# High intensity laser driven sources of gammas and positrons using BELLA PW Laser Dual Beamlines.

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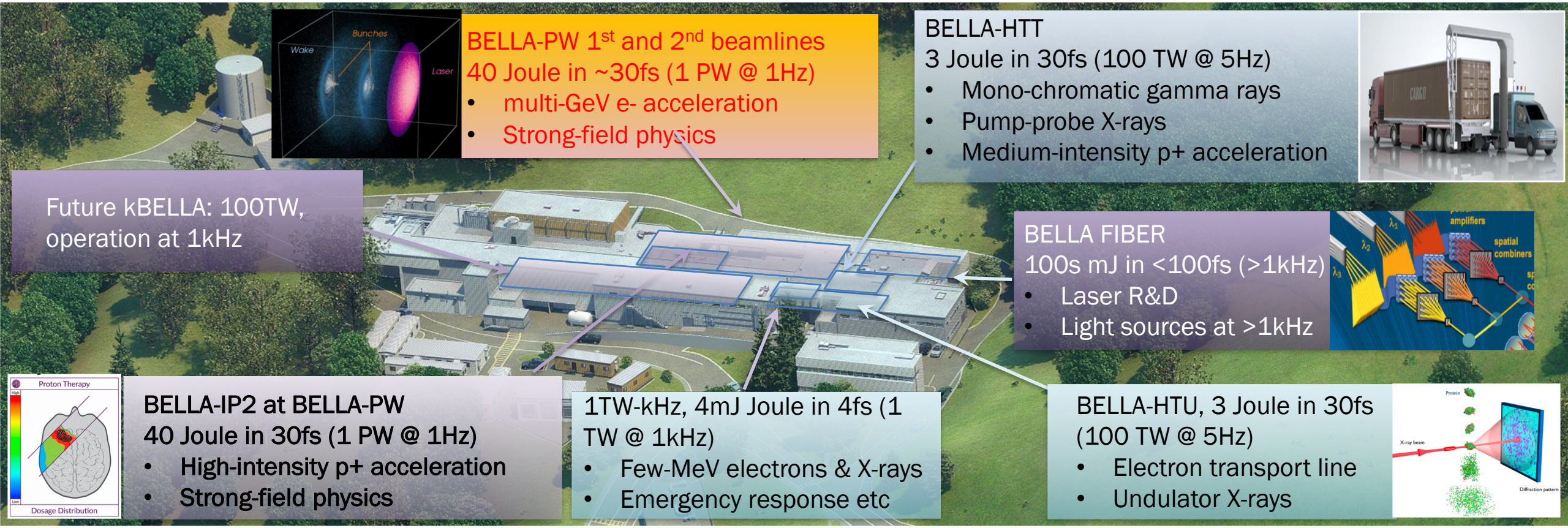
# BELLA Center houses multiple laser facilities addressing laser, accelerator, and light source R&D and applications, including laser ion acceleration.

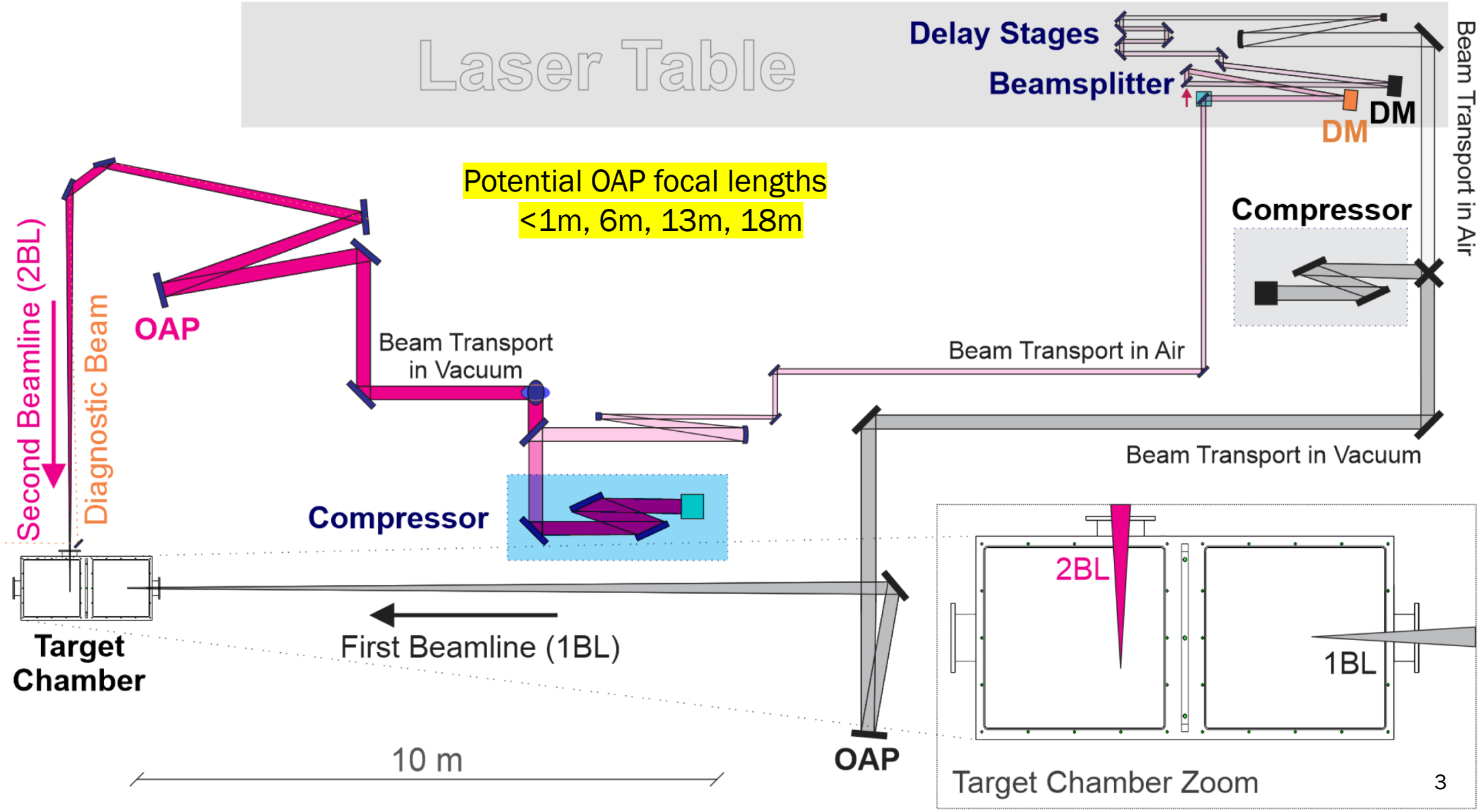



**All systems are Ti:sapphire-based except for the fiber system under construction**

# BELLA 2nd bemline (2BL) adds additional laser pulse to the target chamber for the next generation of laser plasma accelerator experiments

