Particle acceleration and plasma heating in magnetized plasmas by large-amplitude electromagnetic waves

Takayoshi Sano
(Institute of Laser Engineering, Osaka University)

Collaborators:
S. Isayama, S. Matsukiyo (Kyushu U), M. Hata (QST),
K. Sugimoto (Kyoto U), Y. Sentoku (Osaka U)

Keihan Astrophysics Meeting 2024 fall
2024/10/2 (YITP, Kyoto U)

Laser Fusion
Laser Astrophysics

GEKKO(激光) & LFEX

1 kJ

100 um

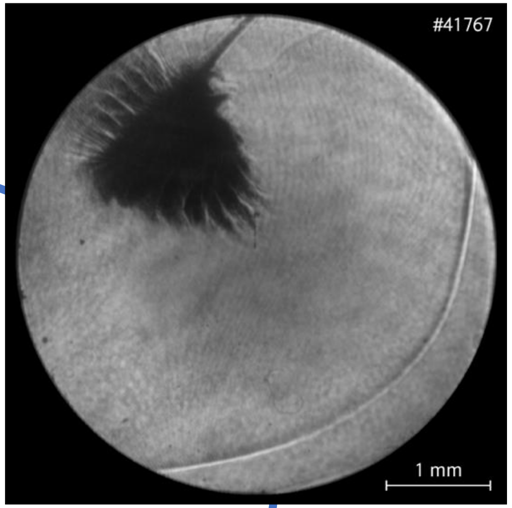
ns laser ↔ ps laser

10 GPa ↔ 10 PPa

High Energy Density (High Pressure) State

$$I_L = \frac{E_L}{\tau_L A} \sim 10^{20}\ [\mathrm{W/cm^2}]$$

$$P = \frac{I_L}{c} \sim 10\ [\mathrm{PPa}]$$

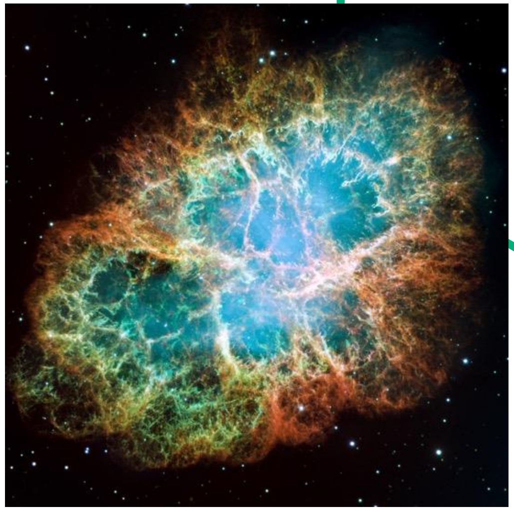


Laser Plasma

Plasma Processes

Collisionless Shock
Turbulence
Magnetic Reconnection etc.

Astrophysical Plasma



Laser Experiment
Numerical Simulation

High Intensity Laser (Relativisitic Intensity Laser)

- Equation of Motion for Electrons in Electromagntic Fields

$$\frac{d\boldsymbol{p}}{dt} = -e\boldsymbol{E} \xrightarrow{\text{Normalized}} \frac{d\widetilde{\boldsymbol{p}}}{d\widetilde{t}} = -\boldsymbol{a}_0$$

$$\widetilde{\boldsymbol{p}} = \frac{\boldsymbol{p}}{m_e c} \qquad \widetilde{t} = \omega_0 t \qquad \boldsymbol{a}_0 = \frac{e\boldsymbol{E}}{m_e c \omega_0}$$

Typical Energy

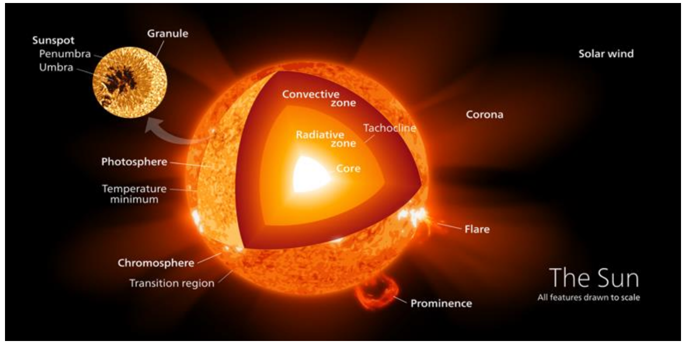
$$\widetilde{p} \sim a_0$$

$$\gamma - 1 \sim \sqrt{1 + \widetilde{p}^2} - 1 \sim a_0$$

- Relativistic Intensity: $a_0 > 1$
- For a Typical Laser Case (Wavelength = 1 micron)

$$I > 10^{18}\ [\mathrm{W/cm^2}]$$

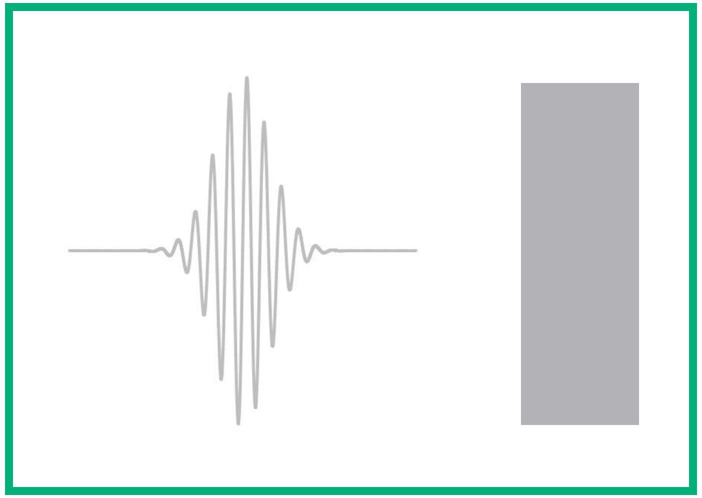
$$P \sim 10 \left(\frac{I}{10^{20}} \right)\ [\mathrm{PPa}]$$



Laser Plasma Parameters (1)

- Laser Parameter (Characteristic)

$$\lambda_0 = 1\ \mu\mathrm{m} \qquad \omega_0 = 2\pi c/\lambda_0 \qquad \tau_0 = 3\ \mathrm{fs}$$



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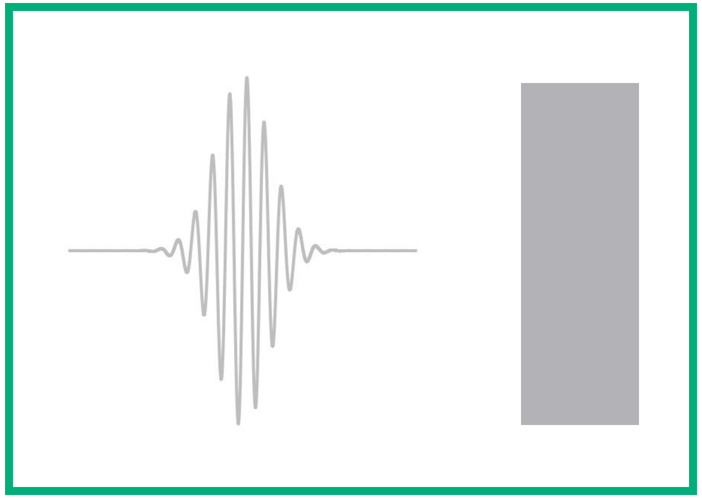
- Laser Parameter (Characteristic)

$$\lambda_0 = 1\ \mu\mathrm{m} \qquad \omega_0 = 2\pi c/\lambda_0 \qquad \tau_0 = 3\ \mathrm{fs}$$

Laser Amplitude

$$a_0 = \frac{eE_0}{mc\omega_0}$$



Plasma Density

$$\tilde{n}_e = \frac{n_e}{n_c} = \frac{\omega_{pe}^2}{\omega_0^2}$$

$$\frac{d\boldsymbol{p}}{dt} = -e\boldsymbol{E} \xrightarrow{\text{Normalized}} \frac{d\tilde{\boldsymbol{p}}}{d\tilde{t}} = -\boldsymbol{a}_0$$

$$\tilde{\boldsymbol{p}} = \frac{\boldsymbol{p}}{m_e c} \qquad \tilde{t} = \omega_0 t$$

$$n_c \sim 10^{21} \left(\frac{\lambda_0}{1\ \mu\mathrm{m}}\right)^{-1} \quad [\mathrm{cm}^{-3}]$$

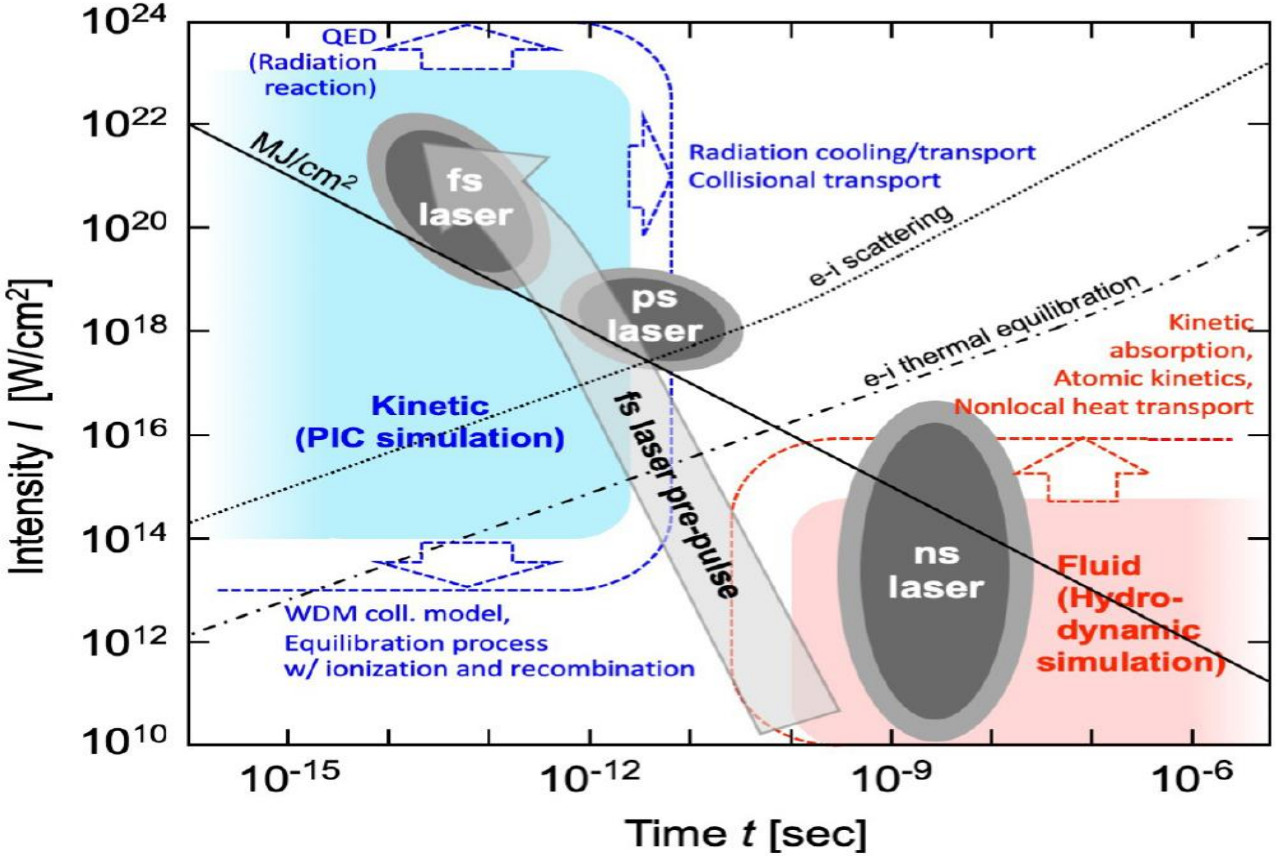
Laser Plasma Parameters (2)

