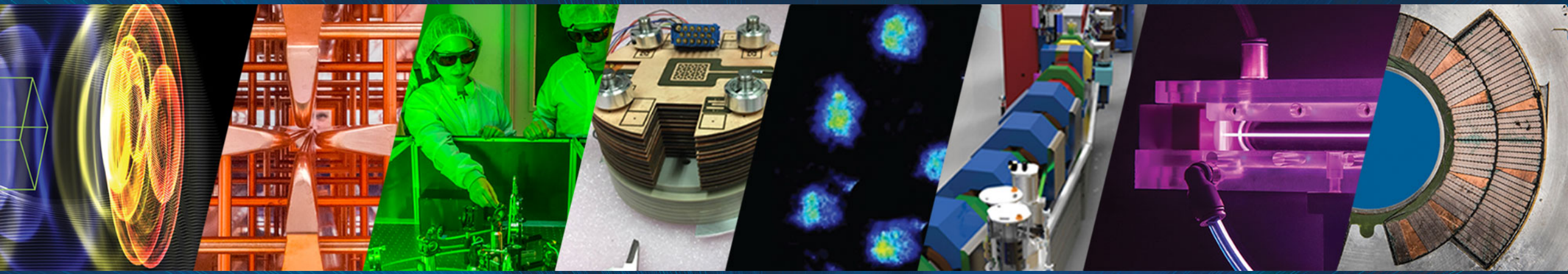
LCWS2023
INTERNATIONAL WORKSHOP ON LINEAR COLLIDERS

High energy physics studies at PW-class laser and advanced accelerator linear collider facilities



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U.S. DEPARTMENT OF ENERGY | Office of Science

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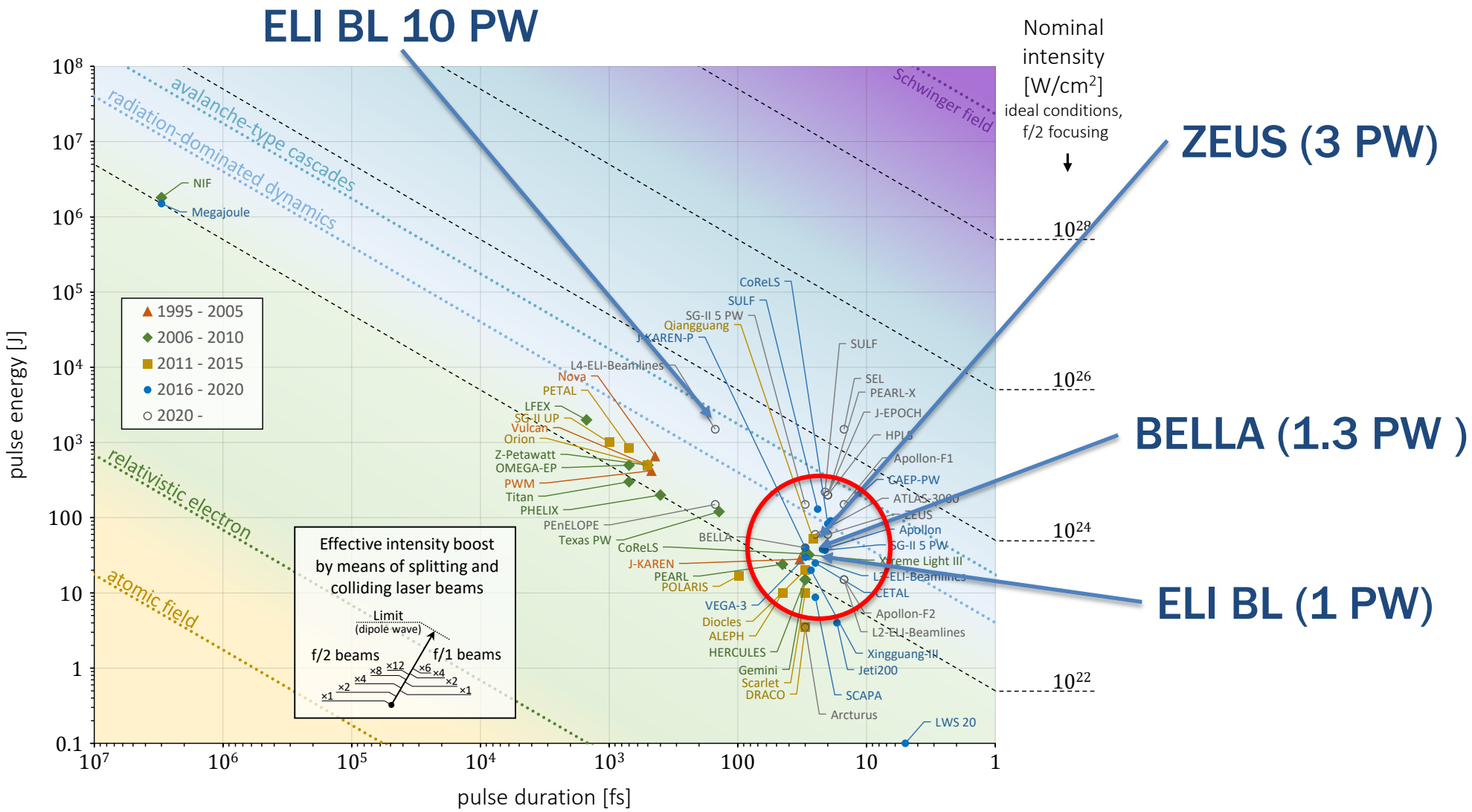
High-power lasers are able to generate strong electromagnetic fields, which can probe different regimes of charged particle interactions



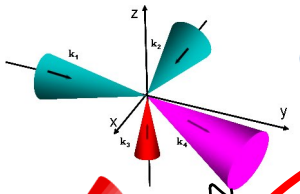
Charged particle motion and radiation in strong electromagnetic fields A. Gonoskov, T. G. Blackburn, M. Marklund, and S. S. Bulanov, Rev. Mod. Phys. (2022)

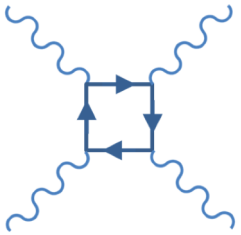
Strong Field Quantum Electrodynamics describes the phenomena in strong EM fields in the environments where the field strength is large relative to the QED critical field

Laser fields may provide both strong electromagnetic fields and generate high-energy particles and therefore represent a particularly interesting environment for studying a number of High Intensity Particle Physics effects.

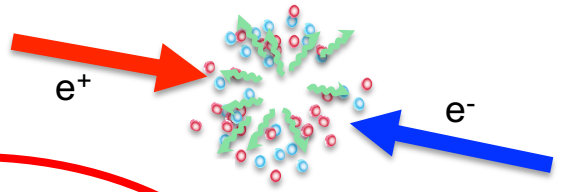
4-wave mixing

(Lundström et al, 2006)

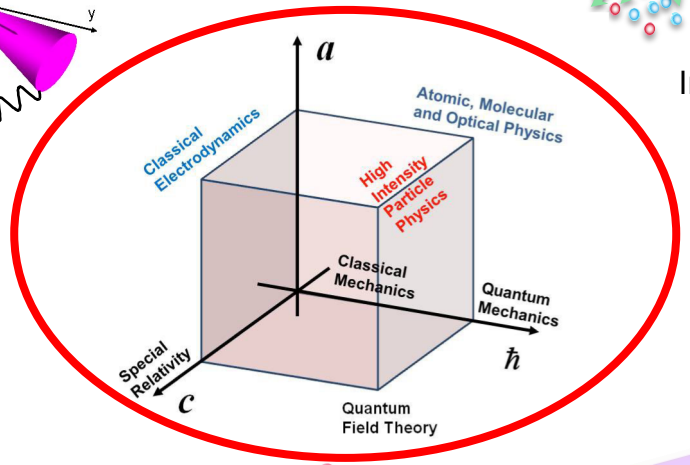




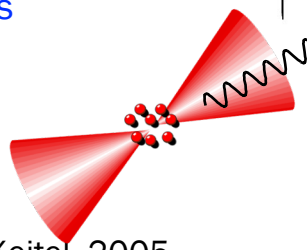
Photon-photon scattering via relativistic mirrors (Koga et al (2012))



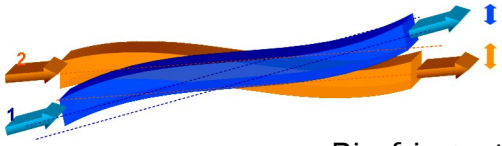
- Nonperturbative Quantum Field Theory
- Matter in Extreme conditions
- Next generation lasers
  - Day-to-day operation
  - New applications
- Future lepton colliders
- Future $\gamma\gamma$ colliders
- Various astrophysical phenomena



