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Laser-Particle Collider for High-field High-energy Physics Studies

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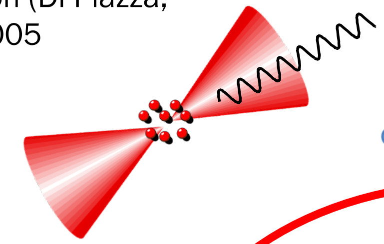
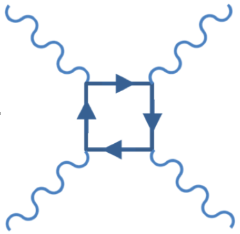
High Intensity Particle Physics describes the phenomena in strong EM fields in the environments where the field strength is comparable to the QED critical field

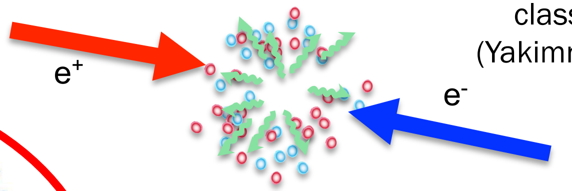
High order harmonic generation (Di Piazza, Hatsagortsyan, C. H. Keitel, 2005 Fedotov & Narozhny, 2006)





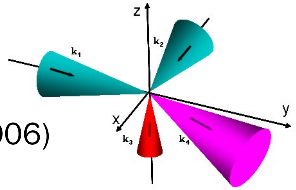
Photon-photon scattering via relativistic mirrors (Koga et al (2012))

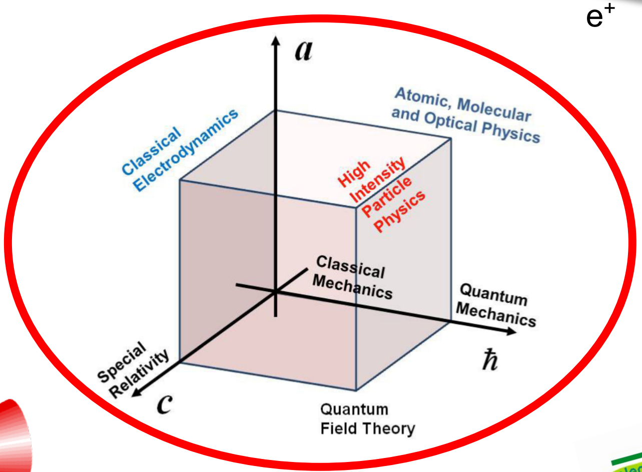
Interaction point physics at future TeV-class lepton colliders (Yakimneko et al, 2019)

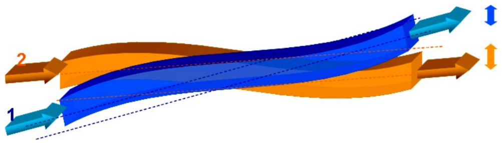


4-wave mixing

(Lundström et al, 2006)

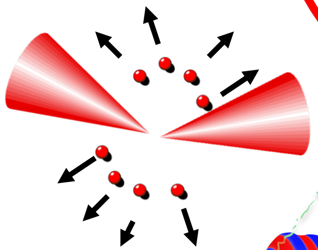


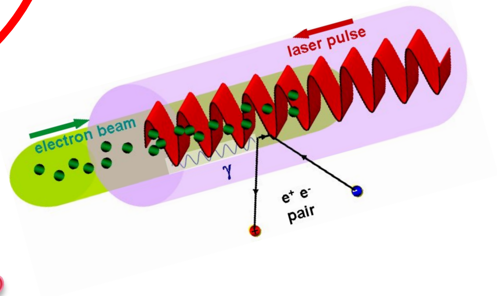


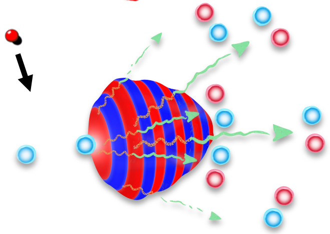


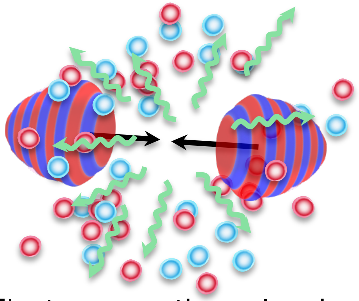
Birefringent e.m. vacuum (Rozanov, 1993)

Electron positron pair production from vacuum (Schwinger, 1951)









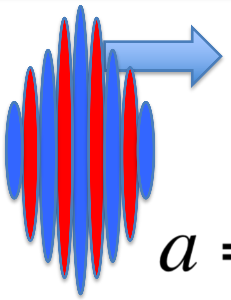
Mulitphoton Compton and Breit-Wheeler processes
A. I. Nikishov, V. I. Ritus (1964);
Bula et al (1996); Burke et al (1997)
Cole et al (2018); Poder et al (2018)

- Electromagnetic shower-type cascades

- Electromagnetic avalanche-type cascades (Bell&Kirk, 2008)

Behavior of particles and fields is characterized by Lorentz invariant parameters

Classical nonlinearity parameter



$$a = \frac{eE}{m\omega c}$$

Electron energy gain over laser wavelength in units of *mc*²

$a = 1$ ⇒ Relativistic regime of interaction $\lambda = 1\ \mu m$

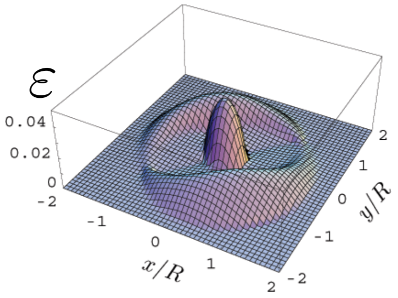
Critical QED field can create an electron-positron pair at Compton length, $\lambda_C = 3.86 \times 10^{-11}$ cm

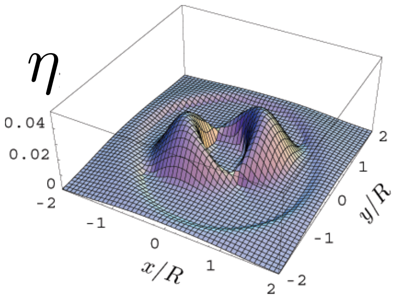
$$E_S = \frac{m^2c^3}{e\hbar} = 1.32\times10^{16}\ V/cm \quad \Rightarrow \quad a_s = \frac{\hbar\omega}{mc^2} = 4.1\times10^5$$

$$n_{e^+e^-} = \frac{e^2E_S^2}{4\pi\hbar^2 c}\varepsilon\eta \coth\left[\frac{\pi\eta}{\varepsilon}\right]\exp\left[\frac{\pi}{\varepsilon}\right]$$

$$\varepsilon = \frac{1}{E_S}\sqrt{(\mathcal{F}^2+\mathcal{G}^2)^{1/2}+\mathcal{F}} \qquad \eta = \frac{1}{E_S}\sqrt{(\mathcal{F}^2+\mathcal{G}^2)^{1/2}-\mathcal{F}}$$

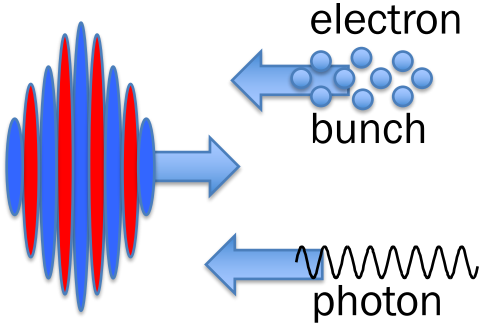
$$\mathcal{F} = (\mathbf{E}^2-\mathbf{B}^2)/2 \qquad \mathcal{G} = \mathbf{E}\cdot\mathbf{B}$$





Behavior of particles and fields is characterized by Lorentz invariant parameters