fs Laser
J-KAREN-P @ QST
Duration $10\ \tau_0$

ps Laser
LFEX @ Osaka U
Duration $10^3\ \tau_0$

ns Laser
GEKKO @ Osaka U
Duration $10^6\ \tau_0$

Kinetic
PIC



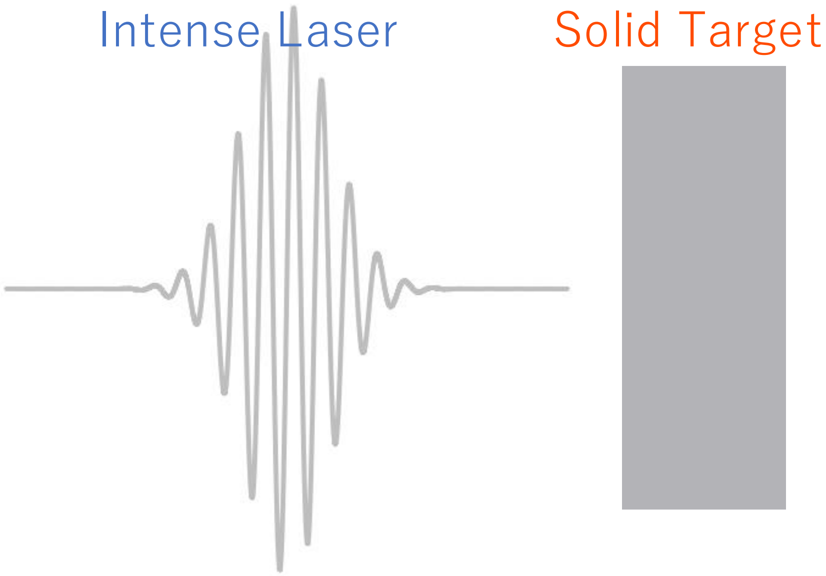
Fluid
MHD

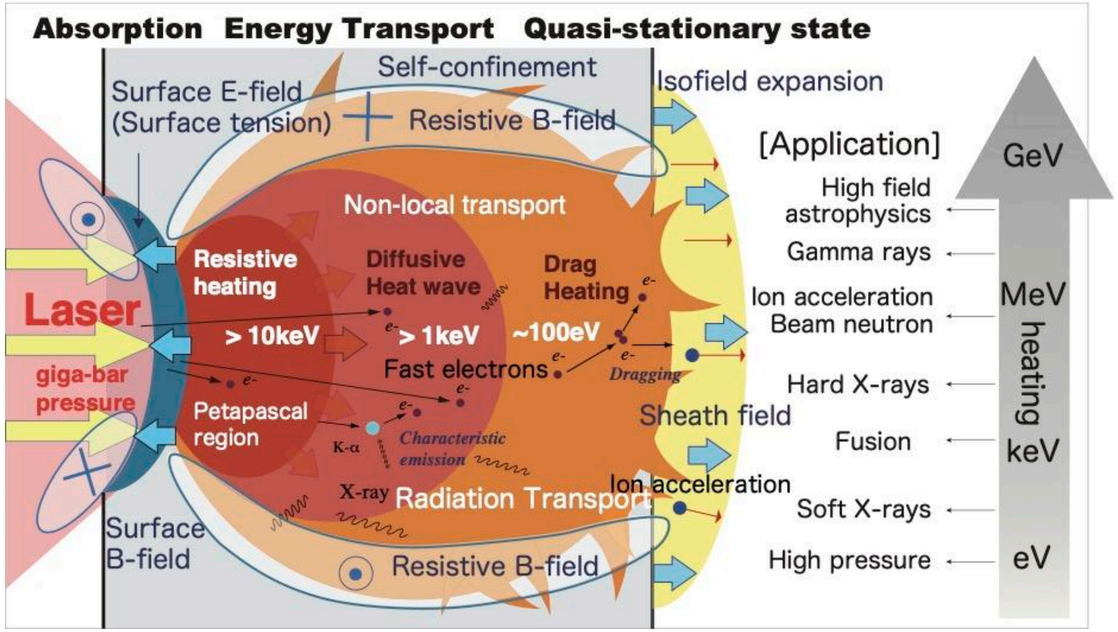
Iwata et al. (2019)

GOAL of Laser Plasma Physics:
Efficient Plasma Heating by Laser (EM Wave)

- Laser-plasma interaction is the most essential process.

Courtesy of Y. Sentoku





- Understand Energy Transport Processes
  - Laser (Electro-Magnetic Wave)
  - Electron (Hot, Bulk)
  - Ion

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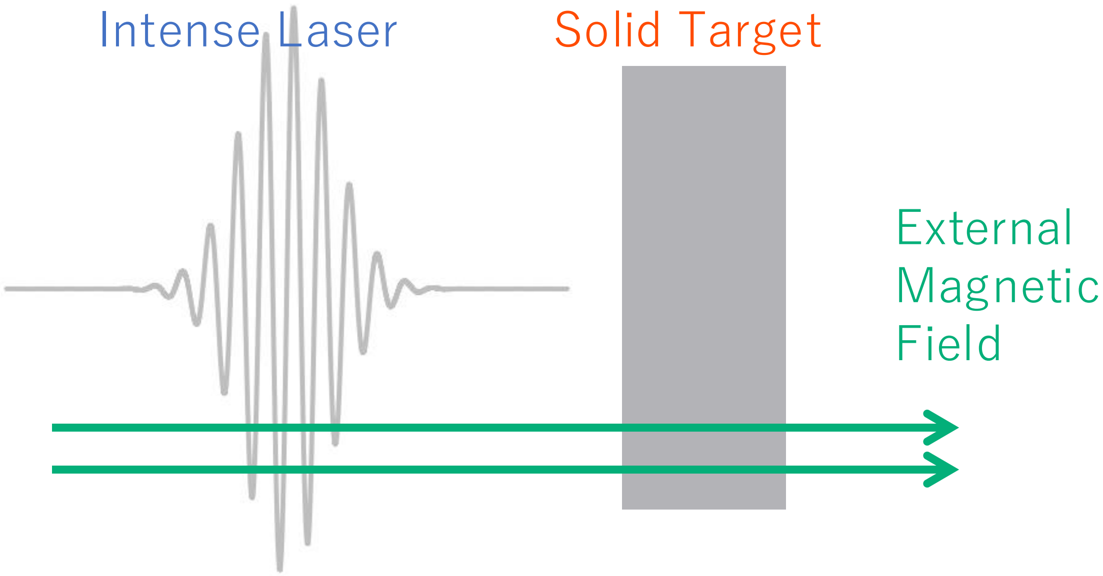
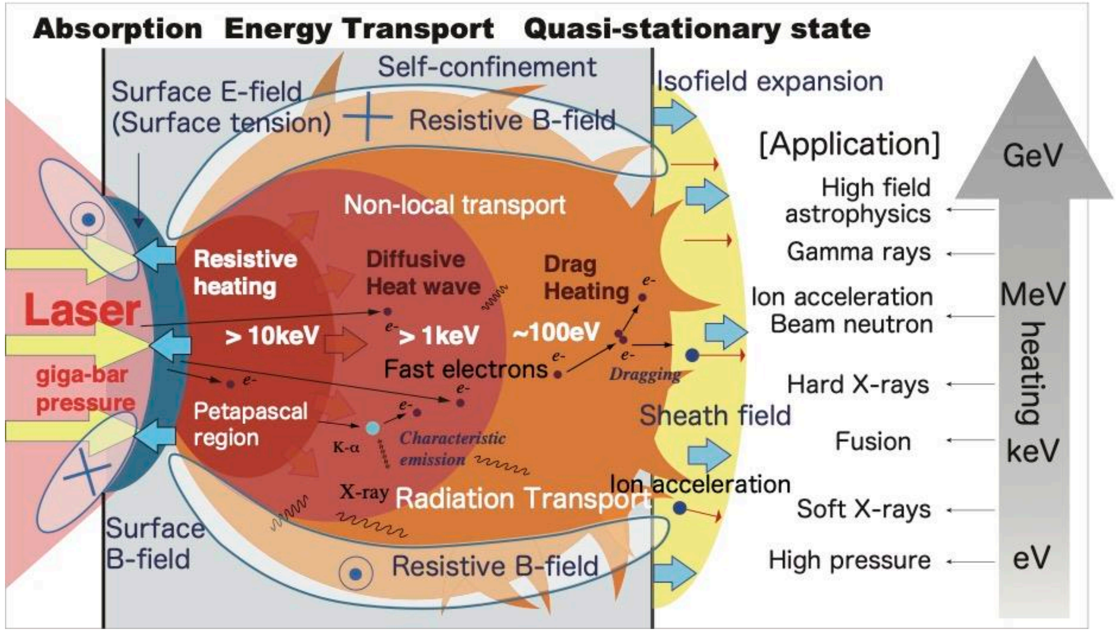


Intense Laser

Solid Target

External Magnetic Field

Courtesy of Y. Sentoku



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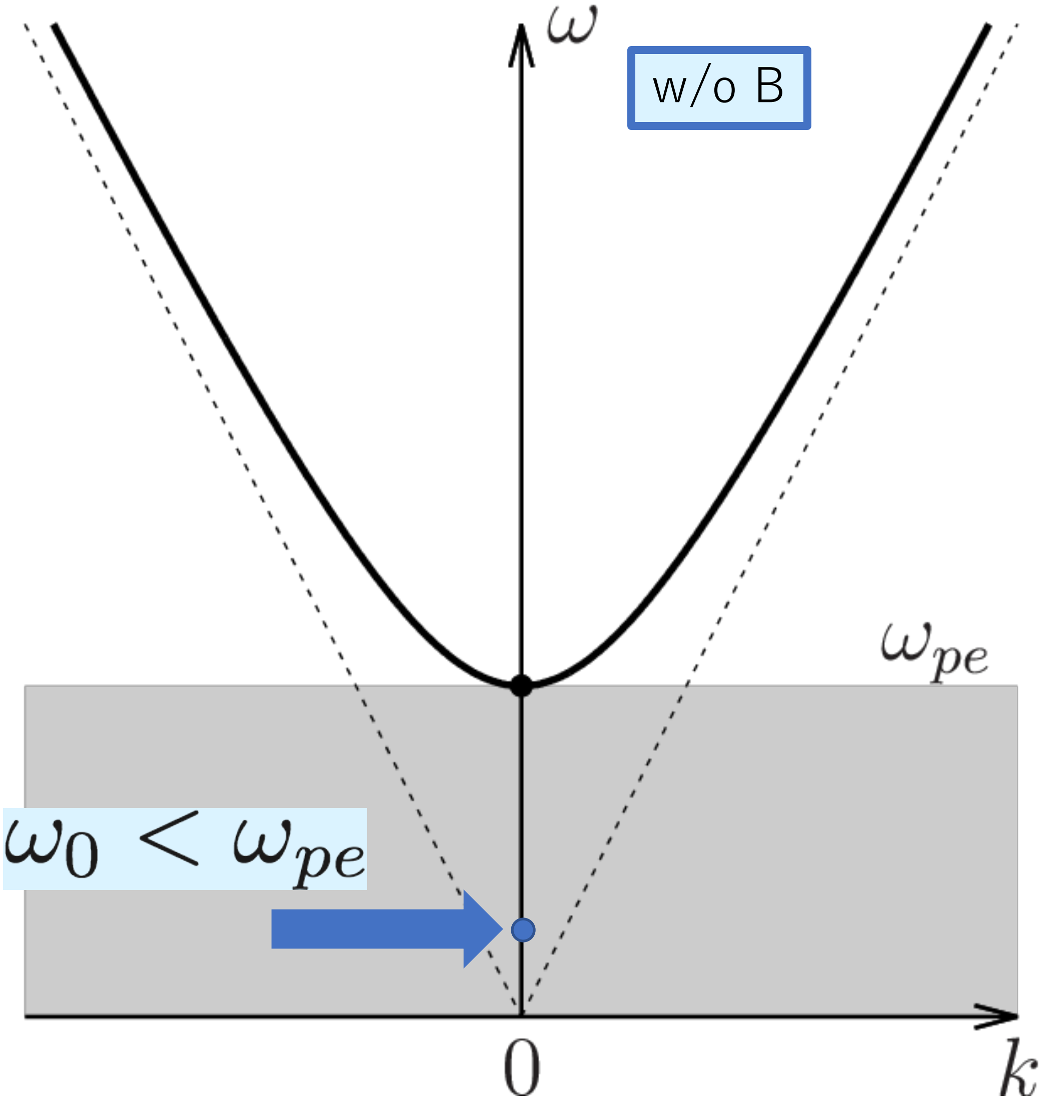
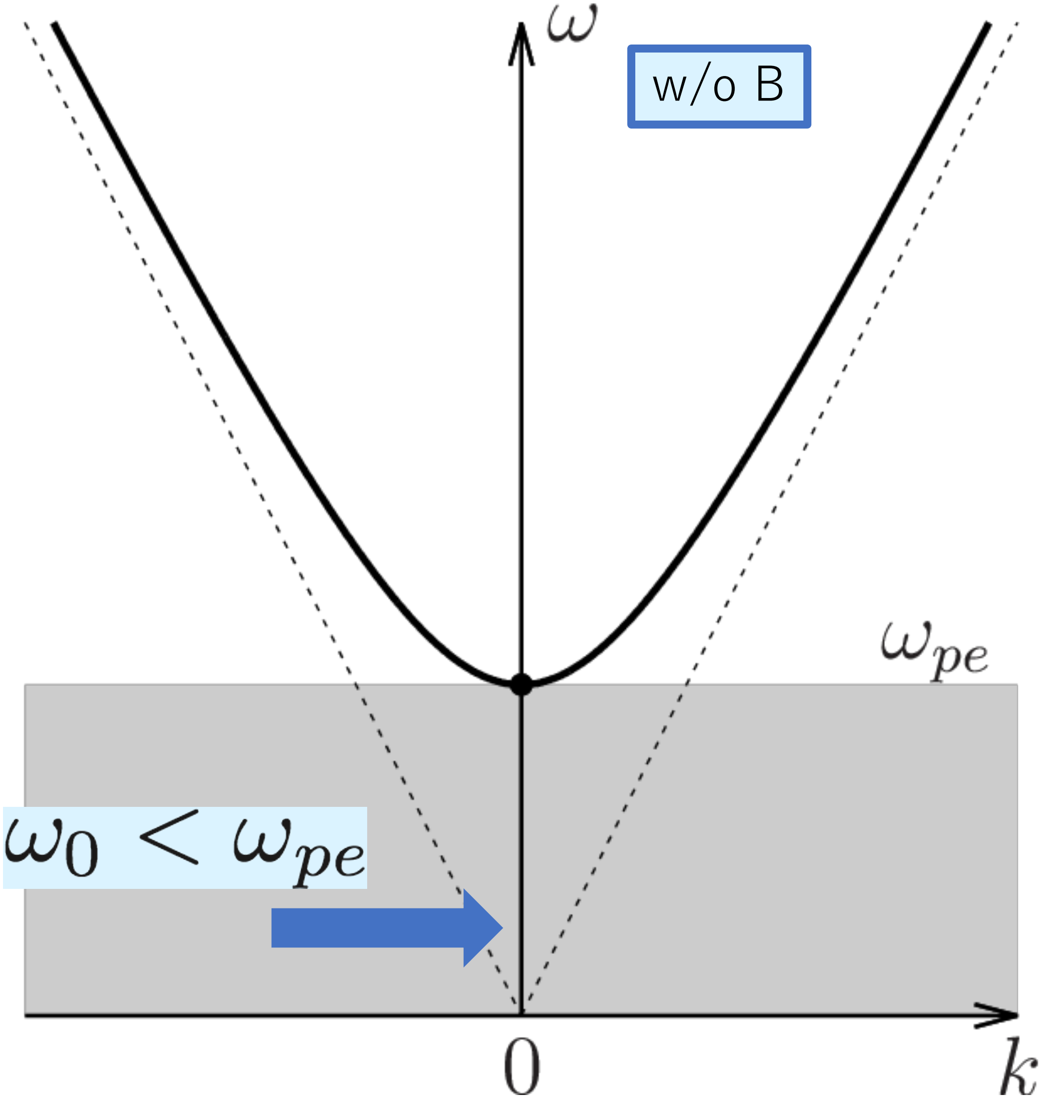
Relativistic
wave-particle interaction
under
a strong magnetic field

