Photon-Photon Scattering with Intense PW or multi-PW lasers.

Luis Roso

Director

Apollon Users Meeting
February 12th, 2016

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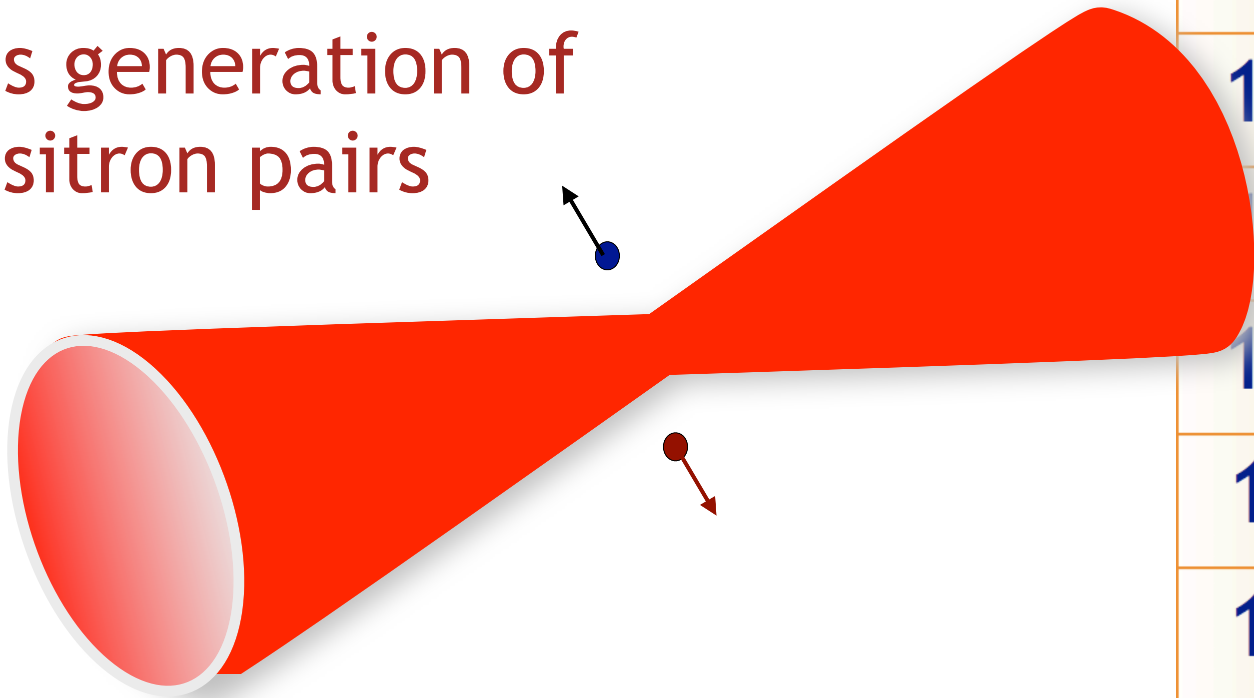
The Schwinger limit

Vacuum anihilation: Schwinger

Spontaneous generation of electron-positron pairs

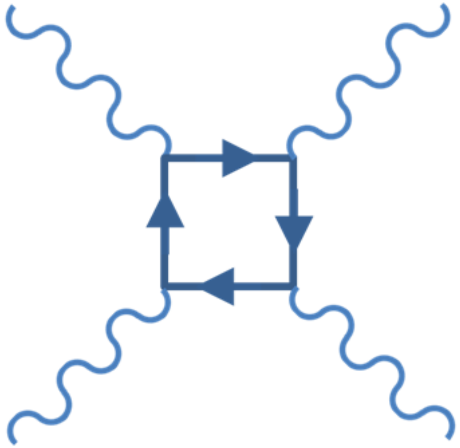


Non-linear QED

Beyond 10^{29} W/cm^2 vacuum seems to be unstable

- 10^{21} W/cm^2
- 10^{22} W/cm^2
- 10^{23} W/cm^2
- 10^{24} W/cm^2
- 10^{25} W/cm^2
- 10^{26} W/cm^2
- 10^{27} W/cm^2
- 10^{28} W/cm^2
- 10^{29} W/cm^2
- 10^{30} W/cm^2
- 10^{31} W/cm^2

Quantum vacuum



10^{18} W/cm^2

10^{19} W/cm^2

10^{20} W/cm^2

10^{21} W/cm^2

10^{22} W/cm^2

10^{23} W/cm^2

10^{24} W/cm^2

10^{25} W/cm^2

10^{26} W/cm^2

10^{27} W/cm^2

10^{28} W/cm^2

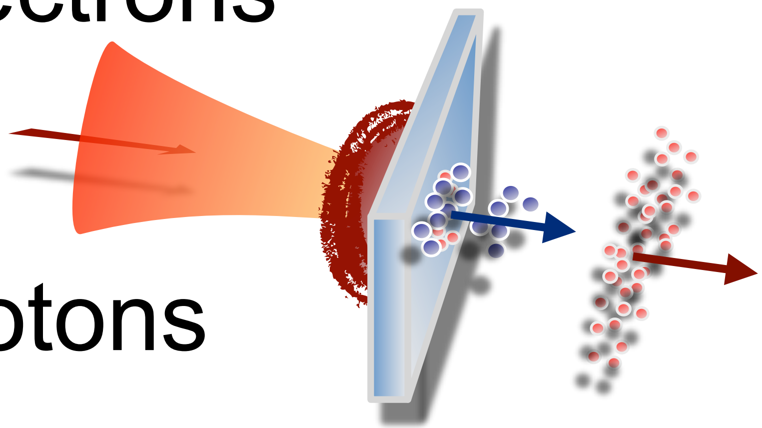
Intensity where virtual pairs start to be relevant ???

Generation of real pairs

10^{14} W/cm^2
10^{15} W/cm^2
10^{16} W/cm^2
10^{17} W/cm^2
10^{18} W/cm^2
10^{19} W/cm^2
10^{20} W/cm^2
10^{21} W/cm^2
10^{22} W/cm^2
10^{23} W/cm^2

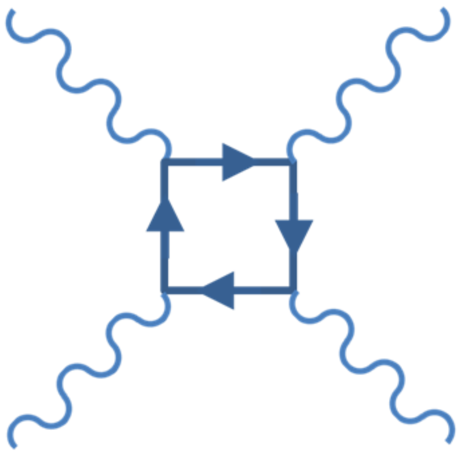
Atomic unit of intensity

Relativistic electrons



Relativistic protons

World record



10^{18} W/cm^2

10^{19} W/cm^2

10^{20} W/cm^2

10^{21} W/cm^2

10^{22} W/cm^2

10^{23} W/cm^2

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10^{25} W/cm^2

10^{26} W/cm^2

10^{27} W/cm^2

10^{28} W/cm^2

Intensity where virtual pairs start to be relevant ???

