LWFA Electron beam-laser collisions on BELLAi

Alec Thomas
Center for Ultrafast Optical Science
Department of Nuclear Engineering and Radiological Sciences
Department of Physics
University of Michigan, Ann Arbor, MI, USA

Workshop on High Energy Density Physics with BELLA-i
LBNL, Berkeley
Jan 19-22 2016

Acknowledgements

Collaborators at Michigan

Peng Zhang, John Nees, Bixue Hu, Vladimir Chykov, Louise Willingale, Tolya Maksimchuk, Victor Yanovsky, Karl Krushelnick, Zhaohan He, Will Schumacher, Franklin Dollar, Chris McGuffey, Tony Zhao, Keegan Behm, Anthony Raymond, Thomas Batson, Mike Vargas,

And collaborators at **University Of Connecticut, (Gerald Dunne)**
Queens University Belfast, (Gianluca Sarri, Matt Zepf)
Imperial College London, (Stuart Mangles)
University Of California Los Angeles, (Warren Mori, Chan Joshi)
University Of York, (Chris Ridger, Chris Murphy)

Contents

- Strong Field Physics
- Nonlinear Compton Scattering
- Multiphoton Breit-Wheeler Pair production
- Experiment on BELLAi

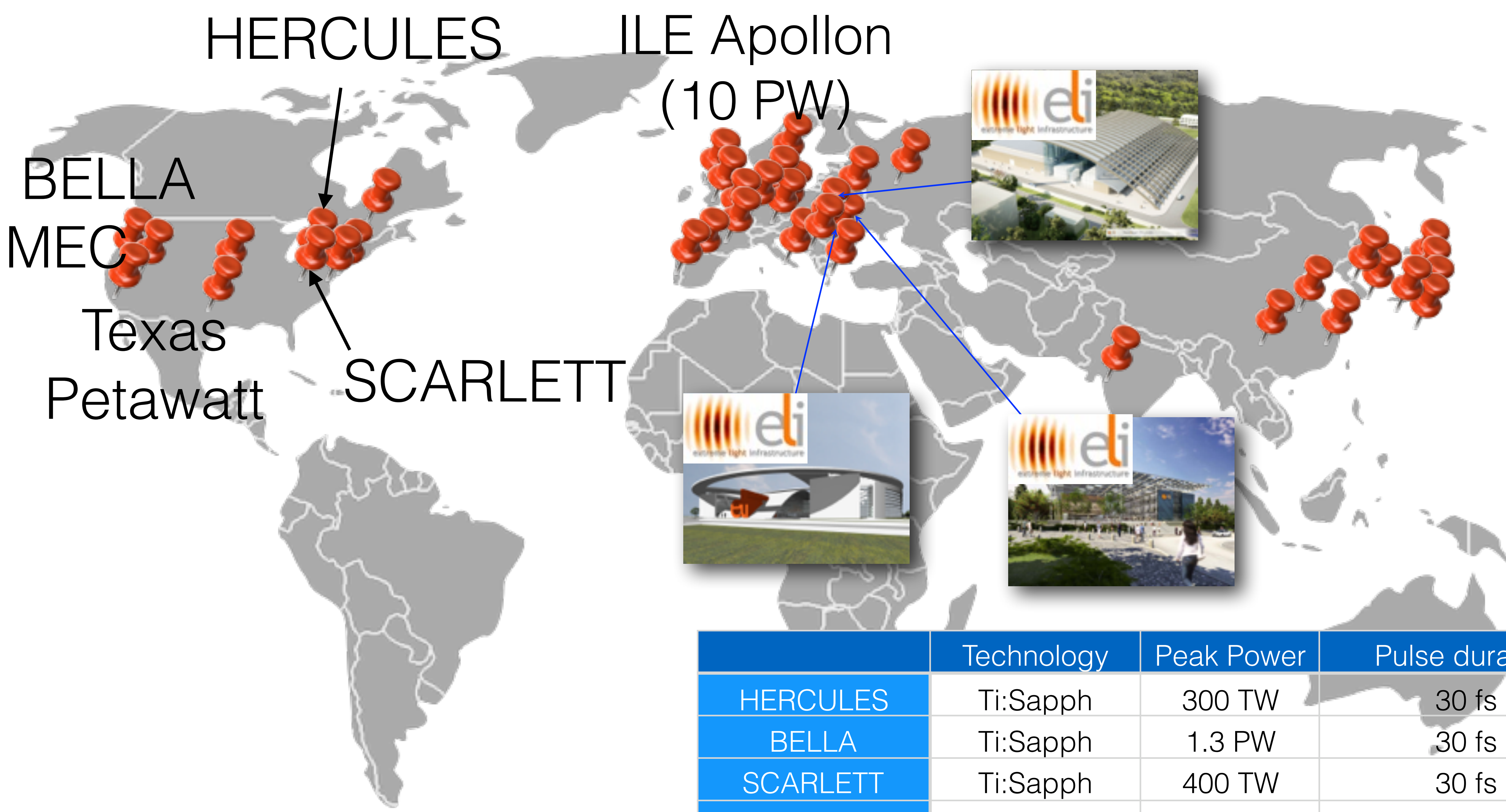
“High Energy Density Physics” with Short Pulse Lasers

- HEDP is defined as matter under pressure >1Mbar
- Laser intensity 10^{22} Wcm^{-2} corresponds to radiation pressure of 10^{12} Bar!
- Generate MeV “temperature” at solid density over small volume - very high energy density
- Rapid delivery of energy leads to extremely far-from equilibrium distributions

Frontiers in High Field Physics

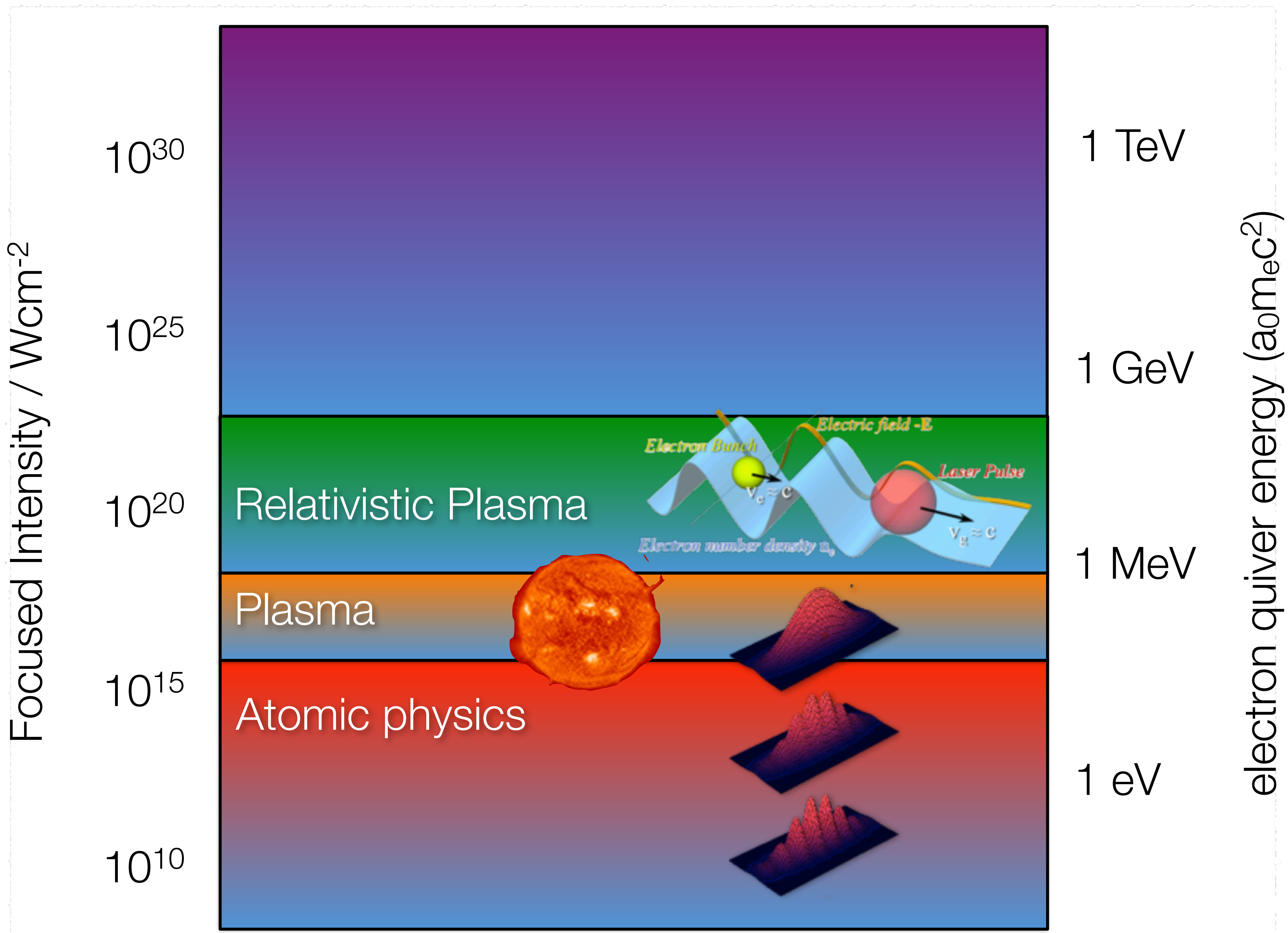
- How does matter behave in extreme electromagnetic fields? (Analogues with Condensed Matter Physics)
- Can lasers and plasmas enable high energy physics and next generation particle sources on a tabletop?
- Can we better understand the physics of neutron star atmospheres, relativistic astrophysical jets, gamma ray bursts and supernovae?
- Can we “boil” the vacuum?

High field science facilities worldwide

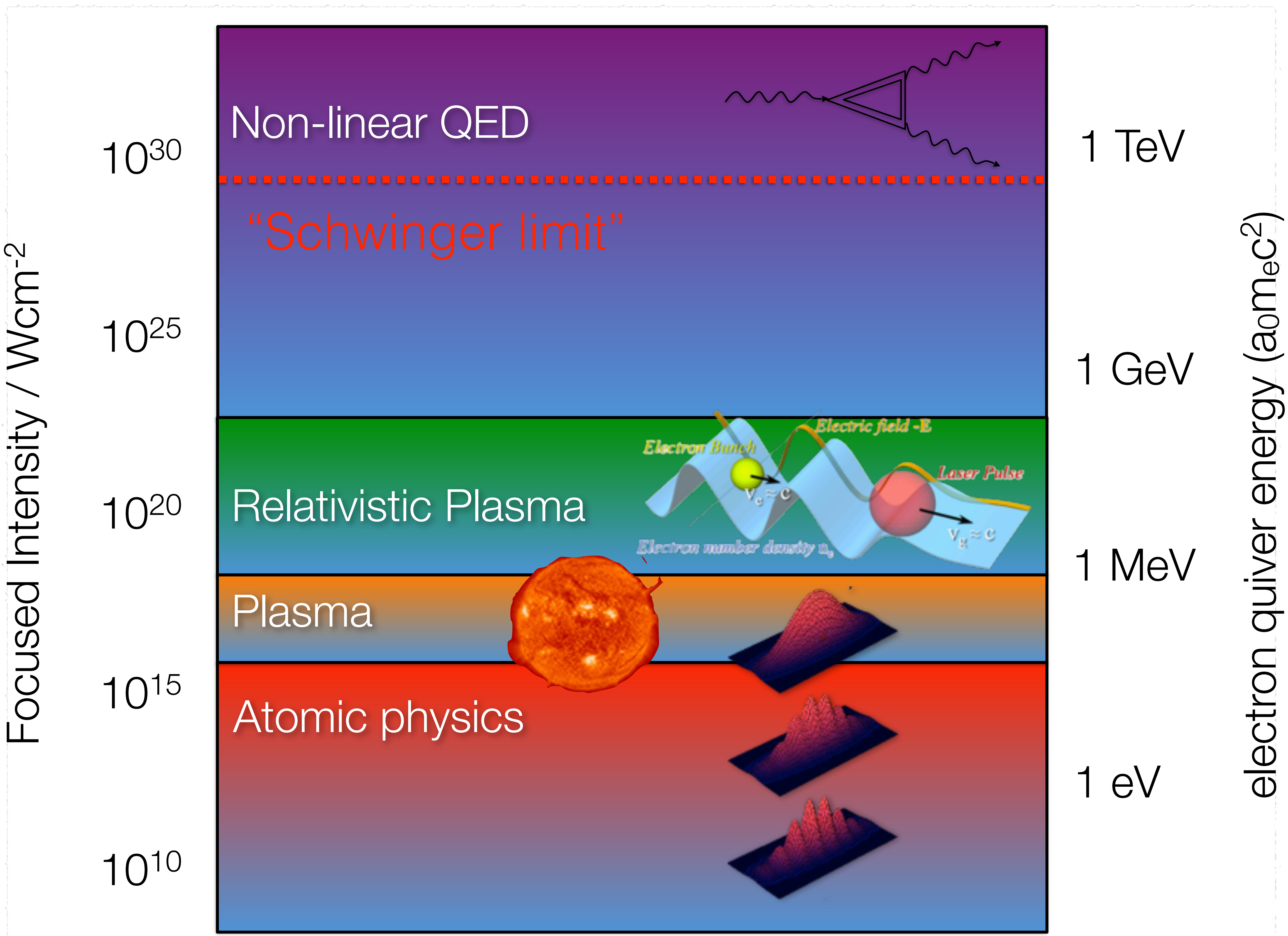


	Technology	Peak Power	Pulse duration
HERCULES	Ti:Sapph	300 TW	30 fs
BELLA	Ti:Sapph	1.3 PW	30 fs
SCARLETT	Ti:Sapph	400 TW	30 fs
Texas Petawatt	Glass	1.1 PW	170 fs
MEC at LCLS	Ti:Sapph	100 TW	30 fs

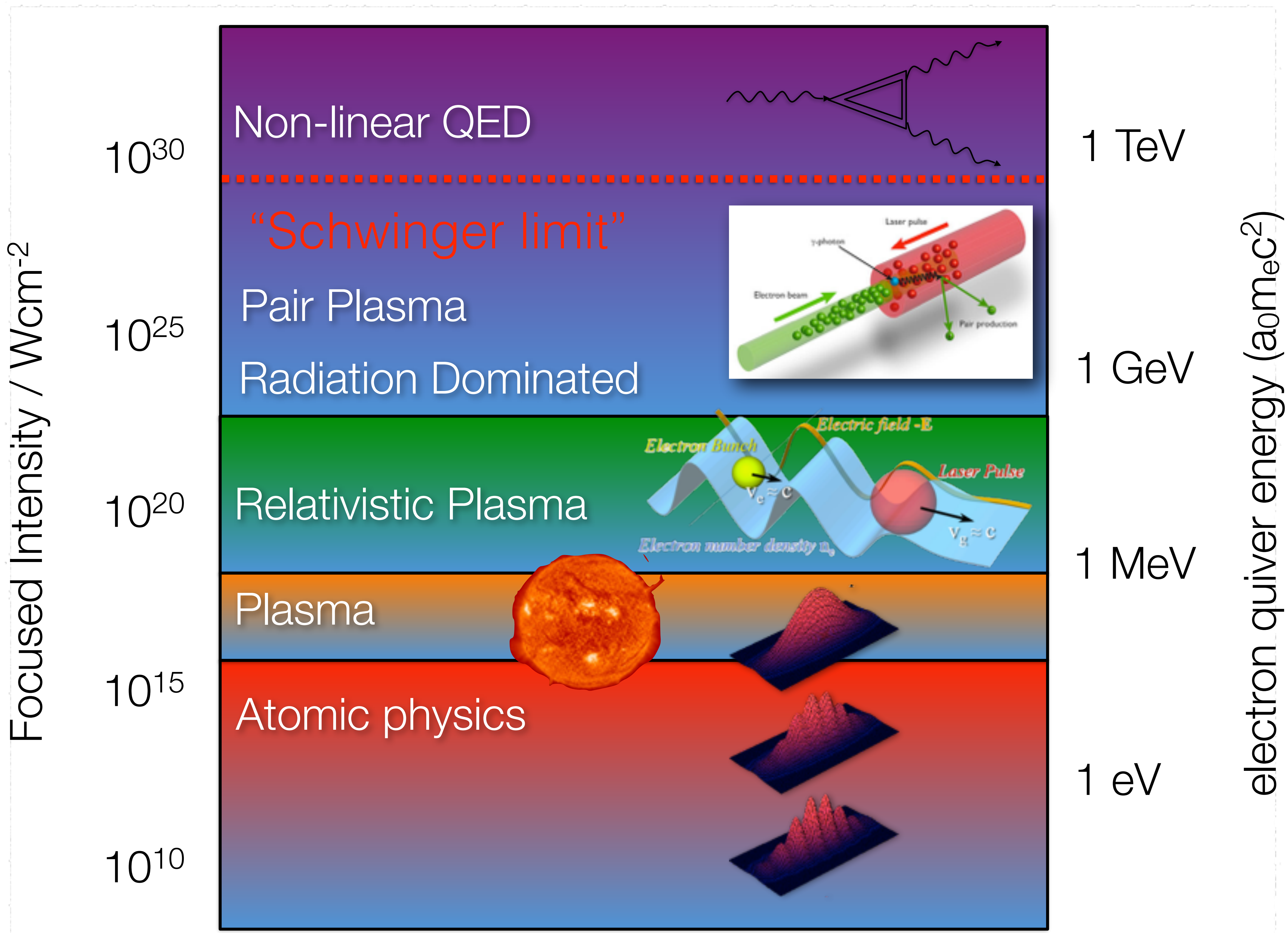
As field strength increases, QED effects start to become important



As field strength increases, QED effects start to become important



As field strength increases, QED effects start to become important



Physical Parameters for High Field Physics

- **Classical** nonlinearity parameter

$$a = \frac{1}{2\pi}\frac{eE\lambda}{m_c c^2} = \frac{\text{Quiver energy of electron}}{m_e c^2}$$

- **Quantum** nonlinearity parameters

$$\chi_e = \frac{||F_{\mu\nu} v^\nu||}{E_{cr}} \quad = \frac{\text{Amplitude of } E \text{ in e rest frame}}{E_{cr}}$$

$$\chi_\gamma = \frac{||F_{\mu\nu} \hbar k^\nu||}{m_e E_{cr}} \quad = \frac{\text{Amplitude of } E \text{ in } e^+e^- \text{ center of mass}}{E_{cr}}$$

Other relations

- "Keldysh" adiabaticity parameter

$$\gamma \equiv \frac{\omega}{\omega_t} = \frac{m\,c\,\omega}{e\,\mathcal{E}} \equiv \frac{1}{a_0}$$

- Average number of photons per laser cycle $N_{\hbar\omega} \propto a_0^2$

- Critical field $eE_c\bar{\lambda}_C = m_e c^2$

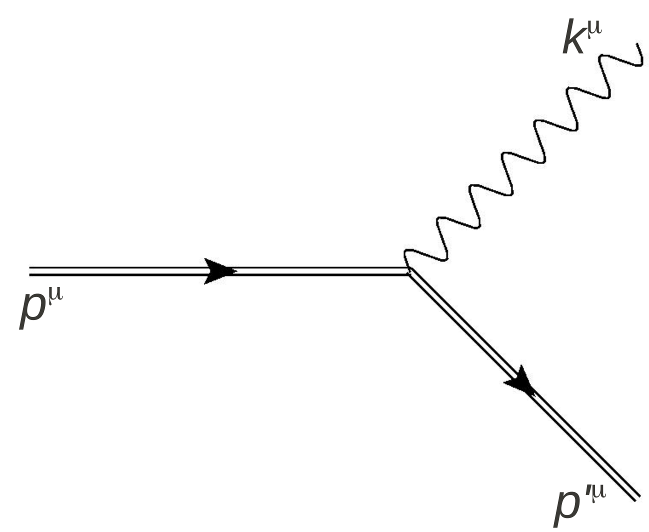
- QED Lagrangian $\mathcal{L} = \overline{\psi}\left(i\hbar\bar{D} - mc\right)\psi - \frac{1}{4}F_{\mu\nu}F^{\mu\nu}$

$l \to l/\bar{\lambda}_C$ $A \to eA/mc$ ⟶ $E \to eE\hbar/m^2c^2$

Strong field QED processes

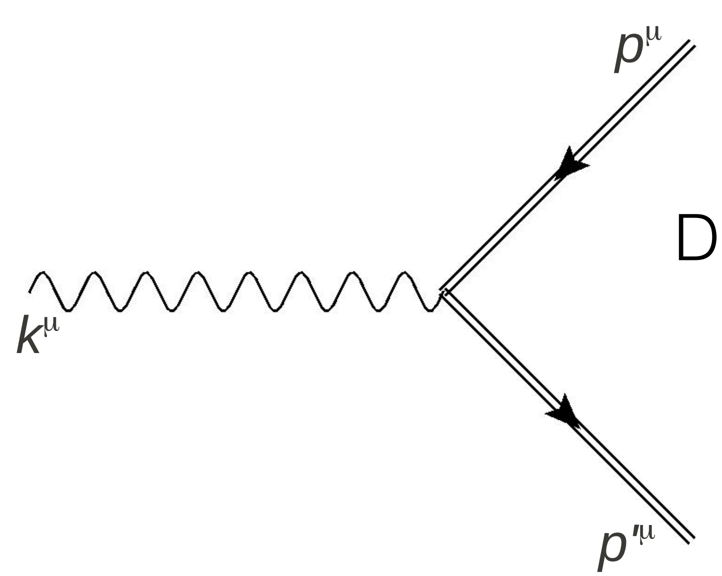
Photon emission by (dressed) electron

Nonlinear Compton emission



$$\chi_e = \frac{||F_{\mu\nu} v^\nu||}{E_{cr}}$$

$$\chi_\gamma = \frac{||F_{\mu\nu} \hbar k^\nu||}{m_e E_{cr}}$$



Decay of photon to (dressed) pair

Multiphoton Breit-Wheeler

Radiation Reaction

- The emission of large numbers (a>>1) of low energy (chi<1) photons results in effective force on particle
  - Lorentz-Abraham-Dirac; Landau-Lifshitz; …

$$\frac{d}{d\tau}v^{\mu} = -\frac{e}{m_e}F^{\nu}_{\alpha}v_{\nu}\left[\eta^{\alpha\mu} - g(\chi_e)\tau_0\frac{e}{m_e c^2}v_{\nu}v^{\mu}F^{\alpha\nu}\right] ,$$

