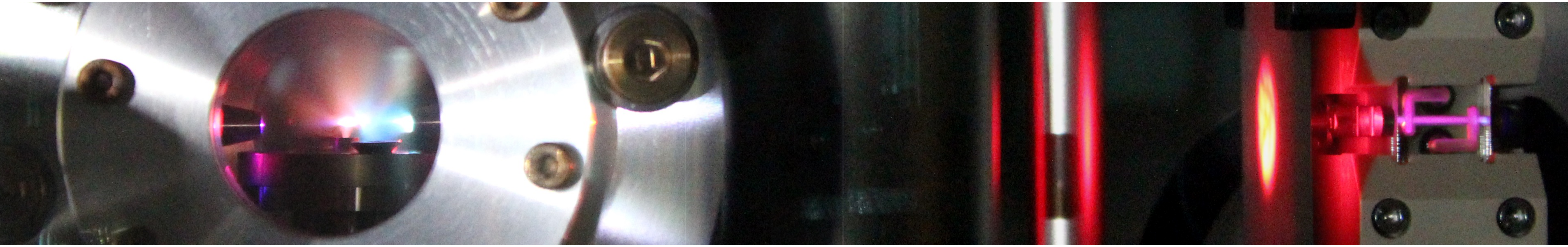


INTRODUCTION TO LASER-PLASMA-ACCELERATOR-DRIVEN ELECTRON SOURCES

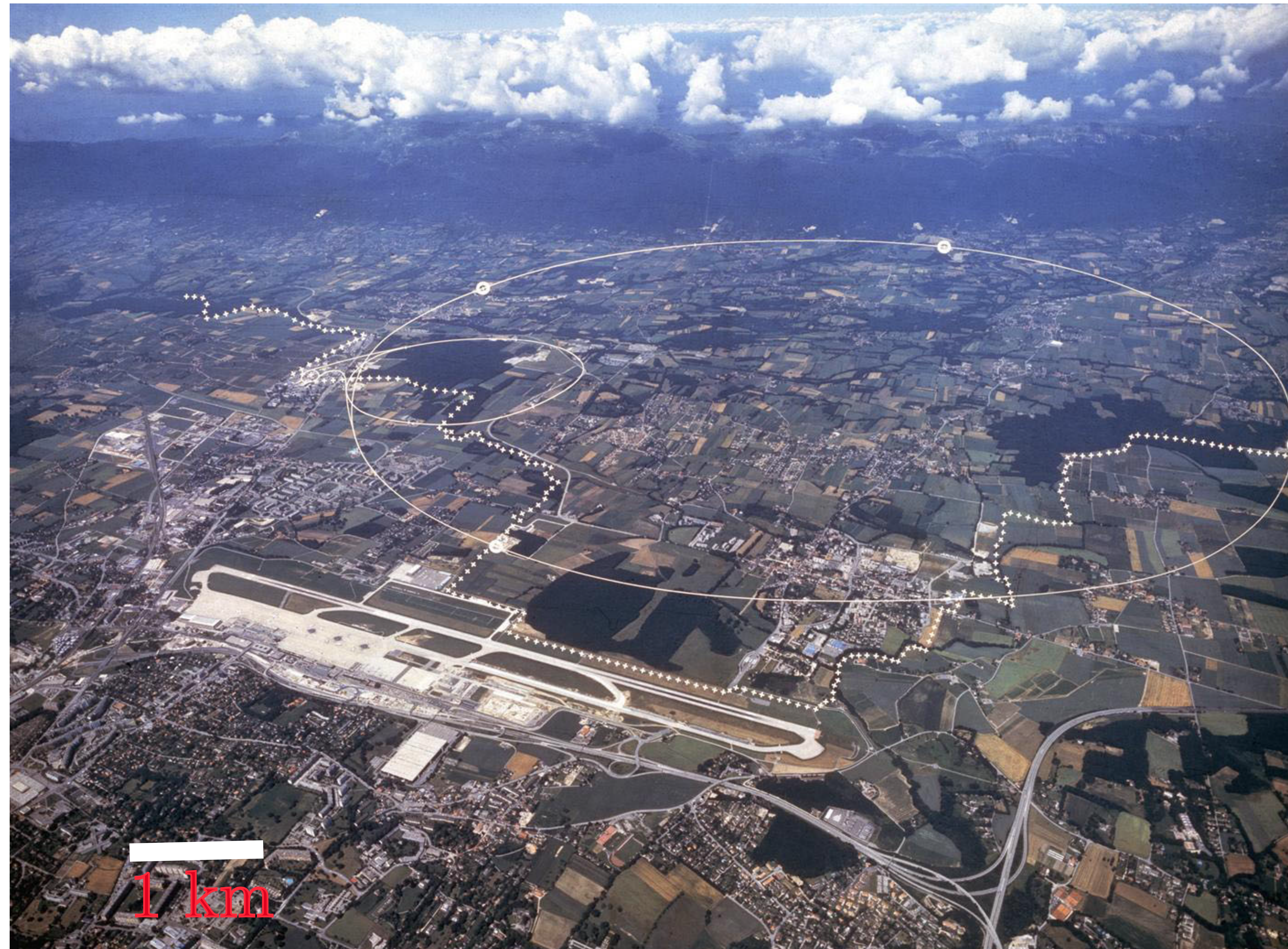
Dr Kristjan Põder

Subgroup Leader Laser Plasma Accelerators and Applications
kristjan.poder@desy.de
Deutsches Elektronen-Synchrotron DESY, Machine Division, Hamburg, Germany

Accelerator Research and Development, Matter and Technologies
Helmholtz Association of German Research Centres, Berlin, Germany

Particle accelerators are an integral part of modern physics

So-called "Discovery machines" are widely used outside science, too!



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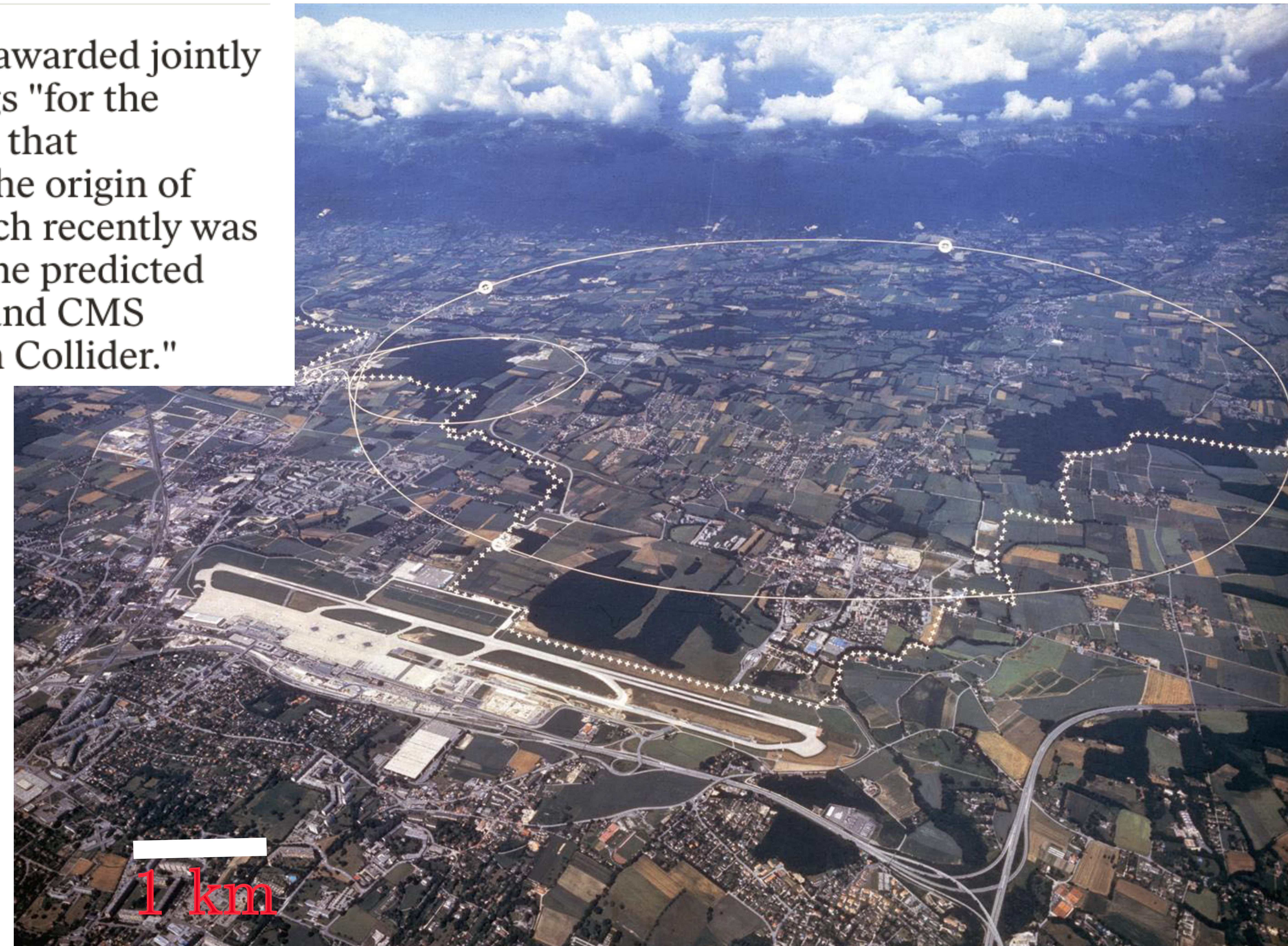

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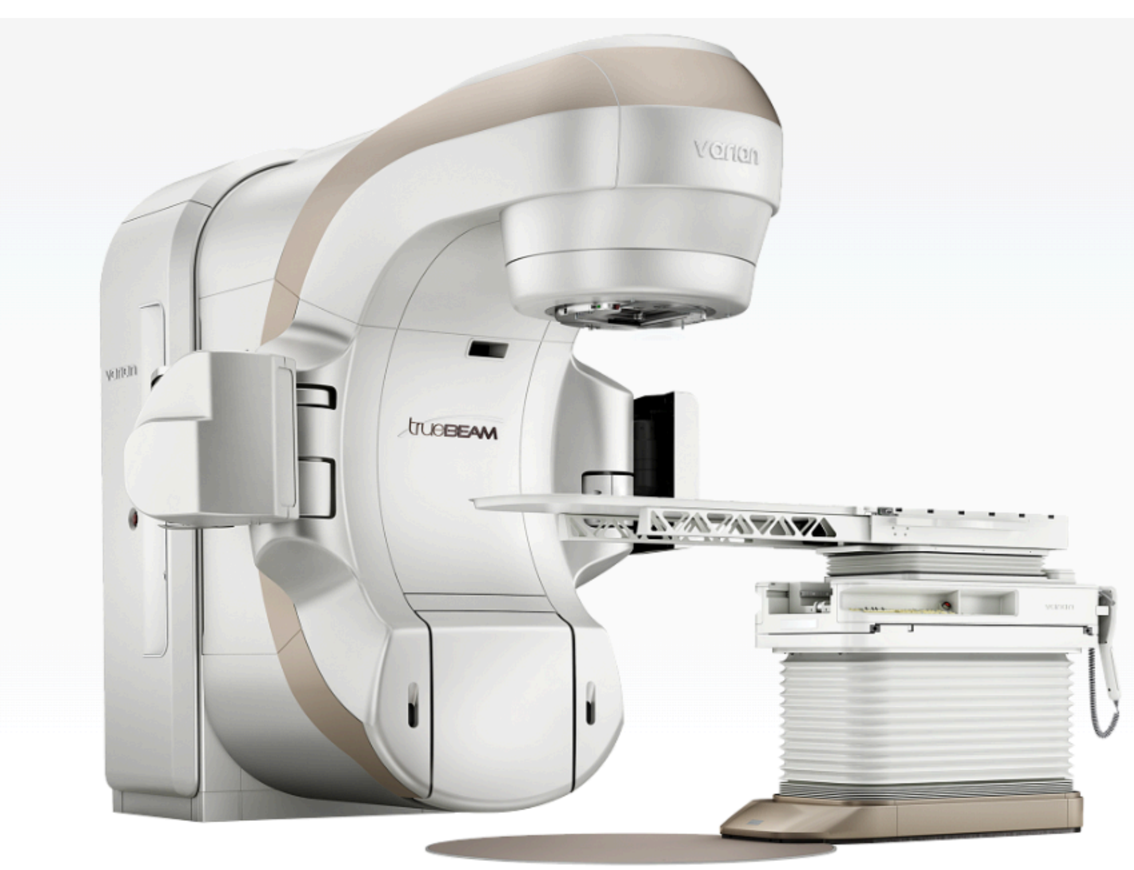

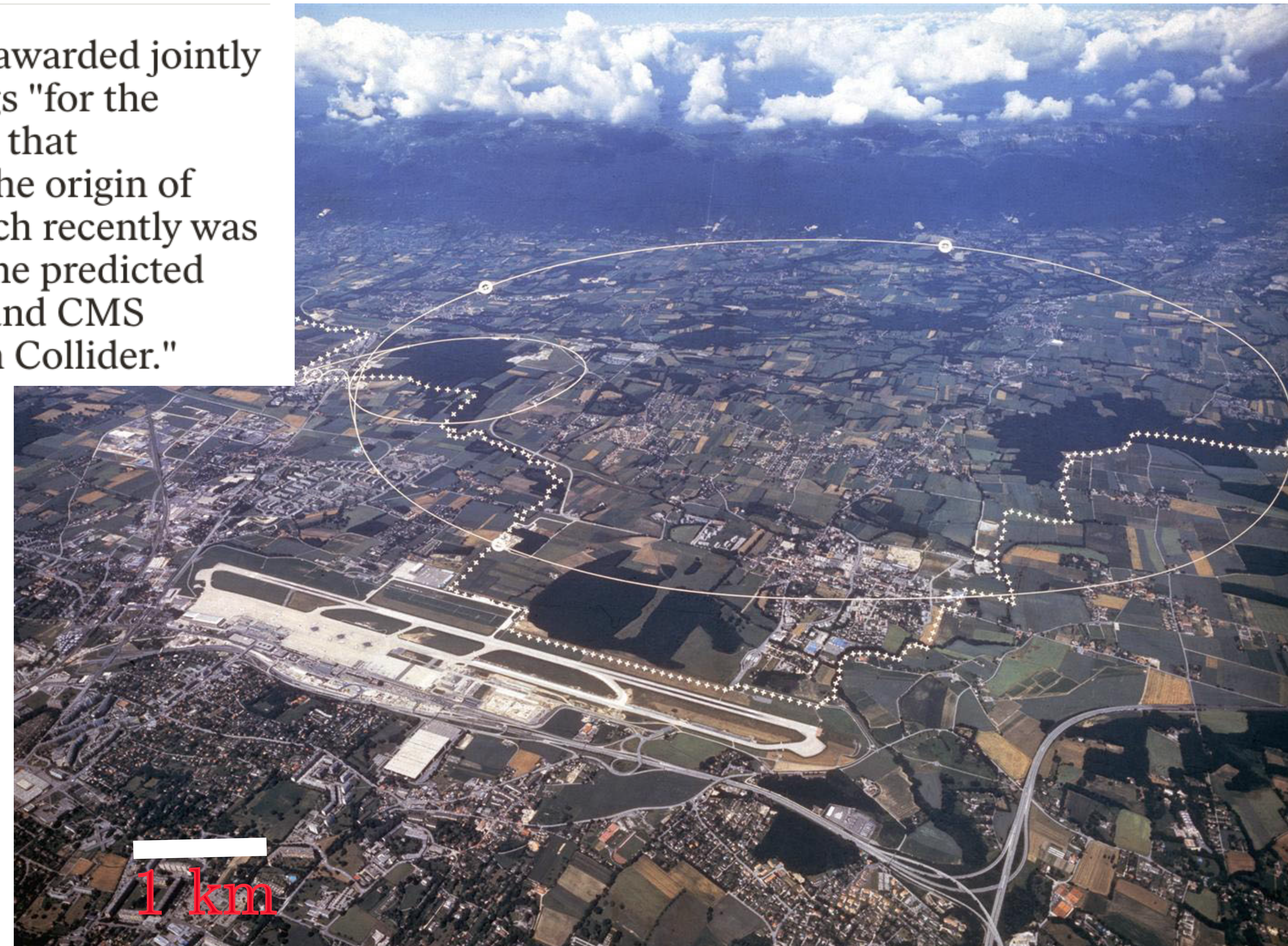

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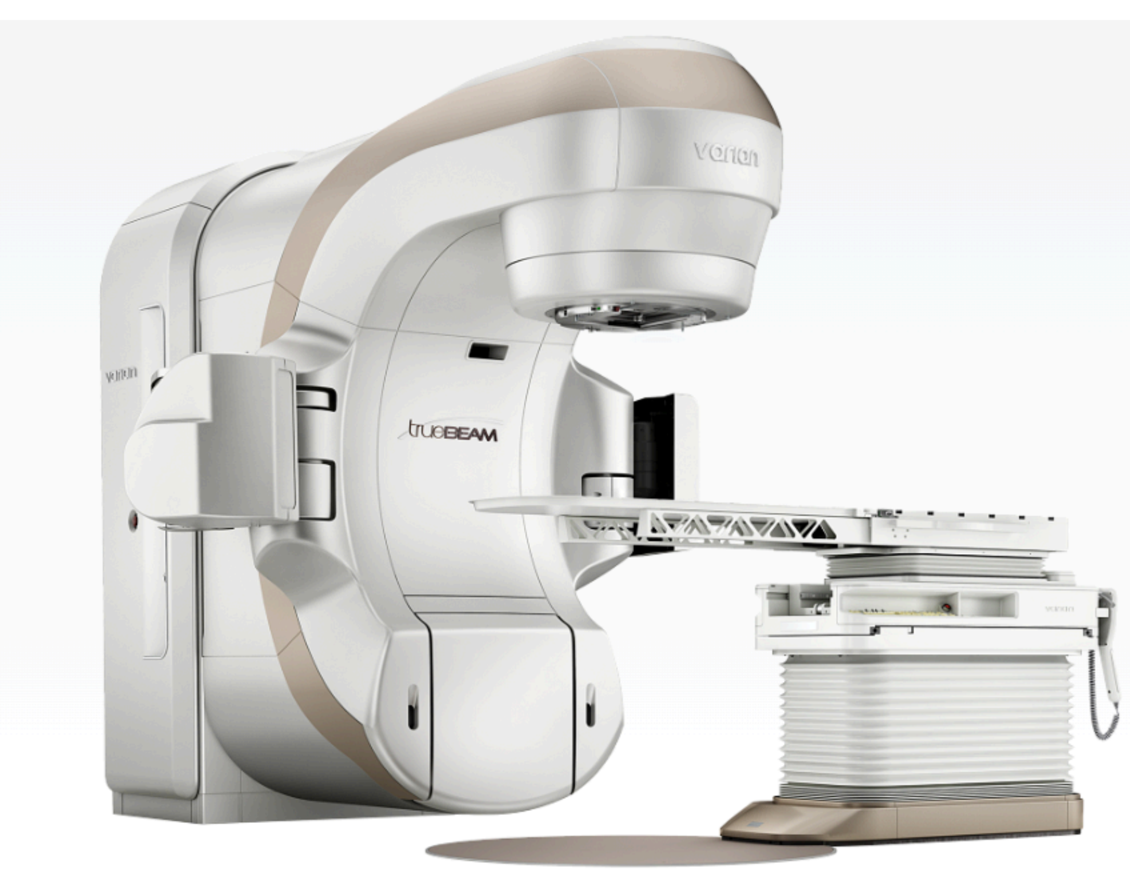

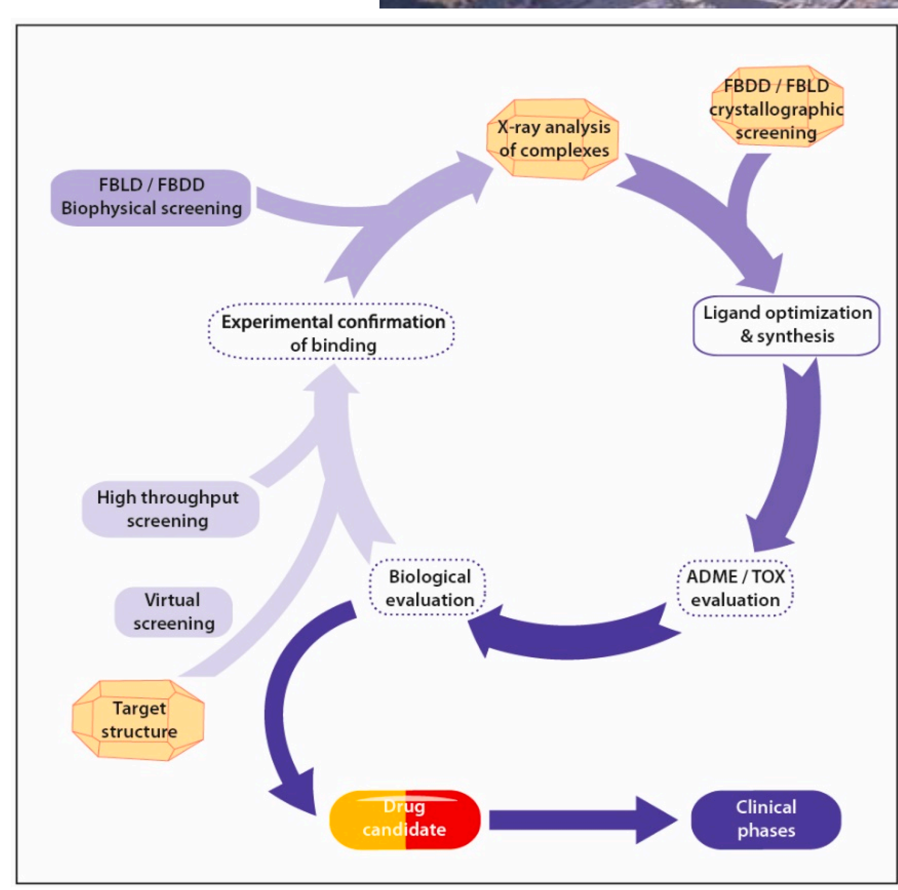

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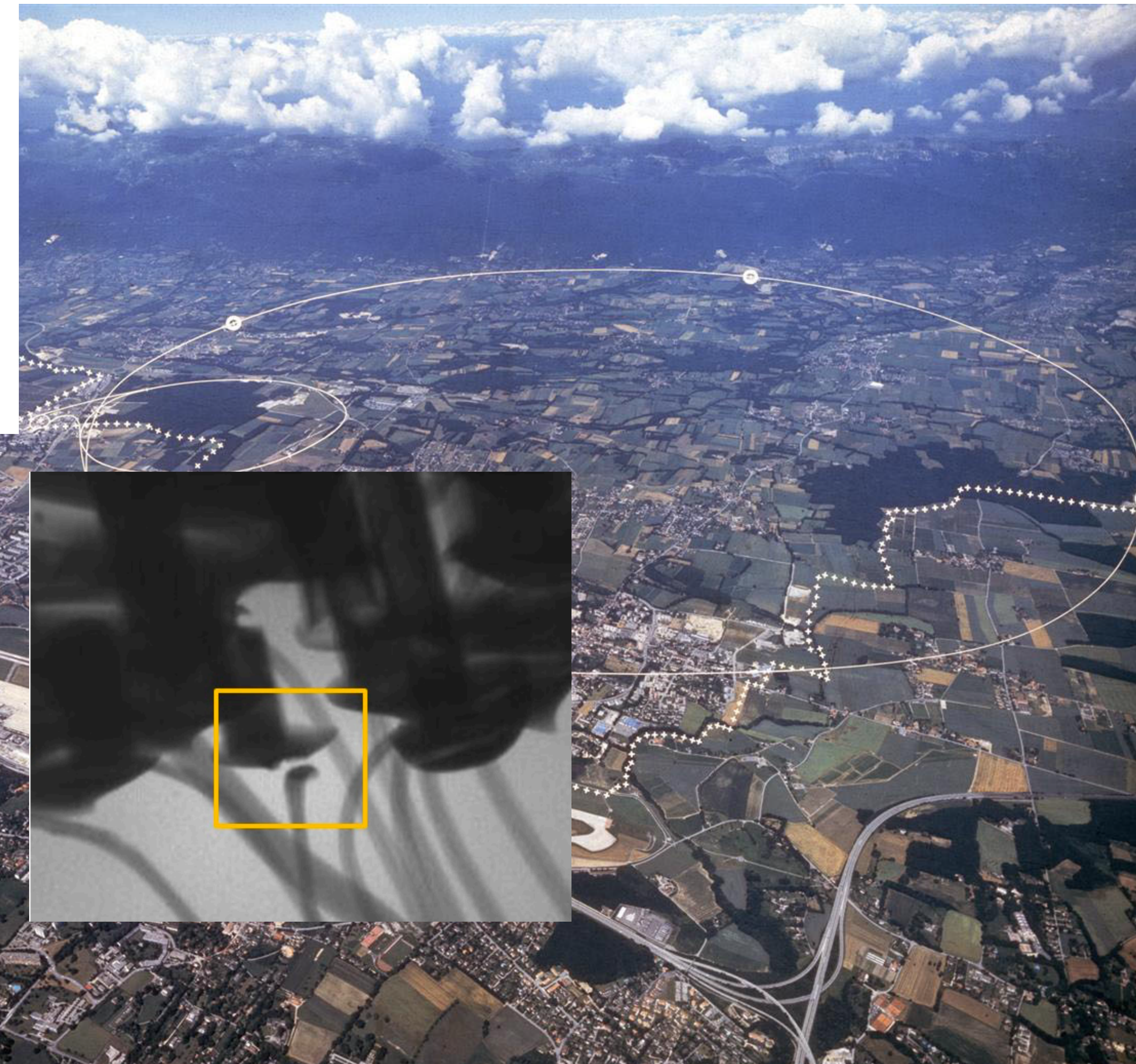

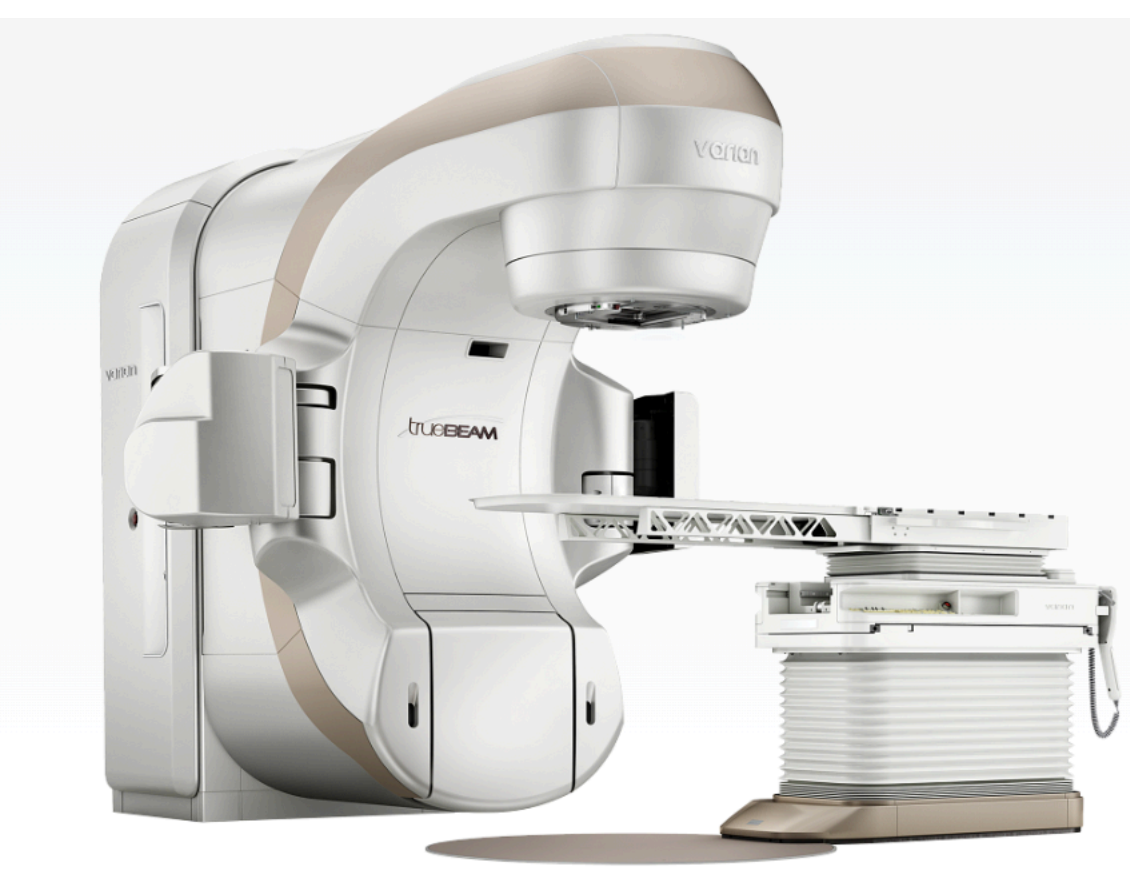

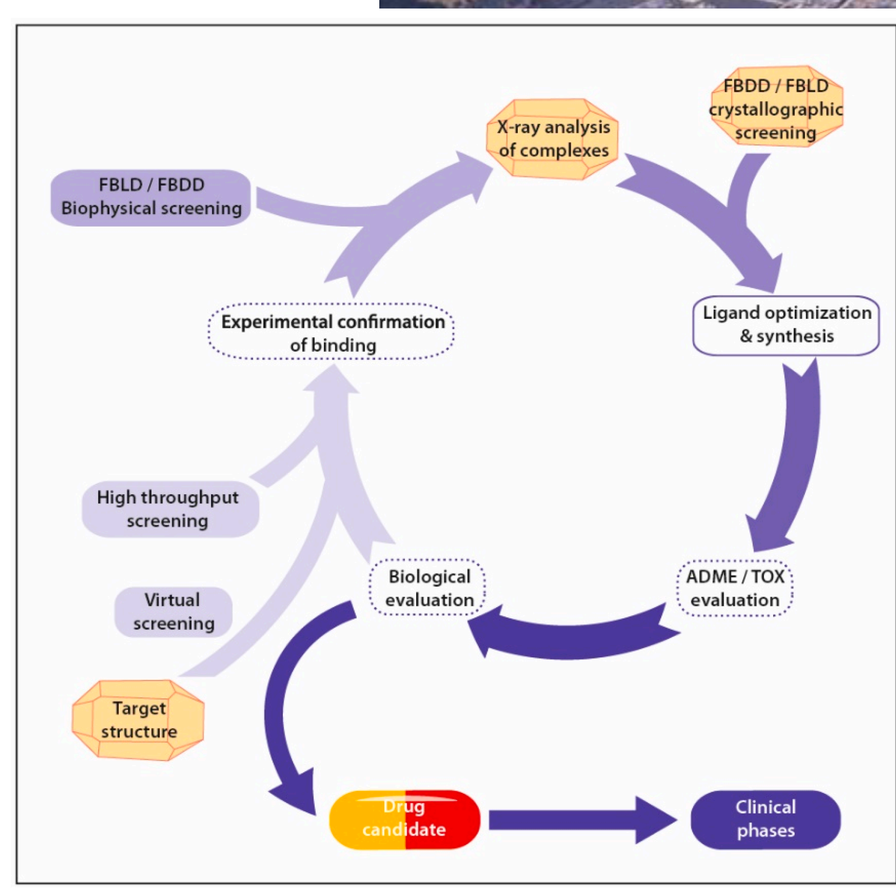

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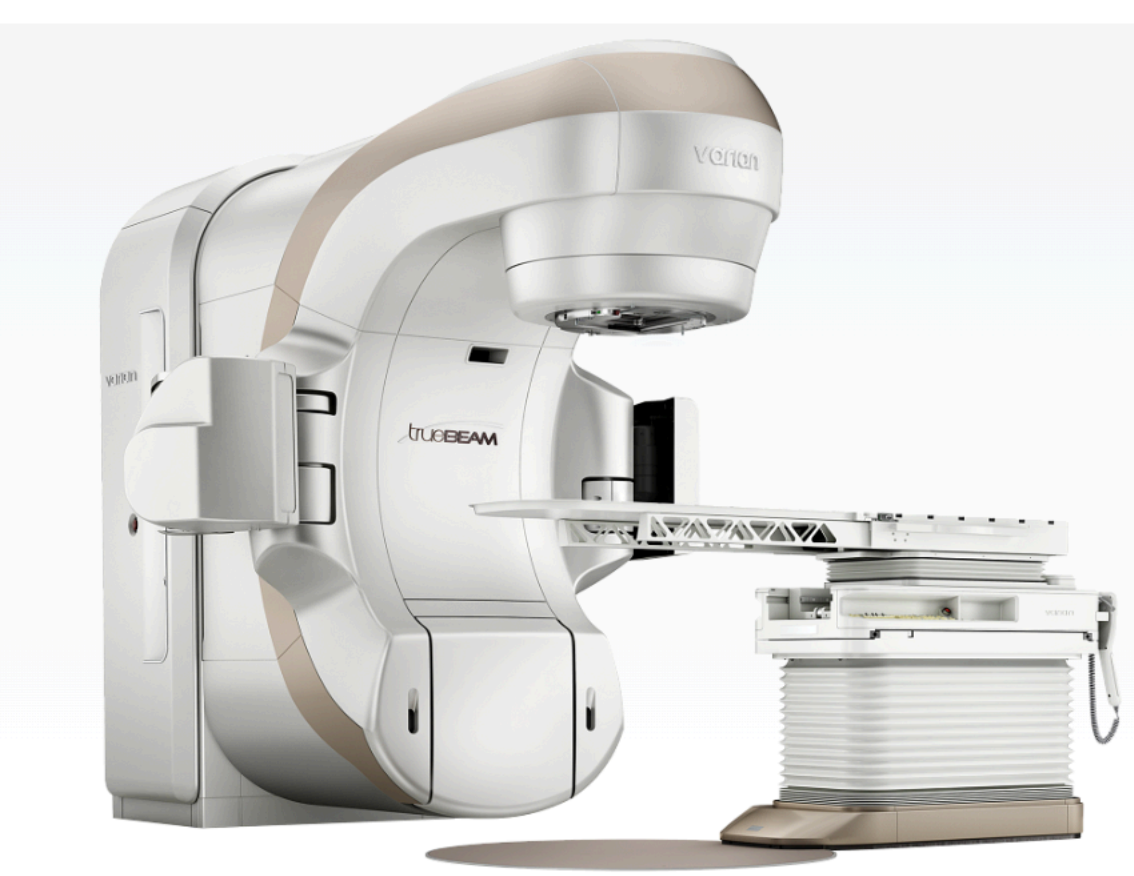

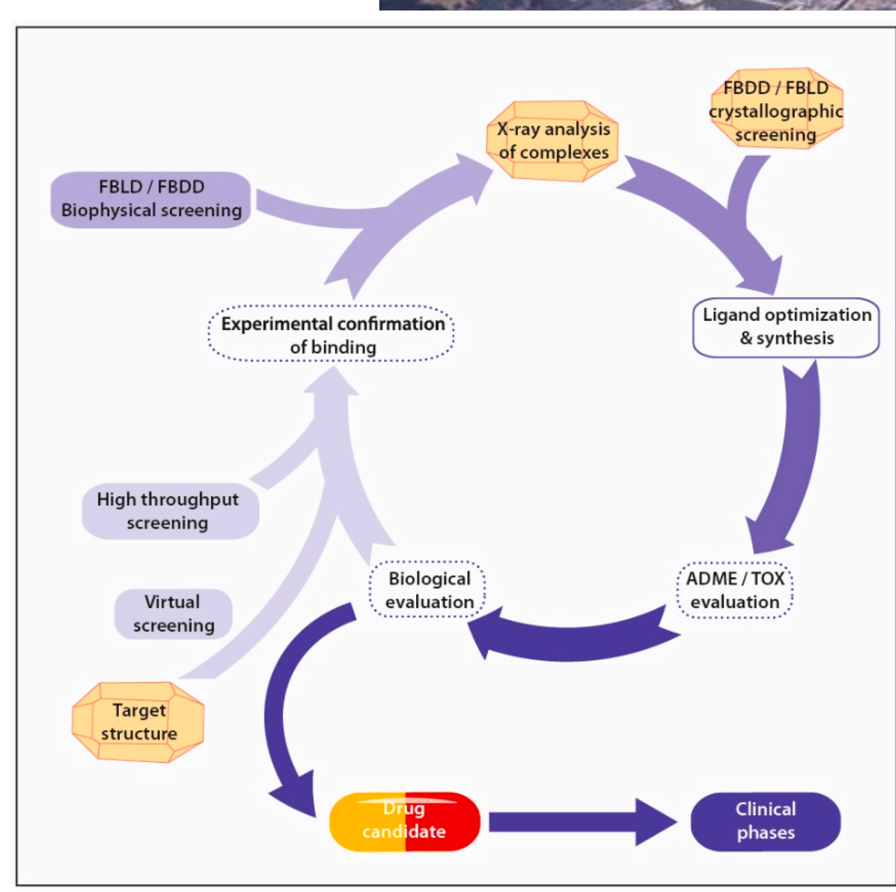

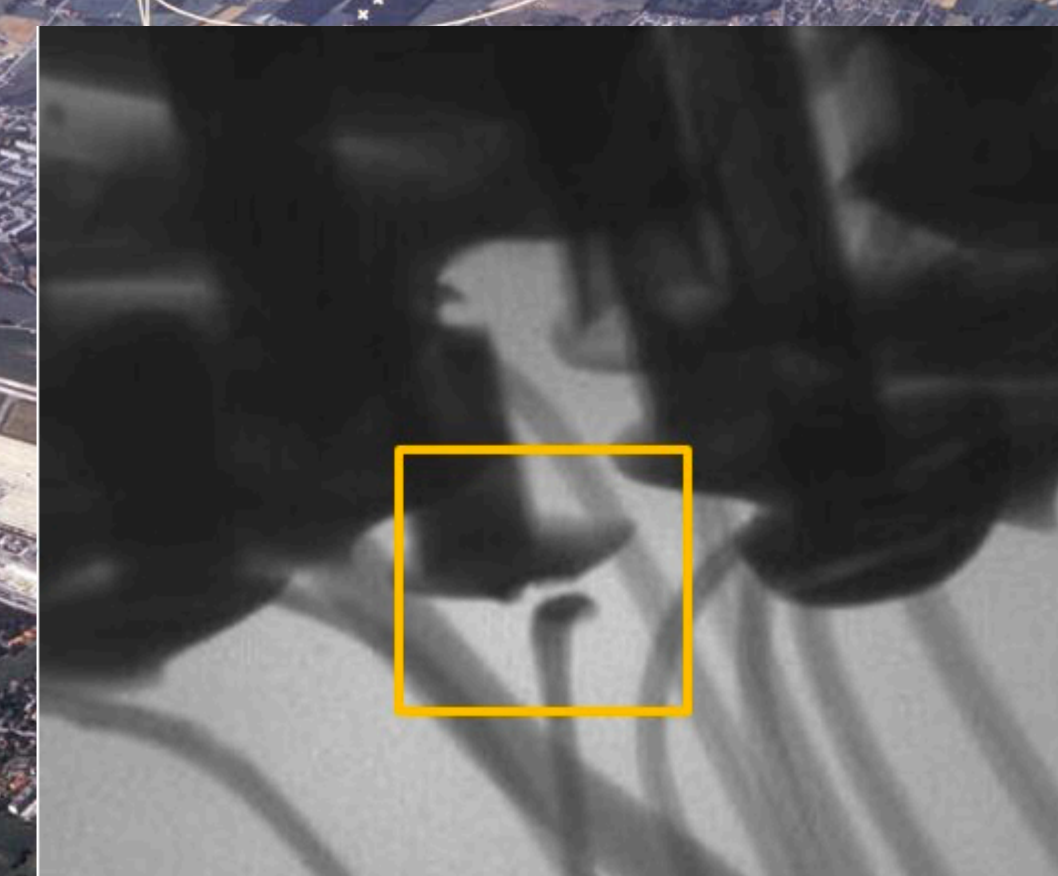

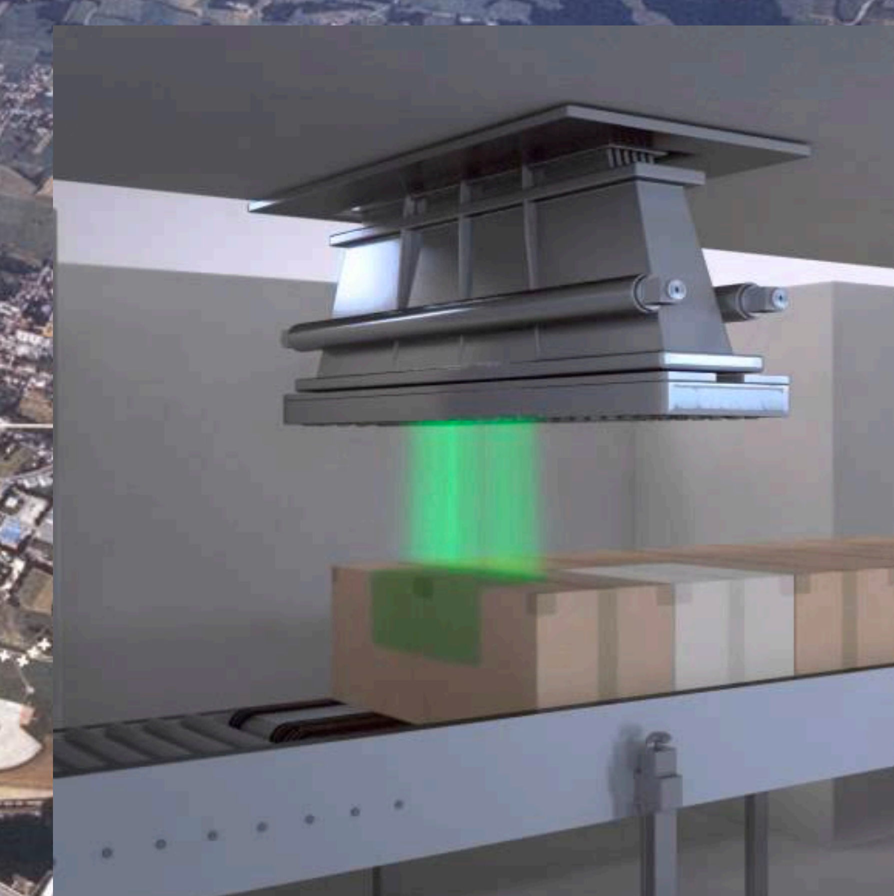

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Acceleration gradient limit leads to some ‘interesting’ ideas

