Time-resolved sensing of electromagnetic fields with single electron interferometry

Gerbold Ménard

Superconducting Devices for Quantum Optics and Quantum Simulations

7th October 2025 - Trento

Research team

Y. Jin et al., Marseille 25/04 (2023)

ENS Team:

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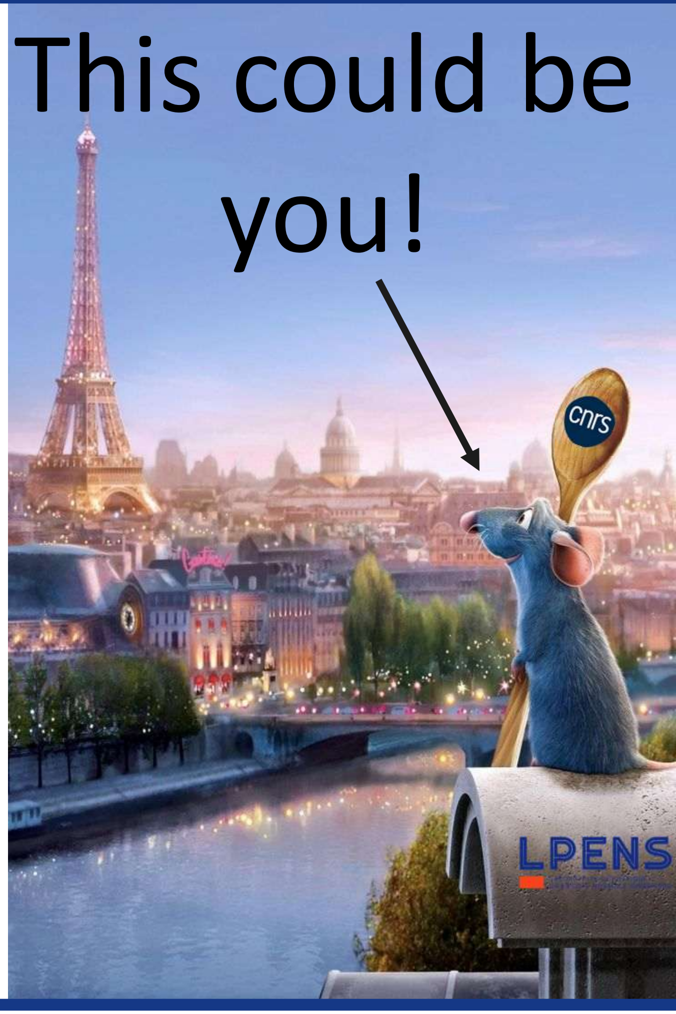
- Ines Safi

Advertisement

Open post-doc position in Paris
at LPENS !!



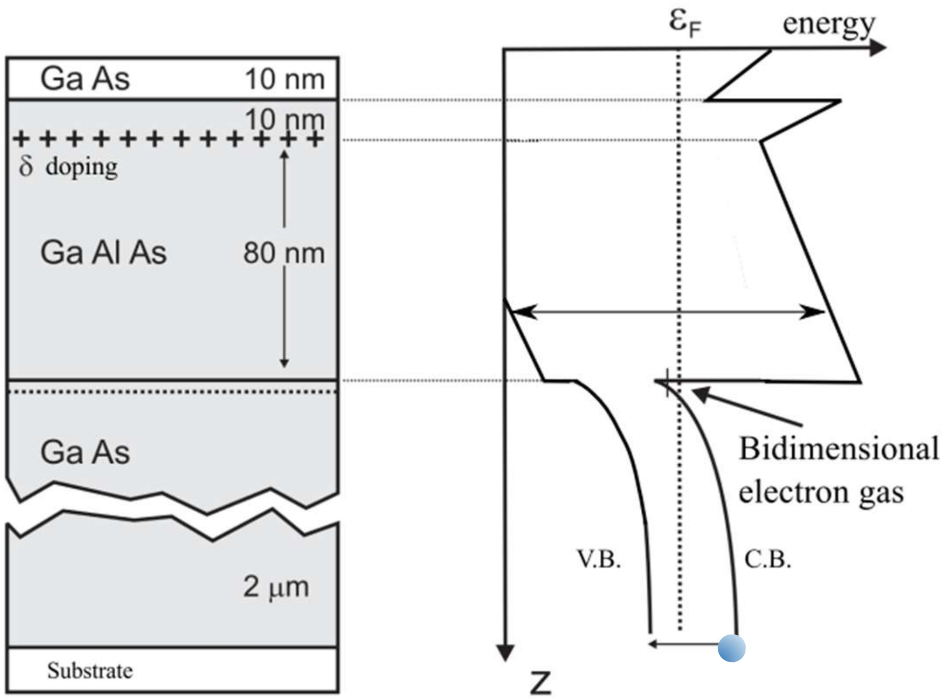
Outline:

- The quantum Hall effect
- Electron quantum optics
- Fabry-Perot interferometry

The quantum Hall effect: GaAs heterostructures

Two-dimensional electron gas in a magnetic field: quantum Hall effect

GaAs based 2D electron gas (2DEG)



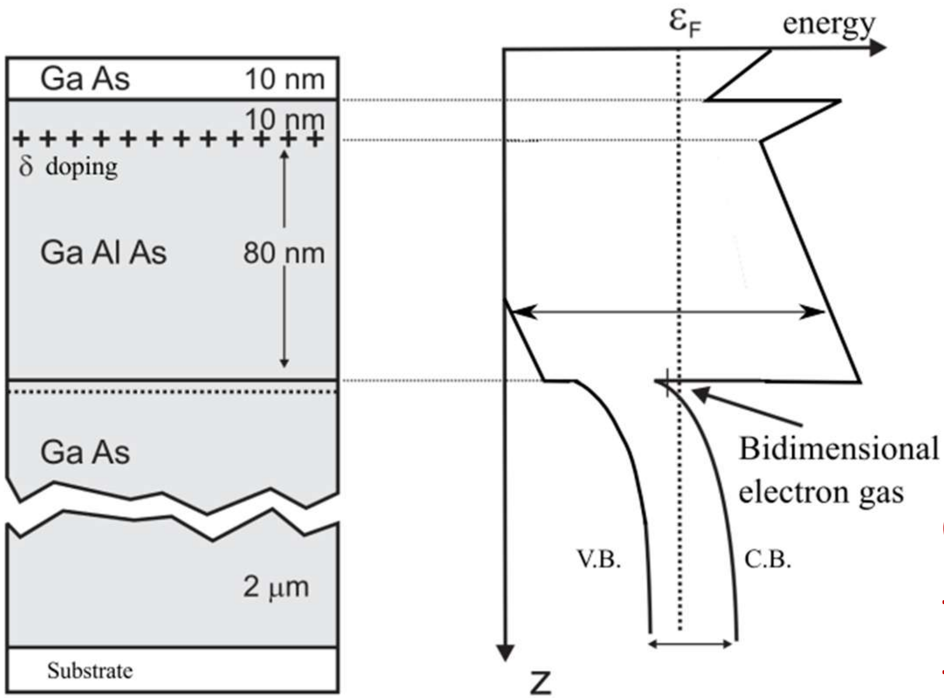
J. Gabelli, PhD thesis (2006)

Creation of a potential trap for electrons through band engineering

The quantum Hall effect: Edge states

Two-dimensional electron gas in a magnetic field: quantum Hall effect

GaAs based 2D electron gas (2DEG)



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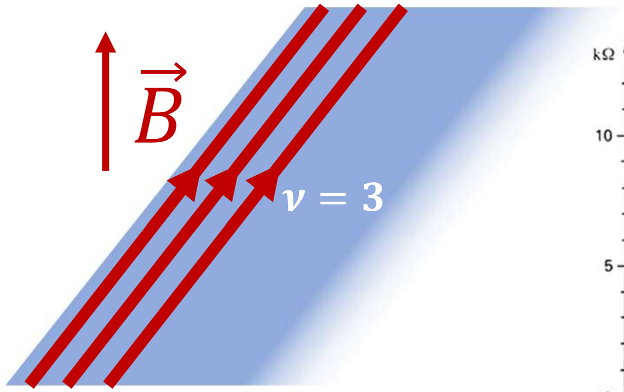
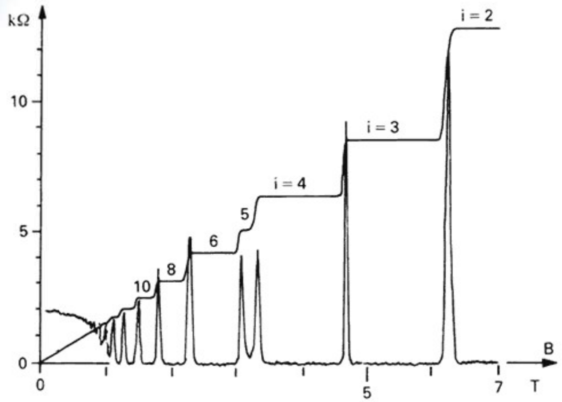




K. Von Klitzing, Rev. Mod. Phys. **58**, 519 (1986)

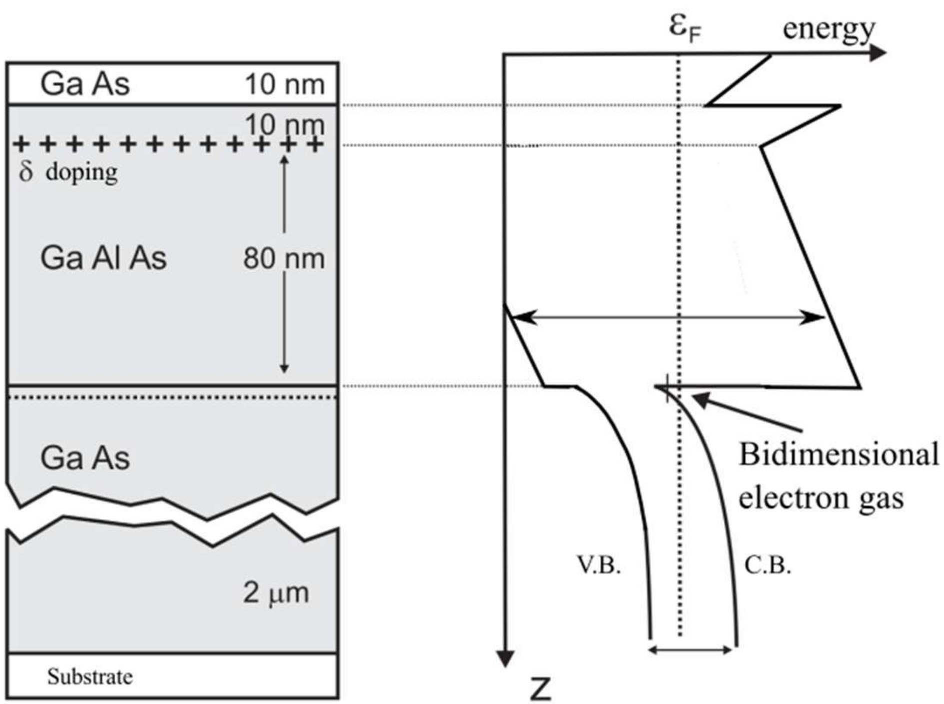
Quantum picture:

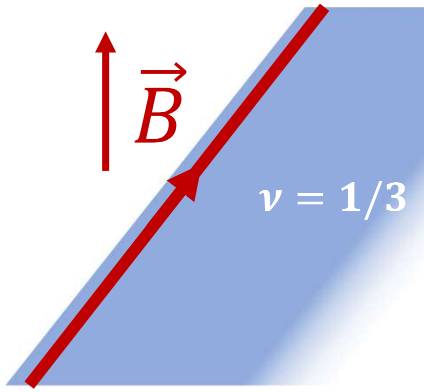
- Insulating bulk, chiral edge states
- Edge channels with quantized conductance

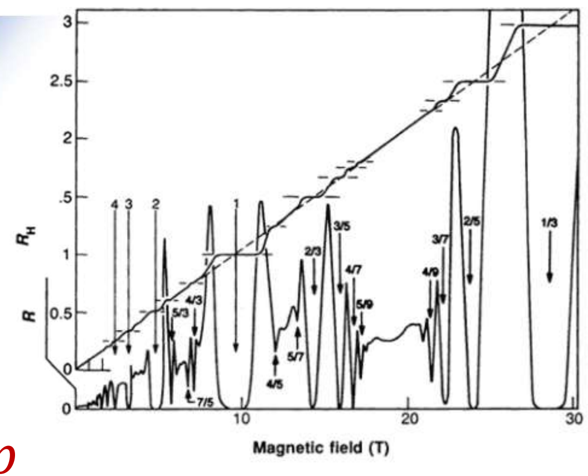
$$\rho = \nu e^2/h\,, \qquad \nu = h n_{2D}/eB \in \mathbb{N}$$

The quantum Hall effect

High purity 2DEG: fractionnal quantum Hall effect







$$\nu = \frac{p}{q}$$

Excitations have a fractionnal charge e^*

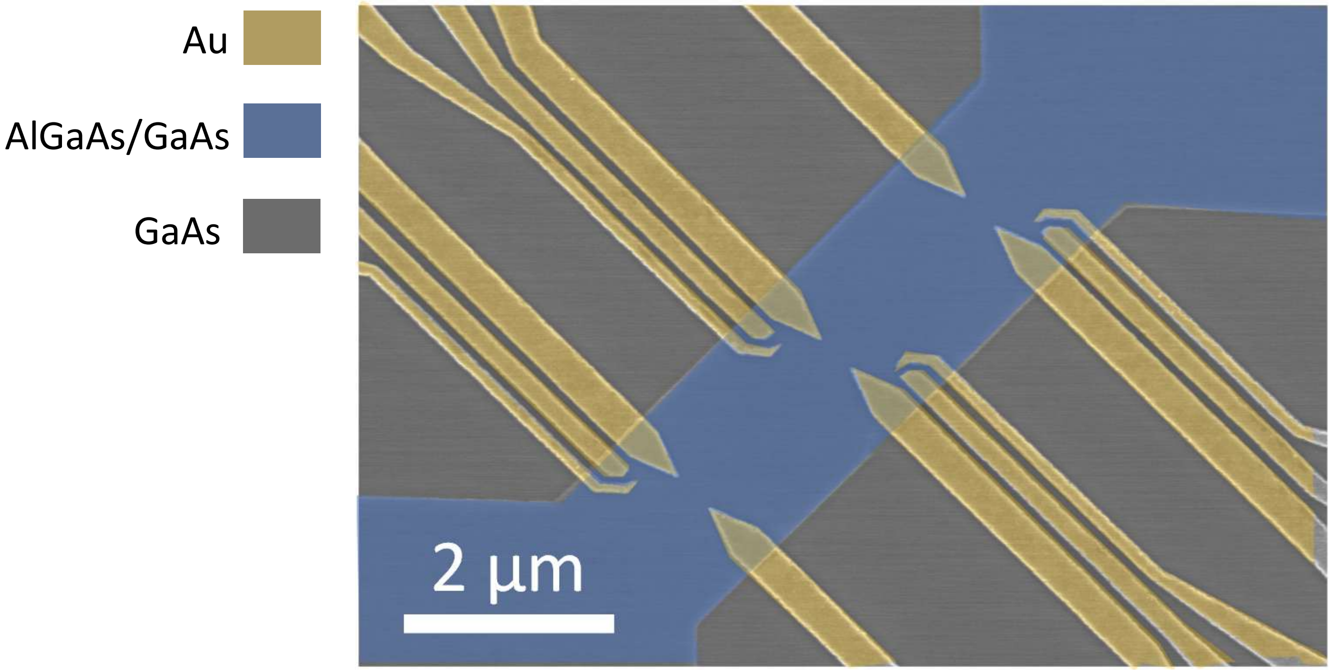
Topological properties

JP Eisenstein and HL Stormer, “The fractional quantum Hall effect,” Science 248, 1510–1516 (1990).

