Journal Club:
Exotic looped trajectories of photons in three-slit interference

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Exotic looped trajectories of photons in three-slit interference

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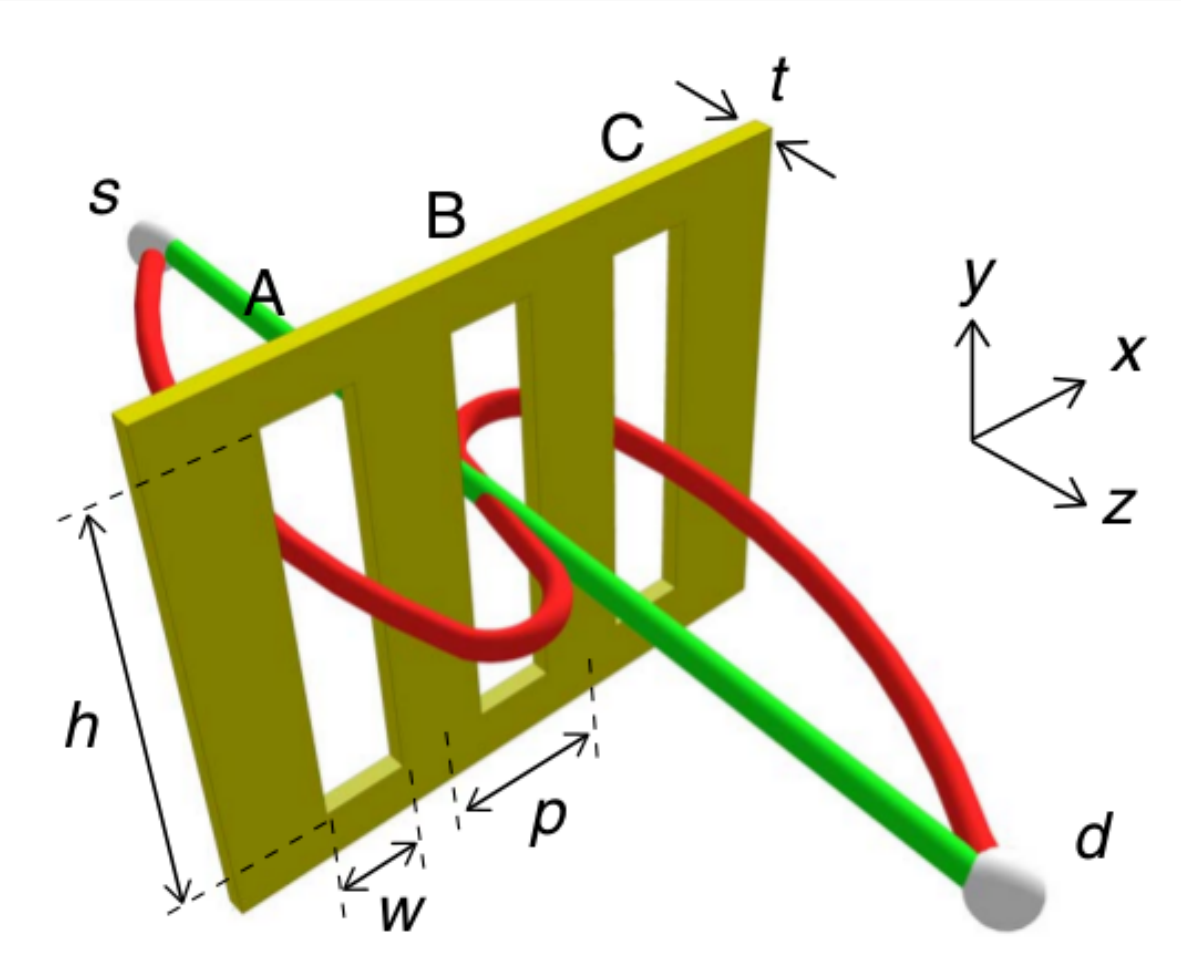
The validity of the superposition principle and of Born's rule are well-accepted tenants of quantum mechanics. Surprisingly, it has been predicted that the intensity pattern formed in a three-slit experiment is seemingly in contradiction with the most conventional form of the superposition principle when exotic looped trajectories are taken into account. However, the probability of observing such paths is typically very small, thus rendering them extremely difficult to measure. Here we confirm the validity of Born's rule and present the first experimental observation of exotic trajectories as additional paths for the light by directly measuring their contribution to the formation of optical interference fringes. We accomplish this by enhancing the electromagnetic near-fields in the vicinity of the slits through the excitation of surface plasmons. This process increases the probability of occurrence of these exotic trajectories, demonstrating that they are related to the near-field component of the photon's wavefunction.

