Gravitational distortion on photon near the Earth

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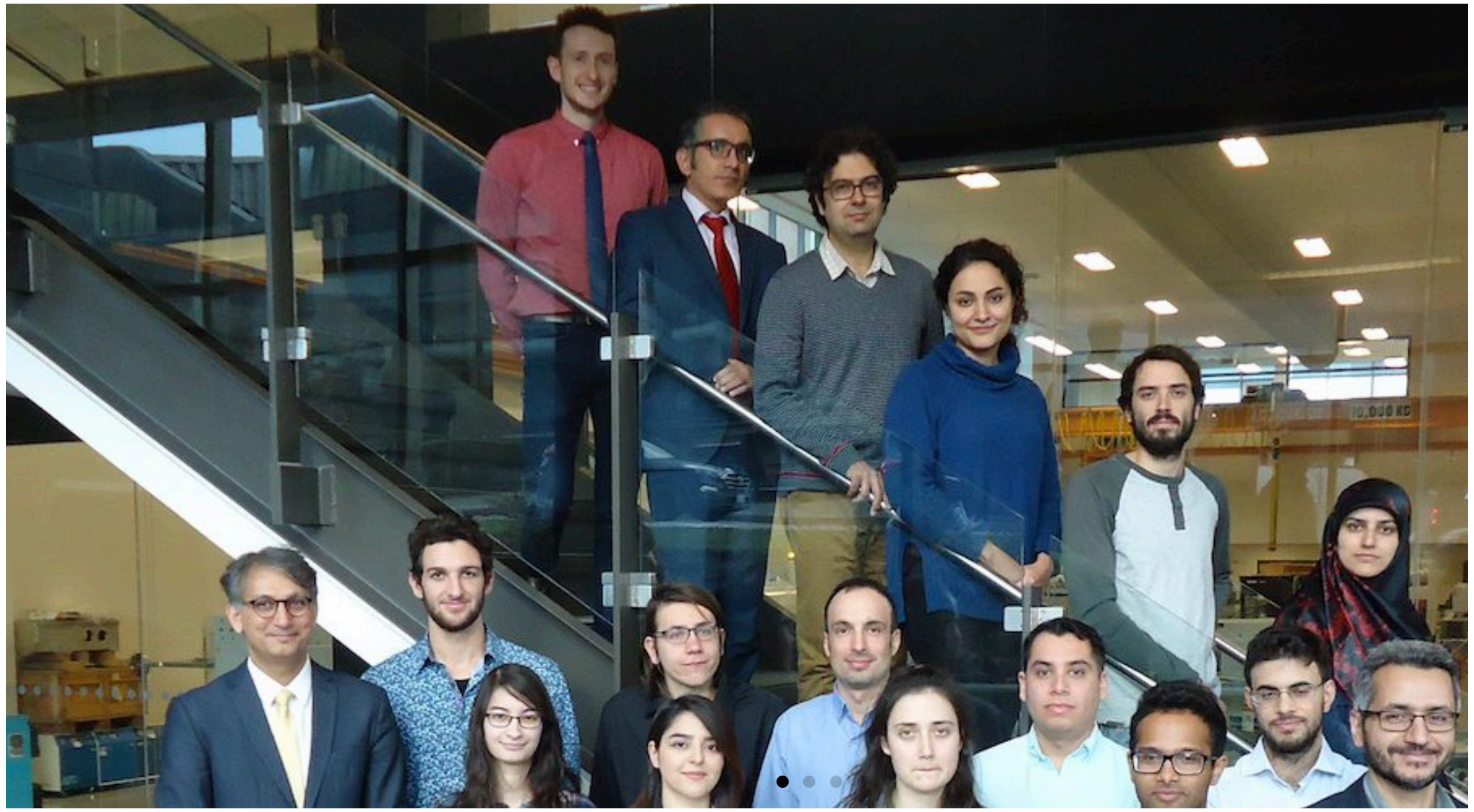
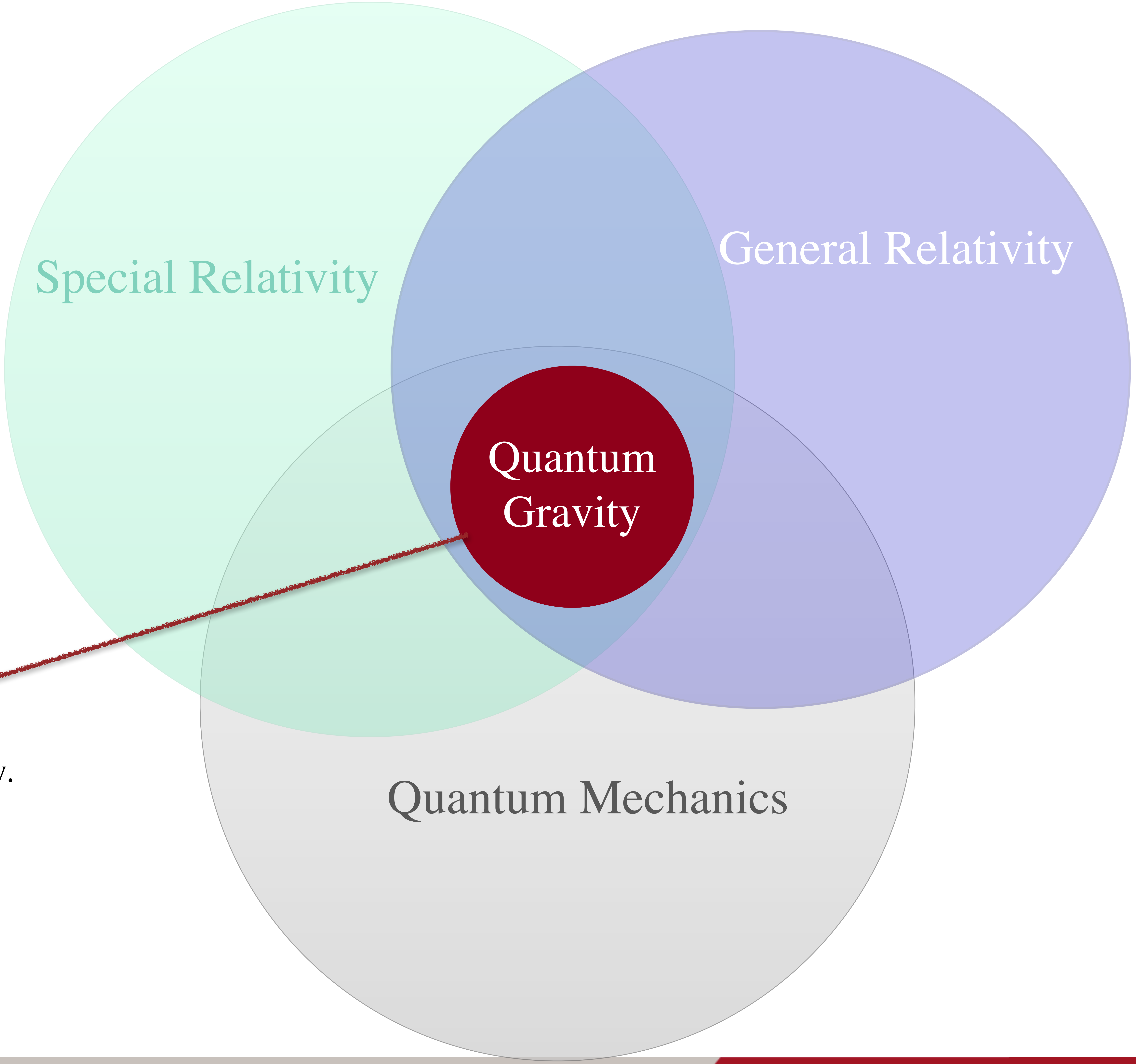


