The Astrophysical Journal, 891:92 (20pp), 2020 March 1

Coherent emission driven by energetic ring-beam electrons in the solar corona

via 2.5D PIC Simulations

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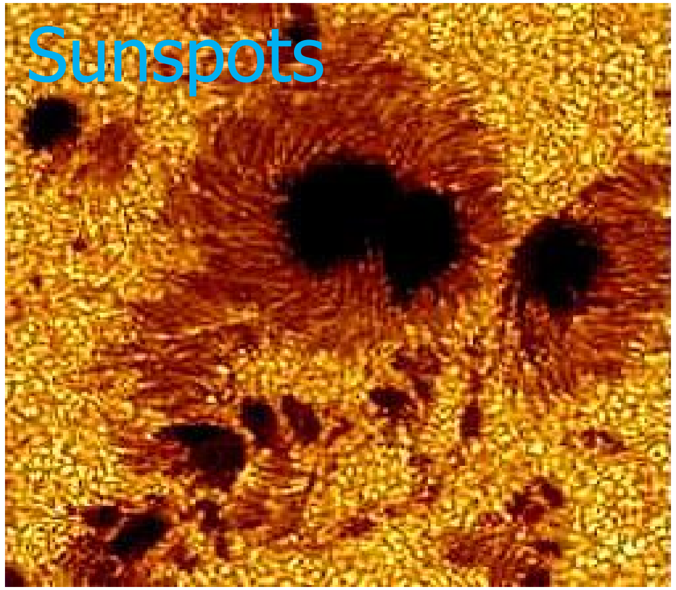
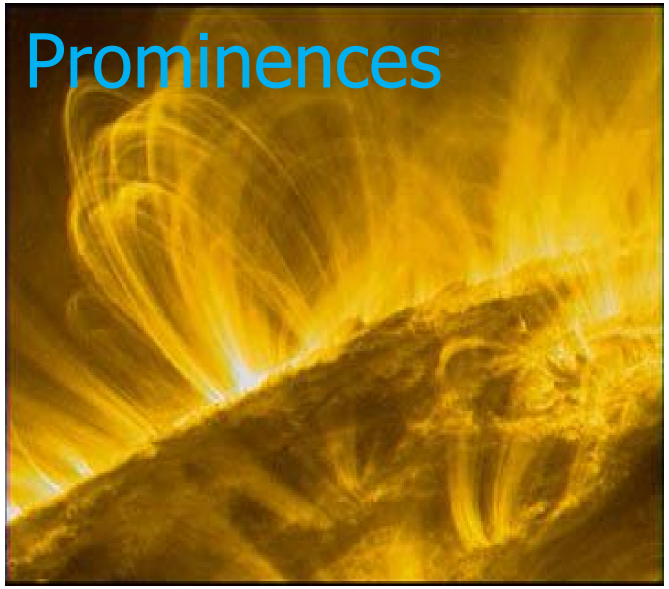
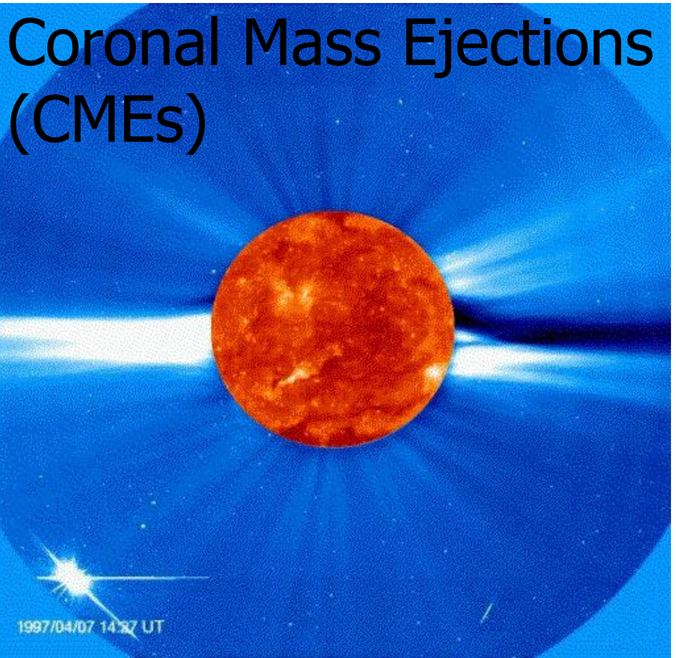
Outline

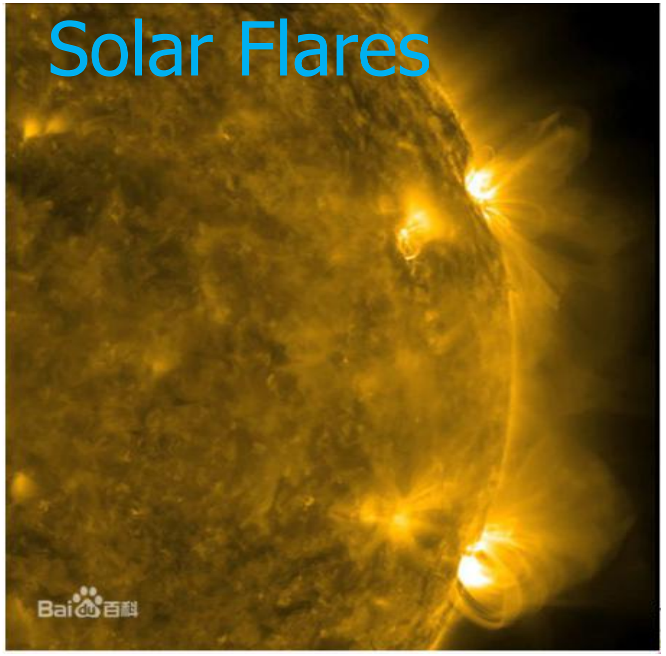
1. Motivation
2. Method
3. Results
4. Conclusion

1. Motivation --- Solar Activity









Solar Flares:

1. The most powerful eruptions ----- emit energies up to 10^{32} ergs

2. Energetic particles from flares (e.g., Miller et al. 1997)
   - Solar Energetic Particle (SEP) Events
   - Solar Radio Bursts
   - Auroras

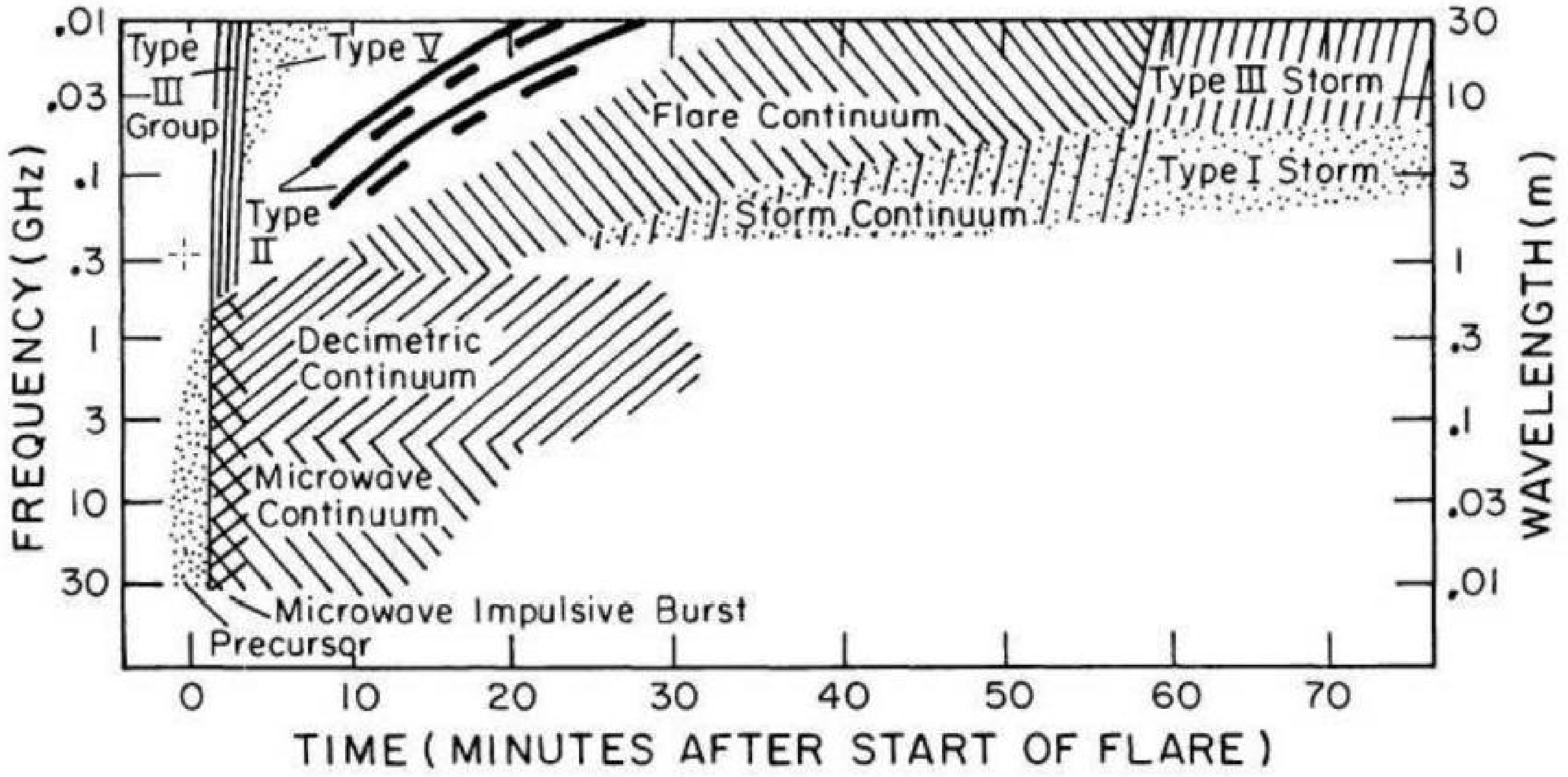
3. Radiation crosses the entire electromagnetic spectrum from radio to gamma rays
   - x-rays and gamma rays require telescopes in space
   - radio and optical emissions can penetrate the Earth's atmosphere & be observed with telescopes on the Earth.

