Light Source I

Takashi TANAKA (RIKEN SPring-8 Center)

CONTENTS

Light Source I

- Introduction
- Fundamentals of Light and SR
- Overview of SR Light Source
- Characteristics of SR (1)

Light Source II

- Characteristics of SR (2)
- Practical Knowledge on SR

Introduction

SR Facility and Light Source

- SR: Definition
  - Electromagnetic wave emitted by a charged particle deflected by a magnetic force
- SR Facility
  - Accelerators to generate a high-energy electron beam
  - **Magnetic devices (SR light source) to generate intense SR**
  - Optical elements (monochromators, mirrors,..)
  - Experimental stations

SR as a Probe for Research

- SR has a lot of advantages over other conventional light sources
  - Highly collimated (laser-like)
  - Wavelength tunability
  - Polarization
  - .....
- However, the total radiation power does not differ significantly.

Comprehensive understanding of SR (and light source) is required for efficient experiments.

Topics in This Lecture (1)

- Fundamentals of Light and SR
  - Why we need SR?
  - Physical quantity of light
  - Uncertainty of light: Fourier and diffraction limits
  - SR: Light from a moving electron
- Overview of SR Light Source
  - Types of light sources
  - Magnet configuration
- Characteristics of SR (1)
  - Radiation from bending magnets

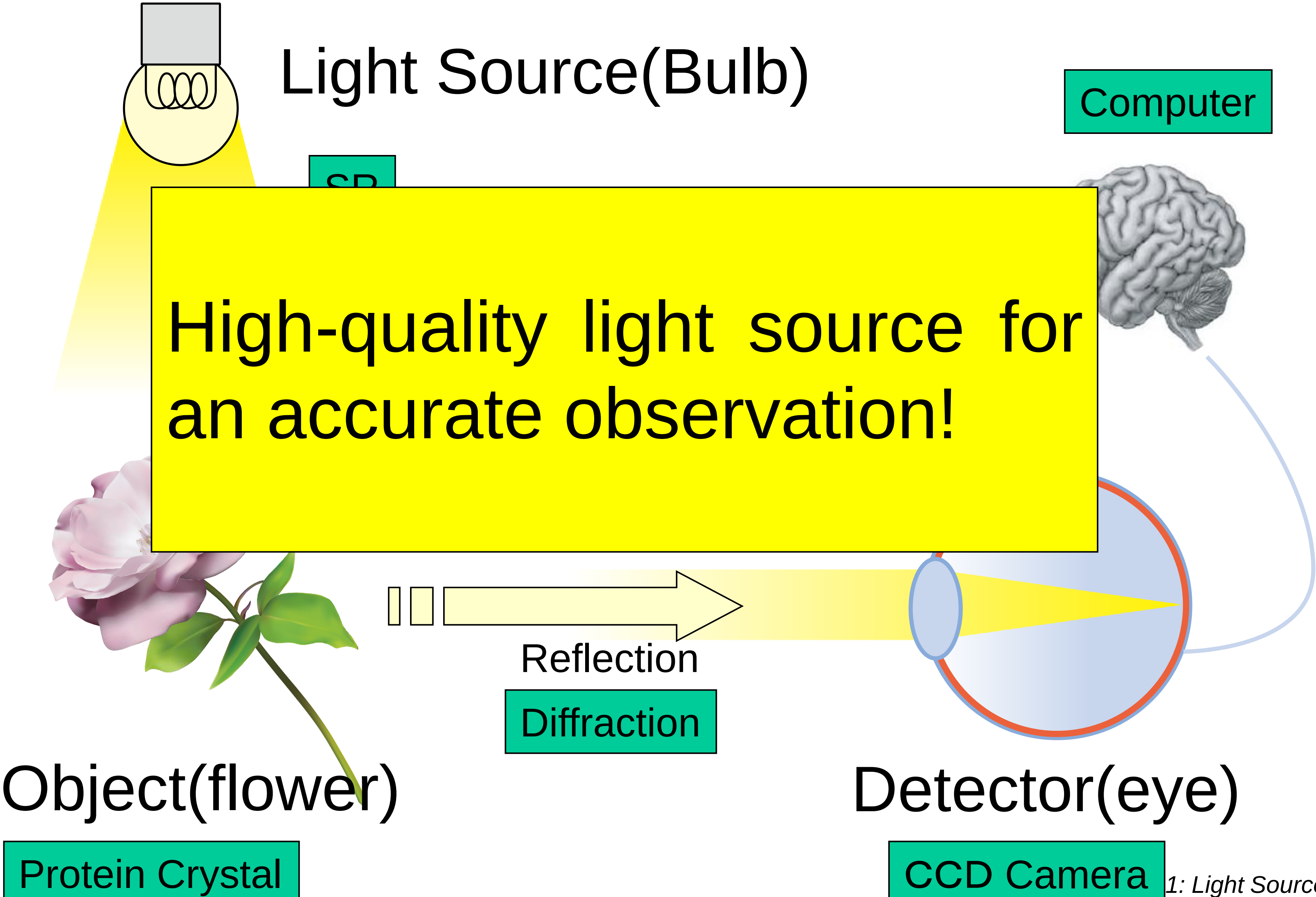
Topics in This Lecture (2)

- Characteristics of SR (2)
  - Electron Trajectory in IDs
  - Radiation from wigglers
  - Radiation from undulators
- Practical Knowledge on SR
  - Finite emittance and energy spread
  - Heat load and photon flux
  - Evaluation of optical properties of SR
  - Definition of undulators and wigglers
  - Numerical examples

Fundamentals of Light and SR

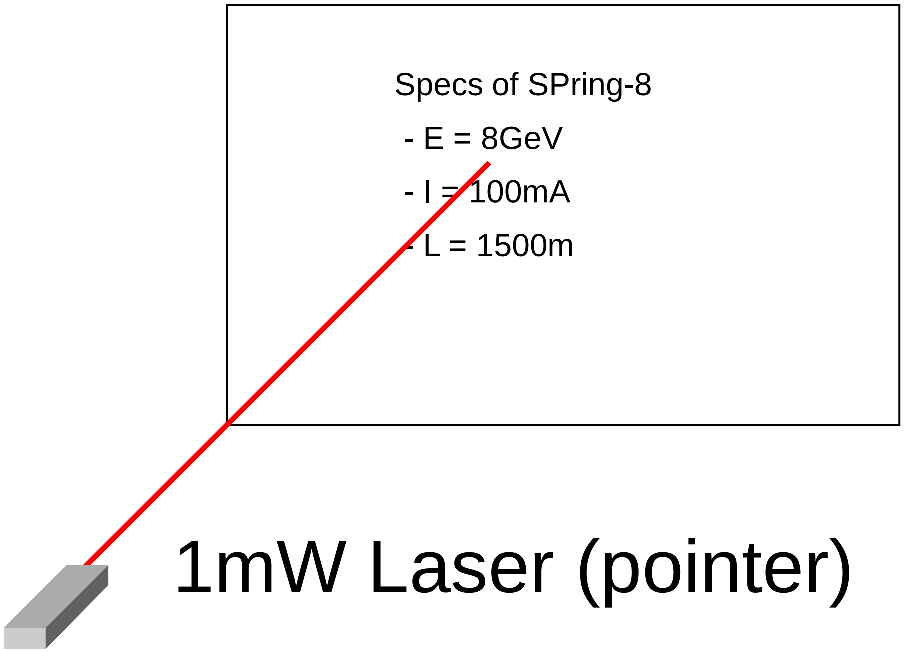
- Why we need SR?
- Physical Quantity of Light
- Uncertainty of Light
- SR: Light from a Moving Electron

Observation with Light

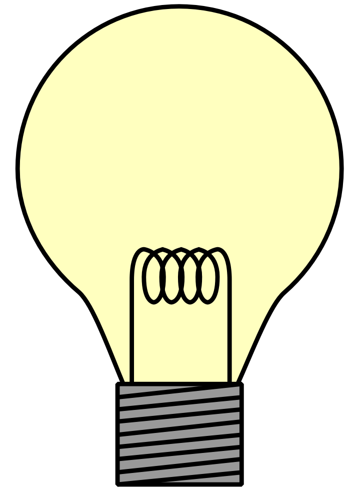


High-quality light source for an accurate observation!

Which Quality is Better?



1mW Laser (pointer)



100W Bulb

Lighting equipment in a room:	Bulb
Pointer during a presentation:	Laser

Depends on the Object!

How to Define the Quality of Light?(1)

- The performance of the light source depends on the dimension of the object and the method to detect light.
- For observation, the photons emitted by the light source should be
  - illuminated on the object for interaction
  - recognized by the detector for analysis

Quality of Light Source:
How efficiently the above conditions are satisfied?

How to Define the Quality of Light?(2)

Important Features of the Light Source

	Object		Related Items
	Flower	Protein	
Radiation Power	◎	○	# Emitted Photons
Source Size	×	◎	Illuminated Area
Directivity	△	◎	
Monochromaticity	△	◎	Accuracy of Analysis

Brilliance

What is Brilliance?

$$\text{Brilliance(photons/sec/mm}^2\text{/mrad}^2\text{/0.1\%B.W.)} \sim \frac{\text{Total Power}}{\text{Source Size x Angular Divergence x Band Width}}$$

- Brilliance specifies the quality of light for observation of microscopic objects.
- The brilliance of a light source with a high total power is not necessarily high.

Examples of Brilliance

	Bulb	Laser Pointer
Total Power (W)	100	10^{-3}
Angular Div. ($mrad^2$)	$4\pi x10^6$	1
Source Size: (mm^2)	10^2	1
Bandwidth: (%)	100	0.01
Brilliance (photons/sec/....)	$\sim 10^8$	$\sim 10^{16}$

Laser is the best light source to observe the microscopic object!

