MAX-PLANCK-INSTITUT FÜR KERNPHYSIK

Laboratory-based intense gamma-ray and lepton beams for strong-field QED and laboratory astrophysics

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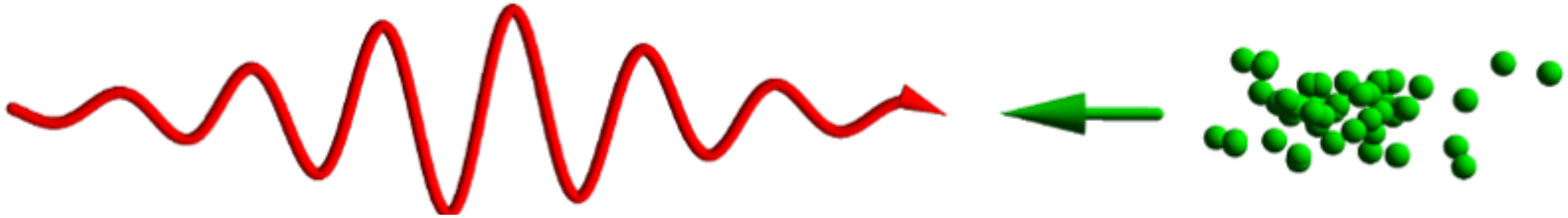
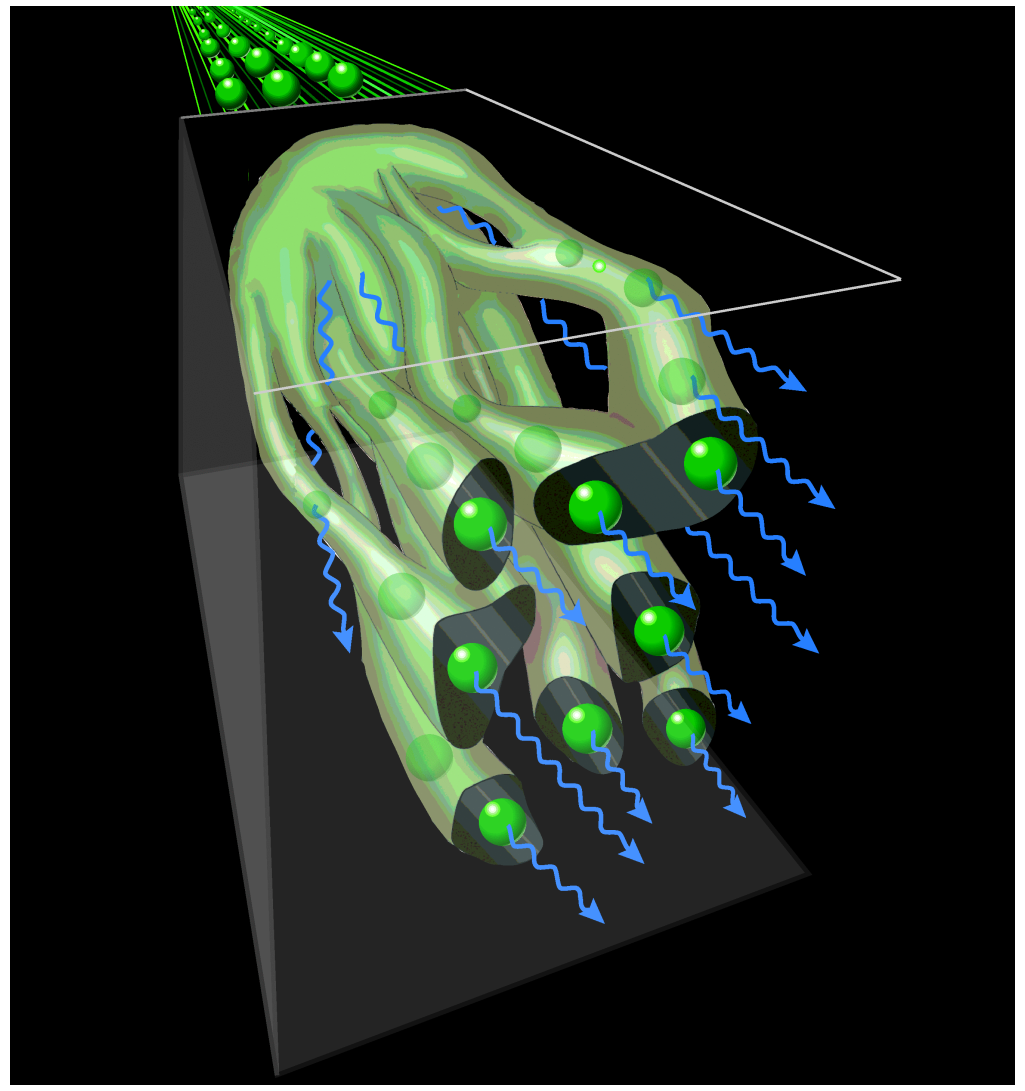
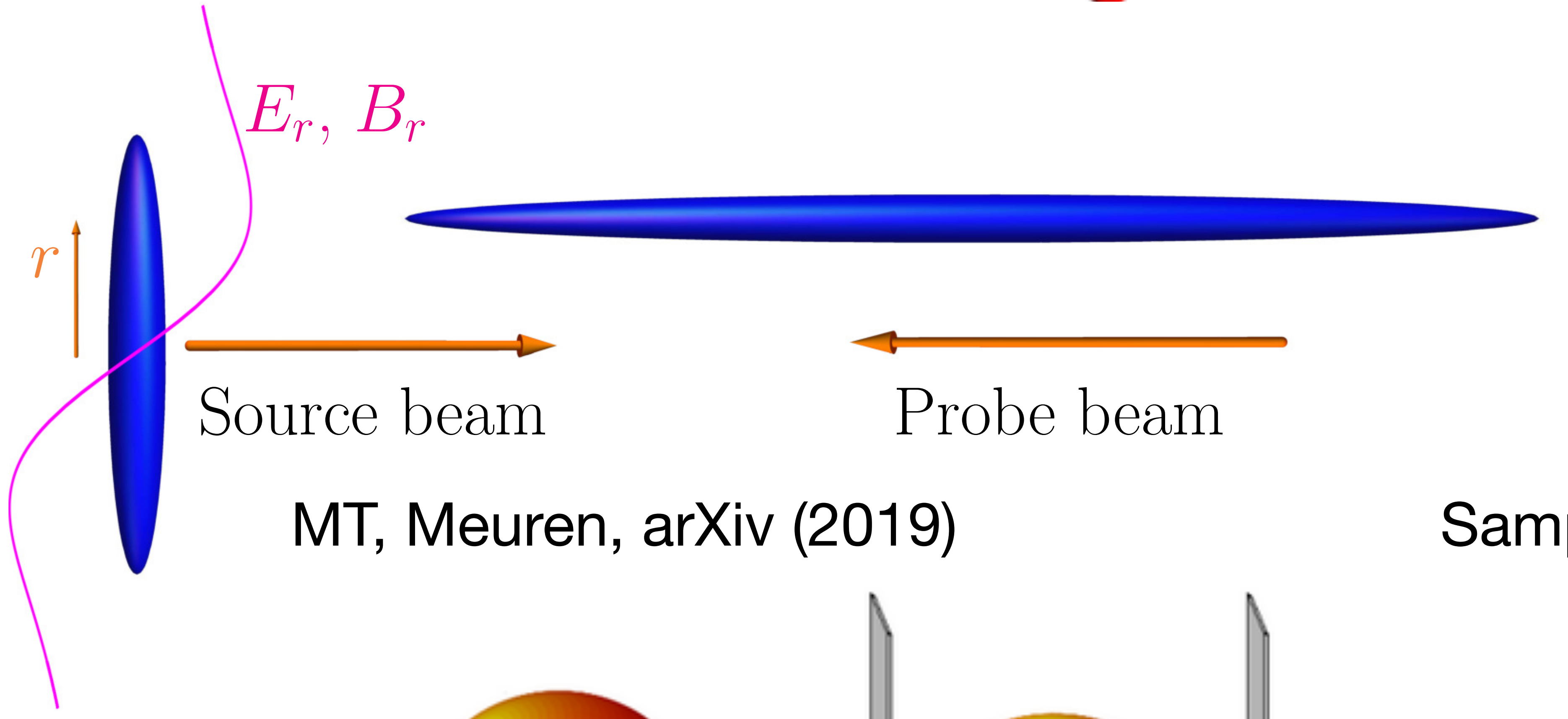
Sixteenth Marcel Grossmann Meeting, 9 July 2021