**Gray / Black:** elements that existed before 2BL upgrade.

**Colored:** elements installed / modified because of 2BL installation.



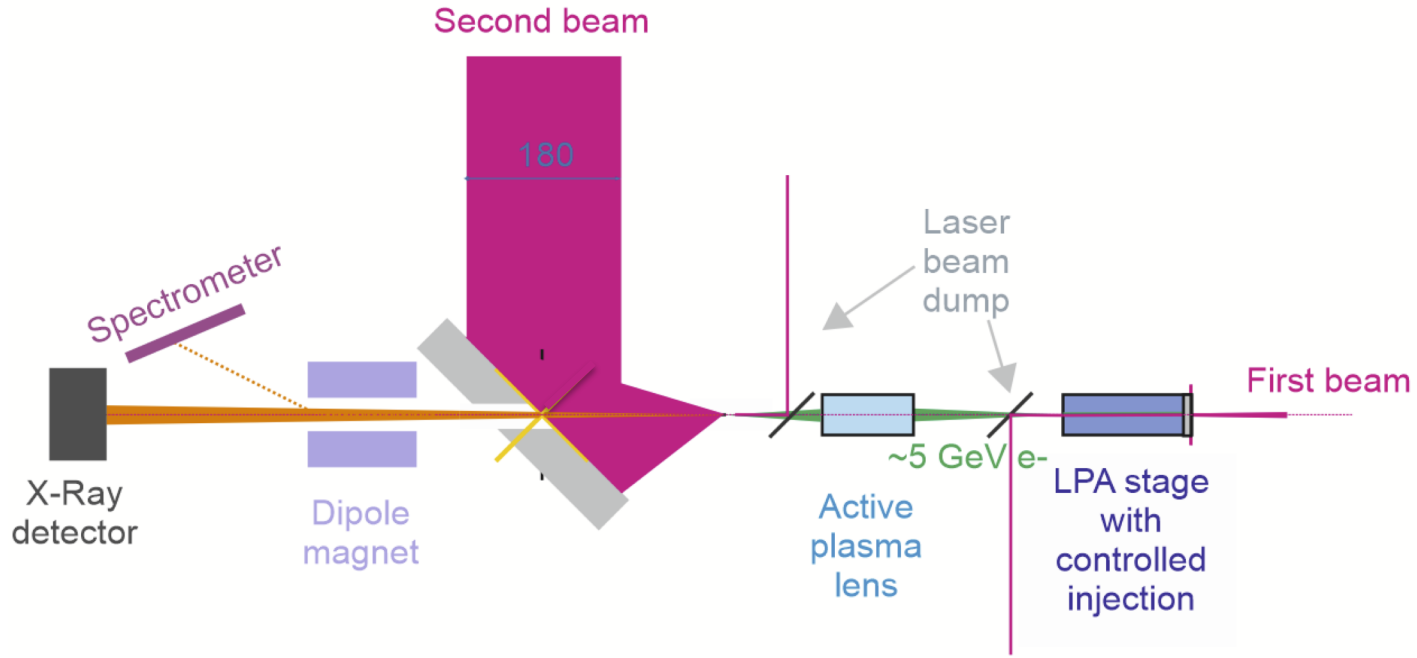
# SF QED experiment design study performed for BELLA 2nd beamline

BELLA PW 1st beamline:

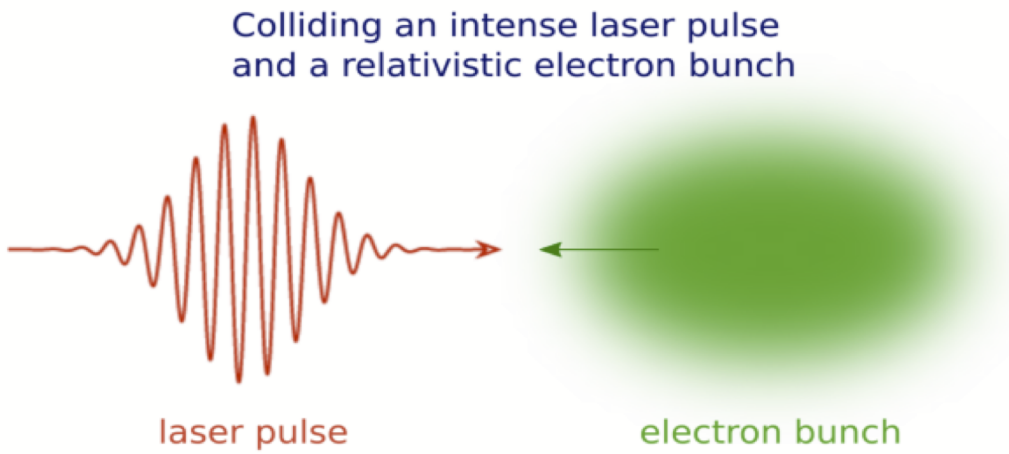
- ~20 J laser pulse energy to produce LWFA electron with energies ~5 GeV

BELLA PW 2nd beamline:

- ~20 J pulse energy together with a short focal length OAP to reach $a_0 > 10$




**Note: Need target chamber upgrade for full 2BL beam diameter**




Nonlinear quantum parameter

$\chi$ >1 possible with proven technologies:

- laser $a_0$ = 42,
- laser pulse focal spot size $w_0$ = 2.5 um,
- electron beam energy = 4 GeV,
- electron bunch size = 2.5 um.
- Number of positrons = 5 x $10^{-3}$ * #electrons
- $\chi$ =1.7

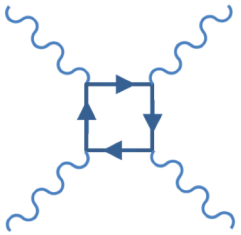
M. Turner et al., EPJ D (2022). Simulations were performed using the code **Ptarmigan**, T. G. Blackburn *et al* 2021 *New J. Phys.* 23 085008

# 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

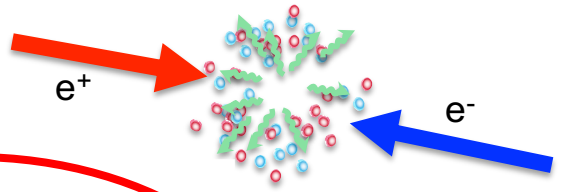
Laser fields may provide both strong electromagnetic fields and generate high-energy particles and therefore represent a particularly interesting environment for studying a number of High Intensity Particle Physics effects.

4-wave mixing

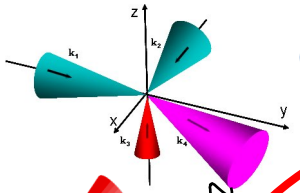
(Lundström et al, 2006)

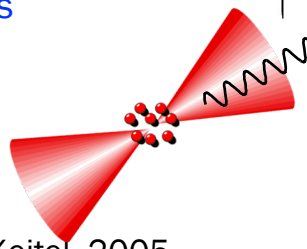


Photon-photon scattering via relativistic mirrors (Koga et al (2012))

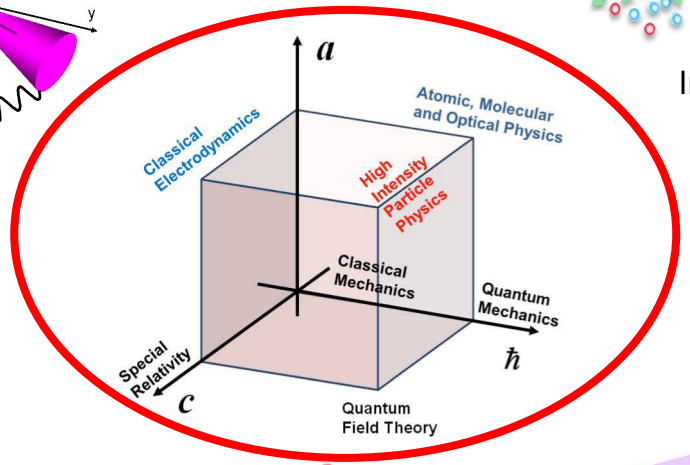



- Nonperturbative Quantum Field Theory
- Matter in Extreme conditions
- Next generation lasers
  - Day-to-day operation
  - New applications
- Future lepton colliders
- Future $\gamma\gamma$ colliders
- Various astrophysical phenomena

