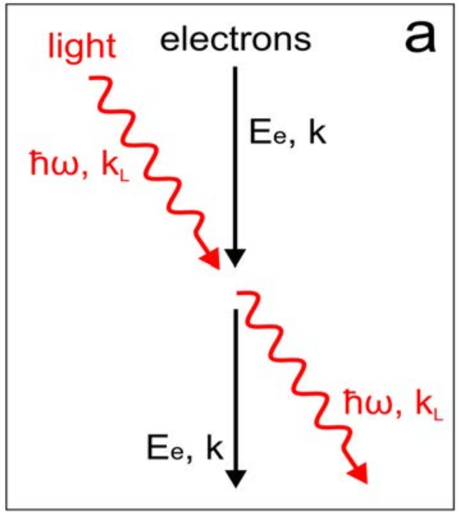
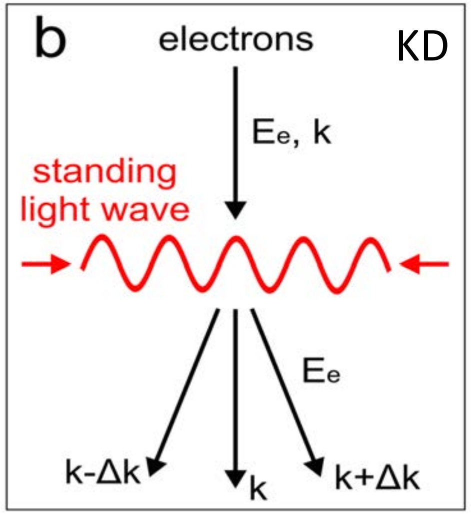
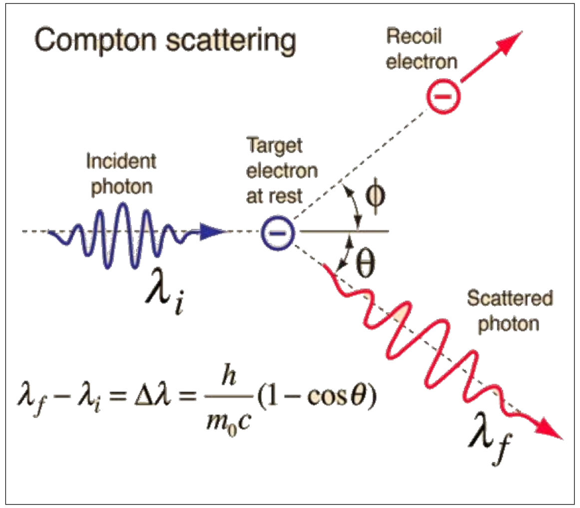
Coherent control of light electrons interaction

How can light and e^- interact?

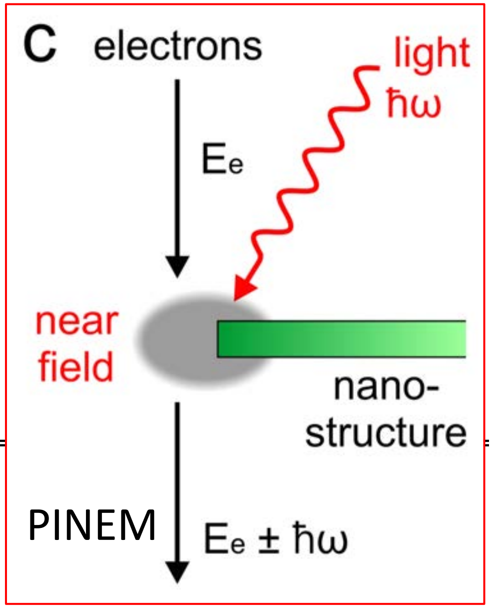


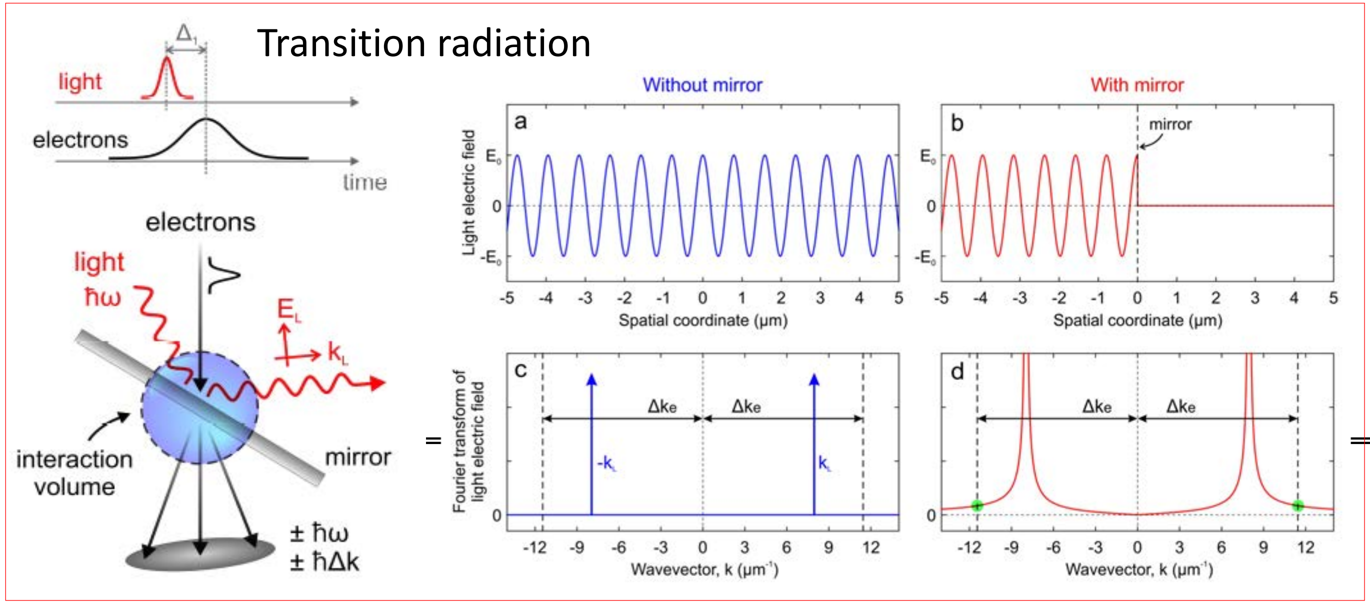




$$\lambda_f - \lambda_i = \Delta\lambda = \frac{h}{m_0 c}(1-\cos\theta)$$

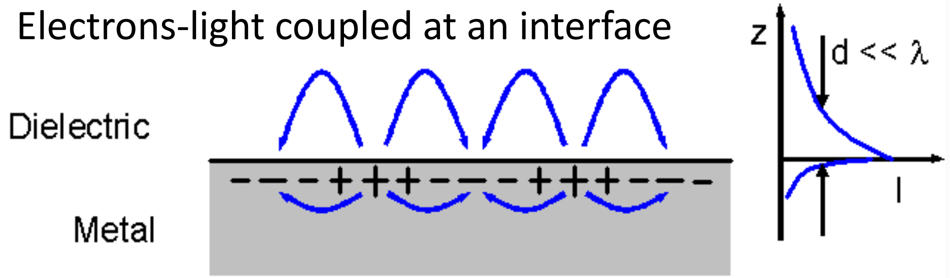
See in the lab

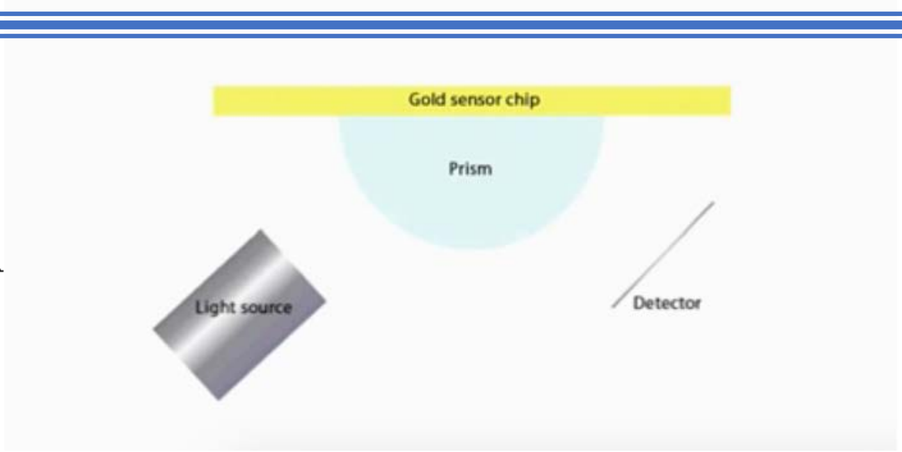



Transition radiation

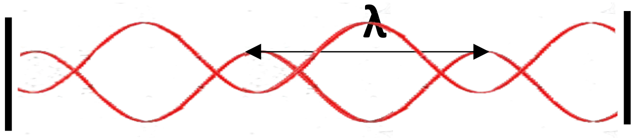
Surface plasmons polaritons and plasma resonances

Surface plasmon:
Electrons-light coupled at an interface

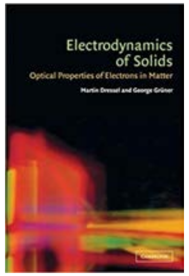




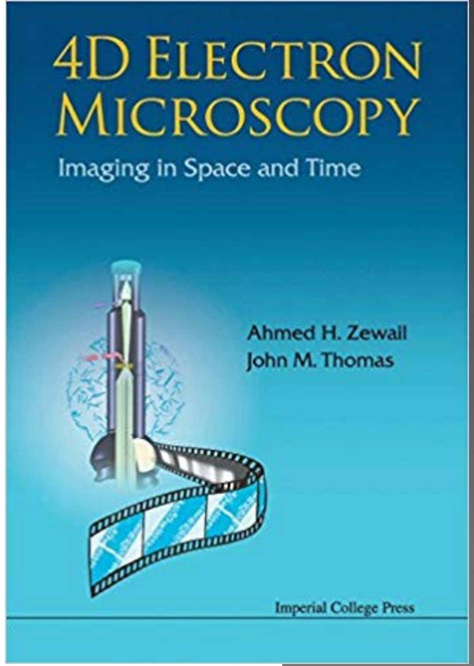
Plasma resonance



Suggested reading: Dressel, “Electrodynamics of solids”