Sample fabrication

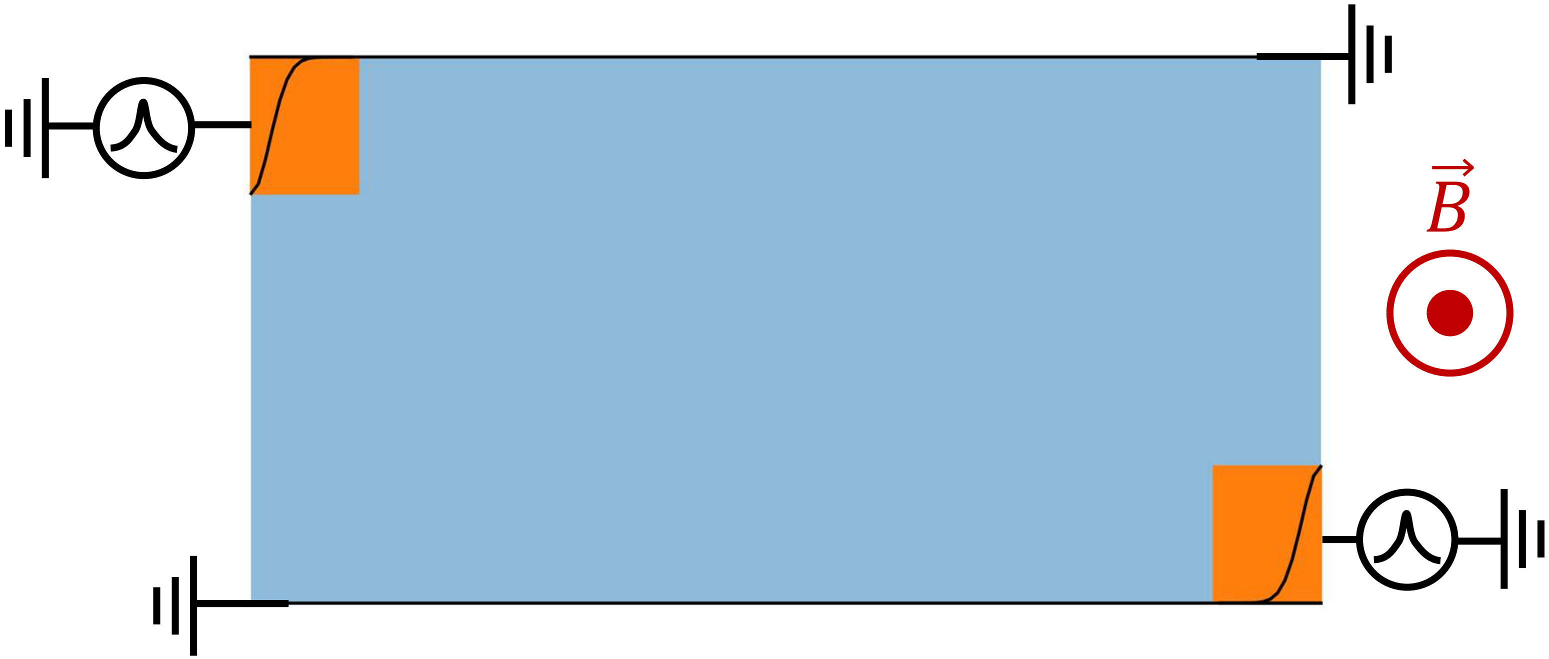
Using electronic lithography we can define gates with $\simeq$ 10 nm resolution or etch away the AlGaAs layer.

Allow for control of edge states.



Electron quantum optics

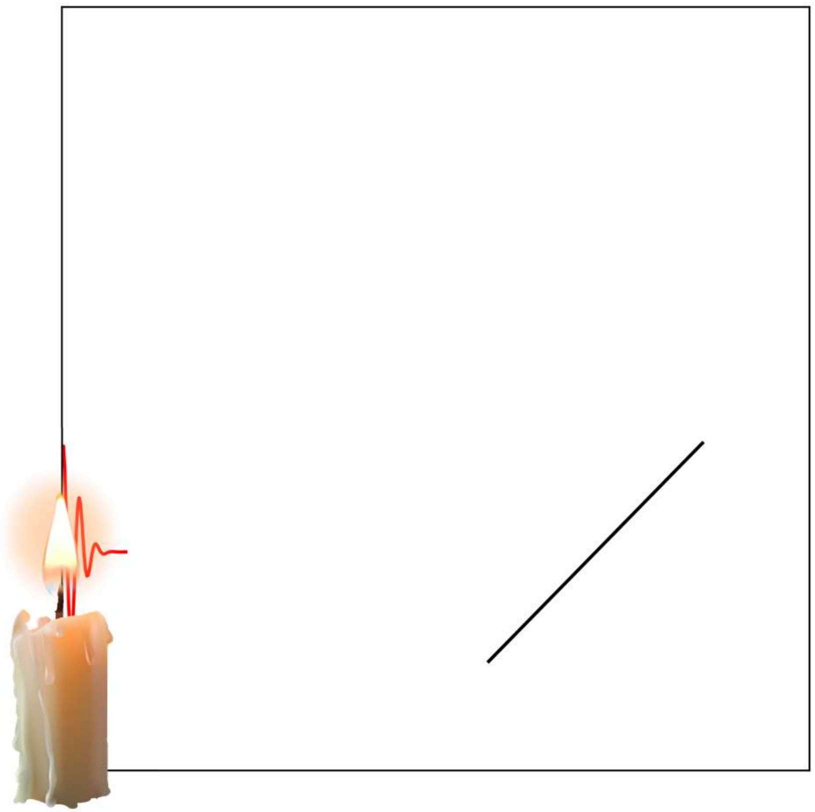
Using rf EM fields we can generate plasmonic excitations of the edges called edge magnetoplasmons (EMPs)



Electron quantum optics

In optics, a beam splitter can be realized by using a semi-transparent mirror.

Quantum optics

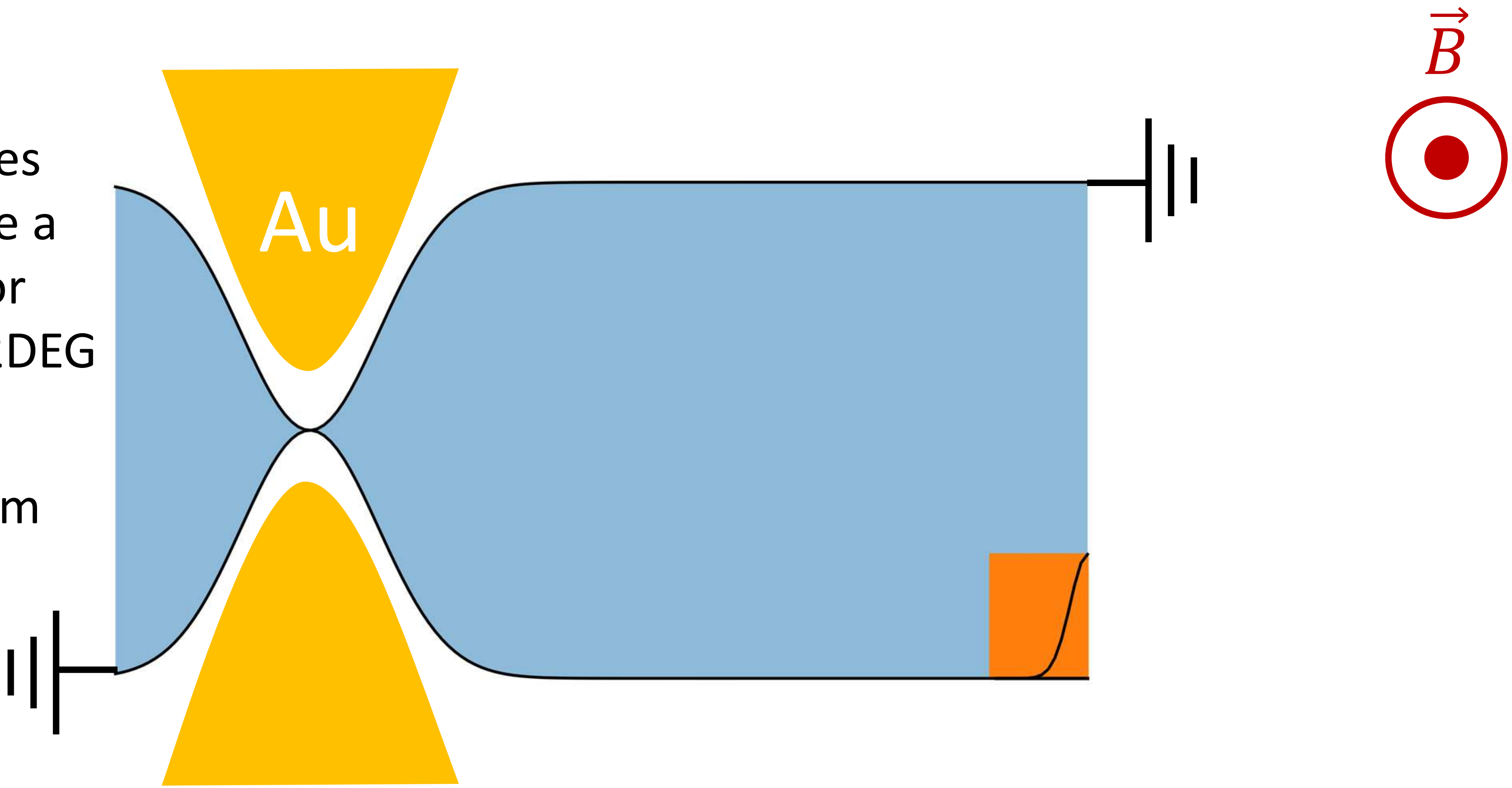


Single photon candle
(not sold at Ikea)

Electron quantum optics

Electrostatic gates allow us to realize a beam splitter for excitations of the 2DEG

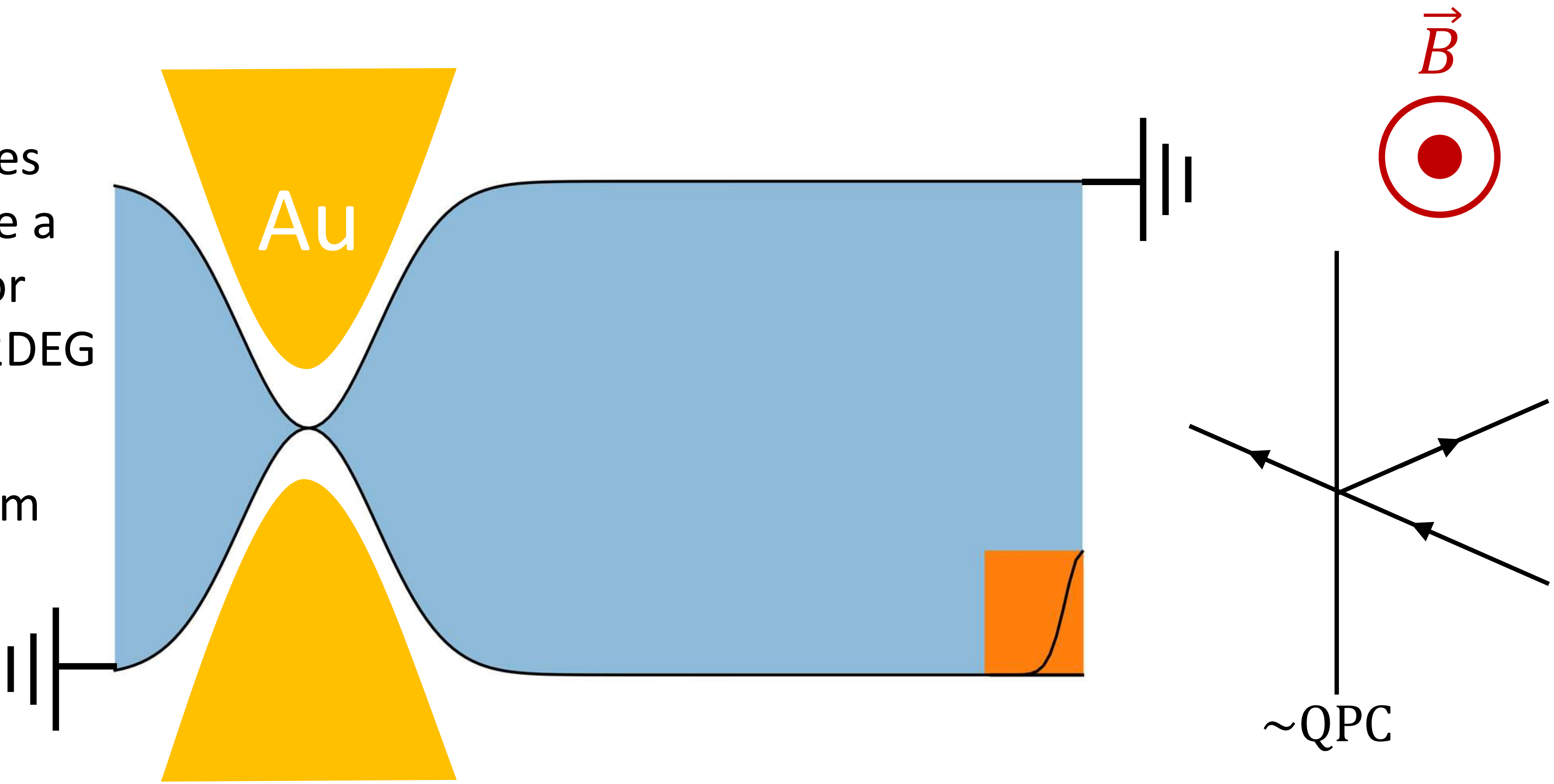
Electron quantum optics



Electron quantum optics

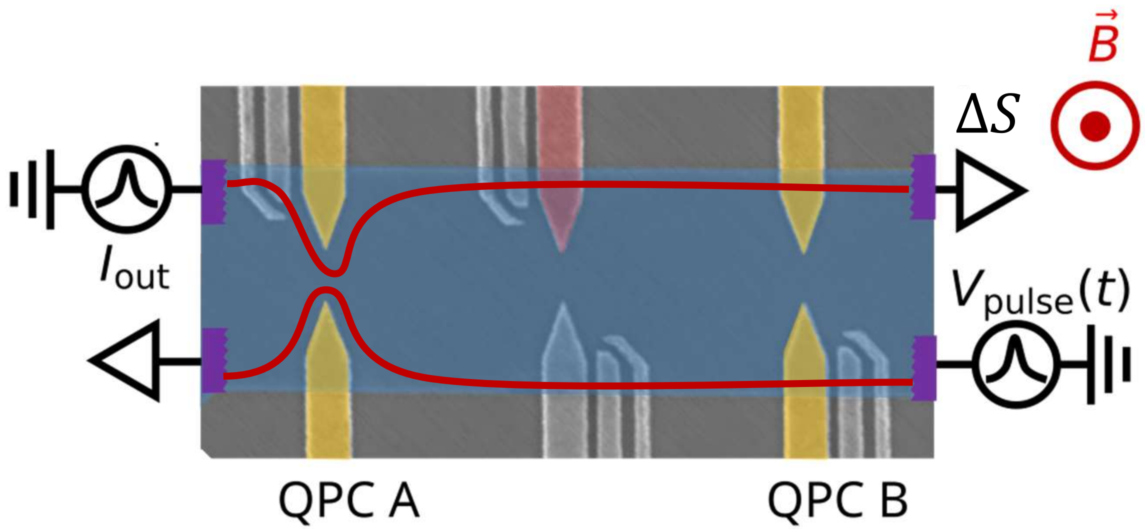
Electrostatic gates allow us to realize a beam splitter for excitations of the 2DEG