X ray as a Probe

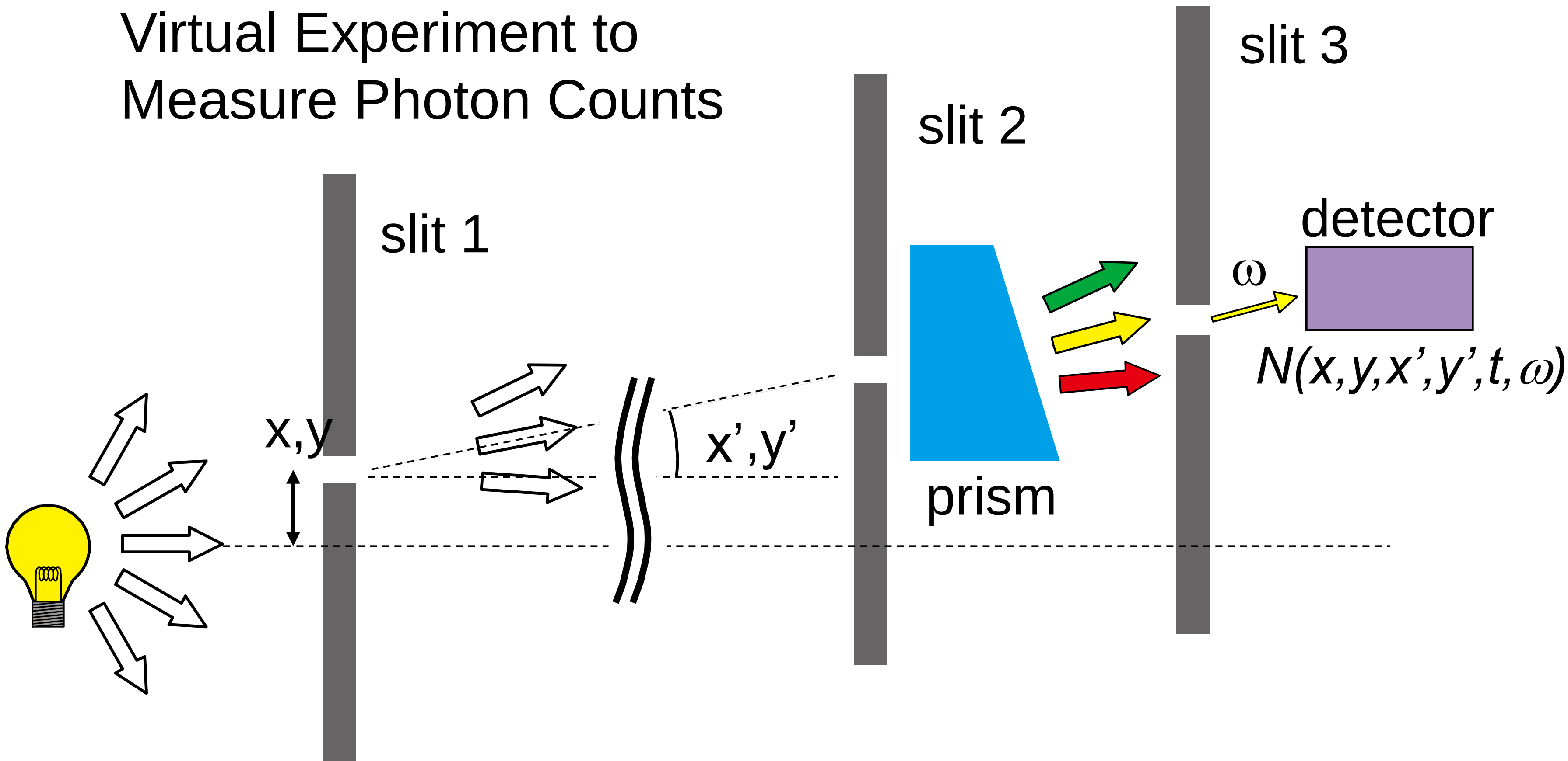
- Definition (not unique)
  - Electromagnetic wave (= light) with λ of 10 nm(10^{-8} m) ~ 0.1 Å (10^{-11} m)
- Properties
  - High Energy/Photon
  - High Penetration (Roentgen etc..)
- Application to Microscopic Objects
  - X-ray Diffraction
  - Fluorescent X-ray Analysis
- **No Practical Lasers!!**

→ Synchrotron Radation(SR)

Fundamentals of Light and SR

- Why we need SR?
- Physical Quantity of Light
- Uncertainty of Light
- SR: Light from a Moving Electron

Phase Space



$$n = \boxed{\frac{N(x,y,x',y',\omega,t)}{\Delta x \Delta y \Delta x' \Delta y' \Delta t \Delta\omega/\omega}} \equiv \frac{N}{\boxed{\Delta\Omega}}$$

Av. Photon Density

Volume in 6-D Phase Space

Brilliance (Brightness)

- Brilliance (photons/sec/mm^2/mrad^2/0.1%B.W.) is defined as the photon density in the 6D phase space, i.e.,

$$B = \lim_{\Delta\Omega \to 0} n = \frac{d^6 N(x, y, x', y', t, \omega)}{dx\,dy\,dx'\,dy'\,dt\,d\omega/\omega}$$

- In practice, $\Delta\Omega$ can never be 0 due to uncertainty of light, thus brilliance is not a physical quantity that can be actually measured.

Photon Flux and Flux Density

- Removing the 1st slit gives the angular flux density (photons/sec/mrad^2/0.1%B.W), i.e.,

$$\frac{d^2F}{dx'dy'} = \iint Bdxdy$$

- Removing the 1st & 2nd slits gives the total flux (photons/sec/0.1%B.W), i.e.,

$$F = \iiiint Bdxdydx'dy'$$

- Estimation of number of photons to be delivered to the sample.

Radiation Power and Power Density

- Removing the 1st & 3rd slits gives the angular power density (W/mrad^2), i.e.,

$$\frac{d^2P}{dx'dy'} = 10^3 Q_e \hbar \int \frac{d^2F}{dx'dy'} d\omega$$

conversion from photons/sec/0.1%B.W. to W

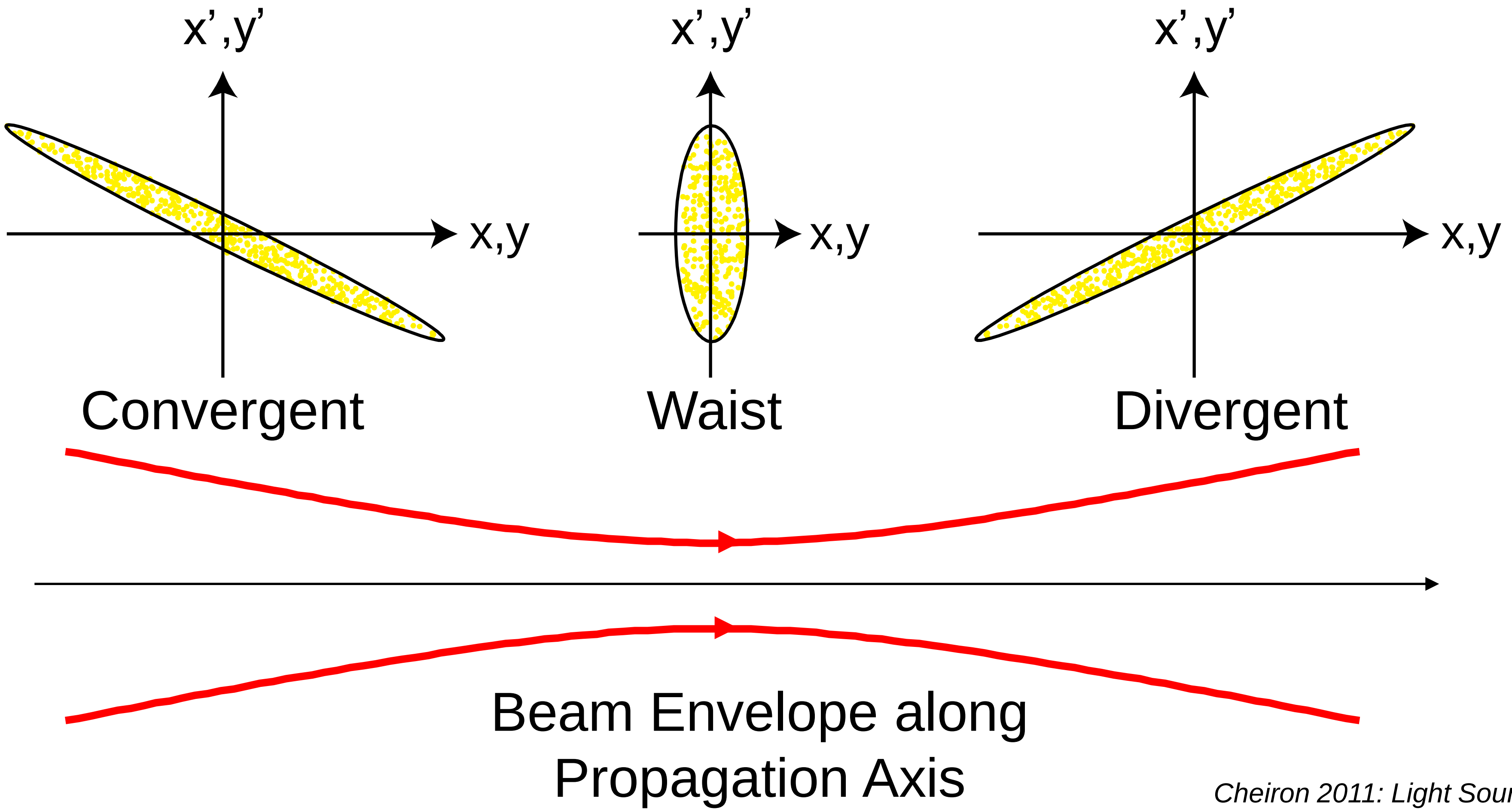
- Removing all the slits gives the total power (W), i.e.,

$$P = 10^3 Q_e \hbar \iiint \frac{d^2F}{dx'dy'} d\omega dx' dy'$$

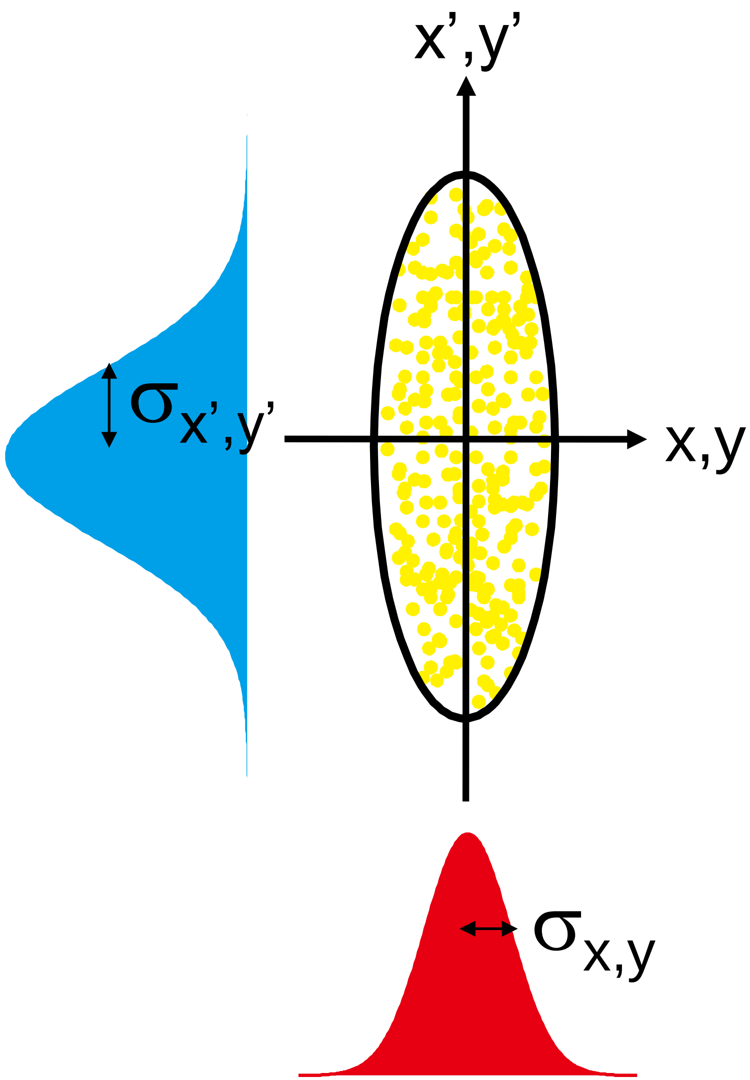
- Estimation of heat load on BL components.