Ultrafast Transmission Electron Microscopy

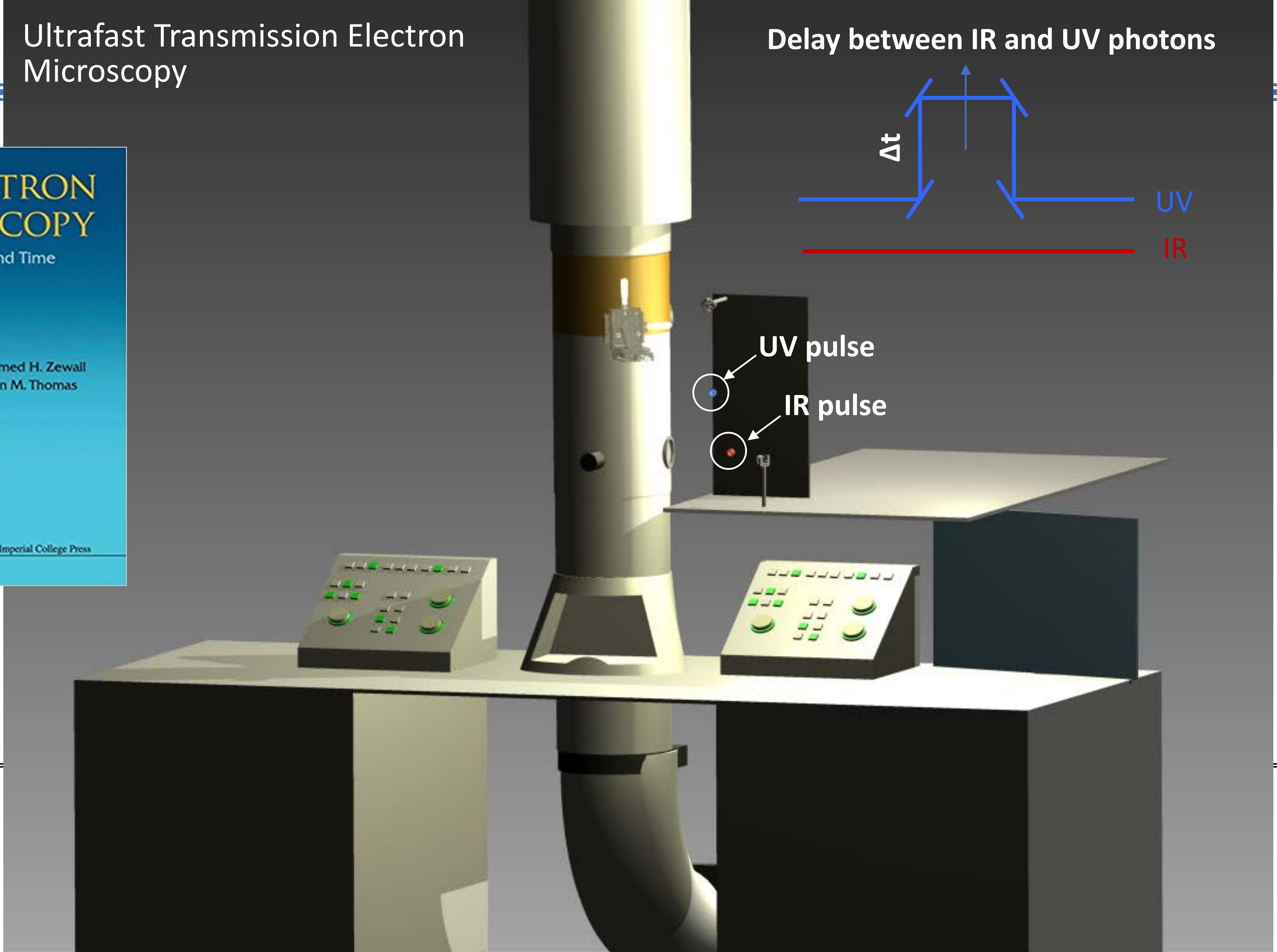


4D ELECTRON MICROSCOPY

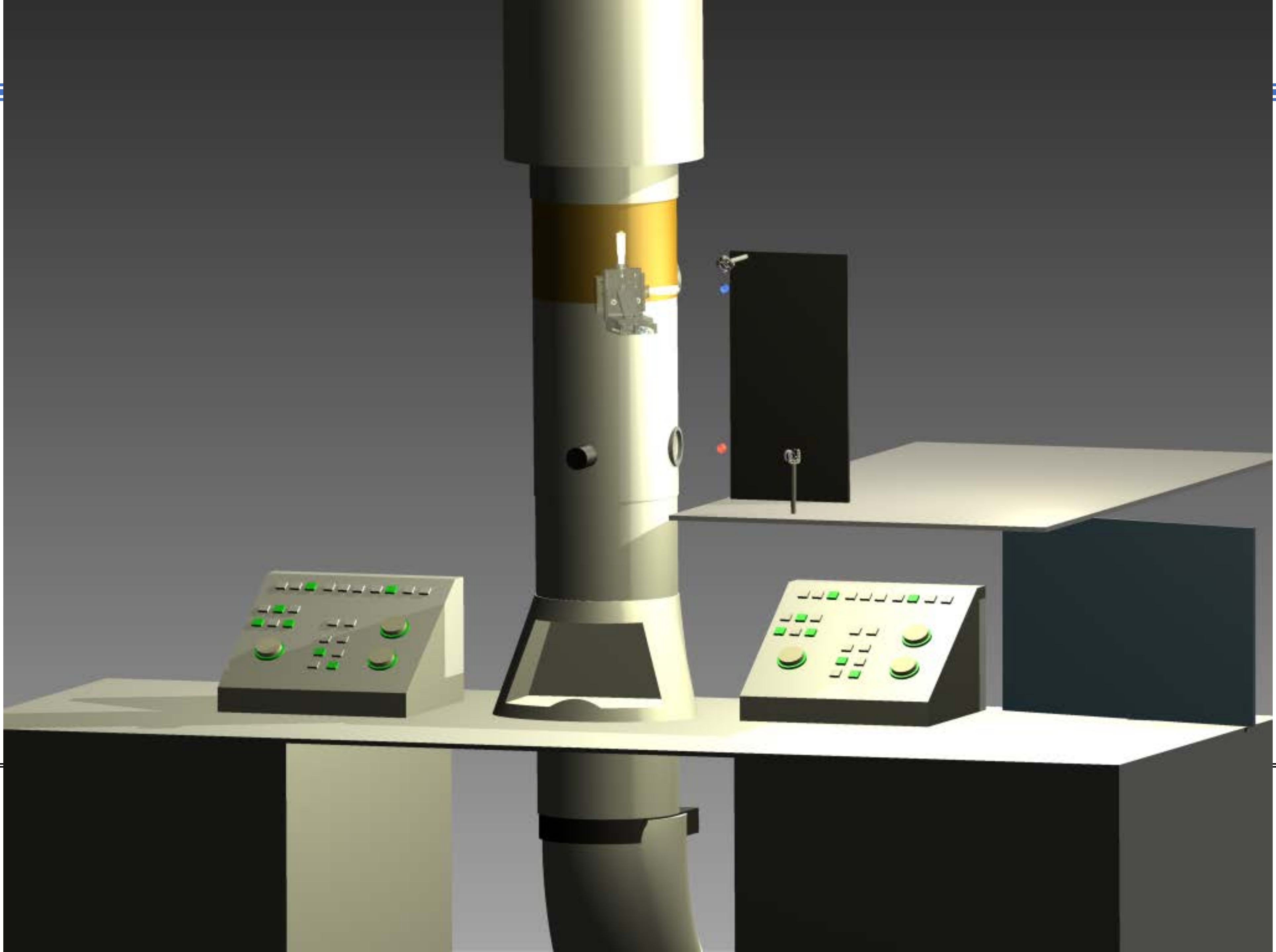
Imaging in Space and Time

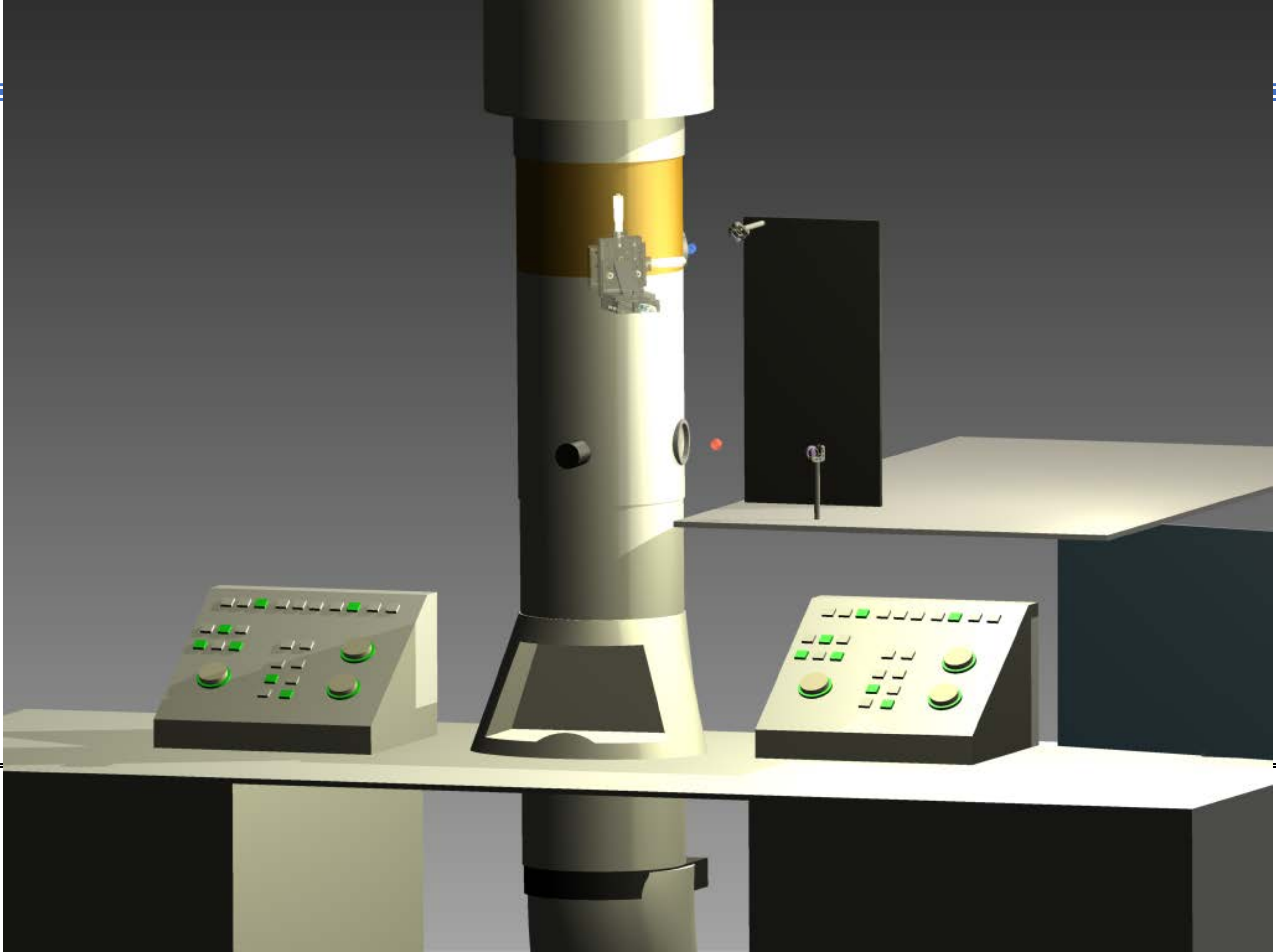
Ahmed H. Zewail
John M. Thomas

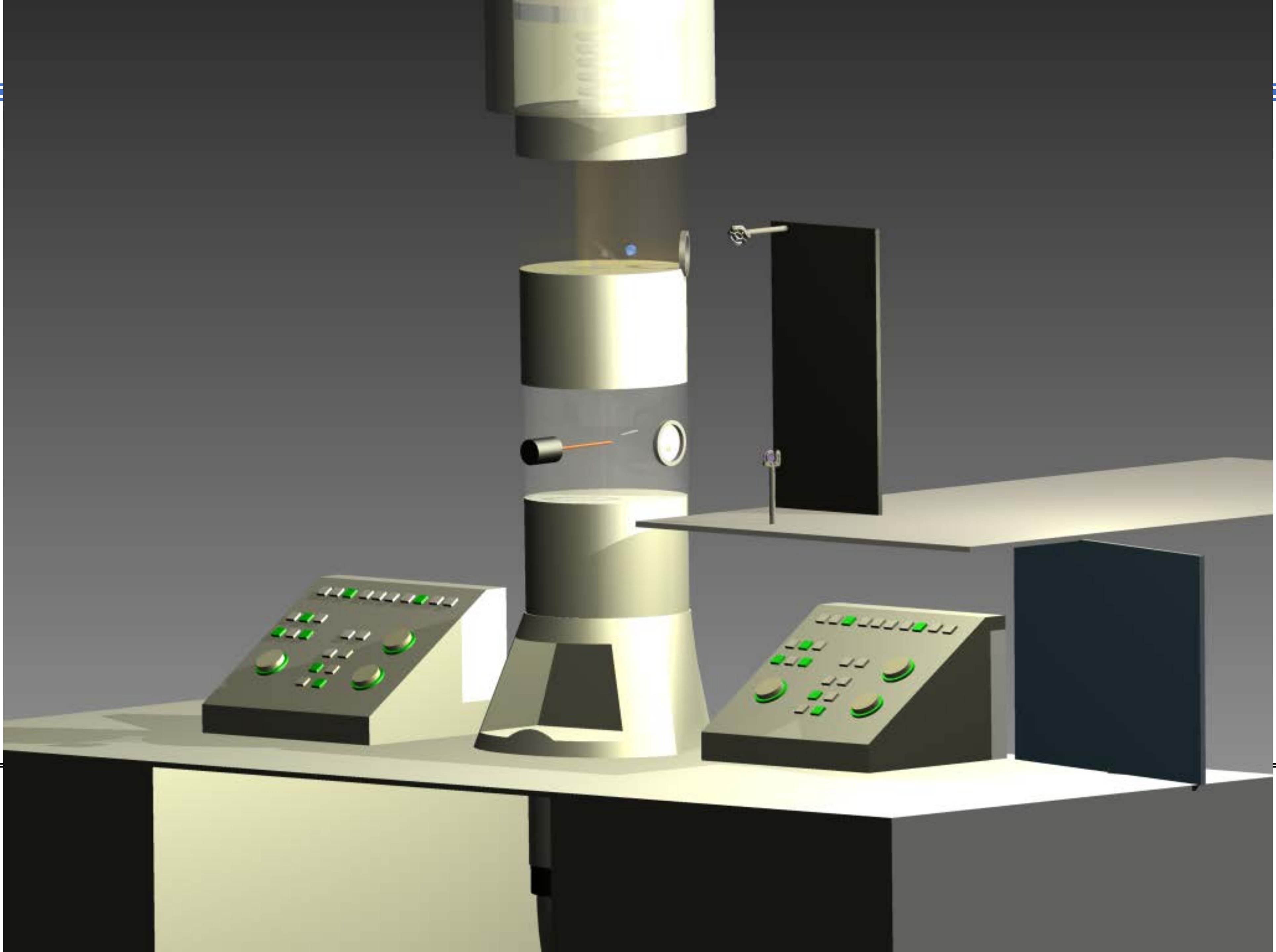
Imperial College Press

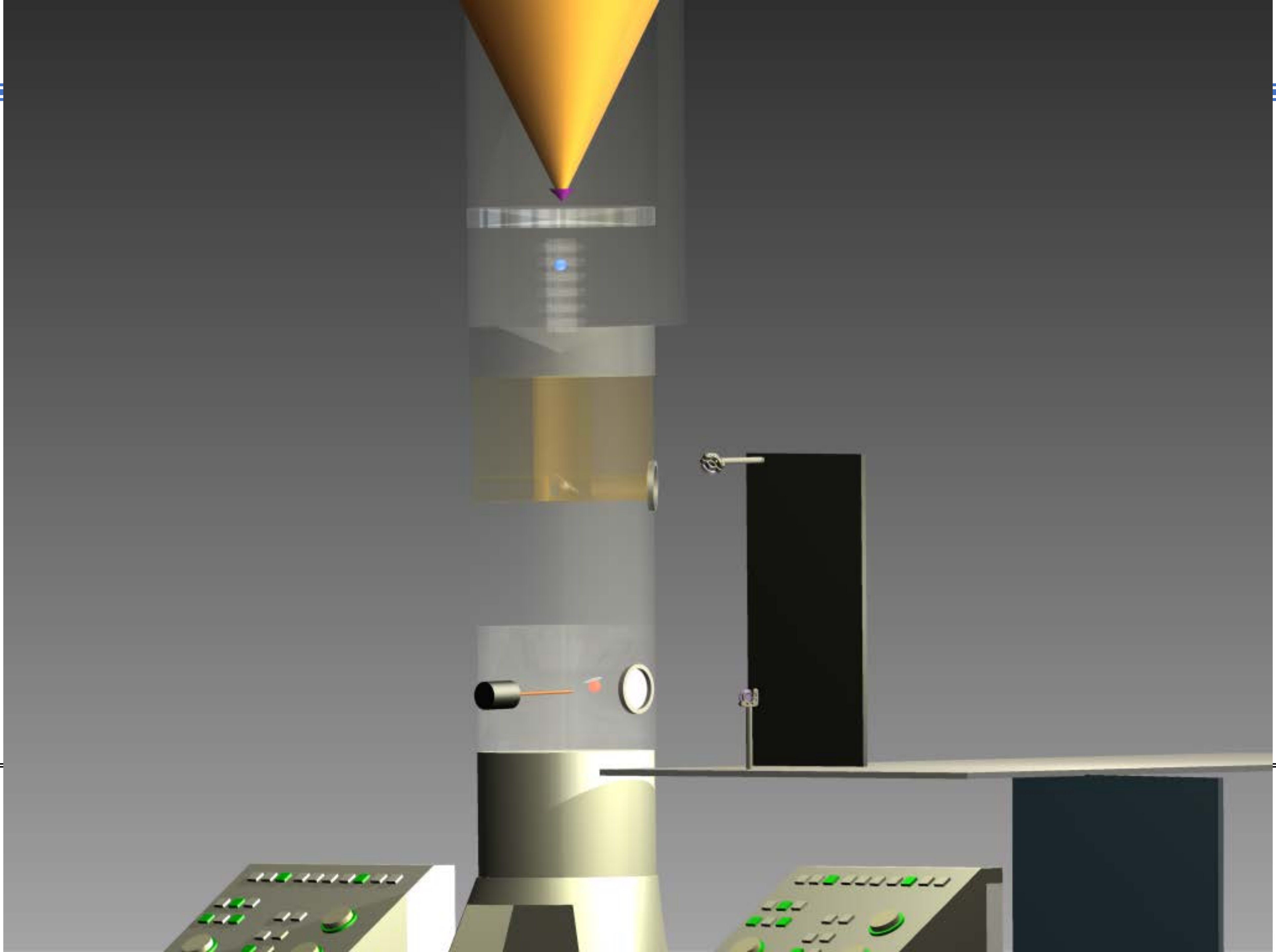


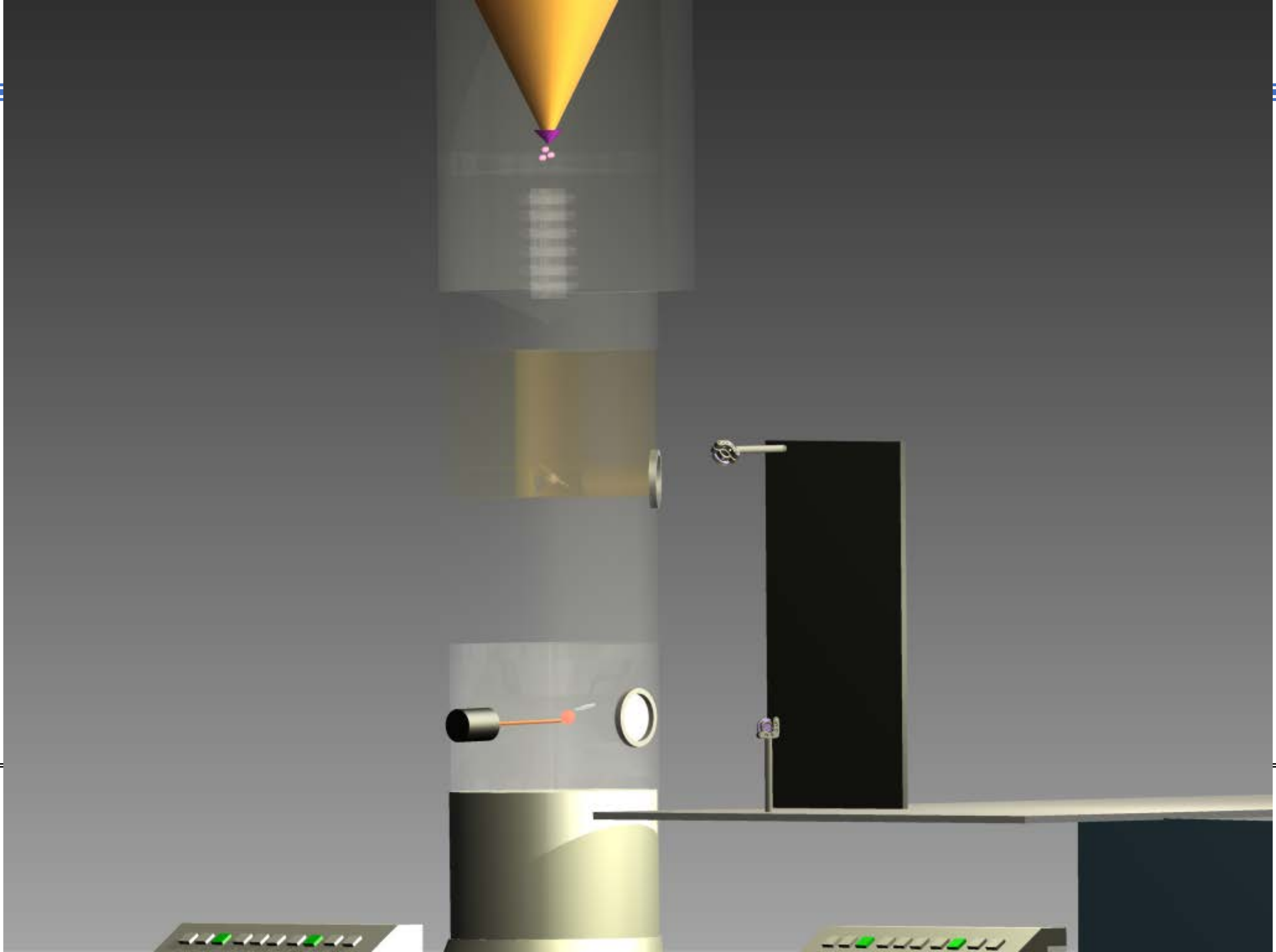
Delay between IR and UV photons

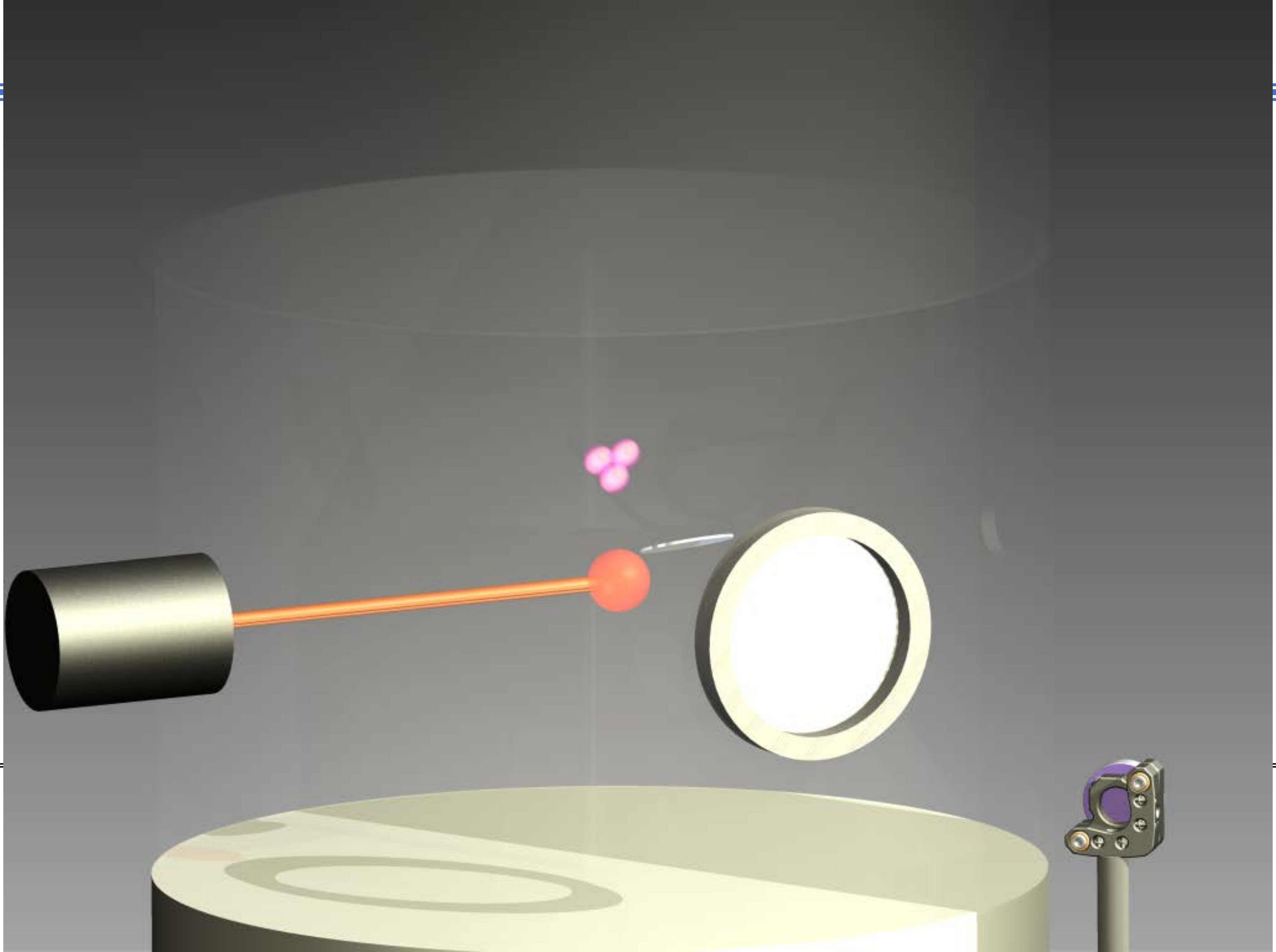


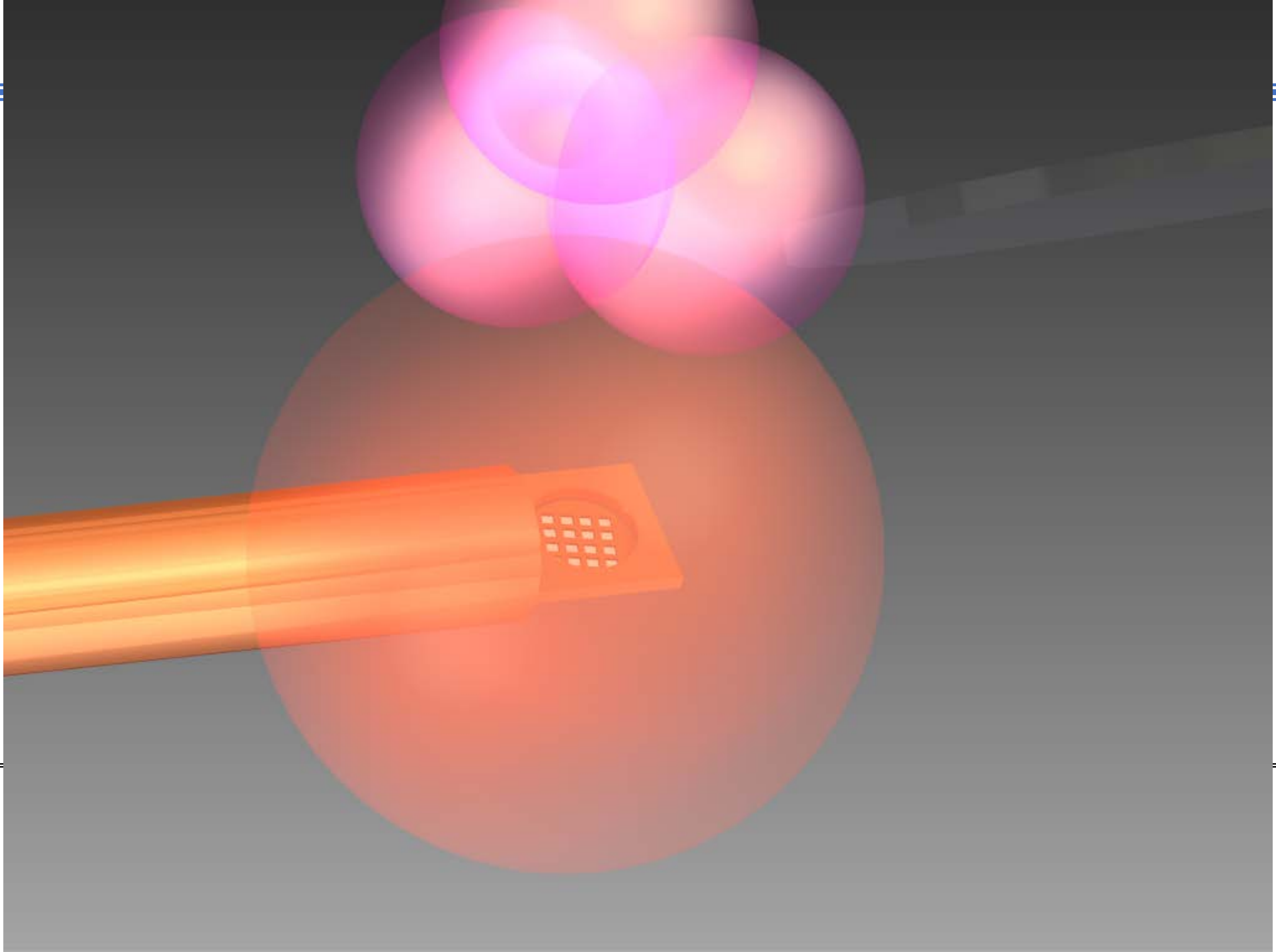


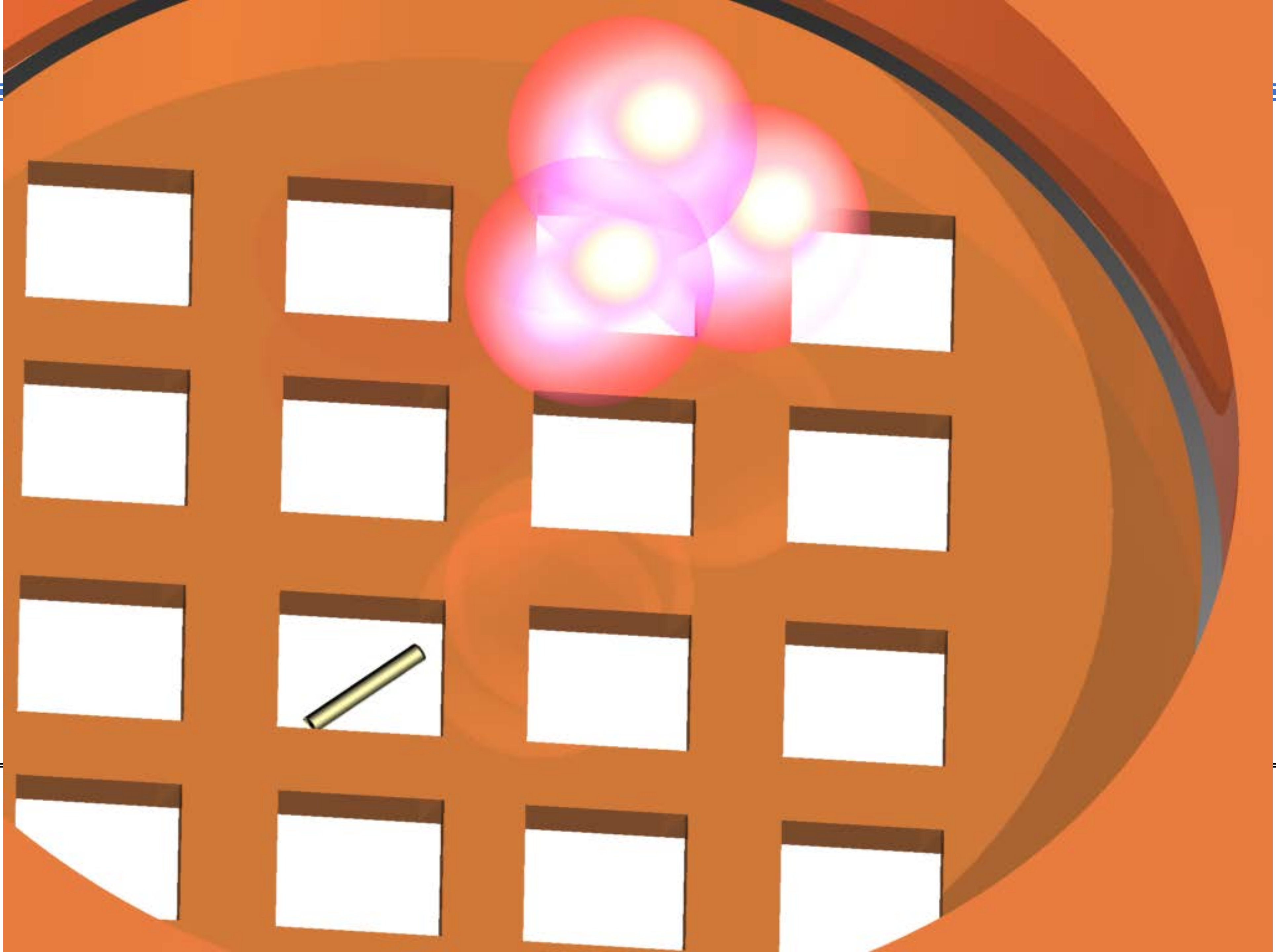


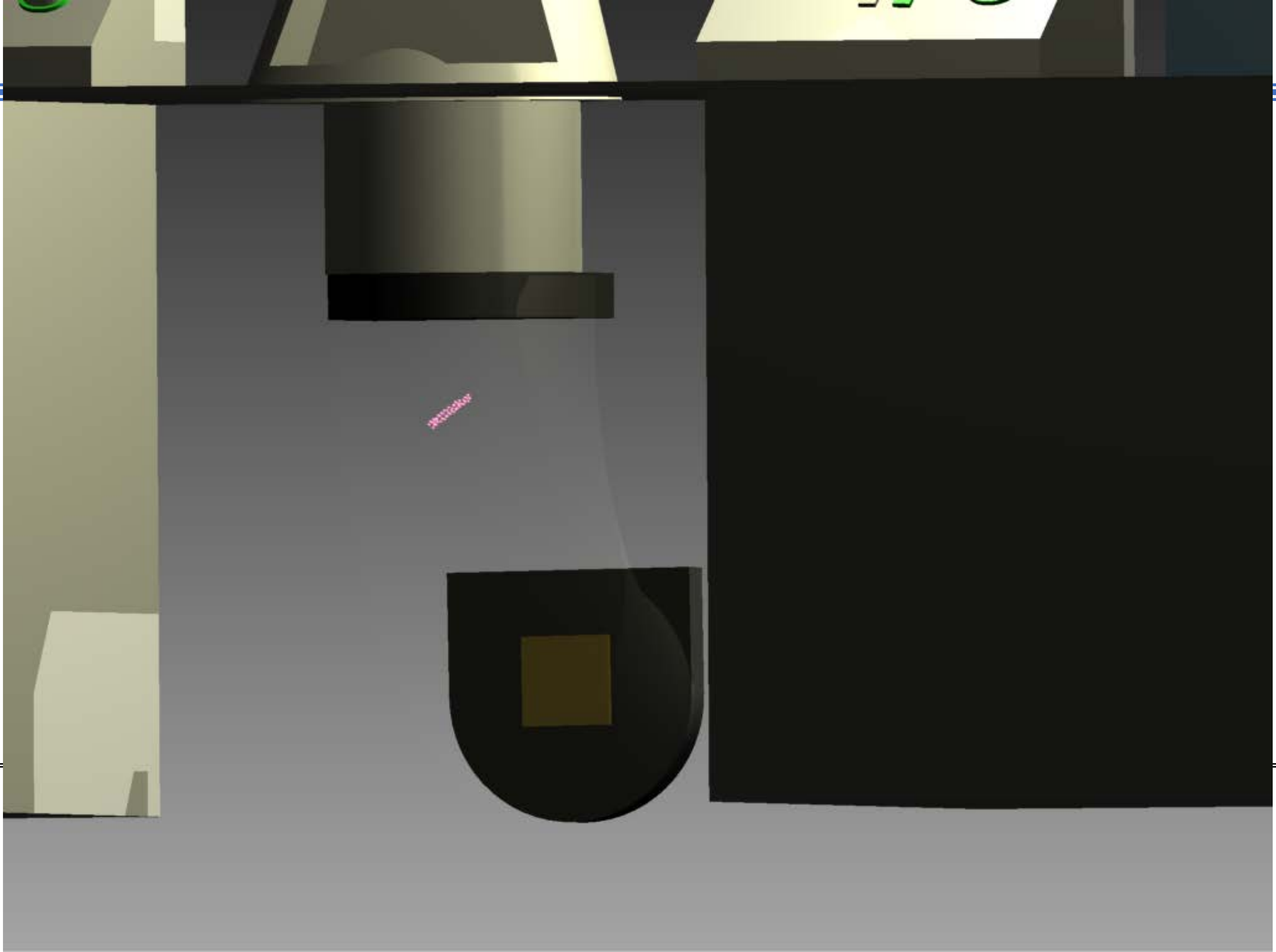


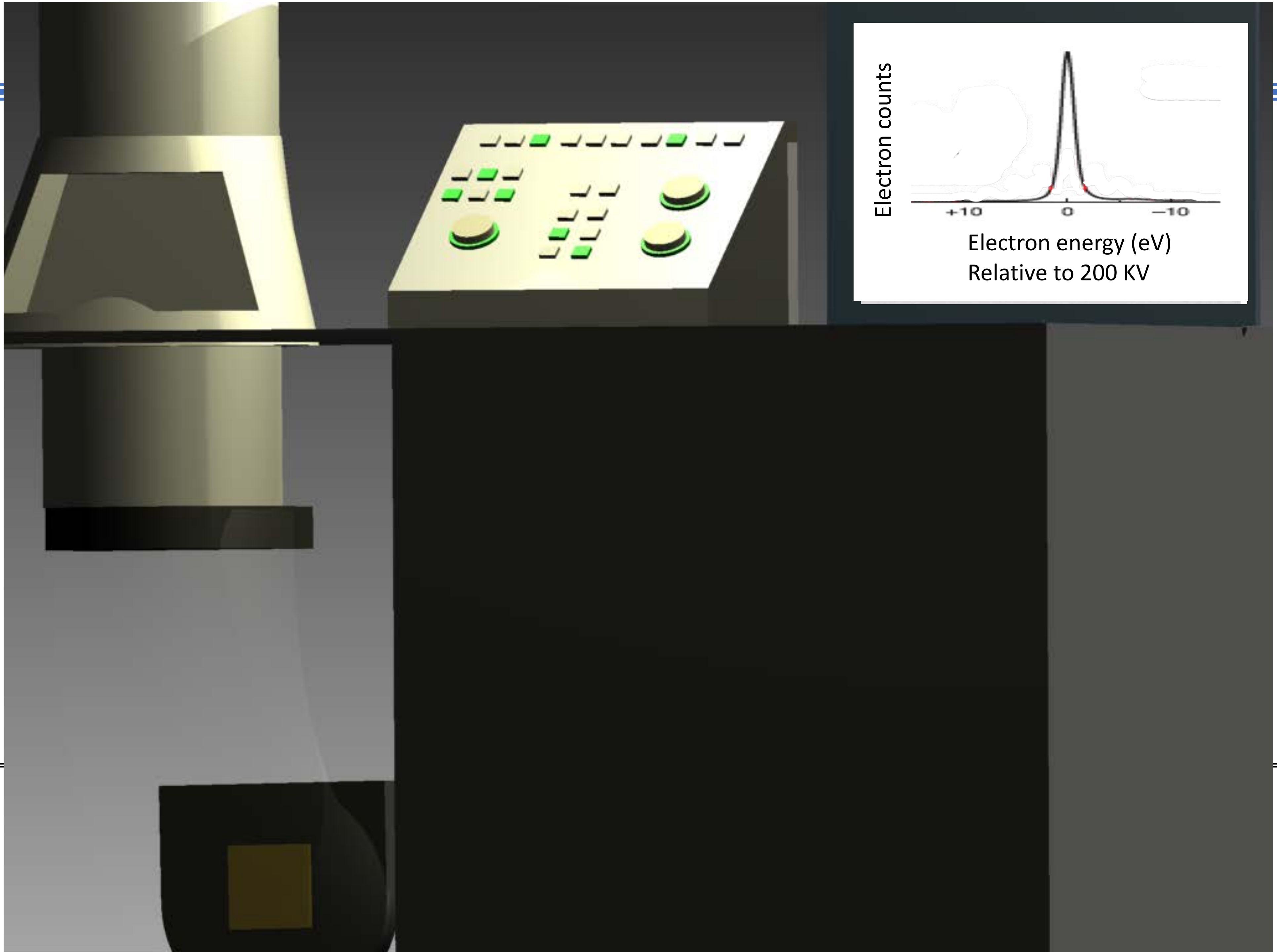


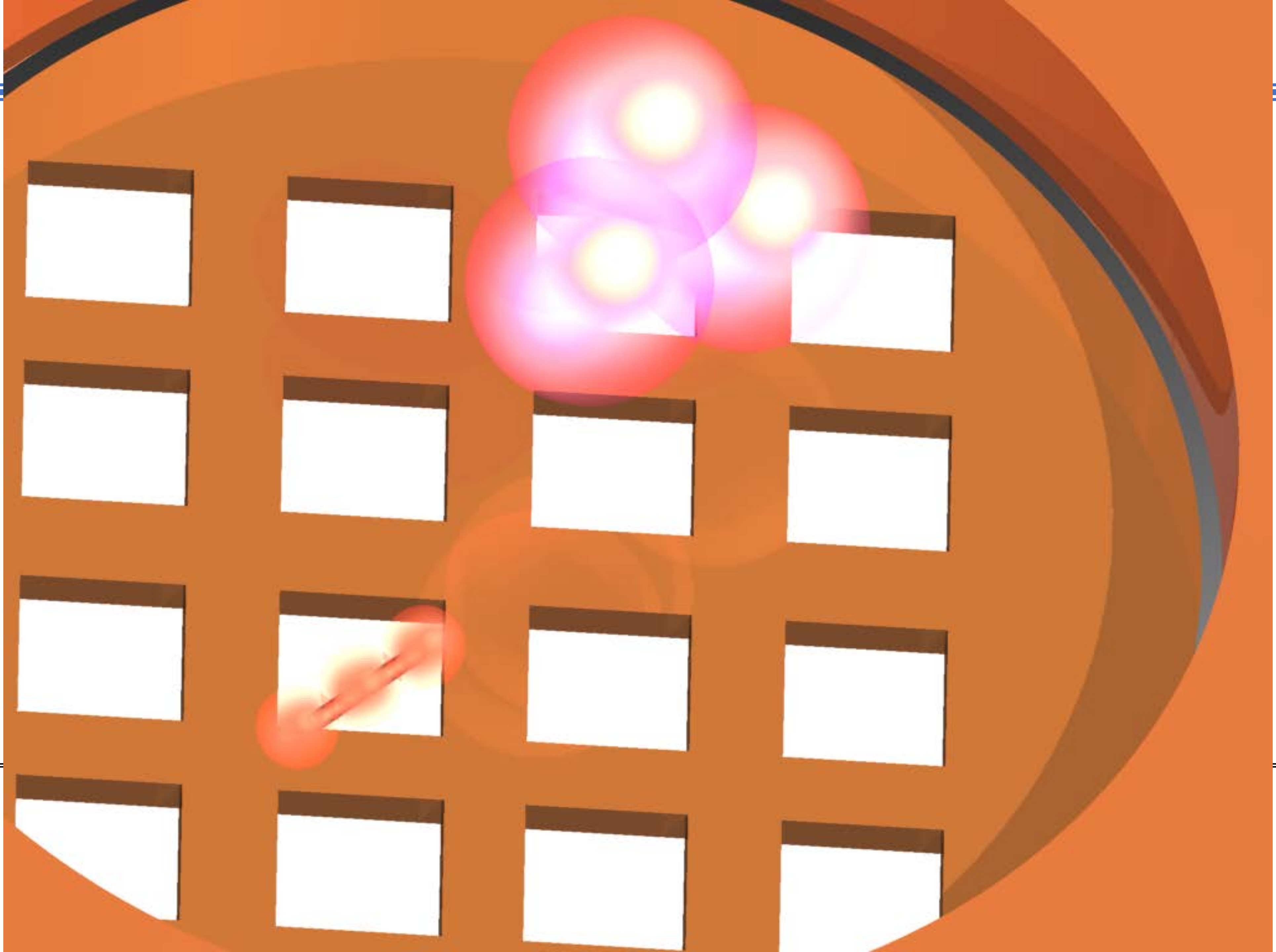


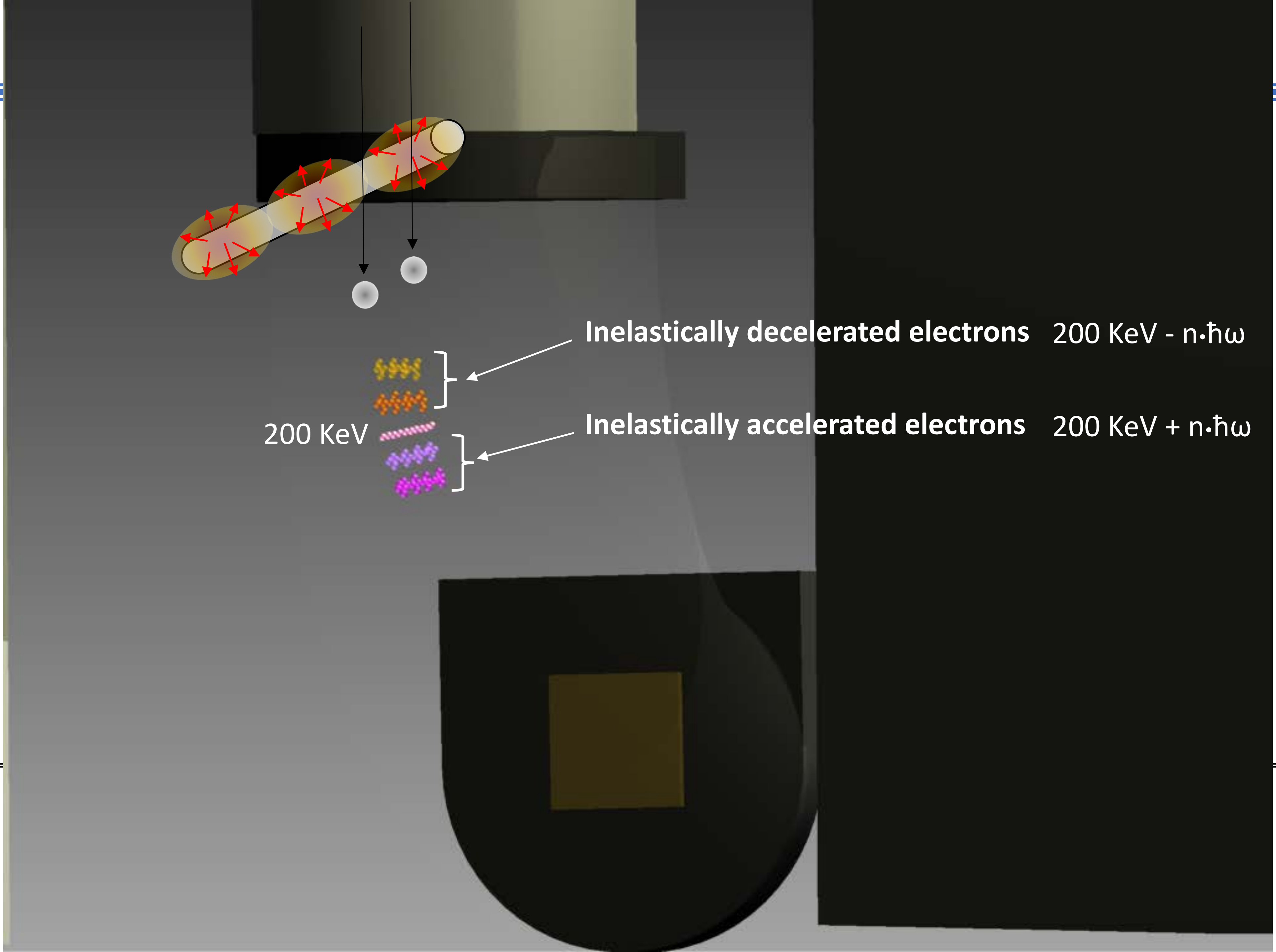







Electron counts
+10
0
−10
Electron energy (eV)
Relative to 200 KV

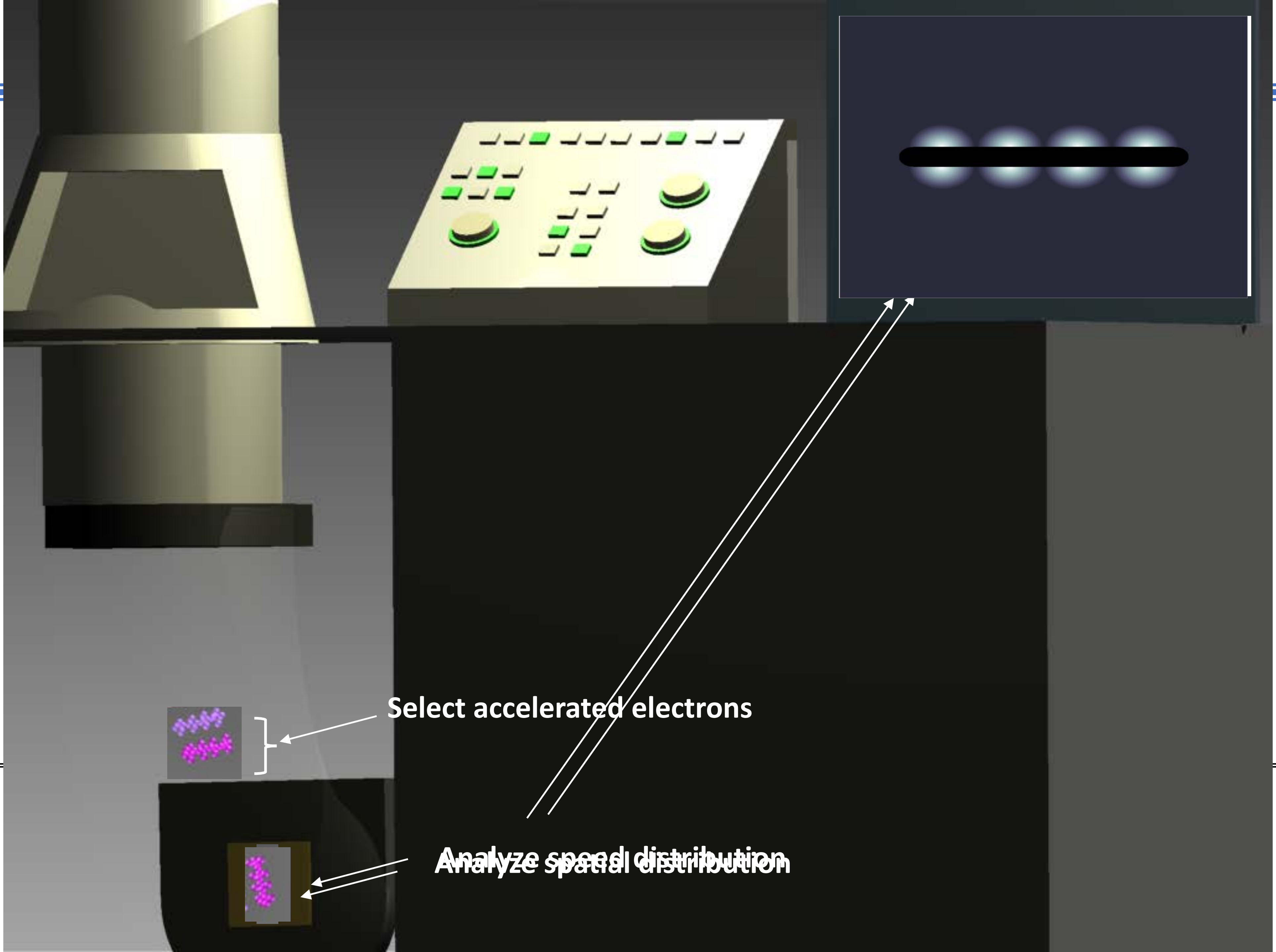




Inelastically decelerated electrons 200 KeV - n·ħω

200 KeV

Inelastically accelerated electrons 200 KeV + n·ħω



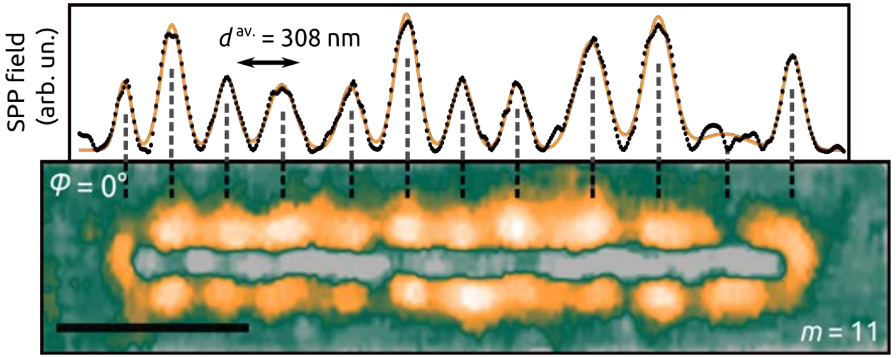
Select accelerated electrons

Analyze speed distribution

Analyze spatial distribution

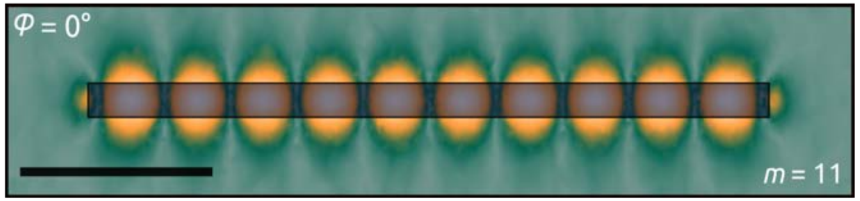
LUMES

Filming plasma resonances

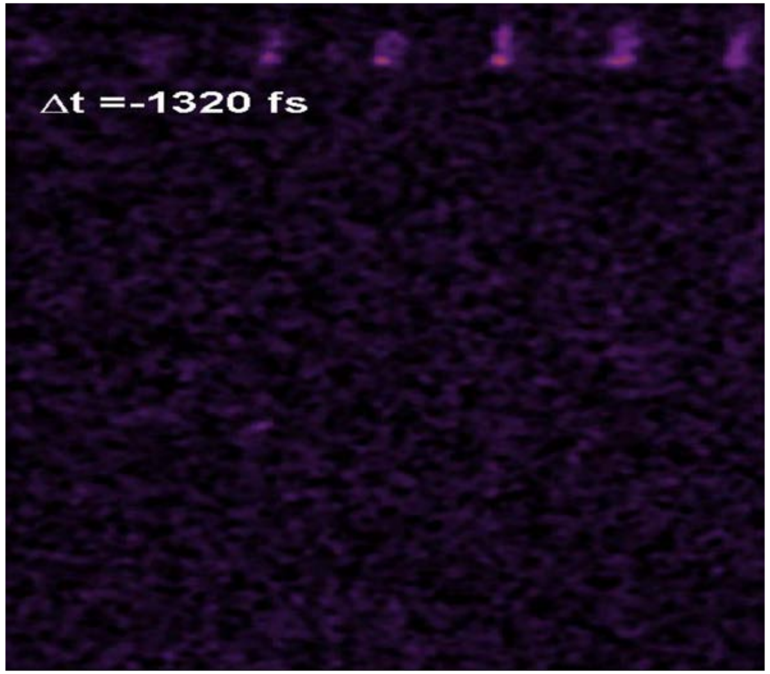


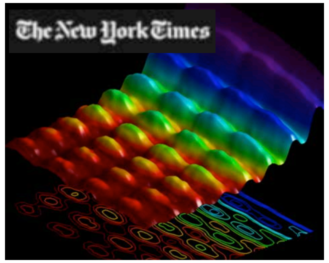
Experiment

Polarization ⟷



Simulation





Piazza et al., **Nat. Comm.** 6 6407 (2015)

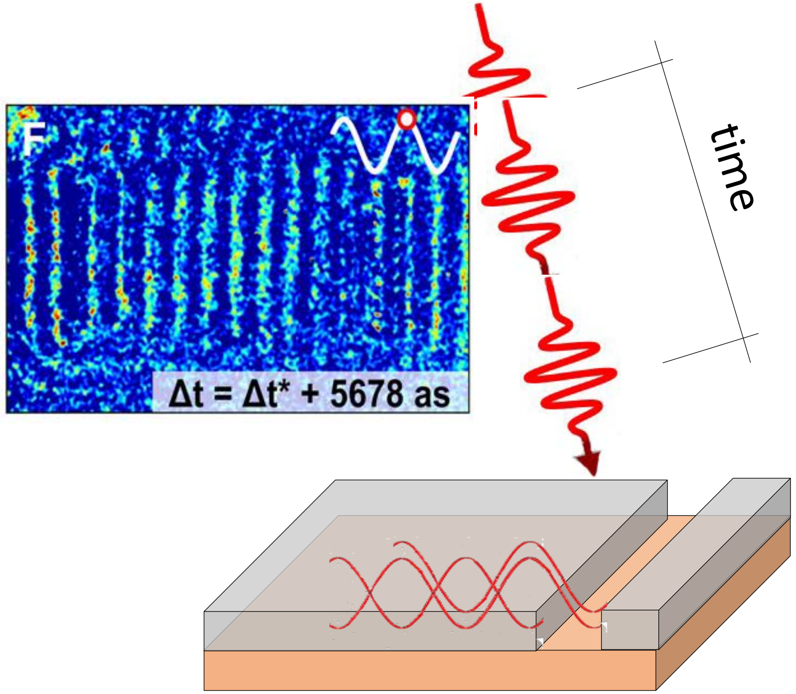
Most cited article in Nat Comm since 2015

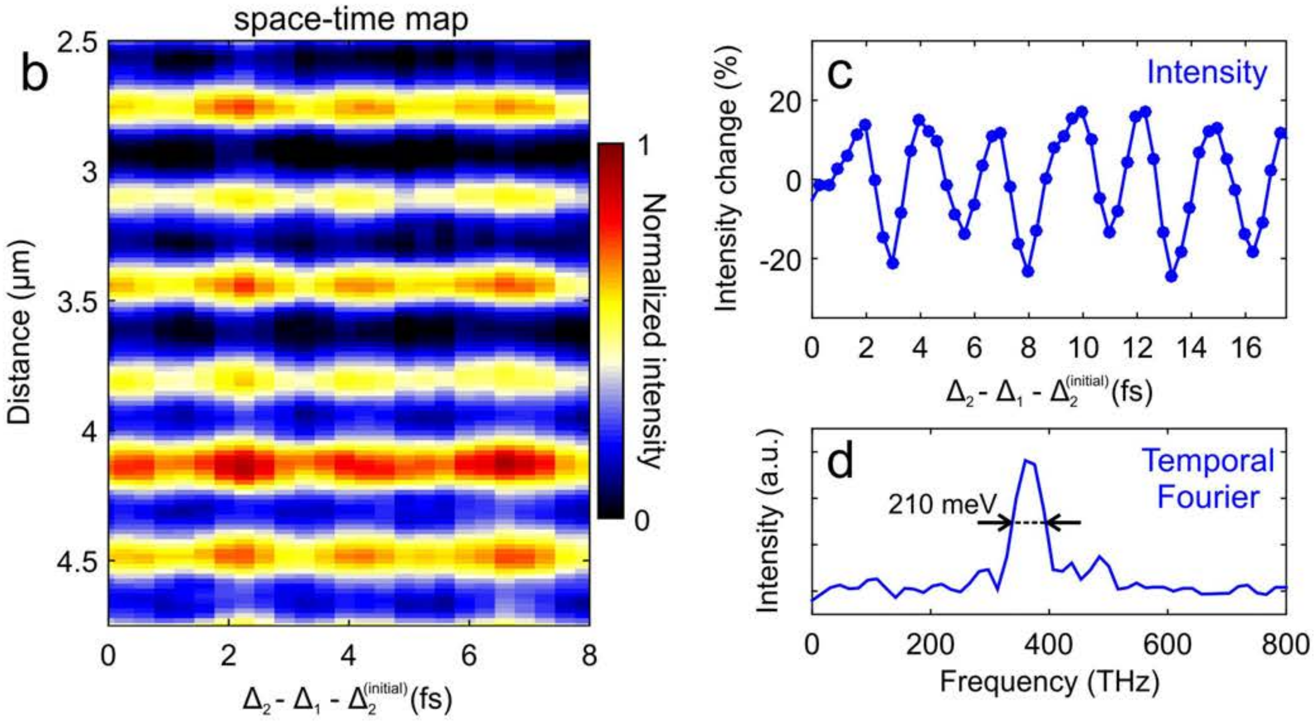
Now product manager at Dectris, Zurich

Lummen et al., **Nat. Comm.** 7 13156 (2016)

Now senior scientist at ETHZ

Coherent control of plasma resonances

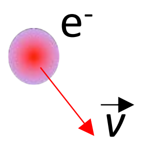


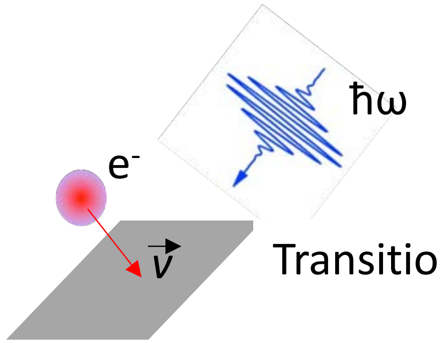


Vanacore, et al. **Nat. Comm** 9 2694 (2018)

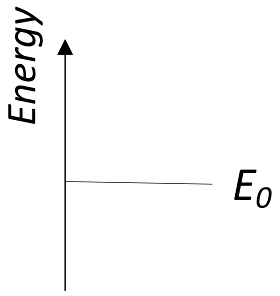
Now tenure track professor at the University of Milan Bicocca

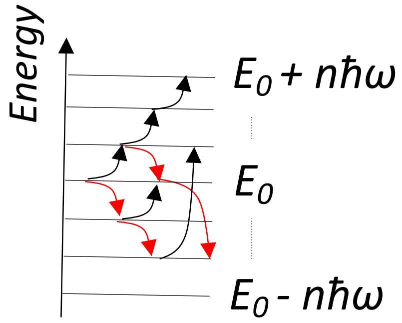
What about the e^- after these interactions?





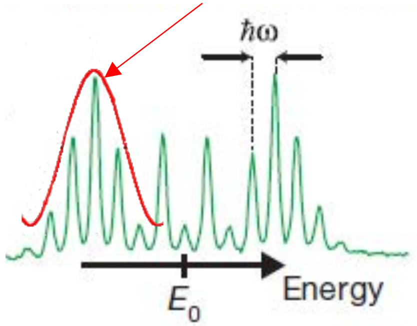
Transition radiation





e^- wavefunction split in
a multilevel quantum
ladder

Levels population depends
on quantum interference between paths:
Rabi oscillations



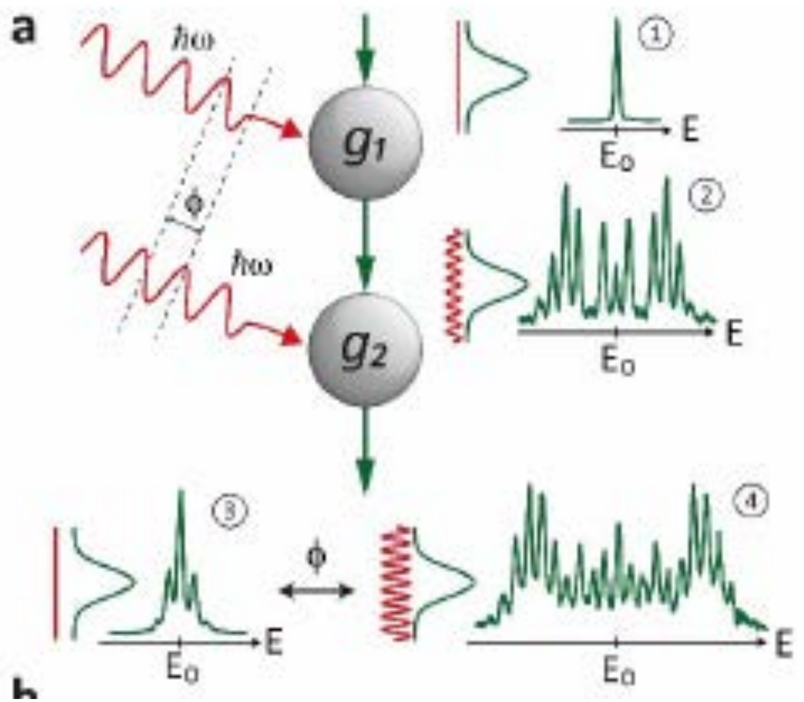
See in
the lab

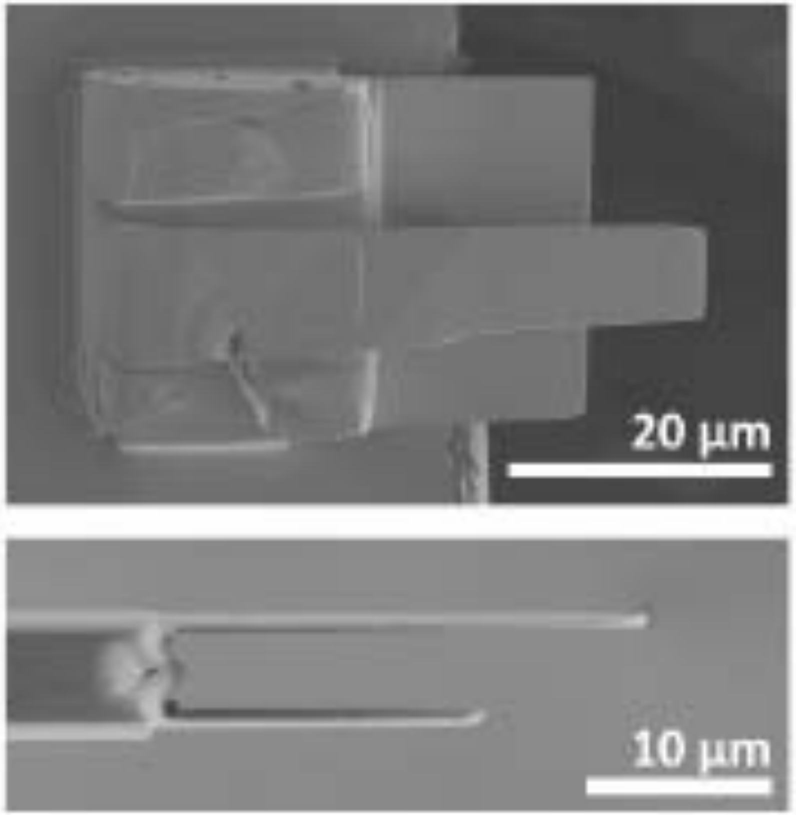
