Particle acceleration & radiation in the plasma waves

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

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RIKEN

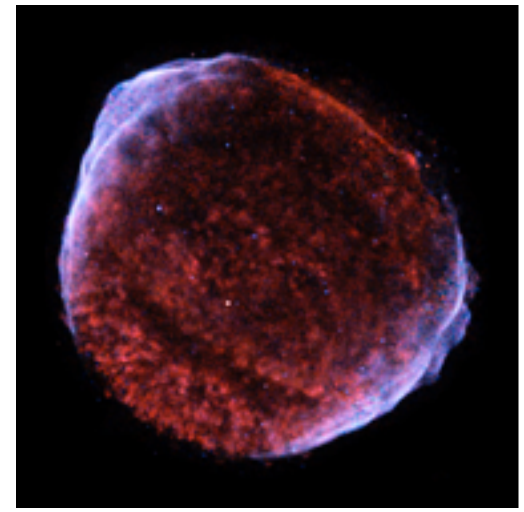
Programs for Junior Scientists

High Energy Astrophysical Objects

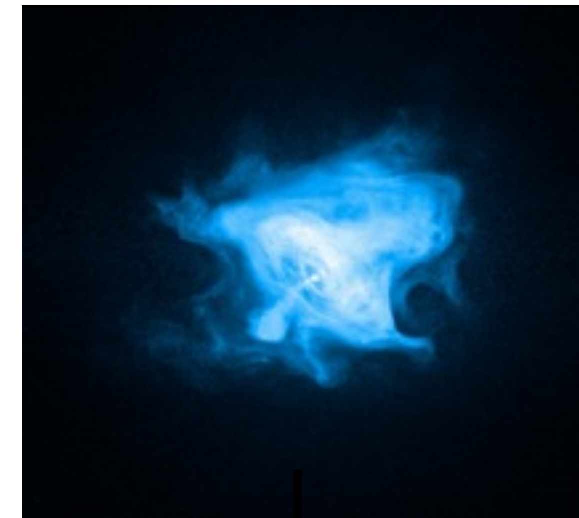
AGN jet M87 (HST)

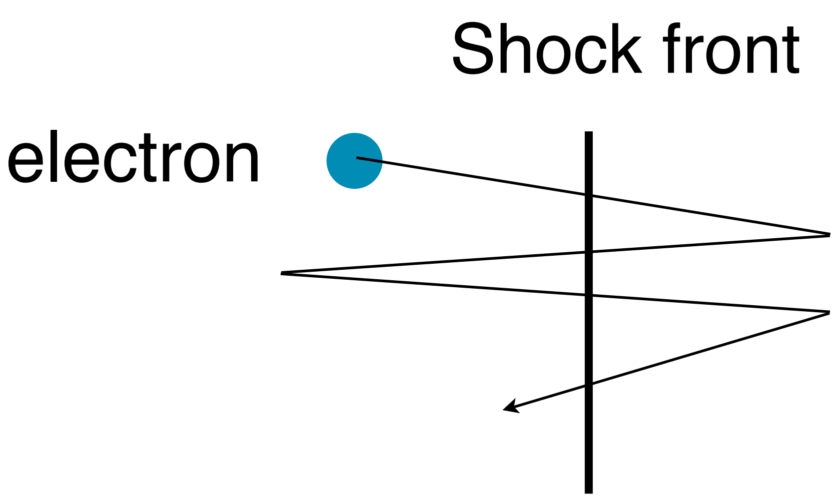
GRB （NASA cartoon）

SN1006 (Chandra)



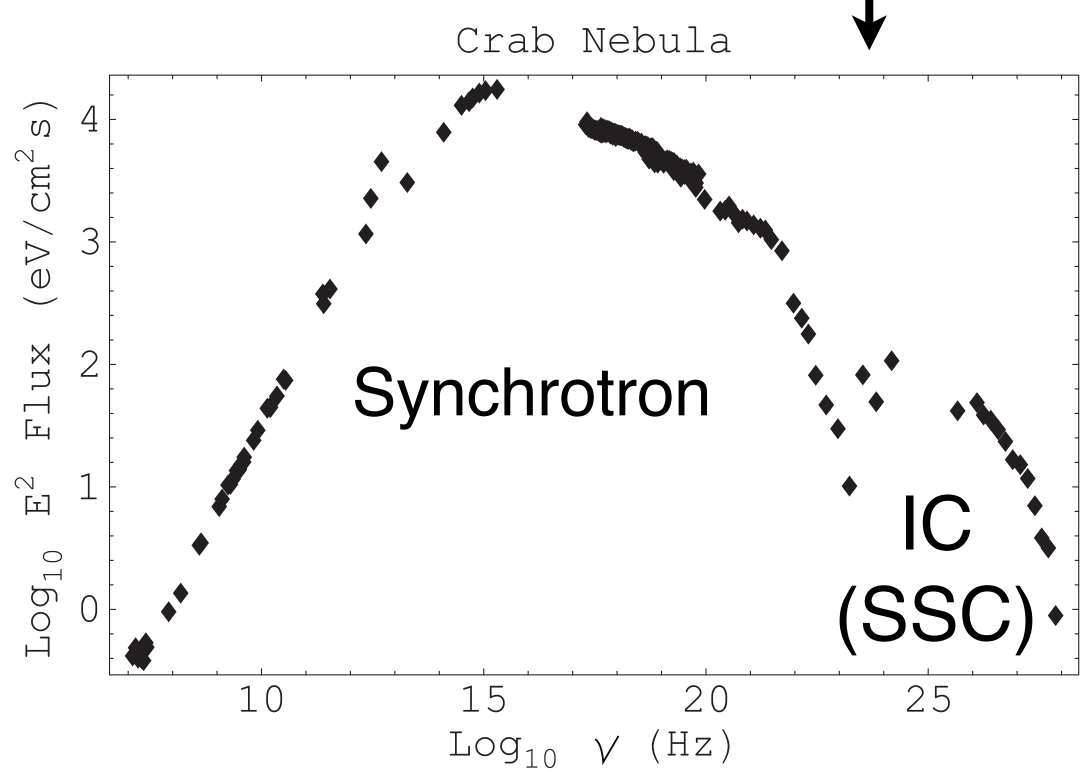
PWN Crab nebula (Chandra)





