WIGGLER RADIATION IN LANGMUIR TURBULENCE

~ A POSSIBLE EMISSION MECHANISM OF GRB ~

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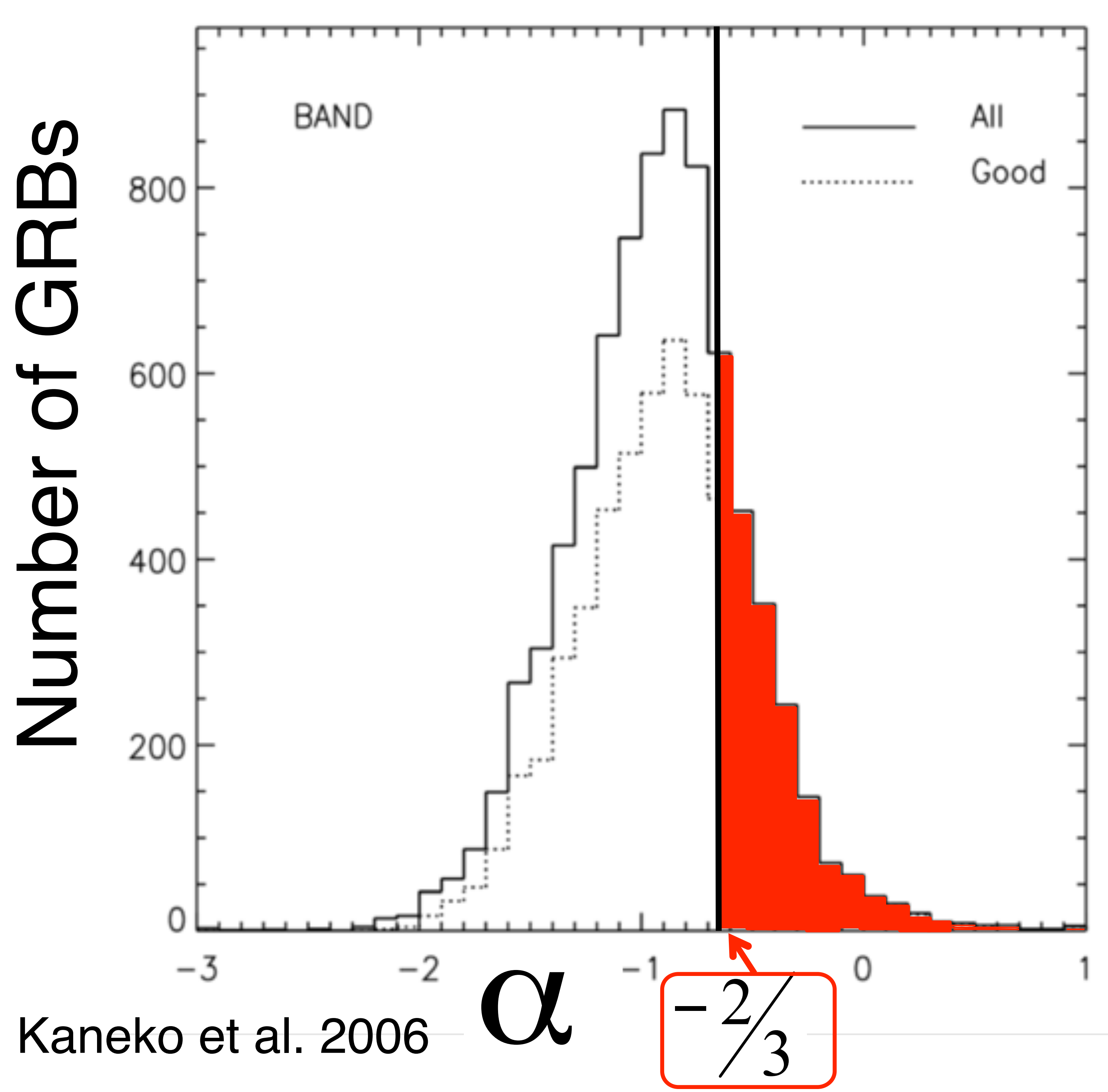
Refs. [1] Teraki & Takahara, 2014, ApJ, 787, 28