Park *et al.*, **New J. Phys.** 12, 123028 (2010)

García de Abajo *et al.*, **Nano Lett.** 10, 1859 (2010)

Feist *et al.*, **Nature** 521, 14463 (2015)

Coherent control of the longitudinal electron wavefunction by plasma resonances





Echternkamp et al. 12 1000 **Nat. Phys.** (2016)

What about the e$^-$ after these interactions?

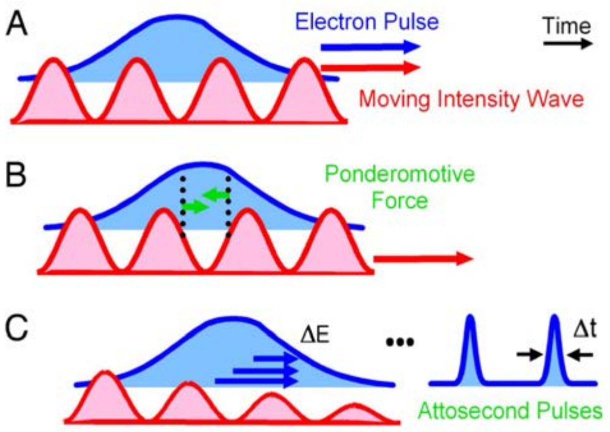


Fig. 2. Concept of optical compression in a moving intensity grating. (*A*) An electron packet (blue) copropagates at a velocity of less than the speed of light with the maxima and minima of a moving intensity wave (red), synthesized from two counterpropagating laser pulses of different frequencies (see text). (*B*) The ponderomotive forces (green arrows) push electrons out of regions with high intensity. Within every optical cycle, the parts of the electron packets that are located at a falling slope are accelerated (left green arrow) and the parts located at a rising slope are retarded (right green arrow). (*C*) The resultant momentum and velocity distribution Δ*p* leads into self-compression to the final attosecond duration (Δ*t*) within every optical cycle (see text).

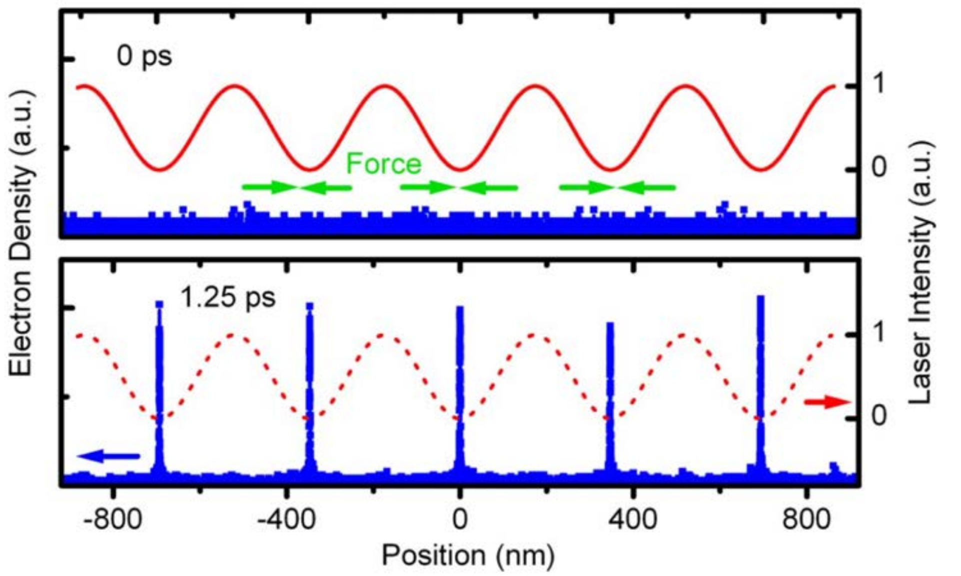
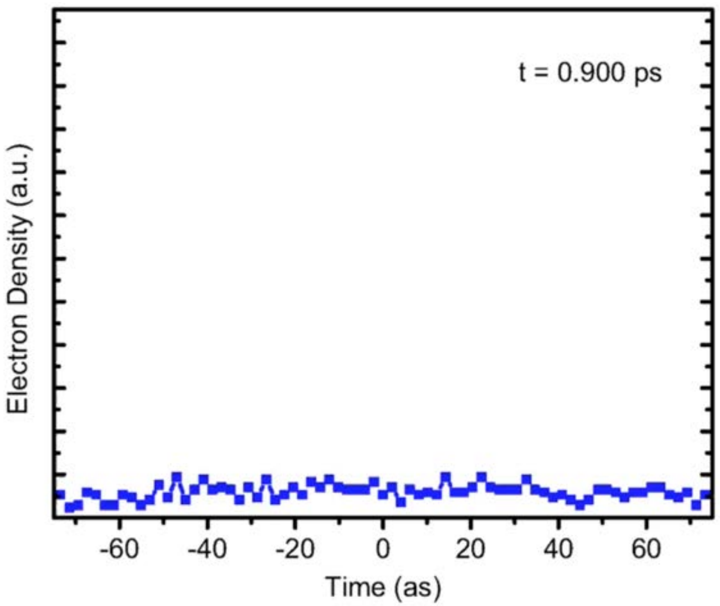


Fig. 4. Trajectory calculations showing the compression. (*Upper*) A long electron packet (blue) is overlapped with a moving intensity wave (red wave). Over time, the ponderomotive force (green arrows) accumulates and initiates self-compression. (*Lower*) At later times, when the intensity wave has faded (red, dotted wave), the electron density shows marked peaks of attosecond duration, which are located at the minima of the intensity wave. Note that the position scale is relative to the electron packet center.



Attosecond electron pulses for 4D diffraction and microscopy

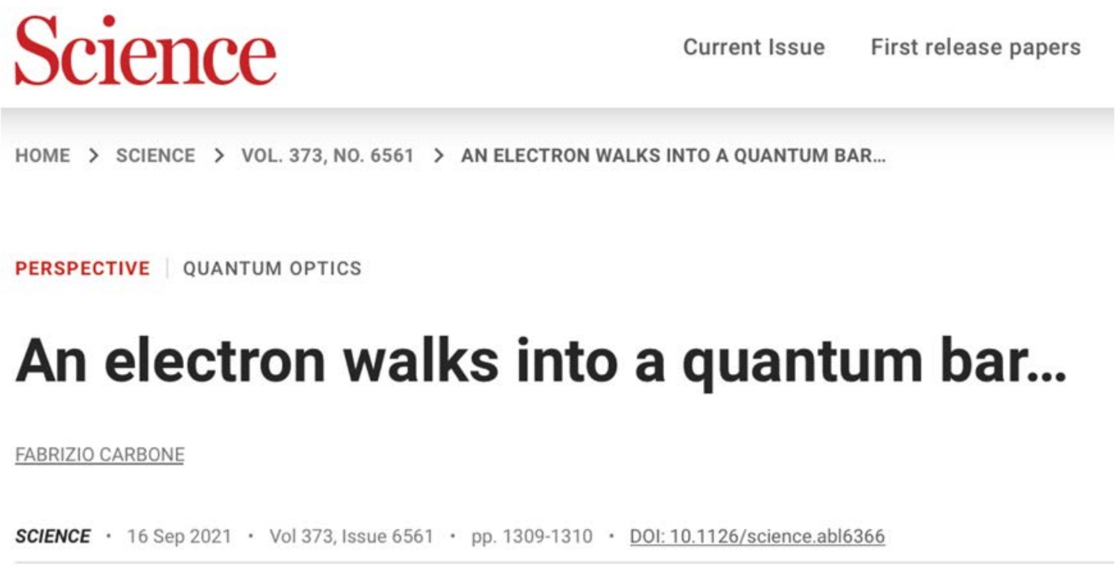
Peter Baum and Ahmed H. Zewail*

Physical Biology Center for Ultrafast Science and Technology, Arthur Amos Noyes Laboratory of Chemical Physics, California Institute of Technology, Pasadena, CA 91125

Contributed by Ahmed H. Zewail, September 27, 2007 (sent for review September 12, 2007)

But what if an electron interacts with **incoherent** light?

