INFN

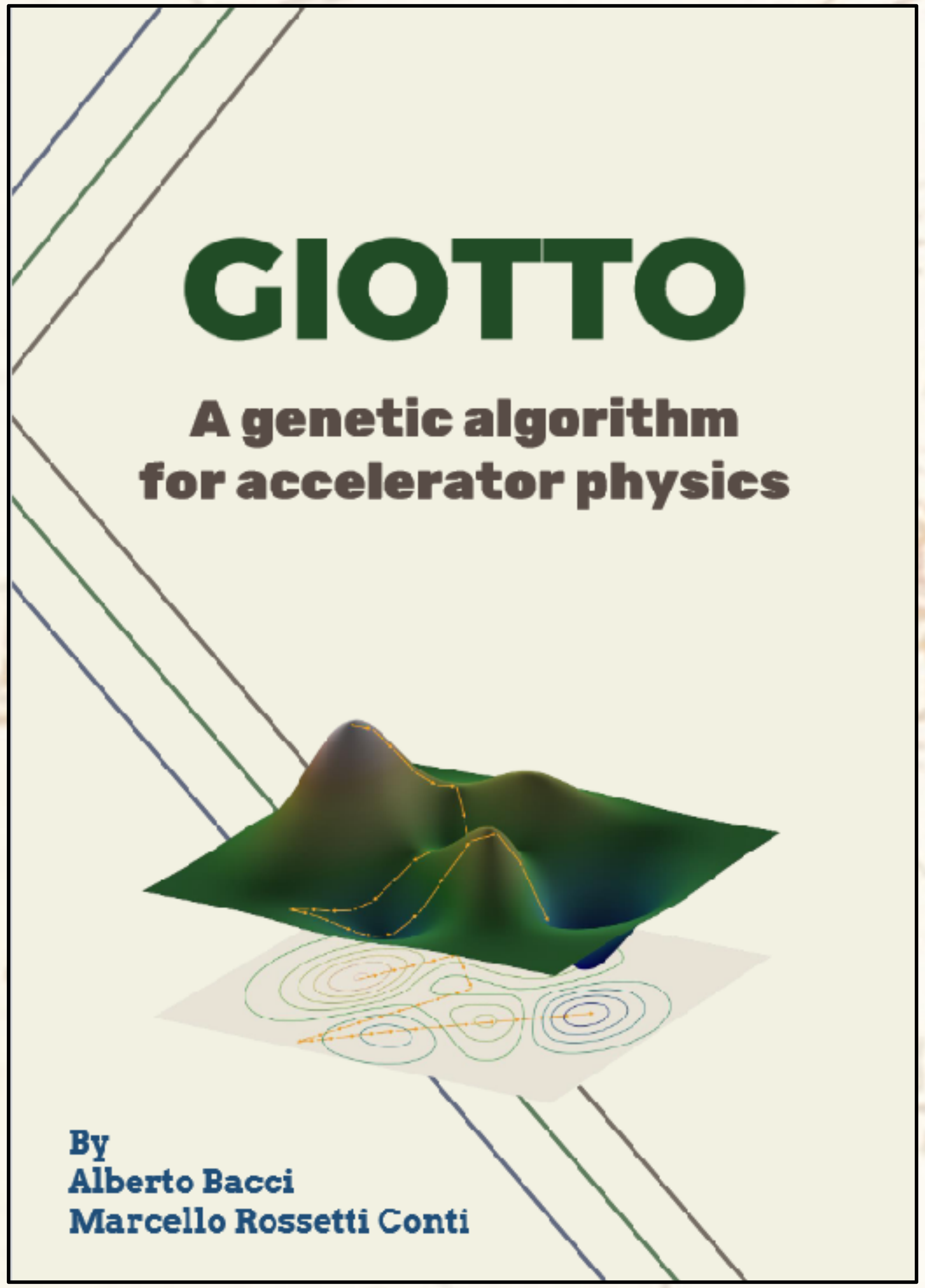
Istituto Nazionale di Fisica Nucleare

R&D Accelerators

Andrea R. Rossi

ESPP meeting

Beam line optimization by AI



GIOTTO

A genetic algorithm for accelerator physics

By
Alberto Bacci
Marcello Rossetti Conti

One of first AI codes for **beam line design & optimization**.

Solves complex multi-objective problems (correlated parameters, space-charge like) & statistical analysis (machine jitters studies).

Drives the beam dynamics PIC code **ASTRA**. Natively compatible with **NameList** std.

V. 13.0 for **Linux** & **Windows**, parallelized with **MPI**.

Successfully used in important projects, as:

Some contributions to publications:

- *New approach to space charge dominated beamline design* – PRAB **26** (2023)
- *Two-pass two-way acceleration in a superconducting CW linac to drive low jitter x-ray FEL*–PRAB **22** (2019)
- *Electron beam transfer line design for a plasma driven Free Electron Laser* – NIM A **909** (2019)
- *Electron Linac design to drive bright Compton back-scattering gamma-ray sources* – JAP **133** (2013)

Milan ESPP-related activities

Four research lines:

- Energy Recovery Linac
- Positron source & capture line (in collaboration with INFN Ferrara)
- High gradient and novel acceleration (EuPRAXIA collaboration)
- New possible experimental setups

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ERL technology for FC

- **Key Benefits for Future Colliders:**
  - **Energy Efficiency:** Significant reduction in energy consumption by recovering beam energy.
  - **High Beam Intensity:** ERLs enable high-luminosity electron beams, essential for frequent and precise collisions.
  - **Low Emittance Beams:** Provides stable, focused beams, improving experimental resolution.

iSAS - Milan

$$\mathcal{L} = \frac{N_1 N_2}{4\pi\sigma^2} f$$

- **Impact on Particle Physics:**
  - **Ideal** for **Future Electron-Positron colliders**, where energy efficiency and **high luminosity** are crucial.
  - Enables **exploration** of **new energy frontiers** while maintaining operational **sustainability**.

- **Sustainability:**
  ERL technology **reduces the environmental impact**, making large accelerators more sustainable for the future.

☞ The Development of Energy-Recovery Linacs - chap 5. **arXiv:2207.02095**

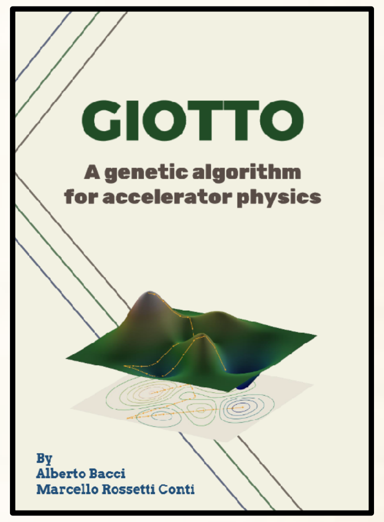
Milan and **LASA** provide key expertise in ERL technology through their research on **BriXSinO**.

INFN ERL-related activity: BriXSinO

- High flux dual light source (100 MHz rep. rate) based on an Energy Recovery Linac.
- Up to 5 mA average current - 50 pC bunches.
- Test machine for Two-Pass Two-Way acceleration.