Electromagntic Wave along a Magnetic Field

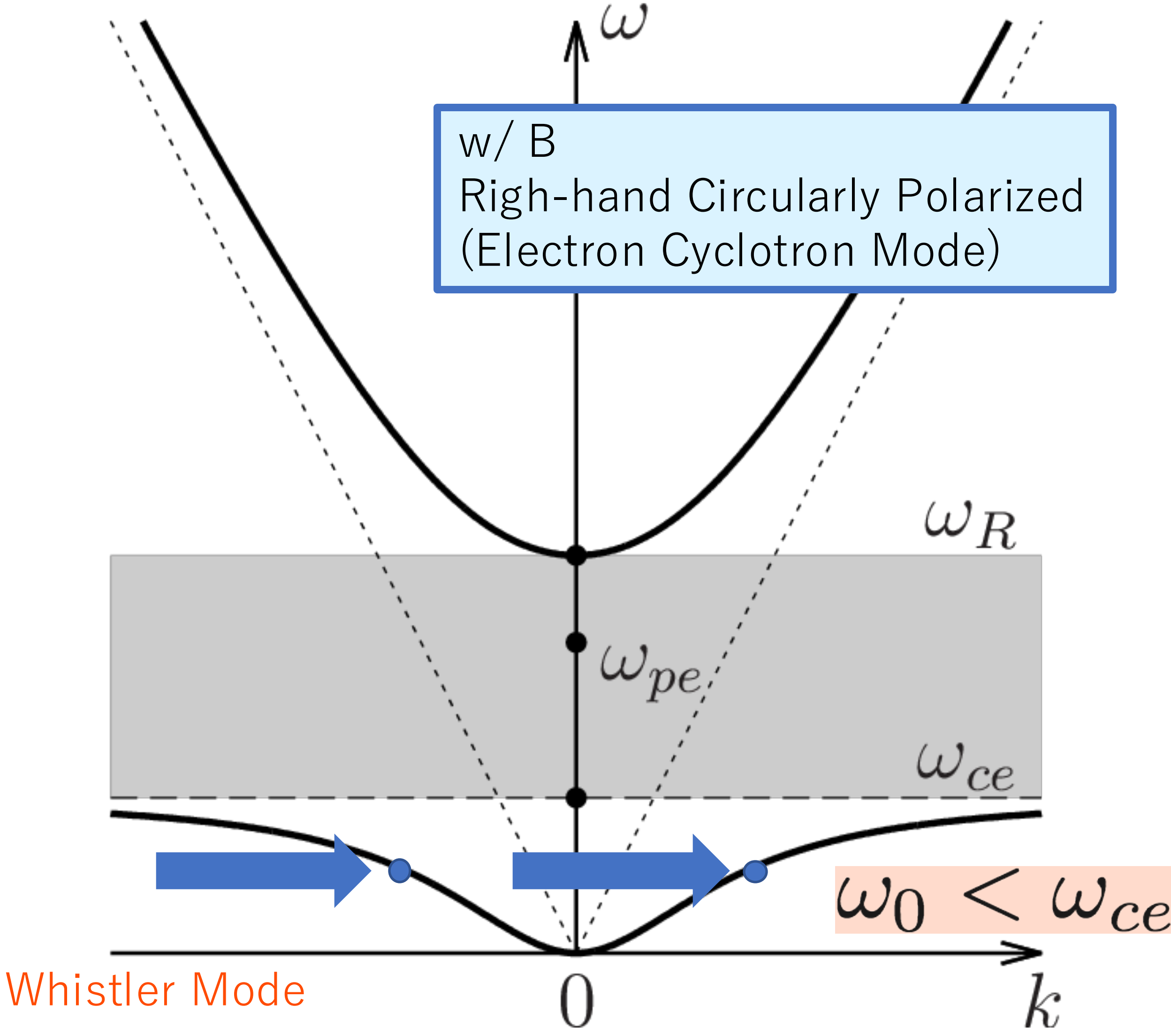


Electromagntic Wave along a Magnetic Field



w/o B

$\omega_0 < \omega_{pe}$



w/ B
Righ-hand Circularly Polarized
(Electron Cyclotron Mode)

$\omega_0 < \omega_{ce}$

Whistler Mode

Why Whistler Wave?

Great Advantages for Plasma Heating

- No Cut-off Density: Direct Interaction with Dense Plasma
- Right-hand Circlarly Polarized: Cyclotroron Resonance with Electrons

→ Energy Conversion from EM Waves to Ions and Electrons

Strong External B Field

$$\widetilde{B} = \frac{B_{\text{ext}}}{B_c} = \frac{\omega_{ce}}{\omega_0} \gg 1$$

Large Amplitude EM Wave

$$a_0 = \frac{eE_0}{m_e c \omega_0} \gg 1$$

Plasma Conditions: "Strong" Magnetic Field and "Relativistic-amplitude" Laser (Electromagnetic Wave)

- External Magnetic Field

Strong Field

$$\widetilde{B} = \frac{B_{\mathrm{ext}}}{B_c} = \frac{\omega_{ce}}{\omega_0}$$

$$B_c \equiv \frac{m_e \omega_0}{e}$$

$$B_c \sim 10 \left(\frac{\lambda_0}{1\ \mu\mathrm{m}} \right)^{-1} [\mathrm{kT}]$$

100 MG

- Laser Amplitude

Relativistic Intensity

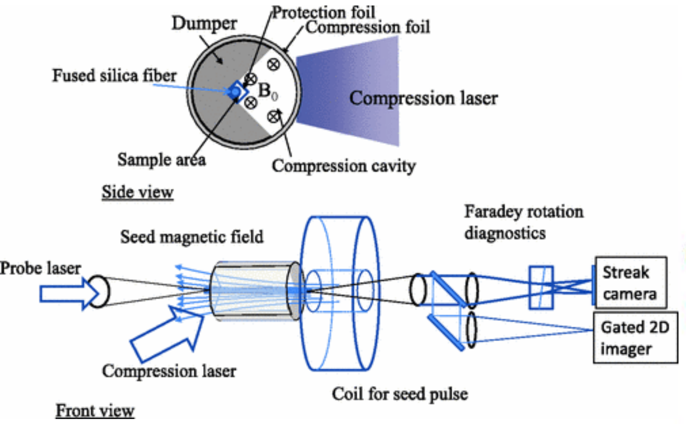
$$a_0 = \frac{eE_0}{m_e c \omega_0}$$

Generation of kilo-Tesla magnetic fields has been achieved by high-power lasers.

- Strong B Field Available in Laser Exp.
- Method (Using GEKKO Laser in Osaka)
  - Coil + Compression
  - Capacitor Coil

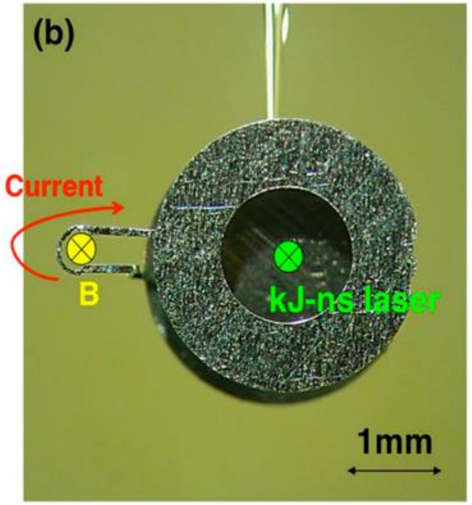
Motivation：
To Control Electron Dynamics by Strong Magnetic Fields

