From double-slit experiments with single electrons to two-electron entanglement in space-time: A Europe-Asia Physics Project

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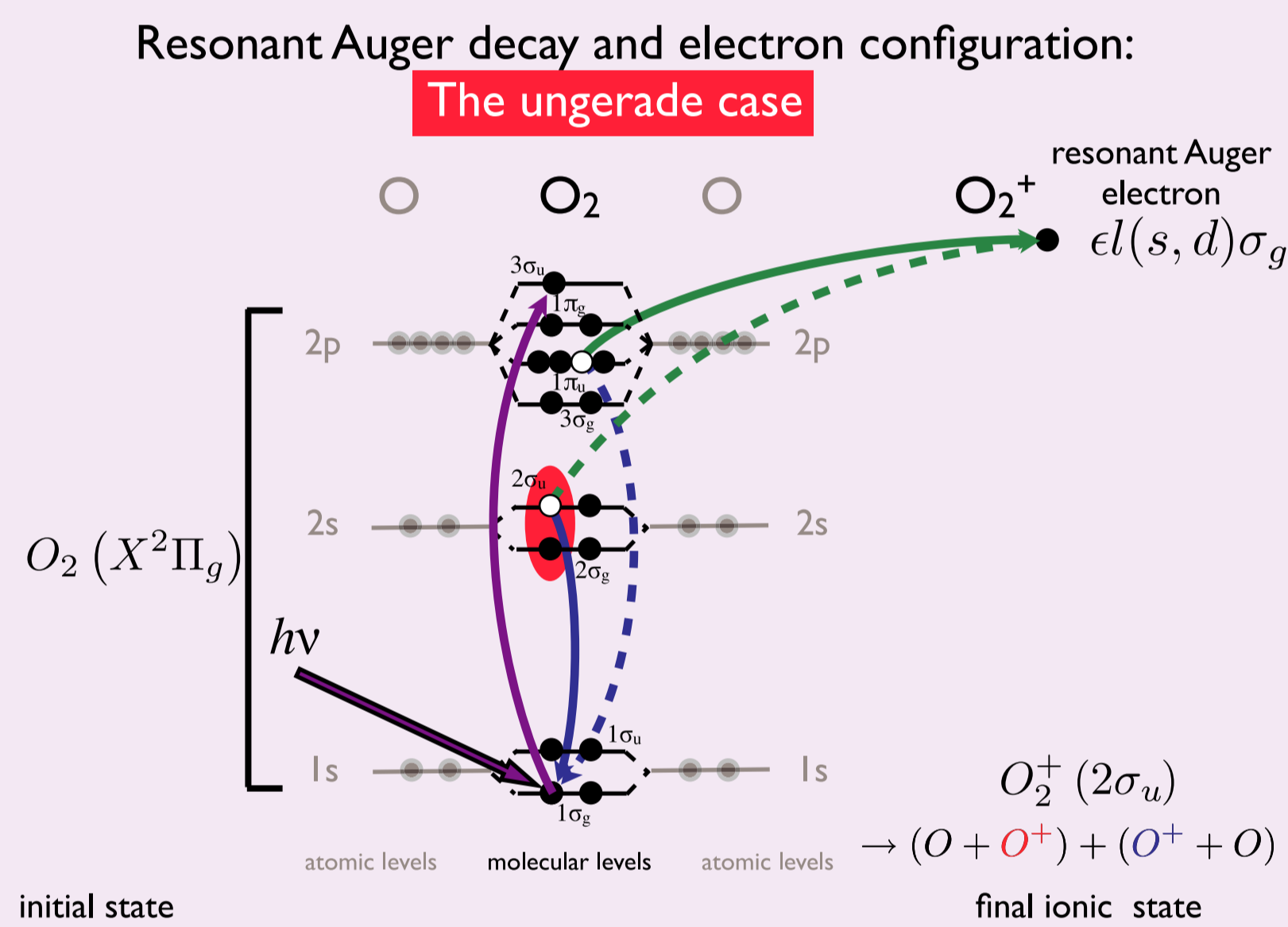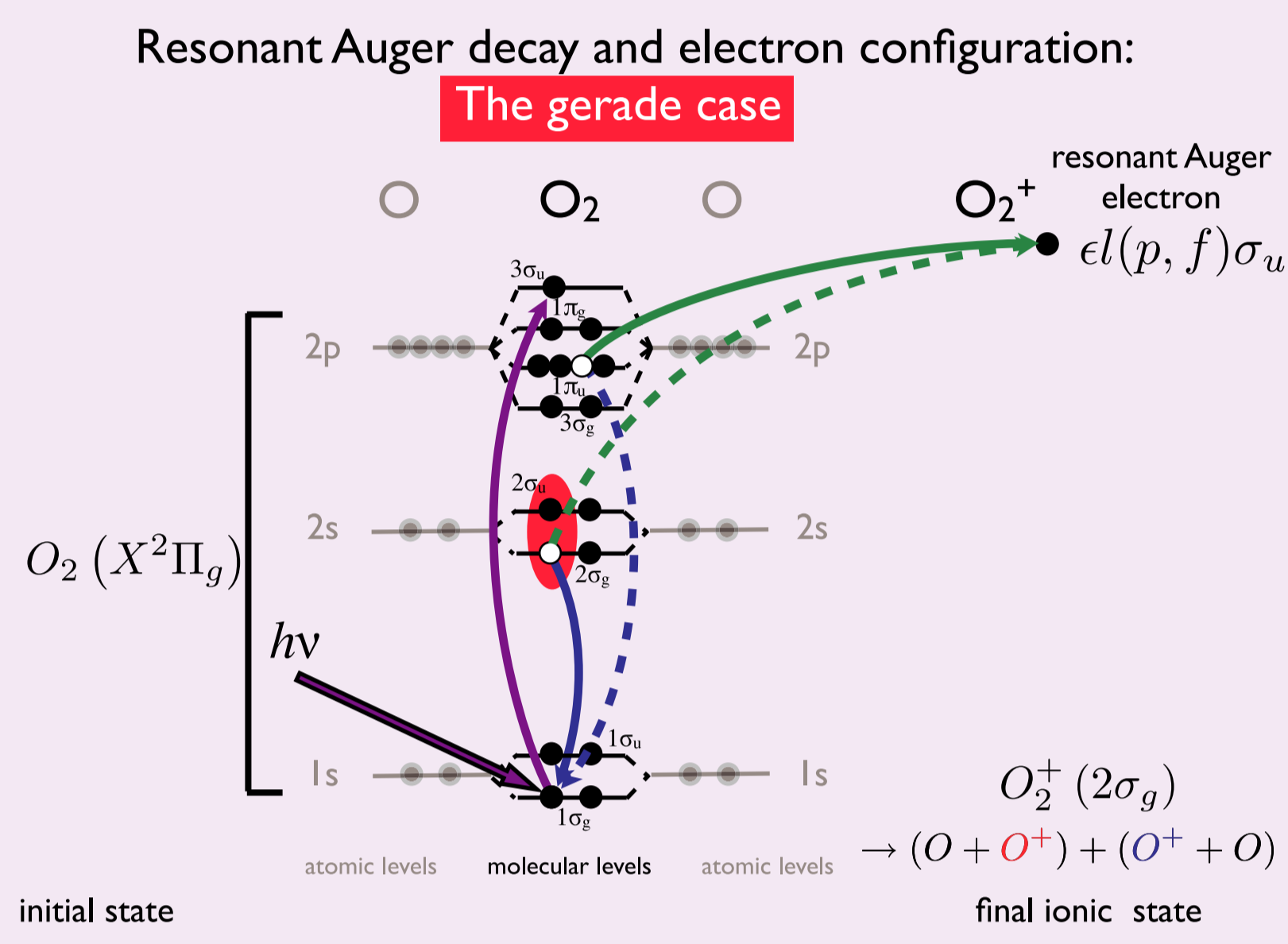
During the last decade a sneaking paradigm change has been taken place regarding the compatibility of quantum physics, in particular its consequences for entangled pairs of particles [1], and special relativity. Tim Maudlin of Rutgers University wrote a book on "quantum non-locality and relativity" in 1994 [2] which highlighted that the compatibility of non-locality and special relativity was a much more subtle question than the traditional arguments based on instantaneous messages would have us believed. He shows that special relativity is compatible with a variety of faster-than-light transmission mechanisms, however, they would have to fulfill certain requirements. What is in last consequence uncanny about the way quantum objects can non-locally influence one another is the fact that it does not depend on the particles spatial arrangements and their intrinsic physical characteristics, but