HB²TF. Call funded: 1 M€ 2023 - 2025

BriXSinO ongoing activities



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Invited Talks

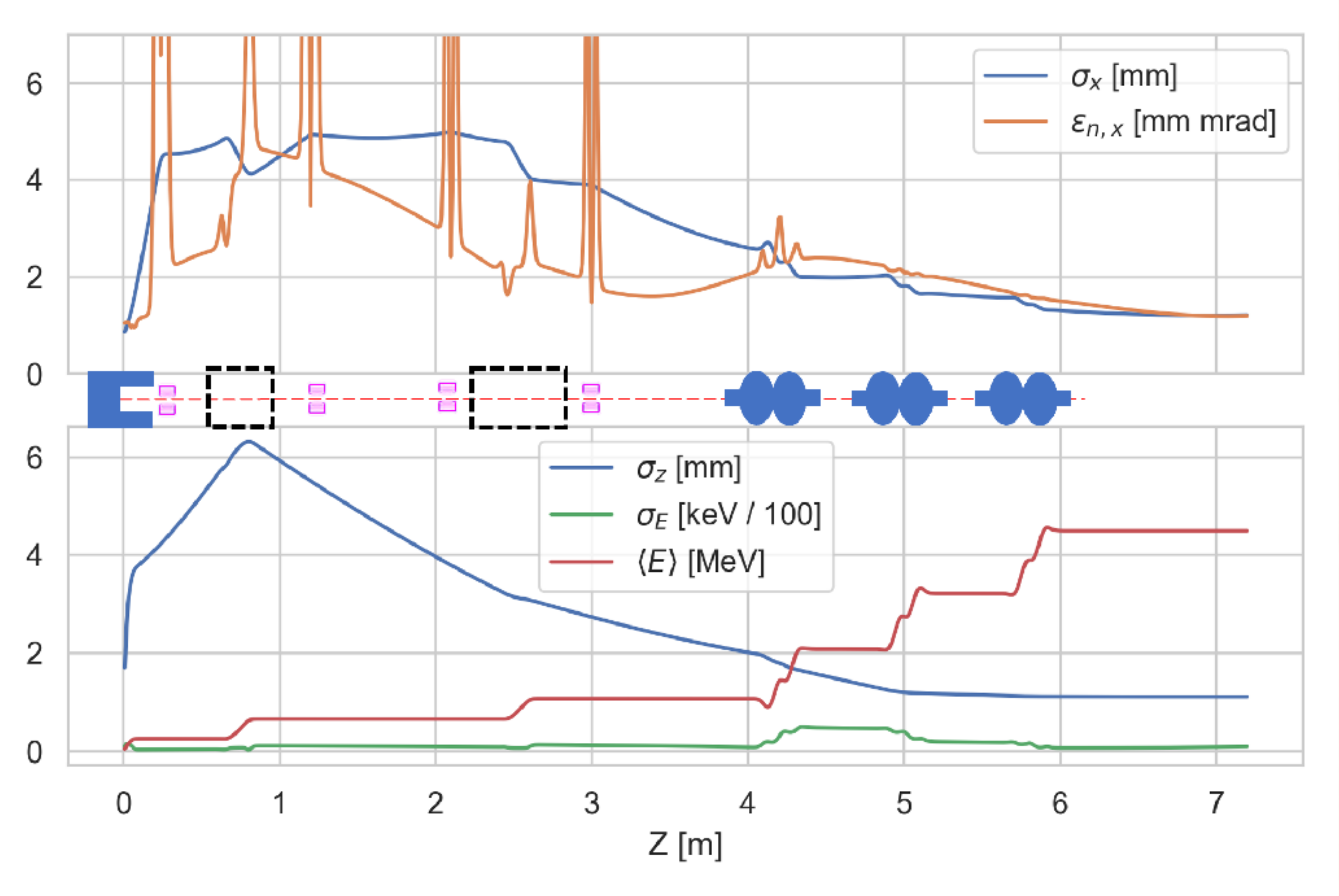
- ***M. Rossetti Conti:*** *Improved techniques for space charge dominated beamline design –* ***ERL 24***
- ***D. Giove:*** *BriXSinO: an ERL proposed facility at INFN Milan LASA Laboratory –* ***ERL 24***
- ***I. Drebot:*** *BriXSinO high-flux dual X-ray and THz radiation source based on ERLs –* ***IPAC 22***
- ***+ S. Samsam:*** *Elevating beam quality and stability in accelerators through HOM analysis -* ***IPAC 25 (soon)***

Some contributions to publications:

- *New approach to space charge dominated beamline design –* PRAB **26** (2023)

Coming soon:

- *Innovative solutions for high-brightness low-energy ERL injector design: the BriXSinO approach*



A possible home for BriXSinO

INFN funded a bunker in LASA with dimensions compatible with BriXSinO

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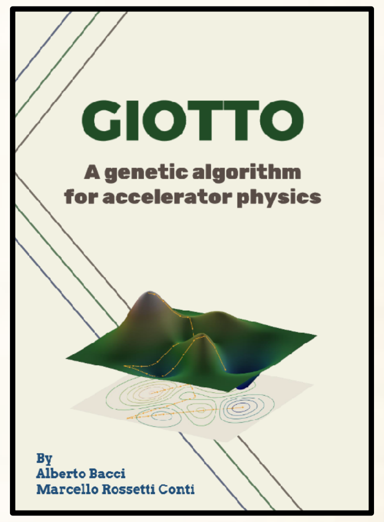
Positron source related activity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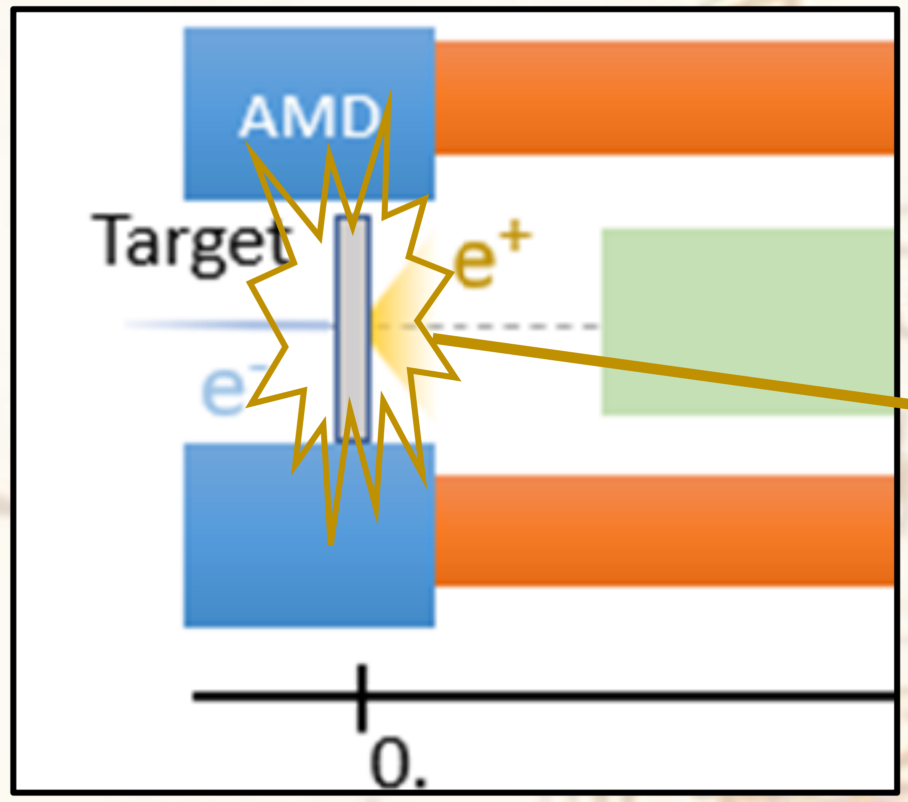
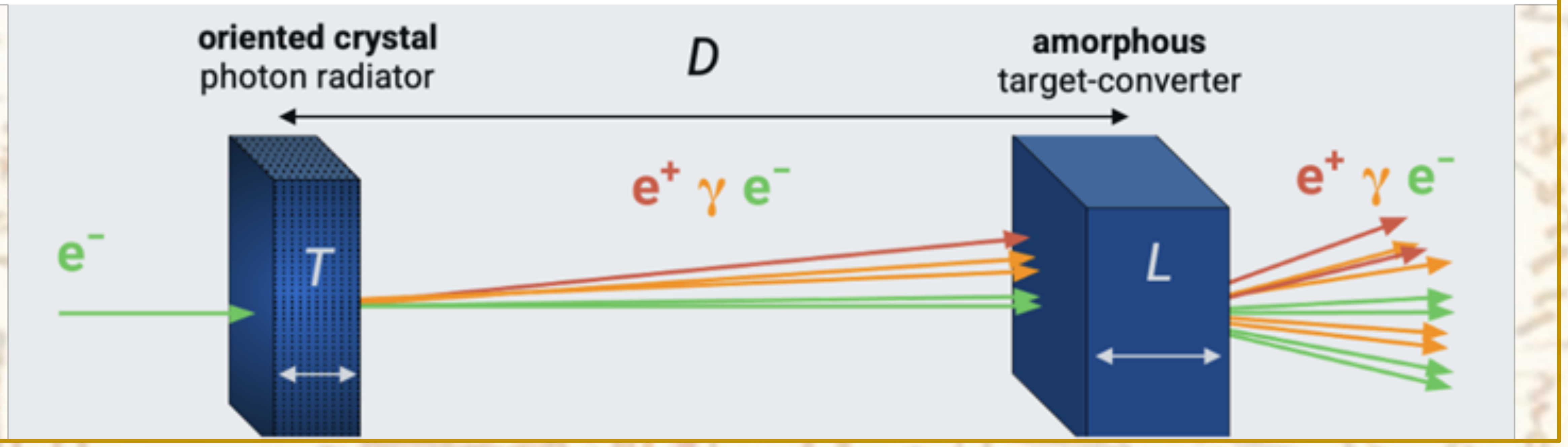


e^+ Hybrid target scheme (INFN-FE)

L. Bandiera et al., Eur. Phys. J. C (2022) 82:699



Optimization of the e^+ target that is done by two step: a first target named photon radiator and a second one named converter.