Poder, MT *et al.*, Phys. Rev. X (2018)

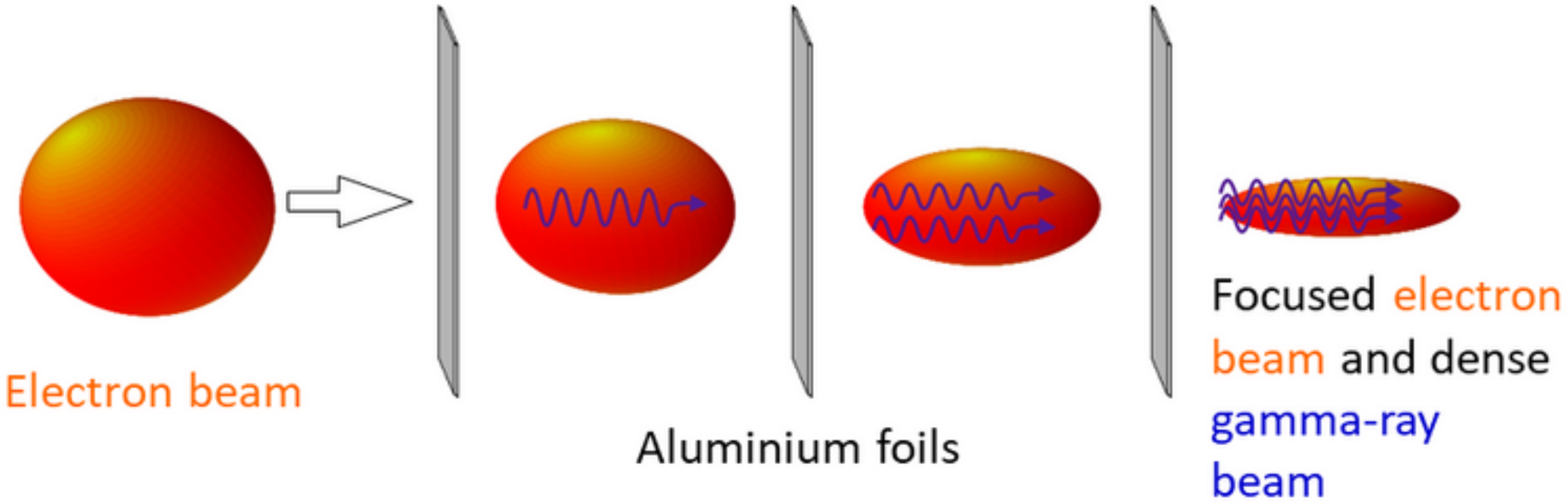


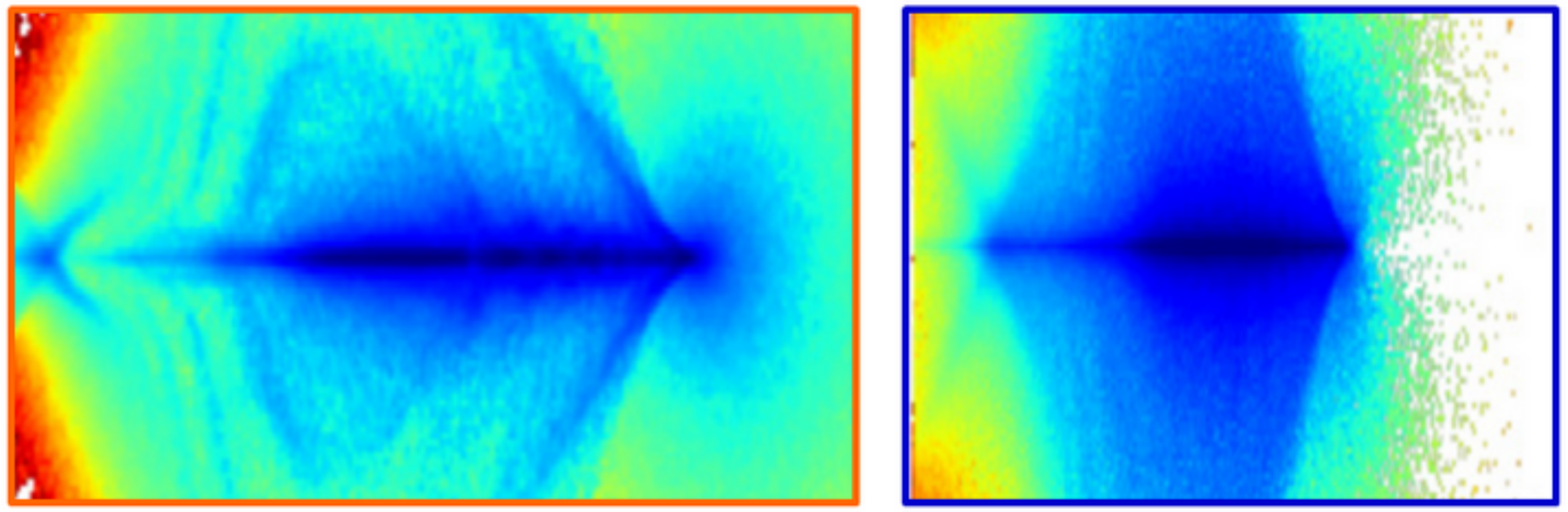
Benedetti, MT, Keitel, Nat. Photon. (2018)



MT, Meuren, arXiv (2019)

Sampath, ..., MT, Phys. Rev. Lett. (2021)





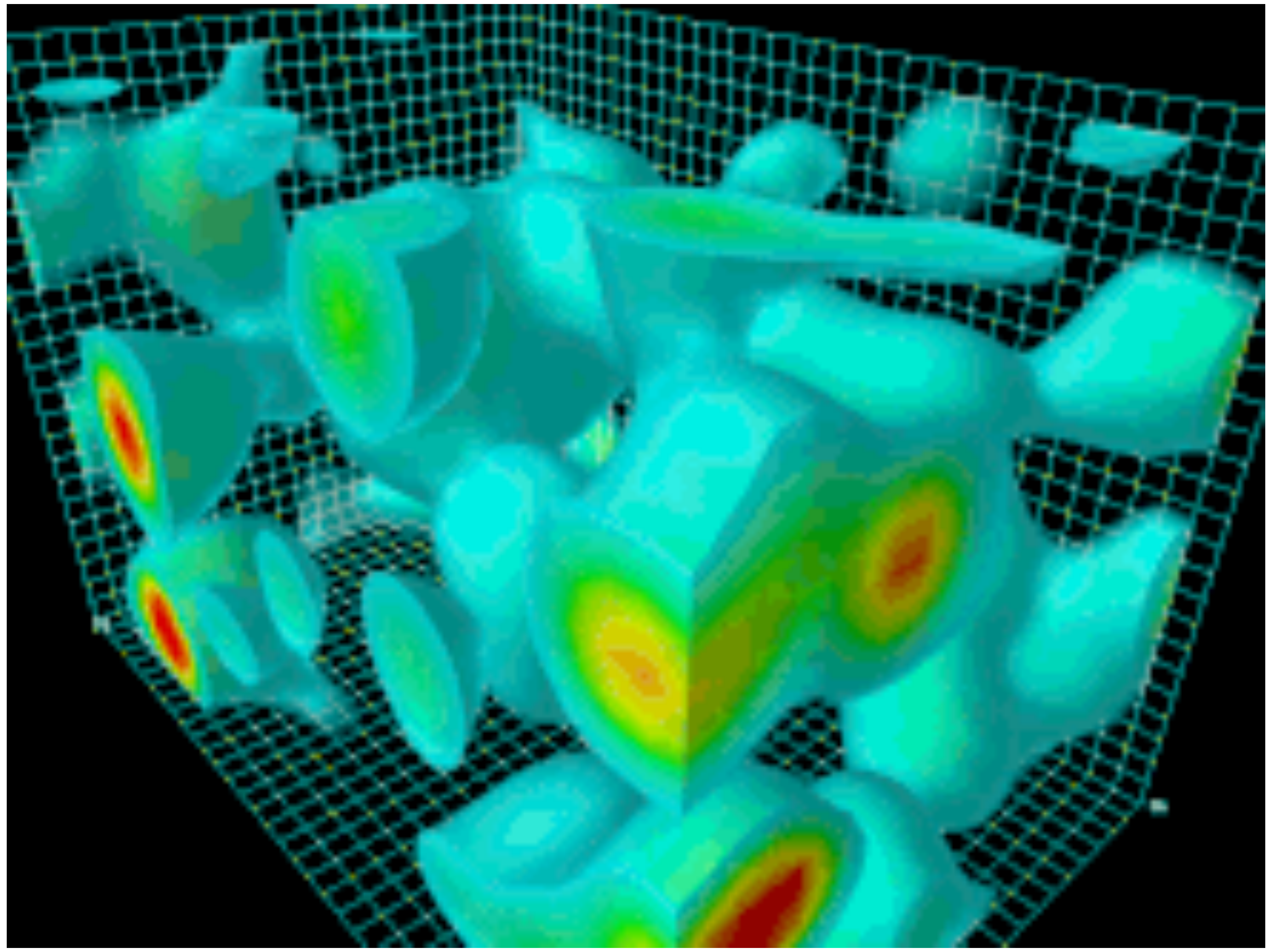
Outline

- Introduction
  - Motivations for intense particle beams
  - Strong-field QED processes
- Generation of extremely-dense lepton & gamma-ray beams: new opportunities for extreme plasma physics and laboratory astrophysics
- Outlook & Summary

