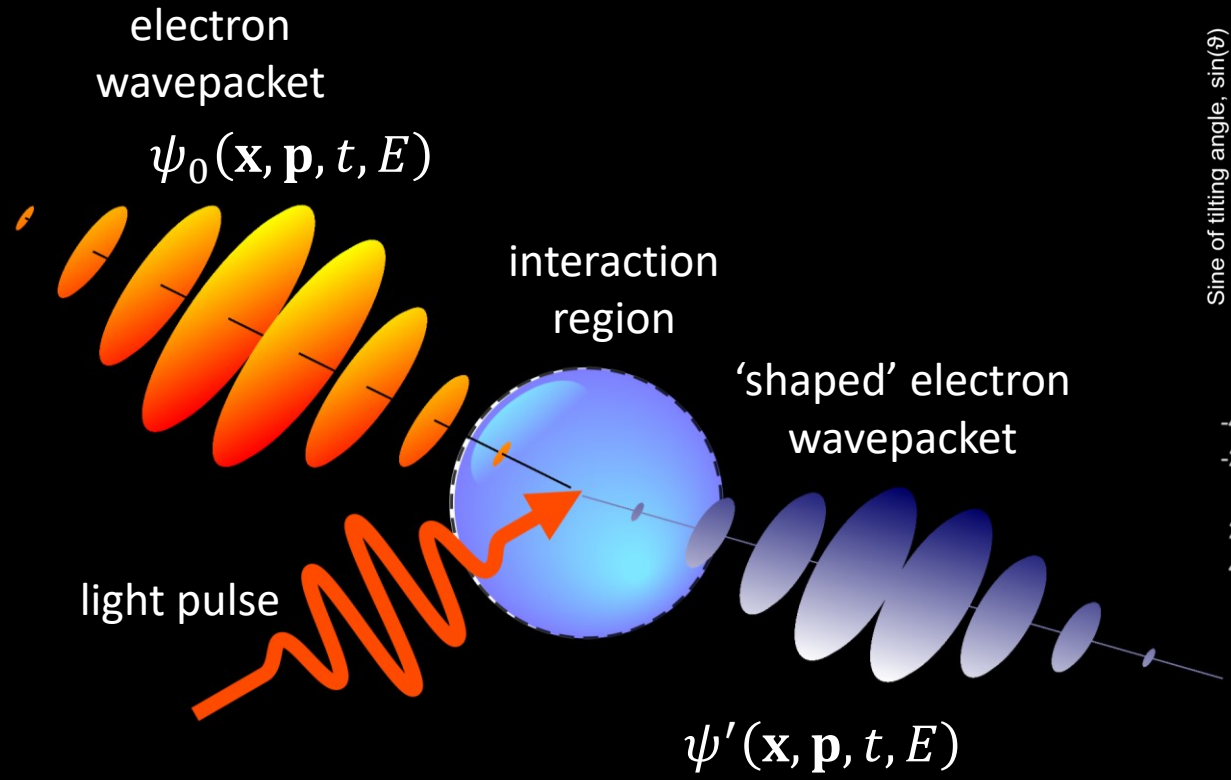
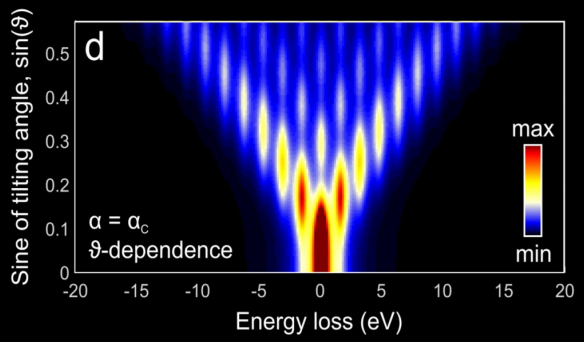
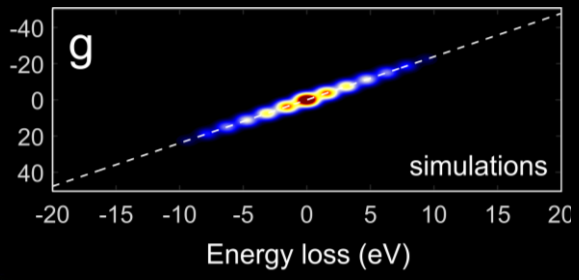
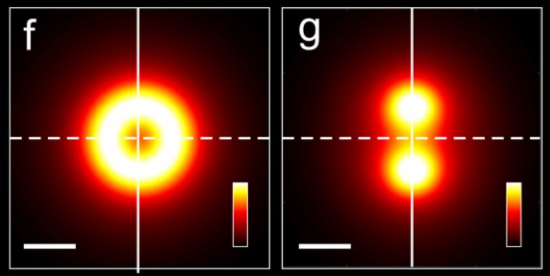
Ultrafast coherent manipulation of a free-electron wave function *via* electron-light quantum interaction









Giovanni Maria Vanacore

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Laboratory of Ultrafast Microscopy for Nanoscale Dynamics (LUMiNaD),
Department of Materials Science,
University of Milano-Bicocca (Italy)

Ultrafast coherent manipulation of a free-electron wave function *via* electron-light quantum interaction

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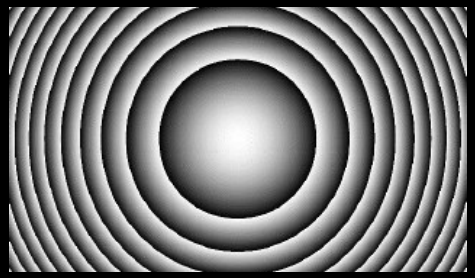
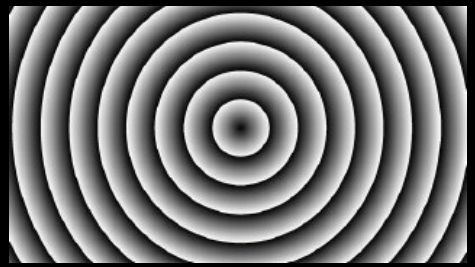
University of Milano-Bicocca, Italy

A recent revolution in light optics

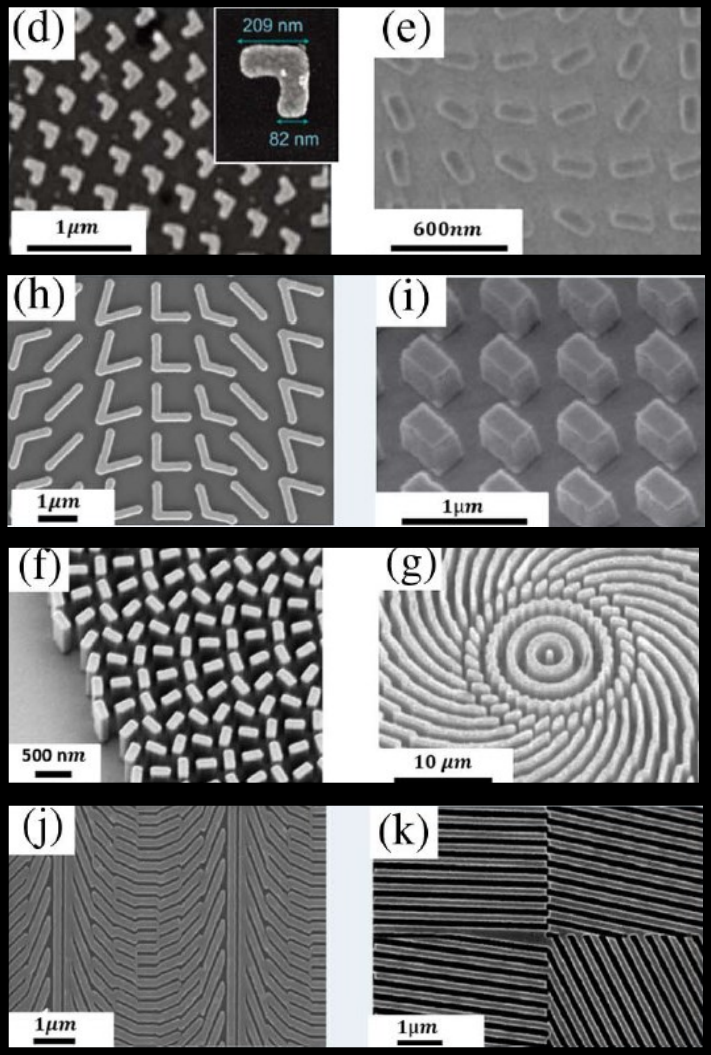
Traditional optics
(glass elements)

Digital optics
(Spatial Light Modulators)



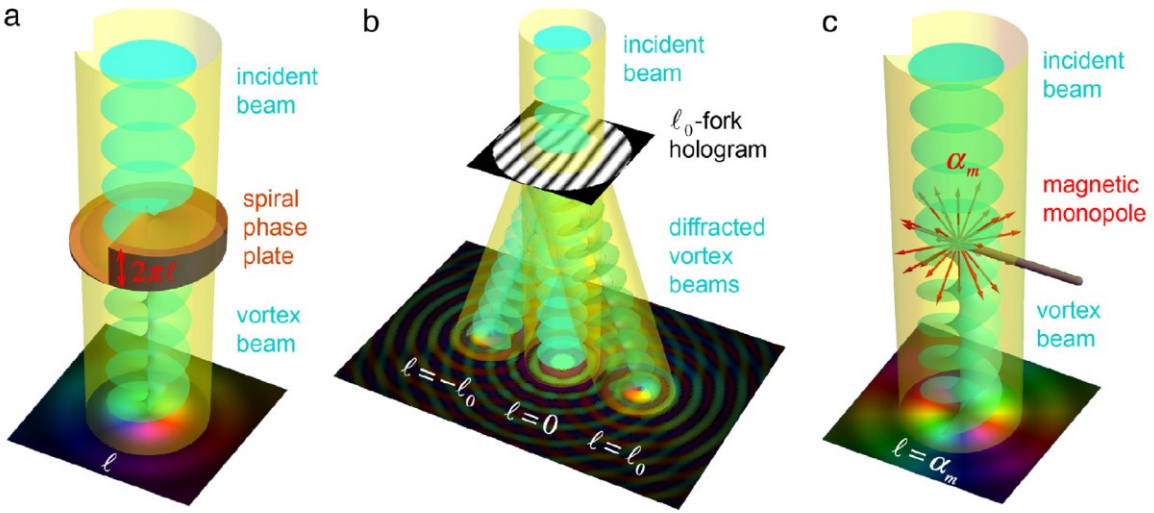


Meta-Optics



P. Genevet et al., Optica **4**, 139 (2017)

State-of-the-art in electron beam shaping



K.Y. Bliokh et al. Physics Reports **690**, 1–70 (2017)

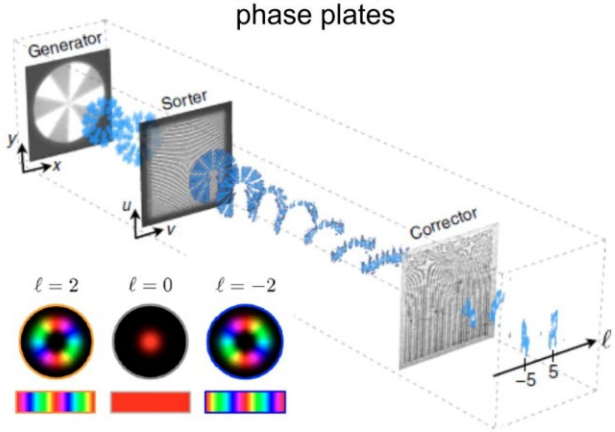
See also:

Bliokh et al., *Phys. Rev. Lett.* **99**, 190404 (2007).