This configuration seems to by **more performing from the e+ production vs the power density deposited into the target**. A configuration more robust in terms of heating and target damages.

Three main parameters must be optimized, T, L and D (see the picture) and the magnetic field surrounding the device

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FCC-ee positron capture line improvement

An FCC-ee test bench: capture line dedicate to the P^3 – experiment test activity (@ PSI)

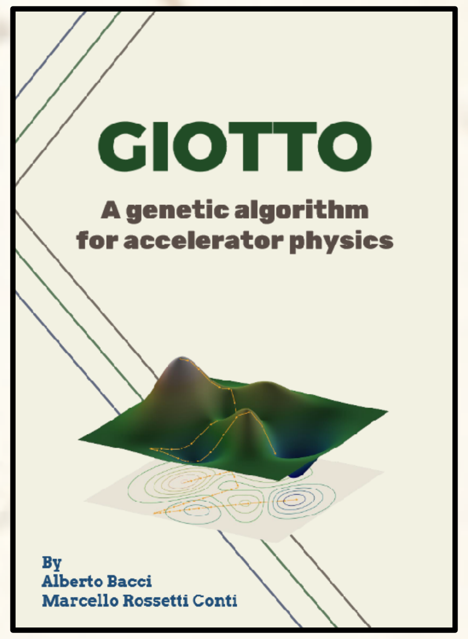
	Genetic knobs:	Variation range:
🟦	HTS: position (for optimal capture)	± 2 cm
🟦	HTS: peak field	± 2 T
🟩 🟧	Cavities + Helm. Coils: postion (moved as a block)	± 5 cm
🟩	Cavity 1: inj. phase	± 180°
🟩	Cavity 2: inj. phase	± 180°
🟩	Cavity 1: acc. gradient	± 5 MV/m
🟩	Cavity 2: acc. gradient	± 5 MV/m
🟧	Cavity 1: Helmholtz coils peak field	± 0.2 T
🟧	Cavity 2: Helmholtz coils peak field	± 0.2 T

1. Complex beam line design and optimization (GIOTTO):

We'll test a **low β Buncher** (500 MHz) a new rf device as linac start capable to improve the positron capture

2. AI-based optimization methods comparison:

We'll benchmark the working points obtained through **GIOTTO** (INFN **genetic algorithm**) and a **Bayesian code** (IJCLab)



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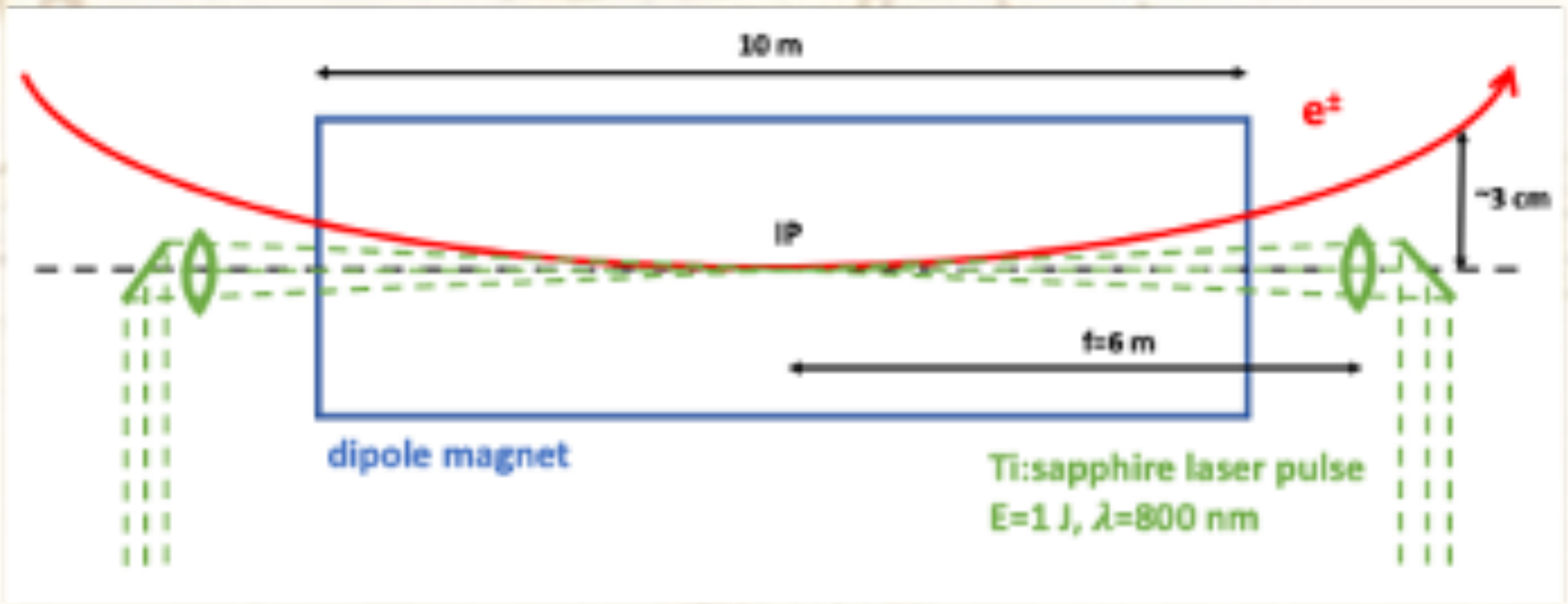
Inverse Compton Scattering beam control

A scheme for preventing flip-flop instability during stabilization

Work in progress :

- Improve IP (LASER / e^- e^+ beams interaction) inside the bending magnet
- Find optimum between bunch charge reduction (flip-flop instability) VS emittance degradation
- e^-e^+ energy optimization exploiting the dispersion inside IP bending magnet
- Study possibility to reduce beam halo using Donuts-shaped laser beam

Sketch: e+ beam vs laser interaction inside a dipole magnet



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EuPRAXIA and ESPP

EuPRAXIA, if properly supported, will be able to shade light among some still open issues relevant for a LC design:

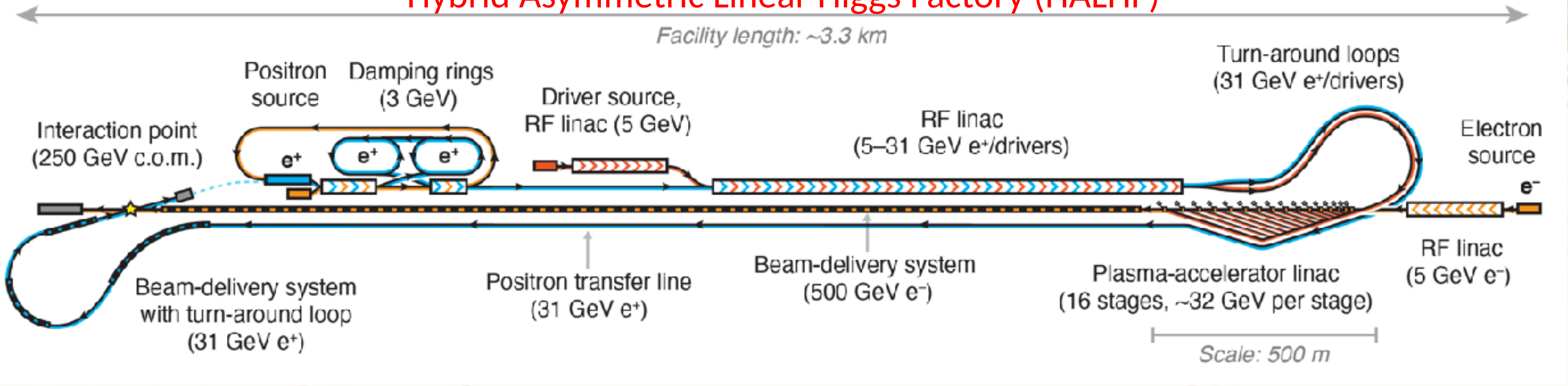
- **Plasma accelerator theory and simulations (LNF, MI, RM1,RM2, Pisa, ITS, QUB)**
- **High repetition rate plasma module (LNF, LNS)**
- **High efficiency plasma acceleration, high tranformer ratio mode (LNF, RM1, MI)**
- **Positron source and acceleration (QUB, LNF, RM2)**
- **Scalable laser driver technology (Pisa, LNF)**

In addition it may provide fundamental information about long term machine operation and its reliability and, also very important, training of the next generation Accelerator Scientist.