Motivations for fundamental physics and relativistic laboratory astrophysics

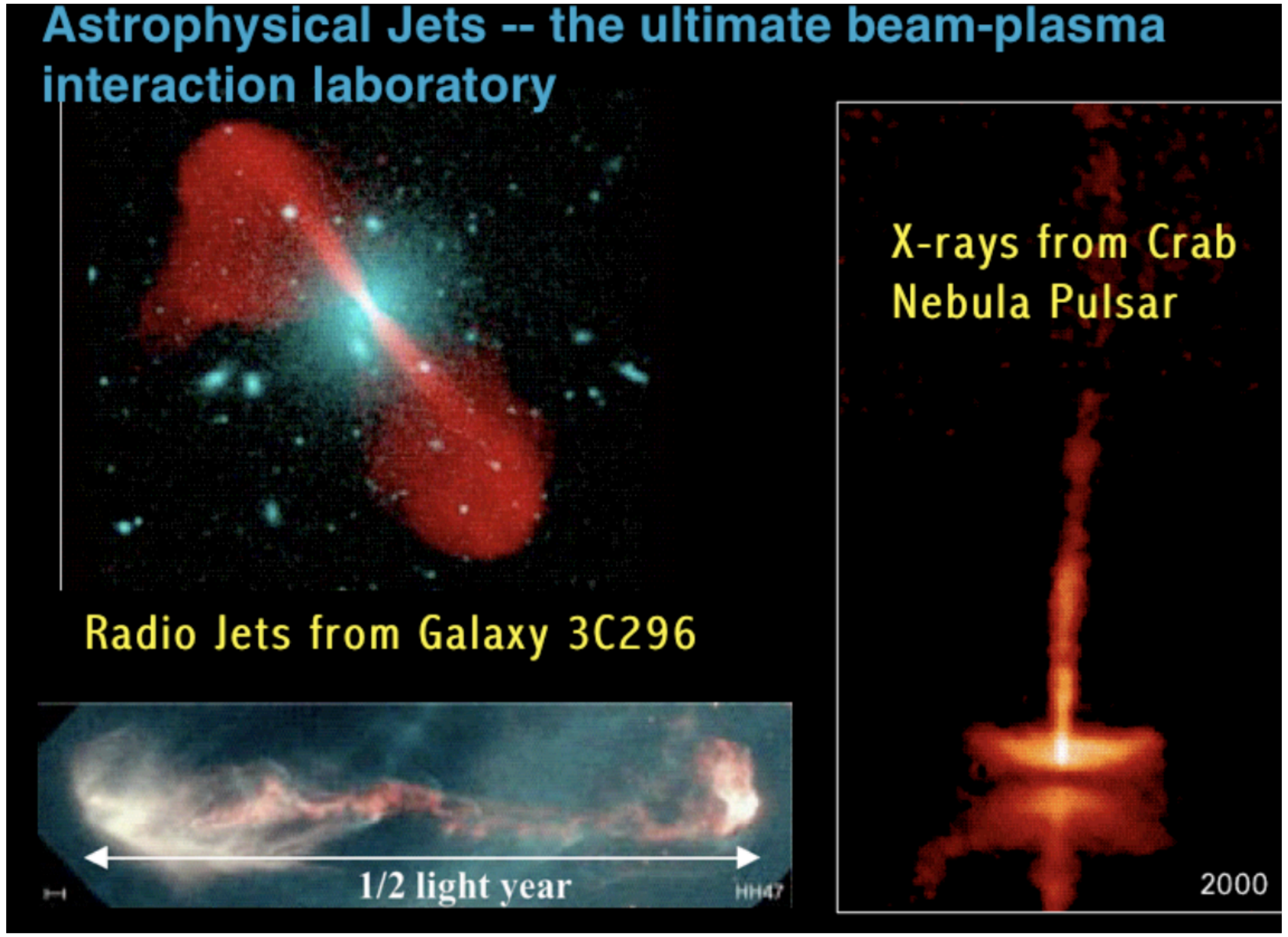
Intense high-energy gamma-ray beams allow

- probe the quantum vacuum (birefringence and dichroism in strong e.m. fields),
- photon-photon physics and beyond SM physics ($\gamma+\gamma\to\gamma+\gamma$, $\gamma+\gamma\to e^-+e^+$, $\gamma+\gamma\to X+\bar{X}$)

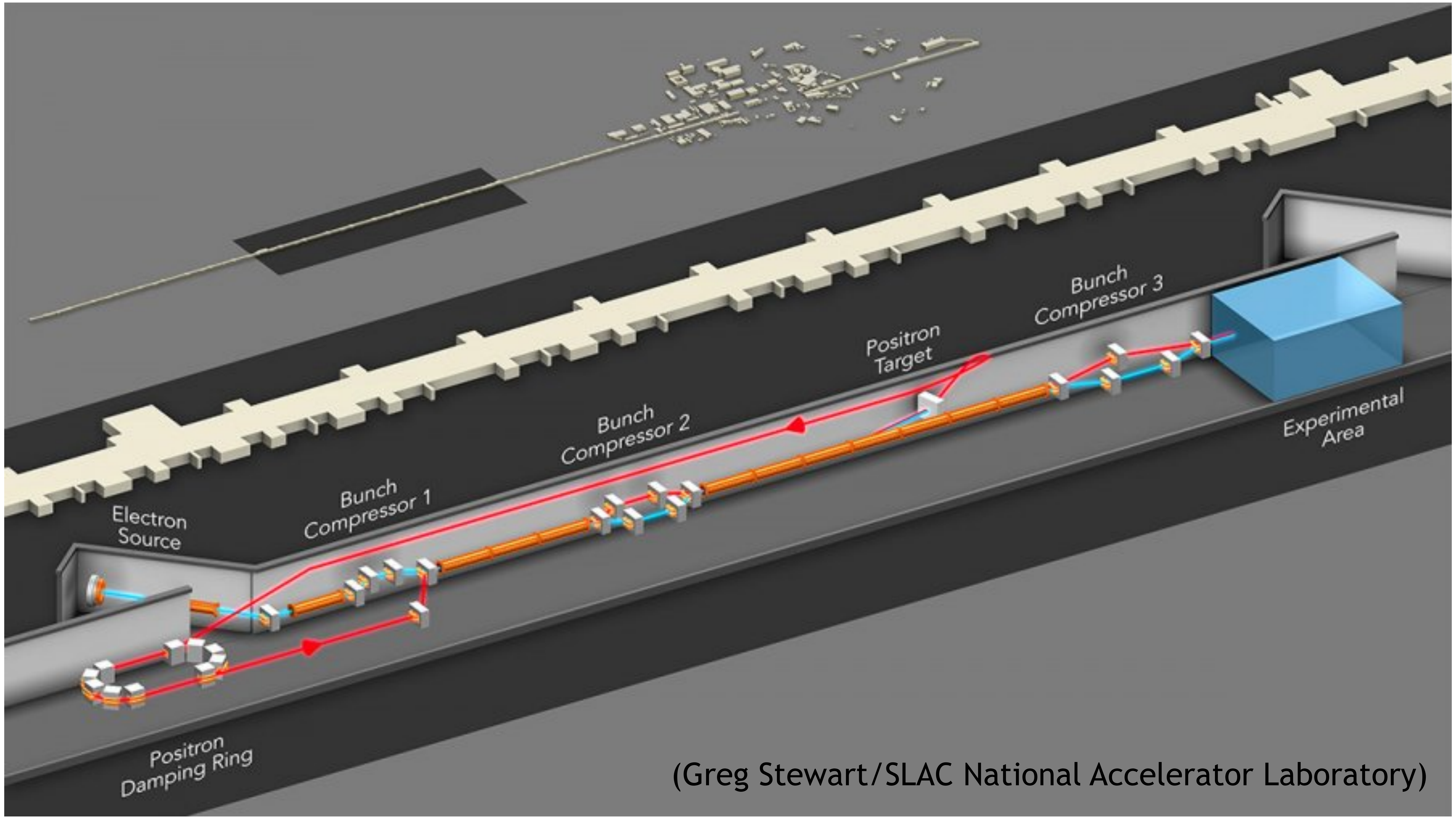


Dense lepton beams

- Probe SFQED with a single e^- beam and no lasers (self-generated surface and bulk fields in plasma)
- Collective dynamics of electron-positron pair jets for relativistic laboratory astrophysics