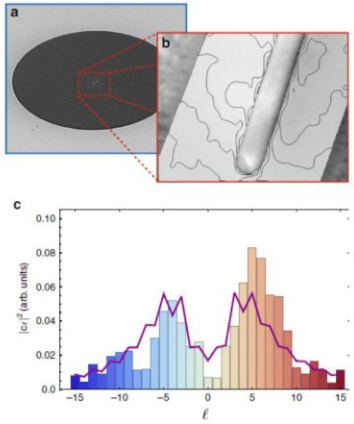
Verbeeck et al., *Nature* **467**, 301-304 (2010).

McMorran et al., *Science* **331**, 192-194 (2011).

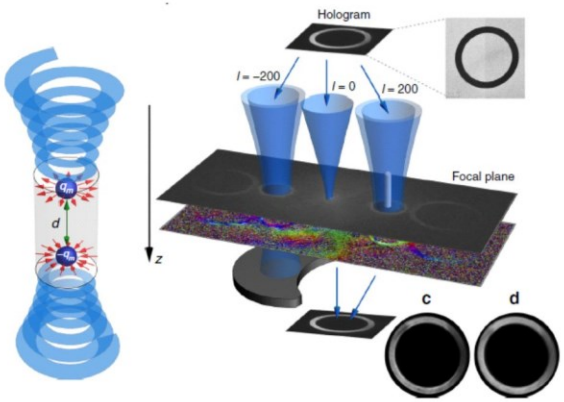
OAM sorting via nano-patterned phase plates



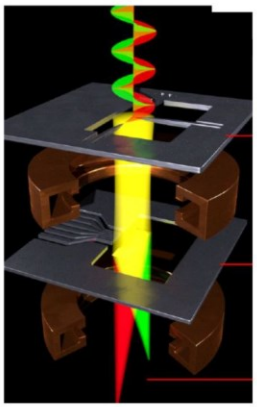
Magnetic transverse interaction



Magnetic longitudinal interaction



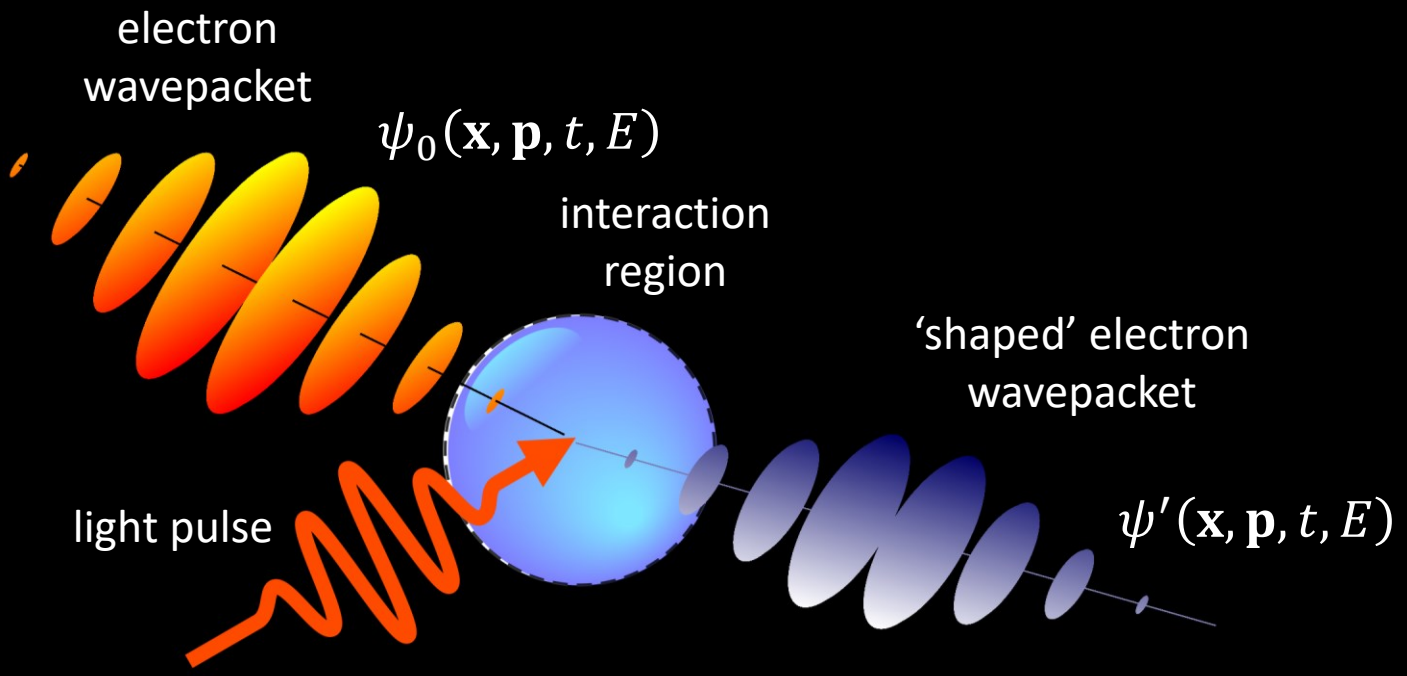
Magnetic OAM sorter



V. Grillo et al., Nature Commun. **8**, 15536 (2017);
A. H. Tavabi, […], V. Grillo, Phys. Rev. Lett. **126**, 094802 (2021)

Light-mediated electron modulation

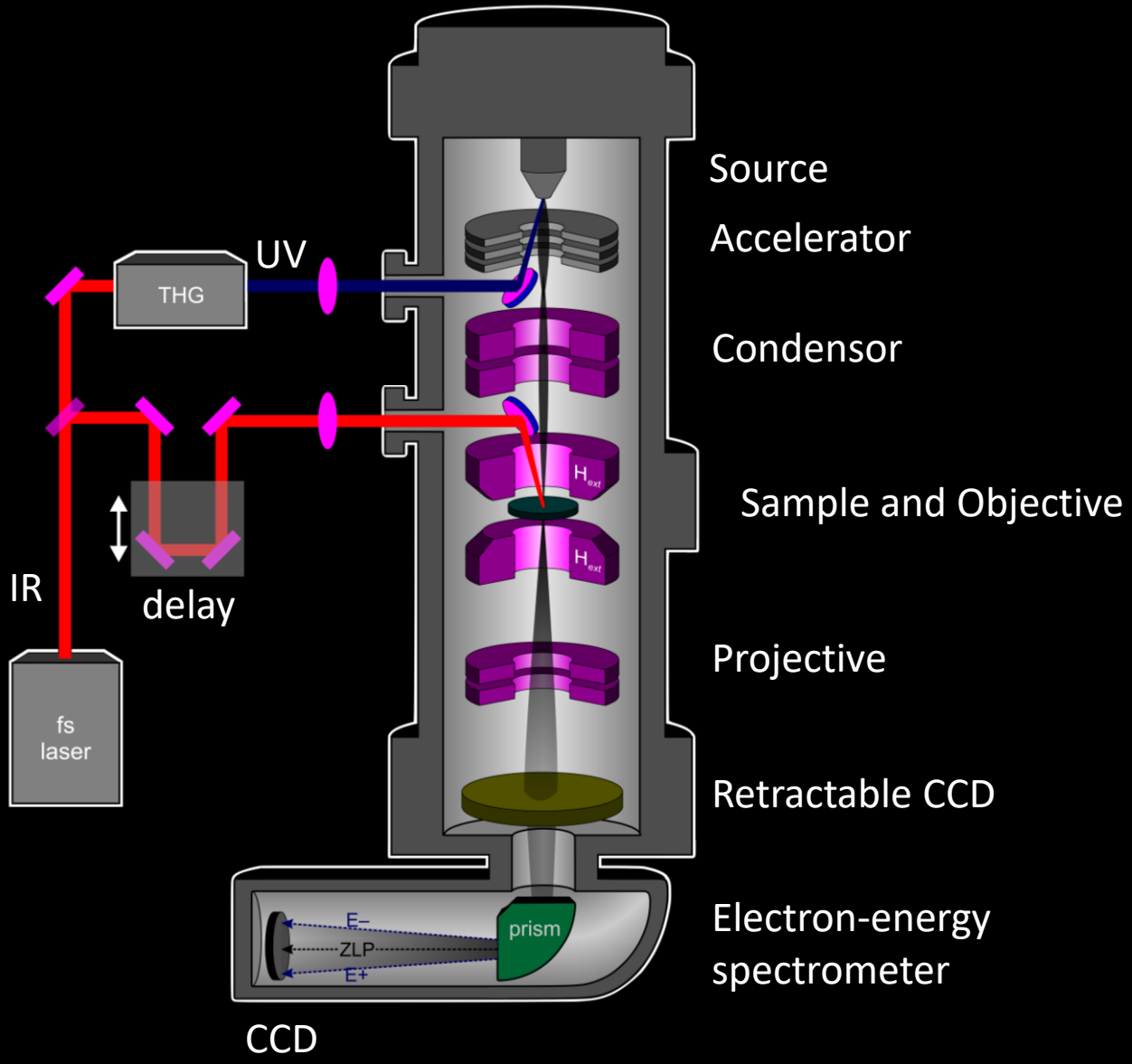
The vision behind the SMART-electron project relies on a light-mediated coherent modulation of the longitudinal and transverse phase of an electron wave function, exploiting the strong interaction between free electrons and optical fields in illuminated nanostructures.



$$\beta(x,y) = \frac{e}{\hbar\omega} \int_{-\infty}^{+\infty} E_z(x,y) e^{\left(-i\frac{\omega z}{v}\right)} dz$$

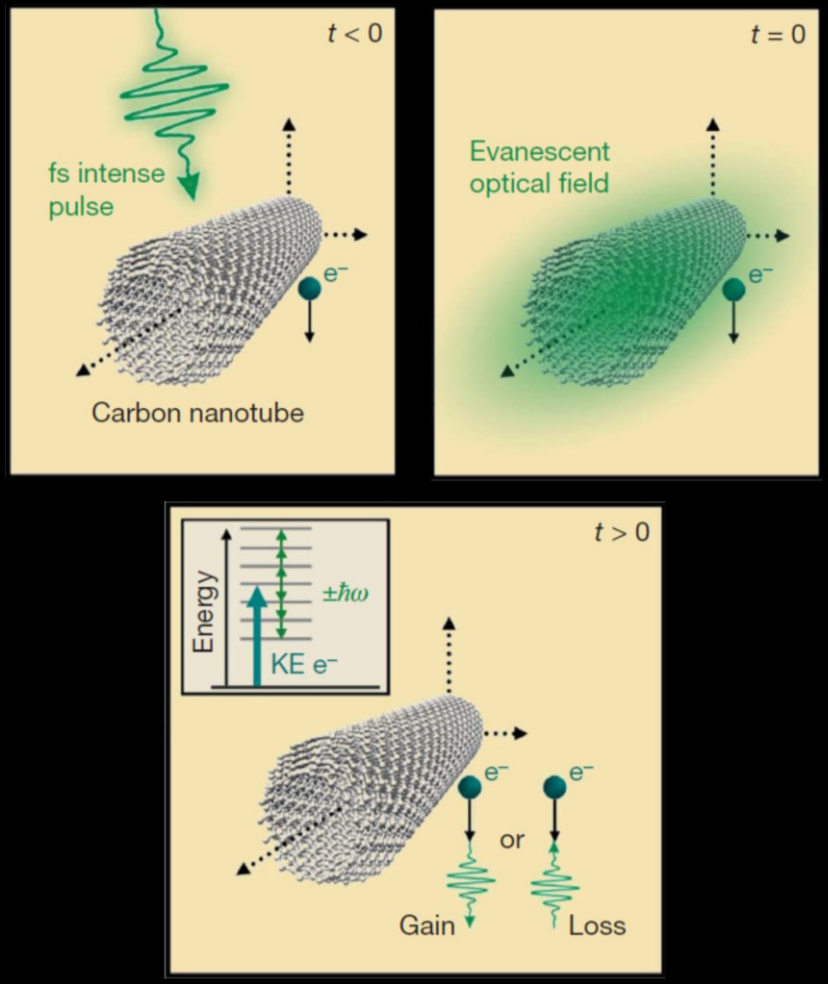
$$\psi_\ell(x,y,t) = \psi_0 \cdot \mathrm{J}_\ell(2|\beta|) e^{\left(i\ell \arg\{-\beta\} + i\ell\omega\left(\frac{z}{v} - t\right)\right)}$$

