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HIGH-FREQUENCY ELECTROMAGNETIC WAVES DESTABILIZED BY RUNAWAY ELECTRONS IN A NEAR-CRITICAL ELECTRIC FIELD

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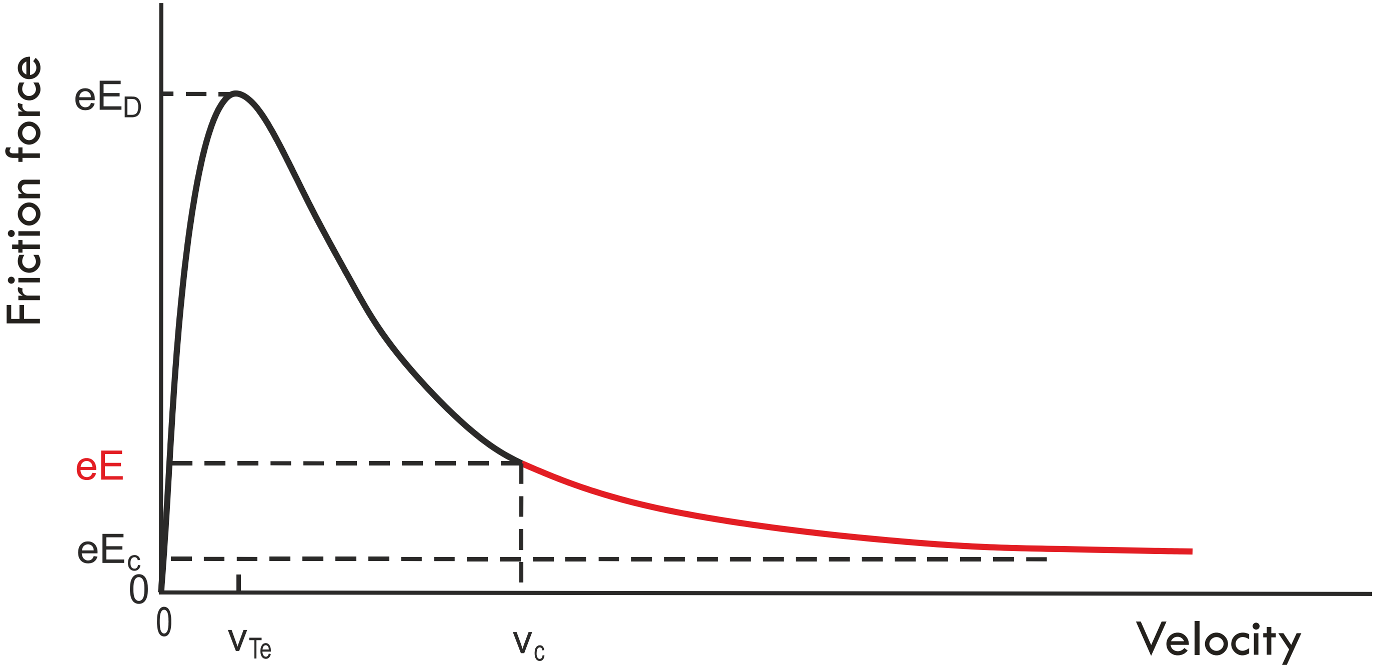
Runaway electrons



- For electric fields higher than the critical field: accelerating force exceeds the friction force → *runaway electrons*

Particle-wave interaction

Dispersion relation of the plasma waves:

$$\boxed{\underline{\underline{\varepsilon}} = \underline{\underline{1}} + \underline{\underline{\chi}}^{e} + \underline{\underline{\chi}}^{i}}$$

