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From laser-driven x-ray sources to efficient gamma-ray sources

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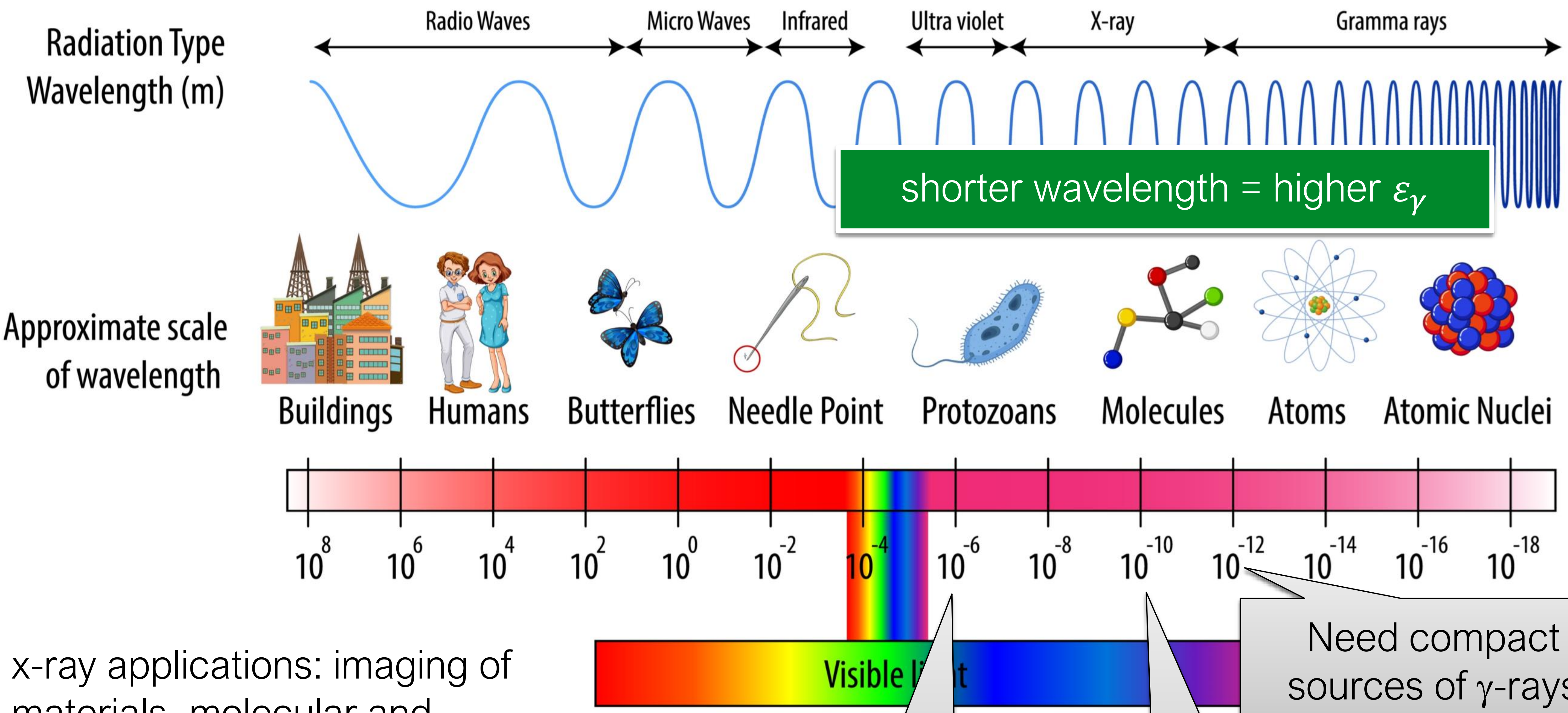
Electromagnetic spectrum



shorter wavelength = higher ε_γ

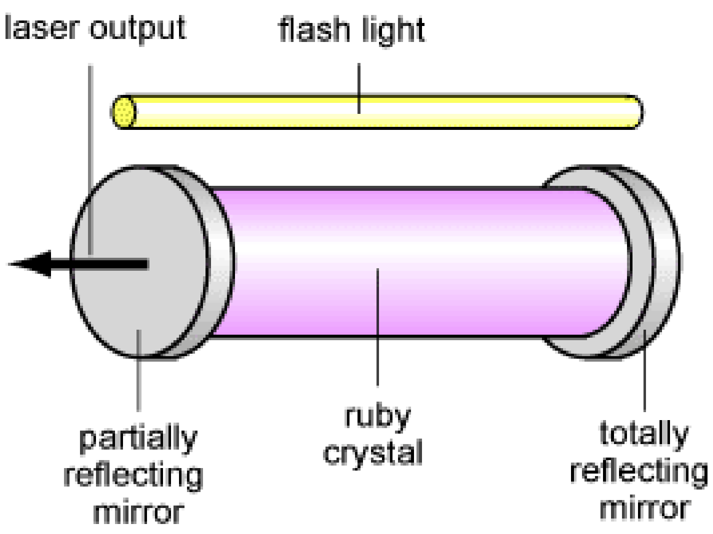
Need compact sources of γ-rays 100 keV – multi-MeV

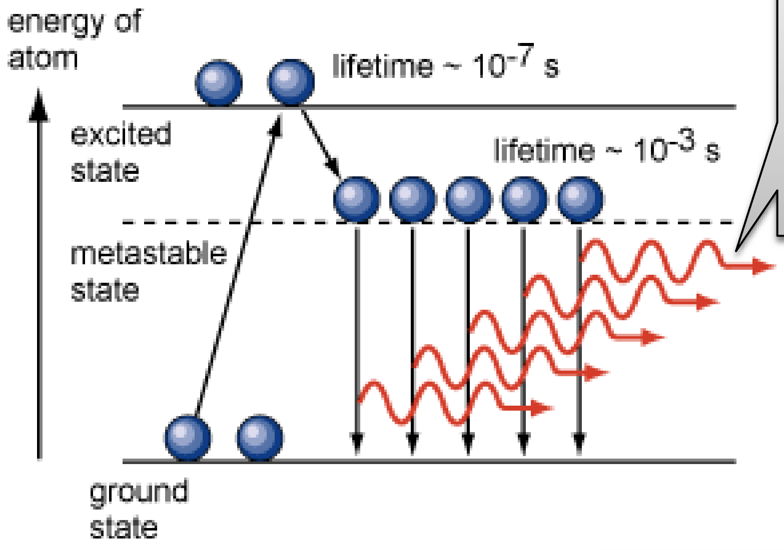
Optical laser
$\lambda \sim 1\ \mu\text{m}$
$\varepsilon_\gamma \sim 1\ \text{eV}$

XFEL
$\varepsilon_\gamma \sim 10\ \text{keV}$

- x-ray applications: imaging of materials, molecular and ultrafast studies
- γ-rays can be used for imaging high-z materials, nuclear physics

Optical laser vs XFEL





Optical laser
$\varepsilon_\gamma \sim 1\ \mathrm{eV}$

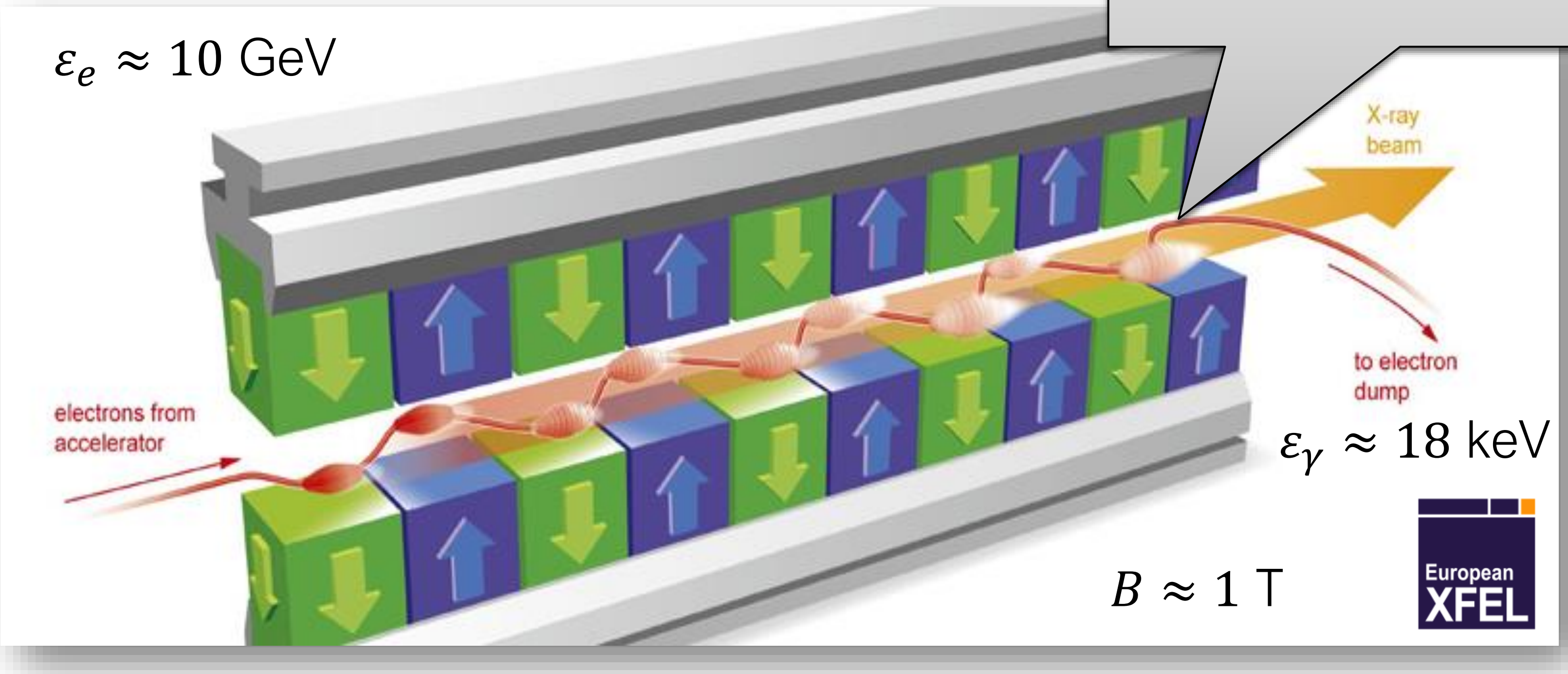
Emission caused by electron deflection

$$\varepsilon_\gamma / \varepsilon_e \approx 1.5\chi_e$$

$$\varepsilon_e = \gamma m c^2$$

$$\chi_e \approx \frac{\gamma B}{B_c}$$

$$B_c \approx 4.4 \times 10^9\ \mathrm{T}$$



$\varepsilon_e \approx 10$ GeV

$\varepsilon_\gamma \approx 18$ keV

$B \approx 1$ T

Options for scalability towards γ-rays

- Conventional B-fields are limited to several T.