Photons in 4D Phase Space

- Photon distribution in the 4-D phase space at different longitudinal positions.



Beam Size, Divergence, Emittance



- Beam size ($\sigma_{x,y}$) is defined as the beam envelope at the beam waist position.
- Angular divergence ($\sigma_{x',y'}$) is constant along the axis of propagation, as far as no optical elements are present.
- Emittance (ε_x,ε_y) is defined as $\sigma_{x,y} \times \sigma_{x',y'}$, which is equal to the area of the phase ellipse divided by π.

Fundamentals of Light and SR

- Why we need SR?
- Physical Quantity of Light
- Uncertainty of Light
- SR: Light from a Moving Electron

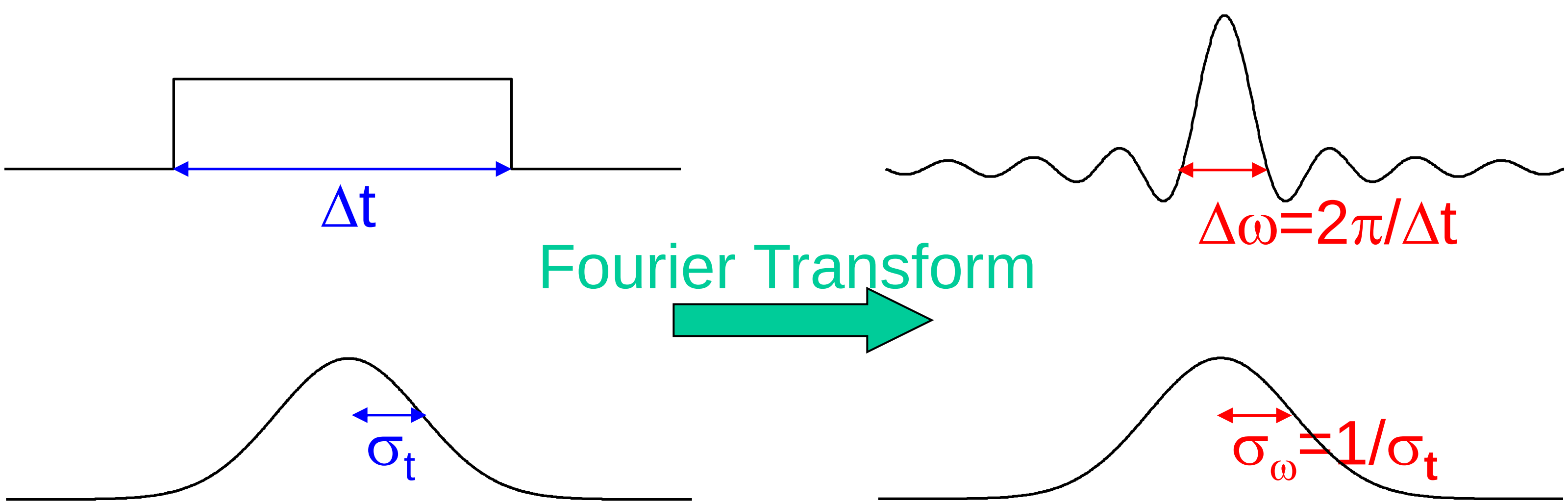
Uncertainty of Light

- The photon distribution in the 6D phase space (x,y,x',y',t,ω) gives us the full information on the properties of SR.
- Due to wave nature of light, however, we have two uncertainty relations to take care, which are well characterized by the Fourier transform.
- These relations imposes two restrictions on SR, Fourier and Diffraction limits.

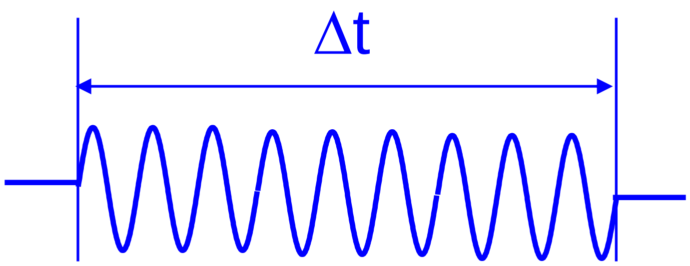
Fourier Transform: Example

Important Fourier Transform in SR Formulae

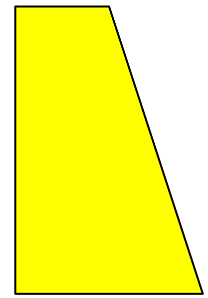
$F(t)$	$f(\omega) = \int_{-\infty}^{\infty} F(t) \mathrm{e}^{i\omega t}$
$\begin{cases} 1/\Delta t; & -\Delta t/2 \le t \le \Delta t/2 \\ 0; & t < -\Delta t/2, \Delta t/2 < t \end{cases}$	$\dfrac{\sin \omega \Delta t/2}{\omega \Delta t/2} \equiv \mathrm{sinc}(\omega \Delta t/2)$
$\dfrac{1}{\sqrt{2\pi}\sigma_t} \exp\left(-\dfrac{t^2}{2\sigma_t^2}\right)$	$\exp\left(-\dfrac{\omega^2 \sigma_t^2}{2}\right)$

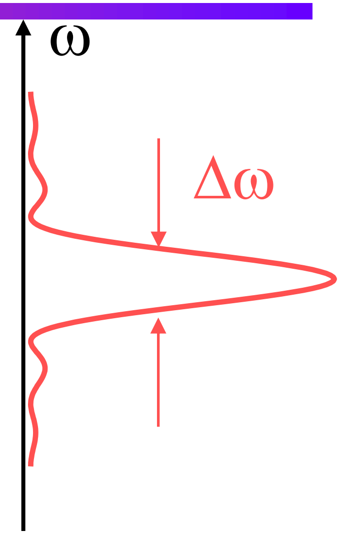


Temporal Fourier Transform

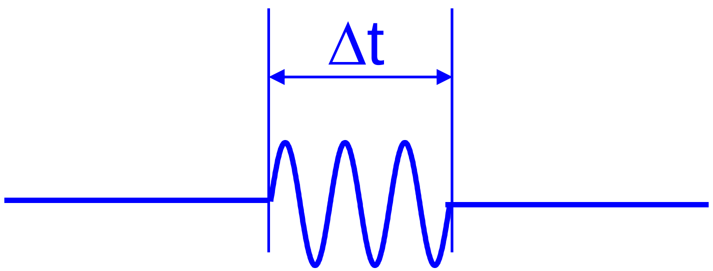


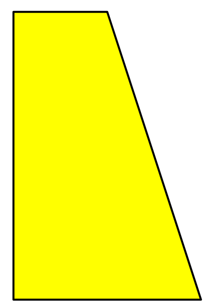
Light with a finite
time duration of Δt

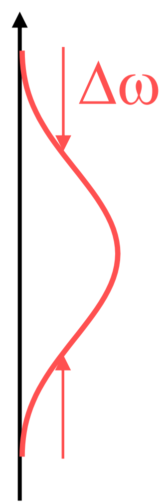




spectrometer =
temporal Fourier transform







If the light is monochromatic,
then $\Delta\omega\Delta t$=const.

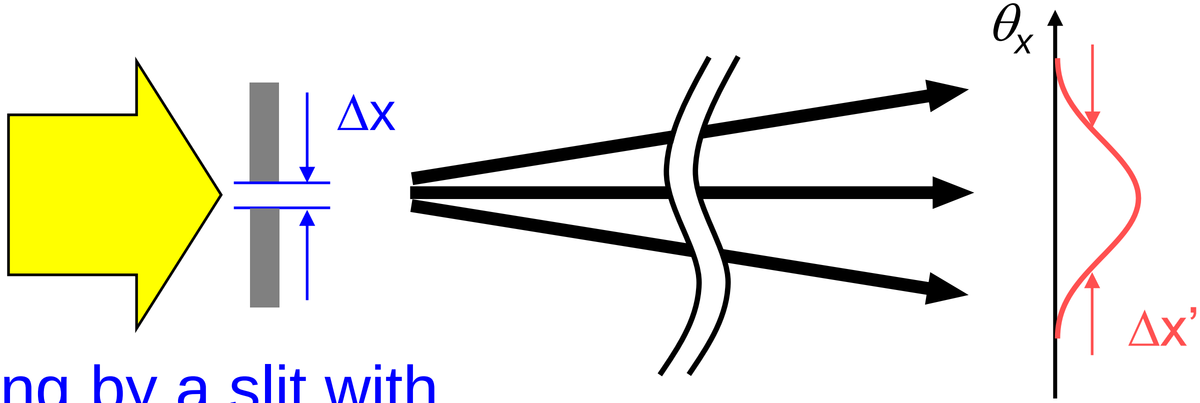
Fourier Limit of Light

- Temporal Fourier transform imposes

$$\Delta\omega\Delta t \geq \mathrm{const.}$$

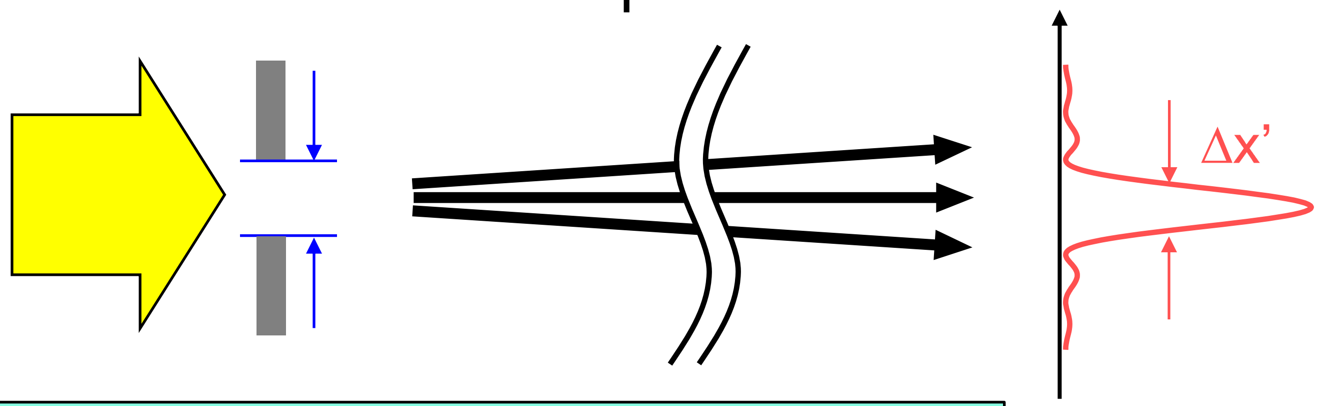
- Uncertainty of light in the (ω,t) plane.
- When equality holds, light is said to be
  - Fourier-limited
  - Temporally coherent
- Important to understand the spectral properties of SR.

