Towards the measurement of the quantum-vacuum Lagrangian coupling coefficients using two counterpropagating super-intense laser pulses

Luis Roso,

CLPU Director

MAP OF UNIQUE SCIENTIFIC AND TECHNICAL INFRASTRUCTURES (ICTS)

CLPU CENTRO DE LÁSERES PULSADOS

ExHILP 2021 Jena

4th Extremely High Intensity Laser Physics Conference

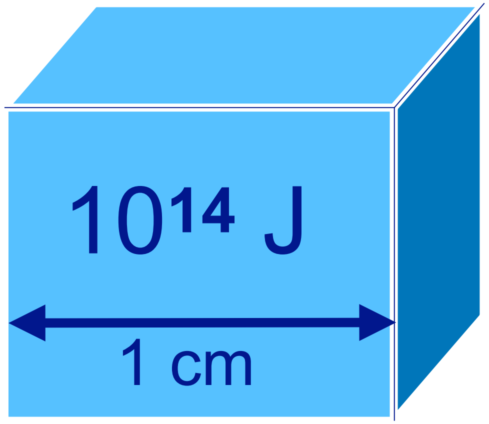
EXHILP 2021

Dense light

We are talking about **heavy** light!!!

$$E = mc^2 \Leftrightarrow I = \rho_e c = \rho_m c^3$$

energy density mass density

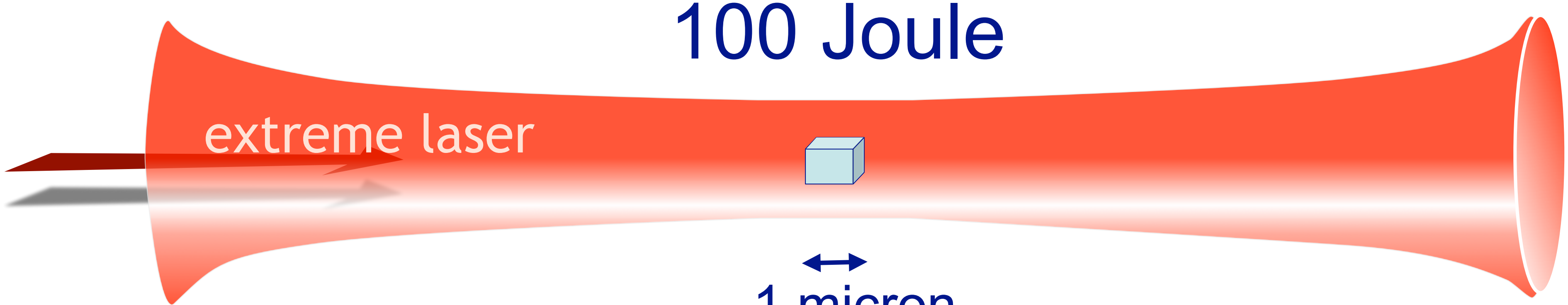


water density
1 gram/cm^3

10^{24} W/cm^2

same energy density as liquid water !!!

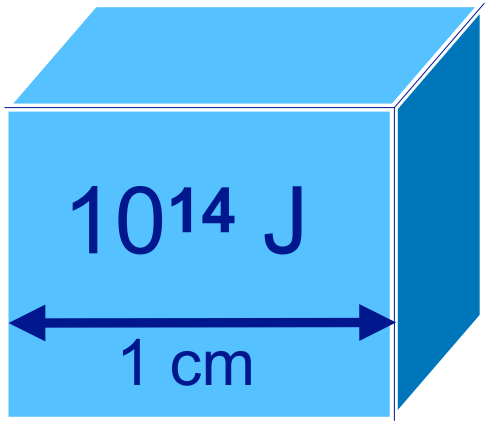
100 Joule



1 micron

We are talking about **heavy** light!!!

$$E = mc^2 \Leftrightarrow I = \rho_e c = \rho_m c^3$$



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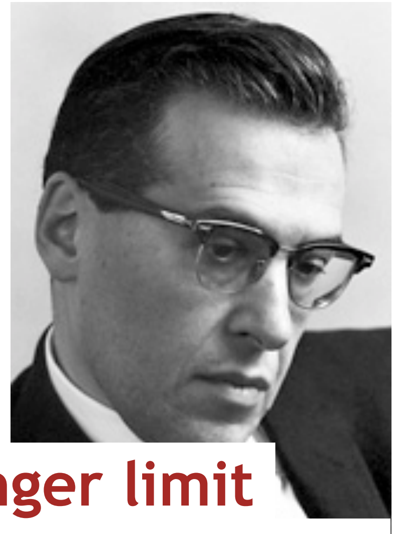
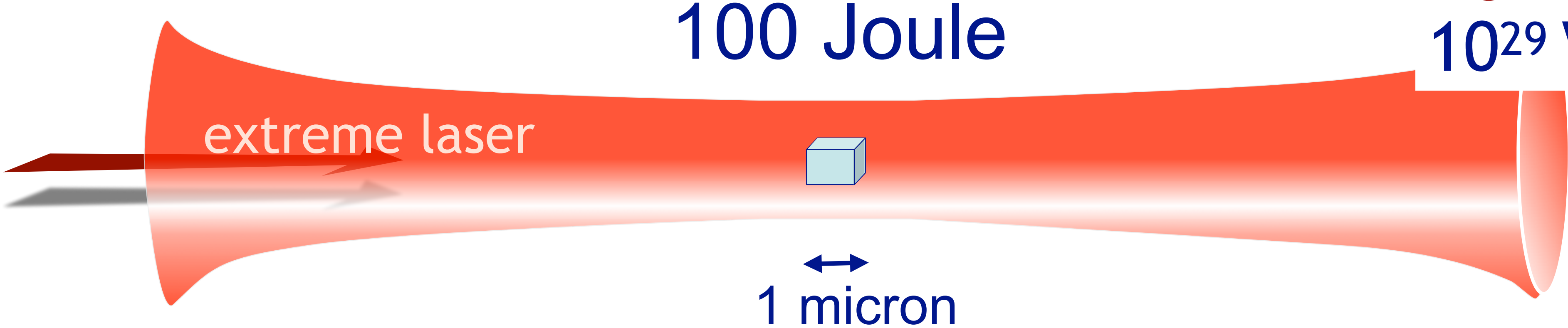


Schwinger limit

10^{29} W/cm^2



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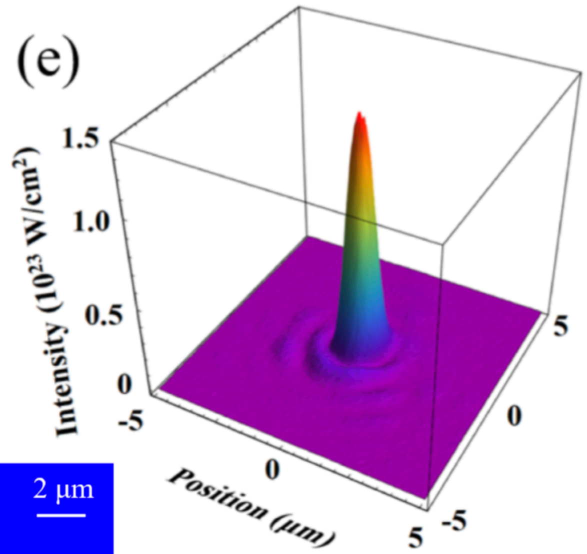
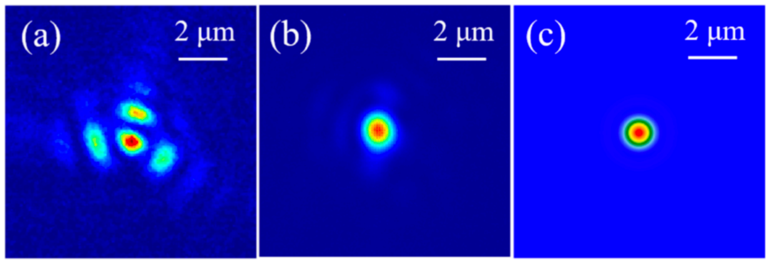
Record High Intensity 10^{23} W/cm^2

World record





CoReLS

Chang Hee Nam

Gwangju

Rep of Korea

4 petawatt laser

f /1.1

off-axis parabolic mirror

(OAP; *f* = 300 mm)

pulse duration 20 fs

optica May 2021

Realization of laser intensity over 10^{23} W/cm^2

JIN WOO YOON,[1,2,†] YEONG GYU KIM,[1,3,†] IL WOO CHOI,[1,2] JAE HEE SUNG,[1,2] HWANG WOON LEE,[1] SEONG KU LEE,[1,2,4] AND CHANG HEE NAM[1,3,5]

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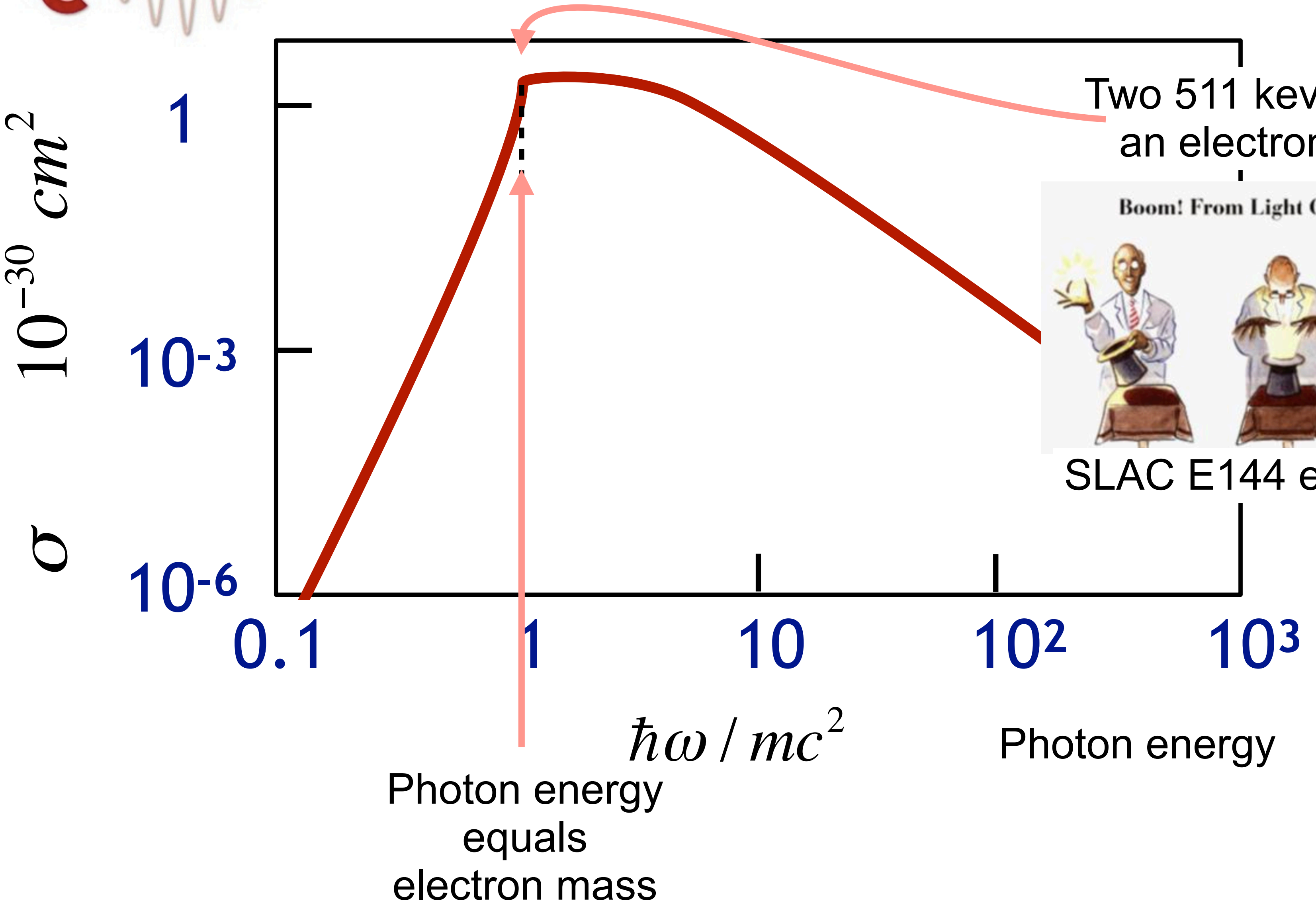
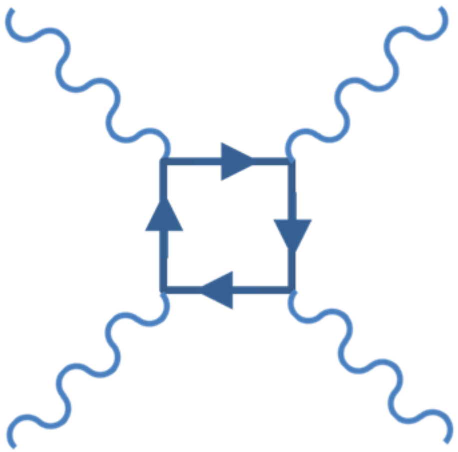
Photon-photon

Photon-photon coupling



SLAC E144 experiment, 1997

Key question

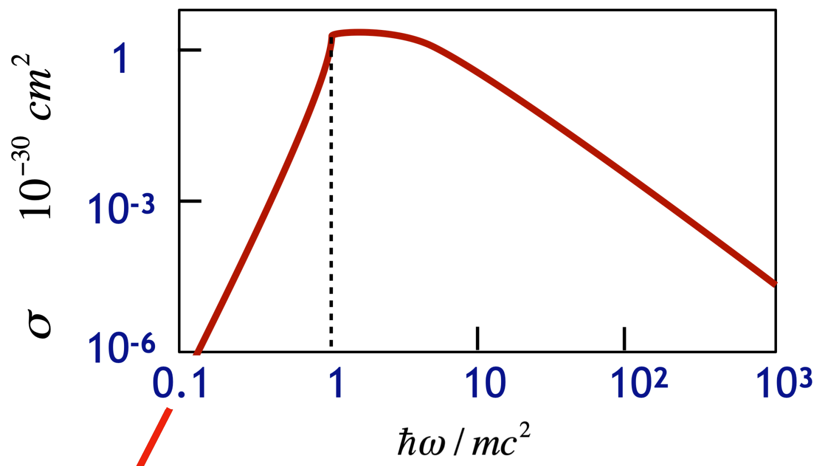


What is the intensity where virtual pairs start having a measurable effect?

Generation of real pairs

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
10^{29} W/cm^2

Infrared-infrared collisions



at optical wavelengths

Goal: measure optical photon-photon coupling

$$\sigma_{\gamma-\gamma} \lesssim 10^{-60} m^2$$

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QED lagrangian

QED Lagrangian

for $h\nu \ll m_e c^2$ as should be with optical photons

$$\mathcal{L} = \mathcal{L}_0 + \quad \mathcal{L}_0^2 + \quad \mathcal{G}^2$$

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

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

two coupling coefficients to determine

What is the contribution of those nonlinear terms?

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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)

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

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

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.

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More contributions

for $h\nu \ll m_e c^2$ as should be with optical photons

$$\mathcal{L} = \mathcal{L}_0 + \textbf{?}\,\mathcal{L}_0^2 + \textbf{?}\;\mathcal{G}^2$$

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

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

The presence of particles beyond the Standard Model can modify the coupling coefficients:

- Axions
- Minicharged particles (scalar or vector)
- ...

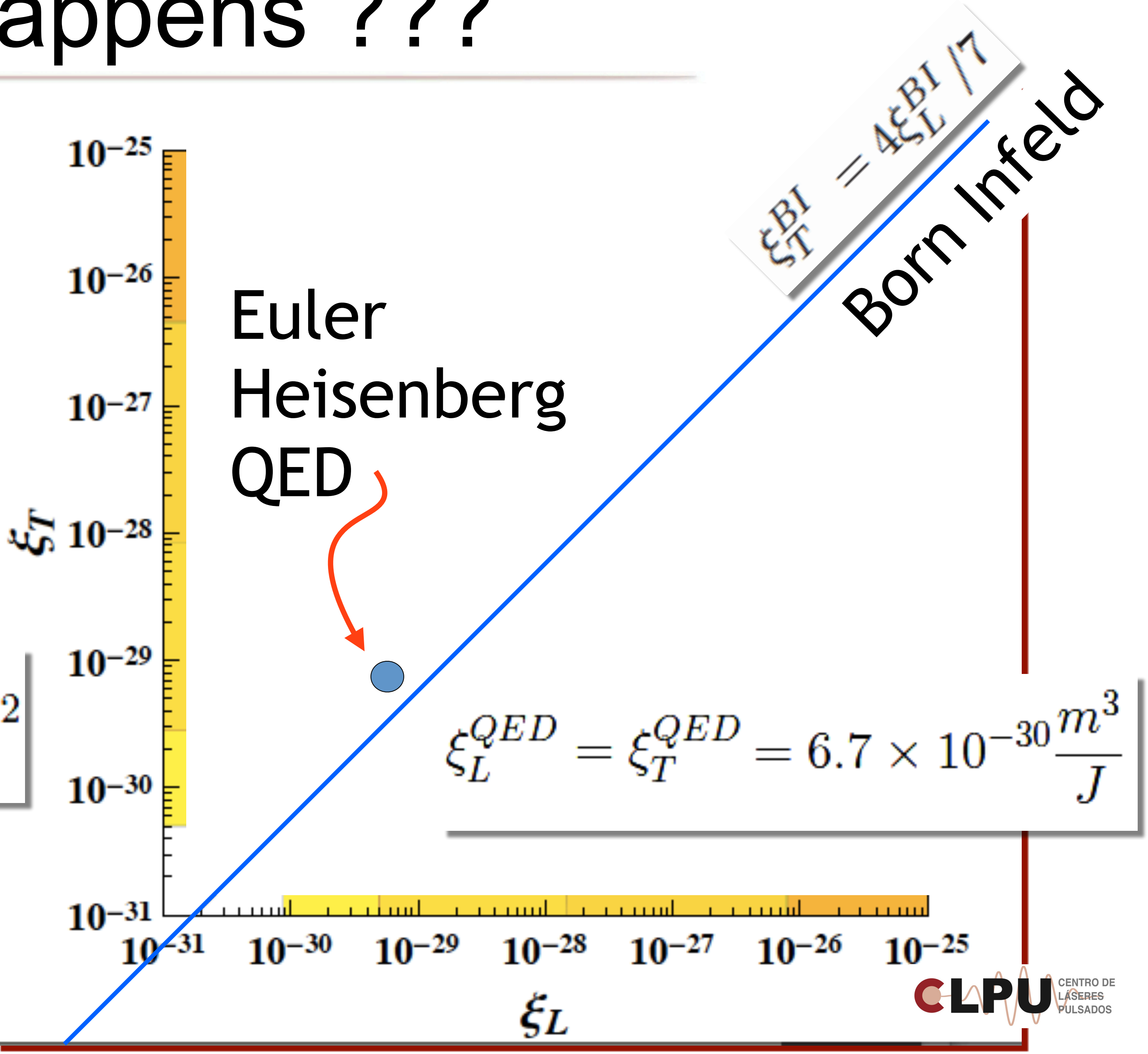
What happens ???