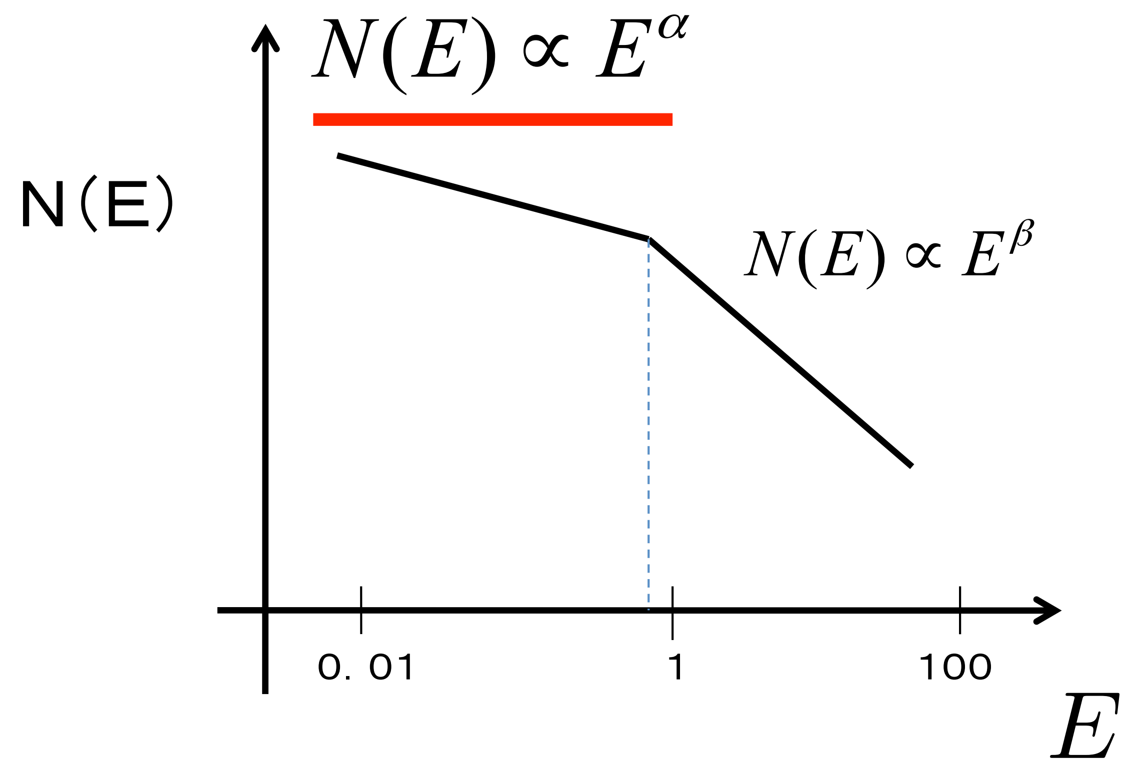
Introduction

α-distribution in GRB



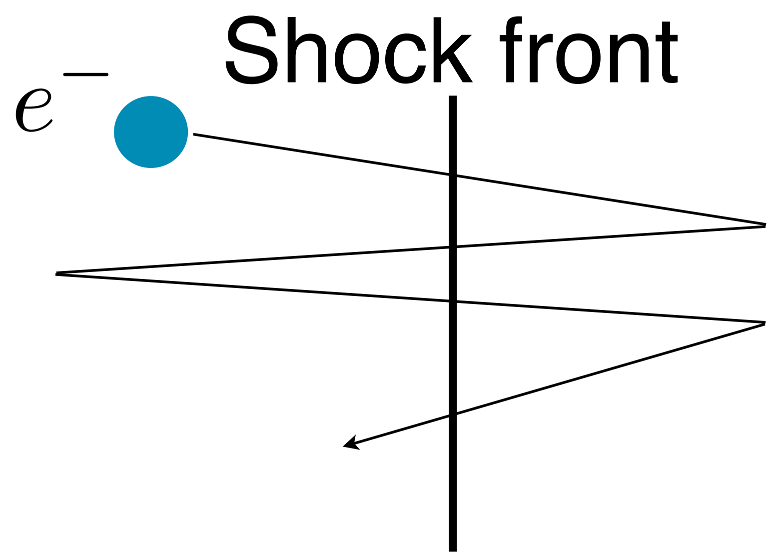
Kaneko et al. 2006

Photon spectrum $\propto \mathrm{erg/s/Hz^2}$



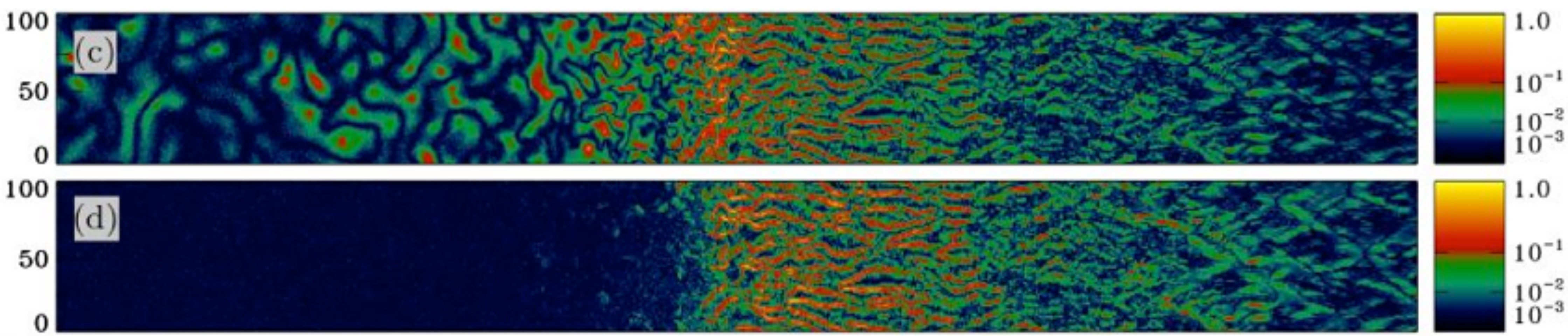
Inconsistent
with
synchrotron theory

Emission Region



Turbulent
electromagnetic field

Debye length



ϵ_B magnetic

ϵ_E electric

Sironi & Spitkovsky 2009

$$\epsilon_B = \frac{B^2/8\pi}{\Gamma n m c^2}$$

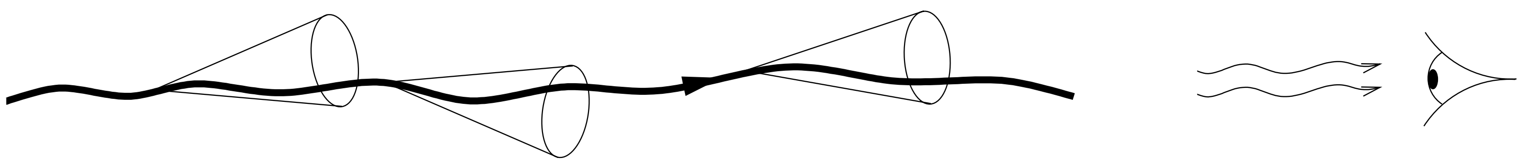
We do not know the radiation perfectly for this case!

Turbulent field and radiation

jitter radiation

small scale magnetic field

$$\lambda_{\mathrm{B}} \ll \frac{mc^2}{eB}$$



Medvedev 2000

Landau & Lifshitz 1979

rectilinear trajectory & perturbative acceleration

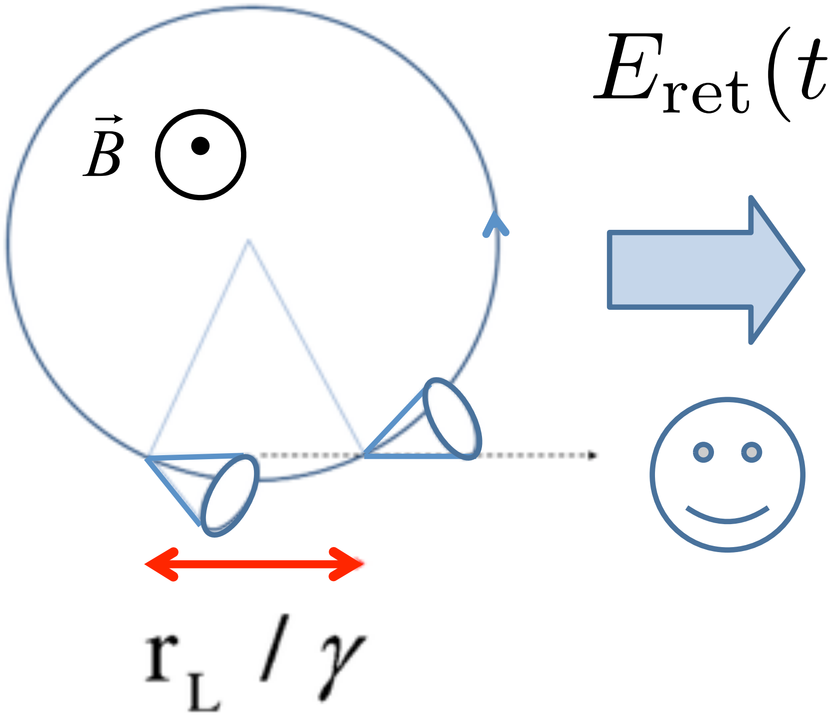
Of course, not general!

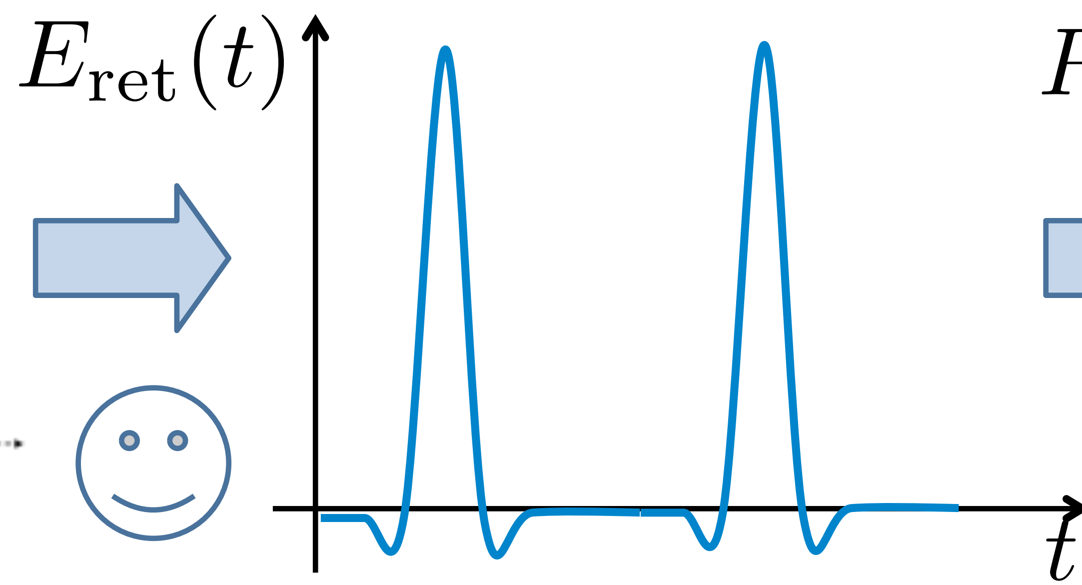
Strong field?