$$E = \gamma m c^2, \ \gamma \gg 1$$

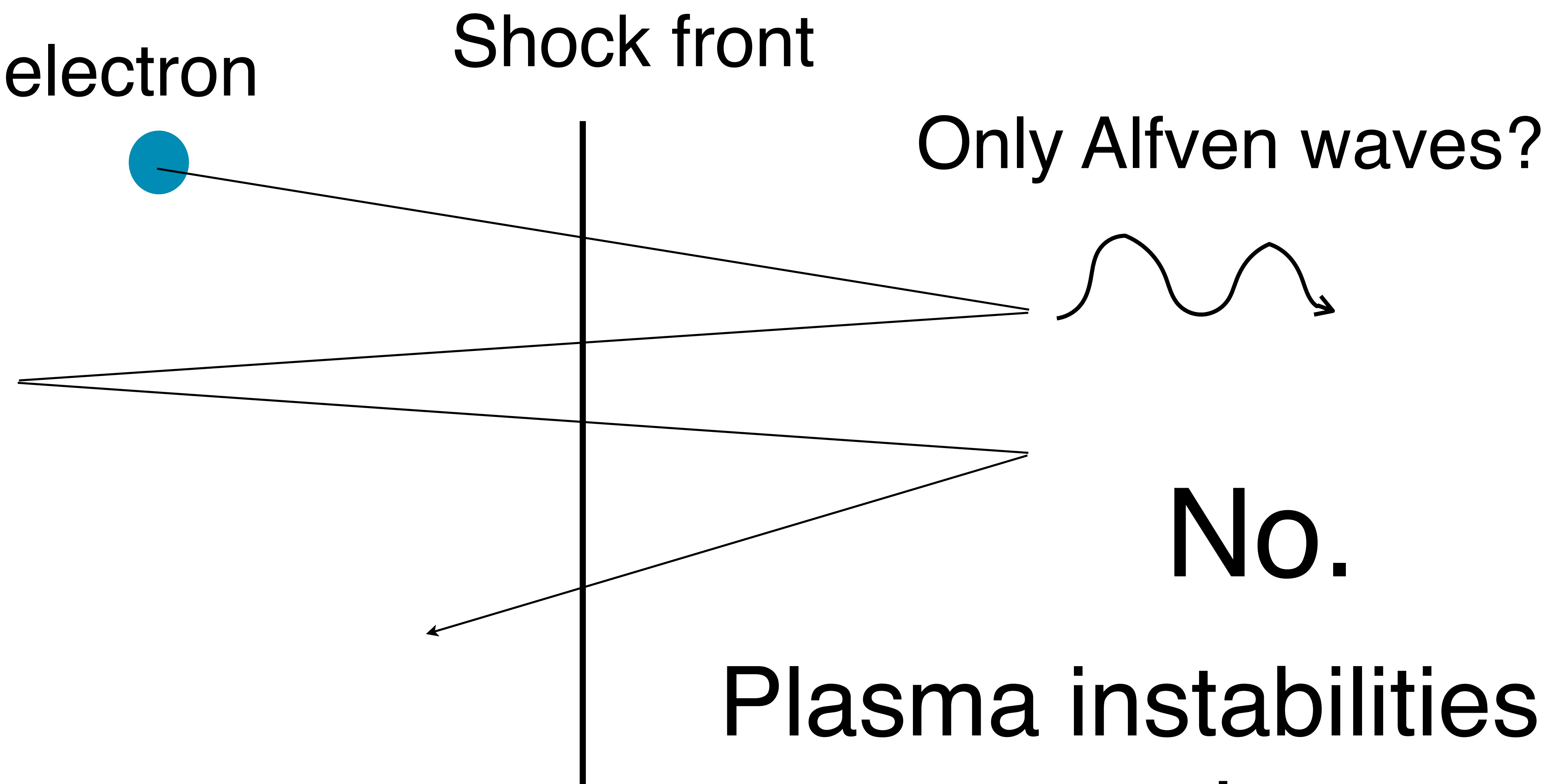
Particle acceleration



Kirk et al. 2009

Radiation

DSA / Synchrotron & IC?



No.

Plasma instabilities make many other waves
&
they affect acceleration and radiation

Magnetic entropy wave
Langmuir wave
Super luminal EM wave
etc..

Outline

1, Basic concepts of radiation mechanisms

2, Radiation spectra from electrons in the turbulent field

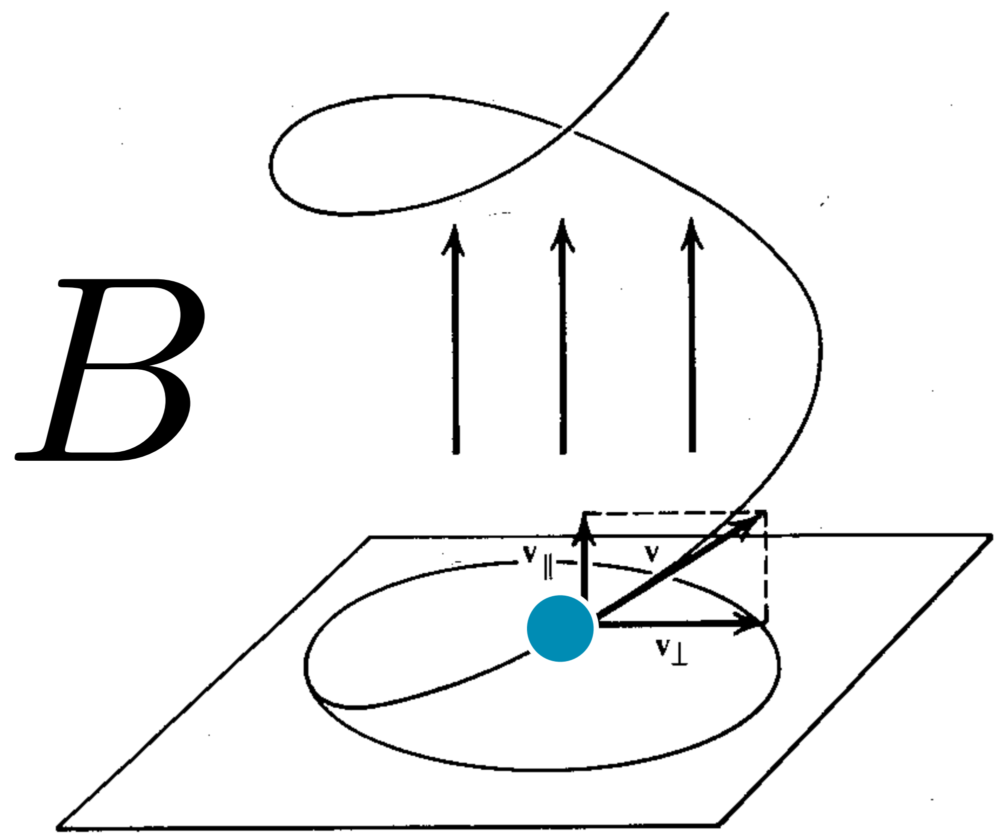
2-1 magnetic static turbulence
2-2 Langmuir turbulence

