Time-resolved nano-optics in electron microscopy

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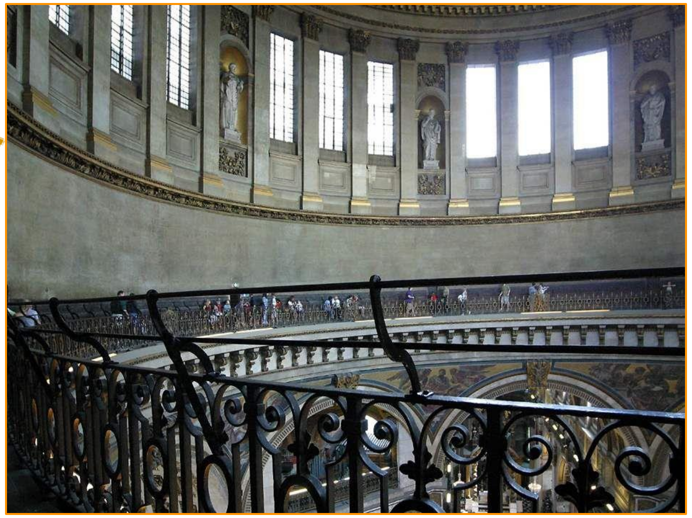
QEM Summer School, 20-05-2025

Dôme de La Grave, Toulouse

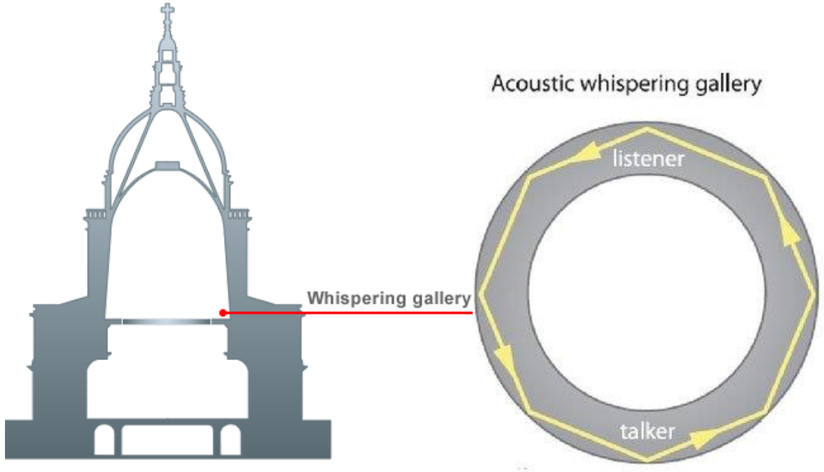
Acoustic whispering gallery mode

Foreman *et al.*, Adv. Opt. Photon. **7**, 168-240 (2015)

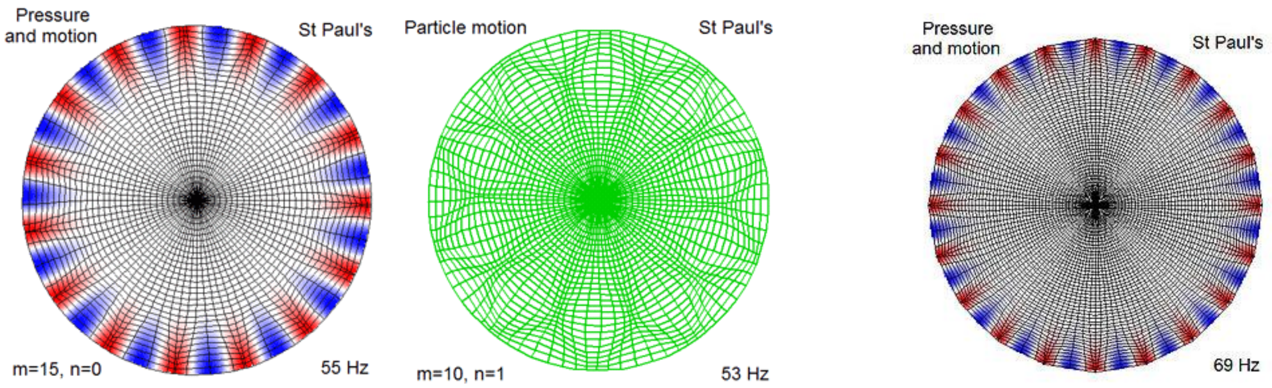
St Paul's Cathedral, London (Wikipedia)



The Whispering Gallery



Lord Rayleigh



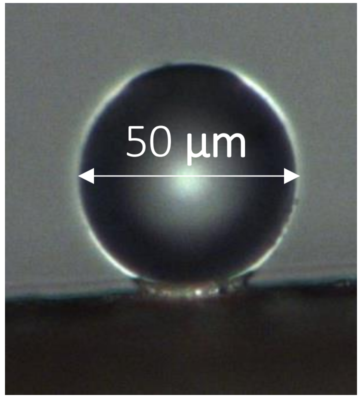
Acoustic Whispering-gallery modes (WGM)

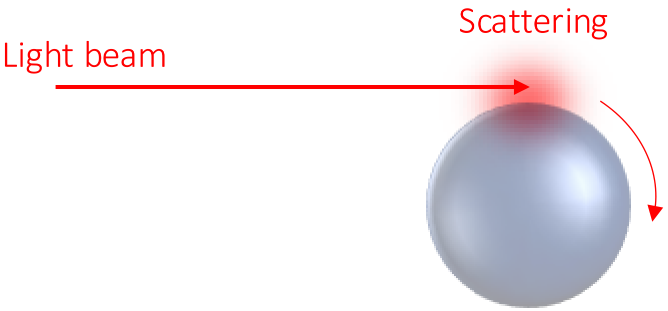
Length scale : **m**
Time scale : **s**

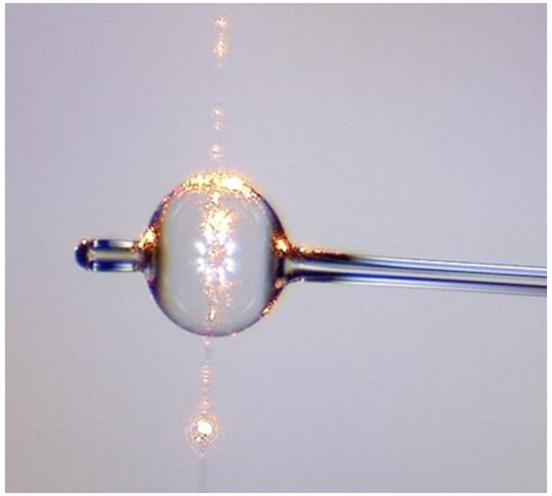
Matsuda & Tsuchiya, "Watching whispering-gallery waves », Laboratory of Applied Solid-State Physics, Hokkaido University

Optical whispering gallery mode

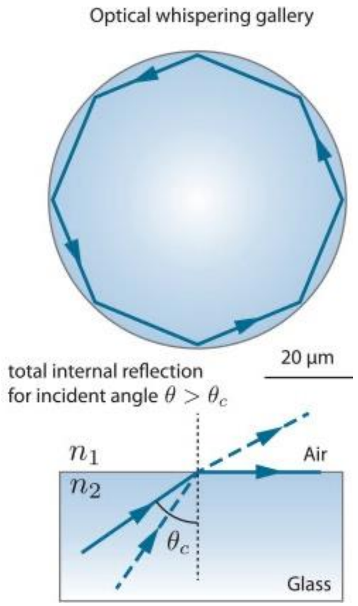
Glass micro-sphere







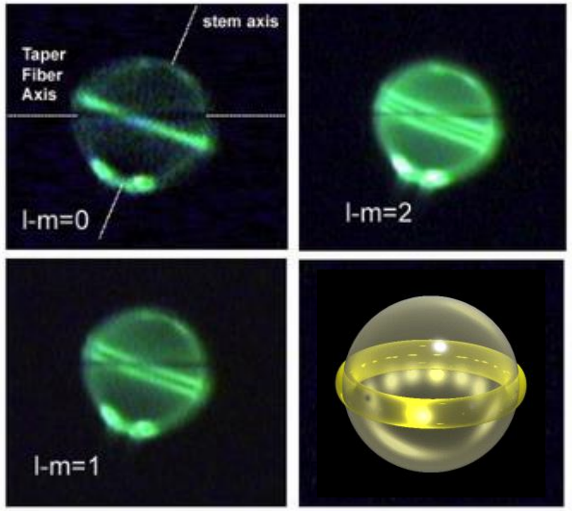
Source: OIST



Foreman *et al.*, Adv. Opt. Photon. **7**, 168-240 (2015)

Optical Whispering-gallery modes (WGM)

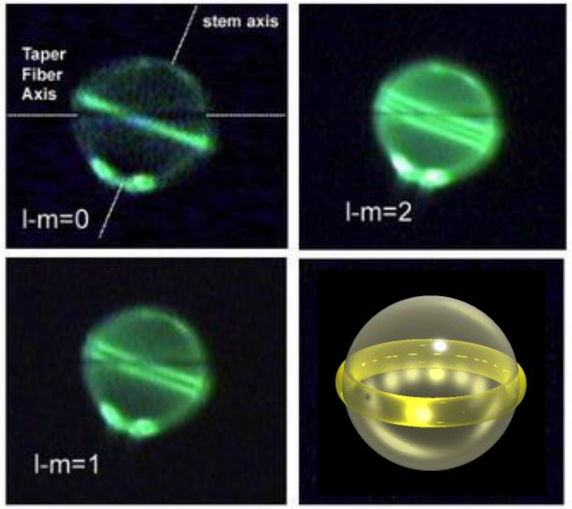
Length scale : **µm**
Time scale : **fs-ps**



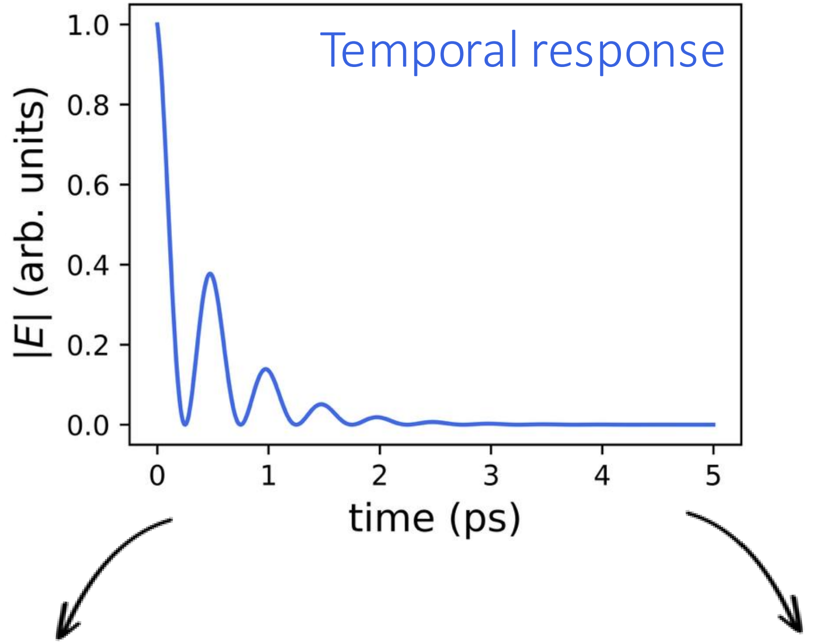
Optical whispering gallery mode

Optical Whispering-gallery modes (WGM)

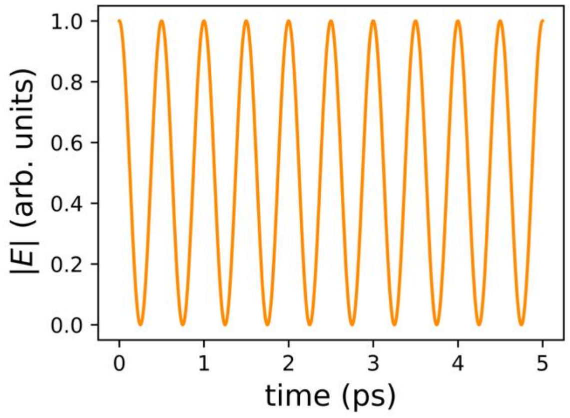
Length scale : **µm**
Time scale : f**s-ps**



- Period of the round trip : **fs**
- Typical time of decay: **ps**

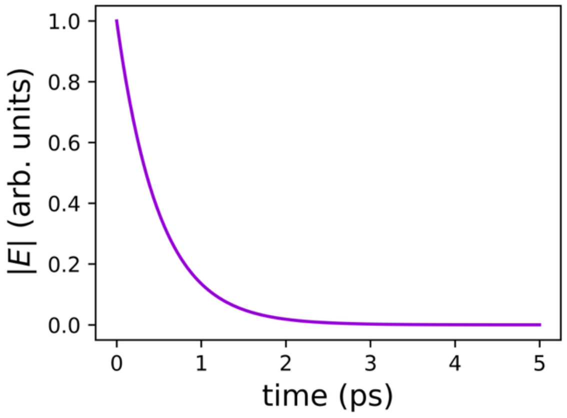


Oscillatory part



×

Decay part



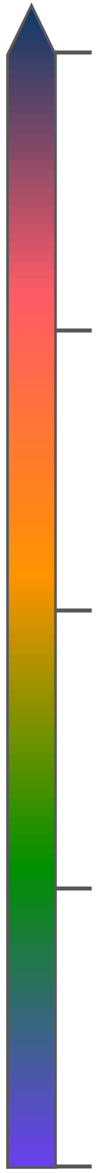
What do we mean by being time-resolved?

Hummingbird wings beating ~ 70 Hz

High speed camera ~ 500 Hz

Movie by Anand Varna[1]

The time scales of (nano-)optics



1 nanosecond

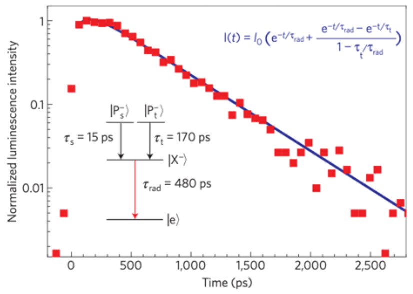
1 picosecond

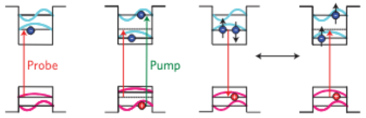
1 femtosecond

1 attosecond

1 zeptosecond

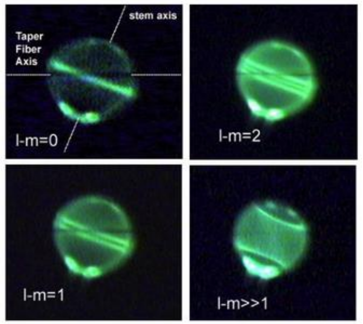
Dynamics of excitations in **semi-conductors**



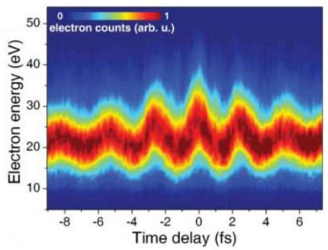


Trion decay in CdSe/ZnSe(001) quantum dot
Sotier et al., Nat. Phys. **5**, 352–356 (2009)

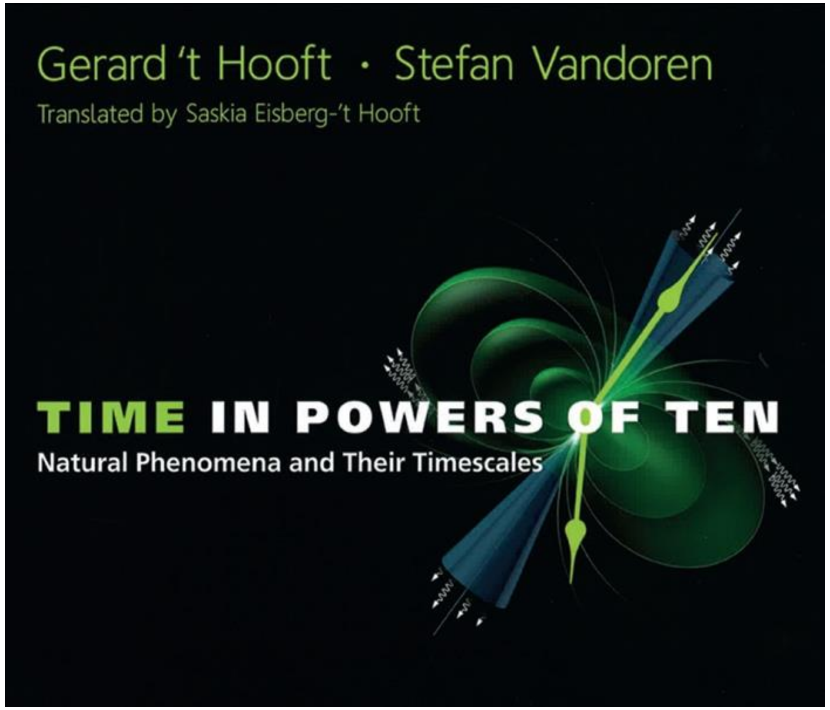
Dynamics of WGM, most of **photonic excitations** (e.g. surface plasmon)



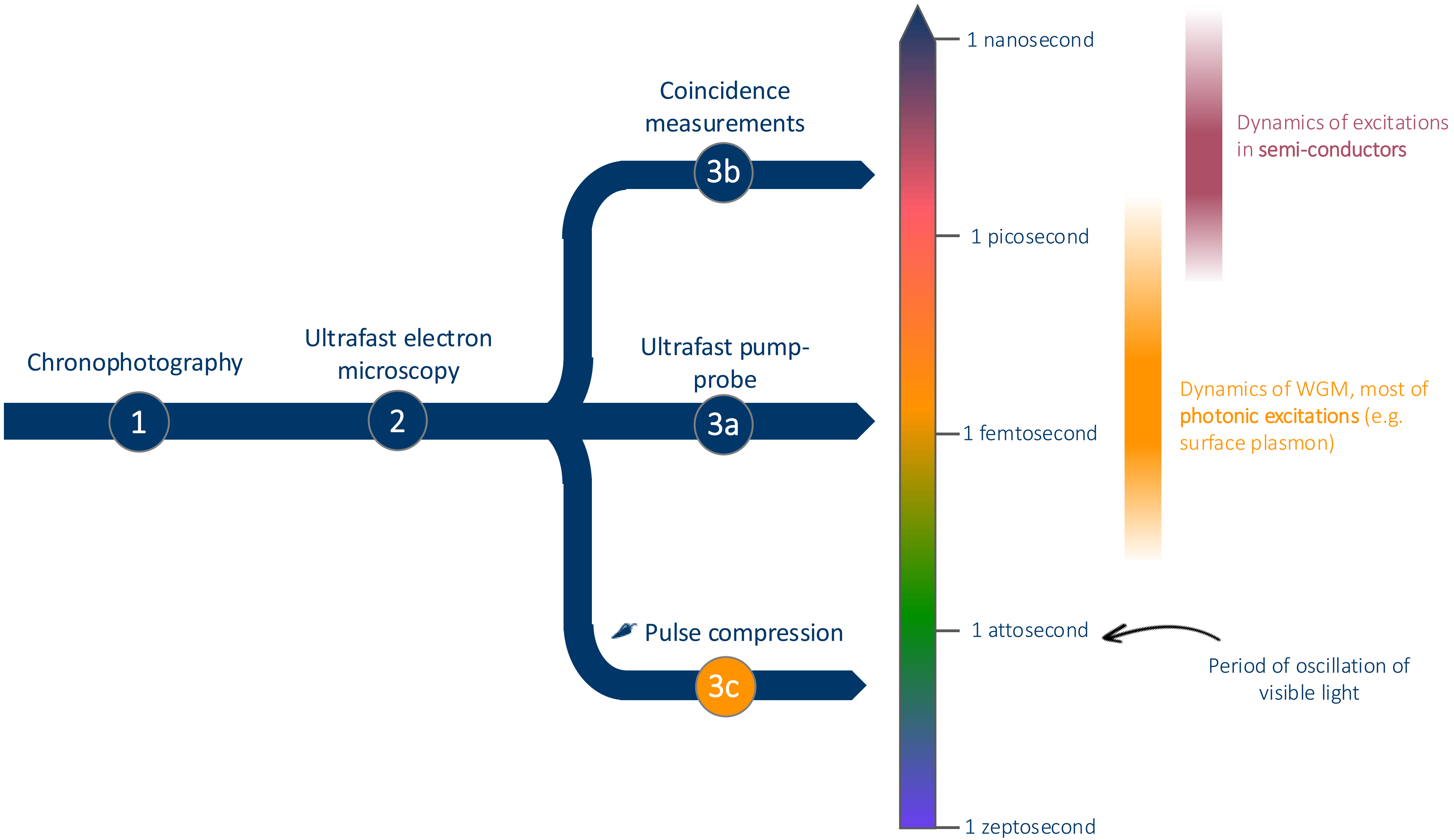
Period of oscillation of visible light



Sansone et al., Science **314**, 5798, 443-446 (2006)

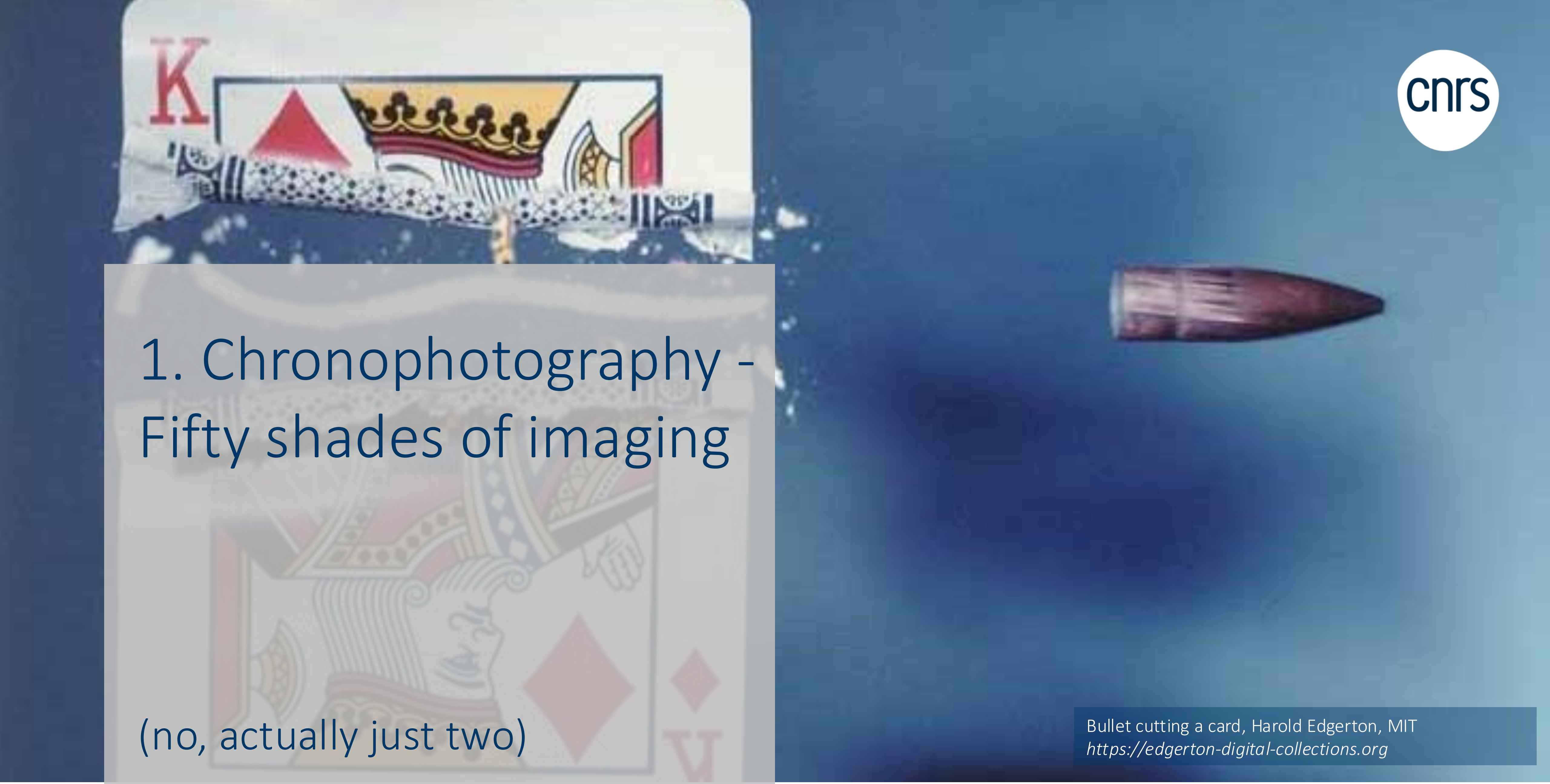


Outline of the course (if $t \to \infty$)



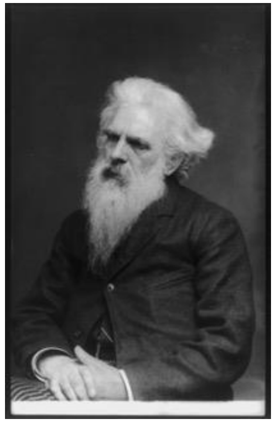
1. Chronophotography - Fifty shades of imaging

(no, actually just two)



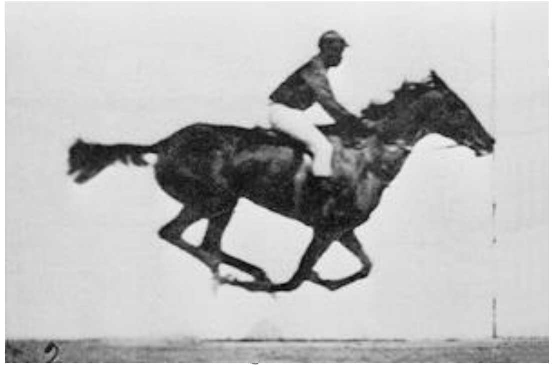
Bullet cutting a card, Harold Edgerton, MIT
https://edgerton-digital-collections.org

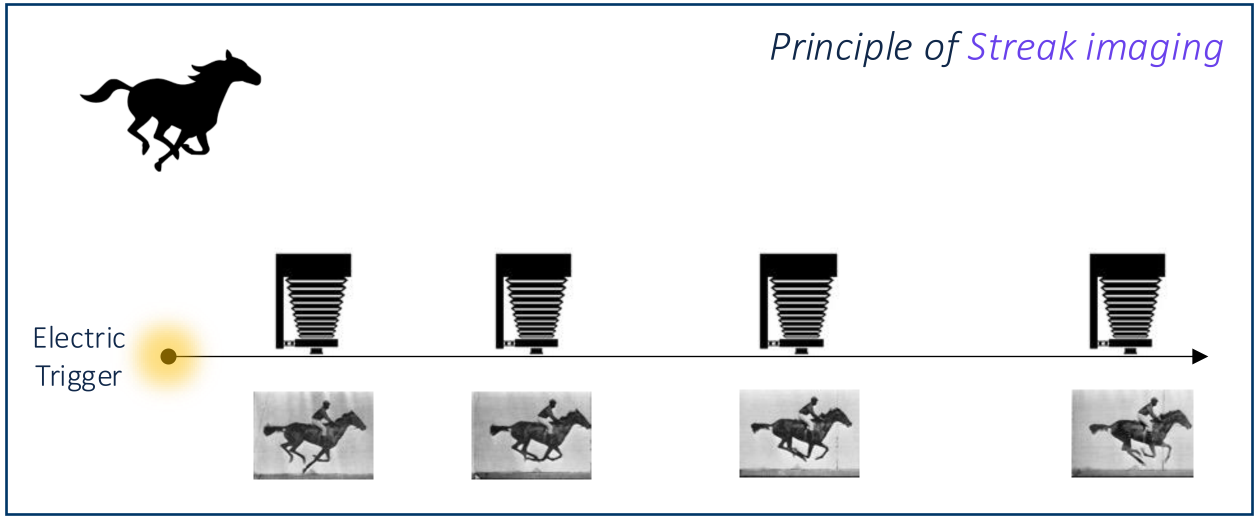
A brief history of Chronophotography



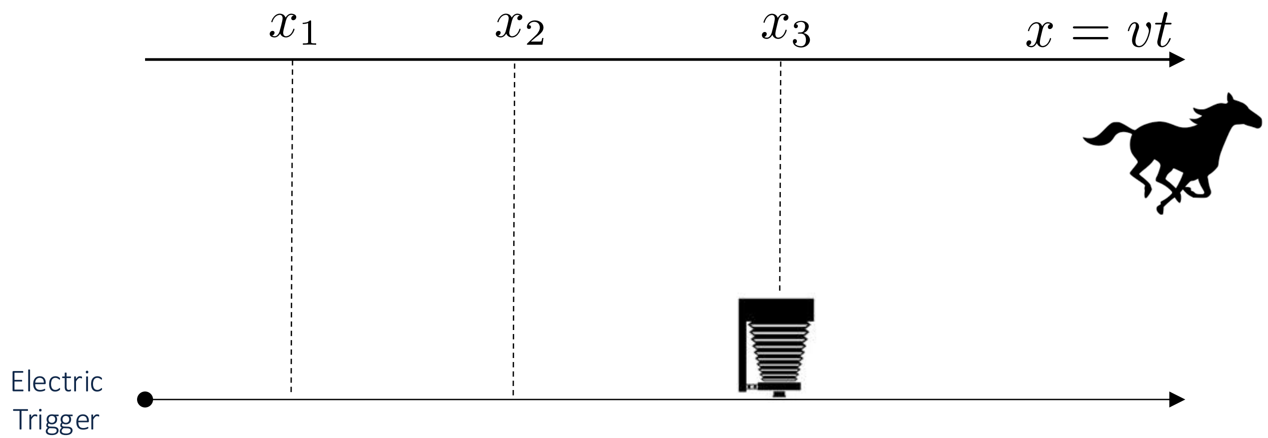
Eadweard Muybridge
(1830-1904)

The Horse in Motion (1878)





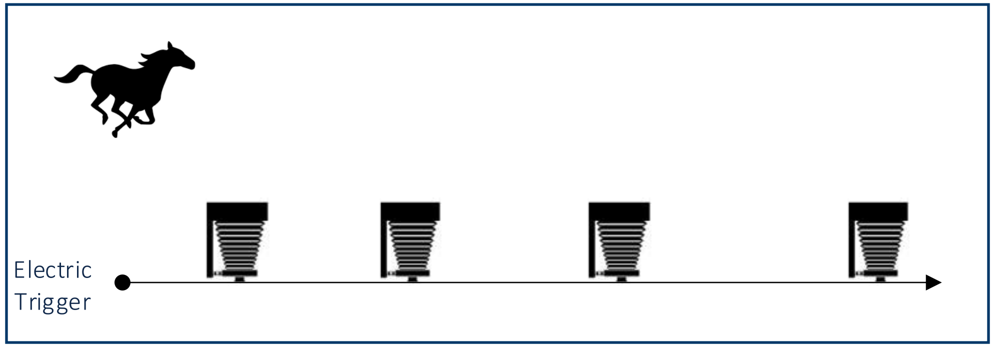
A brief history of Chronophotography



⚠ The process needs to be **reversible**

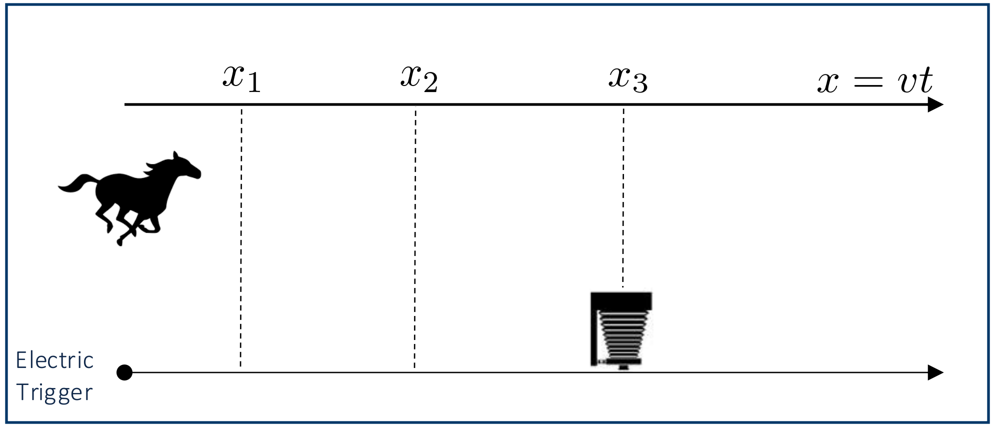
Dynamic vs. Ultrafast transmission electron microscopy

Principle of Streak imaging (single shot)



Irreversible processes

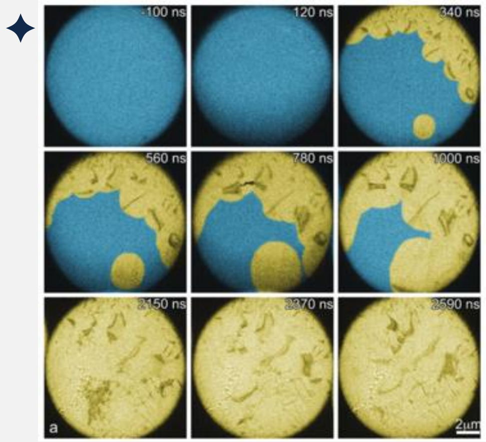
Principle of Pump-Probe imaging (stroboscopic)



Reversible processes

Dynamic Transmission Electron Microscope* (**DTEM**)

✦



*High-speed transmission electron microscopy

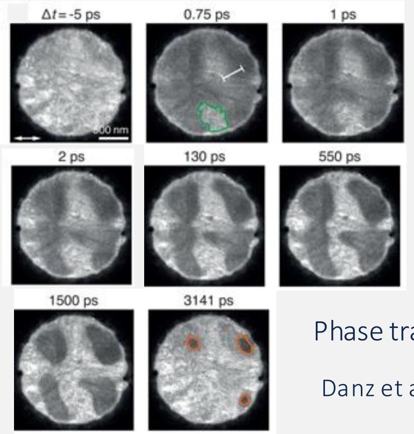
- O. Bostanjoglo, TU Berlin (1980s)
- G.H. Campbell, Lawrence Livermore National Laboratory

Dömer and Bostanjoglo, Review of Scientific Instruments **74**, 4369 (2003)
Kim et al., Science **321**, 1472-1475 (2008)
Campbell et al., Applied Physics Review **1**, 041101 (2014)
✦ Santala et al., Applied Physics Letter **102**, 174105 (2013)

Phase transition in GeTe (ns)

∼ ns

Ultrafast Transmission Electron Microscope (**UTEM**)



- A. Zewail, Caltech (2010s)

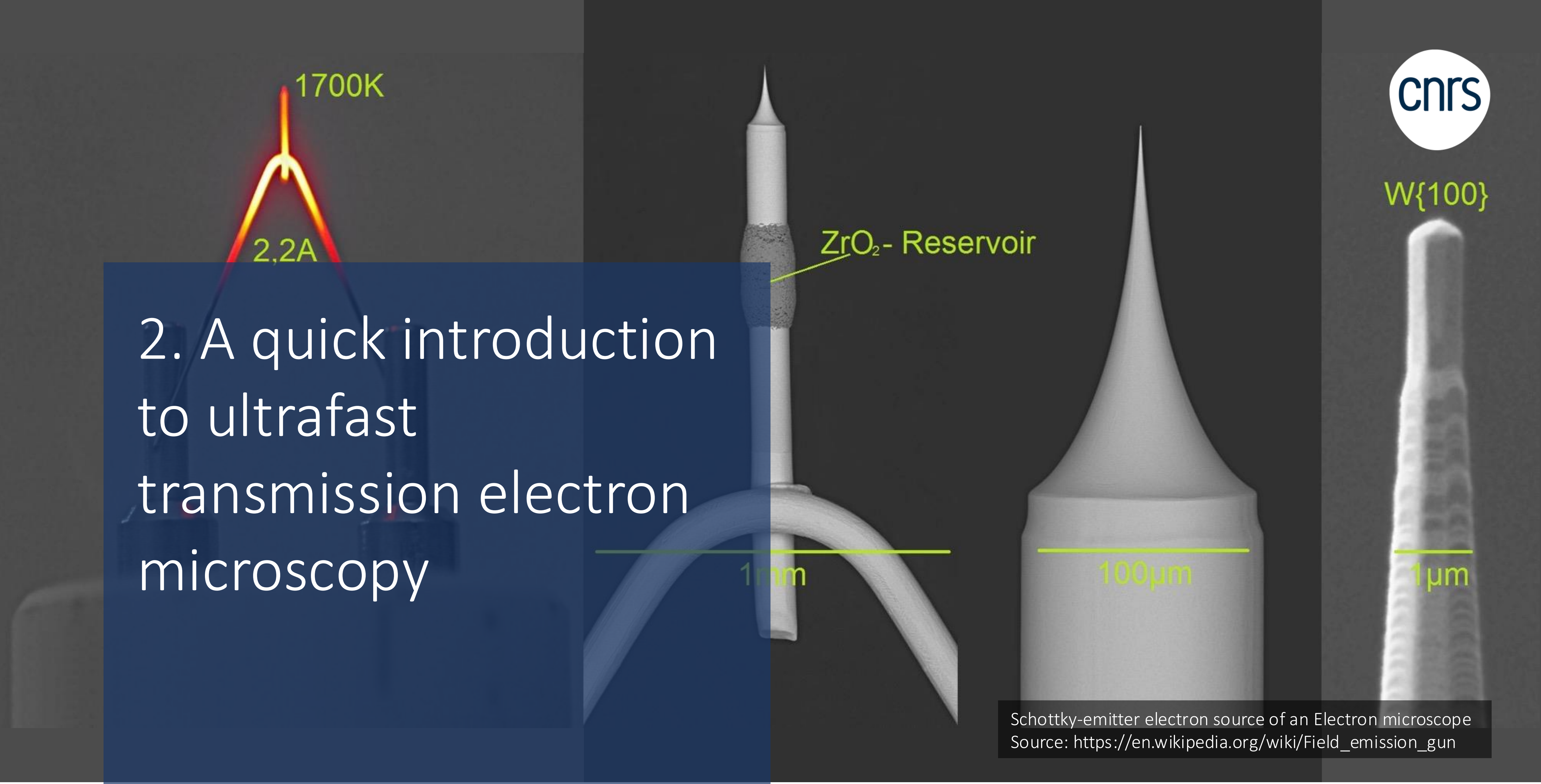
Phase transition in 1T-TaS2 (fs-ps)

Danz et al., Science **371**, 371-374 (2021)

∼ ps/fs

Femto-photography: Light-in-flight recording

See the work of Philipp Haslinger:
http://seecphotography.com/

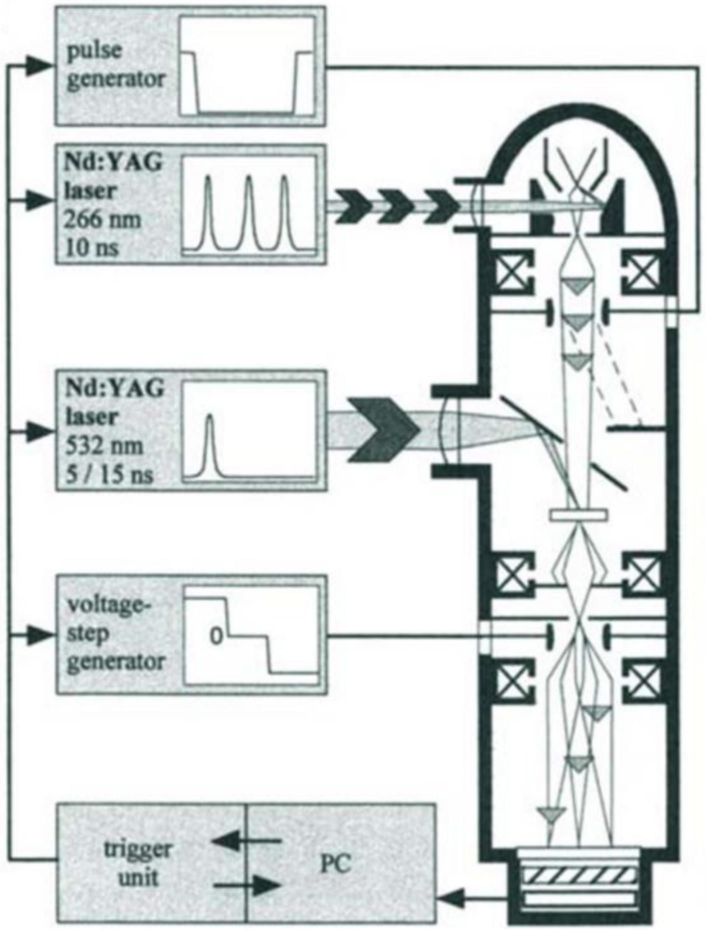


2. A quick introduction to ultrafast transmission electron microscopy

Schottky-emitter electron source of an Electron microscope
Source: https://en.wikipedia.org/wiki/Field_emission_gun

How does it look like?