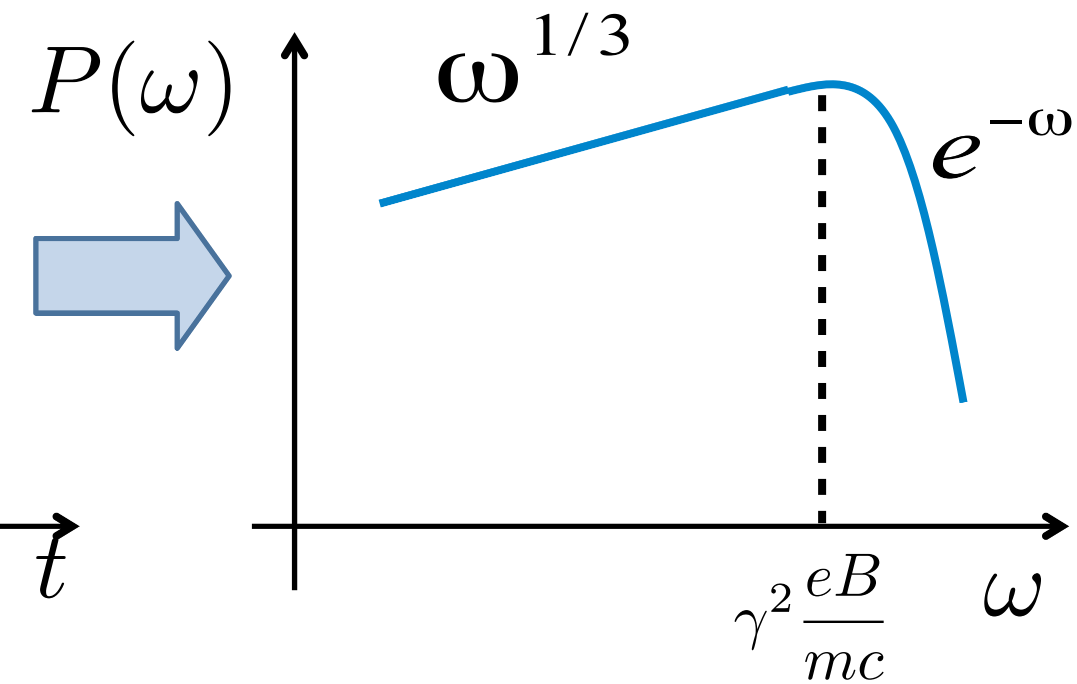
Electric field?

Oscillation of field?

Photon Formation Time (Length) for synchrotron peak







$= \dfrac{mc^2}{eB}$ Photon Formation Length → $\dfrac{mc}{eB}$ Photon Formation Time (PFT)

spatial fluctuation scale

oscillation timescale

Langmuir (Electrostatic) waves

Generated by
two stream instability

Dieckmann 2005

typical scale = inertial length $c/\omega_{\rm pe}$

crossing time $T \sim 1/\omega_{\rm pe}$

Silva 2006

$\epsilon_{\rm E} \sim 0.1$ ⇒ $\frac{eE}{mc} \equiv \omega_{\rm st} \sim \omega_{\rm pe}$

Dispersion relation
of Langmuir wave

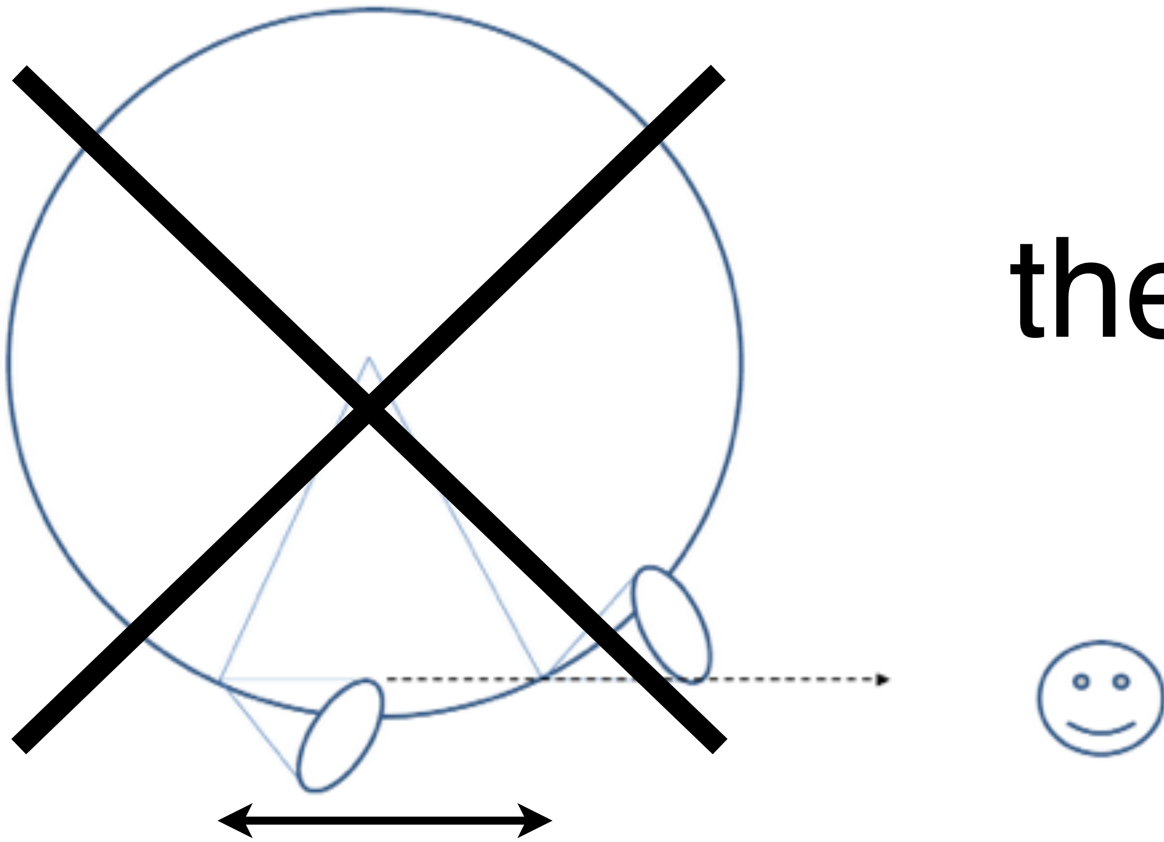
$$\omega^2 = \omega_{\rm pe}^2 + \frac{3}{2}k^2 v_{\rm e}^2$$

Neglect

$$\omega = \omega_{\rm pe}$$

Strong, fast oscillating electrostatic turbulence!

Summarizing...



$$\frac{c}{\omega_{\rm st}}$$

We cannot ignore
the spatial fluctuation nor
time variability!