only on whether or not the particles in question are quantum mechanically entangled with one another. Hence the kind of non-locality seems to call for an absolute simultaneity, which would pose a very real and ominous threat to special relativity.
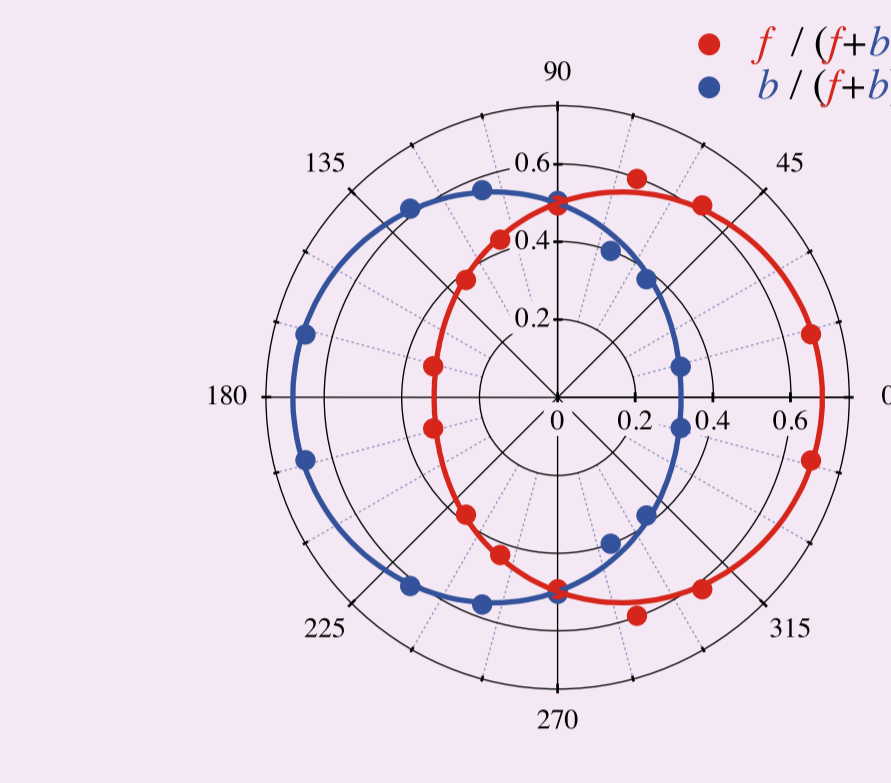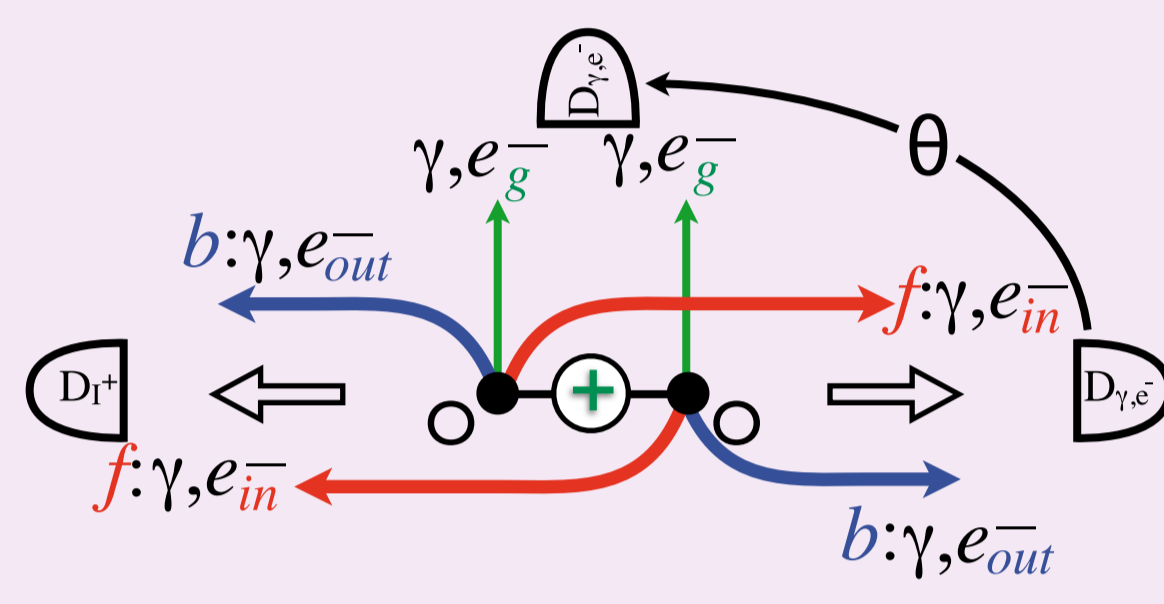
Two new ideas have emerged from this situation in the past few years. The first one was a paper by Roderich Tomulka from Rutgers University [3] who showed, that a non-local modification of Ghirardi-Rimini-Weber (GRW) theory, a theory promoting a philosophical realistic way to subsume the predictions of quantum mechanics, would provide a peaceful coexistence between quantum mechanical non-locality and special relativity. The price for this coexistence is however, that one has to introduce a new variety of non-locality into the laws of nature, a non-locality not merely in space but in time. The other approach to solve the conflict between quantum-mechanical non-locality and special relativity is concentrated on the character of quantum mechanical wave functions in the sense of a "many world" interpretation of our reality [4,5].