Three-slit interference



Three-slit interference

Interference from two slits: superposition principle

$$\psi_{\mathrm{AB}} = \psi_{\mathrm{A}} + \psi_{\mathrm{B}}$$

Probability of detection

$$P_{\mathrm{AB}} = |\psi_{\mathrm{AB}}|^2 = P_{\mathrm{A}} + P_{\mathrm{B}} + \psi_{\mathrm{A}}^* \psi_{\mathrm{B}} + \psi_{\mathrm{B}}^* \psi_{\mathrm{A}}$$

Naïve application for three slits:

$$\psi_{\mathrm{ABC}} = \psi_{\mathrm{A}} + \psi_{\mathrm{B}} + \psi_{\mathrm{C}}$$

results in

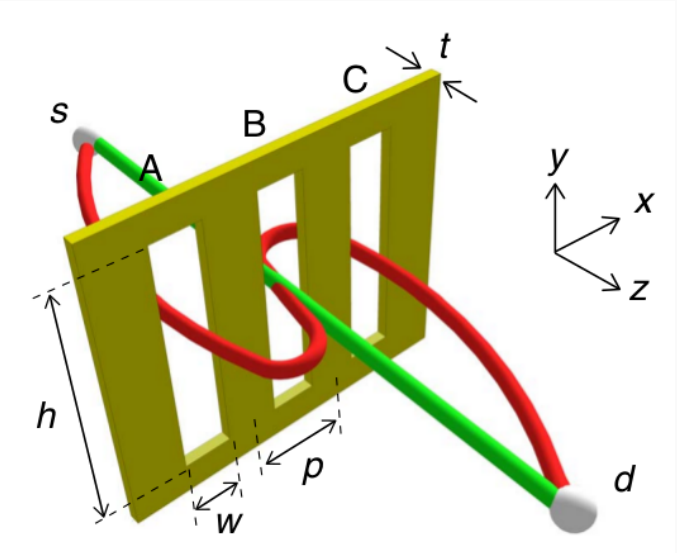
$$P_{\mathrm{ABC}} = P_{\mathrm{AB}} + P_{\mathrm{BC}} + P_{\mathrm{AC}} - P_{\mathrm{A}} - P_{\mathrm{B}} - P_{\mathrm{C}}$$

Sorkin parameter

$$\epsilon = P_{\mathrm{ABC}} - P_{\mathrm{AB}} - P_{\mathrm{BC}} - P_{\mathrm{AC}} + P_{\mathrm{A}} + P_{\mathrm{B}} + P_{\mathrm{C}}$$

Three-slit interference

- It seems that $\epsilon = 0$. But this is wrong!
- The reason: looped trajectories
- Extremely low probability of occurrence



Looped trajectories of photons

Problem

Extremely low probability of occurrence of looped trajectories

Looped trajectories of photons

- The looped trajectories of photons are physically due to the near-field components of the wavefunction
- By controlling the strengths of the near-fields around the slits it is possible to drastically increase the probability of photons to undergo looped trajectories

