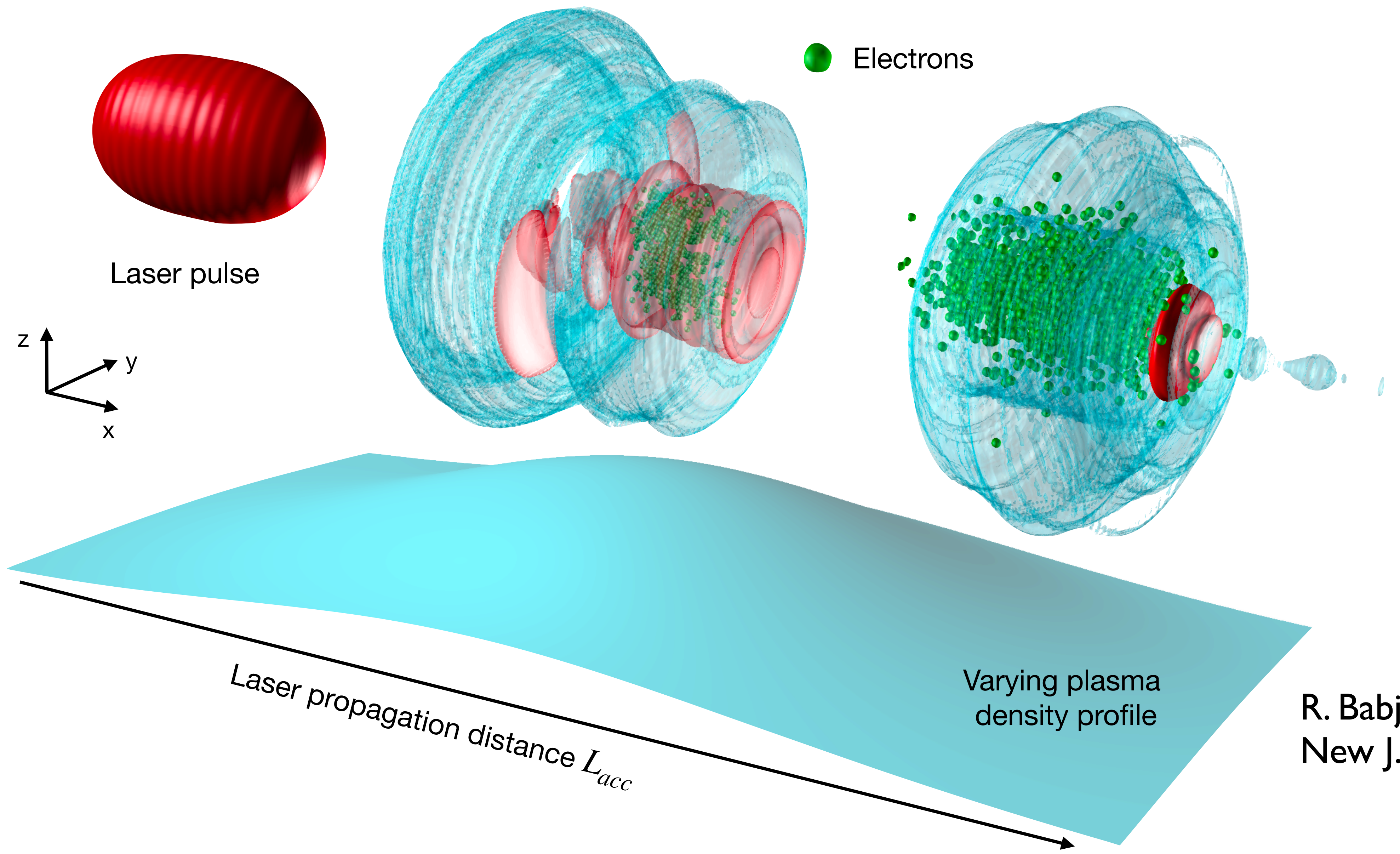
Direct laser acceleration

(and what you can do with it)



R. Babjak et al, New J. Phys. (2024)

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golp ipfn INSTITUTO DE PLASMAS E FUSÃO NUCLEAR TÉCNICO LISBOA erc INPAIRS Funded by the European Union fct PRACE

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EuroHPC Joint Undertaking

PRACE

RNCA REDE NACIONAL DE COMPUTAÇÃO AVANÇADA

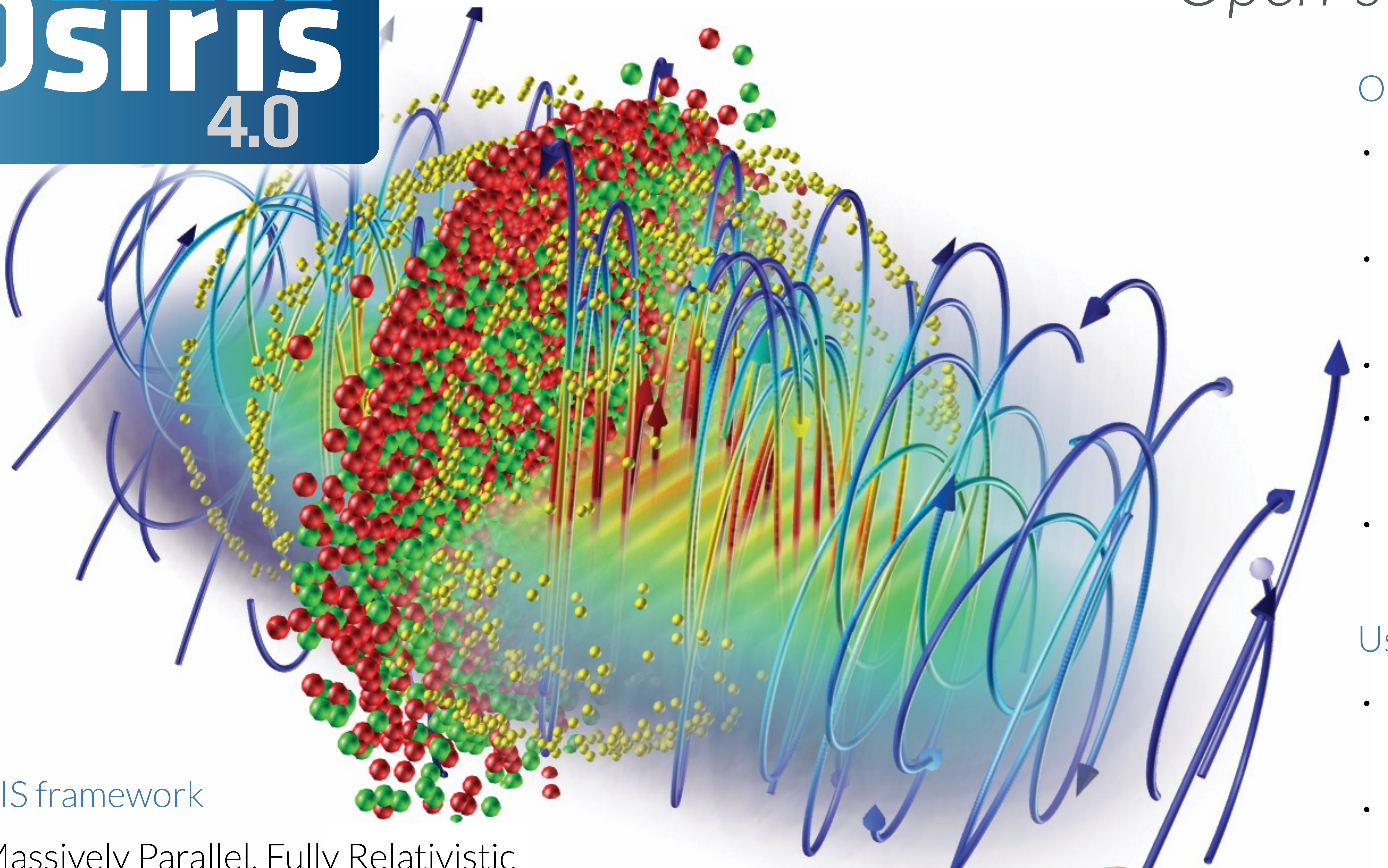
FCCN UNIDADE DA FCT Tecnologia para o Conhecimento

IT4I

RES RED ESPAÑOLA DE SUPERCOMPUTACIÓN

OSIRIS 4.0

Open-source version available



Open-access model

- 40+ research groups worldwide are using OSIRIS
- 400+ publications in leading scientific journals
- Large developer and user community
- Detailed documentation and sample inputs files available
- Support for education and training

Using OSIRIS 4.0

- The code can be used freely by research institutions after signing an MoU
- Open-source version at:

https://osiris-code.github.io/

OSIRIS framework

- Massively Parallel, Fully Relativistic Particle-in-Cell Code
- Support for advanced CPU / GPU architectures
- Extended physics/simulation models
- AI/ML surrogate models and data-driven discovery

visXD

University of Michigan · UCLA · Técnico Lisboa

Ricardo Fonseca: ricardo.fonseca@tecnico.ulisboa.pt

Contents

Introducing electron acceleration with DLA

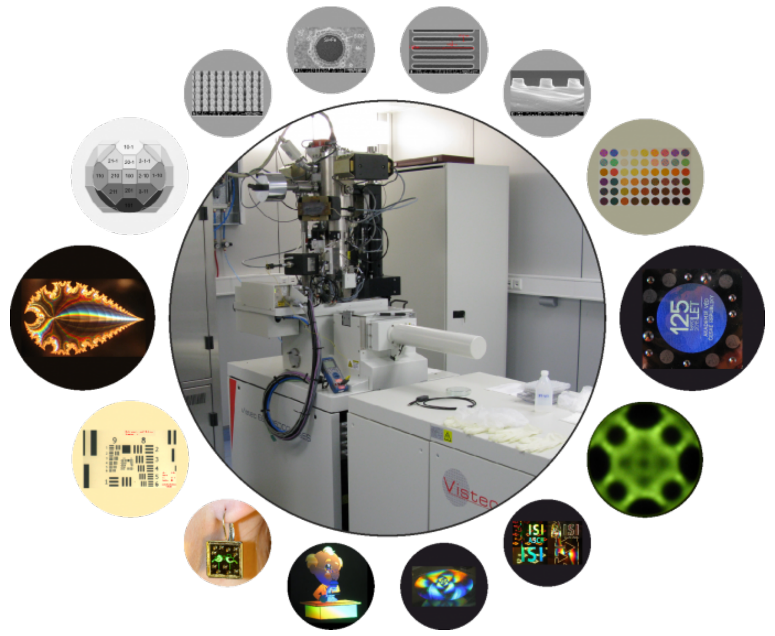
Why accelerating electrons? And why with DLA?

Electron acceleration

Medicine

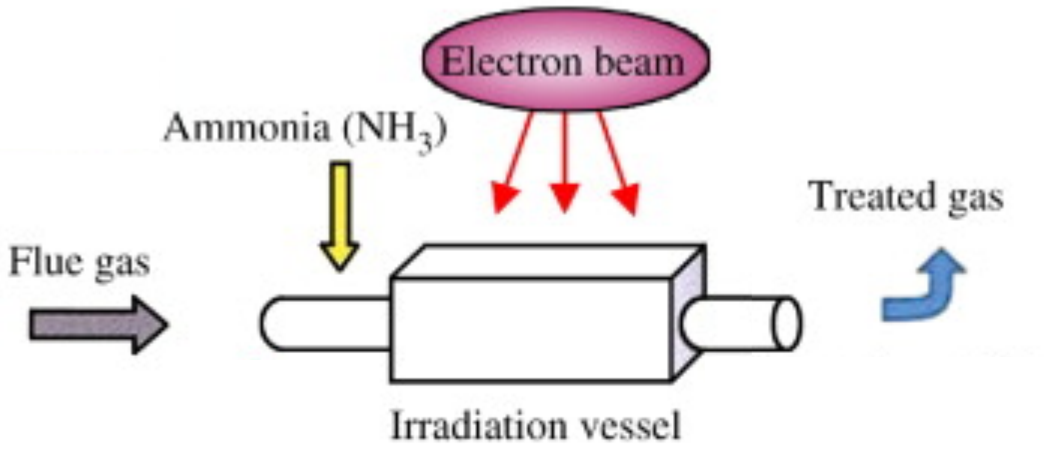
Credits: National Cancer Institute

Industry



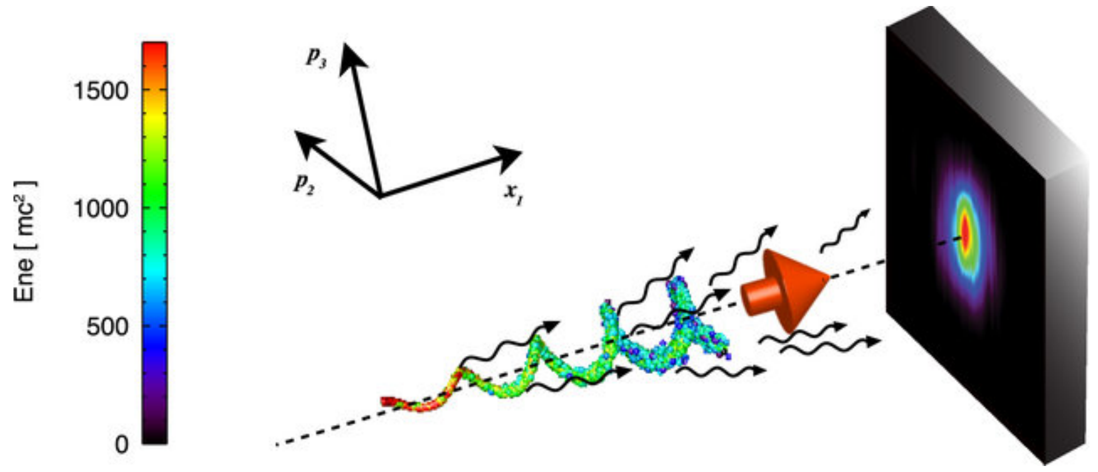
Credits: Institute of Scientific Instruments
Czech Academy of Sciences

Environment



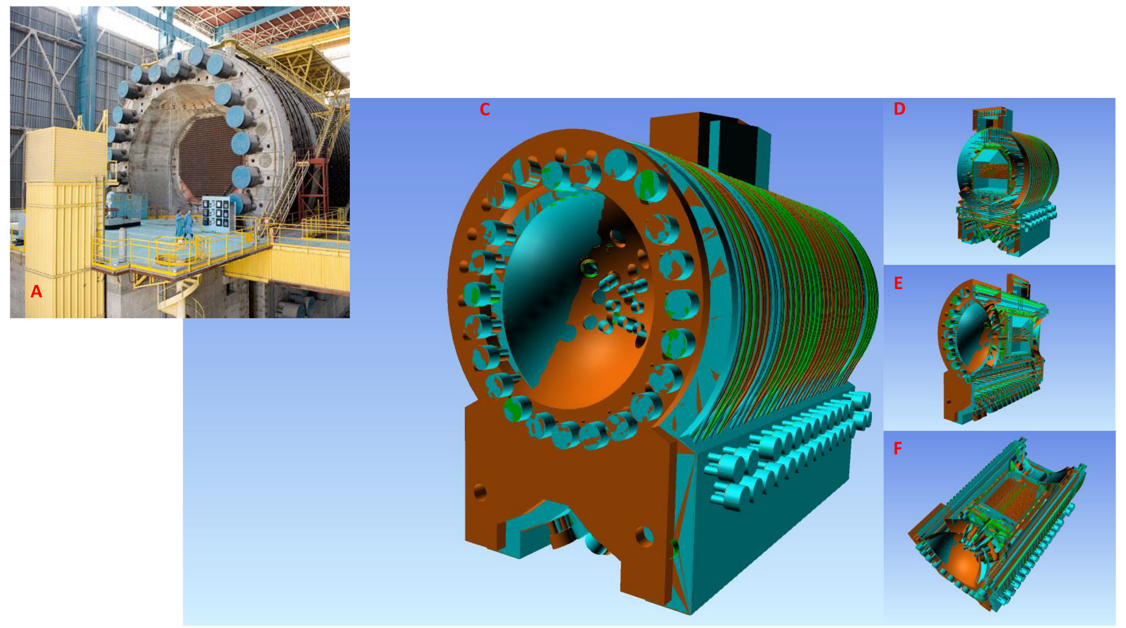
M. Callen et al, Fuel Process. Technol. (2007)

Science & emerging technologies



M.Vranic et al, New J. Phys. (2016)

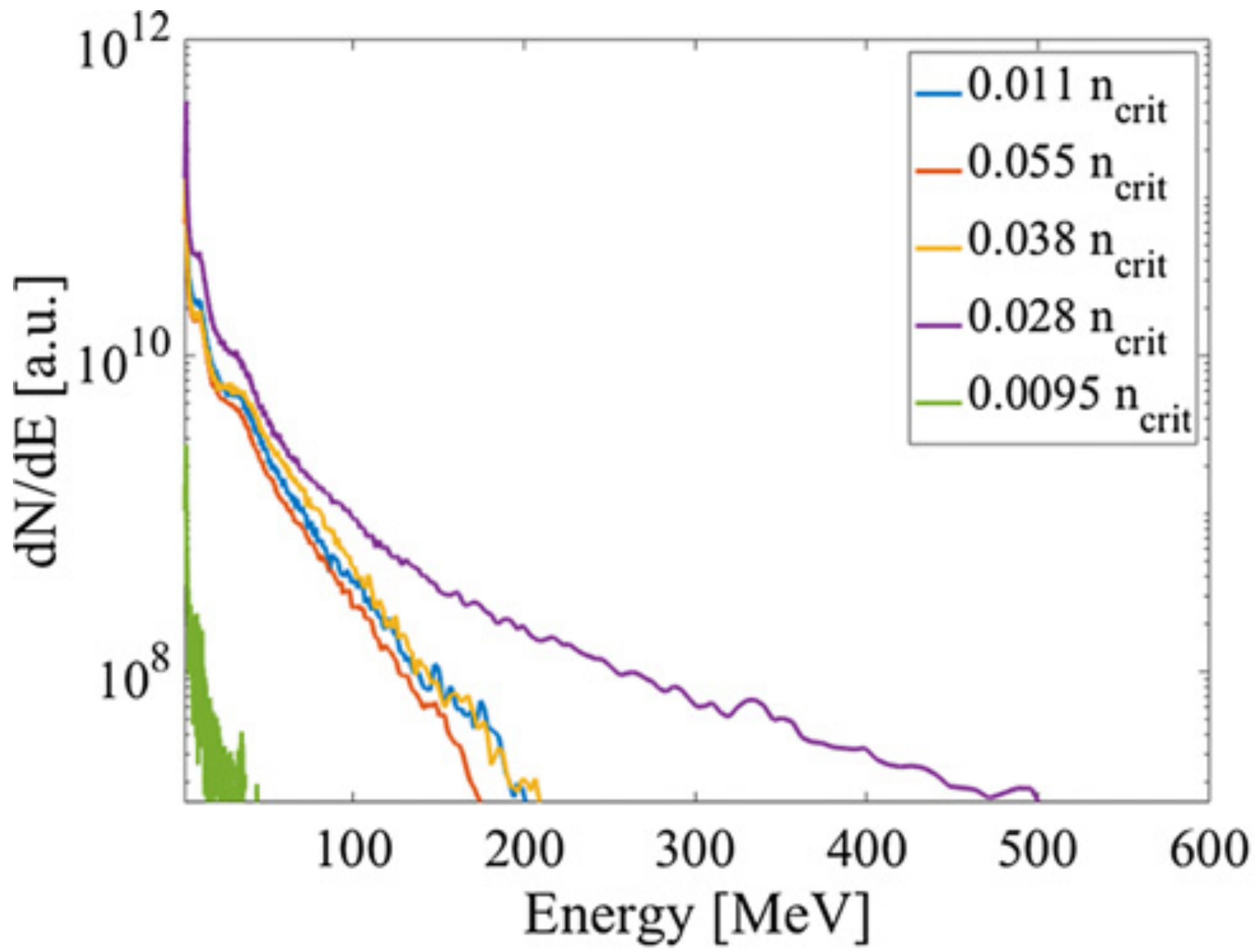
- Radiation sources
- Particle sources
- Material science
- Safety of nuclear devices



S. Procureur et al, Sci. Adv. (2023)

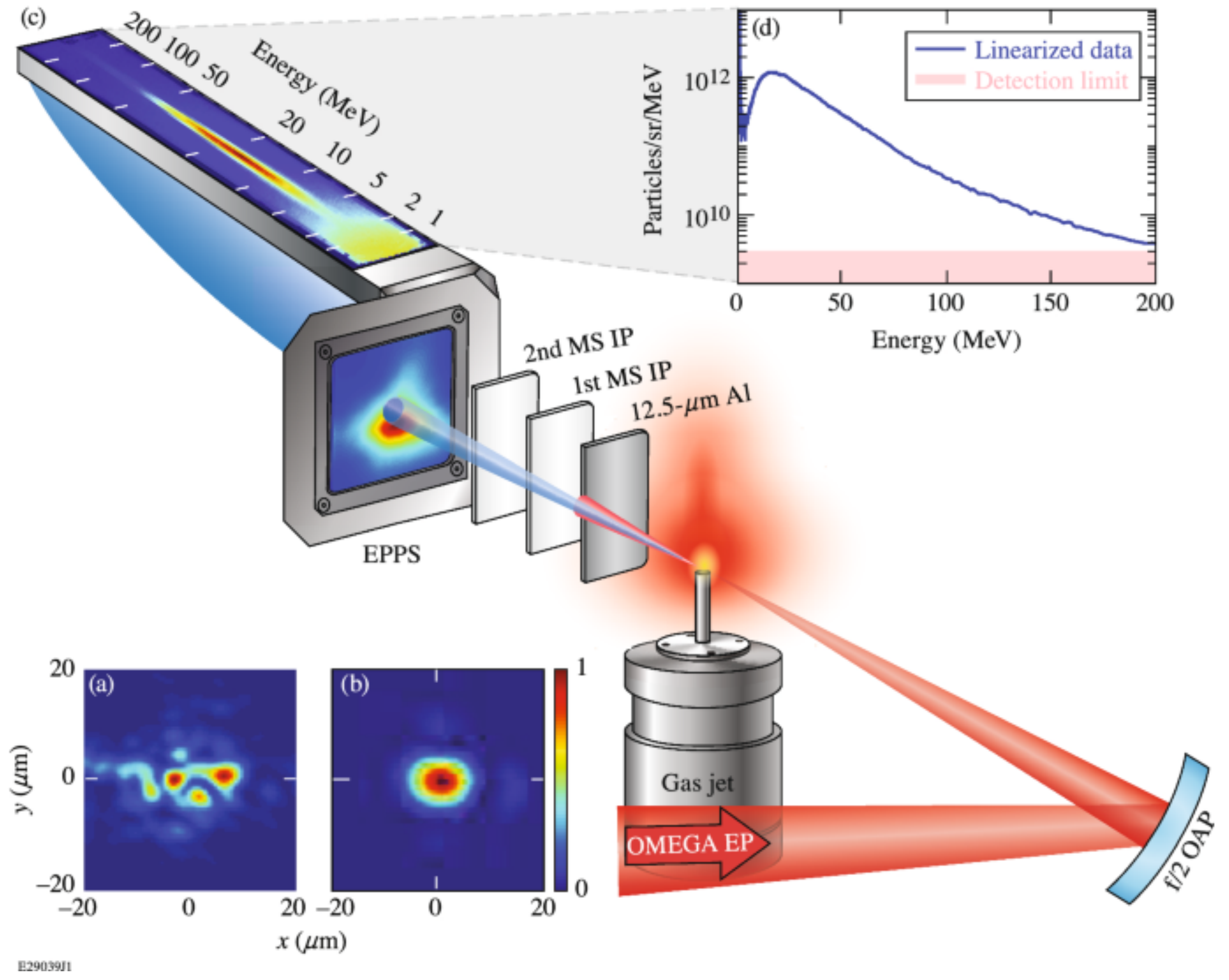
Direct laser acceleration produces high-charge electron beams

100s MeVs with micro-Couloumb charge obtained so far (micrometer-level source size)



Charge > 100 nC

A. Hussein et al., New J. Phys (2021)



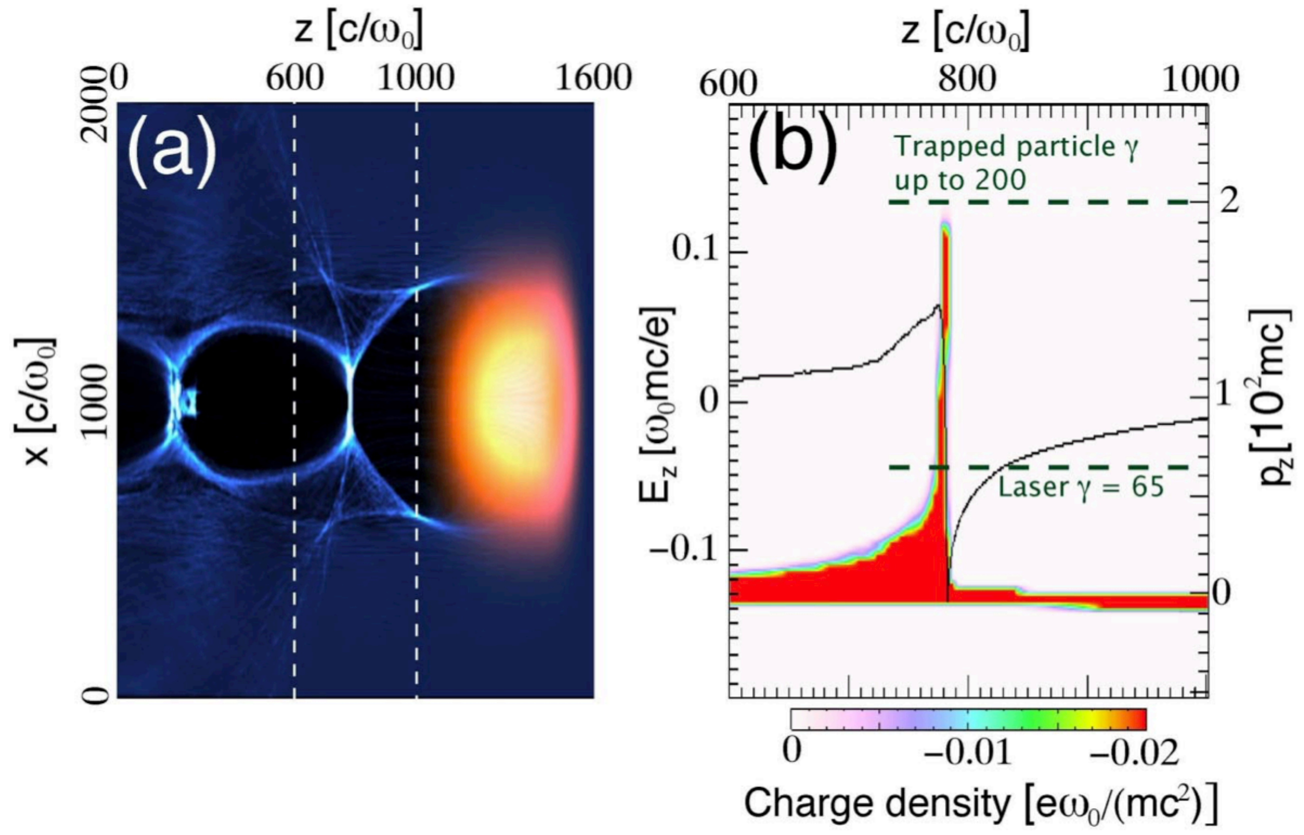
Charge ~ 0.7 μC

J. Shaw et al., Sci. Rep (2021)

10-1000x more electrons than LWFA, and 100x higher density

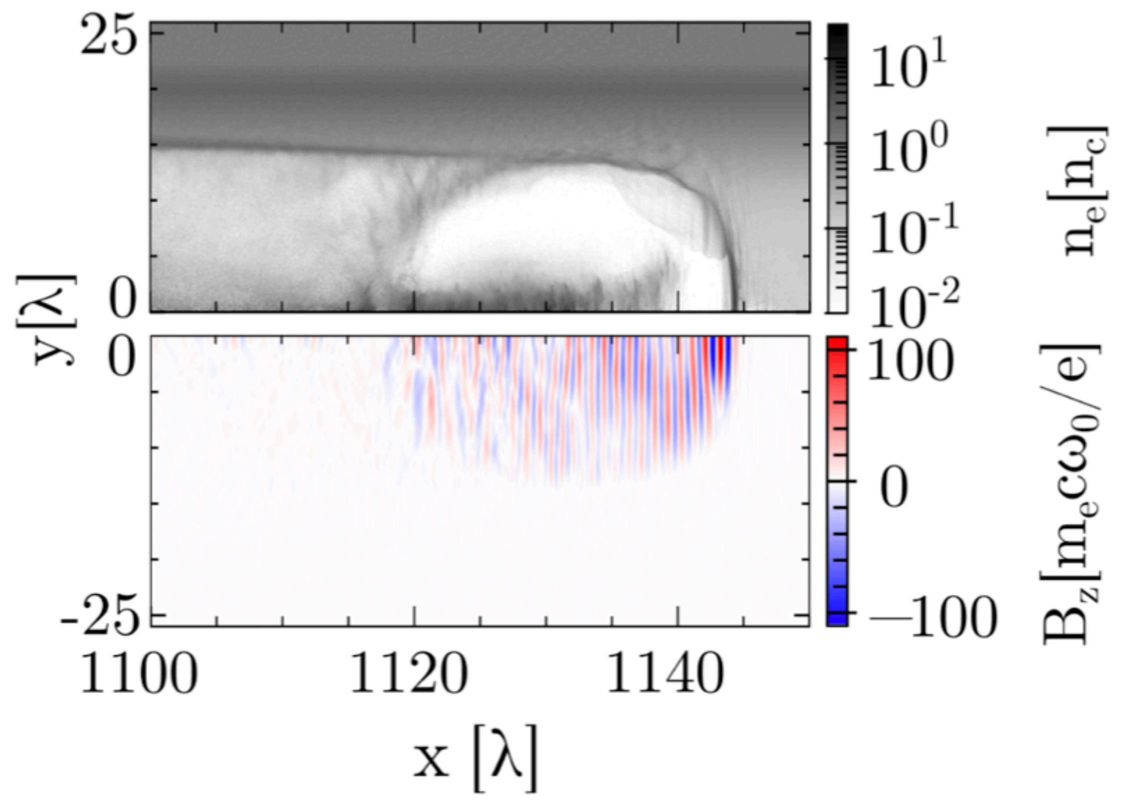
Can we accelerate these beams to multi-GeV?