cf.) 1 kT = 10 MG, Permanent Magnet ～1 T

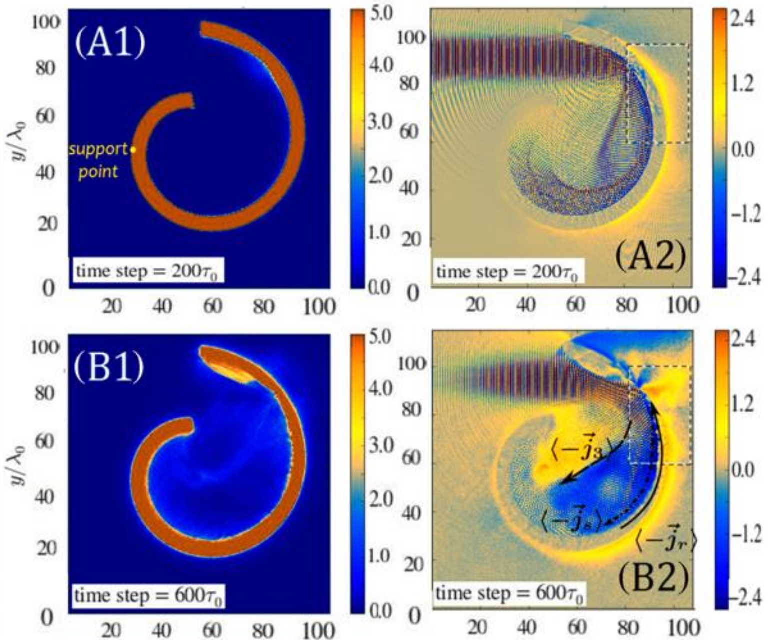


Yoneda+ 2012

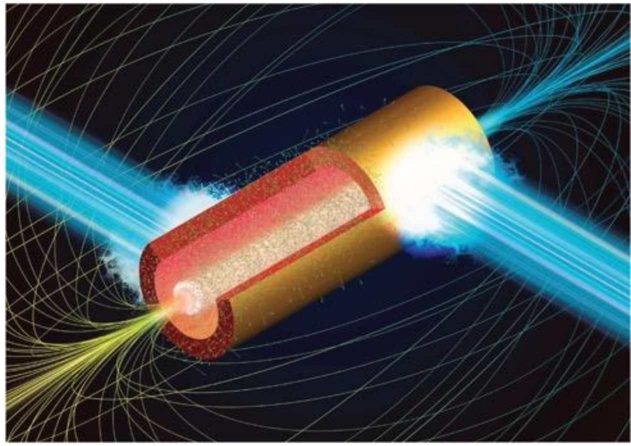
Fujioka+ 2013



Korneev+ 2015

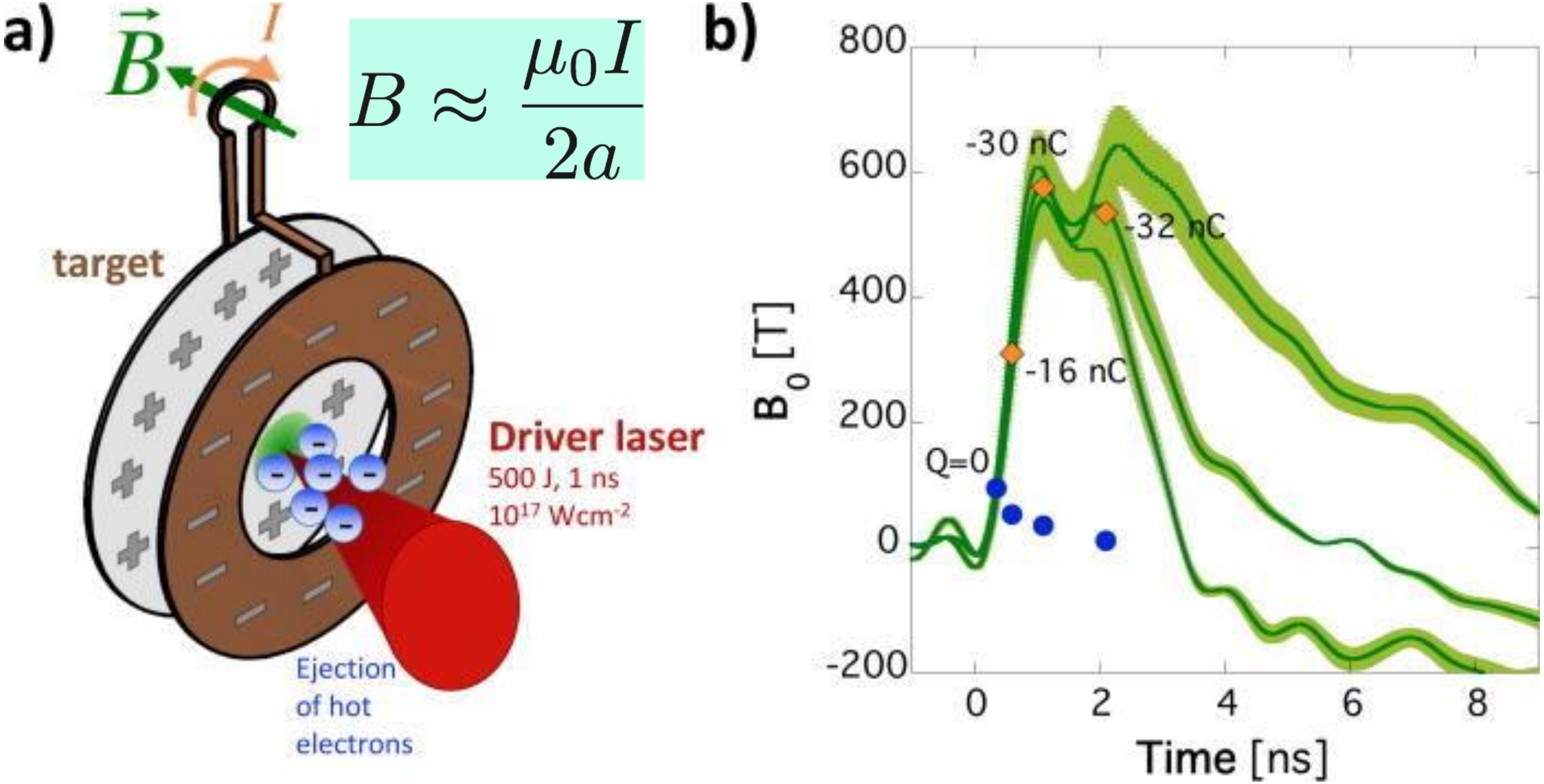


Mega Tesla?
(10^{10} G)



Shokov+ 2022

Capacitor Coil Target for B Generation



$$B \approx \frac{\mu_0 I}{2a}$$

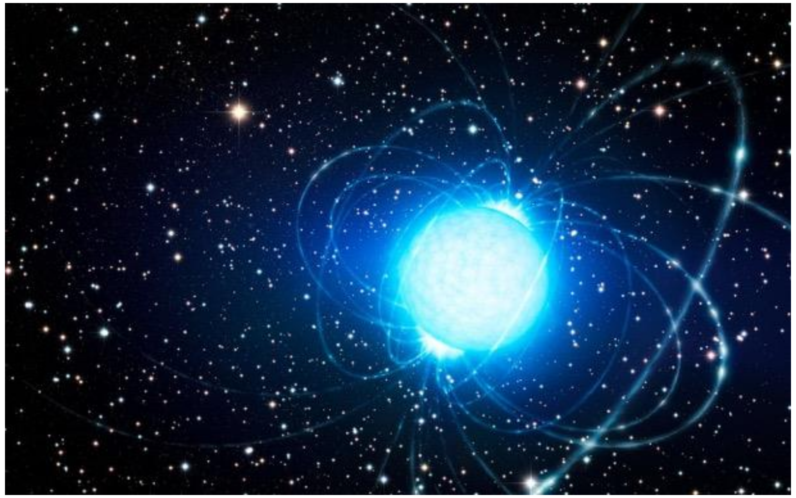
Santos+ 2018 (LULI2000)
Daido+ 1986, Fujioka+ 2013, Law+ 2016 (GEKKO)

Magnetosphere of neutron star has similar plasma parameters to laser experiments.

- Fast Radio Burst (FRB)
- Emission mechanism is still unclear.
- At least one FRB is associated with a magnetar.
- Key Question: Can a strong radio wave escape the magnetosphere of magnetar?

Beloborodov (2021; 2022)

Qu+ (2022)

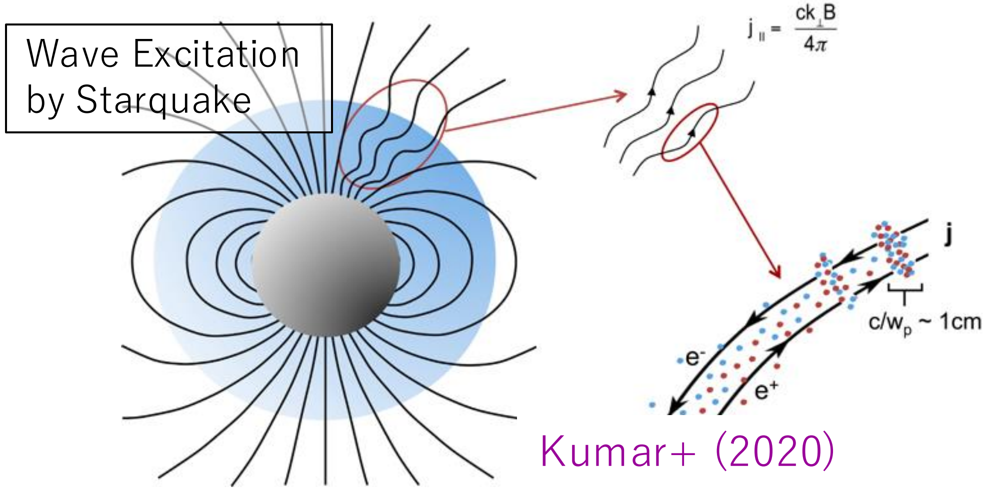


- Alfven Wave in Magnetosphere of Magnetar

$\tilde{n} \sim 10^3$ High Density

$\tilde{B} \sim 10^4$ Strong Field

$a_0 \sim 10^4$ Relativistic Amplitude



Wave Excitation by Starquake

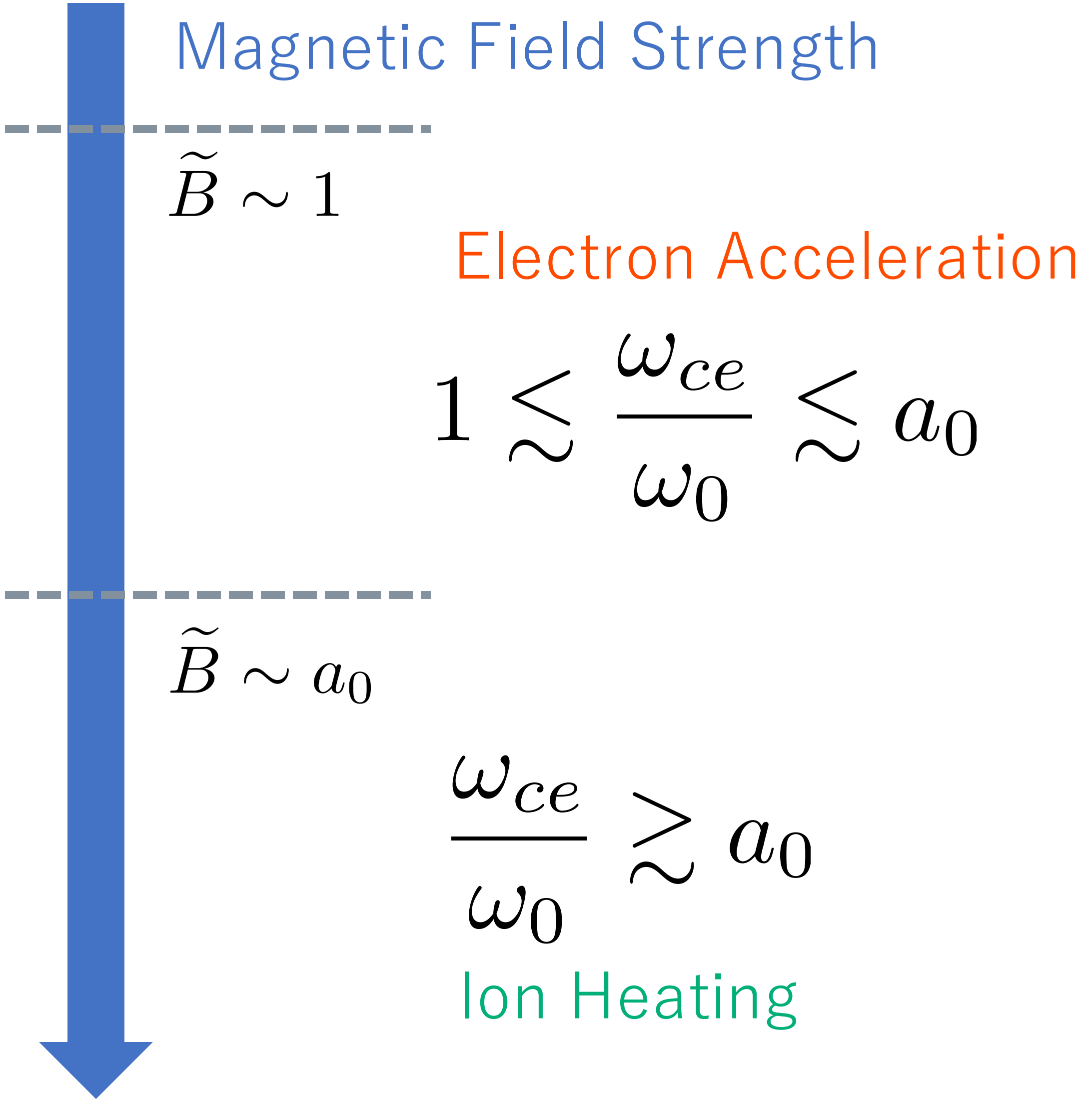
Kumar+ (2020)

Short Summary

- Standing whistler waves can accelerate either electrons or ions depending on the external magnetic field strength.

$$\widetilde{B} = \frac{B_{\mathrm{ext}}}{B_c} = \frac{\omega_{ce}}{\omega_0}$$

- If magnetic fields in excess of 10 kT become available, this could be the subject of new laser astrophysics experiments.



