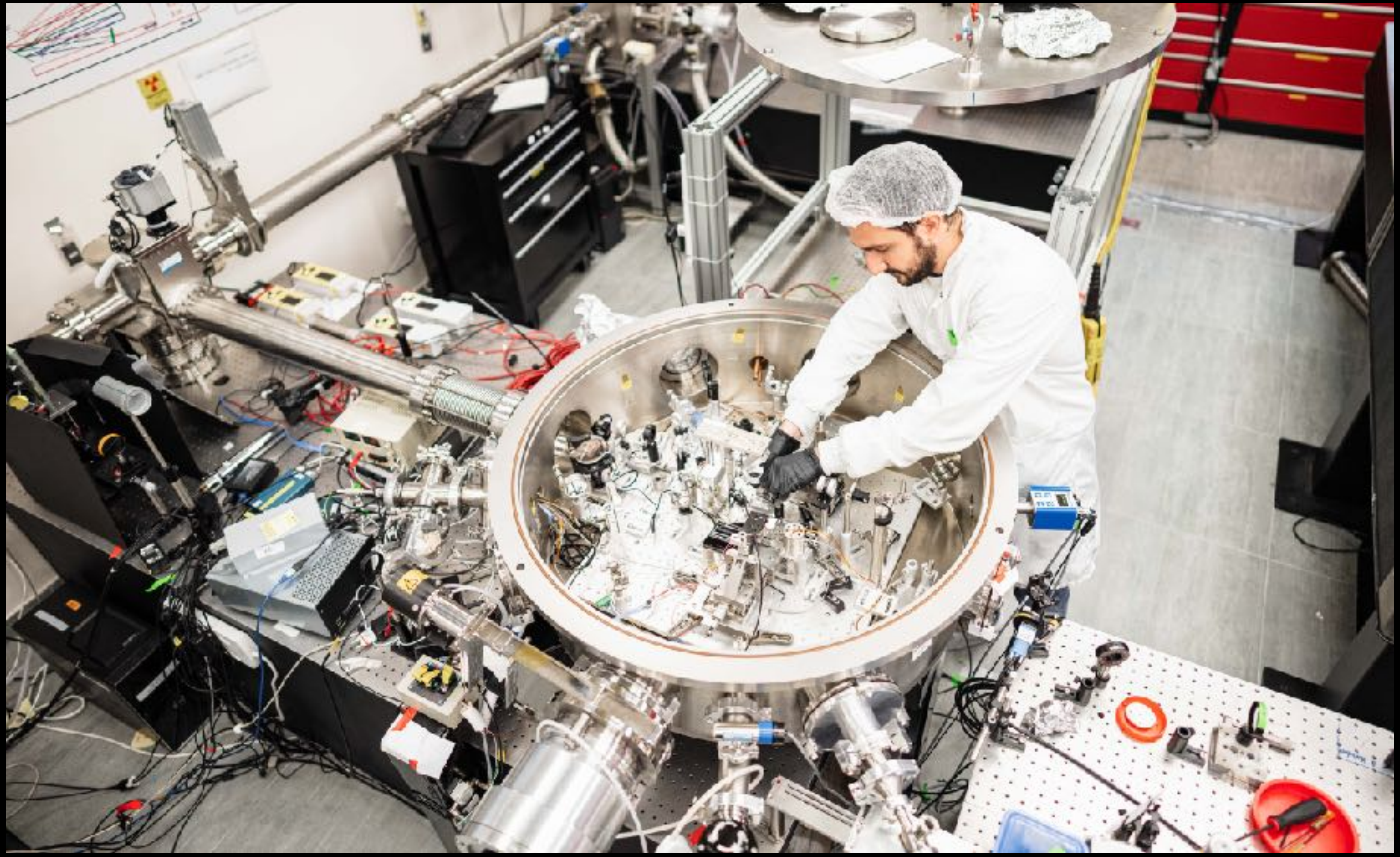
Nuclear Photonics



Ishay Pomerantz

The School of Physics and Astronomy, Tel Aviv University

NePTUN

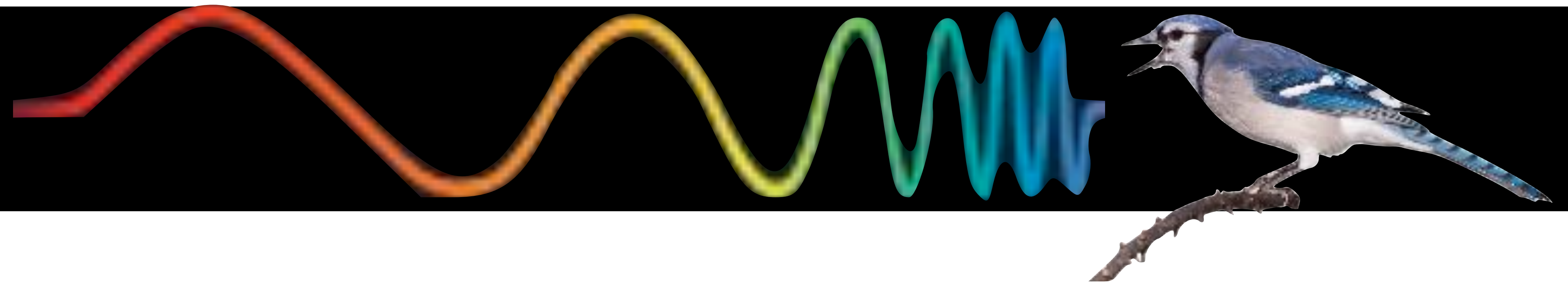
Nuclear Photonics
at Tel-aviv University
research group

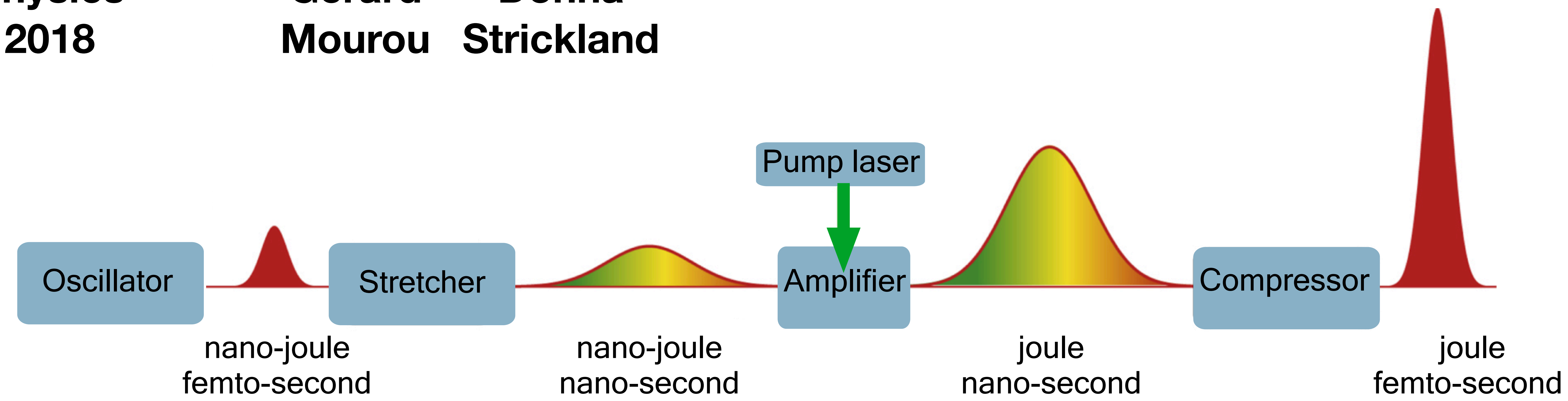
CHIRPED PULSE AMPLIFICATION

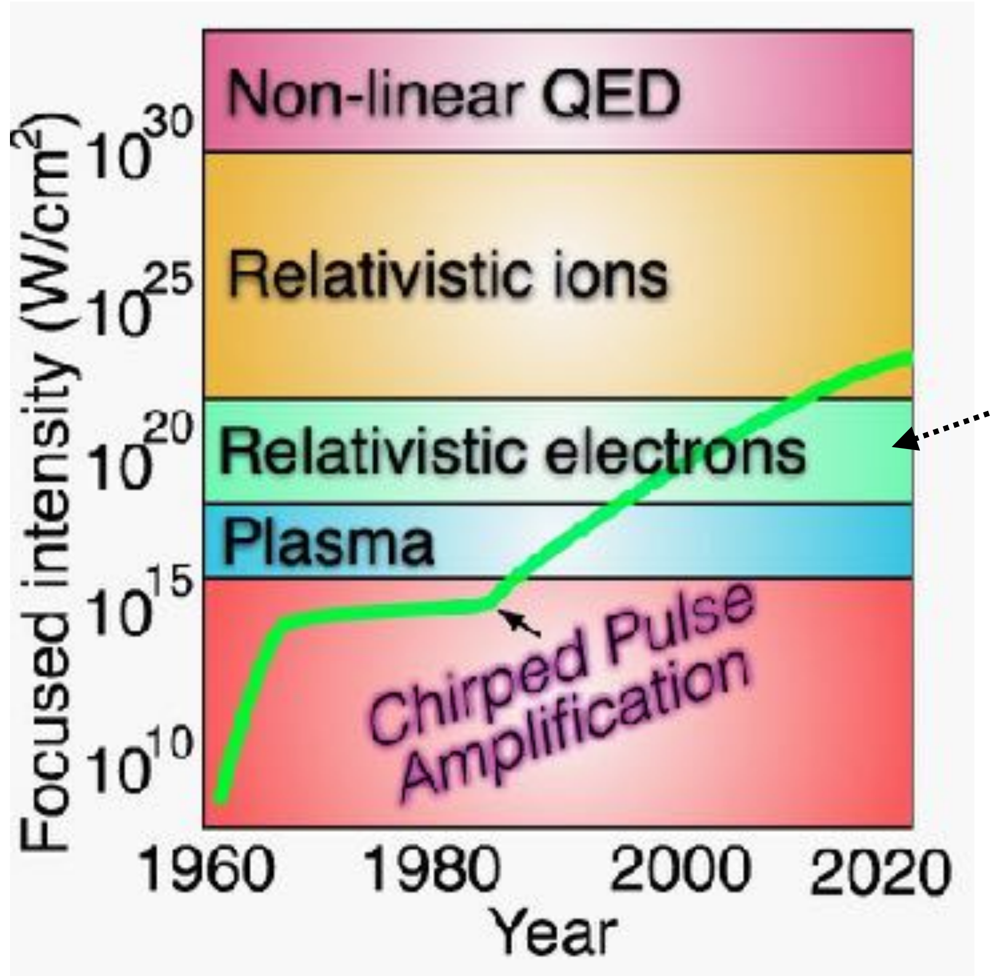
Physics 2018

Gérard Mourou

Donna Strickland





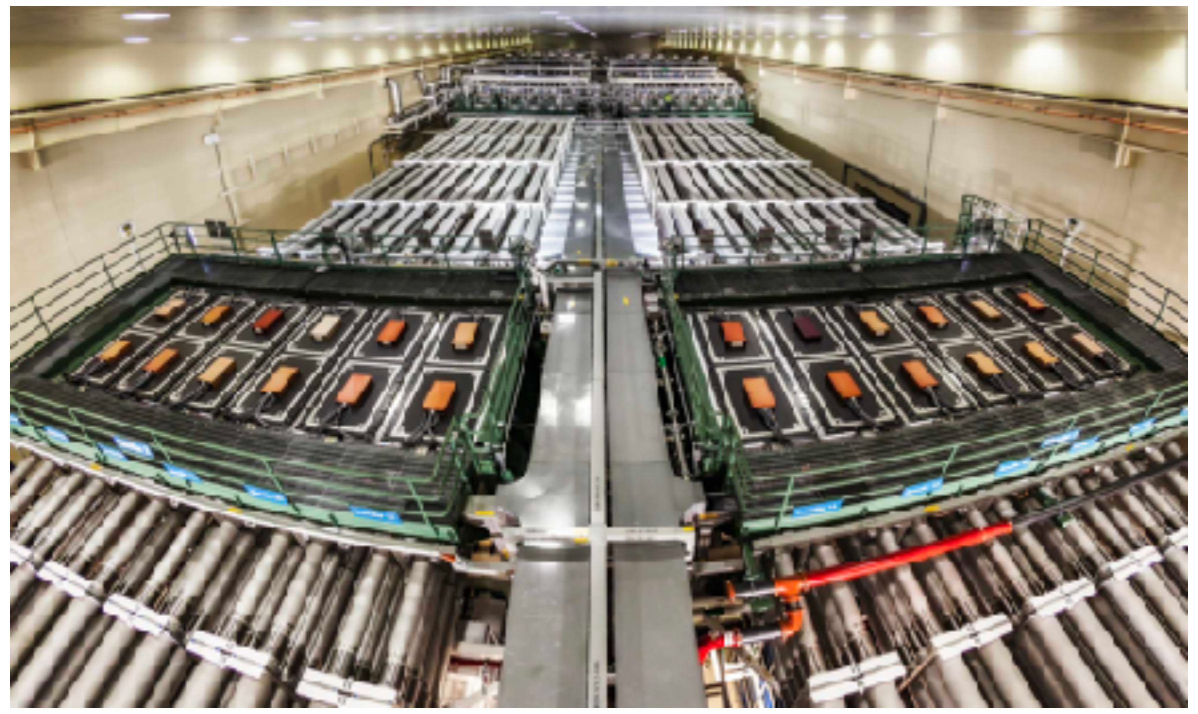


$I_{rel} = 1.37 \times 10^{18}\ \mathrm{W/cm^2} \times (\mu\mathrm{m}/\lambda)^2$

A (lucky) electron might gain its rest-mass over half an optical cycle

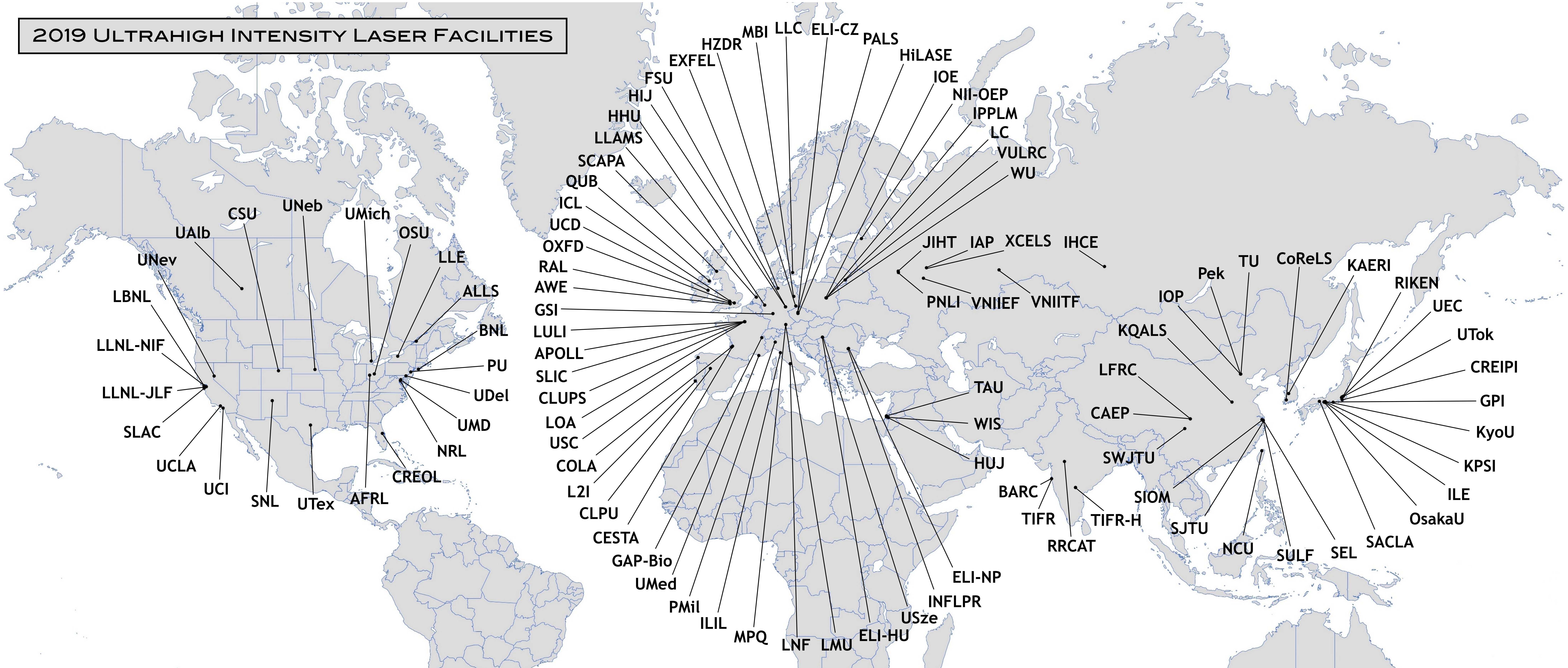
$$\epsilon \times \frac{\lambda}{2} = \sqrt{\frac{2I_{rel}}{\epsilon_0 c}} \times \frac{\lambda}{2} \approx m_e$$

NIF: 2 MJ / 4 ns = 500 TW



CPA laser: 15 J / 30 fs = 500 TW

CHIRPED PULSE AMPLIFICATION



International Committee On Ultrahigh Intensity Lasers www.icuil.org		
AFRL	Air Force Research Laboratory	Dayton
ALLS	Advanced Laser Light Source	Varennes
APOLL	APOLLON at Université Paris Saclay	Saclay
AWE	Atomic Weapons Establishment	Aldermaston
BARC	Bhabha Atomic Research Centre	Mumbai
BNL	Brookhaven National Lab, ATF	Upton
CAEP	Chinese Academy of Engineering Physics	Mianyang
COLA	Centre Optique et Laser en Aquitaine	Bordeaux
CESTA	Centre d'Etudes Scientifiques et Techniques d'Aquitaine	Le Barp
CLPU	Centro de Laseres Pulsados	Salamanca
CLUPS	Laser Center of the University of Paris - Sud	Paris
CoReLS	Center for Relativistic Laser Science	Gwangju
CRIEPI	Central Research Institute of Electric Power Industry	Yokosuka
CREOL	Center for Research in Electo-Optics and Lasers	Orlando
CSU	Colorado State University	Fort Collins
ELI-HU	Extreme Light Infrastructure Attosecond Light Pulse Source	Szeged
ELI-CZ	Extreme Light Infrastructure Beamlines	Dolní Břežany
ELI-NP	Extreme Light Infrastructure Nuclear Physics	Magurele
EXFEL	European XFEL, High Energy Density Group	Schenefeld

FSU	IOQ/Friedrich Schiller University of Jena	Jena
GAP-Bio	Université de Genève, GAP-Biophotonics	Carouge
GPI	Graduate School for the Creation of New Photonics Industries	Hamamatsu
GSI	GSI-Helmholtzzentrum fuer Schwerionenforschung GmbH	Darmstadt
HHU	Heinrich Heine Universität	Düsseldorf
HIJ	Helmholtz Institute Jena	Jena
HiLASE	HiLASE	Dolní Břežany
HUJ	Hebrew University of Jerusalem	Jerusalem
HZDR	Helmholtz Zentrum Dresden- Rossendorf	Dresden
IAP	Institute of Applied Physics, Russian Academy of Sciences	Nizhny Novgorod
ICL	Imperial College London	London
IHCE	Institute of High Current Electronics	Tomsk
ILE	Institute for Laser Engineering, Osaka University	Osaka
ILIL	Intense Laser Radiation Laboratory	Pisa
INFLPR	National Institute for Laser, Plasma, and Radiation Physics	Magurele
IOE	Instytut Optoelektroniki, Wojskowa Akademia Technology	Warsaw
IOP	Institute of Physics, Chinese Academy of Sciences	Beijing
IPPLM	Institute of Plasma Physics and Laser Microfusion	Warsaw
JIHT	Joint Institute for High Temperatures	Moscow
KAERI	Korean Atomic Energy Research Institute	Daejoen
KPSI	Kansai Photon Science Institute	Kizugawa
KQALS	Kaifeng Qiyuan Advanced Light Source Research Institute	Kaifeng

KyoU	Kyoto University, Institute for Chemical Research	Kyoto
L2I	Laboratory for Intense Lasers (L2I)	Lisbon
LBNL	Lawrence Berkeley National Laboratory	Berkeley
LC	Centrum Laserowe, Instytutu Chemii Fizycznej	Warsaw
LFRC	Laser Fusion Research Center at the CAEP	Mianyang
LLAMS	LaserLab Amsterdam	Amsterdam
LLC	Lund Laser Center	Lund
LLE	Laboratory for Laser Energetics	Rochester
LLNL-NIF	Lawrence Livermore National Lab - National Ignition Facility	Livermore
LLNL-JLF	Lawrence Livermore National Lab - Jupiter Laser Facility	Livermore
LMU	Ludwig Maximilians- Universität	München
LNF	Laboratori Nazionali di Frascati, SPARC Lab	Frascati
LOA	Laboratoire d'Optique Appliquée-ENSTA-Ecole Polytech.	Palaiseau
LULI	Laboratoire pour l'Utilisation des Lasers Intenses	Palaiseau
MBI	Max Born Institute	Berlin
MPQ	Max Planck Institute for Quantum Optics	Garching
NCU	National Central University	Taoyuan City
NII-OEP	Scientific Research Inst. for Optoelectronic Instrum. Engin.	Сосновый Бор
NRL	Naval Research Laboratory	Washington DC
OsaU	Osaka University	Osaka
OSU	Ohio State University, Scarlet Laser Facility	Columbus
OXFD	University of Oxford	Oxford

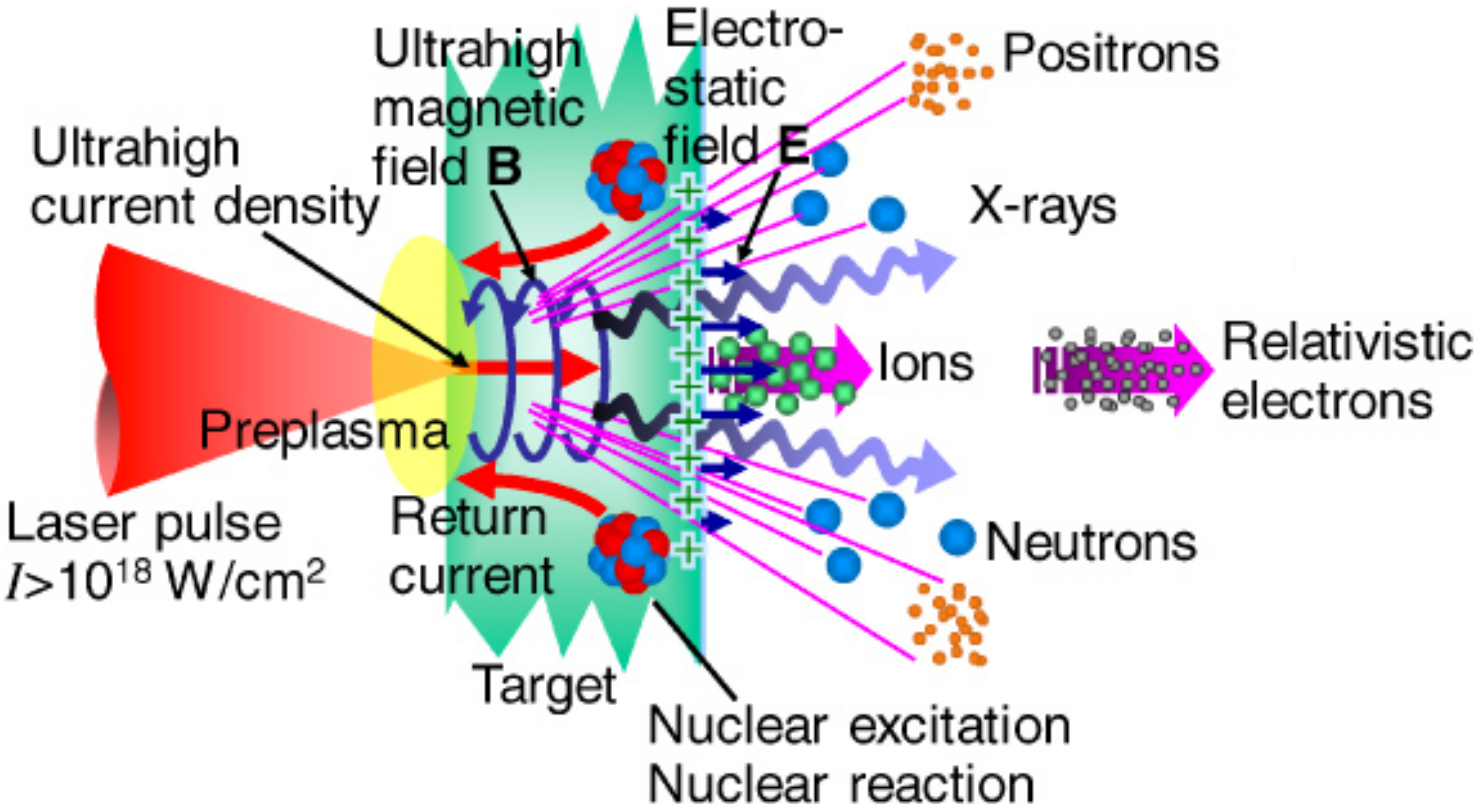
PALS	Prague Asterix Laser System Research Centre	Prague
Pek	Peking University	Peking
PMil	Politecnico Milano	Milan
PNLI	PN Lebedev Institute of Russian Academy of Science	Moscow
PU	Princeton University, Extreme Light-Matter Interactions Lab	Princeton
QUB	Queen's University Belfast, Centre for Plasma Physics	Belfast
RAL	STFC Rutherford Appleton Laboratory, Central Laser Facility	Didcot
RIKEN	Rikagaku Kenkyusho	Tokyo
RRCAT	Raja Ramanna Centre for Advanced Technology	Indore
SACLA	Spring-8 Angstrom Compact Free Electron Laser	Sayo
SCAPA	Scottish Centre for the Appl. of Plasma-based Accelerators	Glasgow
SEL	Station for Extreme Light	Shanghai
SIOM	Shanghai Institute of Optics and Fine Mechanics	Shanghai
SJTU	Shanghai Jiao Tong University	Shanghai
SLAC	Stanford Linear Accelerator Center	Stanford
SLIC	Saclay Laser-matter Interaction Center	Saclay
SNL	Sandia National Laboratory	Albuquerque
SULF	Shanghai Superintense Ultrafast Laser Facility	Shanghai
SWJTU	Southwest Jiaotong University	Emeishan
TAU	Tel Aviv Univ., Intense Lasers and Ultrafast Science Group	Tel Aviv
TIFR	Tata Institute of Fundamental Research	Mumbai
TIFR-H	Tata Institute of Fundamental Research, Hyderabad	Hyderabad

TU	Tsinghua University	Beijing
UAlb	University of Alberta	Edmonton
UCD	University College Dublin	Dublin
UCI	University of California, Irvine	Irvine
UCLA	University of California, Los Angeles	Los Angeles
UDel	University of Delaware	Newark
UEC	University of Electro-Communications Inst. for Laser Science	Tokyo
UMD	University of Maryland	College Park
UMed	Université de la Méditerranée, Laboratoire LP3	Marseilles
UMich	University of Michigan, Center for Ultrafast Optical Science	Ann Arbor
UNeb	University of Nebraska- Lincoln, Extreme Light Laboratory	Lincoln
UNev	University of Nevada at Reno, Nevada Terawatt Facility	Reno
USC	University of Santiago de Compostela, L2A2	Santiago
USze	University of Szeged	Szeged
UTex	University of Texas at Austin	Austin
UTok	University of Tokyo, Institute for Solid State Physics	Tokyo
VNIIEF	RFNC- All-Russian Research Institute of Experimental Phys.	Sarov
VNIITF	RFNC- Russian Research Institute of Technical Physics	Снежинск
VULRC	Vilnius University Laser Research Center	Lithuania
WIS	Weizman Institute of Science	Rehovot
WU	Warsaw University, Ultrafast Phenomena Lab	Warsaw
XCELS	Exawatt Center for Extreme Light Studies	Nizhny Novgorod

CPJ Barty & M Seggebruch

COMPACT PARTICLE ACCELERATORS

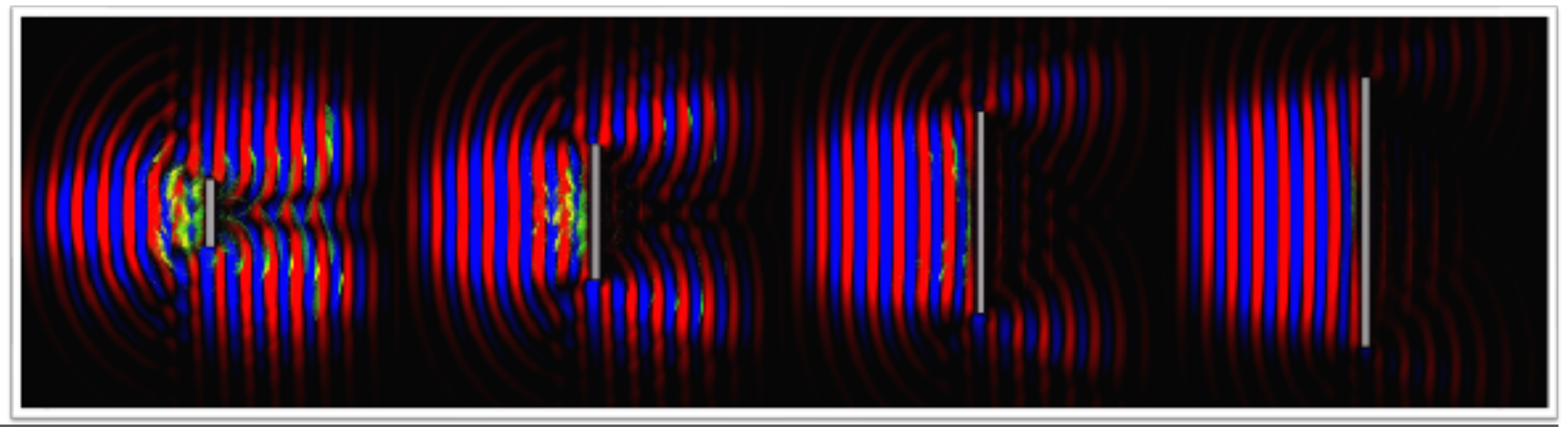
Nuclear Photonics is about taming relativistic light-matter interaction



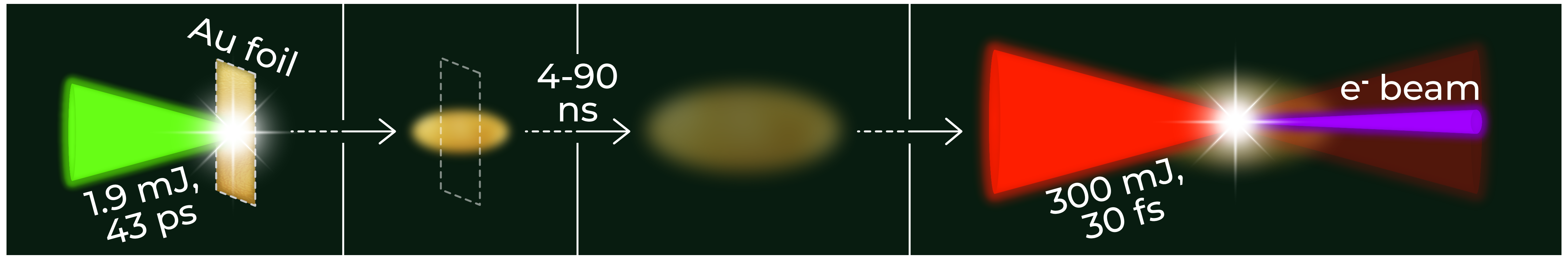
OUTLINE

- The Nuclear Photonics lab at TAU

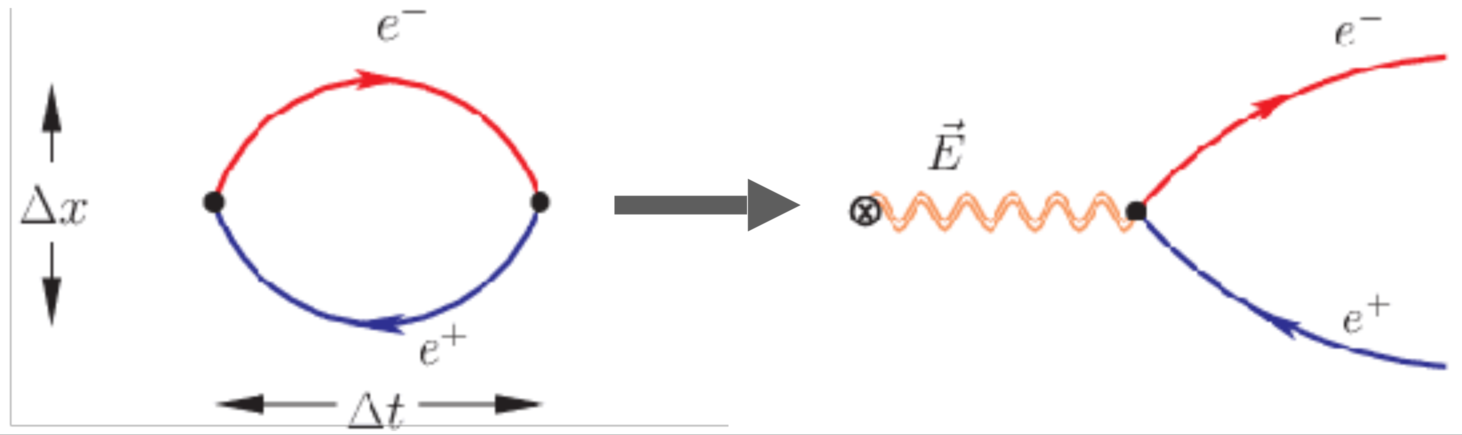
- The interaction of relativistic light with wavelength-scale objects



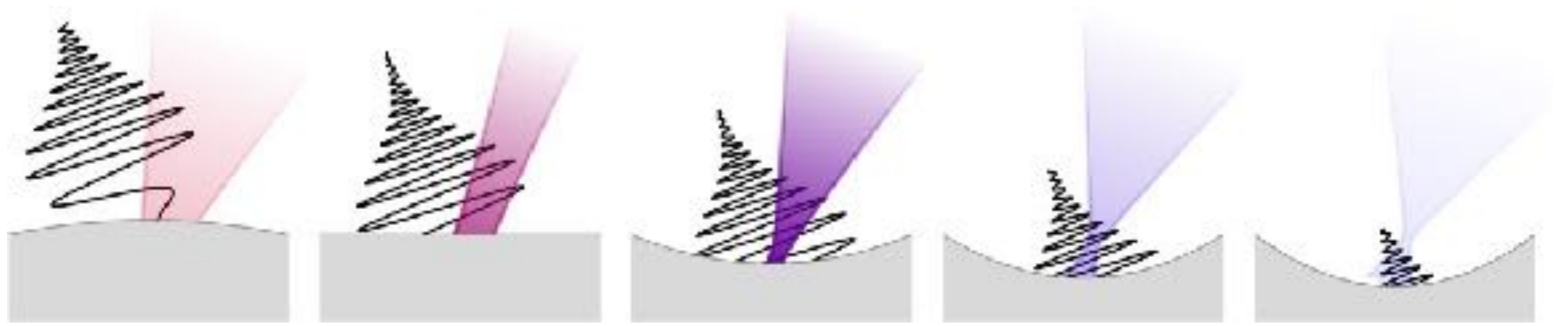
- Undepleted direct laser acceleration and neutron generation



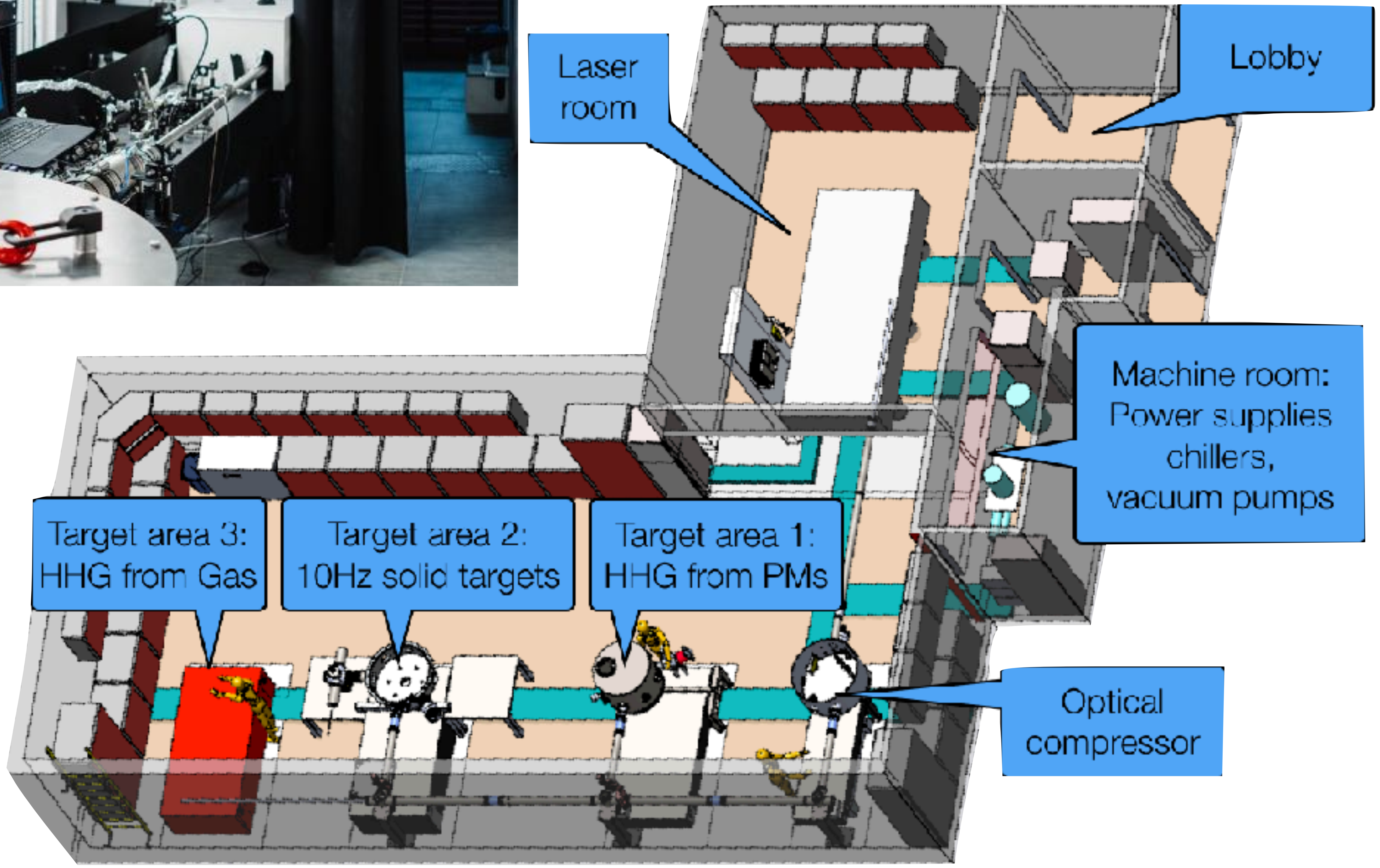
- Tests of strong-field QED at LUXE



- High harmonic generation from Plasma Mirrors



THE NUCLEAR PHOTONICS RESEARCH GROUP AT TEL-AVIV UNIVERSITY



PI
Dr. Ishay Pomerantz

Laser Scientist
Dr. Assaf Levanon

Laboratory manager
Dr. Lior Perlmuter

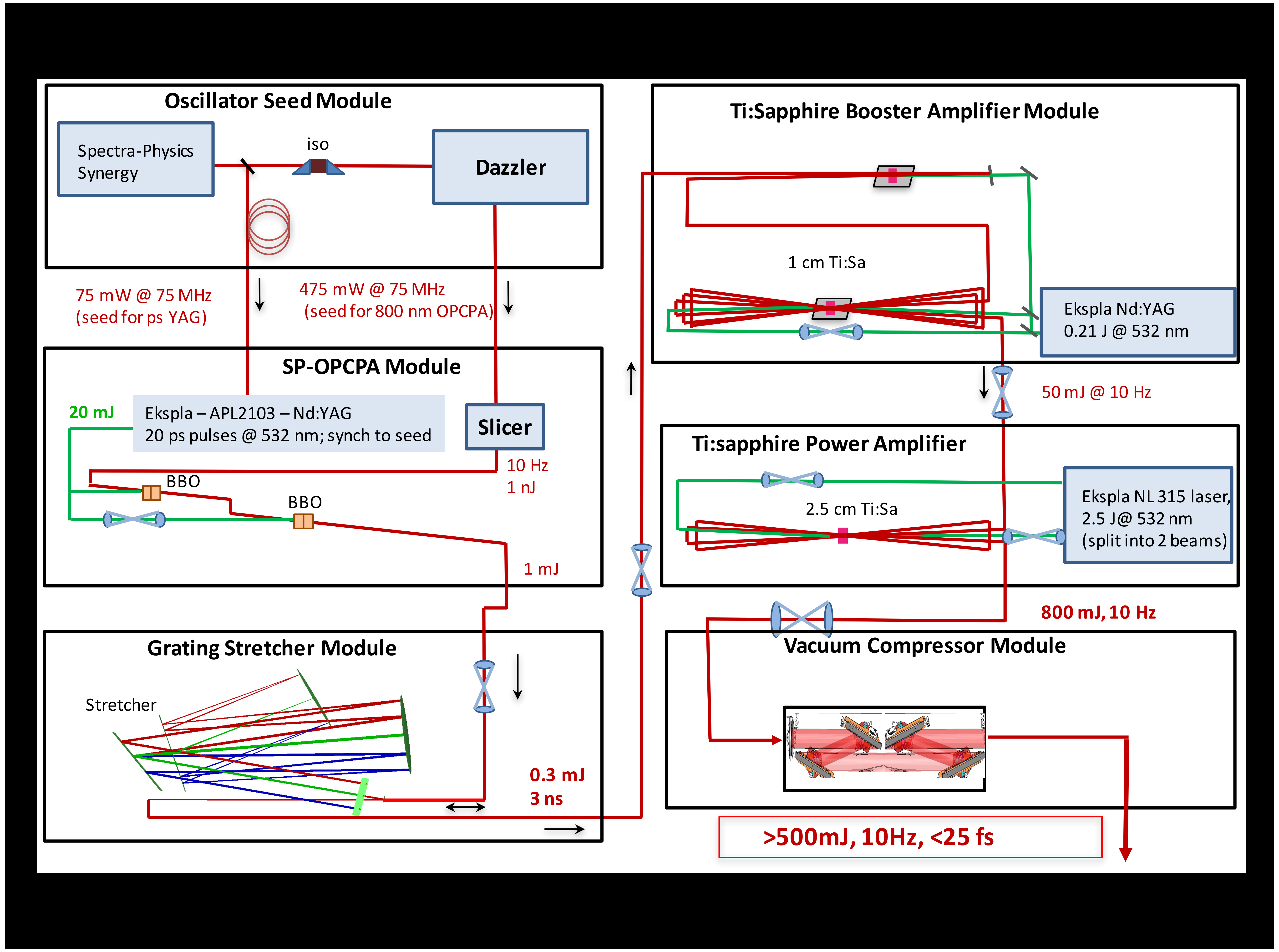
Ph.D. students
Elkana Porat
Raz Halifa-Levi
Itamar Cohen
Michal Elkind

Undergraduate RAs
Noam Popper
Tomer Catbi
Aviv Levinson
Afik Ben-Shimol

M.Sc. students
Talia Meir
Omry Noam
Hadar Yehuda

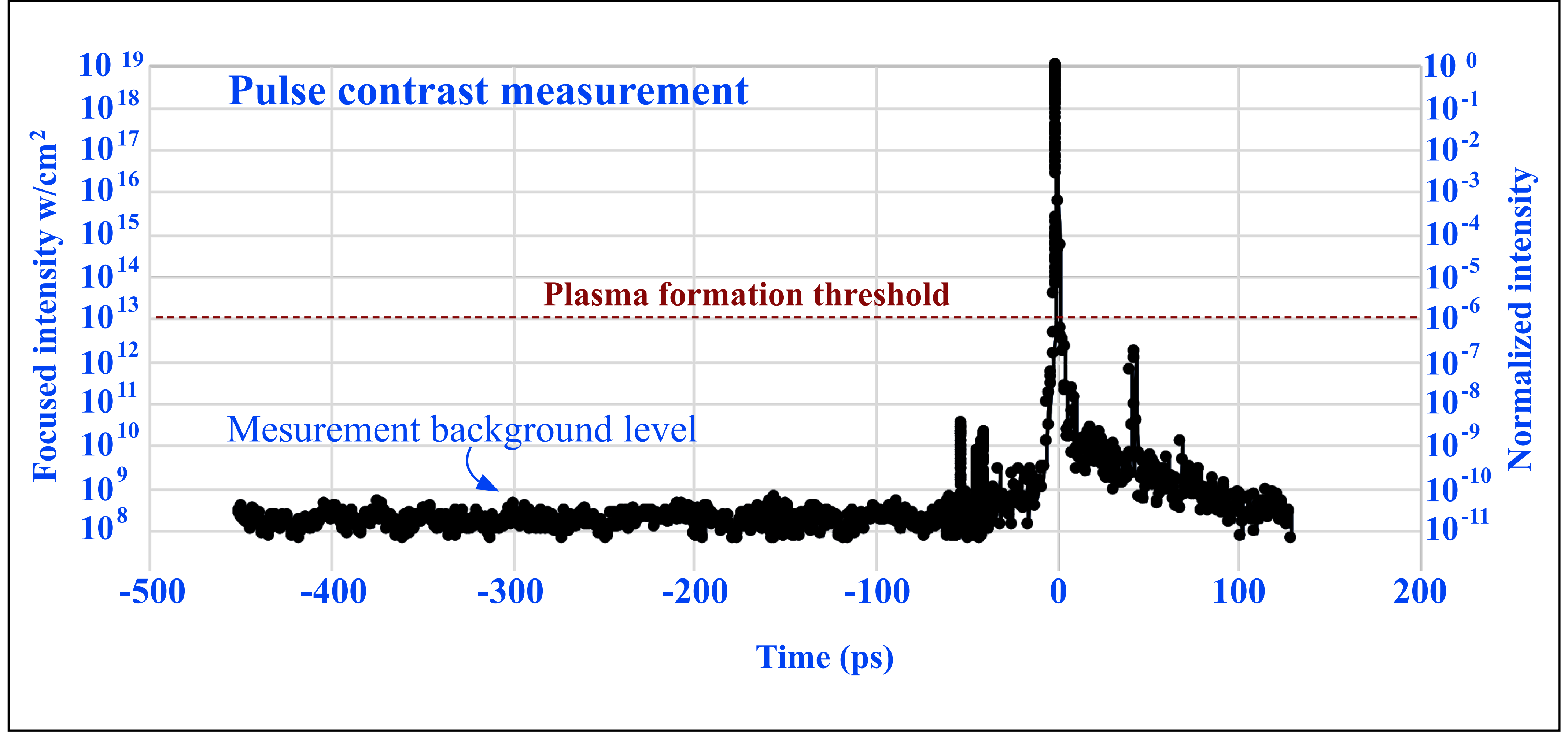
Israel Science Foundation
Zuckerman STEM Leadership Program
I-CORE Israeli Centers of Research Excellence
PAZY
Israel Ministry of Science & Technology
BSF United States - Israel Binational Science Foundation
Ministry of Energy www.energy.gov.il

THE LASER SYSTEM



- 10 Hz / 500 mJ on-target / 25 fs
- Front-end is based on picosecond OPCPA
- Contrast <10^{-11} @70 ps

THIRD ORDER CROSS-CORELLATION MEASUREMENT



RESEARCH PROJECTS

Porat, E, et al. "Spectral detuning of relativistic surface harmonics." *Physical Review Research* 4.2 (2022): L022036.

Porat, E, et al. "Spiral phase plasma mirror." *Journal of Optics* 24.8 (2022): 085501.

Yehuda, H, et al. "Annular coherent wake emission." *Optics Letters* 46.18 (2021): 4674-4677.

Porat, E., et al. "Diffraction-limited coherent wake emission." *Physical Review Research* 3.3 (2021): L032059.

Cohen, I, et al. "Optically switchable MeV ion/electron accelerator." *Applied Sciences* 11.12 (2021): 5424.

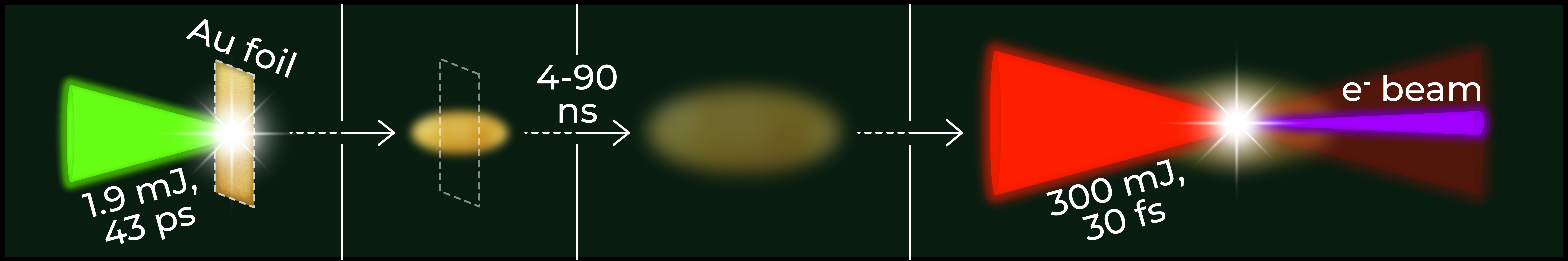
Gershuni, Y, et al. "Automated Delivery of Microfabricated Targets for Intense Laser Irradiation Experiments." *JoVE* 167 (2021): e61056.

Noam, O, et al. "Fast neutron resonance radiography with full time-series digitization." *NIM-A,* 955 (2020): 163309.

Gershuni, Y, et al. "A gatling-gun target delivery system for high-intensity laser irradiation experiments." *NIM-A* 934 (2019): 58-62.

Kishon, I., et al. "Laser based neutron spectroscopy." *NIM-A* 932 (2019): 27-30.

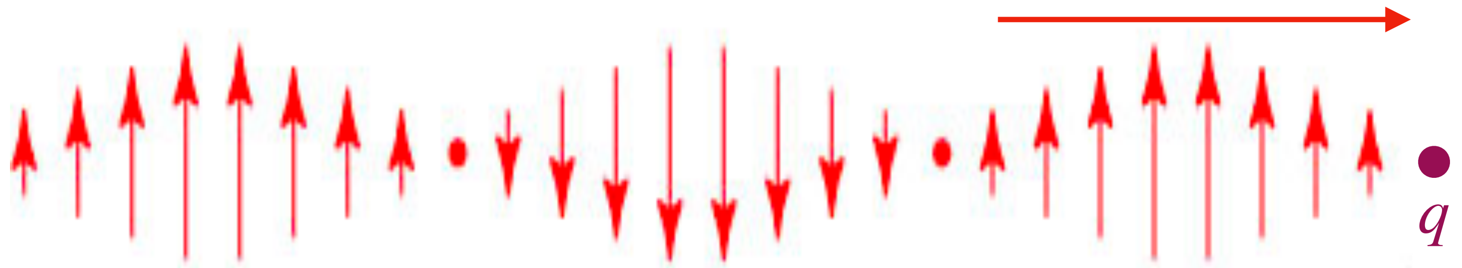
UNDEPLETED DIRECT LASER ACCELERATION



ACCELERATING CHARGED PARTICLES USING LIGHT

Single electron under the force of an EM plane wave

$\vec{A} = A_0 cos(kx - \omega t)\hat{y}$



$a_0 \equiv \frac{eA_0}{m_e c^2}$

$\gamma_0 \equiv \sqrt{1 + a_0^2/2}$

$kx = \frac{a_0^2}{8\gamma_0} sin2\phi$

$ky = -\frac{a_0}{\gamma_0} sin\phi$

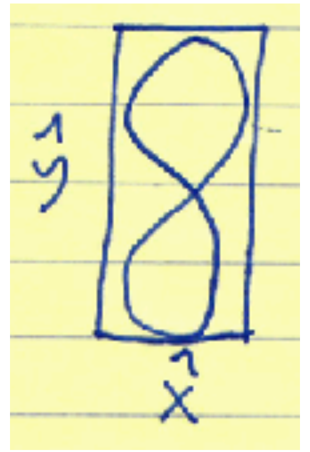


Figure-8 motion in some moving frame of reference no net energy coupling

The ponderomotive force

Add a slowly changing spatial envelope $\vec{\tilde{E}}$ to the plane wave

$\vec{E}(\vec{r}, t) = Re\{ \ \vec{\tilde{E}}(\vec{r}, t)e^{-i\omega t}\}$

Separate the charge position to an oscillating and a slow component

$\vec{r}(t) = \vec{r_o}(t) + \vec{r_s}(t)$

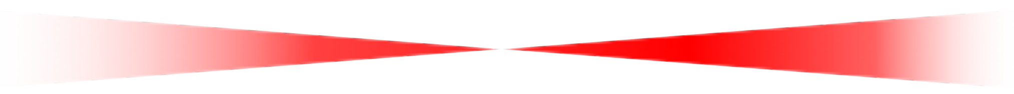
$\langle \vec{r_o}(t) \rangle = 0$

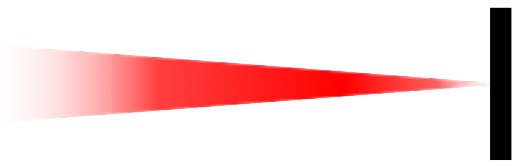
$\langle \vec{r}(t) \rangle = \langle \vec{r_s}(t) \rangle = \vec{r_s}(t)$

$\vec{f_p} \equiv m_e \frac{d}{dt} \langle \vec{v} \rangle = -\frac{e^2}{2m_e\omega^2} \nabla \langle \vec{\tilde{E}}^2(\vec{r_s}(t), t) \rangle$

$\xrightarrow[\gamma >> 1]{} - m_e c^2 \nabla \sqrt{1 + \langle a^2 \rangle}$

Focusing / defocusing beam: acceleration / deceleration



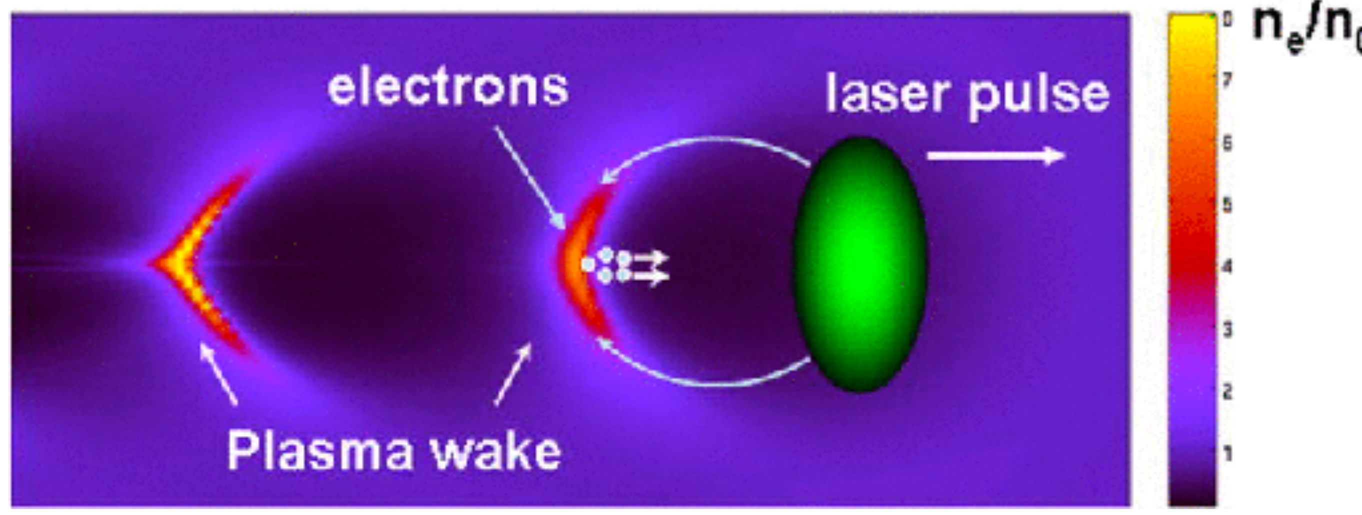


Employ the plasma's collective response, for example: laser wakefield acceleration

Use the ponderomotive force to excite plasma waves

Electrons are trapped and accelerated in the wake

Malka, V. (2012). Laser plasma accelerators. *Physics of Plasmas*, *19*(5), 055501.



State-of-art:

Energies as high as 8 GeV

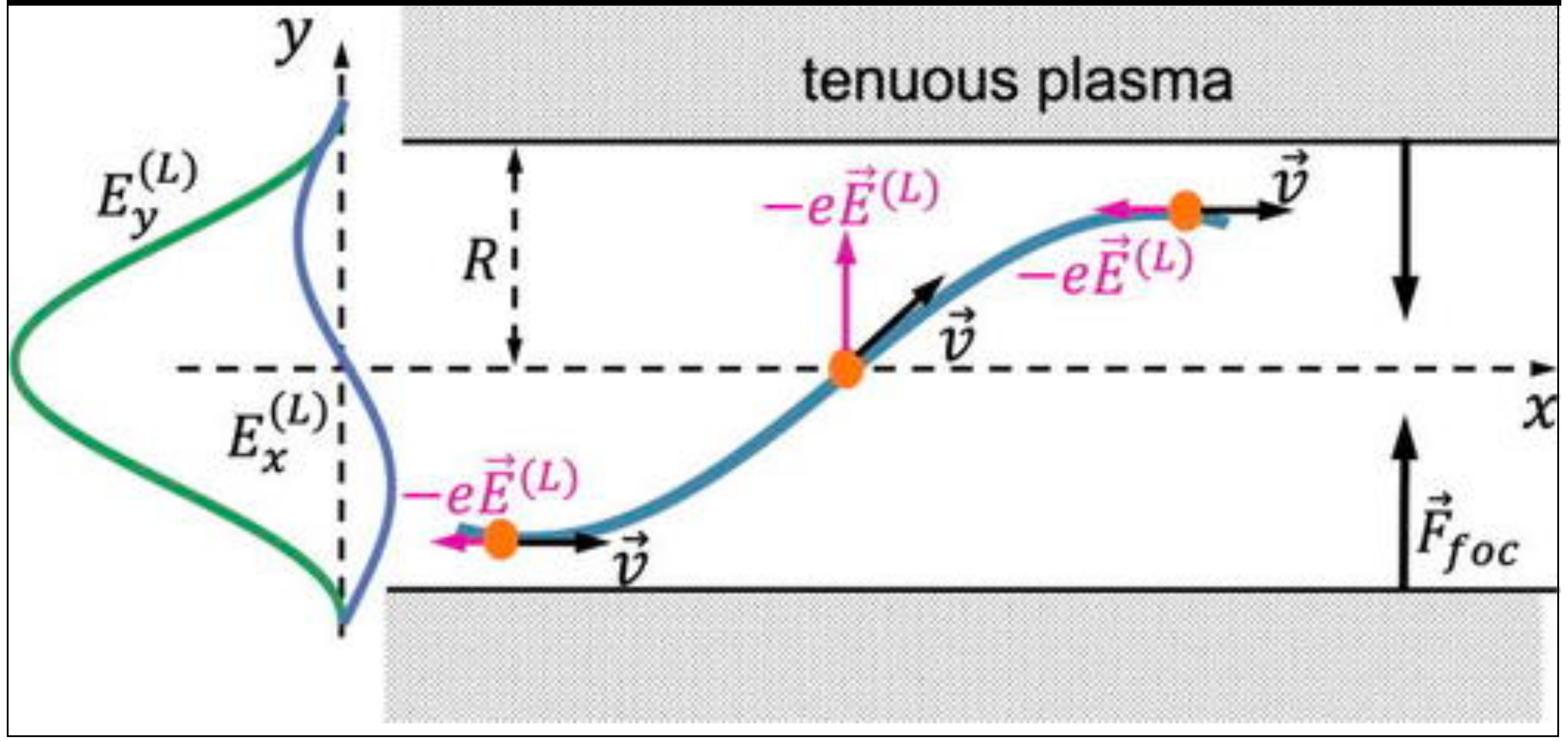
Reasonable control over spectral features

Only nanocolumb charge

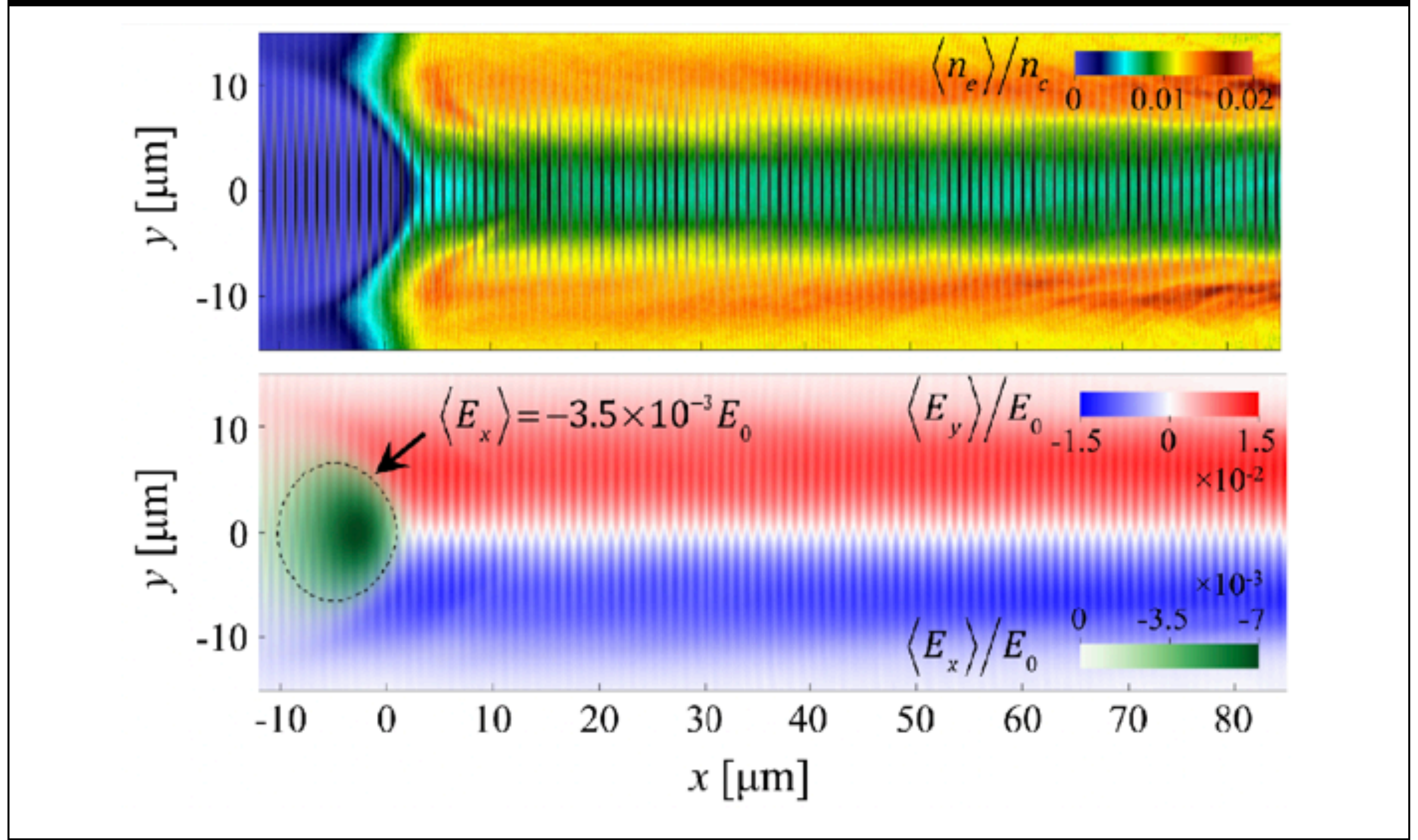
DIRECT LASER ACCELERATION (DLA)

- The ponderomotive force of the leading part of the laser pulse expels electrons and forms a slowly evolving quasi-stationary ion channel
- The laser electric field transfers energy into transverse (betatron) oscillations
- This energy is redirected by the magnetic field of the laser into the longitudinal direction

WANG ET. AL, POP 26, 083101 (2019)



AREFIEV ET. AL, POP 23, 056704 (2016)

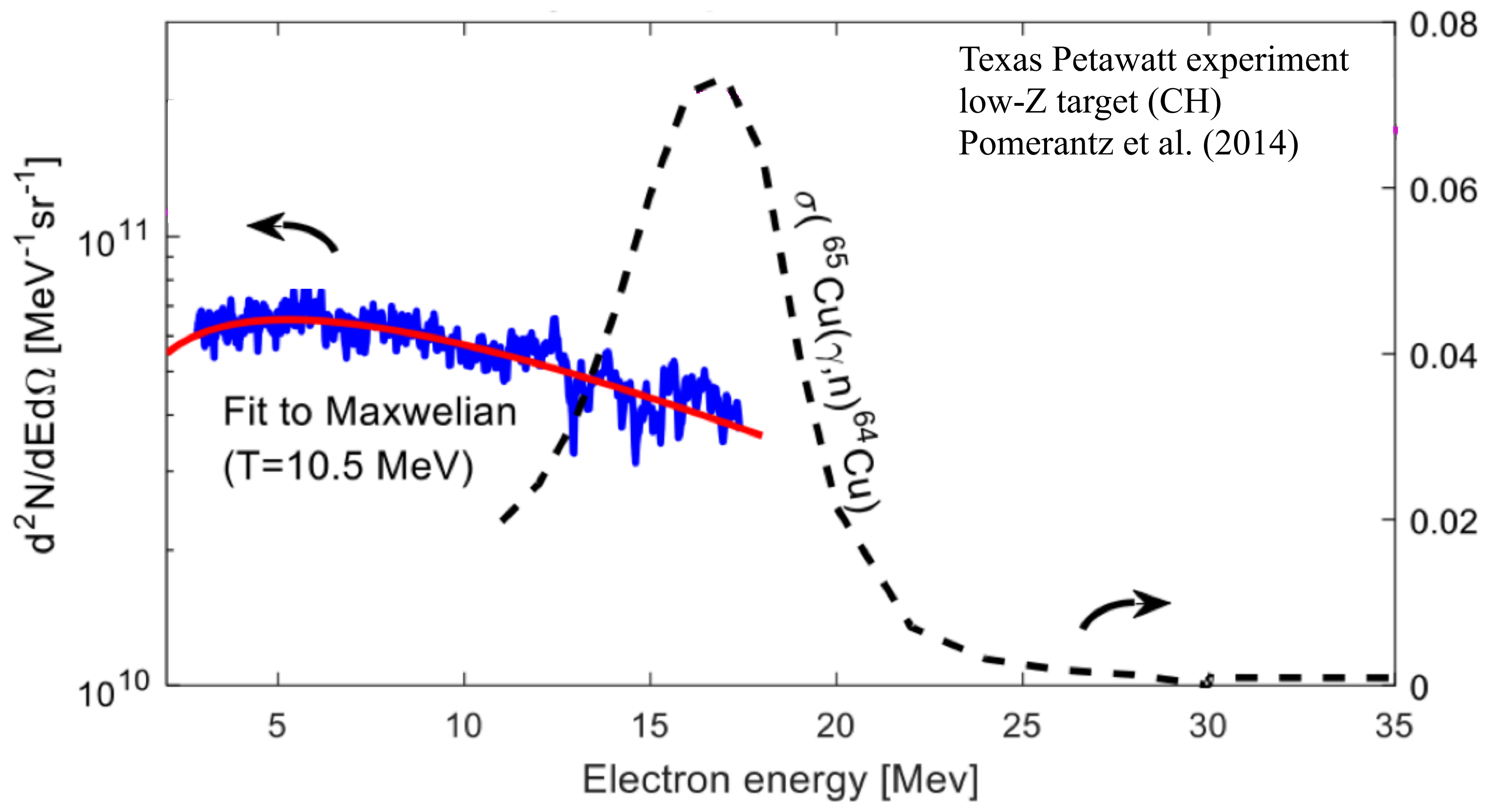


DIRECT LASER ACCELERATION (DLA)

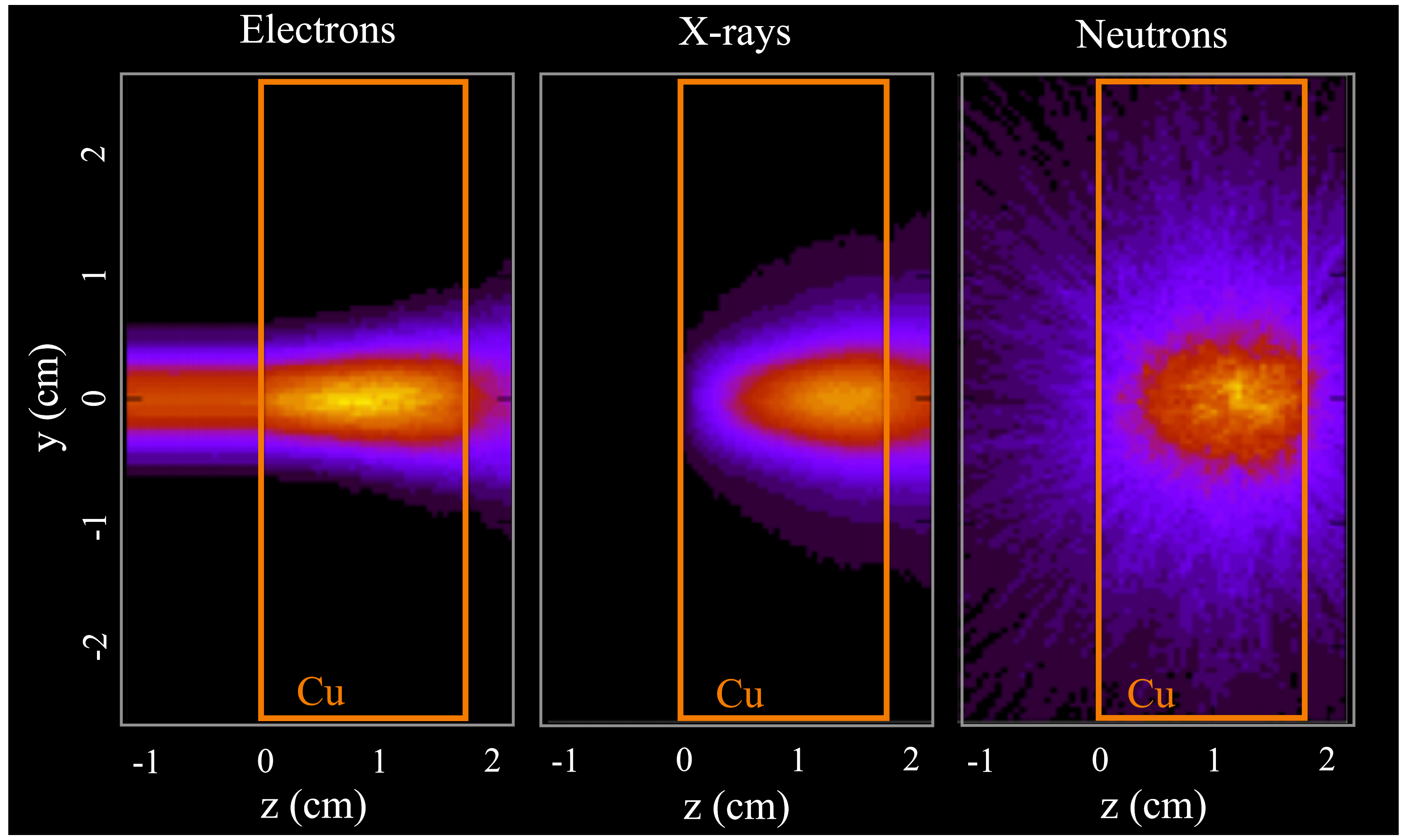
- DLA has been observed in experiments for 25 years
- These experiments used low-Z targets (plastic foils or gas jets)

- DLA produce MeV-level, continuous electron spectrum
- Reported conversion efficiency of laser energy to electrons of over 25%
- An ideal method for generating a large number of photo-nuclear reactions

Malka, G., et al., Physical Review Letters, 79 (11), 2053 (1997).
Malka, G., et al., Physical Review Letters, 78 (17), 3314 (1997).
Gahn, C., et al., (1999). Physical Review Letters, 83 (23), 4772–4775.
D. Giulietti, et al., Phys. Rev. E 64, 15402 (2001).
D. Giulietti, et ak., Phys. Plasmas 9, 3655 (2002).
Willingale, L., et al., New Journal of Physics,15 (2), 025023 (2013).
Rosmej O. N., et al, New Journal of Physics, 21 (4), 043044 (2019).
Rosmej O. N. , Plasma Phys. Control. Fusion 62, 115024 (2020).
Shaw, J.L., et al., Sci Rep 11, 7498 (2021).
Gorlova, et al. (2022). Laser Physics Letters, 19 (7), 075401.
Gunther, et al., (2022). Nature Communications 2022 13:1, 13 (1), 1–13.



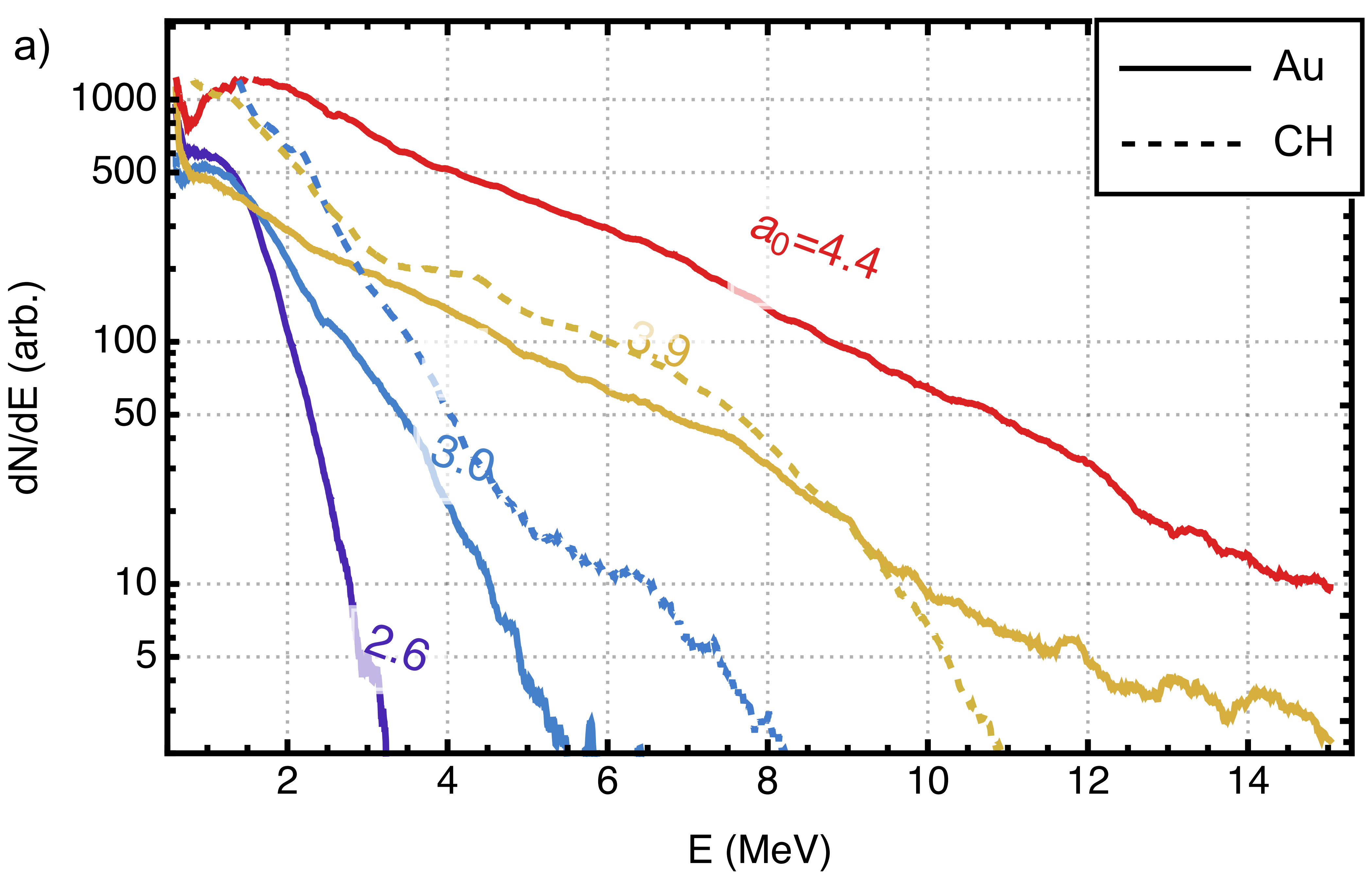
Pomerantz I., et al., Physical Review Letters, 113 (18), 1–6 (2014).