Laser wakefield acceleration



W.Lu et al., Phys. Rev. Acc. Beams (2007)

Direct laser acceleration



R. Babjak et al., Phys. Rev. Lett. (2024)

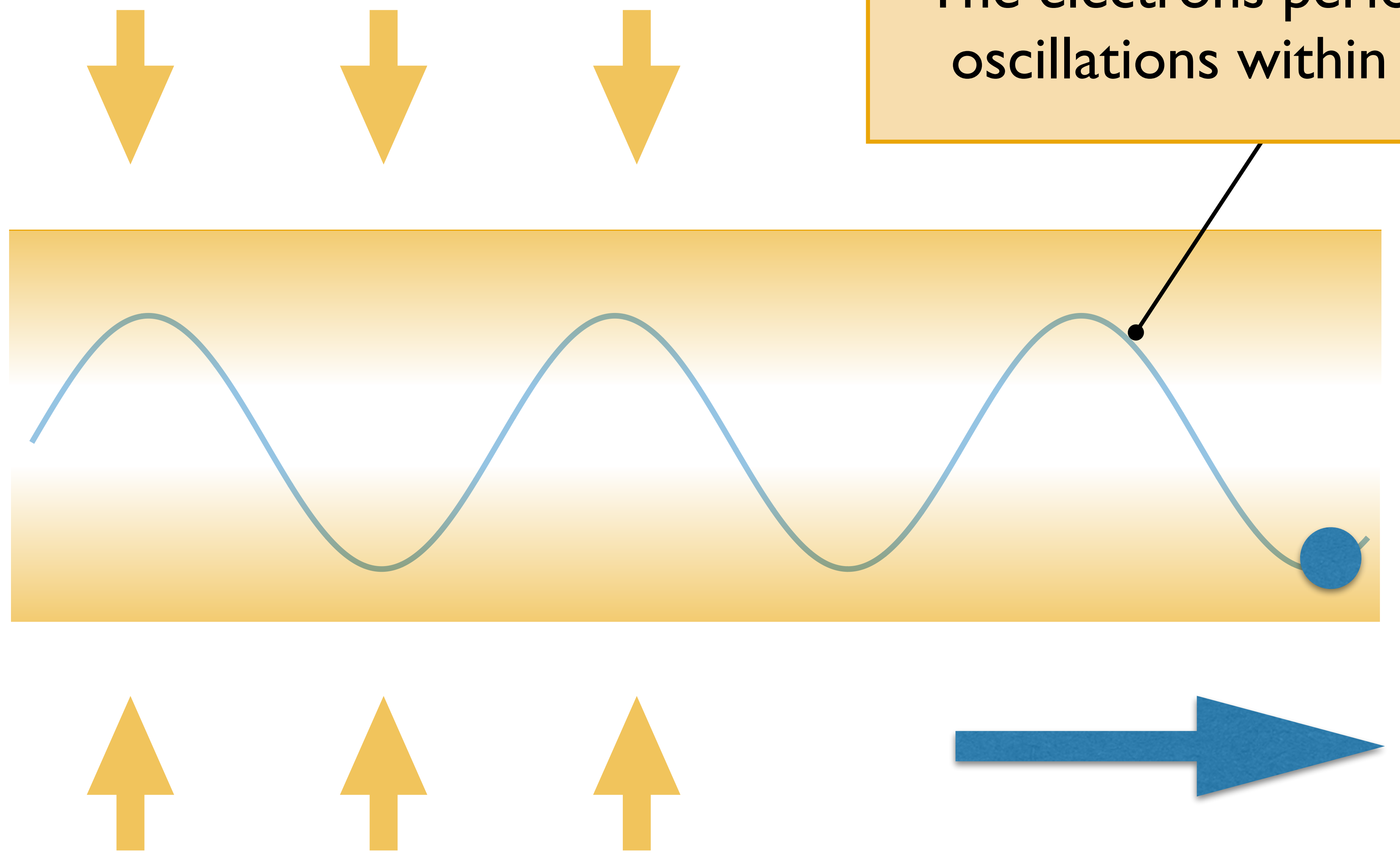
	LWFA	DLA
Total Charge	10s - 100s of pC	10s - 100s of nC
Beam Density	$< 10^{19}\ \mathrm{cm}^{-3}$	$< 10^{21}\ \mathrm{cm}^{-3}$
Energy Distribution	Quasi-Monoenergetic - 1s GeV	Maxwellian - 100s MeV
Beam Length	10s fs	10s - 100s fs

Introducing the physics of DLA

Basic idea behind the DLA mechanism

Transverse Lorentz force due to the channel fields

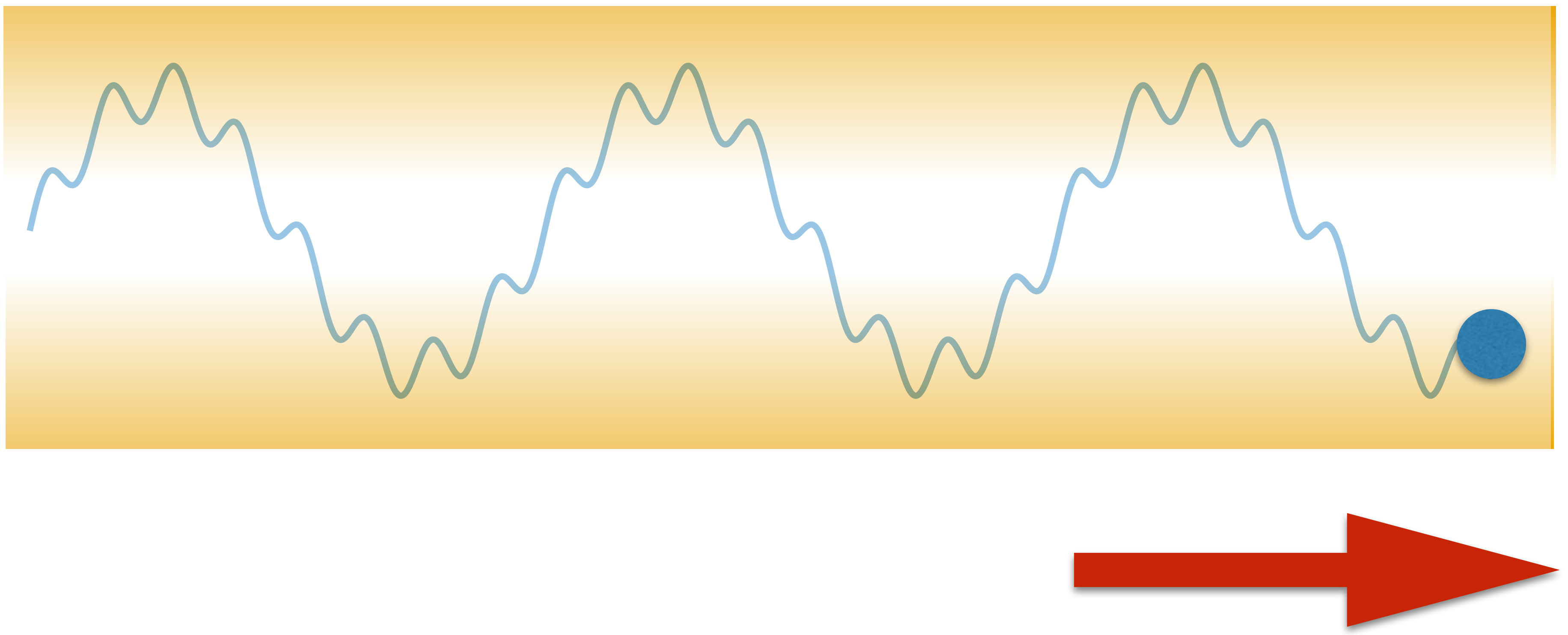
The electrons perform betatron oscillations within the channel



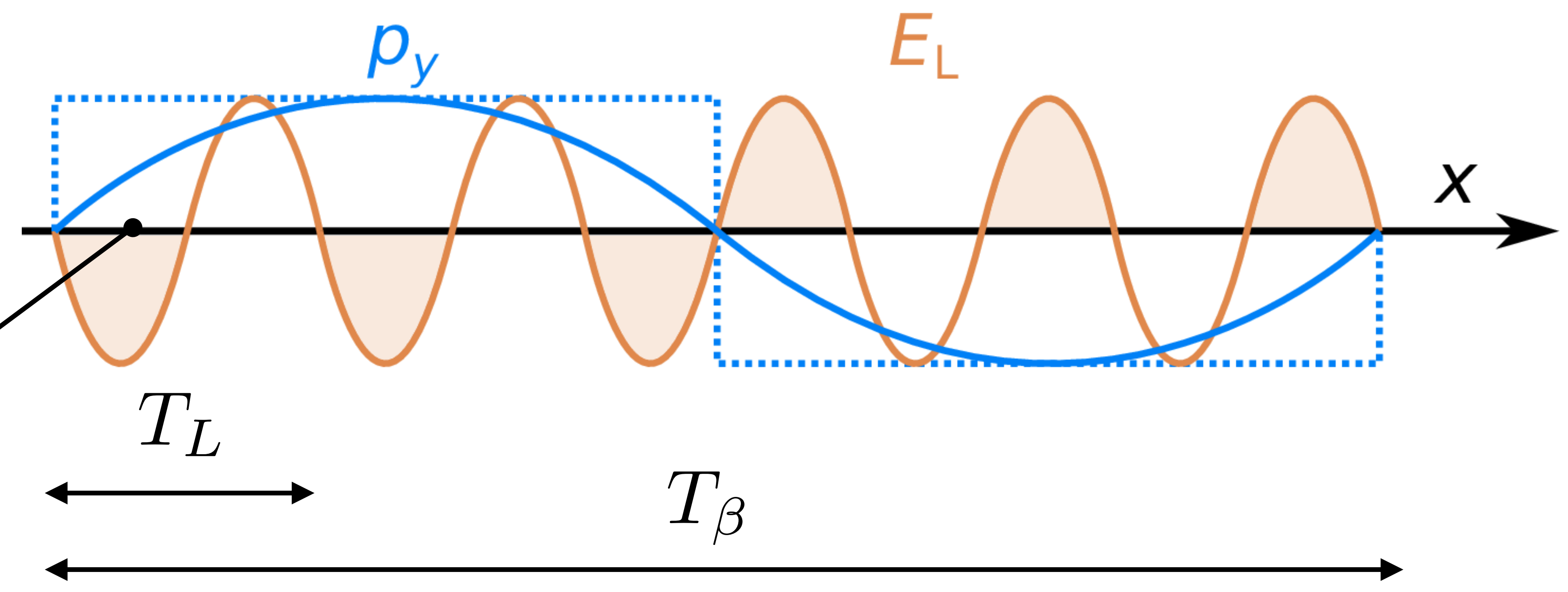
Transverse Lorentz force due to the channel fields

Relativistic electron direction of motion

When laser co-propagates with electrons



Laser propagation direction



Regions where the work of the laser field is "constructive" on e-.

Electron motion in laser + channel field can become resonant

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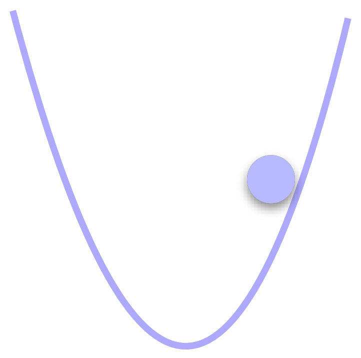
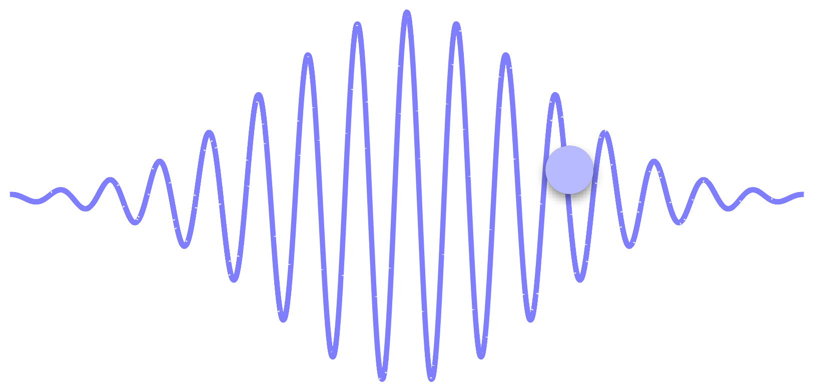
Harmonic oscillator



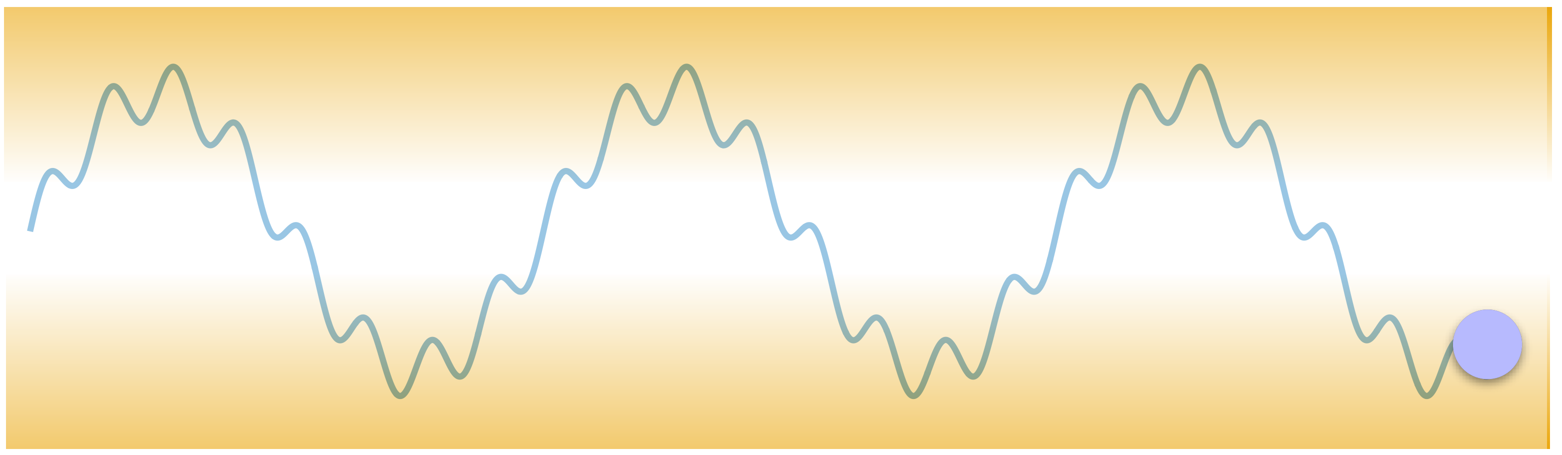
$$I \sim mgh_{\max} \sim \text{const.} \times R^2$$

Electron in an intense plane wave



$$I \sim \gamma - \frac{p_x}{mc}$$

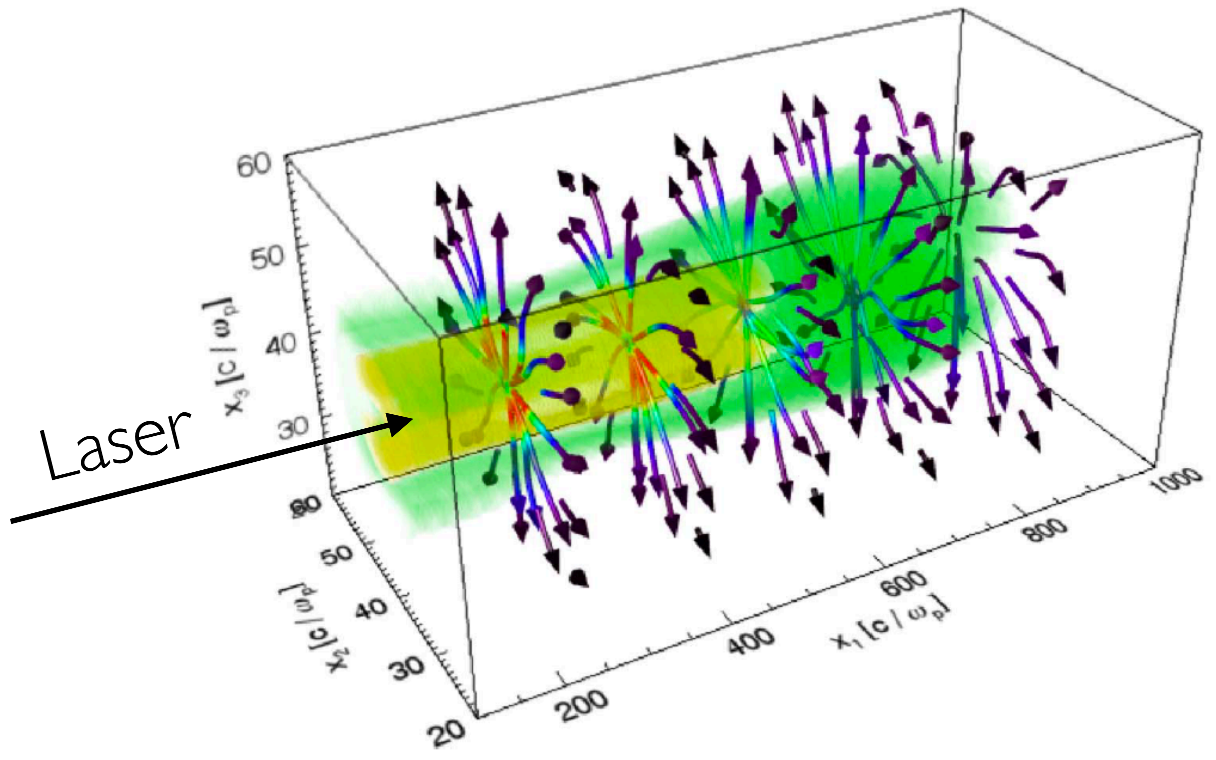
Electron in a plasma channel + intense wave

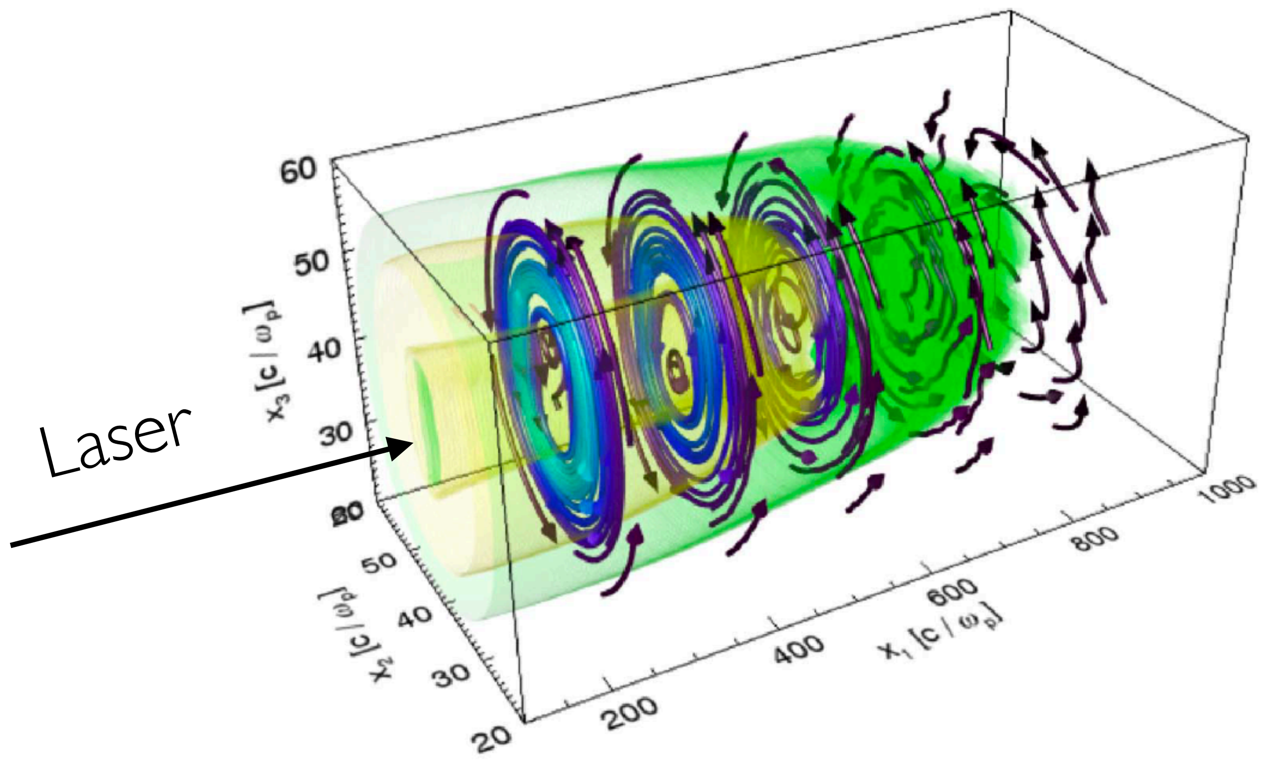


$$\omega_L \simeq \omega_0 \frac{I}{\gamma} \cos^2 \psi$$

$$\omega_\beta \simeq \frac{\omega_p}{\sqrt{2\gamma}}$$

$$I \sim \gamma - \frac{p_x}{mc} + \frac{\omega_p^2}{4c^2} R^2$$





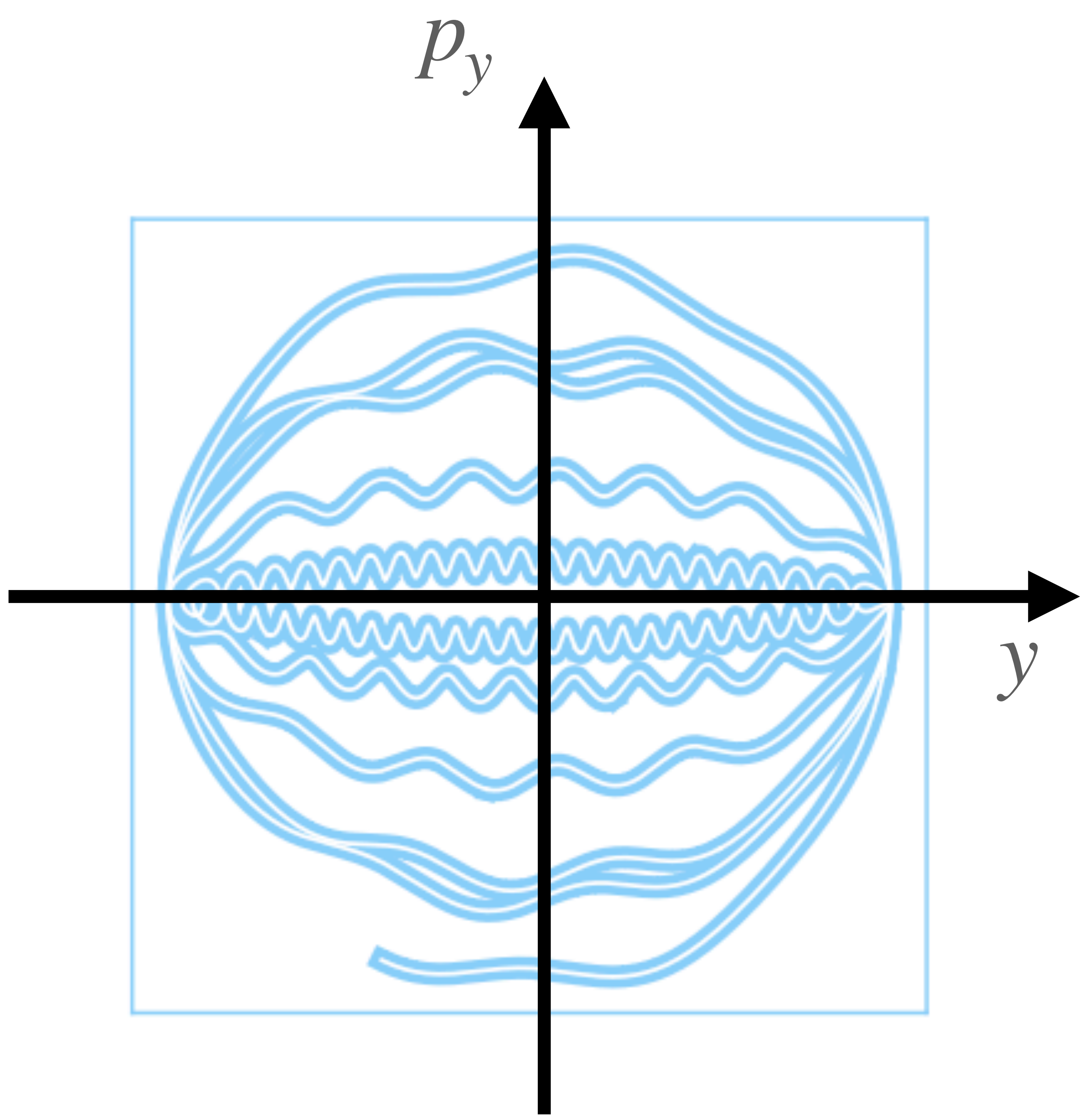
Resonant condition

$$\omega_\beta \simeq \omega_L \qquad \gamma * \simeq 2I^2 \left(\frac{\omega_0}{\omega_p}\right)^2 \cos^4 \psi$$