- Increasing ε_e is the only option for reaching higher ε_γ:
  - $\varepsilon_e = 10$ GeV → $\varepsilon_\gamma \approx 18$ keV
  - $\varepsilon_e = 100$ GeV → $\varepsilon_\gamma \approx 1.8$ MeV

- Alternative: use laser or quasi-static laser-driven plasma fields.

- These fields are much stronger than the static fields and thus offer a promising solution for generation of hard x-rays and γ-rays.

$$\varepsilon_\gamma / \varepsilon_e \approx 0.4\chi_e \qquad \chi_e \approx \frac{\gamma B}{B_c} \qquad B_c \approx 4.4 \times 10^9 \text{ T}$$

Objectives & Outline

- Objectives:
  - provide a qualitative picture of electromagnetic emission by energetic electrons in strong laser and plasma fields
  - provide a framework that can be used to understand current research
- Outline:
  - review the fundamentals of emission by relativistic electrons
  - introduce basic setups for laser-driven x-ray sources
  - introduce a basic setup for a laser-driven gamma-ray source

Dipole emission

- Constant velocity = no radiation.

- Acceleration (w) causes a non-relativistic electron to emit electromagnetic waves:

Power

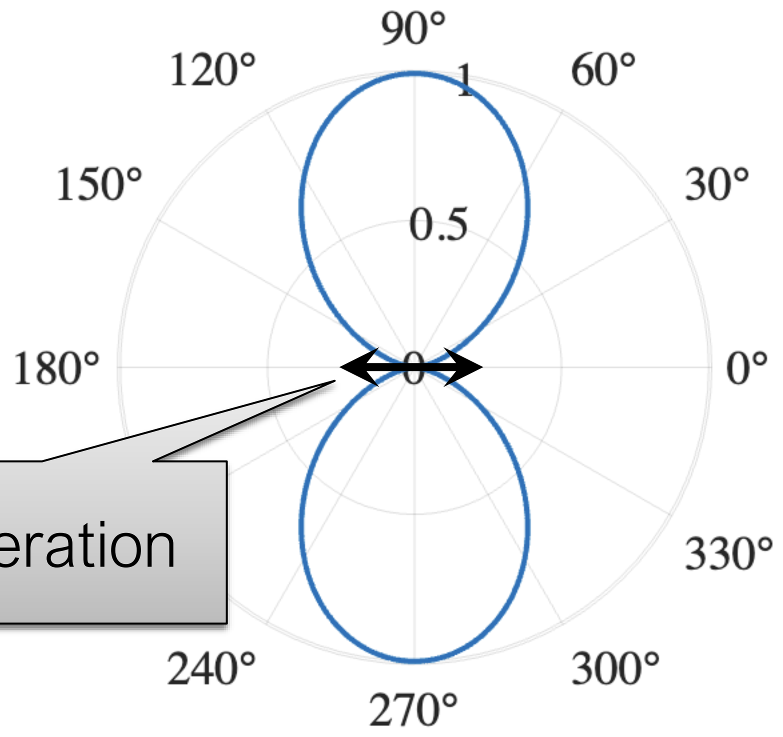
$$P = \frac{2}{3}\frac{e^2}{c^3}|\vec{w}|^2$$

$$|\vec{w}|^2 = \frac{e^2}{m^2}\left|\vec{E} + \frac{1}{c}[\vec{v} \times \vec{B}]\right|^2$$

- Angular dependence the emitted power:

$$\frac{dP}{d\Omega} = \frac{3P}{8\pi}\sin^2\theta$$

Polar angle with respect to $\vec{w}$



Acceleration

Emission by relativistic electron

- Instantaneous rest frame: nonrelativistic motion ⟶ dipole emission

- Lab frame: emission is determined by the acceleration in the instantaneous rest frame ($v_{rest} = 0$)

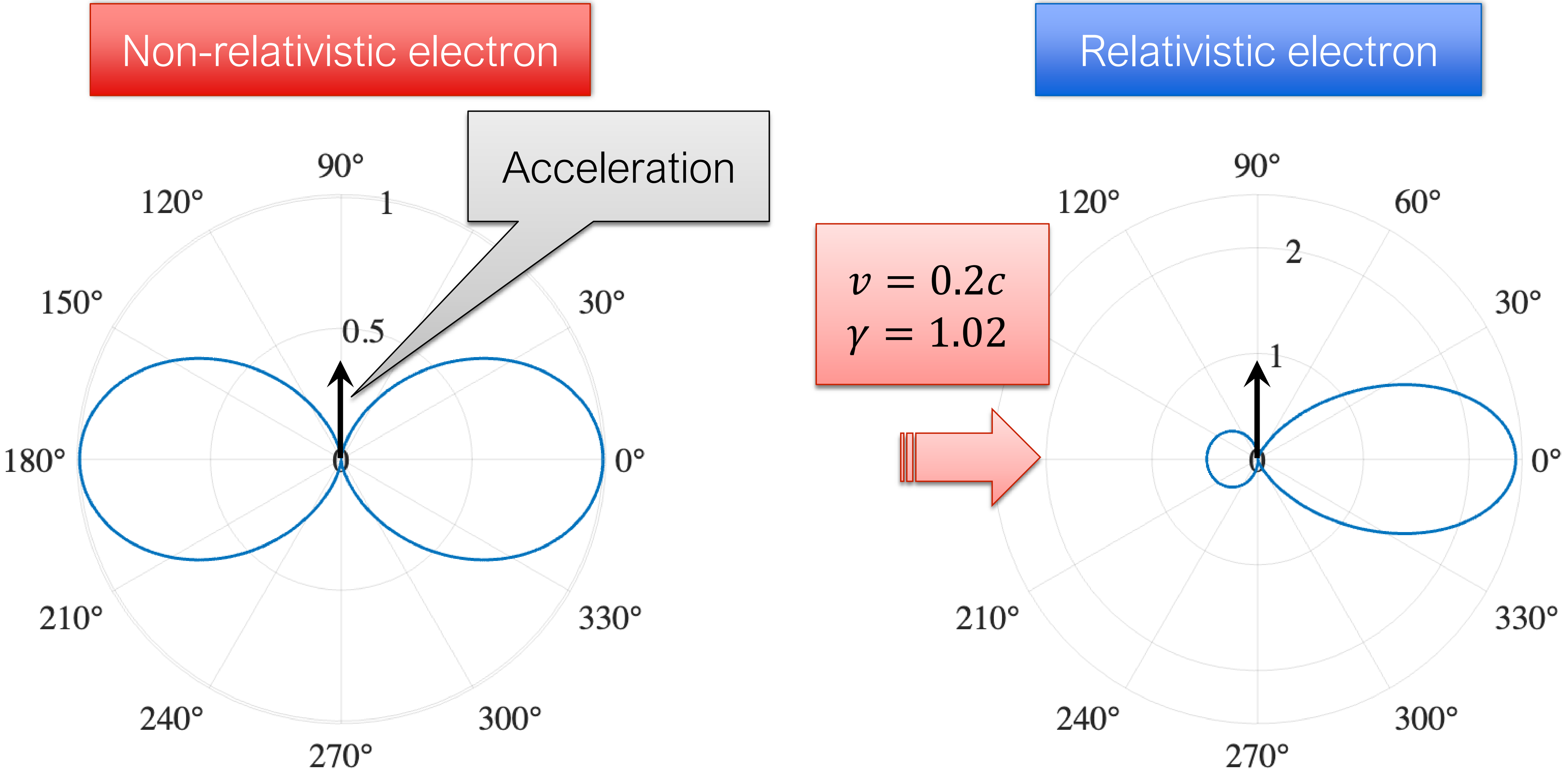
$$P = \frac{2}{3}\frac{e^2}{c^3}|\vec{w}_{rest}|^2 = \frac{2}{3}\frac{e^4}{m^2c^3}\left(\left|\vec{E}_{\parallel rest}\right|^2 + \left|\vec{E}_{\perp rest}\right|^2\right)$$

- Transverse acceleration of a relativistic electron can be greatly enhanced because of the field enhancement:

$$\vec{E}_{\perp rest} = \gamma\left(\vec{E}_\perp + \frac{1}{c}[\vec{v} \times \vec{B}]\right) \qquad \vec{E}_{\parallel rest} = \vec{E}_\parallel$$

- Transverse acceleration is more effective in inducing emission of ultra-relativistic electrons.

