SEQUOIA
Single-electron quantum optics for metrology

Frank Hohls (PTB)

SEQUOIA Consortium:

PTB – Physikalisch-Technische Bundesanstalt Braunschweig und Berlin

NPL – National Physical Laboratory

LNE – Laboratoire National de Métrologie et d'Essais

(NMIs)

cea – SPEC Saclay

cnrs – lpa laboratoire pierre aigrain

University of Latvia

(academic)

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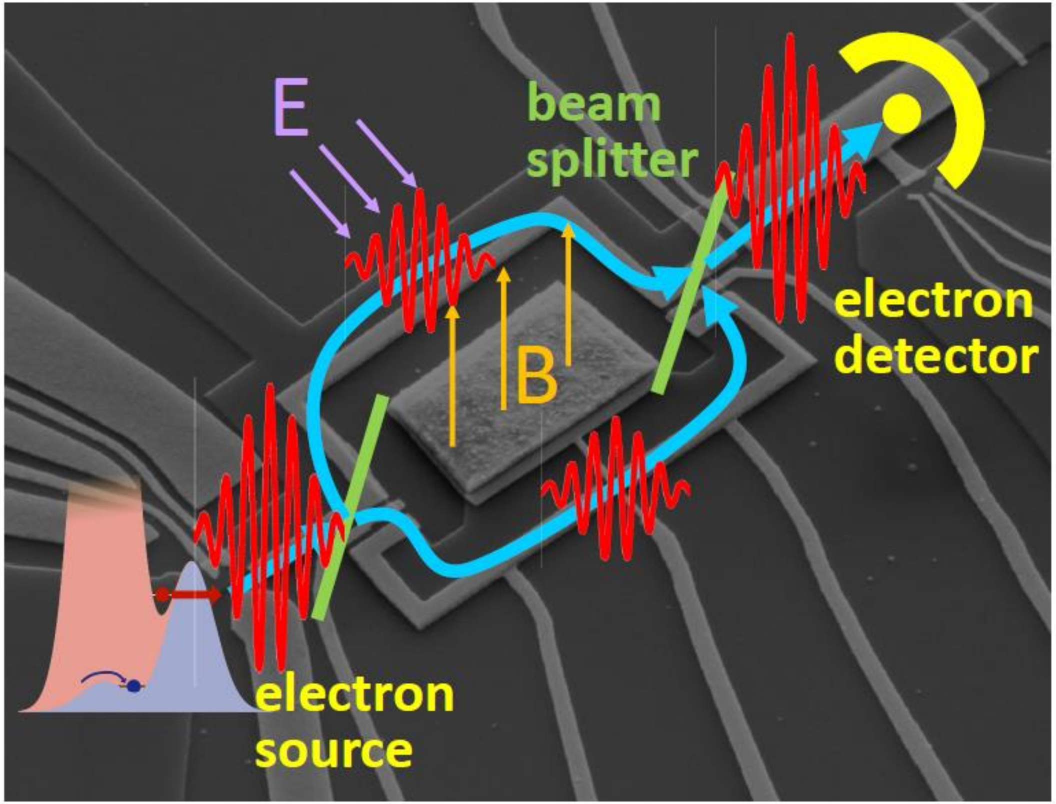
Metrology for and with single-electron wave packets



Idea: Metrological tools for quantum technology and sensing using **single-electron wave packets**

Implementation by **single-electron quantum optics** techniques

High time resolution expected due to short (~ 10 ps) wave packets

Integrates naturally with electrical solid state quantum technology

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Objectives

1. Components for single-electron quantum optics based sensing and state tomography
2. Metrological tools for single-electron sources and wave packet states
3. Experimental techniques for on-demand single-electron wave packet interferometry for sensing
4. Theory for a full quantum state tomography, enabling quantum enhanced measurements
5. To evaluate the potential of single-electrons for quantum metrology and to foster the European capabilities

Components and metrology for single-electron wave packets	Metrological application using single-electron wave packets

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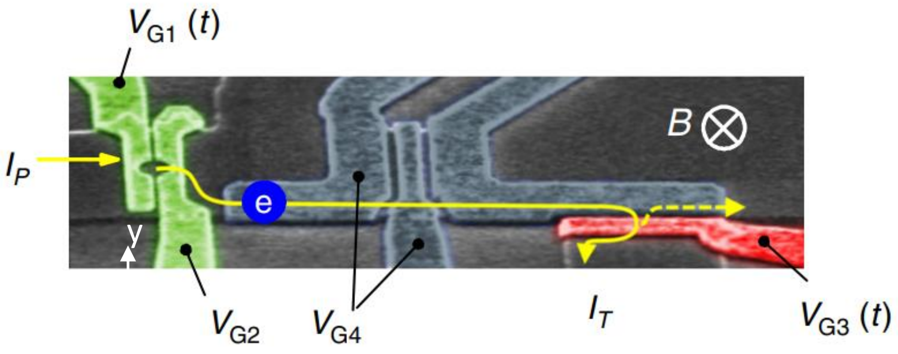
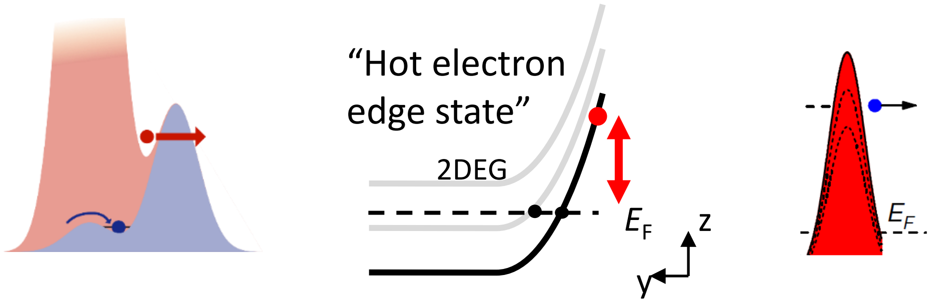
Focus here: Single-electron wave packet characterization for high energy electrons





Hot electron emission *Propagation at edge* *Energy filtering*

- On-demand electron pumps as source for fast sensing schemes
- High energy (~100 meV) on ~picosecond time scales (~1 nanosecond repeat rate)
- 'Wigner distribution' of electron emission is a key to establish quantum-limited probe

Device technology: 2DES in GaAs/AlGaAs, mesa etch, metal top gates

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What might the Wigner distribution look like?

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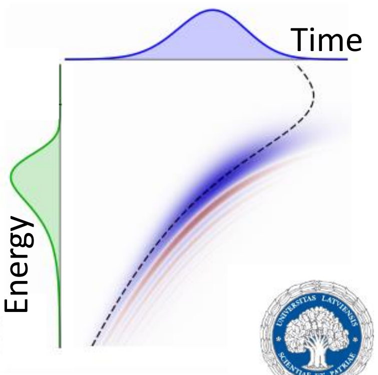
Theory

$t_0,\ \sigma_t$

$E_0,\ \sigma_E$



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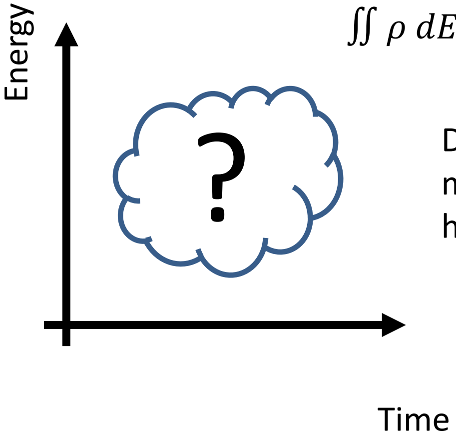
Potentially rich structure, including quantum effects …
depends on electron ejection parameters

Kashcheyevs and Samuelsson PRB (2016)

Experiment



$\iint \rho \, dEdt = 1$ [electron/cycle]

DC metrology can measure charge…but how is it distributed?

Experimental effects: Noise, jitter, charge fluctuations, energy resolution …

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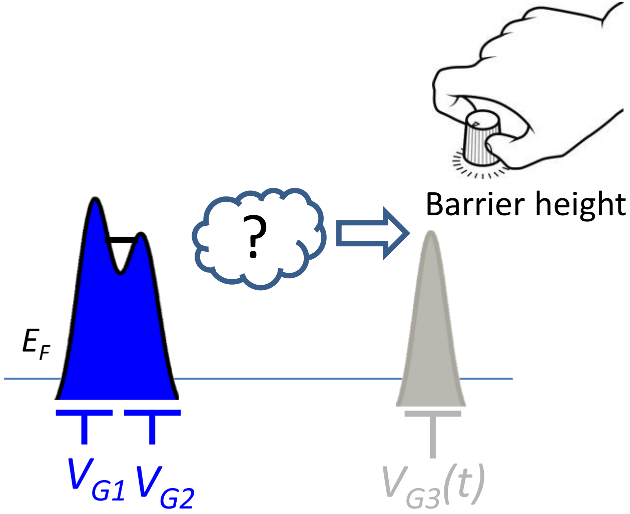
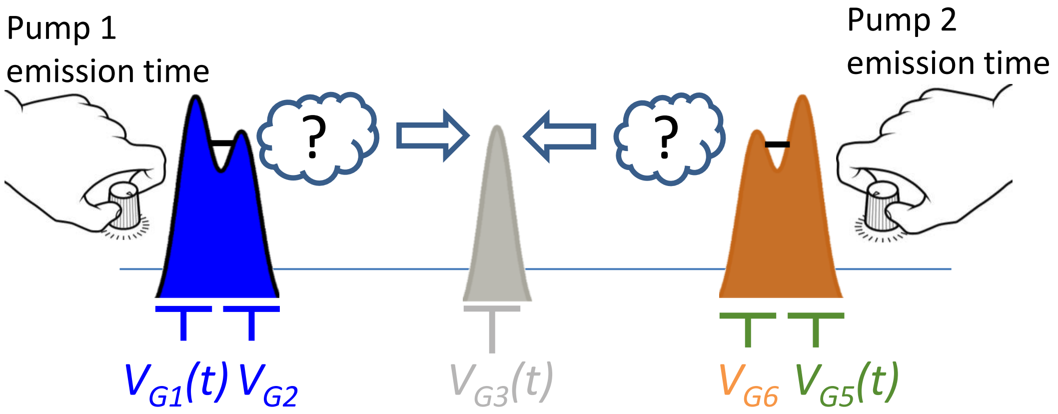
Approaches to measuring emission distributions





Approach 1:
Interaction with barrier
(Tomographic approach)

Approach 2:
Interaction between electrons
(HOM geometry…*tiny fermion collider*)

Examples: Helium atoms Kurtseifer *et al. Nature* (1997)
'Leviton' excitations, Jullien *et al. Nature* (2014)

Examples: Hong, Ou & Mandel PRL (1987)
Bellantani et al. PRB 99, 245415 (2019)

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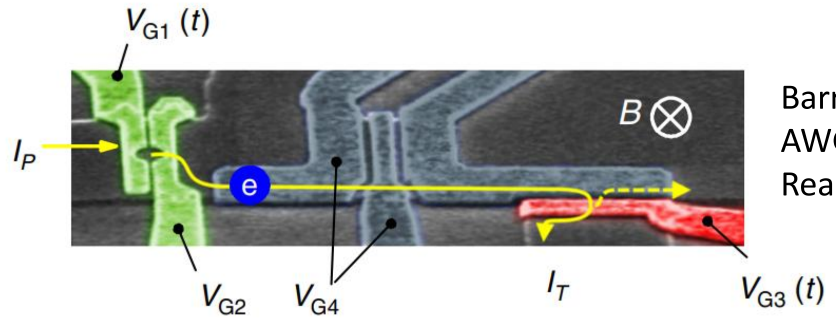
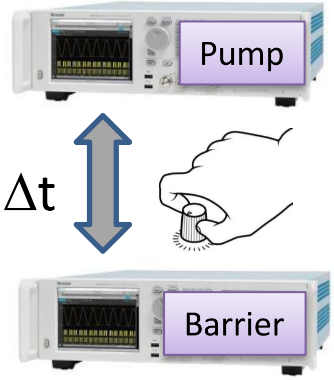
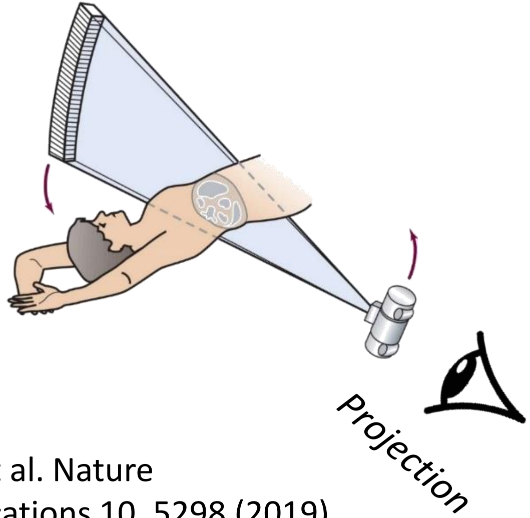
Approach 1: Tomography

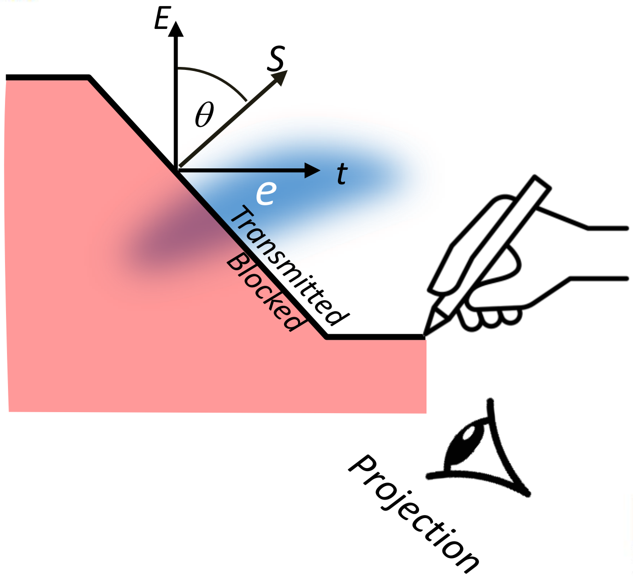


Barrier height verses time (set by AWG) defines ‘projection’
Readout: $I_T(S, \theta)$



~Picosecond synchronised 50 GS/s **arbitrary waveforms** (~15 GHz BW)





Fletcher et al. Nature Communications 10, 5298 (2019)

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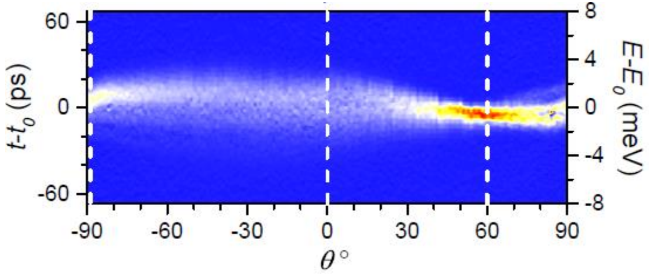
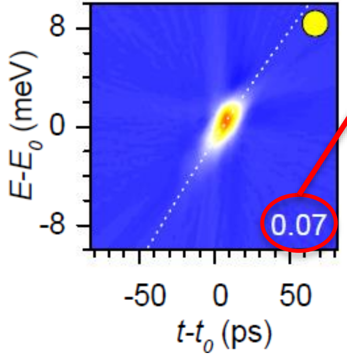
Approach 1: Tomography Results

Projections 'Sinogram'



Inverse radon transform

Backprojection



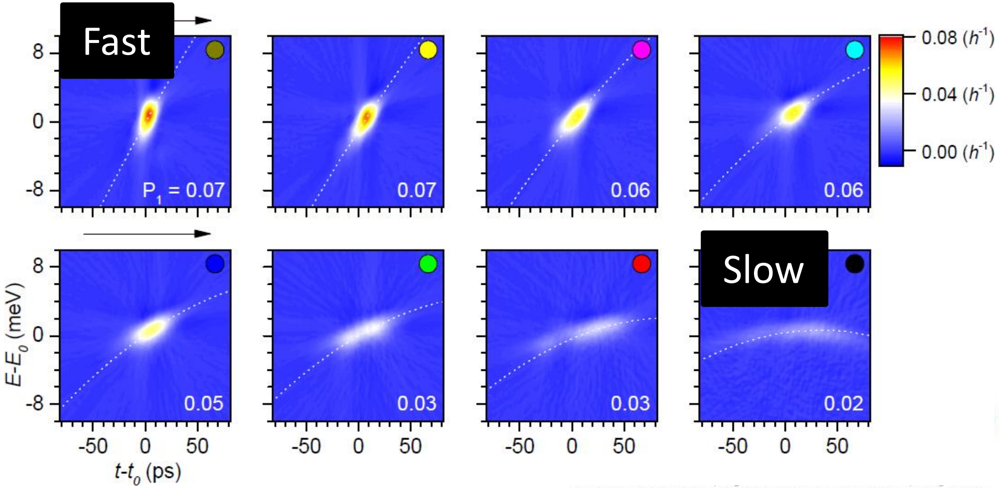
'Purity' is lower than expected

Cycle-to-cycle jitter?

Wave packet control

- Time of emission
- Energy of emission
- Speed of emission (sets 'chirp angle')

→ Helps to understand resolution limits of single-electron-based techniques



Fletcher et al. Nature Communications 10, 5298 (2019)

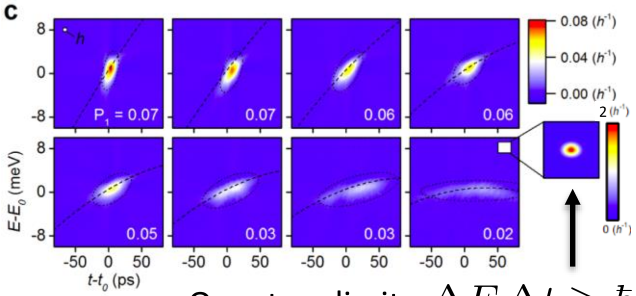
Interlude:
Quantum limits of single-electronics

- Single-electron energy-time `wavelet`
  = phase-space Wigner representation of quantum density matrix

- Quantum theory for dynamical scattering
  - Quantifies tomography resolution limits
  - Non-local point-spread-function for signal sampling
  - Connection to mesoscopic physics

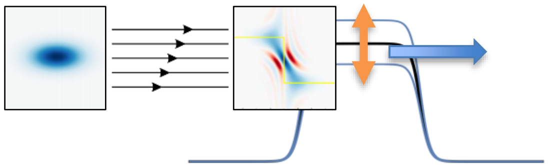
- Optimizing towards the quantum limit:
  - Unlock coherence for interferometry
  - Access `natural orbitals` a.k.a.
    `atoms of quantum information`

Roussel *et al.*, PRX Quantum **2**, 020314 (2021)

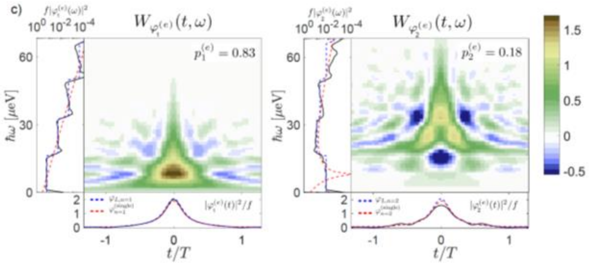


Quantum limit: $\Delta E\,\Delta t \geq \hbar/2$

Fletcher *et al.*, Nat. Comm **10**, 5298 (2019)



Locane *et al.*, New J. Phys. **10**, 3379 (2019)



Bisogni *et al.*, Nat. Comm. **10**, 3379 (2019)

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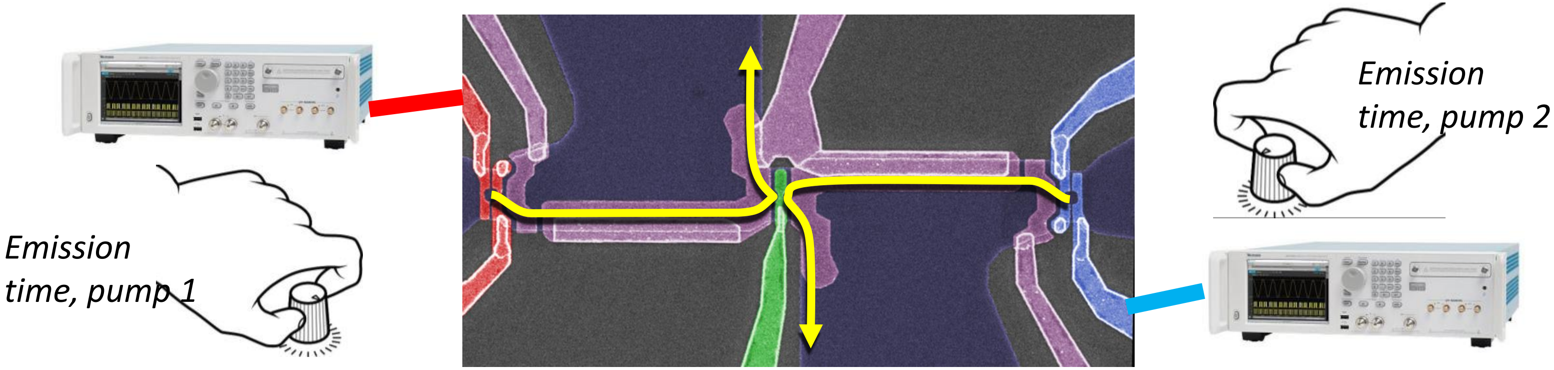
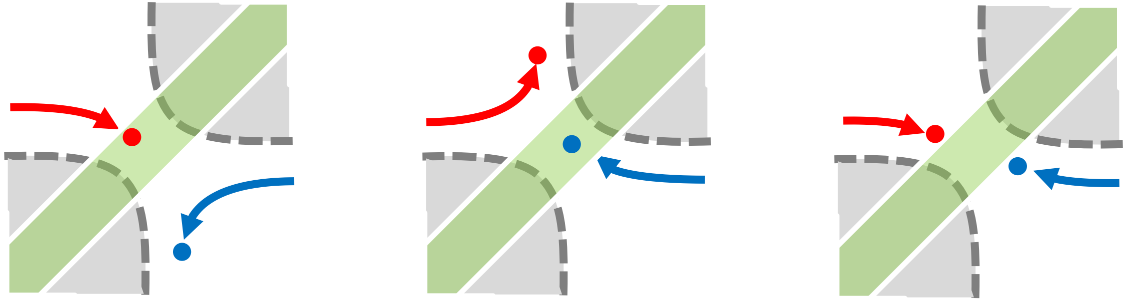
Approach 2: Interaction effects



Tune MEAN time of arrival difference and use electrical readout (current, shot noise) to see interactions.



Electron 1 first   Electron 2 first   Arrival at the same time

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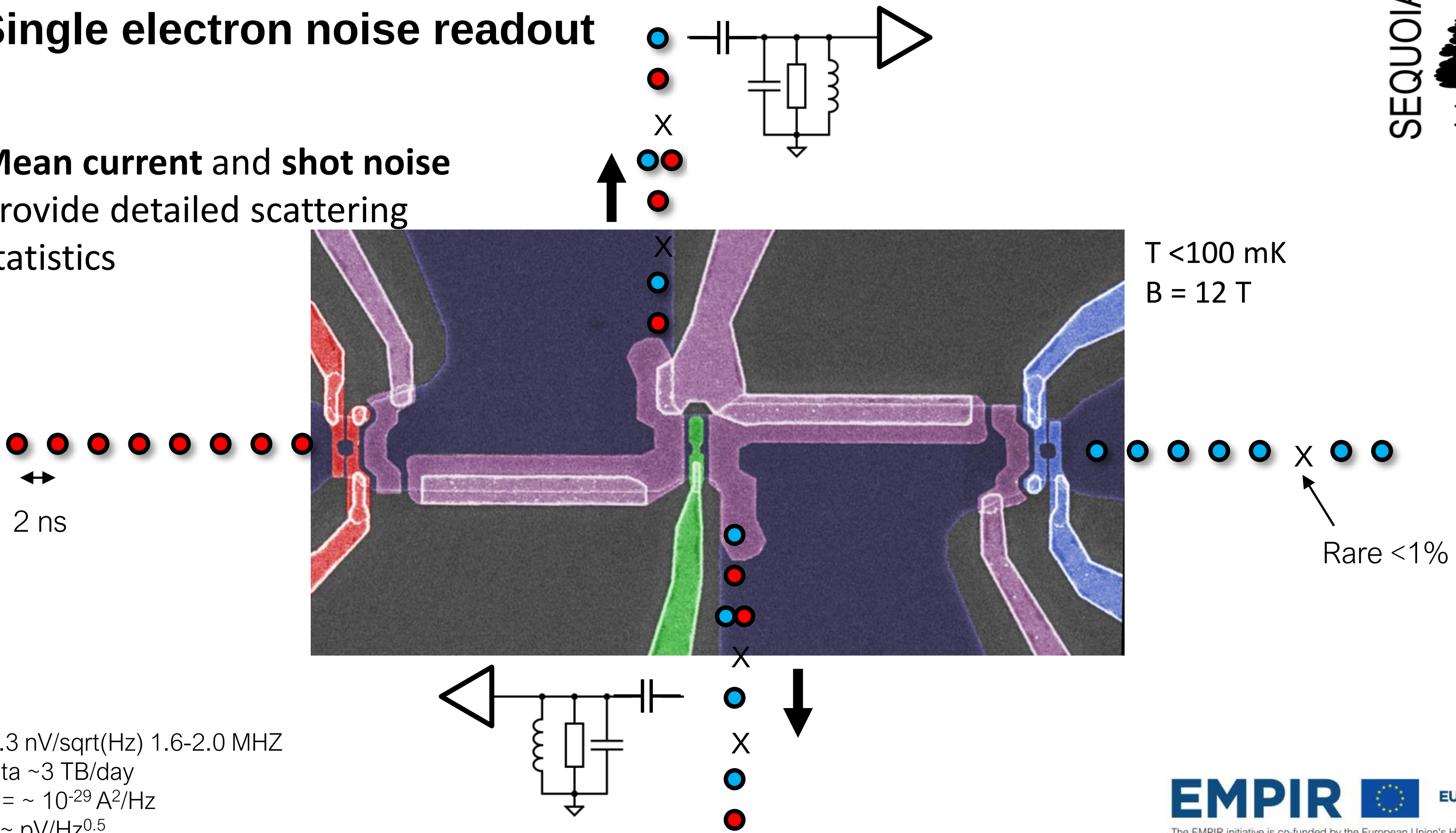
Single electron noise readout

Mean current and **shot noise** provide detailed scattering statistics



<0.3 nV/sqrt(Hz) 1.6-2.0 MHZ
Data ~3 TB/day
S_T = ~ 10^{-29} A^2/Hz
S_V ~ pV/$Hz^{0.5}$

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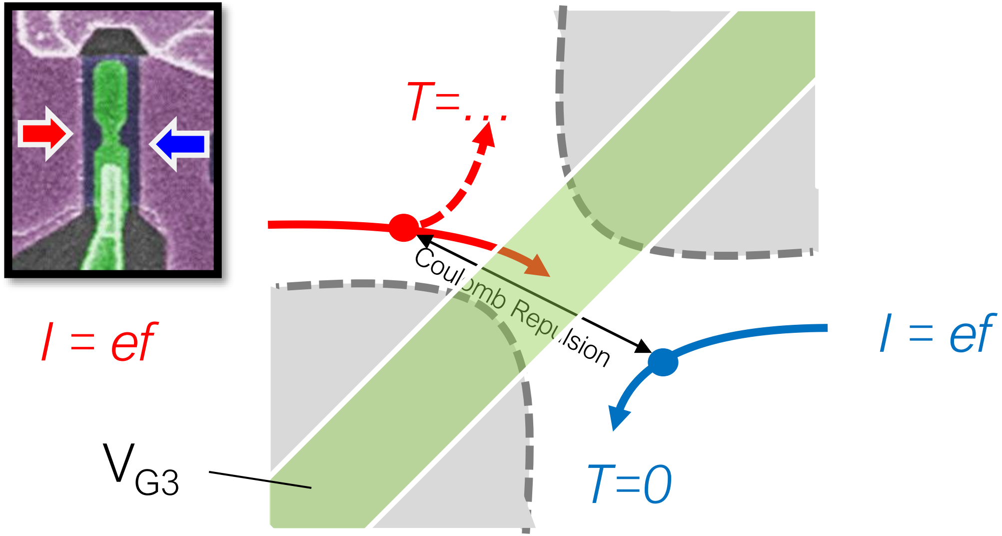
Approach 2: Interaction effects



Access emission distribution via ***interaction between pairs of single electrons.***

Examine: Coulomb interaction versus quantum/exchange statistics.

Fletcher *et al.* in preparation

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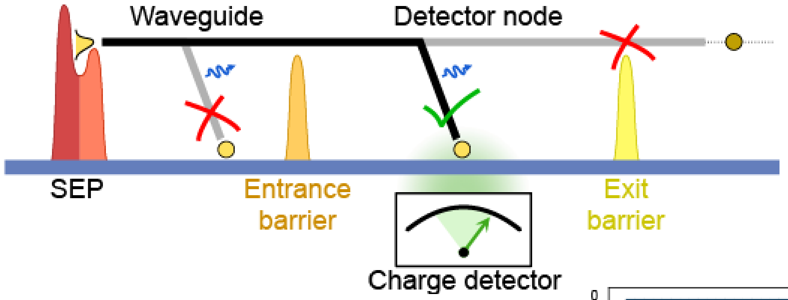
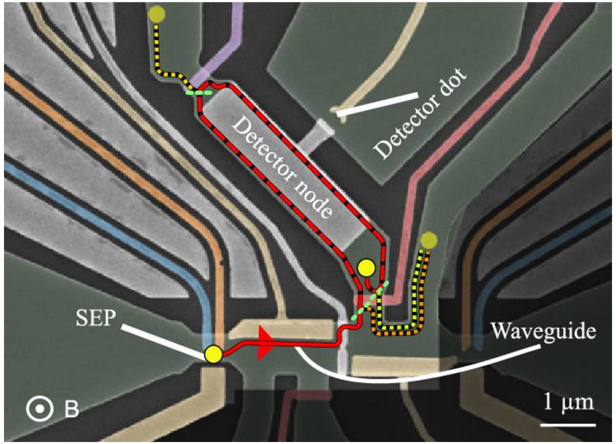
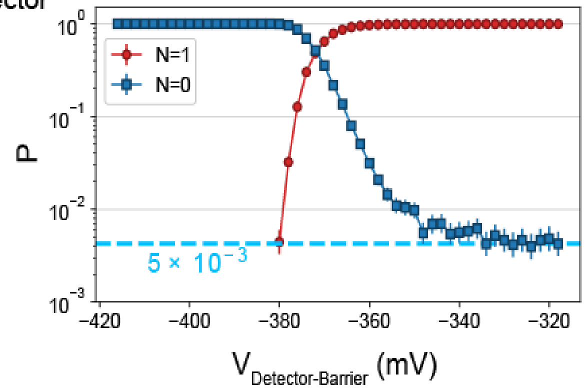
Interlude 2:
Electron Quantum Optics with single charge resolution

- Utilize on-demand generation, controlled propagation, capture and detection of single-electron wave packets
- Circuit components :
  - Waveguide transmitting wave packets ballistically without energy loss
  - Trapping of electrons on detector node by **controlled energy relaxation**
  - Read out of detector charge with single electron resolution
- Electrons trapped and detected with high fidelity (η=0.996)
- Time and energy selective single-charge readout







Freise et al , Phys. Rev. Lett. 124, 127701

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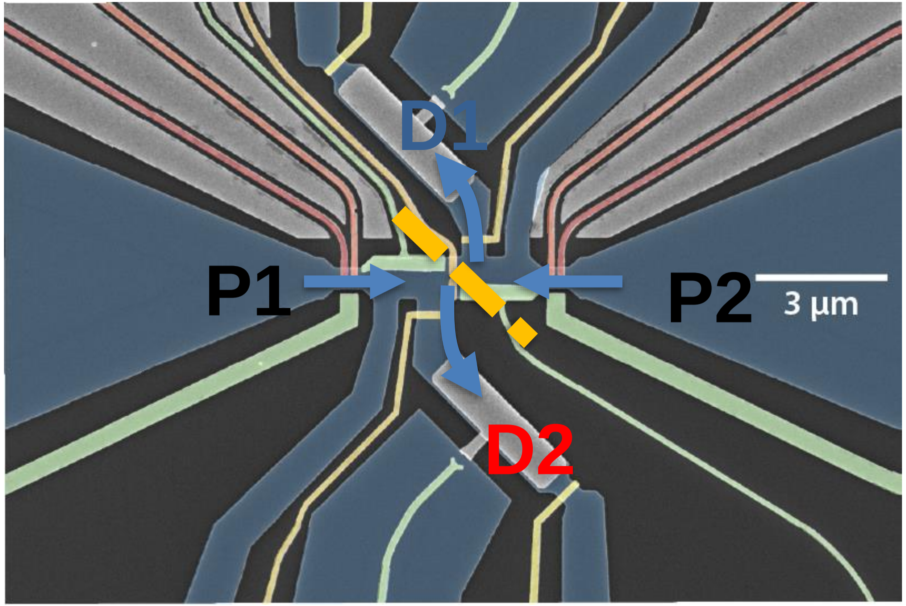
Approach 2: Interaction effects
with single-electron wave packet detection



Ubbelohde *et al.* in preparation

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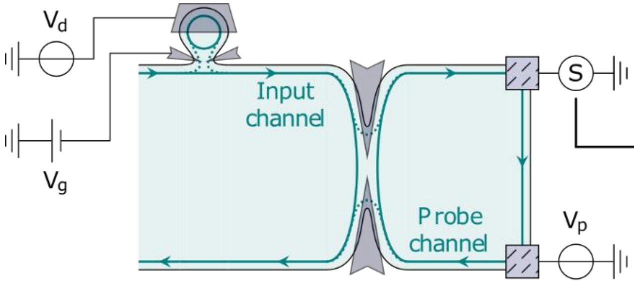
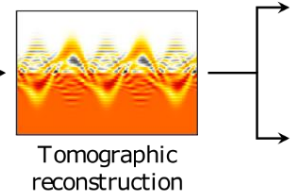
Signal processing of quantum electrical currents

Development of toolbox for processing, analyzing and representing the quantum information embedded in quantum electrical currents.

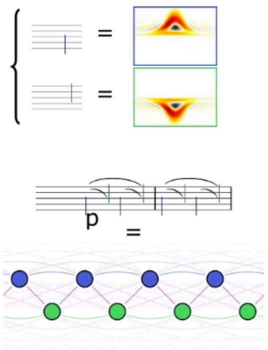
Using a general algorithm, the single particle wavefunctions present within a time-periodic quantum electrical current, their emission probabilities and mutual coherences are extracted.



Hong-Ou-Mandel setup extracts single electron coherence from noise measurements



Reconstructed single electron coherence (Wigner representation)



Signal processing extracts the electronic wavefunctions and their emission probability for each period and arrange them in a ‘quantum coherence score’

B Roussel, C Cabart, G Fève, P Degiovanni, PRX Quantum 2, 020314 (2021)

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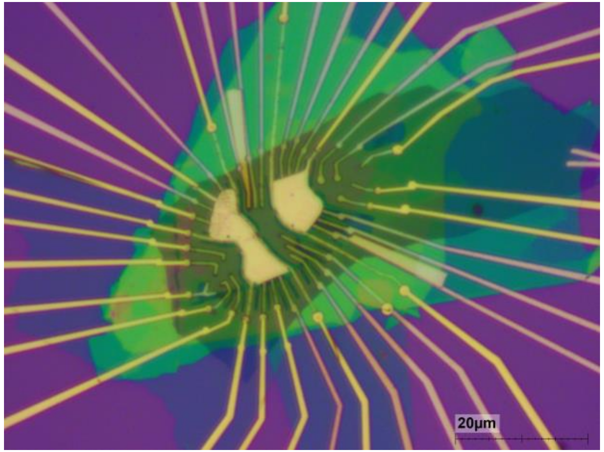
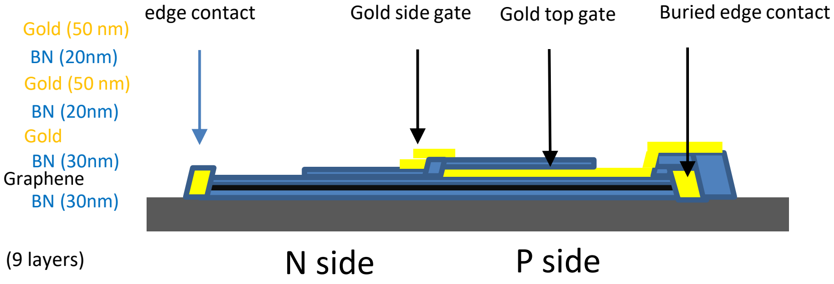
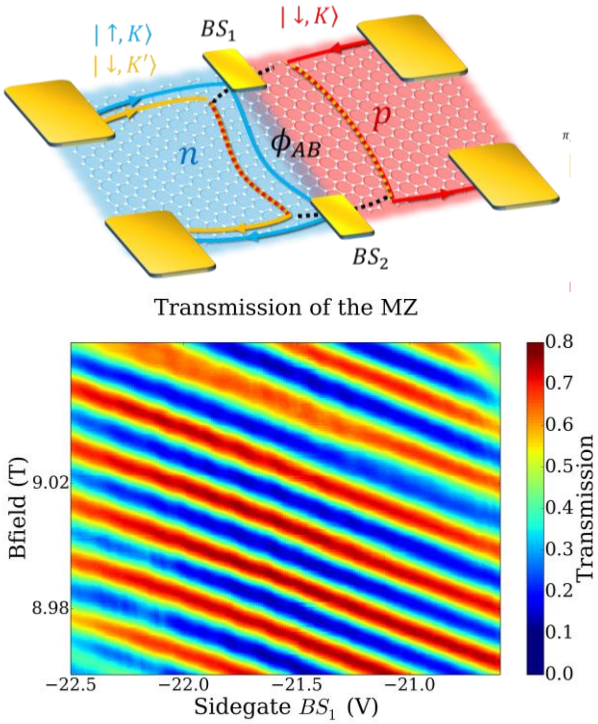
Interference:
Electron optics in graphene: p-n junction interferometer







$T_{BS_1} = 1/2$

$T_{BS_2} = 1/2$

Record visibility of 87 %

M. Jo et al. Phys. Rev. Lett. **126**, 146803 (2021)

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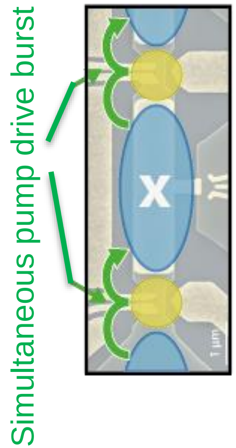
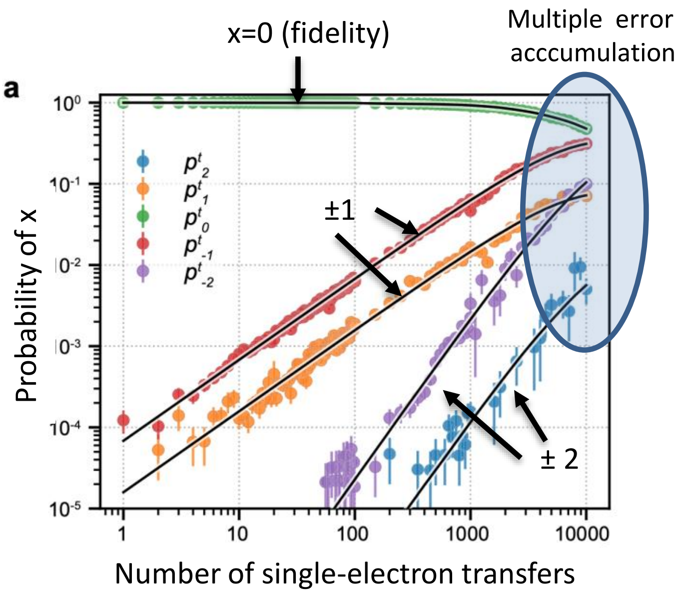
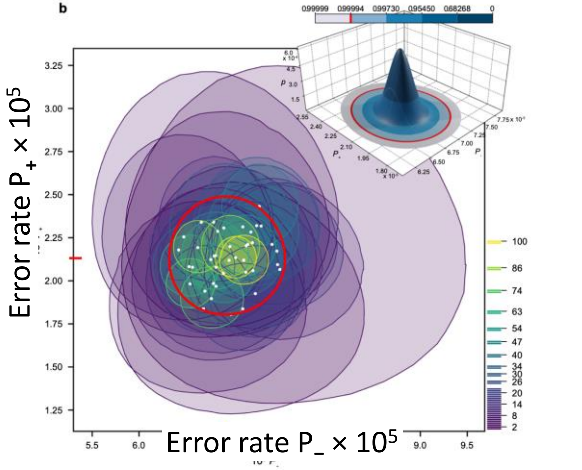
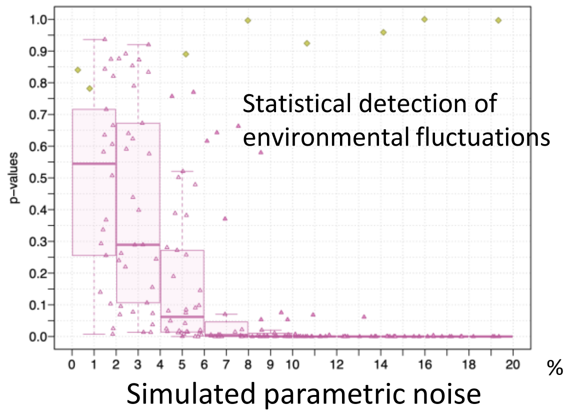
Offspring: **Random-walk benchmarking of single-electron circuits**

Mesured excess charge x=0, ±1, ±2,…









- **Consistency tests** for independent error accumulation
- Accurate single-step **error rate estimation**
- Detection and quantification of **correlated excess noise**

Physikalisch-Technische Bundesanstalt Braunschweig und Berlin

UNIVERSITY OF LATVIA

Reifert, Kokainis, Ambainis, Kashcheyevs, Ubbelohde, Nature Communications **12**, 285 (2021)

Summary

- Establishing techniques for a quantum metrology for and with single-electron wave packets for quantum physics and technologies
  - Tomography
  - Collision experiments
  - Detection of single ballistic electrons
  - Quantum limits of single-electronics
- Good progress towards sensing with single electrons
- Transfer of SEQUOIA single-electron control and detection techniques

<u>Slides collected from:</u>
Jonathan Fletcher (NLP), Slava Kashcheyevs (LatU), Niels Ubbelohde (PTB), Gwendal Feve (CNRS), Masaya Kataoka (NPL), Preden Roulleau (CEA)

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