Looped trajectories of photons

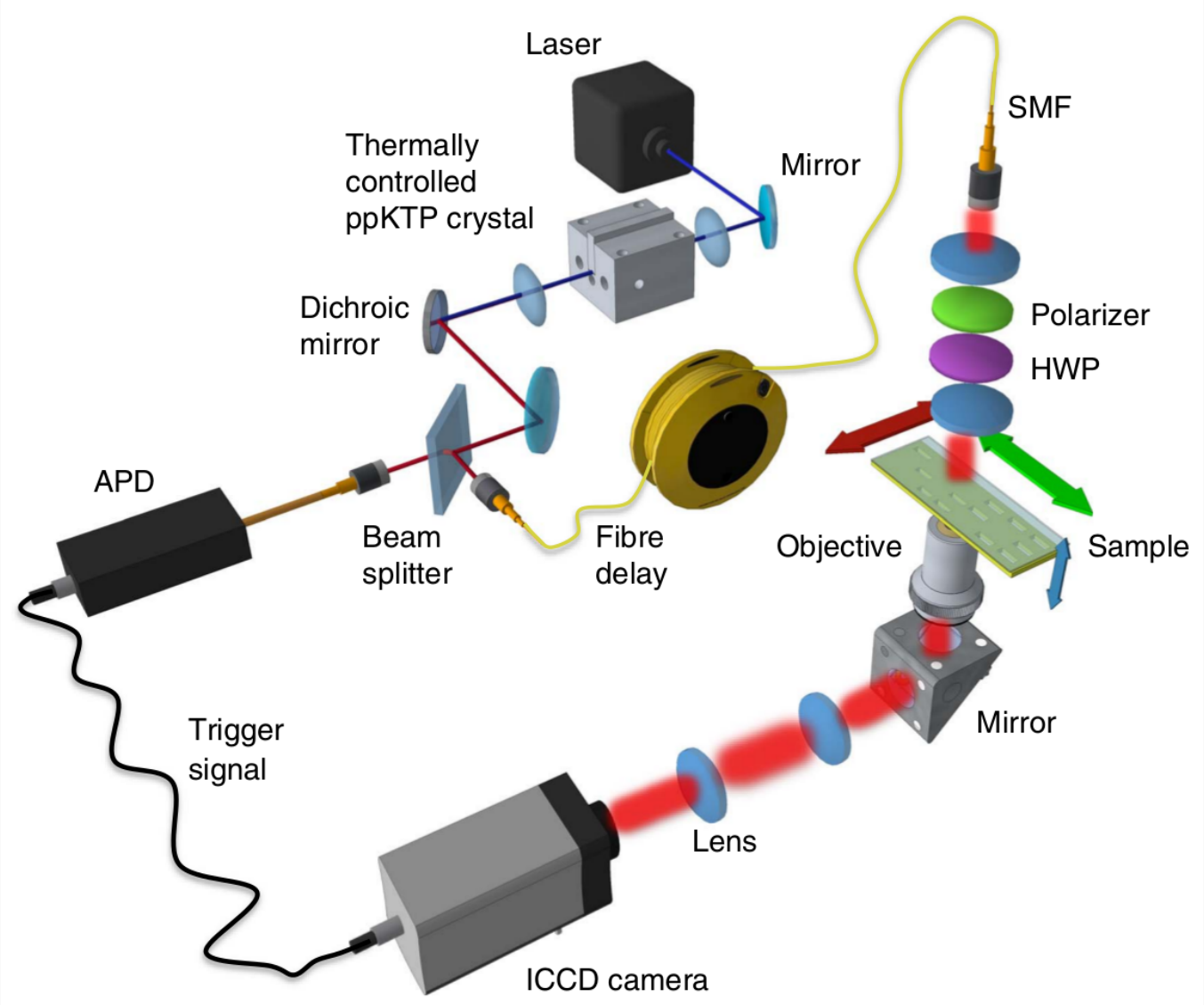
Solution

Three-slit structure that supports surface plasmons

Looped trajectories of photons

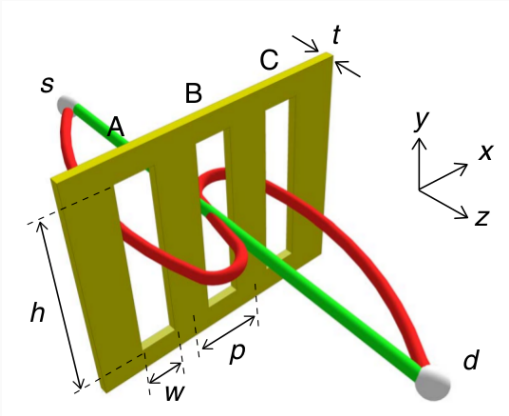
- Surface plasmons—strongly confined electromagnetic fields that exist at the surface of metals
- The existence of these surface waves results in near fields that extend over the entire region covering the three slits

