“CMA diagram” for laser-plasma interaction

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概要

- 強磁場中での高強度レーザーと高密度プラズマの相互作用に着目
- 解析手法は一次元PICシミュレーション

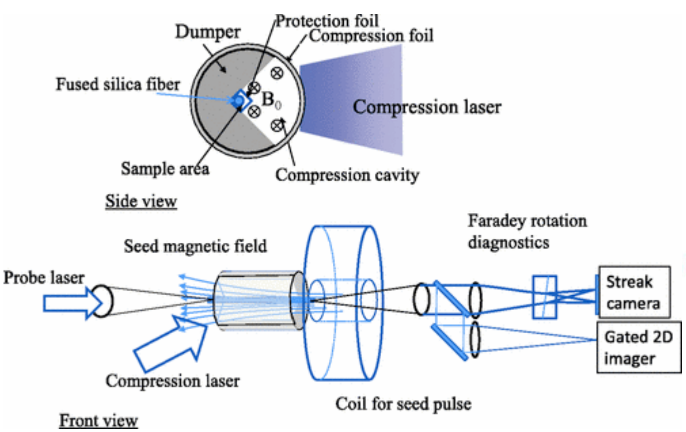
強磁場の効果によって、、、

1. 相対論的電子のサイクロトロン共鳴による吸収率の増大
2. ブリルアン不安定による超臨界密度プラズマ中のイオンの直接加熱

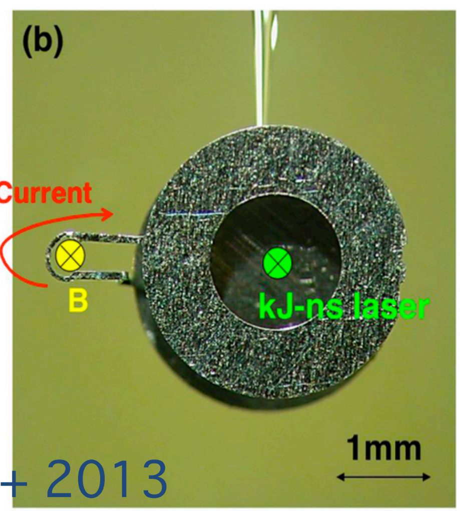
Generation of Kilo-Tesla Field

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

cf.) 1kT = 10MG, Permanent Magnet ～1T

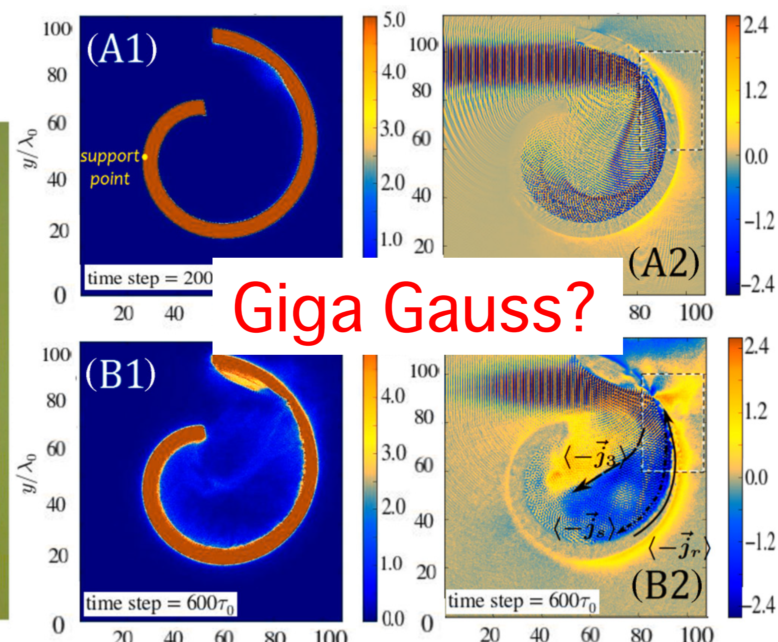


Yoneda+ 2012



Fujioka+ 2013

Korneev+ 2015



Giga Gauss?

Kilo-Tesla Field

- "Strong" Field for Laser Plasma
  - Defined as Cyclotron Freq. > Laser Freq.

$$\boxed{\omega_{ce} > \omega_0}$$

$$\omega_{ce} \equiv \frac{eB_{\mathrm{ext}}}{m_e}$$

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- Critical Field Strength

$$B_{\mathrm{ext}} > \frac{m_e \omega_0}{e} \equiv B_c$$

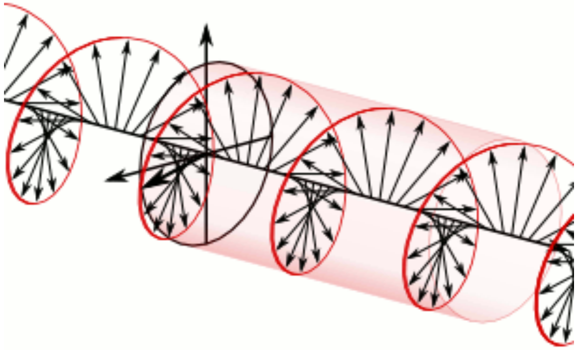
$$\Rightarrow \quad B_c = 13 \left(\frac{\lambda_0}{0.8\ \mu\mathrm{m}} \right)^{-1} [\mathrm{kT}]$$

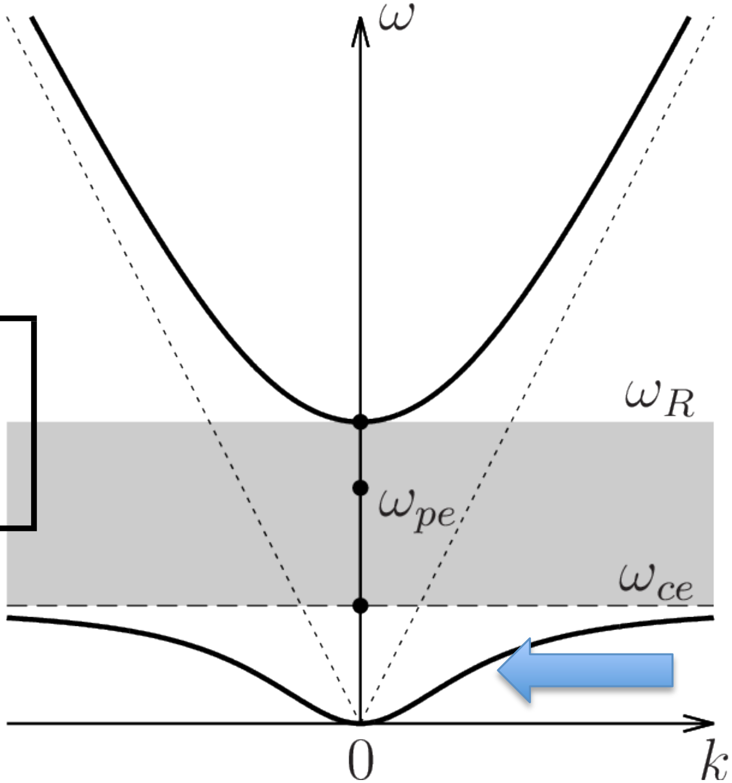
Laser along B Field Line

- Circularly Polarized R Wave & L Wave
- Dispersion Relation for R Wave (→)
- Propagation Region at Lower Freq. = Whistler Mode

$$B_{\mathrm{ext}} > B_c$$

- NO CUTOFF!!





