New Horizons in High-Energy-Density Physics: Above the Schwinger Limit and Harnessing Cosmic Particle Acceleration

Presented by:

OSA

Short Wavelength Sources and
Attosecond/High Field Physics
Technical Group

The OSA Short Wavelength Sources and Attosecond/High Field Physics Technical Group Welcomes You!

NEW HORIZONS IN HIGH-ENERGY-DENSITY PHYSICS: ABOVE THE SCHWINGER LIMIT & HARNESSING COSMIC PARTICLE ACCELERATION

7 March 2019 • 14:00 EST

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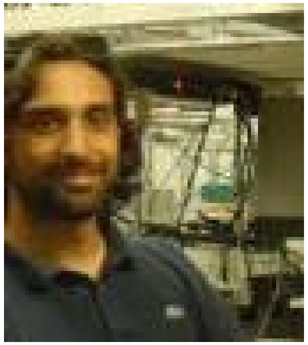
Technical Group Leadership 2019



Giulio Vampa
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Stanford PULSE Institute

Eric Cunningham
SLAC National Accelerator Laboratory

Hanieh Fattahi
Max-Planck-Institute of Quantumoptics

Benjamin Webb
Laboratory for Laser Energetics,
University Of Rochester

Zhiyi Wei
Institute of Physics,
Chinese Academy of Sciences

Technical Group at a Glance

- Focus
  - Development and application of high intensity lasers as well as novel XUV and x-ray sources
  - The physics of high intensity light interactions with matter
  - Short wavelength sources including insertion devices for storage rings (undulators and wigglers), plasma X-ray lasers, electron beam based sources and X-ray free electron lasers.
- Mission
  - To benefit *YOU* and to strengthen *OUR* community
  - Webinars, podcasts, publications, technical events, business events, outreach
  - Interested in presenting your research? Have ideas for TG events? Contact us at TGactivities@osa.org.
- Find us here
  - Website: www.osa.org/OH
  - Facebook: www.facebook.com/OSAShortWavelengthTG
  - LinkedIn: www.linkedin.com/groups/8356401

Today's Webinar

Short Wavelength Sources and Attosecond/High Field Physics Technical Group

Exploring extreme laser-plasma conditions: from laboratory astrophysics to compact accelerators

Dr. Frederico Fiuza

Theory Group Leader, High Energy Density Science Division
SLAC National Accelerator Laboratory, USA
Fiuza@slac.stanford.edu

Speaker's Short Bio:

Diploma in Physics Engineering and Ph.D. in Plasma Physics from Instituto Superior Tecnico, Portugal in 2012. Lawrence postdoctoral fellow at LLNL. European Physical Society PhD Research Award. DOE Early Carer Research Program Award. APS Thomas H. Stix Award. Currently a Staff Scientist at SLAC, USA

SLAC NATIONAL ACCELERATOR LABORATORY

Today’s Webinar

Short Wavelength Sources and
Attosecond/High Field Physics
Technical Group

Reaching for the brightest light at SLAC’s FACET-II

Dr. Sebastian Meuren

Postdoctoral Researcher and PI of a strong-field QED experimental campaign at SLAC’s FACET-II
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smeuren@pppl.gov

Speaker’s Short Bio:
Ph.D. degree from Heidelberg University/Max Planck Institute for Nuclear Physics in 2015. Otto Hahn Medal from the Max Planck Society. Currently a postdoctoral researcher in the department of Astrophysical Sciences at Princeton University.

PRINCETON
UNIVERSITY

Exploring extreme laser-plasma conditions: from compact accelerators to laboratory astrophysics

Frederico Fiúza

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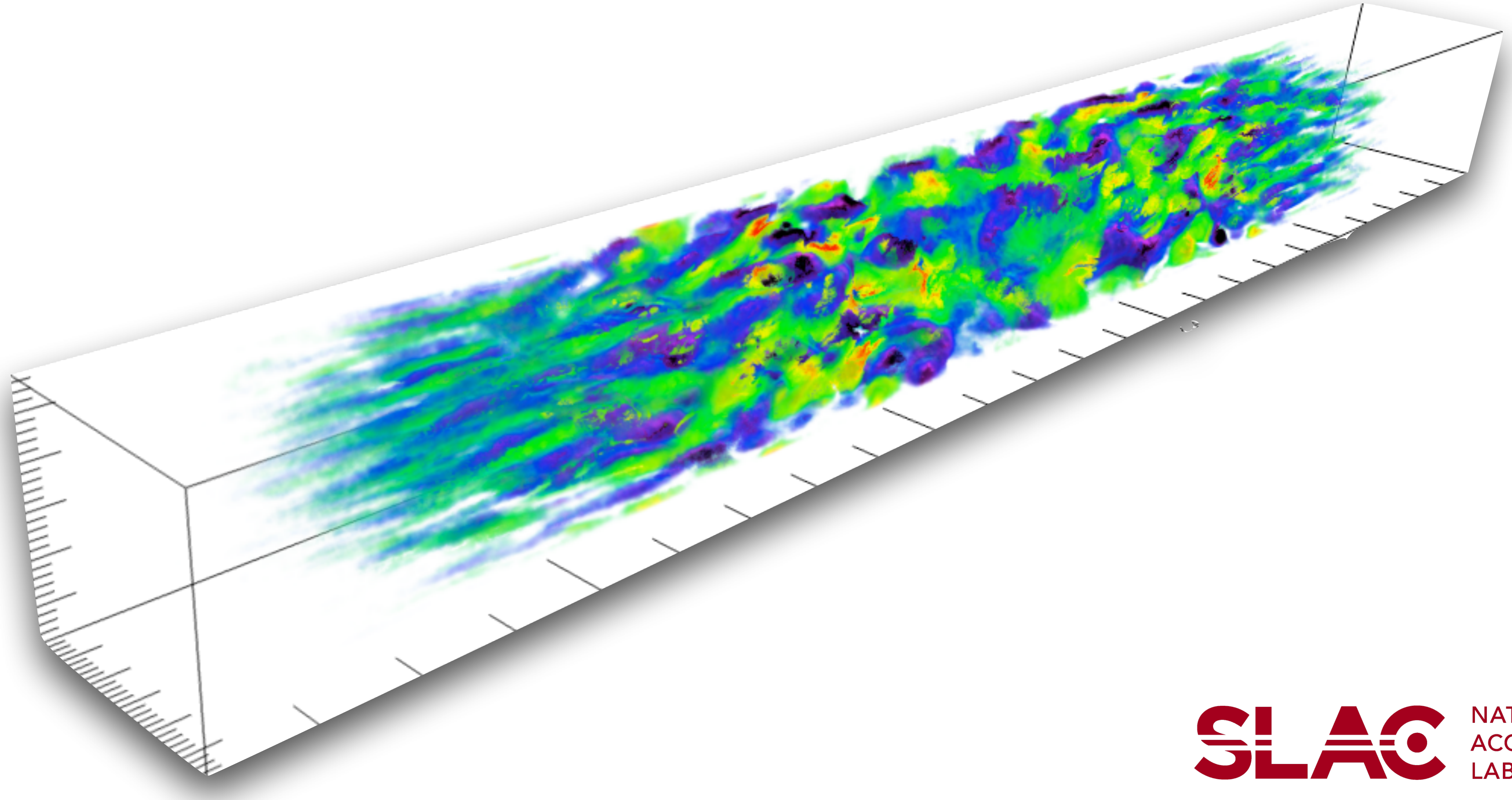
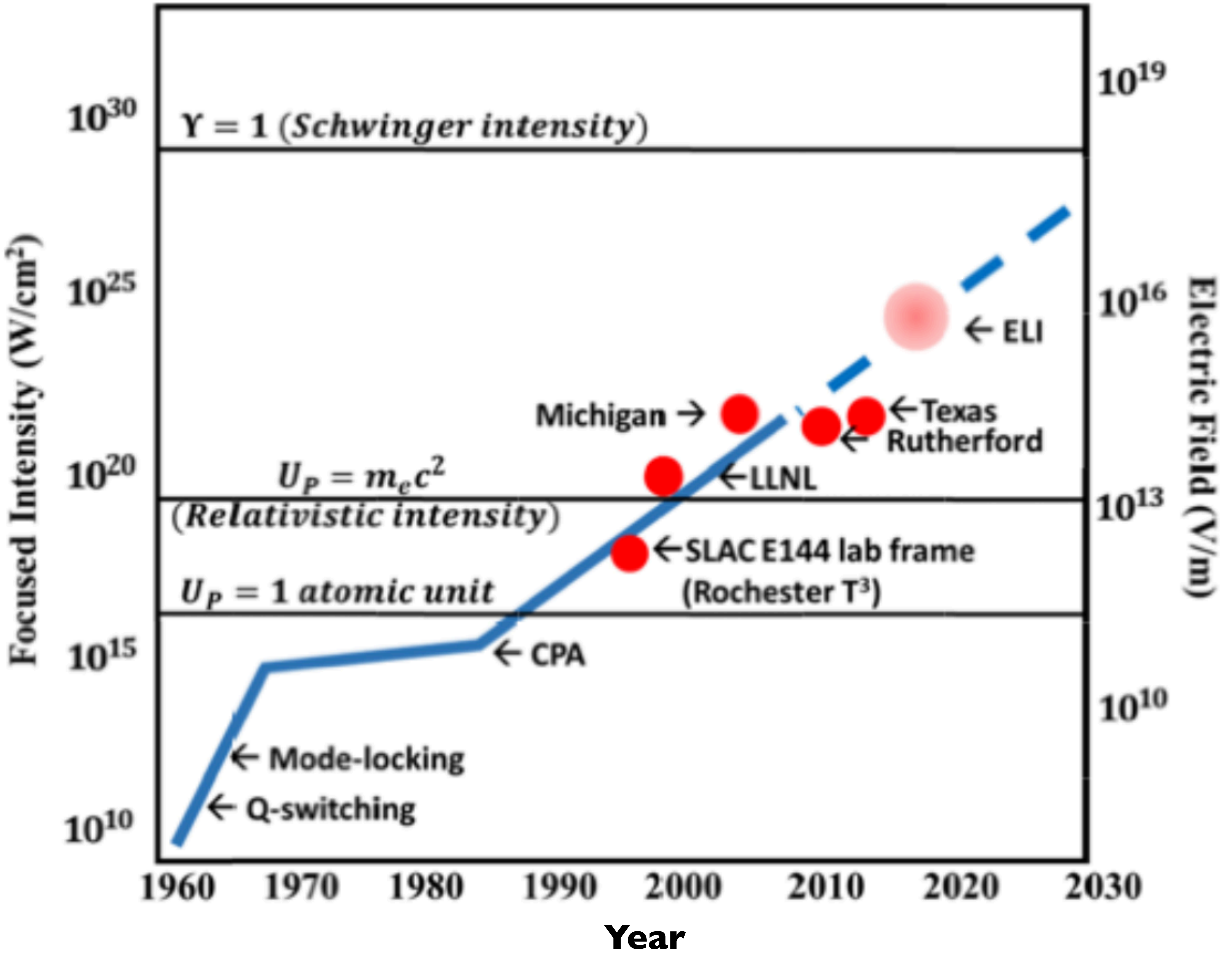


U.S. DEPARTMENT OF ENERGY
Office of Science

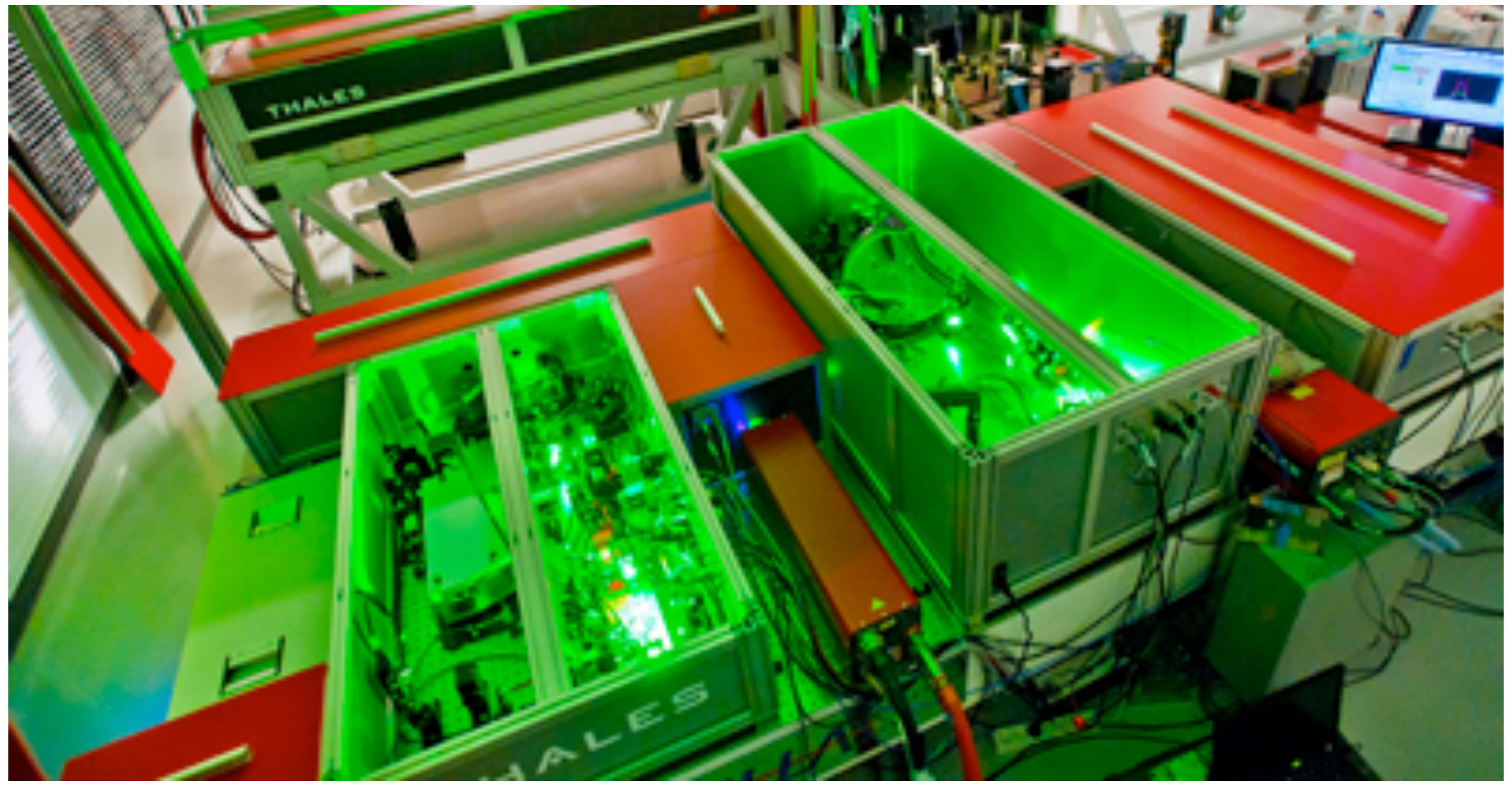
SLAC NATIONAL ACCELERATOR LABORATORY

CPA led to tremendous progress in high-power lasers over the last decades

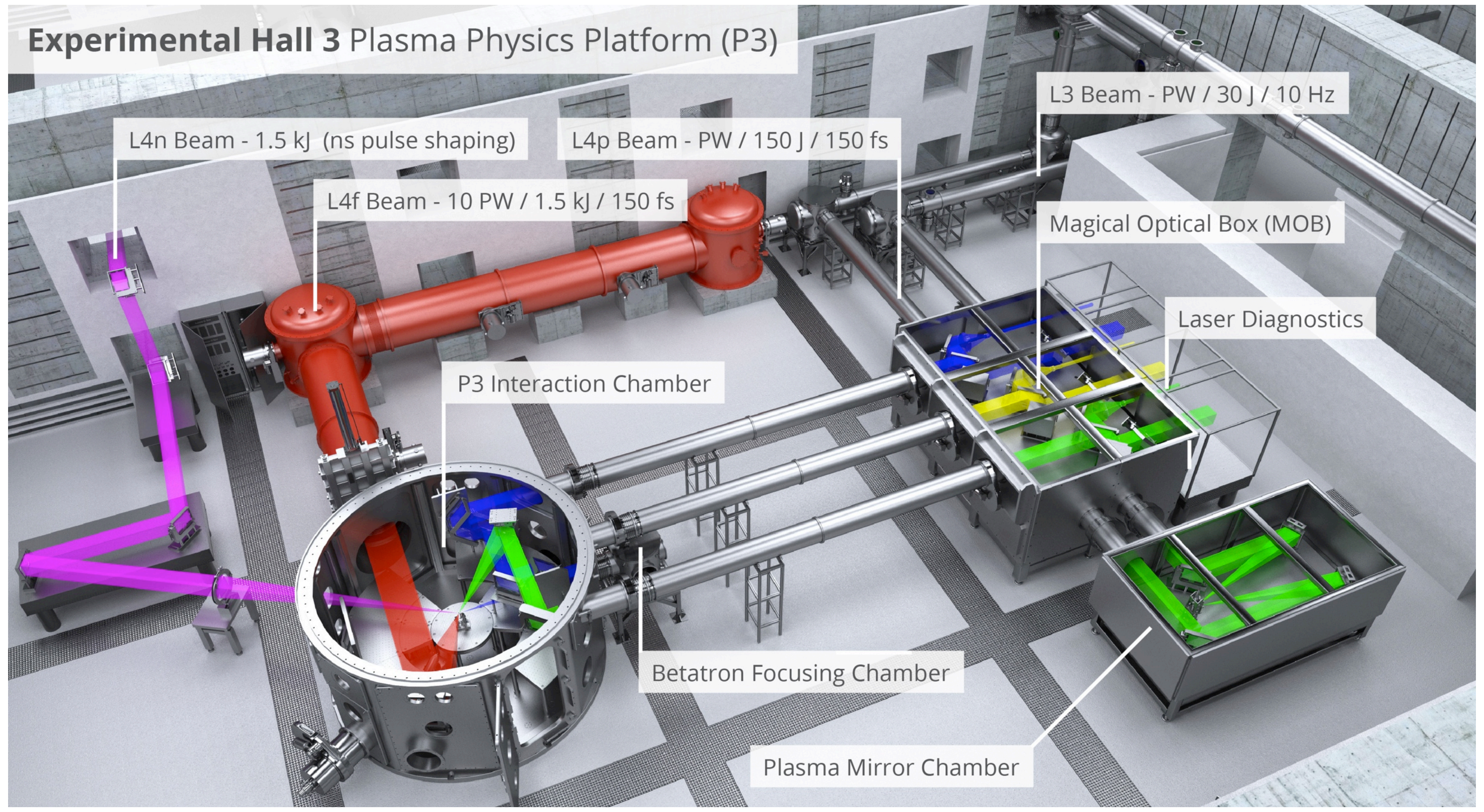


NAS report 2018: Opportunities in Intense Ultrafast Lasers

BELLA PW laser at LBNL



Soon to be available 10 PW at ELI (Europe)

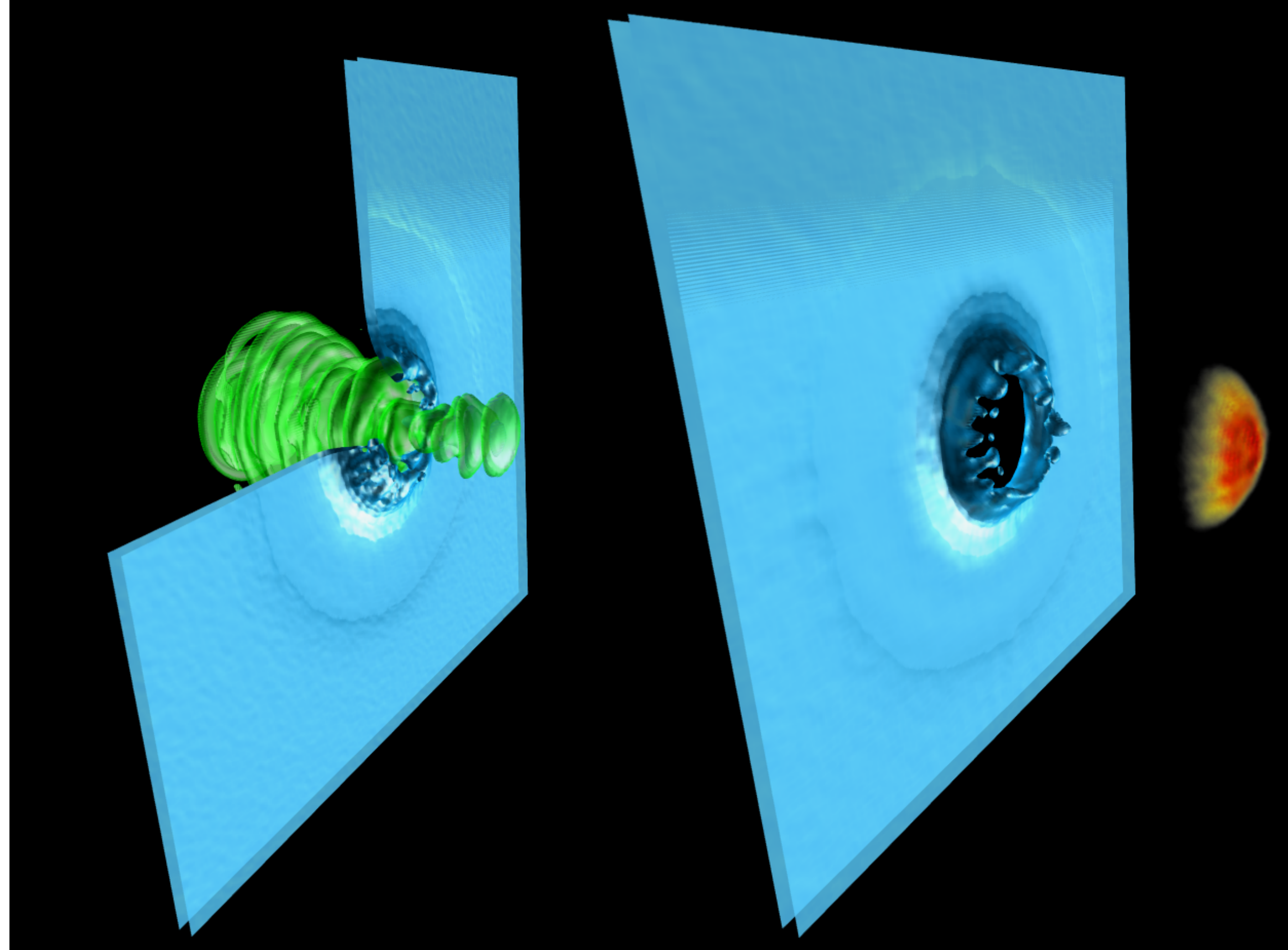


PW lasers allows us to drive and explore extreme states of matter

High-energy-density matter

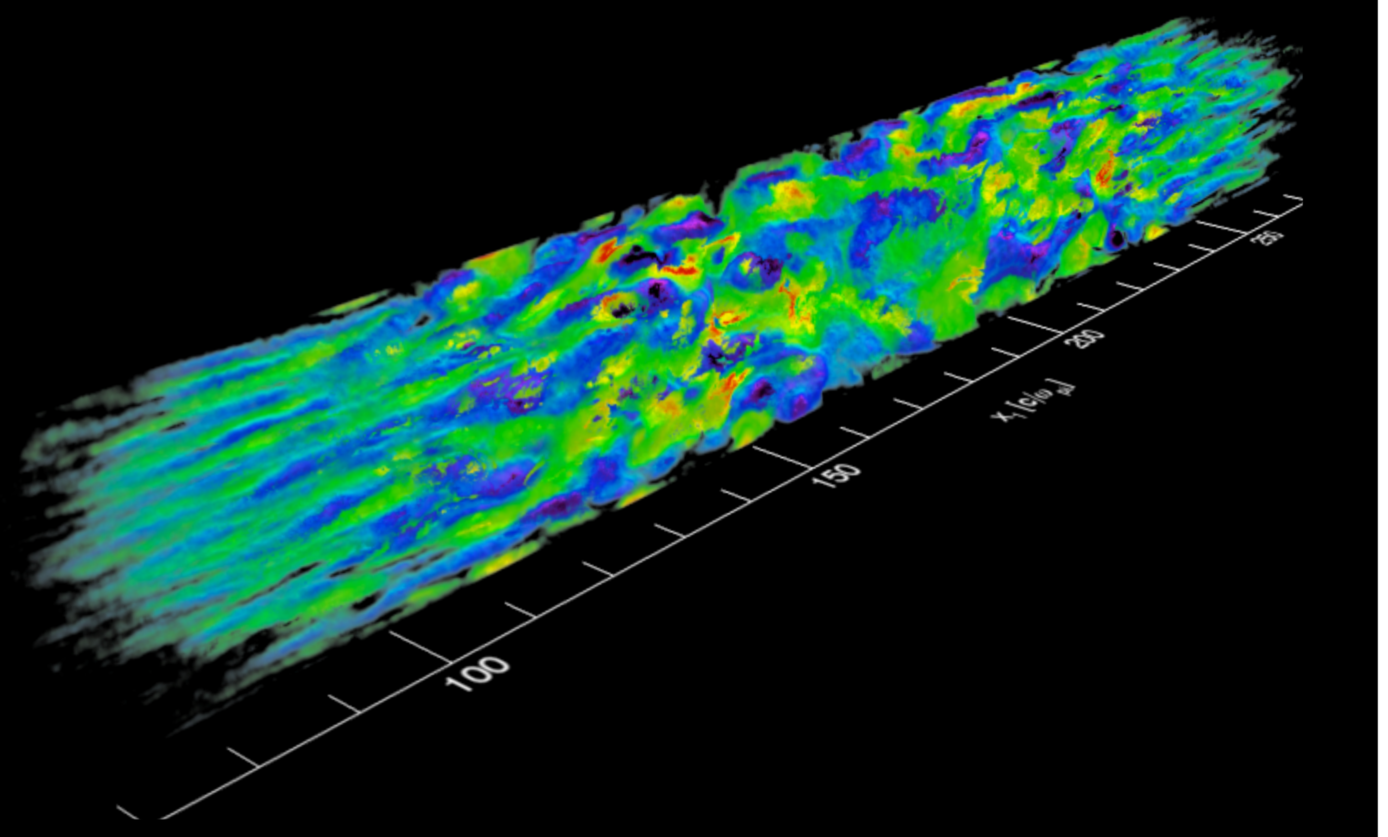
Compress and heat materials to conditions similar to planet interiors and fusion plasmas

