Laser absorption in plasmas: from nano-targets to QED regime

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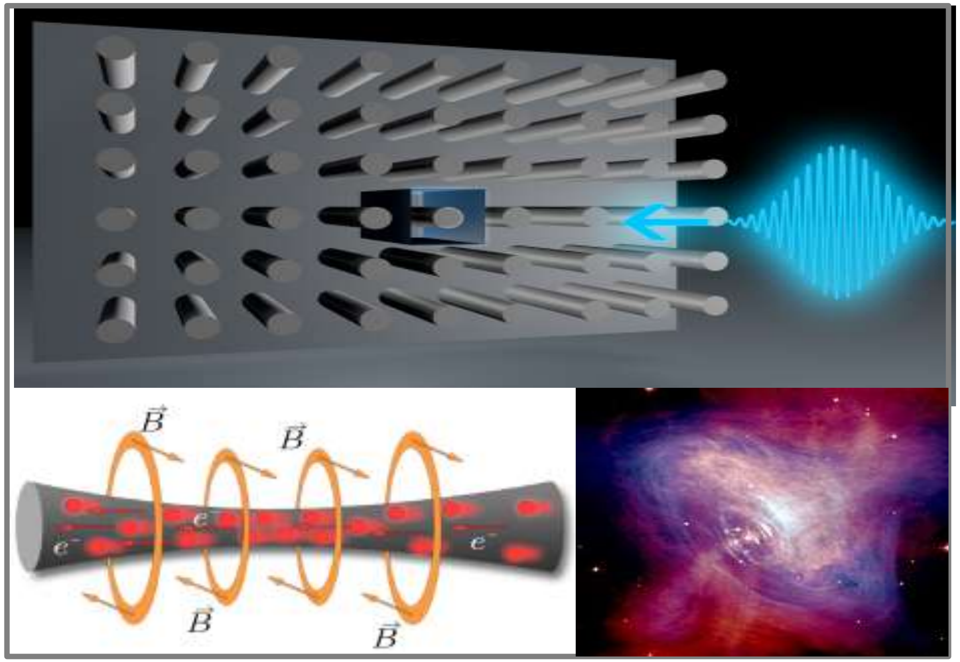
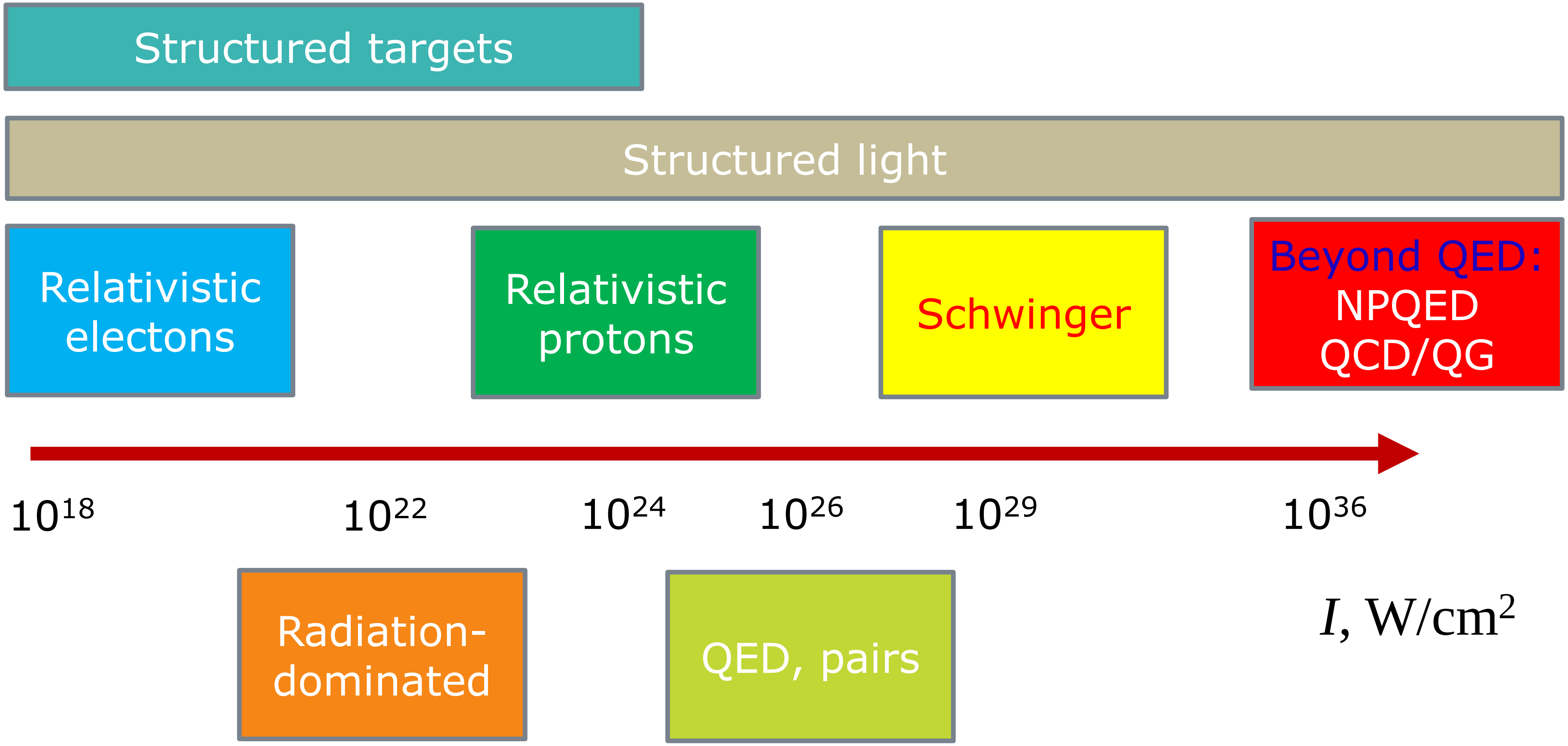


Outline

- **Nanostructured targets:**
  - relativistic plasma nano-photonics
- **Relativistic nano-pinch**
- **Ultra-High Energy Density and Terabar pressures**
- **Structured light with orbital moment: attosecond electron bunches**
- **Energy conversion channels in QED regime**
- **Path beyond QED: non-perturbative regime $\alpha\chi^{2/3}>1$**

New physics at high intensities



Structured targets

Structured light

Relativistic electons

Relativistic protons

Schwinger

Beyond QED: NPQED QCD/QG

10^{18} 10^{22} 10^{24} 10^{26} 10^{29} 10^{36}

I, W/cm^2

Radiation-dominated

QED, pairs

Structured plasmas:
Relativistic plasma nano-photonics

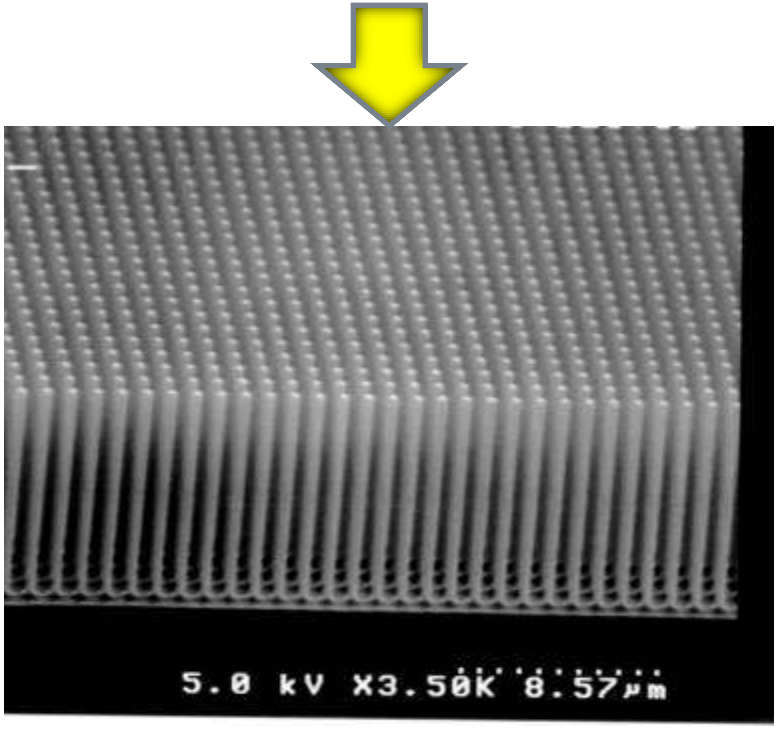
Purvis et al. *Nature Photonics* (2013)

“**Nanograss**”:
array of nanowires.

Structured material
of high average density

- What is the absorption mechanism?
- Is it a way to create
  high density hot plasma?
- What is the optimal structure?
- New nonlinear physics

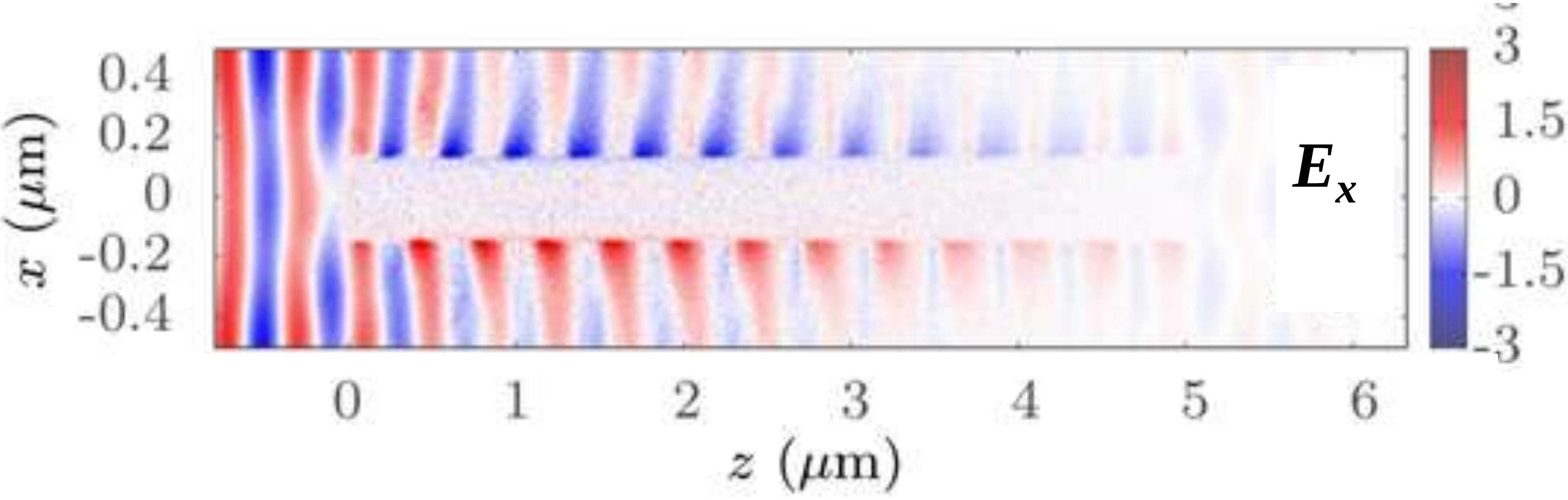
Laser, $10^{18} \ldots 10^{22}$ W/cm^2



RAC Nanotech LLC

Laser wave propagation inside the nanowire array

The head of a 400nm laser pulse penetrating the nanowire array



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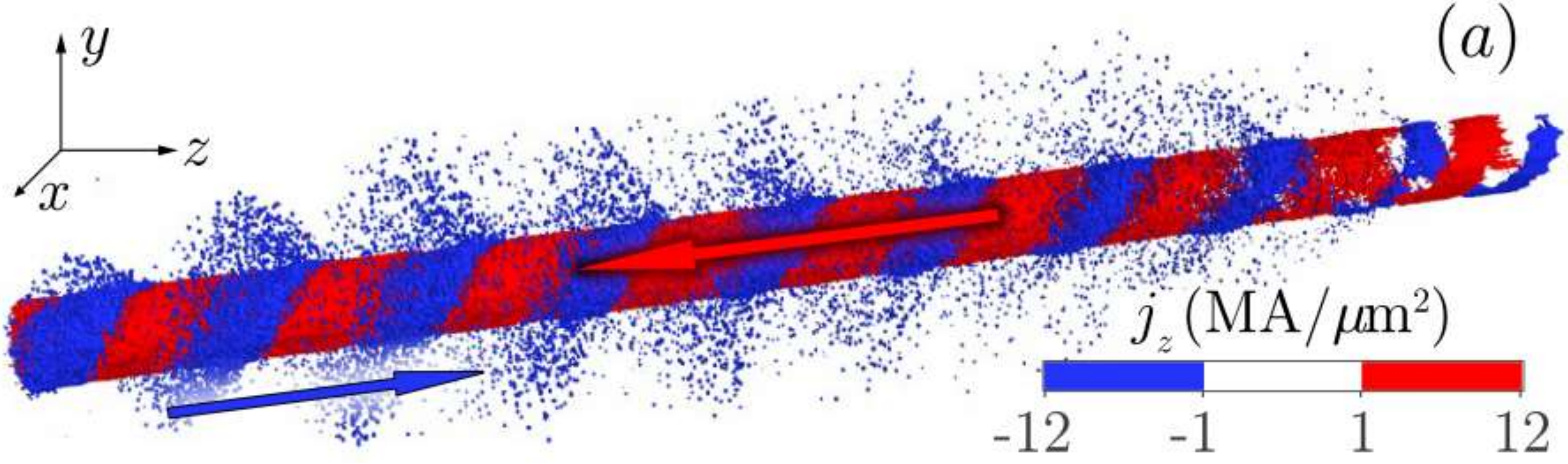
Kaymak et al, PRL **117**, 035004 (2016)

Nanoscale Ultradense Z -Pinch

Longitudinal current distribution



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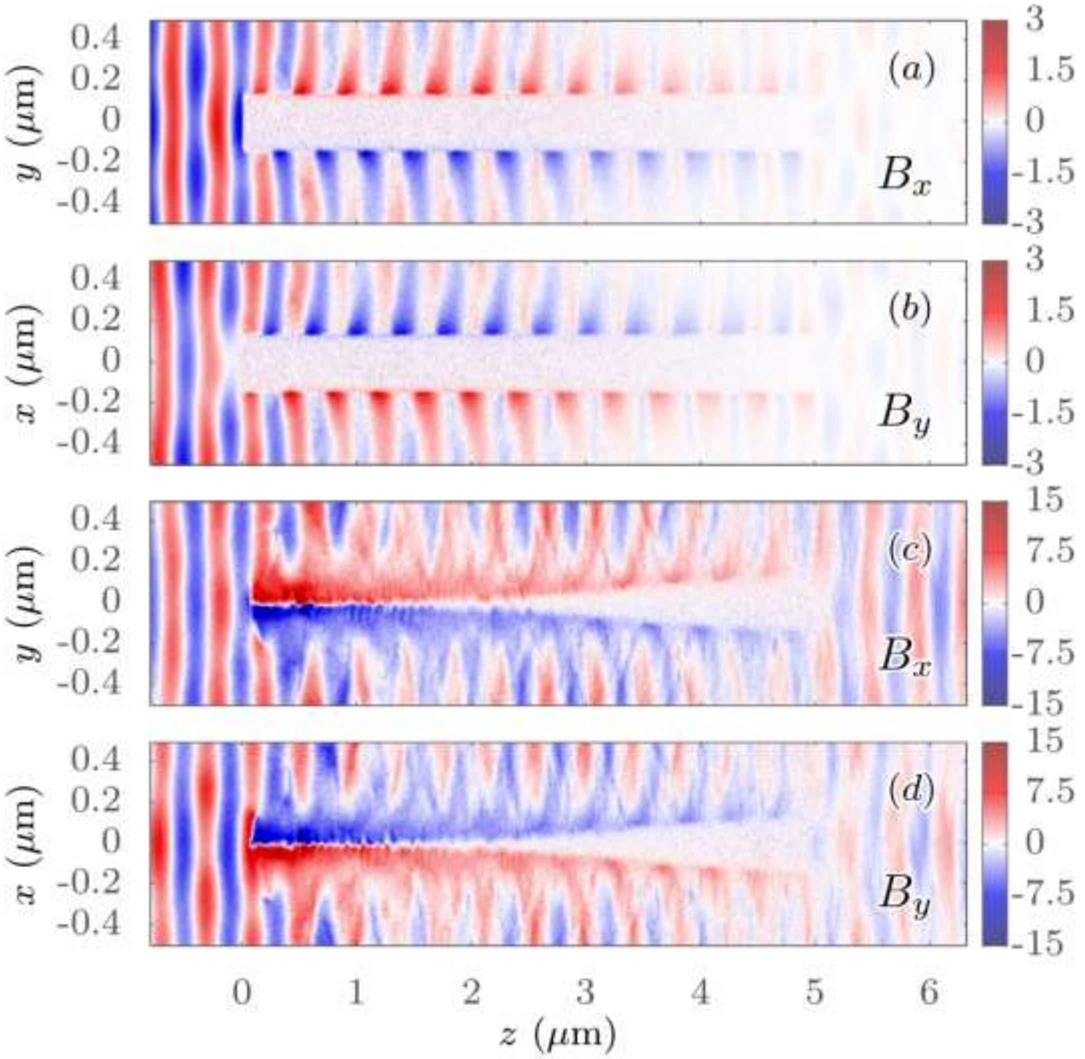
Kaymak et al, PRL **117**, 035004 (2016)

Nanoscale Ultradense Z-Pinch

The quasistatic B-field around the nanorods is larger than the laser field

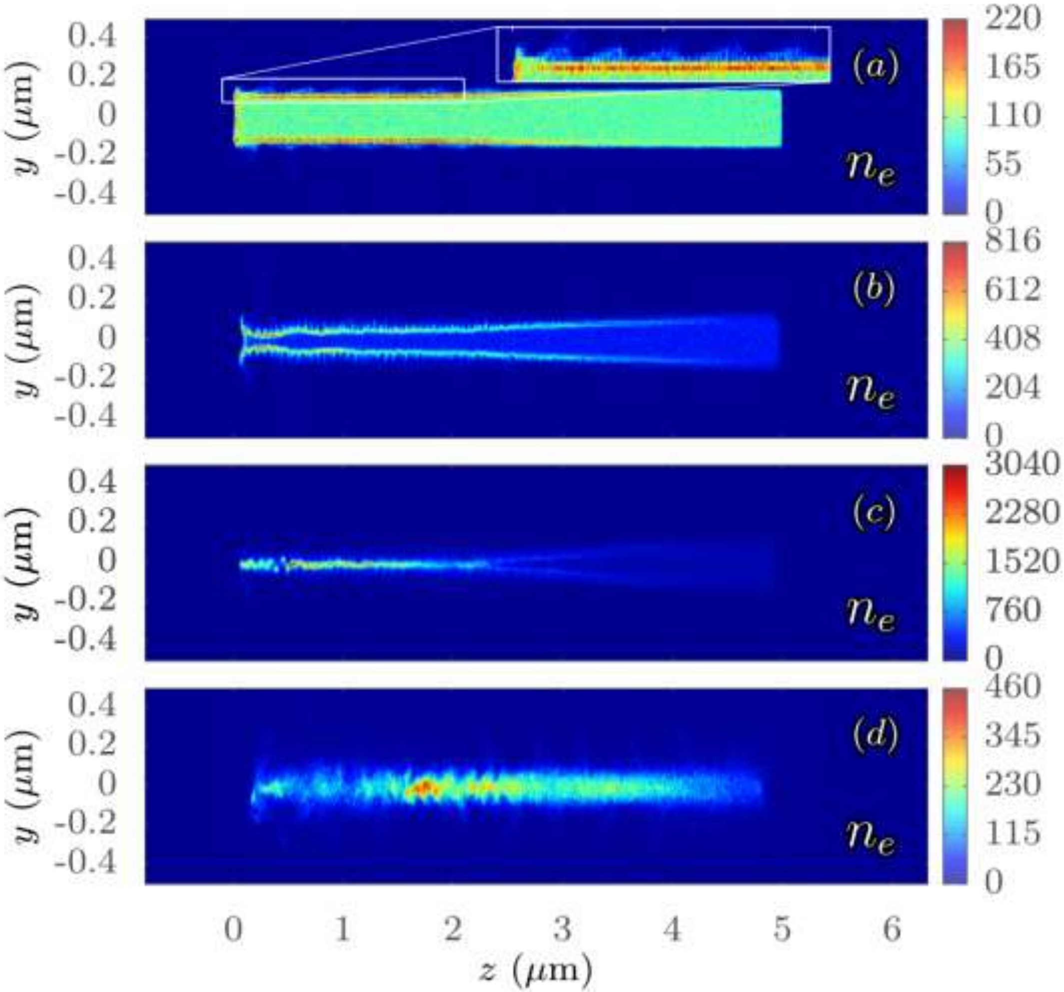
B **> 150 kT**

eB/mcω **= 15**



Kaymak et al, PRL **117**, 035004 (2016)

Nanoscale Ultradense Z -Pinch



Evolution of electron density

Passage through the pinch

Bargsten et al, *Science advances 3 (1), e1601558* (2017)

Ultra-High Energy Density Plasmas

Arrays of nanowires allow for high density high temperature plasmas

Can we scale it to Terabar Pressures near thermal equilibrium?