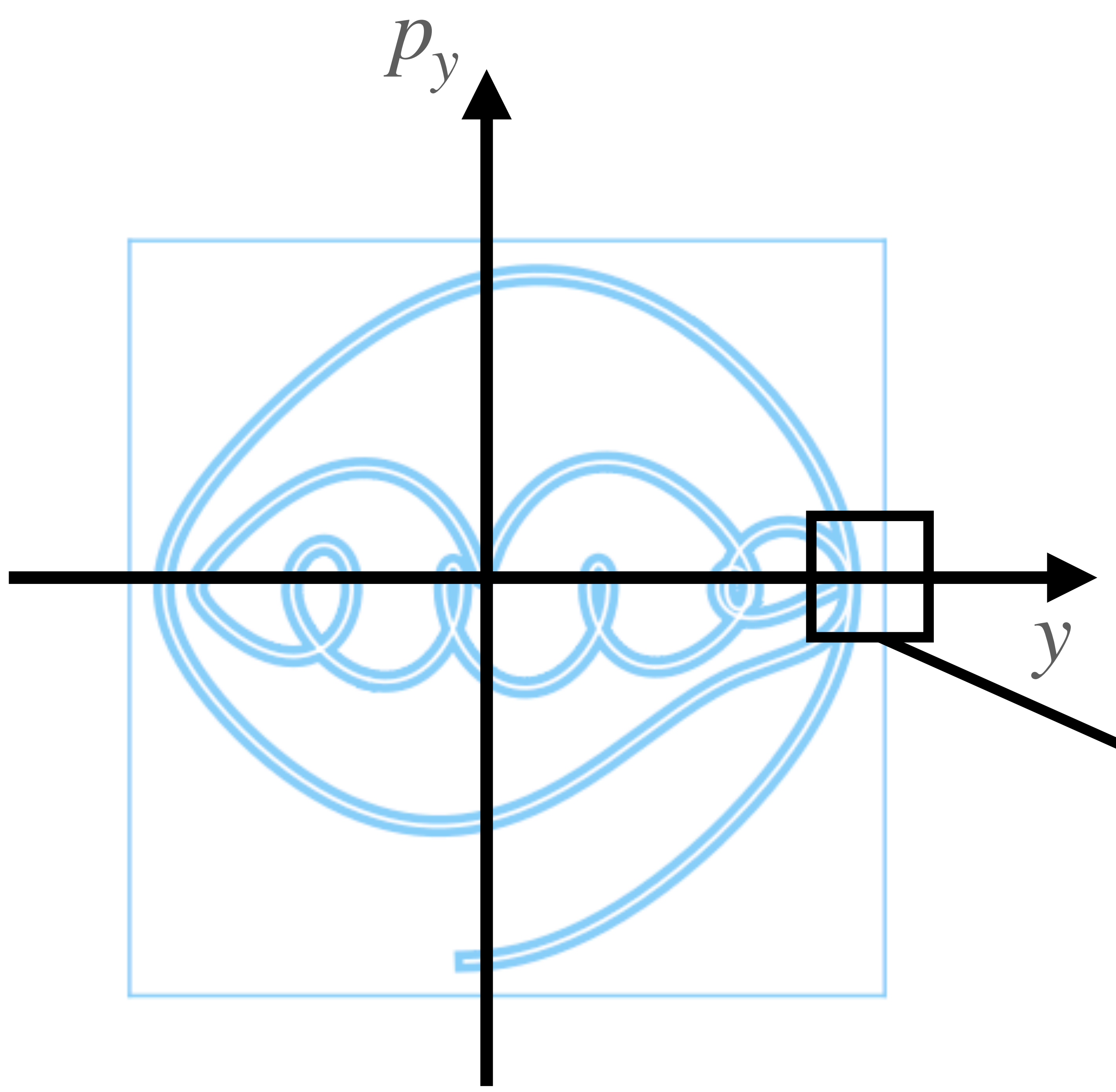
A. Pukhov et al., PoP (1999), A. Arefiev et al., PoP (2014), V. Khudik et al., PoP(2016)

Acceleration bursts off-resonance happen at the maximum distance y from the axis (two consecutive accelerating half-cycles)

Transverse phase space



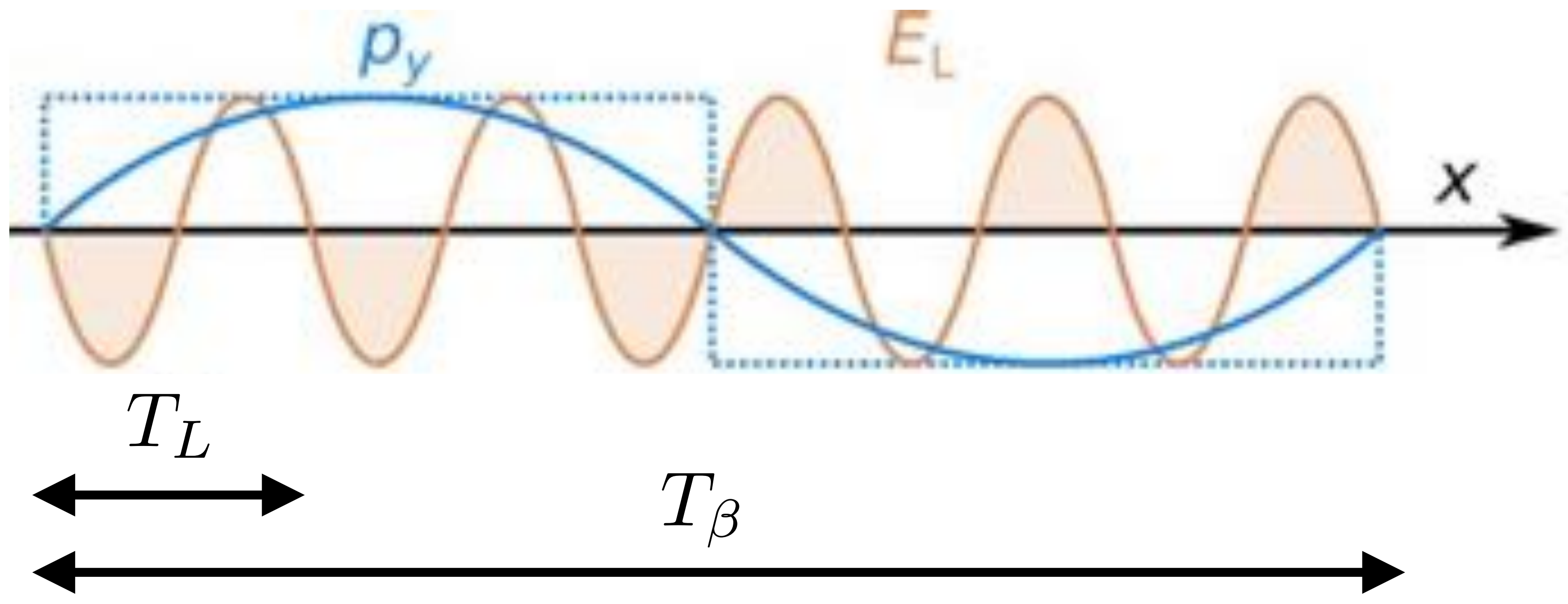
Transverse phase space



$$\varepsilon = \frac{\omega_p a_0}{\omega_0 I^{3/2}}$$

A. Arefiev et al., Phys. Plasmas (2014)
V. Khudik et al., Phys. Plasmas (2016)

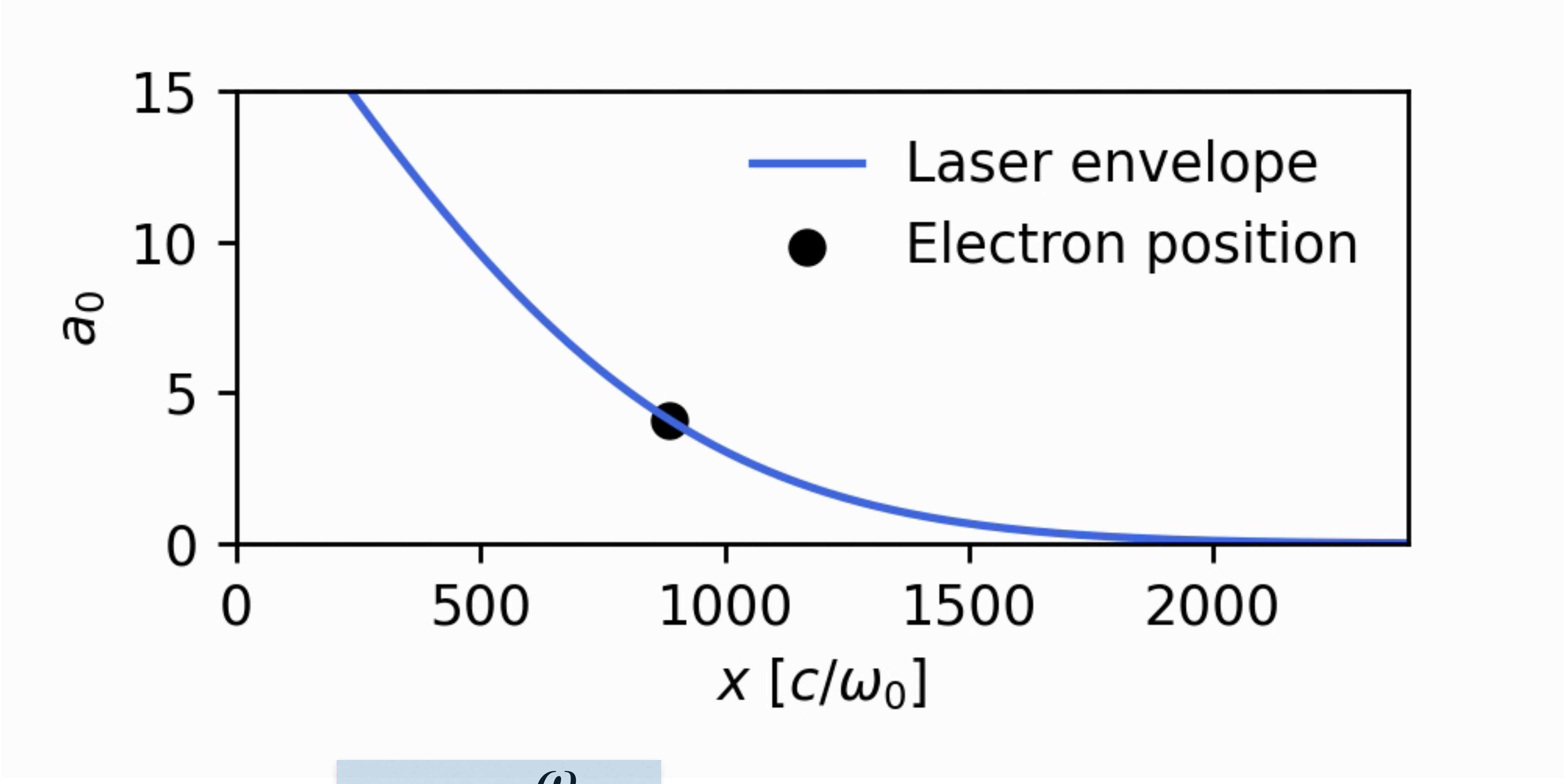
$$\Delta W \sim \varepsilon \, \gamma \, 8\pi$$

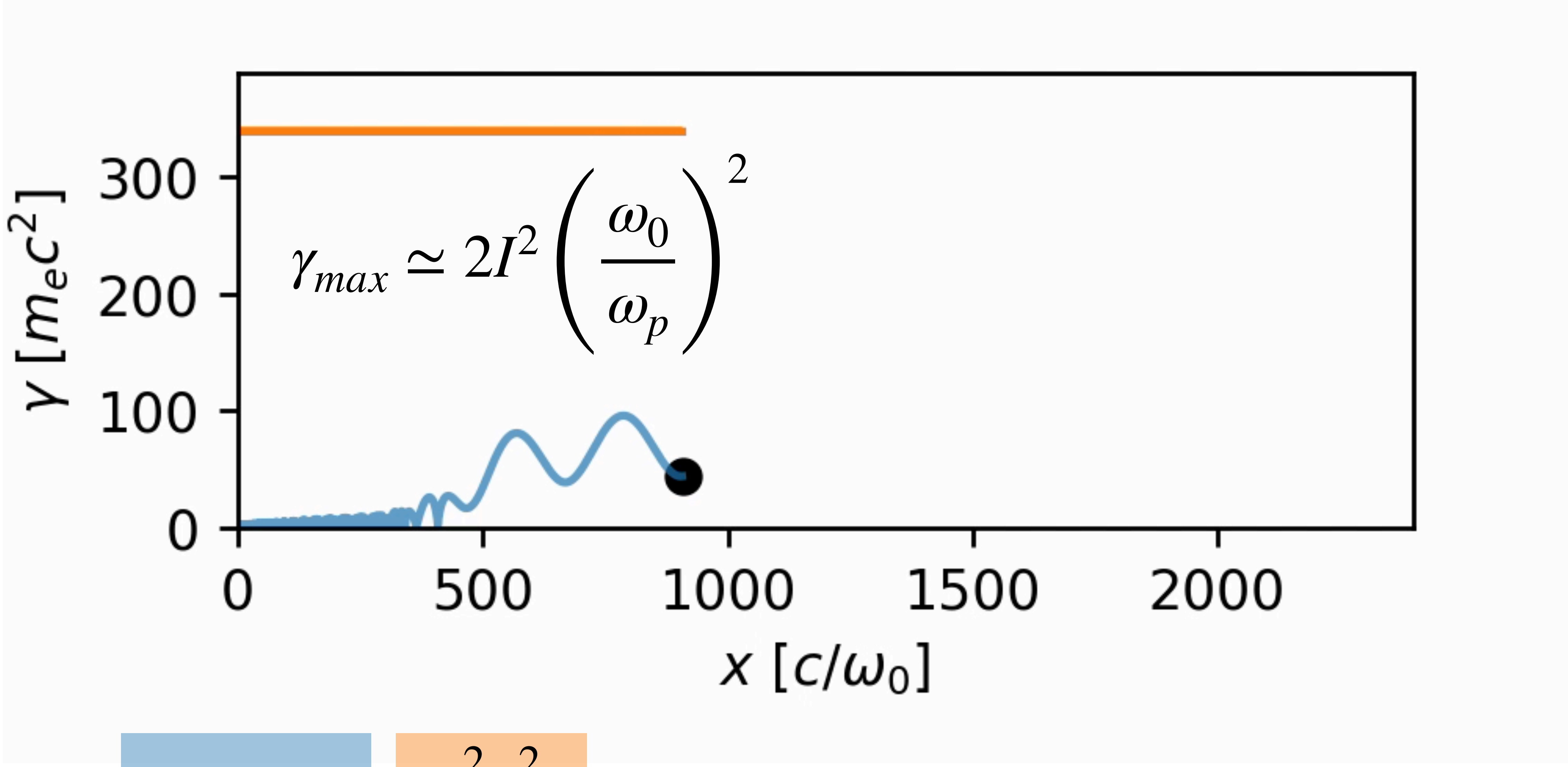


R. Babjak et al, Phys. Rev. Lett. (2024)

Off-resonance there is usually no net acceleration, because each electron experiences acceleration when $p_y \uparrow\downarrow E_y$ followed by deceleration when $p_y \uparrow\uparrow E_y$

Transition into resonance and acceleration afterwards



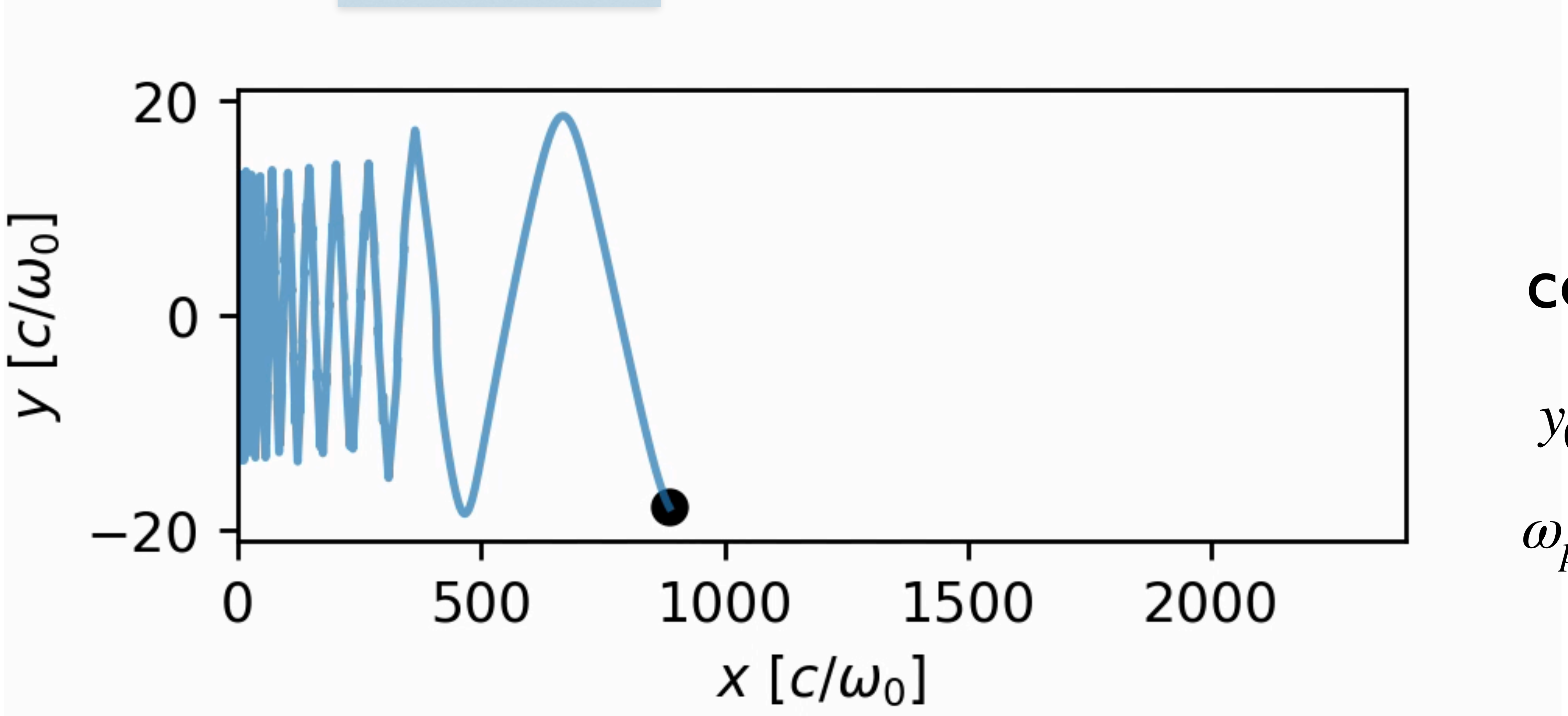


$$\omega_\beta = \frac{\omega_p}{\sqrt{2\gamma}}$$

Betatron frequency

$$I = \gamma - \frac{p_x}{m_e c} + \frac{\omega_p^2 y^2}{4c^2}$$

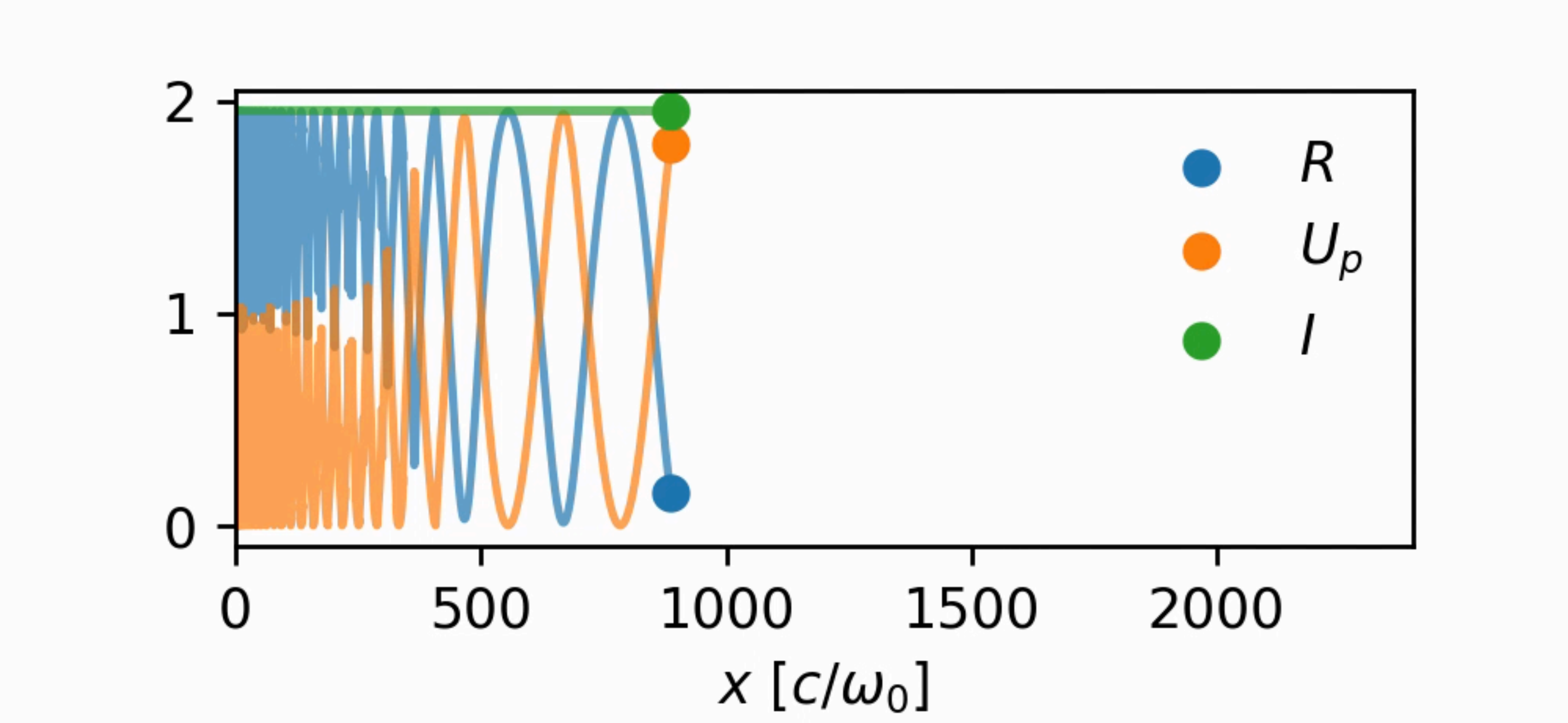
Integral of motion



Initial conditions

$y_0 = 19c/\omega_0$

$\omega_p/\omega_0 = 0.15$



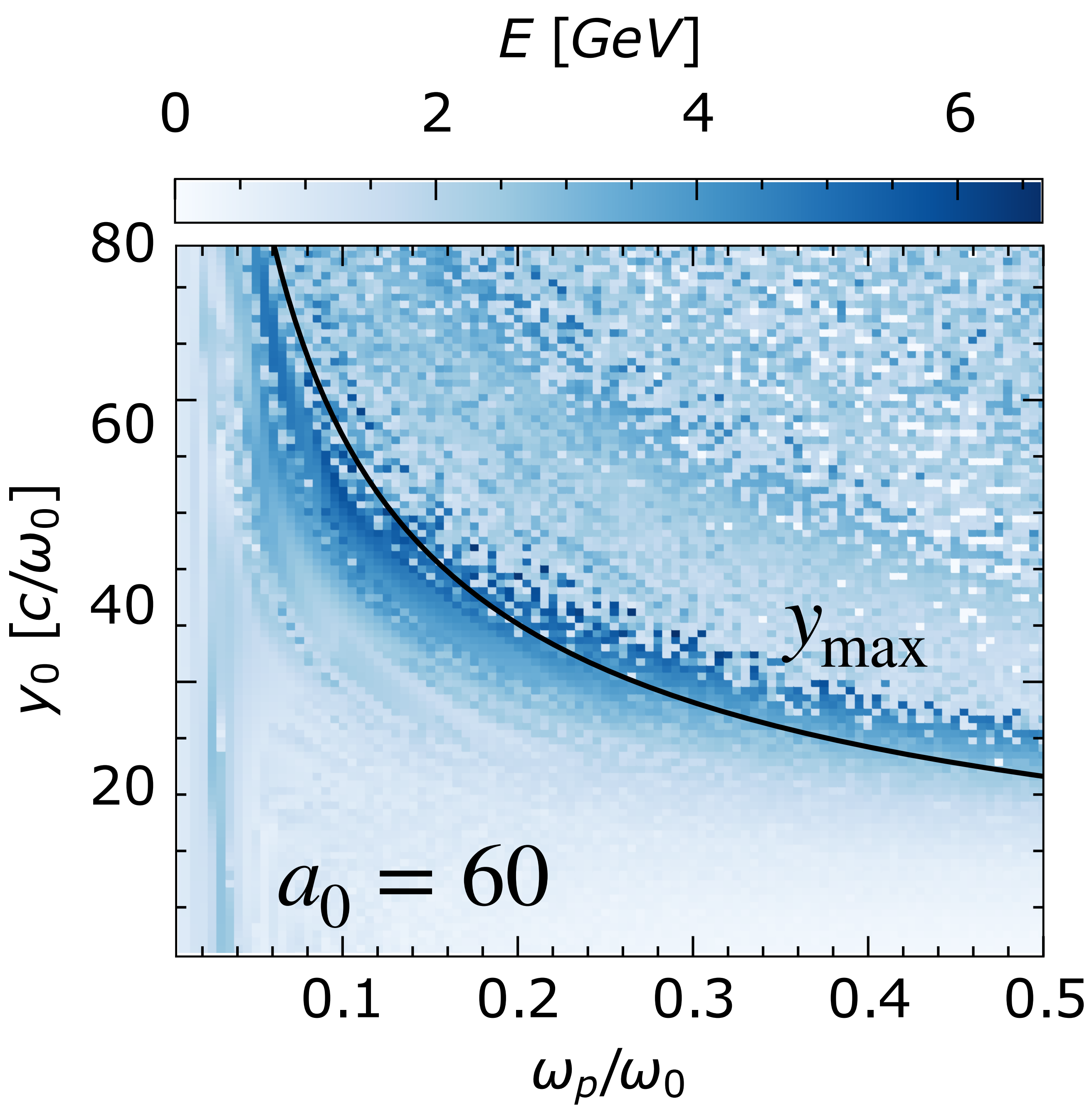
R. Babjak et al, Phys. Rev. Lett. (2024)

What are the optimal laser conditions for DLA?