Rohrlich PRE 2008

Radiation reaction is a fundamental unsolved problem in both classical and quantum electrodynamics

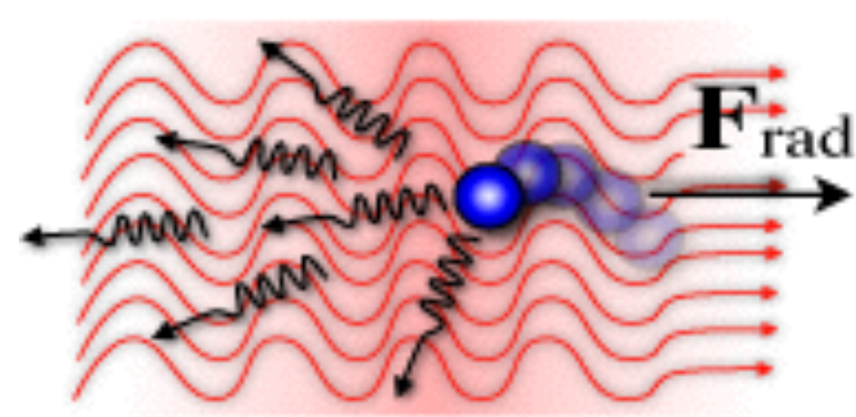
- Many semi-classical prescriptions: Lorentz-Abraham-Dirac; Landau-Lifshitz; …

- Relative strength of radiation reaction force (compared with EM force)

$$\psi = \alpha \chi_e a$$

- Classical radiation reaction regime:

$$\chi_e \ll 1\,, \quad \psi \sim 1$$

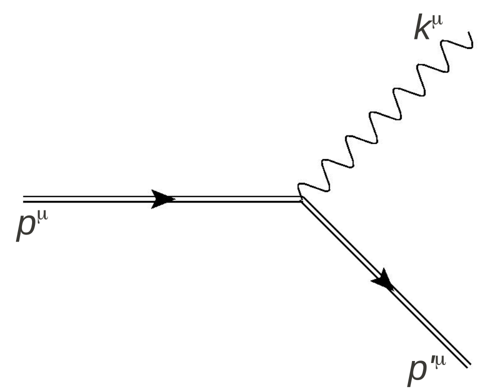


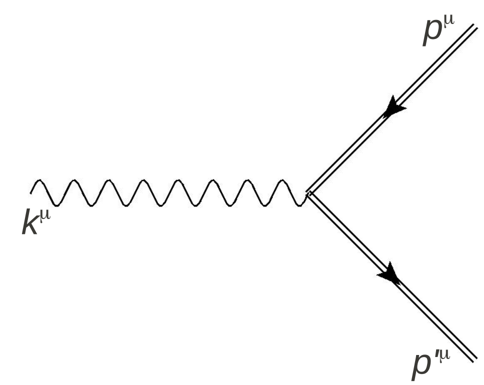
- Quantum radiation reaction regime:

$$\chi_e \sim 1$$

Strong field QED processes

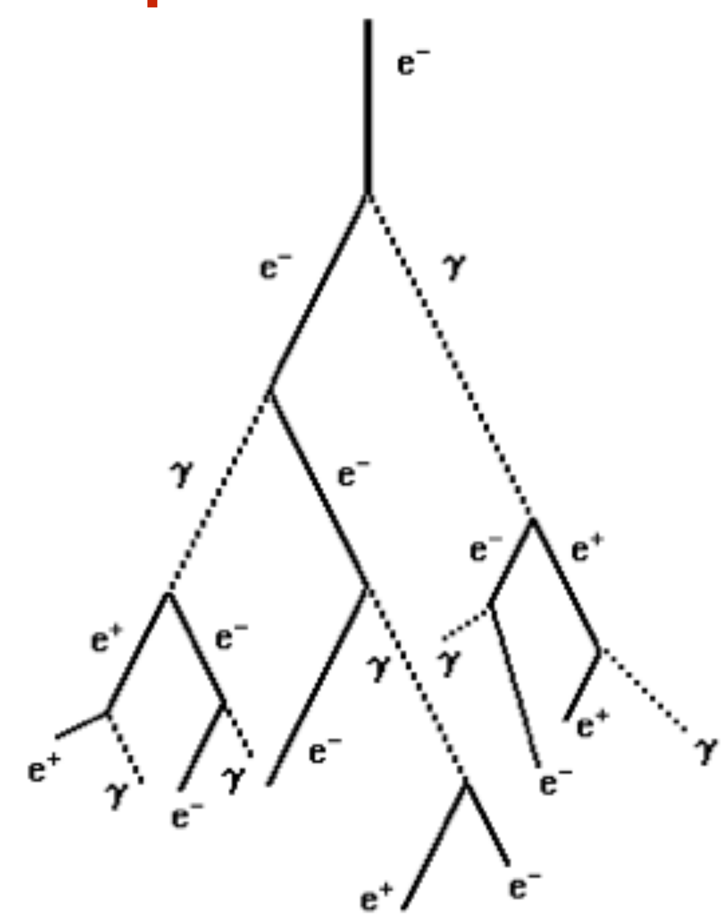
Bremsstrahlung emission





Multiphoton Breit-Wheeler

electron-positron pair cascade



- Rates strongly depend on χ_e, χ_γ

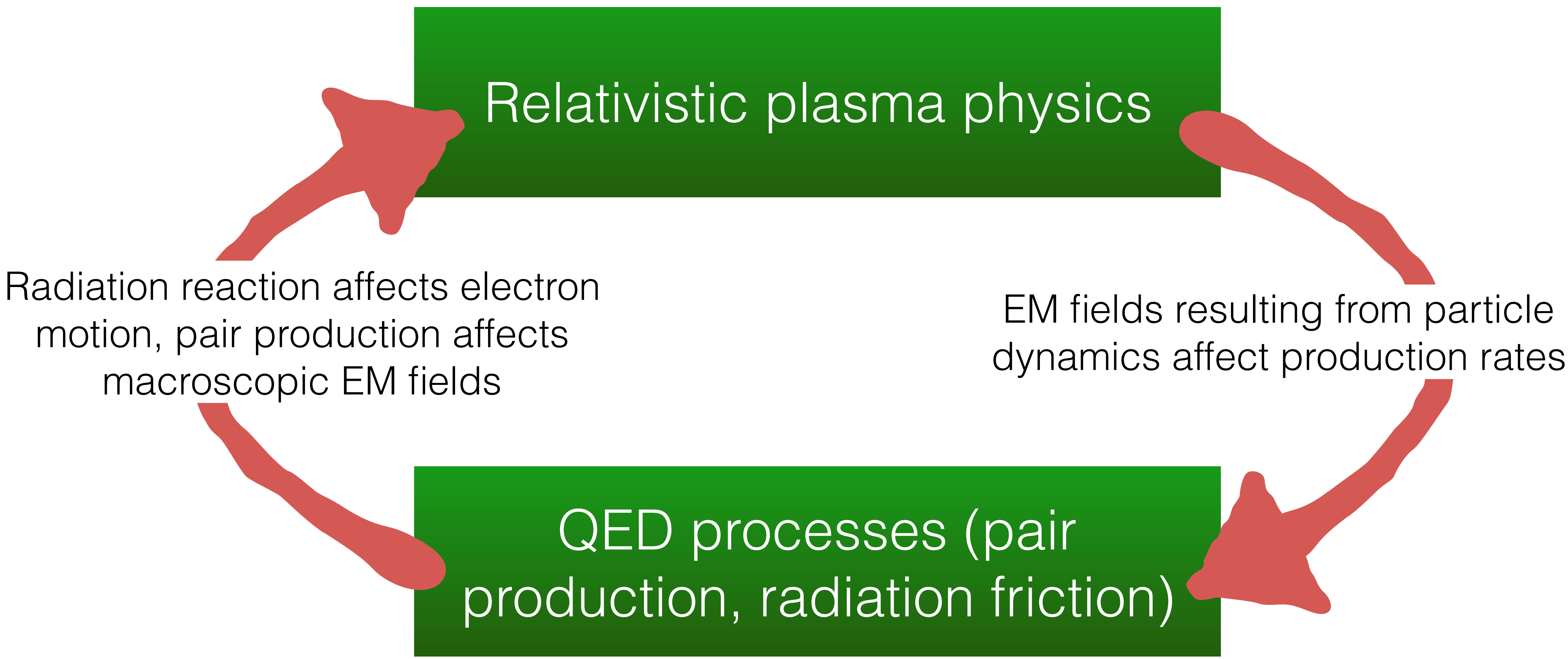
  - gamma emission probability for small χ_γ

$$P \propto \chi_e$$

  - pair production probability for small χ_γ

$$P \propto \chi_\gamma \exp\left(-\frac{2}{3\chi_\gamma}\right)$$

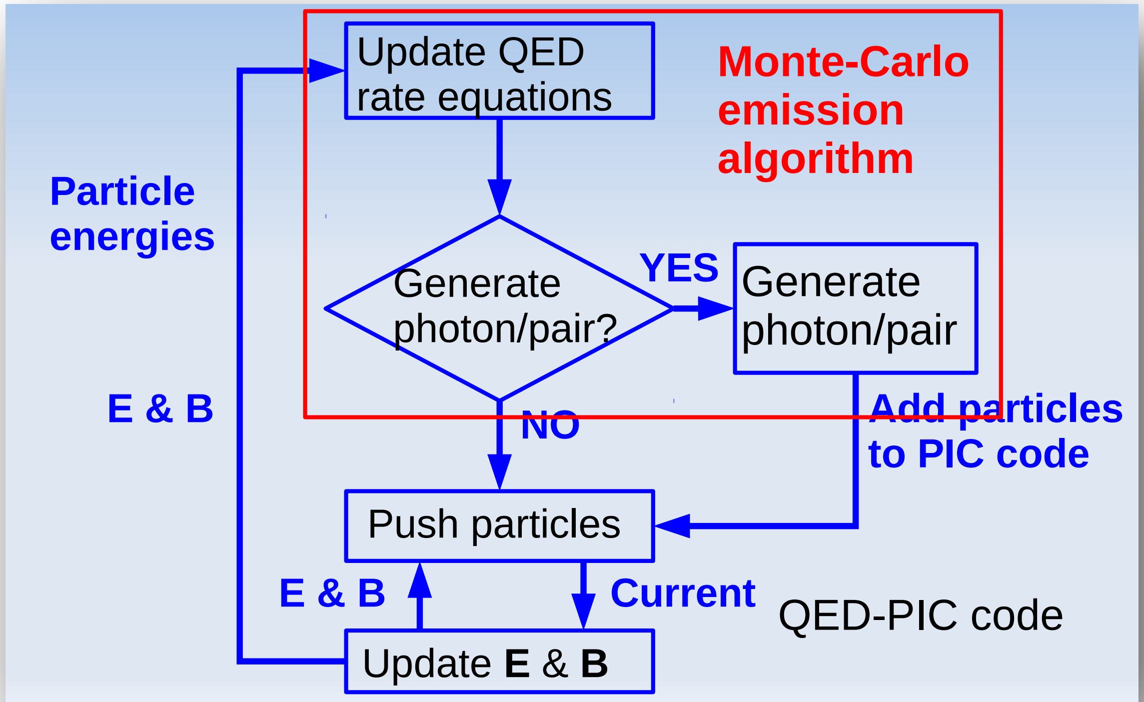
“QED-plasma” state



Coupling between relativistic plasma dynamics and QED particle interactions

QED-plasma PIC codes

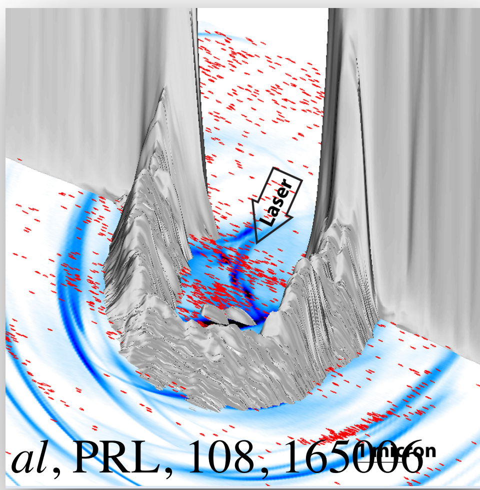
- …Extend the Vlasov-Maxwell system to include the synchrotron radiation and pair production
  - *[C. S. Brady and T. D. Arber, Plasma Phys. Controlled Fusion 53, 015001 (2011)]*
- QED effects are included using Monte Carlo method using Strong Field QED formalism
  - *[R. Duclous, J. G. Kirk, and A. R. Bell, Plasma Phys. Controlled Fusion 53, 015009 (2011)]*
  - -> EPOCH code
- Many other implementations (e.g. I. Sokolov, H. Ruhl, OSIRIS 3.0, UCLA/IST… etc.)



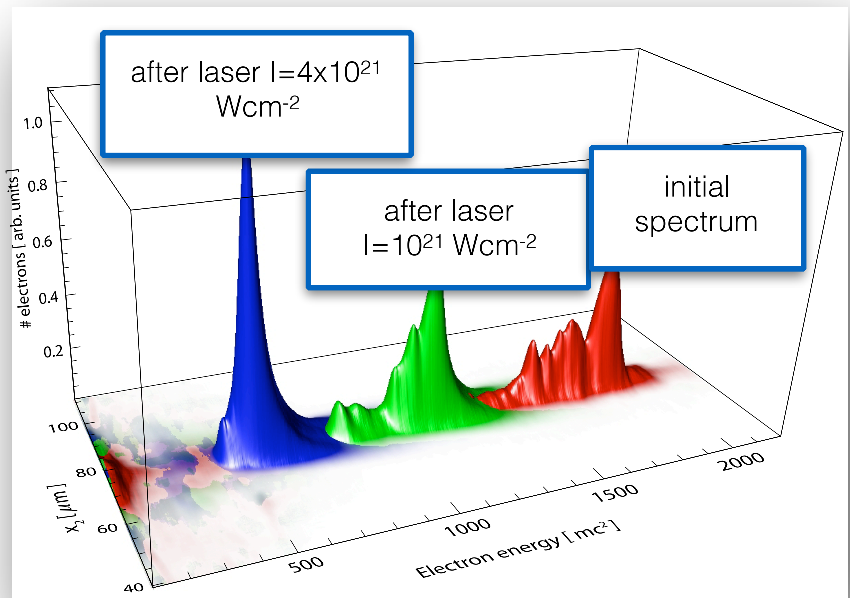
- EPOCH: Modified standard particle-in-cell algorithm to include Monte-Carlo QED interactions

Exploring this new physics regime

Intense gamma ray sources



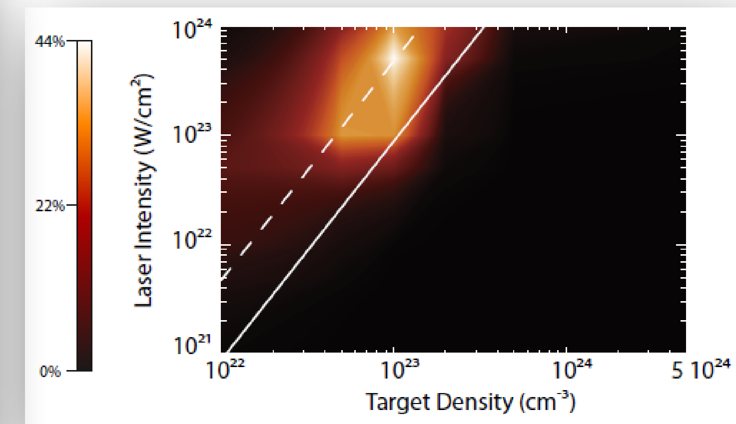
C.P. Ridgers, *et al*, PRL, 108, 165006 (2012)



Colliding pulse pair production

T. Blackburn et al, PRL (2014)
M. Vranic et al, PRL 113, 1348001(2014)

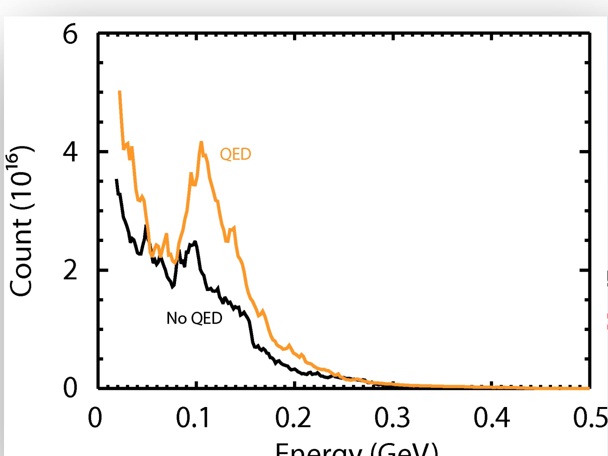
Absorption



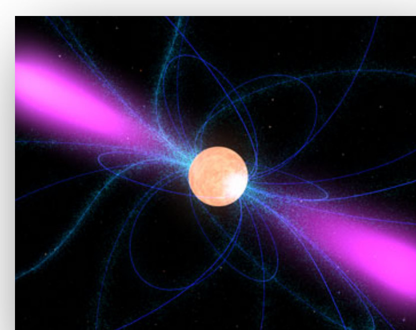
L.L. Ji, *et al*, Phys. Plas., 23, 023109 (2014

Zhang et al, New J. Phys. (2015)

Effects on ion acceleration



C.P. Ridgers, *et al*, Phys. Plas., 20, 056701 (2013)
M. Tamburini *et al*, New J Phys, 12, 123005 (2010)



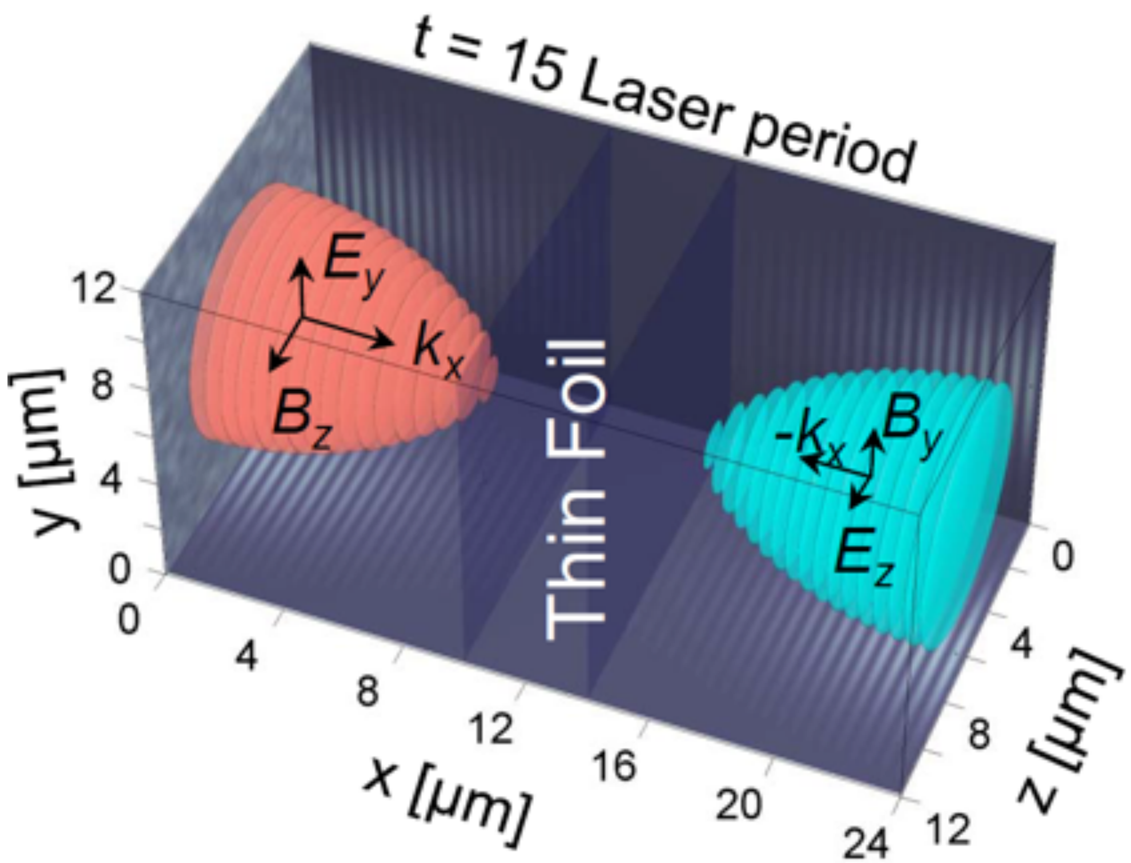
Pulsar atmospheres

Many others….

Bell and Kirk PRL 2008
Fedotov et al PRL 2010
Bulanov et al PRL 2010
Sokolov PRL 2010
Nerush et al PRL 2011
Brady et al PRL 2011
Bulanov et al Phys Plasm. 2012
and more….