Magnetic Field Strength

$\widetilde{B} \sim 1$

Electron Acceleration

$$1 \lesssim \frac{\omega_{ce}}{\omega_0} \lesssim a_0$$

$\widetilde{B} \sim a_0$

$$\frac{\omega_{ce}}{\omega_0} \gtrsim a_0$$

Ion Heating

Electron Acceleration in Standing Whistler Waves

Sano et al. PRE (2017)
Isayama et al. ApJ (2023)
Sano et al. PRE submitted

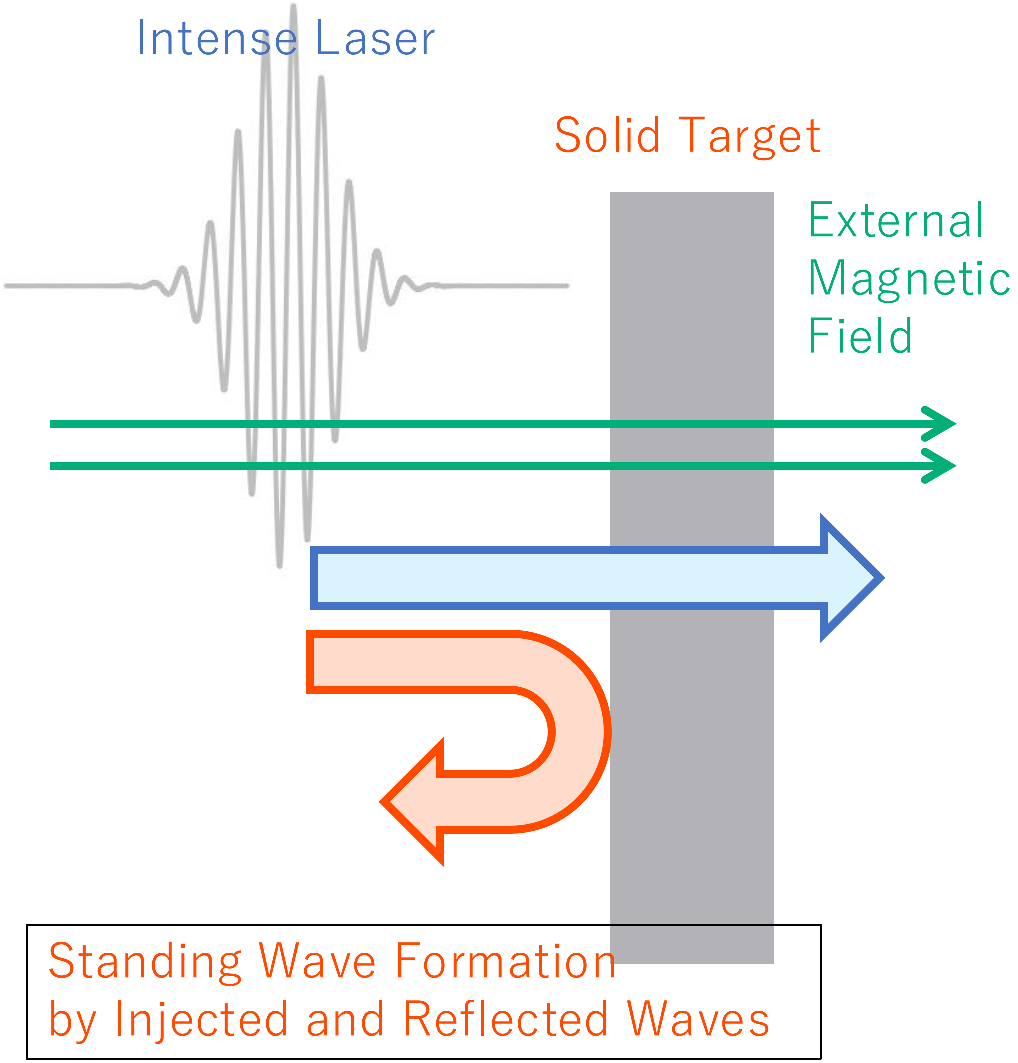
Electron acceleration in standing whistler wave is examined by1D PIC simulation

- Target:
  - Thin Carbon Foil (Diamond)
  - Thickness = 1 um + Preplasma （Scale Length = 1 um)
- External Magnetic Field:
  - Parallel to Laser Injection
- Laser:
  - Right-hand Circularly Polarized
  - Wavelength = 1 um
  - Pulse Duration = 30 fs

$$\widetilde{n} = 600$$

$$\widetilde{B} = 30$$

$$a_0 = 30$$

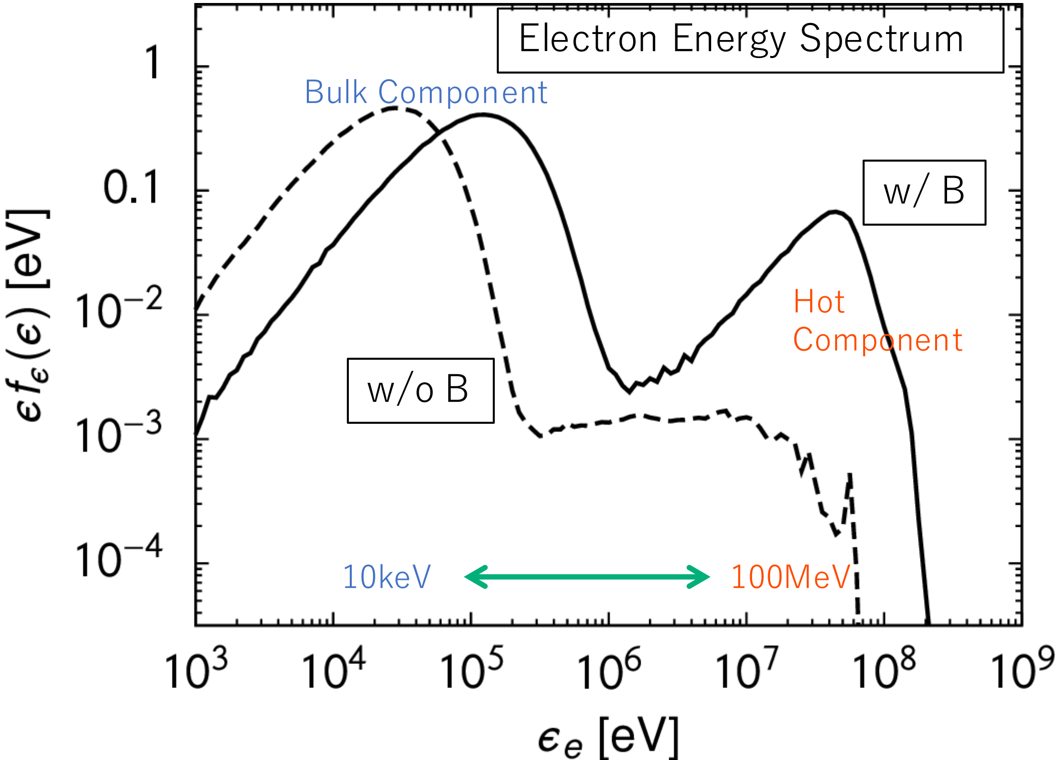


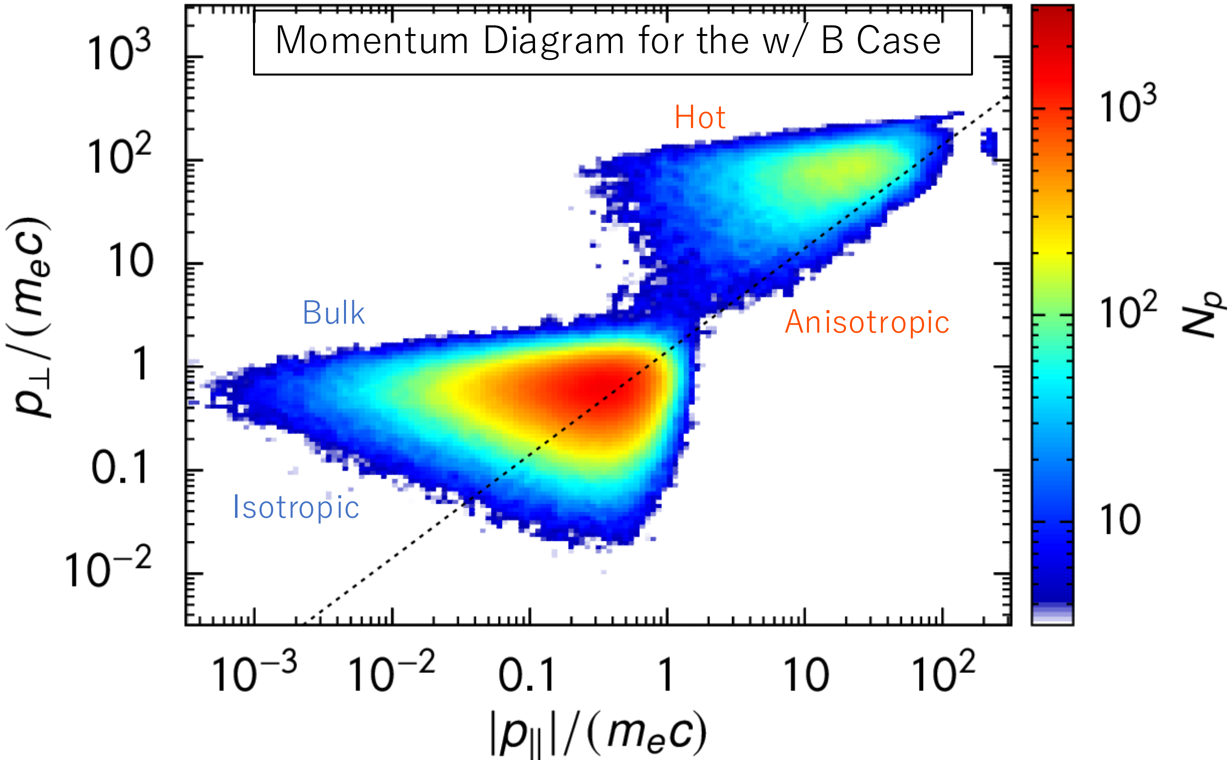
Standing Wave Formation by Injected and Reflected Waves

Applying magnetic field enhances the energy and number fraction of relativistic electron.