Too-many Lagrangians

Two parameter space

No assumptions
Just try to measure
these two coupling
constants

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



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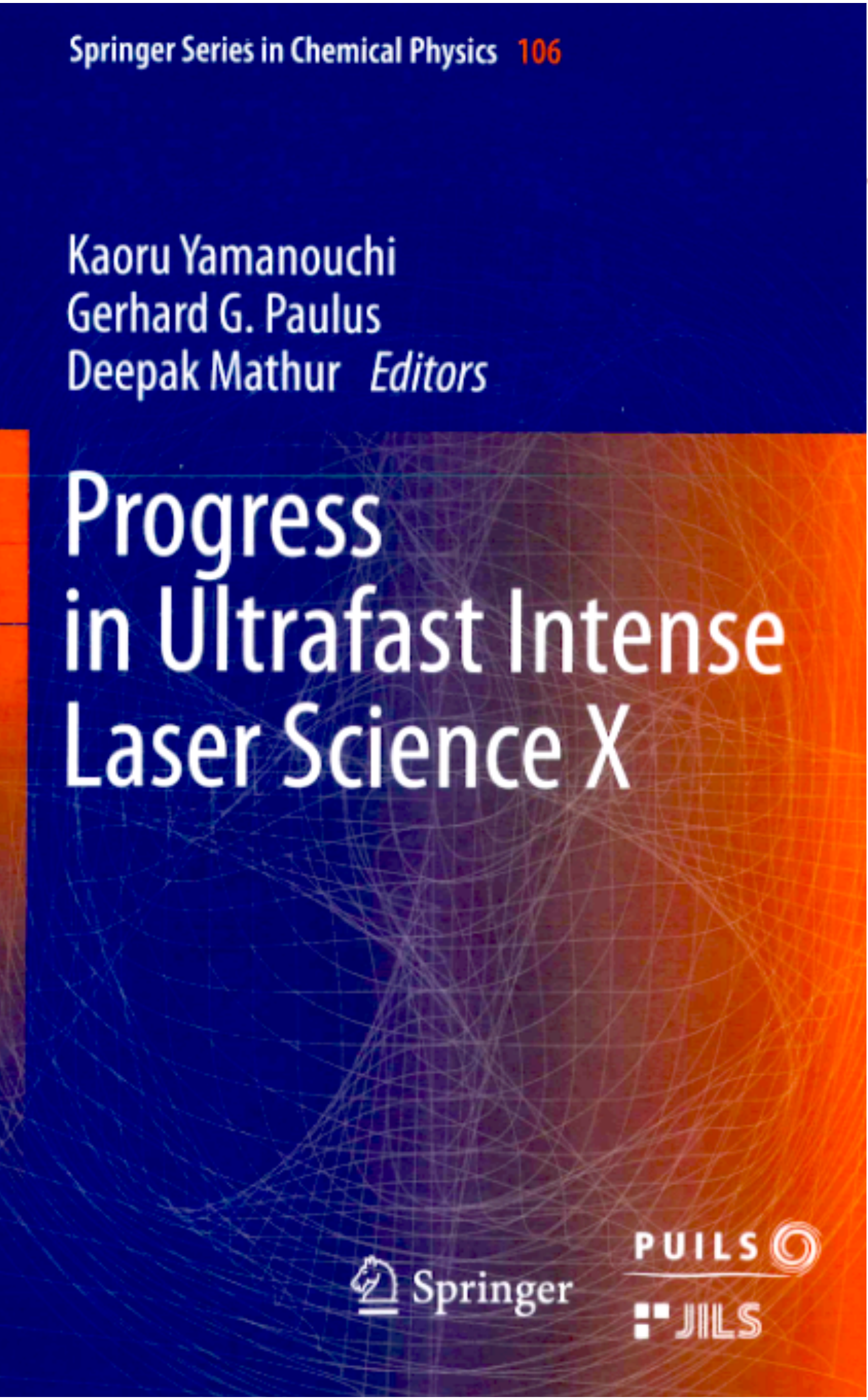

Chapter 9.-

Quantum Vacuum Polarization Searches with High Power Lasers Below the Pair Production Regime

Daniele Tommasini,
David Novoa and Luis Roso

PUILS X, 2014

Original paper
Detecting photon-photon scattering in vacuum at exawatt lasers
Daniele Tommasini, et al Phys Rev A 77 (2008)

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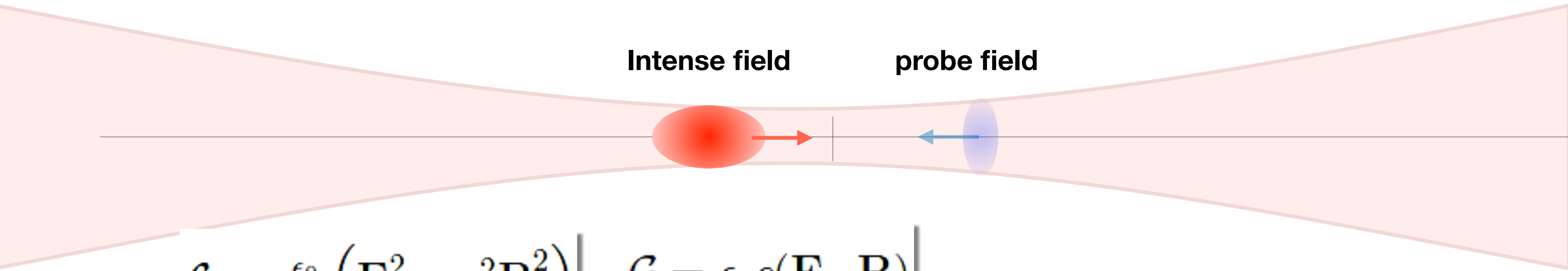
Optical signal

Optical-optical interaction: pump-probe

Key Point: QED coefficients result directly in a phase change of the probe field



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

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

$$E_{tot} = E_{pump} + E_{probe}$$

$$E_{tot}^2 = \left(E_{pump} + E_{probe}\right)^2 = E_{pump}^2 + 2E_{pump}E_{probe} + E_{probe}^2$$

τ pulse duration
I Intensity
k wavector

Detecting photon-photon scattering in vacuum at exawatt lasers
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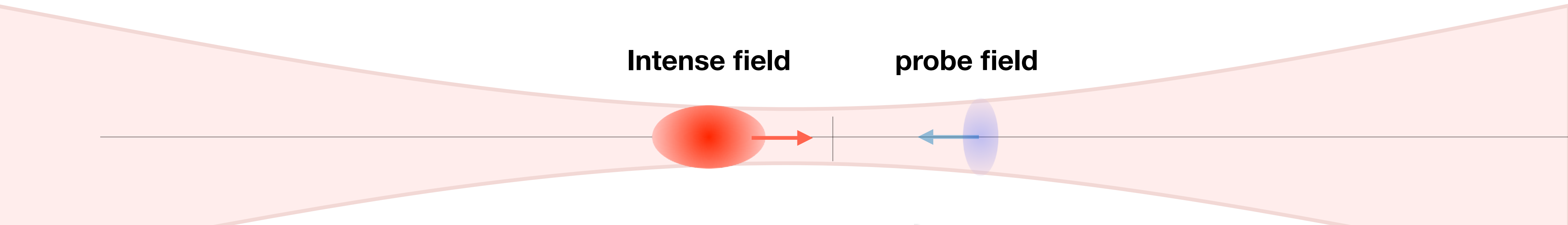
Optical-optical interaction: pump-probe

Key Point: QED coefficients result directly in a phase change of the probe field

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



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τ pulse duration
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From the idea to a real experiment

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Frontiers in Theoretical and Applied Physics/UAE 2017 (FTAPS 2017) IOP Publishing
IOP Conf. Series: Journal of Physics: Conf. Series **869** (2017) 012015 doi:10.1088/1742-6596/869/1/012015

Probing the quantum vacuum with petawatt lasers

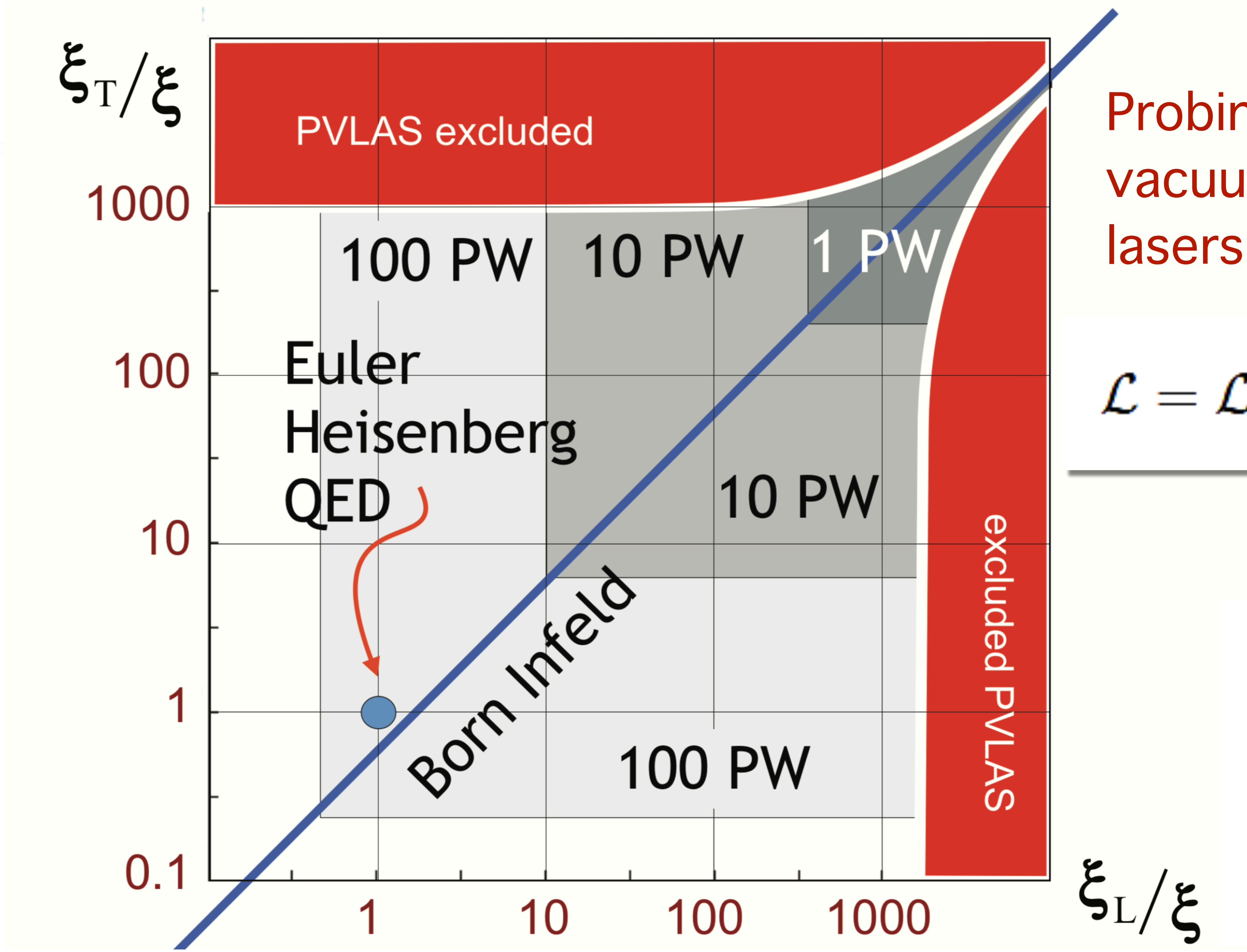
W T Hill III[1] and L Roso[2]

[1]Joint Quantum Institute, Institute for Physical Science and Technology and Department of Physics, University of Maryland, College Park, MD 20742, USA
[2]Centro de Láseres Pulsados, CLPU, Salamanca, Spain

E-mail: wth@umd.edu

Abstract. Due to the bosonic nature of the photon, increasing the peak intensity through a combination of raising the pulse energy and decreasing the pulse duration will pile up more and more photons within the same finite region of space. In the absence of material, this continues until the vacuum is stressed to the point of breakdown and virtual particles become real. The critical intensity where this occurs for electrons and positrons – the so-called Schwinger limit – is predicted to be $\sim 10^{29}$ W/cm^2. At substantially lower intensities, however, nonlinear aspects of the *quantum vacuum* associated with polarization of the vacuum can be explored. These studies become viable at the petawatt level where 10^{23} W/cm^2 and above can be reached. This is an era into which we are just embarking that will provide critical tests of QED and theories beyond the *Standard Model* of particle physics.

Probing the quantum vacuum with petawatt lasers



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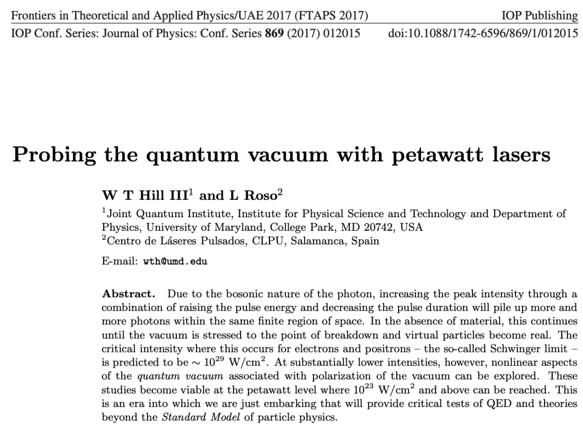

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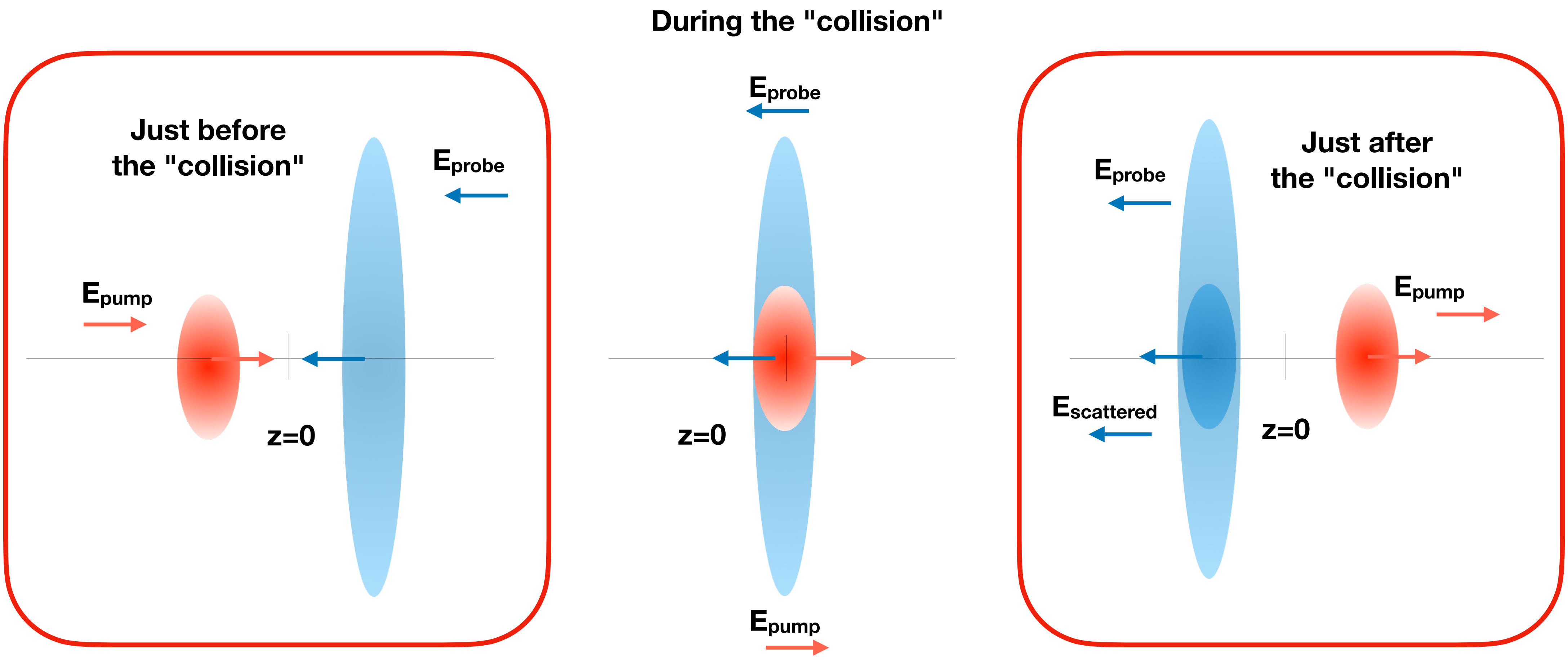
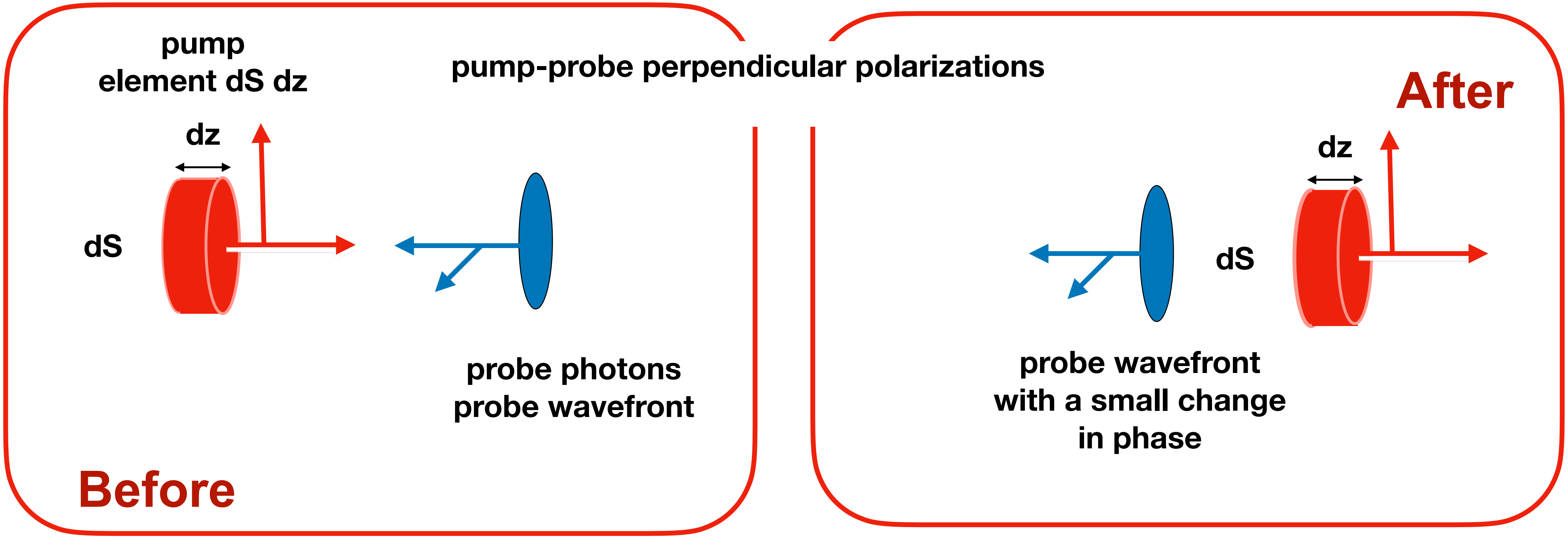
Hill Roso J Phys Conf Ser 869 (2017) 012015