Dielectric tensor

$$\left(\varepsilon_{11}-\frac{k_\parallel^2c^2}{\omega^2}\right)\cdot\left(\varepsilon_{22}-\frac{k^2c^2}{\omega^2}\right)+\varepsilon_{12}^2\begin{cases} =0 \\ =\boxed{\chi_{11}^r}\left(\frac{k^2c^2}{\omega^2}-\varepsilon_{22}\right)+\boxed{\chi_{22}^r}\left(\frac{k_\parallel^2c^2}{\omega^2}-\varepsilon_{11}\right) \\ 2\boxed{\chi_{12}^r}\cdot\varepsilon_{12}\end{cases}$$

k: wave number

ω: wave frequency

c: speed of light

→ $\delta\omega$ response → Growth rate

Perturbative analysis

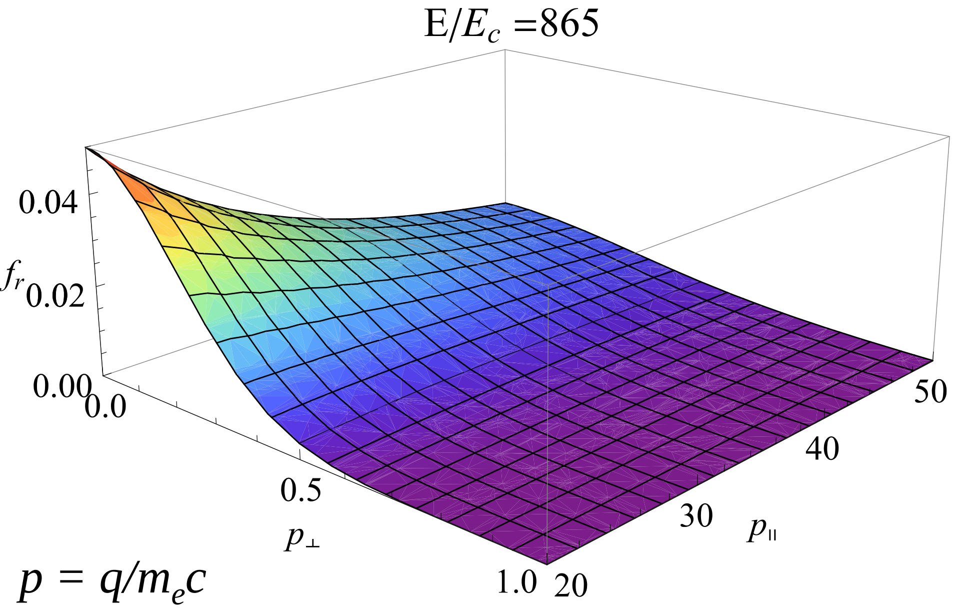
Imaginary part

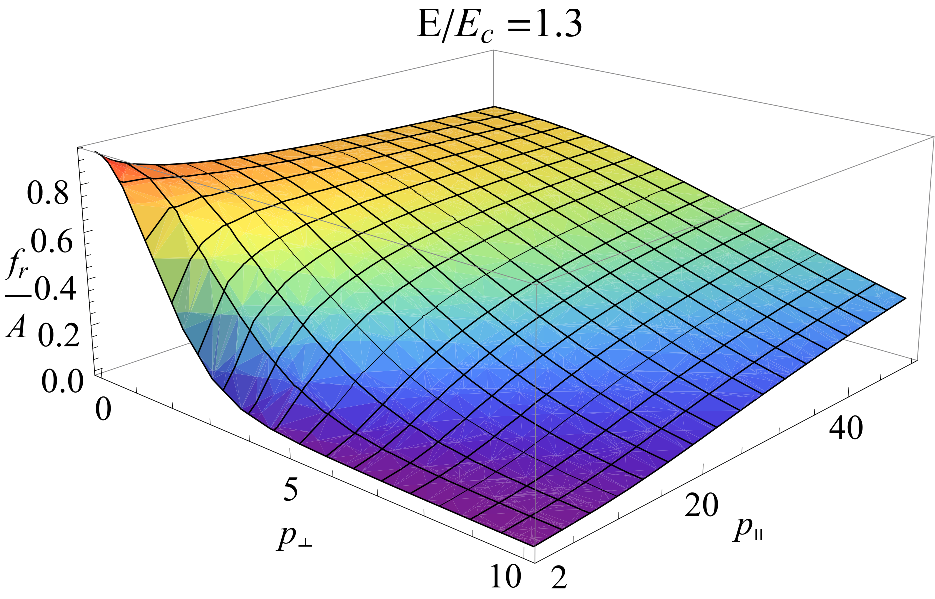
$$\gamma_i = \mathrm{Im}(\delta\omega)$$