Spatial Fourier Transform



Clipping by a slit with a finite width of Δx

diffraction pattern in the far region
= spatial Fourier transform



If the injected light is a plane wave, then ΔxΔx’=const.

Diffraction Limit of Light

- Spatial Fourier transform imposes

$$\Delta x \Delta k_x \geq \text{const.}$$

$$\xrightarrow{k_x=(2\pi/\lambda)x'} \Delta x \Delta x' \geq \lambda \times \text{const.}$$

- Uncertainty of light in (x,x') plane
- When equality holds, light is said to be
  - Diffraction limited
  - Spatially coherent
- In the case of Gaussian beam,

$$\sigma_x \sigma_{x'} \geq \boxed{\lambda/(4\pi)}$$

Natural emittance of light

Fundamentals of Light and SR

- Why we need SR?
- Physical Quantity of Light
- Uncertainty of Light
- SR: Light from a Moving Electron

SR: Light from a Moving Electron

- Unlike the ordinary light source (sun, light bulb,...), the light emitter of SR (electron) is ultra-relativistic.
- The characteristics of SR is thus quite different due to relativistic effects.
- What we have to take care is:
  1. Speed-of-light limit
  2. Squeezing of light pulse
  3. Conversion of the emission angles

Speed-of-Light Limit

Within the framework of relativity, the velocity of an electron never exceeds the speed of light.

$$v/c = \beta = \sqrt{1-\gamma^{-2}}$$
$$\sim 1 - \frac{1}{2\gamma^2}$$

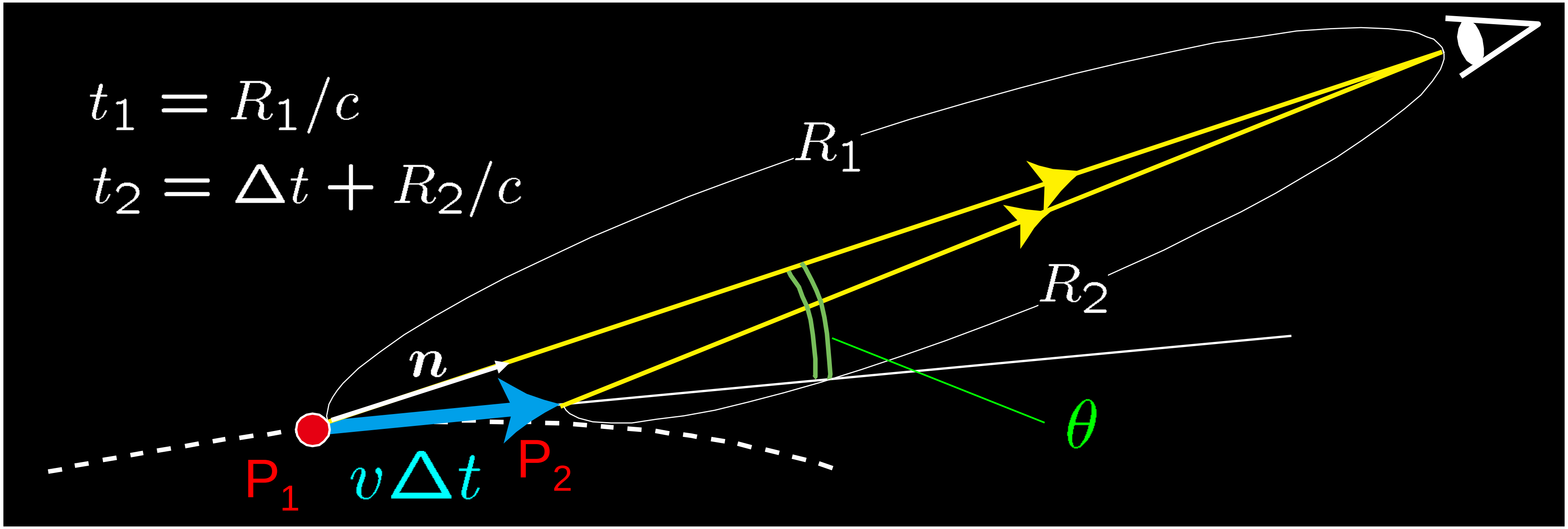
Energy	β
1MeV	0.941
10MeV	0.9988
100MeV	0.999987
8GeV	0.999999998

$$\gamma = \frac{E}{mc^2}$$

:Lorentz Factor

(relative electron energy, mc^2=0.511MeV)

Squeezing of Light Pulse Duration

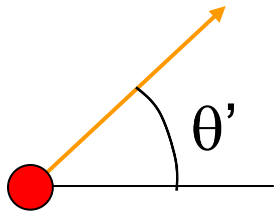


$$
\begin{aligned}
R_2 &= \sqrt{(R_1)^2 + (v\Delta t)^2 - 2R_1 v\Delta t\cos\theta} \\
&\sim R_1 - (\boldsymbol{v}\cdot\boldsymbol{n})\Delta t \\
\Delta\tau &= t_2 - t_1 = \Delta t + R_2/c - R_1/c \\
&= \Delta t\,\boxed{(1-\boldsymbol{\beta}\cdot\boldsymbol{n})} = \boxed{\frac{\Delta t}{2\gamma^2}}
\end{aligned}
$$

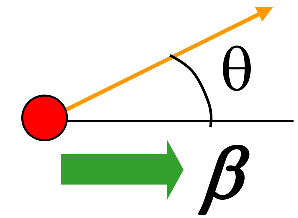
$\gamma \gg 1, \theta = 0$

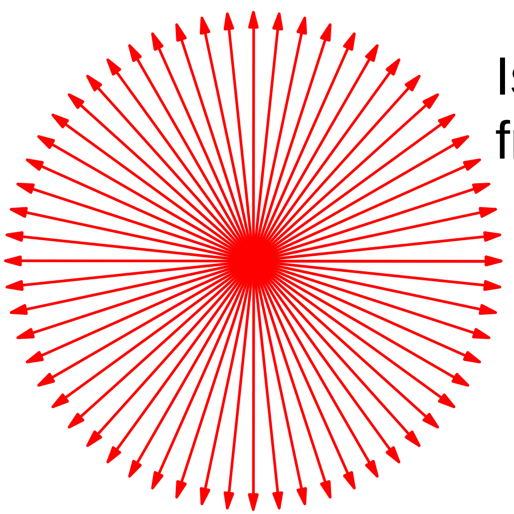
time squeezing

Conversion of Emission Angles



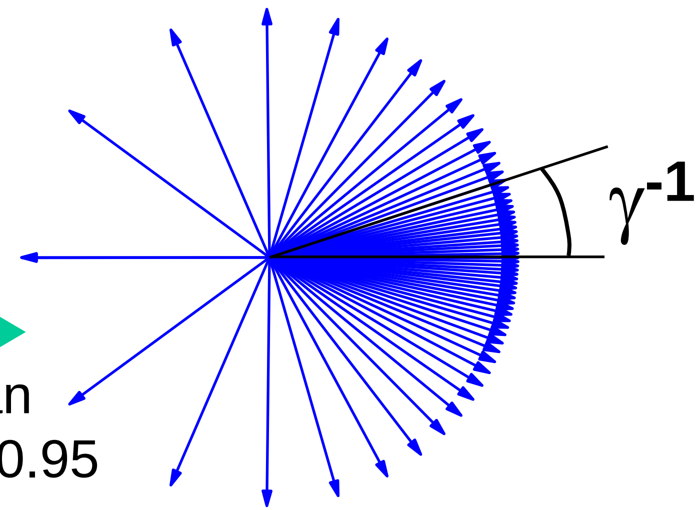
$$\theta = \tan^{-1}\left(\frac{\gamma^{-1}\sin\theta'}{\beta + \cos\theta'}\right)$$





