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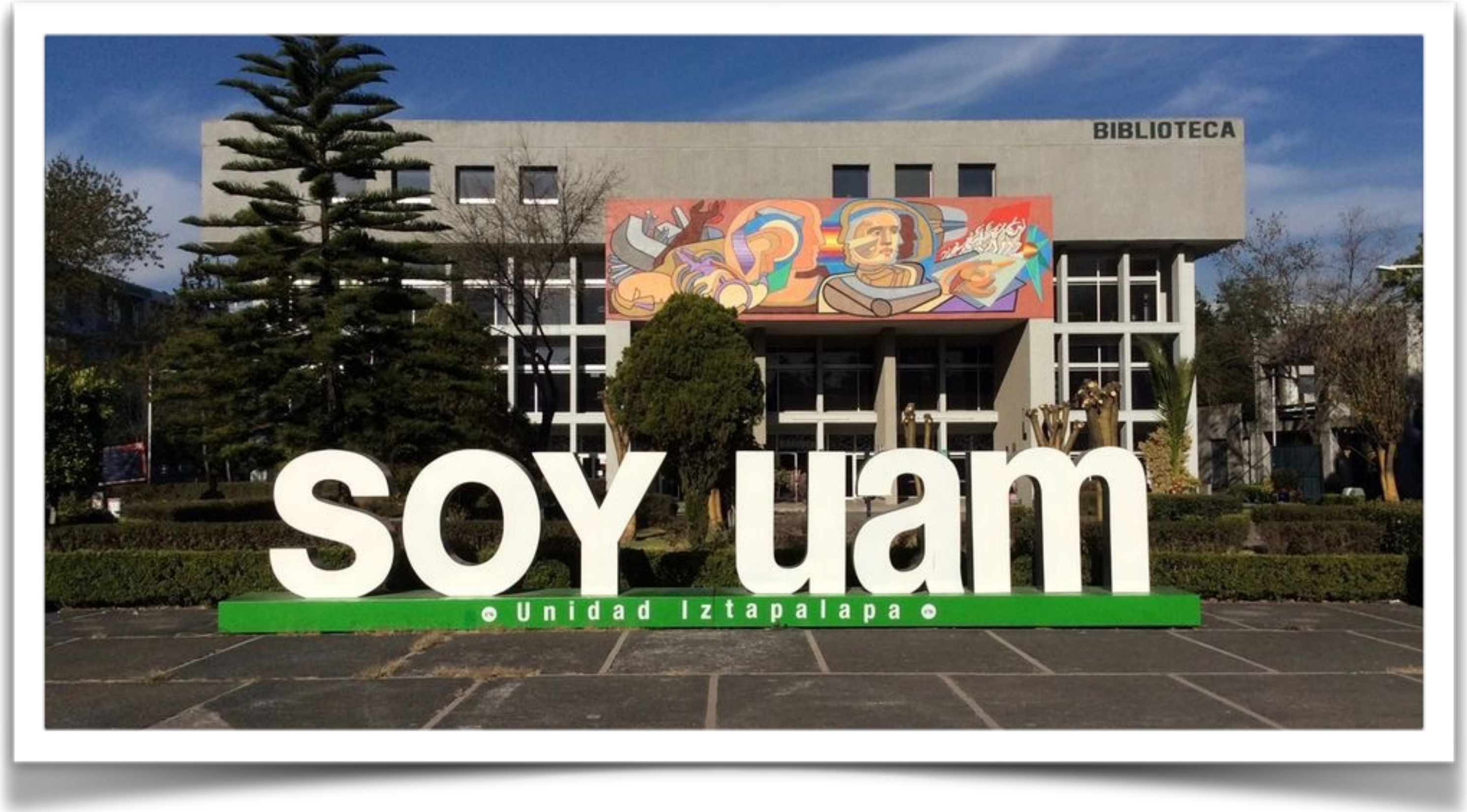
Division of Particles and Fields of the Mexican Physical Society

On deviations from Lorentz invariance



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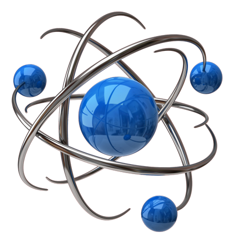
Outline