Maximum resonant distance gives the maximum possible energy

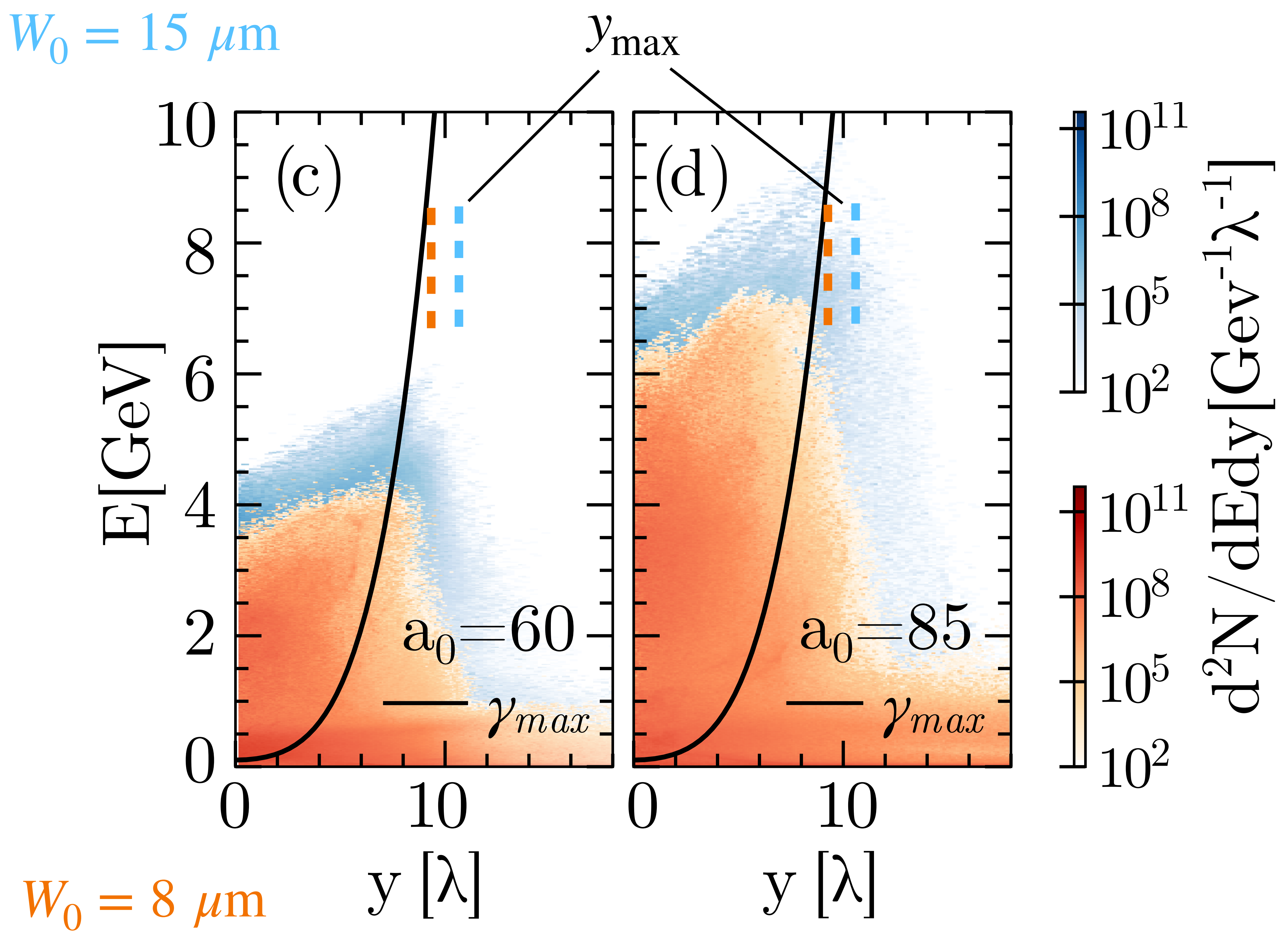
The resonance takes time to be established

Maximum oscillation amplitude



$$y_{\max} = \frac{2c}{\omega_p}\sqrt{\left(\frac{a_0\omega_p}{\varepsilon_{cr}\omega_0}\right)^{2/3} - 1}$$

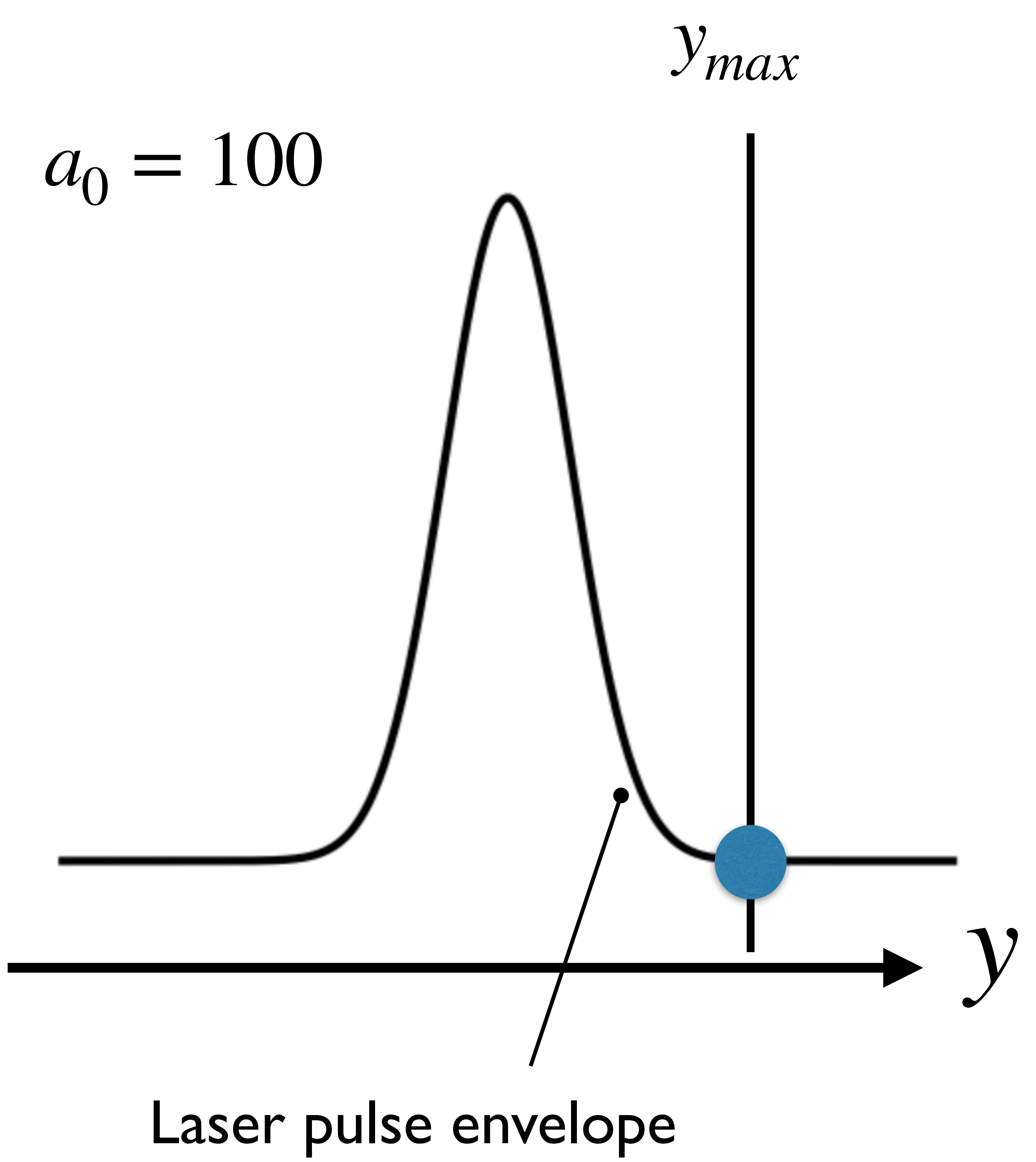
Optimal laser spotsize should be matched $W_0 \gtrsim y_{\max}$



R. Babjak et al, Phys. Rev. Lett. (2024)

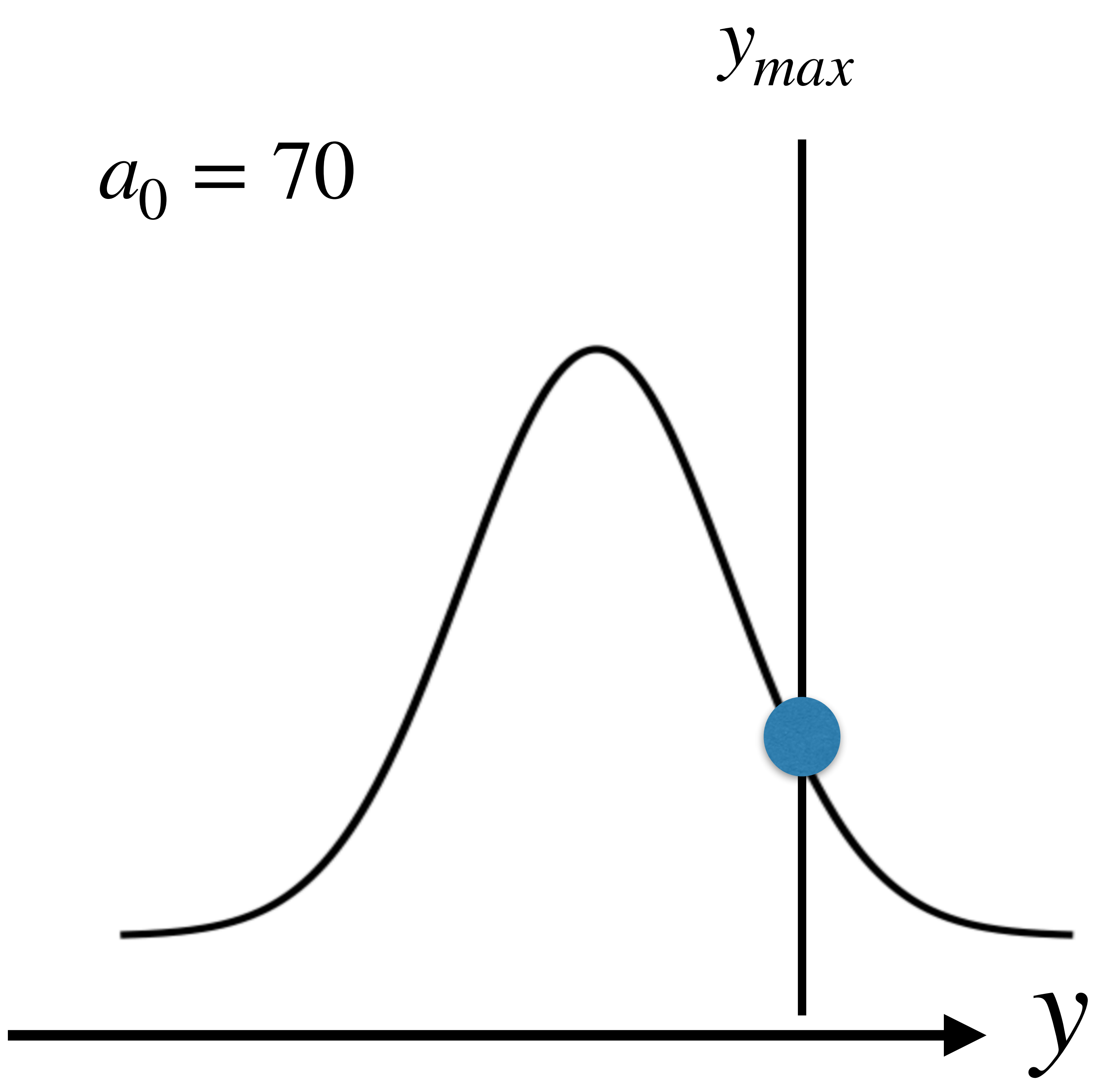
Optimal focusing is key for successful acceleration

Too narrow



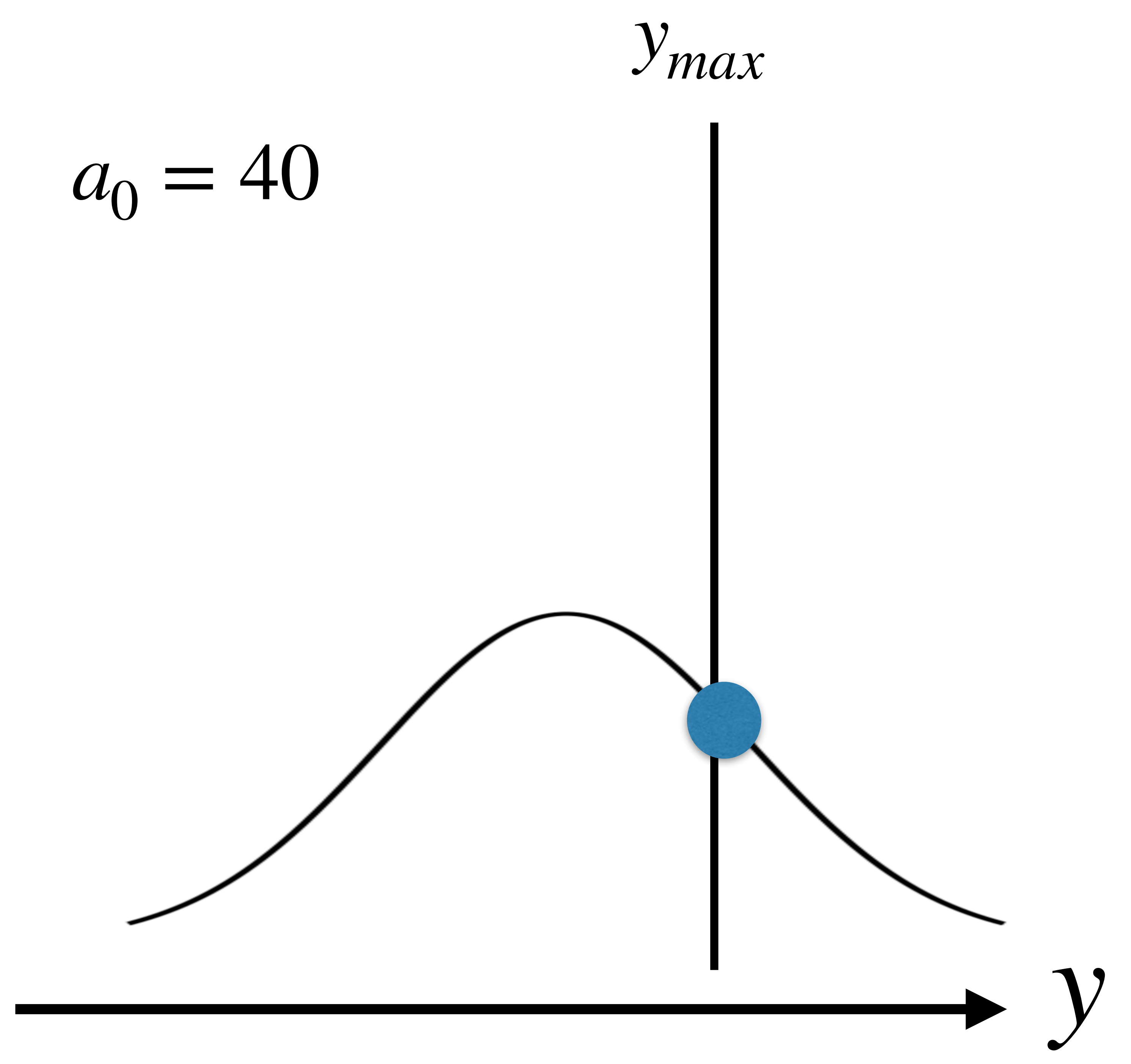
$$a_0 = 0.85\sqrt{I[10^{18}\ \mathrm{W/cm^2}]\ \lambda^2[\mu\mathrm{m}]}$$

Optimal



$$W_0 \approx y_{max}(a_0, \omega_p)$$

Too wide



Optimal focus as a function of the laser power (in uniform plasma)

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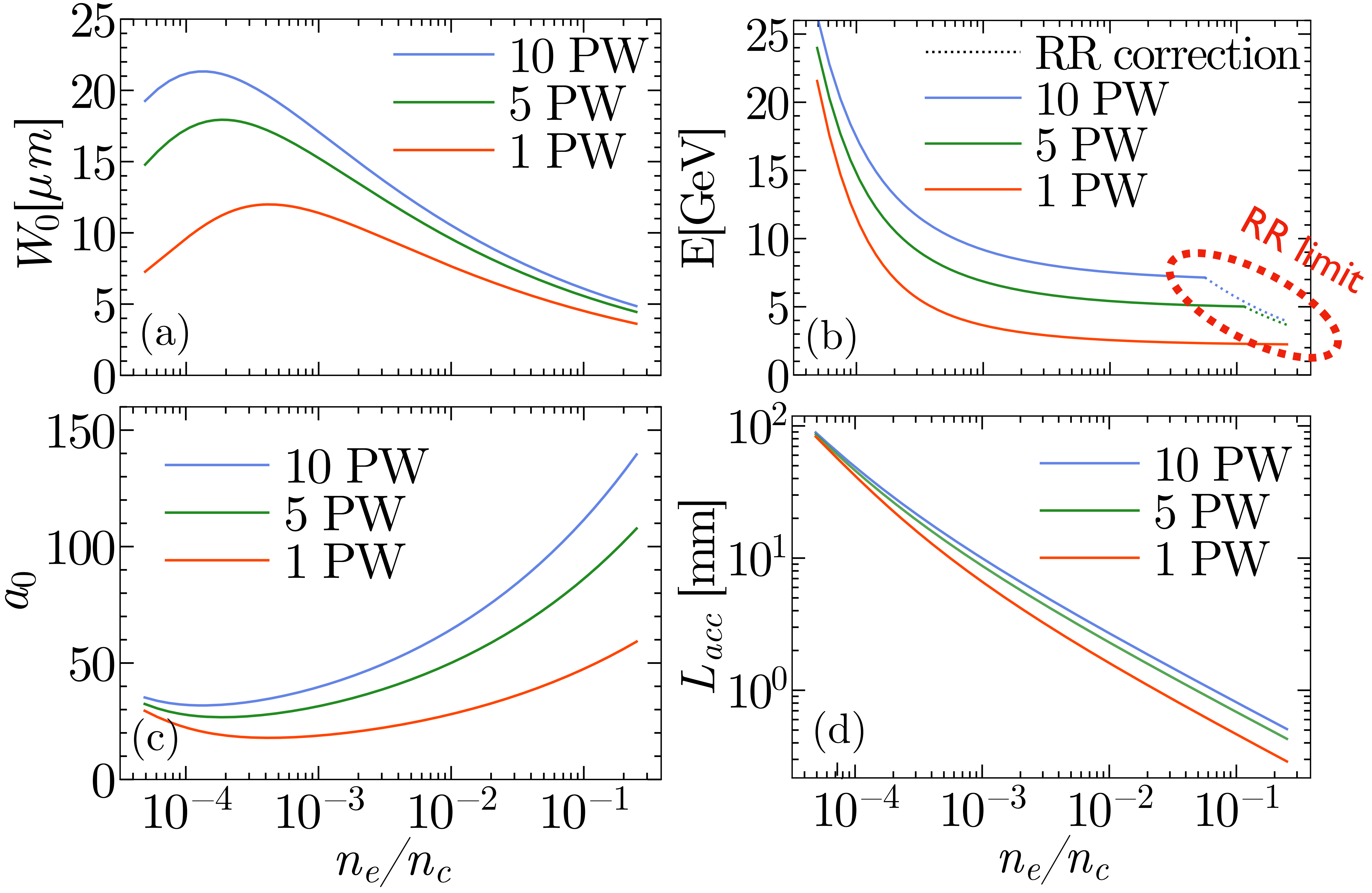
$$W_0^2[\lambda] = \left(\frac{\omega_0}{\omega_p}\frac{1.2}{\pi}\right)^2 \left[\left(\frac{\omega_p}{\omega_0 \varepsilon_{cr}}\sqrt{\frac{\mathrm{P[PW]}}{2.2\times 10^{-5}}}\right)^{2/3} \frac{1}{W_0^{2/3}[\lambda]} - 1\right]$$



Tight focusing is not the best!

Optimal spotsizes are far from tight focusing regime.

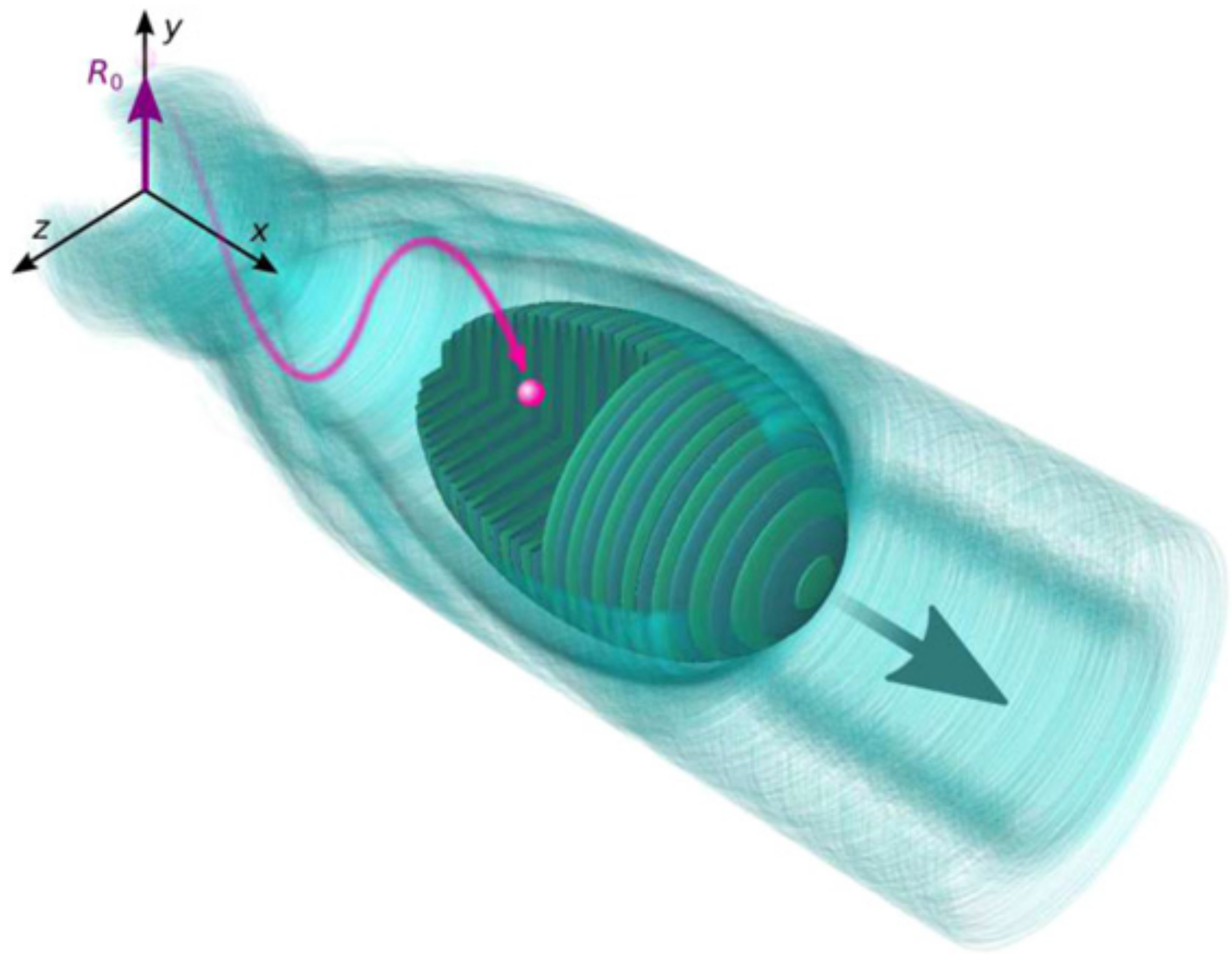
Low densities can give higher energies, but require a long acceleration distance.