Quantum Effects



$$\chi_e = \frac{e\hbar\sqrt{(F_{\mu\nu}p^{\nu})^2}}{m^3c^4}$$

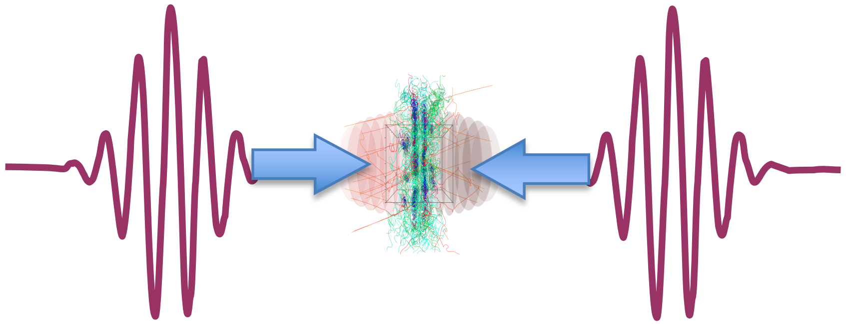
$$\chi_\gamma = \frac{e\hbar\sqrt{(F_{\mu\nu}k^{\nu})^2}}{m^3c^4}$$

counter-propagating laser and electron/photon

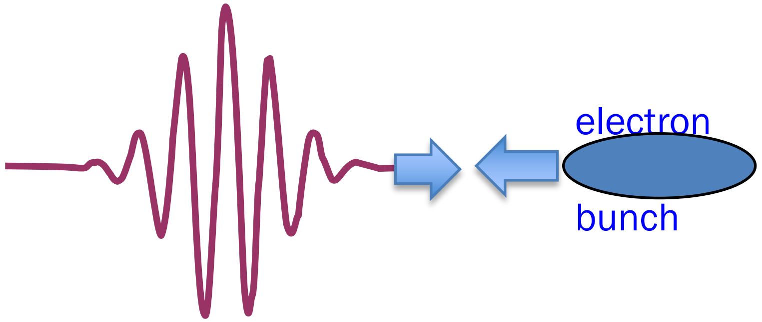
$$\chi_e = 2\gamma\frac{E}{E_S}, \chi_\gamma = 2\frac{\hbar\omega}{mc^2}\frac{E}{E_S}$$

Colliding laser – laser and e-beam – laser provide two principal schemes of the experiments for the study of strong field QED phenomena.

Colliding laser pulses



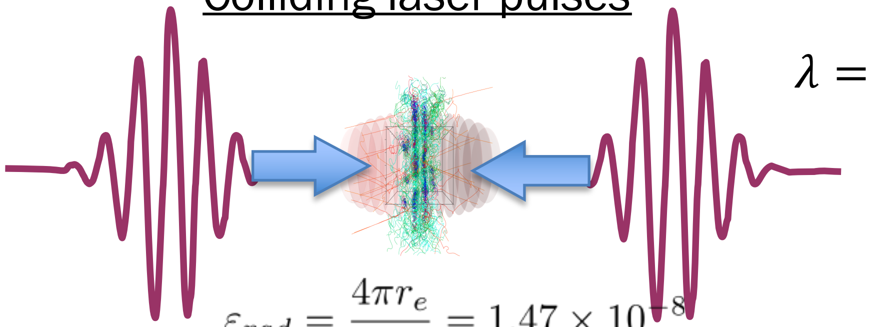
Colliding laser pulse and an electron beam



S. V. Bulanov, T. Zh. Esirkepov, Y. Hayashi, M. Kando, H. Kiriyama, J. K. Koga, K. Kondo, H. Kotaki, A. S. Pirozhkov, S. S. Bulanov, A. G. Zhidkov, P. Chen, D. Neely, Y. Kato, N. B. Narozhny, G. Korn, *Nuclear Instruments and Methods in Physics Research, Section A: Accelerators, Spectrometers, Detectors and Associated Equipment 660, 31 (2011)*

The dependence of the electron energy on the field strength is profoundly different in these two principal interaction schemes, leading to different thresholds

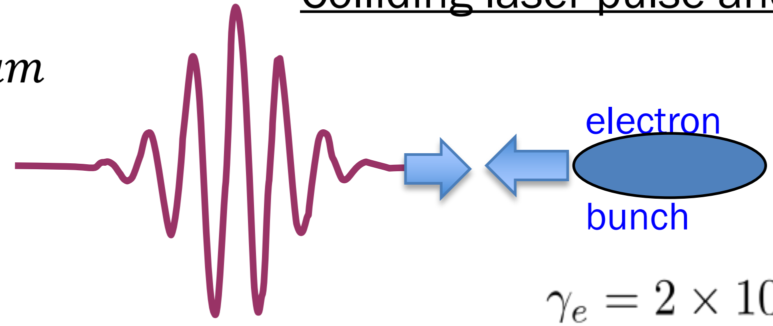
<u>Colliding laser pulses</u>

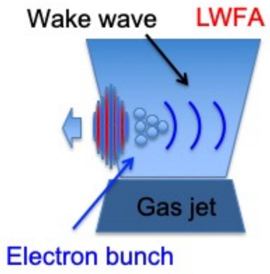


$$\varepsilon_{rad} = \frac{4\pi r_e}{3\lambda_0} = 1.47 \times 10^{-8}$$

$$\lambda = 0.8\ \mu m$$

<u>Colliding laser pulse and an electron beam</u>





$$\gamma_e = 2 \times 10^4$$

Laser Power: 1-10 PW

1. Radiation effects become dominant

$$a > a_{rad} = \varepsilon_{rad}^{-1/3} = 400$$

$$I_{rad} = 3.5 \times 10^{23} \quad W/cm^2$$

2. QED effects become dominant

$$a > a_Q = (2\alpha/3)^2 \varepsilon_{rad}^{-1} = 1.6 \times 10^3$$

$$I_Q = 5.5 \times 10^{24} \quad W/cm^2$$

1. Radiation effects become dominant

$$a > a_{rad} = (\omega \tau_{laser} \gamma_e \epsilon_{rad})^{-1/2} = 10$$

$$I_{rad} = 2 \times 10^{20} \quad W/cm^2$$

2. QED effects become dominant

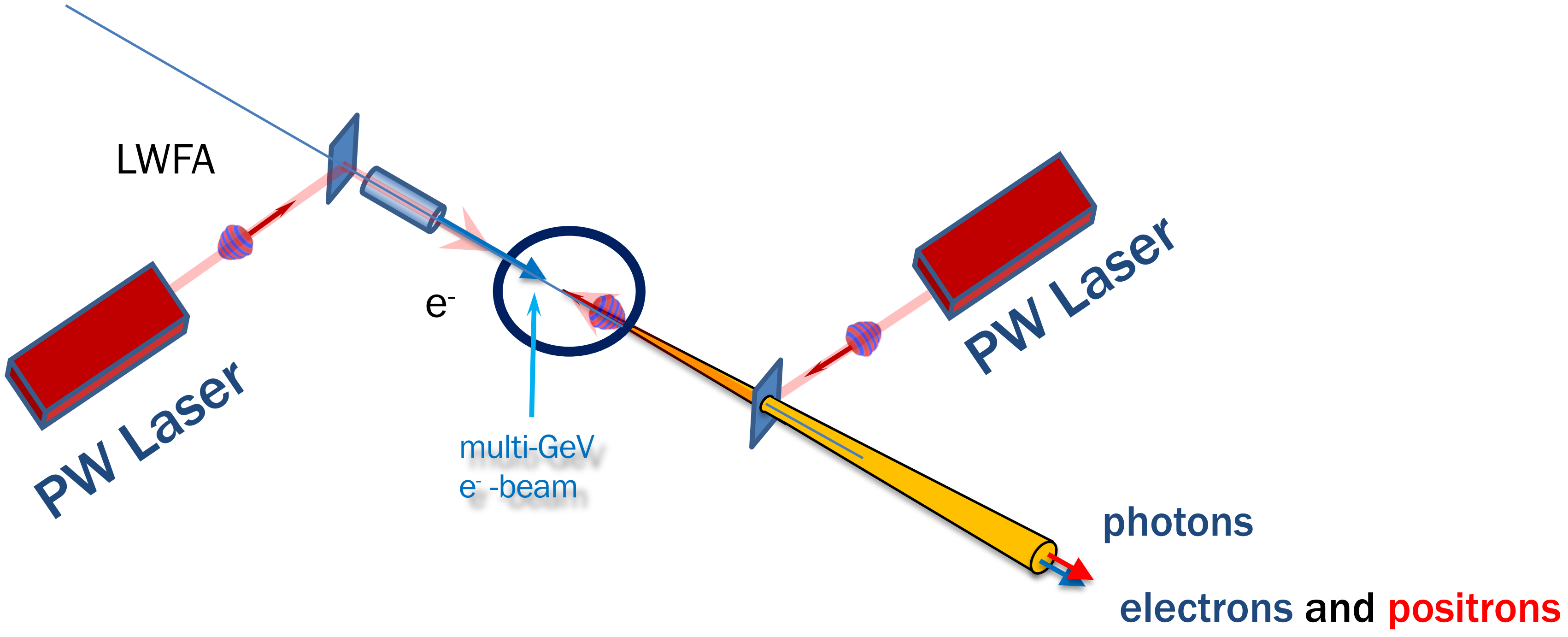
$$a > a_Q = (2\alpha/3) \gamma_e^{-1} \epsilon_{rad}^{-1} = 20$$