If I have more time,

3, Particle acceleration in the strong EM waves

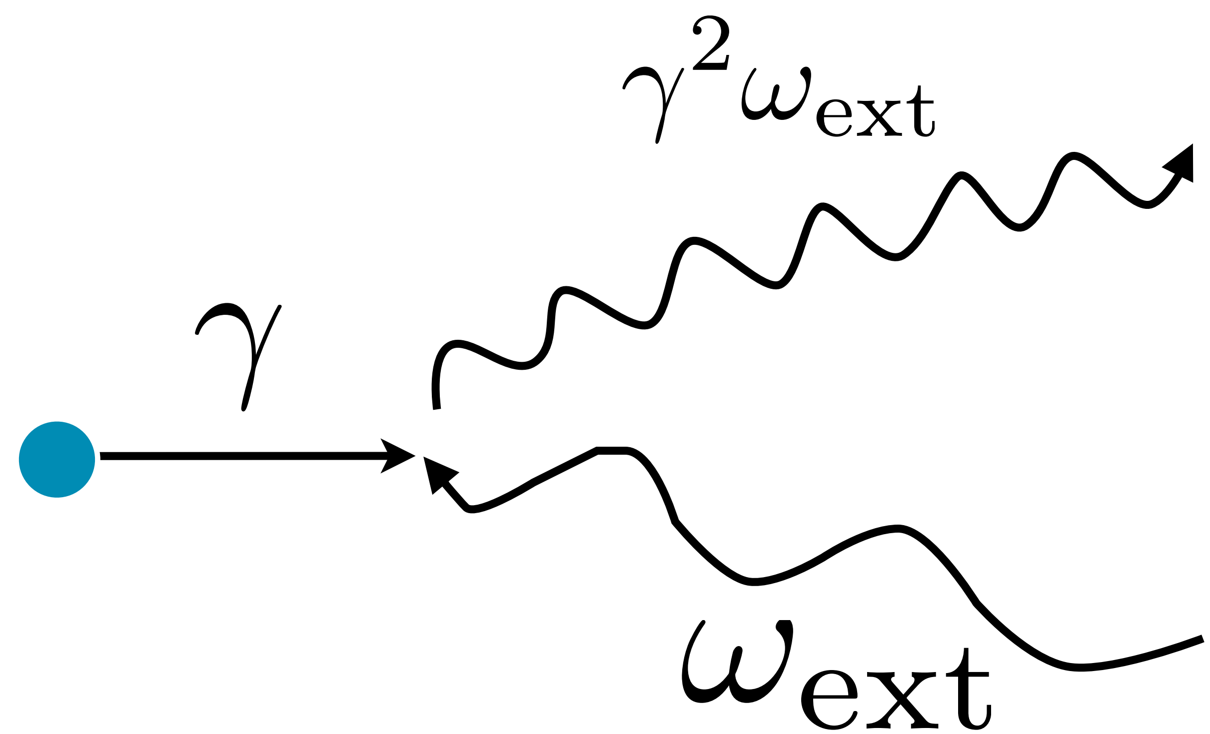
Basics of conventional radiation

Synchrotron radiation



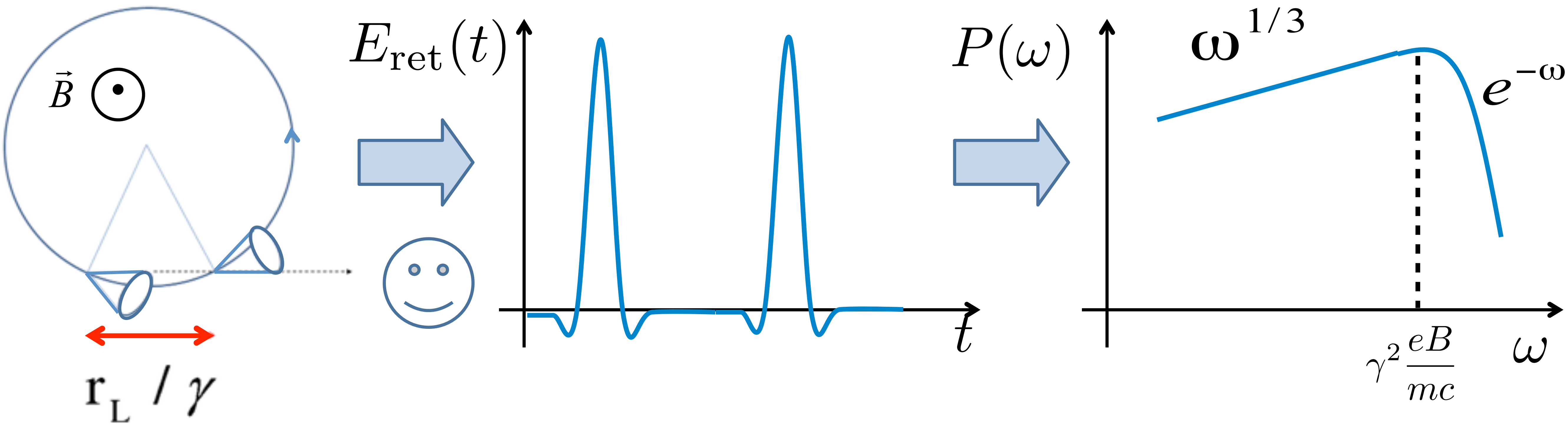
$$\omega_{\rm syn} = \gamma^2 \frac{eB}{mc}$$

Inverse Compton scattering



$$\omega_{\rm IC} = \gamma^2 \omega_{\rm ext}$$

Photon Formation Time (Length)



||

$$\frac{mc^2}{eB}$$ Photon Formation Length

For synchrotron typical frequency,

$$\frac{mc}{eB} \equiv \frac{1}{\omega_{\rm st}}$$ Photon Formation Time (PFT)

Photon Formation Time

- For non relativistic particle

PFT for the radiation with frequency ω $\quad T \sim 1/\omega$

- For relativistic particle

$$T \sim \frac{1}{(1 - v/c)\omega} \sim \gamma^2/\omega$$

Dopper boosting is very efficient

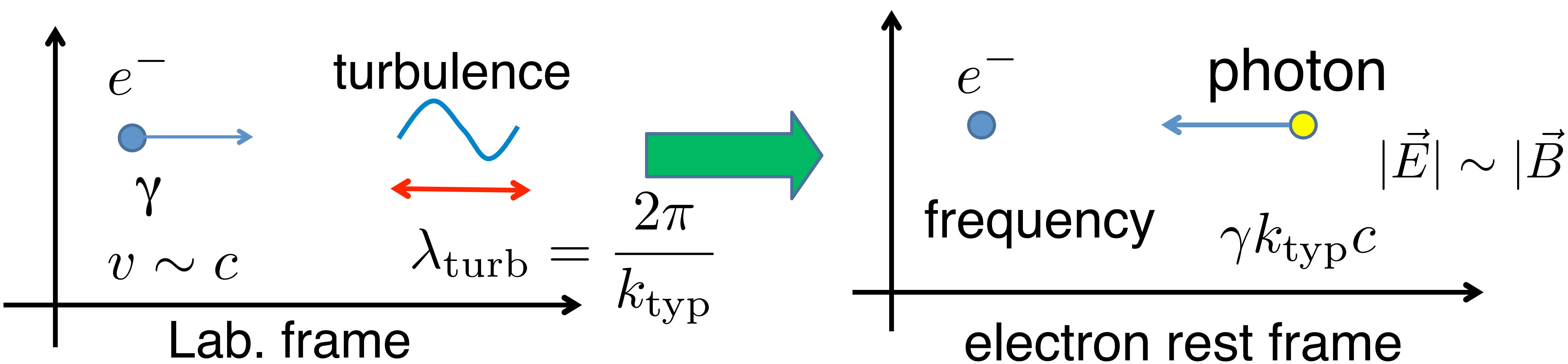
jitter radiation

$$\lambda_B \ll \frac{mc^2}{eB}$$

$$\theta_{\rm def} \ll \frac{1}{\gamma}$$ straight orbit & perturbative acceleration

PFT $T \sim \lambda/v \longrightarrow \omega \sim \gamma^2/T \sim \underline{\gamma^2 k_B c}$

Another interpretation: an analogy of IC



2, Radiation spectra from electrons in the turbulent field

Possible waves

There should be many waves (cf. Matsumoto-san's talk), we now focus on

- Magnetic entropy waves generated by Weibel instability

$$\omega_{\rm w} = 0 \longrightarrow \text{magnetic field only}$$

- Langmuir waves generated by two stream instability

$$\vec{k}_{\rm w} \times \vec{E} = 0 \longrightarrow \text{when } B_0 = 0 \text{ , electric field only}$$

Longitudinal

Turbulent field	Magnetic field	Electric field
Generation	Weibel instability	two stream instability
Mode	transverse	longitudinal
frequency	0	ω_{p} : plasma frequency
wavelength	$\sim c/\omega_{\mathrm{p}}$	$\sim c/\omega_{\mathrm{p}}$
Synchrotron Photon Formation Length (PFL)	$\frac{mc^2}{e\sigma} \equiv \frac{c}{\omega_{\mathrm{st}}} \sim \frac{c}{\omega_{\mathrm{p}}}$	
Synchrotron-like Photon Formation Time (PFT)		$\frac{mc}{e\sigma} = \frac{1}{\omega_{\mathrm{st}}} \sim \frac{1}{\omega_{\mathrm{p}}}$

where $< B^2 >^{\frac{1}{2}} = \sigma$ $\quad < E^2 >^{\frac{1}{2}} = \sigma$

Parametrizing the EM turbulences

Strength parameter

$\dfrac{\text{Spatial scale of turbulence}}{\text{Synchrotron PFL}} : \dfrac{\lambda_{\mathrm{tutb}}}{mc^2/e\sigma}$