Laser-driven compact accelerators



Accelerate particles with field gradients 10^6x larger than solid-state technology

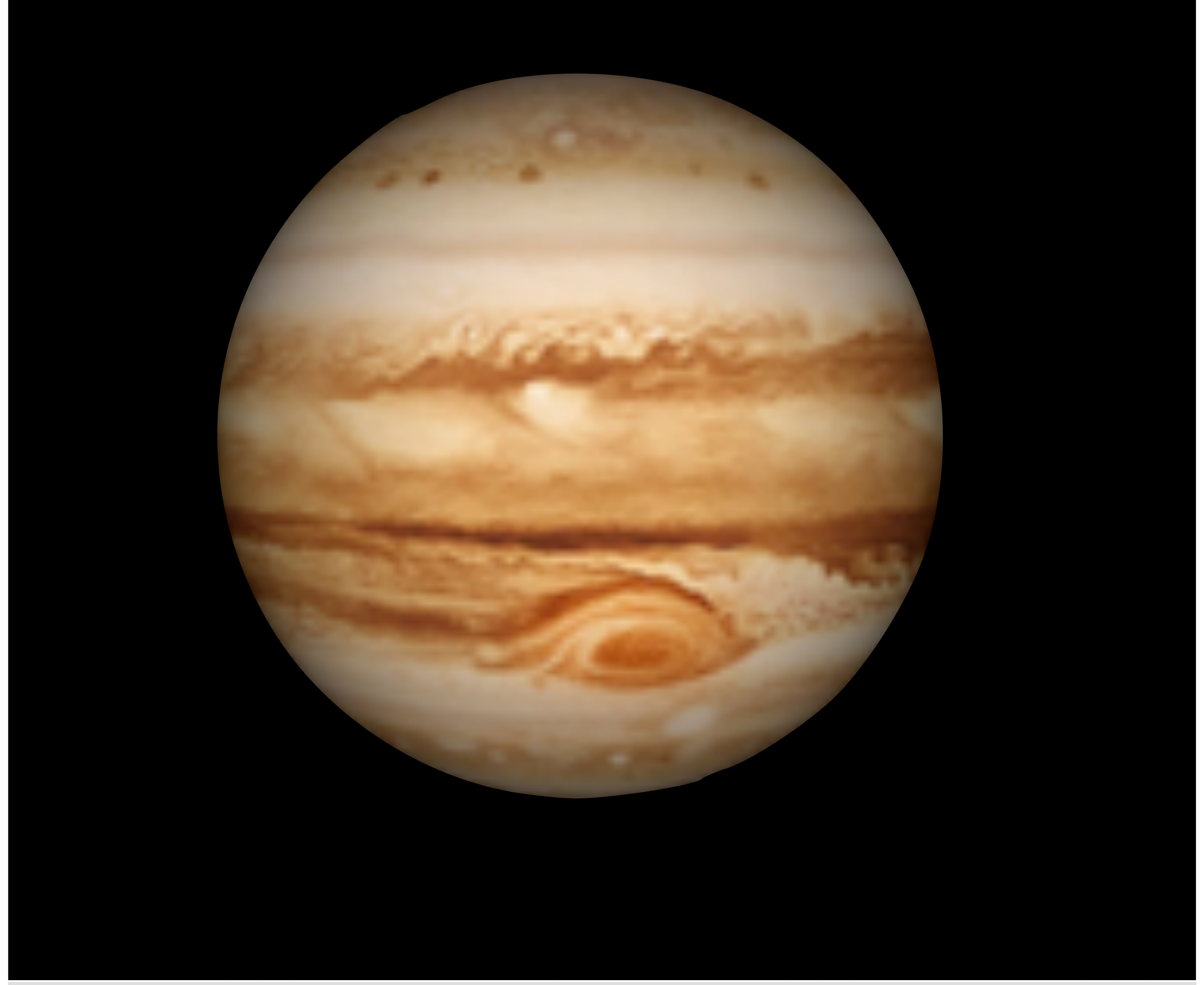
Relativistic lab astrophysics



Drive relativistic plasma processes similar to extreme astrophysical environments

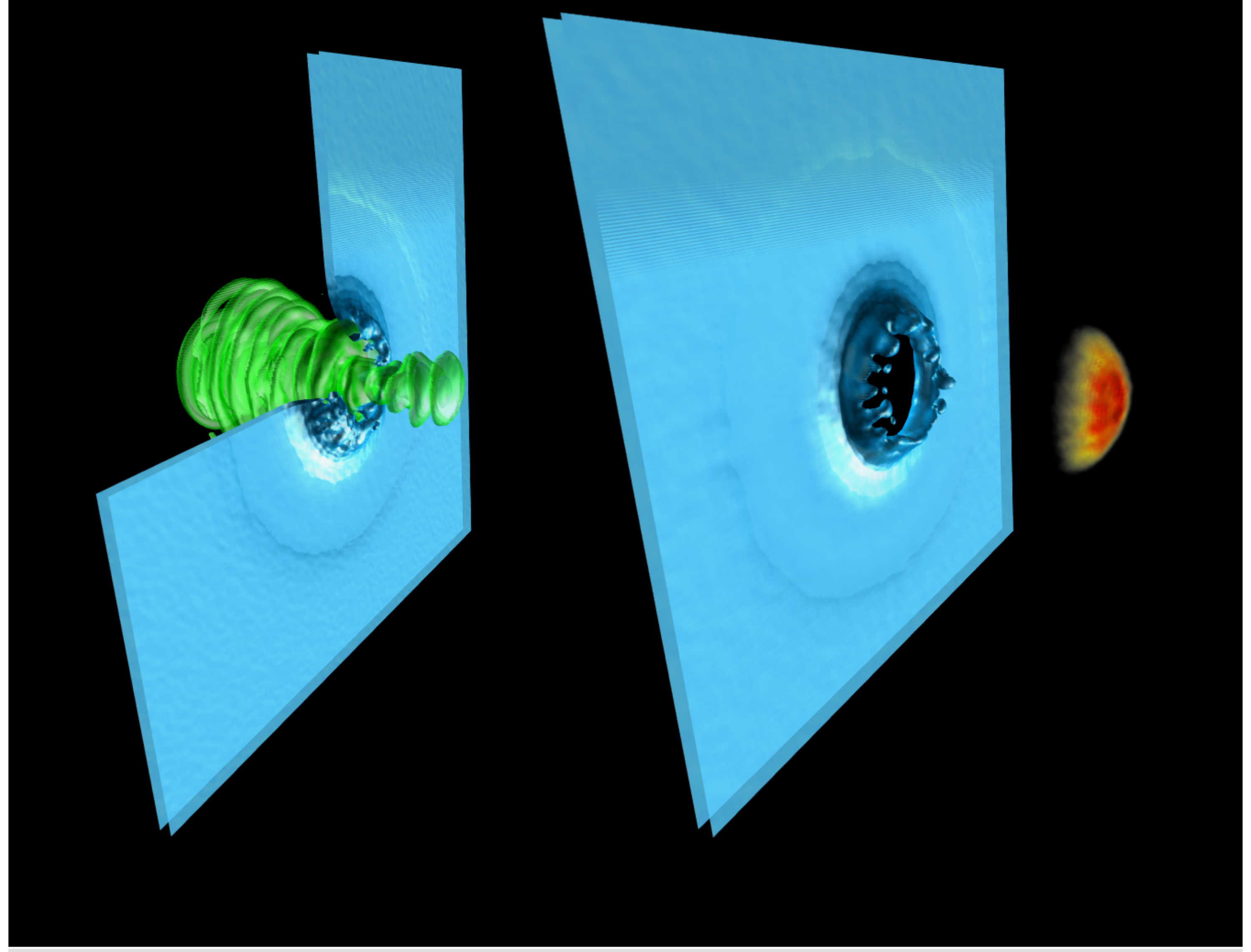
PW lasers allows us to drive and explore extreme states of matter

High-energy-density matter



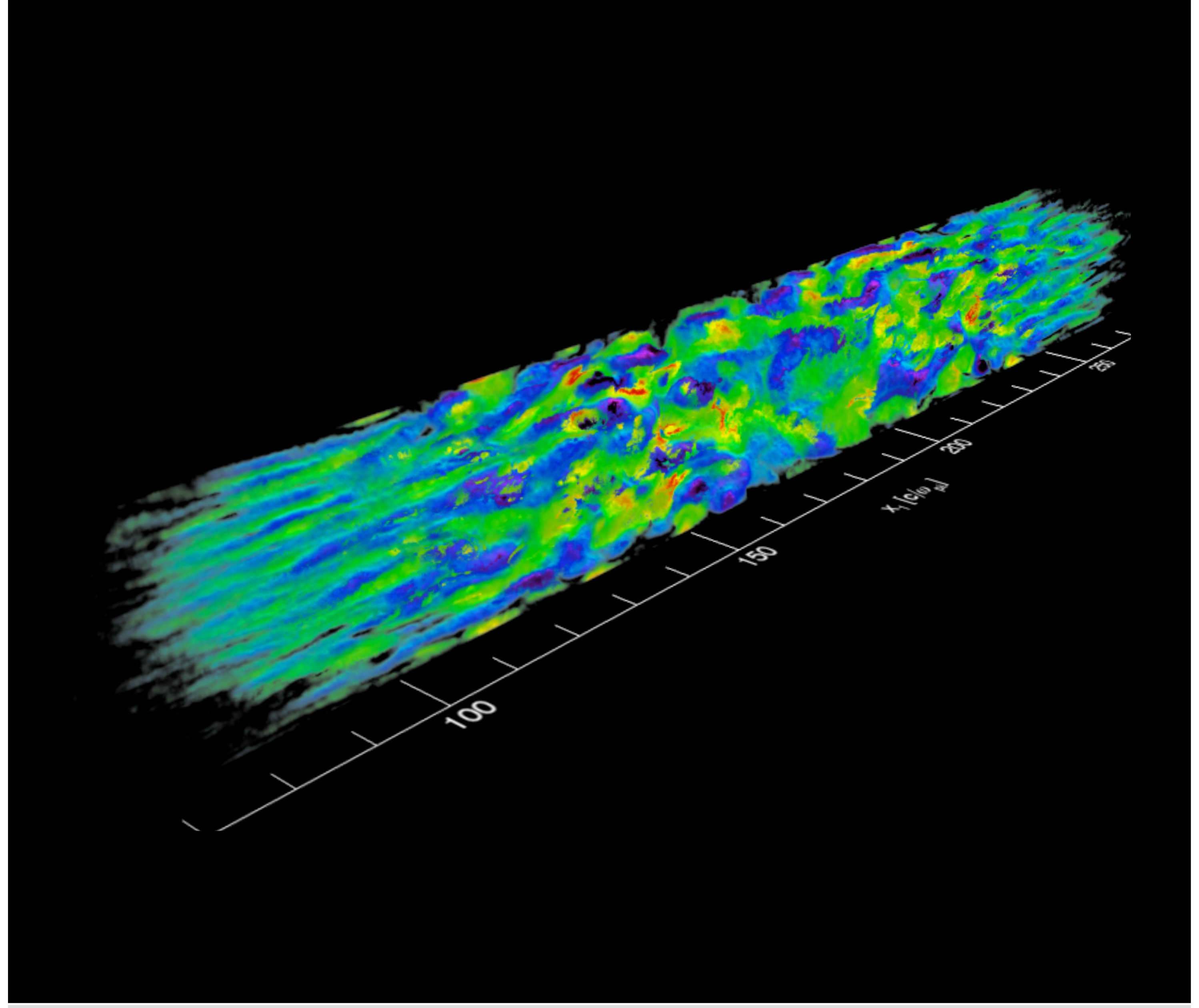
Compress and heat materials to conditions similar to planet interiors and fusion plasmas

Laser-driven compact accelerators



Accelerate particles with field gradients 10^6x larger than solid-state technology

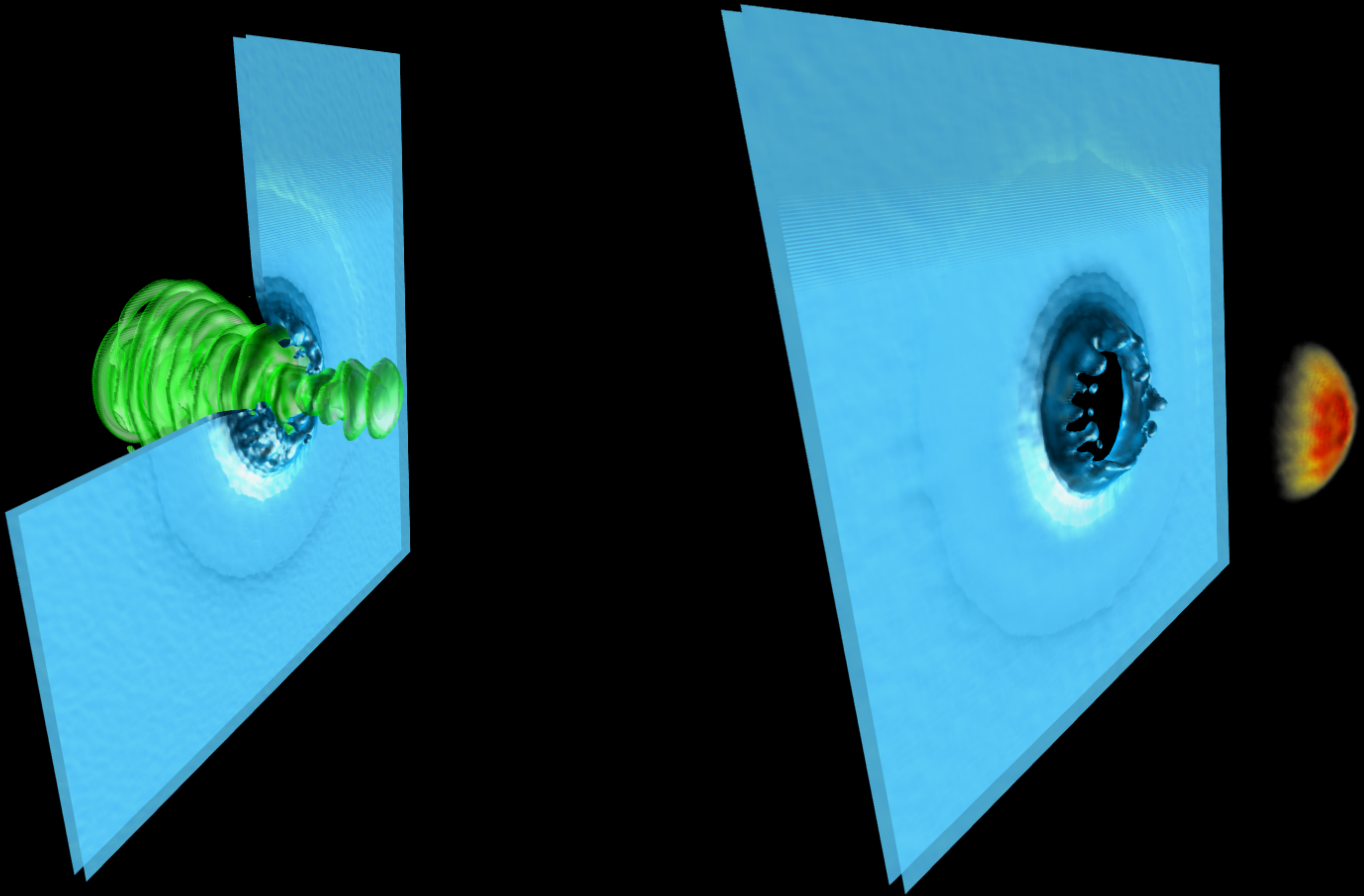
Relativistic lab astrophysics



Drive relativistic plasma processes similar to extreme astrophysical environments

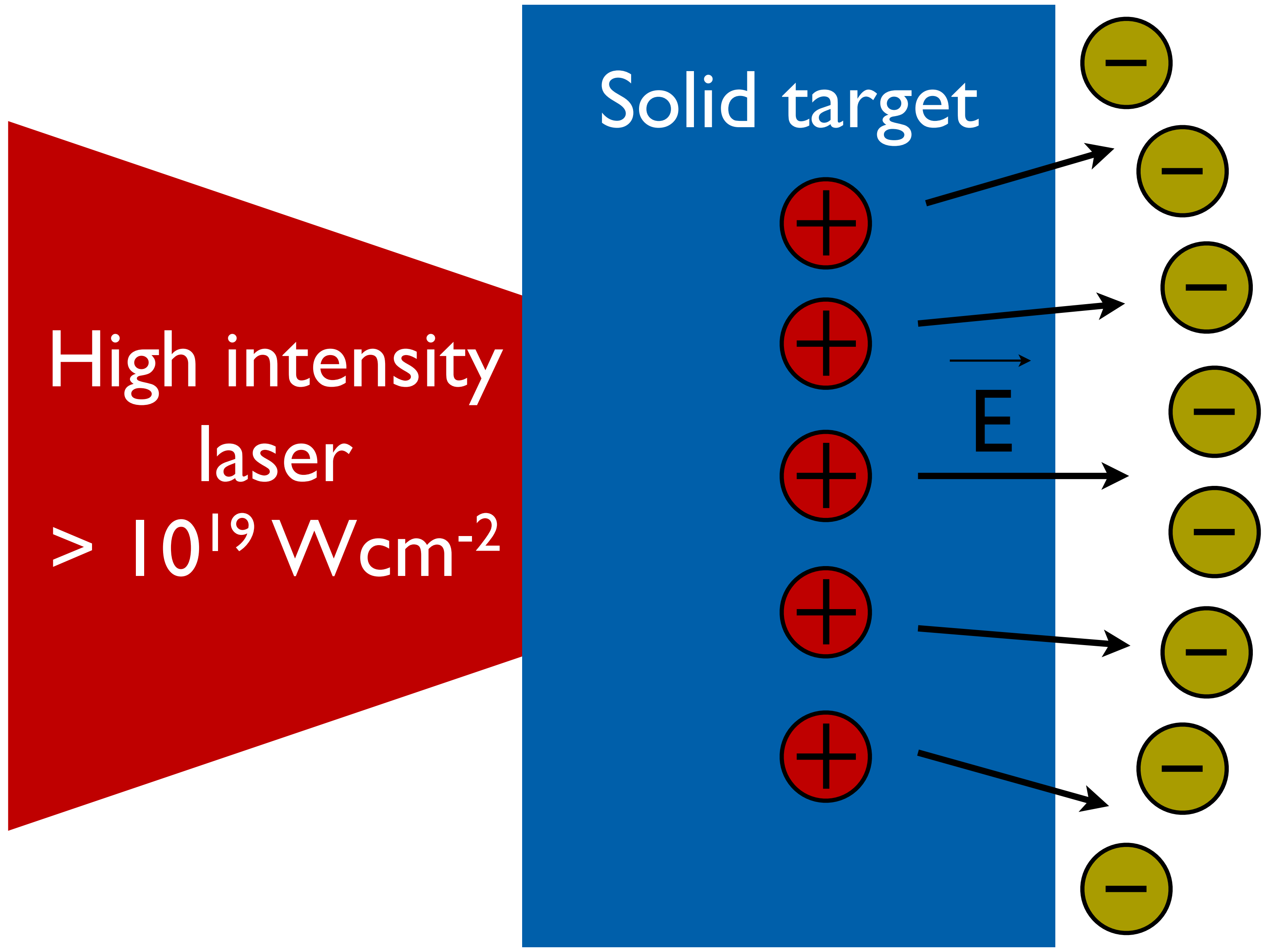
Laser-driven compact radiation sources

from scientific to medical applications

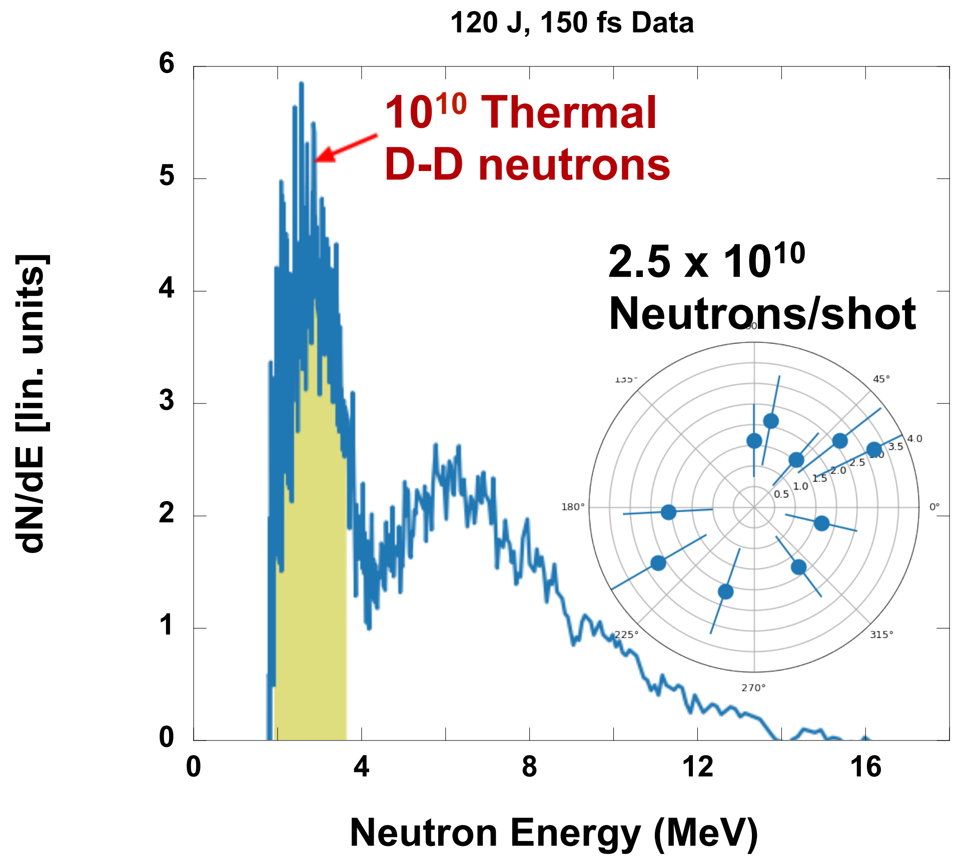


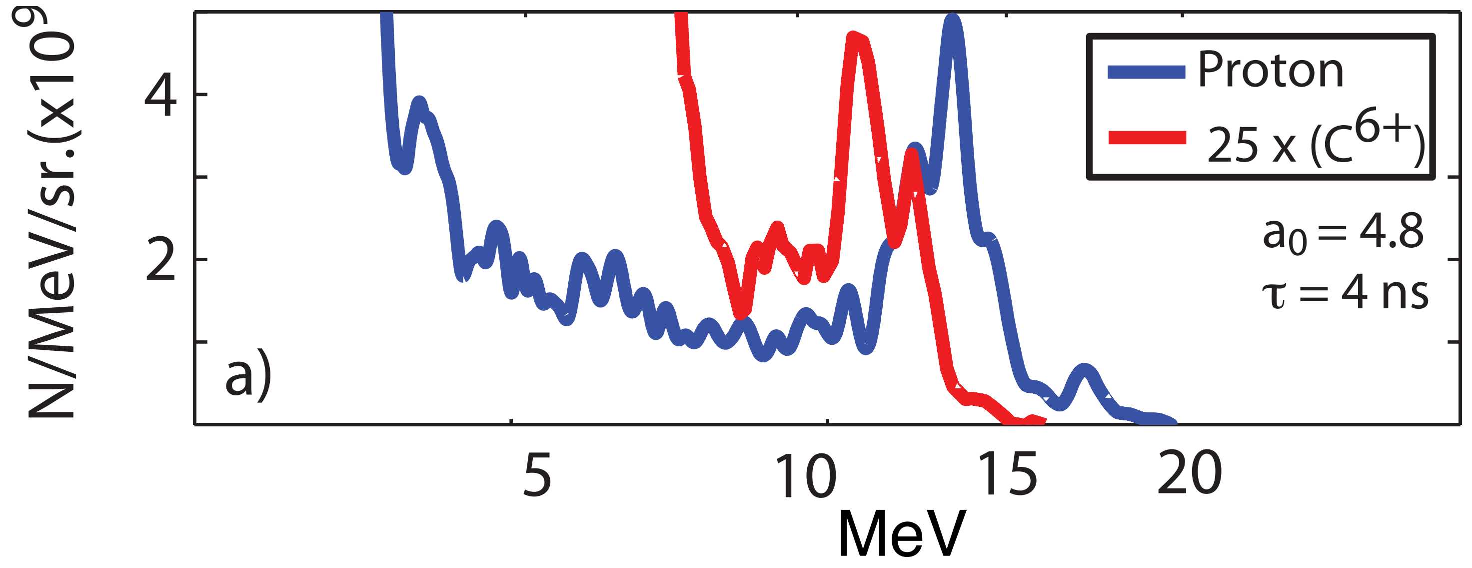
Can we harness the strong fields in plasma to produce compact radiation sources?