Generation of real pairs

Non-linear Compton-Thomson

$$e + n\gamma_L \rightarrow e' + \gamma$$

Vacuum birrefringence

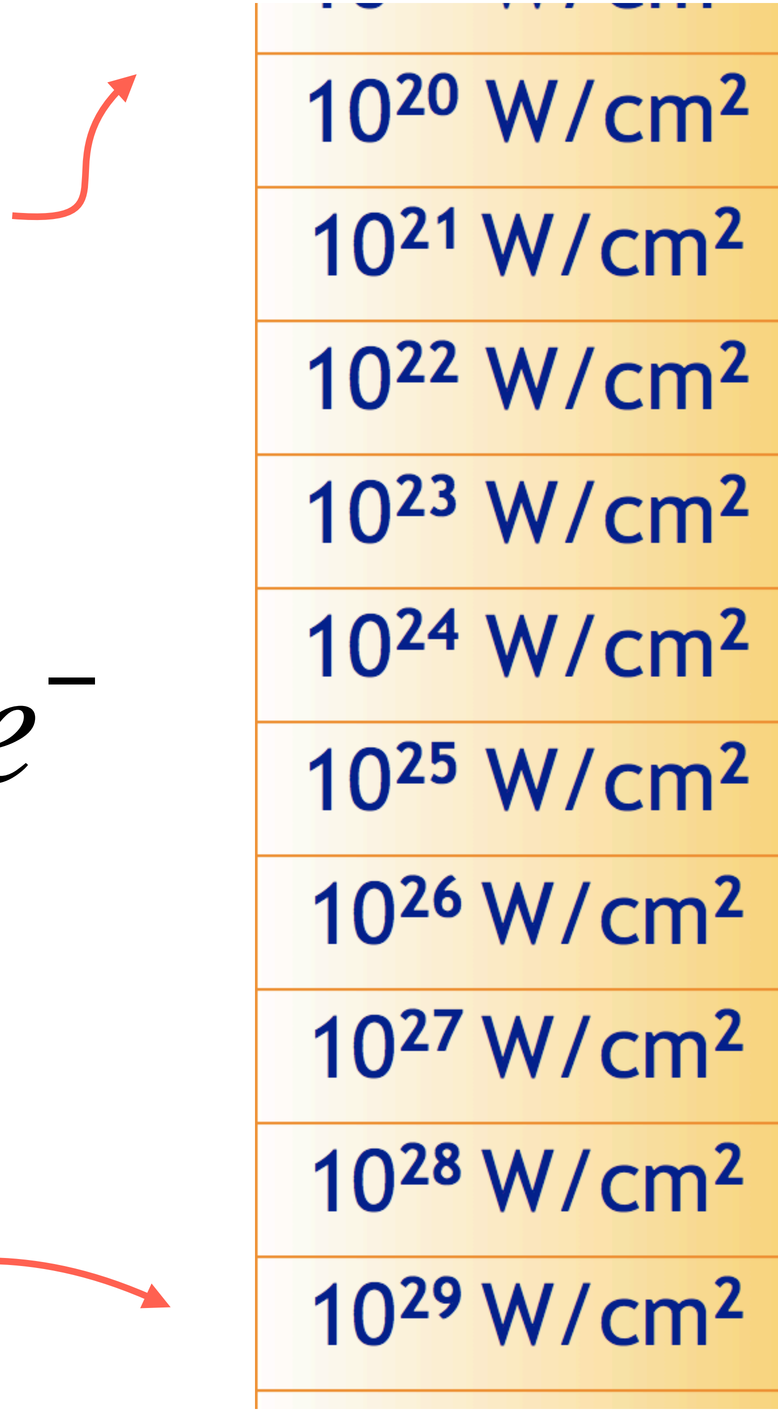
$$\gamma \rightarrow \gamma'$$

Stimulated pair production

$$\gamma + n\gamma_L \rightarrow e^+ + e^-$$

Vacuum pair production

$$vac \rightarrow e^+ + e^-$$



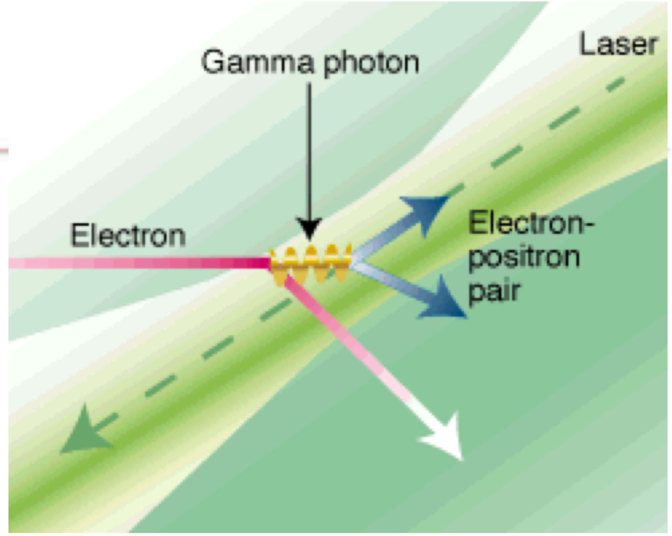
What QED signature can be observed first?

What happens here ?

Schwinger limit: Generation of real pairs

- 10^{21} W/cm^2
- 10^{22} W/cm^2
- 10^{23} W/cm^2
- 10^{24} W/cm^2
- 10^{25} W/cm^2
- 10^{26} W/cm^2
- 10^{27} W/cm^2
- 10^{28} W/cm^2
- 10^{29} W/cm^2
- 10^{30} W/cm^2
- 10^{31} W/cm^2

What can be observed first?



10^{21} W/cm^2
10^{22} W/cm^2
10^{23} W/cm^2
10^{24} W/cm^2
10^{25} W/cm^2

SLAC-144 experiment, 1998

Studies of nonlinear QED in collisions of 46.6 GeV electrons with intense laser pulses

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Department of Physics and Astronomy, University of Rochester, Rochester, New York 14627

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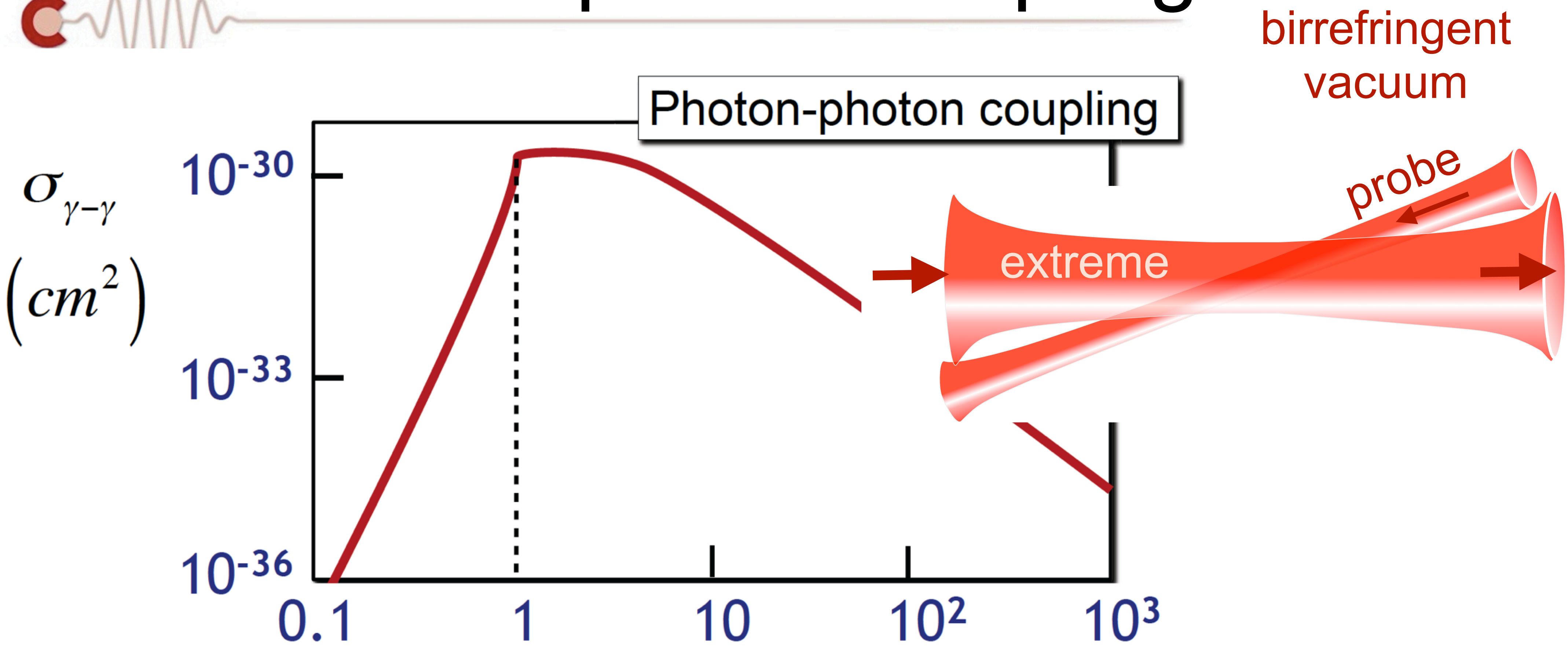
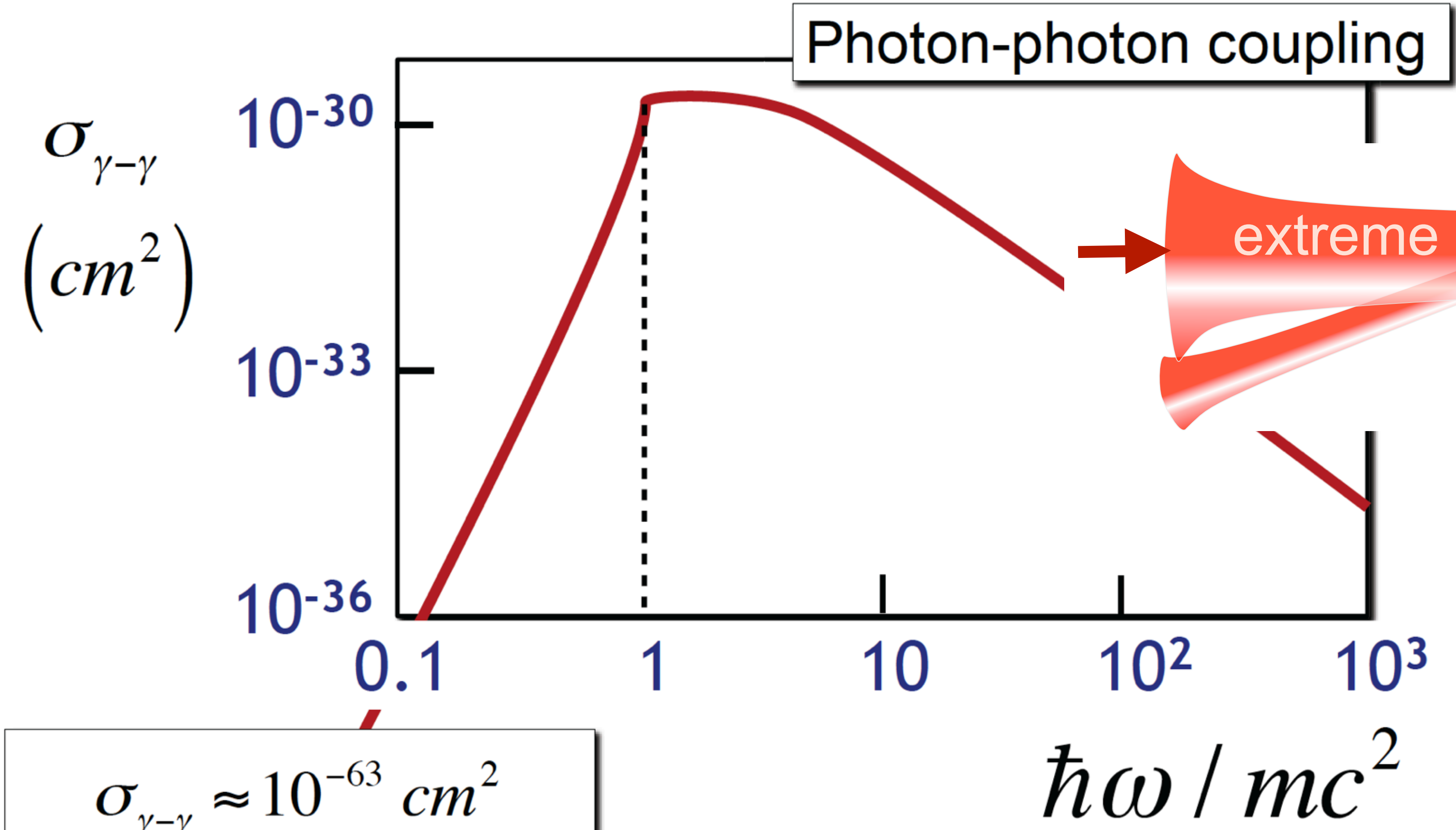
Photon-photon coupling