Open issues relevant for a FC design:

- high quality electron beams production and acceleration,
- high quality positron beams production and acceleration,
- high repetition rate,
- high efficiency,
- multiple modules staging
- polarized beams

Hybrid Asymmetric Linear Higgs Factory (HALHF)



Foster, D'Arcy and Lindstrøm, New J. Phys. 25, 093037 (2023)
Lindstrøm, D'Arcy and Foster, arXiv:2312.04975

Plasma activities in Milan

Development of Simplified Models and Codes

Objective: Develop simplified models and fast running codes that can accurately represent the dynamics of plasma acceleration while reducing computational costs. Include thermal effects in evaluating the acceleration process and its performances.

Development of Lattice Boltzmann Models and Codes

Objective: Lattice Boltzmann it is a mesoscopic method, midway between the macroscopic approach of fluid codes that use macroscopic quantities, and the microscopic one of particle-in-cell methods (PIC). Upgrade of an existing code is proposed.

High efficiency plasma acceleration

Objective: Beamline and plasma simulations to identify suitable working point for high-efficiency and high-quality acceleration. Beam manipulation and masking techniques will be studied to generate the required beam current distributions.

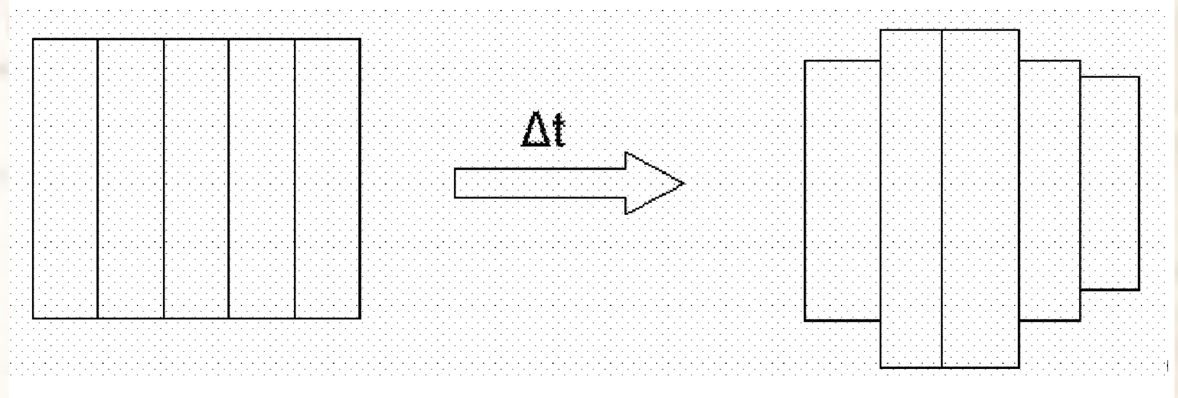
Muon Collider applications

Objective: The high acceleration gradients provided by plasma-based acceleration present a promising approach to minimizing particle losses for the acceleration of both muons and pions. In collaboration with IST (Lisbon) we propose to performe beam dynamics studies with the OSIRIS code of muon acceleration by plasma and design a proper plasma target for muon generation.

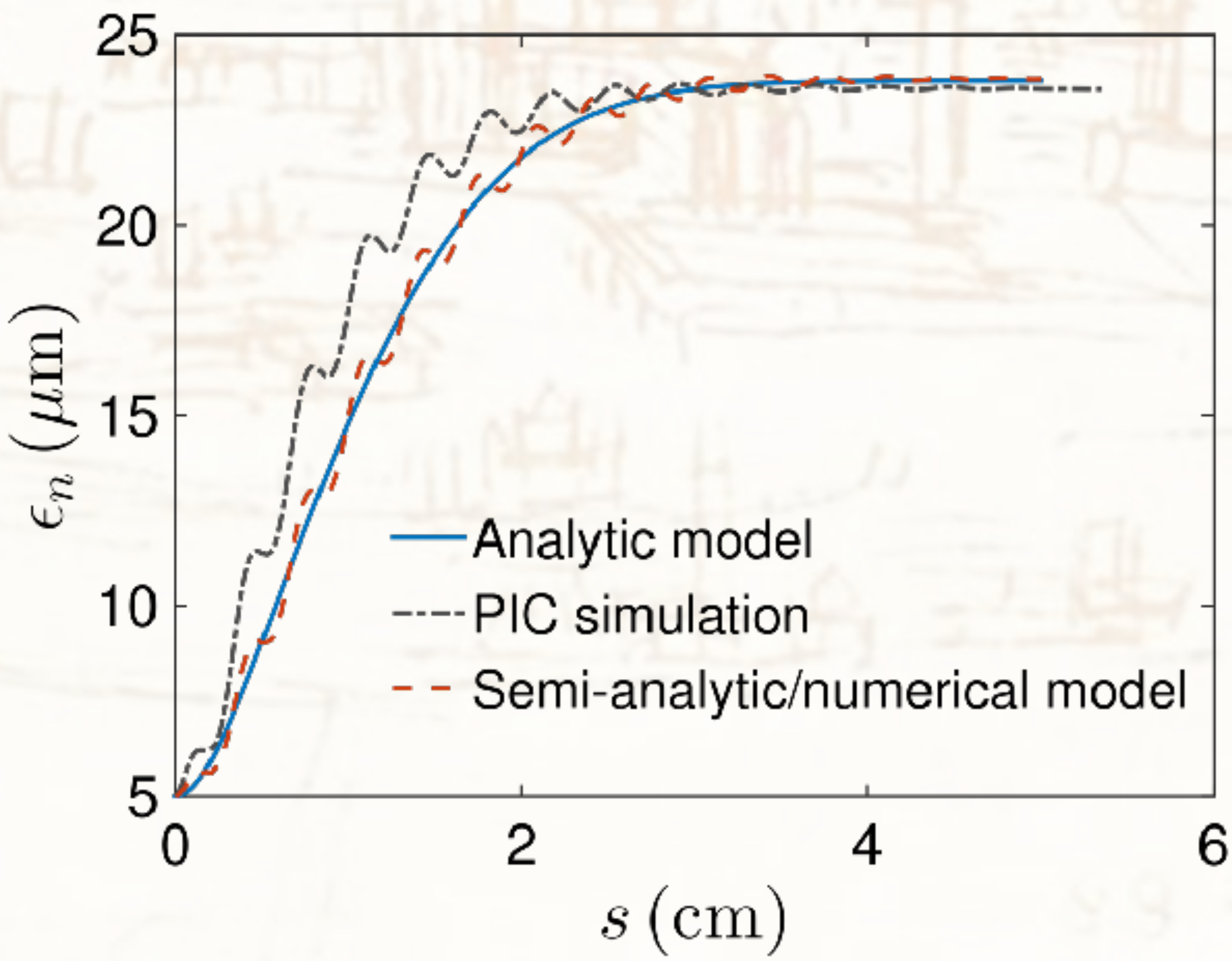
Ellipsoidal plasma bubble model

$$\left.\begin{aligned} E_x &= \frac{3Q_B(1-f)}{4\pi\varepsilon_0(X+Y)Z}\frac{x}{X} = \frac{en_p}{\varepsilon_0}\frac{Y}{X+Y}(1-f)x \\ E_y &= \frac{3Q_B(1-f)}{4\pi\varepsilon_0(X+Y)Z}\frac{y}{Y} = \frac{en_p}{\varepsilon_0}\frac{X}{X+Y}(1-f)y \\ E_z &= \frac{3Q_Bf}{4\pi\varepsilon_0 XY}\frac{z}{Z} = \frac{en_p}{\varepsilon_0}fz \end{aligned}\right\}$$