Experimental setup



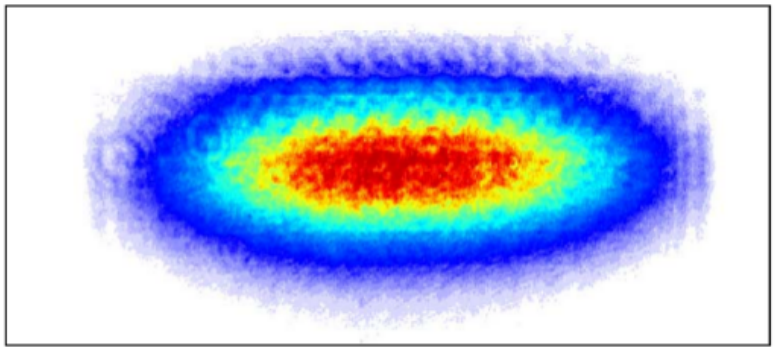
Parameters

- Sample: gold film on a glass substrate
- Dimensions: $w = 200\,\mathrm{nm}$, $p = 4.6\,\mu\mathrm{m}$, $t = 110\,\mathrm{nm}$, $h = 100\,\mu\mathrm{m}$
- Wavelength $\lambda = 810\,\mathrm{nm}$

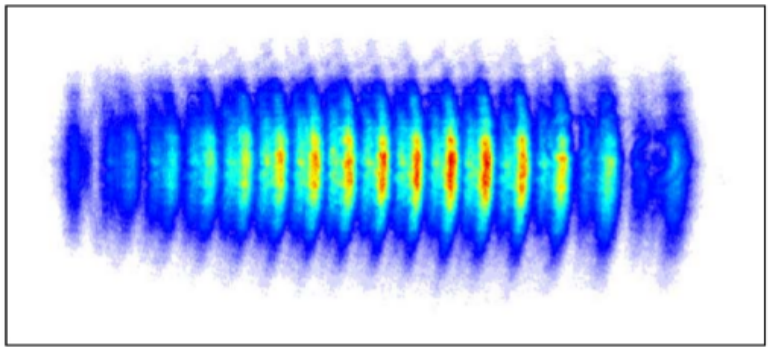


Far-field pattern

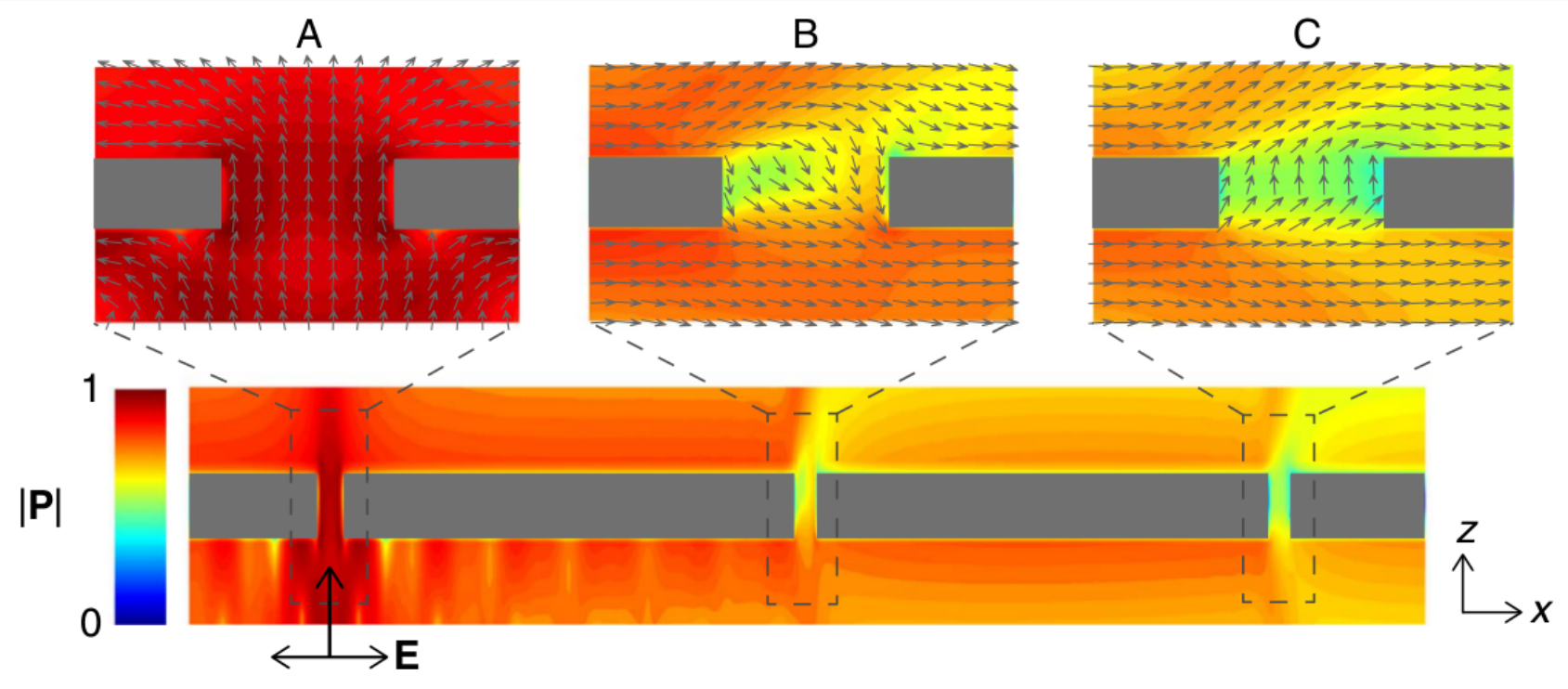
Far-field intensity (a.u)
y-polarization



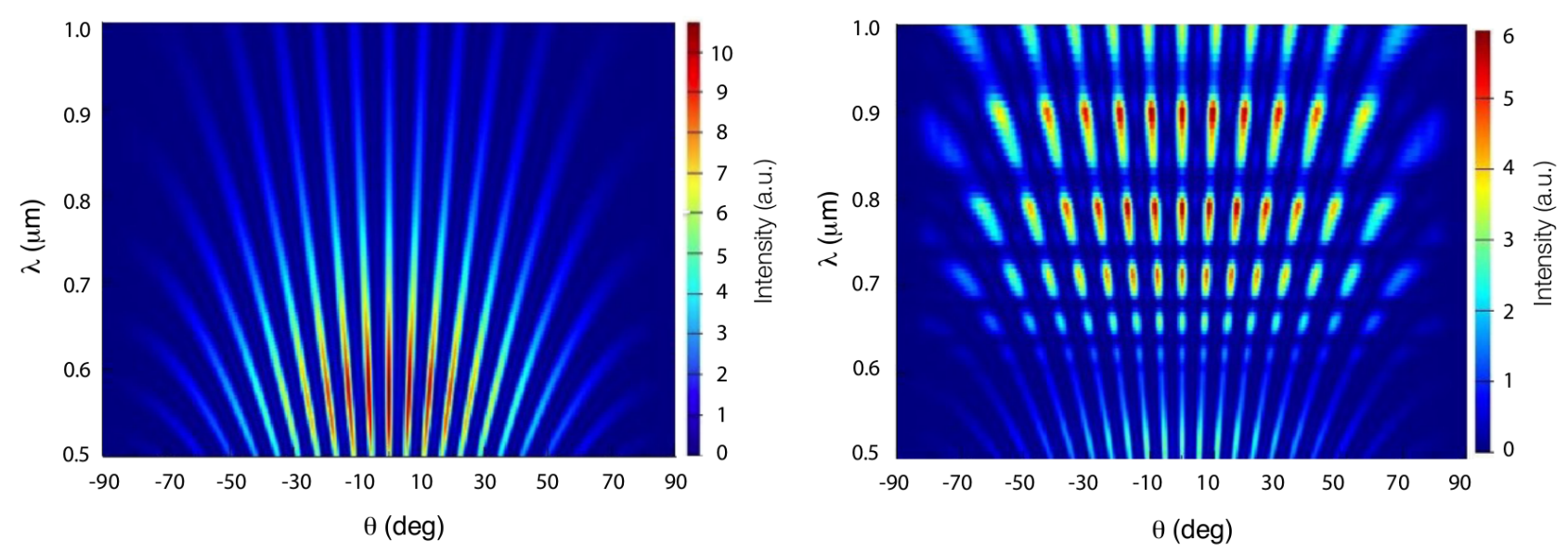
Far-field intensity (a.u)
x-polarization