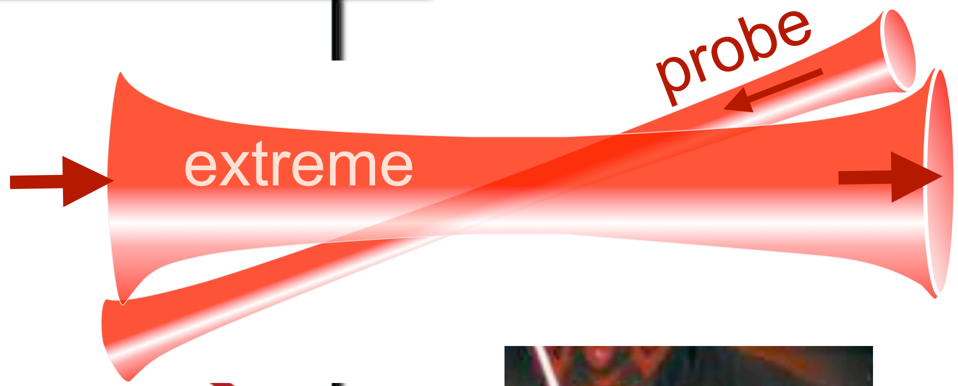
$$\sigma_{\gamma-\gamma} \approx 10^{-63}\ cm^2$$

at optical wavelengths

Photon-photon coupling



birrefringent vacuum



$$\sigma_{\gamma-\gamma} \approx 10^{-63}\ cm^2$$

at optical wavelengths

Lagrangian density, linear

for $h\nu \ll m_e c^2$

$$\mathcal{L}_0 = \frac{\epsilon_0}{2}\left(\mathbf{E}^2 - c^2\mathbf{B}^2\right)$$

For optical photons

Lagrangian QED non-linear

for $h\nu \ll m_e c^2$

$$\mathcal{L} = \mathcal{L}_0 + \xi_L \mathcal{L}_0^2 + \frac{7}{4}\xi_T \mathcal{G}^2$$

being

$$\mathcal{L}_0 = \frac{\epsilon_0}{2}\left(\mathbf{E}^2 - c^2\mathbf{B}^2\right)$$

$$\mathcal{G} = \epsilon_0 c(\mathbf{E} \cdot \mathbf{B})$$

$\mathcal{L}_0^2$ and $\mathcal{G}^2$ are the only two Lorentz-covariant terms that can be formed with the electromagnetic fields at the lowest order above $\mathcal{L}_0$

Effective lagrangian QED

for $h\nu \ll m_e c^2$

$$\mathcal{L} = \mathcal{L}_0 + \xi_L \mathcal{L}_0^2 + \frac{7}{4}\xi_T \mathcal{G}^2$$

being

$$\mathcal{L}_0 = \frac{\epsilon_0}{2}\left(\mathbf{E}^2 - c^2\mathbf{B}^2\right)$$

$$\mathcal{G} = \epsilon_0 c(\mathbf{E} \cdot \mathbf{B})$$

In QED (Euler-Heisenberg)

$$\xi_L^{QED} = \xi_T^{QED} \equiv \xi = \frac{8\alpha^2\hbar^3}{45 m_e^4 c^5} = 6.7 \times 10^{-30} \frac{m^3}{J}$$

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Effective lagrangian QED

for $h\nu \ll m_e c^2$

$$\mathcal{L} = \mathcal{L}_0 + \xi_L \mathcal{L}_0^2 + \frac{7}{4}\xi_T \mathcal{G}^2$$

being $\mathcal{L}_0 = \frac{\epsilon_0}{2}\left(\mathbf{E}^2 - c^2\mathbf{B}^2\right)$ $\mathcal{G} = \epsilon_0 c(\mathbf{E}\cdot\mathbf{B})$

In QED (Euler-Heisenberg)

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W. Heisenberg and H. Euler,Folgerungen aus der Diracschen Theorie des Positrons Z. Phys. 98, 714 (1936).

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Effective Lagrangian BI

for $h\nu \ll m_e c^2$

$$\mathcal{L} = \mathcal{L}_0 + \xi_L \mathcal{L}_0^2 + \frac{7}{4}\xi_T \mathcal{G}^2$$

In the Born-Infeld model

$$\xi_T^{BI} = 4\xi_L^{BI}/7$$

Proposed to remove the divergence of the electron's self-energy in classical electrodynamics by introducing an upper bound of the electric field at the origin

M. Born and L. Infeld, Foundations of the New Field Theory, Proc. Roy. Soc. Lond. 144 (1934) 425.

Other effective Lagrangians

for $h\nu \ll m_e c^2$

$$\mathcal{L} = \mathcal{L}_0 + \xi_L \mathcal{L}_0^2 + \frac{7}{4}\xi_T \mathcal{G}^2$$

Minicharged particles new terms in the Lagrangian

$\Delta\xi_L^{\mathrm{MCP}}$ $\Delta\xi_T^{\mathrm{MCP}}$

Other effective Lagrangians

Minicharged particles

Spin 1/2 fermion

$$\Delta\xi_L^{\text{MCP}} = \Delta\xi_T^{\text{MCP}} = \left(\frac{\epsilon\, m_e}{m_\epsilon}\right)^4 \xi$$

Spin 0 boson

$$\Delta\xi_L^{\text{MCP0}} = \frac{7}{16}\left(\frac{\epsilon\, m_e}{m_\epsilon}\right)^4 \xi$$

$$\Delta\xi_T^{\text{MCP0}} = \frac{1}{28}\left(\frac{\epsilon\, m_e}{m_\epsilon}\right)^4 \xi.$$

Spin 1 boson

$$\Delta\xi_L^{\text{MCP1}} = \frac{261}{16}\left(\frac{\epsilon\, m_e}{m_\epsilon}\right)^4 \xi$$

$$\Delta\xi_T^{\text{MCP1}} = \frac{243}{28}\left(\frac{\epsilon\, m_e}{m_\epsilon}\right)^4 \xi$$

Axions ... if they exist

Axions are hypothetical elementary particle postulated by the Peccei–Quinn theory in 1977 to resolve the strong CP problem in QCD.