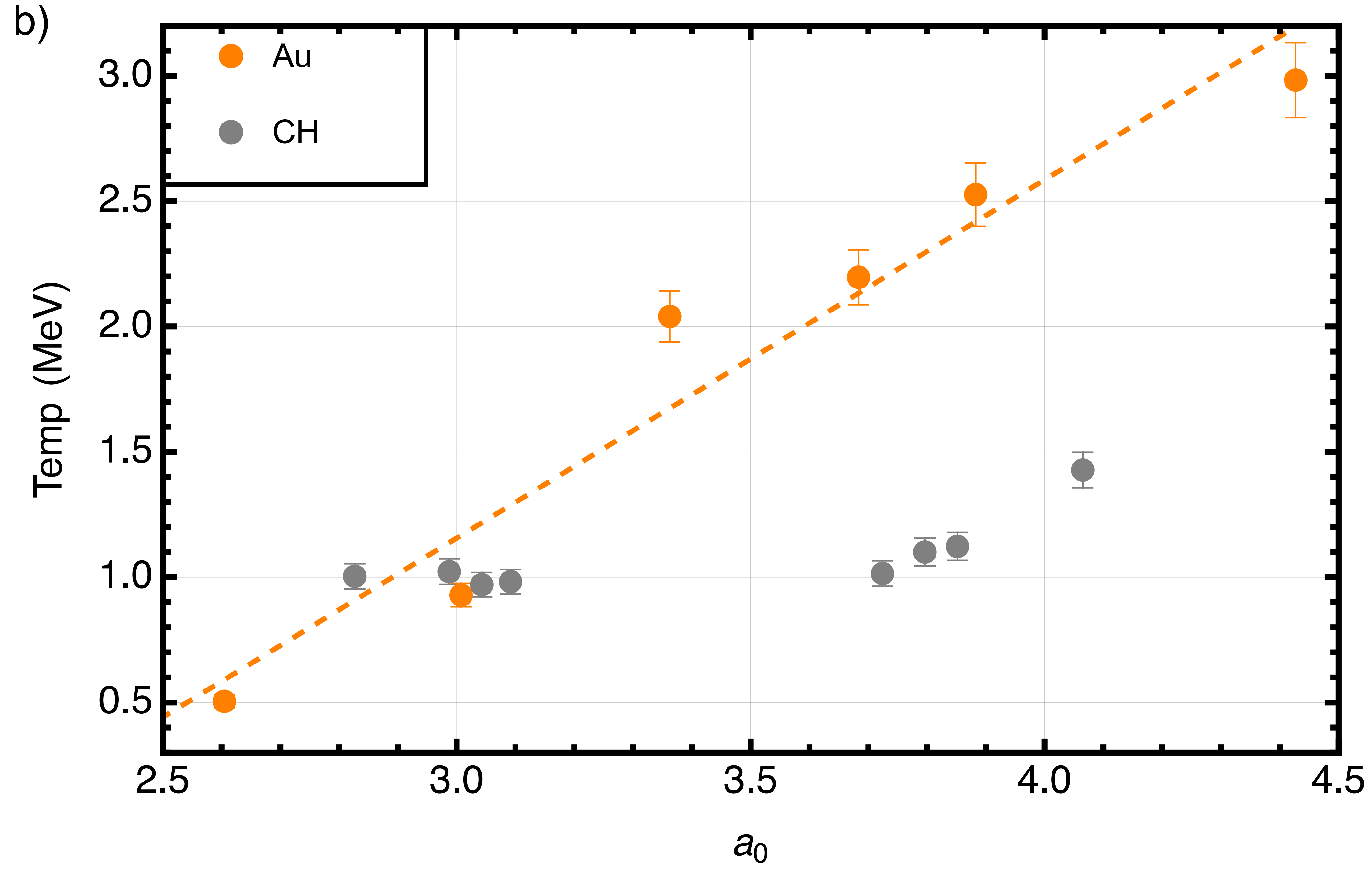


Pukhov scaling prediction: $T_{eff} = \alpha I^{1/2}$ Pukhov et al, PoP 6, 2847 (1999)

DLA: A LOW-Z VS. HIGH-Z PLASMA TARGET

- We generated DLA electron beams from high-Z plasma targets (Au)
- For each plasma type, the plume's density profile was optimized to yield a beam with a maximal electron temperature





- DLA from Au plasma maintains Pukhov scaling, CH plasma does not.

Why?

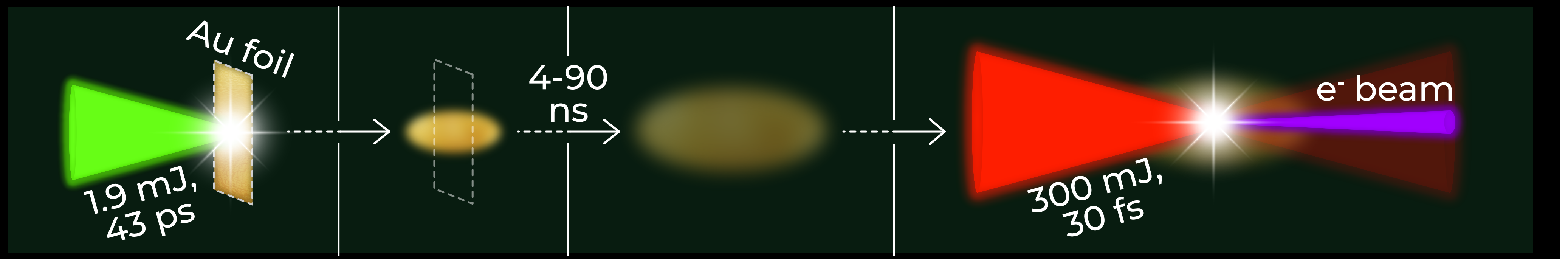
THE DLA SETUP AT TEL-AVIV U.

Itamar Cohen

Main pulse: 100-500 mJ / 25 fs

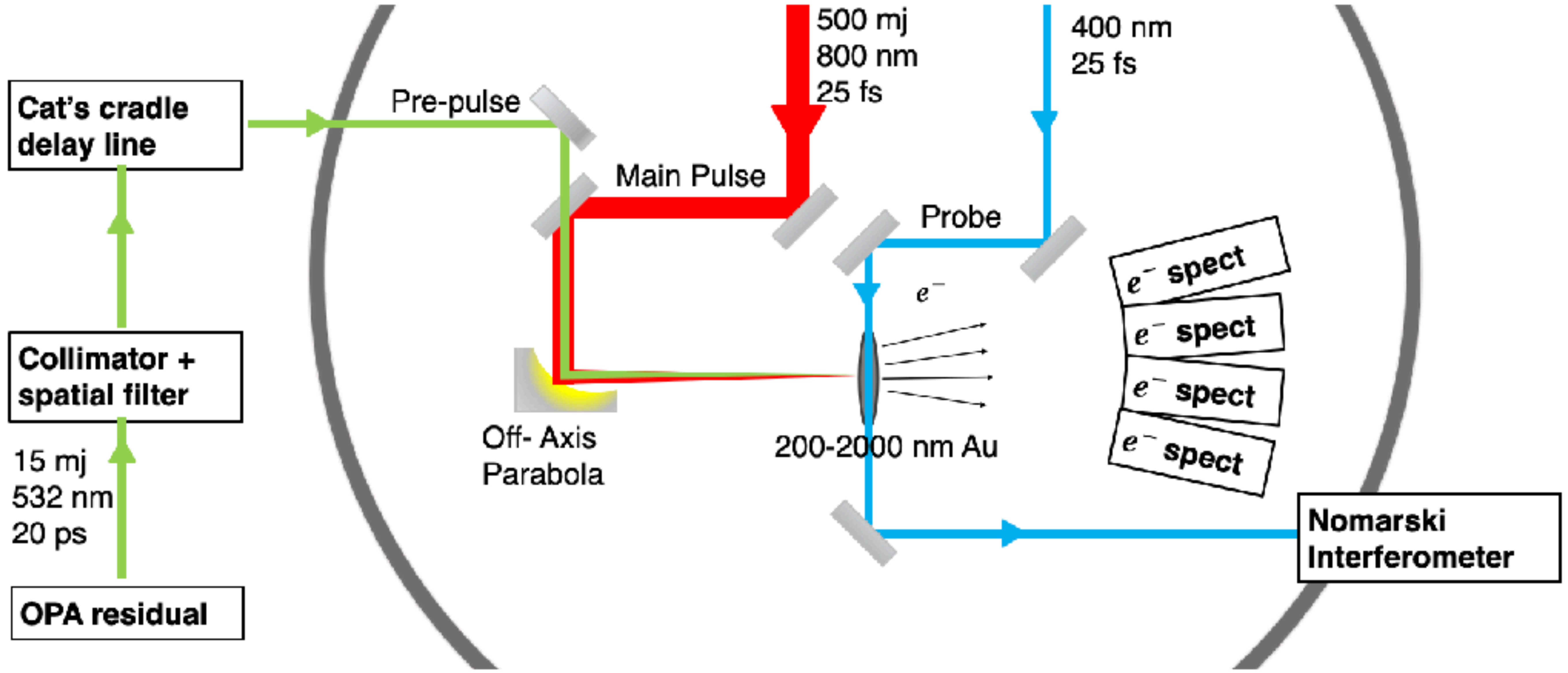
Parametric scan of:

- Target thickness and composition
- Pre-pulse energy
- Pre- to main-pulse delay



For each shot we record:

- Electron spectrum
- Plume's density profile
- NF image of light punching through the plasma

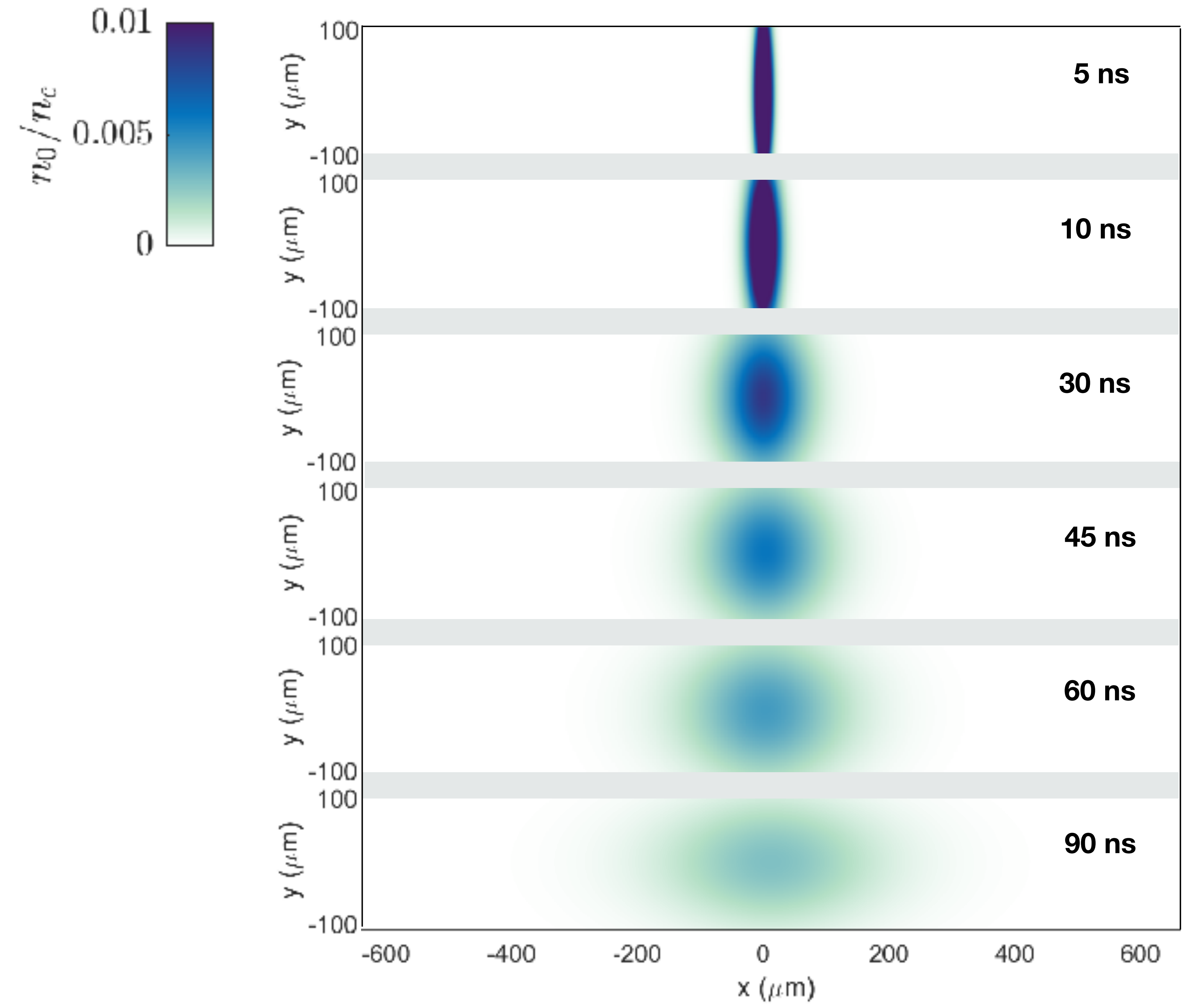


SIMULATION

Talia Meir

- Using the EPOCH-2D code
- Running on Lonestar6
  (ranked world 13th supercomputer)
- Measured plasma plume profiles serve as initial inputs
- Field ionization is implemented in the code