P. Zhang *et al*, New J Phys, 17, 043051 (2015)

3D QED-PIC simulation



Using EPOCH code

$I = 4.5 \times 10^{23}\ W/cm^2$

$\lambda = 0.8\ \mu m$

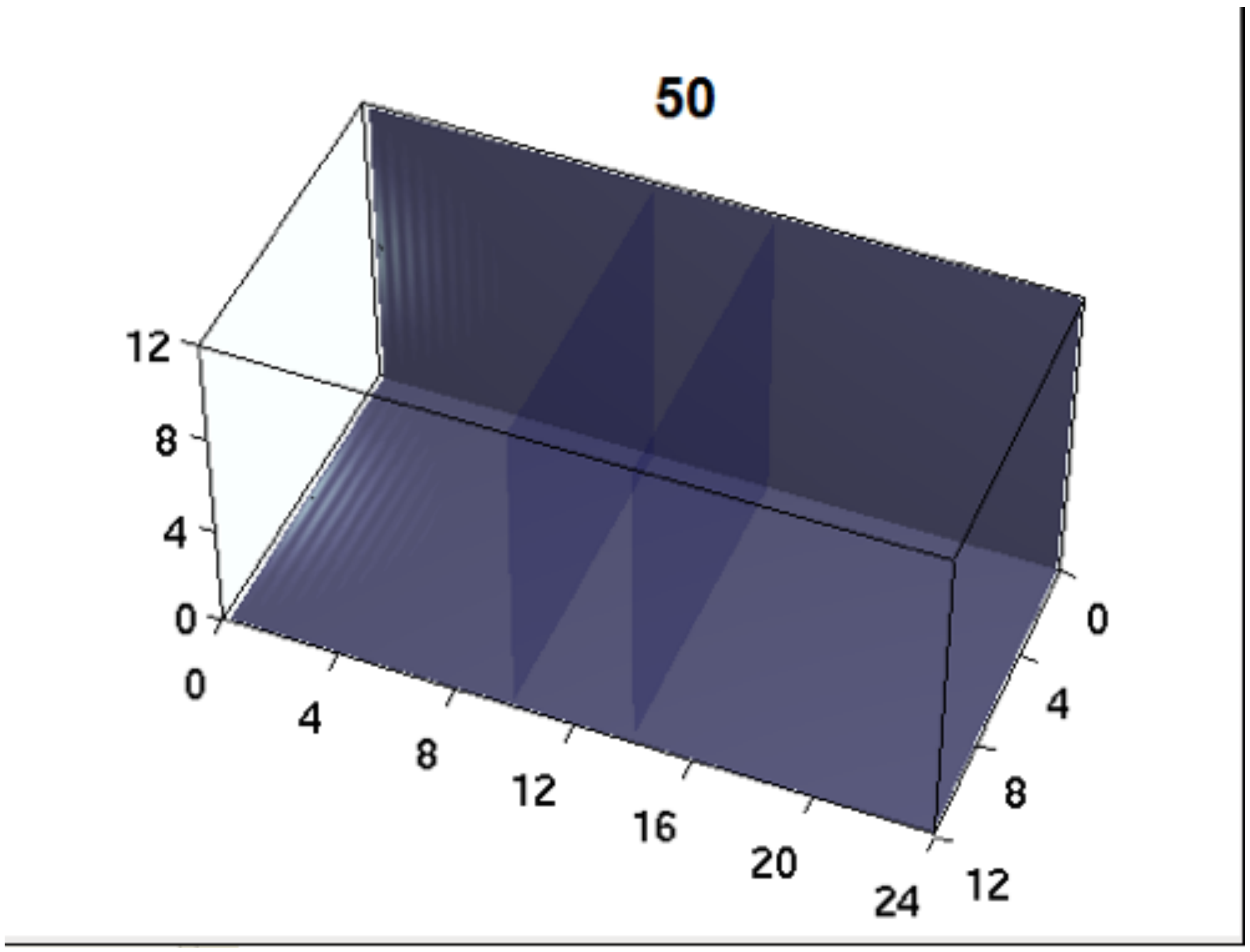
$n = 150\ n_c$

4 μm thick Al slab

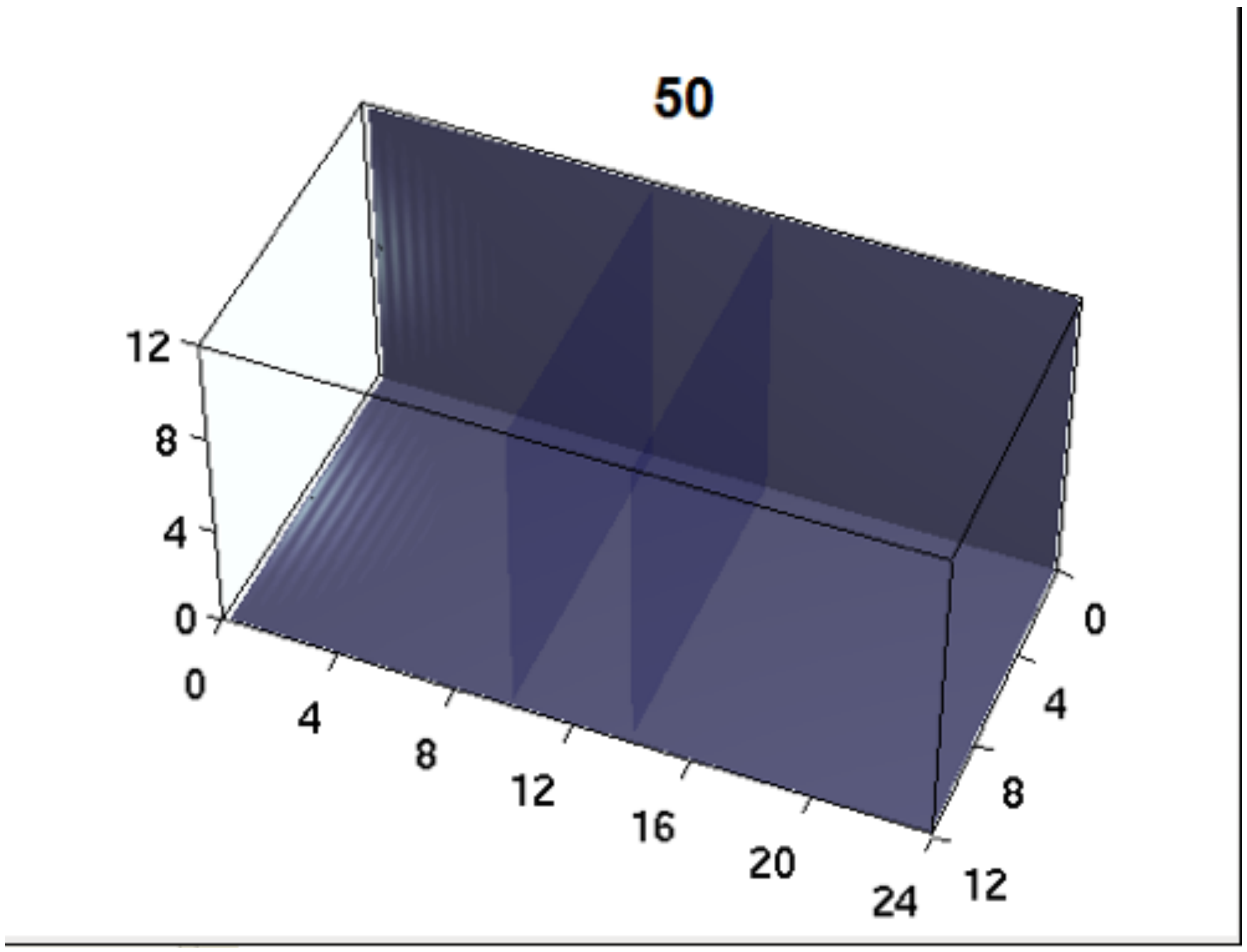
2 μm HWHM spotsize

- Two counter propagating laser pulses with crossed linear polarization impinging on a solid target from both sides
- Transmission of the laser pulses can be easily determined since transmitted field and reflected field have orthogonal polarization