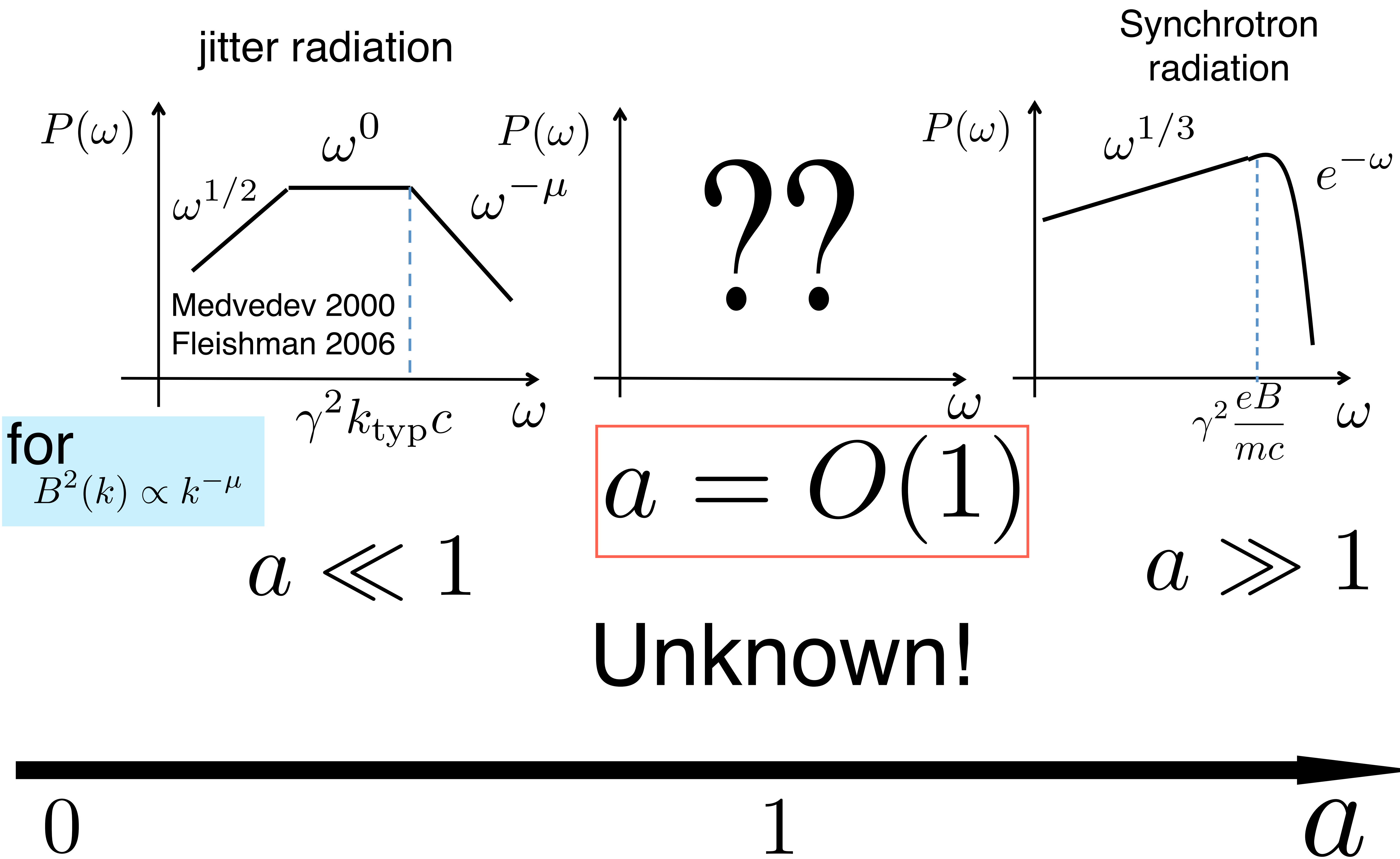
$$a \equiv \frac{e\sigma}{mc^2 k_{\mathrm{typ}}} = \frac{\omega_{\mathrm{st}}}{k_{\mathrm{typ}} c}$$

Oscillation parameter

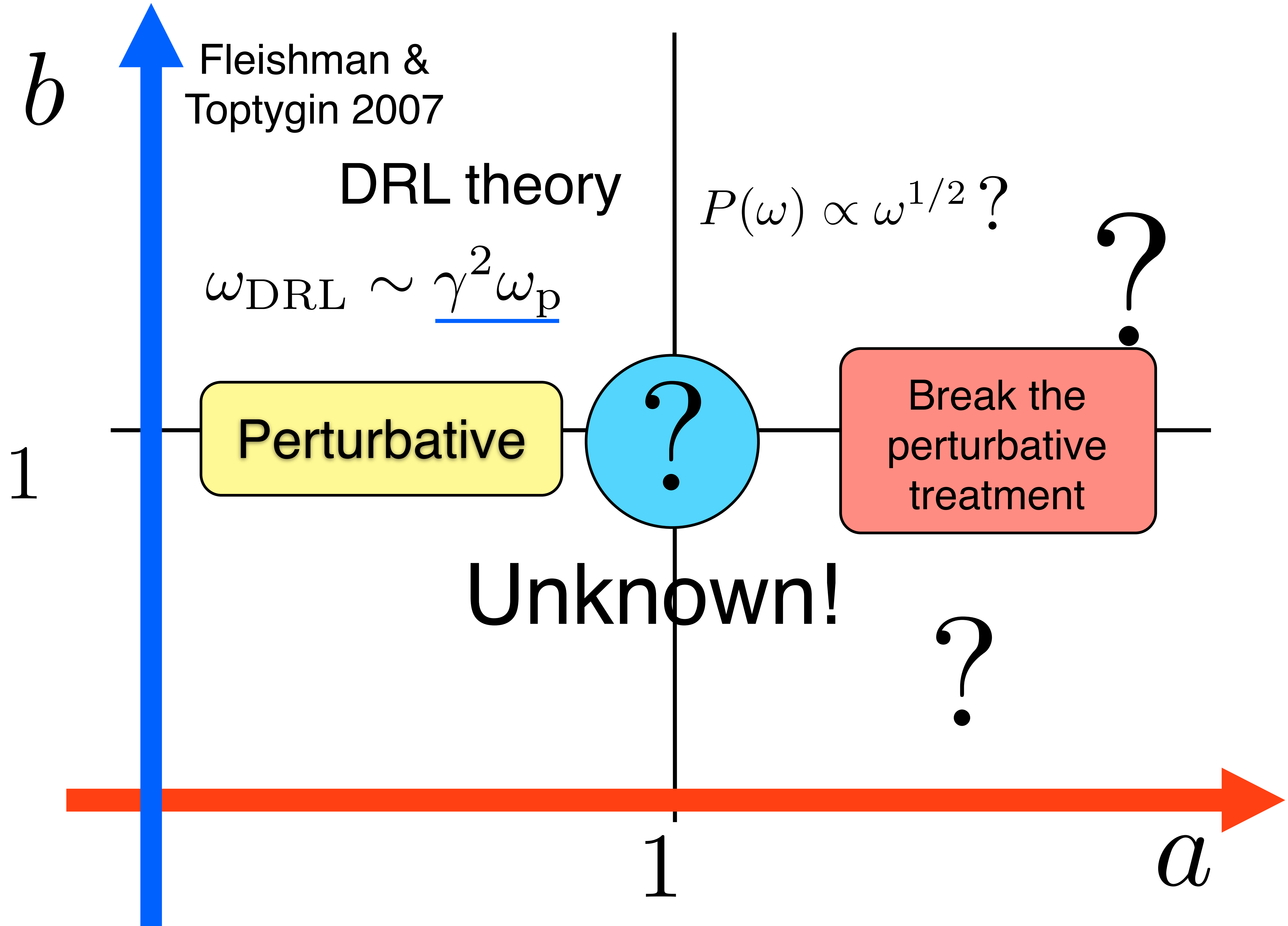
$\dfrac{\text{Crossing time}}{\text{Oscillation timescale}} : \dfrac{\lambda_{\mathrm{turb}}/c}{T}$

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

Radiation spectra for magnetic turbulence ($b = 0$)



For Langmuir turbulence



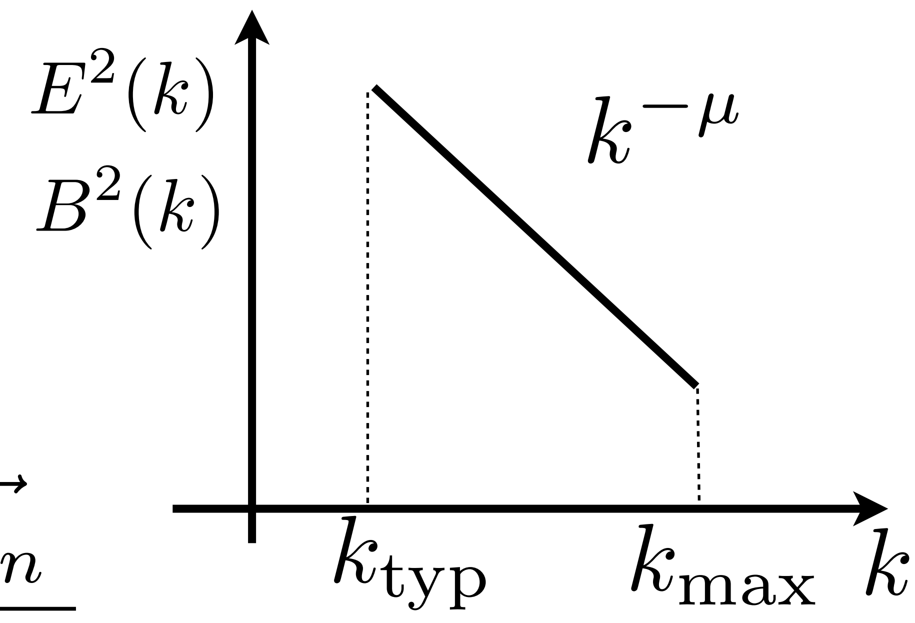
Description of the turbulent EM fields

Superposition the Fourier modes

$$\vec{B}(\vec{x}) = \sum_{n=1}^{N} A_n \exp\{i(\vec{k_n}\cdot\vec{x}+\beta_n)\}\hat{\xi}_n$$