no electric charge,
very small mass, 10^{-6} to 1 eV/c^2

Many world collaborations to look for axions

CAST CERN Axion Solar Telescope

PVLAS Polarizzazione del Vuoto con LASer, Padova

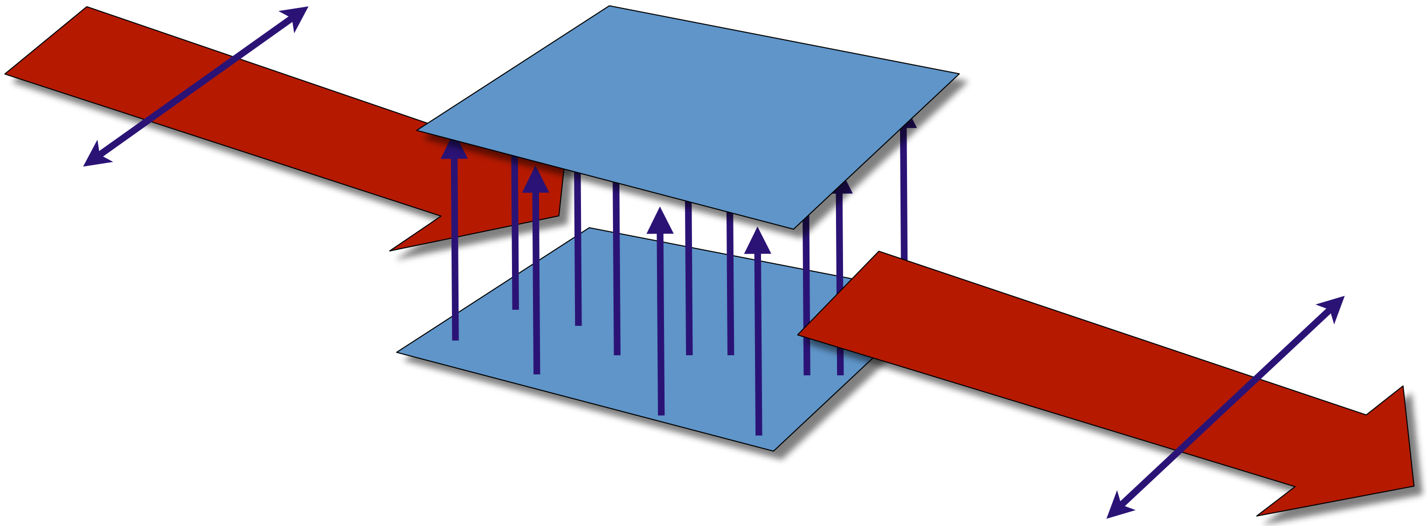
ADMX Axion Dark Matter eXperiment, USA

many others ...

Axions

no electric charge,
very small mass, 10^{-6} to 1 eV/c^2

Coupling to magnetic fields ...



small rotation of polarization plane

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Other effective Lagrangians

Axions

$$\mathcal{L} = \mathcal{L}_0 + \xi_L \mathcal{L}_0^2 + \frac{7}{4}\xi_T \mathcal{G}^2$$

scalar boson

$$\Delta\xi_T = \frac{2\hbar^3 g_P^2}{7c\, m_\Phi^2}$$

$$\Delta\xi_L = 0$$

pseudoscalar boson

$$\Delta\xi_T = 0$$

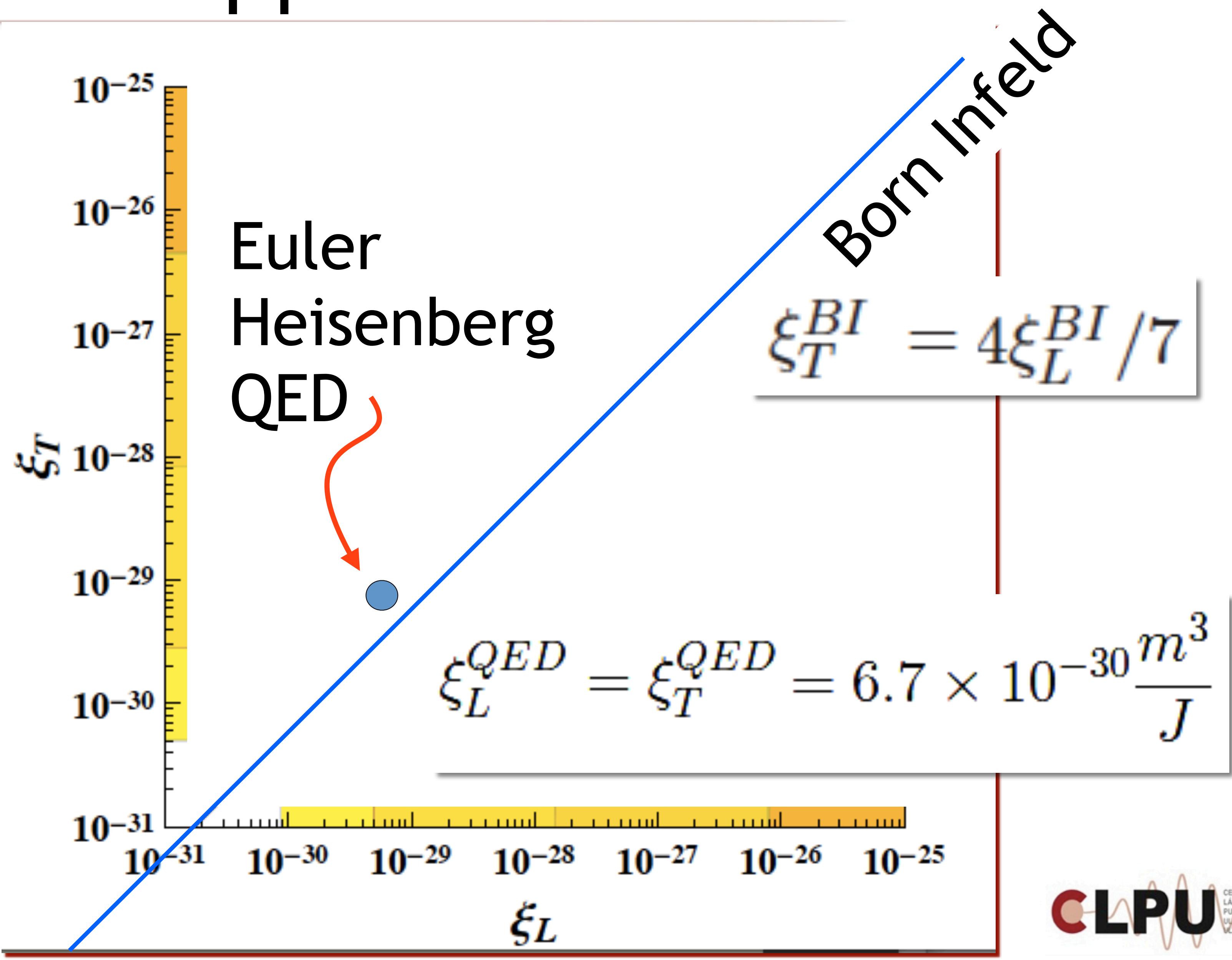
$$\Delta\xi_L = \frac{\hbar^3 g_S^2}{2c\, m_\Phi^2}$$

R D Peccei, and H R Quinn
CP Conservation in the Presence of Pseudoparticles
Phys Rev Lett, 1977

What happens ???

Too-many Lagrangians

Two parameter space



Too many Lagragians

of the same kind

$$\mathcal{L} = \mathcal{L}_0 + \xi_L \mathcal{L}_0^2 + \frac{7}{4}\xi_T \mathcal{G}^2$$

How to select the correct one ???

With a laser ..

$$\Delta\phi_L = 4\xi_L I k\tau$$

$$\Delta\phi_T = 7\xi_T I k\tau$$

D Tommasini, A Ferrando, H Michinel et M Seco
Precision tests of QED and non-standard models by searching photon-photon scattering in vacuum with high power lasers, JHEP, 2009

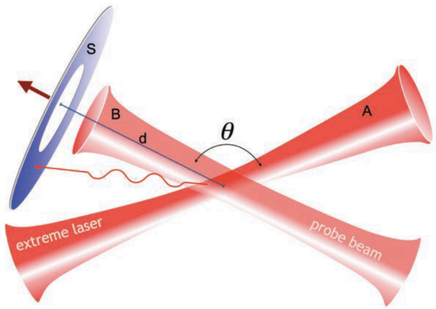
Why lasers ...

$$\Delta\phi_L = 4\xi_L I k\tau$$
$$\Delta\phi_T = 7\xi_T I k\tau$$

Photon-photon coupling results in a phase shift of the probe

$$N_D^{\mathcal{N}} = \frac{8 f \mathcal{N}}{\pi\hbar c} \frac{E_A^2 E_B w_0^2}{\lambda_B w_A^4 w_B^2} \left(e^{-\frac{2r_0^2}{w_D^2}} - e^{-\frac{2R^2}{w_D^2}} \right) (a\xi)^2_{L,T}$$