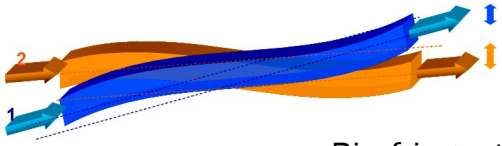




High order harmonic generation (Di Piazza, Hatsagortsyan, C. H. Keitel, 2005 Fedotov & Narozhny, 2006)

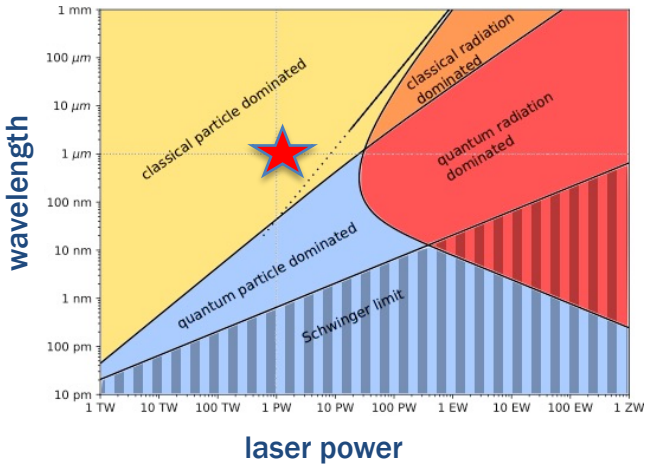


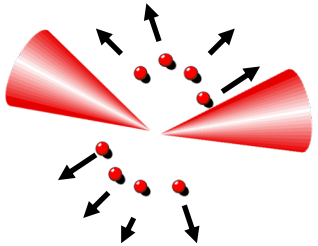

Interaction point physics at future TeV- class lepton colliders (Yakimenko et al, 2019)



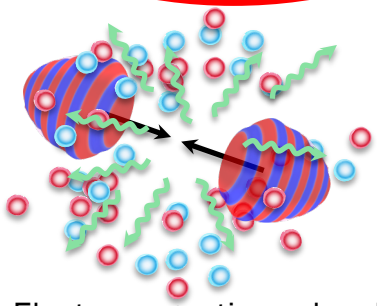
Birefringent e.m. vacuum

(Rozanov, 1993)



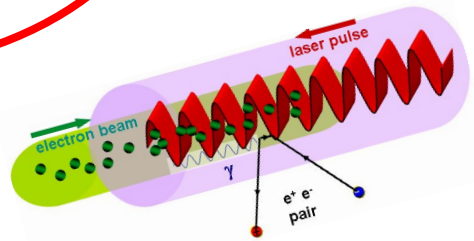



Electron positron pair production from vacuum (Schwinger, 1951)



- 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?

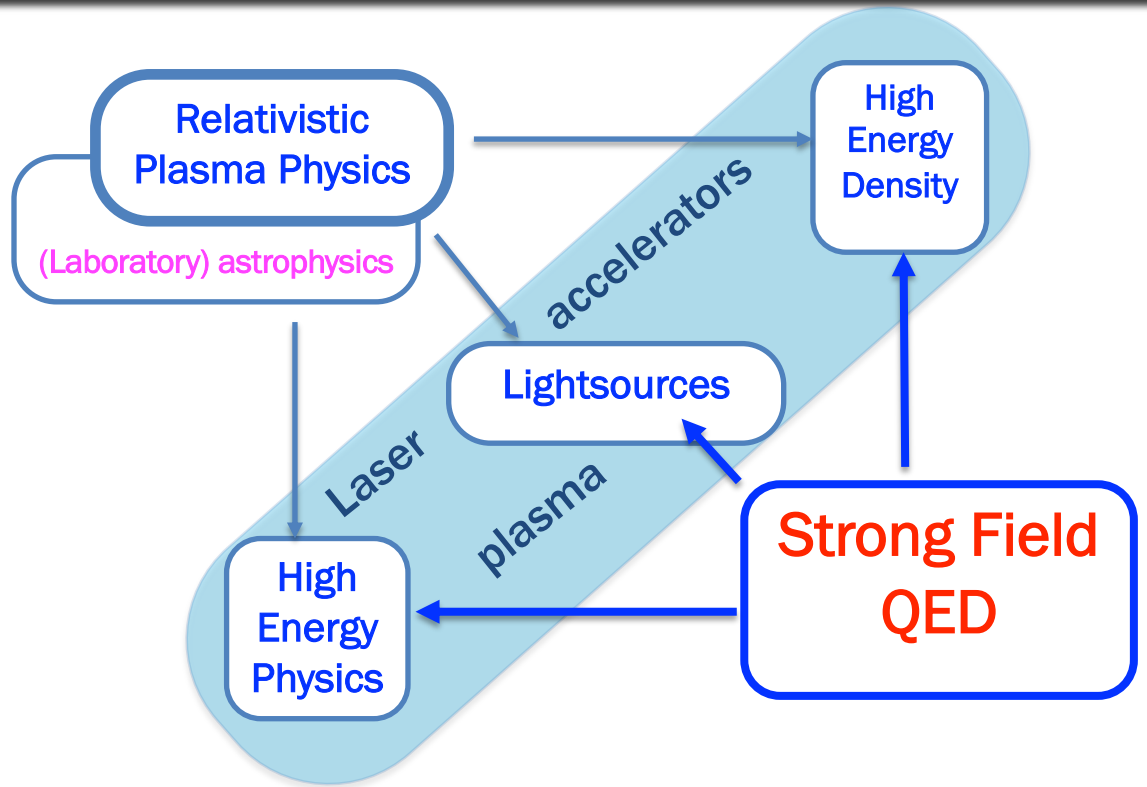
1. The magnetic fields surrounding compact astrophysical objects, such as pulsars, magnetars and black holes

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.

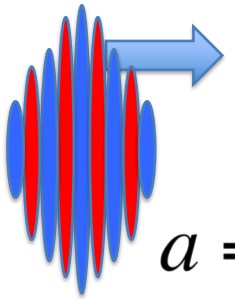



Acceleration of particles and generation of new sources of radiation is a major part of the scientific case for new high-power laser facilities. Since the regimes of these applications will be affected or even dominated by the interplay between collective plasma effects and strong field quantum processes,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

# 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

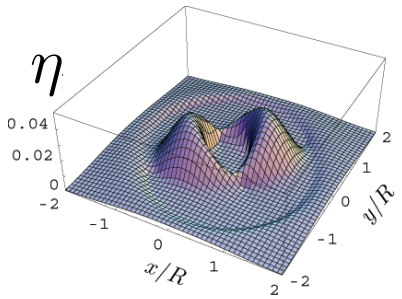
$$E_S = \frac{m^2c^3}{e\hbar} = 1.32\times10^{16}\ V/cm \quad \rightarrow \quad a_s = \frac{\hbar\omega}{mc^2} = 4.1\times10^5$$