1. Motivation

- A solar radio burst is a structure in frequency space that changes with time. Type I, II, III, IV, V + subtypes.

- high brightness temperature T_B;
- short-eruptive time scale;
- narrow frequency bandwidth;
- strong polarization.

[Aschwanden and Benz, 1997; Barta et al., 2008; Benz et al., 2009]



1. Motivation

Radio Emission Mechanisms during Solar Fares

[Aschwanden, 2002]

- high brightness temperature T_B;
- short-eruptive time scale;
- narrow frequency bandwidth;
- strong polarization.

Emission mechanism	Frequency	Source/Exciter
(1) Incoherent radio emission:		
(1a) Free-free emission (bremsstrahlung)	$\nu \gtrsim 1$ GHz	Thermal plasma
– Microwave postbursts		Thermal plasma
(1b) Gyroemission	$\omega = s\Omega_e$	
Gyroresonance emission	$(s = 1, 2, 3, 4)$	Thermal electrons
Gyrosynchrotron emission	$(s \approx 10 - 100)$	Mildly relativistic electrons
– Type IV moving		Trapped electrons
– Microwave type IV		Trapped electrons
(2) Coherent radio emission:		
(2a) Plasma emission	$\nu_{pe} = 9000\sqrt{n_e}$	Electron beams
– Type I storms		Langmuir turbulence
– Type II bursts		Beams from shocks
– Type III bursts		Upward propagating beams
– Reverse slope (RS) bursts		Downward propagating beams
– Type J bursts		Beams along closed loops
– Type U bursts		Beams along closed loops
– Type IV continuum		Trapped electrons
– Type V		Slow electron beams
(2b) Electron-cyclotron maser:	$\omega = s\Omega_e/\gamma + k_{\parallel} v_{\parallel}$	Losscones
- Decimetric ms spike bursts		Losscones

1. Motivation

- **Incoherent emission**
  - the total emission of a collection of elections == summing over the emission by single electron
  - Types: e.g., synchrotron radiation, bremsstrahlung radiation

- **Coherent emission**
  - involve some plasma instabilities, collective (kinetic) plasma radiation processes
    - high brightness temperature T_B;
    - short-eruptive time scale;
    - narrow frequency bandwidth;
    - strong polarization, e.g., solar radio bursts [Aschwanden and Benz, 1997; Barta et al., 2008; Benz et al., 2009]
  - Types: plasma emission, electron cyclotron maser emission, pulsar radio emission...

[Melrose, 2017]

1. Motivation

Mechanism 1:

(ω_{pe} ---- plasma frequency)

$$L \rightarrow L' + S$$

$$L \rightarrow S + T(\omega_{pe})$$

$$L + L' \rightarrow T(2\omega_{pe})$$

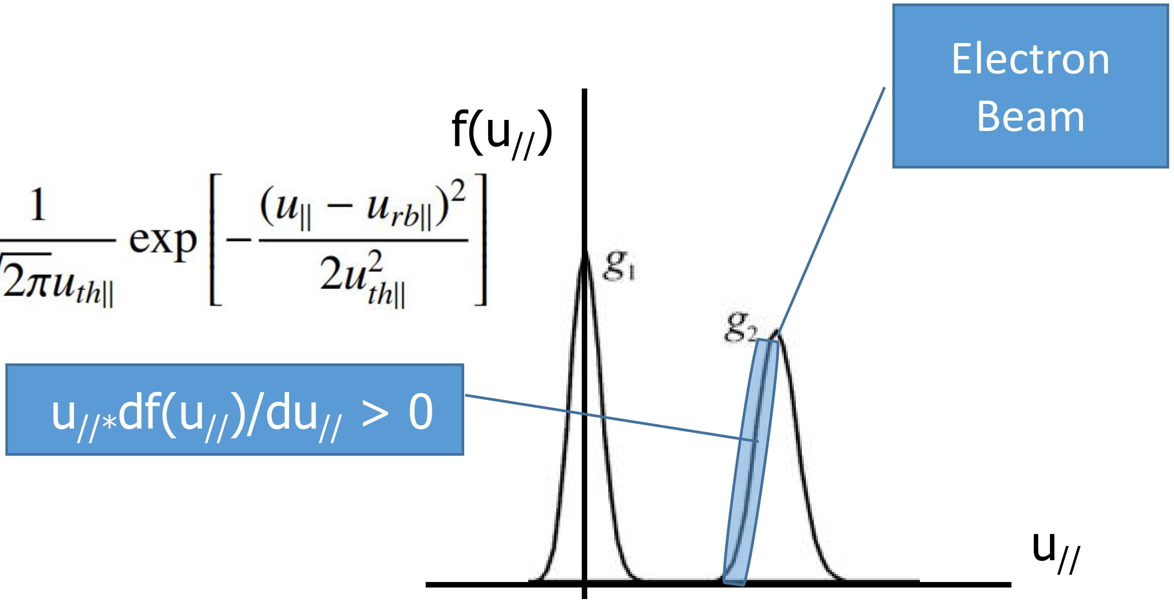
(Ganse et al, 2012)

Plasma Emission (Ginzburg and Zheleznyakov 1958; Melrose, 1985; Robinson and Cairns, 1998):

a non-linear multi-stage process: beam instability + three-wave interaction processes
Langmuir waves (L)
backward Langmuir waves (L')
sound waves (S)
transverse electromagnetic waves (T)

Driver ------ a positive gradient ($u_{//*}df(u_{//})/du_{//} > 0$) in the electron distribution function

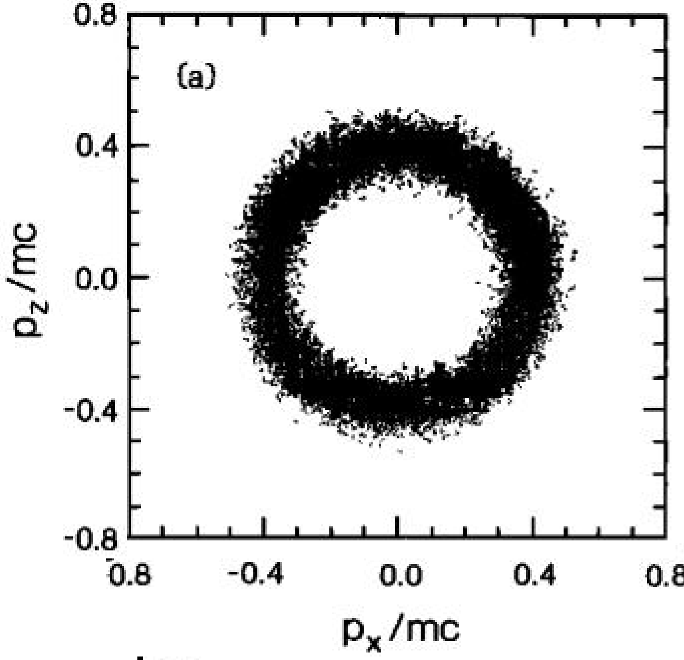
$$F_{rb\|}(u_\|) = \frac{1}{\sqrt{2\pi}u_{th\|}} \exp\left[-\frac{(u_\| - u_{rb\|})^2}{2u_{th\|}^2}\right]$$



1. Motivation

Mechanism 2:

Ring Distribution



Electron Cyclotron Maser Emission (ECME)

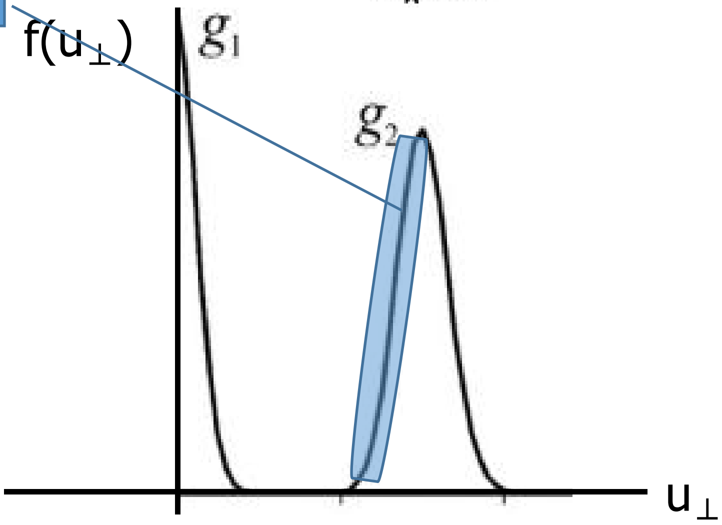
----- Linear instability (Wild, 1985; C. S. Wu, 2012; D. J. Wu, 2014; Wu et al., 2014):

$$F_{rb\perp}(u_\perp) = \frac{1}{2\pi u_{th\perp}^2 A_\perp} \exp\left[-\frac{(u_\perp - u_{rb\perp})^2}{2u_{th\perp}^2}\right]$$

Two necessary conditions:

(1) free energy --- positive perpendicular velocity gradient ($df(u_\perp)/du_\perp > 0$, e.g., ring distribution, loss cone distribution)

$df(u_\perp)/du_\perp > 0$



(2) local electron cyclotron frequency ω_{ce} > plasma frequency ω_{pe} ($\omega_{ce} / \omega_{pe} \propto B^2/n_e$, e.g., density cavity) to satisfy the escape condition

ECME ----- auroral kilometric radiation (AKR) in the Earth (e.g., Strangeway et al., 2001; Louarn, 2006, Melrose, 2017).

1. Motivation

Properties of wave excitation driven by energetic ring-beam electrons in the environment of solar corona?

