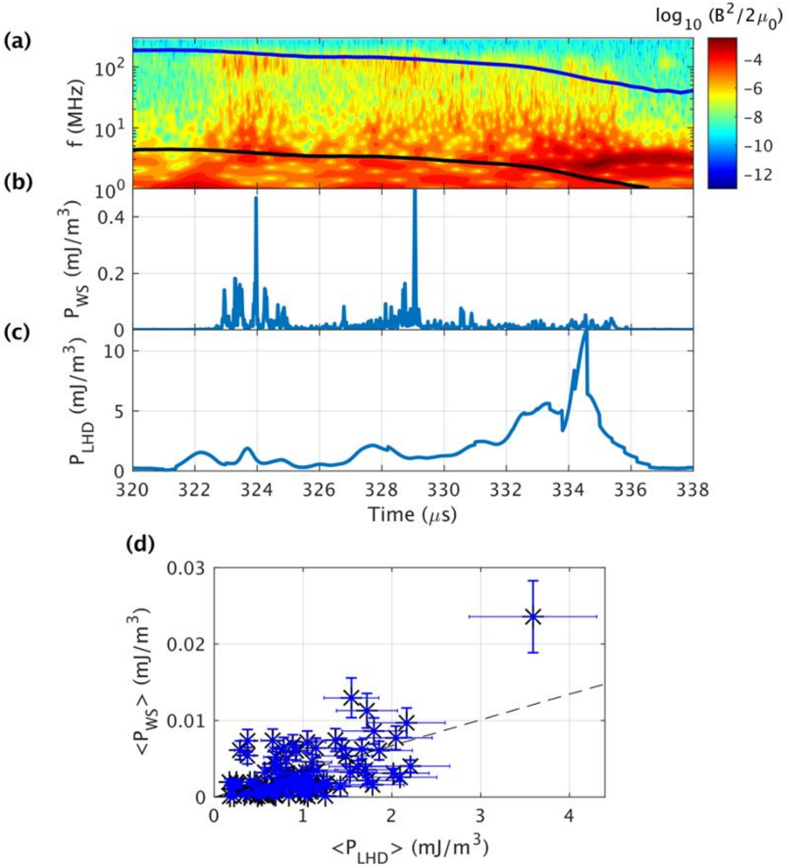
Physics of Anisotropy-driven Whistler Waves

- Whistlers are generated by electrons at a parallel resonant velocity (V_{res}):
  - $\omega - V_{res}k_{||} = \omega_{ce}$.
  - Cold plasma dispersion: $kd_e = [\omega/(\omega_{ce}\cos\theta-\omega)]0.5$.
  - With $\theta = 0$ and $k_{||}>0$, the cold plasma dispersion gives us:
  - $V_{res} = - V_{Ae}(1 - \omega/\omega_{ce})^{1.5}(\omega/\omega_{ce})^{-0.5}$.
  - At $\omega = 0.5\omega_{ce}$, $V_{res} = -0.5V_{Ae}$.
- Under usual conditions in the magnetosphere, the resonance velocity is much larger than v_{the}.
- For a double-Gaussian distribution, $T_{\perp} > T_{||}$ in the tail is the necessary condition for whistler generation [Kennel and Petschek, 1996].