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

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

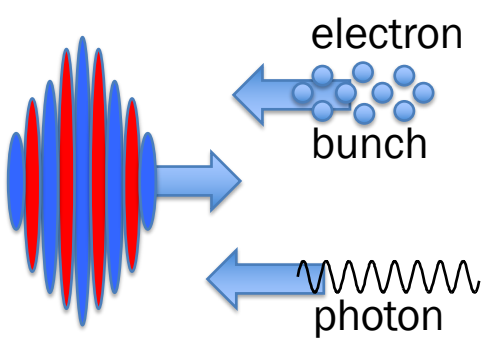
$$\mathcal{F} = (\mathbf{E}^2-\mathbf{B}^2)/2 \qquad \mathcal{G} = \mathbf{E}\cdot\mathbf{B}$$

$$\varepsilon \quad E_S = \frac{m^2c^3}{e\hbar} = 1.32\times10^{16}\ V/cm$$



# Behavior of particles and fields is characterized by Lorentz invariant parameters

Quantum Effects



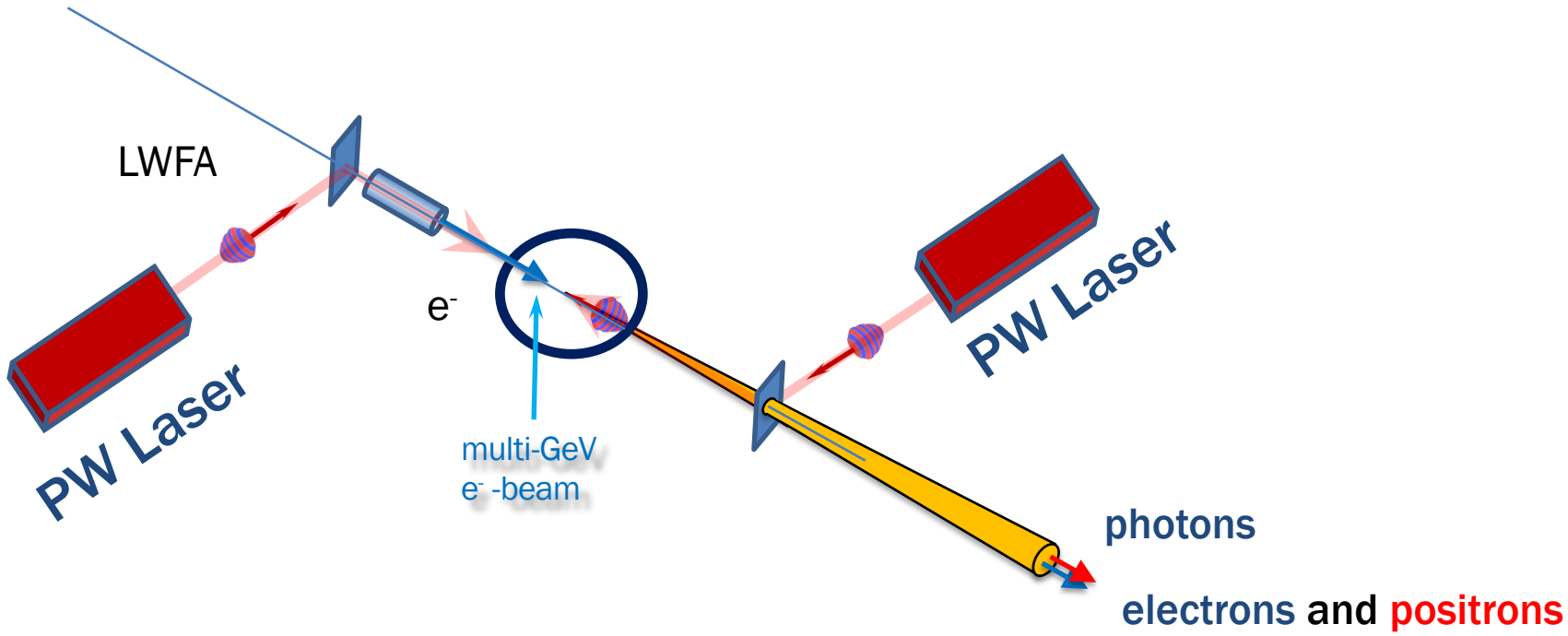

$$\chi_e = \frac{e\hbar\sqrt{(F_{\mu\nu}p^\nu)^2}}{m^3c^4}$$

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

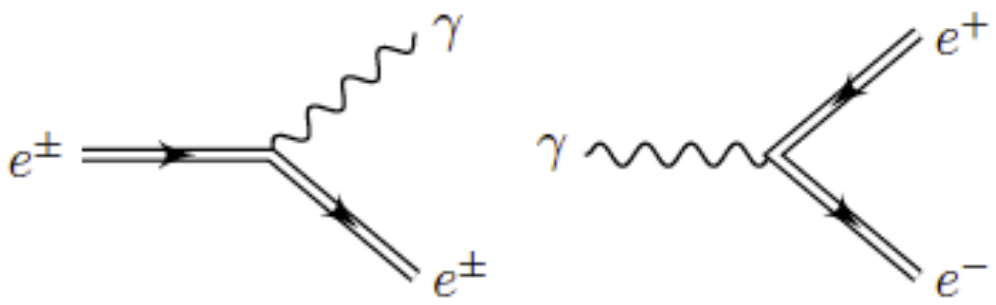
counter-propagating laser and electron/photon

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

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



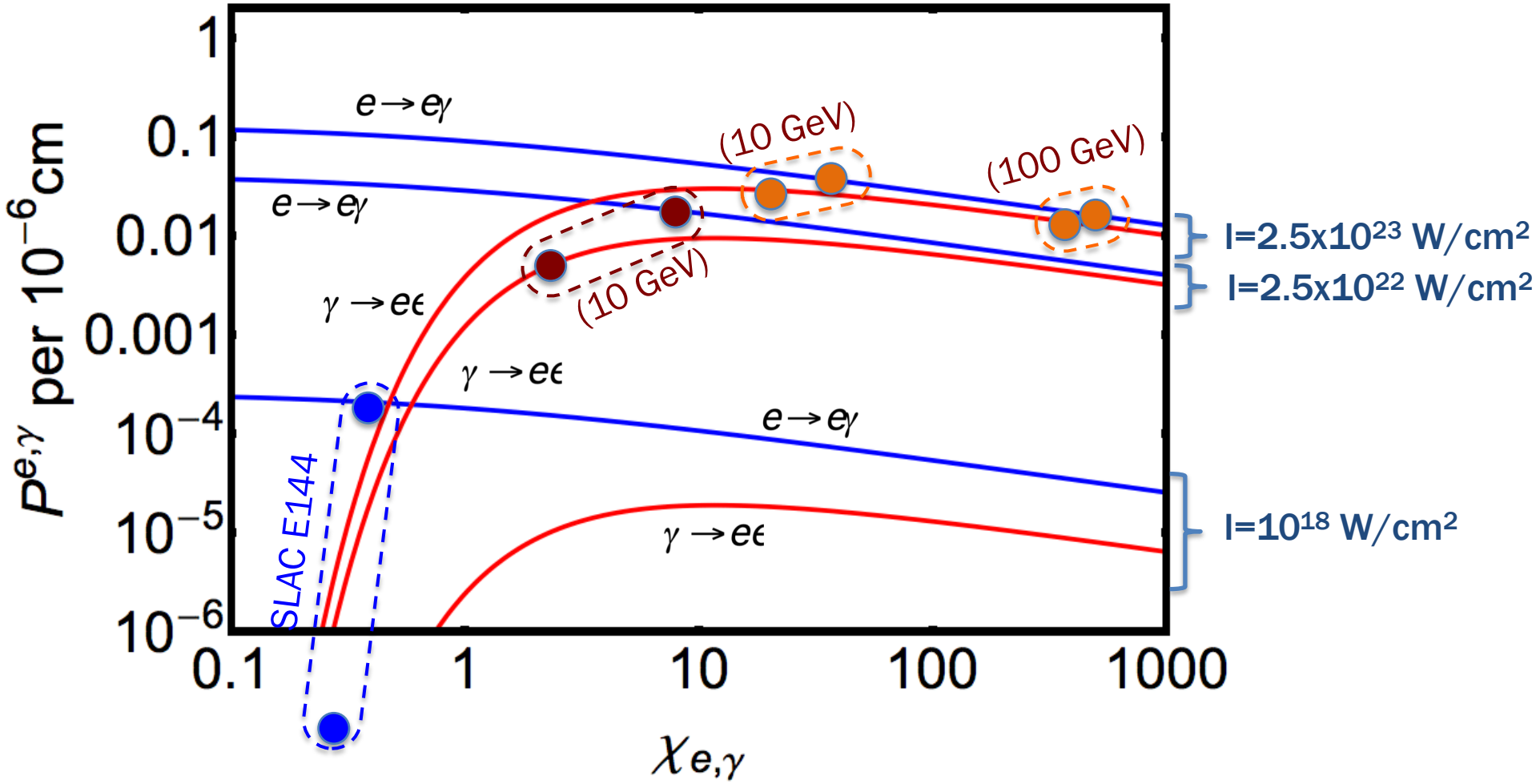
# The photons will be produced via the multi-photon Compton process and electron-positron pairs by the multi-photon Breit-Wheeler process



