Mesoscopic research with Quantum Hall electronic interferometer

Hyungkook Choi
Weizmann Institute of Science

Emil Weisz, Itamar Sivan, Amir Rosenblatt
Vladimir Umansky, Diana Mahalu
Yuval Gefen
Moty Heiblum

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WEIZMANN INSTITUTE OF SCIENCE

can interference be recovered ?

Uncertainty vs. Complementarity

Which one is more fundamental?

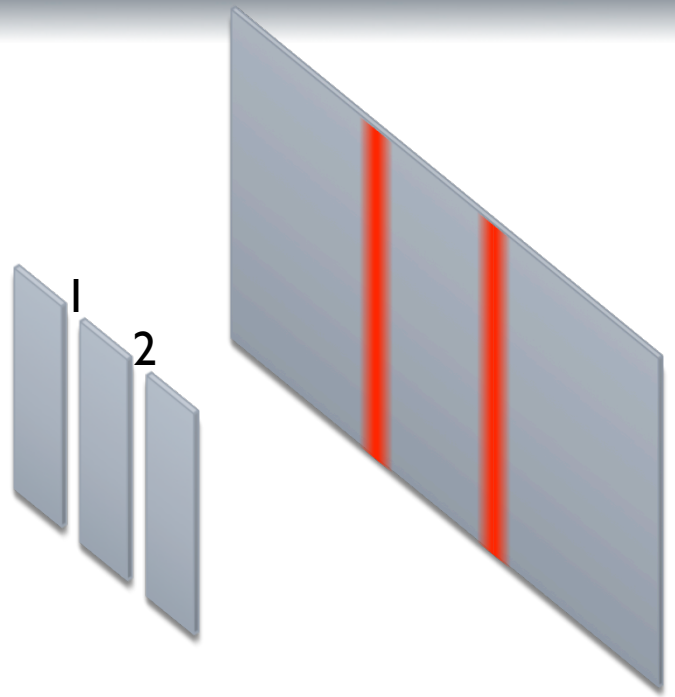
Uncertainty principle

"*It is impossible to design an apparatus to determine which hole the electron passes through, that will not at the same time disturb the electron enough to destroy the interference pattern*" R. Feynman (1965)

Complementarity

"*It is possible to design experiments which provide which path information via detectors which do not disturb the system in any noticeable way*" M.O. Scully (1991)

Quantum eraser



2'

1'