$$I_Q = 5.8 \times 10^{20} \quad W/cm^2$$

Laser Power: 1-10 PW

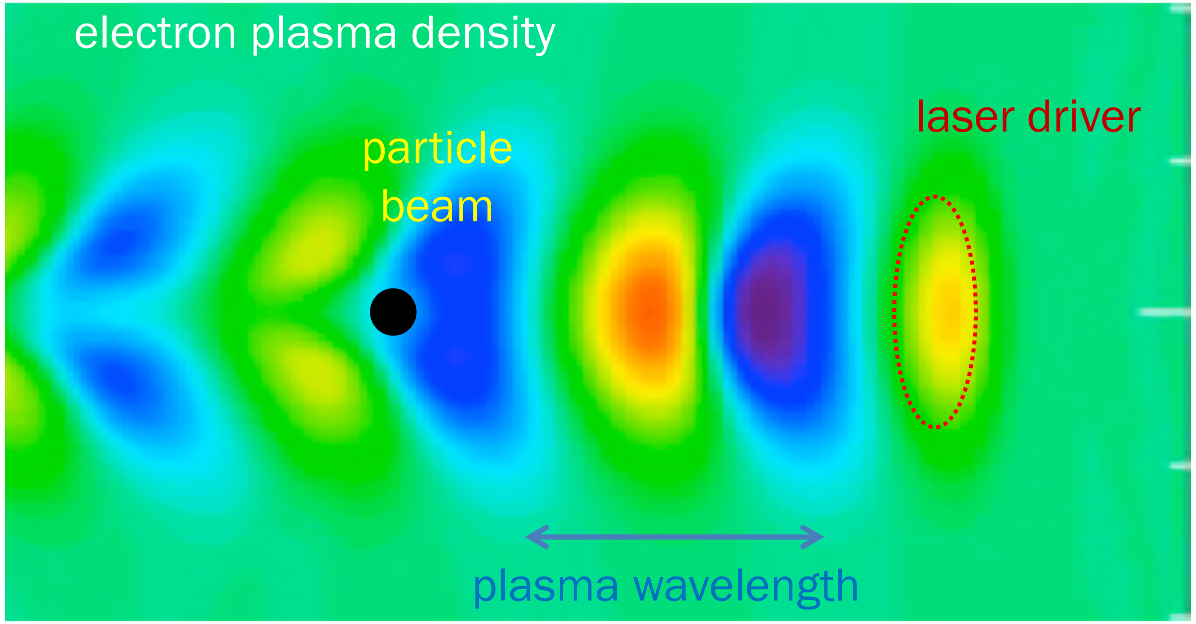
S. V. Bulanov, T. Zh. Esirkepov, Y. Hayashi, M. Kando, H. Kiriyama, J. K. Koga, K. Kondo, H. Kotaki, A. S. Pirozhkov, S. S. Bulanov, A. G. Zhidkov, P. Chen, D. Neely, Y. Kato, N. B. Narozhny, G. Korn, *Nuclear Instruments and Methods in Physics Research, Section A: Accelerators, Spectrometers, Detectors and Associated Equipment 660, 31 (2011)*

The interaction of a multi-GeV electron beam with a PW class laser pulse will produce copious amount of photons, electrons, and positrons.



Can this interaction setup be optimized to serve as a source of multi-GeV photons?
Or a platform to study EM showers and avalanches?

Laser-driven plasma-based acceleration



$$\lambda_p[\mu\mathrm{m}] = 2\pi c/\omega_p = \frac{3.3 \times 10^{10}}{\sqrt{n_0[\mathrm{cm}^{-3}]}}$$

$$(\partial_t^2 + \omega_p^2)\vec{E}/E_0 = \omega_p c \nabla a^2/4$$

Plasma wave: electron density perturbation

Laser ponderomotive force (radiation pressure)

Plasma wave excitation requires:

- Relativistically intense laser ($I>10^{18}$ W/cm^2; a~1)
- short pulse duration (~ c/ω_p<100 fs), resonant with plasma

- Ultra-high gradients (~10 GV/m) enable compact accelerators

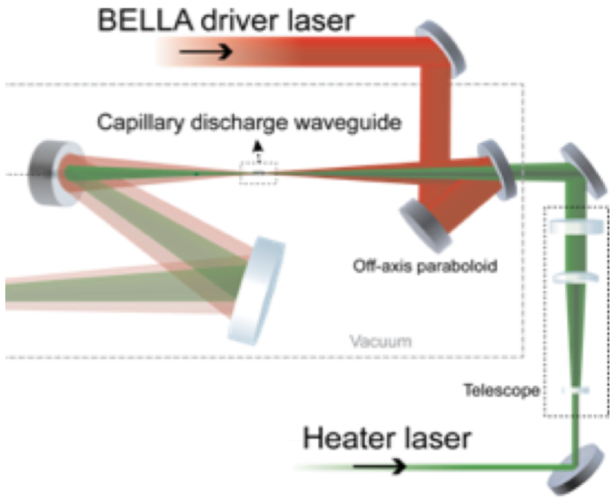
$$E \sim E_0 = m_e c \omega_p / e \simeq 96\sqrt{n_0[\mathrm{cm}^{-3}]}$$

Esarey, Schroeder, Leemans. Rev. Mod. Phys. (2009)

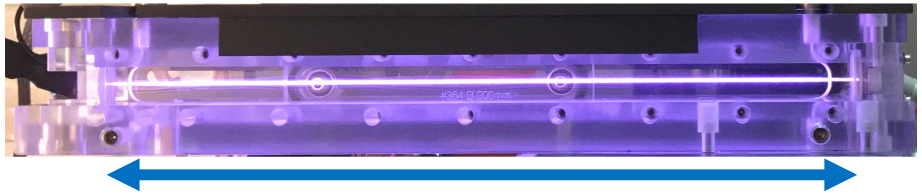
This slide is courtesy of C. B. Schroeder

Laser-plasma accelerator state-of-the-art: 8 GeV using PW laser

- Single laser-plasma accelerator achieved multi-GeV acceleration:
- 8 GeV energy gain in 20 cm (40 GV/m), at $n=3\times10^{17}$ cm^{-3} using 0.85 PW (BELLA) laser

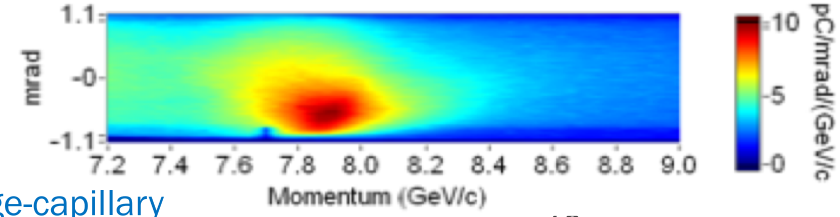


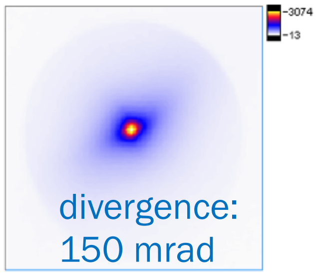
Laser-heater-assisted discharge-capillary plasma waveguide