What is the possible energy density?

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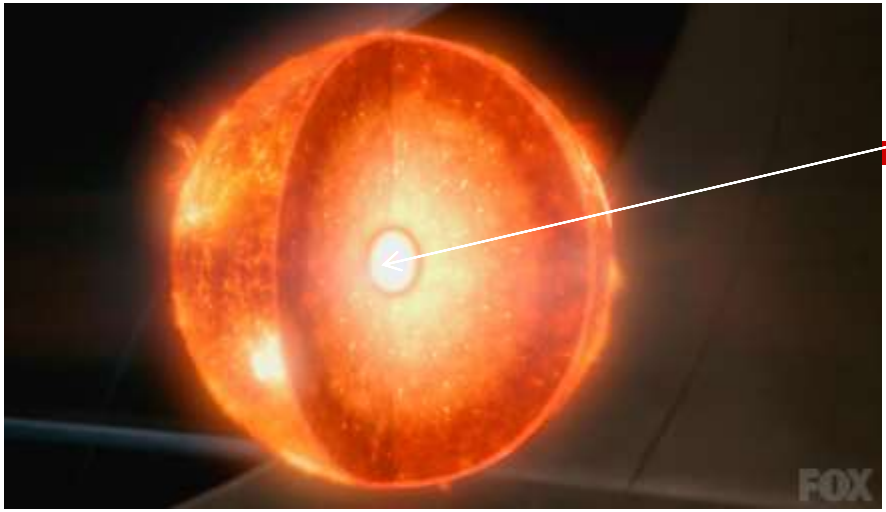
Path to Extreme pressures by irradiation of aligned nanowire arrays

Rocca et al. LASER FOCUS WORLD 53 (5), 21-26 (2017)

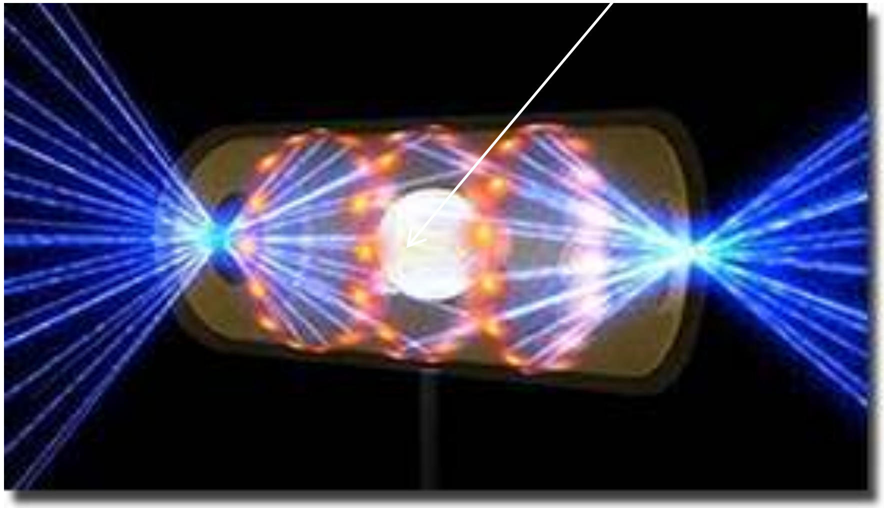


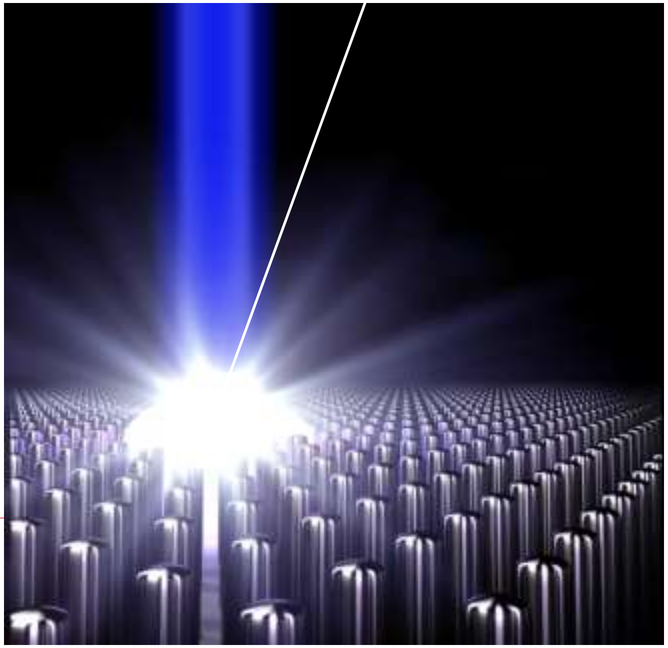
Sun Core
240 Gbar

Nanowire array plasma

$I = 1 \times 10^{22}$ W cm^{-2}

NIF Implosion
150 Gbar





R Hollinger, et al., Optica **4**, 1344 (2017)

Ultra-High Energy Density Plasmas for efficient picosecond X ray sources

Required conditions:

Hydrodynamic confinement time longer than radiative cooling time:
$T_{\mathrm{conf}} > T_{\mathrm{cool}}$

Fast thermal equilibration:
$T_{\mathrm{conf}} > T_{\mathrm{equil}}$

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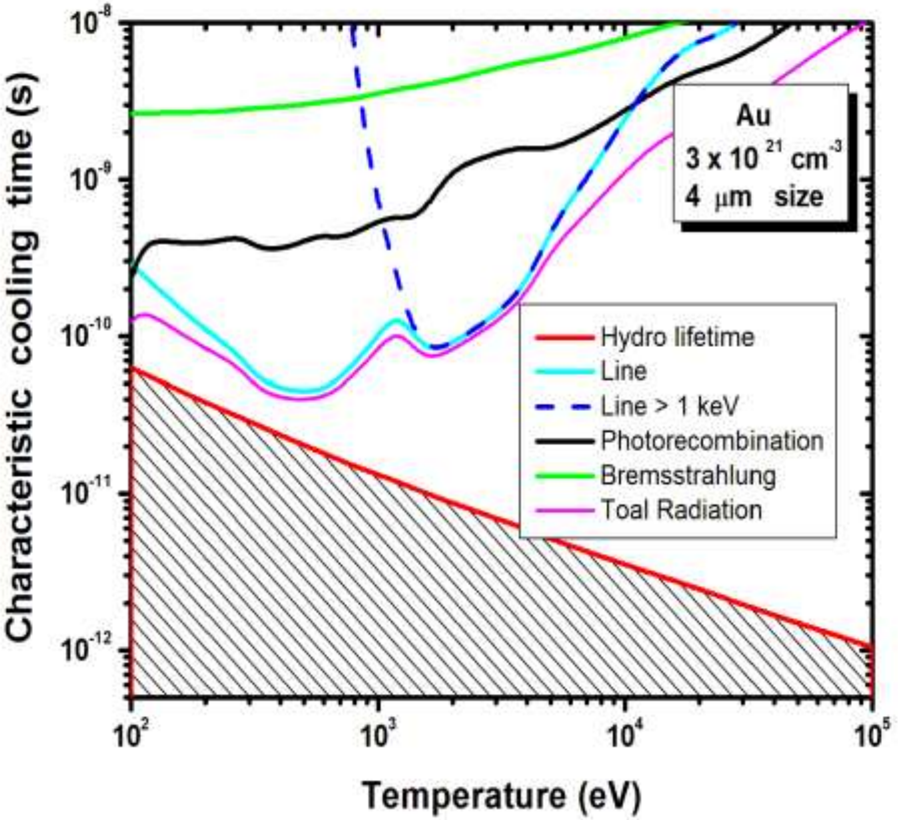
R Hollinger, et al., Optica **4**, 1344 (2017)

Lifetimes of plasma at the critical density for 400nm light



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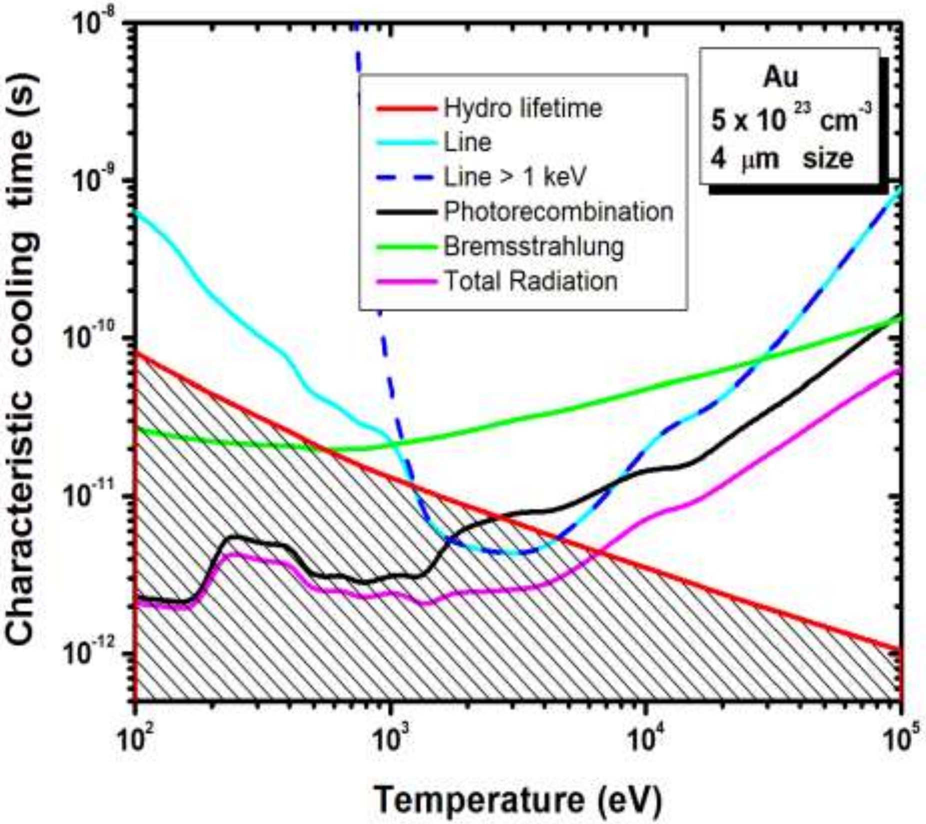
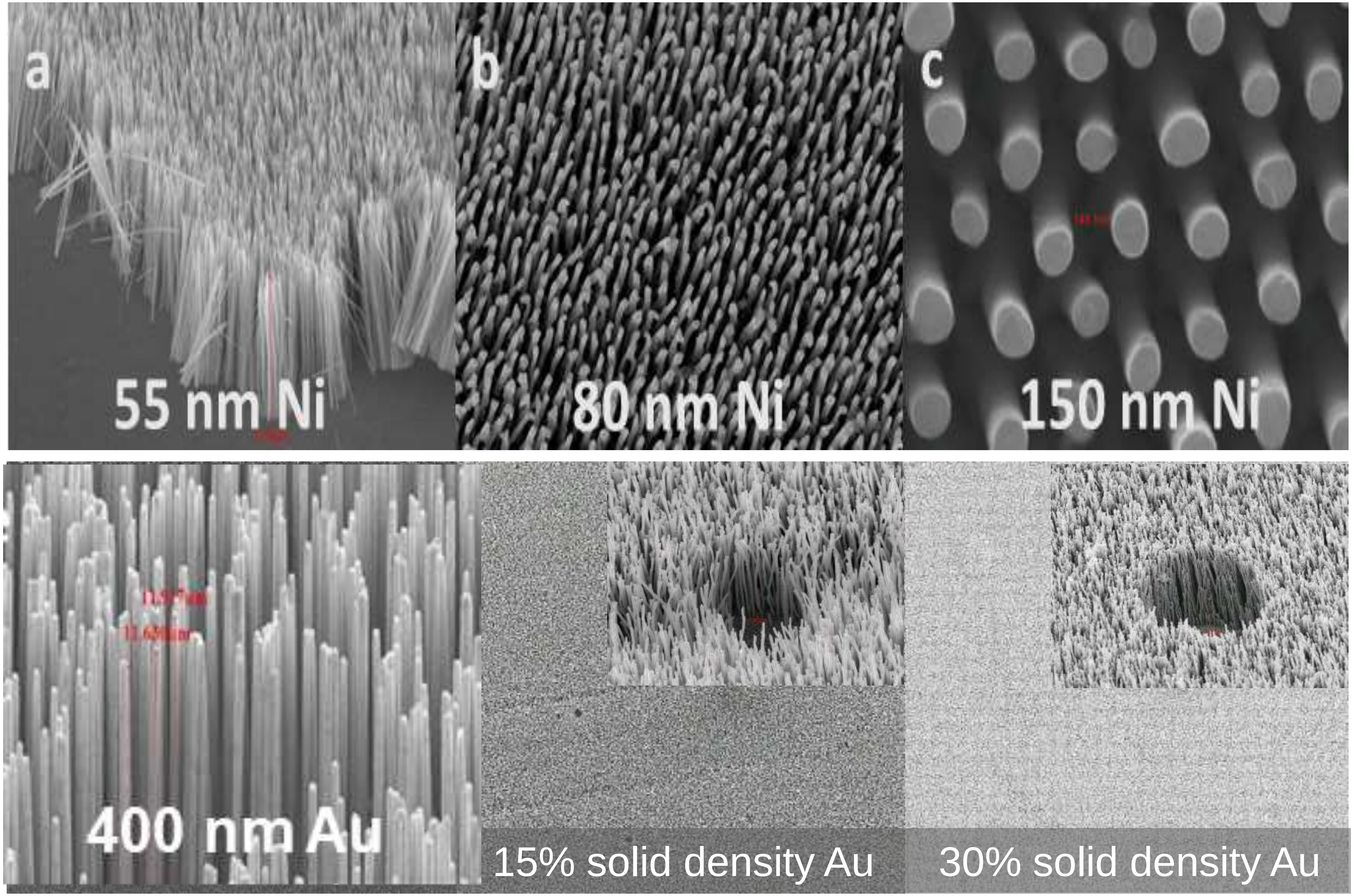
R Hollinger, et al., Optica **4**, 1344 (2017)

Lifetimes of plasma at 100x n_c for 400nm light



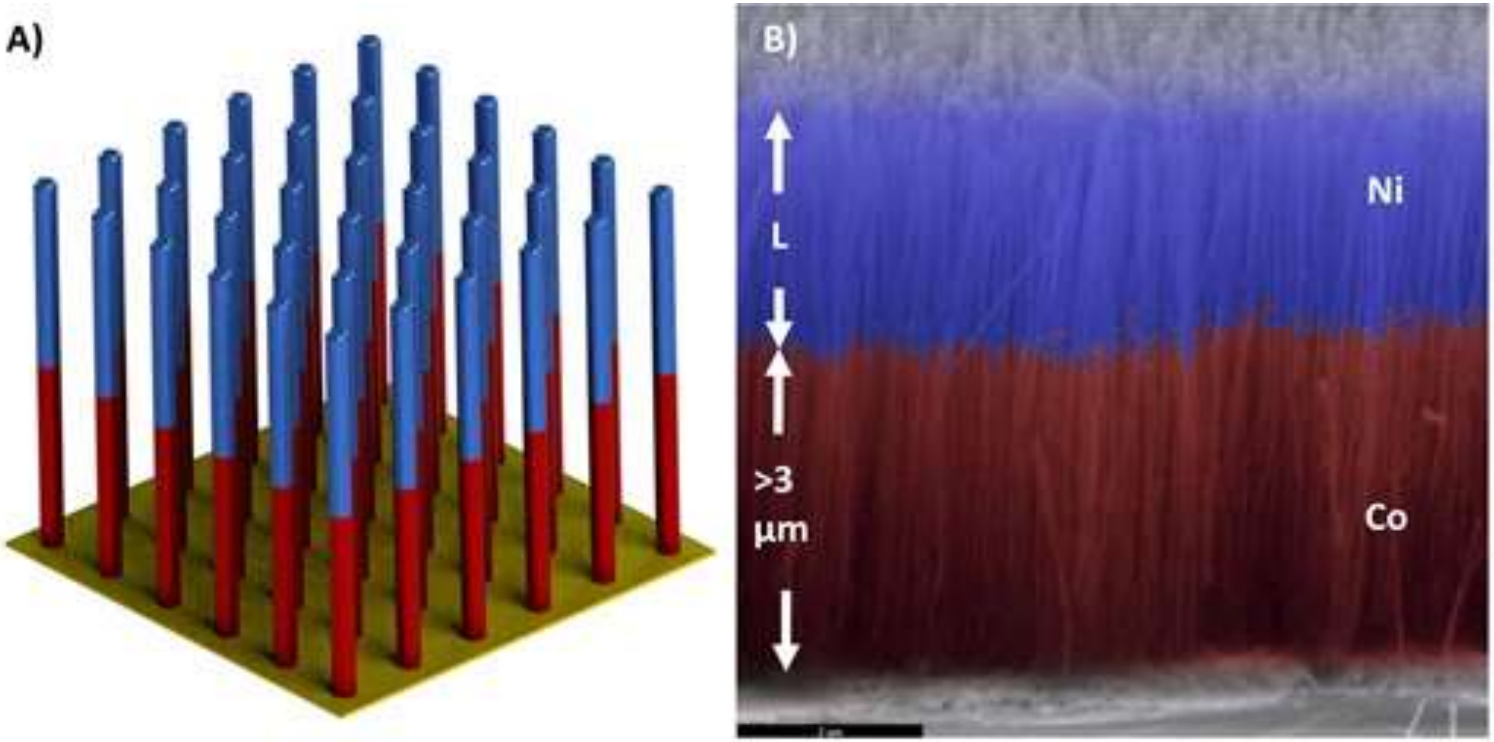
Nanowire array SEM Images



Bargsten et al, *Science advances 3 (1), e1601558* (2017)