Multi-slice approximation



Moment equations



$$\varepsilon^2(\tau) = \varepsilon_0^2\left\{1 + \frac{\sigma_\gamma^2}{2} - \frac{1}{2}\sigma_\gamma^2 e^{-\frac{1}{2}\sigma_\gamma^2\tau^2}\cos\left(2\tau + \phi(\tau)\right)\right\}$$

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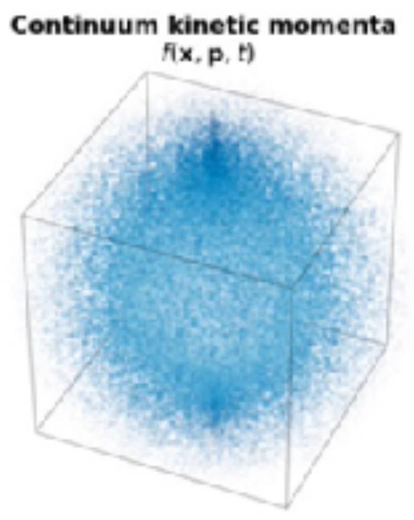
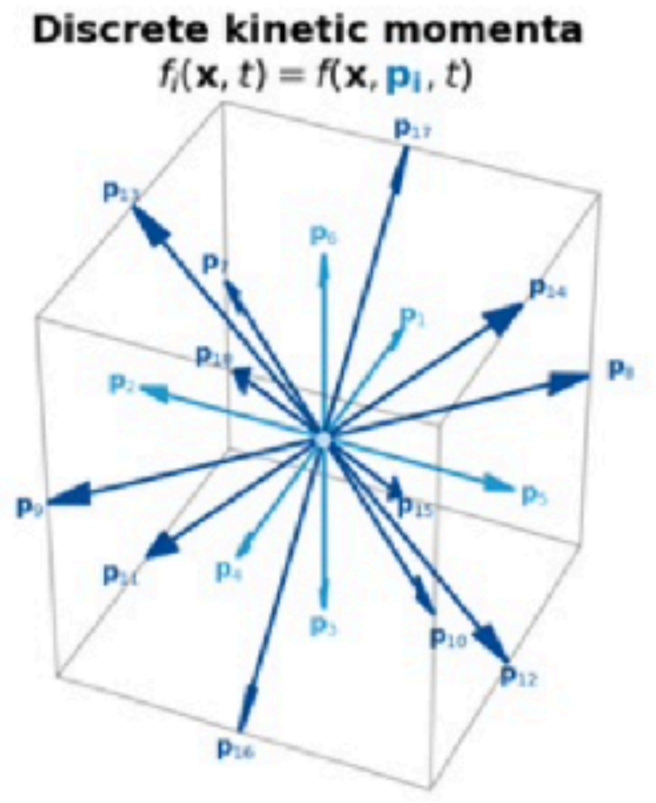
Microscopic simulations
Continuum kinetic momenta



PIC

- ✓ Able to catch most of the physics
  High computational cost

Mesoscopic simulation
Discrete kinetic momenta

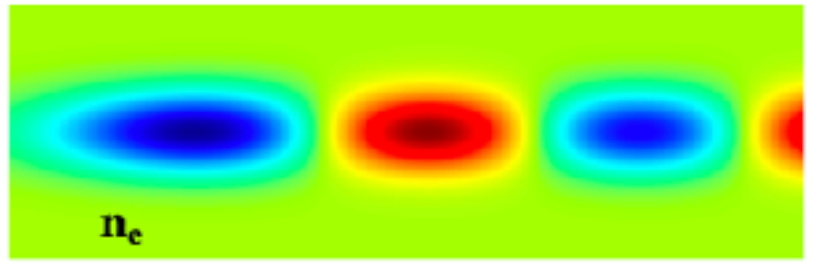


Lattice Boltzmann

- ✓ Low computational cost
- ✓ Able to catch most of physical effects

Macroscopic simulation
No kinetic momenta

Macroscopic quantities



Fluid

- ✓ Low computational cost
  Limited reproducible physical effects

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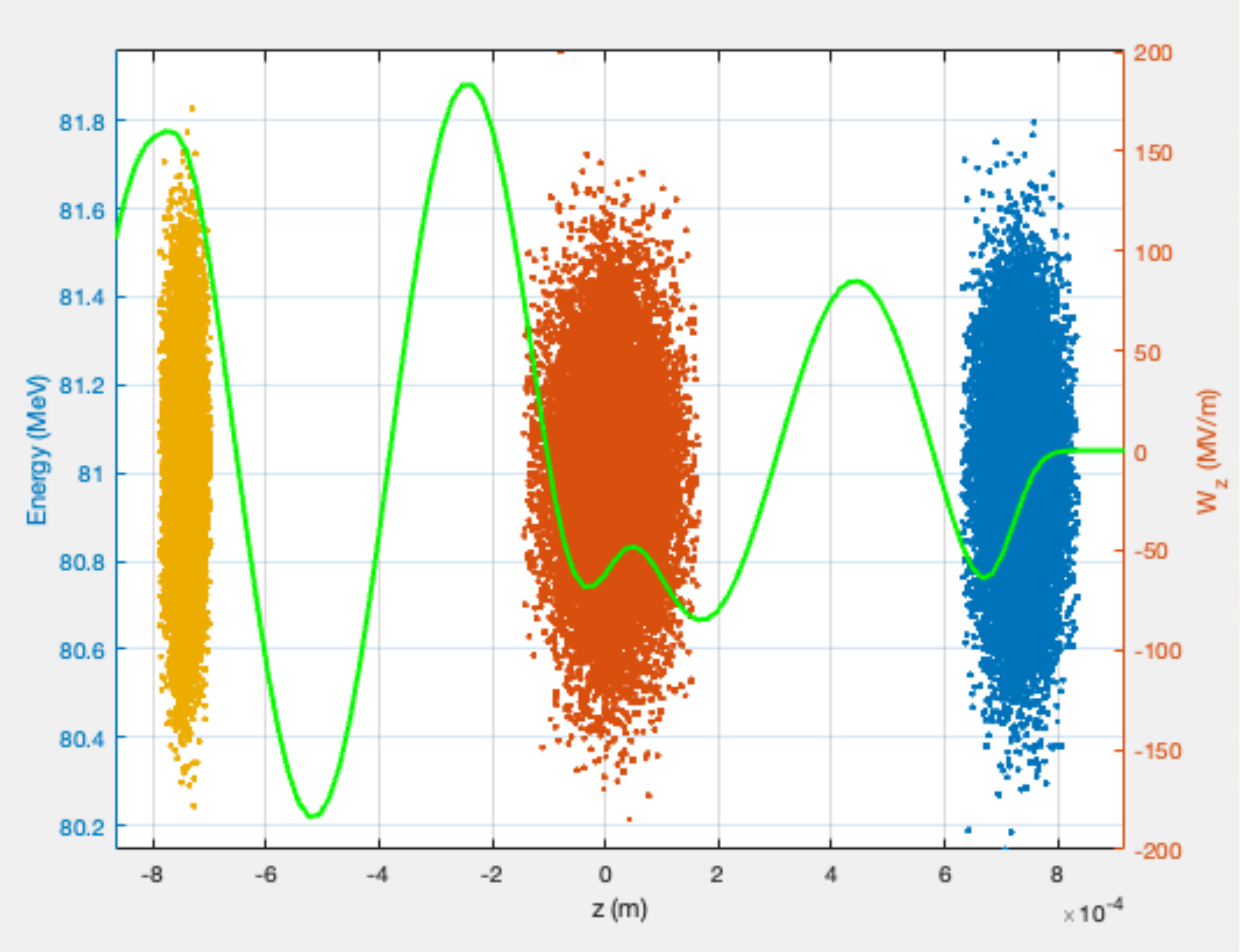