Spatial scale
of turbulences

$$\lambda_{\rm turb} = \frac{2\pi}{k_{\rm typ}} \sim \frac{c}{\omega_{\rm st}}$$

$$1/\omega_{\rm st} \sim 1/\omega_{\rm p}$$

crossing time ~ oscillation timescale

Parametrizing the turbulence

Strength parameter

$$a \equiv \frac{\omega_{\rm st}}{k_{\rm typ} c}$$

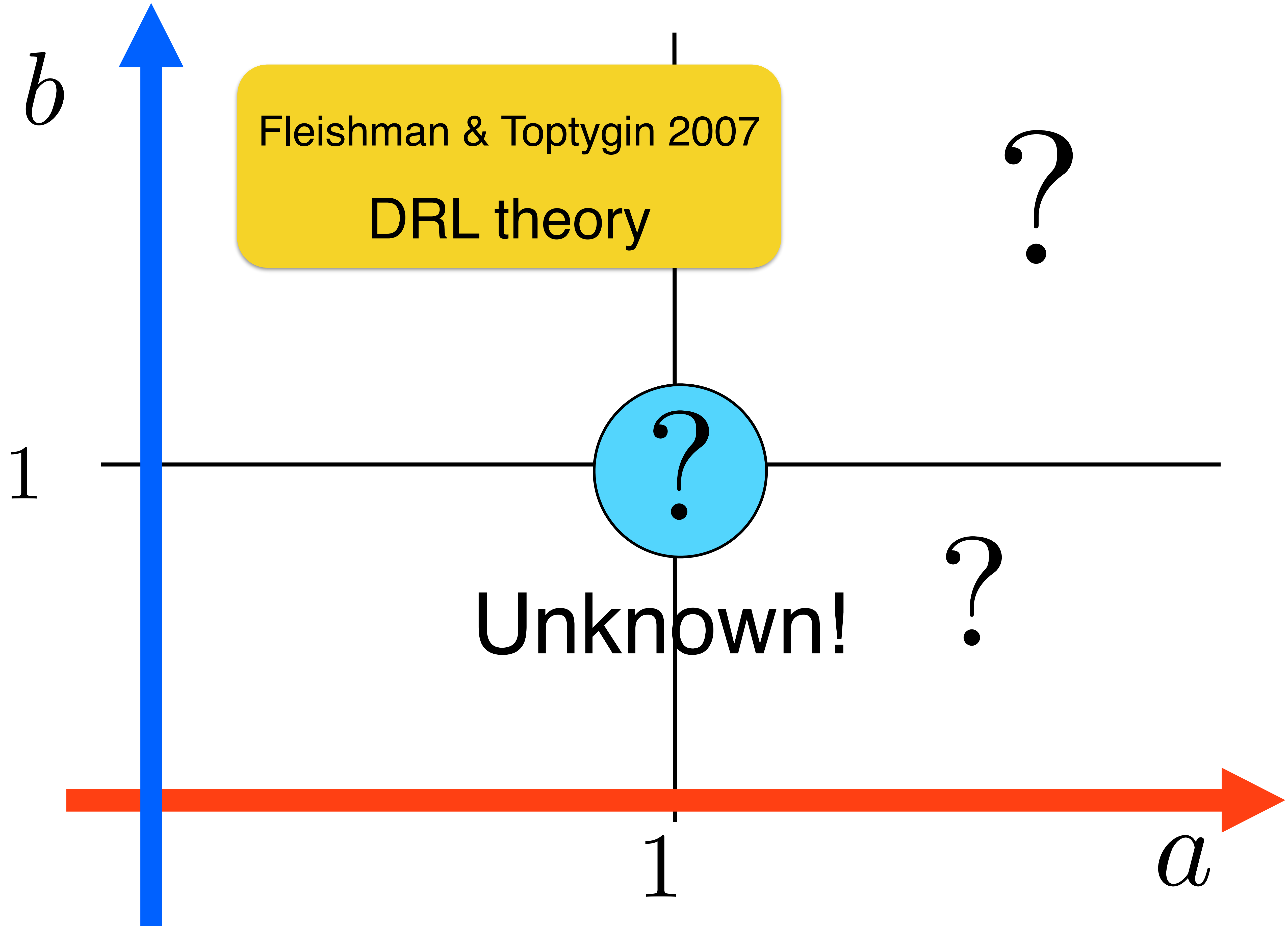
Oscillation parameter

$$b \equiv \frac{\omega_{\rm p}}{k_{\rm typ} c}$$

Typically

$$a \sim b \sim 1$$

Known parameter domain



Mission

Clarify the radiation spectra from electrons in turbulent field for all a and b

strength parameter

$$a \equiv \frac{\omega_{\rm st}}{k_{\rm typ} c}$$

oscillation parameter

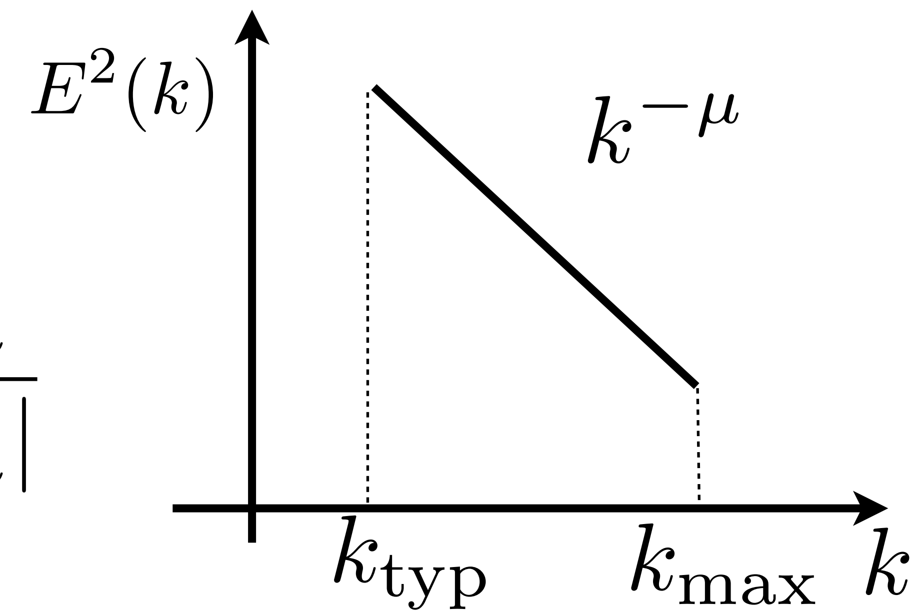
$$b \equiv \frac{\omega_{\rm p}}{k_{\rm typ} c}$$

Numerical Calculation

Description of the turbulent fields

Superposition the Fourier modes

$$\vec{E}(\vec{x}) = \sum_{n=1}^{N} A_n \cos\left(\vec{k_n}\cdot\vec{x} - \omega_{\mathrm{p}} t + \beta_n\right)\frac{\vec{k_n}}{|k_n|}$$