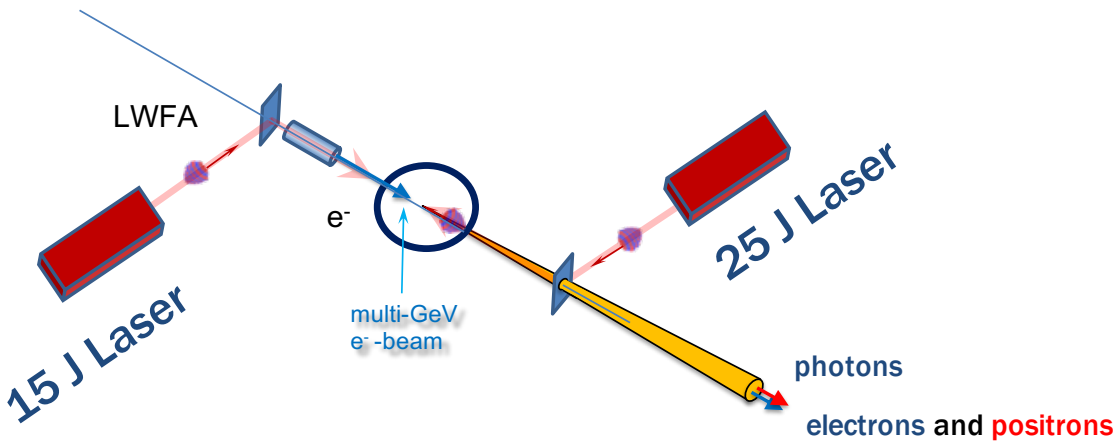

The Feynman diagrams of the Compton ($e \to e\gamma$) and Breit-Wheeler ($\gamma \to ee$) processes. Double fermion lines indicate that the process occurs in an external field.

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

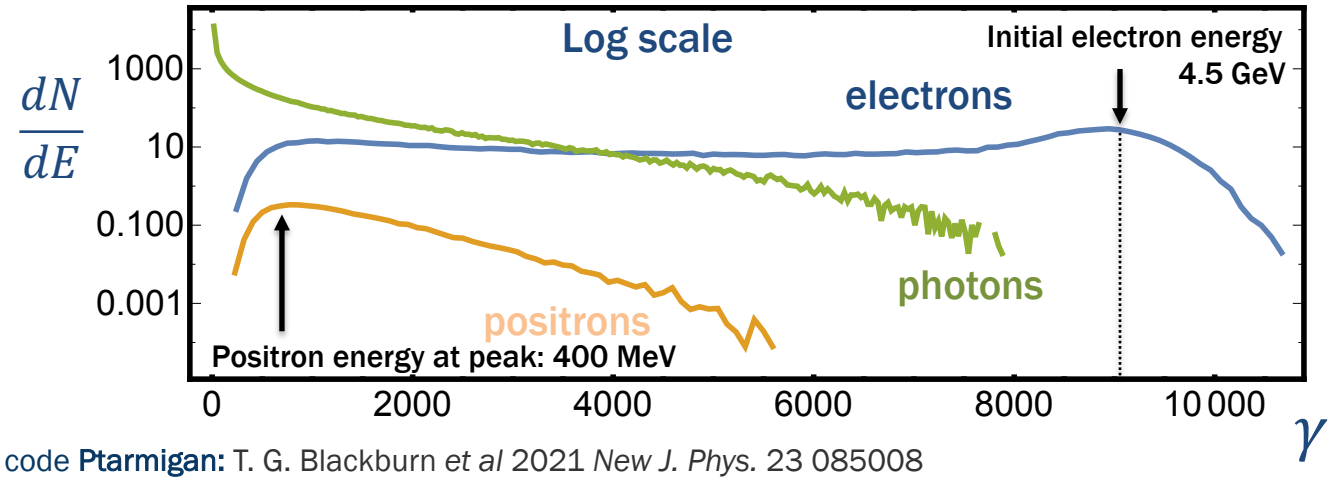
# Probabilities of multiphoton Compton and Breit-Wheeler processes



# The collision of a self-guided LPA electron beam and an intense laser pulse leads to 2 pC positron beam production with an energy of 400 MeV




Particle spectra




code **Ptarmigan:** T. G. Blackburn *et al* 2021 *New J. Phys.* 23 085008

Simulation input:

- laser peak $a_0$ = 42
- laser pulse focal spot size $w_0$ = 2.5 um
- laser duration = 30 fs
- electron beam energy = 4.5 GeV (+-5%)
- electron bunch size = 2.5 um
- electron beam charge = 450 pC

$\chi_e = 1.8$

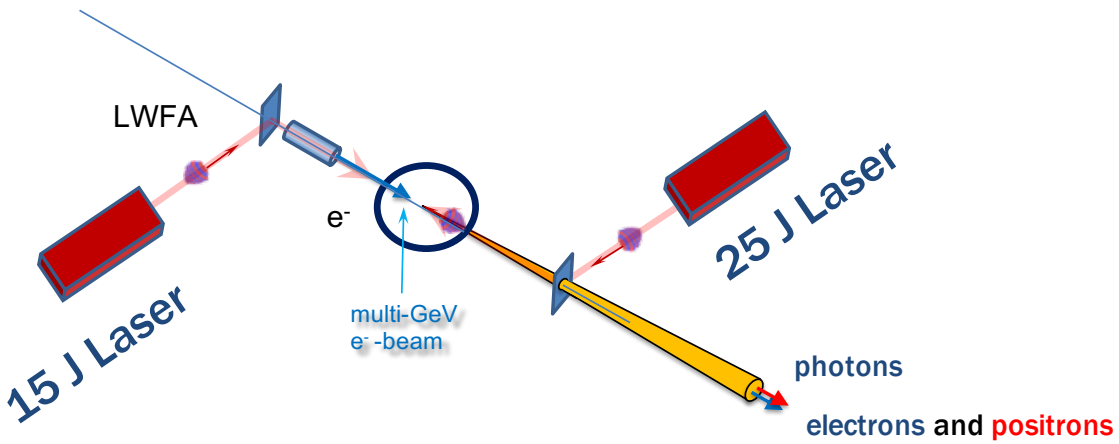
**Self-guided LPA (nonlinear / bubble regime*)**