Electron quantum optics



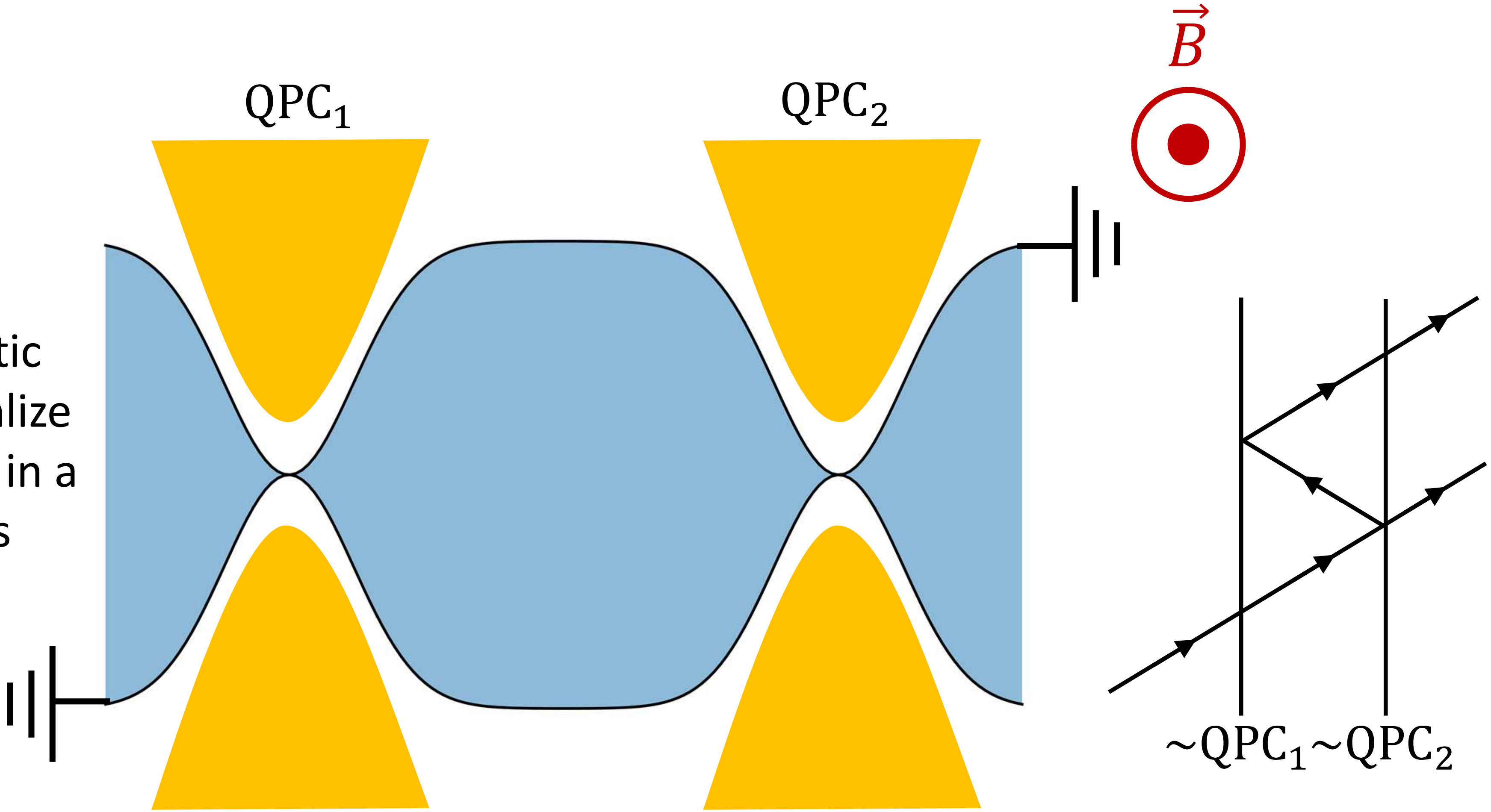
Calibration of pulse: shot noise

HOM configuration to measure shot noise & characterize Lorentzian pulse



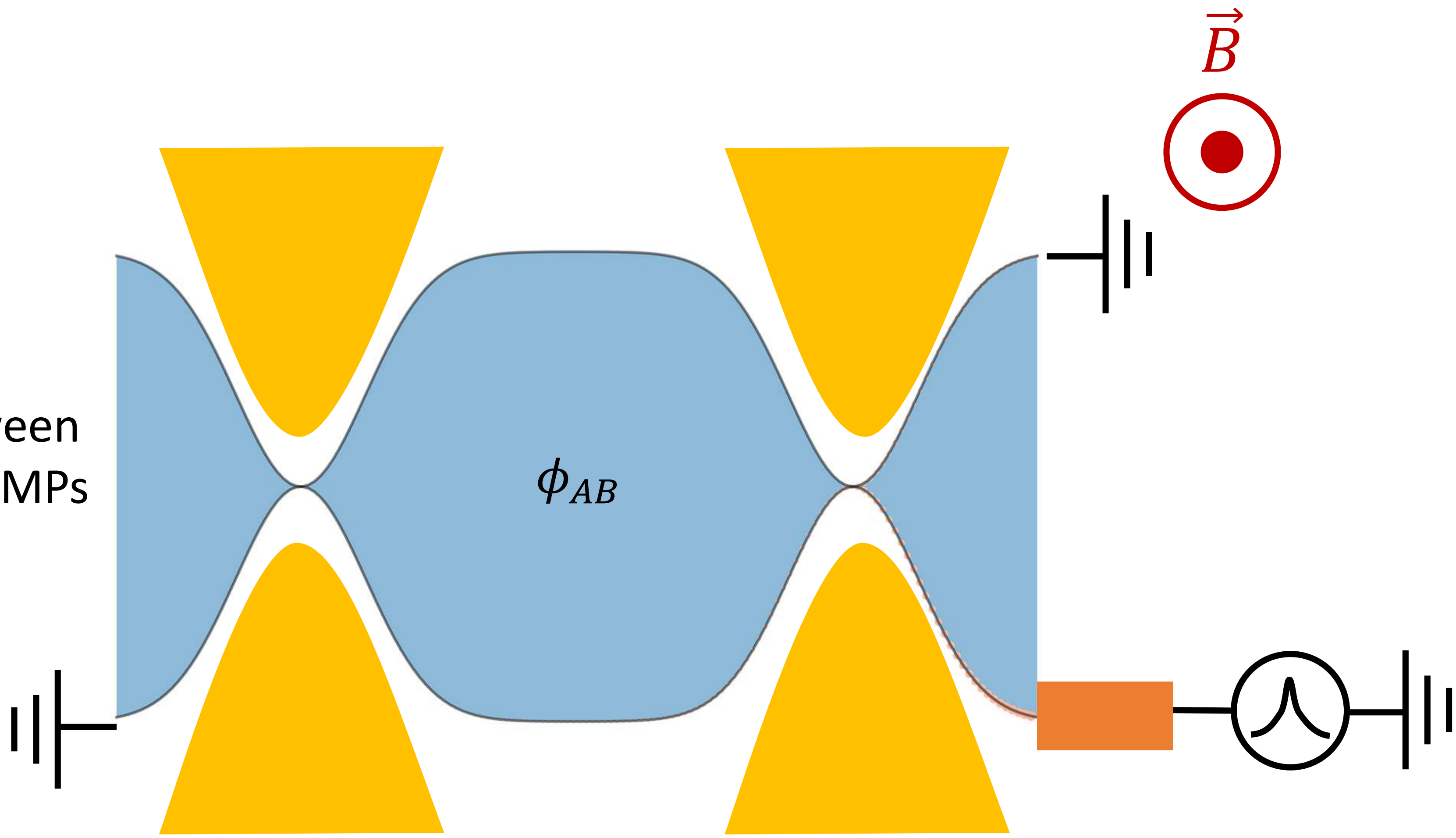
Electron quantum optics

Using electrostatic gating, we can realize an interferometer in a 2D electron gas



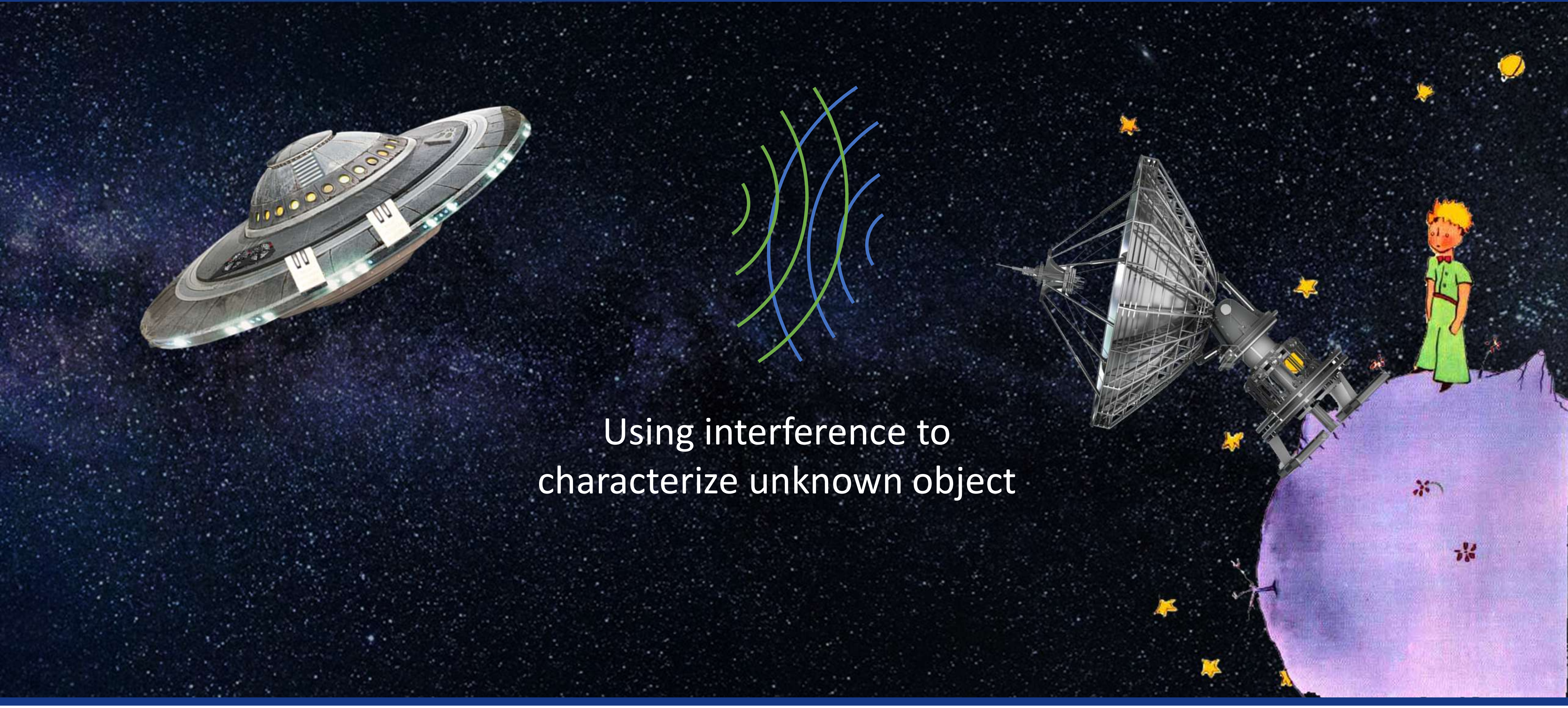
Electron quantum optics

Probing the interference between two paths of the EMPs

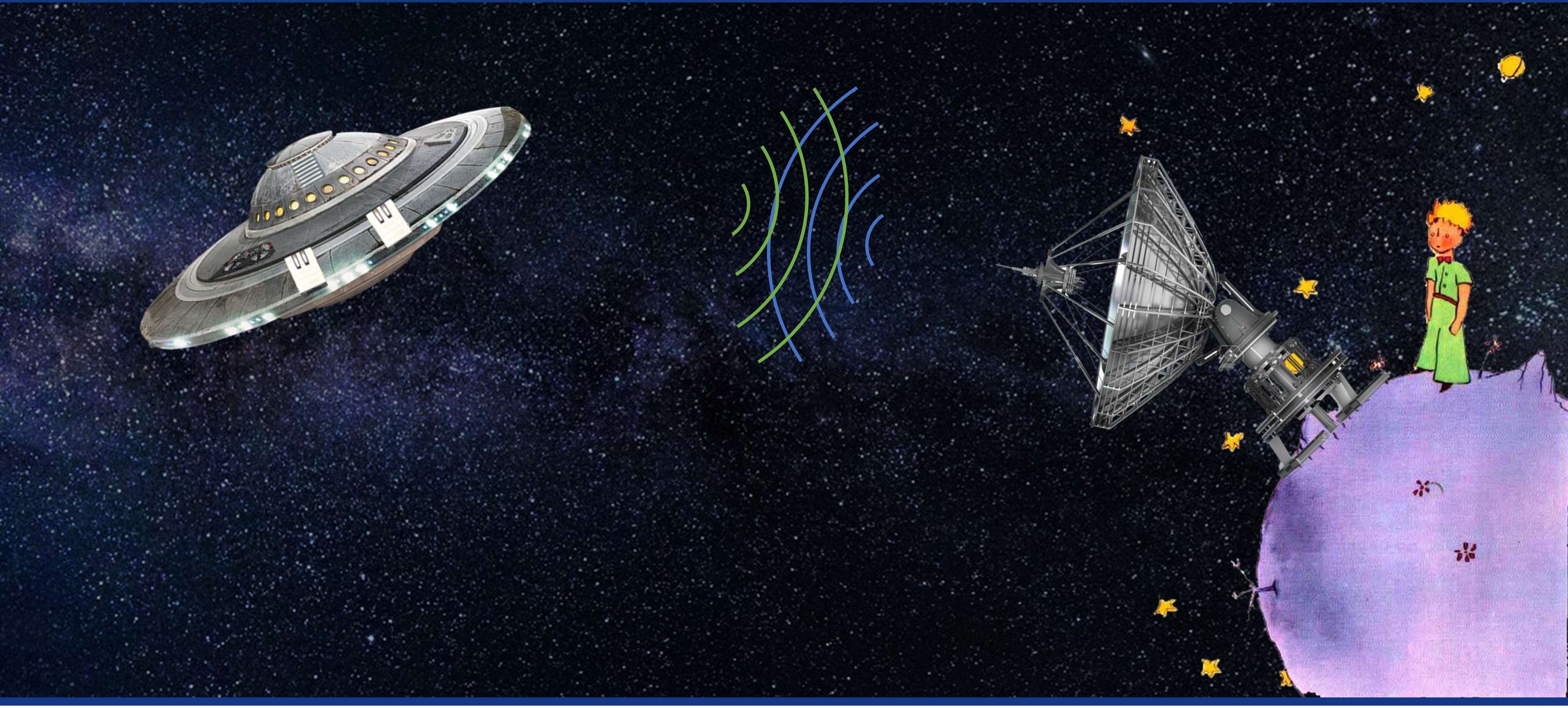


Fabry-Perot interferometry: Quantum radar

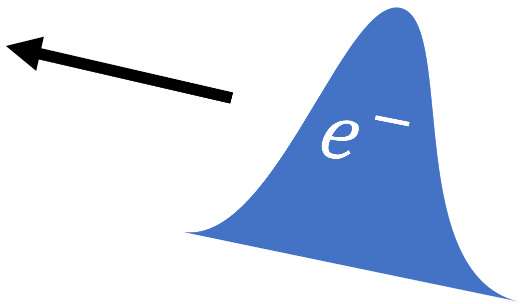
Fabry-Perot interferometry: Quantum radar



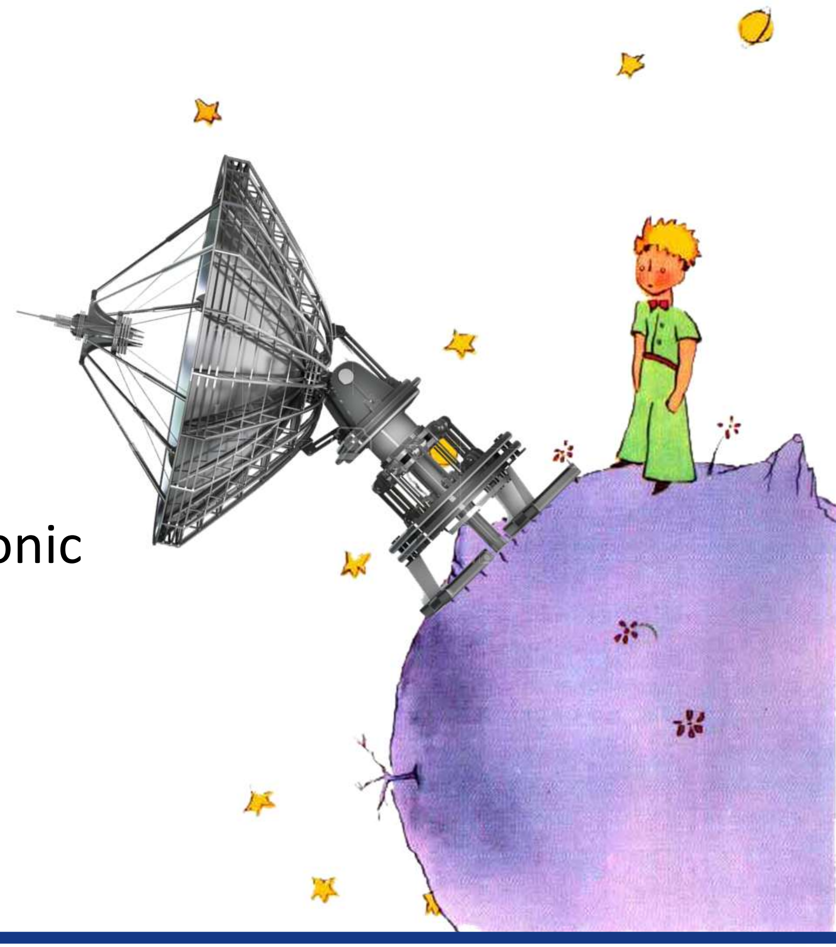
Fabry-Perot interferometry: Quantum radar