- Coherent light can be easily described as a wave (in the high intensity limit)
- Incoherent light needs a quantum description of its noise distribution



Science

Current Issue First release papers

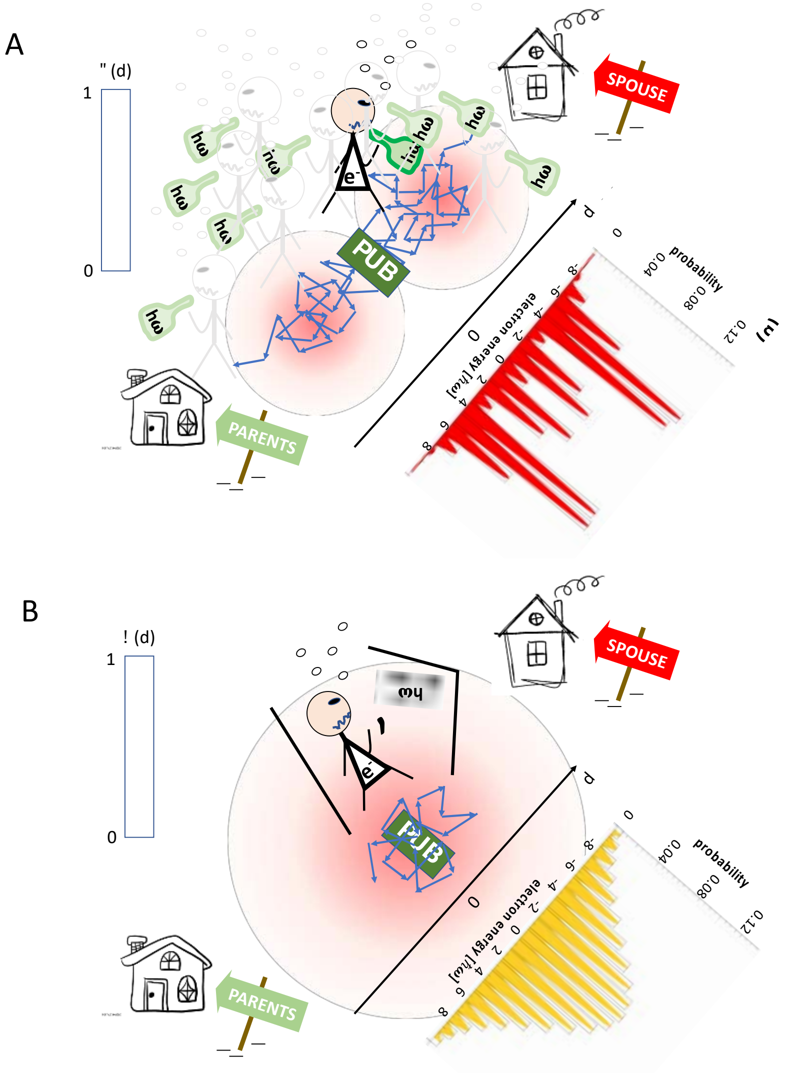
HOME > SCIENCE > VOL. 373, NO. 6561 > AN ELECTRON WALKS INTO A QUANTUM BAR...

PERSPECTIVE | QUANTUM OPTICS

An electron walks into a quantum bar...

FABRIZIO CARBONE

SCIENCE • 16 Sep 2021 • Vol 373, Issue 6561 • pp. 1309-1310 • DOI: 10.1126/science.abl6366



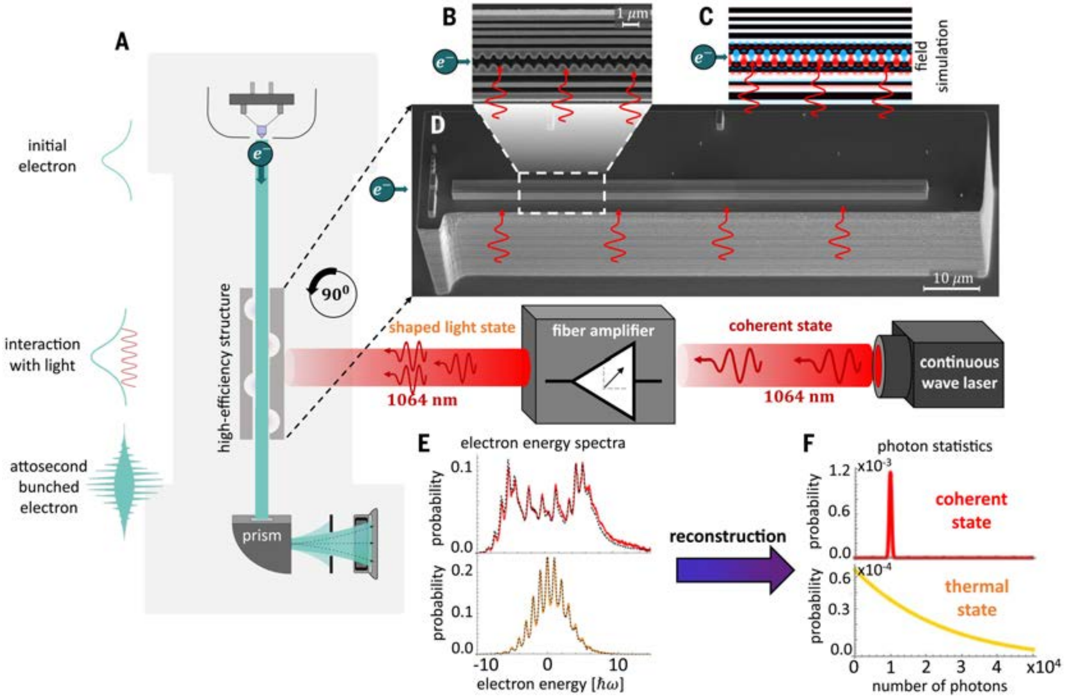
LUMES

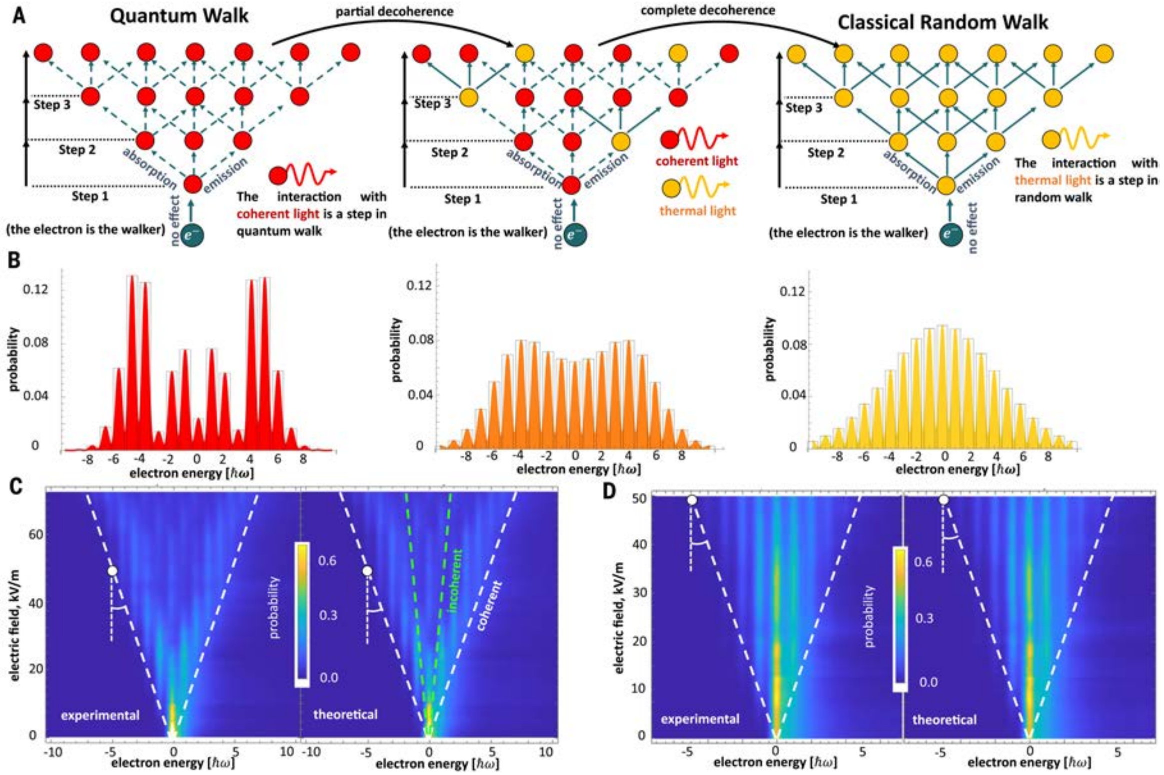
R. Dahan et al., *Science* **373**, eabj7128 (2021).

But what if an electron interacts with **incoherent** light?

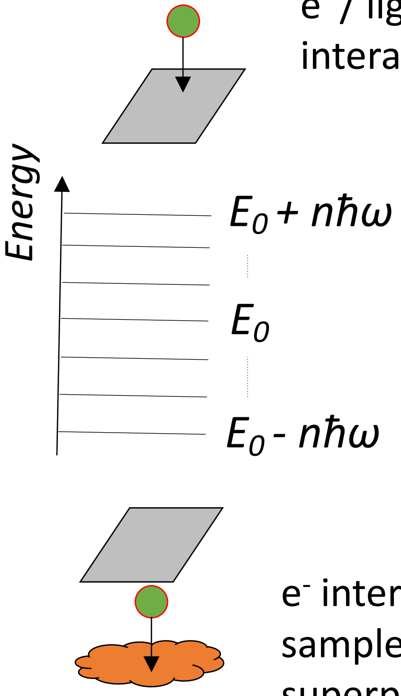
R. Dahan et al., *Science* **373**, eabj7128 (2021).

See in
the lab





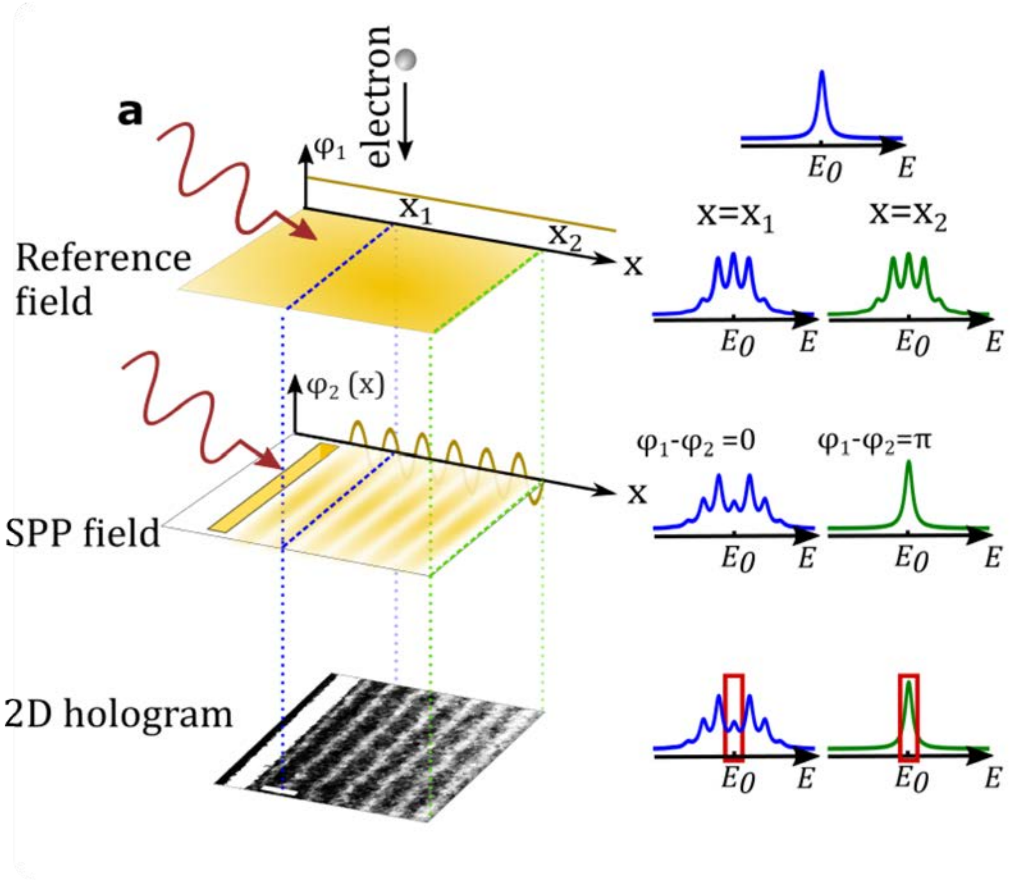
Quantum holography



e^- / light field interaction

e^- WF split in a quantum ladder

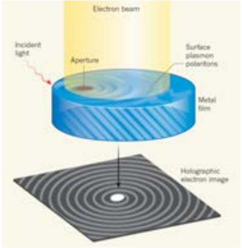
e^- interacts with sample while in a superposition of states



Vary dt between the two interactions

Madan et al, **Science Advances** 6 eaav8358 (2019)
News and Views article: Ropers, **Nature** 571, 331 (2019)

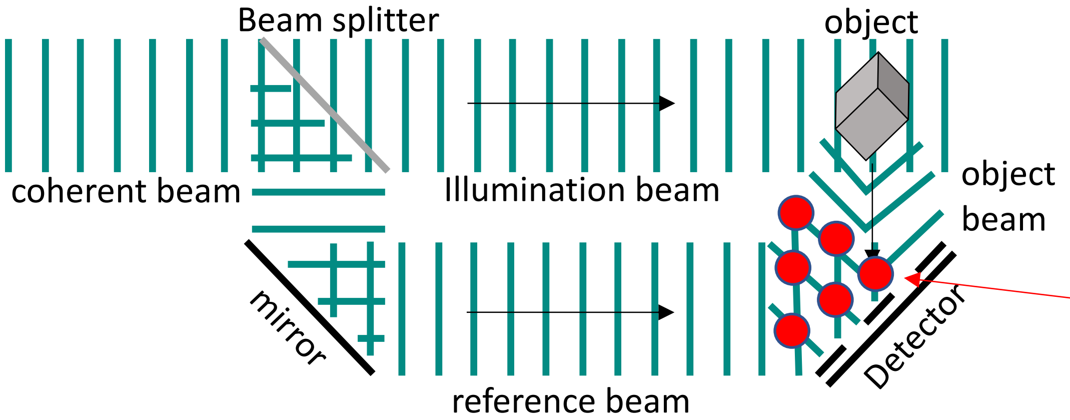
https://actu.epfl.ch/news/new-holographic-technique-opens-the-way-for-quantu/
https://www.youtube.com/watch?v=s2iiBbTuZn4&feature=emb_logo



Holographic imaging of electromagnetic fields via electron-light quantum interference

SCIENCE ADVANCES | RESEARCH ARTICLE

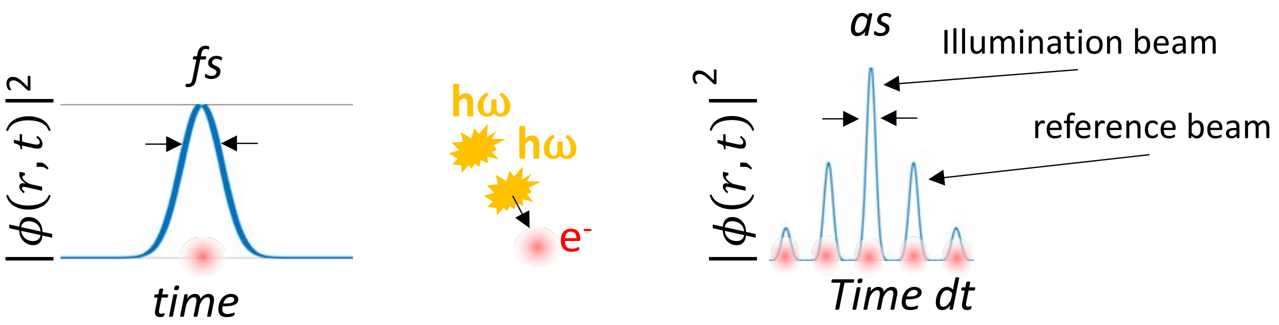
Madan *et al.*, *Sci. Adv.* 2019;**5**:eaav8358   3 May 2019



Conventional holography:
two **coherent** beams are separated in space to provide signal and reference

Count interferences
deduce depth information

Quantum holography: two beams (made of **one e$^-$**) are separated in time to provide as-resolved signal and references



nature NEWS & VIEWS

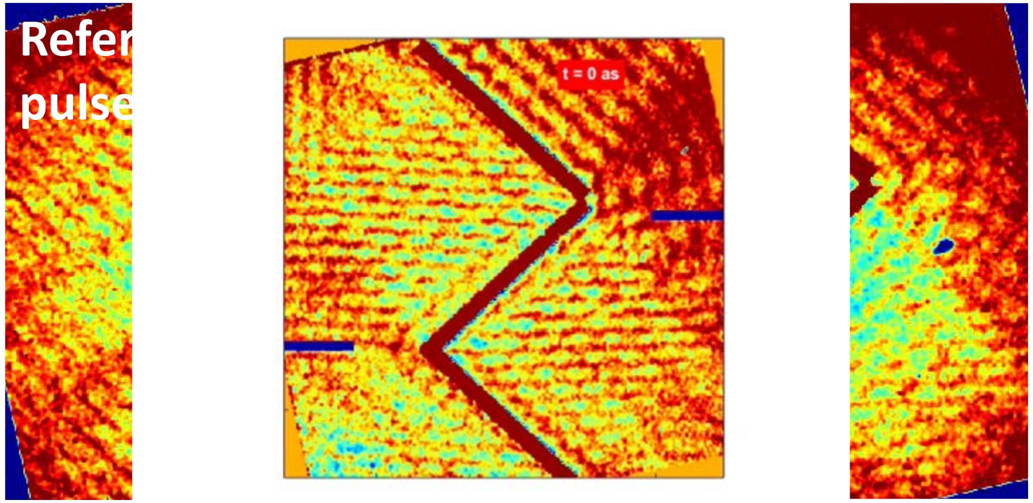
IMAGING TECHNIQUES

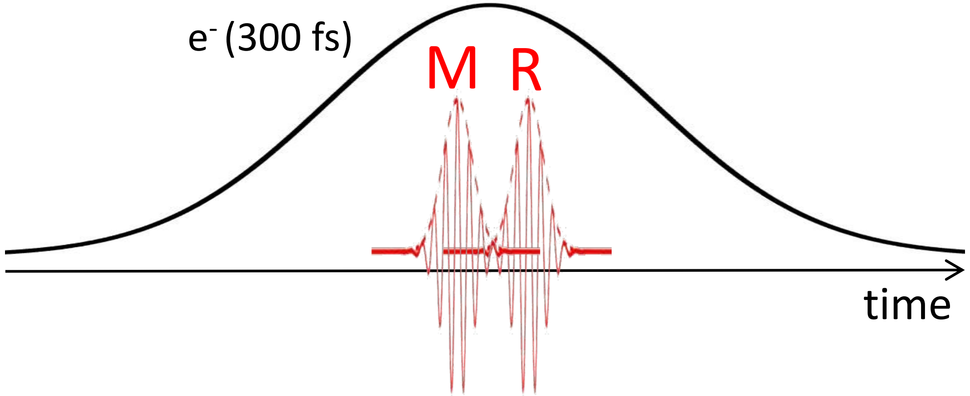
Light scatters electrons to make holograms

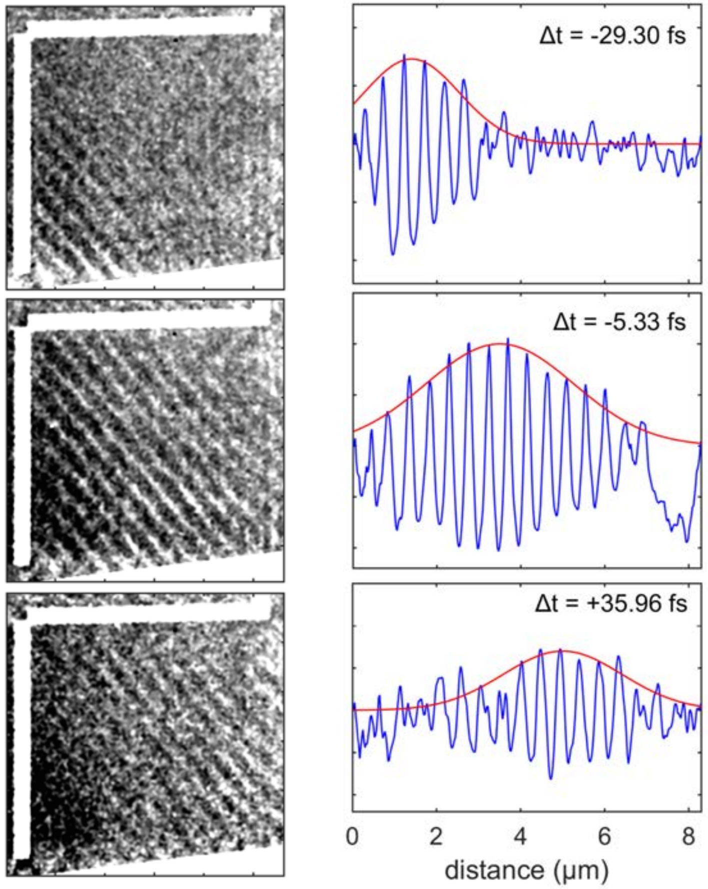
CLAUS ROPERS

as-nm microscopic **quantum holography** of guided light in a nanostructure
Image the sample with WF-manipulated e$^-$

Holography of plasma resonance



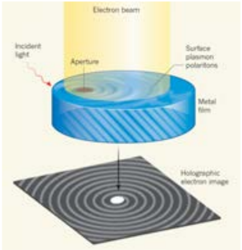




- Attosecond mapping of plasmon propagation
- Direct measurement of group and phase velocity

Madan et al, **Science Advances** 6 eaav8358 (2019)
News and Views article: Ropers, **Nature** 571, 331 (2019)

https://actu.epfl.ch/news/new-holographic-technique-opens-the-way-for-quantu/
https://www.youtube.com/watch?v=s2iiBbTuZn4&feature=emb_logo



Article

Attosecond electron microscopy of sub-cycle optical dynamics

https://doi.org/10.1038/s41586-023-06074-9
Received: 12 October 2022
Accepted: 12 April 2023

David Nabben[1,2], Joel Kuttruff[1,2], Levin Stolz[1], Andrey Ryabov[1] ✉ & Peter Baum[1] ✉

The primary step of almost any interaction between light and materials is the electrodynamic response of the electrons to the optical cycles of the impinging light wave on sub-wavelength and sub-cycle dimensions[1]. Understanding and controlling the electromagnetic responses of a material[2–11] is therefore essential for modern optics and nanophotonics[12–19]. Although the small de Broglie wavelength of electron beams should allow access to attosecond and ångström dimensions[20], the time resolution of ultrafast electron microscopy[21] and diffraction[22] has so far been limited to the femtosecond domain[16–18], which is insufficient for recording fundamental material responses on the scale of the cycles of light[1,2,10]. Here we advance transmission electron microscopy to attosecond time resolution of optical responses within one cycle of excitation light[23]. We apply a continuous-wave laser[24] to modulate the electron wave function into a rapid sequence of electron pulses, and use an energy filter to resolve electromagnetic near-fields in and around a material as a movie in space and time. Experiments on nanostructured needle tips, dielectric resonators and metamaterial antennas reveal a directional launch of chiral surface waves, a delay between dipole and quadrupole dynamics, a subluminal buried waveguide field and a symmetry-broken multi-antenna response. These results signify the value of combining electron microscopy and attosecond laser science to understand light–matter interactions in terms of their fundamental dimensions in space and time.

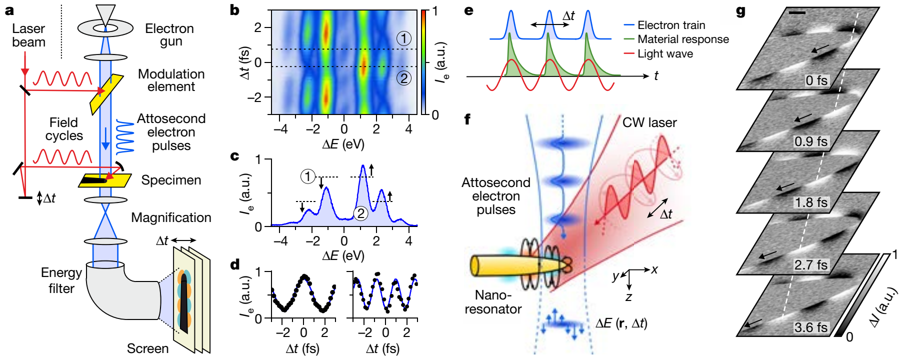


Fig. 1 | Attosecond field-cycle-contrast electron microscopy. a, A continuous-wave (CW) laser (red) excites a compression membrane (yellow) and a nanophotonic material (black). A train of attosecond electron pulses (blue) probes the material and energy changes are recorded as a function of the time delay, Δ*t*. **b**, Measured time–energy spectrogram with asymmetric gains and losses. The material is a 200-nm-thick silicon membrane. I_e, electron current; a.u., arbitrary units. **c**, Measured maximum-gain spectrum at delay 2 in comparison with the sideband levels at delay 1. Black arrows show the direction of change. **d**, Time traces at $\Delta E = hc/\lambda$ (left) and $\Delta E = 0$ (right). **e**, Timing in our microscopy. We can resolve all processes that are reversible within one optical-cycle period. Image shows light wave (red), electron train (blue) and material response (green). **f**, Details of our first experiment. Attosecond electron pulses (blue) probe the *z*-component of the local electric fields (orange and cyan) around a tungsten needle (yellow) as a function of space (**r**) and delay time (Δ*t*). Light-cycle contrast appears because of spatiotemporal electron energy changes, $\Delta E(\mathbf{r},\Delta t)$. **g**, Measured energy-gain images for varying times within one optical cycle of the exciting laser wave. Regions of energy gain (white) and energy loss (black) are resolved with nanometre and attosecond precision. Black arrows and white line indicate the space–time propagation. Scale bar, 500 nm. Δ*I* is electron current change. See Supplementary Video 1 for full data.

LETTERS
https://doi.org/10.1038/s41567-017-0007-6
nature physics

Diffraction and microscopy with attosecond electron pulse trains

Yuya Morimoto[1,2] and Peter Baum[1,2*]

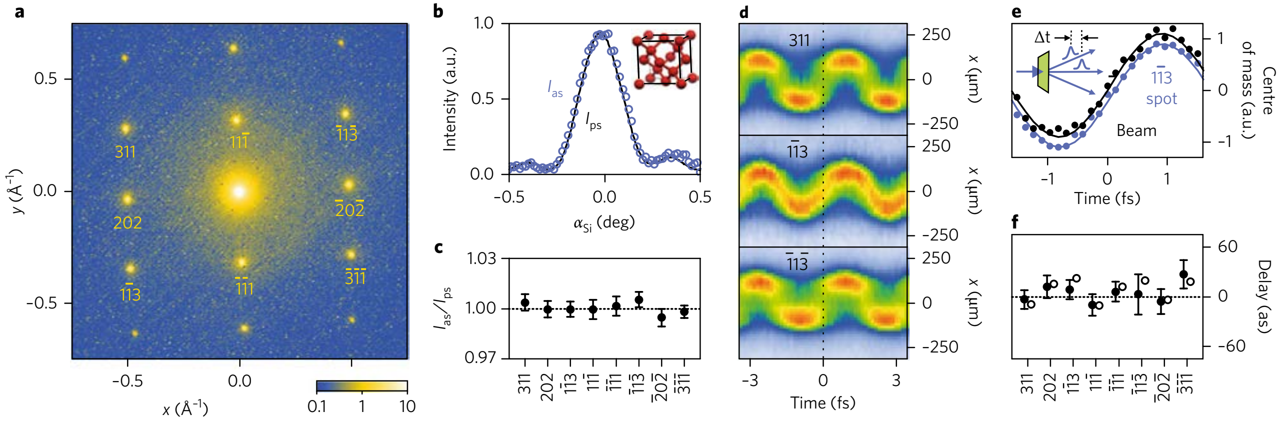


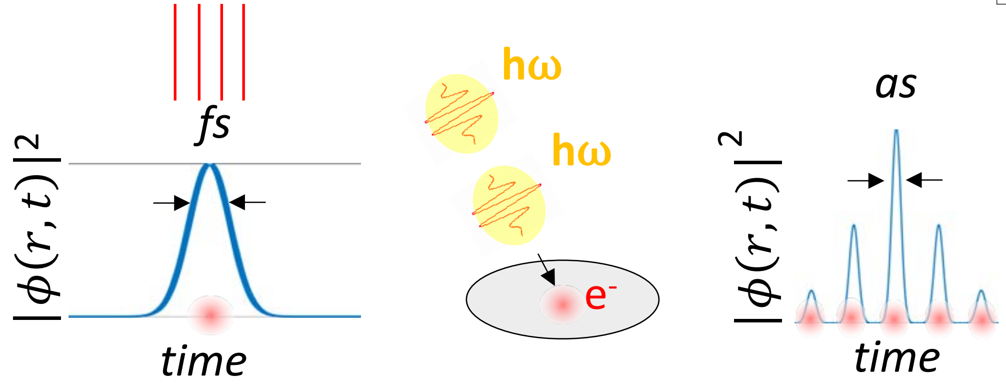
Fig. 3 | Atomic diffraction with attosecond electron pulses. a, Diffraction pattern of single-crystalline silicon, taken with the attosecond electron pulse train. The non-labelled Bragg spots are forbidden but visible via multiple scattering. **b**, Rocking curve of the $1\bar{1}3$ spot for picosecond pulses in comparison with the attosecond electron pulse train. Inset, crystal structure of silicon. **c**, Absolute intensity of all Bragg spots, measured with the attosecond pulses and normalized to the picosecond case. The error bars denote the shot noise of the measurement (~140 s integration). **d**, Streaking deflectograms of three example Bragg spots; all of them behave similarly. **e**, Centre-of-mass of the deflectogram of the $1\bar{1}3$ spot versus the direct beam for delay analysis. Inset, illustration of delays in Bragg spot emission. **f**, Measured attosecond-level delay of different Bragg spot emissions with respect to the direct beam. The filled and open circles are the results of centre-of-mass analysis and deflectogram fitting, respectively. The error bars represent standard deviation. The average delay is (4.6 ± 5.4) as.