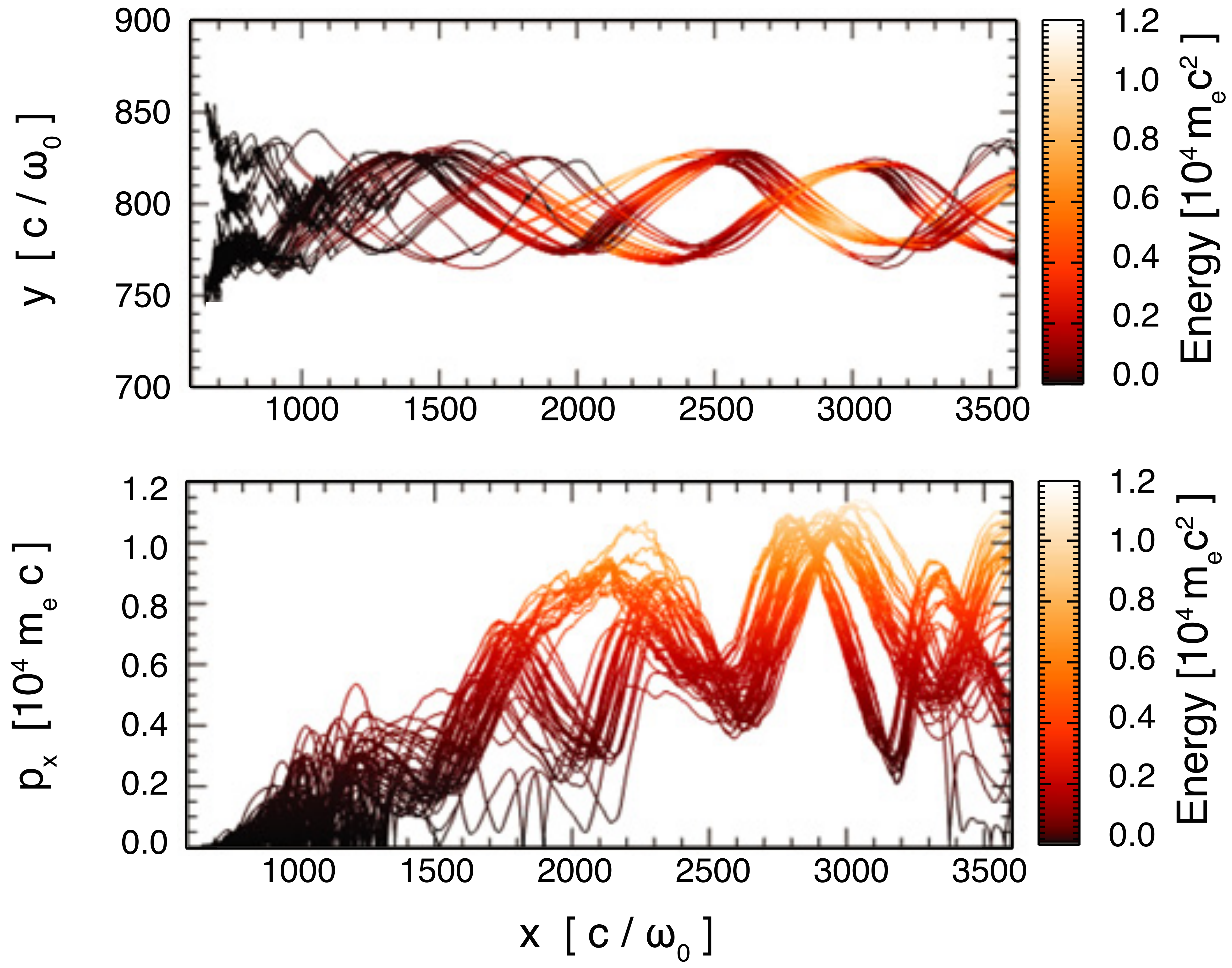
Laser guiding may be easier for middle-densities ~ 0.01 nc.

R. Babjak et al, Phys. Rev. Lett. (2024)

Radiation reaction establishes the asymptotic energy limit

The energy is limited to the value when maximum constructive work = total loss to radiation over one resonant oscillation



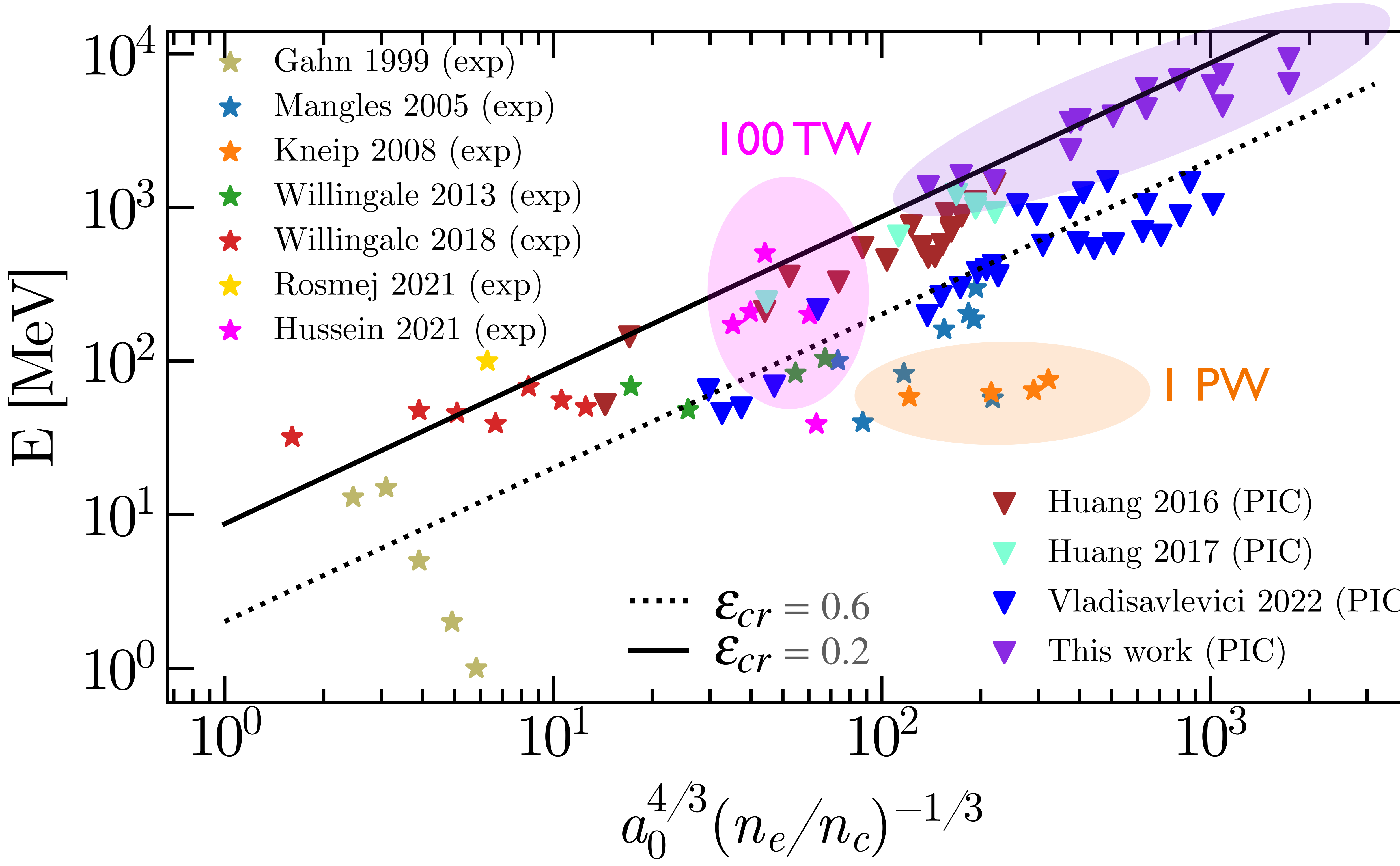


Direct laser acceleration (DLA) can accelerate electrons to ~10 GeVs. Could positrons be accelerated as well?

M. Jirka et al, New J. Phys. (2020)

Maximum energies achieved in experiments (and simulations)

$$W_0^2[\lambda] = \left(\frac{\omega_0}{\omega_p}\frac{1.2}{\pi}\right)^2 \left[\left(\frac{\omega_p}{\omega_0 \varepsilon_{cr}}\sqrt{\frac{\mathrm{P[PW]}}{2.2\times 10^{-5}}}\right)^{2/3}\frac{1}{W_0^{2/3}[\lambda]} - 1\right]$$



Multi-factor optimisation is required

It is not easy to obtain maximum allowed energy even in simulations!

Understanding all the important factors (and having the optimisation strategy), it will get easier to plan the experiments.

R. Babjak et al, Phys. Rev. Lett. (2024)

What happens when we have a varying density profile?

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Different conserved quantity

Constant density		Varying density
✓	$I = \gamma - \frac{p_x}{m_e c} + \frac{y^2 \omega_p^2}{4c^2}$	✗
✓	$\gamma_{max} = 2I^2 \left(\frac{\omega_0}{\omega_p}\right)^2$	✓

This change affects the maximum allowed energy!

What is different in terms of maximum energy?

Both I and ω_p are changing as electron propagates

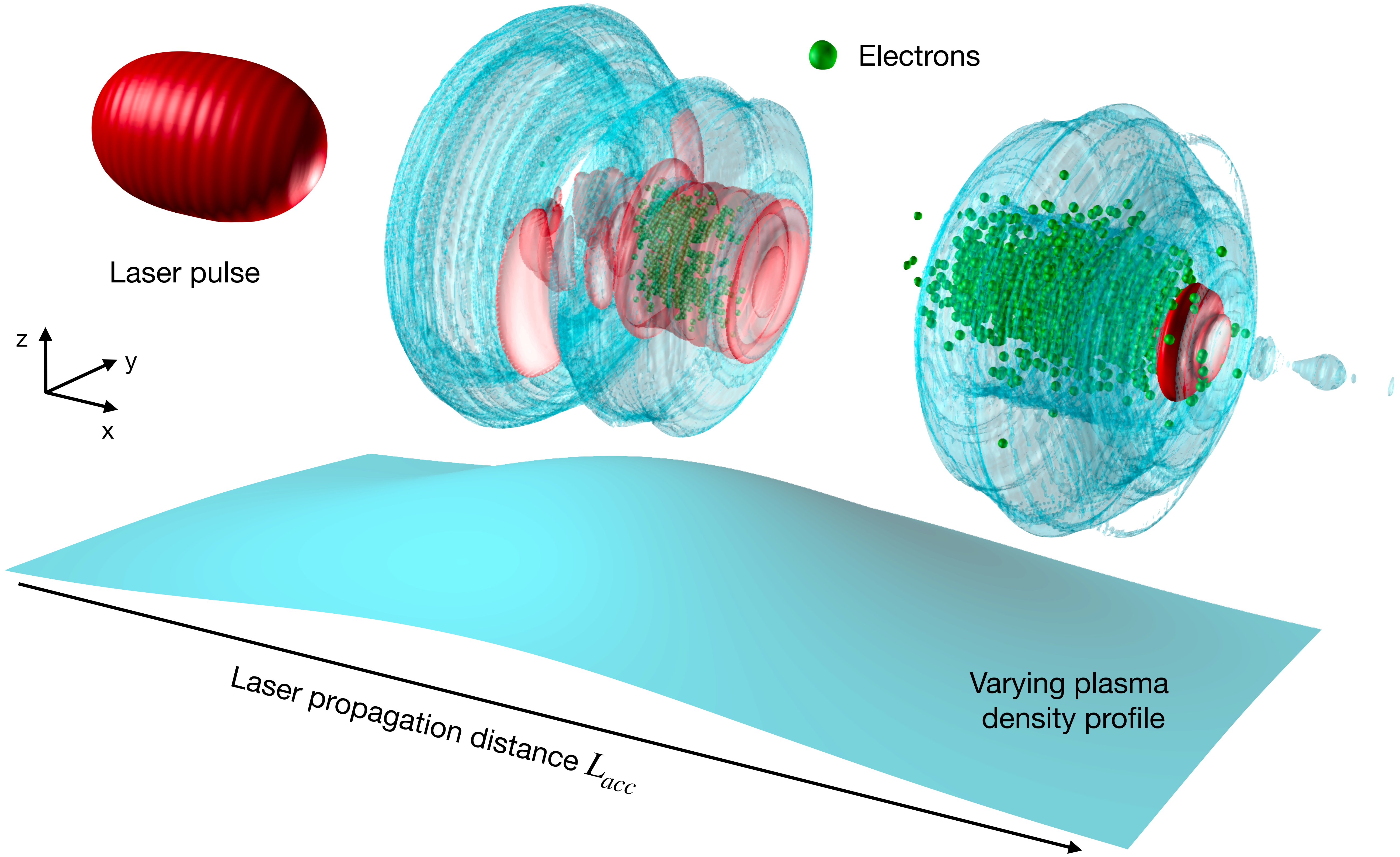
↓

To extend the energy scaling law we need to know the evolution of I

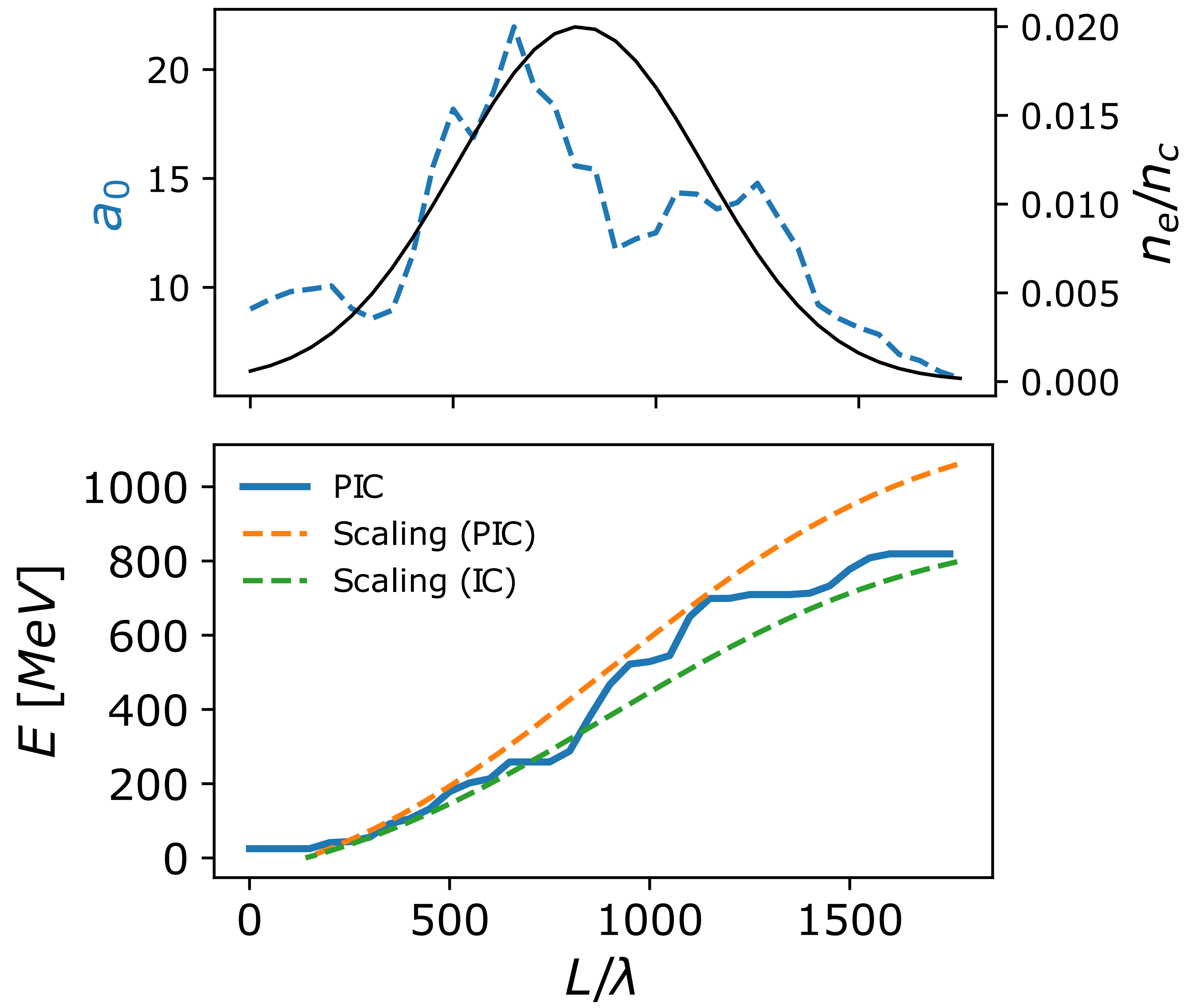
$$\frac{d\gamma}{dt} \sim \frac{a_0}{\sqrt{I}} \frac{\omega_p}{\omega_0}$$

R. Babjak et al, arXiv: 2406.10702 (2024)

The theory can be extended to varying density plasma profiles



Analytical energy estimate vs. PIC



$$\frac{d\gamma}{dx} \sim a_0 \left(\frac{2}{\gamma_{max}}\right)^{1/4} \sqrt{\frac{\omega_p(x)}{\omega_0}}$$

R. Babjak et al, New J. Phys. (2024)

The density where the resonance is achieved defines max. energy

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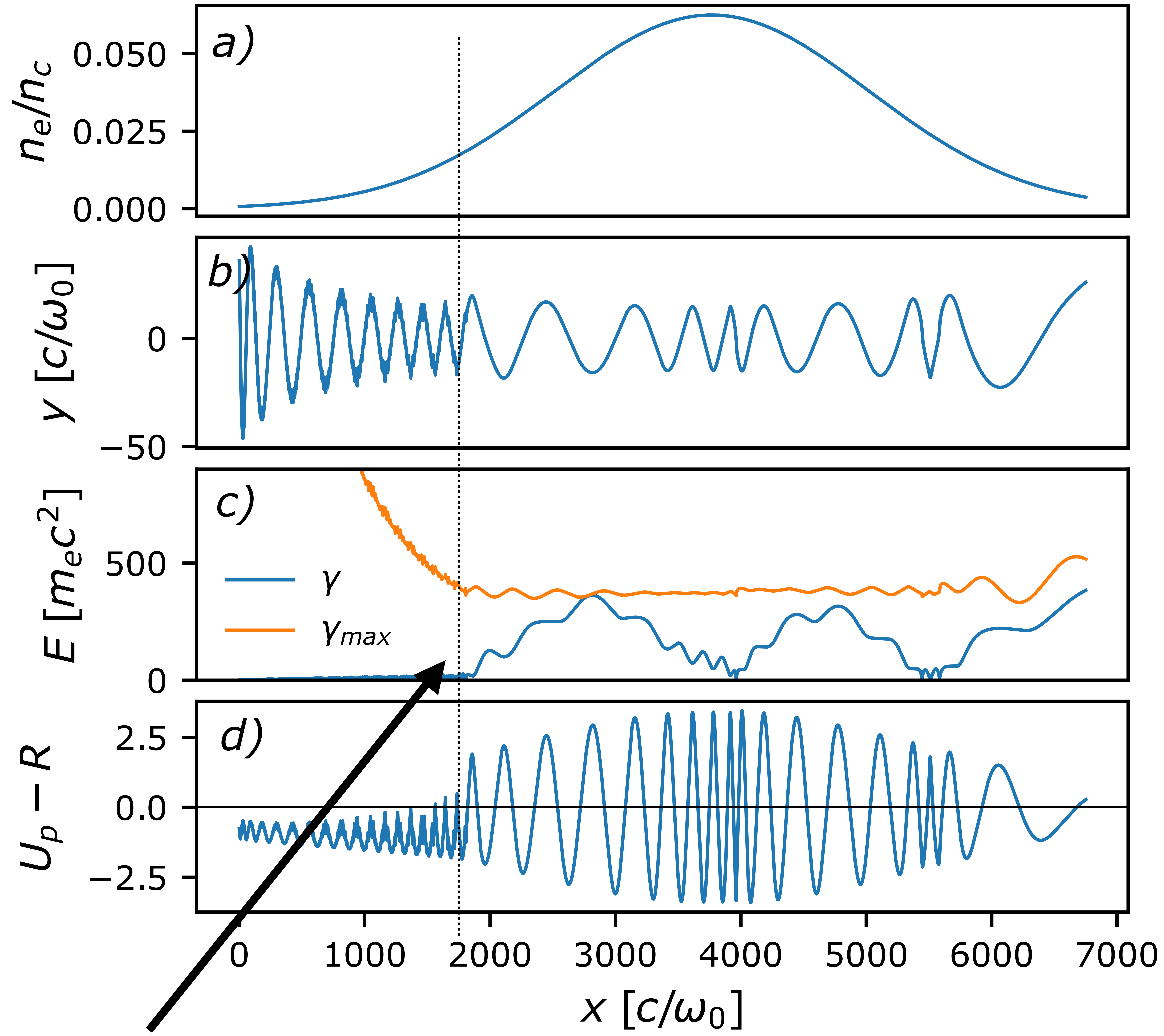
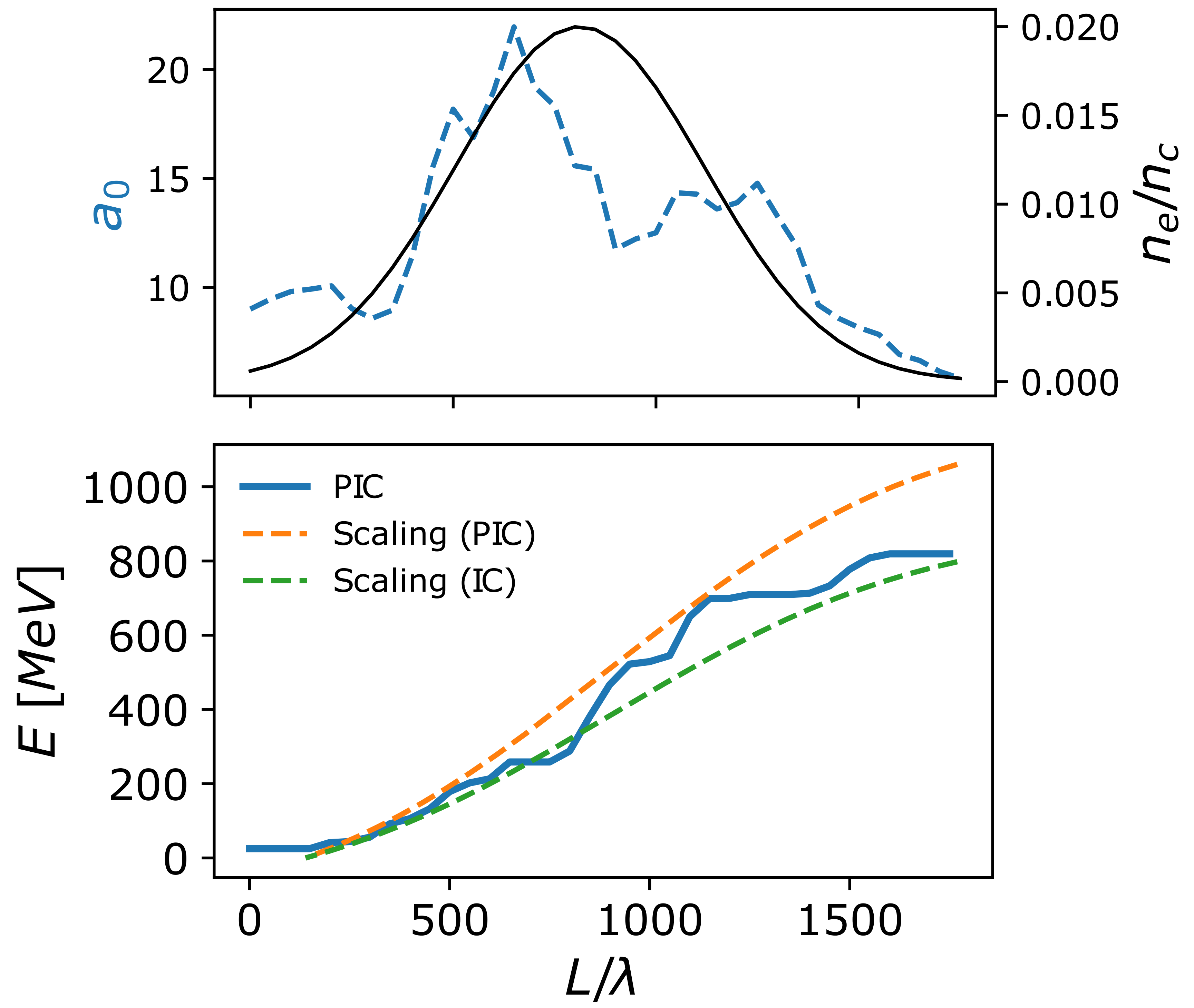