Spatial scale $\omega_0 \equiv k_{\mathrm{typ}} c$

Time scale ω_{p}

Mean strength $\omega_{\mathrm{st}} \equiv \dfrac{e\sigma}{mc}$

$$A_n^2 = \sigma^2 G_n \left[\sum_{n=1}^{N} G_n\right]^{-1},$$

$$G_n = \frac{4\pi k_n^2 \Delta k_n}{1+(k_n L_{\mathrm{c}})^{\alpha}},$$

$$L_{\mathrm{c}} = 2\pi / k_{\mathrm{typ}}$$

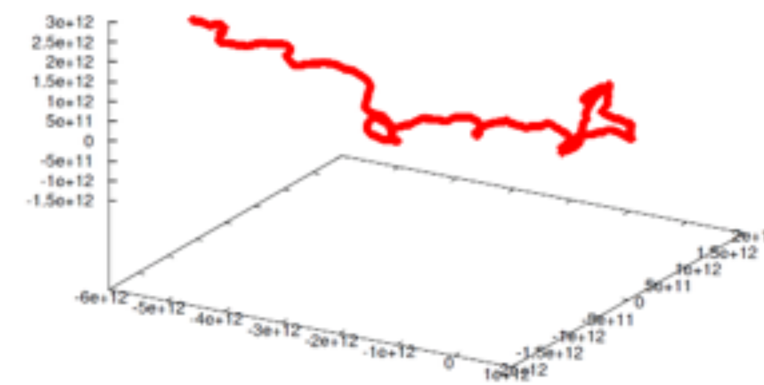
$$\sigma \equiv < E^2 >^{1/2}$$

$$\hat{e}'_z = \frac{\vec{k_n}}{|k_n|}$$

Calculation the radiation spectra

Inject electrons with $\gamma_{\rm init} = 10$

An example of the trajectory



Solve the EOM $$\frac{d}{dt}(\gamma m_{\rm e}\vec{v}) = e\vec{E}$$

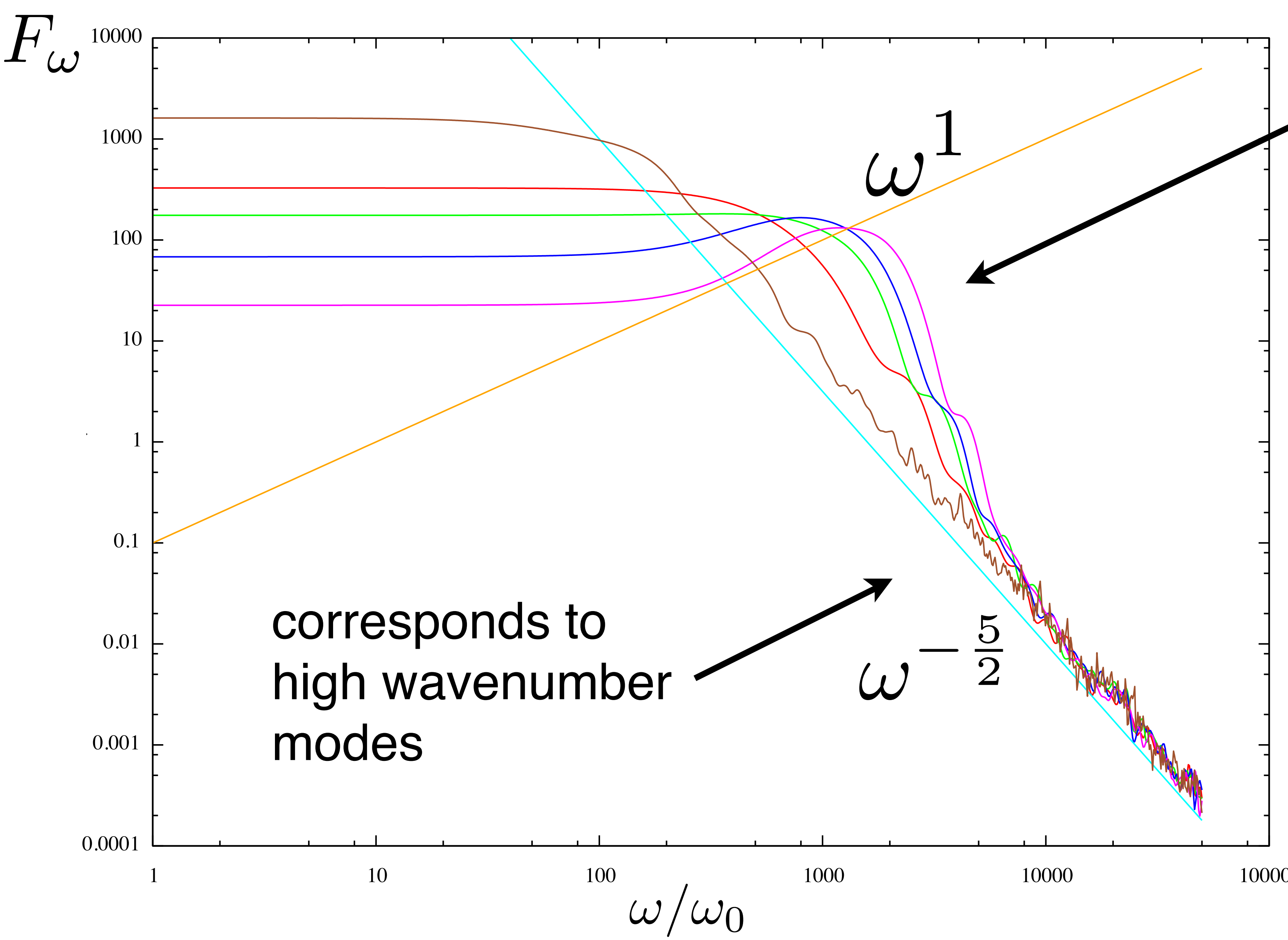
Use the Lienard-Wiechert potential directly

$$\frac{dW}{d\omega d\Omega} = \frac{e^2}{4\pi c^2}\left|\int_{-\infty}^{\infty} dt' \frac{\vec{n}\times[(\vec{n}-\vec{\beta})\times\dot{\vec{\beta}}]}{(1-\vec{\beta}\cdot\vec{n})^2}\exp\{i\omega(t'-\frac{\vec{n}\cdot\vec{r}(t')}{c})\}\right|^2$$

$\vec{n}$ Unit vector toward observer

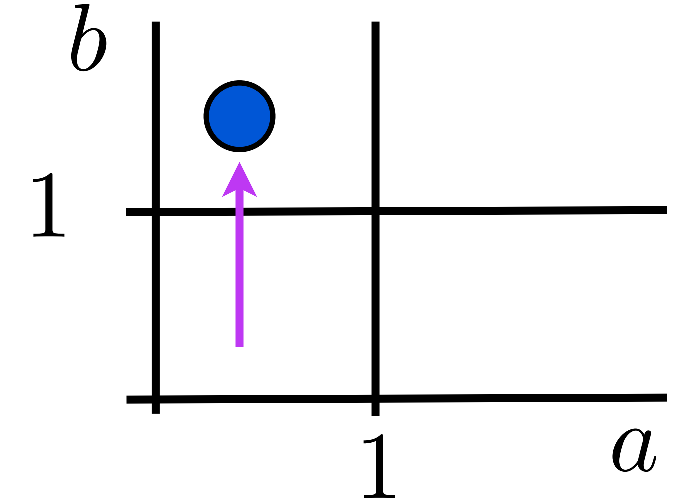
t' Retarded time

$$a = \frac{\omega_{\rm st}}{\omega_0} = 10^{-2} \qquad b = \frac{\omega_{\rm p}}{\omega_0} = 0.1, 1, 5, 7, 10 \qquad \mu = 5/2$$