Change in emission pattern



Non-relativistic electron

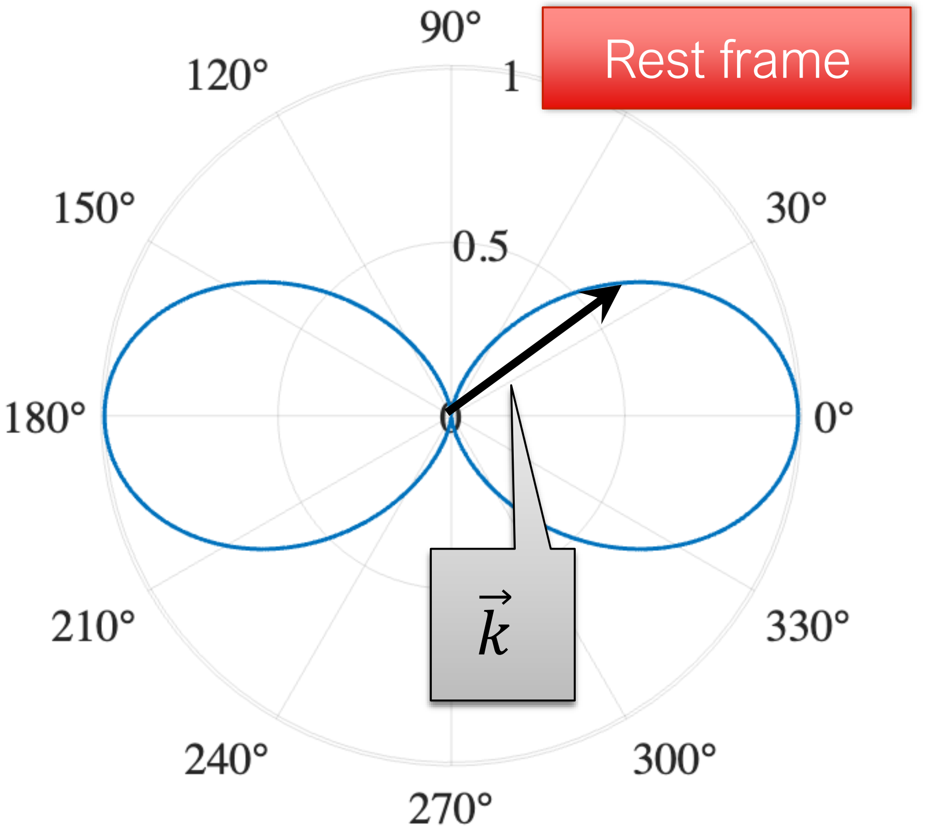
Acceleration

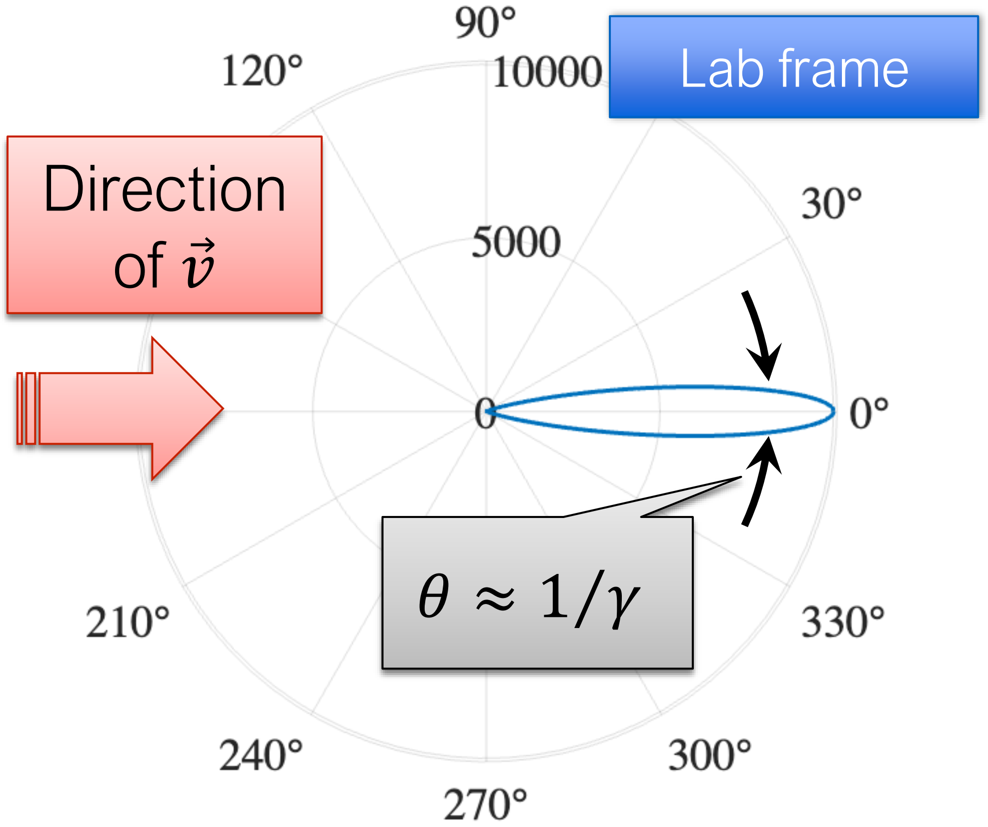
Relativistic electron

$v = 0.2c$
$\gamma = 1.02$

- Amplitude of the forward wave seen by an observer is stronger by a factor of γ^4.
- The emission becomes forward-directed.

Emission cone





- **Rest frame:** wide angle emission with $k_\perp \sim k_\parallel$

- Lorentz transform to the lab frame for the forward emitted wave:

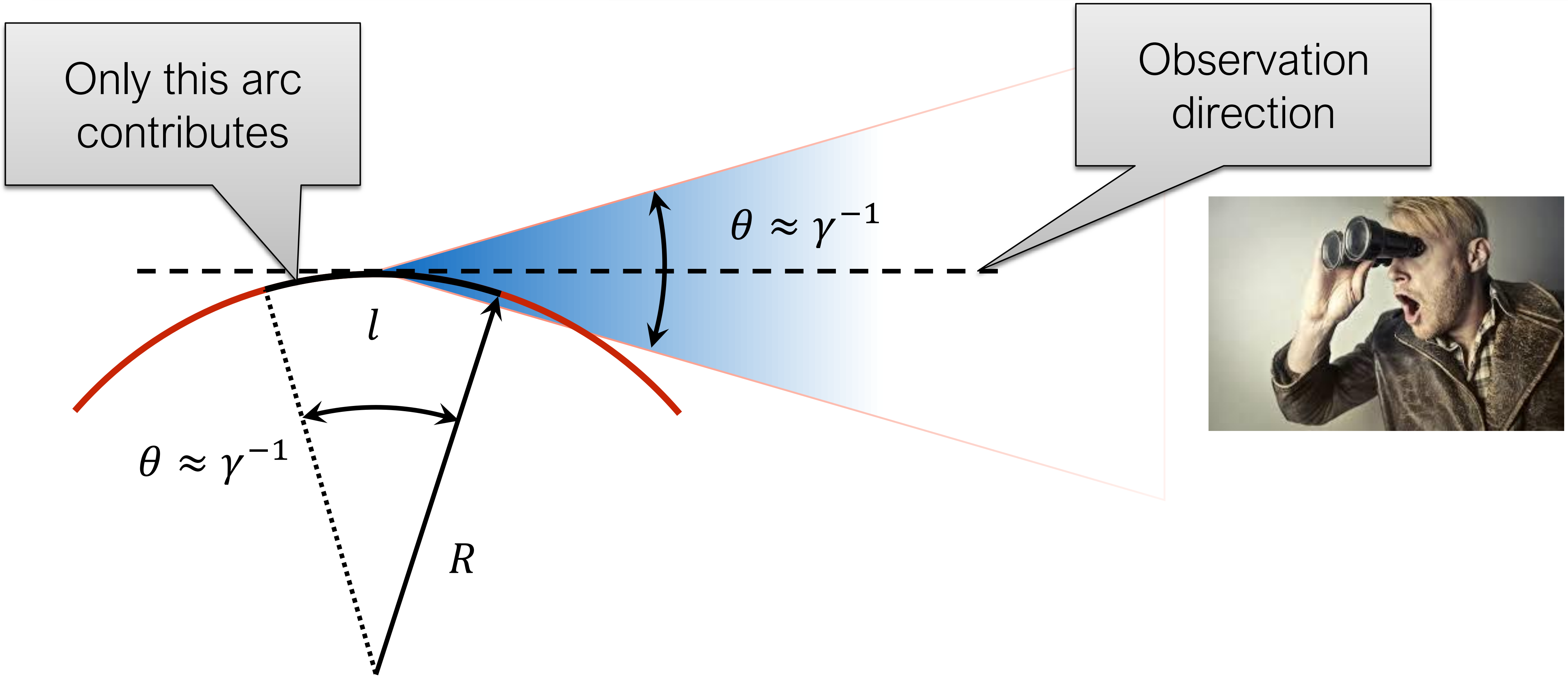
  $k_\perp$ is unchanged

  $k_\parallel$ is increased by a factor of γ

- Emission is concentrated within a forward cone with an opening angle of $1/\gamma$

- Example: 100 MeV electron ⟶ opening angle of 0.3°

Emission spectrum



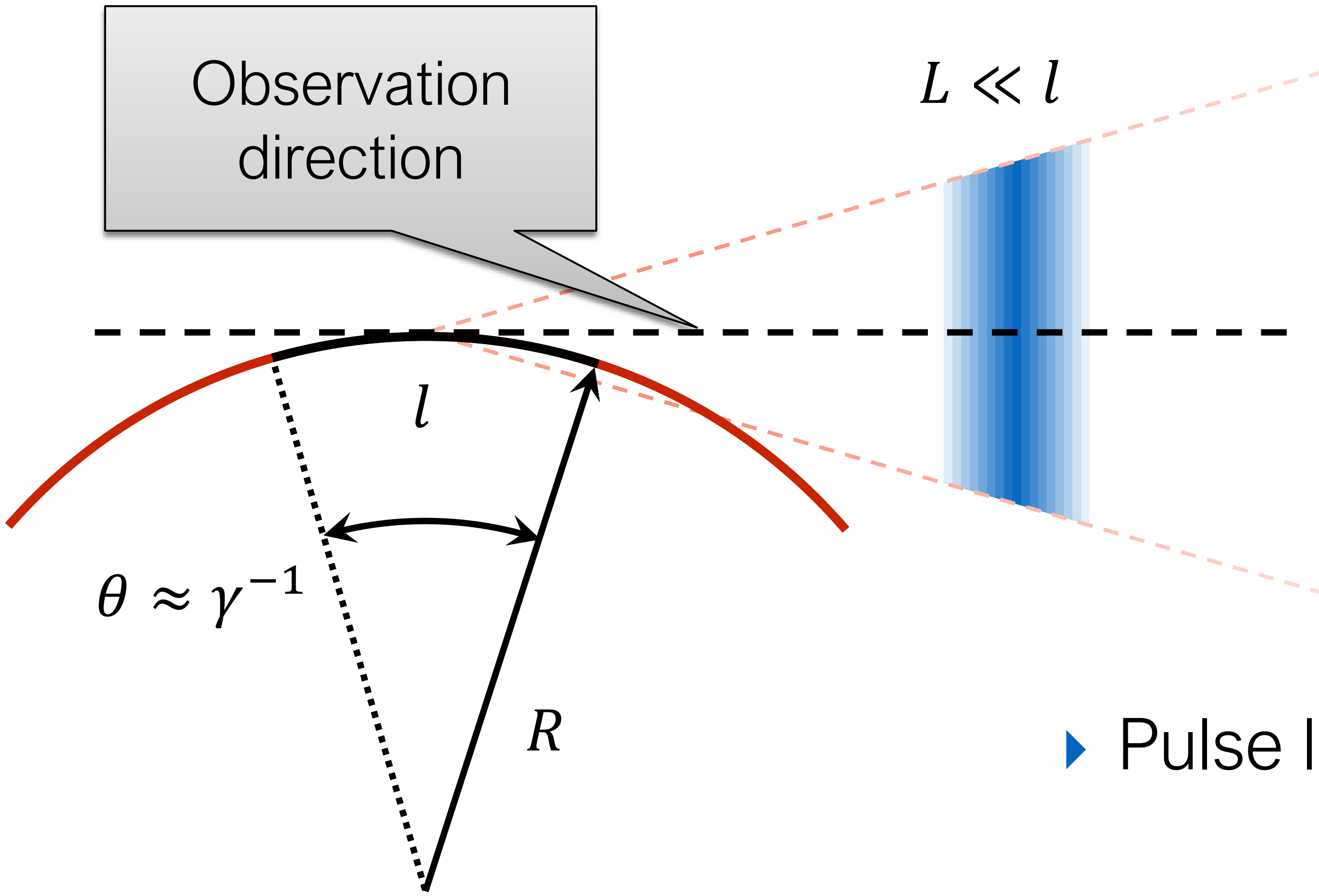
Only this arc contributes

Observation direction

- Distance travelled by electron during emission: $l \approx \theta R$

- Duration of emission: $\Delta t \approx l/v$

Emission spectrum



Relativistic electron emits high frequency radiation :

$$\omega_c \approx \gamma^3 \frac{c}{R} \approx \gamma^3 \omega_0$$

$$\varepsilon_\gamma = \hbar\omega_c \approx \gamma^3 \hbar\omega_0$$

- Distance travelled by electron during emission: $l \approx \theta R \approx R/\gamma$
- Duration of emission: $\Delta t \approx l/v$
- Pulse length: $L \approx c\Delta t - l \approx l/\gamma^2$
- $L \ll l \ll R$ for ultra-relativistic electrons

$$L \approx R/\gamma^3$$

- Typical frequency: $\omega_c \approx c/L$
- Fundamental frequency: $\omega_0 \approx c/R$

Key takeaways

- Emitted power and characteristic photon energy are set by the quantum nonlinearity parameter χ_e:

$$P = \frac{2}{3}\frac{me^2}{\hbar^2}mc^3\chi_e^2$$

$$\boxed{\varepsilon_\gamma/\varepsilon_e = 1.5\chi_e}$$

$$\chi_e \equiv \frac{\gamma}{E_s}\left[\left(\vec{E} + \frac{1}{c}[\vec{v}\times\vec{B}]\right)^2 - \frac{1}{c^2}(\vec{E}\cdot\vec{v})^2\right]^{1/2}$$

$$E_S = 1.3\times 10^{18}\ \mathrm{V/m}$$

- Ultra-relativistic electrons emit forward.