We present here results supporting the first scenario of interpretation of our reality. The experimental data obtained from angle resolved coincident detection of photo- and Auger electrons in the molecule frame of homonuclea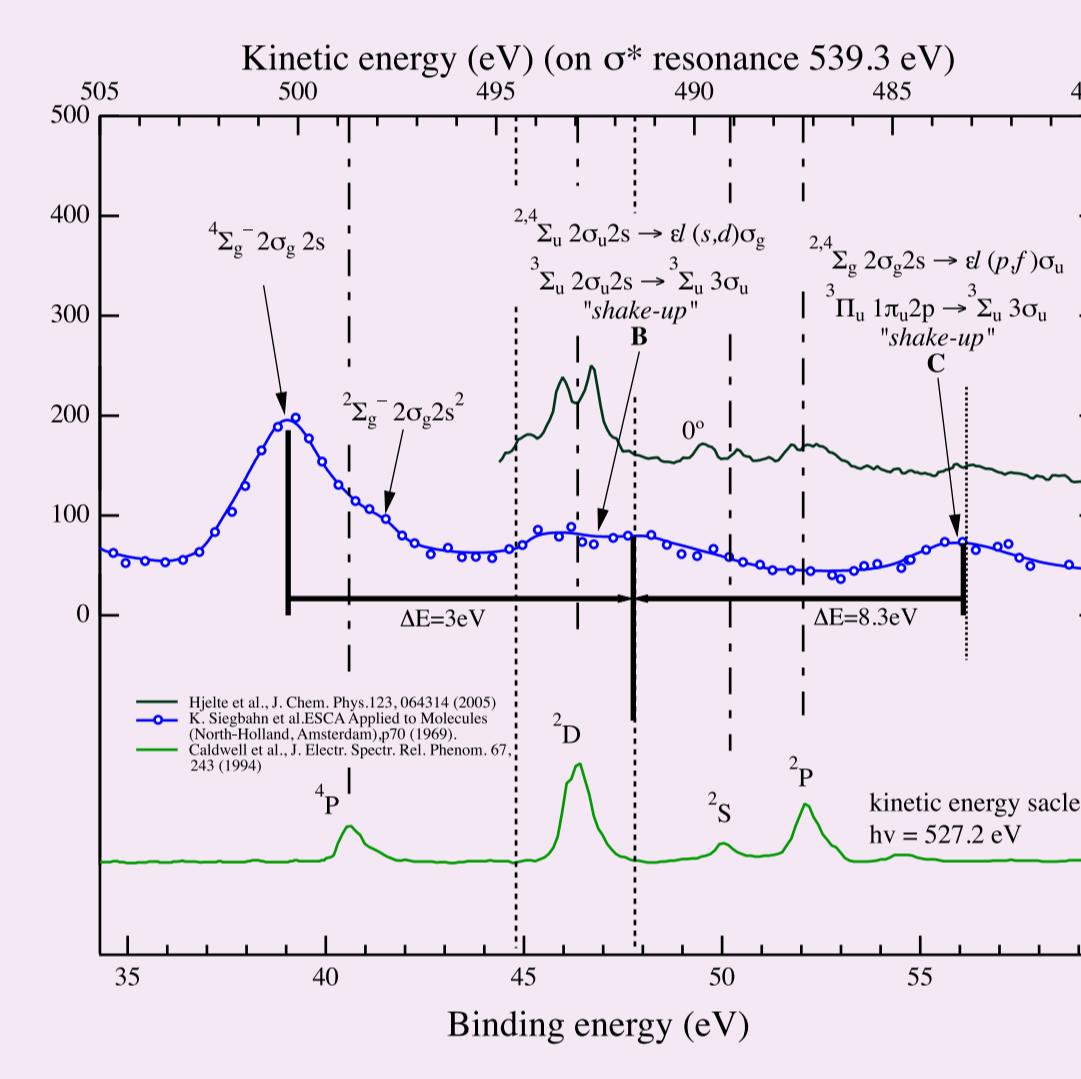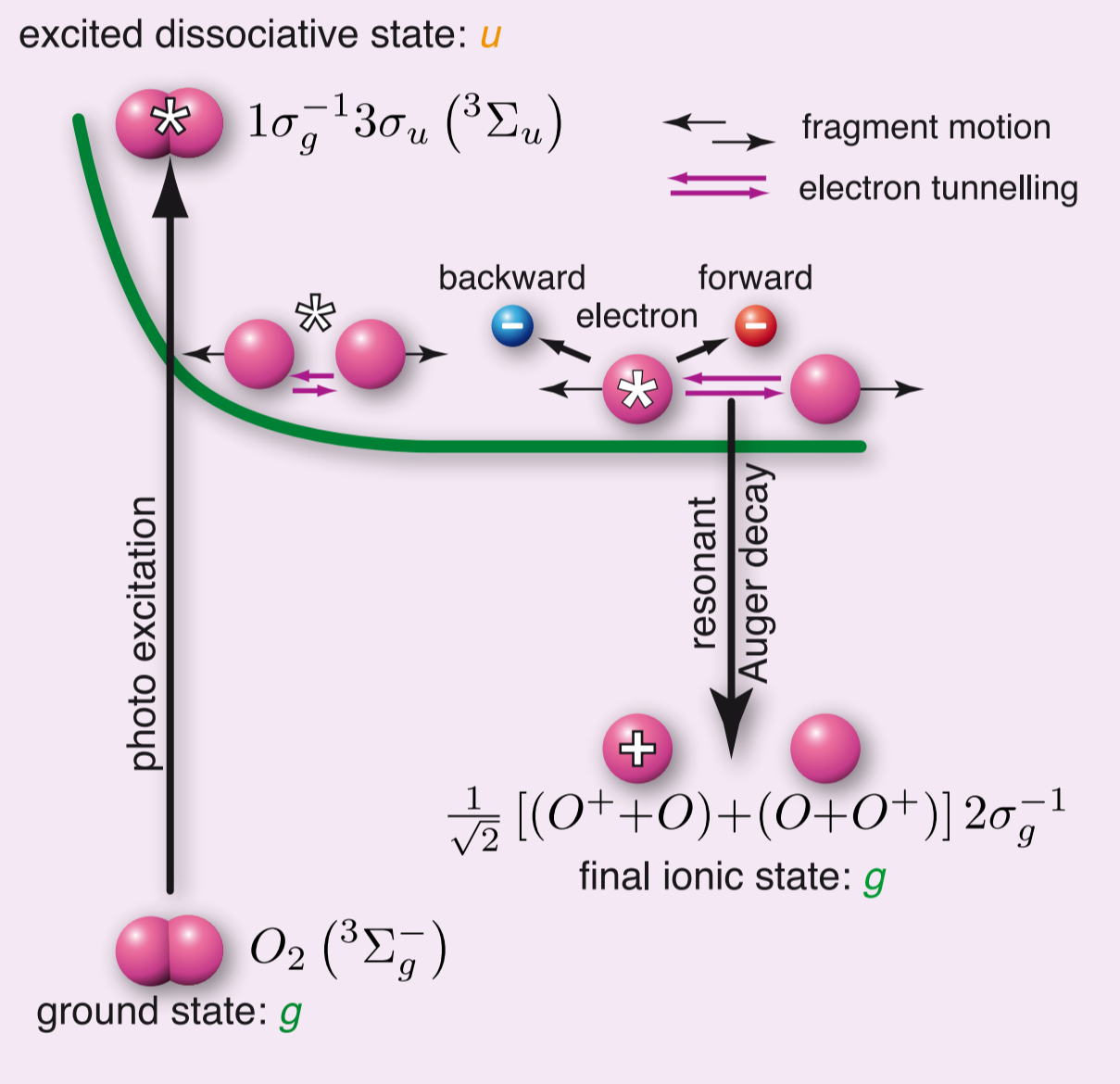r diatomic molecules, here N_2, prove that the corresponding emitted electrons are indeed spatially entangled [6]. This entanglement is based on the spatial properties of the parity eigenstates gerade and ungerade which constitute dichotomic variables of the continuous variable position. These eigenstates are distinguished by their non-degenerate energy values giving rise to an energy difference specific tunneling time. The parity and hence energy eigenstates g and u have