Attosecond coherent control of free-electron wave functions using semi-infinite light fields

Vanacore et al, **9** 2694 (2018)

$$\phi(r,t) = e^{(ikr-\omega t)}$$

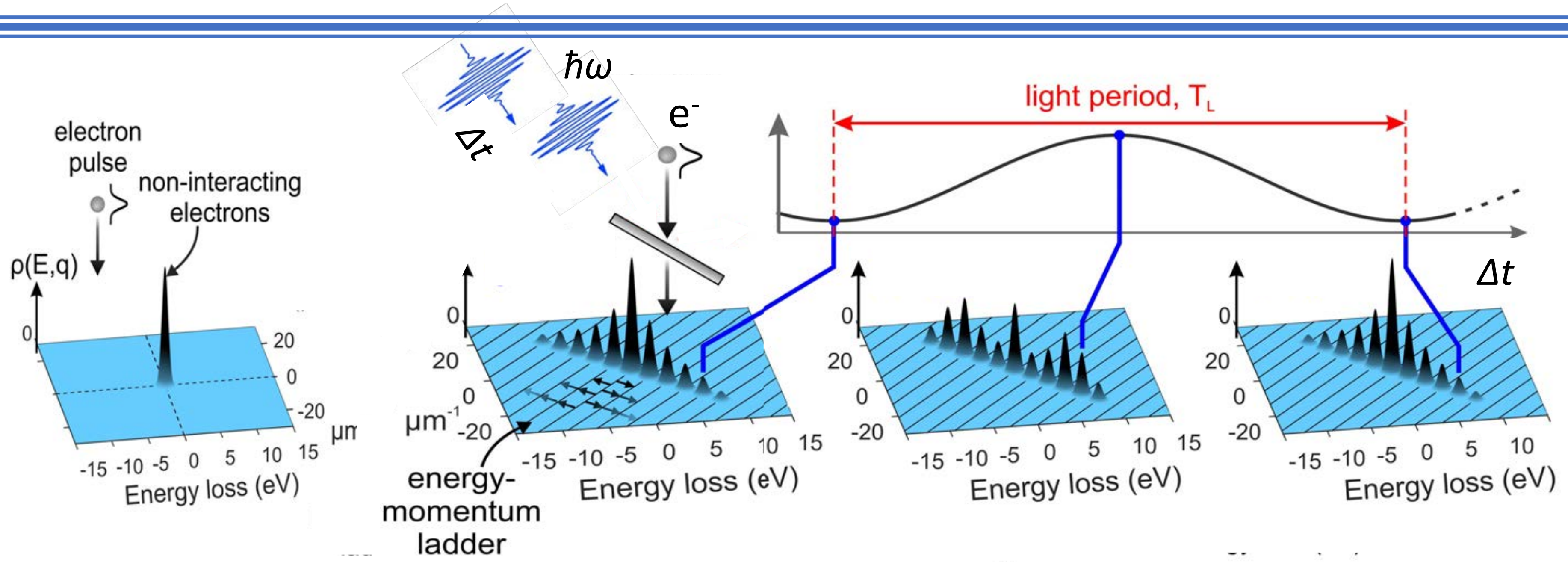
$$\phi(\mathbf{r},t) = \phi_0(\mathbf{r} - \mathbf{v}t) \boxed{\sum_{\ell=-\infty}^{\infty} J_\ell(2|\beta|)\mathrm{e}^{\mathrm{i}\ell\,\arg\{-\beta\}+\mathrm{i}\ell\omega(z/v-t)}}$$

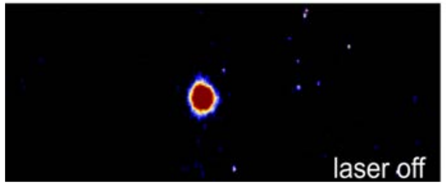


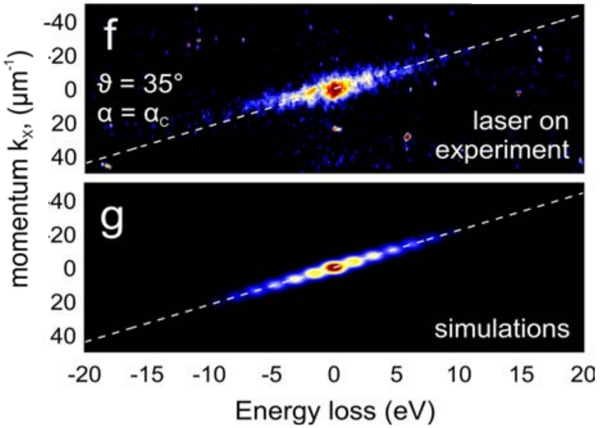
Temporal Tomography of the e⁻ wavefunction

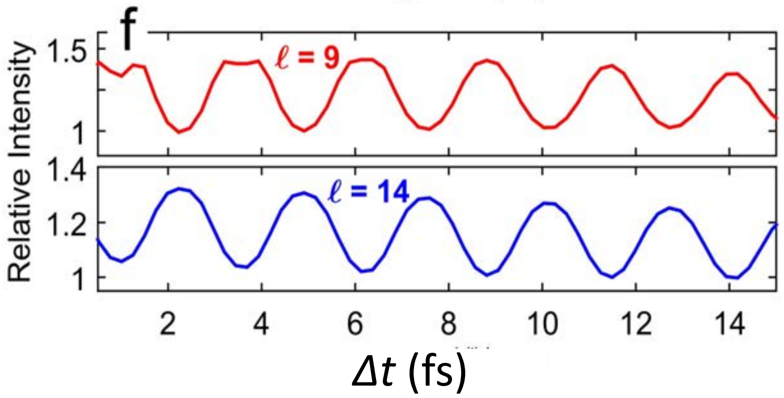
Image electrons

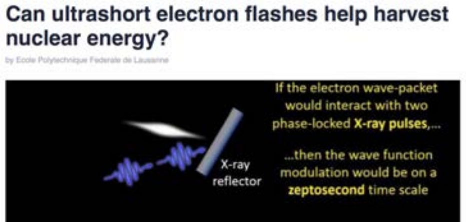
Coherent control of the longitudinal electron wavefunction by transition radiation











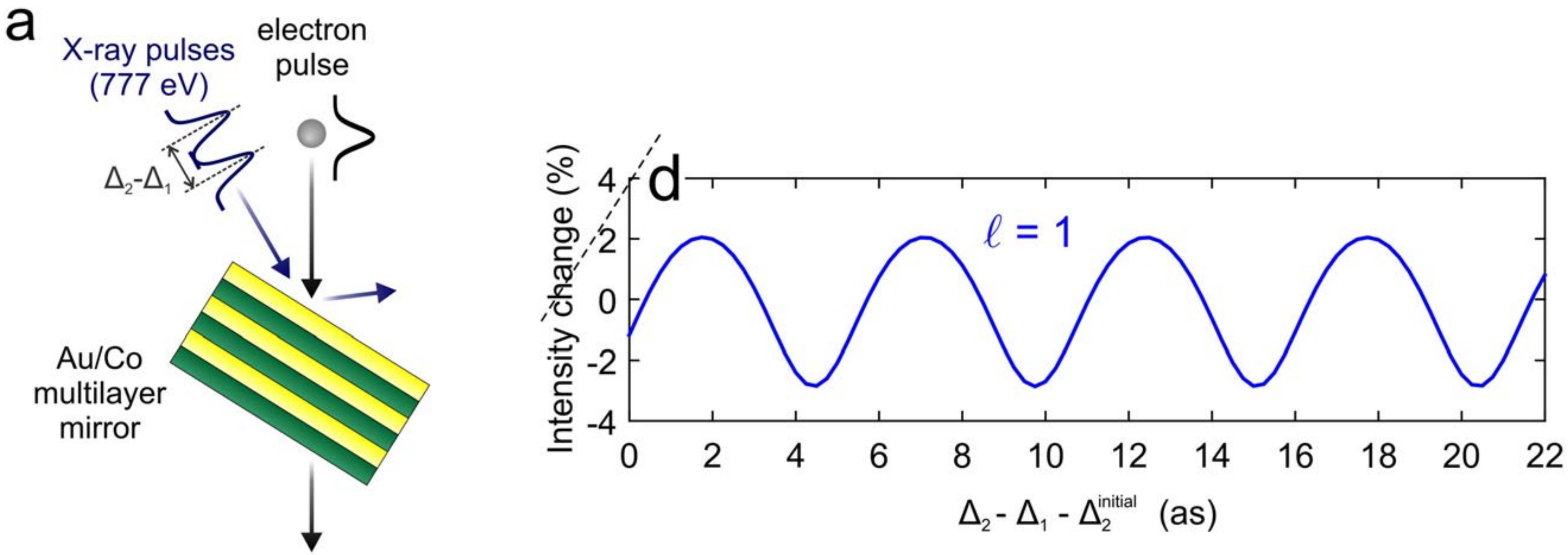
Can ultrashort electron flashes help harvest nuclear energy?

by Ecole Polytechnique Federale de Lausanne

Vanacore, et al **Nat. Comm** 9 2694 (2018)

https://phys.org/news/2018-07-ultrashort-electron-harvest-nuclear-energy.html

Zeptoseconds (10^{-21}) electron pulses



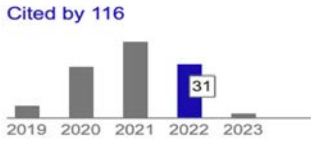
Zeptosecond physics:

- Nuclear processes (electron capture, core-level photoemission)
- Intramolecular processes (charge transfer)

Ultrafast generation and control of an electron vortex beam via chiral plasmonic near fields

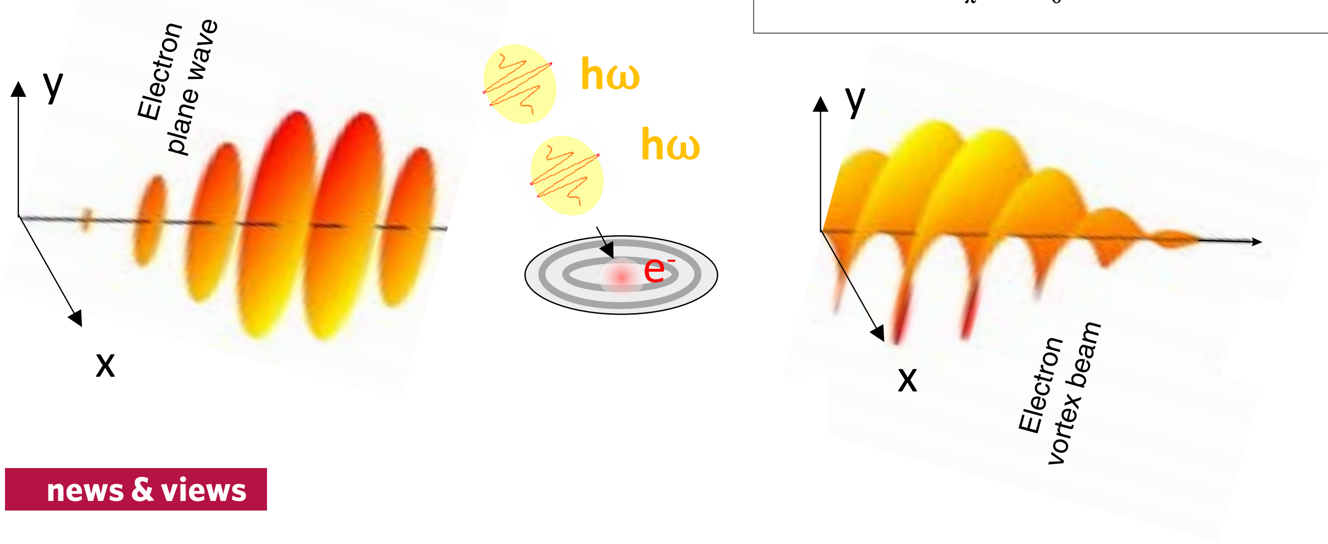
nature materials

Vanacore et al., **18** 573 (2019)



$$\phi(r,t) = e^{(ikr-\omega t)}$$

$$\phi(r) = \int_{-\pi}^{\pi} \mathrm{d}\phi \int_{0}^{+\infty} R\mathrm{d}R \exp(-i\mathbf{k}_{\perp}\cdot\mathbf{R})\psi_{\ell}(R,\phi)$$



news & views

PHOTONICS

Vorticity induced by chiral plasmonic fields

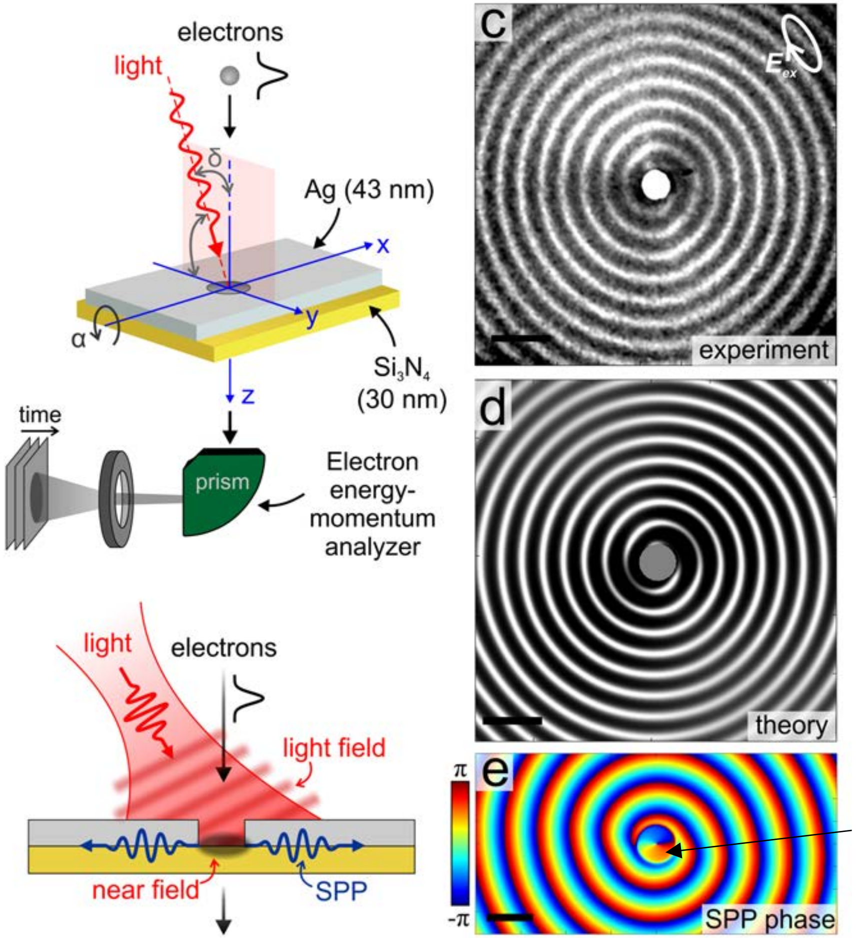
Coherent shaping of matter waves in temporal and spatial domains by photon-induced near fields opens up new possibilities for the quantum control of matter.

Jun Yuan

Spatial Tomography of the e$^-$ wavefunction

Image the electrons

Coherent control of the transverse electron wavefunction



- Chiral SPP launched by elliptically polarized light

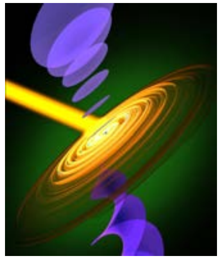
- Simulated Chiral SPP

- A chiral plasmonic field can impart a phase singularity onto the transverse component of an e^- wavefunction

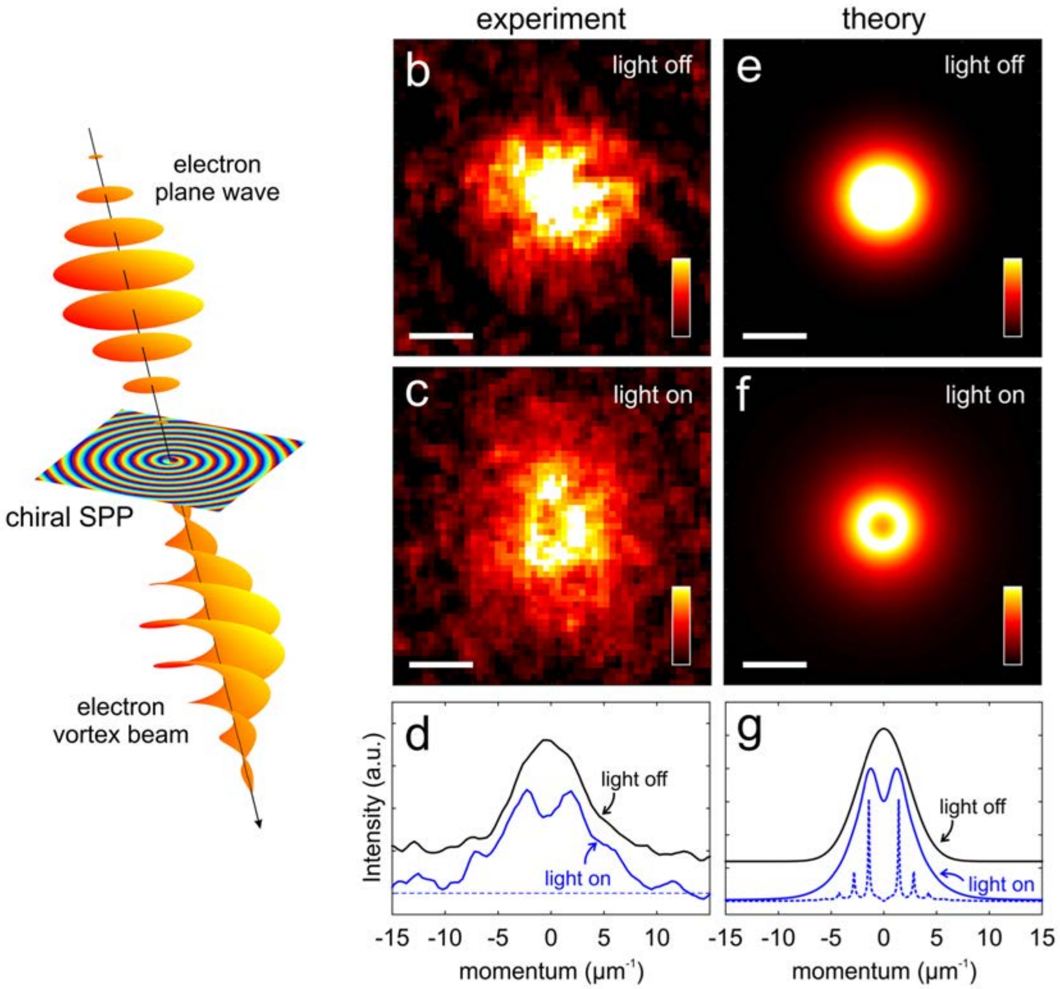
Vanacore et al., **Nature Materials** 18, 573 (2019)

New and Views article: Jun Yuan **Nature Materials** 18, 533 (2019)

https://actu.epfl.ch/news/twisting-whirlpools-of-electrons/
https://www.youtube.com/watch?time_continue=5&v=TIJ-mlh2LSI&feature=emb_logo



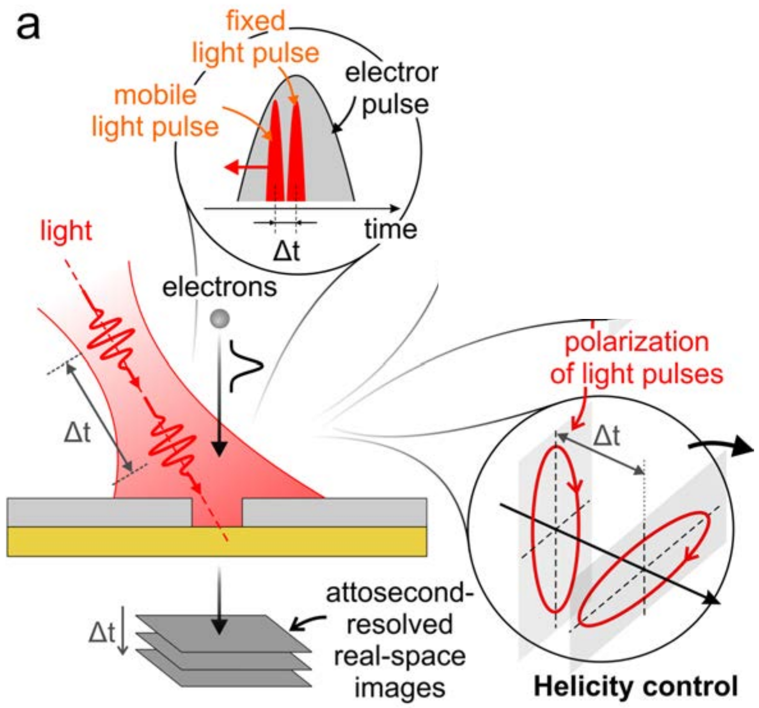
Generation of electron vortex beams

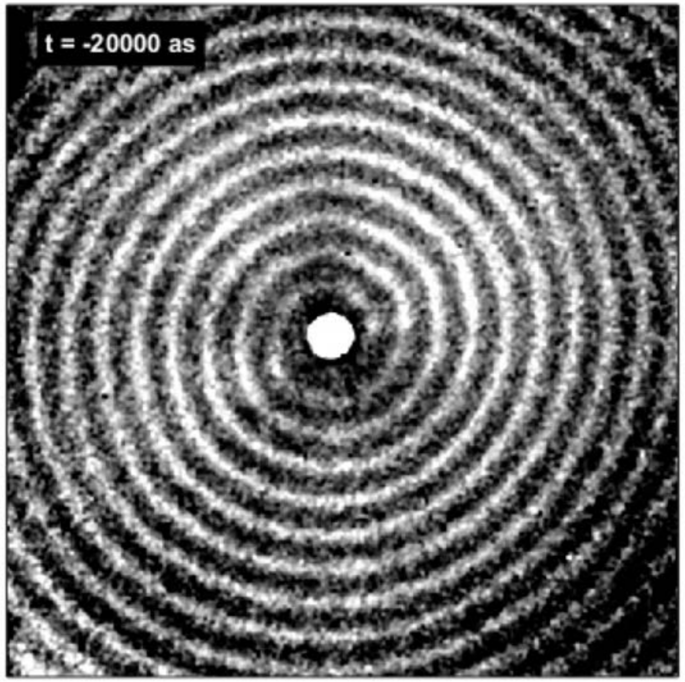


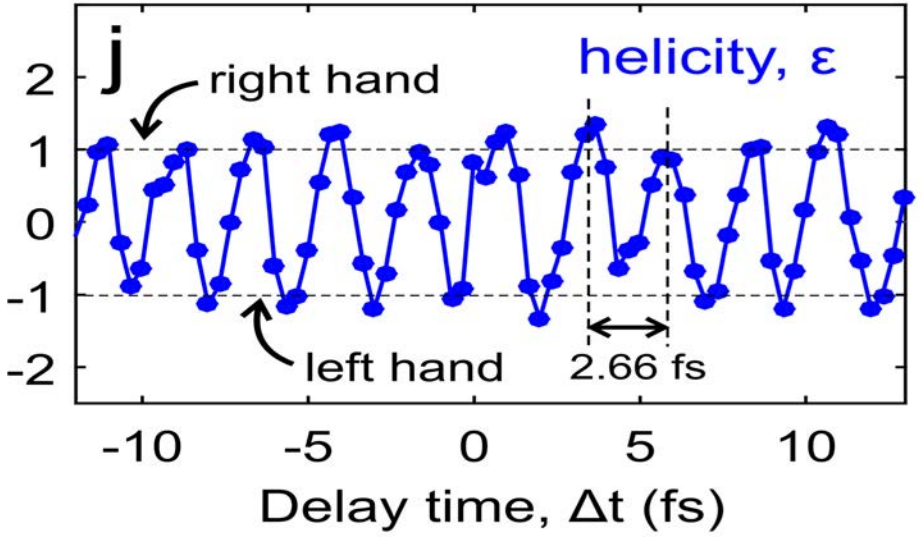
Electron wavefunction microscopy
in momentum space

Vanacore et al., **Nature Materials** 18, 573 (2019)

Coherent control of vortex beams





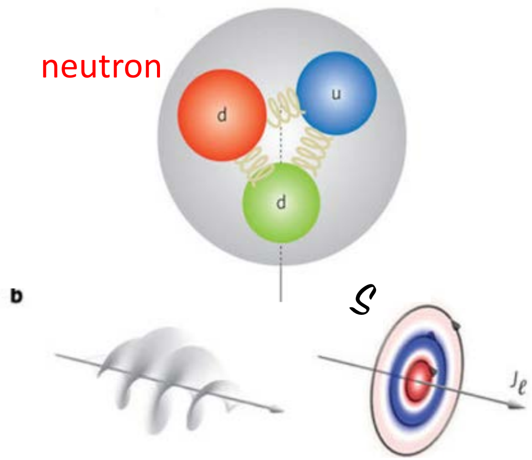


Three pulses experiment: attosecond control of the topological charge of an e$^-$ wavefunction between +1 and. -1

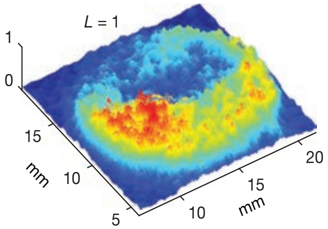
Vanacore et al., **Nature Materials** 18, 573 (2019)

Application of vortex beams

Twisted neutrons



Neutron orbital angular momentum



Make a particle with a fine structure spiral reveals its inner structure

- Can we twist protons as well?
- Can we twist atoms and ions?
- Exploit the different radiation/matter interaction for selective tissue ablation (ongoing project with ADAM and CERN)

Vortex beams, magnetic sensing

- Spin-polarized TEM does not exist yet
- Left handed/right handed vortex beams are sensitive to magnetization orientation
- Transfer topological charge from e^- vortex beam to spins in materials

Clark et al., Nature 525, 504 (2015)

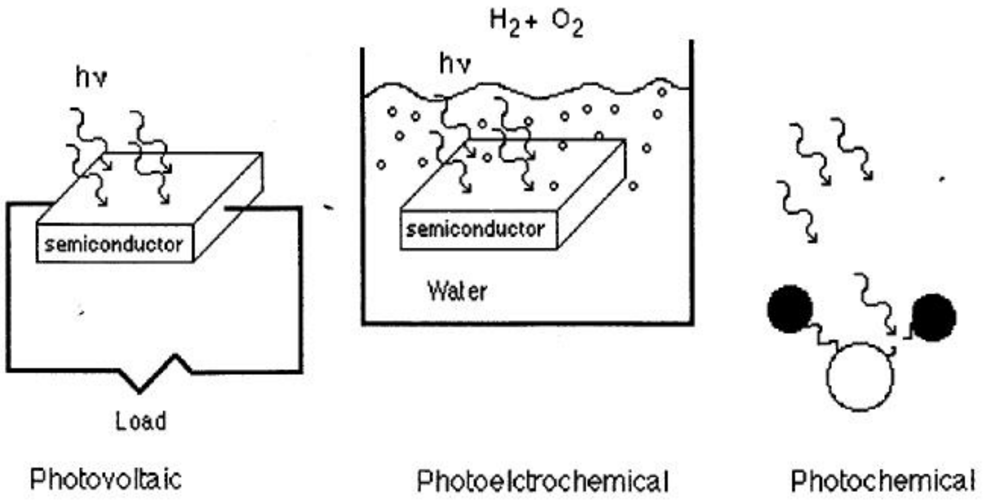
Laroque et al., Nat. Phys. 14 1 (2018)