Deviations from Lorentz symmetry

- Introduction
- Motivations



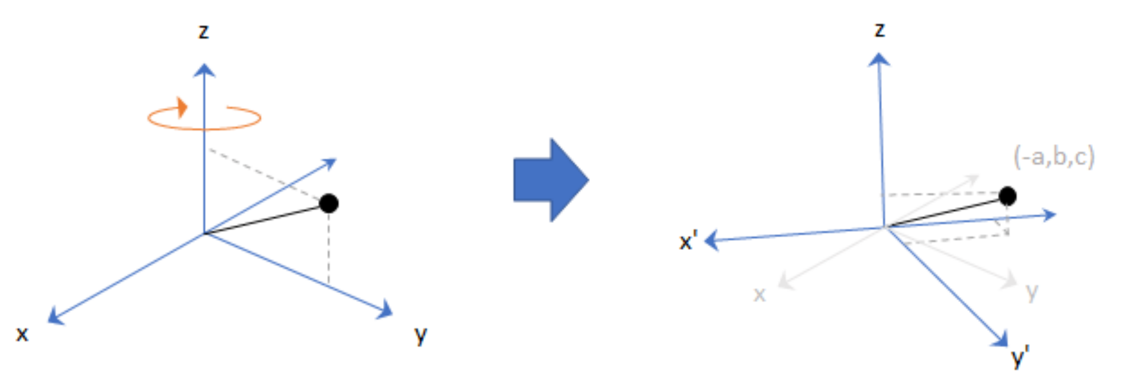
Spontaneous Lorentz Symmetry Breaking (SLSB)

- Casimir effect
- Optical beam's propagation

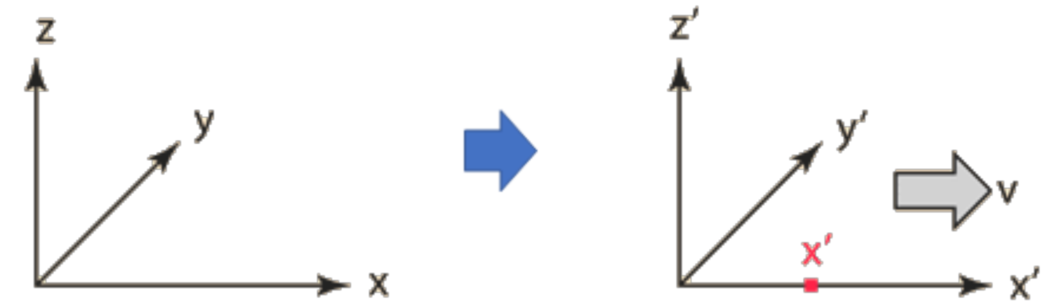
Lorentz symmetry

Spacetime symmetries

3 Rotations



3 Boosts



CPT symmetry: Charge conjugation (C), Parity transformation (P) and Time reversal (T)

QFT

Locality + Unitarity + Lorentz symmetry

CPT theorem
(Bell, Luders, Pauli, 1954)