- Enhancement of Hot Electron Energy
- Clear Dichotomization with Bulk Component (Double Peak in the Spectrum)

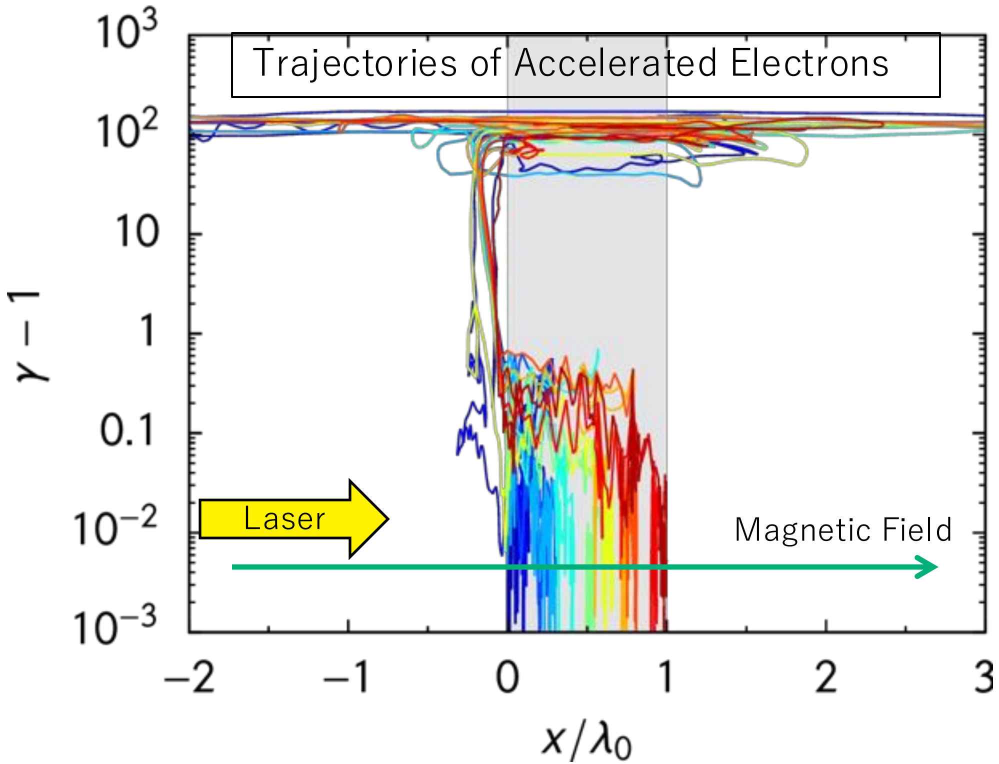
$$\widetilde{n} = 600 \quad \widetilde{B} = 30 \quad a_0 = 30$$



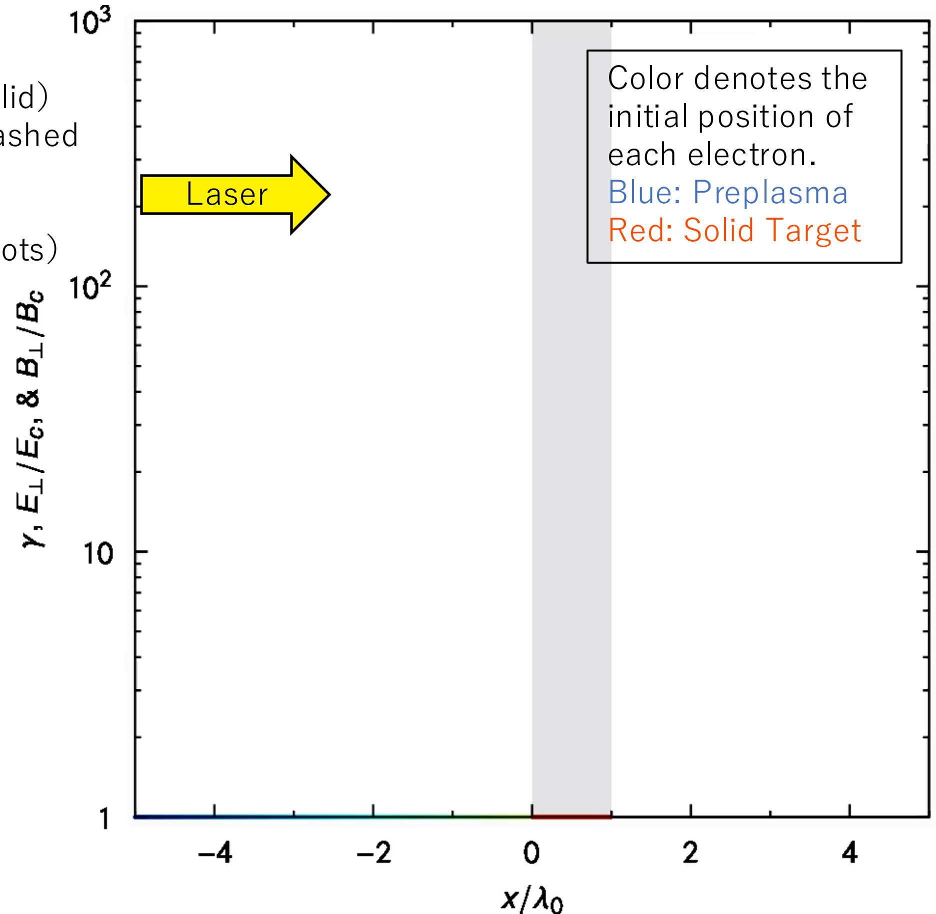


Acceleration occurs in standing whistler wave at the target surface without exception.

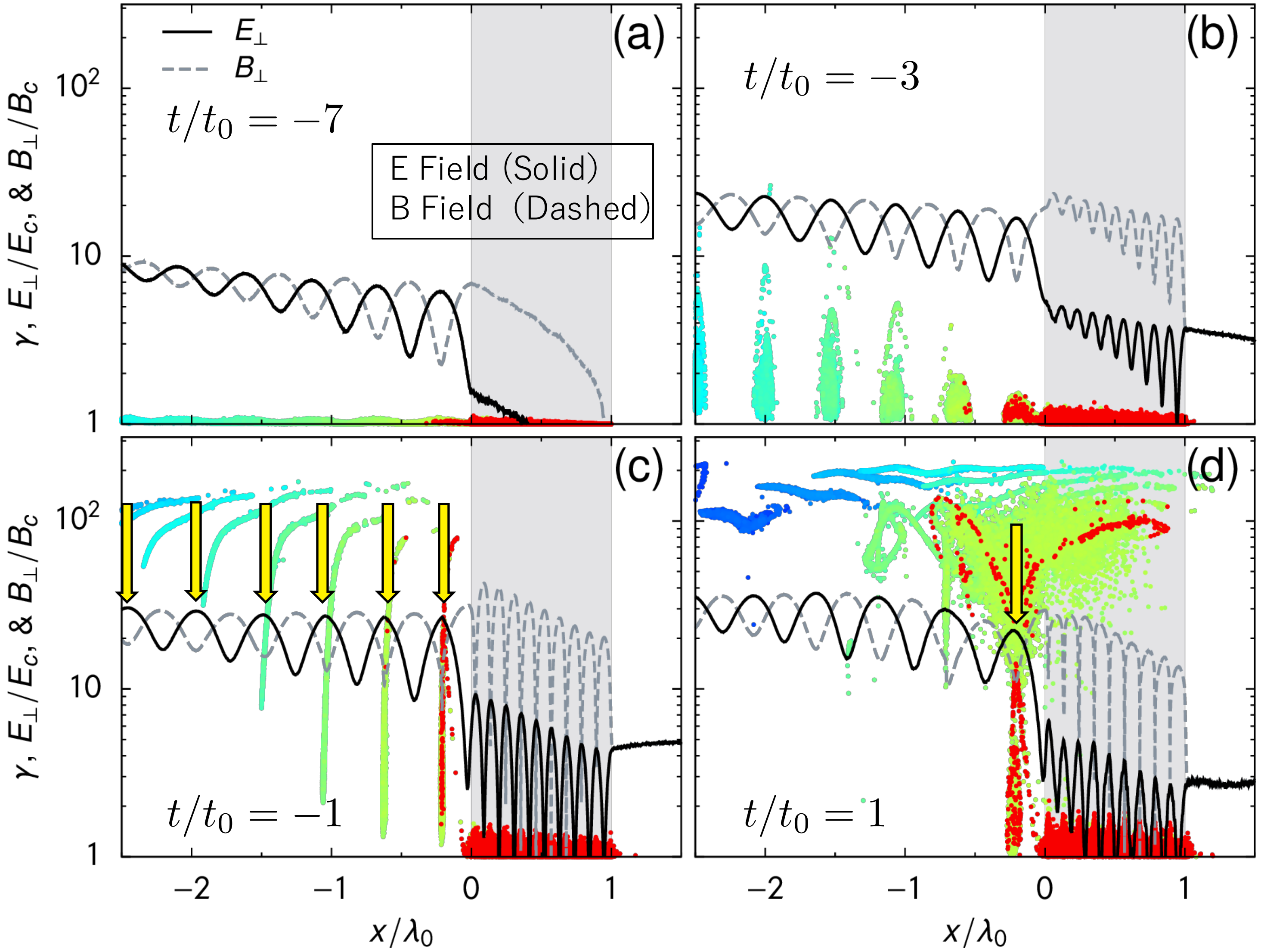
- Acceleration point is just outside of the front surface.
- Acceleration takes place at the same location from non-relativistic velocity to relativistic at once.
- Standing wave is essential.



E Field (Solid)
B Field (Dashed)
e Energy (Colored Dots)


Color denotes the initial position of each electron.
Blue: Preplasma
Red: Solid Target

Acceleration always takes place at the trough of magnetic field in standing wave.



Sano et al. PRE submitted

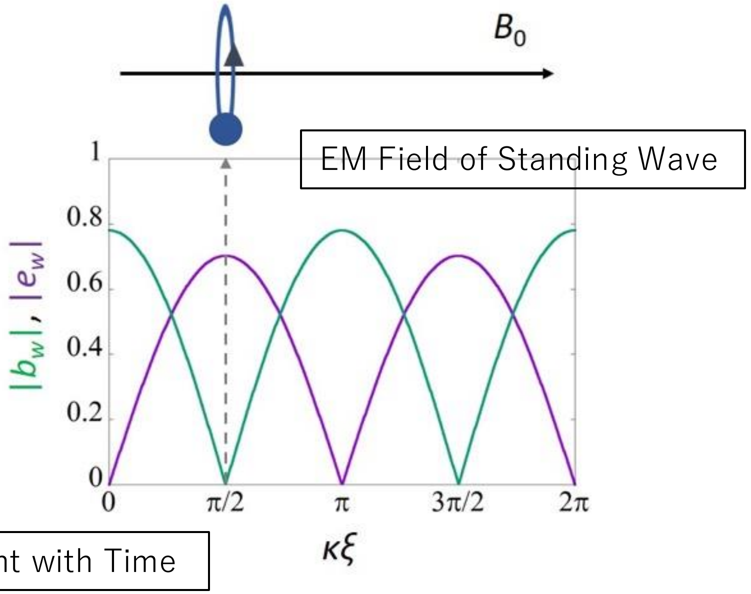
Phase Transition in Electron Trajectory: Free from the "Injection Problem"

- Momentum Equation at the Acceleration Point

Matsukiyo & Hada (2009)

$$\frac{d\widetilde{p}_\perp}{d\widetilde{t}} = 2a_0 \cos\psi$$

$$\frac{d\psi}{d\widetilde{t}} = -\frac{2a_0}{\widetilde{p}_\perp}\sin\psi + \frac{\widetilde{B}_{\mathrm{ext}}}{\gamma} - 1$$



EM Field of Standing Wave

Constant with Time

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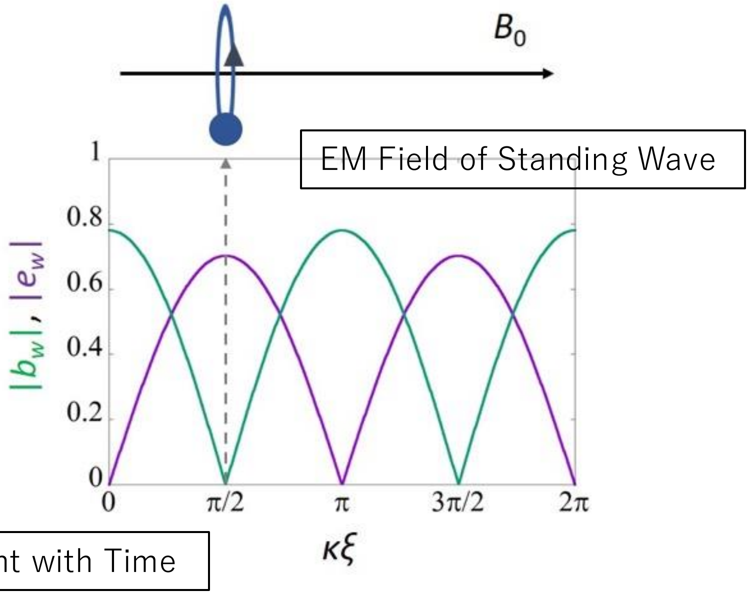
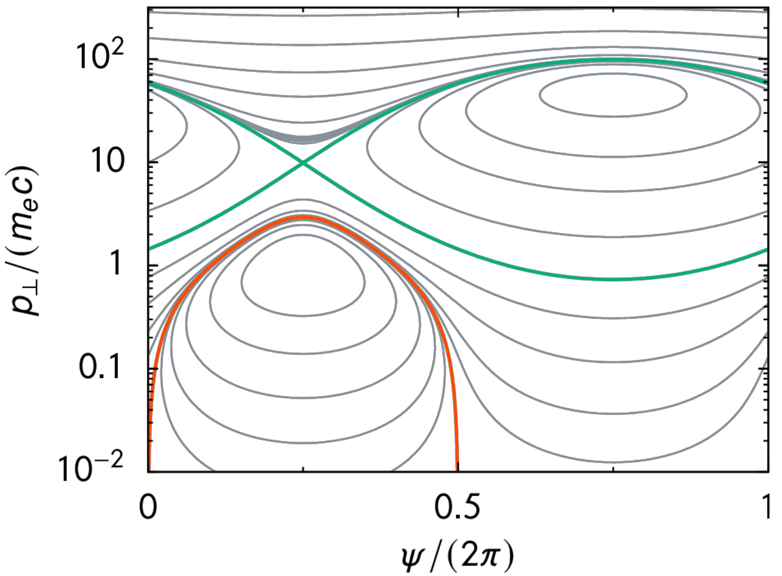


EM Field of Standing Wave

Constant with Time

Electron Trajectory in Momentum-Phase Diagram

Obtained as countour line of Hamiltonian



Small Amplitude Wave

- Non-relativistic and relativistic orbits are separated.