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

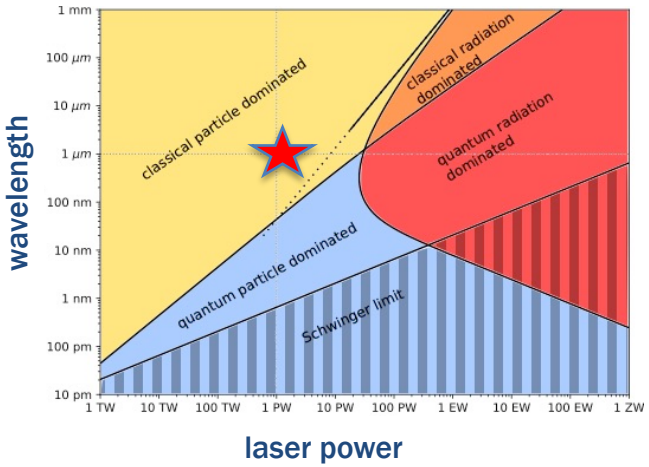


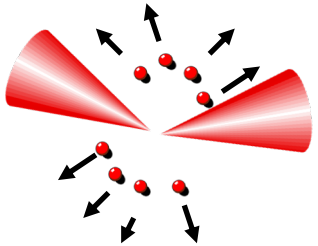
High order harmonic generation (Di Piazza, Hatsagortsyan, C. H. Keitel, 2005 Fedotov & Narozhny, 2006)



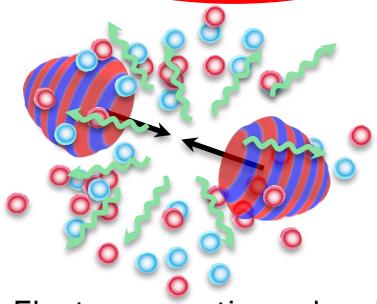
Birefringent e.m. vacuum

(Rozanov, 1993)



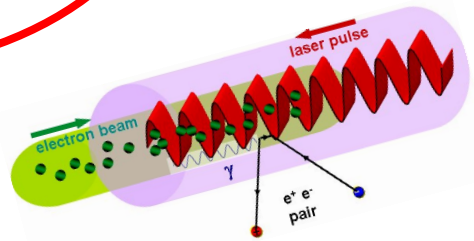


Electron positron pair production from vacuum (Schwinger, 1951)



- Electromagnetic avalanches
- Electromagnetic cascades

(Bell&Kirk, 2008)



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)

Sources of strong fields and why focus on lasers?

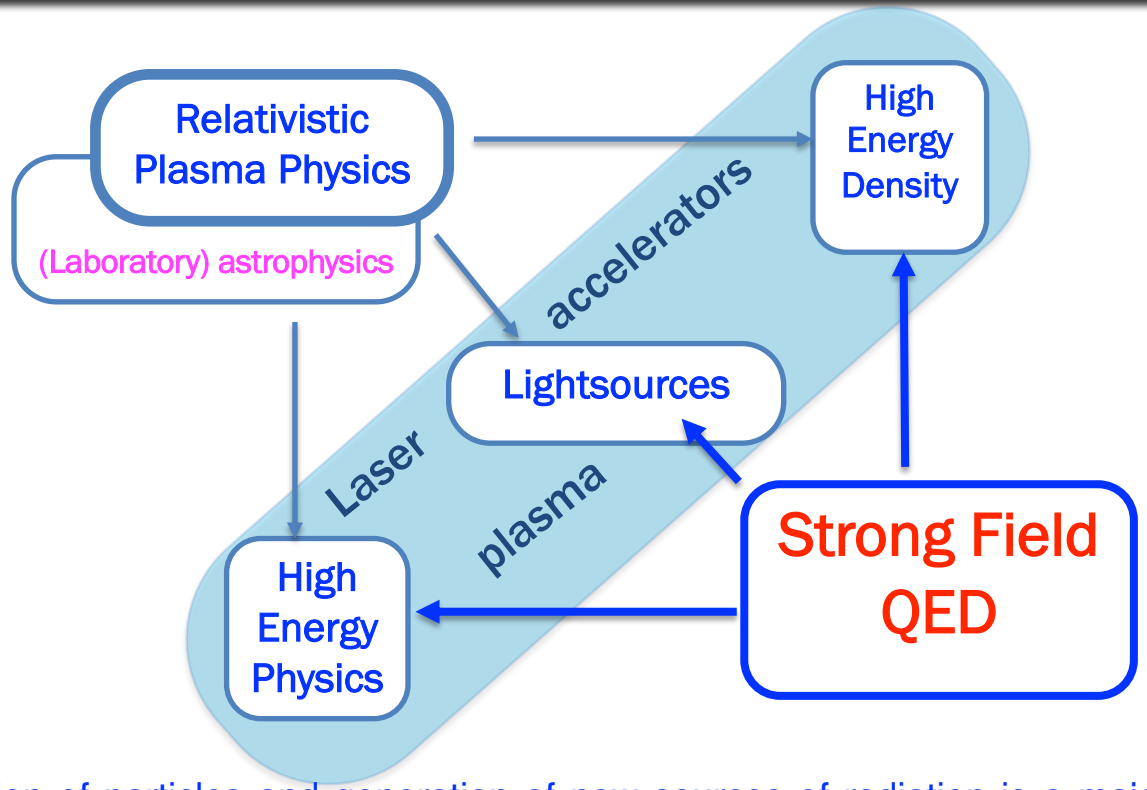
1. The magnetic fields surrounding compact astrophysical objects, such as pulsars, magnetars and black holes

2. The boosted, collective Coulomb fields of ultrarelativistic, dense lepton bunches, as found at the final focus of conventional particle accelerators

3. The electric fields around high-Z nuclei

4. The coherently summed, nuclear electric fields observed by ultrarelativistic leptons travelling through a crystal along an axis of symmetry

5. The electromagnetic fields produced by focusing of high-power lasers.



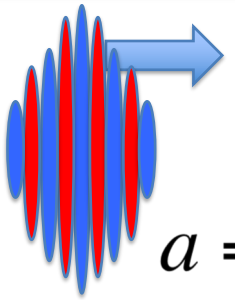
Acceleration of particles and generation of new sources of radiation is a major part of the scientific case for new high-power laser facilities. Since the regimes of these applications will be affected or even dominated by the interplay between collective plasma effects and strong field quantum processes, it is of paramount importance that such studies become an integral part of the scientific program.

Moreover, the architecture of such laser accelerator facilities makes it natural to study SFQED on-site.

P. Zhang, et al, PoP 2020

Behavior of particles and fields is characterized by Lorentz invariant parameters

Classical nonlinearity parameter



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

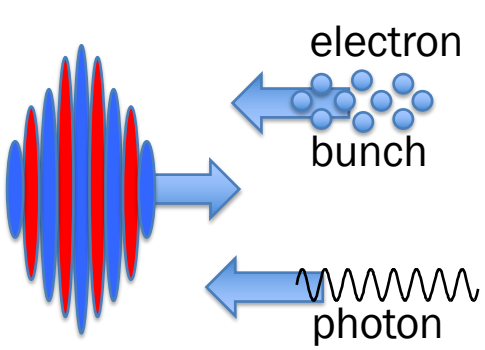
Electron energy gain over laser wavelength in units of mc^2