Overdense-Plasma Heating

- Whistler Wave
  - No Critical Density (No Cutoff)
  - Electron Cyclotron Resonance

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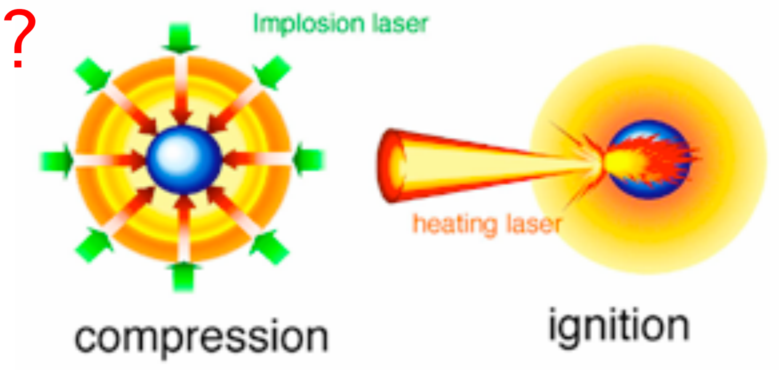
- Application to Inertial Confinement Fusion
  - Compression + Heating

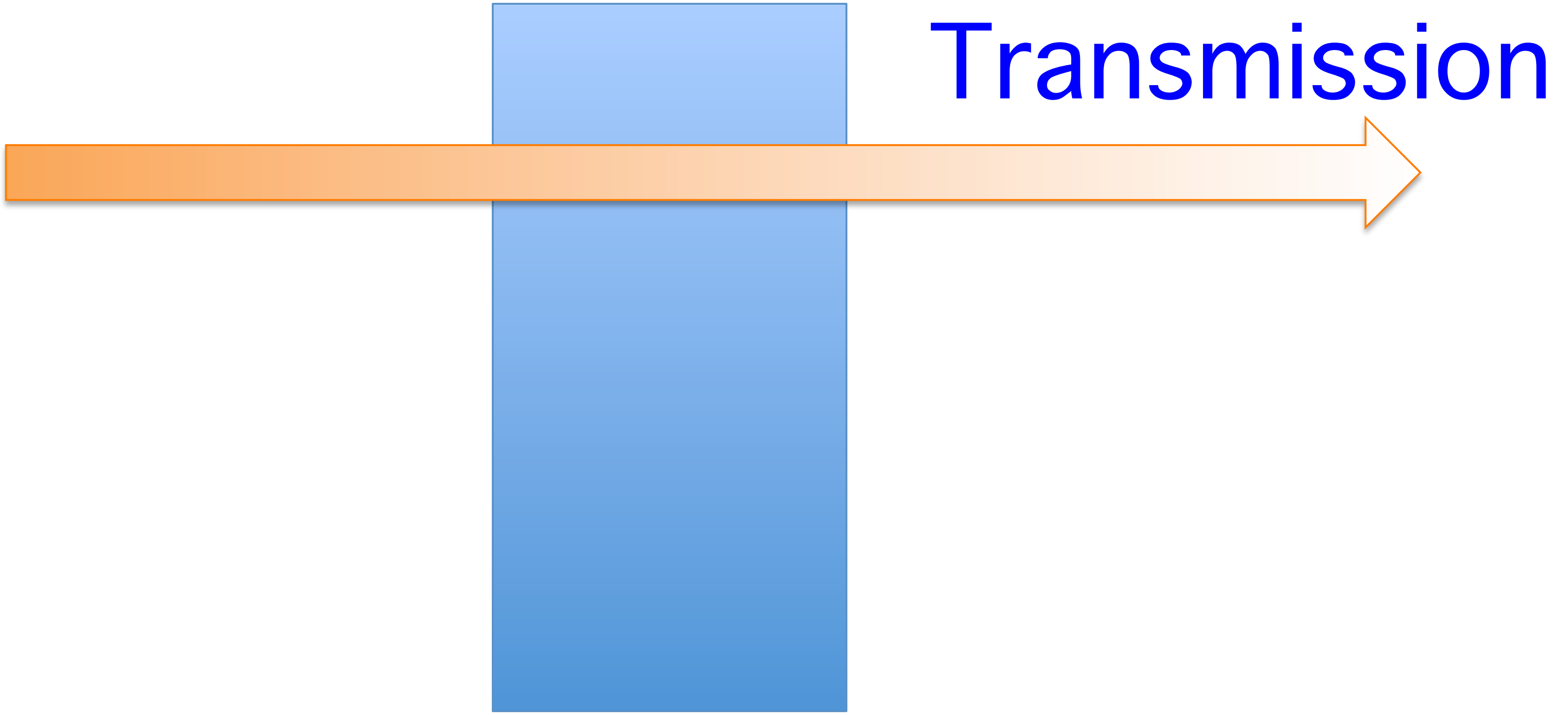
Fast Ignition ("Division of Labor") Kodama+ 2000 Fujioka+ 2015

  - Laser → Hot Electron ?→? Core Heating
  - Laser → Direct Heating?



Overdense Plasma w/ B

- Laser can propagate in overdense plasma, BUT ...



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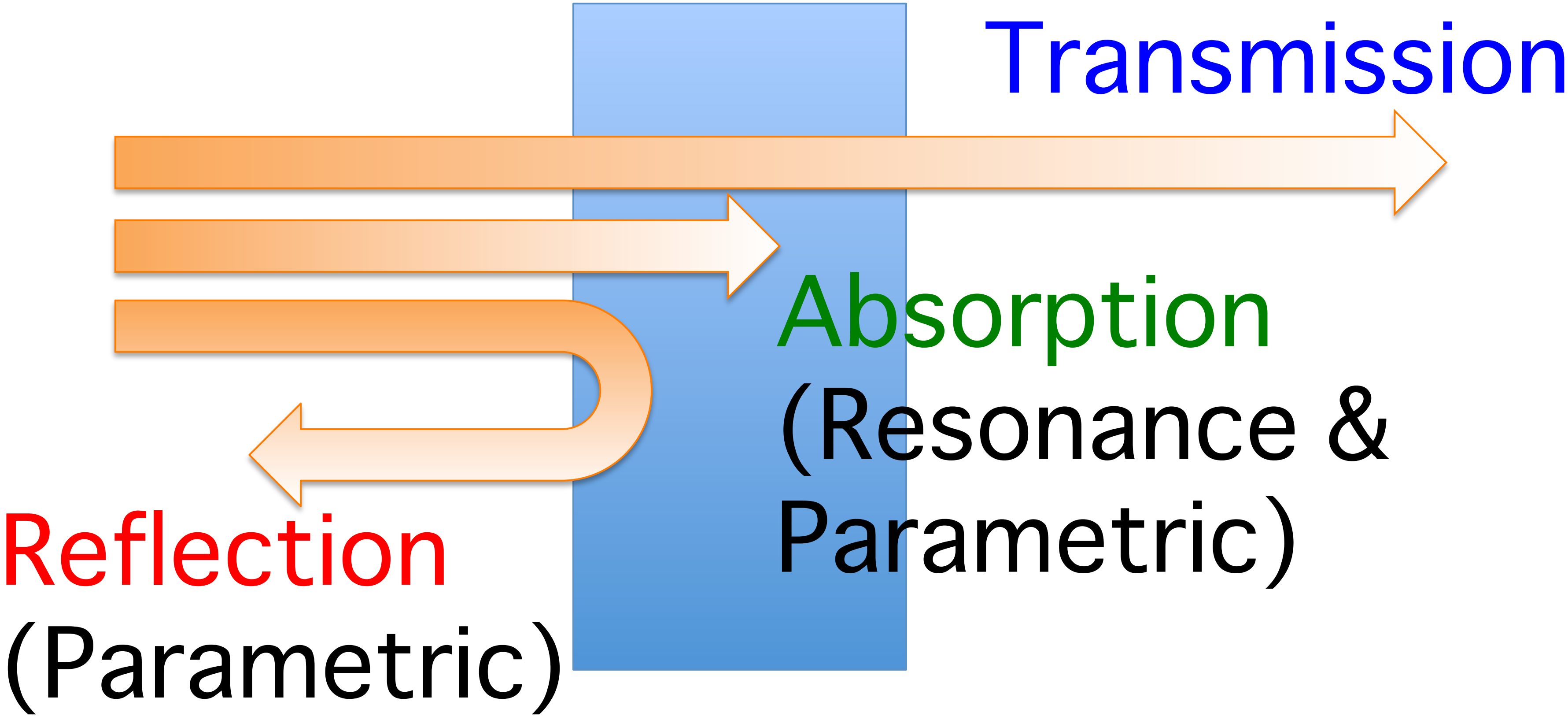