Emission induced

by

electromagnetic waves

Laser field strength

- Laser field strength increases with laser intensity:

$$E[\mathrm{TV/m}] \approx 2.7\sqrt{I[10^{18}\ \mathrm{W/cm^2}]} \qquad B[\mathrm{MT}] \approx \sqrt{I[10^{22}\ \mathrm{W/cm^2}]}$$

- Current record: $I \approx 10^{23}\ \mathrm{W/cm^2} \longrightarrow E \approx 1.5\times 10^{14}\ \mathrm{V/m}$ & $B \approx 3$ MT
- Not even close to the Schwinger field strength: $E_S = 1.3\times 10^{18}\ \mathrm{V/m}$
- Convenient formula for estimates:

This is always a small parameter

$$\frac{E}{E_S} \approx 2\times 10^{-6}\sqrt{I[10^{18}\ \mathrm{W/cm^2}]}$$

Plane wave and forward-moving electron

- Electron in a plane EM wave propagating in vacuum ($E = B$):

$$\chi_e \equiv \frac{\gamma}{E_s}\left[\left(\vec{E} + \frac{1}{c}[\vec{v} \times \vec{B}]\right)^2 - \frac{1}{c^2}(\vec{E} \cdot \vec{v})^2\right]^{1/2} = \frac{\gamma E}{E_s}\left(1 - \frac{v}{c}\cos\theta\right)$$

- The effects of B and E cancel each other out ⟶ strong suppression

$\theta = 0$

$$1 - \frac{v}{c}\cos\theta = 1 - \frac{v}{c} \approx \frac{1}{\sqrt{2}\gamma}$$

$$\chi_e \approx \frac{1}{\sqrt{2}}\frac{E}{E_s} \qquad \varepsilon_\gamma/\varepsilon_e = 1.5\chi_e \approx \frac{E}{E_s}$$

Very small ratio

- Emission of forward moving electrons is inefficient.

Plane wave and backward-moving electron

- No suppression for a backward moving electron ($\theta = \pi$):

$$\chi_e = \frac{\gamma E}{E_s}\left(1 - \frac{v}{c}\cos\theta\right)$$

$\theta = \pi$

$$1 - \frac{v}{c}\cos\theta = 1 + \frac{v}{c} \approx 2$$

$$\chi_e \approx 2\gamma\frac{E}{E_s}$$

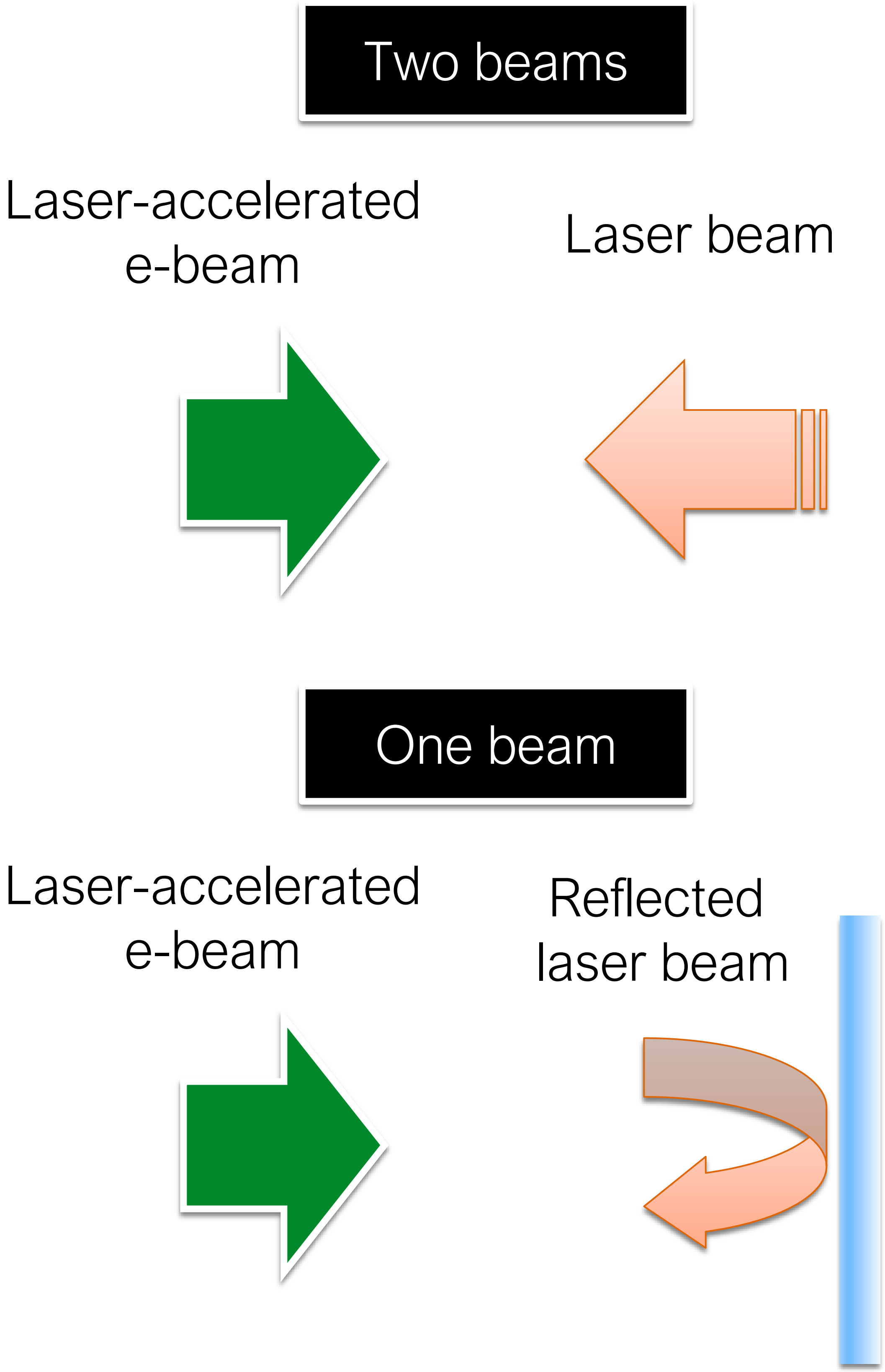
The smallness of E/E$_S$ is offset by γ

- Counter-propagating geometry is effective for the emission of energetic photons

$$\varepsilon_\gamma/\varepsilon_e = 1.5\chi_e \approx 3\gamma\frac{E}{E_s}$$

The smallness of E/E$_S$ is partially offset by γ

All-optical counter-propagating setups



Two beams

Laser-accelerated e-beam

Laser beam

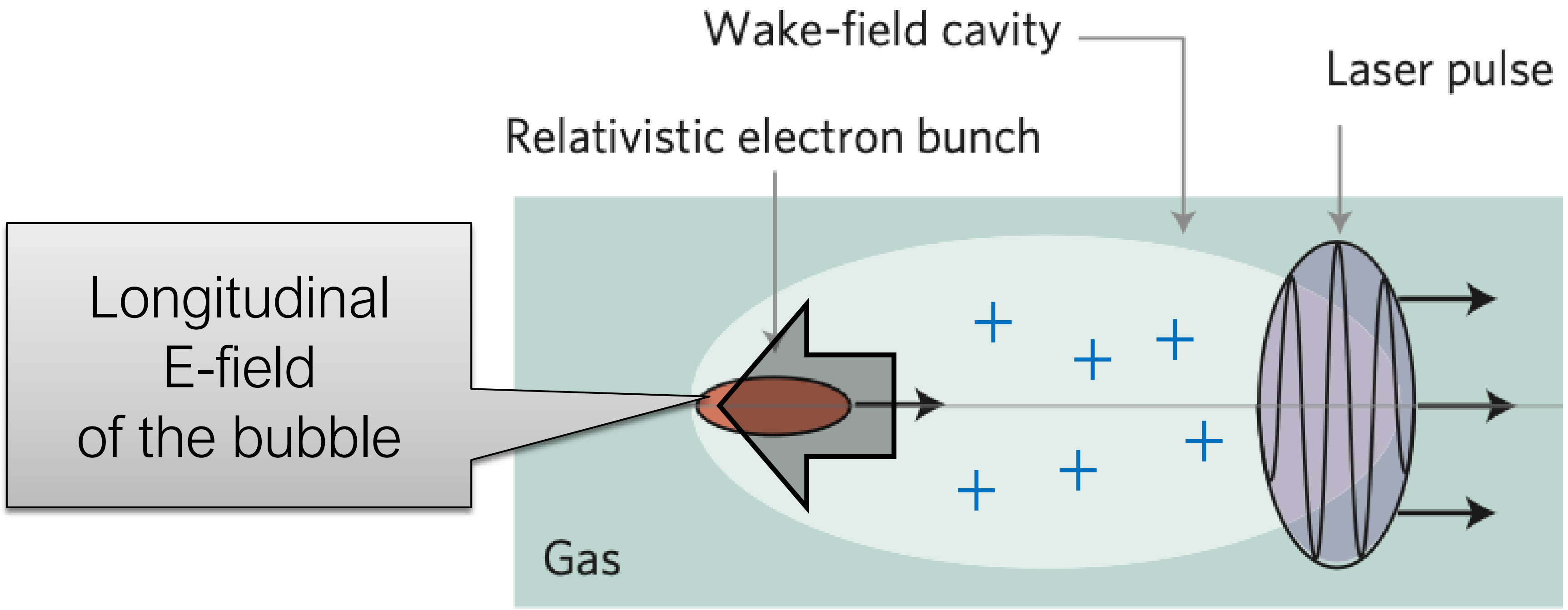
One beam

Laser-accelerated e-beam

Reflected laser beam

- All-optical counter-propagating setups can be achieved using two (a) or one (b) laser beam.
- Laser Wakefield Acceleration (LWFA) has been the preferred mechanism for generating electrons with $\varepsilon_e \geq 100$ MeV.
- LWFA requires a moderately relativistic intensity of $I \sim 5 \times 10^{18}$ W/cm^2.