A.R. Rossi

ESPP meeting

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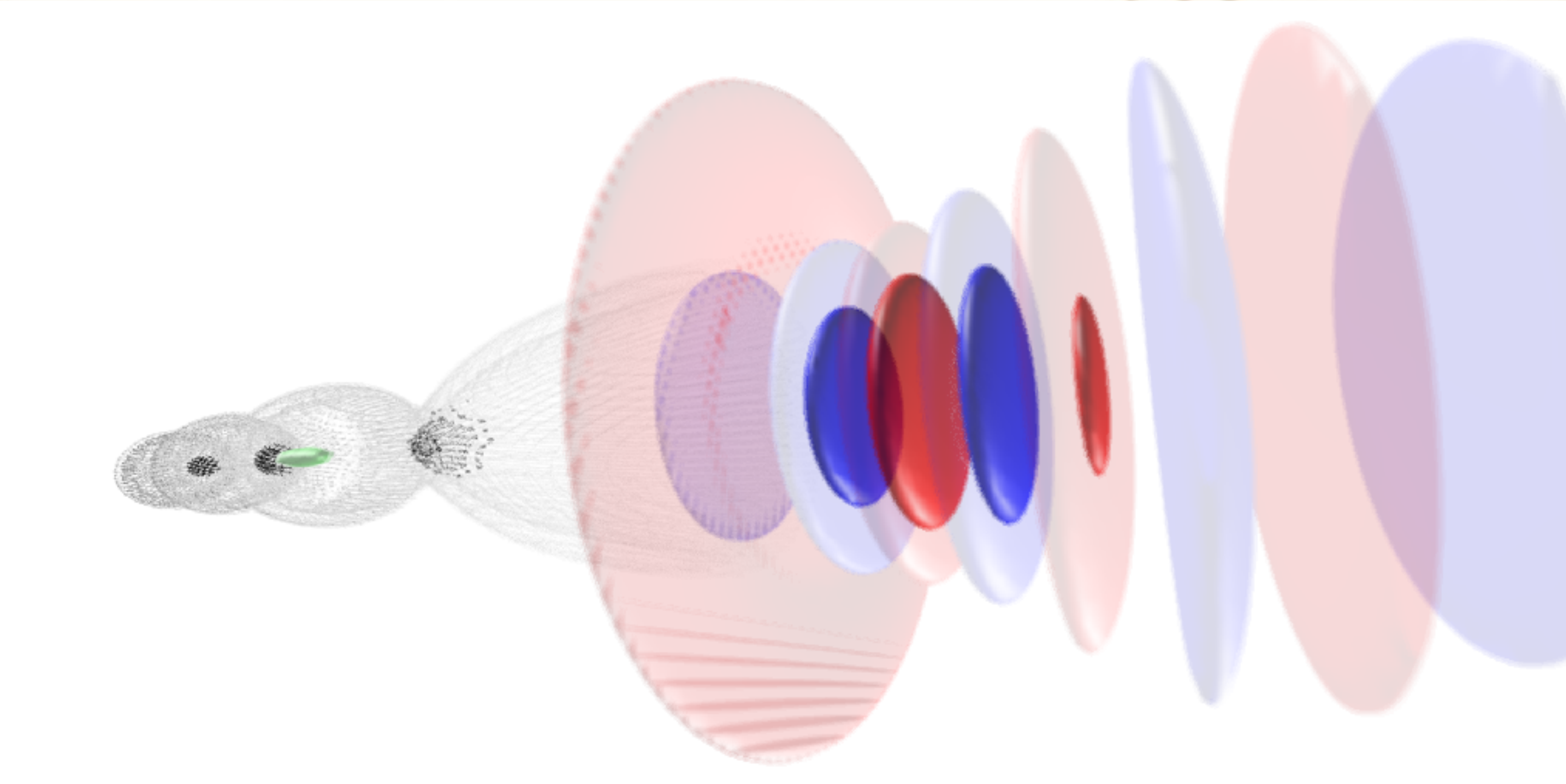

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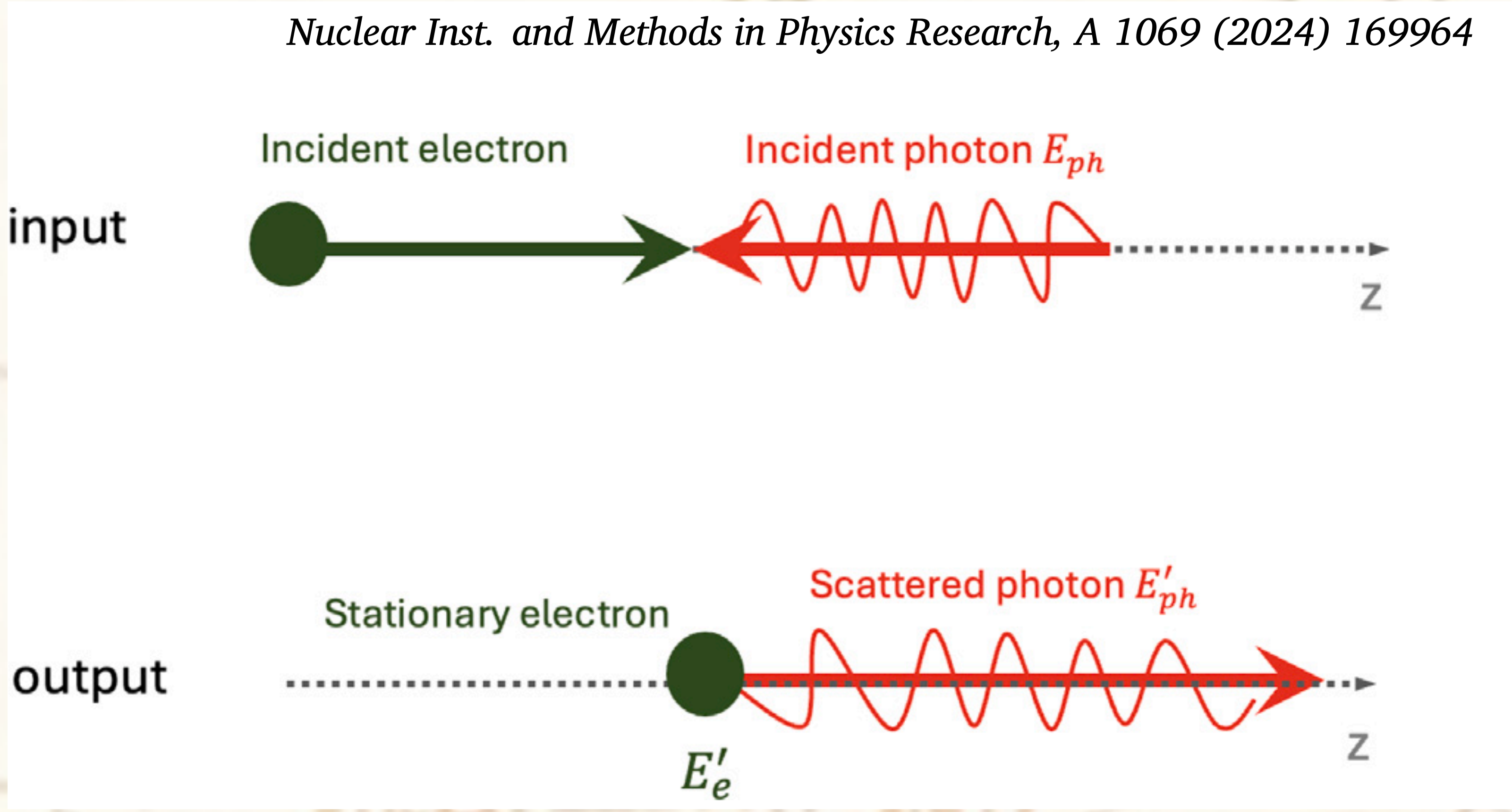
New experiments for new physics?