CPT invariance

CPT symmetry violation

O. W. Greenberg,
Phys. Rev. Lett. 89, 231602 (2002)

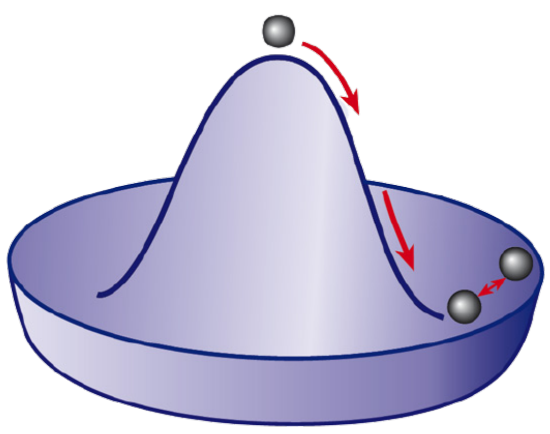
Lorentz symmetry violation

Spontaneous symmetry breaking

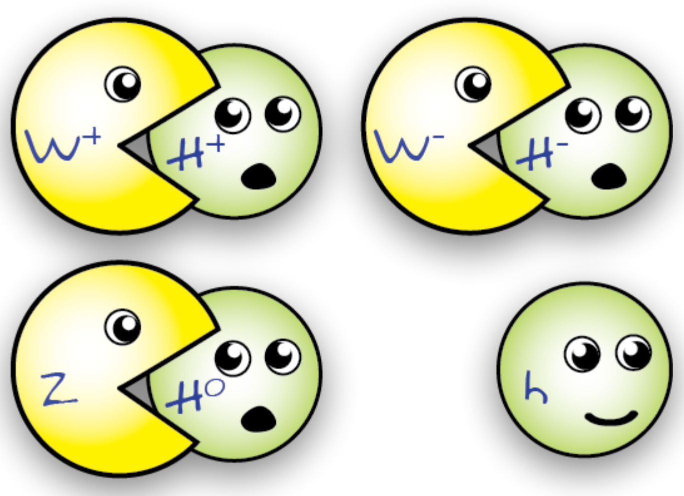
It is the phenomenon in which a stable state of a system (for example the ground state) is not symmetric under a symmetry of its Hamiltonian, Lagrangian, or action.

Examples

- Higgs mechanism
- Chiral symmetry
- Condensed matter physics



Mexican hat potential



Higgs mechanism

Goldstone Theorem

For every spontaneously broken global symmetry the theory must contain a massless particle.

On Lorentz symmetry breaking

W. Pauli, Hanbuch der Physik (Julius Springer, Berlin, 1933): *Wir möchten hierin einen Hinweis dafür erblicken, daß nicht nur der Feldbegriff, sondern auch der Raum-Zeit-Begriff im kleinen einer grundsätzlichen Modifikation bedarf.*

We may see herein an indication that not only the field concept, but also the spacetime concept in the microscale requieres a principal modification.

Is there an Æther?,

P. A. M Dirac, Nature volume 168, pages 906–907(1951)

Quantum electrodynamics in nonlinear gauge,

Y. Nambu, Prog. There. Phys. Supplement E68, 190 (1968)

$$A_\mu(x)A^\mu(x) = \lambda$$

On Lorentz symmetry breaking

Spontaneous Breaking of Lorentz Symmetry in String Theory
Kostelecky and Samuel, Phys. Rev. D 39, 683 (1989).

↓

D. Colladay and V. A. Kostelecky, Phys. Rev. D 57, 6760 (1997).
D. Colladay and V. A. Kostelecky, Phys. Rev. D 58, 116002 (1998).

↓

The Standard-Model Extension

It is a framework designed to parameterize Lorentz violation effects

- It is conceived as an effective field theory
- Known physics is incorporated
- Lorentz-violating terms are included

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \frac{1}{2}(k_{AF})^{\kappa}\epsilon_{\kappa\lambda\mu\nu}A^{\lambda}F^{\mu\nu} - \frac{1}{4}(k_F)_{\alpha\beta\mu\nu}F^{\alpha\beta}F^{\mu\nu}$$

(Minimal photon sector)

On Lorentz symmetry breaking

Motivations to study LSB

- Physics is an experimental science
- There could be a Lorentz violation coming from a fundamental theory (string theory, loop quantum gravity, noncommutative spacetime)

What if there is no Lorentz symmetry breaking?

- It is not evident that Lorentz violation can be ruled out
- It can give us, hopefully, some clues about the elusive quantum gravity theory
- We have learned and generated a lot of valuable knowledge along the way

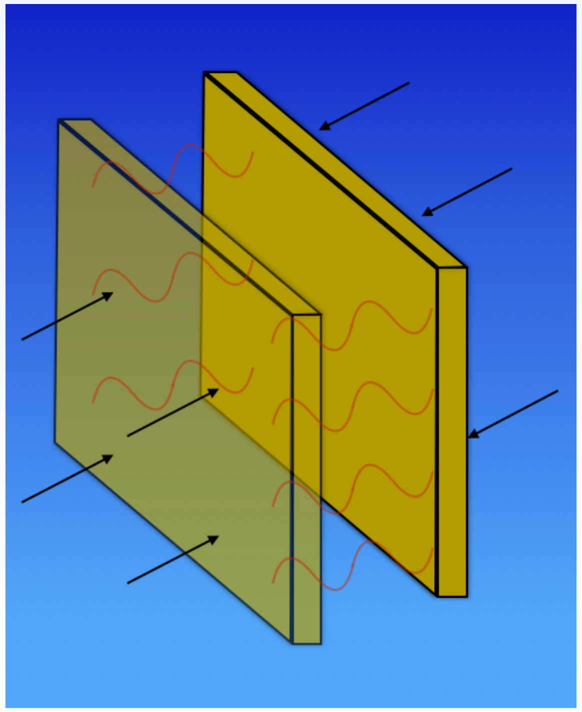
Casimir effect

Parallel plates

$$\mathcal{L} = \frac{1}{2} h^{\mu\nu} \partial_\mu \phi \, \partial_\nu \phi - \frac{1}{2} m^2 \phi^2$$

$h_{\mu\nu}$ acts as a background and breaks Lorentz invariance.