as complementary system concerning their entanglement the eigenfunctions of the Fourier integral of energy, which is nothing else than time. Hence our results are the first proof of entanglement between two particles based on time, which means a proof of non-locality of time! This non-locality means that two entangled particles have the same clock starting from the same origin in space independently of their separation in space. This would make quantum mechanical non-locality and special relativity compatible to each other, providing an unexpected peaceful solution to the famous controversy between the two most contradictory opponents of the interpretation of our physical reality in the last century, Albert Einstein and Nils Bohr.
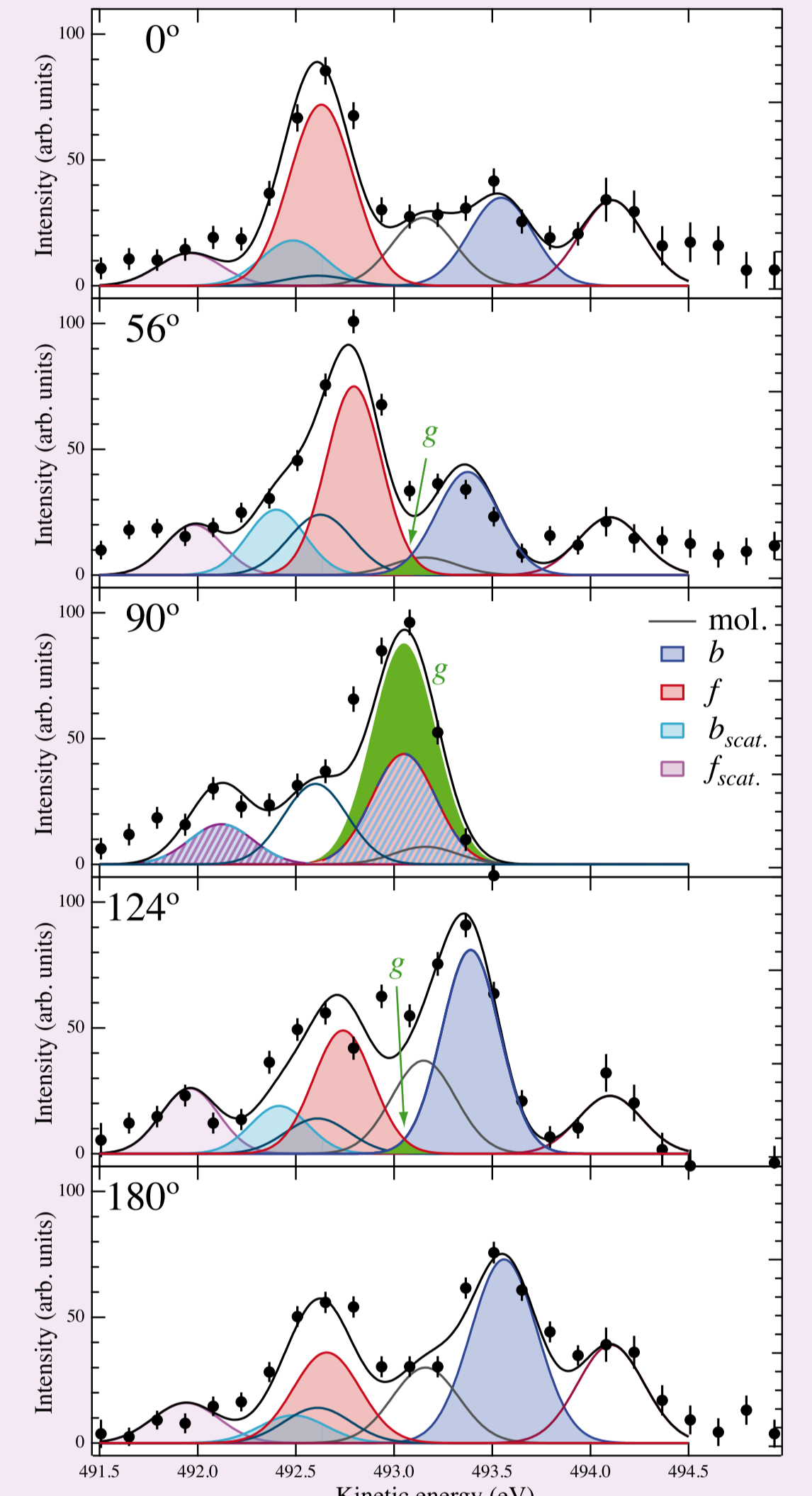