Collision scenario

Optical-optical interaction



Optical-optical interaction

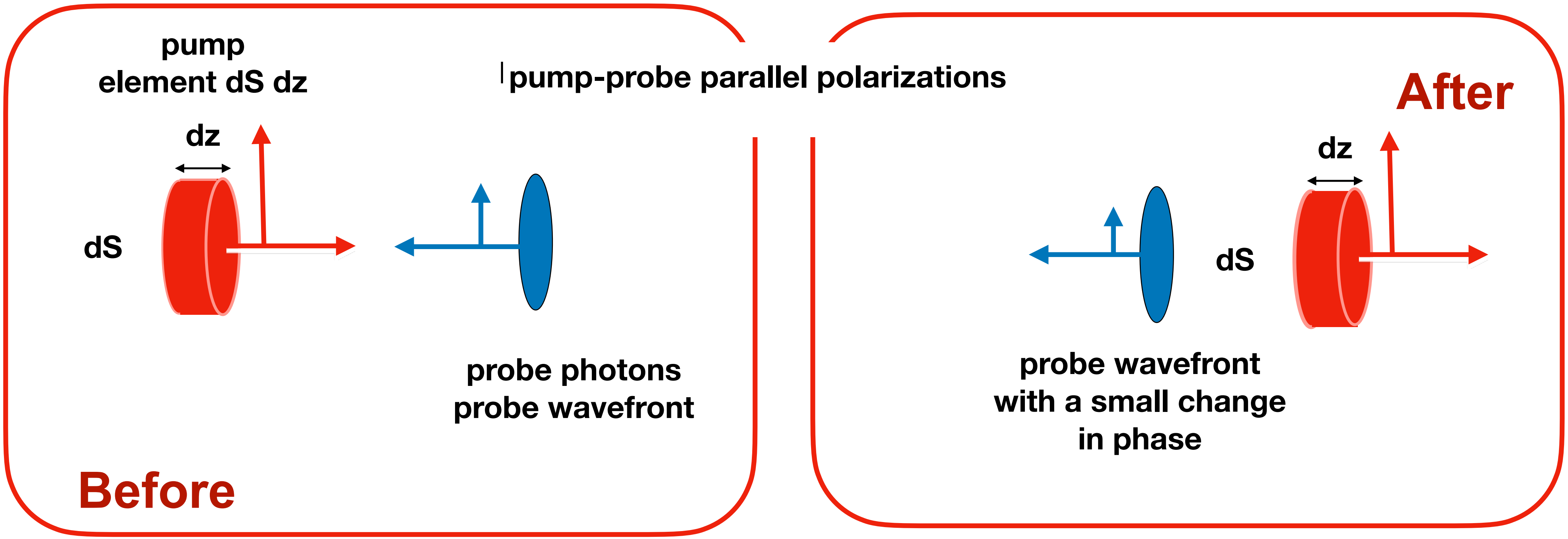


$$d\phi_T = 7\xi_T k_{probe}\rho_e dz$$

D Tommasini et al
Precision tests of QED and non-standard models by searching photon-photon scattering in vacuum with high power lasers
JHEP, 2009

Beam A
element x,y

Optical-optical interaction



$$d\phi_L = 4\xi_L k_{probe} \rho_e dz$$

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Beam A
element x,y

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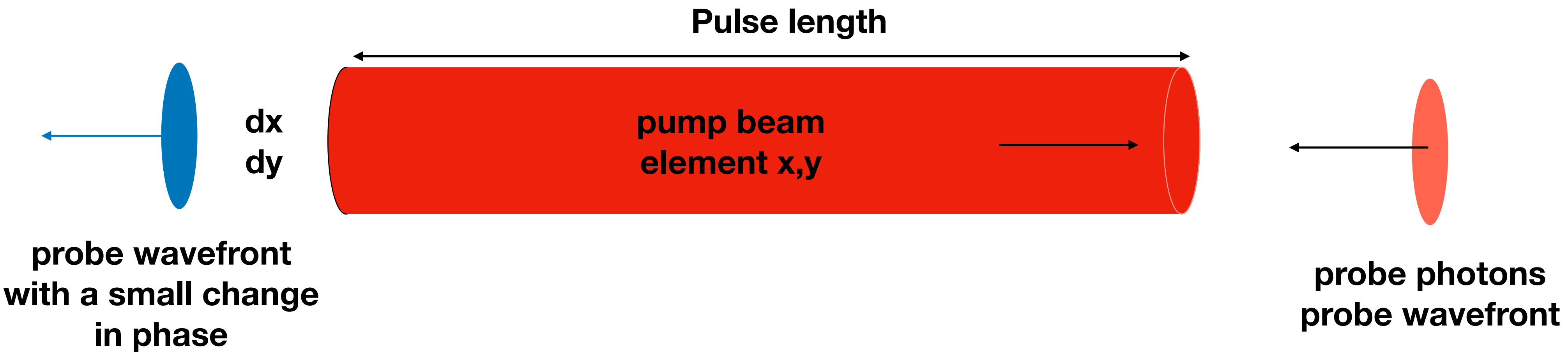
Optical-optical interaction



$$\Delta\phi_L = 4\xi_L k_{probe}\rho_e c\,\tau_{probe} = 4\xi_L k_{probe}\, I_{probe}\,\tau_{probe}$$

$$\Delta\phi_T = 7\xi_T k_{probe}\rho_e c\,\tau_{probe} = 7\xi_T k_{probe}\, I_{probe}\,\tau_{probe}$$

Optical-optical interaction

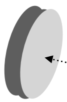
Pump 10^{23} W/cm^2 - 10^{24} W/cm^2 more ...
Probe 10^{20} W/cm^2

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

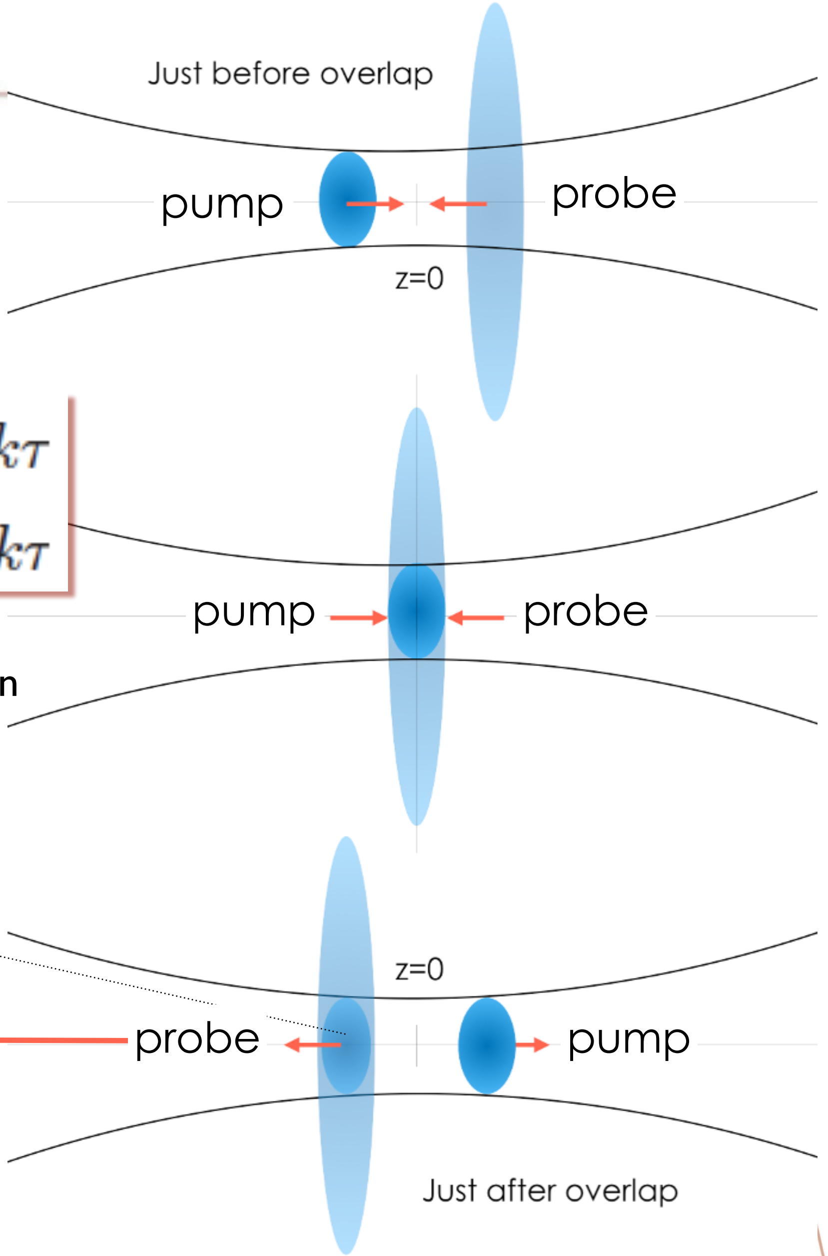
Very few photons scattered 1:10^{18} !!!

τ pulse duration
I Intensity
k wavector

Detector



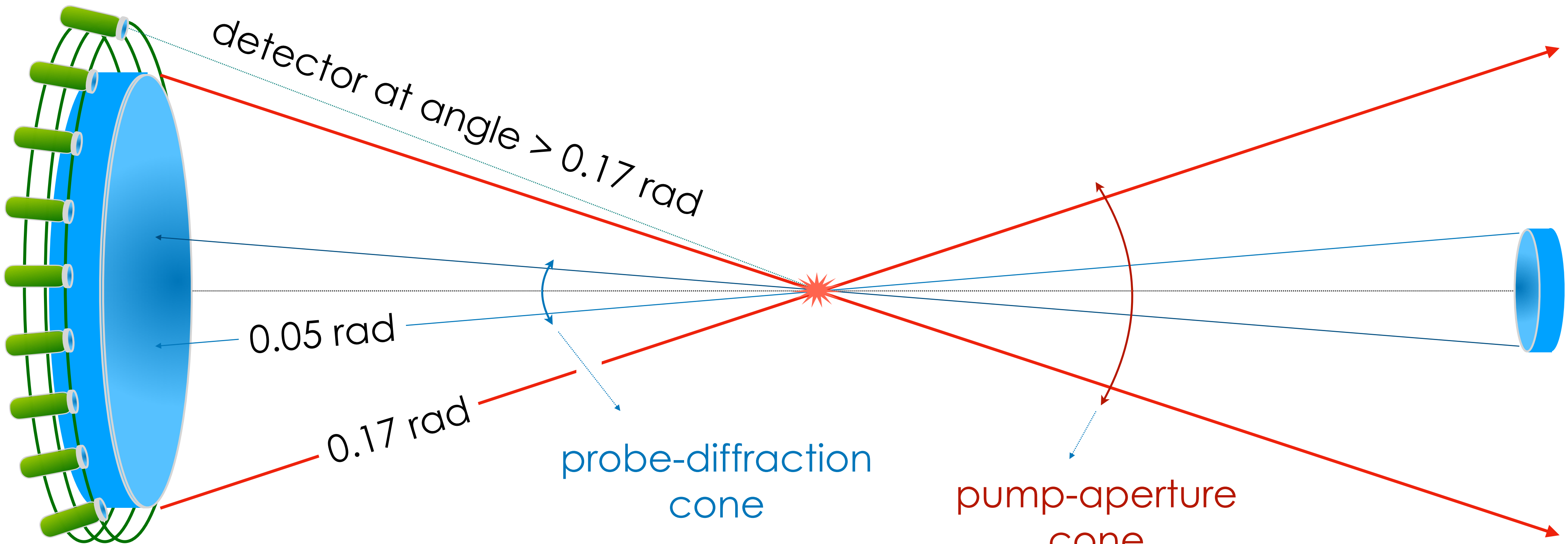
Scattered photons due to quantum vacuum



Most of the probe photons continue their linear propagation

Pump 800 nm Airy f-number 3
Probe 800 nm Gauss waist 16 μm

Short focus / high f-number / wide angle



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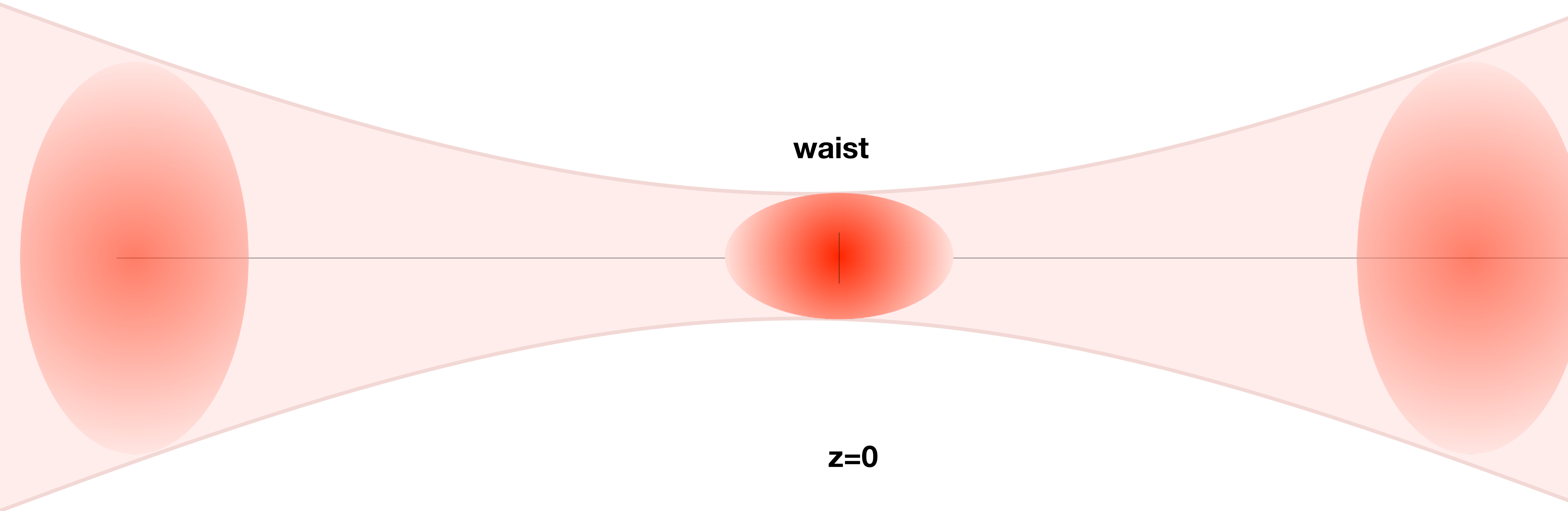
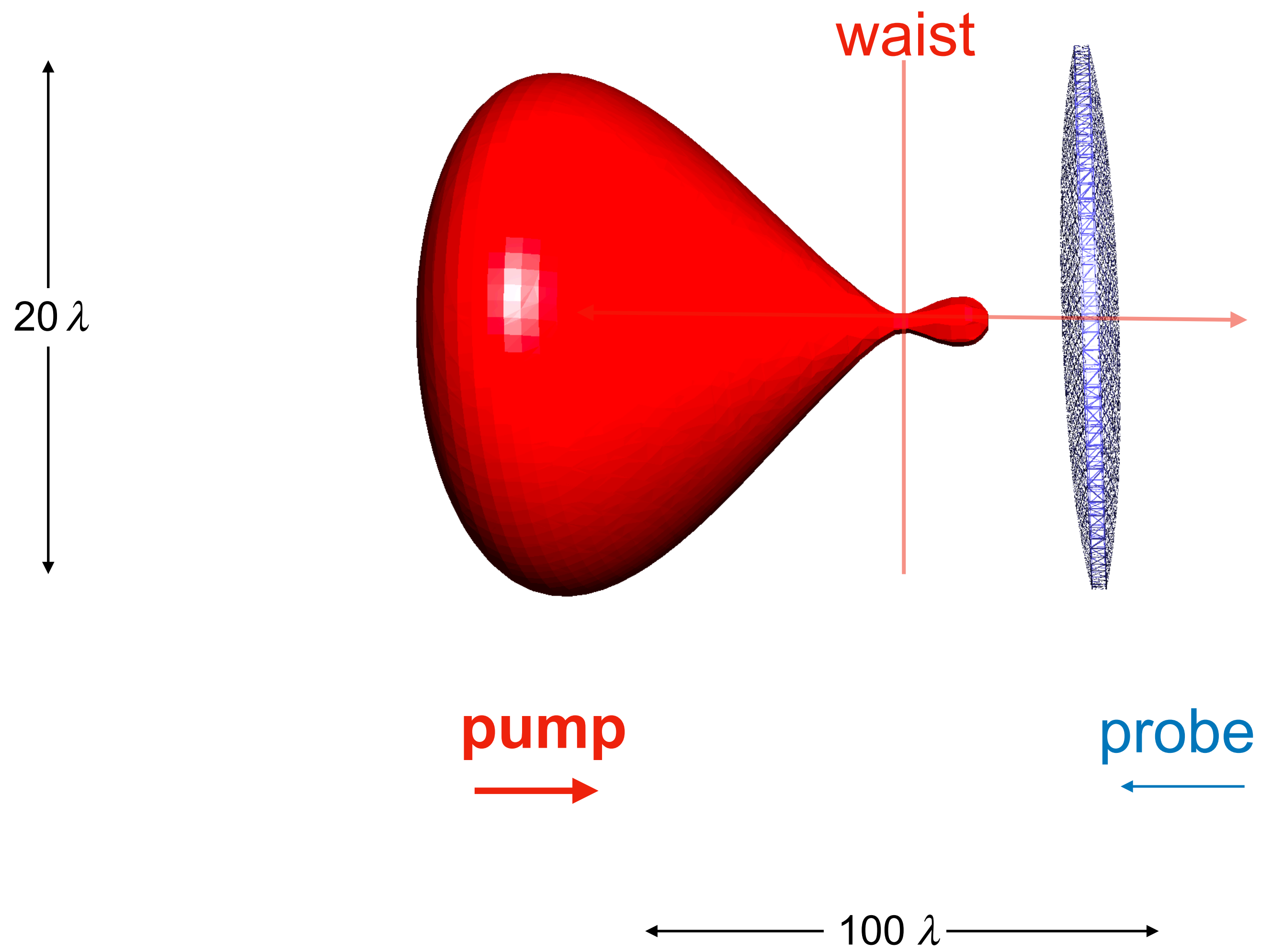
Pump duration