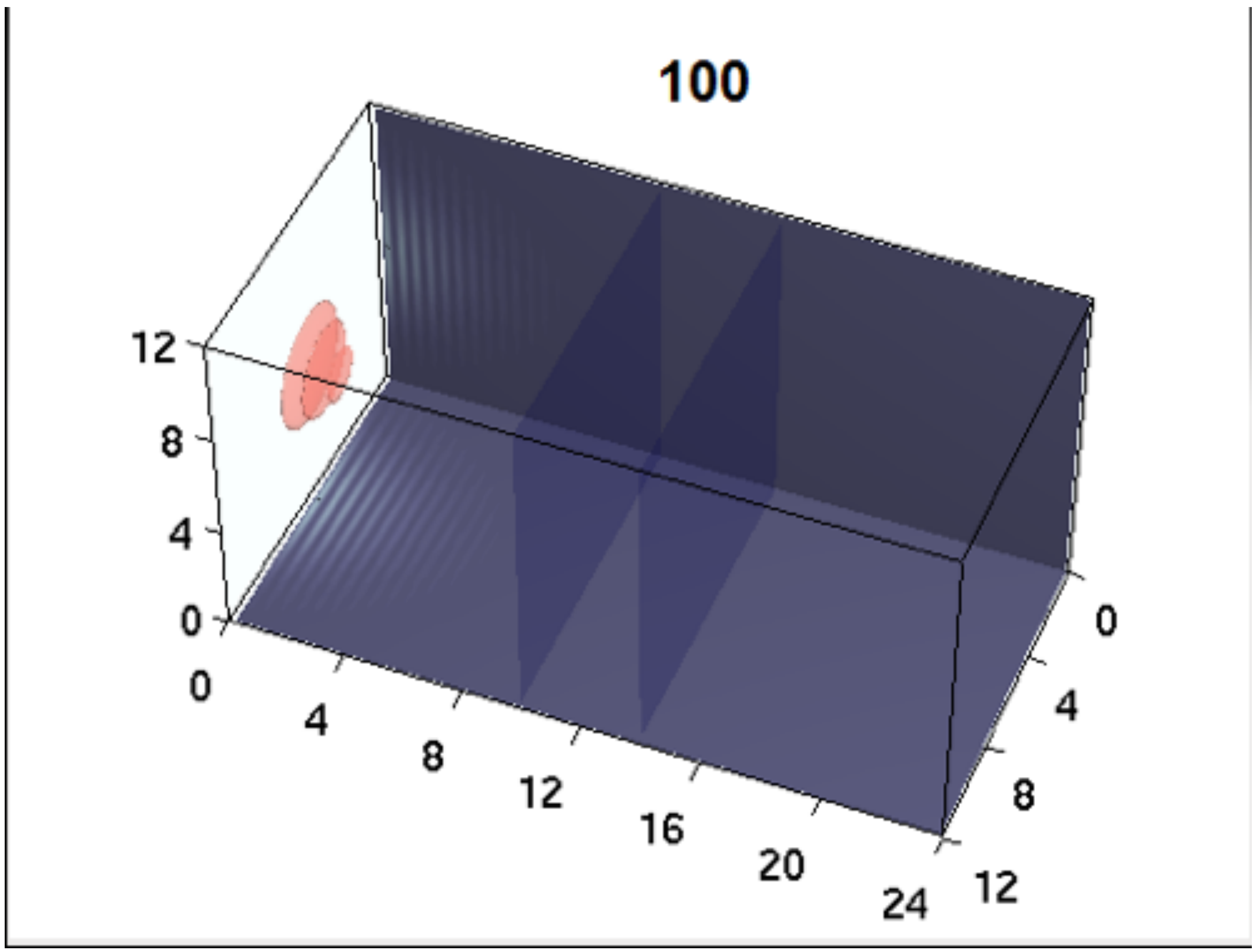
QED OFF



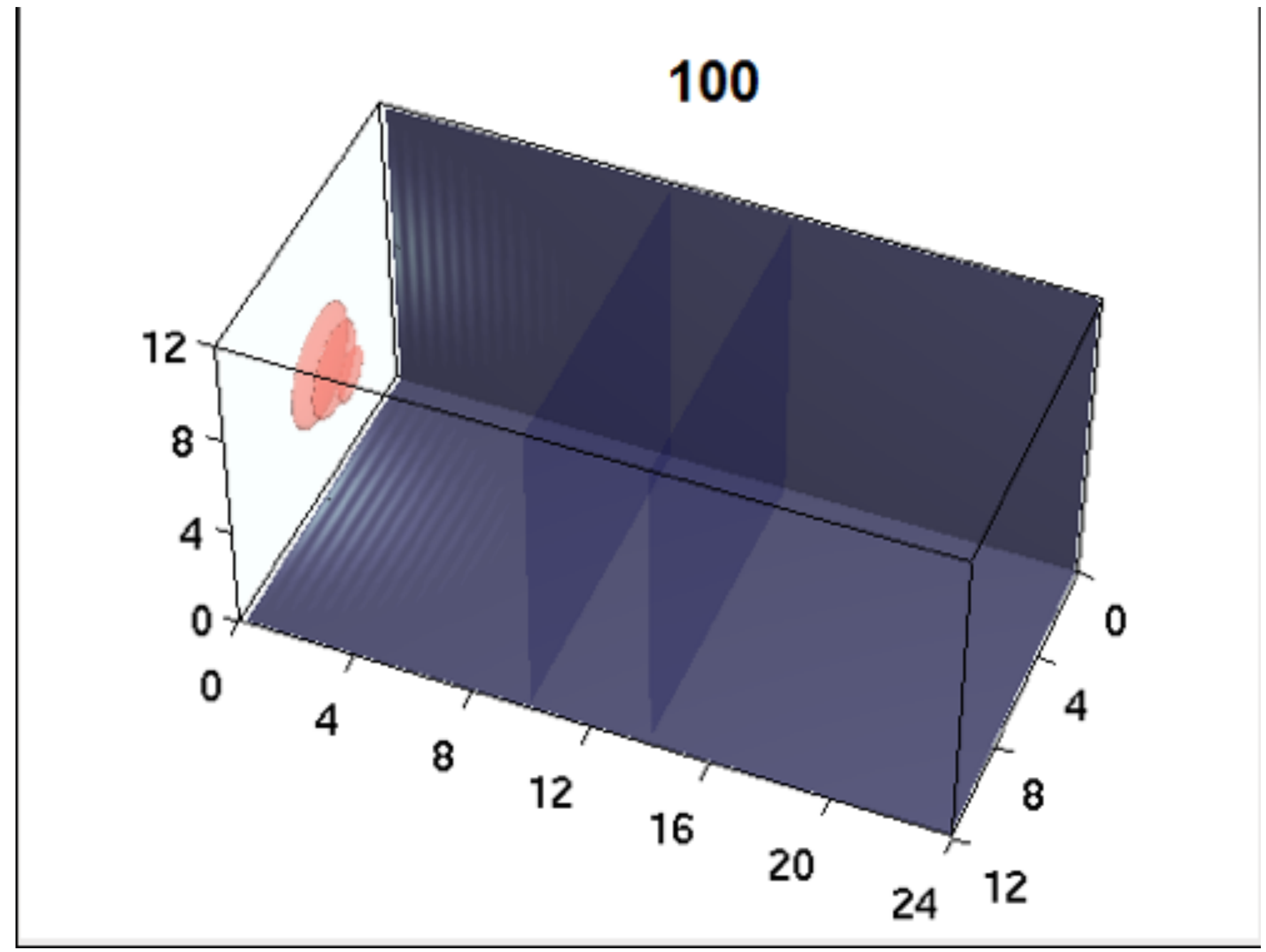
QED ON



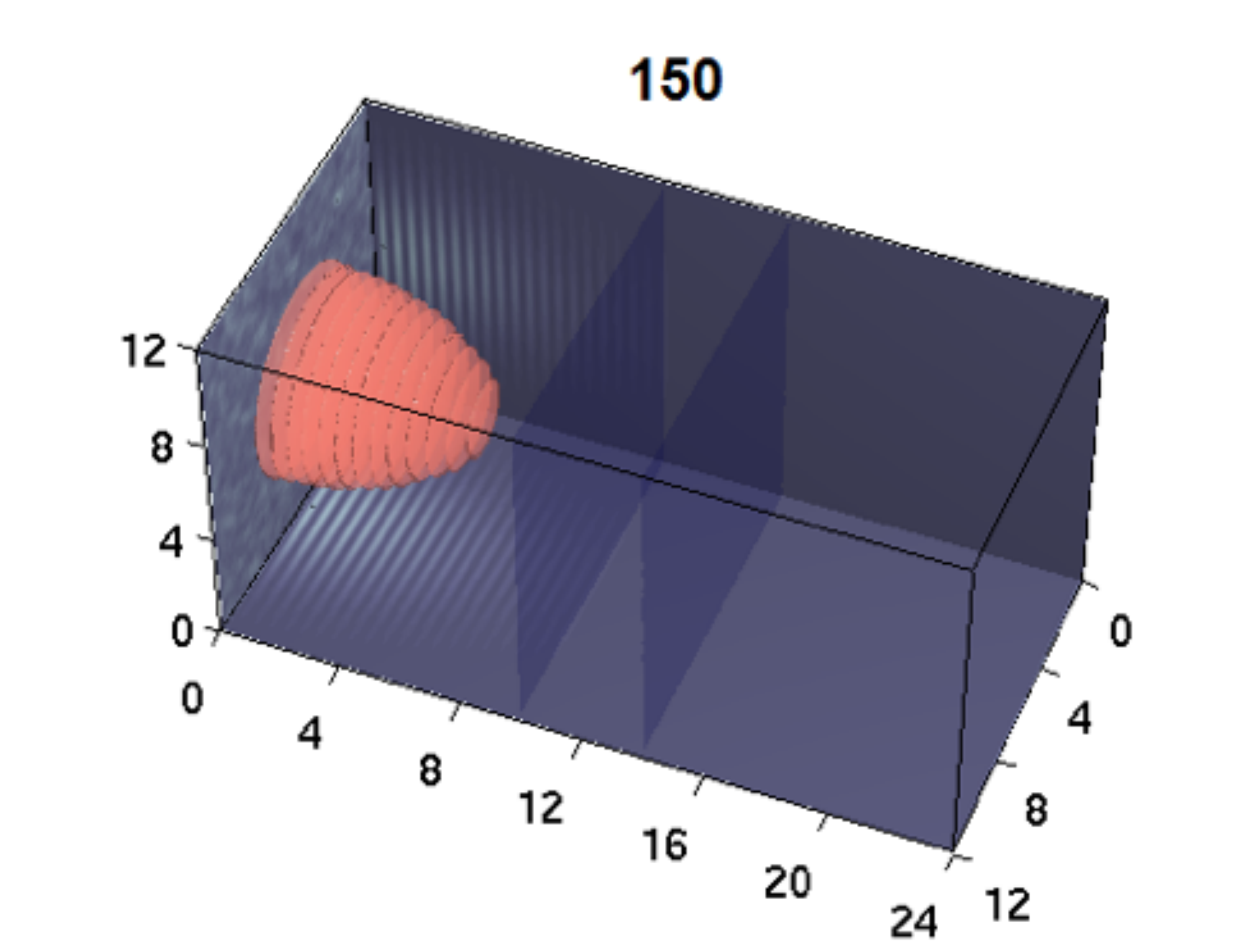
QED OFF



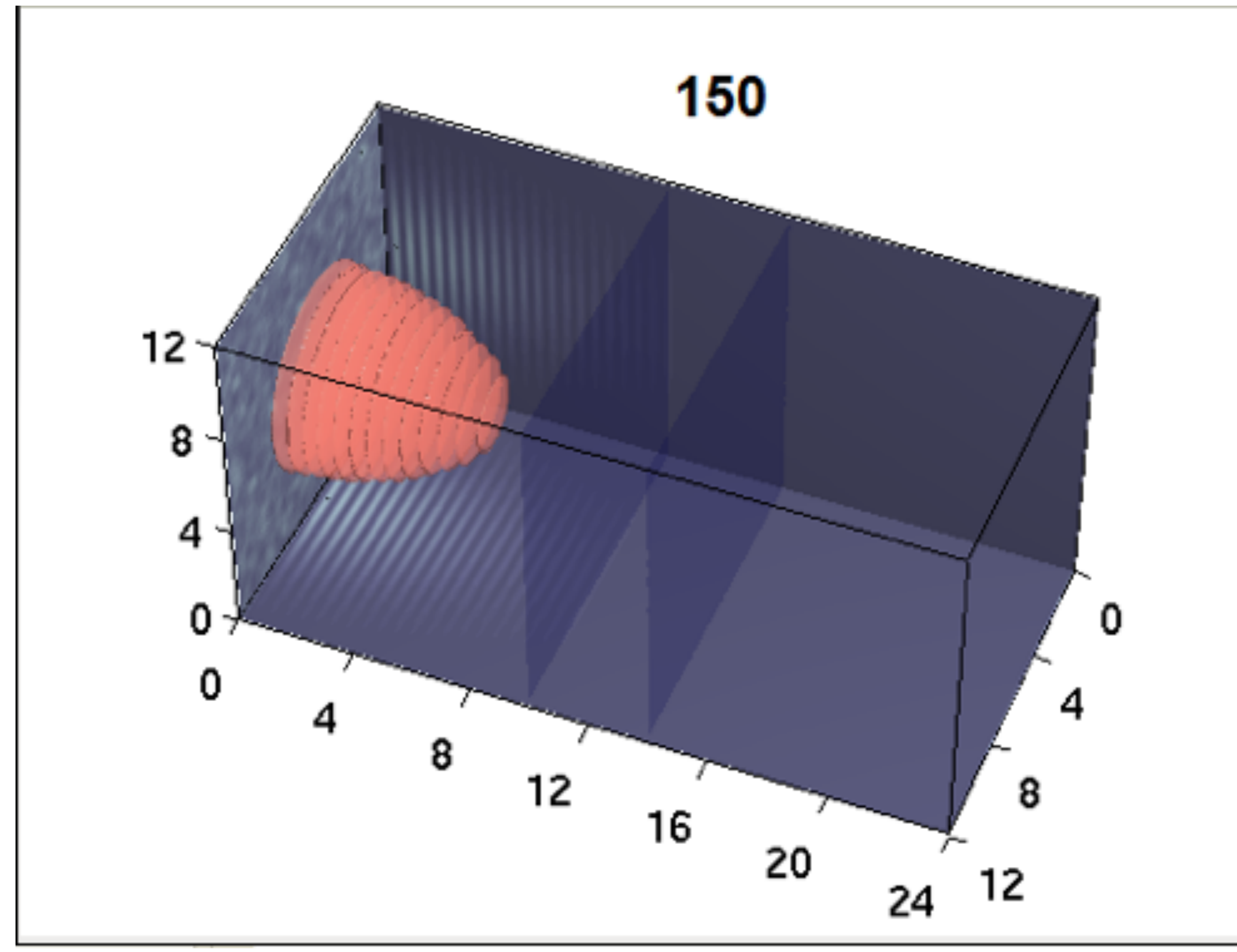
QED ON



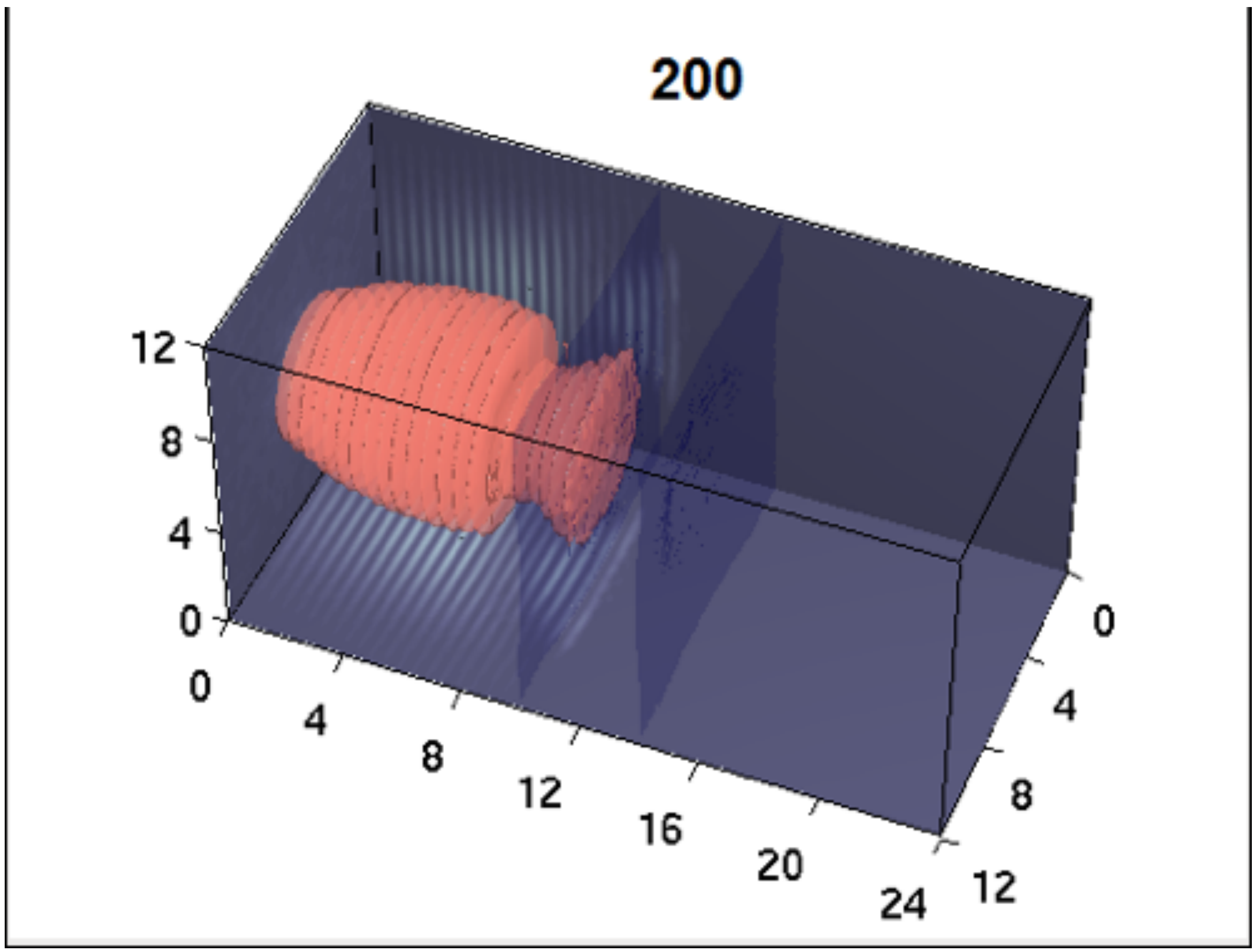
QED OFF



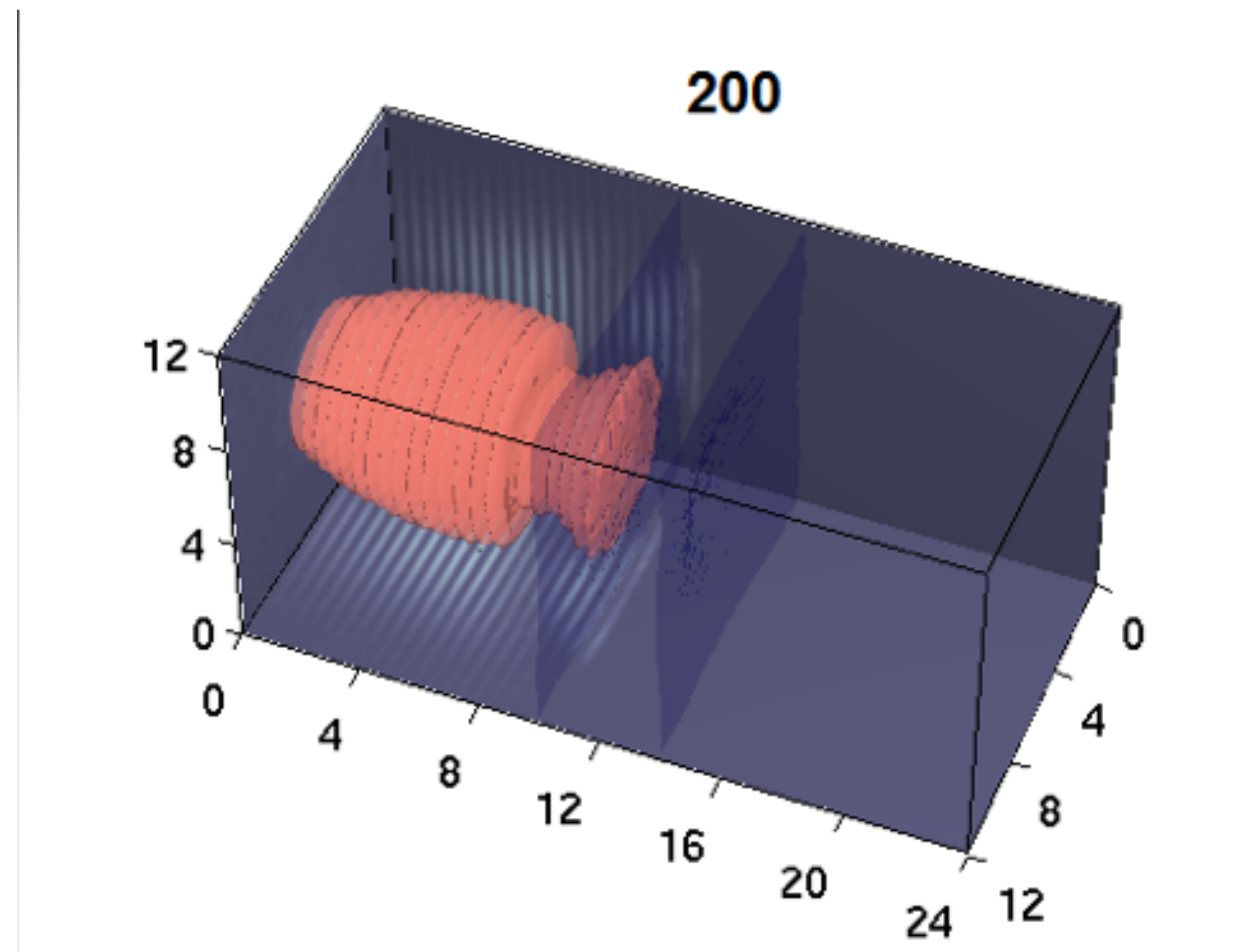
QED ON



QED OFF

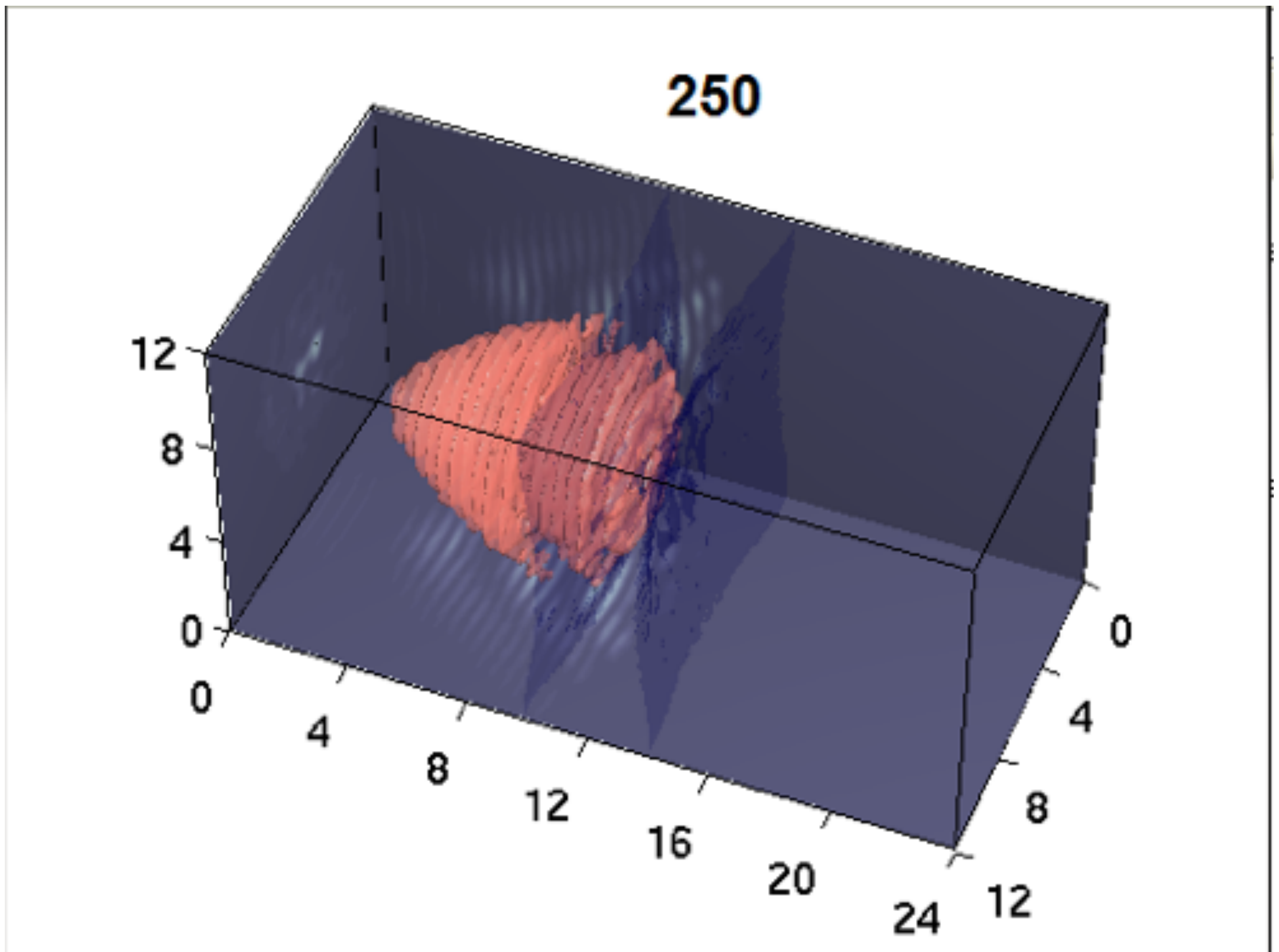


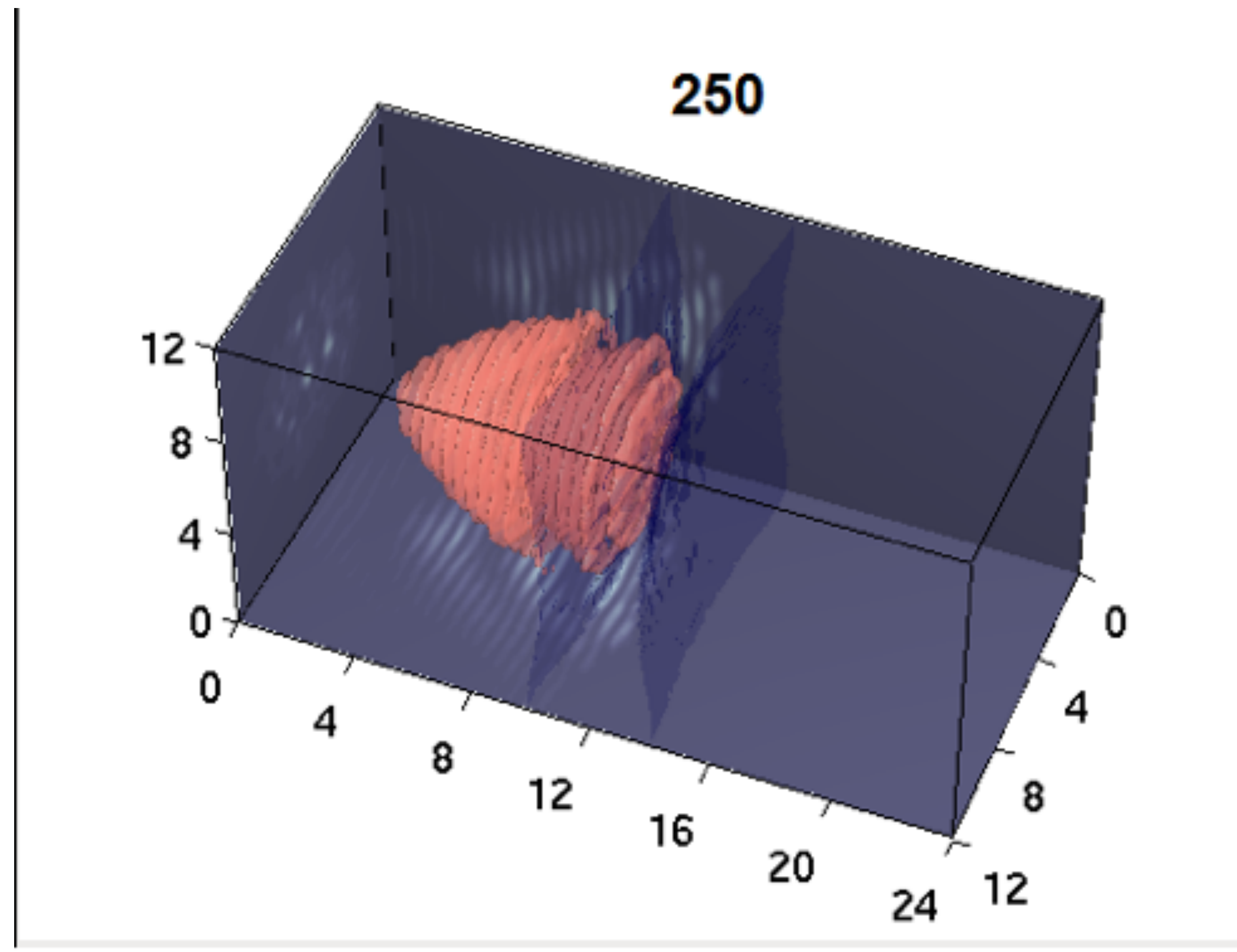
QED ON



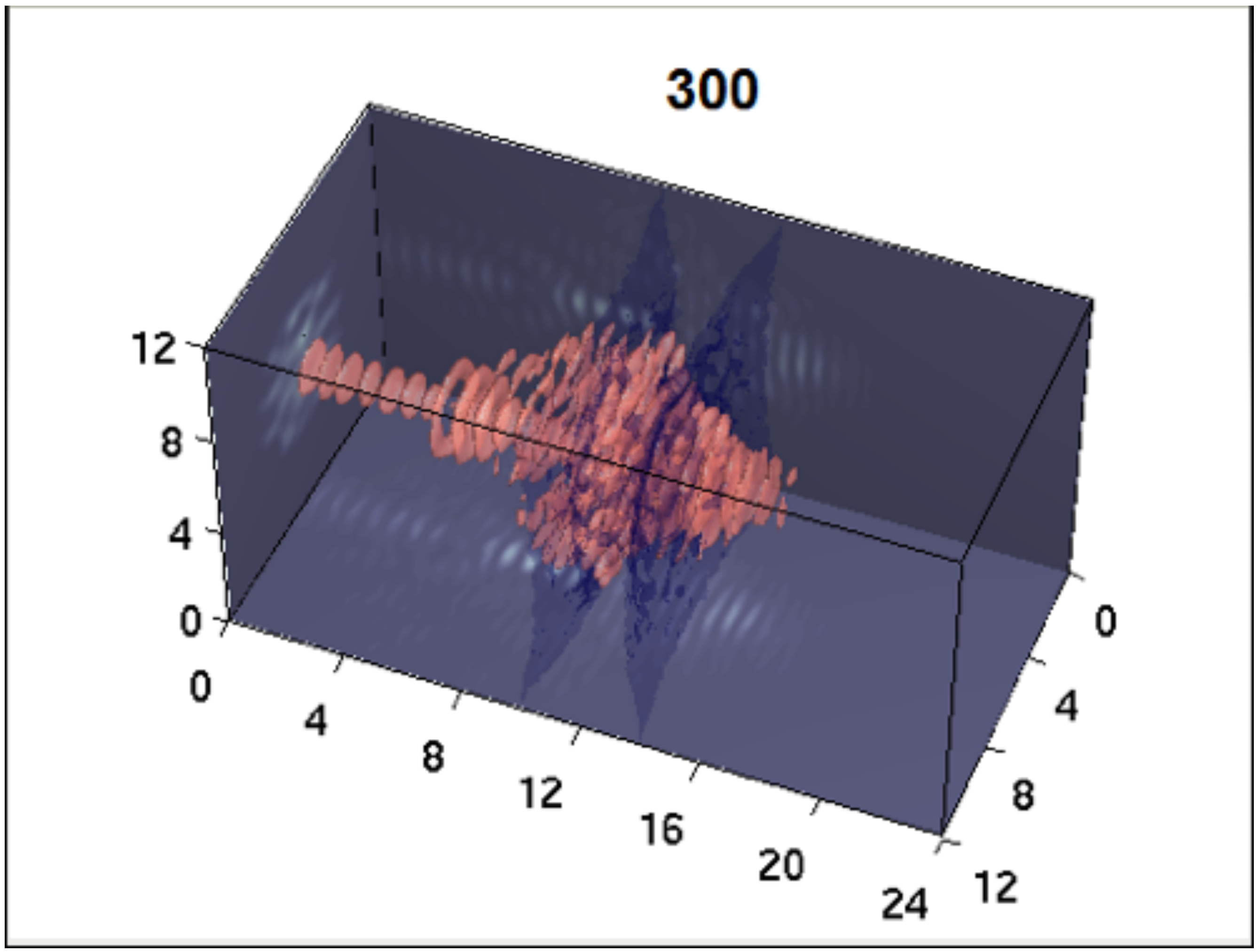
QED OFF

QED ON

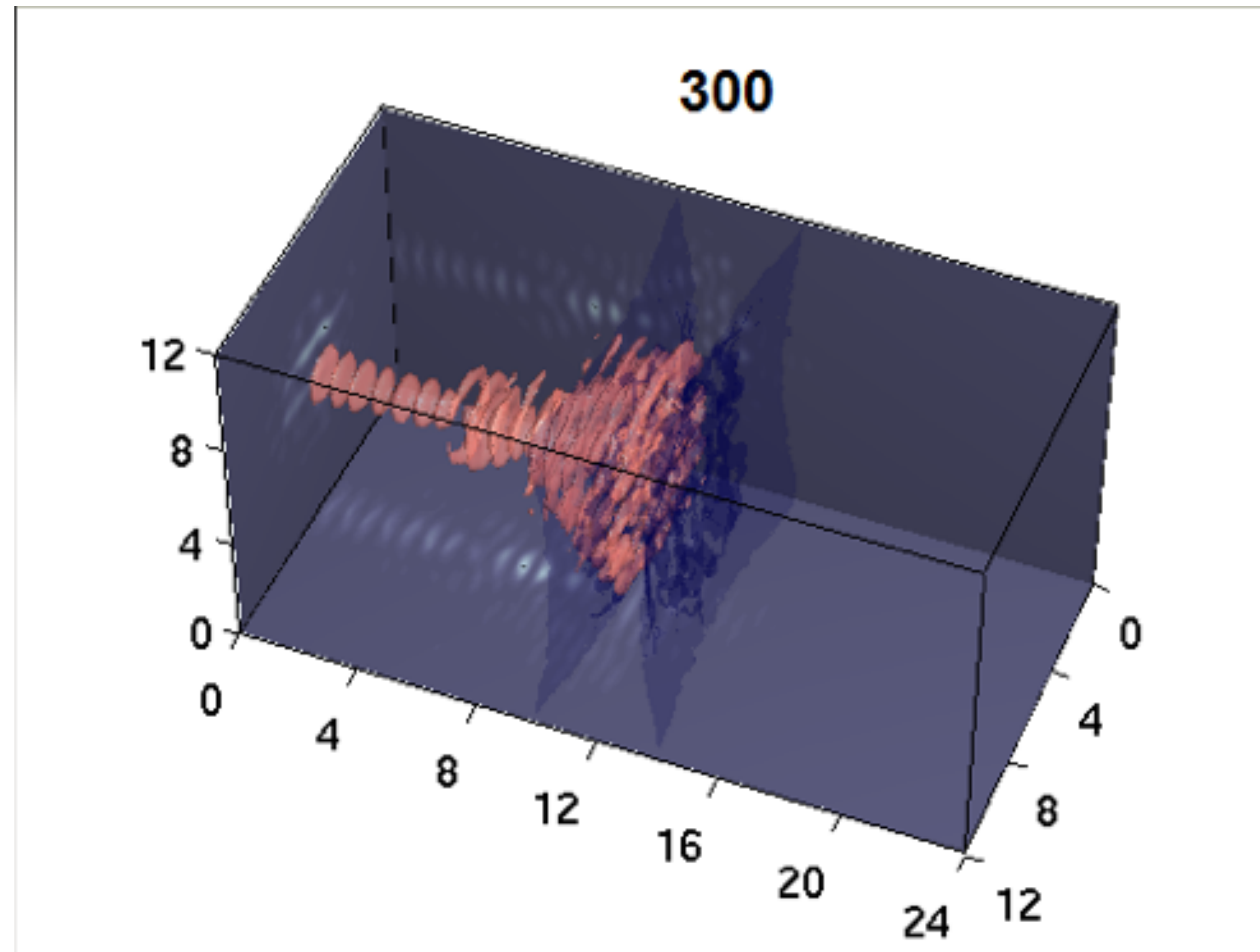