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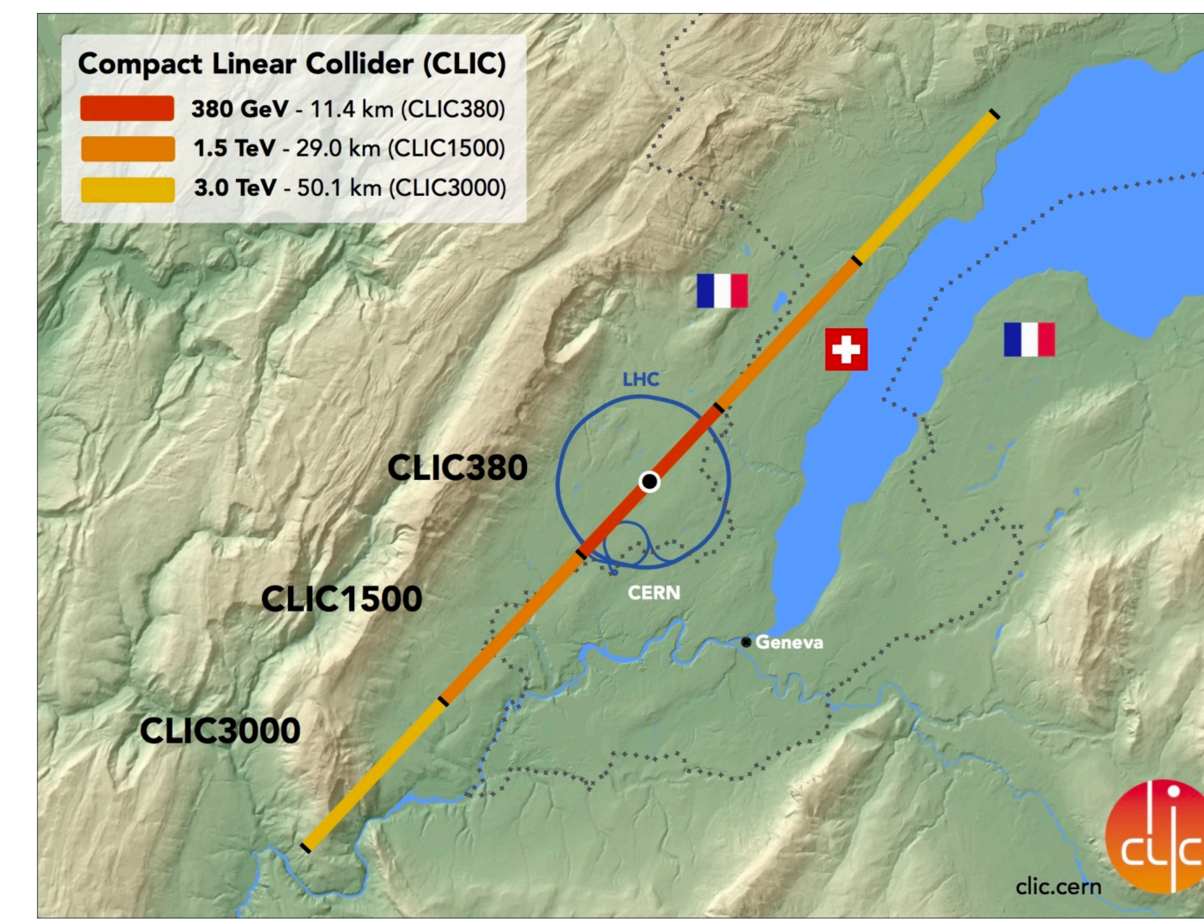

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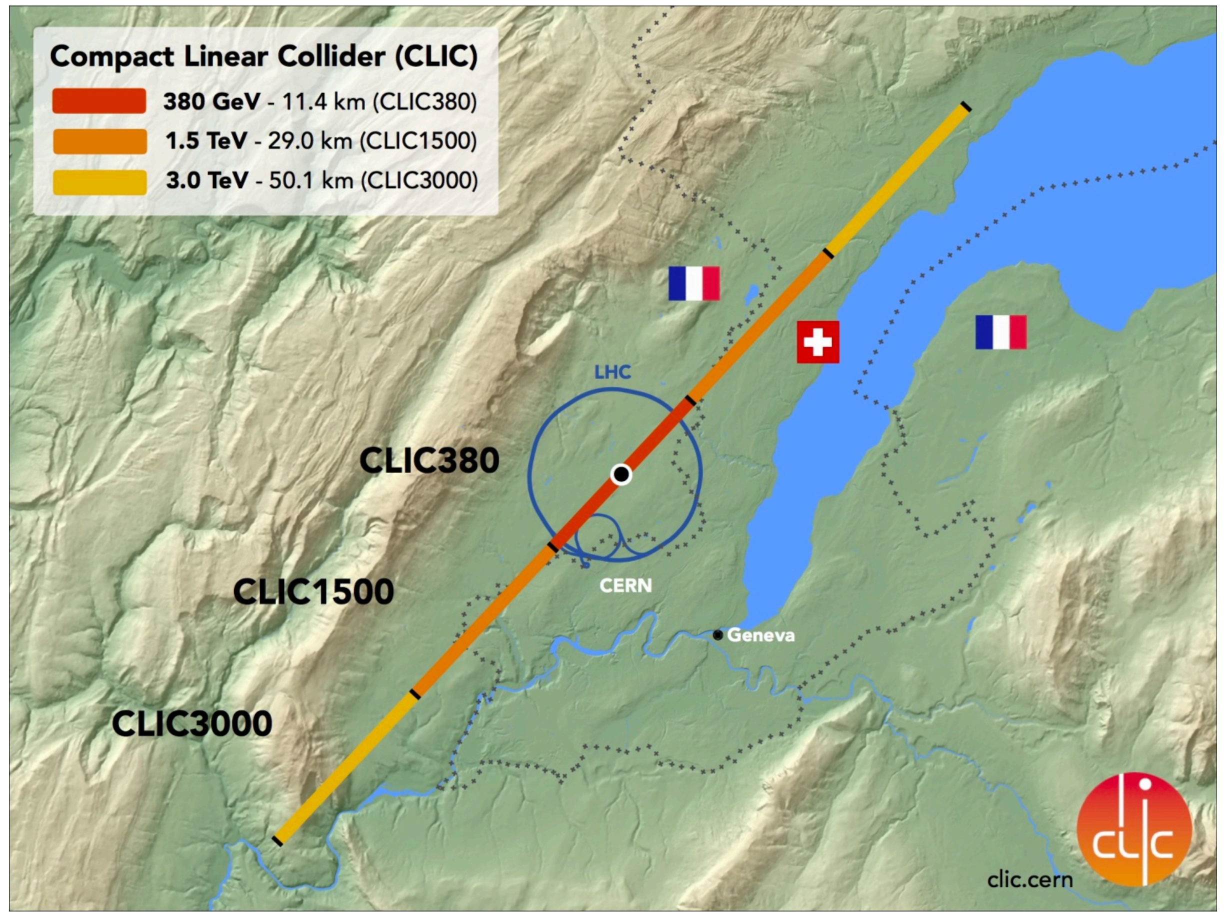

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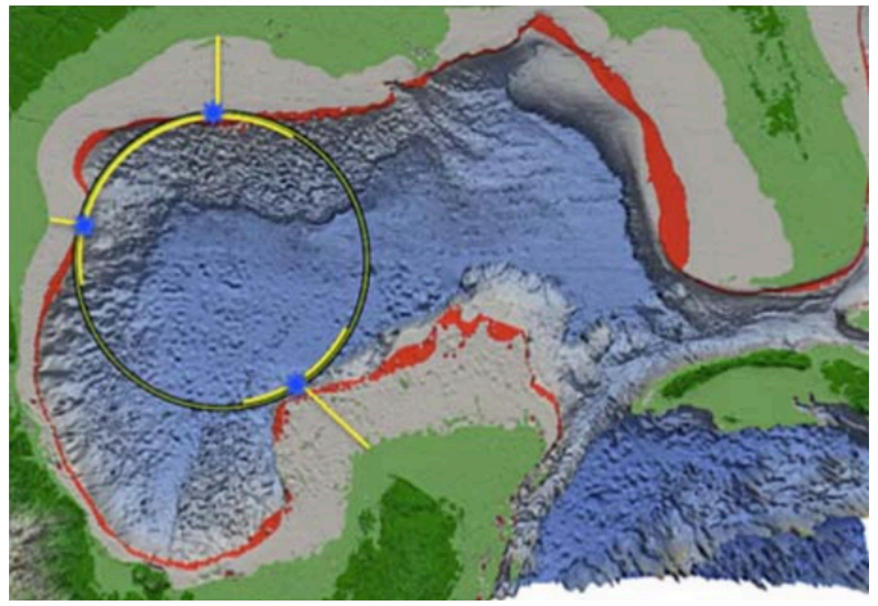

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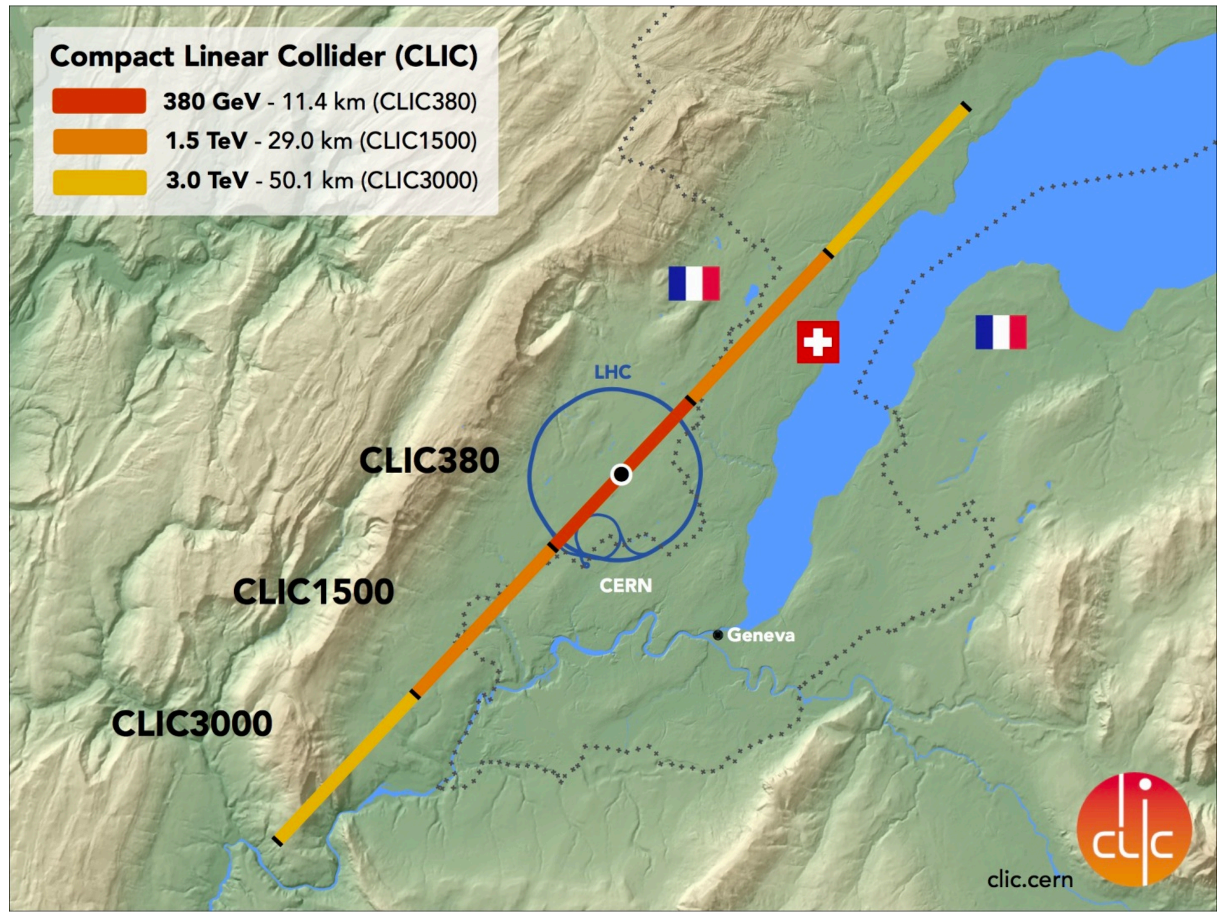

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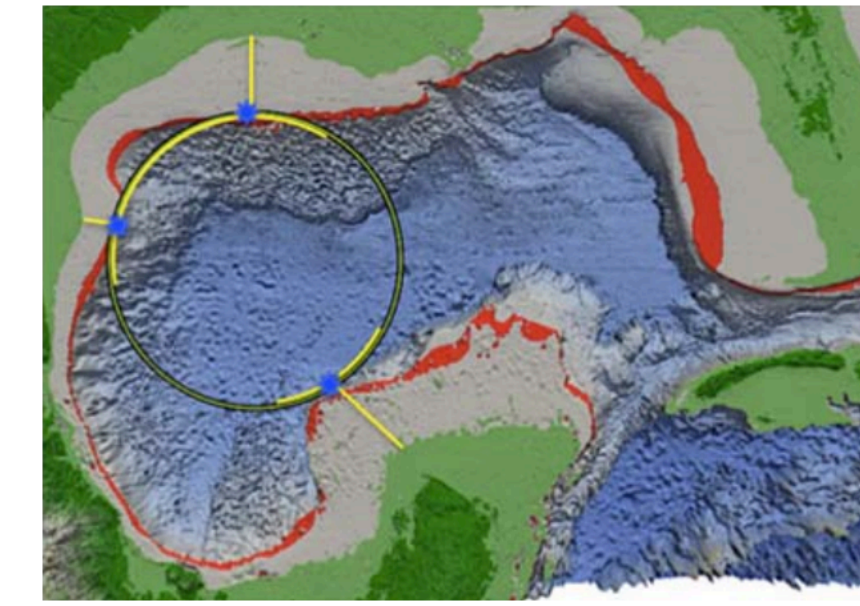

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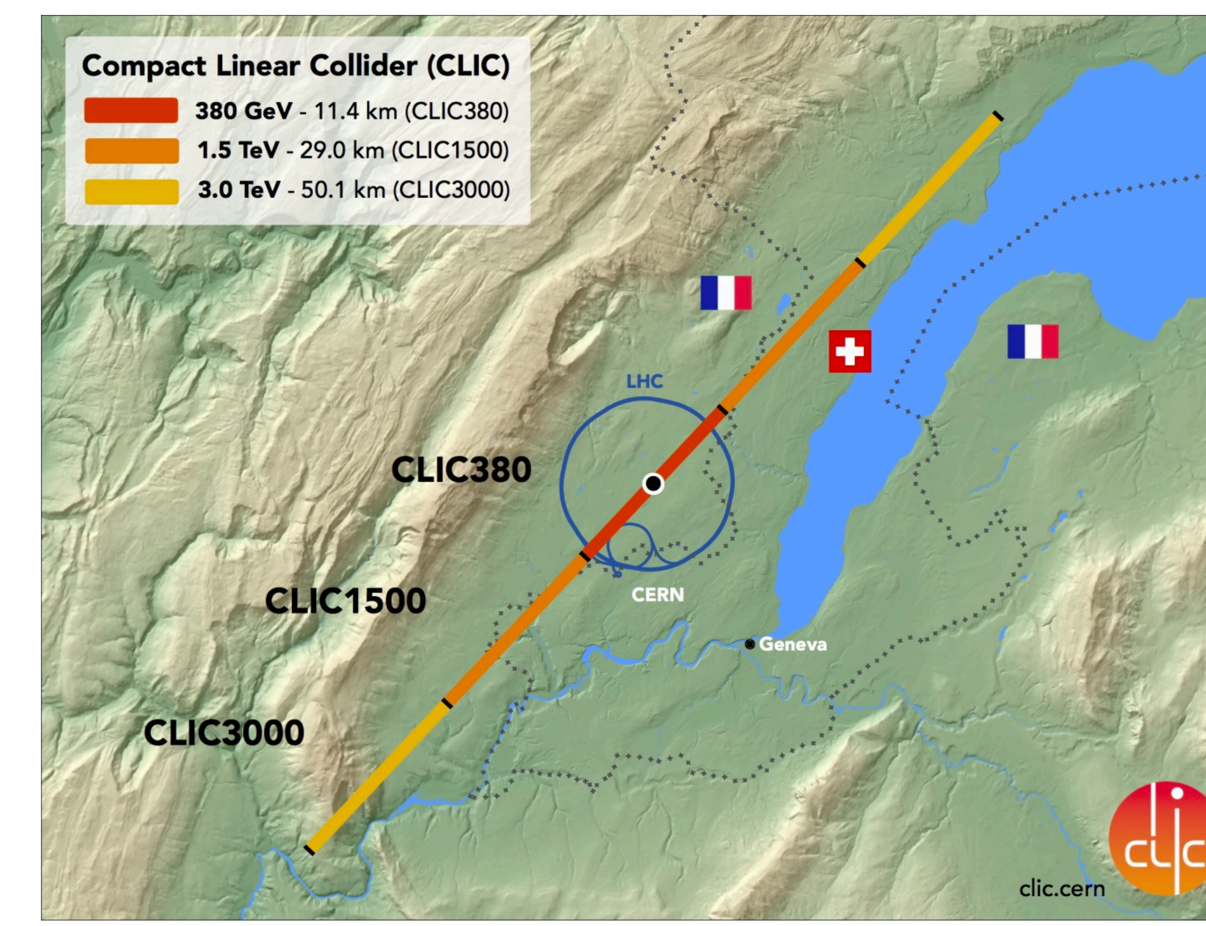

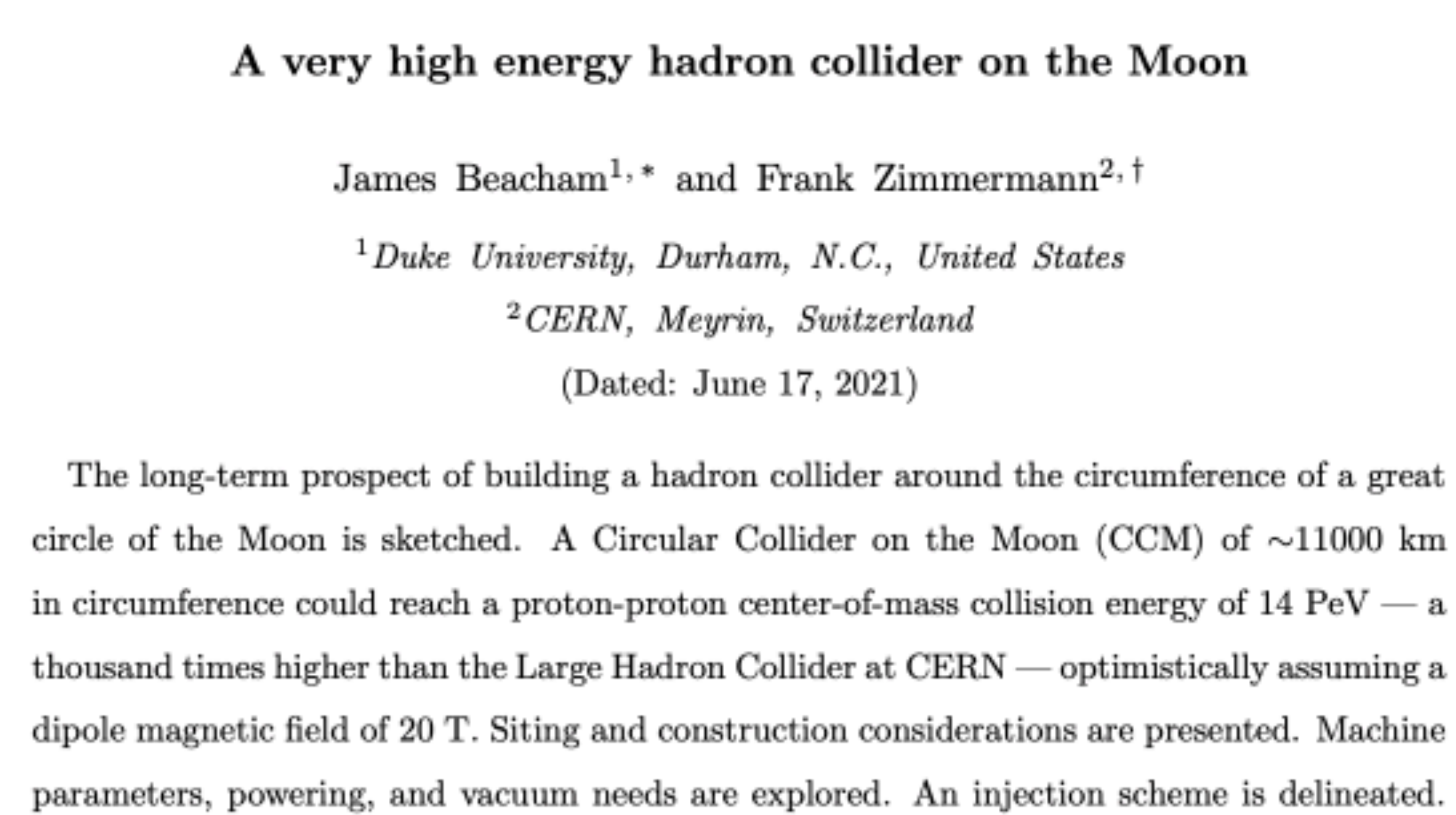
A very high energy hadron collider on the Moon

James Beacham[1,*] and Frank Zimmermann[2,†]

[1]Duke University, Durham, N.C., United States

[2]CERN, Meyrin, Switzerland

(Dated: June 17, 2021)

The long-term prospect of building a hadron collider around the circumference of a great circle of the Moon is sketched. A Circular Collider on the Moon (CCM) of ∼11000 km in circumference could reach a proton-proton center-of-mass collision energy of 14 PeV — a thousand times higher than the Large Hadron Collider at CERN — optimistically assuming a dipole magnetic field of 20 T. Siting and construction considerations are presented. Machine parameters, powering, and vacuum needs are explored. An injection scheme is delineated.

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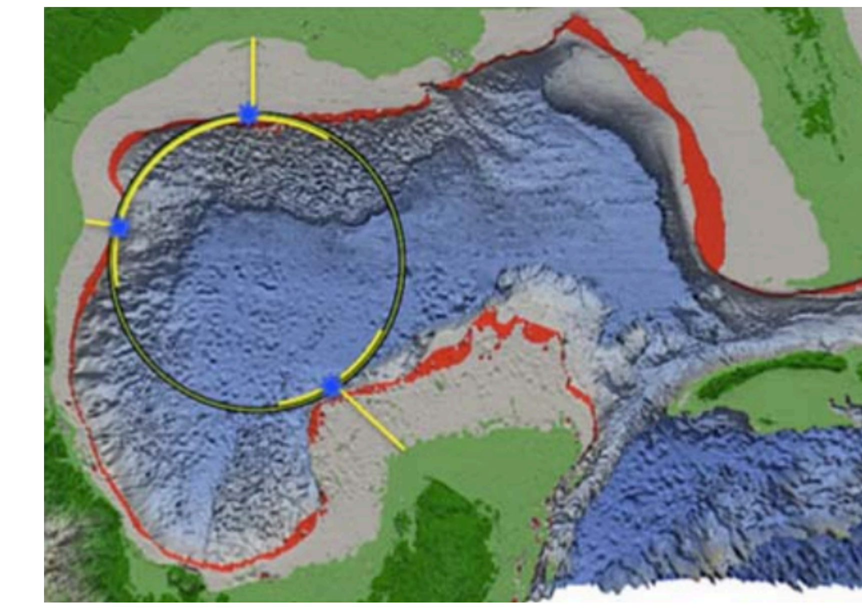

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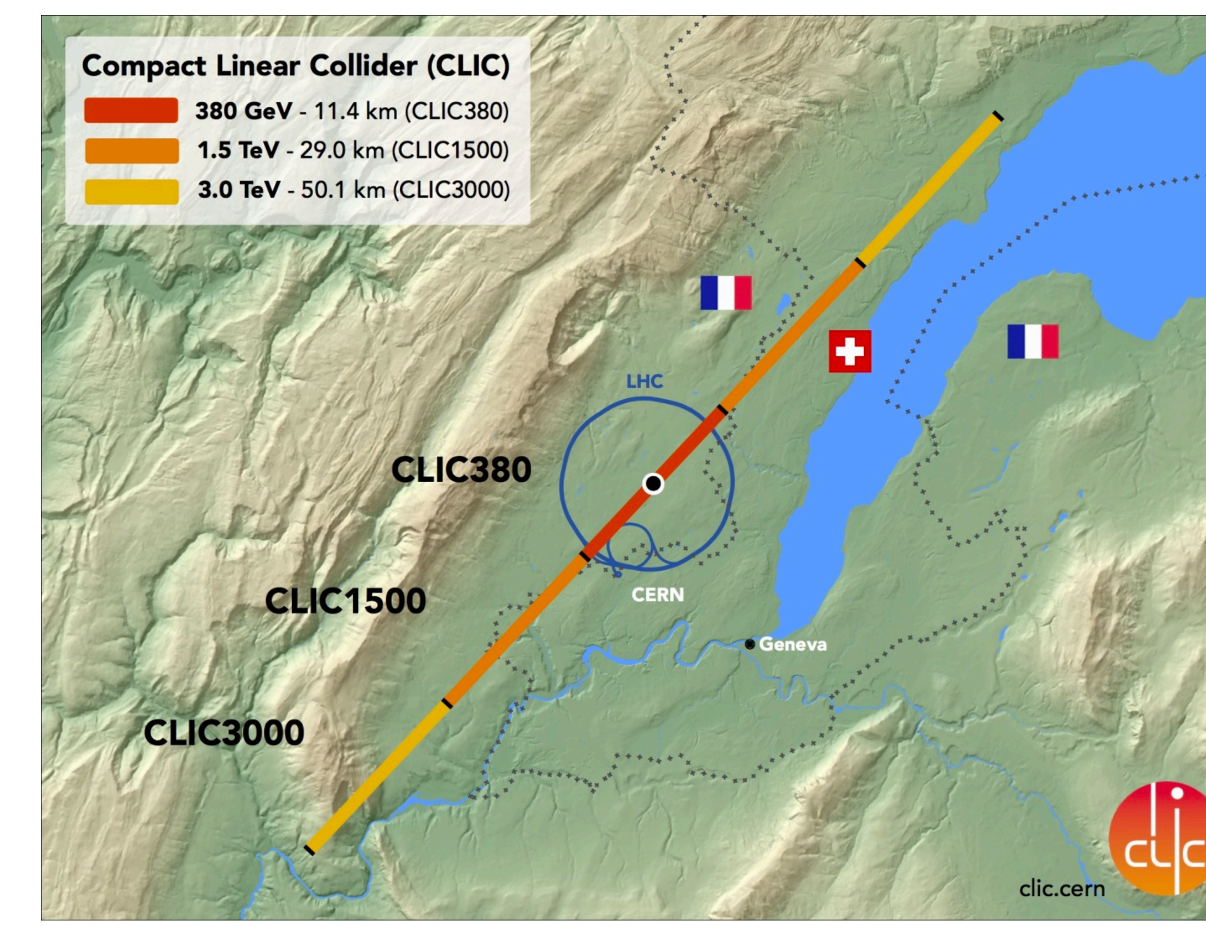

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Potential solution: use materials already broken down!

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Also known as wakefield accelerators, plasma allows coupling energy from driver to witness

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VOLUME 43, NUMBER 4 PHYSICAL REVIEW LETTERS 23 JULY 1979

Laser Electron Accelerator

T. Tajima and J. M. Dawson
Department of Physics, University of California, Los Angeles, California 90024
(Received 9 March 1979)

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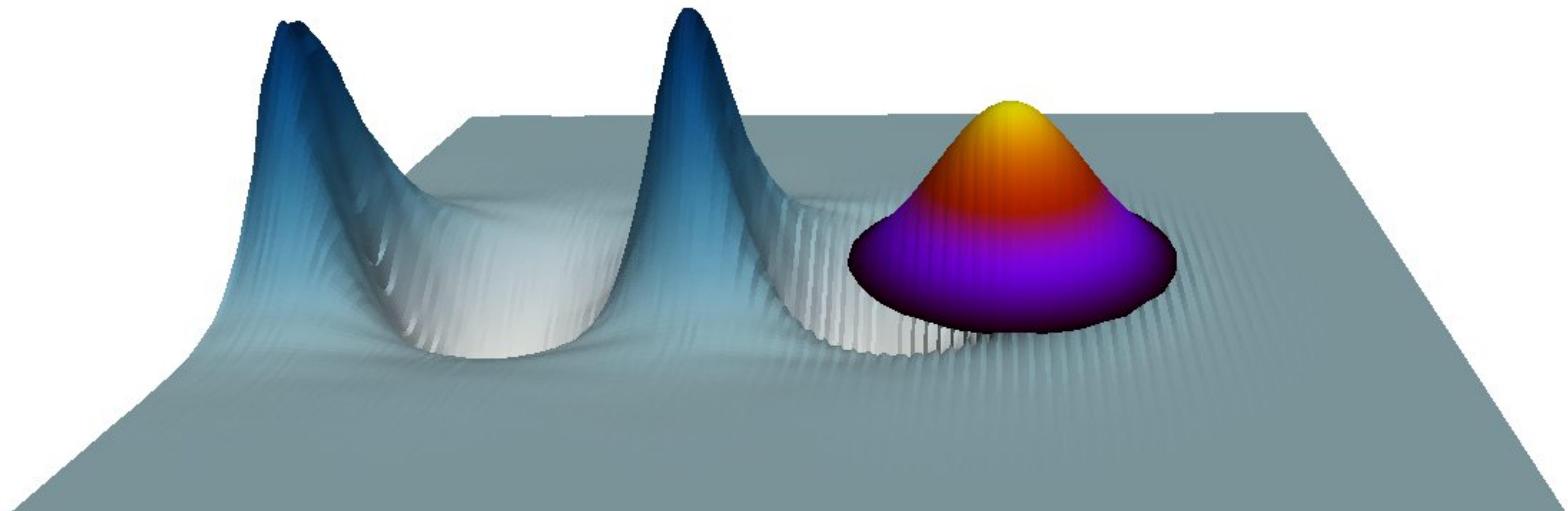

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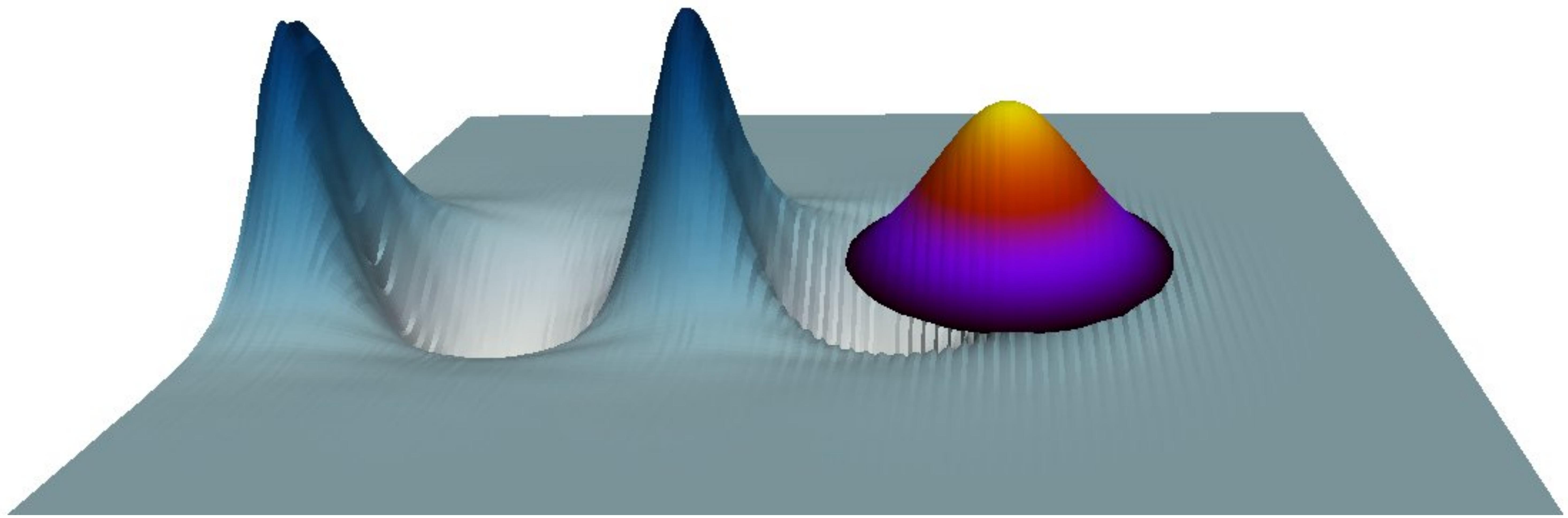
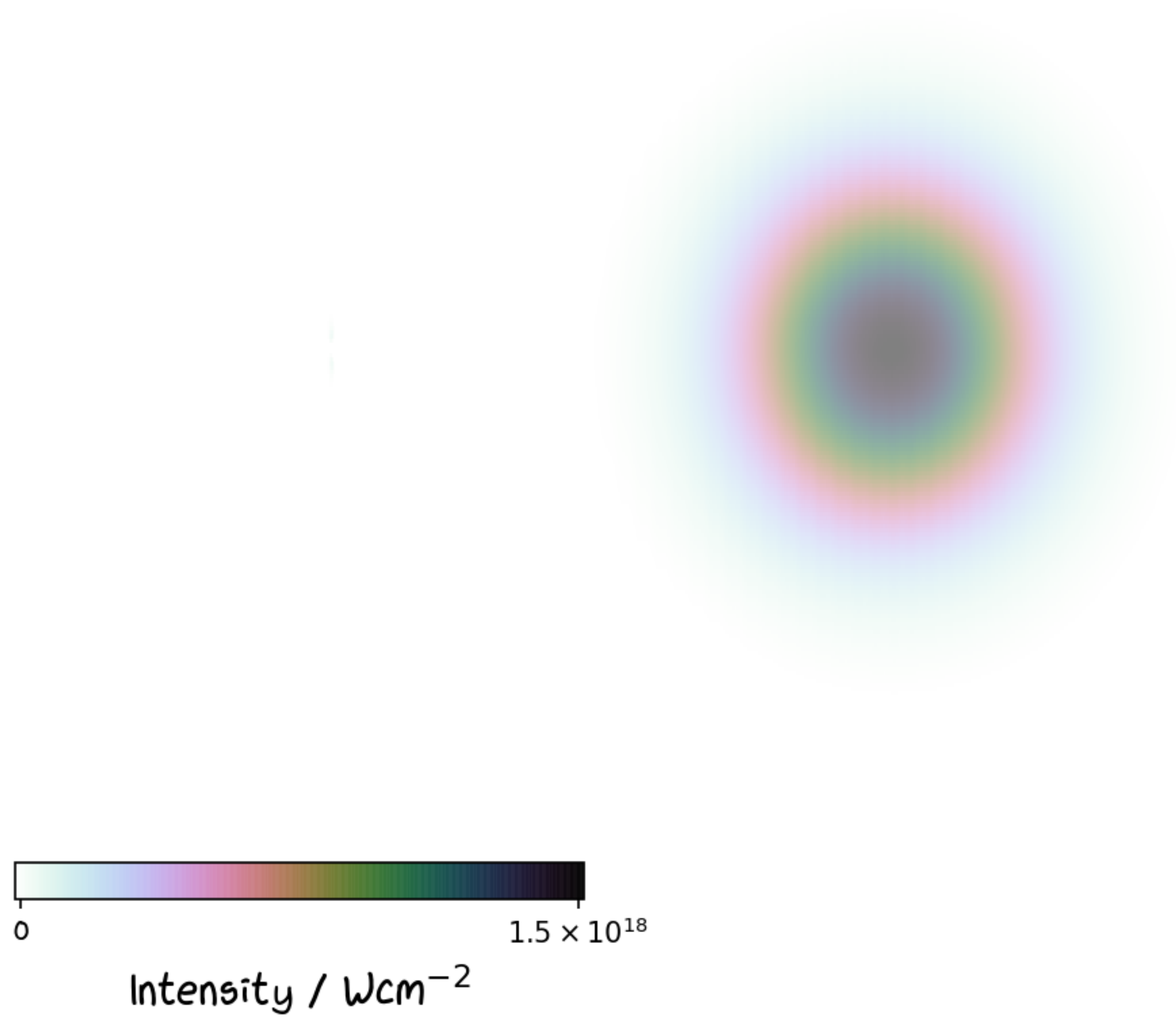


Basic physics of laser plasma accelerators

Driver beam creates plasma wave in its wake, supporting fields beyond 100 GV/m



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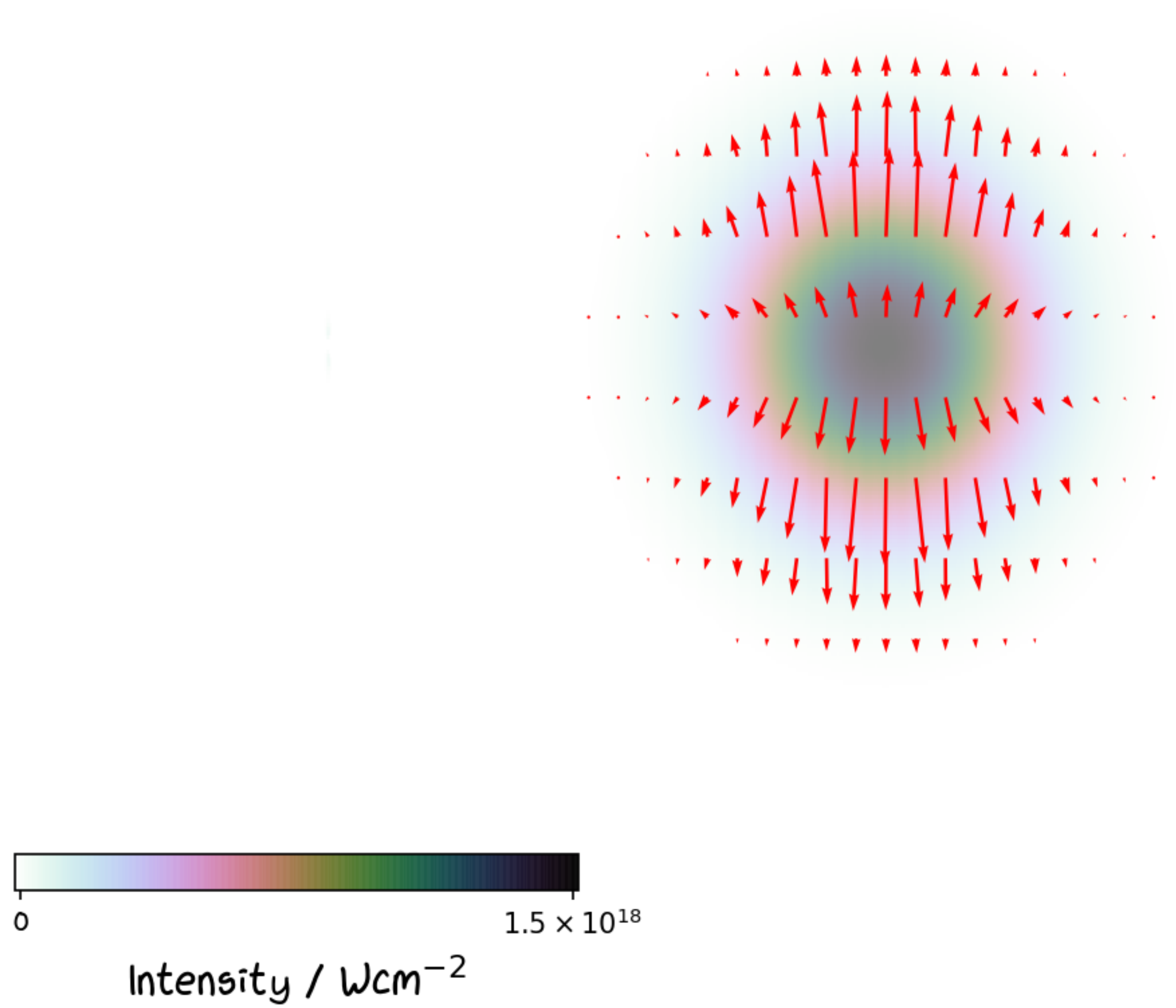

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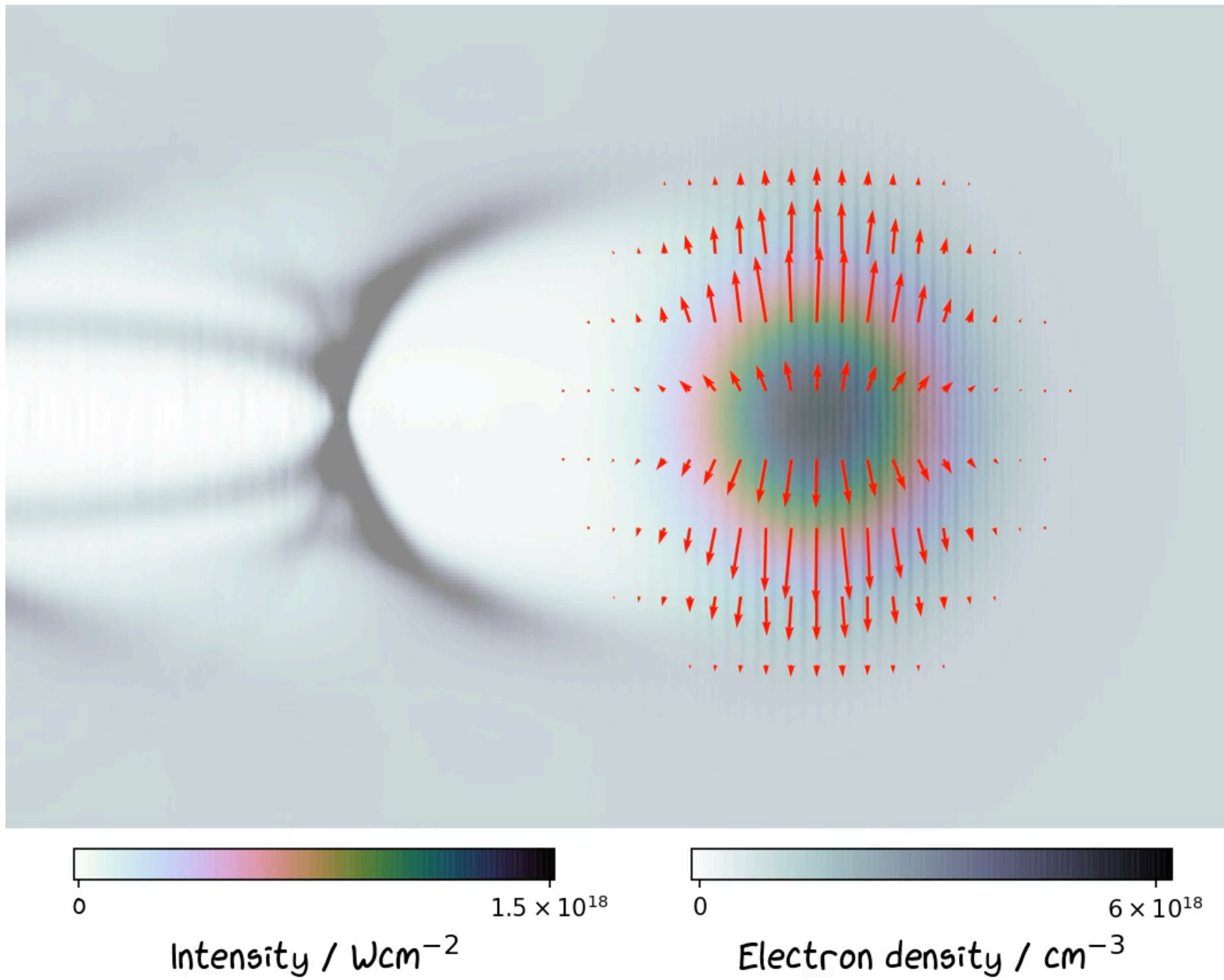

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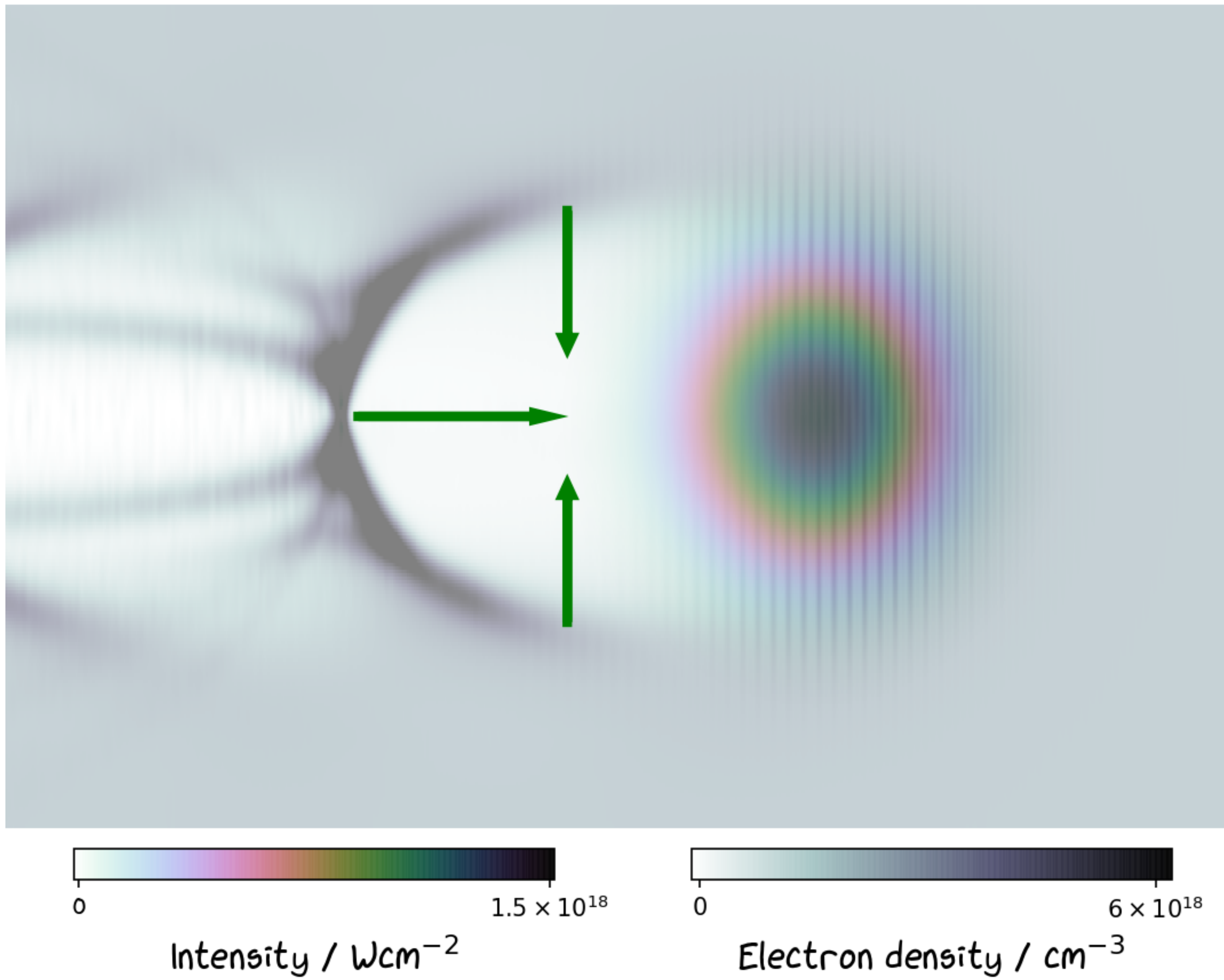