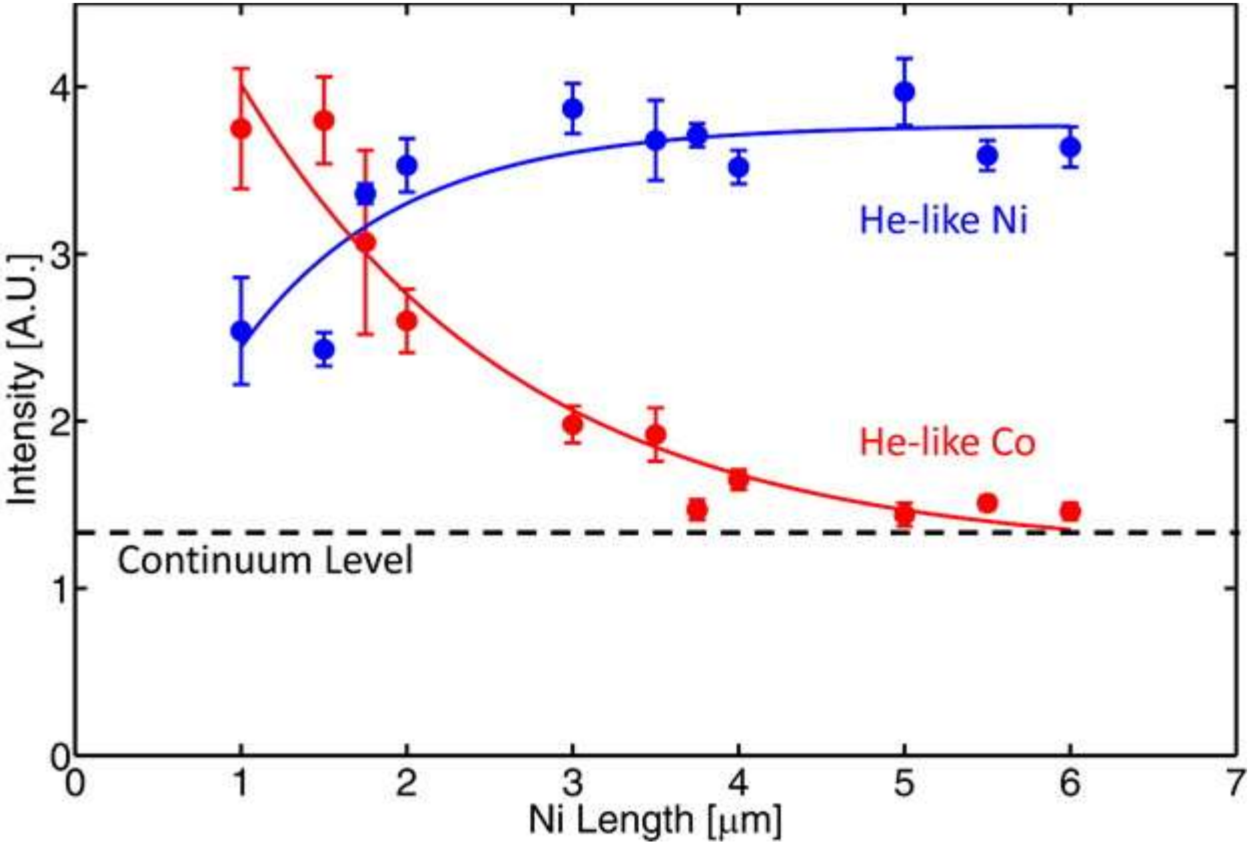
Ultra-High Energy Density Plasmas

Experiment at Colorado State University with composite nanowire arrays



Bargsten et al, *Science advances 3 (1), e1601558* (2017)

Ultra-High Energy Density Plasmas



Measured intensities of the He-like Co and He-like Ni lines as a function of the Ni length

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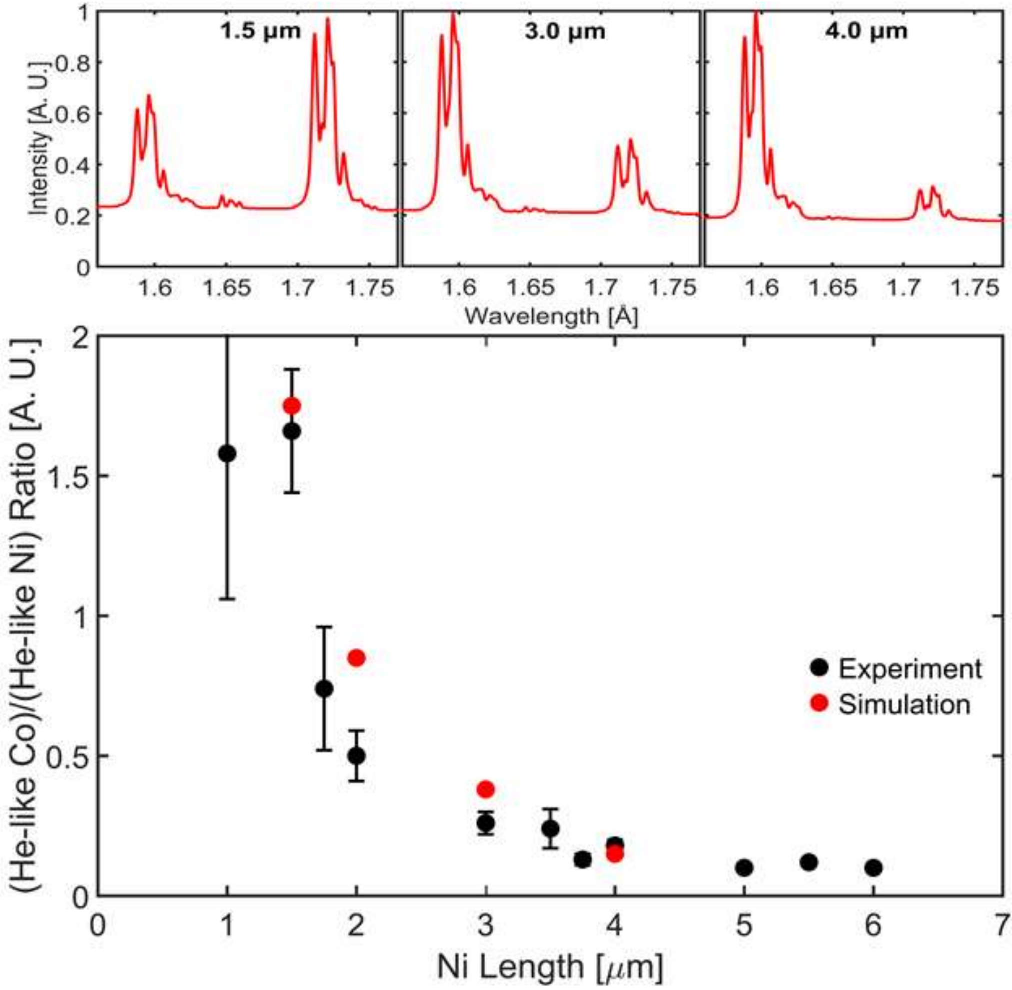
Bargsten et al, *Science advances 3 (1), e1601558* (2017)

Ultra-High Energy Density Plasmas



Simulated spectra corresponding to arrays with different wire lengths used in the experiment

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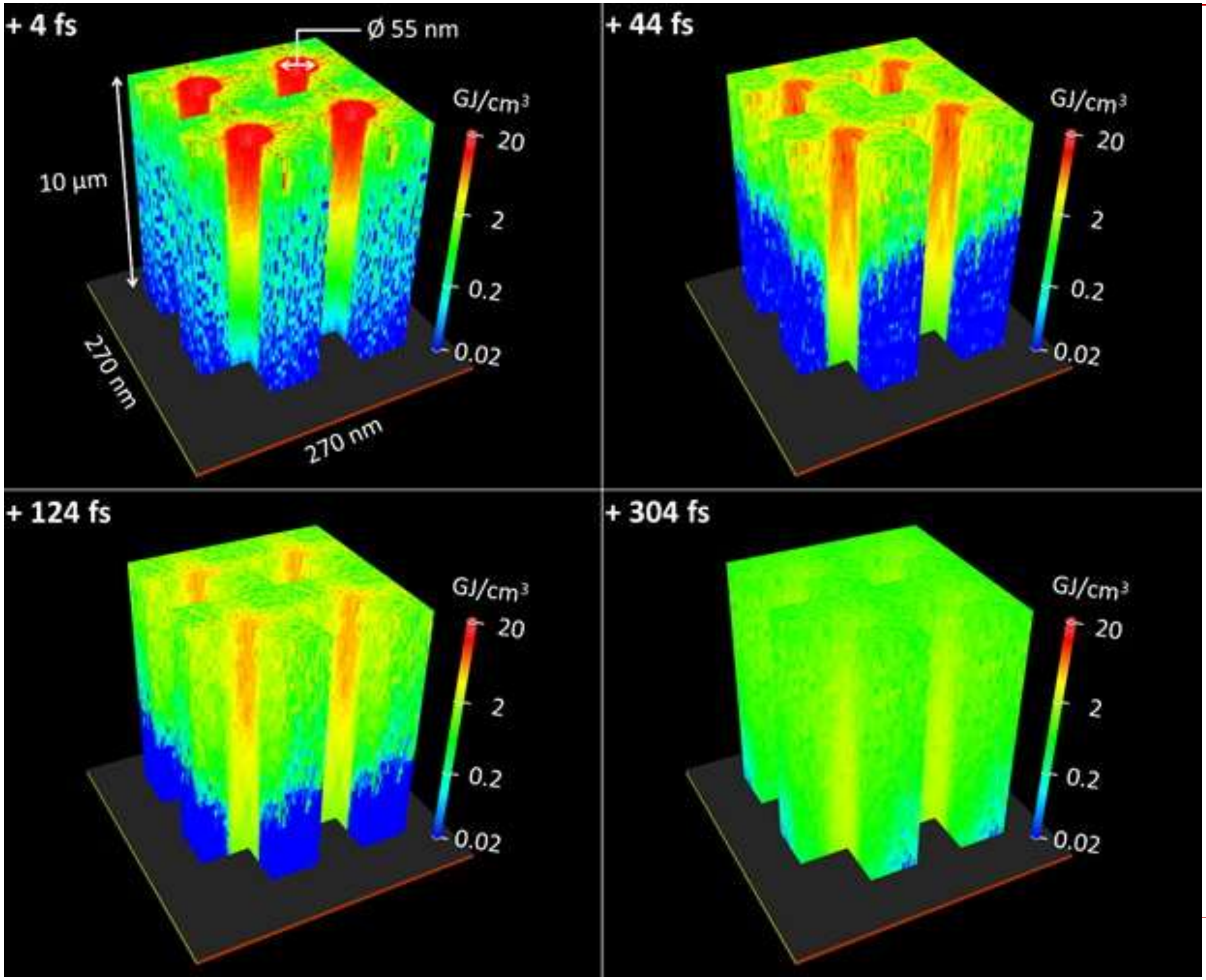
Bargsten et al, *Science advances 3 (1), e1601558* (2017)

Ultra-High Energy Density Plasmas

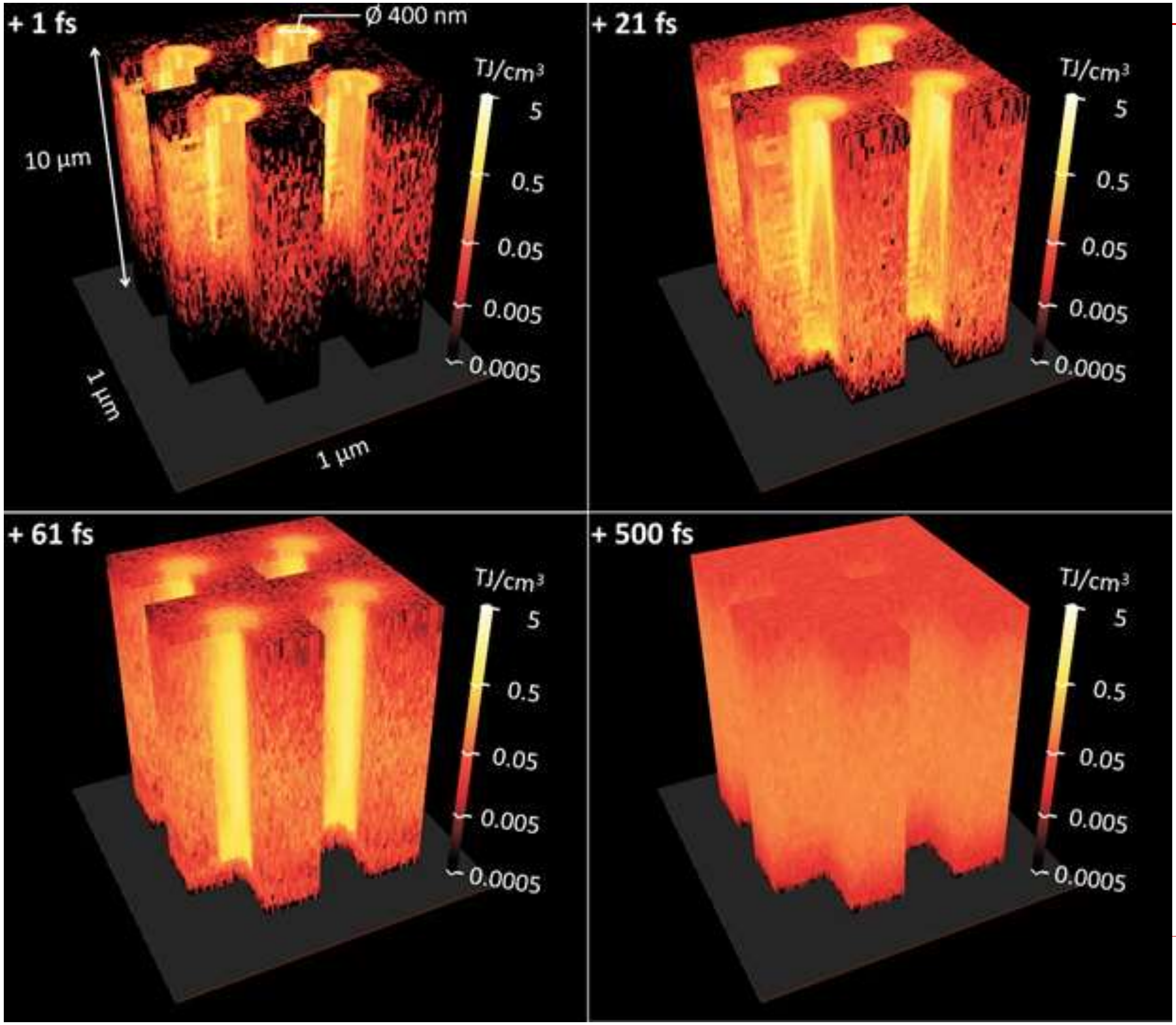


Energy density distribution computed by PIC simulation

Fast homogensation

Bargsten et al, *Science advances 3 (1), e1601558* (2017)

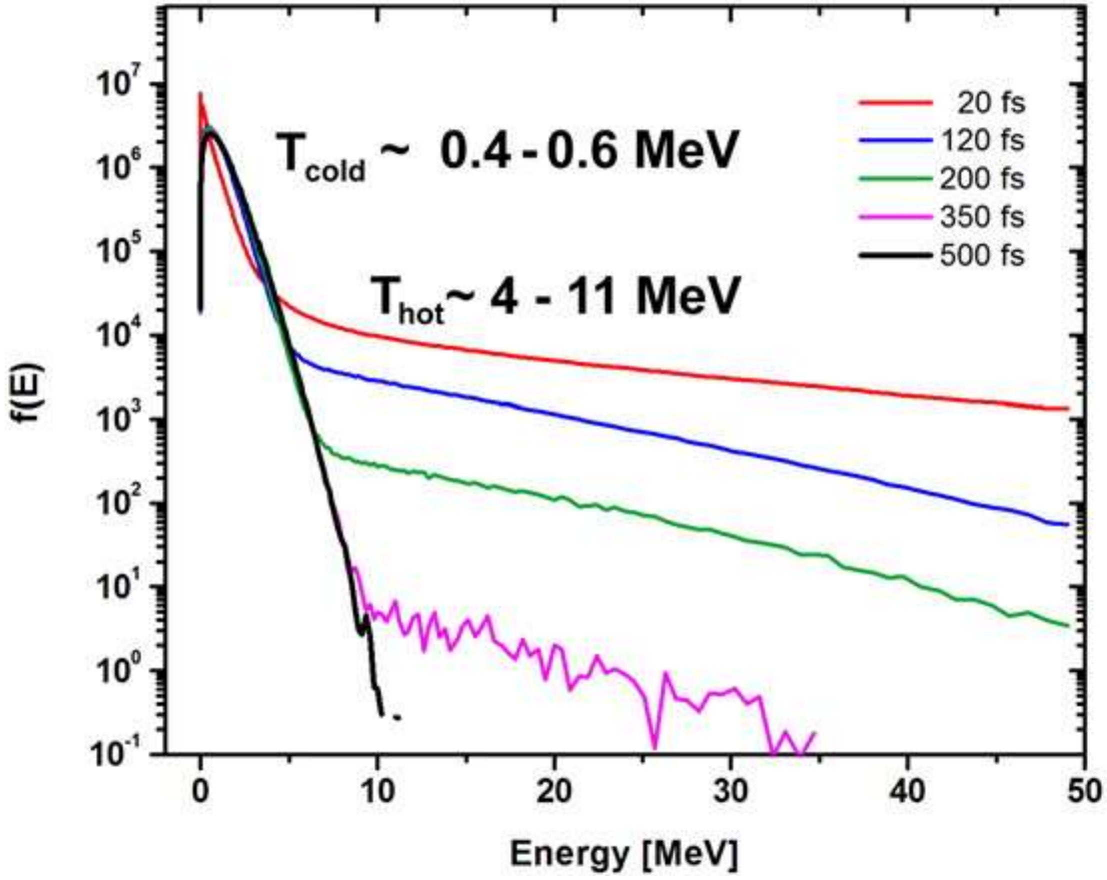
Ultra-High Energy Density Plasmas



PIC simulated energy density distribution in an array of vertically aligned **Au nanowires** of **400 nm diameter** irradiated with an intensity of **1×10^{22} W cm^{-2}** (**$a_0 = 34$**) using a 400 nm wavelength pulse of 30 fs duration.