Electric fields produced in plasma reach ~10-100 TeV/m

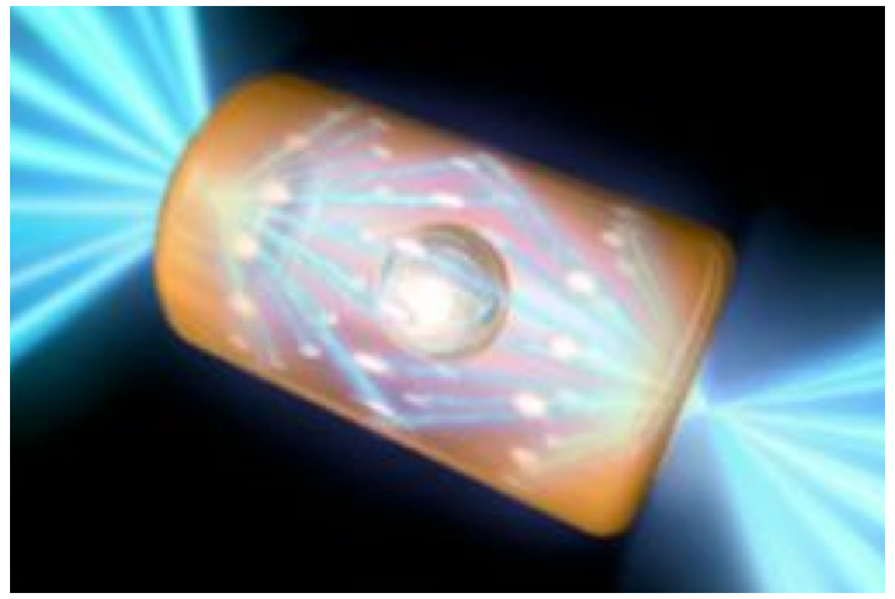


Produce high-energy protons, electrons, neutrons, gammas

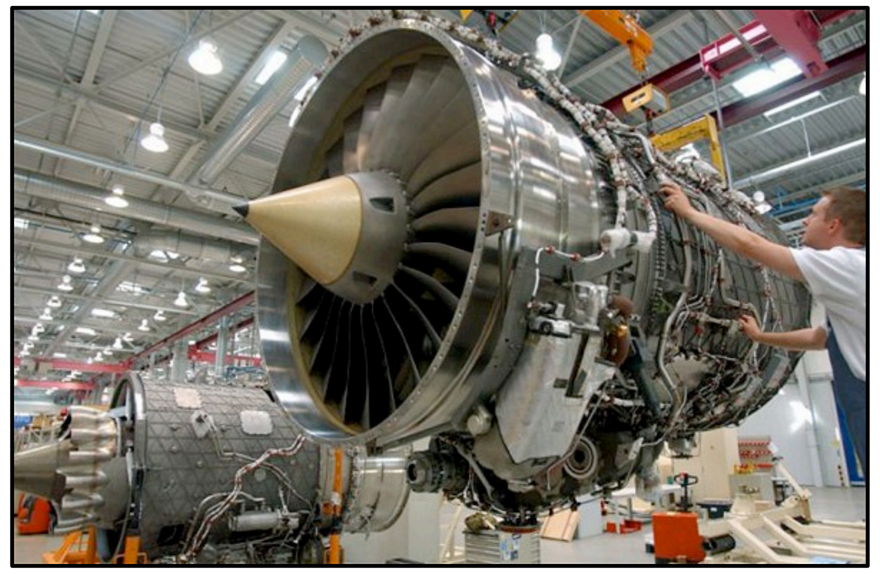




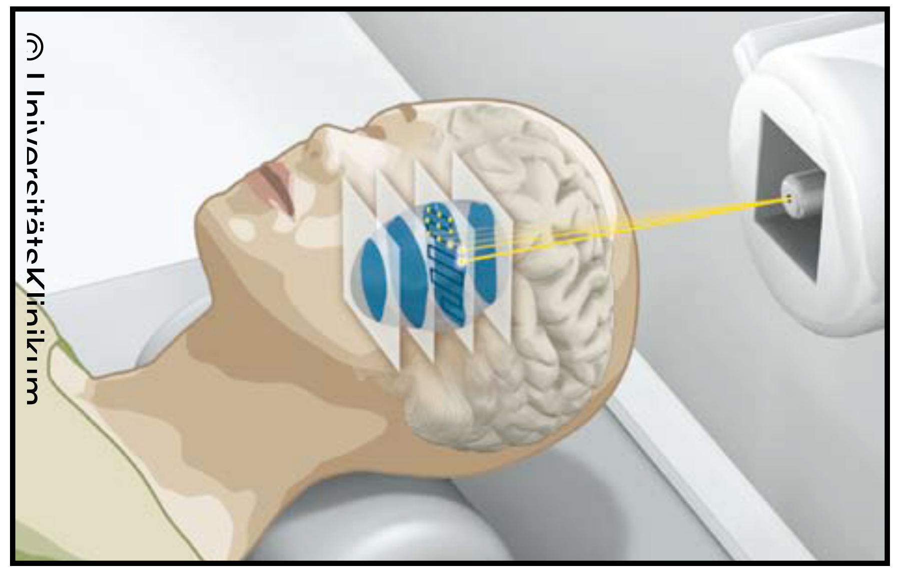
Fusion energy



Materials



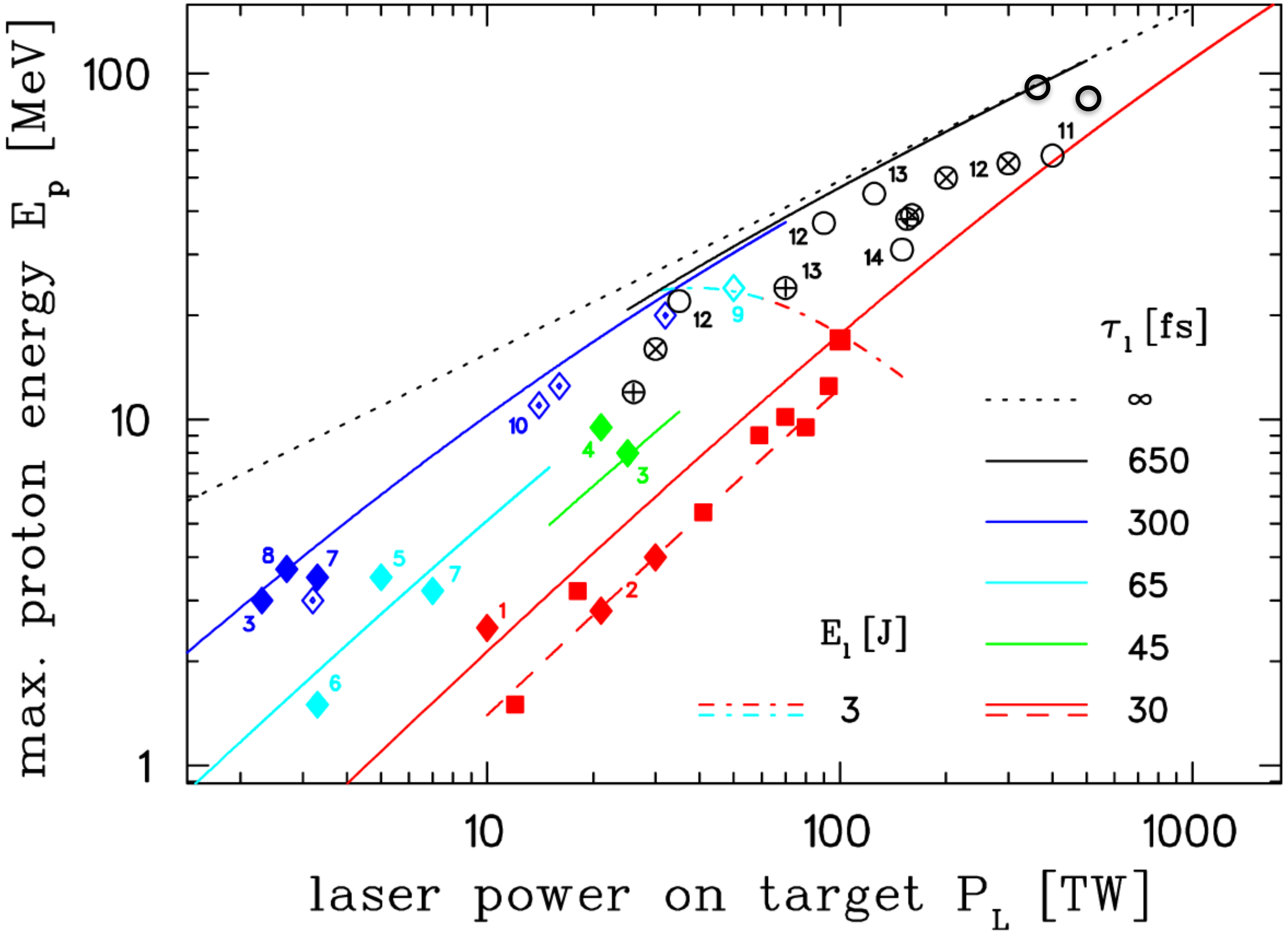
Medicine



Detailed understanding and control of highly nonlinear plasma processes is critical to use laser-produced secondary sources for applications

Proton beams with energies of ~ 100 MeV are now being produced

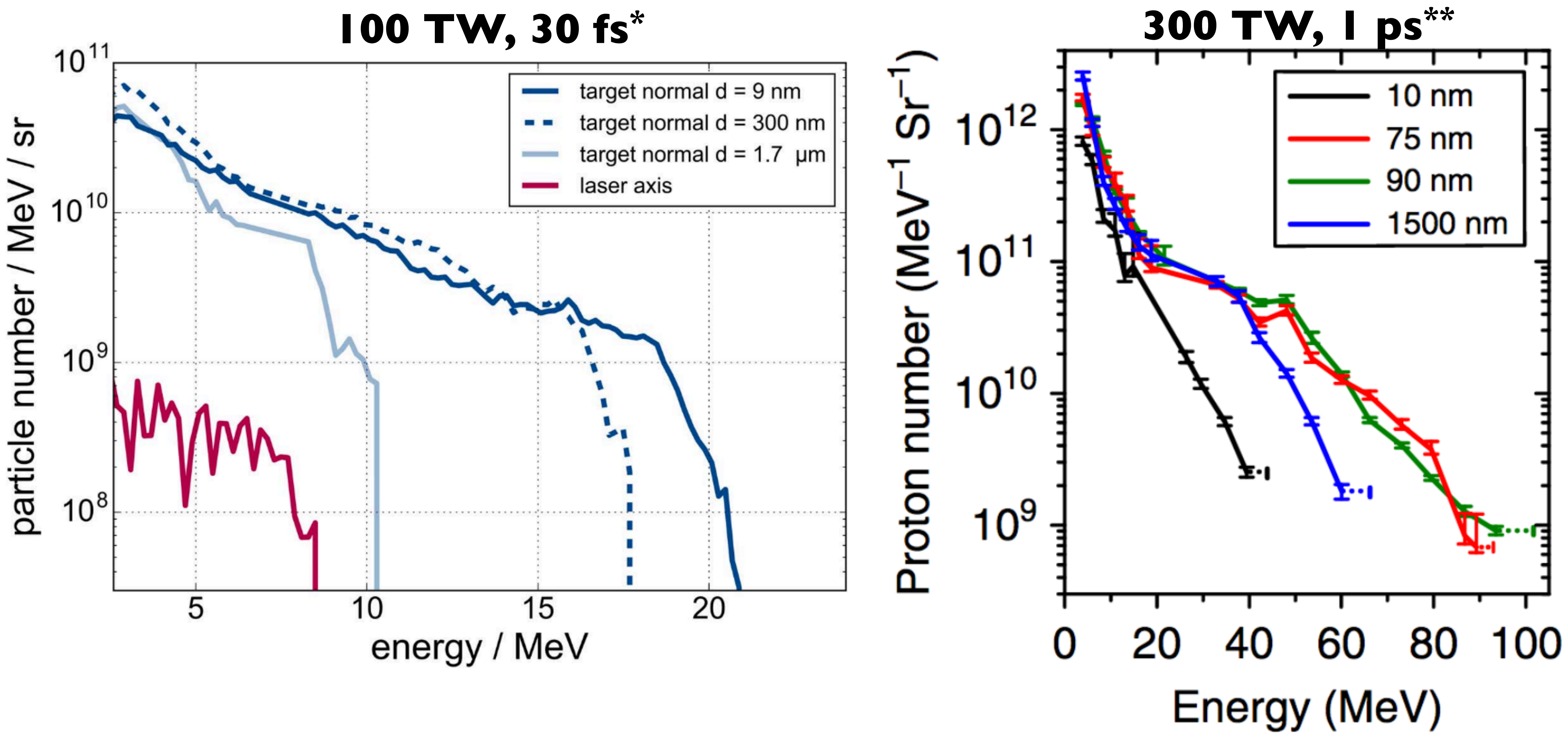
Proton energy as function of laser power



plot adapted from K. Zeil et al., New J. Phys. 12, 045015 (2010)

For a review see A. Macchi, M. Borghesi, M. Passoni, Rev. Mod. Phys. 84, 751 (2013)

Typical proton spectrum is exponential


100 TW, 30 fs*

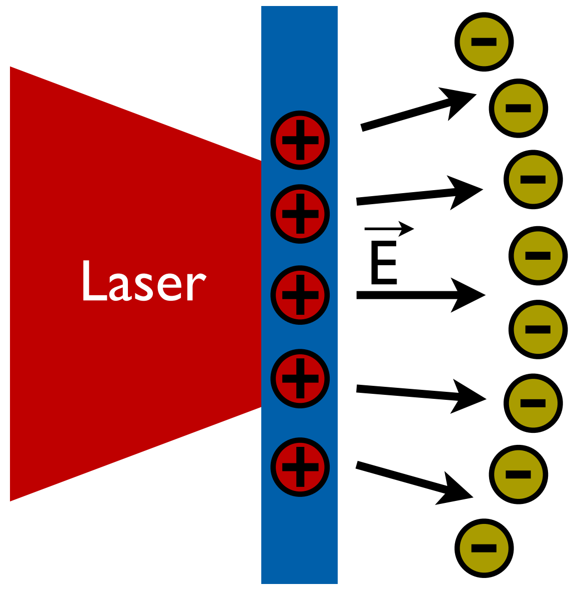
300 TW, 1 ps**

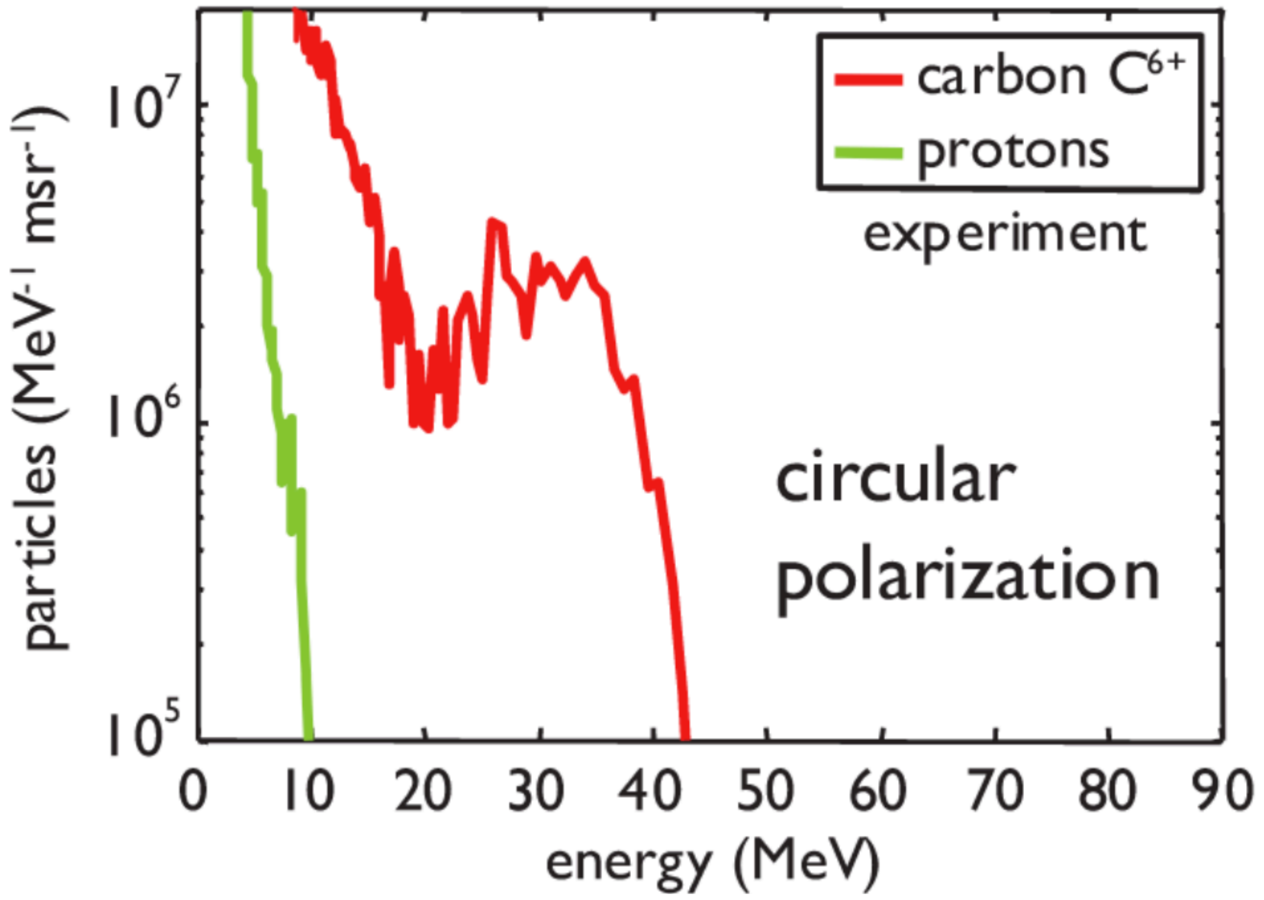
Typical laser-proton conversion efficiency of 1-10%
Divergence angle is ~ 10°
Transverse emittance is ~ 0.01 mm mrad
Duration is ~ 1 ps

* P. L. Poole et al., New J. Phys. 20, 013019 (2018)
**A. Higginson et al., Nat. Comm. 9, 724 (2018)

Different schemes are being pursued to control spectrum of accelerated particles

Acceleration by laser radiation pressure*

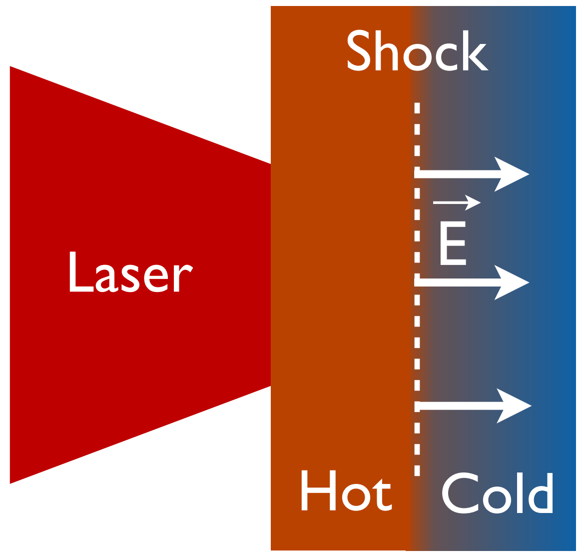




laser radiation pressure pushes electrons and creates strong space-charge field that accelerates protons with velocity:

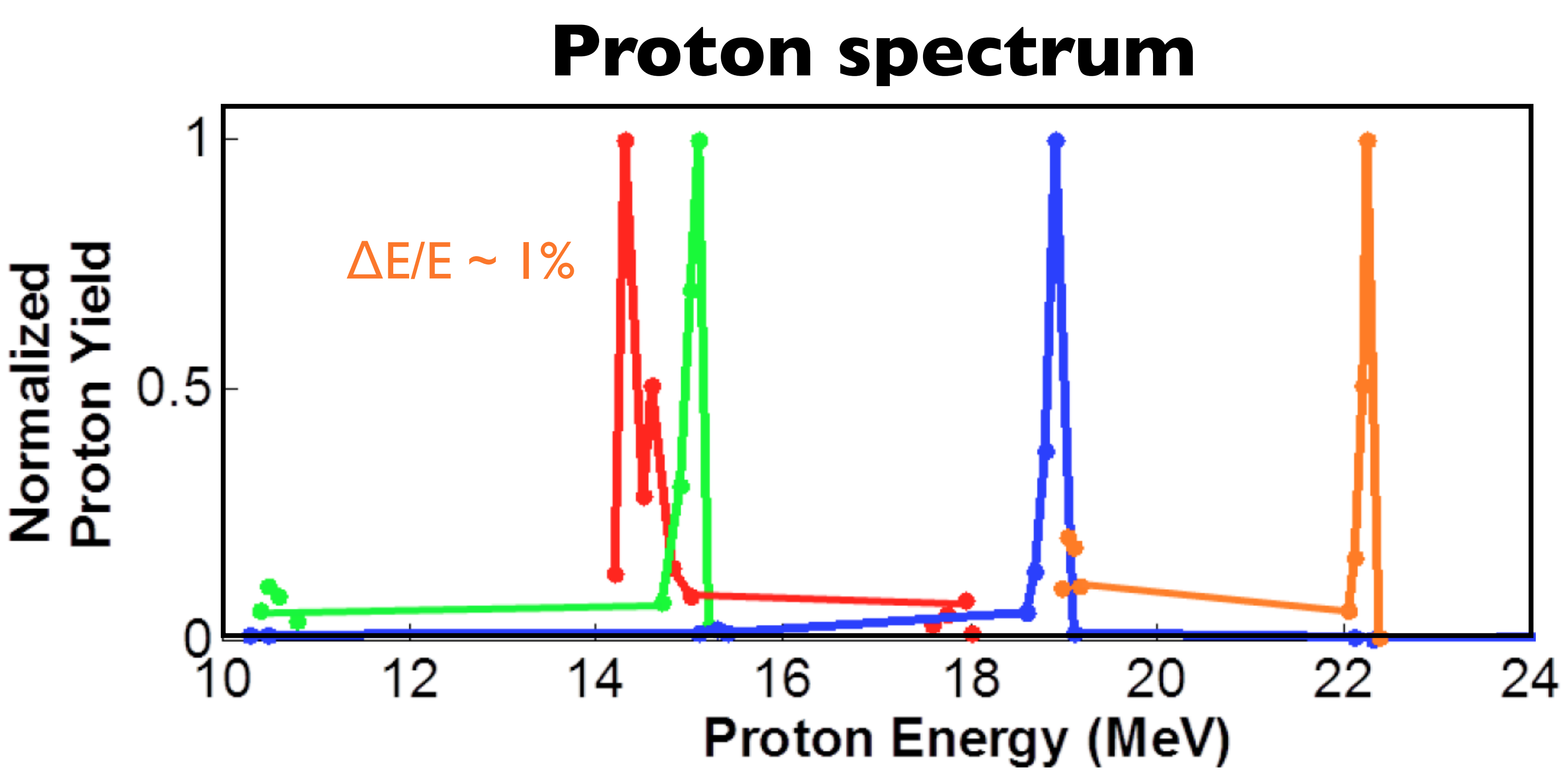
$$v_{hb} = c a_0 \sqrt{\frac{R}{2}\frac{Z m_e}{A m_i}\frac{n_c}{n_e}}$$