Resonant Auger decay and electron configuration: The gerade case

Resonant Auger decay and electron configuration: The ungerade case

Which way information versus interference pattern

Electron emission in dissociating O_2

Resonant Auger decay following core electron excitation to the dissociative $1\sigma_g^{-1}3\sigma_u\,(^3\Sigma_u)$ state.

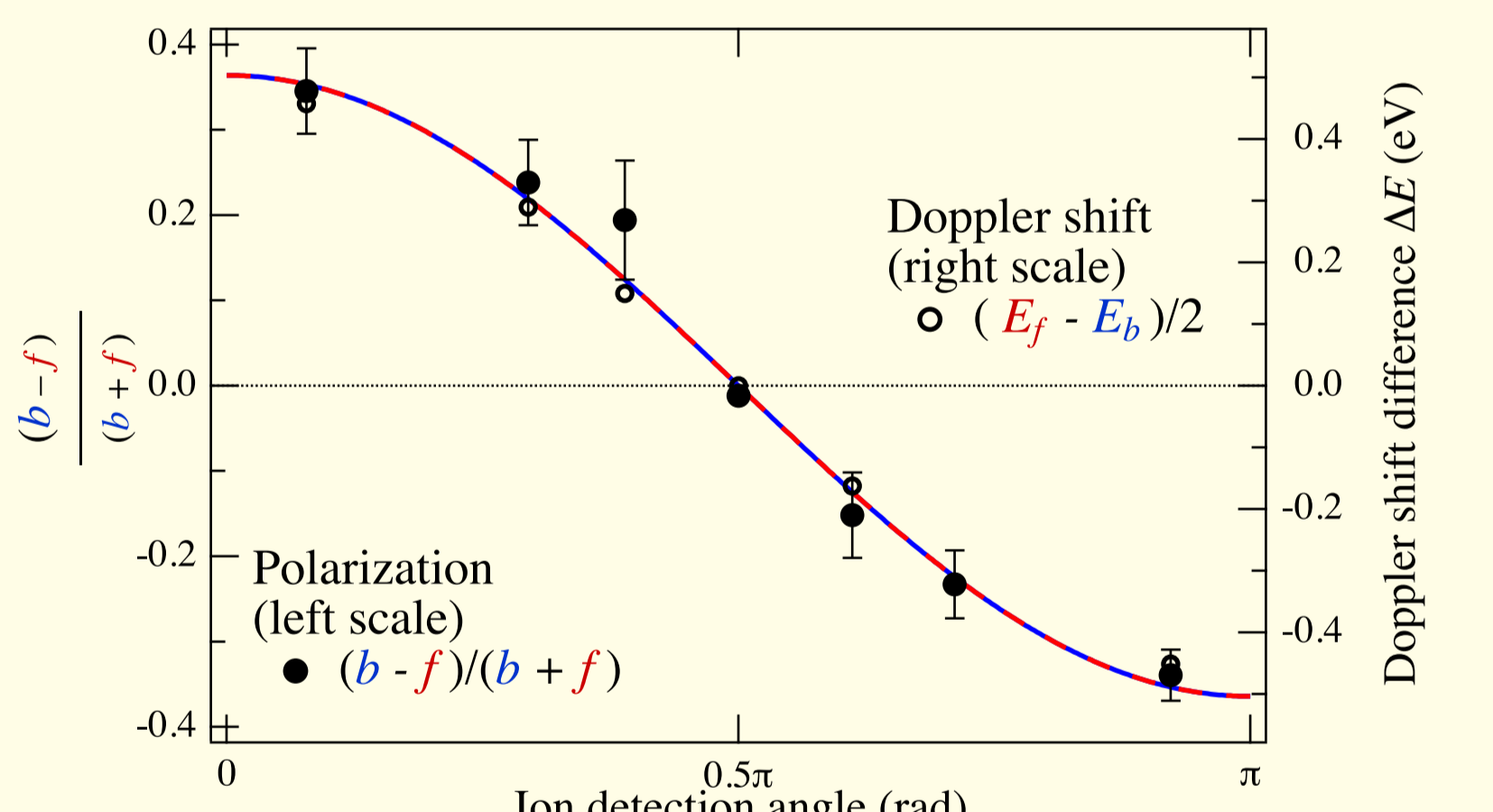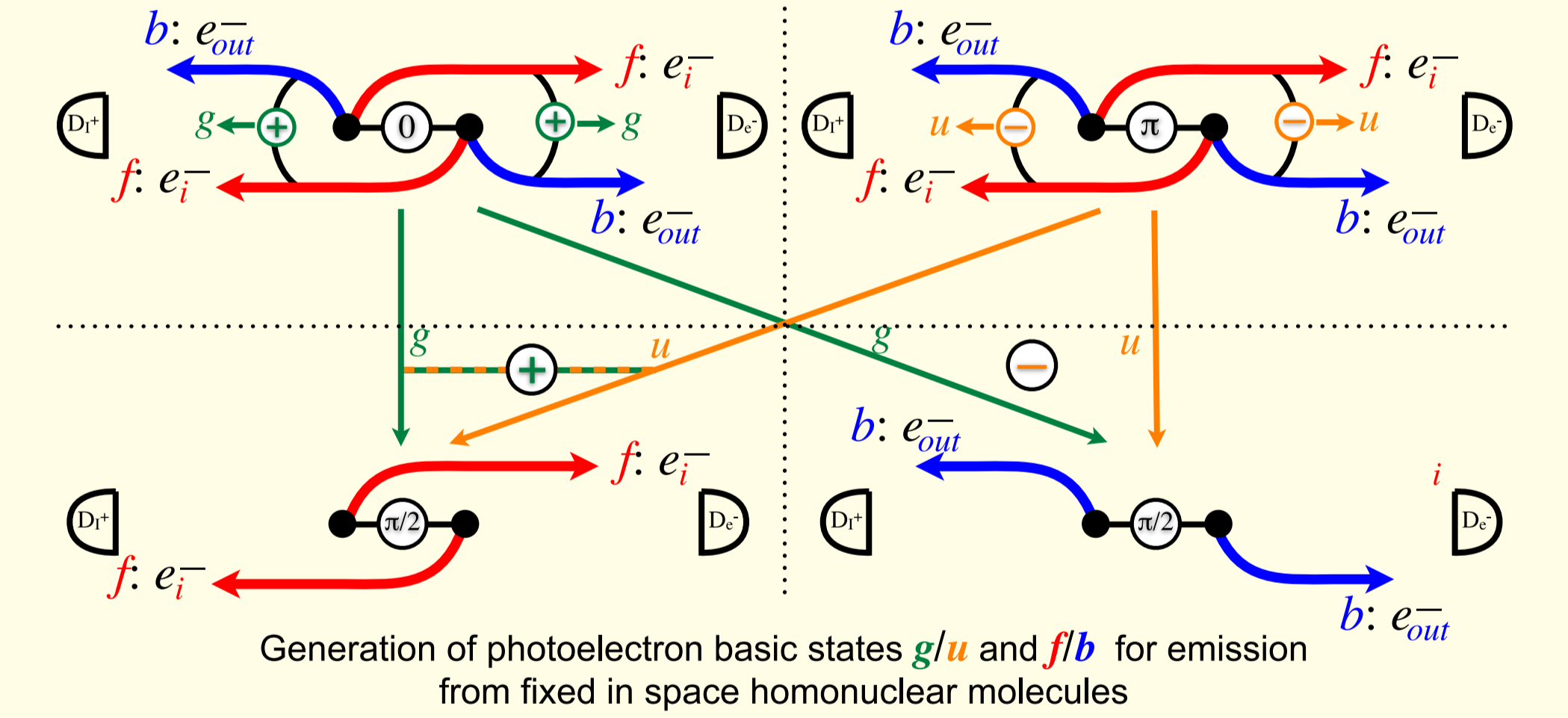Comparison between regular photoelectron and resonant Auger decay spectrum.