FACET-II facility for advanced accelerator experimental tests



(Greg Stewart/SLAC National Accelerator Laboratory)

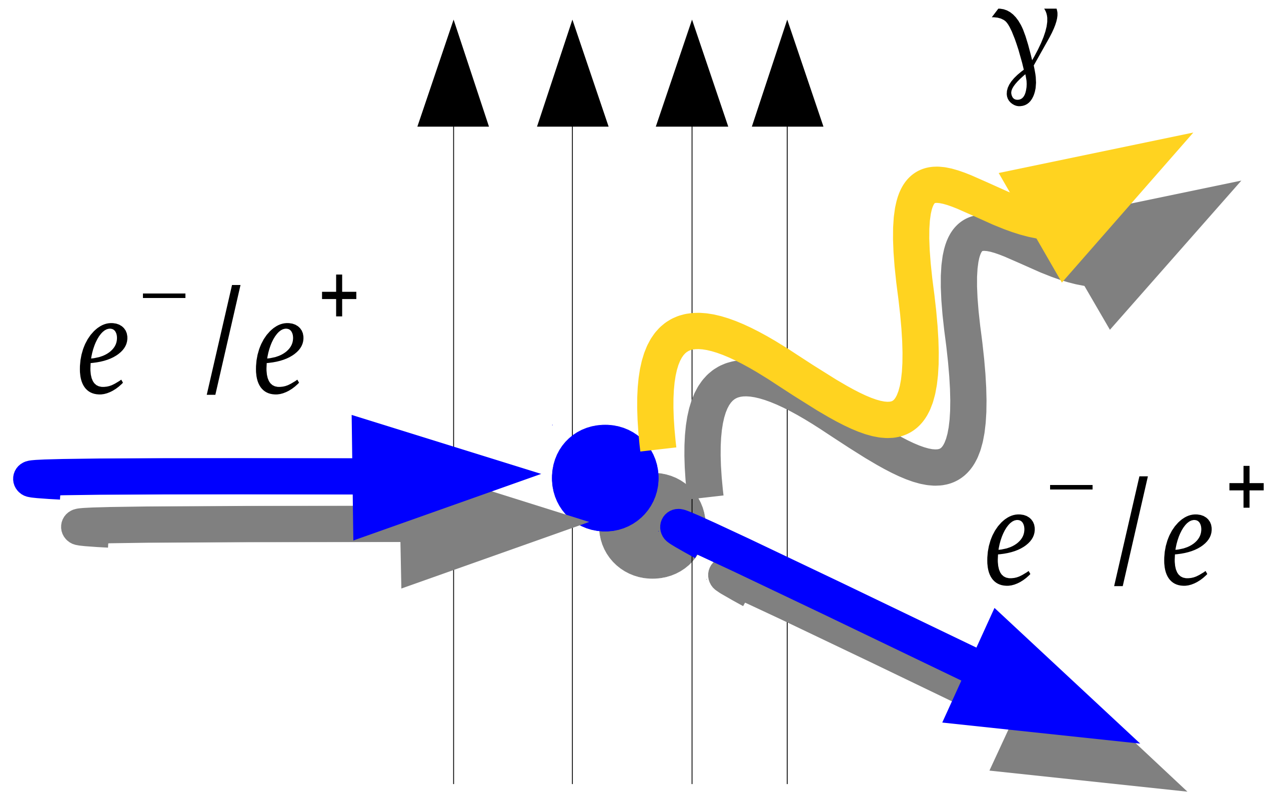
Unique beam capabilities

Electron Beam	
Beam Type	e-
Beam energy (GeV)	10
Repetition Rate (Hz) (range)	10 1-30
Bunch Charge (nC) (range)	2 0.5-3
Bunch Length (σ, μm) (range)	20 1-100
Beam Spot size (σ, μm) (range)	10 5-200

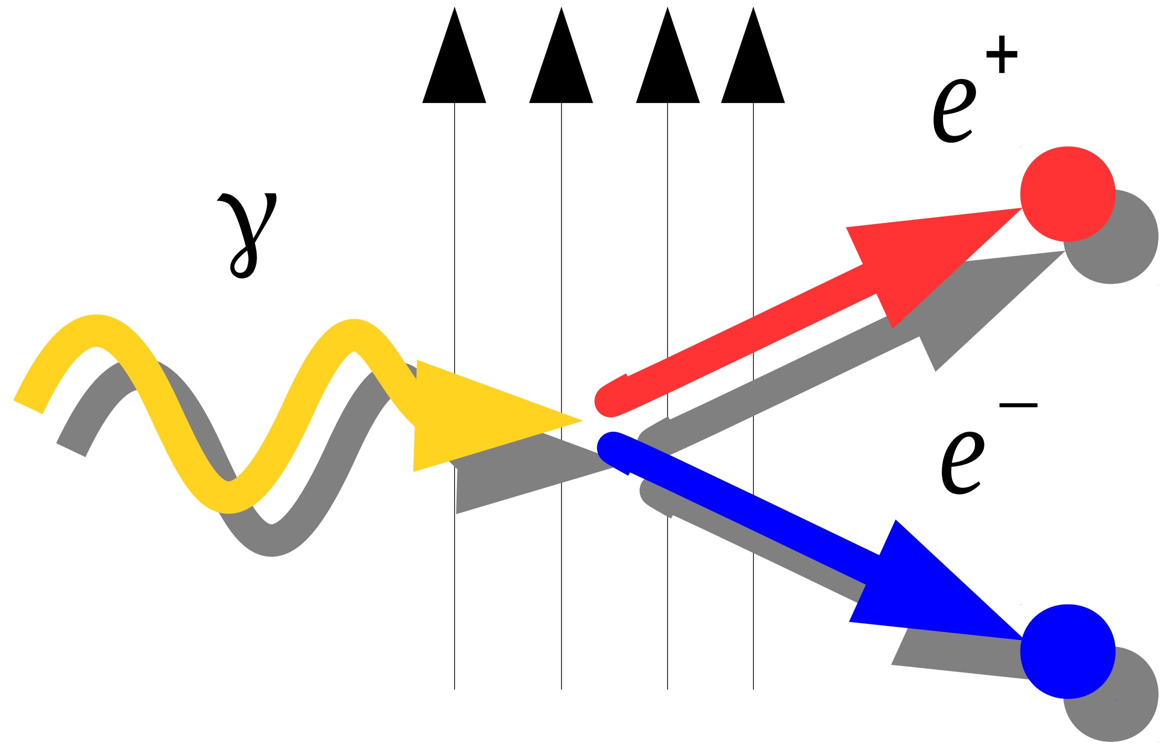
The electron source sends a beam of electrons (bottom, blue line) from the electron source (bottom left) to the experimental area (bottom right), where it arrives with an energy of 10 GeV. The design allows for adding the capability to produce and accelerate positrons (bottom, red line) later.