Doctrine of three paradigms



We have no experimental data about Quantum Gravity.
We have no experimental data wherein the three paradigms are equally important.

Types of Effects in quantum gravity

- **Hard effects:** The large effects that alter the notion of the space-time geometry, or resolve classical singularities.
- **Soft effects:** The minuscule effects of the curved space-time geometry in the quantum mechanics.

Experimental detection of soft effects of quantum gravity

Observe the behaviour of a quantum system (that we call the **quantum probe**) in a curved space-time geometry with the precision that the effects of the curved geometry is observable.

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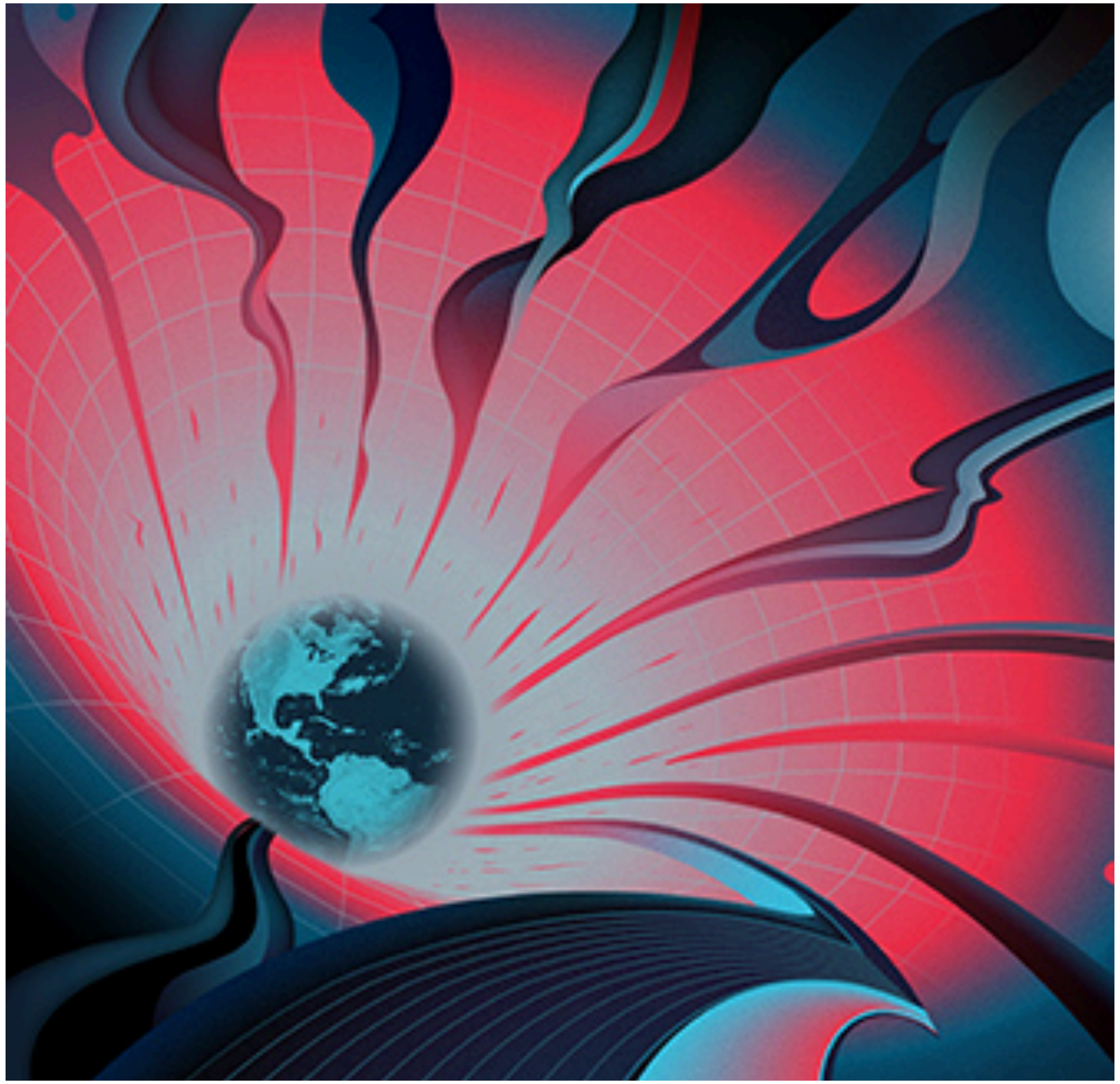
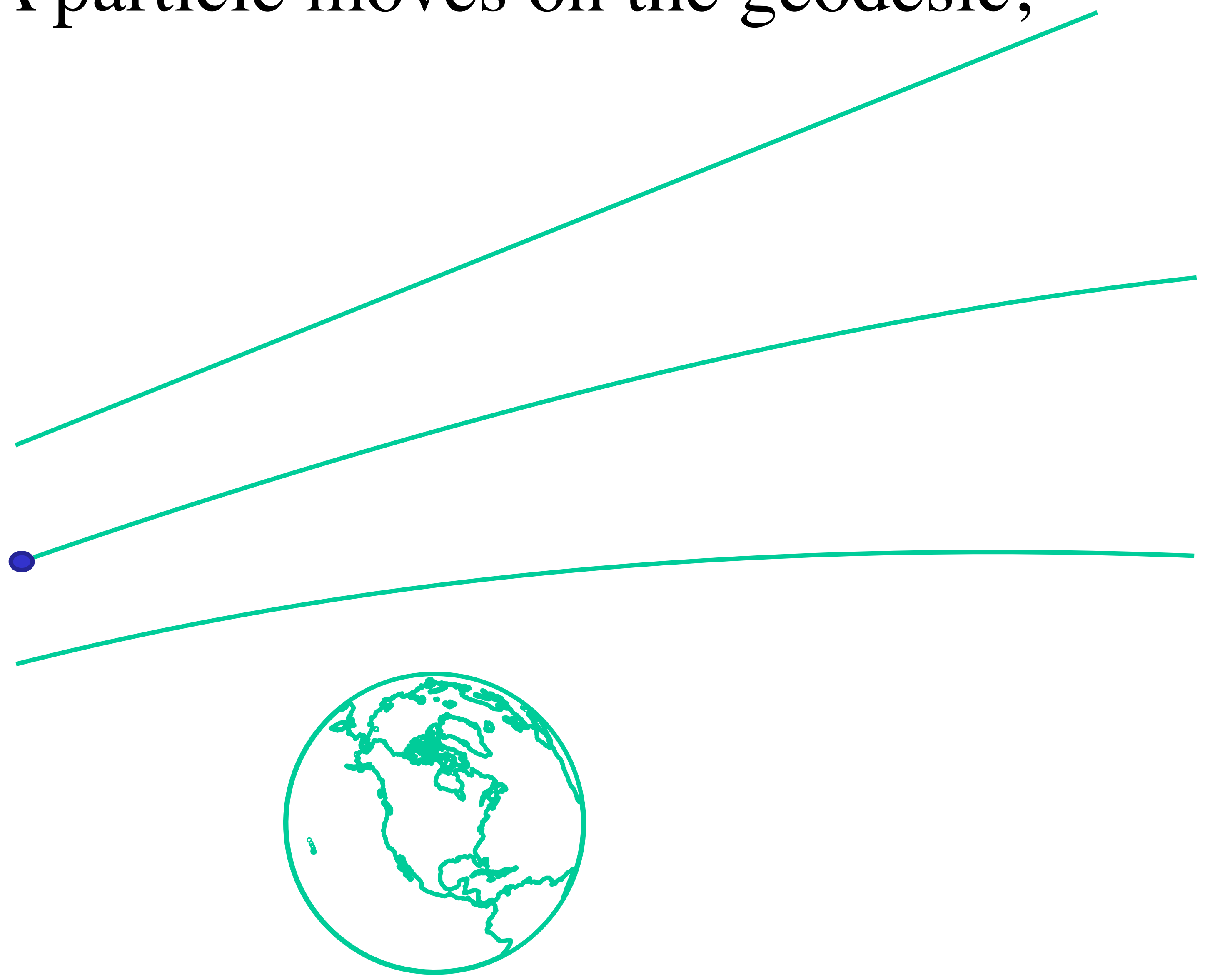
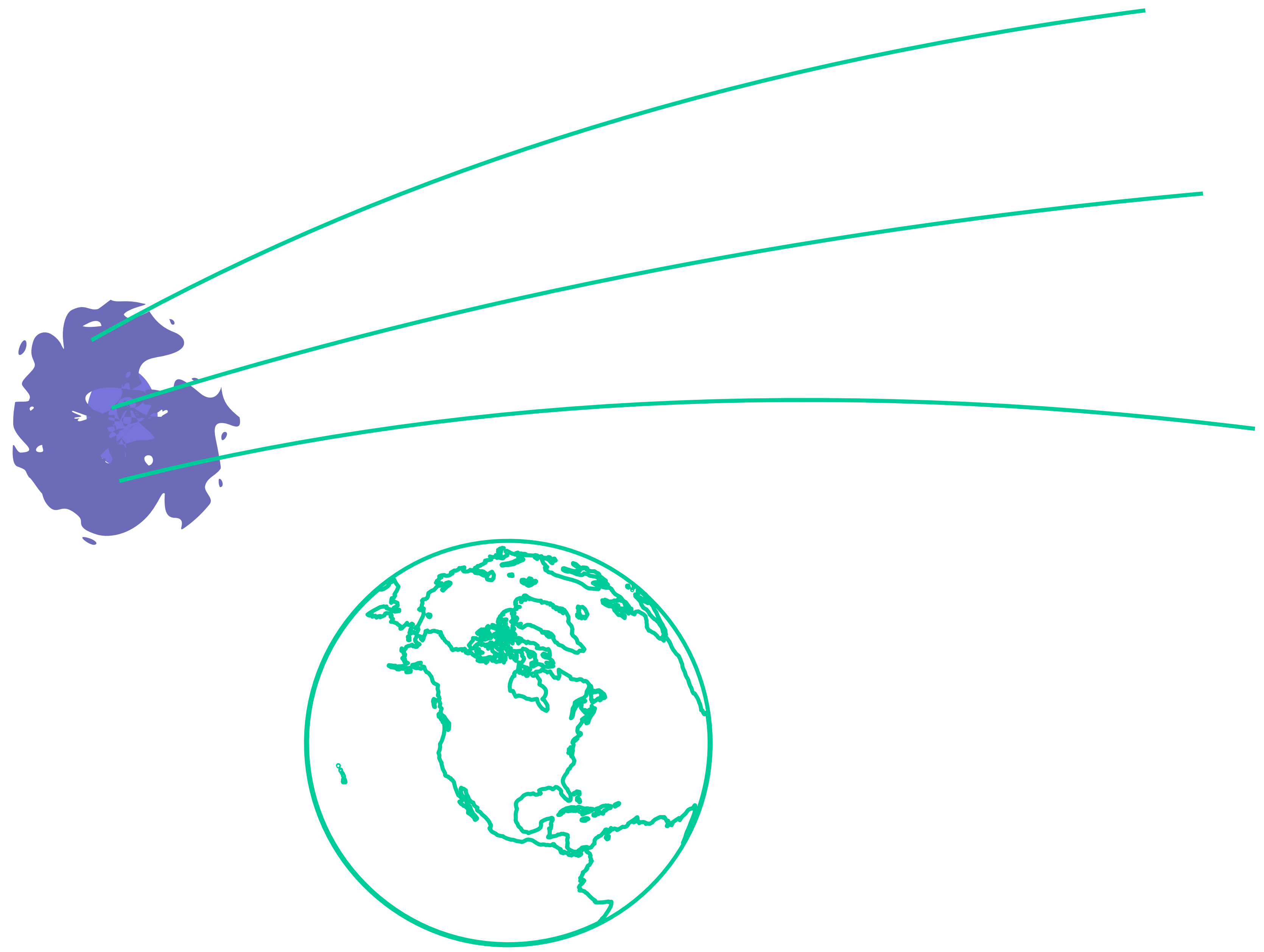