Fabry-Perot interferometry: Quantum radar

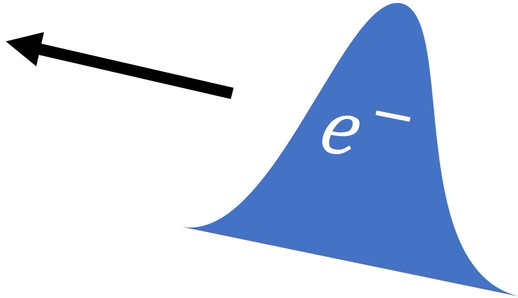


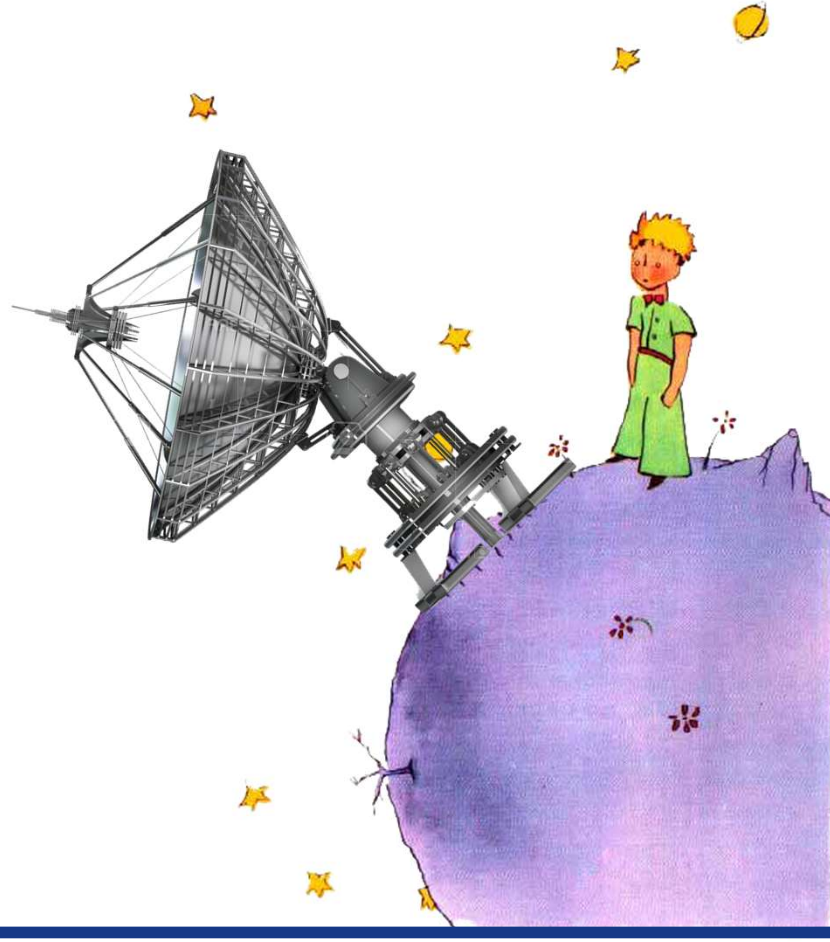
Lorentzian electronic pulse



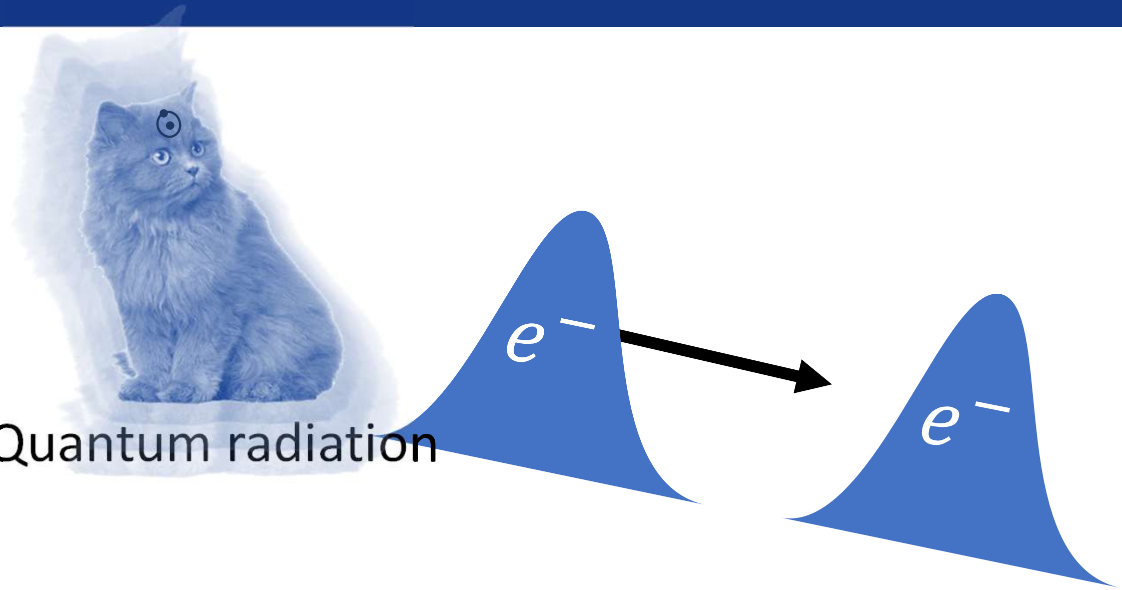
Fabry-Perot interferometry: Quantum radar

Quantum radiation

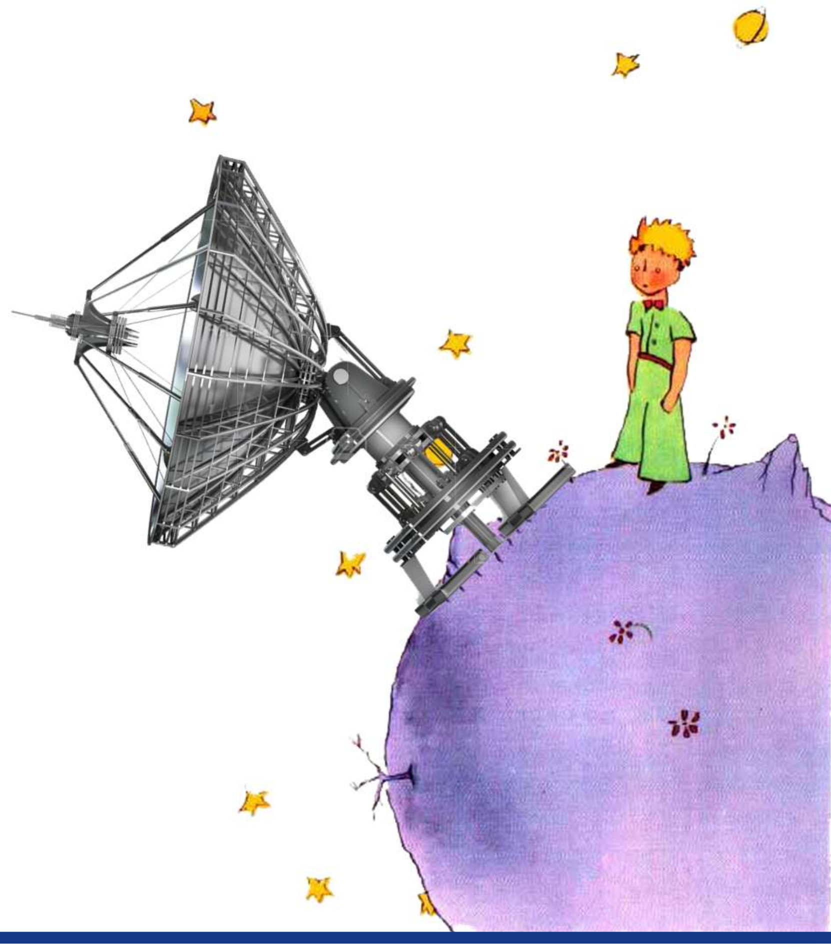




Fabry-Perot interferometry: Quantum radar

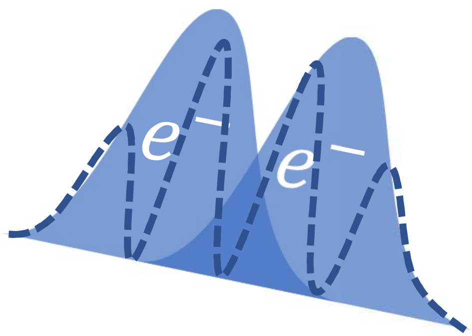


Quantum radar

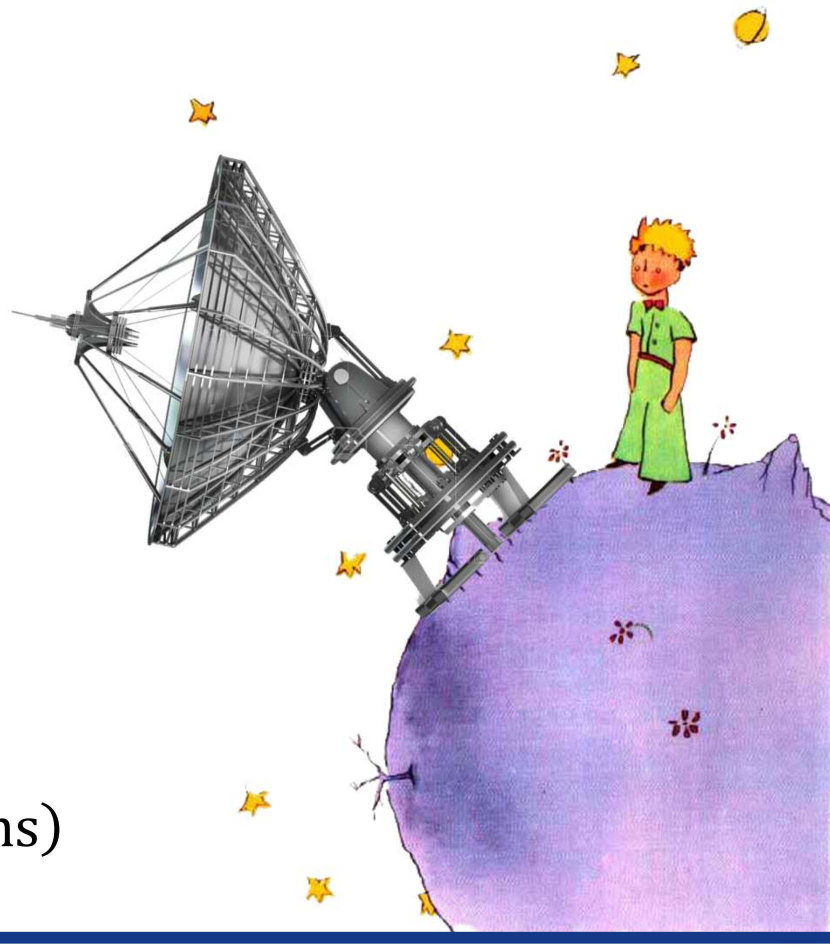


Fabry-Perot interferometry: Quantum radar

Quantum radiation



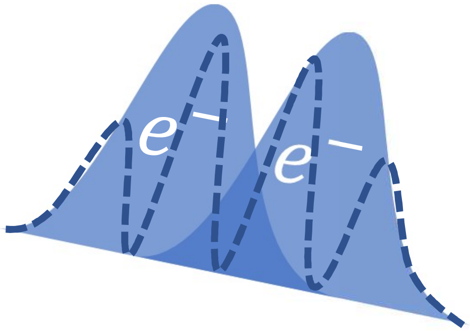
Fabry-Perot
interferometer



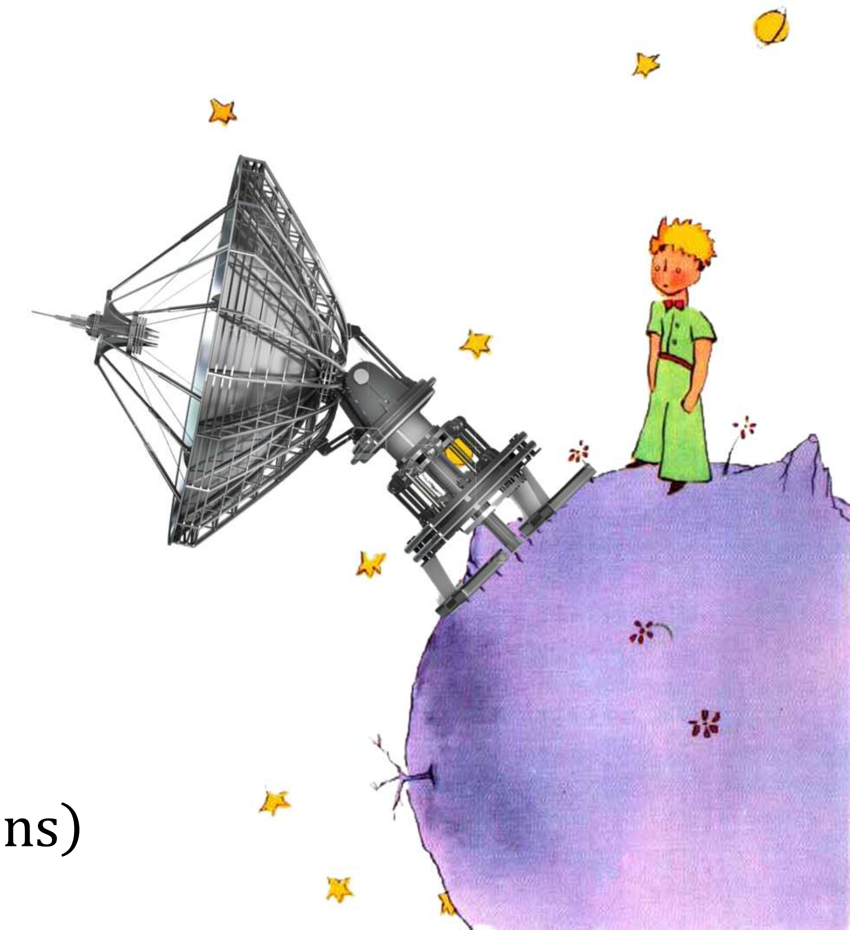
Short-time resolution (≈ 20 ps)
High sensitivity to field ($\approx 50\ \mu V \equiv 10$ photons)

Fabry-Perot interferometry: Quantum radar

Quantum radiation



Fabry-Perot interferometer

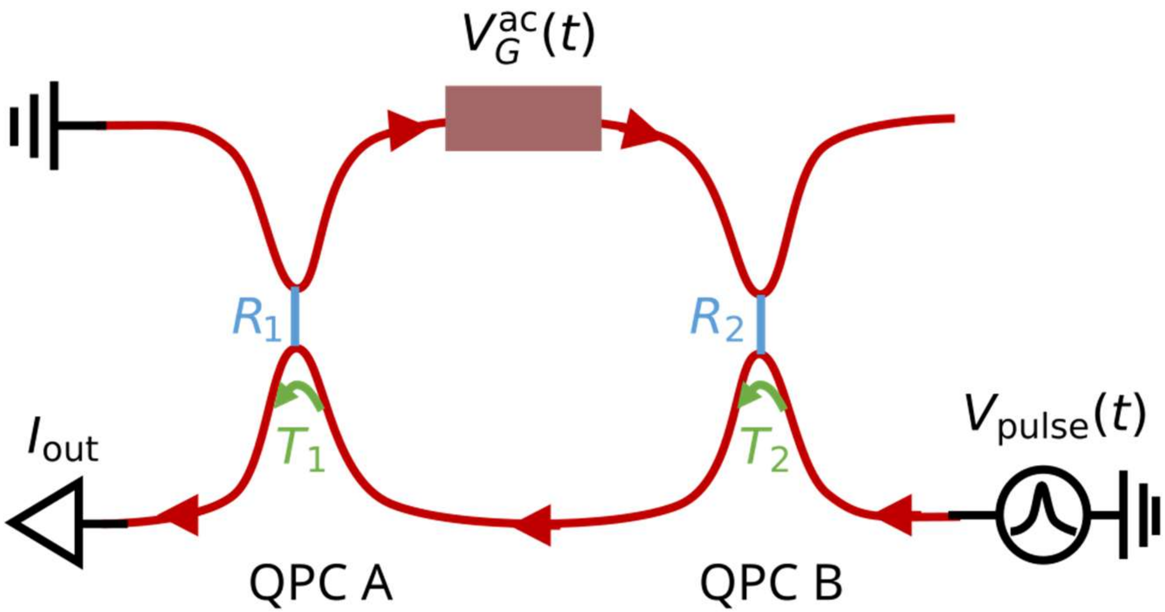


Short-time resolution (≈ 20 ps)

High sensitivity to field ($\approx 50\ \mu V \equiv 10$ photons)

Fabry-Perot interferometry

Using Lorentzian shaped pulse
to probe classical voltage $V_G^{\mathrm{ac}}(t)$



Fabry-Perot interferometry

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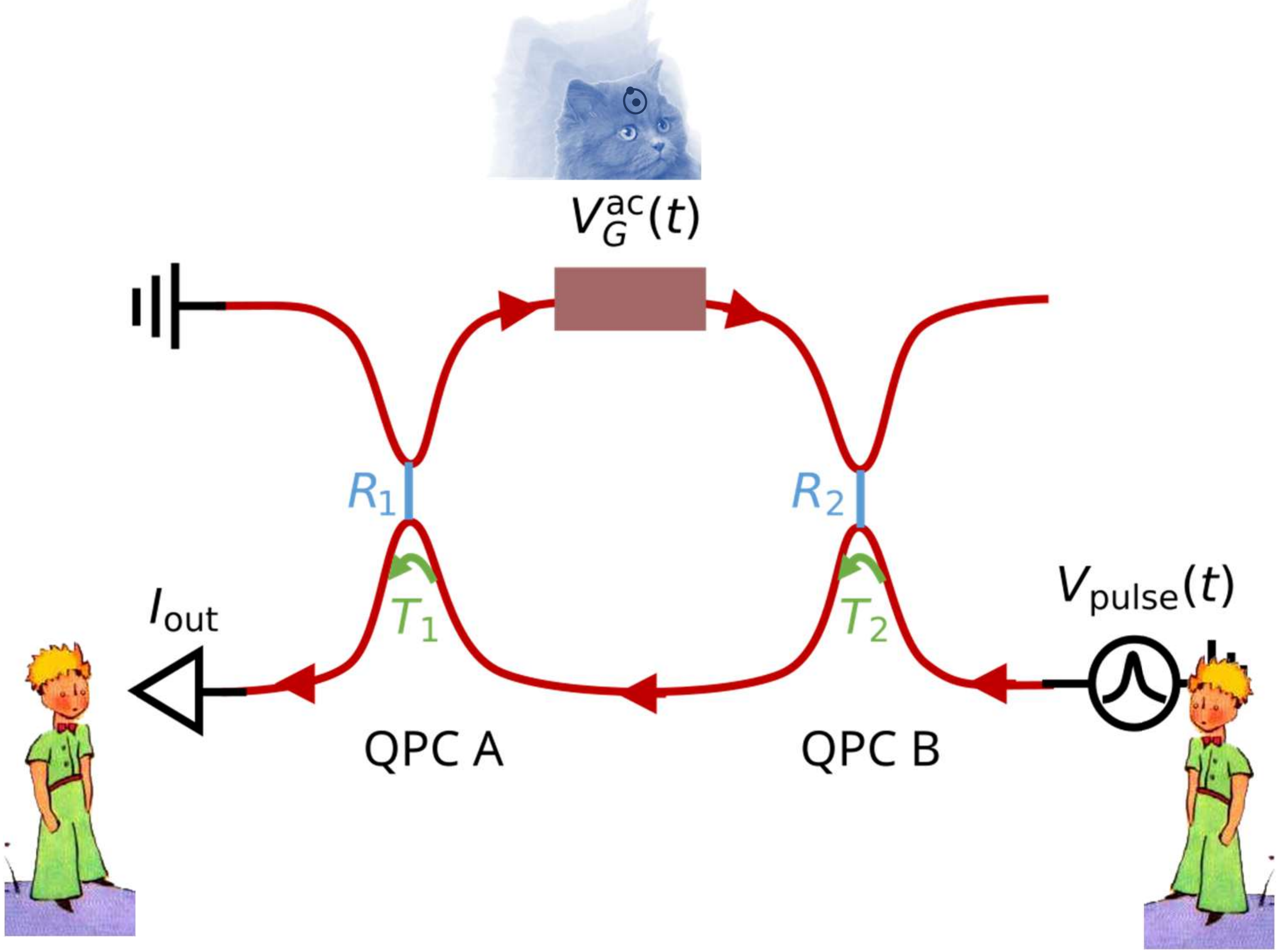
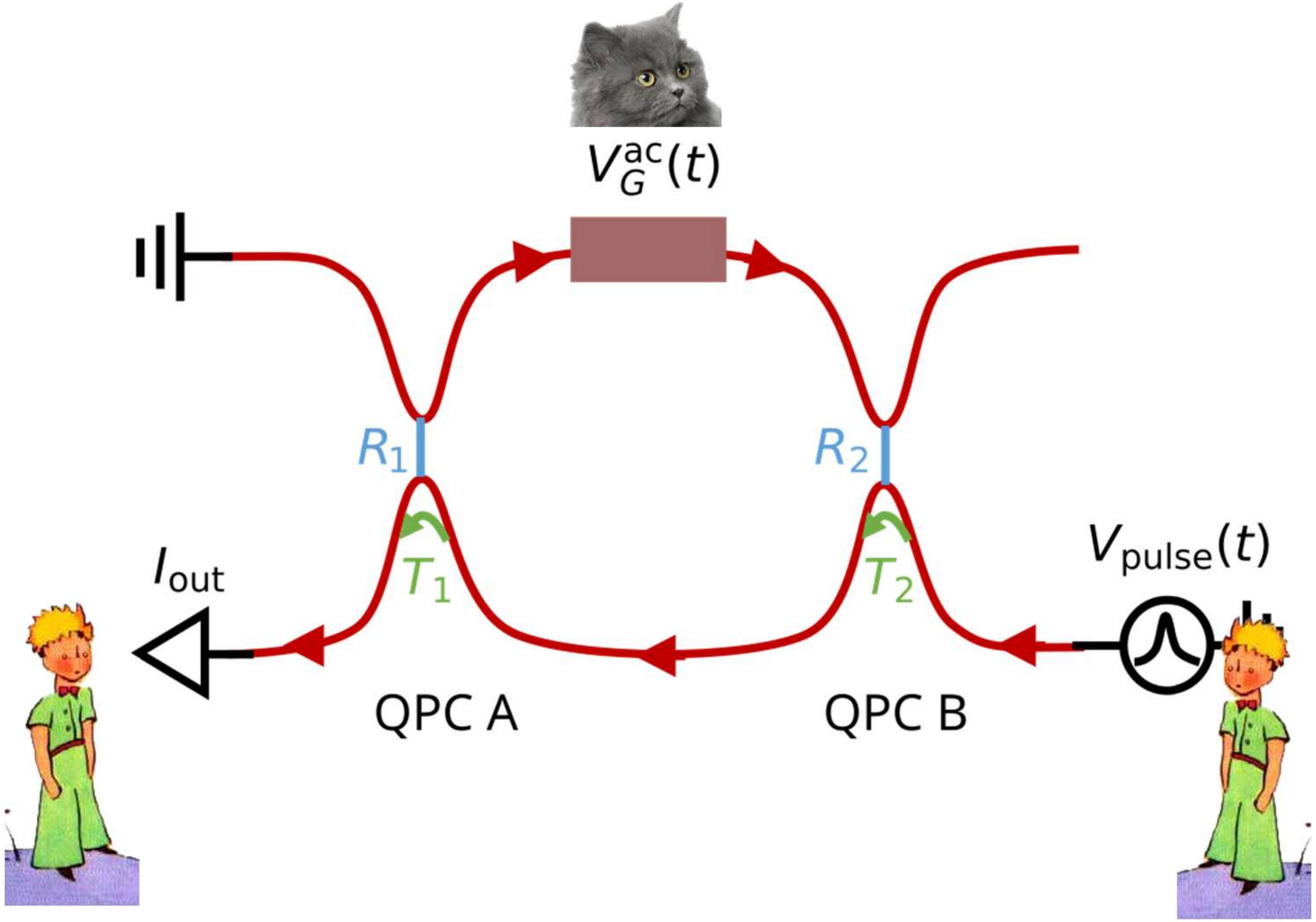


Fabry-Perot interferometry

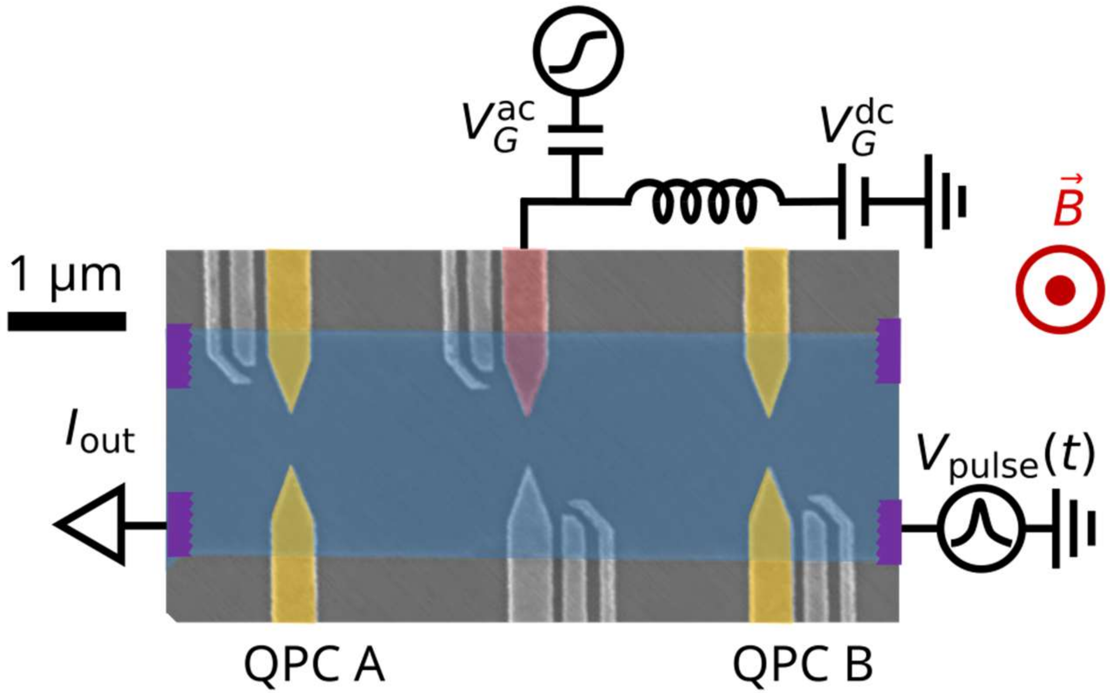
Using Lorentzian shaped pulse to probe **classical** voltage $V_G^{ac}(t)$



Fabry-Perot interferometry

AlGaAs/GaAs based 2DEG

2 QPCs & 1 excitation gate



Bartolomei, H et al. Nat. Nanotechnology **20**, 596-601 (2025).

Fabry-Perot interferometry

AlGaAs/GaAs based 2DEG

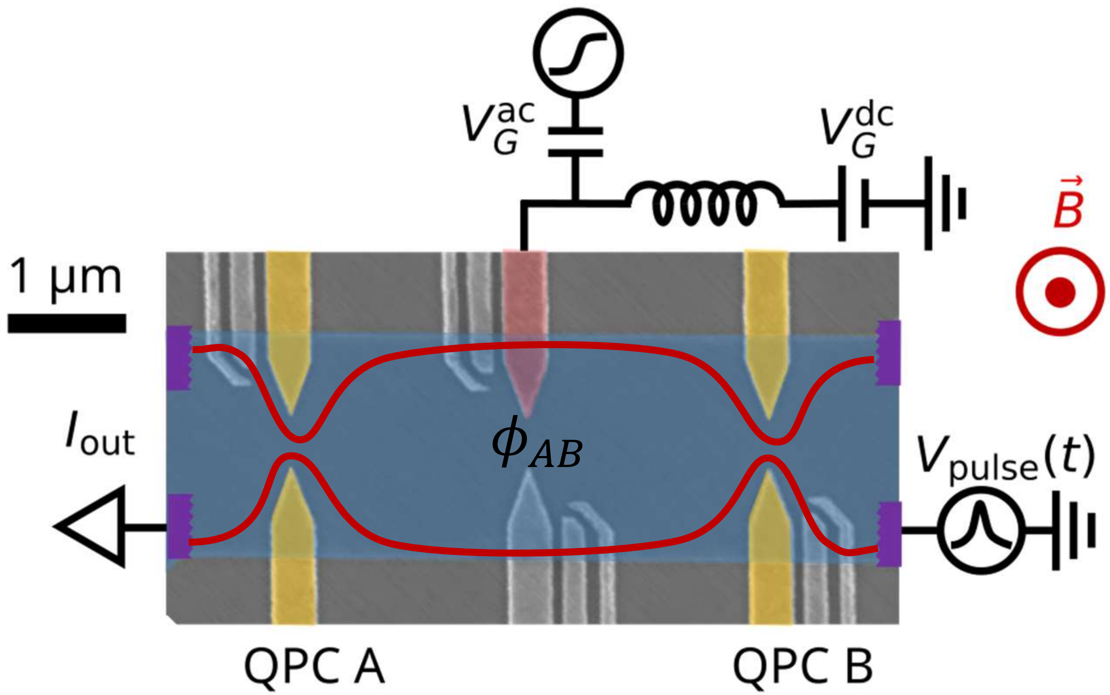
2 QPCs & 1 excitation gate

Device can be used in Fabry-Perot mode

Typical time:

τ_L =30 ps

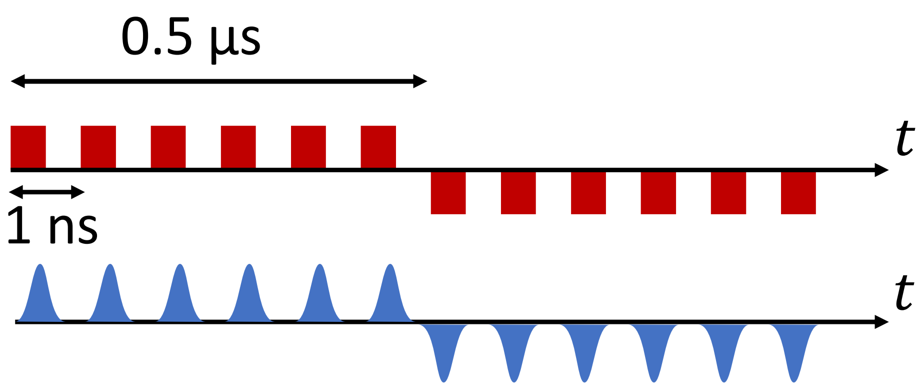
$\tau_e = 35 - 113$ ps

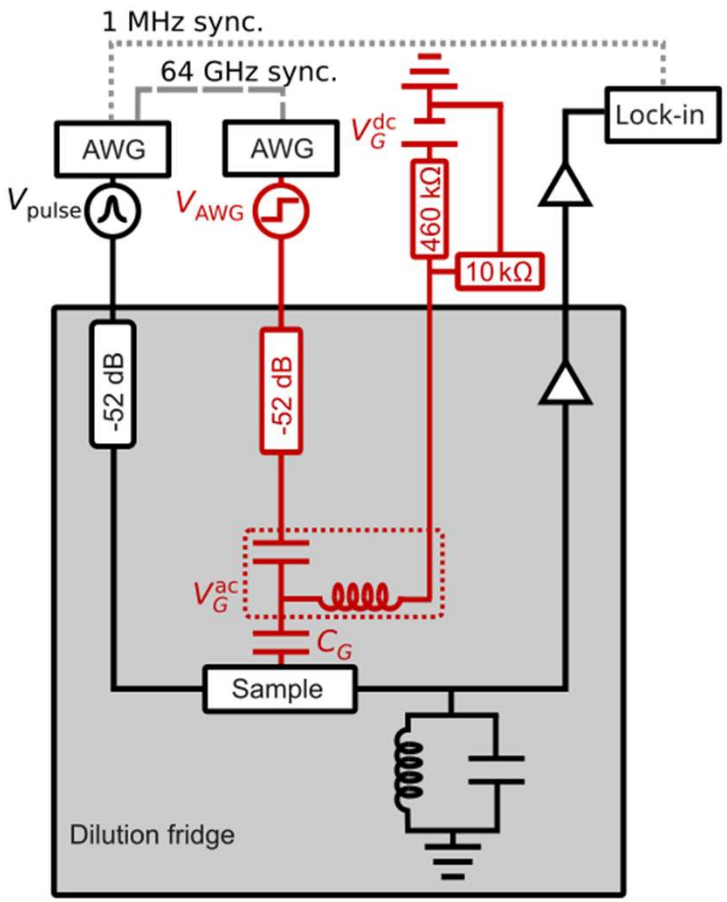


Bartolomei, H et al. Nat. Nanotechnology **20**, 596-601 (2025).

Fabry-Perot interferometry

10 GHz pulse/drive period
1 MHz cycle
Detection through tank circuit





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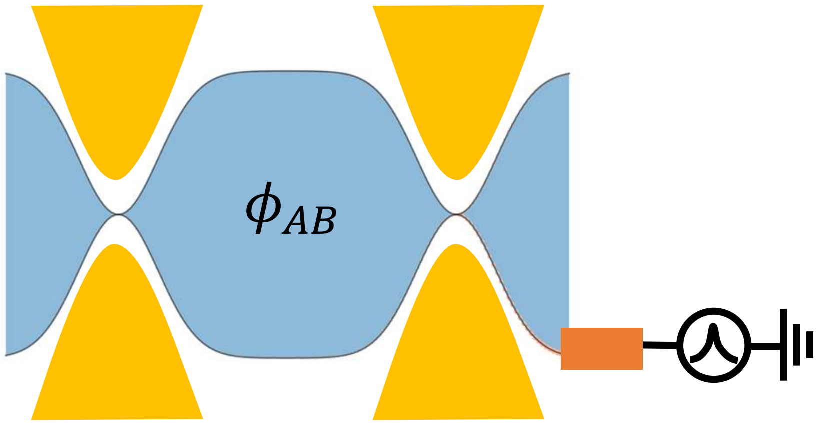
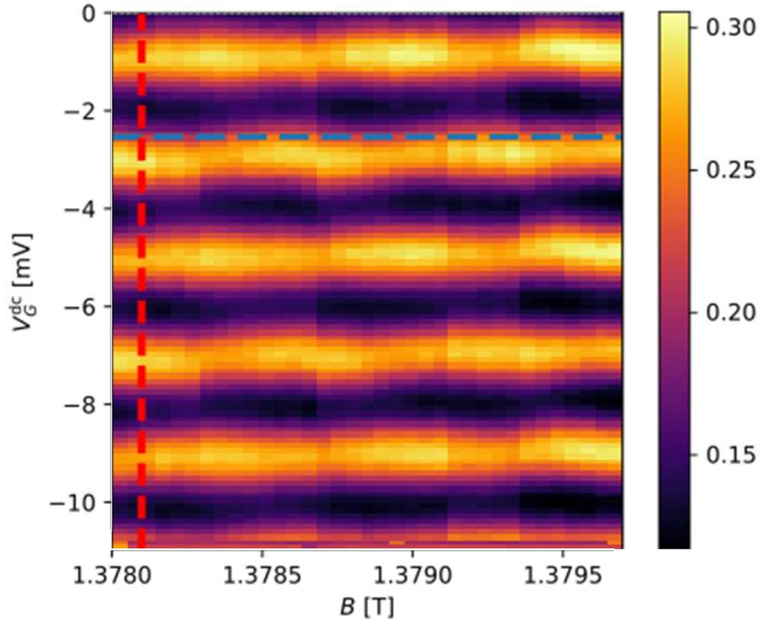
Fabry-Perot interferometry

Oscillating behavior as a function of
B and V_G^{dc} ($V_G^{\mathrm{ac}} = 0$)





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Fabry-Perot interferometry

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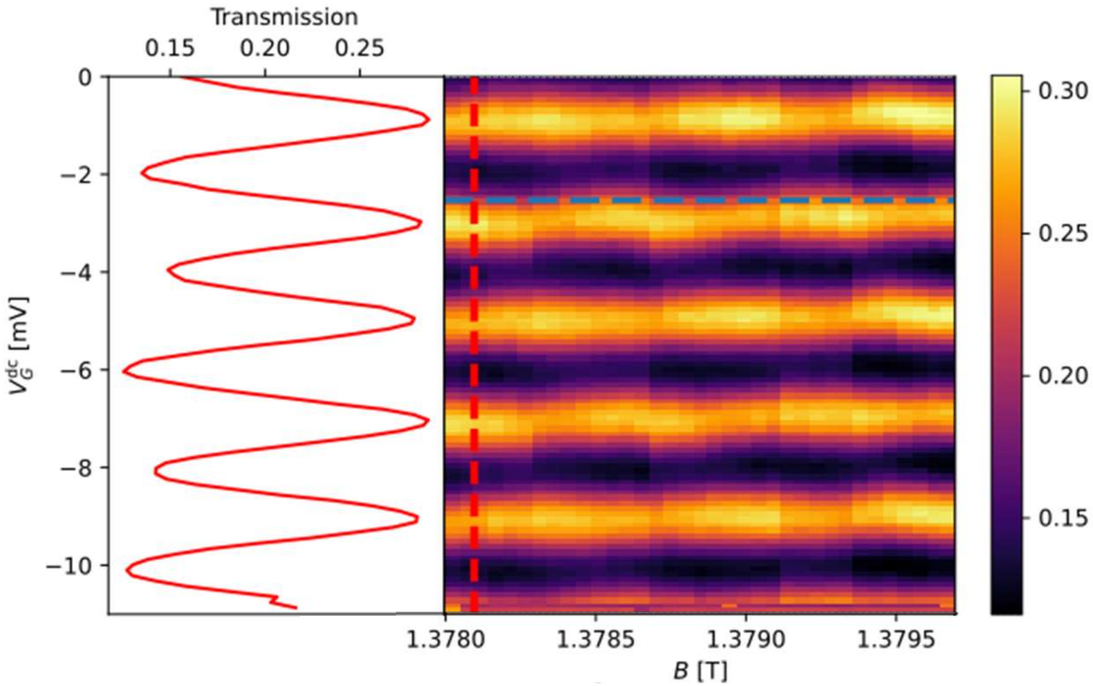
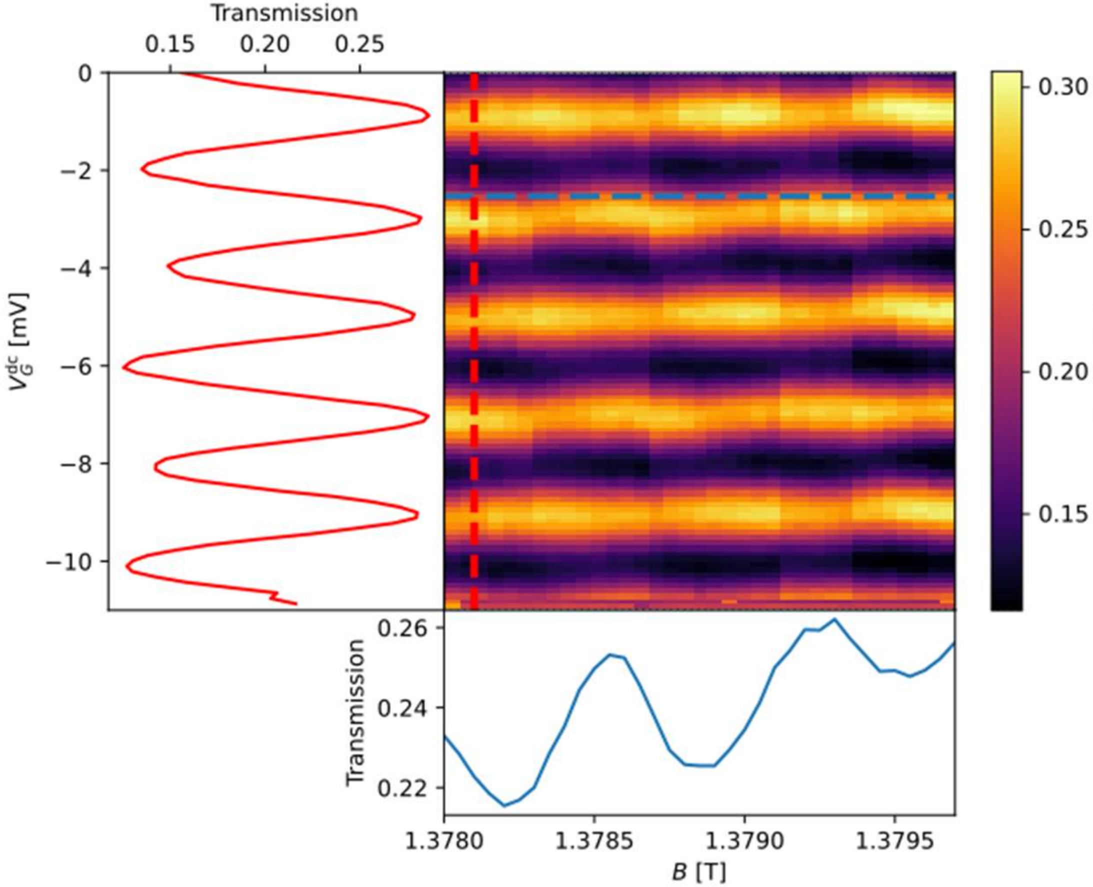


Bartolomei, H et al. Nat. Nanotechnology **20**, 596-601 (2025).

Fabry-Perot interferometry

Oscillating behavior as a function of B and V_G^{dc} ($V_G^{\mathrm{ac}} = 0$)

Amplitudes are much stronger along V_G^{dc} axis due to Coulomb effect



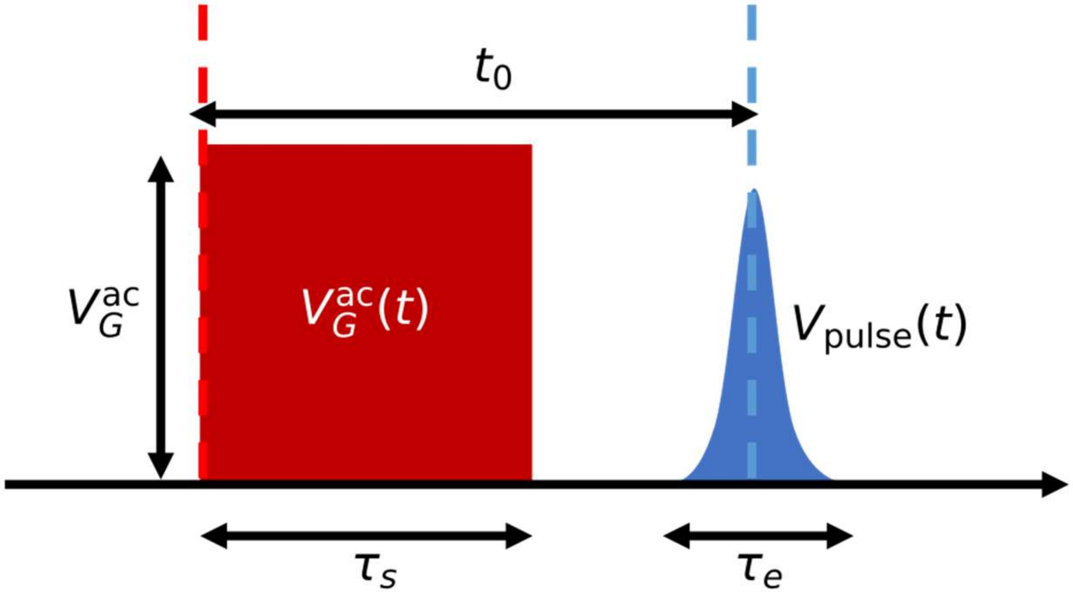
Bartolomei, H et al. Nat. Nanotechnology **20**, 596-601 (2025).

Fabry-Perot interferometry

Square drive probed by Lorentzian pulse.

τ_e: pulse width
t_0: time delay
τ_L: time cavity round-trip

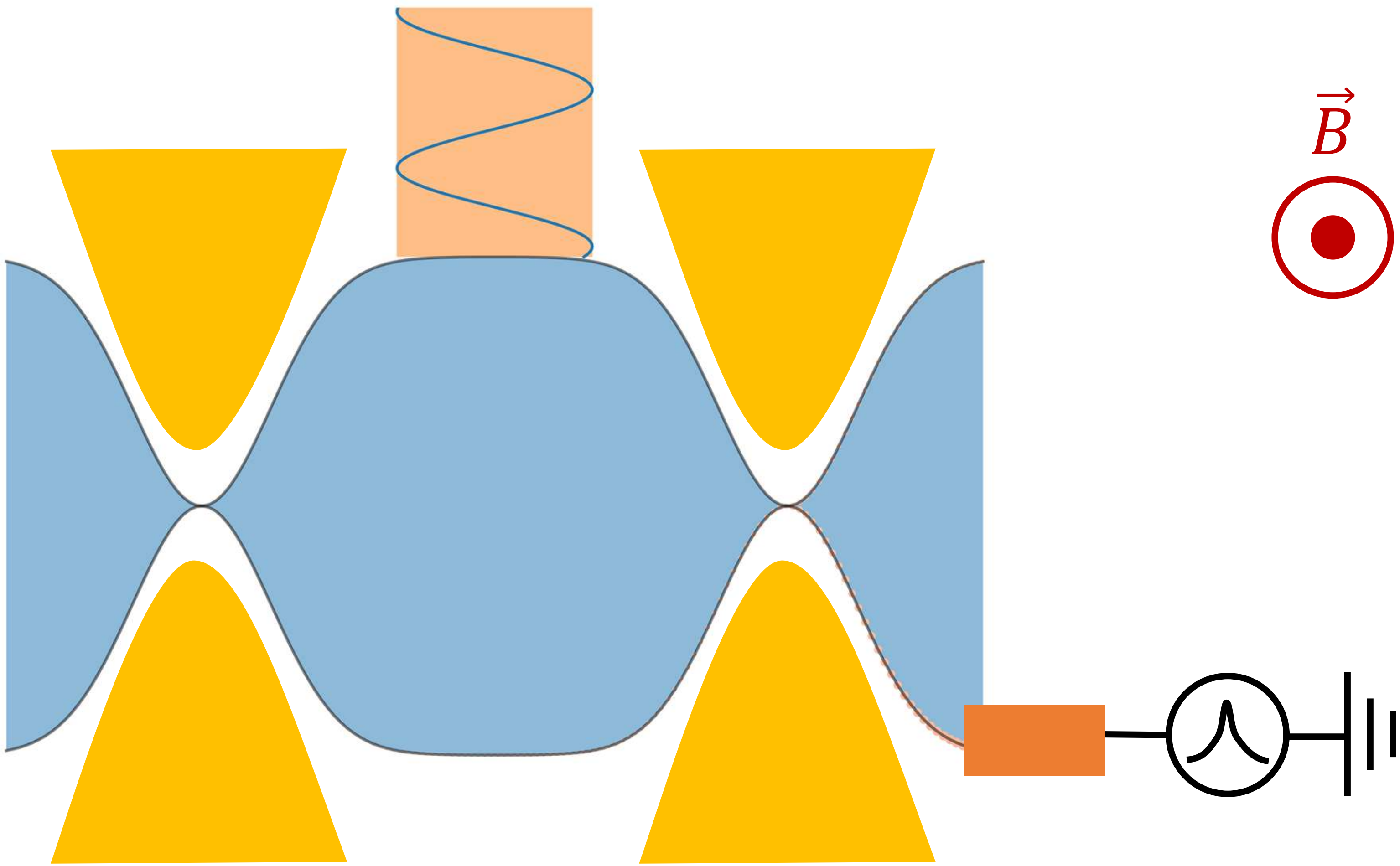
V_G^{ac}: Amplitude drive



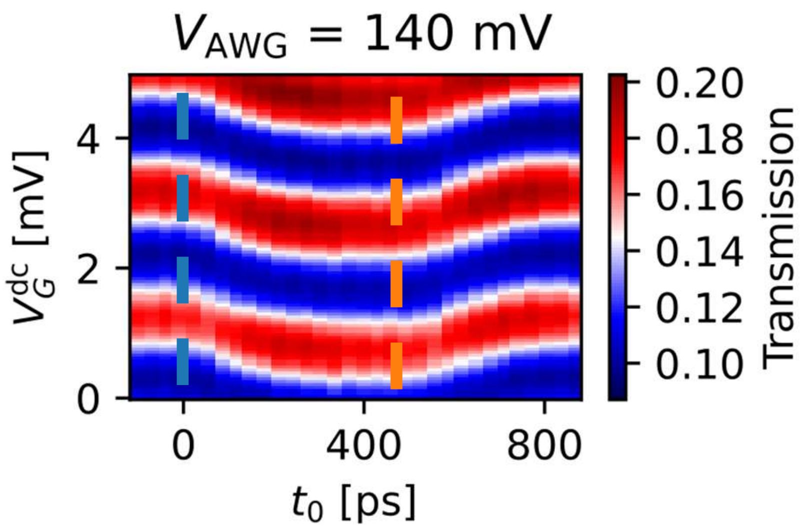
Bartolomei, H et al. Nat. Nanotechnol. **20**, 596-601 (2025).

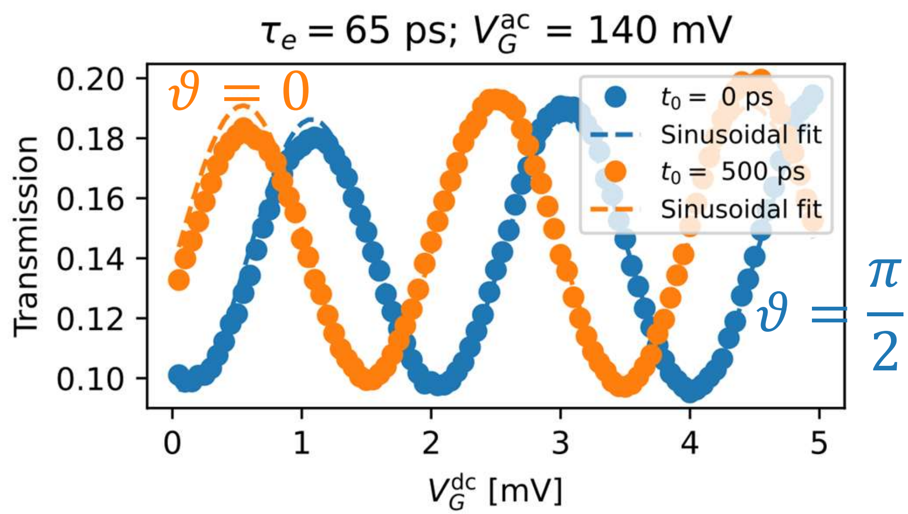
Fabry-Perot interferometry

Cavity comparable
to EMP size



Fabry-Perot interferometry: results





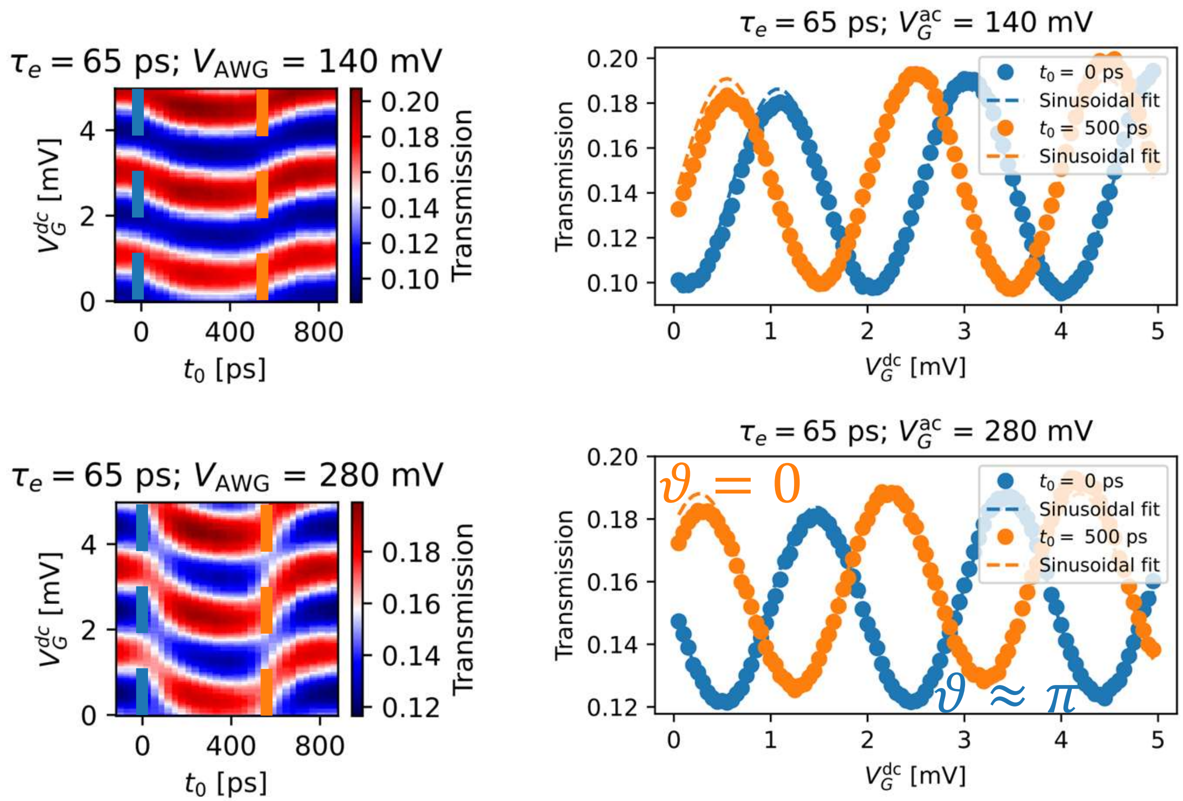
A phase ϑ and contrast C are extracted from sinusoidal fits of the transmission at fixed values of t_0

Bartolomei, H et al. Nat. Nanotechnol. **20**, 596-601 (2025).

Fabry-Perot interferometry: results

The phase-shift depends on the amplitude of the drive V_G^{ac}.

$140 \text{ mV} \rightarrow \pi/2$ shift
$280 \text{ mV} \rightarrow \pi$ shift

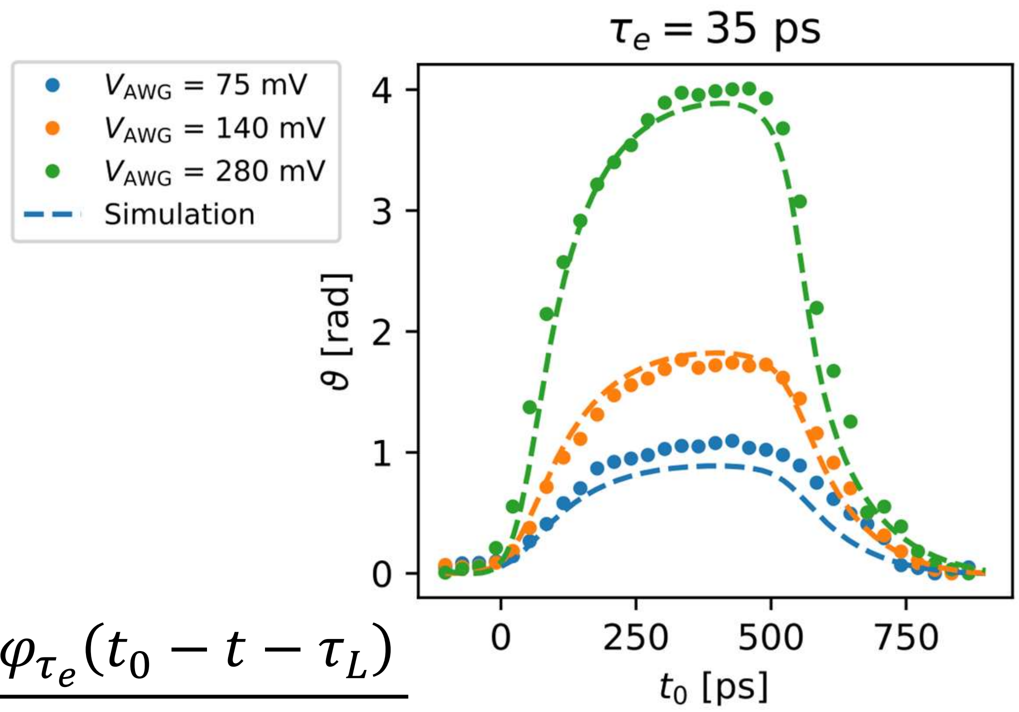


Bartolomei, H et al. Nat. Nanotechnol. **20**, 596-601 (2025).

Fabry-Perot interferometry: results

Effect of the drive amplitude:

- phase shift is proportionnal to V_{AWG} with very good agreement
- Theory follows contrast qualitatively but is underestimated. Reproduces well contrast dips.



$$C(t_0)e^{i\vartheta(t_0)} = \frac{\int dt\, e^{2i\,\frac{C_G}{e}V_G^{\mathrm{ac}}(t)}\varphi^*_{\tau_e}(t_0-t)\varphi_{\tau_e}(t_0-t-\tau_L)}{\int dt\, \varphi^*_{\tau_e}(t)\varphi\_\tau_e(t-t_L)}$$

Bartolomei, H et al. Nat. Nanotechnol. **20**, 596-601 (2025).

Fabry-Perot interferometry: results

Effect of the drive amplitude:

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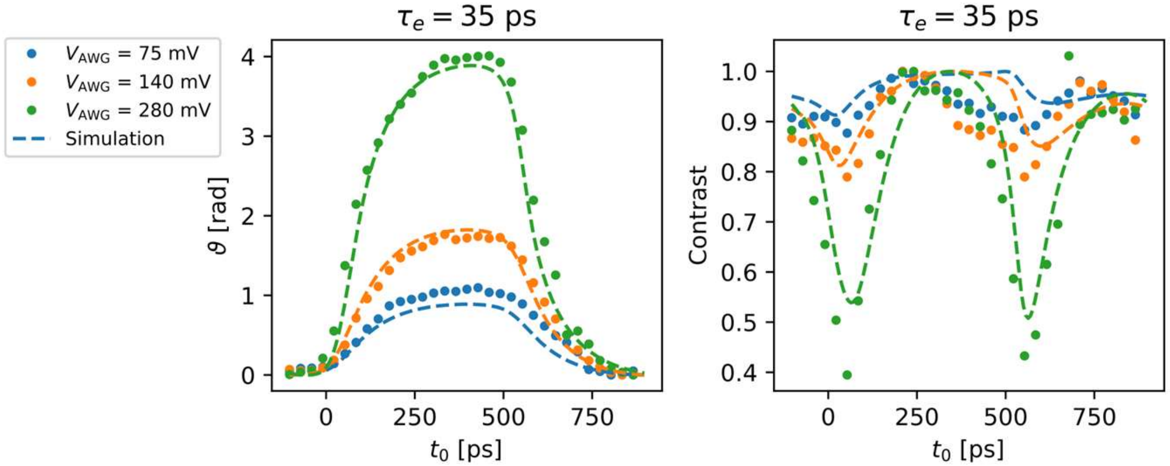
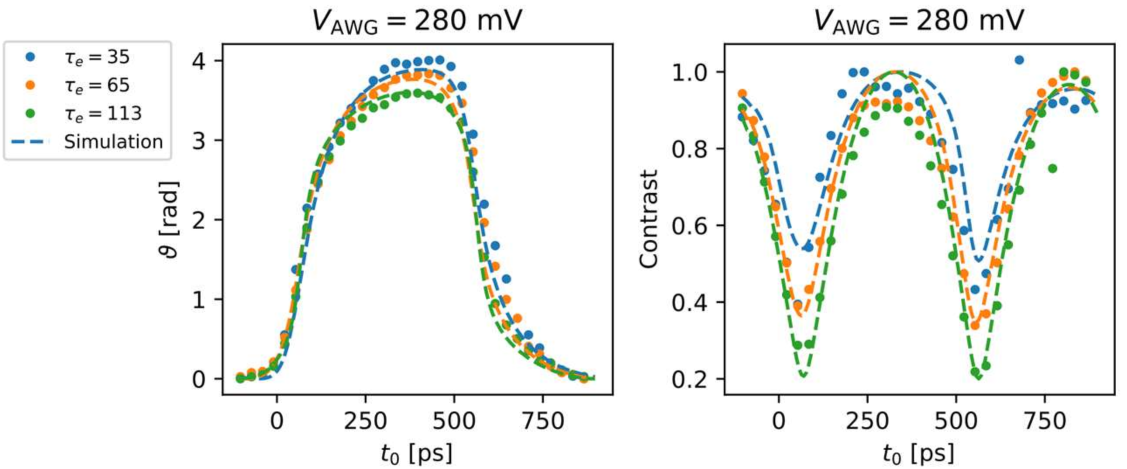


Bartolomei, H et al. Nat. Nanotechnol. **20**, 596-601 (2025).

Fabry-Perot interferometry: results

Effect of the pulse width:

- Much smaller effect on both phase & amplitude
- Longer pulse diminishes contrast
- Resolution of $50\ \mu\text{V}$.



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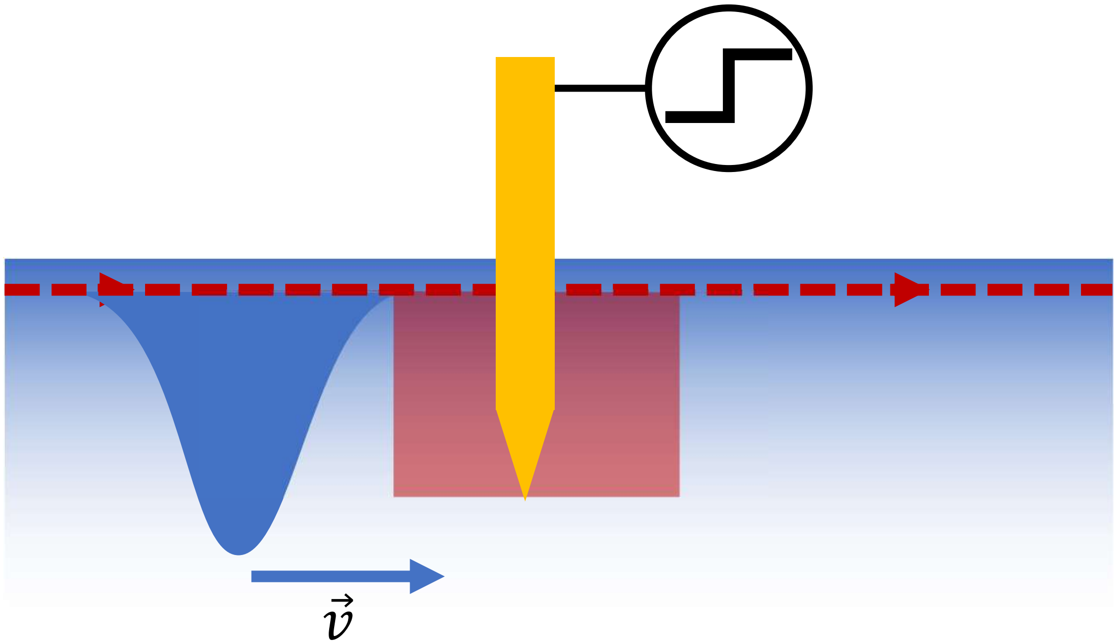
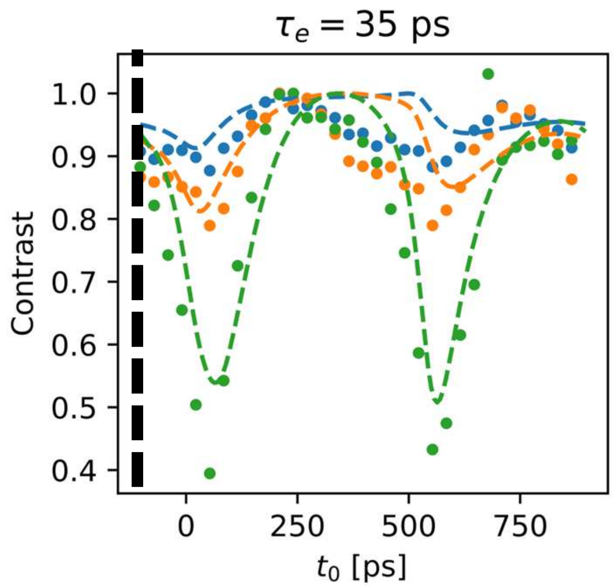
Fabry-Perot interferometry: results

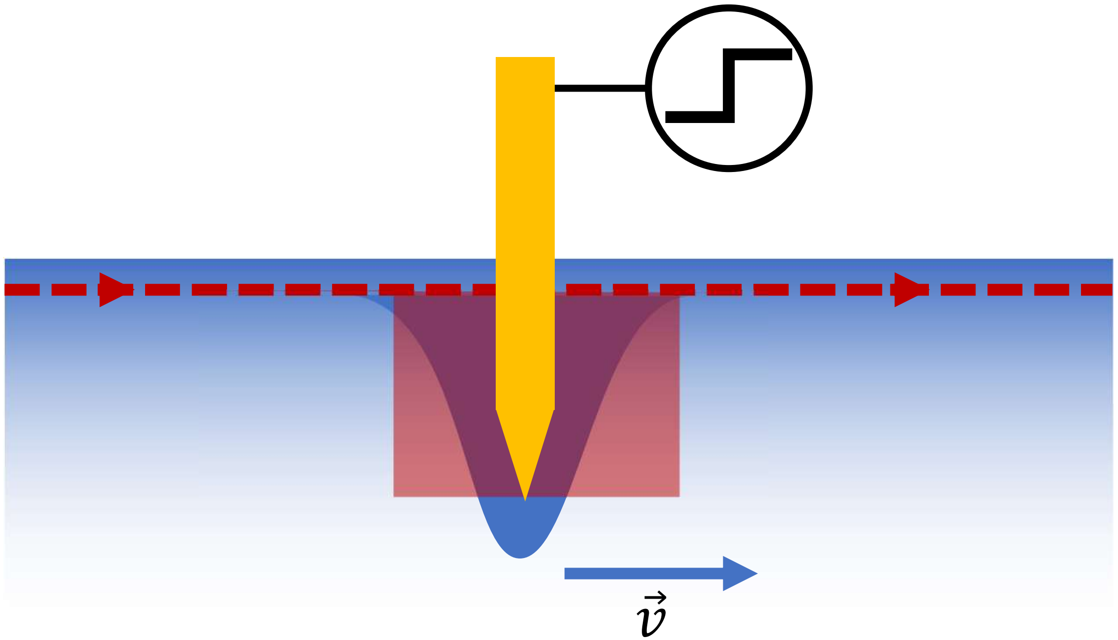


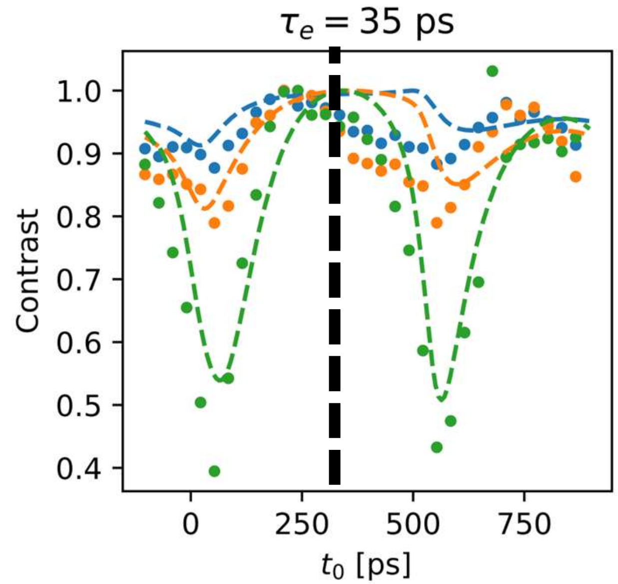


For small t_0, no overlap between wave function and drive

Bartolomei, H et al. Nat. Nanotechnol. **20**, 596-601 (2025).

Fabry-Perot interferometry: results

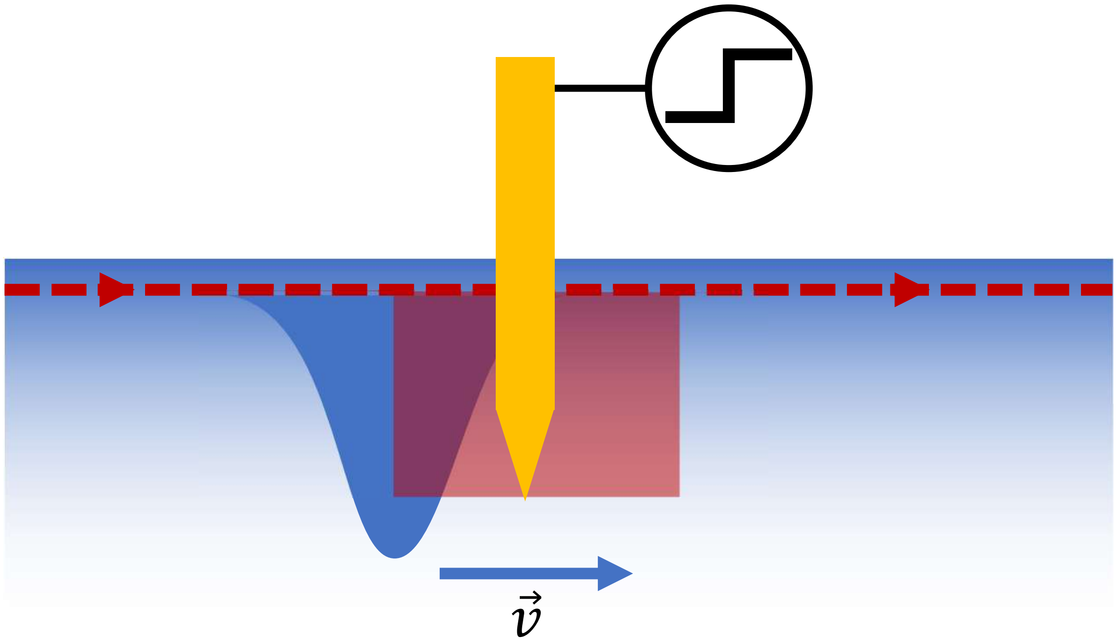


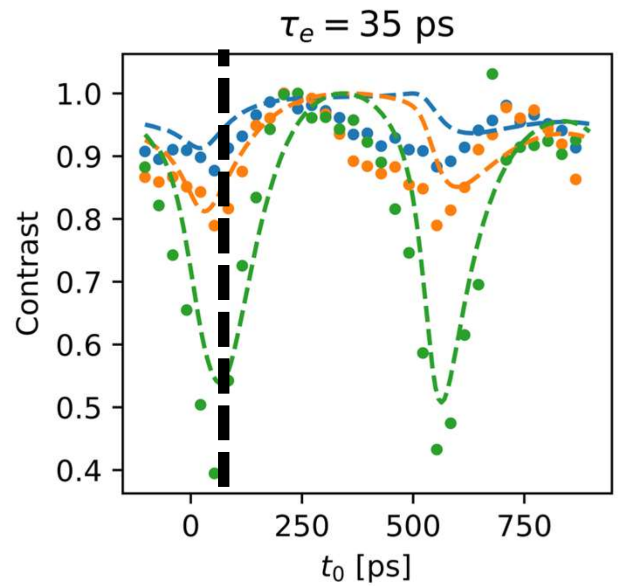


When both drive and pulse coincide, the contrast is roughly identical to that in absence of drive

Bartolomei, H et al. Nat. Nanotechnol. **20**, 596-601 (2025).

Fabry-Perot interferometry: results



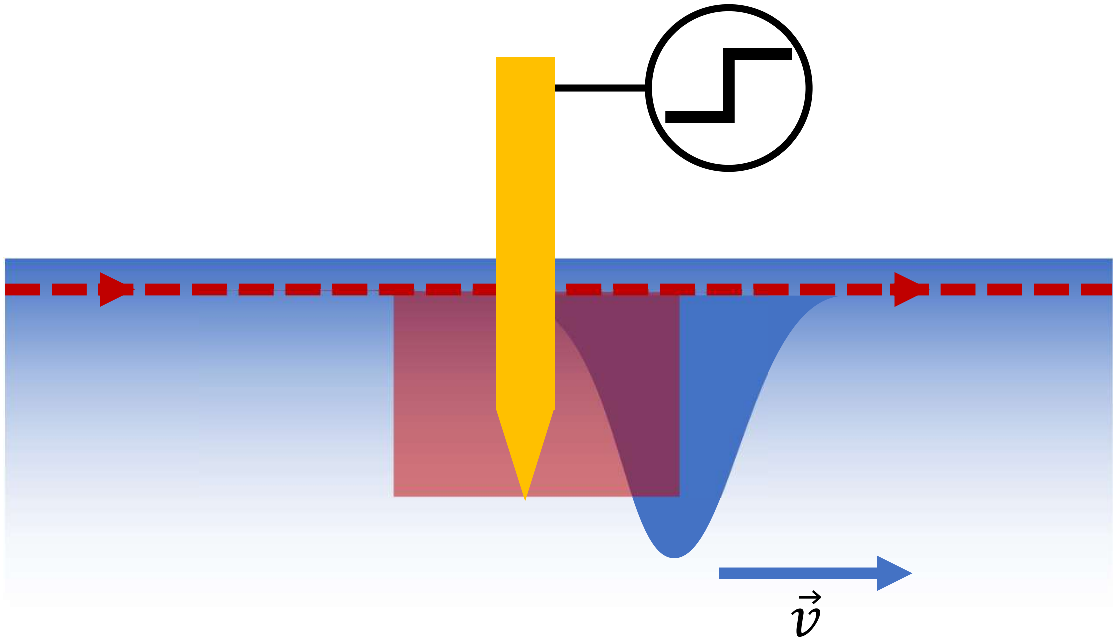


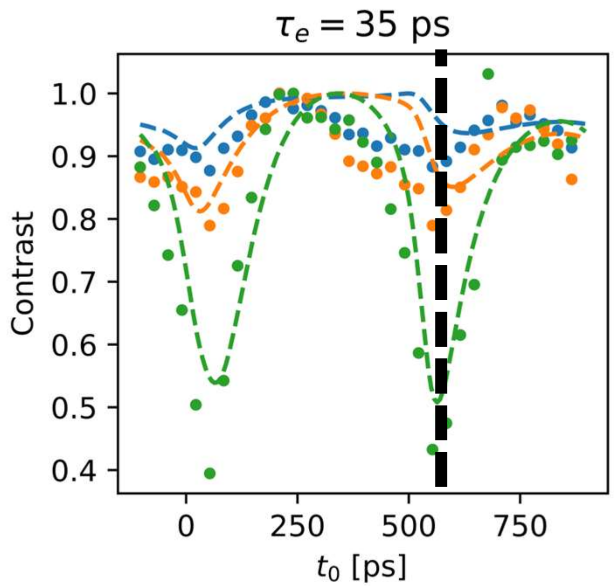
When pulse only partially overlaps with drive, wavepacket spread reduces contrast depending on position of the electron.

Bartolomei, H et al. Nat. Nanotechnol. **20**, 596-601 (2025).

LABORATOIRE DE PHYSIQUE DE L'ÉCOLE NORMALE SUPÉRIEURE

Fabry-Perot interferometry: results



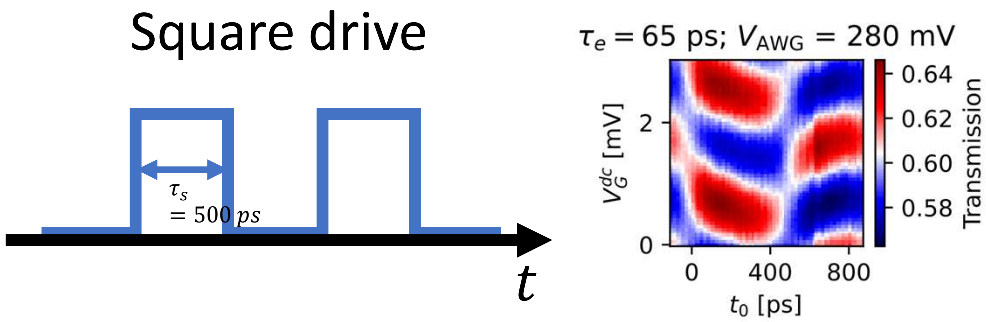


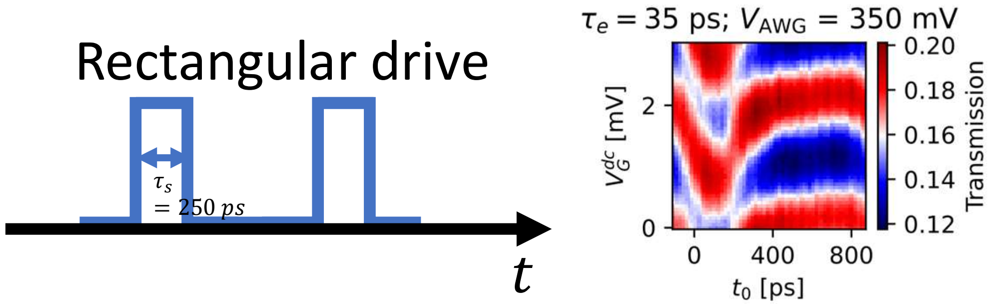
Same on other side

Bartolomei, H et al. Nat. Nanotechnol. **20**, 596-601 (2025).

Fabry-Perot interferometry: results

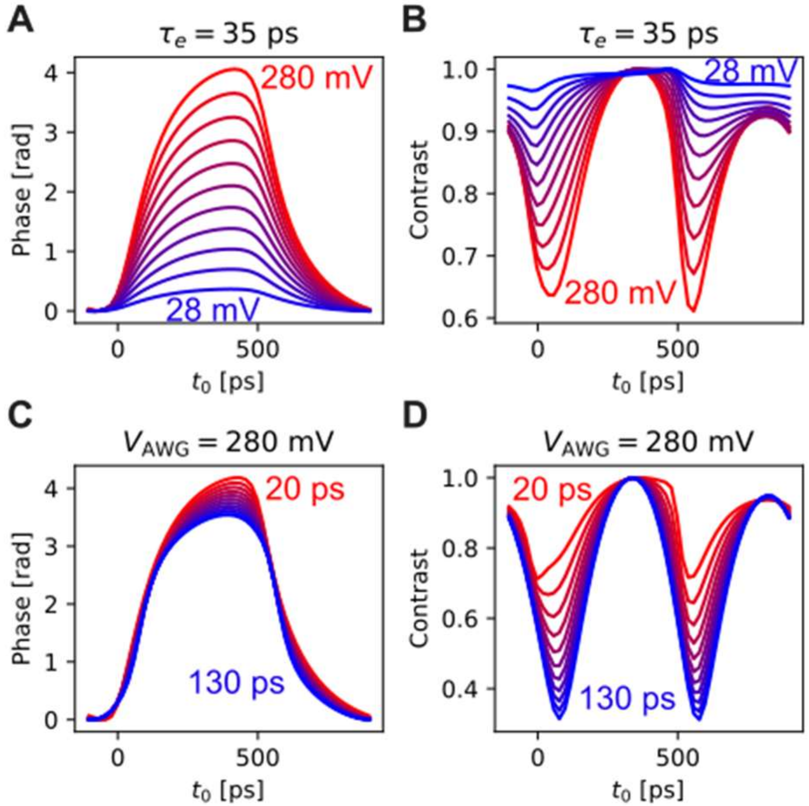
Changing shape of drive from square ($\tau_s = 500$ ps) to rectangular ($\tau_s = 250$ ps).





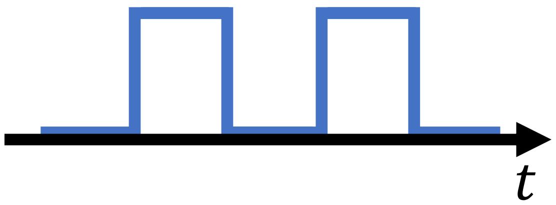
Bartolomei, H et al. Nat. Nanotechnol. **20**, 596-601 (2025).

Varying amplitude of and width of pulse

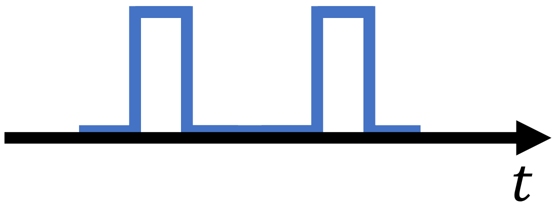


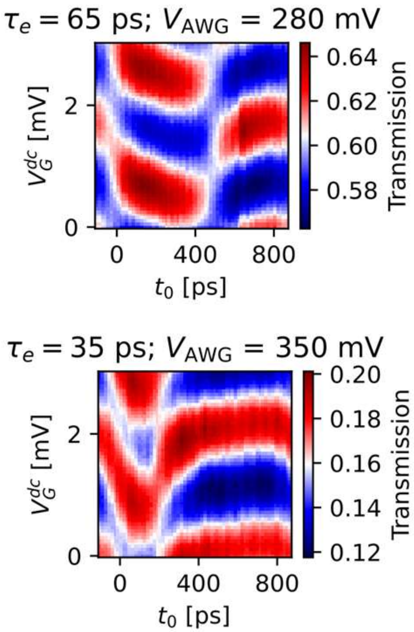
Fabry-Perot interferometry: results

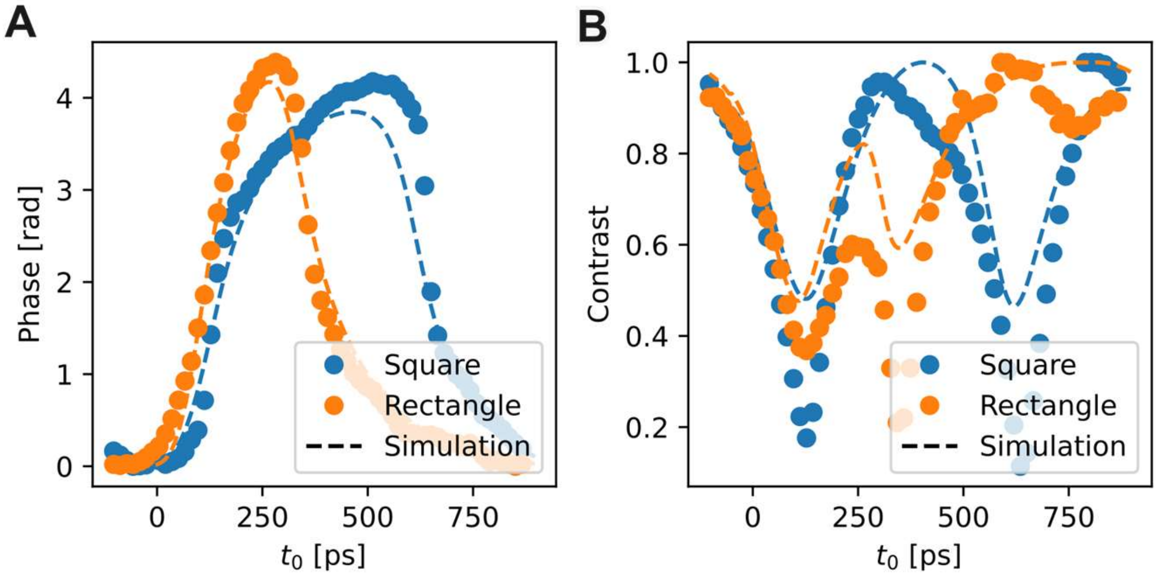
Square drive



Rectangular drive







Good agreement on the phase (limited by τ_r). Contrast has quantitative difference but good position of dips.

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Conclusions

- Fast sensing probe of time-dependent voltage
- Few 10s of ps time-resolution
- Limited by gate polarization rise-time
- Sensitivity ≈ 10 photons but could be easily improved
- Potential application to detection of squeezing, EMP resonance, field tomography…

Thank you for your attention!