The basic QED processes in a strong background electromagnetic field

Photon emission by an e^-/e^+



Photon conversion into an e^-/e^+ pair



Strong-field QED processes are controlled by the quantum parameter

$$\chi_{e/\gamma} = |F_{\mu\nu}p^{\nu}_{e/\gamma}|/E_{cr}mc = E^*/E_{cr}, \quad E_{cr} = m^2c^3/\hbar|e| \approx 1.3 \times 10^{18}\ \textbf{V/m}$$

for an electron, it is proportional to the electric field in its instantaneous rest frame

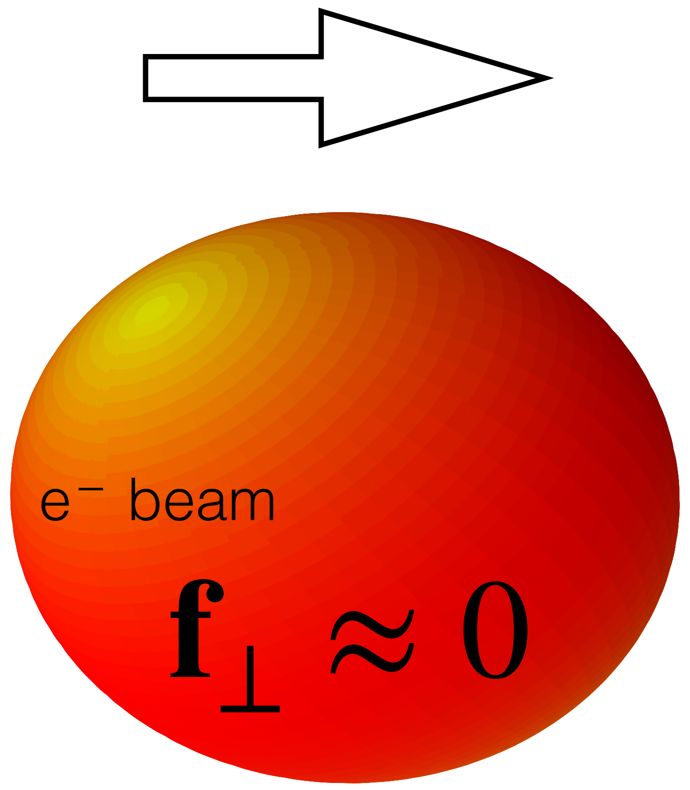
$$\chi_e \sim 1$$

Emitted photon energy ~ initial electron energy

$$\chi_\gamma \sim 1$$

Photon conversion into e^-e^+ becomes probable

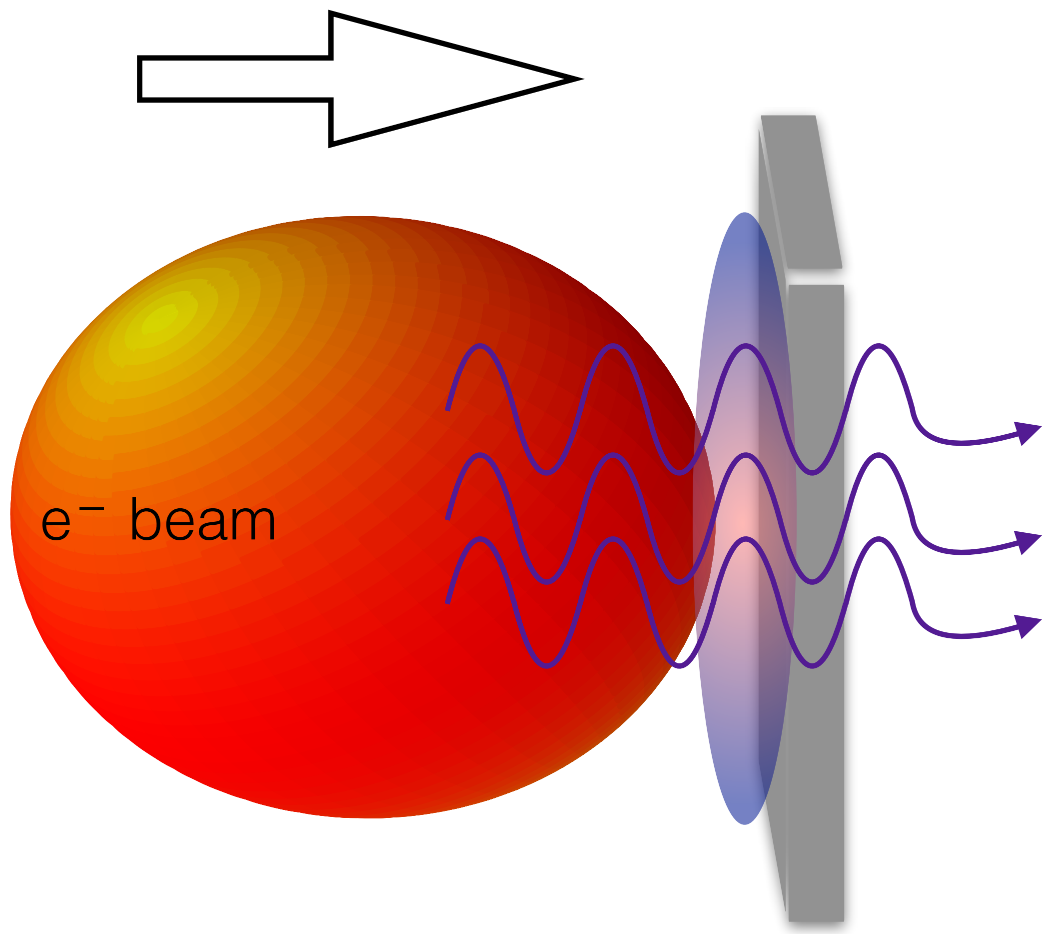
Solid-density gamma & lepton beam generation in beam-foil collision



$$\mathbf{B} = \beta \times \mathbf{E}_\perp$$

$$\mathbf{f}_\perp = e\,[\mathbf{E}_\perp + \beta \times \mathbf{B}] = e\,[\mathbf{E}_\perp + \beta \times (\beta \times \mathbf{E}_\perp)] = e\,\frac{\mathbf{E}_\perp}{\gamma^2}$$

Nearly ballistic propagation in vacuum

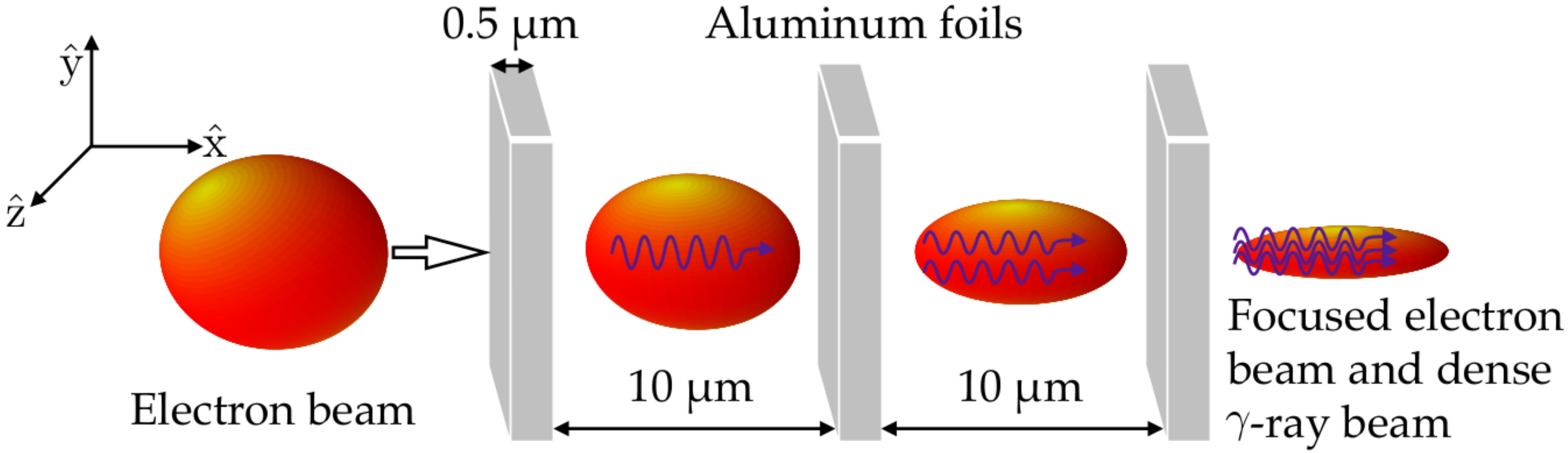


$\mathbf{E}_\perp \approx 0 \quad \mathbf{B} \approx 2\mathbf{B}_{free}$

For **pancake-shape** ($\sigma_\perp \lesssim \sigma_{||}$, i.e. transverse$\lesssim$longitudinal beam size) and in the limit of infinite conductivity the process of beam collision with a solid conductor can be **visualized as a beam colliding with its image charge beam.**

In the **collision of a dense beam with its image,** $\chi \gtrsim 1 \Rightarrow$ **SFQED effects** can play a key role, with each single photon emission carrying away a large fraction of the emitting electron energy.