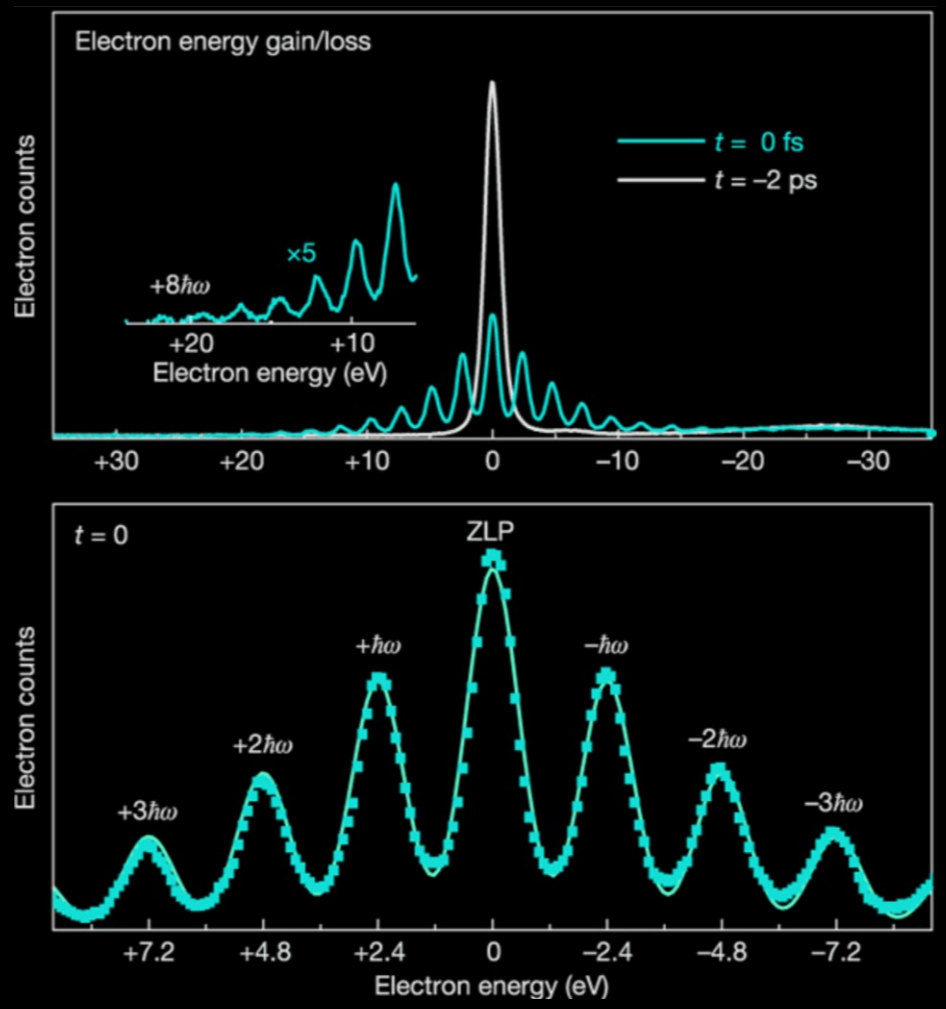
Ultrafast Electron Microscopy (UEM)



Vanacore, Fitzpatripck and Zewail, *Nano Today* **11**, 228-249 (2016)

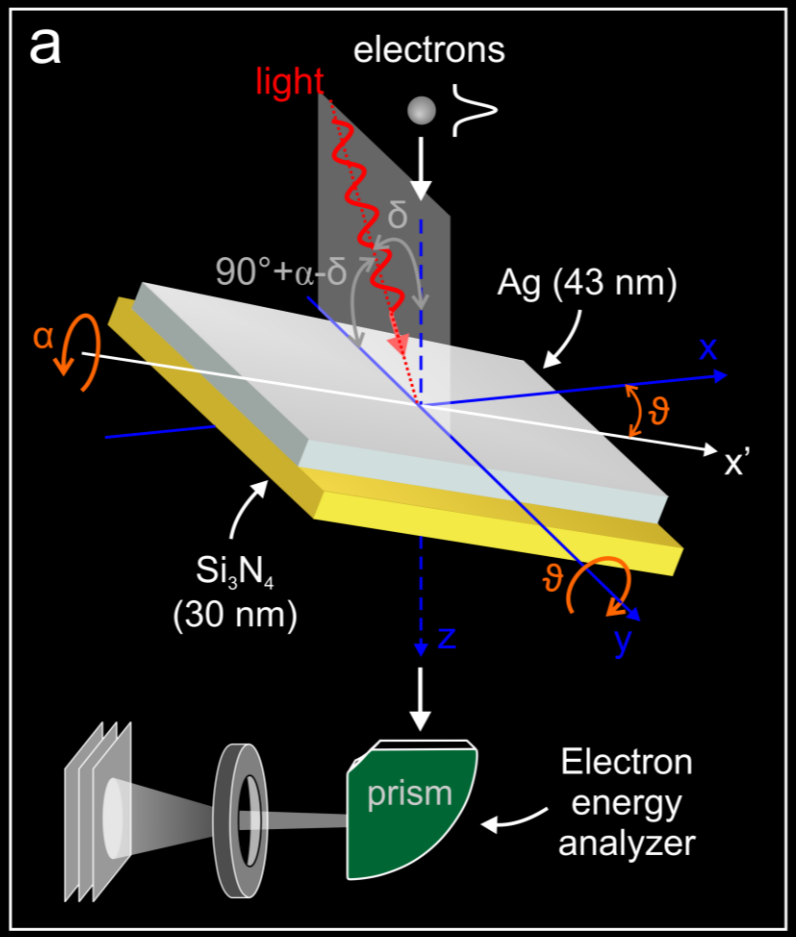
Photon-Induced Near-Field EM (PINEM)

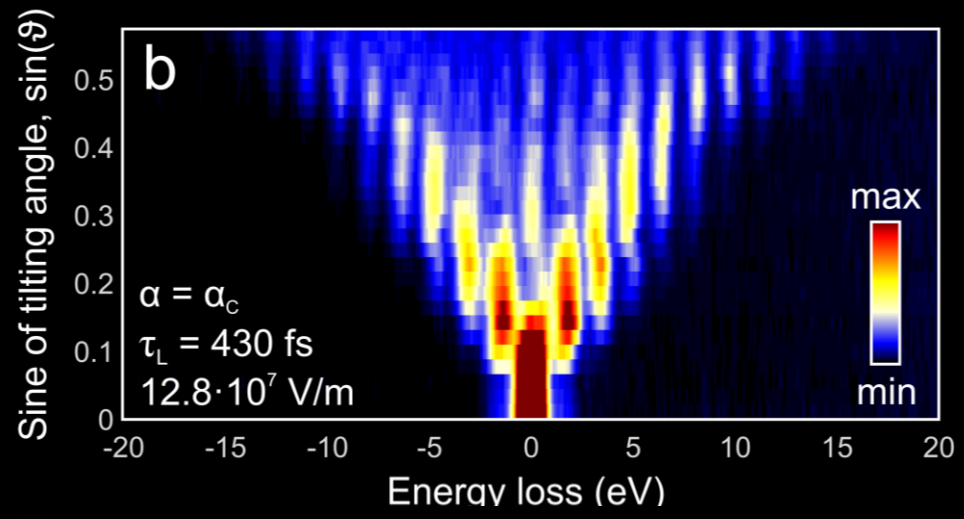


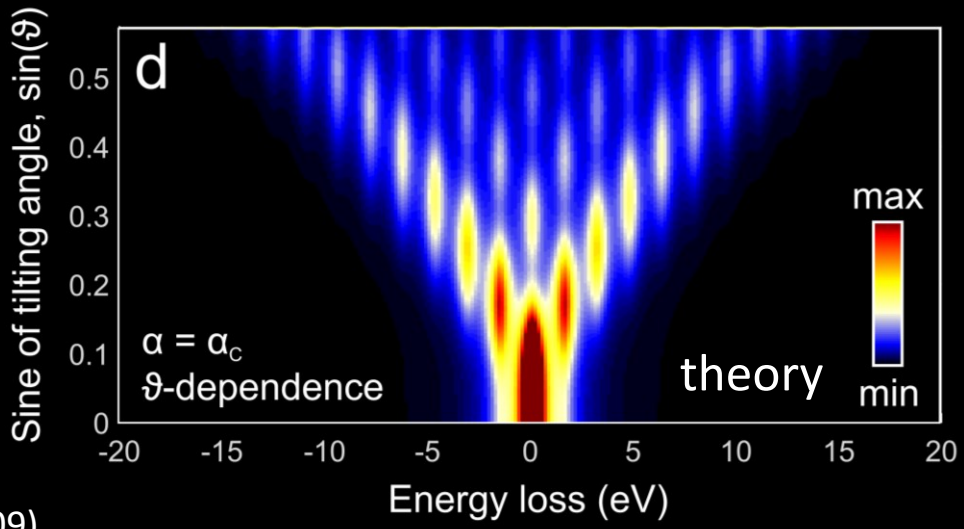


Barwick, Flannigan, and Zewail, *Nature* **462**, 902-906 (2009)