$a = 1$ → 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

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

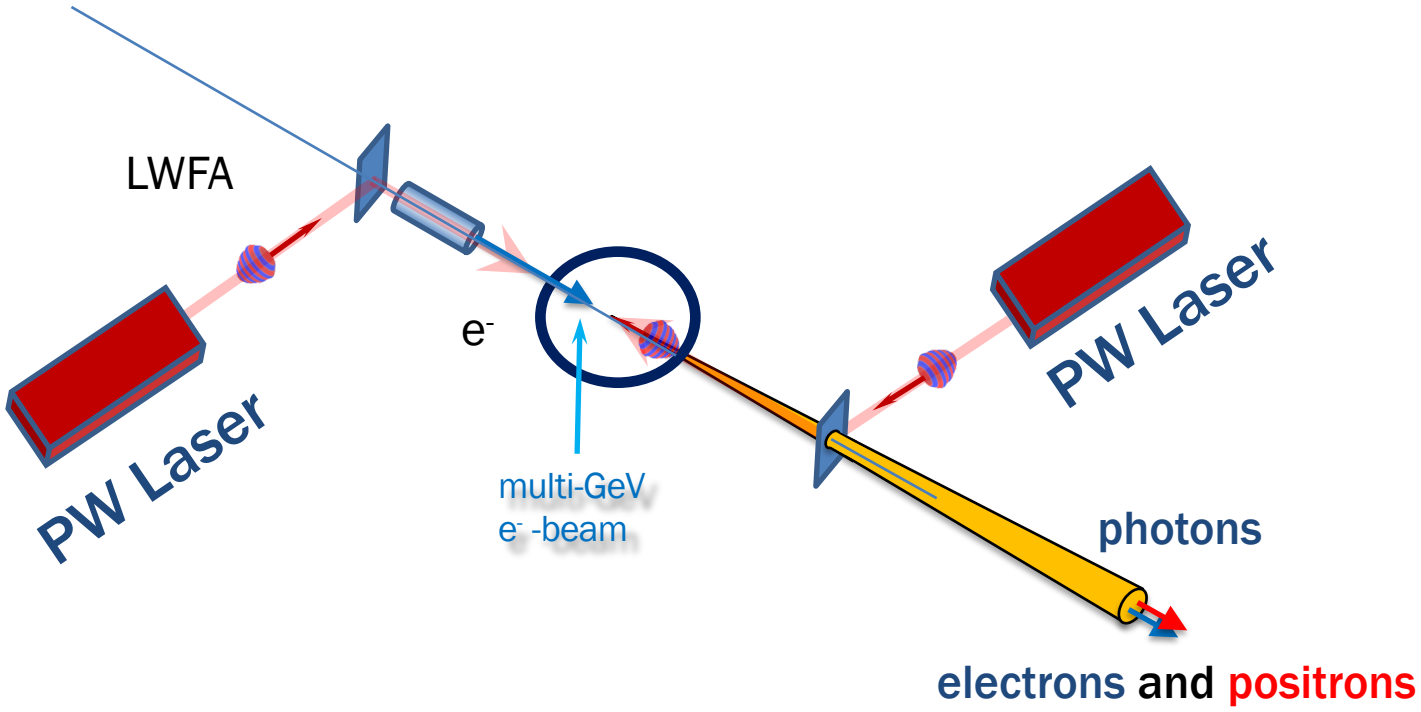
Quantum Effects

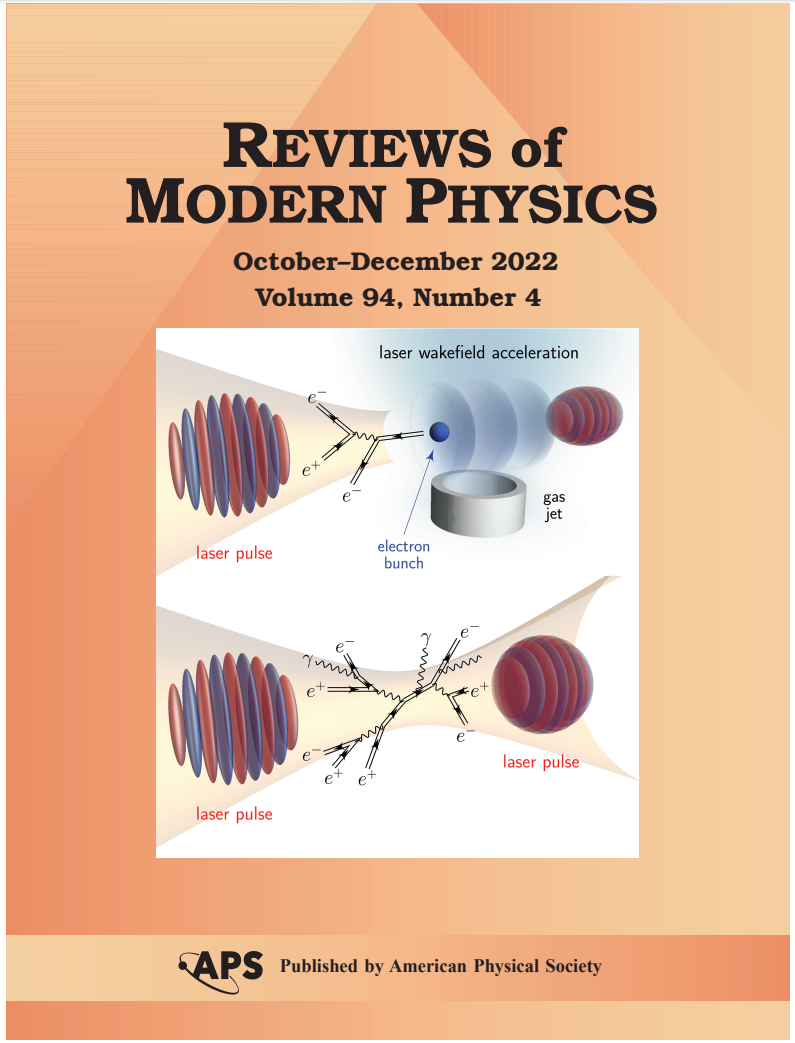


$$\chi_e = \frac{e\hbar\sqrt{(F_{\mu\nu}p^\nu)^2}}{m^3c^4}$$

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

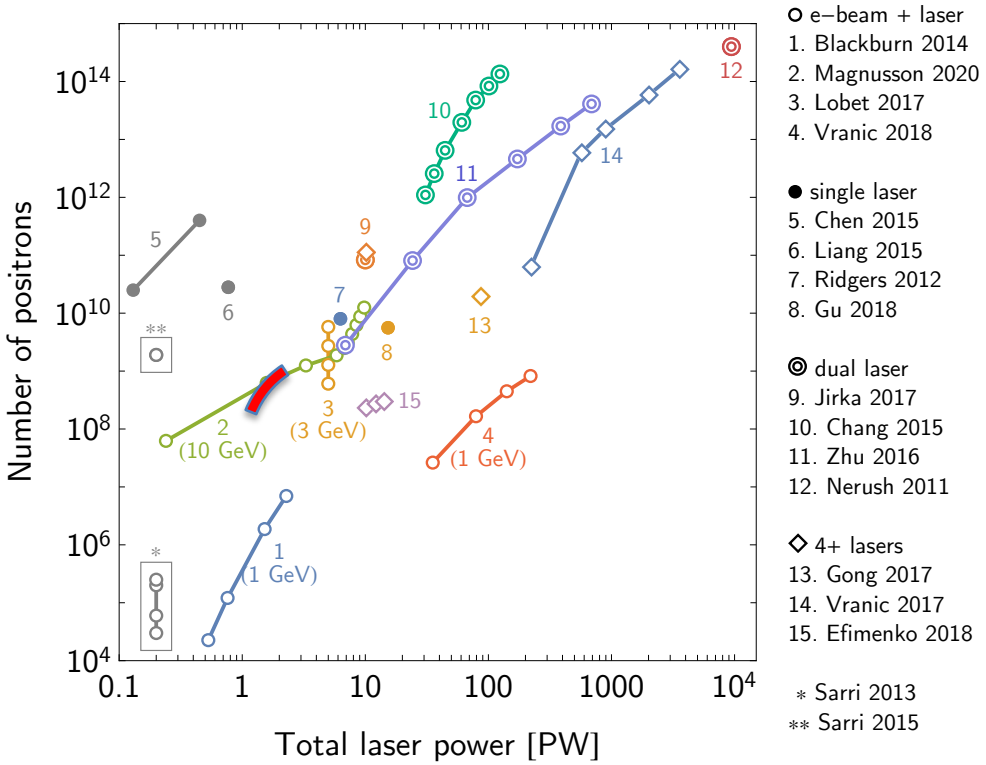
The interaction of a multi-GeV electron beam with a PW class laser pulse will produce photons and electron-positron pairs.