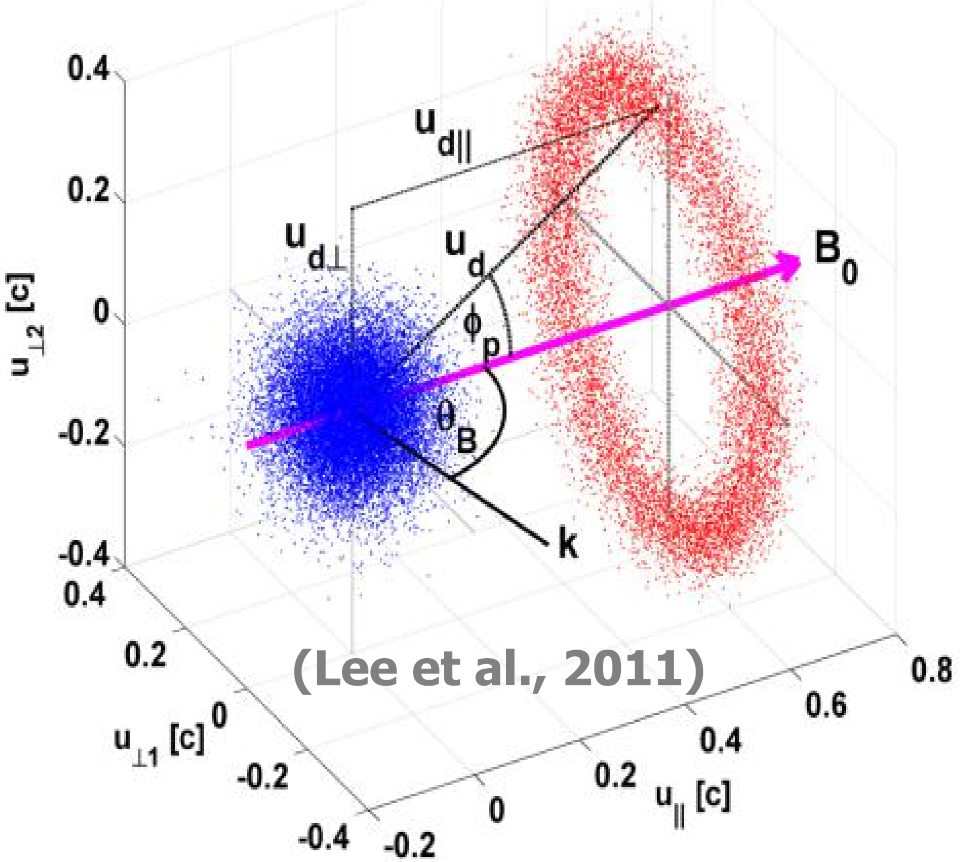
- Intensity of excited waves
- Polarization

$$F_{rb}(u_{\|}, u_{\perp}) = F_{rb\|}(u_{\|}) F_{rb\perp}(u_{\perp})$$

$$F_{rb\|}(u_{\|}) = \frac{1}{\sqrt{2\pi} u_{th\|}} \exp\left[-\frac{(u_{\|} - u_{rb\|})^2}{2u_{th\|}^2}\right]$$

$$F_{rb\perp}(u_{\perp}) = \frac{1}{2\pi u_{th\perp}^2 A_{\perp}} \exp\left[-\frac{(u_{\perp} - u_{rb\perp})^2}{2u_{th\perp}^2}\right]$$

$$A_{\perp} = \exp\left[-\frac{u_{rb\perp}^2}{2u_{th\perp}^2}\right] + \sqrt{\frac{\pi}{2}} \frac{u_{rb\perp}}{u_{th\perp}} \operatorname{erfc}\left[-\frac{u_{rb\perp}}{\sqrt{2} u_{th\perp}}\right]$$



(Lee et al., 2011)

1. Motivation

JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 89, NO. A10, PAGES 8957–8970, OCTOBER 1, 1984

Relativistic Dispersion, the Cyclotron Maser Instability, and Auroral Kilometric Radiation

P. L. PRITCHETT

ring distribution via therical analysis and 2D PIC simulation with

PRL 103, 105101 (2009) PHYSICAL REVIEW LETTERS week ending 4 SEPTEMBER 2009

Nonlinear Saturation of Cyclotron Maser Instability Associated with Energetic Ring-Beam Electrons

K. H. Lee,[1] Y. Omura,[2] L. C. Lee,[1] and C. S. Wu[1]

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(Received 25 November 2008; published 31 August 2009)

ring-beam distribution via 1D PIC simulation

PHYSICS OF PLASMAS 18, 092110 (2011)

A 2D simulation study of Langmuir, whistler, and cyclotron maser instabilities induced by an electron ring-beam distribution

K. H. Lee,[1] Y. Omura,[2] and L. C. Lee[1]

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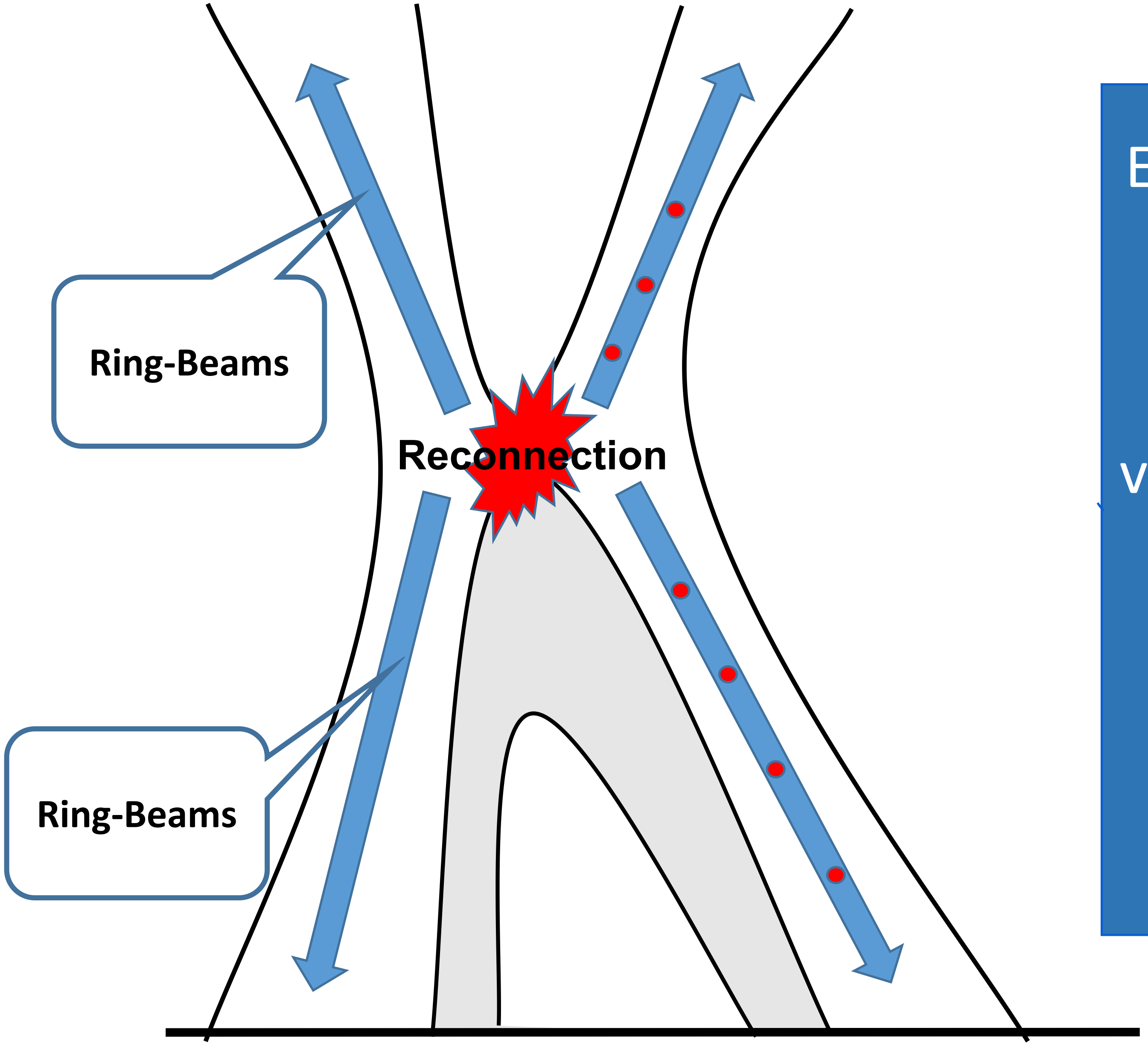
ring-beam distribution, in dependence on the energy and pitch angle of the energetic ring-beam electrons via 2.5D PIC simulation

1. Motivation



Emission differences along the trajectory of the energetic ring-beam electrons

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varying the ring-beam electron density and ambient magnetic field strength

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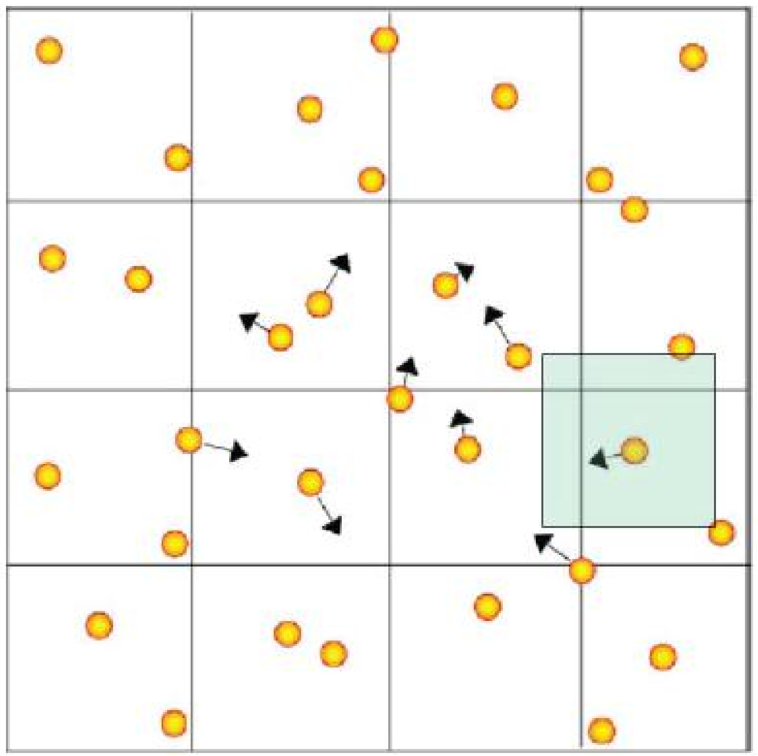
2.5D PIC simulations

2. Method --- Fully-kinetic PIC Simulation



Fully-kinetic PIC Code:

1. Evolutions of the particles (electrons & ions) and electromagnetic fields are self-consistent ----- feedback

2. collisionless ---- dissipation via wave-particle interactions

3. Code: ACRONYM (**Advanced Code for Relativistic Objects, Now with Yee-Lattice and Macroparticles**, Kilian et al., 2012, http://plasma.nerd2nerd.org/)