The moment of resonance controls the maximum energy

Analytical energy estimate vs. PIC

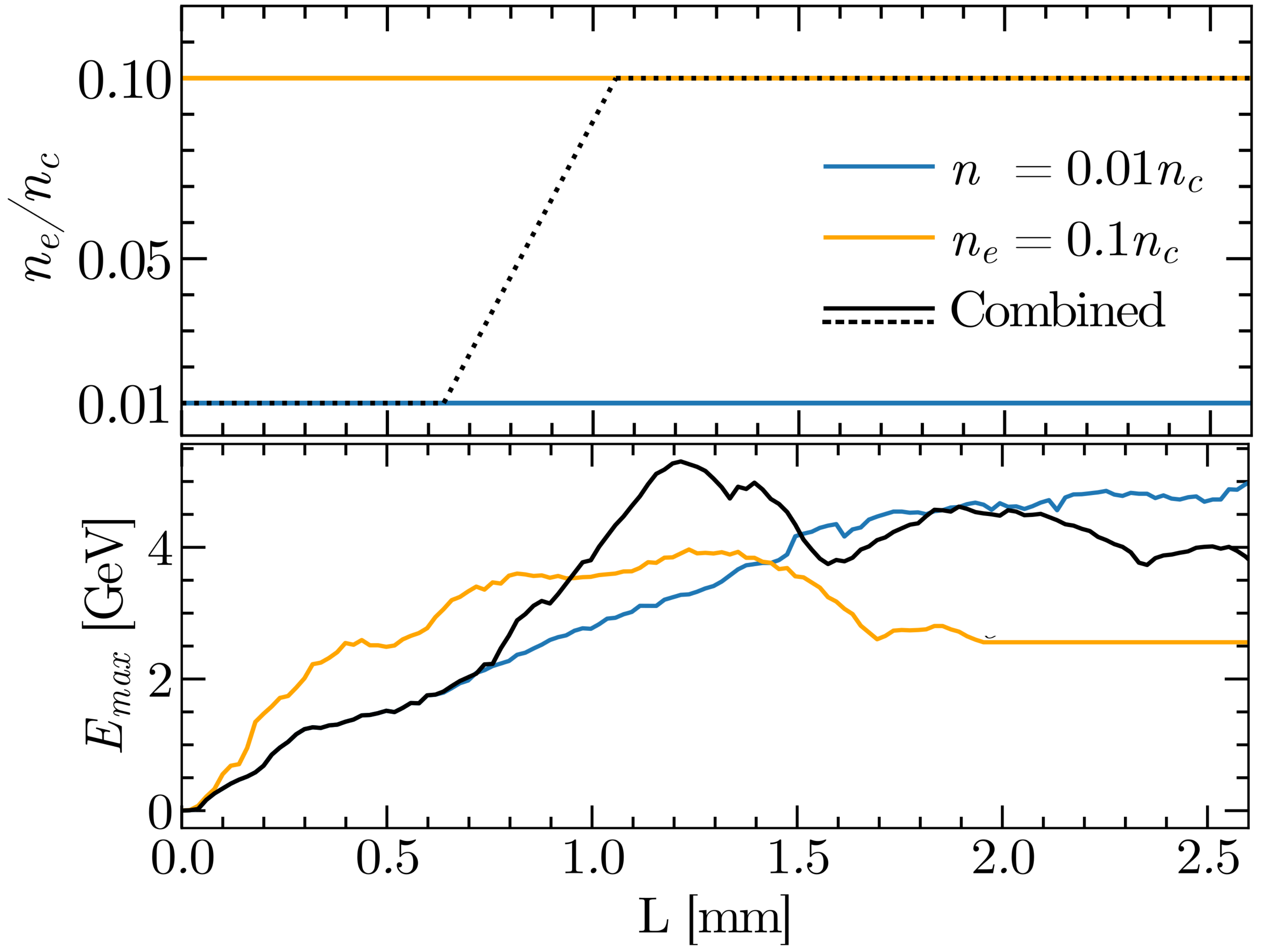


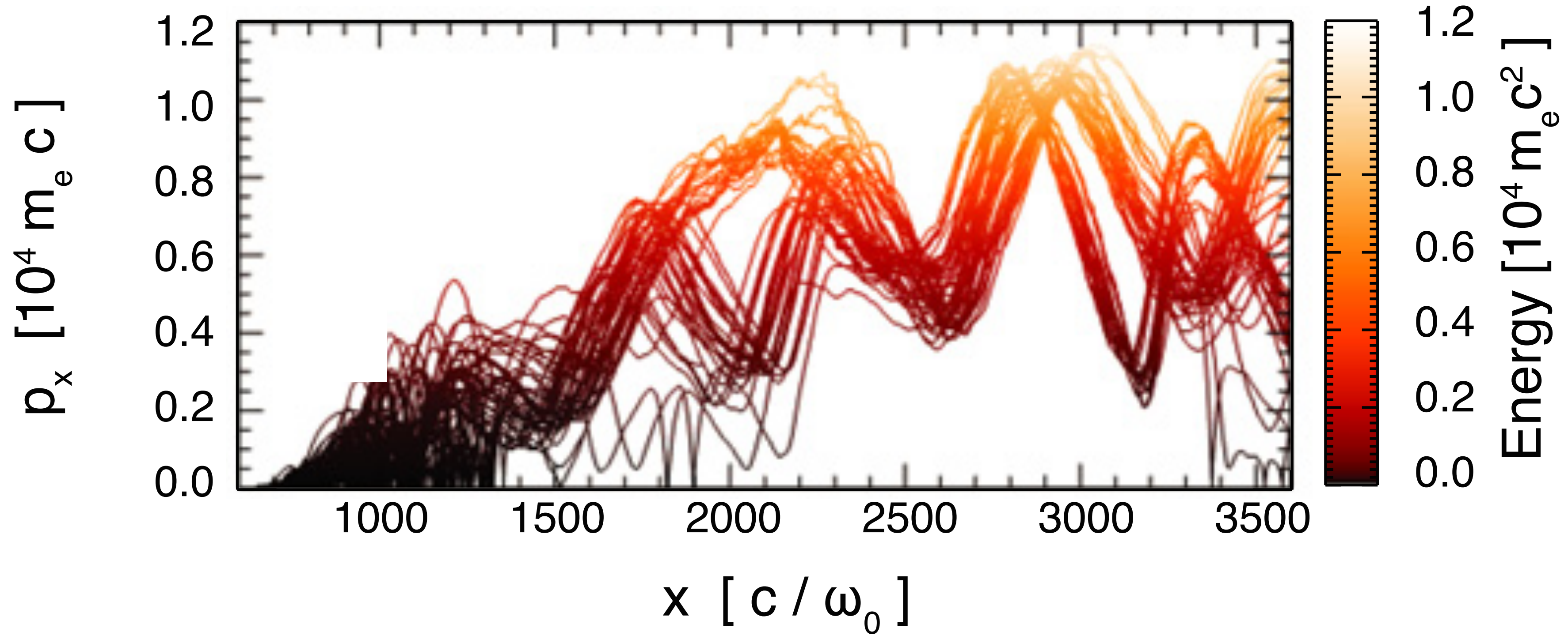
$$\frac{d\gamma}{dx} \sim a_0 \left(\frac{2}{\gamma_{max}}\right)^{1/4} \sqrt{\frac{\omega_p(x)}{\omega_0}}$$

R. Babjak et al, arXiv: 2406.10702 (2024)

Tailoring the plasma profile can shorten the acceleration distance

Or allow acceleration beyond the radiation reaction limit





M. Jirka et al, New J. Phys. (2020)

5 GeV in 1 mm instead of 2!

Limited by work of E = radiation losses

R. Babjak et al, New J. Phys. (2024)

Contents

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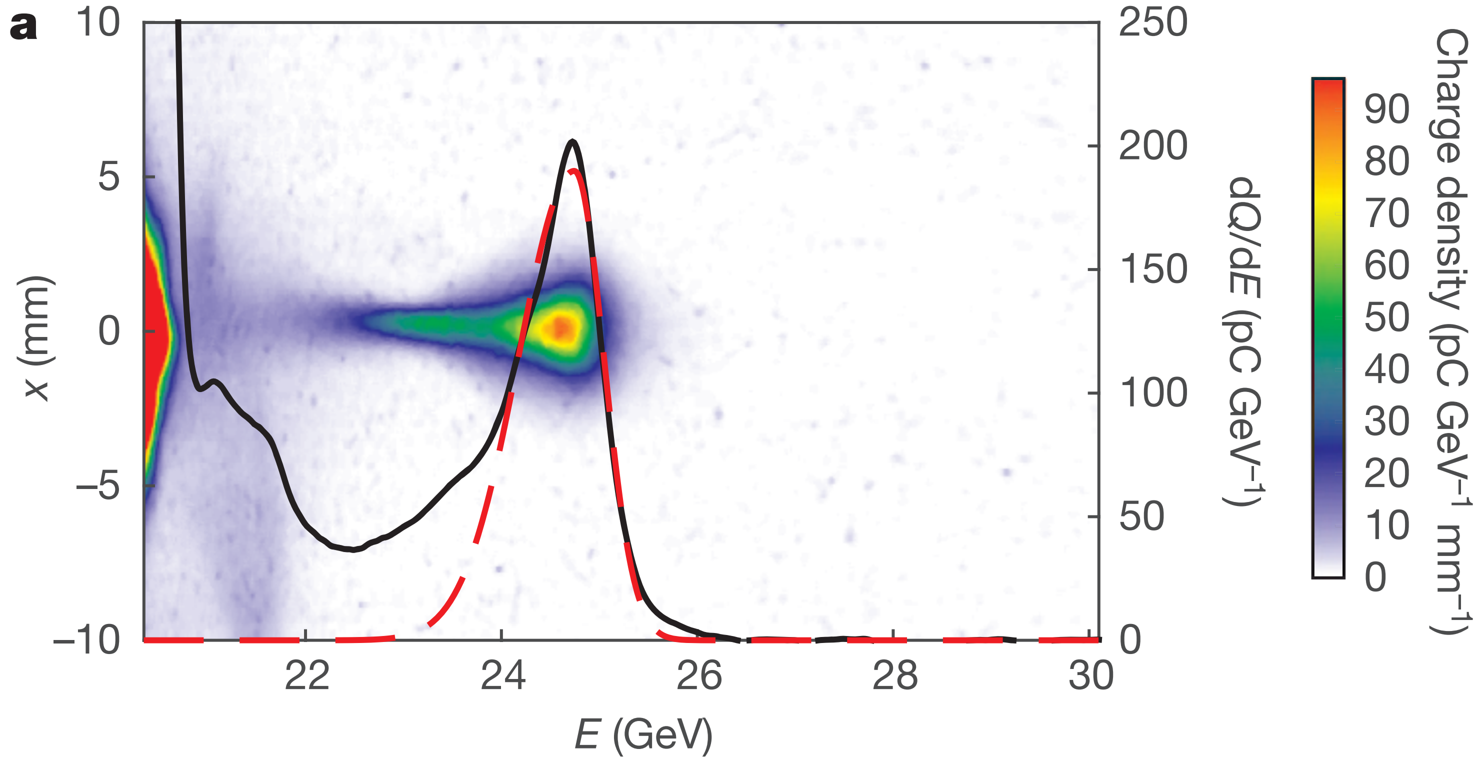
Electron acceleration

Positron creation and acceleration

Radiation generation

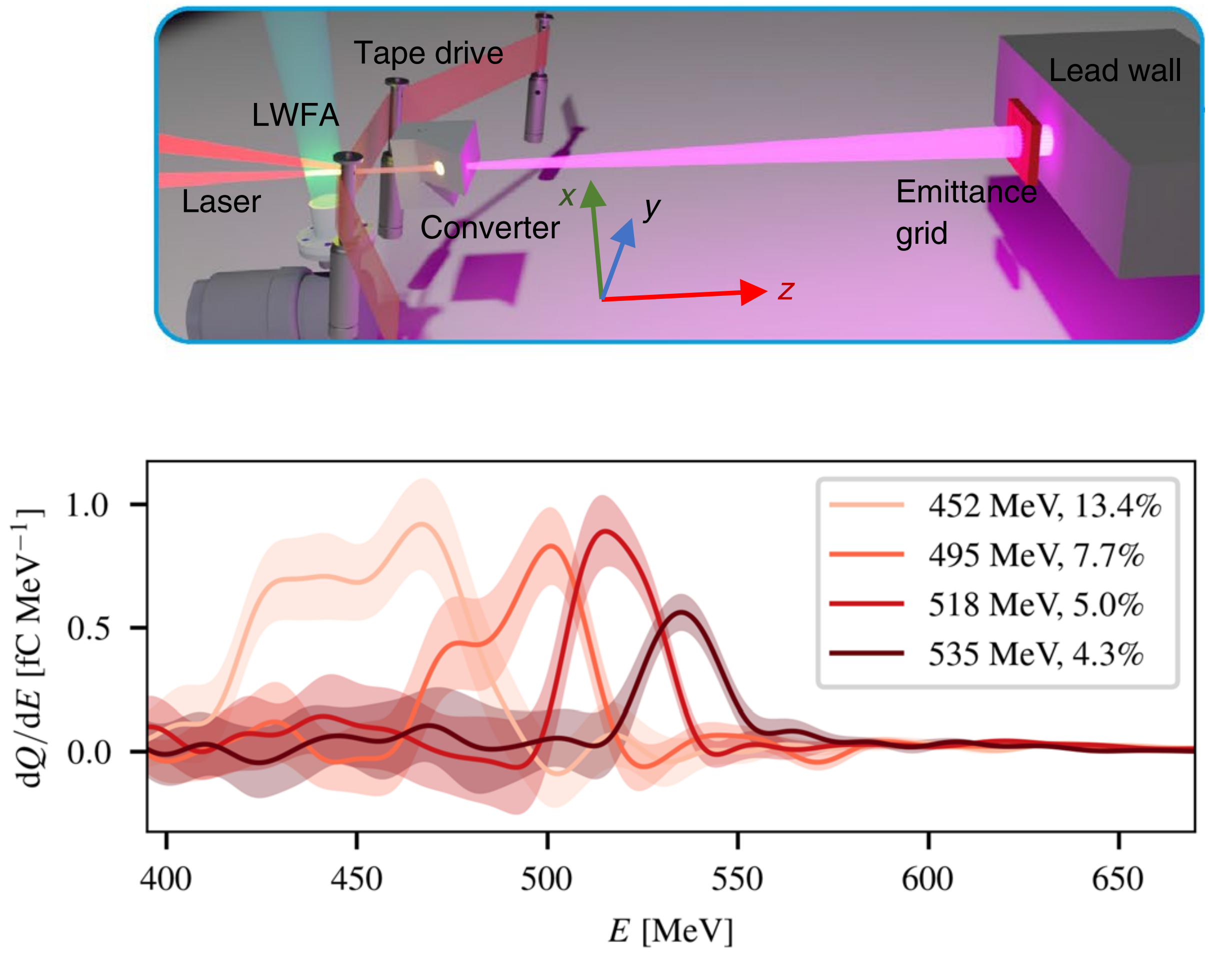
Why positrons? And why with DLA?

Positron creation and acceleration



S. Corde et al, Nature 524, 442 (2015)

We can accelerate them in plasma



A. Doche et al, Sci. Rep. 7 14180 (2017)

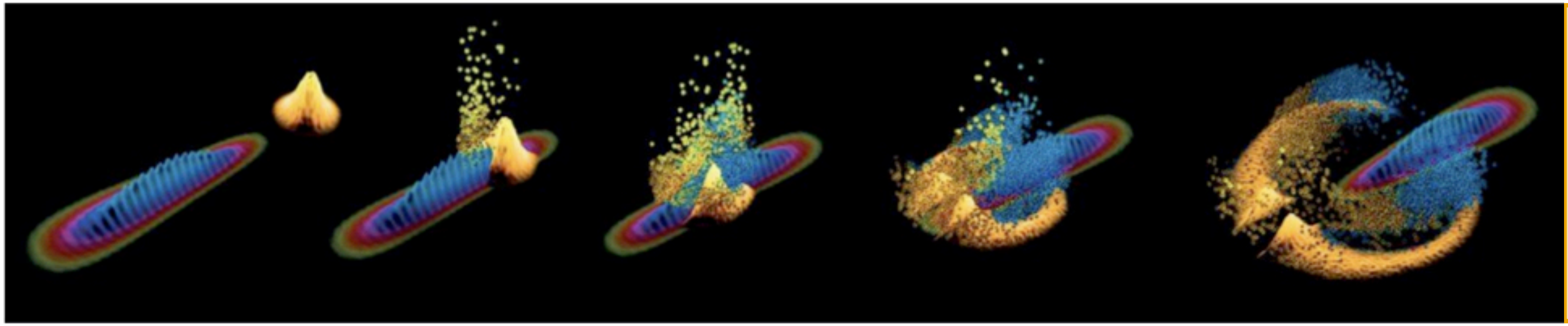
We can post-select the desired energy range

Challenges

- Generate enough e+
- Injection & synchronization
- Acceleration & guiding

How do we create positrons, inject and guide them?
Can we control where they go?

Scattering an intense laser with an electron beam - Schwinger field can be attained in the electron rest frame



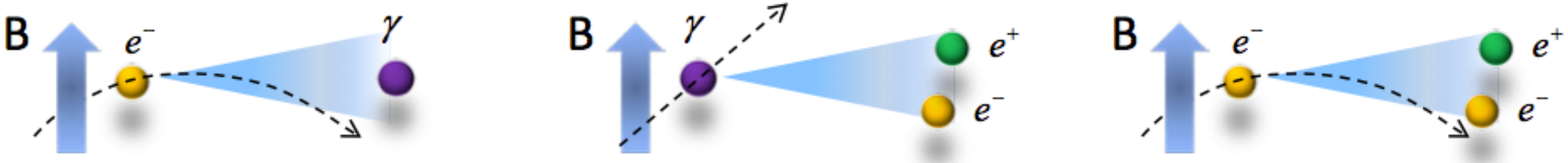
$$E_S = \frac{m^2c^3}{e\hbar}$$

First QED processes

Non-linear Compton emission

Non-linear Breit-Wheeler pair creation

EM trident pair creation



Credit: M. Lobet, B. Martinez

QScatter

Numerical Framework for Fast Prediction of Particle Distributions in Electron-Laser Scattering

Features

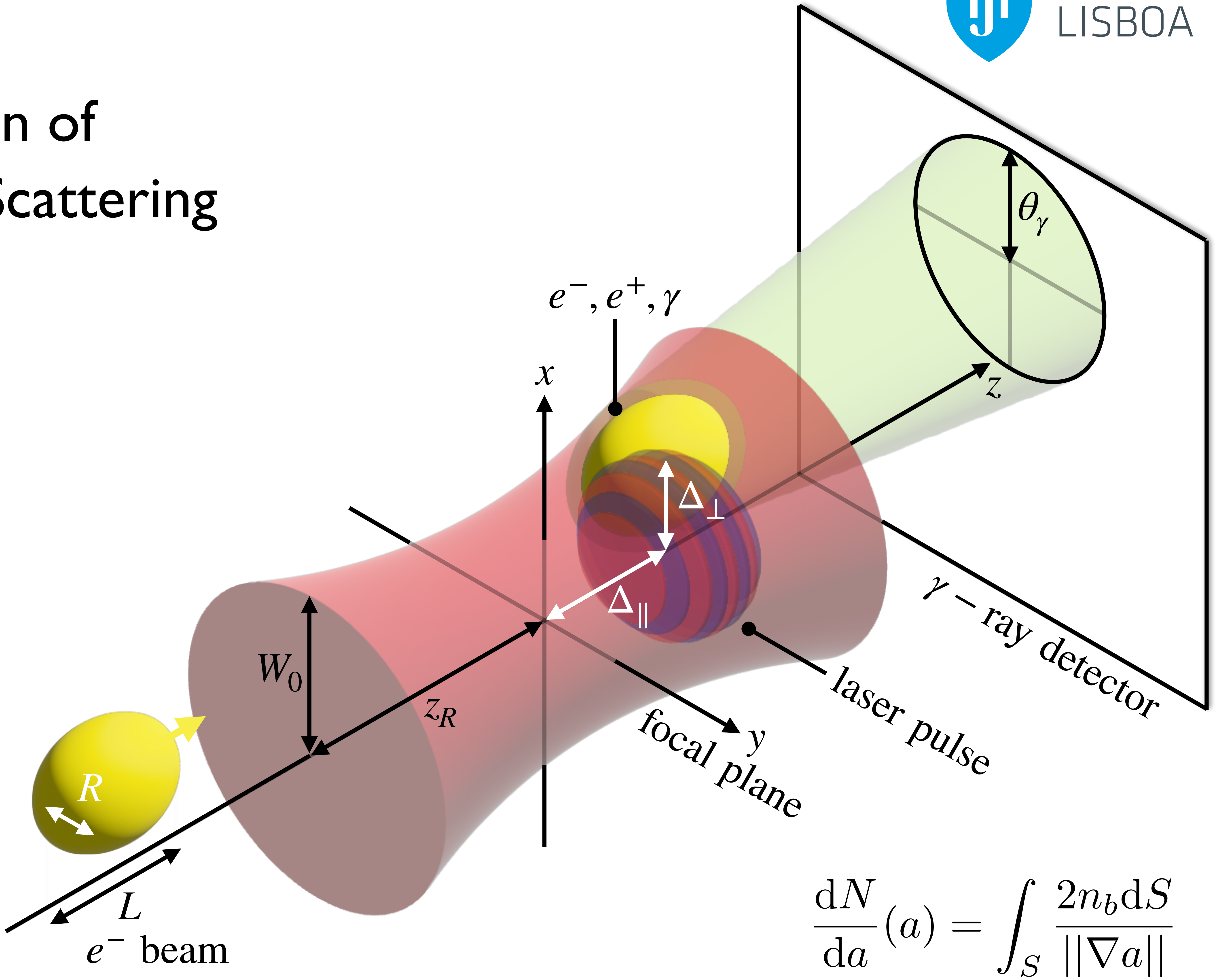
- Takes into account non-ideal spatio-temporal synchronization of the collision
- Option to map 1D Wavepacket results to 3D-geometry
- Calculates observables after the collision (e.g. particle and photon distributions)

Example applications

- Obtaining optimal laser spotsize for positron production with a fixed pulse energy
- Extensive parameter scans for final $e^{\pm}, \gamma$ spectra, running on a laptop; multiple-variable optimization
- Simultaneous multiple variable optimization

Papers and open-source code

- O. Amaro, M. Vranic, New J. Phys. 23, 115001 (2021)
- O. Amaro, M. Vranic, Plasma Phys. Control. F. 66, 045006 (2024)
- https://github.com/OsAmaro/QScatter



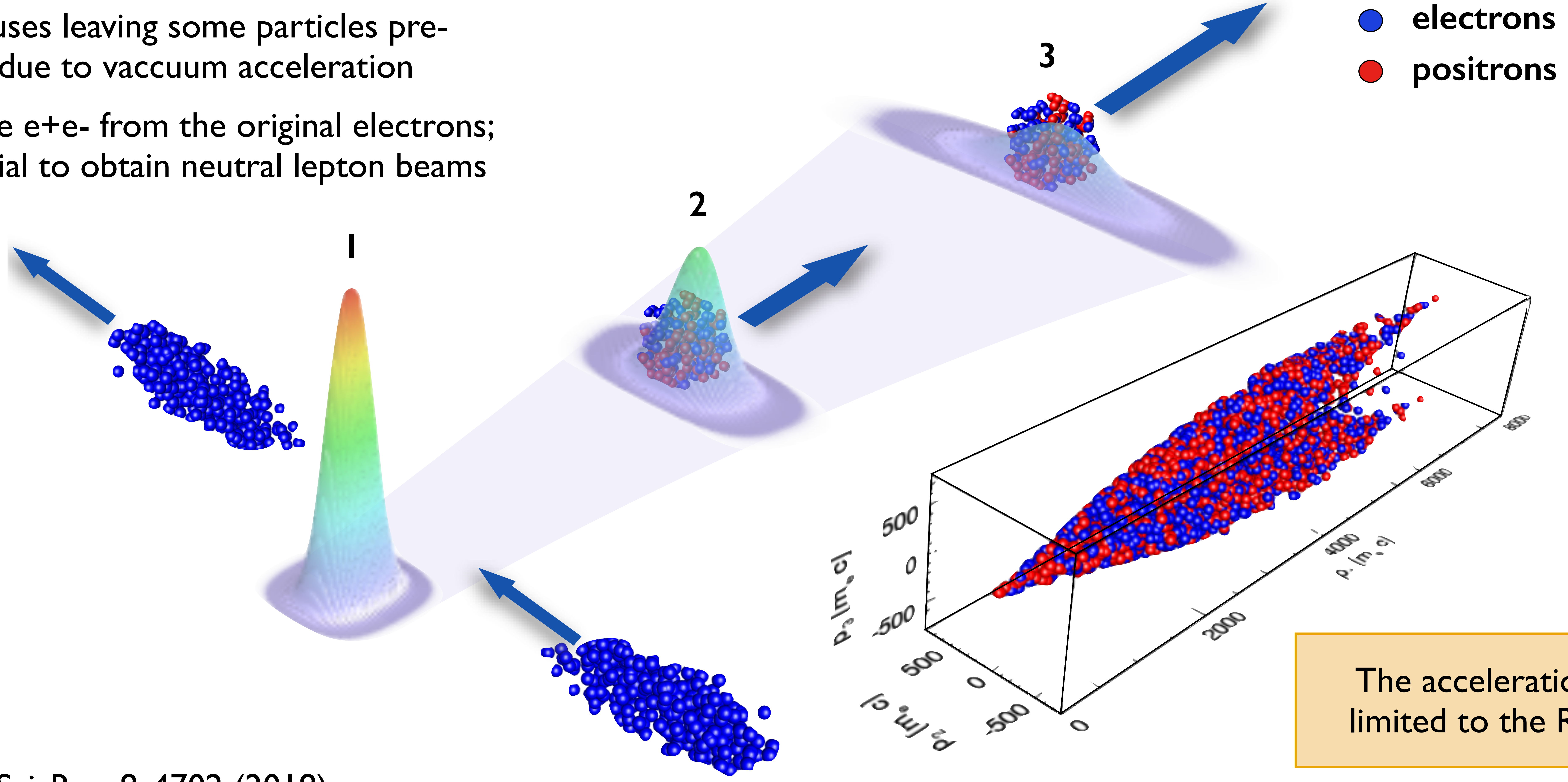
$$\frac{\mathrm{d}N}{\mathrm{d}a}(a) = \int_S \frac{2n_b \mathrm{d}S}{||\nabla a||}$$

$$\frac{\mathrm{d}N^{3D}}{\mathrm{d}\gamma}(\gamma; a_0) = \sum_{\text{PW data}} \frac{\mathrm{d}N}{\mathrm{d}\gamma}^{\text{PW}}(\gamma; a_i) \frac{\mathrm{d}N}{\mathrm{d}a}(a_i)$$

Óscar Amaro: oscar.amaro@tecnico.ulisboa.pt Marija Vranic: marija.vranic@tecnico.ulisboa.pt

Scattering at 90 degrees - e+e- can be accelerated in vacuum

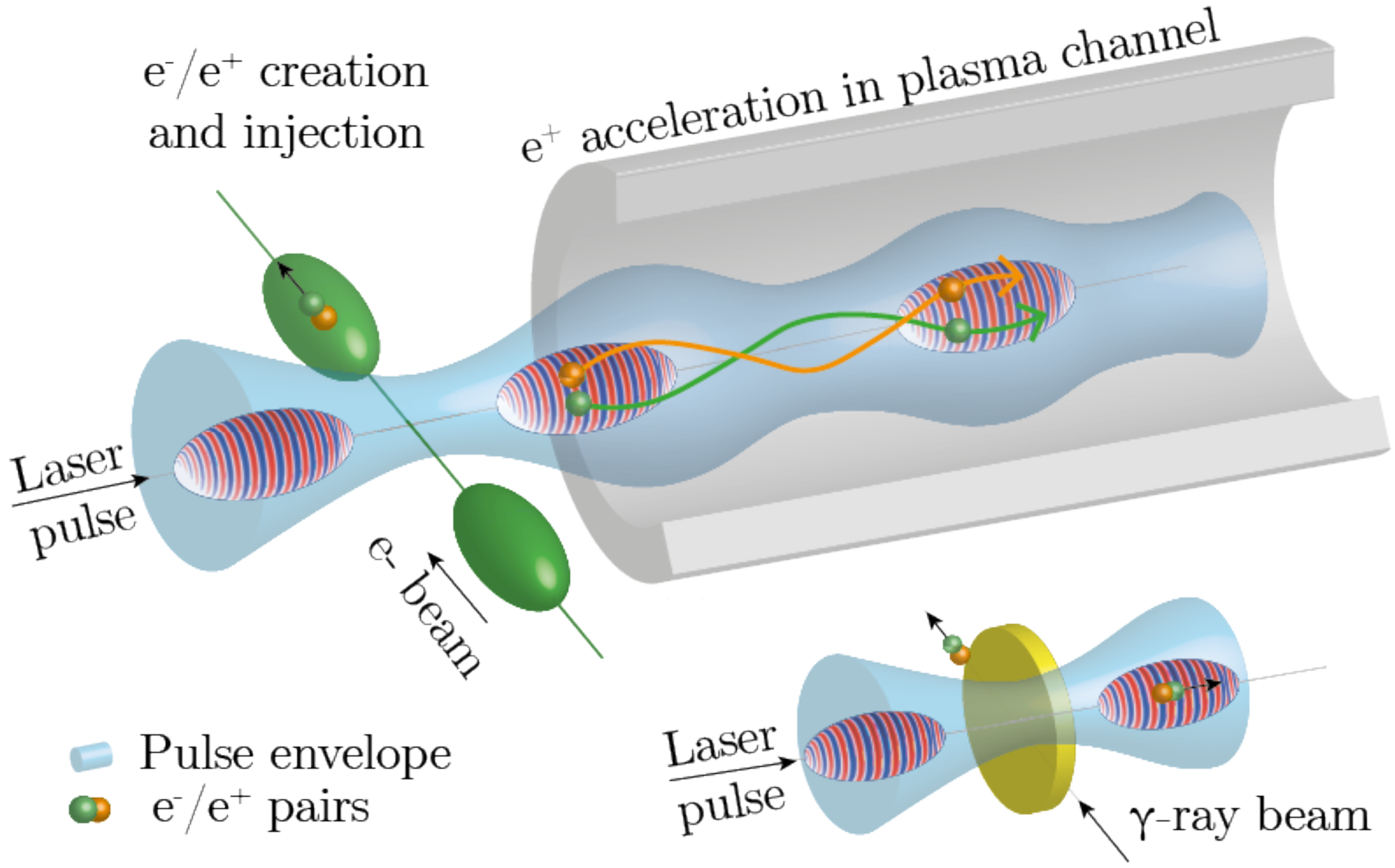
- Electrons collide with the laser; pairs are produced in the highest field region
- E+e- beam is accelerated by the laser in vacuum
- Laser defocuses leaving some particles pre-accelerated due to vaccuum acceleration
- Can separate e+e- from the original electrons; gives potential to obtain neutral lepton beams