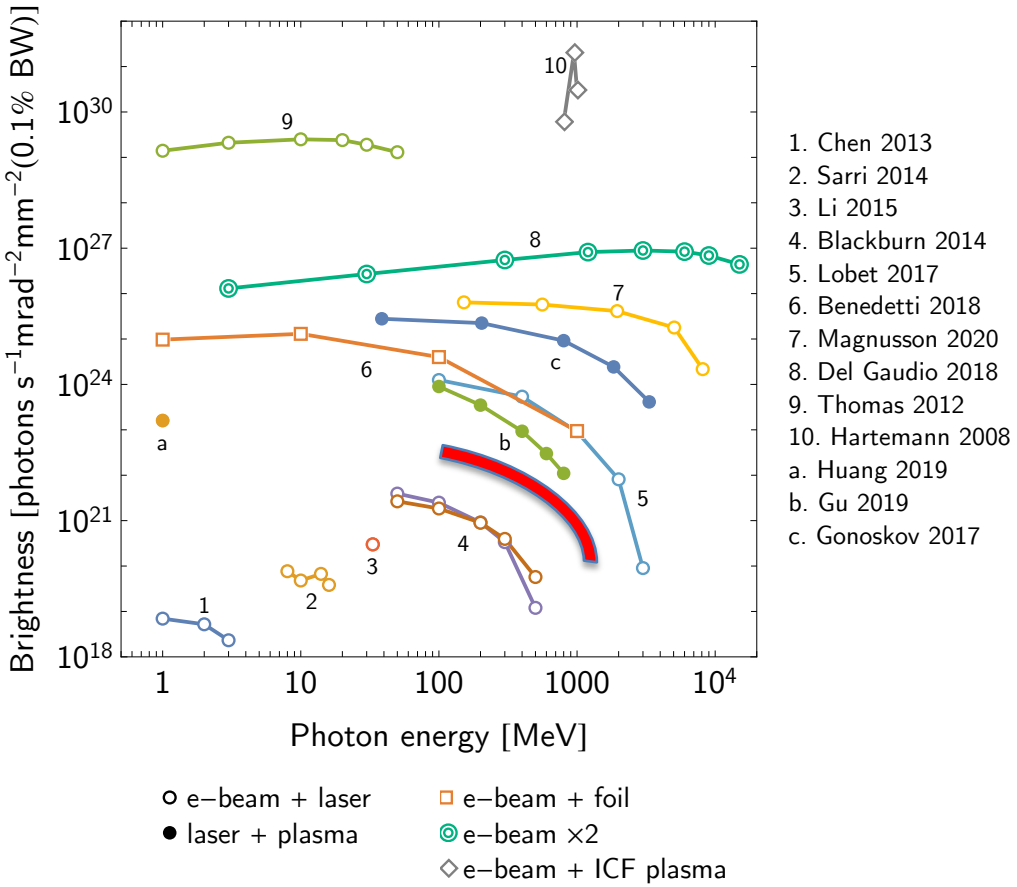


Charged particle motion and radiation in strong electromagnetic fields, A. Gonoskov, T. G. Blackburn, M. Marklund, and S. S. Bulanov, Rev. Mod. Phys. (2022)

What can be expected in terms of positron and photon production by high intensity lasers?



Number of positrons produced in high-intensity laser-plasma interactions. For laser-electron beam interactions (open circles), the energy of the electron beam is noted in brackets. Points marked with asterisks indicate experimental results from LWFA electron-beam interactions with high-Z foils; in these cases the laser power is not indicated.



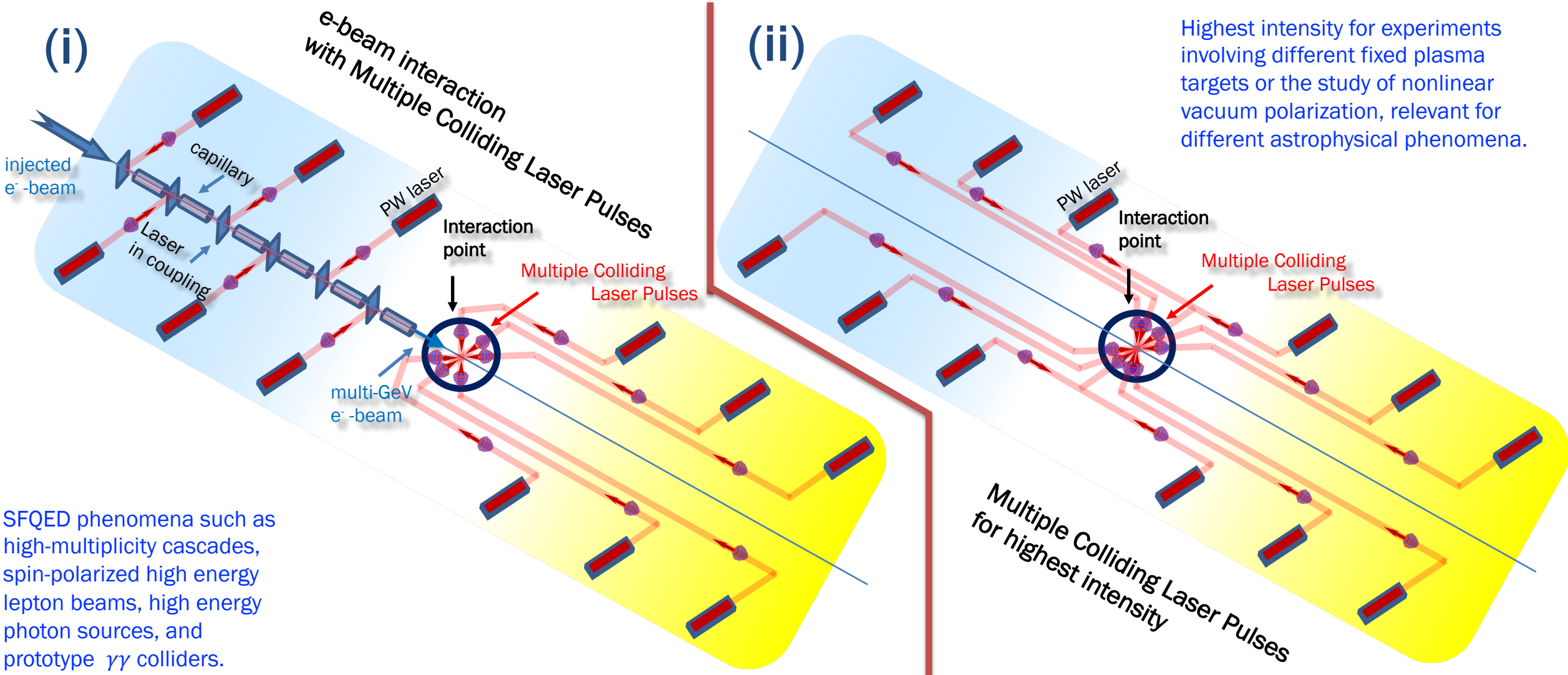
Brightness of radiation emitted in high-intensity laser interactions with electron beams (open circles) or plasma targets (filled circles), as well as in non-laser strong-field environments, as (1-2) measured in recent experiments and (3-) predicted by simulations.

Charged particle motion and radiation in strong electromagnetic fields, A. Gonoskov, T. G. Blackburn, M. Marklund, and S. S. Bulanov, Rev. Mod.Phys. (2022)

How higher electromagnetic field strength can be achieved?

Multi-PW and Multiple-beam laser facility is expected to reach new regimes of SFQED

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



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

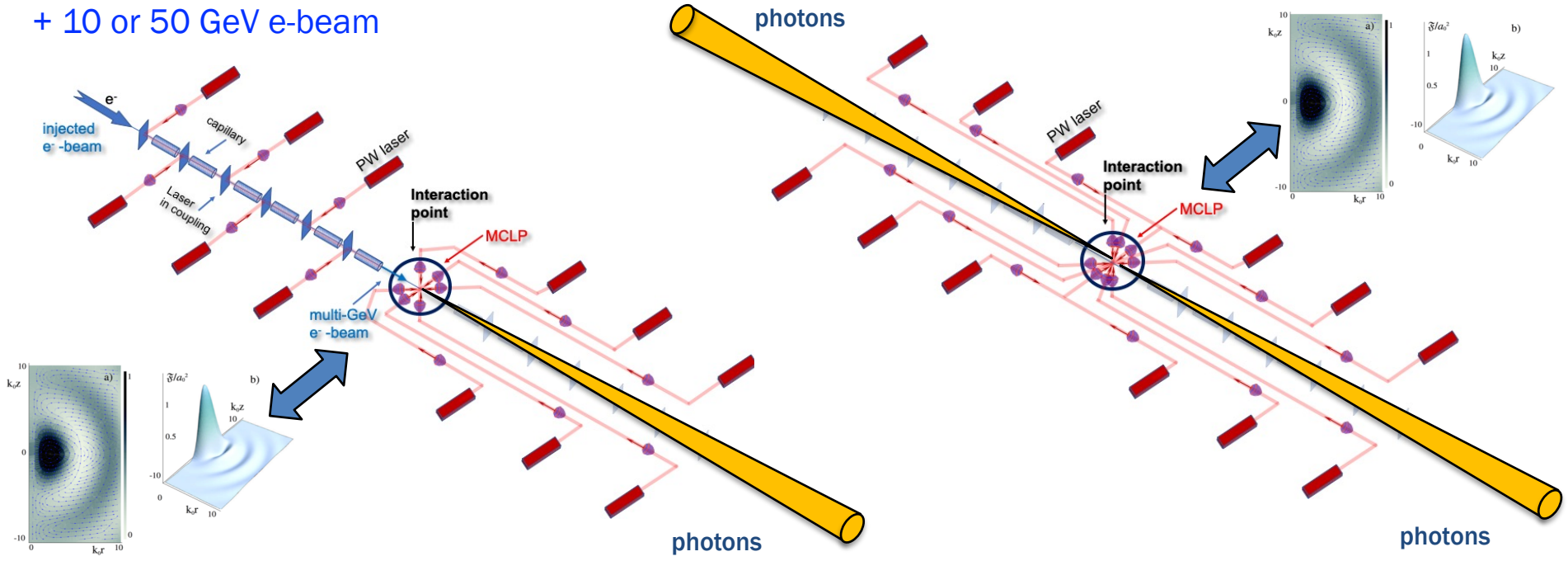
SFQED phenomena such as high-multiplicity cascades, spin-polarized high energy lepton beams, high energy photon sources, and prototype $\gamma\gamma$ colliders.