Mechanism of Laser Wakefield Acceleration



Example:

laser

- 30 TW, 1 J
- 5×10^{18} W/cm^2

electrons

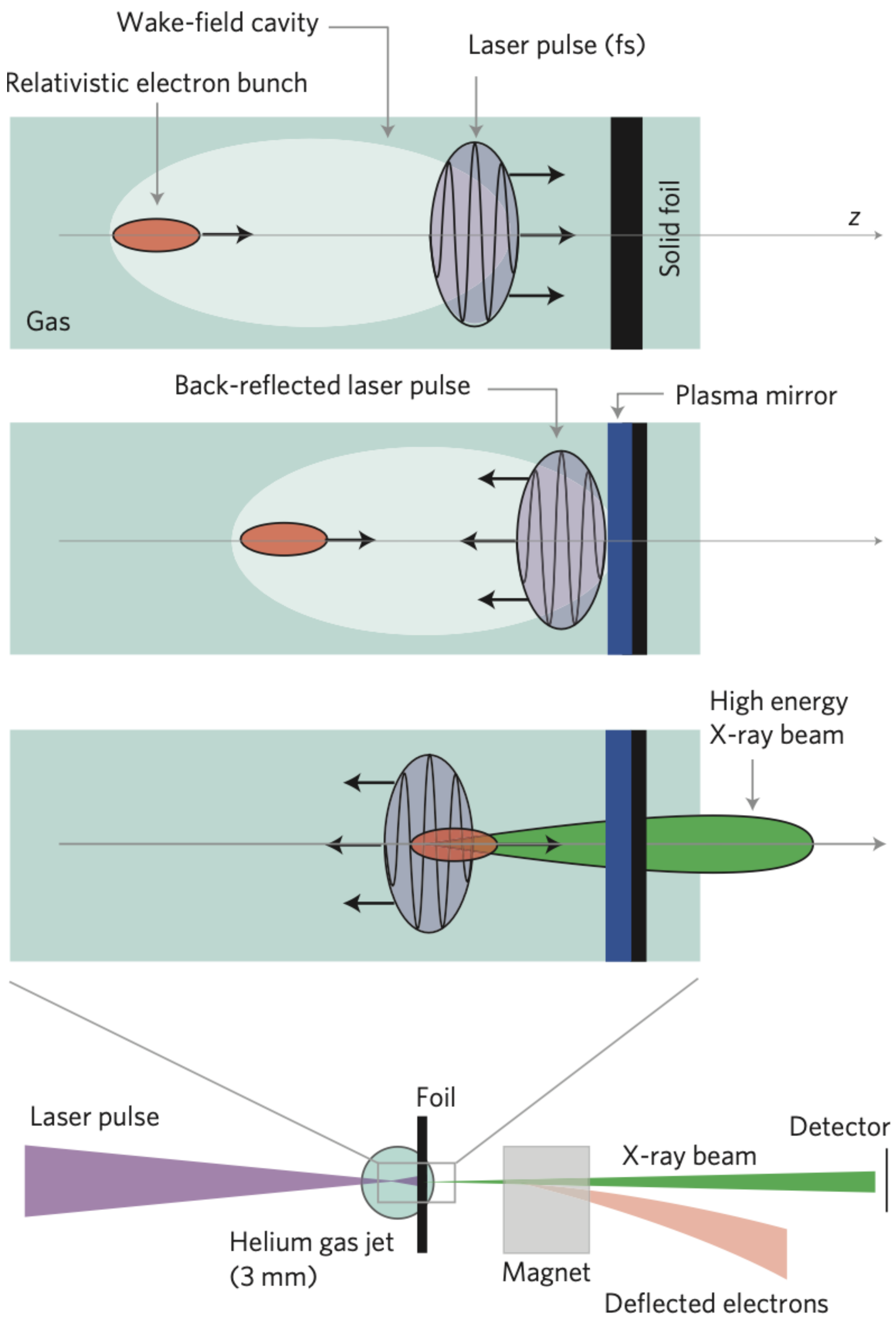
- $\varepsilon_e \approx 80$ MeV

Ta Phuoc et al., Nat. Photonics **6**, 308 (2012)

- Laser pulse expels electrons, creating a positively charged cavity.
- The cavity (bubble) generates a forward-moving longitudinal E-field.
- Electrons injected at the back of the bubble are accelerated forward.

X-ray source using a reflecting mirror

Ta Phuoc et al., Nat. Photonics **6**, 308 (2012)



- Electron energy: $\varepsilon_e \approx 80$ MeV
- Laser field strength at 5×10^{18} W/cm^2:

$$E/E_S \approx 2 \times 10^3 \sqrt{I} \approx 4.5 \times 10^{-6}$$

- Dimensionless parameter:

$$\chi_e \approx 2\gamma\, E/E_S \approx 1.4 \times 10^{-3}$$

significant increase

- Photon energy: $\varepsilon_\gamma = 1.5\chi_e\varepsilon_e \approx 170$ keV
- 10^8 photons were measured → 10^{-6} J
- Energy conversion efficiency: 10^{-6}

Emission induced

by

plasma fields

Argument for using plasma fields

- Emission of electrons co-propagating with the laser is inefficient:

$$\chi_e \equiv \frac{\gamma}{E_s}\left[\left(\vec{E}+\frac{1}{c}[\vec{v}\times\vec{B}]\right)^2-\frac{1}{c^2}(\vec{E}\cdot\vec{v})^2\right]^{1/2} \Rightarrow \chi_e^{laser} \approx \frac{1}{\sqrt{2}}\frac{E^{laser}}{E_s}$$

$\ll \left(E^{laser}\right)^2$

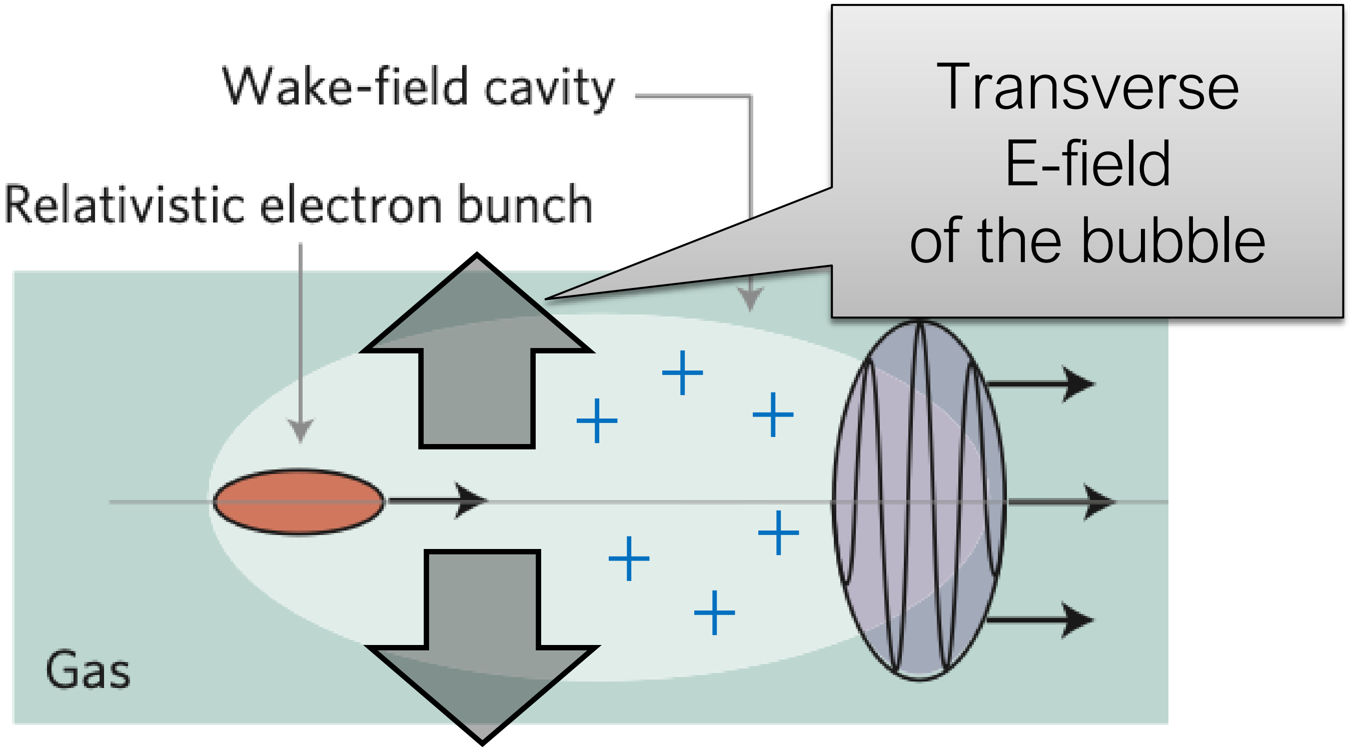
- Plasma can generate a strong transverse quasi-static E field without a B-field counter-part to cancel out the effect:

$$\chi_e^{pl} = \chi_e \approx \frac{\gamma E_{\perp}^{pl}}{E_s}$$

- In a co-propagating setup, plasma fields can be effective in inducing photon emission: $\chi_e^{pl} \gg \chi_e^{laser}$ for $E_{\perp}^{pl} \ll E^{laser}$

- The same applies to strong laser-driven plasma B-fields.

LWFA x-ray source without reflection



Transverse
E-field
of the bubble

- Field of the bubble is the field of a uniform cylinder:

$$E_{\perp} \approx r\,\omega_{pe}^{2}/2$$

$$\omega_{pe}^{2} = 4\pi n_e e^{2}/m$$

- Transverse E-field of the bubble causes electron oscillations.