Soft quantum gravity's corrections: Theoretical glimpse

A particle moves on the geodesic,





Its quantum wave-function interact with the curved space-time around the geodesic and gets distorted

How does the Riemann tensor of the curved space-time geometry distort the wave-function in quantum mechanics?

1. Consider Quantum Field Theory in a general curved space-time geometry.
2. Select the space-time geometry, and identify the geodesic that the quantum probe moves on.
3. Expand the metric in Fermi coordinates adapted to the geodesic.
4. Go to the low energy limit of the theory to find the interaction between Riemann tensor and quantum mechanics.
5. Calculate the interaction and find if it can lead to an observation by the current technology.

The magnitude of interaction between Riemann tensor and local quantum mechanics depends on:

1. The background curved space-time geometry.
2. The geodesic that the quantum probe moves along.
3. The details of the quantum probe.

We have studied two quantum probes: The hydrogen atom and a photon

Hydrogen atom in the Schwarzschild black hole : the simplest example

No technologically observable effect. However as the hydrogen atom in its ground state falls in or is scattered by the black hole, the curvature of the space-time geometry excites it. The excited state decays into the ground state by spontaneous emission and emits a photon. The emitted photon extracts energy from the black hole and causes the decay of the black hole into the flat space-time geometry.

The interaction of quantum matter with a black hole causes the black hole to evaporate.

Q. Exirifard, E. Karimi; *Schrödinger equation in curved space-time geometry, arXiv:2105.13896*

Photons as produced in the lab:

Photons/coherent lights produced by a laser possesses the following properties:

1. Polarizations,
2. A profile for amplitude and phase which are typically identified by the mean frequency and the line-width,
3. May have non-trivial spatial modes.

In the paraxial approximation, the electric field of light with a sharp frequency can be represented by Hermite-Gaussian or Laguerre-Gaussian modes. These describe photons/electromagnetic fields that carry orbital angular momentum.

On the exact internal degrees of photon in flat space-time geometry

We found that Dirac light cone coordinates can be utilized to find the exact solutions corresponded to the paraxial approximation to the electromagnetism.

$$ds^2 = 2dx^+dx^- + \delta_{ab}dx^a dx^b$$

$$< x_1, x_2 | \omega, l, n > = \frac{2^{-\frac{l+n}{2}}(-1)^{l+n}}{\pi w_0^{l+n+1} w(x^+)} H_l\left(\frac{\sqrt{2}x_1}{w(x^+)}\right) H_n\left(\frac{\sqrt{2}x_2}{w(x^+)}\right) \times \exp\left(-\frac{\omega(x_1^2 + x_2^2)}{2z_R - 2ix^+} + i\psi(x^+)\right)$$

Q. Exirifard, E. Culf, E. Karimi; *Towards communications in curved space-time geometry,* Communications Physics, volume **4**, Article number: 171 (2021).