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

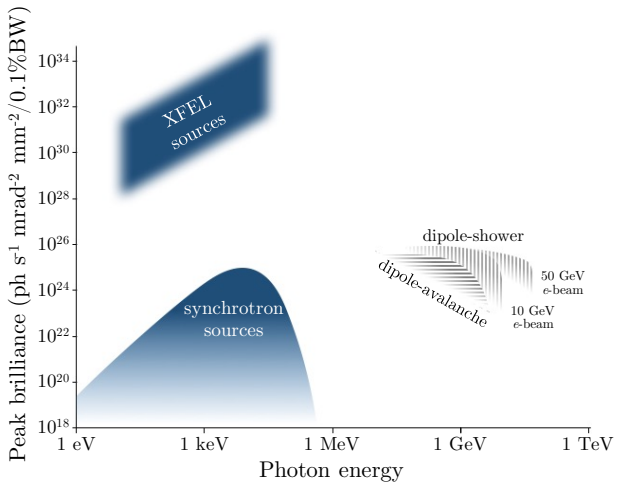
Multiple-Beam laser facility can efficiently produce multi-GeV photon beam with high peak brilliance and high average flux

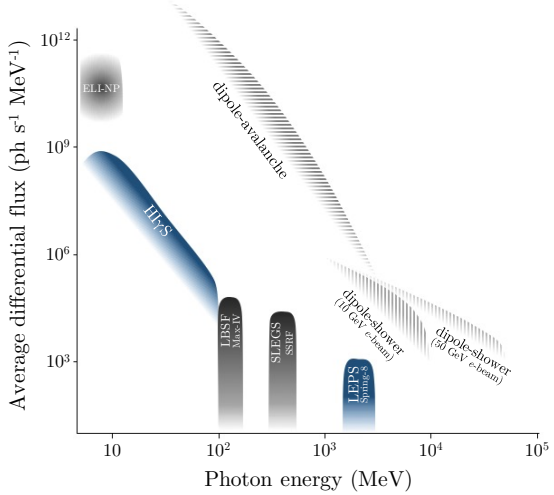
e-beam interaction with
Multiple Colliding Laser Pulses
dipole-shower:
0.4 PW total laser power
+ 10 or 50 GeV e-beam

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



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

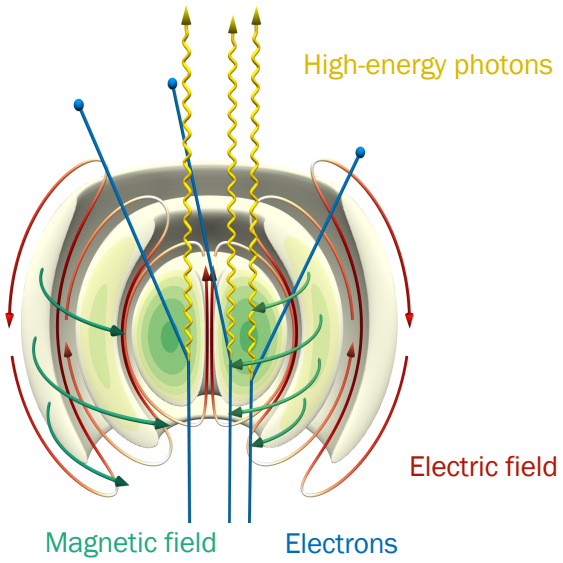


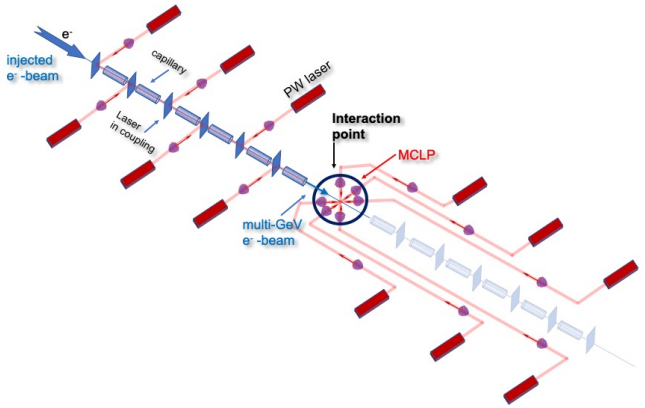


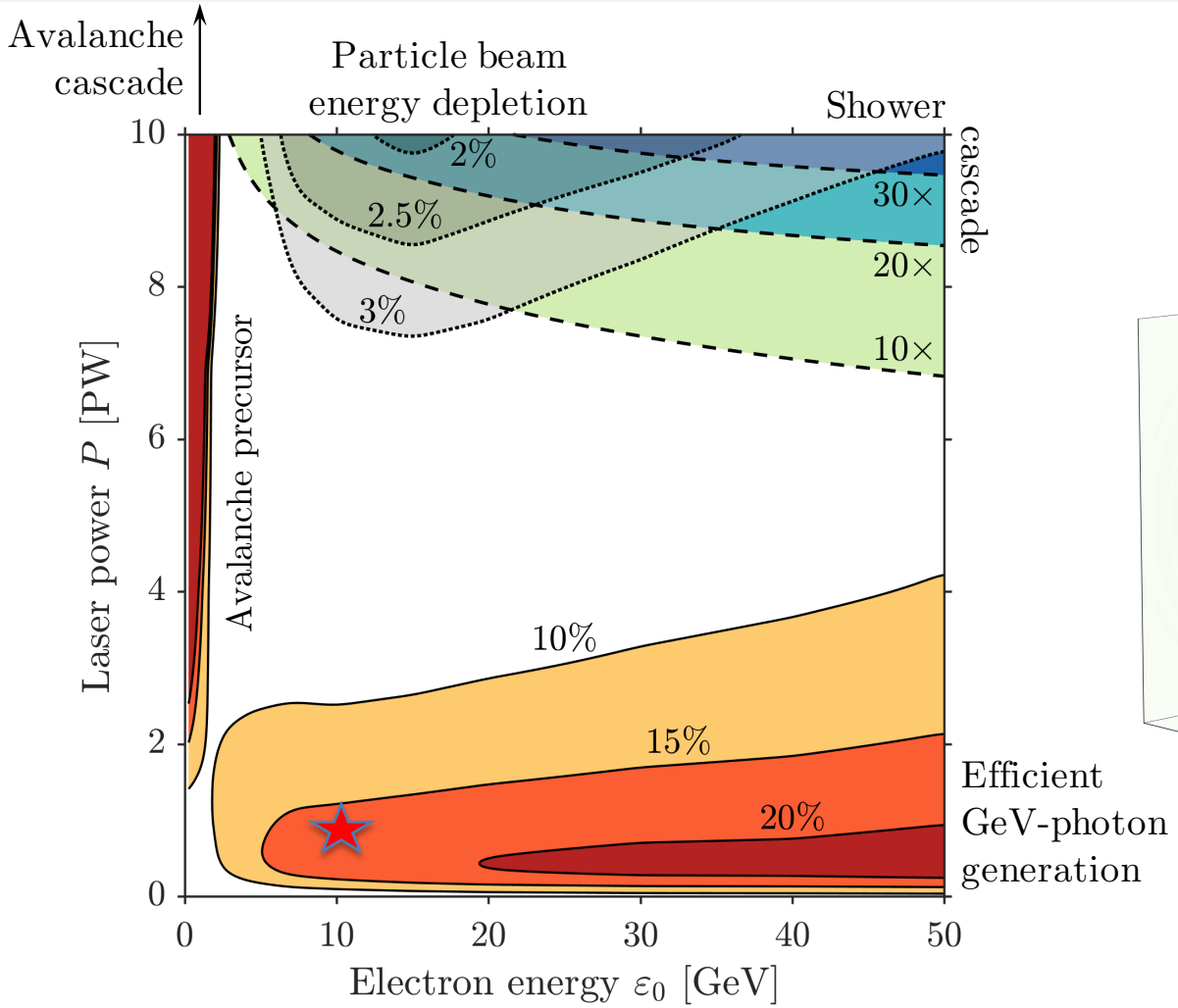
J. Magnusson, et al, Phys. Rev. Lett. 122, 254801 (2019)
J. Magnusson, et al, Phys. Rev. A 100, 063404 (2019)