Linear Analysis Agrees with Measurements

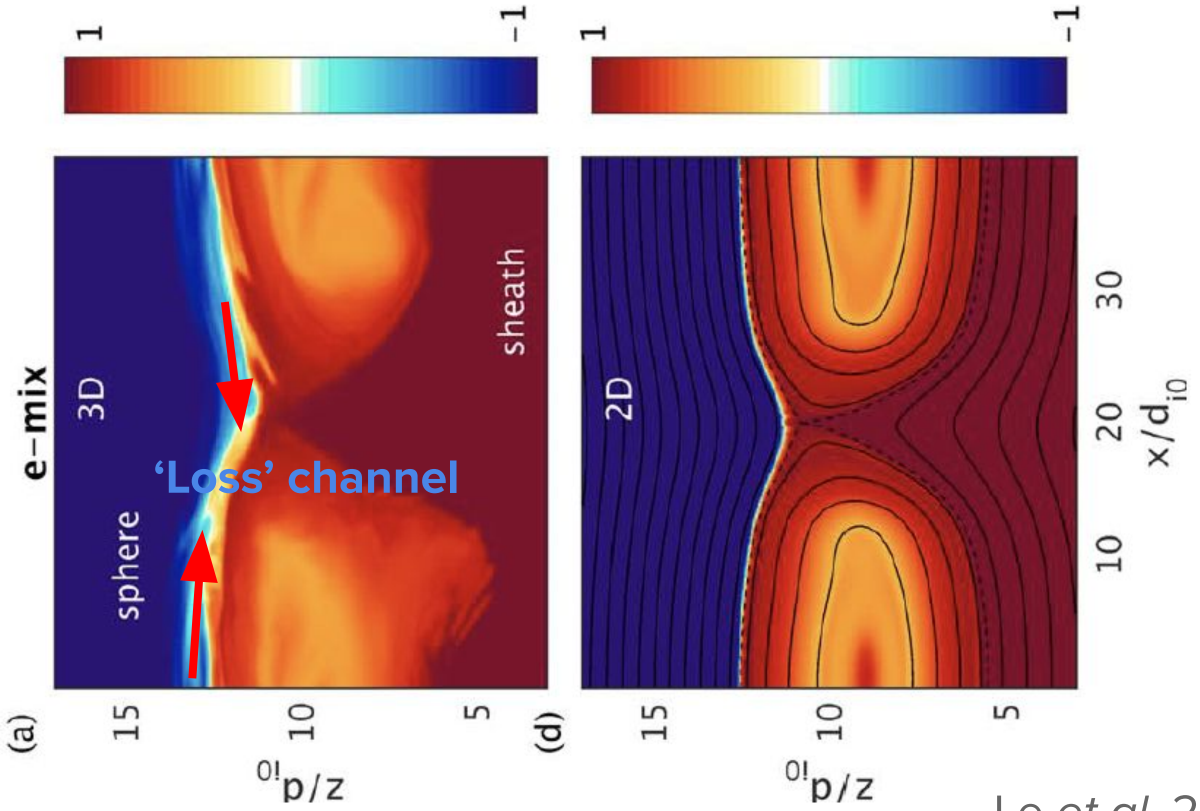


Similar Observations of Whistler Waves in MRX



- Whistler waves near the low-density side separatrix in MRX.
  - ○ $f \sim 0.5\, f_{ce}$.
- Similar to space observations, you also see increased activities of LHDI at similar times.

LHDI-driven Mixing may Explain Observed Features



‘Loss’ channel

- We have observed:
    - Local density increase by particles coming from the exhaust.
    - Loss of electrons with a high parallel velocity.
    - Enhanced LHDI power.
- Electrons with a dominant parallel velocity are ‘lost’ to the exhaust first through the ‘mixing’ zone by LHDI turbulence.

Le *et al.* 2017

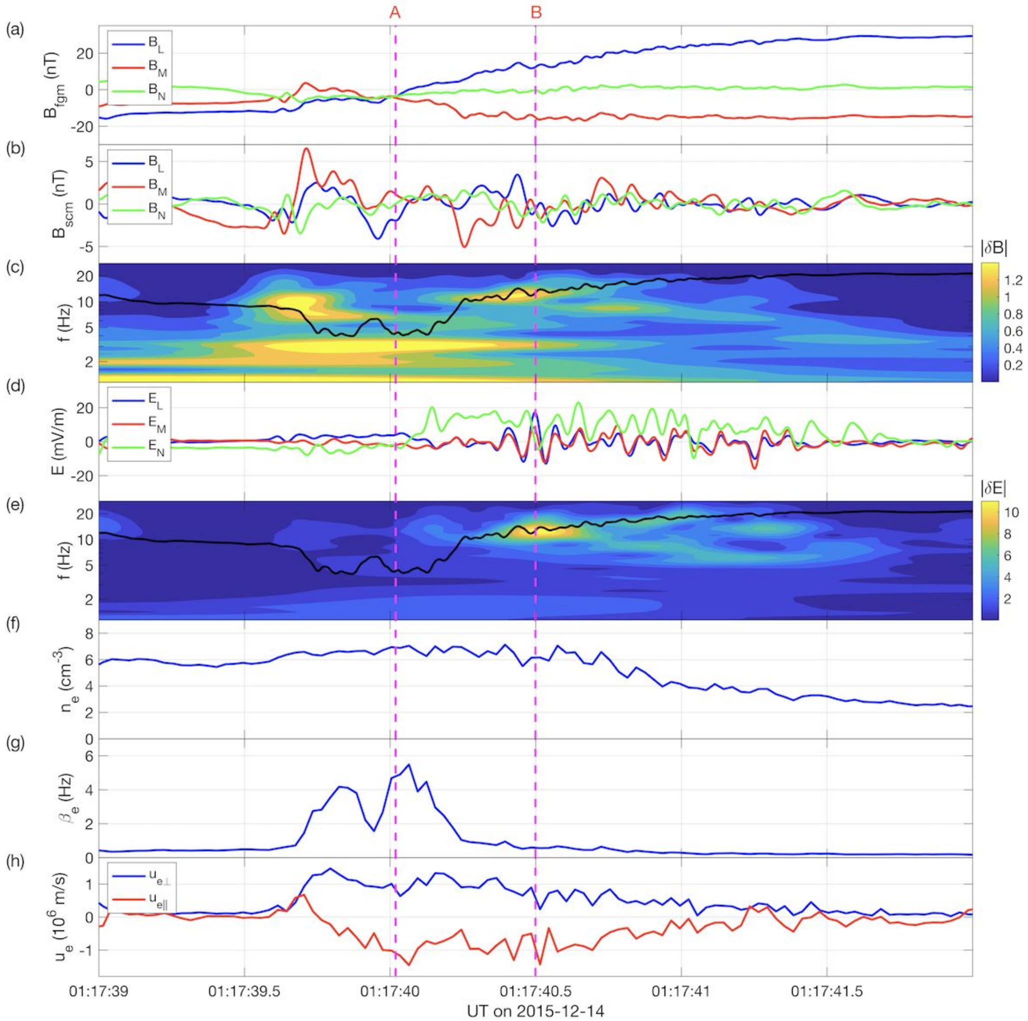
Brief Overview of Lower Hybrid Drift Waves (LHDW) during Magnetic Reconnection

- Free energy source - current perpendicular to **B**, associated with pressure gradients.
- Fast-growing, quasi-electrostatic LHDW (e.g. Davidson et al. 1977) - ES-LHDW (low β_e)
  - Propagating perpendicular to **B**.
  - Characterized by large electric field fluctuations.
  - Observed away from the electron diffusion region. (e.g. Carter et al. 2001, Roytershteyn et al. 2012).
  - Associated with lower hybrid drift instability near the low-density side separatrix. (e.g. Yoo et al. 2014, 2017).
- Electromagnetic LHDW - EM-LHDW (high β_e)
  - Propagating obliquely to **B**.
  - Characterized by magnetic field fluctuations.
  - Observed in the electron diffusion region. (e.g. Ji et al. 2004, Roytershteyn et al. 2012).
  - Concluded that it does not play an important role in supporting reconnection electric field under typical magnetospheric parameters (Roytershteyn et al. 2012).
- These two waves is the same mode with different characteristics.
  - Wave characteristics depend on β_e and the relative drift velocity between electrons and ions.