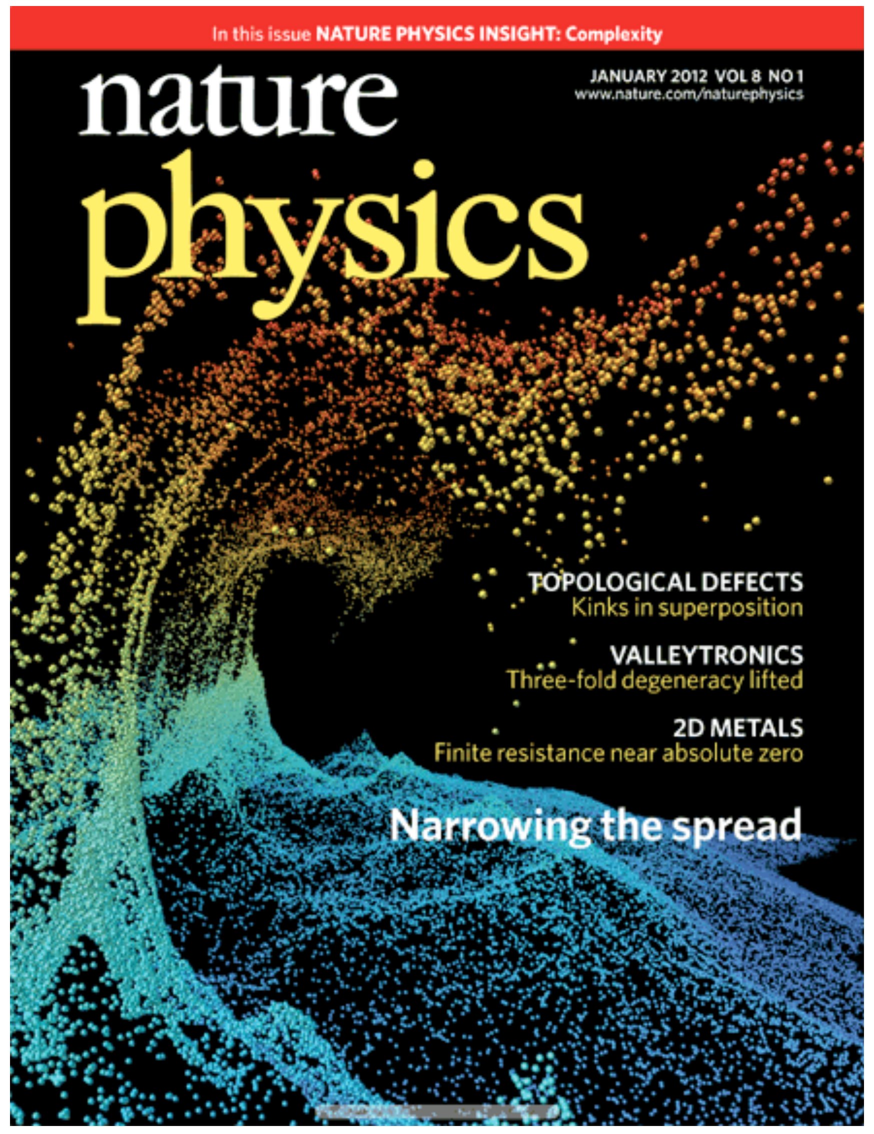
Acceleration by electrostatic shock wave**



protons reflected by electrostatic potential of shock:

$$\phi_{\text{shock}} > \frac{1}{2}\frac{m_i}{q_i}v_i^2$$





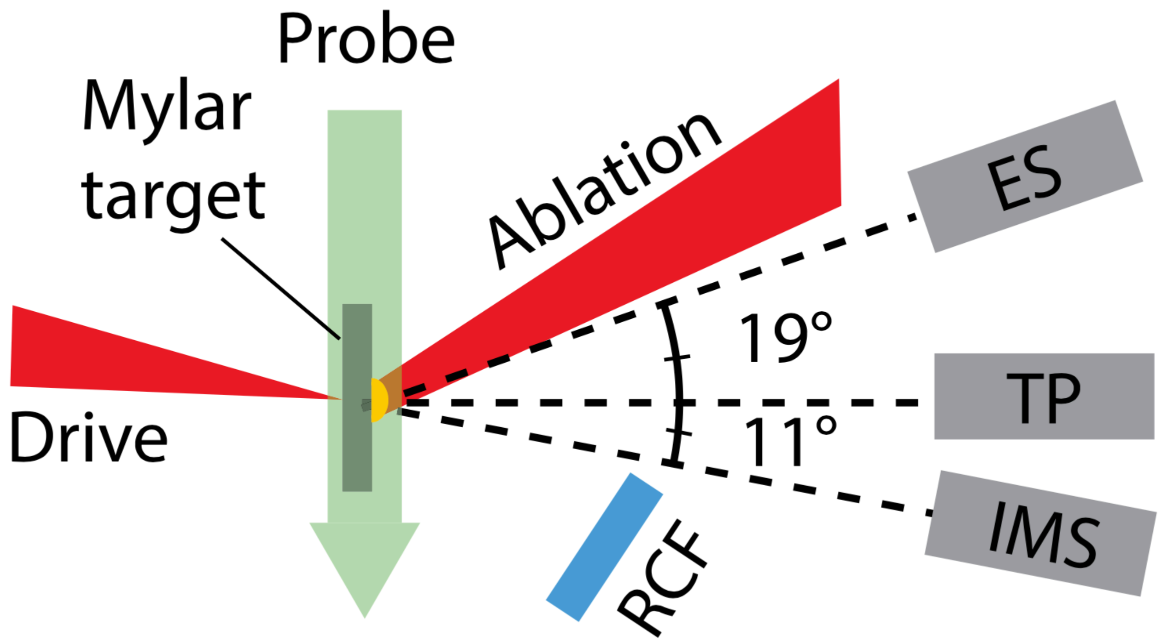
Accelerated proton beams exhibit narrow energy spread (1%-30%)

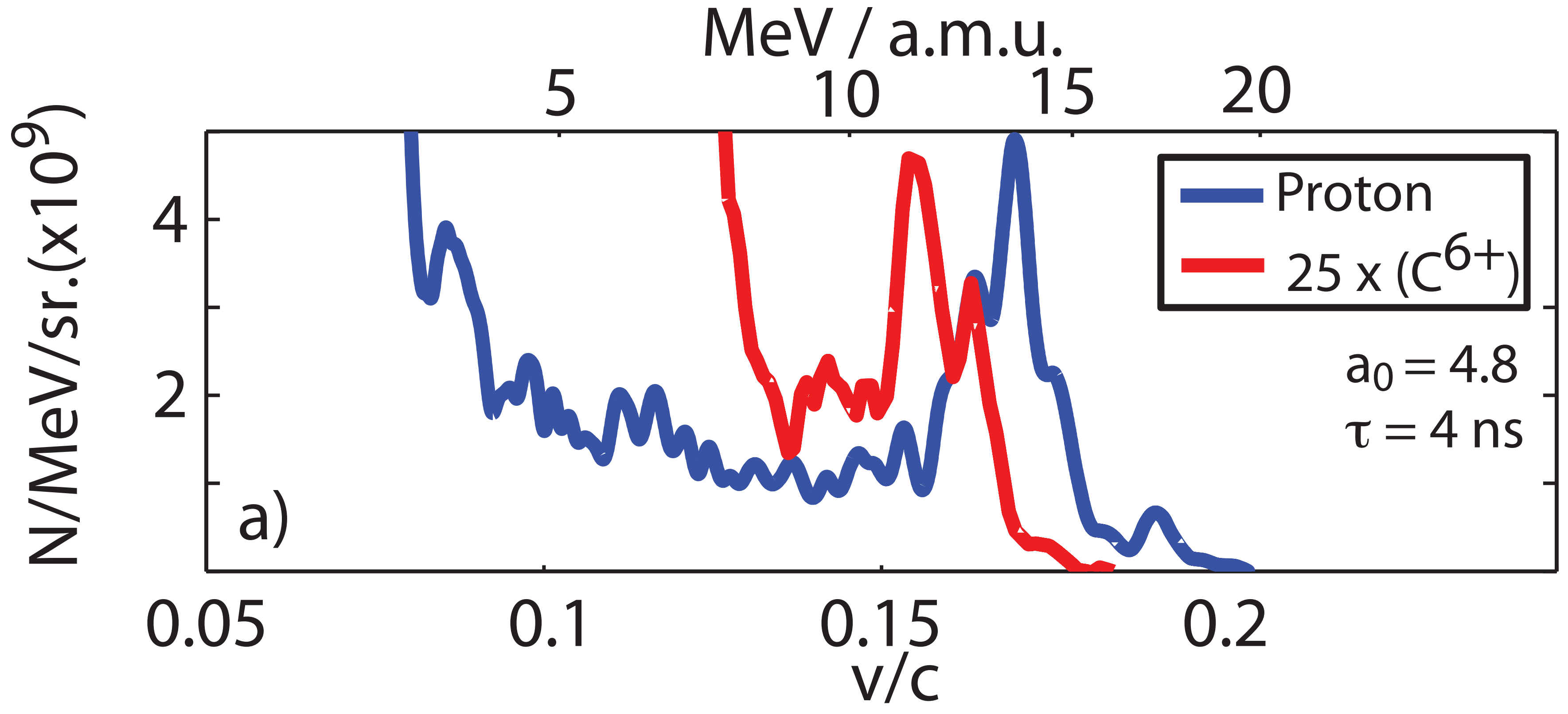
* T. Esirkepov et al., Phys. Rev. Lett. 92, 175002 (2004)
A. Henig et al., Phys. Rev. Lett. 103, 245003 (2009)
B. Qiao et la., Phys. Rev. Lett. 102, 145002, (2009)

** L. O. Silva et al., Phys. Rev. Lett. 92, 015002 (2004)
D. Haberberger, S. Tochitsky, F. Fiuza et al., Nature Physics 8, 95 (2012)
F. Fiuza *et al.* Phys. Rev. Lett. 109, 215001 (2012)

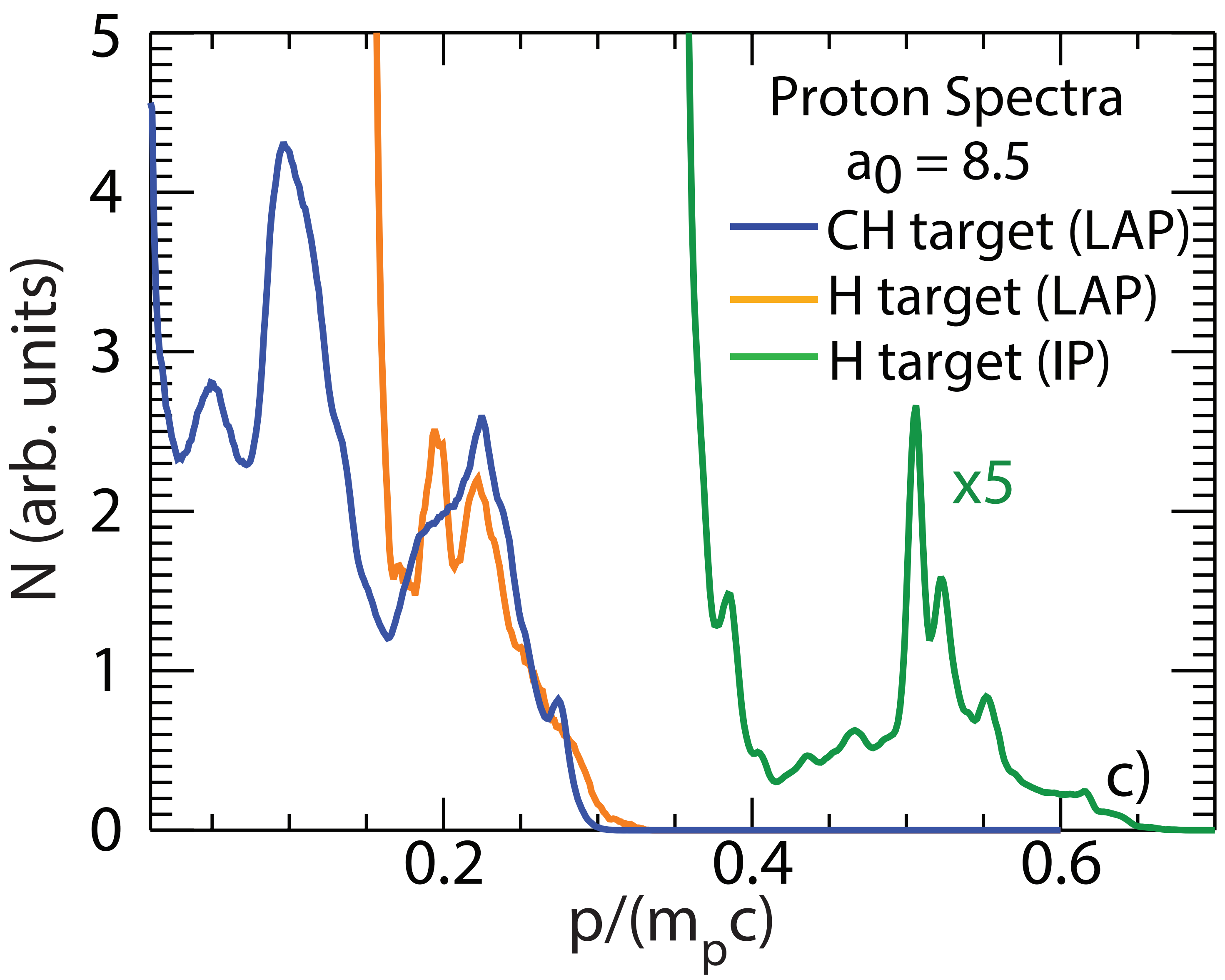
Recent demonstration of narrow energy spread protons beams scalable to > 100 MeV

Experimental results on shock acceleration

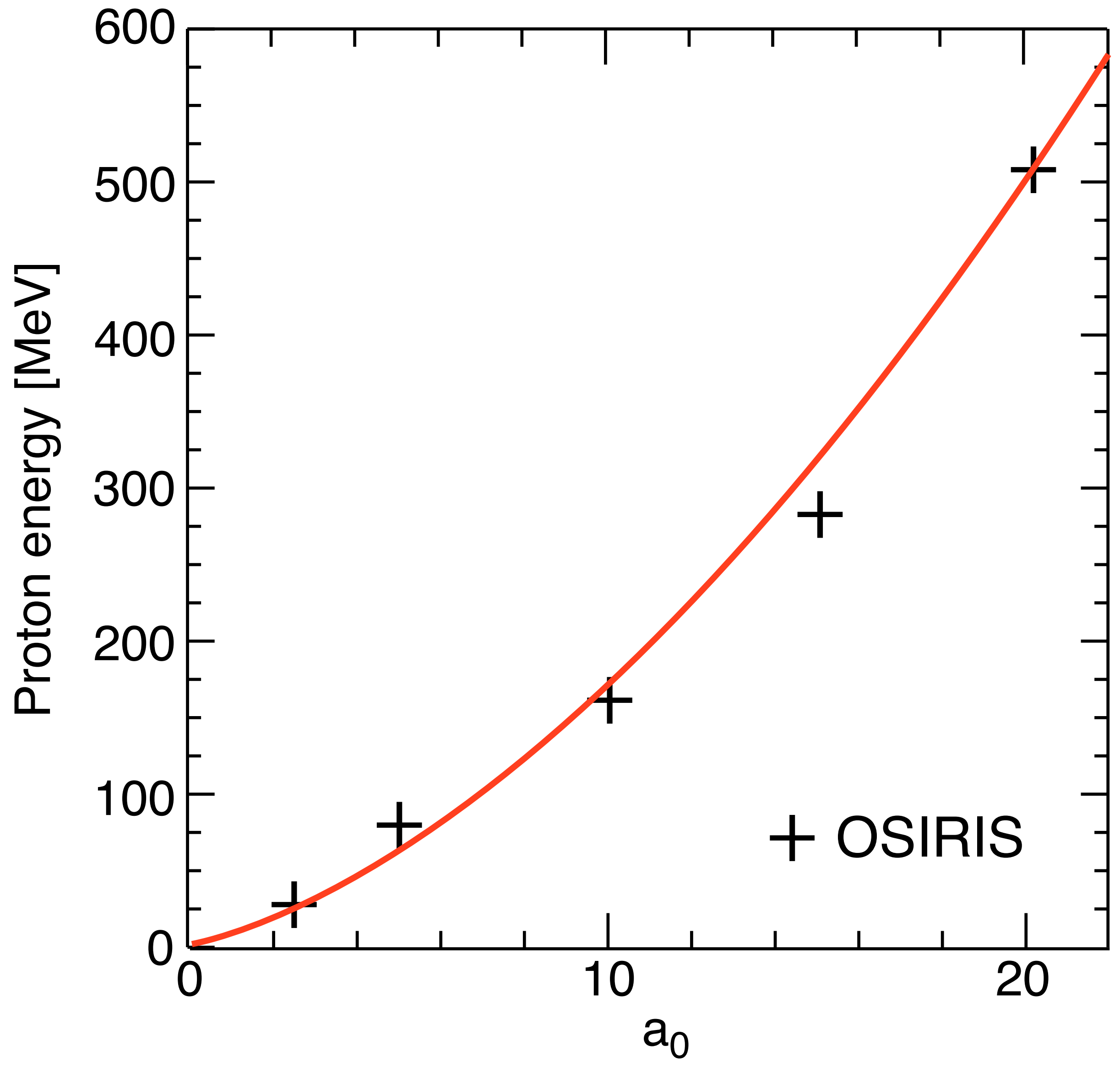




Simulations



Theoretical scaling

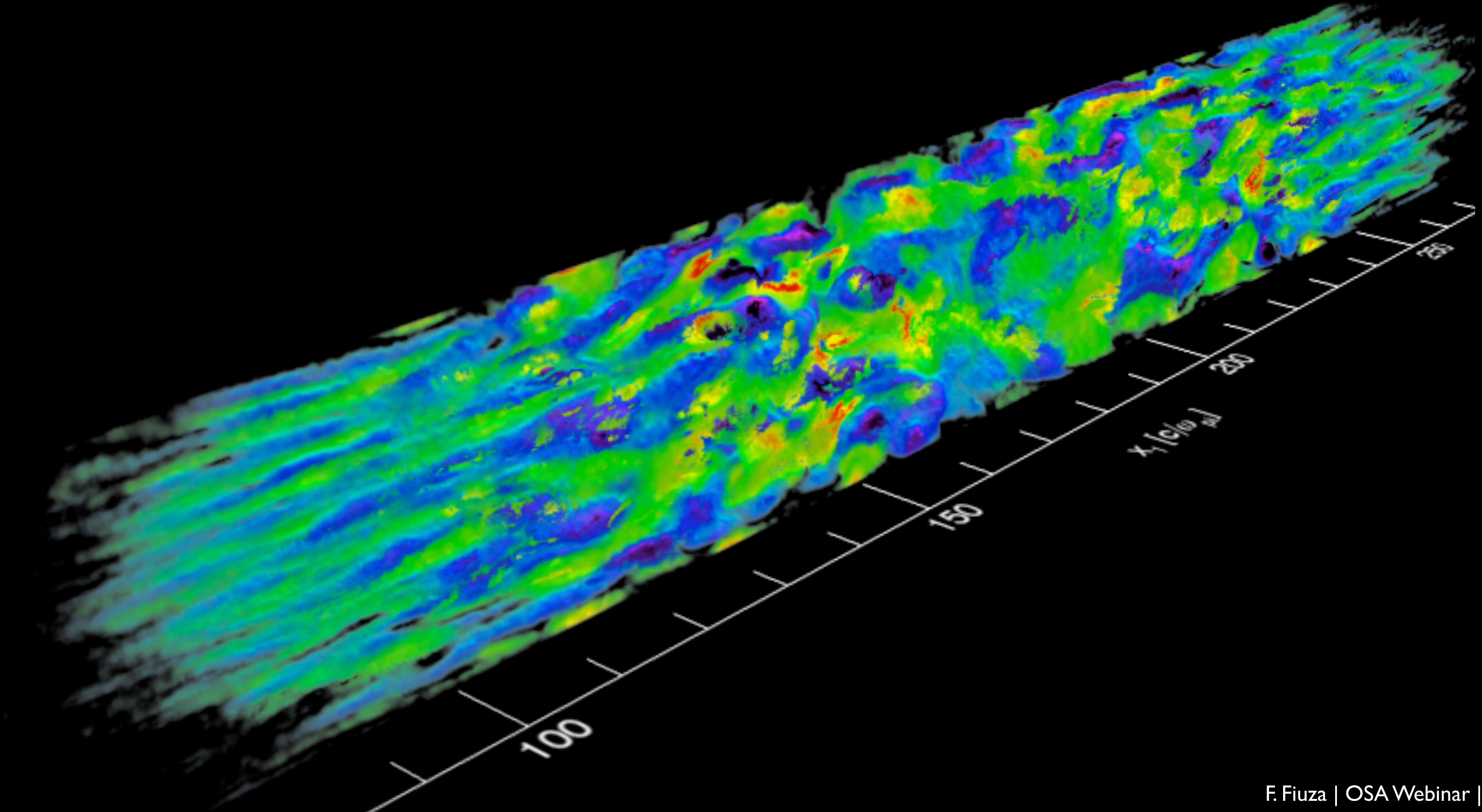


Possibility to generate high-quality proton beams for medical applications (>100 MeV) with current laser systems

F. Fiuza *et al.* Phys. Rev. Lett. 109, 215001 (2012)
A. Pak et al., Phys. Rev. Accel. Beams 21, 103401 (2018)

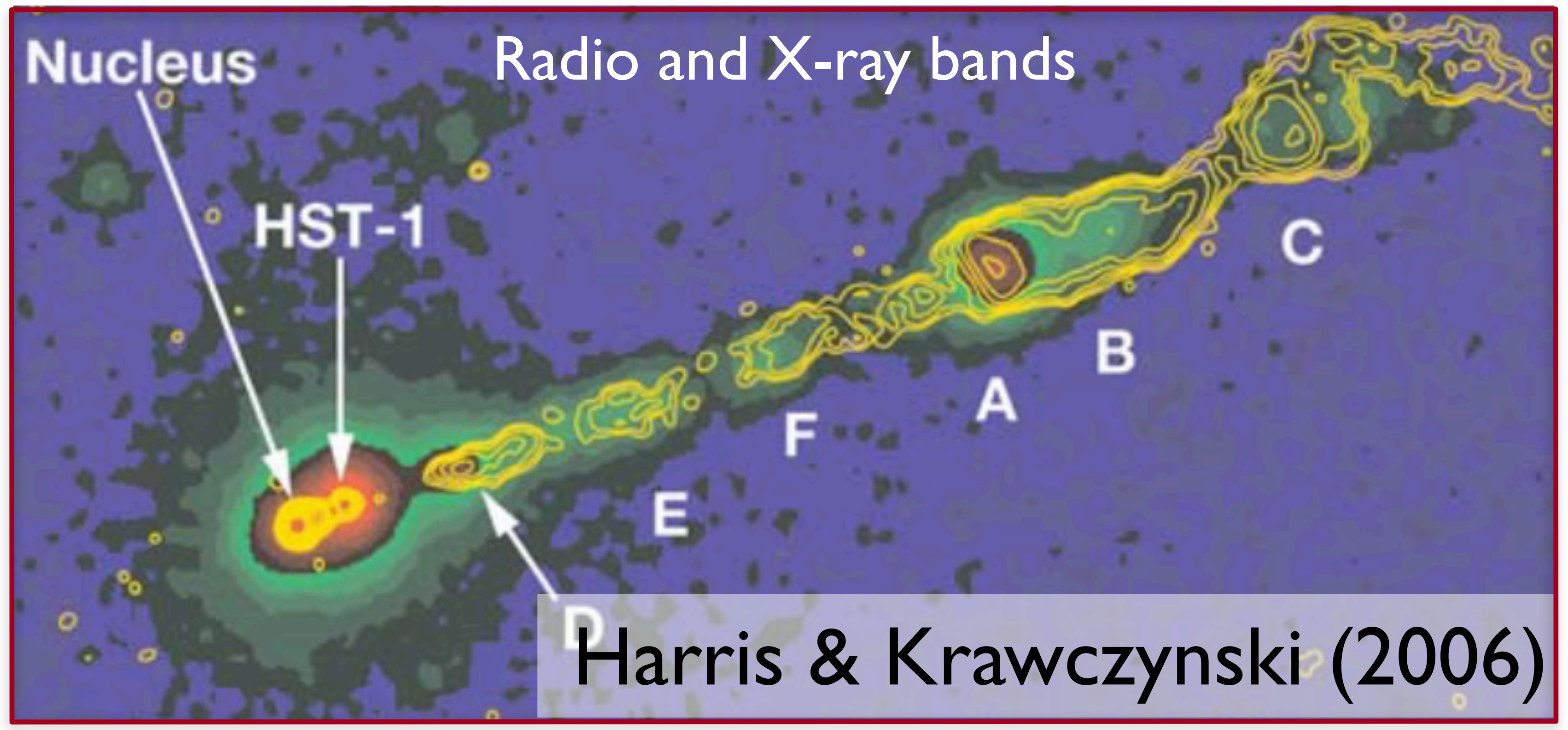
Relativistic laboratory astrophysics

the (micro)secrets of magnetic field dynamics and particle acceleration



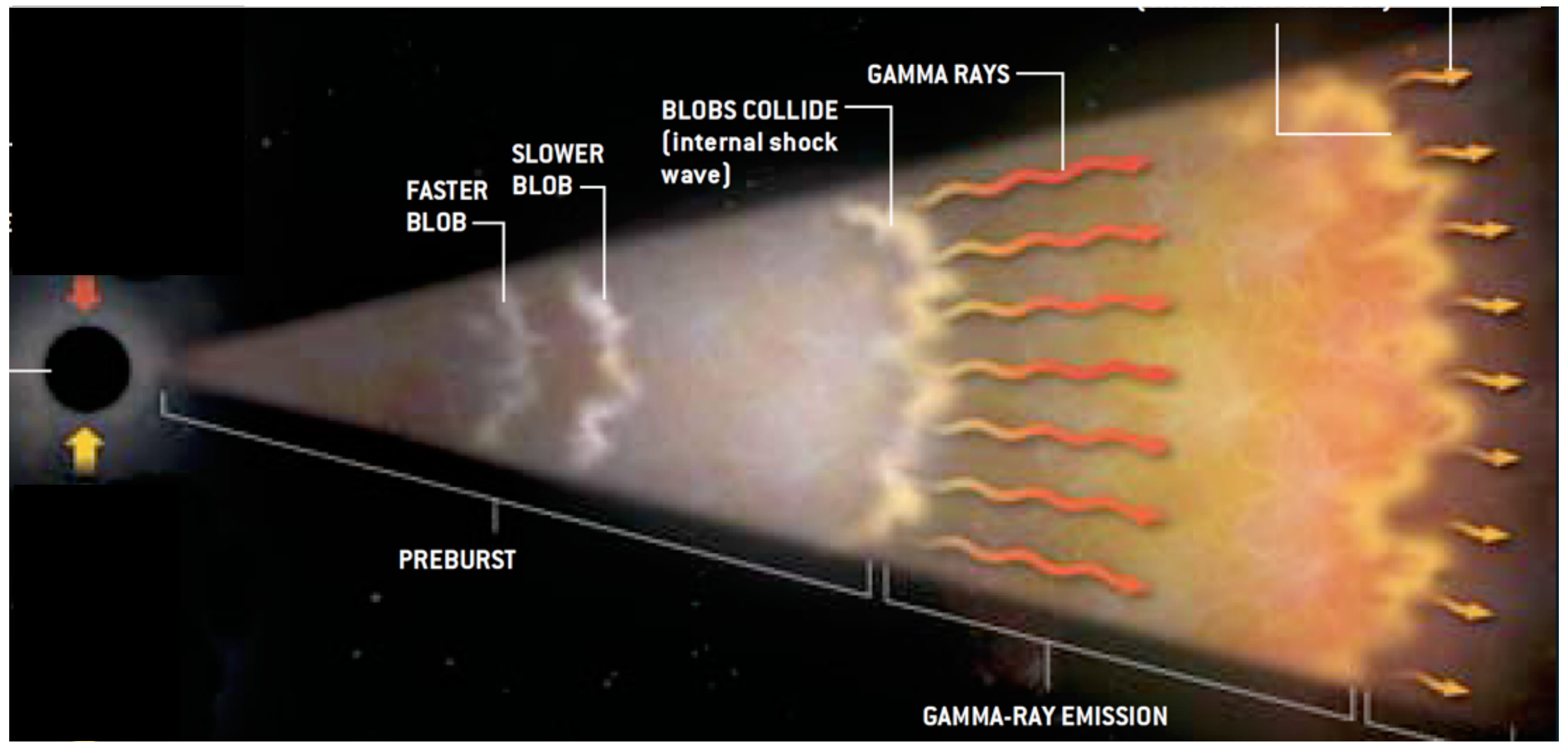
Astrophysical plasmas are known to be efficient particle accelerators

AGN relativistic jets

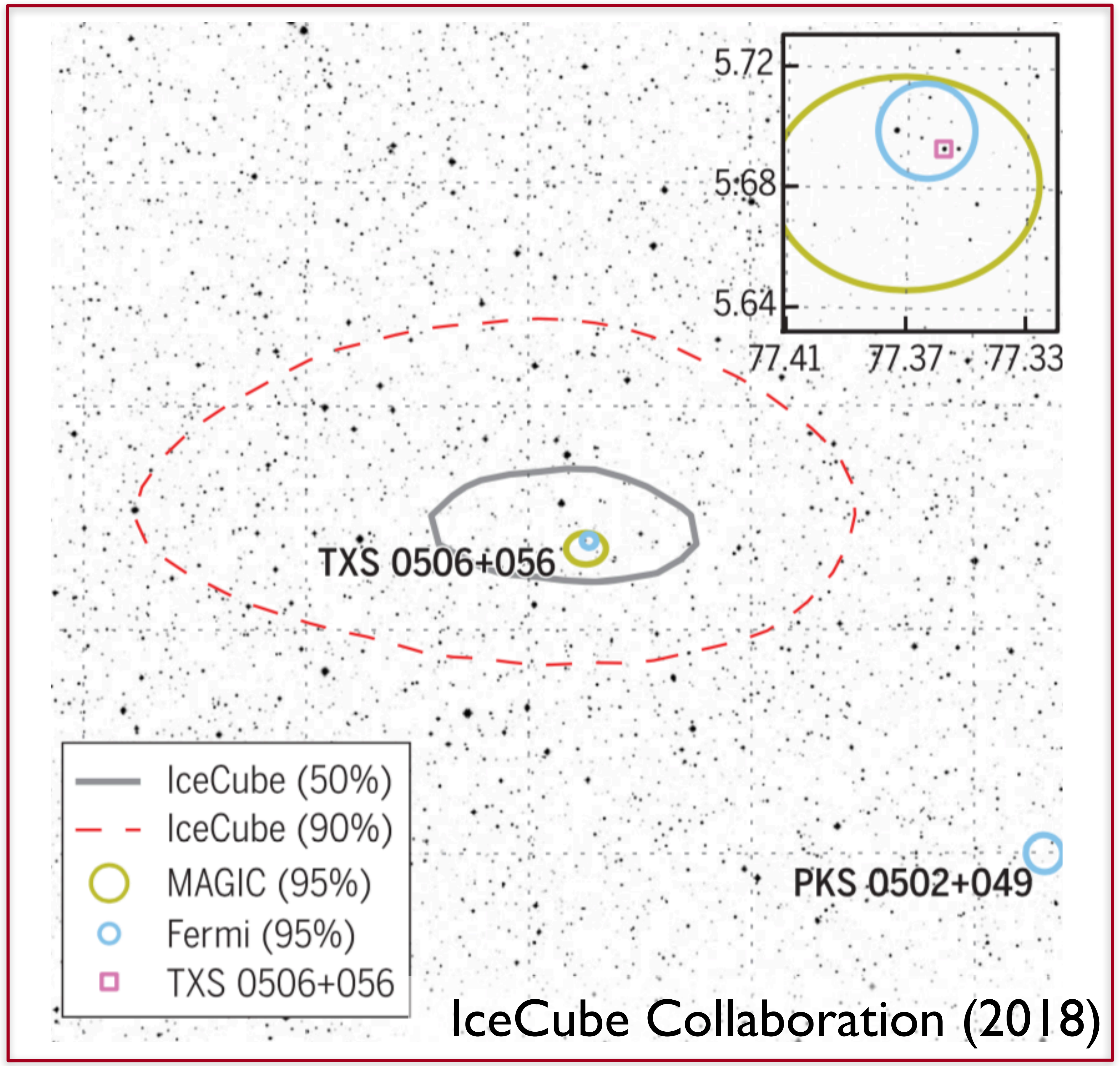


Harris & Krawczynski (2006)

Fireball model of gamma-ray bursts



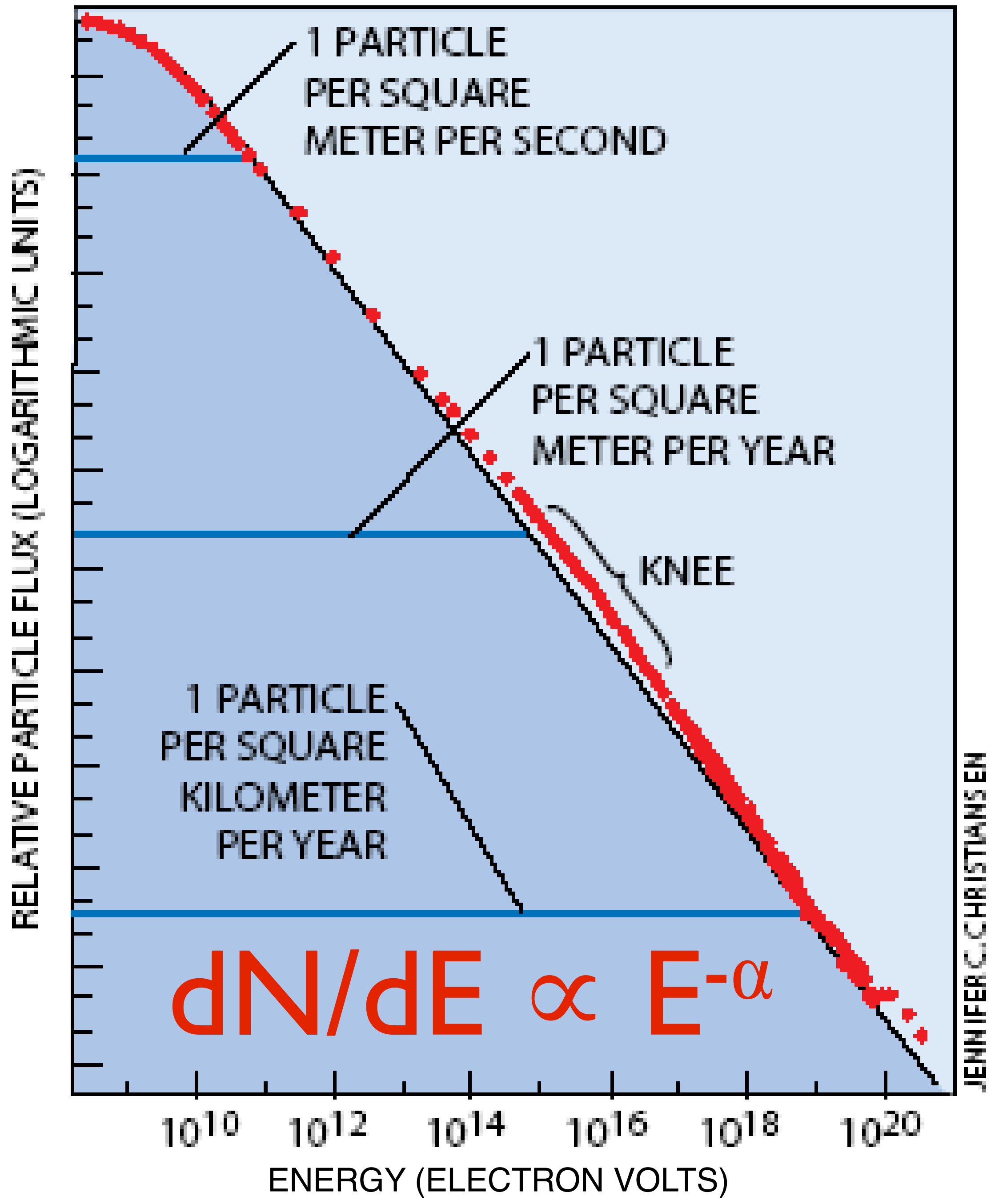
Sources of high-energy cosmic rays



IceCube Collaboration (2018)

What controls CR acceleration?

Scientific American, (c) 1998

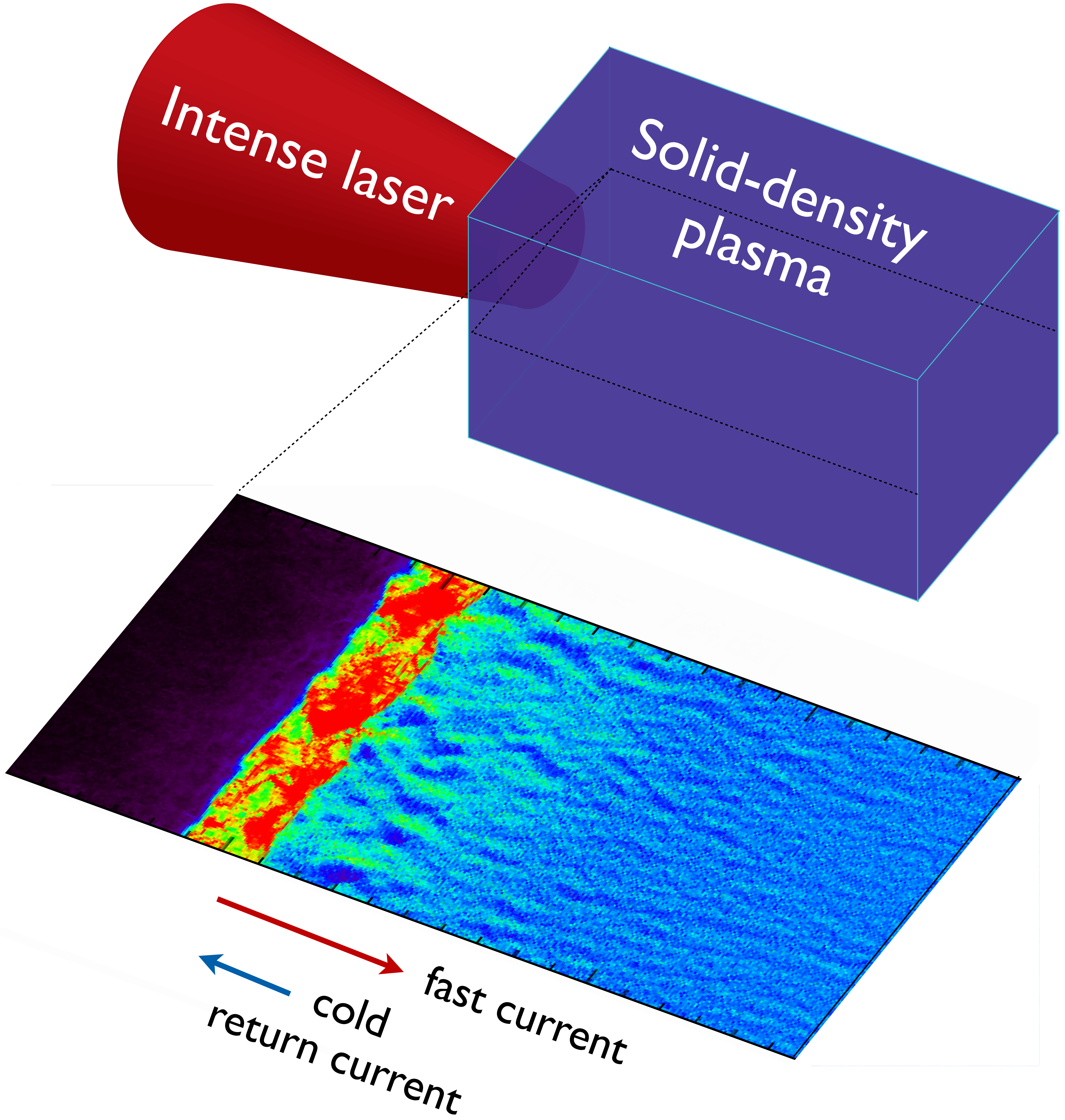


$dN/dE \propto E^{-\alpha}$

The (micro)physics of particle acceleration remains poorly understood

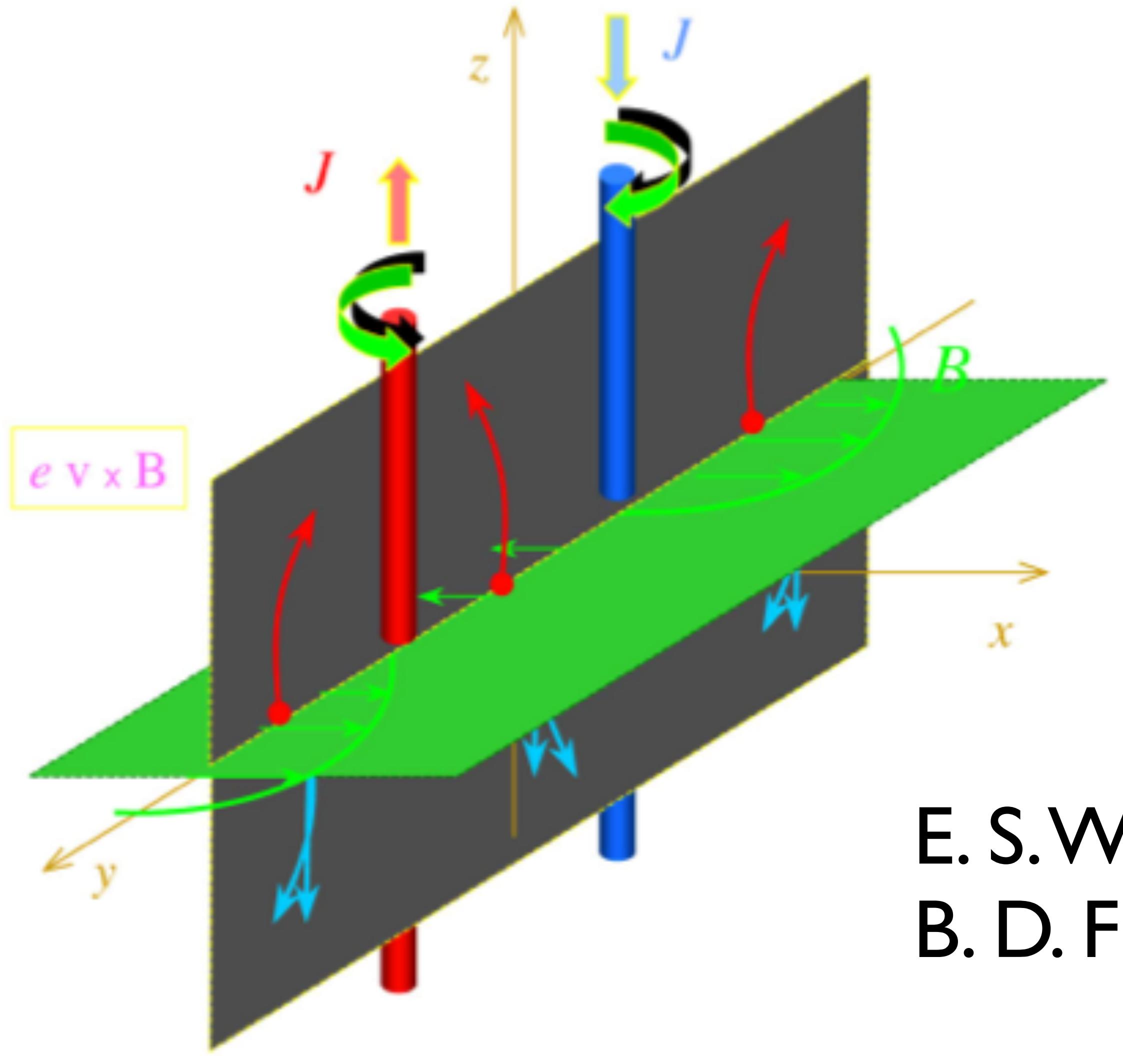
N. Gehrels, L. Piro, and P.J.T. Leonard, Scientific American (2002)
IceCube+, Science 361, eaat1378 (2018), M.G. Aartsen et al., Science 361, 147-151 (2018)

Can we probe relativistic processes behind particle acceleration in the lab?



F. Fiuza *et al.* Phys. Rev. Lett. 108, 235004 (2012)

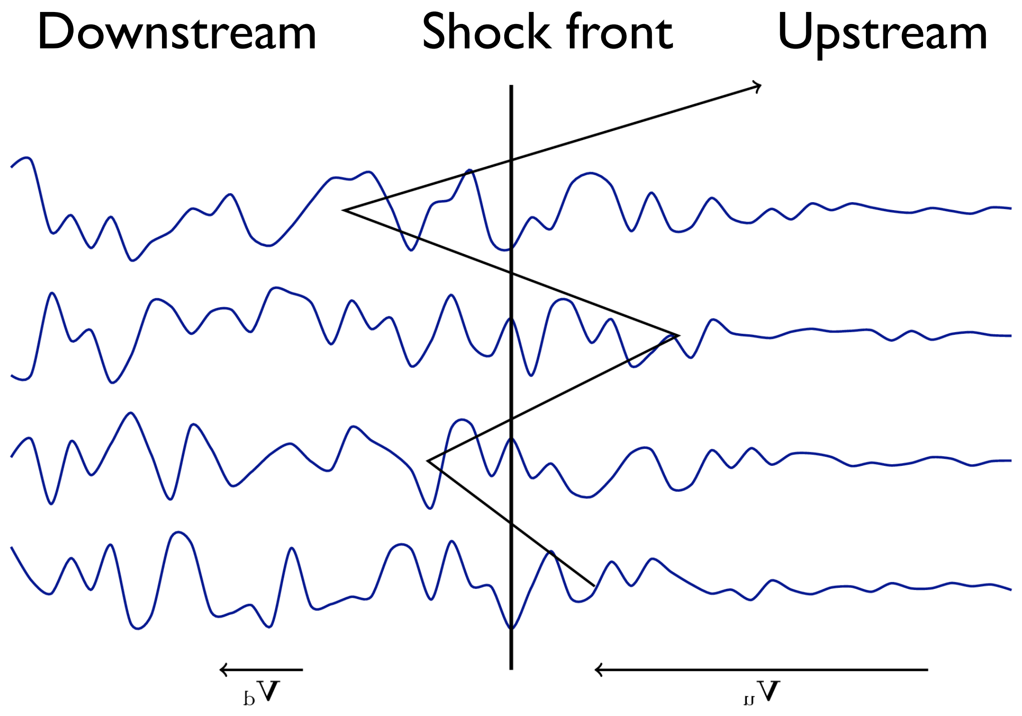
Magnetic field amplification by Weibel instability



$$\Gamma_W = \frac{v_0}{c}\frac{\omega_p}{\gamma_0^{1/2}}$$

E. S. Weibel, PRL 2, 83 (1959)
B. D. Fried, Phys. Fluids 2, 337 (1959)

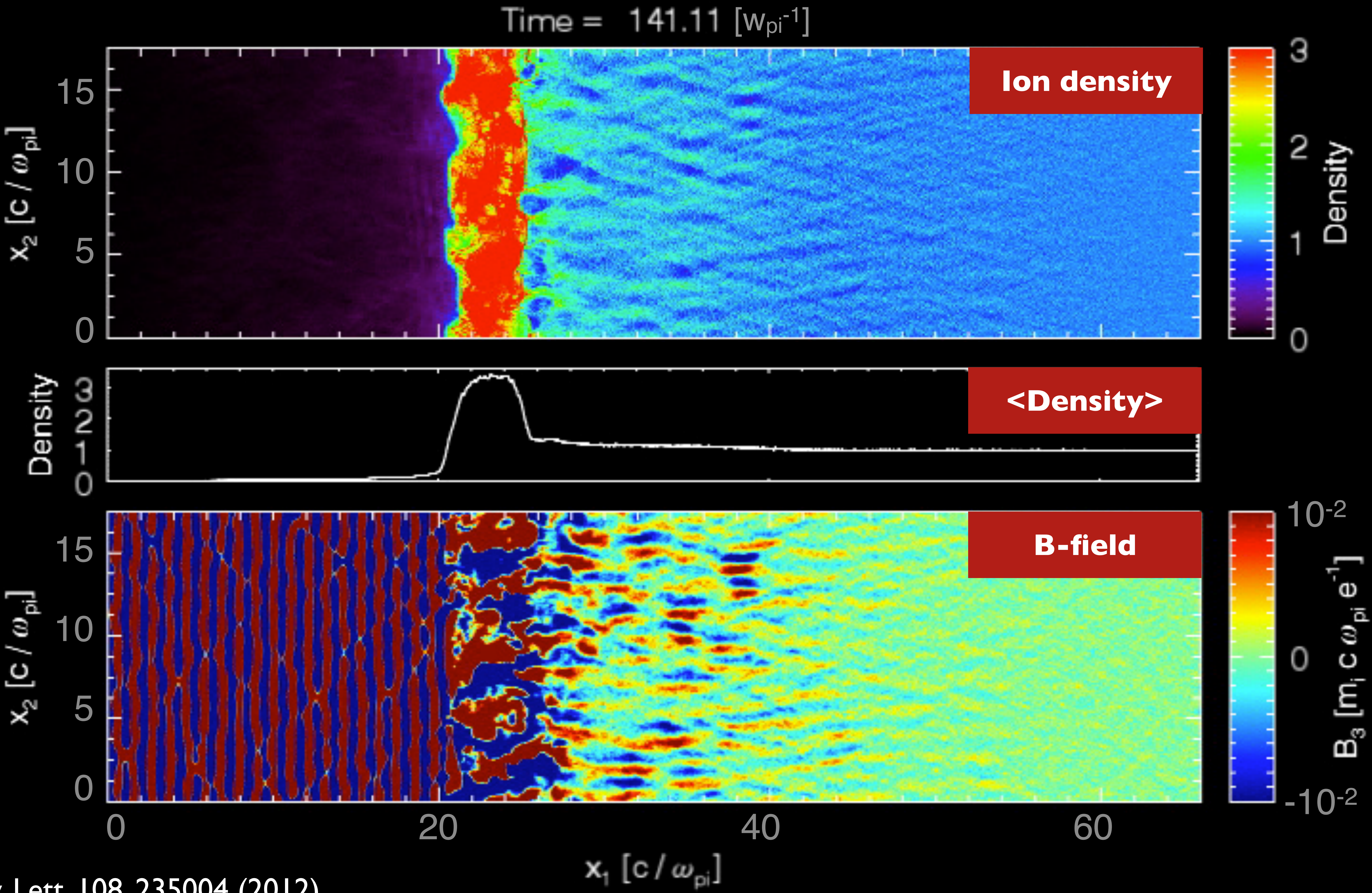
Cosmic rays accelerated by Fermi process