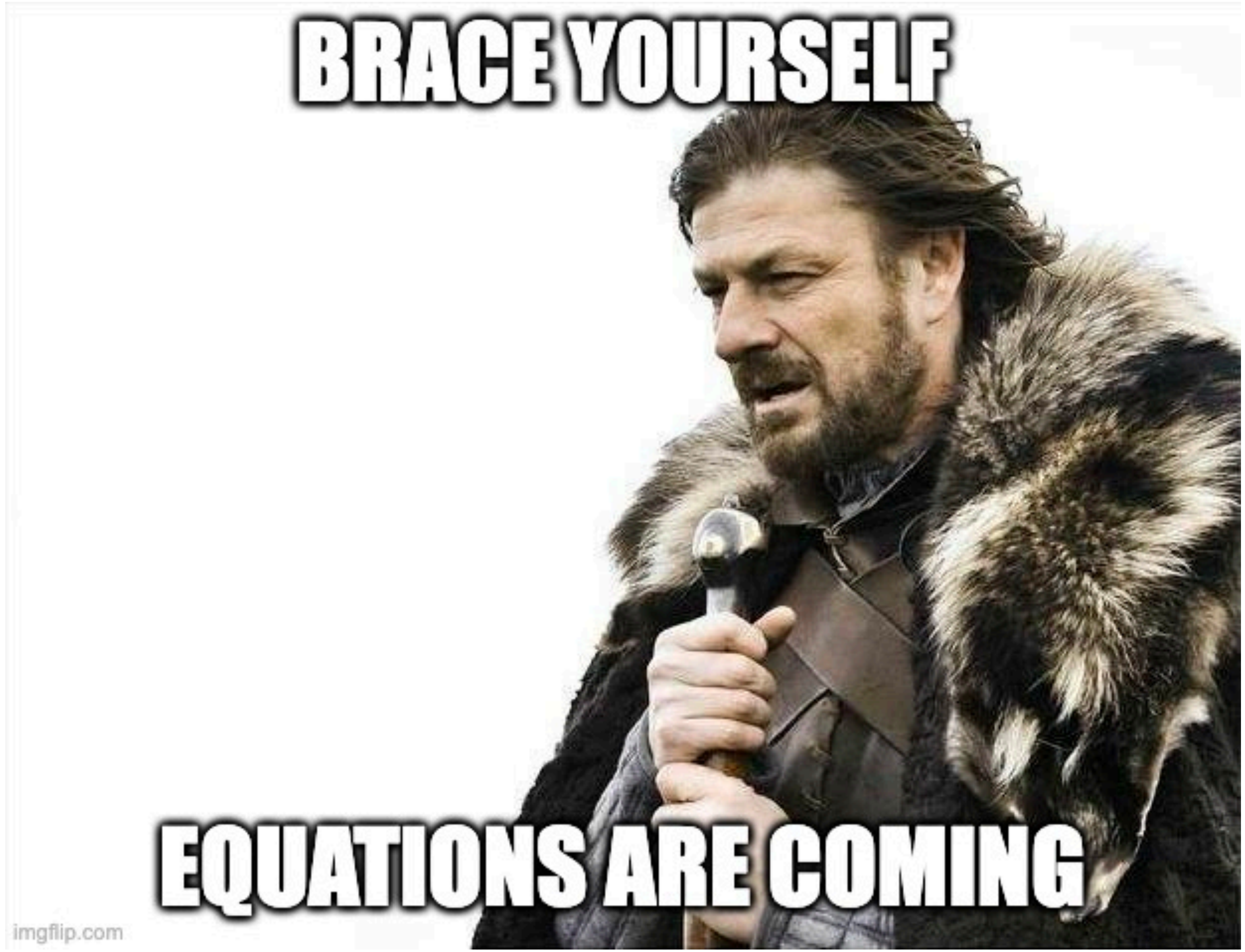
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EQUATIONS ARE COMING
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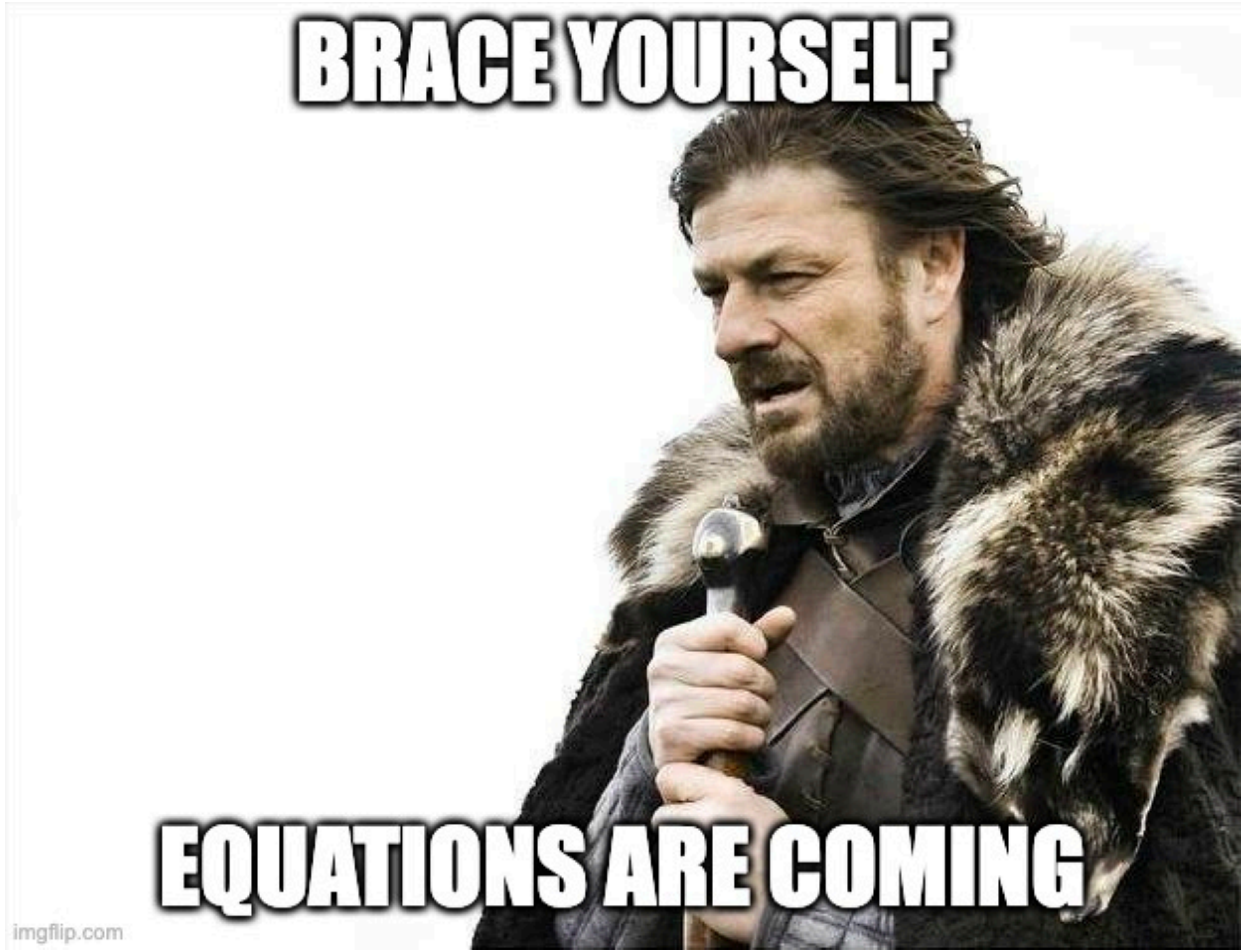

**For Gen Z: this is a 'meme'. It depicts Ned Stark from Game of Thrones*

LPAs are based on plasma electron waves

Plasma like to oscillate© and can do so sustaining very high amplitudes

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Laser propagation in plasmas

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$$n_c = \frac{m_e \epsilon_0 \omega_L^2}{e^2}$$

> Laser intensity determines plasma response. Convenient to work with normalised vector potential

$$a_0 = \frac{eE}{m_e \omega_p c} \approx 0.856\, \lambda_L[\mu\mathrm{m}]\, \sqrt{I[10^{18}\mathrm{W/cm^2}]}$$

Laser pulses drive plasma waves

Resonant driving of wake-fields leads to high accelerating fields

[6] Gorbunov et al, Soviet Physics JETP **66**, 290 (1987)
[7] Spangle et al, Appl Phys Lett **53**, 2146 (1998)

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- The 3D response of the plasma to a propagating laser is given by [6,7]

$$\left(\frac{\partial^2}{\partial t^2} + \omega_p^2\right)\frac{n_1}{n_0} = c^2\nabla^2\frac{a^2}{2}$$

  - Driven oscillator, driving term is ponderomotive force!

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Resonant driving of wake-fields leads to high accelerating fields

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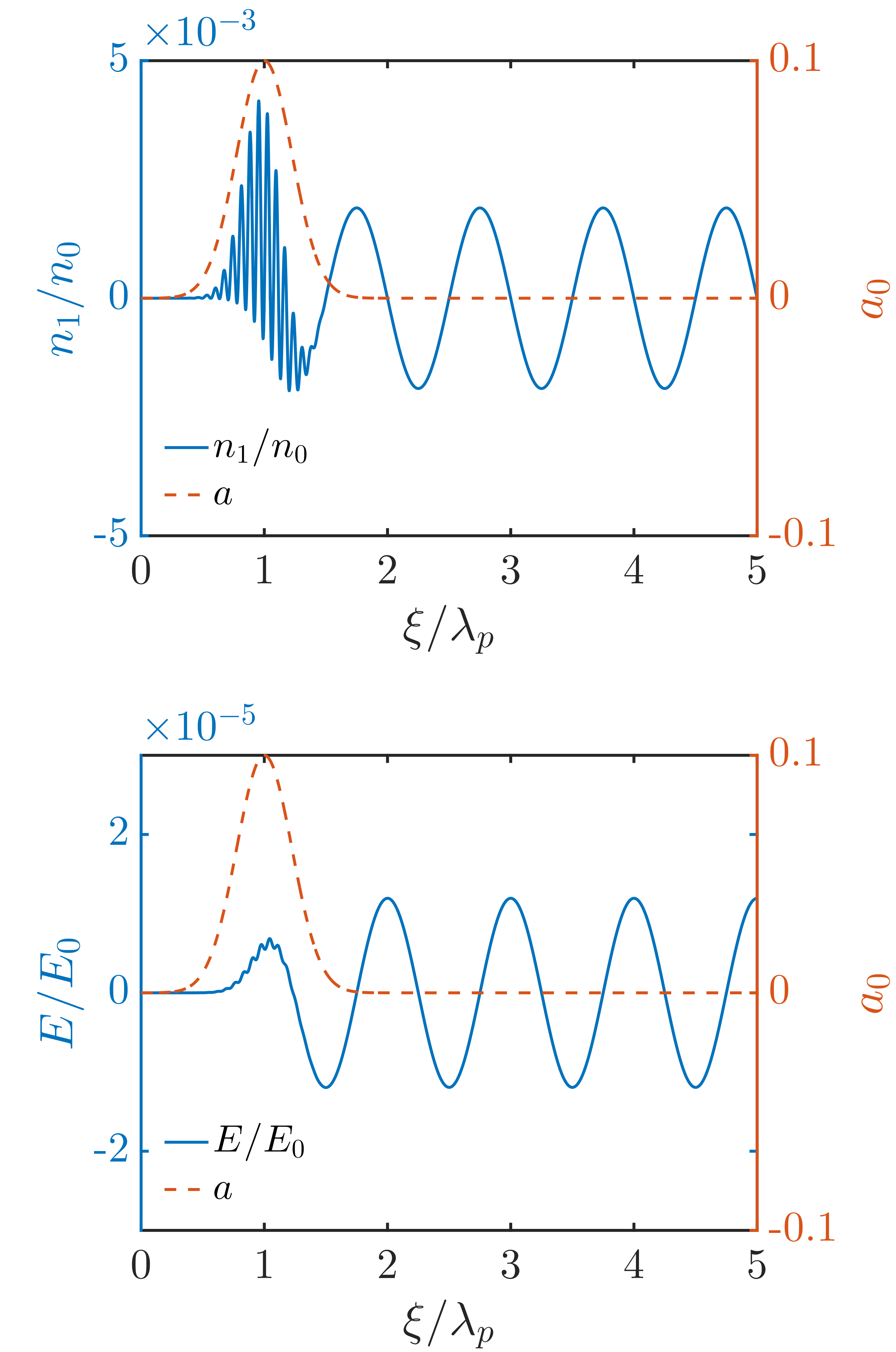

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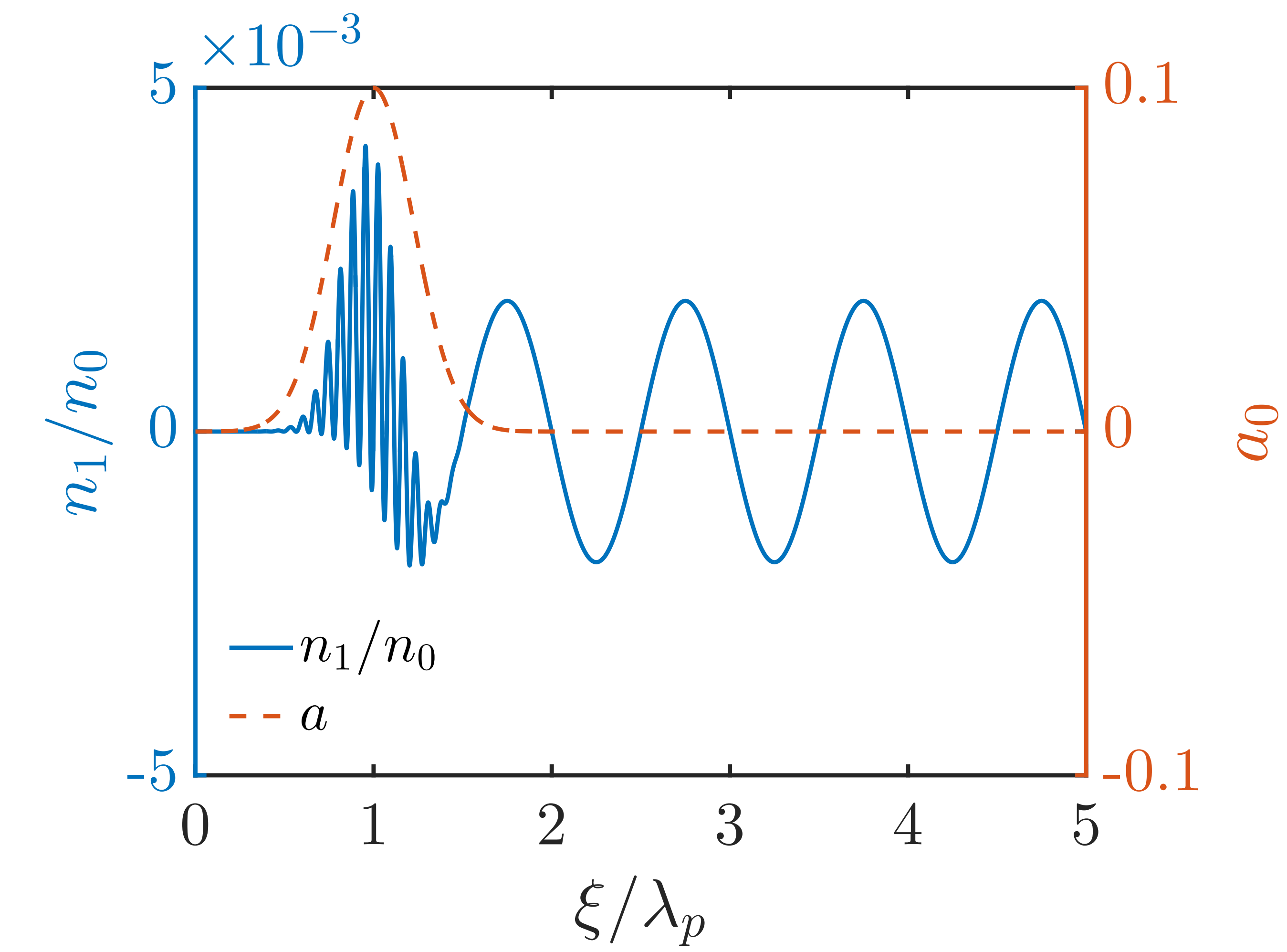

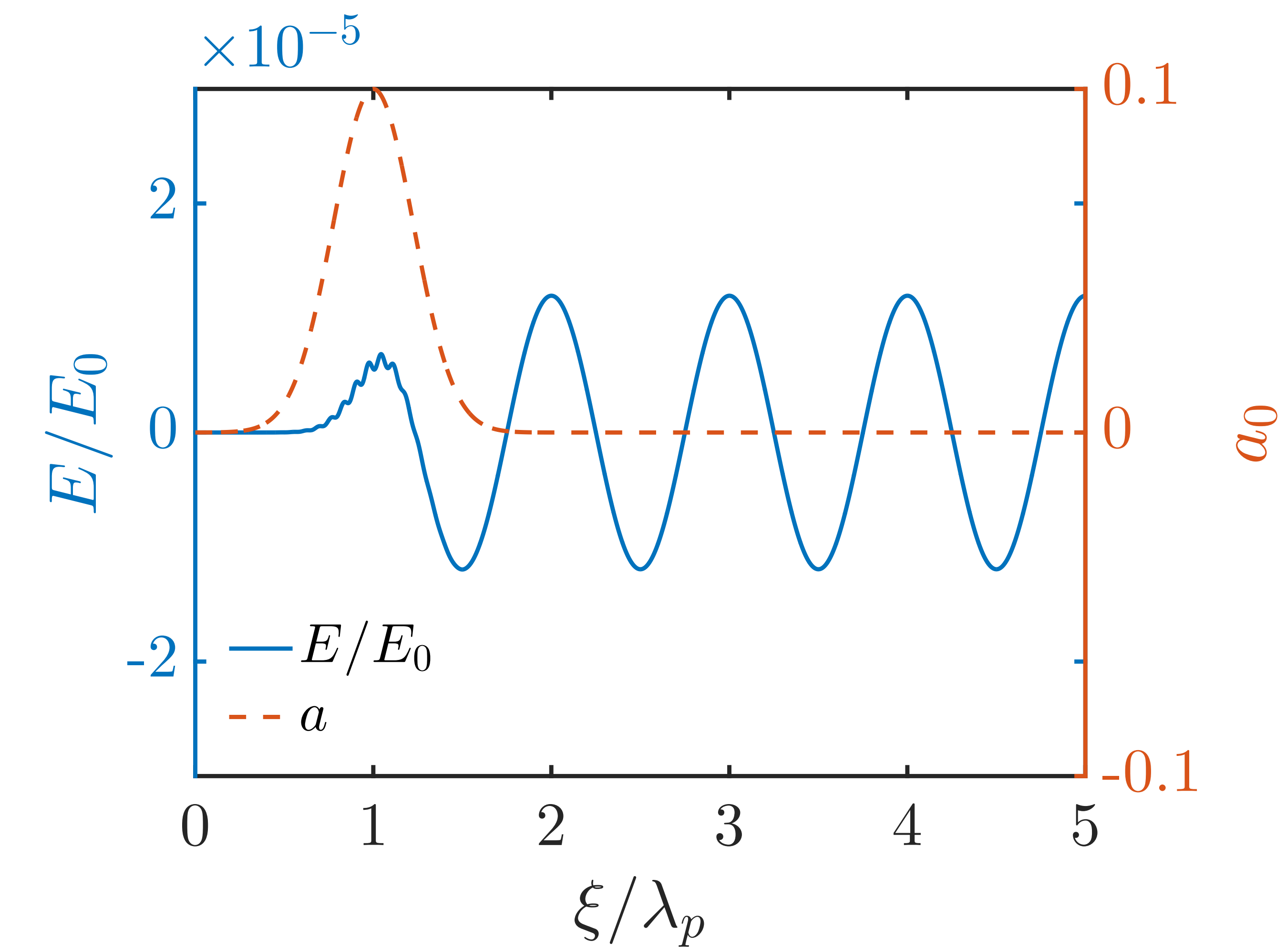

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  - Phase velocity of the plasma wave given by group velocity of laser, for underdone plasmas one has

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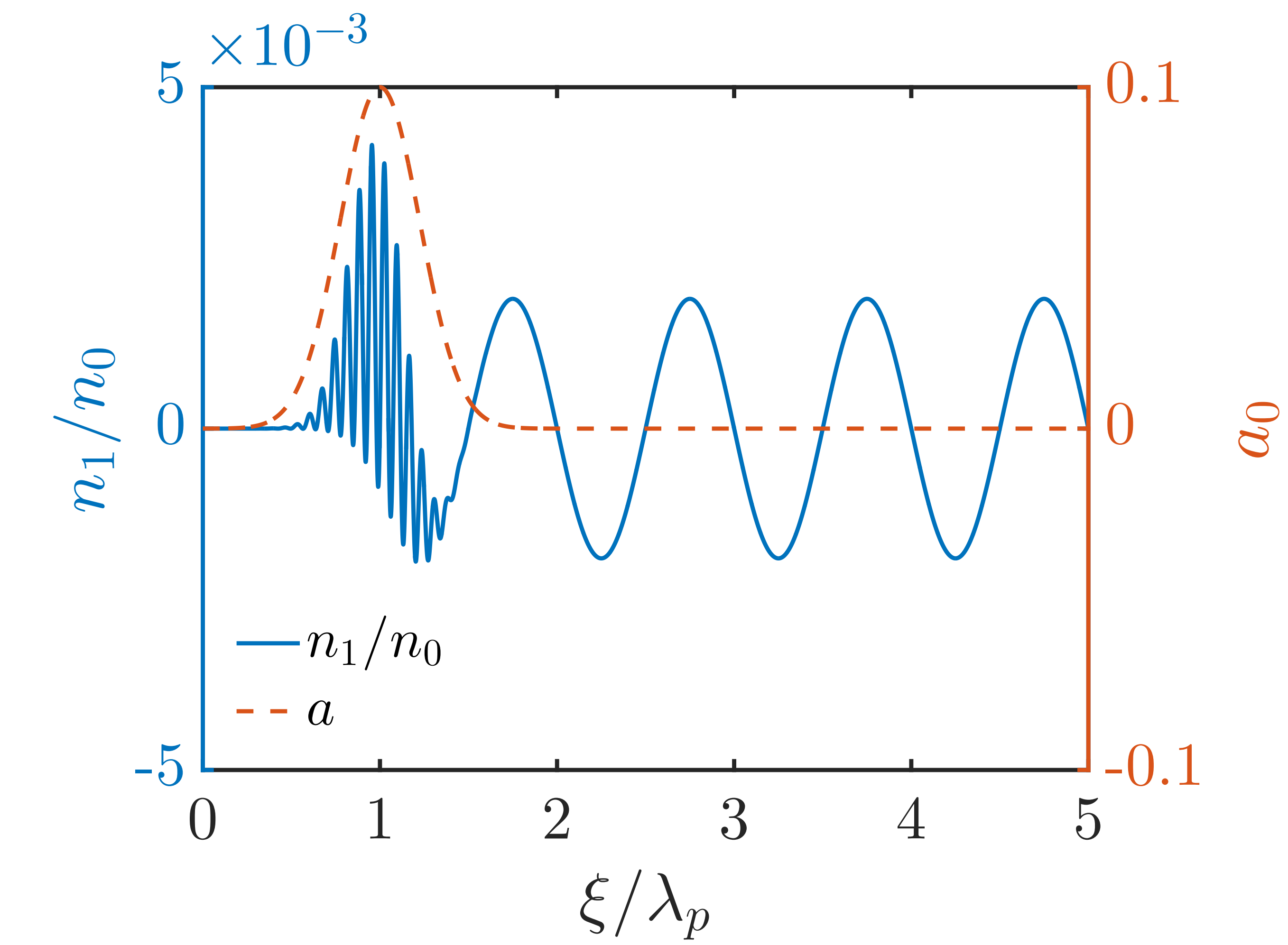

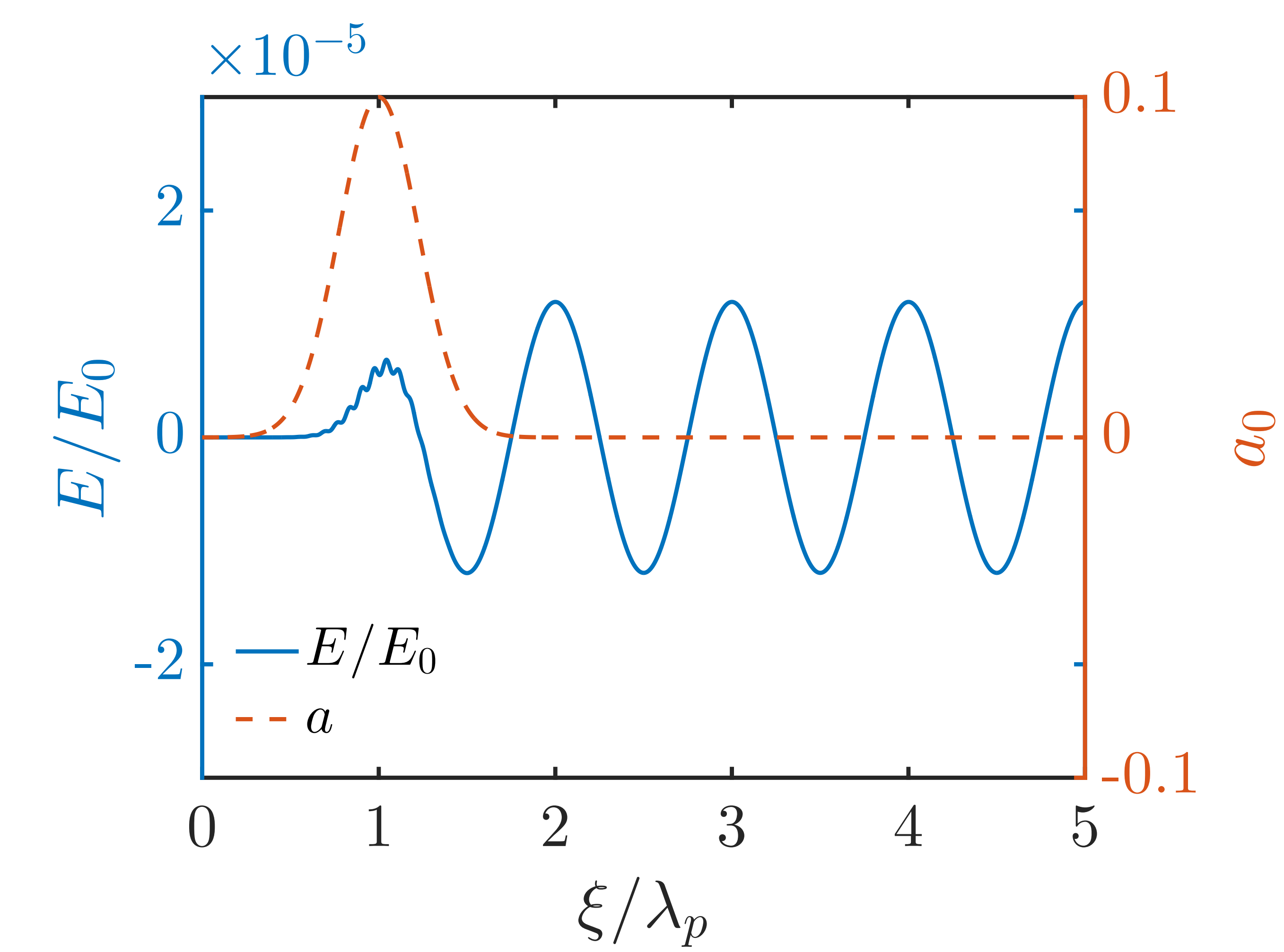

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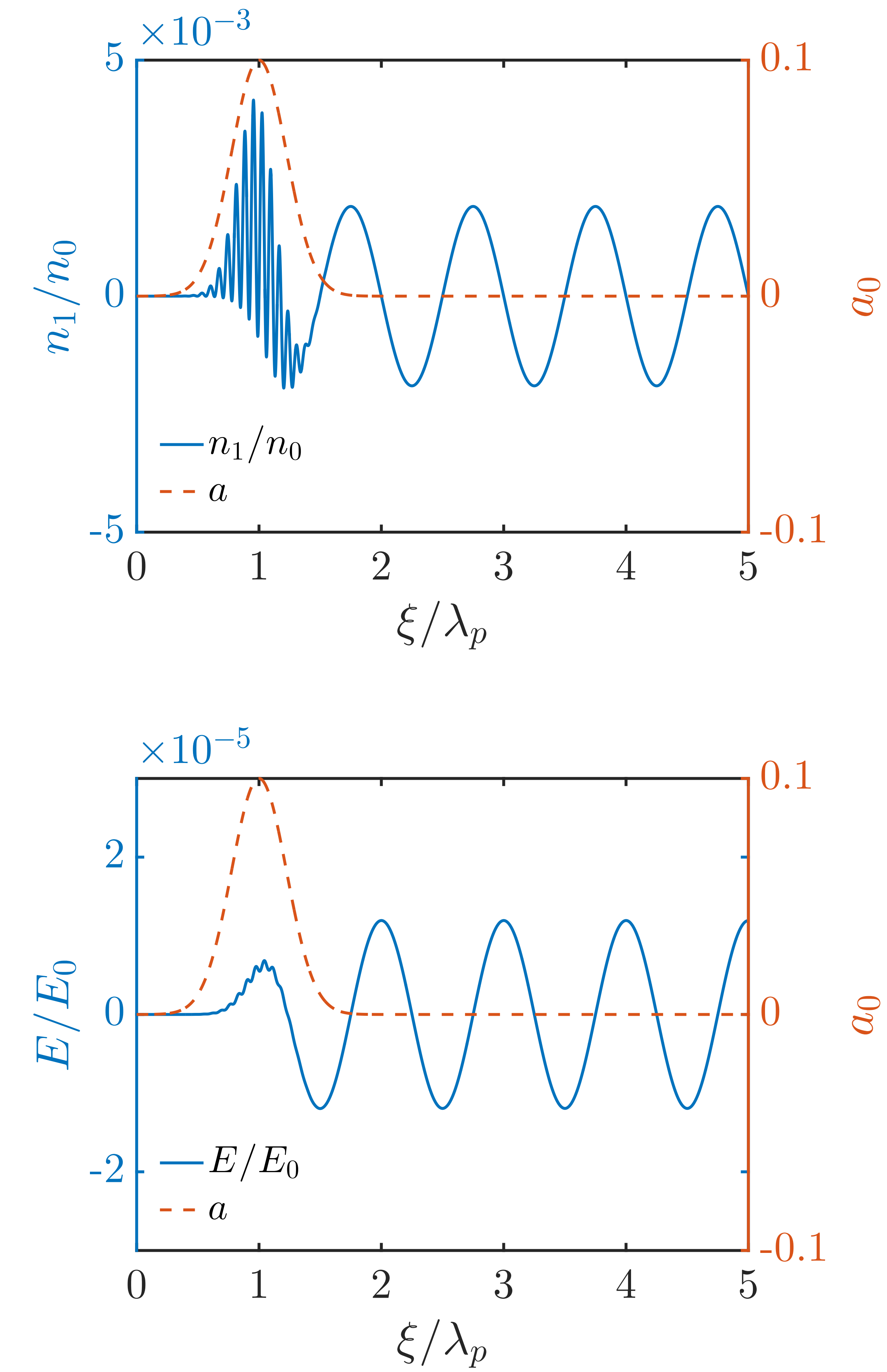
High laser intensities lead to relativistic non-linear effects

Non-linearly increased accelerating field beneficial for LPAs



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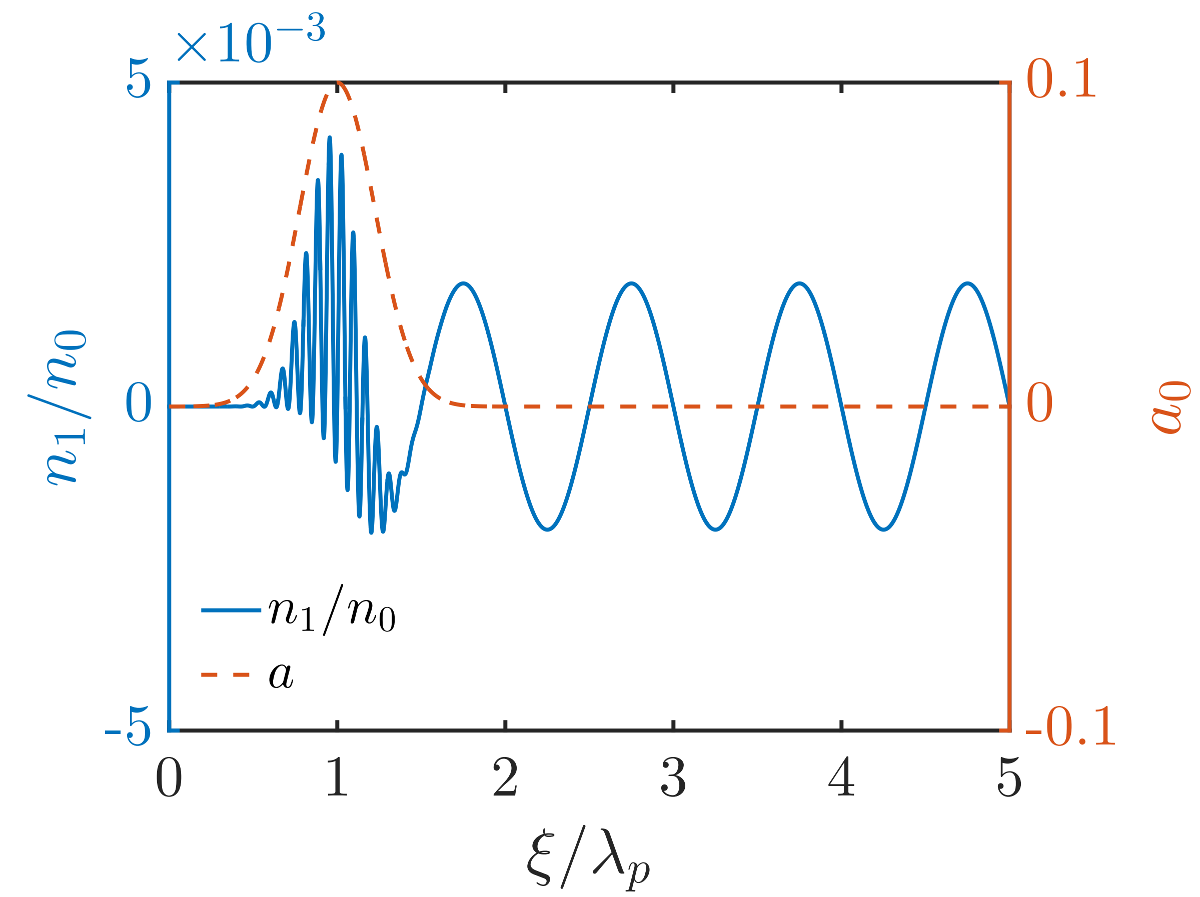

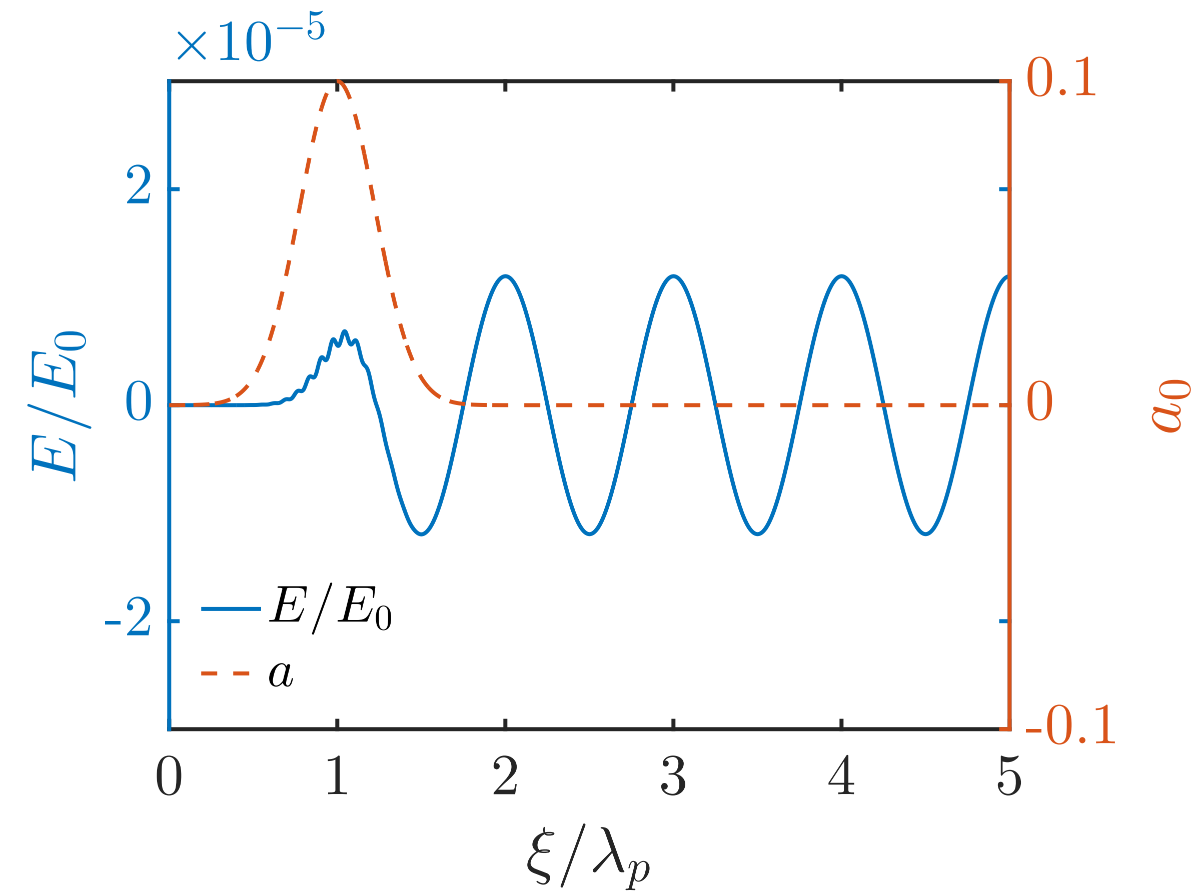

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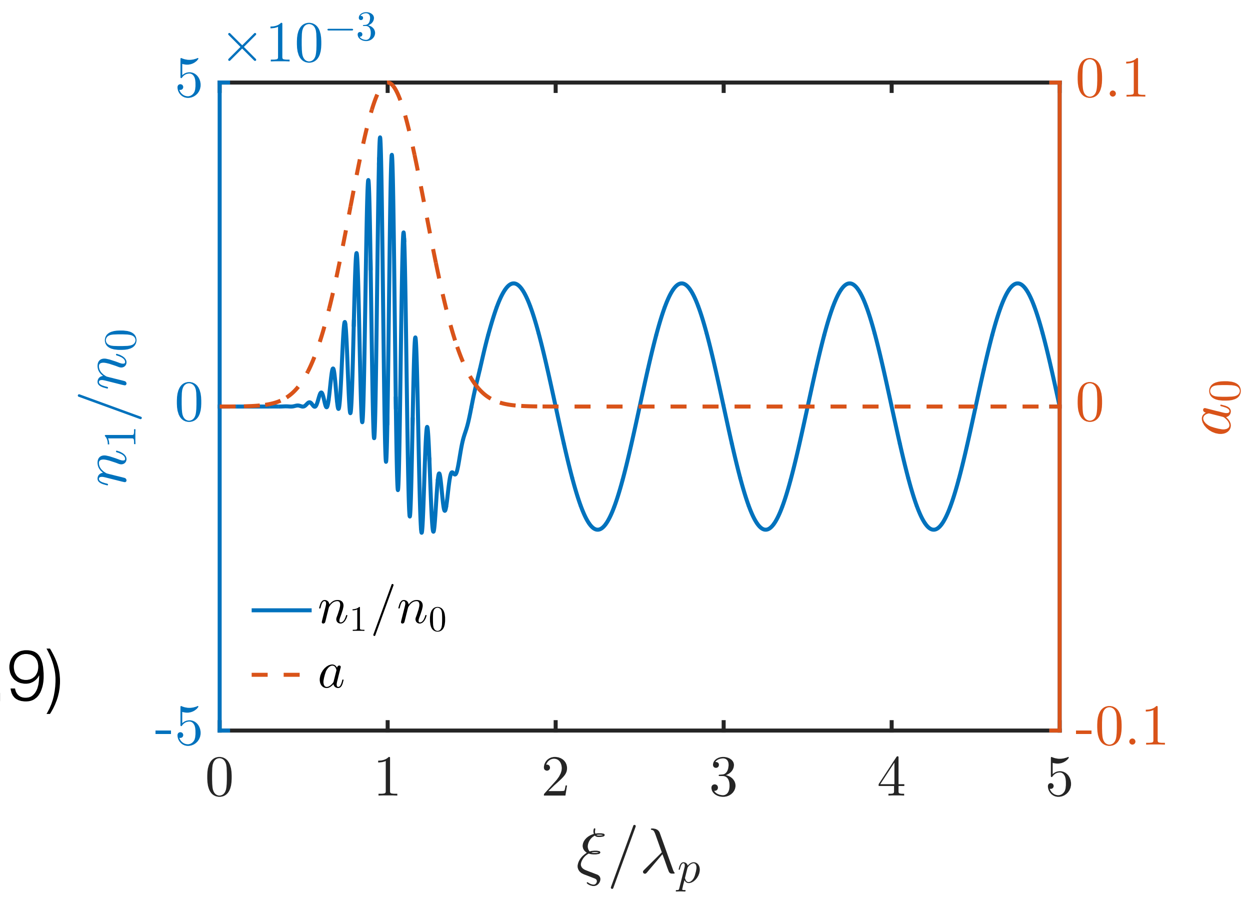