Energy-Momentum quantized exchange



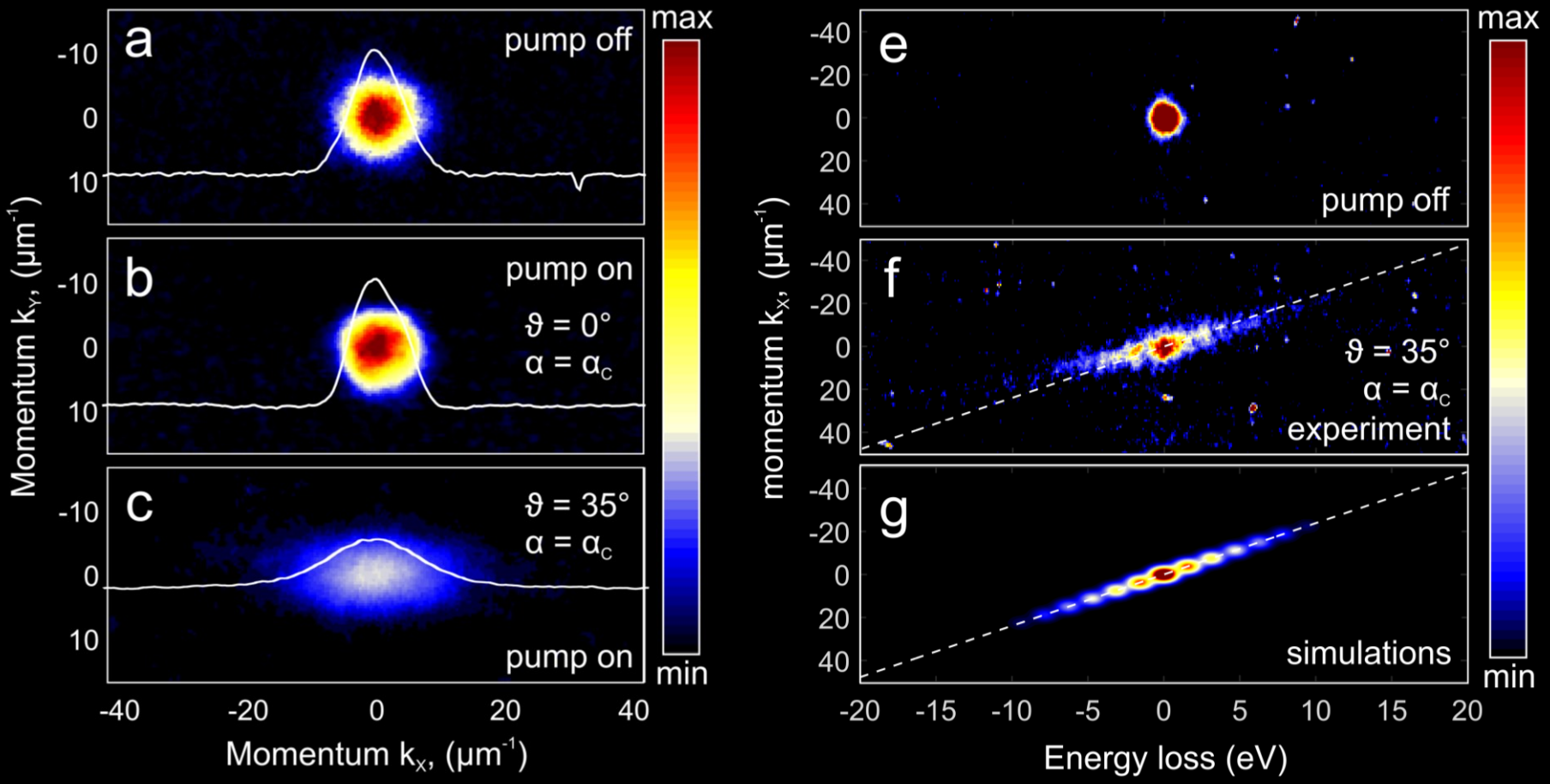




See also:
Barwick et al., Nature 462, 902-906 (2009)
Feist et al., Nature 521, 200–203 (2015)
Morimoto and Baum, Phys. Rev. A 97, 033815 (2018).

G. M. Vanacore, […], I. Kaminer, […], F. J. García de Abajo, F. Carbone, *Nature Commun.* **9**, 2694 (2018)

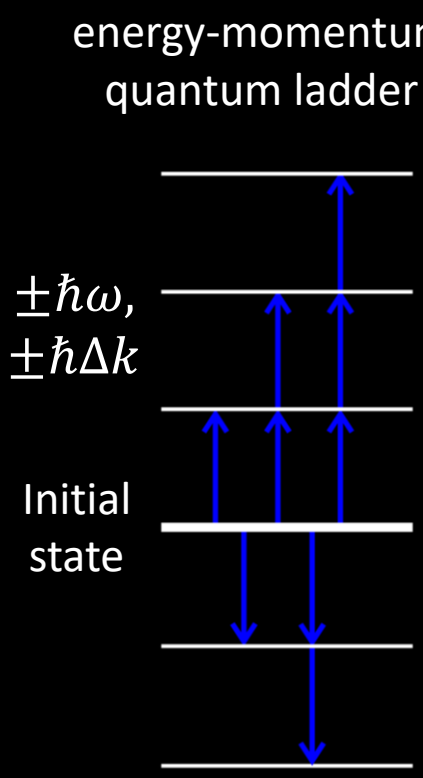
Energy-Momentum quantized exchange

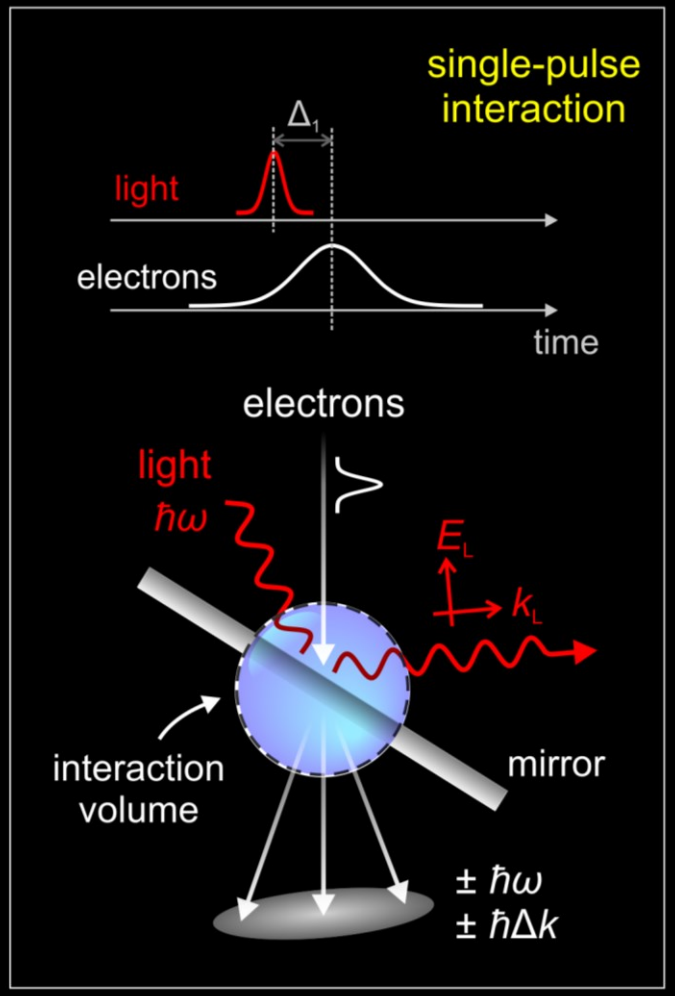


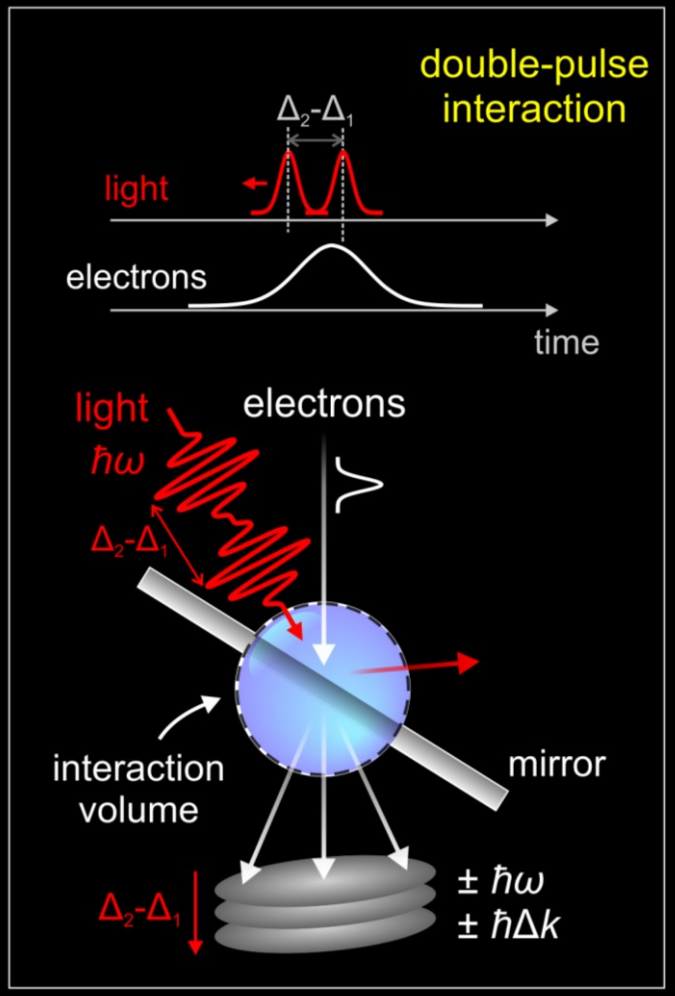
See also: Feist et al., Nature Phys. Rev. Research 2, 043227 (2020)