Isotropic emission from a rest electron

Emission from an electron with β=0.95



Light emitted from a moving object (β~1) concentrates within γ^{-1}

SR from a High-Energy Electron

High energy electron

$$\beta \sim 1 = 1 - \frac{1}{2\gamma^2}$$

Large Time Squeezing

Short Wavelength

$$\theta \leq \gamma^{-1} \ll 1$$

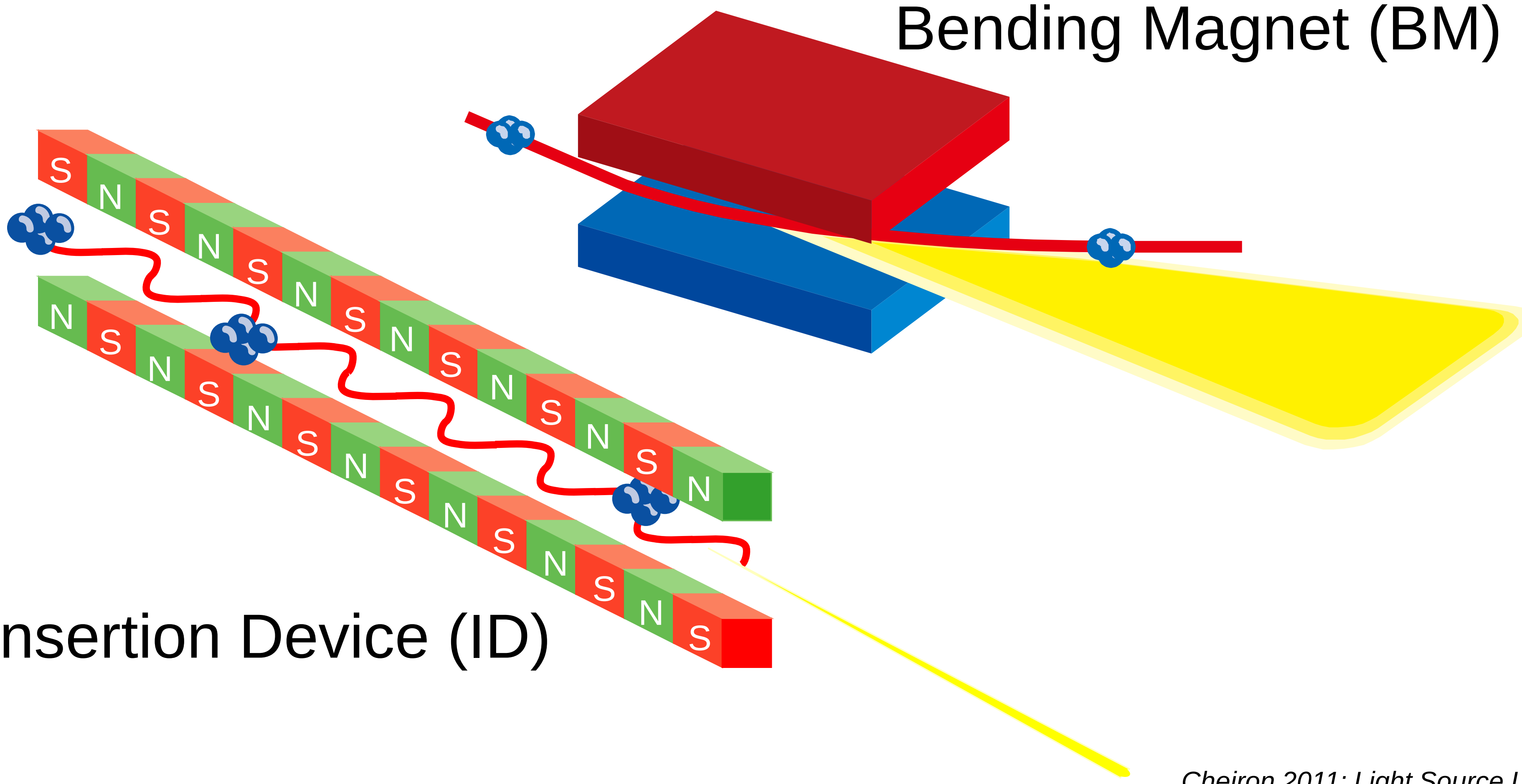
Radiation in the Forward Direction

High Directivity

Overview of SR Light Source

What is SR Light Source?

Magnets to deflect the electron beam and generate SR.



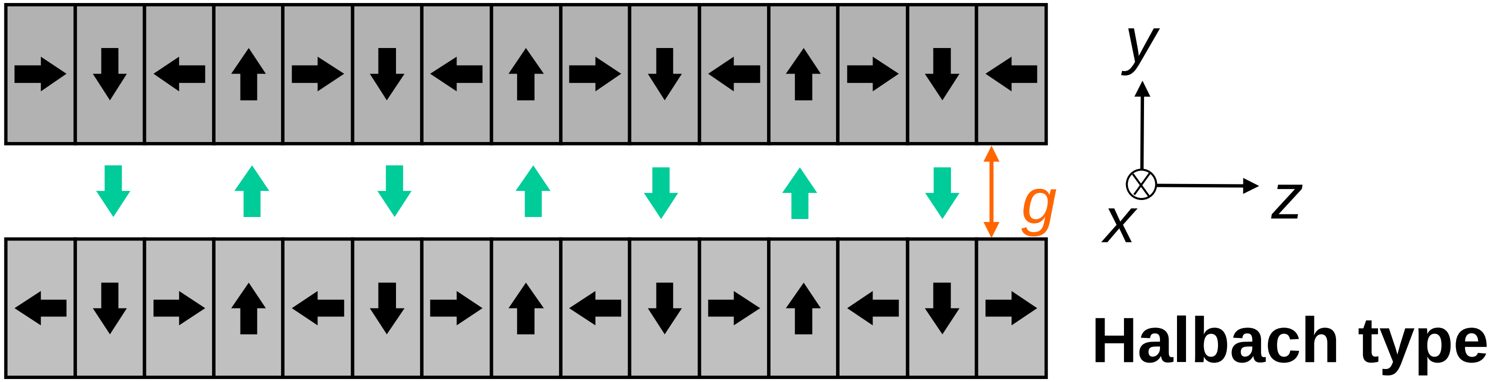
Bending Magnet

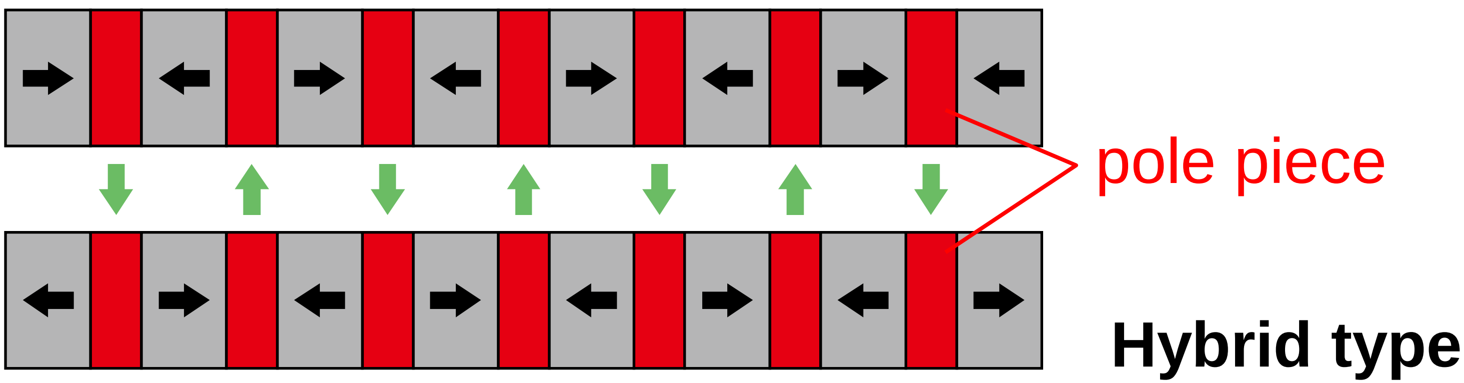
- One of the accelerator components in the storage ring.
- Generate uniform field to guide the electron beam into a circular orbit.
- EMs combined with highly-stable power supplies are adopted in most BMs due to stringent requirement on field quality and stability.
- Superconducting magnets are used in a few facilities in pursuit of harder x rays.

Insertion Device

- Installed (inserted) into the straight section of the storage ring between two adjacent BMs.
- Generate a periodic magnetic field to let the injected electron beam move along a periodic trajectory.
- Most IDs are composed of PMs, while EMs are used for special use such as helicity switching.
- Classified into wigglers and undulators.

Magnetic Circuit of IDs



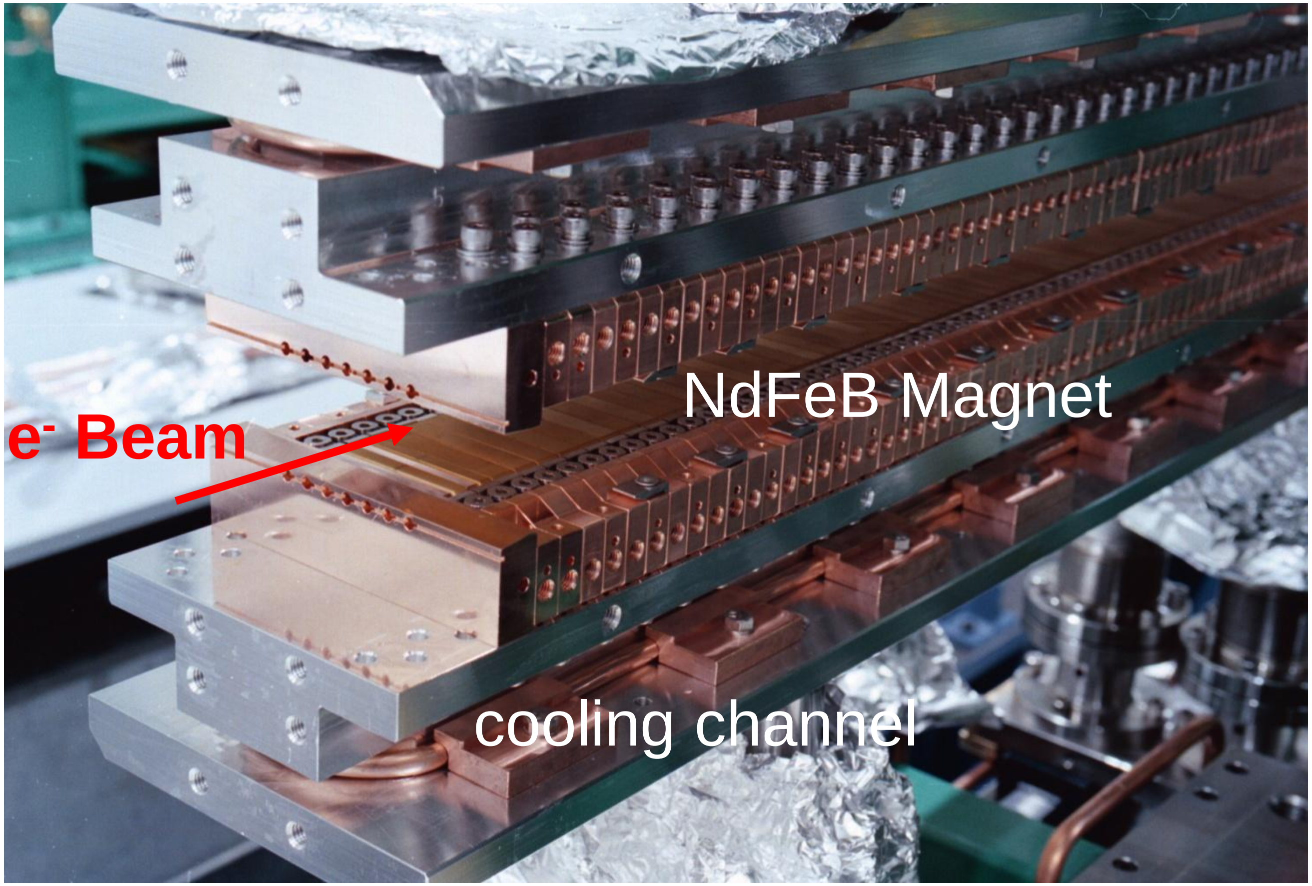


In each type, a sinusoidal magnetic field is obtained:

$$B_y(z) \sim B_0(B_r, g/\lambda_u) \sin\left(\frac{2\pi z}{\lambda_u}\right)$$

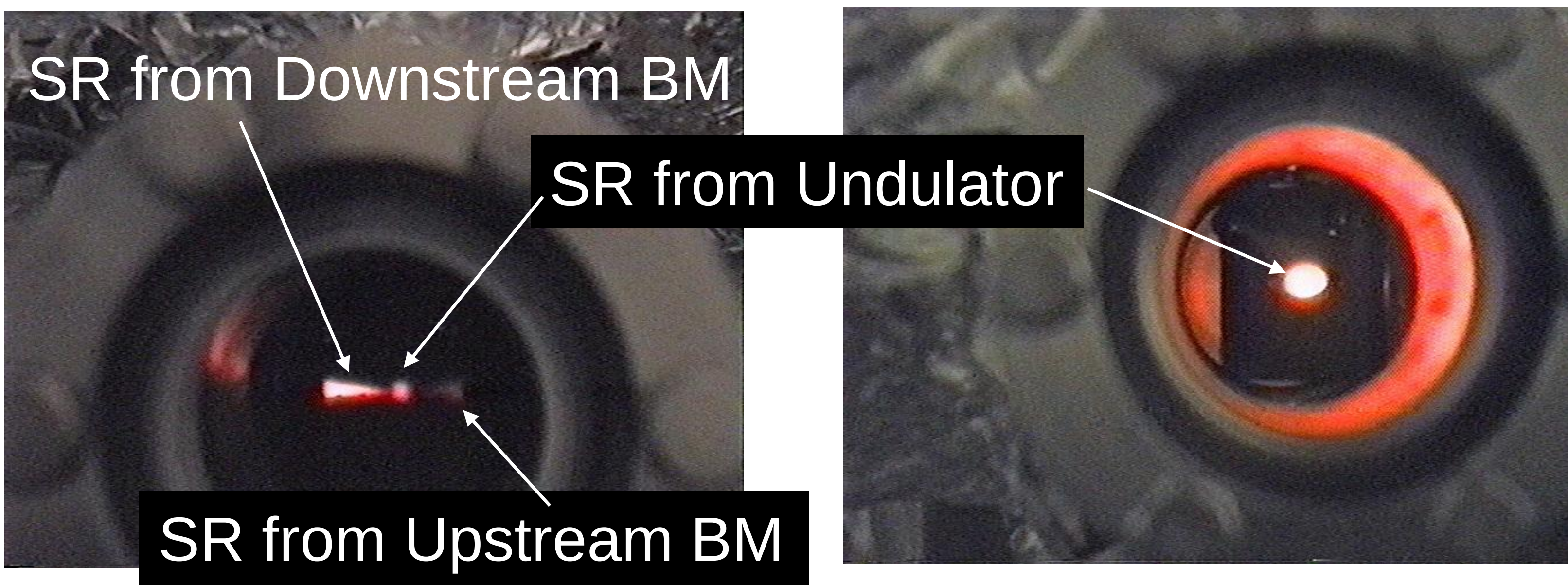
Example of ID Magnets

Halbach-type Magnet Array for SPring-8 Standard Undulators



Example of SR Image

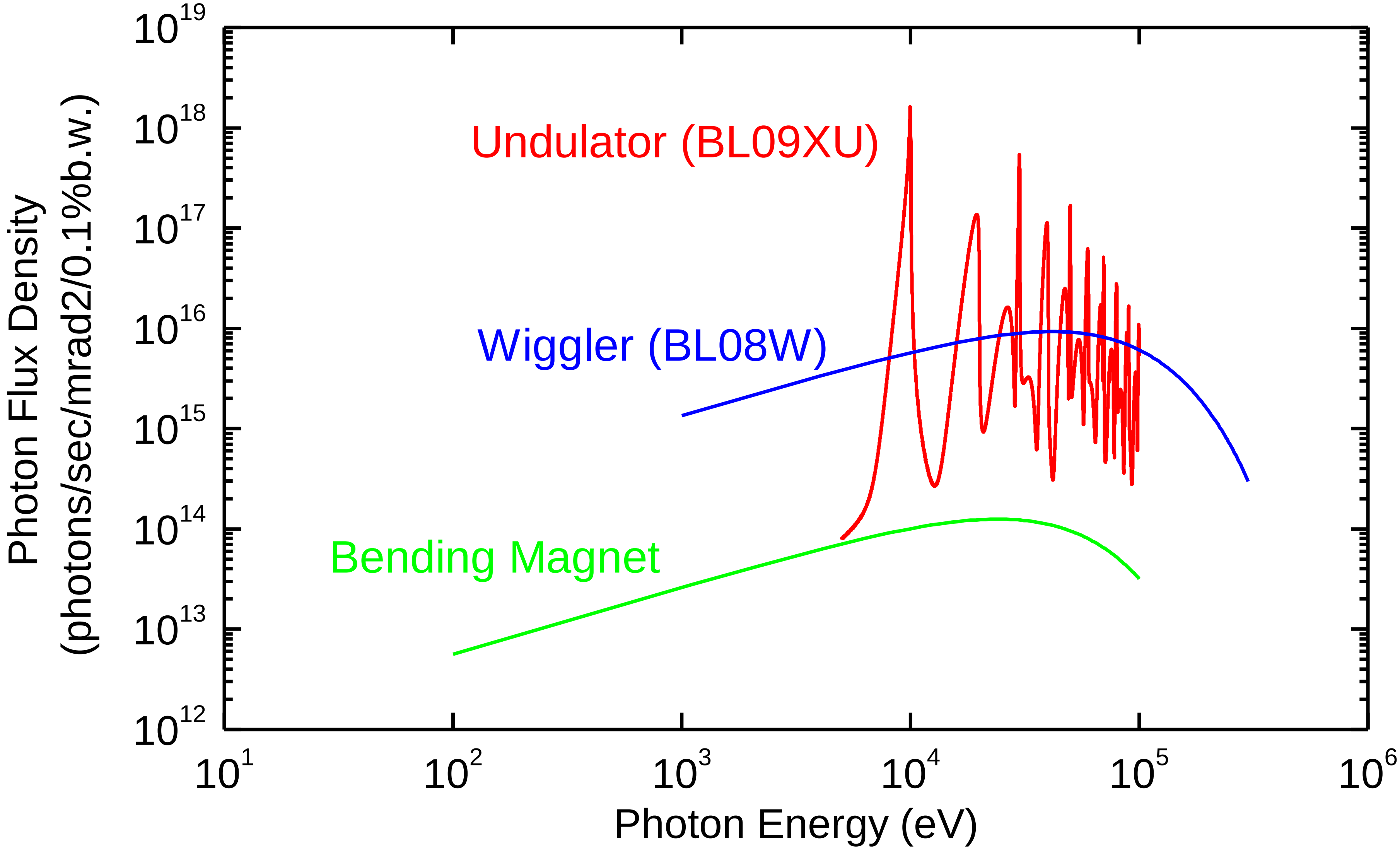
BL47XU@SP-8, first image of SR
with a fluorescent screen (<0.1mA)



Undulator Gap = 50 mm

Undulator Gap = 20 mm

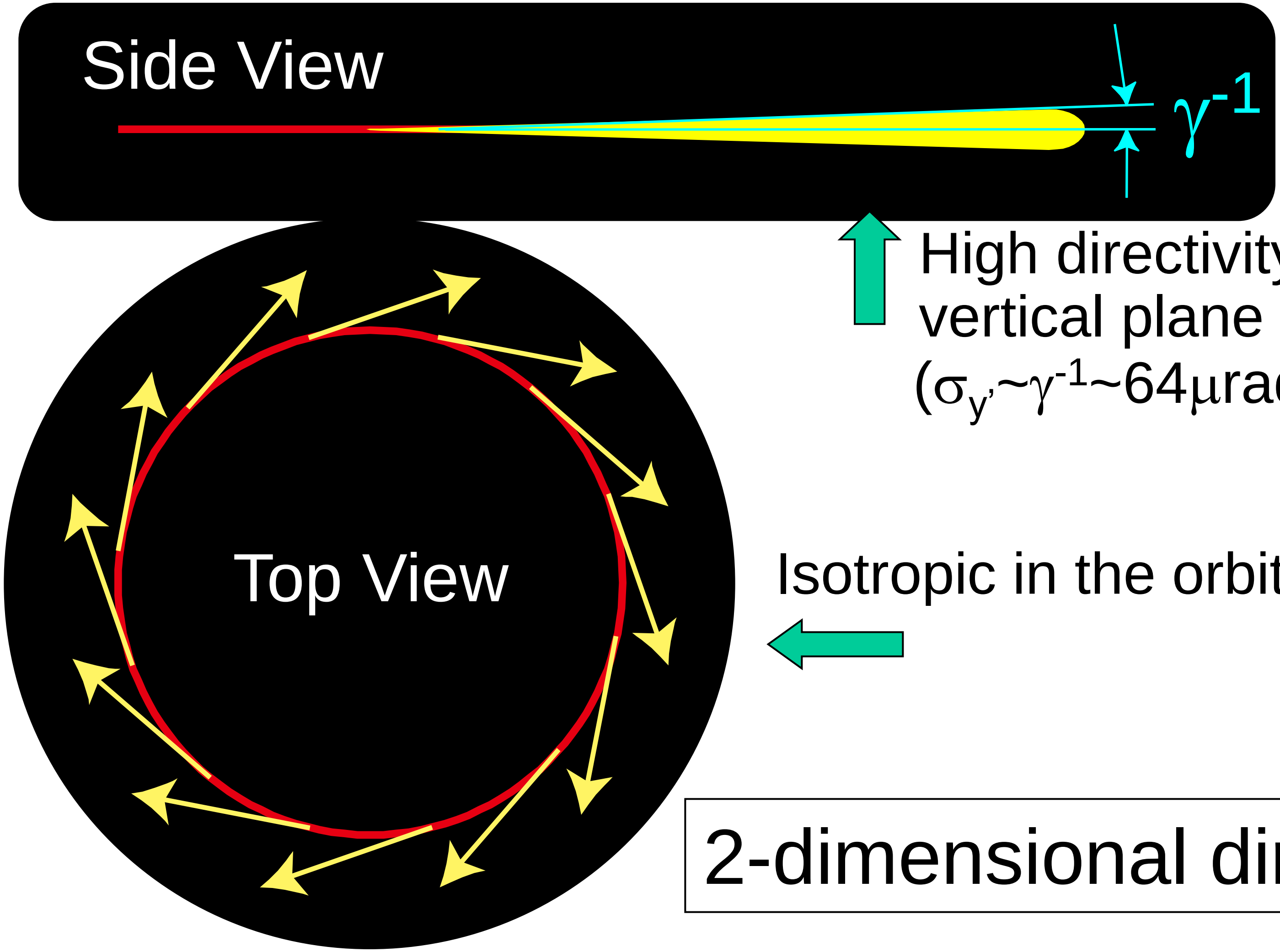
Comparison of Light Sources



Characteristics of SR (1)