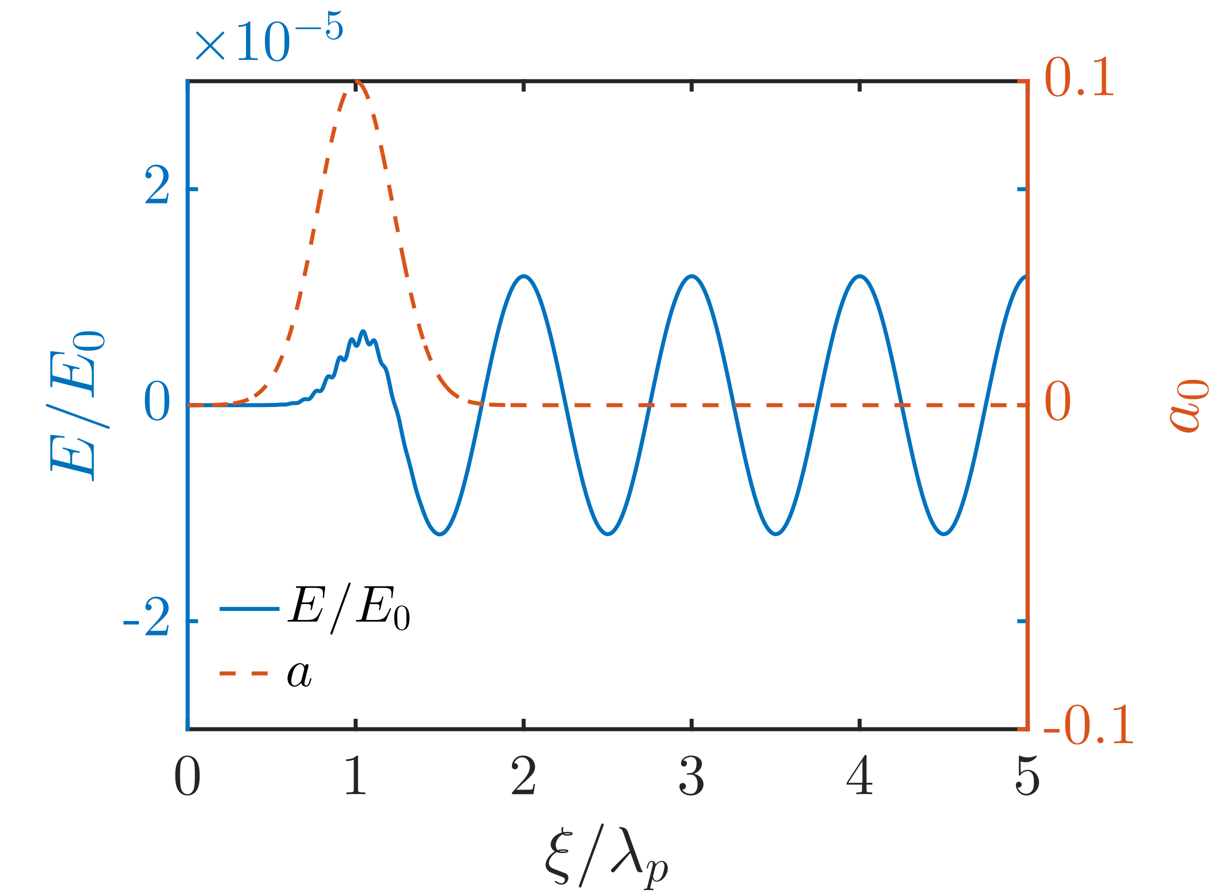

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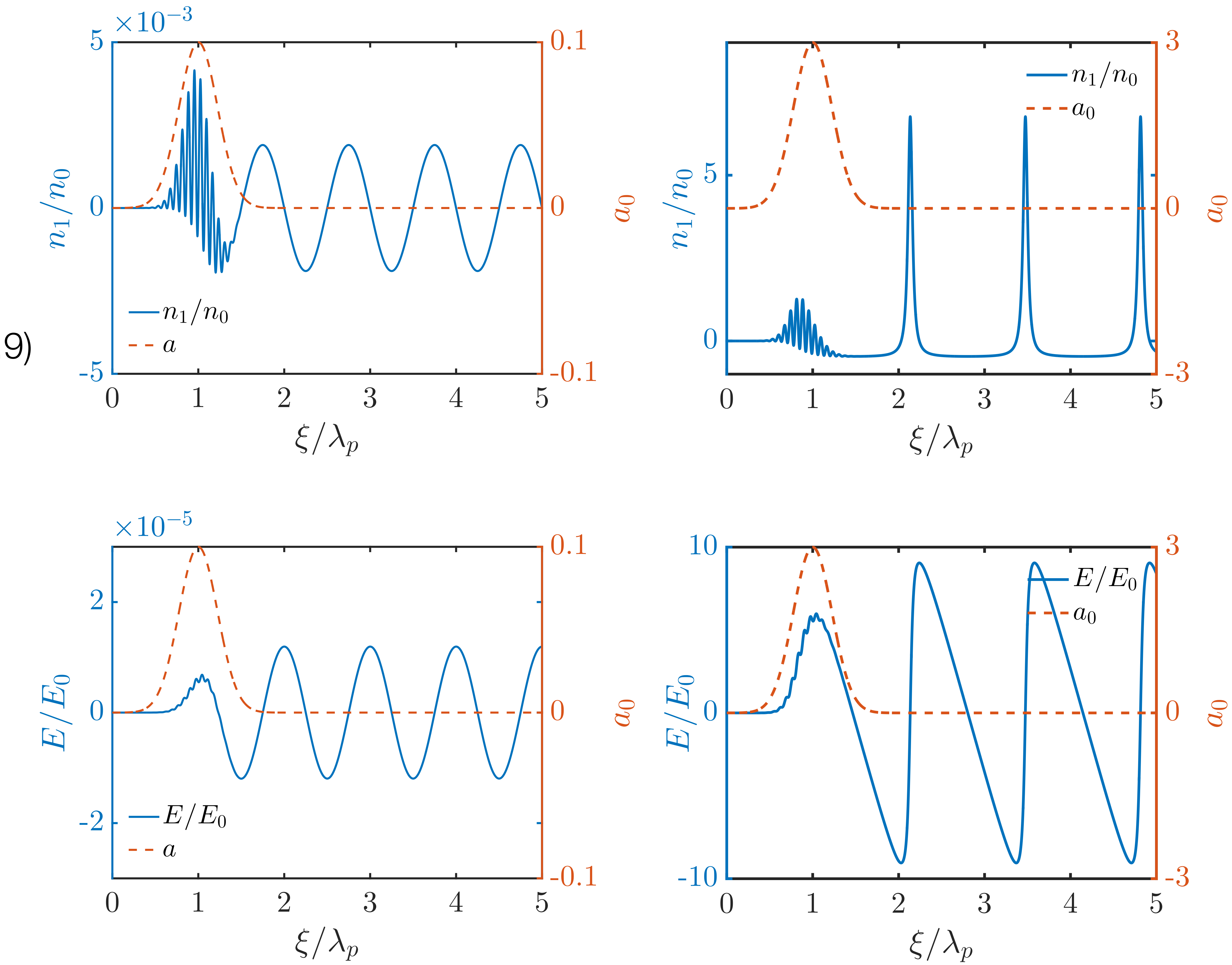

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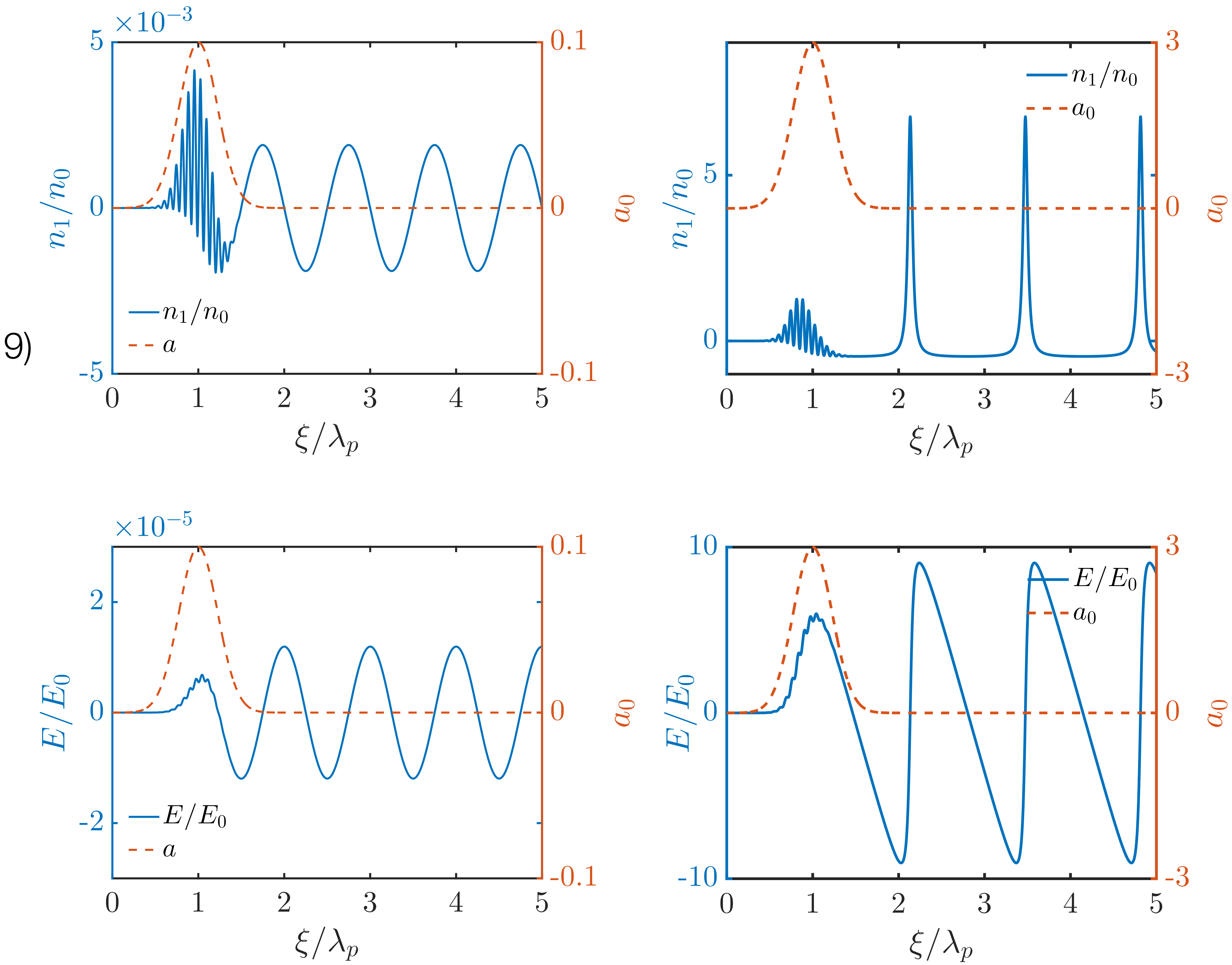

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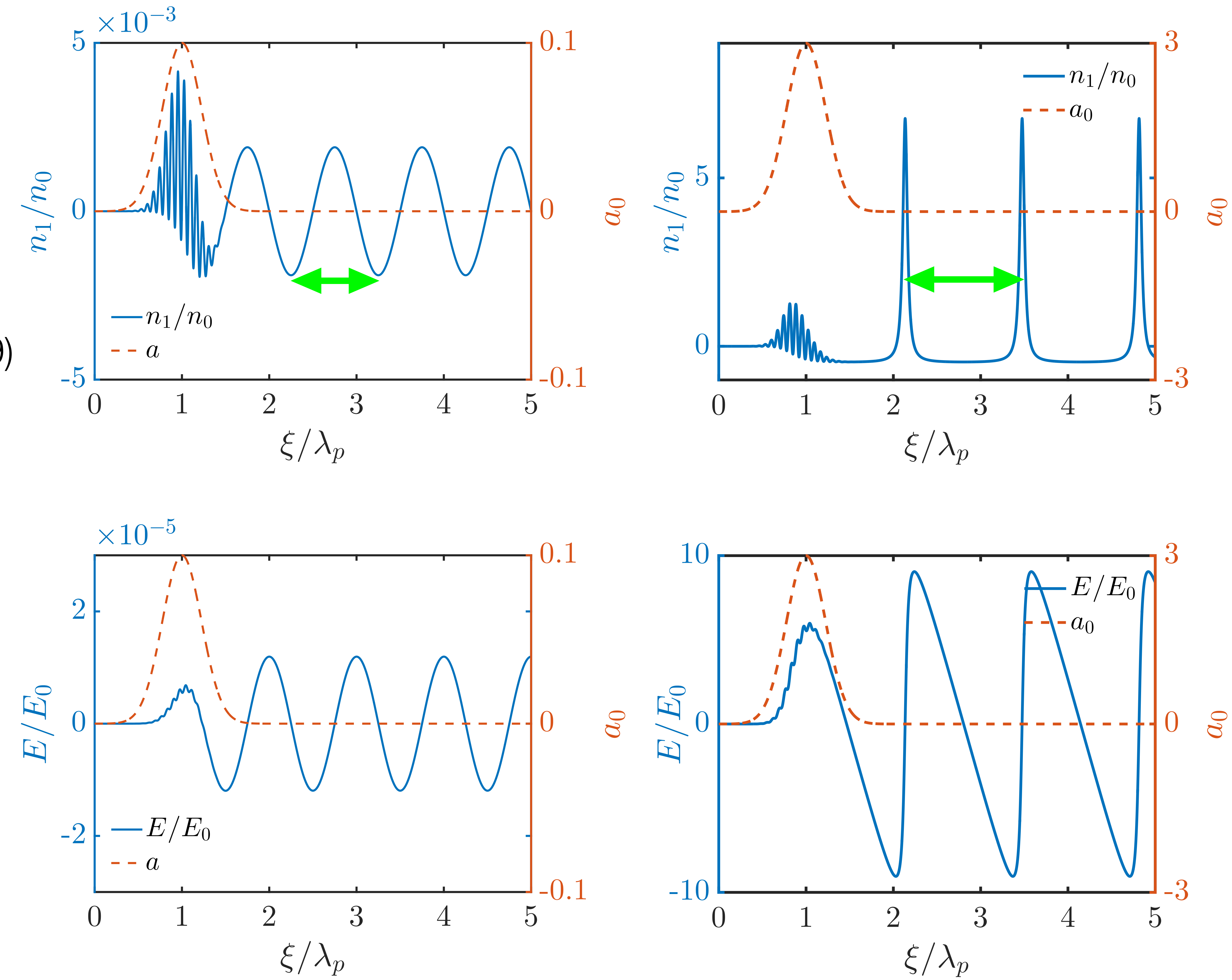

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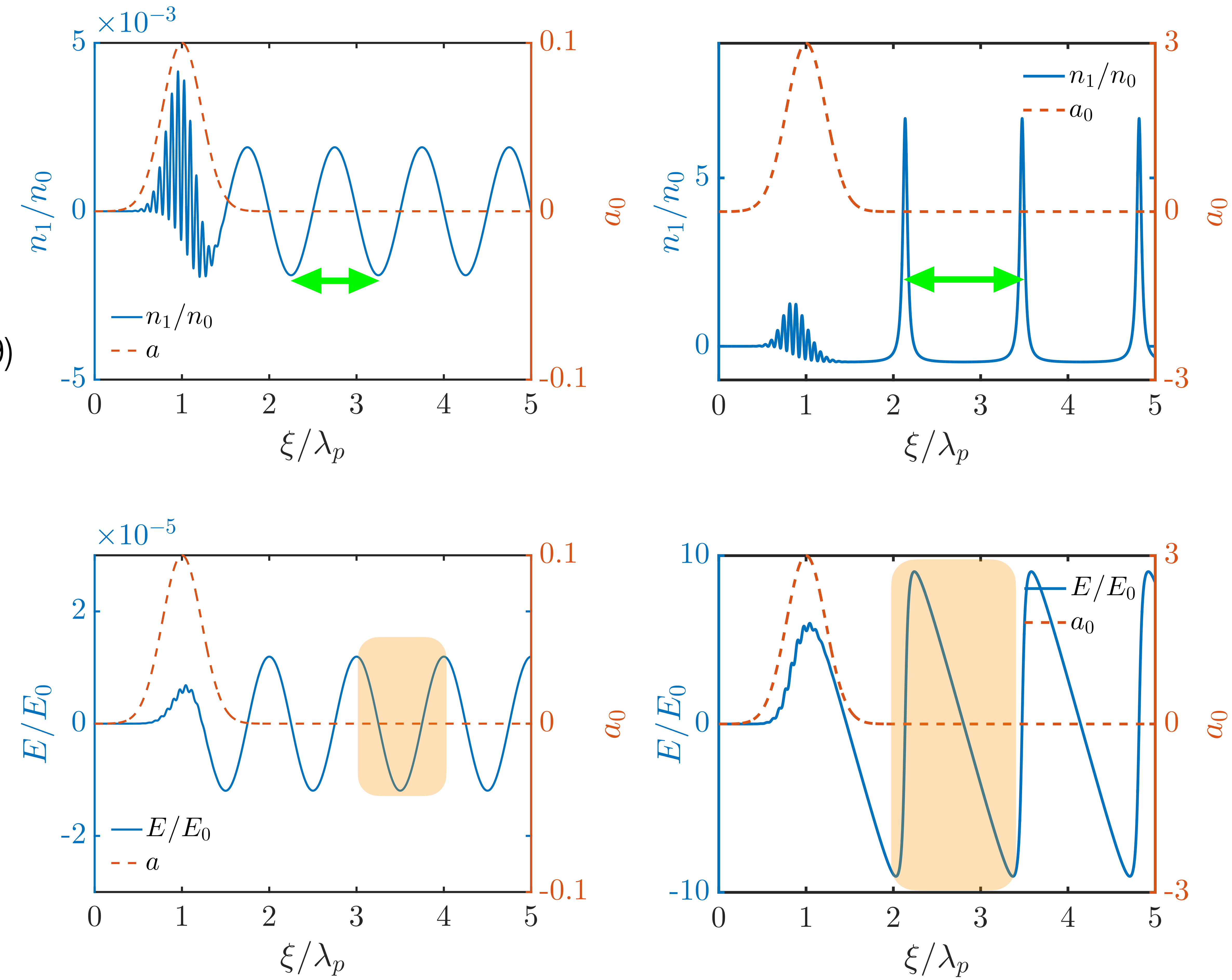

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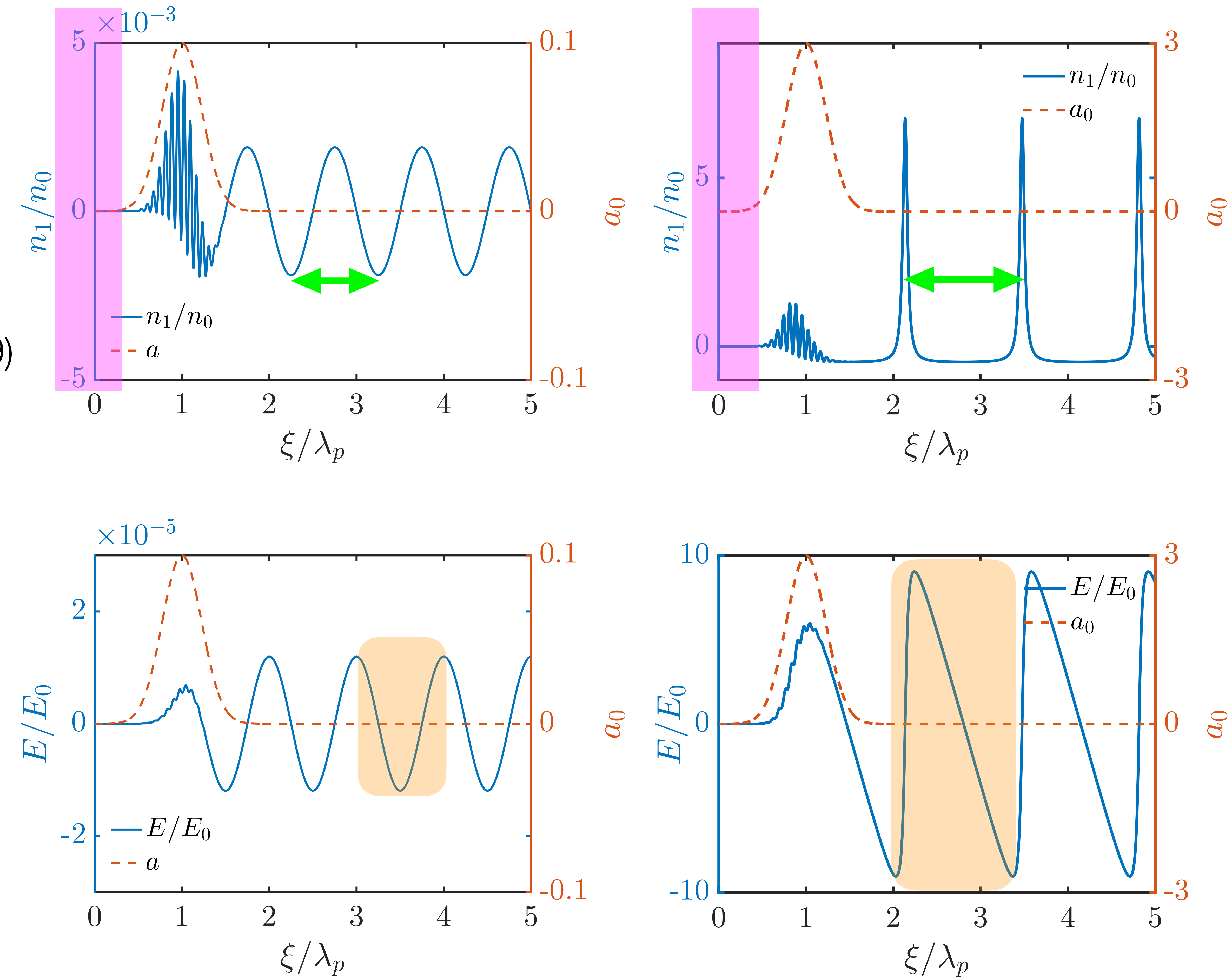

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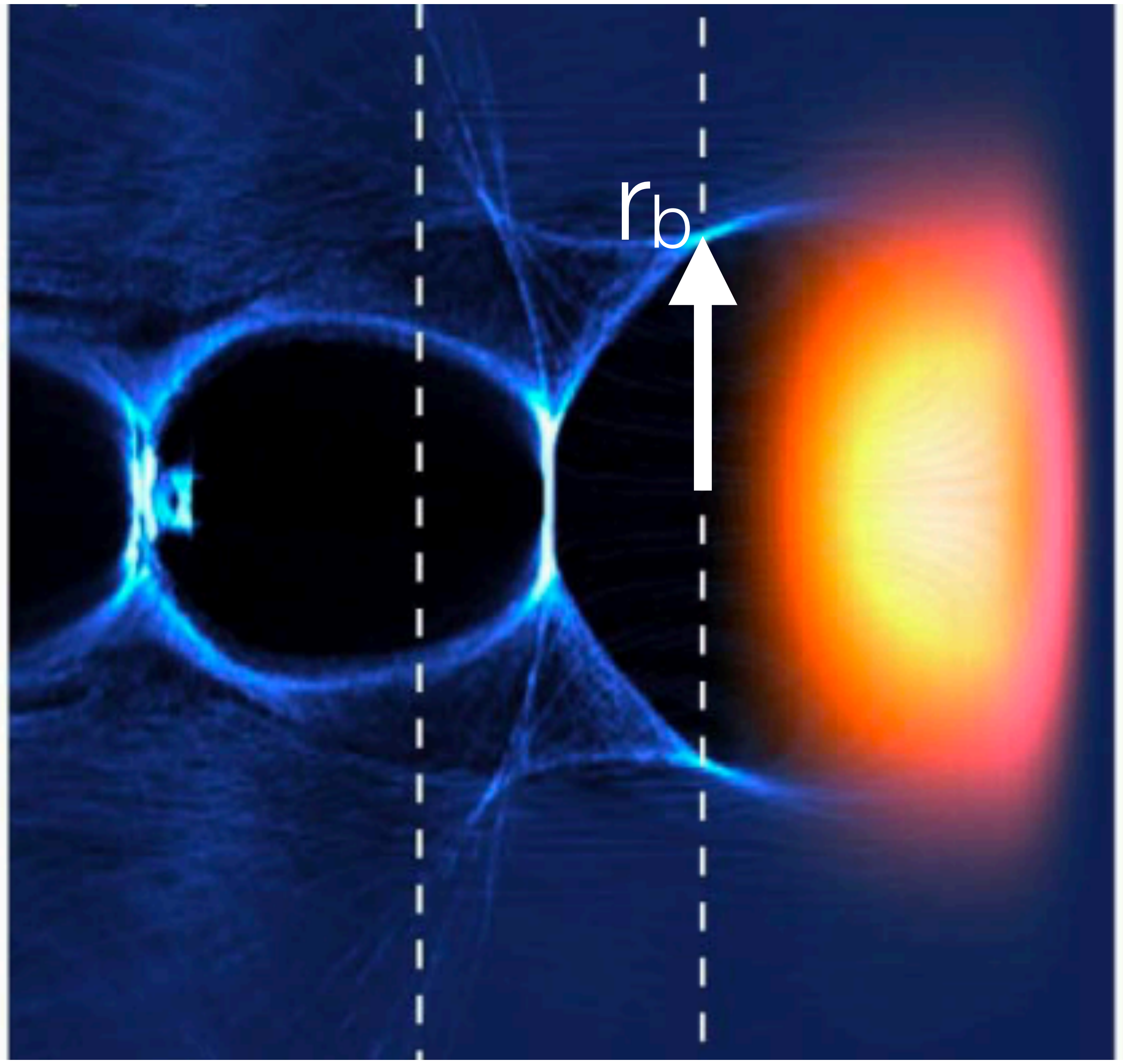

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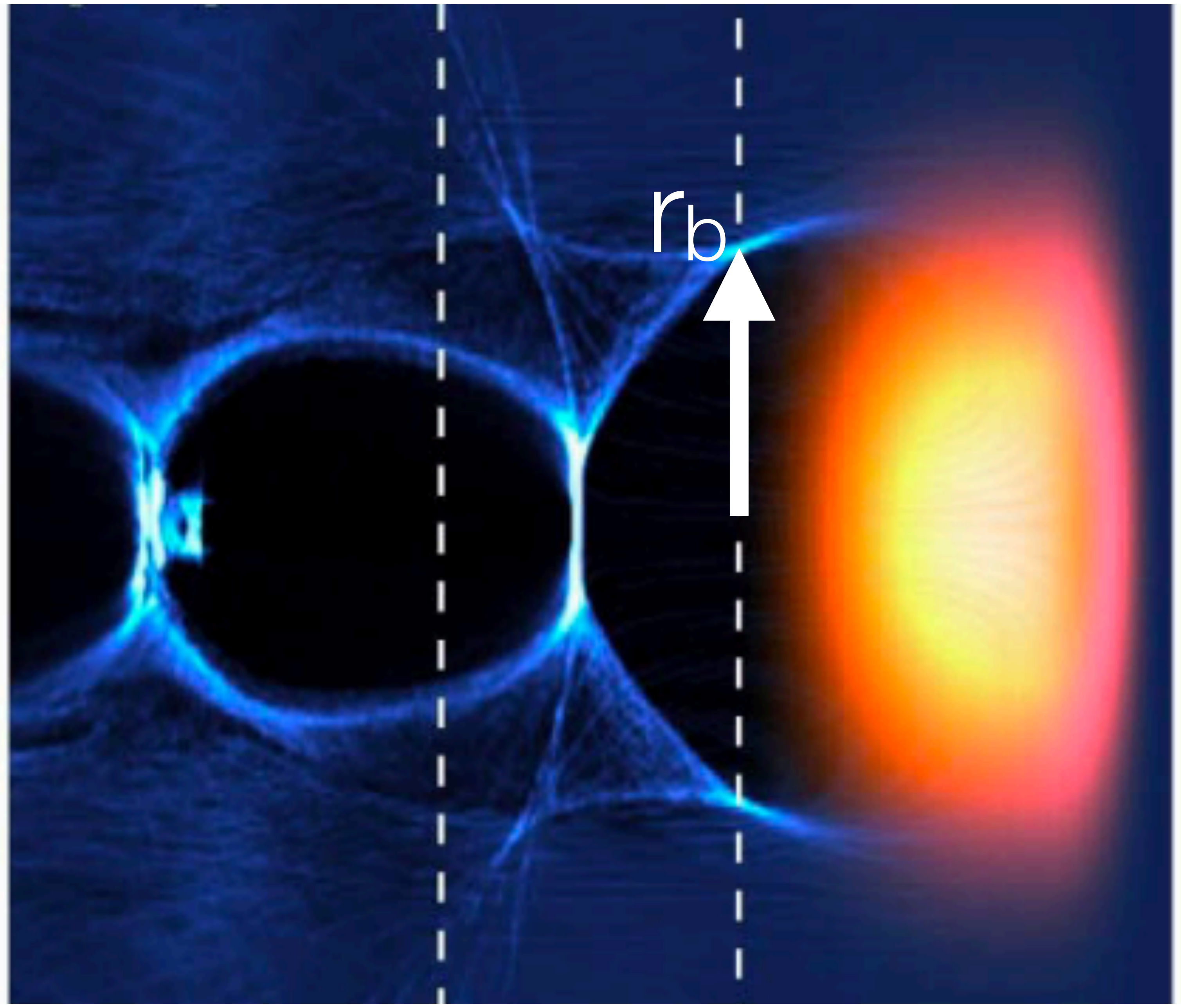

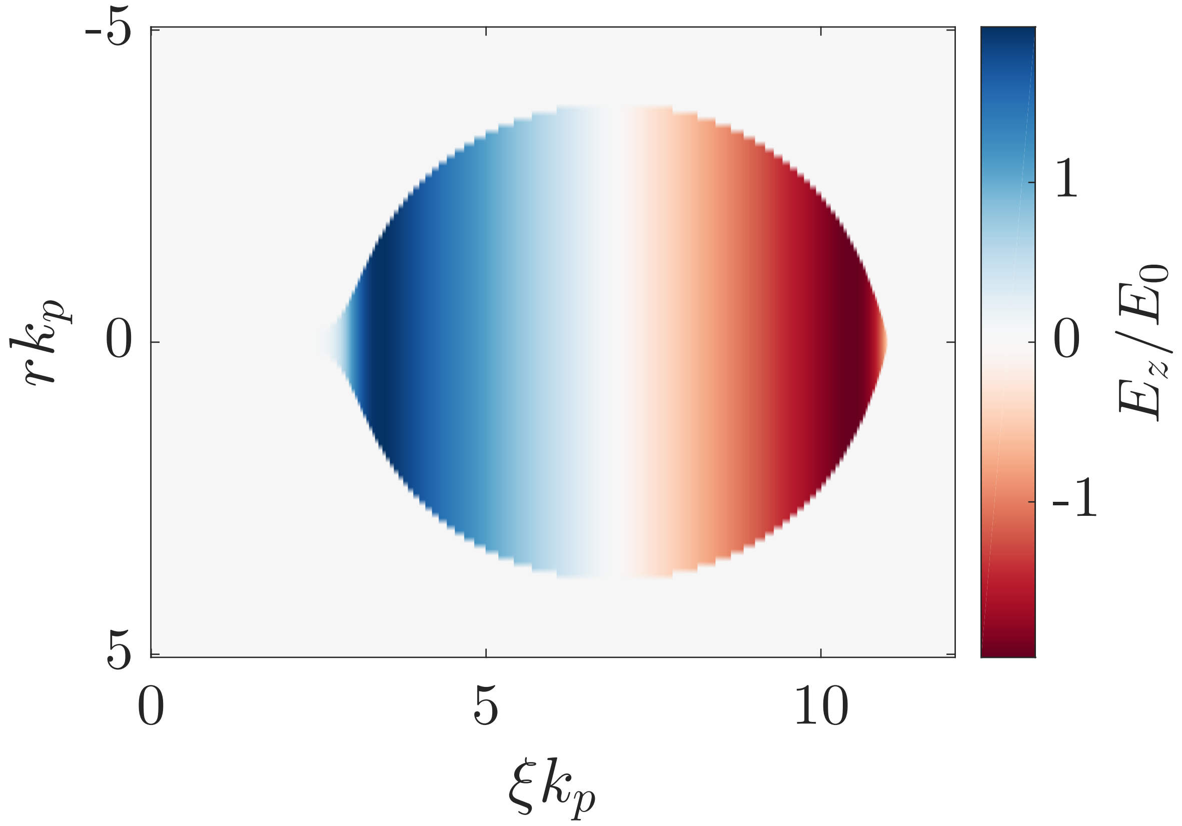

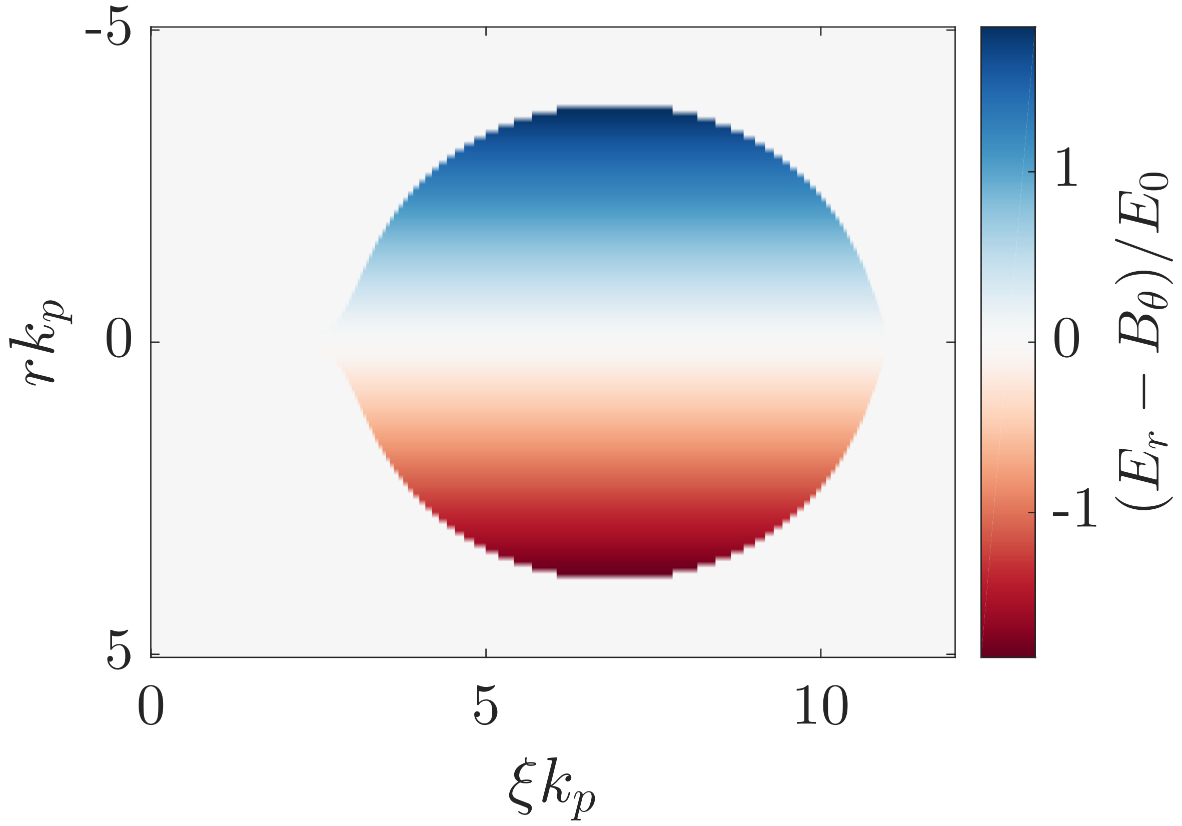

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- Intensity dependent matched spot size

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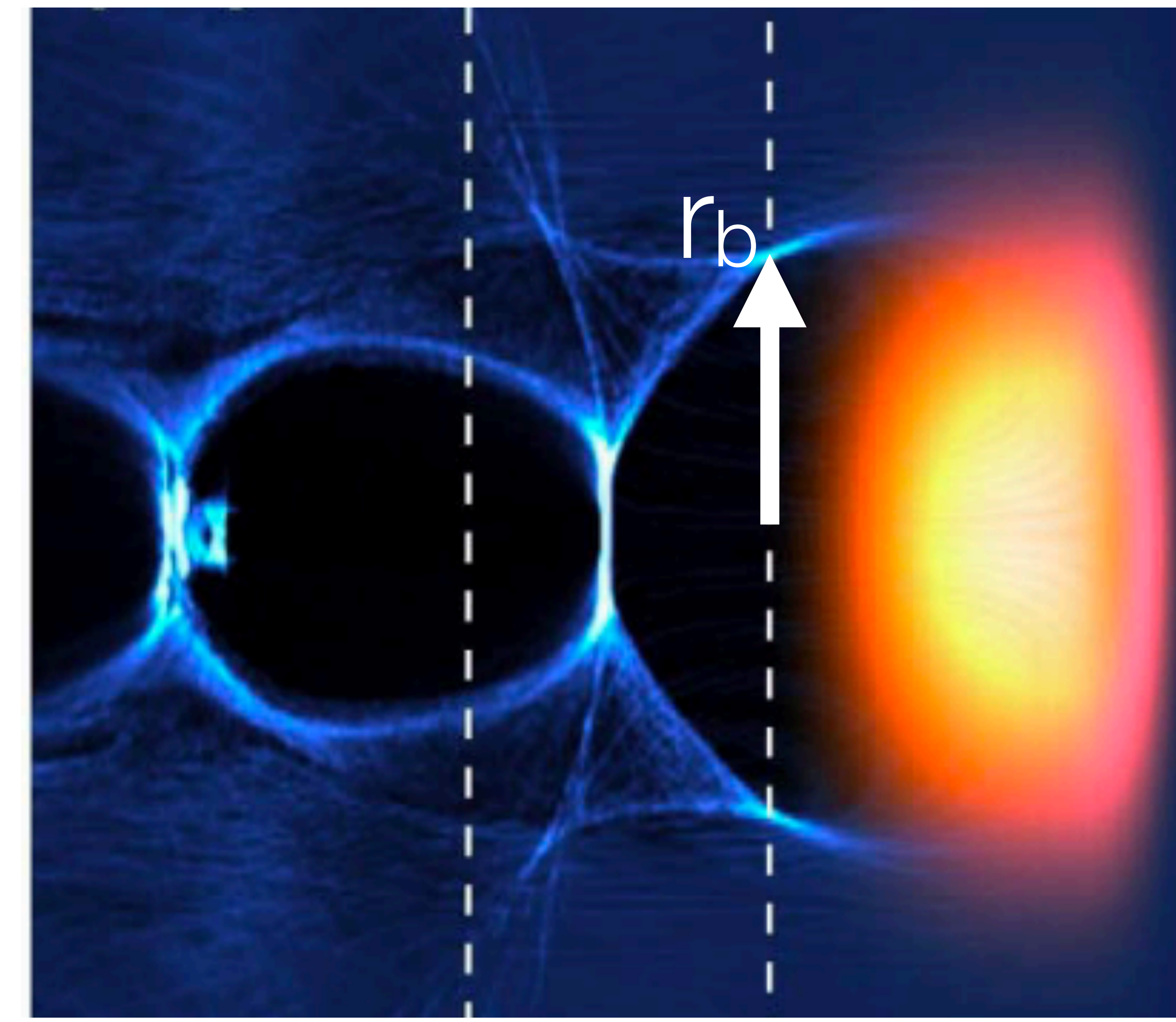

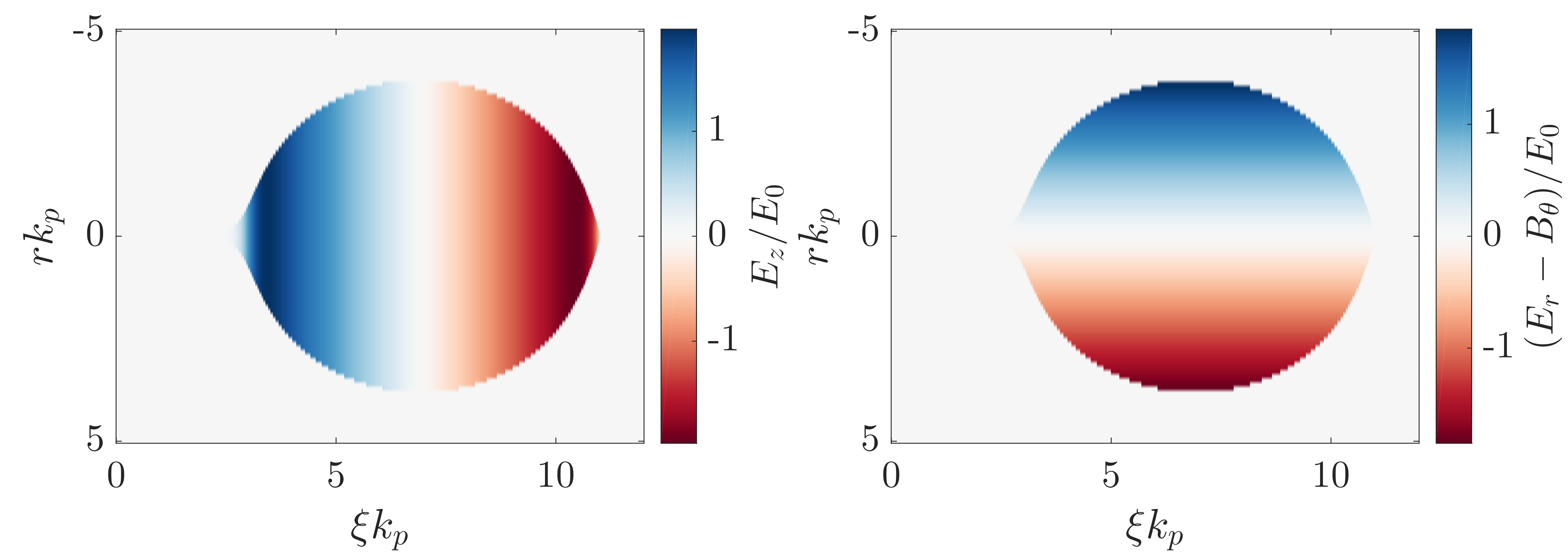

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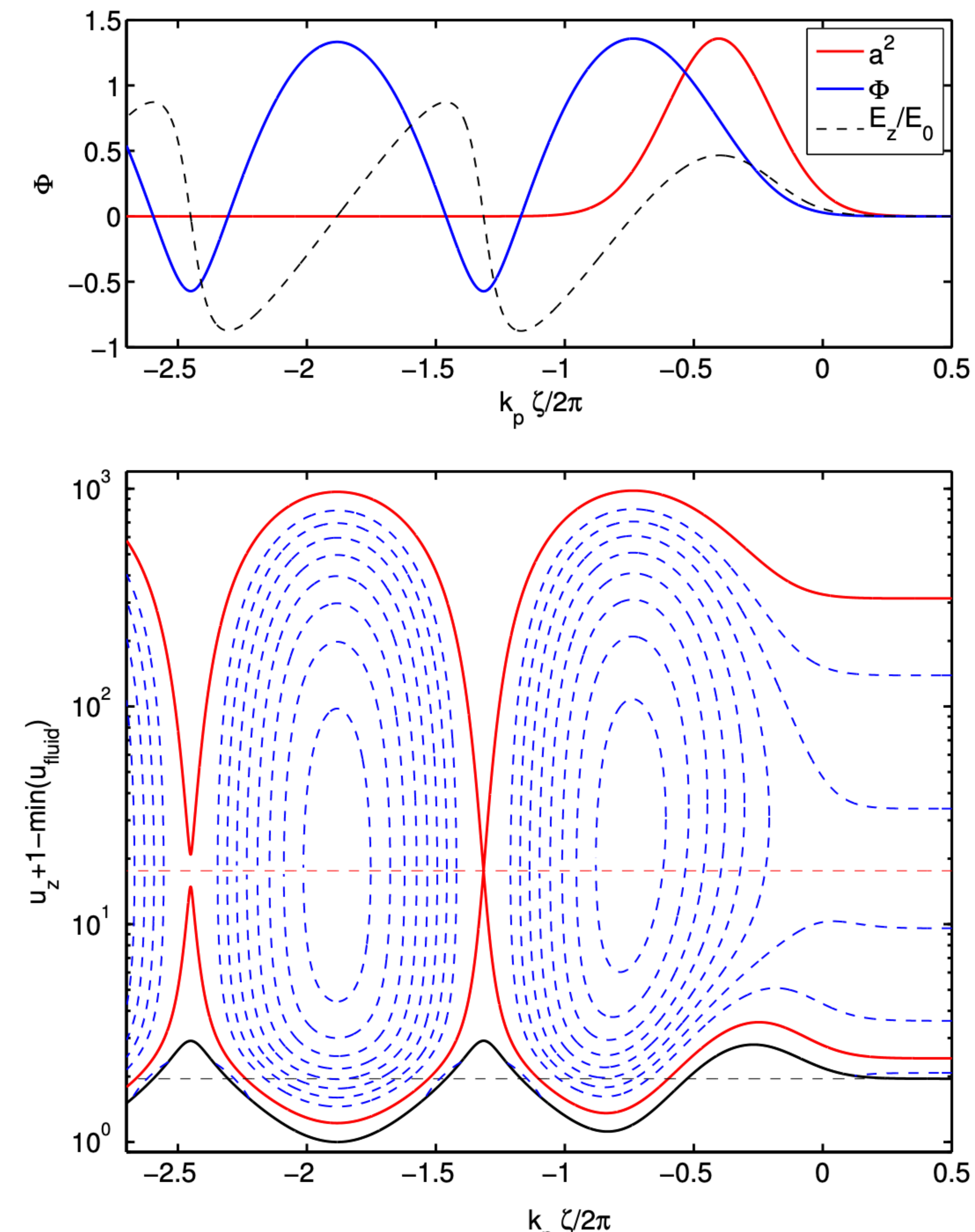