Distribution function

High electric field

Near-critical field





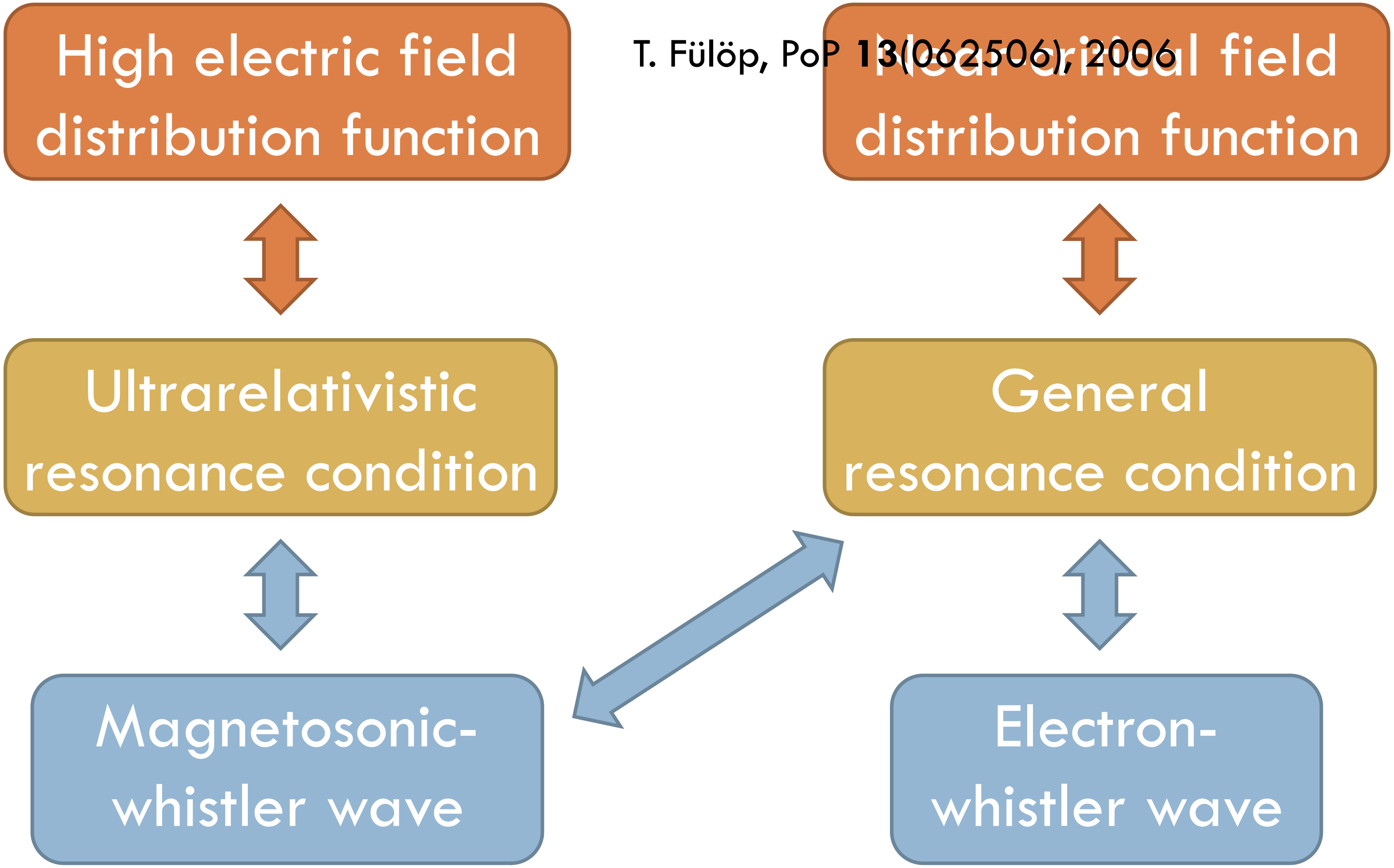
$p = q/m_e c$

normalized momentum

T. Fülöp, PoP **13**(062506), 2006

P. Sandquist, PoP **13**(072108), 2006

New approximations



T. Fülöp, PoP 13(062506), 2006

High electric field distribution function

Near-critical field distribution function

Ultrarelativistic resonance condition

General resonance condition