Hump

$\gamma^2\omega_{\rm p} = 10^4$



Time variability dominated

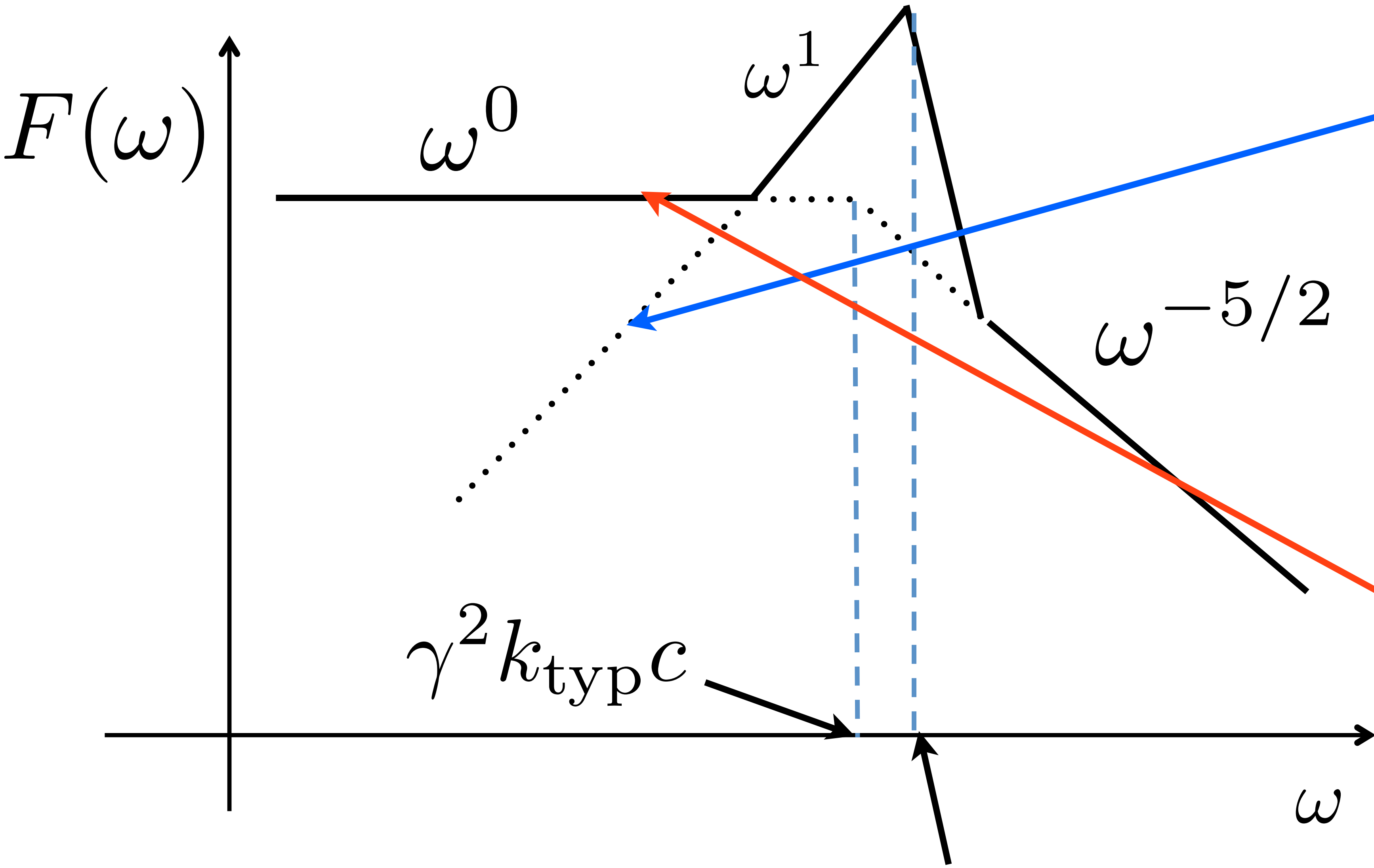
Typical frequency

$$\omega_{\rm typ} = \gamma^2 \omega_{\rm p}$$

Spectral index

$$F_\omega \propto \omega^1$$

Origin of the spectral shape for $a \ll 1$ & $b > 1$



weakly beamed
&
oscillation origin

$\omega' = \omega_{\rm p}$
& σ

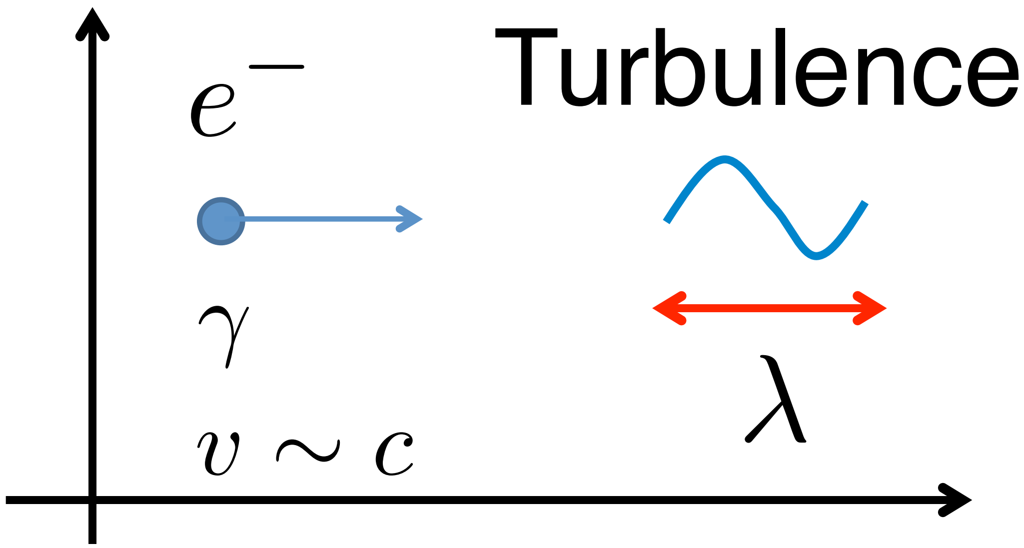
strongly beamed
&
wavenumber origin

$\omega' = k_{\rm typ} c \cos\theta$
& $E(k_{\rm typ})$

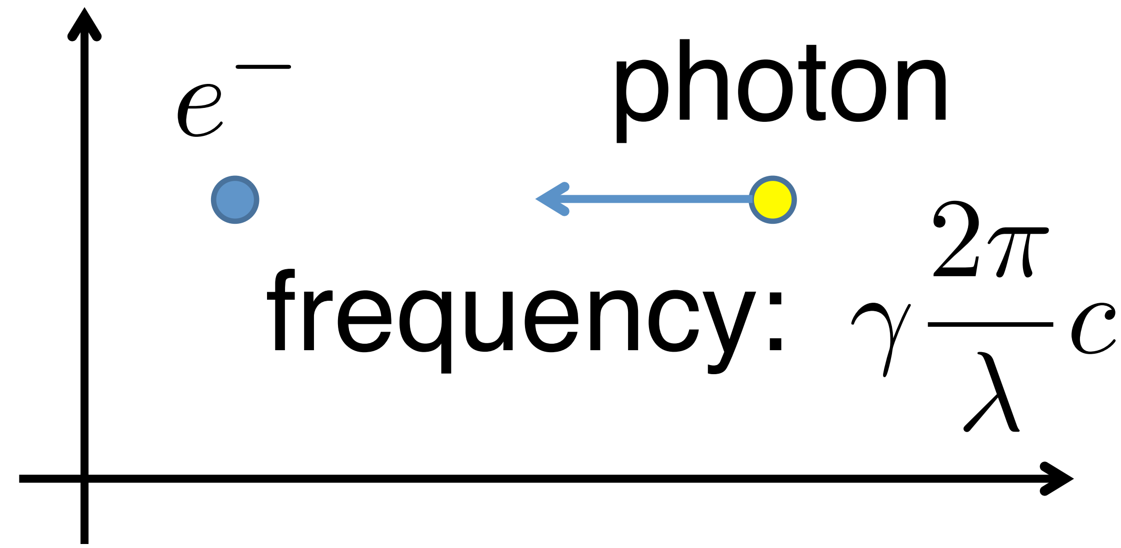
Doppler boosted oscillation
with $\omega_{\rm p}$