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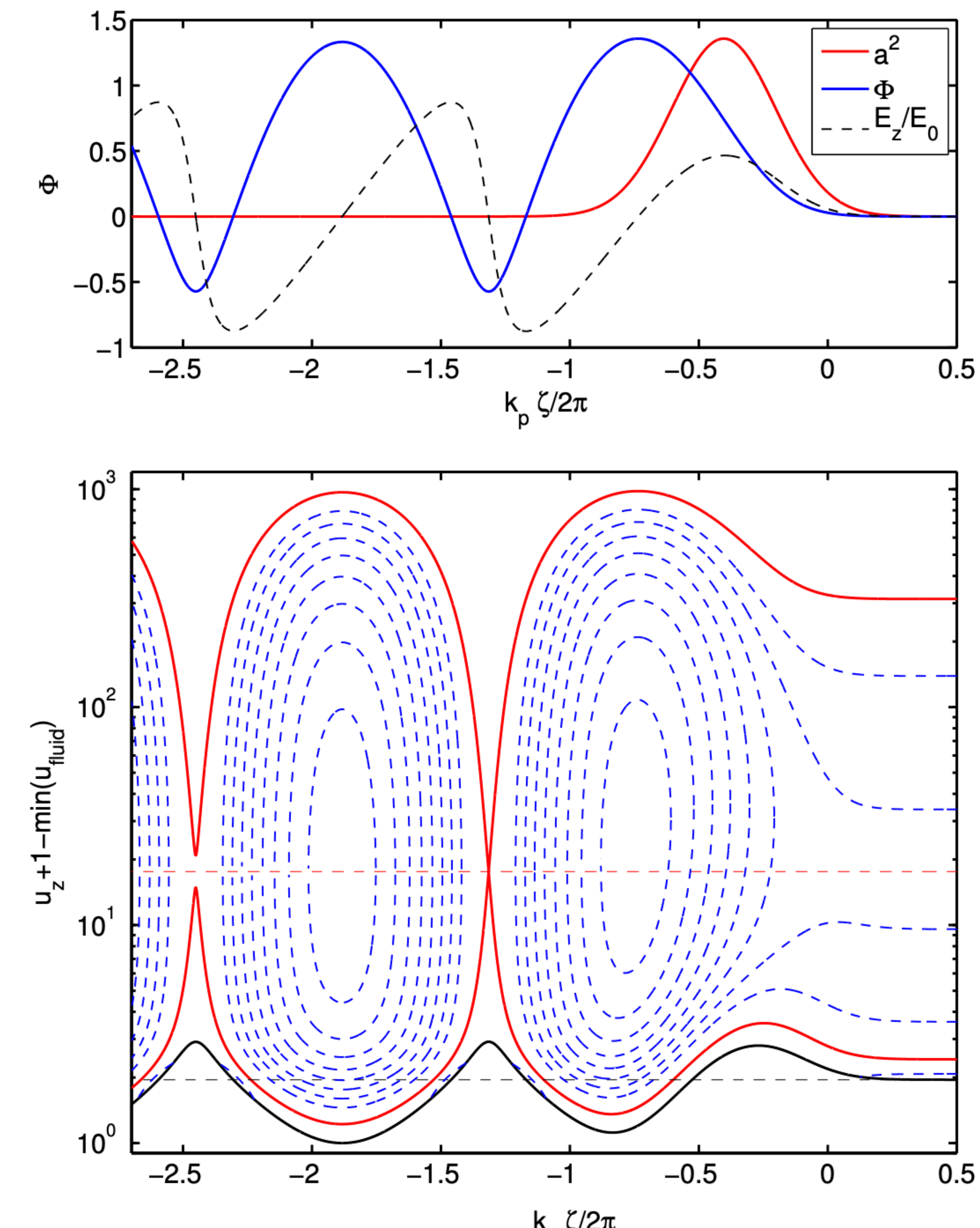

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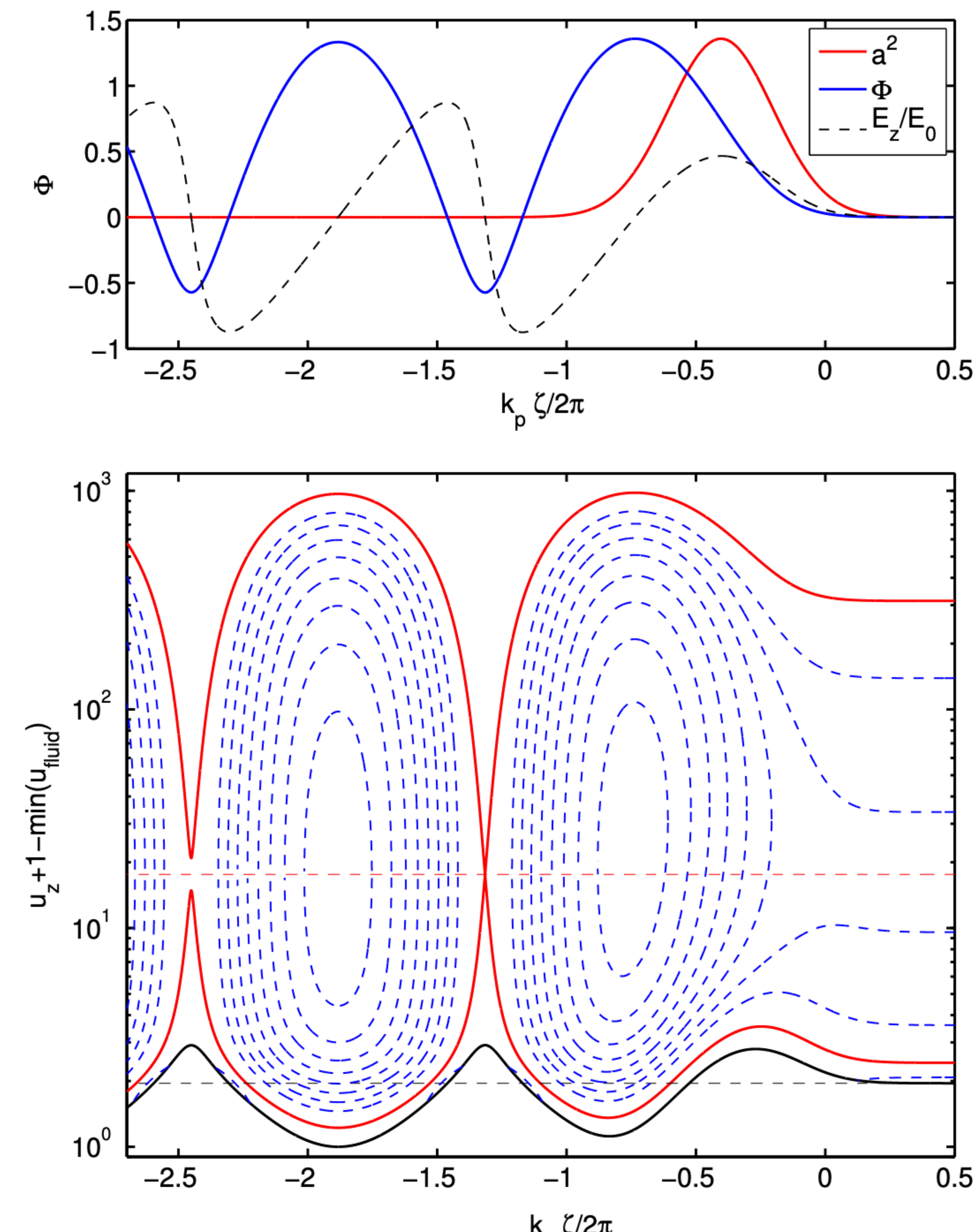

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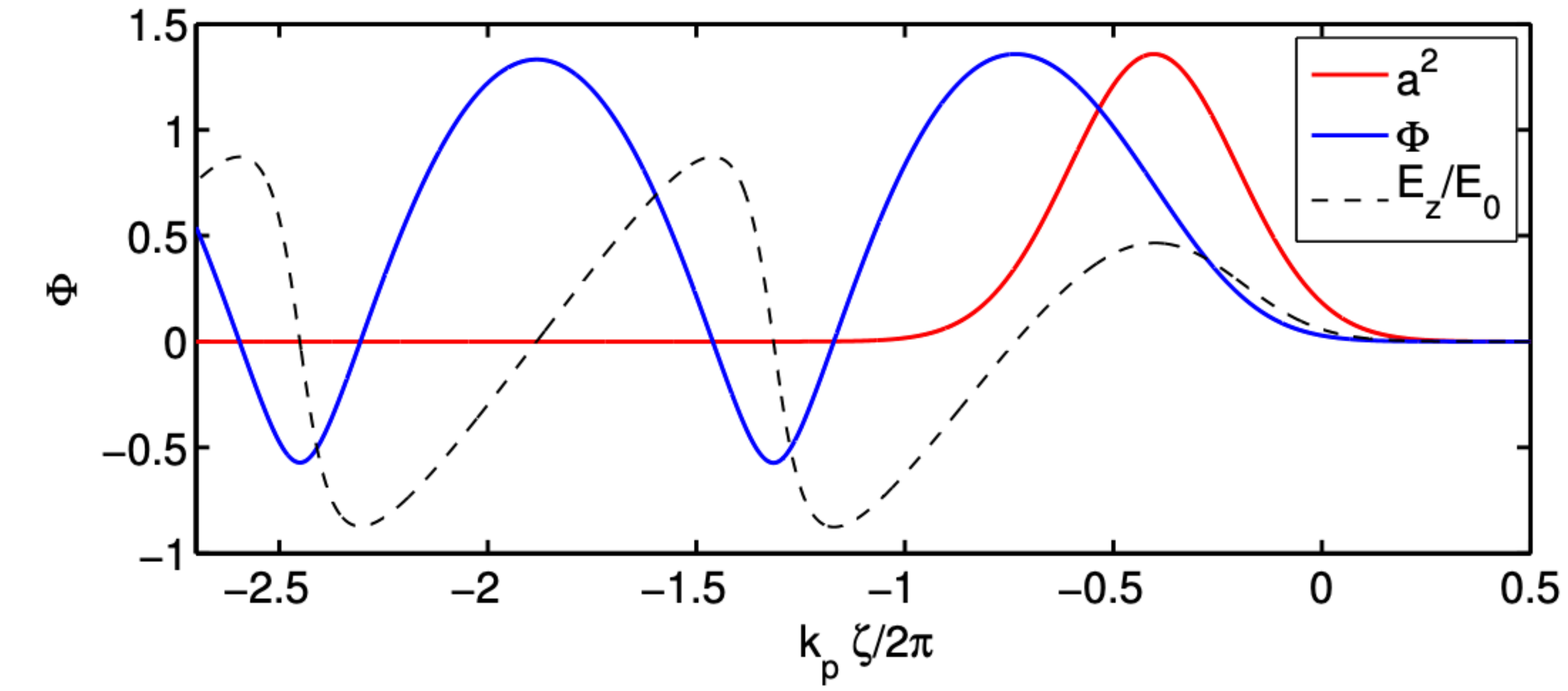

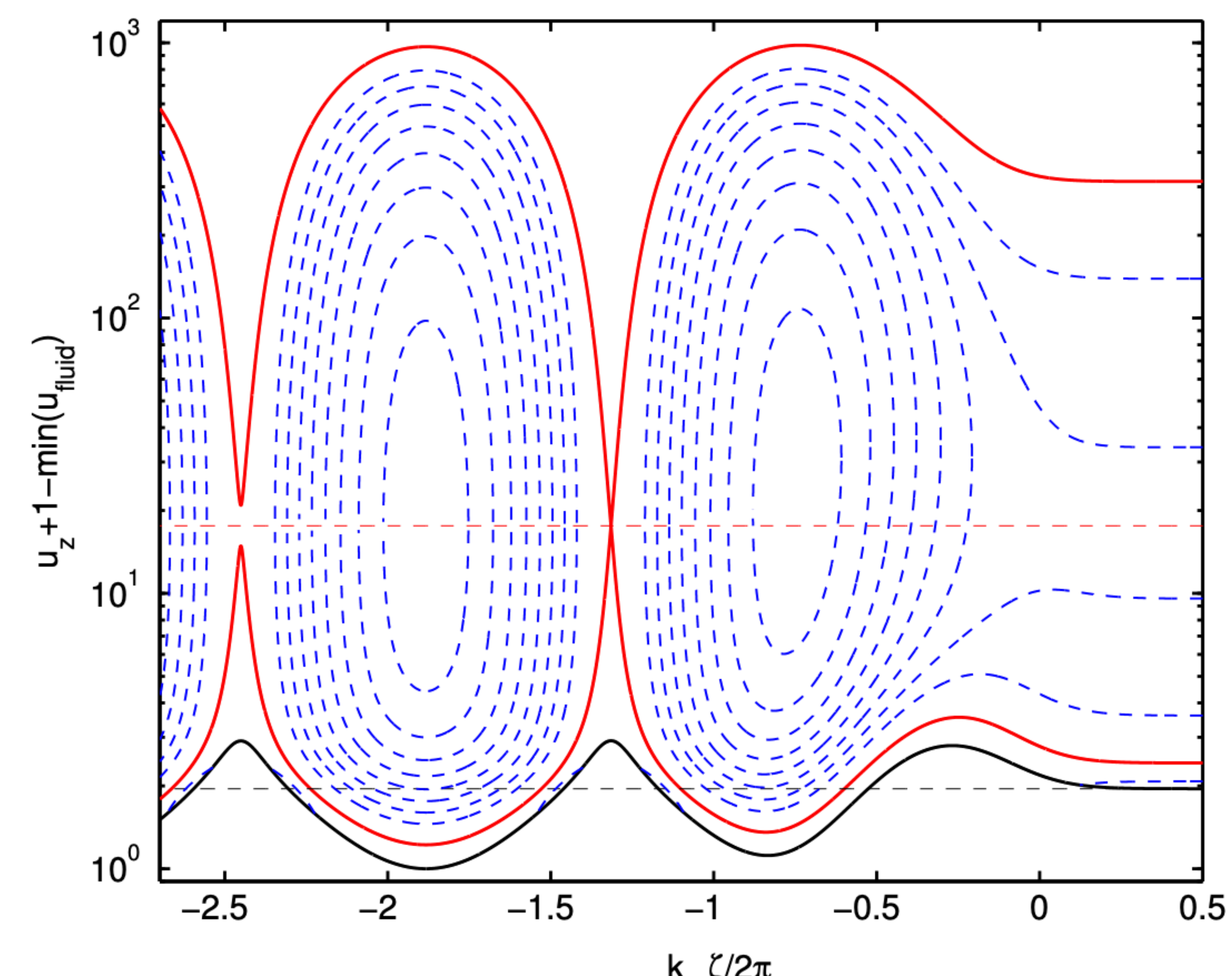

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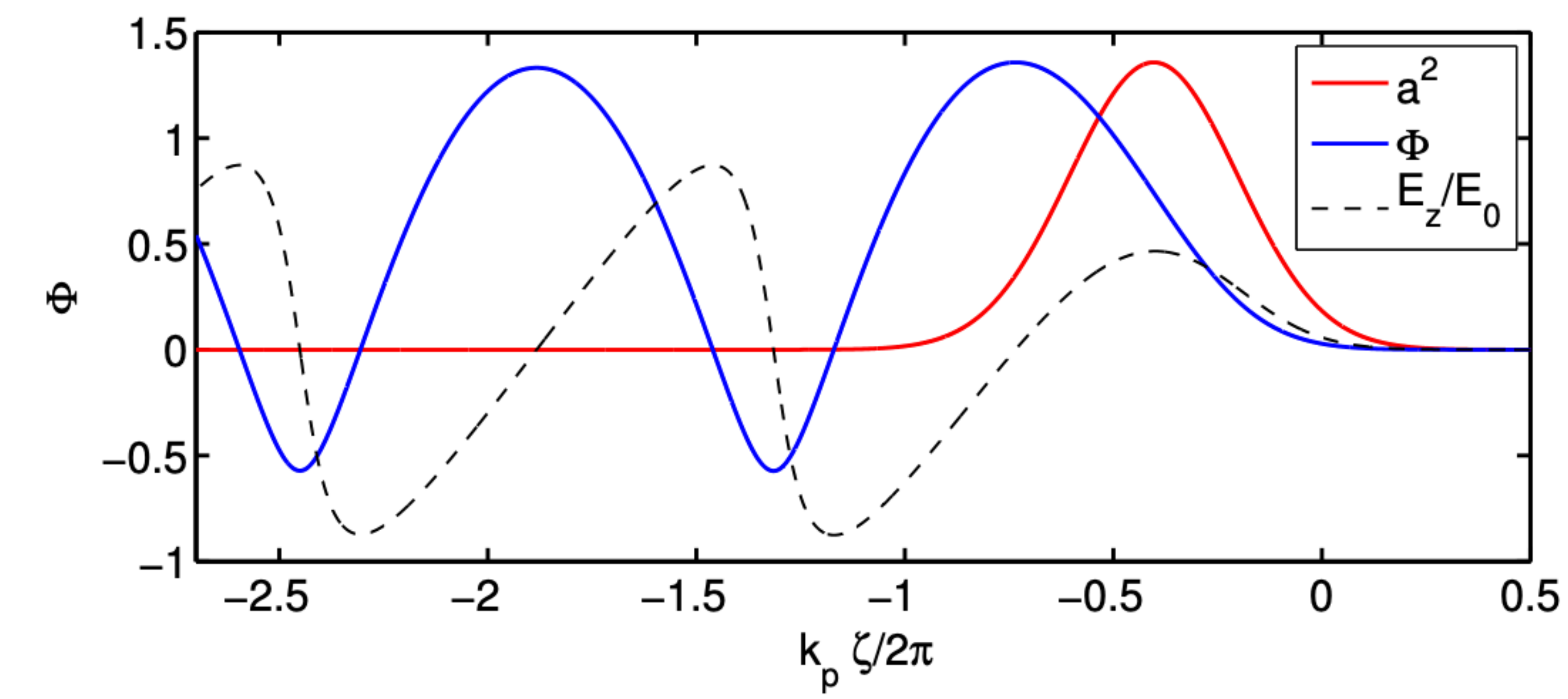

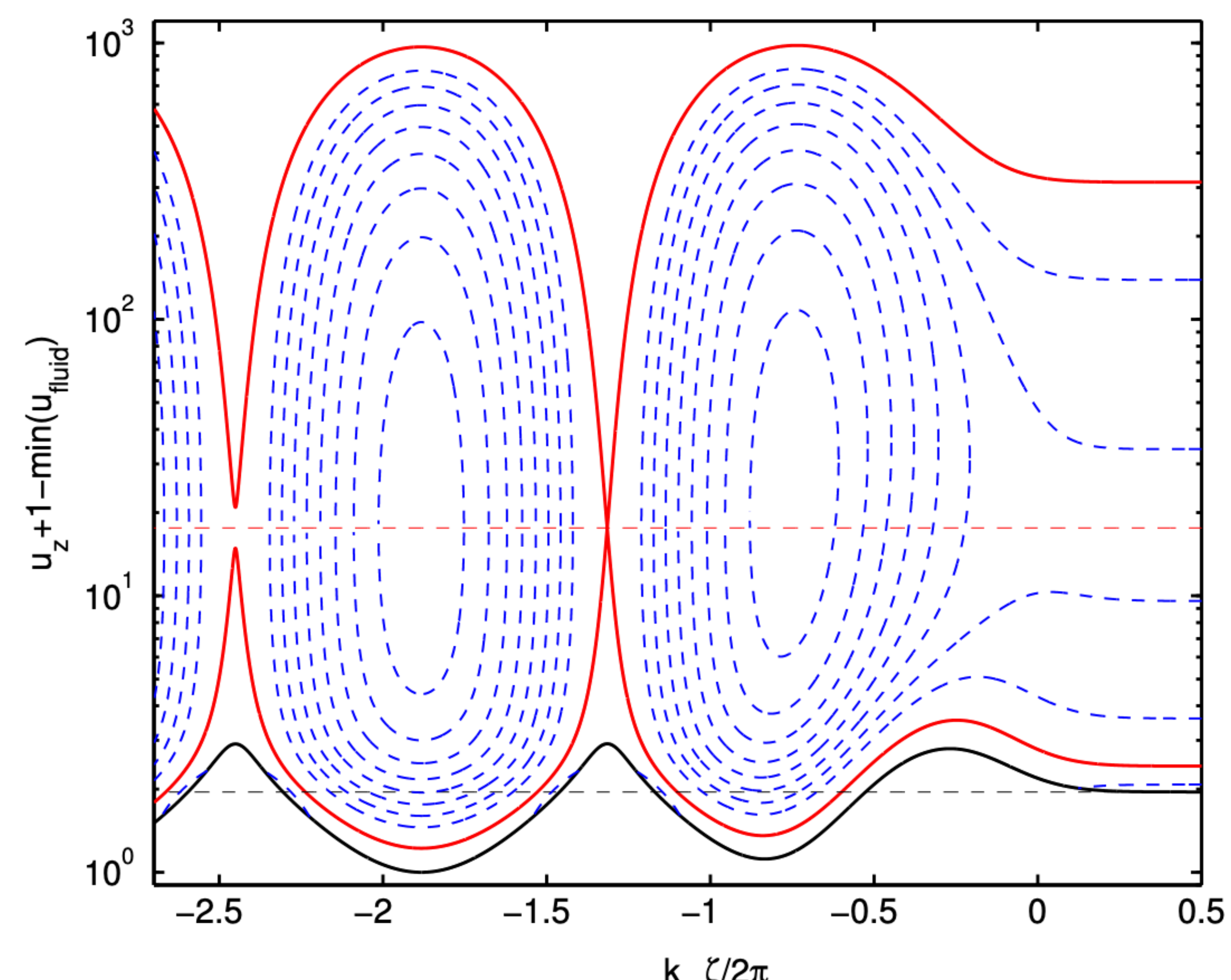

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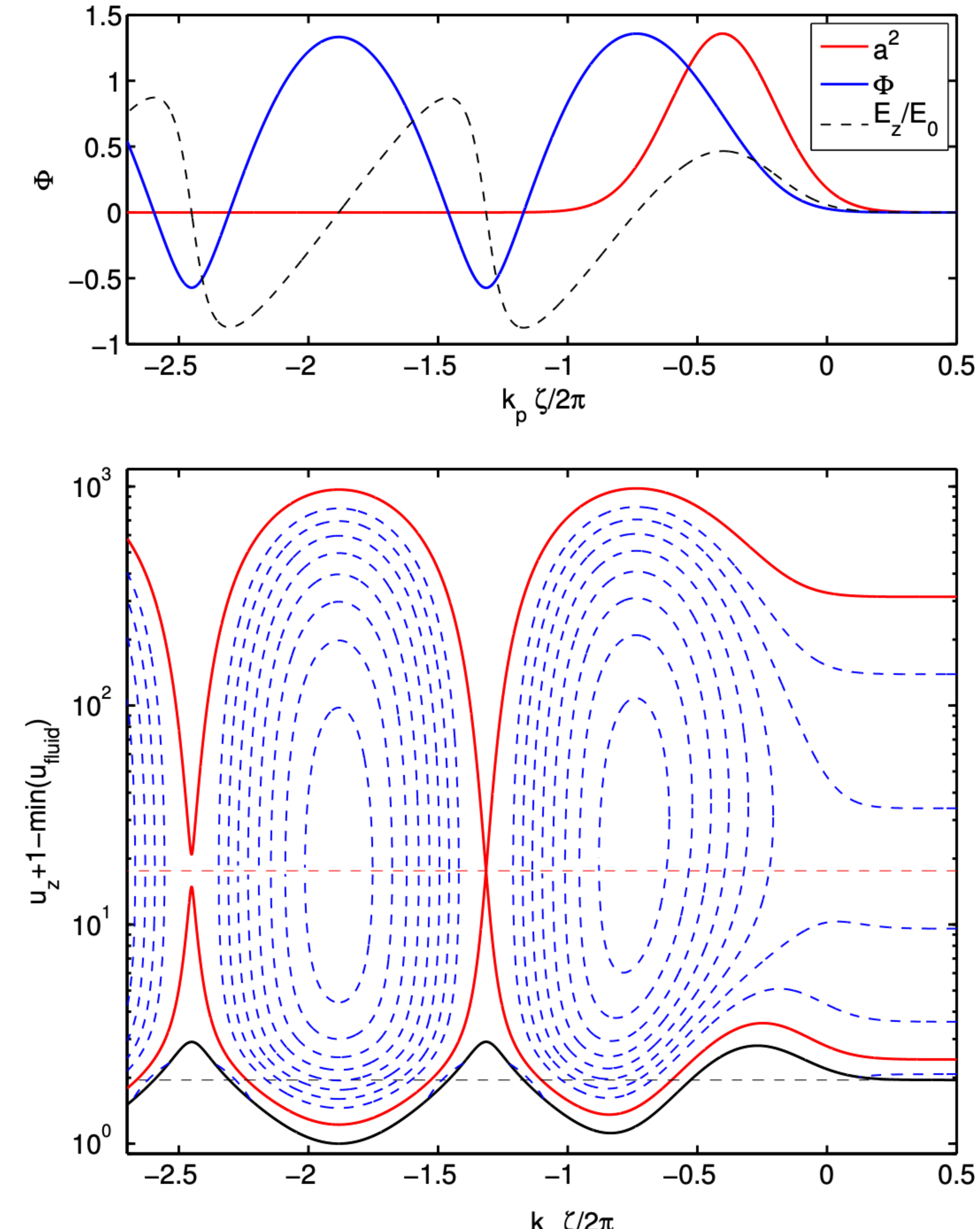

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Injection is key to beam quality in plasma accelerators

Different injection techniques lead to greatly differing beam parameters and use cases

- Injection is the process of putting electrons into the acceleration cavity [5,13]
  - Wake moves at ~c, plasma electrons ~stationary.
  - Plasma electrons need long. momentum!
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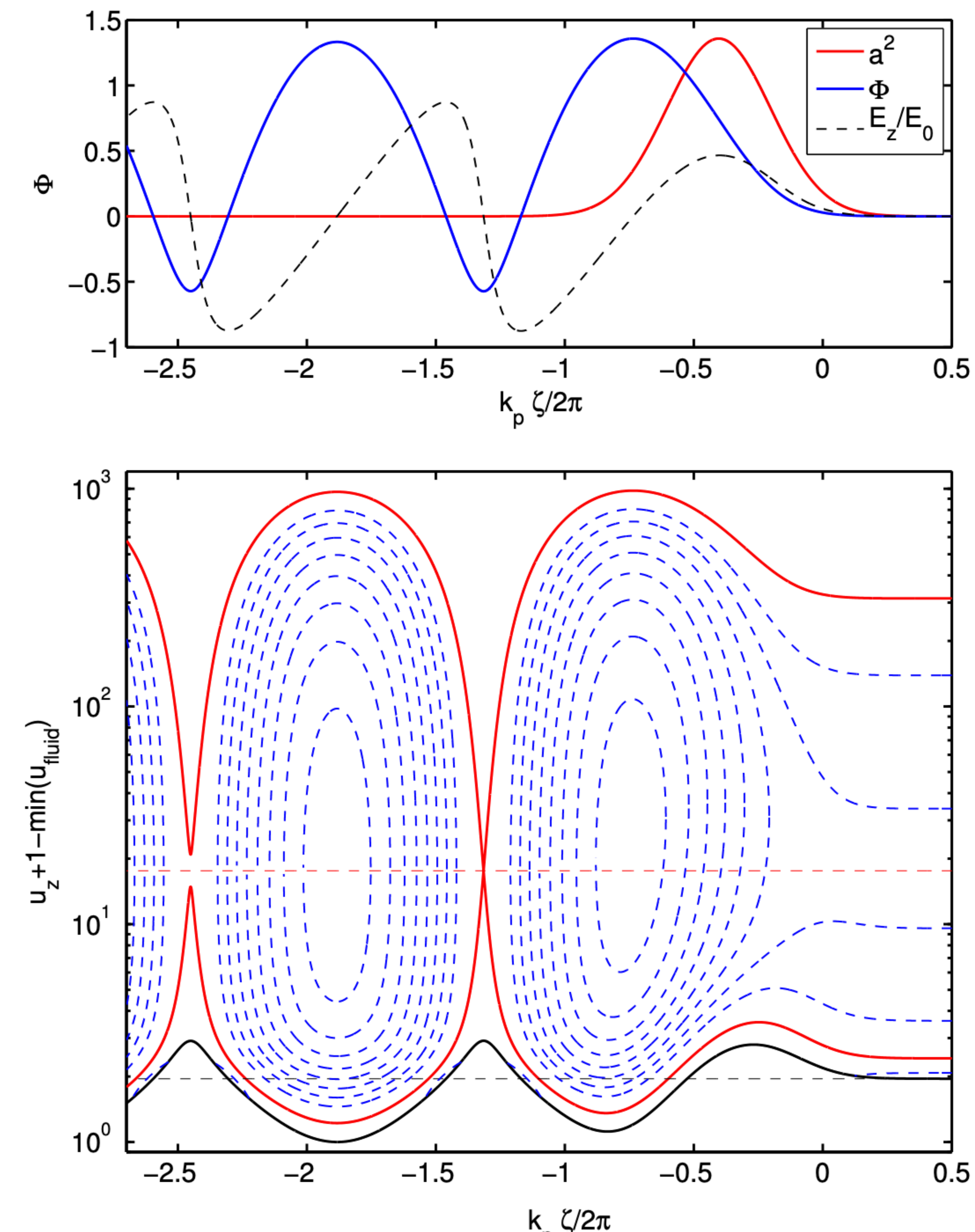

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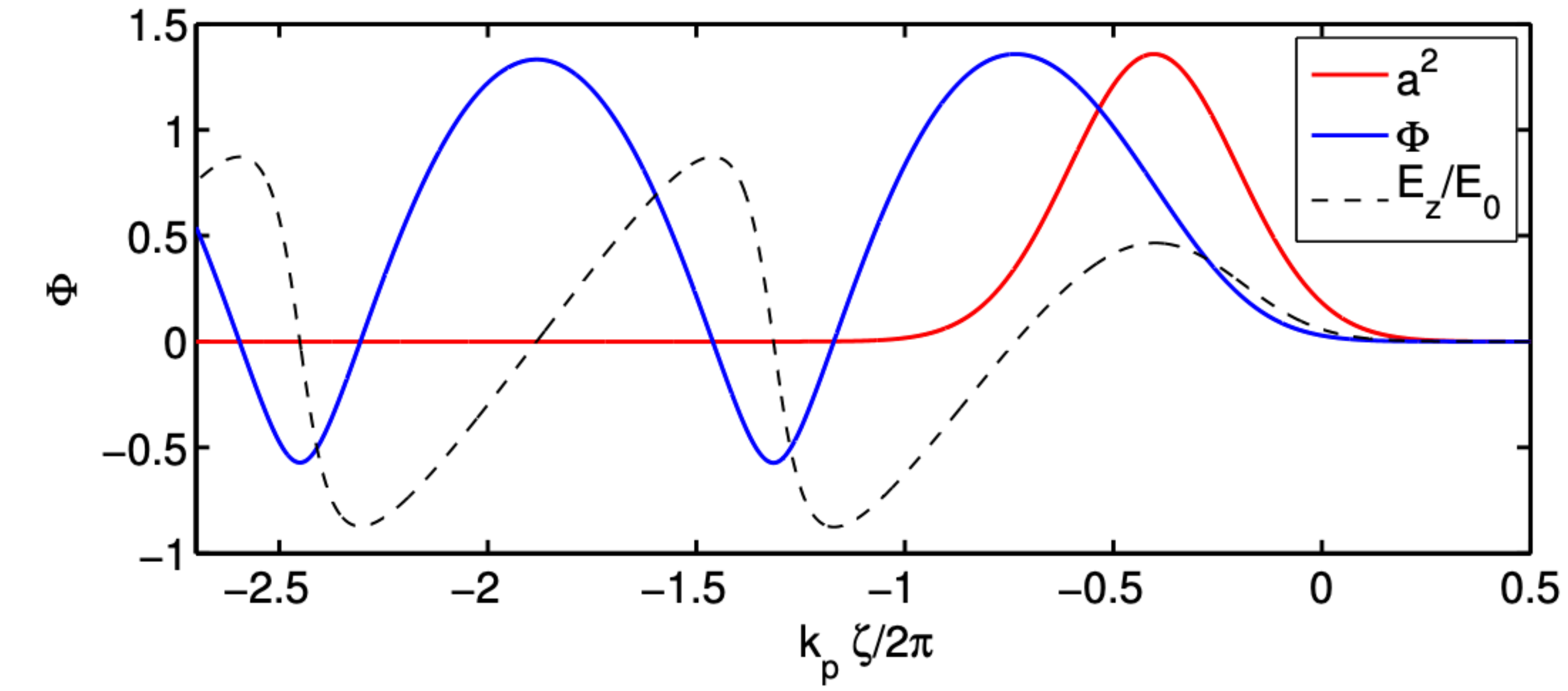

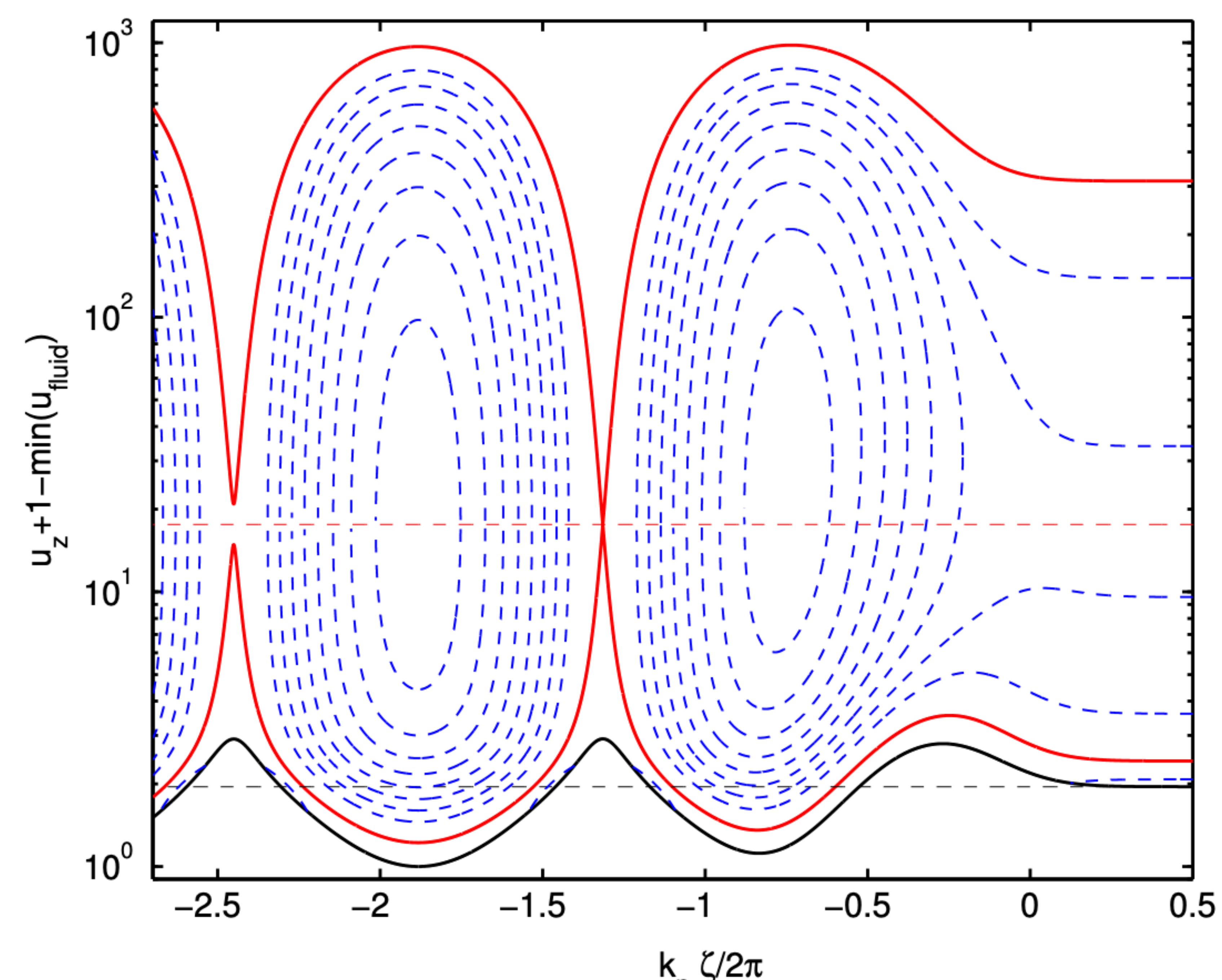

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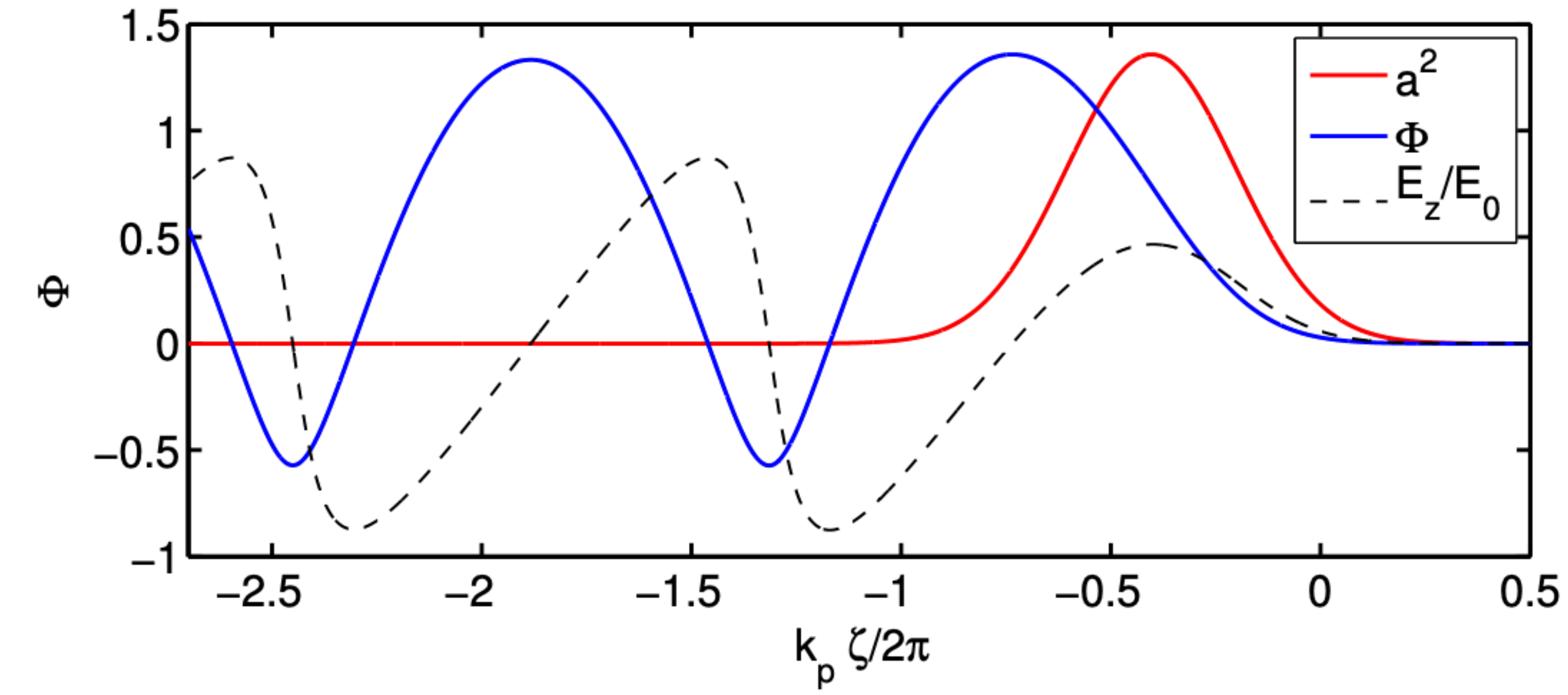

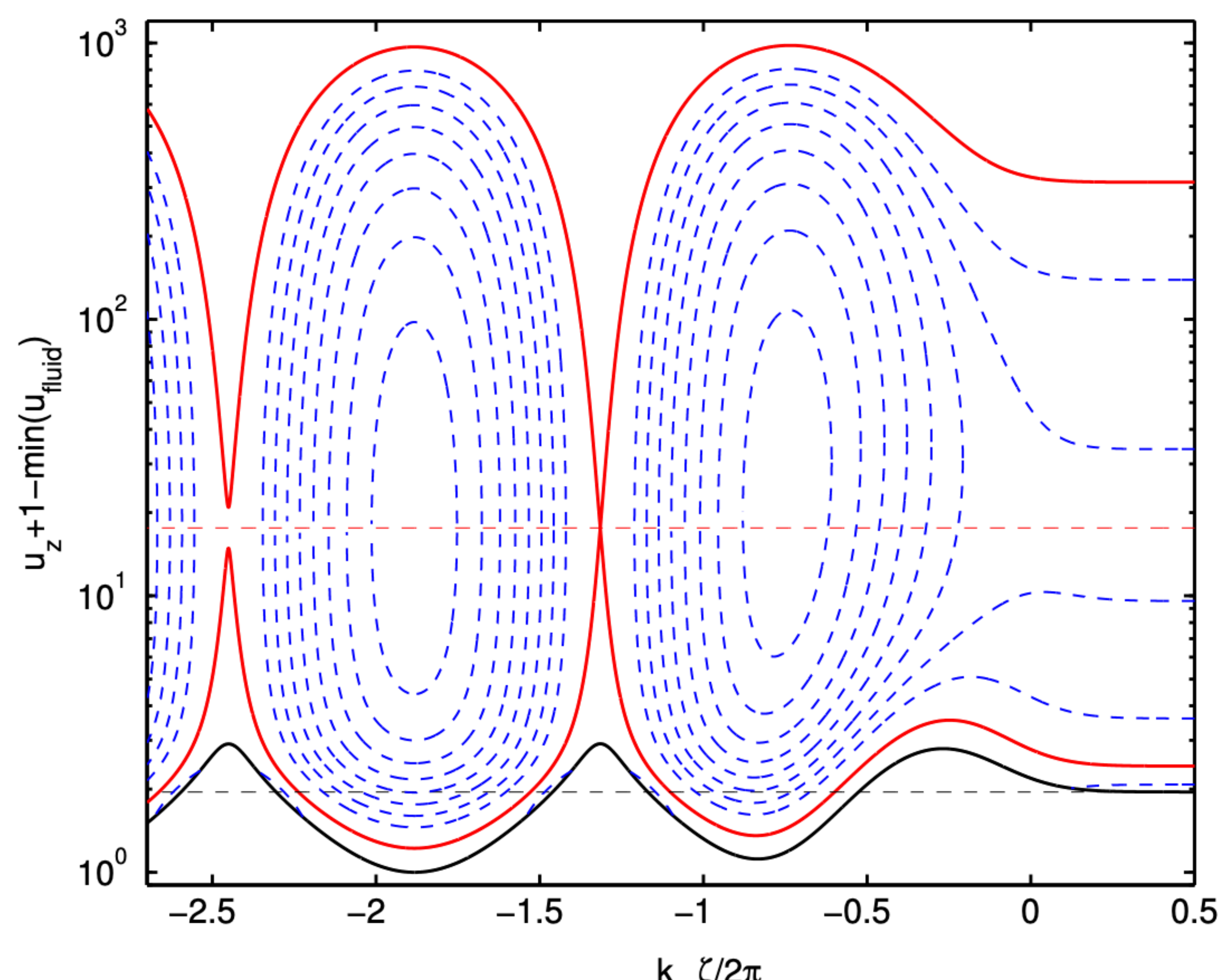

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Limitations of plasma accelerators

The so called 3Ds are fundamental limits for LPAs - but can be overcome with clever design

Dephasing

$$v_{e^-} > v_g$$

Relativistic electrons outrun the wake

$$k_p L_d = \frac{4}{3} \left(\frac{\omega_L}{\omega_p} \right)^2 \sqrt{a_0}$$

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Depletion

$$\nu_{etch} = c\left(\frac{\omega_p}{\omega_L}\right)^2$$

Laser pulse loses its energy driving the wake

$$L_{pd} = \left(\frac{\omega_L}{\omega_p}\right)^2 c\tau$$

Need longer pulse durations

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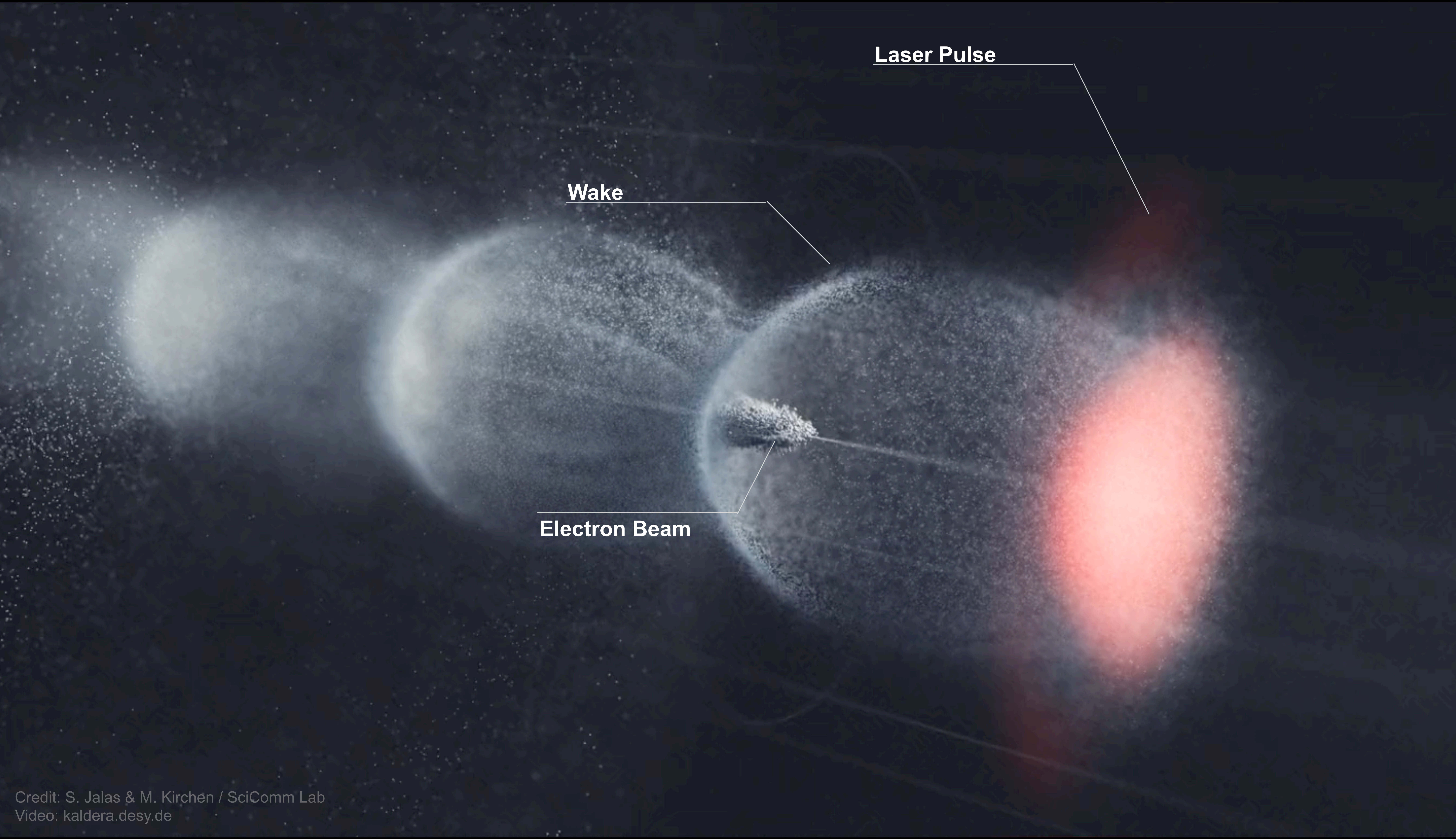
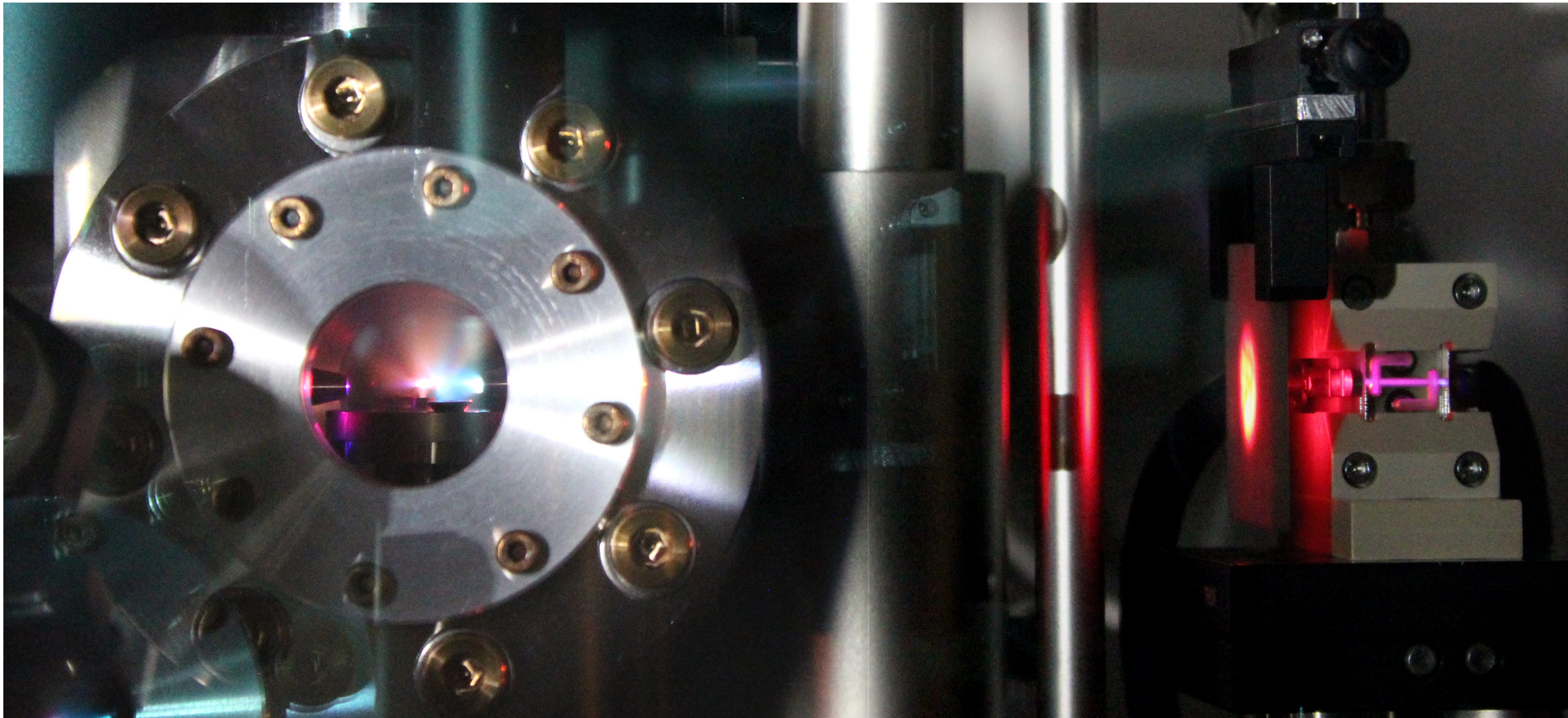

Laser Pulse
Wake
Electron Beam
Credit: S. Jalas & M. Kirchen / SciComm Lab
Video: kaldera.desy.de

Laser plasma accelerator in action

Compact plasma technology also spans plasma-based focussing optics



Plasma accelerators have undergone huge progress

2004 “Dream Beam” experiments sparked intense effort across the world

letters to nature

Monoenergetic beams of relativistic electrons from intense laser–plasma interactions

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[2] *Central Laser Facility, Rutherford Appleton Laboratory, Chilton, Didcot, Oxon, OX11 0QX, UK*
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GeV electron beams from a centimetre-scale accelerator

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[2]University of Oxford, Clarendon Laboratory, Parks Road, Oxford OX1 3PU, UK
[3]Nuclear Professional School, University of Tokyo, 22-2 Shirane-shirakata, Tokai, Naka, Ibaraki 319-1188, Japan
*Also at: Physics Department, University of Nevada, Reno, Nevada 89557, USA
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ARTICLE

Received 2 Dec 2012 | Accepted 8 May 2013 | Published 11 Jun 2013 DOI: 10.1038/ncomms2988 OPEN

Quasi-monoenergetic laser-plasma acceleration of electrons to 2 GeV

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Selected for a Viewpoint in *Physics*
PRL **113,** 245002 (2014) PHYSICAL REVIEW LETTERS week ending 12 DECEMBER 2014

Multi-GeV Electron Beams from Capillary-Discharge-Guided Subpetawatt Laser Pulses in the Self-Trapping Regime

W. P. Leemans,[1,2,*] A. J. Gonsalves,[1] H.-S. Mao,[1] K. Nakamura,[1] C. Benedetti,[1] C. B. Schroeder,[1] Cs. Tóth,[1] J. Daniels,[1]
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[1]*Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA*
[2]*Department of Physics, University of California, Berkeley, California 94720, USA*

(Received 3 July 2014; revised manuscript received 11 September 2014; published 8 December 2014)

Multi-GeV electron beams with energy up to 4.2 GeV, 6% rms energy spread, 6 pC charge, and 0.3 mrad rms divergence have been produced from a 9-cm-long capillary discharge waveguide with a plasma density of $\approx 7 \times 10^{17}$ cm^{-3}, powered by laser pulses with peak power up to 0.3 PW. Preformed plasma waveguides

Plasma accelerators have undergone huge progress

2004 “Dream Beam” experiments sparked intense effort across the world

PHYSICAL REVIEW LETTERS **122,** 084801 (2019)

Editors' Suggestion | Featured in Physics

Petawatt Laser Guiding and Electron Beam Acceleration to 8 GeV in a Laser-Heated Capillary Discharge Waveguide

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[4]*National Research Nuclear University MEPhI (Moscow Engineering Physics Institute), Moscow 115409, Russia*
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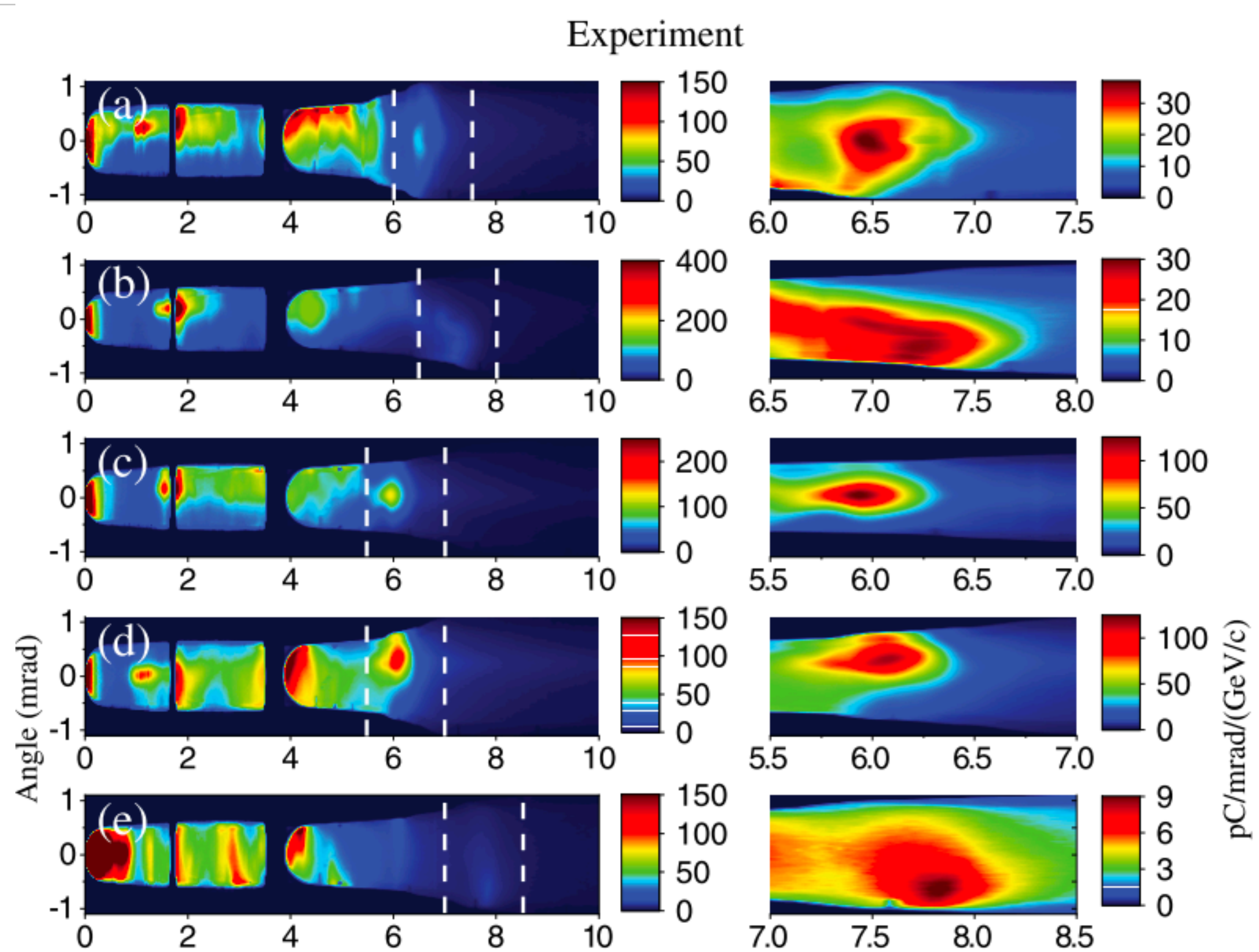

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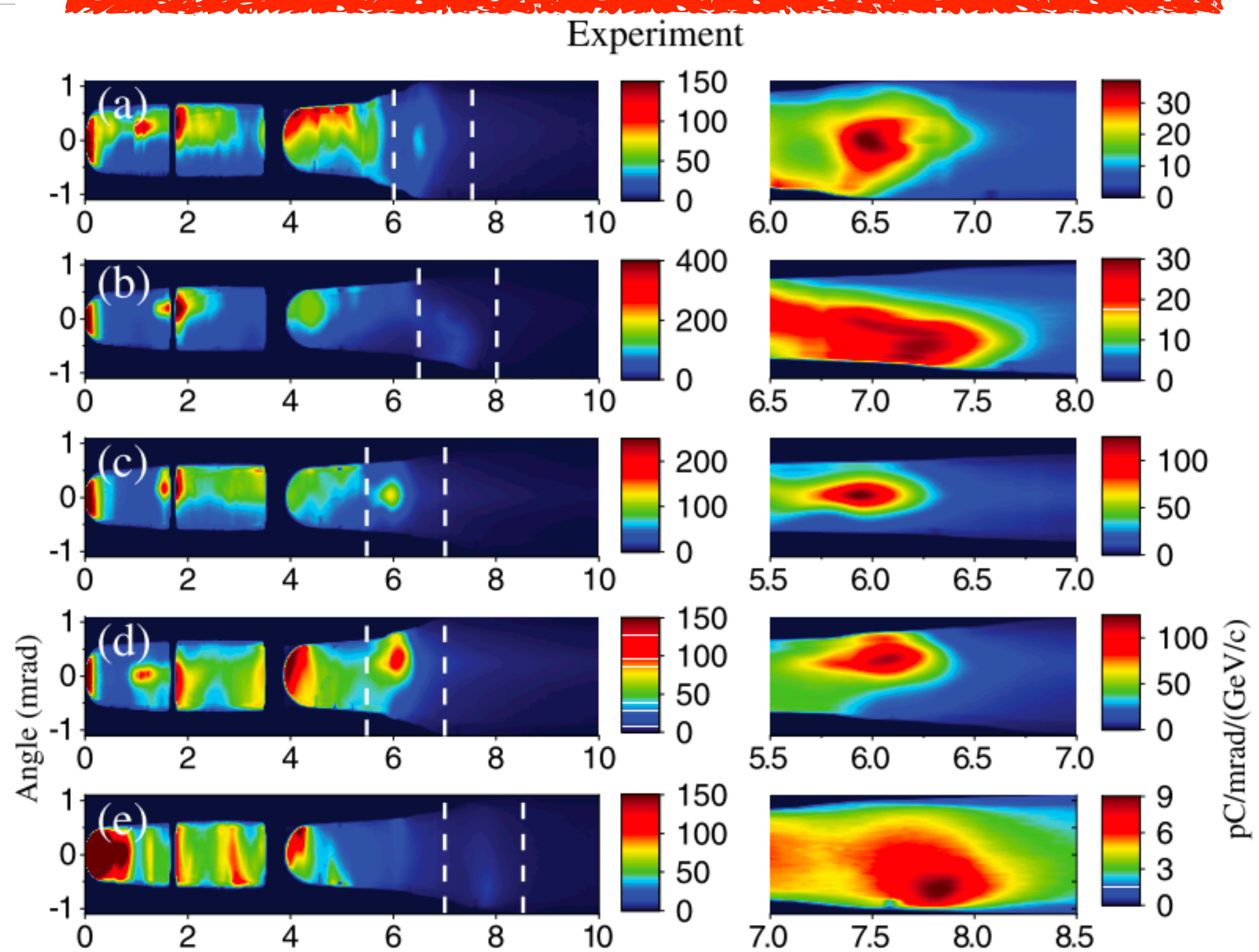
8 GeV, 0.2m: 40 GV/m!



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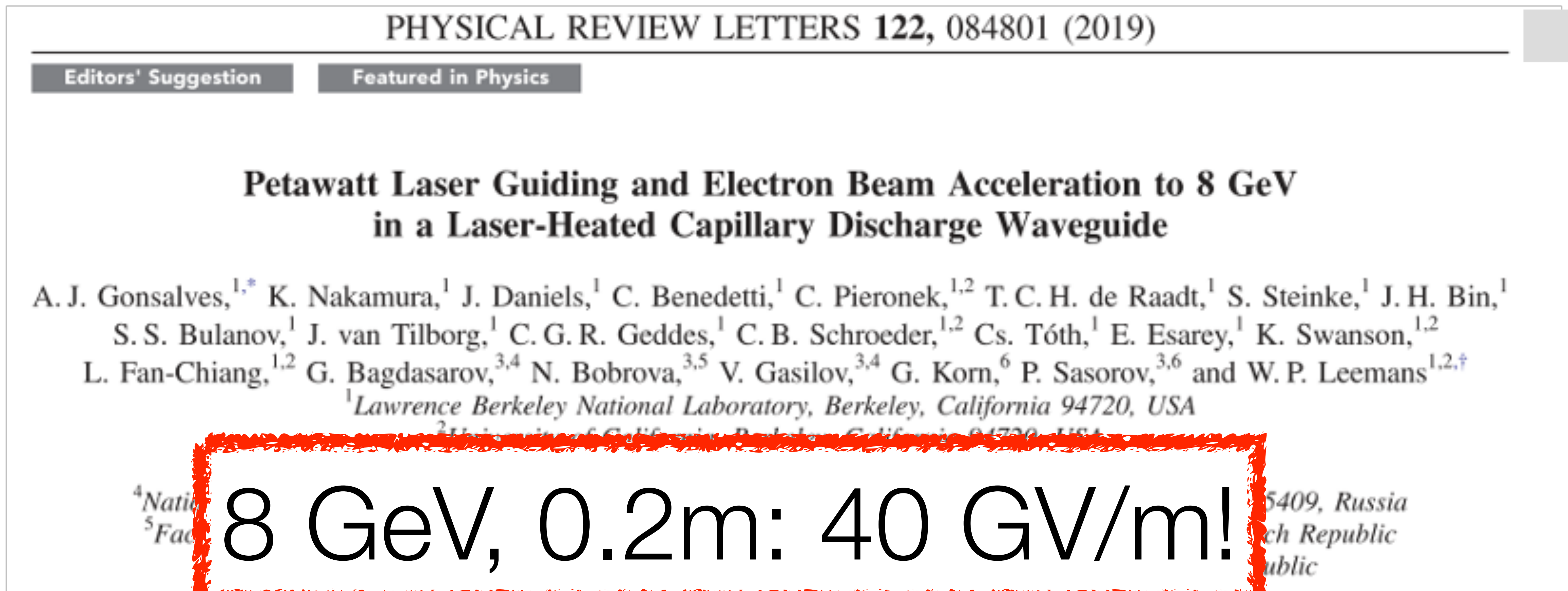
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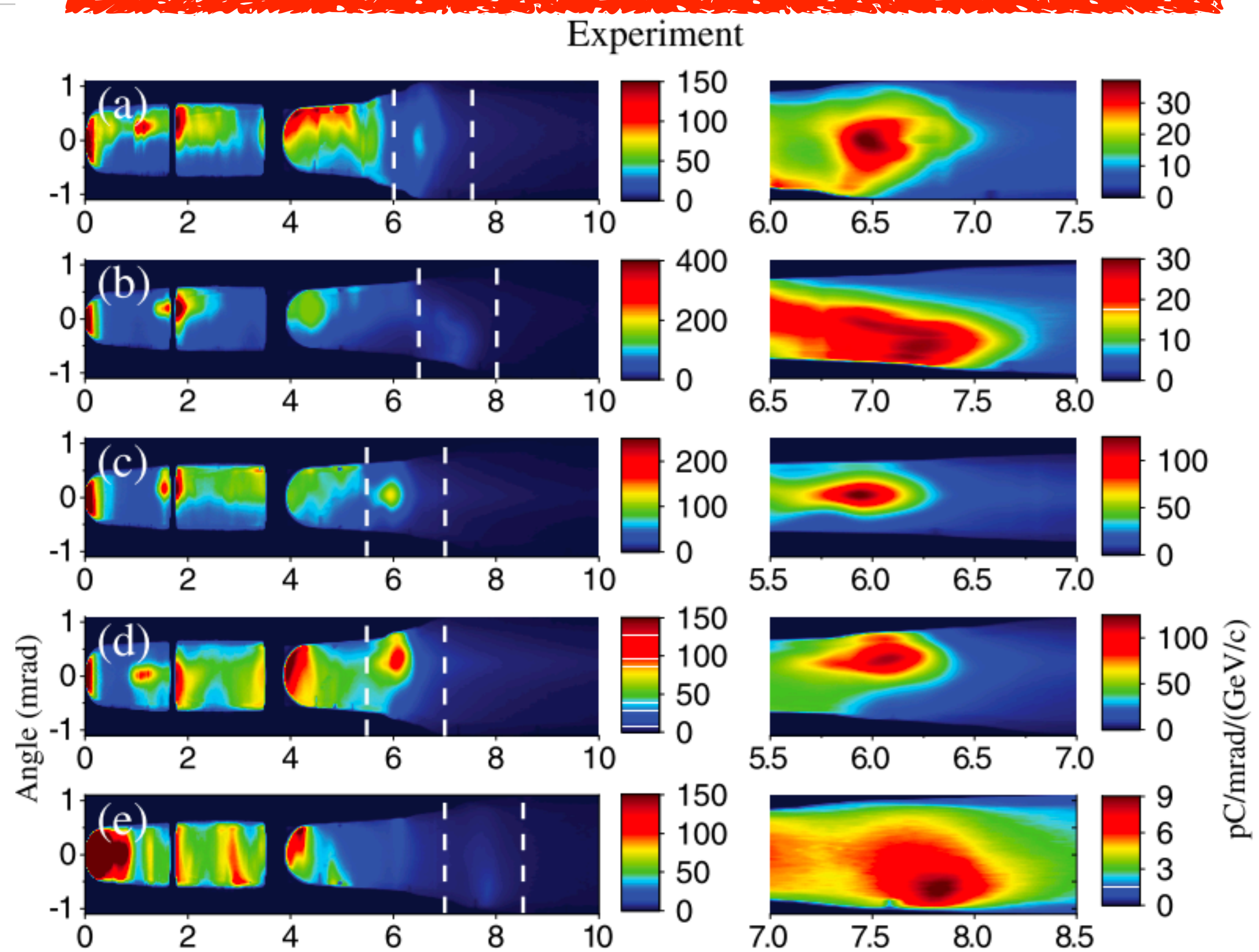

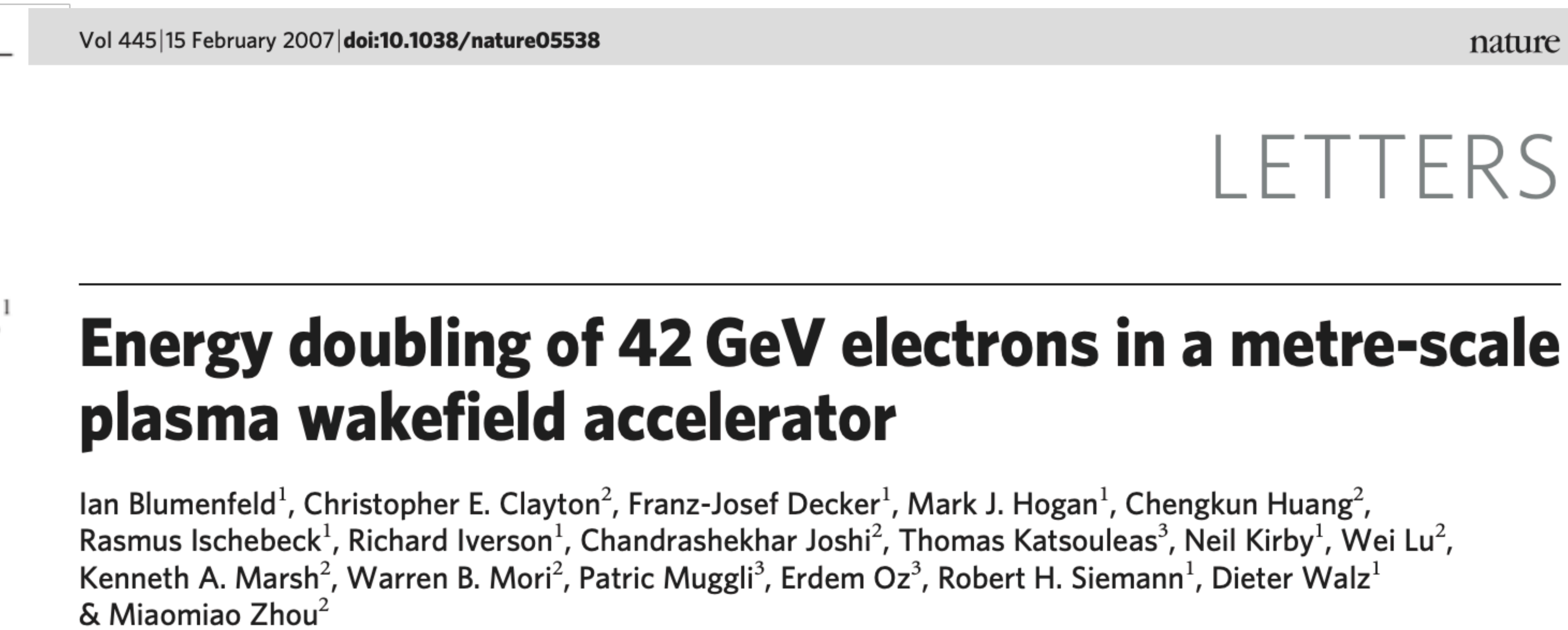
Vol 445|15 February 2007|doi:10.1038/nature05538
nature

LETTERS

Energy doubling of 42 GeV electrons in a metre-scale plasma wakefield accelerator

Ian Blumenfeld[1], Christopher E. Clayton[2], Franz-Josef Decker[1], Mark J. Hogan[1], Chengkun Huang[2], Rasmus Ischebeck[1], Richard Iverson[1], Chandrashekhar Joshi[2], Thomas Katsouleas[3], Neil Kirby[1], Wei Lu[2], Kenneth A. Marsh[2], Warren B. Mori[2], Patric Muggli[3], Erdem Oz[3], Robert H. Siemann[1], Dieter Walz[1] & Miaomiao Zhou[2]

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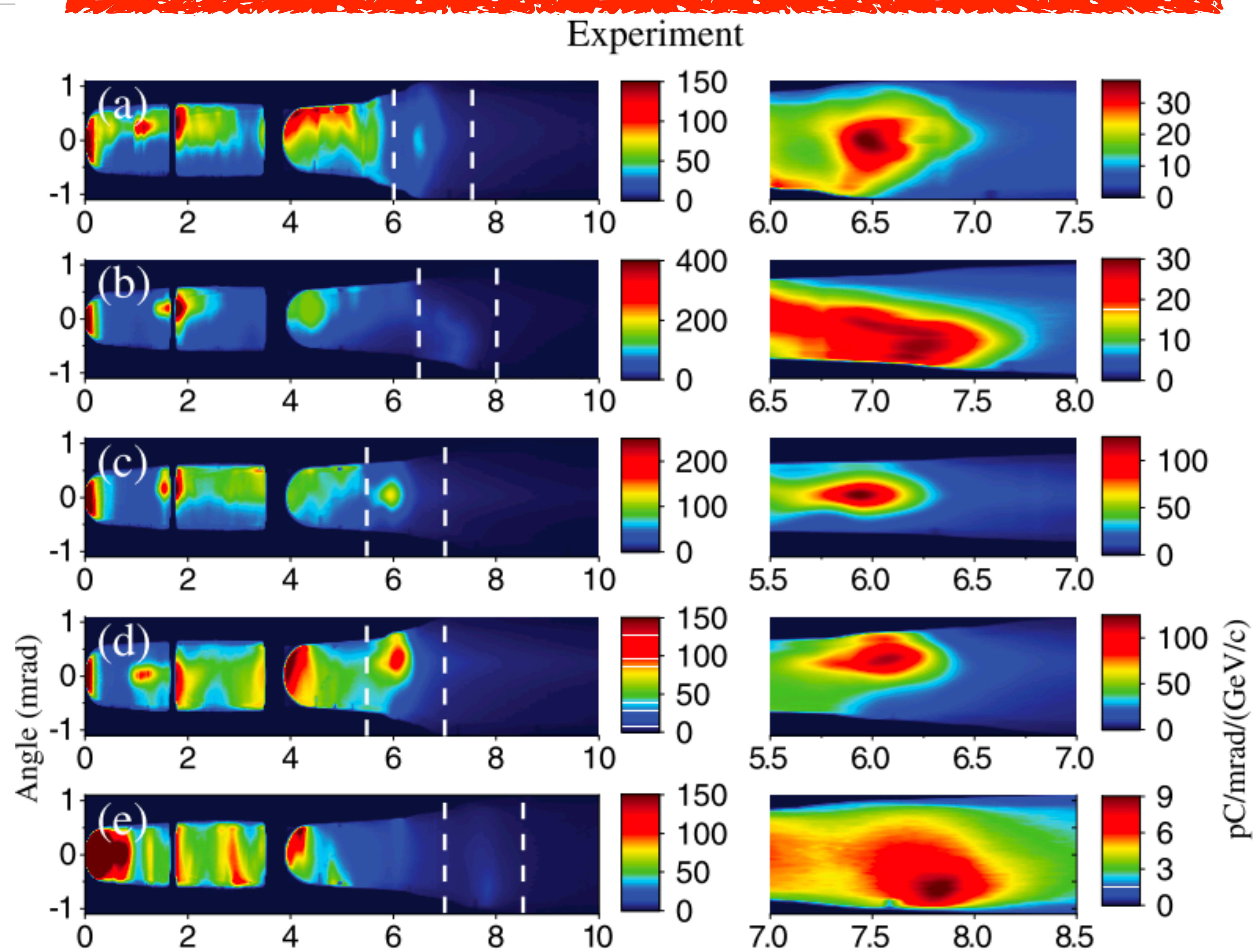

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Energy doubling of 42 GeV electrons in a metre-scale plasma wakefield accelerator

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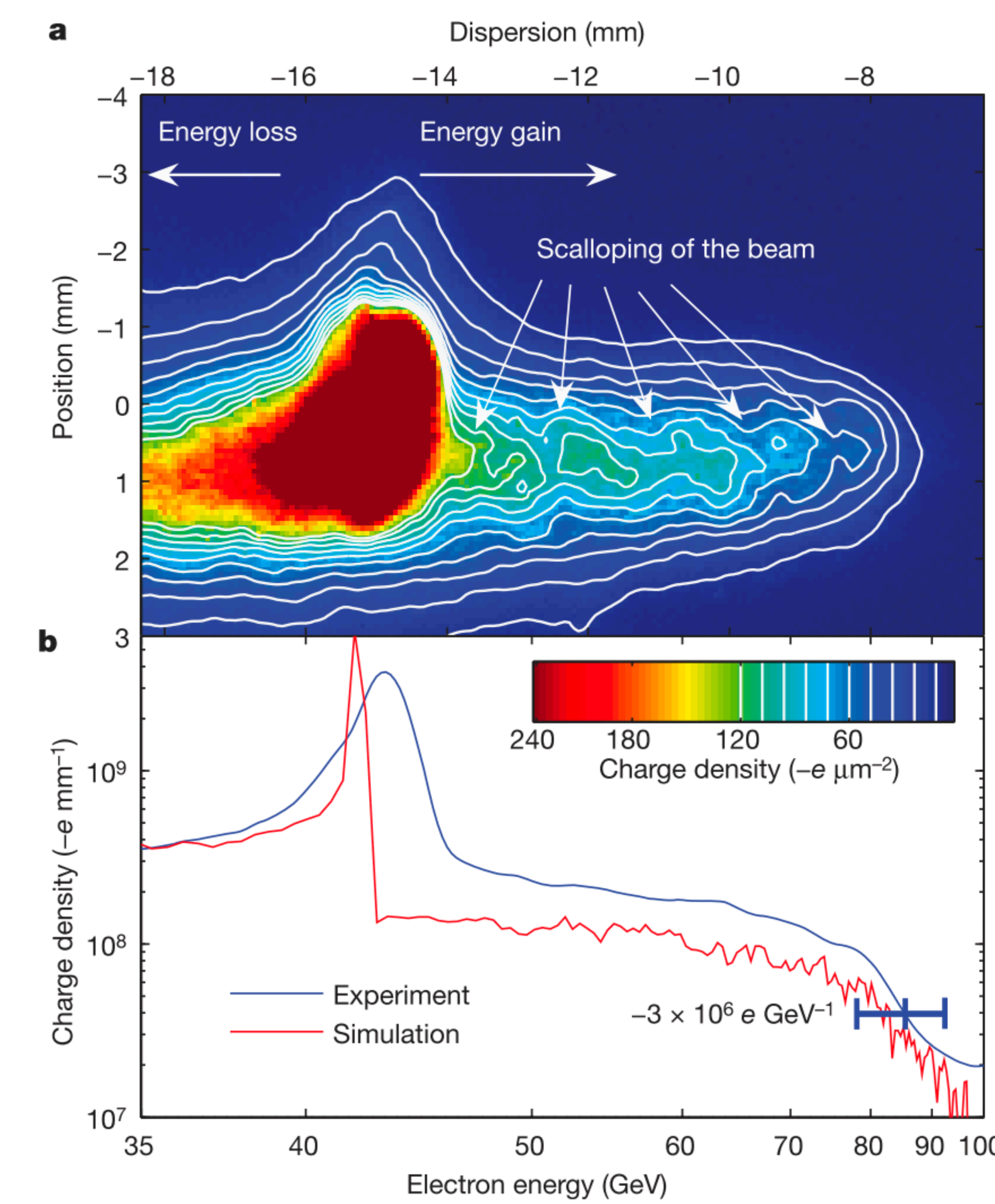


Plasma accelerators have undergone huge progress

2004 “Dream Beam” experiments sparked intense effort across the world

PHYSICAL REVIEW LETTERS **122,** 084801 (2019)

Editors' Suggestion | Featured in Physics

Petawatt Laser Guiding and Electron Beam Acceleration to 8 GeV in a Laser-Heated Capillary Discharge Waveguide

A. J. Gonsalves,[1,*] K. Nakamura,[1] J. Daniels,[1] C. Benedetti,[1] C. Pieronek,[1,2] T. C. H. de Raadt,[1] S. Steinke,[1] J. H. Bin,[1] S. S. Bulanov,[1] J. van Tilborg,[1] C. G. R. Geddes,[1] C. B. Schroeder,[1,2] Cs. Tóth,[1] E. Esarey,[1] K. Swanson,[1,2] L. Fan-Chiang,[1,2] G. Bagdasarov,[3,4] N. Bobrova,[3,5] V. Gasilov,[3,4] G. Korn,[6] P. Sasorov,[3,6] and W. P. Leemans[1,2,†]

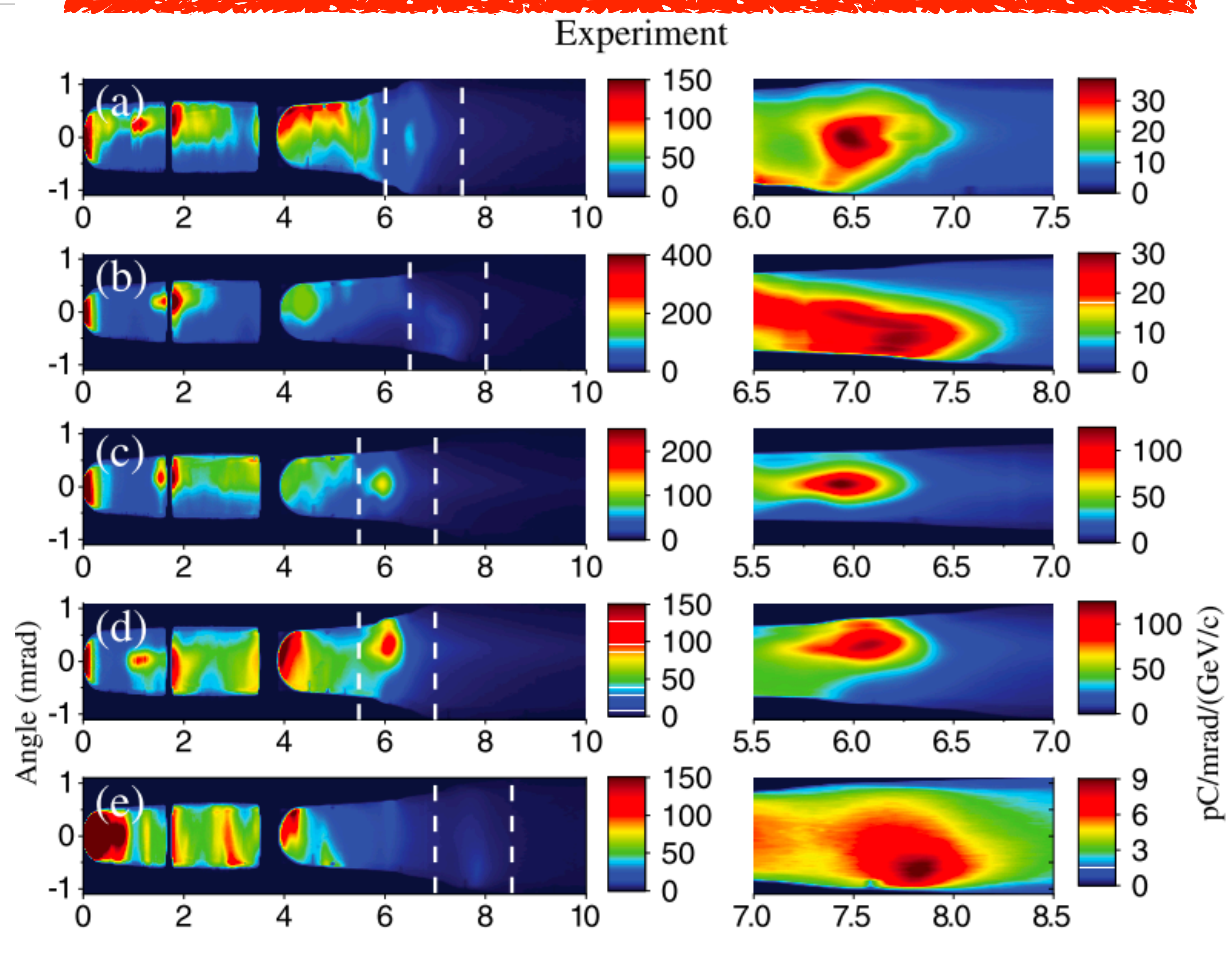
[1]*Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA*

[4]*Nati*… *5409, Russia*

[5]*Fac*… *ch Republic*

…*ublic*

8 GeV, 0.2m: 40 GV/m!



Vol 445 | 15 February 2007 | doi:10.1038/nature05538

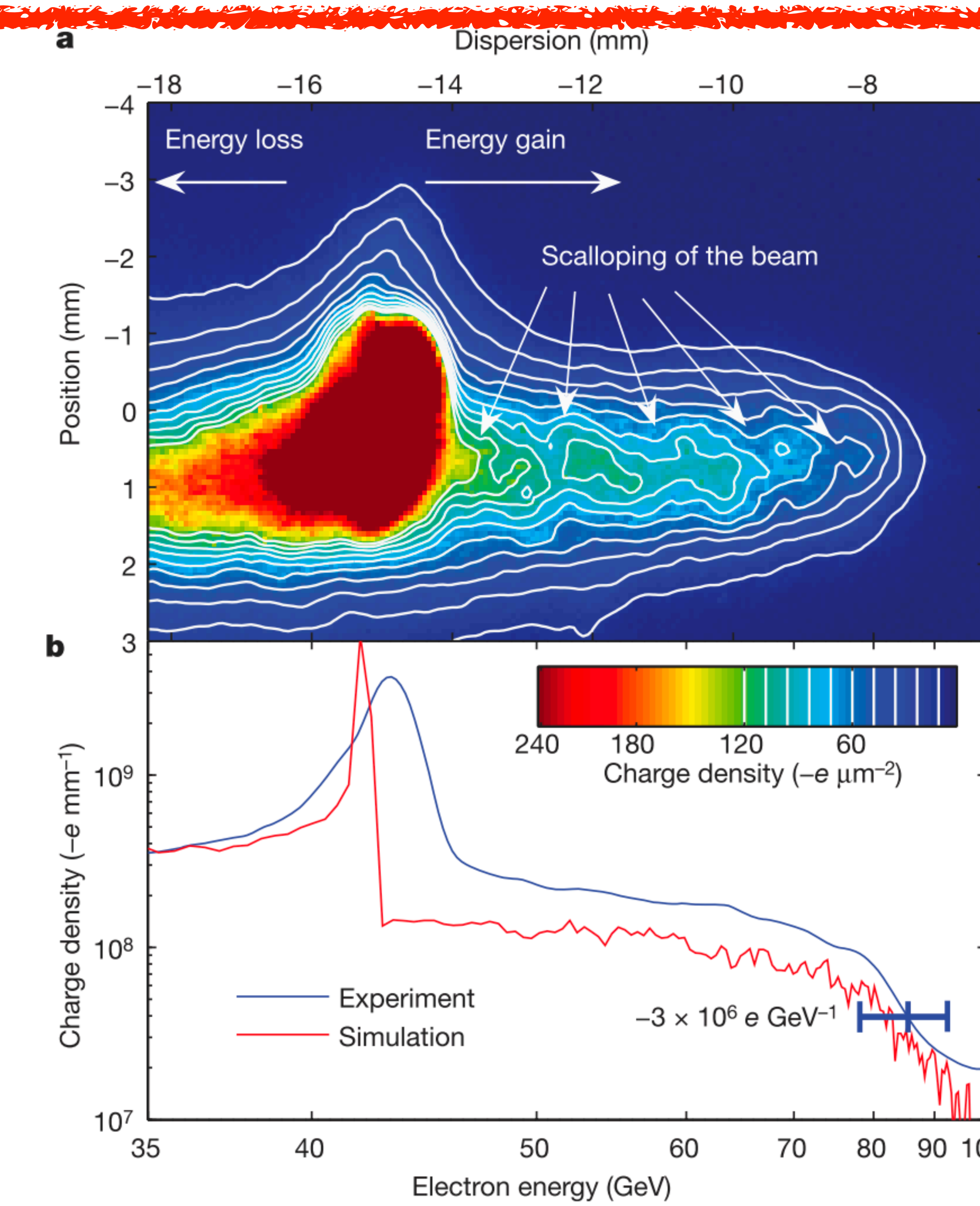
nature

LETTERS

Energy doubling of 42 GeV electrons in a metre-scale plasma wakefield accelerator

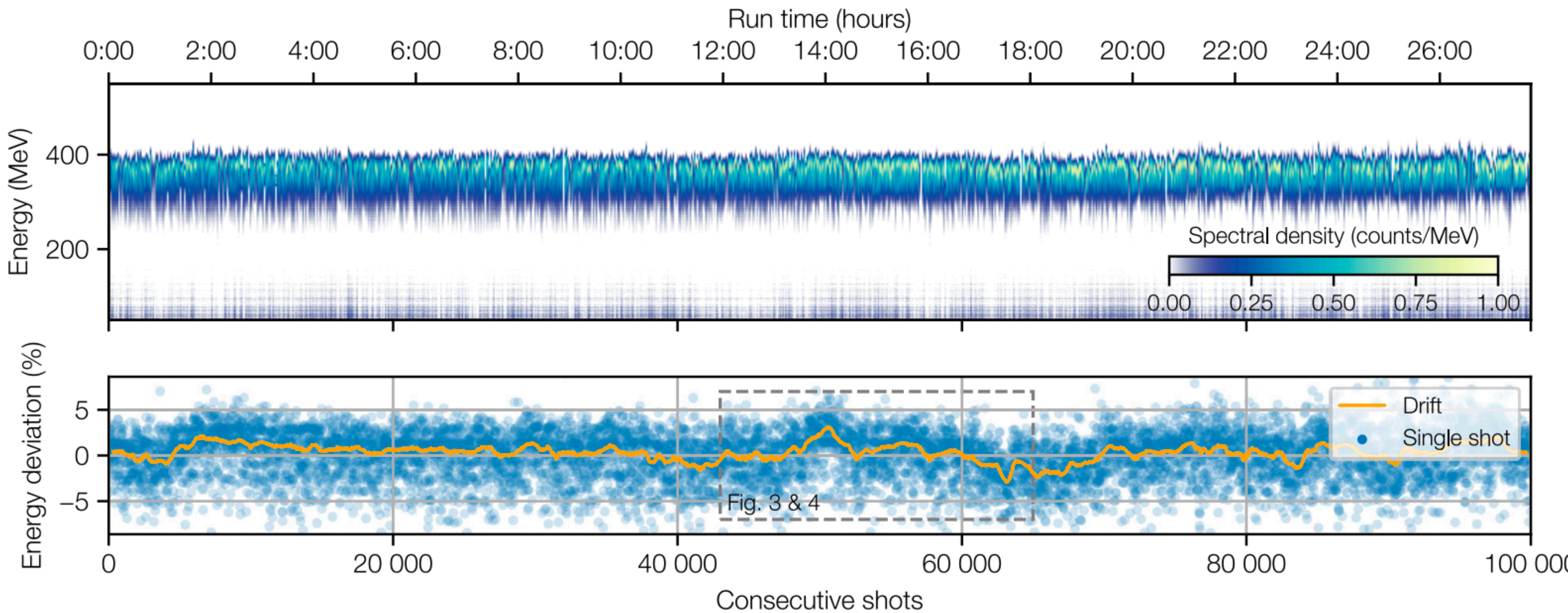
Ian Blu… Rasmus… Kennet… & Miao…

44 GeV, 0.85m: 52 GV/m!



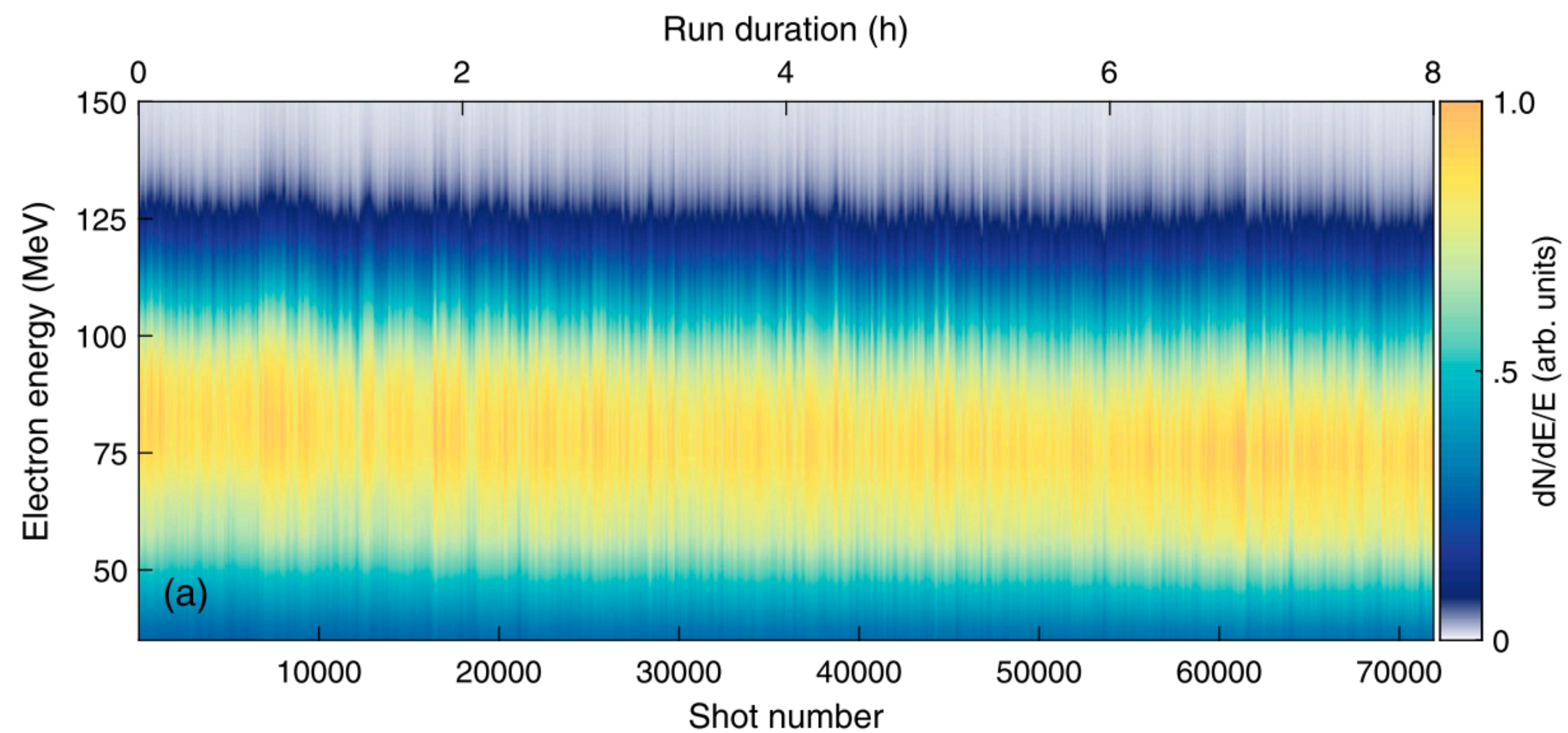
LPAs are moving towards mainstream acceptance

Demonstration of reliability, fine-control and beam quality pave way for wide-spread adoption



100-TW LPA operated 28h in a row!

12-TW LPA operated 8h in a row!



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LPAs have demonstrated key milestones

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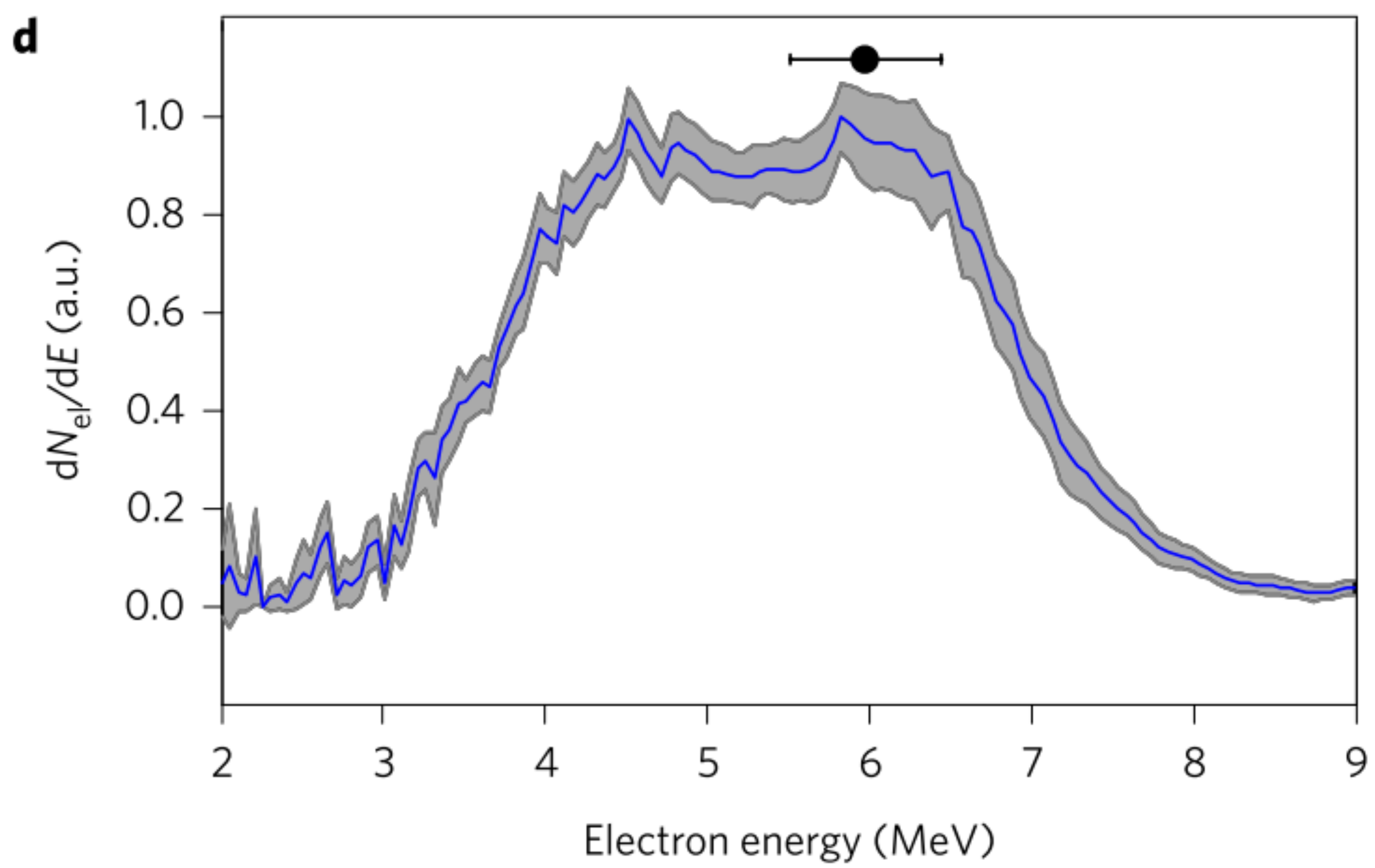
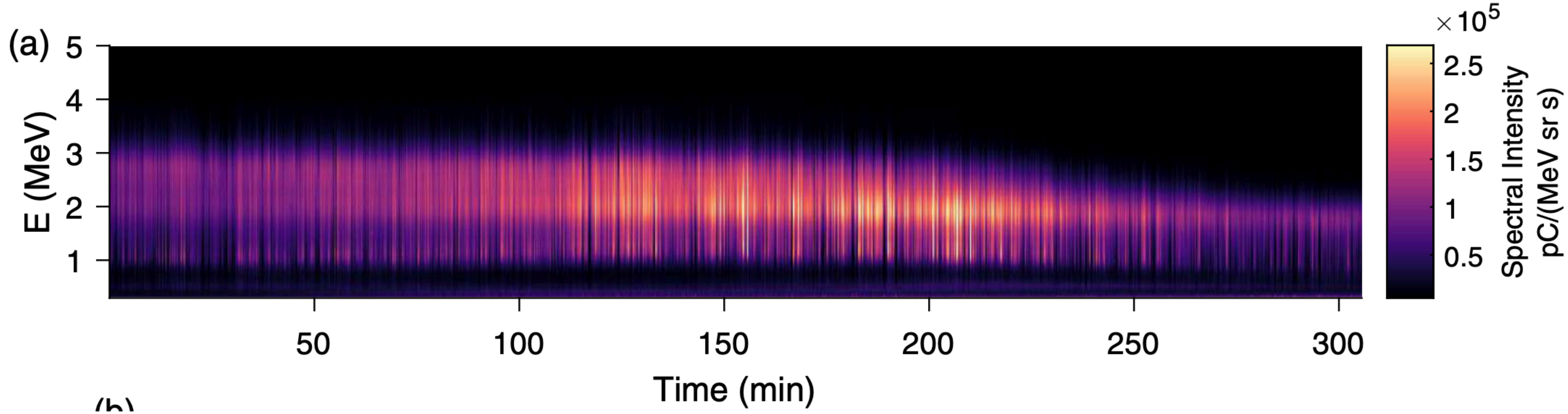


Single-cycle, mJ system delivers kHz electrons



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[24] Rovige et al, Phys Rev AB **23**, 093401 (2020)

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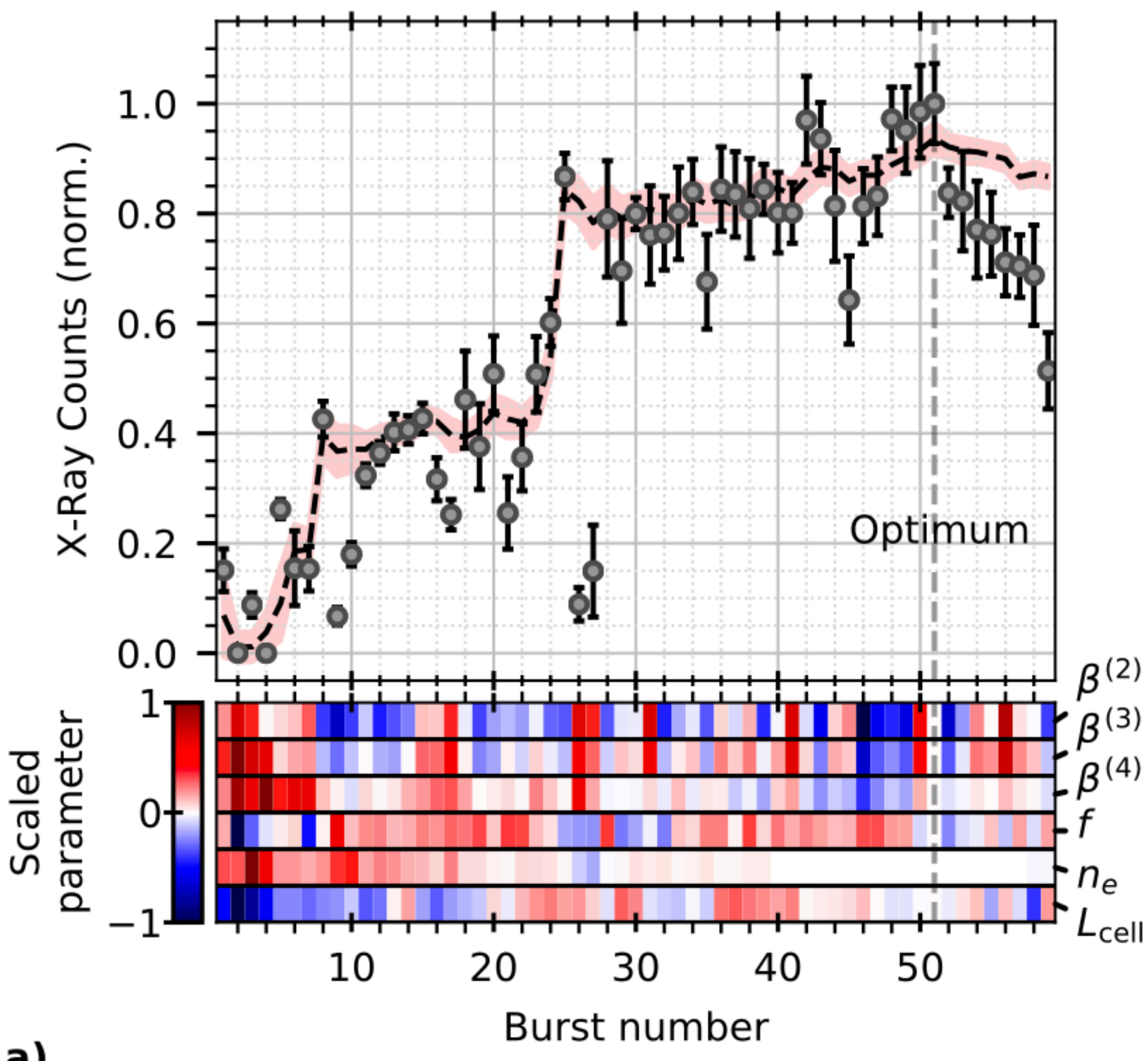
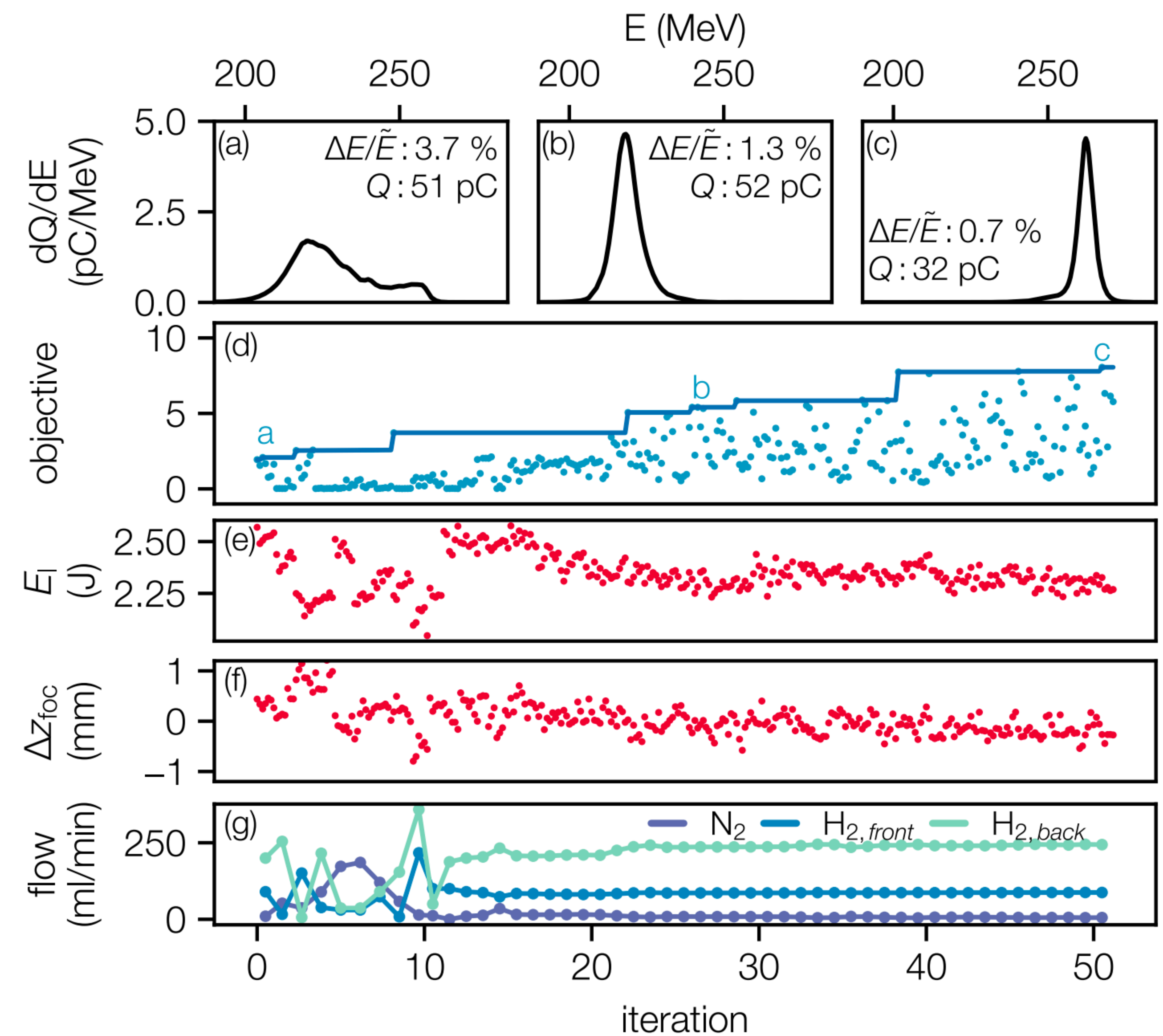
Machine-learning-driven optimisation of LPAs





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[26] Jalas et al, Phys Rev Lett **126**, 104801 (2021)

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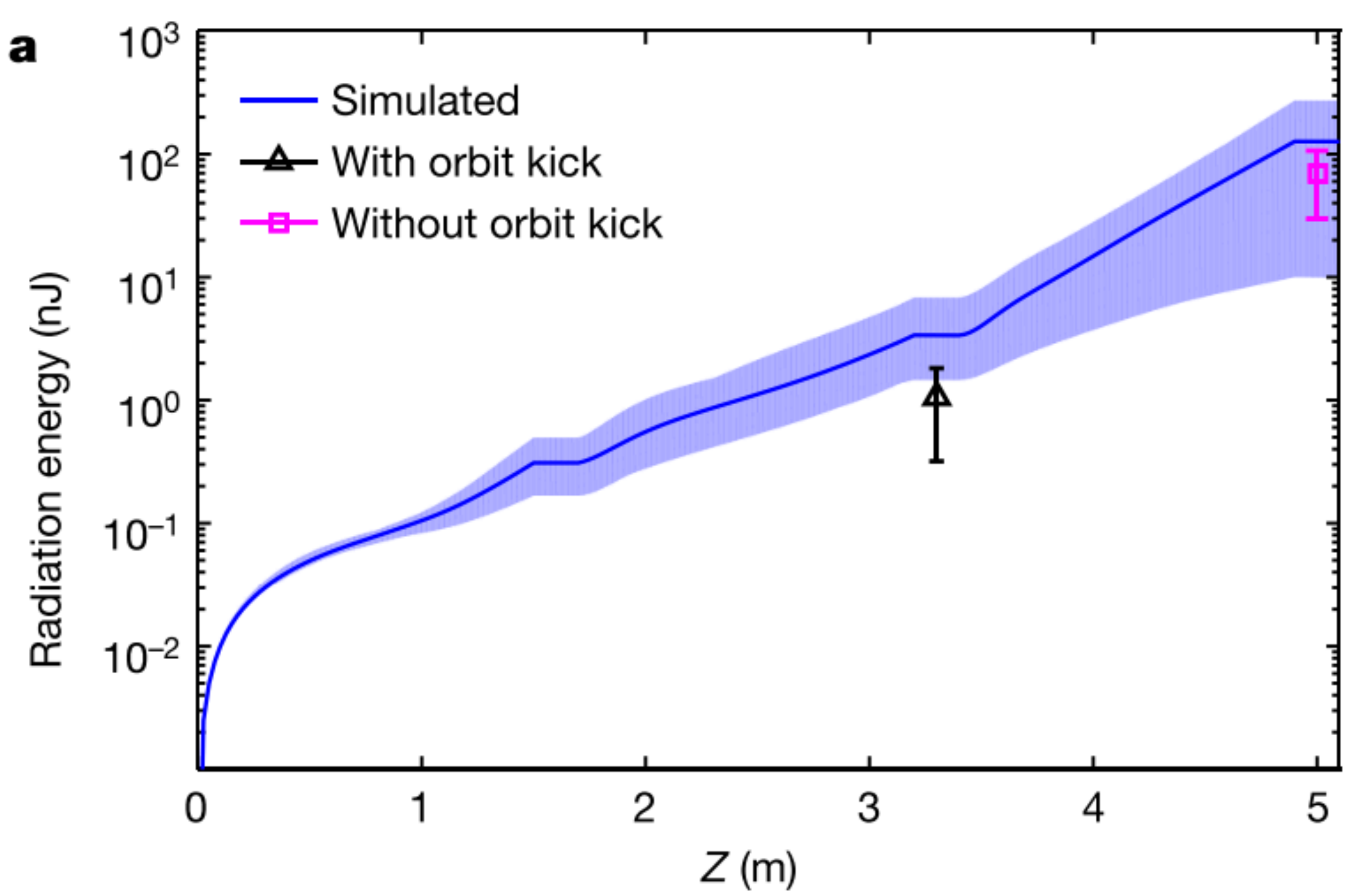
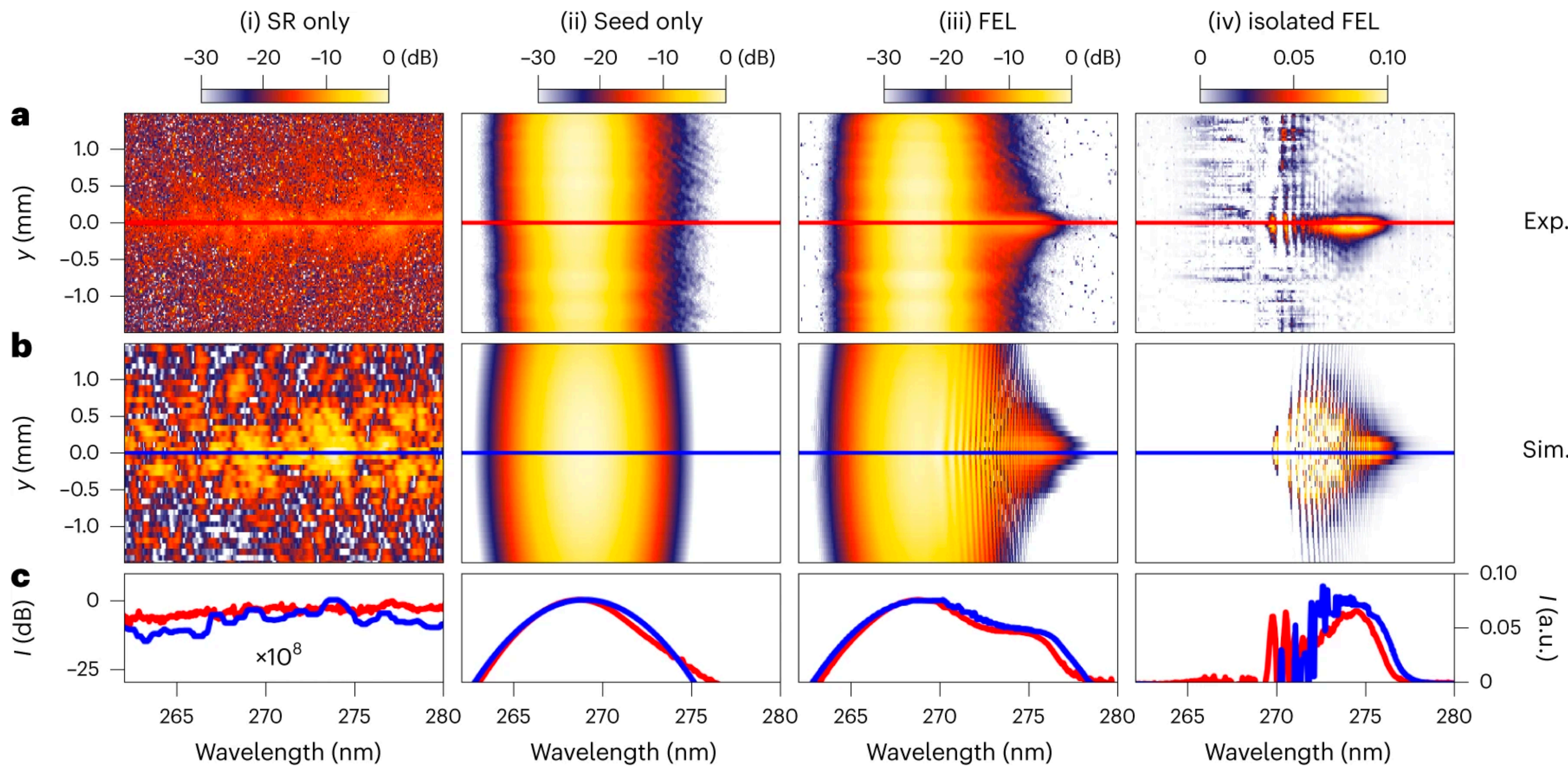
FEL lasing achieved with an LPA driver





(27) Wang et al, Nature **595**, 516-520 (2021)
(28) Labat et al, Nat Phot. **17**, 150 (2022)

State-of-the-art LPAs

Depending on driver laser, very different beam parameters can be generated

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- Rep rate: ~1 Hz to 1 kHz
  - Small laser can fire more often!

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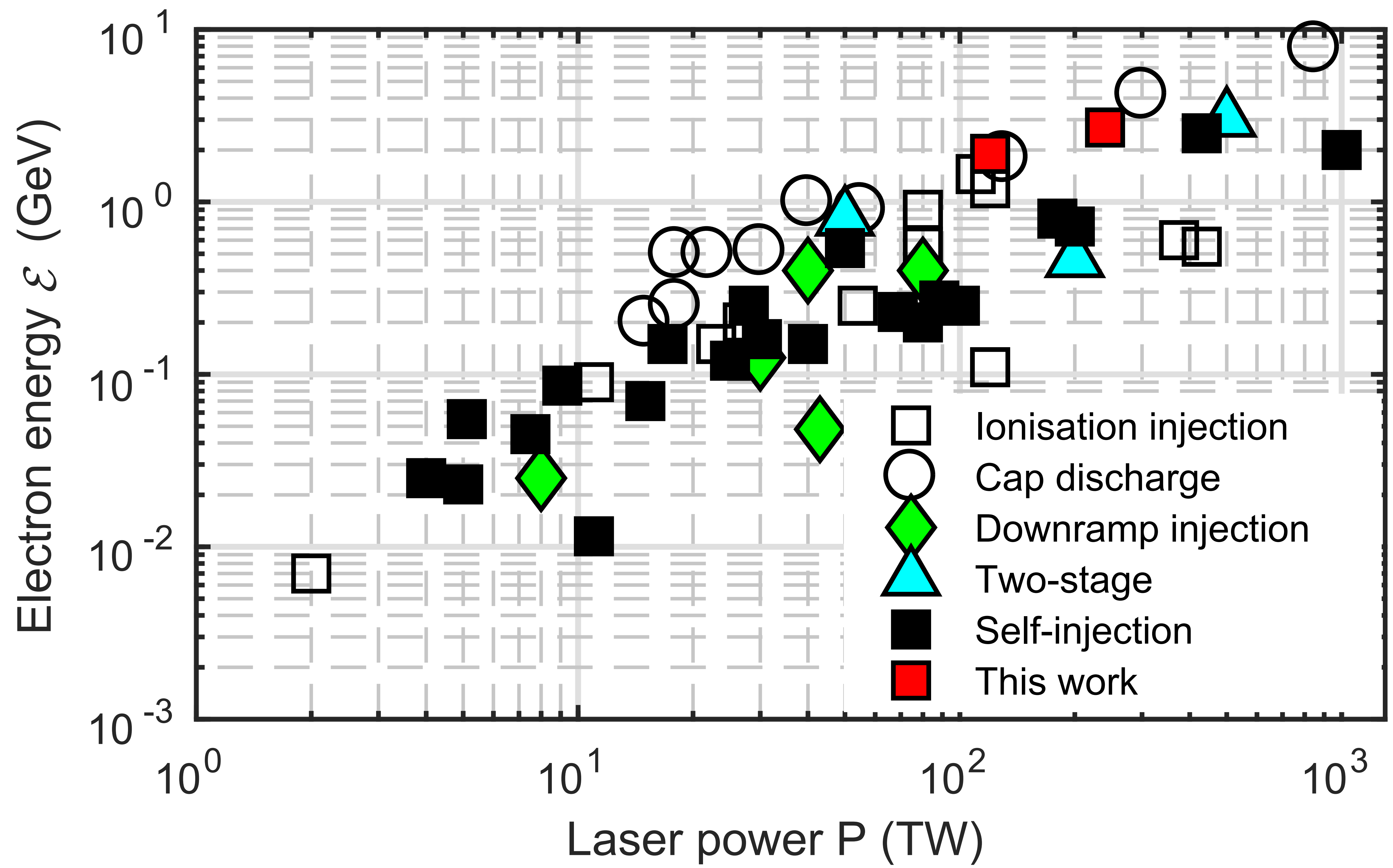

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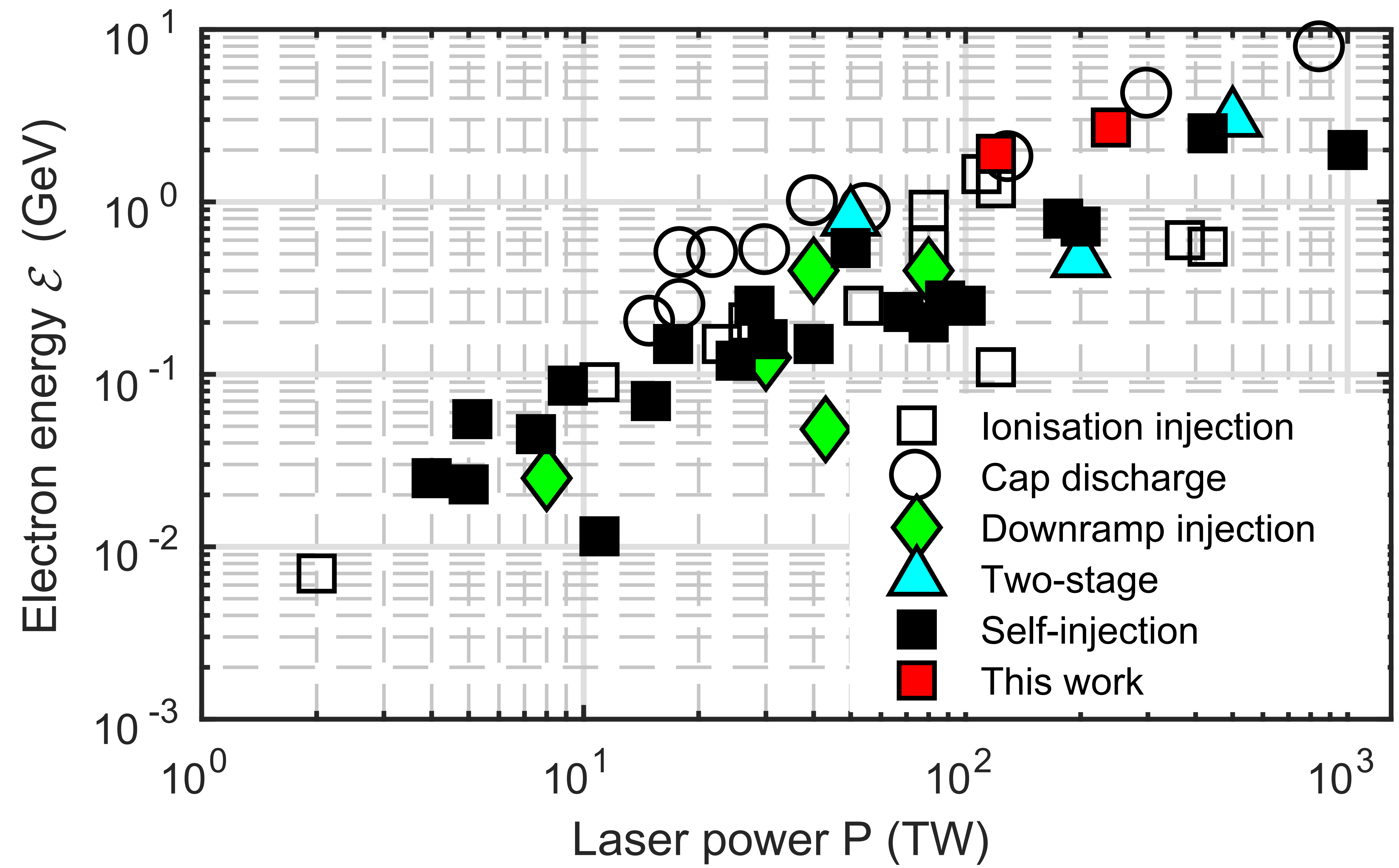

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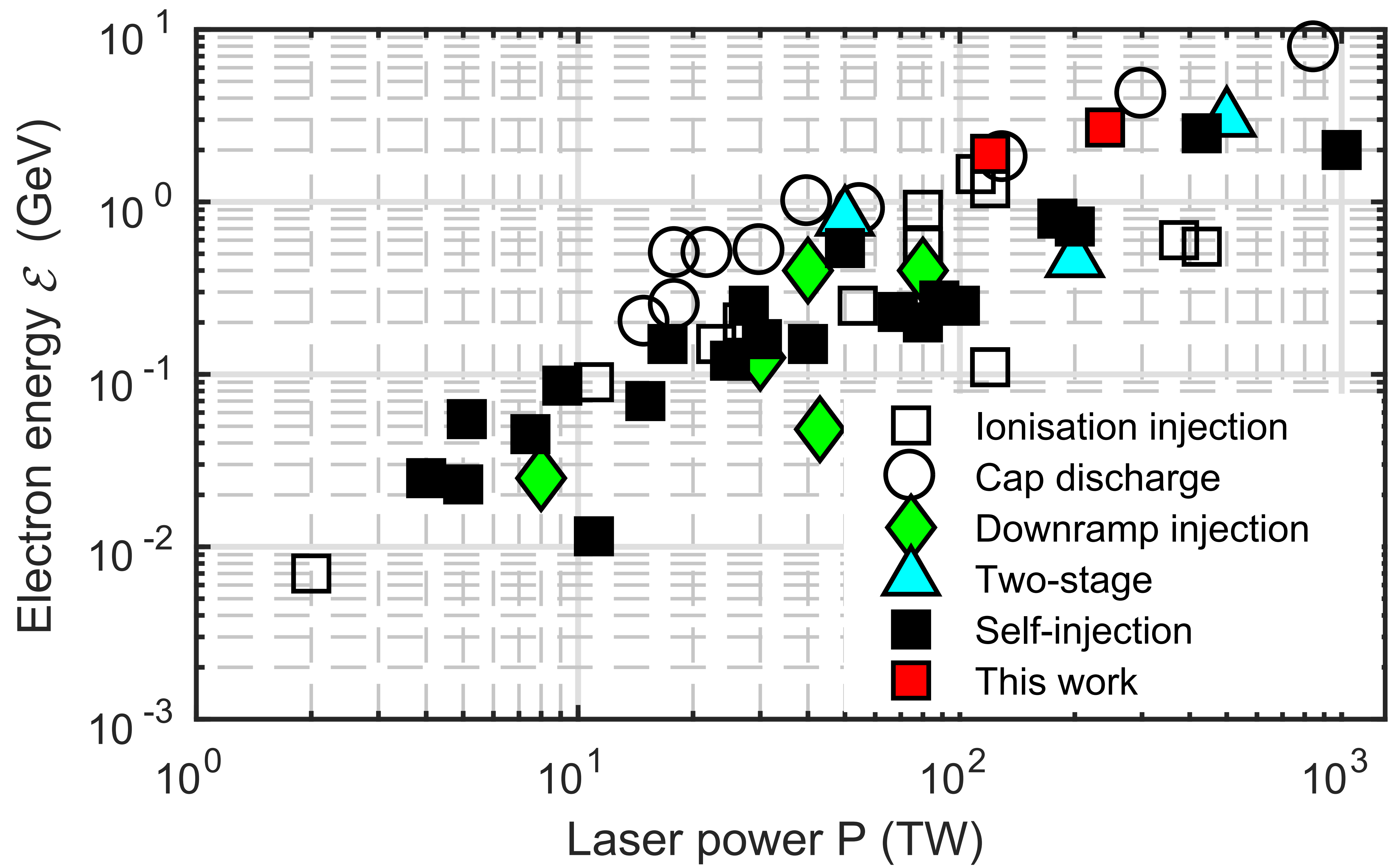

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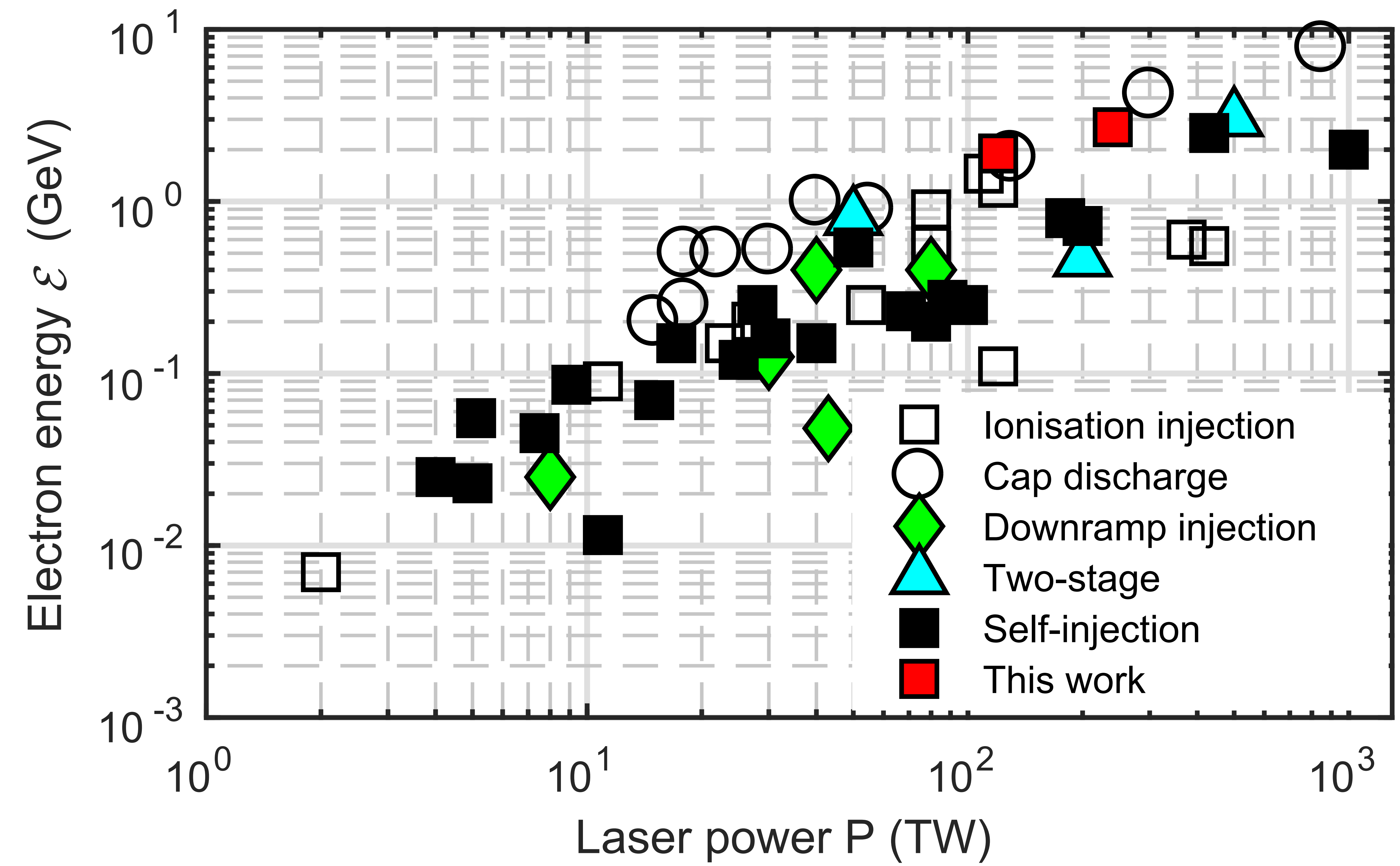