Measured coincident electron spectra

Measured resonant Auger spectra in dependence of the molecular axis

References:
[1] A. Einstein, B. Podolsky, N. Rosen, Phys. Rev. **47**, 777-780 (1935).
[2] T. Maudlin, *Quantum Non-Locality and Relativity: metaphysical intimations of modern physics.* (Oxford: Basil Blackwell, 1994).
[3] R. Tumulka, J. Statist. Phys. **125**, 825 (2006).
[4] H. Everett, *The Theory of the Universal Wave Function*, in *The Many-Worlds Interpretation of Quantum Mechanics* by B. S. DeWitt, R. N. Graham, eds, (Princeton Series in Physics, (Princeton University Press, 1973), pp 3-140.
[5] D. Albert and R. Galchen, Scient. Am. **300**, 32 (2009).
[6] Schöffler *et al.*, Science **320**, 920 (2008).

Which way information (D; distinguishability) vs. interference fringes (V; visibility)

Generation of photoelectron basic states g/u and f/b for emission from fixed in space homonuclear molecules

The emitter site polarization $(b-f)/(b+f)$, respectively, in dependence of the molecular axis direction. In the resonant Auger case this corresponds to the ion detection angle.

Two-fold double slit experiment: The molecular version of EPR's idea to prove the completeness of QM

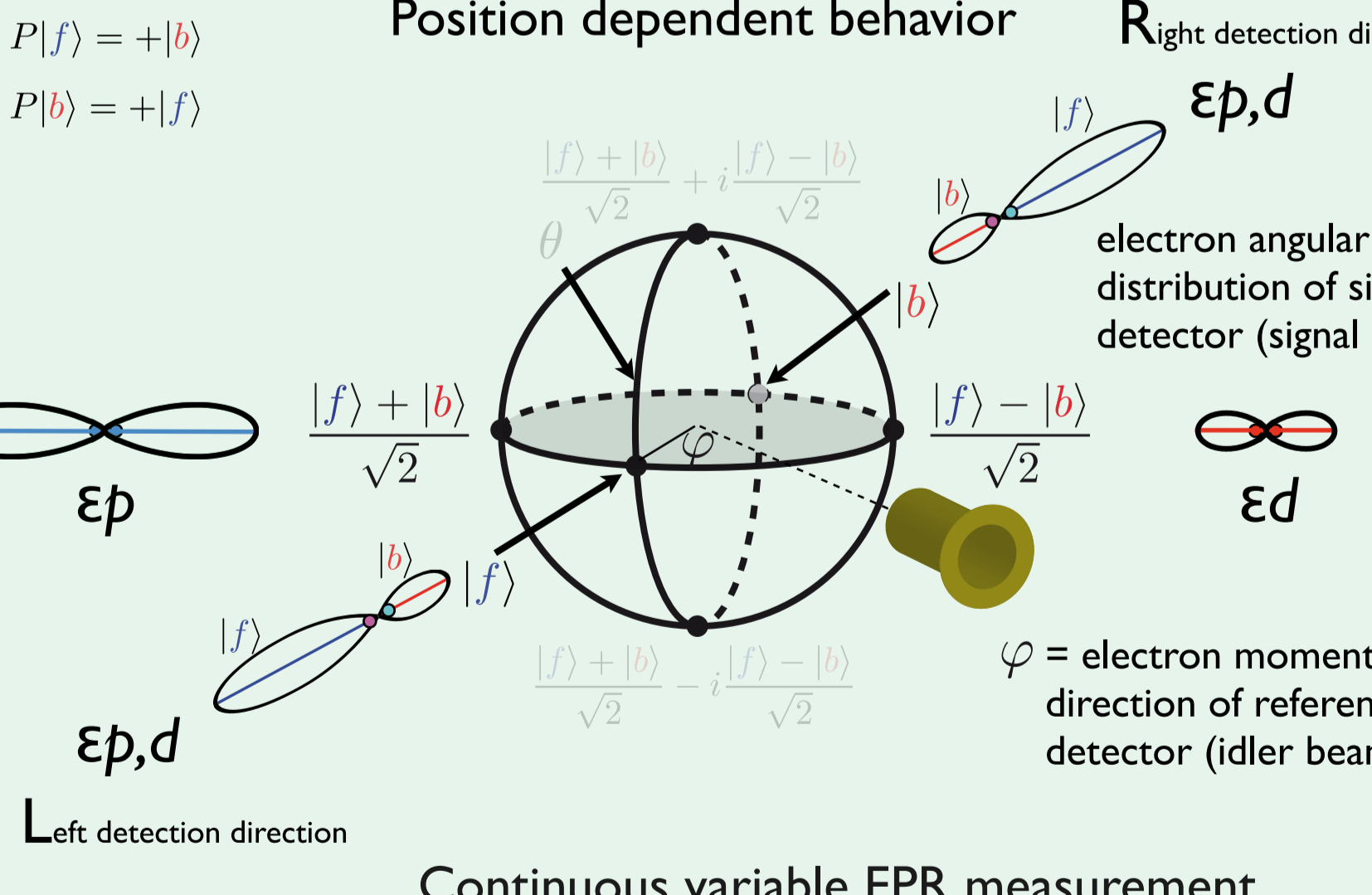Photo and Auger-electron emission in coincidence
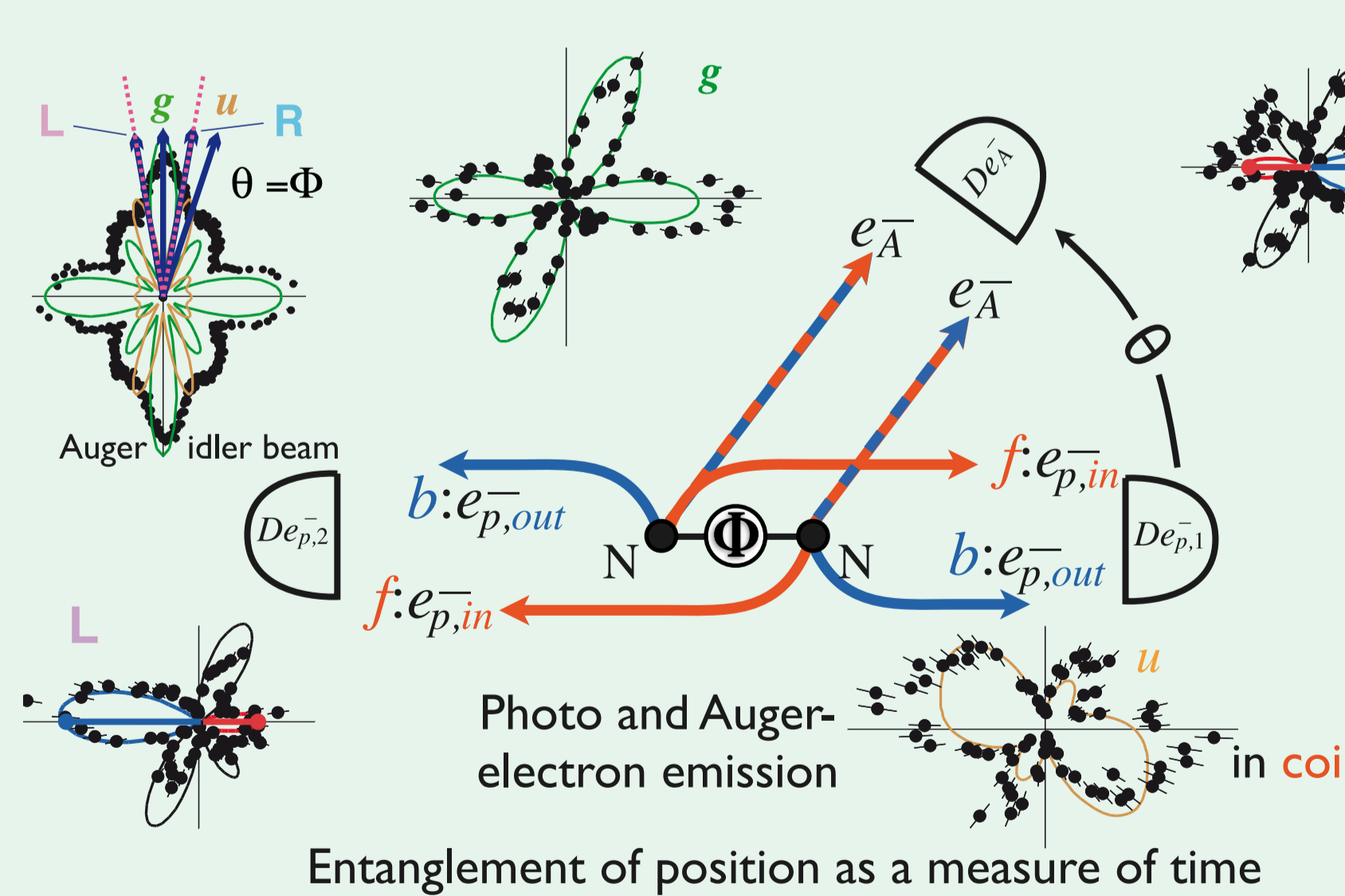
Entanglement of position as a measure of time