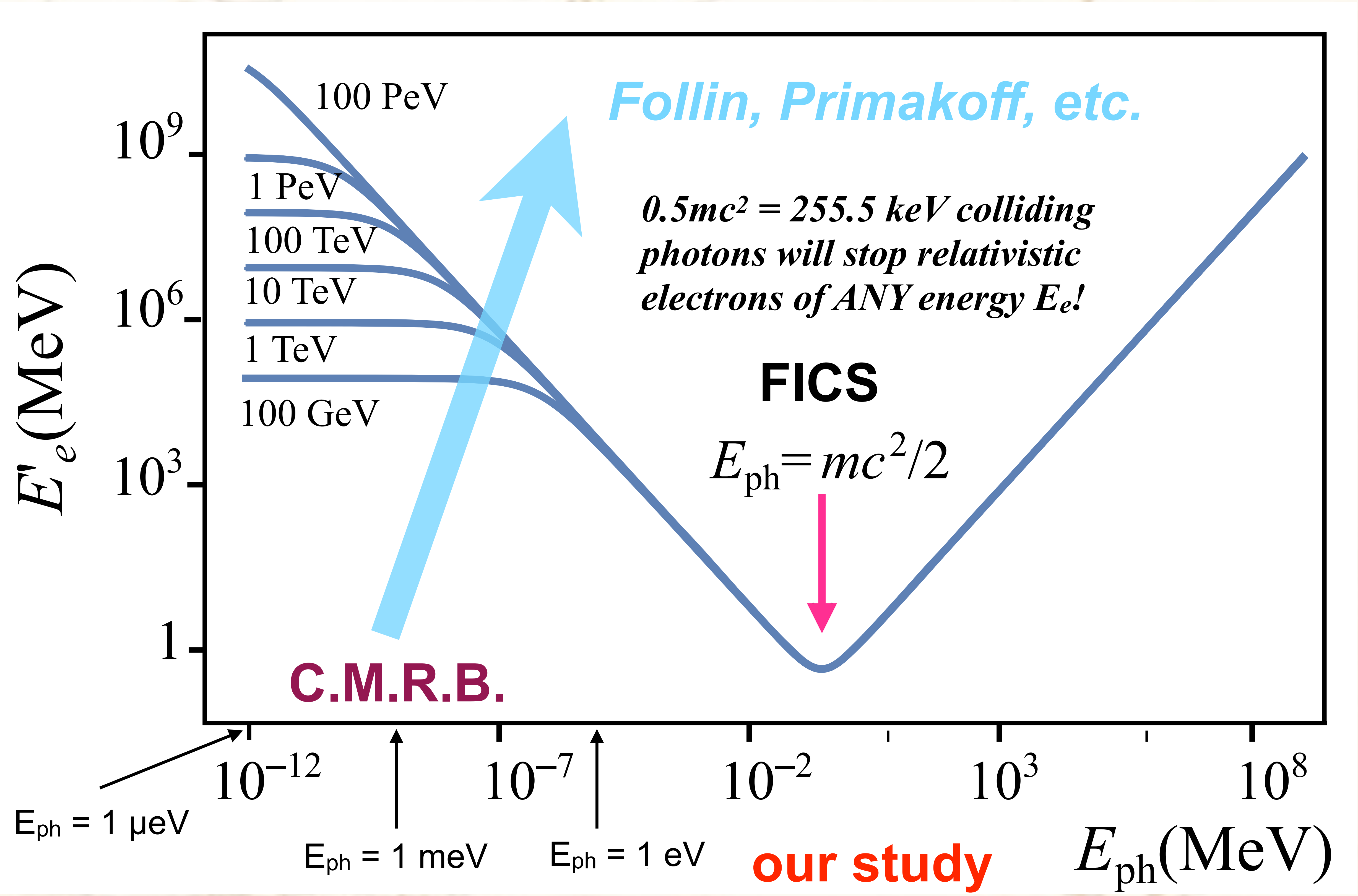
The Full Inverse Compton Scattering, FICS

Can electrons emit photons of energy larger than their own?



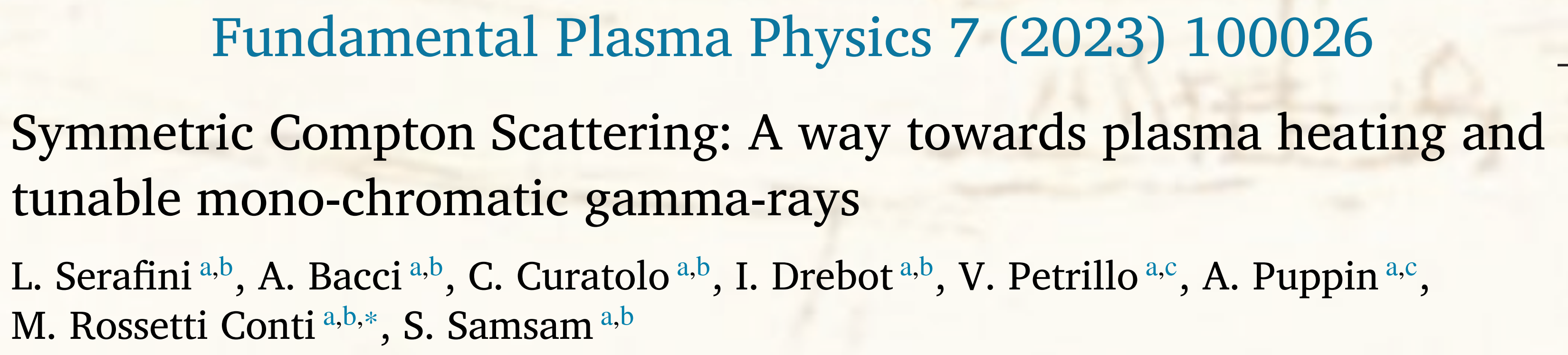
Nuclear Inst. and Methods in Physics Research, A 1069 (2024) 169964

$$T'_e = 0 \quad ; E'_{ph} = T_e + 0.5mc^2$$



Impacts in several fields:

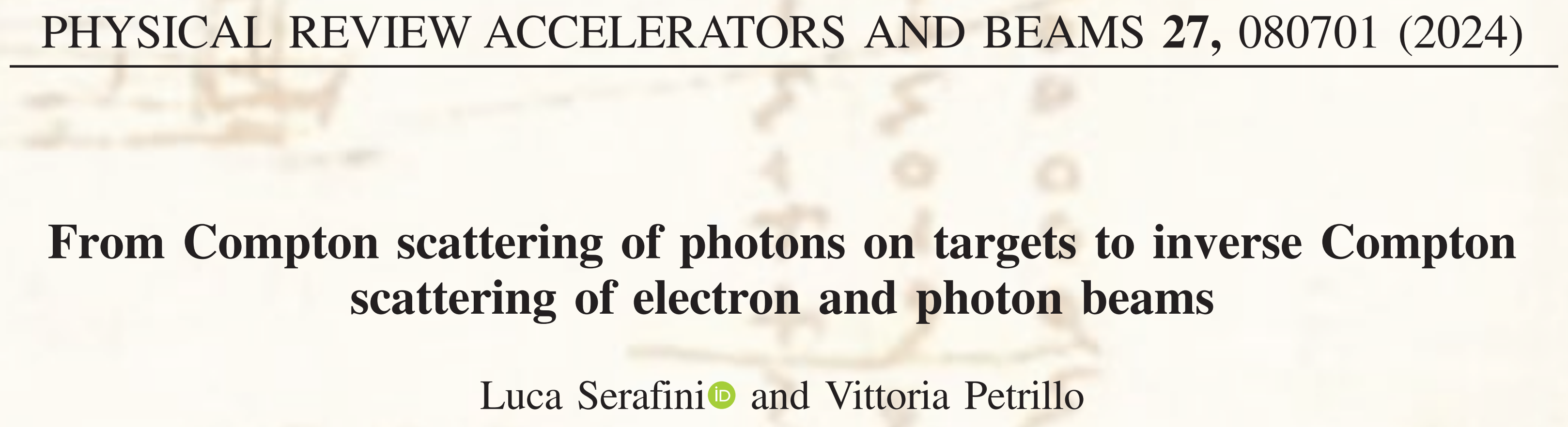
- *Plasma Physics (e^- / e^+ trapping in plasma mirrors)*
- *Astro-Physics (cosmic γ-ray sources)*
- *QED (overcoming the Schwinger limit)*
- *Quantum Gravity (Unruh radiation)*
- *measuring neutrino mass?*