The acceleration distance is limited to the Rayleigh range

M.Vranic et. al., Sci. Rep. 8, 4702 (2018)

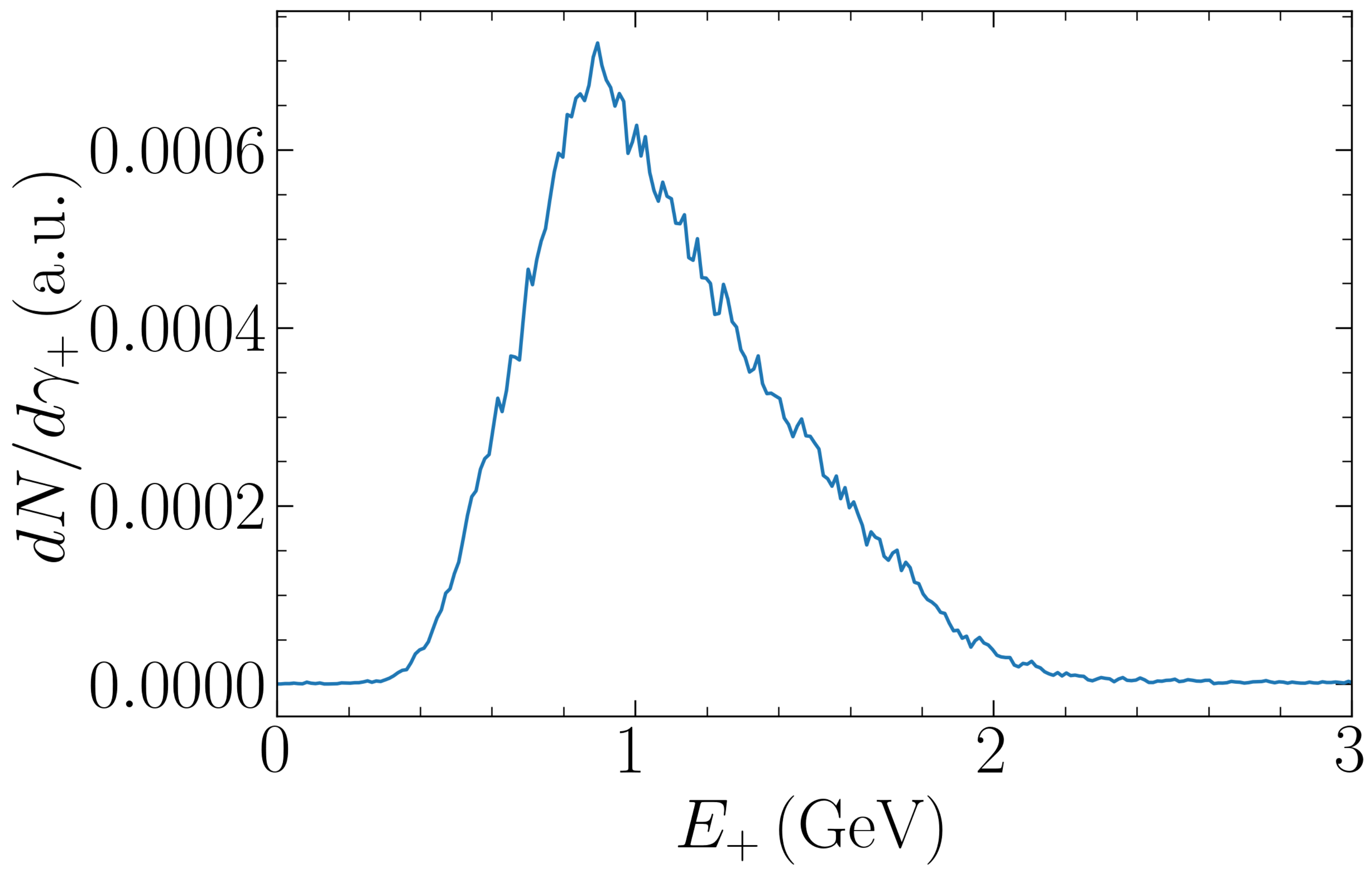
Pairs can also be accelerated within a plasma channel



2 GeV e-, charge ~ $10\,\mathrm{pC}$

This can be modelled in Quasi-3D geometry**

Positron spectra



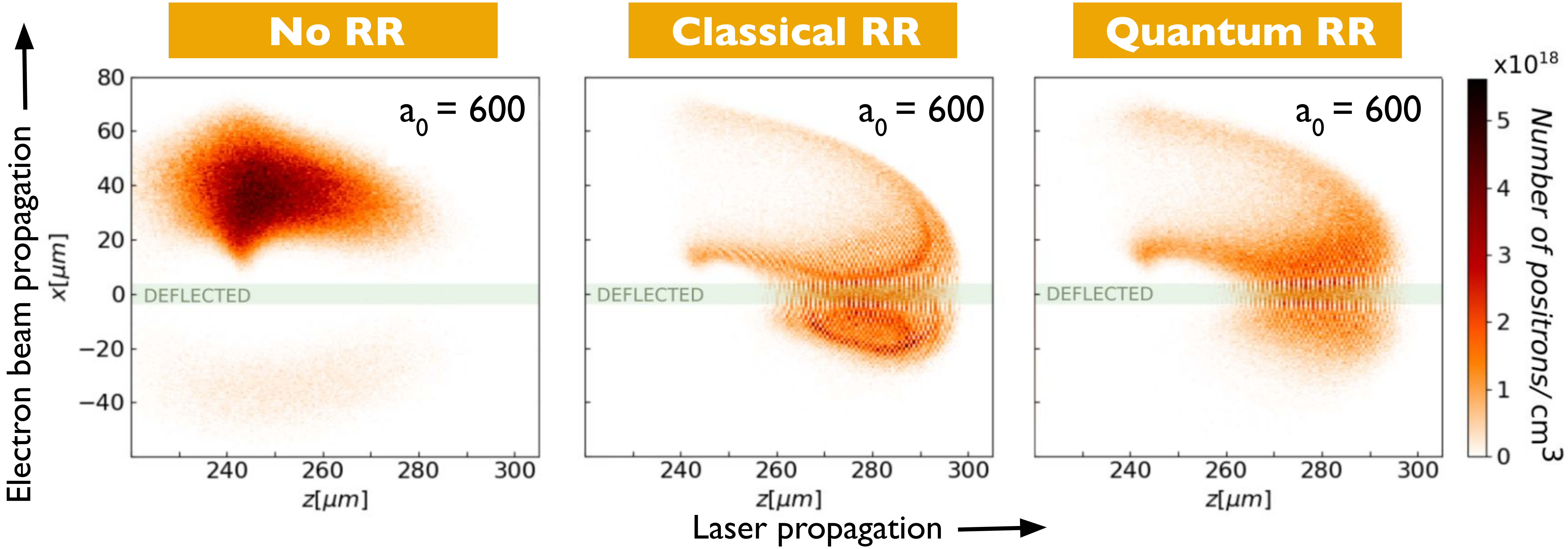
Energy peak around 1 GeV

Charge of $\sim 0.1\,\mathrm{pC}$

B. Martinez et al, Phys. Rev. A (2023)

Radiation reaction is vital for injection of positrons

Without RR, there is no deflection after 200 fs, and no injection in the plasma channel



Large initial transverse momenta lead to escape: No injection!

RR reduces transverse momentum and makes injection possible.

$\chi \sim 0.1 - 5$

$W_0 \sim 3.2\ \mu m$

D. Maslarova et al, Phys. Plasmas (2023)

Significant electron beam loading is necessary to guide e+

How are positrons guided?

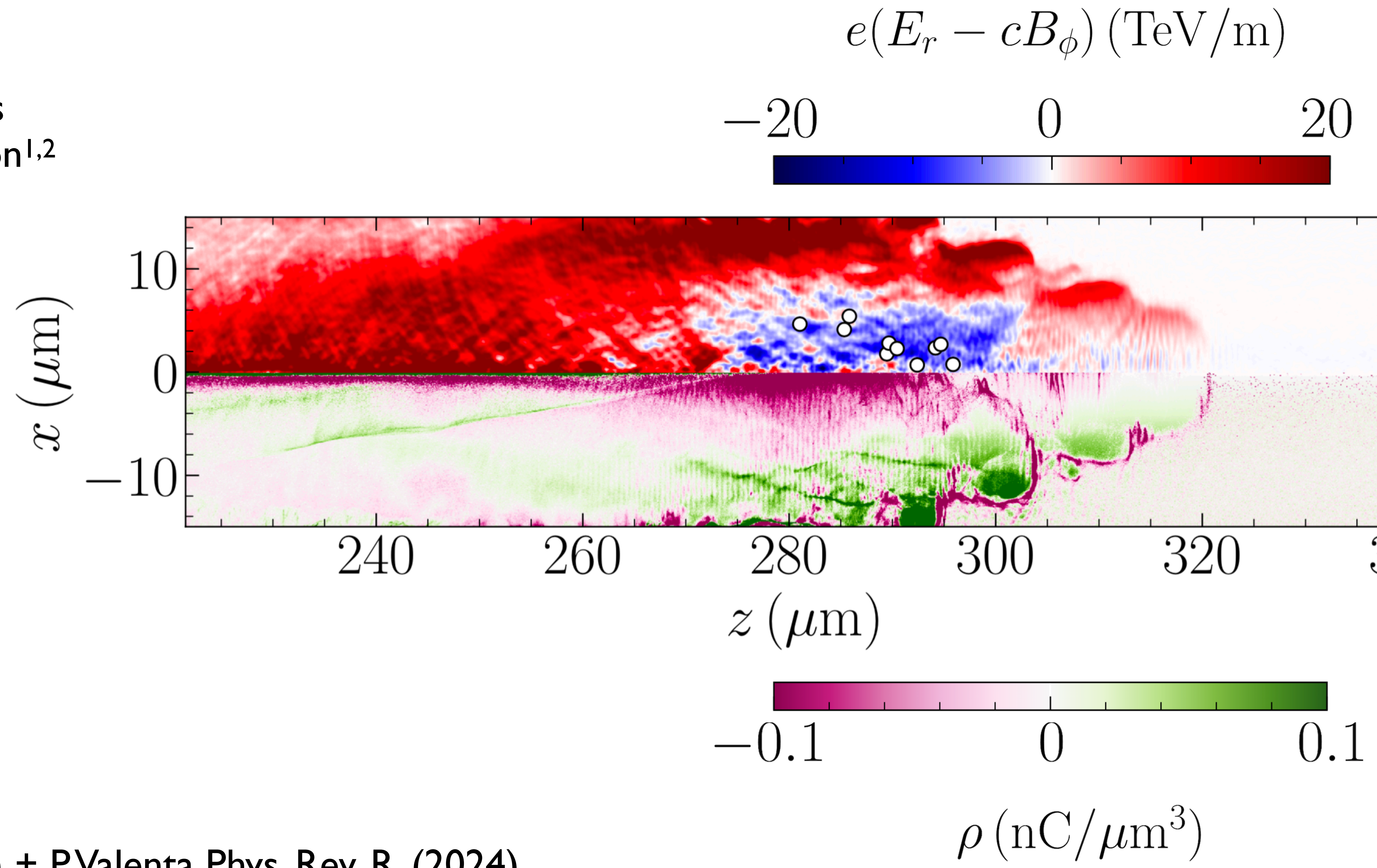
Large e^- density in channel walls
+ ion motion[1,3,4] + radiation reaction[1,2]

↓

Large central e^-beam loading
(**800** nC)

↓

Positron
focusing fields



B. Martinez et al, Phys. Rev. AB (2023) + P. Valenta Phys. Rev. R. (2024)

Direct laser acceleration of positrons takes place in the channel

Positron creation → Positron deflection → Positron acceleration

Consistent simulation of positron creation and acceleration

Laser pulse (red/blue)

$150\,\mathrm{fs}$ duration

Peak amplitude $5 \times 10^{23}\,\mathrm{W/cm^2}$

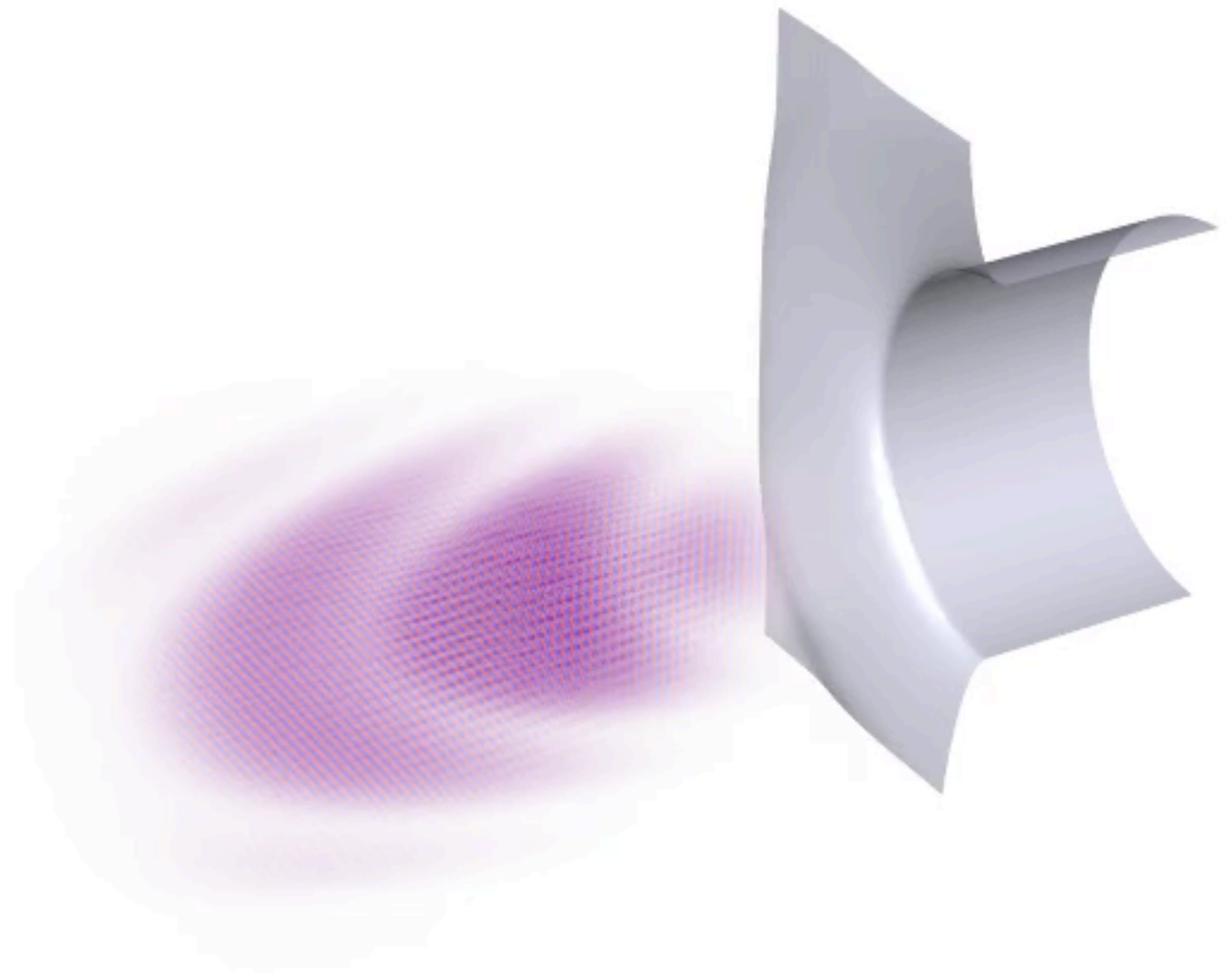
Photon beam

Synchrotron energy profile

Transverse periodic boundary condition

Plasma channel (gray)

Transverse density profile is parabolic



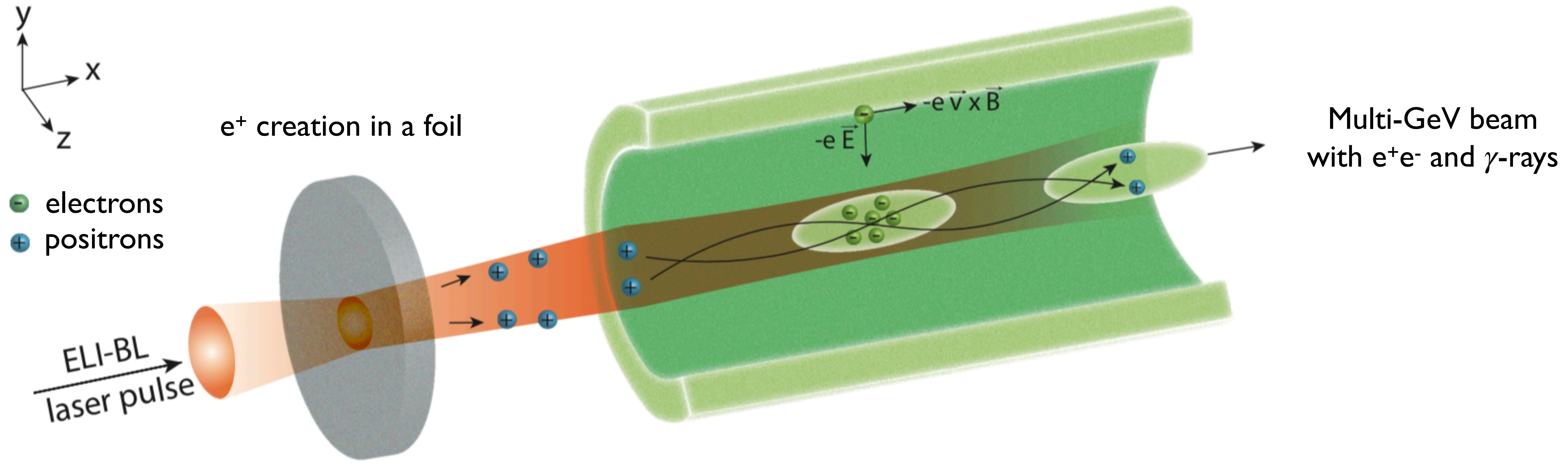
After ~ 400 µm of propagation

$\sim 10^5$ positrons with a $\sim 1\,\mathrm{GeV}$ peaked spectrum

Emittance $\epsilon_{\mathrm{rms}} = 0.5\,\mathrm{mm\,.\,mrad}$

B. Martinez et al, Phys. Rev. AB (2023)

Positrons can also be created by Bethe-Heitler and accelerated



~10x better e+ retention for a target in the middle of the plasma

B. Martinez et al, Phys. Rev. E (2025)
L. Inigo-Gamiz et al, PPCF (2025)

Contents

What does the radiation look like?

Why consider DLA-based radiation sources?