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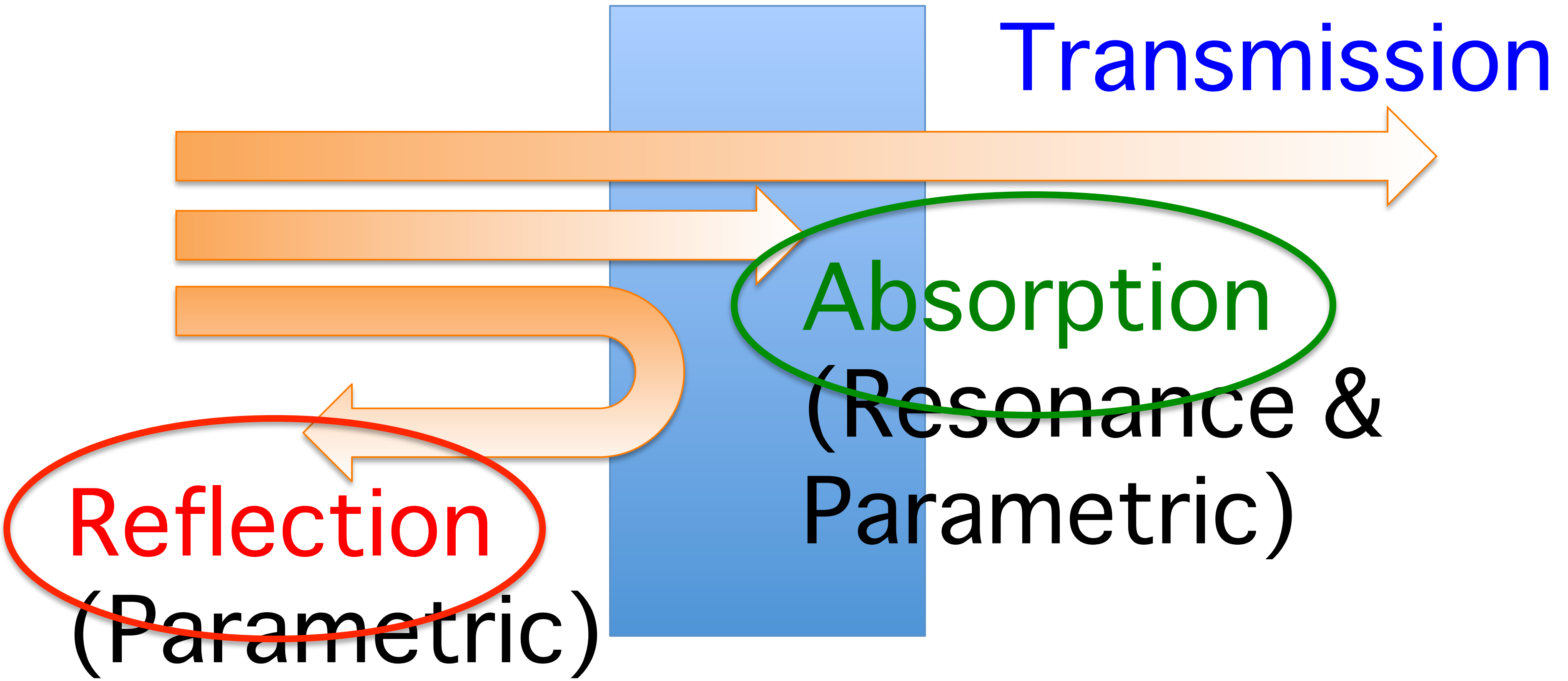
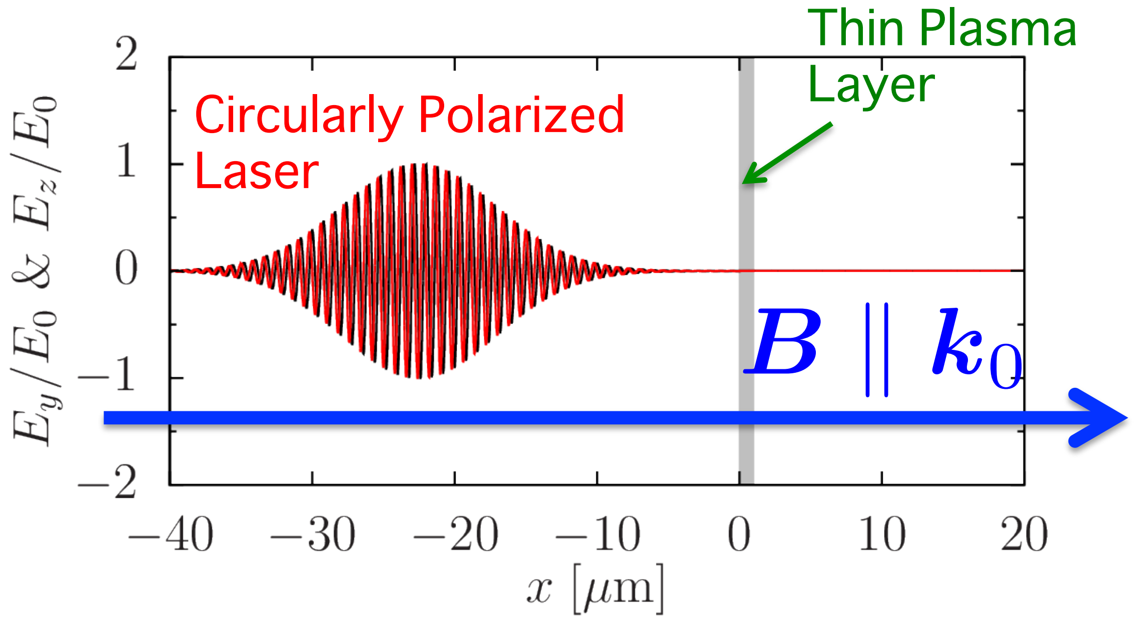