E. Fermi, Phys. Rev. 75, 1169 (1949)
R. Blandford & D. Eichler, Physics Reports 154, 1 (1987)

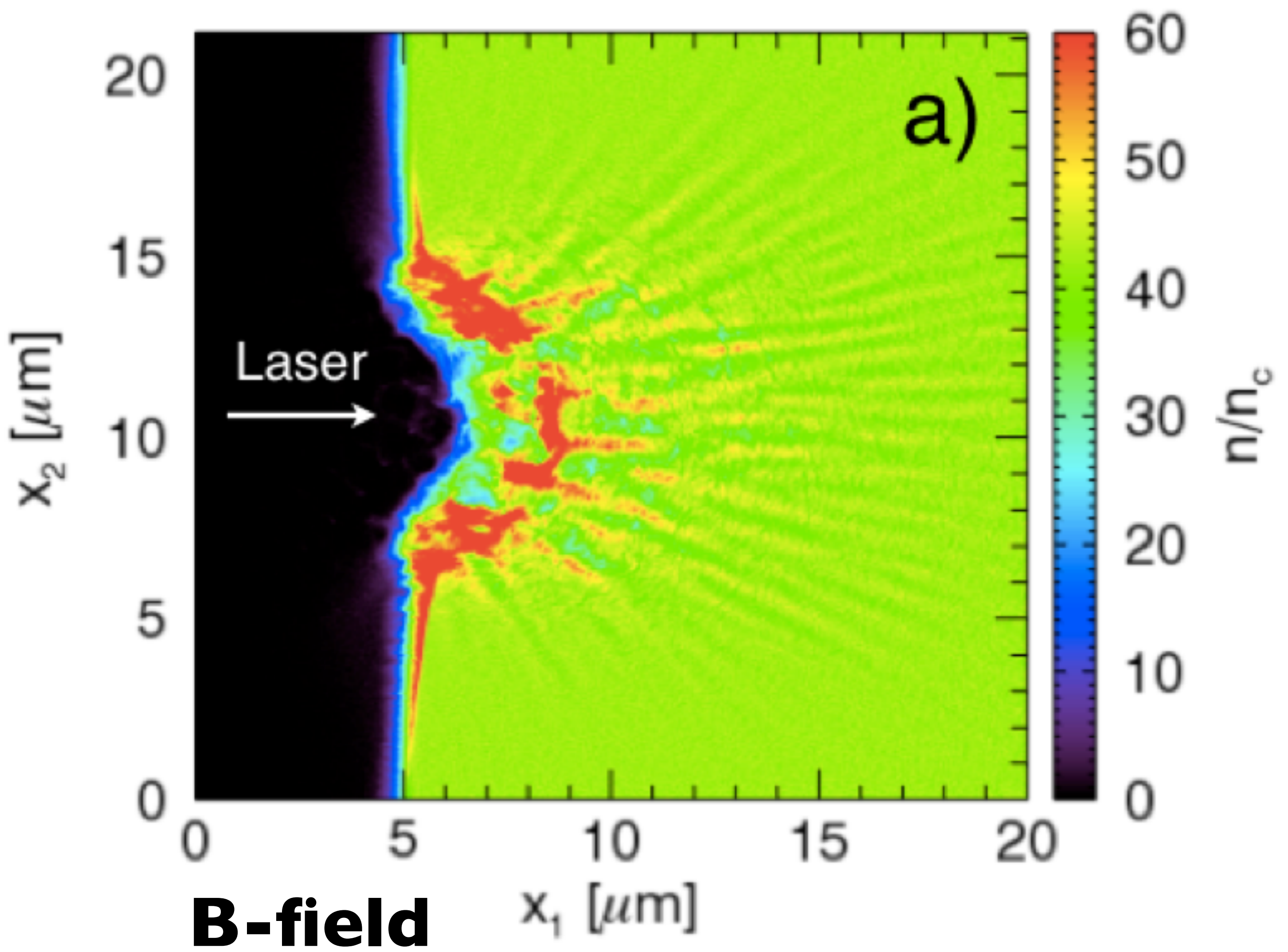
Collisionless shock driven by an ultraintense laser

Laser
I ~ 10^{21} W/cm^2

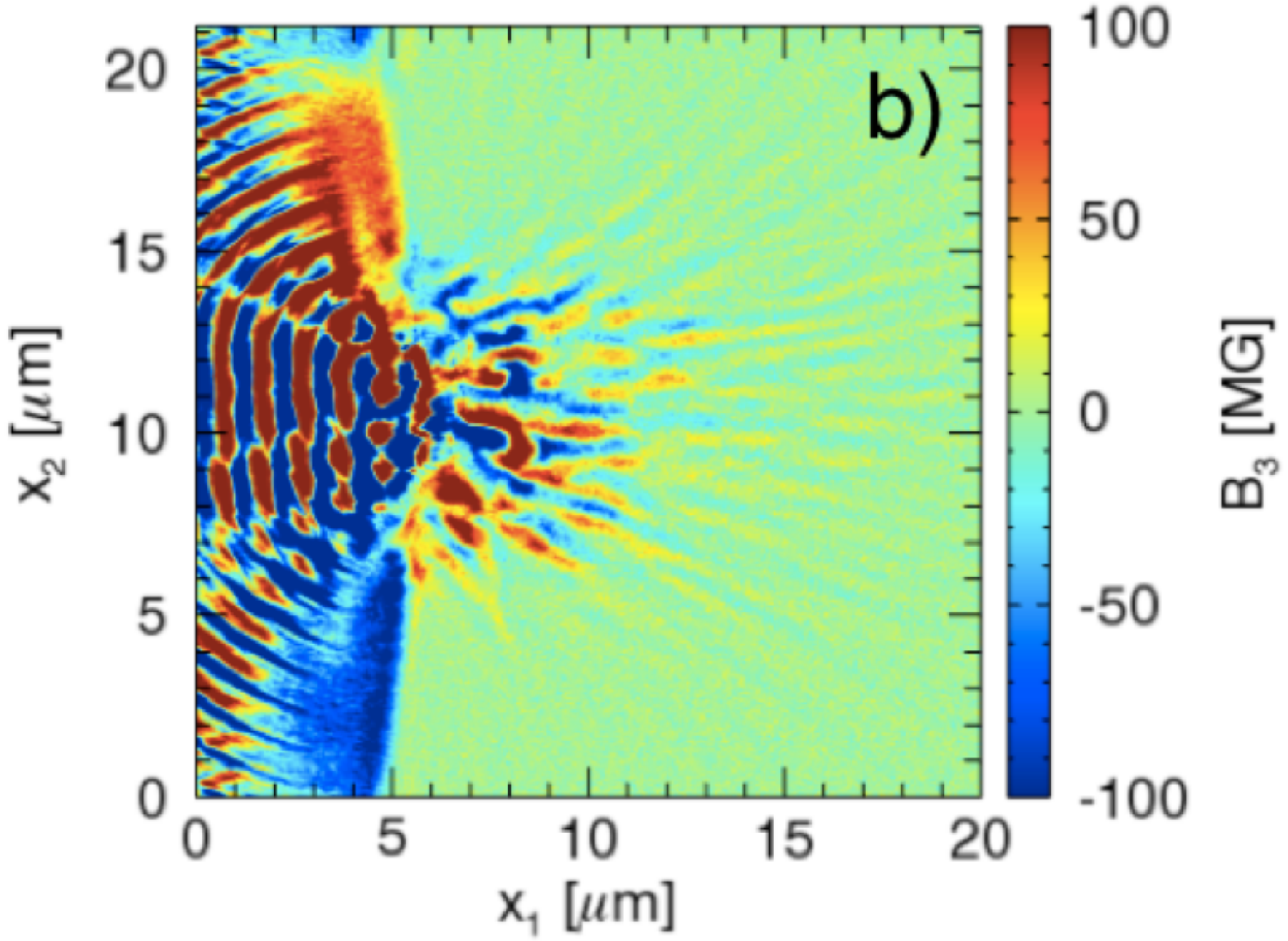


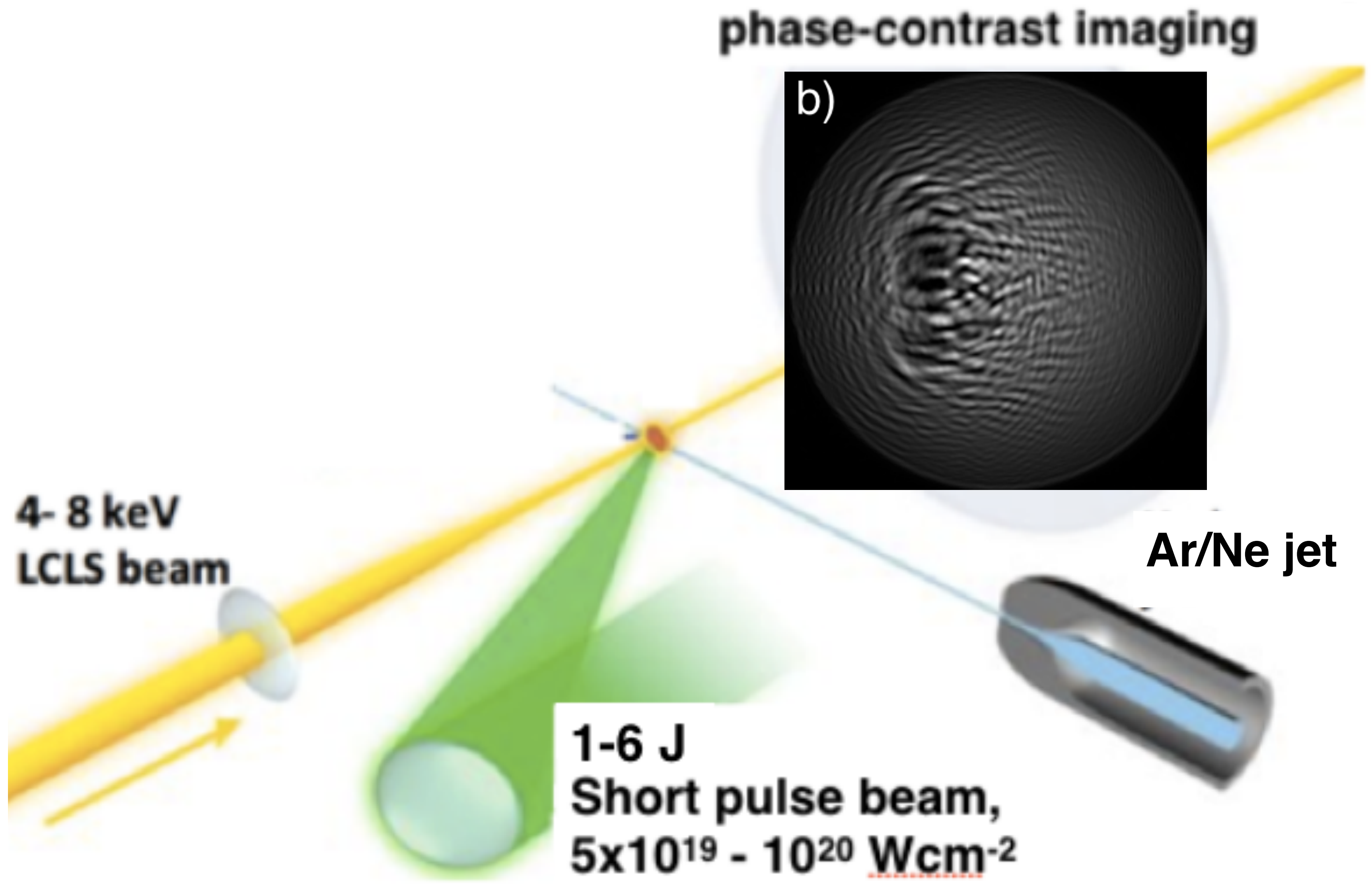
F. Fiuza *et al.* Phys. Rev. Lett. 108, 235004 (2012)

Spatio-temporal evolution of instabilities can be probed with LCLS



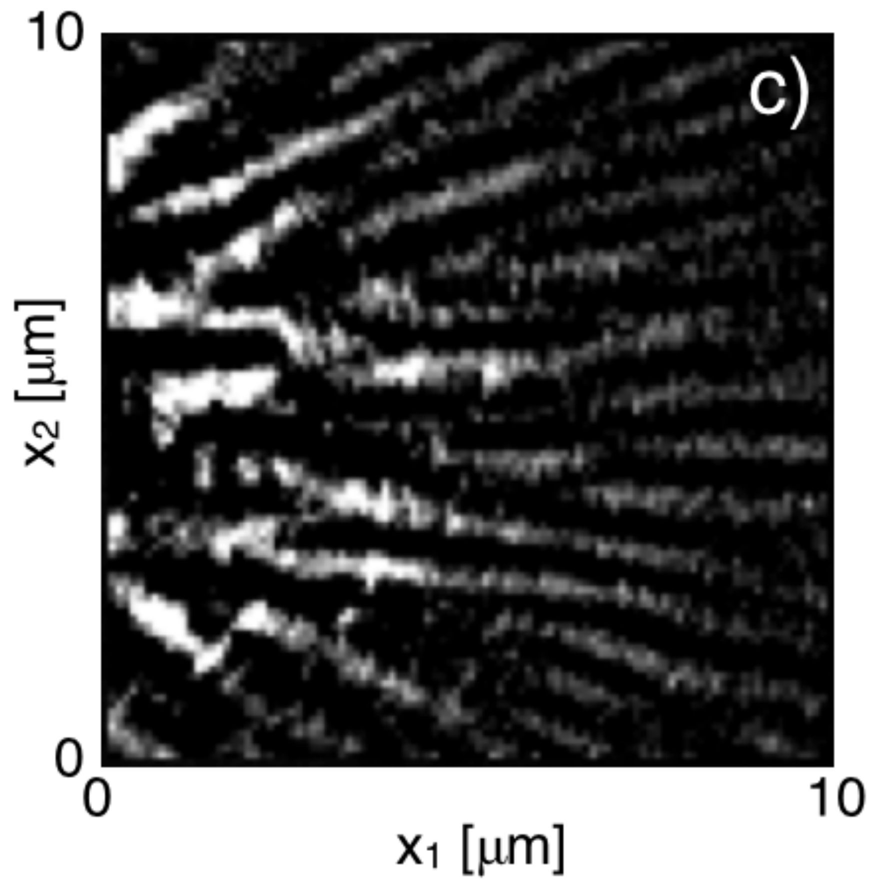
B-field





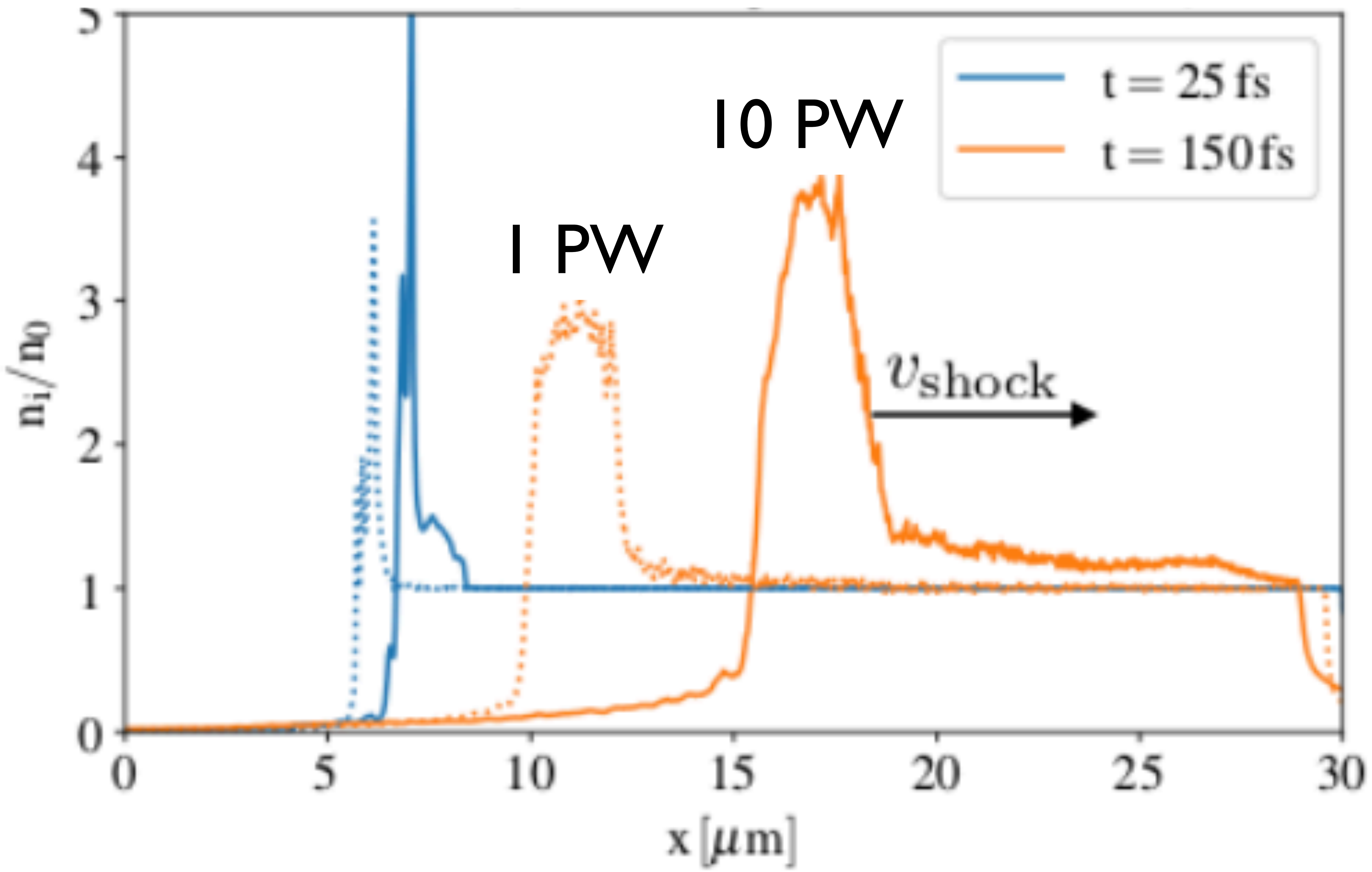
1-6 J
Short pulse beam,
5×10^{19} - 10^{20} Wcm^{-2}