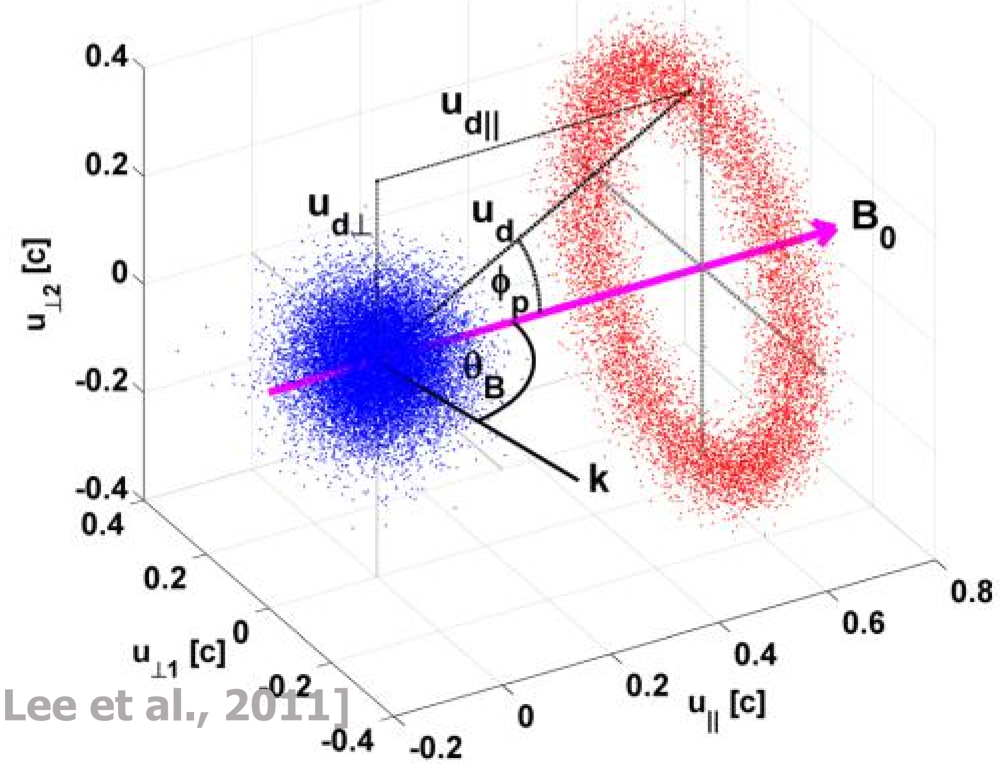
2 Initial Setup

$$F_{rb}(u_{\|}, u_{\perp}) = F_{rb\|}(u_{\|})F_{rb\perp}(u_{\perp})$$

$$F_{rb\|}(u_{\|}) = \frac{1}{\sqrt{2\pi}u_{th\|}} \exp\left[-\frac{(u_{\|} - u_{rb\|})^2}{2u_{th\|}^2}\right]$$

$$F_{rb\perp}(u_{\perp}) = \frac{1}{2\pi u_{th\perp}^2 A_{\perp}} \exp\left[-\frac{(u_{\perp} - u_{rb\perp})^2}{2u_{th\perp}^2}\right]$$

$$A_{\perp} = \exp\left[-\frac{u_{rb\perp}^2}{2u_{th\perp}^2}\right] + \sqrt{\frac{\pi}{2}}\frac{u_{rb\perp}}{u_{th\perp}} \operatorname{erfc}\left[-\frac{u_{rb\perp}}{\sqrt{2}u_{th\perp}}\right]$$



[Lee et al., 2011]

- (1024, 1024) grid points, periodic boundaries
- 1000 electrons/cell (n_{total} fixed), **homogeneous**, neutral charge
- ω_{pe} fixed; m_p:m_e = 1836
- background magnetic field ----- **uniform** ---- along X-axis
- $u_{th//} = u_{th\perp} = 0.025c$
- $u_{th\text{-}background} = 0.05c$
- $\gamma=[1+(u_{rb\perp}^2 + u_{rb//}^2)/c^2]^{1/2}=1.2$~100keV
- $u_{rb\perp} / u_{rb//} = \tan(30^0)$
- neutral current ---- $u_{background//} = u_{rb//} * n_{rb}/n_{background}$

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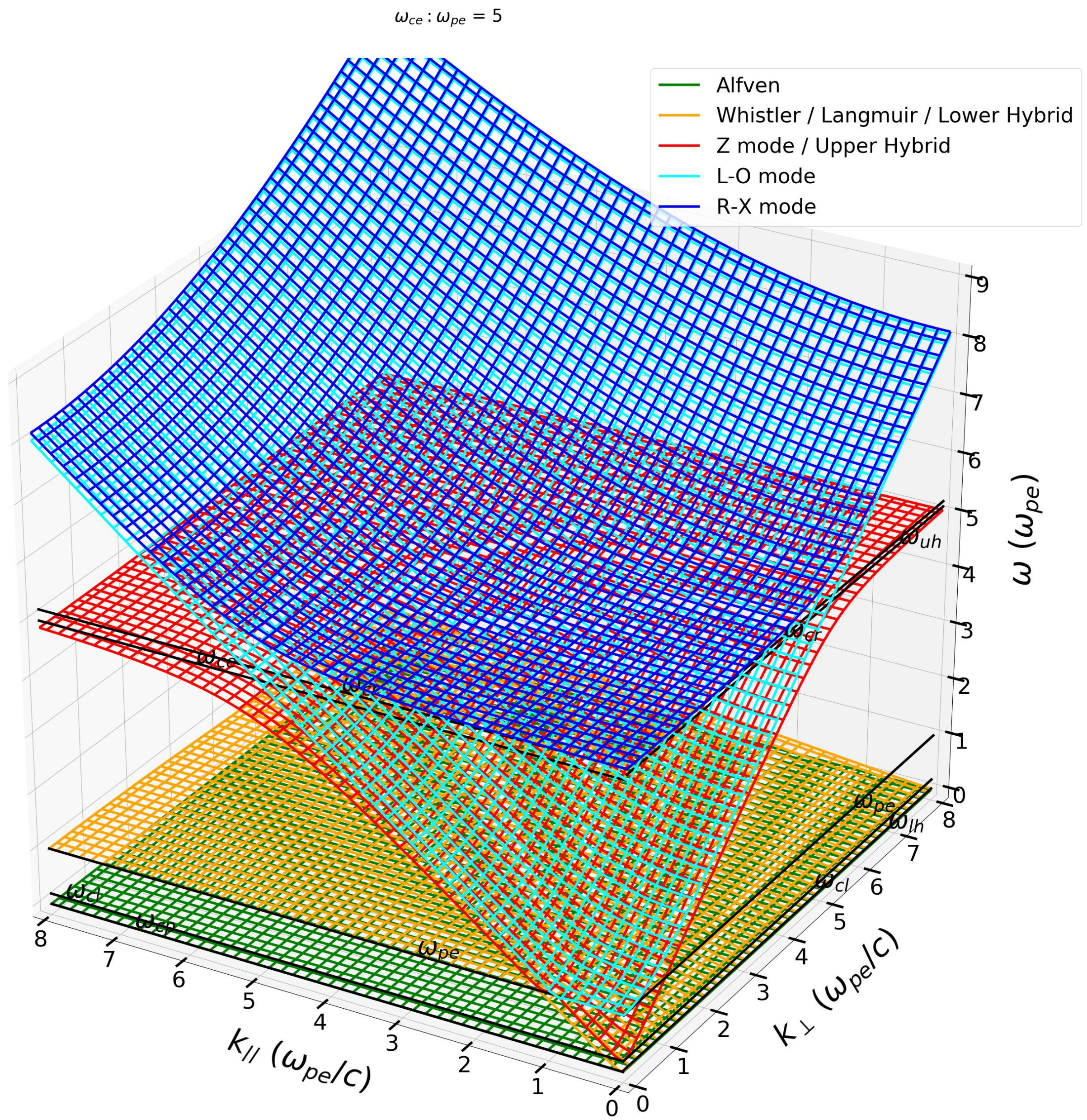
- **n_{rb}: n_{total} = 5%, 10%, 20%, 30%, 40%, 50% (with ω_{ce}:ω_{pe} = 5)**
- **ω_{ce}:ω_{pe} = 0.2, 0.3, 0.5, 1, 2, 3, 5 (n_{rb}: n_{total} = 5%)**