Magnetosonic-whistler wave

Electron-whistler wave

Whistler waves

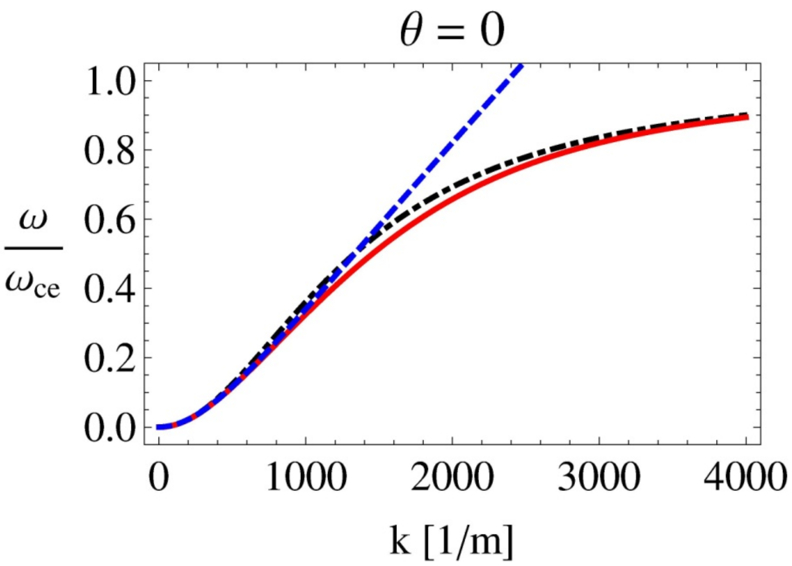
- ☐ **Electron-whistler wave**
  A. Kómár, BSc thesis, BME TTK, 2011

$$\omega_{ci} << \omega \qquad \omega_{ce}\sqrt{m_e / m_i} << \omega$$

- ☐ **Magnetosonic-whistler wave**
  T. Fülöp et al., PoP **13**(062506), 2006

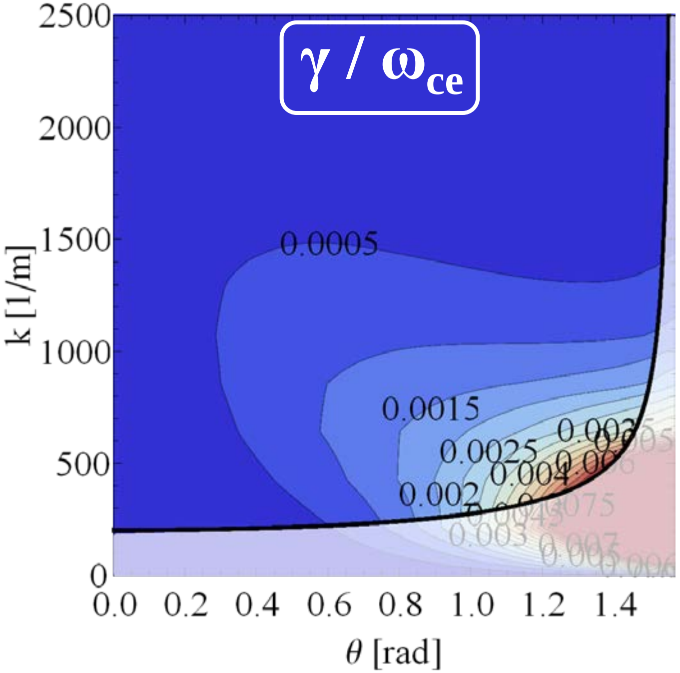
$$\omega_{ci} << \omega << \omega_{ce}$$