Concept for a CTR-based and single electron beam γ-ray source



Schematic of the experiment. A collimated and high-current electron beam collides with a series of foils therefore undergoing strong-focusing by NF-CTR with the generation of a solid density gamma-ray pulse

Sampath, …, MT, Phys. Rev. Lett. (2021)

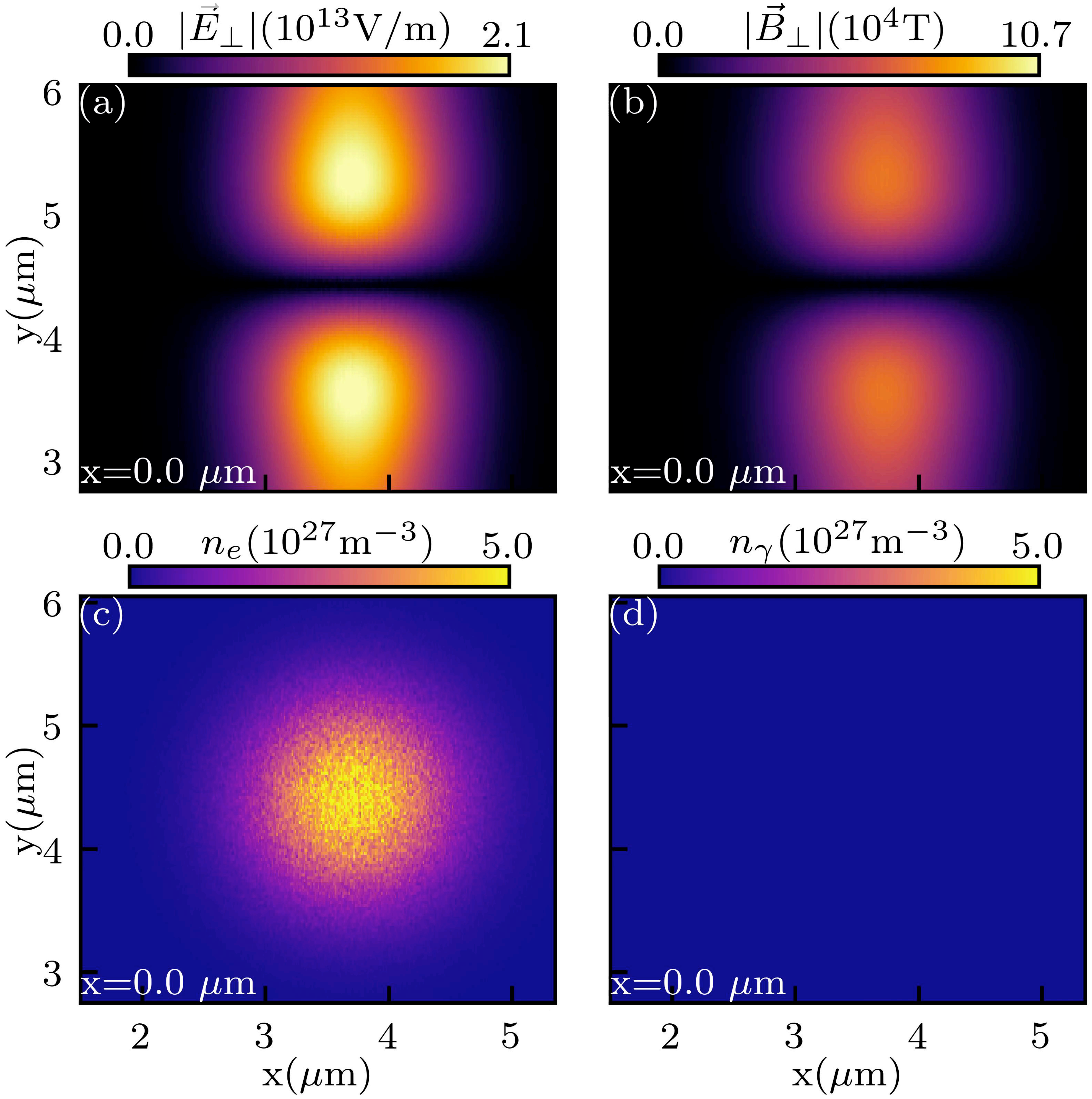
Beam evolution in beam-multifoil collisions

3D PIC simulation with advance FACET-II-like beam parameters: 2 nC beam, Gaussian spatial and momentum distribution with $\sigma_\perp = \sigma_\| = 0.55\ \mu$m, 10 GeV mean energy, 212 MeV FWHM energy spread, 3 mm-mrad normalized emittance.

The beam collides with 20 consecutive aluminum foils with 0.5 μm thickness, and 10 μm interfoil distance.

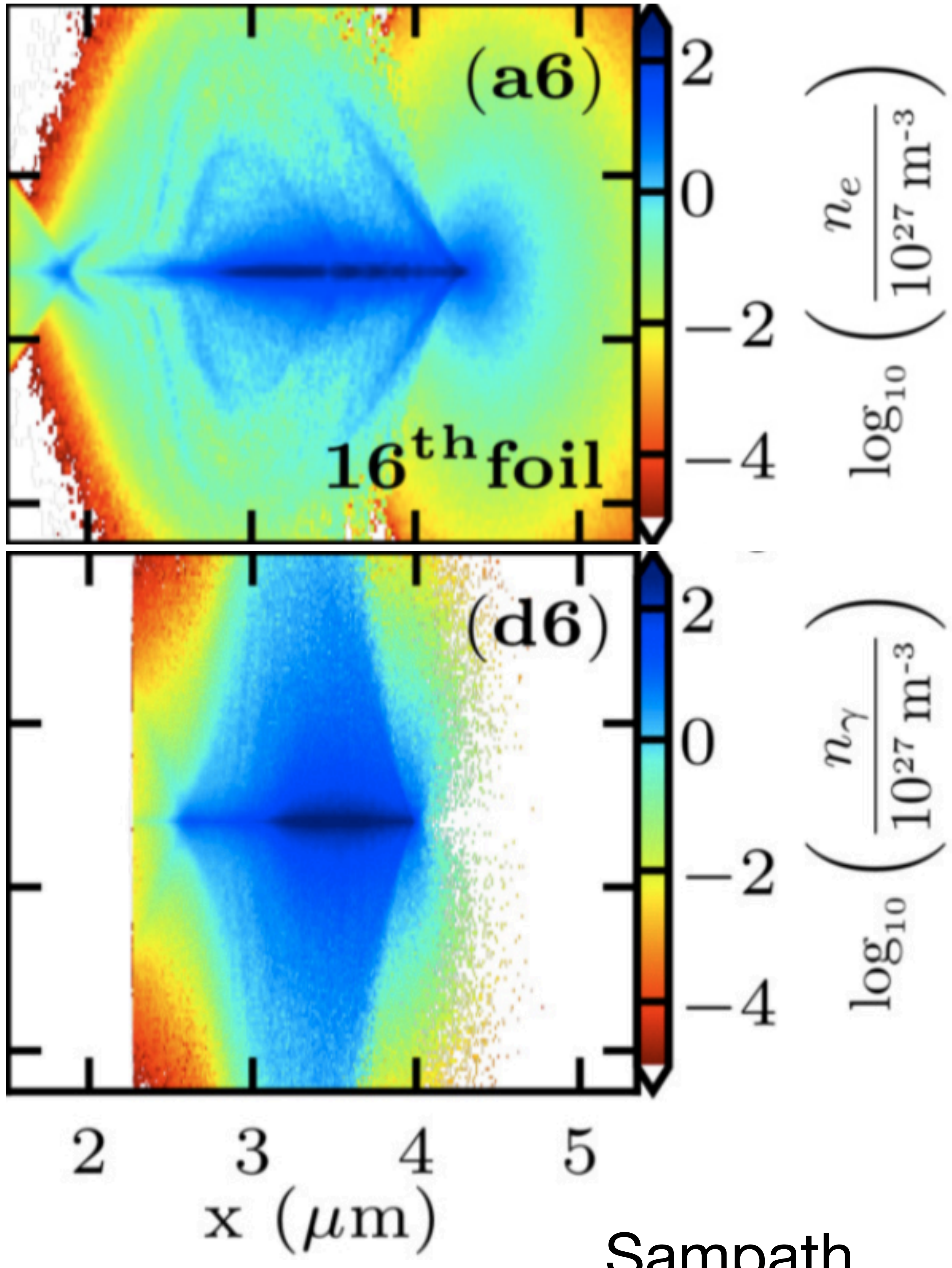
Physics included in the simulation:

- initial self-consistent beam fields,
- field and collisional ionization,
- binary Coulomb collisions,
- synchrotron and bremsstrahlung emission,
- multiphoton Breit-Wheeler,
- Bethe-Heitler pair production.