Isayama et al. (2023)

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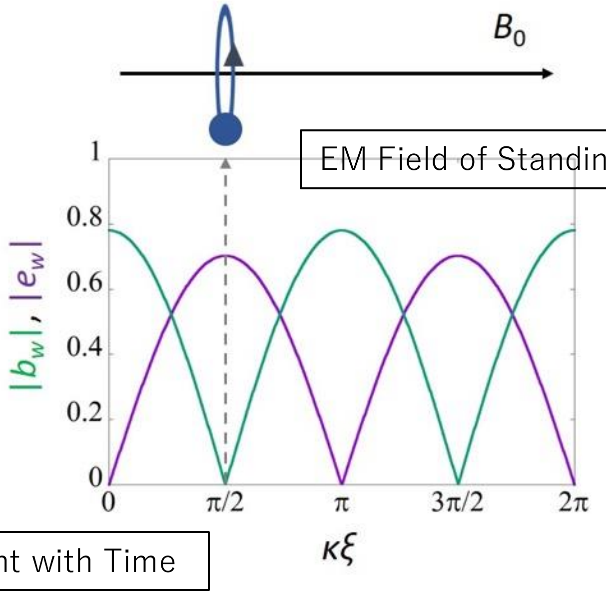

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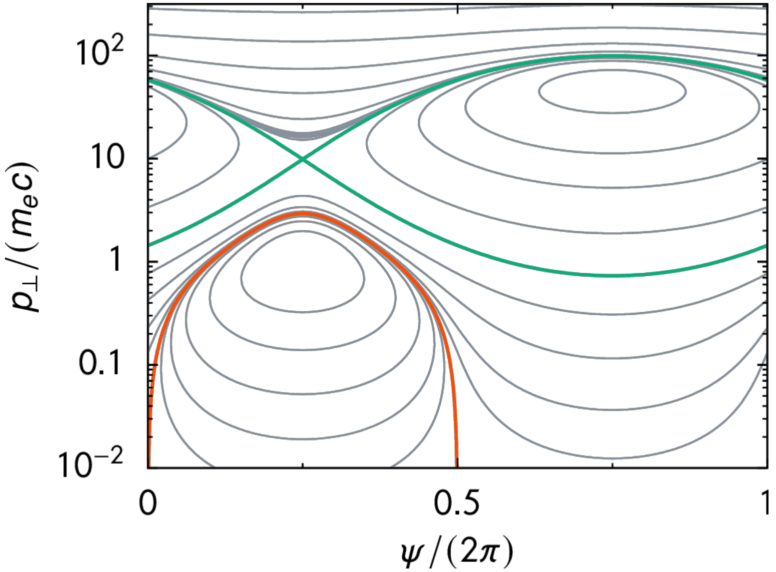
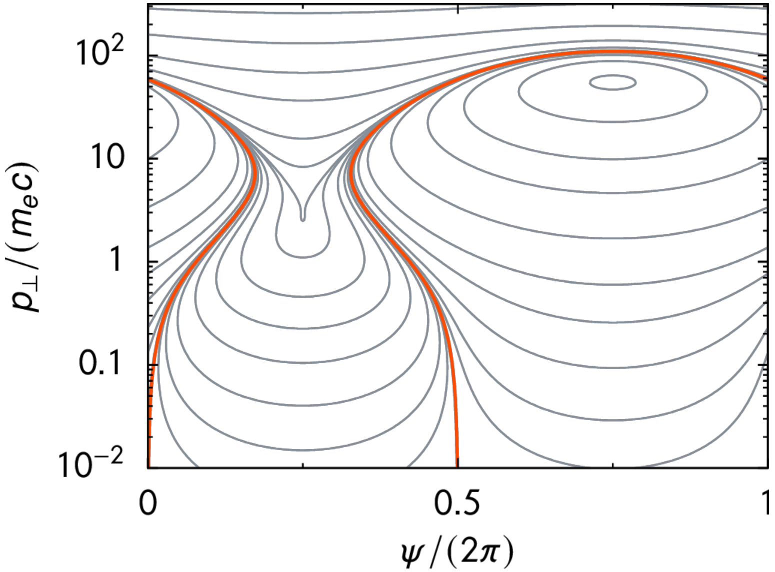




Small Amplitude Wave

- Non-relativistic and relativistic orbits are separated.

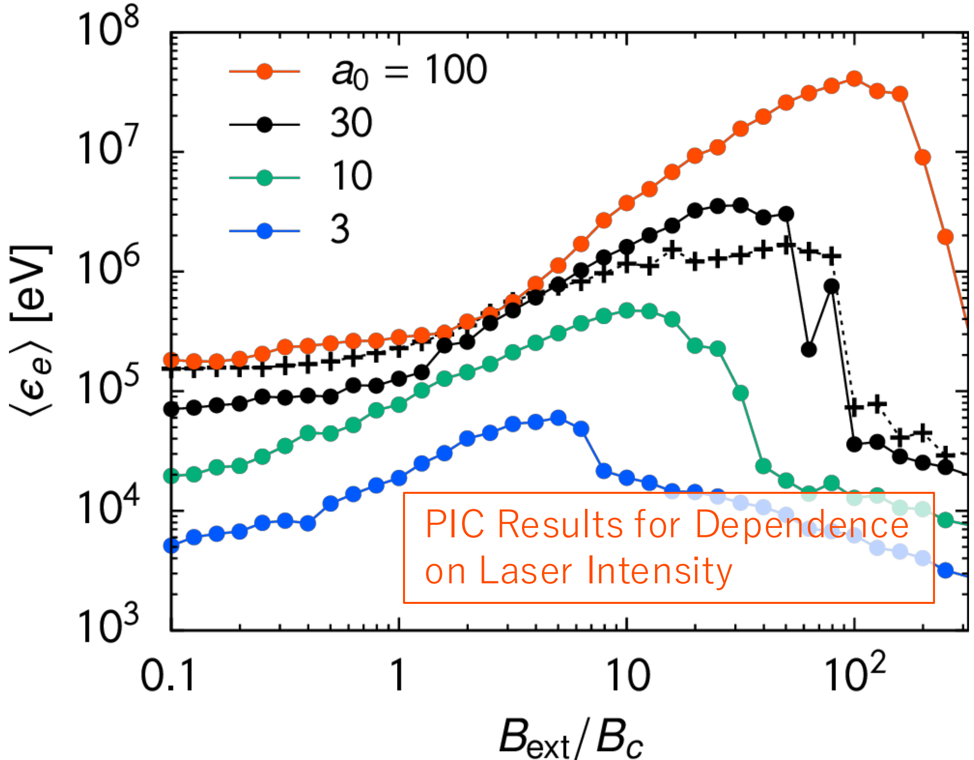
Large Amplitude Wave

- All electrons can gain relativistic velocities
- Two-wave resonance

Isayama et al. (2023)

Requirement for phase transition is that wave amplitude is larger than the external field.

- Condition for Phase Transition $2a_0 \gtrsim (\widetilde{B}^{2/3} - 1)^{3/2}$



PIC Results for Dependence on Laser Intensity

Sano et al. PRE submitted

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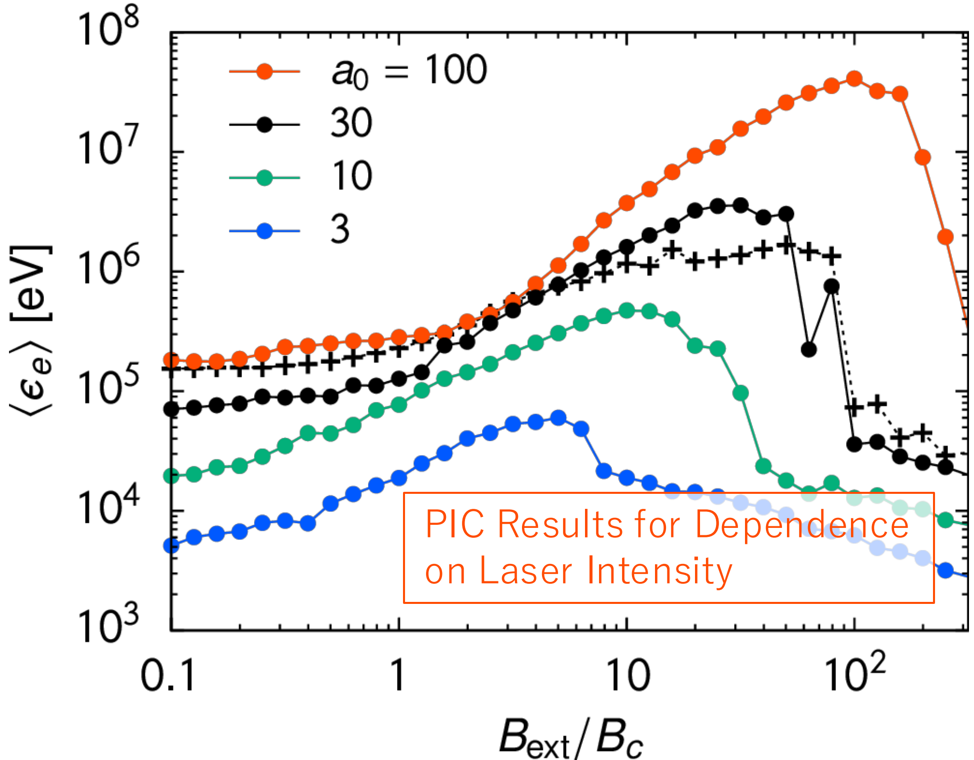


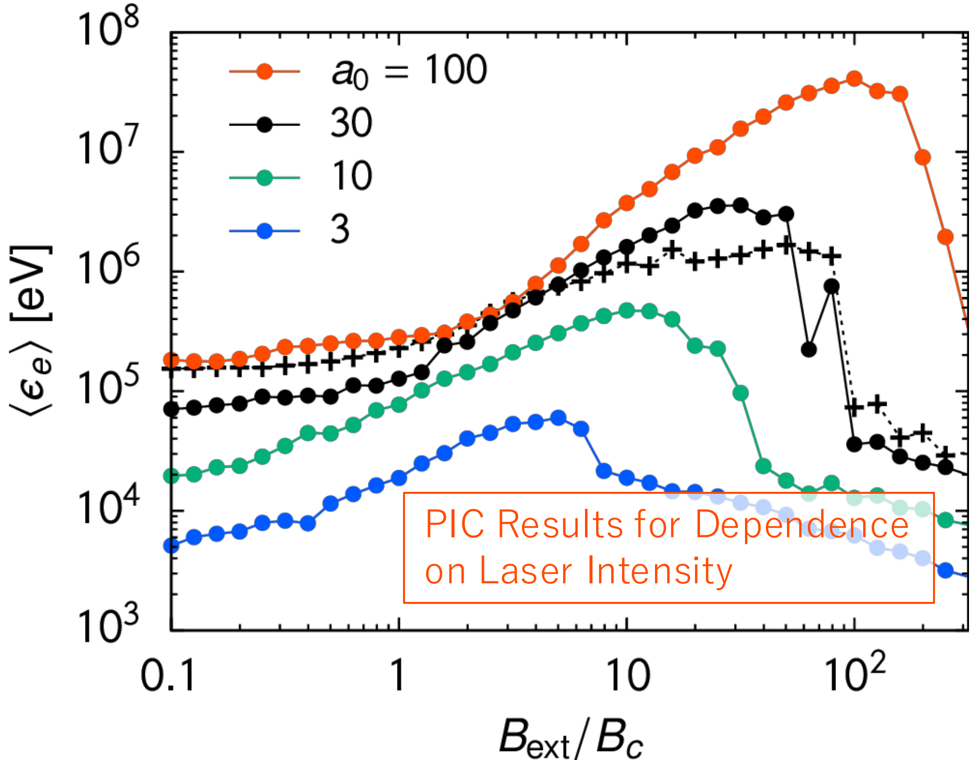
PIC Results for Dependence on Laser Intensity

Sano et al. PRE submitted

Requirement for phase transition is that wave amplitude is larger than the external field.