Why Revisit LHDW?

- With a guide field, the ES-LHDW may exist inside the current sheet since the guide field decreases β.
- Recent space observations show that ES-LHDW can impact on electron dynamics in the current sheet (L.-J. Chen *et al.* 2020 *Phys. Rev. Lett.*, J. Yoo *et al.* 2020 *Geophys. Res. Lett.*, Graham *et al.* 2019 and 2022).
  - Non-gyrotropic electron heating and vortical flows
  - Capable of generating anomalous resistivity (momentum transfer) - $\langle \delta n_e \delta E_{rec} \rangle / n_{e0}$

Lower Hybrid Drift Wave in Space



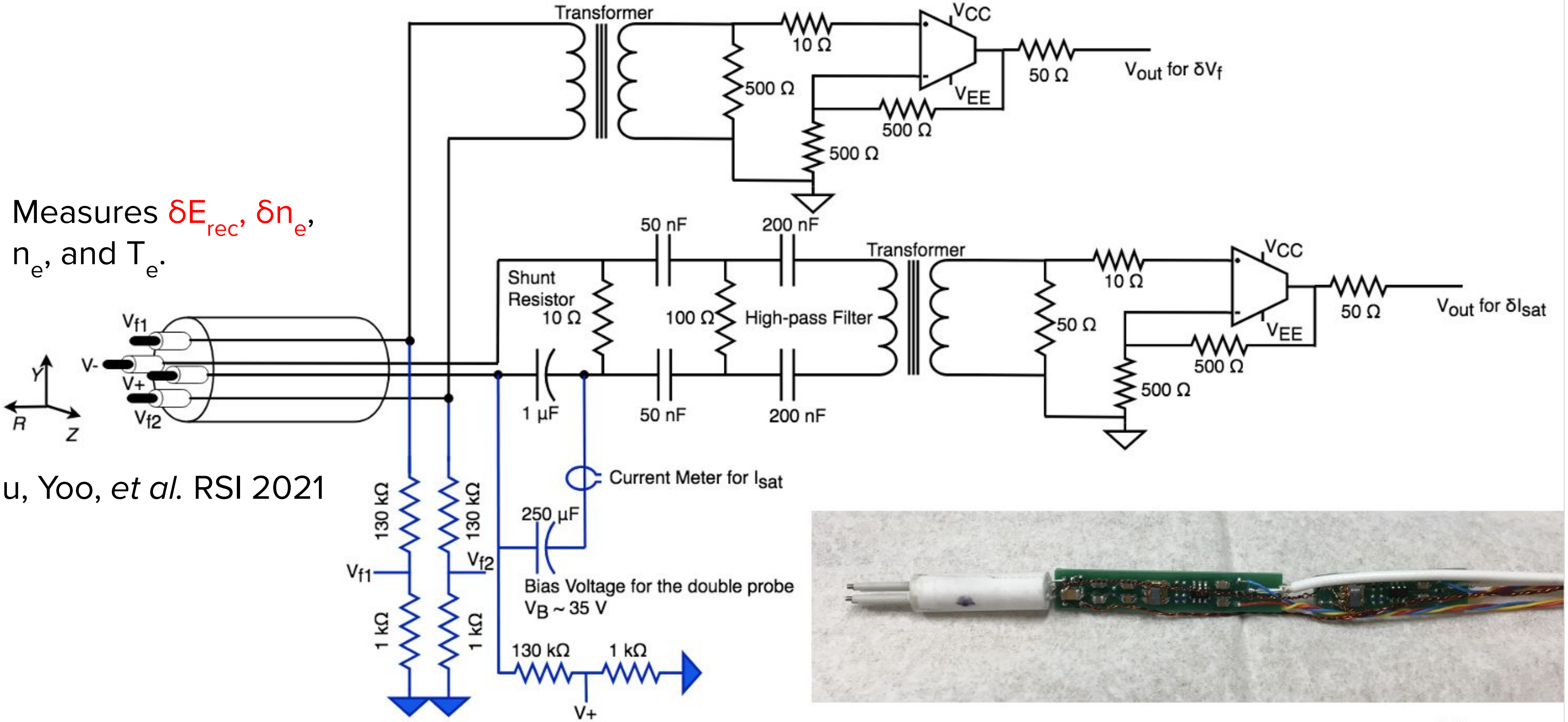
- Observed by MMS at the magnetopause (Ergun et al. 2017, Chen et al. 2017).
- $B_g \sim 0.5B_{rec}$.
- The density ratio across the current sheet is about 3.
- Region A (electron diffusion region)
  - fluctuations in **B**.
- Region B (inside the current sheet)
  - Strong fluctuations in **E** and n_e.
  - $k\rho_e \sim 0.7$.
  - Propagating almost perpendicular to **B**.