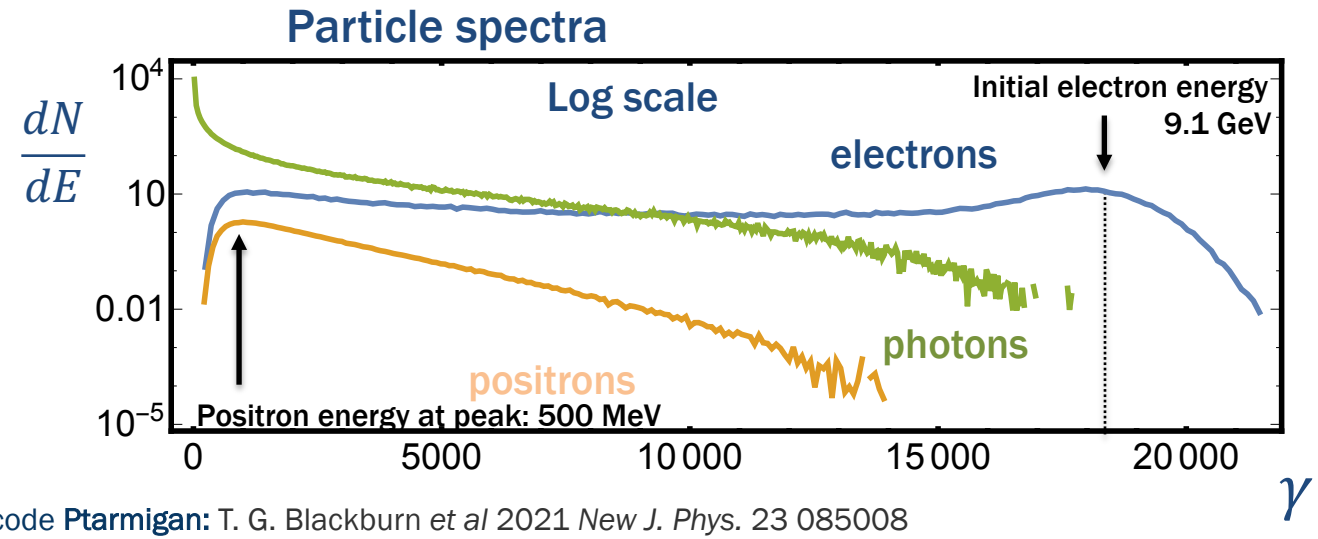
Simulation results:

- electron beam energy loss = 37%
- positron beam charge = 2 pC
- positron energy at peak = 400 MeV
- number of photons per electron ~ 10

Electron LPA: **INF&RNO**

# The collision of a channel-guided LPA electron beam and an intense laser pulse leads to 5 pC positron beam production with an energy of 500 MeV




Simulation input:

- laser peak $a_0$ = 42
- laser pulse focal spot size $w_0$ = 2.5 um
- laser duration = 30 fs
- electron beam energy = 9.1 GeV (+-5%)
- electron bunch size = 2.5 um
- electron beam charge = 120 pC

$\chi_e = 3.7$

**Channel-guided LPA (quasi-linear regime)**

Simulation results:

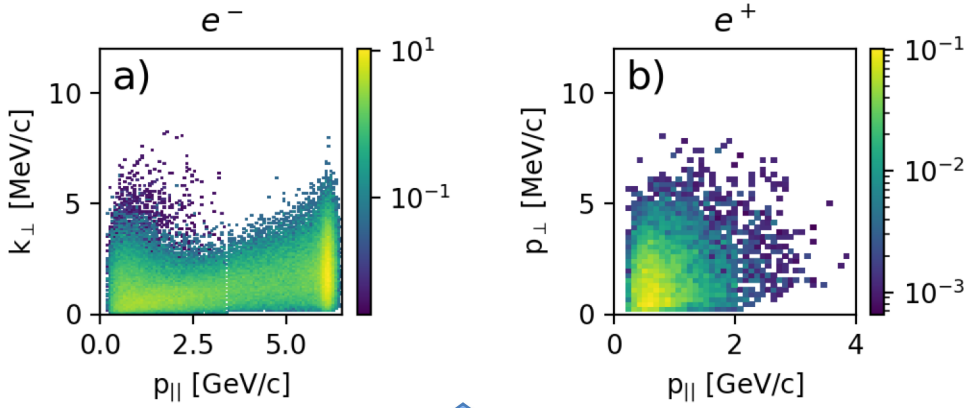
- electron beam energy loss = 42%
- positron beam charge = 5 pC
- positron energy at peak = 500 MeV
- number of photons per electron ~ 10