$$\frac{1}{(1 - v/c)}\omega_{\rm p} \sim \underline{\gamma^2 \omega_{\rm p}}$$

$\gamma^2 kc$ & power law component



initial frame



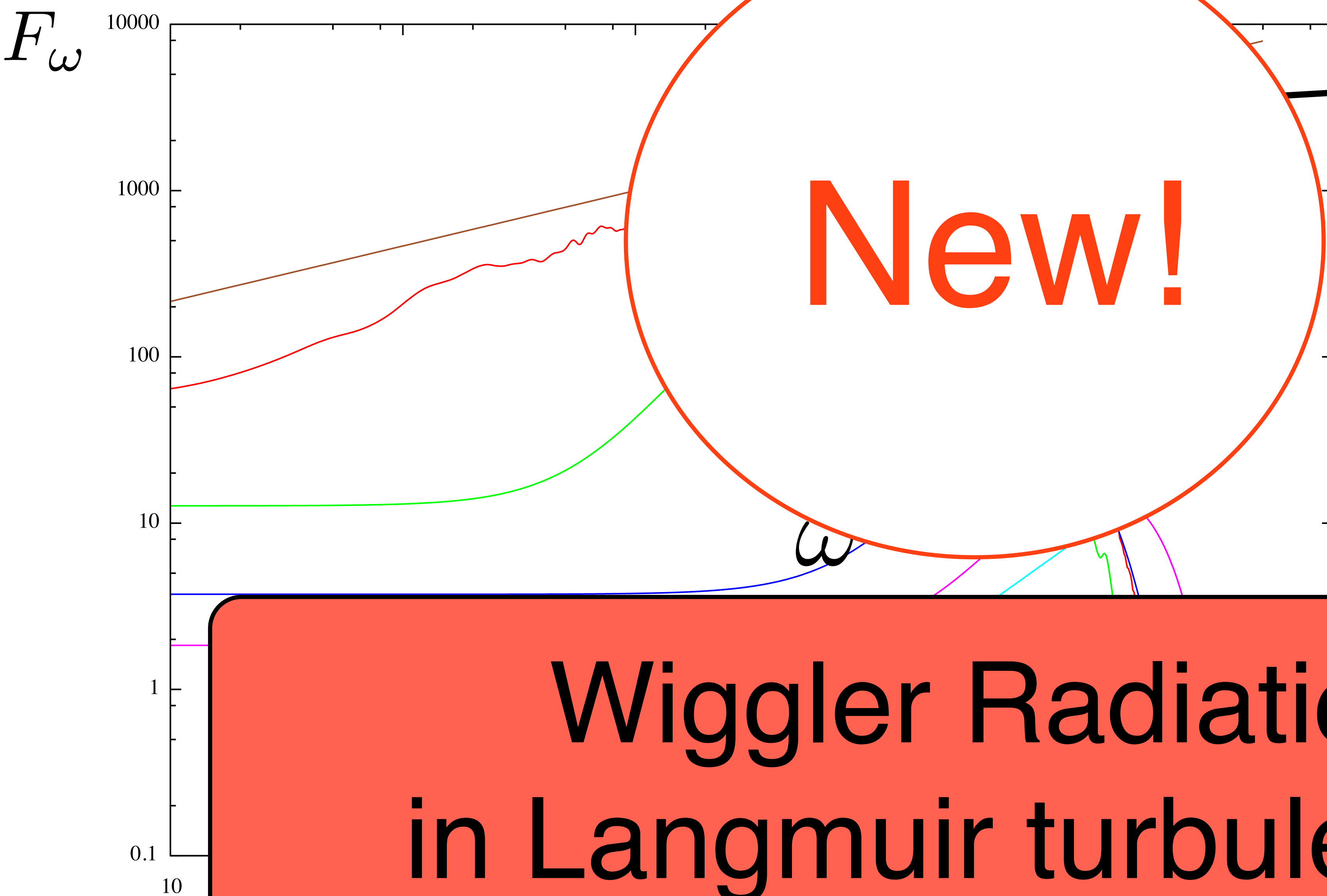
electron rest frame

$|\vec{E}| \sim |\vec{B}|$ ⇒ imaginary photon

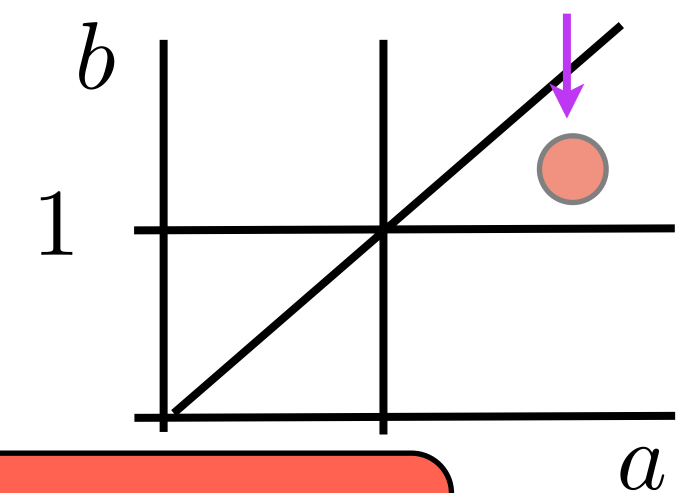
$$\omega \sim \gamma^2 \frac{2\pi}{\lambda} c = \gamma^2 kc$$

$E^2(k) \propto k^{-5/2}$ ⇒ $F_\omega \propto \omega^{-5/2}$

$$a = 100, b = 20, 90, 400, 800 \qquad \mu = 5/2$$



Softer than $F_\omega \propto \omega^1$



New!

Wiggler Radiation
in Langmuir turbulemce
(WRL)

gth
ated

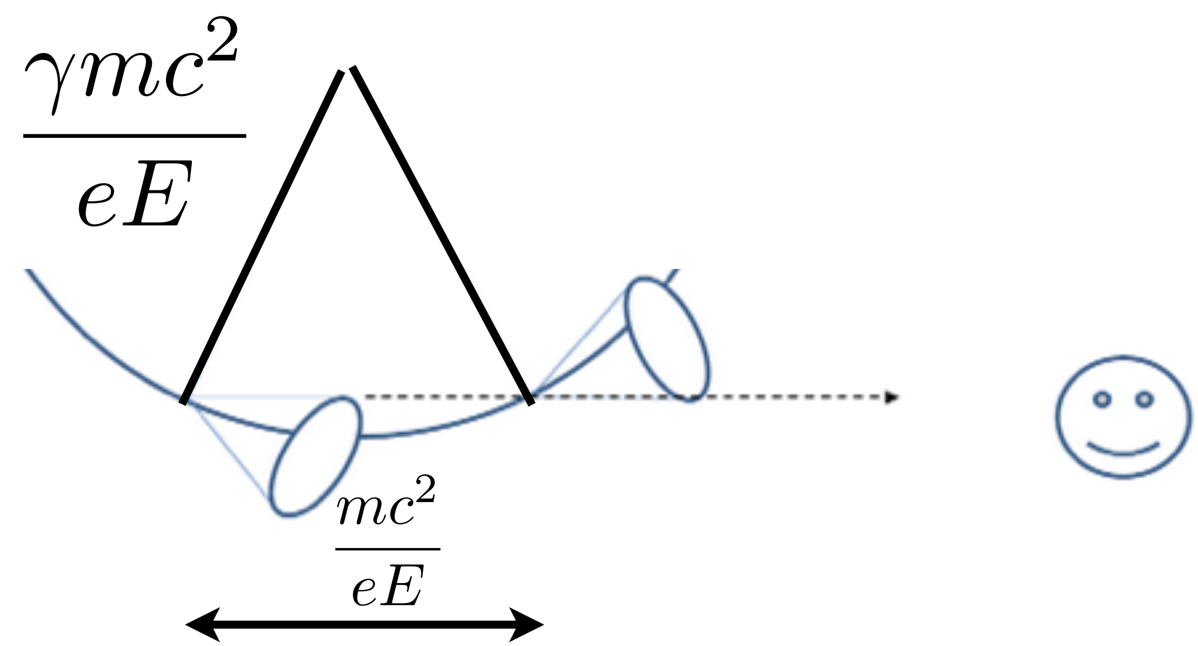
Typi

$$\omega_{\rm typ} = \gamma^2 \omega_{\rm st}, (> \gamma^2 \omega_{\rm p}) \qquad F_\omega \propto \omega^{\frac{1}{3}}$$

Discussion in observer frame

peak frequency

$$(1-\frac{v}{c})\frac{1}{\frac{mc^2}{eE}\frac{1}{c}} \sim \gamma^2\omega_{\rm st}$$



when $\omega_{\rm st} > \omega_{\rm p}$ circular orbit approximation should be applicable in the timescale of $1/\omega_{\rm st}$

We discuss the validity for this approximation

parallel v.s. perpendicular

E.O.M. $$\frac{d\vec{p}}{dt} = m\left[\gamma\frac{d\vec{v}}{dt} + \frac{\gamma^3}{c^2}\left(\vec{v}\cdot\frac{d\vec{v}}{dt}\right)\vec{v}\right]$$

$$\vec{v} \parallel \frac{d\vec{v}}{dt} \longrightarrow \vec{F} = m\gamma^3\frac{d\vec{v}}{dt}$$

$$\vec{v} \perp \frac{d\vec{v}}{dt} \longrightarrow \vec{F} = m\gamma\frac{d\vec{v}}{dt}$$

inertia

γ^2 times larger

➡ be accelerated almost perpendicular

$$P = \frac{2e^2}{3c^3}\gamma^4\left[\left(\frac{dv_\perp}{dt}\right)^2 + \gamma^2\left(\frac{dv_\parallel}{dt}\right)^2\right]$$

$\frac{dv_\perp}{dt} \leftarrow \frac{F}{m\gamma}$, $\quad \frac{dv_\parallel}{dt} \leftarrow \frac{F}{m\gamma^3}$