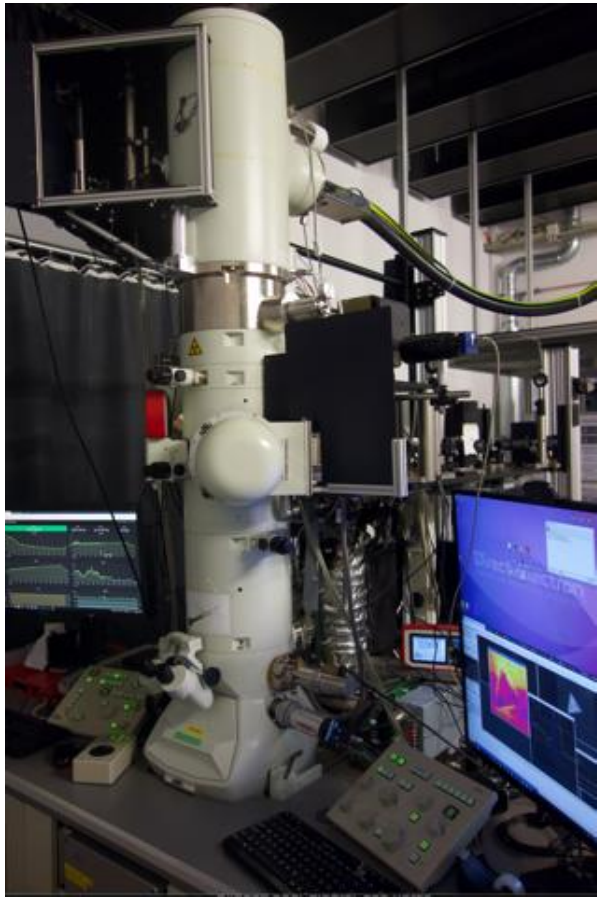
- **High-Speed TEM**: The modified Siemens Elmiskop 1A at TU Berlin (1990s')

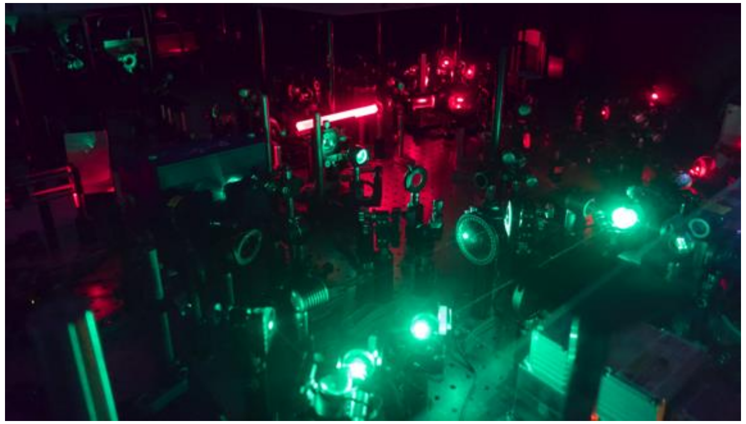


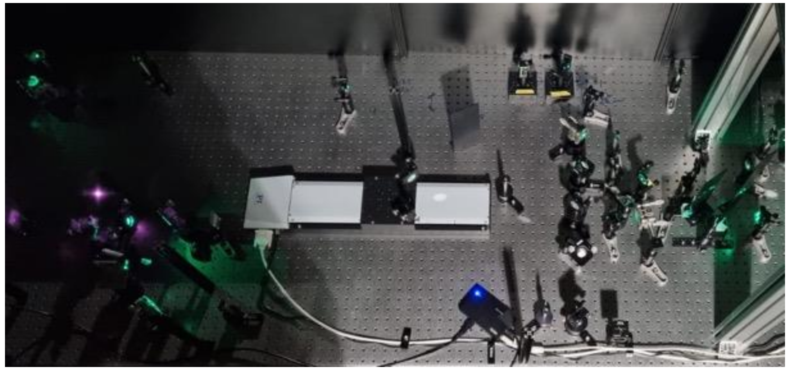
Oleg Bostanjoglo, Advances in Imaging and Electron Physics Volume **121**, 1-51 (2002)

How does it look like?

- **Schottky-FEG UTEM**:
The modified JEOL 2100F at the university of Göttingen (2020)

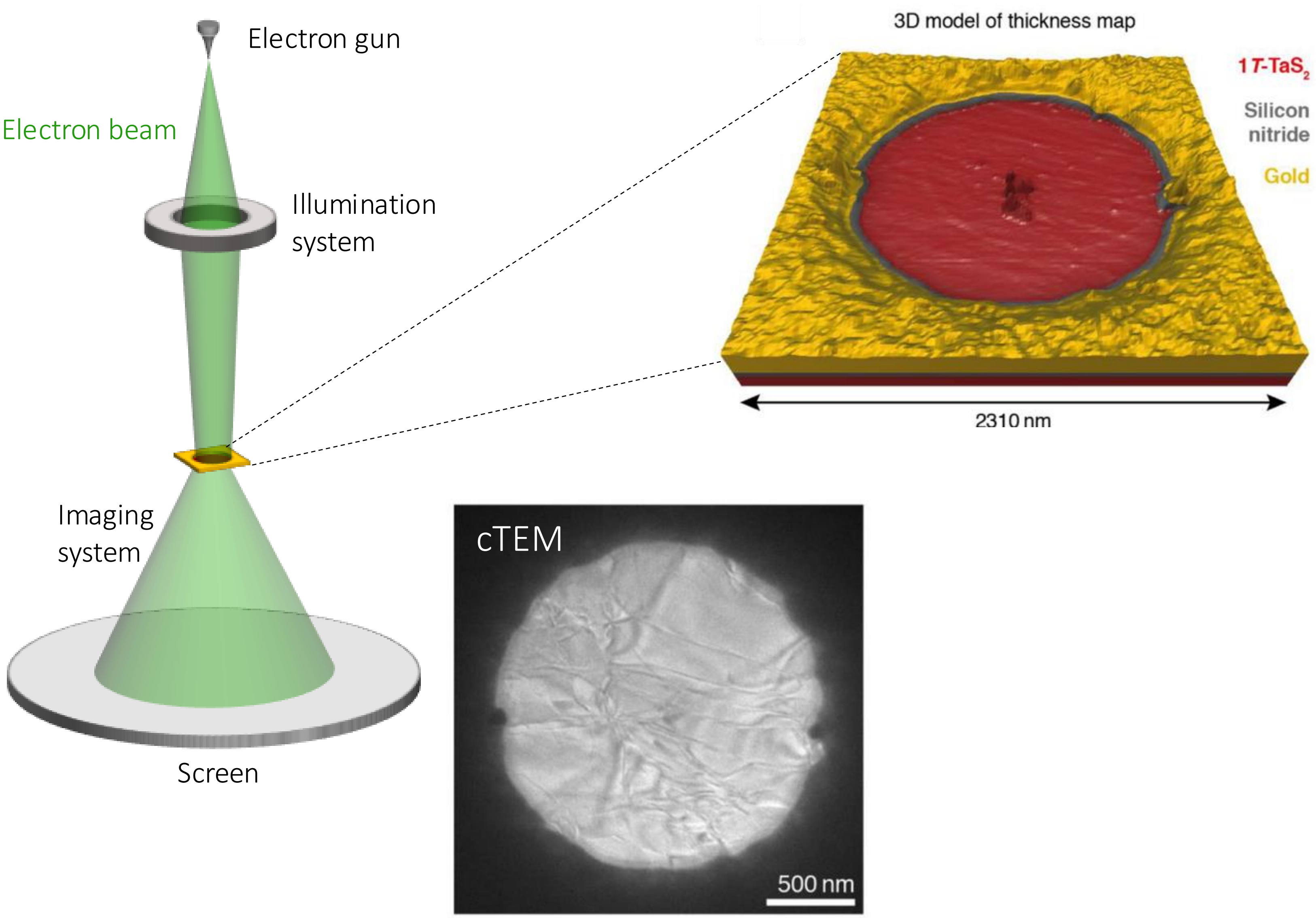






- **Cold-FEG UTEM**:
The modified Hitachi 3300 in CEMES Toulouse (2024)

Principle of ultrafast electron transmission microscopy



Danz et al., Science **371**, 371-374 (2021)

Ultrafast photo-emission

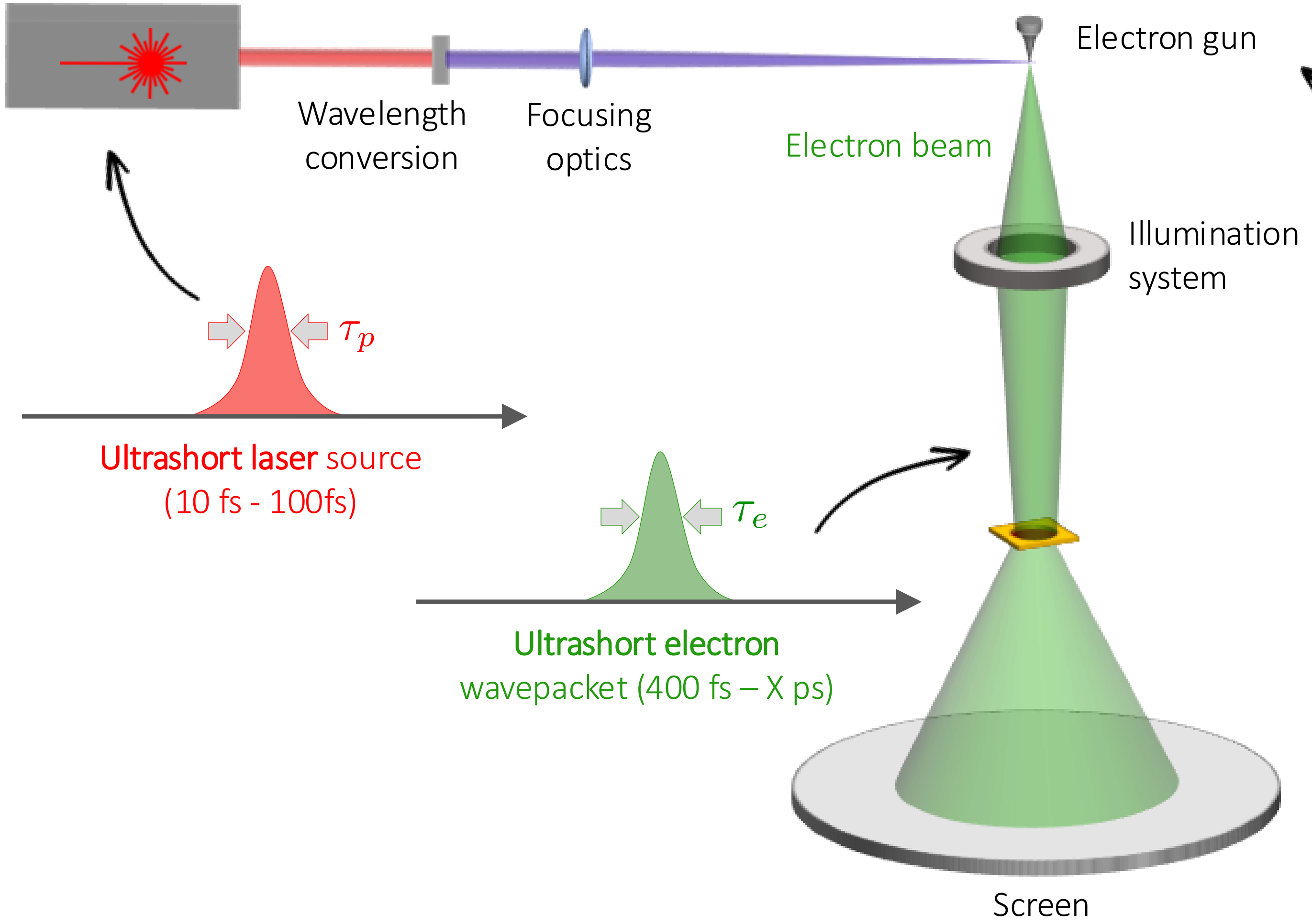
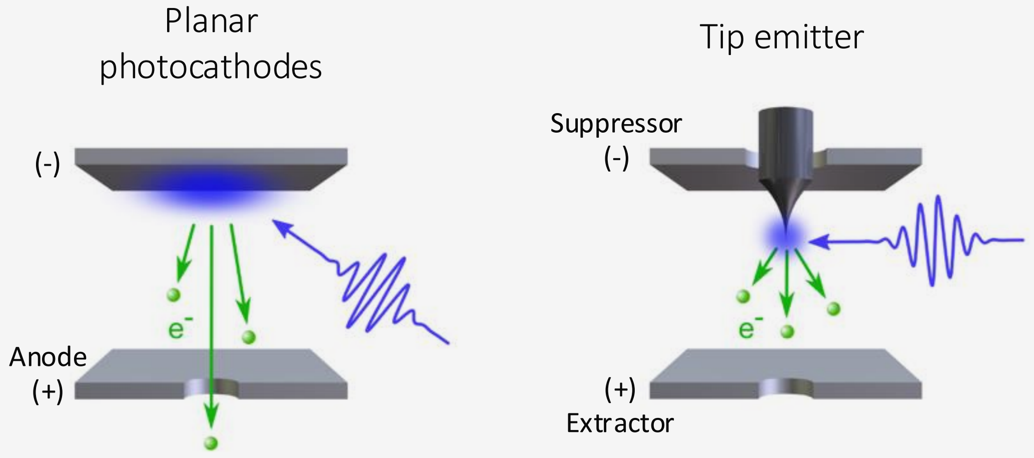


Photo-emission process

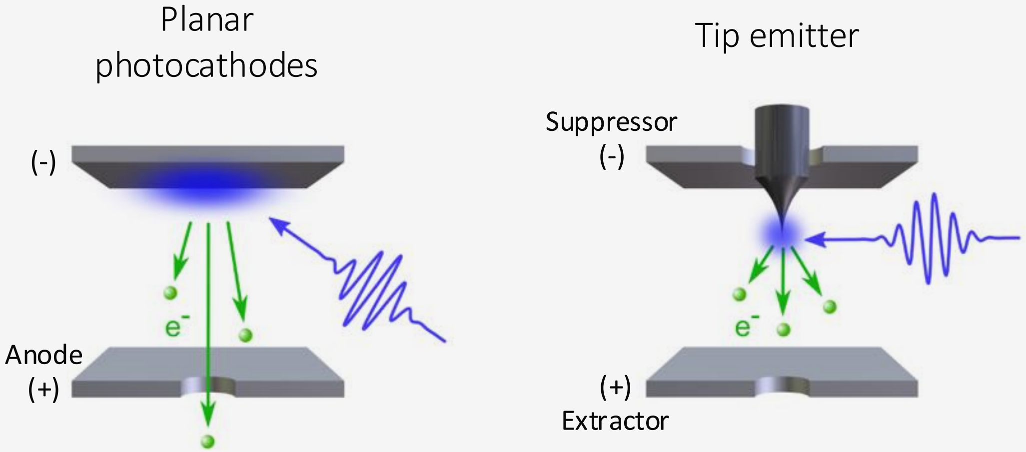


N. Bach *et al.* Ultramicroscopy **176**, 63-73 (2017)
P. Olshin *et al.*, Structural Dynamics **7** (5), 054304 (2020)
L. Zhang *et al.*, Structural Dynamics **6**, 051501 (2019)

Generation of an ultra-short electron wavepacket with a precise trigger time, therefore arrival time on the sample.

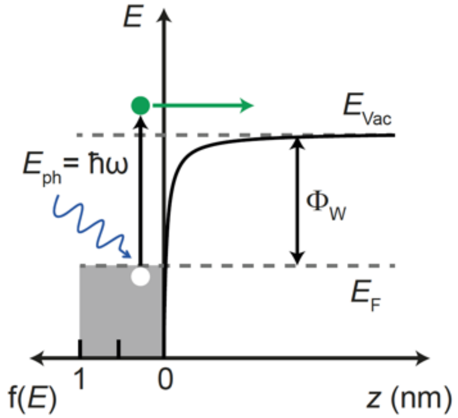
Different type of electron photo-emitters

Photo-emission process

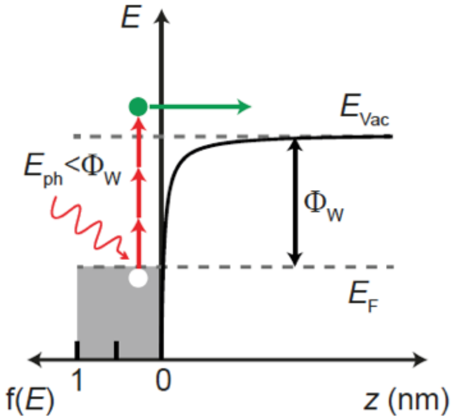


N. Bach *et al.* Ultramicroscopy **176**, 63-73 (2017)
P. Olshin *et al.*, Structural Dynamics **7** (5), 054304 (2020)
L. Zhang *et al.*, Structural Dynamics **6**, 051501 (2019)

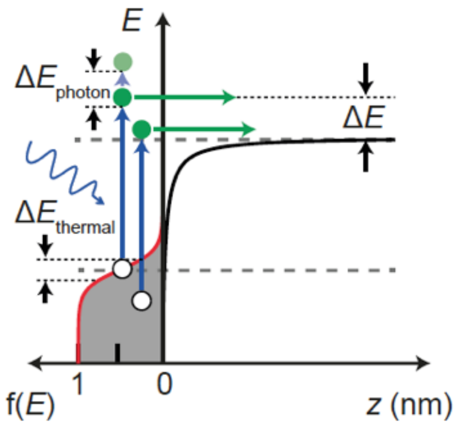
1 photon PE



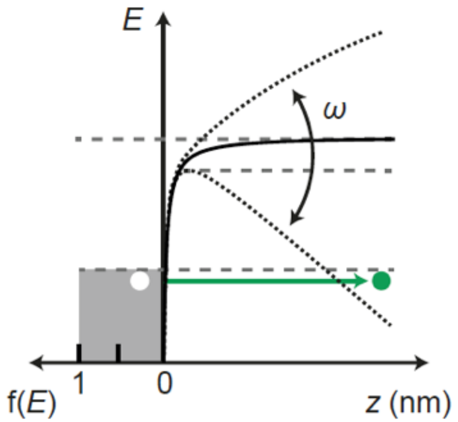
N photons PE



“Schottky ”1 photon PE



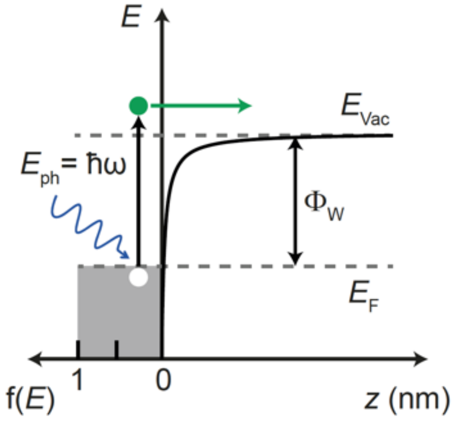
Strong-field PE



Armin Feist, PhD thesis (2018)

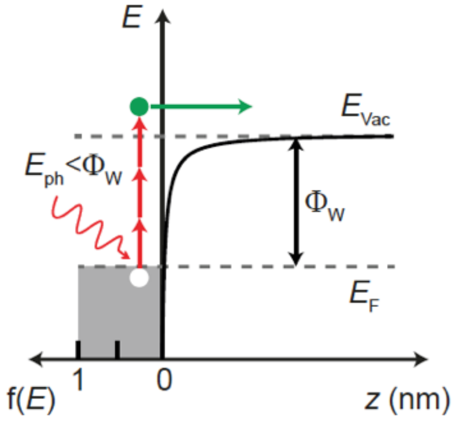
Different type of electron photo-emitters

1 photon PE



$$J_{1\mathrm{PPE}} \propto I_{\mathrm{laser}}$$

N photons PE



$$J_{\mathrm{NPPE}} \propto a_N I_{\mathrm{laser}}^N$$

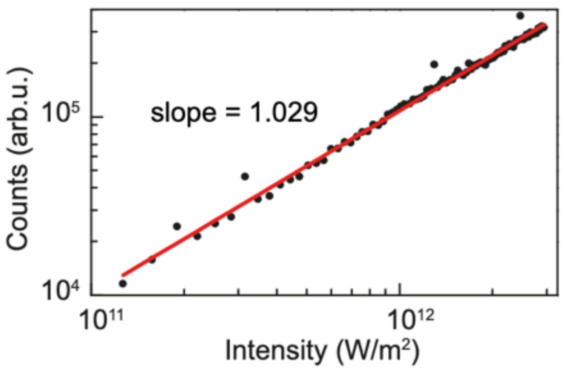
- Electron energy width

$$\Delta E = N\hbar\omega - \phi_W + \Delta E_{\mathrm{kin}} + \Delta E_{\mathrm{thermal}} + \Delta E_{\mathrm{laser}}$$

- Ideal case:

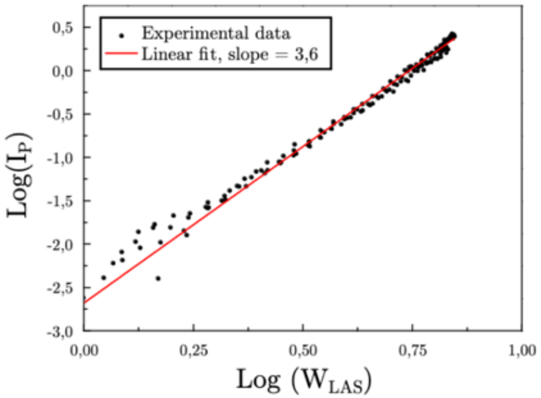
- 1 photon photo-emission
- Cold source
- Close to the work function

Göttingen JEOL 2100F UTEM

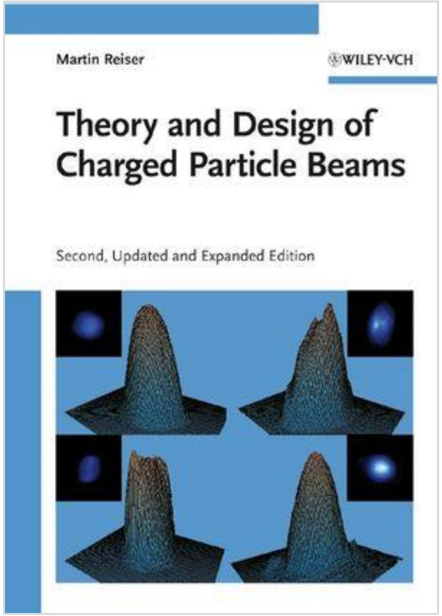


A. Feist et al, Ultramicroscopy **176**, 63-73 (2017)

Toulouse HF2000 FemtoTEM



What are the properties of this ultrashort electron pulse?



Typical TEM figures of merit

- Source brightness
- Effective source size (as reduced by apertures)
- Source energy spread
- Emission stability.

UTEM adds more !

- The electron pulse duration
- Number of electrons per pulse
- The repetition rate
- Impact of Coulomb repulsion for high density electron pulses.
- The electron and laser chirp
- .....

A short bibliography on tip photo-emitters

Ultrafast Electron Pulses from a Tungsten Tip Triggered by Low-Power Femtosecond Laser Pulses
P. Hommelhoff *et al.*, Phys. Rev. Lett. **97** (2006)

Attosecond control of electrons emitted from a nanoscale metal tip
M. Krüger *et al.*, Nature **475,** 78–81 (2011)

Localized Multiphoton Emission of Femtosecond Electron Pulses from Metal Nanotips
C. Ropers *et al.*, Phys. Rev. Lett. **98** (2007)

Laser-induced ultrafast electron emission from a field emission tip
B. Barwick *et al.*, New J. Phys. **9** (2007)

Tip-Enhanced Strong-Field Photoemission
R. Bormann *et al.*, Phys. Rev. Lett. **105** (2010)

Field-driven photoemission from nanostructures quenches the quiver motion
G. Herink *et al.*, Nature **483** (2012)

Highly coherent electron beam from a laser-triggered tungsten needle tip.
D. Ehberger *et al. Phys. Rev. Lett.* **114** (2015).

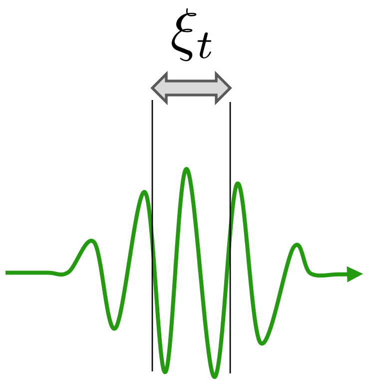
An ultrafast electron microscope gun driven by two-photon photoemission from a nanotip cathode
R. Bormann *et al.*, J. Appl. Phys. **118** (2015)

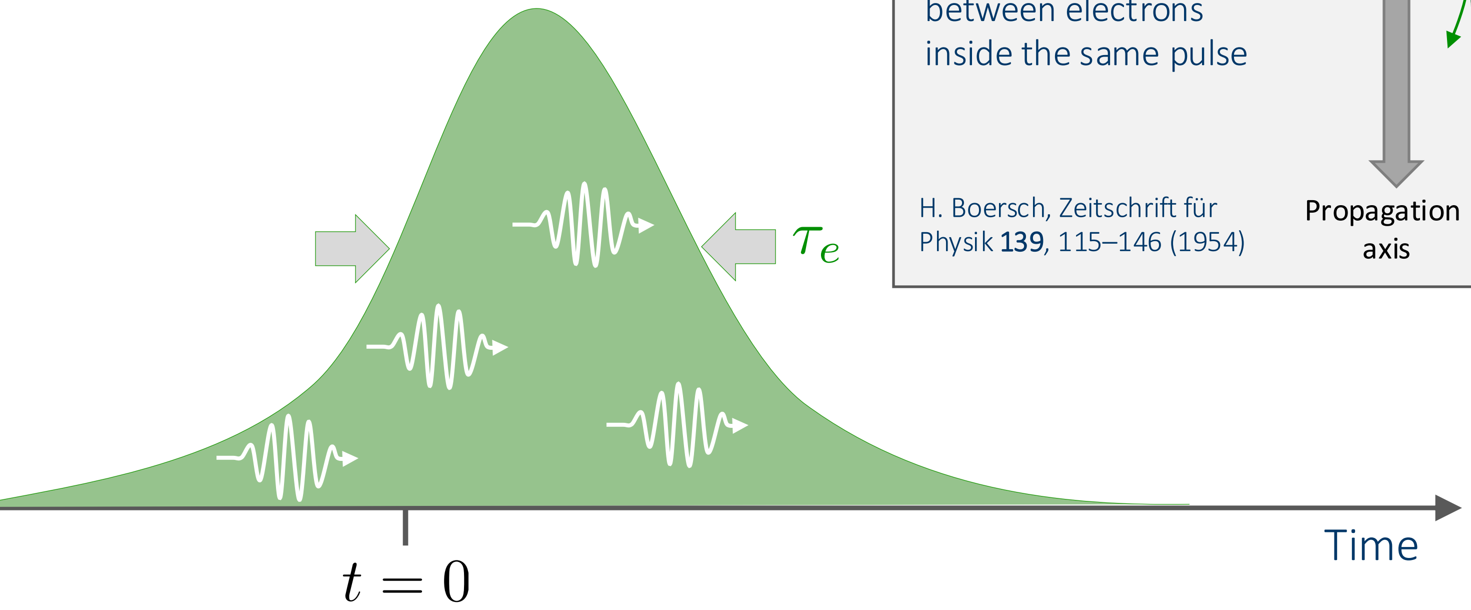
Longitudinal properties of ultrashort electron pulses

Inversely proportional to the energy spread of the source:

$$\xi_t = \frac{\hbar v_e}{\sigma_E}$$

Temporal coherence length

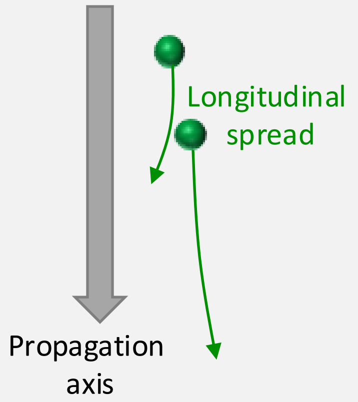




Boersch effect

Coulomb repulsion between electrons inside the same pulse

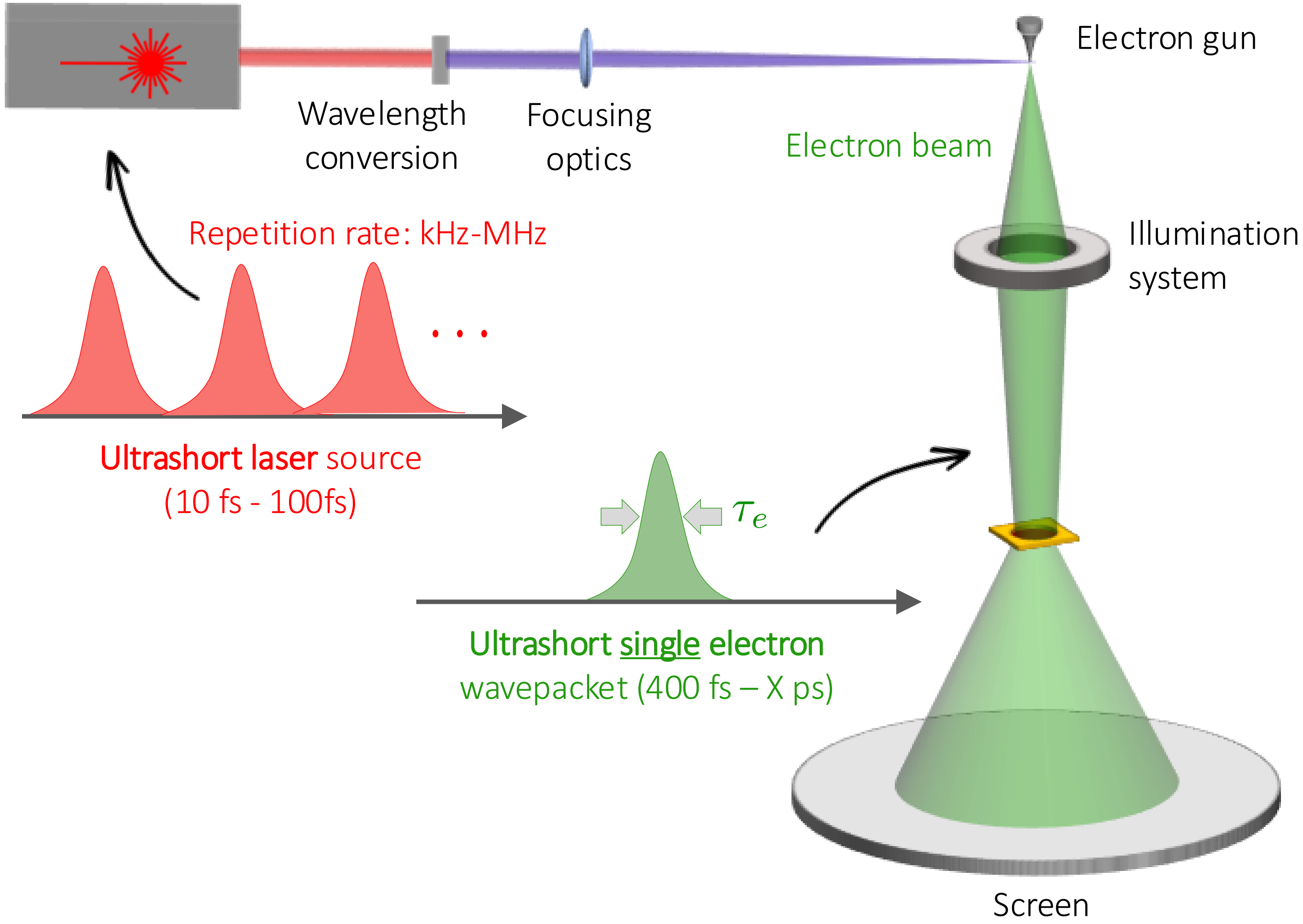
H. Boersch, Zeitschrift für Physik **139**, 115–146 (1954)



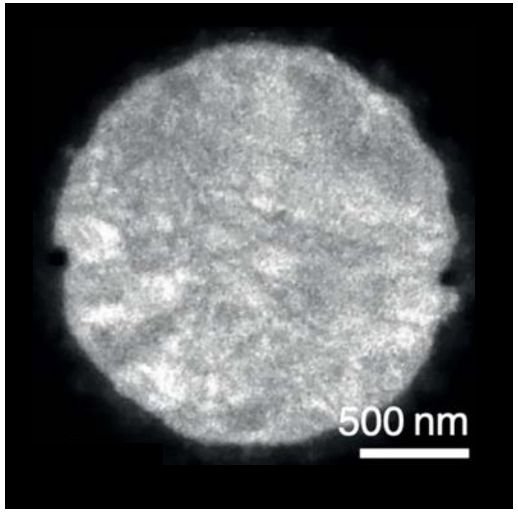
A strong temporal coherence does <u>not</u> equal a short pulse duration!