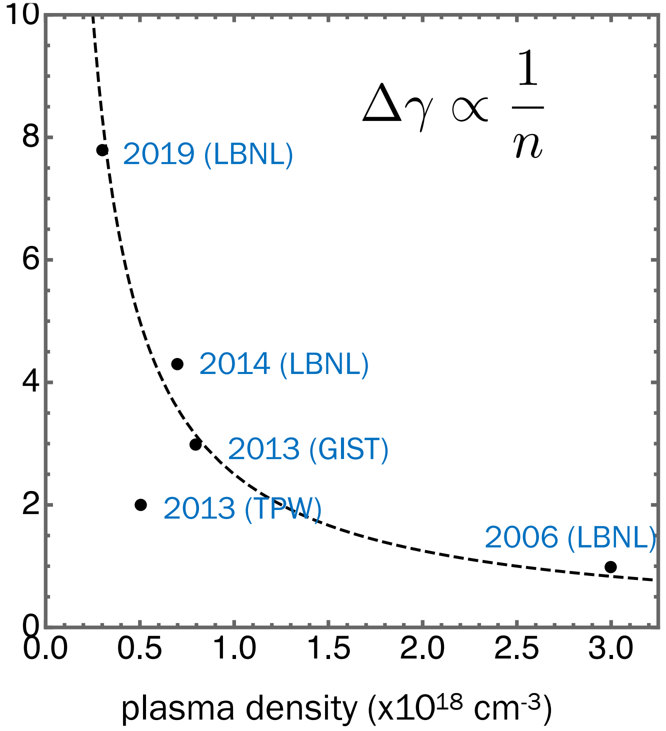
20 cm

Gonsalves et al. PRL (2019)





divergence: 150 mrad

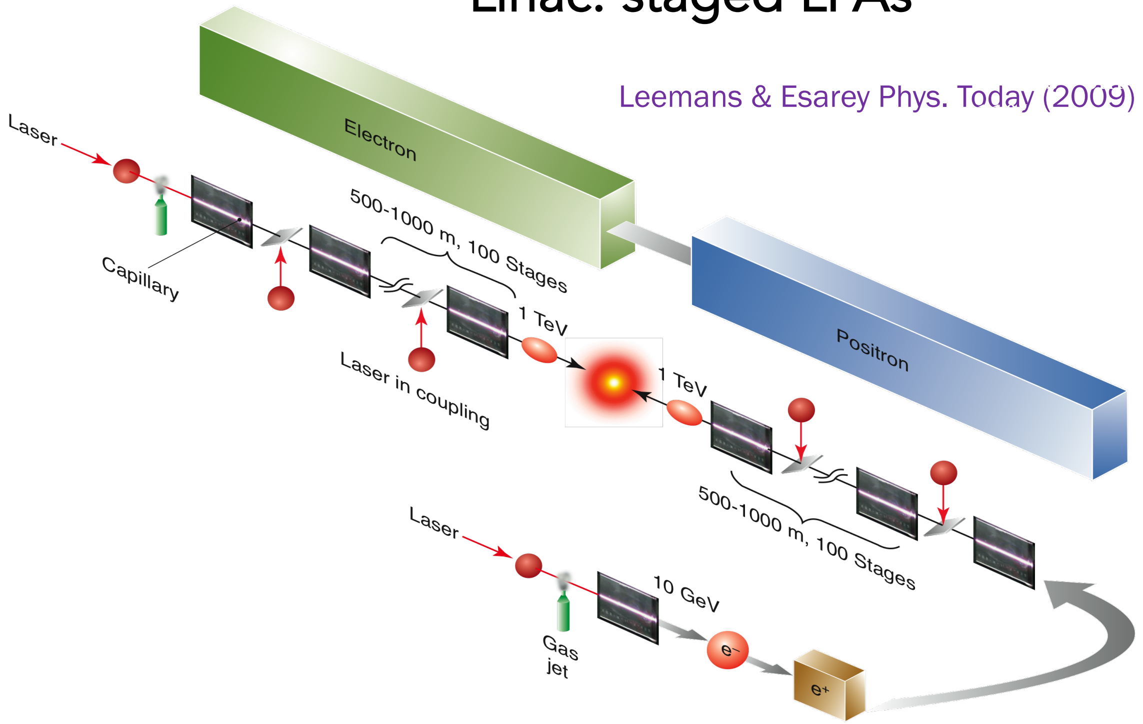


- *Key technology*: plasma channel creation for guiding at low density (3×10^{17} cm^{-3}) – discharge capillary + laser heater
- 1 Hz rep. rate

This slide is courtesy of C. B. Schroeder

Basic configuration of a laser-plasma linear collider

Linac: staged LPAs



- **Plasma density optimization: n ~ 10^{17} cm^{-3}**
- Staging & laser coupling into plasma channels:
  - J-class laser energy/stage required
  - multi-GeV energy gain/stage
- 10s of kHz rep. rate to achieve luminosity (100s kW)
- High laser efficiency required (tens %)

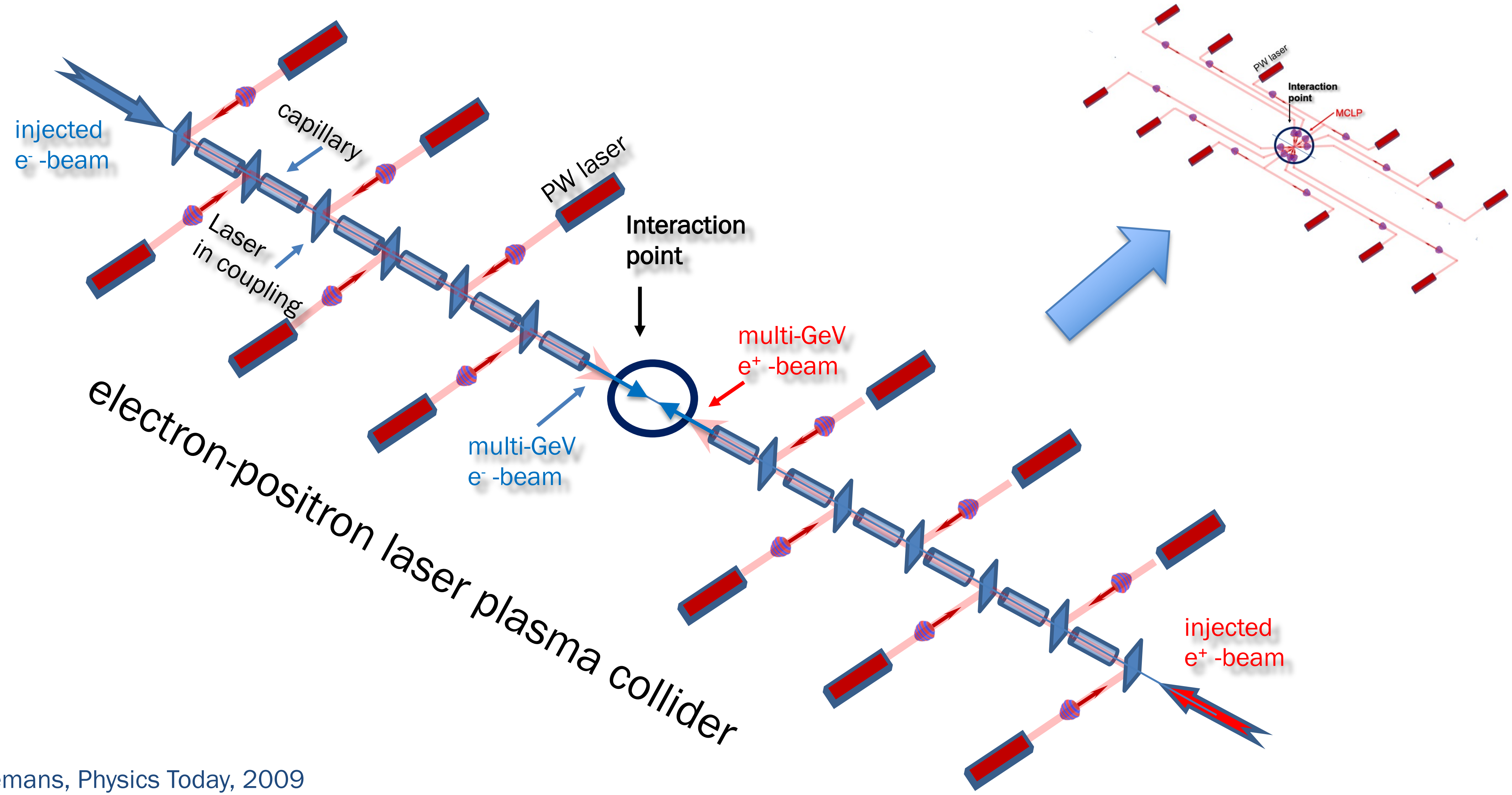
Event rate = (cross section)x(Luminosity)

$$\mathcal{L} \propto f N_b^2 \propto N_b P_b \propto N_b P_{\mathrm{avg.laser}}$$

- Average laser power requirement determined by luminosity goal
- Maximize charge/bunch to reduce average laser power requirements
- To reach luminosity ~10^{34} s^{-1} cm^{-2} requires tens of kHz rep rates (100s kW average laser power)

This slide is courtesy of C. B. Schroeder

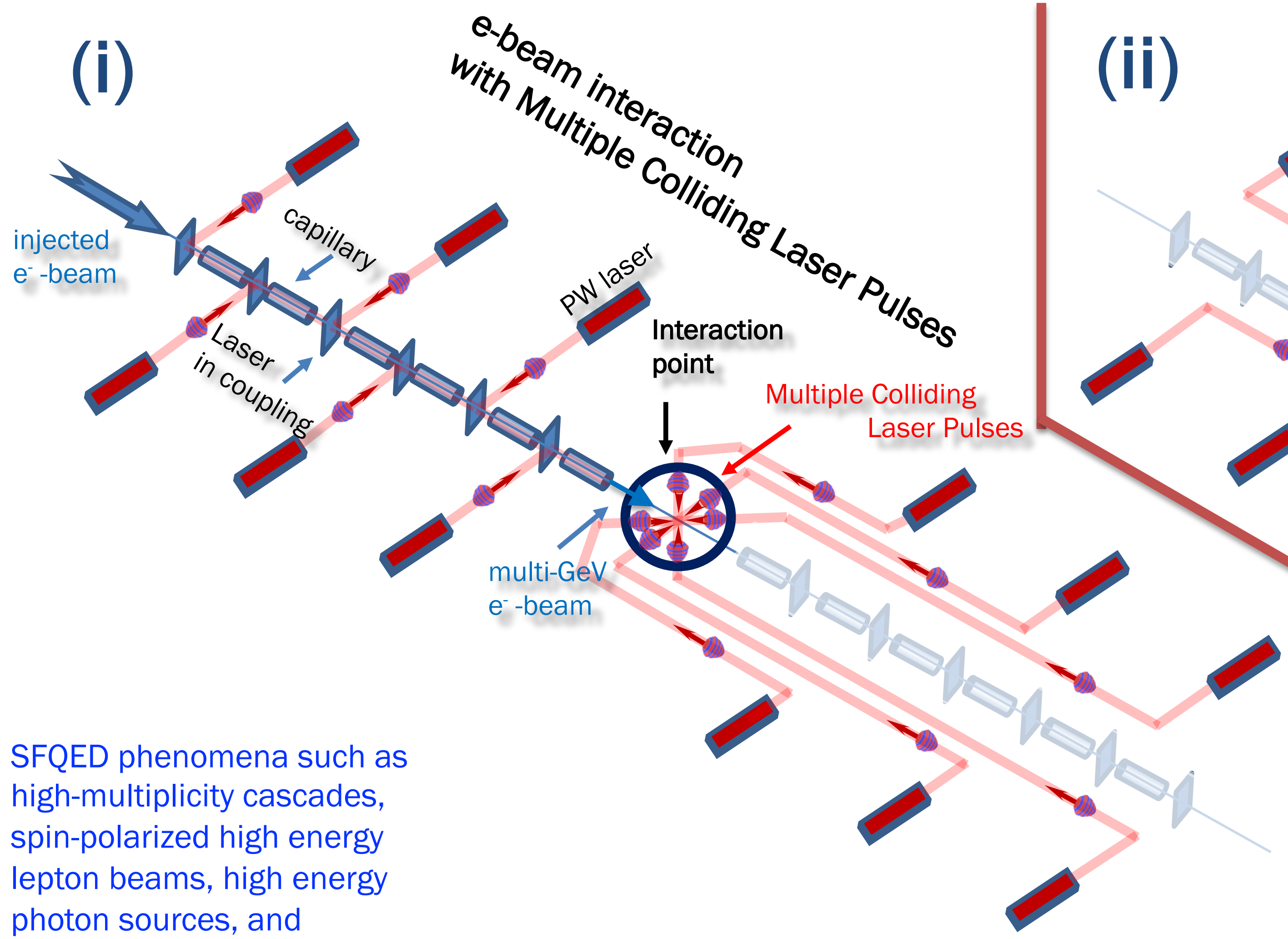
Plasma based collider can easily be made multi-purpose with minimal adjustments to its configuration



E. Esarey, W. P. Leemans, Physics Today, 2009

Two configurations are possible:
(i) e-beam laser interaction and (ii) laser – laser interaction

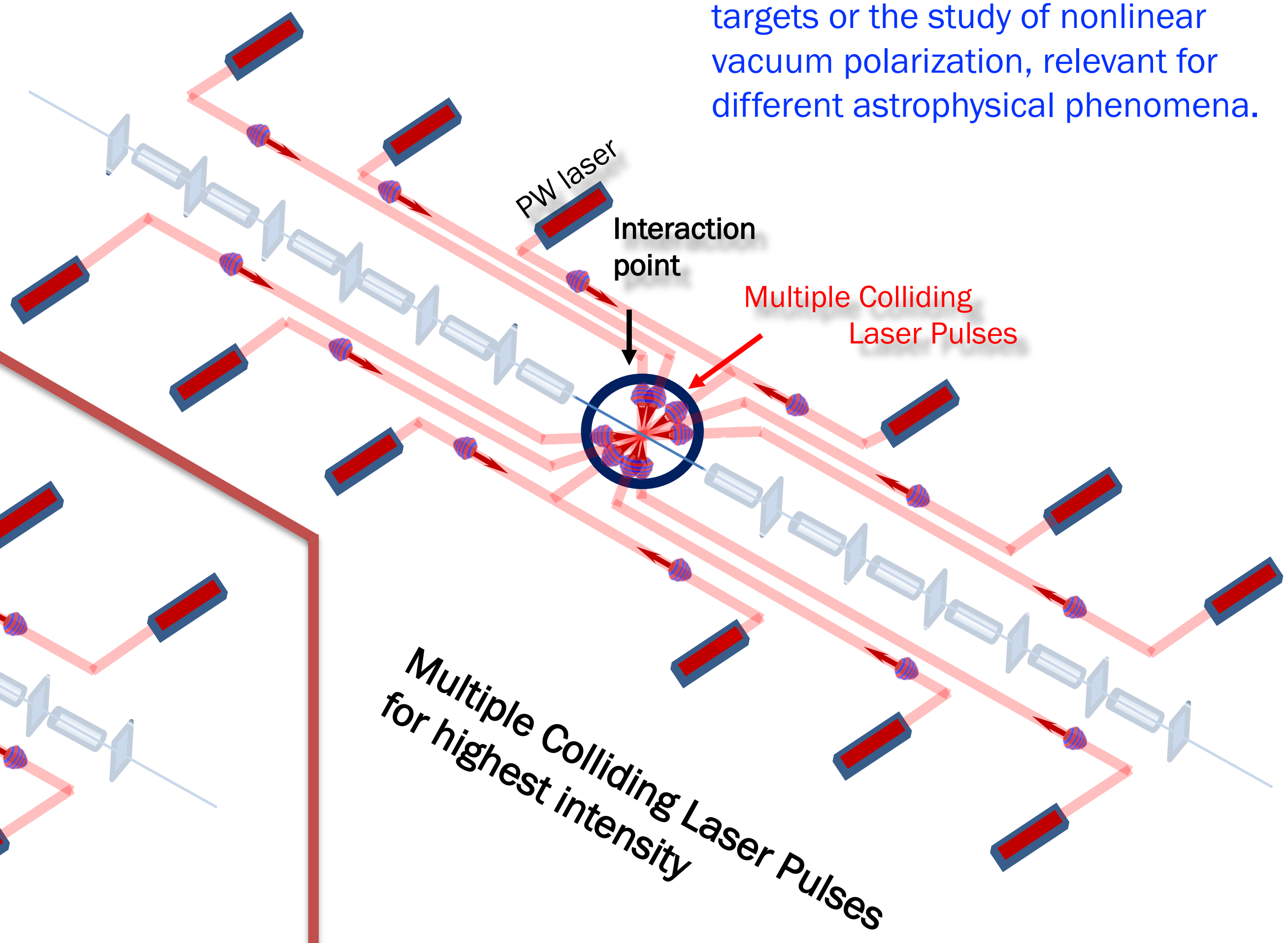
(i)



SFQED phenomena such as high-multiplicity cascades, spin-polarized high energy lepton beams, high energy photon sources, and prototype $\gamma\gamma$ colliders.

(ii)

Highest intensity for experiments involving different fixed plasma targets or the study of nonlinear vacuum polarization, relevant for different astrophysical phenomena.



P. Zhang, S. S. Bulanov, D. Seipt, A. V. Arefiev, and A. G. R. Thomas, Phys. Plasmas 27, 050601 (2020)

Optimal focusing of laser radiation can be obtained using multiple colliding laser pulses (MCLP)

- Optimal focusing in terms of a dipole wave

I.M. Bassett, Opt. Acta **33**, 279 (1986);
I. Gonoskov et al., PRA **86**, 053836 (2012).