Bargsten et al, *Science advances 3 (1), e1601558* (2017)

Ultra-High Energy Density Plasmas



Rapid thermalization seen in electron distribution function

PIC simulated array of vertically aligned **Au nanowires** of **400 nm diameter** irradiated with an intensity of **1 x 10^{22} W cm^{-2}** (**a_0= 34**) using a 400 nm wavelength pulse of 30 fs duration.

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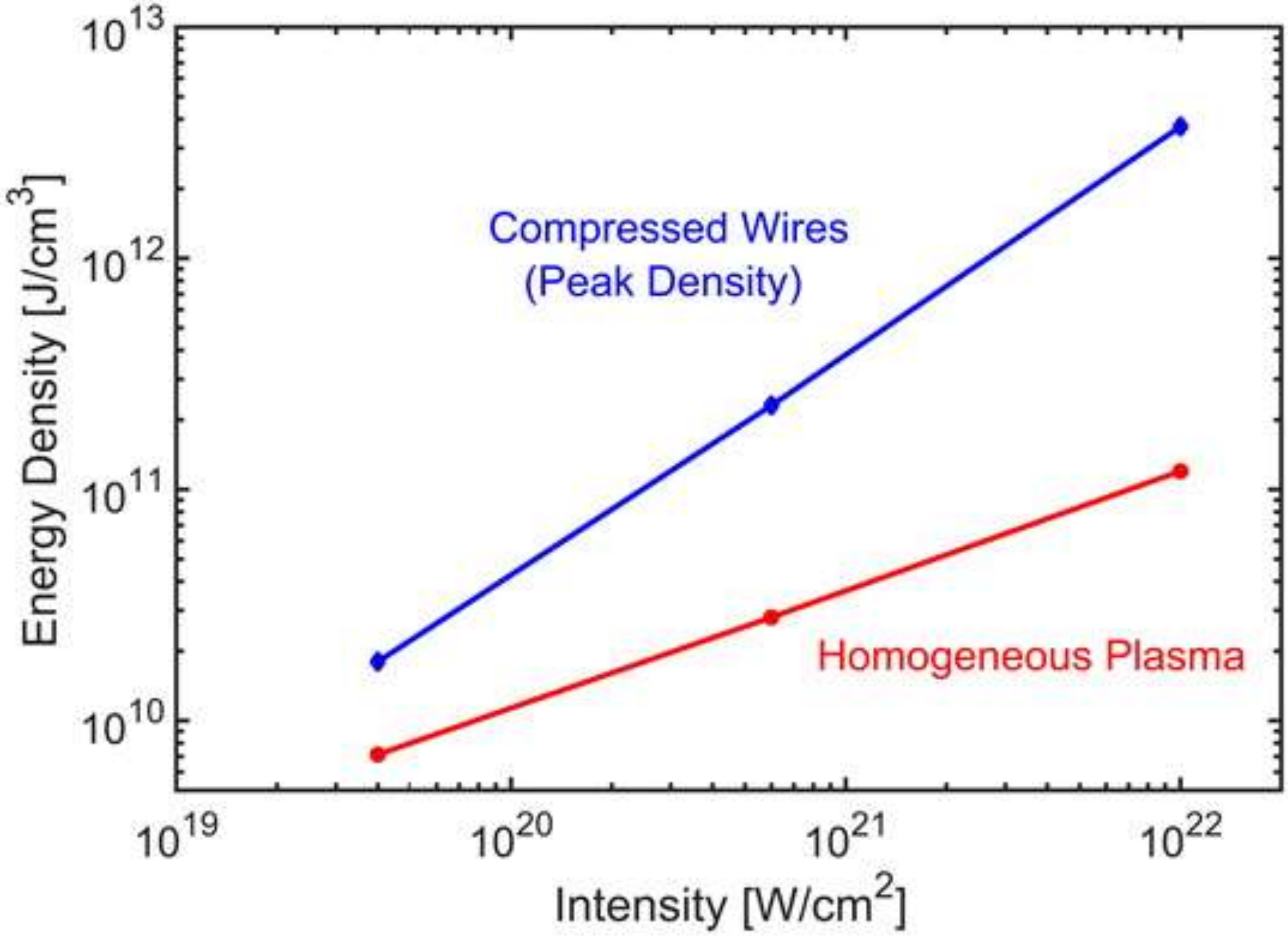
Bargsten et al, *Science advances 3 (1), e1601558* (2017)

Ultra-High Energy Density Plasmas

UHED scaling



Curtis et al, *Nature Comm*, **9**, 1077 (2018)

Average particle energy in nanowire array plasmas

Assuming total laser energy absorption
and volumetric heating of the target,
the average energy per particle can be estimated to be:

$$E_{av}\approx \frac{{a_0}^2}{2} mc^2 \frac{n_c}{n_{av}} \frac{Z}{(Z+1)} \frac{c\tau}{L}$$

where $n_c = m\omega_0^2/4\pi e^2$ is the critical electron density, τ is the laser pulse duration and L is the absorption depth in the target with the average particle density n_{av} , Z is the ionization charge state.

For the conditions of the experiments

a_0~3.3, λ = 400 nm, n_{av}=0.2n_{solid} , T= 55 fs, and L~ 5 µm

E_{av} can be calculated to be ~ **0.6 MeV**.

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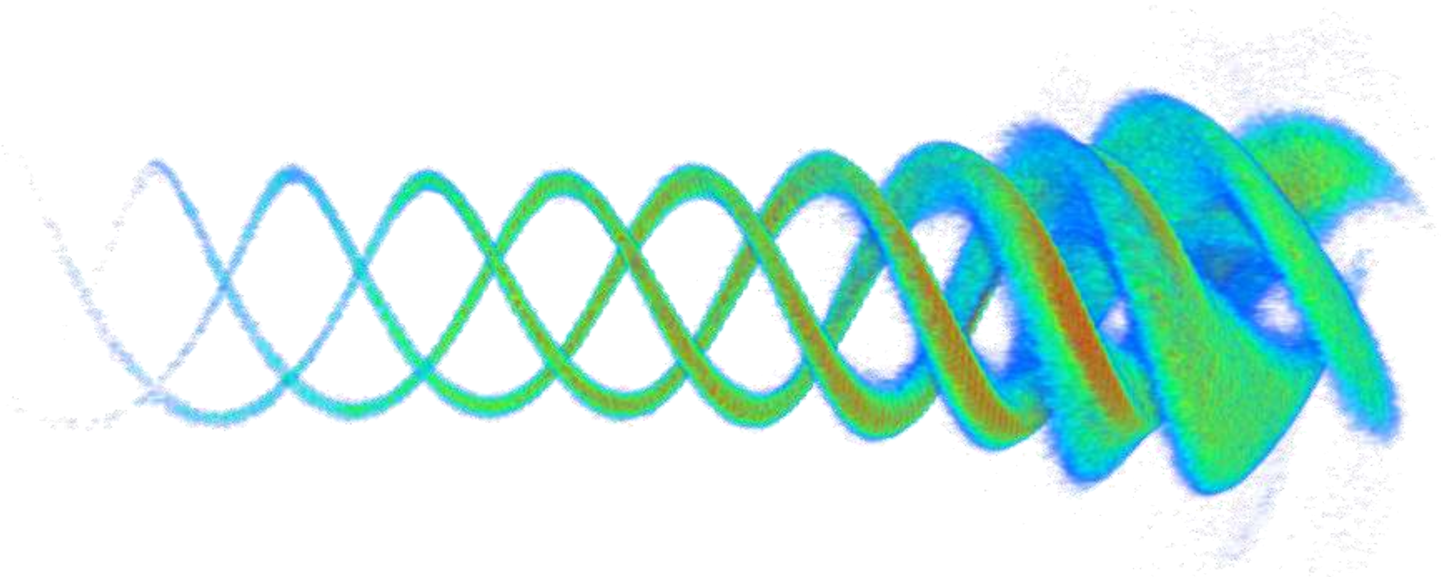
Laser pulses and electron bunches with orbital momentum

Structured light



Baumann & Pukhov, Physics of Plasmas 25, 083114 (2018)

Structured light:
Laser pulses with orbital momentum

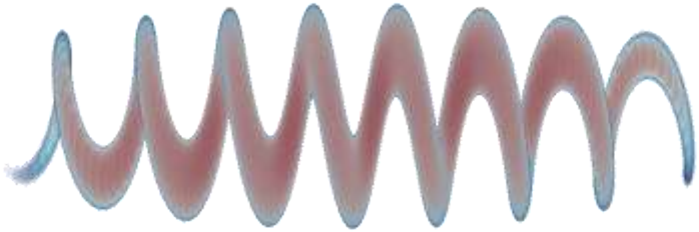
Laguerre-Gaussian pulses are twisted

$$\begin{aligned}\mathbf{E}_{\perp} = {} & a_0 C_p^{|m|} \frac{w_0}{w(z)} \left(\frac{\sqrt{2}r}{w(z)}\right)^{|m|} L_p^{|m|}\left(\frac{2r^2}{w^2(z)}\right) \\ & \times \exp\left[-\frac{r^2}{w^2(z)} - \frac{(z-ct)^2}{2\tau^2}\right] \\ & \times \exp\left[i(\omega_0 t - k_0 z - m\varphi) + i\phi_p^{|m|}(r,z)\right] (i\hat{\mathbf{e}}_x + s\hat{\mathbf{e}}_y),\end{aligned}$$

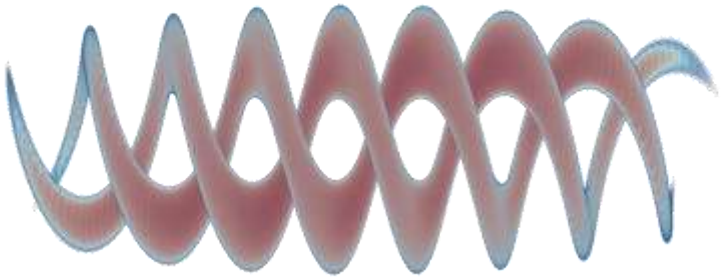
Baumann & Pukhov, Physics of Plasmas 25, 083114 (2018)

Structured light:
Laser pulses with orbital momentum

Phase fronts of Laguerre-Gaussian pulses



p=0, m=-1



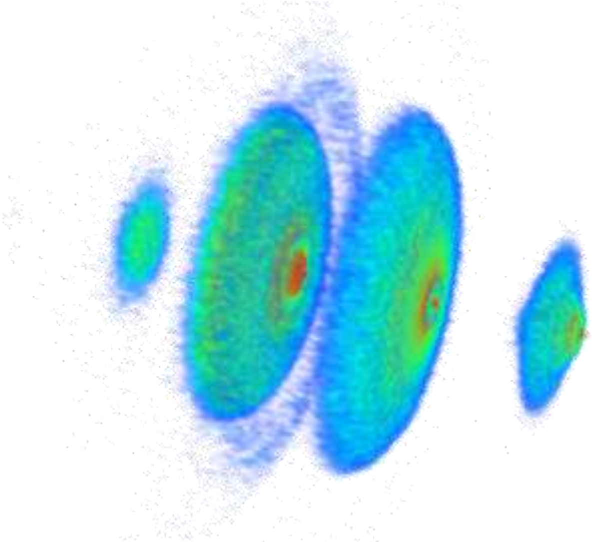
p=0, m=-2

Baumann & Pukhov, Physics of Plasmas 25, 083114 (2018)

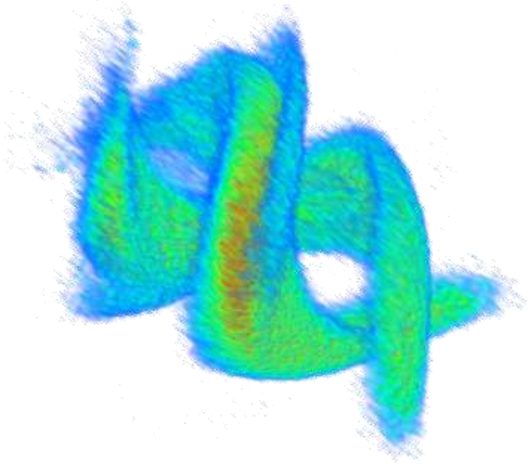
Structured electron bunches with orbital momentum

Left- vs righthand polarization in LG pulses

$$\exp\left[i(\omega_0 t - k_0 z - m\varphi) + i\phi_p^{|m|}(r,z)\right]\left(i\hat{\mathbf{e}}_x + s\hat{\mathbf{e}}_y\right)$$



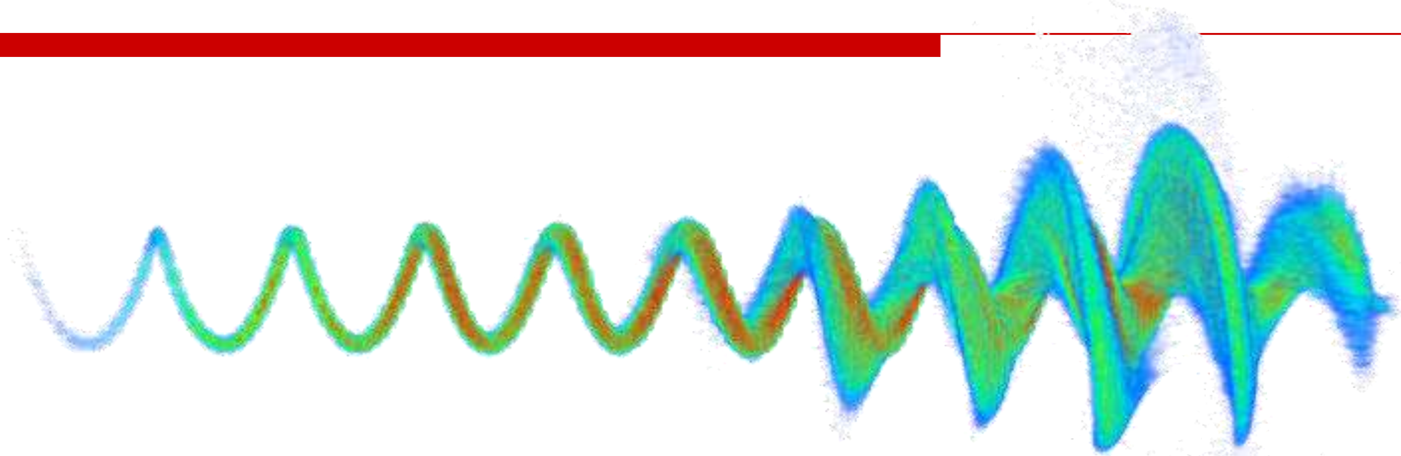
p=0, m=-1, s=1



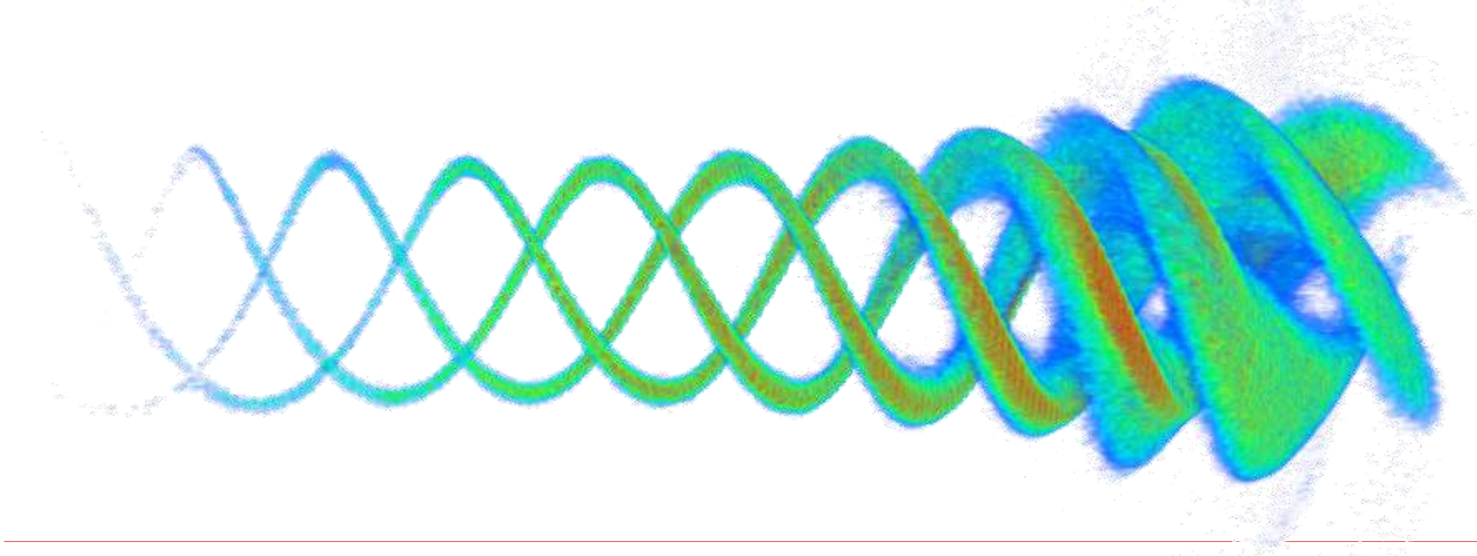
p=0, m=-1, s=-1

Baumann & Pukhov, Physics of Plasmas 25, 083114 (2018)

Structured electron bunches:
Laser pulses with orbital momentum



p=0
m=-2
s=1



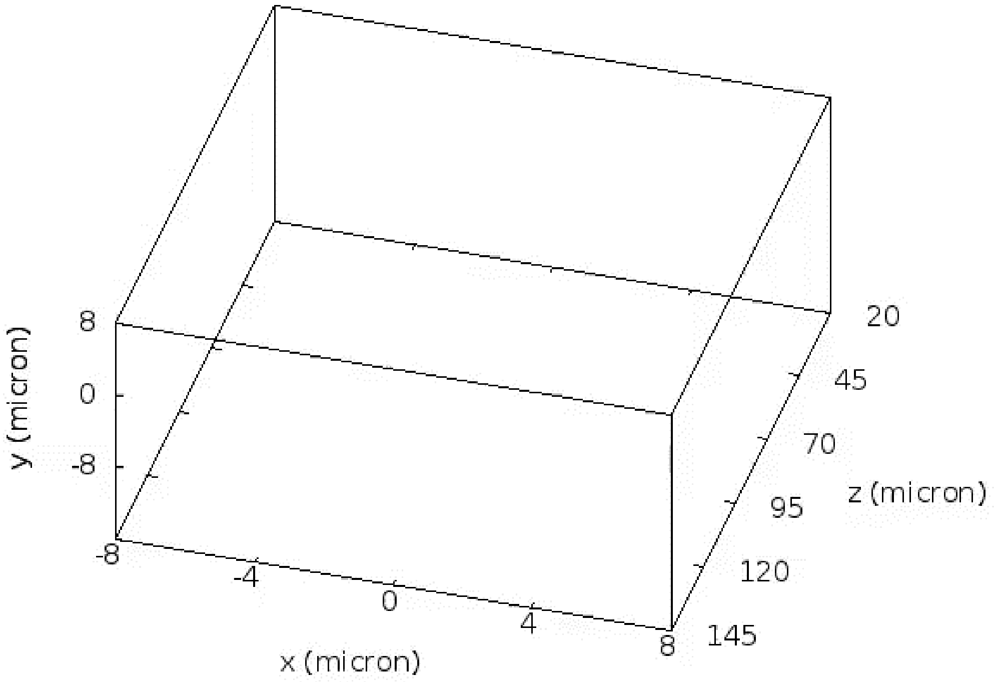
p=0
m=-2
s=-1

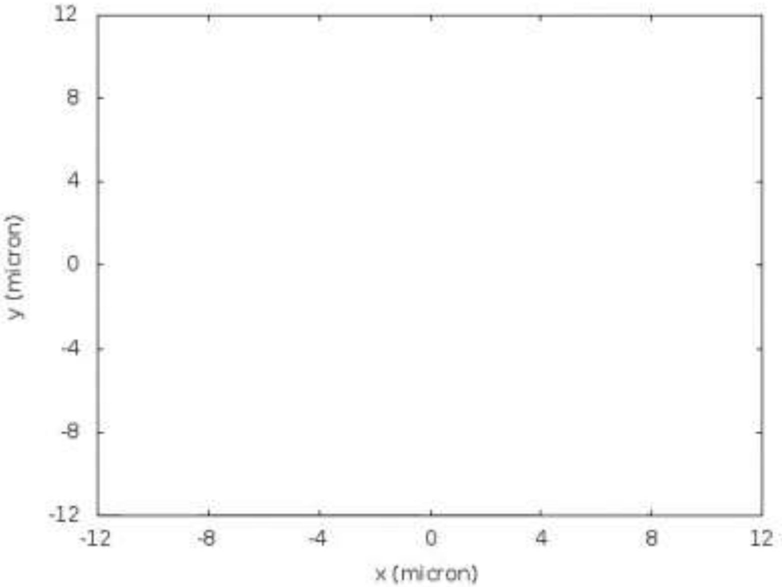
Baumann & Pukhov, Physics of Plasmas 25, 083114 (2018)

Structured electron bunches:

Laser pulses with orbital momentum

p=0 m=-2 s=-1





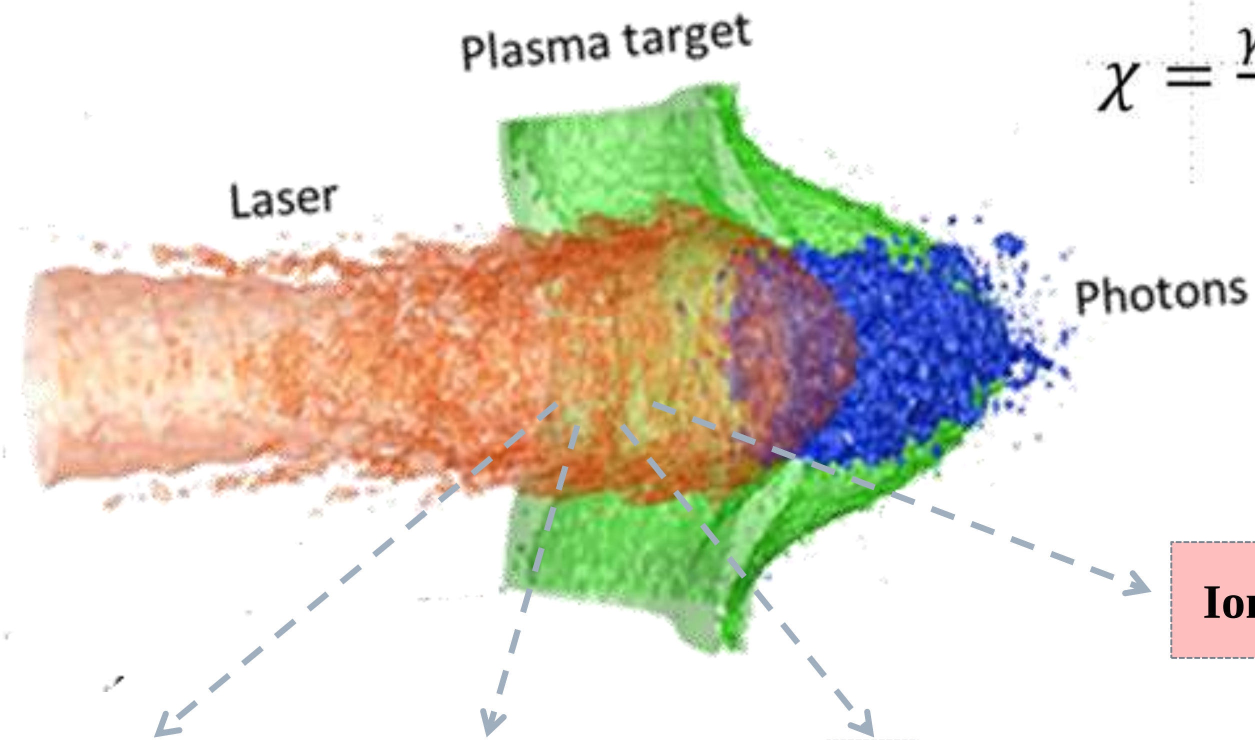
$I > 10^{23}$ W/cm^2

QED

ELI, iZEST, iCAN, XCELS:

Laser-plasma interaction in the near-QED regime, $I > 10^{23}$ W/cm².

$$\chi = \frac{\gamma E \sin\theta}{E_{crit}}$$



Ion

e^- → Laser field → γ-photon → Laser field → e^+ → γ-photon

e^- → γ-photon

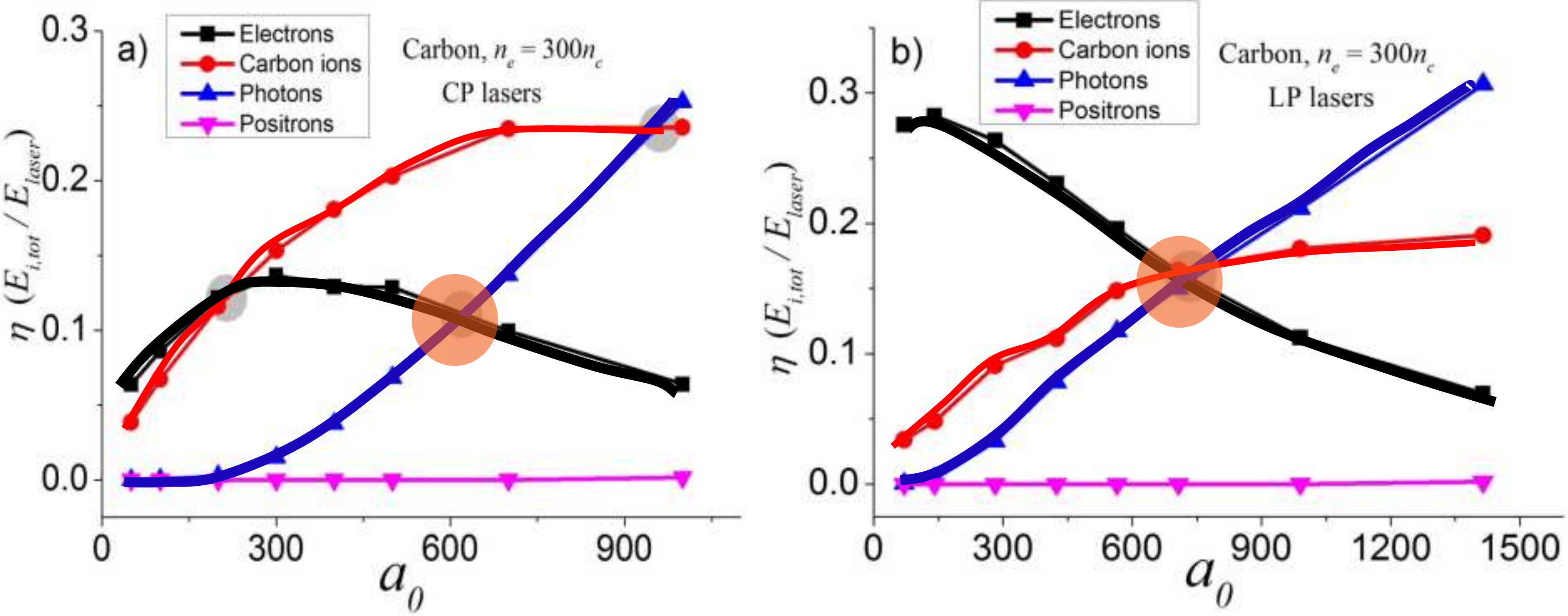
……

L. Ji et al, *Phys. Plasmas*, **21**, 023109 (2014)

Carbon target: absorption channels

CP lasers

LP lasers

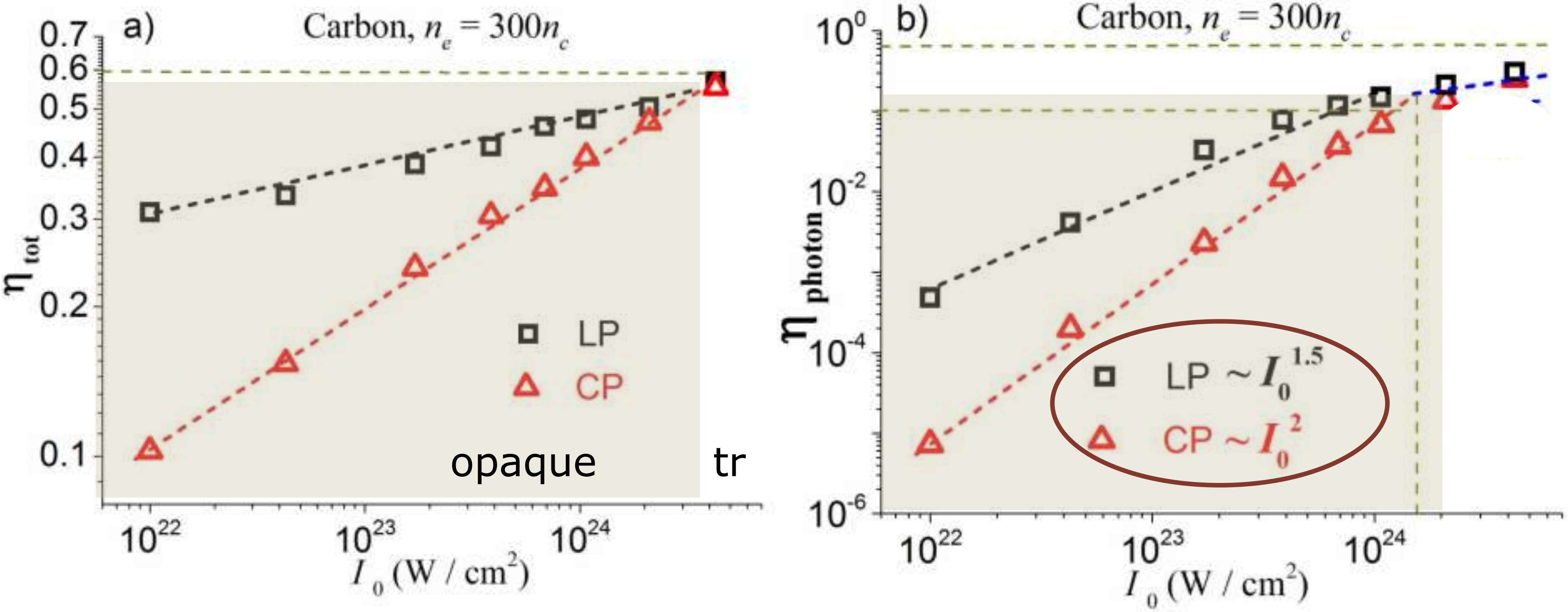


L. Ji et al, *Phys. Plasmas*, **21**, 023109 (2014)

Carbon target: power laws

$$\eta_{tot} = \eta_{e^- + c^{6+} + \gamma + e^+}$$

Power-laws converge at $I_0 > 10^{24}$ W/cm^2



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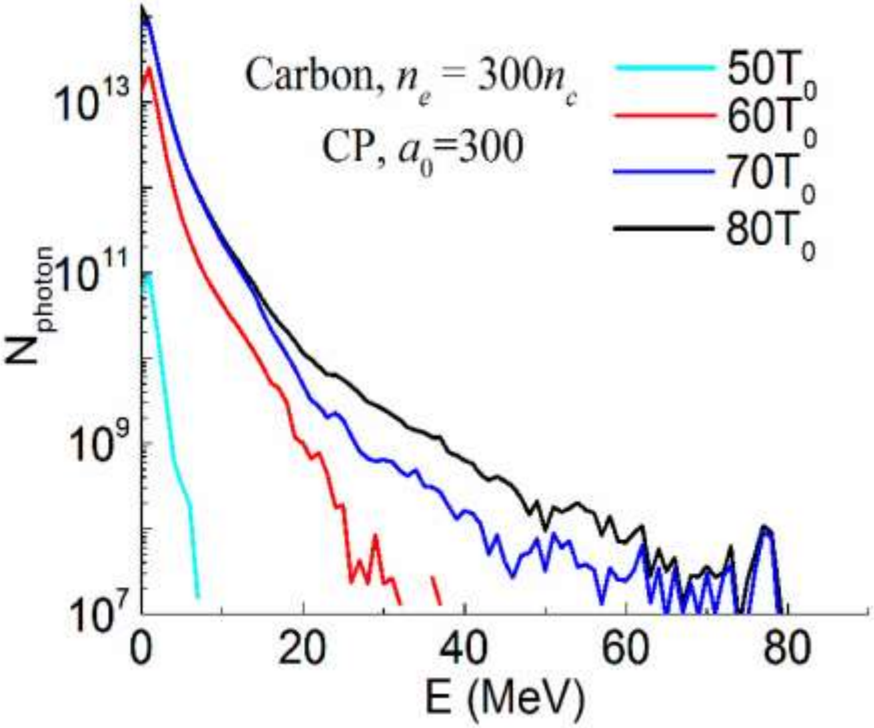
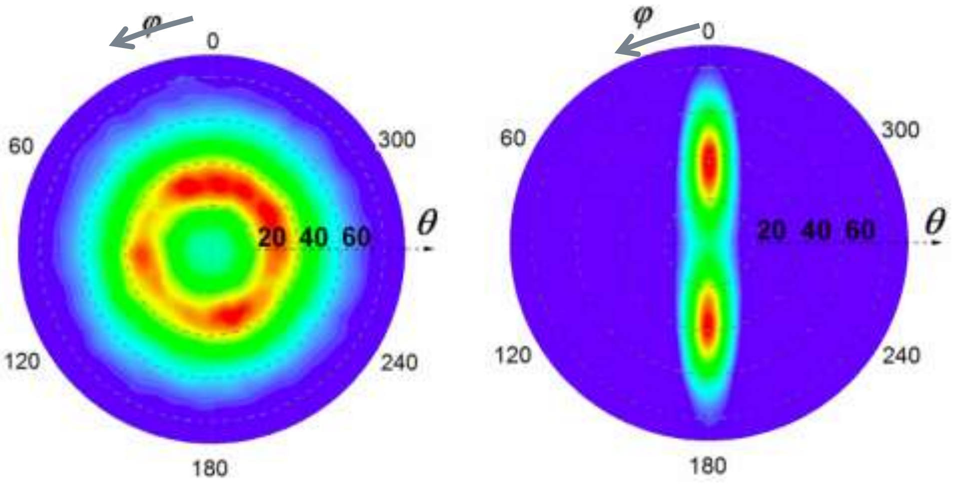
L. Ji et al, *Phys. Plasmas*, **21**, 023109 (2014)

Near-QED regime:
plasma is an efficient γ-ray source

$\eta_{\gamma,\,\max} \sim 35\%$





CP

LP

Radiative trapping

L. Ji et al, PRL **112**, 145003 (2014)

Unexpected:
radiative trapping
in a plasma channel

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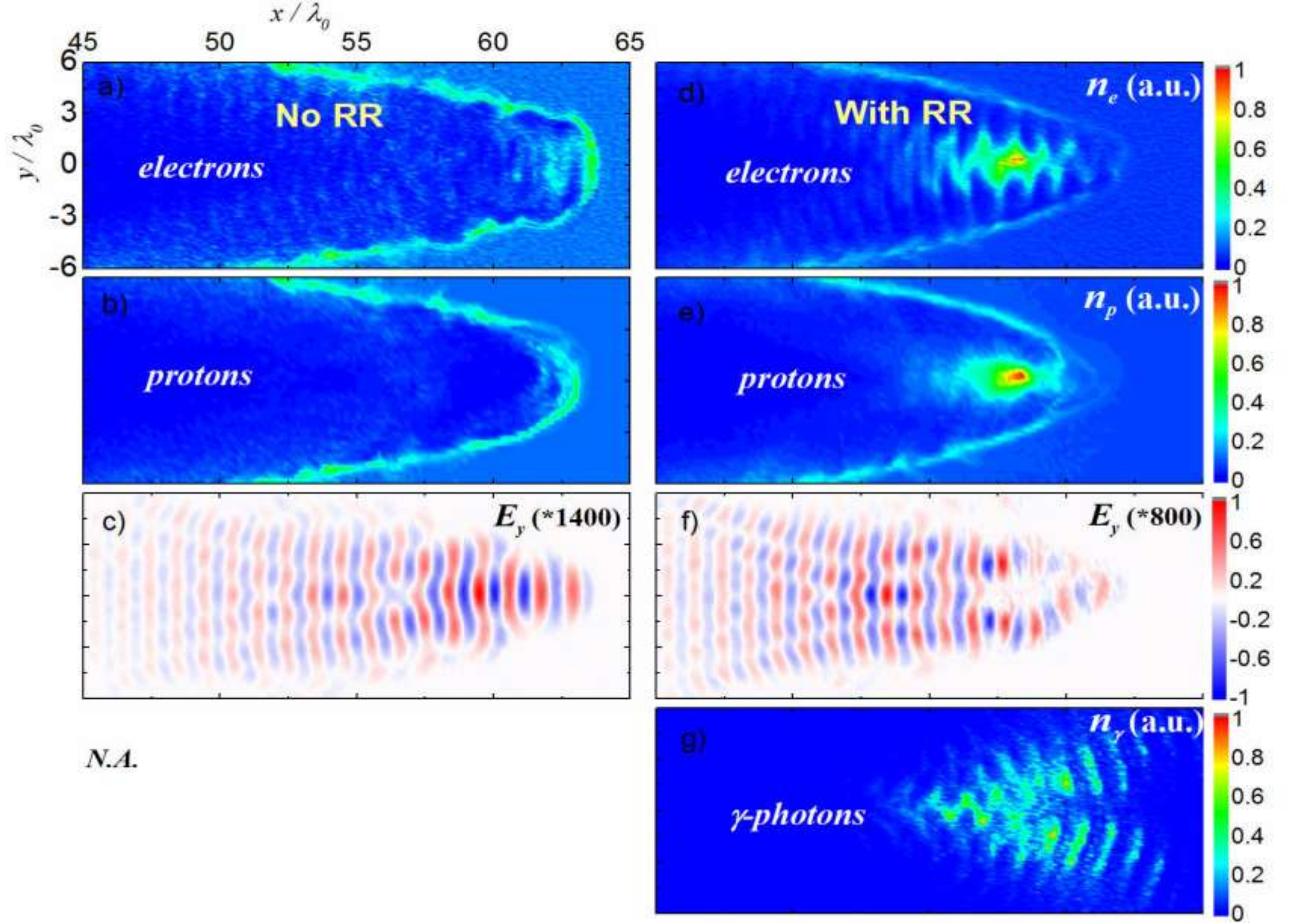
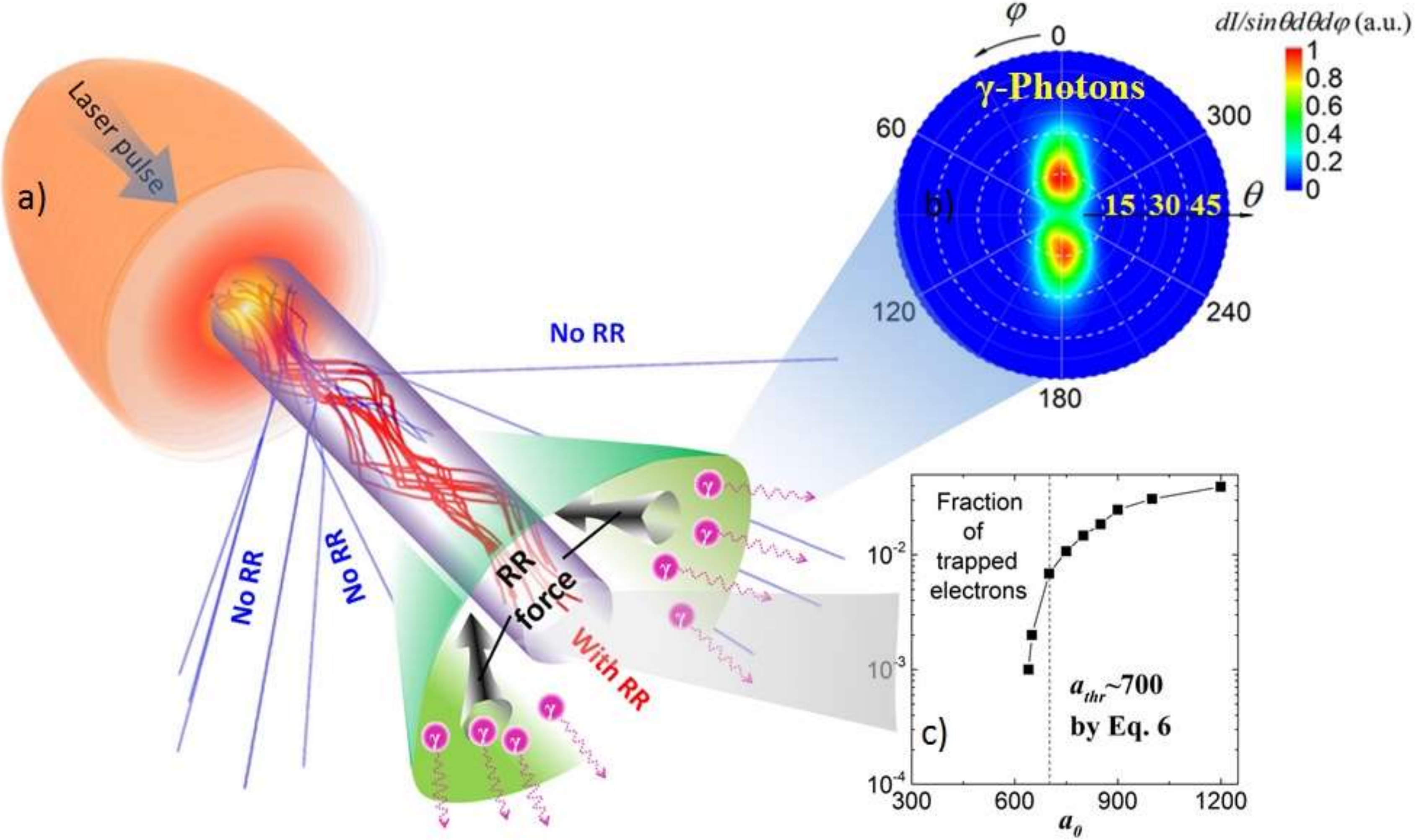
L. Ji et al, PRL **112**, 145003 (2014)

Radiative trapping in a channel



L. Ji et al, PRL **112**, 145003 (2014)

Physics of radiative trapping



$I > 10^{36}$ W/cm^2

Beyond QED

$$\chi > 1600$$

Yakimenko et al. PRL 122, 190404 (2019)

Path beyond QED
Non-perturbative strong field QED:

QED is in excellent agreement with experiment in the perturbative regime $\chi \ll 1$ due to the smallness of the fine structure constant $\alpha = 1/137$

According to Nikishov & Ritus (1972), the actual smallness parameter is $\alpha\chi^{2/3}$
No theory exists so far for $\alpha\chi^{2/3} > 1$

This translates to $\chi > 1600$ – the NpQED threshold

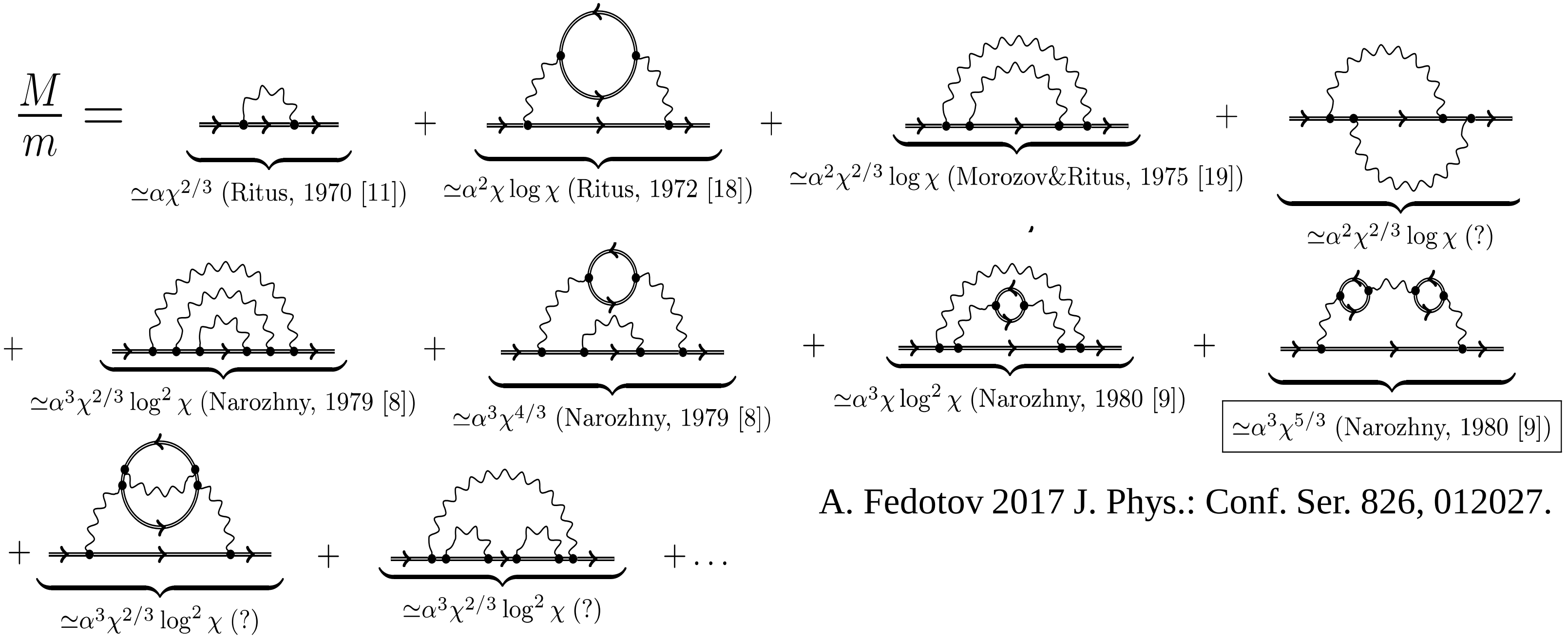
Yakimenko et al. PRL 122, 190404 (2019)

Path beyond QED

Non-perturbative strong field QED:

QED is in excellent agreement with experiment in the perturbative regime $\chi \ll 1$ due to the smallness of the fine structure constant $\alpha = 1/137$

The smallness parameter is $\alpha\chi^{2/3}$



A. Fedotov 2017 J. Phys.: Conf. Ser. 826, 012027.

Yakimenko et al. PRL 122, 190404 (2019)

Path beyond standard QED
Non-perturbative strong field QED:

According to Nikishov & Ritus (1972), the actual smallness parameter is $\alpha\chi^{2/3}$
No theory exists so far for $\chi > 1600$

$\chi > 1600$ corresponds to fields of a laser with intensity

$$I > 10^{35}\ \mathrm{W/cm^2}$$

Fortunately, there is a Lorentz boost:

$$\chi = \gamma E/E_{crit}$$

Particles with high γ may see $\chi > 1600$
with reasonable lasers

Yakimenko et al. PRL 122, 190404 (2019)

Is NpQED reachable experimentally?

The huge $\chi = \frac{\gamma E}{E_S} \sim 1600$ can be achieved only using highly relativistic electrons with $\gamma \gg 1$

The relativistic electron however radiates and loses its energy during the time $\tau \sim \frac{\gamma \tau_c}{\alpha \chi^{2/3}}$,

where $\tau_c = \frac{\lambda_c}{c} = 1.3\ 10^{-21}\ s$ is the Compton time

For a characteristic laser time of 3 fs, multi-TeV electrons would be required

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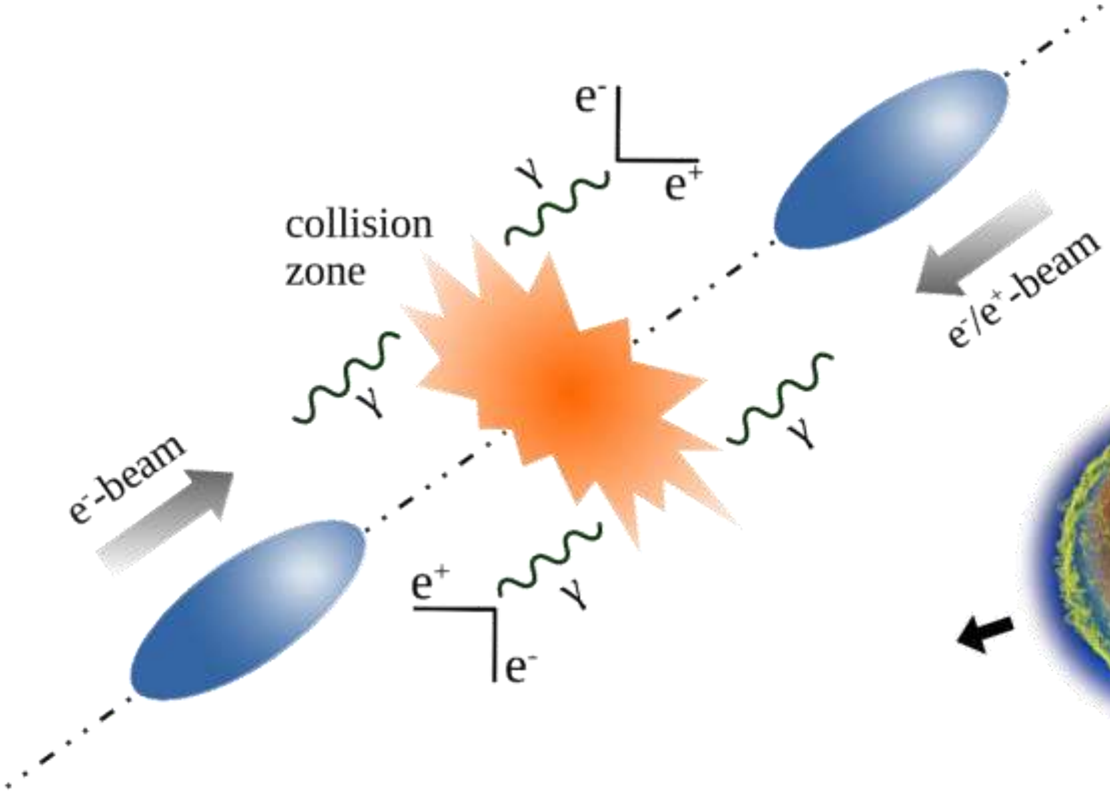
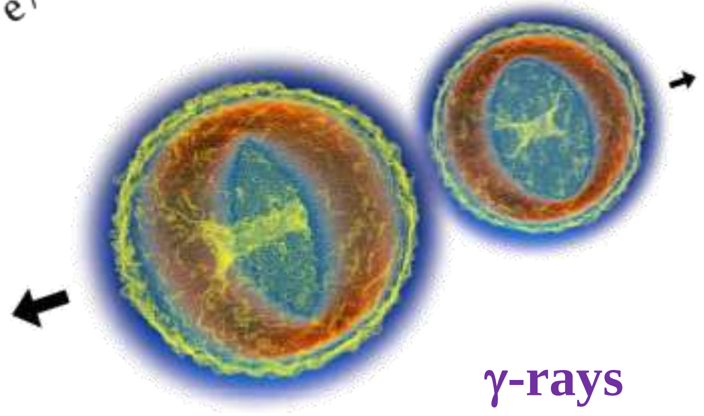
Yakimenko et al. PRL 122, 190404 (2019)

Possible realization at FACET-2 150 GeV e^-e^+ bunches



10 nm bunches
MA current



γ-rays
(OSIRIS 3D)

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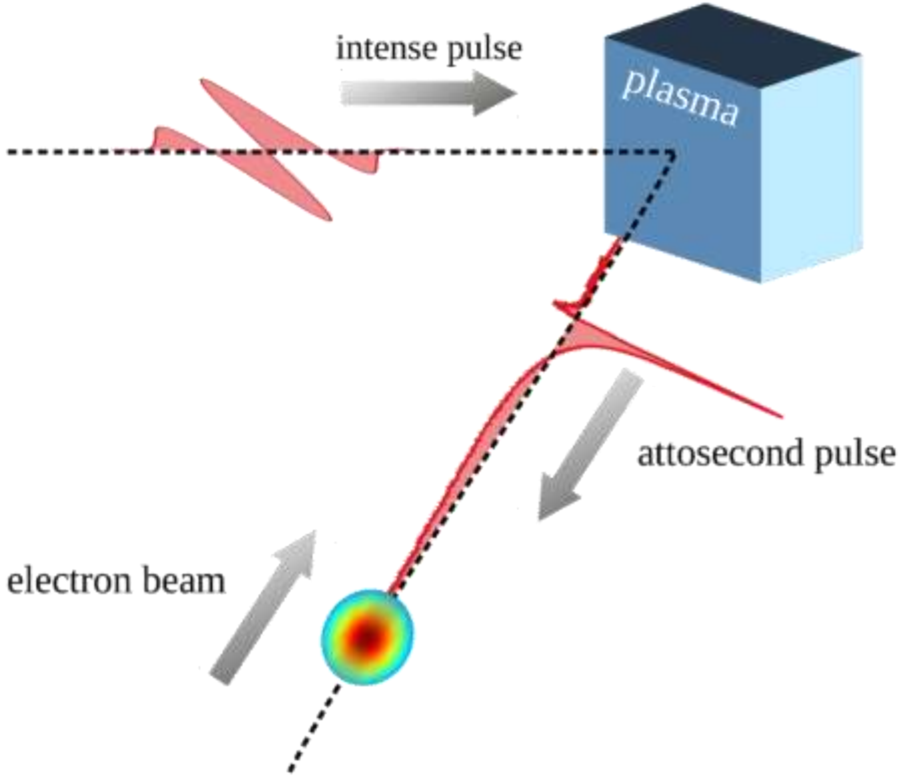
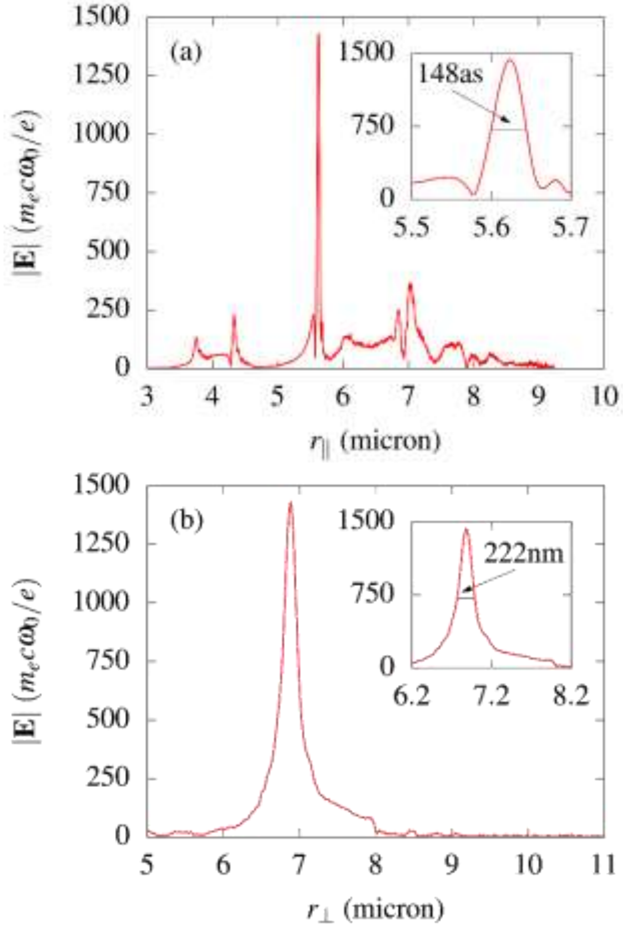
Baumann et al. Sci. Rep. (2019) 9:9407
D. an der Bruegge PhysPlasmas **17** 033110 (2010)

Laser-generated attosecond pulse and 150 GeV electron bunch





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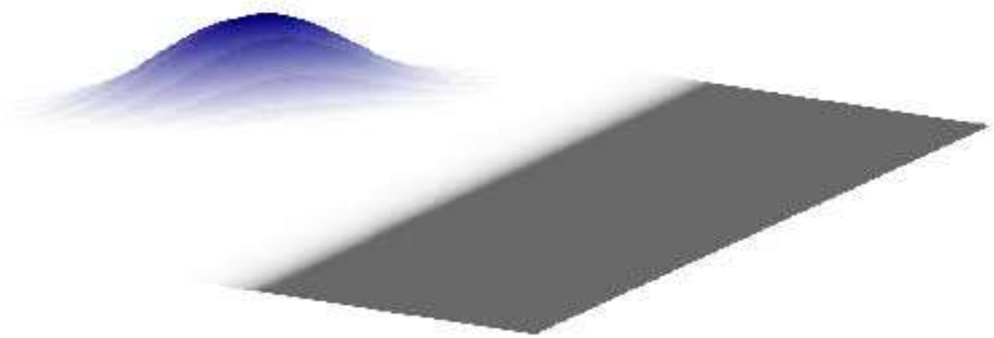
Baumann et al. Sci. Rep. (2019) 9:9407
D.an der Bruegge PhysPlasmas **17** 033110 (2010)

Laser-generated attosecond pulse and 150 GeV electron bunch

Single cycle laser
a_0=350
I=2x10^{23} W/cm^2



03.03.2020

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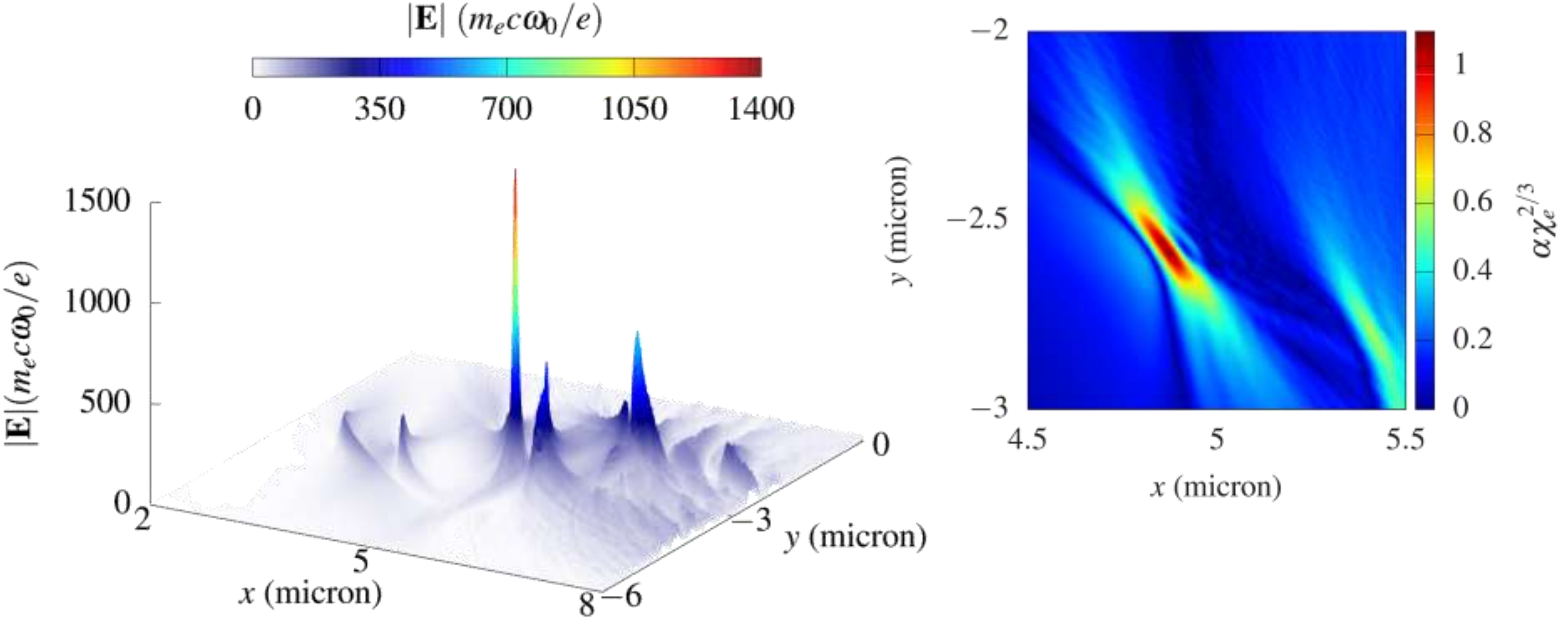
Baumann et al. Sci. Rep. (2019) 9:9407

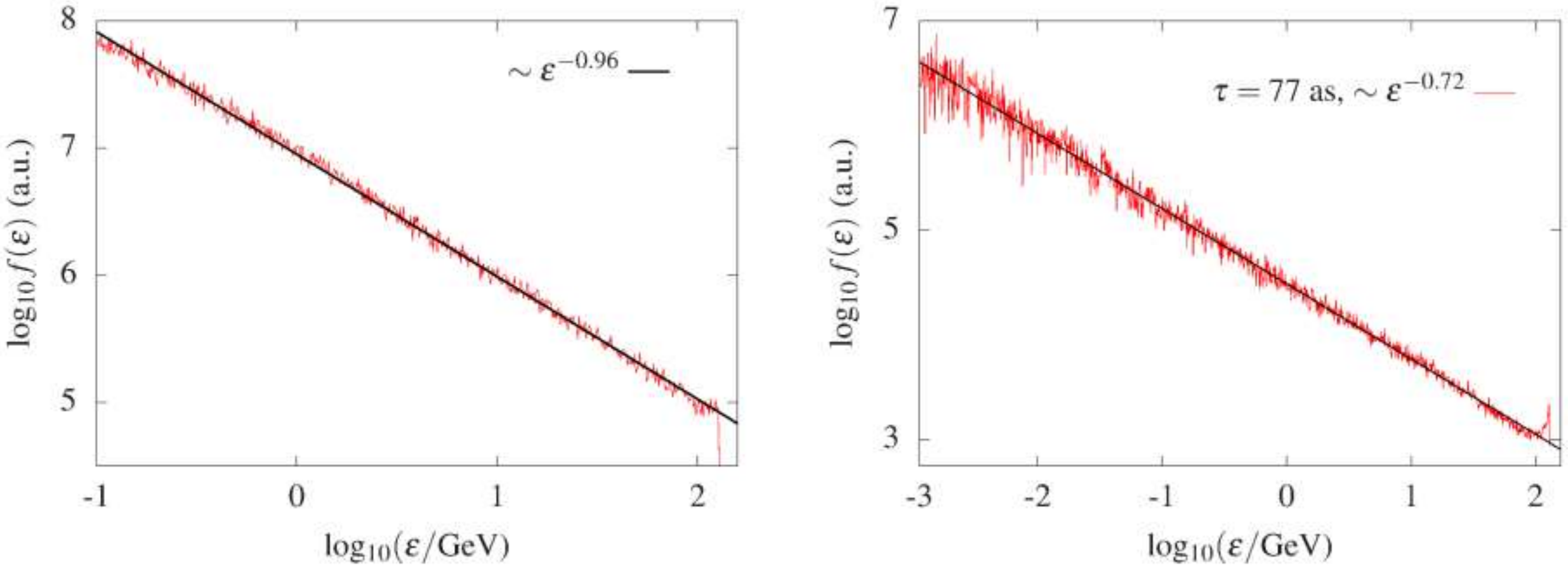
2d pulse structure and the extreme χ values



Baumann et al. Sci. Rep. (2019) 9:9407

γ-ray spectrum

Existing theory predicts power-law exponent -2/3



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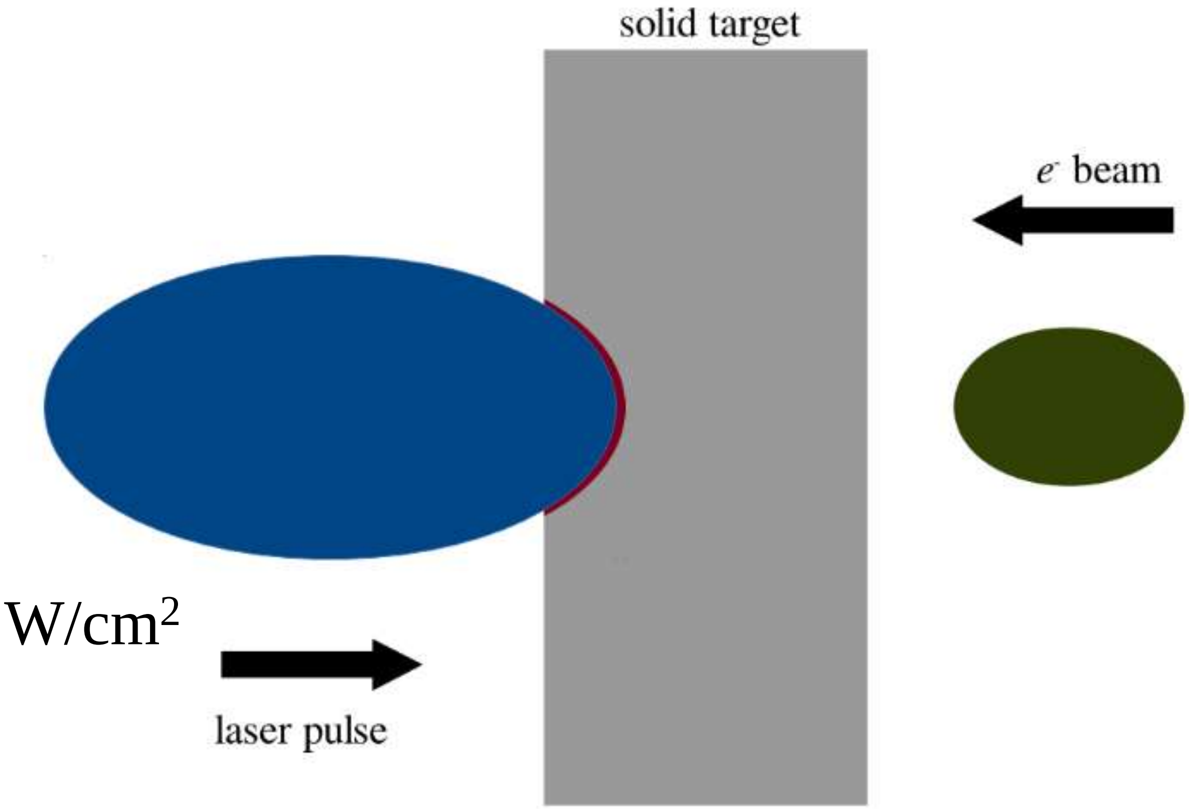
Alternative approach: Skin on solid state target



150 GeV

a_0=1400
I=3x10^{24} W/cm^2

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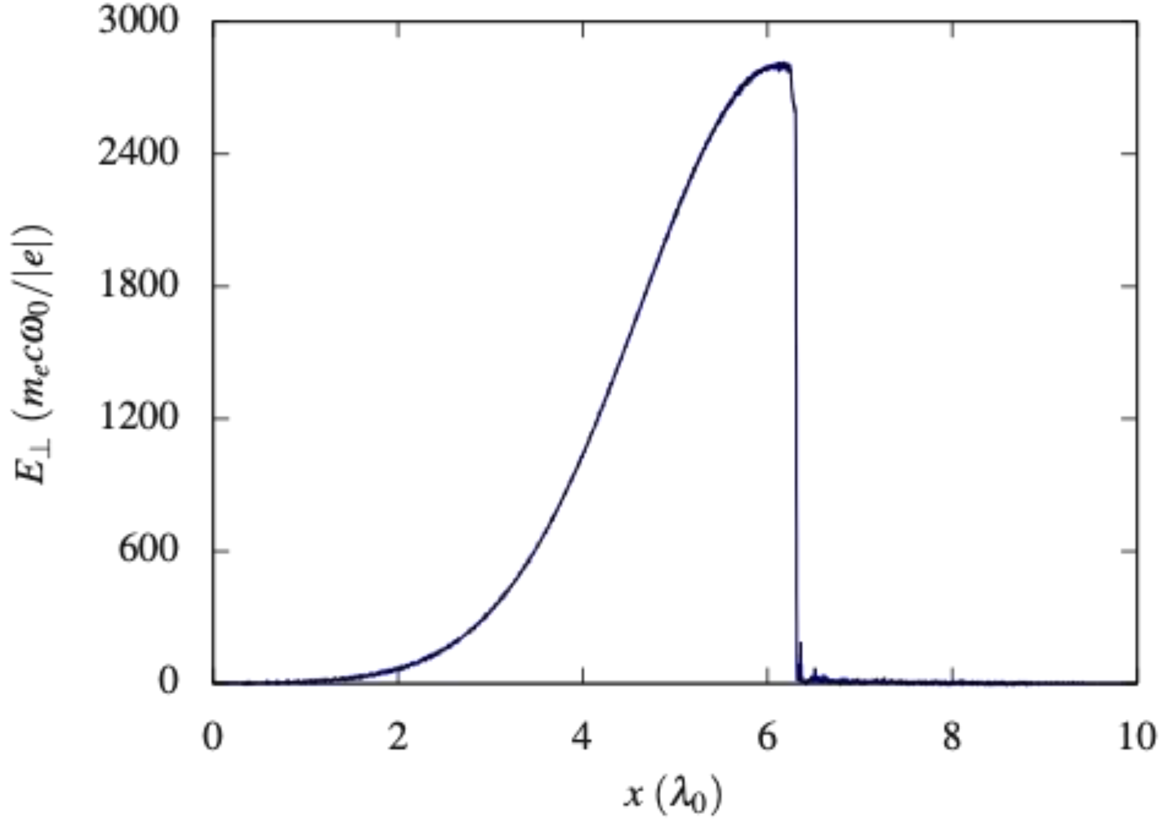
Field structure on solid state target: skin effect



→ Sharp interface (≈ 20 nm) separating field-free from intense-field region

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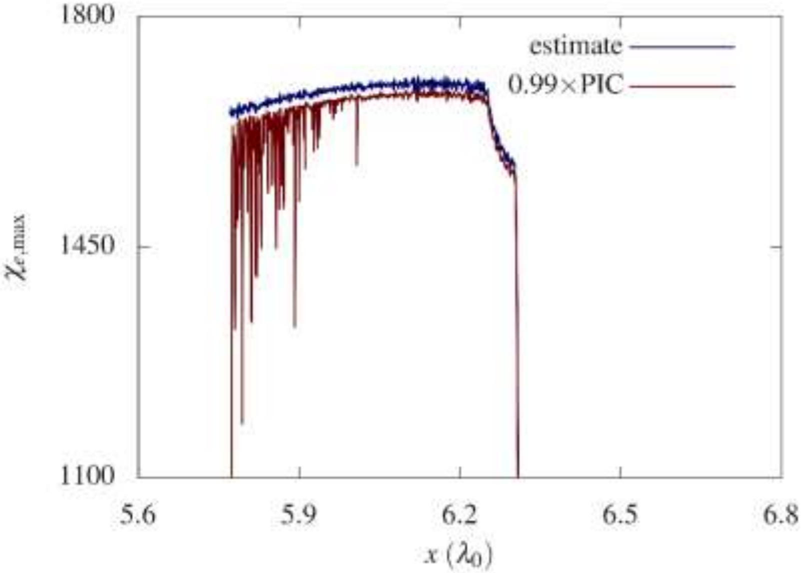
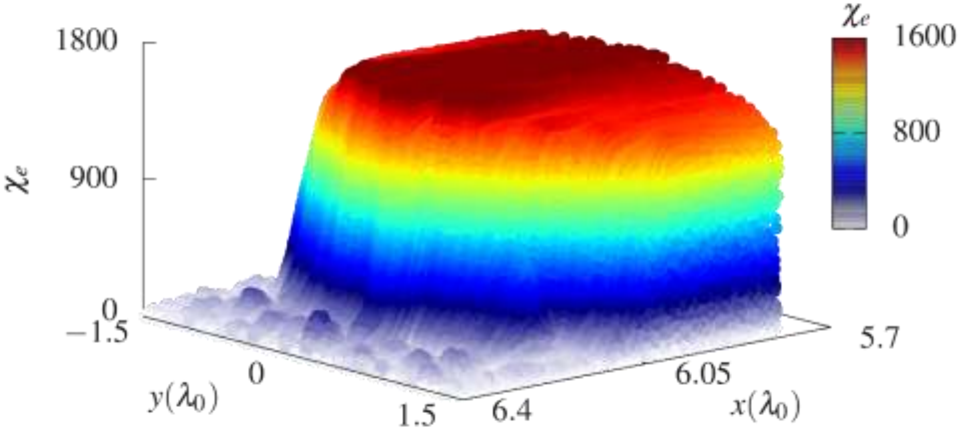
Field structure on solid state target: skin effect

One-dimensional results:



Two-dimensional results:



$$\text{Estimate} = \frac{\varepsilon}{m_e c^2}\frac{E_\perp}{E_{\text{QED}}}$$

What are the observables of NP-QED ?

3/3/2020

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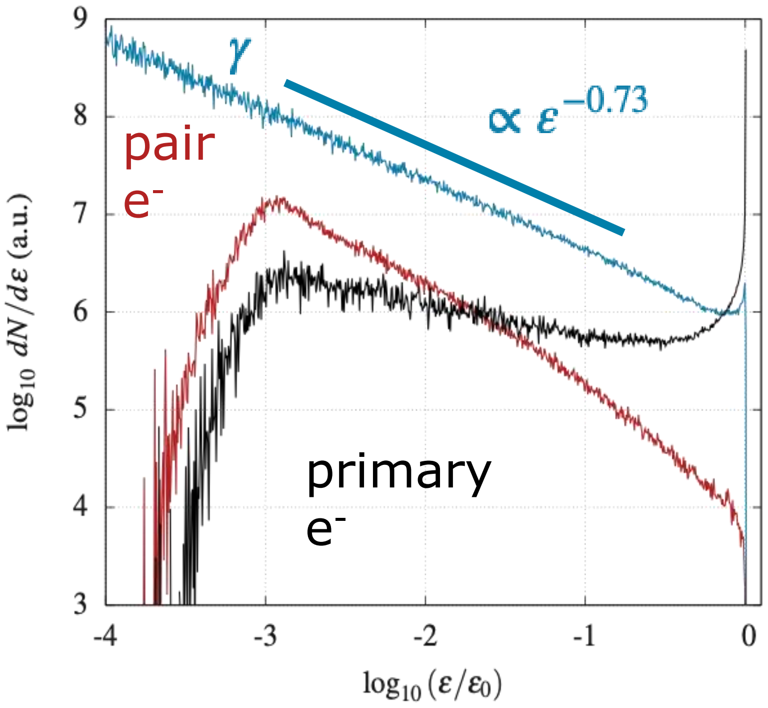
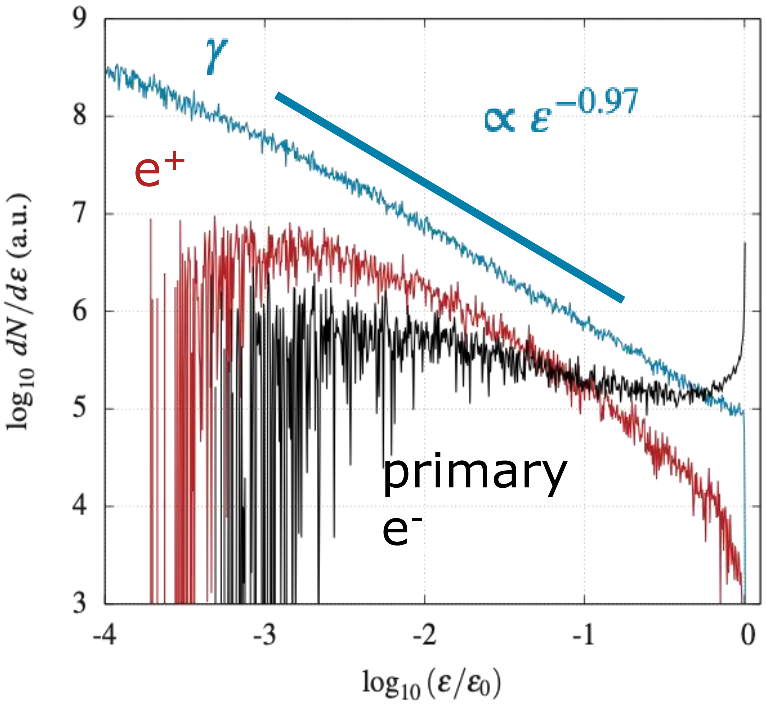
Power-law particle spectra

npQED collider:



attosecond setup:



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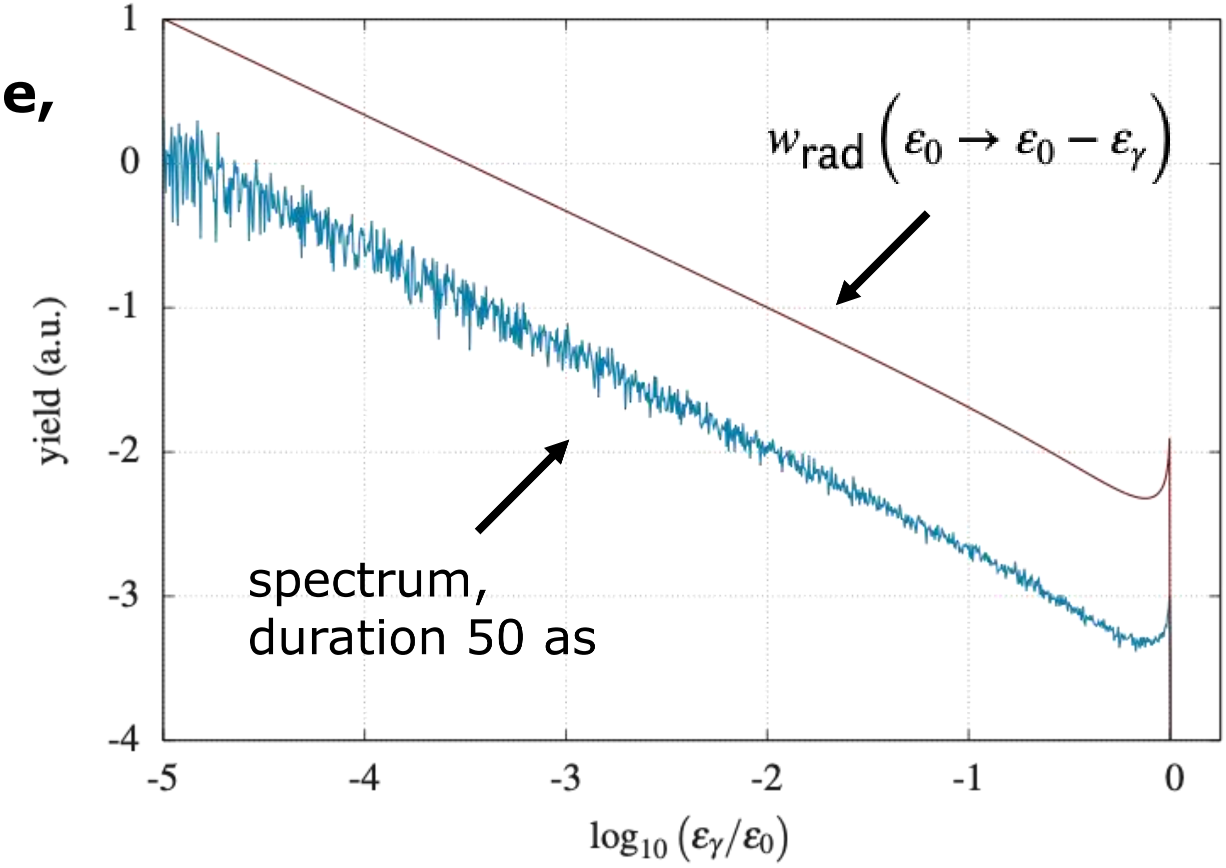
Differential photon emission rate

Attosecond pulse,

$$\tau \ll t_{\mathrm{rad}}$$



$w_{\mathrm{rad}}\left(\varepsilon_0 \to \varepsilon_0 - \varepsilon_\gamma\right)$

spectrum,
duration 50 as

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Power law in first order

For secondary particles with $1 \ll \chi \ll \chi_0$ rate is given by

$$w_{\mathrm{rad}}\left(\varepsilon_0 \to \varepsilon\right) \simeq \frac{\nu}{\varepsilon_0^{4/3}} \frac{1+\eta^2}{\eta^{1/3}\left(1-\eta\right)^{2/3}} \left(\frac{H}{H_{\mathrm{crit}}}\right)^{2/3}, \quad \eta = \frac{\varepsilon}{\varepsilon_0}$$

E. N. Nerush *et al.*, Phys. Plasmas **18**, 083107 (2011)

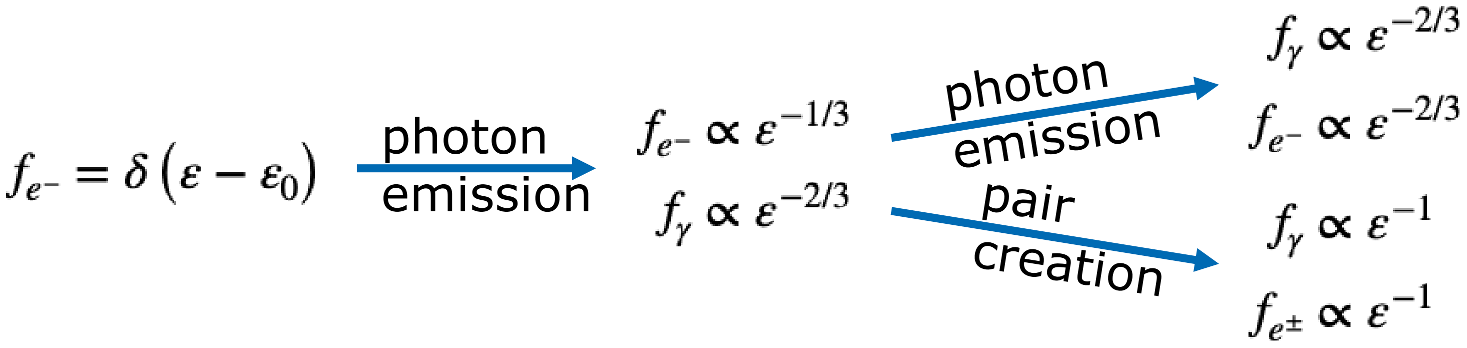
Power law spectra in first order

$$f_\gamma^{(1)}(\varepsilon) \propto \varepsilon^{-2/3}, \; f_{e^-}^{(1)}(\varepsilon) \propto \varepsilon^{-1/3}$$

Spectra in the second order

Power-law $f^{(i)}(\varepsilon) \propto \varepsilon^{s}$ gives again power-law $f^{(i+1)}(\varepsilon) \propto \varepsilon^{s-1/3}$ in next order perturbation theory

For example:



$f_{e^-} = \delta\left(\varepsilon - \varepsilon_0\right)$ photon emission → $f_{e^-} \propto \varepsilon^{-1/3}$, $f_{\gamma} \propto \varepsilon^{-2/3}$

photon emission → $f_{\gamma} \propto \varepsilon^{-2/3}$, $f_{e^-} \propto \varepsilon^{-2/3}$

pair creation → $f_{\gamma} \propto \varepsilon^{-1}$, $f_{e^{\pm}} \propto \varepsilon^{-1}$

2nd order spectra

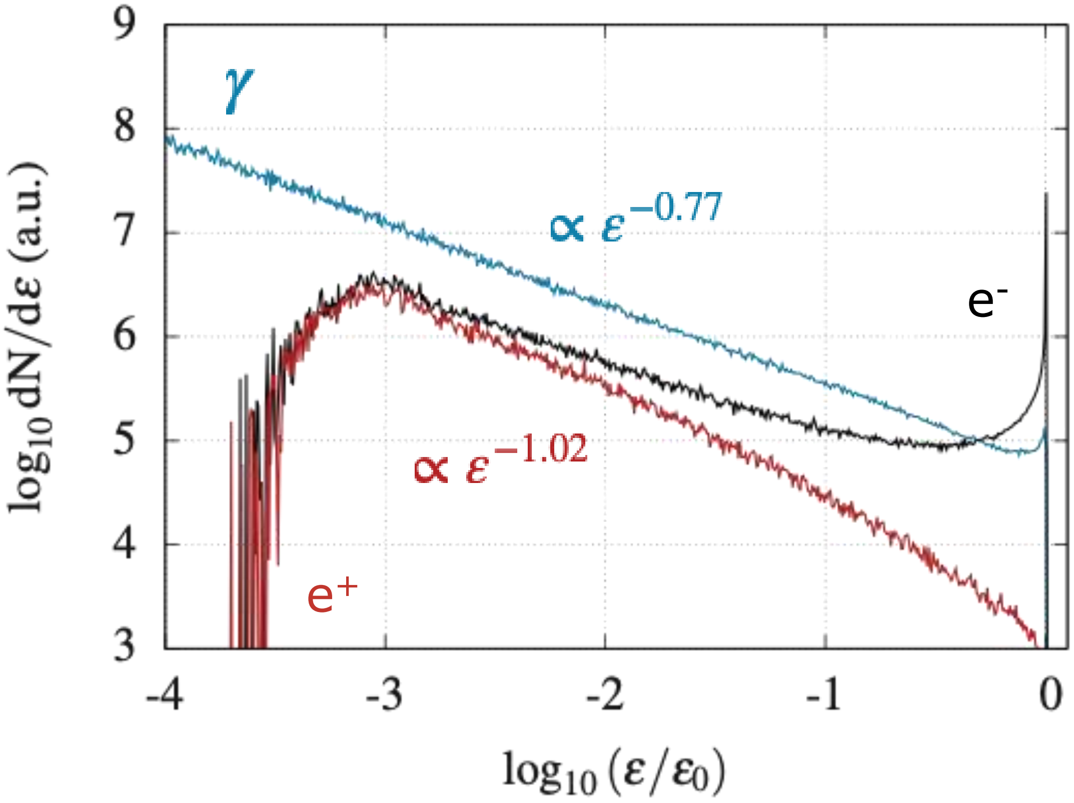
125 GeV electrons

interaction time is 150 as

2nd order model

in reasonable agreement,

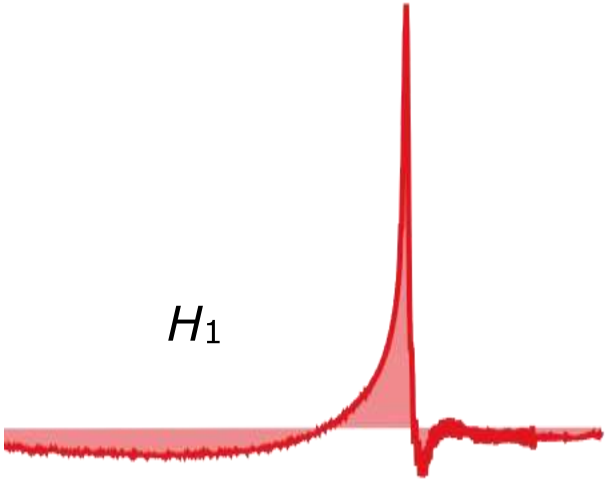
especially for positrons

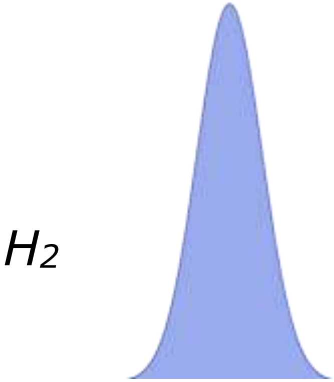


C. Baumann, E. N. Nerush, A. Pukhov, and I. Yu. Kostyukov, Sci. Rep. **9**, 9407 (2019)

$H^{2/3}$-correspondence

Consider electrons in two systems 1 and 2 interacting with different fields





Spectra will be the same if

$$\int_0^t H_1^{2/3}(t')\,\mathrm{d}t' = \int_0^t H_2^{2/3}(t')\,\mathrm{d}t'$$

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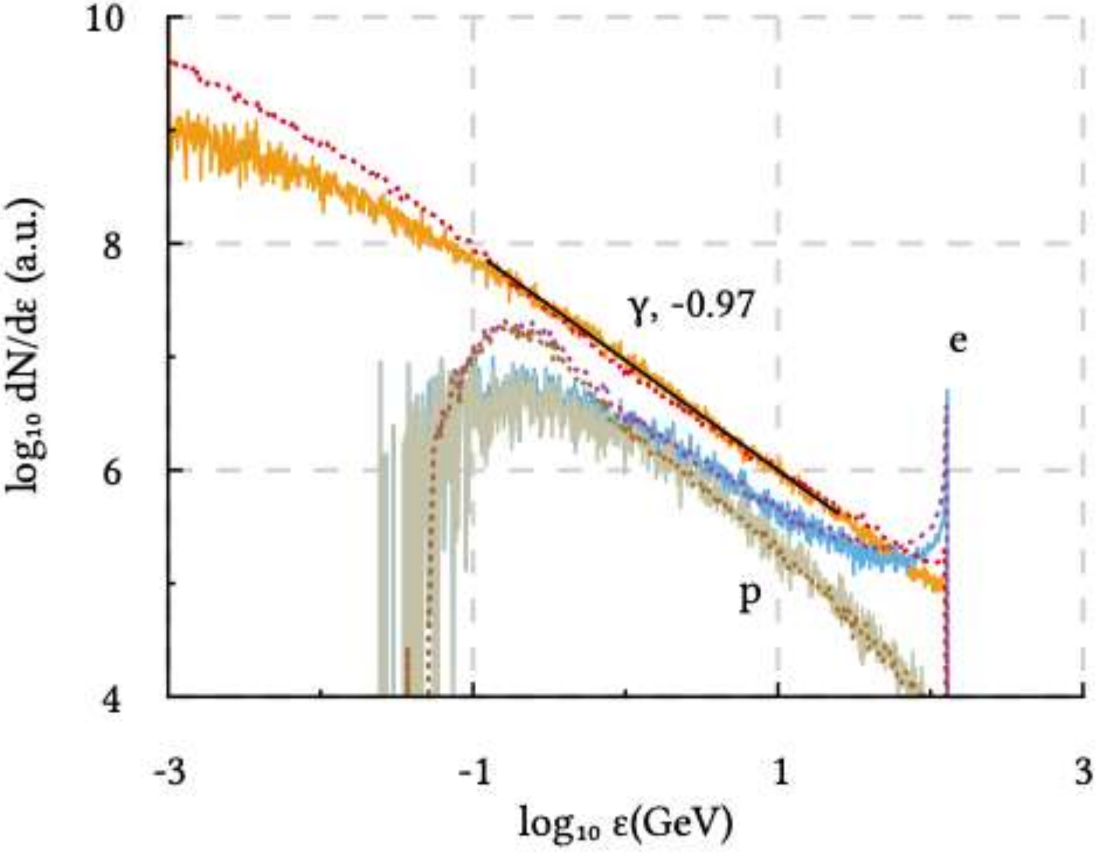
Applying *$H^{2/3}$*-correspondence

Attosecond pulse setup (solid)
vs
clean EM pulse
of 350 as duration (dotted)



Failure of $H^{2/3}$-correspondence
might identify break of theory

C. Baumann, E. N. Nerush, A. Pukhov, and I. Yu. Kostyukov, Sci. Rep. **9**, 9407 (2019)

Summary

- **Novel interaction physics in engineered targets**
  - relativistic nanophotonics
  - relativistic nano-pinch
  - path to Ultra-High Energy Density
- **Structured laser pulses:**
  - electron bunches with orbital momentum
- **Near-QED interaction:**
  - power-law scalings for absorption
  - very high efficiency of laser energy conversion into x- and γ-rays
  - Radiative trapping of electrons is revealed.
- **Non-perturbative strong field QED could be achieved experimentally**
  - FACET-2 electron-positron collider
  - ultra-intense attosecond laser-produced pulses
  - skin interaction with solid targets