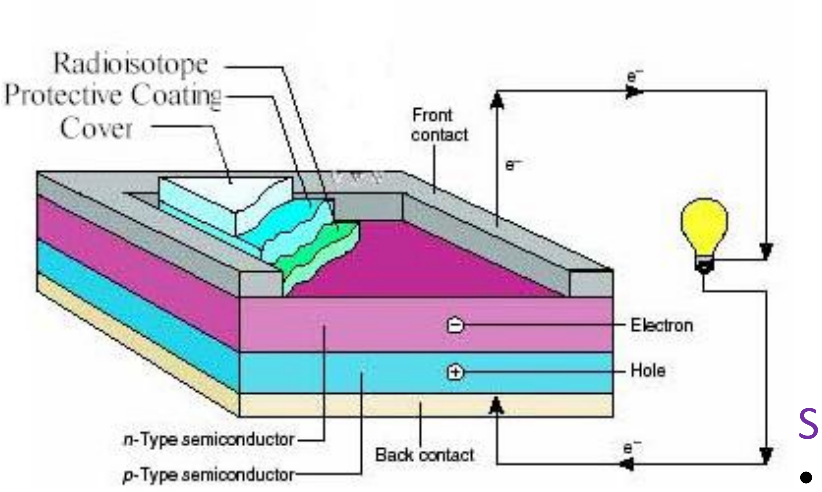
Coherent control of nuclear reactions

Manipulating the element transmutation

Dreamt of: 1600
Observed and used: 1950s to now
Controlled: **not yet**

Nuclear batteries



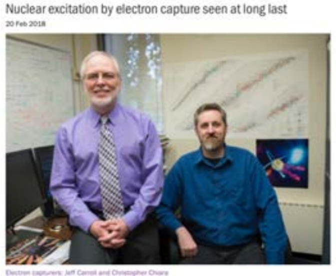


Nuclear

Major plus
- 4-5 orders of magnitude higher **energy** density
- Long-lasting (even 100s of years, use in satellites)

Major minus
- Low **power** density (slow energy release process)
- Dangerous/poisonous materials (not eco-friendly)
- Low nuclear to electric energy conversion efficiency

Solutions:
- Control decay-rates: control power delivery
- Transiently induce radioactivity in stable elements: reduce environmental hazard, cost, danger
- Electrons and light technology can be integrated. Common nuclear technology cannot



Nuclear excitation by electron capture seen at long last

20 Feb 2018

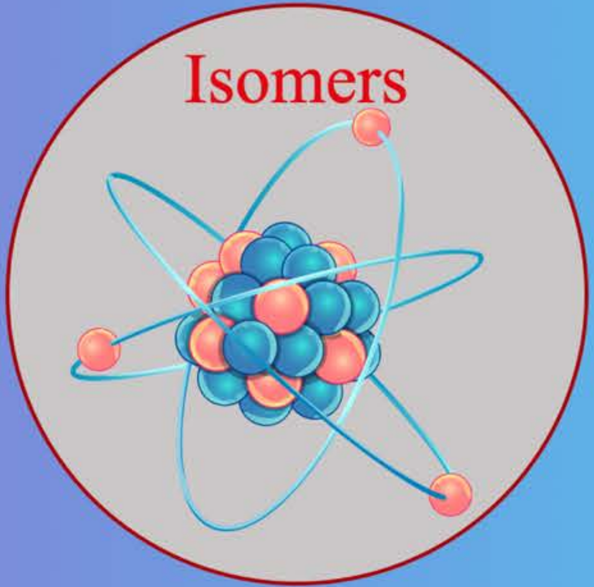
Electron capturers: Jeff Carroll and Christopher Chiara

https://physicsworld.com/a/nuclear-excitation-by-electron-capture-seen-at-long-last/

Essence and Significance of Isomers

Astrophysical Plasma

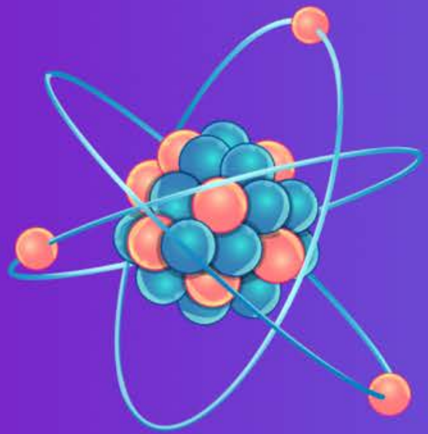
Medicine



Compact energy storage

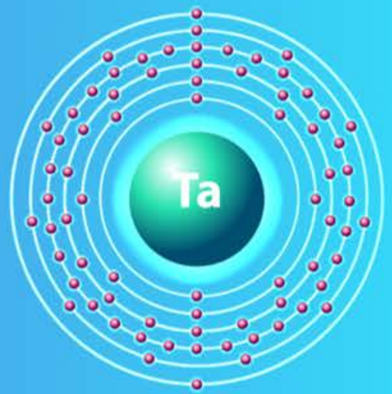
Optical Nuclear Clocks

Dark Matter Search



^{235}U fission releases 200 MeV/nucleus

~ TJ in a hour



De-excitation of ^{180m}Ta isomeric state releases 77 keV, $t_{1/2} > 10^{16}\ yr$

1 cm^3 of pure ^{180m}Ta can release 690 MJ

1 cm^3 of pure ^{178}Hf can release 17 GJ

Has yet to be discovered an efficient releasing mechanism.

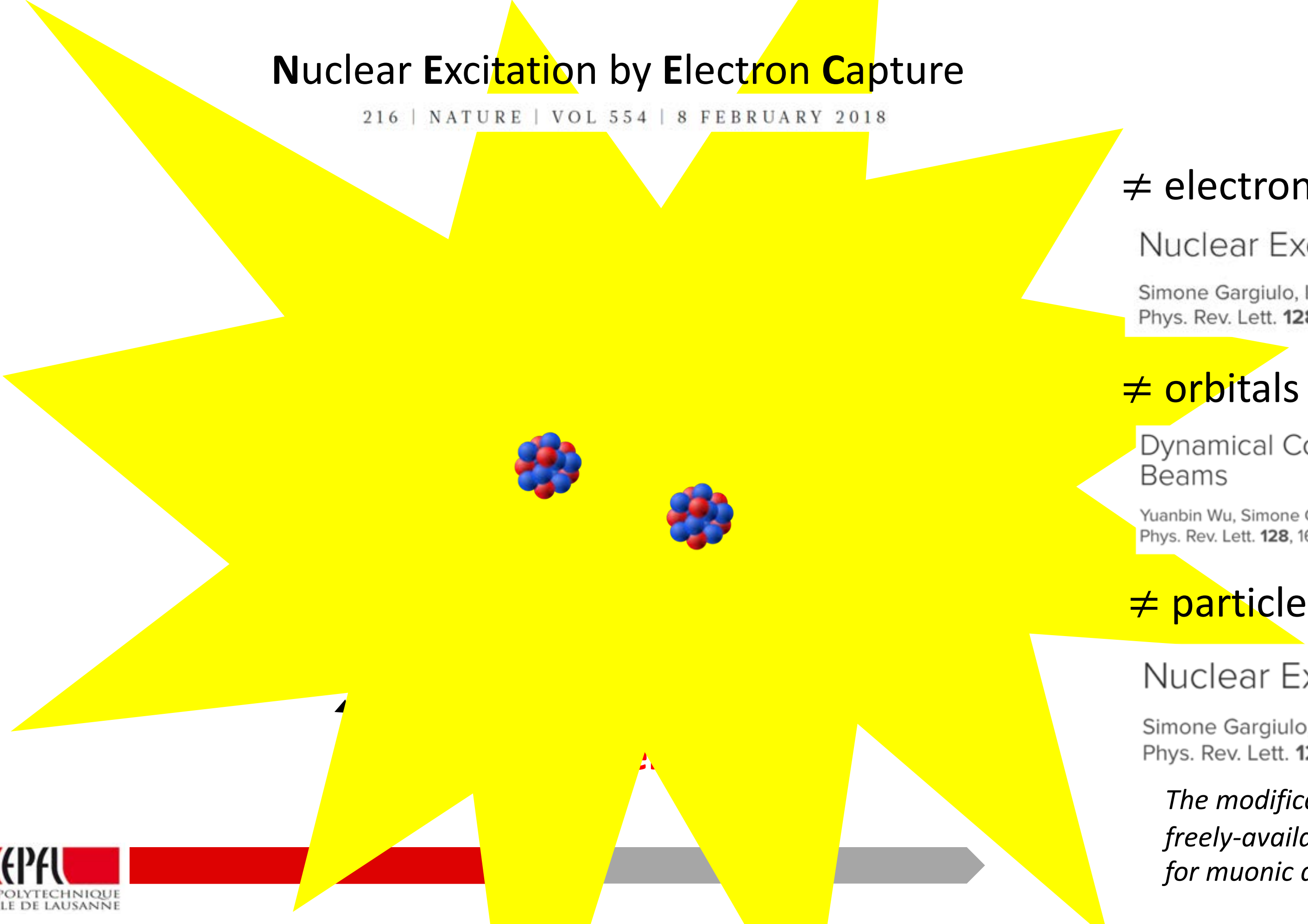
Coherent control of nuclei

Can we use out of equilibrium methods to control the release of nuclear energy?

- Speed up the decay of nuclear waste
- Engineer long-lasting/high power nuclear batteries
- Induce radioactivity on demand in stable atoms

Nuclear **E**xcitation by **E**lectron **C**apture

216 | NATURE | VOL 554 | 8 FEBRUARY 2018



$\neq$ electronic configurations $\neq$ channels available

Nuclear Excitation by Electron Capture in Excited Ions

Simone Gargiulo, Ivan Madan, and Fabrizio Carbone
Phys. Rev. Lett. **128**, 212502 – Published 27 May 2022

$\neq$ orbitals $\neq$ cross section (10^6 higher!)

Dynamical Control of Nuclear Isomer Depletion via Electron Vortex Beams

Yuanbin Wu, Simone Gargiulo, Fabrizio Carbone, Christoph H. Keitel, and Adriana Pálffy
Phys. Rev. Lett. **128**, 162501 – Published 22 April 2022

$\neq$ particles $\neq$ effect (induced fission)

Nuclear Excitation by Free Muon Capture

Simone Gargiulo, Ming Feng Gu, Fabrizio Carbone, and Ivan Madan
Phys. Rev. Lett. **129**, 142501 – Published 27 September 2022

The modifications of the FAC code made it the only freely-available online tool that can solve the Dirac equations for muonic atoms

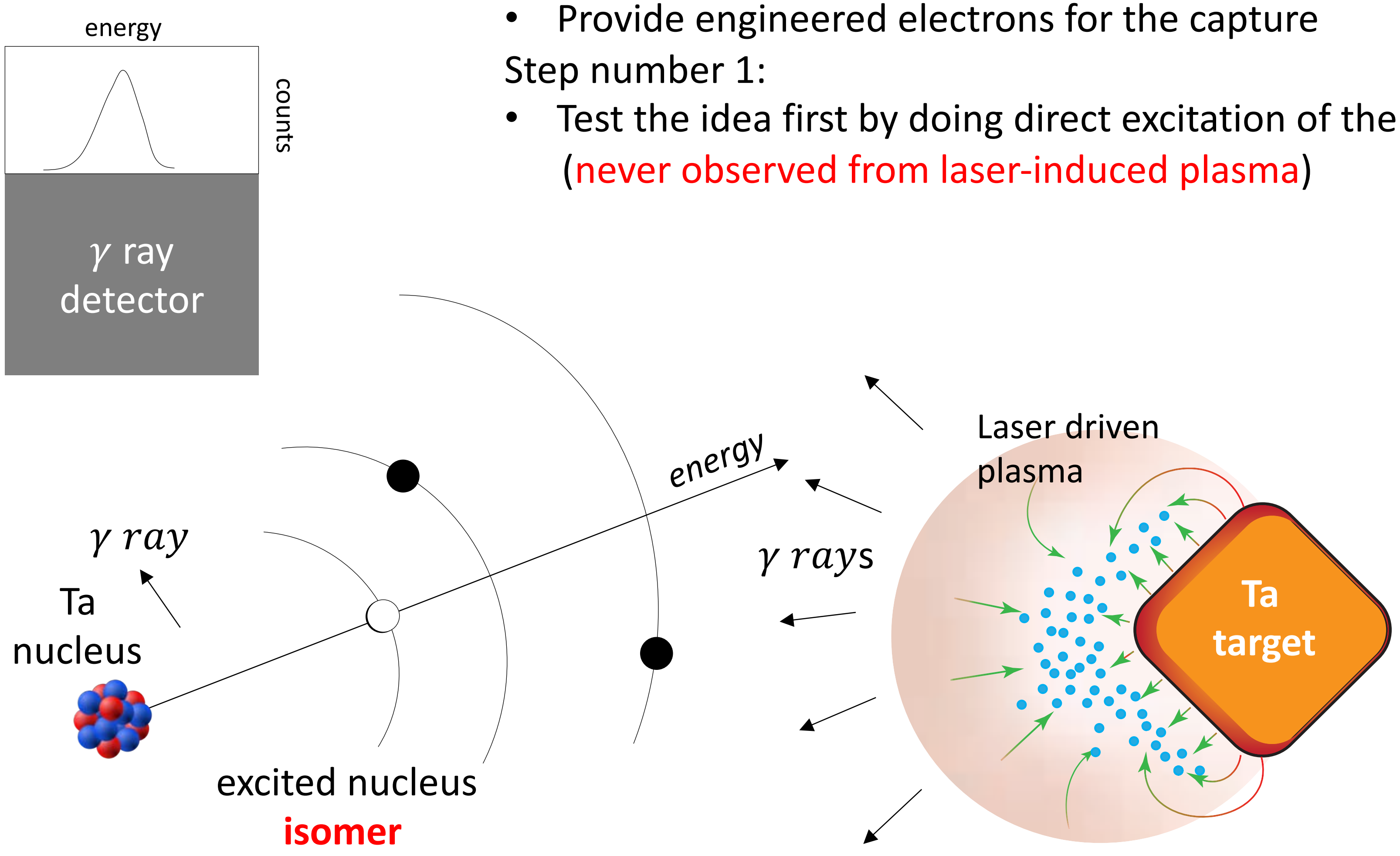
Experimental Implementation

Logic:

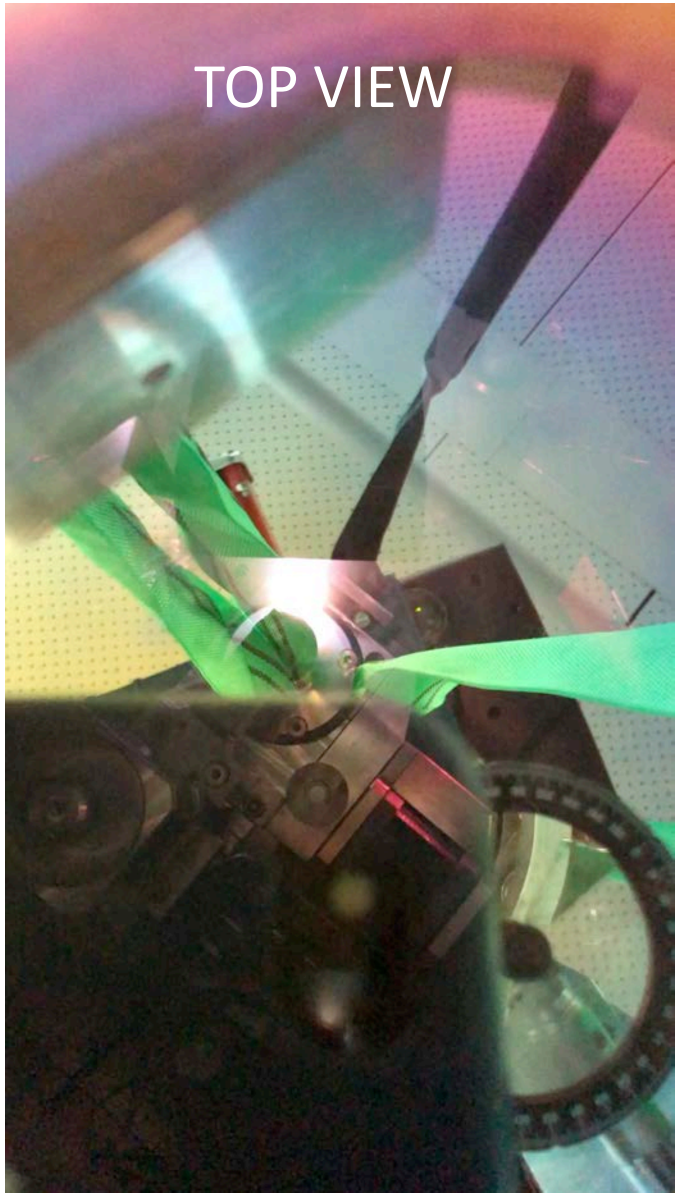
- Induce vacancies with laser in the correct orbital
- Provide engineered electrons for the capture

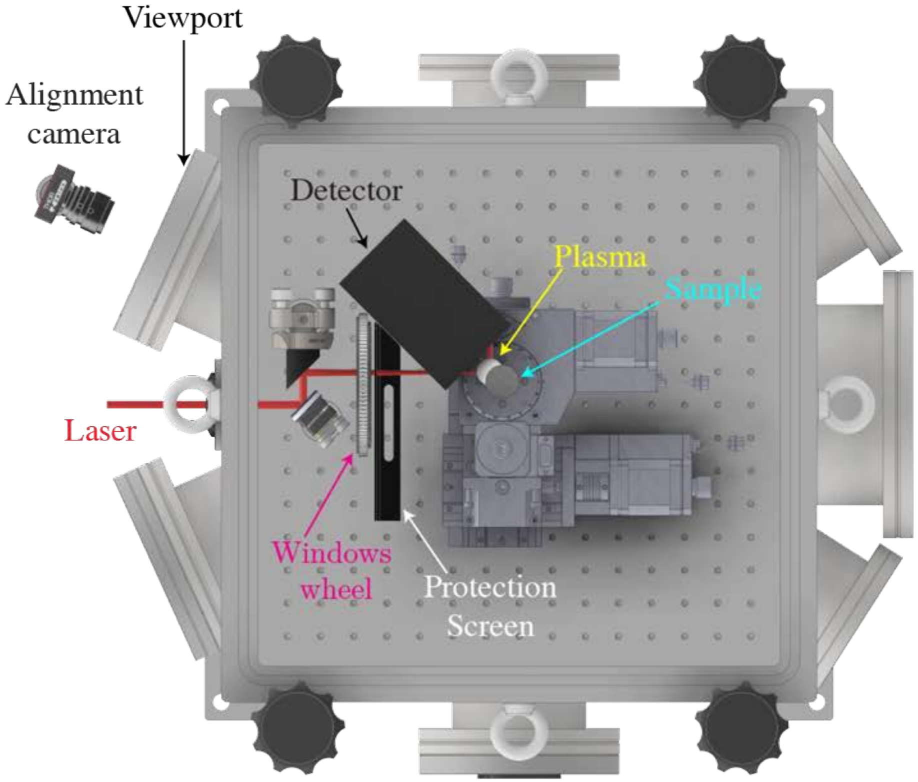
Step number 1:

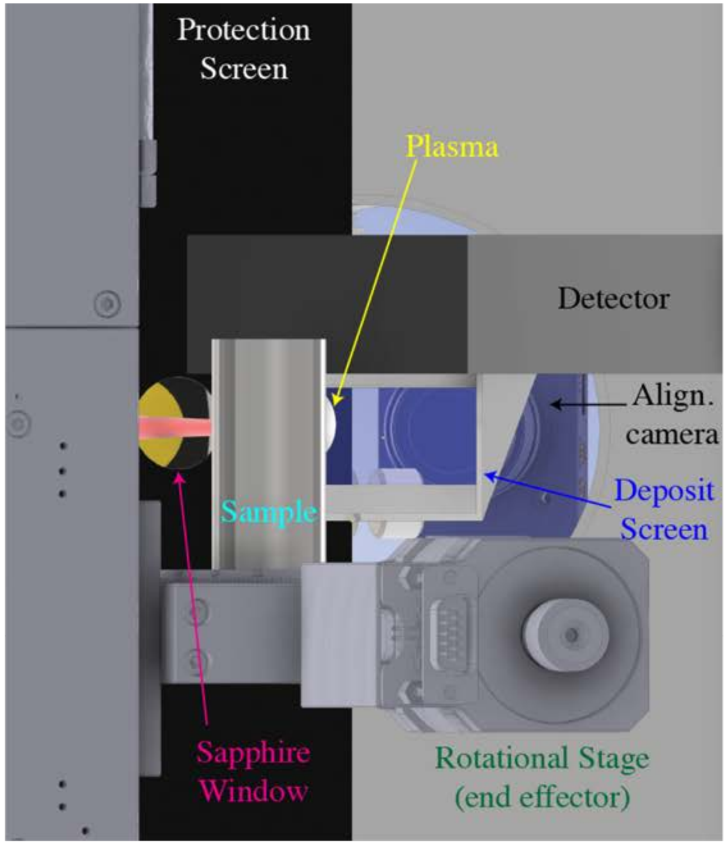
- Test the idea first by doing direct excitation of the nucleus (never observed from laser-induced plasma)



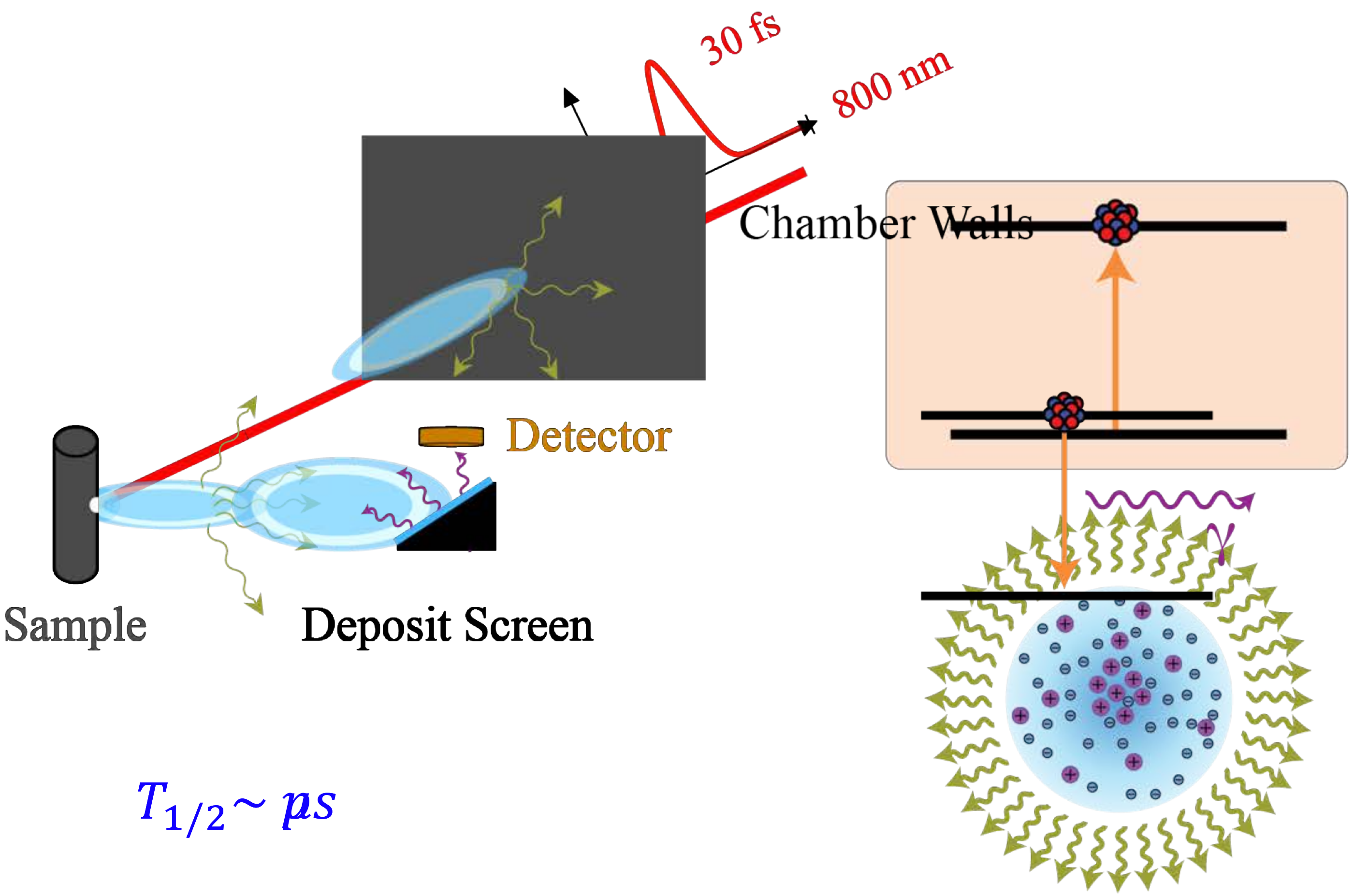
Our Experimental Setup







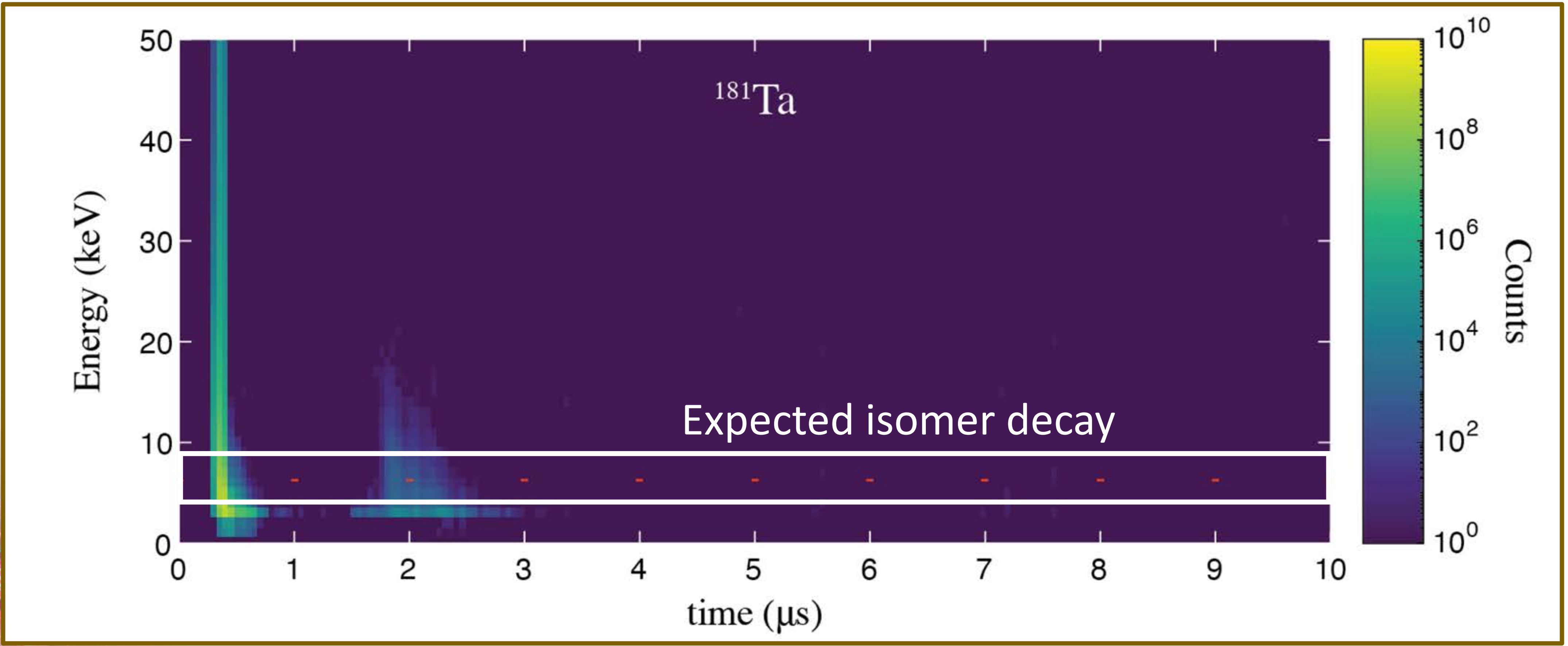
Dynamics of Events in Laser-Plasma scenario