- e^+e^- pair production by MCLP

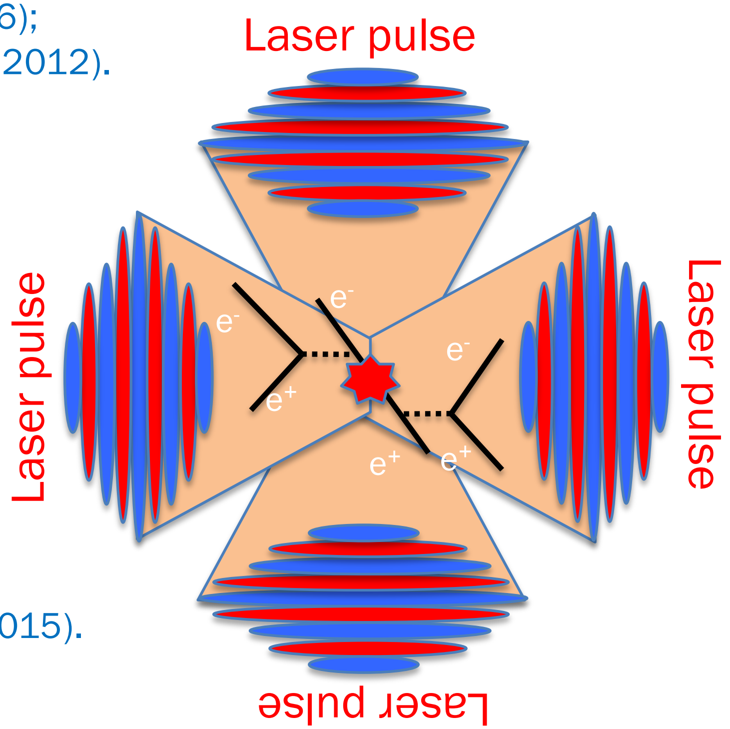
S.S. Bulanov et al., PRL **104**, 220404 (2010);
S.S. Bulanov et al., PRL **105**, 220407 (2010);
A. Gonoskov et al., PRL **111**, 060404 (2013).

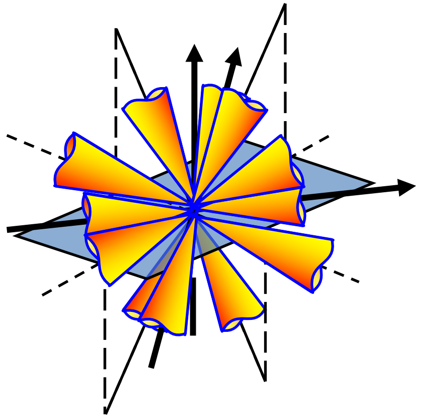
- EM cascades in MCLP

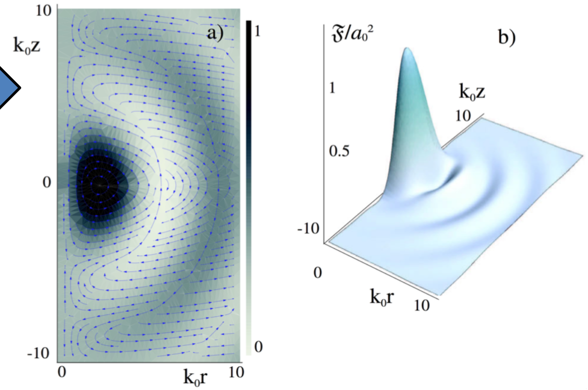
A. Gonoskov et al., PRL **113**, 014801 (2014).
E. G. Gelfer et al., Phys. Rev. A 92, 022113 (2015).
M. Vranic et al., PPCF **59**, 014040 (2017).
Z. Gong et al., PRE **95**, 013210 (2017).

- Directed source of GeV photons

A. Gonoskov et al., Phys. Rev. X 7, 041003 (2017).







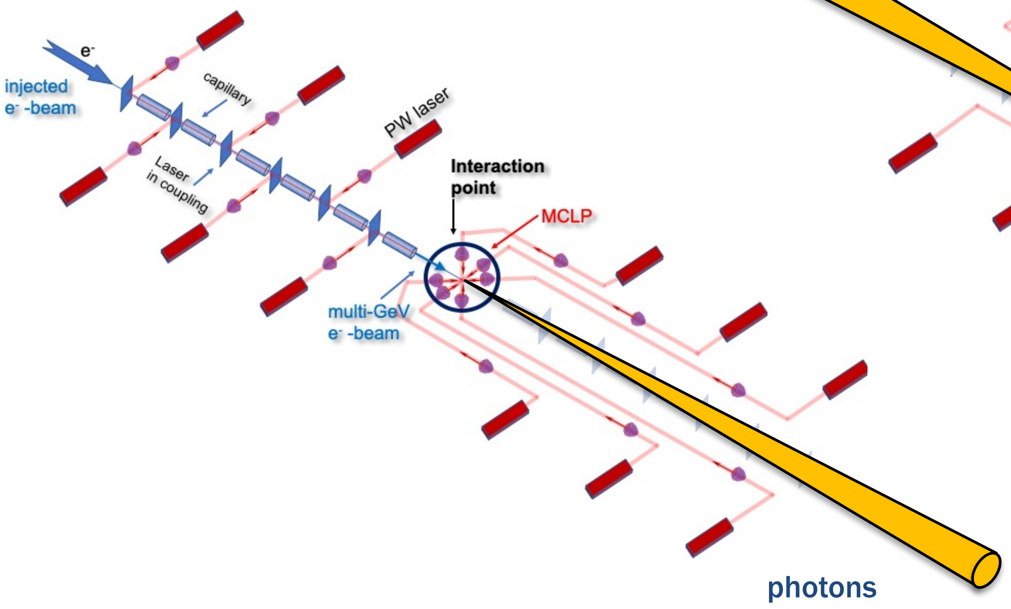
- MCLP + e-beam = Basis for studying high-energy high-intensity physics

$$a_0 \sim 800\sqrt{\mathcal{P}\,[\mathrm{PW}]}$$

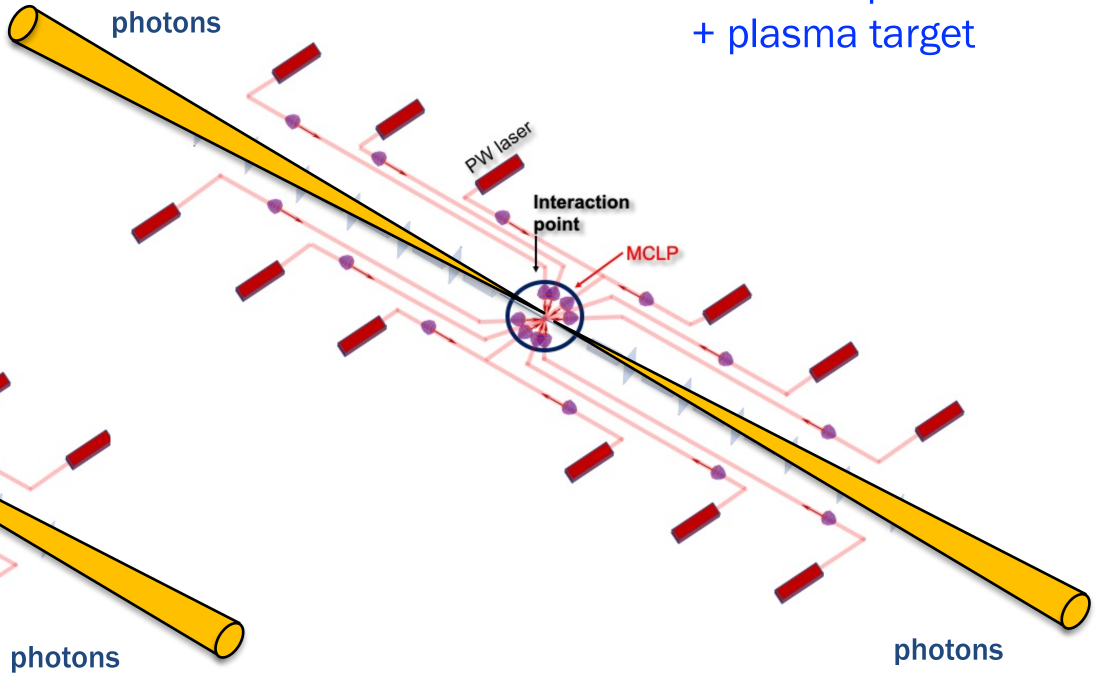
J. Magnusson, et al, Phys. Rev. Lett. 122, 254801 (2019)
J. Magnusson, et al, Phys. Rev. A 100, 063404 (2019)