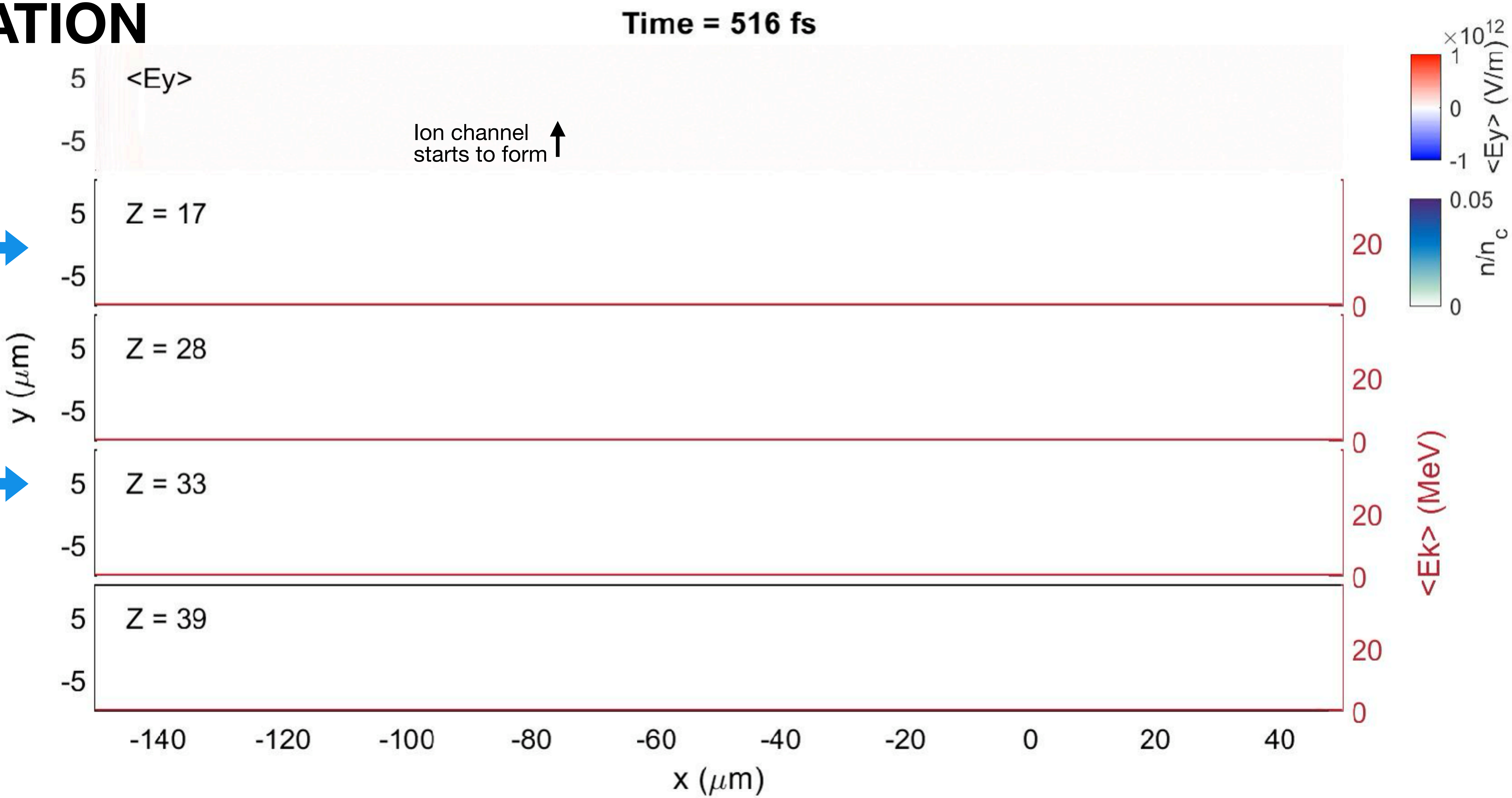
INPUT PLASMA PROFILES (FROM MEASUREMENT)



SIMULATION

Low-Z electrons are ionized prematurely, before the ion channel is formed

High-Z electrons are ionized later when the channel is already formed



For low-z targets, the target is depleted from all of its ionization electrons too early, resulting in inefficient DLA

ELECTRON AND NEUTRON YIELDS

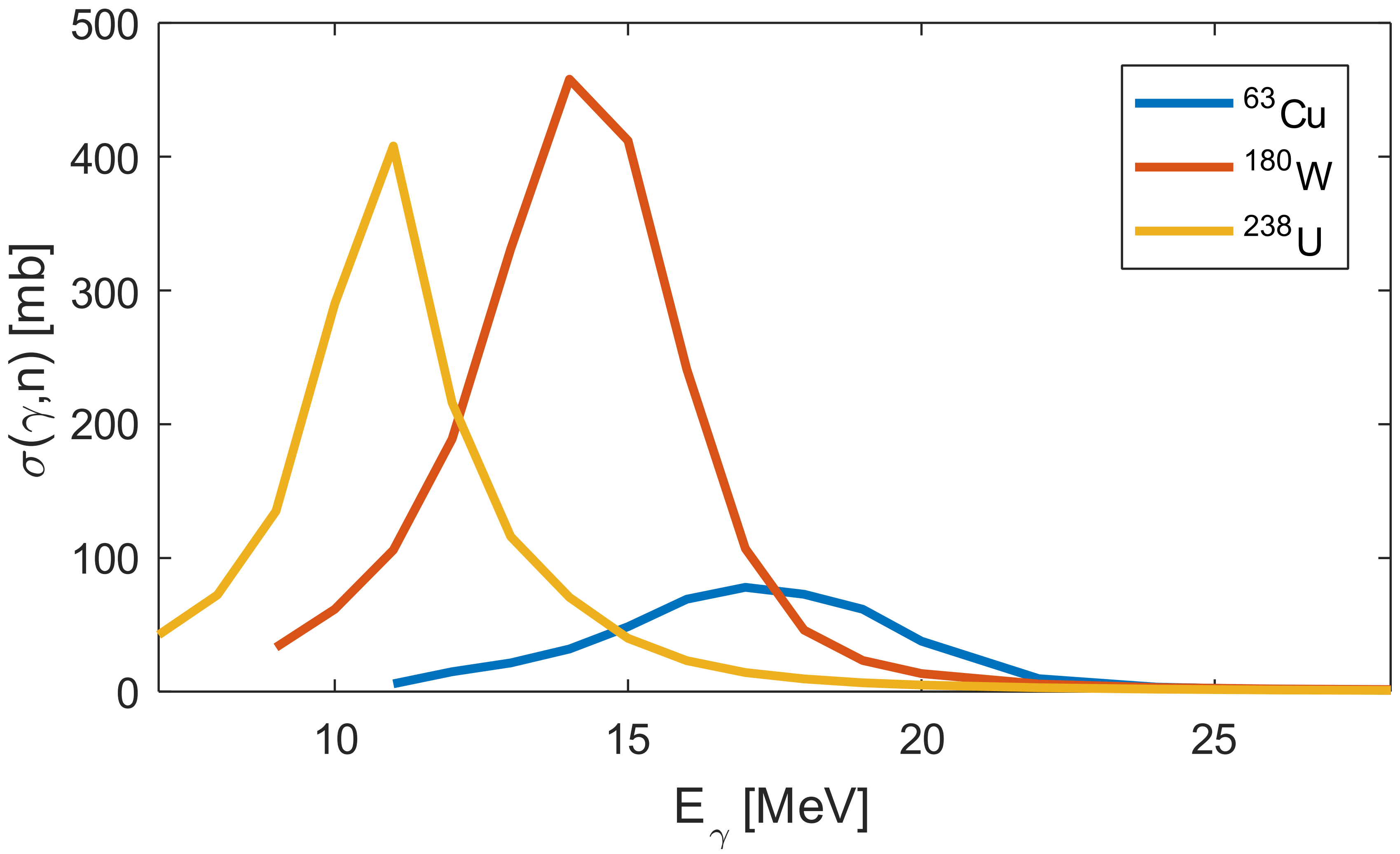
Highest performance with a_0 = 4.5, 800 nm thick Au targets, pre-pulse of 1.9 mJ at t= -60 ns

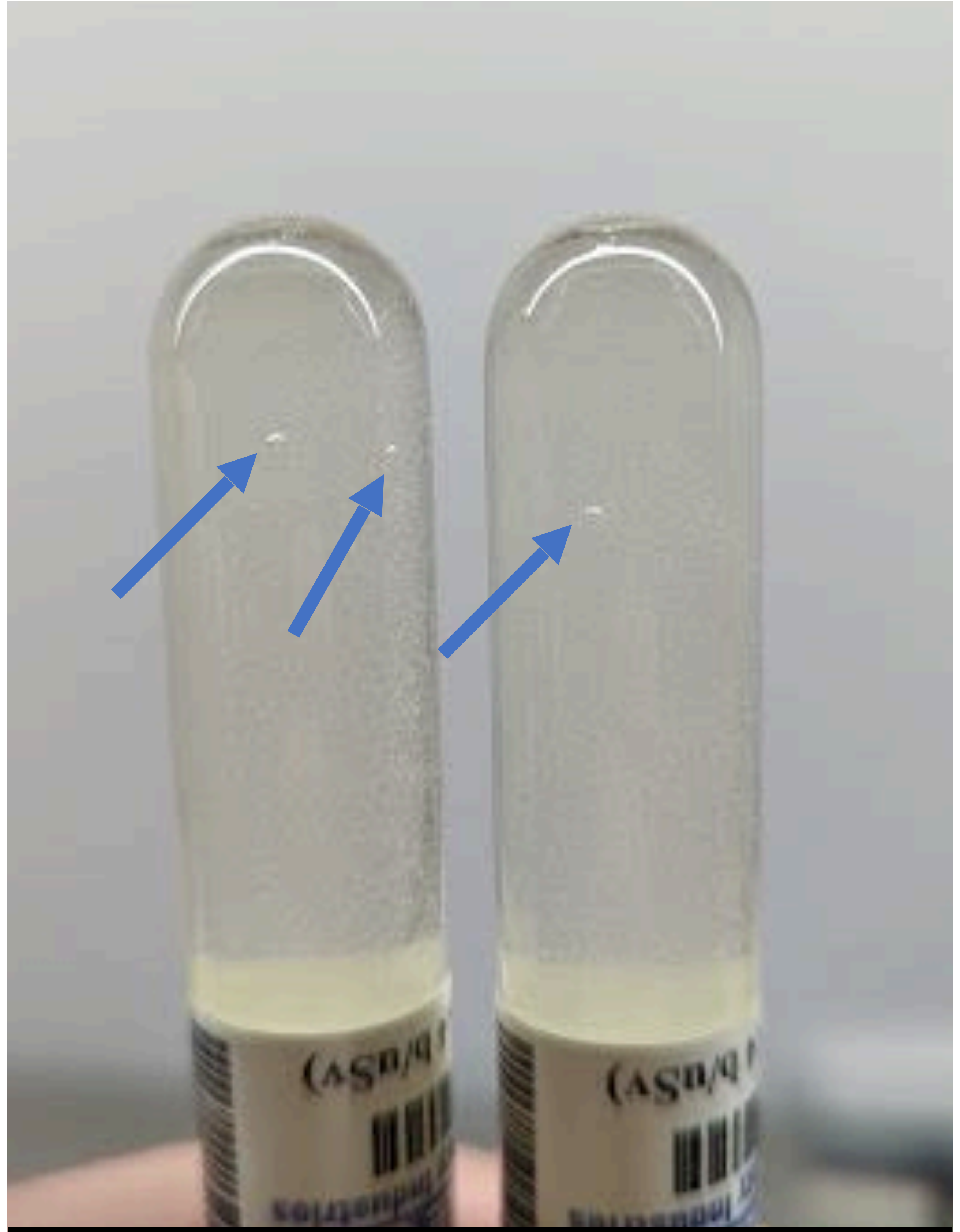
- >20% conversion efficiency from laser energy to E>0.5 MeV electrons

- We used the electron beam to generate neutrons

  1 cm thick ^{238}U converter

  3×10^5 neutrons per shot
  (assuming a 4π distribution)





BUBBLES DOSIMETERS