On the physics of ultrashort single-electron pulses for time-resolved microscopy and diffraction
Peter Baum, Chemical Physics **423**, 55-61 (2013)

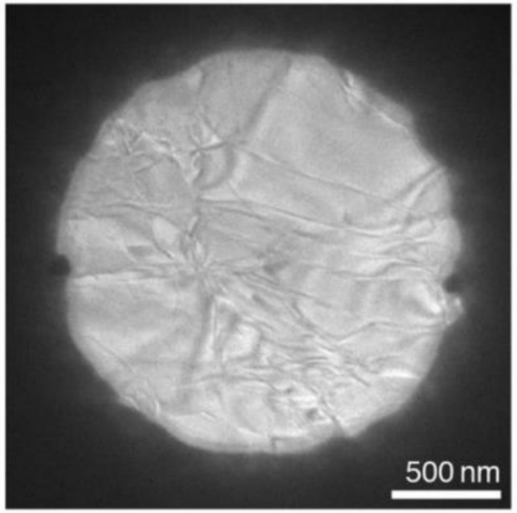
Principle of ultrafast electron transmission microscopy



UTEM image

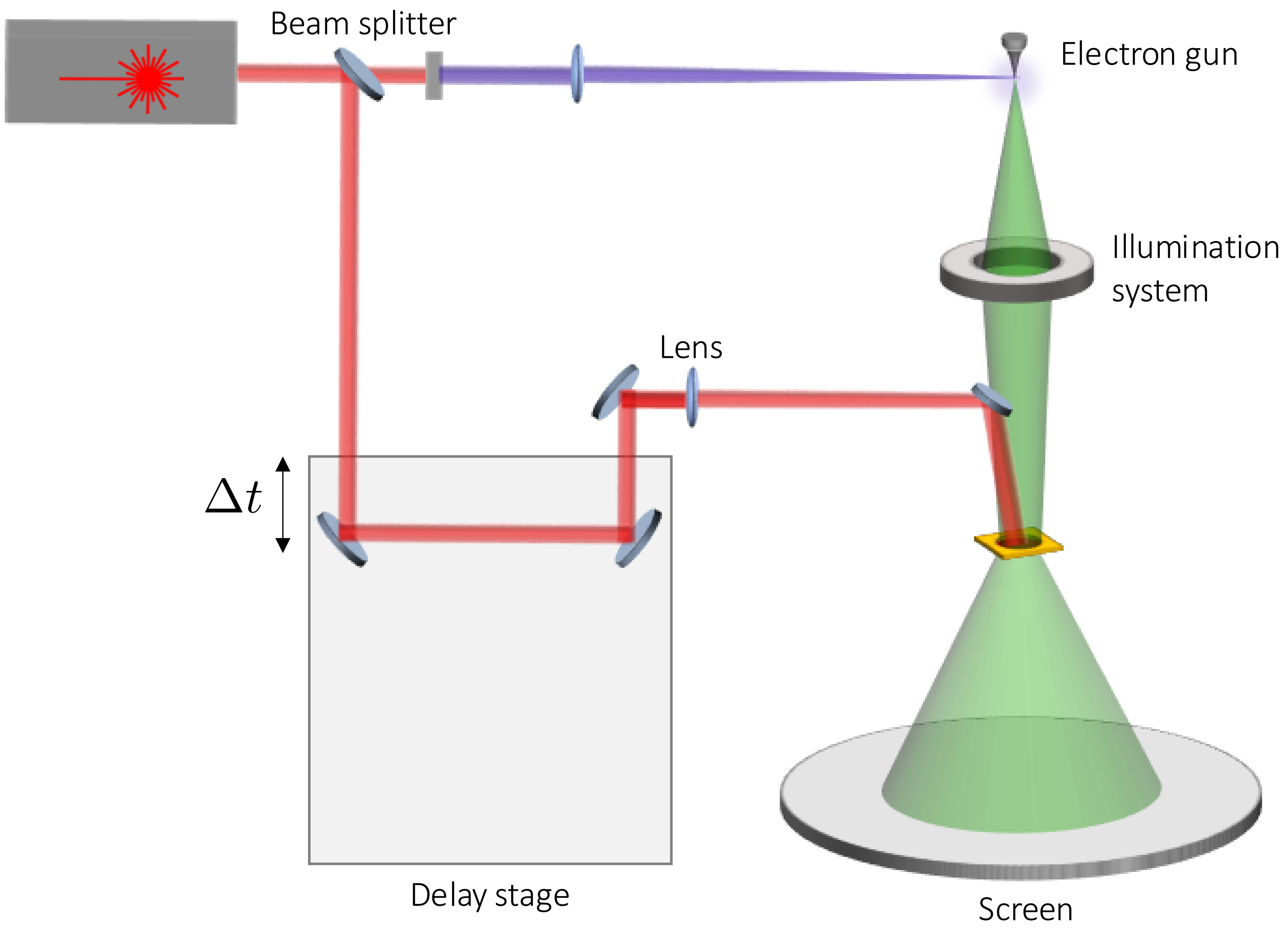


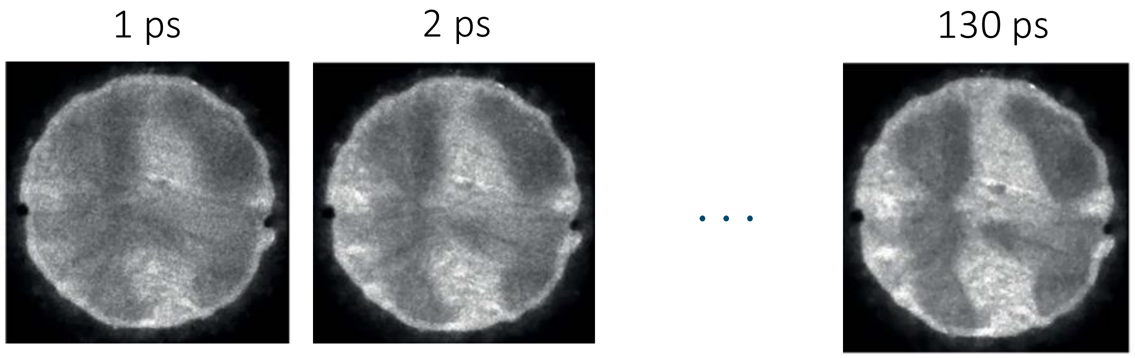
cTEM image



Danz et al., Science **371**, 371-374 (2021)

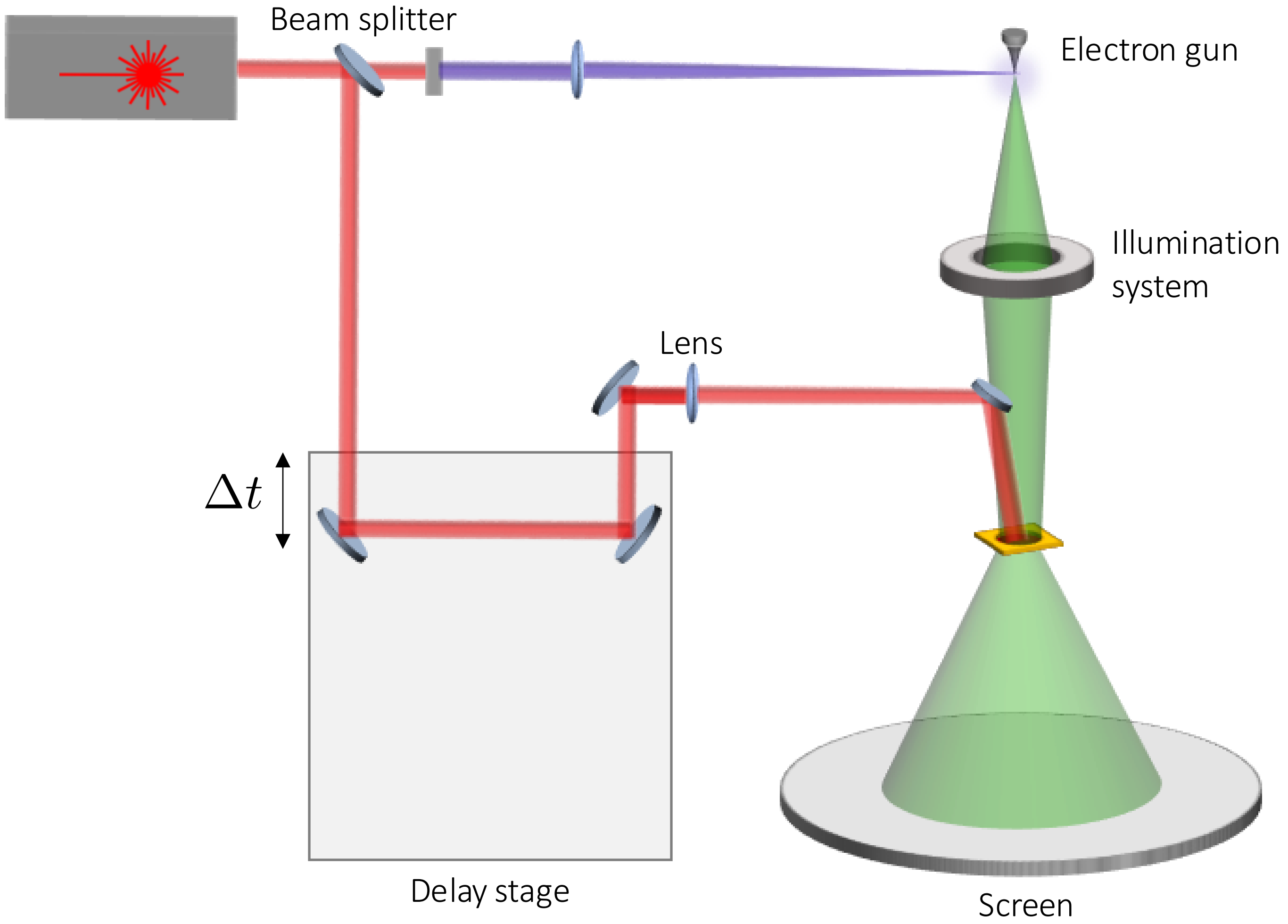
Principle of ultrafast electron transmission microscopy

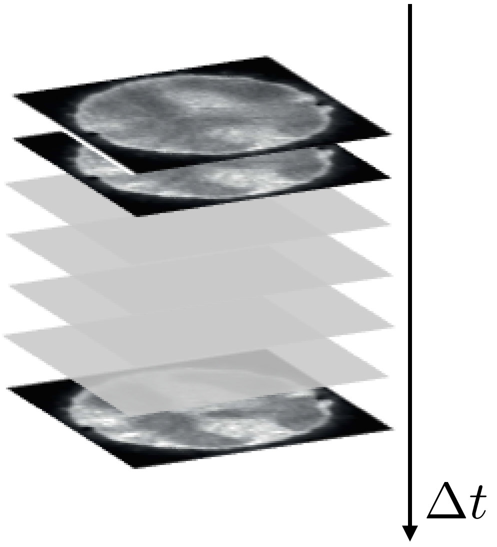




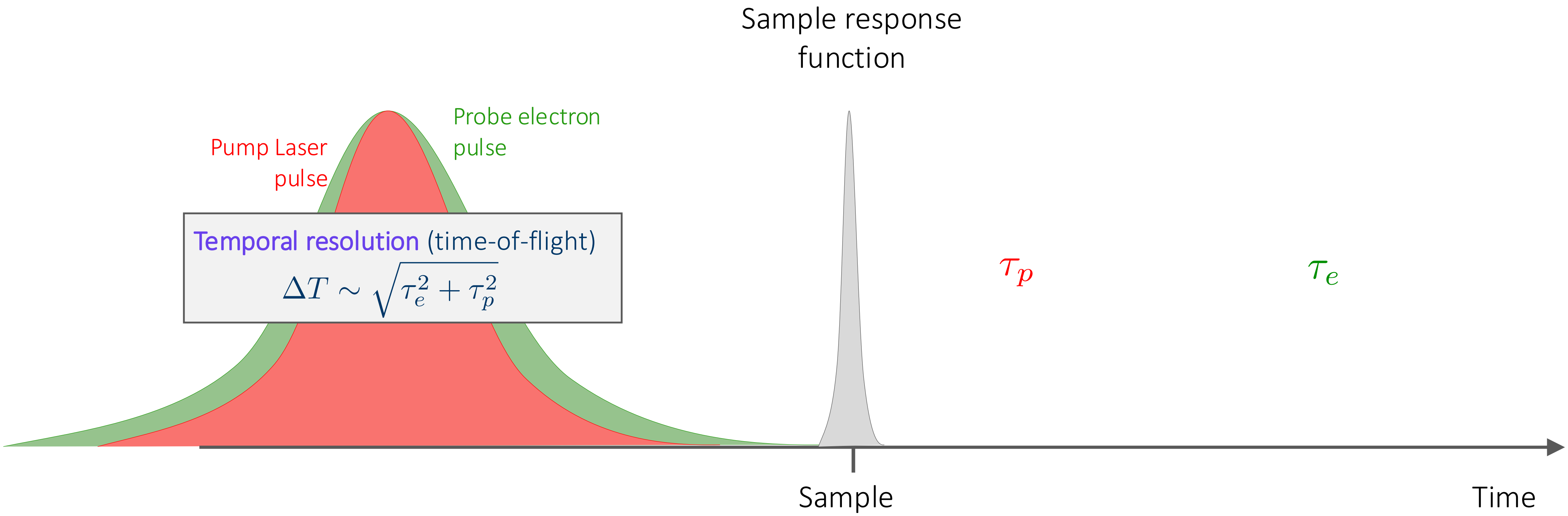
Danz et al., Science **371**, 371-374 (2021)

Principle of ultrafast electron transmission microscopy





What is the temporal resolution?



Temporal resolution (time-of-flight)

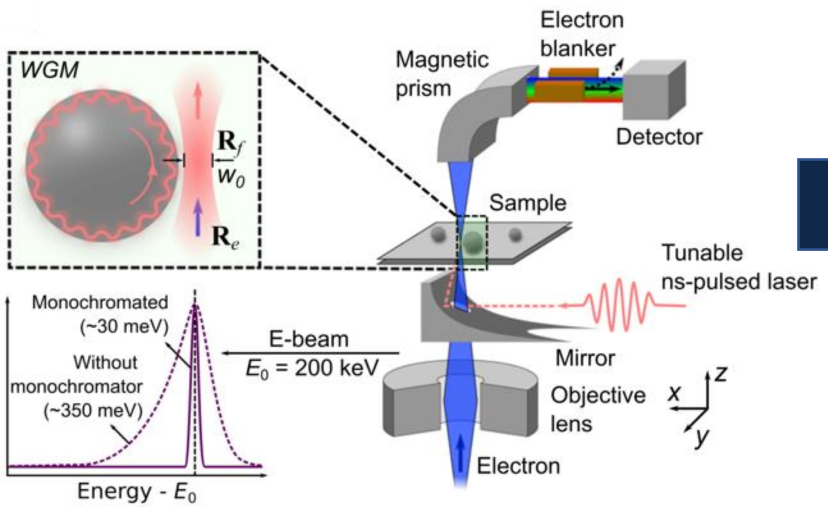
$$\Delta T \sim \sqrt{\tau_e^2 + \tau_p^2}$$

Quantum Improvement of Time Transfer between Remote Clocks

B. Lamine, et al., Physical Review Letters **101** (12) (2008)

Other time-resolved methods not based on photo-emission

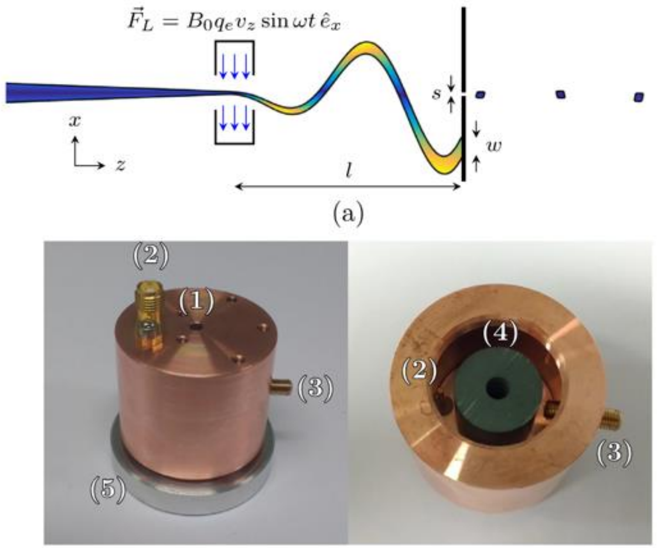
- Fast Electron beam blankers



~ ns

Y. Auad et al., Nature Communications **14**, 4442 (2023)
P. Das et al., Ultramicroscopy **203**, 44-51 (2019)
Liu et al., ACS Photonics **6** (10), 2499–2508 (2019)
Collette et al., J. Chem. Phys. **153**, 044711 (2020)
Collette et al., Scientific Reports **10**, 12537 (2020)
Garfinkel et al., ACS Appl. Nano Mater. **5** (2) 1798–1807 (2022)

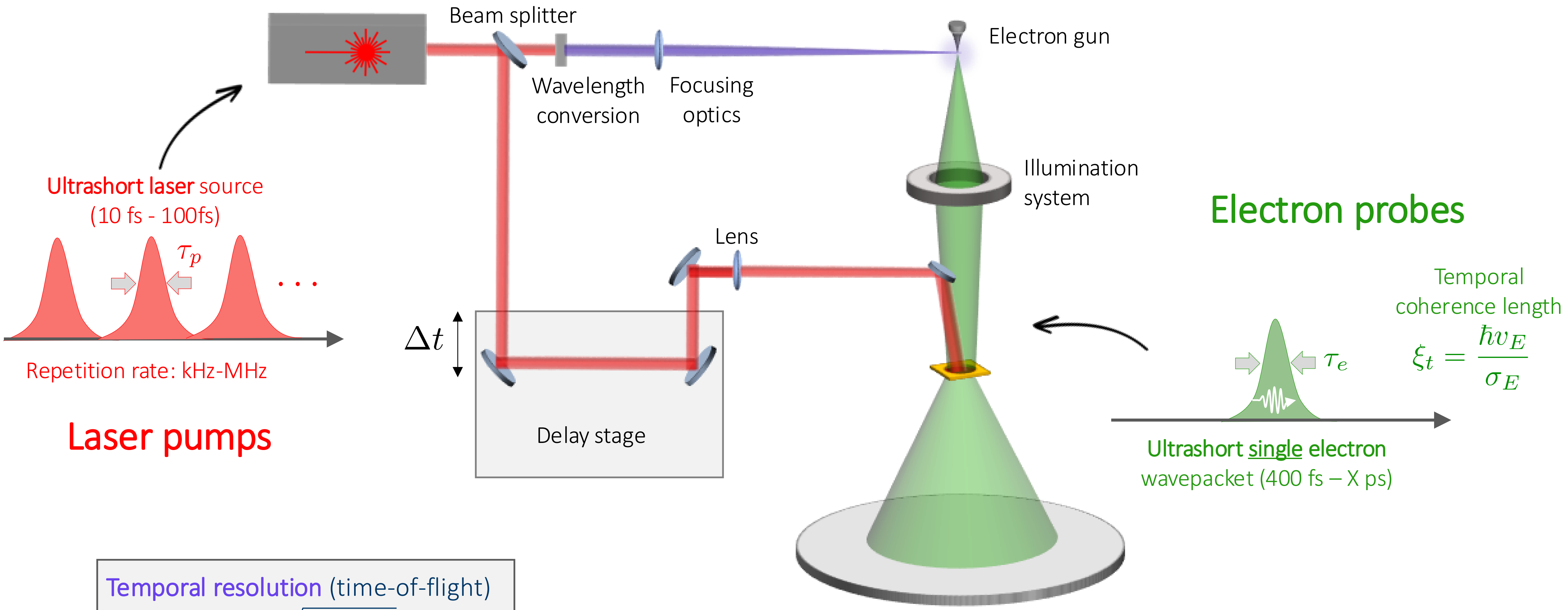
- Microwave cavity choppers and camera streaking



~ ps

W. Verhoeven et al., Ultramicroscopy, 188, 85–89 (2018)
S. A. Reisbick et al., Ultramicroscopy **235**, 113497 (2022)

Summary: Ultrafast electron transmission microscopy (UTEM)



Temporal resolution (time-of-flight)

$$\Delta T \sim \sqrt{\tau_e^2 + \tau_p^2}$$

Cross-correlations

From the Schwarz-Hora effect to PINEM

Helmut Schwarz

Heinrich Hora

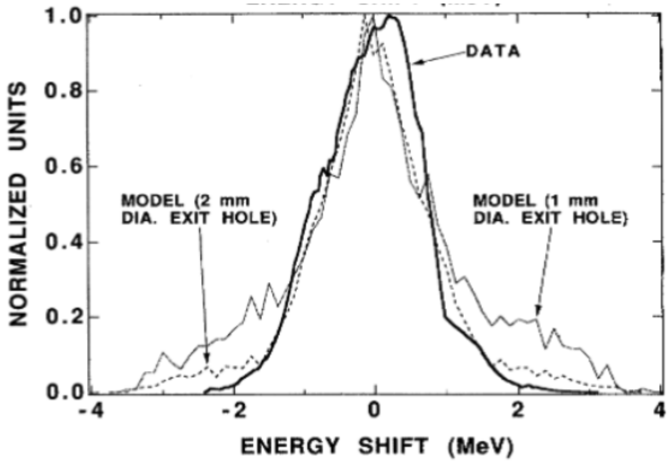
H. Schwarz & H. Hora, Appl. Phys. Lett. **15**, 349–351 (1969)

Brett Barwick

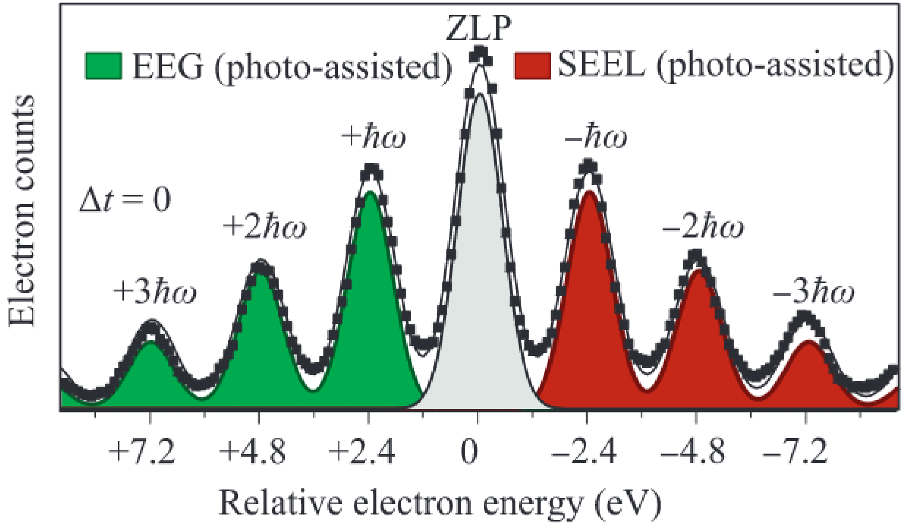
David J. Flannigan

Ahmed H. Zewail

Brookhaven National Laboratory Accelerator Test Facility (ATF)

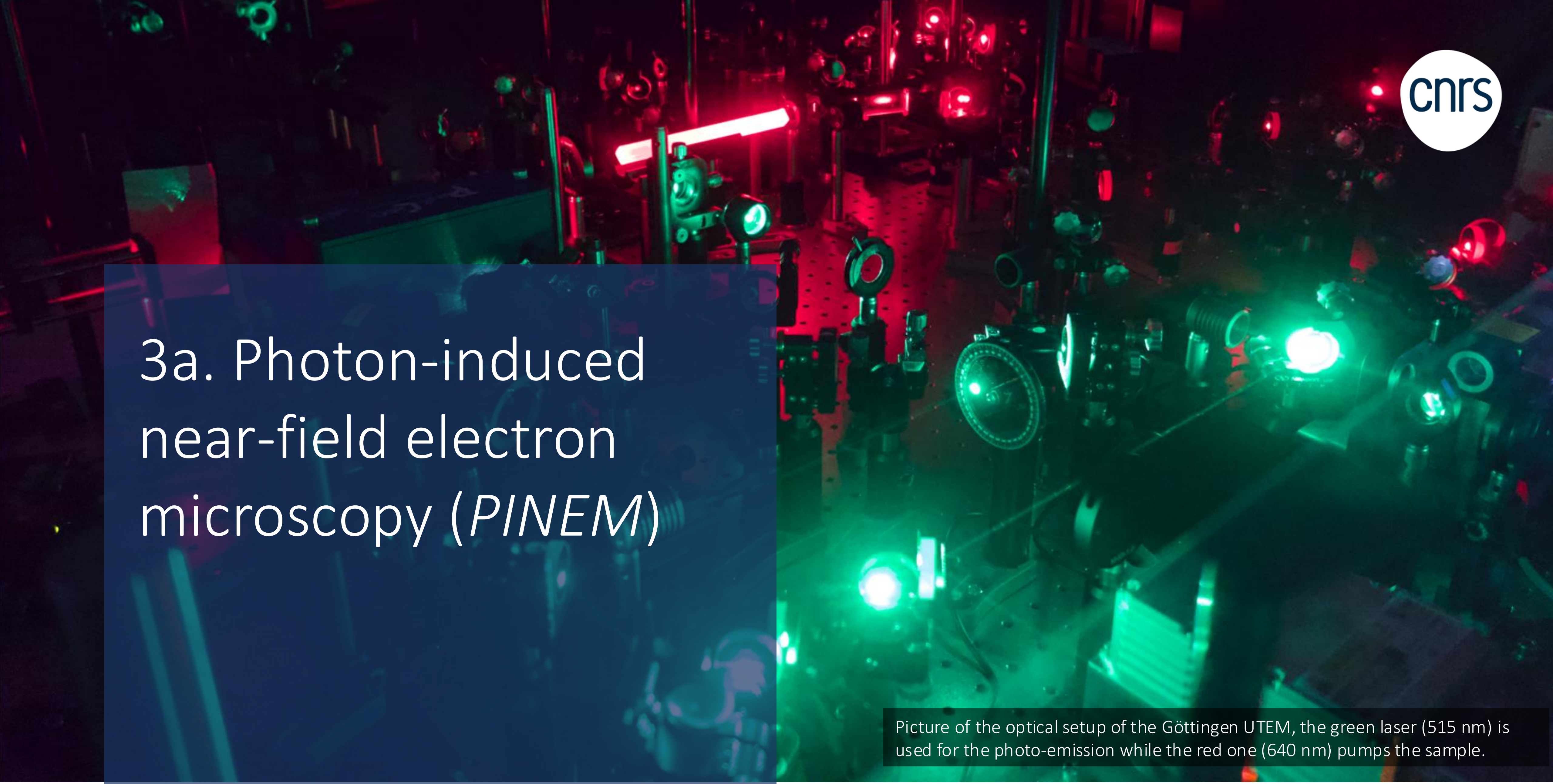


W. D. Kimura *et al.*, Phys. Rev. Lett. 74, 546 (1995)



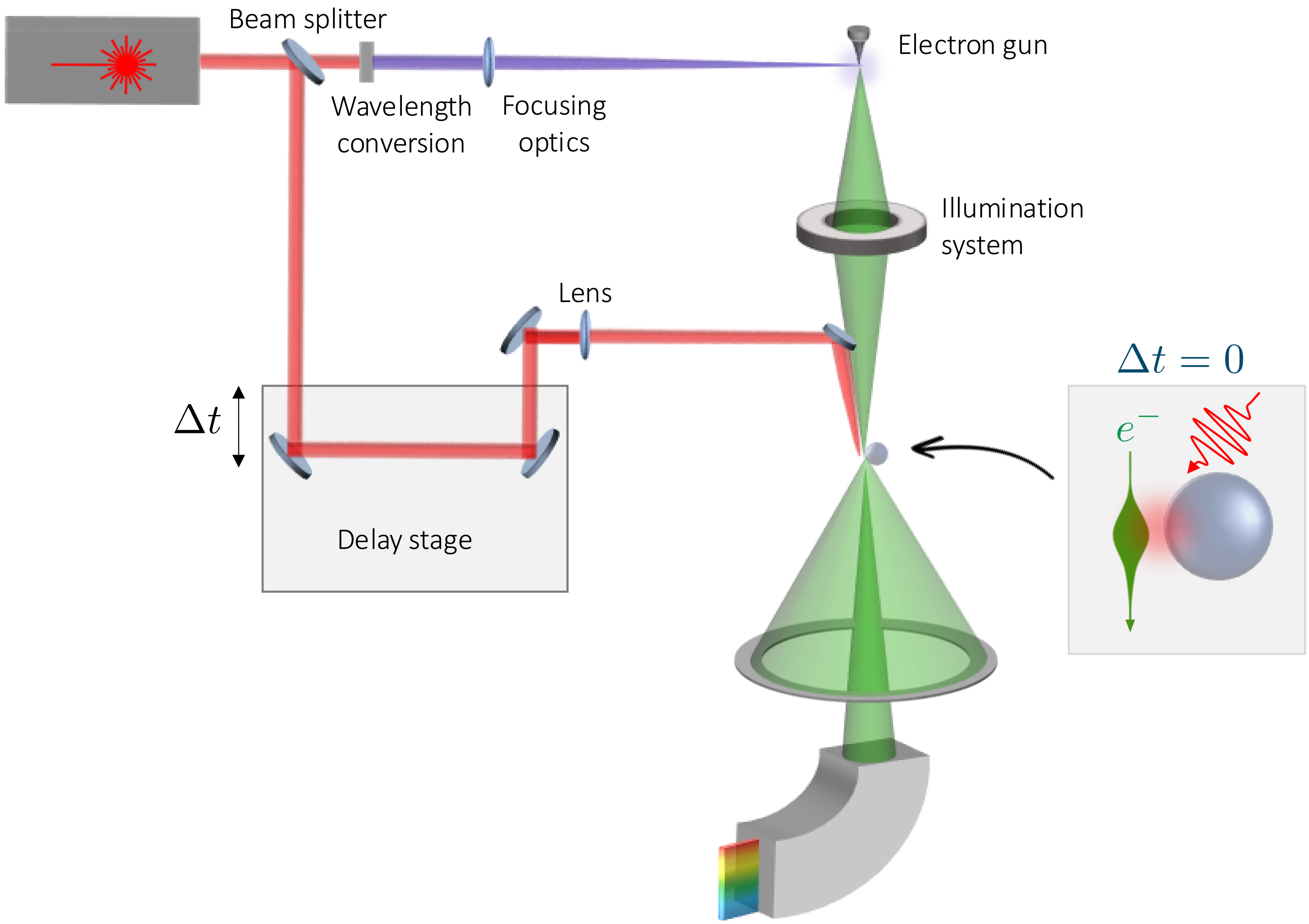
Barwick *et al.*, Nature **462**, 902–906 (2009)

3a. Photon-induced near-field electron microscopy (*PINEM*)

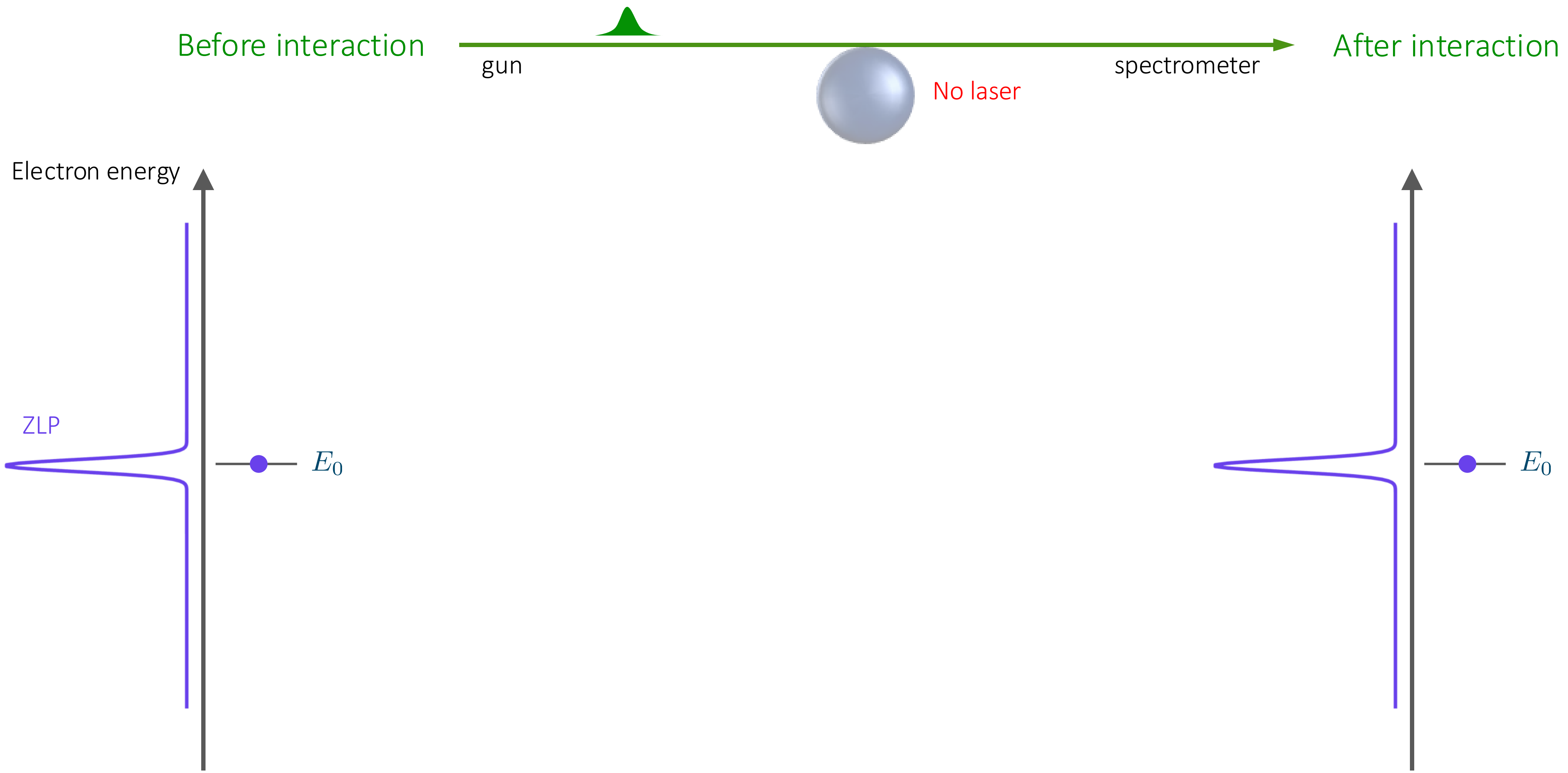


Picture of the optical setup of the Göttingen UTEM, the green laser (515 nm) is used for the photo-emission while the red one (640 nm) pumps the sample.