- Stress-Energy Tensor
- Green's function
- Vacuum expectation value
- Renormalization process



- Casimir energy

$$\mathcal{E}_C(L) = \sqrt{\frac{h^{nn}}{h}} \mathcal{E}_0 \left(\frac{L}{\sqrt{-h^{nn}}} \right)$$

$\mathcal{E}_0$ is the Casimir energy in the Lorentz invariant case.

- Local effects
- Finite temperature effects

Phys. Lett. B 807, 135567 (2020)

C. A, Escobar, A. Martín-Ruiz, M. García and O. Franca

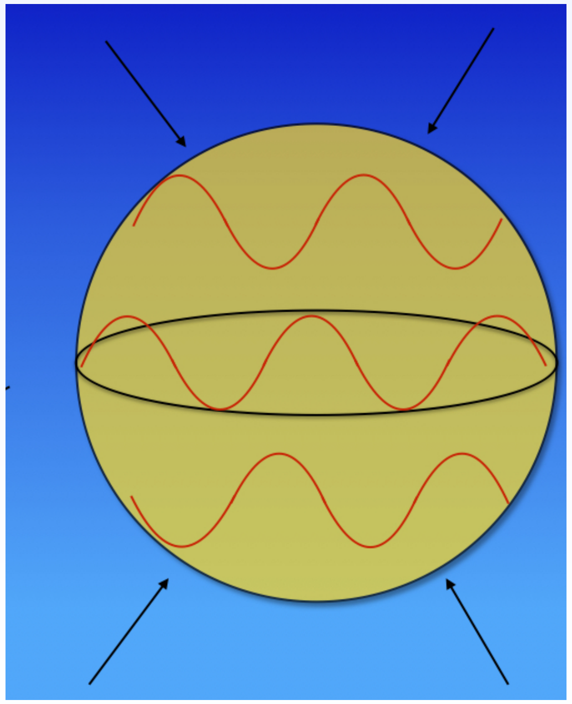
Casimir effect

Spherical Geometry

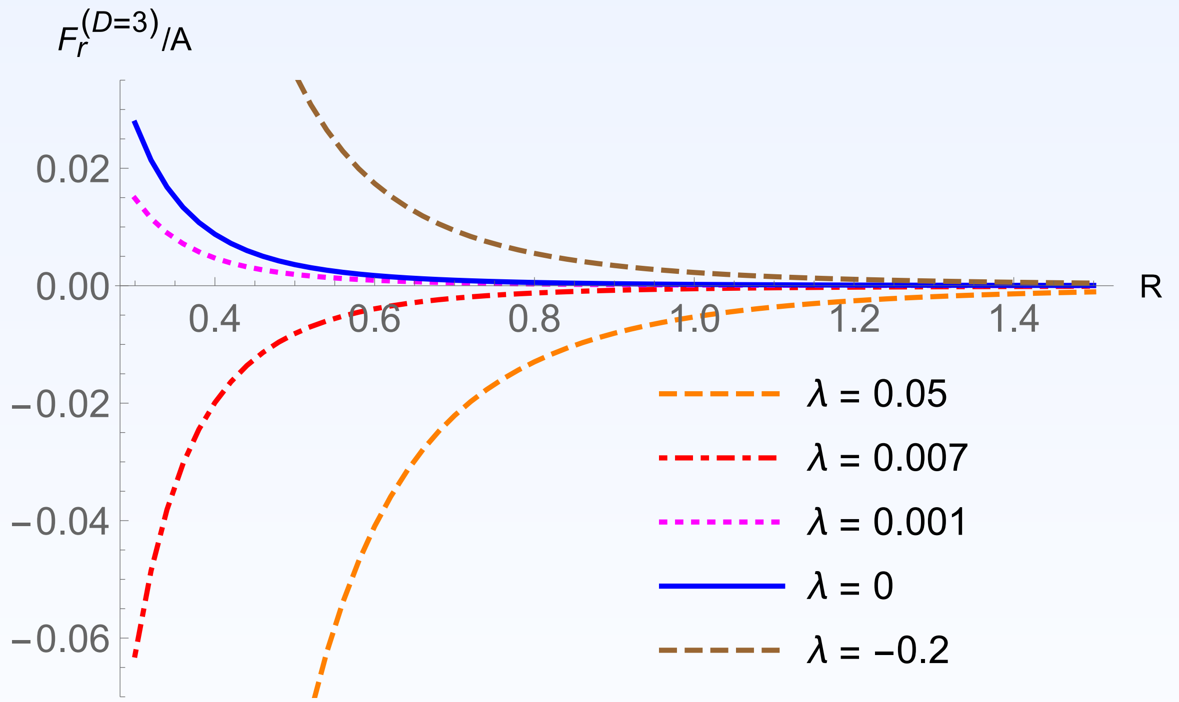
$$\mathcal{L} = \frac{1}{2}\left[\partial_\mu\phi\,\partial^\mu\phi + \lambda\,(u^\mu\,\partial_\mu\phi)^2 - m^2\,\phi^2\right]$$

u^μ acts as a background and breaks Lorentz invariance.

- Stress-Energy Tensor
- Green's function
- Vacuum expectation value
- Renormalization process



Casimir force



Radial spacelike case
$\lambda_{\text{crit}} \approx 0.0025$

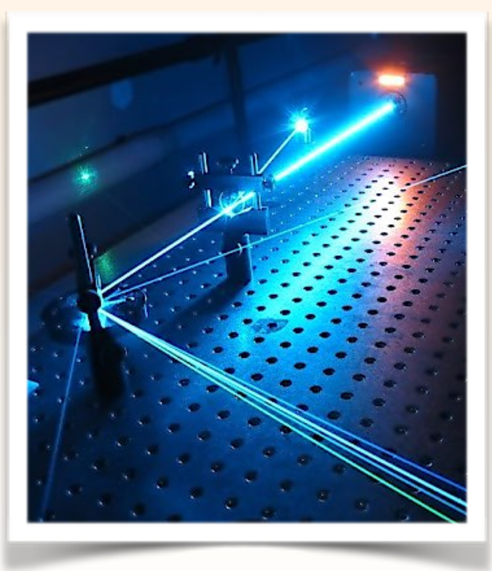
Phys. Rev. D 102, 015027 (2020)

On the Propagation of Optical Beams in a non trivial background (cylindrical geometry)

$$\mathcal{L} = \frac{1}{2}\left(\partial_\mu\phi\partial^\mu\phi + \xi(u^\mu\partial_\mu\phi)^2\right)$$

- Green's function
- Intensity profiles
- Beam's properties

$$\phi(\vec{r}_\perp, z) = \int G(\vec{r}_\perp, z; \vec{r}\,'_\perp, z')\phi(\vec{r}\,'_\perp, z\,')\, d^2\vec{r}\,',$$

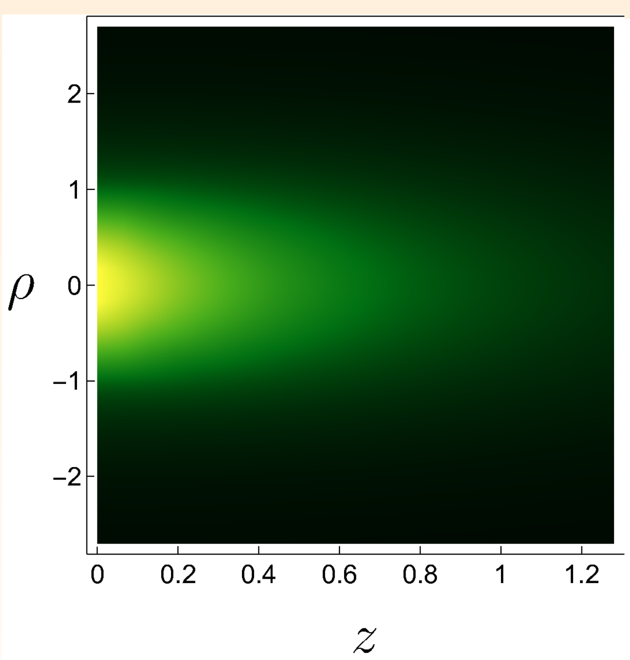


$$I(r_\perp, z) = \phi\,\phi^*$$

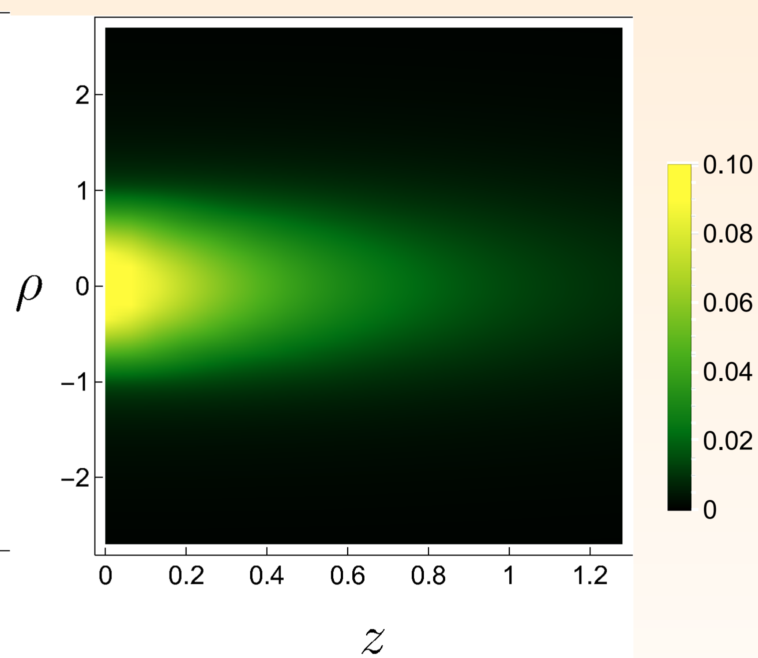
On the Propagation of Optical Beams in a non trivial background (cylindrical geometry $\vec{u} = (r, \theta, z)$)

Gaussian Beams
$$\phi(\vec{r}\,'_\perp, z\,') = \sqrt{\frac{2}{\pi}}\frac{1}{w}\frac{1}{\sqrt{1 - e^{-2\frac{\rho_0^2}{w^2}}}}\, e^{-\frac{\rho'^{\,2}}{w^2}}\,\Theta(\rho_0 - \rho),$$

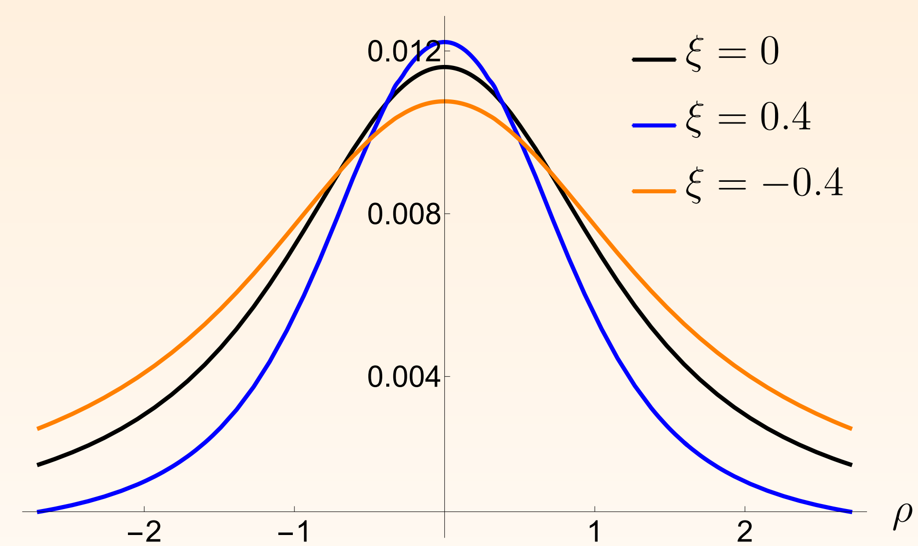
- Rayleigh range
- Gouy phase



$\xi = 0$



$\xi = 0.4$

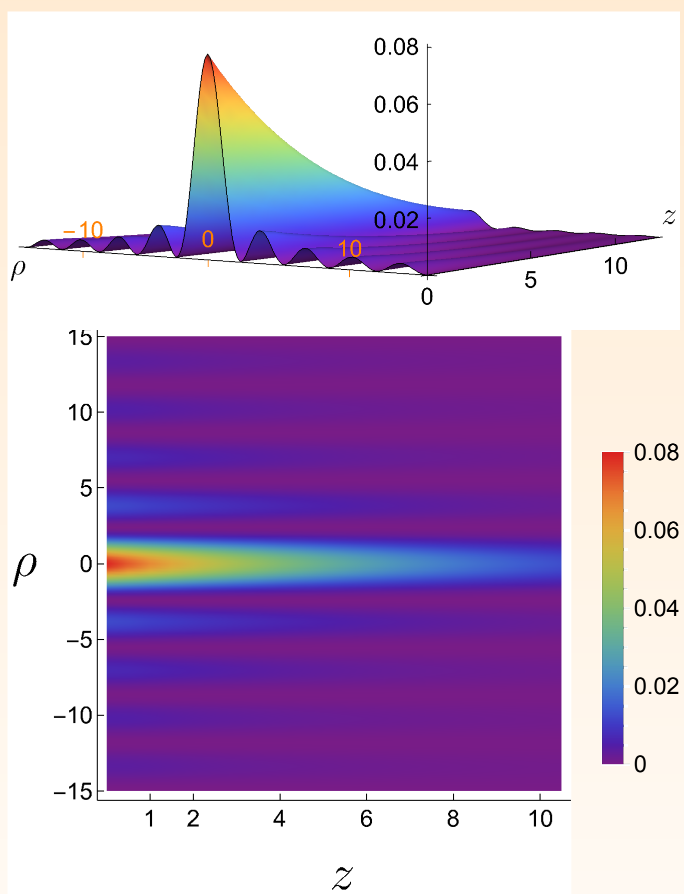


$z = 1.088$

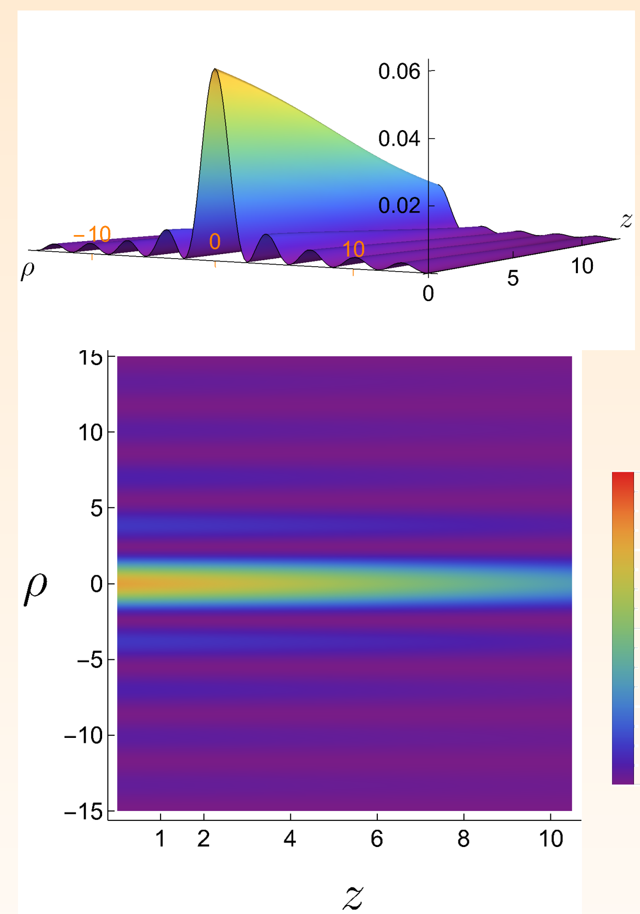
On the Propagation of Optical Beams in a non trivial background (cylindrical geometry)

Bessel Beams

$$\phi(\vec{r}\,'_\perp, z') = \frac{1}{\sqrt{\pi}\rho_0} \frac{1}{\sqrt{J_0^2(\rho_0/a) + J_1^2(\rho_0/a)}} J_0(\rho'/a)\,\Theta(\rho_0 - \rho')$$



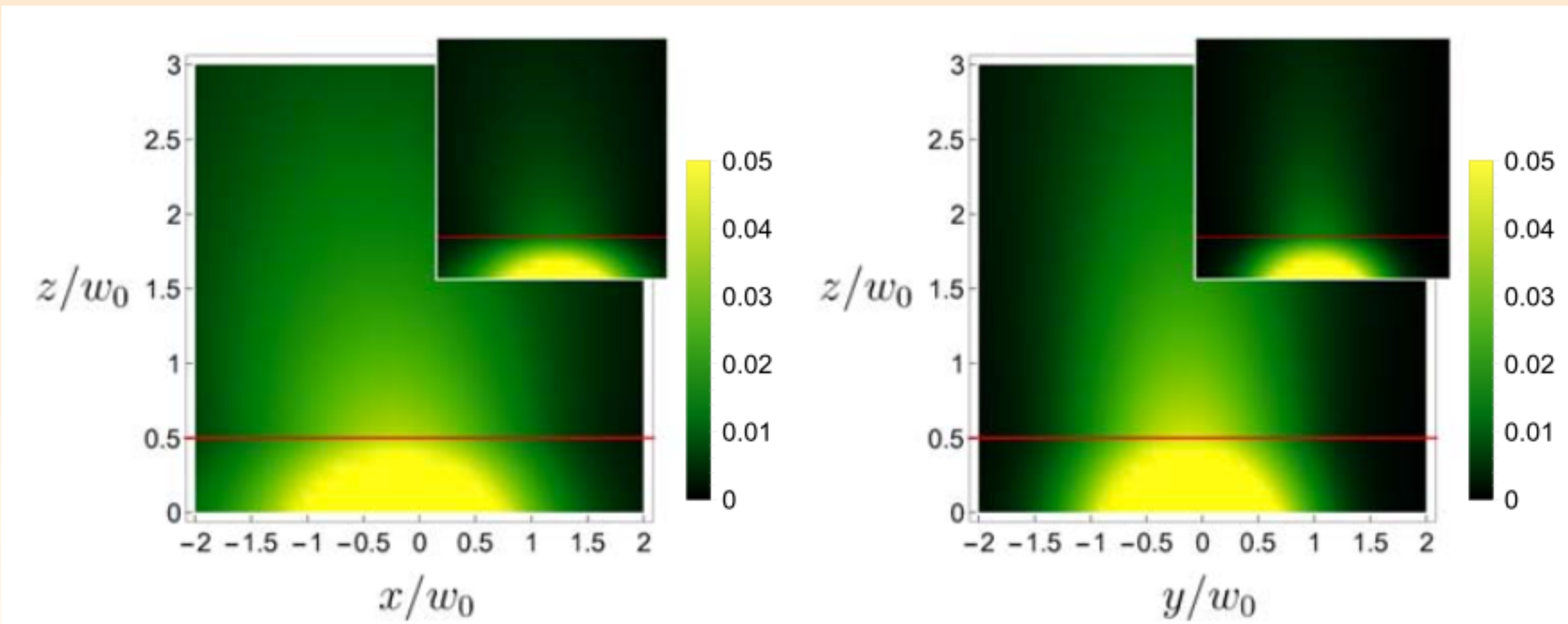
$\xi = 0$



$\xi = 0.04$

On the Propagation of Optical Beams
in a non trivial background
with semitransparent mirrors
cartesian geometry $\vec{u} = (u_x, u_y, u_z)$

Gaussian Beams
$$\phi(\vec{r}\,'_\perp, z') = \sqrt{\frac{2}{\pi}}\frac{1}{w}\frac{1}{\sqrt{1-e^{-2\frac{\rho_0^2}{w^2}}}}\, e^{-\frac{\rho'^2}{w^2}}\Theta(\rho_0-\rho),$$



(a) (b)

$u_x = 0.4$ $u_y = 0.8$

Physica Scripta **98** 085527 (2023)

Conclusions

- We are far from understanding the structure of the spacetime at the Planck scale.
- The study of Lorentz symmetry could provide signals of physics beyond the standard model.
- Studies on deviations from Lorentz invariance cover a wide range of branches of the physics.

Thank you !!