Yoo, *et al. GRL* 2020

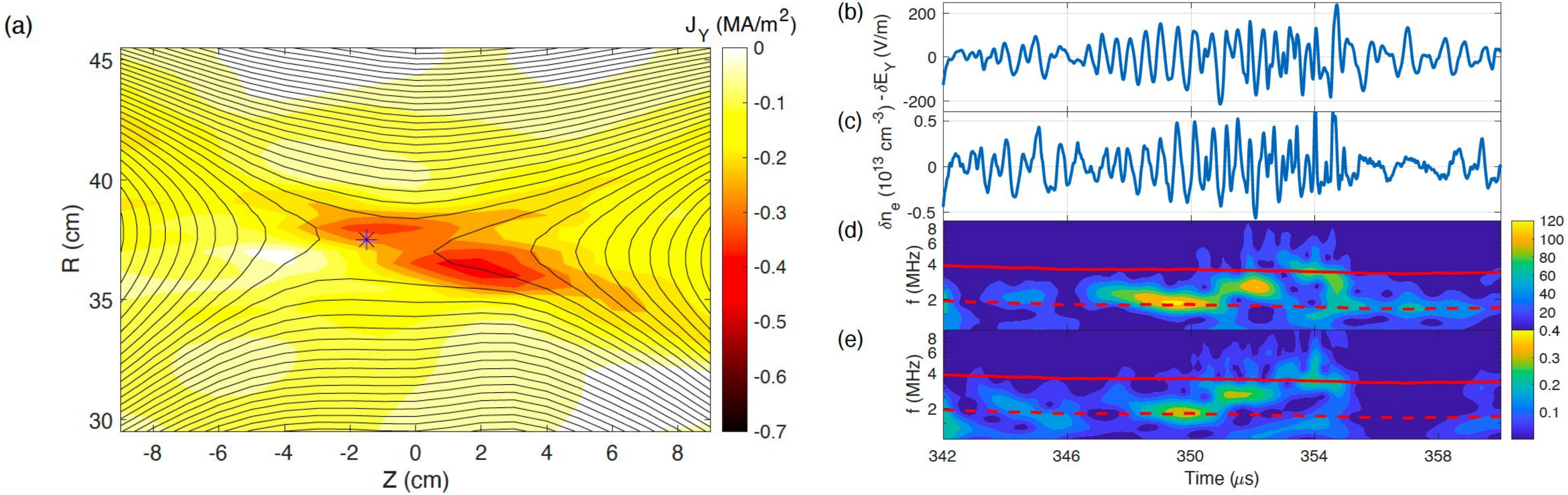
Special Probe has been Constructed for Study of Electron Heating and Momentum Transfer Associated with LHDWs in MRX

Measures δE_{rec}, δn_e, n_e, and T_e.

Hu, Yoo, *et al.* RSI 2021

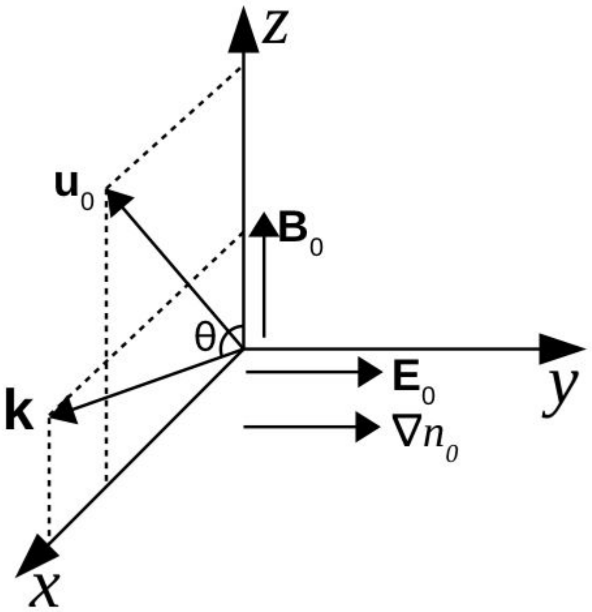


A moderate GF ~ 0.7 (#191235) case with ES-LHDW activity



- Correlated density and electric fluctuations inside the electron diffusion region - anomalous resistivity (drag).
- Wave energy is concentrated below f_{LH}.

Local Linear Models have been Developed for Study of LHDWs in the current sheet



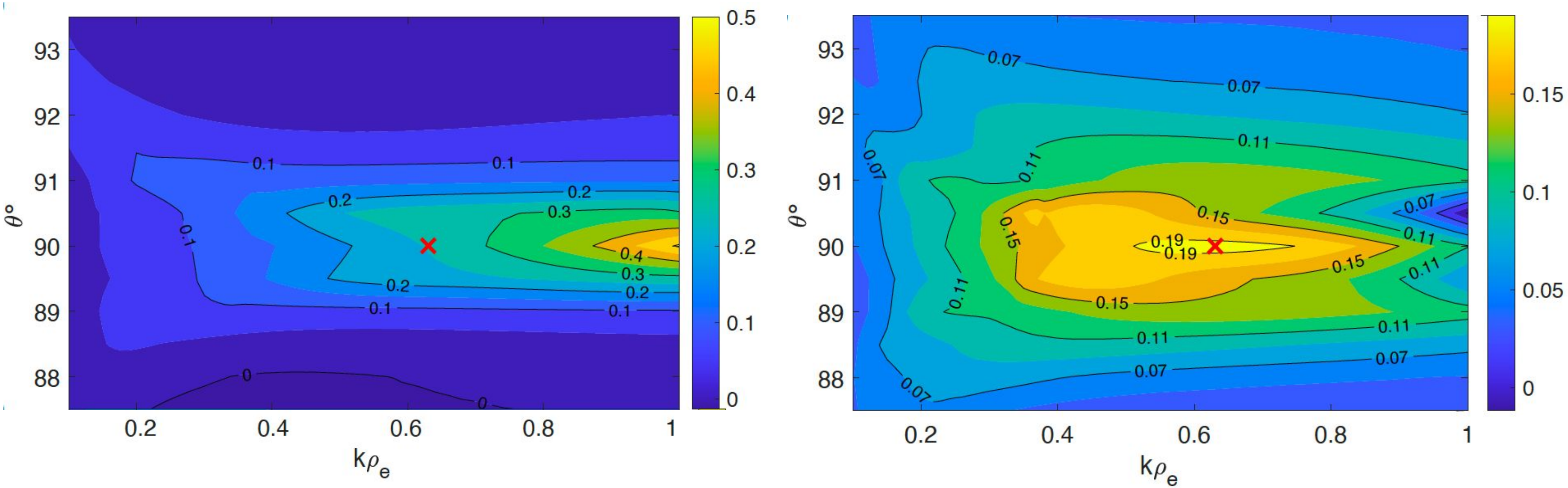
- Following Ji et al. 2005,
  - Ion rest frame.
  - No temperature gradient.
  - No k_y – local analysis.
  - Kinetic treatment for ions (isotropic Maxwellian).
  - Fluid treatment for electrons.
- The parallel electron velocity component is added.