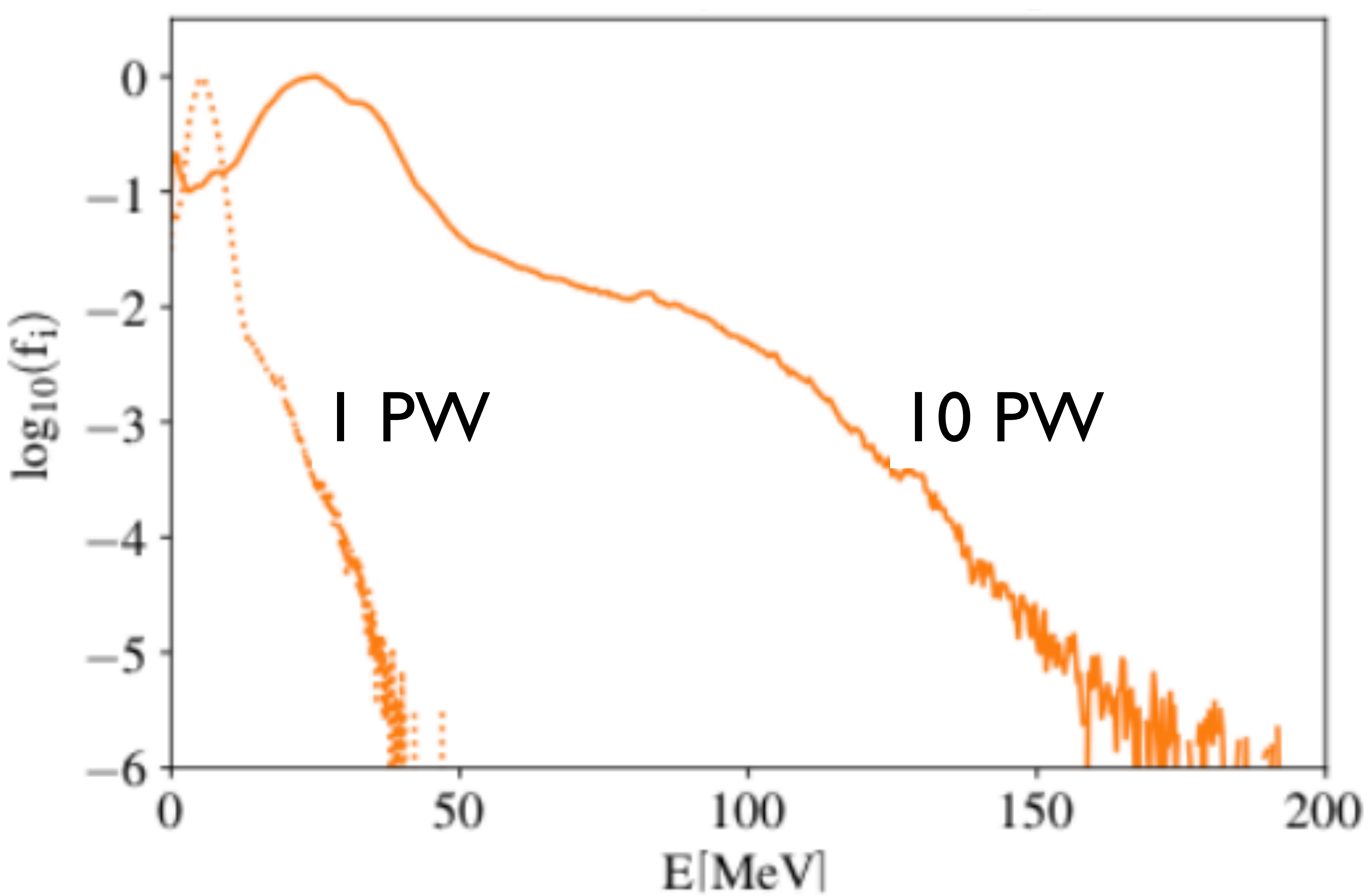
Reconstructed density profile



C. Ruyer and F. Fiuza, Phys. Rev. Lett. 120, 245002 (2018)

Multi-PW laser will allow study of particle acceleration in shocks

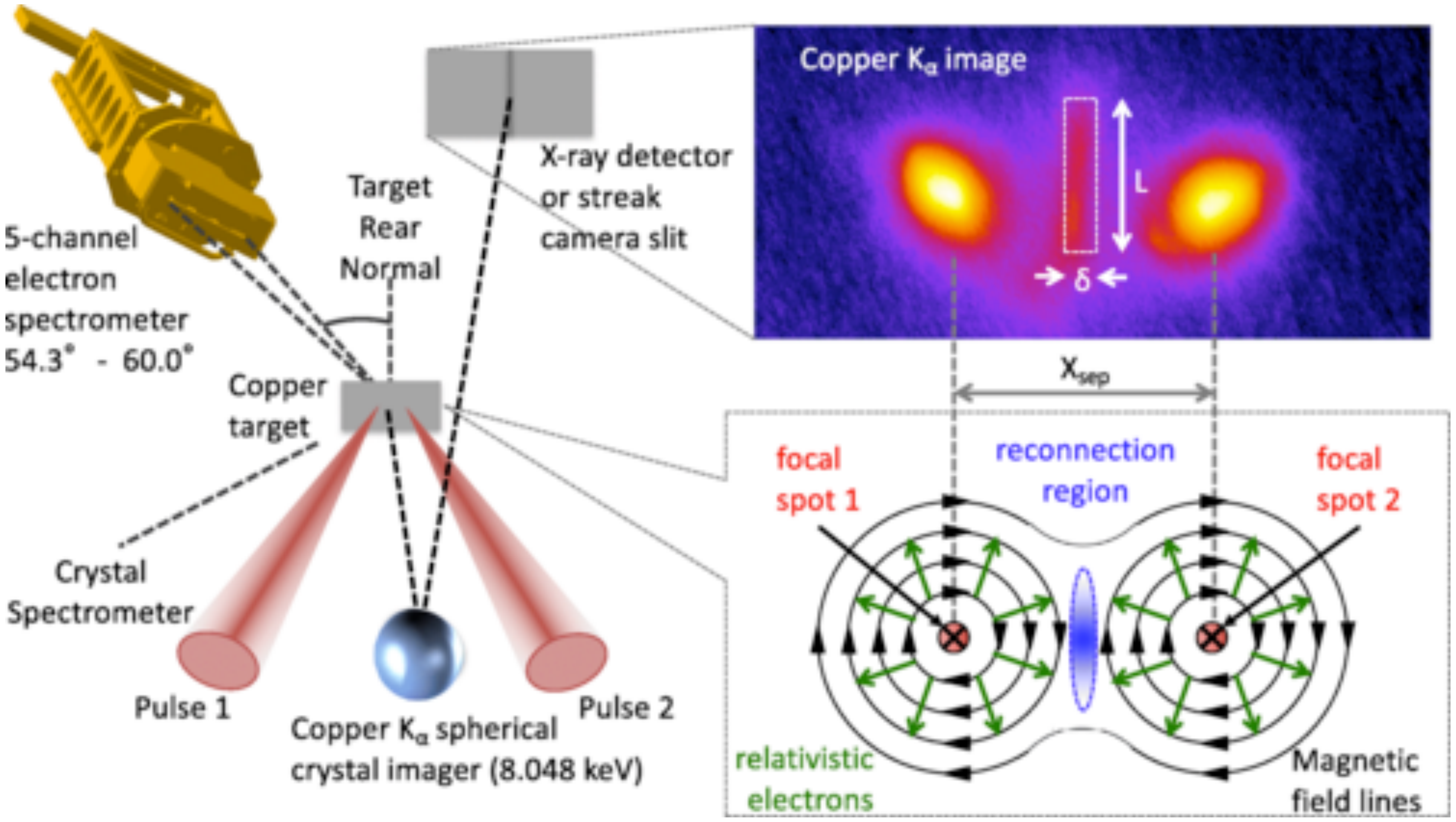


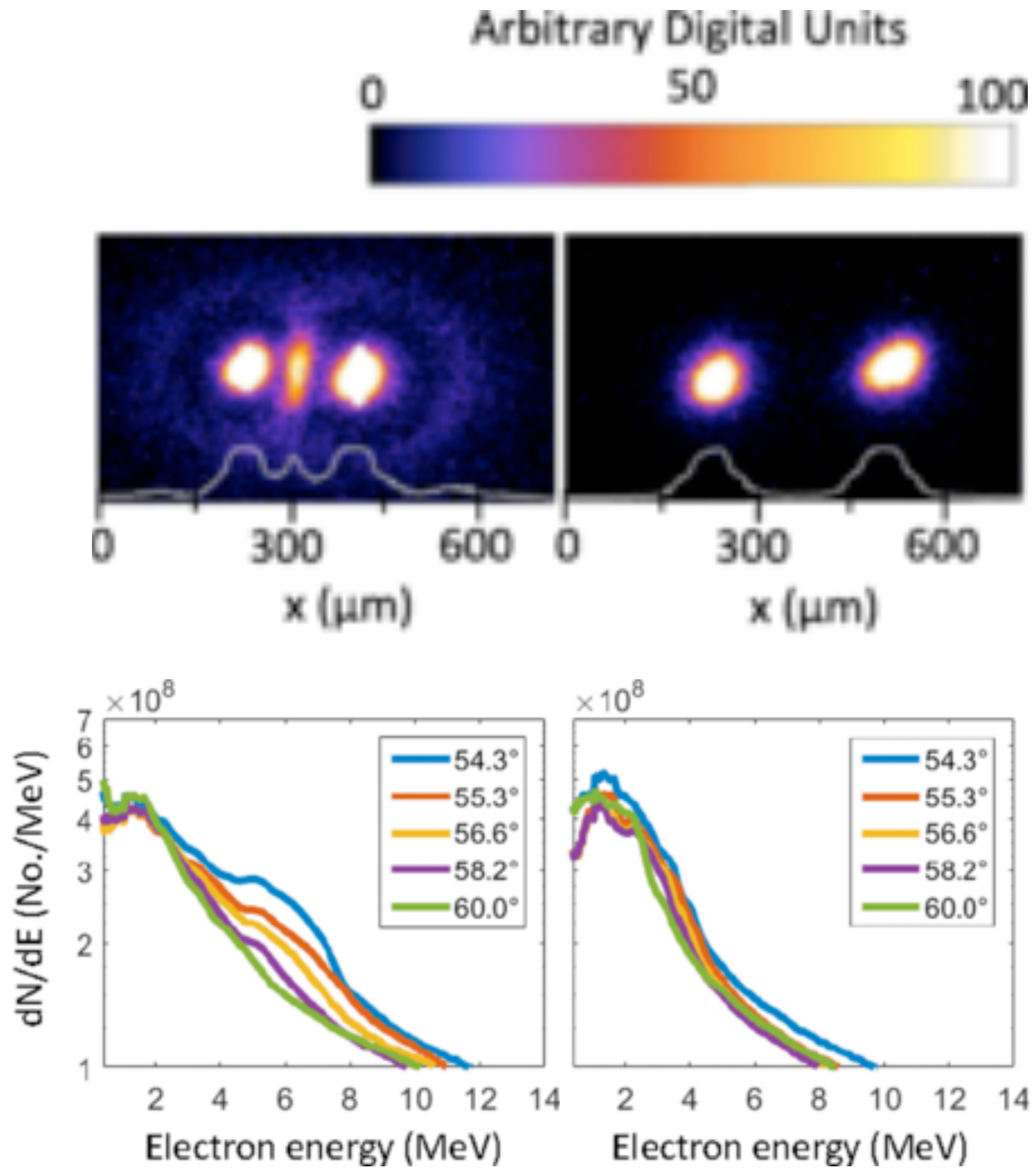


$$\varepsilon_{Hillas} = e\, v_{sh}/c\; B\; L \sim 100\; v_{sh}[0.3c]\; B[10^9 G]\; L\, [10\; \mu m]\;\; \mathrm{MeV}$$

A. Grassi et al., 2018

Relativistic magnetic reconnection recently studied for the first time in the lab

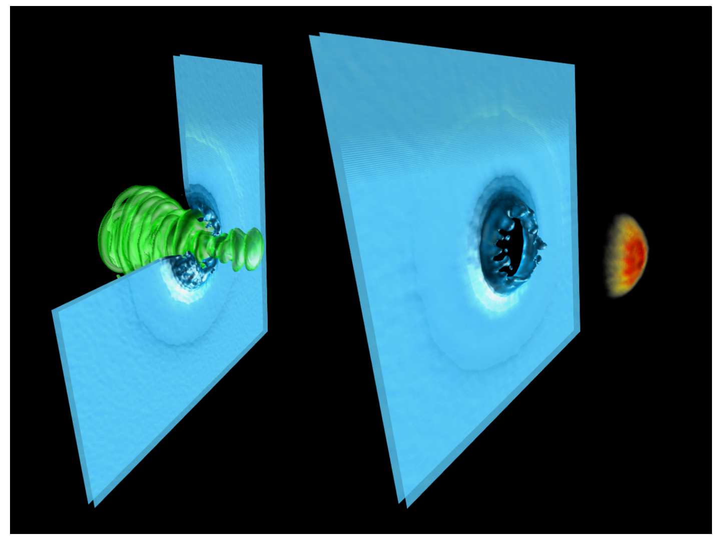


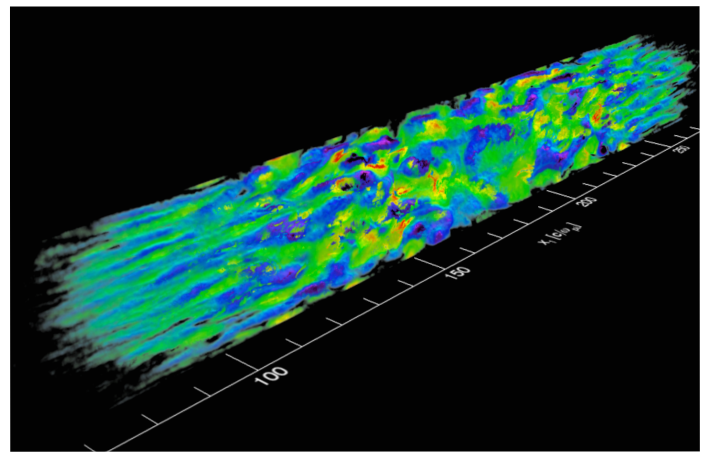


A. Raymond et al., Phys. Rev. E 98, 043207 (2018)

Conclusions

High Energy Density Science with PW lasers





- **PW-class optical lasers are opening unique opportunities to create and probe extreme states of matter in the laboratory**
- **Electric fields produced by lasers in solid-density plasma can exceed by a million times typical accelerating fields in solid-state technology**
- **High-flux beams of ions/protons and neutrons are being produced for applications that range from fusion energy to materials research to medical therapy**
- **PW laser-plasma interactions are also opening a window to study relativistic plasma processes associated with magnetic field dynamics and particle acceleration in high-energy astrophysical environments**

New Horizons in High-Energy-Density Physics: Above the Schwinger Limit and Harnessing Cosmic Particle Acceleration

OSA Technical Group webinar

March 7, 2018

Sebastian Meuren

Department of Astrophysical Sciences, Princeton University (New Jersey, USA)

Acknowledgements

I am grateful to many people, including:

Fabrízio Del Gaudio Thomas Grismayer Luis O. Silva Marija Vranic	Instituto Superior Técnico (Lisbon, Portugal)
Sergey Bragin Antonino Di Piazza Christoph Keitel Matteo Tamburini	Max Planck Institute for Nuclear Physics (Heidelberg, Germany)
Alexander M. Fedotov Arseny Mironov	National Research Nuclear University MEPhI (Moscow, Russia)
Nathaniel J. Fisch	Princeton University (New Jersey, US)

Roger Blandford, Stanley Brodsky, Phil Bucksbaum, Frederico Fiuza, Siegfried Glenzer
Mark Hogan, Michael Peskin, David Reis, Glen White, Vitaly Yakimenko

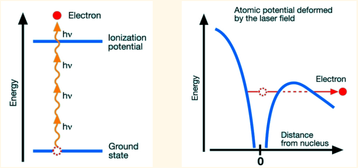
SLAC National Accelerator Laboratory
(California, US)

Strong-field physics: from atoms to the quantum vacuum

Atomic scales

Energy	$\mathcal{E}_a = \alpha^2 \mathcal{E}$	$10\,\mathrm{eV}$
Length	$a_B = \lambda\!\!\!^{-}_C / \alpha$	$10^{-10}\,\mathrm{m}$
Field	$E_a = \alpha^3 E_{cr}$	$10^{11}\,\mathrm{V/m}$

$\sim 10^{16}\,\mathrm{W/cm^2}$



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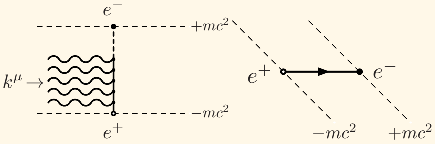
- Around $\sim 10^{16}\,\mathrm{W/cm^2}$: laser and Coulomb field are of the same order
  "Atomic strong-field revolution": Corkum, PRL **71**, 1994 (1993)

QED scales

Energy	$\mathcal{E} = mc^2$	$10^6\,\mathrm{eV}$
Length	$\lambda\!\!\!^{-}_C = \hbar/(mc)$	$10^{-13}\,\mathrm{m}$
Field	$E_{cr} = m^2c^3/(\lvert e\rvert\hbar)$	$10^{18}\,\mathrm{V/m}$

$\sim 10^{29}\,\mathrm{W/cm^2}$



- Around $\sim 10^{29}\,\mathrm{W/cm^2}$: "Schwinger limit", QED vacuum becomes unstable
  "Tunnel ionization of the quantum vacuum": Schwinger PR **82**, 664 (1951)

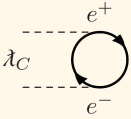
Intuitive derivation of the QED critical (Schwinger) field

- Quantum mechanics ⟶ uncertainty principle ⟶ virtual particles
  pictorial speaking: vacuum filled with virtual electron-positron pairs
- Spatial scale of quantum fluctuations in QED: $\lambdabar_C = \hbar/(mc)$
  $\Delta E = mc^2 \longrightarrow \Delta t \sim \hbar/(\Delta E) \longrightarrow \Delta x \sim c\Delta t \sim \hbar/(mc)$
- Energy transfer $\Delta\mathcal{E}$ by a uniform electric field (magnitude E):

$$\Delta\mathcal{E} = c\,|e|\,E\Delta t \overset{!}{=} \Delta E \quad \longrightarrow \quad E = E_{\mathrm{cr}} = m^2c^3/(|e|\,\hbar)$$

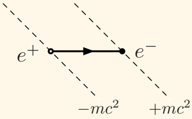
Pair becomes real after an energy transfer $\Delta\mathcal{E} \sim mc^2$:
life time is no longer limited by the uncertainty principle

Vacuum fluctuations



Instead of being empty, the vacuum is filled with quantum fluctuations

Heuristic tunneling picture

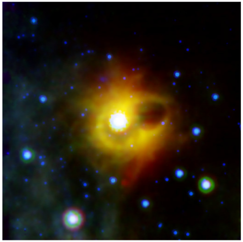


"Tilted" energy levels ⟶ tunneling
Probability: $\sim \exp\left(-\pi E_{\mathrm{cr}}/E\right)$

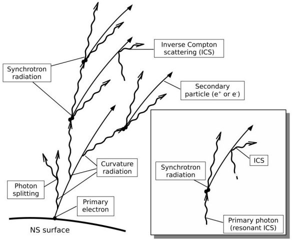
QED critical field in astrophysics

Extreme magnetic fields: magnetars

Magnetar SGR 1900+14

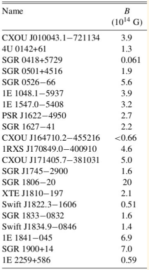


© Wikipedia



Mon. Not. R. Astron. Soc. **406,** 1379–1404 (2010)

THE McGILL MAGNETAR CATALOG



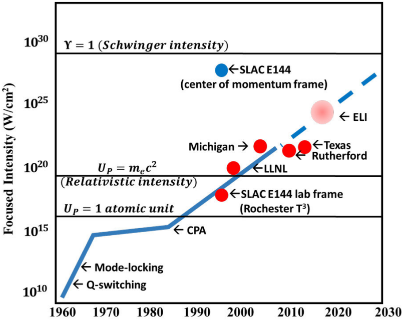
Name	B (10^{14} G)
CXOU J010043.1−721134	3.9
4U 0142+61	1.3
SGR 0418+5729	0.061
SGR 0501+4516	1.9
SGR 0526−66	5.6
1E 1048.1−5937	3.9
1E 1547.0−5408	3.2
PSR J1622−4950	2.7
SGR 1627−41	2.2
CXOU J164710.2−455216	<0.66
1RXS J170849.0−400910	4.6
CXOU J171405.7−381031	5.0
SGR J1745−2900	1.6
SGR 1806−20	20
XTE J1810−197	2.1
Swift J1822.3−1606	0.51
SGR 1833−0832	1.6
Swift J1834.9−0846	1.4
1E 1841−045	6.9
SGR 1900+14	7.0
1E 2259+586	0.59

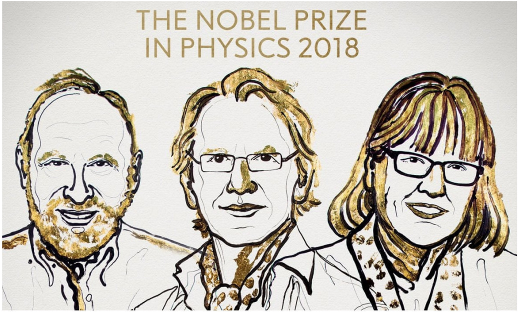
Ultrastrong electromagnetic fields + highly energetic particles

- Interior of neutron stars
- Magnetospheres of magnetars: $B \gtrsim B_{\mathrm{cr}}$ $[B_{\mathrm{cr}} = m^2c^2/(\hbar e) \approx 0.4 \times 10^{14}\,\mathrm{G}]$ (e.g., electromagnetic cascades, vacuum birefringence)
- Central engines of supernovae and gamma ray bursts
- Magnetosphere of rotating Black holes

Uzdensky and Rightley, Plasma physics of extreme astrophysical environments
Rep. Prog. Phys. **77**, 036902 (2014)

Reaching the QED critical field with lasers

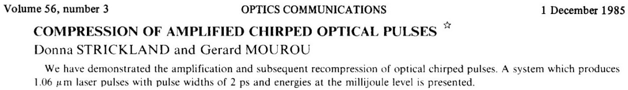




QED critical field:

$$E_{\mathrm{cr}} \approx 1.3 \times 10^{18}\,\mathrm{V/m}$$

$$I_{\mathrm{cr}} \approx 4.6 \times 10^{29}\,\mathrm{W/cm^2}$$



Volume 56, number 3 OPTICS COMMUNICATIONS 1 December 1985

COMPRESSION OF AMPLIFIED CHIRPED OPTICAL PULSES ☆

Donna STRICKLAND and Gerard MOUROU

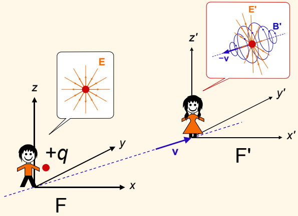
We have demonstrated the amplification and subsequent recompression of optical chirped pulses. A system which produces 1.06 μm laser pulses with pulse widths of 2 ps and energies at the millijoule level is presented.

		facility	current	future
optical	$1\,\mathrm{eV}$	APOLLON, ELI,...	$10^{22}\,\mathrm{W/cm^2}$	$10^{24-25}\,\mathrm{W/cm^2}$
x-ray	$10\,\mathrm{keV}$	LCLS-II, XFEL,...	$10^{21}\,\mathrm{W/cm^2}$	$10^{27}\,\mathrm{W/cm^2}$ (if focused)

We need the Lorentz boost of ultra-relativistic particles to probe the QED critical field!

Reaching the QED critical field with lasers

Lorentz transformation: electromagnetic field & intensity



© Wikipedia

$$\boldsymbol{E}' = \gamma(\boldsymbol{E} + \boldsymbol{\beta} \times \boldsymbol{B}) - \frac{\gamma^2}{\gamma+1}\boldsymbol{\beta}(\boldsymbol{\beta}\boldsymbol{E}),$$

$$\boldsymbol{B}' = \gamma(\boldsymbol{B} - \boldsymbol{\beta} \times \boldsymbol{E}) - \frac{\gamma^2}{\gamma+1}\boldsymbol{\beta}(\boldsymbol{\beta}\boldsymbol{B}),$$

Intensity: $I' \sim \gamma^2 I$

Quantum parameter

- QED critical field: $E_{\mathrm{cr}} \approx 1.3 \times 10^{18}\,\mathrm{V/m} \longleftrightarrow I_{\mathrm{cr}} \approx 4.6 \times 10^{29}\,\mathrm{W/cm^2}$ is not reachable in the laboratory frame (with existing technology)
- Decisive: electromagnetic field ($F^{\mu\nu}$) in the electron rest frame (E^*)

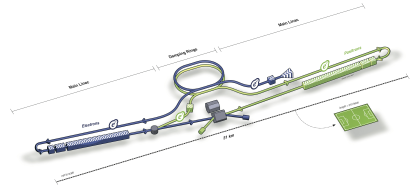
$$\boxed{\chi = \Upsilon = \frac{\sqrt{pF^2p}}{E_{\mathrm{cr}}mc} = \frac{E^*}{E_{\mathrm{cr}}} \approx 0.57\,\frac{\epsilon}{10\,\mathrm{GeV}}\sqrt{\frac{I}{10^{20}\,\mathrm{W/cm^2}}}}$$

I: laser intensity ϵ: electron energy (last relation: head-on electron-laser collision)

Ritus, J. Sov. Laser Res. **6**, 497–617 (1985); Di Piazza et al., Rev. Mod. Phys. **84**, 1177 (2012)

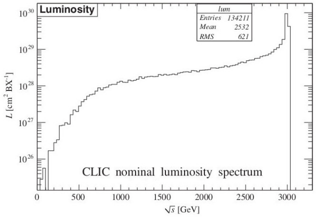
Reaching the QED critical field in future linear colliders

Lepton collider (electron-positron)



ILC $\chi = \mathbf{0.1 - 0.3}$ $(0.25 - 0.5\,\mathrm{TeV})$
CLIC $\chi = \mathbf{1.5 - 12}$ $(0.2 - 1.5\,\mathrm{TeV})$

Stochastic beamstrahlung



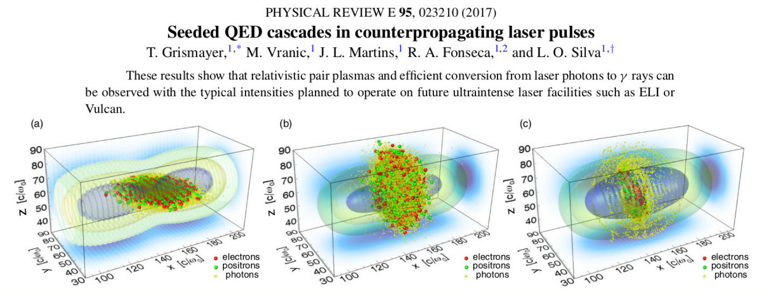
SFQED determines energy/luminosity

Esberg et al., PRSTAB **17**, 051003 (2014)

- **Problems of protron-proton collider:**
  - Nontrivial initial state: protons are not elementary particles
  - PDFs: smaller effective energy, complicated background
- **Problems of linear electron-positron collider:**
  - High luminosity → high charge density → strong fields → beamstrahlung
  - Stochastic photon emission + large recoil: nontrivial energy distribution, modified transverse beam structure (beam broadening → focusing quality)

Understanding of beamstrahlung is crucial

QED critical field in plasma physics and HEDP science

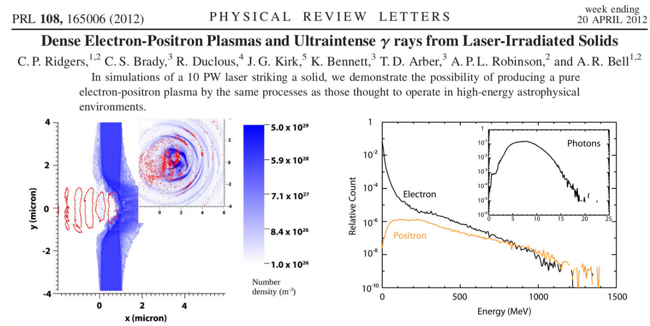


PHYSICAL REVIEW E **95**, 023210 (2017)

Seeded QED cascades in counterpropagating laser pulses

T. Grismayer,[1,*] M. Vranic,[1] J. L. Martins,[1] R. A. Fonseca,[1,2] and L. O. Silva[1,†]

These results show that relativistic pair plasmas and efficient conversion from laser photons to γ rays can be observed with the typical intensities planned to operate on future ultraintense laser facilities such as ELI or Vulcan.



PRL **108,** 165006 (2012) PHYSICAL REVIEW LETTERS week ending 20 APRIL 2012

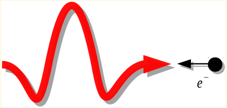
Dense Electron-Positron Plasmas and Ultraintense γ rays from Laser-Irradiated Solids

C. P. Ridgers,[1,2] C. S. Brady,[3] R. Duclous,[4] J. G. Kirk,[5] K. Bennett,[3] T. D. Arber,[3] A. P. L. Robinson,[2] and A. R. Bell[1,2]

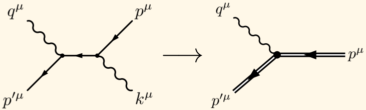
In simulations of a 10 PW laser striking a solid, we demonstrate the possibility of producing a pure electron-positron plasma by the same processes as those thought to operate in high-energy astrophysical environments.