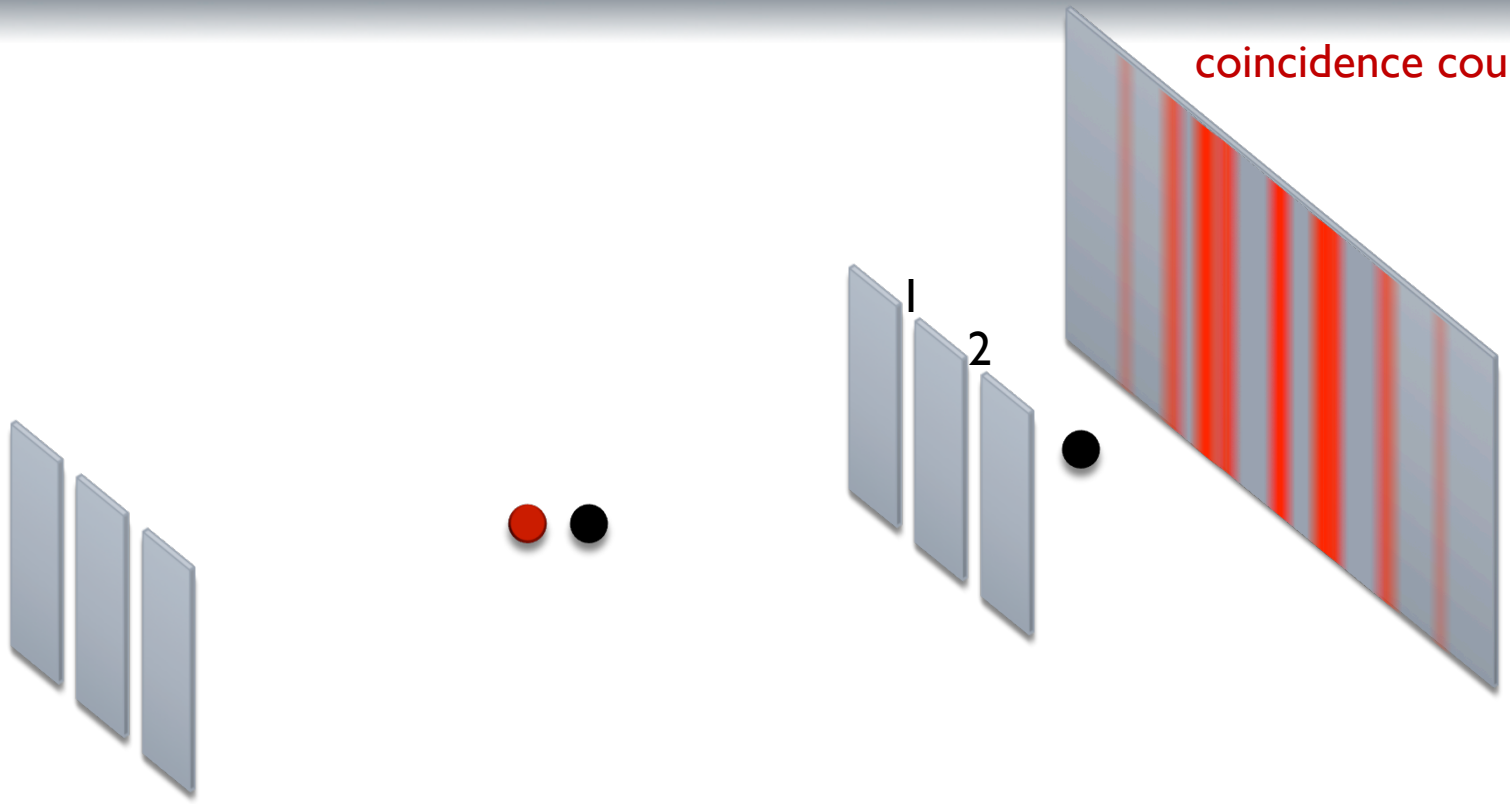
entangled state

$$|\Psi_{total}\rangle = |1\rangle \otimes |1'\rangle + |2\rangle \otimes |2'\rangle$$

$$P = |\langle r \| \Psi_{total} \rangle|^2 = |1|^2 + |2|^2 + (\langle 1|2\rangle + \langle 2|1\rangle)\langle 1'|2'\rangle$$

no interference !!

Quantum eraser



$$P = \left| \psi_{total} \right|^2 = \left| \left(\langle 1' | 1 \rangle + \langle 2' | 2 \rangle \right) \otimes \psi_{total} \right|^2 = \left| | 1' \rangle + | 2' \rangle \right|^2$$

WP information is erased by coincidence count→ interference reappears

What is quantum eraser?

CONCEPT

One can choose whether or not to erase which-path information in the quantum DETECTOR

HOW

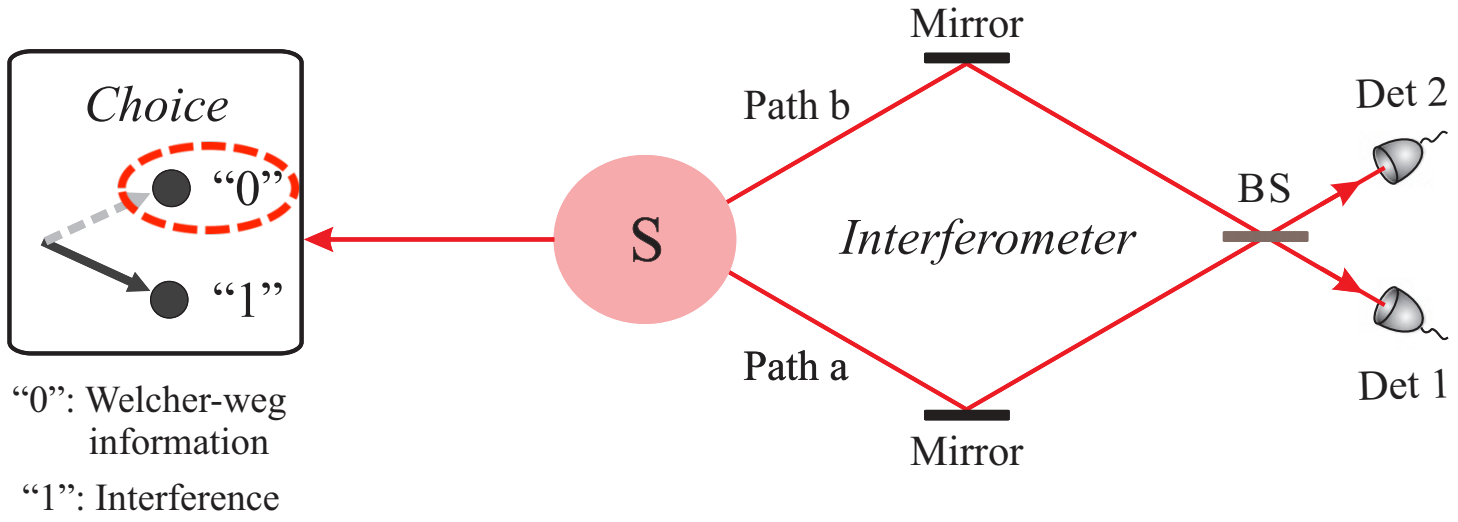
By performing a suitable measurement on quantum DETECTOR

Measurement: projecting wavefunction on a particular basis

Possible to observe its wave nature or particle nature at will !!