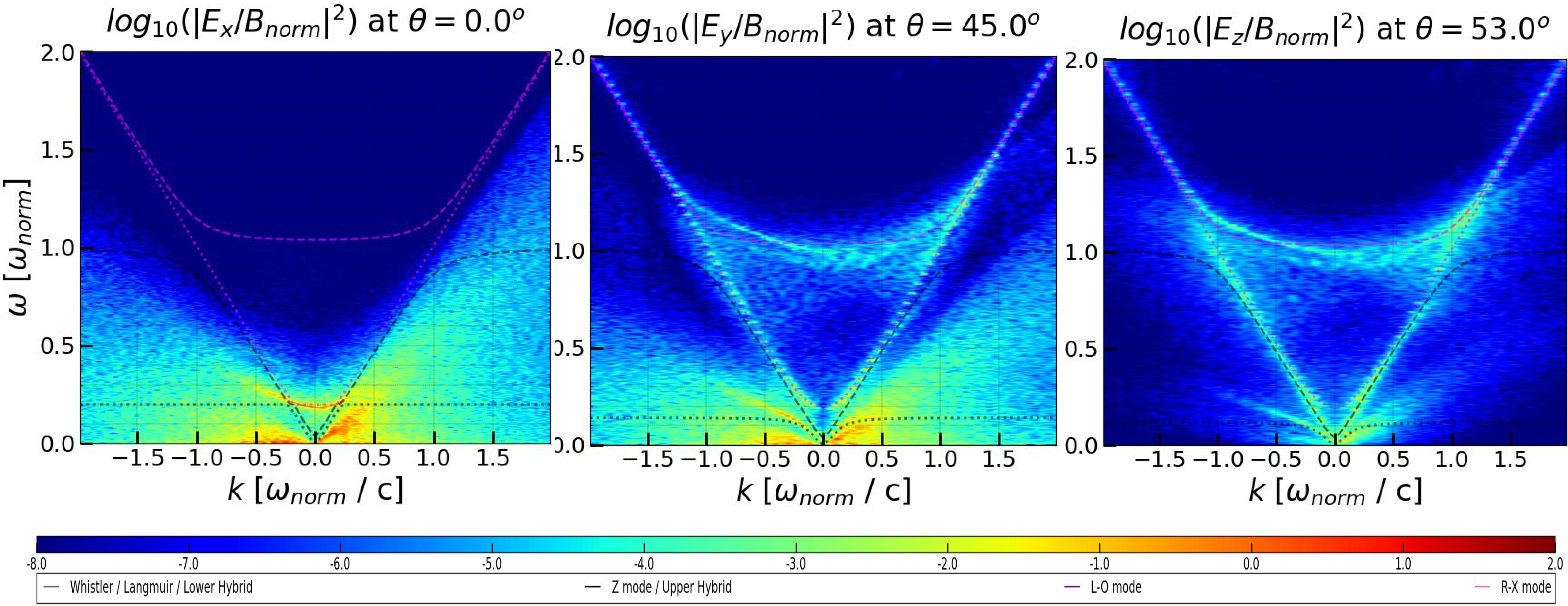
2. Wave modes in cold plasma

Dispersion Relation in the Cold Plasma



3. n_{rb}: n_{total} Results --- dispersion relation spectrum

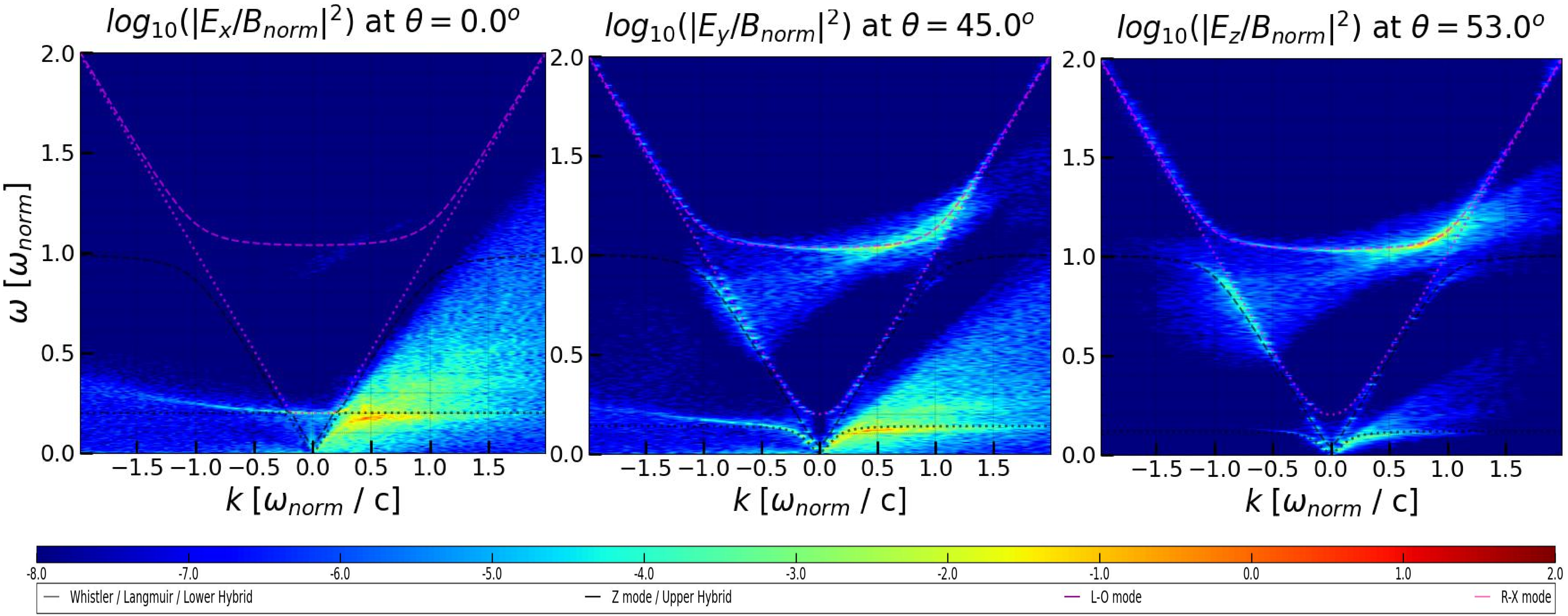
(n_{rb}: n_{total} = 30%)



$$\omega_{norm} = 5.0\omega_{pe}$$

3. n_{rb}: n_{total} Results --- dispersion relation spectrum

(n_{rb}: n_{total} = 5%)



$$\omega_{norm} = 5.0\omega_{pe}$$

3.1 n_{rb}: n_{total} Results --- Intensity of Different wave modes

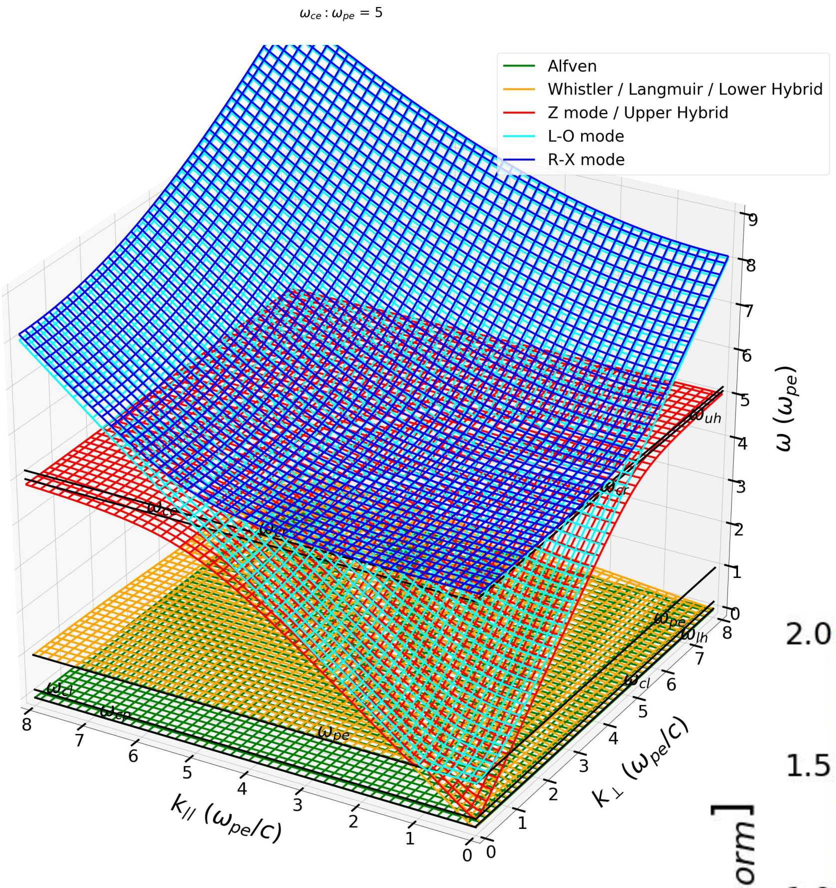
Dispersion Relation in the Cold Plasma

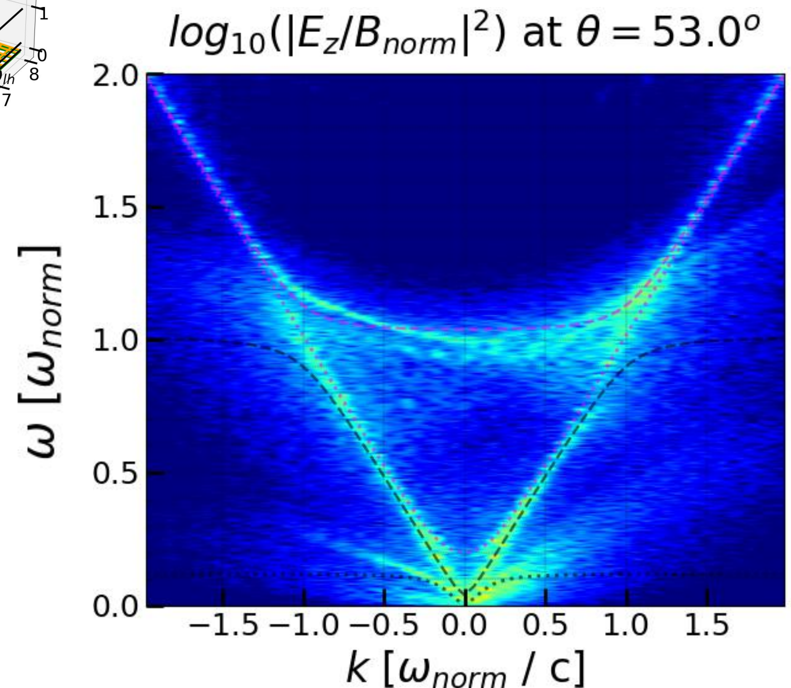
+

$$\varepsilon_M(\vec{k},\omega) = \frac{\varepsilon(\vec{k},\omega)}{\sqrt{2\pi}\sigma}\exp\left[-\frac{\left(\omega-\omega_{Mcold}(\vec{k})\right)^2}{2\sigma^2}\right]$$