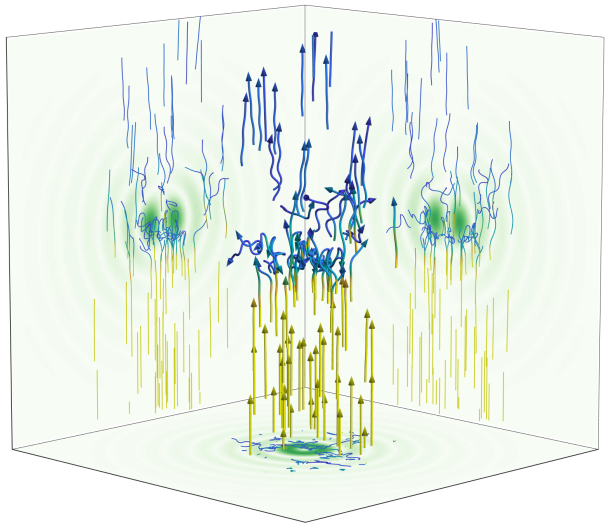
A. Gonoskov, et al, Phys. Rev. X 7, 041003 (2017).

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







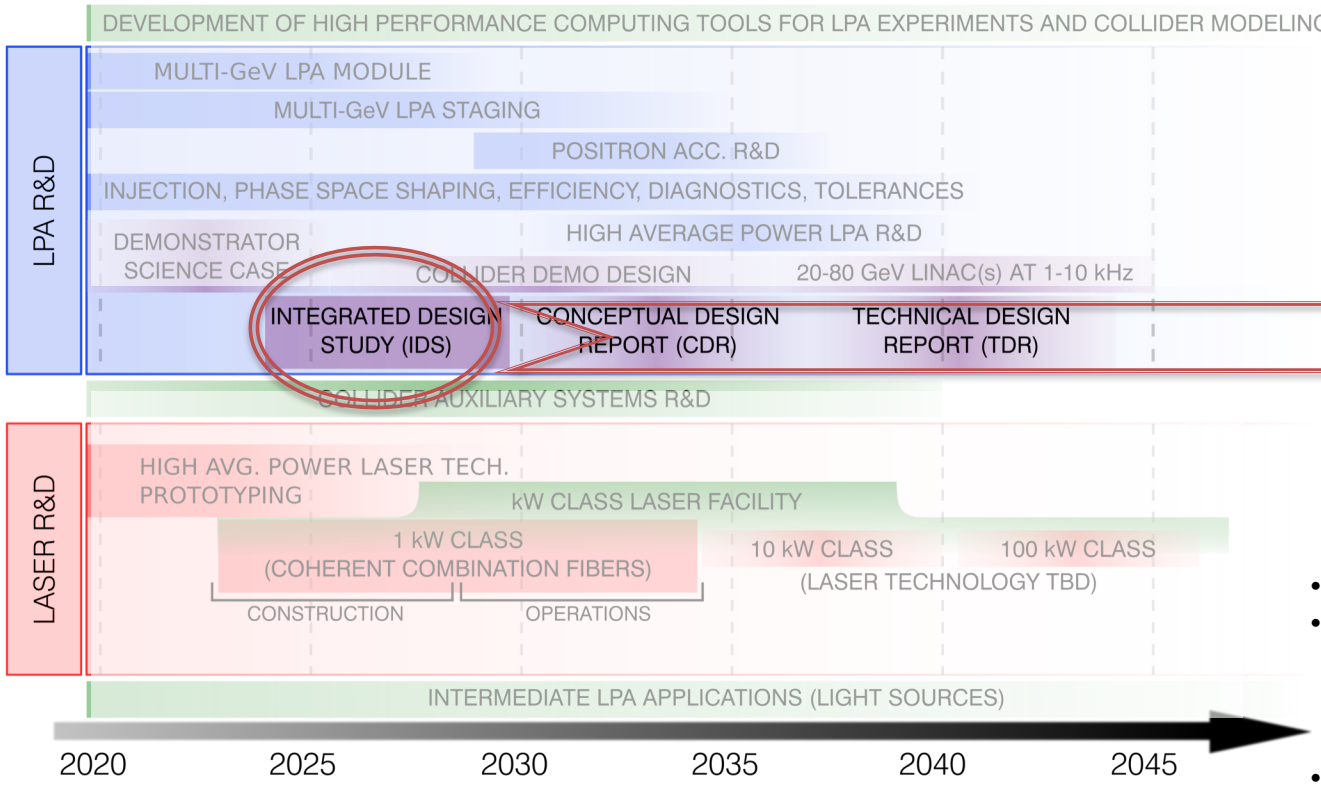


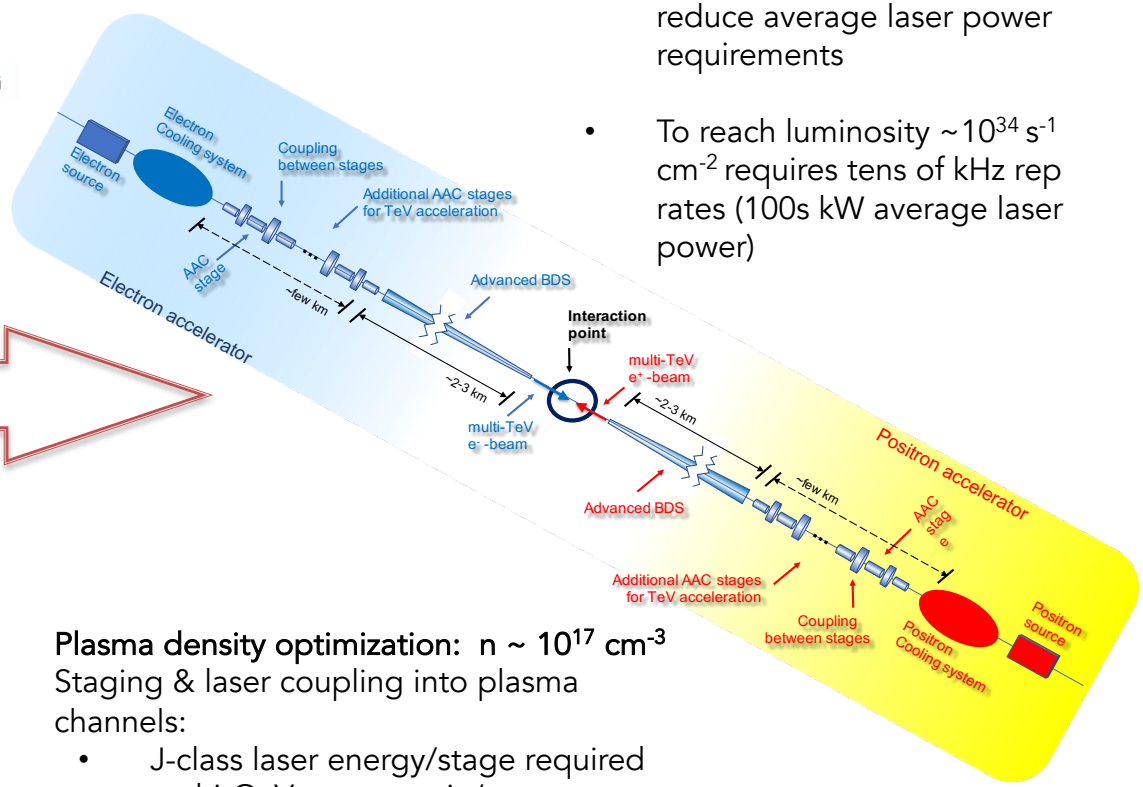
QED PIC code ELMIS: A. Gonoskov, et al., Phys. Rev. E 92, 023305 (2015)