or

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



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

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

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

$$\hat{\xi}_n = \cos\psi_n \hat{e}'_x + i\sin\psi_n \hat{e}'_y$$

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

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

Time scale $\omega_{\rm p}$

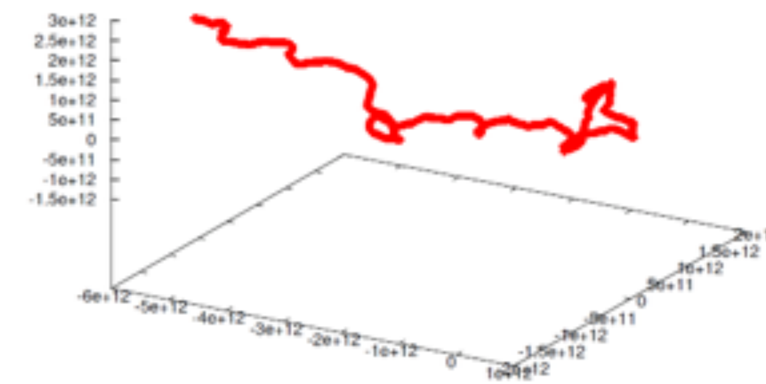
Mean strength $\omega_{\rm st} \equiv \frac{e\sigma}{mc}$

Calculation the radiation spectra

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

Solve the EOM
$$\frac{d}{dt}(\gamma m_{\mathrm{e}} \vec{v}) = e(\vec{E} + \frac{\vec{v}}{c} \times \vec{B})$$

An example of the trajectory



Use the Lienard-Wiechert potential directly

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

$\vec{n}$ Unit vector toward observer

t' Retarded time

For Langmuir turbulences

We want to know instantaneous spectra

Integration time is $100\times$ PFT of the each typical frequency

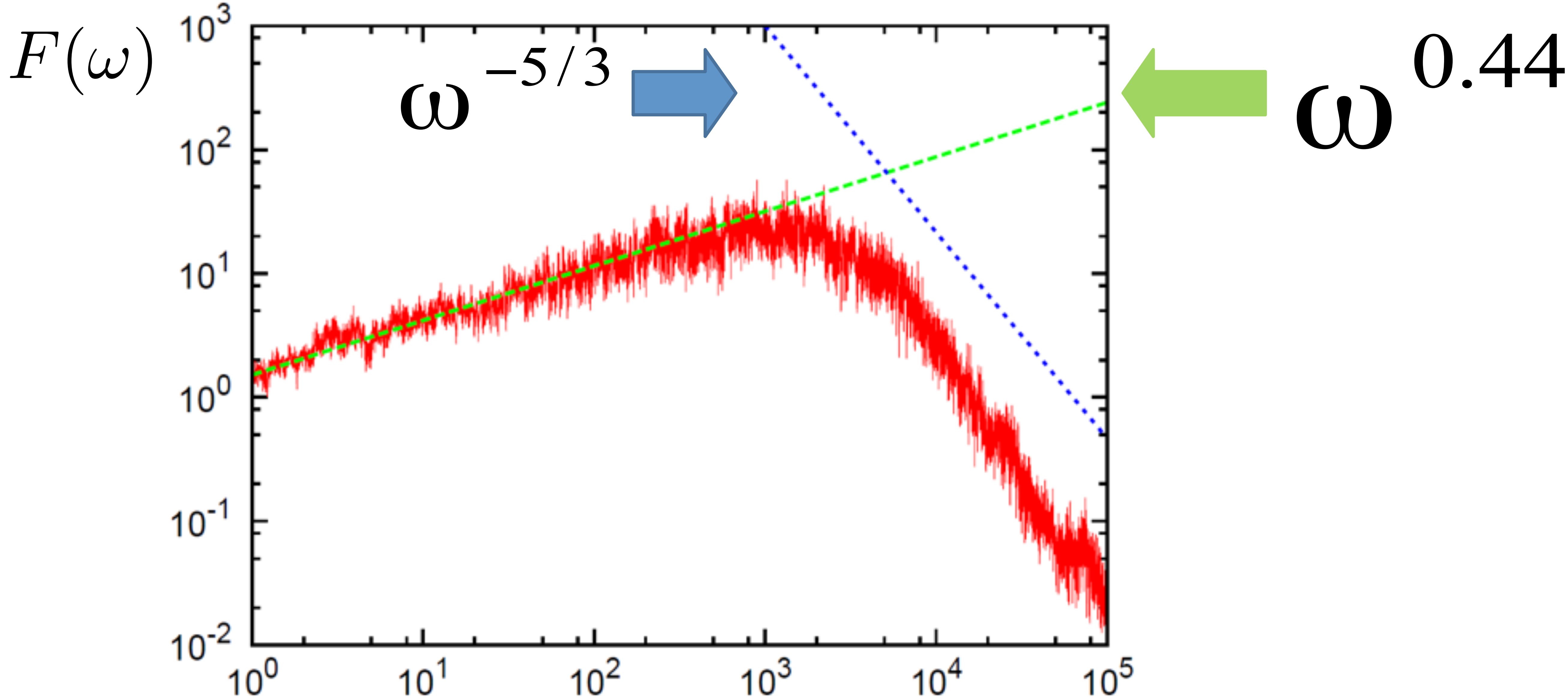
2-1 Magnetic turbulence

parameters:

$$a \equiv \frac{e\sigma}{mc^2 k_{\mathrm{typ}}} = \frac{\omega_{\mathrm{st}}}{\omega_0}$$