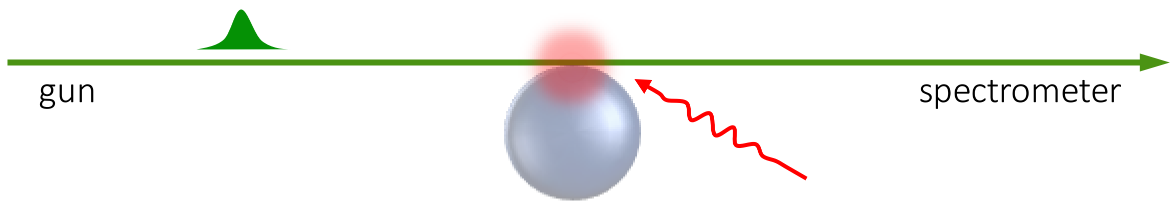
Photon-induced near-field electron microscopy (PINEM)

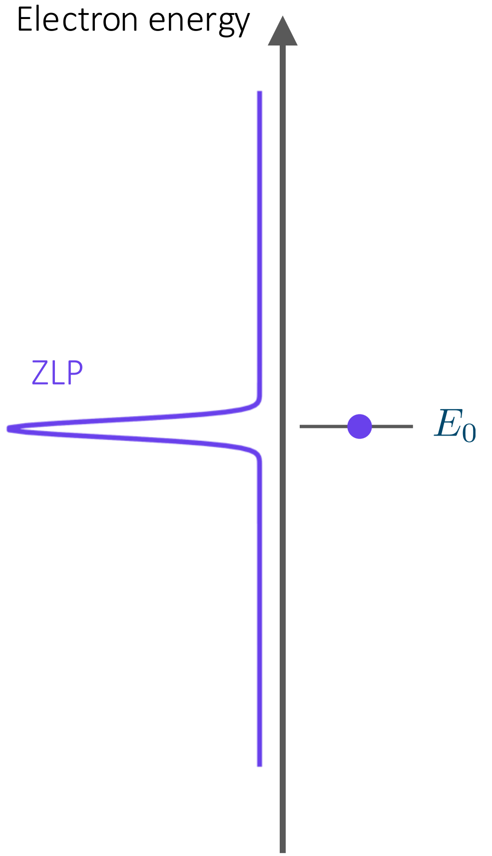


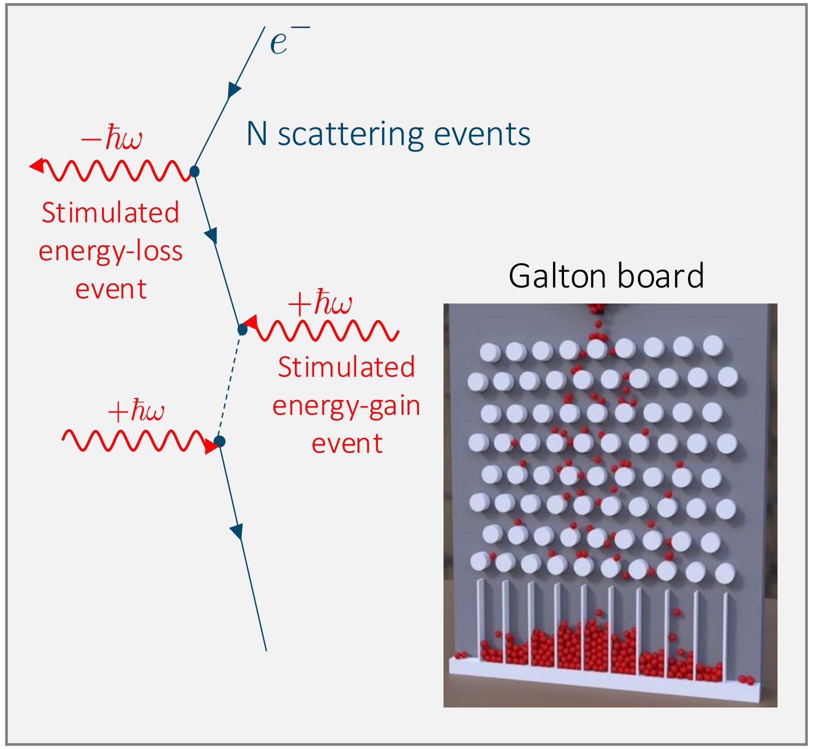
Photon-induced near-field electron microscopy (PINEM)



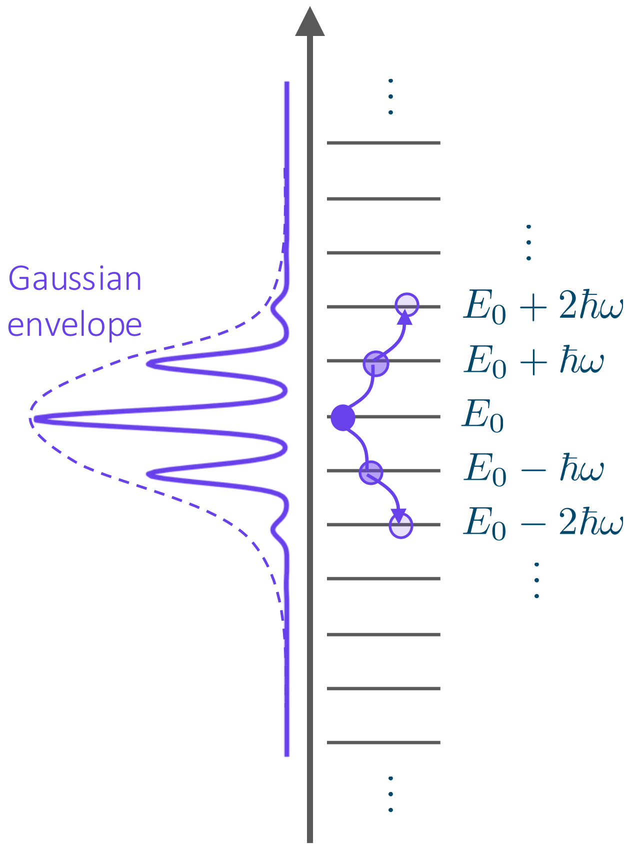
Photon-induced near-field electron microscopy (PINEM)



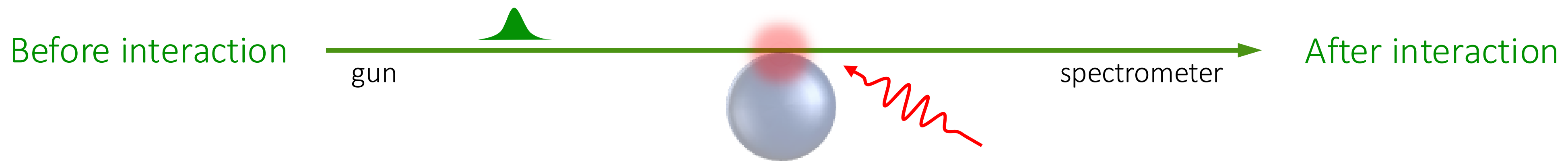


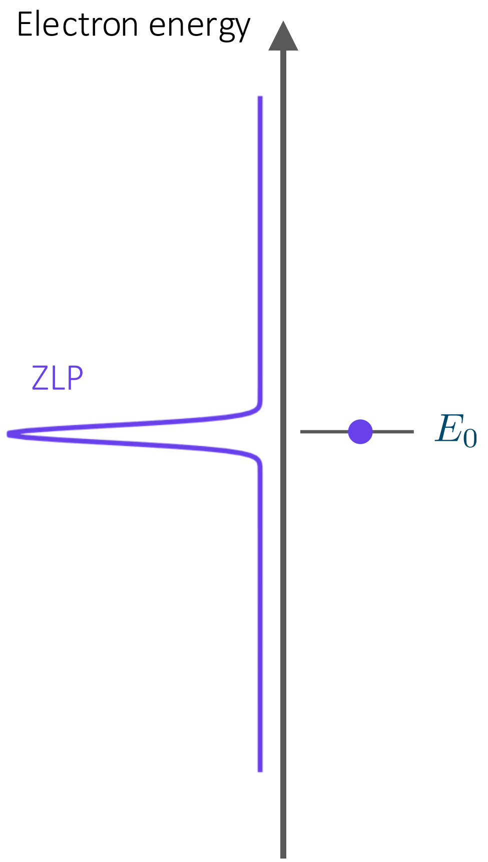


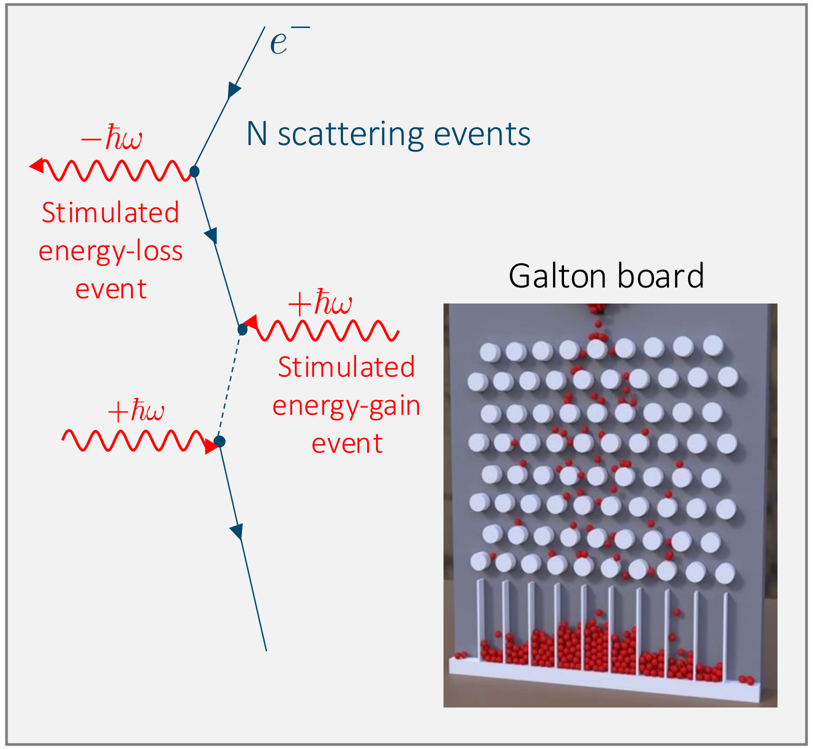
Classical random walk on the energy ladder



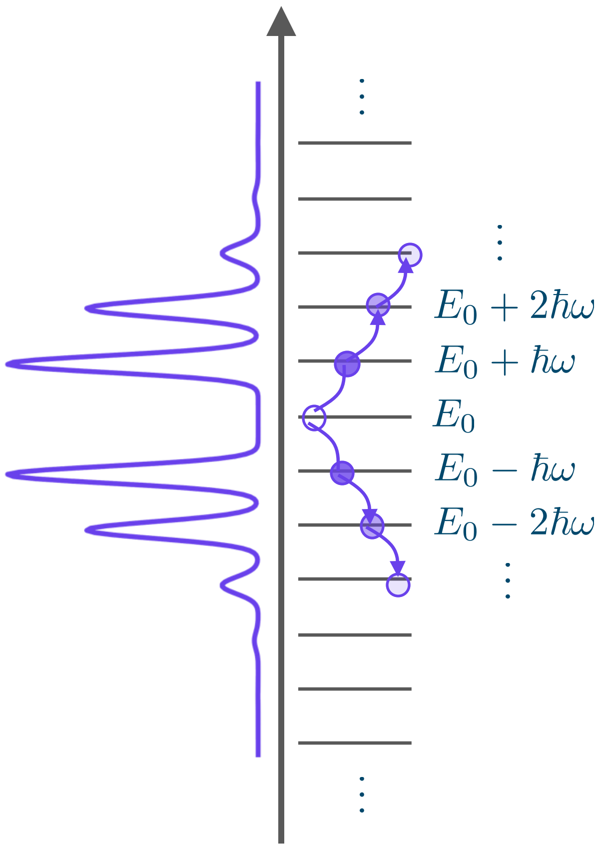
Photon-induced near-field electron microscopy (PINEM)



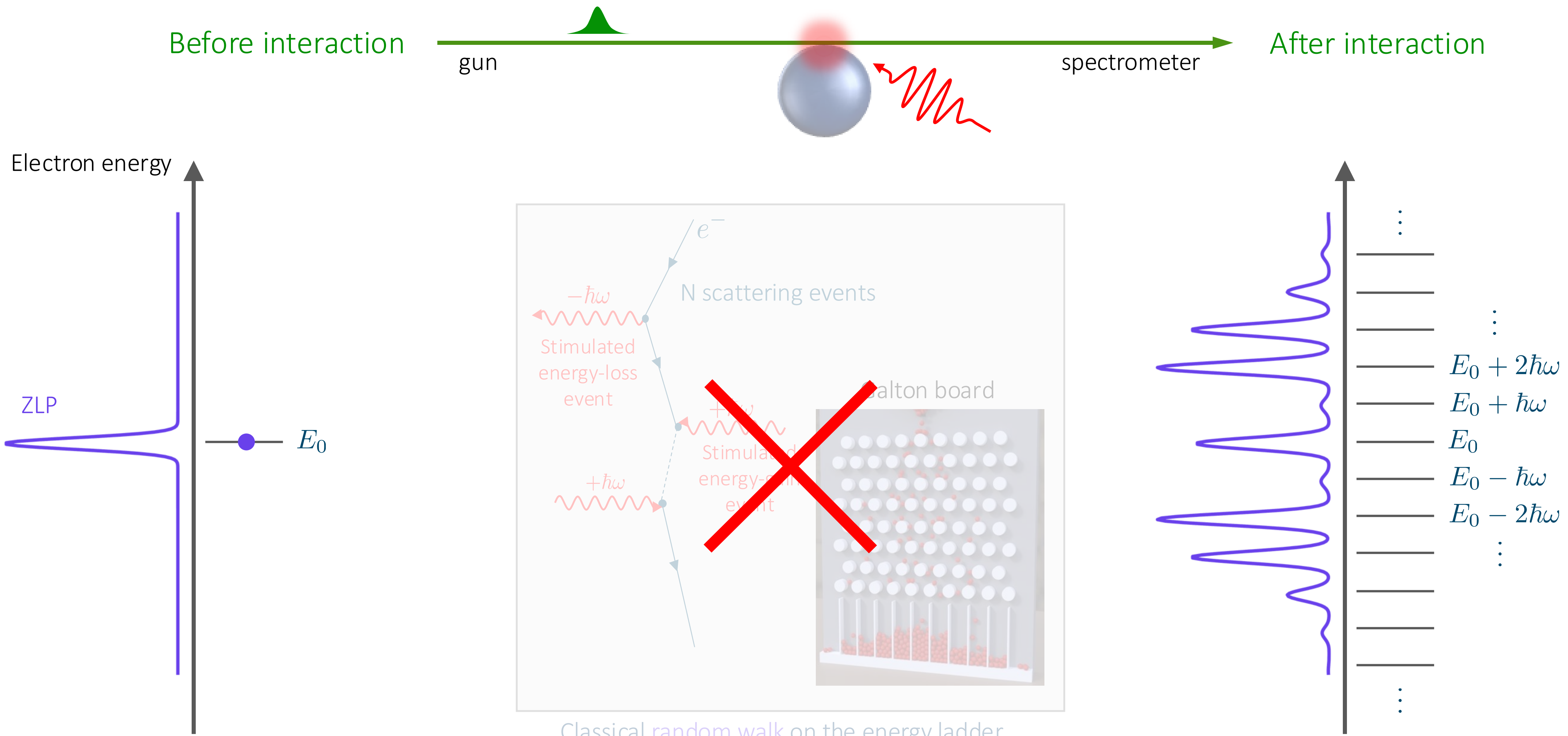




Classical random walk on the energy ladder



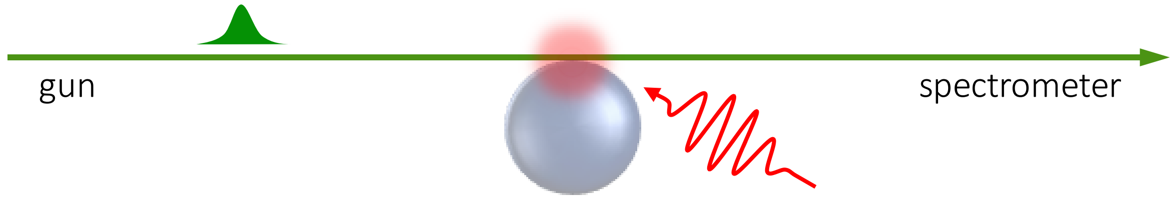
Photon-induced near-field electron microscopy (PINEM)



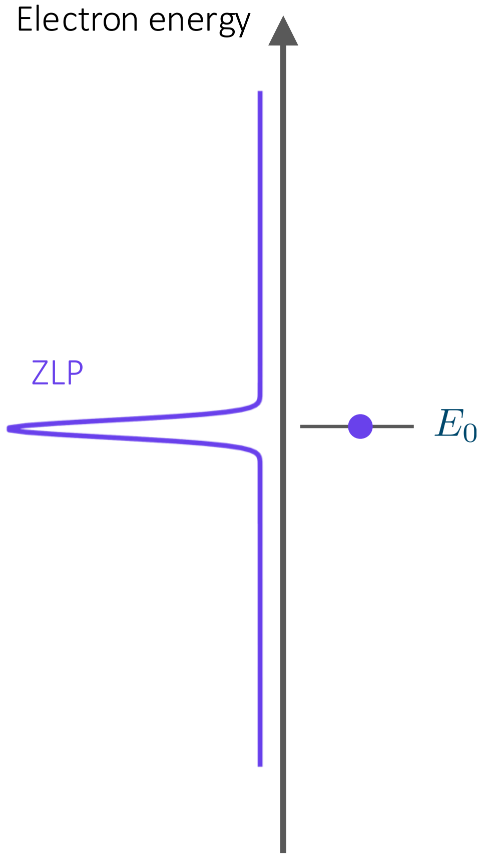
Classical random walk on the energy ladder

Photon-induced near-field electron microscopy (PINEM)

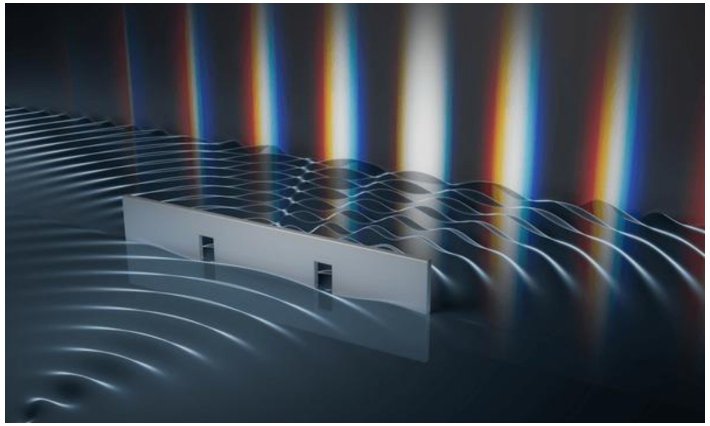
Before interaction

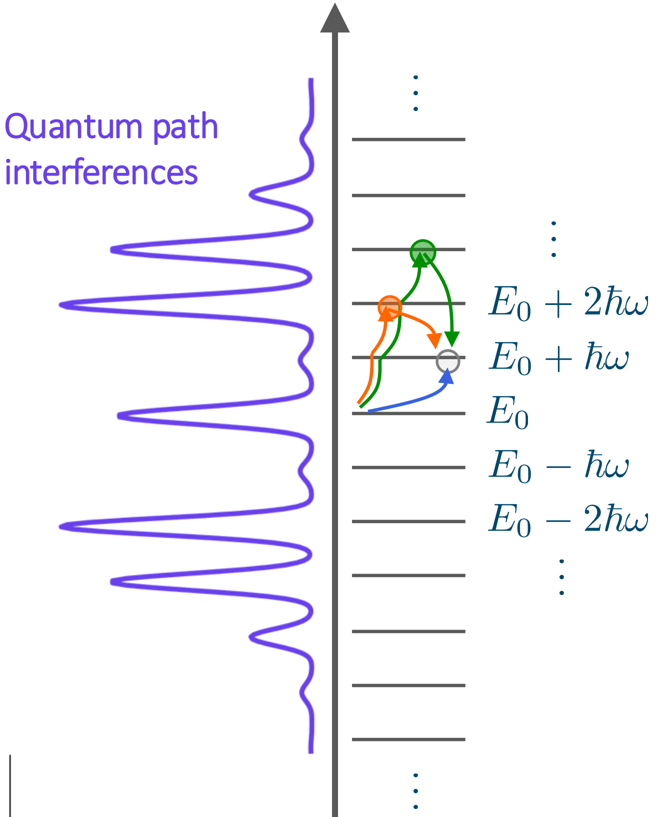


After interaction

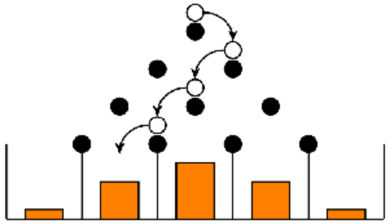


Double slit interferences

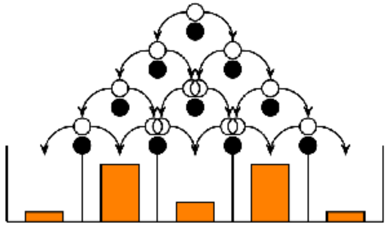




Classical Random Walk



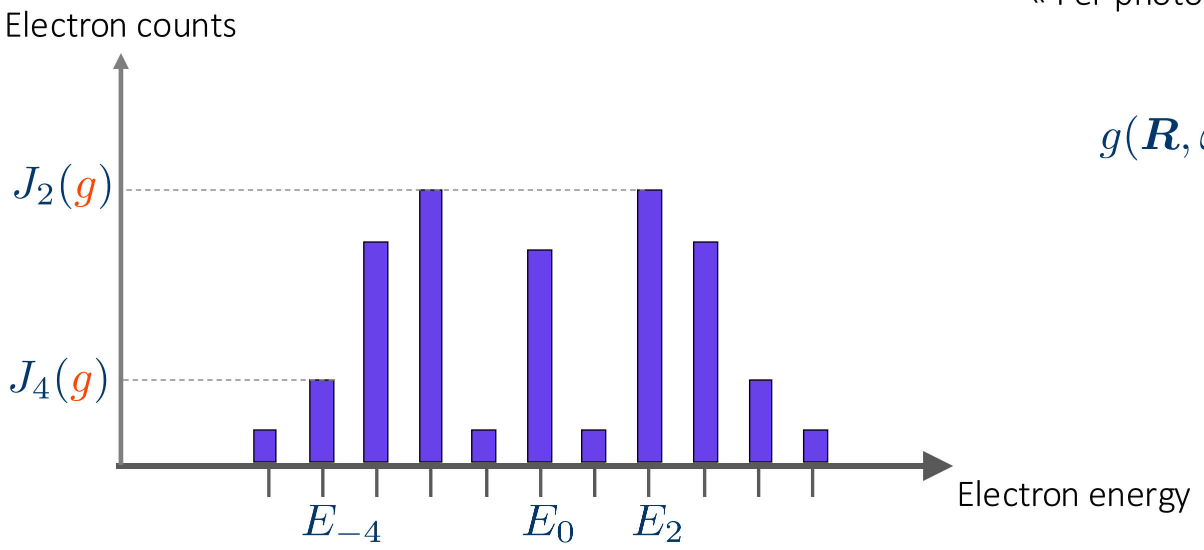
Quantum Random Walk



Each electron follow one random sequence of photon emission/absorption

Each electron follow all random sequences of photon emission/absorption

Photon-induced near-field electron microscopy (PINEM)



Electron-light coupling constant

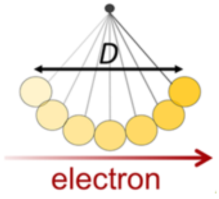
« Per photon »

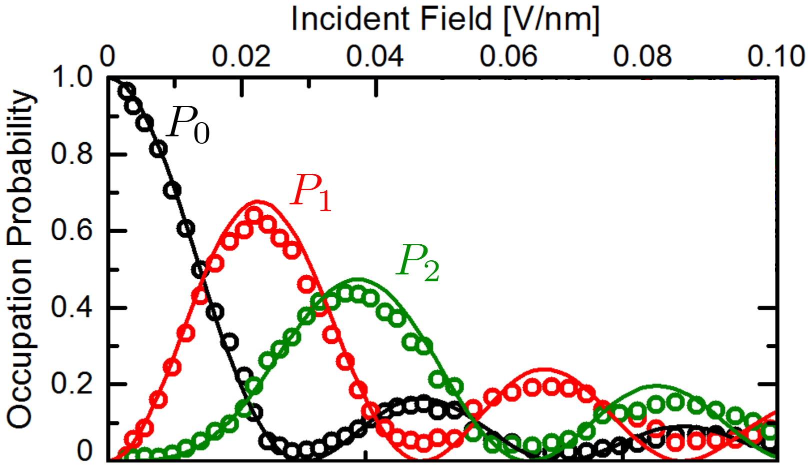
~ Lorentz force

Phase-matching condition

$$g(\boldsymbol{R},\omega) = \left| \frac{1}{\hbar\omega} \int_{\mathcal{L}} e\, E_z(\boldsymbol{R}, z, \omega)\, e^{-i\frac{\omega}{v}z} dz \right|$$

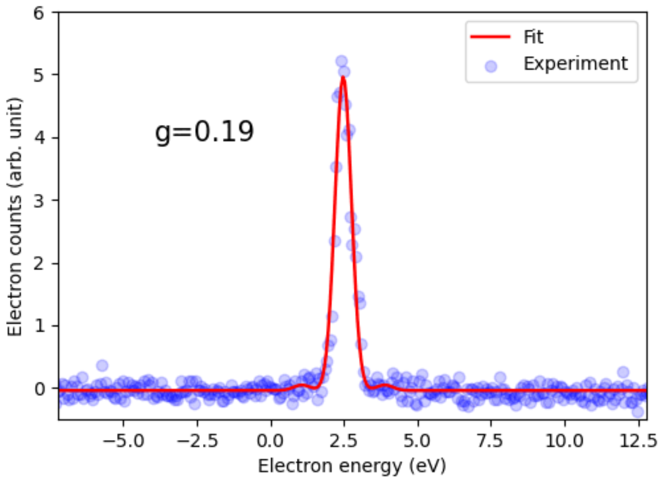
Sum over trajectory



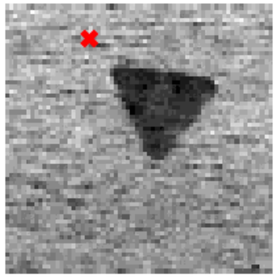


A. Feist *et al.*, Nature **521**, 200–203 (2015)

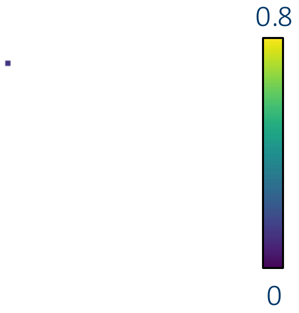
Photon-induced near-field electron microscopy (**PINEM**)



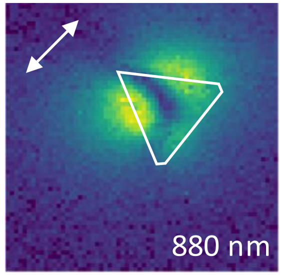
Bright field



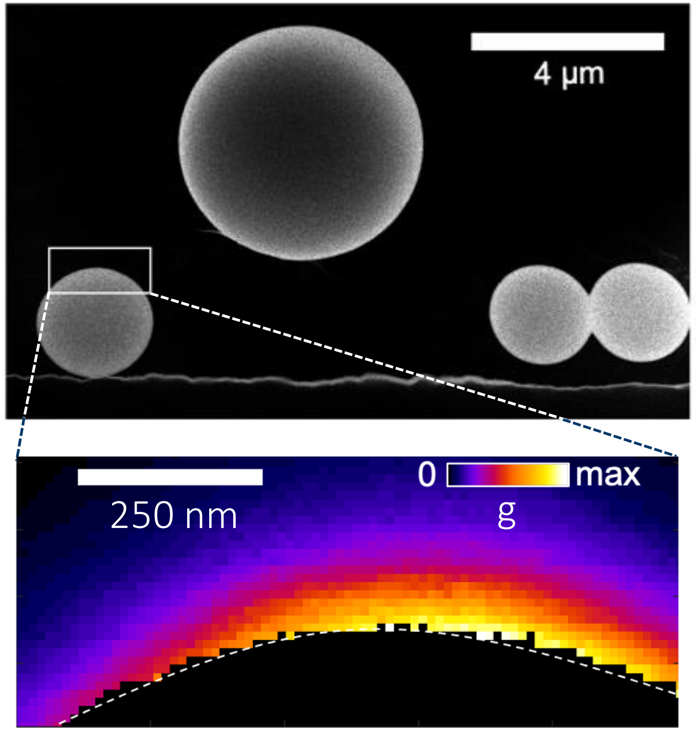
g-map



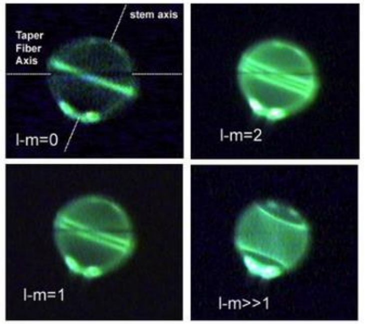
$g \sim E_z$



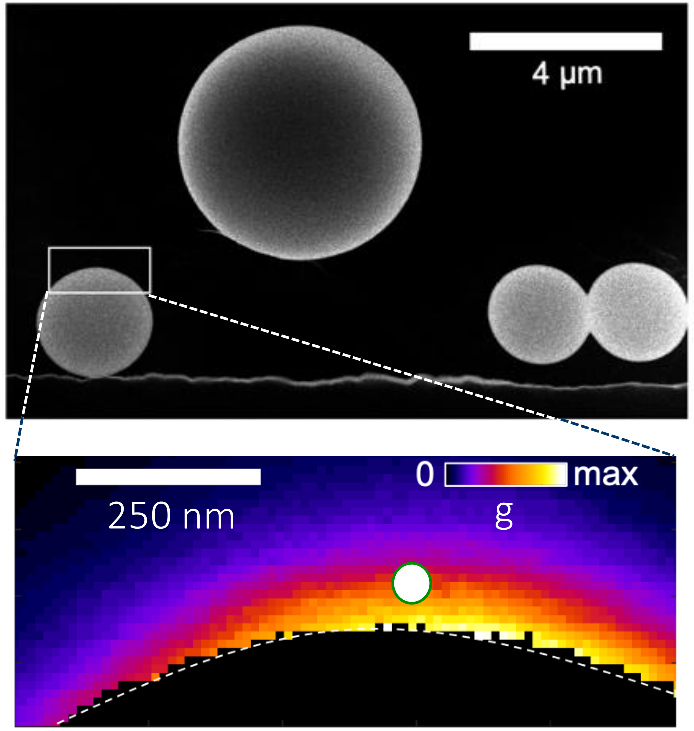
Map of the laser-induced optical near-field



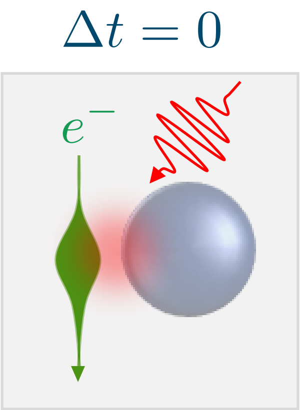
Kfir *et al.*, **Nature 582,** 46–49 (2020)

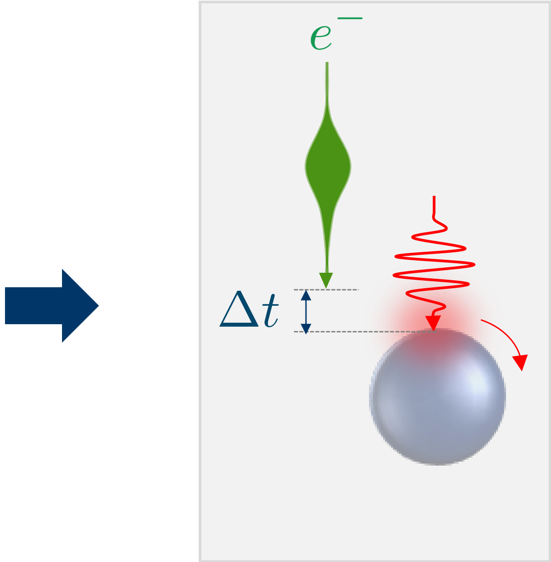


Where is the time resolution?

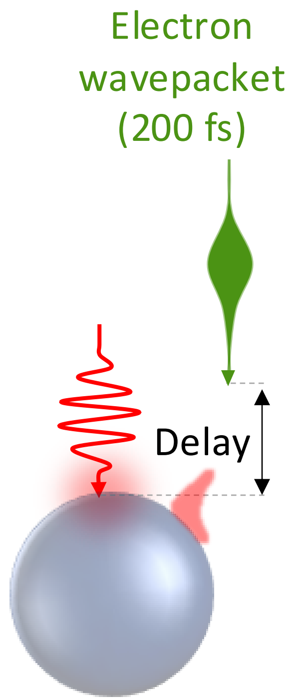


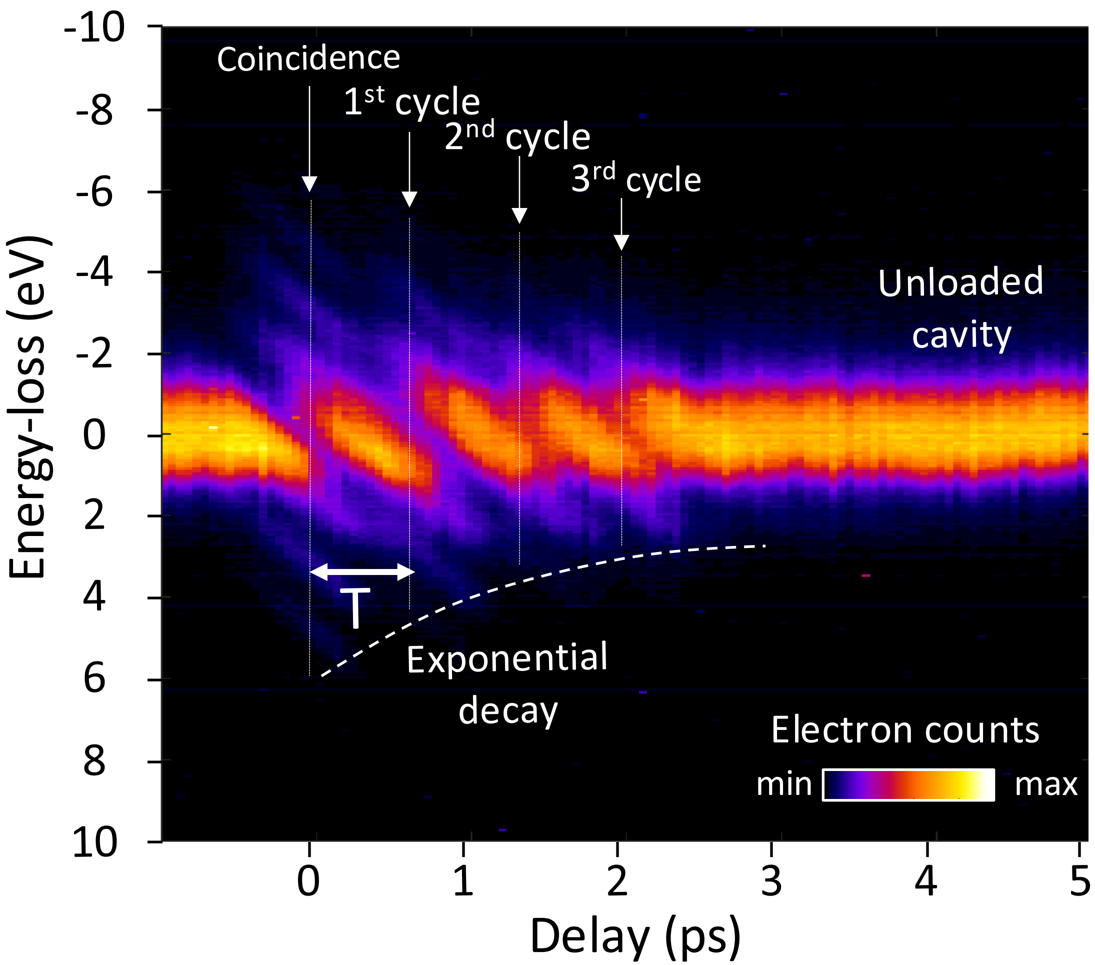
Kfir *et al.*, **Nature 582,** 46–49 (2020)

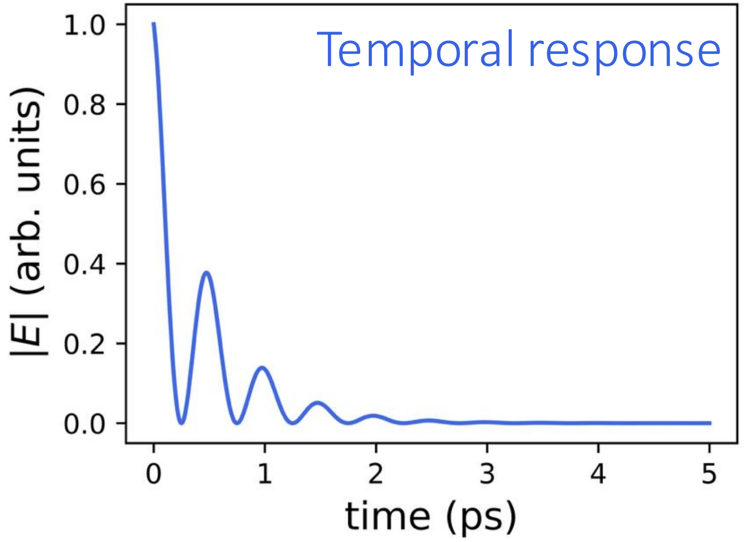




Where is the time resolution?



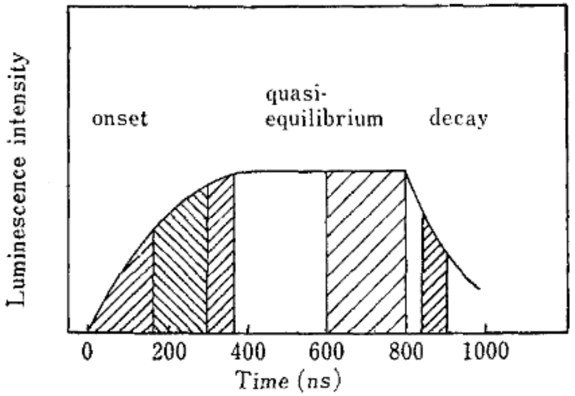


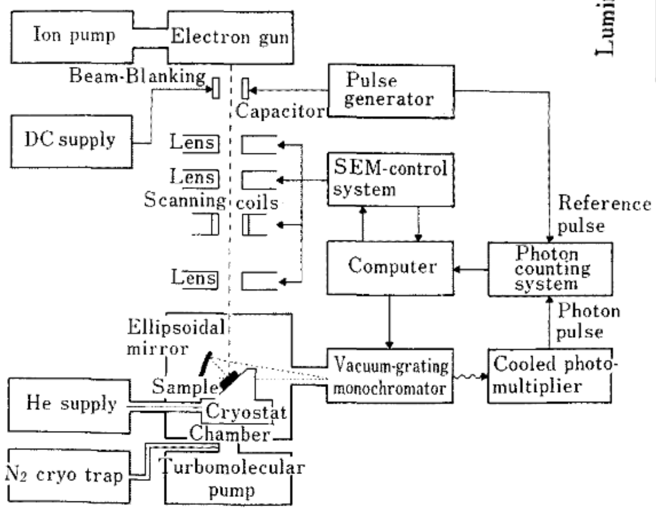


Time-resolved Cathodoluminescence (TR-CL)

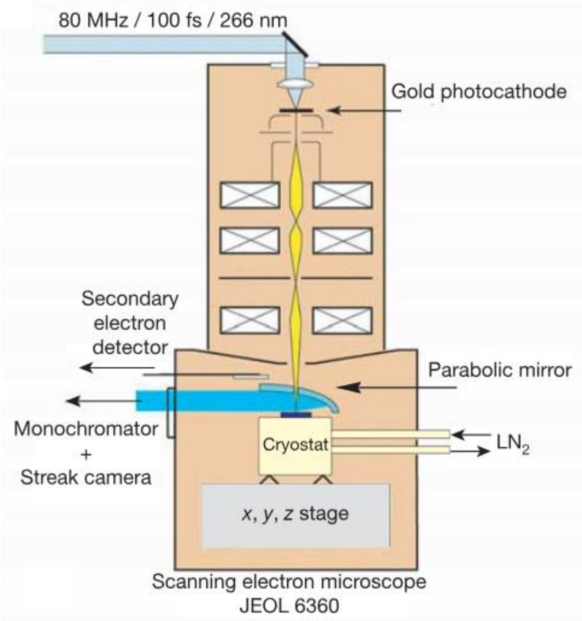
Jürgen Christen

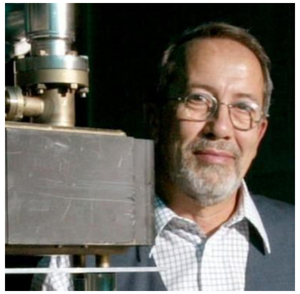
Dieter Bimberg



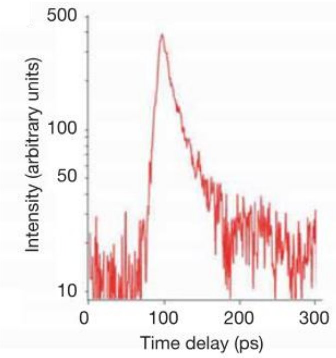


Christen and Bimberg, Oyo Buturi **57**, 69-77 (1988)



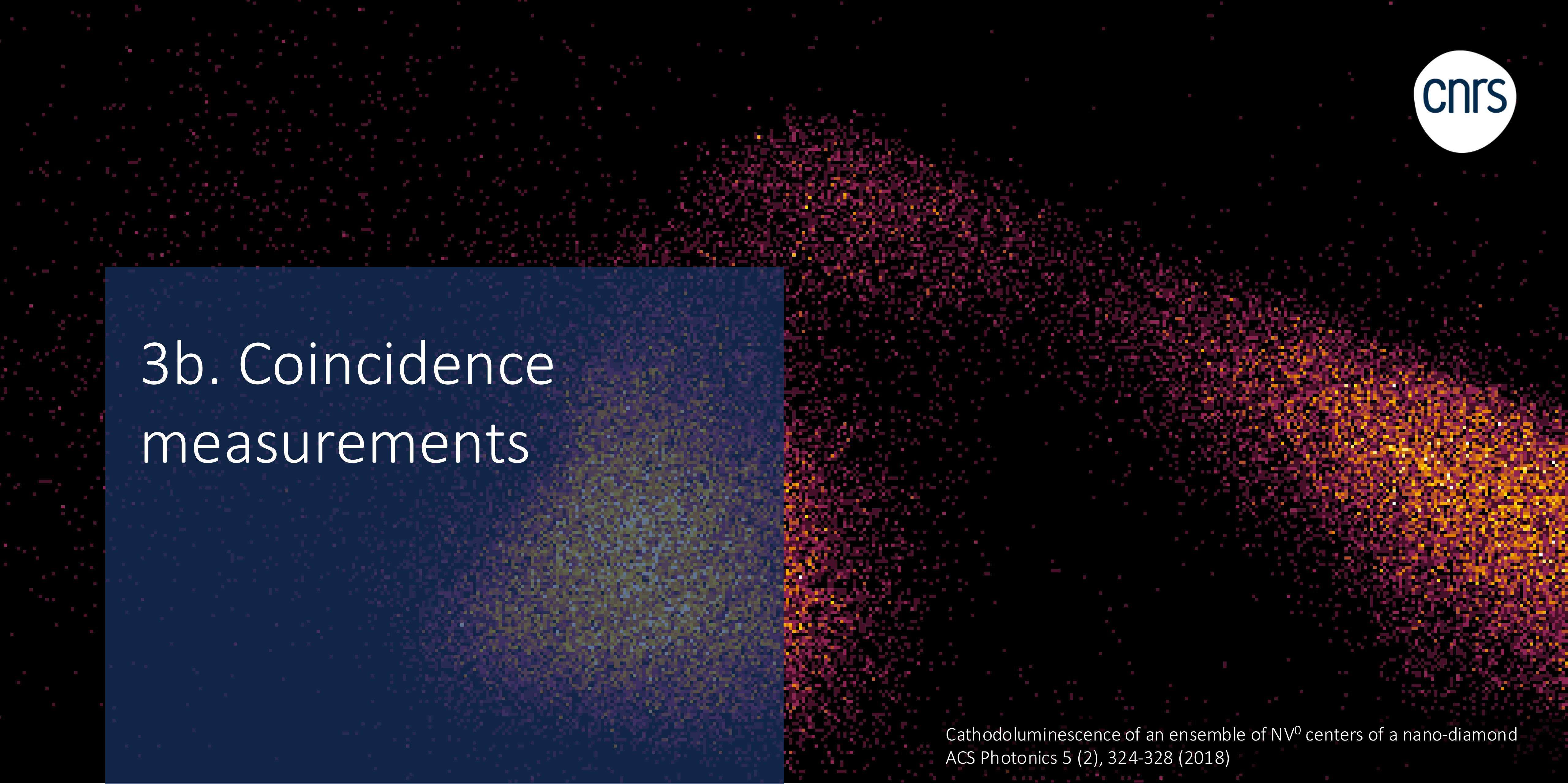


Jean-Daniel Ganiere



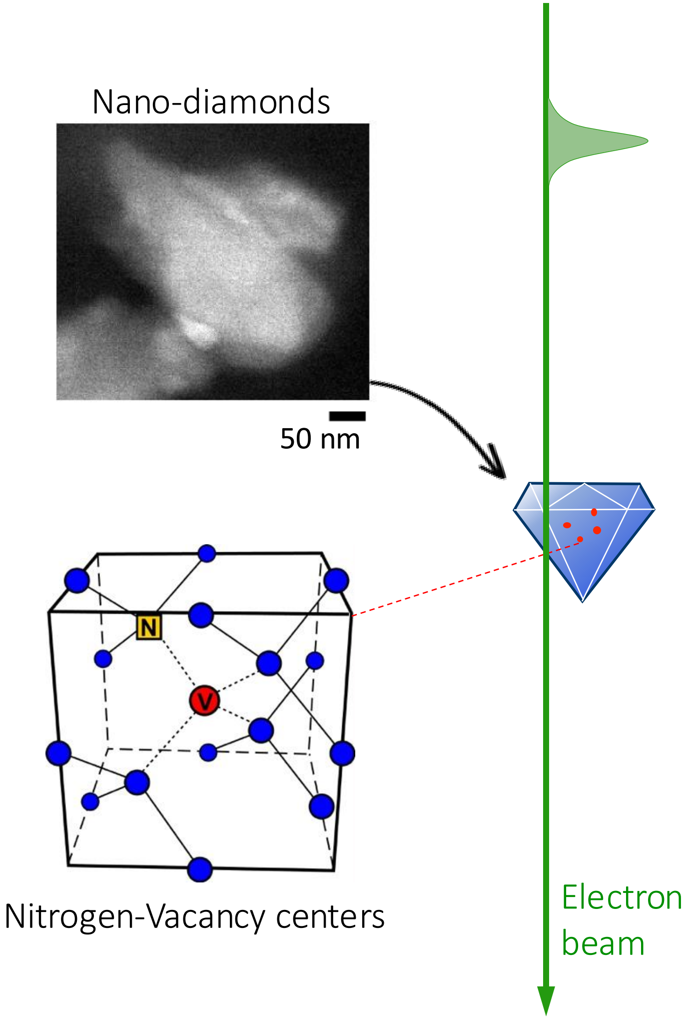
Merano, et al. Nature **438**, 479–482 (2005)

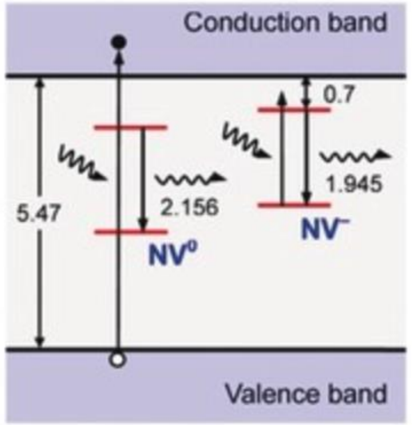
3b. Coincidence measurements



Cathodoluminescence of an ensemble of NV^0 centers of a nano-diamond
ACS Photonics 5 (2), 324-328 (2018)

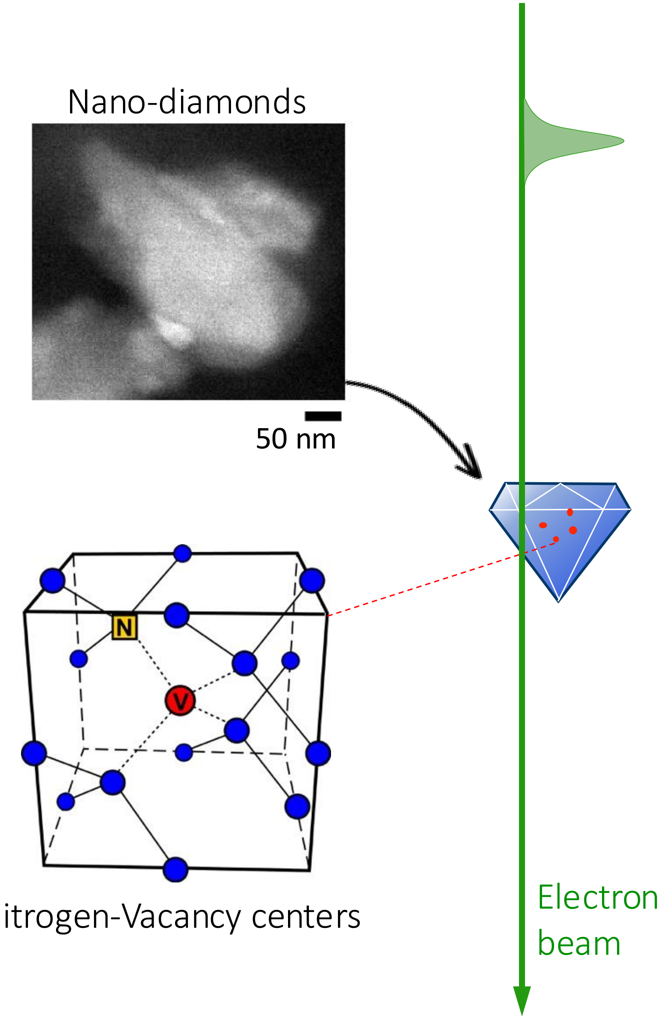
Nitrogen-Vacancy (NV) centers in nano-diamonds



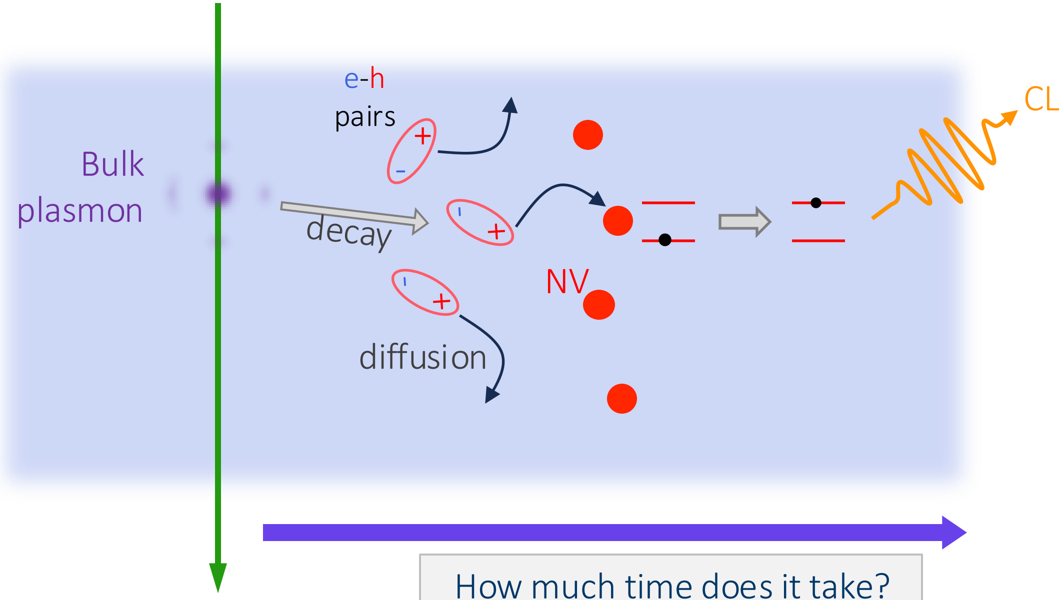


Nitrogen-Vacancy (NV) centers in nano-diamonds

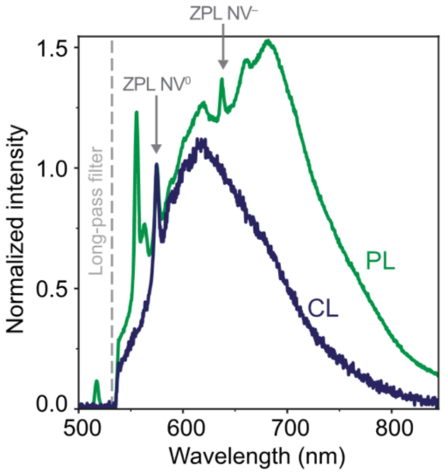
Nano-diamonds



Nitrogen-Vacancy centers

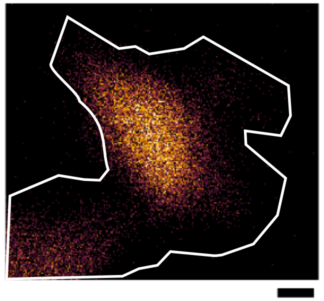


How much time does it take?

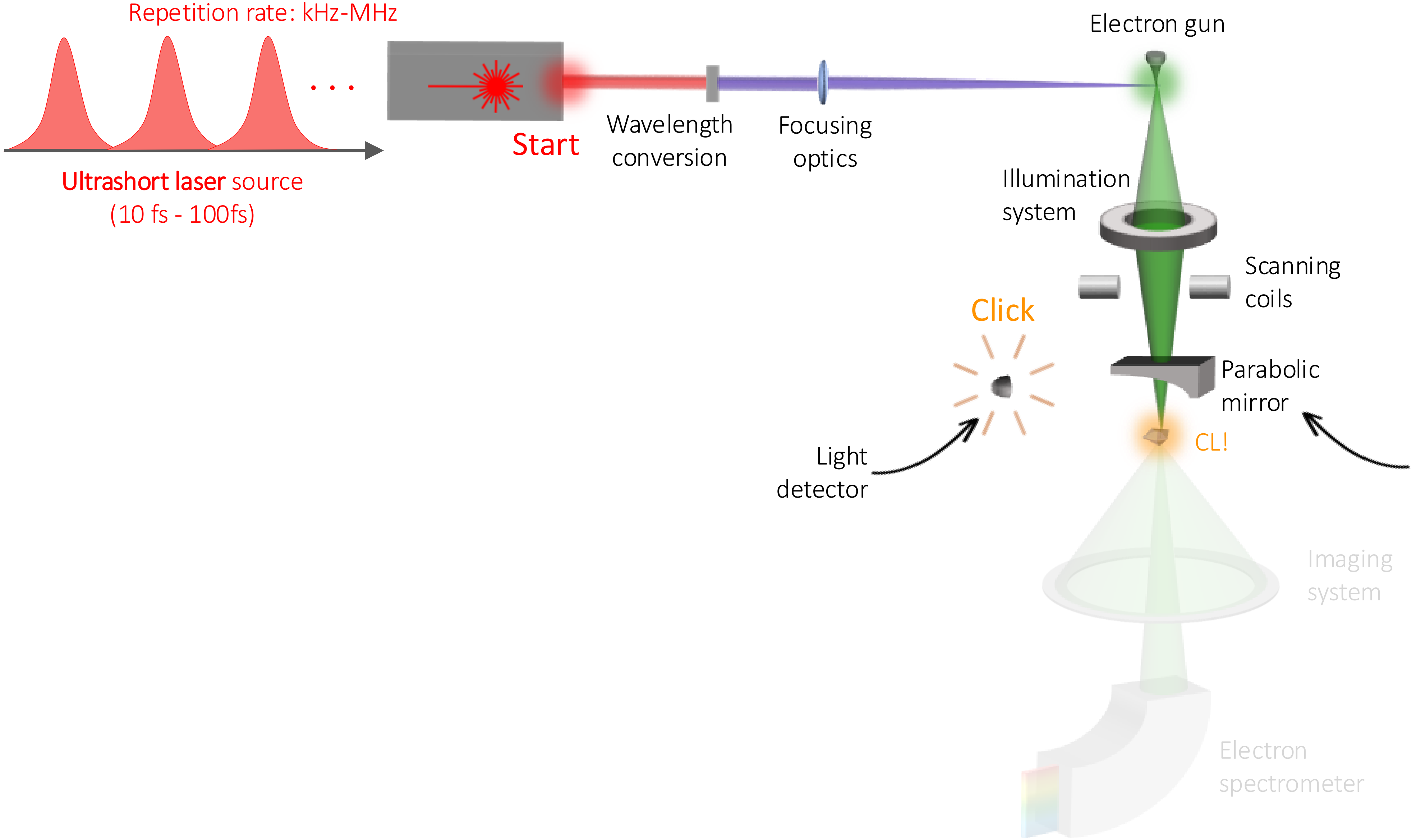


Solà-Garcia, et al. ACS Photonics **7**, 232 (2019)

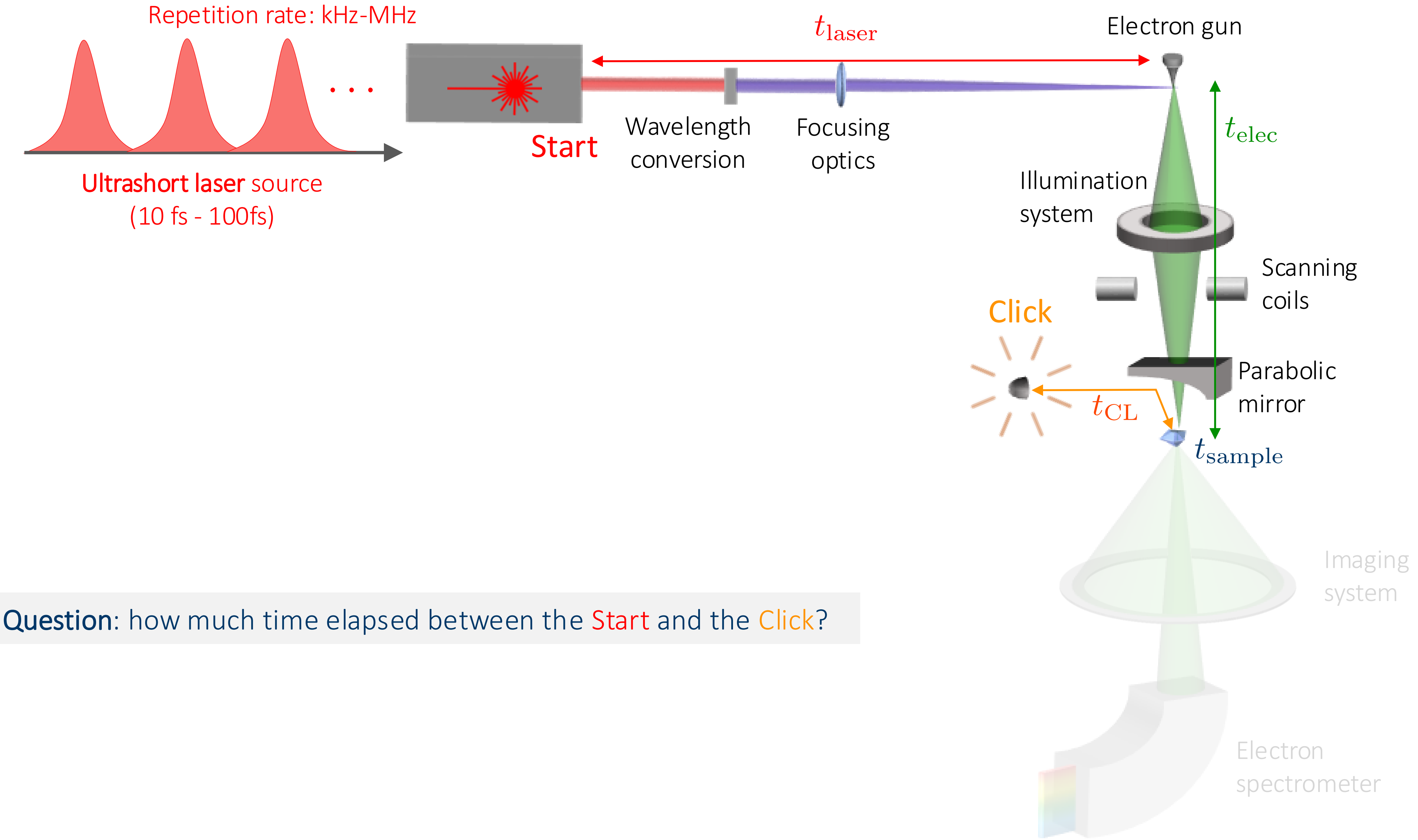
CL map



Time-resolved Cathodoluminescence (TR-CL)

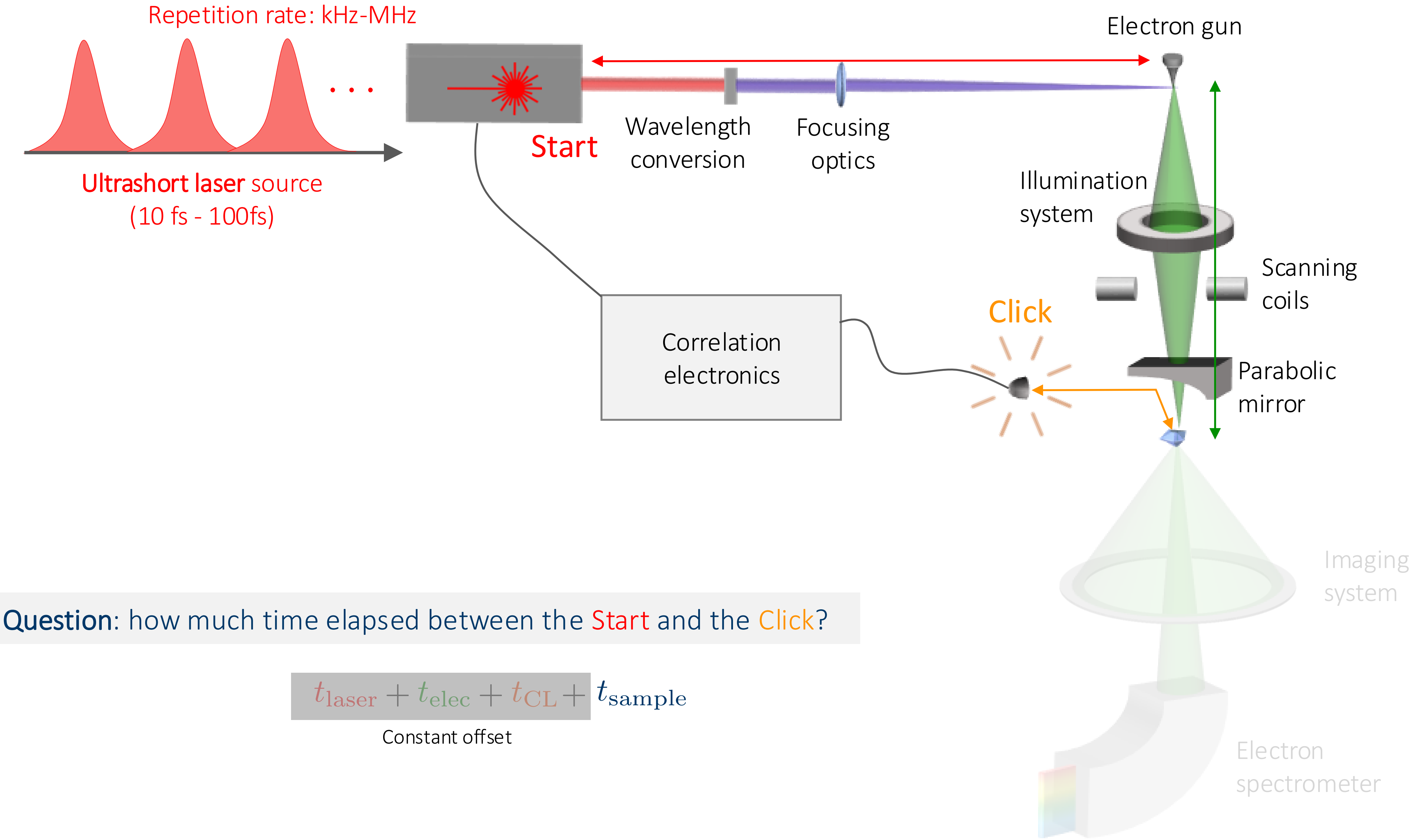


Time-resolved Cathodoluminescence (TR-CL)



Question: how much time elapsed between the Start and the Click?

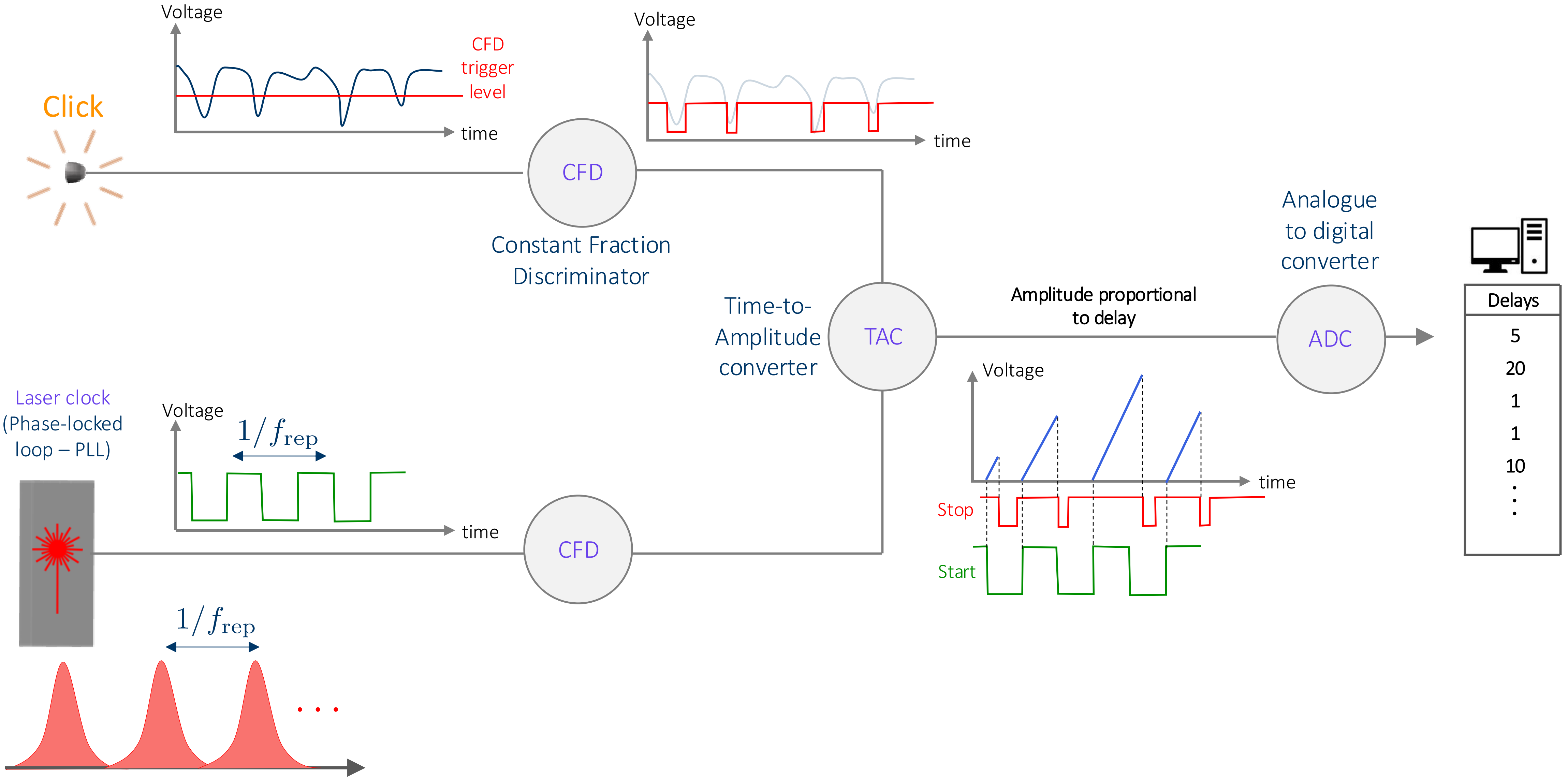
Time-resolved Cathodoluminescence (TR-CL)



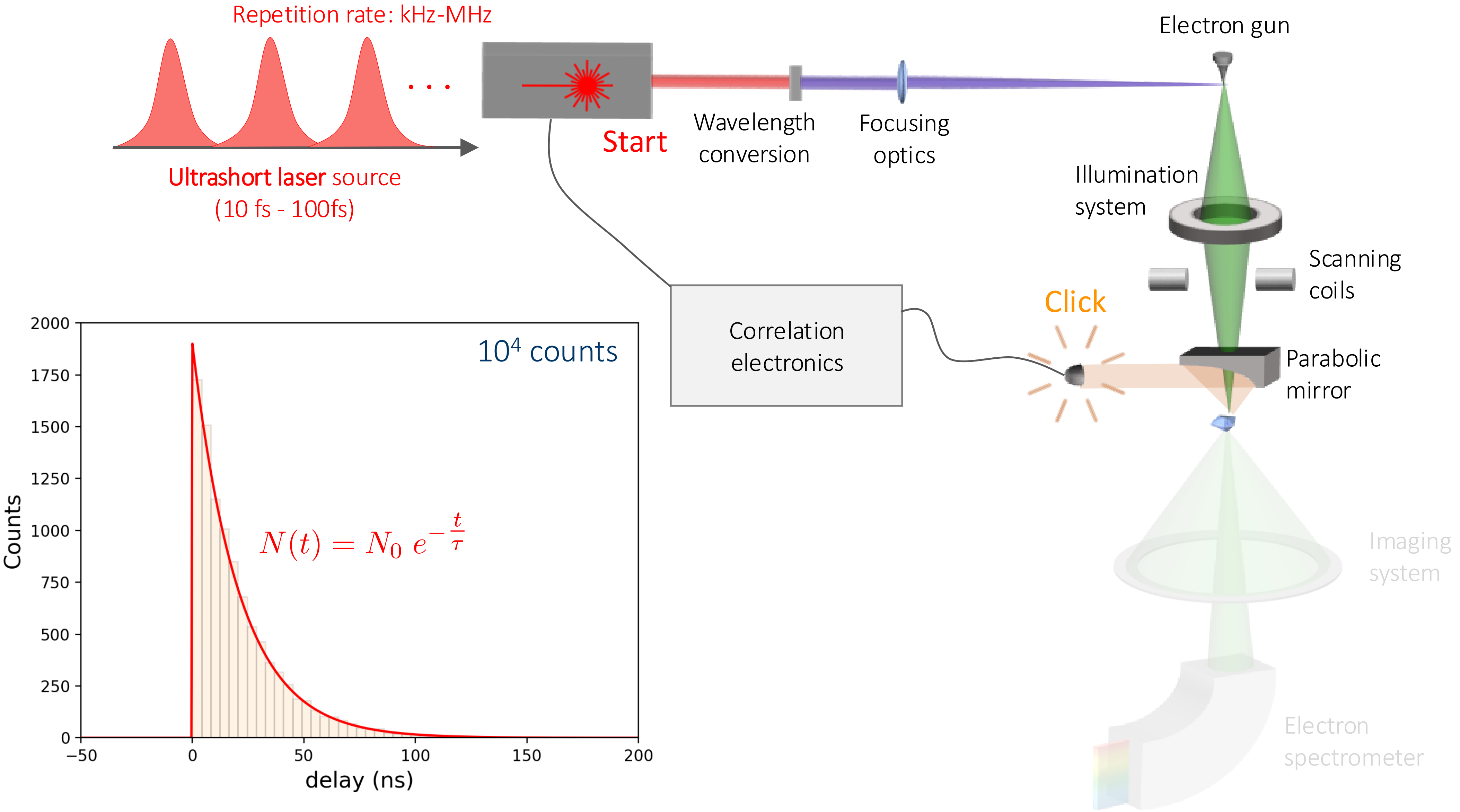
Question: how much time elapsed between the Start and the Click?

$$\underbrace{t_{\mathrm{laser}} + t_{\mathrm{elec}} + t_{\mathrm{CL}} +}_{\text{Constant offset}} t_{\mathrm{sample}}$$

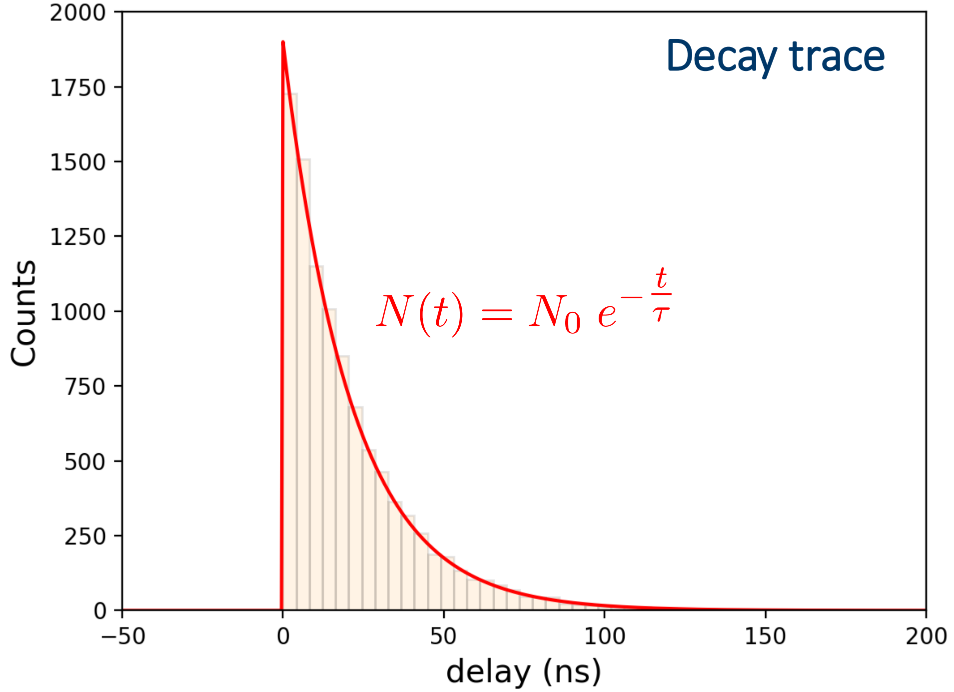
Correlation electronics



Time-resolved Cathodoluminescence (TR-CL)



Time-resolved Cathodoluminescence (TR-CL)

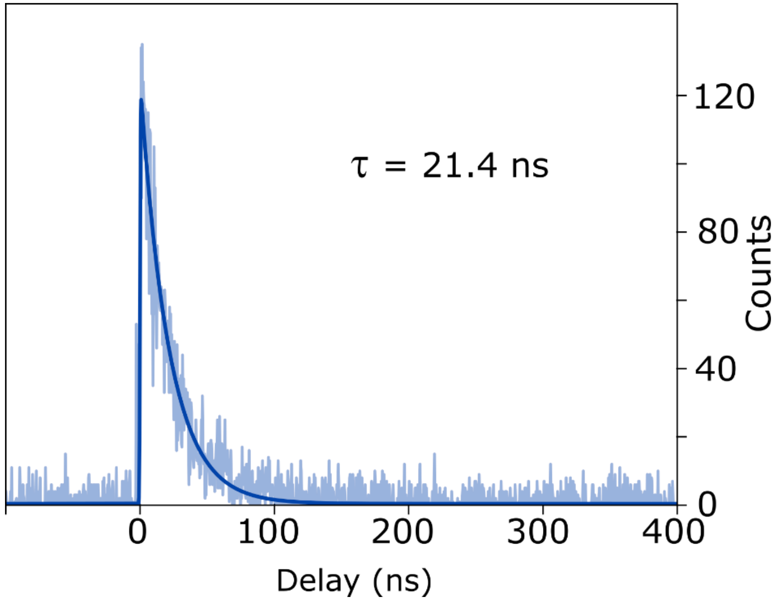


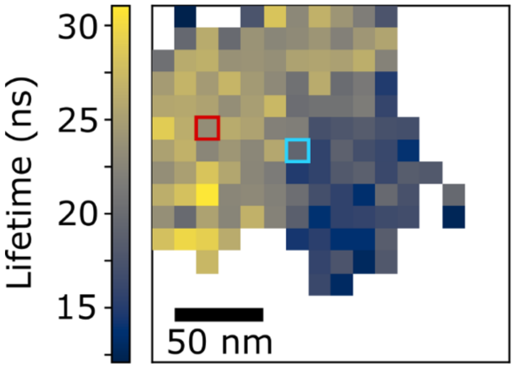
- Signature of a de-excitation process with a constant rate

$$\frac{dN(t)}{dt} = -\frac{N(t)}{\tau}$$

decay time = excitation lifetime

(time when the excitation has probability 1/e of having decayed)

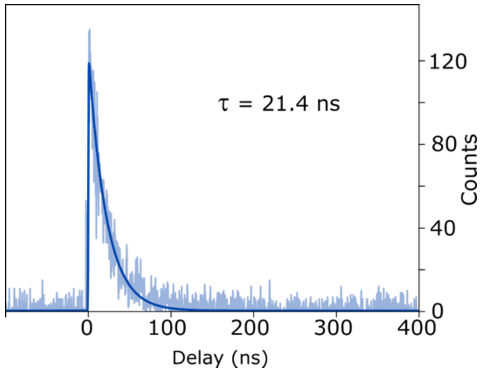




Meuret *et al.*, Appl. Phys. Lett. **119**, 062106 (2021)
Kim and Kwon, ACS Nano **15** (12), 19480–19489 (2021)

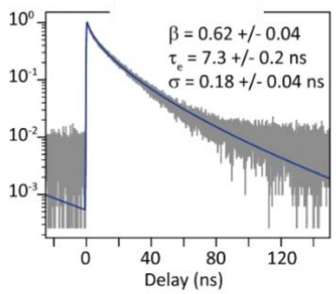
Decay kinetics can be more complex

- Simple exponential



Meuret *et al.*, Appl. Phys. Lett. **119**, 062106 (2021)
Kim and Kwon, ACS Nano **15** (12), 19480–19489 (2021)
Liu, et al. Appl. Phys. Lett. 109, 042101 (2016)
Finot, et al. Appl. Phys. Lett. 117, 221105 (2020)

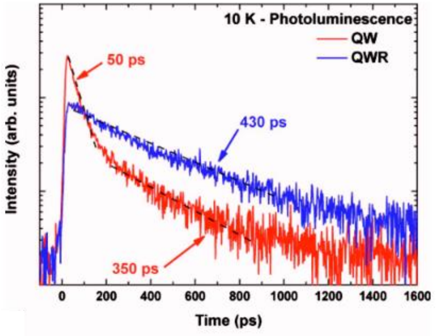
- Stretched exponential (Kohlrausch function)



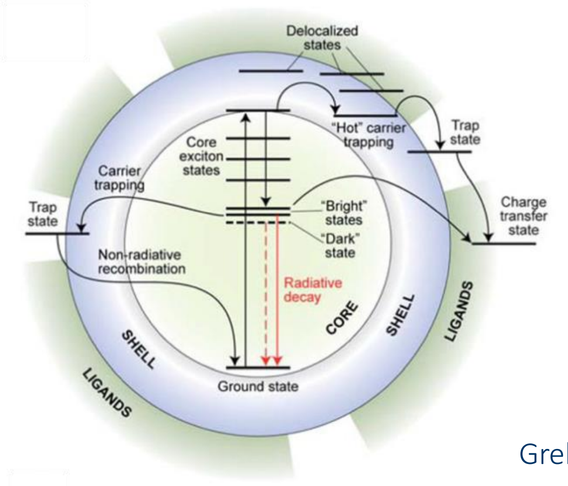
$$N(t) = N_0 \, e^{-\frac{t}{\tau}} e^{-p\left(\frac{t}{\tau}\right)^{\beta}}$$

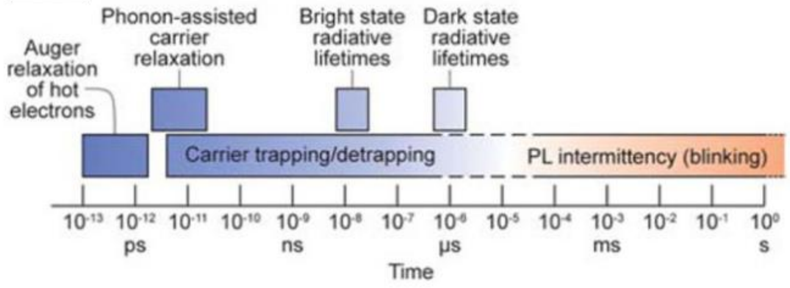
Meuret *et al.*, Ultramicroscopy **197**, 28-38 (2019)
Benny Lee *et al*, Biophysical Journal 81 (3), 1265-1274 (2001)
Martins *et al.*, Phys. Chem. C **126** (48) 20480–20490 (2022)

- Multiple exponentials



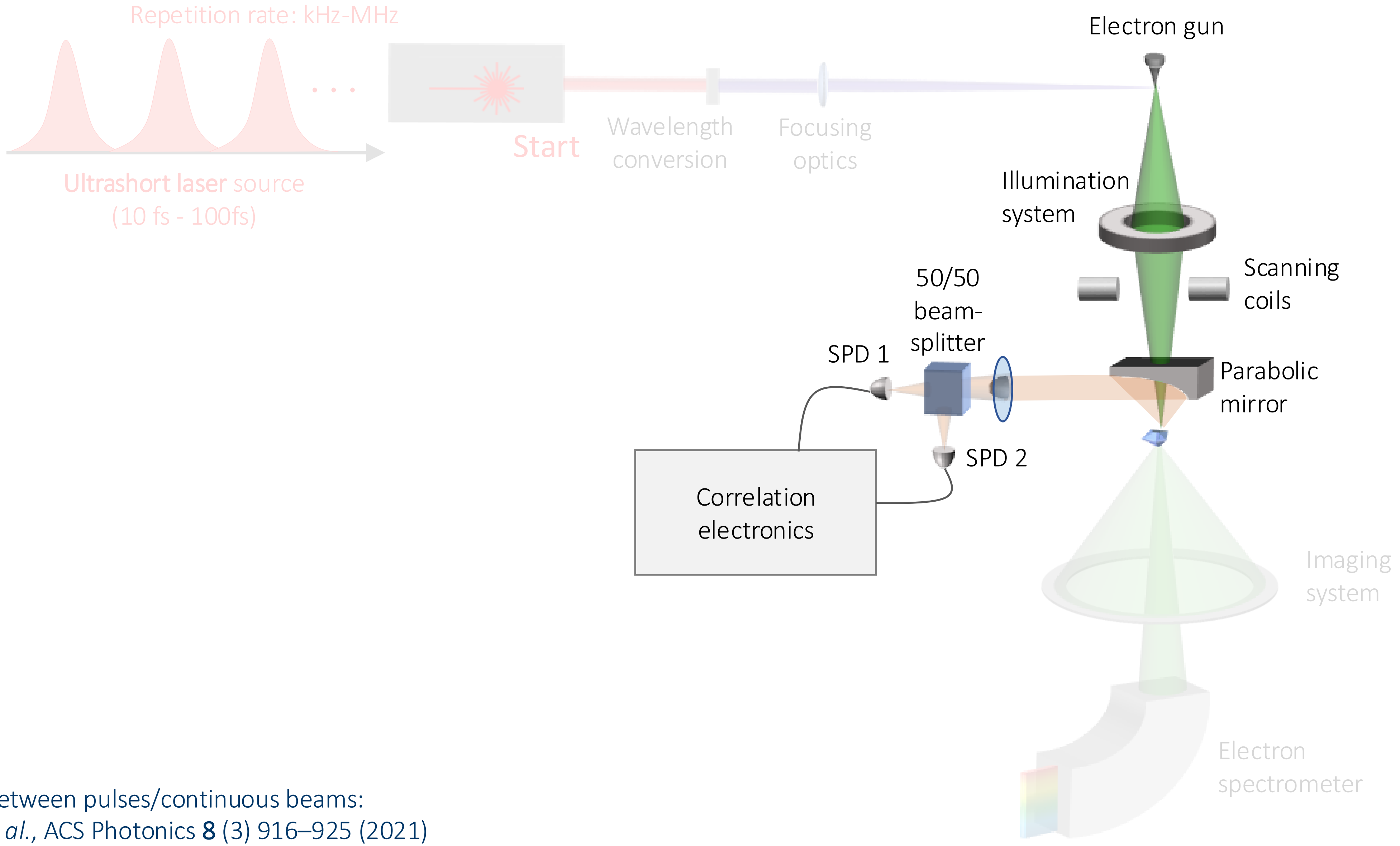
Corfdir et al, J. Appl. Phys. **107**, 043524 (2010)





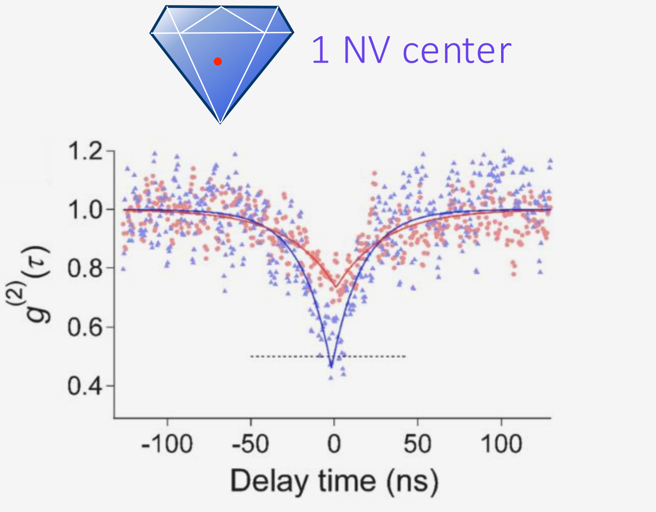
Greben *et al.*, Applied Spectroscopy Reviews, **54** (9), 758–801 (2019)

Measurement of the emitted photon statistics

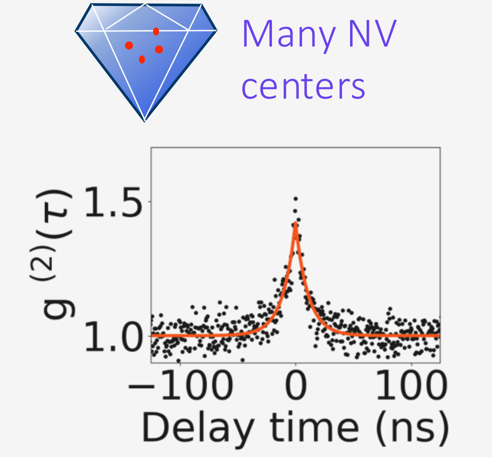


Comparison between pulses/continuous beams:
M. Solà-Garcia *et al.*, ACS Photonics **8** (3) 916–925 (2021)

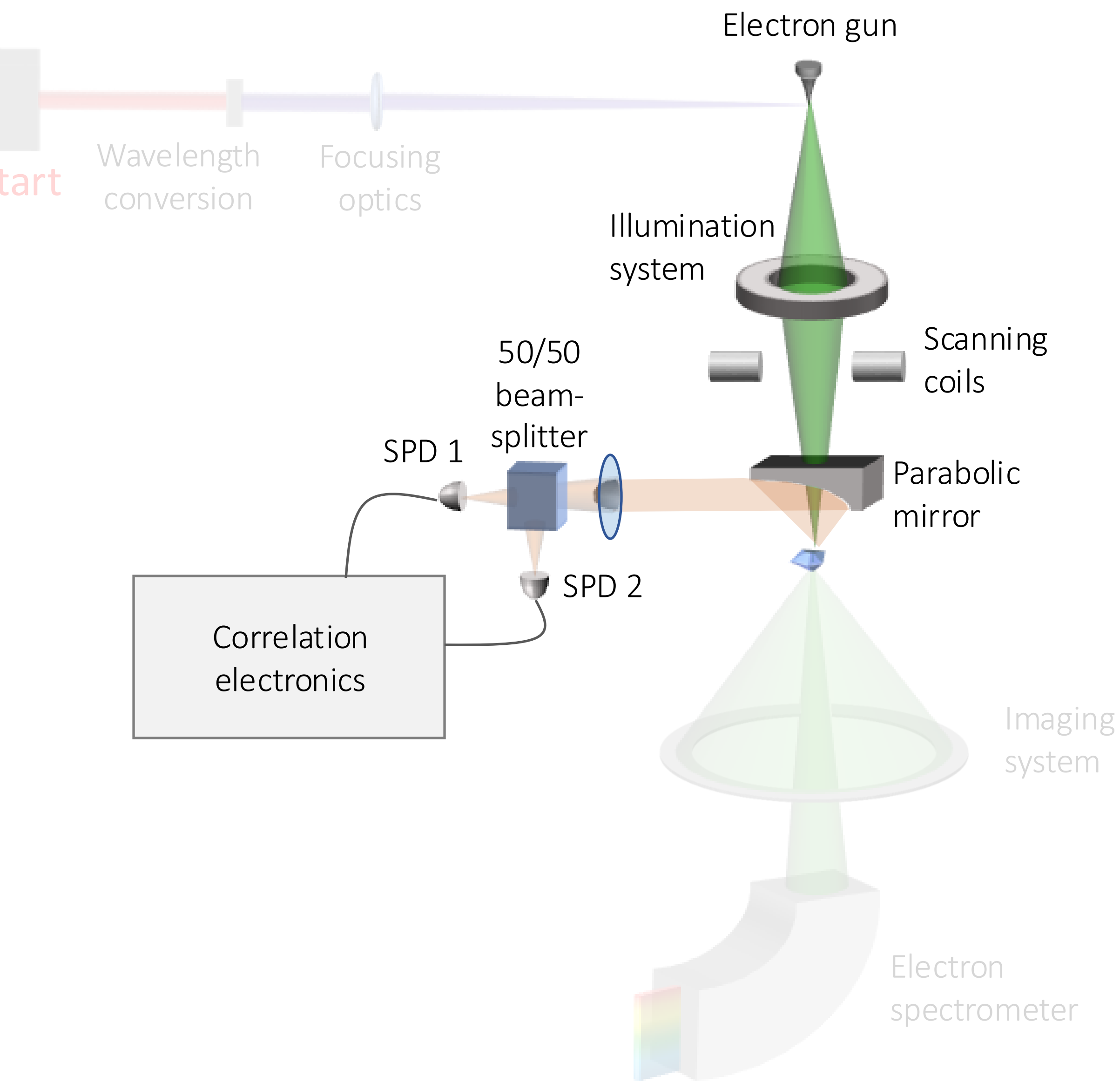
Measurement of the emitted photon statistics



Tizei & Kociak, Phys. Rev. Lett. **110**, 153604 (2013)
Bourrellier *et al.*, Nano Lett. **16** (7), 4317–4321 (2016)



S. Meuret et al., Phys. Rev. Lett. 114, 197401 (2015)
Lourenço-Martins et al., ACS Photonics **5**, 324 (2018)



The Hanbury-Brown and Twiss (HBT) interferometer

Robert Hanbury Brown

Richard Twiss

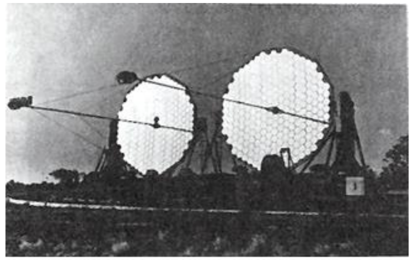
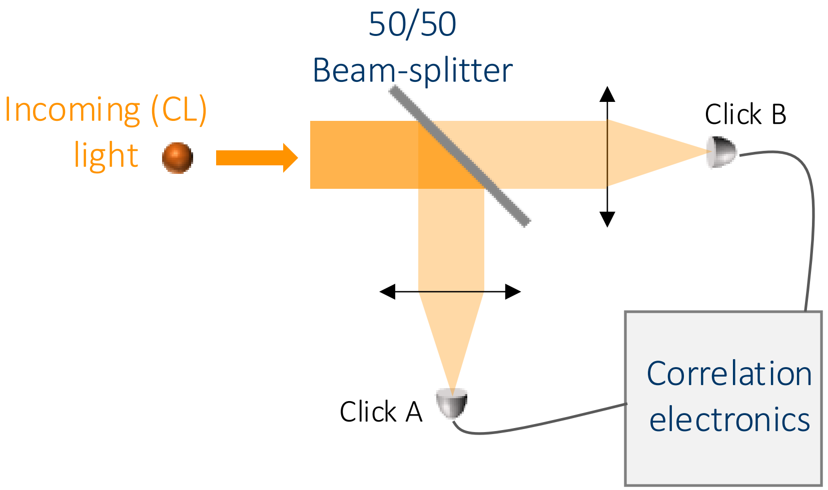
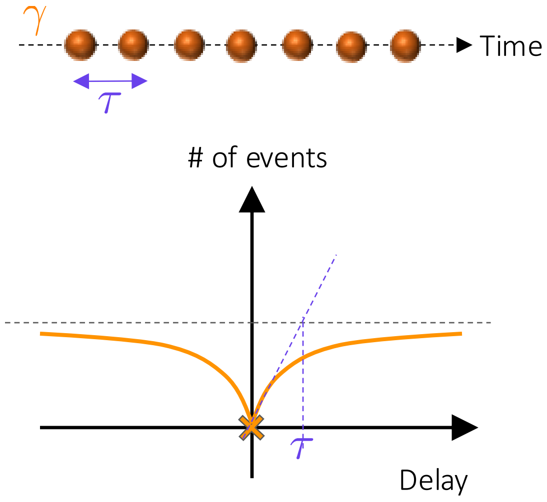


Figure 2. Picture of the two telescopes used in the HBT experiments. The figure was extracted from Ref.[1].

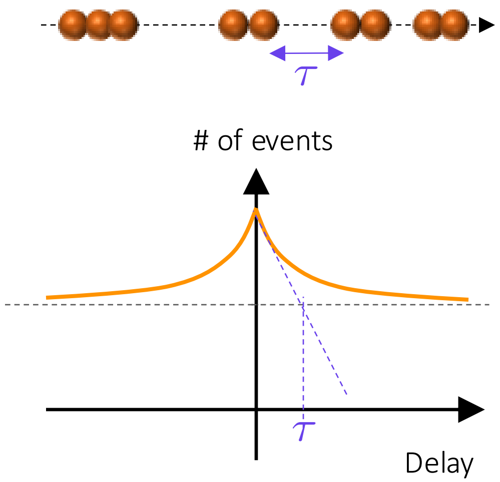


- Each photon comes one by one



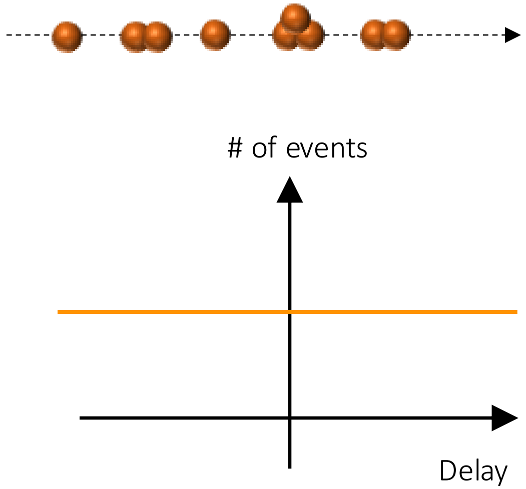
Anti-bunched emission

- Photons come in packets



Bunched emission

- Photons come randomly



Mark Fox, **Quantum Optics: An Introduction**, Oxford University Press (2006)

The Hanbury-Brown and Twiss (HBT) interferometer

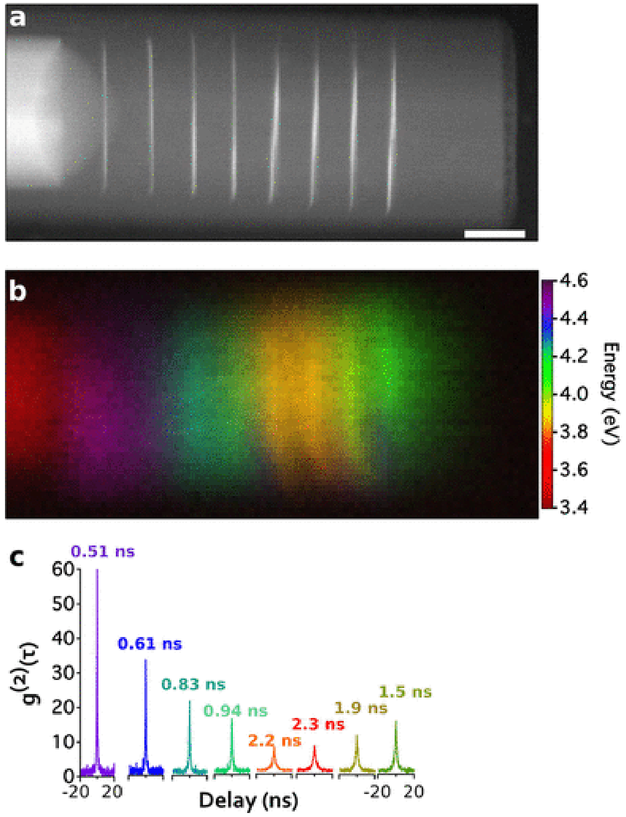
HBT accesses:
- The excitation lifetime
- The emission statistics

Second order correlation function of light

$$g^{(2)}(\tau) = \frac{\langle n_1(t) n_2(t+\tau)\rangle_t}{\langle n_1(t)\rangle_t \, \langle n_2(t)\rangle_t}$$

Glauber, Phys. Rev. **130**, 2529 (1963)

Lifetime mapping at the nano-scale



S. Meuret et al., ACS Photonics 3 (7) 1157–1163 (2016)
S. Meuret et al., Phys. Rev. B **96**, 035308 (2017)
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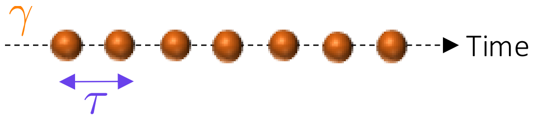
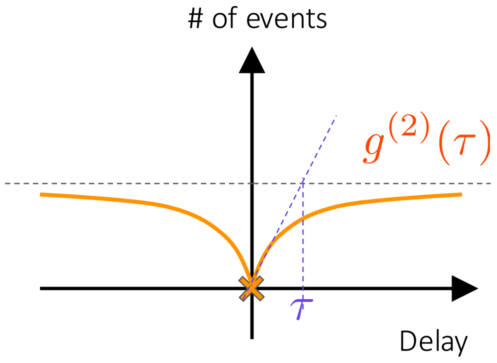
S. Finot et al., Appl. Phys. Lett. **117**, 221105 (2020)
S. Finot et al., ACS Photonics **9**, 173–178 (2022)

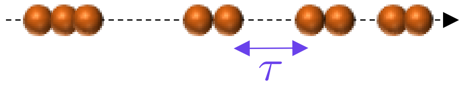
- Each photon comes one by one

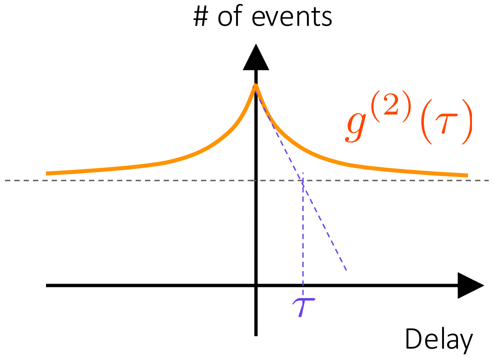




Anti-bunched emission

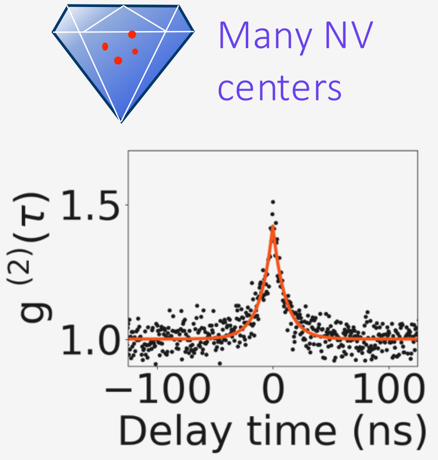
- Photons come in packets





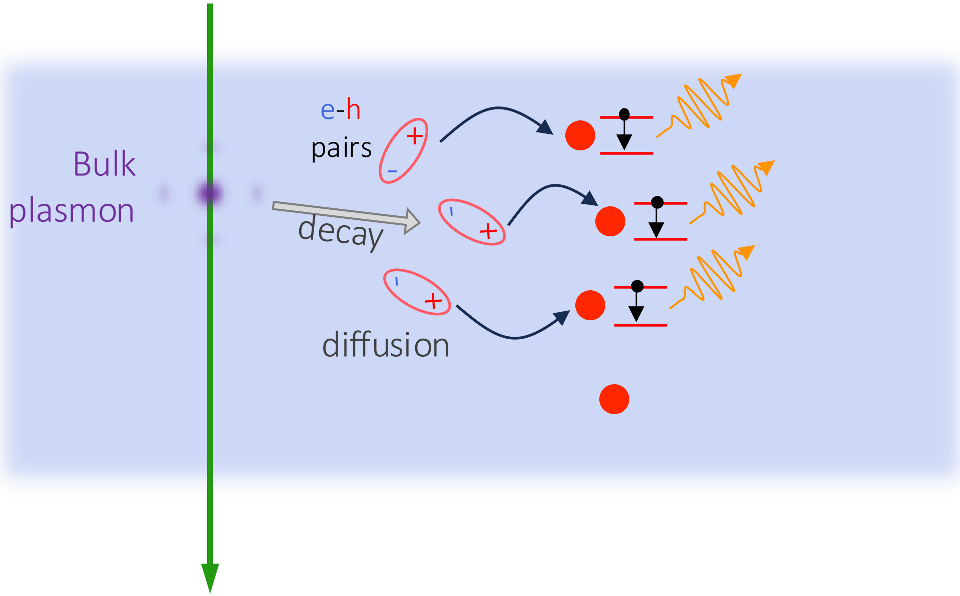
Bunched emission

Bunching in HBT-CL

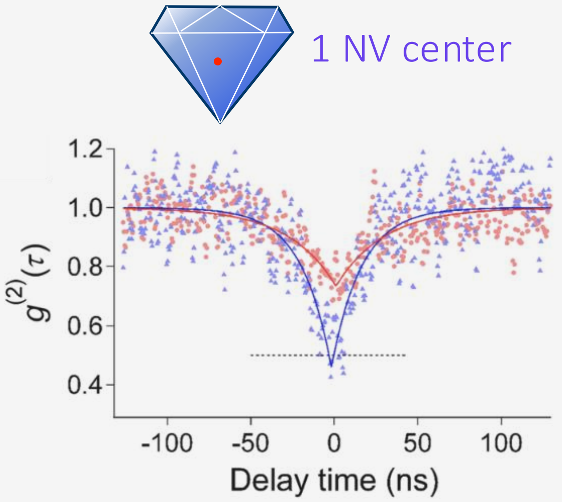


S. Meuret et al., Phys. Rev. Lett. 114, 197401 (2015)
Lourenço-Martins et al., ACS Photonics **5**, 324 (2018)

- Each electron can emit multiple photons

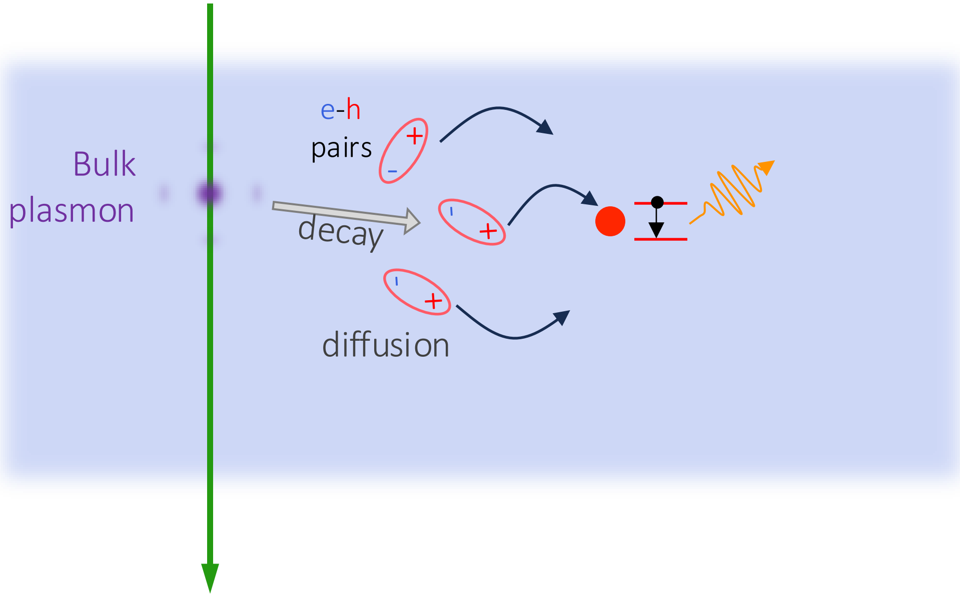


Anti-bunching in HBT-CL

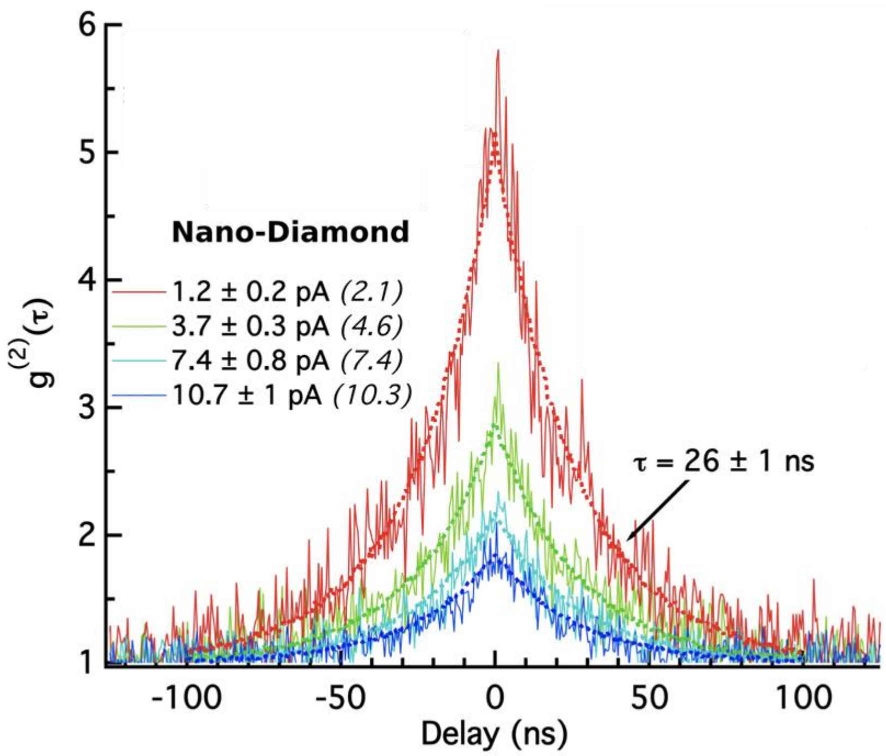


Tizei & Kociak, Phys. Rev. Lett. **110**, 153604 (2013)
Bourrellier *et al.*, Nano Lett. **16** (7), 4317–4321 (2016)

- Each electron can emit only one photon

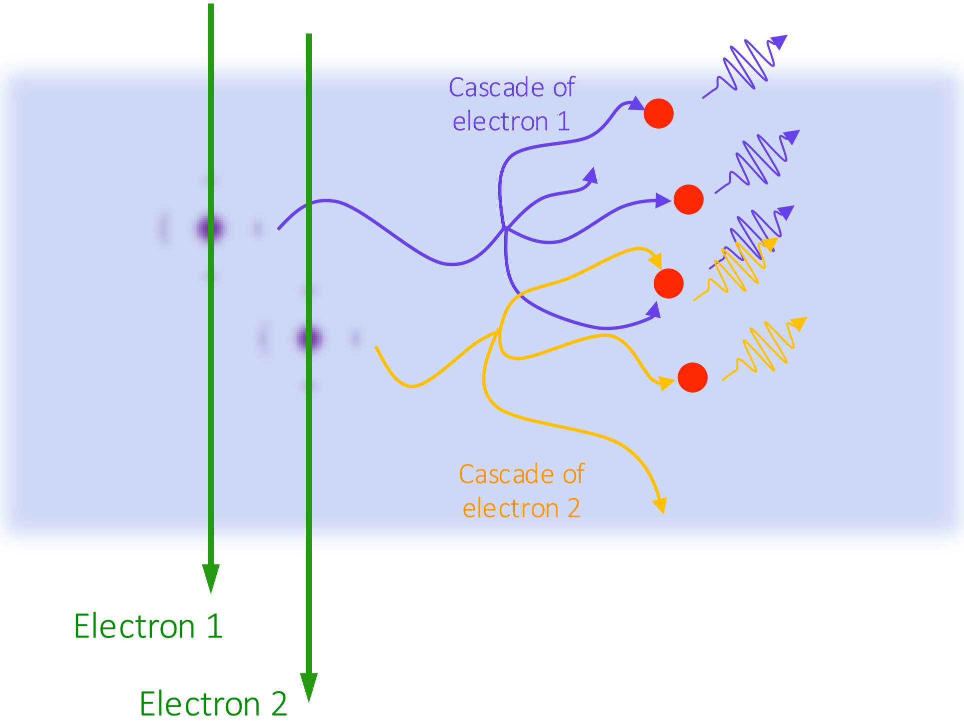


Bunching in HBT-CL – dependence on electron current

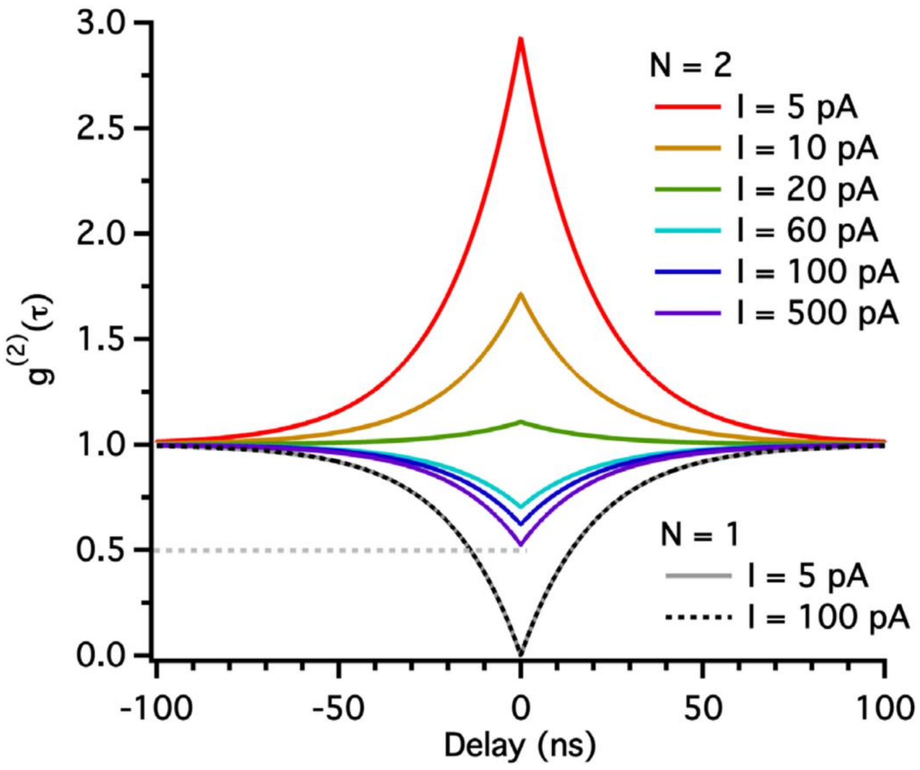


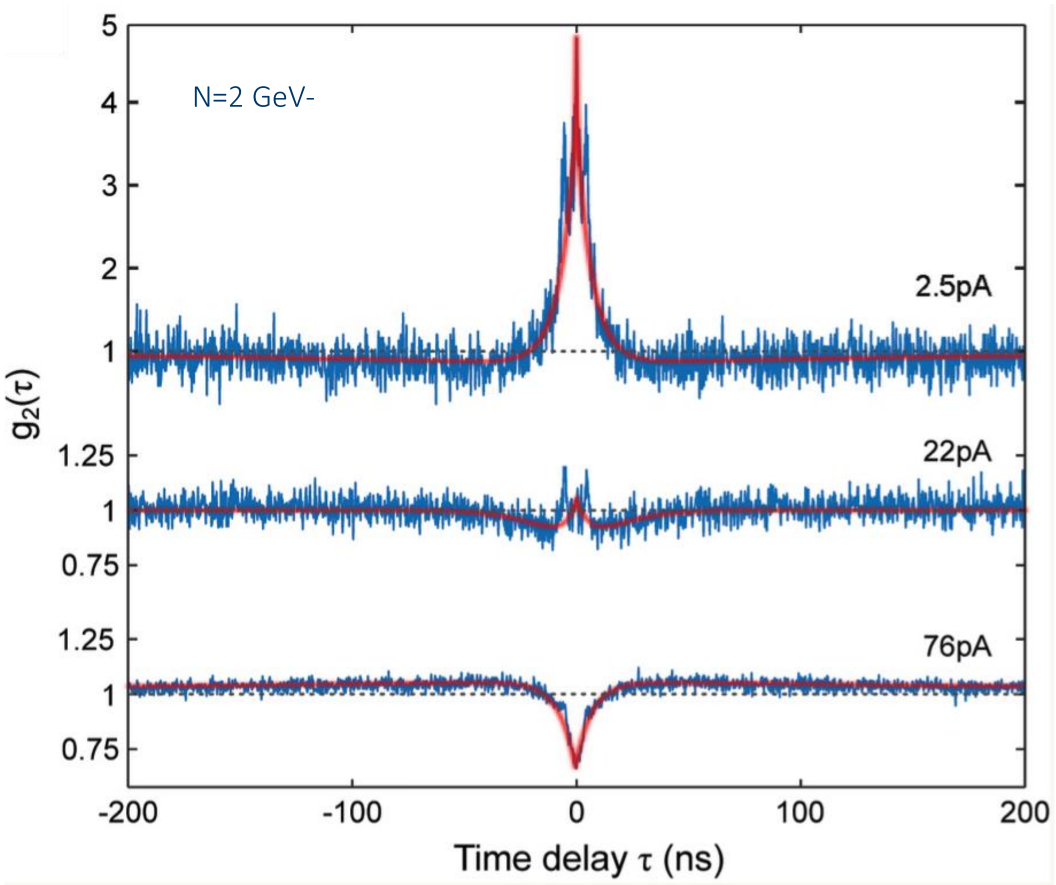
S. Meuret *et al.*, Phys. Rev. Lett. **114**, 197401 (2015)
M. Feldman *et al.*, Phys. Rev. B **97**, 081404 (2018)
M. Solà-Garcia *et al.*, ACS Photonics **8** (3) 916–925 (2021)

- Higher electron current



N=2 centers: Competition between bunching and anti-bunching



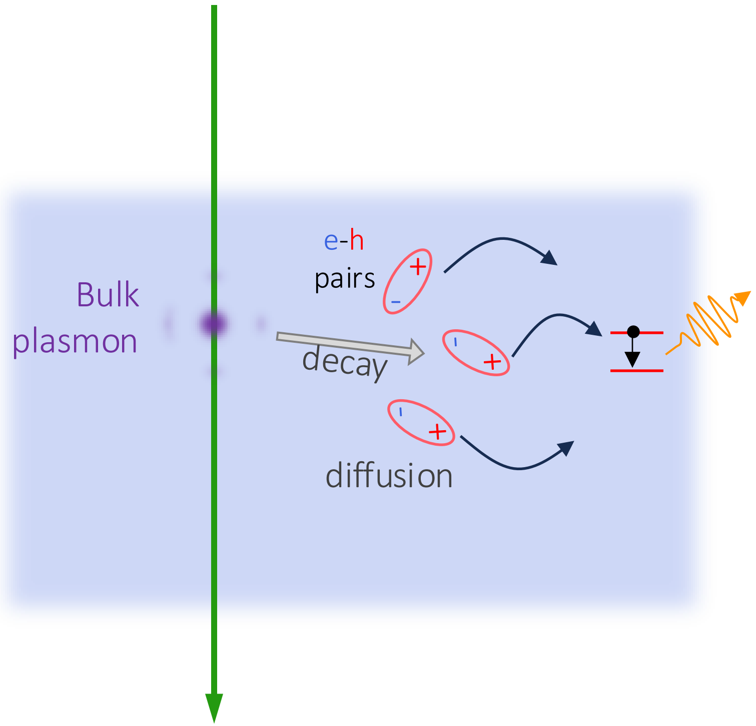


W. Borst & L. Liu, Review of Scientific Instruments **70**, 41 (1999)
S. Meuret *et al.*, Phys. Rev. Lett. **114**, 197401 (2015)
M. Feldman *et al.*, Phys. Rev. B **97**, 081404 (2018)
M. Solà-Garcia *et al.*, ACS Photonics **8** (3) 916–925 (2021)

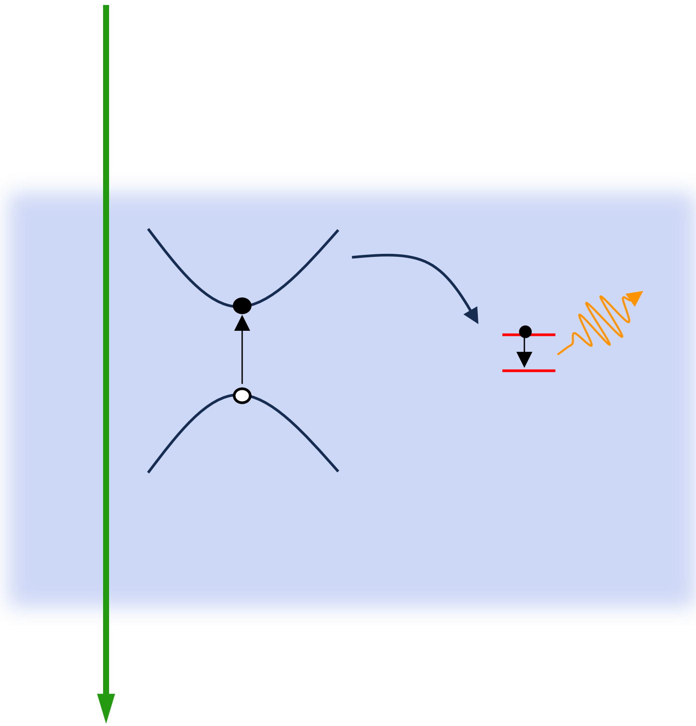
S. Fielder *et al.*, Nanophotonics **12** (12), 2231-2237 (2023)

Photon emission pathways

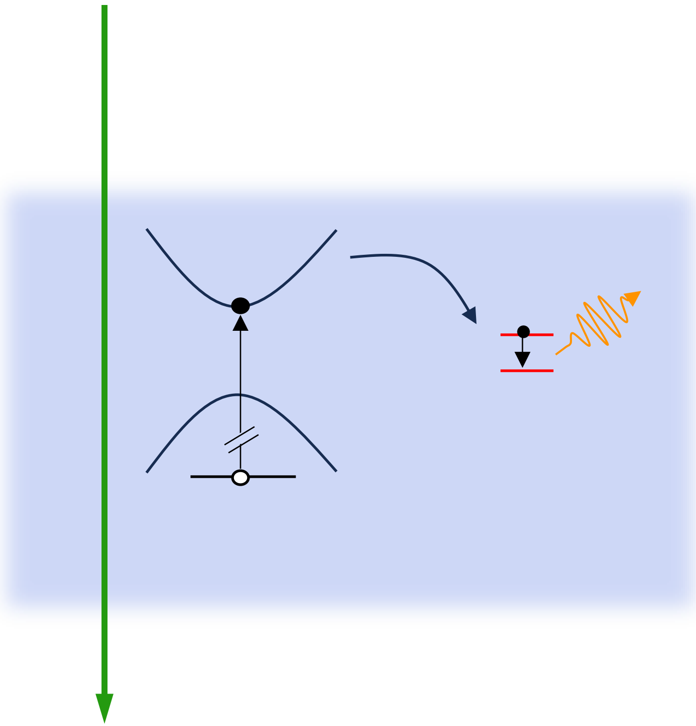
- Bulk plasmon excitations



- Near-Band-Edge transitions

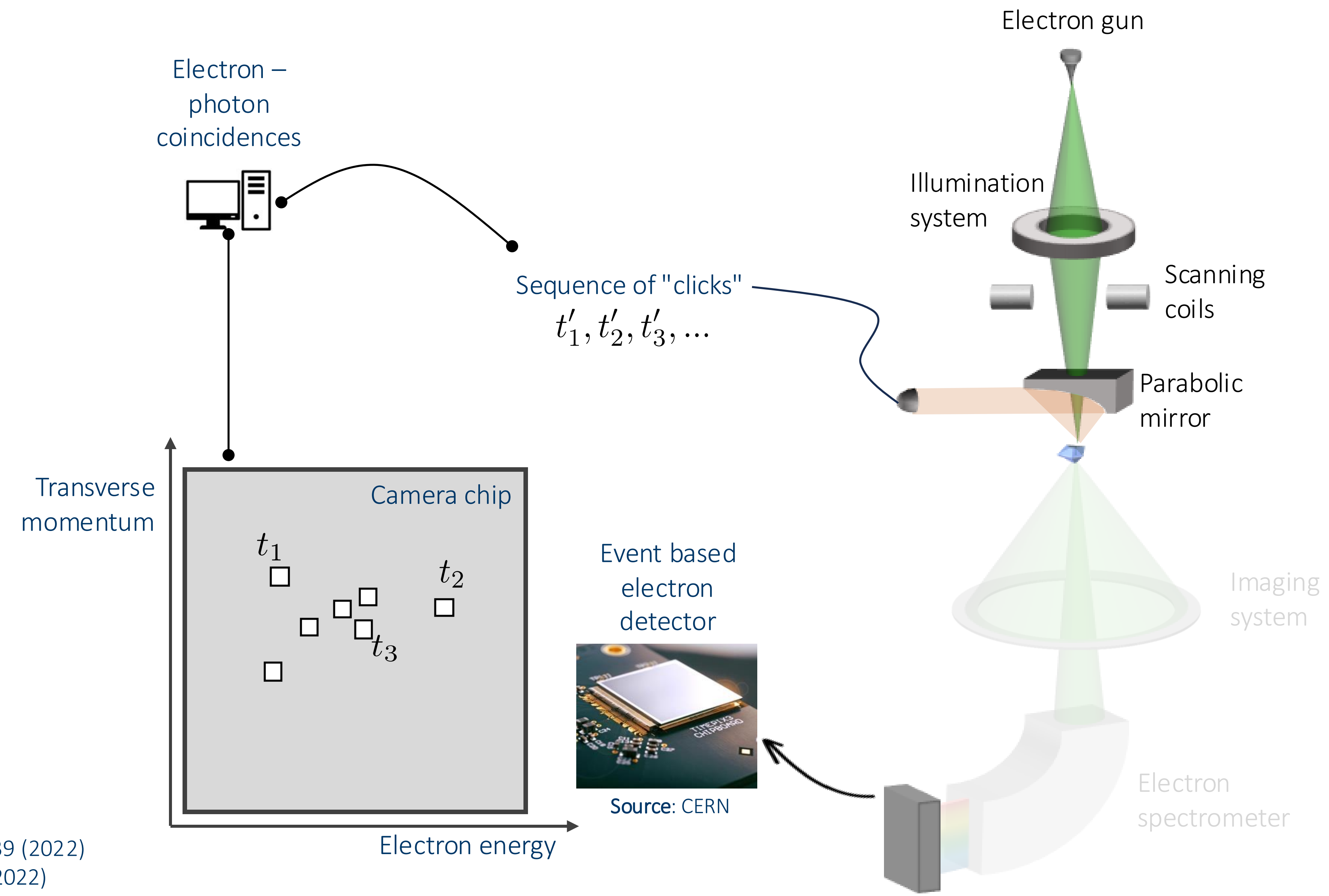


- Core-level transitions



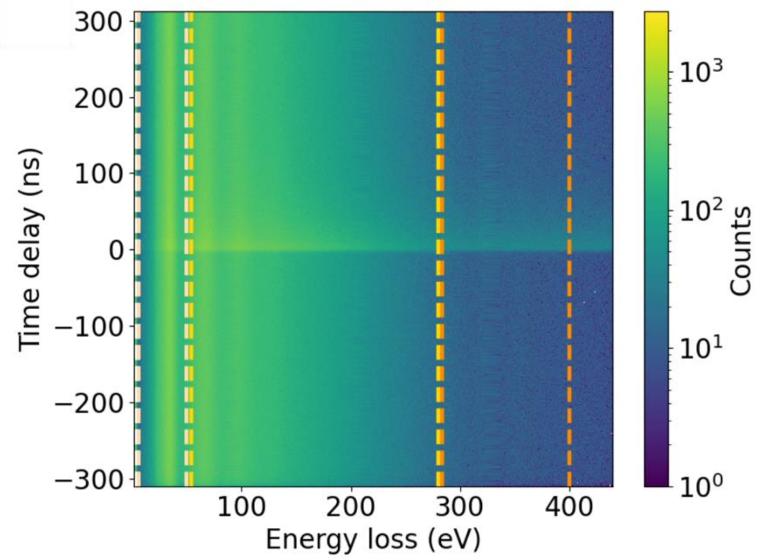
🔑 Several excitations and decay pathways lead to the emission of the same photon

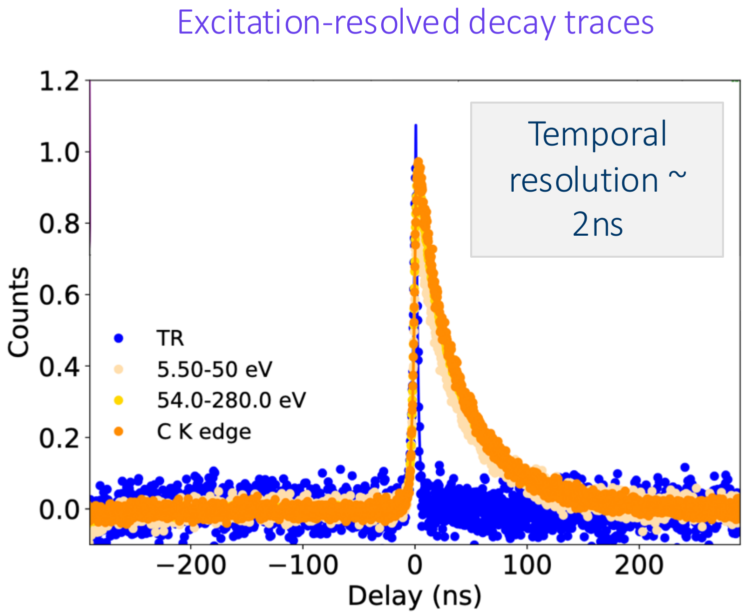
Cathodoluminescence excitation (CLE) spectroscopy

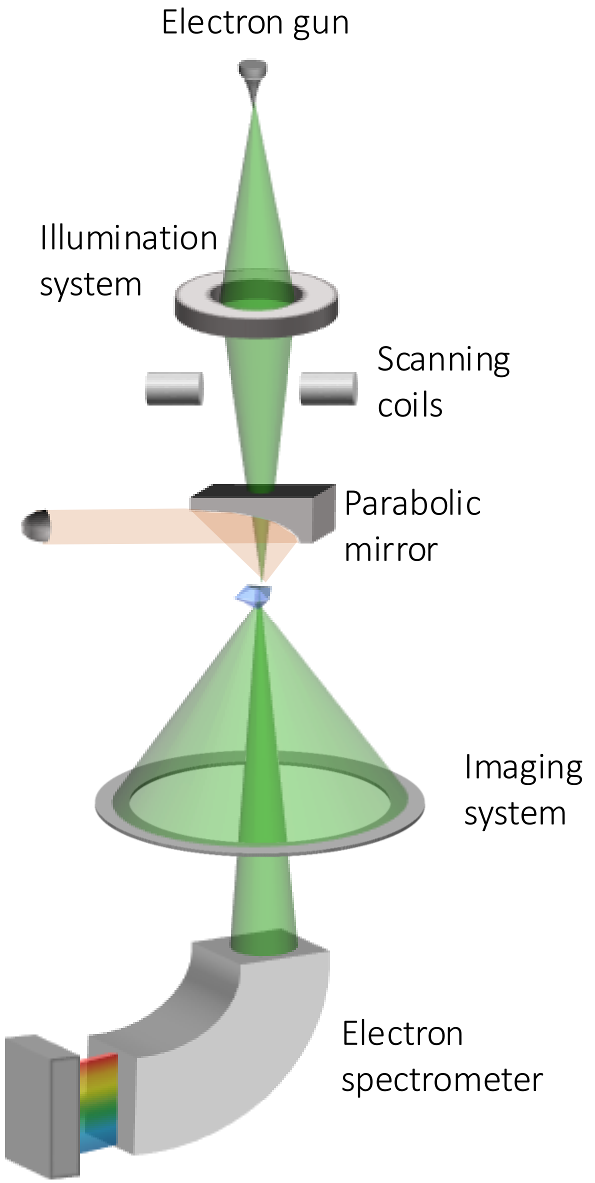


Y. Auad, Ultramicroscopy **239**, 113539 (2022)
Y. Auad, Phd Thesis, U Paris-Saclay (2022)

Cathodoluminescence excitation (CLE) spectroscopy



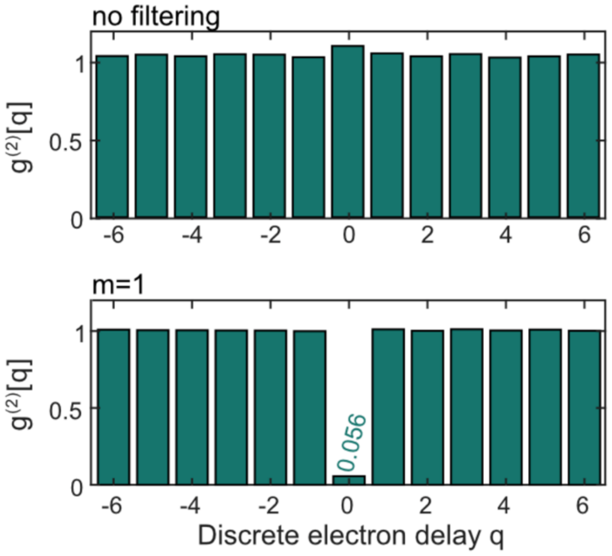




- **Coincidences with X-photons**
  D. Jannis *et al.*, Appl. Phys. Lett. **114**, 143101 (2019)
  D. Jannis *et al.*, Appl. Sci. **11**, 9058 (2021)
- **Coincidences with visible photons**
  N. Varkentina *et al.*, Sci. Adv. **8**, eabq4947 (2022)
  A. Feist *et al.*, Science **377**, 6607, 777-780 (2022)
  N. Varkentina *et al.*, Appl. Phys. Lett. **123**, 223502 (2023)

Cathodoluminescence excitation (CLE) spectroscopy

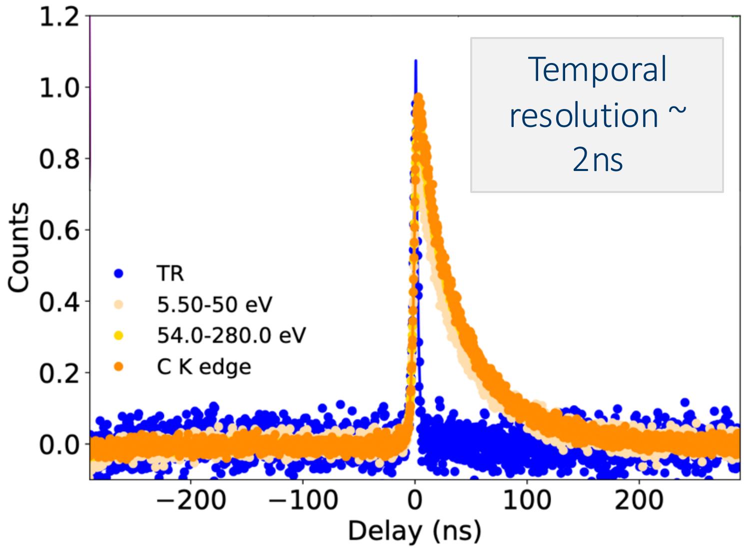
Excitation-resolved HBT-CL



G. Arend *et al.*, arXiv:2409.11300v1 (2024)

🔑 Excitation decay and photon statistics depends on the electron final state

Excitation-resolved decay traces

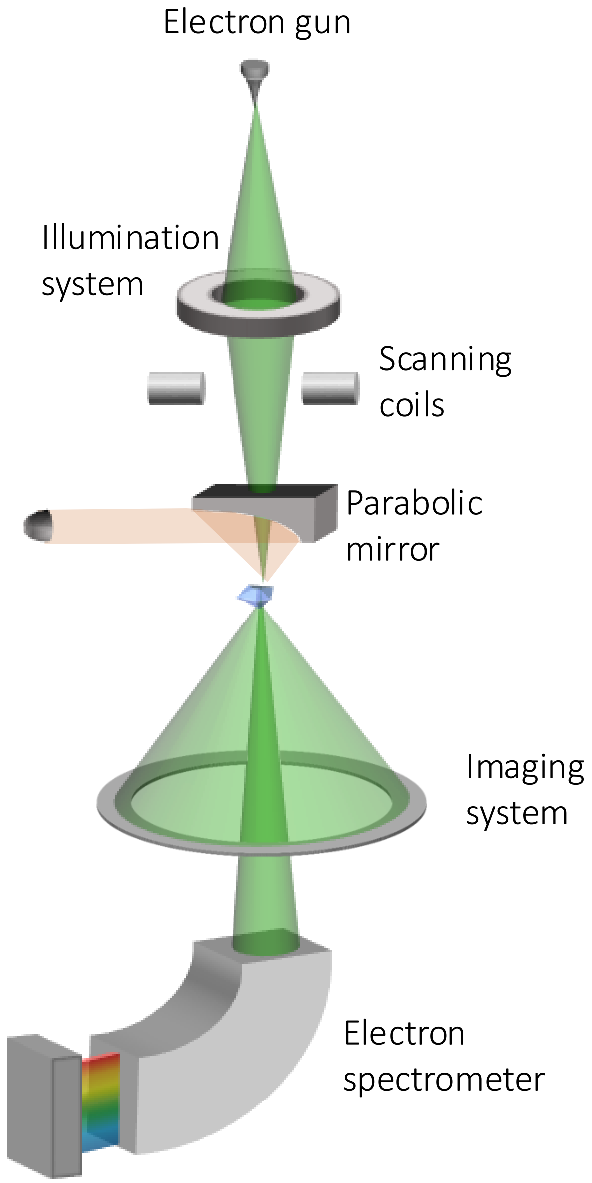


- Coincidences with X-photons

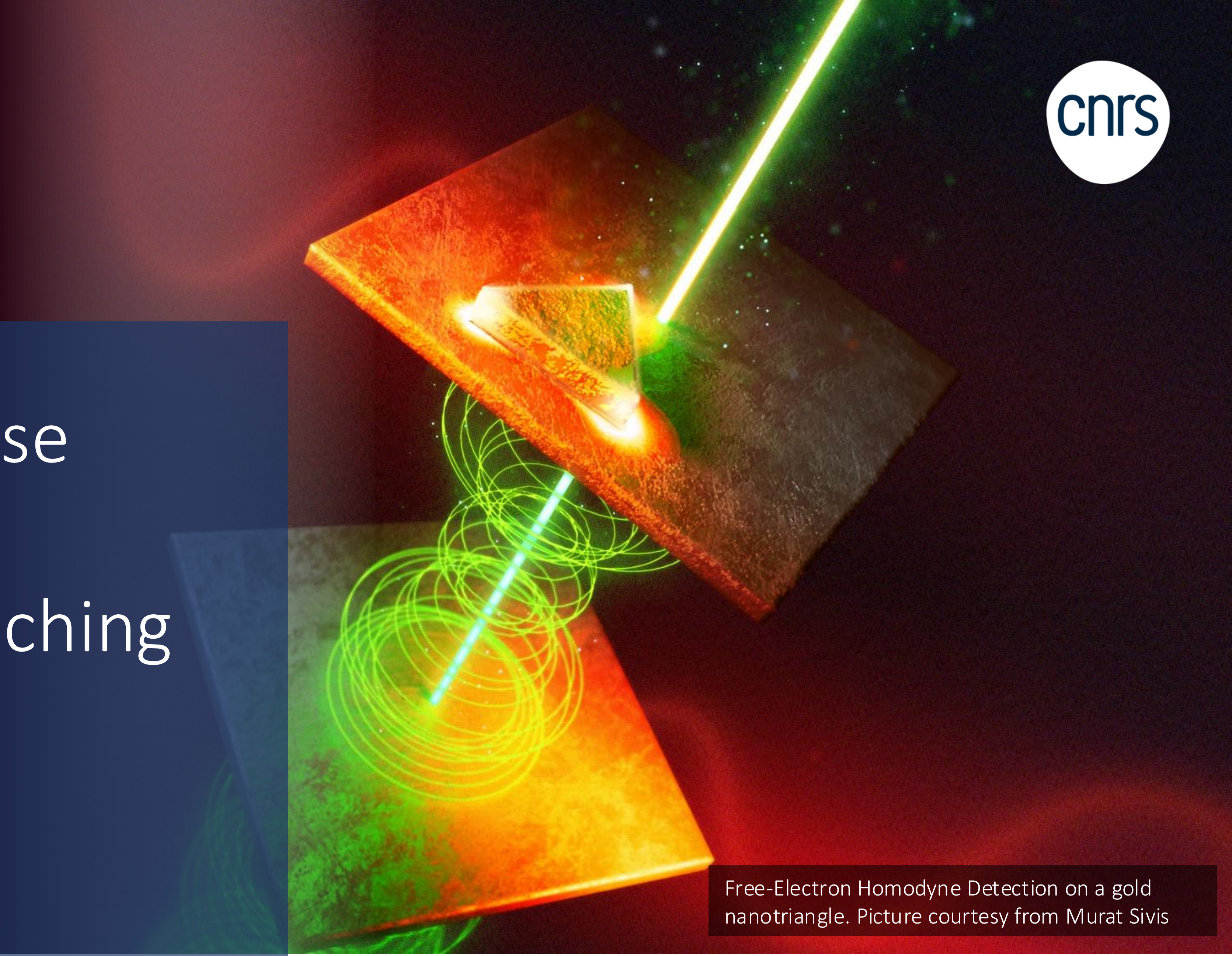
D. Jannis *et al.*, Appl. Phys. Lett. **114**, 143101 (2019)
D. Jannis *et al.*, Appl. Sci. **11**, 9058 (2021)

- Coincidences with visible photons

N. Varkentina *et al.*, Sci. Adv. **8**, eabq4947 (2022)
A. Feist *et al.*, Science **377**, 6607, 777-780 (2022)
N. Varkentina *et al.*, Appl. Phys. Lett. **123**, 223502 (2023)

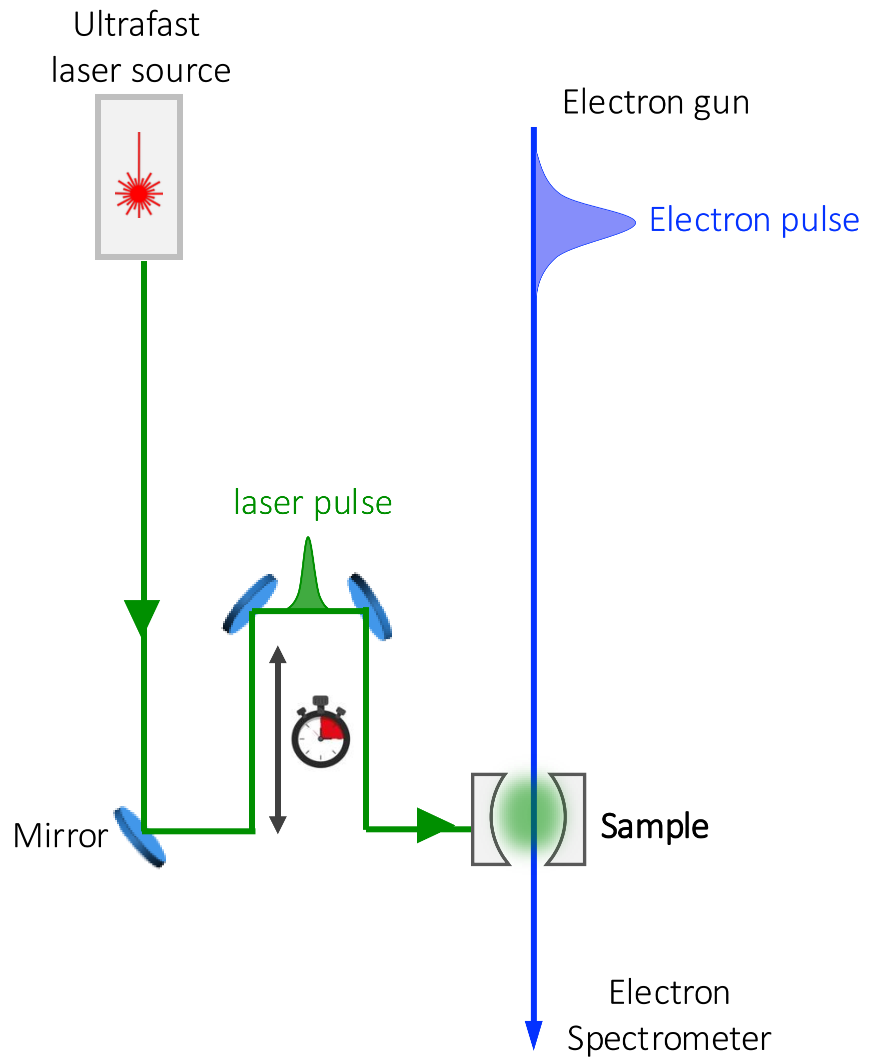


3c. Electron pulse compression – attosecond bunching

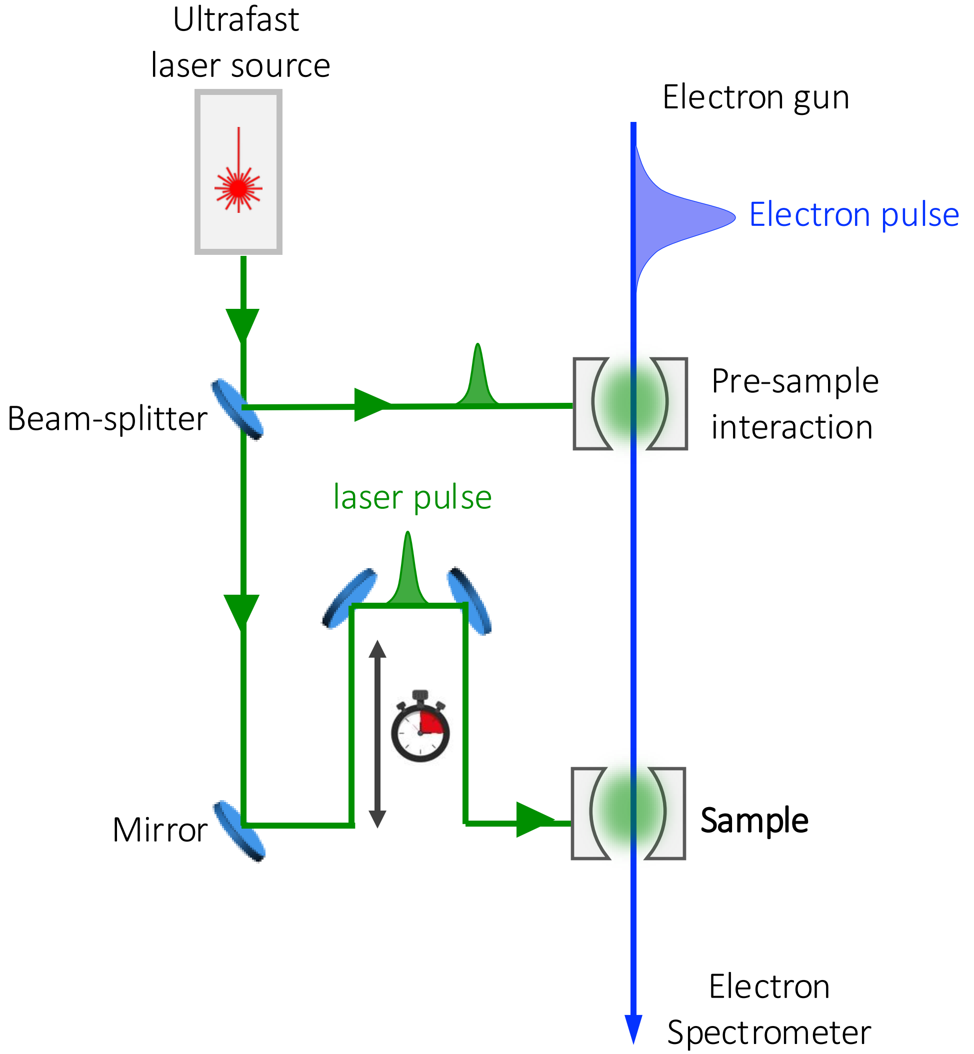


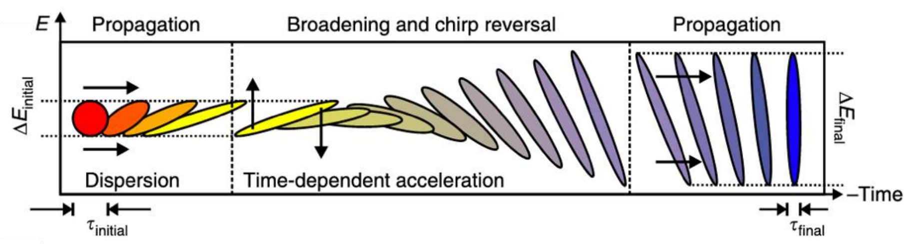
Free-Electron Homodyne Detection on a gold nanotriangle. Picture courtesy from Murat Sivis

Conventional PINEM

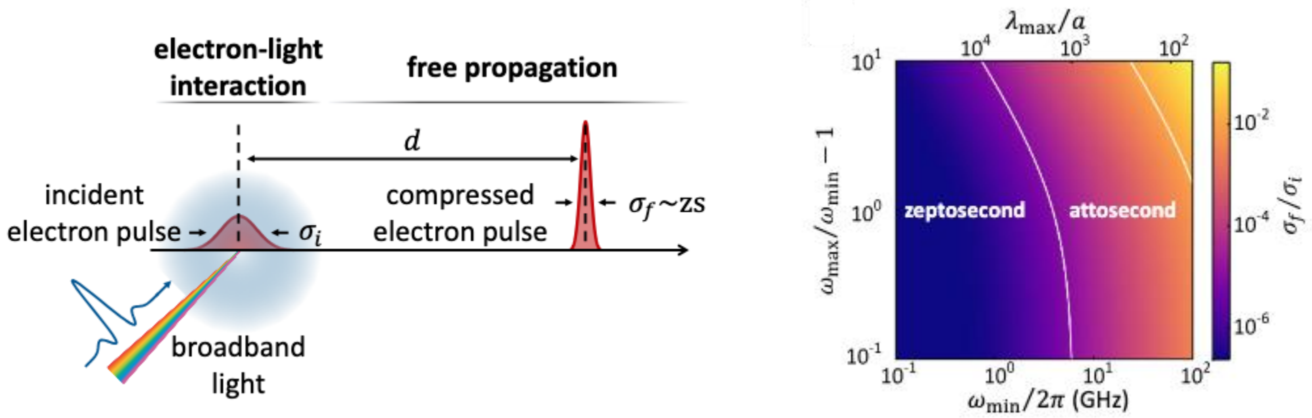


Double PINEM interaction - toward attosecond/zeptosecond resolution



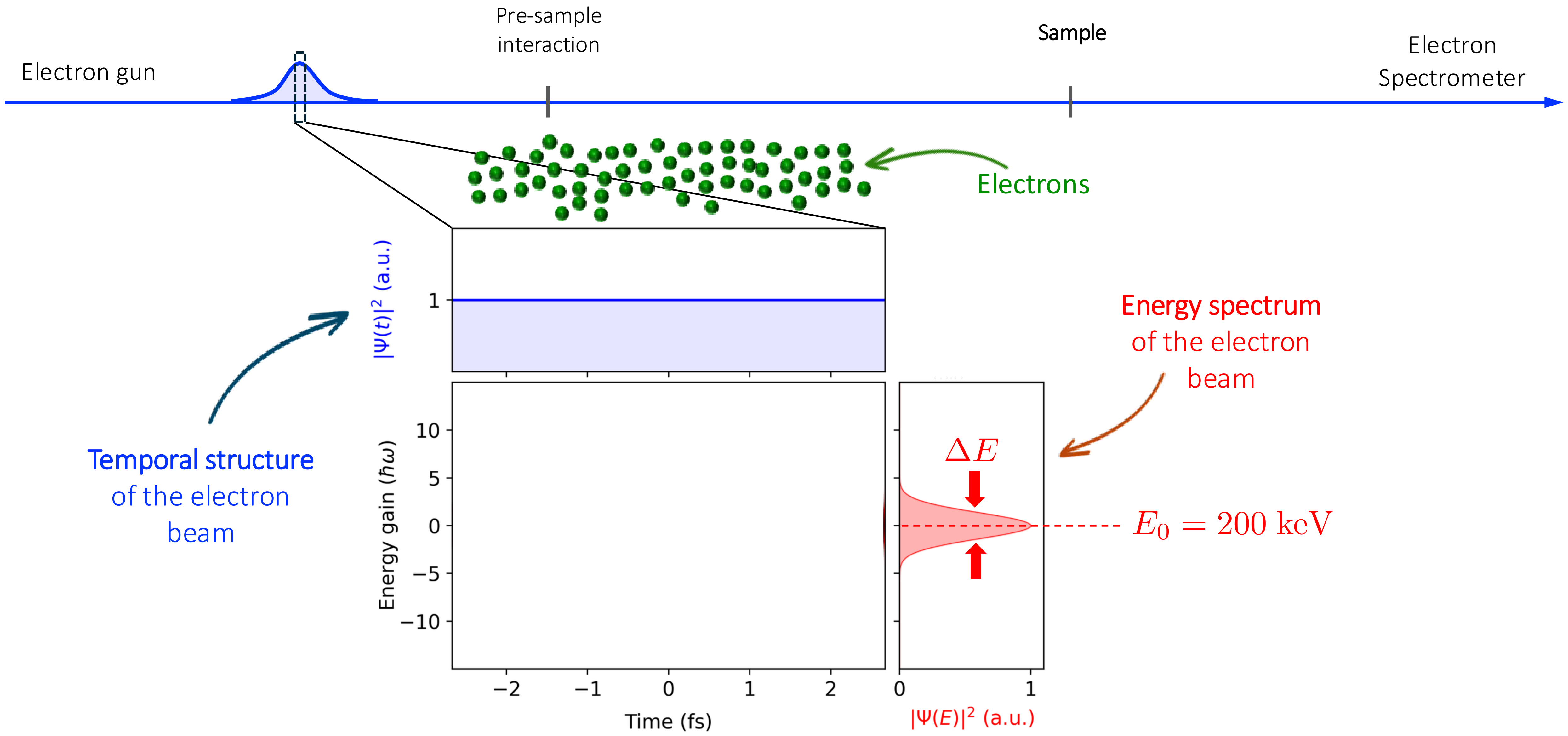


A. Gliserin et al., Nature Communications **6**, 8723 (2015)

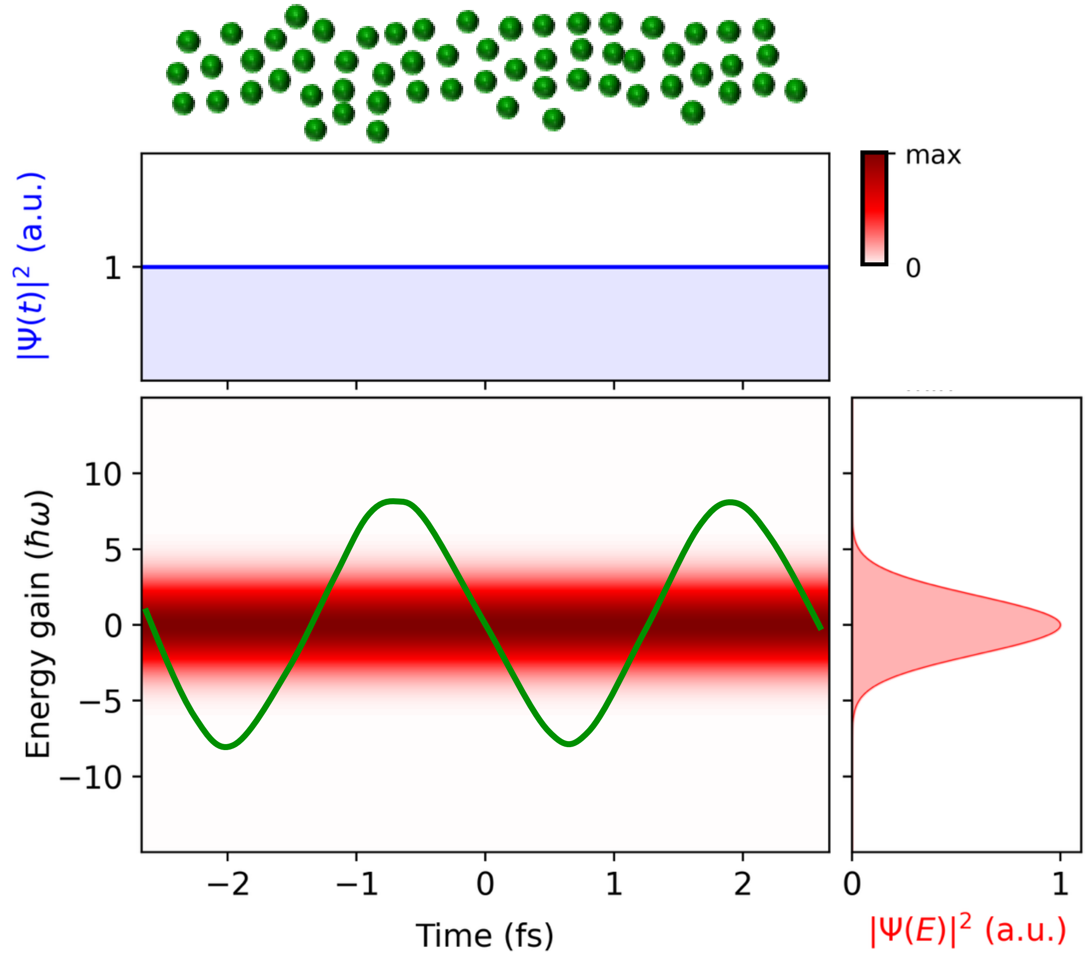


Lin *et al.*, arXiv:2504.17770 (2025)

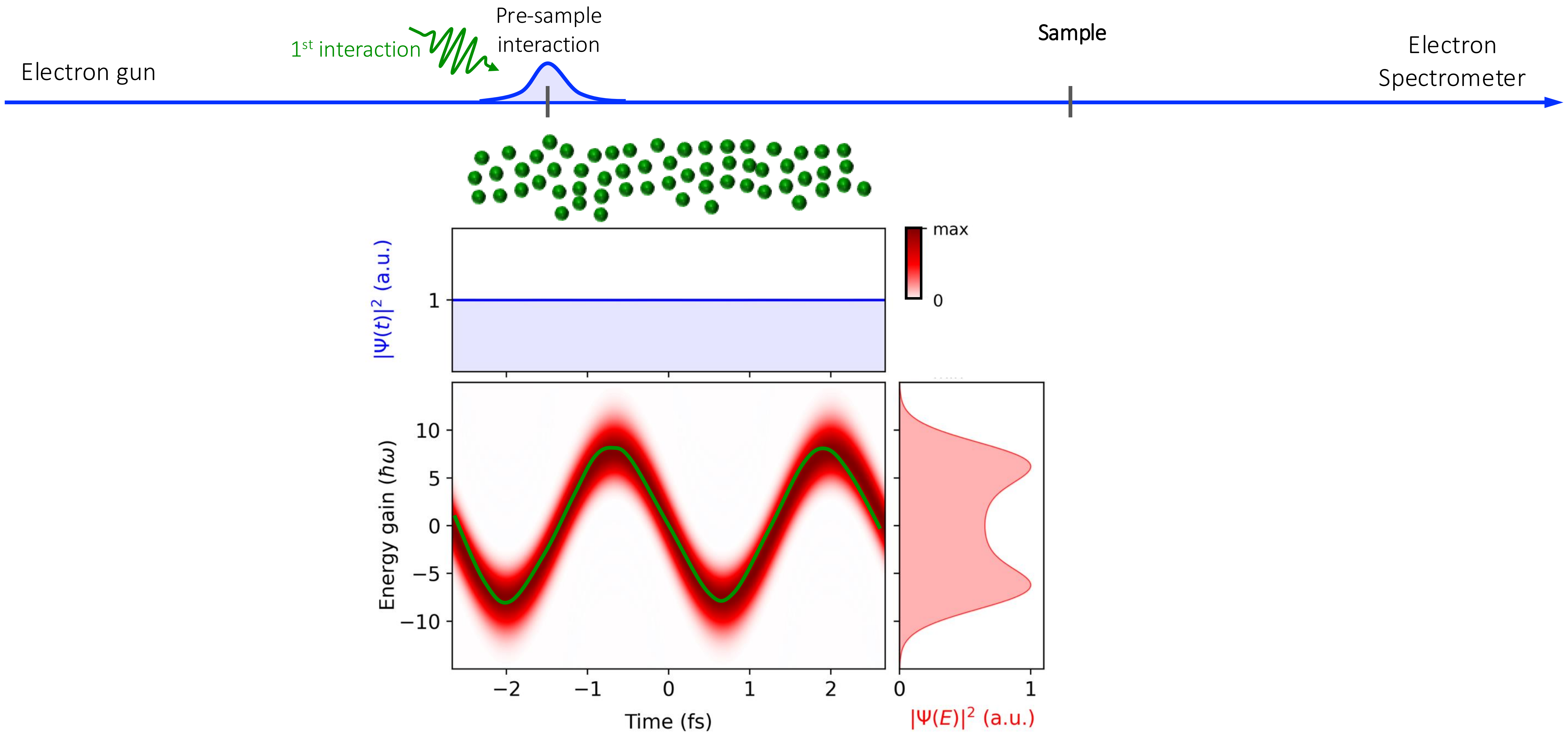
Principle of temporal lensing



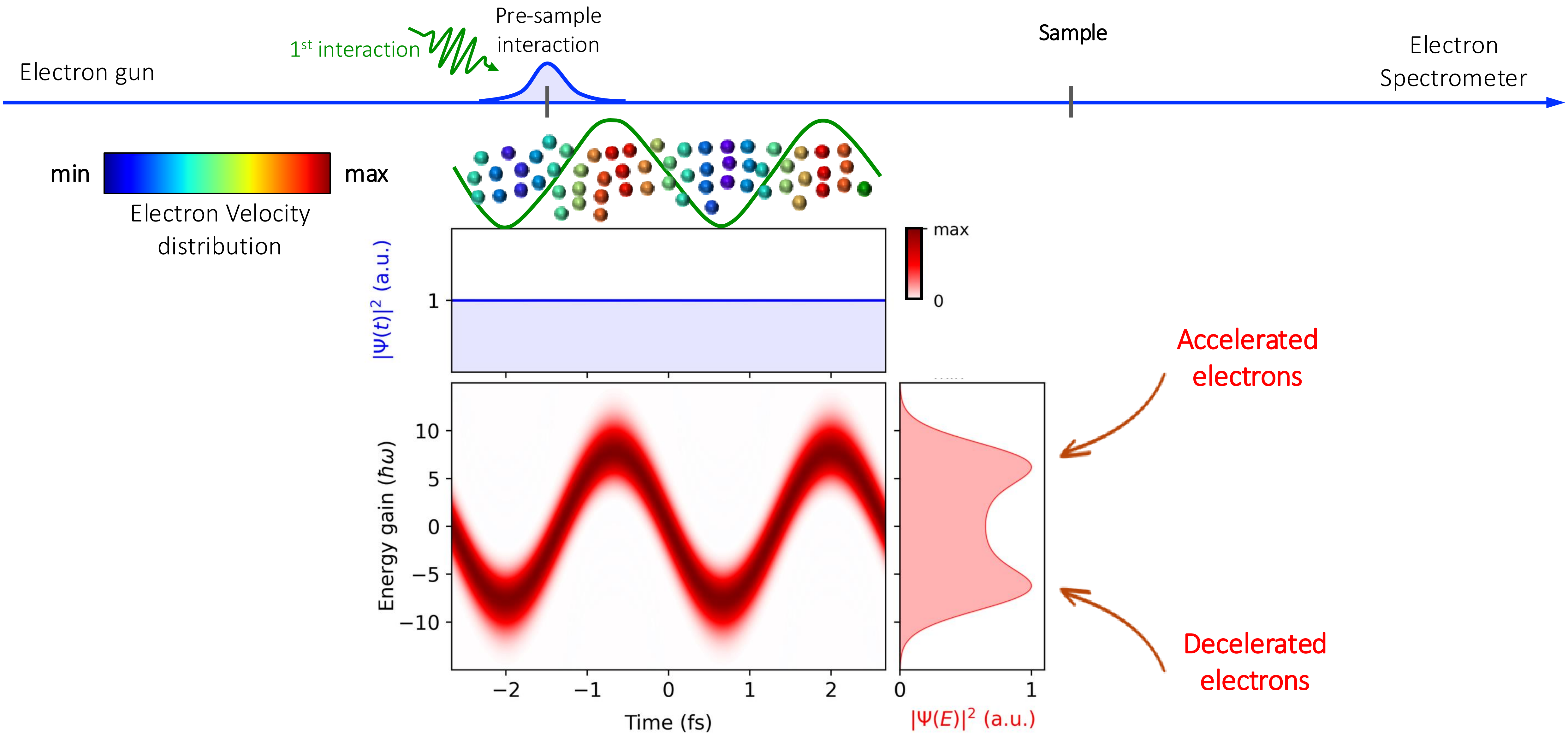
Principle of temporal lensing



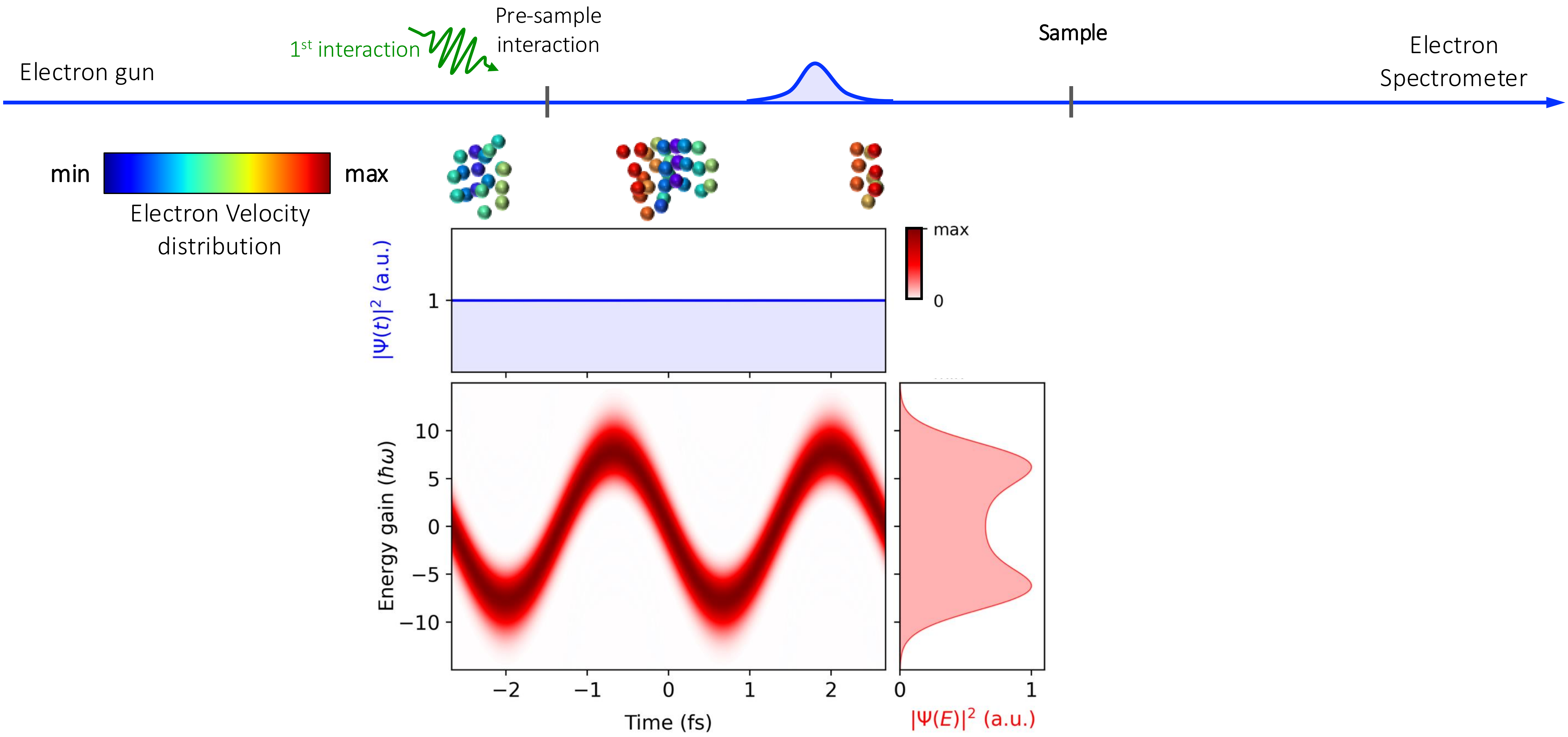
Principle of temporal lensing



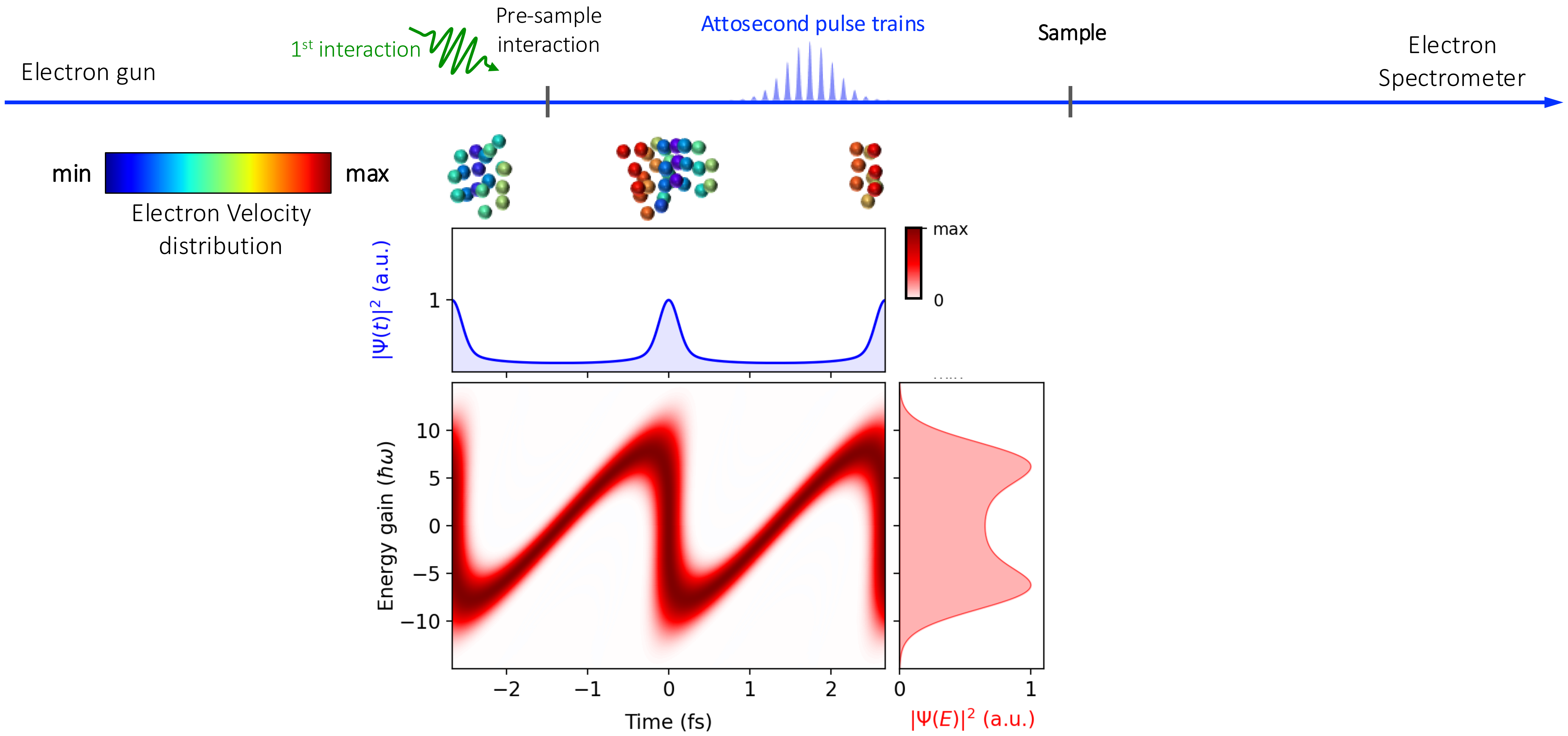
Principle of temporal lensing



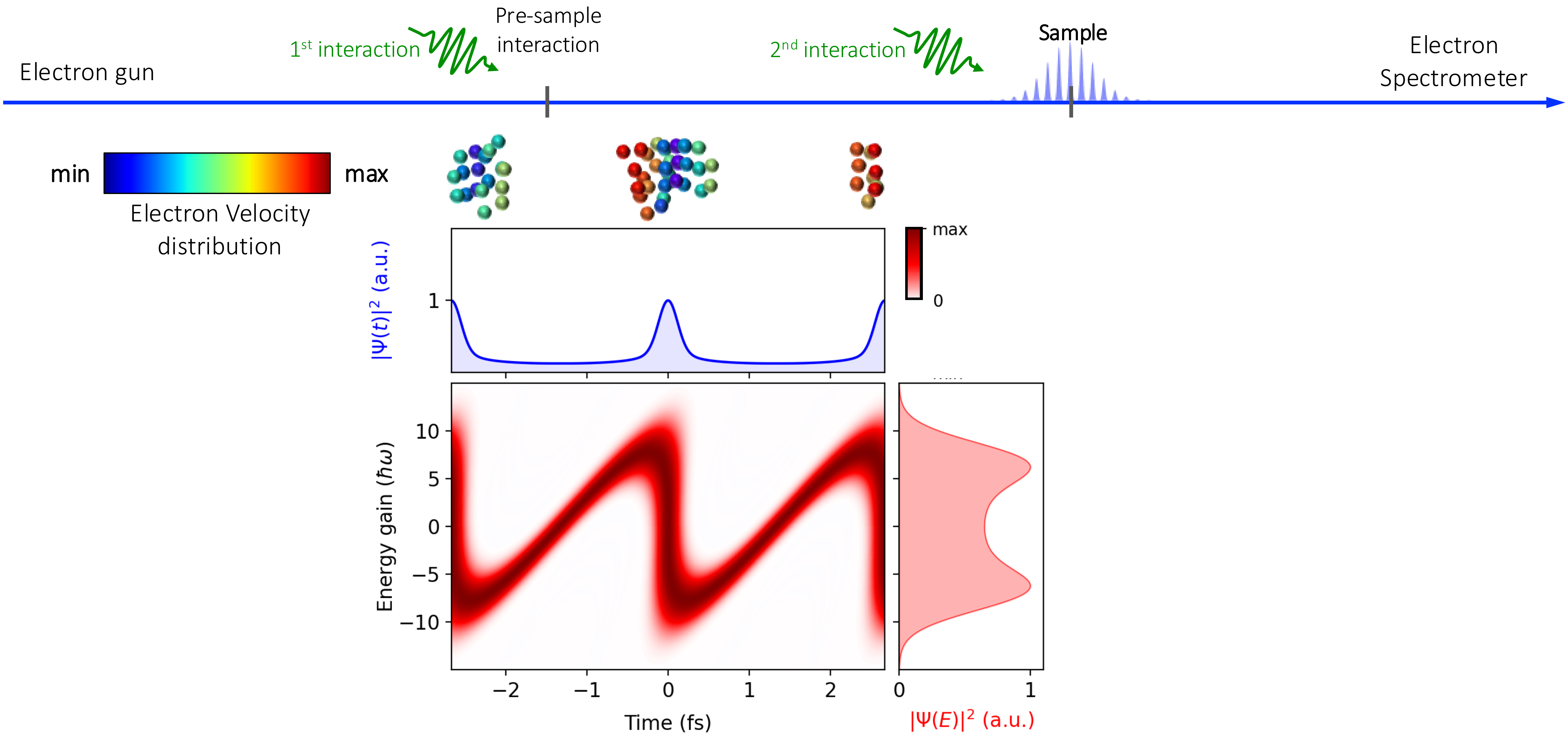
Principle of temporal lensing



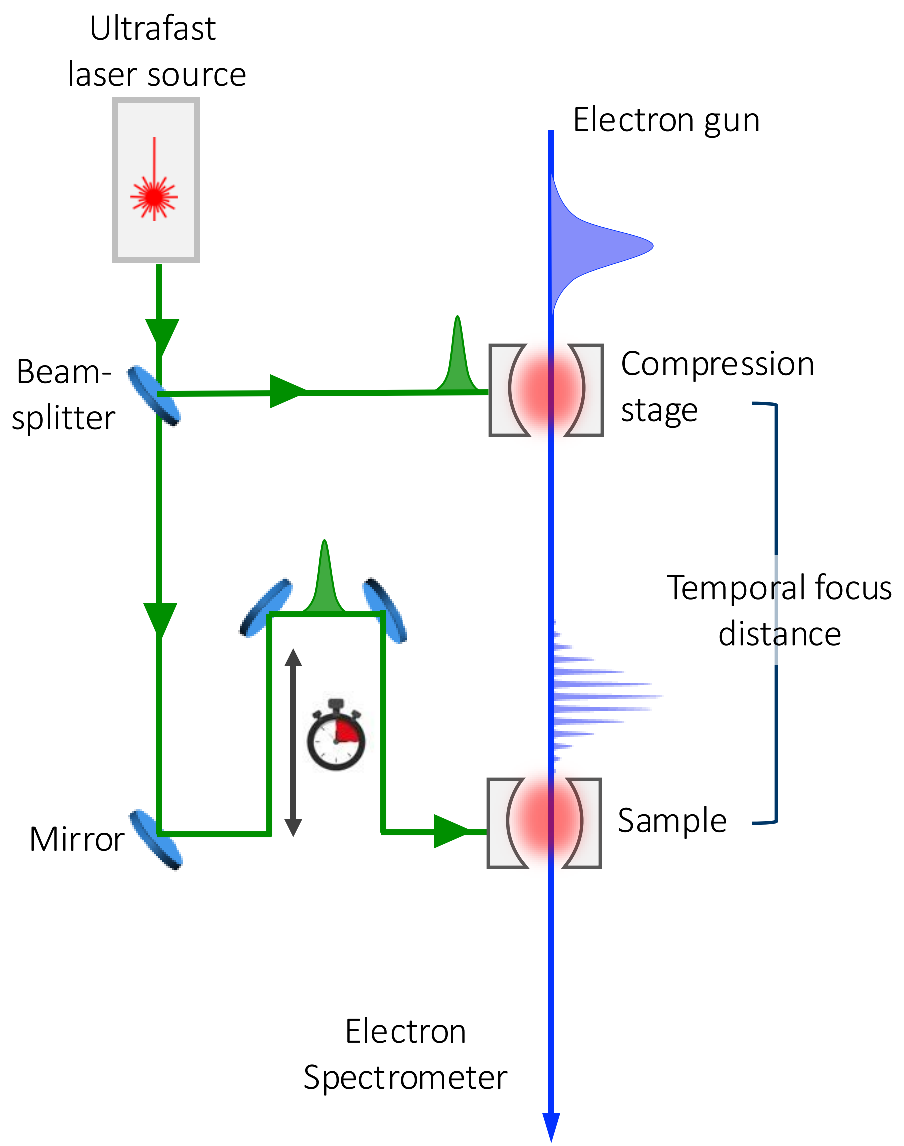
Principle of temporal lensing



Principle of temporal lensing



Propagation of modulated electrons: Temporal lensing



- Experimental realizations

K. Priebe *et al.*, Nature Photonics 11, 793–79 (2017)
A. Ryabov and P. Baum, Science **353**, 6297, 374-377 (2016)
G. Vanacore *et al.*, Nature Communications **9**, 2694 (2018)
M. Kozák *et al.*, Nature Physics **14**, 121–125 (2018)
Y. Morimoto & P. Baum, Nature Physics **14**, 252–256 (2018)
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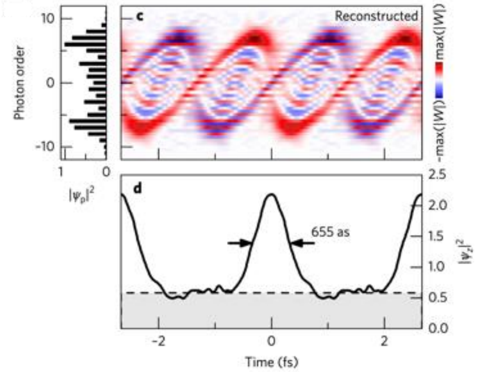
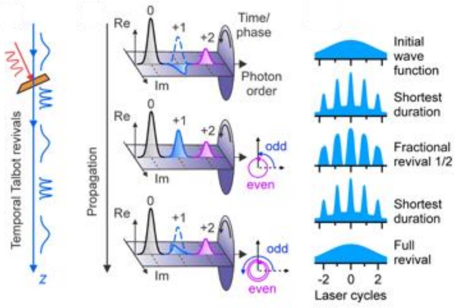
M. Kozák *et al.*, Phys. Rev. Lett. **120**, 103203 (2018)

655 attoseconds



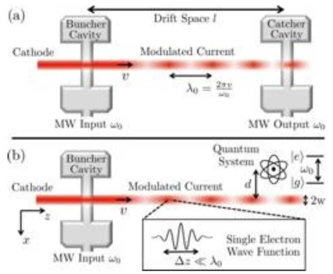


- Improving the pulse compression

Multiple interaction stages
S. Yalunin et al., Phys. Rev. Research 3, L032036 (2021)
Large Talbot revival
M. V. Tsarev et al., Physical Review Research 3 (4), 043033 (2021)
Use quantum states of light
V. Di Giulio & F. Javier García de Abajo, Optica 7 (12), 1820-1830 (2020)

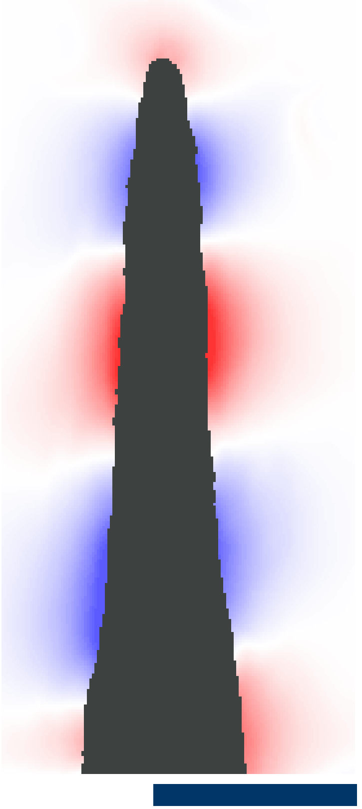
- Application in coherent control

D. Rätzel *et al.*, Phys. Rev. Research 3, 023247 (2021)
Kfir et al., Science Advances 7 (18), eabf6380 (2021)



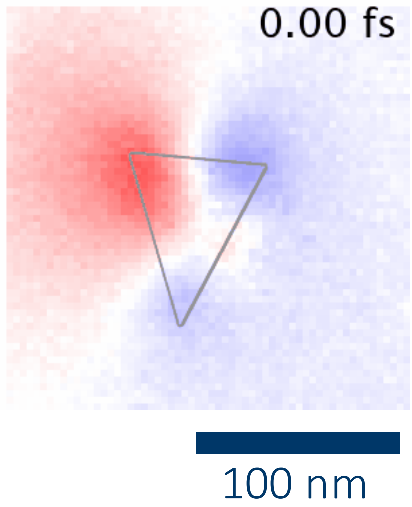
Experimental examples

Surface plasmon Polariton along a gold tip



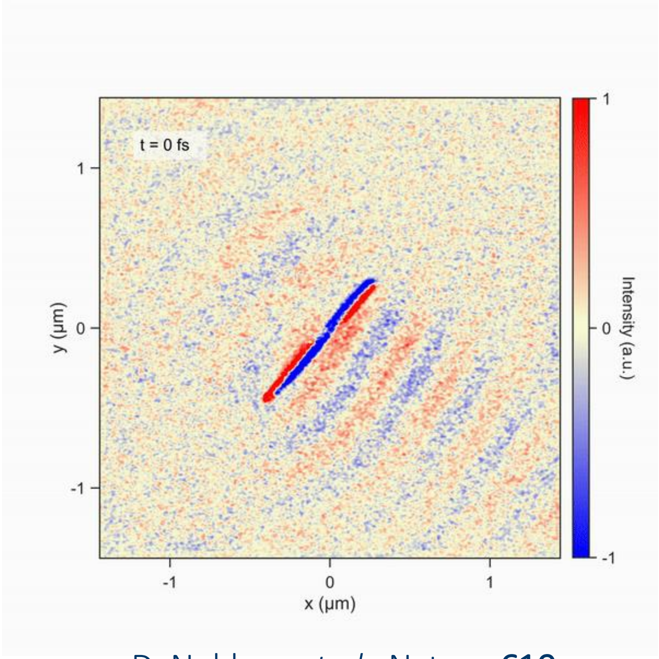
J. Gaida *et al.*, Nature Communication, **14**, 6545 **(2023)**

Surface plasmon Polariton along a gold tip



J. Gaida *et al.*, Nature Photonics **18**, 509–515 (2024)

Dielectric nano-slit



D. Nabben *et al.*. Nature **619**, 63–67 (2023)

See also

T. Bucher *et al.*, Science Advances **9**, 51 (2023)

D. Hui *et al.*, Science Advances **10**, 34 (2024)

Further reading

- Reviews:
  - J. García de Abajo, Rev. Mod. Phys. **82**, 209 (2010)
  - M. Kociak & Zagonel, Ultramicroscopy 176, 112-131 (2017)
  - S. Meuret et al., Ultramicroscopy 197, 28-38 (2019)
  - A. Polman, M. Kociak & J. García de Abajo, Nature Materials **18**, 1158–1171 (2019)
  - P. Dombi *et al.*, Rev. Mod. Phys. 92, 025003 (2020)
  - J. García de Abajo & V. Di Giulio, ACS Photonics **8** (4) 945–974 (2021)

- Books:
  - P. Hommelhoff & M. Kling, *Attosecond Nanophysics: From Basic Science to Applications*, Wiley – VCH (2015)

Thank you for your attention !

For further questions: hugo.lourenco-martins@cnrs.fr