Concept for a CTR-based and single electron beam γ-ray source

Unique properties (solid-density, high electron-to-gamma conversion efficiency)

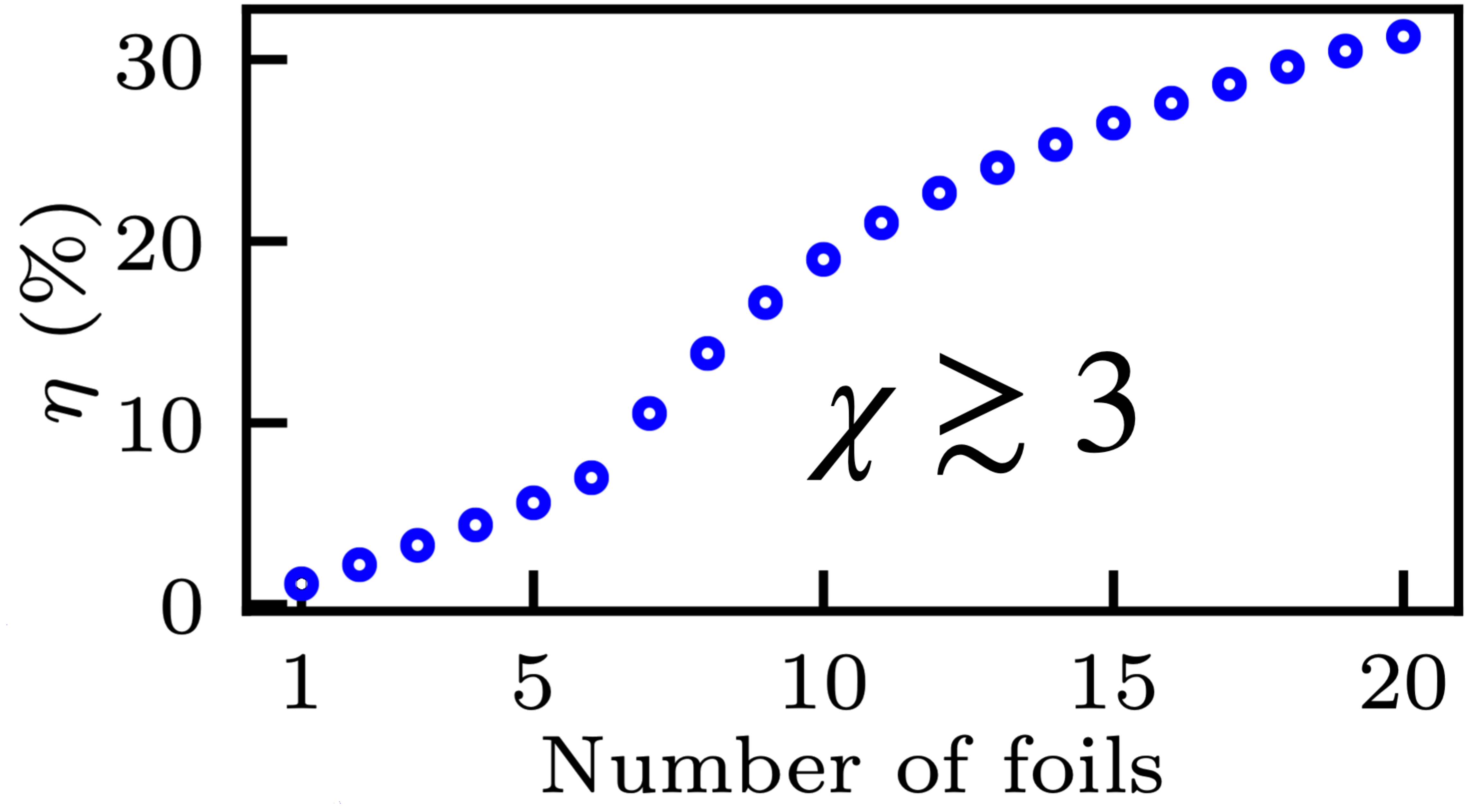


Electron beam density

Two orders of magnitude beam density increase

Gamma beam density

5 mrad aperture, 4 fs FWHM, $3 \times 10^{29}\, m^{-3}$ peak density



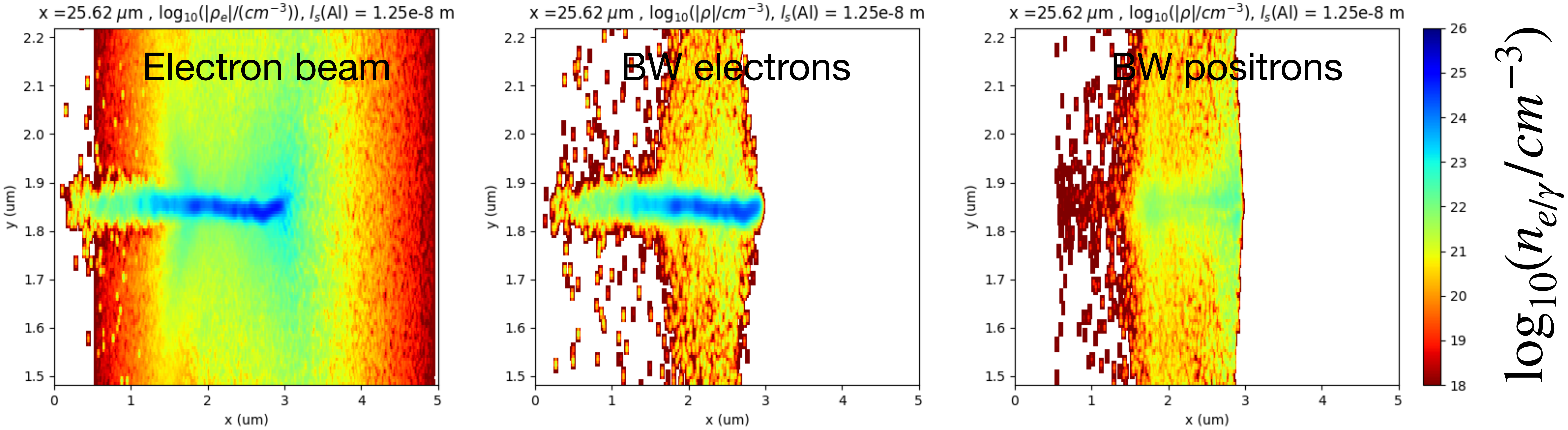
Based on these findings, the E-332 experiment has been devised and approved with maximal ranking by the 2020 Program Advisory Committee at FACET-II.

Sampath, …, MT, Phys. Rev. Lett. (2021)

Outlook: solid-density electron-positron jets in self-generated strong fields

Due to the mass symmetry of electrons and positrons, pair plasmas are systems of primary interest for fundamental plasma physics research and for astrophysics, where they are thought to dominate the matter content of relativistic jets that stream from compact astrophysical objects (pulsars, magnetars, black holes, nuclei of active galaxies).