G. M. Vanacore, [...], I. Kaminer, [...], F. J. García de Abajo, F. Carbone, *Nature Commun.* **9**, 2694 (2018)

“Quantum” interference



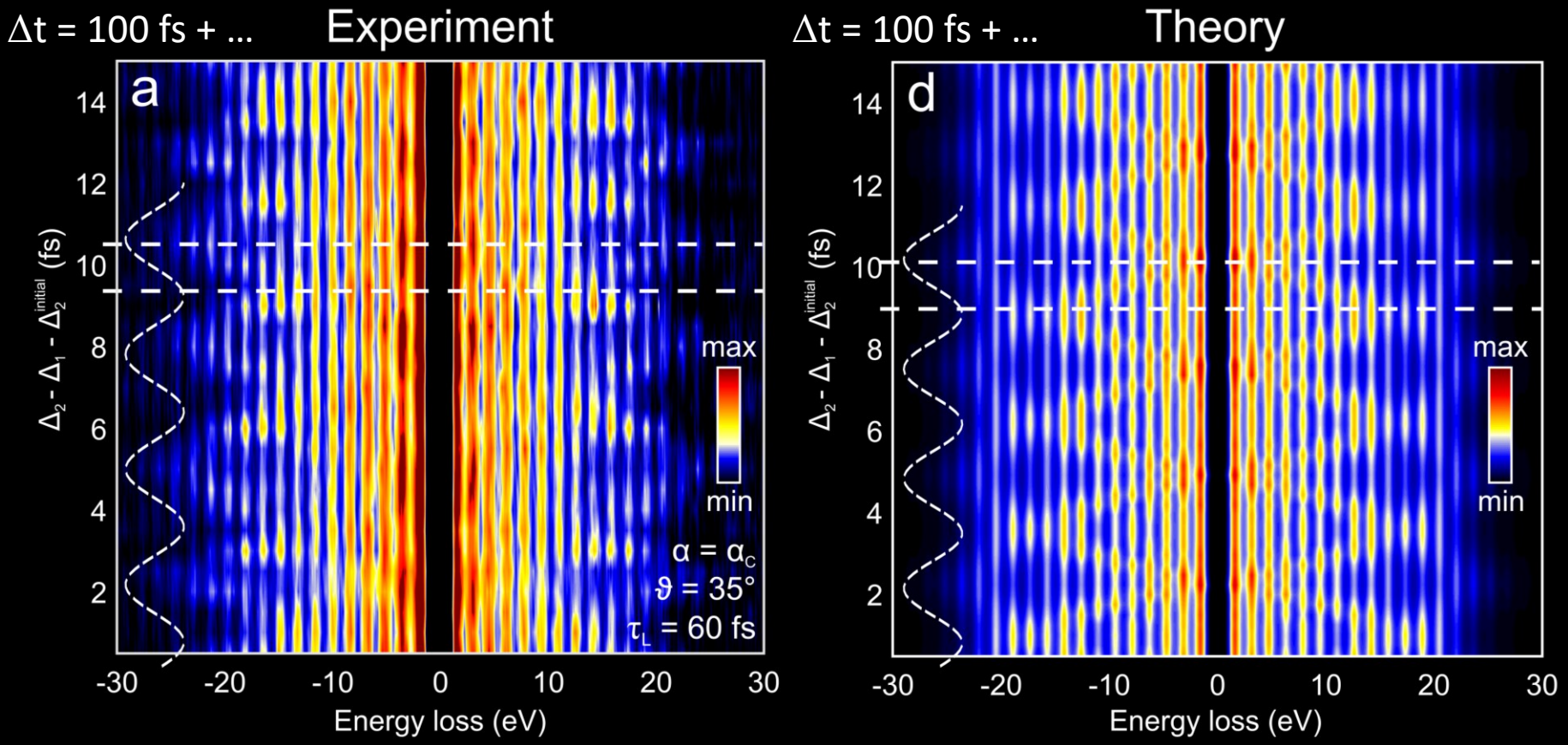




$\Delta t = \Delta_2 - \Delta_1 > 100$ fs

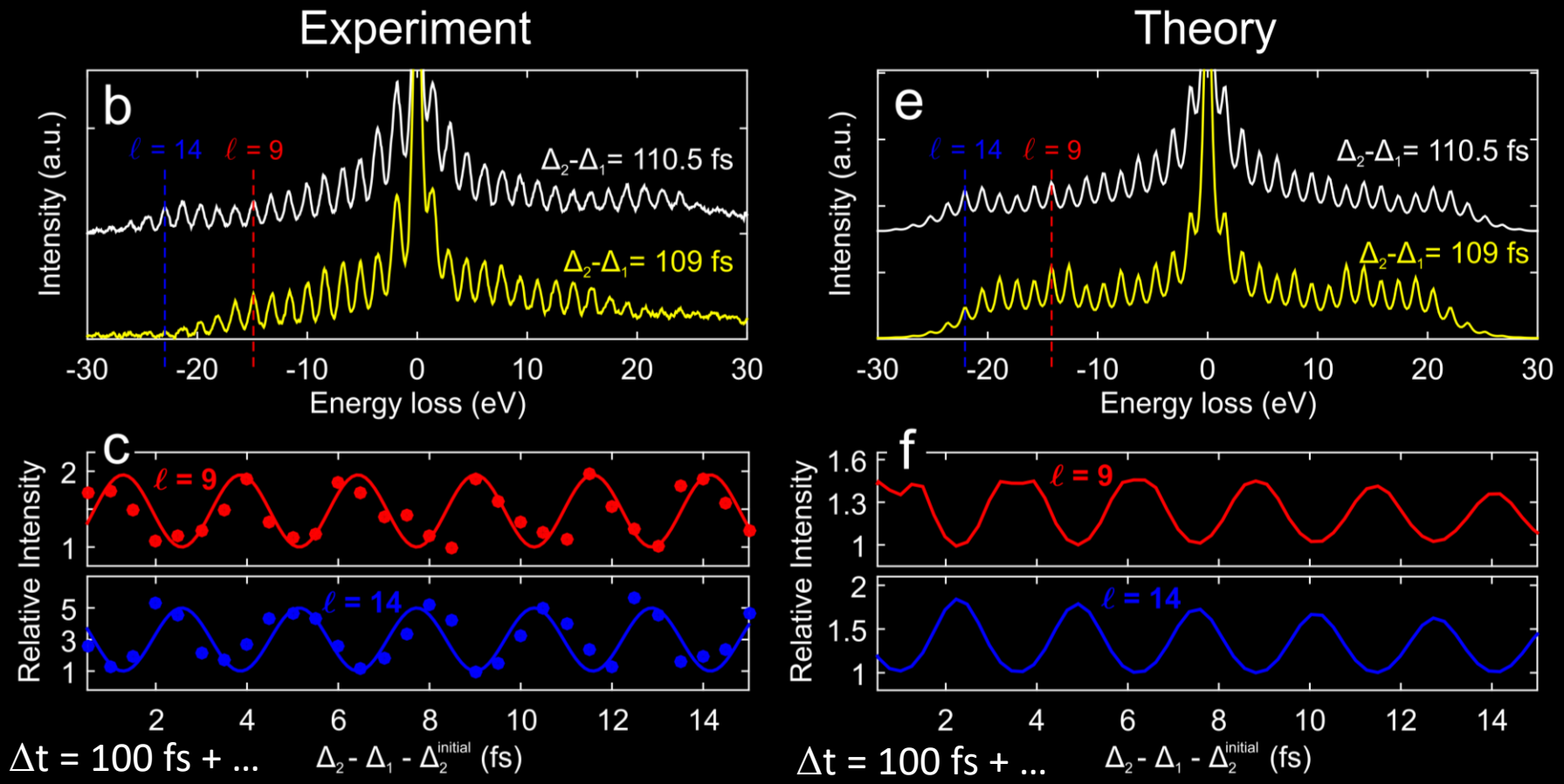
G. M. Vanacore, […], I. Kaminer, […], F. J. García de Abajo, F. Carbone, *Nature Commun.* **9**, 2694 (2018)

Attosecond coherent control



G. M. Vanacore, […], I. Kaminer, […], F. J. García de Abajo, F. Carbone, *Nature Commun.* **9**, 2694 (2018)

Attosecond coherent control



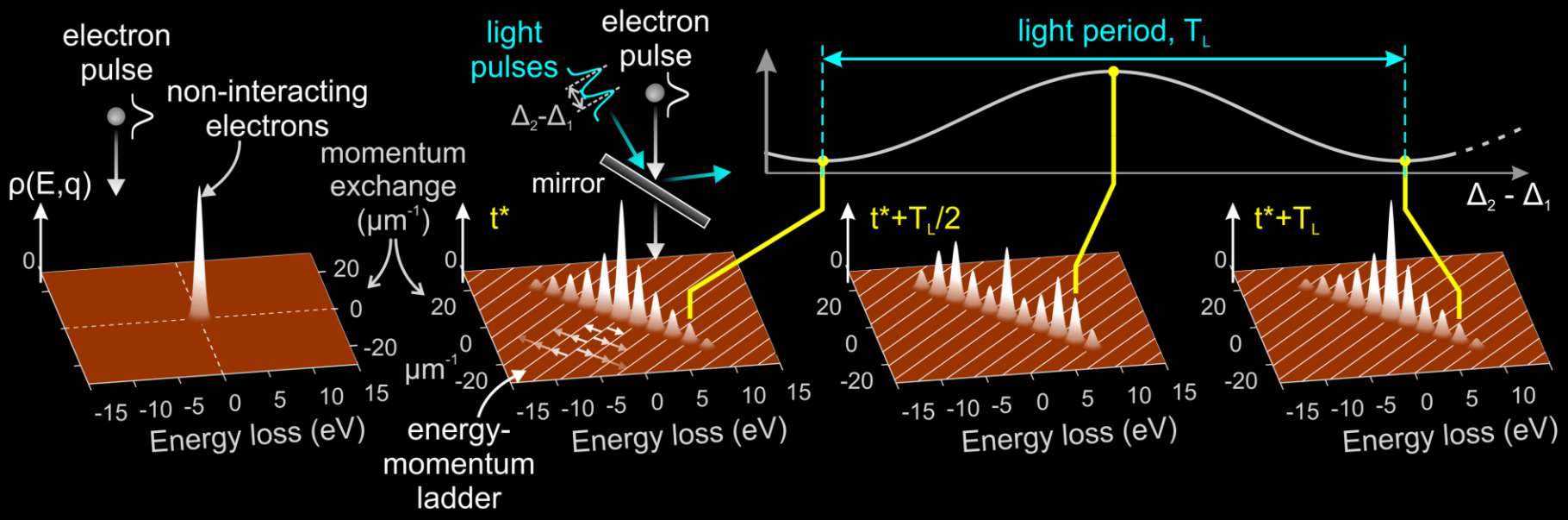
Priebe et al., Nat. Photon. 11, 793–797 (2017)

See also: Morimoto and Baum, Nat. Phys. 14, 252-256 (2018)

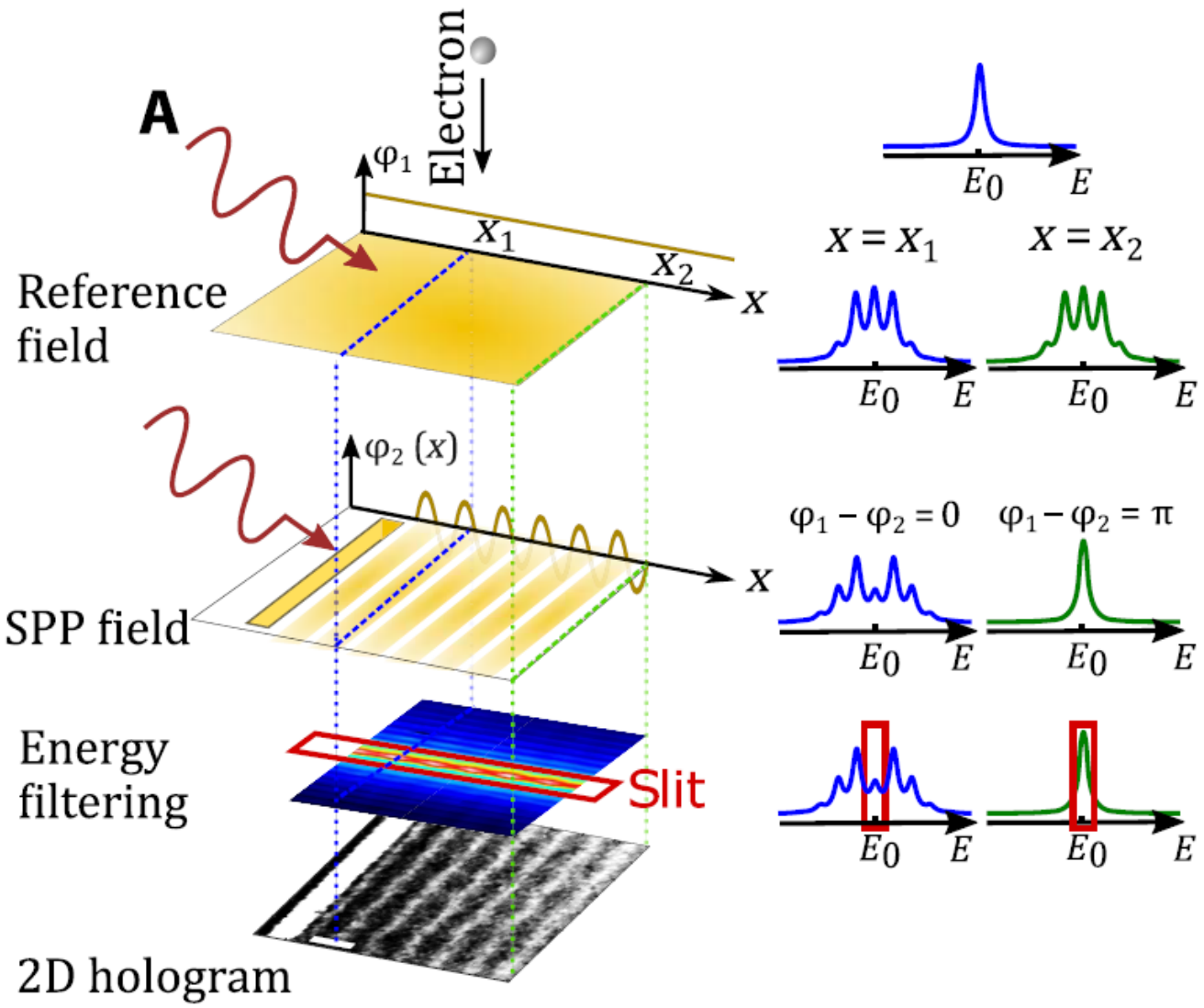
Schönenberger et al., Phys. Rev. Lett. 123, 264803 (2019)