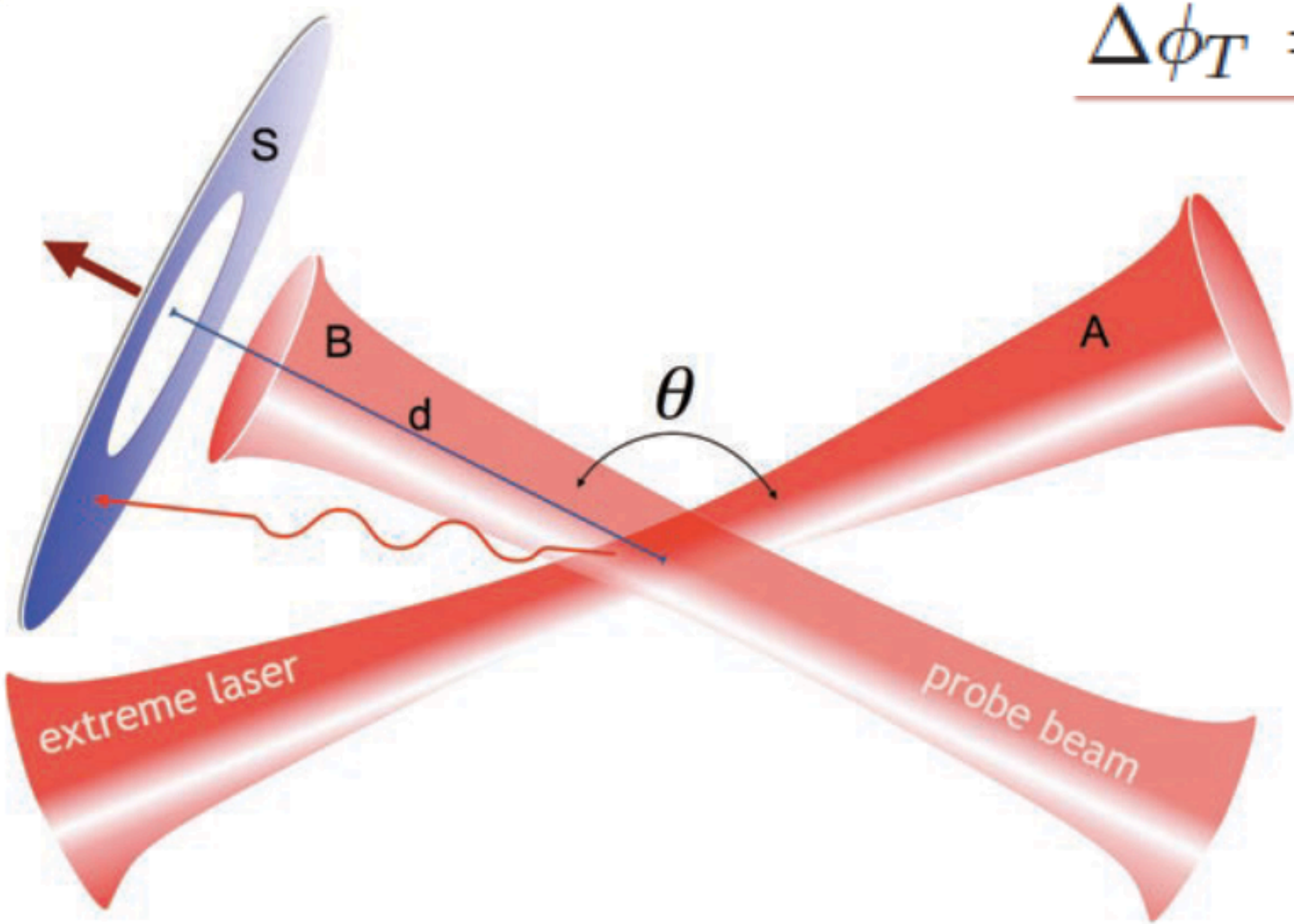
Relation between the number of scattered photons and QED coupling constants



With laser fields ...

$$\Delta\phi_L = 4\xi_L I k\tau$$

$$\Delta\phi_T = 7\xi_T I k\tau$$



Too many Lagragians

of the same kind

$$\mathcal{L} = \mathcal{L}_0 + \xi_L \mathcal{L}_0^2 + \frac{7}{4}\xi_T \mathcal{G}^2$$

Laser-Lagrangian connection

$$\Delta\phi_L = 4\xi_L I k\tau$$
$$\Delta\phi_T = 7\xi_T I k\tau$$

D Tommasini, A Ferrando, H Michinel et M Seco
Precision tests of QED and non-standard models by searching photon-photon scattering in vacuum with high power lasers, JHEP, 2009

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Too many Lagragians

of the same kind

$$\mathcal{L} = \mathcal{L}_0 + \xi_L \mathcal{L}_0^2 + \frac{7}{4}\xi_T \mathcal{G}^2$$

How to select the correct one ???

With a laser ..

- Intensity *I*
- Wavenumber *k*
- Pulse duration τ

$$\Delta\phi_L = 4\xi_L I k \tau$$

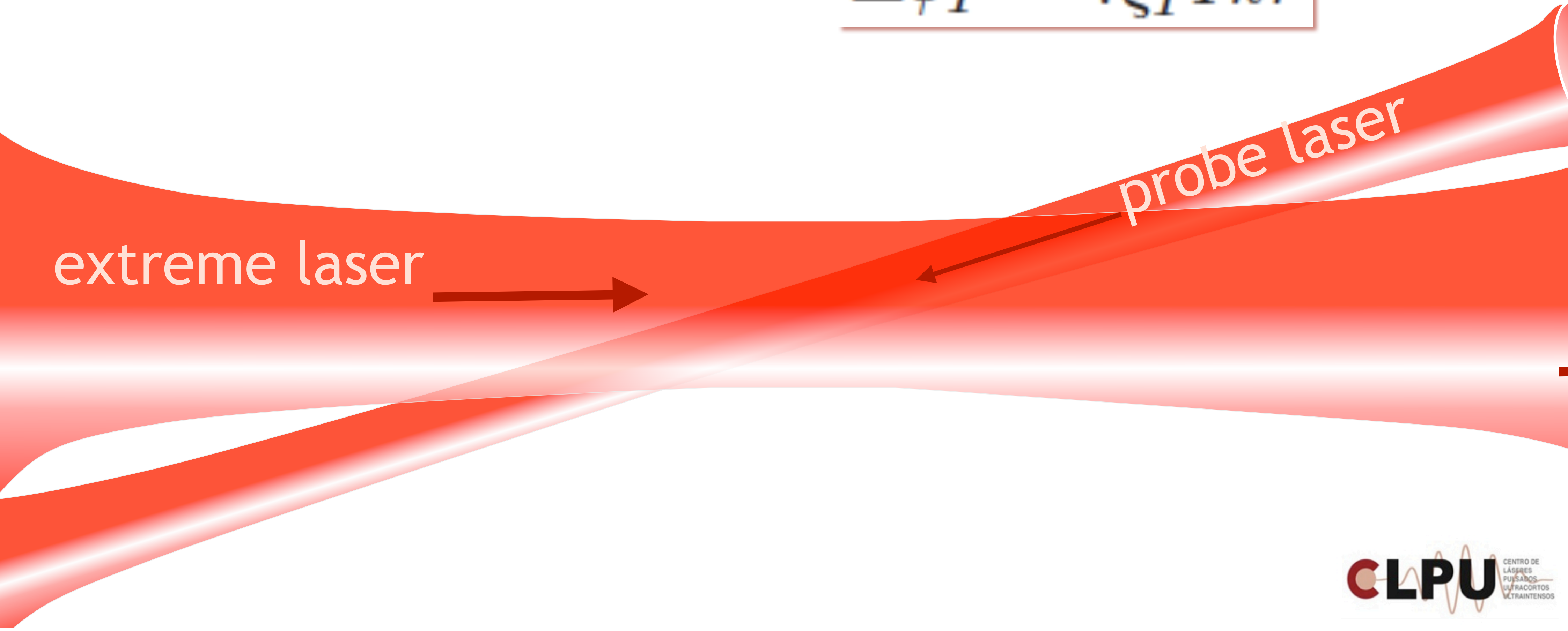
$$\Delta\phi_T = 7\xi_T I k \tau$$

D Tommasini, A Ferrando, H Michinel et M Seco
Precision tests of QED and non-standard models by searching photon-photon scattering in vacuum with high power lasers, JHEP, 2009