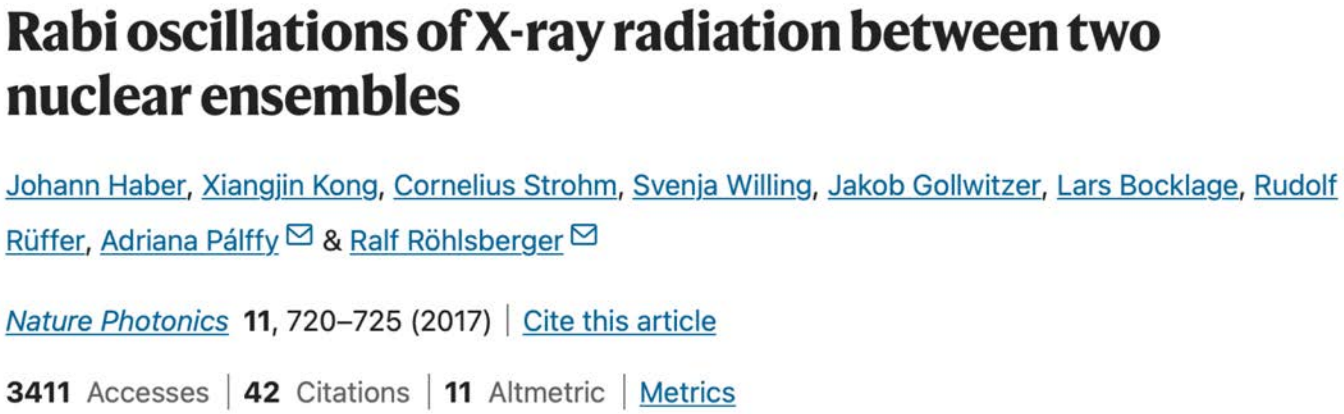
$T_{1/2} \sim ps$

Experimental Results

~10 billion counts



According to Andreev *et al.*, expected $\sim 10^6 - 10^7$ **IMPOSSIBLE**



Rabi oscillations of X-ray radiation between two nuclear ensembles

Johann Haber, Xiangjin Kong, Cornelius Strohm, Svenja Willing, Jakob Gollwitzer, Lars Bocklage, Rudolf Rüffer, Adriana Pálffy ✉ & Ralf Röhlsberger ✉

Nature Photonics **11**, 720–725 (2017) | Cite this article

3411 Accesses | **42** Citations | **11** Altmetric | Metrics

Exploit Fe57 Mossbauer resonance (absorption without recoil, momentum absorbed my coupled atom)

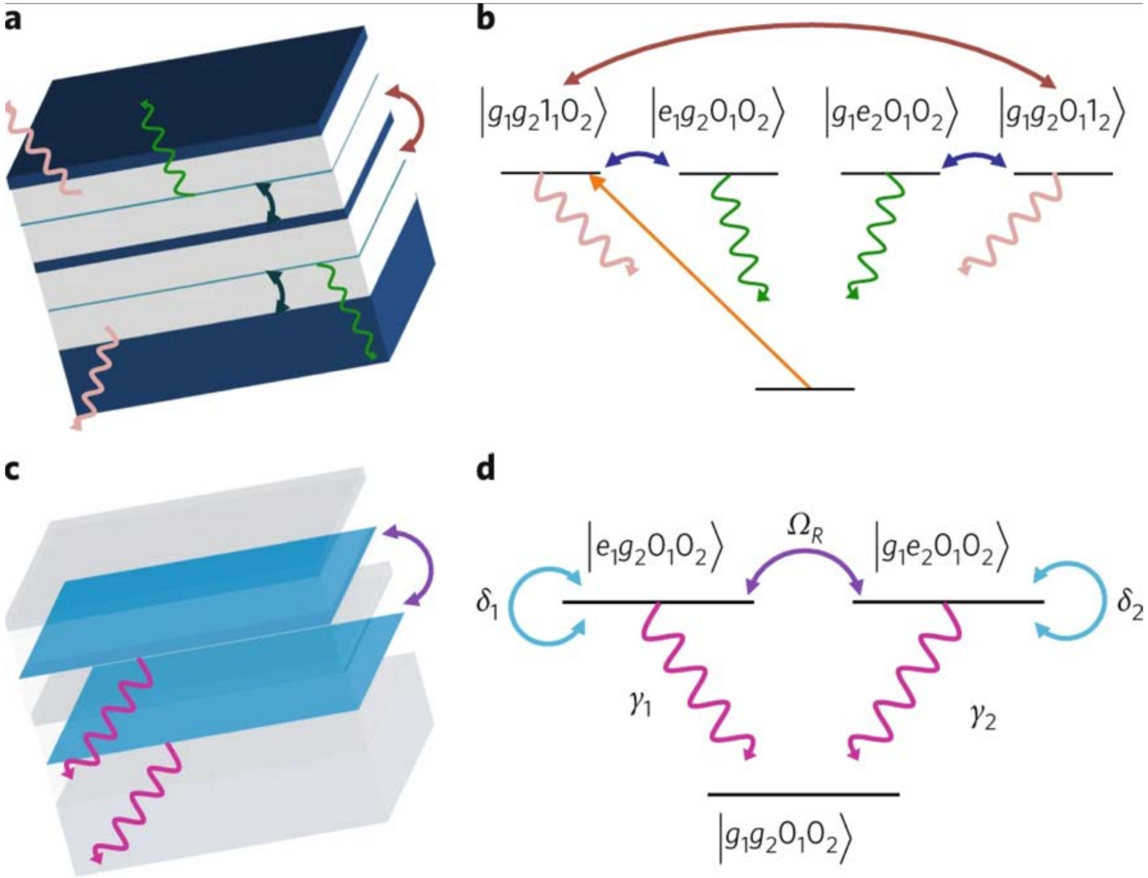
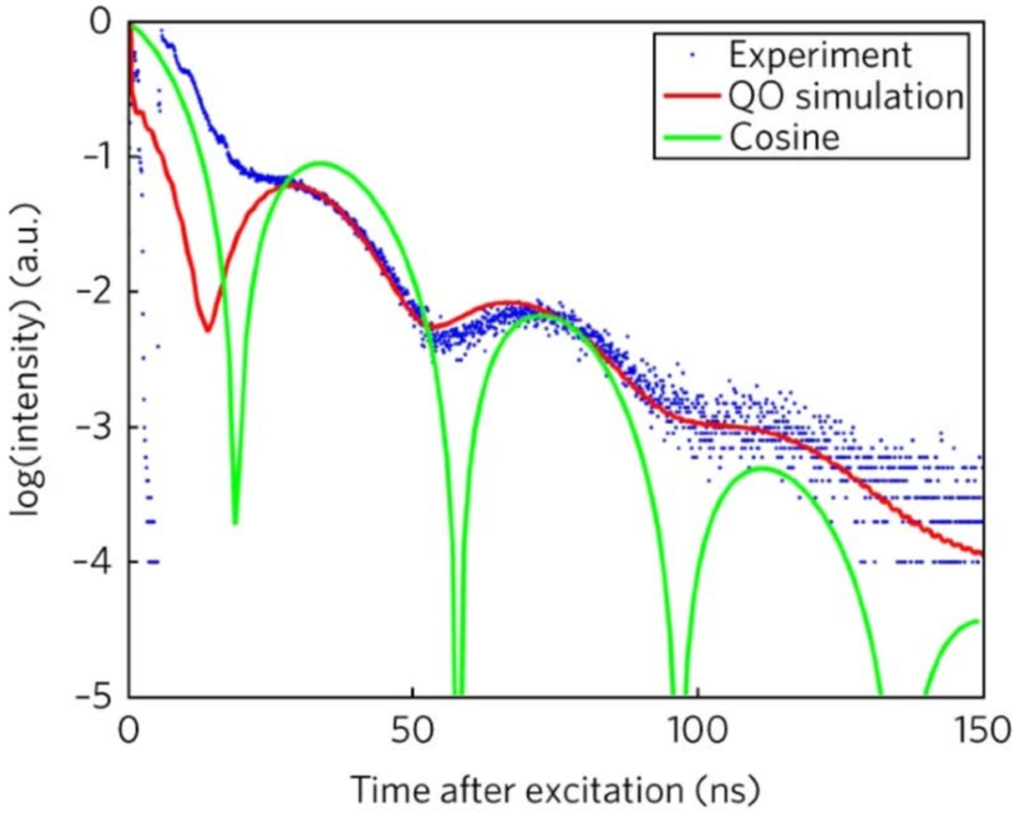


Fig. 3: Measurement of Rabi oscillations



PHYSICAL REVIEW LETTERS

Output Coupler for Bose-Einstein Condensed Atoms

M.-O. Mewes, M. R. Andrews, D. M. Kurn, D. S. Durfee, C. G. Townsend, and W. Ketterle
Phys. Rev. Lett. **78**, 582 – Published 27 January 1997

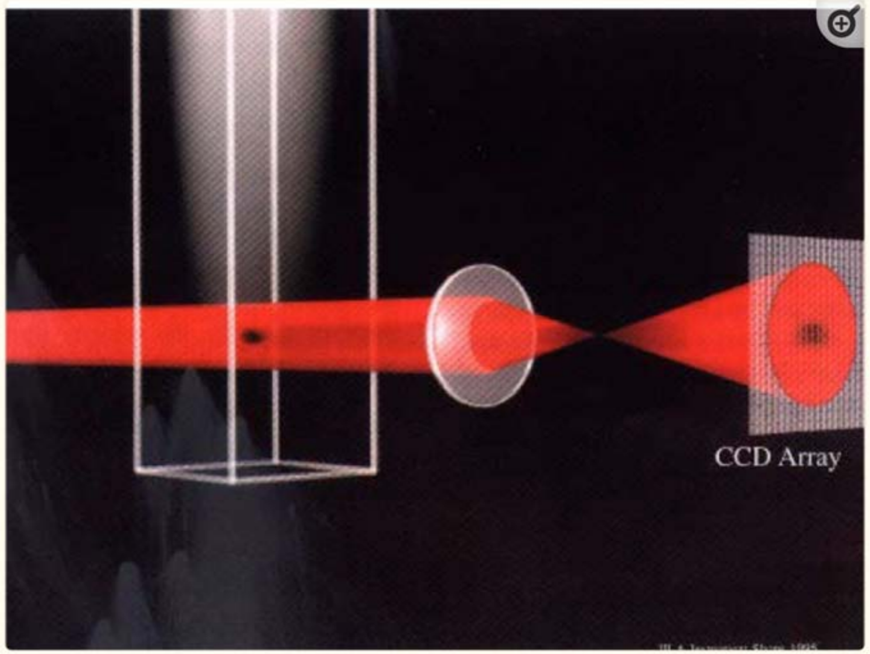
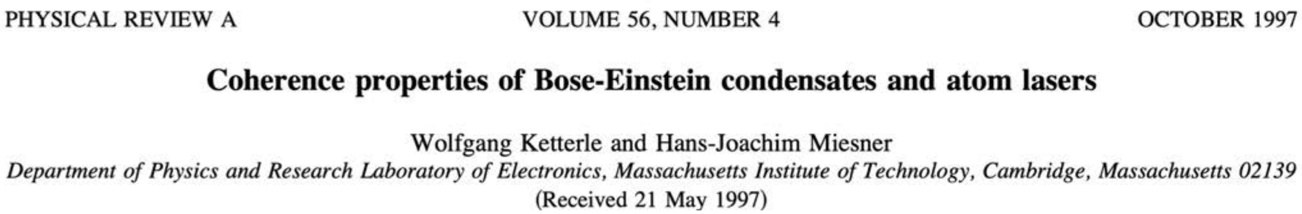


Fig. 10

How atomic clouds are imaged.

Ultracold atoms in a trap condense (BEC)
The trap can be an EM field that can be impulsively switched off by a RF pulse letting a beam of atoms evaporate in a specific Directin (determined by the trap shape and RF pulse shape)



PHYSICAL REVIEW A VOLUME 56, NUMBER 4 OCTOBER 1997

Coherence properties of Bose-Einstein condensates and atom lasers

Wolfgang Ketterle and Hans-Joachim Miesner
Department of Physics and Research Laboratory of Electronics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139
(Received 21 May 1997)

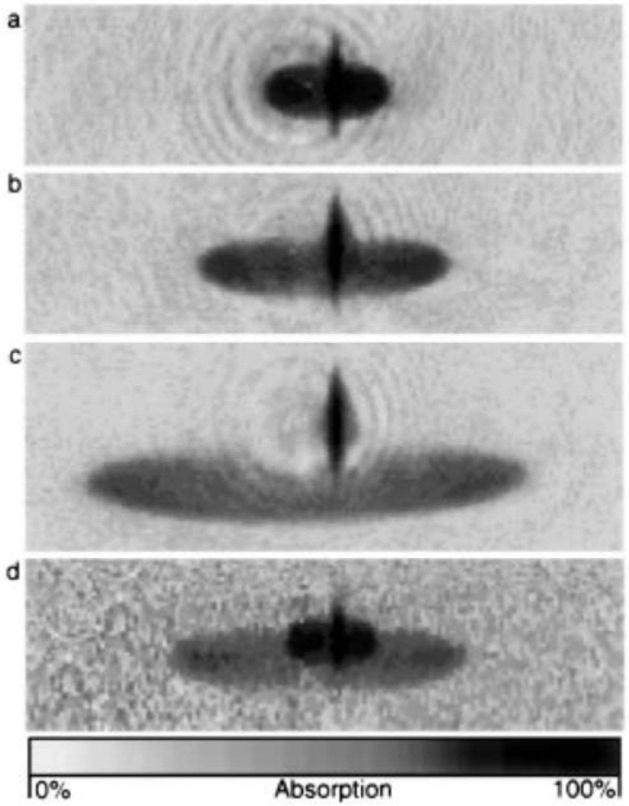
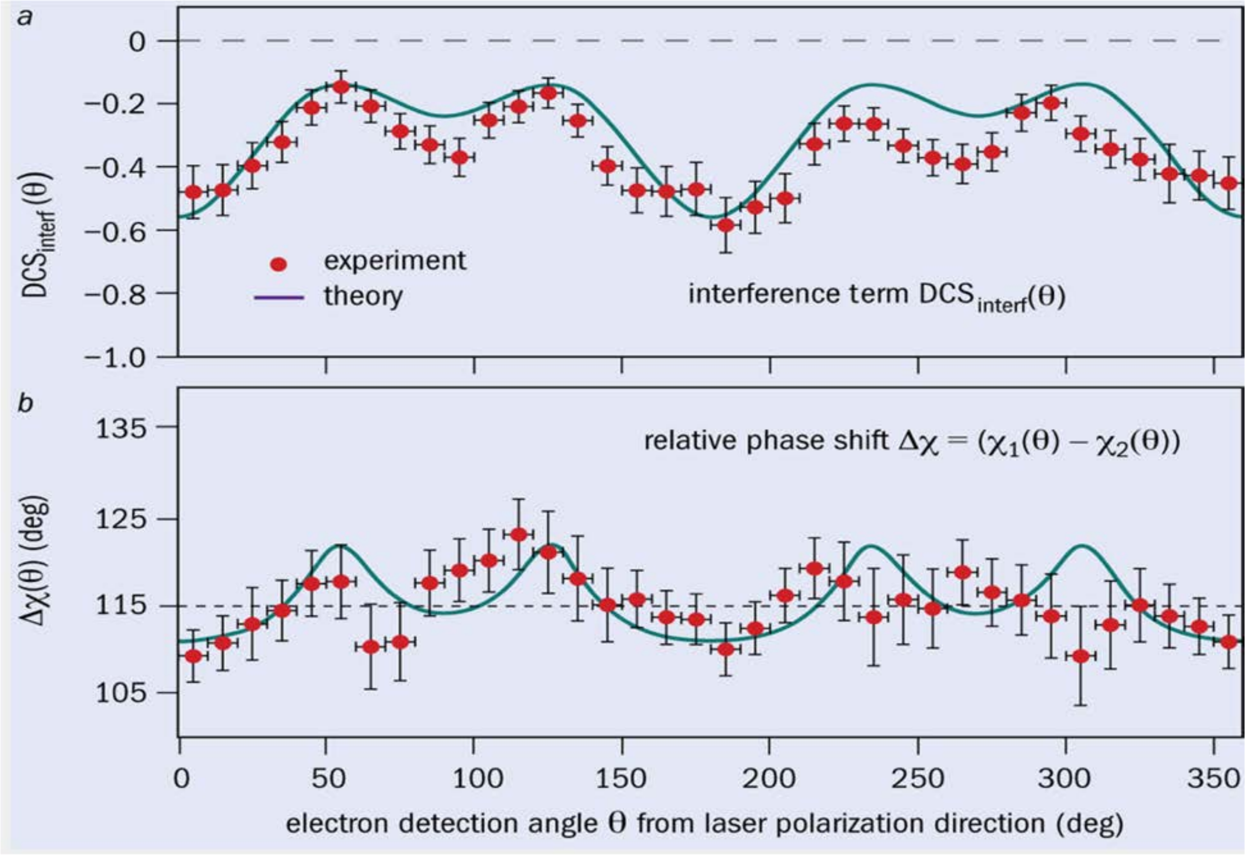
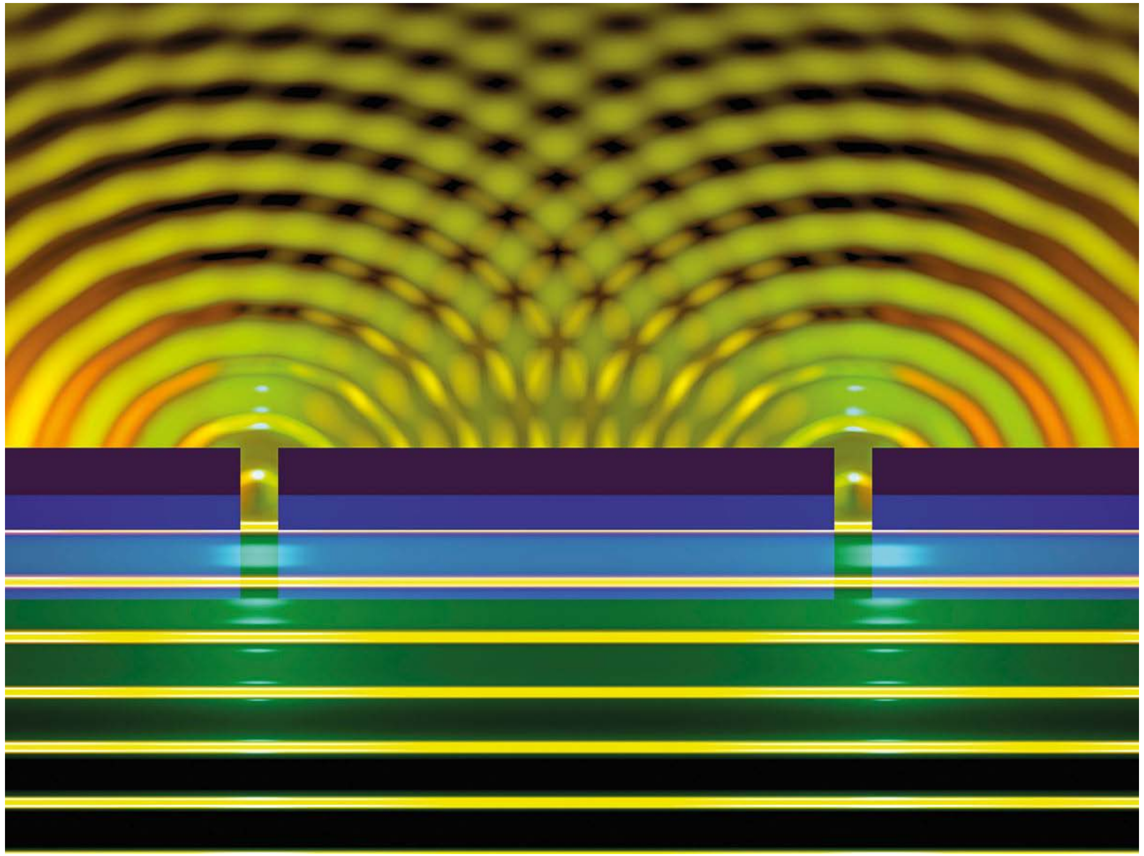


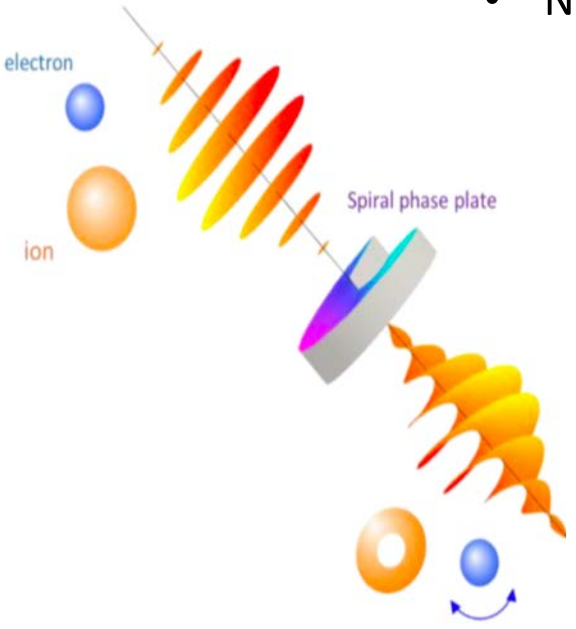
FIG. 1. Absorption images of atoms coupled into the untrapped $F = 1, m_F = 0$ state by a short rf pulse. Images were recorded (a) 14 ms, (b) 20 ms, and (c) 25 ms after the rf pulse using a vertical probe beam. The trapped condensate fraction appears as a thin line in the center of each image. (d) This shows two pulses of $m_F = 0$ atoms coupled out of the same condensate by two consecutive rf pulses spaced 10 ms apart. The image was taken 10 ms after the second rf pulse. It has a noisier background due to lower probe laser power. The width of each image is 3.1 mm.


a
0
−0.2
−0.4
−0.6
−0.8
−1.0
DCS$_{interf}$(θ)
experiment
theory
interference term DCS$_{interf}$(θ)
b
135
125
115
105
Δχ(θ) (deg)
relative phase shift Δχ = (χ$_1$(θ) − χ$_2$(θ))
0
50
100
150
200
250
300
350
electron detection angle θ from laser polarization direction (deg)

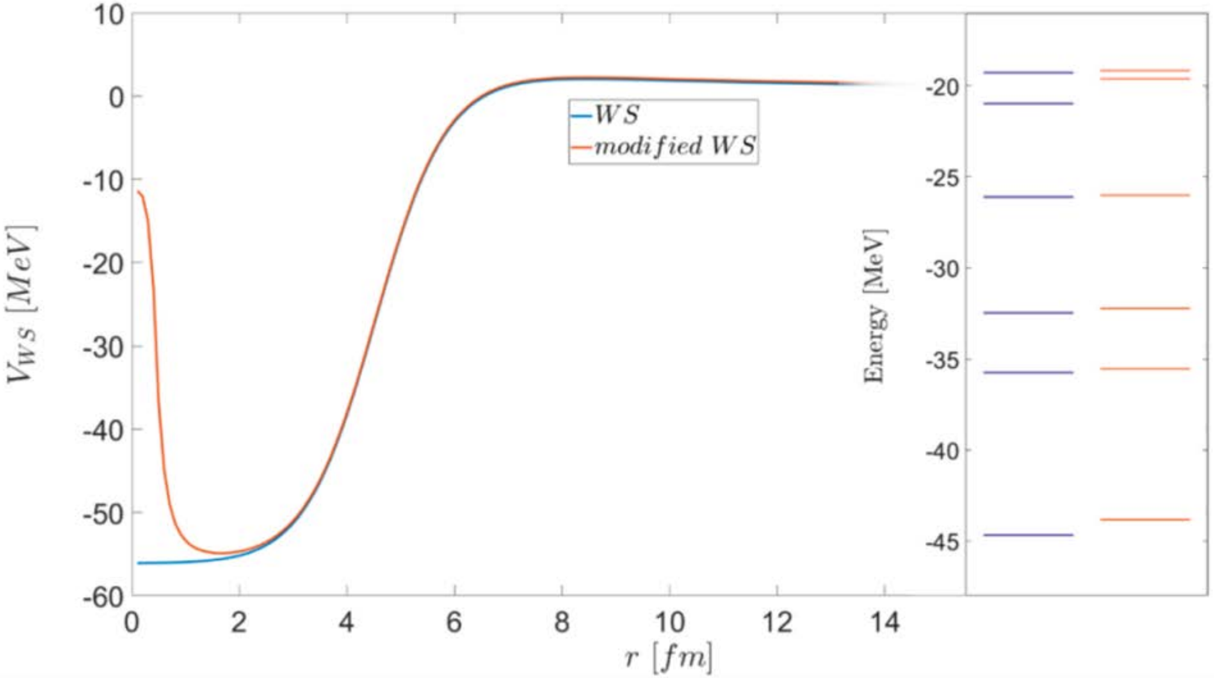


Nuclear physics with vortex beams

- Twisting ions WF modifies nuclear excitations spectrum
- Vortex e^- can be captured in higher l-shells, created ad hoc
- NEEC $\boldsymbol{\sigma}$ up to 6 orders of magnitude (article in preparation) **ENGINEERED NUCLEAR DECAY!!**



Nuclear excitations and nuclear Wood-Saxon potential



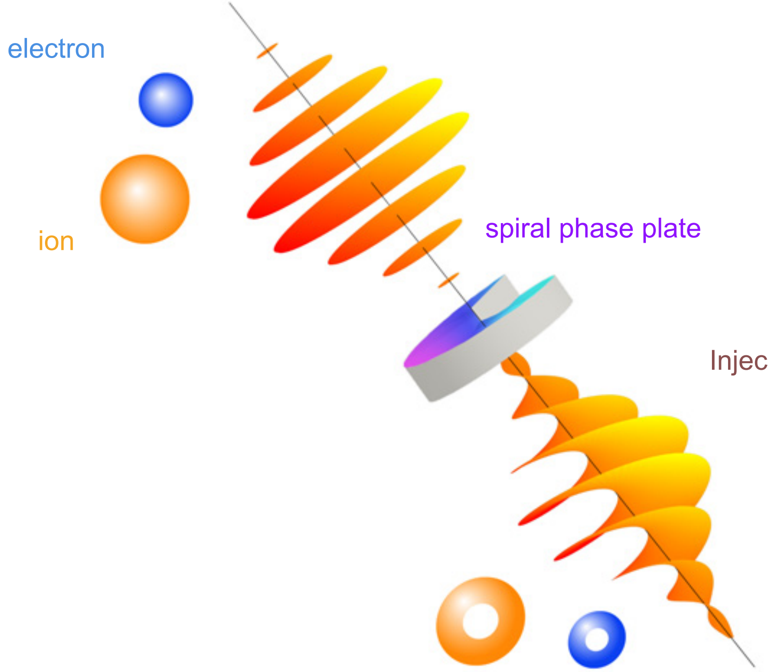
Applied Physics Letters PERSPECTIVE scitation.org/journal/apl

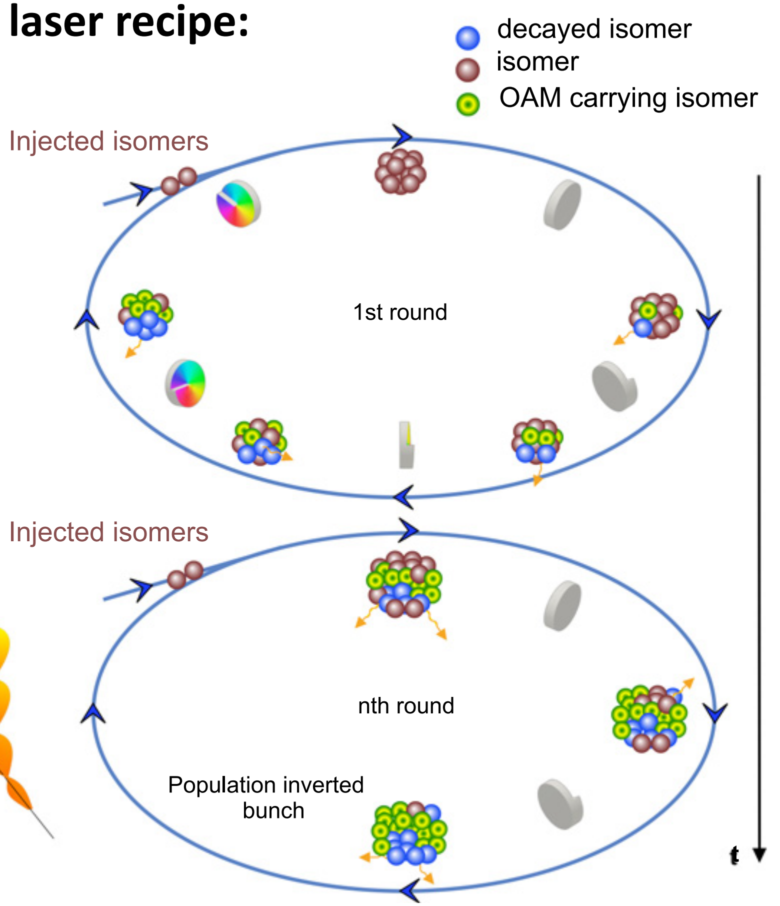
The quantum future of microscopy: Wave function engineering of electrons, ions, and nuclei