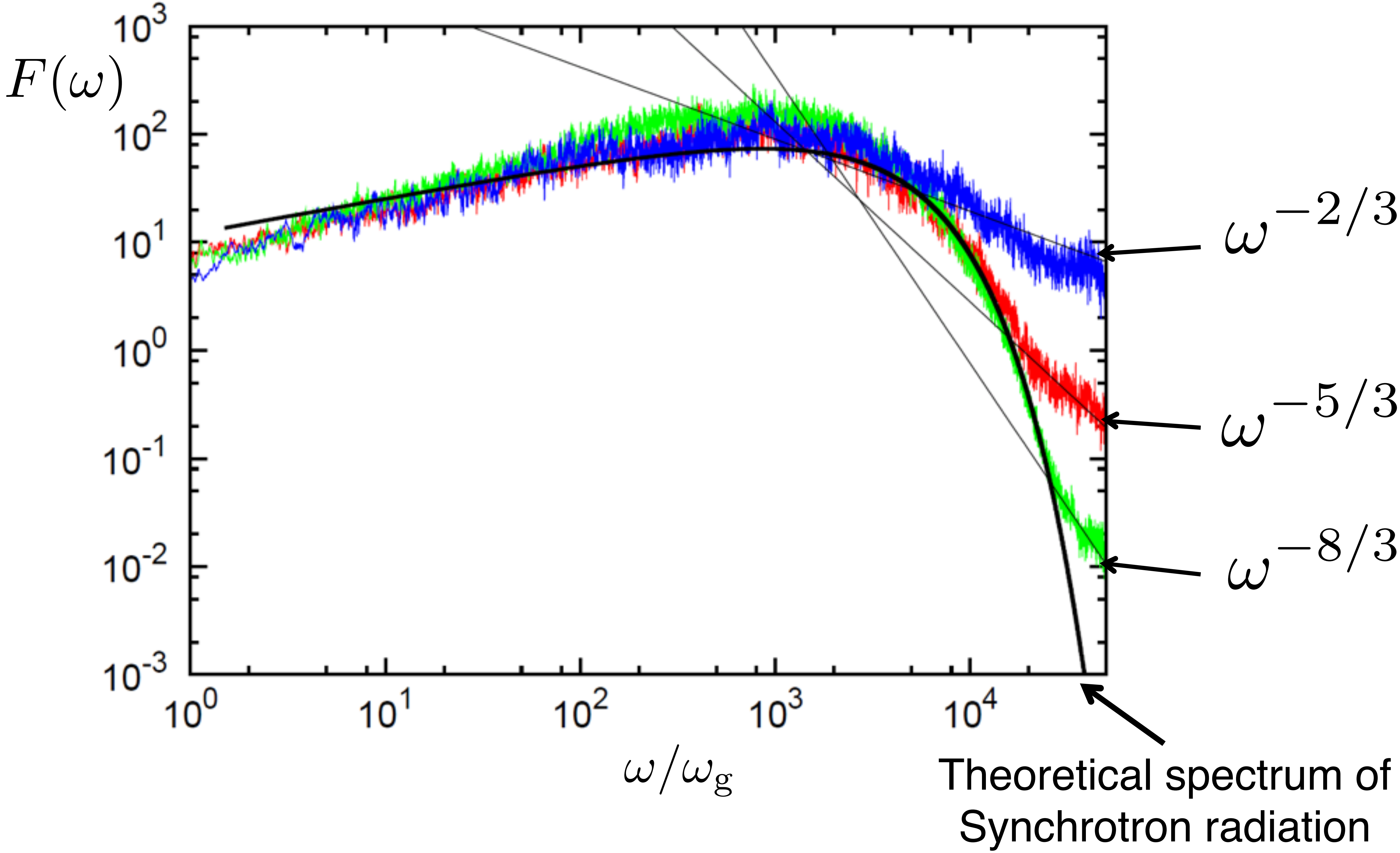
$$b = 0$$ ←static

strength parameter $a = 0.5$ power index of turbulence $\mu = 5/3$

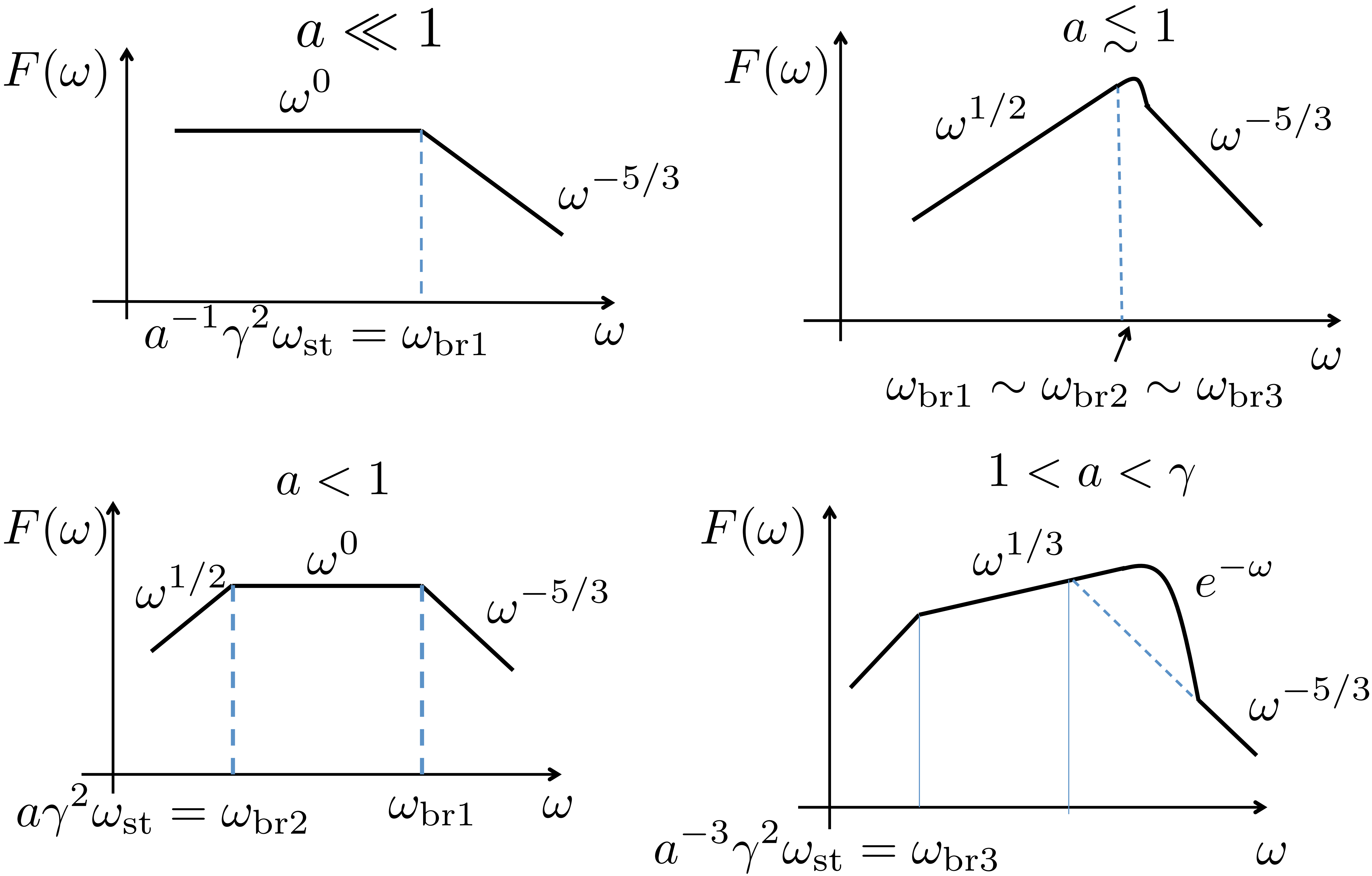


Flat region disappears

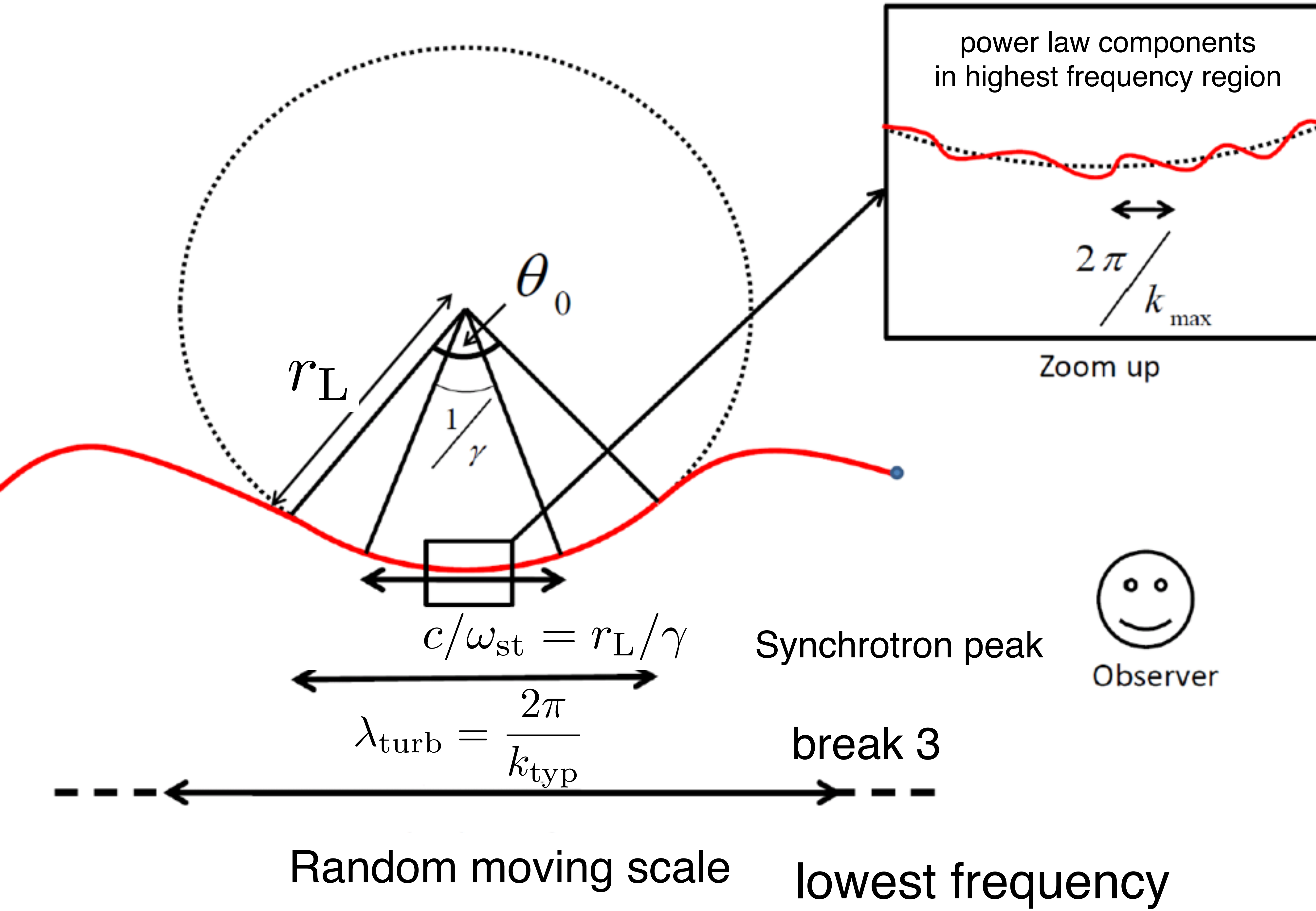
Strength parameter $a = 1.2$ power index of turbulence $\mu = 2/3,\ 5/3,\ 8/3$



Radiation spectra for magnetic turbulence



Electron trajectory for $1 < a < \gamma$



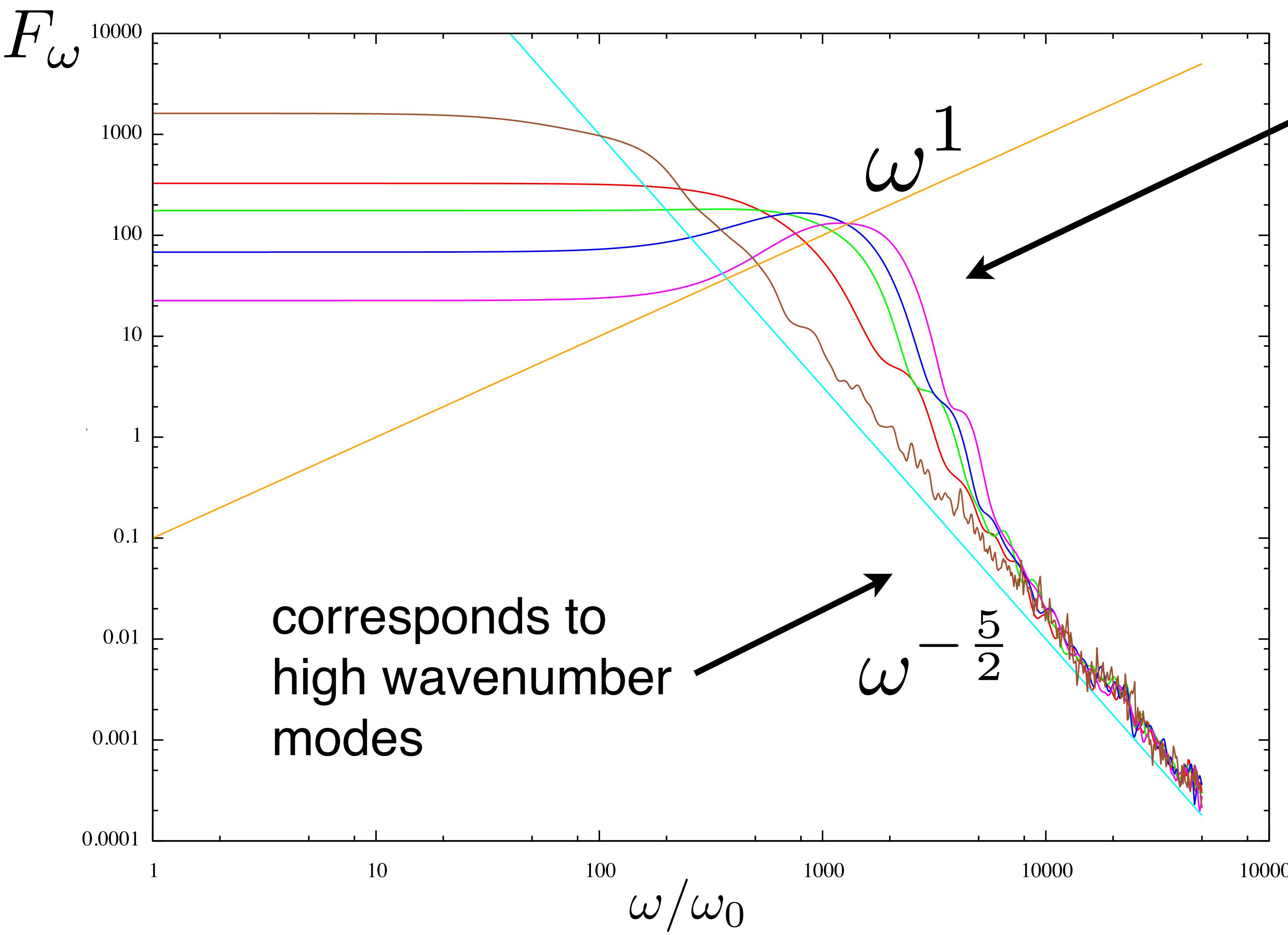
2-2 Langmuir turbulence

parameters:

$$a \equiv \frac{e\sigma}{mc^2 k_{\mathrm{typ}}} = \frac{\omega_{\mathrm{st}}}{\omega_0}$$

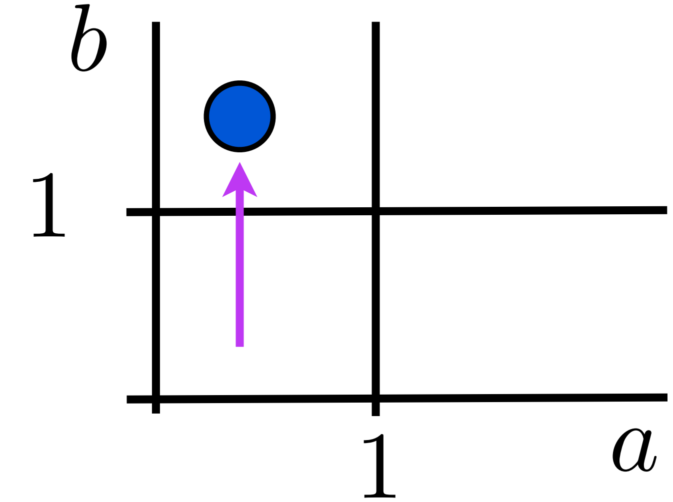
$$b \equiv \frac{\omega_{\mathrm{p}}}{k_{\mathrm{typ}} c} = \frac{\omega_{\mathrm{p}}}{\omega_0}$$