1D Problem Setup

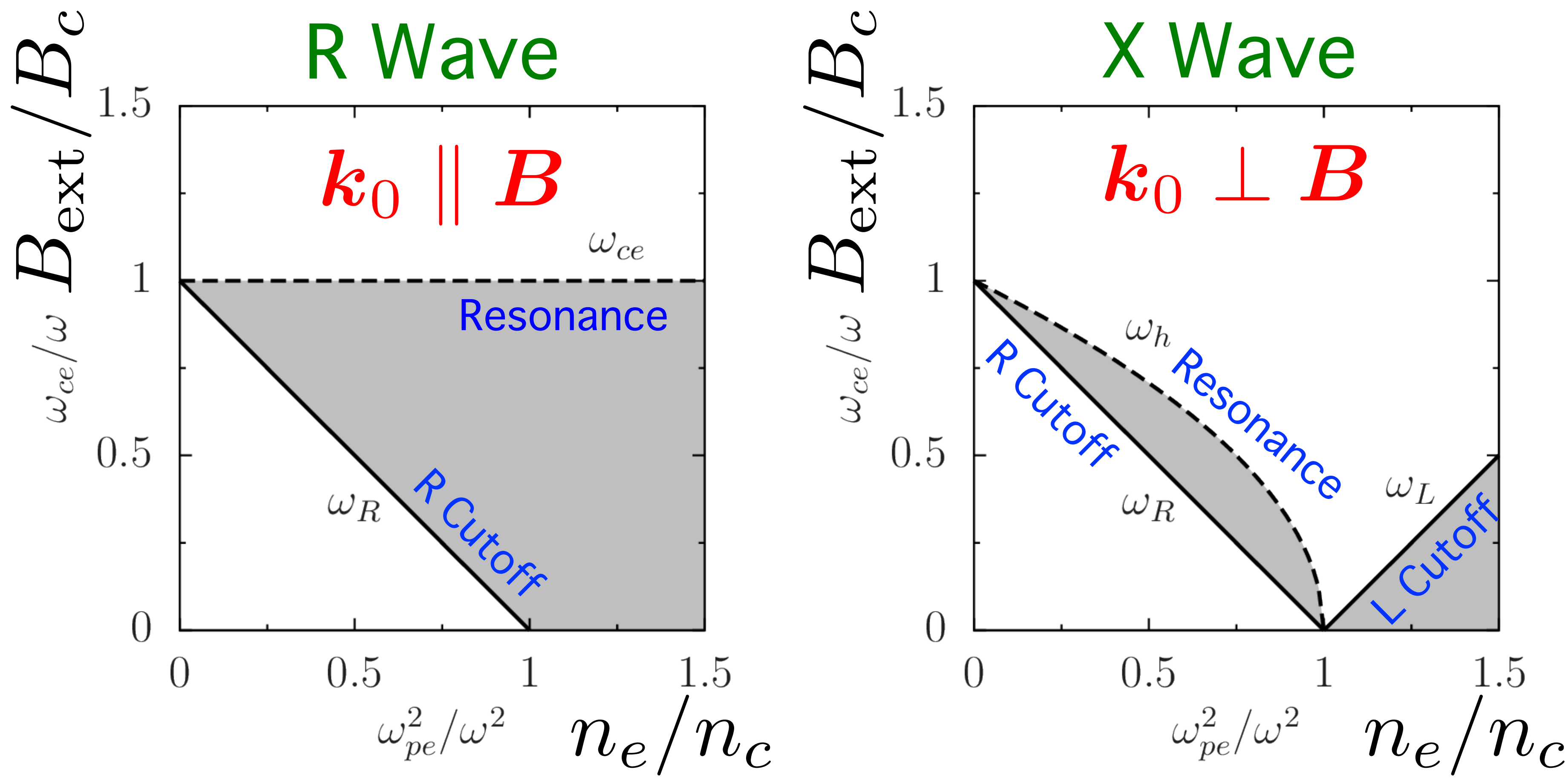
- Whistler Wave + Thin Plasma Foil
- Key Parameters
  - Plasma Density
  - External Magnetic Field Strength



$$\lambda_0 = 0.8\ [\mu\mathrm{m}]$$
$$\tau_0 = 30\ [\mathrm{fs}]$$
$$t_f = 1\ [\mu\mathrm{m}]$$

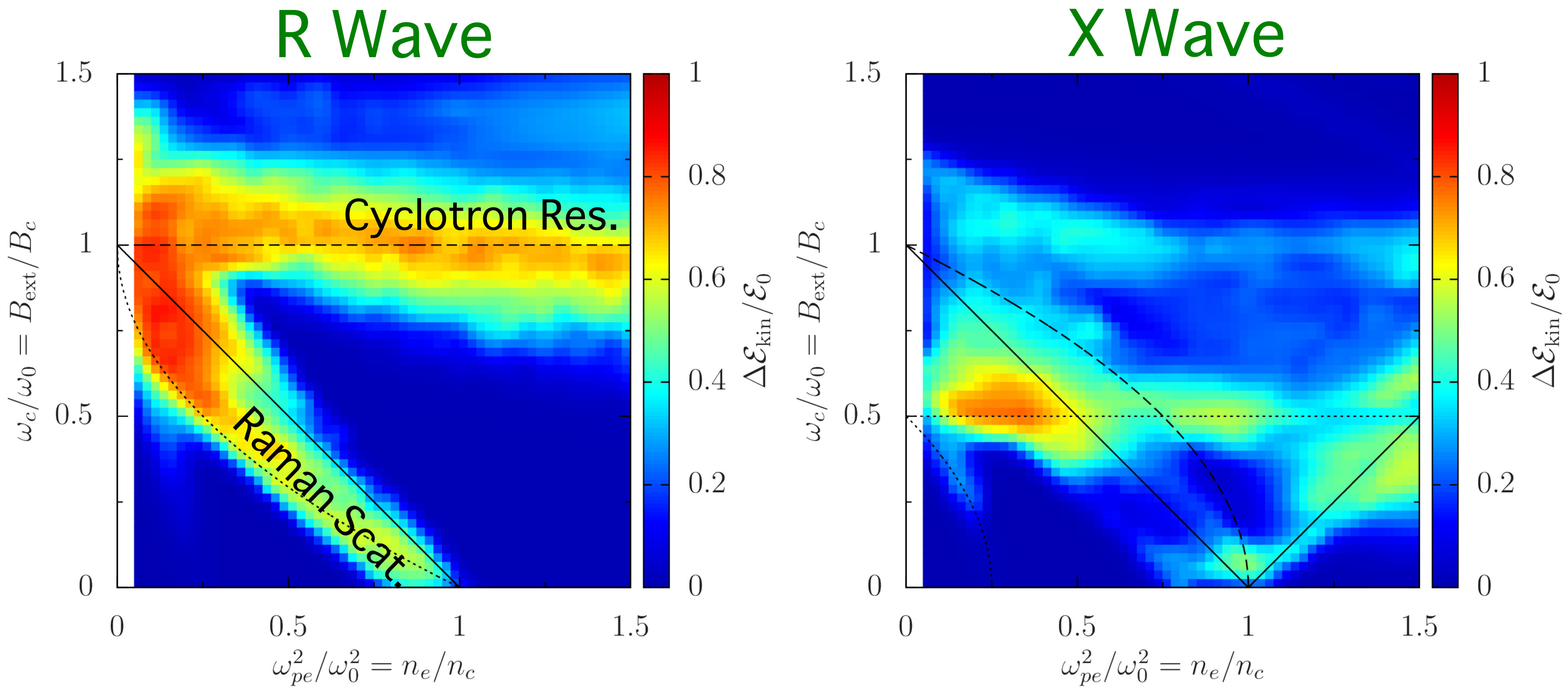
Laser in Magnetized Plasma

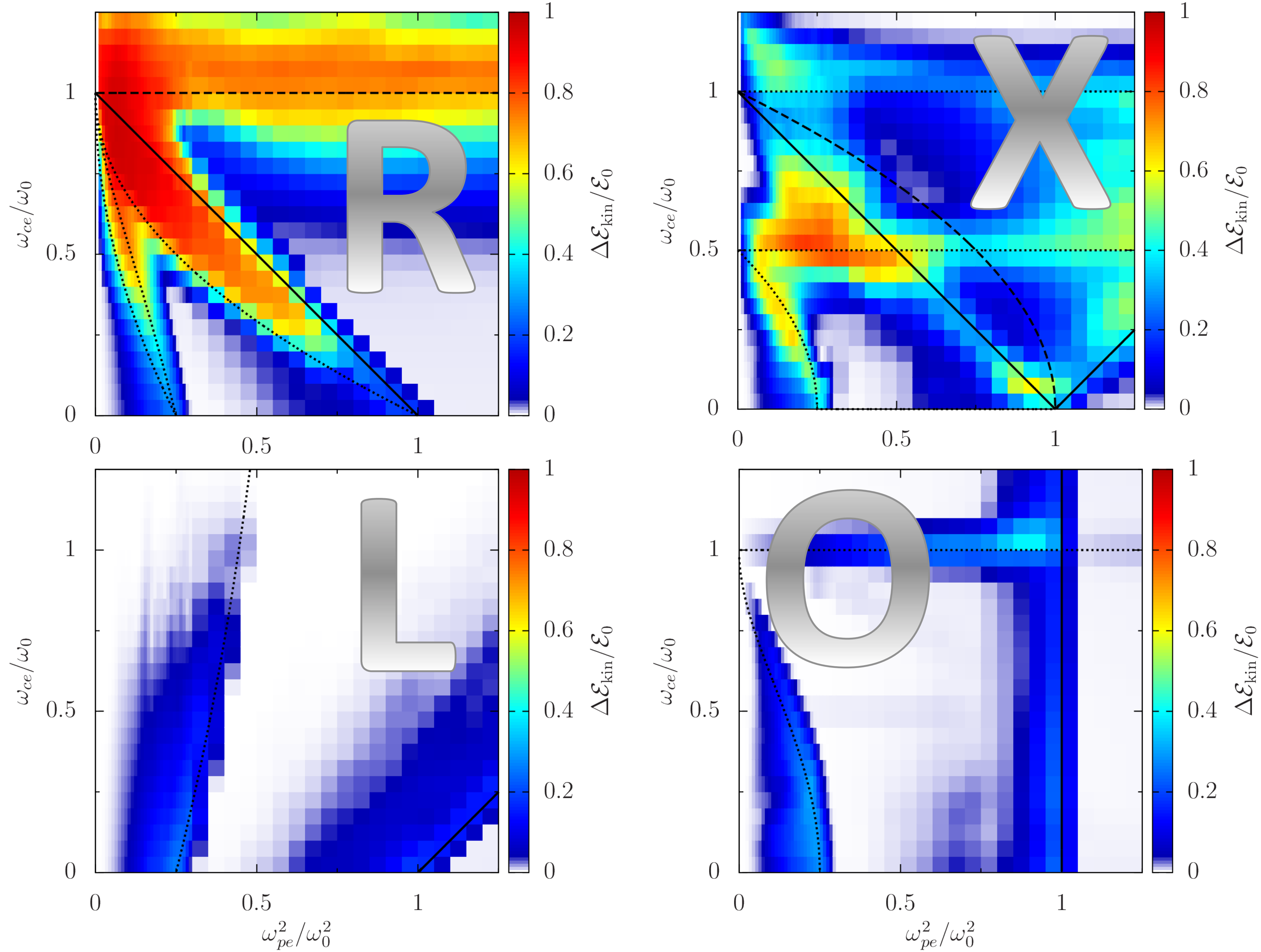
- Various EM Wave Propagation (R, L, X, and O Waves) → CMA Diagram (n vs. B)