Yoo *et al.* 2020 (collsionless), Yoo *et al.* 2022 (collisional)

Improvements over Previous Models

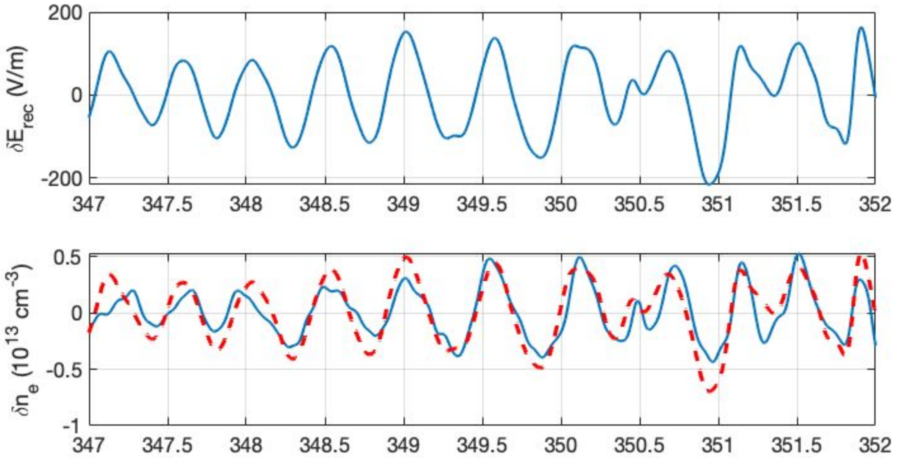
- Dispersion for arbitrary angle θ can be obtained.
    - Only θ = 90° in Davidson et al. 1977.
- Electromagnetic effects are included - Faraday's equation is used.
    - Poisson's equation was used in Davidson *et al.* 1977
- The electron inertia term is included.
- All terms associated with the density gradient, self-consistent with the perpendicular drift are included.
- Electron temperature anisotropy is allowed.
    - Both zeroth and first orders - collisionless model
    - Only first order - collisional model
- Independent calculation of the perturbed electron density to include effects from electrostatics.
    - Important for ES-LHDWs
- The electron heat flux, heat generated by collisions, and resistivity are included.
    - Closures by Ji and Joseph 2018 and Ji and Held 2013

Linear Stability Analysis has been done for Discharge #191235 via Collisional Model



- Maximum growth rate, $0.2\omega_{LH}$ at $(k\rho_e, \Theta) = (0.63, 90°)$.
- Frequency with the maximum growth rate $\sim 0.27 f_{LH}$.
    - In the lab frame, the dominant frequency is about $0.5 f_{LH}$.
    - The difference may be explained by the Doppler shift. ($u_{iz} \sim 5$ km/s)
        - $\omega_{LF} = \omega + \mathbf{k} \cdot \mathbf{u}_i \sim 0.25\,\omega_{LH} + 0.63 u_{iz}/\rho_e \sim 0.45\omega_{LH}$

ES-LHDW is Capable of Generating Anomalous Resistivity



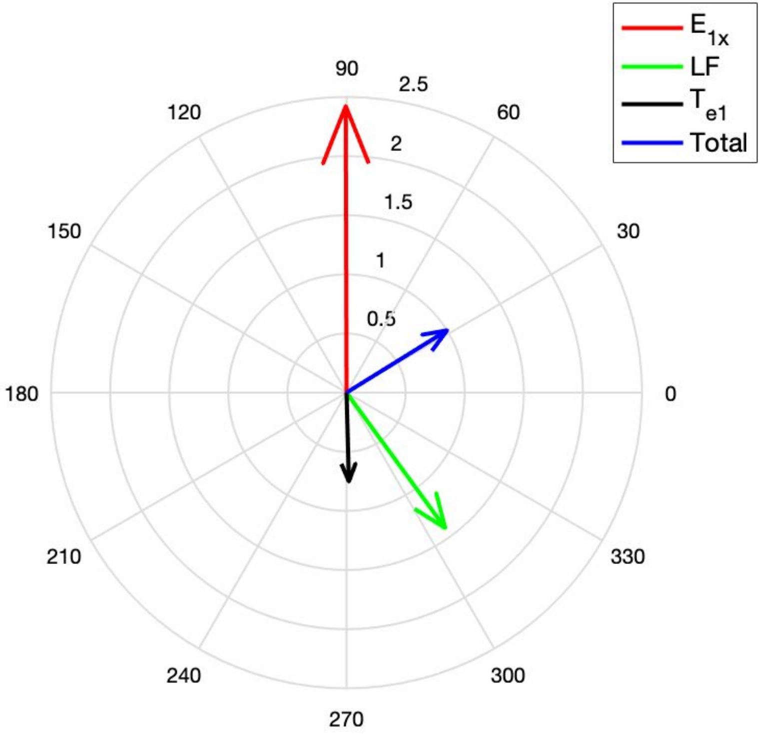
Yoo et al. Phys. Rev. Lett. 2024

- In both space and laboratory observations, ES-LHDW can generate density fluctuations that have positive correlation with fluctuations in the reconnection electric field.
  - Phase difference is typically 30-40 degrees.