Fundamental Plasma Physics 7 (2023) 100026

Symmetric Compton Scattering: A way towards plasma heating and tunable mono-chromatic gamma-rays

L. Serafini [a,b], A. Bacci [a,b], C. Curatolo [a,b], I. Drebot [a,b], V. Petrillo [a,c], A. Puppin [a,c], M. Rossetti Conti [a,b,*], S. Samsam [a,b]



PHYSICAL REVIEW ACCELERATORS AND BEAMS **27,** 080701 (2024)

From Compton scattering of photons on targets to inverse Compton scattering of electron and photon beams

Luca Serafini and Vittoria Petrillo

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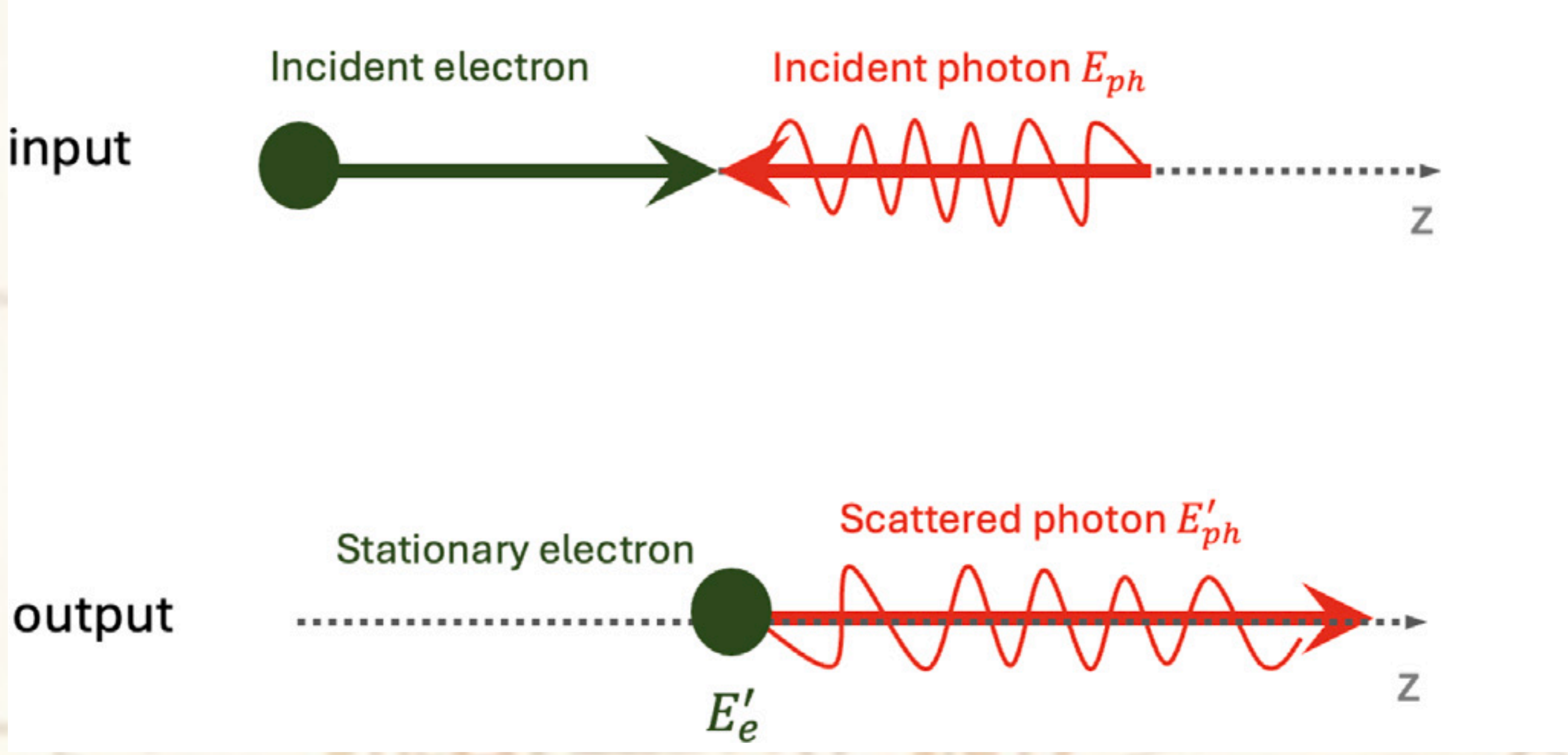

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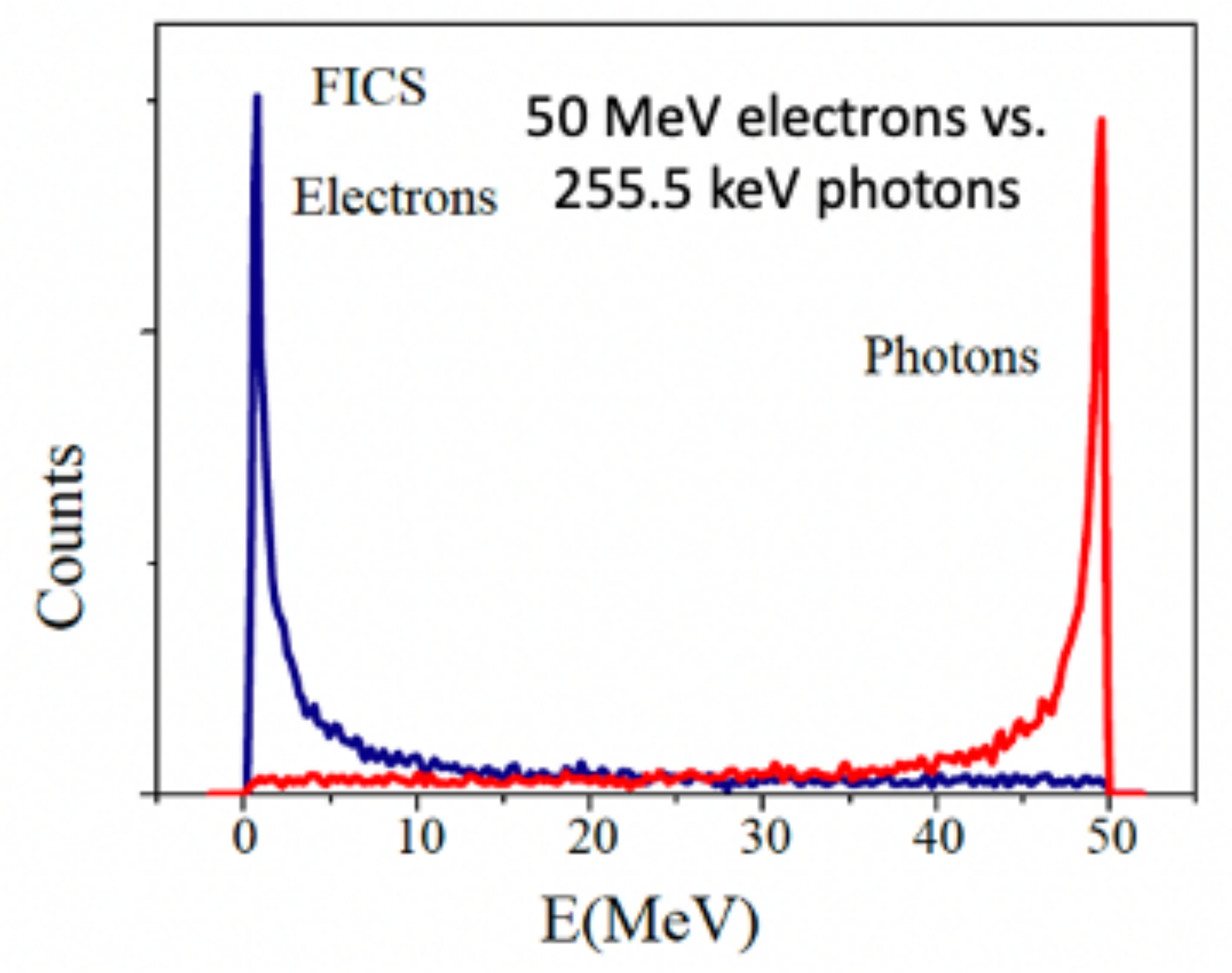

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