CMA Diagram for LPI

- Enhancement of Energy Absorption by
  - Cyclotron Resonance
  - Parametric Instabilities (→ Plasma Wave)




R
X
L
O
ω_{ce}/ω_0
ω_{pe}^2/ω_0^2
$\Delta\mathcal{E}_{\rm kin}/\mathcal{E}_0$
0
0.5
1
0.2
0.4
0.6
0.8

Overdense & Strong Field

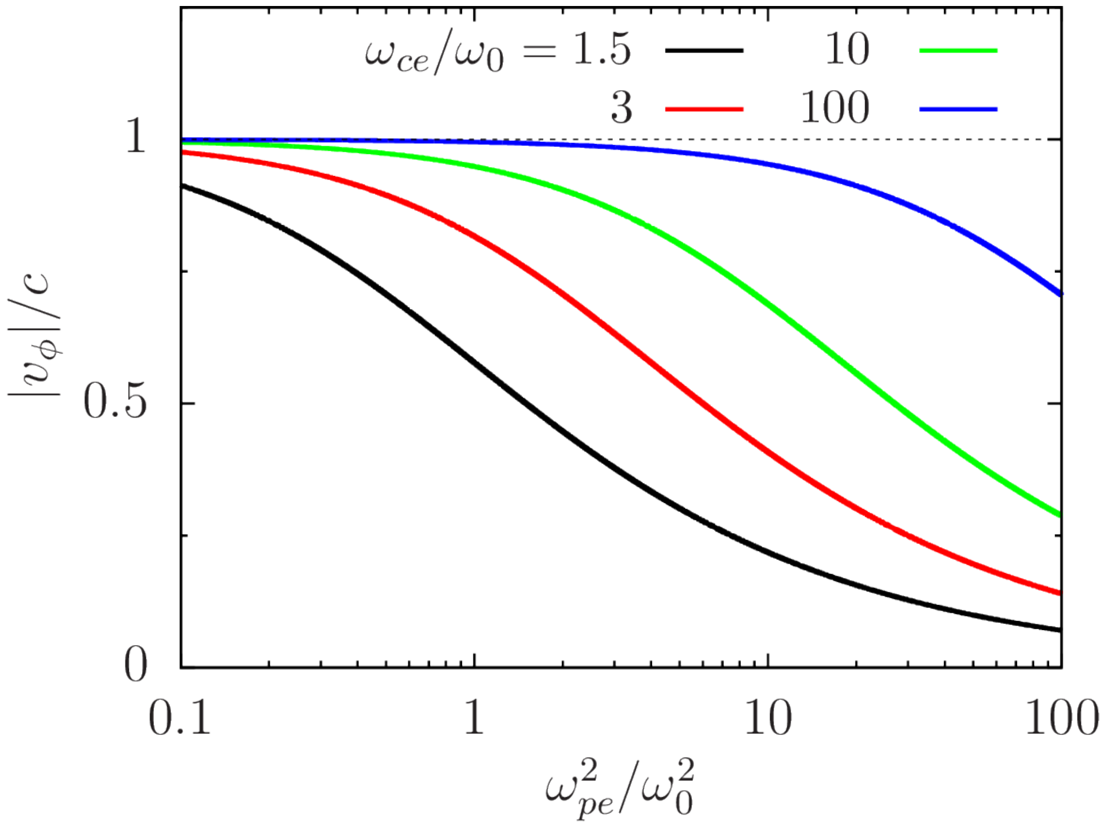
$$\frac{n_e}{n_c} \gg 1 \qquad \frac{B_{\text{ext}}}{B_c} > 1$$

Overdense & Strong Field

計算が意外と難しい??

強磁場PICで必要な計算条件は?

- 高密度→デバイ長、スキン長
- ラーマー半径を分解できているか?
- ホイッスラー波長を分解できているか?



Key Processes

High Intensity Whistler Wave + Strongly Magnetized Plasma = ...