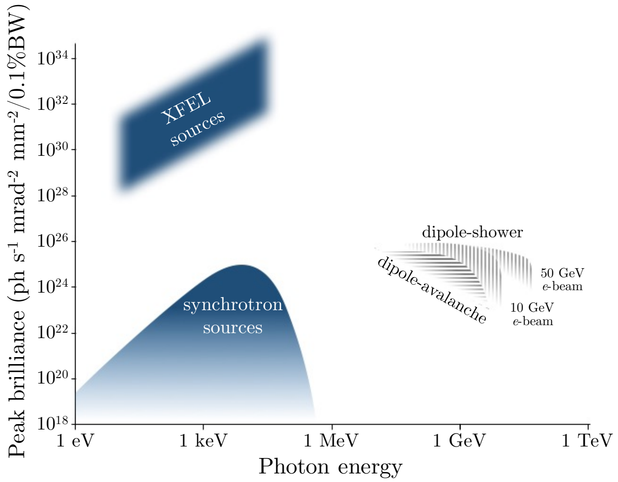
Multiple-Beam laser facility can efficiently produce multi-GeV photon beam with high peak brilliance and high average flux

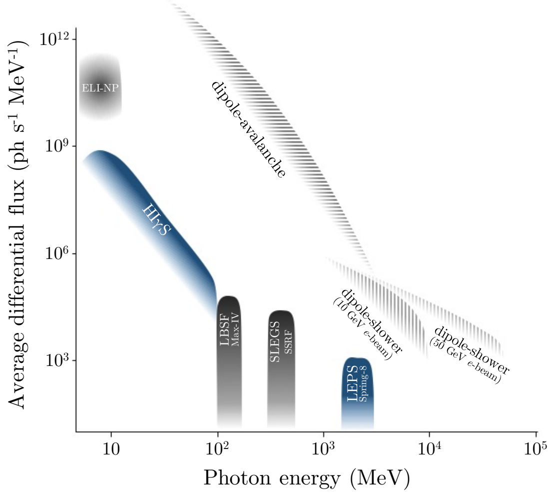
e-beam interaction with
Multiple Colliding Laser Pulses
<u>dipole-shower:</u>
0.4 PW total laser power
+ 10 or 50 GeV e-beam



Multiple Colliding Laser Pulses
<u>dipole-avalanche</u>:
8 PW total laser power
+ plasma target



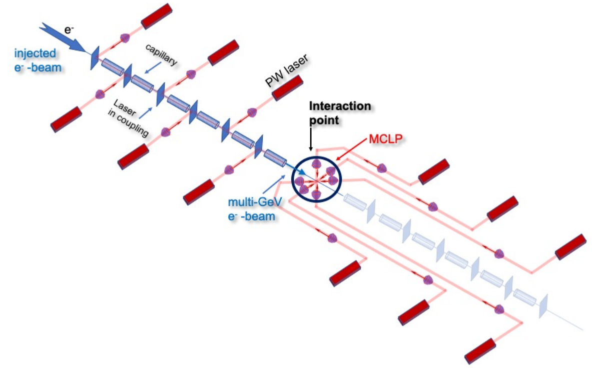


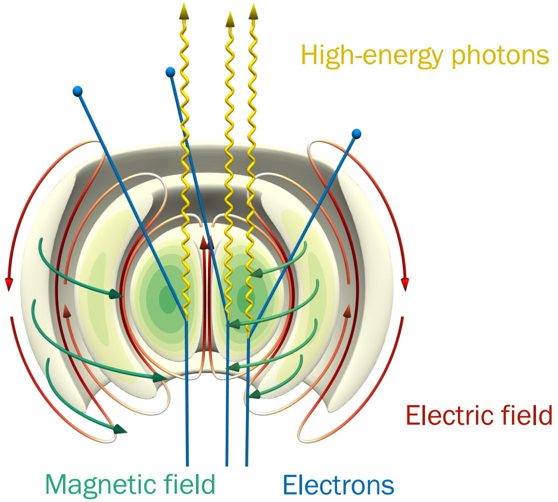


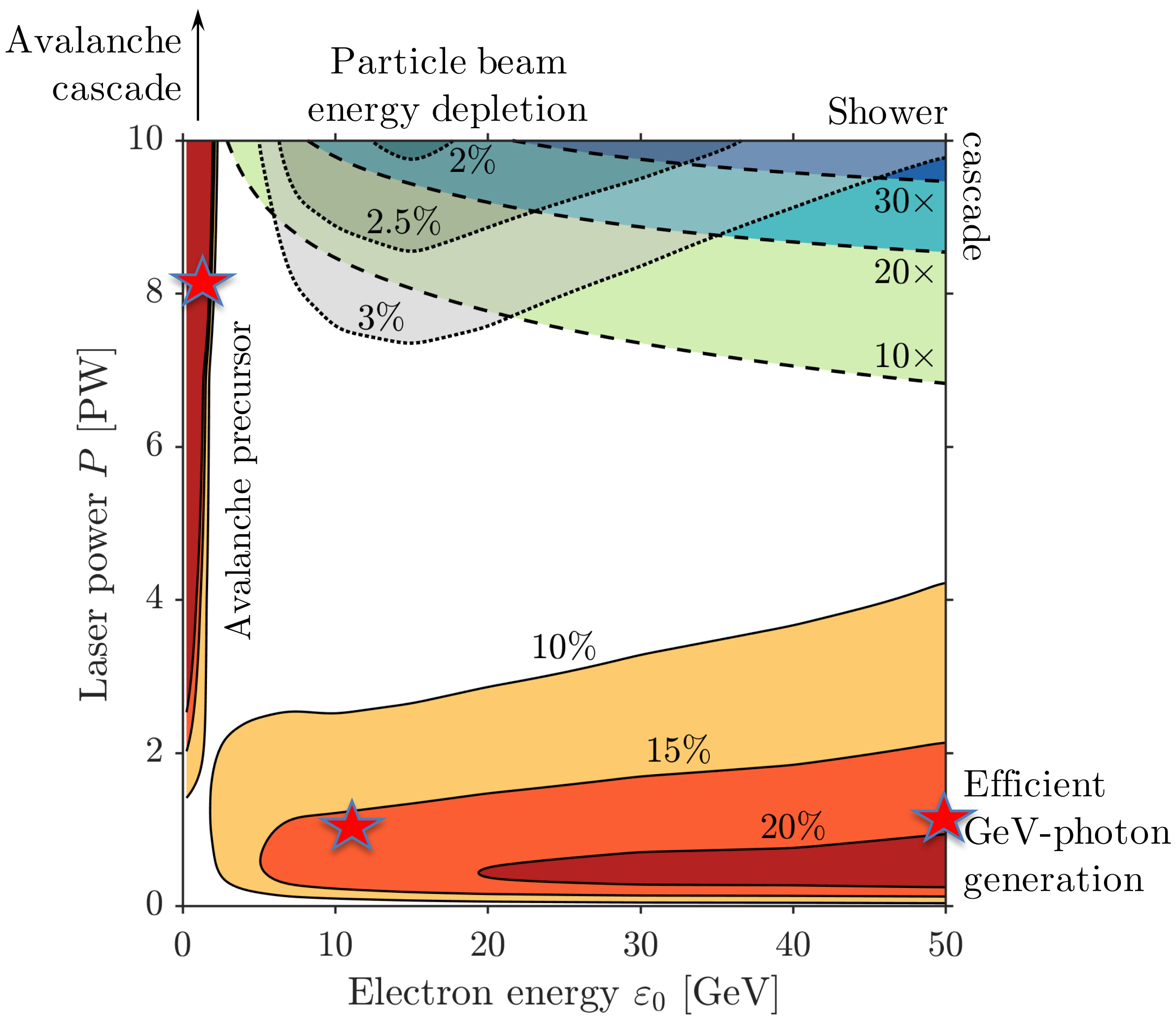
J. Magnusson, et al, Phys. Rev. Lett. 122, 254801 (2019)
J. Magnusson, et al, Phys. Rev. A 100, 063404 (2019)

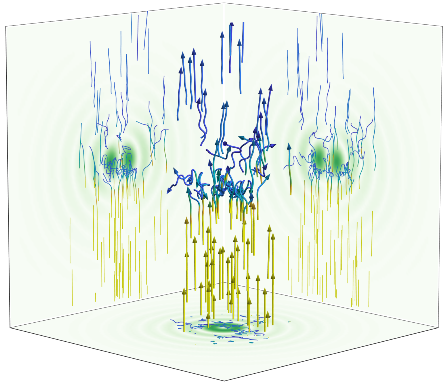
A. Gonoskov, et al, Phys. Rev. X 7, 041003 (2017).