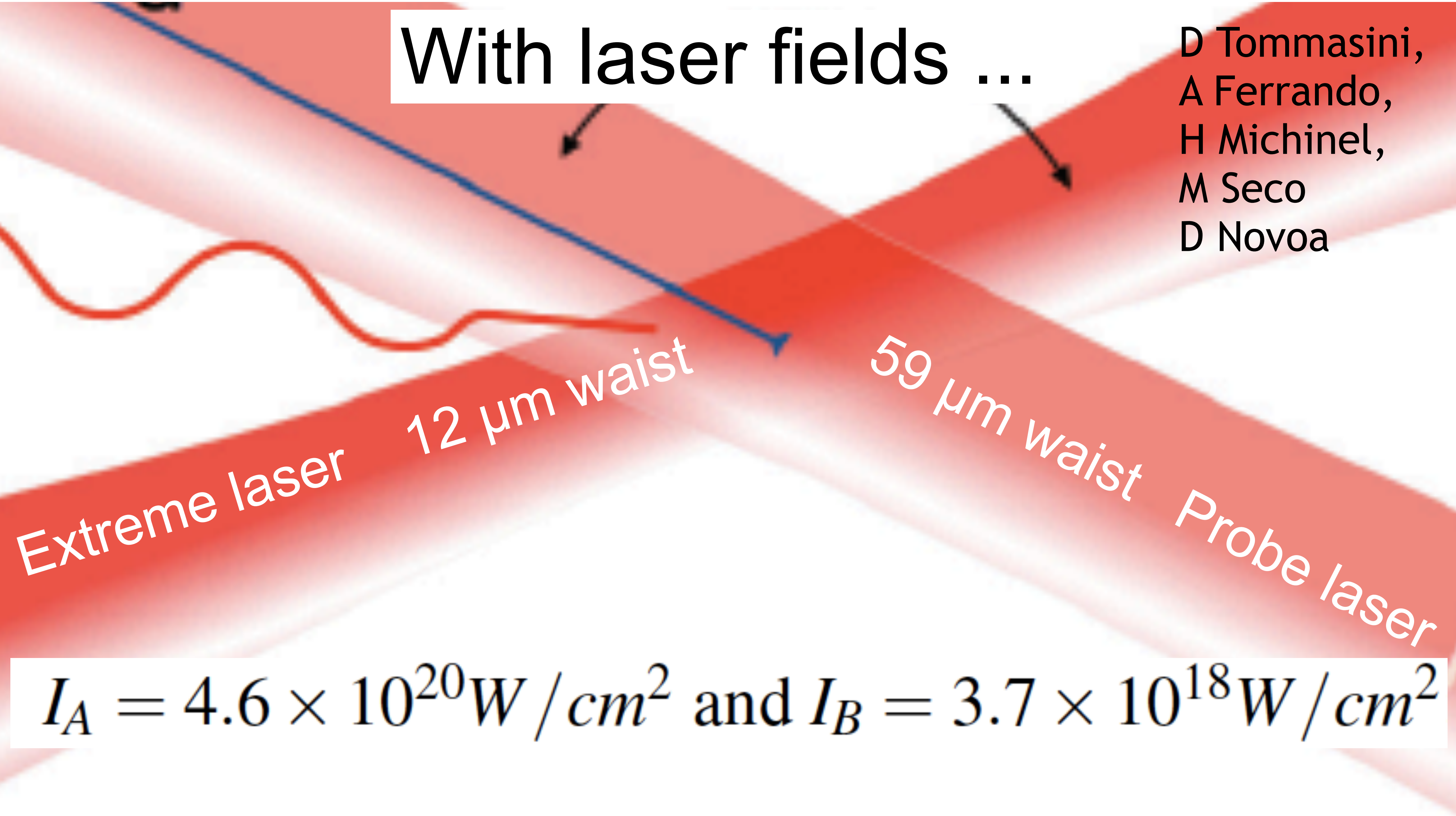
Birrefringent vacuum

$$\Delta\phi_L = 4\xi_L I k\tau$$

$$\Delta\phi_T = 7\xi_T I k\tau$$



With laser fields ...



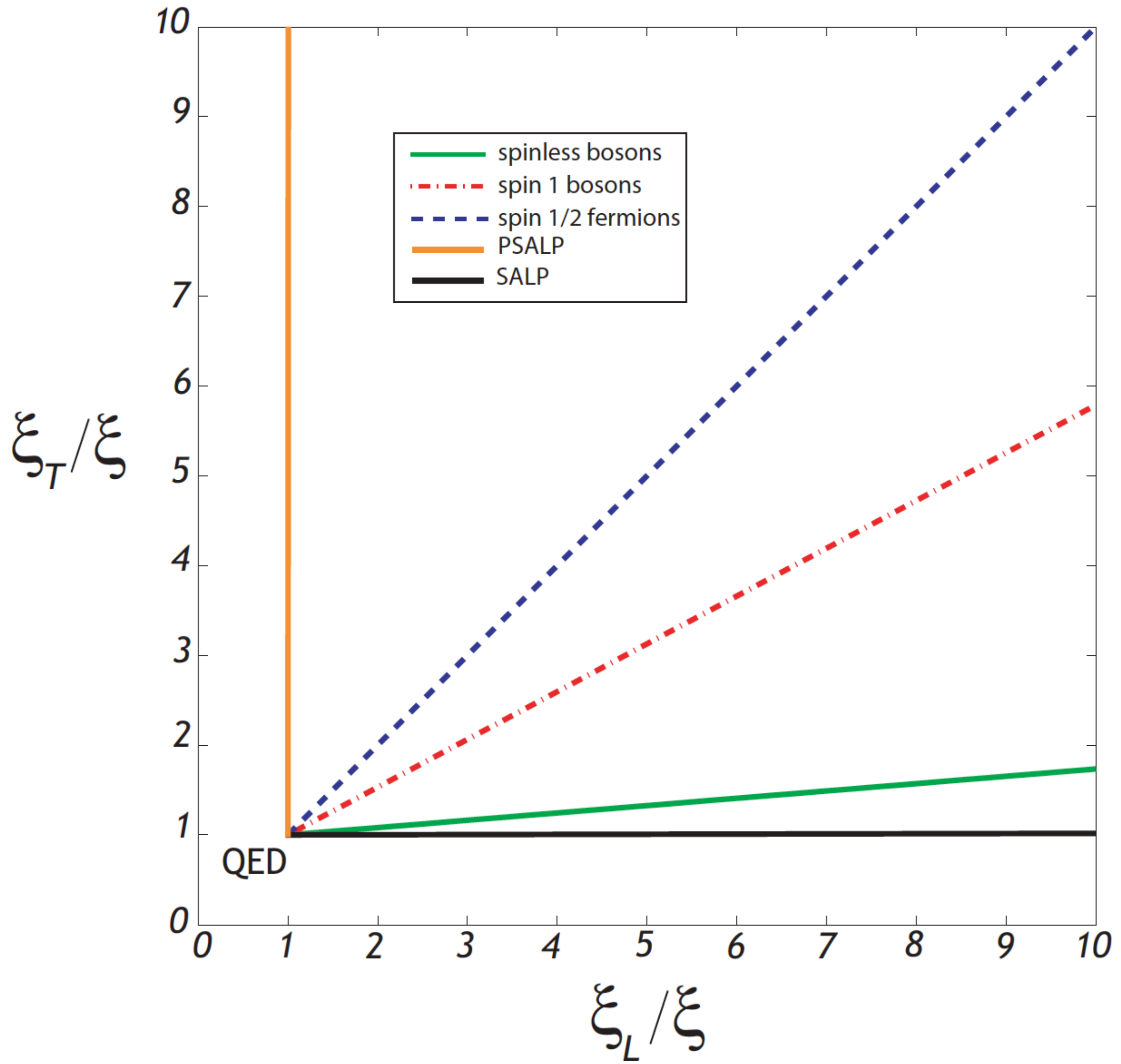
D Tommasini,
A Ferrando,
H Michinel,
M Seco
D Novoa

$$I_A = 4.6 \times 10^{20} W/cm^2 \text{ and } I_B = 3.7 \times 10^{18} W/cm^2$$

Tomasinni et al, PUILS X

With laser fields ..

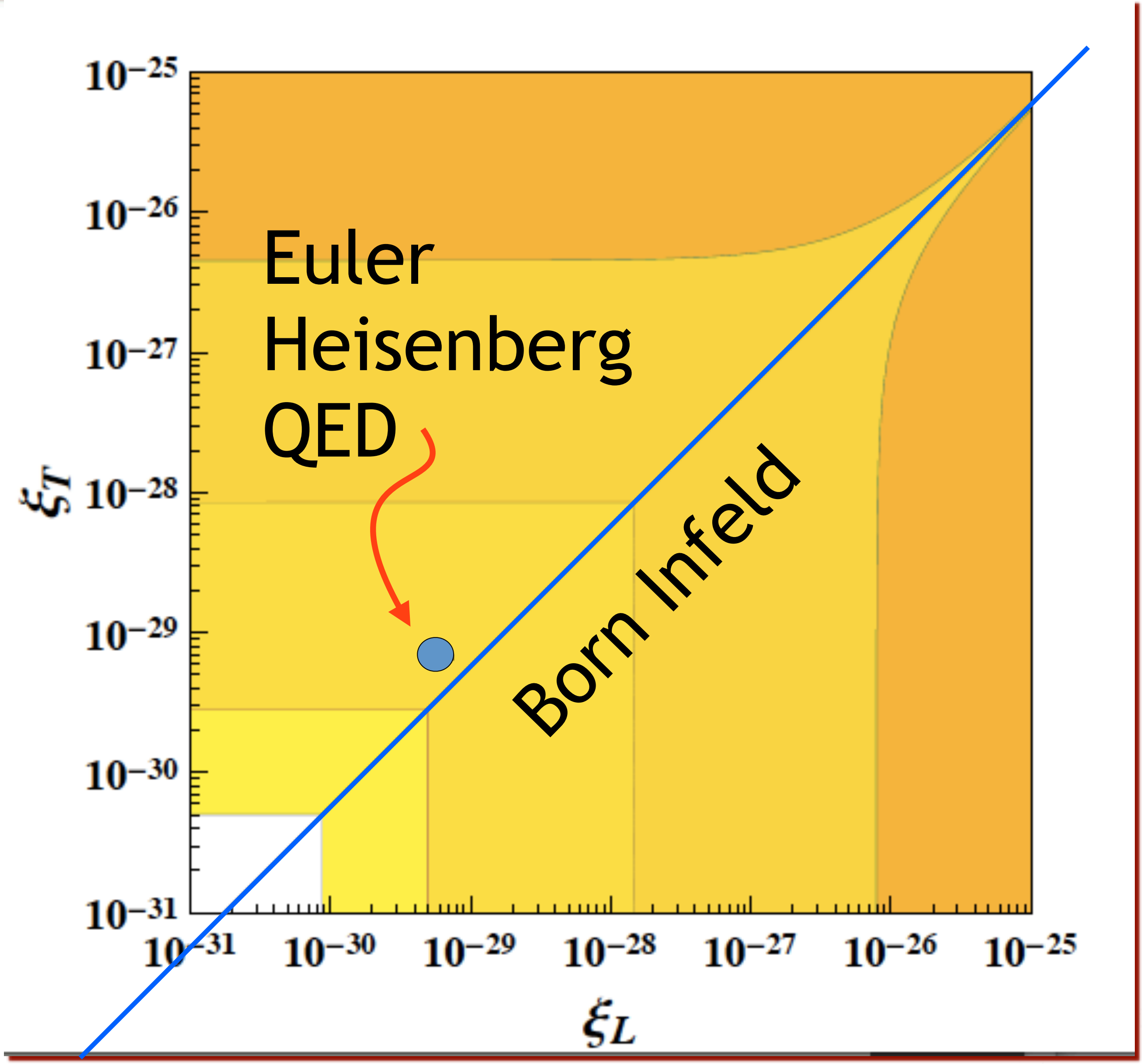
$$\mathcal{L} = \mathcal{L}_0 + \xi_L \mathcal{L}_0^2 + \frac{7}{4}\xi_T \mathcal{G}^2$$



Effective lagrangian QED

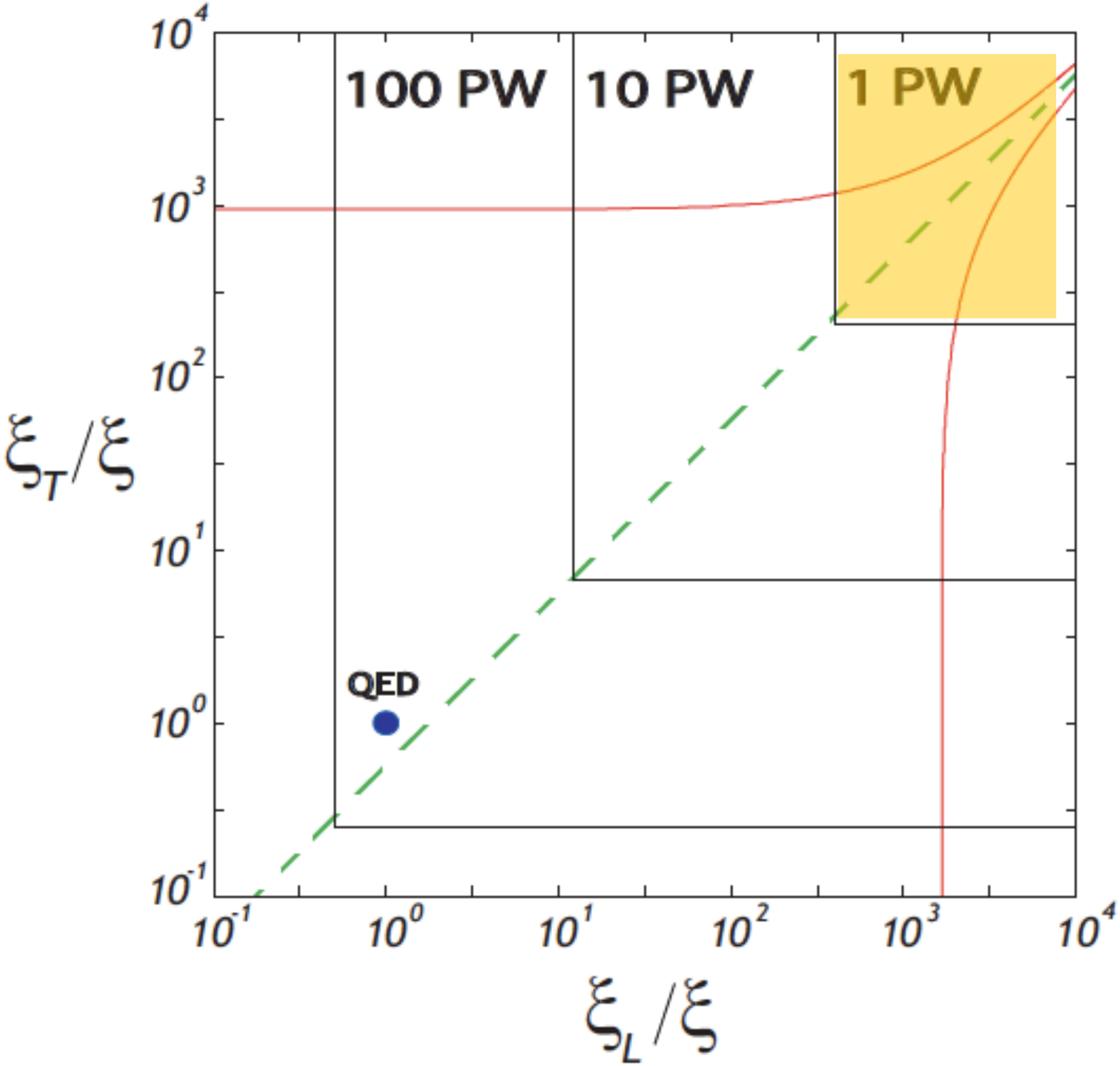
Do axions exist?

I don’t know
but,
if they exist we
can see them
with this kind of
laser experiment



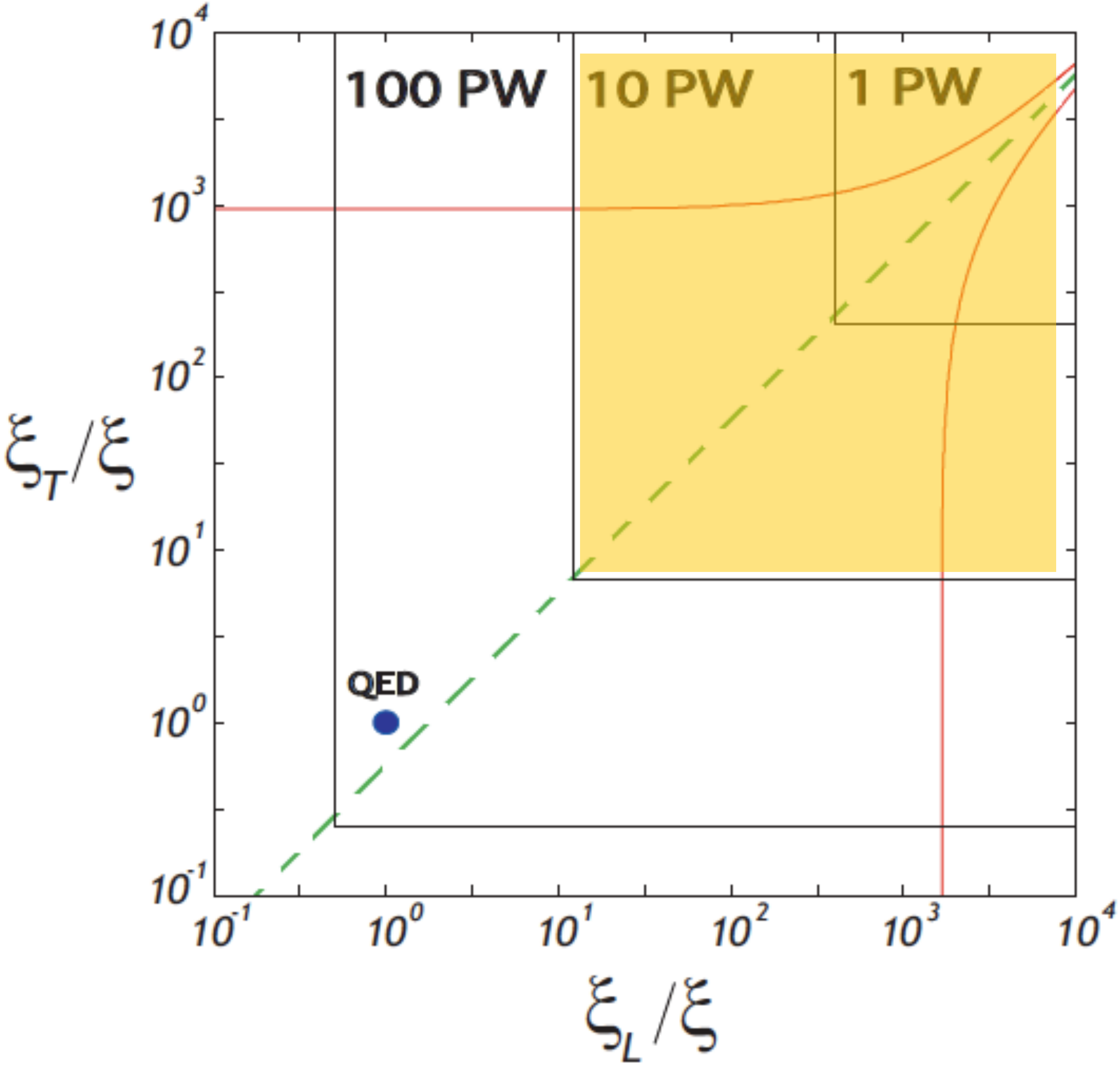
With laser fields ..