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

Multi-PW and Multiple-beam laser facility can be turned into an LPA-based collider

- 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)

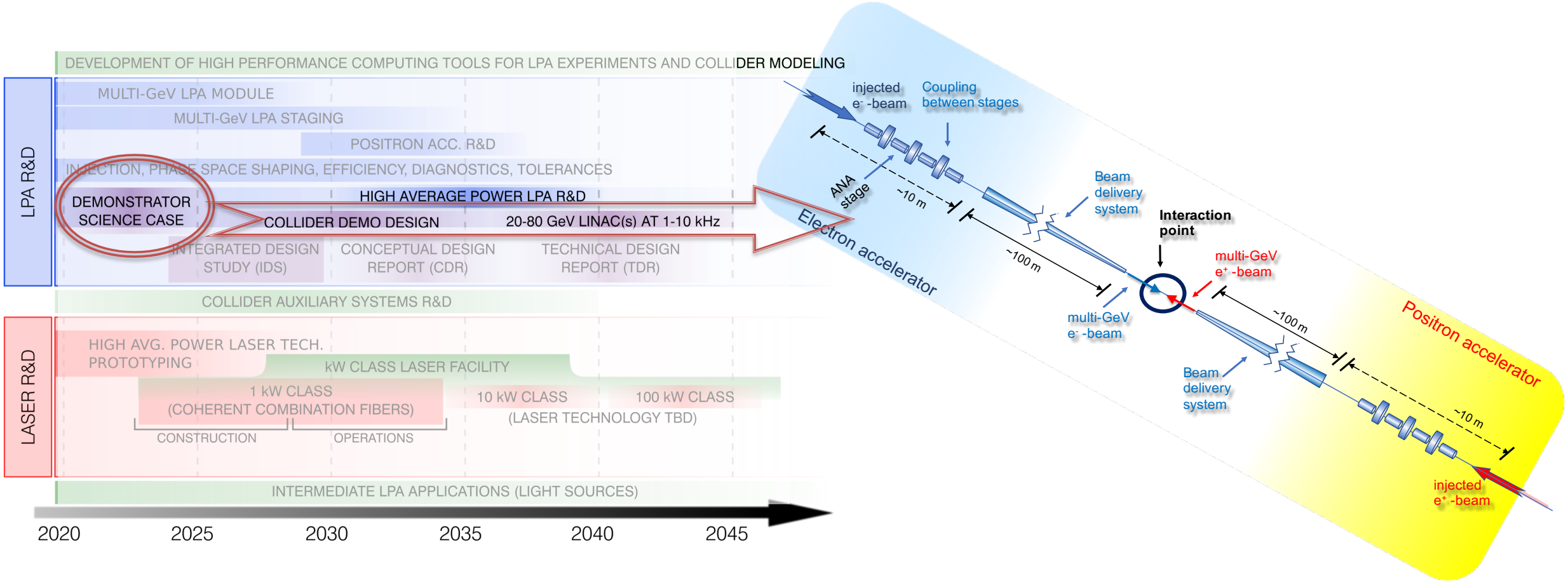




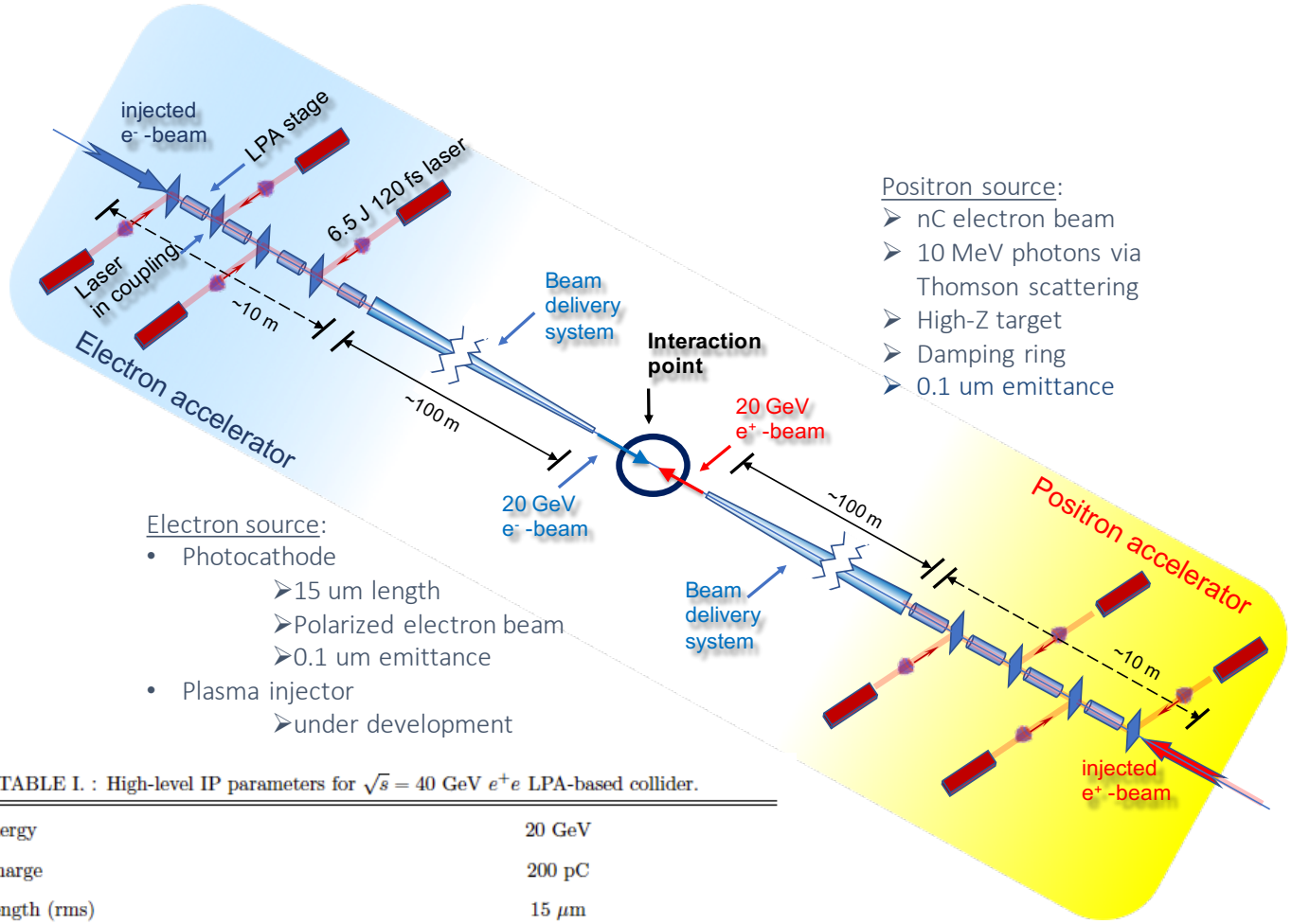
Leemans & Esarey Phys. Today (2009)
Geddes et al., arXiv:2208.13279 (2022)

- **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 %)

Multi-PW and Multiple-beam laser facility can be turned into an LPA-based collider, which needs a demonstration facility at intermediate energy



20-80 GeV LPA-based Collider Design and Possible Applications



Positron source:
- nC electron beam
- 10 MeV photons via Thomson scattering
- High-Z target
- Damping ring
- 0.1 um emittance

Electron source:
- Photocathode
  - 15 um length
  - Polarized electron beam
  - 0.1 um emittance
- Plasma injector
  - under development

TABLE I. : High-level IP parameters for $\sqrt{s} = 40$ GeV e^+e LPA-based collider.