G. M. Vanacore, […], I. Kaminer, […], F. J. García de Abajo, F. Carbone, *Nature Commun.* **9**, 2694 (2018)

Attosecond coherent control



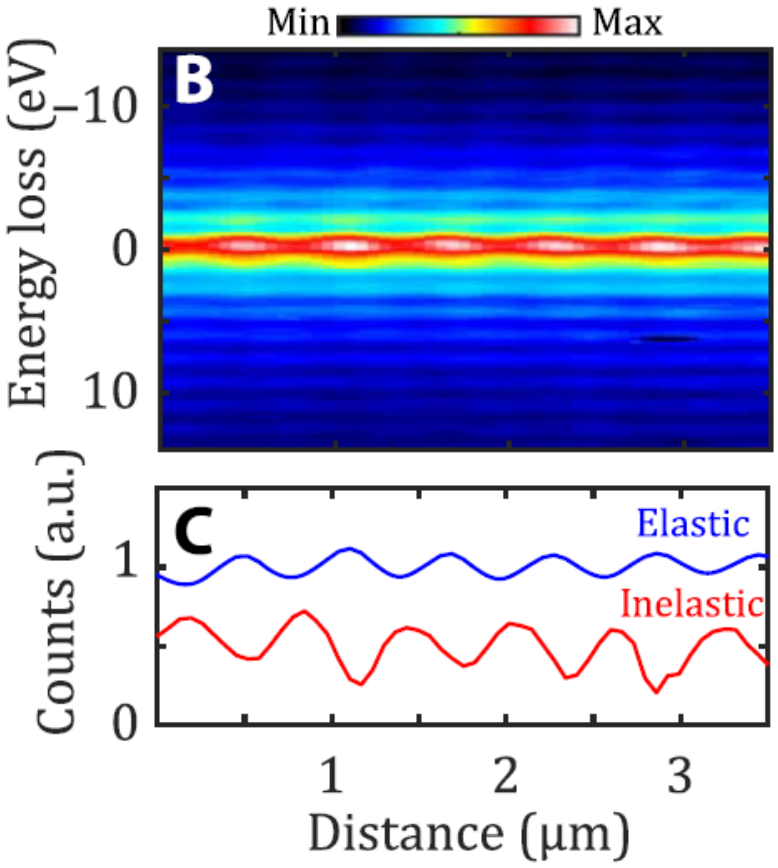
Ramsey-like electron holography (I)

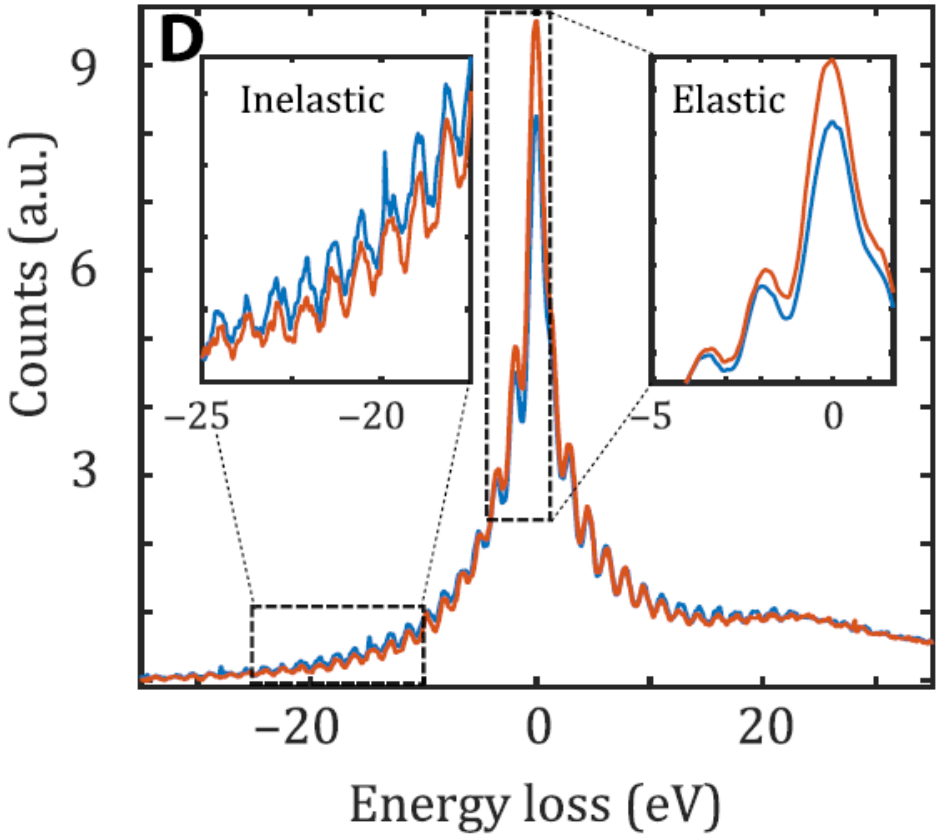


- Homogeneous optical laser field is the *Reference Field* ($\phi \sim \omega t$)
- Nanocavities in Ag layer are sources of propagating SPPs ($\phi \sim \omega t \pm kx$)

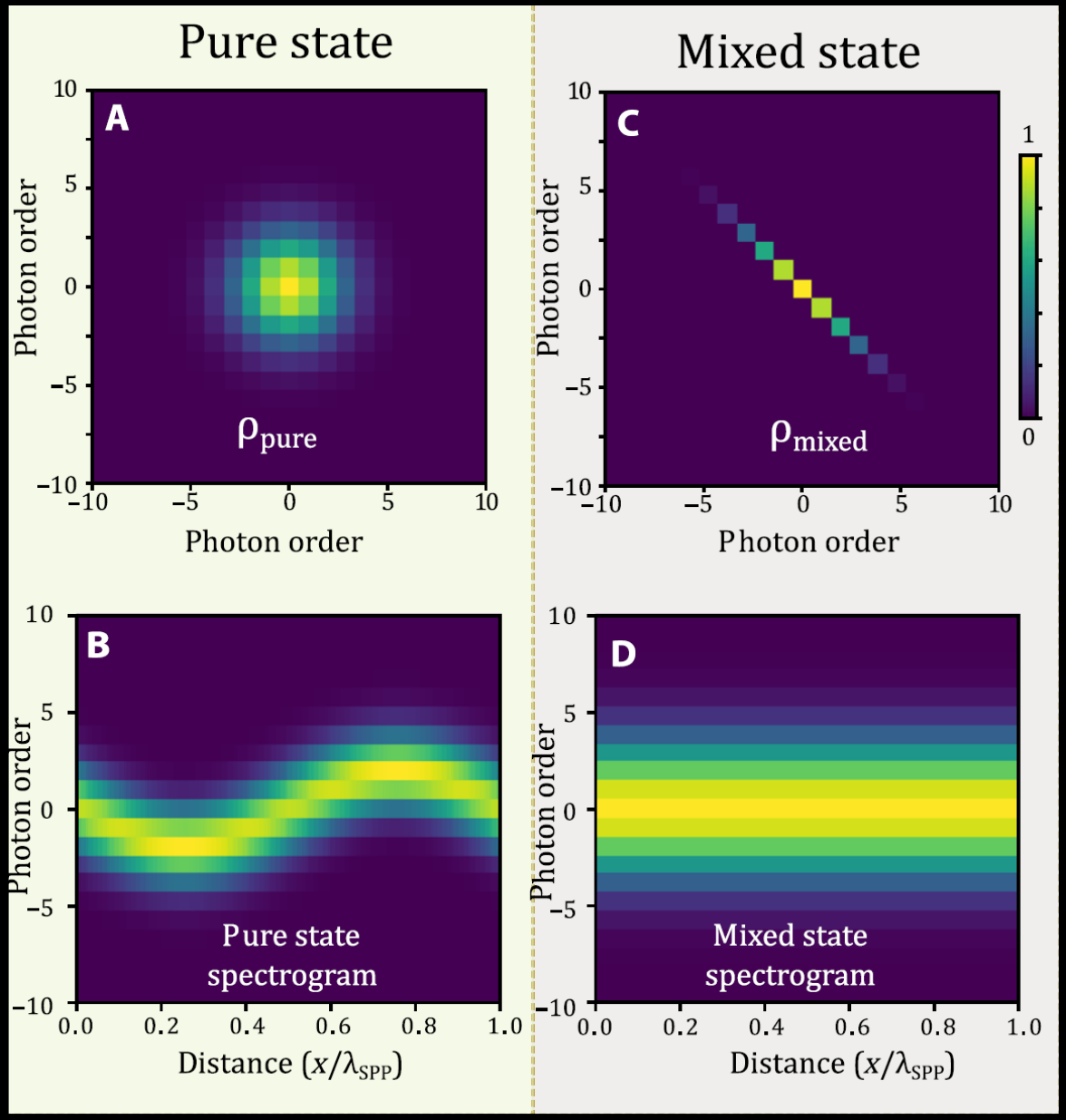
I. Madan*, G. M. Vanacore* et al., *Science Advances* **5,** eaav8358 (2019)

Ramsey-like electron holography (II)