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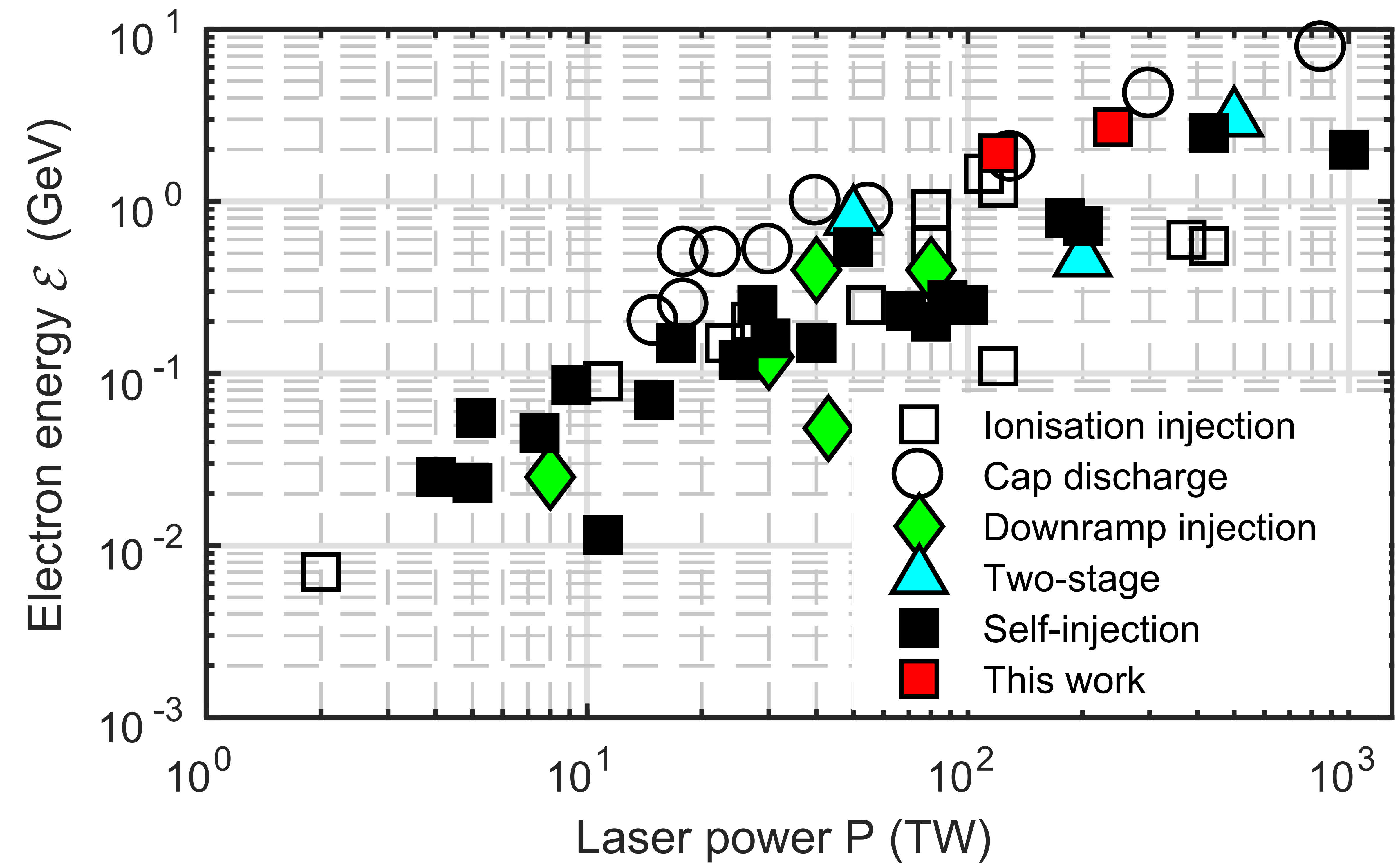

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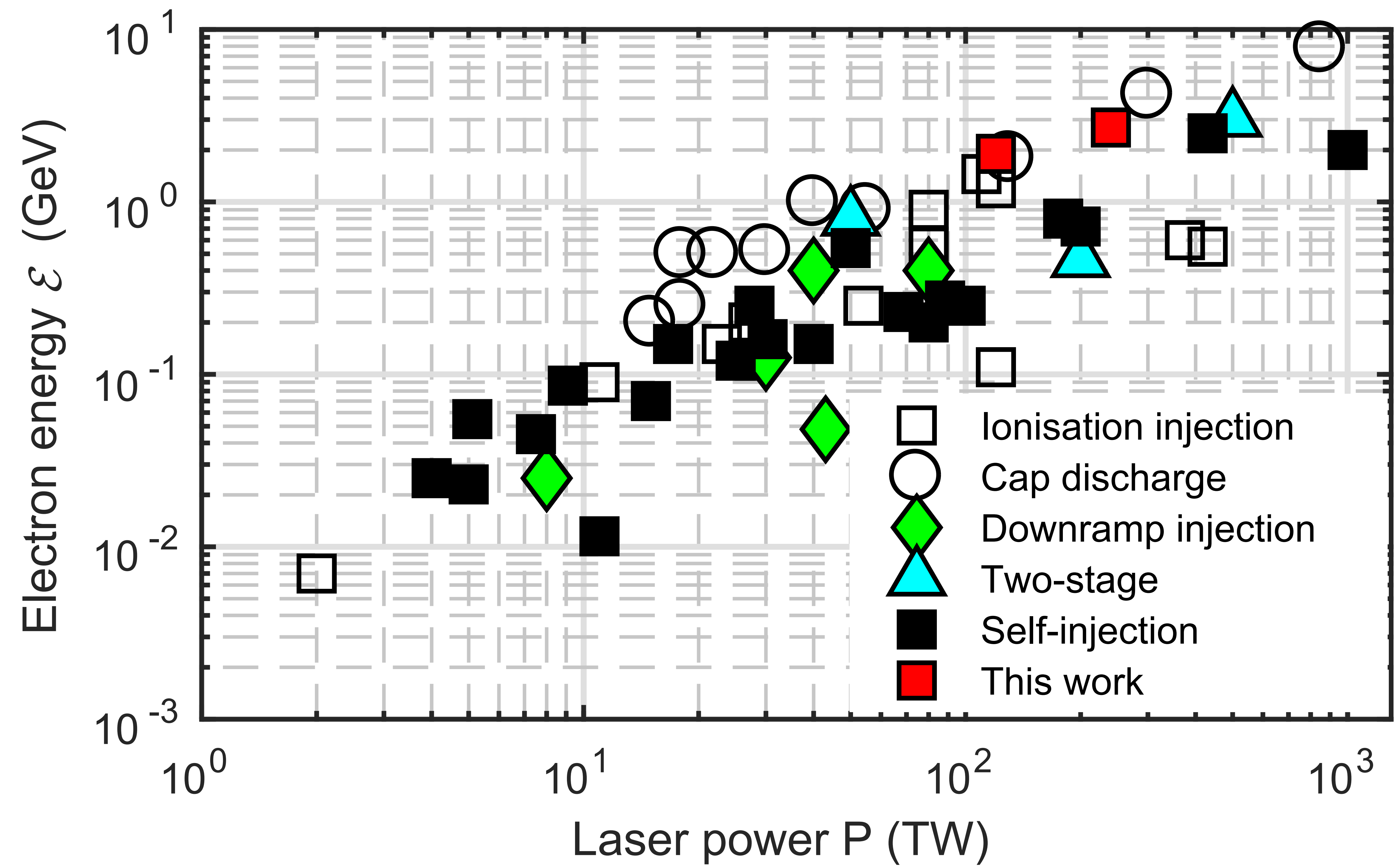
- Stability: down to a few percent



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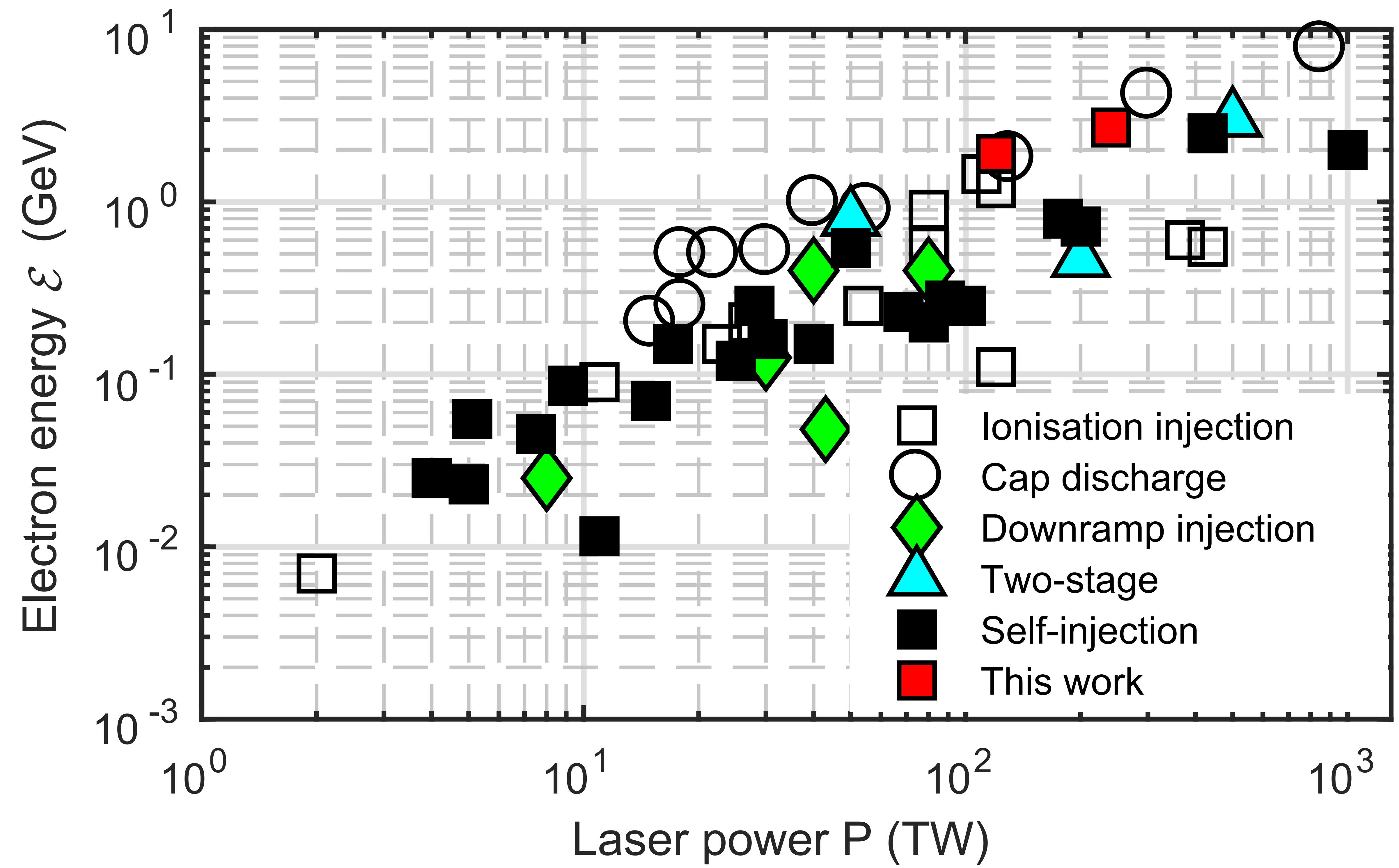
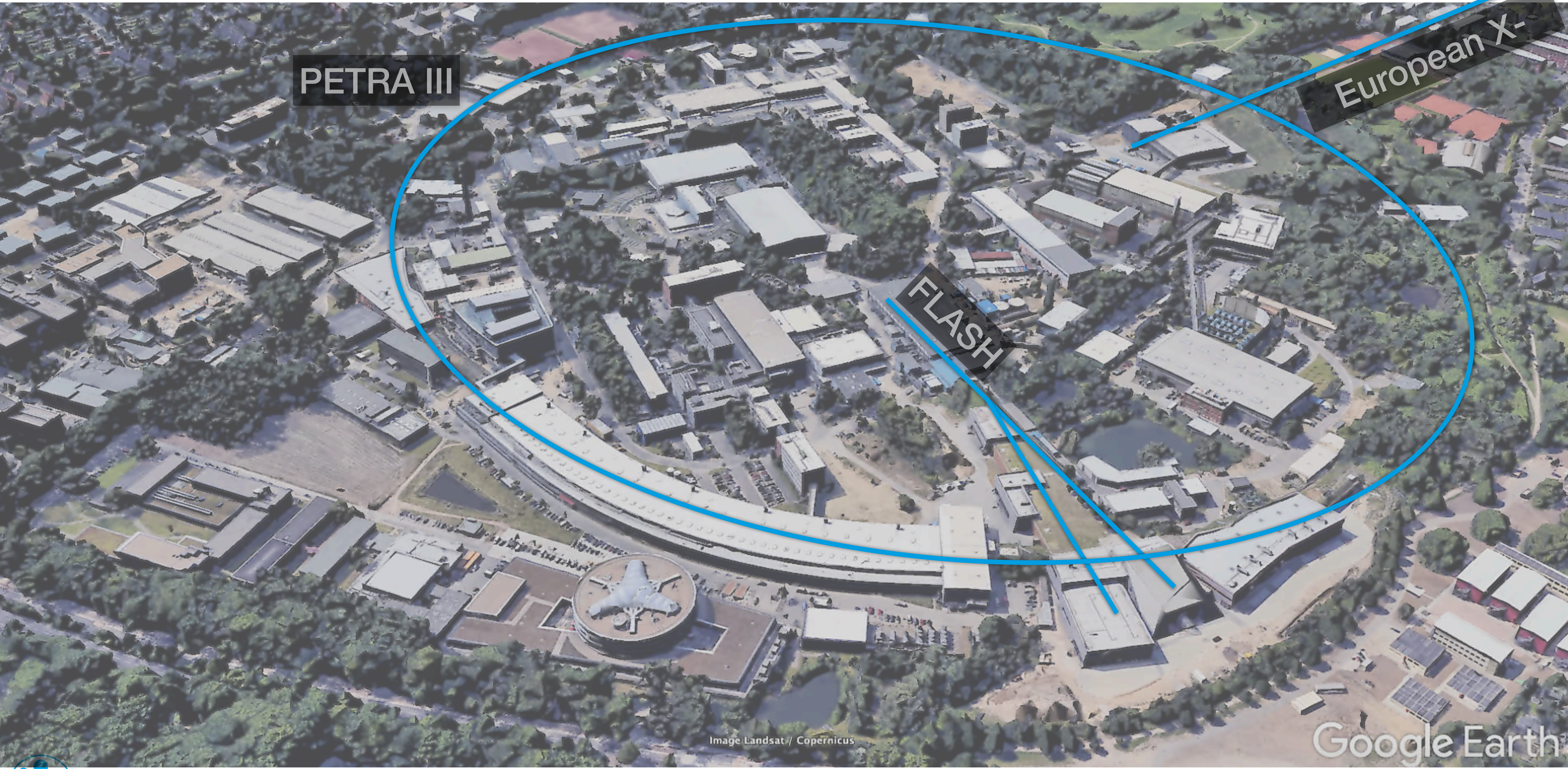
- Normalised emittance: sub-micron
- Plasma length: from 0.1mm to 30 cm
- Stability: down to a few percent
- Efficiency: up to 30% laser-to-electrons



Plasma acceleration is a core priority at DESY

Research focus on high average power and development of practical applications



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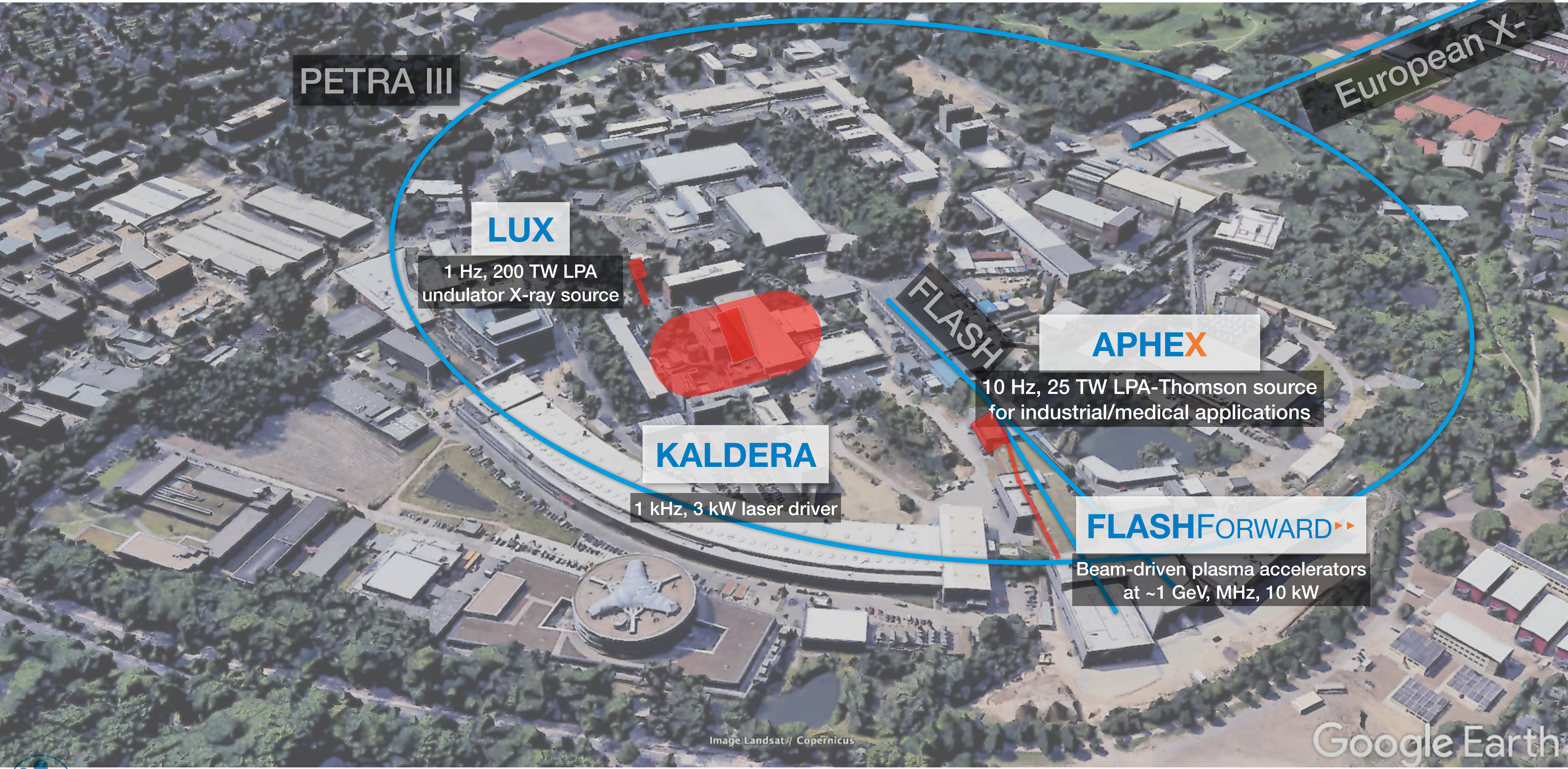

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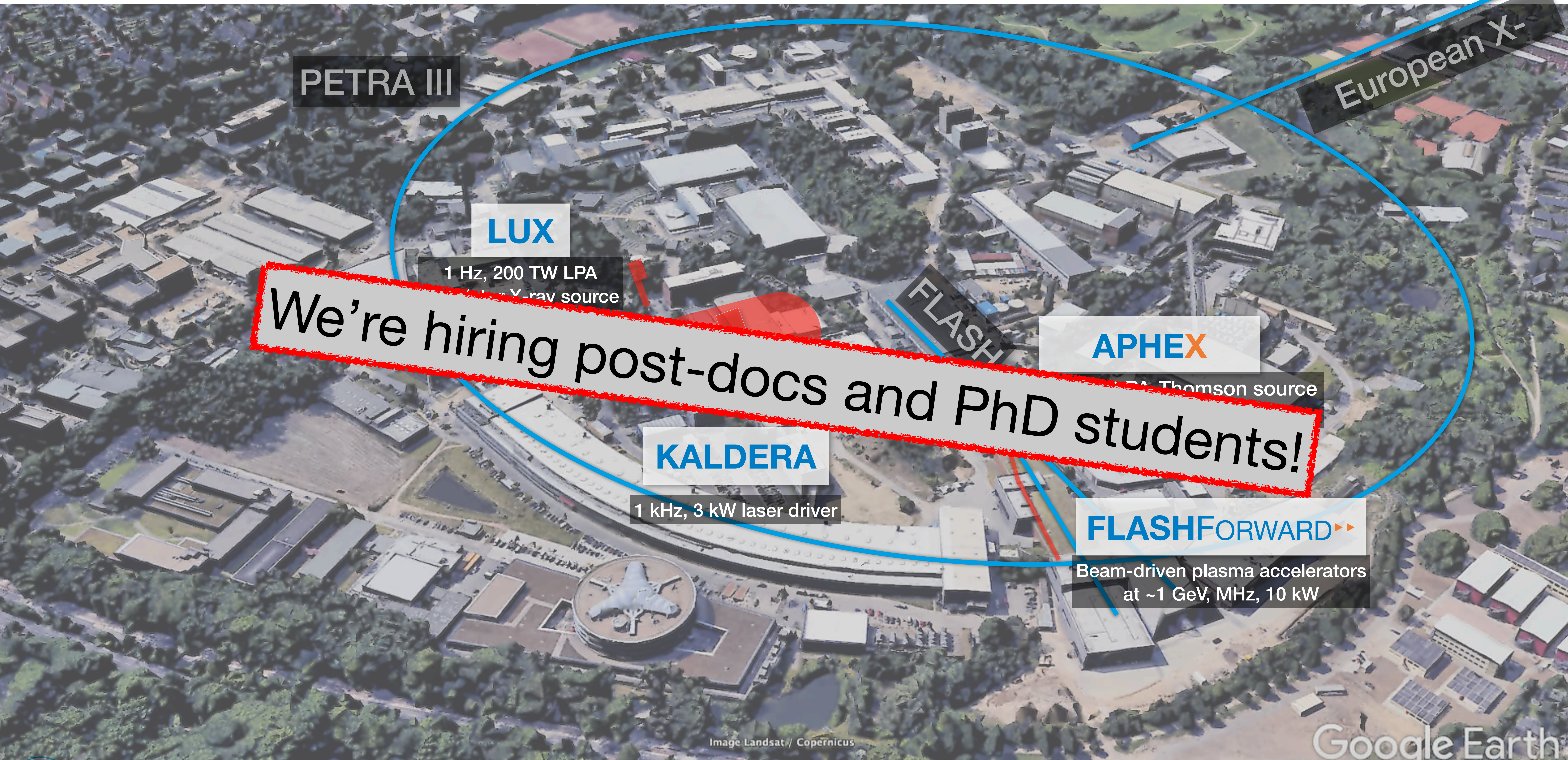
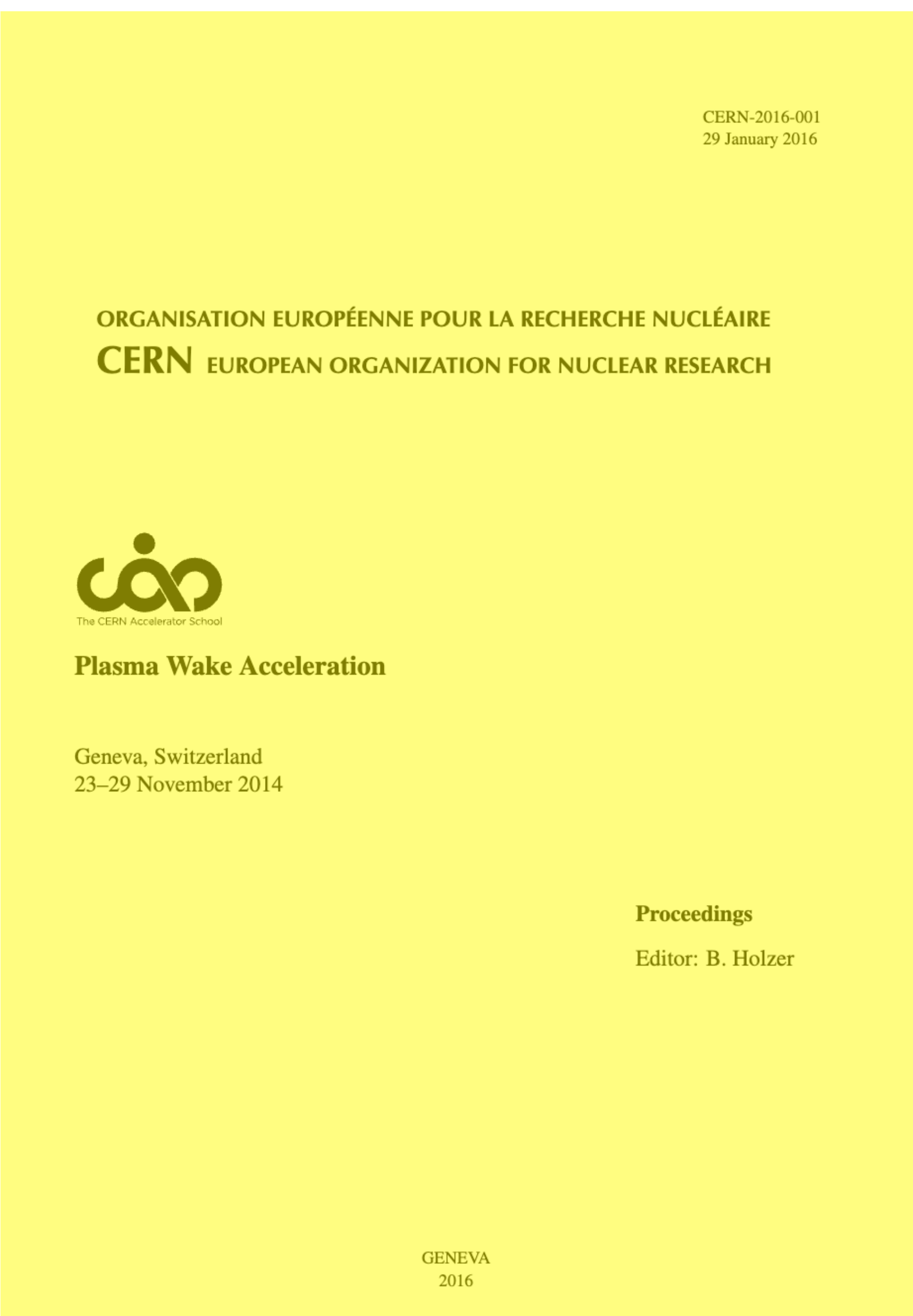


Towards summary: places for further reading

The preceding slides have only served to 'whet your appetite': the main meals are below!

https://doi.org/10.5170/CERN-2016-001

https://doi.org/10.1103/RevModPhys.81.1229



REVIEWS OF MODERN PHYSICS, VOLUME 81, JULY–SEPTEMBER 2009

Physics of laser-driven plasma-based electron accelerators

E. Esarey, C. B. Schroeder, and W. P. Leemans

Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA

(Published 27 August 2009)

Laser-driven plasma-based accelerators, which are capable of supporting fields in excess of 100 GV/m, are reviewed. This includes the laser wakefield accelerator, the plasma beat wave accelerator, the self-modulated laser wakefield accelerator, plasma waves driven by multiple laser pulses, and highly nonlinear regimes. The properties of linear and nonlinear plasma waves are discussed, as well as electron acceleration in plasma waves. Methods for injecting and trapping plasma electrons in plasma waves are also discussed. Limits to the electron energy gain are summarized, including laser pulse diffraction, electron dephasing, laser pulse energy depletion, and beam loading limitations. The basic physics of laser pulse evolution in underdense plasmas is also reviewed. This includes the propagation, self-focusing, and guiding of laser pulses in uniform plasmas and with preformed density channels. Instabilities relevant to intense short-pulse laser-plasma interactions, such as Raman, self-modulation, and hose instabilities, are discussed. Experiments demonstrating key physics, such as the production of high-quality electron bunches at energies of 0.1–1 GeV, are summarized.

DOI: 10.1103/RevModPhys.81.1229 PACS number(s): 52.38.Kd, 41.75.Lx, 52.40.Mj

CONTENTS

I. Introduction 1229
A. Acceleration in plasma 1230
B. Acceleration in vacuum and gases 1231
II. Plasma Waves and Acceleration 1232
A. Ponderomotive force 1233
B. Linear plasma waves 1233
C. Nonlinear plasma waves 1234
D. Wave breaking 1235
E. Electron acceleration and dephasing 1237
F. Plasma wave phase velocity 1238
G. Photon acceleration 1239
III. Laser-Plasma Accelerators 1239
A. Laser wakefield accelerator 1239
B. Plasma beat wave accelerator 1241
C. Multiple laser pulses 1243
D. Self-modulated laser wakefield accelerator 1245
E. Blow-out regime 1248
F. Other laser wakefield acceleration regimes 1251
G. Acceleration limits and scaling laws 1252
H. Beam loading 1253
IV. Electron Trapping and Injection 1255
A. Trapping and dark current 1255
B. Trapping in the self-modulated LWFA 1256
C. Optical injection techniques 1257
1. Ponderomotive injection 1257
2. Colliding pulse injection 1257
D. Density transitions 1260
V. Pulse Propagation and Guiding 1261
A. Optical guiding in plasmas 1262
B. Relativistic optical guiding 1263
C. Preformed plasma density channels 1264
D. Ponderomotive self-channeling 1267
E. Plasma wave guiding 1268
VI. Laser-Plasma Instabilities 1268
A. Stimulated Raman scattering 1268
1. Raman backward scattering 1269
2. Raman forward scattering 1269
B. Self-modulation and laser-hose instabilities 1270
VII. High-Quality Bunch Production 1273
A. High-quality bunches at the 100 MeV level 1274
B. High-quality bunches at the 1 GeV level 1275
C. High-quality bunches from colliding pulse injection 1276
D. High-quality bunches from density transitions 1277
VIII. Conclusions 1277
Acknowledgments 1280
References 1280

I. INTRODUCTION

Laser-driven plasma-based accelerators were originally proposed three decades ago by Tajima and Dawson (1979). Dawson, who passed away in 2001, was responsible for many of the early developments in this field, including the plasma beat wave accelerator, the laser wakefield accelerator, and the photon accelerator (Tajima and Dawson, 1979; Joshi *et al.*, 1984; Wilks *et al.*, 1989). In addition, he was one of the early pioneers of particle-in-cell (PIC) simulation of plasmas (Dawson, 1983; Mori *et al.*, 1988; Birdsall *et al.*, 1991), which is now a widely used tool in the study of plasma-based accelerators. During his lifetime, the field of plasma-based accelerators has grown into a world-wide research effort with ongoing experimental programs in France, Germany, Korea, Japan, Taiwan, the UK, and the United States, to name a few (see, e.g., Schroeder *et al.*, 2009). Much of this growth is due to the rapid development of chirped-pulse amplification (CPA) laser technology, pioneered by Mourou and colleagues (Strickland and Mourou, 1985; Maine *et al.*, 1988; Mourou and Umstadter, 1992; Perry and Mourou, 1994), making readily available compact sources of intense, high-power, ultrashort laser pulses.

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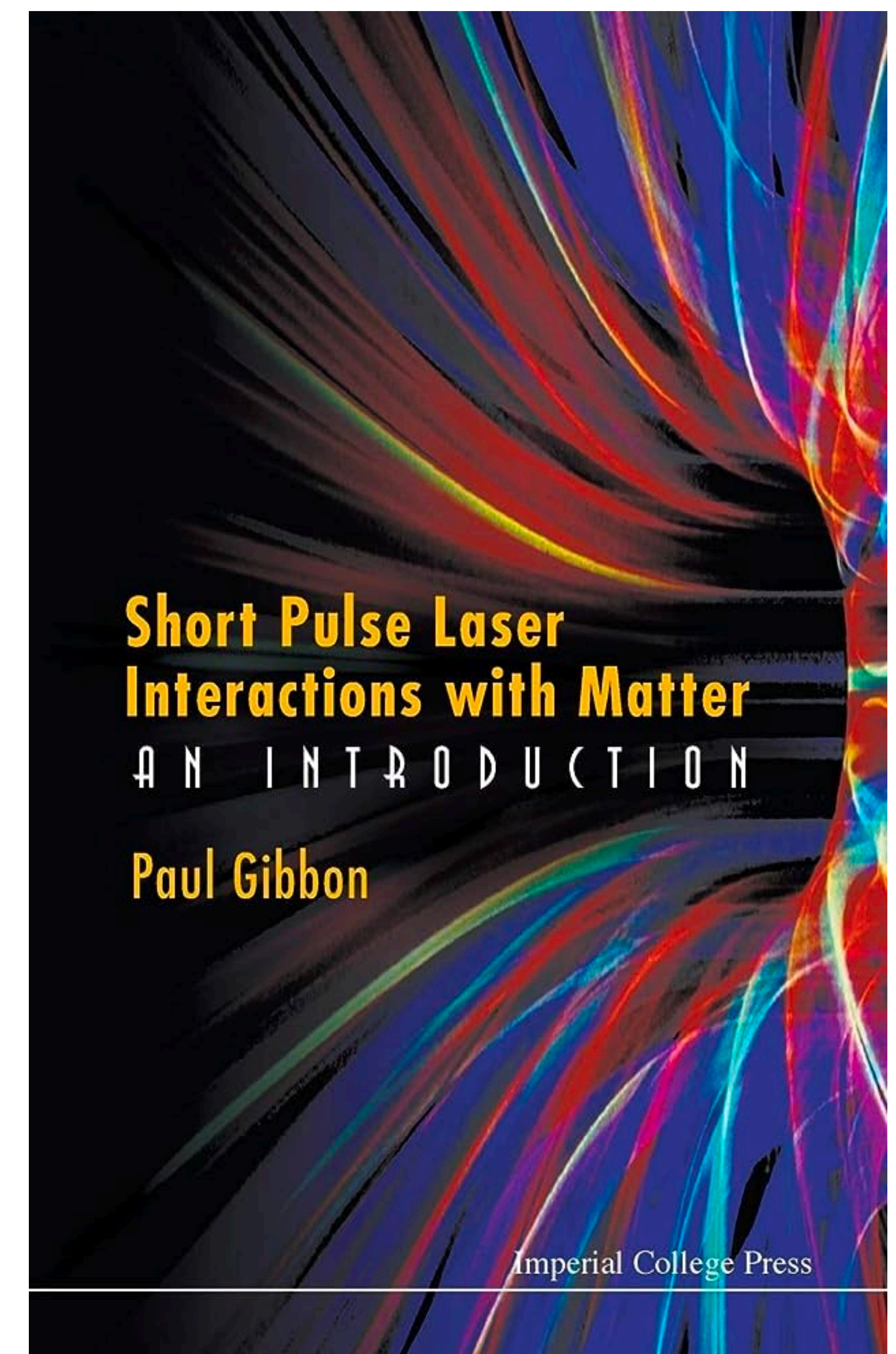

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CERN-2016-001
29 January 2016

ORGANISATION EUROPÉENNE POUR LA RECHERCHE NUCLÉAIRE
CERN EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

The CERN Accelerator School

Plasma Wake Acceleration

Geneva, Switzerland
23–29 November 2014

Proceedings
Editor: B. Holzer

GENEVA
2016

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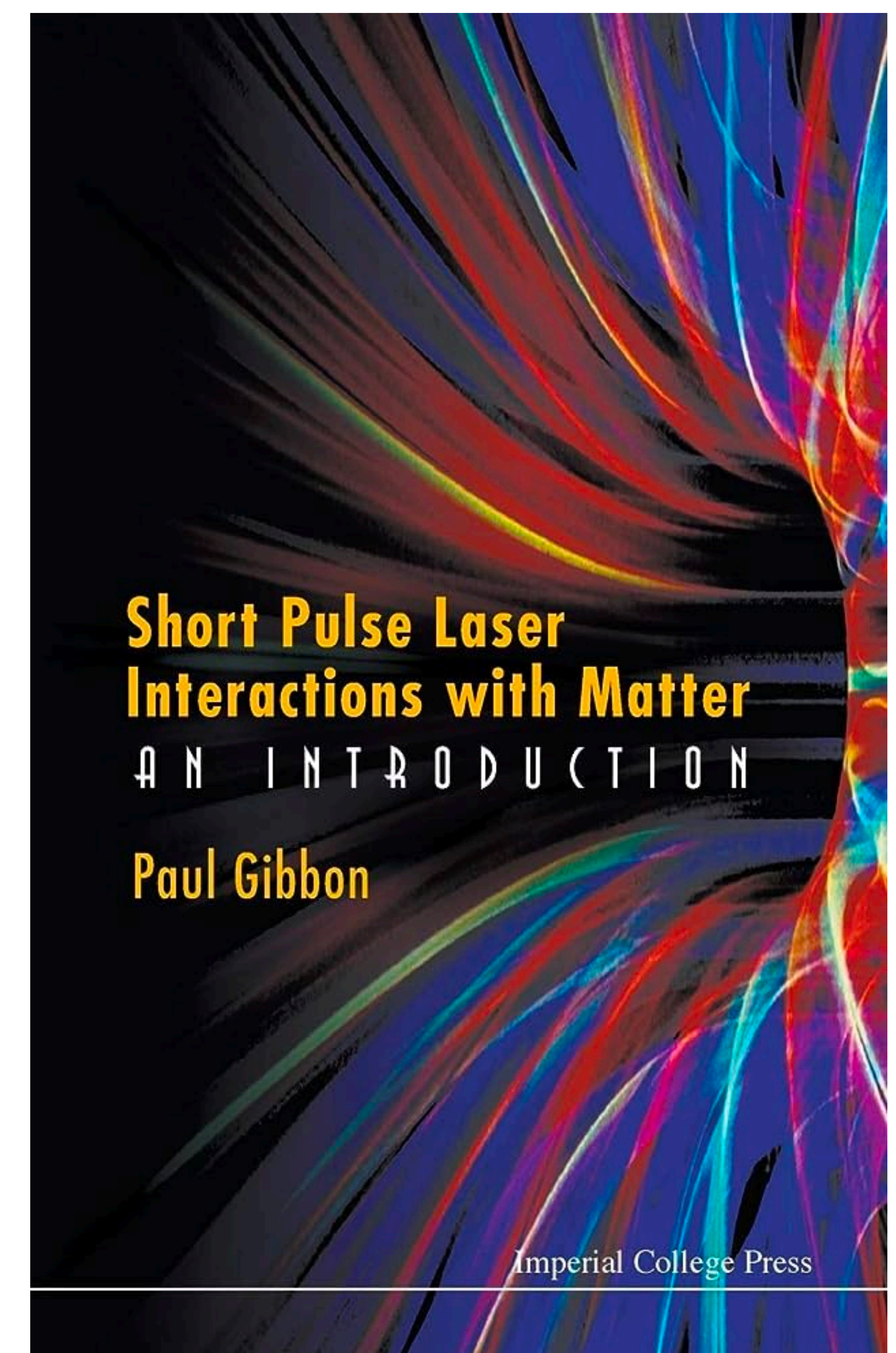

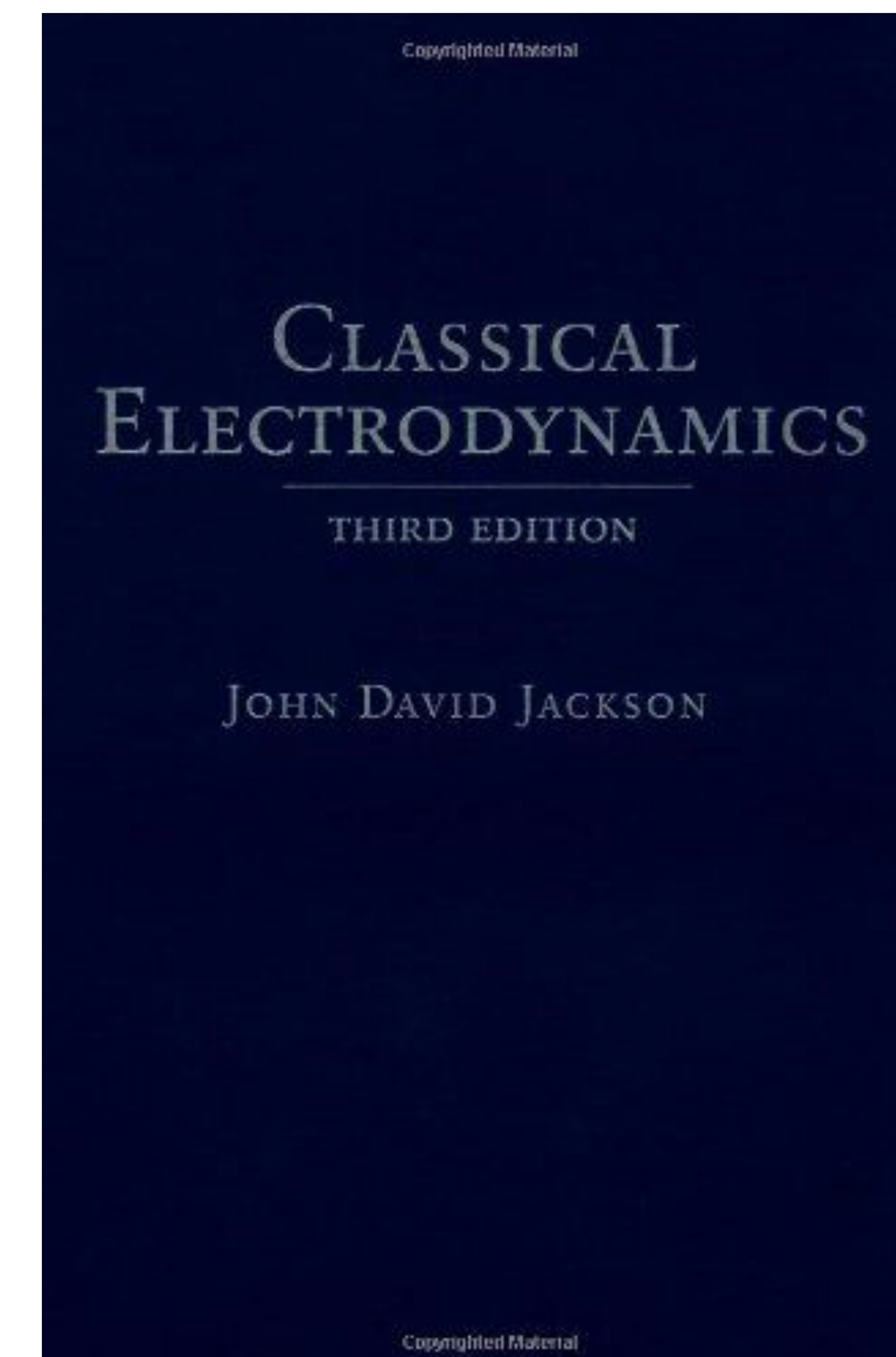

Only under adult supervision!!!

Summary: LPAs are novel flexible sources of electrons

High current, inherent optical synchronisation and compactness allow for novel applications

- Laser plasma accelerators are a compact source of electron beams
  - Applications include X-ray generation, non-destructive testing, radiotherapy, ultrafast diffraction,
- LPAs are complex non-linear systems
- 100 MeV energies possible from mm-long plasmas
- Energy spread, beam transport can be challenging
- Stability requires further work: mostly down to laser stability
- Vibrant, rapidly growing field on the cusp of real-life applications