Cite as: Appl. Phys. Lett. **116**, 230502 (2020); doi: 10.1063/1.5143008
Submitted: 19 December 2019 · Accepted: 29 May 2020 ·
Published Online: 11 June 2020

I. Madan, G. M. Vanacore, S. Gargiulo, T. LaGrange, and F. Carbone[a]

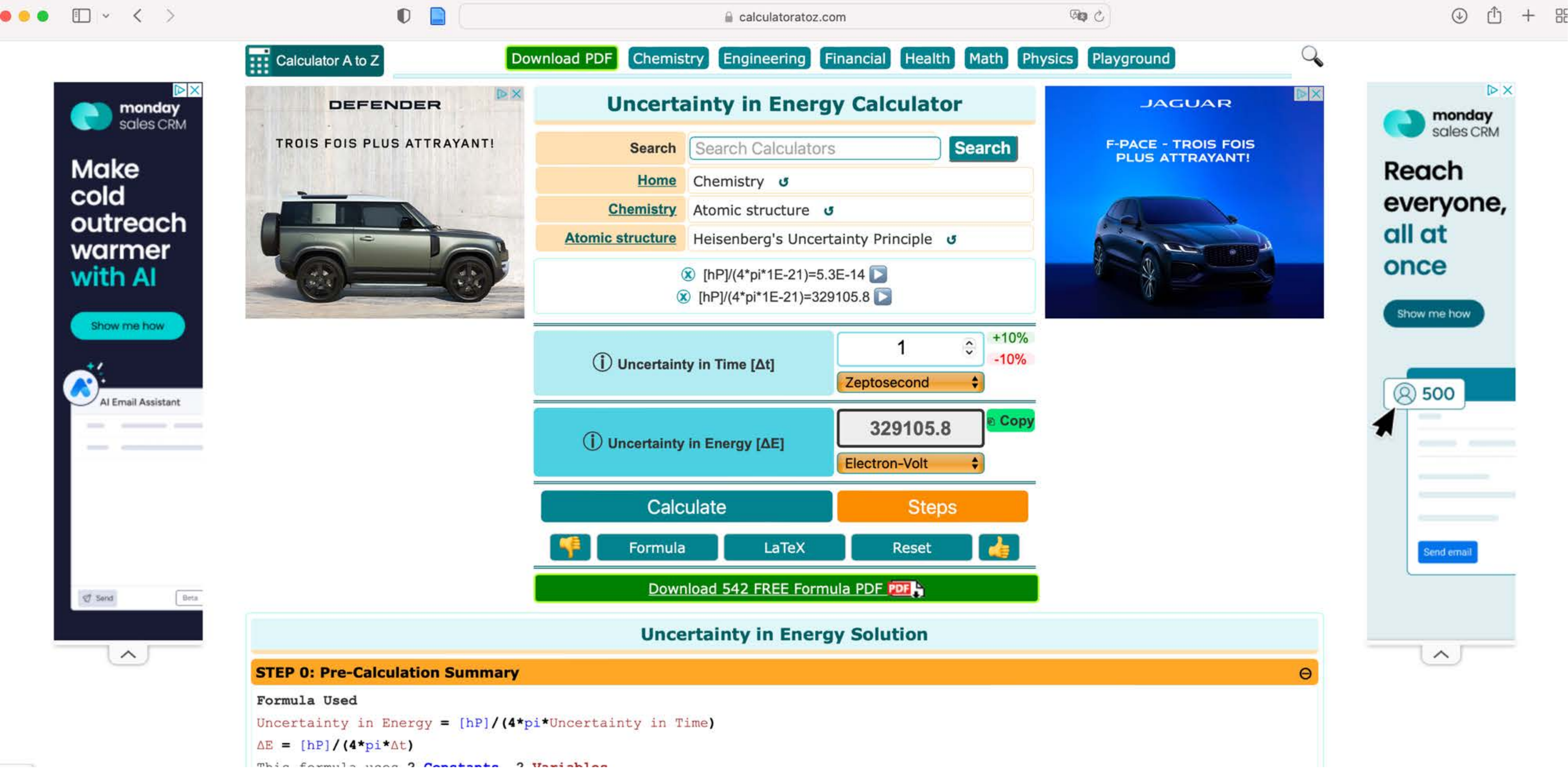
Your grand mother's Gamma-ray laser recipe:





Thank you!

The uncertainty gamma-laser



Uncertainty in Energy Calculator

Search: Search Calculators

Home: Chemistry

Chemistry: Atomic structure

Atomic structure: Heisenberg's Uncertainty Principle

[hP]/(4*pi*1E-21)=5.3E-14

[hP]/(4*pi*1E-21)=329105.8

Uncertainty in Time [Δt]: 1 Zeptosecond

Uncertainty in Energy [ΔE]: 329105.8 Electron-Volt

Download 542 FREE Formula PDF

Uncertainty in Energy Solution

STEP 0: Pre-Calculation Summary

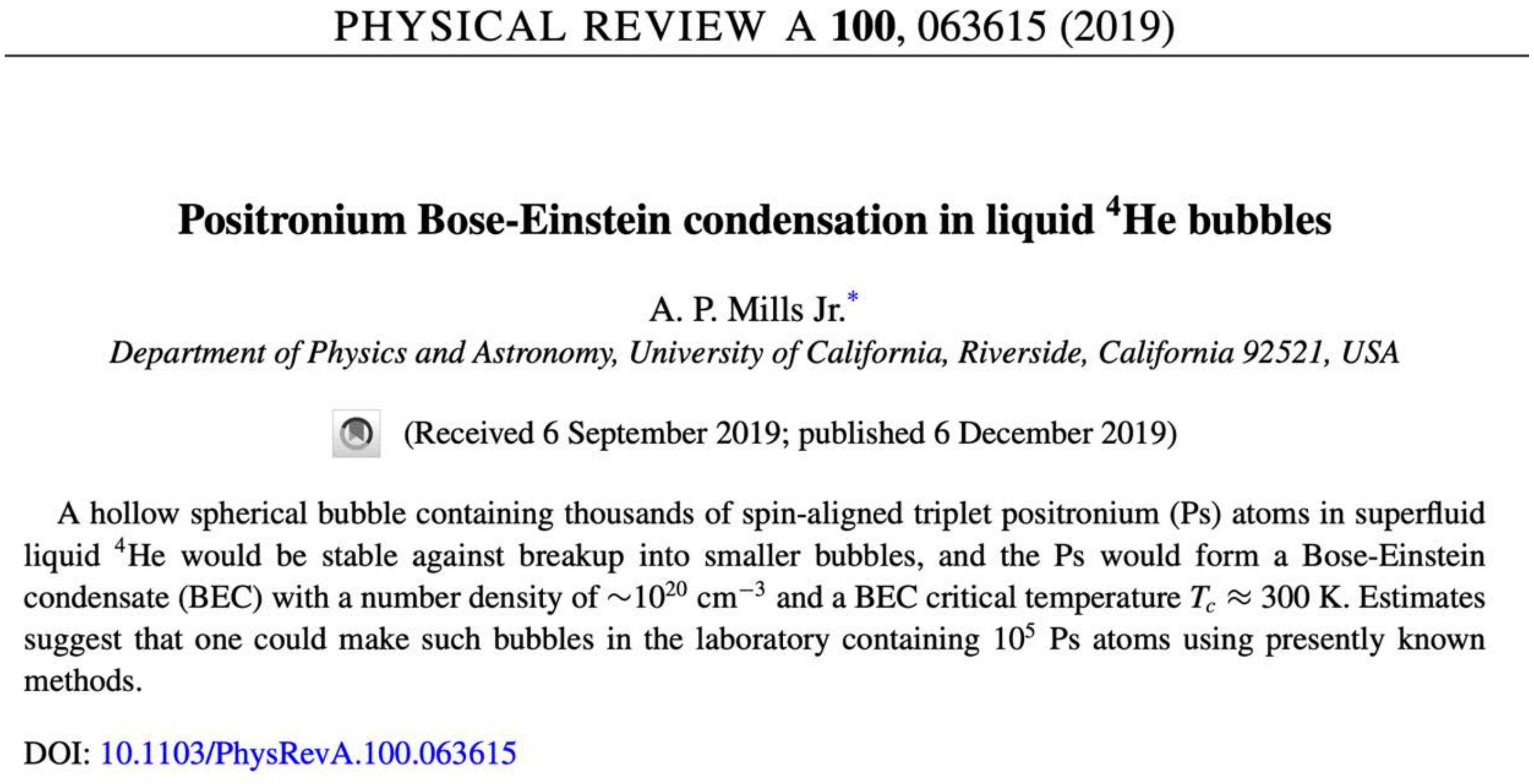
Formula Used

Uncertainty in Energy = [hP]/(4*pi*Uncertainty in Time)

ΔE = [hP]/(4*pi*Δt)

This formula uses 2 Constants, 2 Variables

Matter-Antimatter gamma laser



PHYSICAL REVIEW A **100**, 063615 (2019)

Positronium Bose-Einstein condensation in liquid ^{4}He bubbles

A. P. Mills Jr.*
Department of Physics and Astronomy, University of California, Riverside, California 92521, USA

(Received 6 September 2019; published 6 December 2019)

A hollow spherical bubble containing thousands of spin-aligned triplet positronium (Ps) atoms in superfluid liquid ^{4}He would be stable against breakup into smaller bubbles, and the Ps would form a Bose-Einstein condensate (BEC) with a number density of $\sim 10^{20}$ cm^{-3} and a BEC critical temperature $T_c \approx 300$ K. Estimates suggest that one could make such bubbles in the laboratory containing 10^5 Ps atoms using presently known methods.

DOI: 10.1103/PhysRevA.100.063615

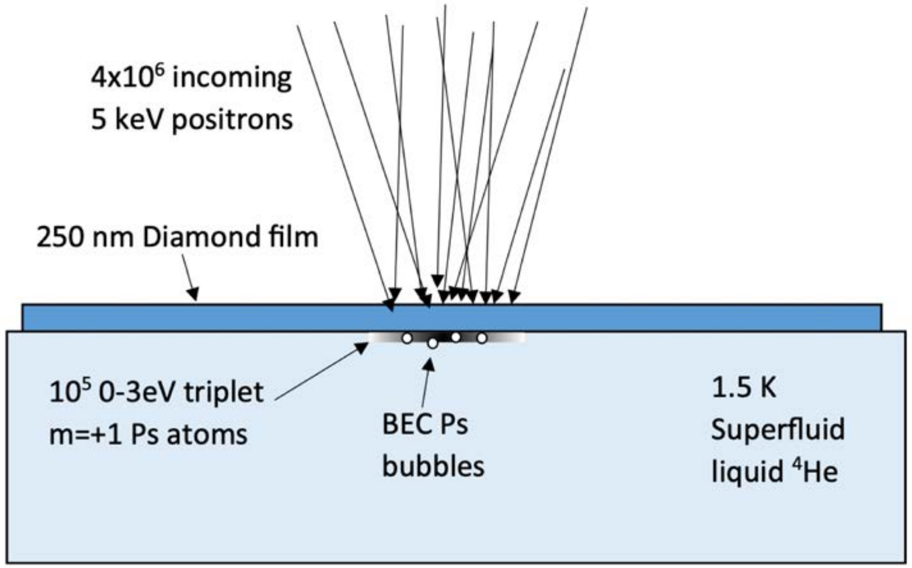
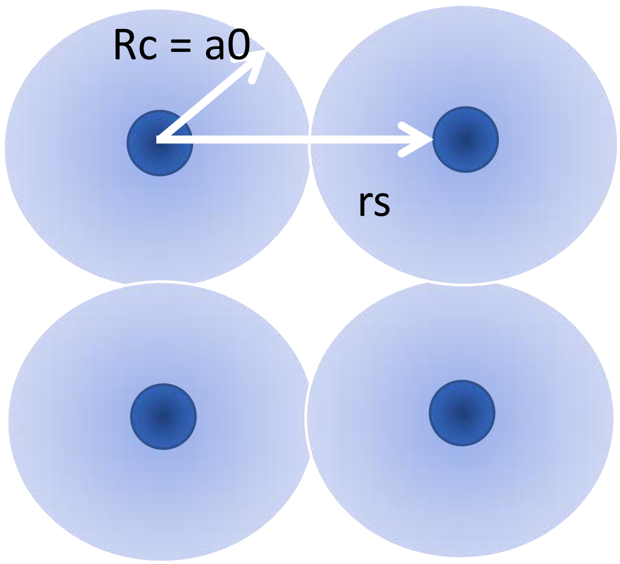


FIG. 2. Geometry of a target for forming BEC positronium bubbles in superfluid He. Energetic positrons stop in a thin diamond film. The positrons thermalize and diffuse to the back surface of the film, and are emitted into the He as positronium which collects into bubbles.

Wigner crystallization



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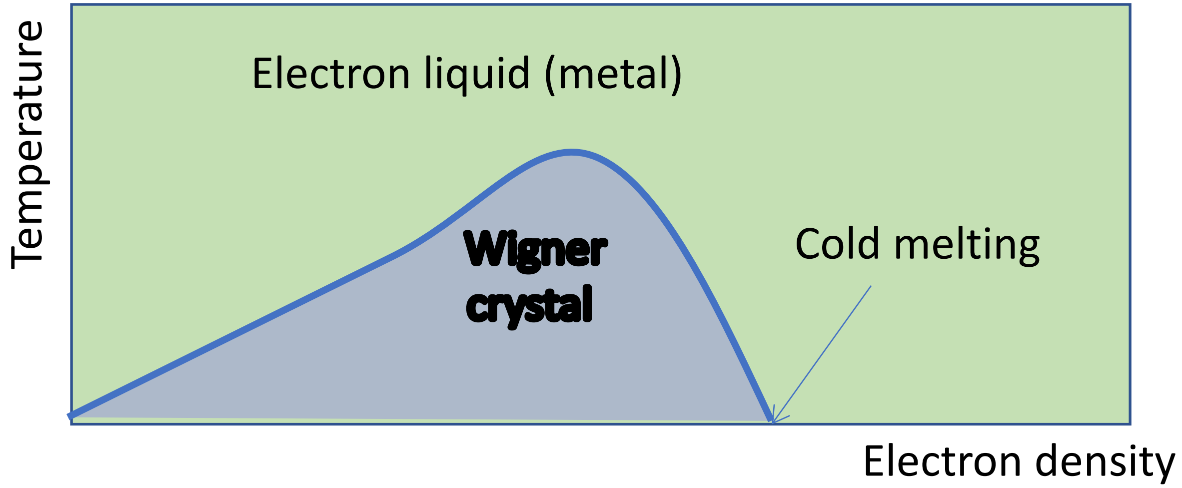
Electrons confined into rc , distanced by rs

$$\triangle E_{kin} = \frac{\hbar}{r_c^3}$$

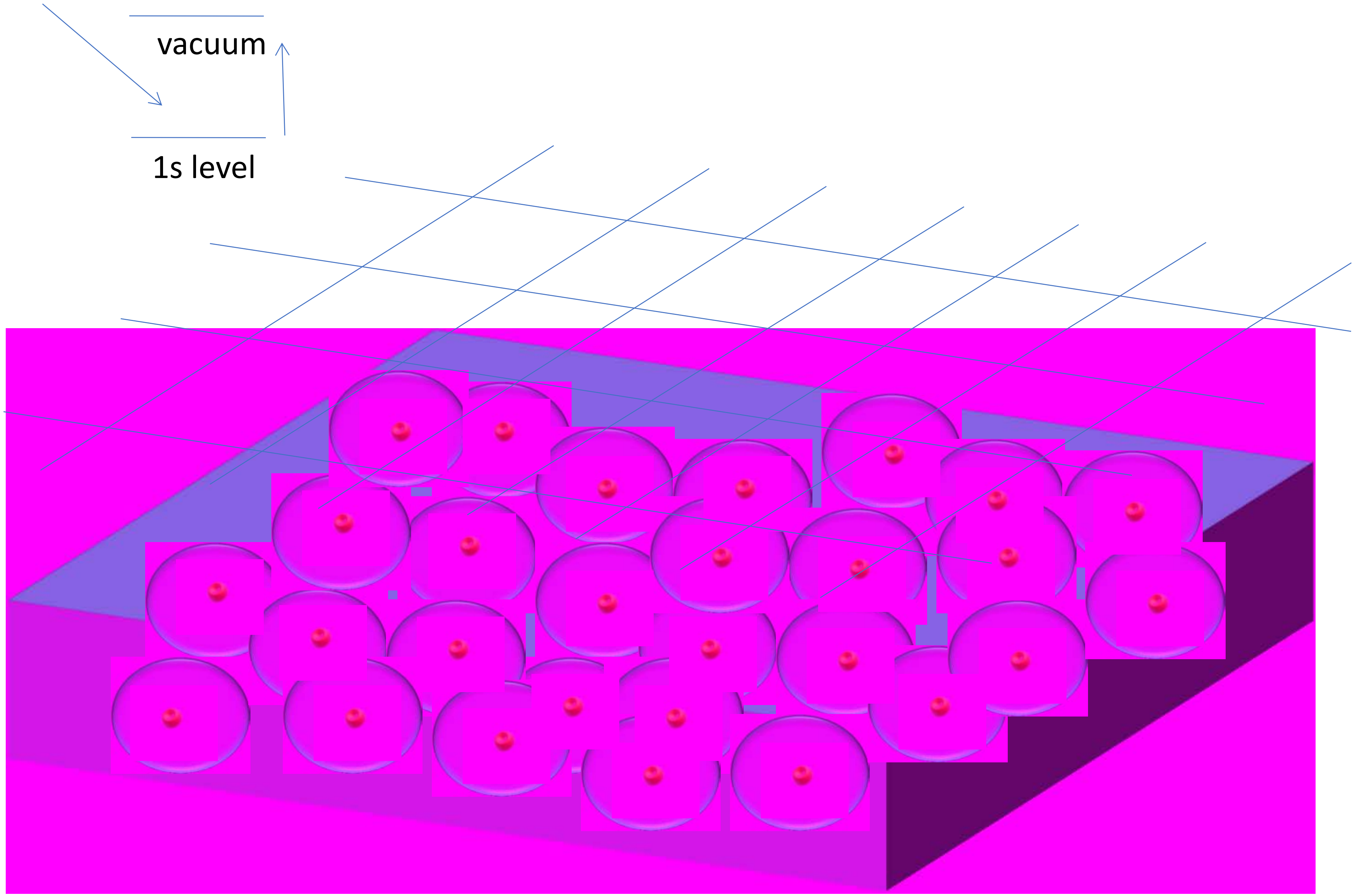
$$\triangle E_{pot} = \frac{e^2}{\triangle r_s}$$

Theoretical spread of values for the density: Rs/a0 = 10 - 170



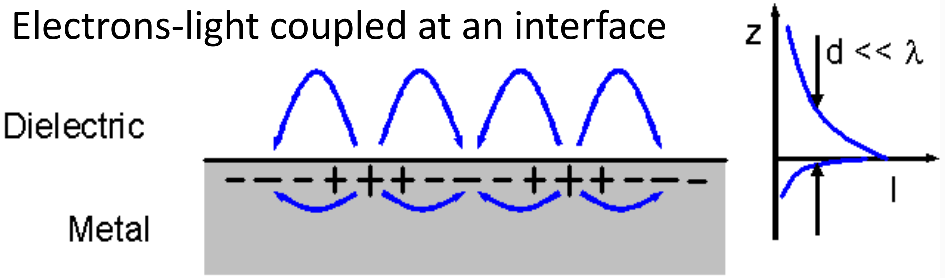
E. Wigner, Phys. Rev. 46, 1002 (1934)

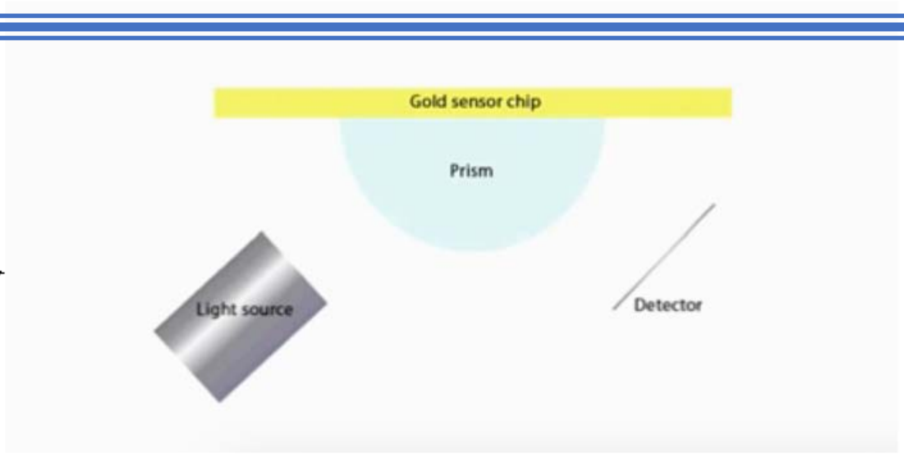
Concept Wigner gamma laser. Phonons of a Wigner crystals will be charges moving at very high speed

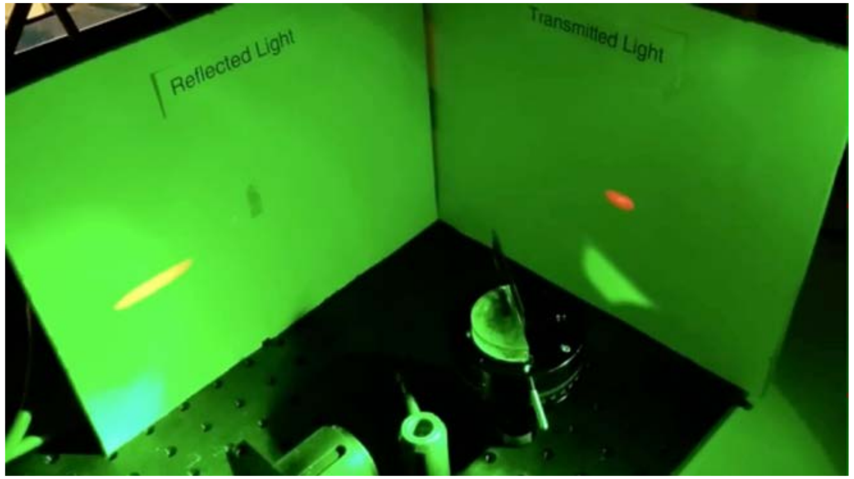


Surface plasmons polaritons and plasma resonances

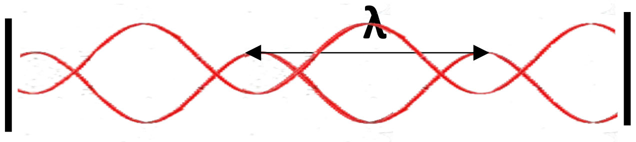
Surface plasmon:
Electrons-light coupled at an interface



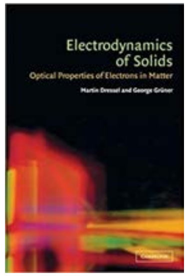




Plasma resonance



Suggested reading: Dressel, “Electrodynamics of solids”



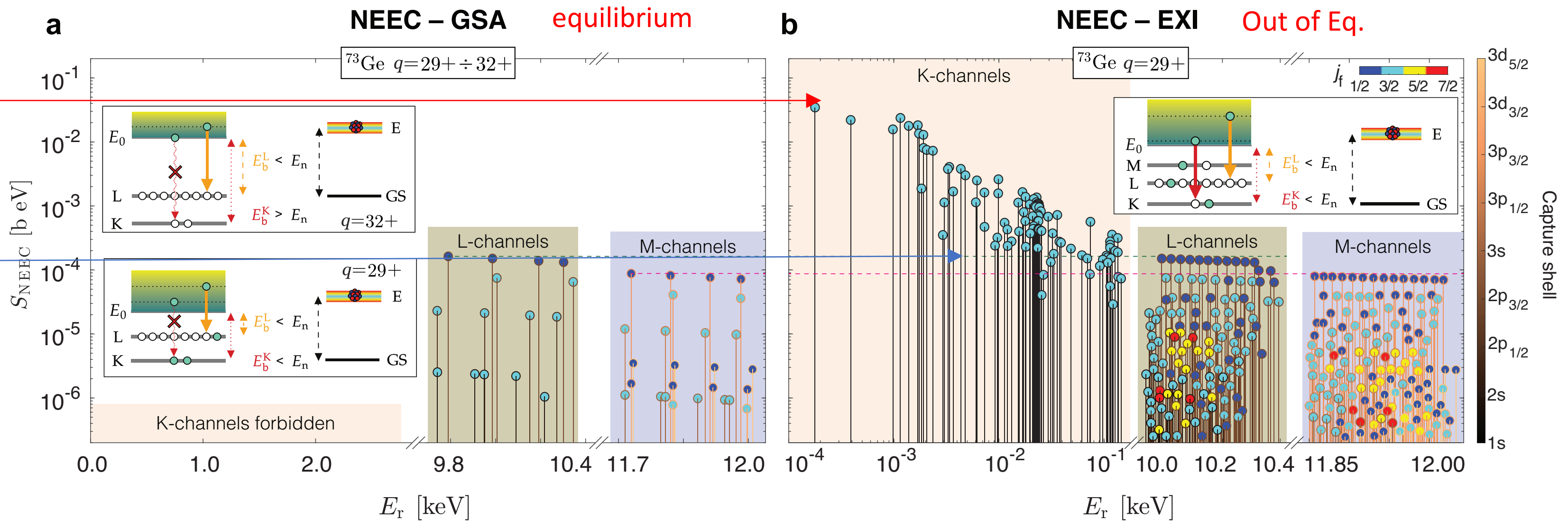
Out of equilibrium nuclear physics:

Observed NEEC $\boldsymbol{\sigma}$ vs theoretical NEEC $\boldsymbol{\sigma}$: 10^{11}

Recalculating $\boldsymbol{\sigma}$ in out of equilibrium ions: 3 orders of magnitude gained, 8 to go

Maximum cross section out of equilibrium

Maximum cross section at equilibrium



Gargiulo et al (submitted to PRL, http://arxiv.org/abs/2102.05718)

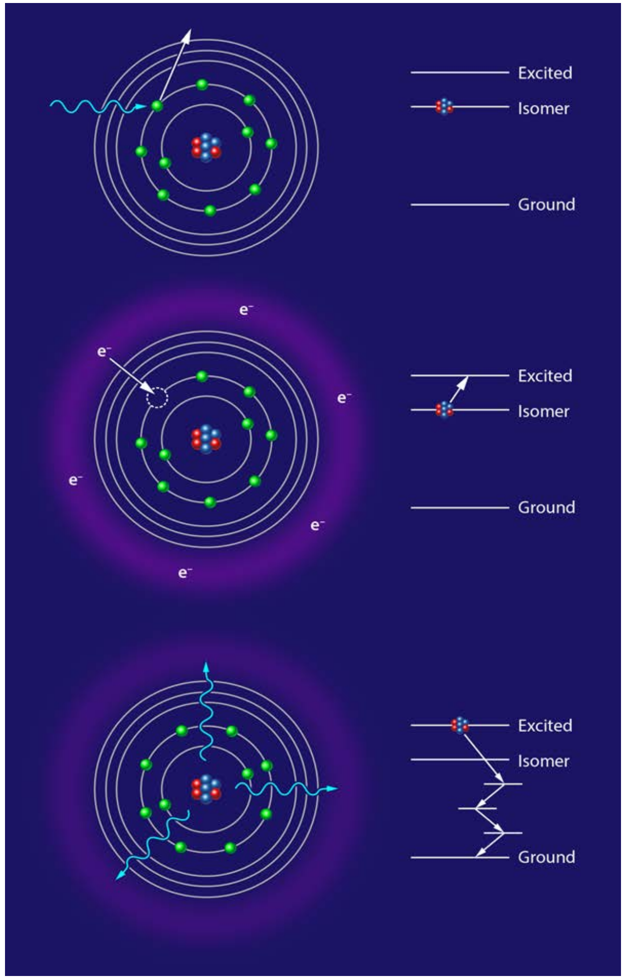
Orbital electron capture

Ionized atom captures a free e$^-$
Instead of Auger recombination with gamma ray emission
the atomic nucleus is excited

Nuclear isomer:
metastable atomic nucleus made of one or more of its nucleons (protons or neutrons) in an excited state.
Half-lives 100 to 1000 times longer (ns) than other excited nuclear states (ps or less)

Create metastable isomers: high energy process
The metastable state is not necessarily the most convenient for EC

Sample short-lived states: impossible until now
Expand parameter space from which to study NEEC



Chiara et al., Nature 554, 216 (2018)

Dynamics of Events in Laser-Plasma scenario