To Understand the Relation between δn_e and δE_{rec}, the x Component of Electron Momentum Equation is Analyzed

- Ignoring the inertial term, resistivity, and Lorentz force, electrostatic modes have:
    - $ik_\perp p_{e1x} + en_0E_{1x} = 0$.
    - In the isotropic limit, $p_{e1x} = n_{e1}T_{e0}$, which means:
        1. $n_{e1}/n_0 = [ie/(k_\perp T_{e0})]E_{1x}$.
- In our formulation for LHDWs, we have four additional terms on RHS
    - Inertial term: $[m_e(\omega-\mathbf{k_0}\cdot\mathbf{u_{e0}})/(k_\perp T_{e0})]u_{e1x}$.
    - Lorentz force term: $[ieB_0/(k_\perp T_{e0})]u_{e1y} - [ieu_{e0z}/(k_\perp T_{e0})]B_{1y}$.
    - Perturbed temperature: $-T_{e1}/T_{e0}$
    - Resistivity term: $-iR_{e1}/(k_\perp n_0 T_{e0})$.

Lorentz Force Terms are the Key for the Anomalous Resistivity by ES-LHDW



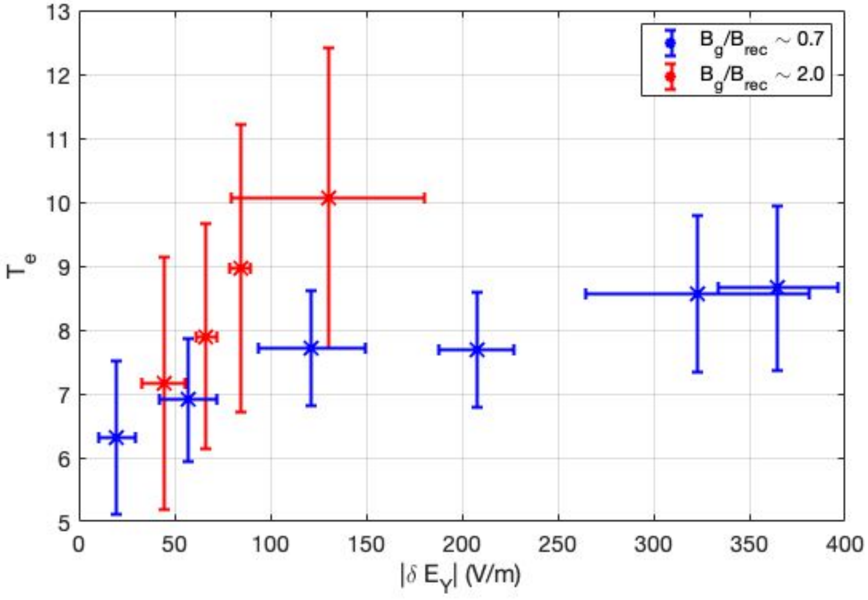
- Only Lorentz force terms have a significant real part, which is the key for anomalous resistivity.
- Contributions from the resistivity and inertial terms are negligible.

Anomalous Momentum Transfer and Heating are Estimated via Quasilinear Analysis

Physical Meaning	Expression	Value
Reconnection electric field	$\langle E_{rec} \rangle$	80 V/m
Anomalous resistivity	$\langle \delta n_e \delta E_{rec} \rangle / n_{e0}$	16 V/m
Classical (Spitzer) resistivity	$\eta_{\|\|} J_{\|\|}$	7 V/m
Anomalous electron heating	$\langle \delta \mathbf{J}_e \cdot \delta \mathbf{R} \rangle$	2.3 MW/m^3
Classical electron heating	$\eta_{\|\|} J_{\|\|}^2 + \eta_\perp J_\perp^2$	2.0 MW/m^3

- Every first-order physical quantities can be expressed in terms of δE_{rec}.
  - For example, $\delta n_e = A \delta E_{rec}$ (A is a complex number), $\langle \delta n_e \delta E_{rec} \rangle = 0.5|A||\delta E_{rec}|^2 \cos \varphi$.

Statistical Analysis of Electron Heating



- In both intermediate and high GF cases, there are positive correlations between $|\delta E_{rec}|$ and T_e.
    - More electron heating is expected with the same wave amplitude for the high GF case.

Low-β Laser-driven Reconnection Experiments - Ion Acoustic Waves and Electron Acoustic Waves