Beam energy	20 GeV
Bunch charge	200 pC
Bunch length (rms)	15 μm
Repetition rate	1 kHz (upgrade to 25 kHz)
Spot size at IP	50 nm
Luminosity	4×10^{30} cm^{-2}s^{-1} (upgrade to 1×10^{32} cm^{-2}s^{-1})

Laser-plasma based production and acceleration of muons:
(i) Testing muon acceleration technologies

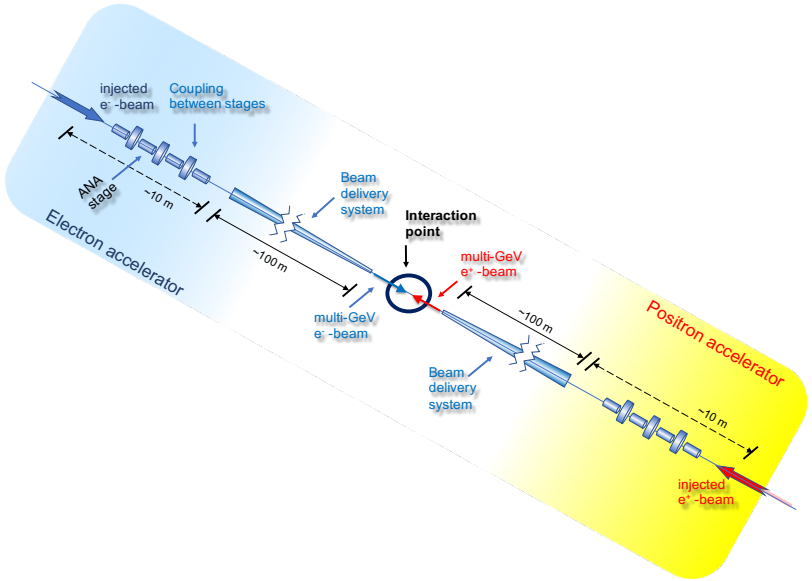
QCD:
(i) Precision α_s measurement
(ii) Measurements to improve simulation modeling
(iii) New QCD measurements: e.g., jet substructure
(iv) New tests of QCD factorization and universality of hadronization effects

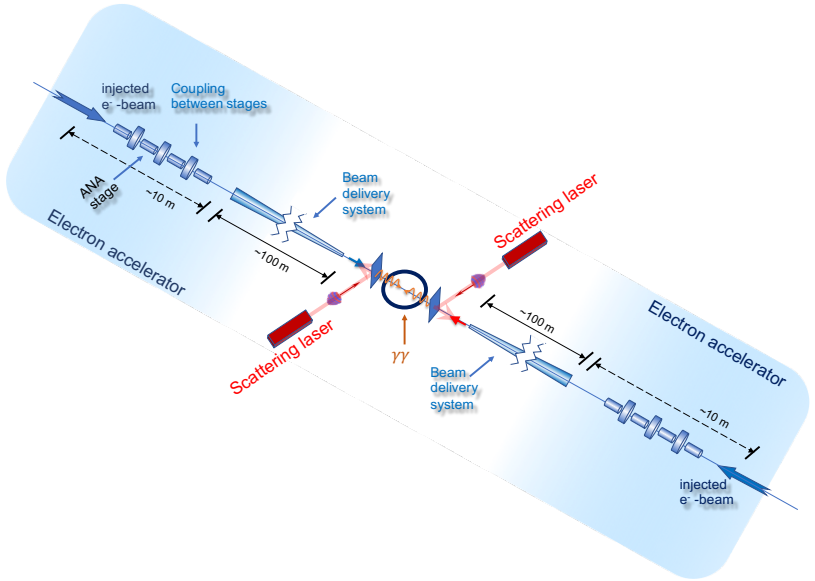
Beyond SM:
(i) Milli-charged particles
(ii) Axion-like particles
(iii) Low mass resonances decaying to hadronic final states

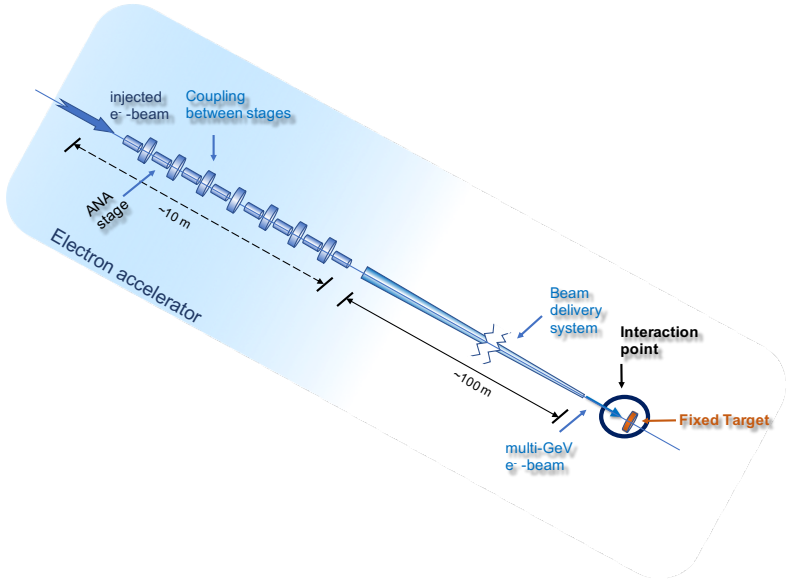
Strong Field QED:
(i) High energy electron/positron/photon interactions with intense EM fields
(ii) Beam delivery system and interaction point limitations due to strong fields

γγ, ep, ee collider studies
μ acceleration
proton acceleration

Can LPA-based Collider be reconfigured for different types of studies?





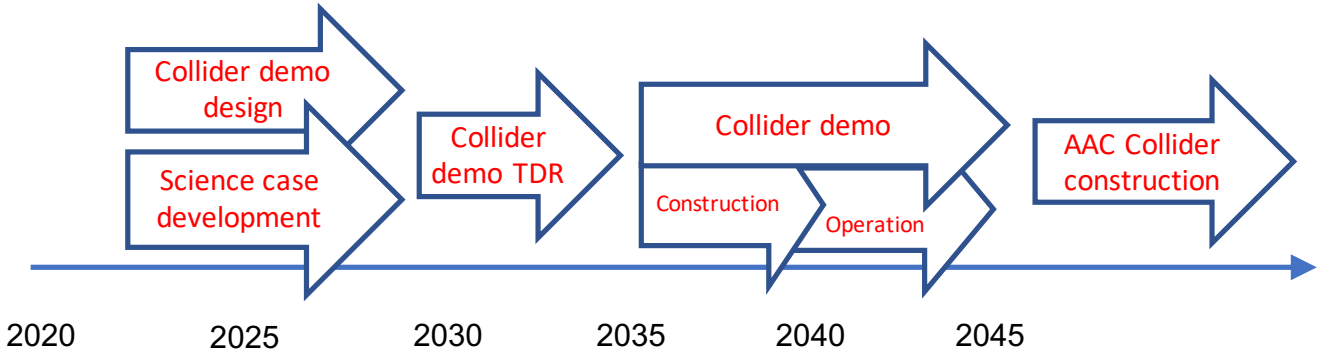


The principal scheme of the advanced accelerator linear collider demonstration facility at intermediate energy with possible reconfiguration into γγ collider and electron-ion collider

ANA – advanced and novel accelerator

Conclusions

- Multi-PW and Multi-beam laser facilities are optimal for the study of a number of SF QED processes (pair production, EM cascades and avalanches, generation of GeV photons).
- 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, such as BELLA, ZEUS, and ELI (BL and NP).
- Realizing the challenge of a TeV collider based on advanced and novel accelerating (ANA) techniques will only be possible with a sustained, decades-long R&D effort.
- Intermediate facilities such as a 20-80 GeV collider will be required to demonstrate key accelerator technologies and subsystems that are compatible with the ANA technology. With sufficient science motivation, such a machine could be pursued, enabling key components to be tested on the path to a TeV collider



The presentation was based on the following papers:

1. J. Magnusson, A. Gonoskov, M. Marklund, T. Zh. Esirkepov, J. K. Koga, K. Kondo, M. Kando, S. V. Bulanov, G. Korn, and S. S. Bulanov, "**Laser-particle collider for multi-GeV photon production**", Phys. Rev. Lett. 122, 254801 (2019);

2. J. Magnusson, A. Gonoskov, M. Marklund, T. Zh. Esirkepov, J. K. Koga, K. Kondo, M. Kando, S. V. Bulanov, G. Korn, C. G. R. Geddes, C. B. Schroeder, E. Esarey, and S. S. Bulanov, "**Multiple-colliding laser pulses as a basis for studying high-field high-energy physics**", Phys. Rev. A 100, 063404 (2019)

3. P. Zhang, S. S. Bulanov, D. Seipt, A. V. Arefiev, and A. G. R. Thomas, "**Relativistic Plasma Physics in Supercritical Fields**", Phys. Plasmas 27, 050601 (2020)

4. M. Turner, S. S. Bulanov, C. Benedetti, A. J. Gonsalves, W. P. Leemans, K. Nakamura, J. van Tilborg, C. B. Schroeder, C. G. R. Geddes, and E. Esarey, "**Strong-Field QED Experiments using the BELLA PW Laser Dual Beamlines**", Eur. Phys. J. D 76, 205 (2022)

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