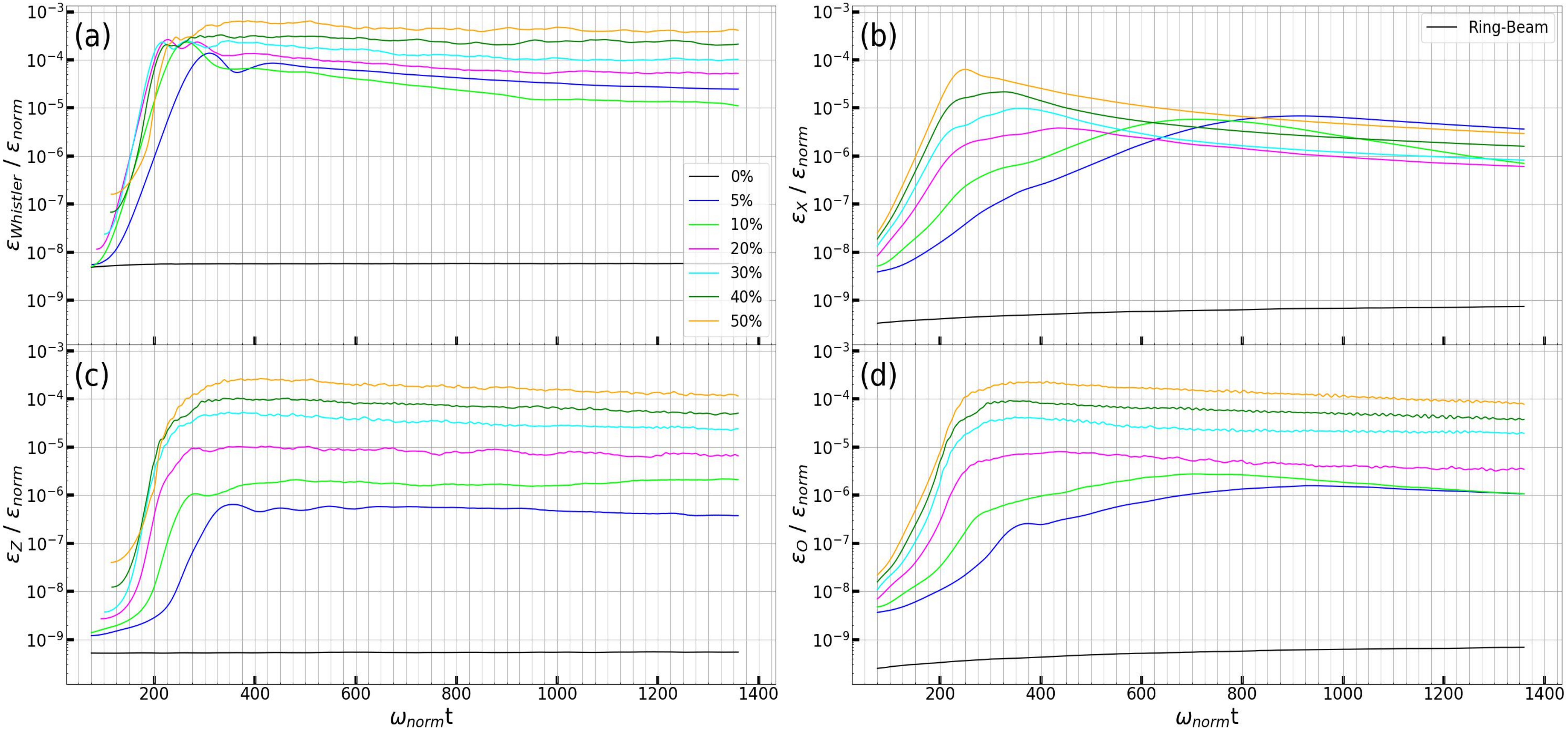
[comisel et al, 2013]

$$\sigma = 0.05\omega_{norm} \qquad \omega_{norm} = 5.0\omega_{pe}$$

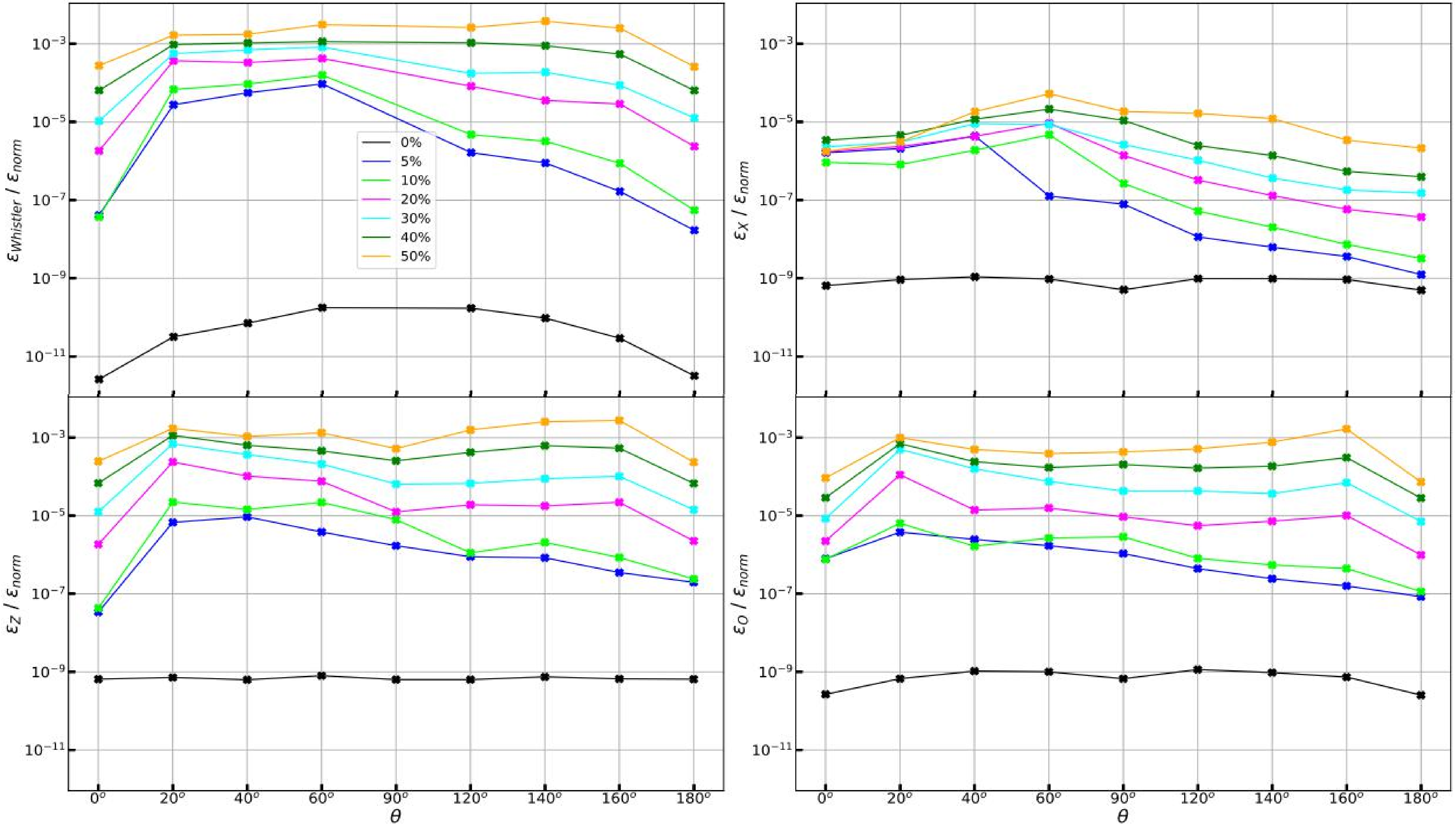




3.1 n_{rb}: n_{total} Results --- Intensity of Different wave modes



3.1 n_{rb}: n_{total} Results --- Intensity Anisotropy



3.1 n_{rb}: n_{total} Results --- Polarization

Polarization Vector (defined with respect to the wave propagation vector, in order to compare with observations (Stix, 1992)):

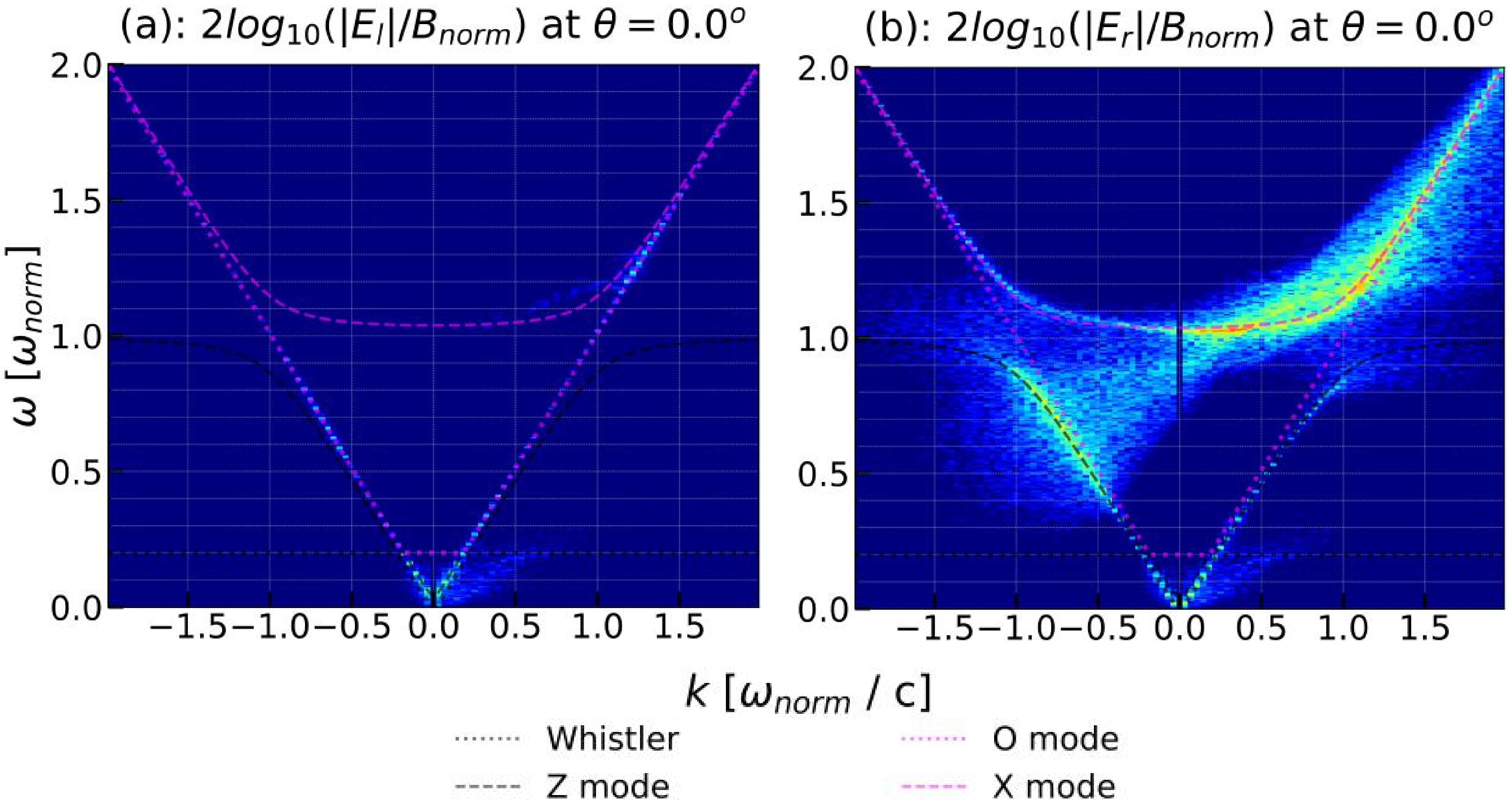
Polarization basis vector

$$e_M = \begin{pmatrix} e_1 = \vec{k} / k \\ e_2 = e_\tau = e_3 \times e_1 \\ e_3 = e_z \end{pmatrix}$$