- Condition for Phase Transition $2a_0 \gtrsim (\widetilde{B}^{2/3} - 1)^{3/2}$
- The maximum energy can also be derived analytically.

$$\widetilde{p}_{\max} \approx 4a_0 + 2[\widetilde{B}(\widetilde{B} - 1)]^{1/2}$$



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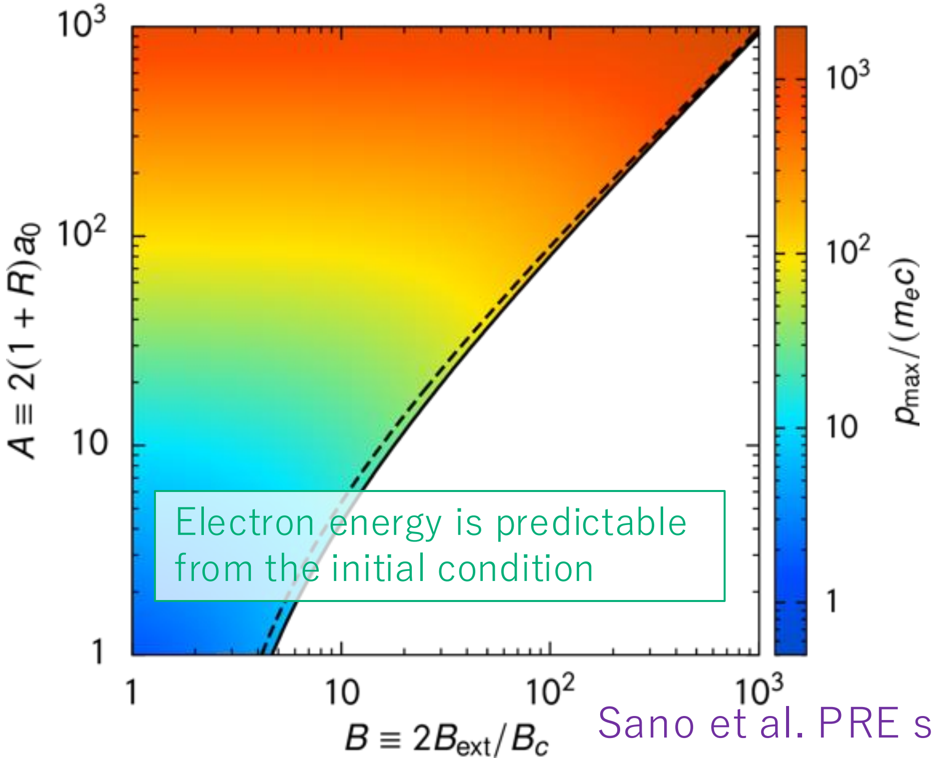
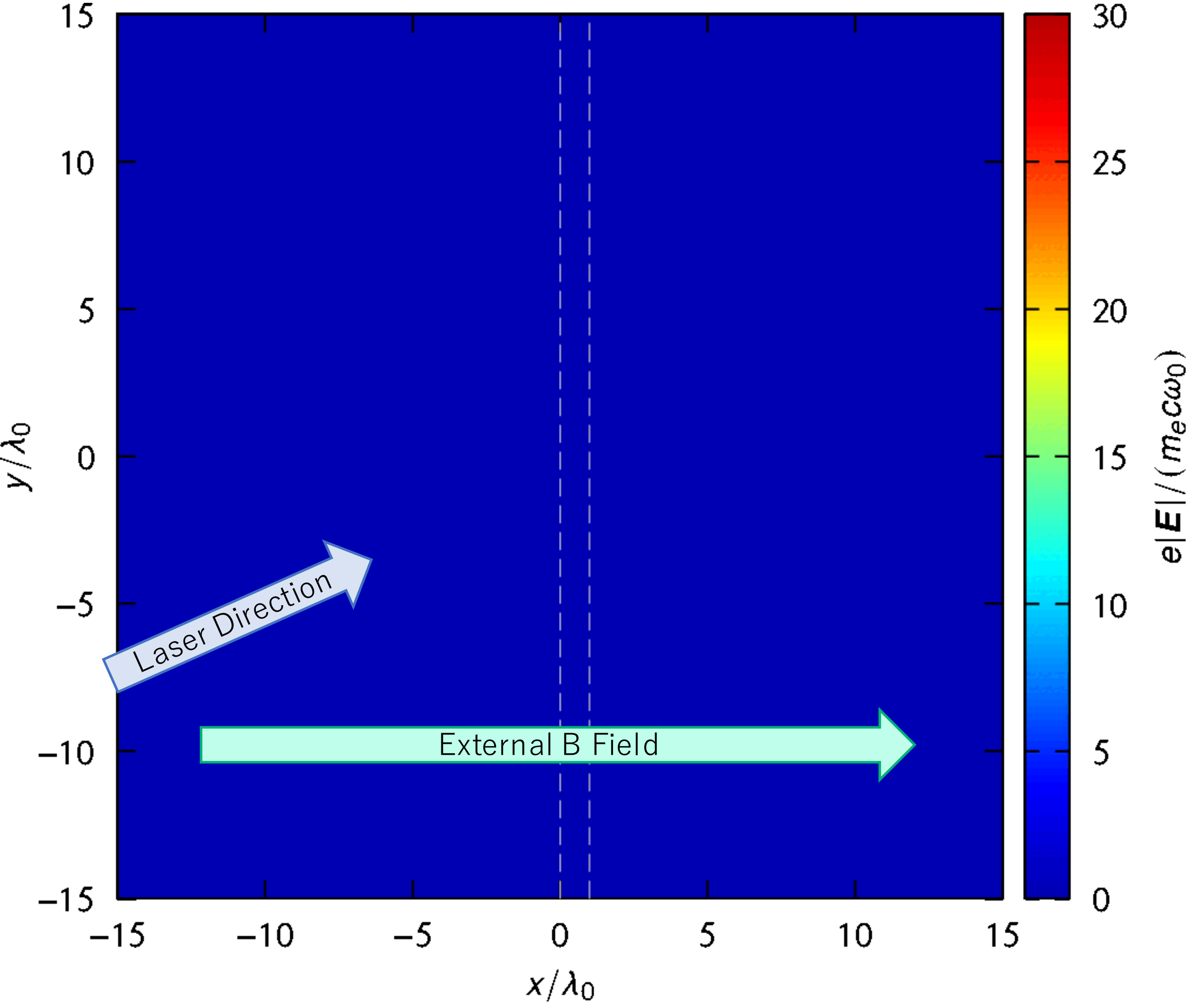


Electron energy is predictable from the initial condition

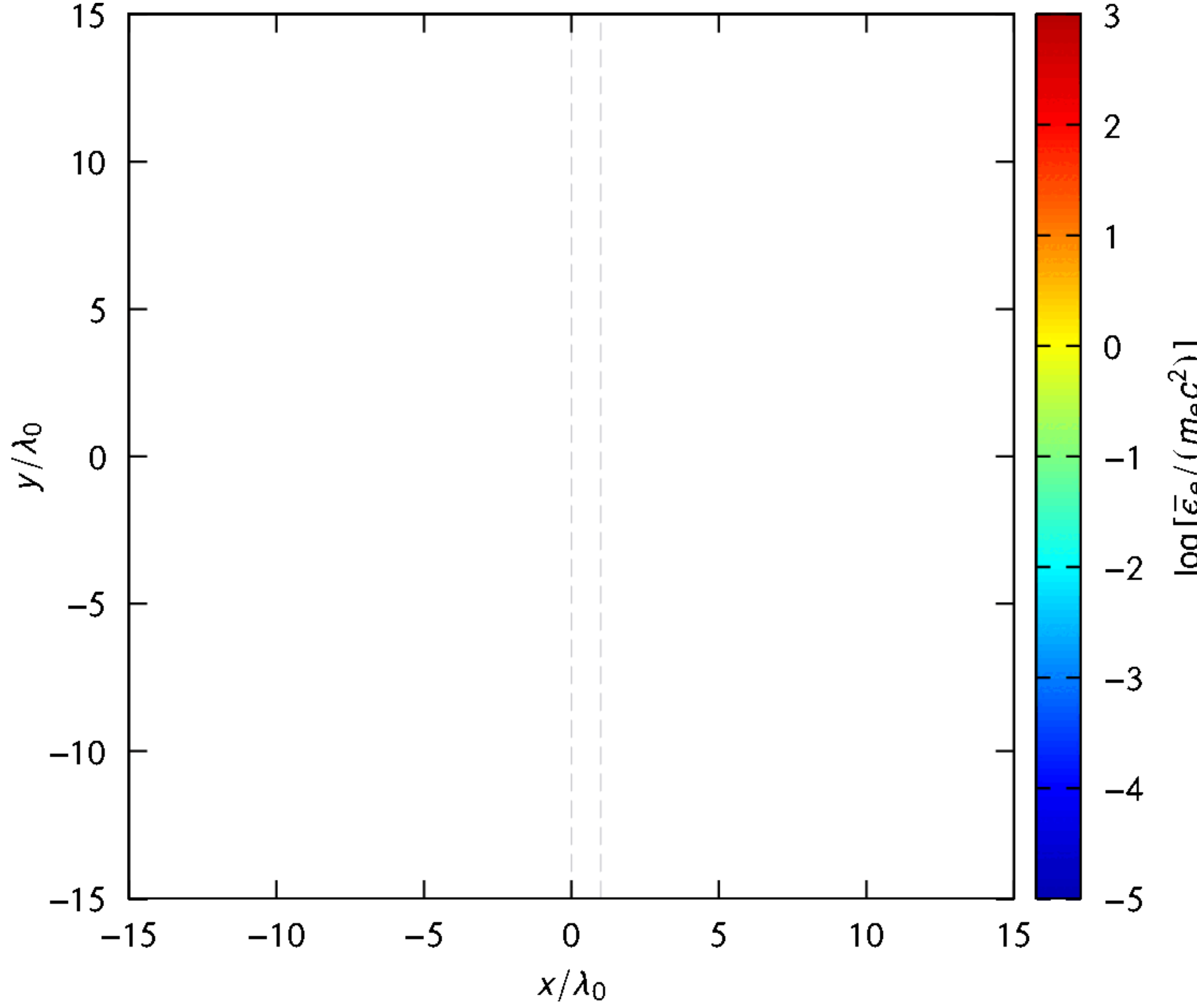
Sano et al. PRE submitted

Hot electrons are generated by the same mechanism evne in 2D PIC simulations.

Electric Field Distribution



Electron Energy Density



Summary

- Laser-plasma interaction in a strong magnetic field is an important process not only in laser plasmas but also in astrophysical phenomena.
- Efficient plasma heating occurs in standing waves created by opposing whistler (Alfven) waves.
- Depending on the strength of the magnetic field, the laser energy is transported to electrons or ions.
- If magnetic fields in excess of 10 kT become available, this could be the subject of new laser astrophysics experiments.

$$\widetilde{n} = \frac{n_e}{n_c} = \frac{\omega_{pe}^2}{\omega_0^2} \qquad \widetilde{B} = \frac{B_{\text{ext}}}{B_c} = \frac{\omega_{ce}}{\omega_0} \qquad a_0 = \frac{eE_0}{m_e c\omega_0}$$

Key parameters are "plasma density", "B field strength", "wave amplitude".