Pump beam duration



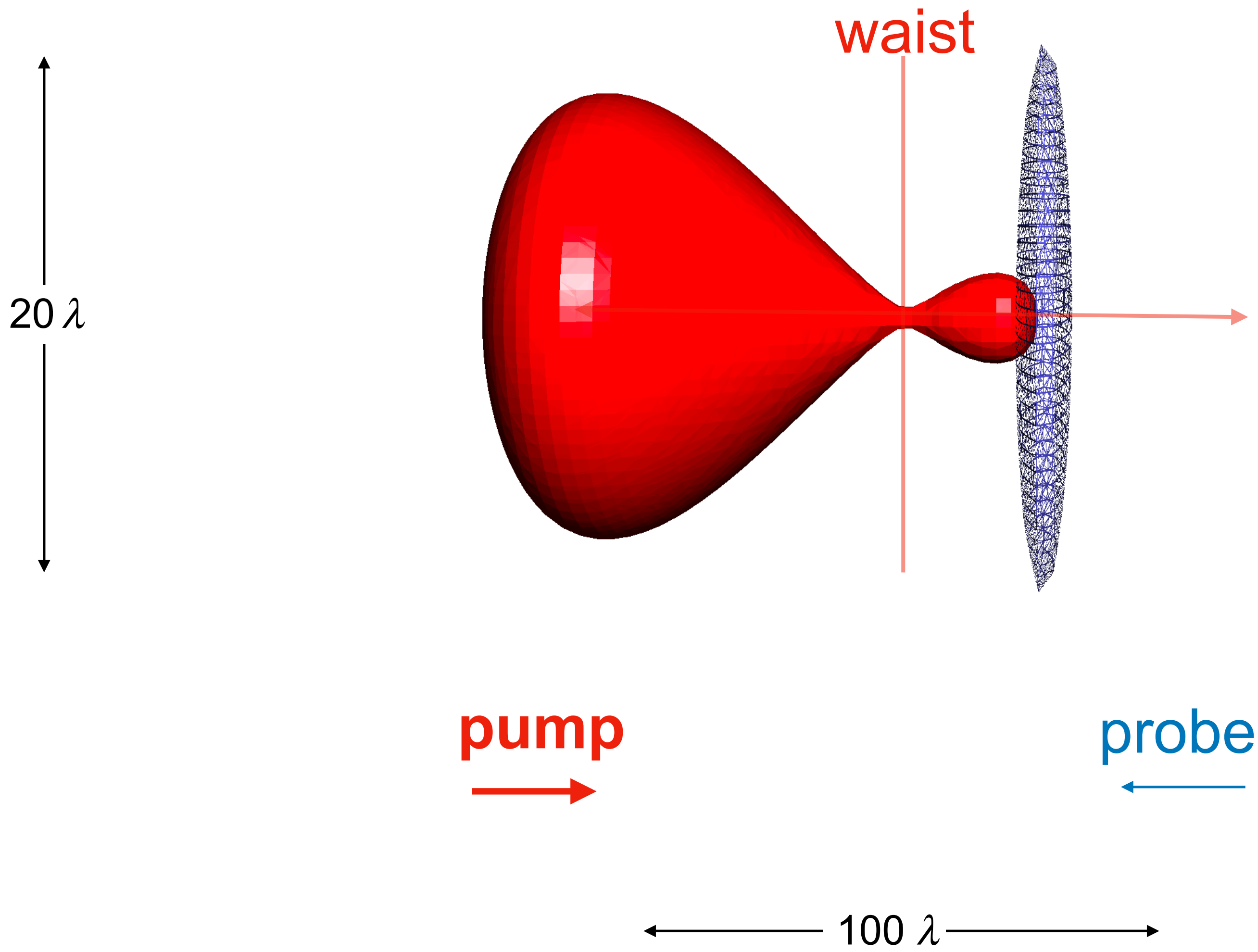
Pulse duration smaller than Rayleigh length of focus to guarantee that all energy of the pump is on the focus at the same time

Pump too long



horizontal scale x 5 = vertical scale

Pump too long



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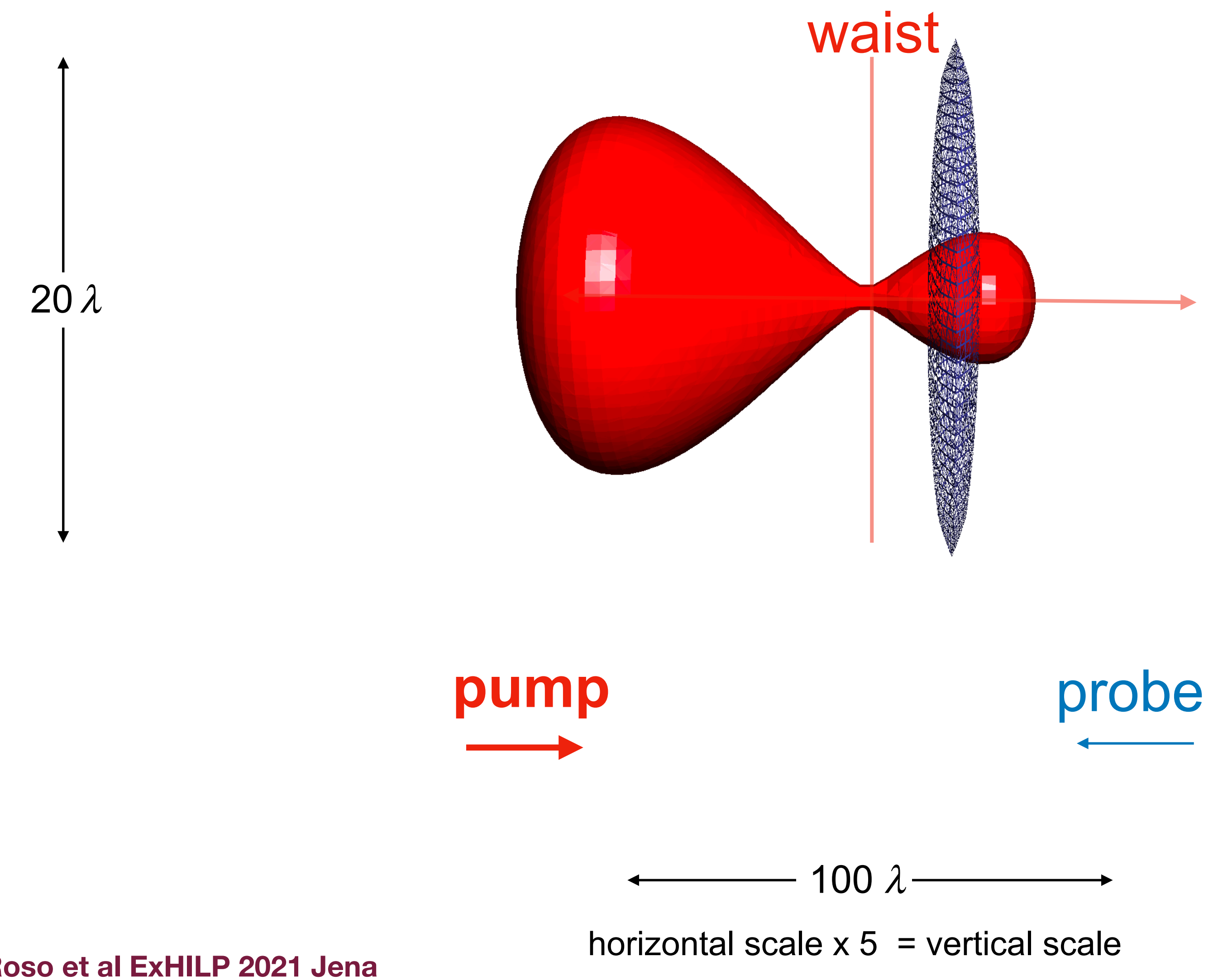

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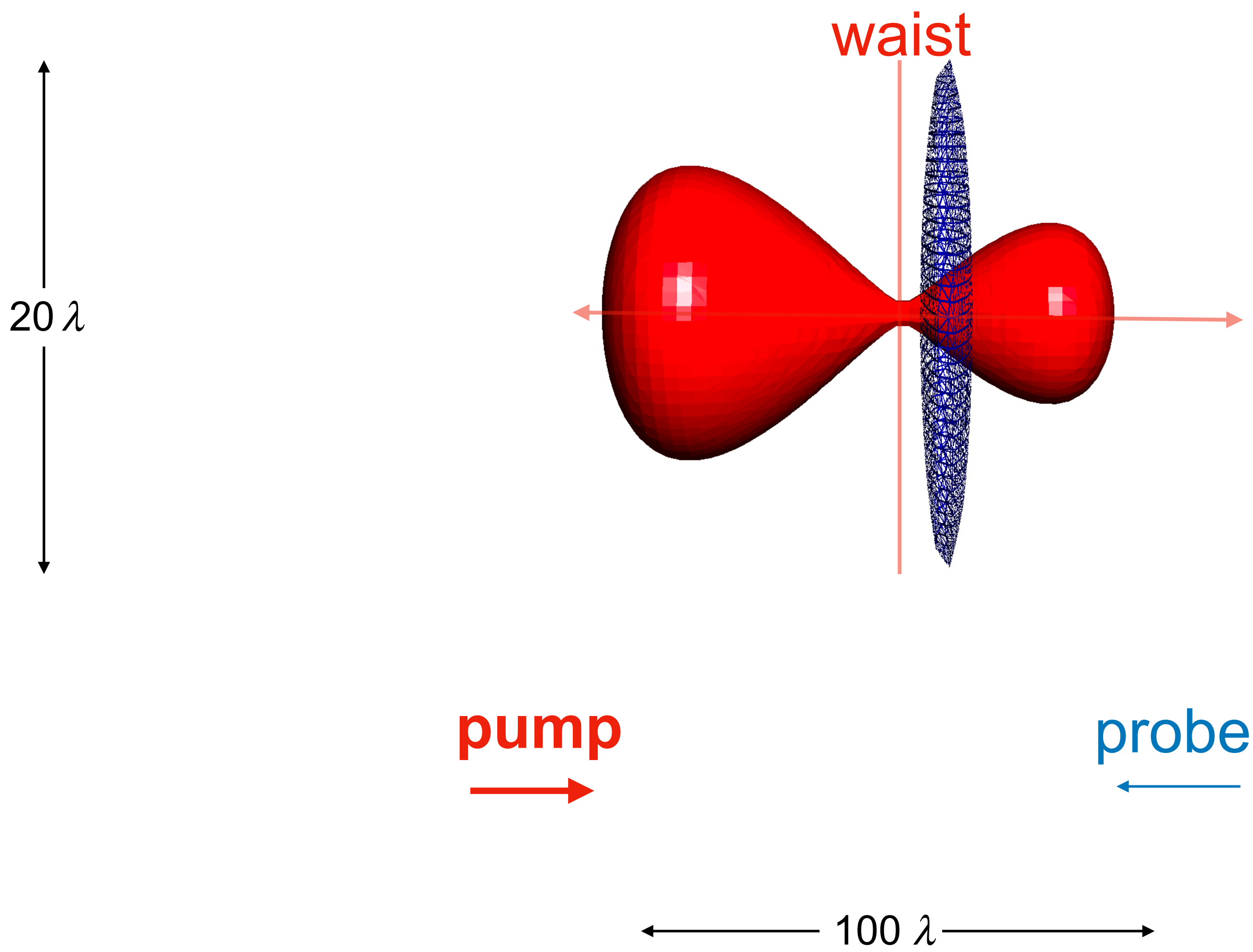

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CENTRO DE LÁSERES PULSADOS

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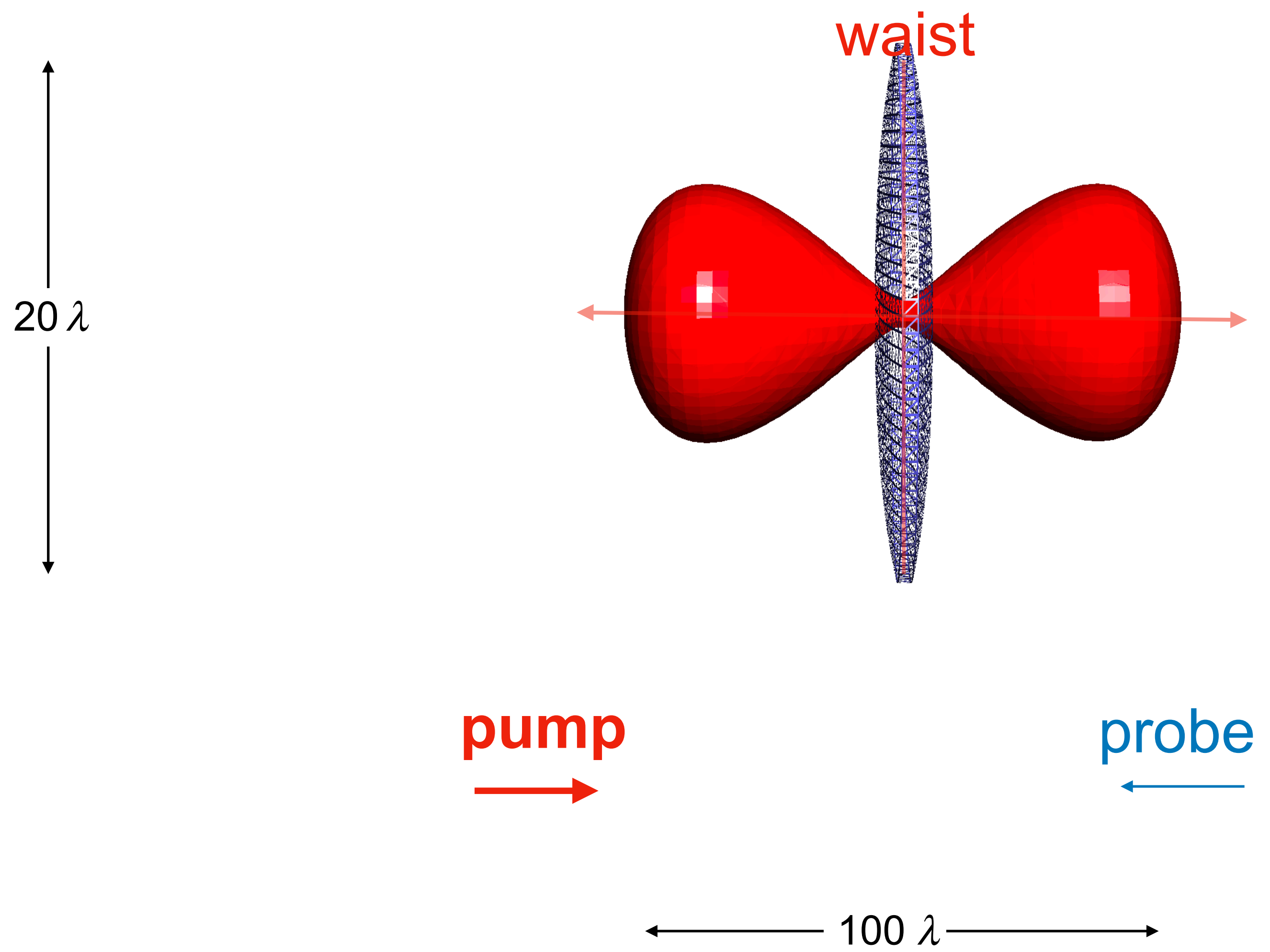