Radiation generation

High energy density

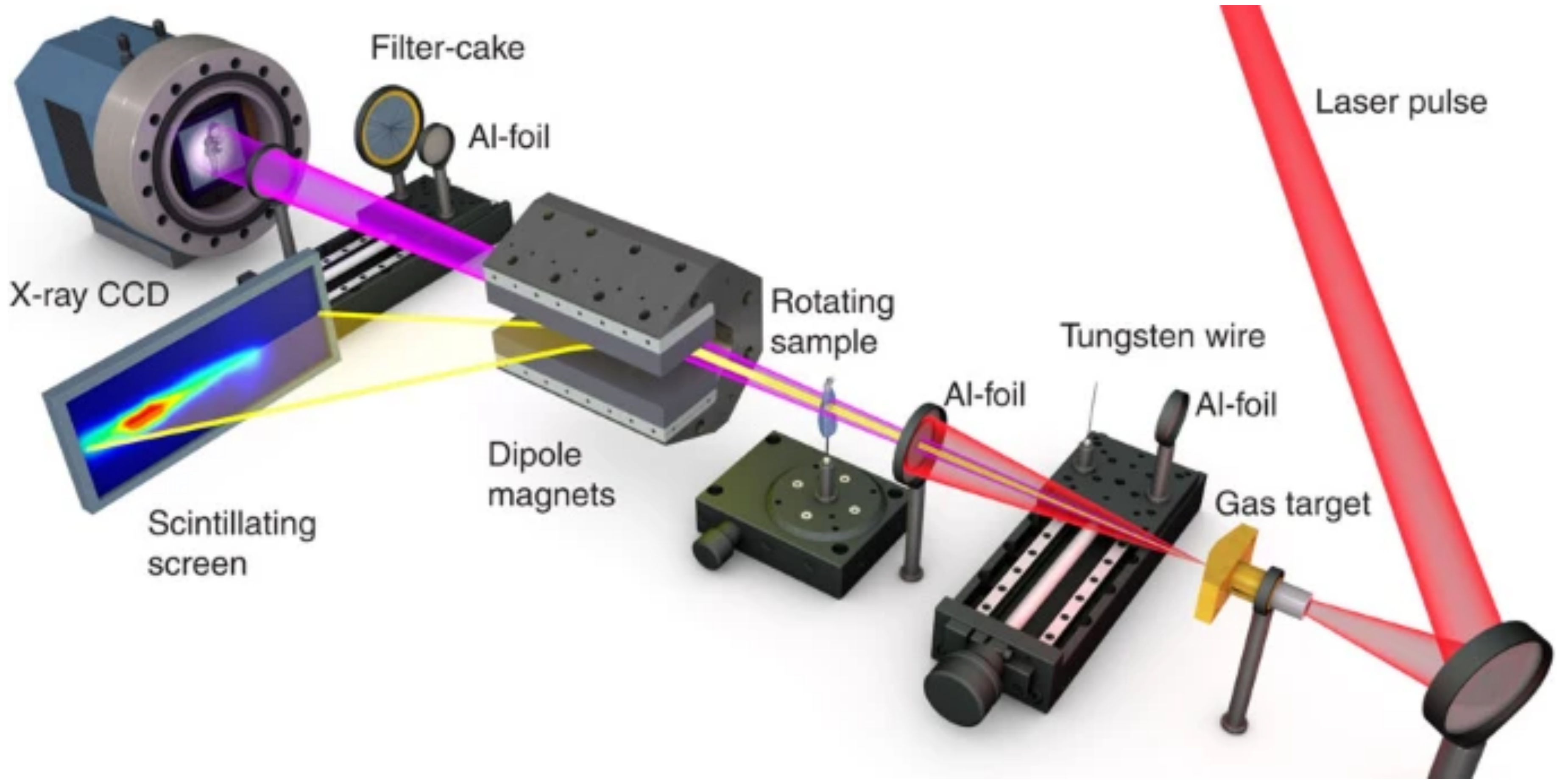
Small source size

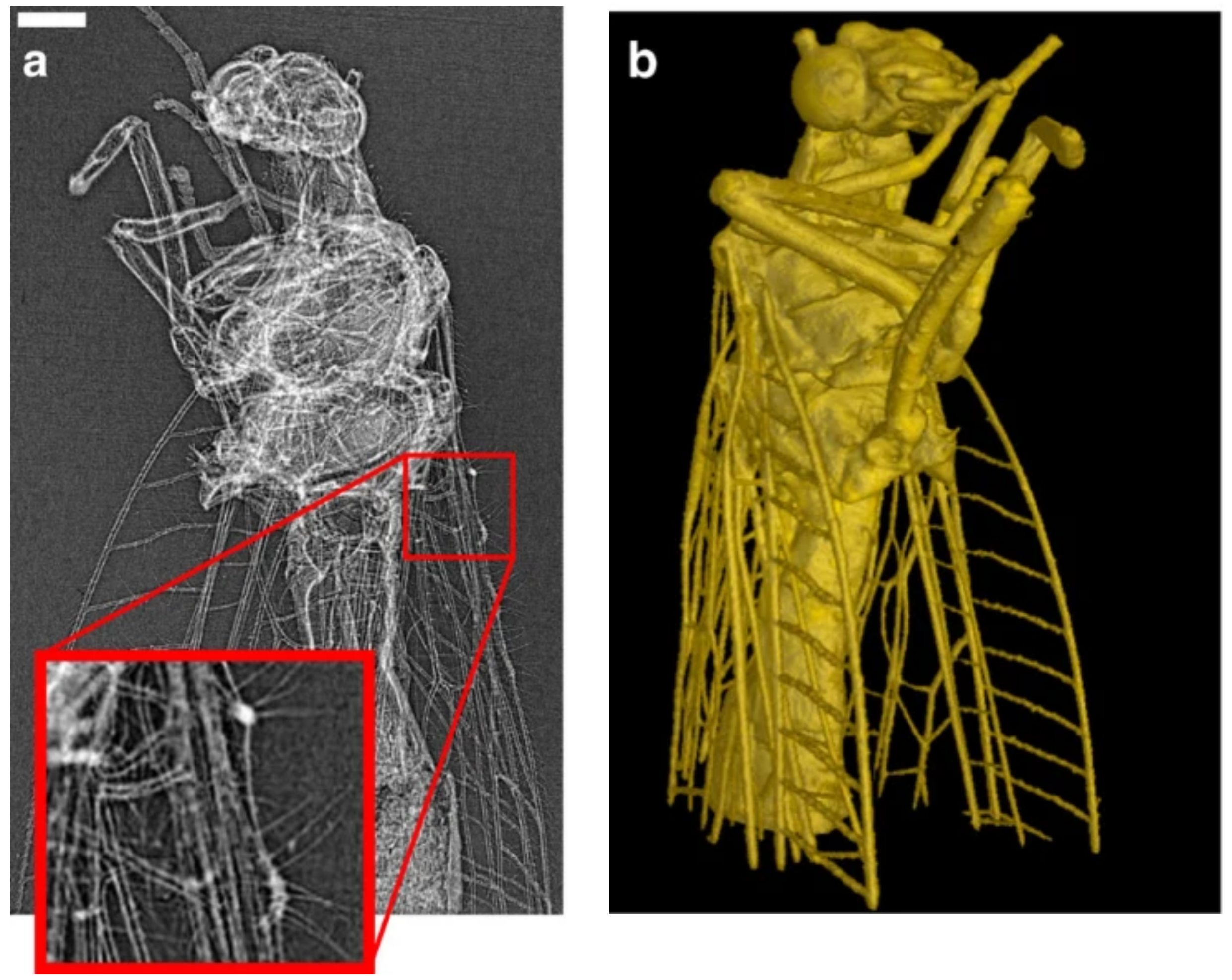
Compactness

Broad wavelength range

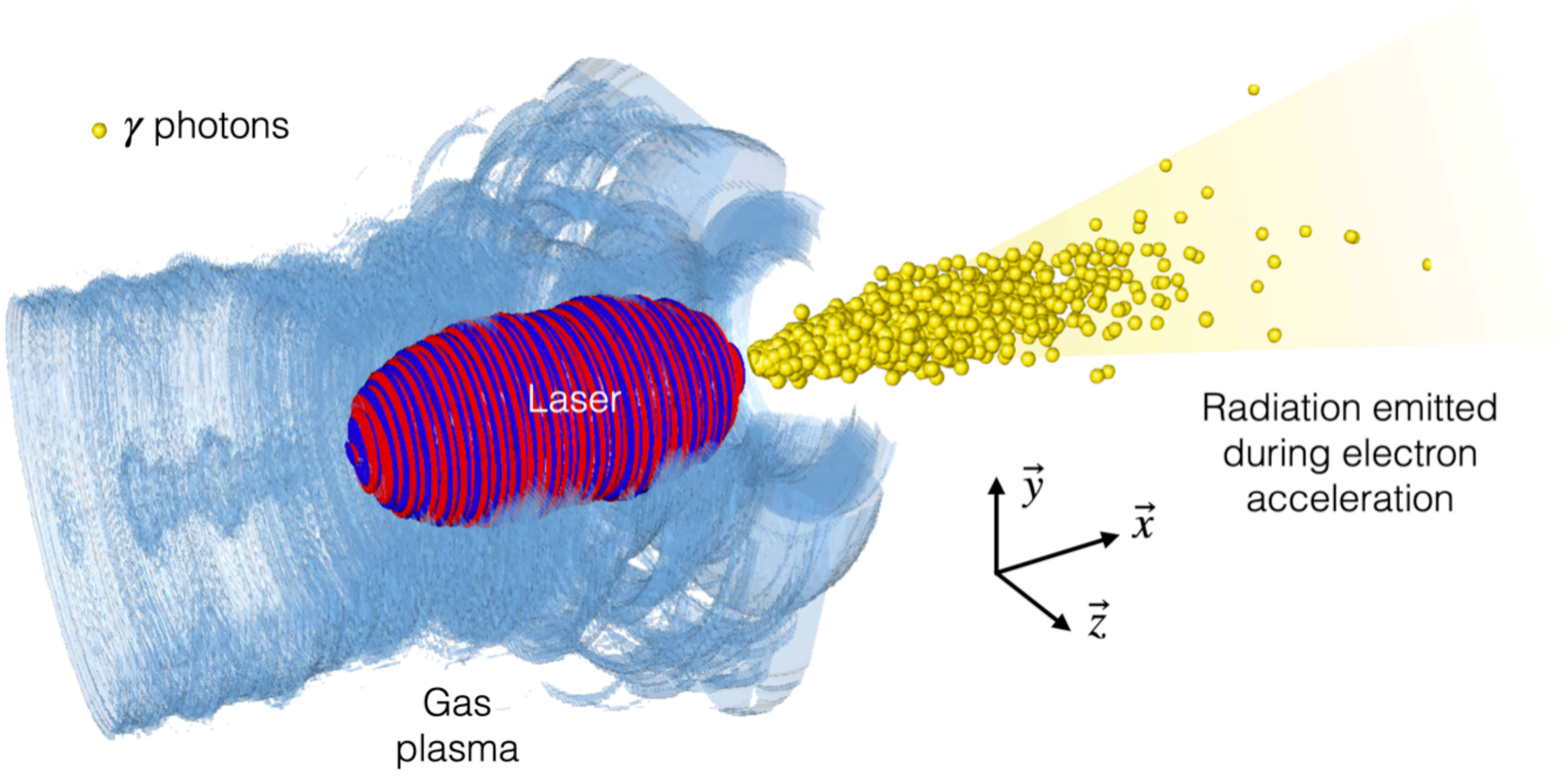
High brightness

Versatility





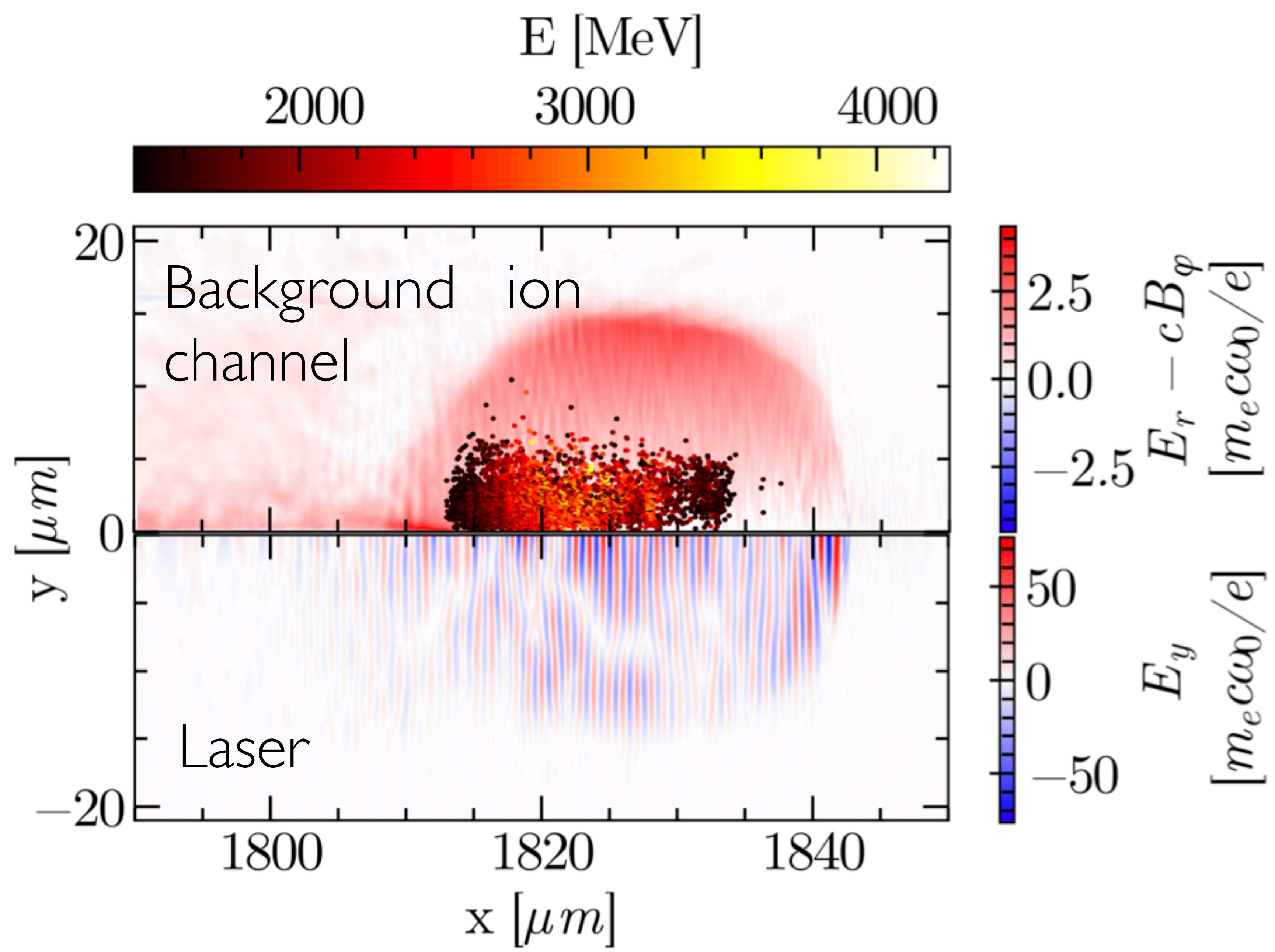
Accelerated electrons emit in the background channel field



While electrons are accelerated by the laser, they perform betatron oscillations transversely to the laser propagation direction. Radiation is emitted in well collimated in the forward direction.

Electric fields acting on electrons

Despite lower field amplitude, background channel field is a dominant source of radiation emitted by accelerated electrons and defines radiation properties such as critical frequency, yield and collimation



R. Babjak et al., arXiv:2502.06744 (submitted)

Radiation properties can be experimentally controlled

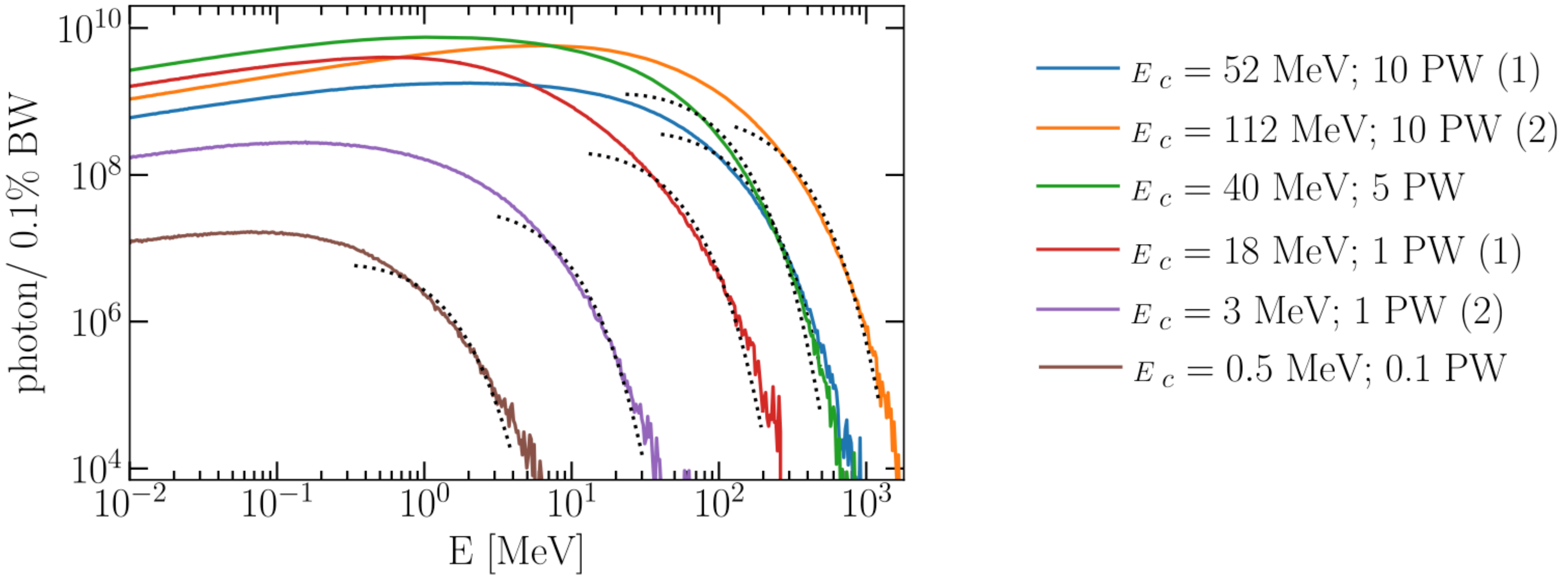
Laser intensity controls spectrum

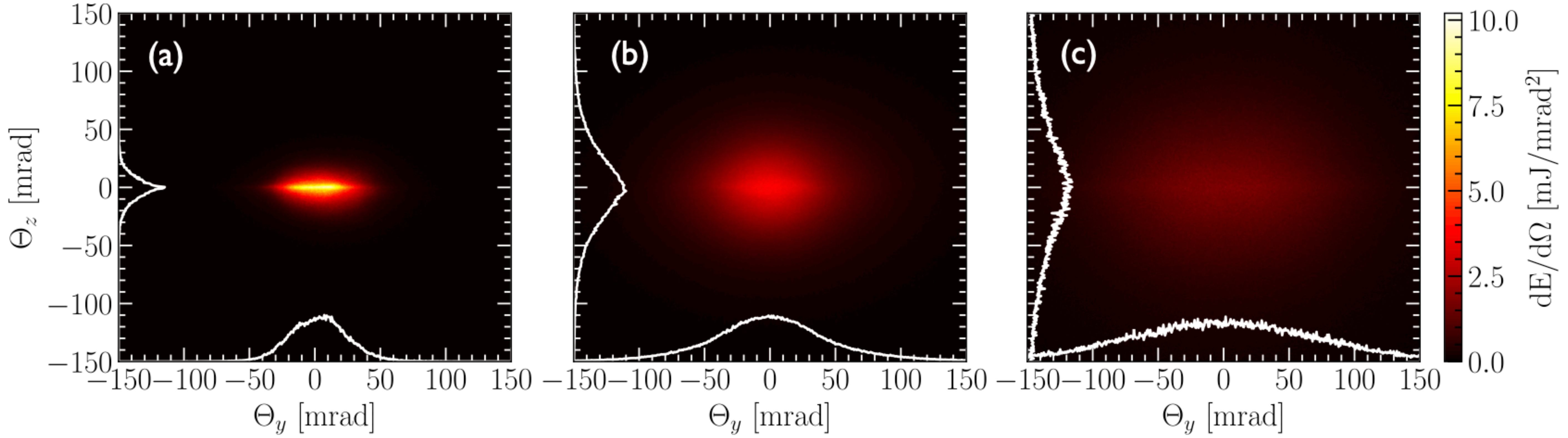
Higher laser intensity can lead to high energy of accelerated electrons, which results in higher frequency of emitted radiation ($E_c \sim \gamma^2$)

$$E_c\ [\mathrm{eV}] \simeq \frac{2.1}{\lambda[\mu\mathrm{m}]}\left(\frac{a_0}{\varepsilon_{cr}}\right)^3$$

Background density also increases frequency of emitted radiation, but lower density results in more collimated radiation

$$\Theta = \left(\frac{n_e\varepsilon_{cr}}{n_c a_0}\right)^{1/3}$$





0.01 n_c 0.05 n_c 0.2 n_c

Background plasma density n_e

R. Babjak et al., arXiv:2502.06744 (submitted)

Brilliance as high as in betatron sources, for 10-1000x higher photon energy

Number of photons: $10^7 - 10^9$ / 0.1% BW
Divergence : ~ 10 mrad
Source size: < 10 μm
Source duration: tens of fs

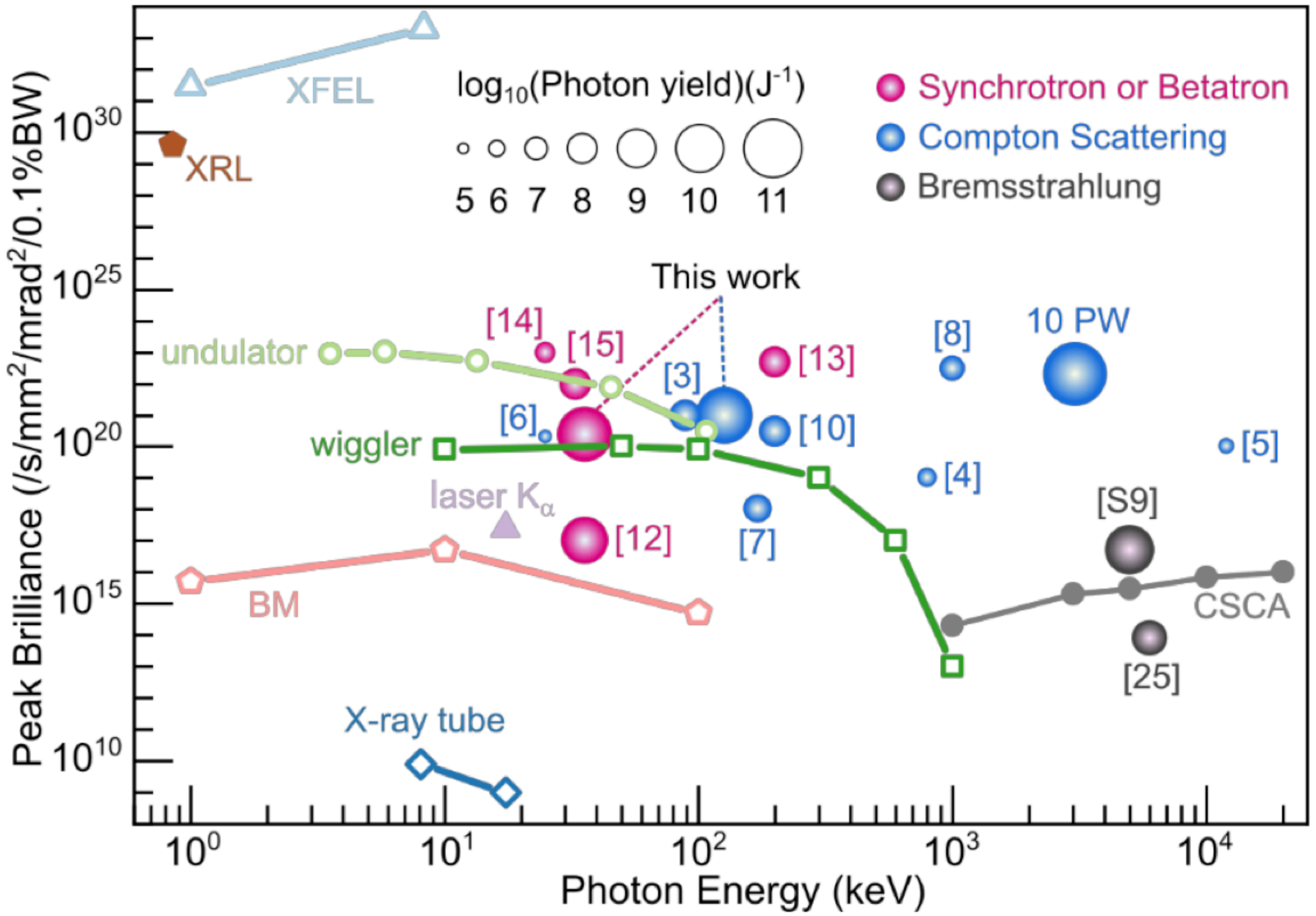


Figure adjusted from Y. Shou et al., Nat. Photonics (2023)

R. Babjak et al, to be submitted (2024)

Brilliance as high as in betatron sources, for 10-1000x higher photon energy

TÉCNICO LISBOA

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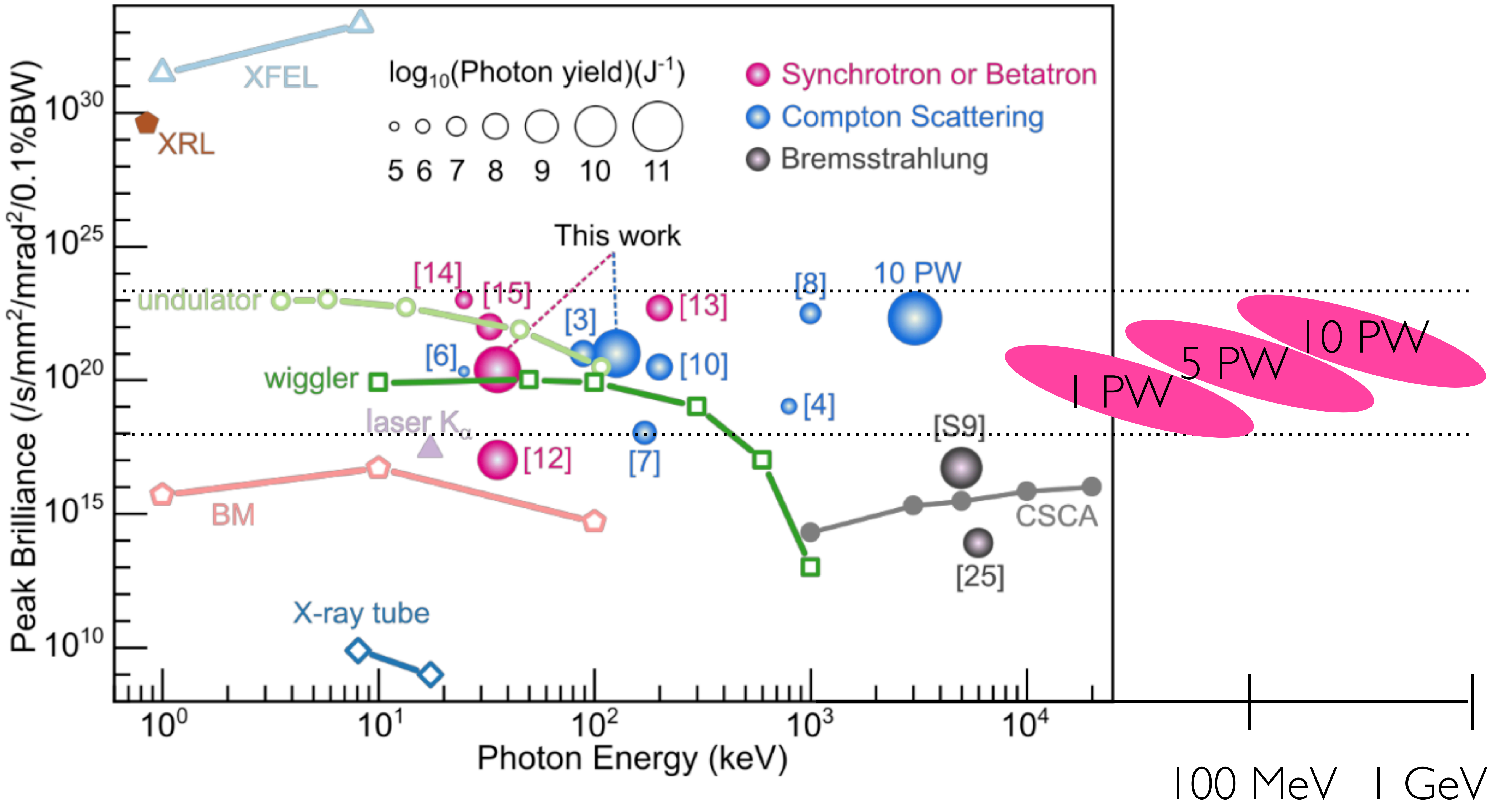


Figure adjusted from Y. Shou et al., Nat. Photonics (2023)

High brilliance made possible

High electron energies ensure low divergence of electrons and consequently photons.

High number of accelerated electrons (> 100 nC) ensures that more photons are radiated.

R. Babjak et al, to be submitted (2024)

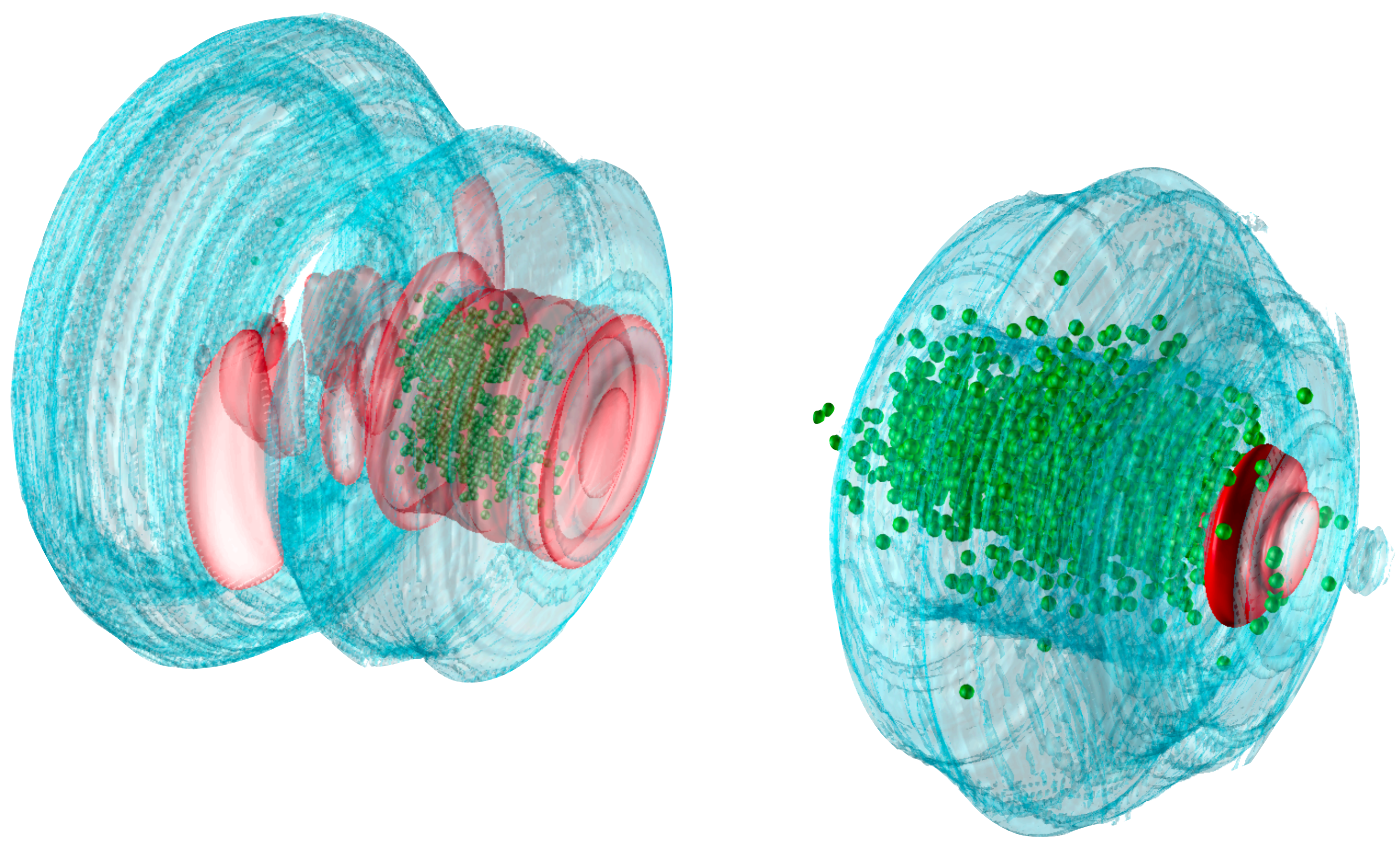
Thank you!

Direct laser acceleration can provide high-charge (> 100 nC), broadband multi-GeV electron beams.

We can optimize the acceleration for a given plasma density. Density tailoring allows to reduce acceleration distance and mitigate RR limit.

Positrons can be created and accelerated by DLA in a single stage with the same laser (e.g. ELI L4).

Direct laser acceleration process can provide high-brilliance gamma-ray beams.



Next steps:

Using DLA + BH can give additional radiation, pairs and muons. Also, DLA beams can be used for seeding QED cascades.