code **Ptarmigan:** T. G. Blackburn *et al* 2021 *New J. Phys.* 23 085008

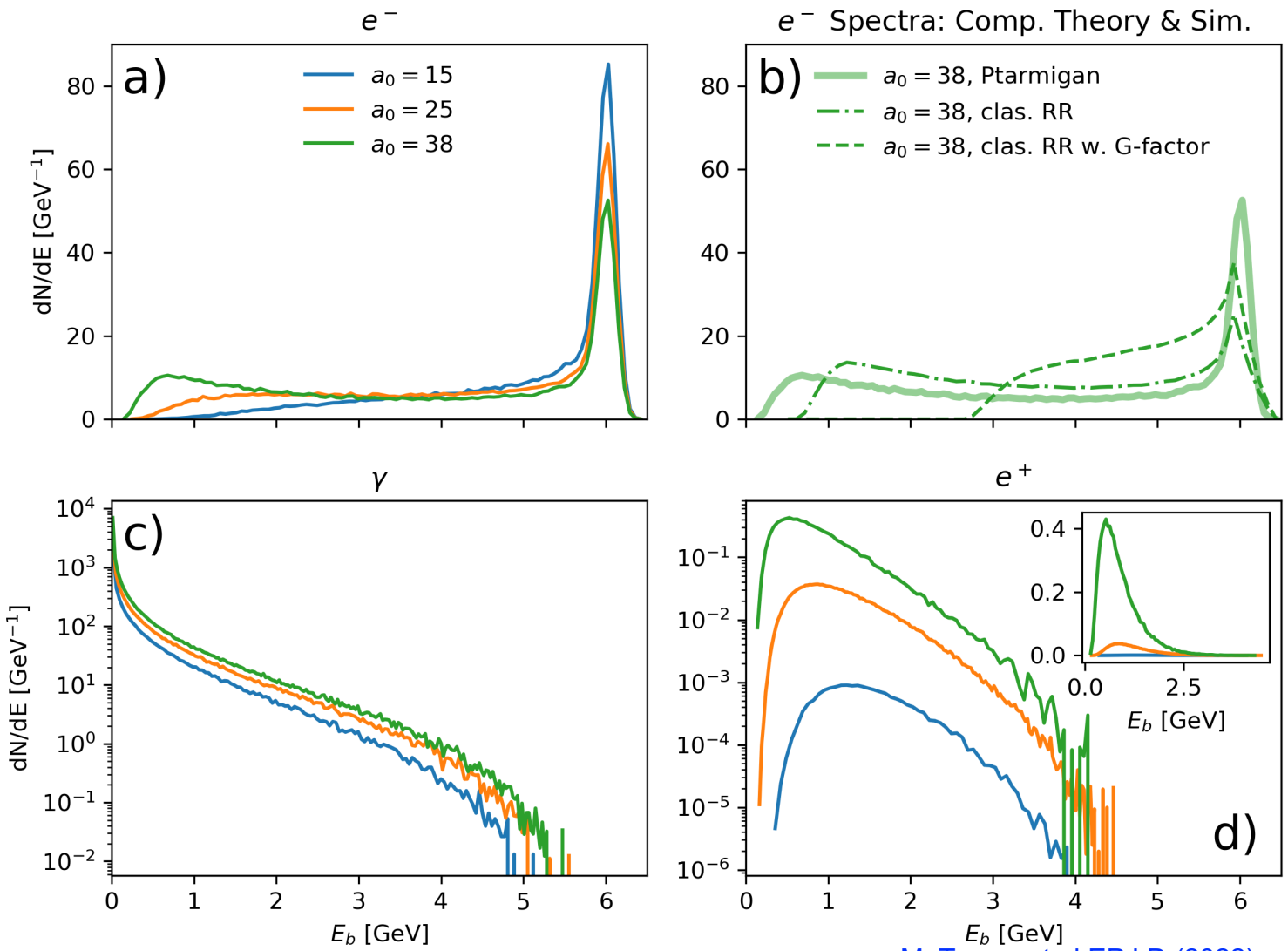
Electron LPA: **INF&RNO**

# Varying laser intensity allows to study the transition from the classical radiation reaction to the quantum radiation reaction

Energy spectra of (a) electrons e−, (c) photons γ and (d) positrons e+ after the interaction of a $E_e$ = 5.9 GeV, $Q_b$ = 22.6 pC electron beam with a counter-propagating laser pulse with $a_0$ = 15 (blue), $a_0$ = 25 (orange) and $a_0$ = 38 (green) as simulated using ptarmigan.



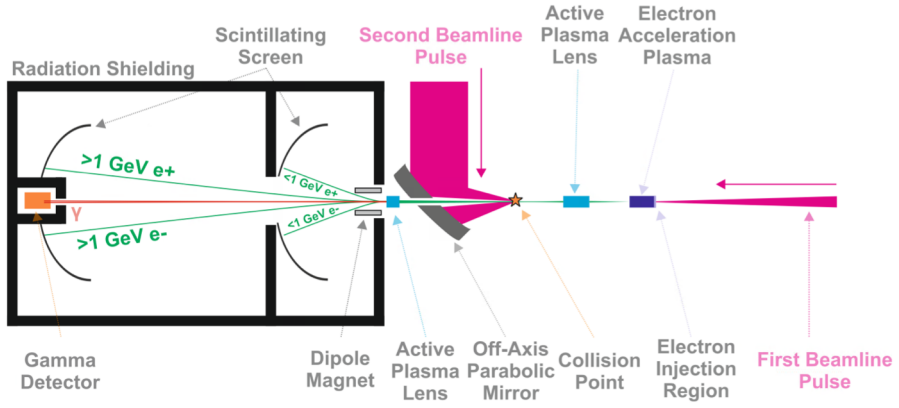

Phase space of electrons $e^-$ (a) and positrons $e^+$ (b) after the head-on collision of a $E_e$ = 5.9 GeV electron beam with a counter-propagating laser pulse pulse with $a_0$ = 38.

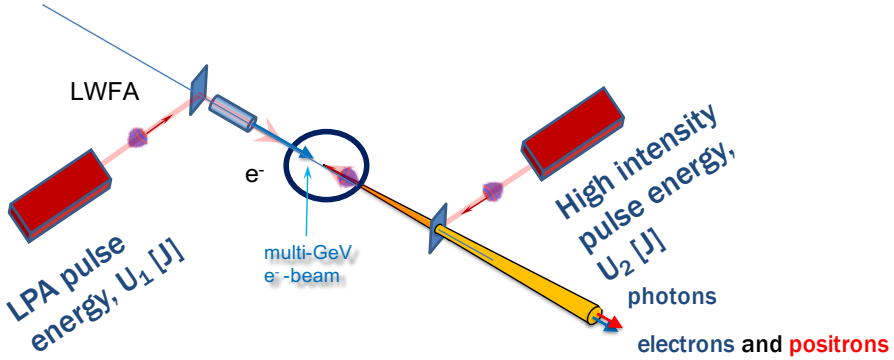



M. Turner et al EPJ D (2022)

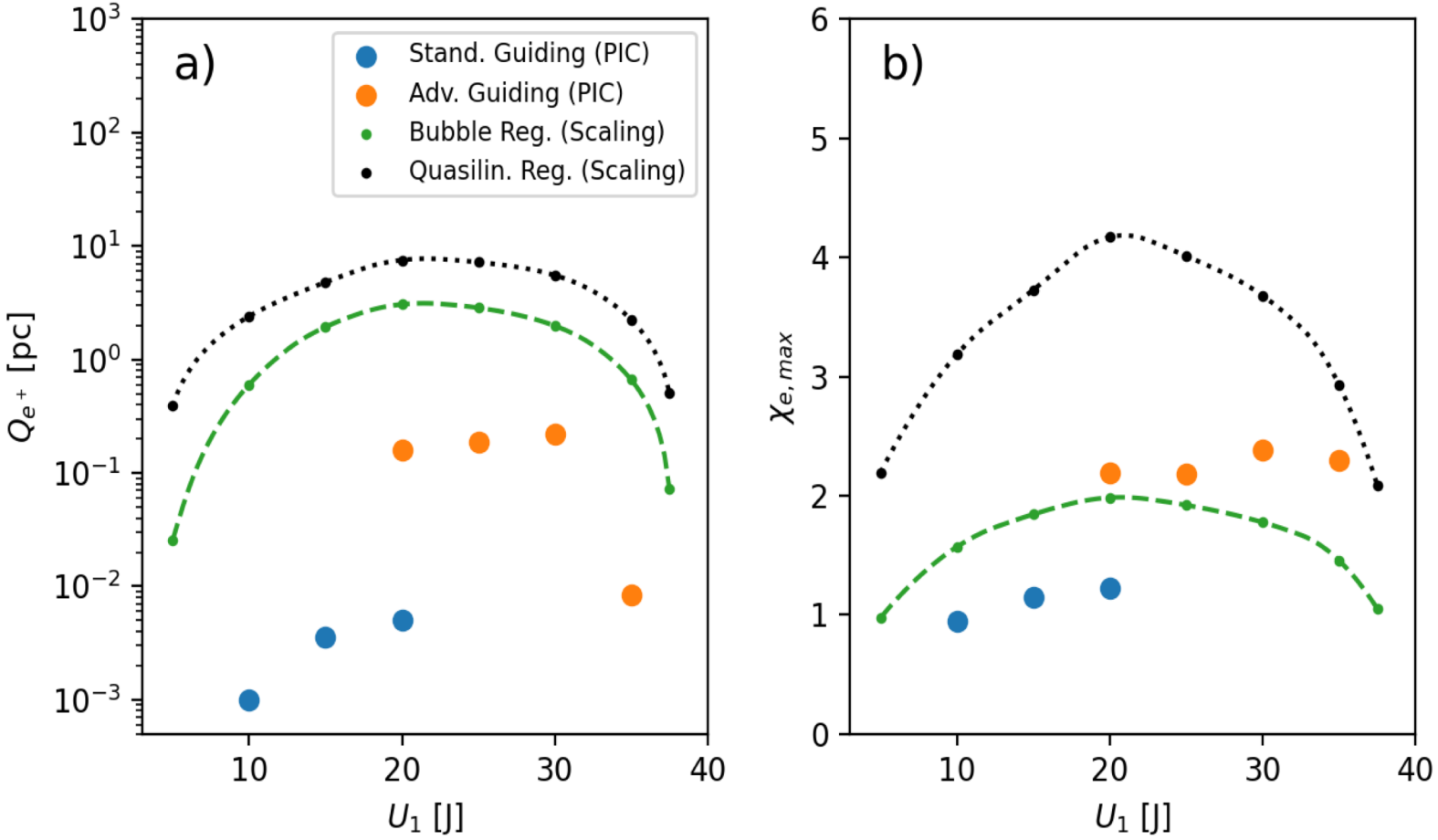
# Positron beam properties depend on the laser energy split between LPA and high intensity beamlines