The space-time geometry around the photon's null geodesic:

$$ds^2 = 2dx^+dx^- + \delta_{ab}dx^a dx^b - [R_{+\bar{a}+\bar{b}}x^{\bar{a}}x^{\bar{b}}(dx^+)^2 + \frac{4}{3}R_{+\bar{b}\bar{a}\bar{c}}x^{\bar{b}}x^{\bar{c}}(dx^+dx^{\bar{a}}) + \frac{1}{3}R_{\bar{a}\bar{c}\bar{b}\bar{d}}x^{\bar{b}}x^{\bar{c}}(dx^{\bar{a}}dx^{\bar{b}})] + O(x^{\bar{a}}x^{\bar{b}}x^{\bar{c}})$$

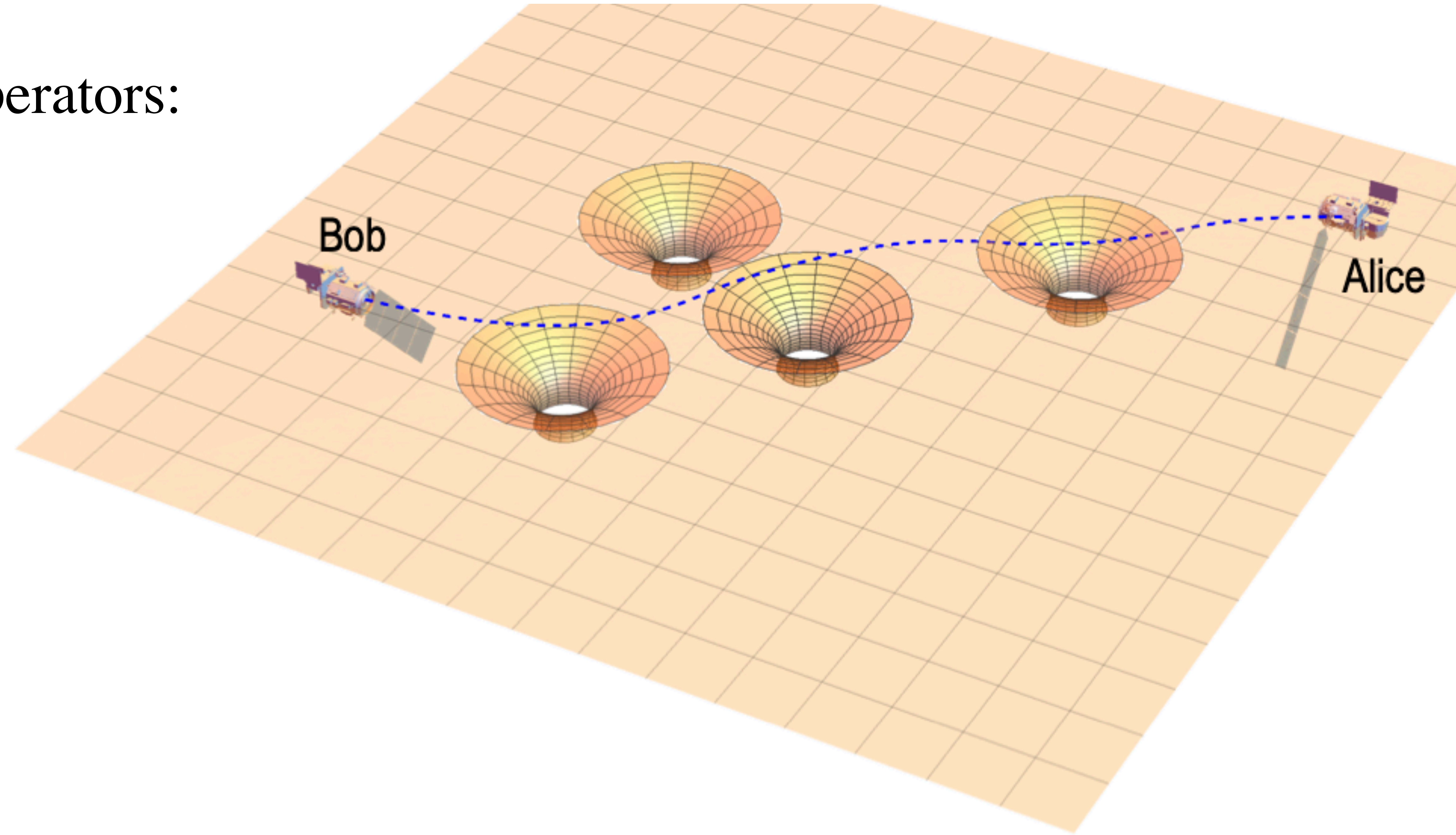
The photon's wave-function is corrected by the following non-trivial operators:

$$\mathcal{O}^{\omega} = -\frac{i\omega}{2}\mathcal{G}_{ab}x^a x^b + \tilde{\mathcal{G}}_{ab}x^a\partial^b + \frac{i}{\omega}\tilde{\tilde{\mathcal{G}}}_{ab}\partial^a\partial^b$$

$$\mathcal{Q}_U^{\omega} = \frac{i}{\omega}\left(1 - \frac{\omega^2}{2}(x^-)^2\right)\mathcal{G}_{--} - ix^-\omega x^a\mathcal{G}_{-a} + x^-\tilde{\mathcal{G}}_{-a}\partial^a,$$

$$\mathcal{Q}_N^{\omega} = x^-\mathcal{G}_{--} + \mathcal{G}_{-a}x^a + \frac{2i}{\omega}\tilde{\mathcal{G}}_{-a}\partial^a,$$

$$\mathcal{G}_{\bar{a}\bar{b}} = \int_0^{\tau} d\tau R_{+\bar{a}+\bar{b}}, \quad \tilde{\mathcal{G}}_{\bar{a}\bar{b}} = \int_0^{\tau} d\tau \mathcal{G}_{\bar{a}\bar{b}}, \quad \tilde{\tilde{\mathcal{G}}}_{\bar{a}\bar{b}} = \int_0^{\tau} d\tau \tilde{\mathcal{G}}_{\bar{a}\bar{b}},$$