The fundamental (strong-field) QED processes

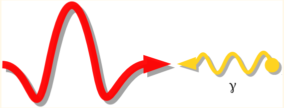
Photon emission



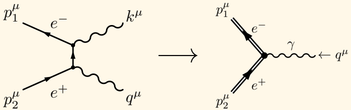
photon emission by an electron/positron



Pair production



photon decay into a lepton pair

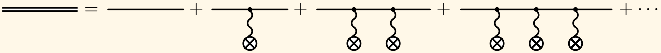


Dressed states

- Perturbative treatment of the laser field breaks down if $\xi \gtrsim 1$

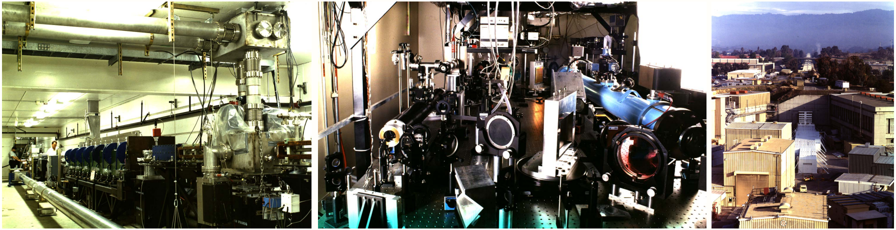
$$\boxed{a_0 = \xi = \eta = \frac{|e|E}{mc\omega} \approx 0.75 \, \frac{\mathrm{eV}}{\hbar\omega} \sqrt{\frac{I}{10^{18}\,\mathrm{W/cm^2}}}}$$

- Dressed states include the classical background field exactly:

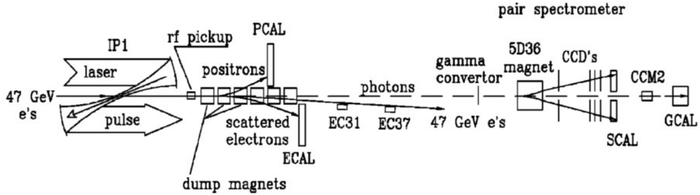


Ritus, J. Sov. Laser Res. **6**, 497–617 (1985); Di Piazza et al., Rev. Mod. Phys. **84**, 1177 (2012)

The seminal SLAC experiment 144 (1990s)

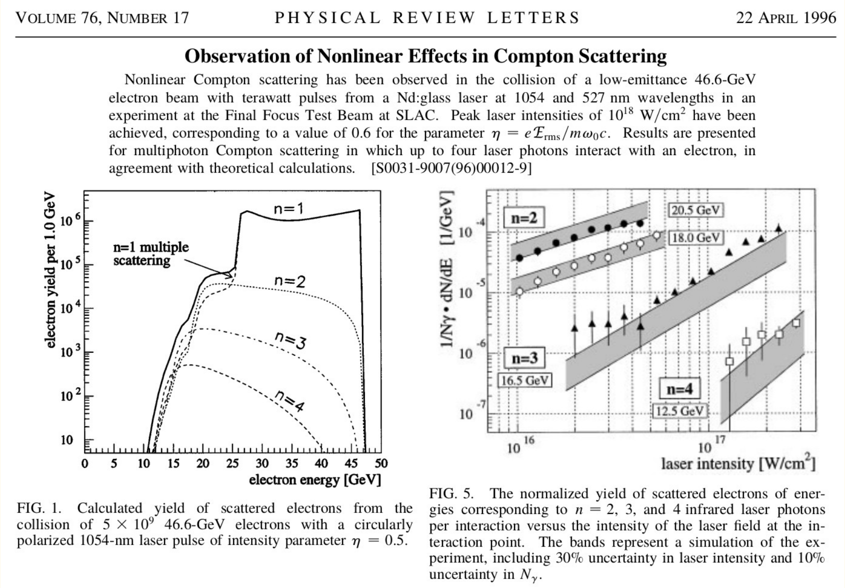


- First laser experiment which probed the QED critical field
- Electron energy: $\epsilon = 46.6\,\mathrm{GeV}$, laser intensity: $I \sim 10^{18}\,\mathrm{W/cm^2}$
  $\longrightarrow$ Onset of nonlinear effects: $\xi = a_0 = \eta \lesssim 0.4$, $\chi = \Upsilon \lesssim 0.25$



C. Bamber et al. "Studies of nonlinear QED in collisions of 46.6 GeV electrons with intense laser pulses." Phys. Rev. D **60**, 092004 (1999).

The seminal SLAC experiment 144 (1990s)



VOLUME 76, NUMBER 17 PHYSICAL REVIEW LETTERS 22 APRIL 1996

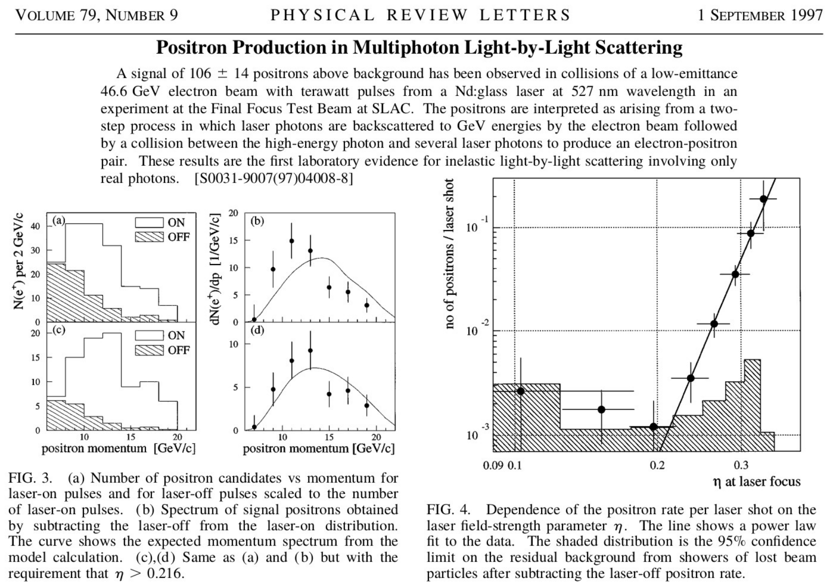
Observation of Nonlinear Effects in Compton Scattering

Nonlinear Compton scattering has been observed in the collision of a low-emittance 46.6-GeV electron beam with terawatt pulses from a Nd:glass laser at 1054 and 527 nm wavelengths in an experiment at the Final Focus Test Beam at SLAC. Peak laser intensities of 10^{18} W/cm^2 have been achieved, corresponding to a value of 0.6 for the parameter $\eta = e\mathcal{E}_{\rm rms}/m\omega_0 c$. Results are presented for multiphoton Compton scattering in which up to four laser photons interact with an electron, in agreement with theoretical calculations. [S0031-9007(96)00012-9]

FIG. 1. Calculated yield of scattered electrons from the collision of 5×10^9 46.6-GeV electrons with a circularly polarized 1054-nm laser pulse of intensity parameter $\eta = 0.5$.

FIG. 5. The normalized yield of scattered electrons of energies corresponding to $n = 2$, 3, and 4 infrared laser photons per interaction versus the intensity of the laser field at the interaction point. The bands represent a simulation of the experiment, including 30% uncertainty in laser intensity and 10% uncertainty in N_γ.

The seminal SLAC experiment 144 (1990s)



VOLUME 79, NUMBER 9 PHYSICAL REVIEW LETTERS 1 SEPTEMBER 1997

Positron Production in Multiphoton Light-by-Light Scattering

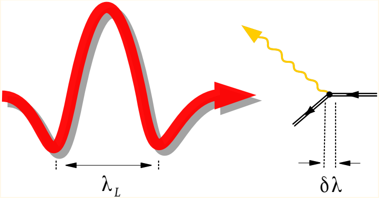
A signal of 106 ± 14 positrons above background has been observed in collisions of a low-emittance 46.6 GeV electron beam with terawatt pulses from a Nd:glass laser at 527 nm wavelength in an experiment at the Final Focus Test Beam at SLAC. The positrons are interpreted as arising from a two-step process in which laser photons are backscattered to GeV energies by the electron beam followed by a collision between the high-energy photon and several laser photons to produce an electron-positron pair. These results are the first laboratory evidence for inelastic light-by-light scattering involving only real photons. [S0031-9007(97)04008-8]

FIG. 3. (a) Number of positron candidates vs momentum for laser-on pulses and for laser-off pulses scaled to the number of laser-on pulses. (b) Spectrum of signal positrons obtained by subtracting the laser-off from the laser-on distribution. The curve shows the expected momentum spectrum from the model calculation. (c),(d) Same as (a) and (b) but with the requirement that $\eta > 0.216$.

FIG. 4. Dependence of the positron rate per laser shot on the laser field-strength parameter η. The line shows a power law fit to the data. The shaded distribution is the 95% confidence limit on the residual background from showers of lost beam particles after subtracting the laser-off positron rate.

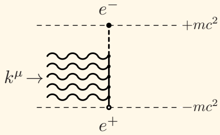
FACET-II: qualitatively different from SLAC E-144

Formation length of SFQED processes

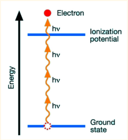


1. λ_L: laser wavelength (scale on which the field changes significantly)
2. $\delta\lambda$: formation region of a fundamental QED processes; $\delta\lambda/\lambda_L \sim 1/a_0$

Large formation length ($a_0 \ll 1$)

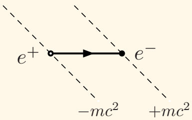


Vacuum/QED

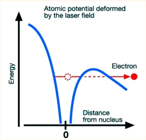


Atoms

Small formation length ($a_0 \gg 1$)



Vacuum/QED

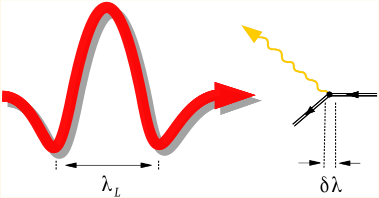


Atoms

- Ionization in atomic physics – Keldysh parameter: $\gamma_K = \omega\sqrt{2mI_p}/(|e|E)$,
- Pair production in SFQED: $\gamma_K(I_p = 2mc^2) \sim 1/a_0 = \omega mc/(|e|E)$

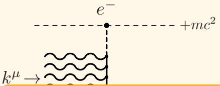
FACET-II: qualitatively different from SLAC E-144

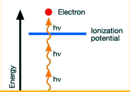
Formation length of SFQED processes



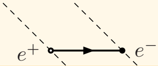
1. λ_L: laser wavelength (scale on which the field changes significantly)
2. $\delta\lambda$: formation region of a fundamental QED processes; $\delta\lambda/\lambda_L \sim 1/a_0$

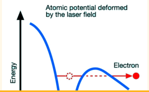
Large formation length ($a_0 \ll 1$)





Small formation length ($a_0 \gg 1$)





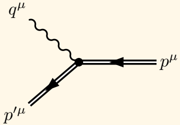
FACET-II vs. SLAC E-144

A qualitatively completely different regime becomes accessible

(similar as transition from multi-photon to tunnel ionization in atoms)

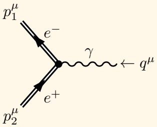
Open research question: do we understand QED cascades?

Photon emission



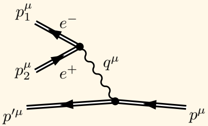
In general an electron can radiate more than only once

Pair production



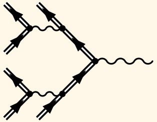
The survival probability of a photon can become exponentially small

Trident pair production



Simplest cascade process

QED cascade



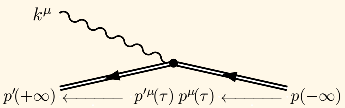
Exponential increase of particles

- Photon emission/pair production happens every $1/(\alpha a_0)$ laser cycles
- The number of particles/vertices grows exponentially with time
- Analytical calculations are impossible, numerical methods required

Bell and Kirk, Phys. Rev. Lett. **101**, 200403 (2008)

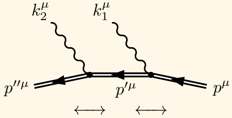
Numerical methods: Monte-Carlo codes, QED-PIC

Semiclassical description



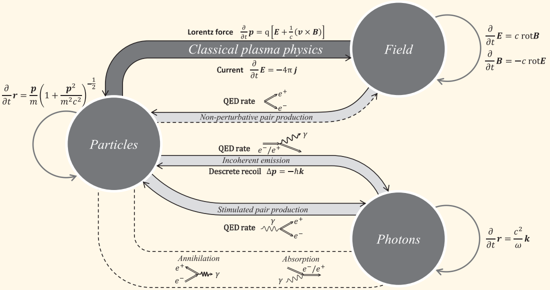
Classical propagation between emissions, instantaneous photon recoil

Incoherent emissions



Small formation regions, different emission vertices are well separated

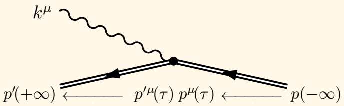
QED-PIC approach



A. Gonoskov, et al. Phys. Rev. E **92**, 023305 (2015)

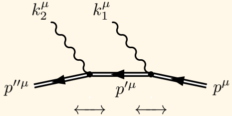
Numerical methods: Monte-Carlo codes, QED-PIC

Semiclassical description



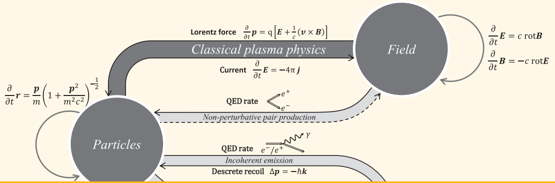
Classical propagation between emissions, instantaneous photon recoil

Incoherent emissions



Small formation regions, different emission vertices are well separated

QED-PIC approach

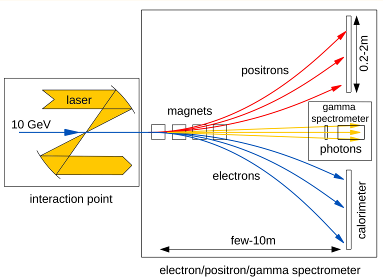


Central research question

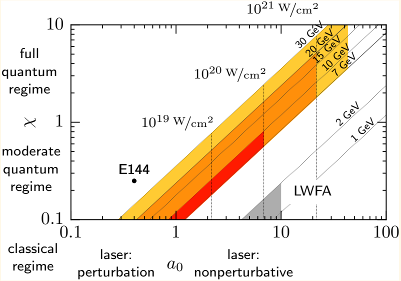
Are the assumptions of current state-of-the-art numerical strong-field QED codes valid?

Probing strong-field QED at SLAC's FACET-II

Sketch of the setup



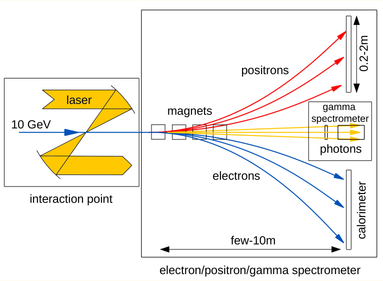
Explorable parameter space



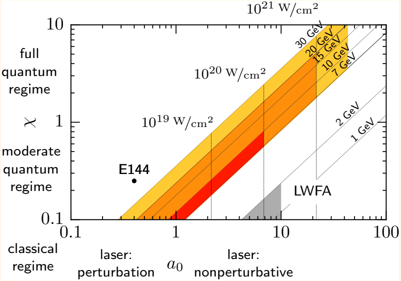
Laser parameters	20 TW (red)	200 TW (orange)	1 PW (yellow)
Pulse energy	0.7 J	8 J	50 J
Pulse duration (FWHM)	35 fs	40 fs	50 fs
Beam waist	2.4 μm	3.0 μm	3.0 μm
Wavelength	0.8 μm	0.8 μm	0.8 μm
Intensity (average)	10^{20} W/cm^2	0.7×10^{21} W/cm^2	3.5×10^{21} W/cm^2
Electron energy	$7-10$ GeV	20 GeV	30 GeV
a_0 (peak)	7	18	40
χ (peak)	0.9	4	14

Probing strong-field QED at SLAC's FACET-II

Sketch of the setup



Explorable parameter space



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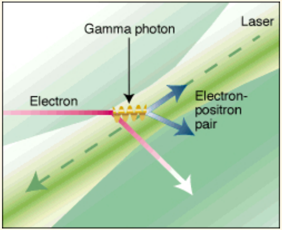
SFQED experiments at FACET-II

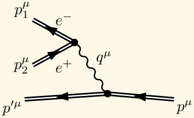
We have an approved user program

FACET-II: first measurement of vacuum breakdown

Vacuum breakdown in static field

©SLAC E-144





Two-step approximation:

1. photon emission
2. pair production

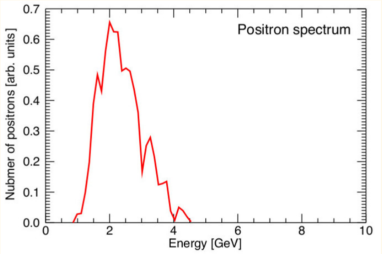
Total probability

w_0	a_0	# positrons per electron	Simulation
3 μm	5.7	1.2×10^{-7}	Tamburini
2.4 μm	7.2	0.9×10^{-6}	
4 μm	5.0	1.9×10^{-7}	Vranic
	8.0	1.7×10^{-5}	

FACET-II beam: 0.6 nC, i.e., 3.7×10^9 electrons

w_0: laser focus spot size

Energy spectrum

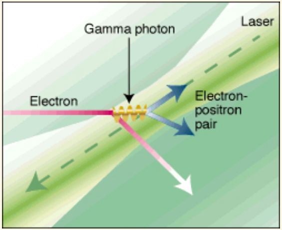


simulated by M. Vranic

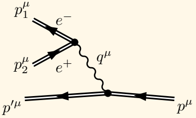
Hu, Müller, and Keitel, RPL **105**, 080401 (2010); Ilderton, PRL **106**, 020404 (2011)

FACET-II: first measurement of vacuum breakdown

Vacuum breakdown in static field



©SLAC E-144



Two-step approximation:

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w_0	a_0	# positrons per electron	Simulation
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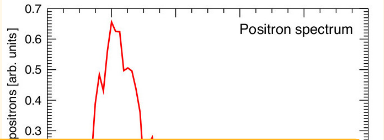
2.4 µm	7.2	0.9×10^{-6}	
4 µm			

FACET-I

Energy spectrum



simulated by M. Vranic

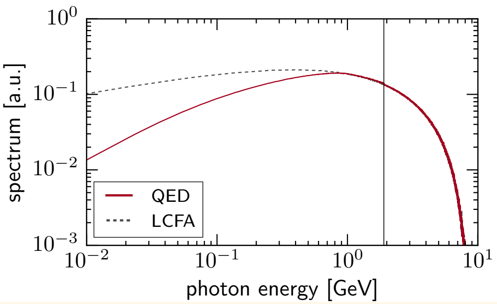
FACET-II vs. SLAC E-144

In comparison with E-144 (<1 pair per shot) we expect prolific pair production (up to 10^4 pairs per shot)

Hu, Mü

FACET-II: first measurement of the LCFA breakdown

Simulation: photon spectrum

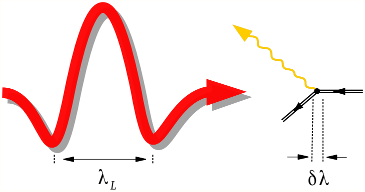


simulated by M. Tamburini

- Formation region depends on photon energy:

$$\delta\lambda \sim \frac{\epsilon}{m^2\chi}\left(1+\frac{\chi}{u}\right)^{1/3}, \quad u = \frac{\omega'}{\epsilon-\omega'}$$

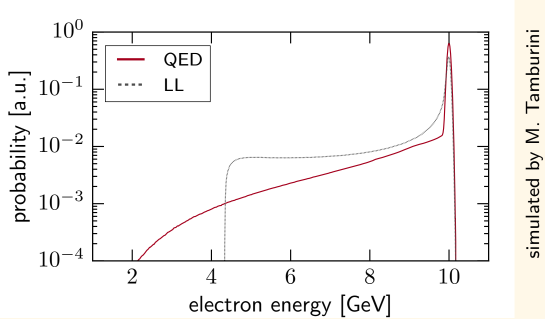
- LCFA breakdown: $\delta\lambda \gtrsim \lambda_L$, i.e., $\omega' \lesssim \epsilon\chi/a_0^3$
- $\epsilon = 10\,\mathrm{GeV}$, $\chi \approx 1$, $a_0 \approx 7$: $\omega' \lesssim 30\,\mathrm{MeV}$



Di Piazza, Tamburini, SM, Keitel, PRA **98**, 012134 (2018) and PRA **99**, 022125 (2019)

FACET-II: clear signitures of quantum radiation reaction

Observable: electron energy distribution



Classical vs. quantum radiation reaction

- **Classical radiation reaction** ($\chi \ll 1$): "frictional force"
  $\longrightarrow$ sharp cutoff of the electron energy spectrum
- **Quantum radiation reaction** ($\chi \gtrsim 1$): stochasticity, "diffusion"
  $\longrightarrow$ edge of the spectrum is smeared out (higher losses!)

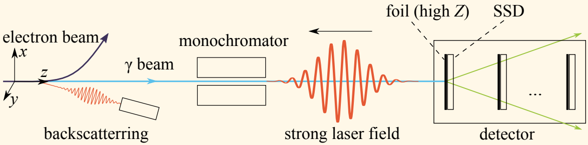
We expect to observe clear deviations form LL at FACET-II

Neitz and Di Piazza, Phys. Rev. Lett. **111**, 054802 (2013)

FACET-II: possible future upgrades

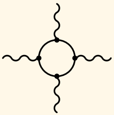
Future upgrade: 200 TW laser – vacuum birefringence

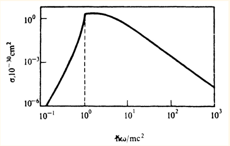
Experimental setup



1. Compton backscattering: highly polarized GeV photons
2. High-intensity laser polarizes the quantum vacuum
3. Pair production (foil): polarization dependent distribution

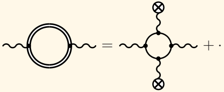
Light-by-light scattering





Landau Lifshitz vol. 4

Vacuum birefringence



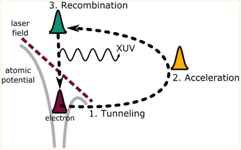
Speed of light depends on polarization
Violation of the superposition principle

- Vacuum birefringence: first observation of light-by-light scattering (real photons)
- FACET-II: GeV photons + 200 TW ⟷ SULF (China): x-ray + 100 PW!

S. Bragin, SM, C. H. Keitel, and A. Di Piazza, Phys. Rev. Lett. **119**, 250403 (2017)

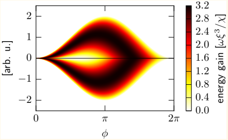
Future upgrade: 20 PW laser – electron-positron recollisions

Atomic physics



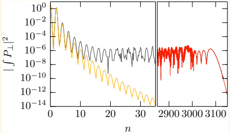
Recollision processes in atoms after tunnel ionization

Strong-field QED



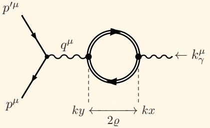
Recollision processes after tunneling pair production

Electron-positron loop: spectrum



Recollisions lead to plateau region

Muon pair production



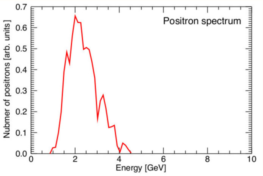
$a_0 \gtrsim 200$, e.g., 20 PW with 2.5 μm spot

Semiclassical three-step picture:

❶ Pair creation ❷ Acceleration by the laser ❸ Recollision

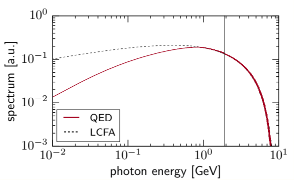
SM, K. Z. Hatsagortsyan, C. H. Keitel, and A. Di Piazza, PRL **114**, 143201 (2015)

Summary: FACET-II 10 GeV electrons + 20 TW laser pulses



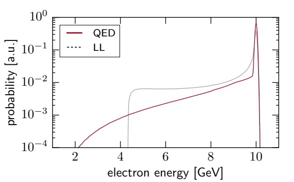
Tunneling pair production/vacuum breakdown

- Pair production inside quasi-static field
- Nonperturbative tunneling exponent
- Much higher statistics: $\sim 10^4$ positrons/shot



Breakdown of the LCFA

- Applicability of the LCFA: vital for numerical codes
- Formation region depends on photon frequency
- LCFA fails: suppression of low-frequency radiation



Quantum radiation reaction (QRR) – energy

- Stochasticity: broadening of the energy distribution
- Quenching: some electrons don't radiate at all
- Quantum corrections to Landau-Lifshitz

To be continued...

Thank you for your attention
and your questions!