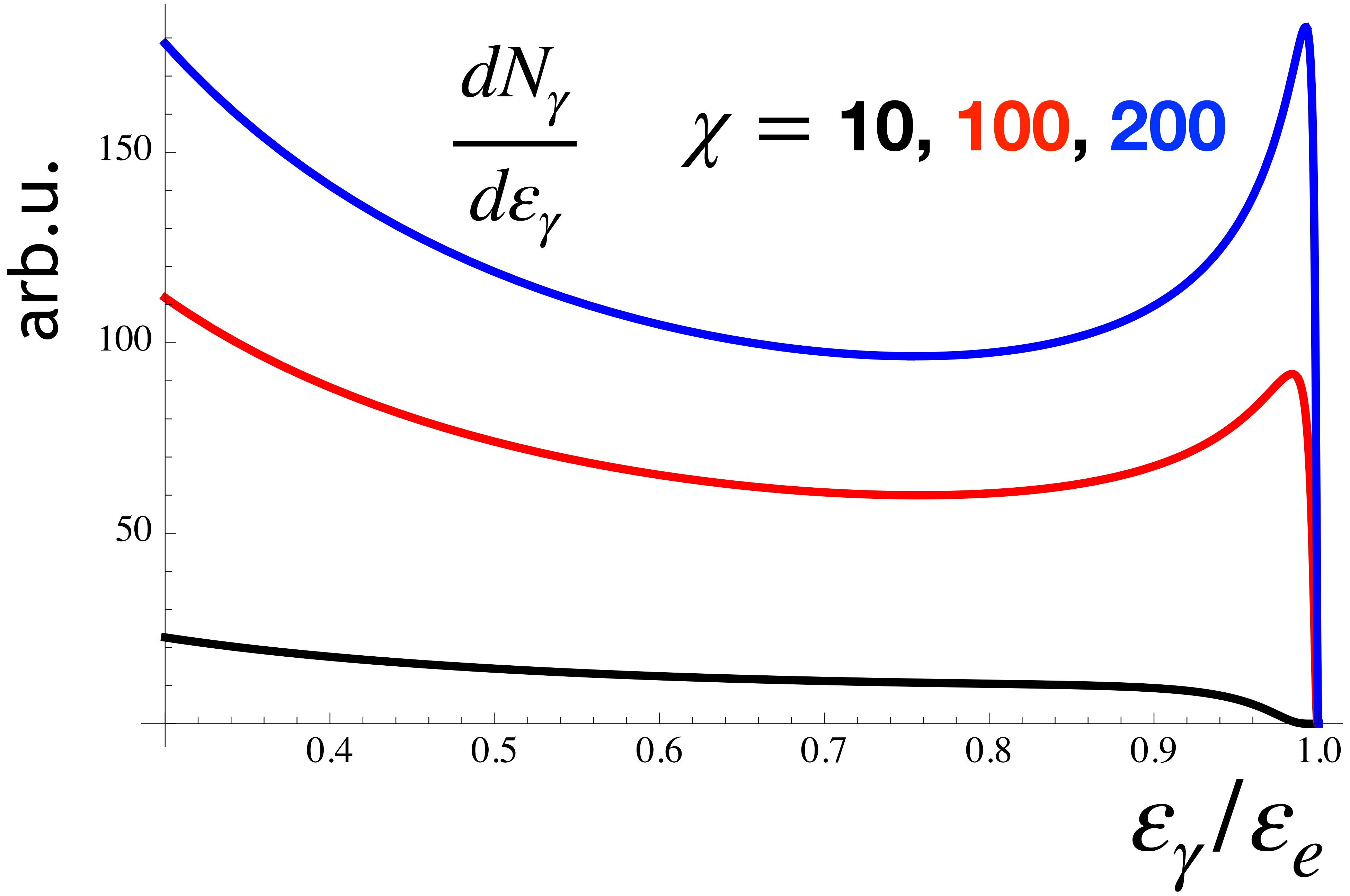
The generation of **dense quasi-neutral gamma-electron-positron plasmas extending over several skin depths** in the laboratory would enable access, for the first time, to a **new regime dominated by the interplay between strong-field QED effects and collective plasma dynamics of relevance for extreme astrophysical environments**.

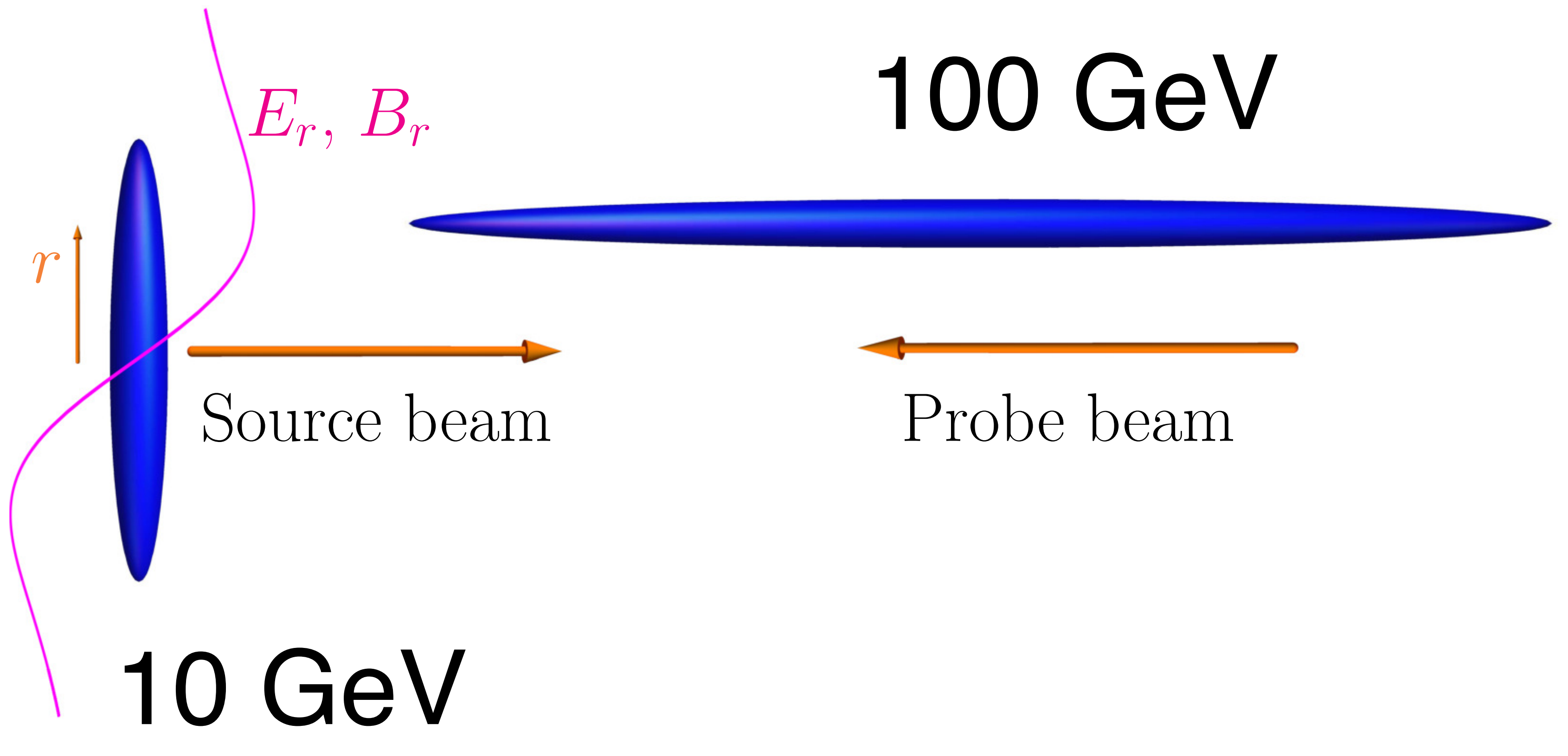


Sampath, MT *et al.*, in preparation

Efficient high-energy photon production in the supercritical QED regime

- The extremely high-energy regime ($\chi \gg 1$) of SFQED is entirely untested and poorly understood theoretically. It has been conjectured that QED becomes strongly-coupled ($\alpha \to \alpha\chi^{2/3} \sim 1 \Rightarrow \chi \sim 1600$, Ritus-Narozhny conjecture. Complementary to the high-coupling regime with high-Z ions where $\alpha \to Z\alpha \sim 1 \Rightarrow Z \sim 137$).
- Already at $\chi \gg 1$ and $\alpha\chi^{2/3} \sim 0.1 \Rightarrow \chi \sim 100$, new qualitative features appear in the photon emission spectrum. **Electron-to-photon energy conversion with a single photon emission** becomes efficient opening up the possibility of realising a **laserless gamma-gamma collider from an electron-electron collider.**





Asymmetric beam-beam collision setup

- Allows to access and to carry out precision measurements of SFQED in the $\chi \gg 1$ regime
- One-to-one correspondence between the height H of the photon peak and the quantum parameter $\chi \gg 1$

If $\chi > 16$

$$H \approx \frac{1.315 + 0.315\chi}{\chi^{2/3}}$$

MT, Meuren, arXiv (2019)

Summary

- Intense gamma-ray & lepton beams open new avenues of research in SFQED, plasma physics, high-energy density beam physics, photon-photon physics, and relativistic laboratory astrophysics.
- The synergy between plasma and SFQED effects enable the efficient generation of gamma-ray and dense lepton beams with unique properties in terms of flux, intensity and energy.
- Following the recent theoretical and technological developments, a new class of experiments at extreme fields are underway, therefore enabling to test for the first time, e.g., the interplay between SFQED and collective effects in a dense electron-positron pair plasma.

Thank you for your attention!