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



Hump

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



Time variability dominated

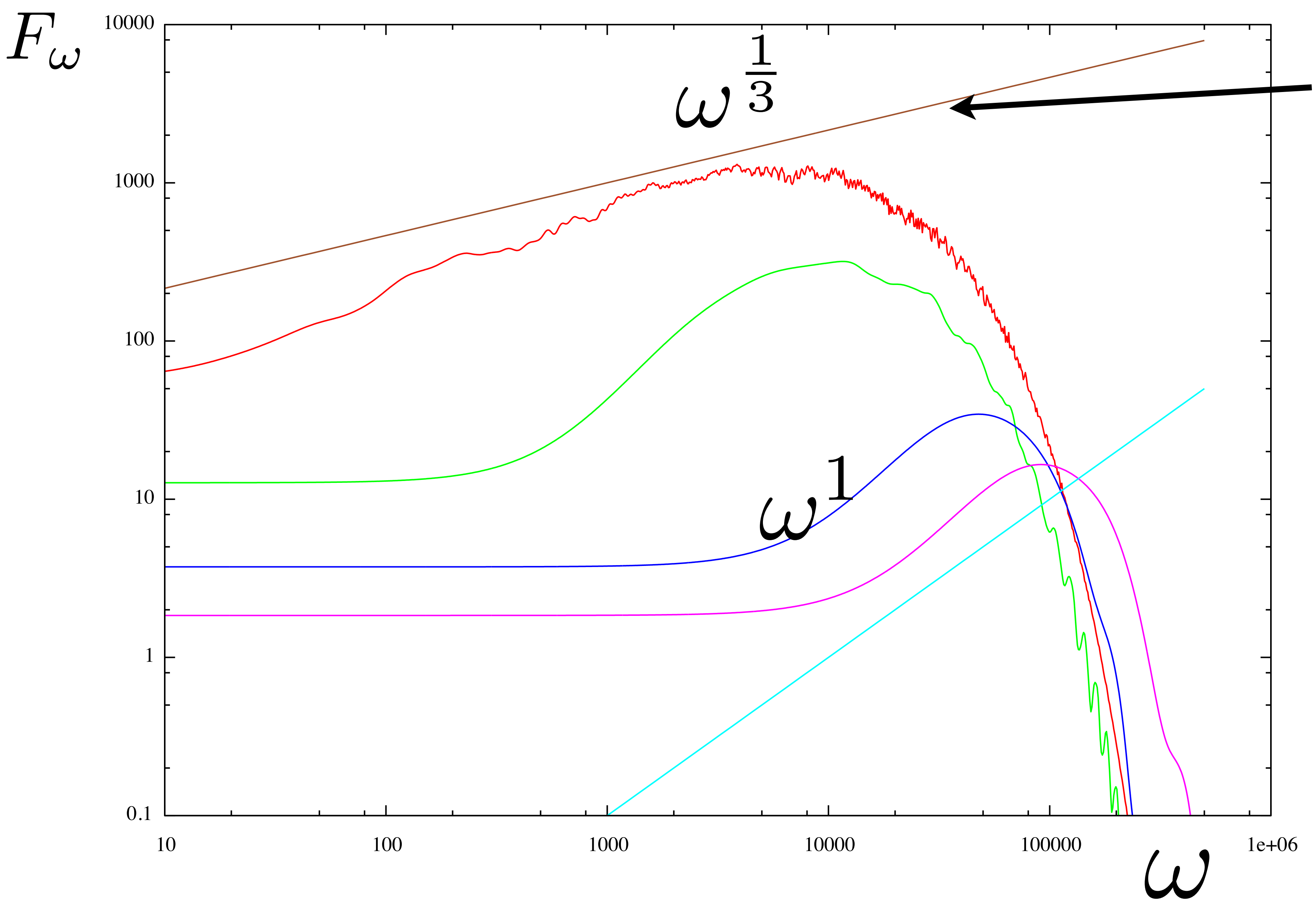
Typical frequency

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

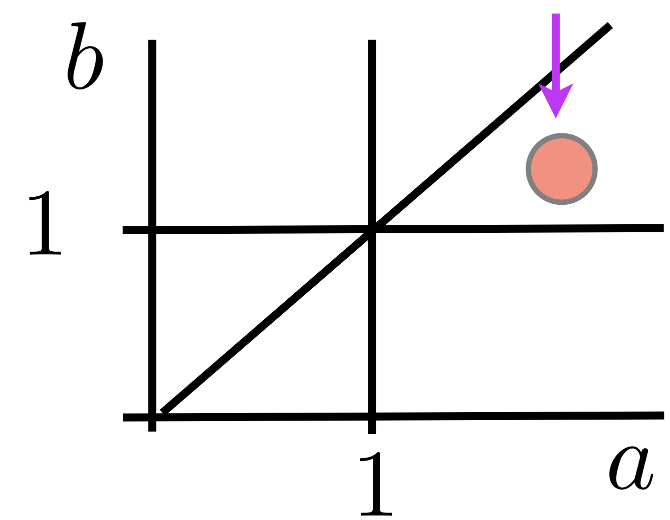
Spectral index

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

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



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



Strength dominated

Typical frequency

$$\omega_{\rm typ} = \gamma^2 \omega_{\rm st}, (> \gamma^2 \omega_{\rm p})$$

Spectral index

$$F_\omega \propto \omega^{\frac{1}{3}}$$

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

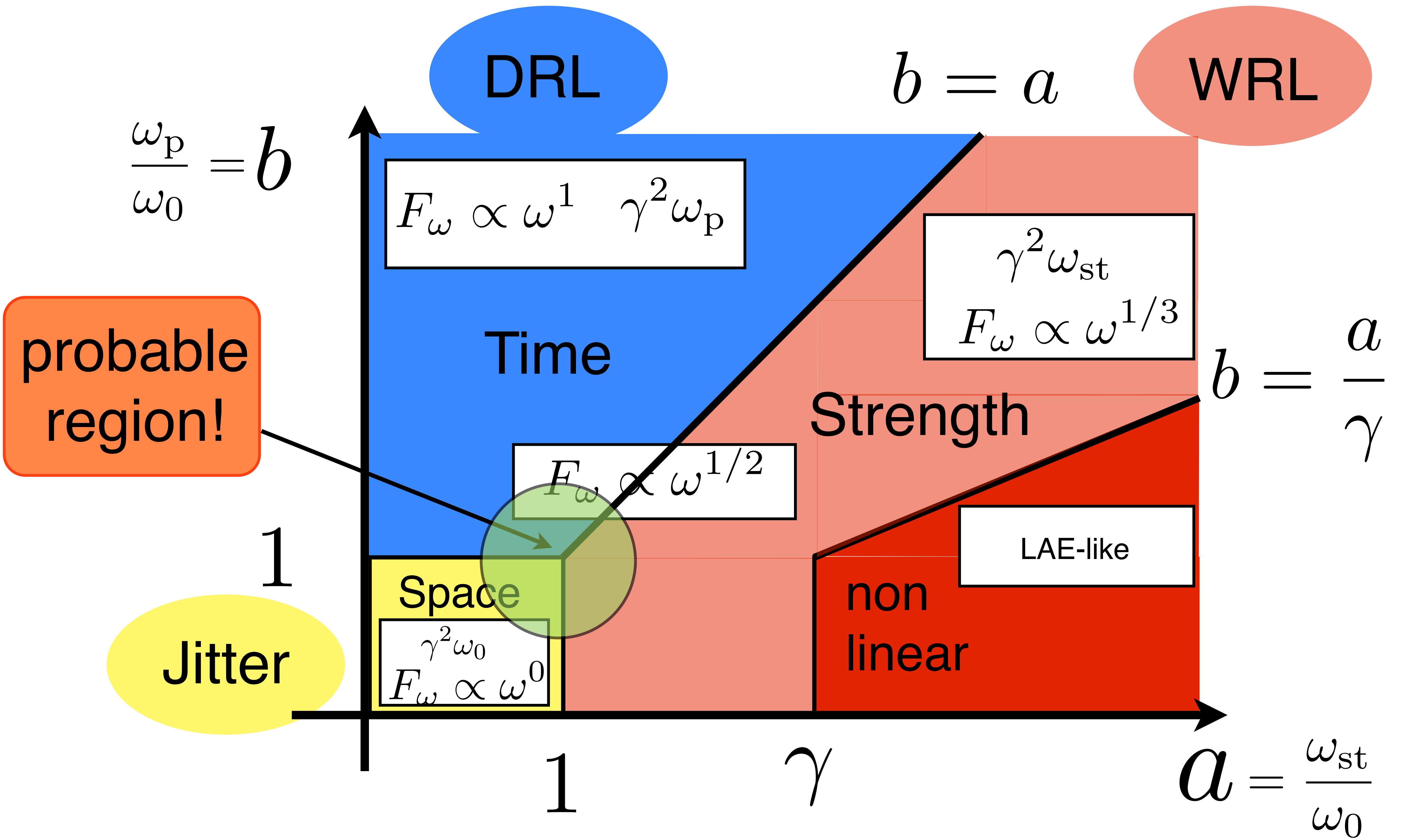
$$P = \frac{2e^2}{3c^3}\gamma^4\left[\left(\frac{dv_\perp}{dt}\right)^2 + \gamma^2\left(\frac{dv_\parallel}{dt}\right)^2\right]$$

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

power

γ^2 times larger

Chart of spectral signatures



Short summary

1. For magnetic turbulence,
we got the radiation spectra for the intermediate regime between synchrotron and jitter.

2. For Langmuir turbulence,
we depicted a chart for spectral signatures including newly found signatures.

3. Radiation signatures strongly depend on the strength parameter and oscillation parameter when they are around unity.