- Deflections by this field induce forward emission of x-rays:

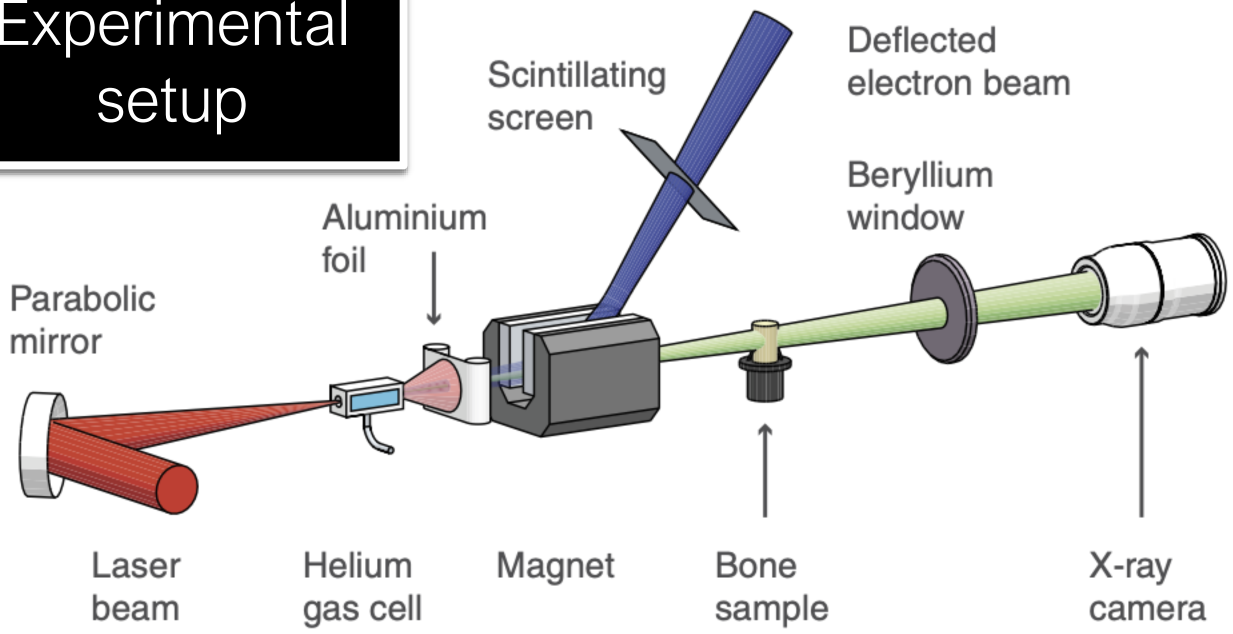
$$\varepsilon_{\gamma} = 1.5\chi_e\varepsilon_e \approx 1.5\varepsilon_e \frac{\gamma E_{\perp}^{plasma}}{E_s} \Rightarrow \varepsilon_{\gamma}[\mathrm{keV}] \approx 5\times 10^{-24} r[\mu\mathrm{m}]\gamma^{2} n_e[\mathrm{cm}^{-3}]$$

Amplitude of
electron oscillations

Hard x-ray source from LWFA

Cole et al., Sci. Rep. **5**, 13244 (2015)

Experimental setup



- Laser driving LWFA:

  300 TW, 11 J at 2×10^{19} W/cm^2

- Electron density

  $n_e \approx 3 \times 10^{18}$ c

Need higher γ than colliding case!

- Accelerated electrons: $\varepsilon_e \approx 720$ MeV

  $\gamma \approx 1.4 \times 10^3$

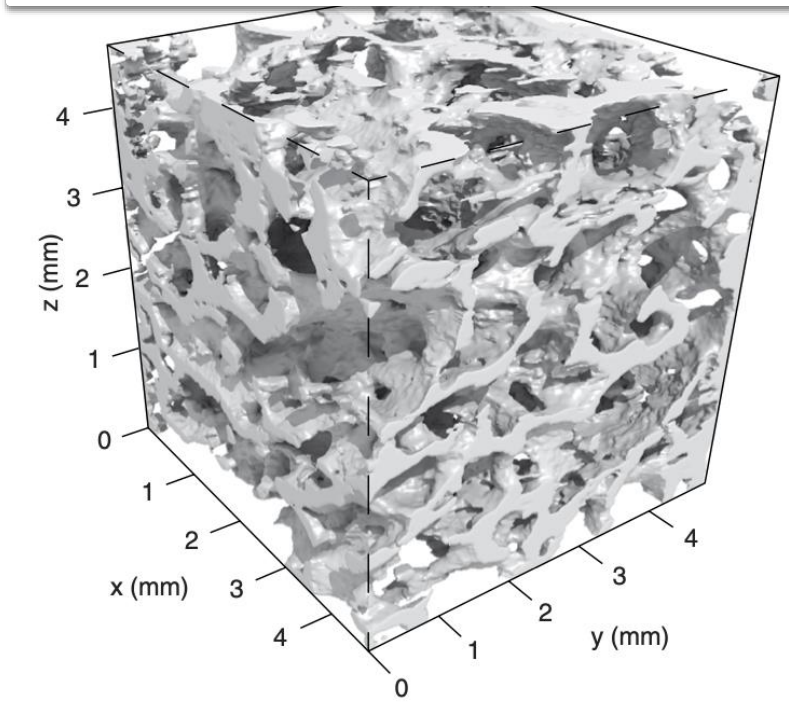
- Emitted x-rays: $\varepsilon_\gamma[\mathrm{keV}] \approx 5 \times 10^{-24} r[\mu\mathrm{m}]\gamma^2 n_e[\mathrm{cm}^{-3}]$

  $\varepsilon_\gamma \approx 59$ keV for $r \approx 2$ μm

- Photon number: 10^9 photons ($\varepsilon_\gamma > 1$ keV)

- Energy conversion efficiency is less than 10^{-5}

Tomographic reconstruction of bone sample



Switch to DLA to generate multi-MeV photons

- LWFA requires the plasma to be underdense:

$$n_e \ll n_{cr} \propto m_e/\lambda_0^2 \approx 10^{21}\ \mathrm{cm^{-3}}$$

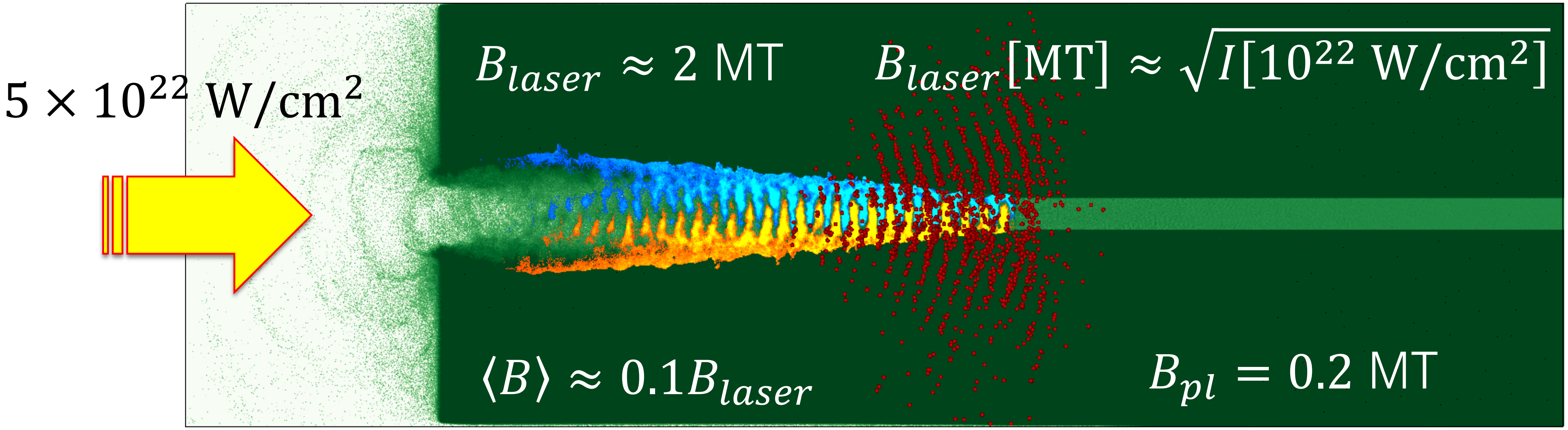
- Increasing n_e to reach $\varepsilon_\gamma > 1$ MeV is not an option.
- We would need to increase γ by a factor of 10 to get to $\varepsilon_\gamma > 1$ MeV.
- Alternative: use an acceleration mechanism not restricted to $n_e \ll n_{cr}$.
- Direct Laser Acceleration (DLA) is a possible candidate that can generate 100 MeV electrons at high laser intensity.

Pukhov et al., POP **6**, 2847 (1999)
Hussein et al., NJP **23**, 023031 (2021)

- Key feature of DLA: pulse length $\gg\ c/\omega_{pe}$

No plasma bubble

Laser-driven plasma B-field



- At sufficiently high n_e, electrons are no longer expelled from the beam.
- The laser beam pushes electrons forward, creating a current filament.
- Plasma serves as a rectifier: "converts" oscillating B_{laser} into static azimuthal $B_{pl} \approx 0.1 B_{laser}$.

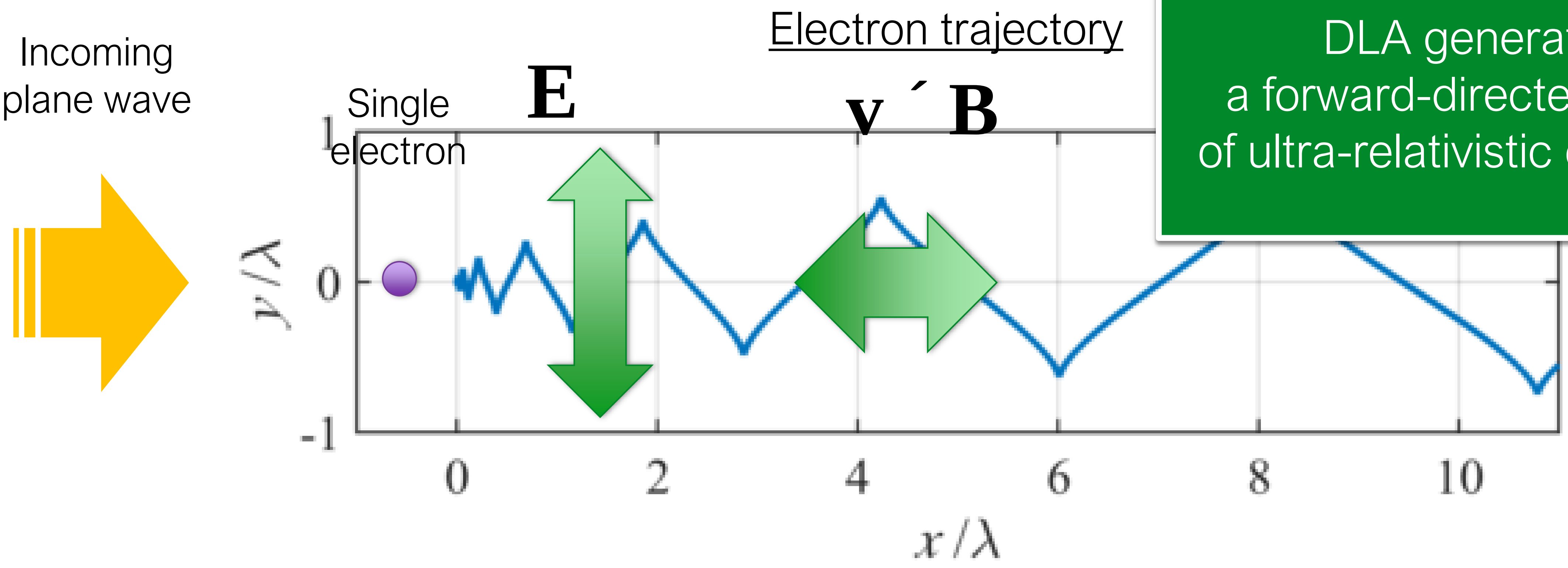
Stark et al., PRL **116**, 185003 (2016)
Rinderknecht et al., NJP **23**, 095009 (2021)