Schematic top-view layout of a head-on SF-QED collision experiment in the BELLA Petawatt interaction chamber.

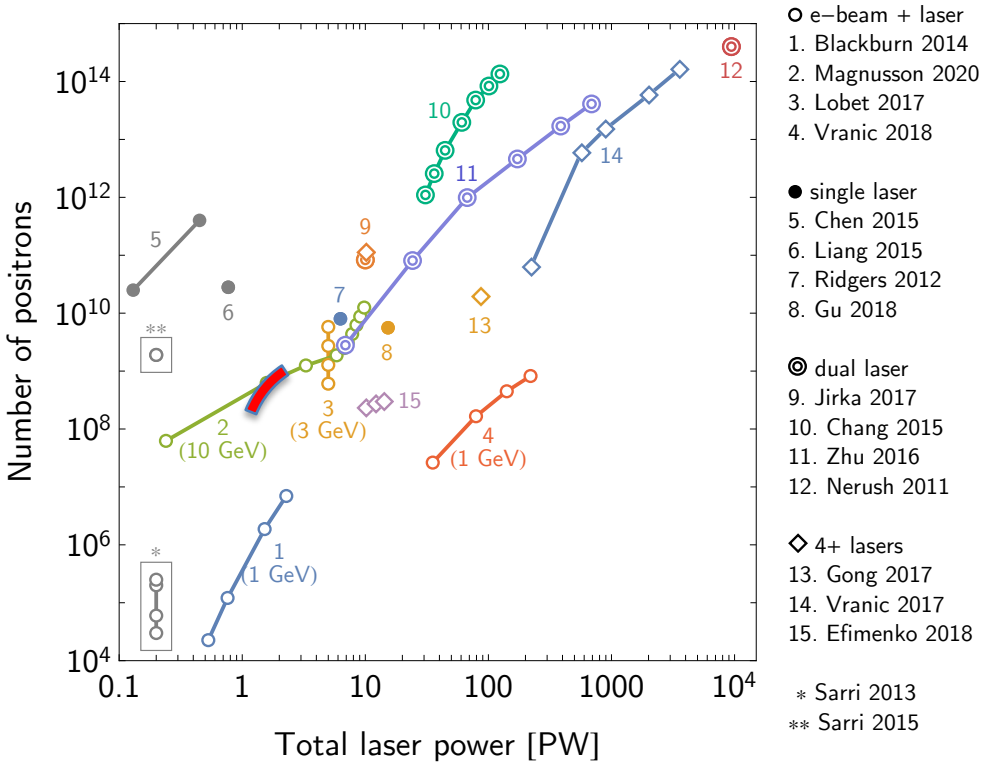


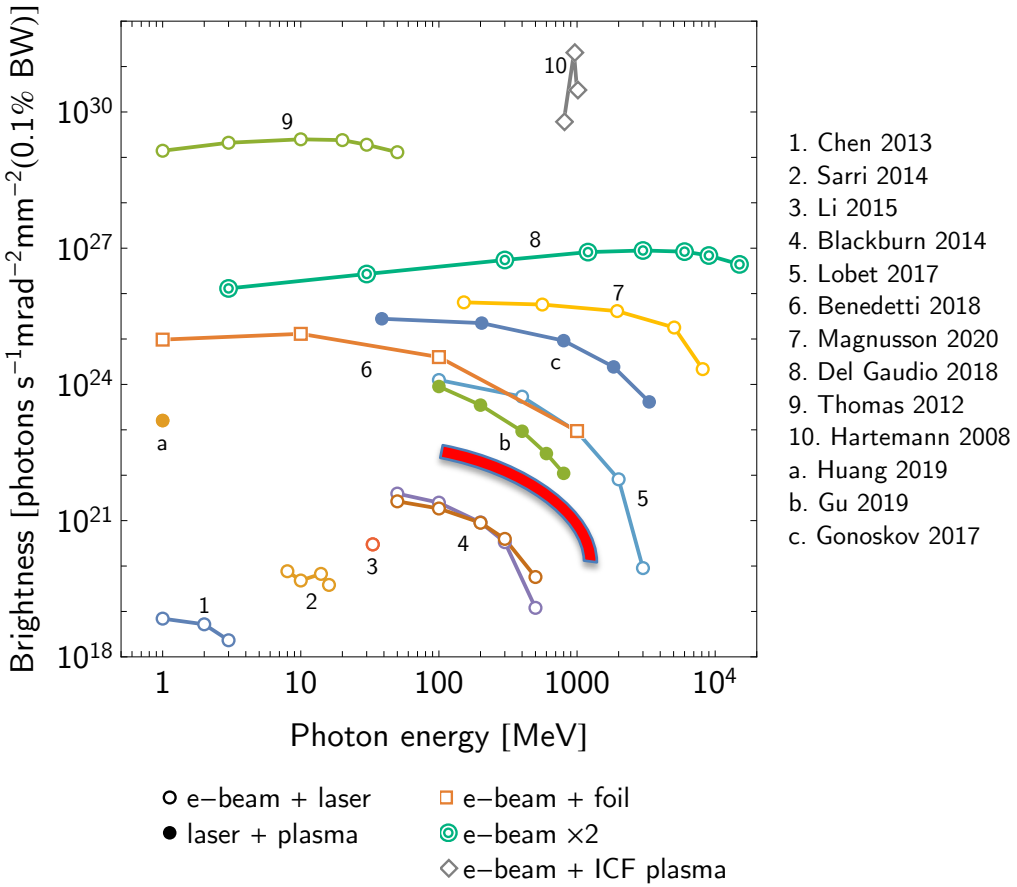

ptarmigan simulation results on the produced positron charge $Q_{e+}$ (a) and maximum $\chi_{e,max}$ (b) reached during the head-on collision of a laser pulse with energy $U_2$ and an LPA electron beam (laser energy $U_1$)



# What can be expected in terms of positron 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)

# Conclusions

- BELLA PW Laser Dual Beamlines will allow the study of SFQED effects in laser - LPA electron beam collisions.

- BELLA PW has enough laser energy to study the transition from the classical radiation reaction regime to the quantum radiation reaction one.

- The laser LPA electron beam collisions is a source of high energy gammas and positrons:
    - 1 PW of laser power is shown to produce up to 5 pC positron beam
    - More efficient positron production can be achieved at higher laser powers: ~100 pC at 2PW and ~300 pC at 3PW

# Thank you!