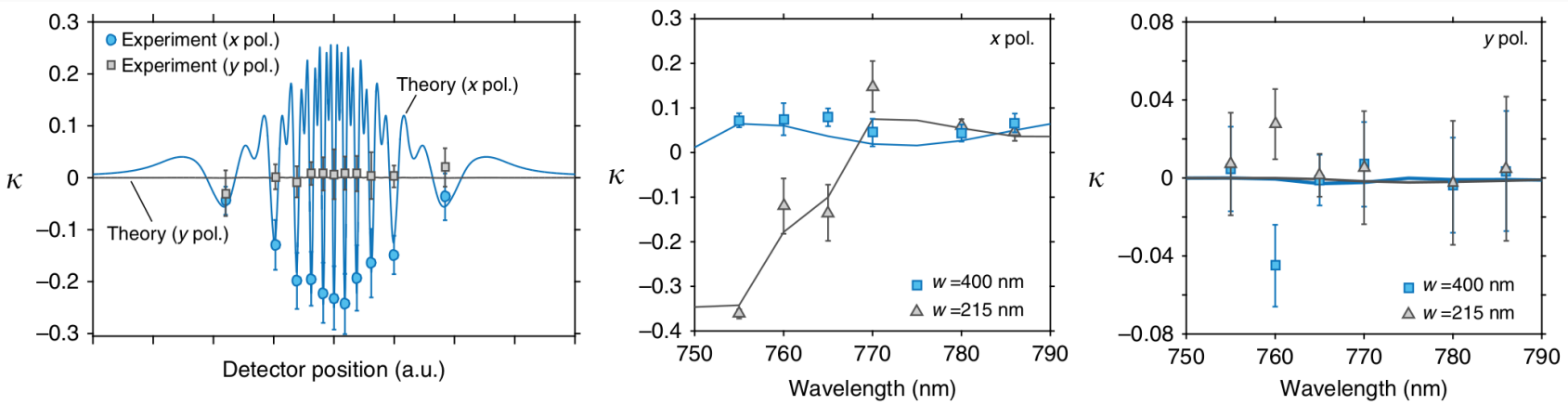
Poynting vector in the vicinity of the three slits



The wavelength-dependent interference pattern



Experimental results: Sorkin parameter



Summary

We have demonstrated that exotic looped paths occur as a physical consequence of the near-field component of the wave equation. As such, it is possible to control the probability of occurrence of such paths by controlling the strength and spatial distribution of the near-fields around the slits. By doing so, we have shown a drastic increase in the probability of photons to follow looped paths, leading to the first experimental observation of such exotic trajectories in the formation of interference fringes. Our work elucidates new properties of light that could be used to enrich protocols that rely on interference effects such as quantum random walks and quantum simulators

Thank you for your attention!