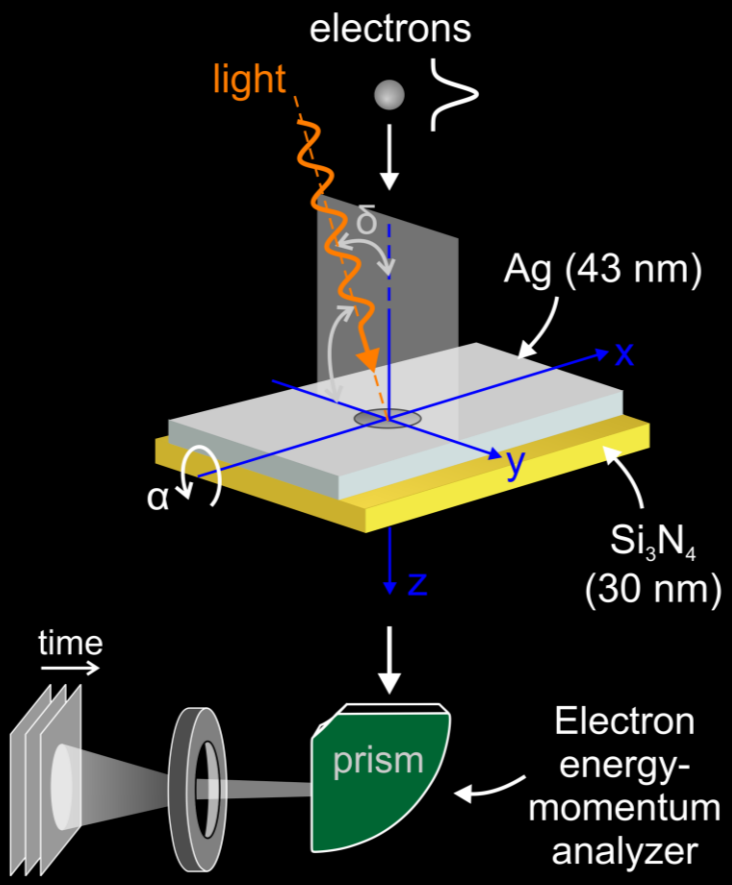


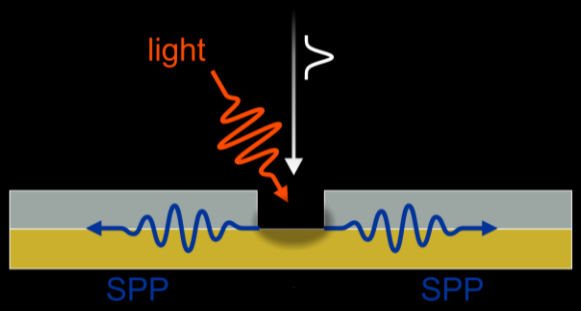


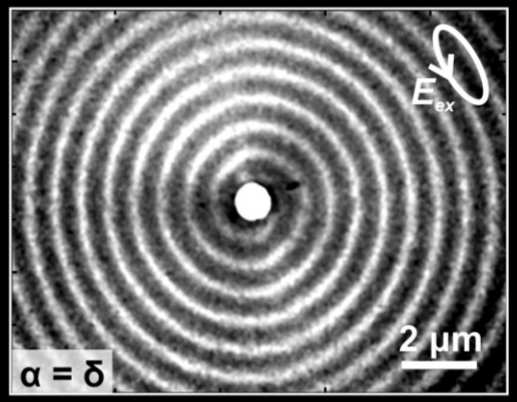
Electron coherence determination

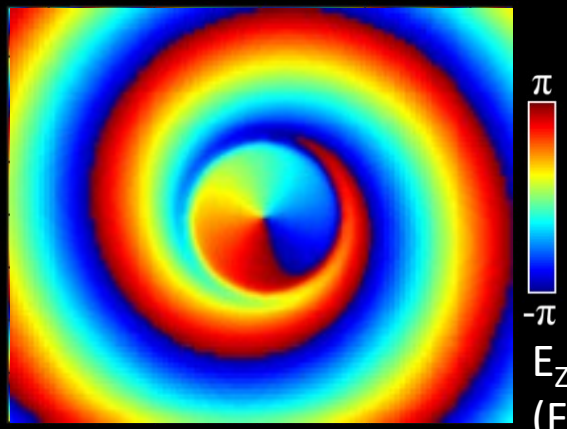


Transverse modulation *via* chiral SPPs





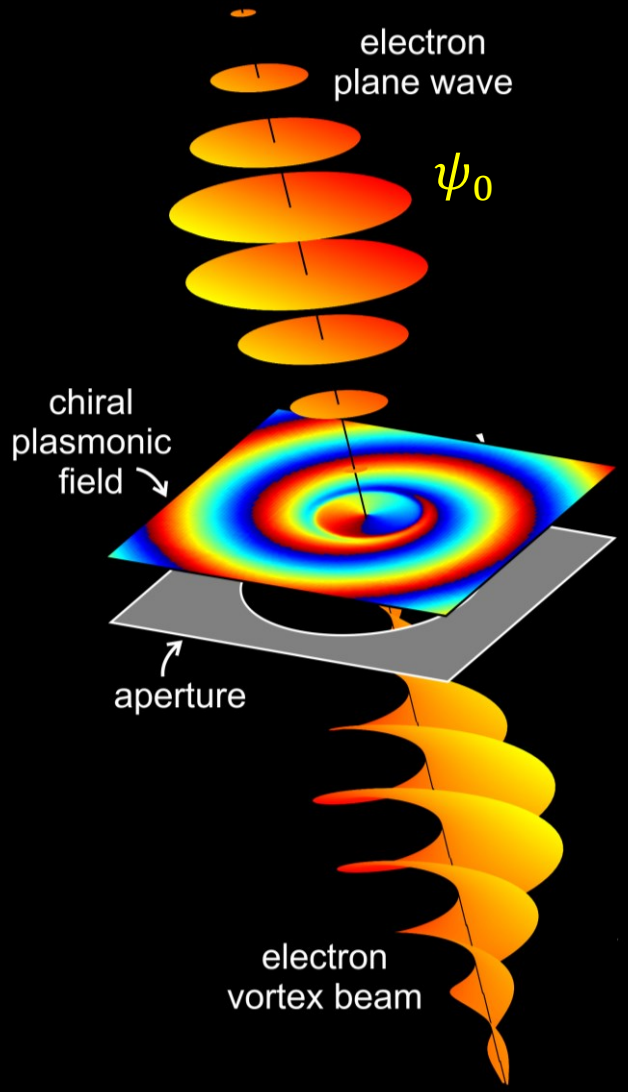




E_Z phase (FDTD)

G. M. Vanacore, […], I. Kaminer, […], V. Grillo. […], F J. García de Abajo, F. Carbone
Nature Materials **18,** 573-579 (2019)

OAM transfer and Vortex electron beam



Inelastically scattered wave function components:

$$\psi_\ell = \psi_0 \cdot \mathrm{J}_\ell(2|\beta|)\exp(i\ell\arg\{-\beta\})$$

Chiral plasmonic field:

$$\beta \propto \exp(im\phi)\frac{\exp(ik_{SPP}R)}{\sqrt{k_{SPP}R}}$$

And therefore:

$$\psi_\ell \propto \psi_0 \exp(i\ell m\phi)$$

Which carries an OAM:

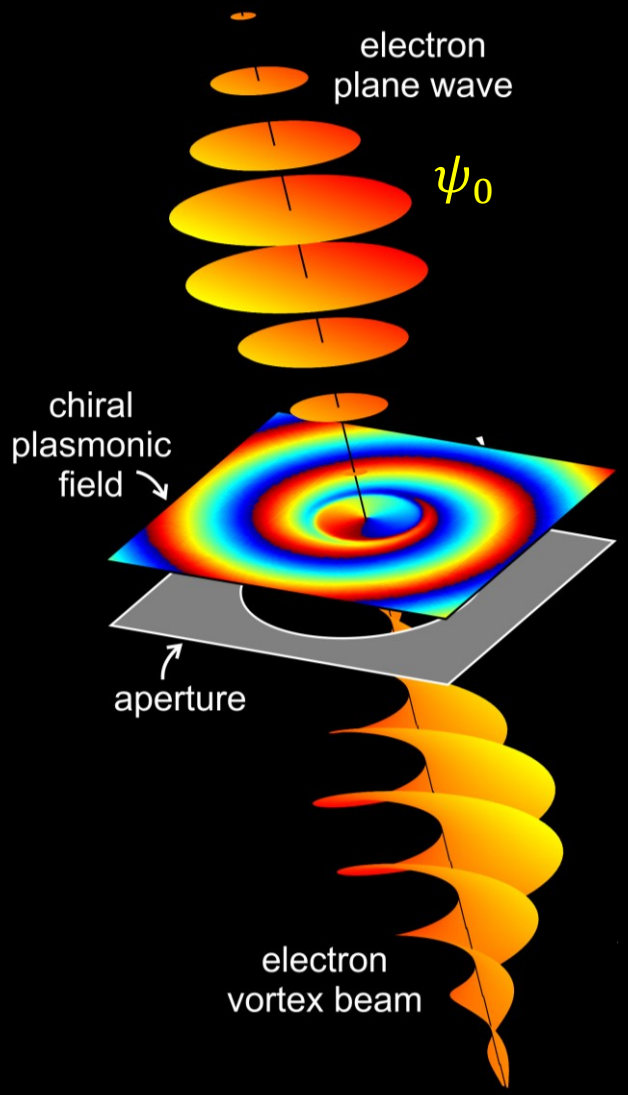
$$\langle L_z \rangle = \ell m\hbar$$

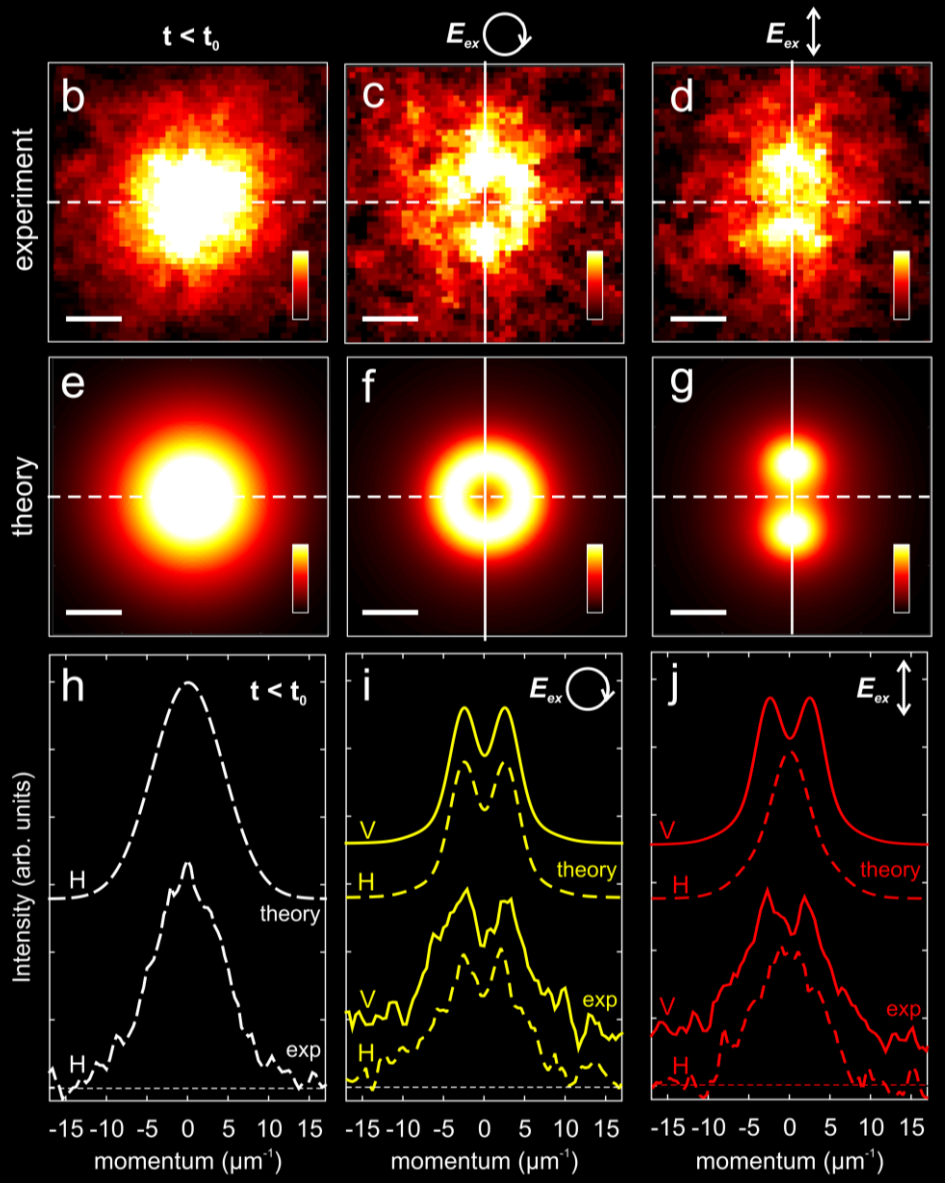
ℓ: number of absorbed/emitted plasmons

m: azimuthal order of the chiral plasmon

G. M. Vanacore, […], I. Kaminer, […], V. Grillo. […], F J. García de Abajo, F. Carbone
Nature Materials **18,** 573-579 (2019)