Direct Laser Acceleration (DLA)

- The strength of the oscillating field is quantified using

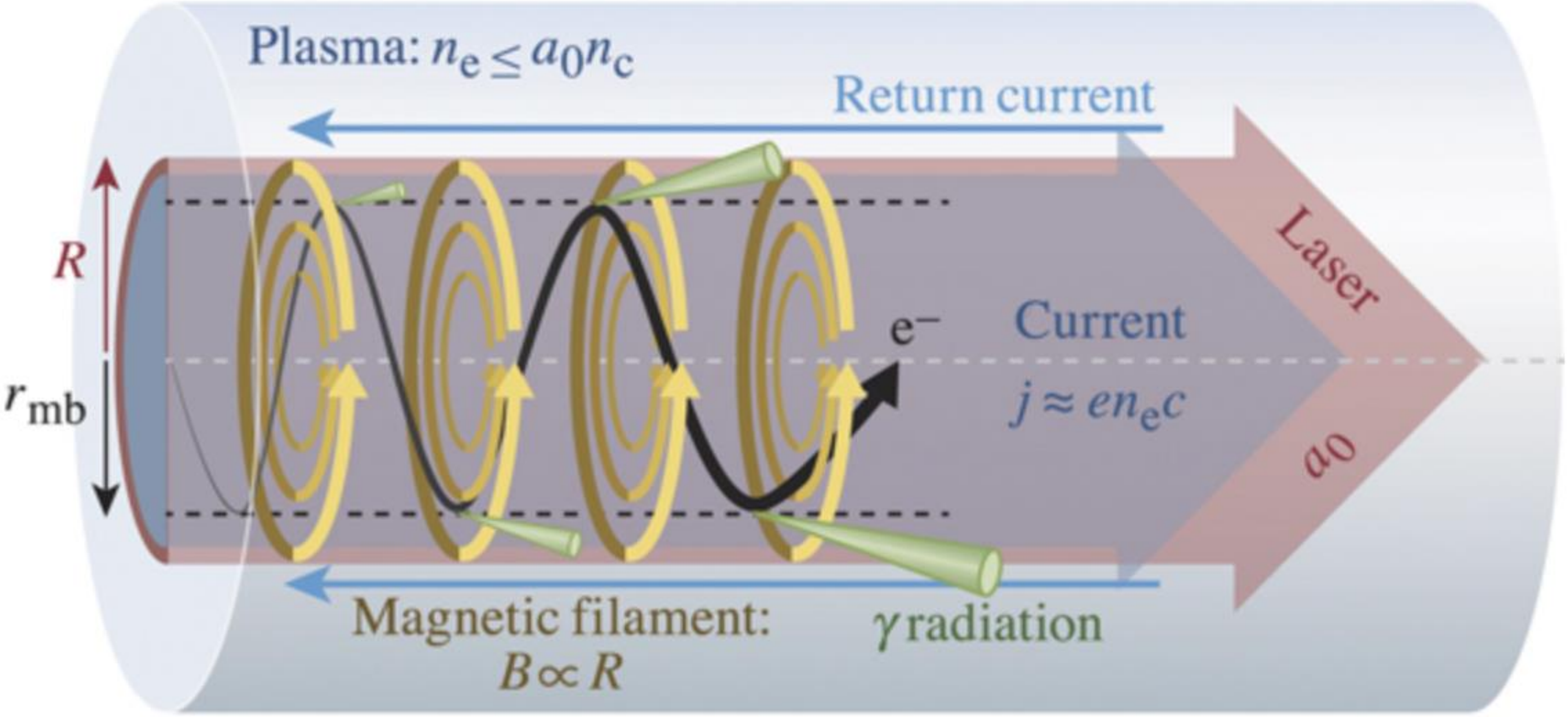
$$a_0 \equiv |e|E_{laser}/m_e\omega_{laser}c \approx 0.85\lambda[\mu\mathrm{m}]\sqrt{I[10^{18}\ \mathrm{W/cm^2}]}$$

- Electrons become relativistic over one laser period at $a_0 > 1$.
- The electron gains energy from $E_\perp$.
- At $a_0 \gg 1$, the push by $\vec{v}_\perp \times \vec{B}_{\perp laser}$ causes the electron to move forward.



DLA generates a forward-directed beam of ultra-relativistic electrons

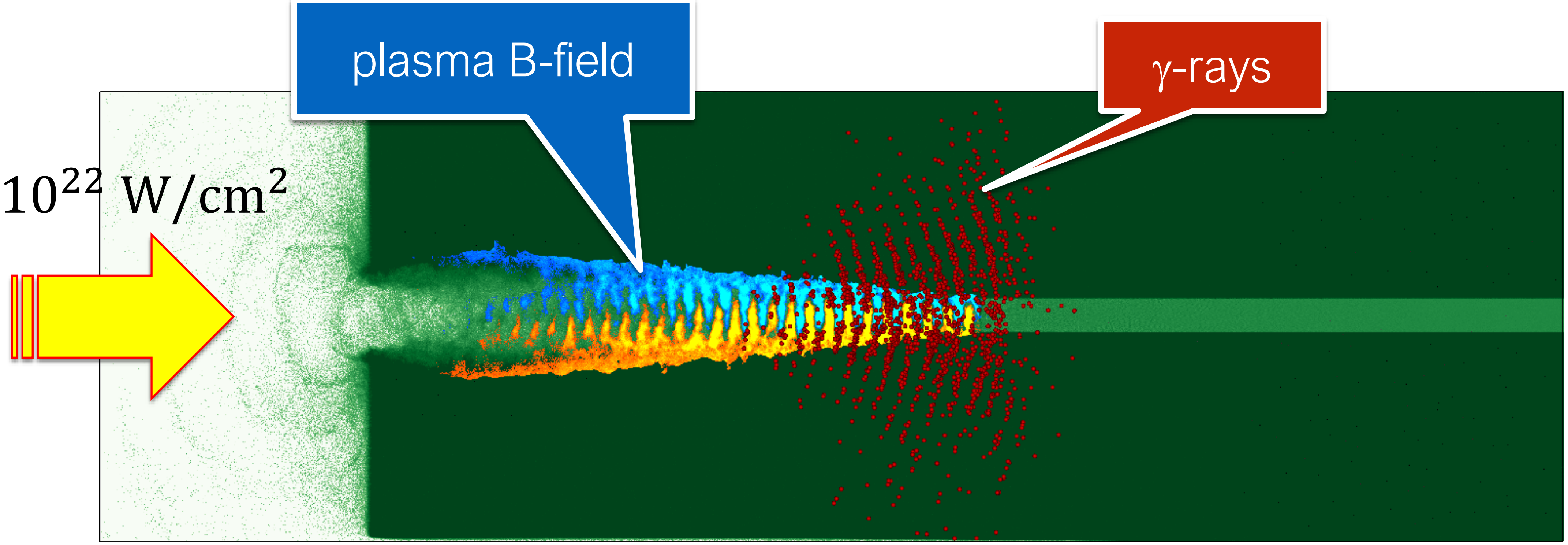
Gamma-ray emission



Rinderknecht et al., NJP **23**, 095009 (2021)

- DLA electrons are flying forward.
- Their energy gain from DLA reaches hundreds of MeV.
- B-field deflections cause the electrons to emit γ-rays.
- Electron beam ⟶ forward-directed emission

Gamma-ray emission



$5 \times 10^{22}\ \mathrm{W/cm^2}$

plasma B-field

γ-rays

- DLA electrons (not shown) are flying forward.
- Their energy gain from DLA reaches hundreds of MeV.
- B-field deflections cause the electrons to emit γ-rays.
- Electron beam ⟶ forward-directed emission

The need for a dense plasma

- Electrons with $\varepsilon_e \approx 100$ MeV require $B_{pl} \approx 150$ kT to emit photons with $\varepsilon_\gamma \approx 1$ MeV
- The current density is limited by n_e: $|j| \approx |e| n_e v_e < |e| n_e c$
- The max B-field of a uniform current filament of radius R:

$$B_{pl}[\mathrm{kT}] \approx 37 \frac{n_e}{n_{cr}} \frac{R[\mu\mathrm{m}]}{(\lambda[\mu\mathrm{m}])^2}$$

- We need $n_e \approx 4 n_{cr}$ for $R \approx 1\ \mu\mathrm{m}$ to achieve $B_{pl} \approx 150$ kT.
- An over-dense plasma ($n_e > n_{cr}$) is needed to generate strong B_{pl}.