- ☐ **Whistler wave**
  S. Sazhin, Whistler-mode waves in a hot plasma, Cambridge Univ. Press, 1993

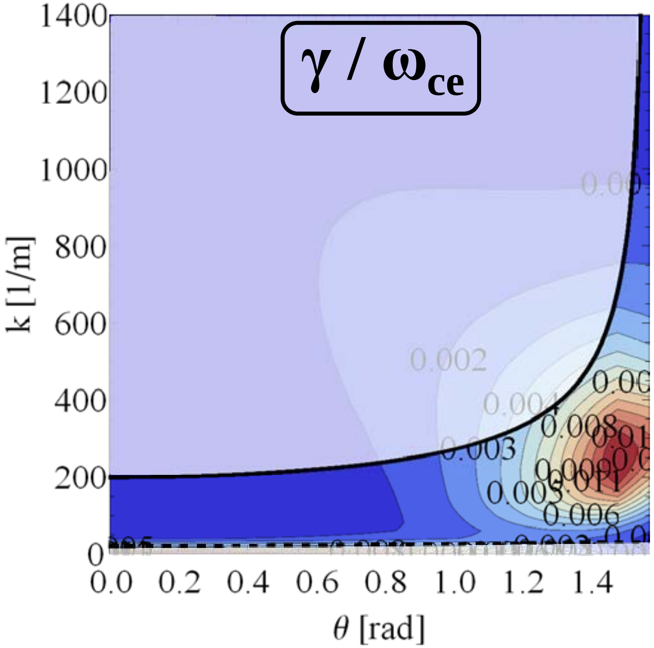


Growth rate in near-critical field

Electron-whistler wave



Magnetosonic-whistler wave

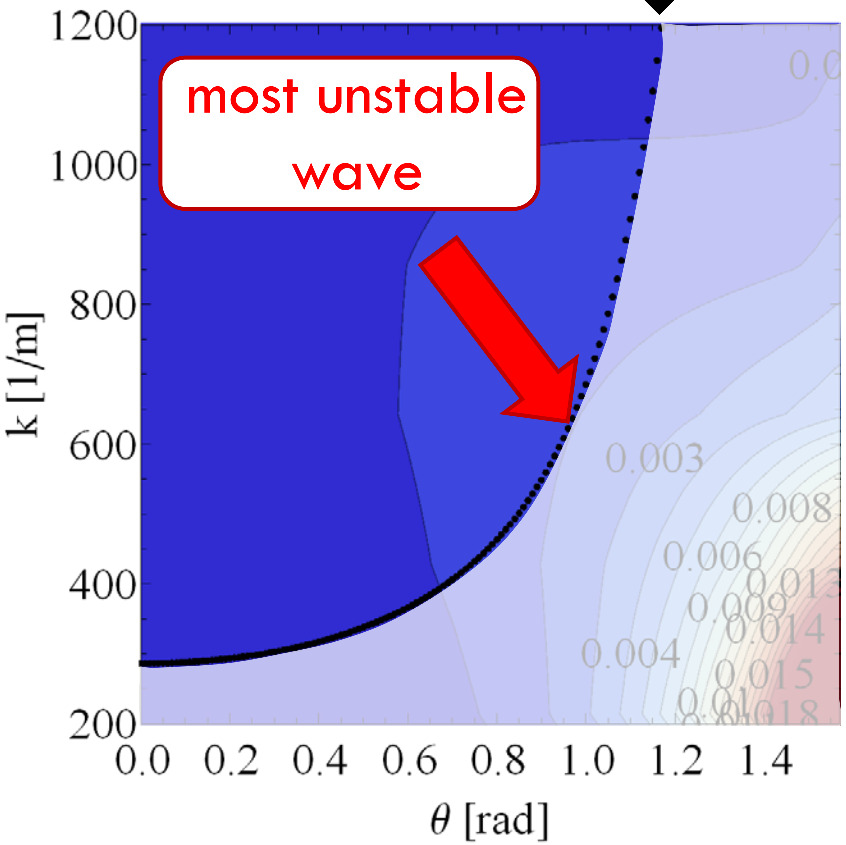


At the energy corresponding to the maximum (10 MeV): no electrons.

$E/E_c = 1.3$, $B = 2$ T, $n_e = 5 \cdot 10^{19}$ m^{-3}, $n_r = 3 \cdot 10^{17}$ m^{-3}