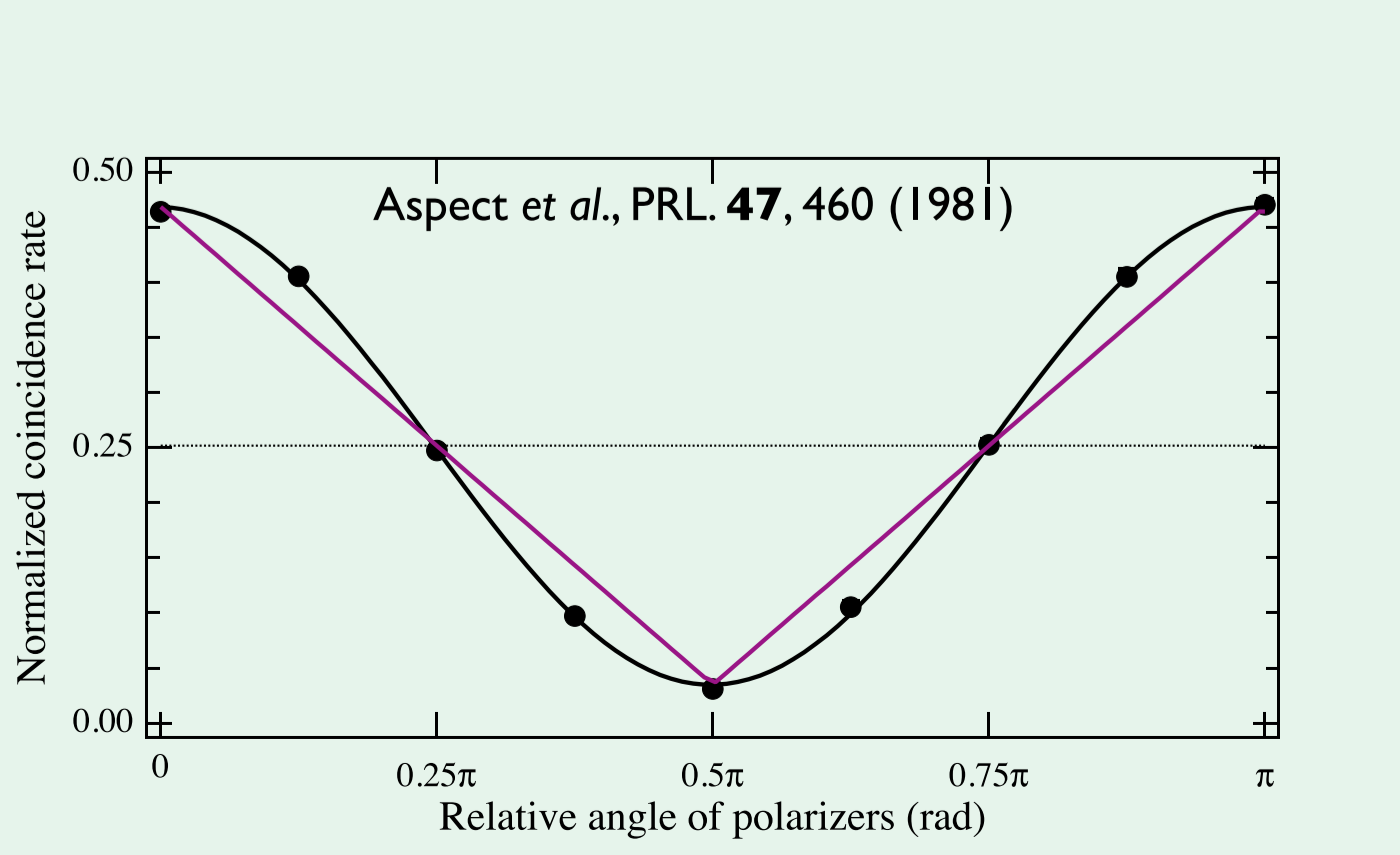Poincaré sphere of energy and its Fourier integral time
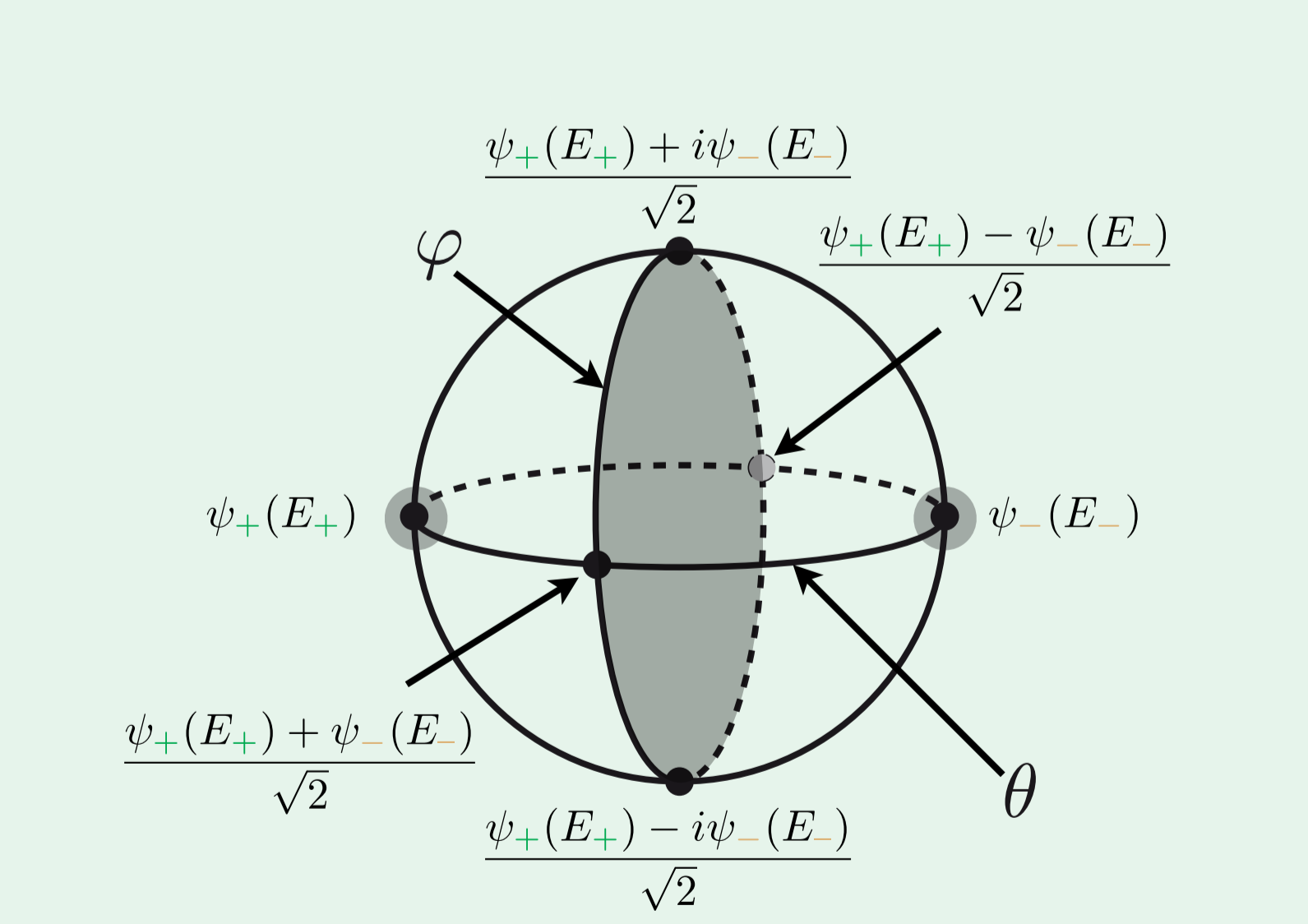
Position based EPR experiment described in momentum space on the f/b-Poincaré sphere
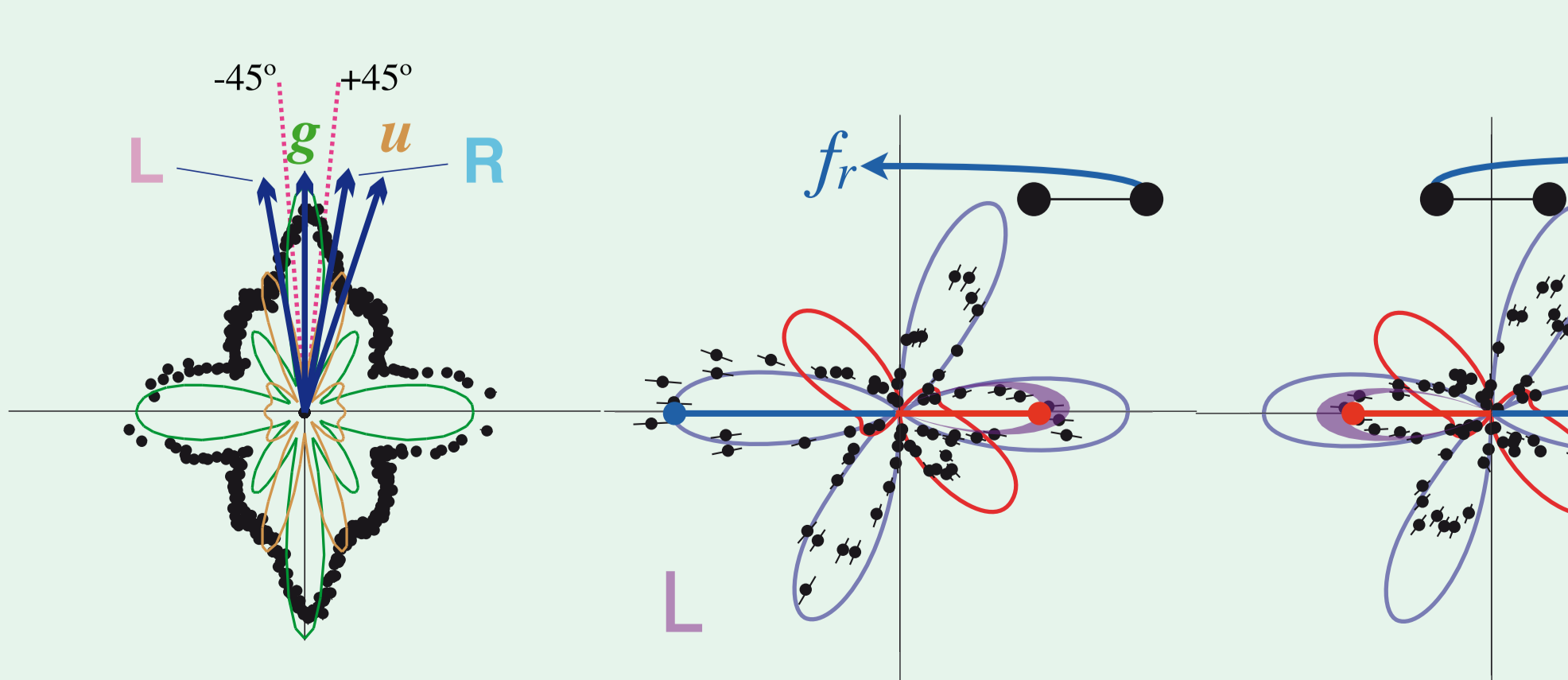
Continuous variable EPR measurement

Polarization correlations in spin space revealed by photon-photon coincidence measurements

Auger electron-Photoelectron coincidences: Evidence for a violation of Bell's inequality.

Polarization correlations in momentum space revealed by electron-electron coincidence measurements: