高出力レーザー (+α) を用いた宇宙物理実験：磁気リコネクションの電子ダイナミクス

境 健太郎

プラズマ量子プロセスユニット

核融合科学研究所

sakai.kentaro at nifs.ac.jp

研究部セミナー

2023/10/13

Kentaro Sakai (境 健太郎)

- National Institute for Fusion Science
- PhD in Engineering in July 2023
  - Advisor: Yasuhiro Kuramitsu
- Research interest: laboratory astrophysics with high-power and intense lasers

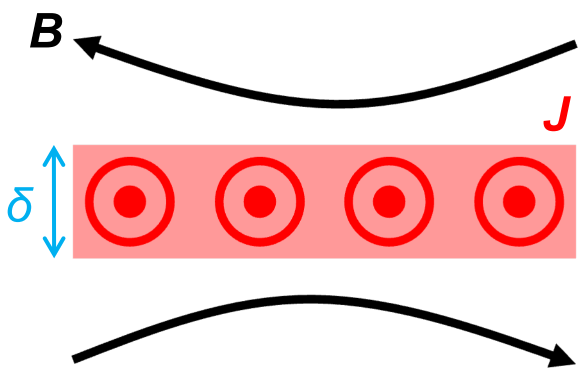
Summary

- Experimental investigations on space and astrophysical plasmas with high-power/intense lasers
- Magnetic reconnection driven by electron dynamics
- Laser +α: multiscale observations of magnetic reconnection with laser + magnetic device

- Others (if I have time)
    - Collective Thomson scattering to measure waves and instabilities
    - Scattering in intense laser beam toward relativistic reconnection experiment

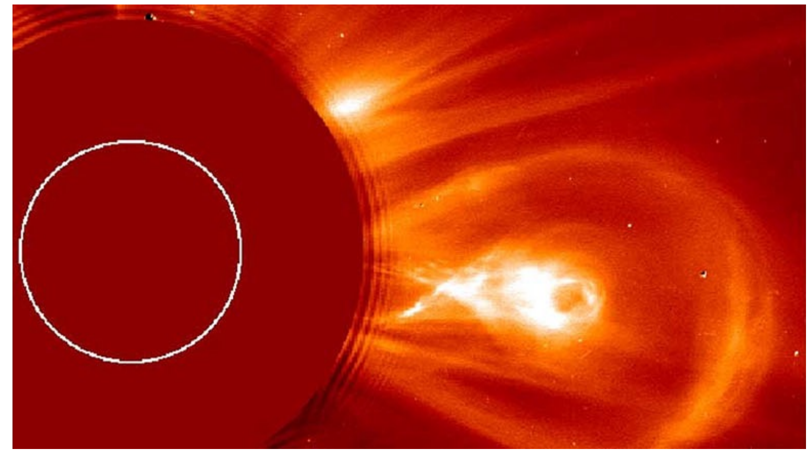
Magnetic reconnection

- Releases magnetic energy into plasma
- Changes <u>macroscopic</u> magnetic field topology
- Role of <u>microscopic</u> electron dynamics
- **Multiscale nature**



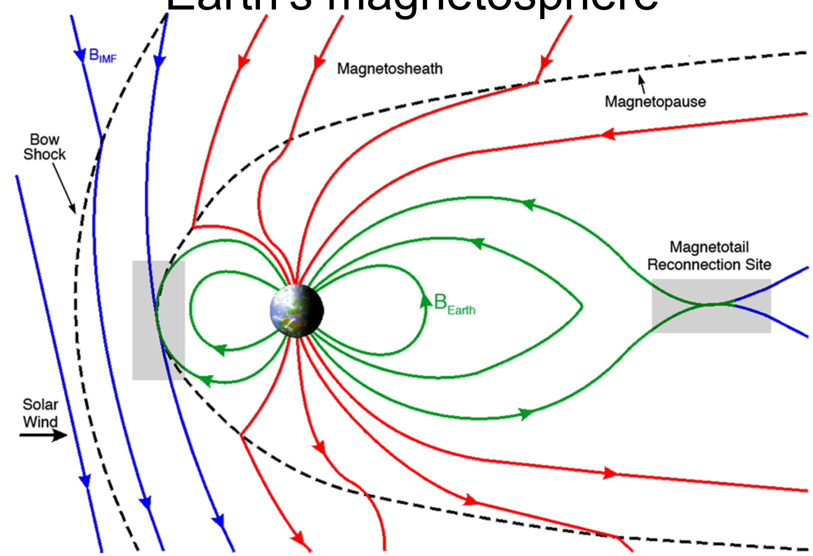
$\delta > r_{gi}$	$\rightarrow$ ion&electron current
$r_{gi} > \delta > r_{ge}$	$\rightarrow$ electron current
$\delta < r_{ge}$	$\rightarrow$ no current→reconnection

Solar flare



A.O. Benz, Living Rev. Sol. Phys. (2017)

Earth's magnetosphere



S. A. Fuselier and W. S. Lewis, Space Sci. Rev. (2011)

Magnetic reconnection

- Releases magnetic energy into plasma
- Changes macroscopic magnetic field topology
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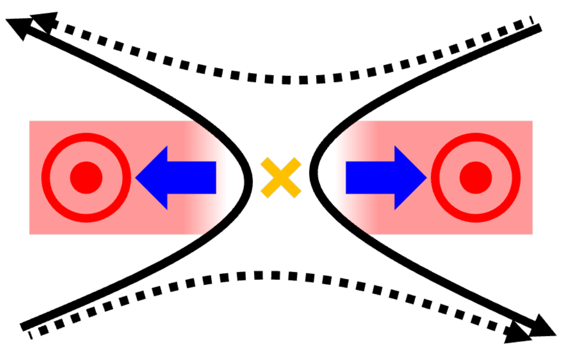
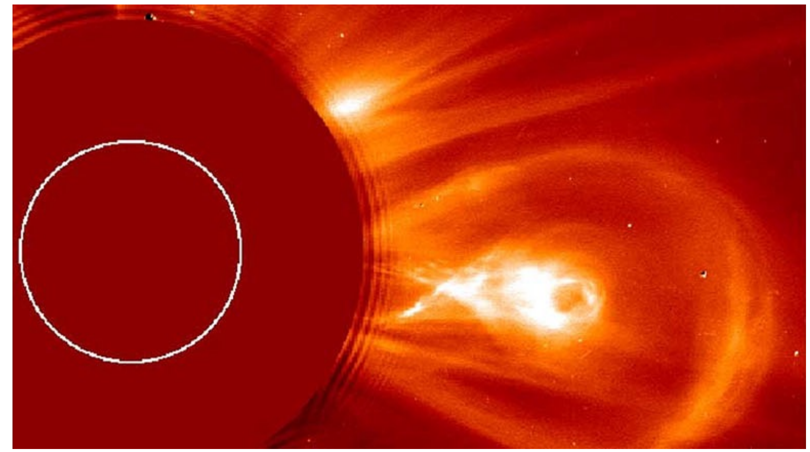


(Electron) outflow
at (electron) Alfvén speed

Solar flare



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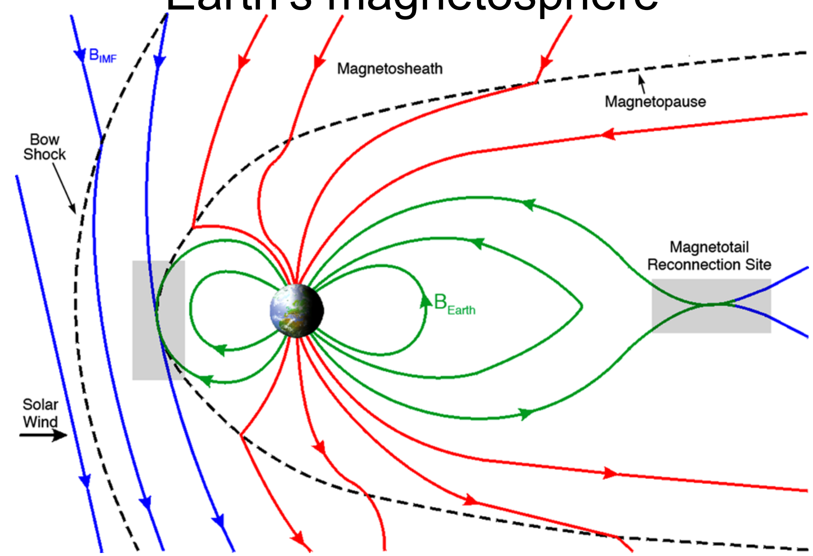
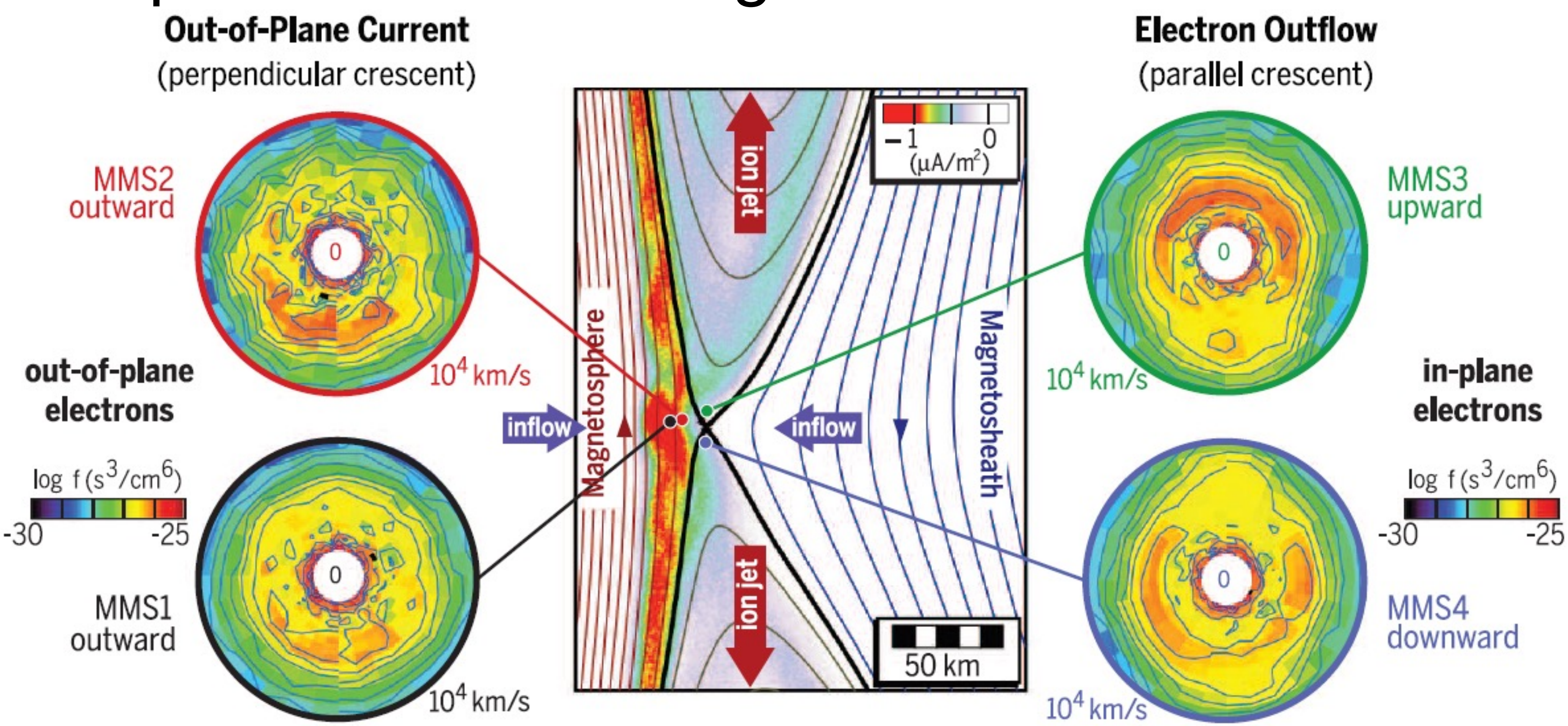


S. A. Fuselier and W. S. Lewis, Space Sci. Rev. (2011)

- No resolution for electrons in astrophysical plasmas
- Local observations with MMS revealed electron dynamics in magnetic reconnection
- No global observations
- Experiment to obtain global/local information

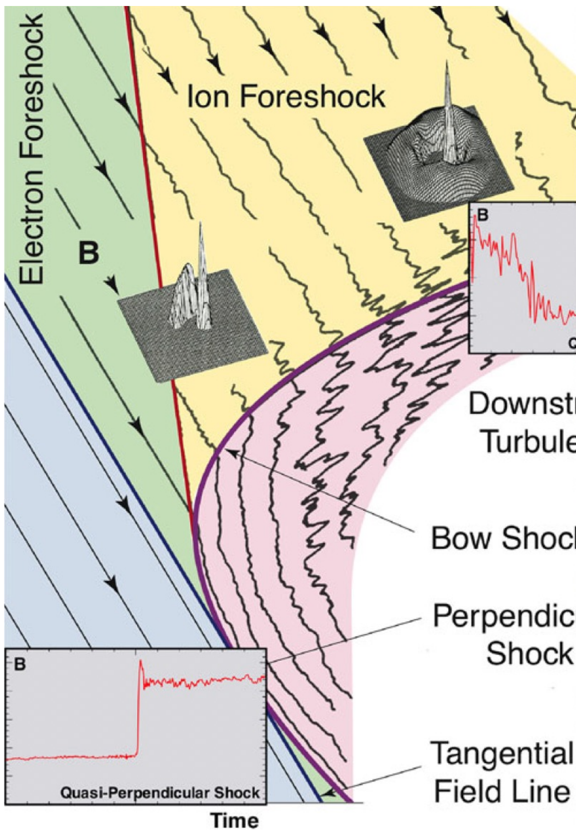


J.L. Burch *et al.*, Science (2016)

Laboratory experiments

- Reproduce space and astrophysical phenomena in laboratory

Space (magnetosphere)

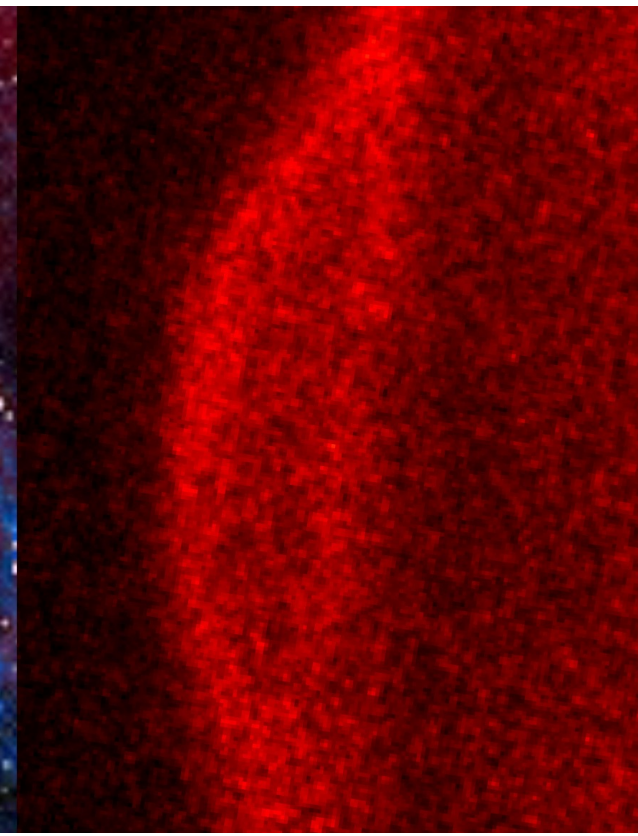


D. Burgess+ SSR (2012)

Astro (SNR)

NASA/NRAO/NOAO

Laboratory (laser)

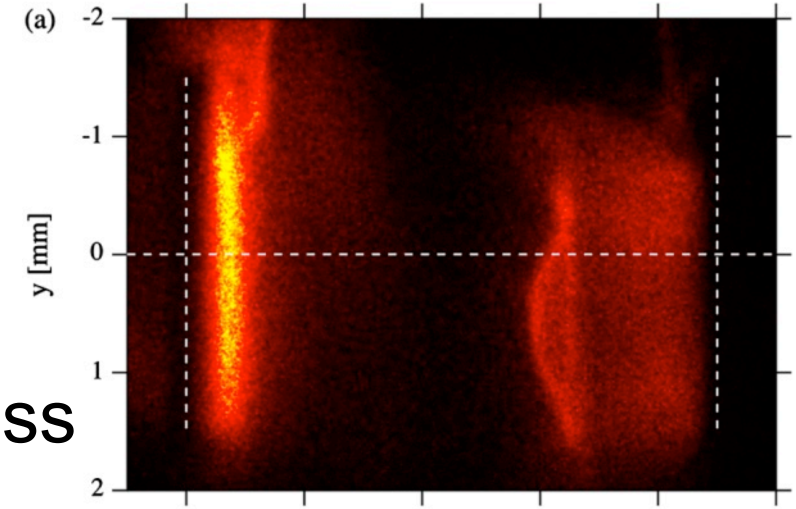


Y. Kuramitsu+ PRL (2011)

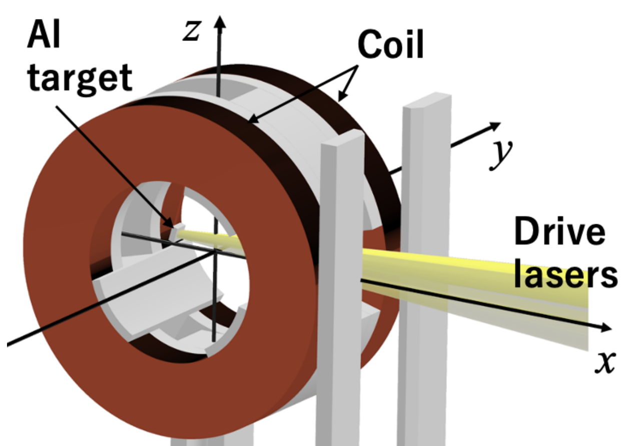
Laboratory experiments

- Active/passive diagnostics
- Global structures
- Local quantities
- Controllability
- Why laser? – easy to access to electron-scale

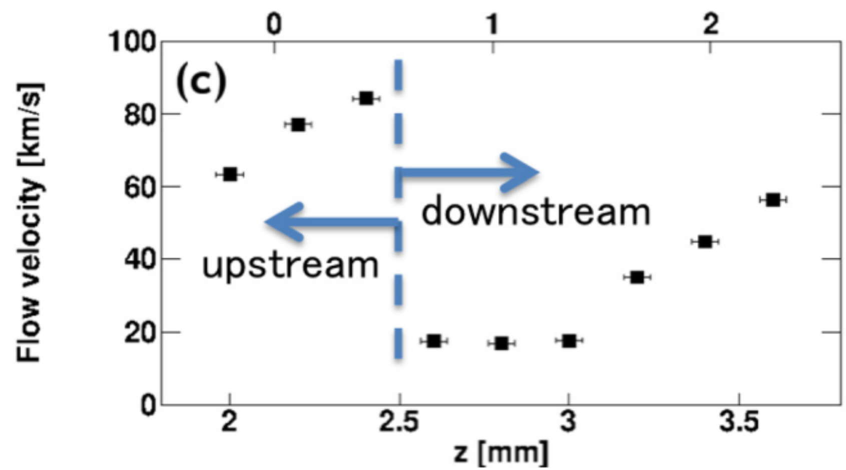
Global structure of collisionless shock
Y. Kuramitsu *et al.*, Phys. Rev. Lett. (2011)



Controlled B field
R. Yamazaki *et al.*, Phys. Rev. E (2022)

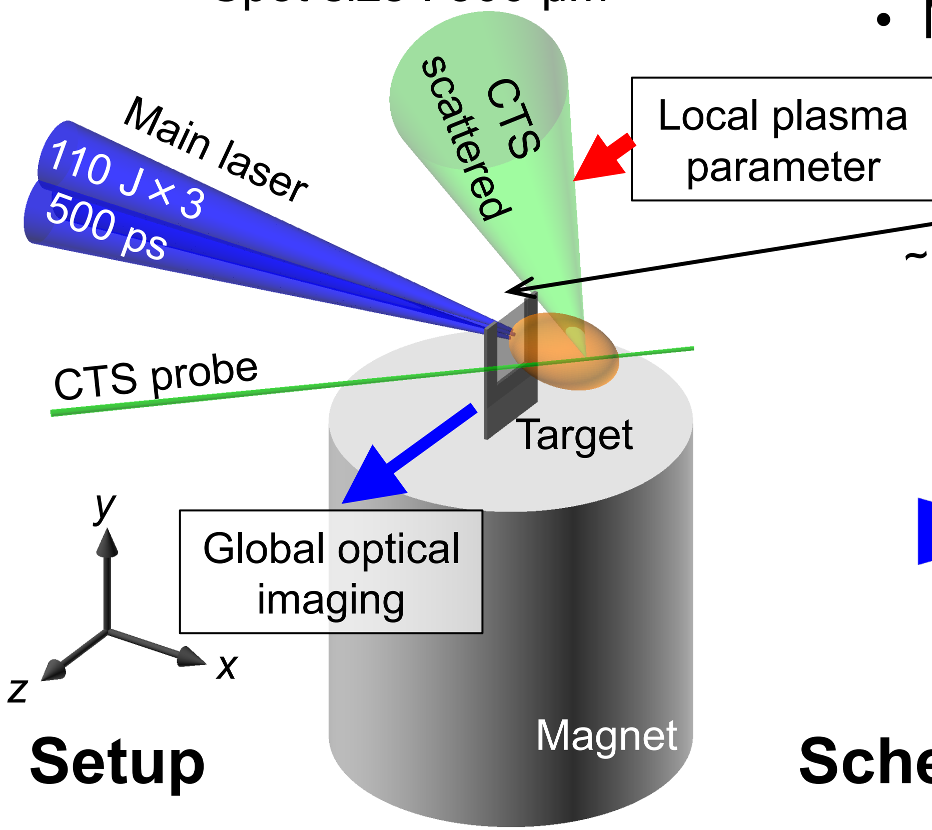


Local velocity field in shock transition
T. Morita *et al.*, Phys. Plasmas (2013)

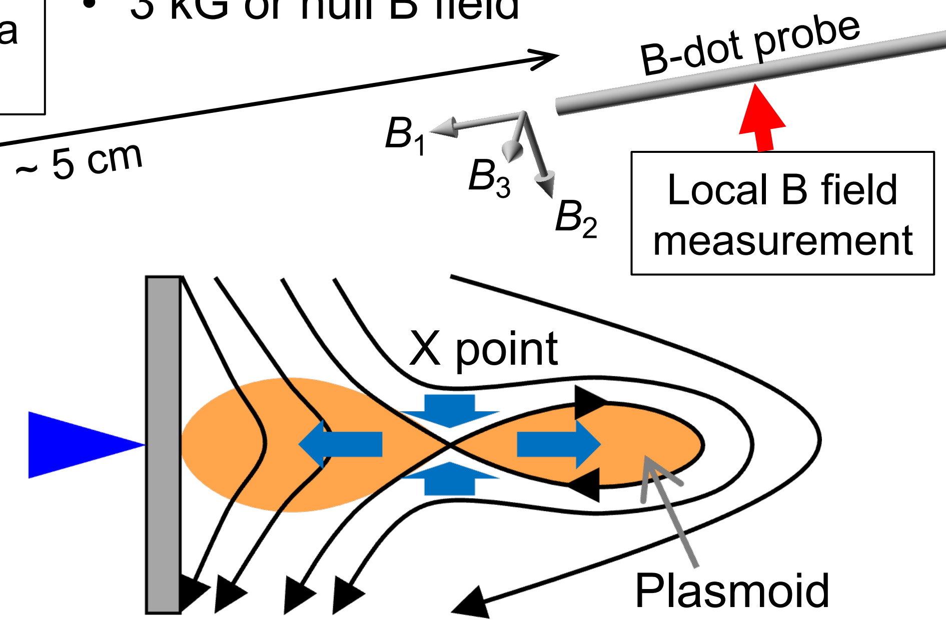


Experimental setup

- GEKKO XII HIPER laser
  - Wavelength : 351 nm
  - Energy : 110 J/beam
  - Pulse duration : 500 ps
  - Spot size : 300 μm
- Target
  - CH foil (thickness 10 μm)
- Ambient gas
  - 5 Torr or 10^{-4} Torr nitrogen
- Magnetic field
  - 3 kG or null B field



Setup

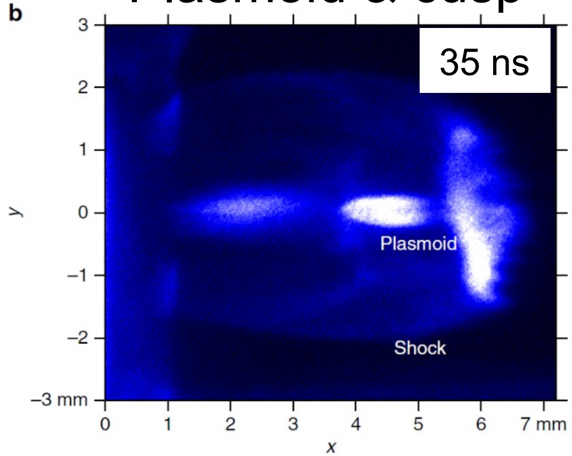


Schematic image of reconnection

Global observations

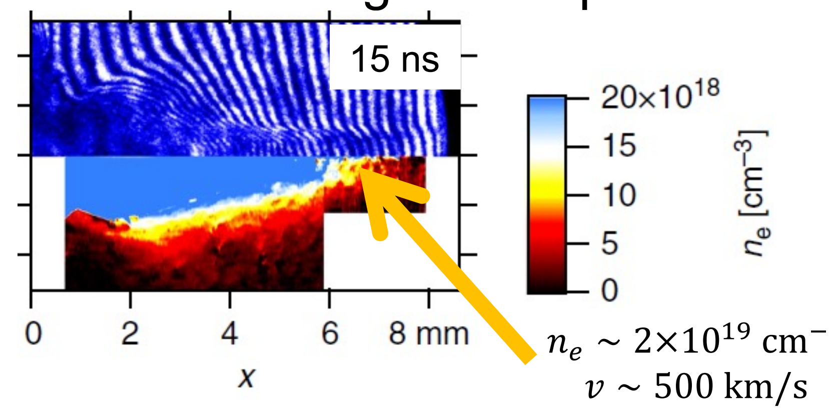
Self-emission image

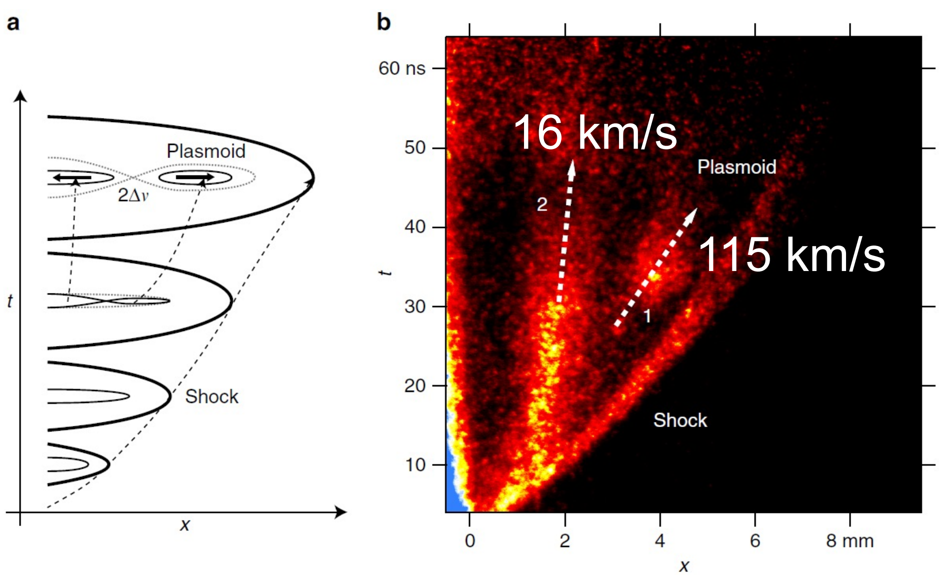
- Plasmoid & cusp



Interferometry

- r_{ge} ~ 9.5 μm, r_{gi} ~ 17 mm
  → electron-magnetized plasma





Streaked self-emission

- Electron Alfvénic outflow

$\Delta v \sim v_{Ae} = B\,(4\pi n_e m_e)^{-1/2} \sim 40\text{–}63$ km/s

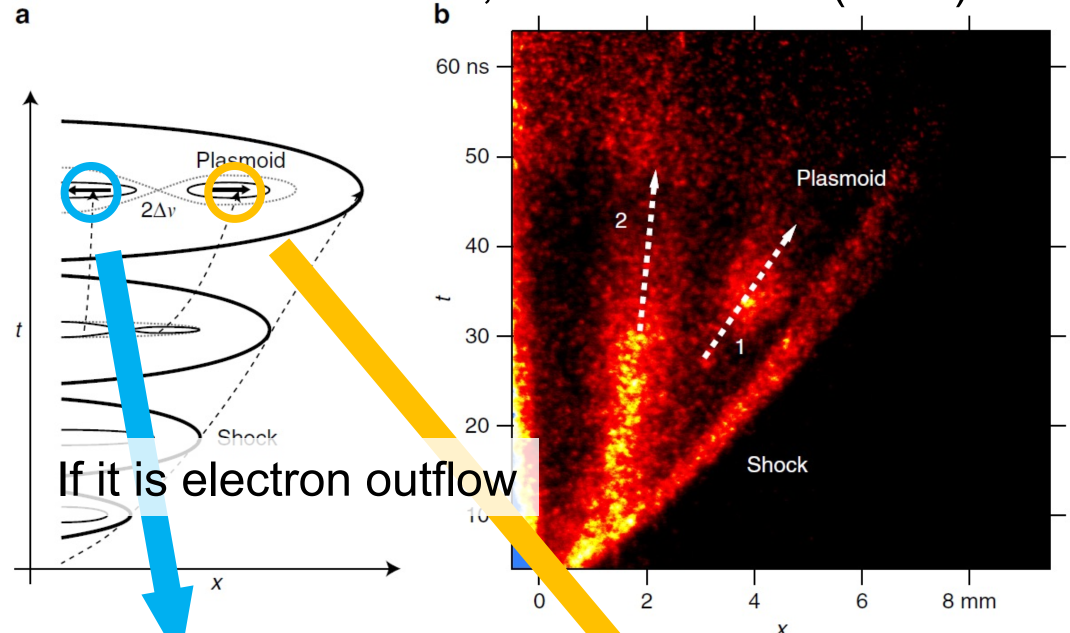
First global observations of
reconnection at electron scale
No local observations

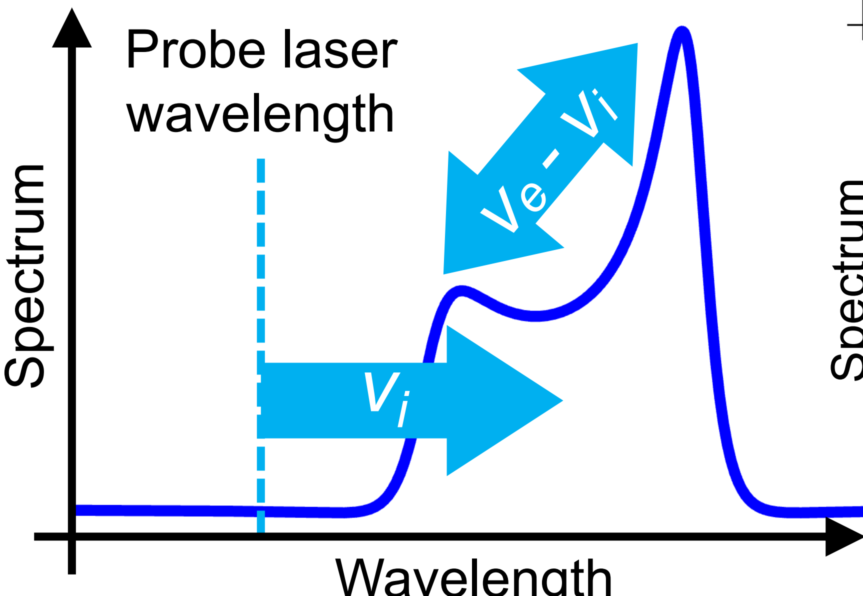
Y. Kuramitsu *et al.*, Nat. Commun. (2018)

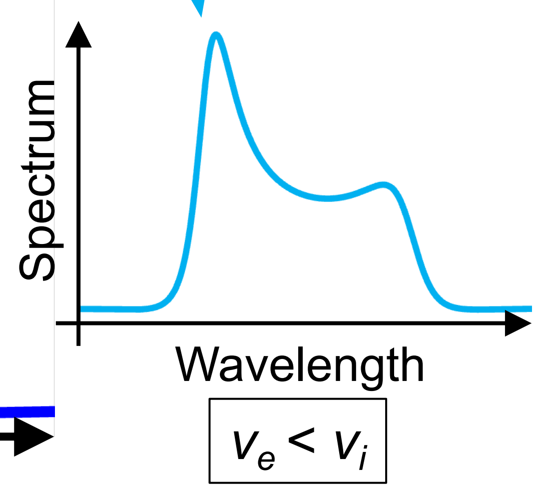
Collective Thomson scattering

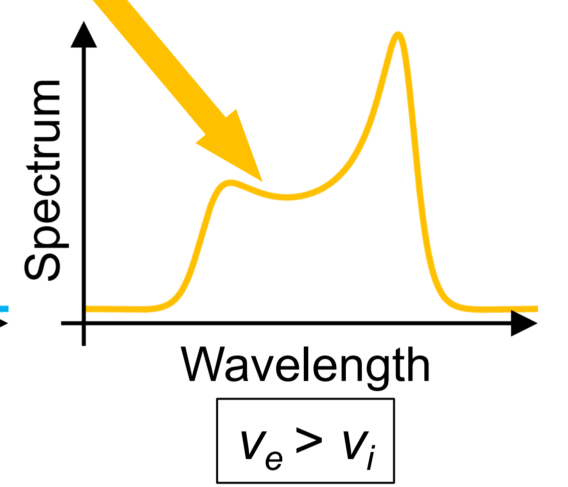
- Local observation
- Ion acoustic wave
- Electron & ion velocities
- Different spectra in different positions

Y. Kuramitsu *et al*., Nat. Commun. (2018)

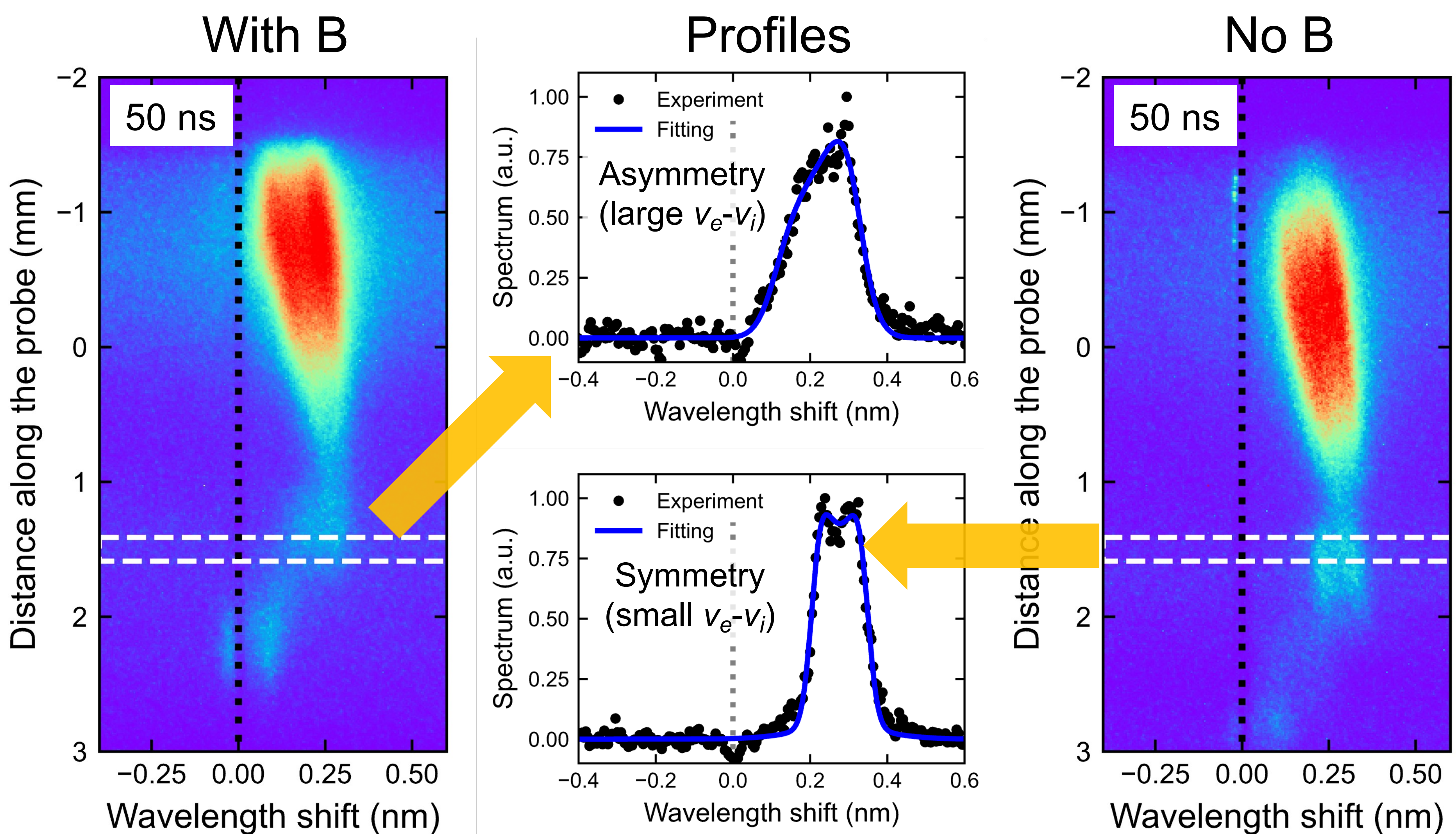








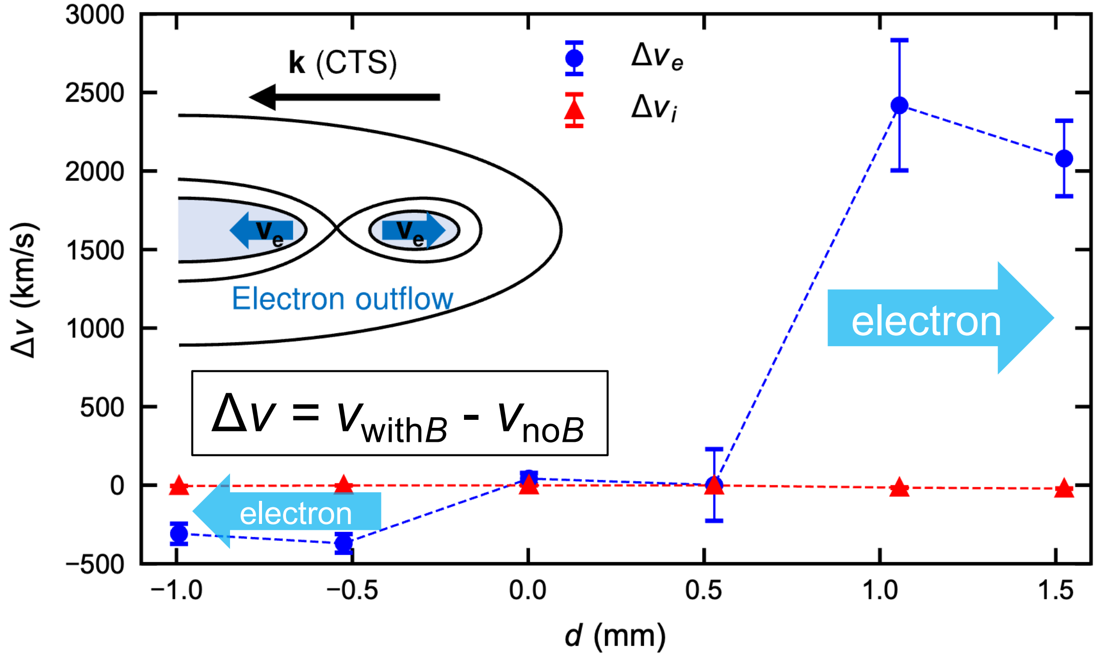
Observed spectrum



K. Sakai *et al.*, Sci. Rep. (2022)

Velocity difference

K. Sakai *et al.*, Sci. Rep. (2022)



- Drastic change of electron velocity whereas unchanged ion motion
- Electron exhaust at *d*~0-0.5 mm with the external B
- Electron outflow without ion outflow

Magnetization

Gyrofrequency: $\Omega = |q|B / (mc)$
Gyroradius: $r_g = mvc / (qB)$
Magnetization: $\sigma = B^2 / (4\pi n m v^2)$

- v_{flow} ~ 100 km/s, $n_e \sim 10^{17}$ cm^{-3} from CTS.
- Scale length of reconnection: L ~ 2 mm
- Electrons are magnetized but ions are not

	Electron	Proton	Carbon
Temperature (T)	10 eV	50 eV	50 eV
Mean velocity $[v_{flow}^2 + 2T/m]^{0.5}$	2000 km/s	140 km/s	100 km/s
Ionization state		+1	+3
Gyroradius (r_g)	36 μm ≪ L	4.9 mm > L	14 mm > L
Gyrofrequency (Ω)	8 GHz	5 MHz	1 MHz
Magnetization (σ)	0.22	$8.7\times10^{-2} \ll 1$	$1.3\times10^{-2} \ll 1$

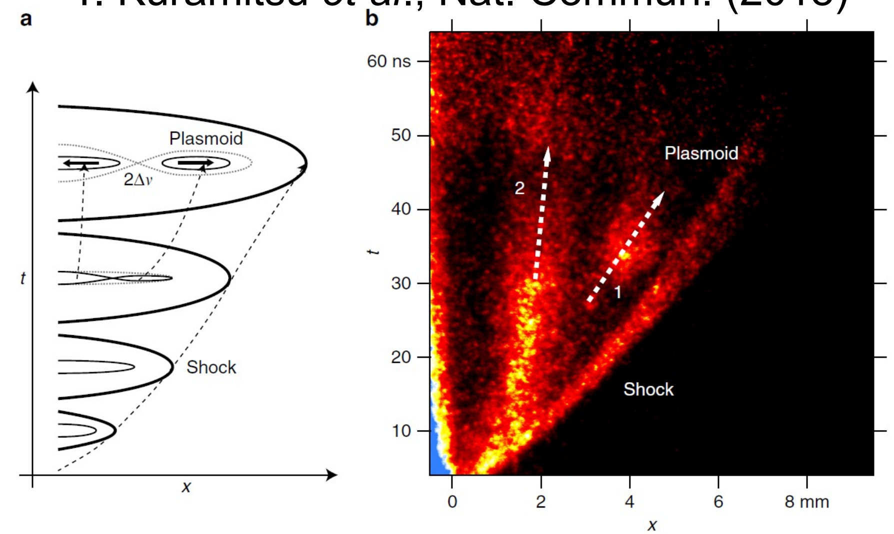
Electrons are magnetized

Ions are rarely influenced by B field

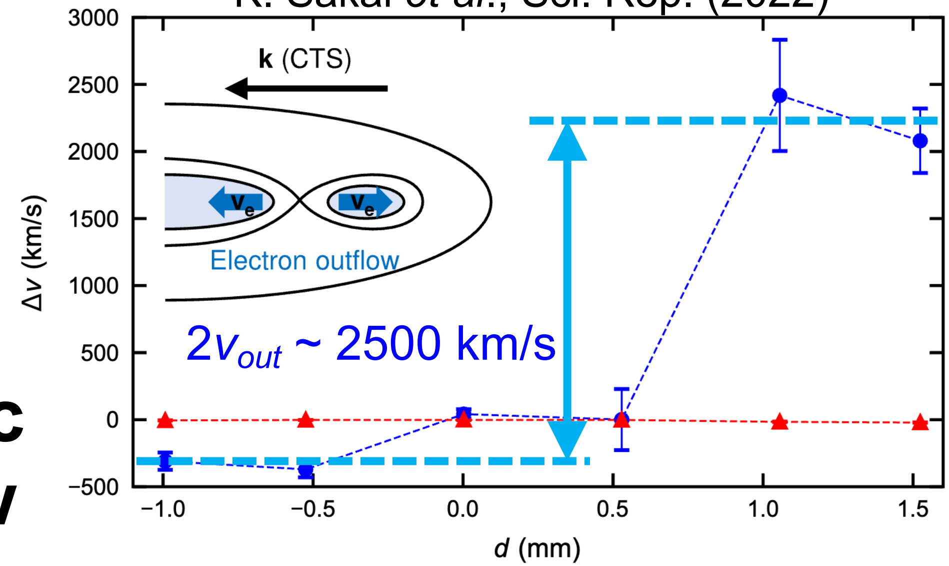
Electron Alfvénic outflow

- Plasma separates at the twice of outflow velocity
- Electron outflow velocity v_{out} ~1250 km/s
- Electron Alfvén speed: $v_{Ae} = B\,(4\pi n_e m_e)^{-0.5}$ ~900 km/s
- Electron-only Alfvénic outflow
- **Magnetic energy is released only to kinetic energy of electron flow**

Y. Kuramitsu *et al.*, Nat. Commun. (2018)

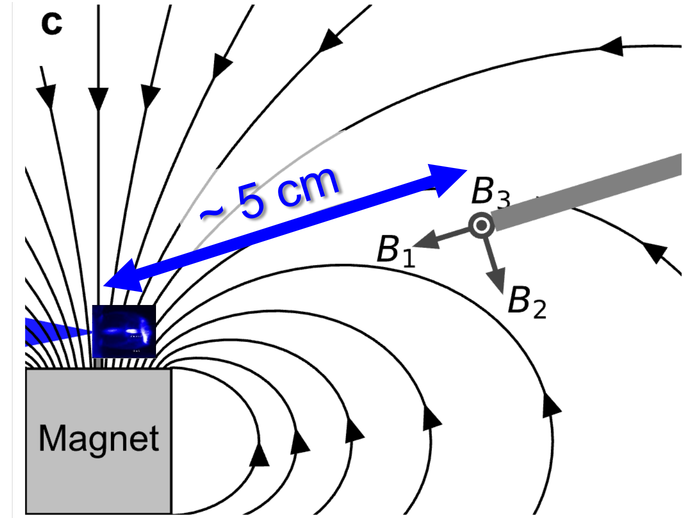


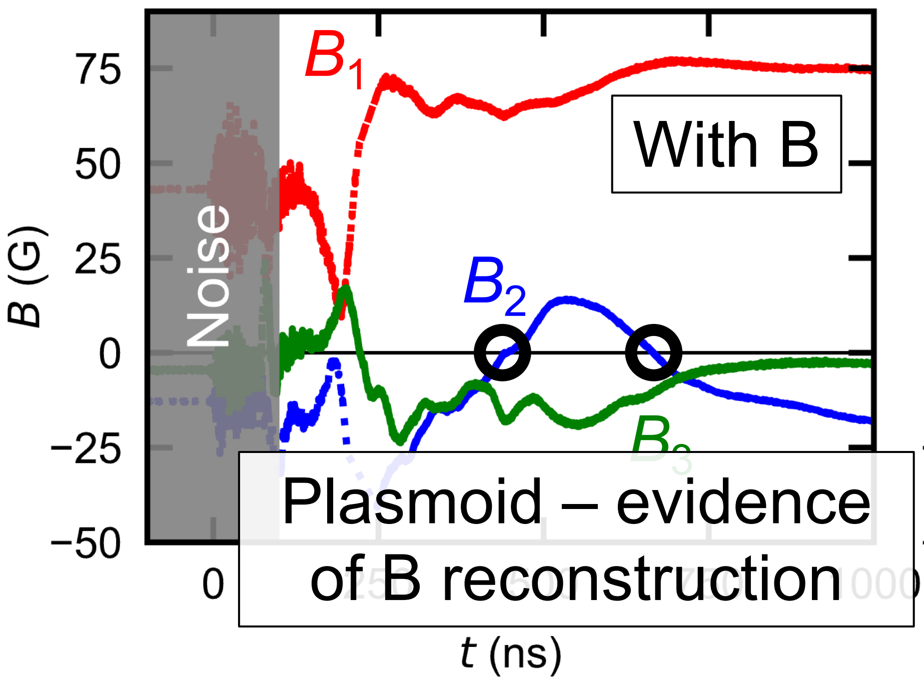
K. Sakai *et al.*, Sci. Rep. (2022)

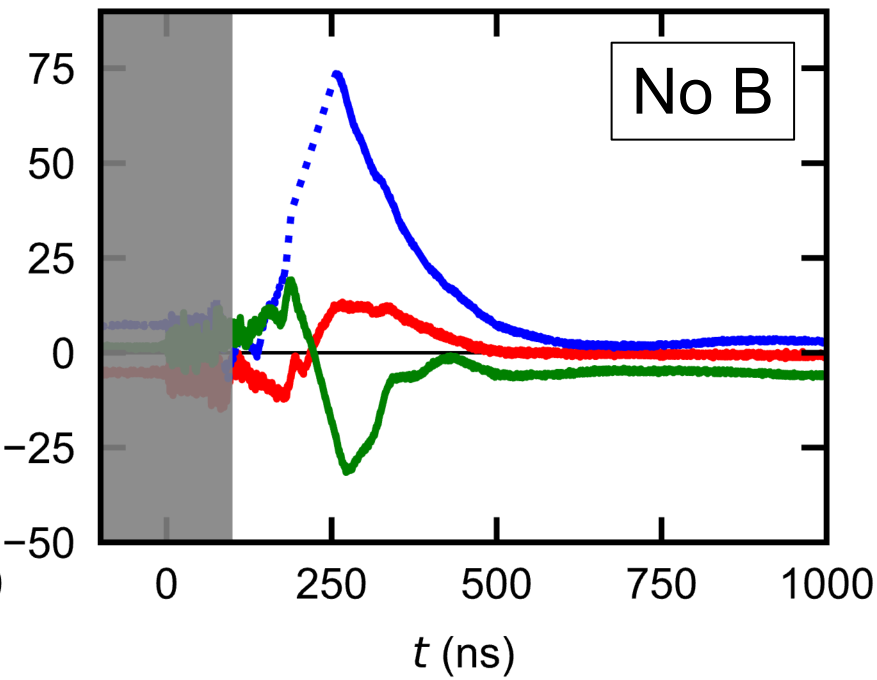


B field measurements

- 3-axis B-dot probe
- Time evolution of local B
  - ~ 5 cm away from the reconnection region
- Magnetic oscillation at ~ 400 ns with B







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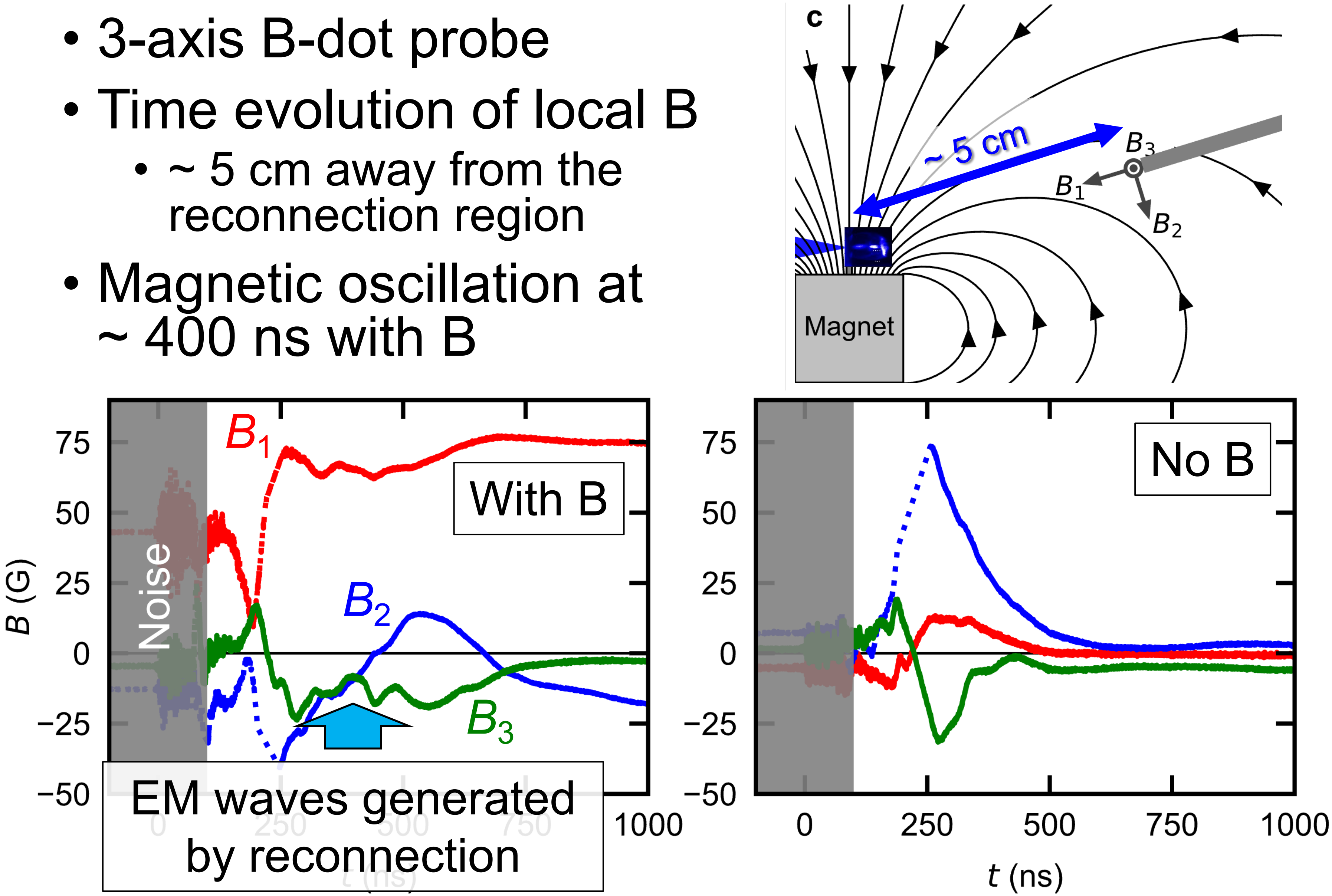
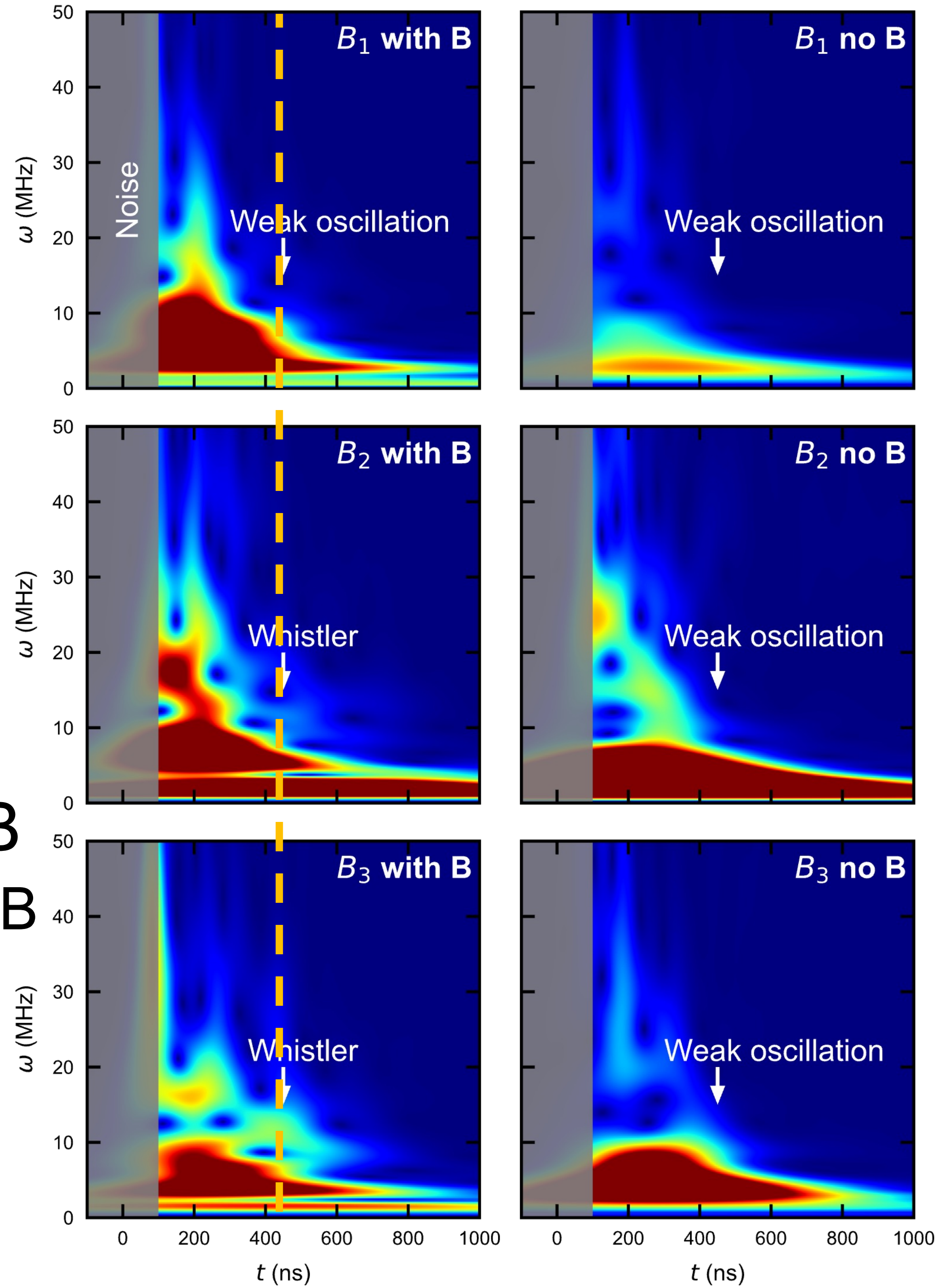
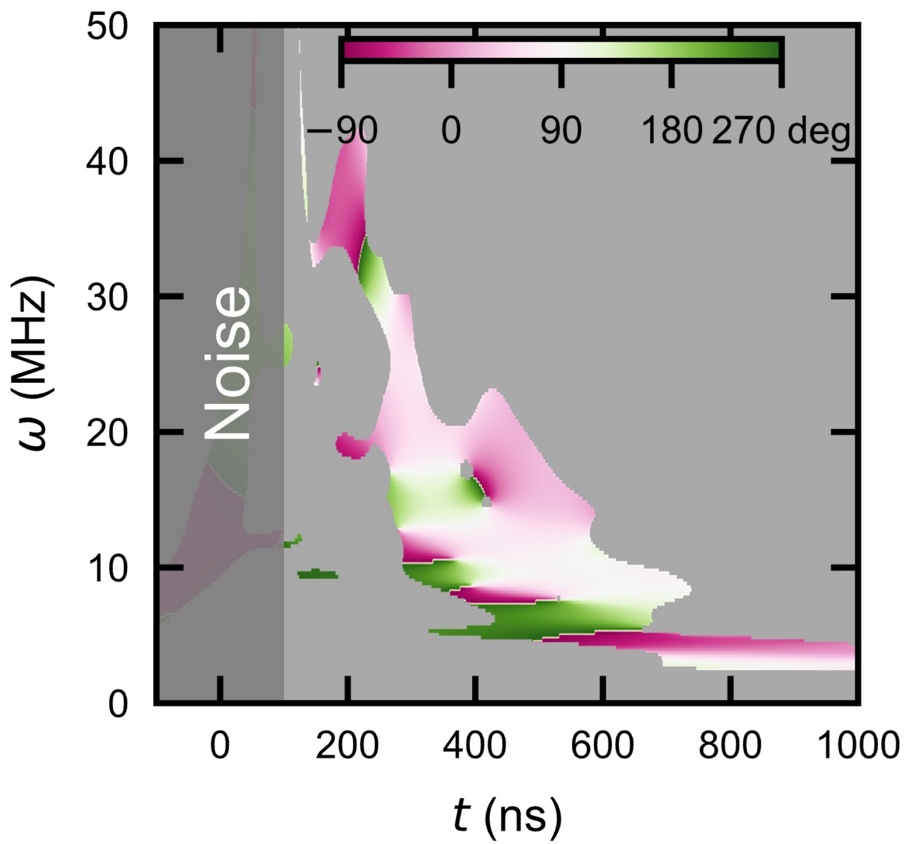


Spectrogram

- B field in the time-frequency domain
- Wavelet analysis
- ~10 MHz at ~400 ns in B_2 & B_3 with B
    - Perpendicular to background B
- Little signal in B_1 with B
    - Parallel to background B
- No clear signal in no B
- $\Omega_i < \omega < \Omega_e \rightarrow$ whistler mode frequency

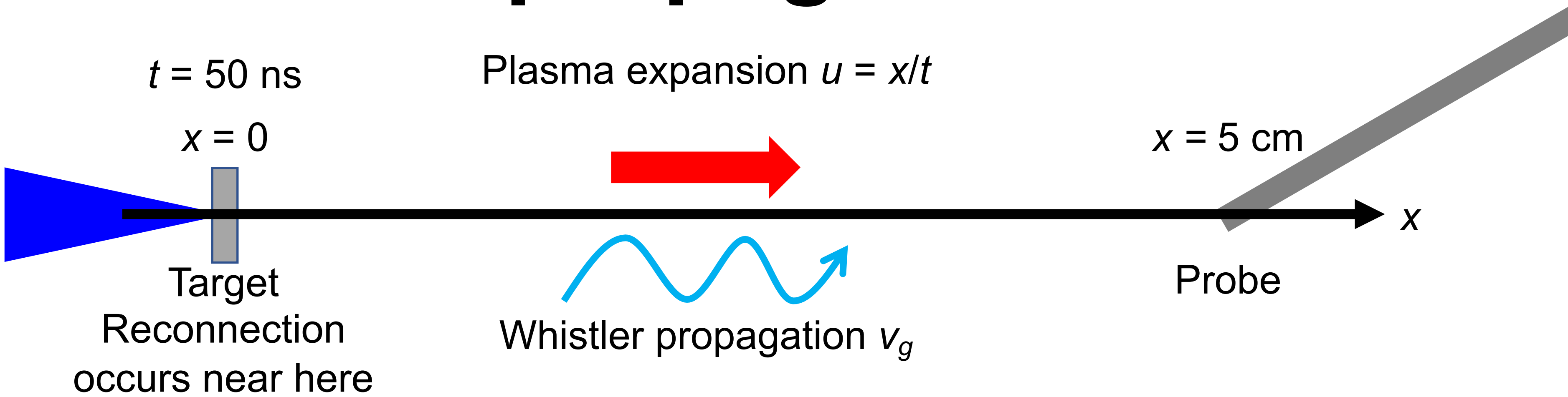


Phase difference of B_2&B_3



- ~ 90 deg. phase difference
  - Right-hand polarization
- Falling tone – “whistler”
- Model calculation explains the frequency chirp
- Whistler waves coming from the reconnection region
- Evidence of electron-scale dynamics

Whistler propagation



- Modeling the arrival timing of whistler waves
- Group velocity of whistler wave (when $\Omega_i \ll \omega \ll \Omega_e$);

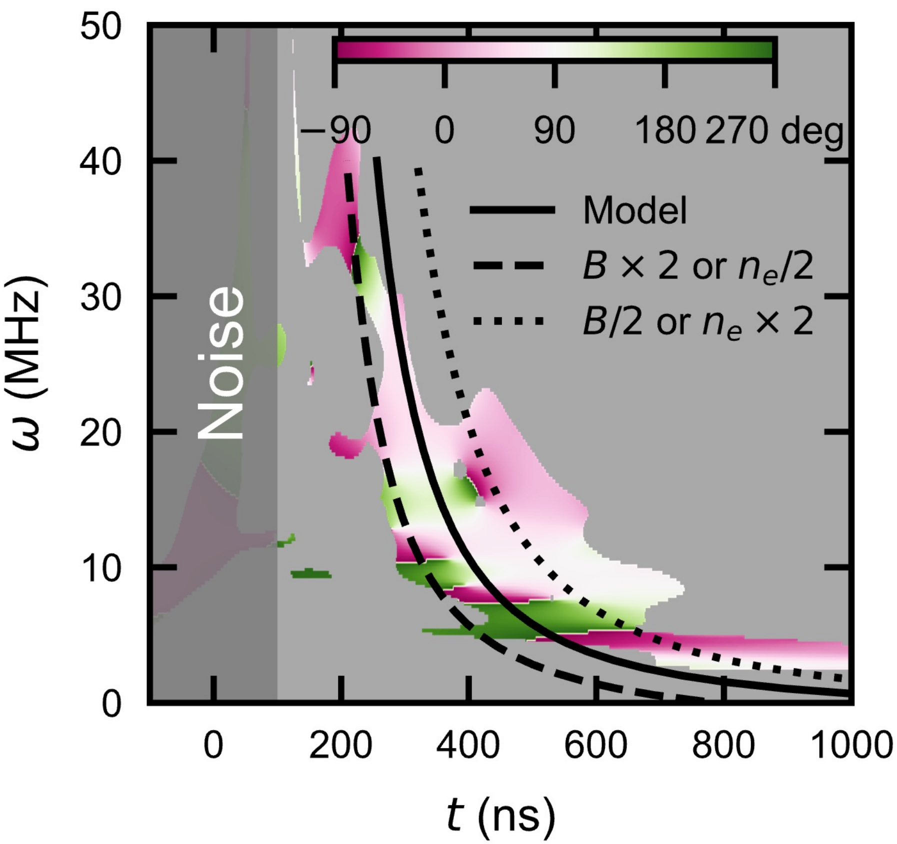
$$v_g \sim \frac{c\sqrt{\omega\Omega_e}}{2\omega_{pe}} \propto \sqrt{\frac{\omega B}{n_e}}$$

- Wavefront propagation velocity in the laboratory frame;

$$\frac{dx}{dt} = \frac{x}{t} + v_g$$

- Initial conditions from observation; $n_e \sim 10^{17}$ cm^{-3}, $B \sim 3$ kG, $t_0 = 50$ ns, $x_0 = 0$ cm

Phase difference of B_2&B_3



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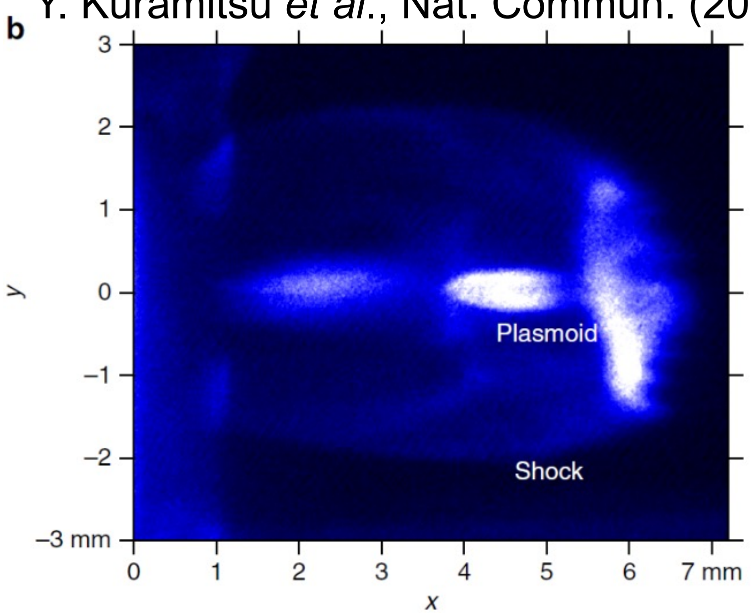
- Model calculation explains the frequency chirp
- Whistler waves coming from the reconnection region
- **Evidence of electron-scale dynamics**

Summary–1

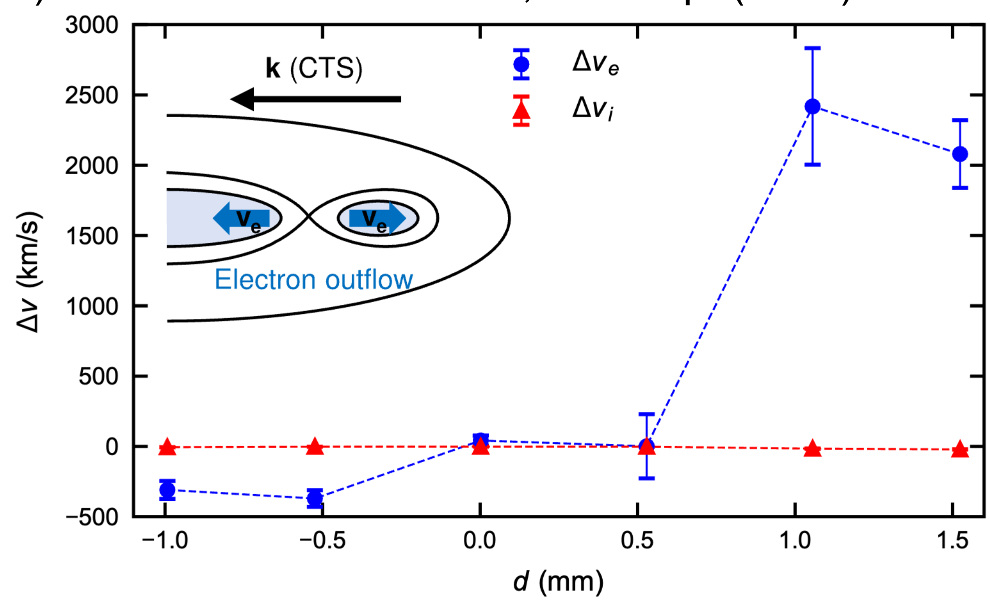
- Magnetic reconnection driven by electron dynamics
- Electron Alfvénic outflow without ion outflow
- Magnetic field inversion relevant to the plasmoid
- Whistler waves associated with electron dynamics

Magnetic energy is released into only electron kinetic energy at the scale less than ion gyroradius

Y. Kuramitsu *et al.*, Nat. Commun. (2018)



K. Sakai *et al.*, Sci. Rep. (2022)



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Y. Kuramitsu, T. Minami, S. Egashira, Y. Sakawa, N. Ozaki, R. Kodama, H. Takabe

K. Sakai, T. Moritaka, M. Ota

T. Morita, S. Matsukiyo

K. Tomita

R. Yamazaki, S. J. Tanaka

T. Takezaki

M. Koenig, B. Albertazzi, P. Mabey

N. Woolsey

M. Hoshino

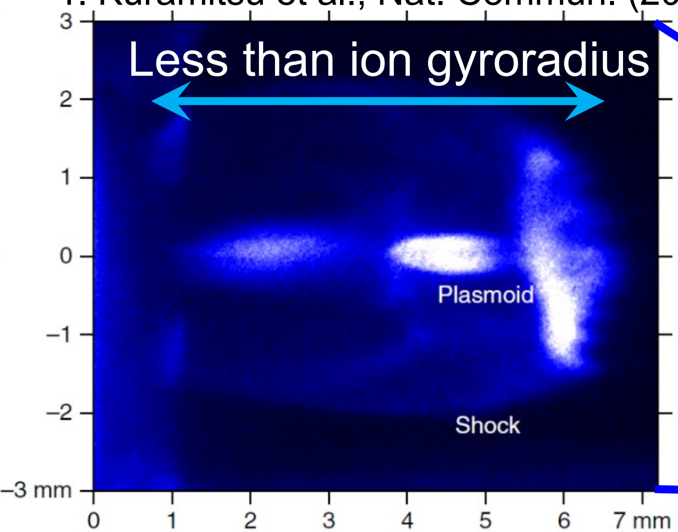
Perspectives

- Multiscale structures in reconnection
  - How microscopic (electron-scale) structures connect to macroscopic (MHD) ones?
  - Laser + magnetic device
- Wave excitations in reconnection
  - Where and what mechanism is the origin of waves such as whistlers?
  - Energy partition
  - Collective Thomson scattering
- Toward relativistic reconnection
  - Intense laser experiment
  - Scattered intense laser beam for diagnostics

What we have investigated

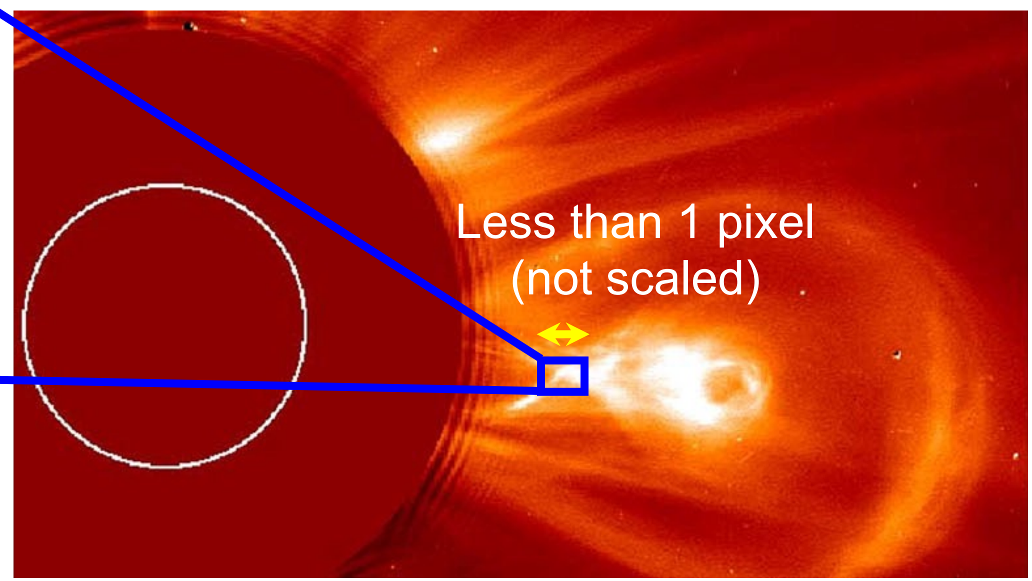
- Very small spatial and temporal scales less than ion gyromotion – electron-scale
- Both global/local observations but no multiscale ones

Y. Kuramitsu et al., Nat. Commun. (2018)



Laboratory experiment
Controlled manner
Global structure

Solar flare



A. O. Benz, Living Rev. Sol. Phys. (2017)

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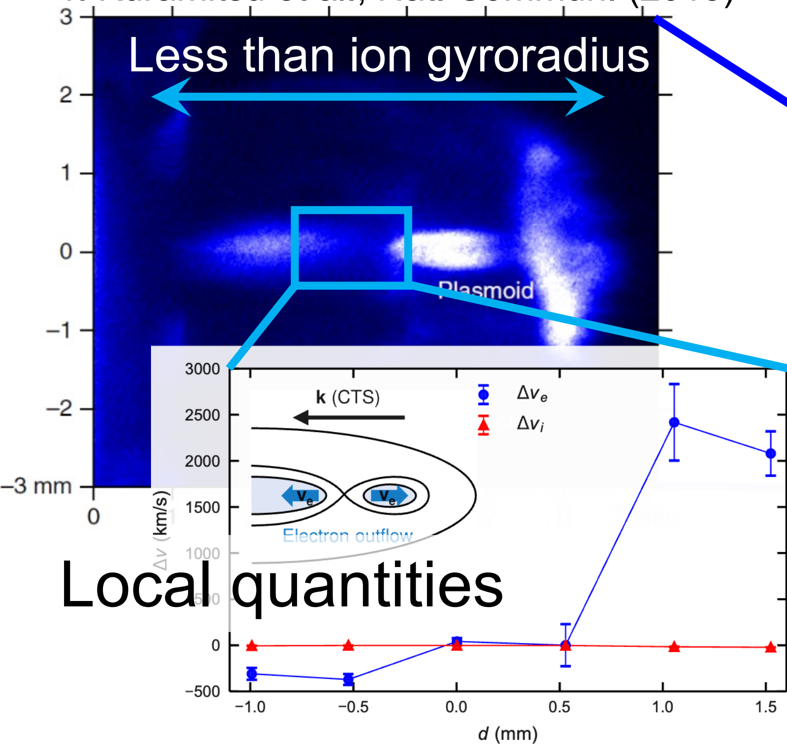
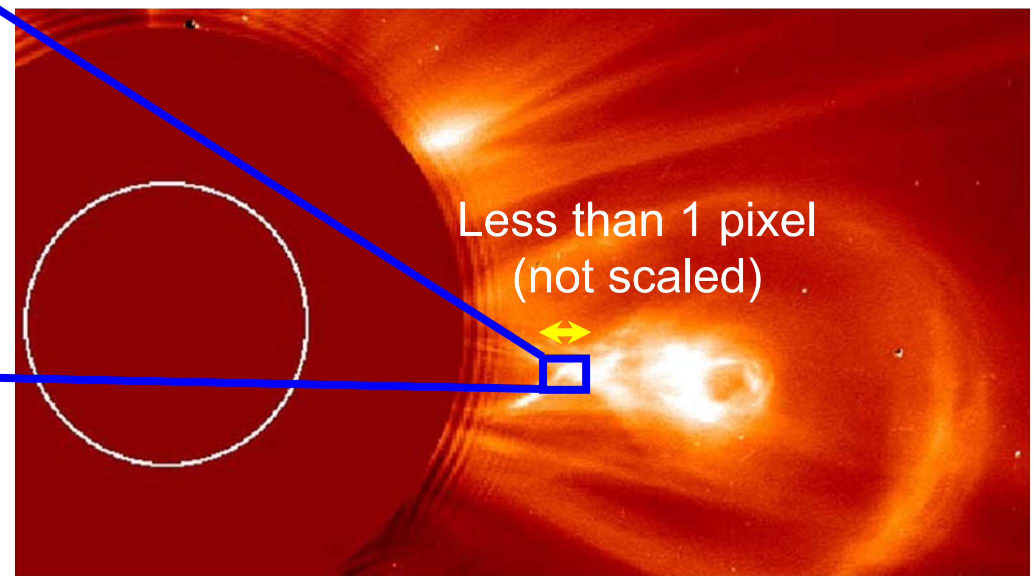


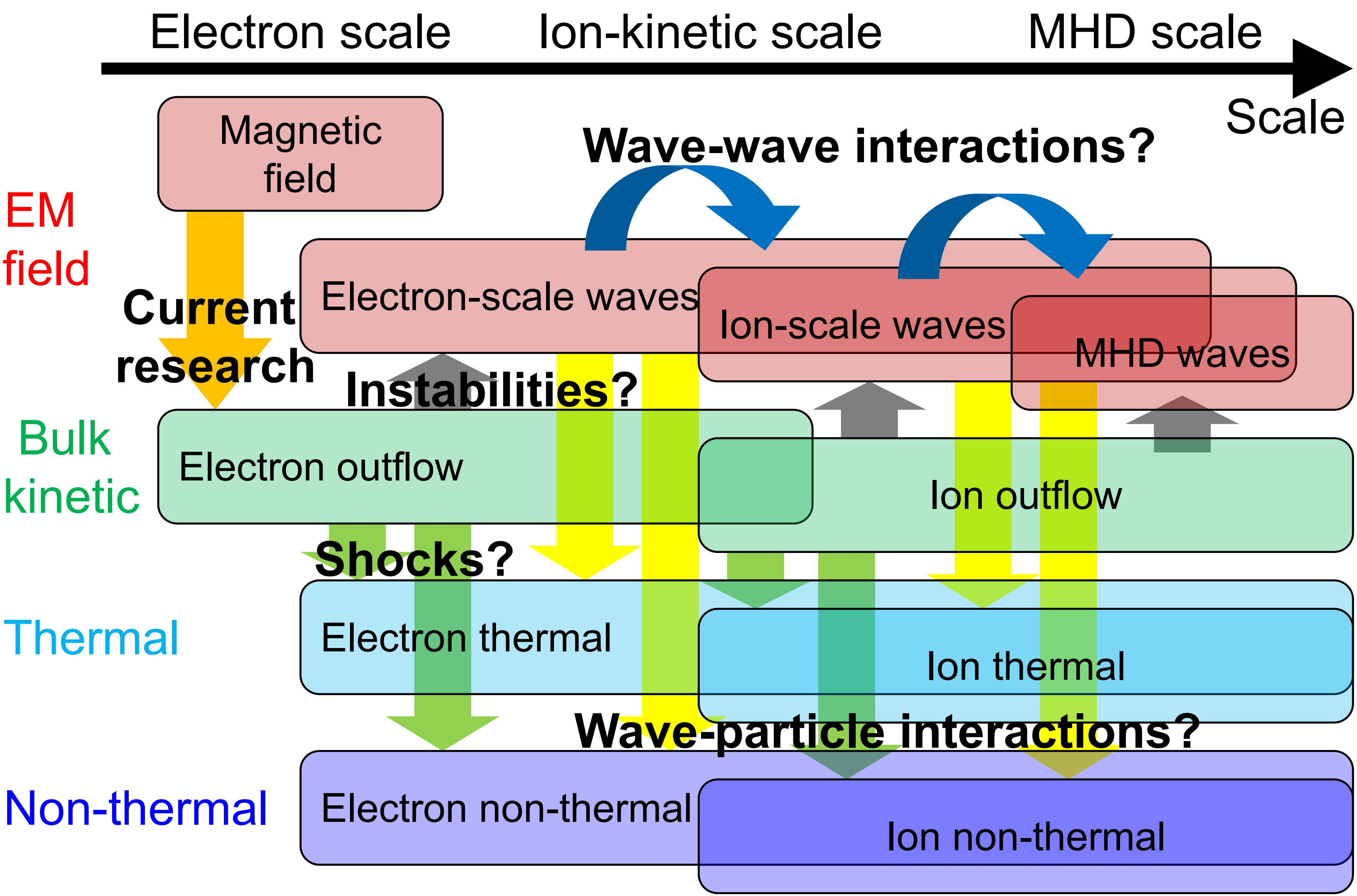
K. Sakai et al., Sci. Rep. (2022)

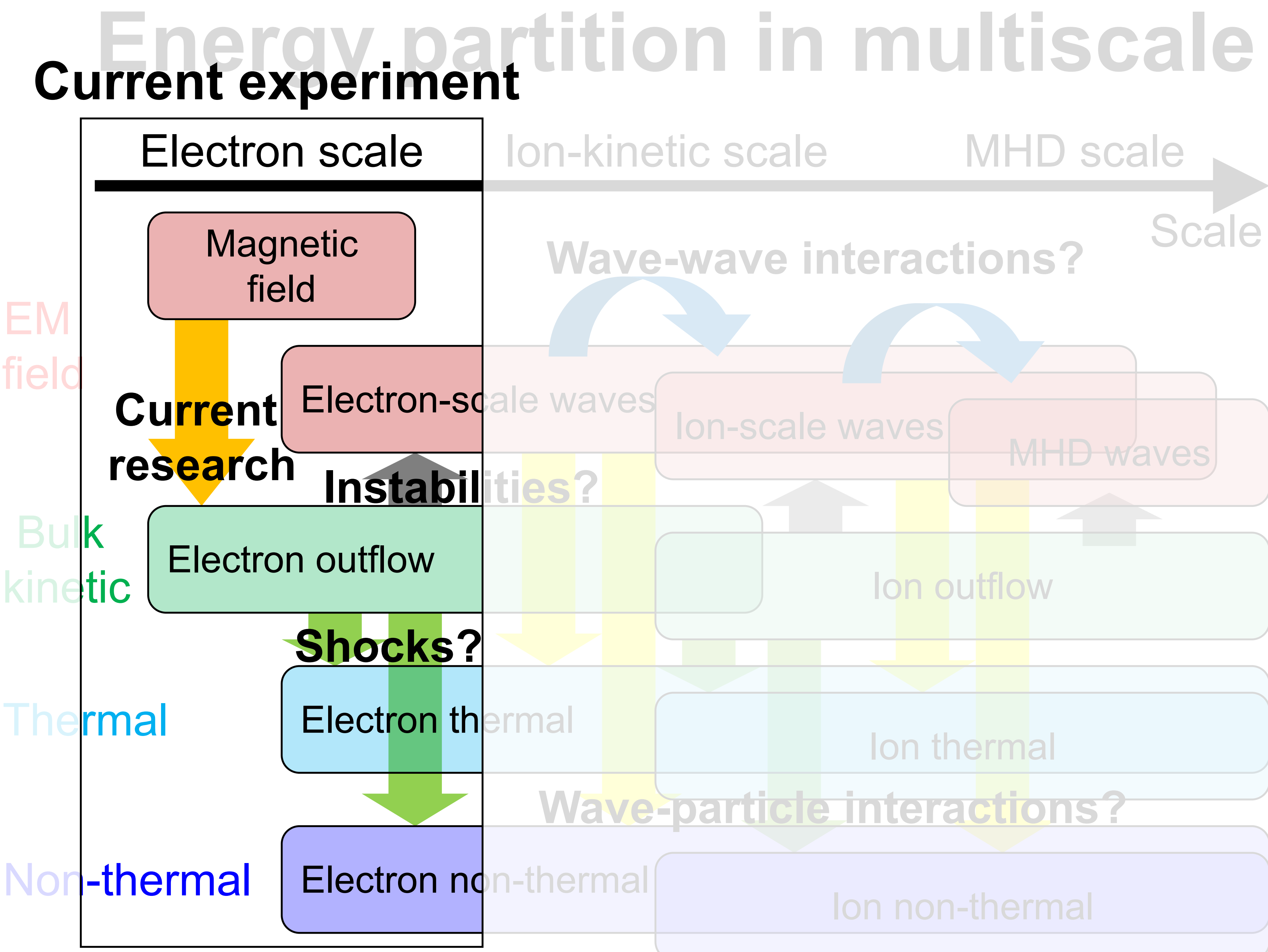
Solar flare



A. O. Benz, Living Rev. Sol. Phys. (2017)

Energy partition in multiscale

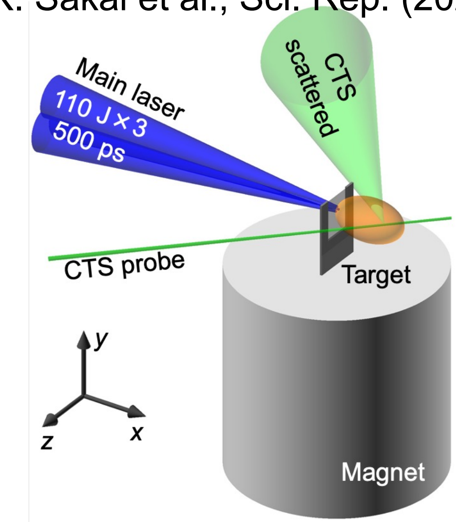



Energy partition in multiscale
Current experiment
Electron scale
Ion-kinetic scale
MHD scale
Scale
Wave-wave interactions?
EM field
Magnetic field
Current research
Electron-scale waves
Ion-scale waves
MHD waves
Instabilities?
Bulk kinetic
Electron outflow
Ion outflow
Shocks?
Thermal
Electron thermal
Ion thermal
Wave-particle interactions?
Non-thermal
Electron non-thermal
Ion non-thermal

Limitations of laser exp.

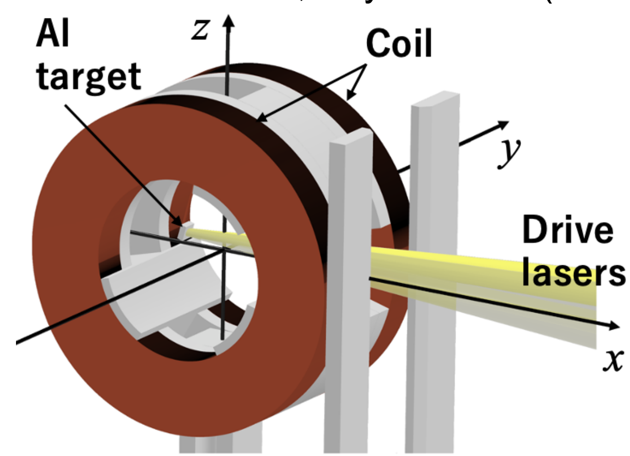
- Laser-produced fast plasma flow enlarges gyroradii
- Limit of B field strength (technical issue)
- Small system size (< 1 cm) compared to ion gyroradii
- Short lifetime (<100 ns) compared to ion gyroperiod
- Difficult to magnetize ions
- No MHD scales

K. Sakai et al., Sci. Rep. (2022)



B ~ 3 kG, r_{gi} ~ 2 cm, L ~ 1 cm

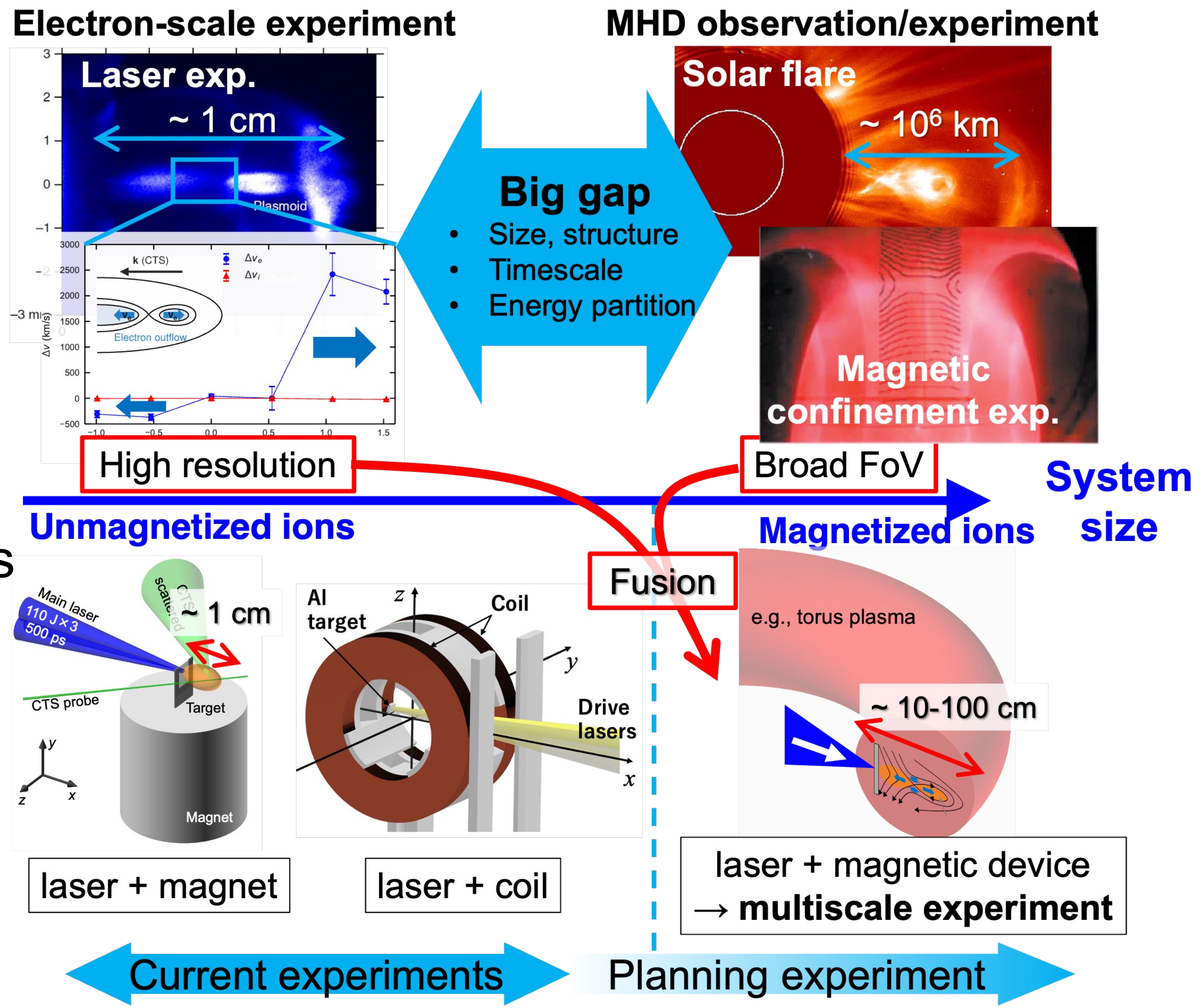
R. Yamazaki et al., Phys. Rev. E (2022)



B ~ 40 kG, r_{gi} ~ 3 mm, L ~ 1 cm

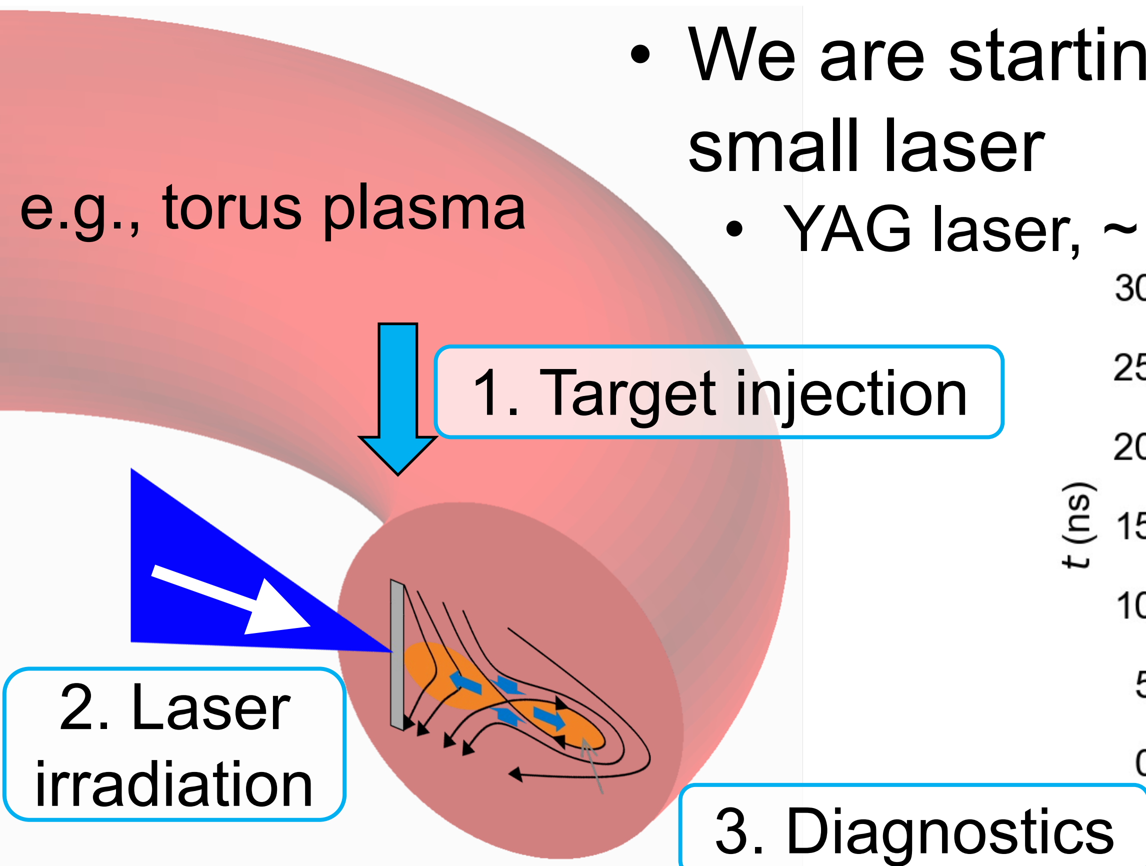
Electron to MHD scales

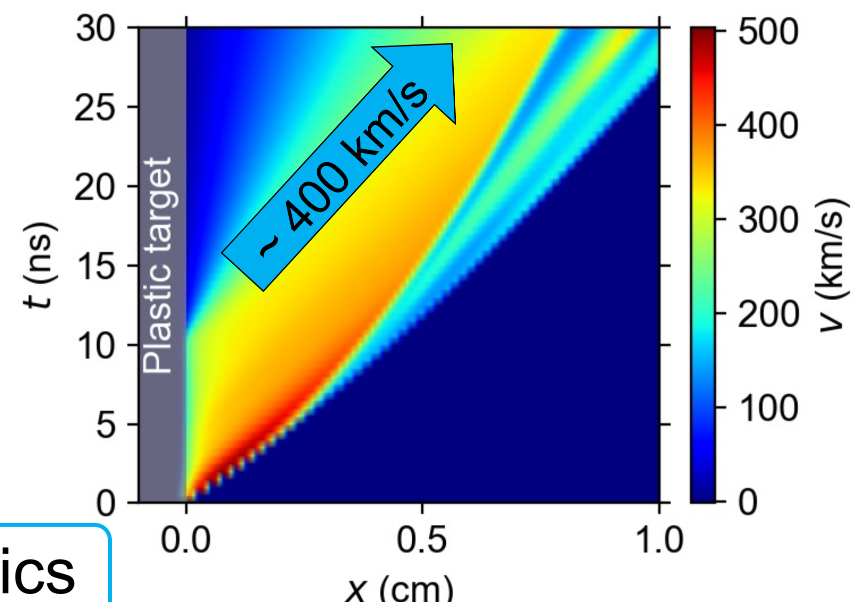
- Larger spatial and temporal scales to reach MHD
  - Magnetically confined plasmas
- Electron-scale measurements
  - Lasers
- “Fusion” of magnetically confined plasmas with lasers



Planning experiment

- The same setup as the previous laser-plasma experiment but the ambient plasma is a magnetically-confined one
- We are starting with a relatively small laser
  - YAG laser, ~ 1 J, 10 ns, ~10^{12} W/cm^2





Radiation hydrodynamic simulation

Perspectives

- Multiscale structures in reconnection
  - How microscopic (electron-scale) structures connect to macroscopic (MHD) ones?
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- Wave excitations in reconnection
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  - Intense laser experiment
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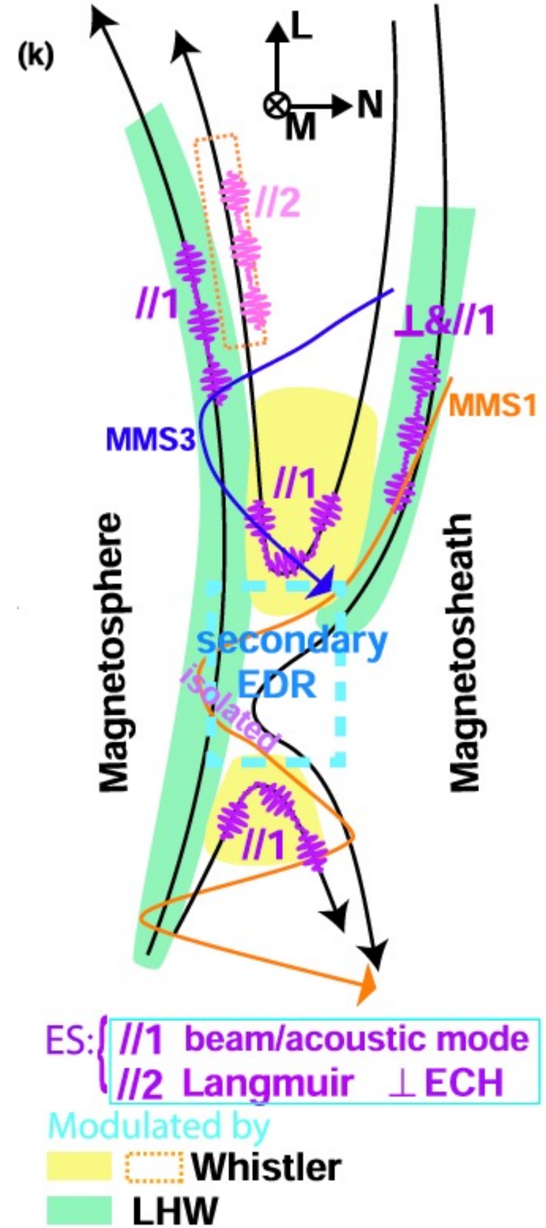
Waves in reconnections

- Free energy of electron outflow can excite waves by instabilities
  - Such as whistler waves
- Waves can heat plasmas and accelerate particles
  - Important to understand energy partition during reconnection
- How can we observe waves and instabilities?

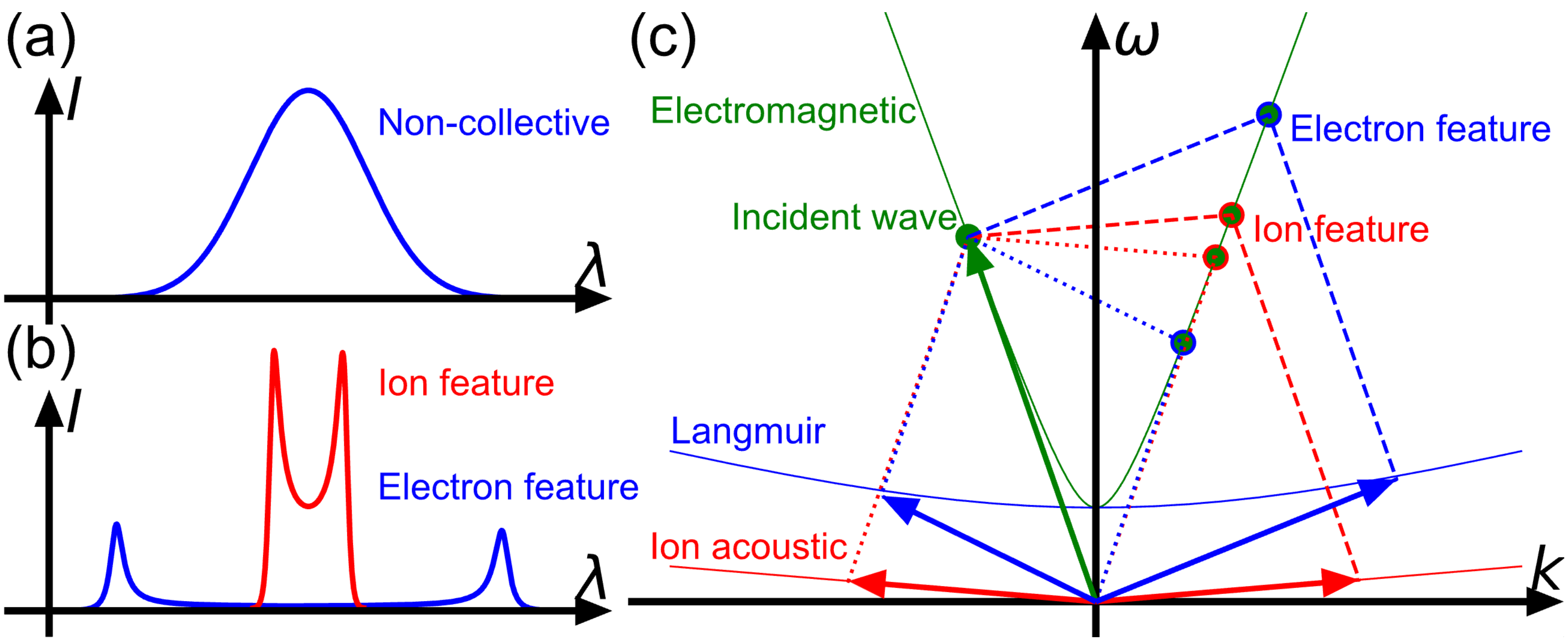
➡ Collective Thomson scattering



S. Wang et al., Geophys. Res. Lett. (2023)

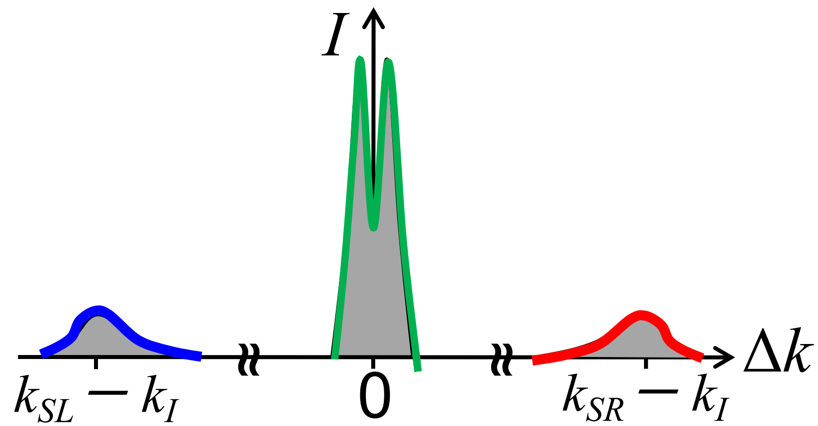
Thomson scattering

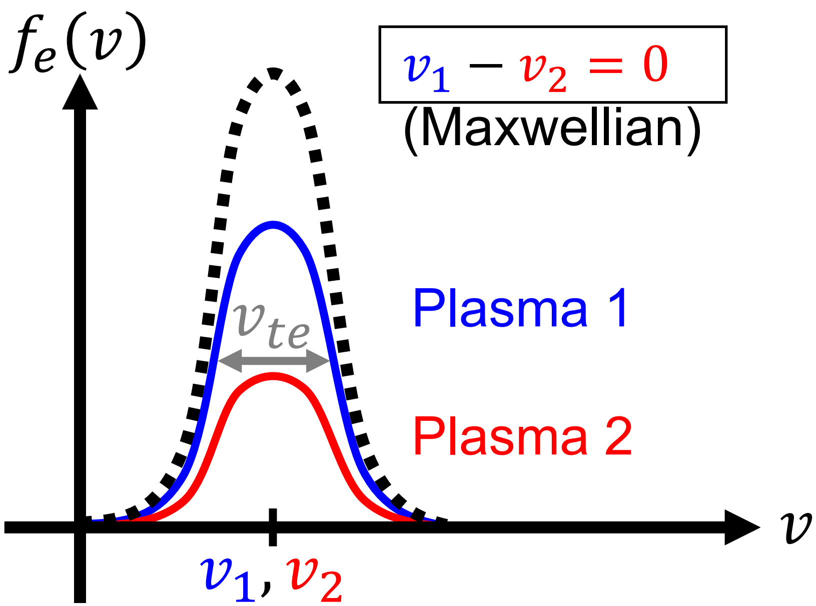
- Light scattering by charged particles (mainly electrons)
- Spectral shape corresponds to $f_e(v)$
- $\lambda_I > \lambda_D$ ➡ collective Thomson scattering (CTS)
- CTS analysis in non-equilibrium plasmas accompanied with wave excitations is not established

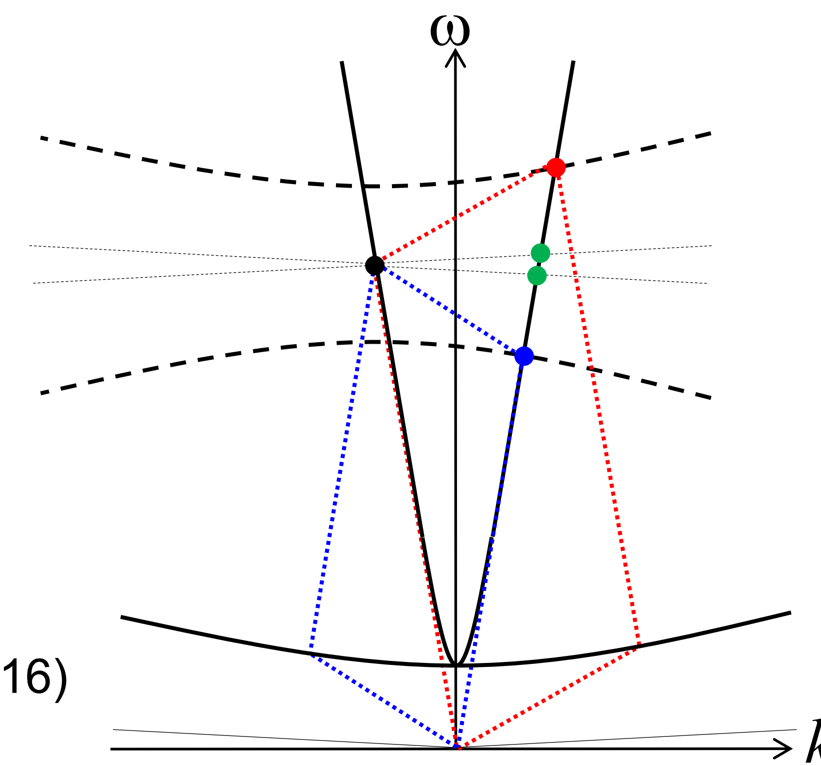


Waves/instabilities in CTS

- Electron two-stream instability as an example
- Landau damping
- Peak associated with the excited wave







S. Matsukiyo *et al*., J. Phys. Conf. Ser. (2016)
K. Sakai *et al*., Phys. Plasmas (2020)

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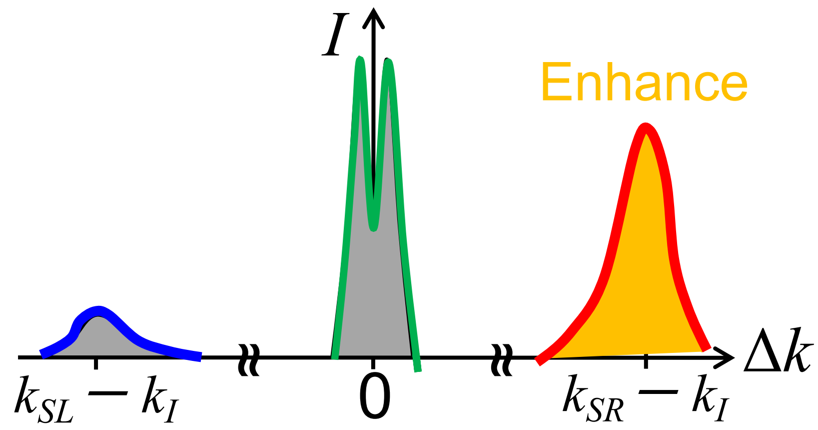
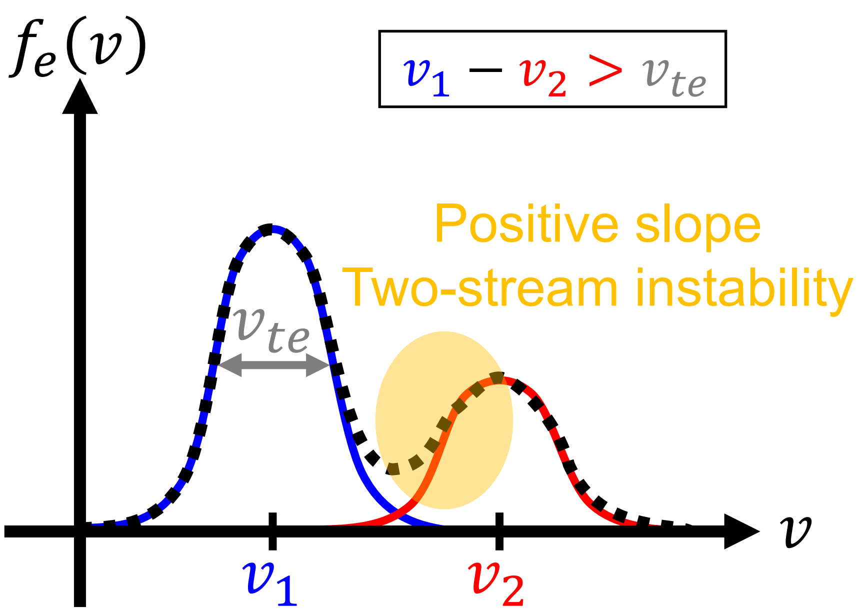
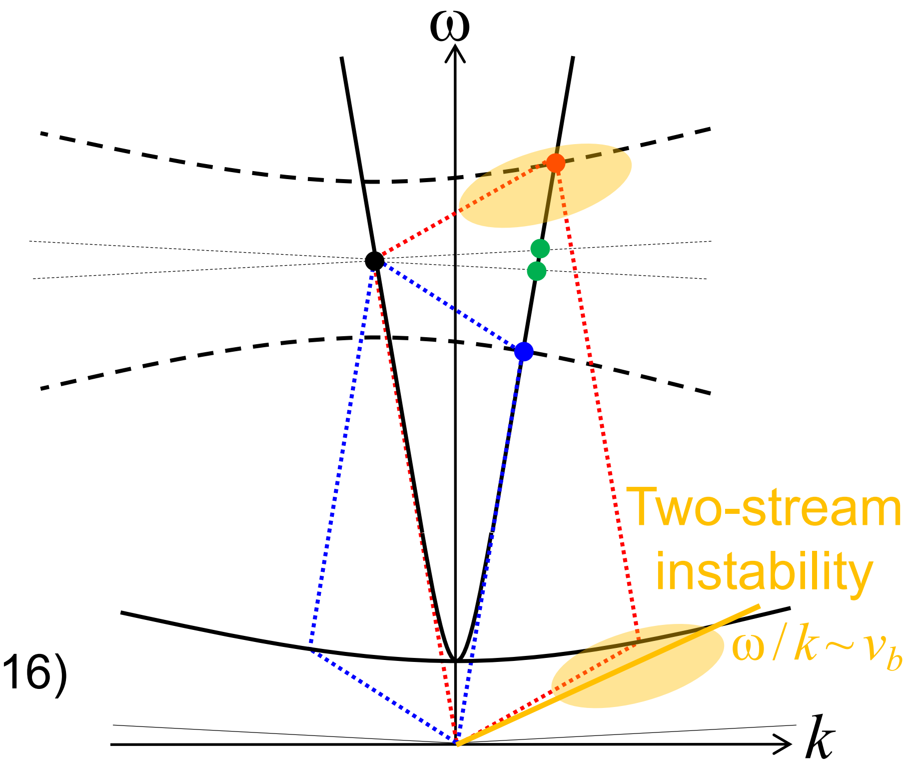






S. Matsukiyo *et al*., J. Phys. Conf. Ser. (2016)
K. Sakai *et al*., Phys. Plasmas (2020)

Numerical simulation

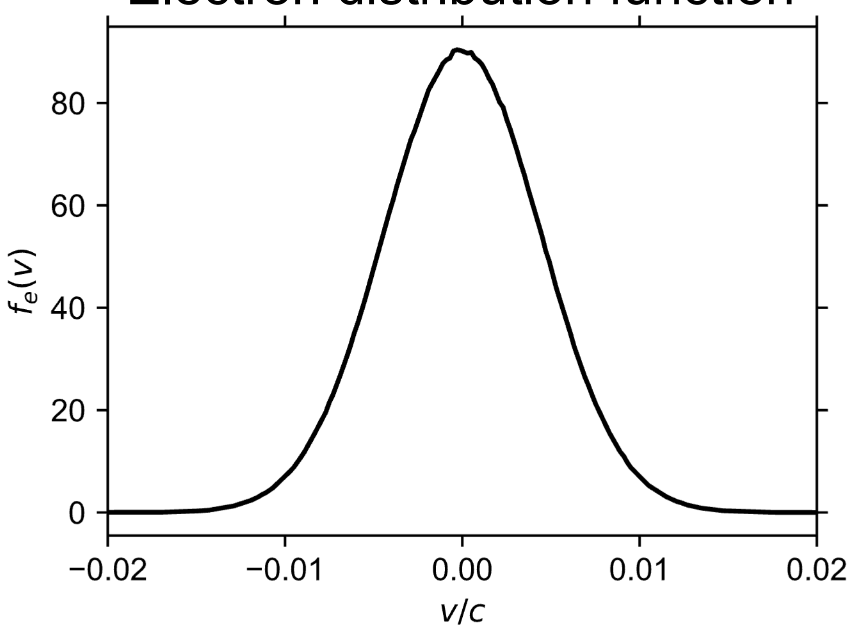
- Spectrum from arbitral distribution function
- Scattered wave solving wave equation

$$\left(-\nabla^2 + \frac{1}{c^2}\frac{\partial^2}{\partial t^2} + \frac{\omega_p^2}{c^2}\right)\boldsymbol{E_S} = \frac{4\pi e}{c^2}\frac{\partial}{\partial t}\left(\boldsymbol{v_{Ie}}\delta n_e - \boldsymbol{v_{Ii}}\delta n_i\right)$$

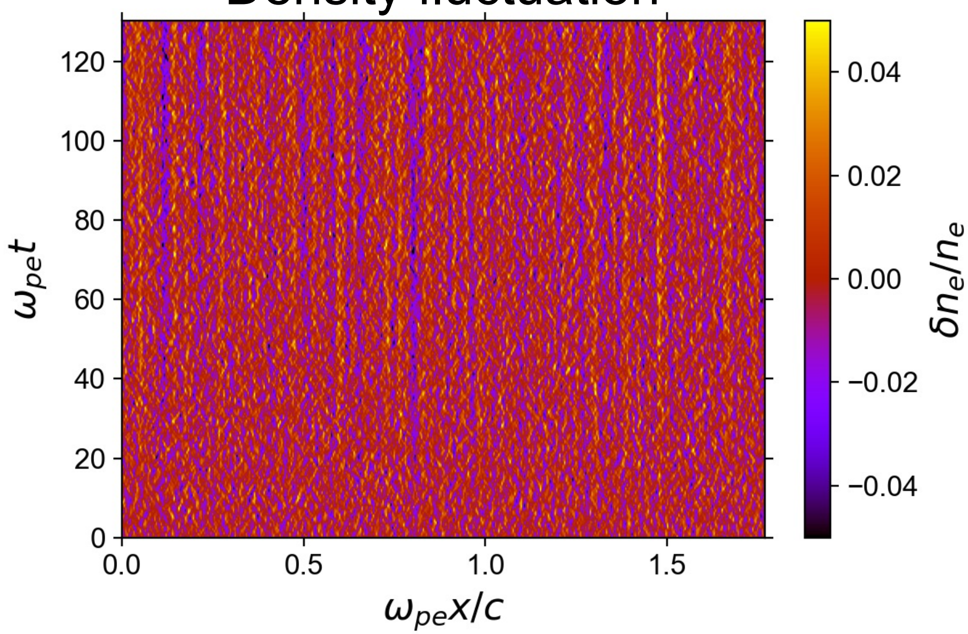
S. Matsukiyo *et al*., J. Phys. Conf. Ser. (2016)

- n_e from particle-in-cell simulation

Electron distribution function



Density fluctuation



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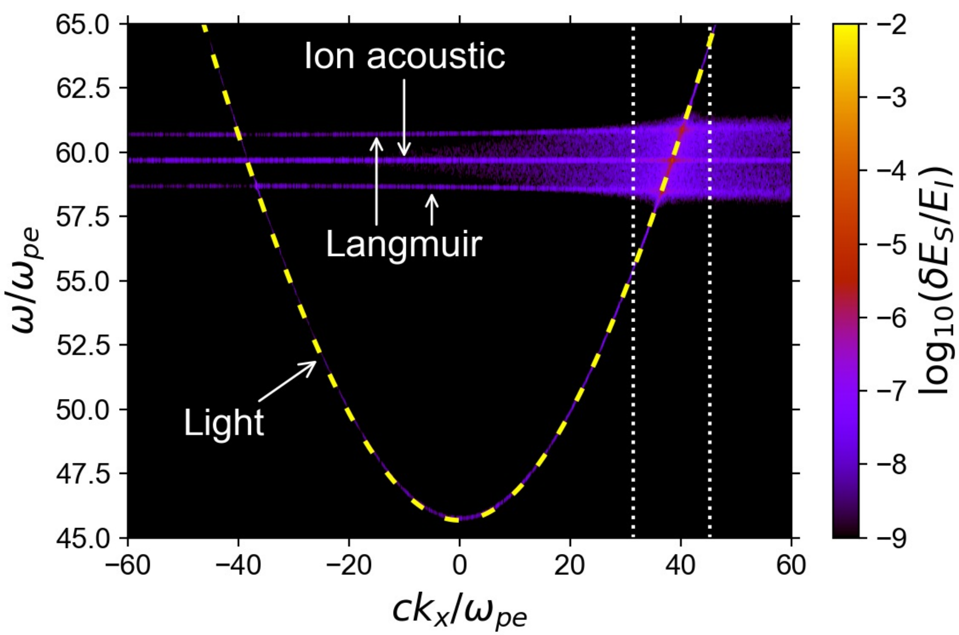
S. Matsukiyo *et al*., J. Phys. Conf. Ser. (2016)

- *E* field of scattered wave in *k*-*ω* space



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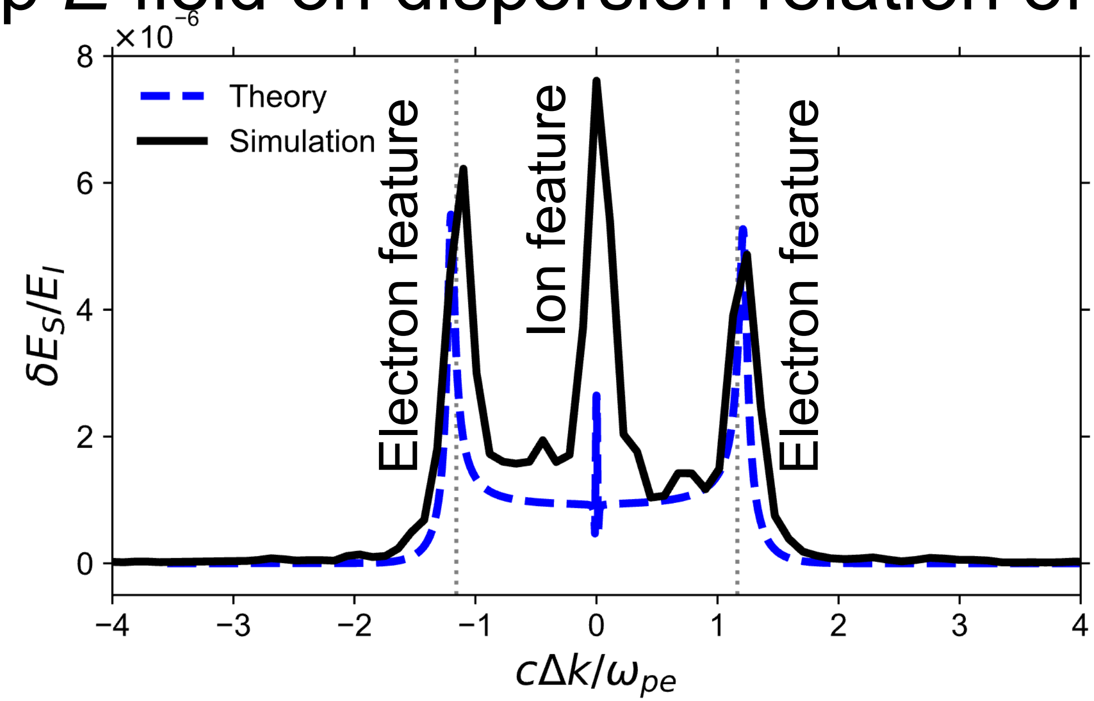
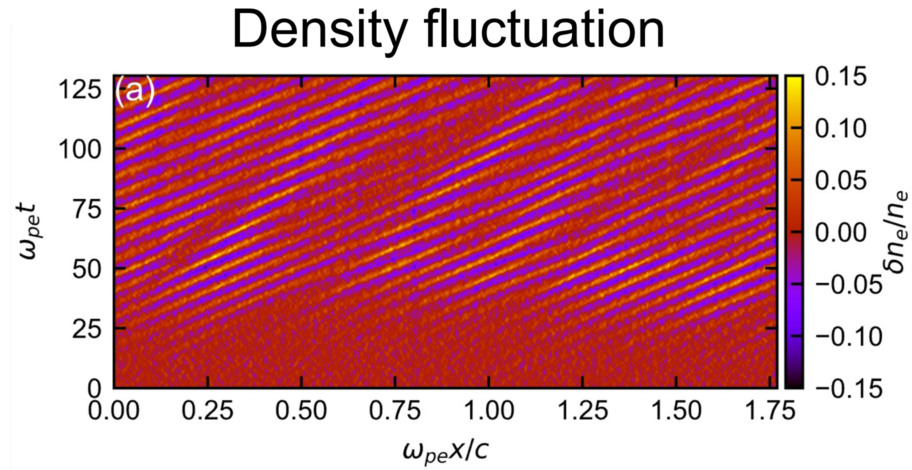
S. Matsukiyo *et al*., J. Phys. Conf. Ser. (2016)

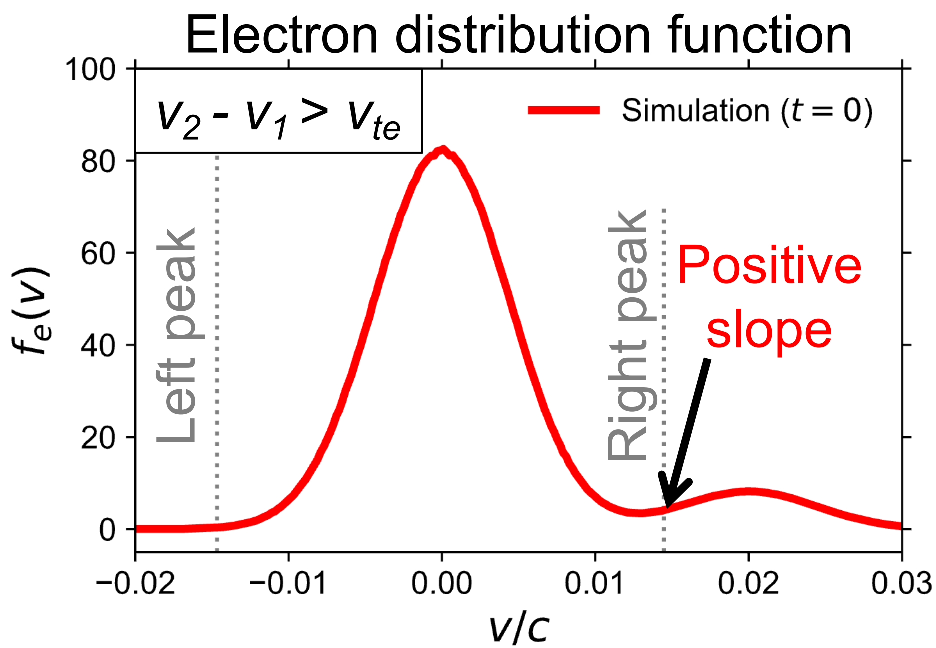
- Pick up *E* field on dispersion relation of light

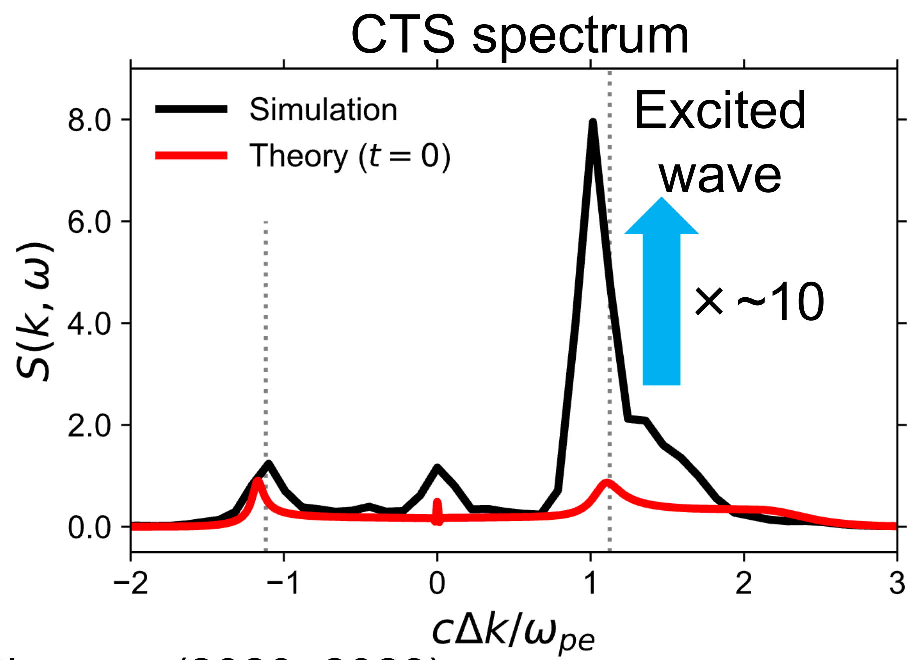


Simulated CTS spectrum

- Electron two-stream instability
- Enhanced spectrum associated with excited waves
- Temporal evolution of electron distribution function explains the spectrum







K. Sakai *et al.*, Phys. Plasmas (2020, 2023)

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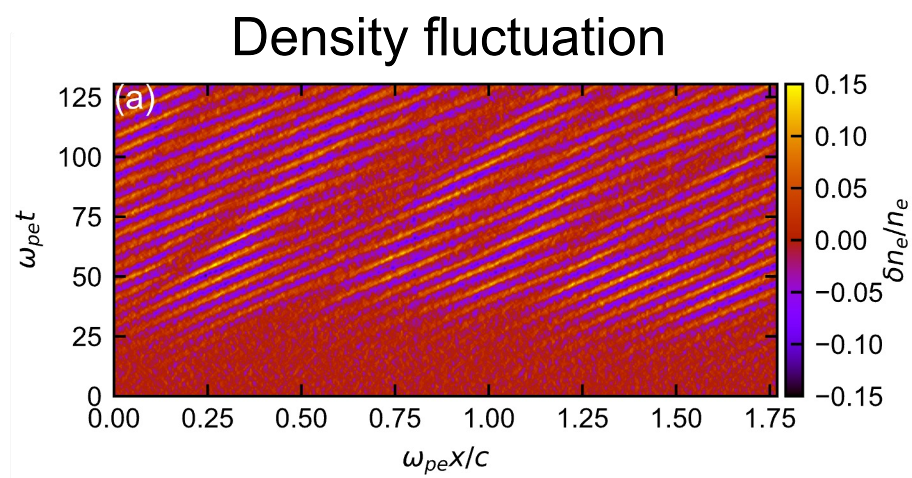

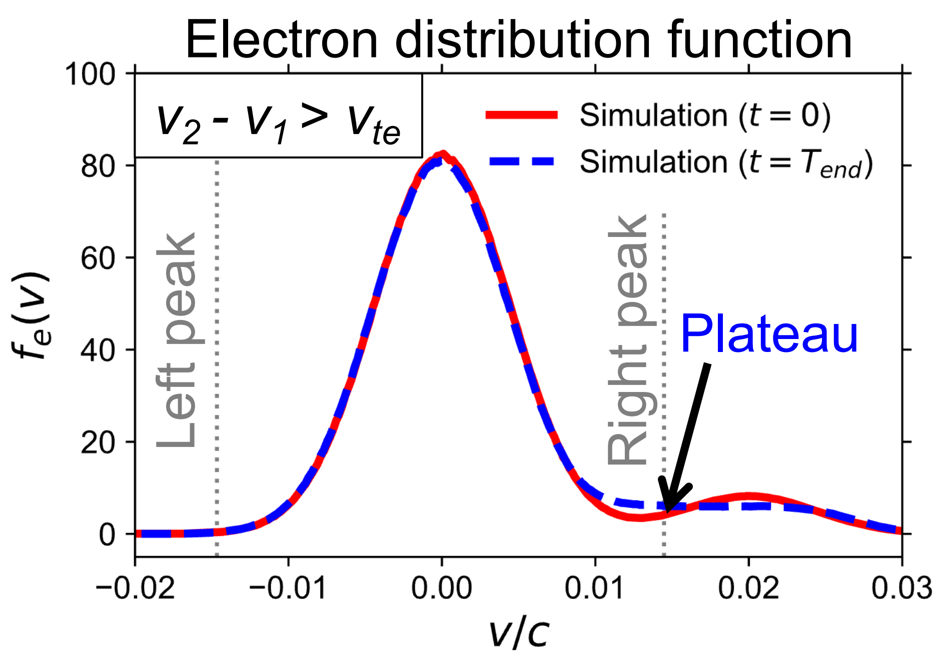

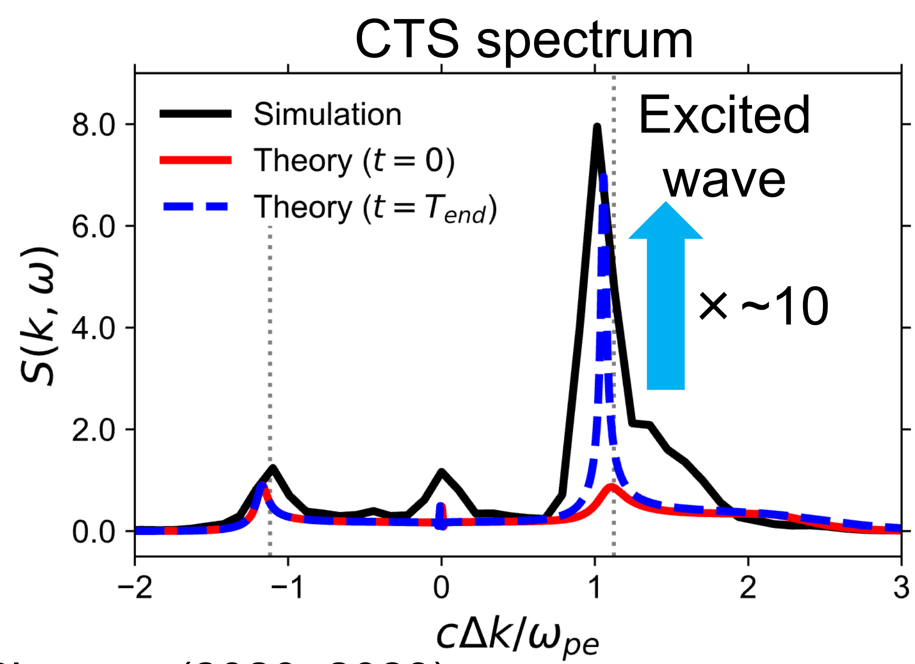

K. Sakai *et al*., Phys. Plasmas (2020, 2023)

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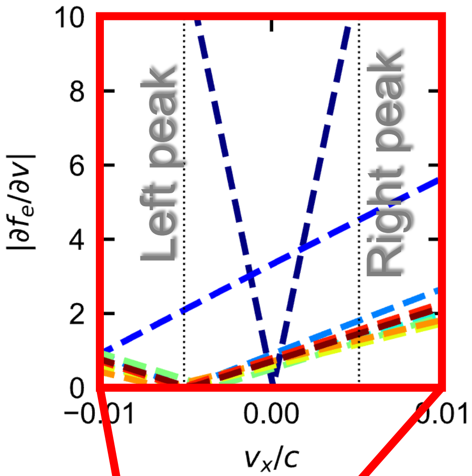
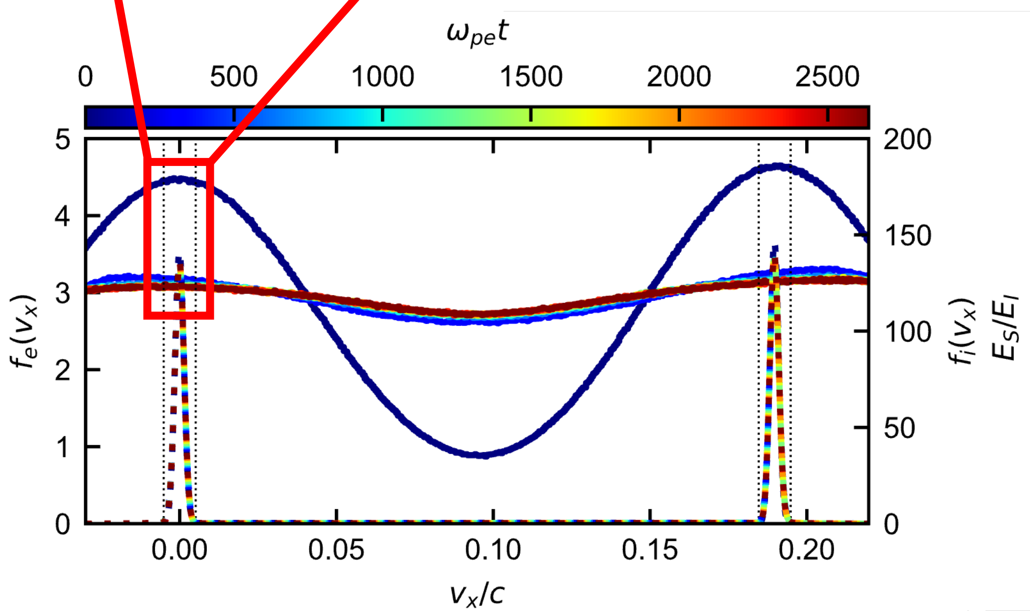
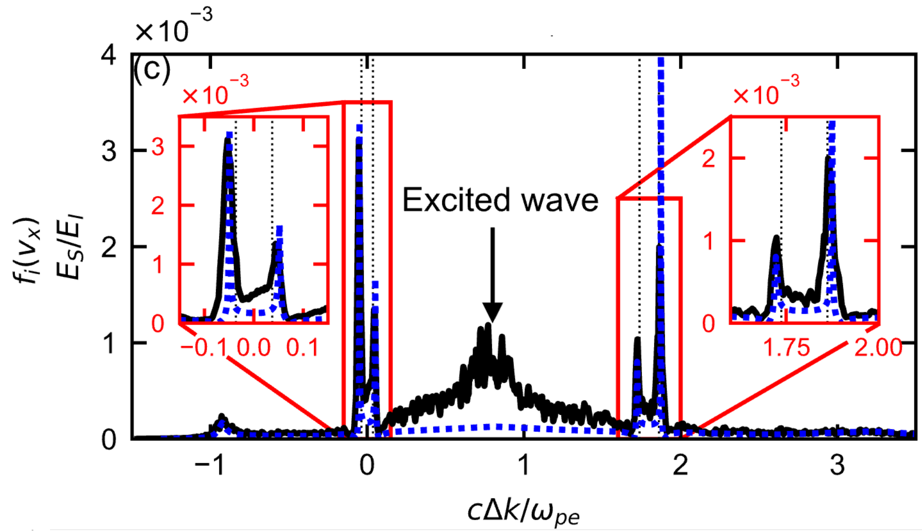


- Asymmetries in ion acoustic feature
- Landau damping rate of ion acoustic wave is different for two peaks

➡ **One can identify two-stream instability by observing excited waves and asymmetries in electron and ion features**

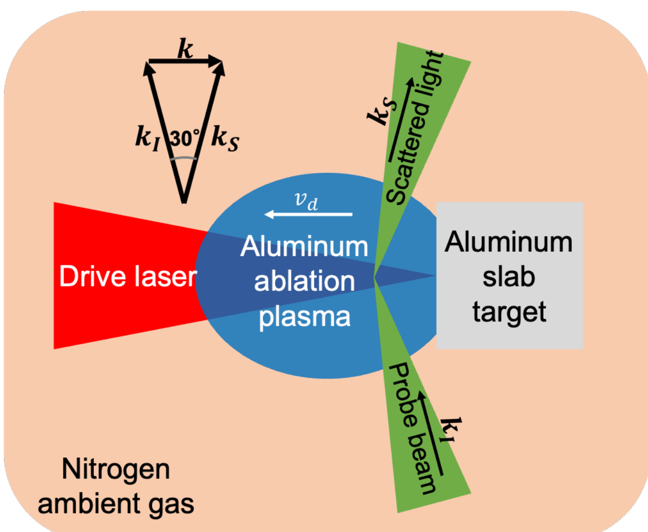


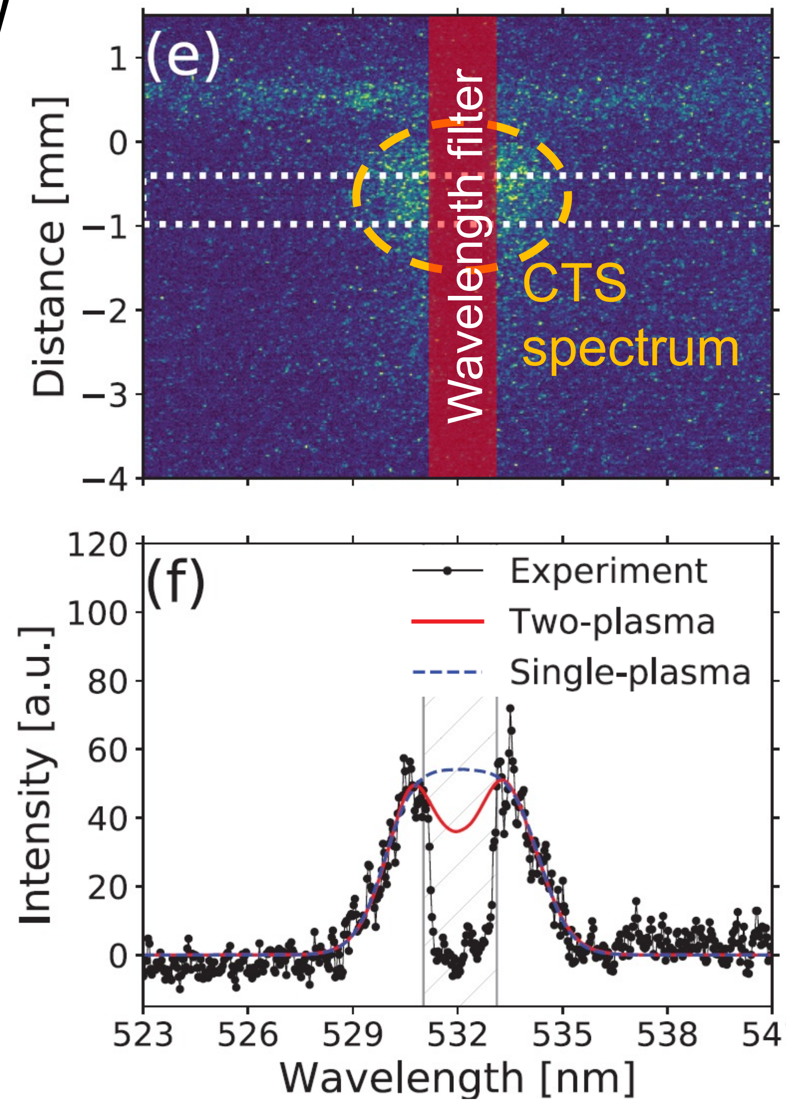


K. Sakai *et al.*, Phys. Plasmas (2020, 2023)

Proof-of-principle experiment

- Ongoing project at NCU 100-TW facility
  - High repetition rate (10 Hz)
  - 3.3 J, 150 ps, ~1×10^{15} W/cm^2
  - Ablation plasma and ambient gas
- Preliminary results
  - Low flow speed
  - No ion feature spectrometer





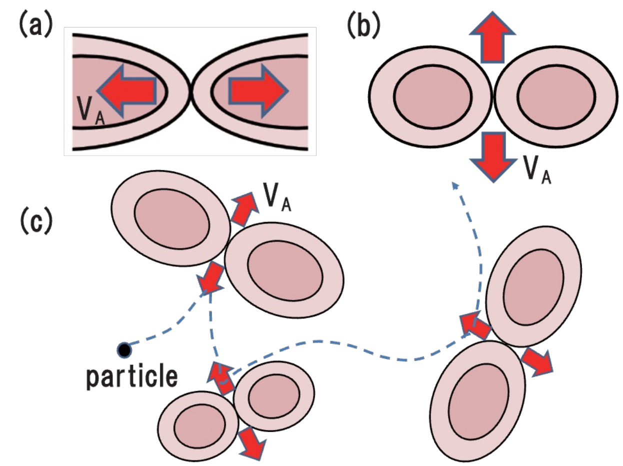
K. Sakai *et al.*, Phys. Plasmas (2020)

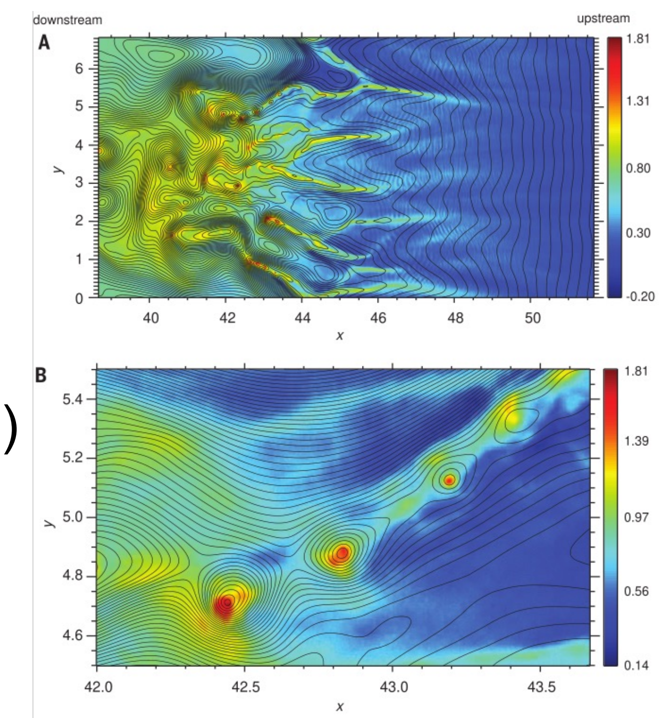
Perspectives

- Multiscale structures in reconnection
  - How microscopic (electron-scale) structures connect to macroscopic (MHD) ones?
  - Laser + magnetic device
- Wave excitations in reconnection
  - Where and what mechanism is the origin of waves such as whistlers?
  - Energy partition
  - Collective Thomson scattering
- Toward relativistic reconnection
  - Intense laser experiment
  - Scattered intense laser beam for diagnostics

Role of magnetic reconnection as a particle accelerator

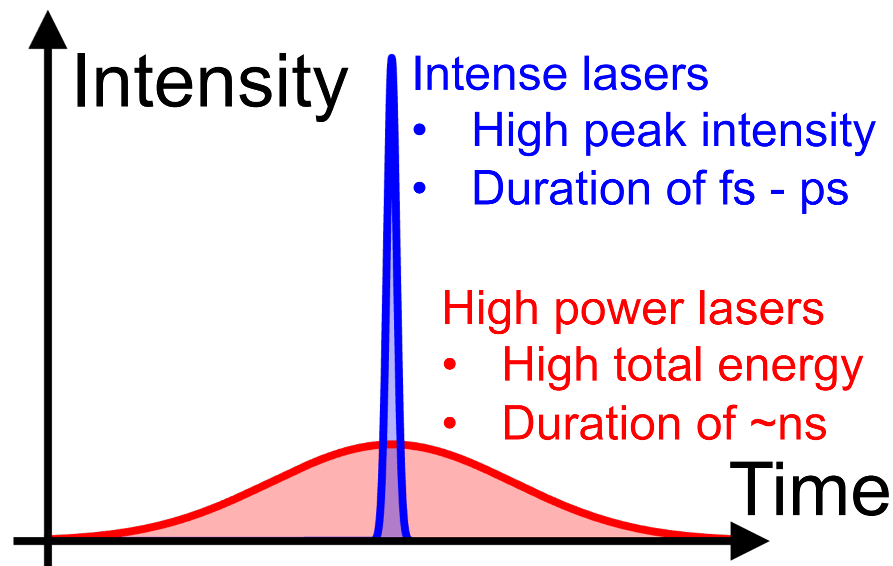
- Multiple reconnection outflows kicking particles many times
  ➡ stochastic acceleration
  M. Hoshino, Phys. Rev. Lett. (2012)
- Stochastic electron acceleration by multiple reconnections in a shock
  Y. Matsumoto *et al*., Science (2015)
- We are planning a model experiment with intense lasers
  Y. Kuramitsu *et al*., Phys. Plasmas (2023)
- “relativistic” laboratory astrophysics





Toward "relativistic" laboratory astrophysics

- High power lasers
  - Generate a large-scale plasma with high flow speed
  - e.g., Gekko XII (ILE, Osaka)
- Intense lasers
  - Generate a plasma flow close to the speed of light
  - e.g., LFEX (ILE, Osaka), J-KAREN (KPSI, QST), NCU 100-TW (National Central Uinv.)
- Limited diagnostics
  - Due to short pulse duration
- Scattered light from intense laser itself



Experimental setup

- 以下未発表データにつき省略

Summary

- Experimental investigations on space and astrophysical plasmas with high-power/intense lasers
- Magnetic reconnection driven by electron dynamics
- Laser +α: multiscale observations of magnetic reconnection with laser + magnetic device
- Collective Thomson scattering to measure waves and instabilities
- Scattering in intense laser beam toward relativistic reconnection experiment

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