- Radiation from BMs

Directivity of BM Radiation

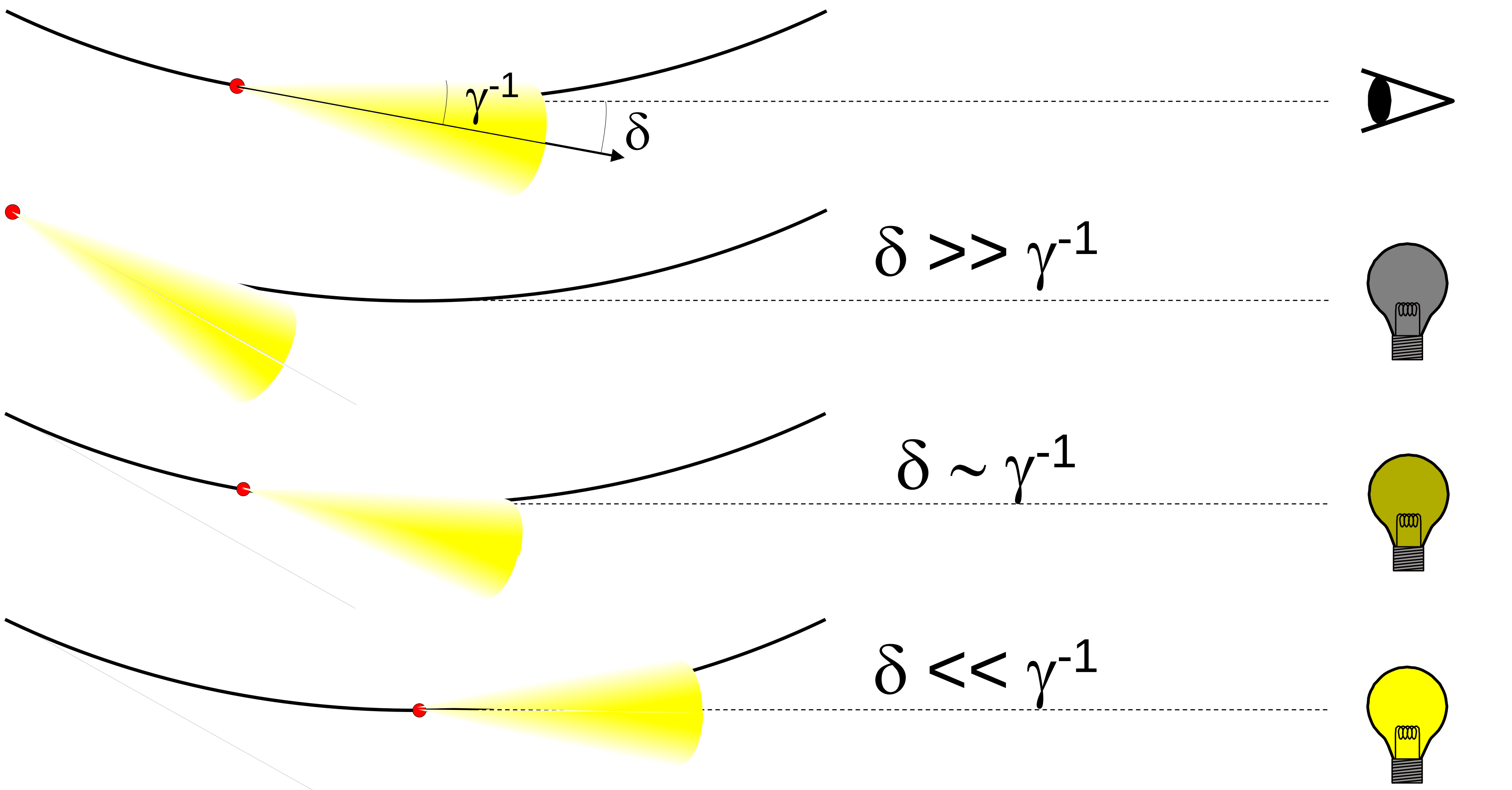


High directivity in the vertical plane ($\sigma_{y'} \sim \gamma^{-1} \sim 64\mu rad$@SP-8)

Isotropic in the orbital plane

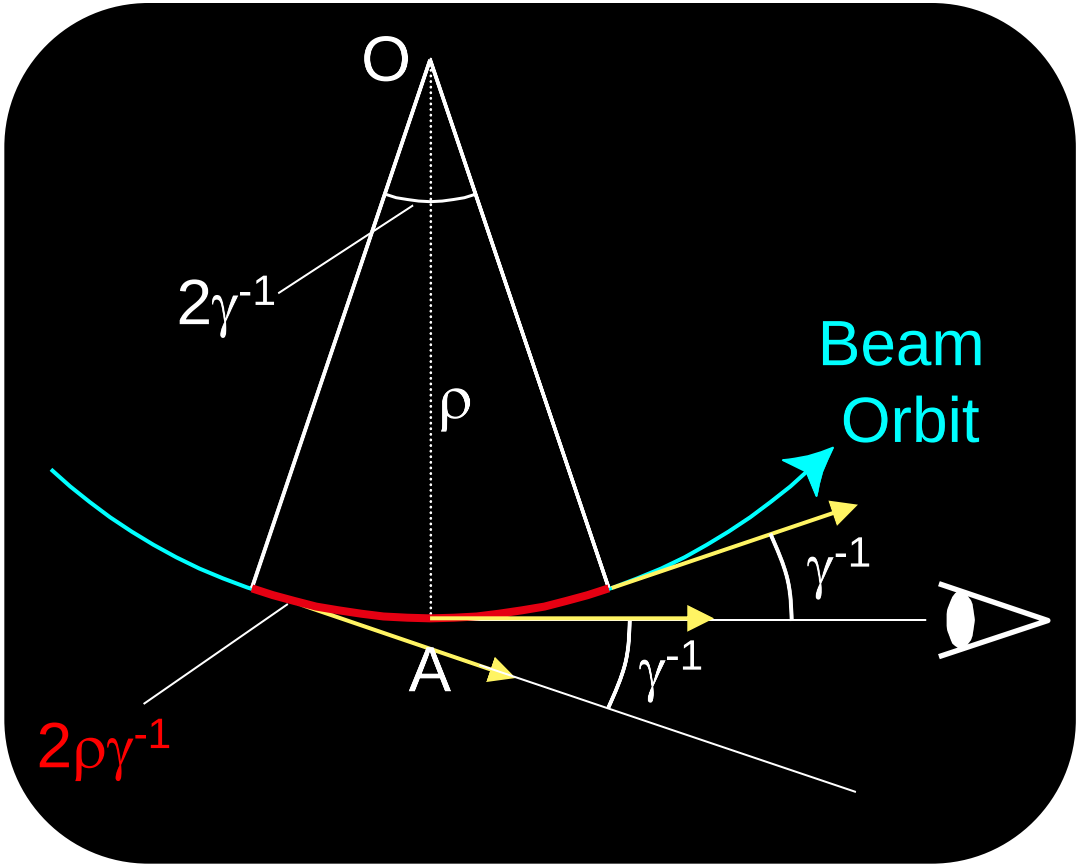
2-dimensional directivity

Spectrum of BM Radiation (1)



Photons emitted when $\delta<\gamma^{-1}$ are detected by the observer

Spectrum of BM Radiation (2)



Major contribution of radiation is from the portion painted red

Pulse duration for e⁻

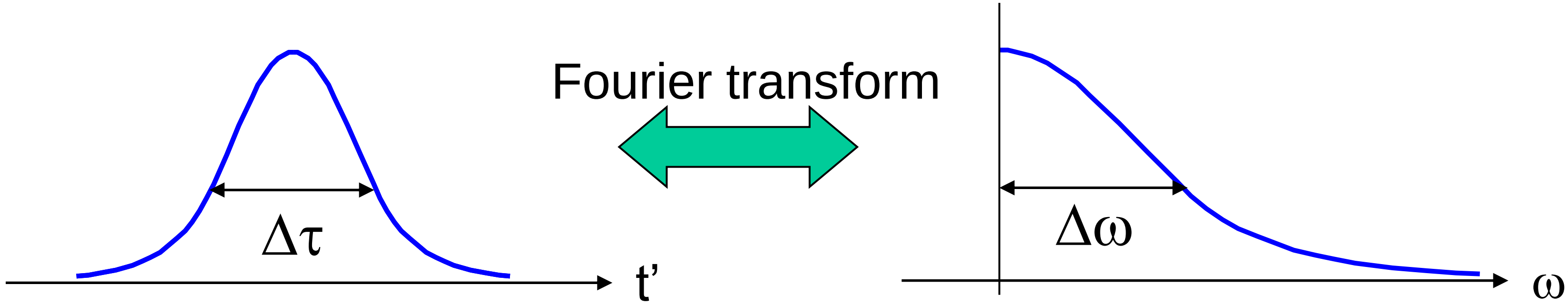
$$\Delta t = 2\rho\gamma^{-1}/c$$

squeezing

Pulse duration for observer

$$\Delta\tau = \frac{\Delta t}{2\gamma^2} = \frac{\rho}{\gamma^3 c}$$

Spectrum of BM Radiation (3)



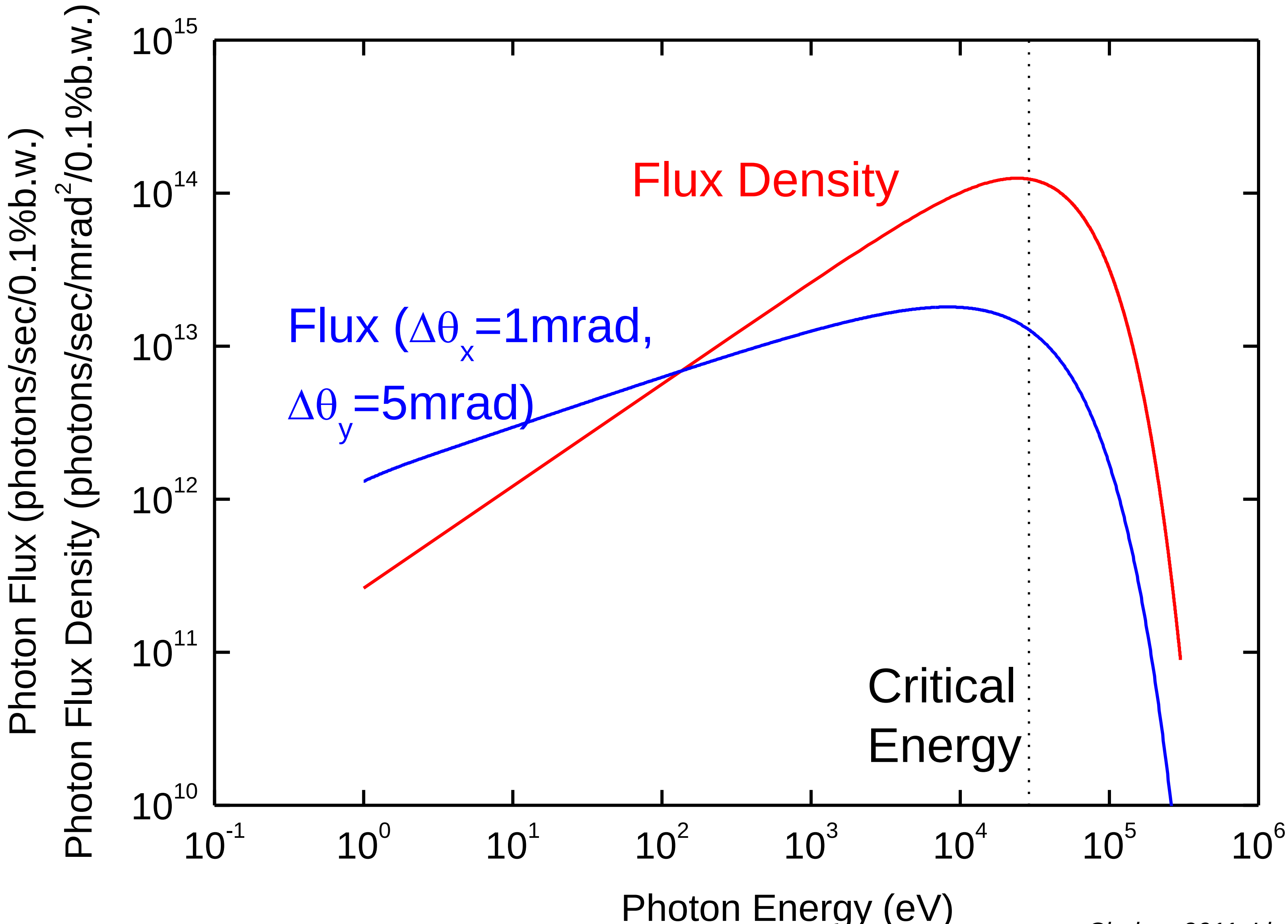
Light pulse with duration of $\Delta\tau$