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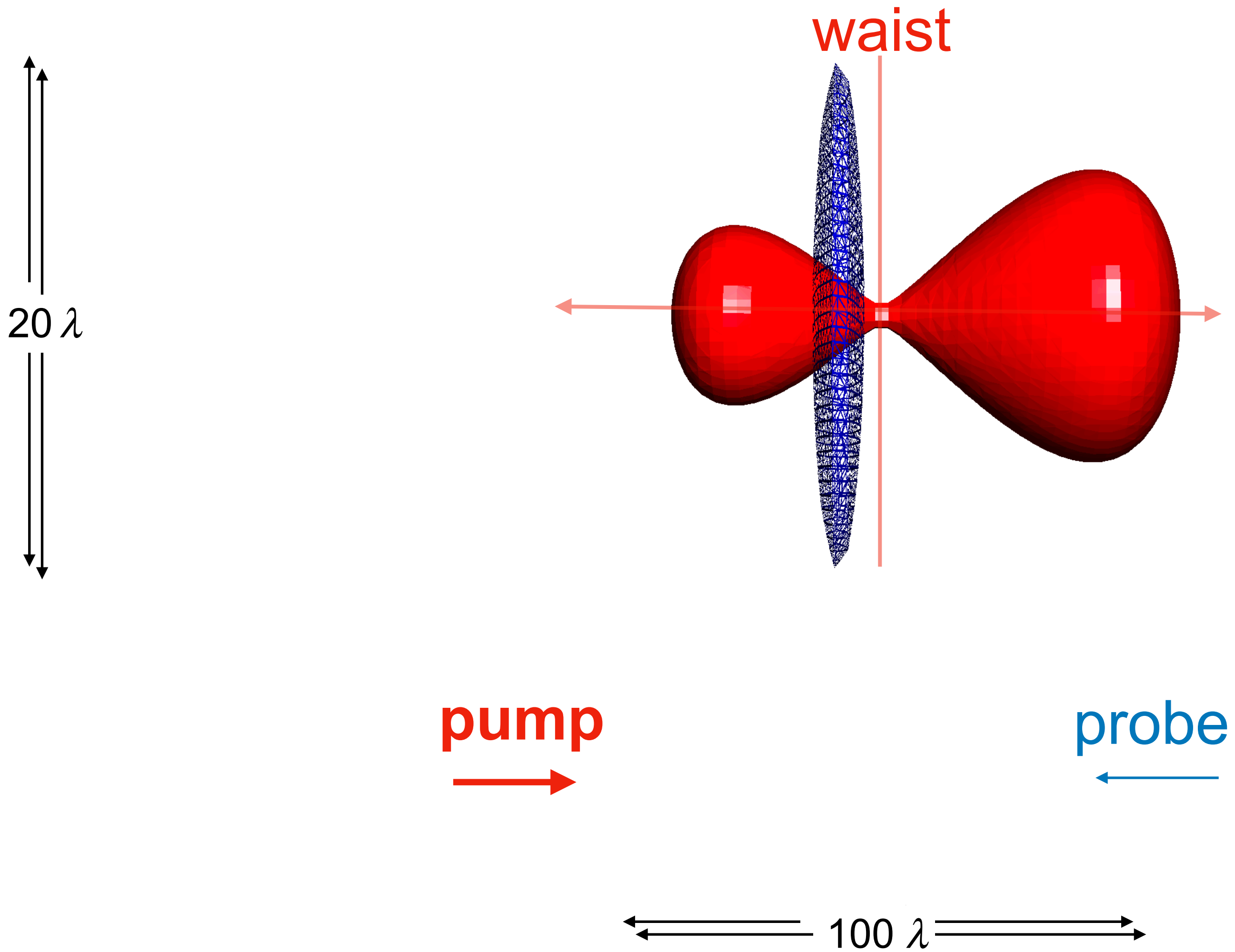
Pump too long



horizontal scale x 5 = vertical scale
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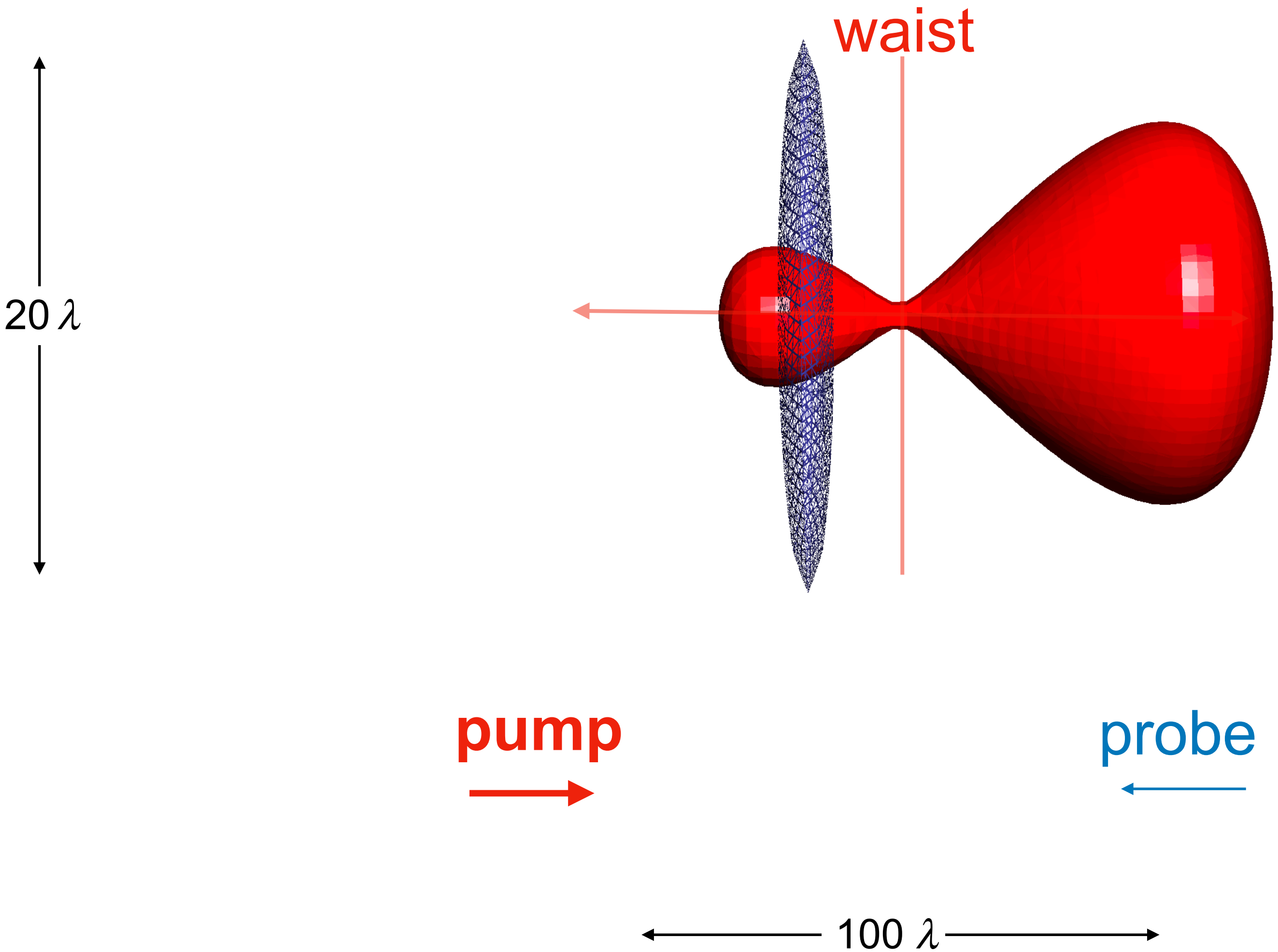
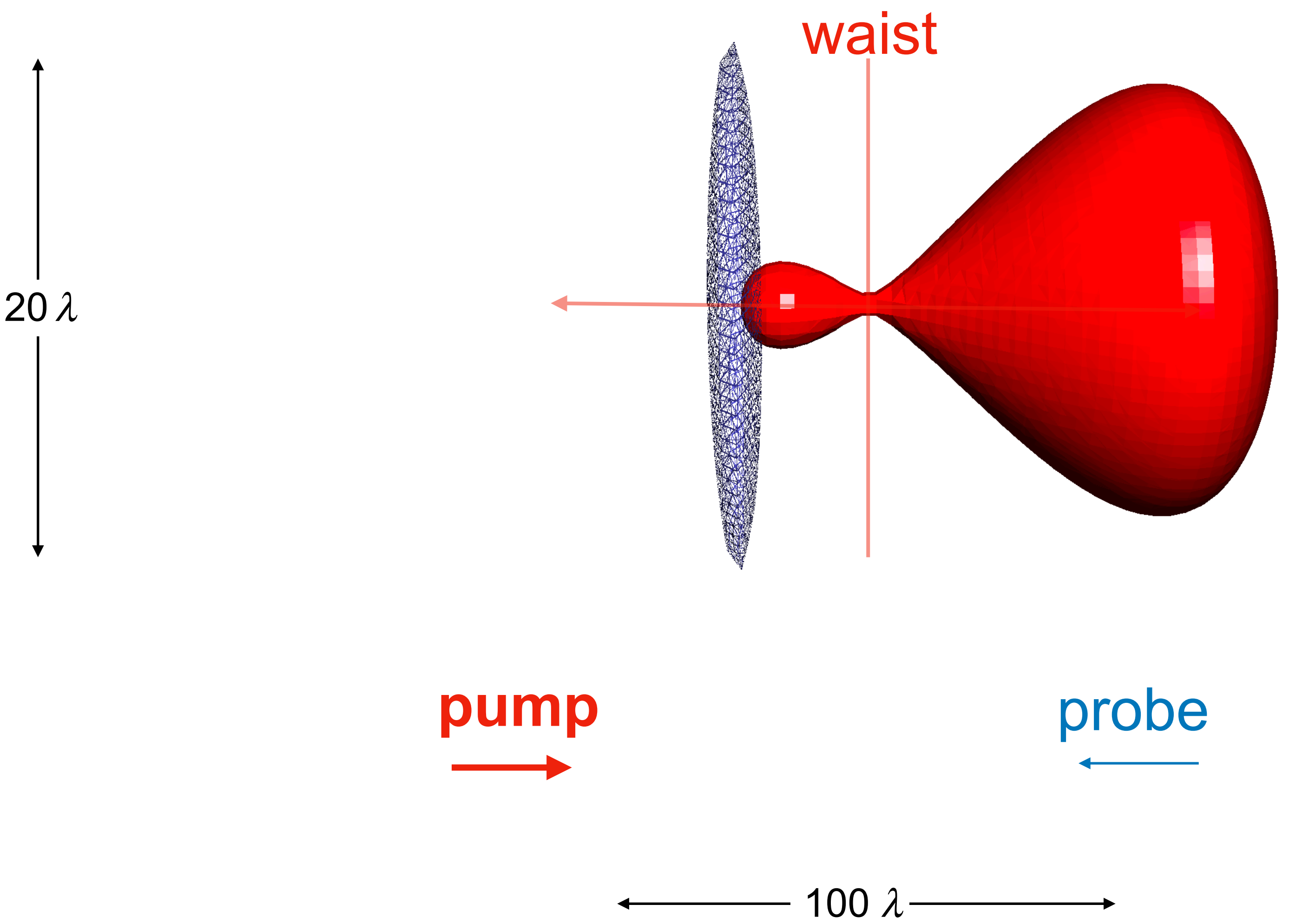
Pump too long