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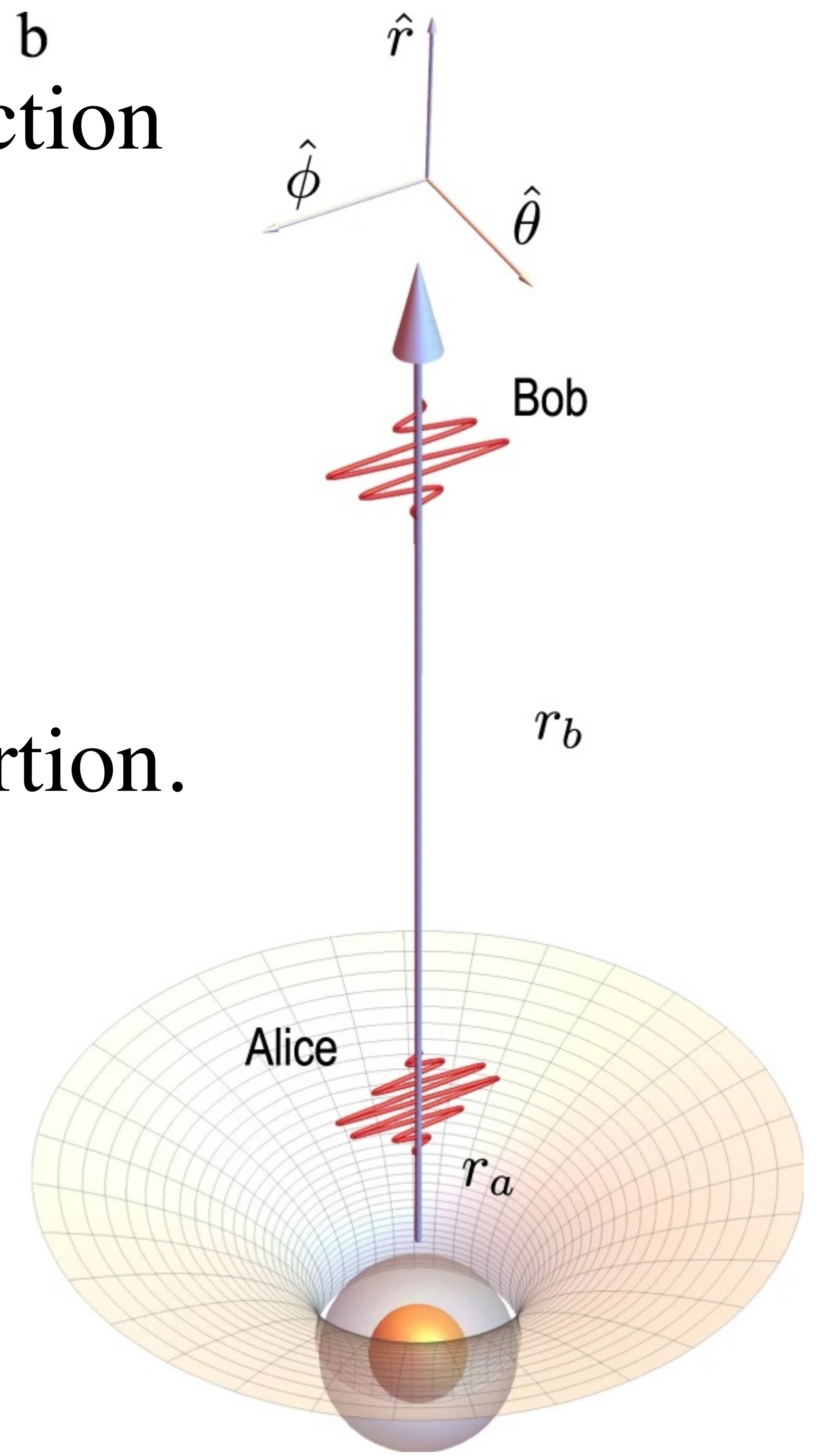
Possibility to measure the distortion to the photon's wave function communicated between Earth and ISS



The effects of the Earth atmosphere, however, washes the distortion.

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A time-bin Gaussian mode of photon:

Hermit Gaussian mode

$$A^{\mu} = \sqrt{2\sigma}\pi^{\frac{1}{4}}e^{-\frac{(\sigma x^{-})^{2}}{2}+i\omega_{0}x^{-}}\boxed{f^{\mu}_{mn}}(\omega_{0}, x^{+}, x^{a}), \quad \mu \in 1{,}2$$