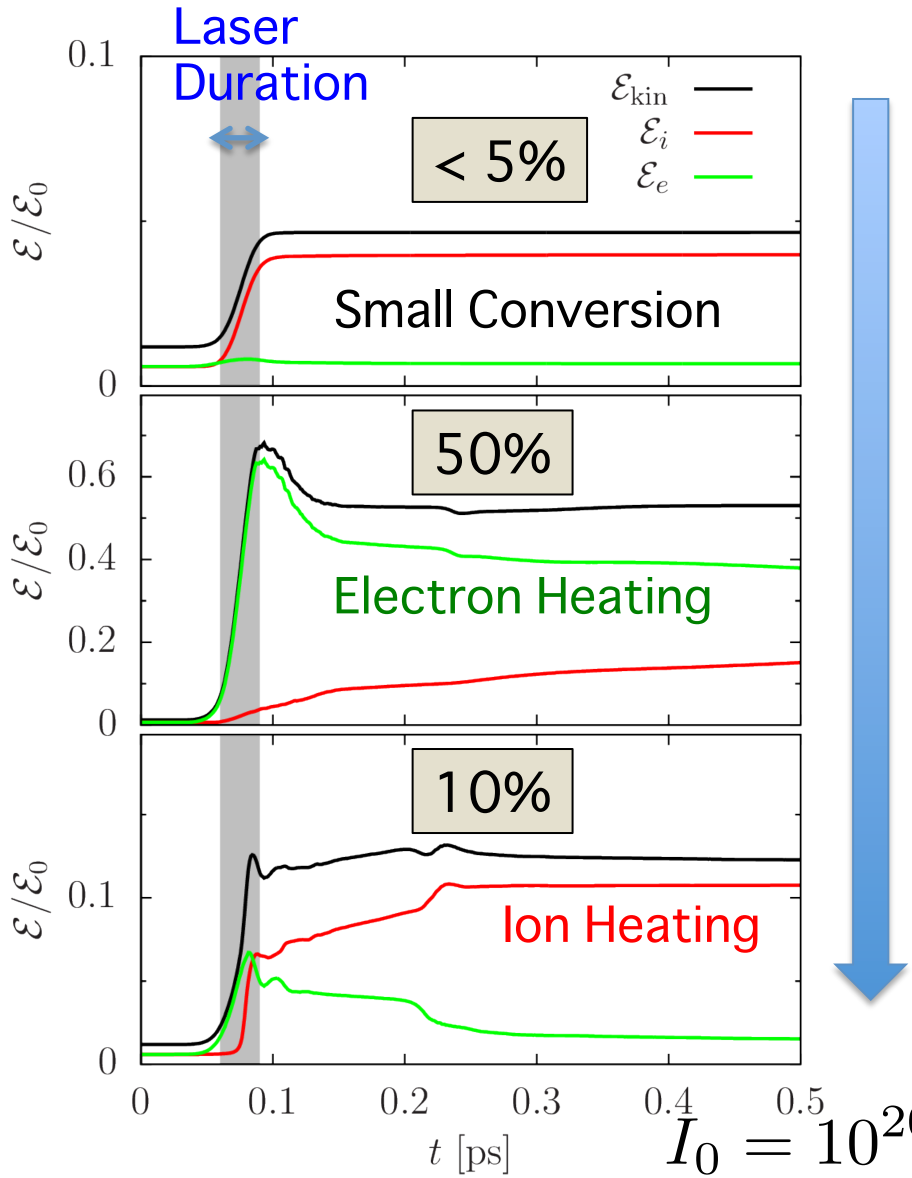
- Overdense Plasma + kT Field

1. Enhanced Absorption by Cyclotron Resonance of Relativistic Electrons
2. Excitation of Ion Acoustic Wave by Brillouin Instability

- Underdense Plasma + kT Field

3. Efficient Electron Heating by Raman Scattering

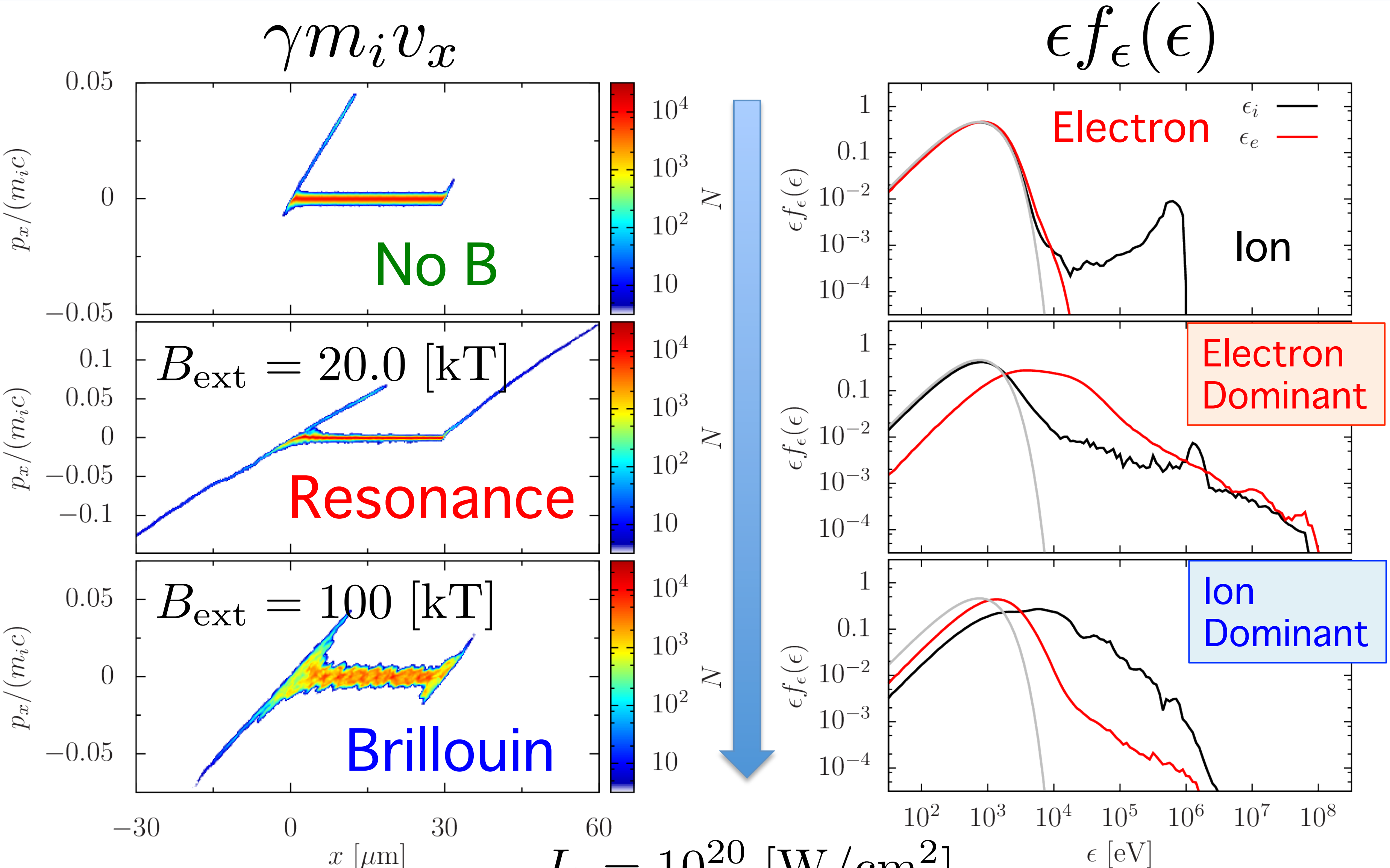
B Effects on "Absorption" Rate



- Weak B
  - Little Interaction Only at Surface
- Around Resonant B
  - Efficient Electron Heating by Cyclotron Resonance
  - Ion Acceleration by TNSA
- Further Strong B
  - Proton Heating by Brillouin Instability