horizontal scale x 5 = vertical scale

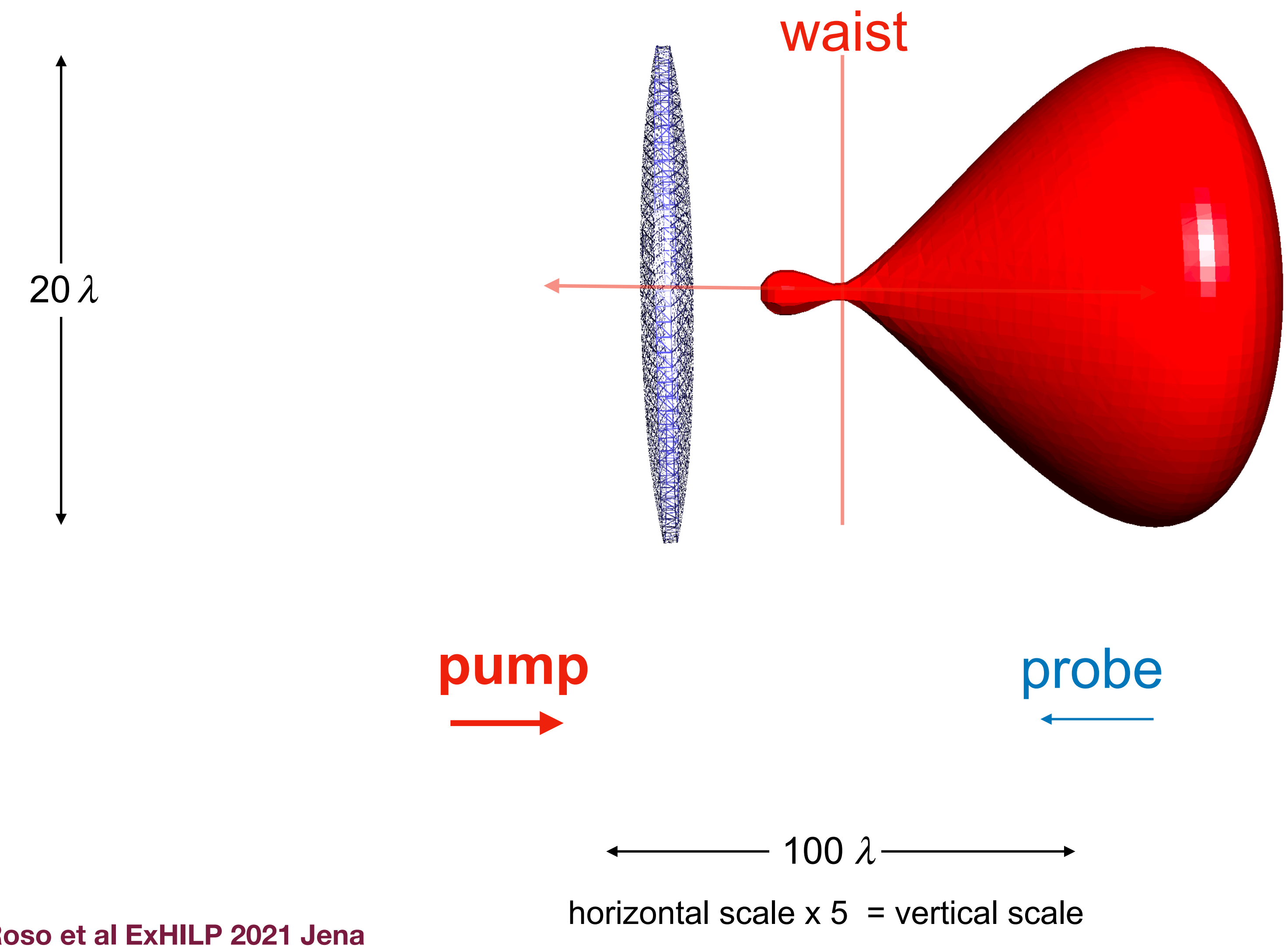
CENTRO DE LÁSERES PULSADOS

Pump too long



horizontal scale x 5 = vertical scale

Pump too long



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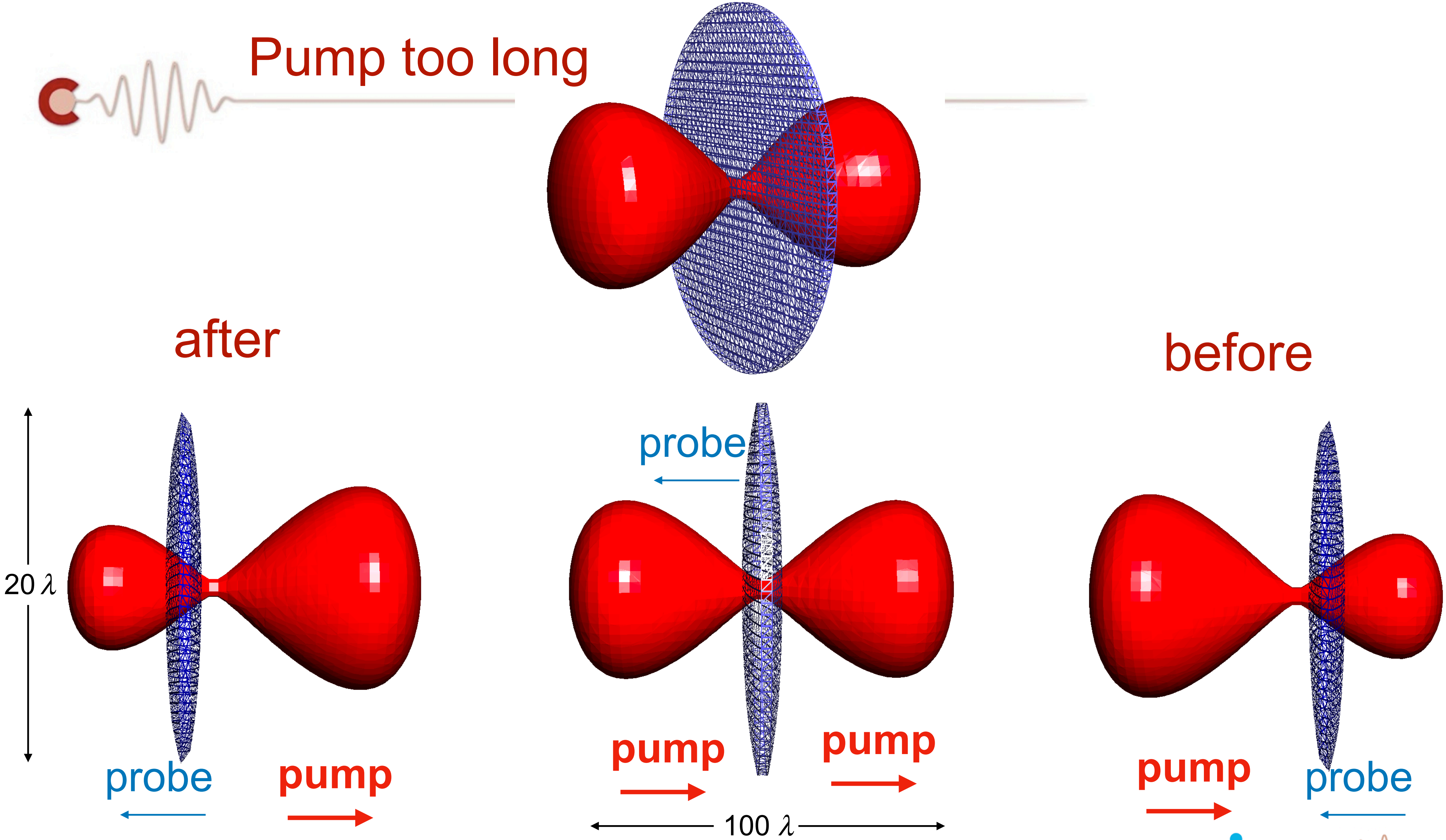
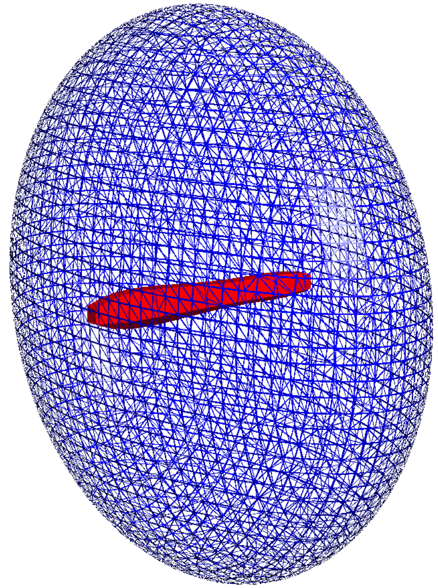
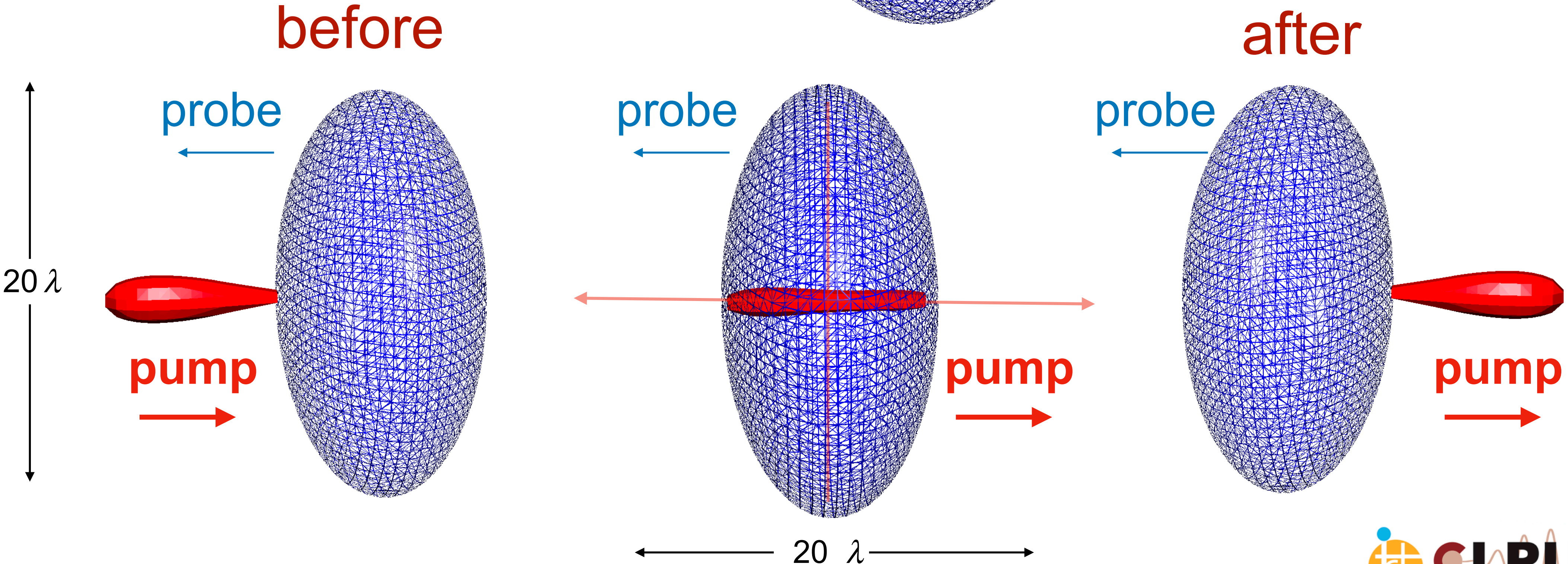


horizontal scale x 5 = vertical scale

Pump short enough

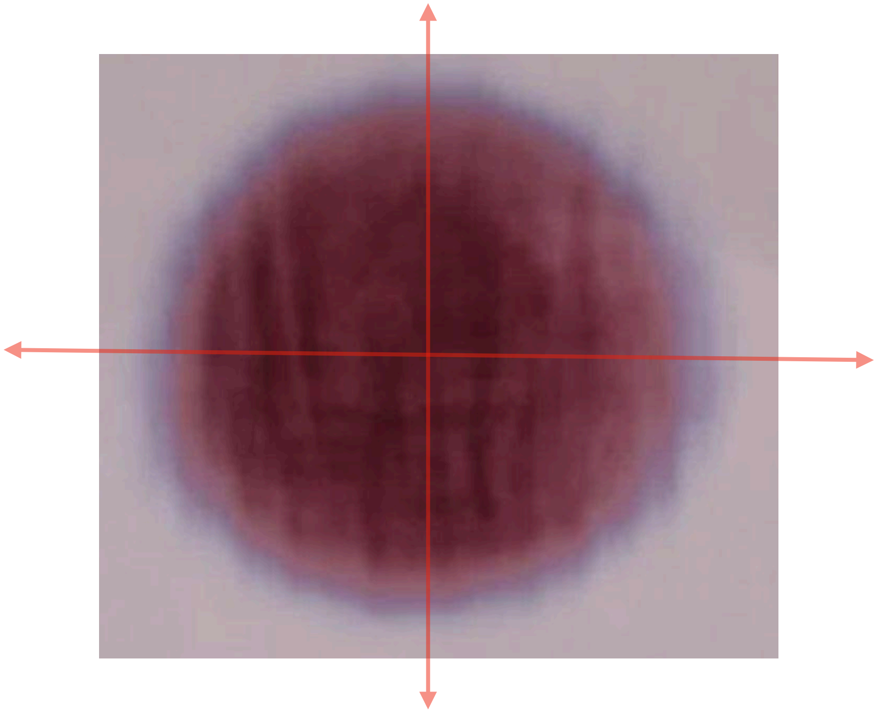




Pump profile

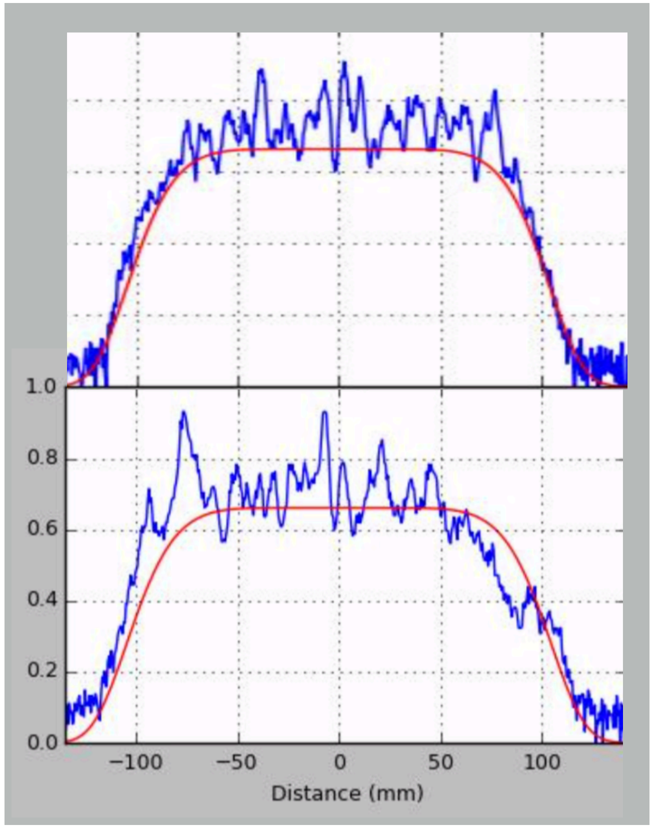
Beam configuration: PUMP

Pump: all photons of the pump are very relevant!
Not filtered
Flat top profile is the most realistic for ultraintese lasers
Tight focus, small focal number



For example

CLPU PW laser beam profile



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Beam configuration: Probe

We need to detect a very small amount of photons scattered out of the probe.

It is fundamental a probe with very low intrinsic diffraction
- High beam quality TEM_{00} as good as possible
- Wide focus to have its intrinsic diffraction pattern inside the pump cone.

Goal:
to minimize the probe diffraction

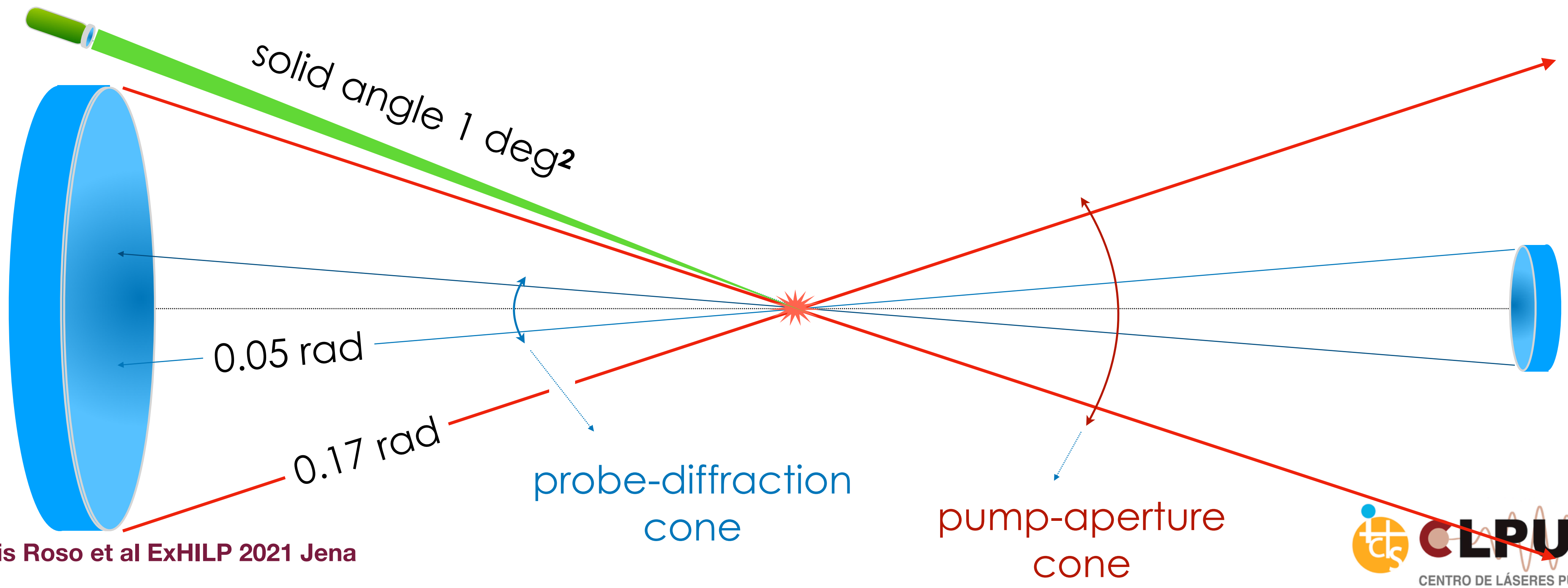
We consider a probe 800 nm
Gaussian TEM_{00}
Intensity 10^{20} W/cm^2
Beam waist 16 microns
Pulse Duration 30 fs

Scattered photons

Number of scattered photons

Probe TEM_{00} at 800 nm
Intensity 10^{20} W/cm^2
Waist 16 microns
Duration 30 fs

Extremely low number of scattered photons
Our calculation considers detection angle of 1 deg^2
On axis this means 3.7×10^{19} photons / shot



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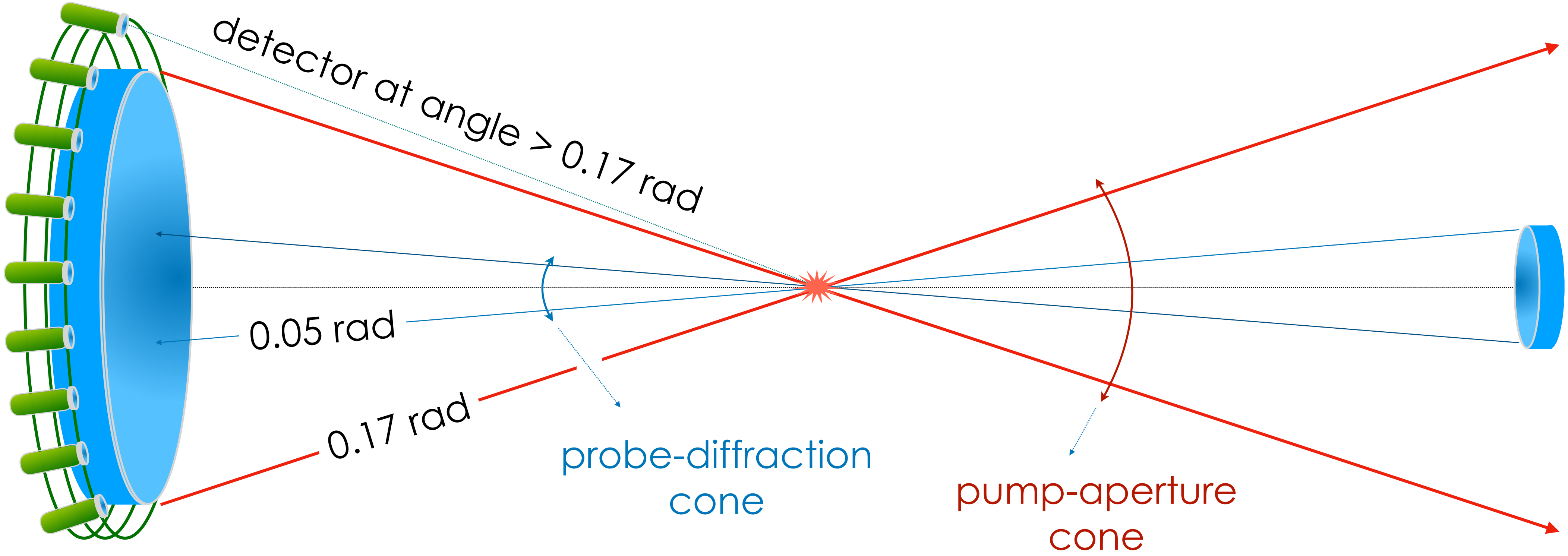

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Number of scattered photons

Probe TEM_{00} at 800 nm
Intensity 10^{20} W/cm^2
Waist 16 microns
Duration 30 fs

Extremely low number of scattered photons
Our calculation considers detection angle of 1 deg^2
On axis this means 3.7×10^{19} photons / shot

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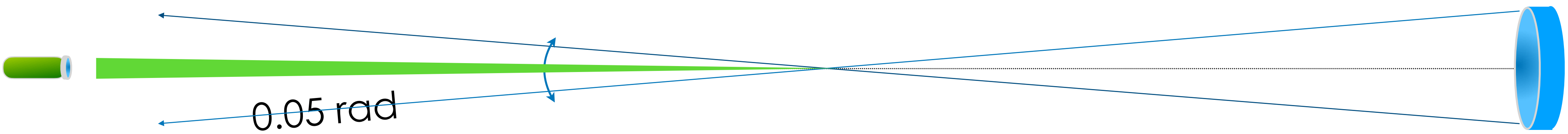

probe-diffraction
cone

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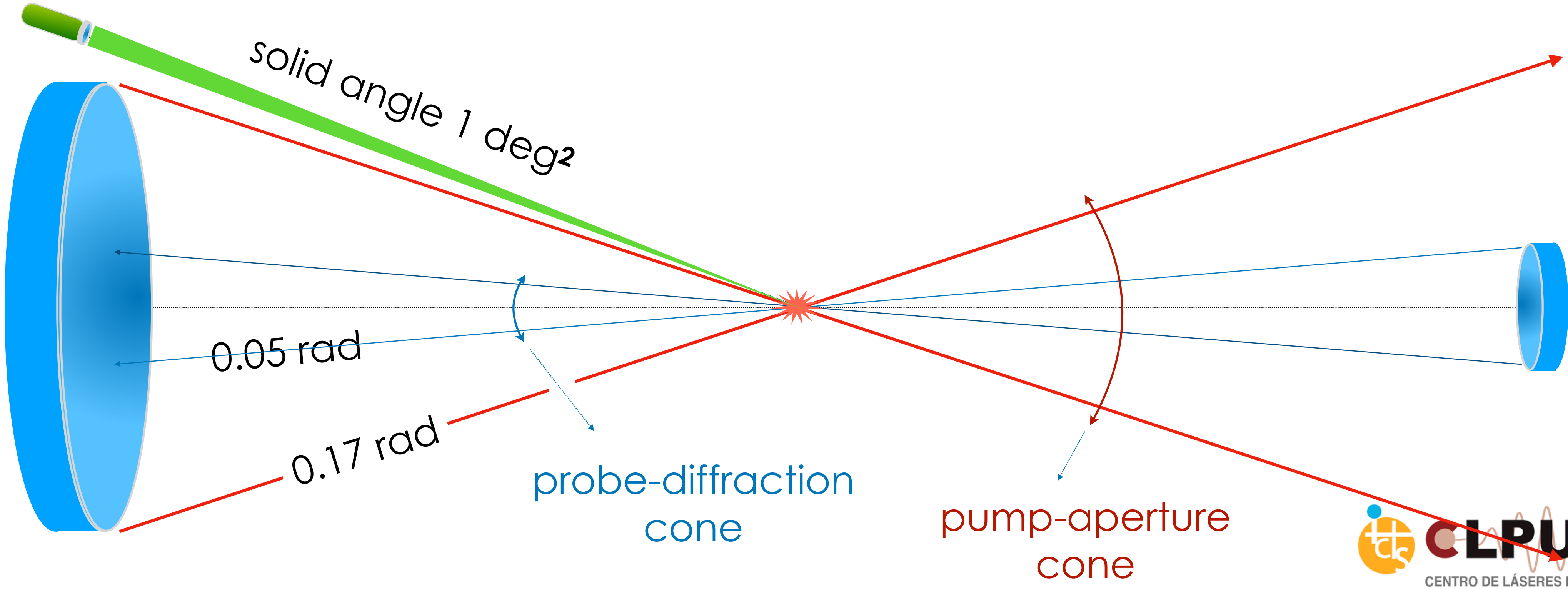

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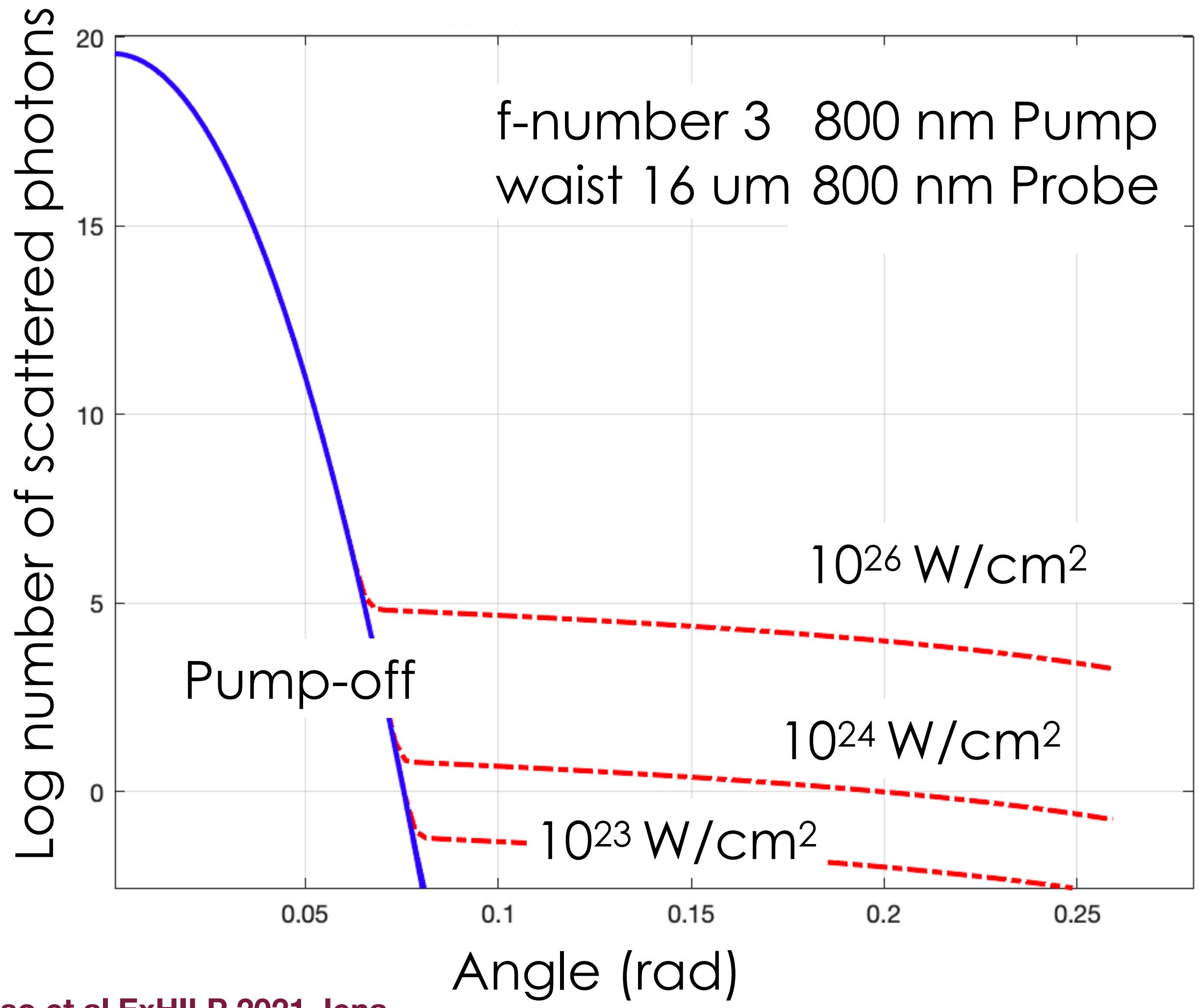
Simulations

Realistic conditions diffraction integrals

$$F^{L}_{signal}\left(\zeta\right) = -\frac{i}{\lambda_B}\int_0^R 2\pi\rho E_{probe}\left(\rho\right)\exp\left(i\phi_L\left(\rho\right)\right)J_0\left(k_B\rho\zeta\right)d\rho$$

Parallel polarizations

Pump 800 nm Airy   f-number 3
Probe 800 nm Gauss waist 16 um



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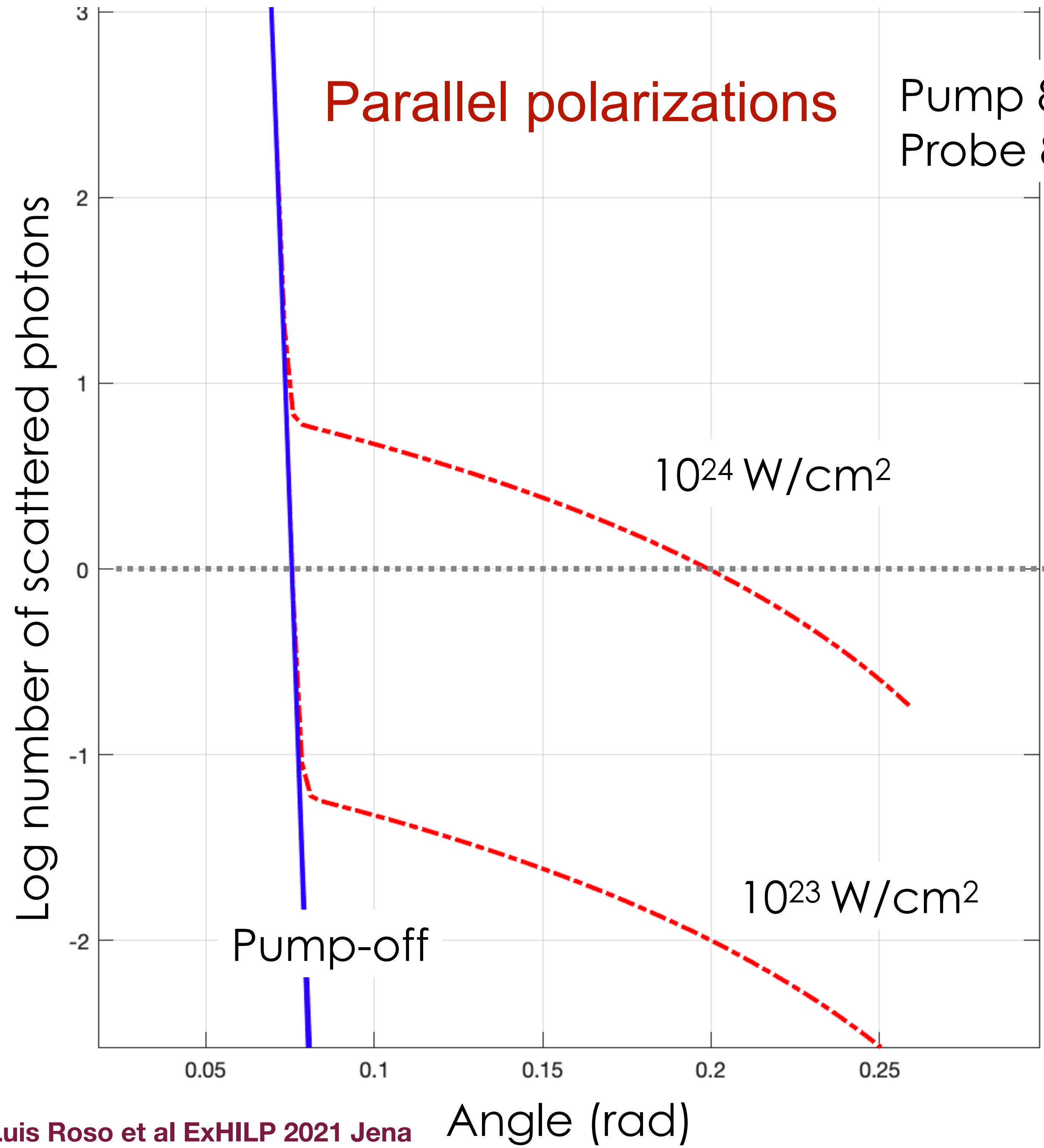

one photon/shot

QVAC signal scales as (pump intensity)^2

$$QVS^{L}(\text{angle}) = C\, q_{L}\, I^{2}_{0\,\text{pump}}(0)\, I_{\text{prob}}$$

one photo/shot for
TEM$_{00}$ probe
- intensity 10^{20} W/cm^2
- waist 16 microns

for
1 deg^2 detector angle

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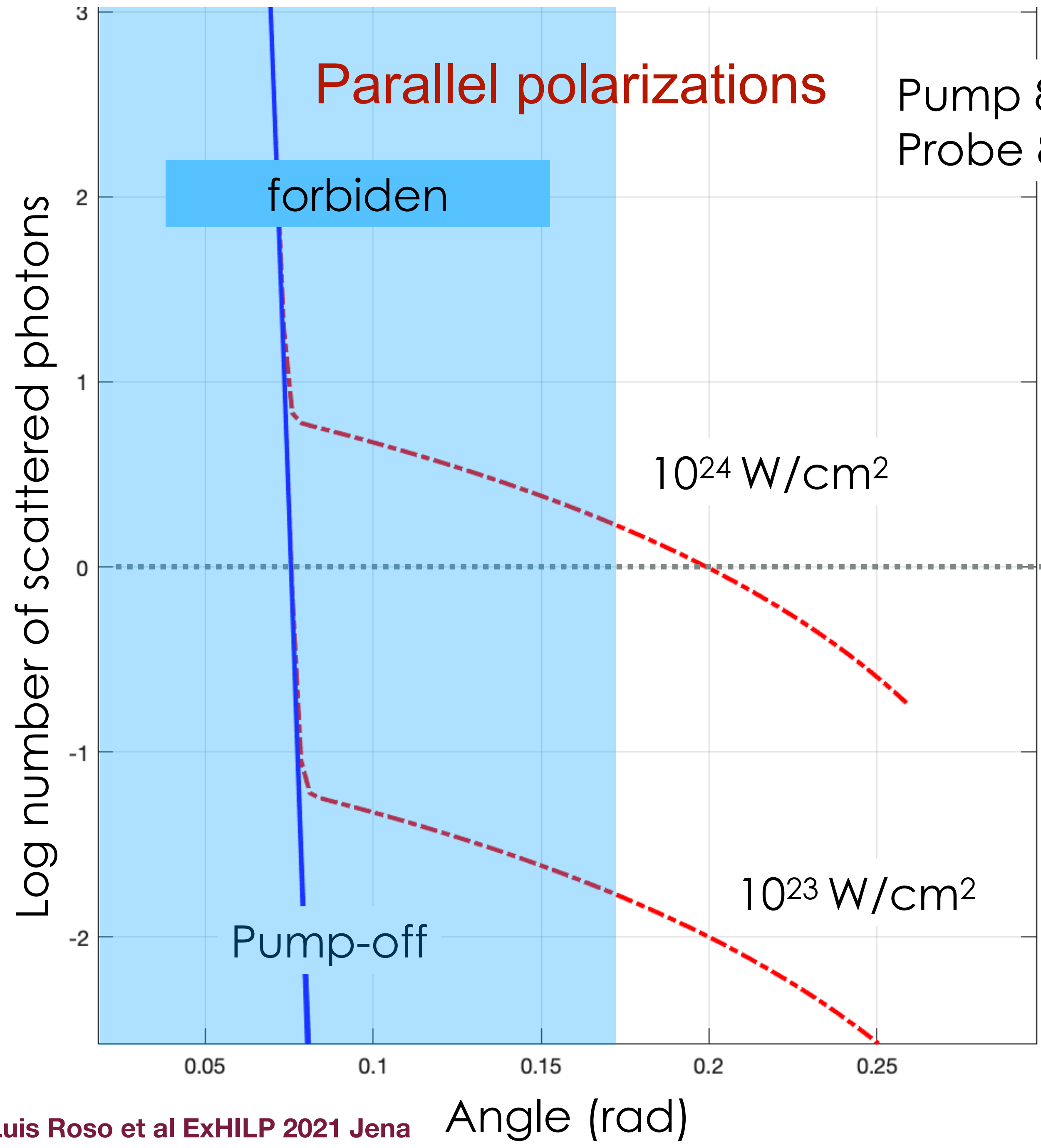
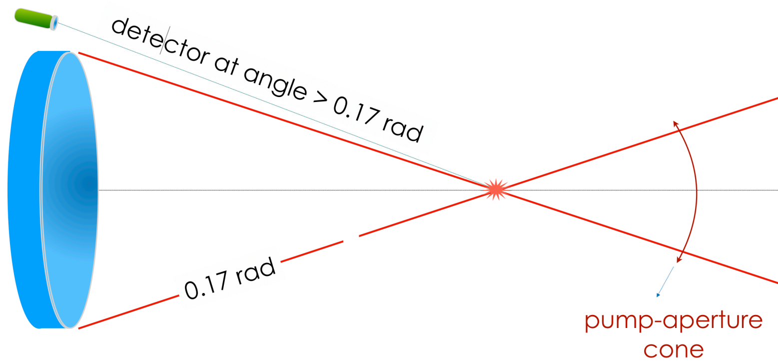


Pump 800 nm Airy f-number 3
Probe 800 nm Gauss waist 16 um

QVAC signal scales as (pump intensity)^2

one photon/shot



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Influence probe wavelength

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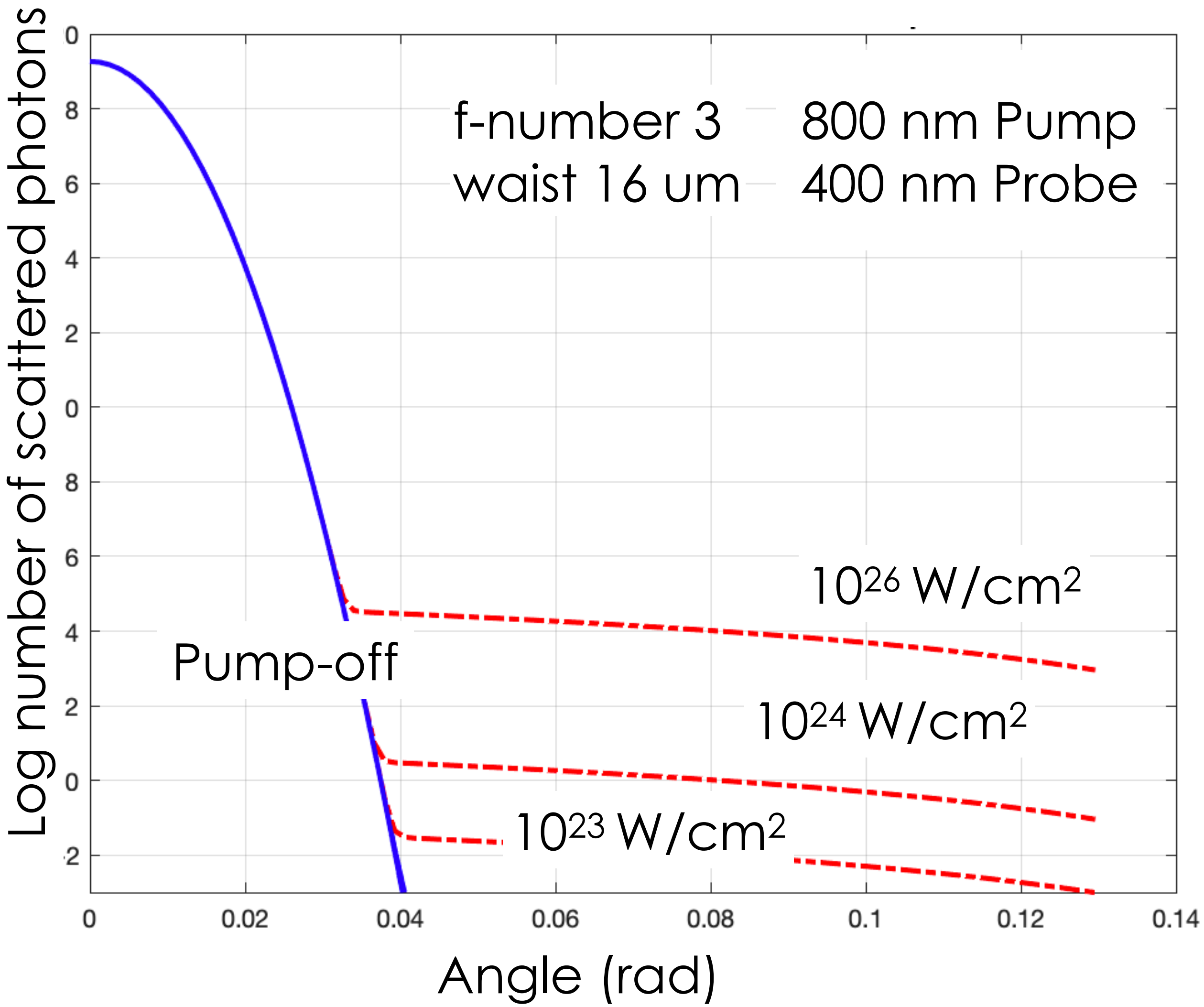
Parallel polarizations

Pump 800 nm Airy f-number 3
Probe 400 nm Gauss waist 16 um



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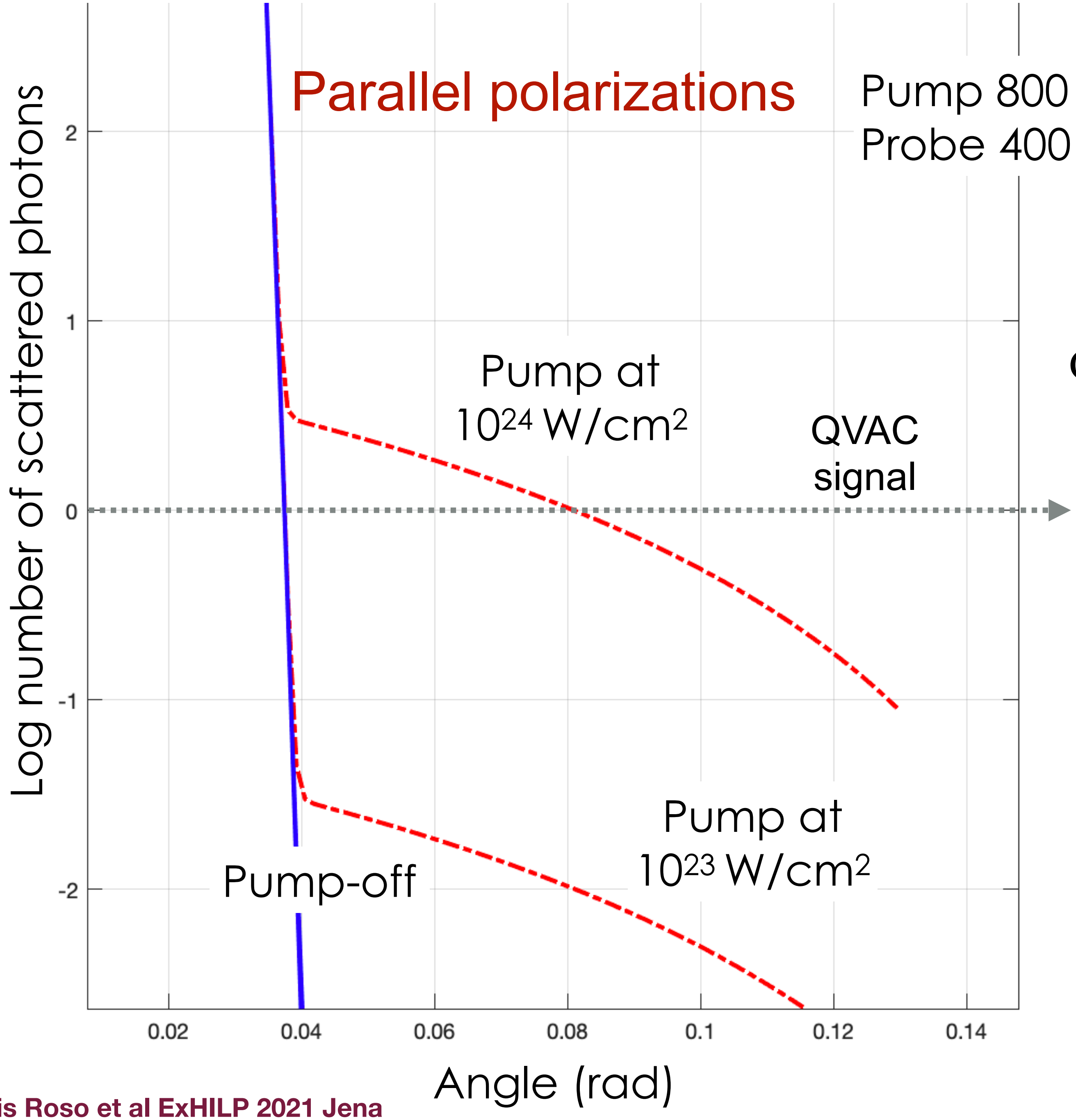
Parallel polarizations

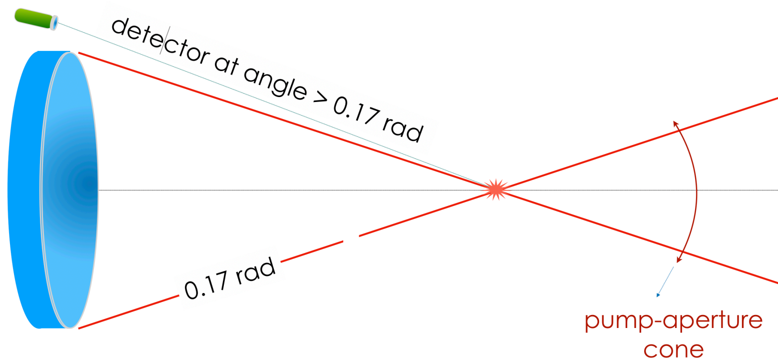


Pump 800 nm Airy f-number 3
Probe 400 nm Gauss waist 16 um

QVAC signal scales as (pump intensity)^2

$$QVS^{L}\left(angle\right) = C\, q_{L}\, I^{2}_{0\,pump}\left(0\right) I_{prob}$$

one photon/shot



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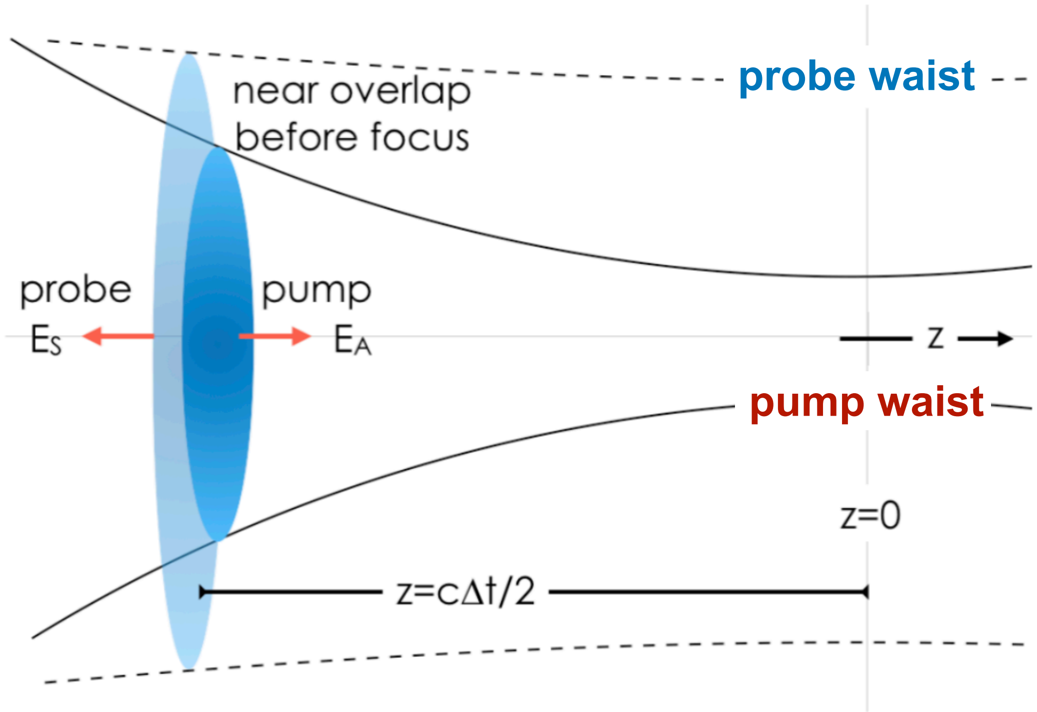
Influence of the offset

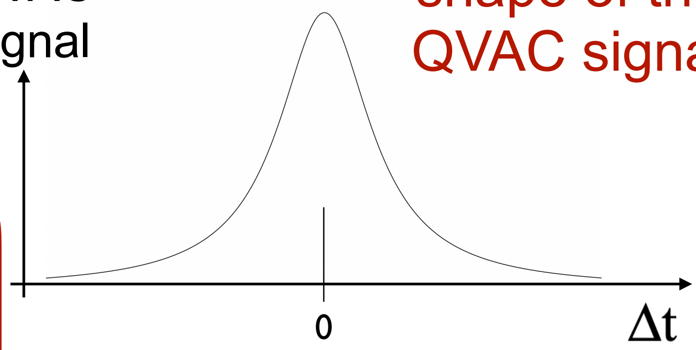
Overlap of the beams Δt

Pump Probe Waist



Short pump-Rayleigh-length
Long probe-Rayleigh-length

Characteristic shape of the QVAC signal



$$QVS^{L}(\text{angle}) = C\, q_L\, I^2_{0\,\text{pump}}\, I_{\text{prob}} \frac{22.6\ \lambda^2_{\text{pump}} N^4}{22.6\, \lambda^2_{\text{pump}} N^4 + c^2 (\Delta t)^2}$$

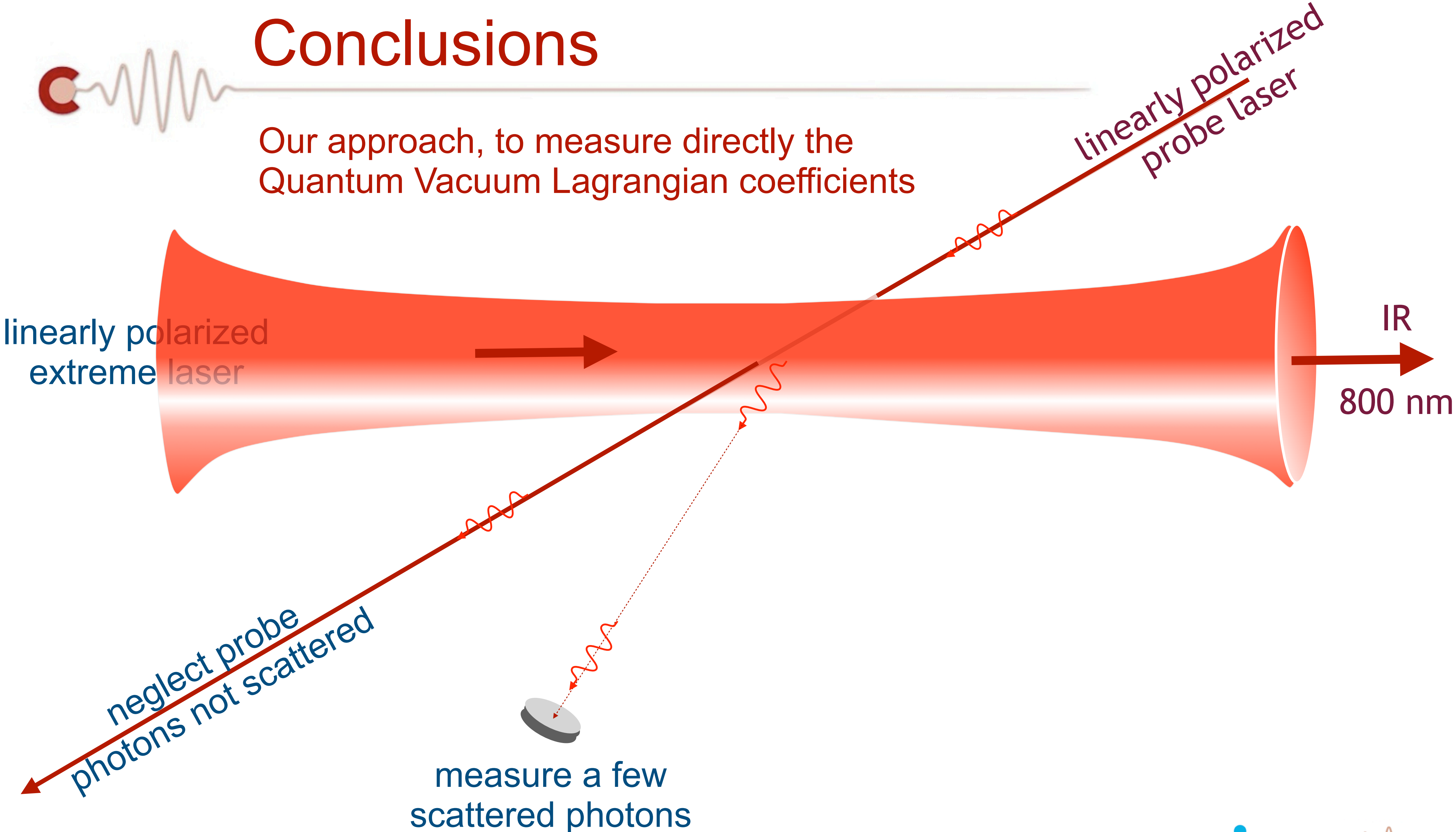
QVAC signal

N pump f/number
Δt relative jitter

Conclusions

Conclusions

Our approach, to measure directly the Quantum Vacuum Lagrangian coefficients



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Possible lasers

Extreme Laser Infrastructure

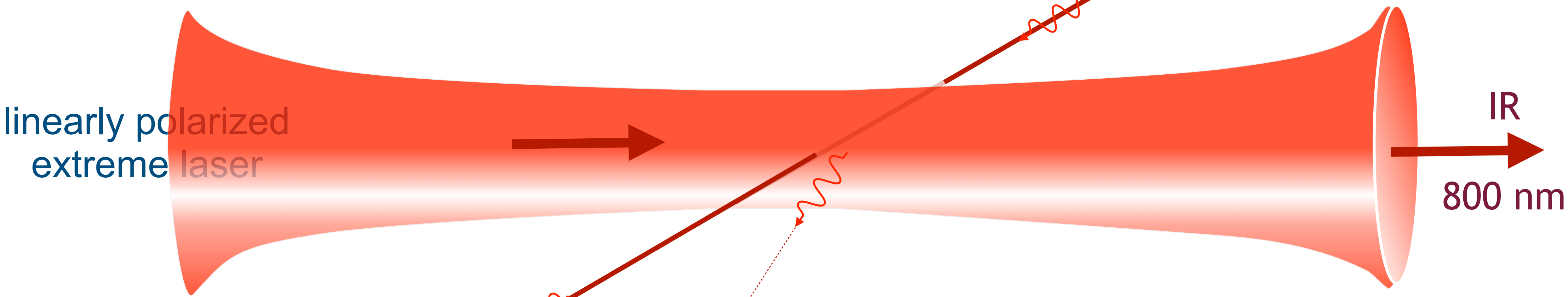
Center	Name	Power	Energy	Duration	Wavelength	Rep Rate
ELI Beams Czech rep	HALPS DUHA	1 PW 100 TW	30 J 30 J	30 fs 30 fs	800 nm 800 nm	10 Hz 50 Hz
ELI Beams Czech rep	ATON	10 PW 1 PW	1500 J 150 J	150 fs 150 fs	1060 nm	1/minute
ELI NP Romania	HPLS	10 PW 10 PW	300 J 300 J	30 fs 30 fs	800 nm	1/minute
ELI NP Romania	HLPS	1 PW 1 PW	30 J 30 J	30 fs 30 fs	800 nm	1 Hz
ELI NP Romania	HPLS	100 TW 100 TW	30 J 30 J	30 fs 30 fs	800 nm	10 Hz
ELI ALPS Hungary	HF	1 PW 100 TW	20 J 1 J	20 fs 10 fs	800 nm	10 Hz

Other projects in Russia (XCELLS), US, China, Korea, Japan

Conclusions

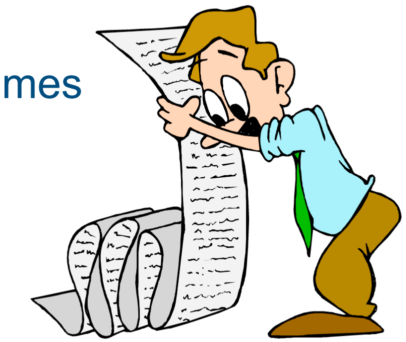
$$\mathscr{L} = \mathscr{L}_0 + \xi_L \mathscr{L}_0^2 + \frac{7}{4}\xi_T \mathscr{G}^2$$

Our approach, to measure directly the Quantum Vacuum Lagrangian coefficients



Work in progress: A huge effort in

Noise reduction techniques
Ultrahigh vacuum over large volumes
IR single photon detectors
Time gated detection
...



Future experiments

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The team

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Smrithan Ravichandran
Andrew Longman
Calvin Z He
José Antonio Pérez-Hernández
Jon I Apiñaniz
Lucas D Smith
Robert Fedosejevs
Wendell T Hill, III

Direct, precision measurement of the quantum-vacuum Lagrangian coupling coefficients using two counter-propagating super-intense laser pulses
NJP Submitted for publication

Towards the measurement of the quantum-vacuum Lagrangian

Work in progress

UNIVERSITY OF ALBERTA

UNIVERSITY OF MARYLAND

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Acknowledgements:
CLPU team: Laserlab Europe V Grant No. 871124, and from Junta de Castilla y León, Grant No. CLP087U16.
Univ of Maryland team: National Science Foundation Grant # PHY2010392.
Univ of Alberta team : Natural Sciences and Eng. Research Council of Canada (RGPIN-2019-05013).

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Thanks !!!
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50% Spanish Central Government (Ministerio de Ciencia)
45% Regional Government (Junta de Castilla y León)
5% University of Salamanca