The interaction of a high energy electron beam with MCLP makes assessible different SF QED phenomena





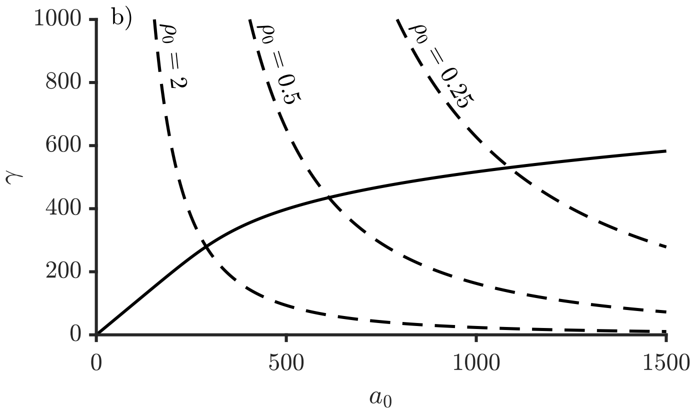




J. Magnusson, et al, Phys. Rev. Lett. 122, 254801 (2019)
J. Magnusson, et al, Phys. Rev. A 100, 063404 (2019)

QED PIC code ELMIS: A. Gonoskov, et al., Phys. Rev. E 92, 023305 (2015)

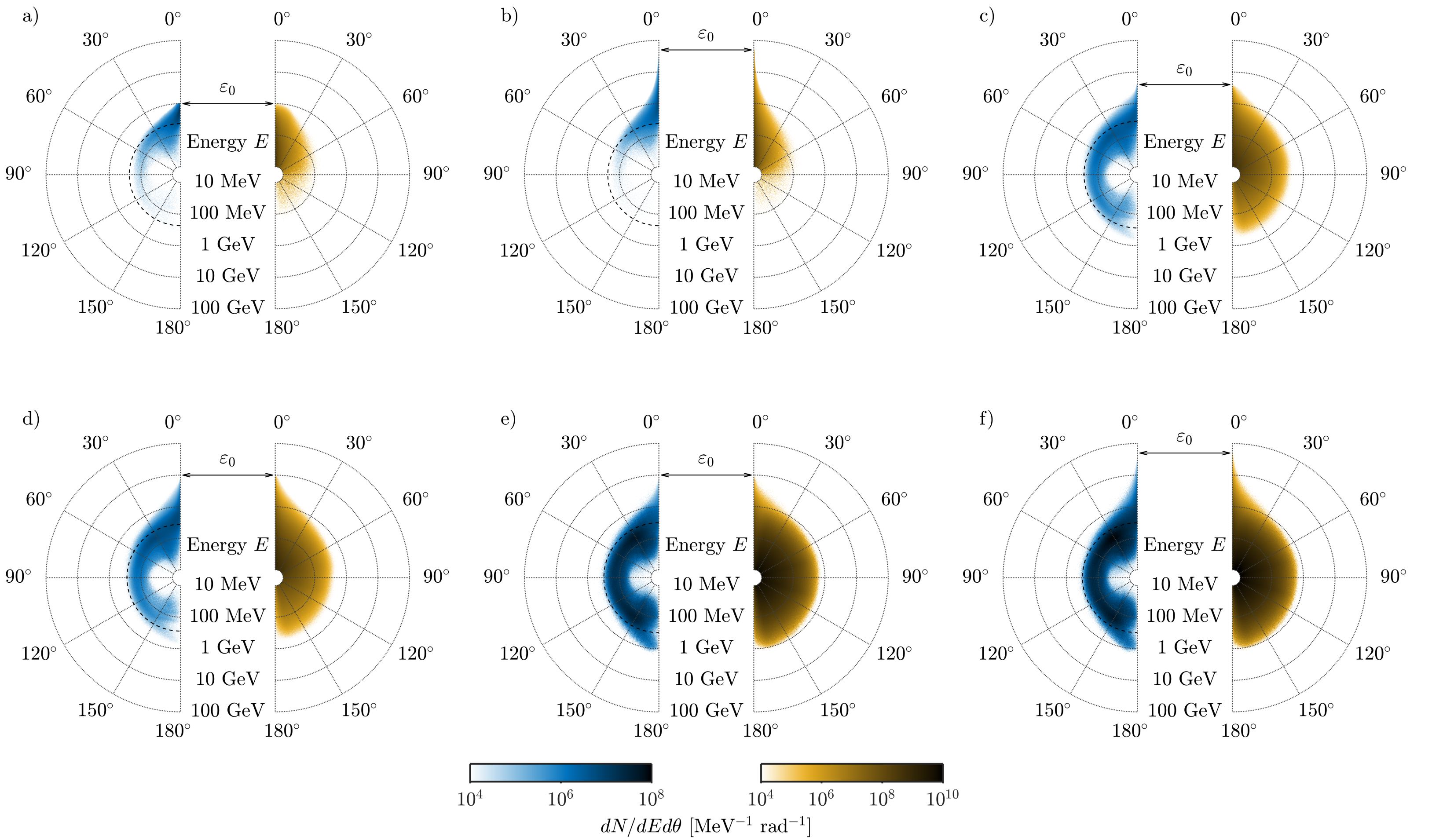
Extreme e-beam energy depletion gives rise to two distinct populations of photons and electron-positron pairs



High energies
The high energy photons and electrons are collimated along the electron beam axis

Low energies
There is a near isotropic emission of lower energy photons and electron-positron pairs

Low energy emission come from the (re)acceleration of decelerated electrons and generated pairs



Energy-angle distributions of electrons (blue, left) and photons (yellow, right) emitted from the interaction for six cases of laser power P and initial electron energy ε_0: (a) 1 PW and 1 GeV, (b) 1 PW and 50 GeV, (c) 4 PW and 4 GeV, (d) 4 PW and 10 GeV, (e) 10 PW and 10 GeV, and (f) 10 PW and 50 GeV.

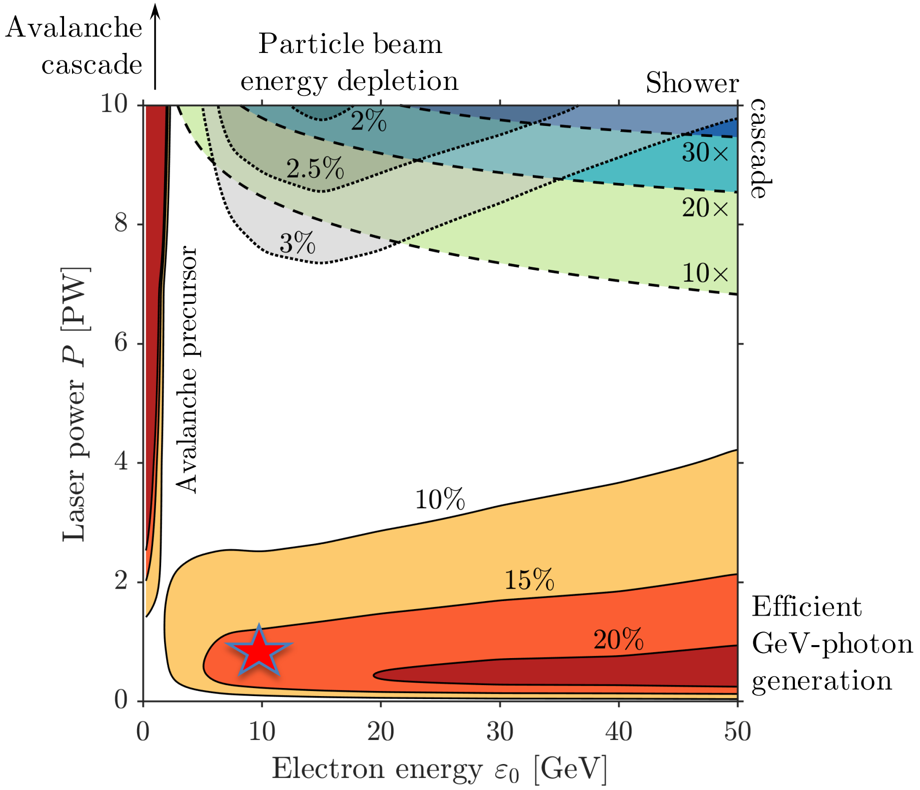
Conclusions

- Optimal for a number of SF QED processes (pair production, EM cascades and avalanches, generation of GeV photons) laser focusing can be realized through the Multiple Colliding Laser Pulses configuration.

- The MCLP configuration when combined with a high energy electron beam provides an effective way of transformation of beam energy into high energy photons.

- The initial electron beam energy and total MCLP power optimal for generation of GeV photons are within reach of PW-class laser facilities.

- The interaction of a high energy electron beam with the MCLP leads to a fast depletion of the electron beam energy.



Thank you!