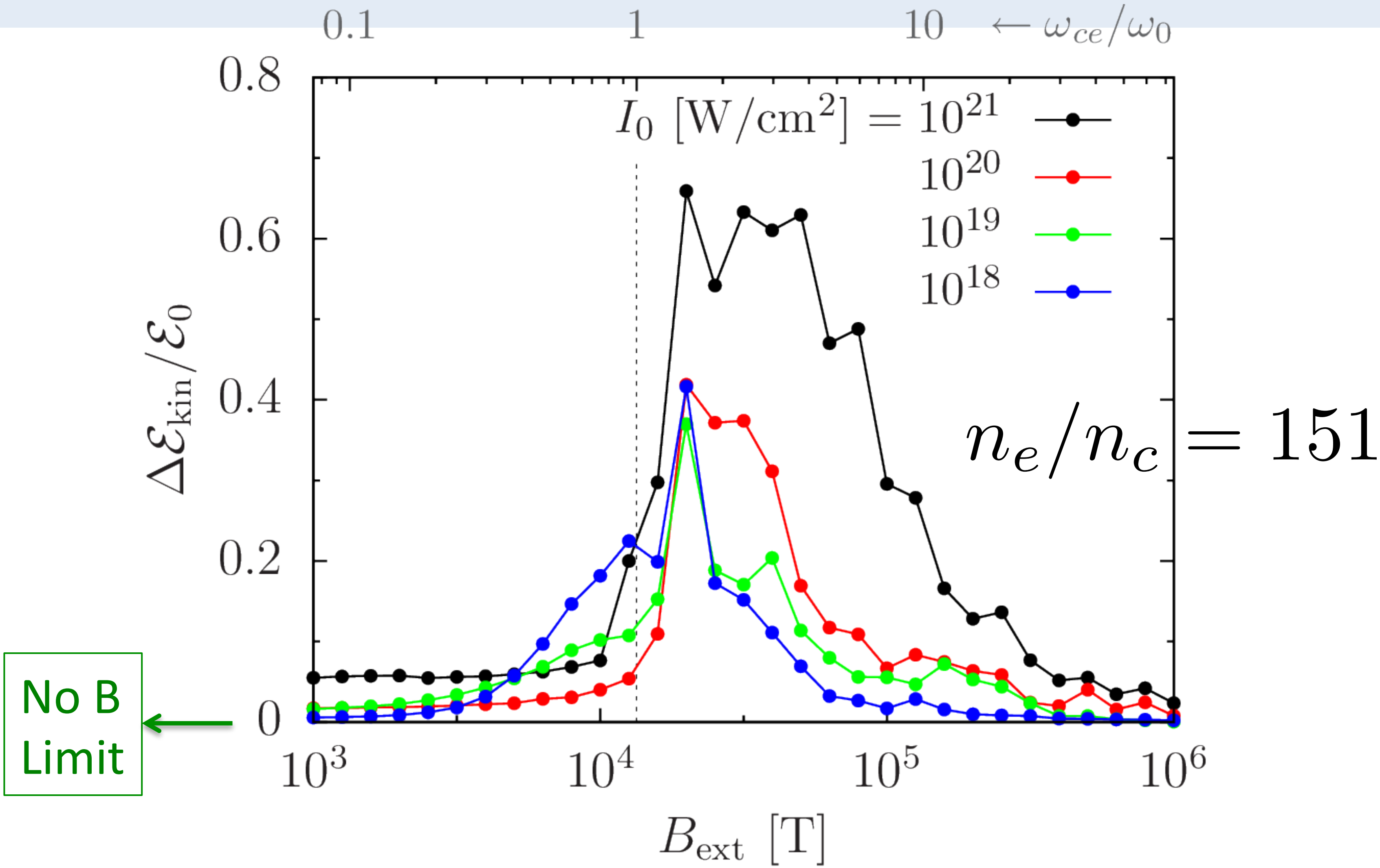
$I_0 = 10^{20}\ [\mathrm{W/cm^2}]$

Resonance or Parametric



$I_0 = 10^{20}$ [W/cm^2]

Absorption Rate (Laser to Plasma)

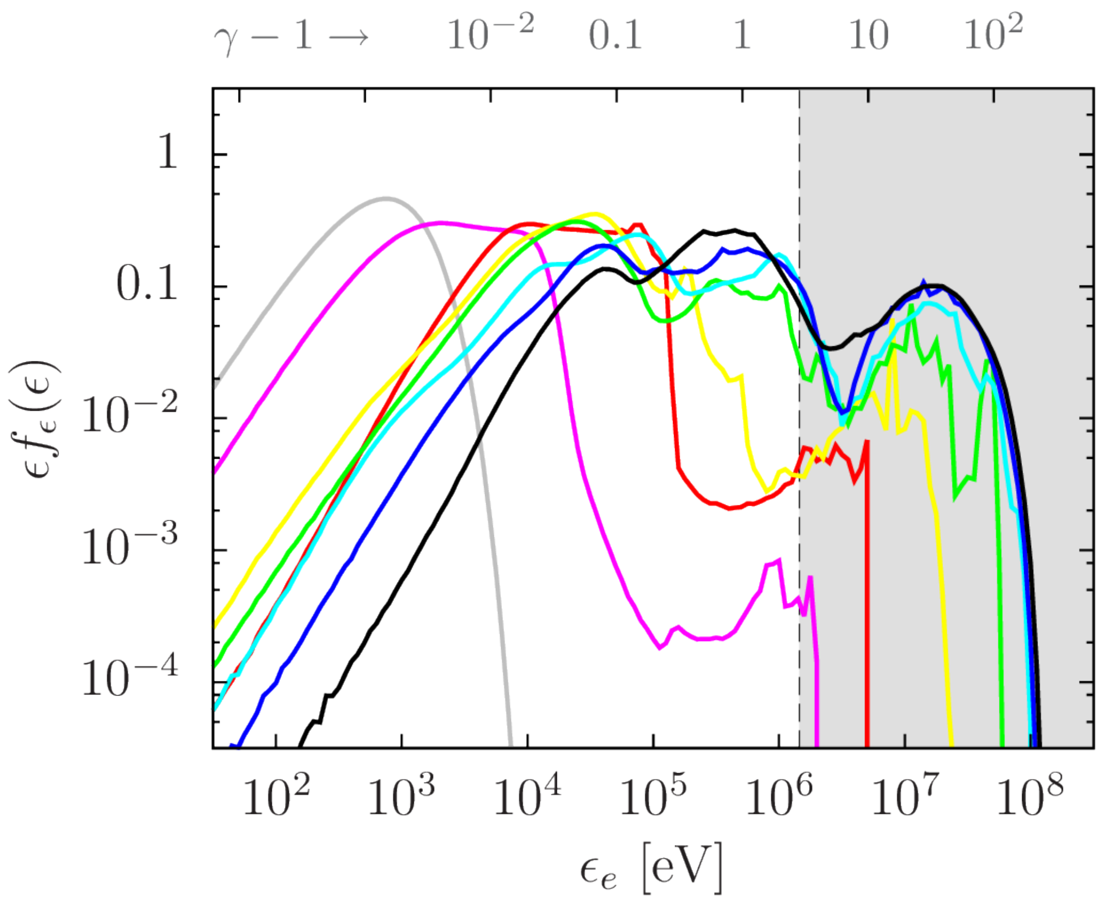


- Huge Enhancement of Energy Absorption at Critical Strength
- Wider Absorption Range as Laser Intensity Increases

Beyond Ponderomotive Scaling

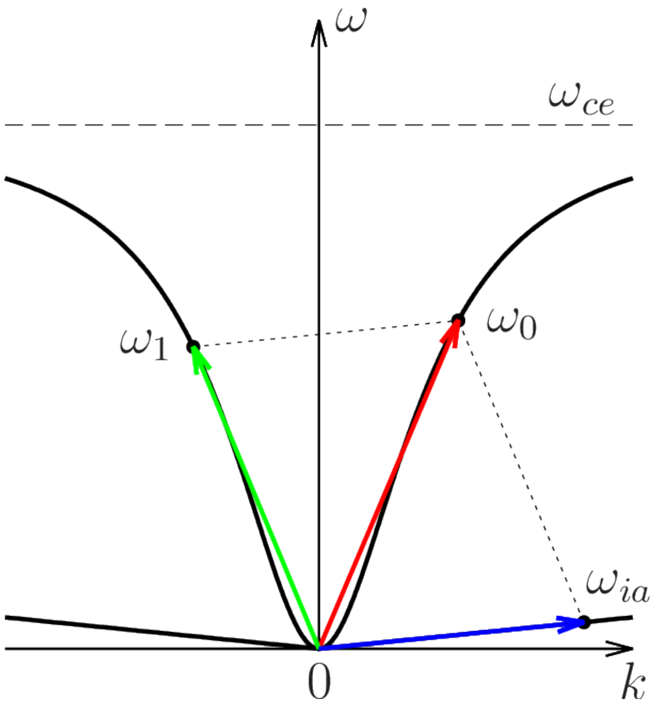
- Electron Energy > Free-Electron Ponderomotive Limit

$$\epsilon_p = \frac{m_e c^2 a_0^2}{2} \approx 60 \text{ [MeV]}$$

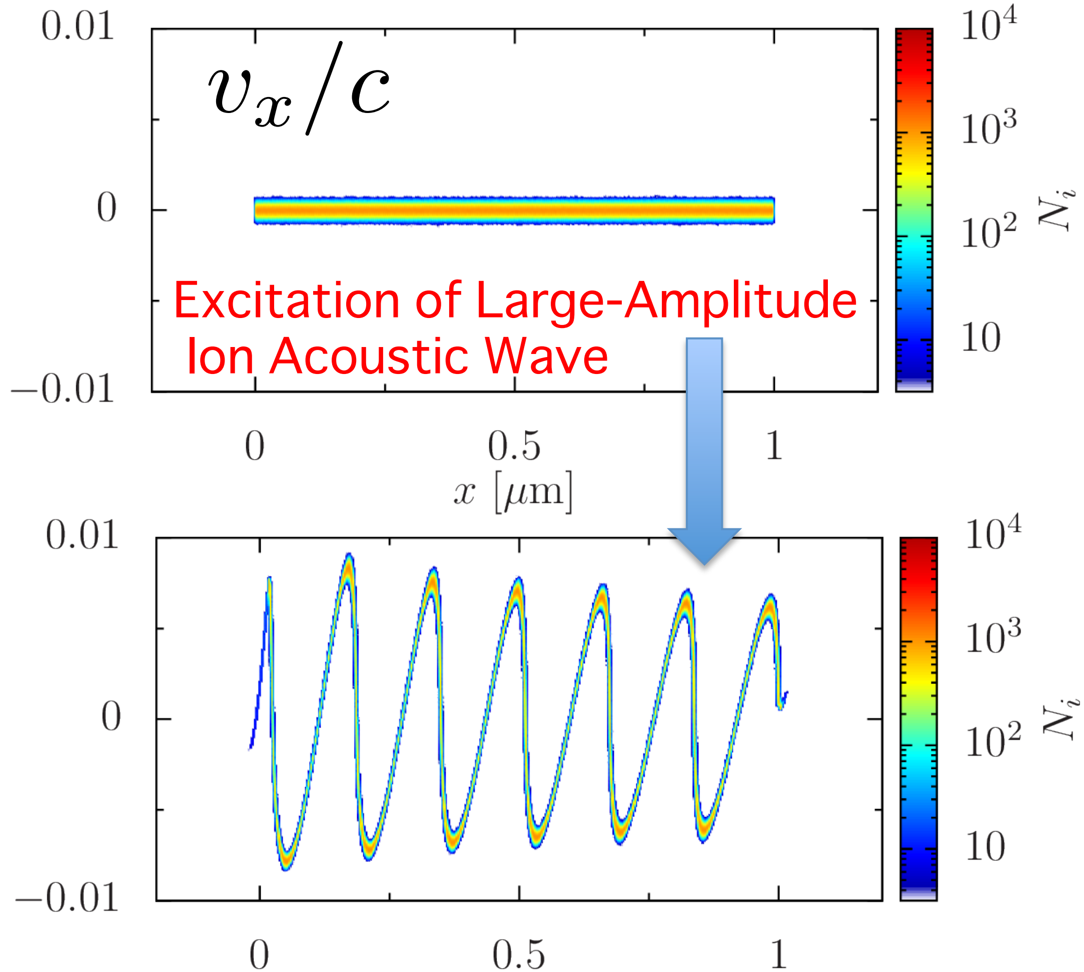


Stimulated Brillouin Scattering

- Direct Ion Heating by Parametric Decay
  - Whistler -> Back-Scattered Whistler + Ion Acoustic Wave

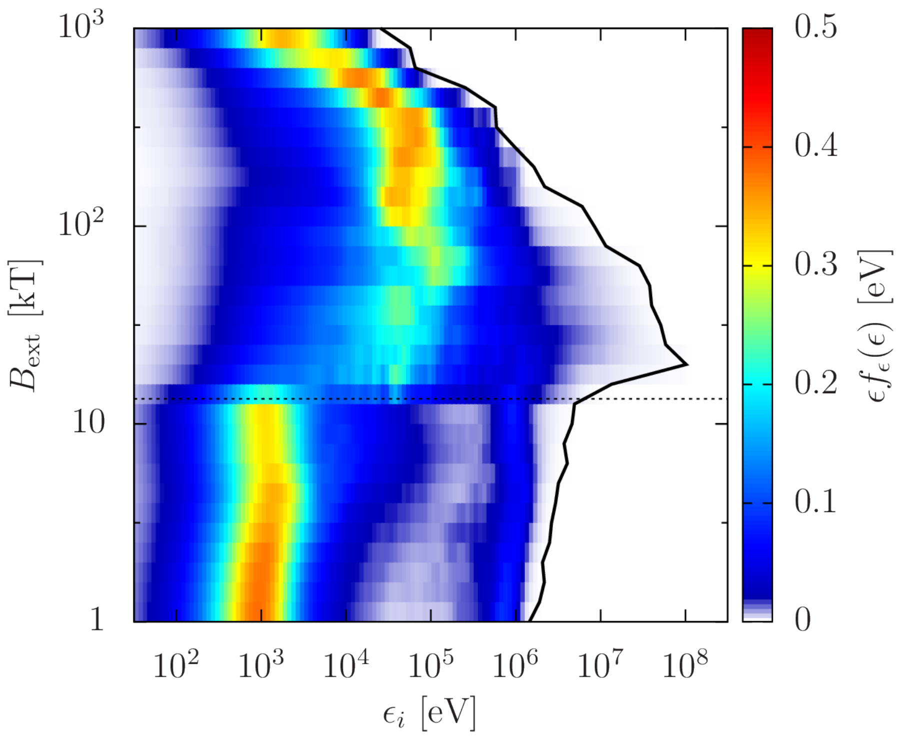


$$\omega_0 = \omega_1 + \omega_{ia}$$
$$k_0 = k_1 + k_{ia}$$



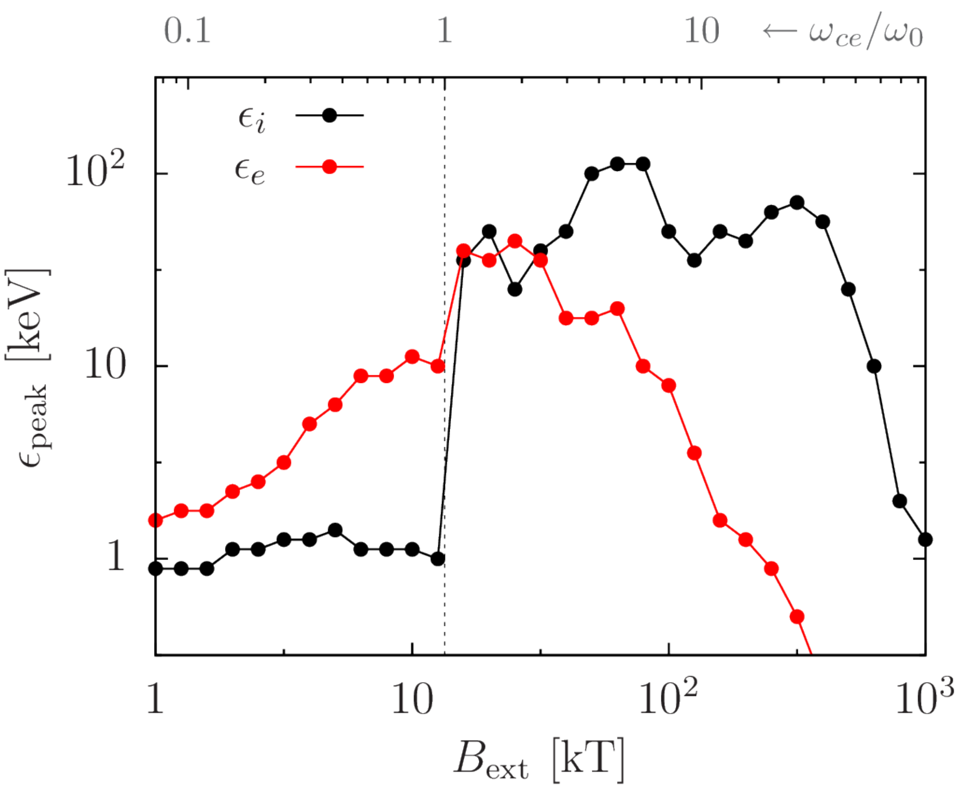
Selective Ion Heating?

- Ion and Electron Temperature Inferred from the Peak of Energy Spectrum



Ion Energy Spectrum

Peak Temp. for Ion & Electron



Summary

- Interaction between Intense Laser and Dense Plasma with Strong Magnetic Field
- Enhancement of
  - Electron Heating by Cyclotron Resonance and Parametric Instabilities (Stimulated Raman Scattering)
  - Ion Heating (Brillouin Instability) and Acceleration (TNSA)
- Application to Laser Fusion Plasma, Planetary Plasma, and Astrophysical Plasma (around Compact Stars?)