White spectrum up to $\omega \sim \Delta\omega \sim 1/\Delta\tau$

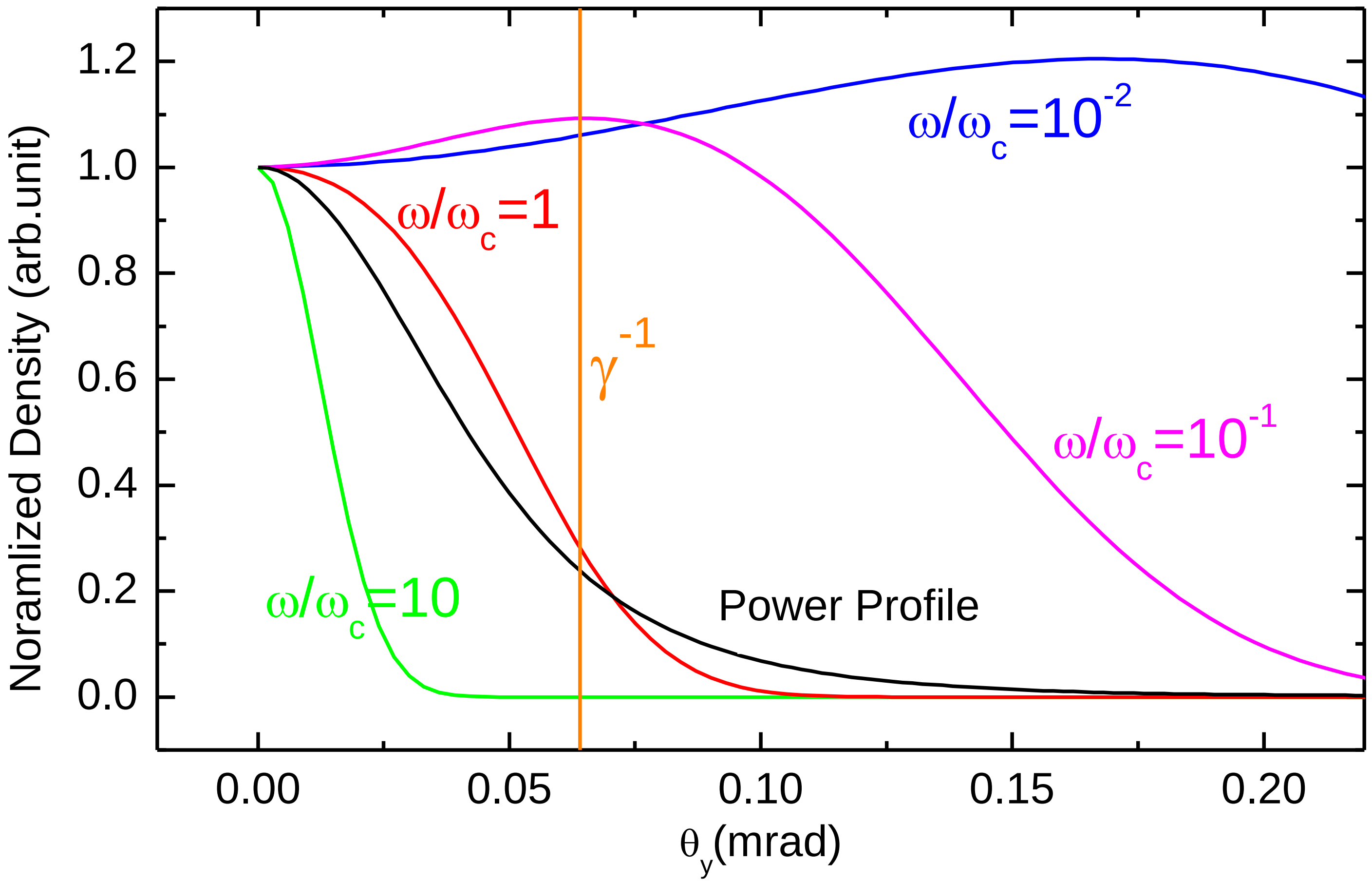
- By definition, $\omega_c = (3/2)/\Delta\tau = 3\gamma^3 c/2\rho$ is called "critical frequency" of SR, which gives a criterion of the maximum energy of SR from a BM.
- In practical units,

$$\hbar\omega_c(\text{keV}) = 0.665 E_e^2(\text{GeV}) B(\text{T})$$

Example of Spectrum



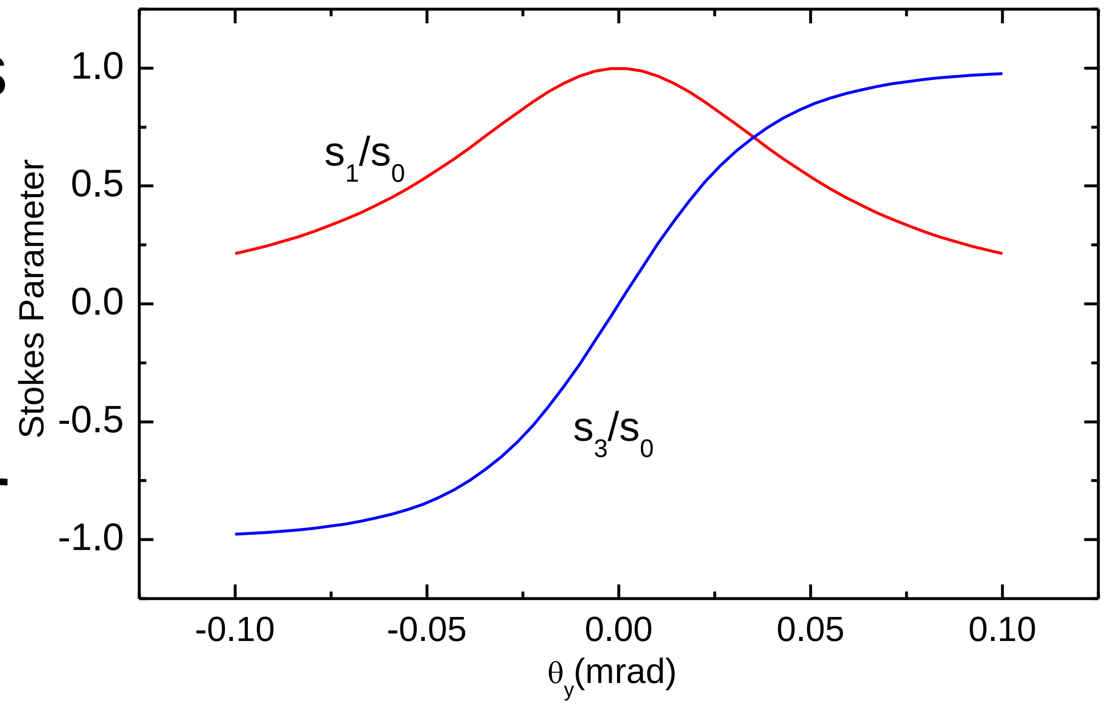
Angular Profile of BM Radiation

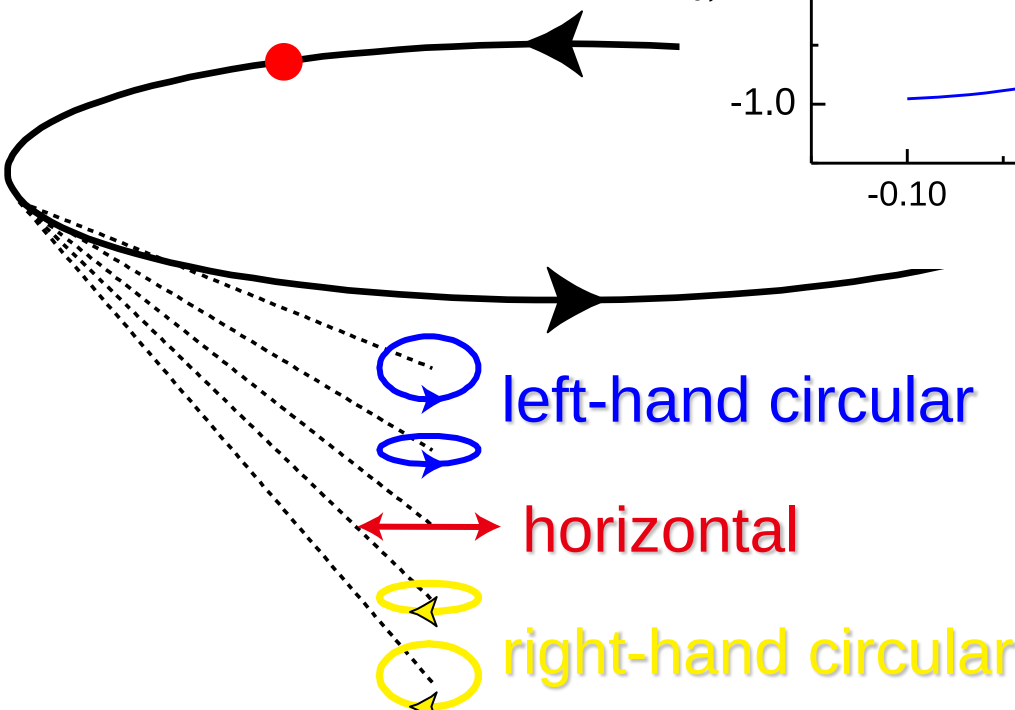


- power profile ~ flux profile@ω/ω_c=1
- larger angular divergence for lower energy

Polarization of BM Radiation

Stokes parameters of BM radiation along vertical axis





Polarization state reflects the apparent motion of electron.