Most unstable wave

- Maximum runaway energy: **2.6 MeV**



$E/E_c = 1.3$

$B = 2$ T

$n_e = 5 \cdot 10^{19}$ m^{-3}

$n_r = 3 \cdot 10^{17}$ m^{-3}

Damping rates of the wave, stability

- Damping rates:
  - Collisional damping: of electron-ion collisions
  - Convective damping: the runaway beam has a finite radius, L_r

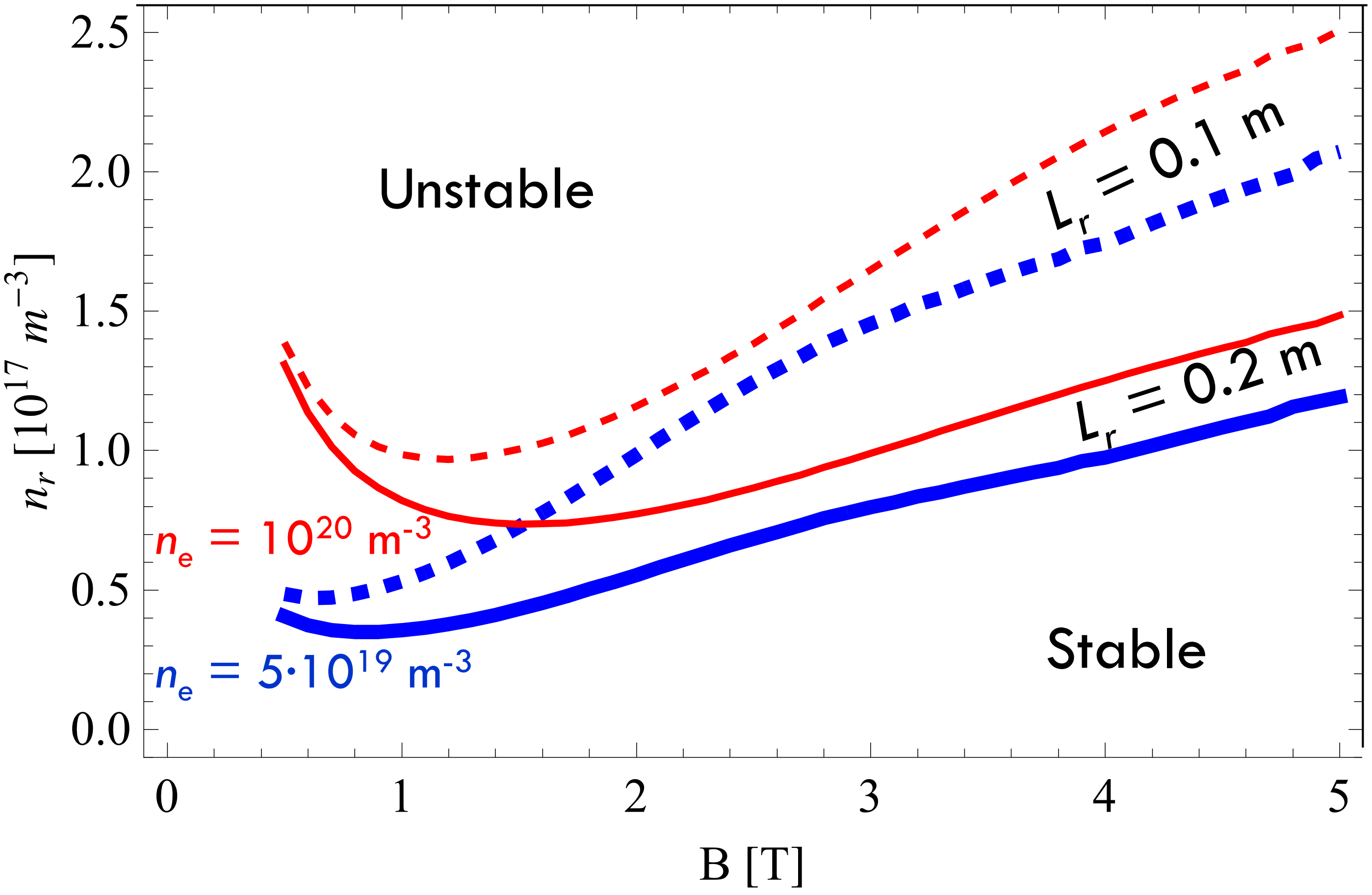
- Stability:

Finding **(Growth rate – Damping rates) = 0** (for the most unstable wave)

⇩

Critical runaway density

Stability limit in near-critical field



Conclusions

- Runaway electron – wave interaction in near-critical electric field
- Extending the previous approximations
  - General resonance condition
  - New whistler approximations
- Linear stability
  - The most unstable wave is an electron-whistler wave, dependent on the maximum runaway energy
  - Stability threshold: higher for higher magnetic field

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General resonance condition

- Runaway susceptibilities:
  calculated based on the distribution function, $\iiint d^3p$
- **Implicit** resonance:

$$p_{par} + \frac{n\omega_{ce} - \omega_0 \cdot \gamma\left(p_{par}, p_{perp}\right)}{k_{\parallel} c} = 0$$

Ultrarelativistic

$$\gamma \approx \left|p_{par}\right|$$

$$p_{res} = \frac{-n\omega_{ce}}{k_{\parallel} c - \omega_0}$$

General case

$$\gamma = \sqrt{1 + p_{perp}{}^2 + p_{par}{}^2}$$

$$p_{res} = \frac{\boxed{-k_{\parallel} c}\,\boxed{n\omega_{ce}} + \boxed{\omega_0}\sqrt{\left(k_{\parallel}{}^2 c^2 - \omega_0{}^2\right)\left(1 + p_{perp}{}^2\right) + \boxed{n^2 \omega_{ce}{}^2}}}{k_{\parallel}{}^2 c^2 - \omega_0{}^2}$$

Why the whistler wave?

- Resonance condition is physical if: $p_{res} > 0$
- In ultrarelativistic approximation:

$$p_{res} = \frac{-n\omega_{ce}}{k_{\|}c - \omega_0} \Rightarrow \boxed{k_{\|}c - \omega_0 > 0 \quad \text{and} \quad n < 0}$$

or

$$\boxed{k_{\|}c - \omega_0 < 0 \quad \text{and} \quad n > 0}$$

- In the general case:

$$\Rightarrow \boxed{k_{\|}c - \omega_0(k,\theta) > 0} \quad \text{and} \quad n \leq 0$$

$\searrow$ **Whistler wave**