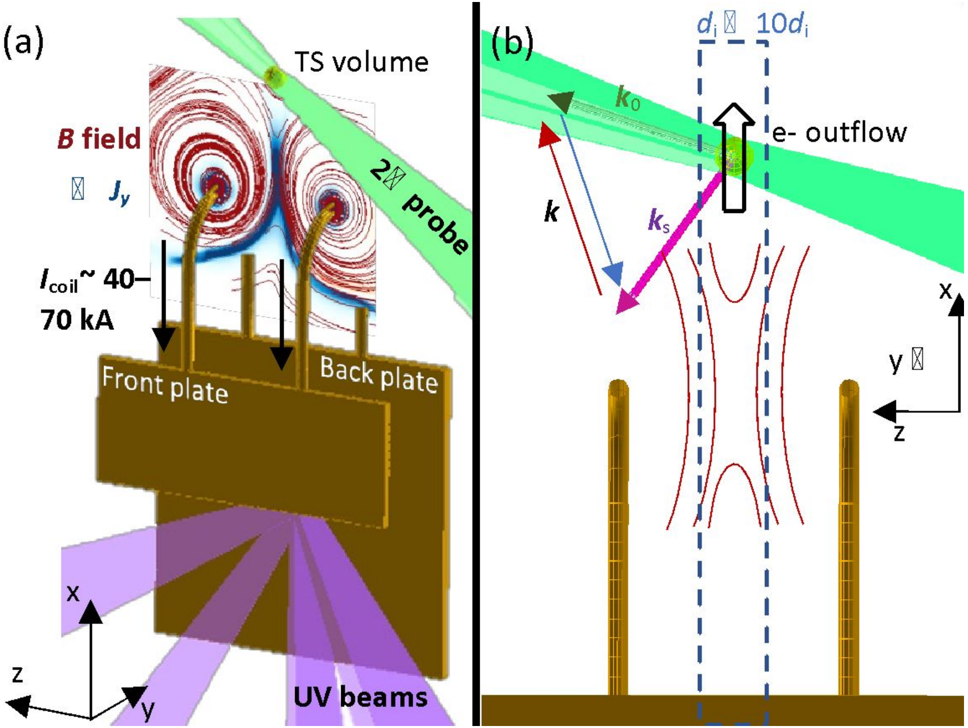
- Free energy source - field aligned current and electron beams
- IAWs require $T_i \ll ZT_e$.

Collective Thomson Scattering:

2ω @ 527 nm

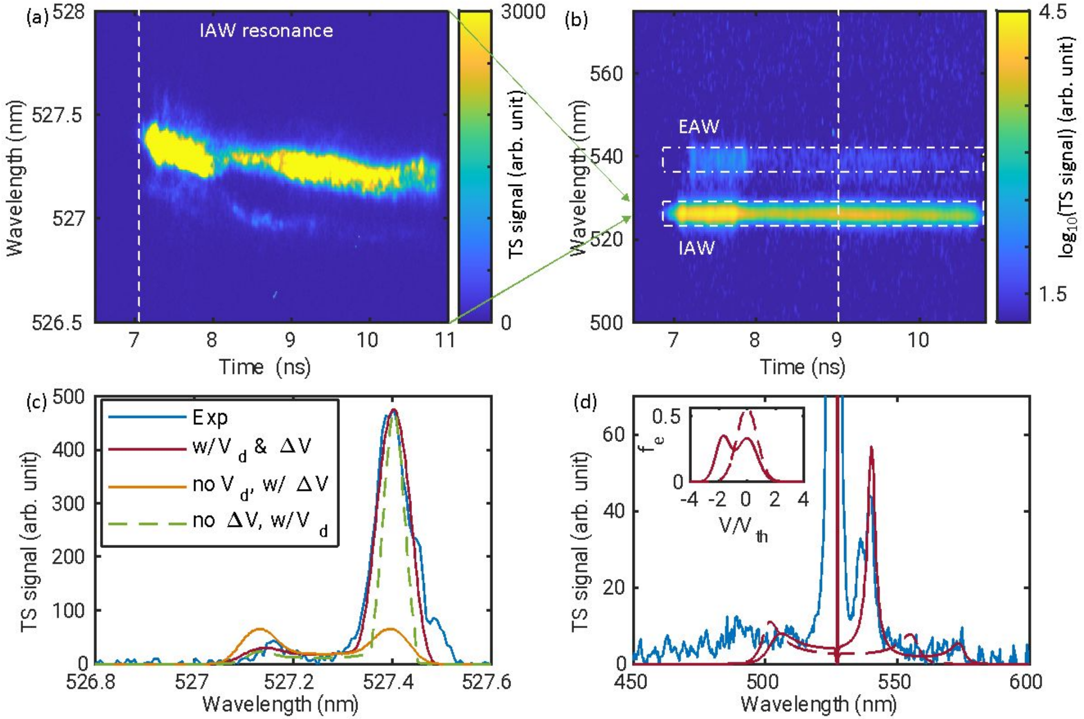
150 J, $60 \times 60 \times 50\ \mu m^3$

f/10 reflective



Zhang *et al.* 2023

Direct Measurement of IAW and EAW during Magnetic Reconnection in a Laboratory Plasma