Relativistically induced transparency

- However, at $a_0 < 1$, the laser can only propagate through a plasma with

$$n_e \ll n_{cr} \propto m_e/\lambda_0^2$$

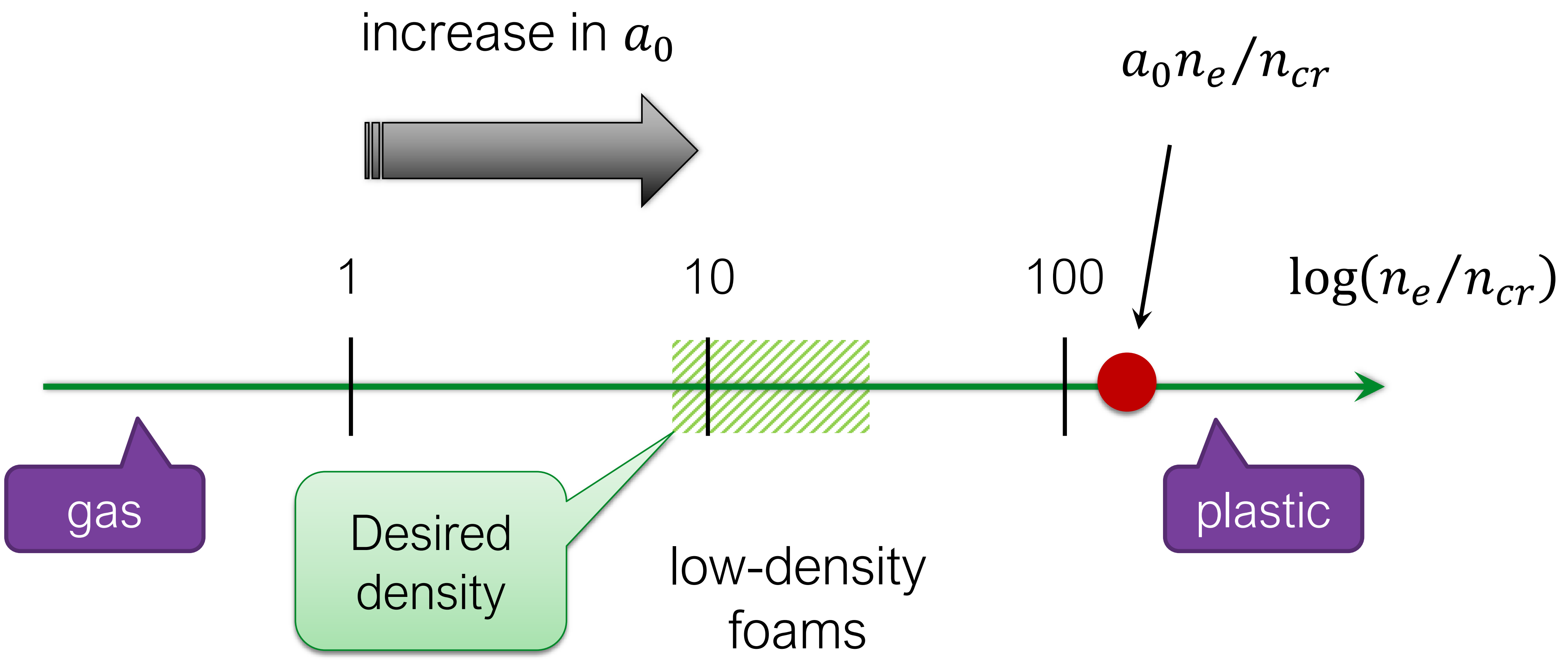
- At $a_0 \gg 1$, plasma electrons become relativistic ($\gamma_e \sim a_0$) and a dense plasma becomes transparent:

$$n_e \ll a_0 n_{cr} \qquad\qquad a_0 \equiv \frac{|e|E_0}{m_e \omega c} \gg 1$$

- Relativistic transparency = effective mass increase to $\gamma_e m_e$

- High laser intensity is the key to driving strong plasma fields:
  for a desired n_e/n_{cr}, we need $a_0 \approx 10\, n_e/n_{cr} \gg 1$

What is the most appropriate target material?



increase in a_0

$a_0 n_e/n_{cr}$

1

10

100

$\log(n_e/n_{cr})$

gas

Desired density

low-density foams

plastic

$I = 5 \times 10^{22}$ W/cm^2;
$\lambda_0 = 0.8$ µm

$a_0 = 150$

$n_e/n_{cr} \approx 150$

- Option #1: plasma expansion

Lezhnin et al, POP **25**, 123105 (2018)

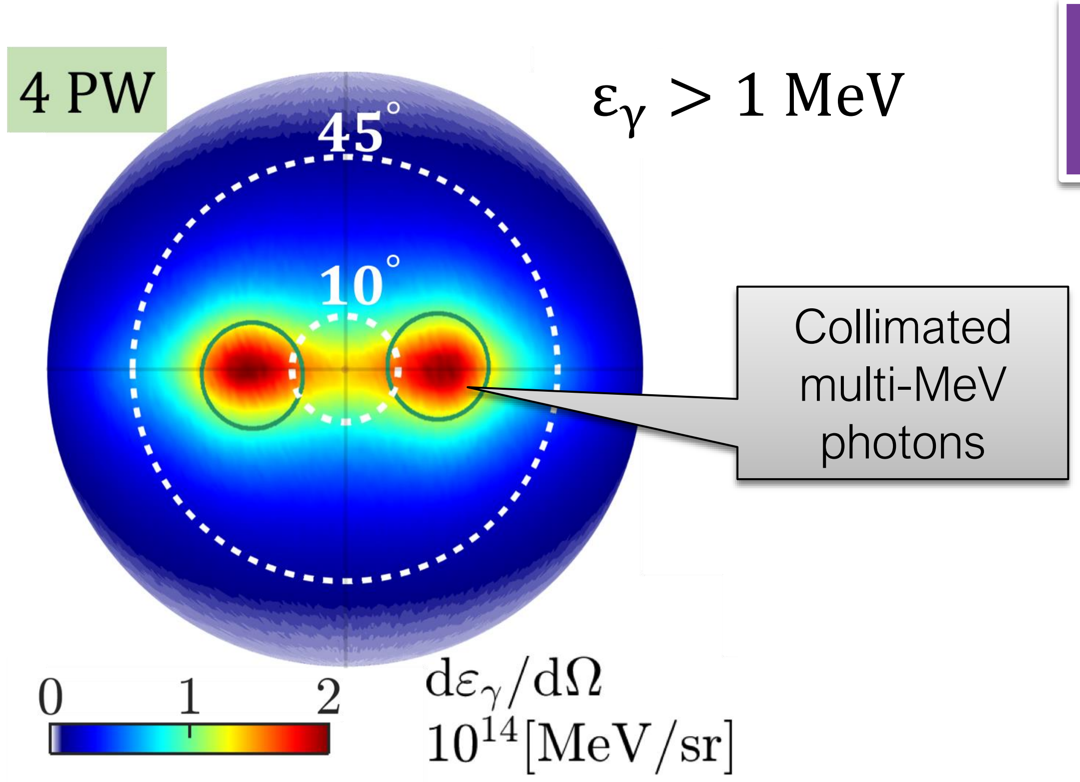
- Option #2: foams with low mass density (10 mg/cm^3) and a small pore size.

Nagai et al, POP **25**, 030501 (2018)

- Foams enable a volumetric interaction with a plasma of a desired density and thickness.

Efficiency of the gamma-ray emission

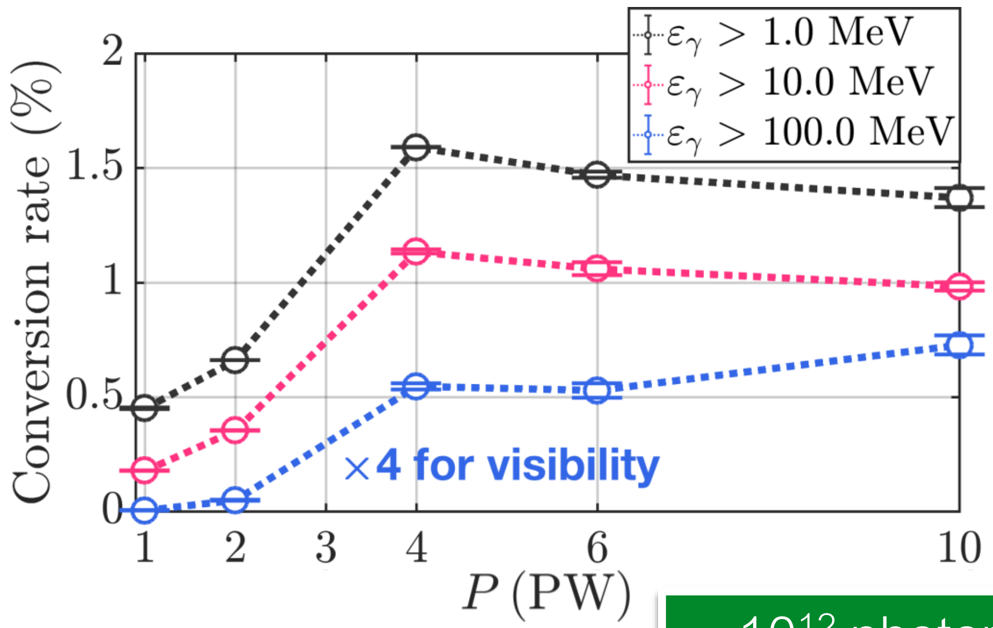
T. Wang et al, Phys. Rev. Applied **13**, 054024 (2020)



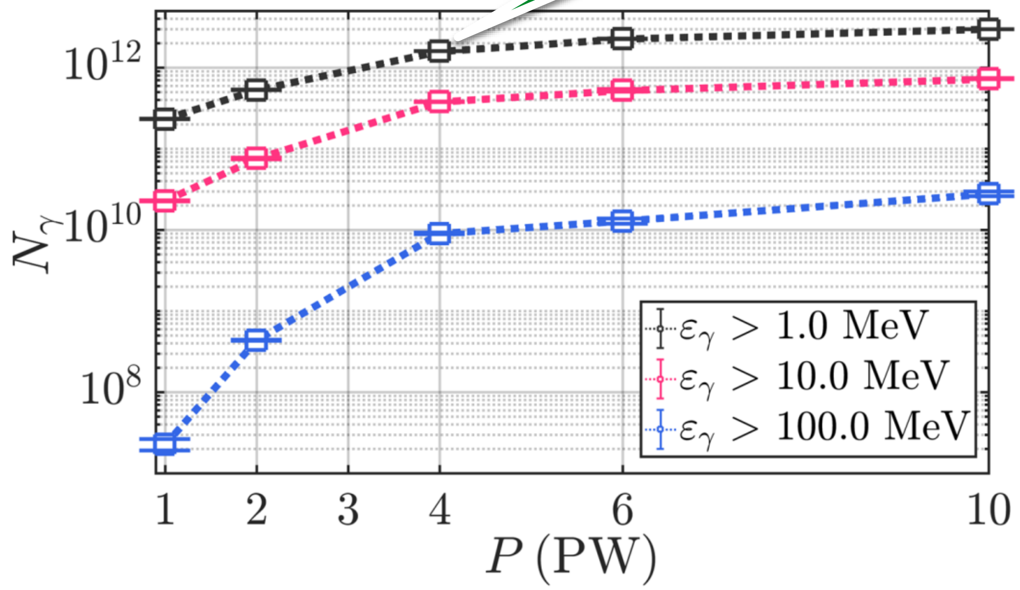
Collimated multi-MeV photons

$a_0 \approx 190$

Power scan at fixed intensity



10^{12} photons into a 10° cone



- Discussed mechanism generates two collimated lobes of gamma-rays.

- High efficiency: 1.5×10^{-2} of laser energy is converted into 10^{12} multi-MeV photons within a single 10° cone.

- Also see:

Stark et al., PRL **116**, 185003 (2016)
Lezhnin et al, POP **25**, 123105 (2018)
Hadjisolomou et al, Sci. Rep. **12**, 17143 (2022)

Summary

- Hard x-rays and multi-MeV γ-rays can be generated by ultra-relativistic laser-accelerated electrons interacting with laser and plasma fields.
- Single laser beam setup: use LWFA for hard x-rays and DLA for γ-rays.
- Efficient γ-ray generation requires a high intensity laser and an over-dense plasma.

Questions?

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