$$\vec{e_l} = \begin{cases} (\vec{e_2} + i\vec{e_3})/\sqrt{2} & (\omega \cdot k_{\|} > 0) \\ (\vec{e_2} - i\vec{e_3})/\sqrt{2} & (\omega \cdot k_{\|} < 0) \end{cases}$$

$$\vec{e_r} = \begin{cases} (\vec{e_2} - i\vec{e_3})/\sqrt{2} & (\omega \cdot k_{\|} > 0) \\ (\vec{e_2} + i\vec{e_3})/\sqrt{2} & (\omega \cdot k_{\|} < 0) \end{cases}$$

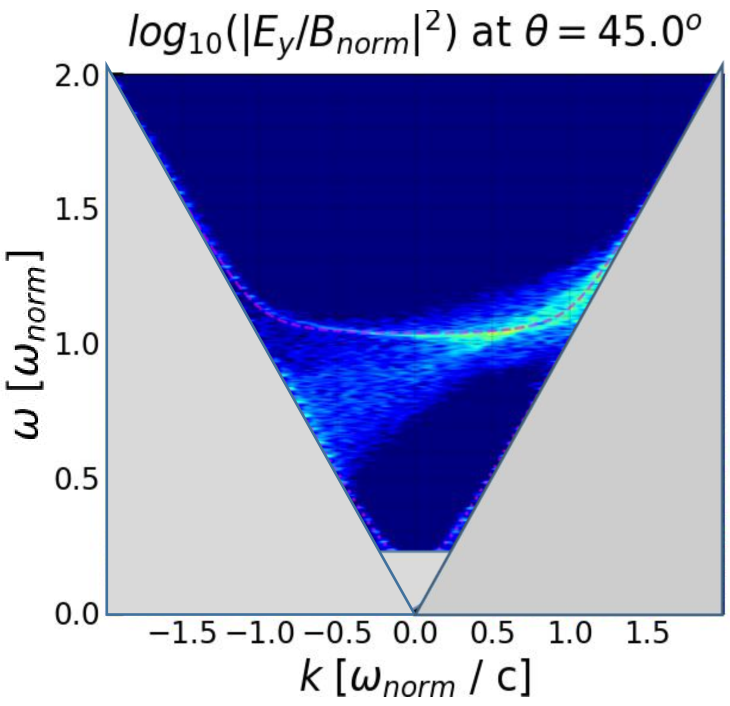
(n_{rb}: n_{total} =5%)

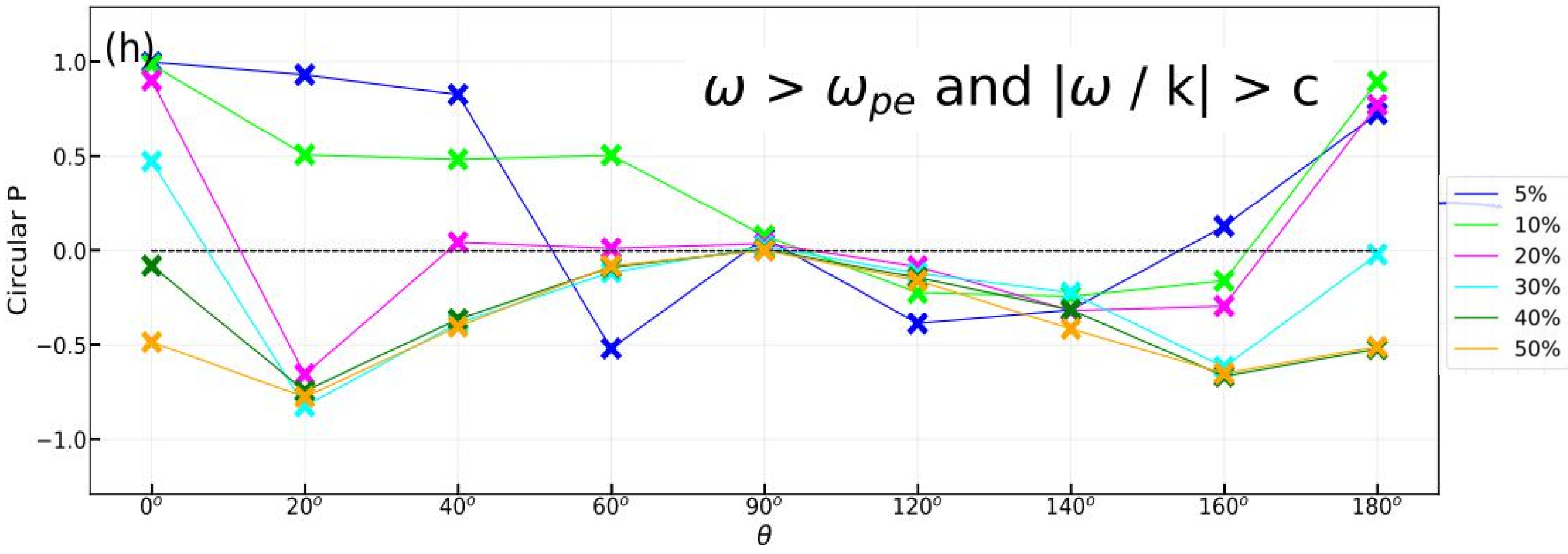


3.1 n_{rb}: n_{total} Results --- Polarization (escaping waves)

Circular Polarization Degree (CPD)

$$P = \frac{\varepsilon_{right} - \varepsilon_{left}}{\varepsilon_{right} + \varepsilon_{left}}$$

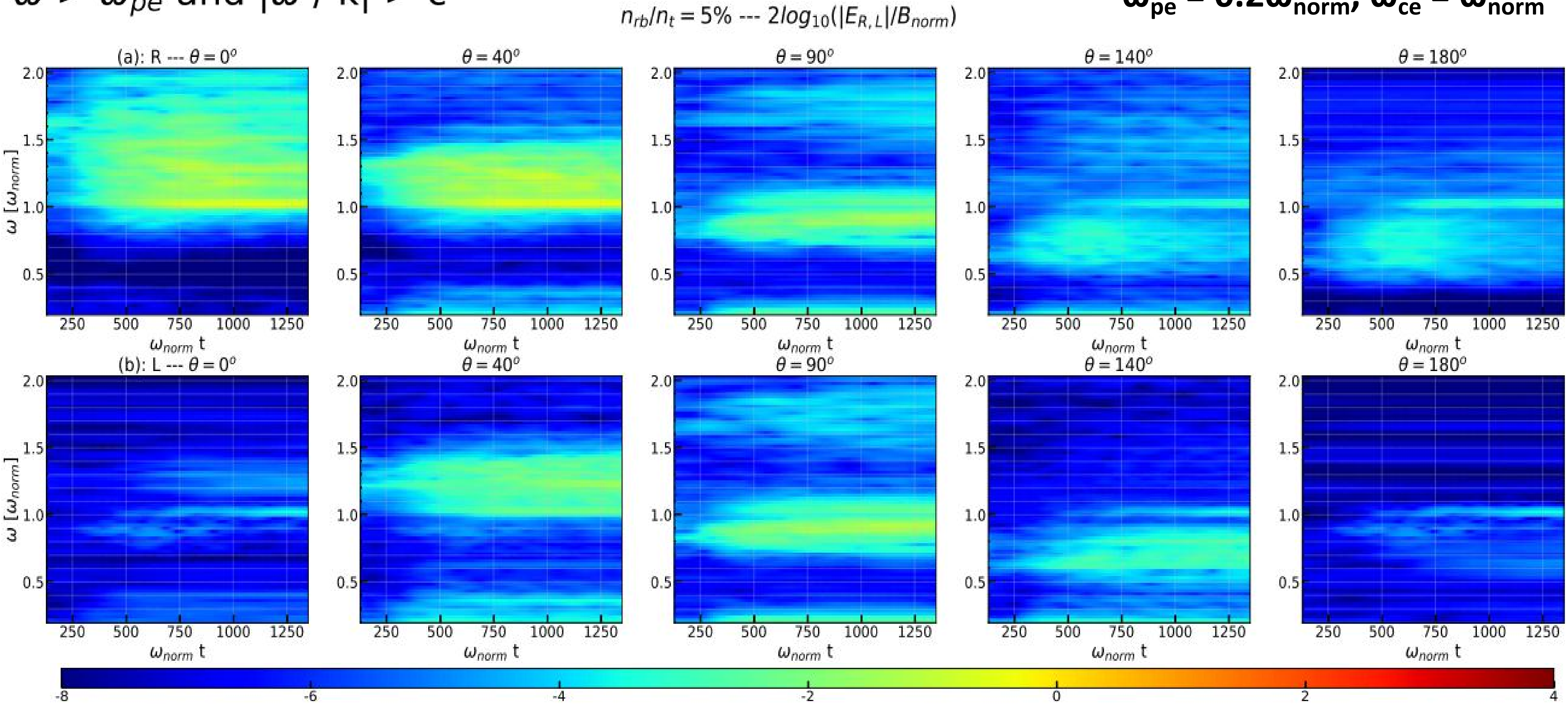




3.1 n_{rb}: n_{total} Results --- Spectrogram (escaping waves)

$\omega > \omega_{pe}$ and $|\omega / k| > c$

$\omega_{pe} = 0.2\omega_{norm}$, $\omega_{ce} = \omega_{norm}$



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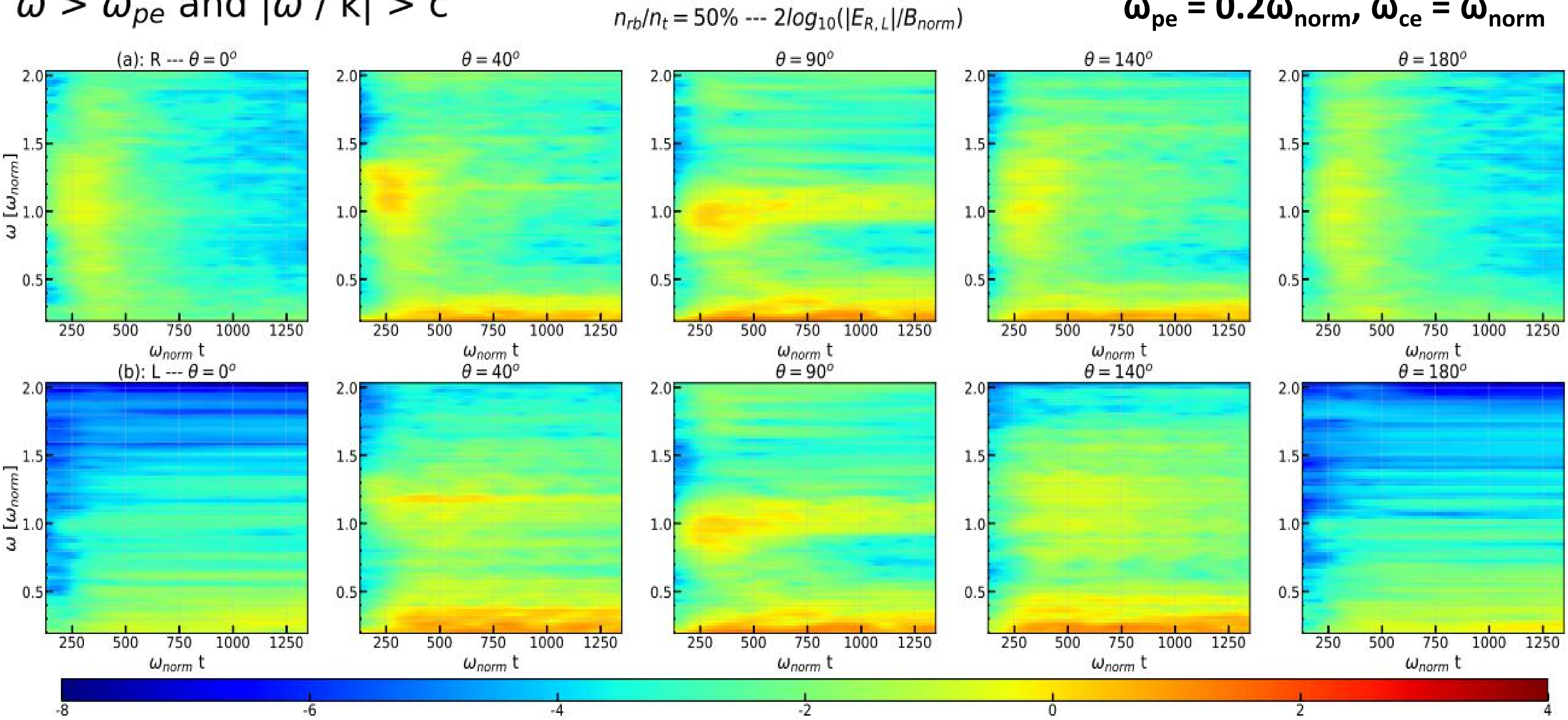
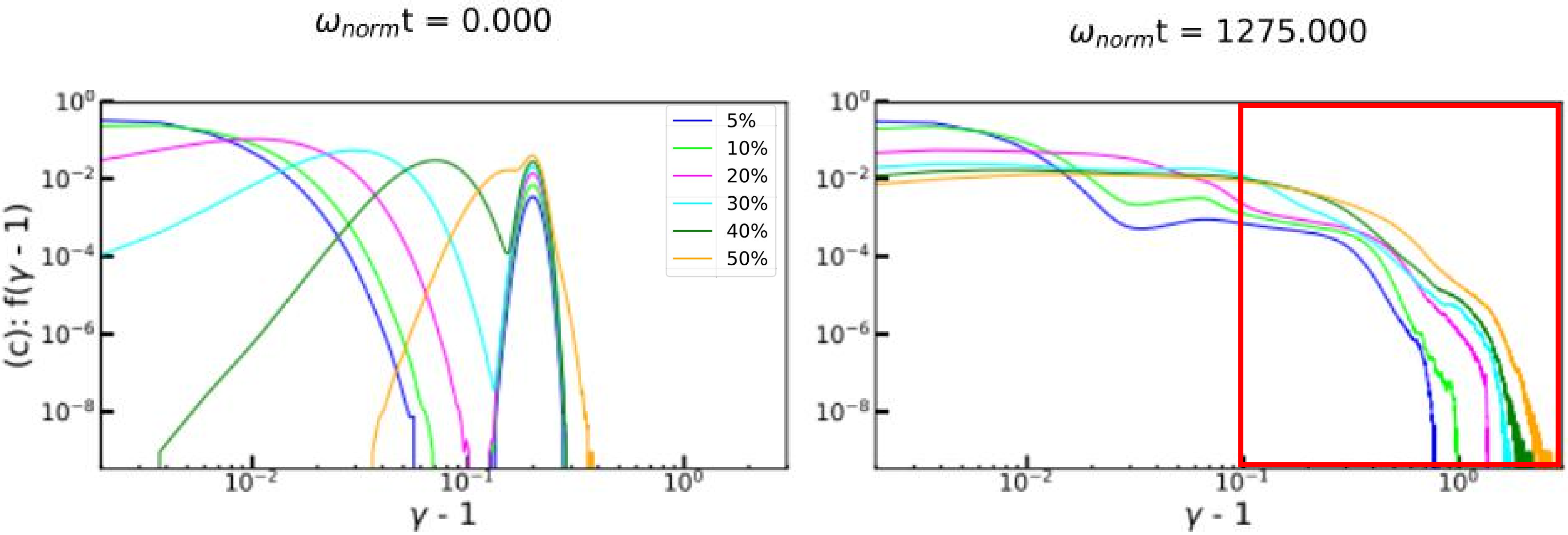


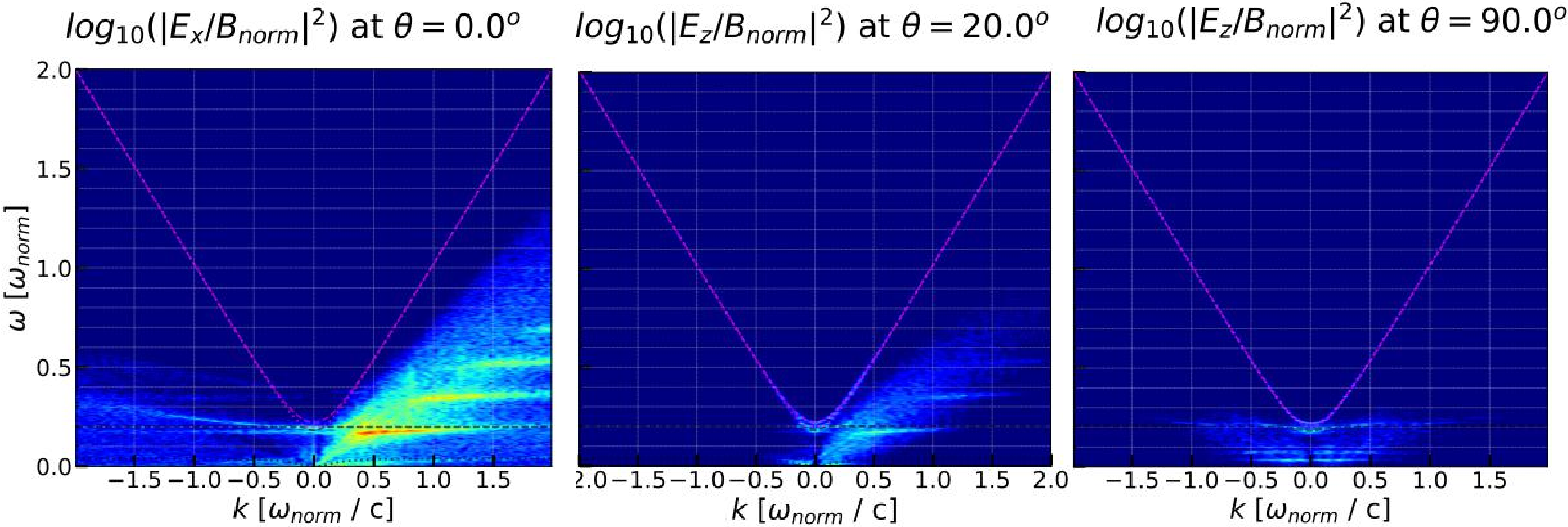
3.1 n_{rb}: n_{total} Results --- Electron energy distribution



Double pow-law distribution in the high energy tail ($\gamma - 1 > 0.1$ ~ 50 keV --------- **Wave-particle Interaction**

3.2 ω_{ce}:ω_{pe} Results --- Dispersion Relation

$n_{rb}/n_t = 5\%$ $\omega_{ce}/\omega_{pe} = 0.2$



$$\omega_{norm} = 5.0\omega_{pe}$$

4. Conclusion

when $\omega_{ce} > \omega_{pe}$ ($\omega_{ce}/\omega_{pe} = 5$)

- Intensity of each wave mode is quite anisotropic, this anisotropy decreases when the ring-beam electron population increase
- Whistler mode waves contain more energy than other modes
- CPDs and spectrogarms of escaping waves strongly depend on their propagation directions and number density ratio n_{rb}: n_{total}, they will be predominantly left-handed polarized over a wide range of propagation directions when energetic ring-beam electron population is denser ---- the diversity in the SRB (e.g, spike bursts Fleishman & Mel’nikov 1998) polarization observations
- Wave-particle Interaction

when $\omega_{ce} < \omega_{pe}$

- Excitation of higher-level harmonic of both ω_{pe} and ω_{ce}, but non-escaping
- Very weak excitation of escaping waves

Thank you for your attention!