power

γ^2 times larger

Energy change & Conclusion

$$\Delta E = e\vec{E} \cdot \vec{v}\Delta t$$

PFT for $\gamma^2\omega_{\rm st}$

Energy

electric field

$$\Delta t = 1/\omega_{\rm st}$$

$$\Delta E \lesssim eEc \times \frac{mc}{eE} = mc^2$$

Conclusion

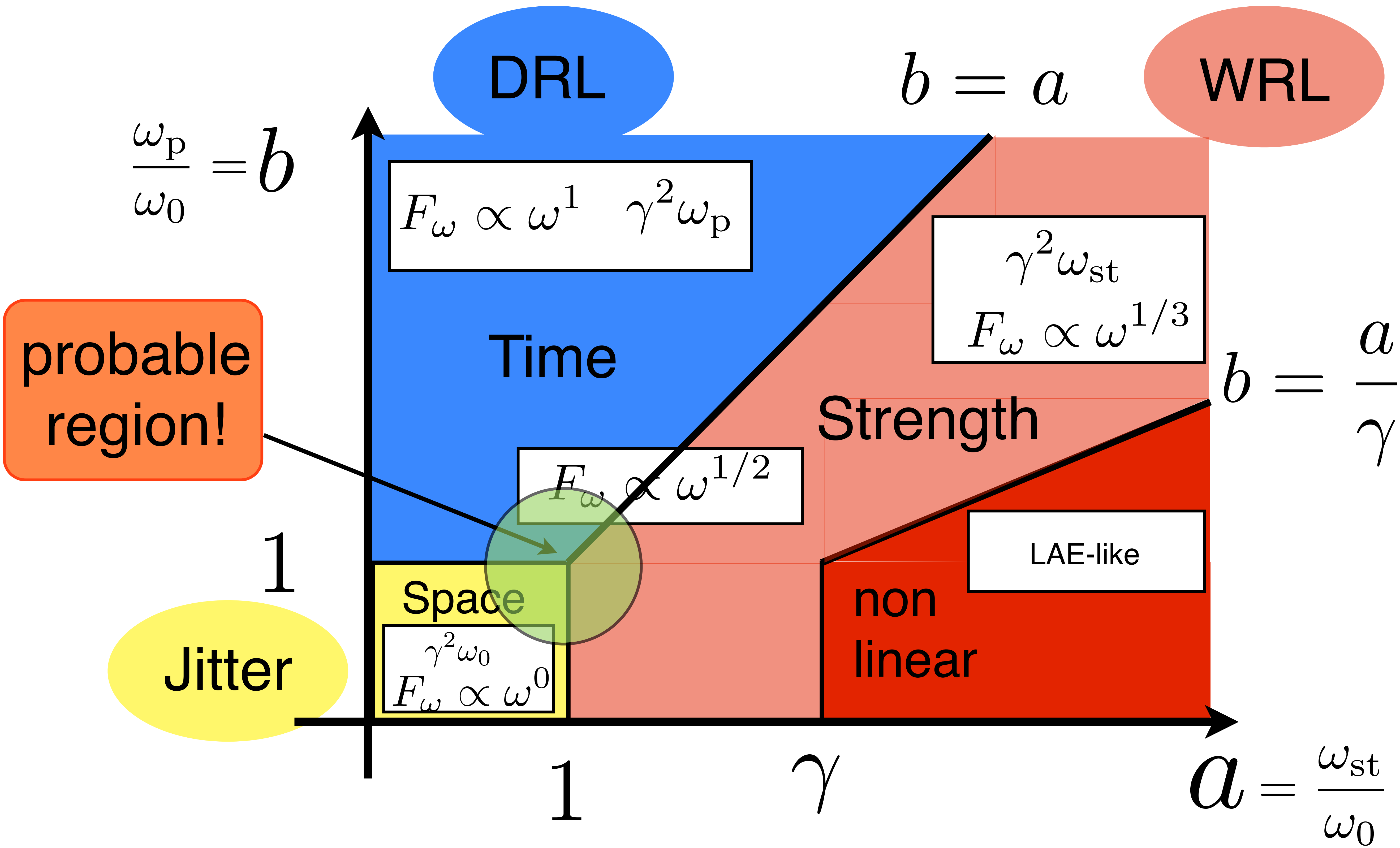
Typical frequency is written as

$$\gamma^2\omega_{\rm st}$$

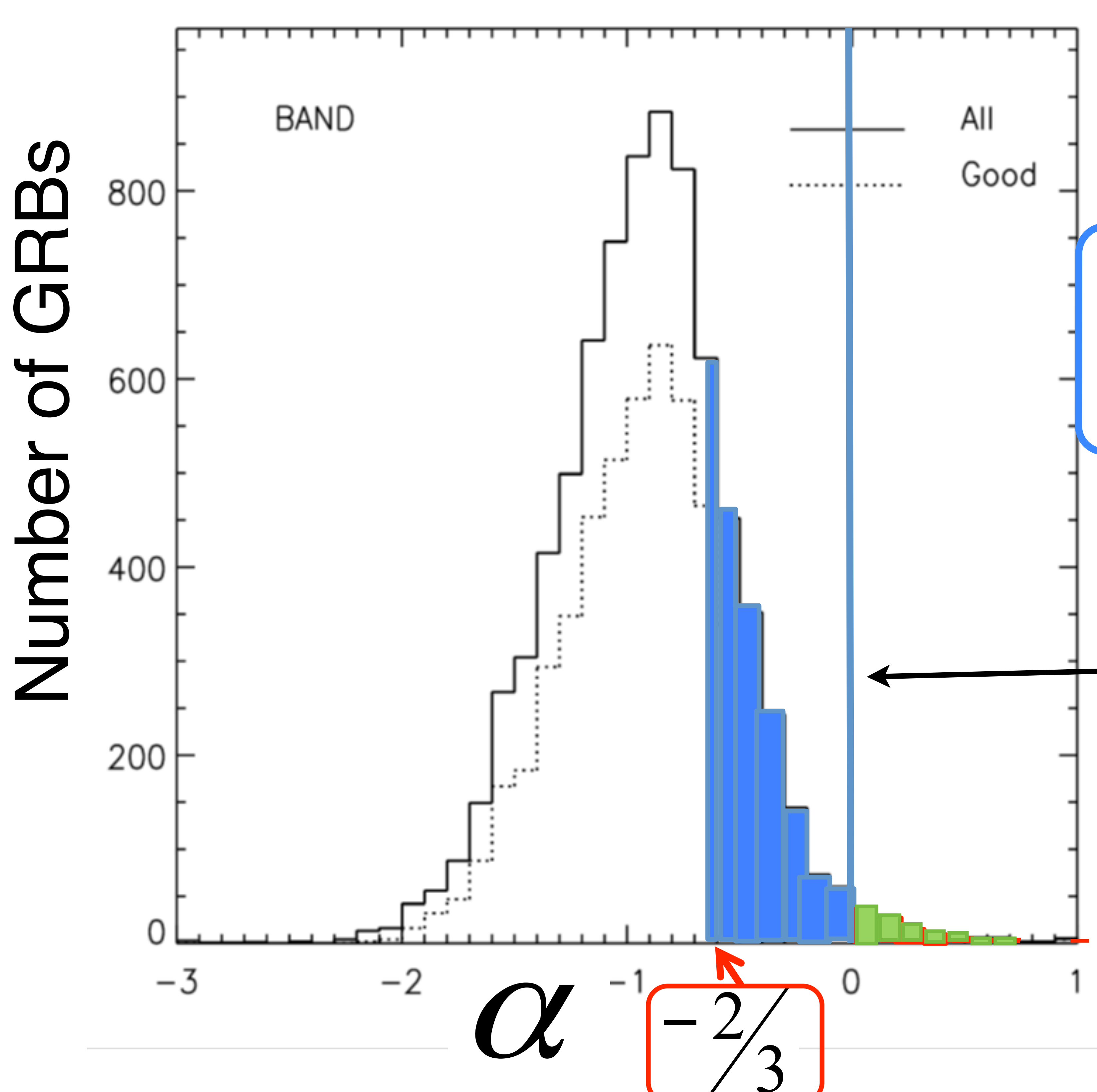
using γ at given time

Application
&
Summary

Chart of spectral signatures



Gamma Ray Bursts



Hard GRBs can be explained

0

Polarization degree and spectral indices

- Some GRBs may have high polarization degree

  e.g. observation of GRB110301A by GAP (Yonetoku et al. 2011)

  $\Pi = 70 \pm 22$ % with 3.7σ

According to our model of GRB emission,

WRL

Soft GRBs with $\alpha < -2/3$ → High Π

Hard GRBs with $\alpha > -2/3$ → Low Π

DRL

It is inverse of the Ito san's prediction!

Summary

1. We studied the radiation spectra from electrons moving in a Langmuir turbulence by using first principle numerical calculation.

2. We clarify the radiation spectra including newly found spectrum; WRL $F_\omega \propto \omega^{1/3}$

3. Hard spectra of GRBs can be explained by this radiation mechanism in realistic parameter range of turbulences in shock region in GRBs.

Thank you!