GEORG-AUGUST-UNIVERSITÄT GÖTTINGEN

MAX PLANCK INSTITUTE FOR MULTIDISCIPLINARY SCIENCES

COULOMB-CORRELATED ELECTRONS IN A TRANSMISSION ELECTRON MICROSCOPE

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Microscopies: New Developments in Chemical/Property Characterization

FCMN 2024
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Monterey Marriott
Monterey, California USA
International Conference on Frontiers of Characterization and Metrology for Nanoelectronics

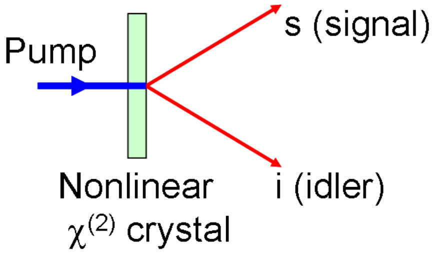
TOWARDS NON-STOCHASTIC ELECTRON SOURCES

- **Problem: Electron emitters are fundamentally non-deterministic.**

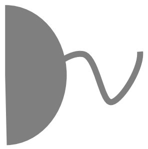
- **Solution from (quantum) optics: Single Photon Sources**

Stochastic single photons

Spontaneous
Parametric
Downconversion



Heralded single photon



Measure one photon

- **How can stochastic fluctuations in electron emission be tackled?**

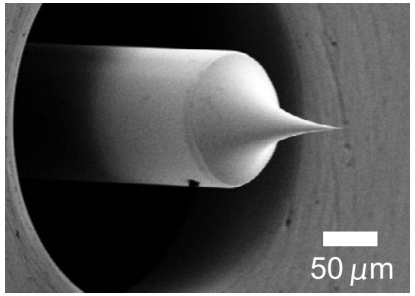
Figure Courtesy:https://en.wikipedia.org/wiki/Spontaneous_parametric_down-conversion

STATE OF THE ART ELECTRON SOURCES FOR MICROSCOPY

Figures of merit for electron emitters

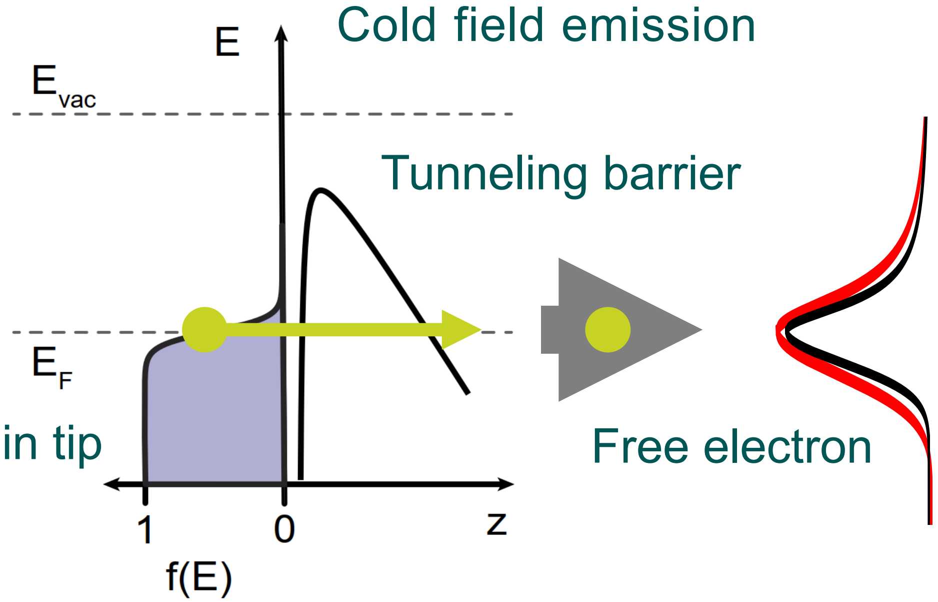
- Beam Brightness: $B = \frac{I}{4\pi^2 \varepsilon_n^2}$
- Spectral resolution ΔE

→ **Nanotip field emitters**



RH et al., Appl. Phys. B 129, 40 (2023)

Nanotip emitter

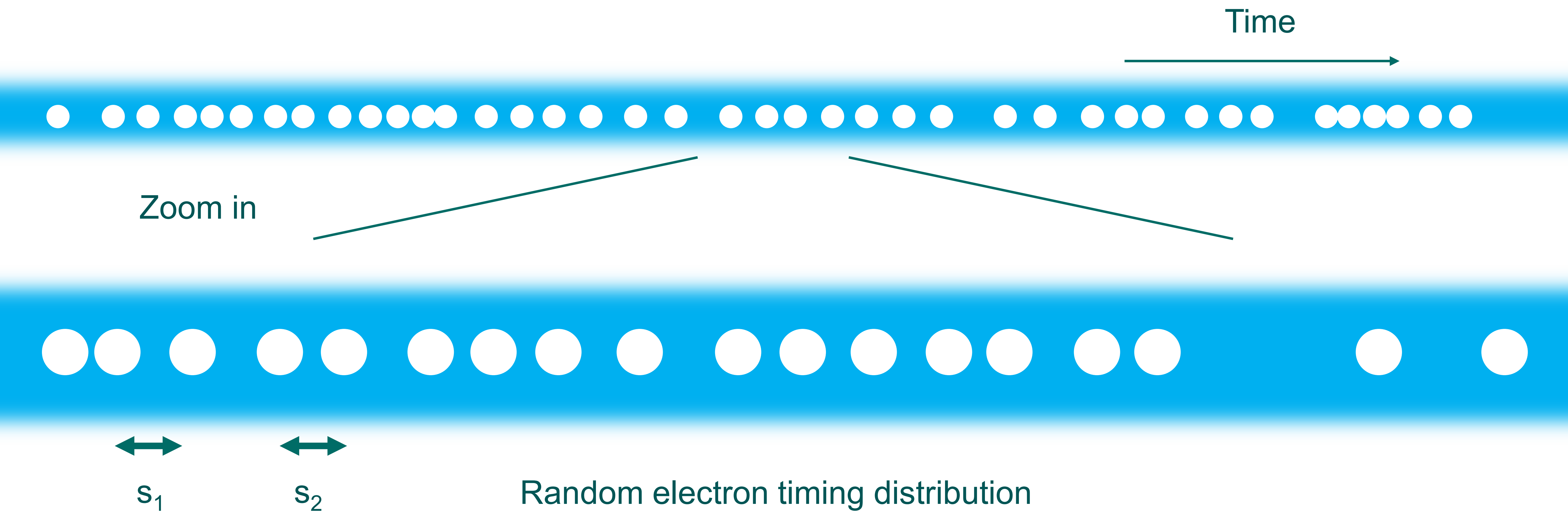


Energy broadening:

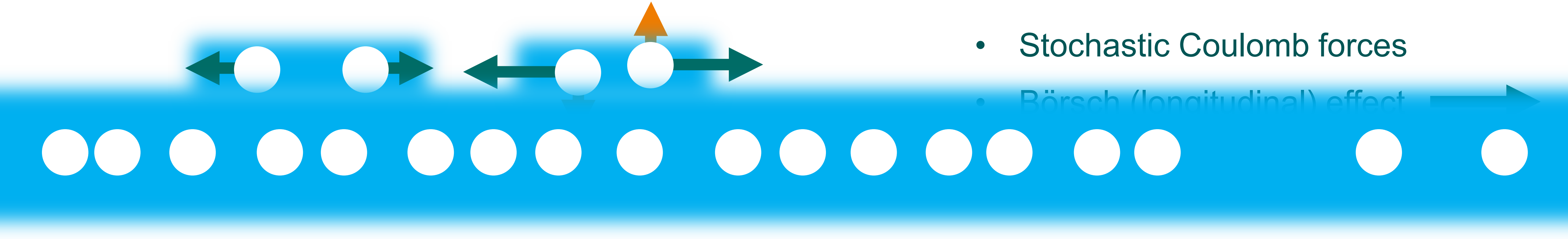
- Emission process
- **Beam dynamics**

TEMPORAL DISTRIBUTION OF ELECTRONS IN A BEAM

Continuous electron beam



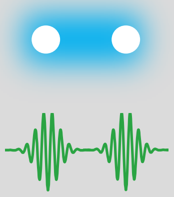
TEMPORAL DISTRIBUTION OF ELECTRONS IN A BEAM



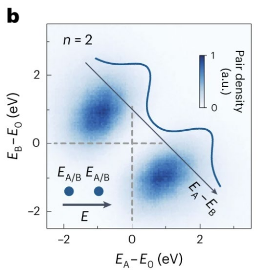
- Stochastic Coulomb forces
- Börsch (longitudinal) effect

OUTLINE

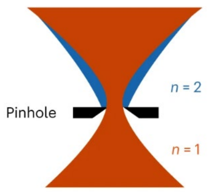
- Controlling stochastic Coulomb interaction by temporal gating



- Coulomb-correlated few-electron states

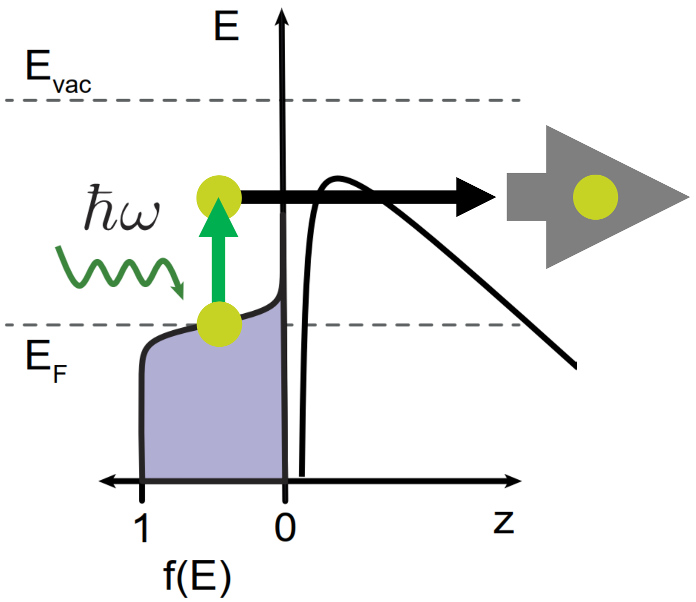


- Applications of Coulomb-correlated electrons



FIELD EMITTER-BASED PULSED ELECTRON SOURCES

Laser-driven field emission from a Schottky or cold field emitter

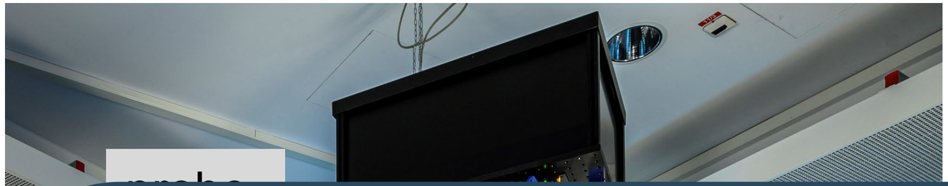


A. Feist *et al.*, Ultramicroscopy **176** (2017)

For cold field emitters: RH et al., Appl. Phys. B 129, **40** (2023)

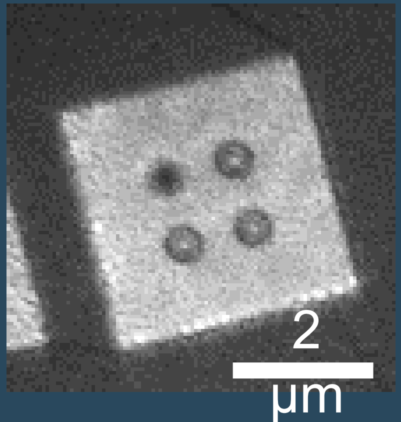
- First, suppress continuous emission by reducing filament current / extraction voltage
- Localized single-photon photoemission from the tip apex

OUR ULTRAFAST TRANSMISSION ELECTRON MICROSCOPE



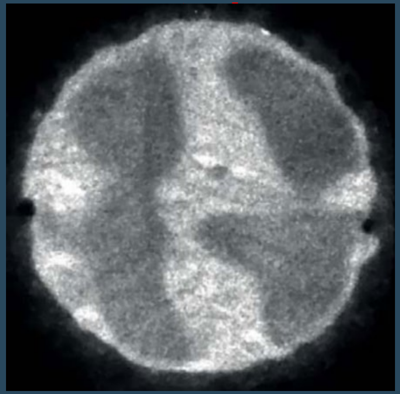
High brightness Electron pulses

phase-sensitive imaging
E/B fields, strain



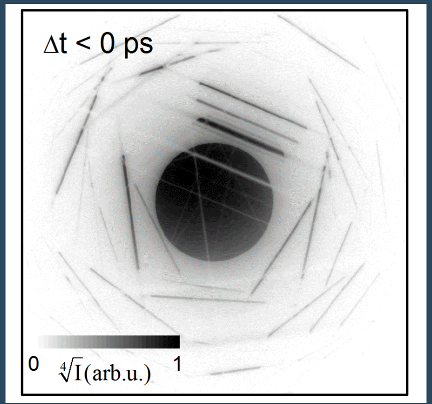
N. Rubiano da Silva *et al.*, *Phys. Rev. X* **8** (2018).
M. Möller *et al.*, *Commun. Phys* **3** (2020).

dark field imaging
structural phase



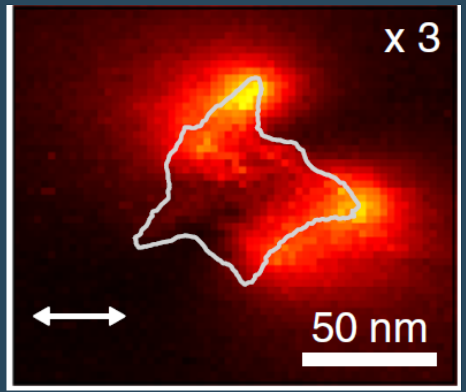
T. Danz *et al.*, *Science* **371** (2021).
T. Domröse et al., *Nat. Mat.* **22** (2023).

local diffractive probing
crystal lattice, temperature



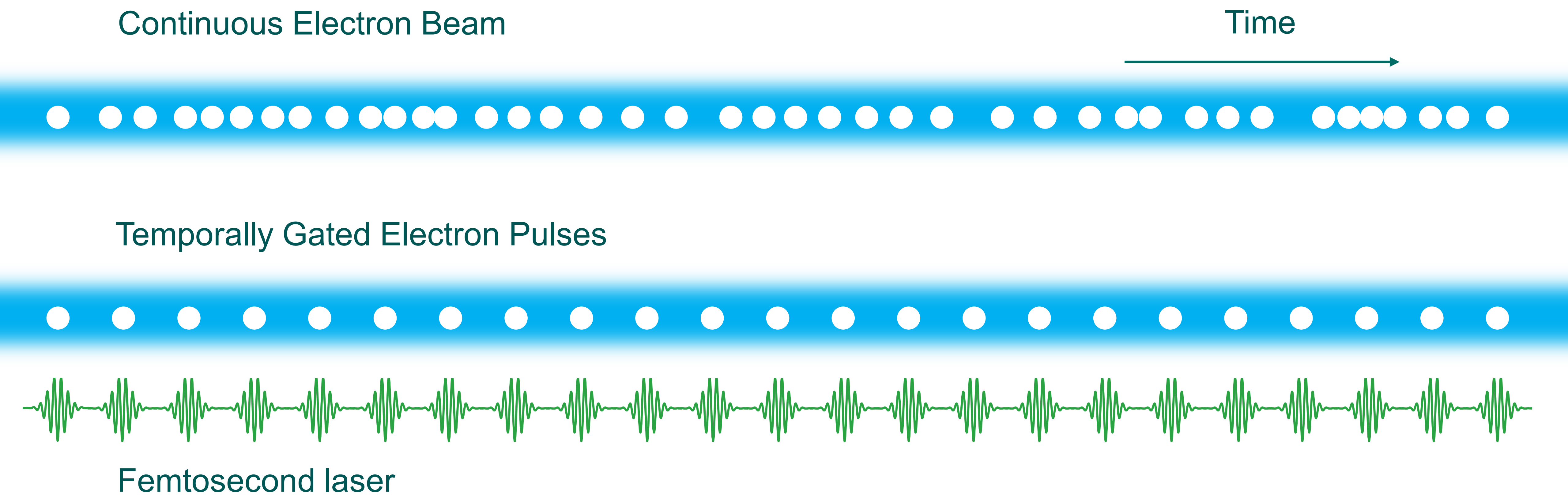
A. Feist *et al.*, *Struct. Dyn.* **5** (2018).
N. Bach et al., *Struct. Dyn.* **9** (2022).

electron spectroscopy
optical near-fields, temperature, valence electronic structure



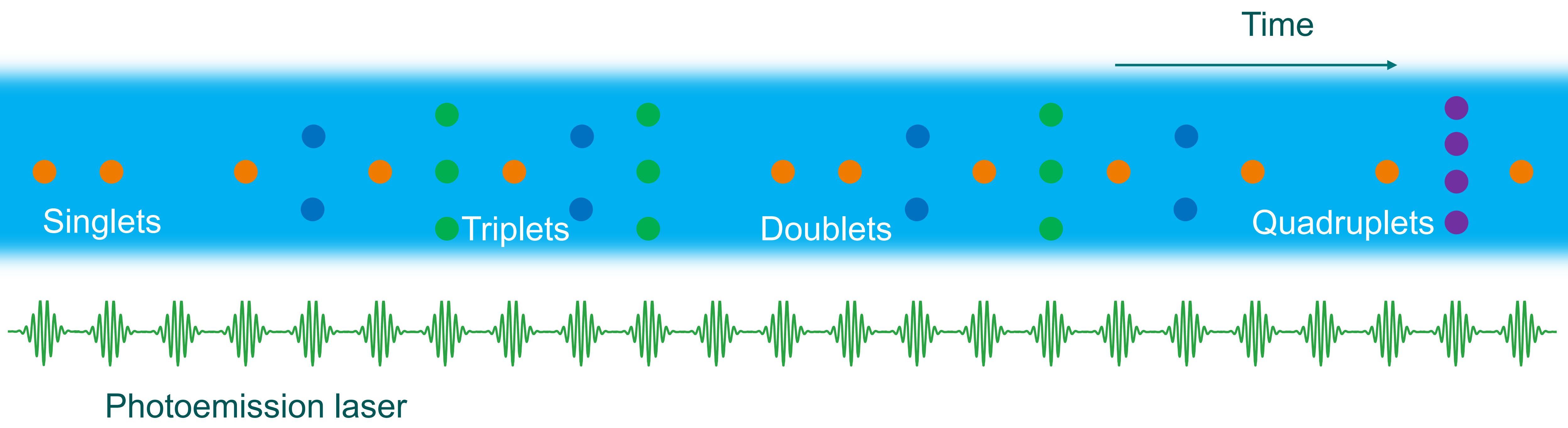
M. Liebtrau *et al.*, *Light Sci Appl* **10** (2021).
J. H. Gaida *et al.*, *Nat. Photon.* (2024).

TEMPORALLY GATED ELECTRON BEAM



Temporal gating enables control of electron timing

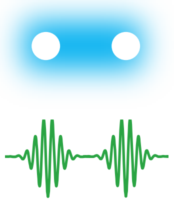
PHOTOEMISSION OF MULTIPLE ELECTRONS



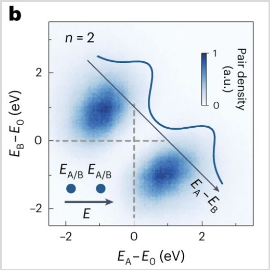
Generation of *n*-states with predictive Coulomb interactions

OUTLINE

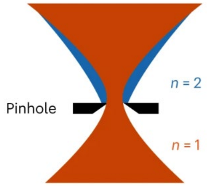
- Controlling stochastic Coulomb interaction by temporal gating



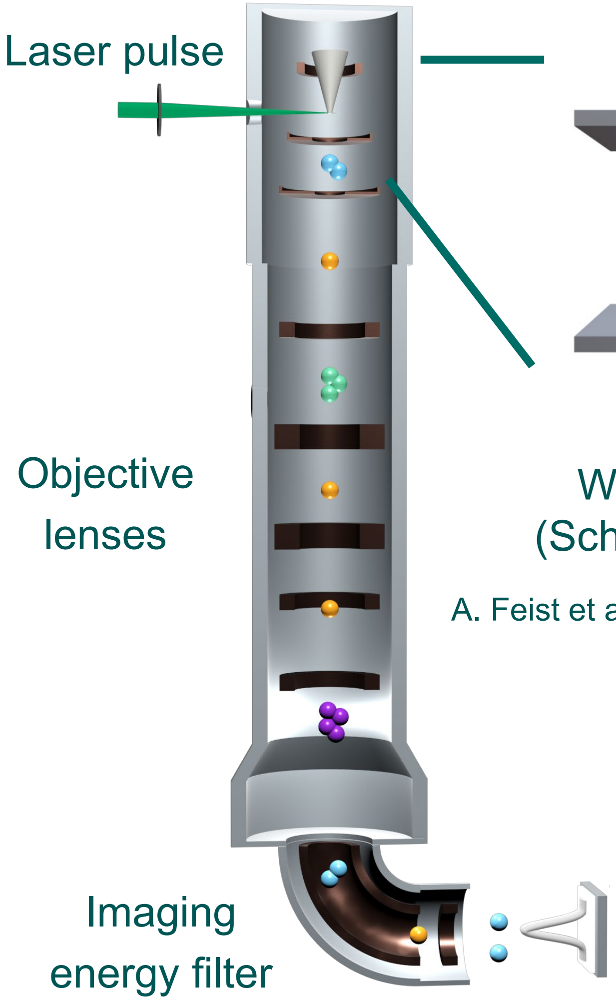
- Coulomb-correlated few-electron states

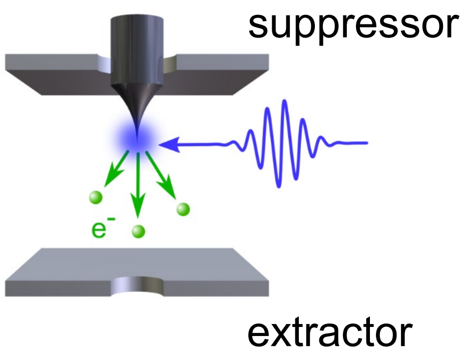


- Applications of Coulomb-correlated electrons



LASER-TRIGGERED ELECTRON MICROSCOPY

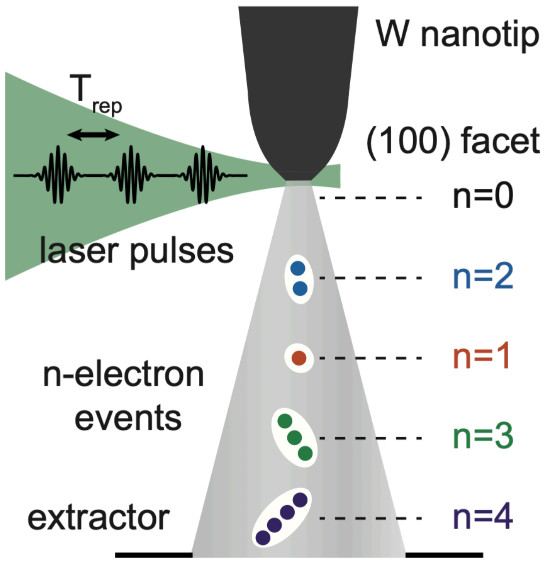




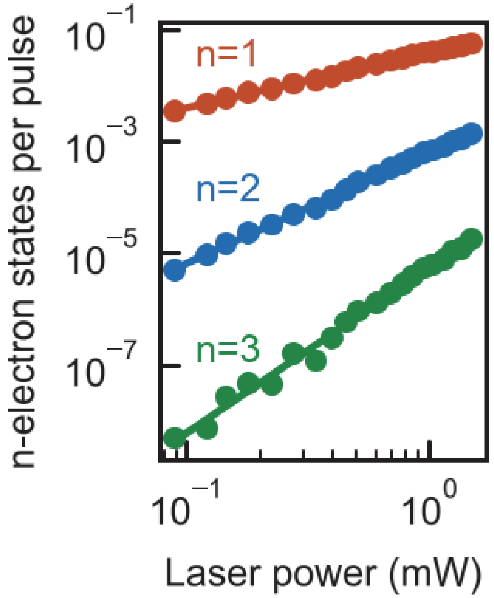
W(100) / ZrO
(Schottky emitter)

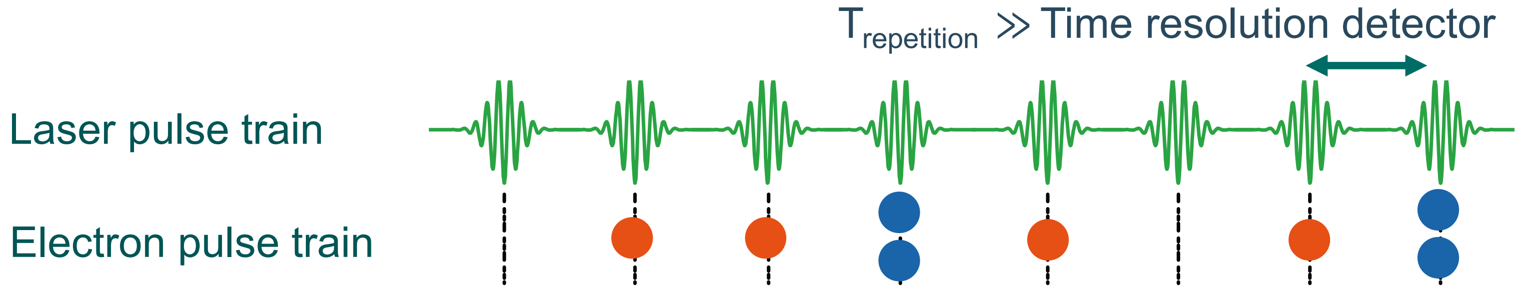
A. Feist et al., *Ultramicroscopy*, **176** (2017)

n-event classification



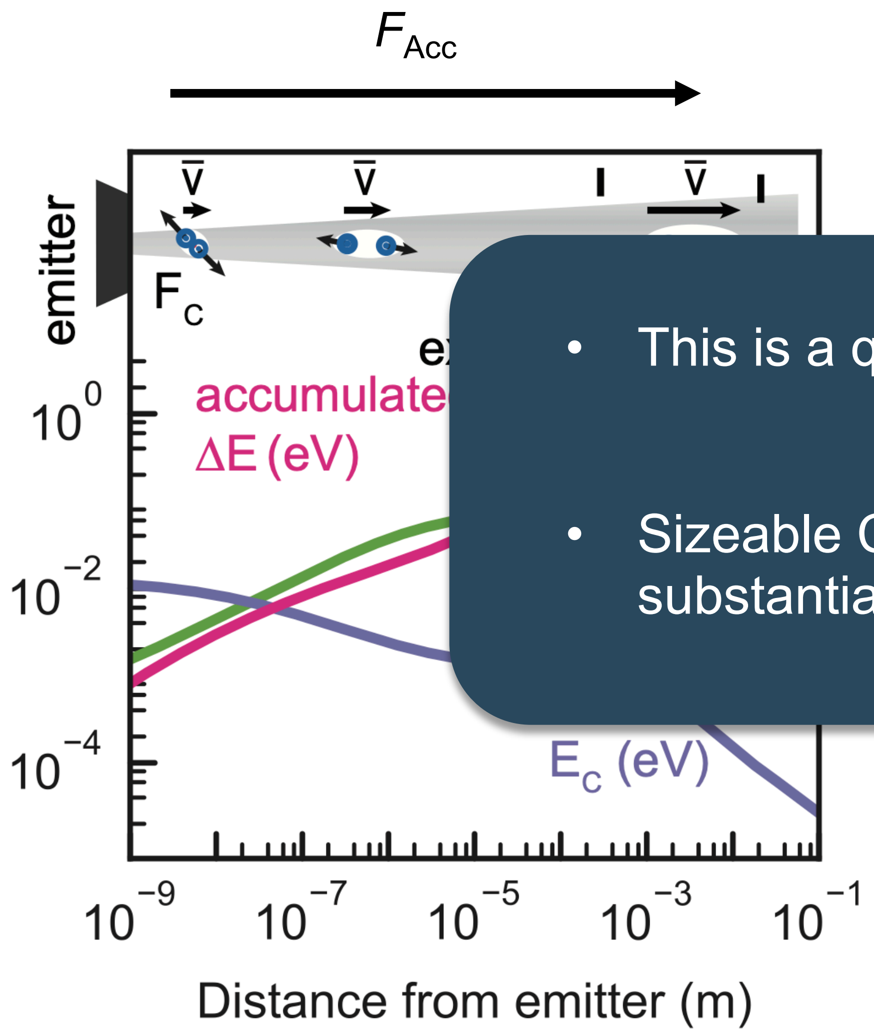
Power scaling





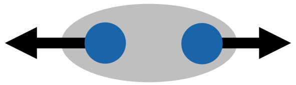
R. Haindl et al., *Nat. Phys.* (2023), see also for pair correlations from free-standing nanotips: S. Meier, J. Heimerl, and P. Hommelhoff, *Nat. Phys.* (2023)

ACCELERATION-ENHANCED COULOMB INTERACTION



R. Haindl et al., *Nat. Phys.* (2023)

- **Center of mass frame**



eV

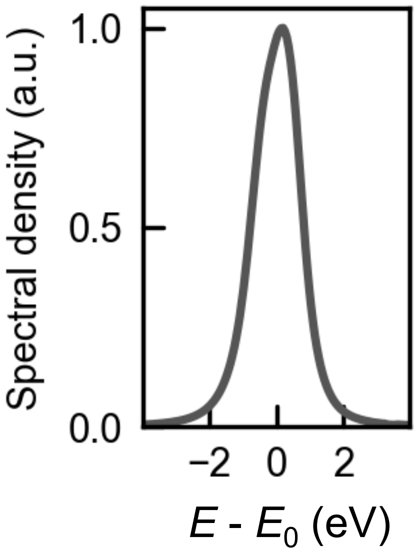
- This is a quasi-one-dimensional system!
- Sizeable Coulomb interaction is possible even after substantial electron travel time!

- Momentary change of energy difference: $P(\mathrm{t}) \propto \bar{\mathrm{v}}(\mathrm{t})\ F_{\mathrm{C}}(\mathrm{t})$
- Integrated energy difference: $\Delta E = \int dt\ P(t)$

SPECTRAL SHAPE OF ELECTRON NUMBER STATES

R. Haindl et al., *Nat. Phys.* (2023)

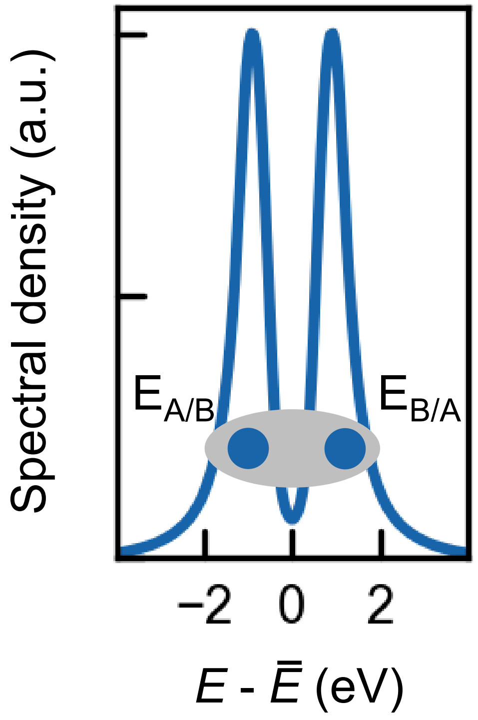
event-averaged



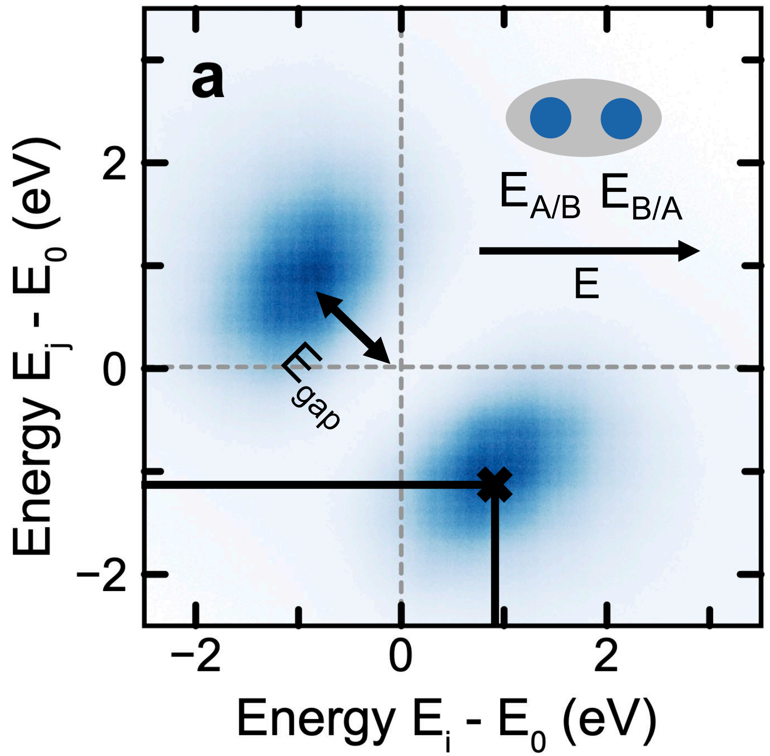
Characteristic peak structure for electron number states

ENERGETIC CORRELATION OF ELECTRON NUMBER STATES

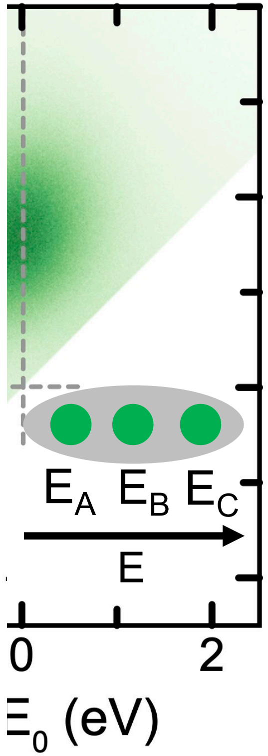
n=2 spectrum



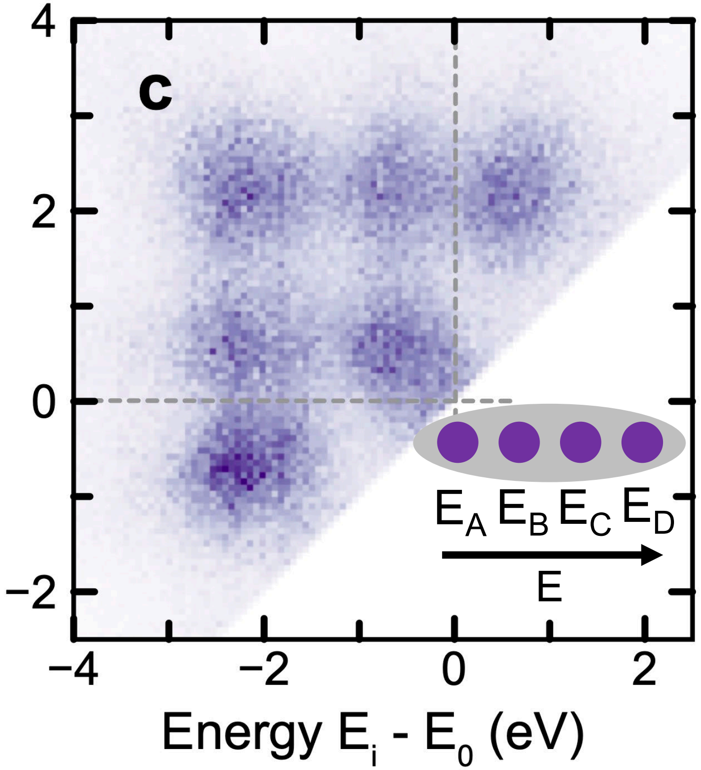
n=2 energy pair histogram



n=3 energy pair histogram

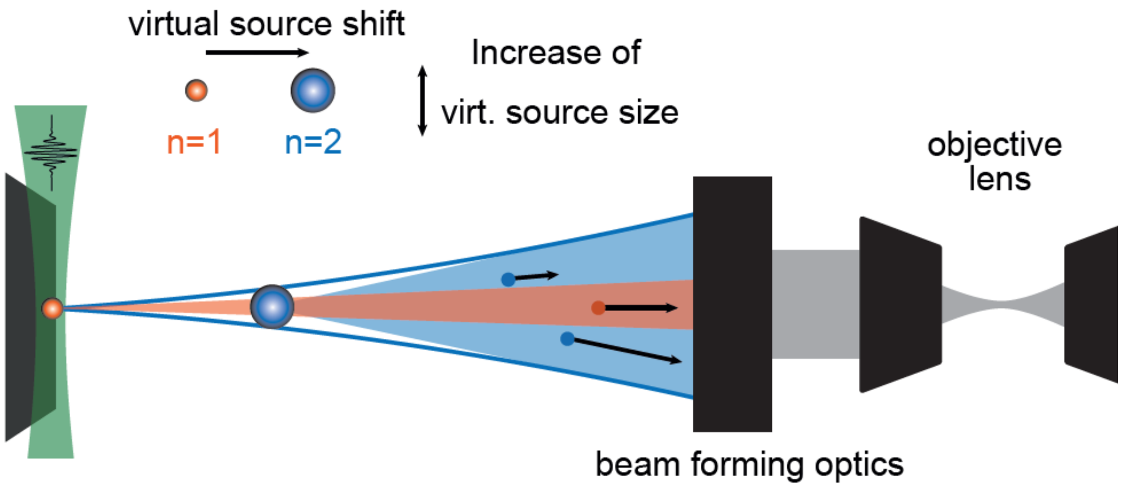


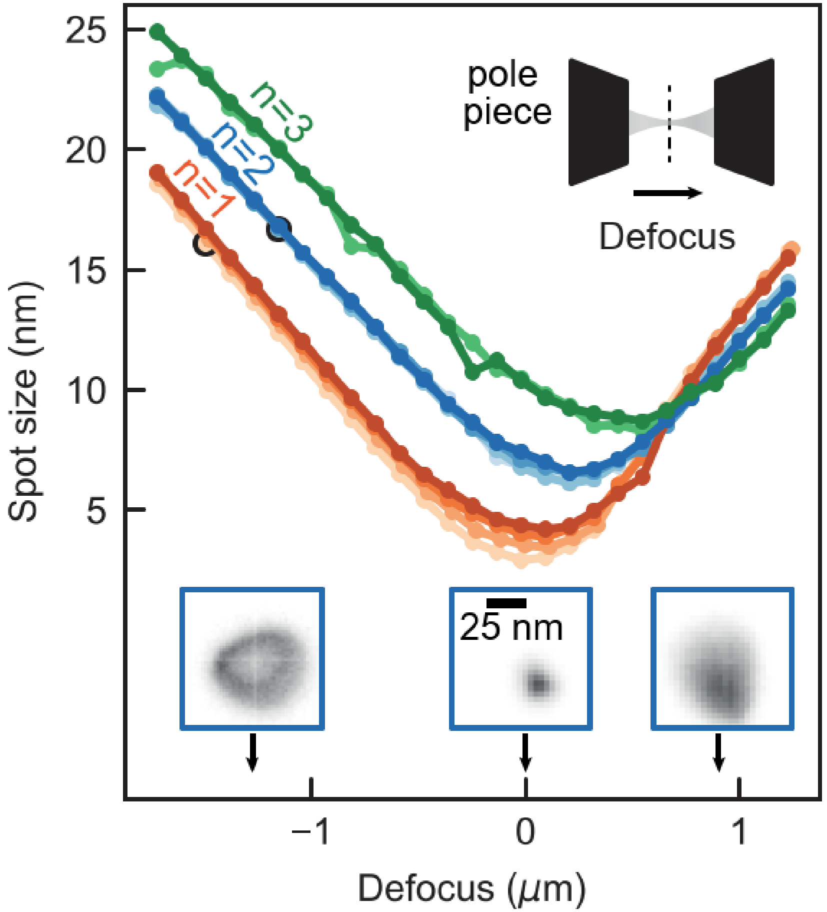
n=4 energy pair histogram

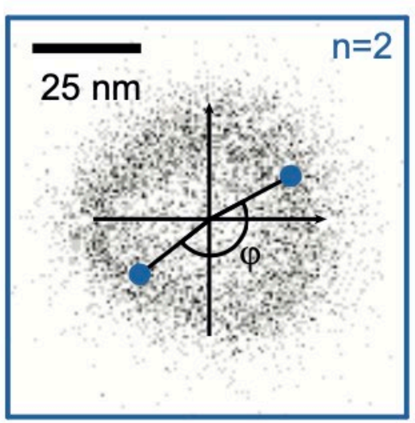


R. Haindl et al., *Nat. Phys.* (2023)

TRANSVERSE CHARACTERIZATION







Few-electron states exhibit…

… *n*-integer virtual source size increase

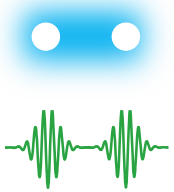
… *n*-integer virtual source size shift

… transverse correlations

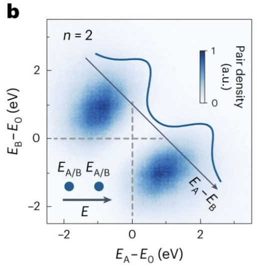
R. Haindl et al., *Nat. Phys.* (2023)

OUTLINE

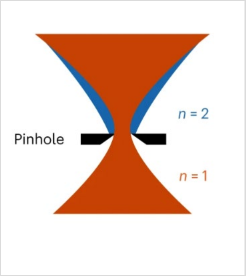
- Controlling stochastic Coulomb interaction by temporal gating



- Coulomb-correlated few-electron states

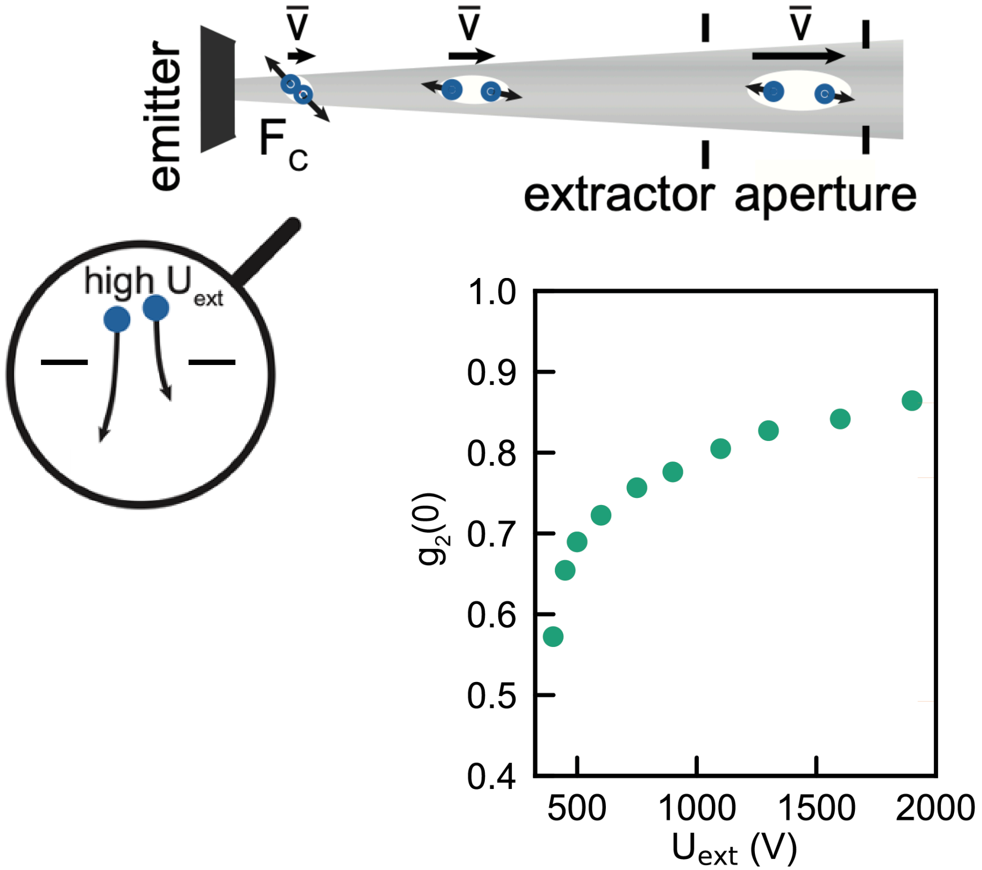


- Applications of Coulomb-correlated electrons



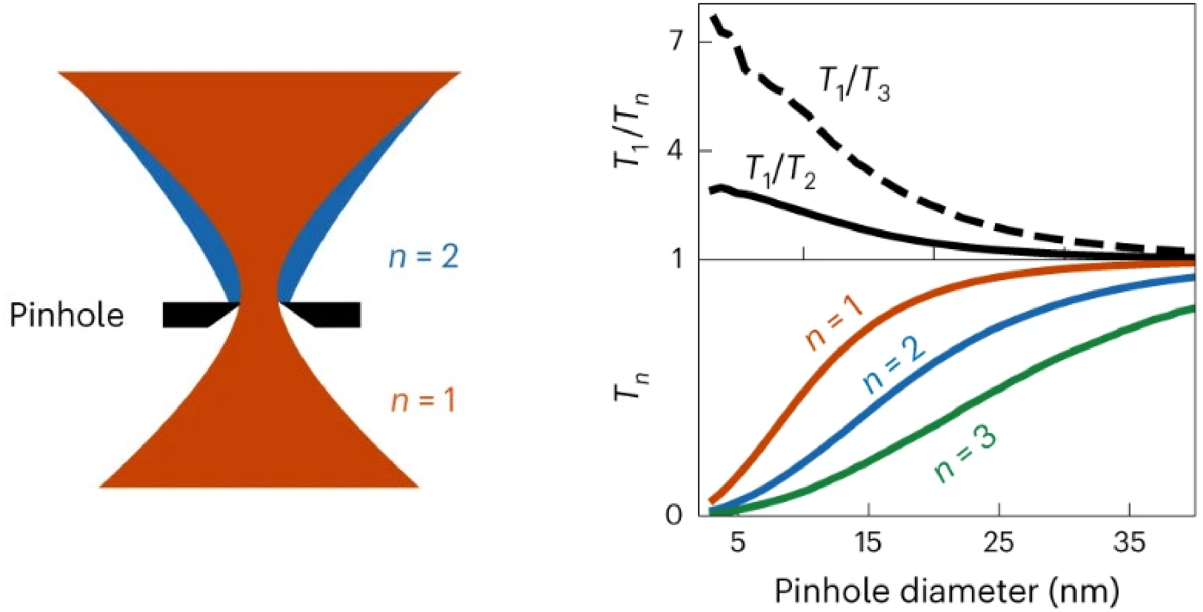
CONTROL OVER THE STATISTICS OF AN ELECTRON BEAM

Antibunching of few-electron states



R. Haindl et al., *Nat. Phys.* (2023)
See also for antibunching: S. Keramati et al., *PRL* 127, 180602 (2021)

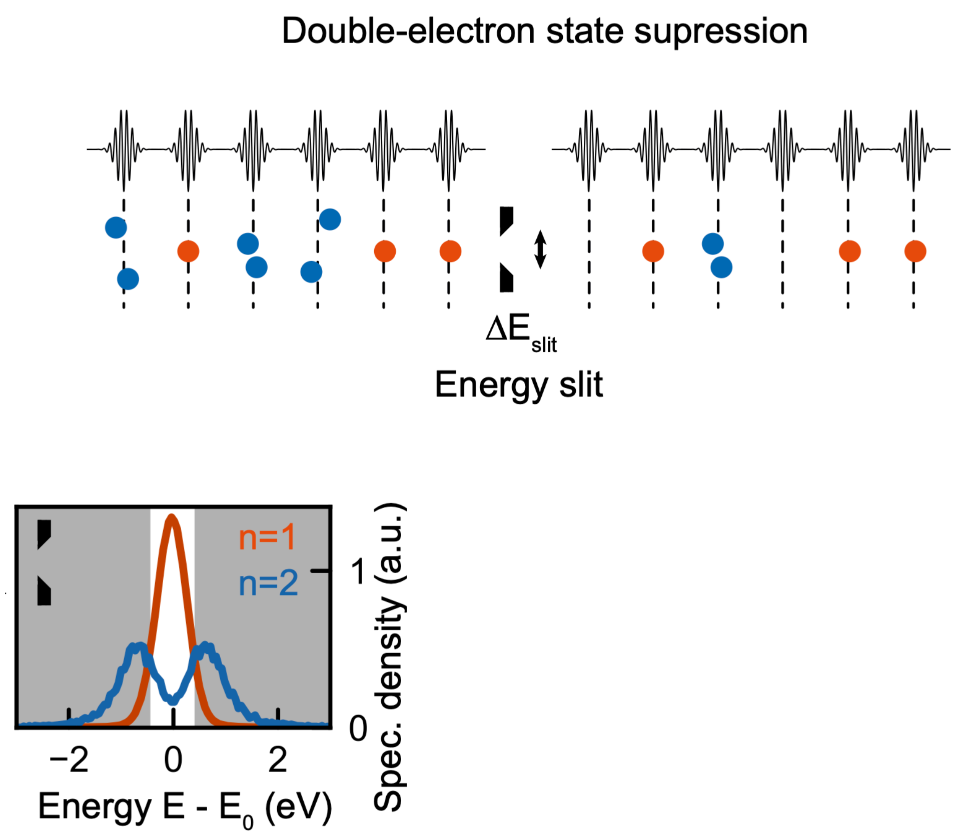
Spatial filtering of electron beams



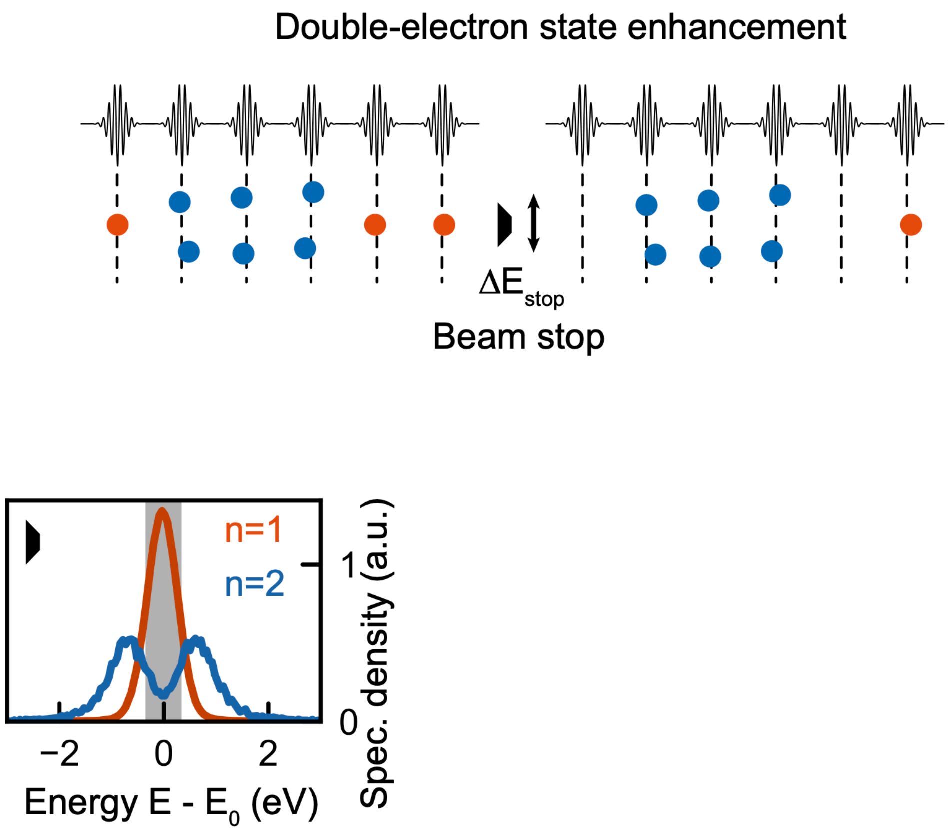
Suppression of higher order electron states

R. Haindl et al., *Nat. Phys.* (2023)

STATISTICAL CONTROL VIA ENERGY FILTERING



Suppression of multi-electron states

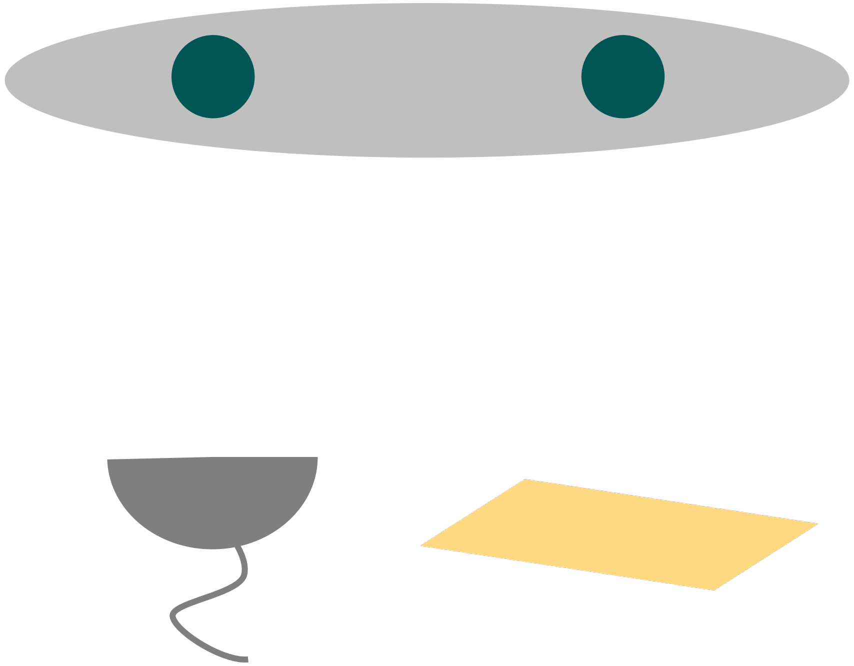


Two-electron state as a source of heralded electrons

R. Haindl et al., *Nat. Phys.* (2023)

STATISTICAL CONTROL APPLICATOINS

Precise dose-counting



Electron detector   Delicate sample

Shot-noise-reduced imaging and lithography

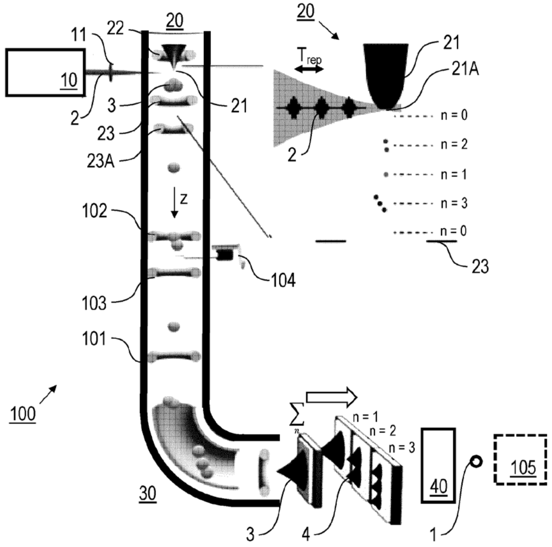


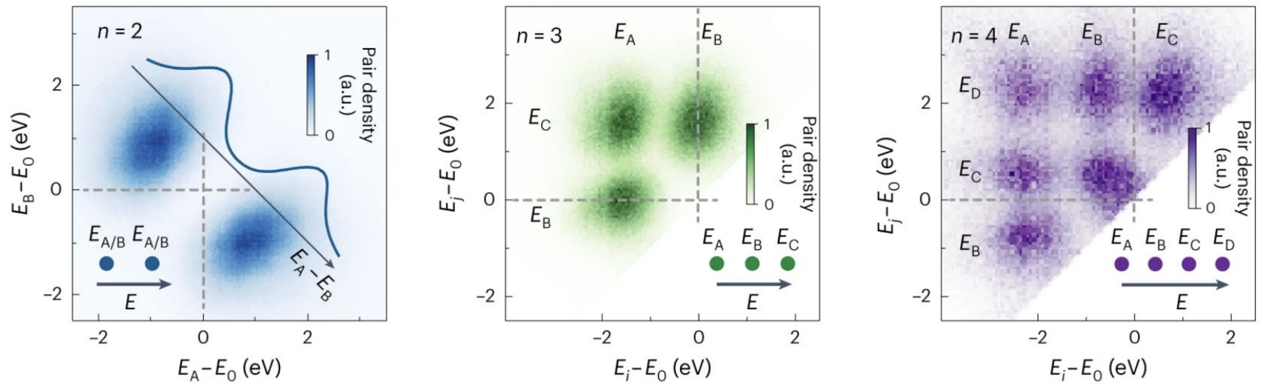
FIG. 9

Novel Electron Source Concept:

- pulsed electron source
- energy dispersive filter
- fast (realtime) electronics

A. Feist, C. Ropers, and R. Haindl, “Electron Beam Apparatus and Method for Generating a Pulsed Electron Beam and Applications Thereof,” (WO2024061773)

Summary & Outlook



- Electron number states with characteristic spectral and spatial correlations
- Applications of correlated few-electron states in correlated probing, imaging and lithography

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OF EXPERIMENT

DFG

Link to publication


Armin Feist


Till Domröse


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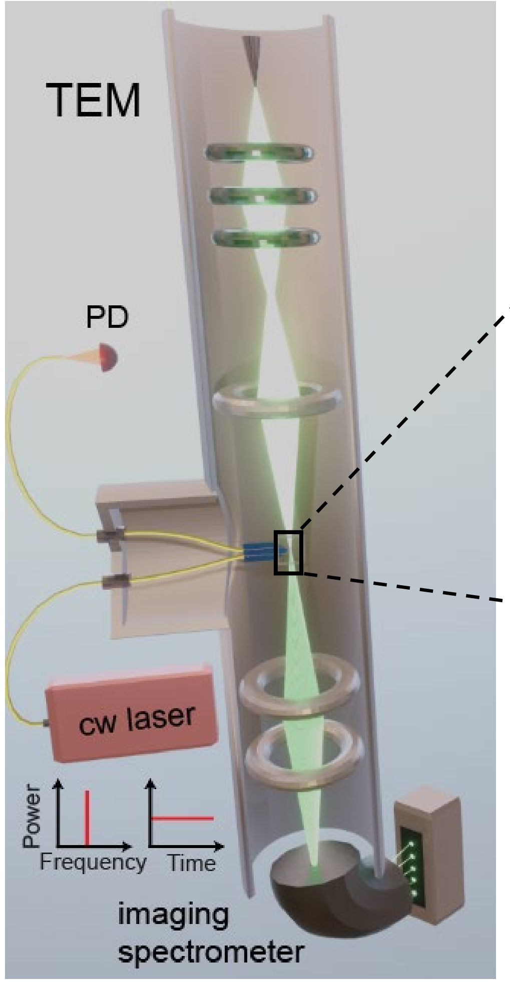
Sergey Yalunin

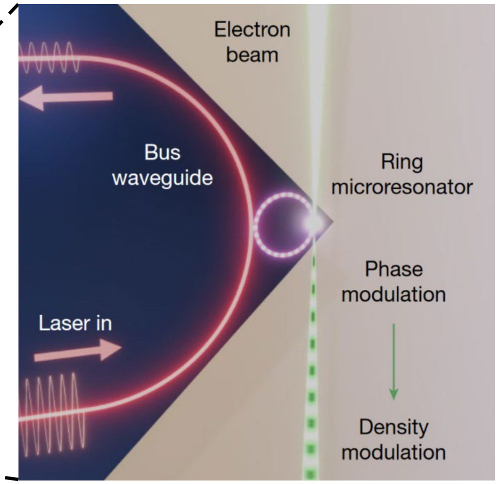

Claus Ropers

MERGING INTEGRATED PHOTONICS AND ELECTRON BEAMS

POSTER BY ARMIN FEIST

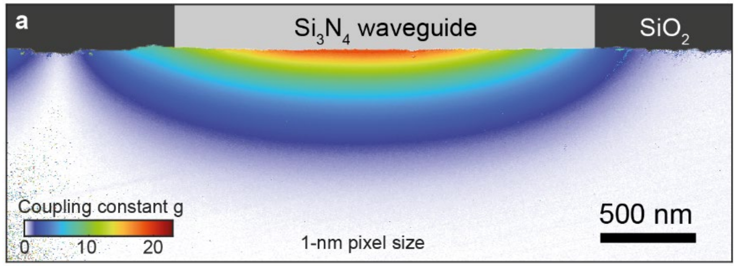


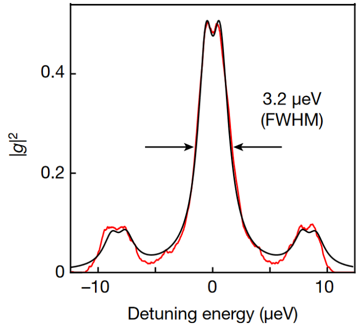
Laser-Driven Electron Optics & GHz-PHz Beam Modulations



Armin
Feist

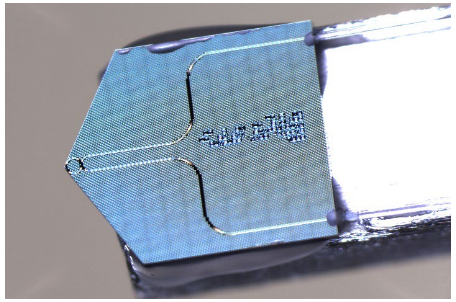
In-situ Metrology of Integrated Photonic Devices

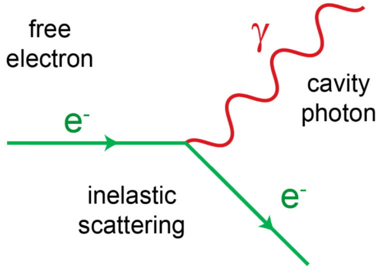




→ nanometer & μeV resolution using e-beams

Generation of Correlated Electron-Photon Pairs





→ heralded single electrons & enhanced imaging