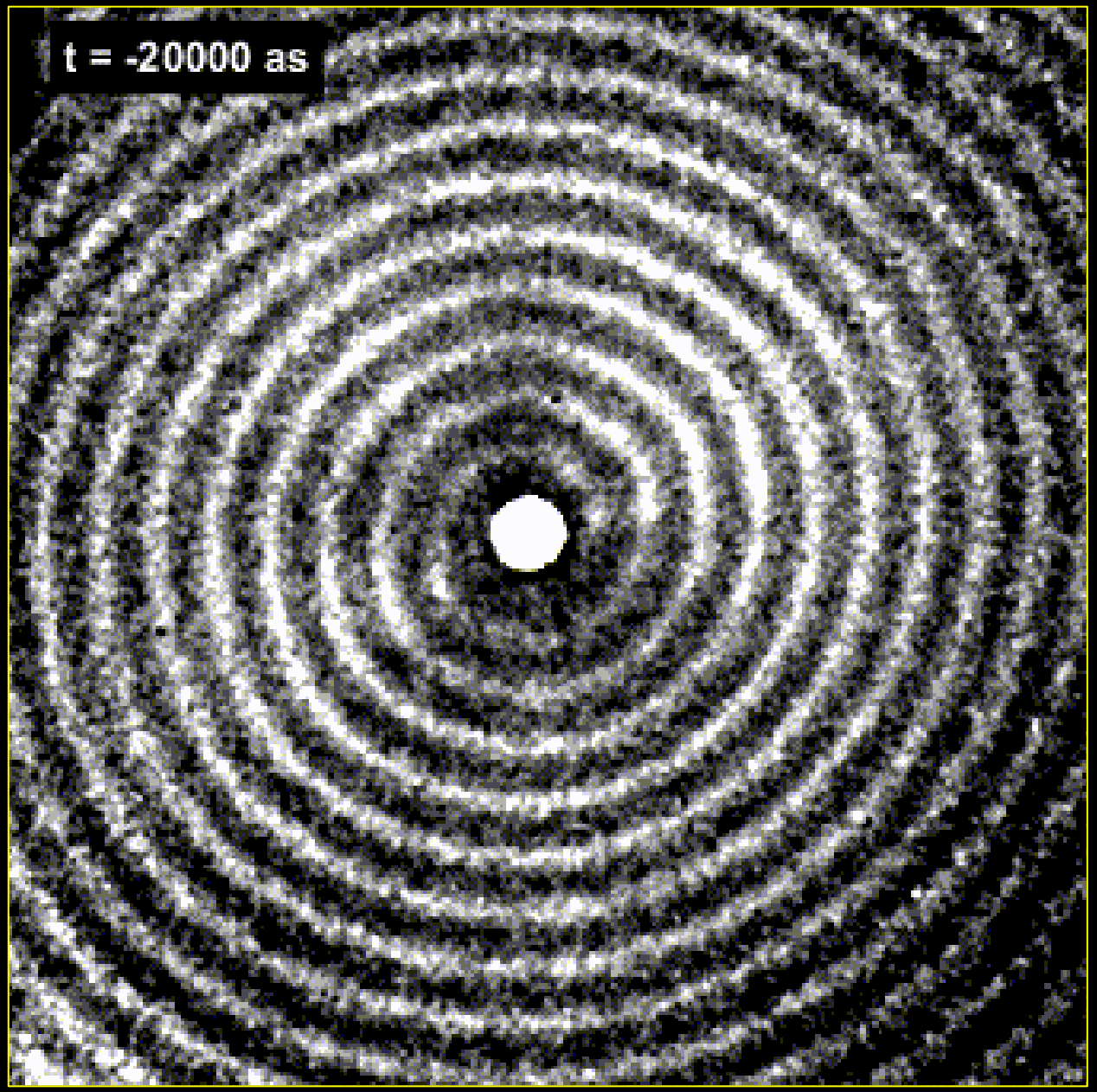
OAM transfer and Vortex electron beam





G. M. Vanacore, [...], I. Kaminer, [...], V. Grillo. [...], F J. García de Abajo, F. Carbone
Nature Materials **18,** 573-579 (2019)

Coherent vortex manipulation



Acknowledgements

École Polytechnique Fédérale de Lausanne (Switzerland)

F. Carbone, I. Madan, G. Berruto, E. Pomarico.

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R. J. Lamb, D. McGrouther.

University of Ottawa (Canada)

H. Larocque, E. Karimi

CNR-Nano (Italy)

V. Grillo

Politecnico di Milano (Italy)

P. Biagioni

Ripon College (USA)

B. Barwick

Technion Israel Institute of Technology (Israel)

I. Kaminer, K. Wang

…and many others.

SMART-electron FET project

Objective:

Developing an innovative technological platform for designing, realizing and operating all-optical rapidly-programmable phase masks for electrons.

Programme: H2020-FETOPEN-2018-2020.
Initial date: May 1st 2021.
Duration: 4 years.
Funding: 3.042 MEuro.

Smart Electron

Partners:

University of Milano-Bicocca (UNIMIB, Italy), Project Coordinator

Swiss Federal Institute of Technology in Lausanne (EPFL, Switzerland)

The Institute of Photonic Sciences (ICFO, Spain)

Technion-Israel Institute of Technology (TECHNION, Israel)

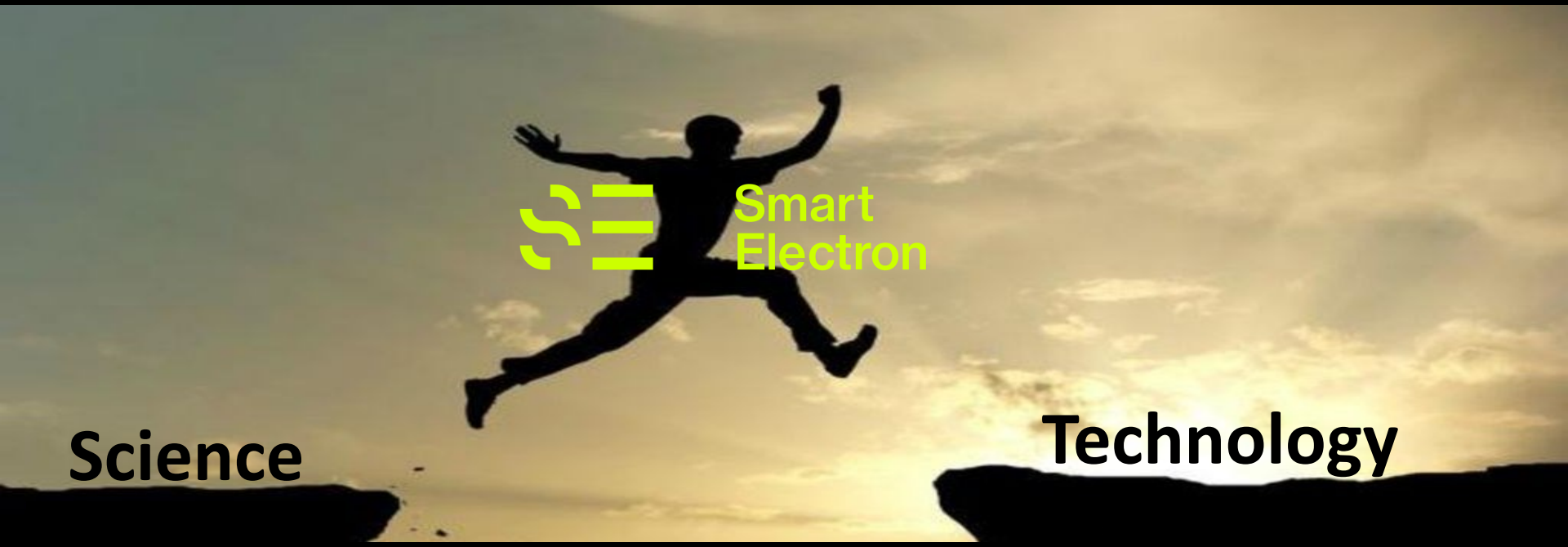
National Research Council (CNR, Italy)

HOLOEYE Photonics AG (Germany)

QED F&S Productions LTD (United Kingdom)

SMART-electron has received funding from the European Union's Horizon 2020 Research and Innovation Programme under Grant Agreement No 964591

Vision of a science-enabled technology



VISION

We want to exploit the power of control reached with light to coherently and dynamically shape electron matter waves, revolutionizing electron microscopy.

MISSION

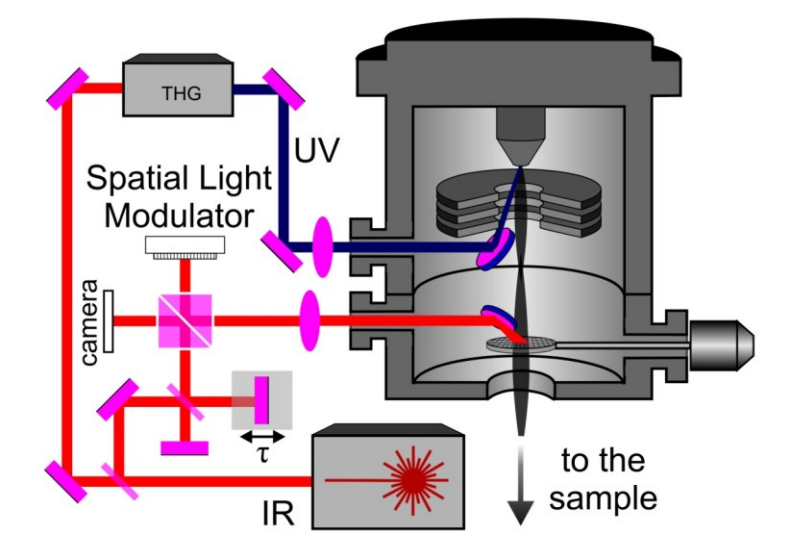
We want to use light pulses with a well-defined modulation of their amplitude and phase profiles to arbitrarily control the electron wave properties down to the fs scale.

GOAL

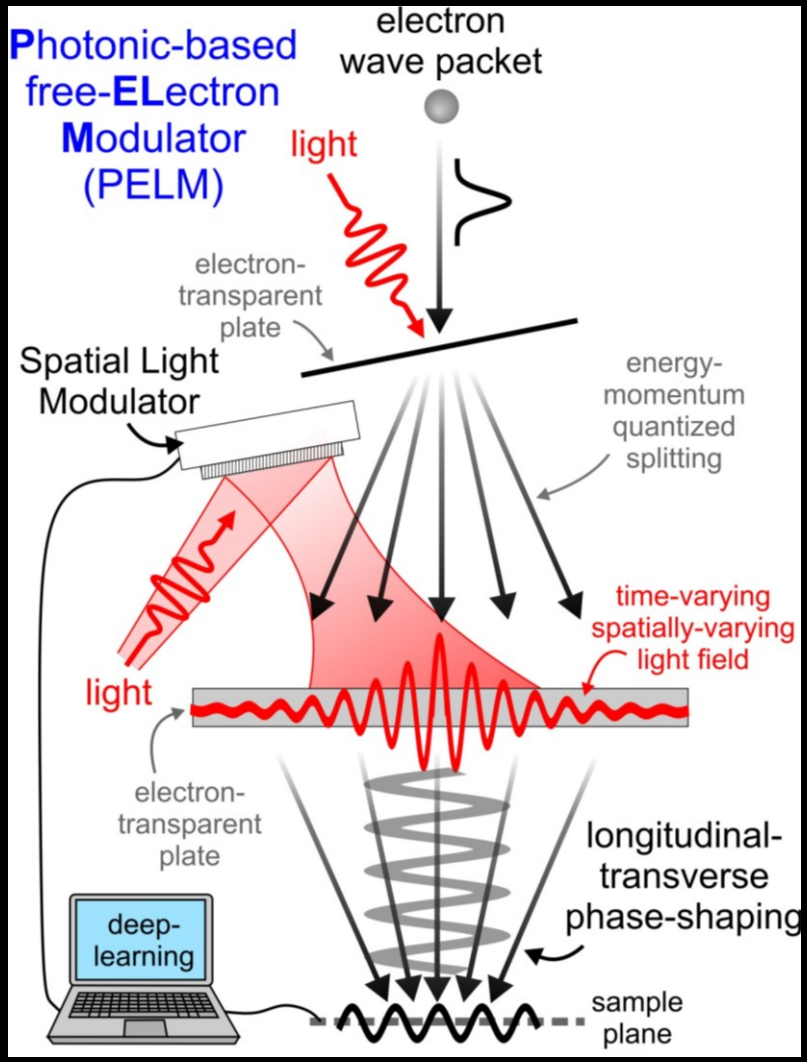
Designing, realizing and operating an all-optical rapidly programmable phase mask for electrons for multi-dimensional phase space engineering.

Photonic free-ELectron Modulator (PELM)

In SMART-electron we propose to use properly synthesized localized electromagnetic fields to create an efficient electron modulator for programmable time/energy and space/momentum control of electron beams.



- Externally-controlled optical pattern is projected from a SLM on a planar or nanopatterned thin film.
- Electron-light interaction will result in the formation of an electron wavepacket with a transversely- and longitudinally-changing phase and amplitude profile
- Such modulation would be able to induce pulse streaking or compression according to the sign of the phase variation.



Opening for a Post-doc position in:

Light-driven coherent shaping of electrons in a Transmission Electron Microscope for enhanced nanomaterial investigation.

Thank you for your attention