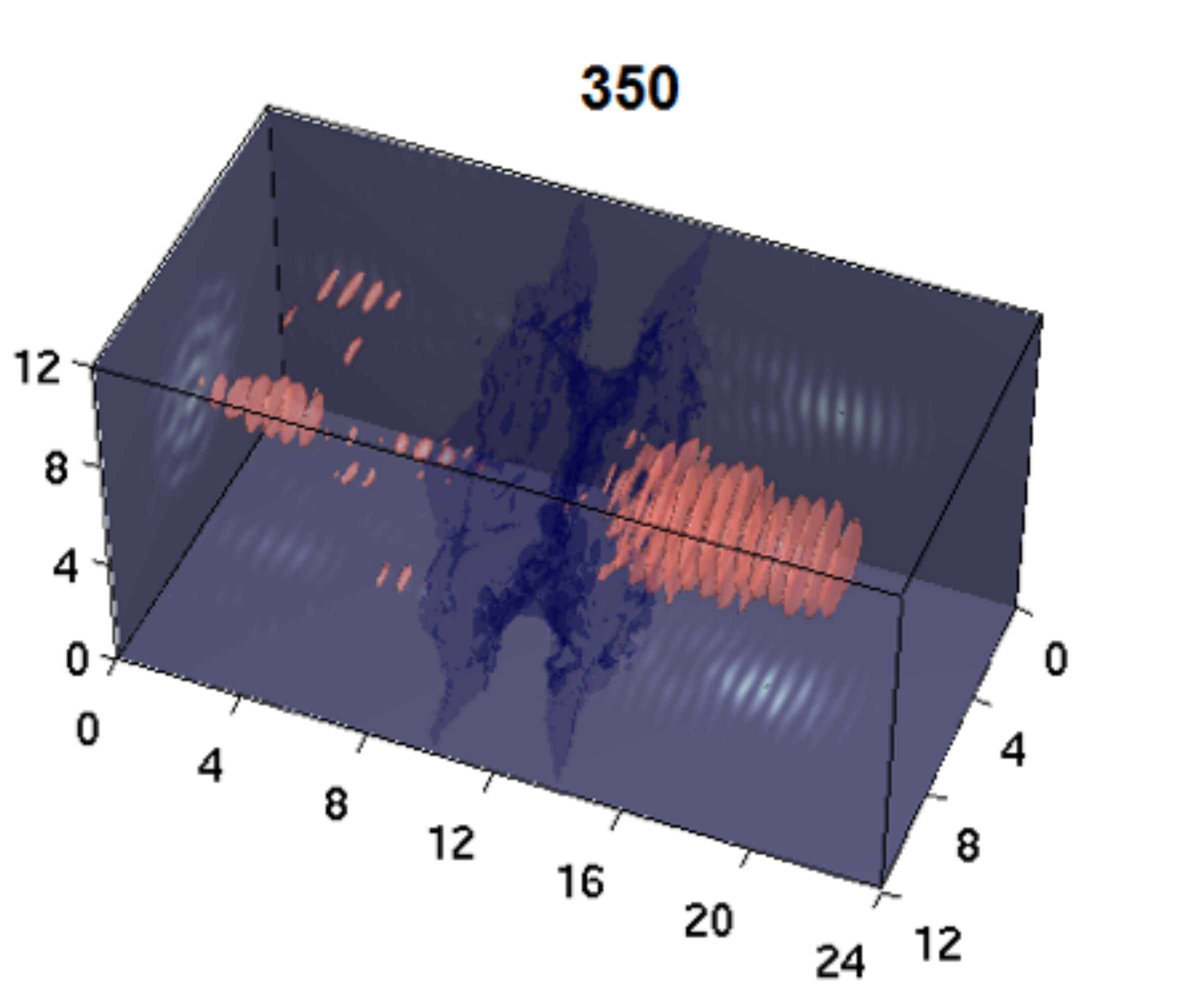
QED OFF



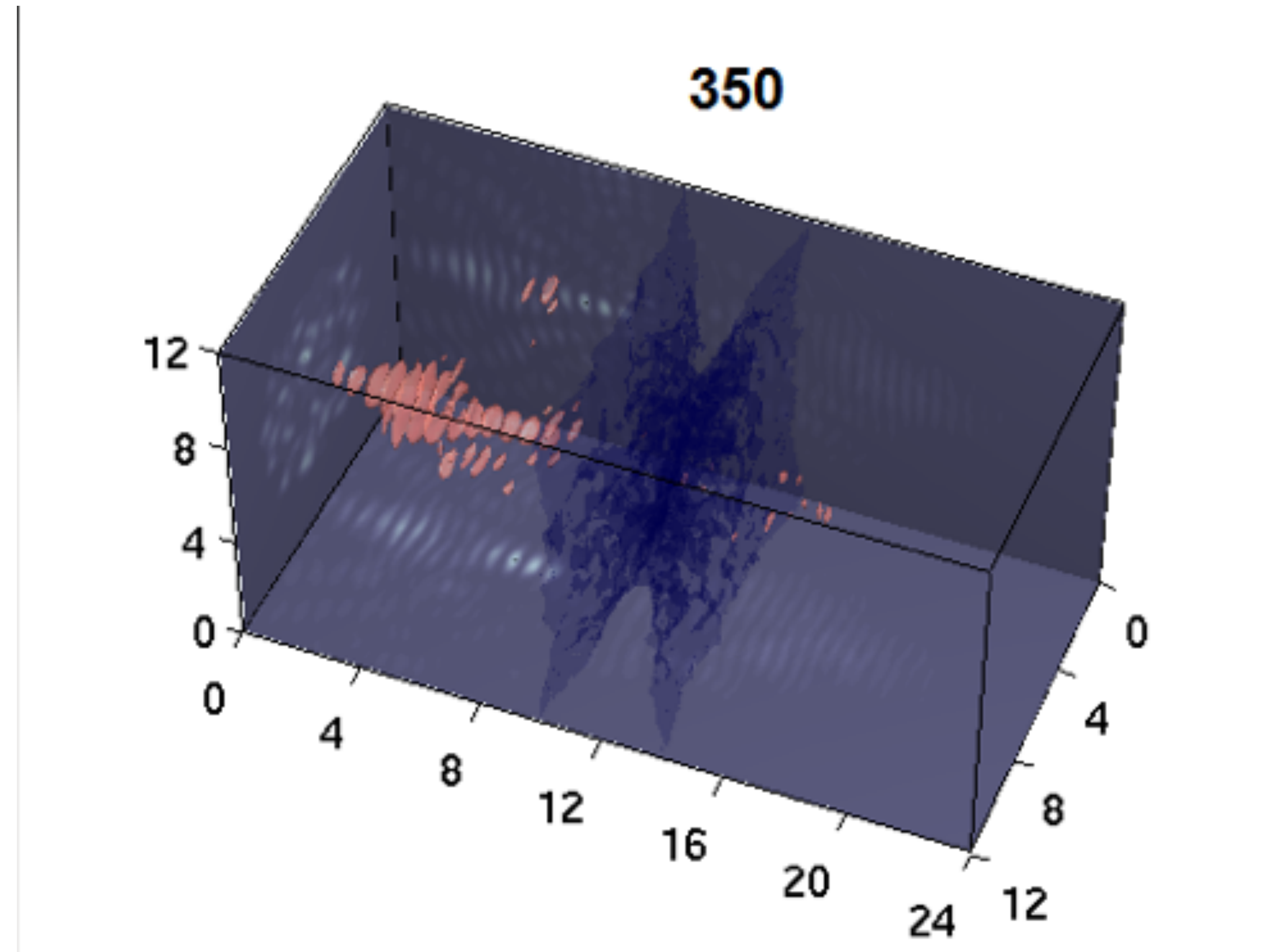
QED ON



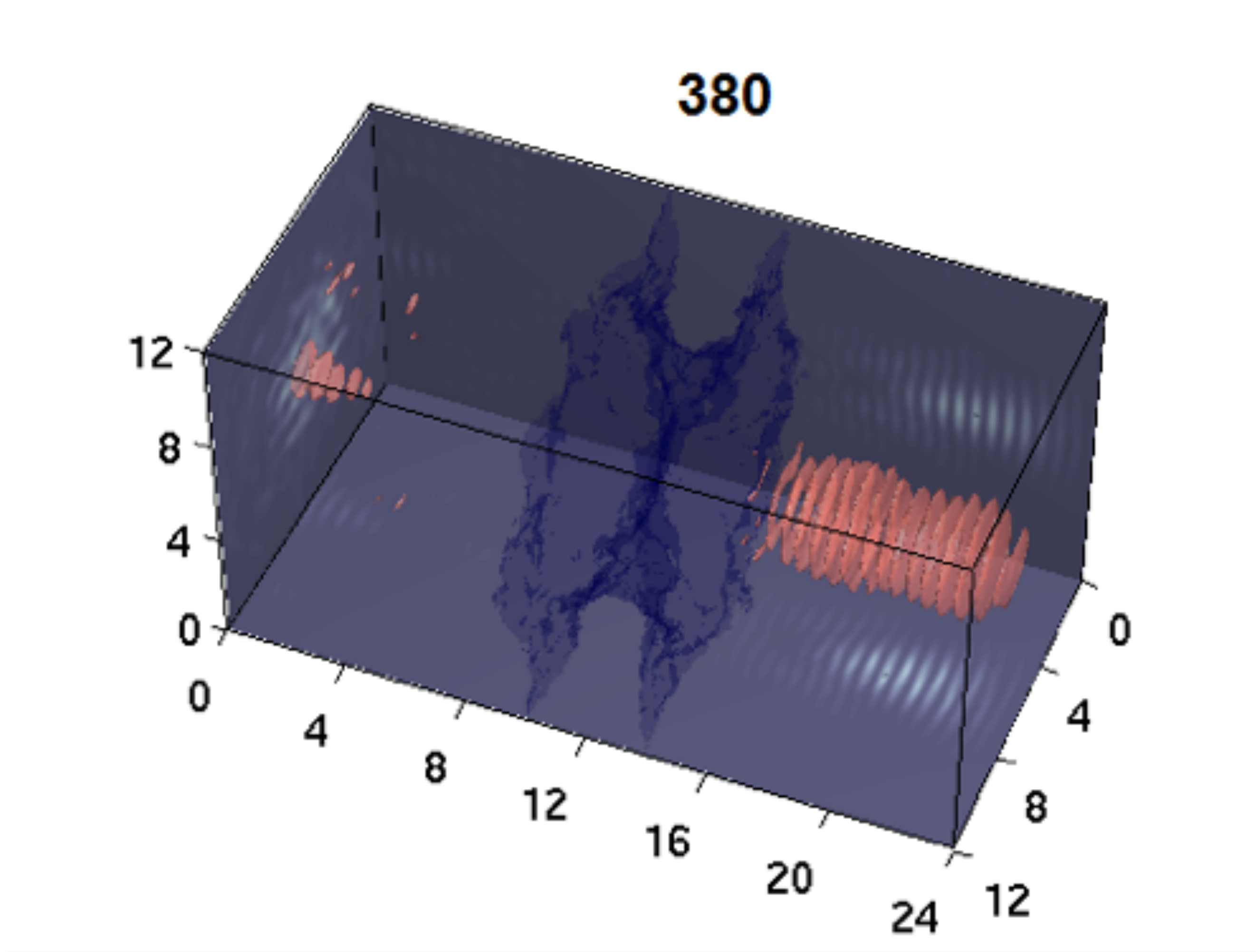
QED OFF



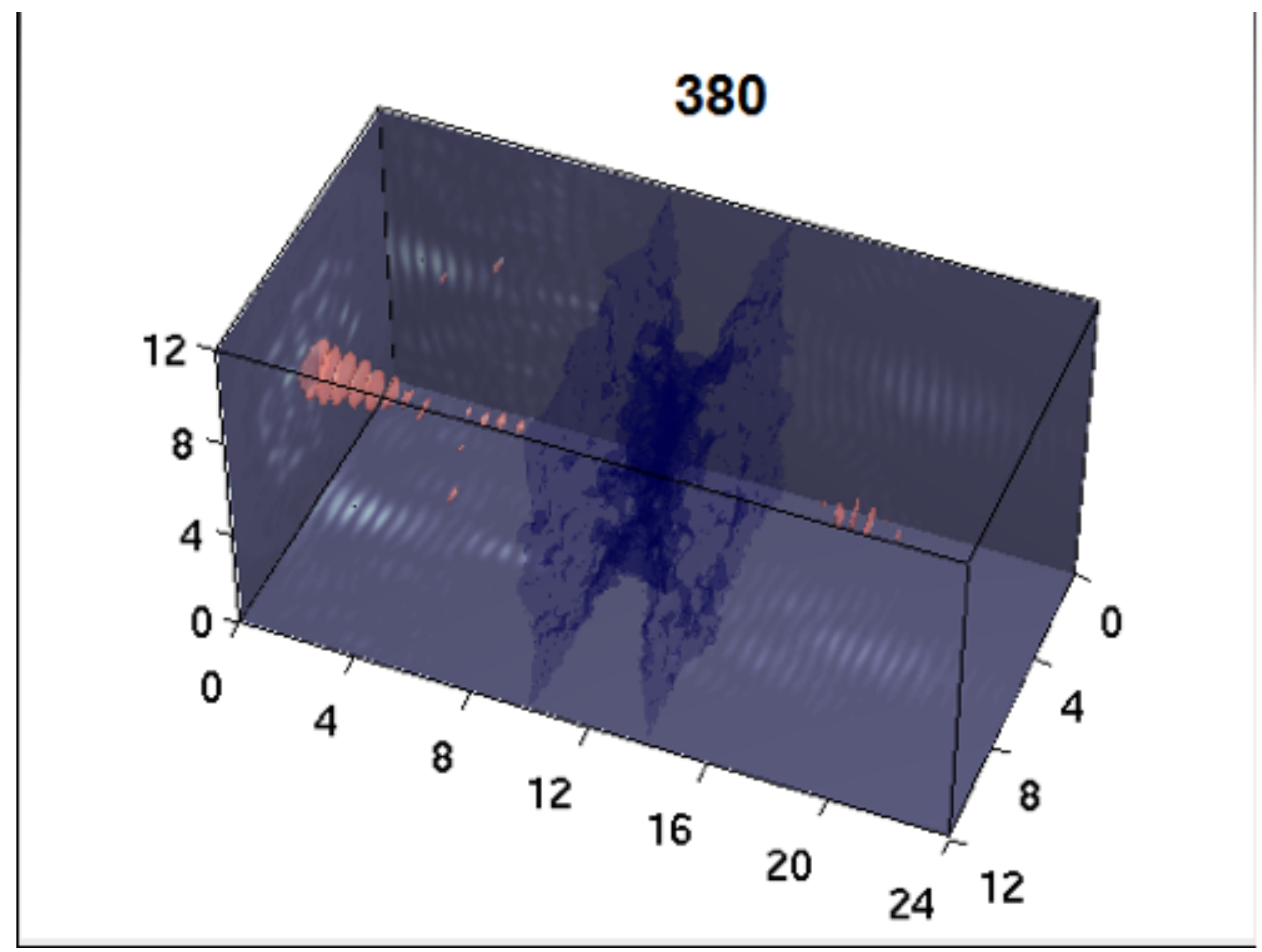
QED ON



QED OFF

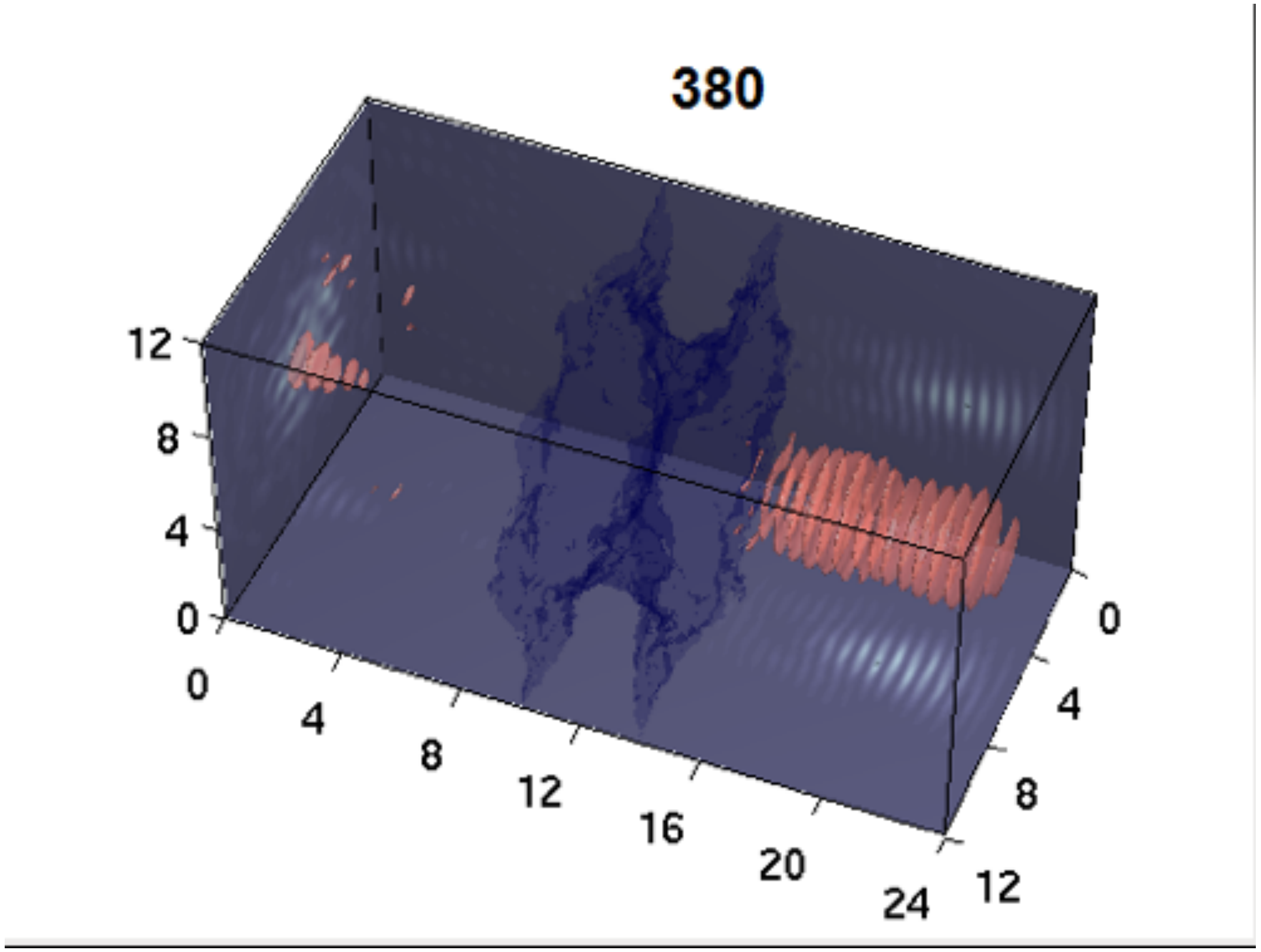


QED ON



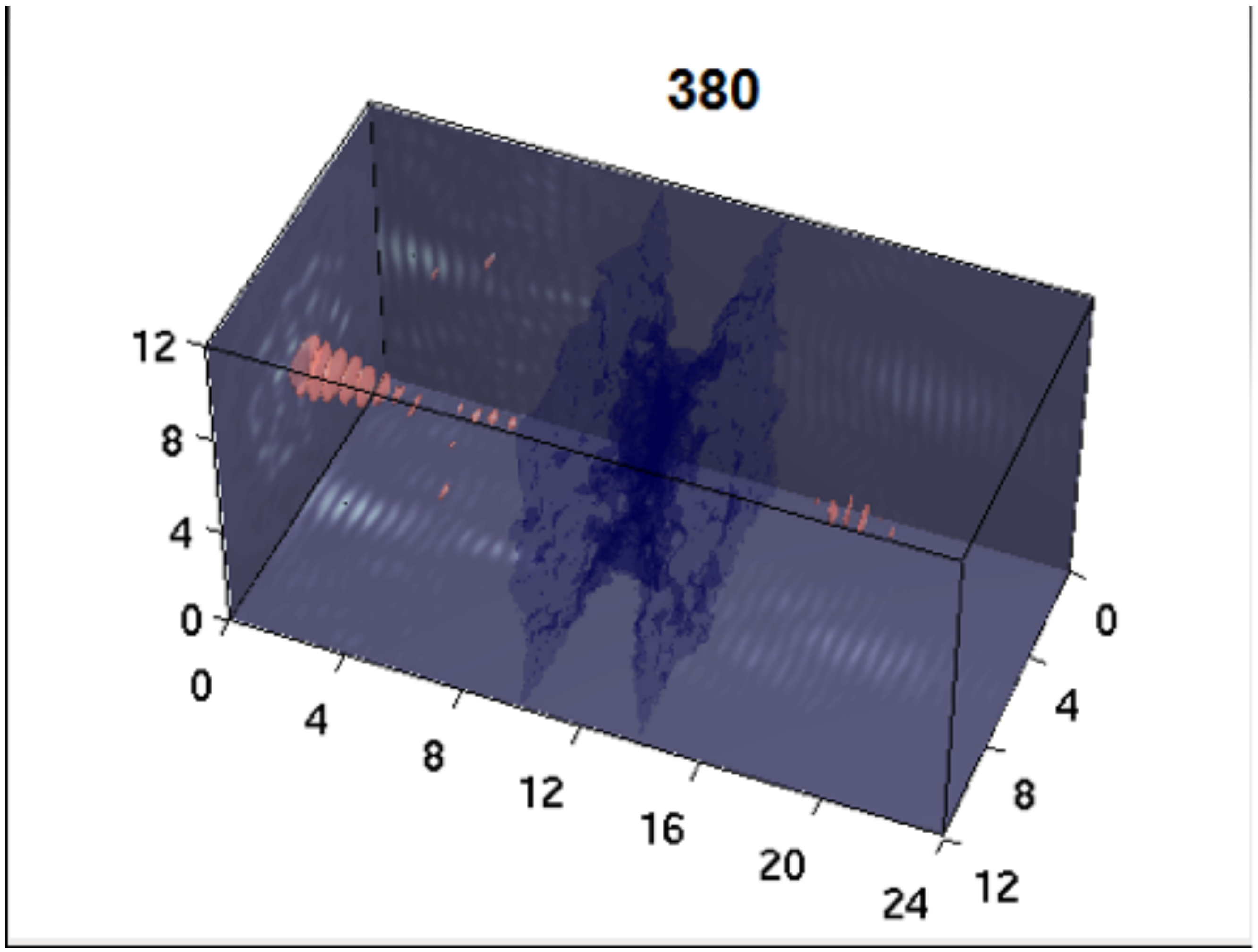
…. near binary result

QED OFF



T=60%

QED ON



T=5%

Relativistic transparency is suppressed by radiation reaction and pair plasma production

What experiments can be designed to *validate* the “QED-plasma” framework?

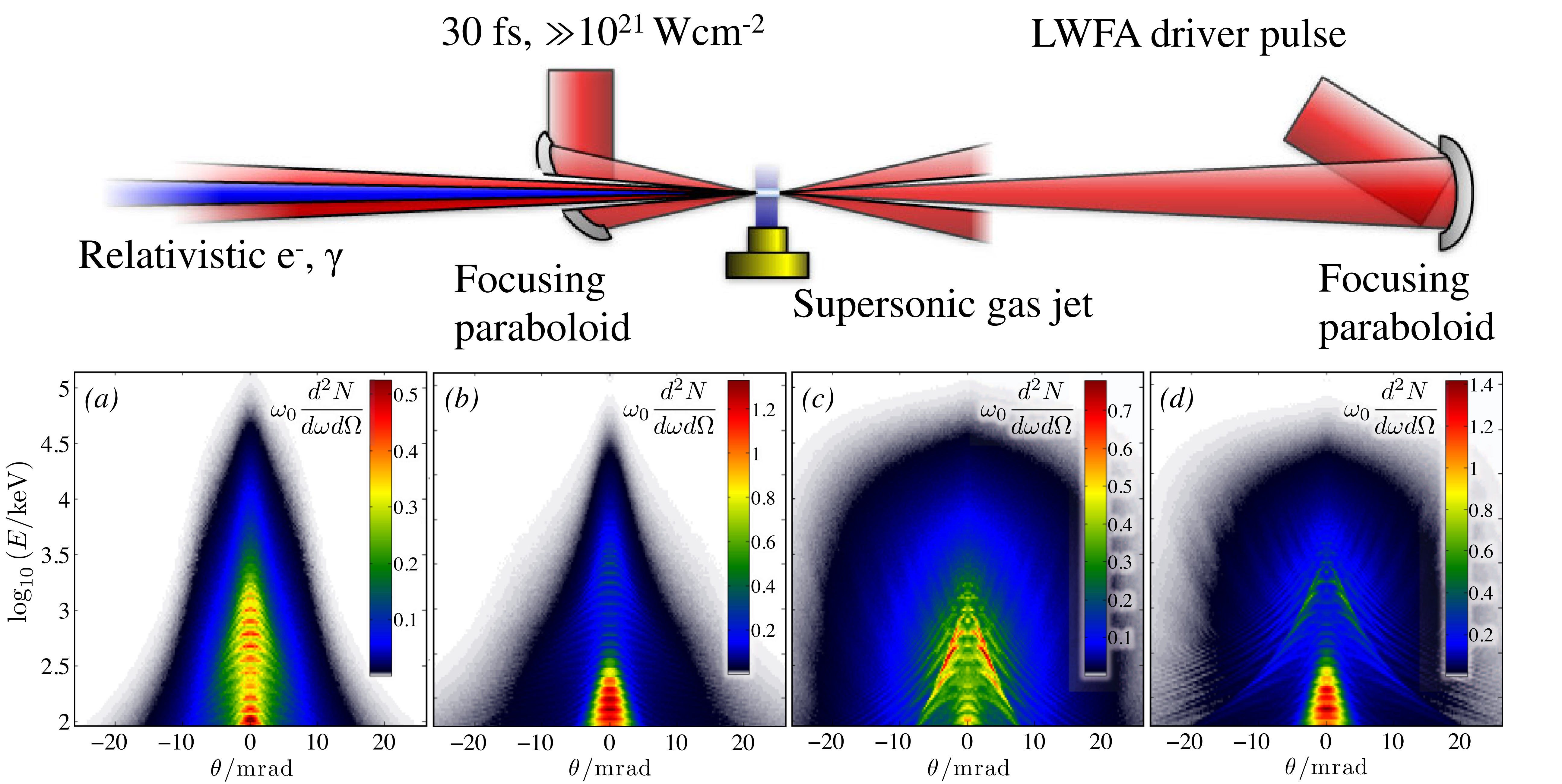
… precision tests, not “first observations”

… with realistic near term laser parameters!

Contents

- Strong Field Physics
- **Nonlinear Compton Scattering**
- Multiphoton Breit-Wheeler Pair production
- Experiment on BELLAi

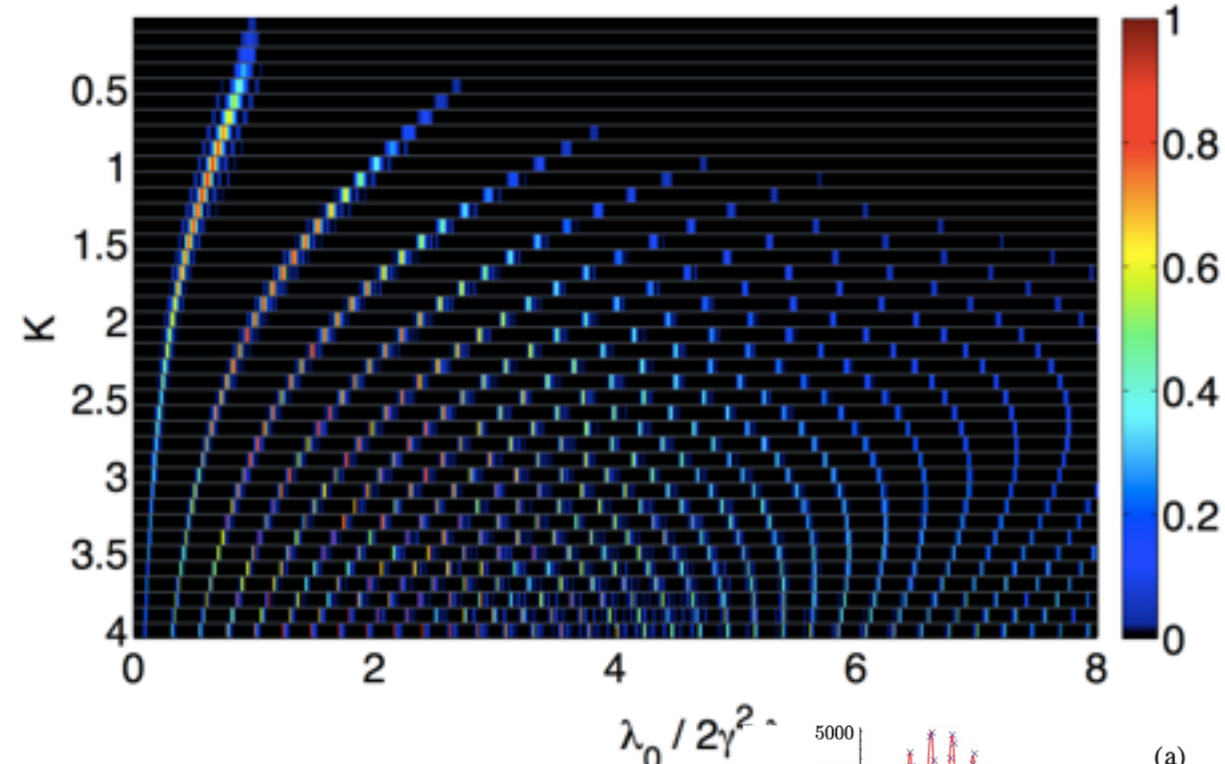
"All-optical" Nonlinear Compton Scattering



A.G.R. Thomas et al, Phys. Rev. X (2012)

Nonlinear Compton Scattering

- a_0 plays role of wiggler parameter for "optical wiggler"
- As a_0 increases, spectrum tends to synchrotron-like spectrum (Esarey PRE 1993)
- Recent work in quantum regime for short laser pulses



Heinzl et al (2009): $a_0 \sim 1$, $\chi \sim 1$
Mackenroth et al (2011): $a_0 >> 1$, $\chi \sim 1$
Seipt et al (2011): pulse shape

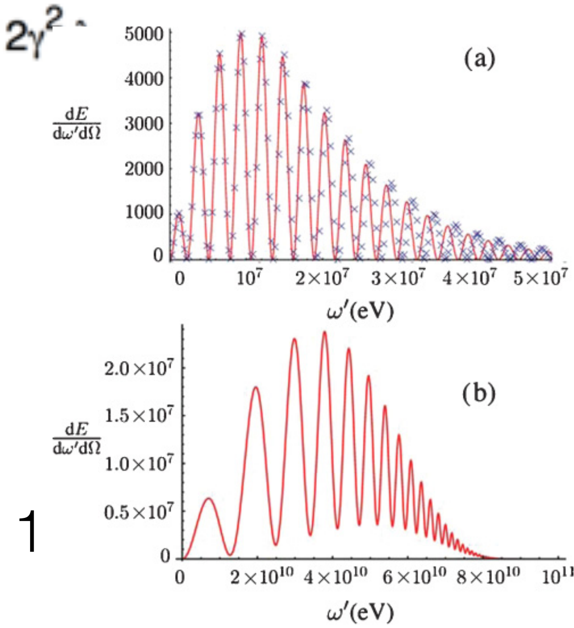


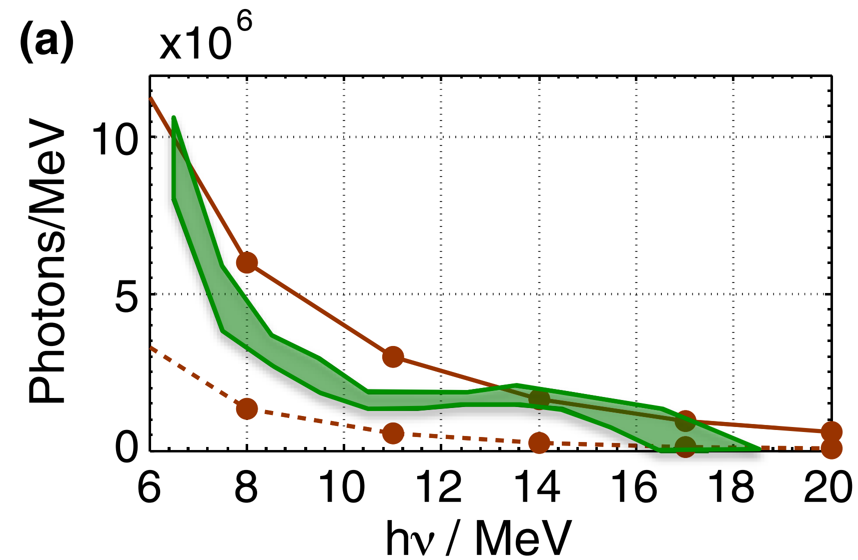
FIG. 10. (Color online) Energy emission spectra for $\xi = 5$ and (a) $\gamma = 2500$ ($\varrho \approx 2.5 \times 10^{-2}$) and (b) $\gamma = 2 \times 10^5$ ($\varrho \approx 0.8$). The crosses in (a) have been obtained by a classical calculation.

(Nonlinear) Inverse Compton Experiments

All optical inverse Compton source

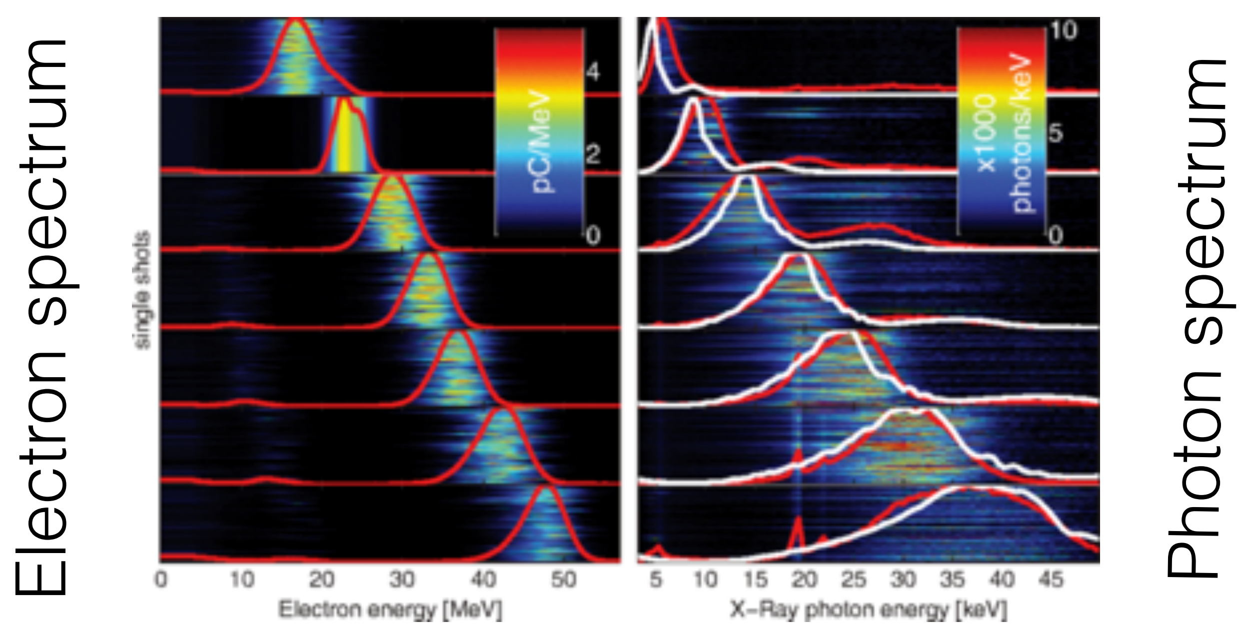
Ta Phuoc Nature Pho. (2012)
Chen PRL (2013)
Powers Nature Pho (2014)
G. Sarri PRL (2014)
Khrennikov et al PRL (2015)

Nonlinear Compton scattering on Gemini (2x500 TW)



G. Sarri et al, PRL (2014)

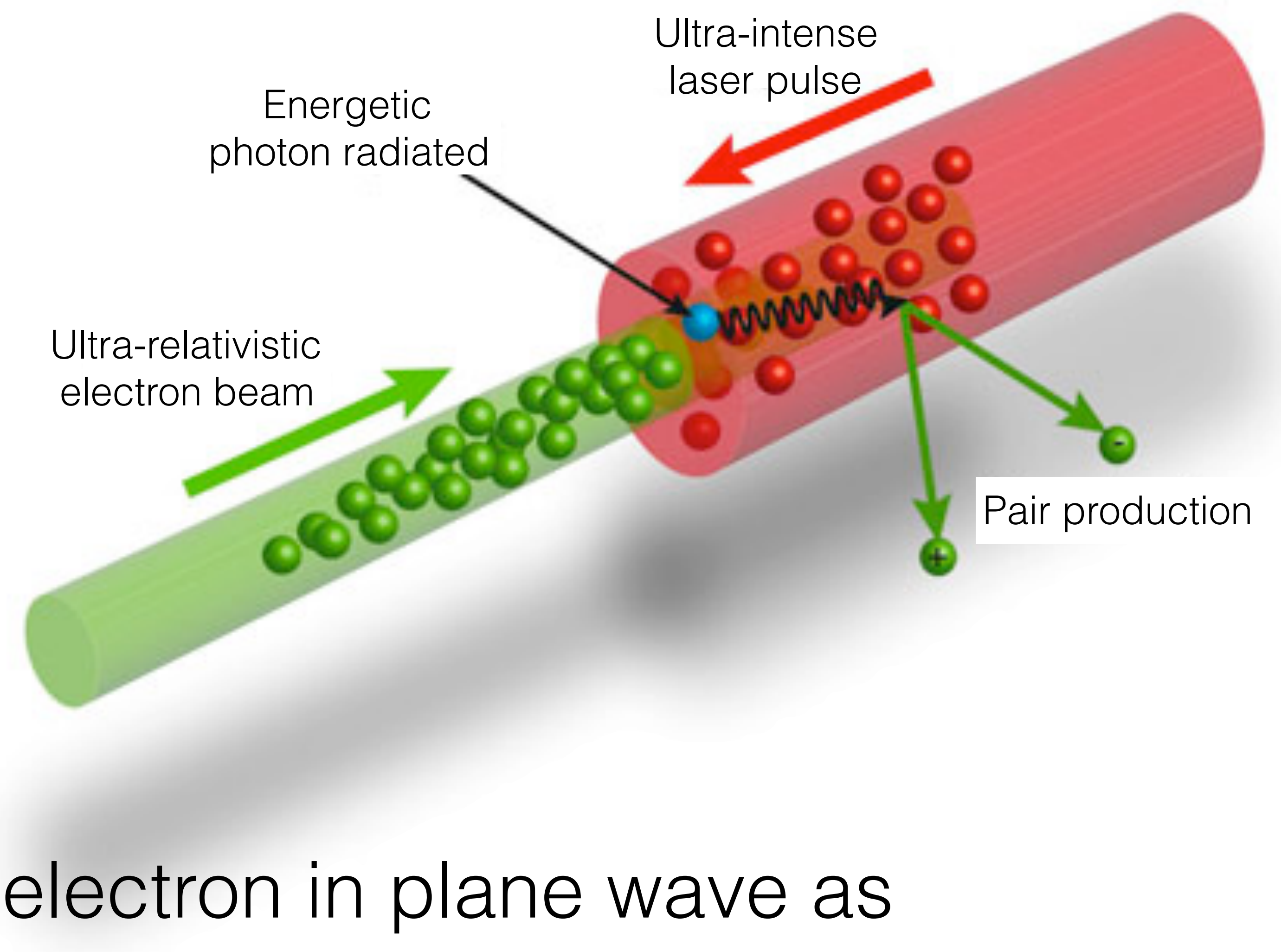
Tunable monochromatic photon source…



Khrennikov et al PRL (2015)

- Only all optical nonlinear Compton data so far
- $a_0 = 2$ (weakly nonlinear)
- Broad energy spread

Colliding LWFA/ laser geometry



$$\chi_e = \frac{||F_{\mu\nu} v^\nu||}{E_{cr}}$$

- Can write this expression for electron in plane wave as

$$\chi_e = \frac{v \cdot k|A|}{E_{cr}} = \gamma a_0 \frac{\lambda_C}{\lambda_0} (1 - \beta \cos\theta)$$

- …Maximized for electron direction opposite to laser propagation
    - for 800 nm laser, colliding

$$\chi_e \approx 0.3 \frac{E}{\text{GeV}} \sqrt{\frac{I}{10^{21}\ \text{Wcm}^{-2}}}$$

BELLA-i - a facility for high energy density physics and discovery plasma science at Berkeley Lab

BELLA-i	1	2	3
peak intensity (W/cm^2)	**2×10^{19}**	~~3×10^{21}~~ 1.5×10^{21} Wcm^{-2}	3×10^{21}
pulse length	**30 fs**	30 fs	30 fs
peak pulse energy	~~40 J~~ 20 J	~~40 J~~ 20 J	40 J
laser spot size	**55 µm**	5 µm	5 µm
peak repetition rate	**1 Hz***	1 Hz*	1 Hz
contrast (ns)	**10^{-10}**	10^{-10}	$>10^{-14}$
diagnostics (details to be determined)	• **optical spectrometers** • ion and electron spectrometers • ... 5 GeV LWFA	• optical pump- probe • betatron x-rays • MeV protons • ...	• same as 2 • beamline for experiments with laser accelerated ions • ...
1st access (estimates)	**2017-2018**	2018-2019	2019-2020

1. **experiments with the existing, long focal length BELLA beamline in the existing cave**

$$\chi_e \approx 0.3 \frac{E}{\mathrm{GeV}} \sqrt{\frac{I}{10^{21}\ \mathrm{Wcm}^{-2}}}$$

Radiation Reaction with Intense Laser-Electron Interactions

- As chi increases, (quantum) radiation reaction starts to modify emission spectrum

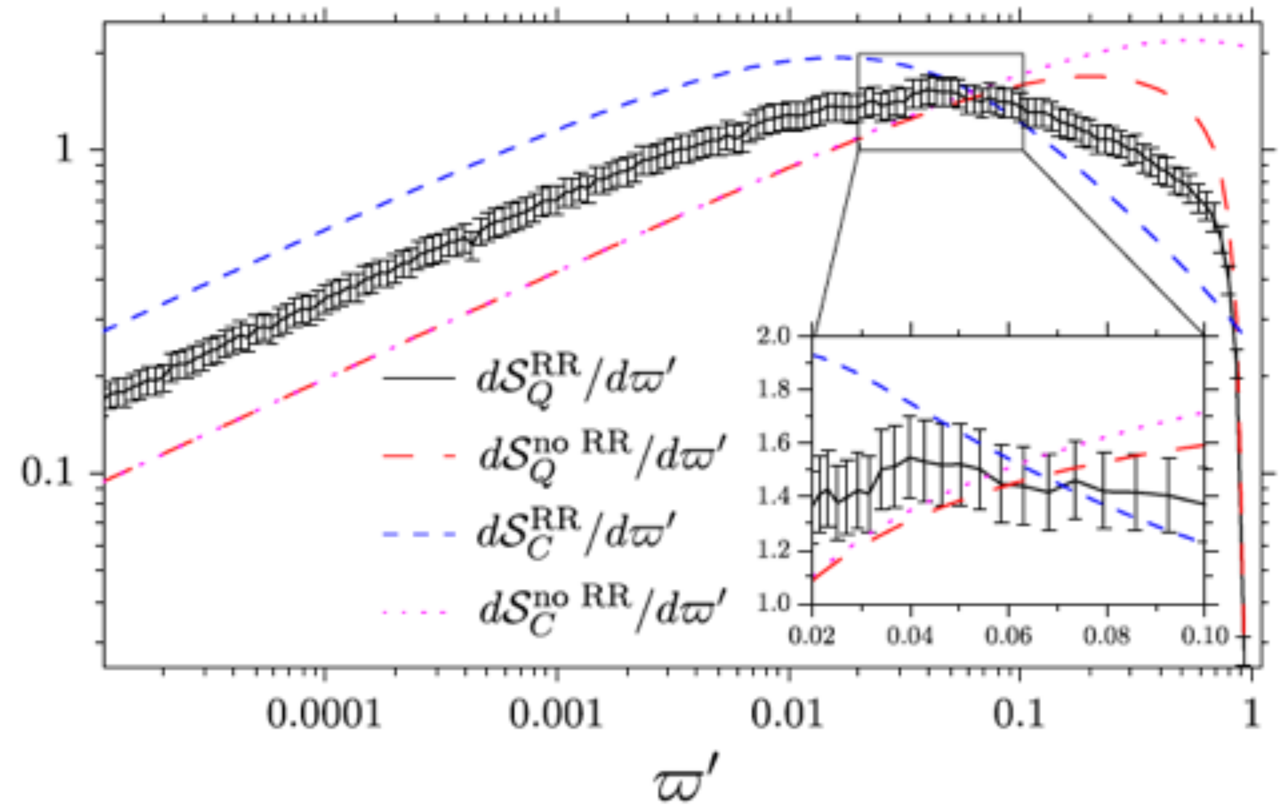
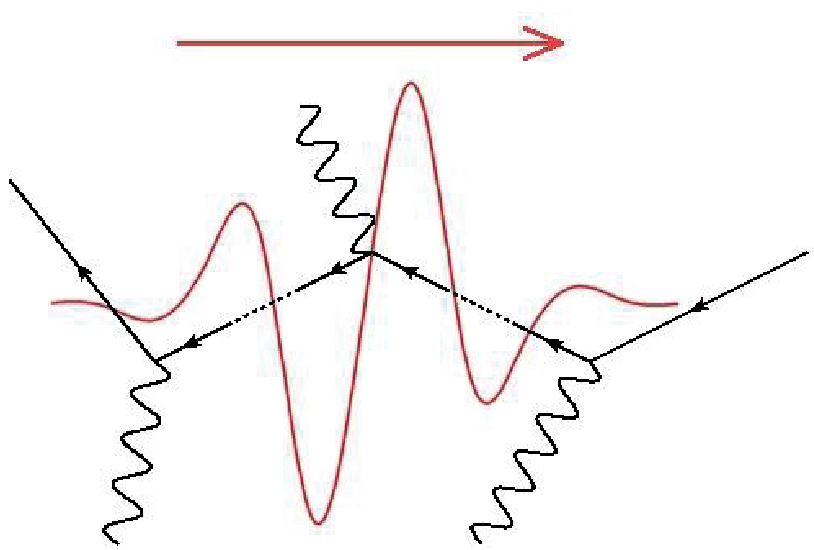


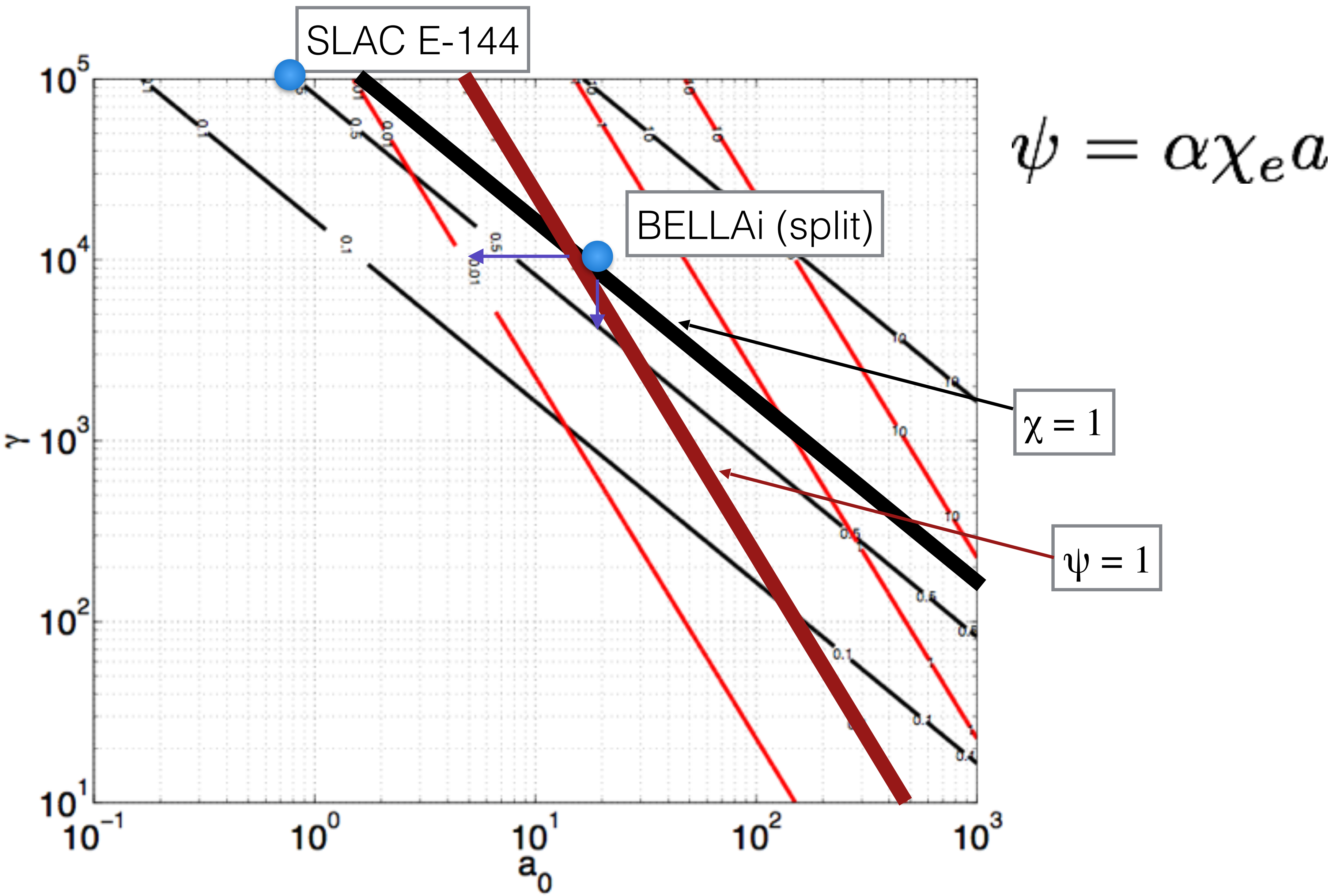
FIG. 11 (color online). Quantum photon spectra as a function of $\varpi' = k'_-/p_{0,-}$ calculated with (solid line) and without (long dashed line) RR and the corresponding classical ones with (short dashed line) and without (dotted line) RR. The error bars in the quantum spectrum with RR stem from numerical uncertainties in multi-dimensional integrations. The numerical parameters in our notation are $\varepsilon_0 = 1$ GeV, $\omega_0 = 1.55$ eV, and $I_0 = 10^{23}$ W/cm^2 ($R_Q = 1.1$ and $\chi_0 = 1.8$). Adapted from Di Piazza, Hatsagortsyan, and Keitel, 2010.



Beyond E-144

	I / Wcm^{-2}	E / GeV	a_0	χ
SLAC E144	10^{18}	46.6	0.8	0.4
BELLAi (2x500 TW)	$1.5\text{x}10^{21}$	5	30	2
BELLA +BELLA10 (10 PW laser)	$3\text{x}10^{22}$	10	120	15

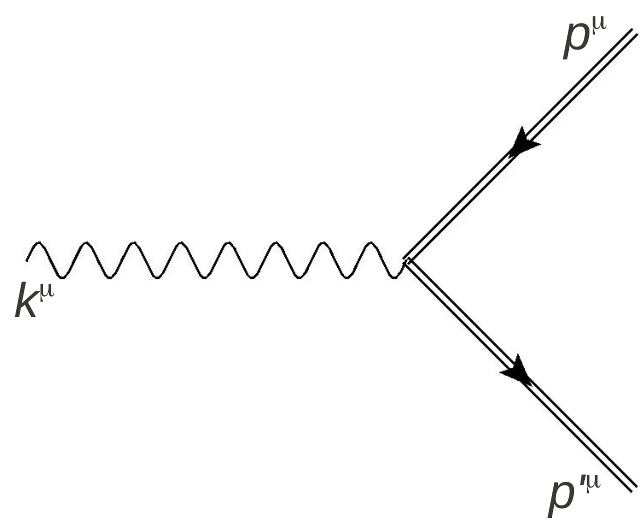
MultiPW lasers can probe QED/RR parameter regimes



Contents

- Strong Field Physics
- Nonlinear Compton Scattering
- **Multiphoton Breit-Wheeler Pair production**
- Experiment on BELLAi

MultiPW lasers can probe QED/RR parameter regimes



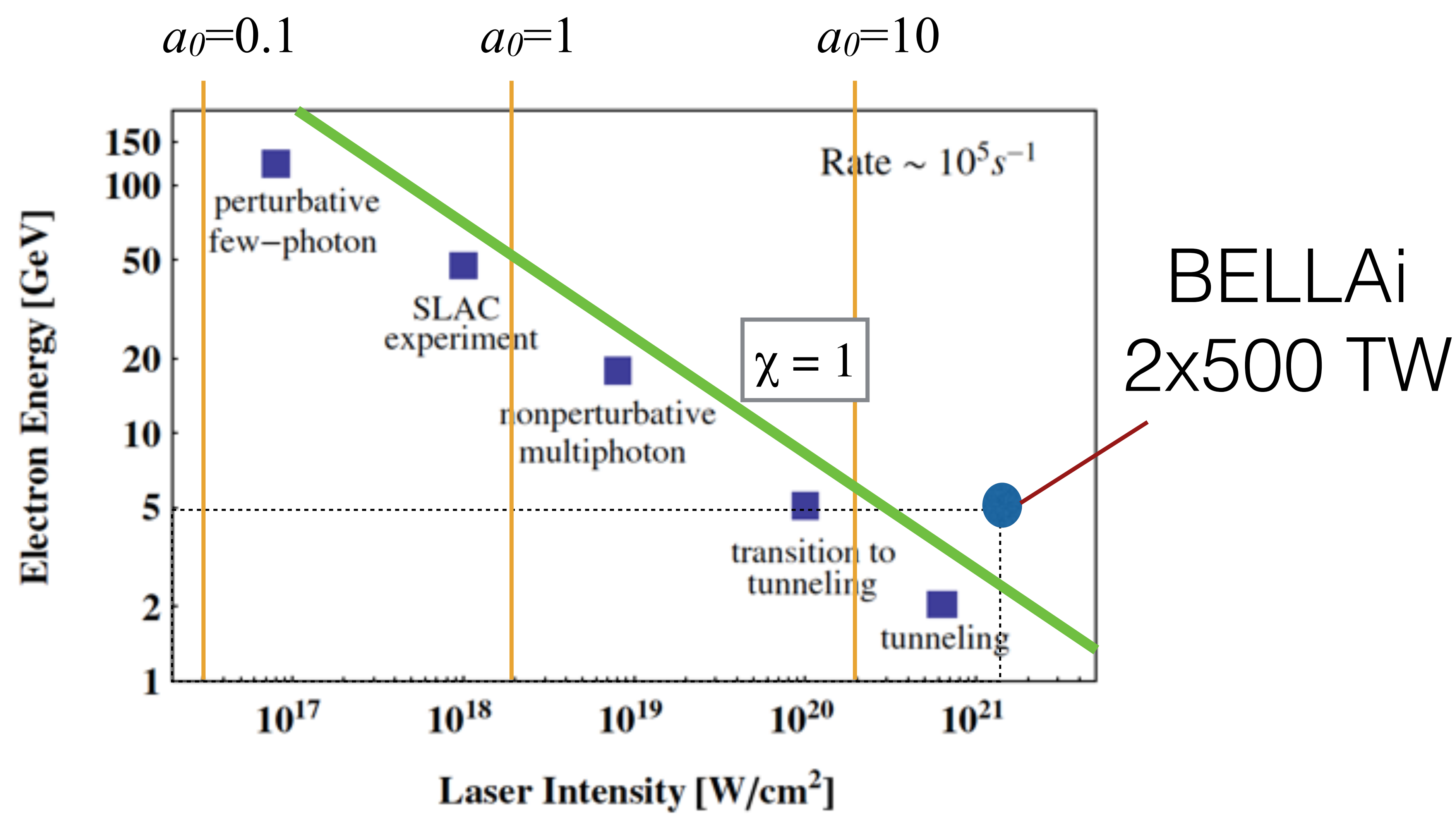
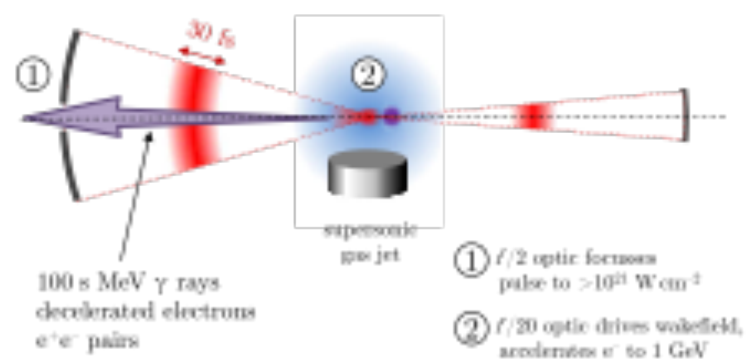


FIG. 17 (color online). Transition from the perturbative to the fully nonperturbative regimes of e^+-e^- pair creation in electron-laser collisions. The laser-photon energy is 2.4 eV. Adapted from Hu, Müller, and Keitel, 2010.

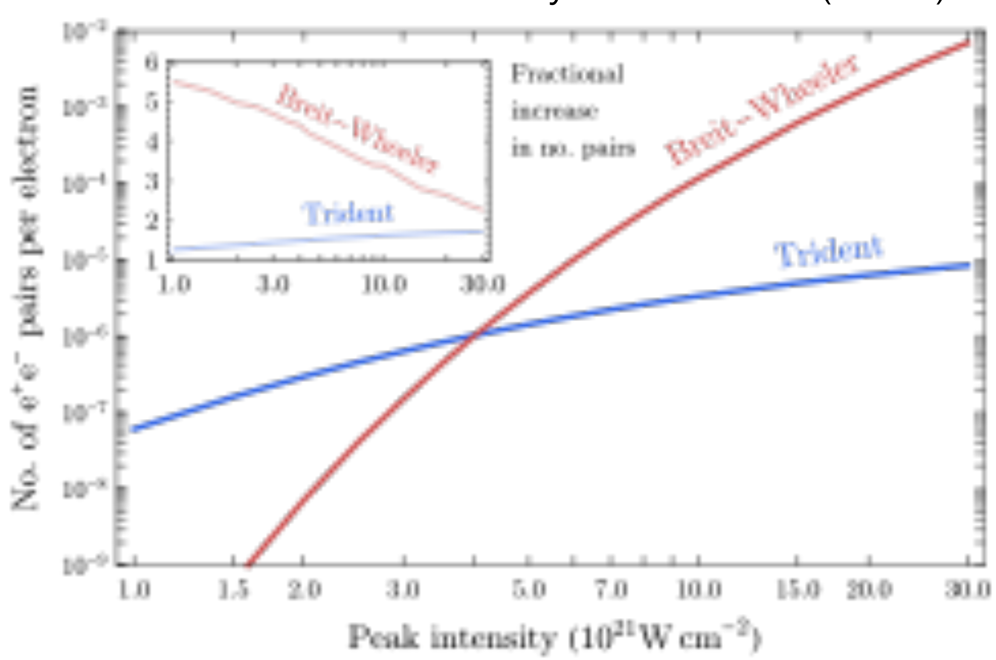
Electron-positron pair production



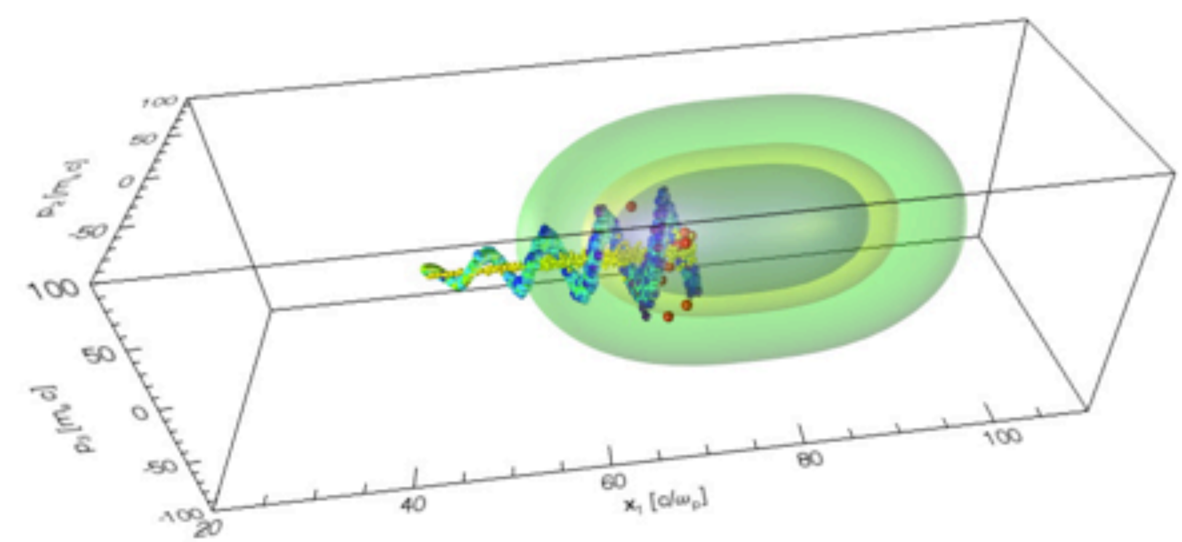
laser **I ~ 10^{21} W/cm^2**, 30 fs, 1 um electron initial energy ~ **3 GeV**

- electron (green)
- positron (red)
- photon (yellow)

Blackburn et al. Phys. Rev. Lett. (2014)



~ 2×10^6 pairs obtained per 10^{10} interacting electrons



- Evidence of "straggling" - probabilistic nature of quantum interaction can affect pair production rates (since electrons can reach maximum field strength)

Marija Vranic and Thomas Grismayer @ GoLP, IST, Lisbon, Portugal

Estimate for BELLAi

- Calculate photon spectrum for mono energetic electron spectrum (assume emission over 1/2t_p)

$$\frac{d^2 N}{d\chi\, dt} = \sqrt{3}\frac{mc^2}{h}\alpha_f b \frac{F(\eta, \chi)}{\chi}$$

Kirk PPCF 2011

- Calculate rate of e+e- generation for given spectrum (2nd half of pulse)

$$\frac{d\tau}{dt} = \alpha_f \frac{mc^2}{\hbar}\frac{mc^2}{h\nu}\chi T_\pm(\chi).$$

- (Calibrate verses Blackburn and Vranic)
- For 5 GeV electron + 1.5x10^{21} Wcm^{-2} laser approximately **0.01 pairs per electron**
- (Actually basically like Blackburn 5 GeV electron + 3x10^{23} Wcm^{-2} case)

Reasonable Estimate for BELLAi

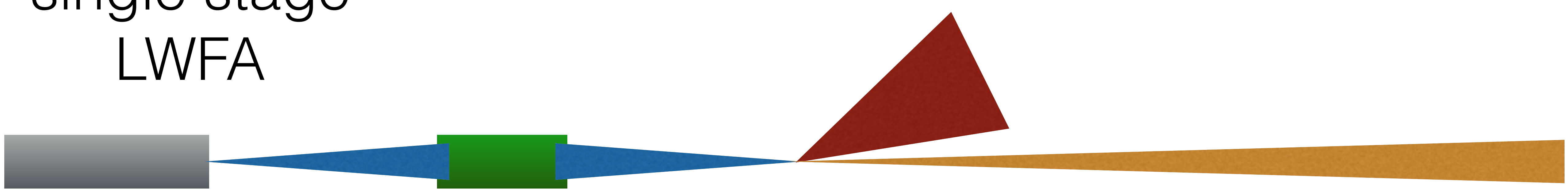
- For BELLAi split into 2 x 500 TW arms, one LWFA
  - Q = 100 pC
  - E = 5 GeV
  - I = 1.5×10^{21} Wcm^{-2}
- Expected number of pairs = 10^7
  - Similar to number produced by 400 MeV beam colliding with a lead converter!

Sarri et al, PRL (2013)

Contents

- Strong Field Physics
- Nonlinear Compton Scattering
- Multiphoton Breit-Wheeler Pair production
- **Experiment on BELLAi**

Experiment on BELLAi

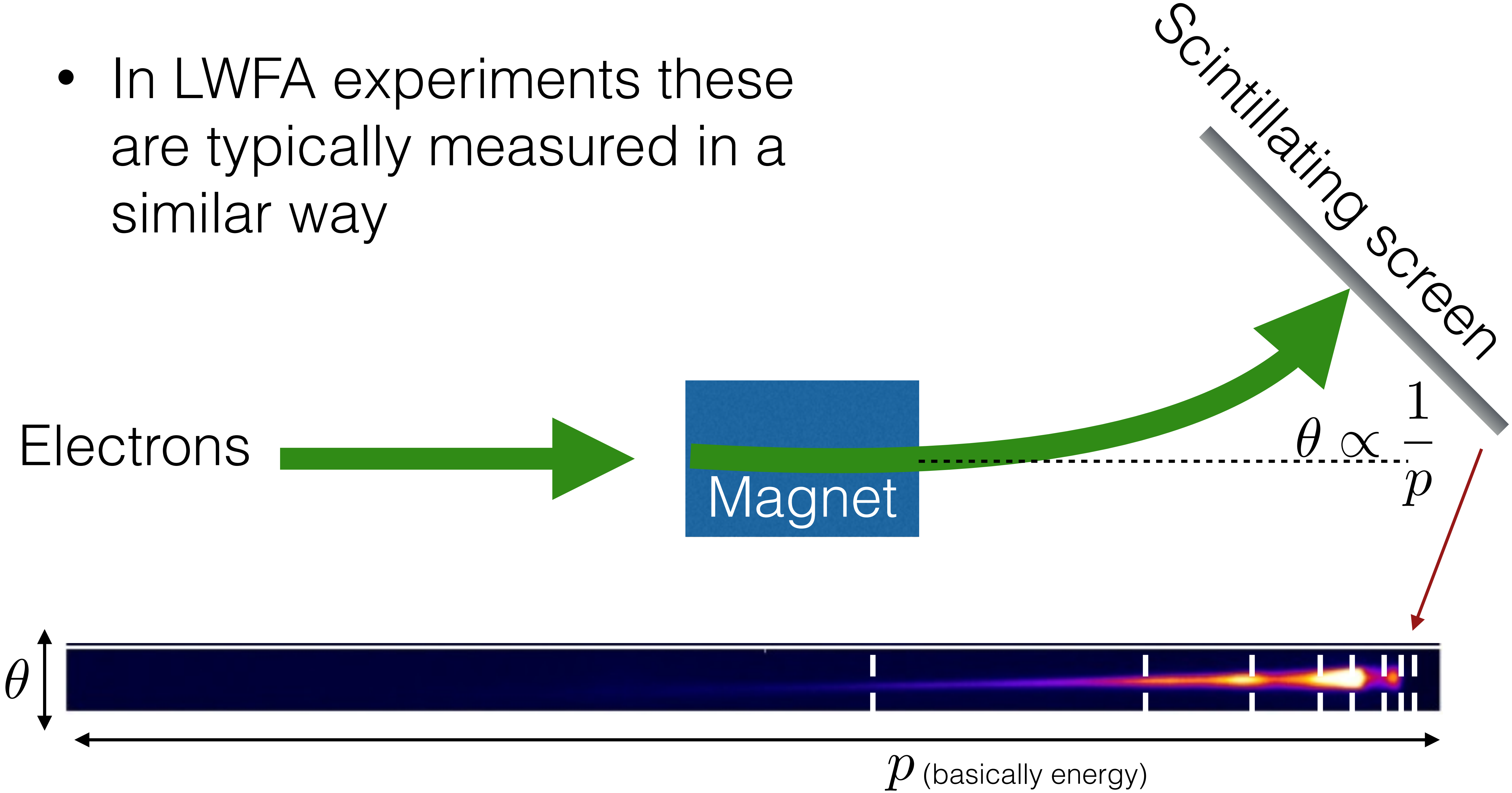


- Compton gamma ray spectrometer
- Scintillator arrays
- Cherenkov detectors
- Si-W calorimeters

Precision measurements:
Examine electron
momentum distribution
Need stability

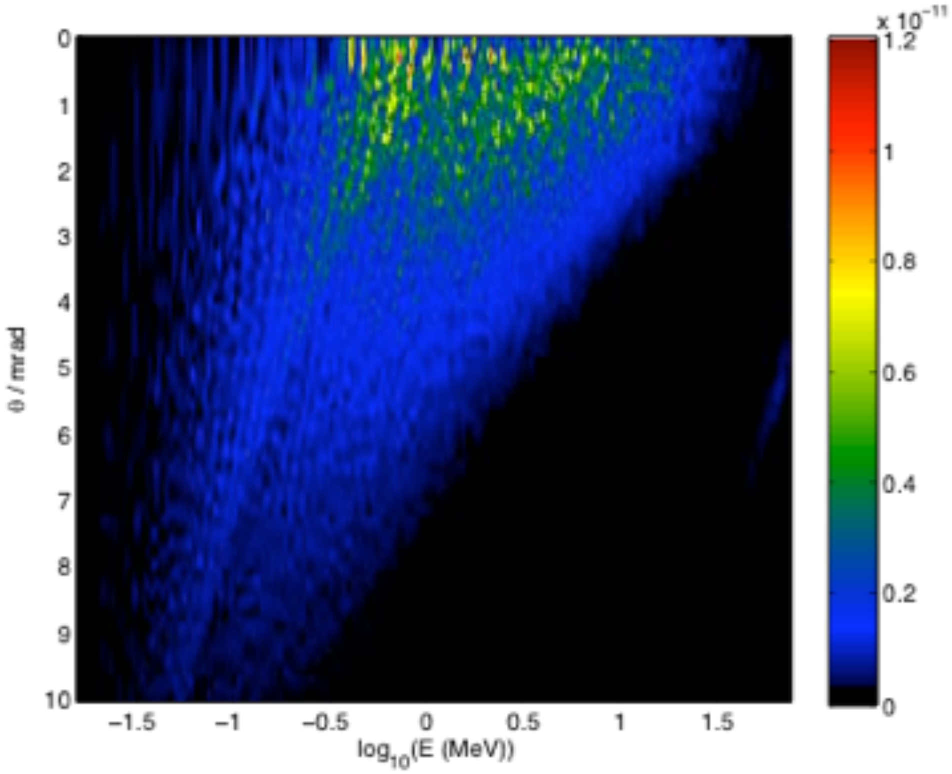
Anatomy of an “electron spectrum”

- In LWFA experiments these are typically measured in a similar way

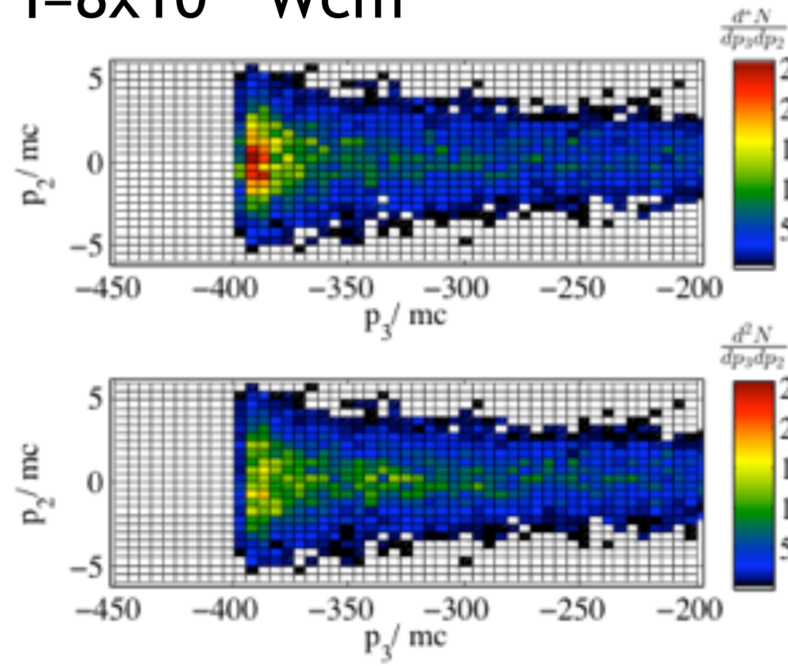


- Image from scintillating screen

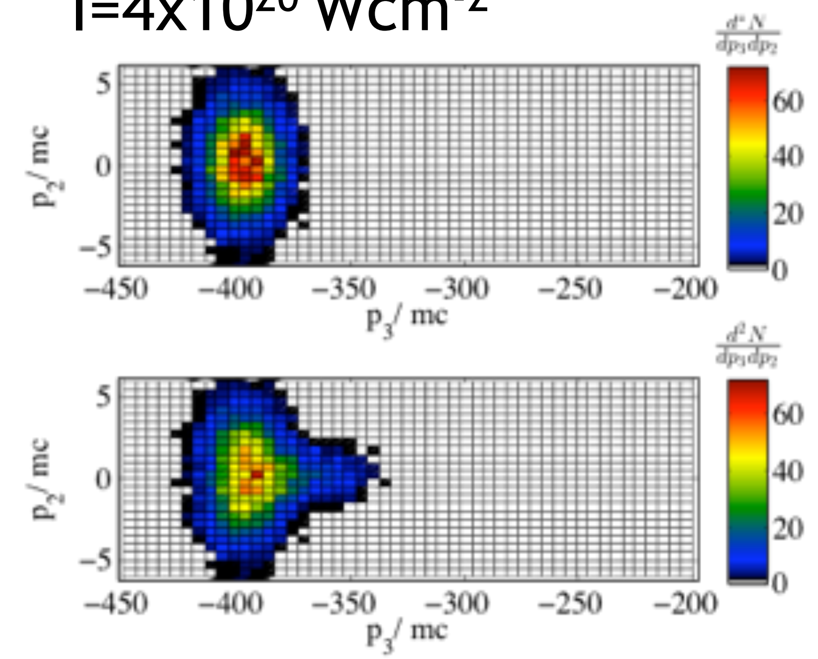
Single particle
angular spectrum
polarization plane
I=4x10^{20} Wcm^{-2}



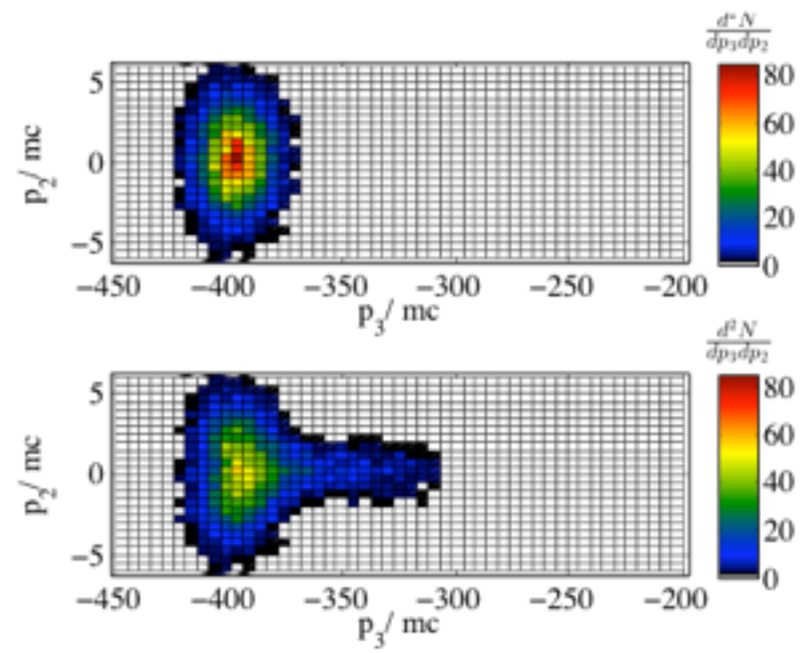
I=8x10^{20} Wcm^{-2}

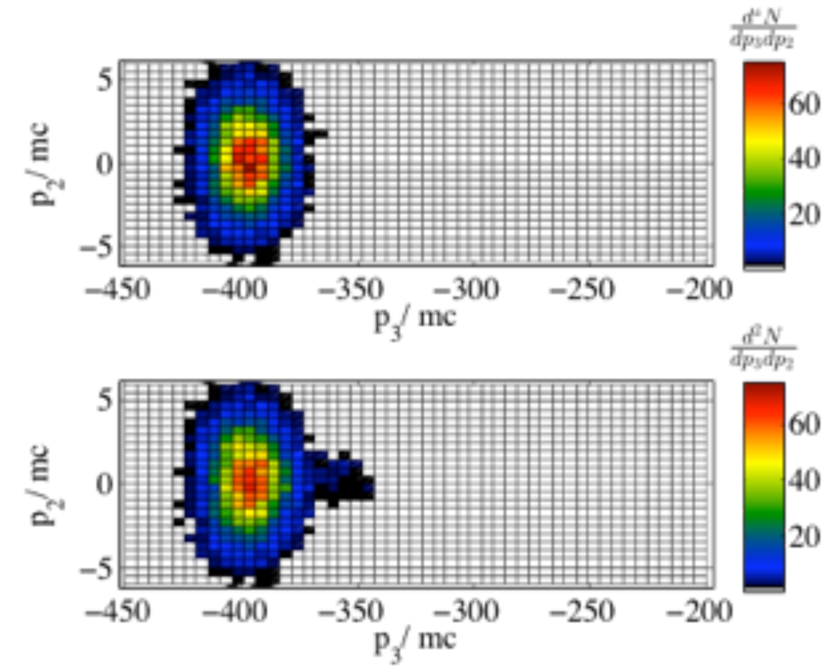


I=4x10^{20} Wcm^{-2}



Zfocus = 500 μm





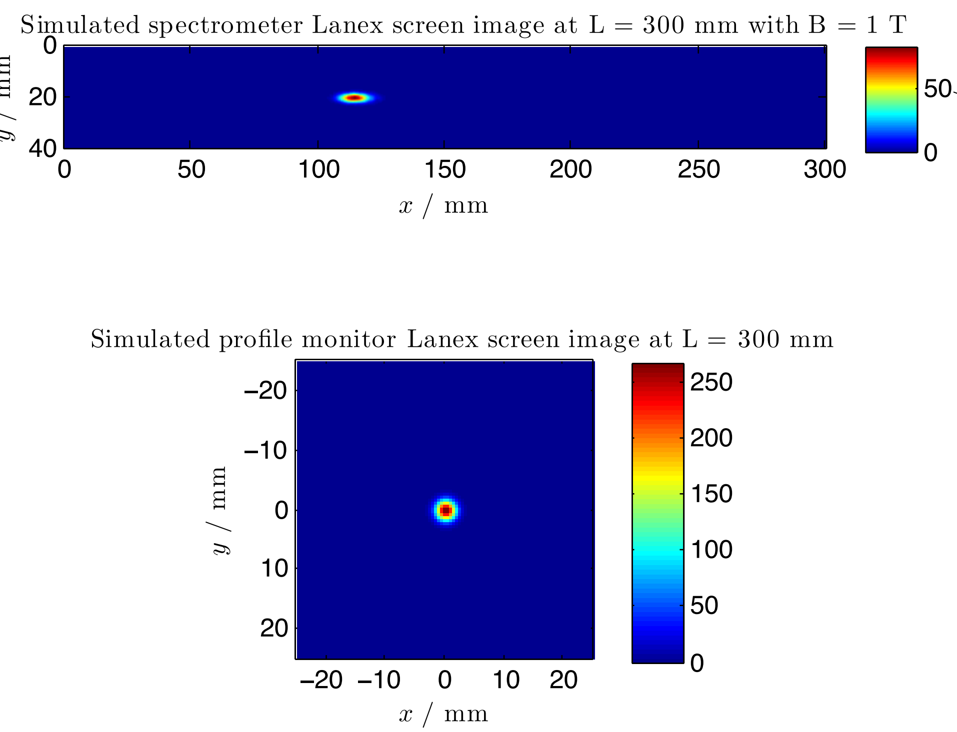
Zfocus = 1000 μm

w_0 = 2 μm
Theta beam = 5 mrad

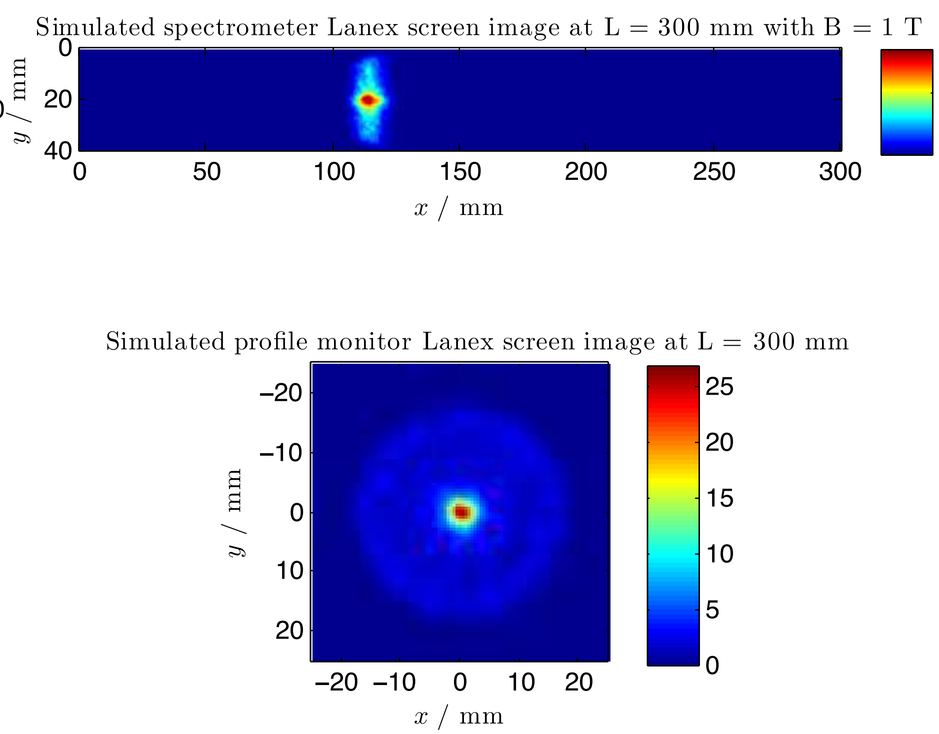
Radiation reaction precision measurements

- Selection of image plane relative to focus / interaction may have advantages

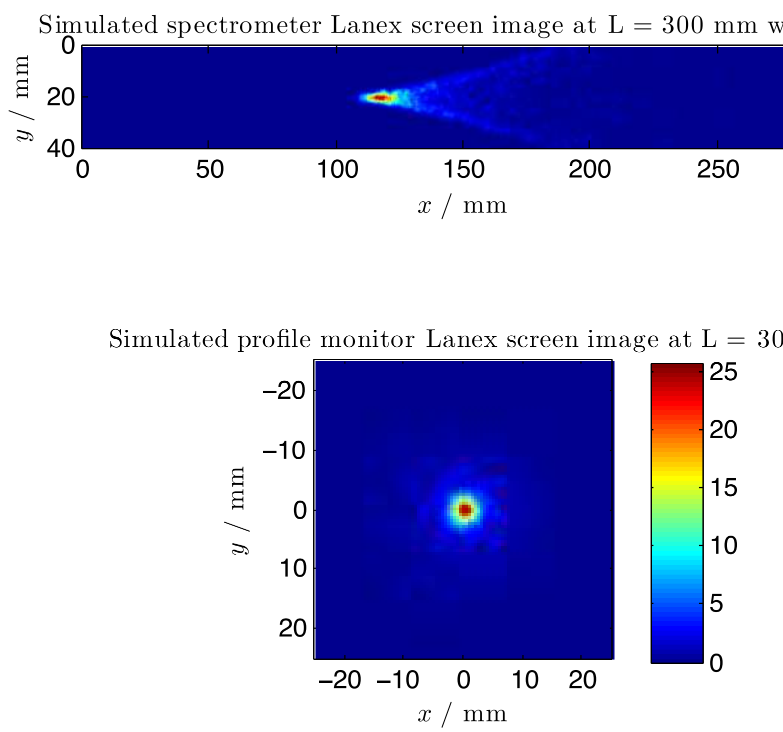
Original



No RR



With RR



Summary

- Strong field QED effects in plasma may be important for >10 PW class lasers
- QED is well tested in high energy / low intensity regime - but not in low energy / high intensity
- Multiphoton Compton scattering, Breit-Wheeler important tests
- BELLAi has properties for precision measurements
    - Sufficient power
    - **Repetition rate**
    - **Good laser quality**

To consider:
Beam focusing
Diagnostics