$$\sigma \ll \omega_{0} \;\&\; \boxed{W_{0}} \ll \frac{c}{\sigma}$$

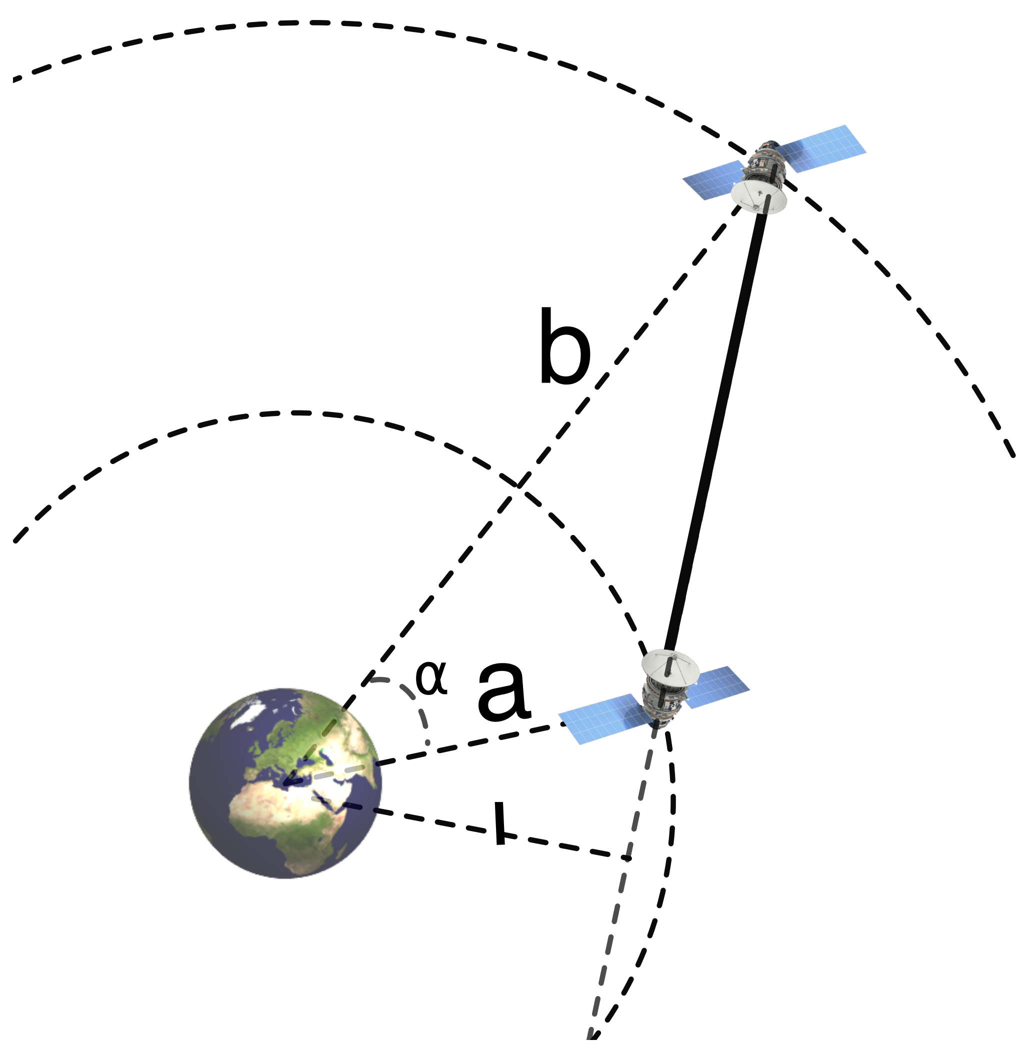
Width of the mode

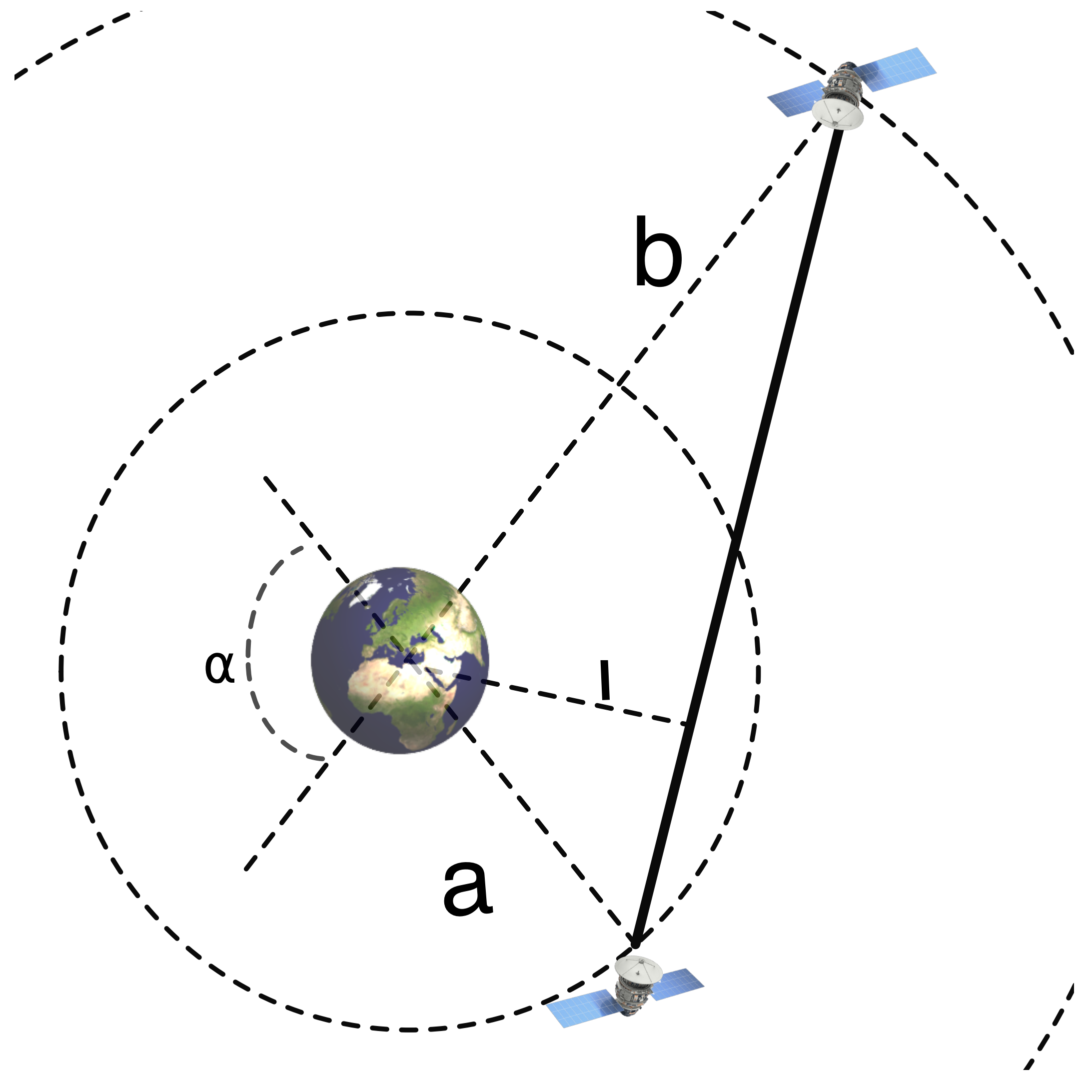
$$A_{\mu} \rightarrow A_{\mu}e^{i\chi_{g}}$$

Geometric Phase

$$\boxed{\chi_{g}} = -\frac{\omega_{0}\left(\int d\tau R_{+-+-}(\tau)\right)}{2\sigma^{2}}(\sigma x^{-})^{2}$$

The geometric phase for communication near earth:





$$\chi_g = +\frac{\omega_0 c m_\oplus (b^2 - a^2)}{4(\sigma ab)^2}\sqrt{\frac{(a-b\cos\alpha)^2}{a^2+b^2-2ab\cos\alpha}}\left(\frac{\sigma x^-}{c}\right)^2$$

$$\chi_g = -\frac{\omega_0 c m_\oplus (b^2 + a^2)}{4(\sigma ab)^2}\sqrt{\frac{(a-b\cos\alpha)^2}{a^2+b^2-2ab\cos\alpha}}\left(\frac{\sigma x^-}{c}\right)^2$$

Note that $m_\oplus$ is the Schwarzschild radius of the Earth: $m_\oplus = 8.87$ mm.

The geometric phase

Mass of the Earth

Photon's energy

$$\frac{\chi_g}{(\sigma x^-)^2} = \boxed{l_p^2} \times \frac{\boxed{(M_\oplus} c^2)\boxed{E_0}}{\boxed{(\Delta E_0})^2} \times \boxed{\tilde{f}(a, b, \alpha)}$$

Planck length

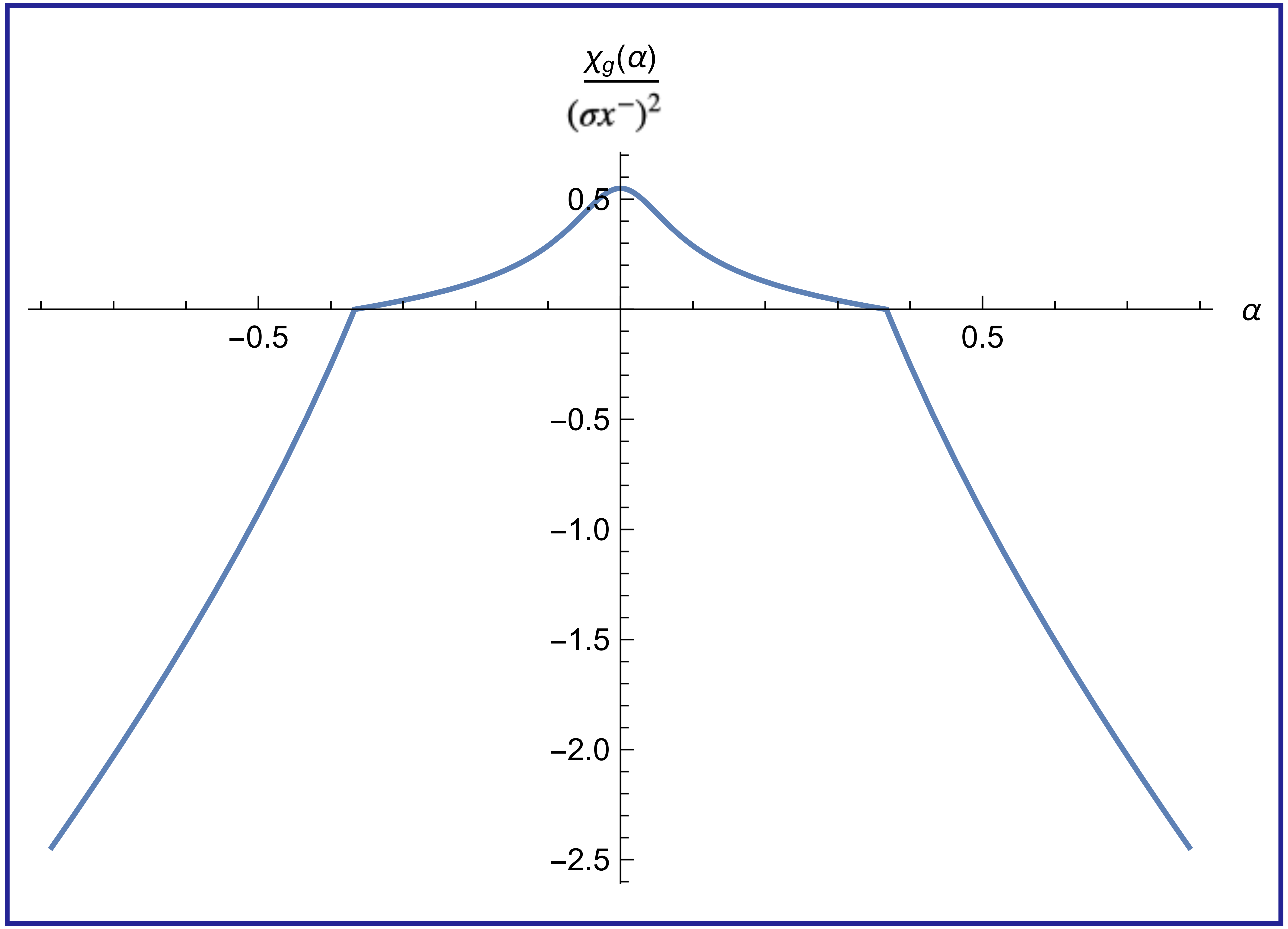
Uncertainty in the photon's energy

Known function of the geodesic

The geometric phase for communication near earth:

The geometrical phase in terms of radians for communication between satellites at orbit 7000 km and 7,500 km. For frequency of $\nu_0^s = 2.87 \times 10^{15}$Hz and bandwidth of $\sigma^s = \Delta\nu = 1$kHz in term of angle of between satellites as seen from the centre of the Earth.

* α is the angle between satellites as seen from the centre of Earth.



Conclusions

The predicted geometric phase is detectable. Its detection provides the first experimental observation on if and how gravity talks to realm of quantum mechanics.

Qasem Exirifard & Ebrahim Karimi , "Gravitational distortion on photon state at the vicinity of the Earth" , arXiv:2110.13990

Our related works

Q. Exirifard, E. Karimi; *Schrödinger equation in curved space-time geometry, arXiv:2105.13896*

Q. Exirifard, E. Culf, E. Karimi; *Towards communications in curved space-time geometry, Communications Physics, volume 4, Article number: 171 (2021).*