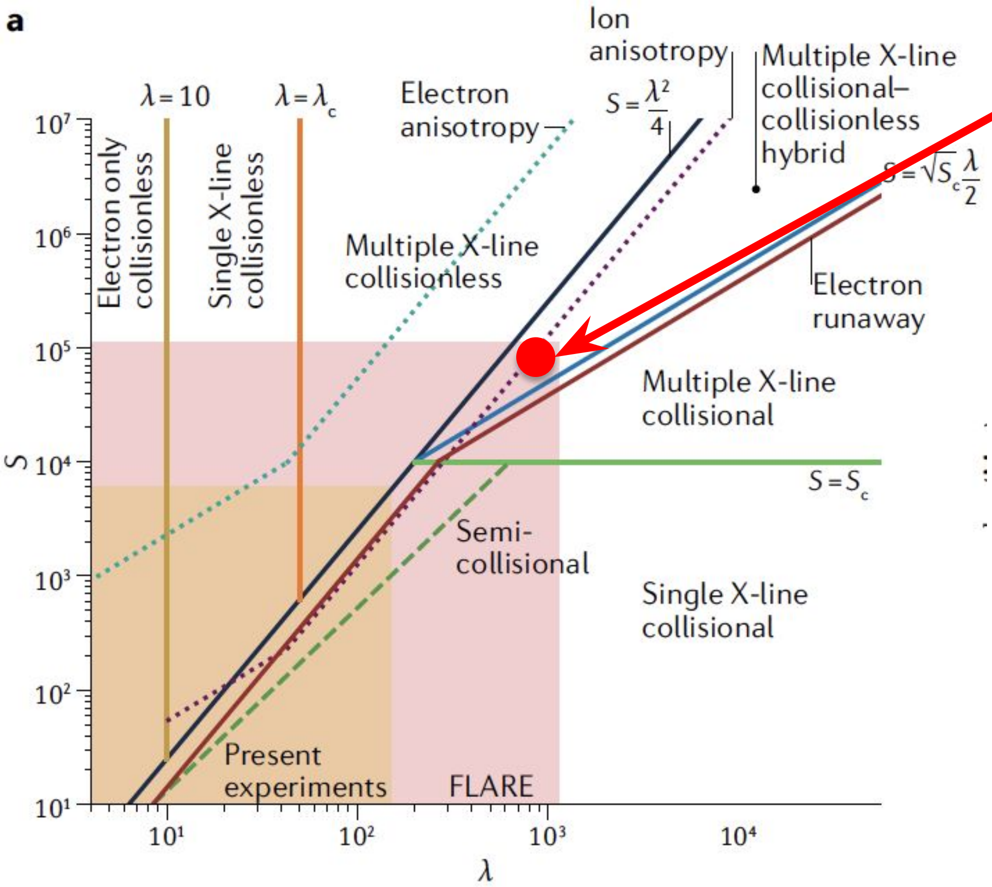
Large electron flow velocity with respect to ions is needed to reproduce the asymmetric IAW and **two-stream electrons** to reproduce EAW peaks

FLARE is under Infrastructure and Power System Upgrade (93% Completion)

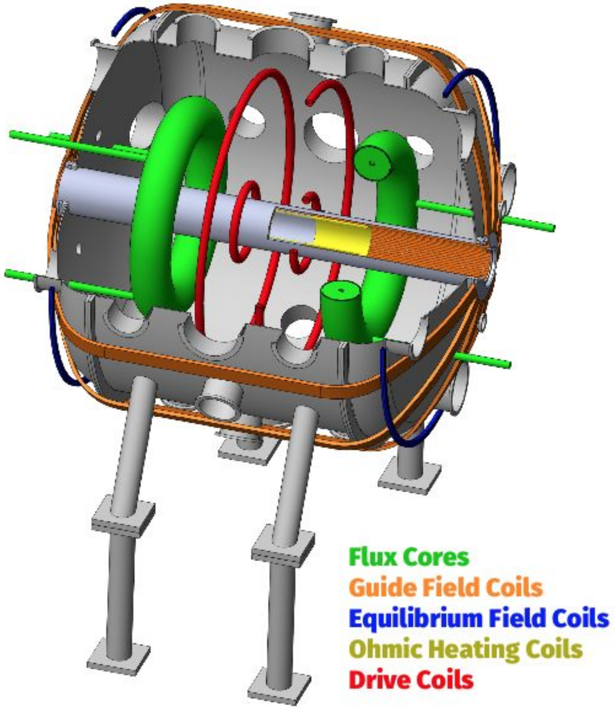
Parameters	MRX	FLARE
Device diameter	1.5 m	3 m
Device length	2 m	3.6 m
Ohmic heating	No	Yes
Reconnection field	0.03T	0.1T
Guide field	0.06T	0.5T
Stored energy	~30 kJ	~6 MJ
S (anti-parallel)	600-1,400	5,000-16,000
Size, $\lambda=(Z/d_i)$	35-10	100-30
S (guide-field)	3,000	100,000
Size, $\lambda=(Z/\rho_s)$	200	1,000

To be operated as a US-DOE collaborative research facility

Reconnection Phase Diagram



Design target for FLARE



Possible FLARE Projects Associated with Waves

1. Lower hybrid waves (very plausible)
   a. Potentially, over 400 measurement points of δ**B** covering the ion diffusion region (IDR) are available with magnetic probe arrays and a new data acquisition system (up to 50 MSPS).
   b. We can study where lower hybrid waves are generated and propagated.
2. Alfvén waves (plausible)
   a. Magnetic probes covering the MHD scale.
   b. Capability to achieve a longer discharge time.
      i. Covering Kinetic Alfvén waves with high guide field is very plausible.
3. Whistler and electron cyclotron waves (need R&D)
   a. Need special probes and data acquisition systems to cover 0.2–2 GHz.
4. Plasma waves (need R&D)
   a. Plan to develop new electrostatic probes to cover 10 GHz range.

Summary

- Whistler waves near the low-density side separatix indicates the precise location of the electron mixing region.
- LHDWs have been observed in both space and laboratory (MRX).
    - Yoo *et al. GRL* 2020, Hu *et al. RSI* 2021, Yoo *et al.* PRL 2024.
- ES-LHDW is capable of generating anomalous resistivity and electron heating.
    - The Lorentz force term is the key for the positive correlation between δn_e and δE_{rec}.
    - Anomalous electron heating exceeds the classical electron heating.
- Ion acoustic waves and electron acoustic waves have been observed in laser-drive magnetic reconnection.
    - Potentially important in certain astrophysical plasmas.
- FLARE will provide good opportunities for studying waves during reconnection.
    - Initial targets - lower hybrid waves - 2D measurements covering the IDR.
    - Kinitic Alfvén waves, whistler waves, and plasma waves in the future.