$$\mathcal{L} = \mathcal{L}_0 + \xi_L \mathcal{L}_0^2 + \frac{7}{4}\xi_T \mathcal{G}^2$$



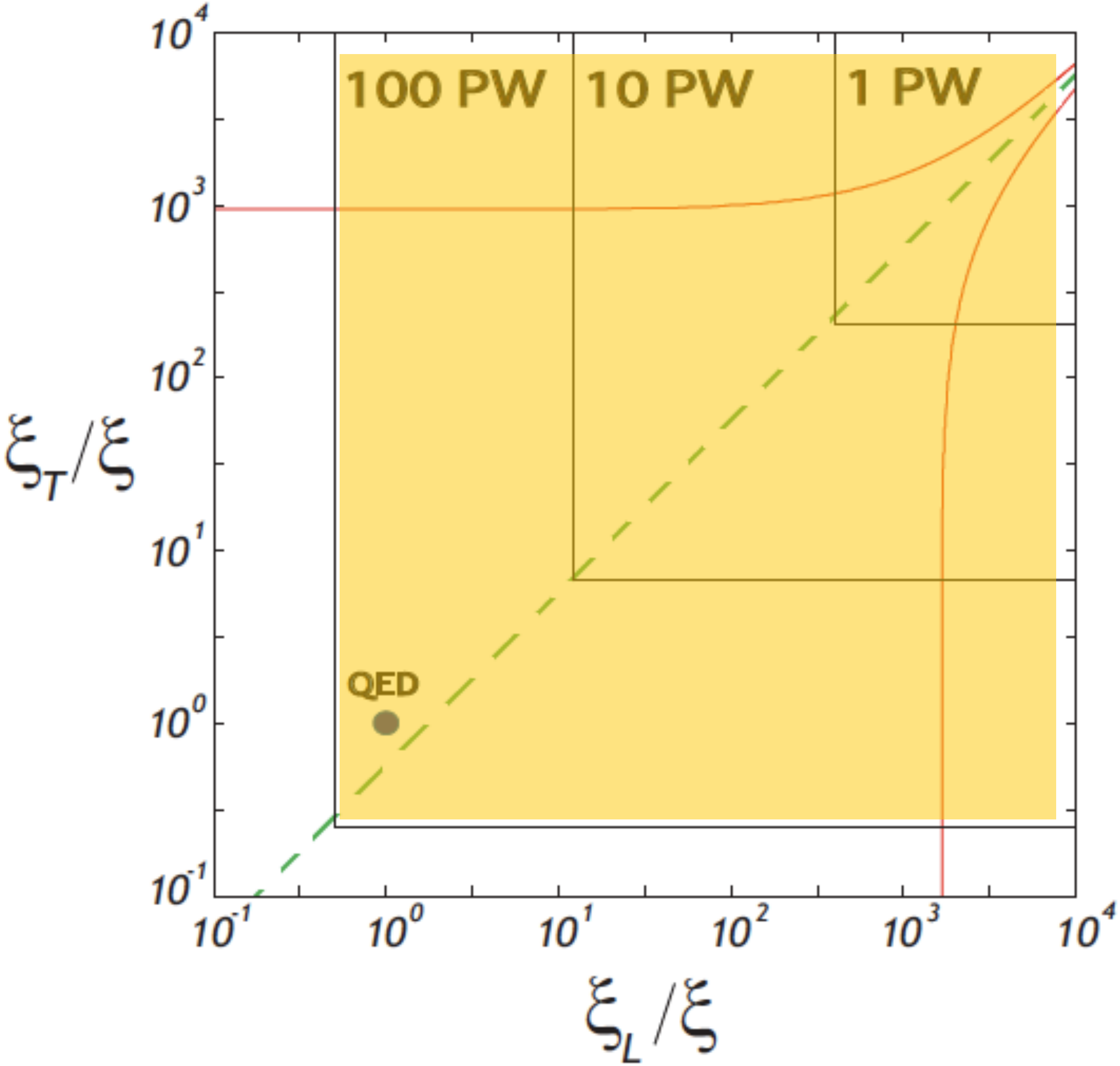
With laser fields ...

$$\mathcal{L} = \mathcal{L}_0 + \xi_L \mathcal{L}_0^2 + \frac{7}{4}\xi_T \mathcal{G}^2$$



With laser fields ..

$$\mathcal{L} = \mathcal{L}_0 + \xi_L \mathcal{L}_0^2 + \frac{7}{4}\xi_T \mathcal{G}^2$$



The VEGA laser

Titanium:sapphire technology
robust and well under control

VEGA	peak power	energy	duration	repetition rate	operation
VEGA 1	20 TW	600 mJ	30 fs	10 / sec	2007
VEGA 2	200 TW	6 J	30 fs	10 / sec	2013
VEGA 3	1 PW	30 J	30 fs	1 /sec	2016

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With laser fields ...

Facility	P (PW)	τ (fs)	λ (nm)	$\xi_T^{\lim}/\xi$	$\xi^{\lim}/\xi^{\text{PVLAS}}$
VEGA	1+0.2	30	800	230	0.1
APOLLON	10	15	800	23	0.01
ELI 10	10	30	800	8	0.003
PETAL	7	500	1053	14	0.006
100 PW	100	30	800	0.24	0.0001

QED 1

$$\mathscr{L} = \mathscr{L}_0 + \xi_L \mathscr{L}_0^2 + \frac{7}{4} \xi_T \mathscr{G}^2$$

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Summary

Background: Quantum Electrodynamics predicts that at very high fields vacuum can become unstable and virtual pairs of particles may begin to have measurable effects. **However there is a big controversy on what effect is going to appear first.**

Objective: To propose a cutting edge but feasible experiment, using world's most intense lasers, to determine those effects and to decide which one is the right QED lagrangian, and how the relativistic Dirac positron sea can play a role without need to generate real pairs.

Impact: This can change our understanding of a big physics facility. A laser, being the most intense field in the world, can trigger unique interactions with such virtual particles. It can also be relevant for neutrino studies and for our understanding of the dark matter of the universe.

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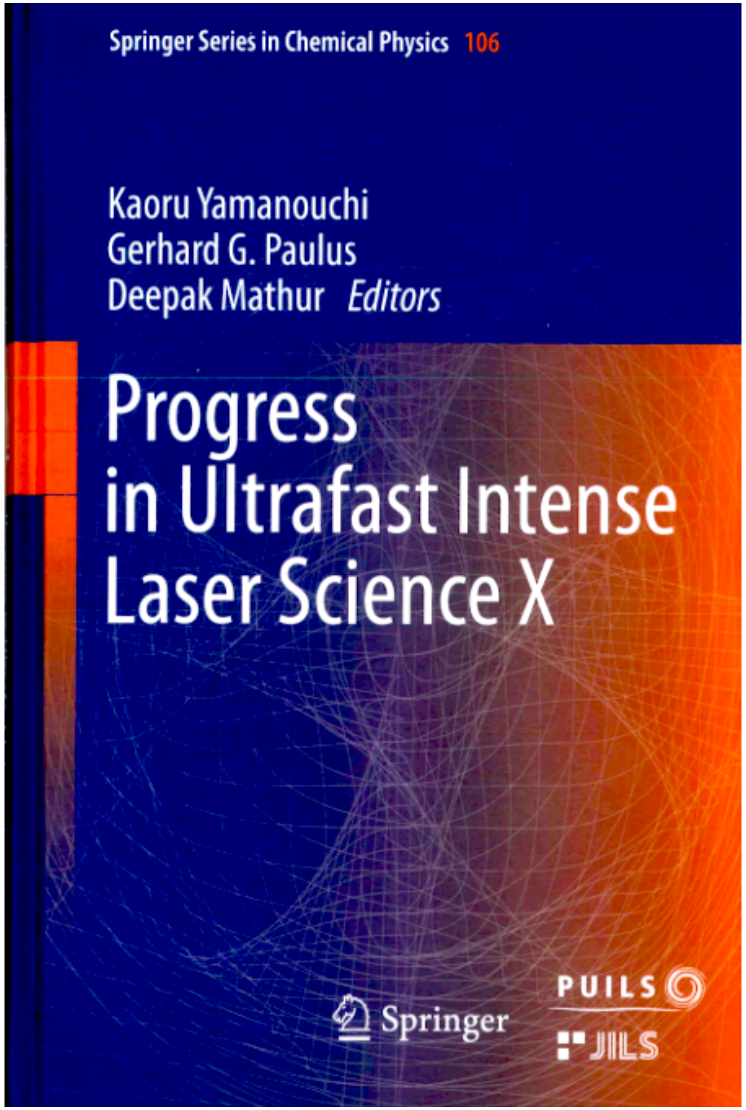
More details



Chapter 9.-
Quantum Vacuum Polarization Searches with High Power Lasers Below the Pair Production Regime

Daniele Tommasini,
David Novoa and
Luis Roso

The collaboration

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Cruz Méndez
...

Orense team
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Roman Sobolewski, Rochester


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