Quantum eraser

Xiao-Song Ma *et al.*, PNAS **110**,1221 (2013)



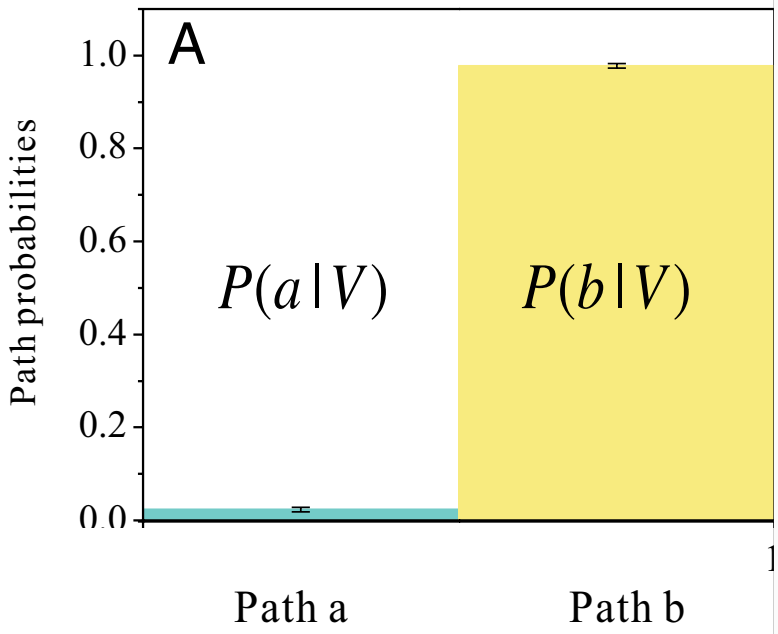
$$\left|\Psi_{\text{hybrid}}\right\rangle_{se} = \frac{1}{\sqrt{2}}\left(\left|\text{b}\right\rangle_s\left|\text{V}\right\rangle_e + \left|\text{a}\right\rangle_s\left|\text{H}\right\rangle_e\right)$$

$\left|V\right\rangle_e$: vertical polarization of environment

$\left|H\right\rangle_e$: horizontal polarization of environment

→ State of environment carries WP information

Conditional probability



$$\left|\Psi_{\text{hybrid}}\right\rangle_{se} = \frac{1}{\sqrt{2}}\left(|\text{b}\rangle_s|\text{V}\rangle_e + |\text{a}\rangle_s|\text{H}\rangle_e\right)$$

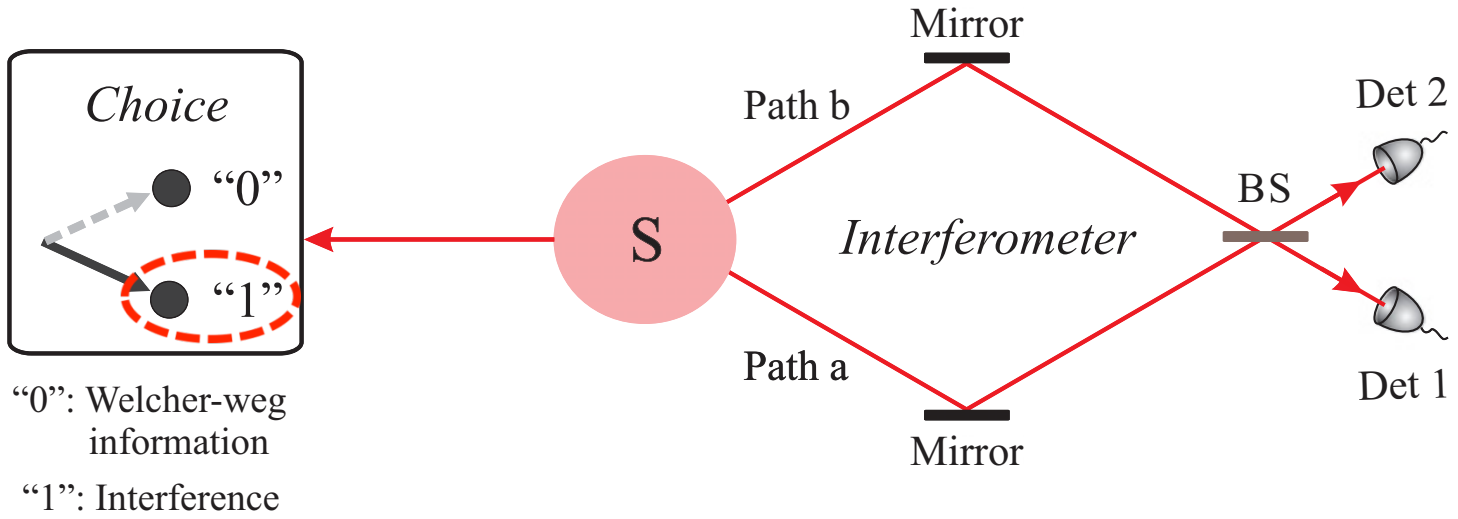
When environment photon is detected in the state $|V\rangle_e$ ⟶ No interference

(H,V : measurement basis)

$$D = \left|P\left(a|V\right) - P\left(b|V\right)\right| \approx 1 \qquad V \approx 0$$

Quantum eraser

Xiao-Song Ma *et al.*, PNAS **110**,1221 (2013)



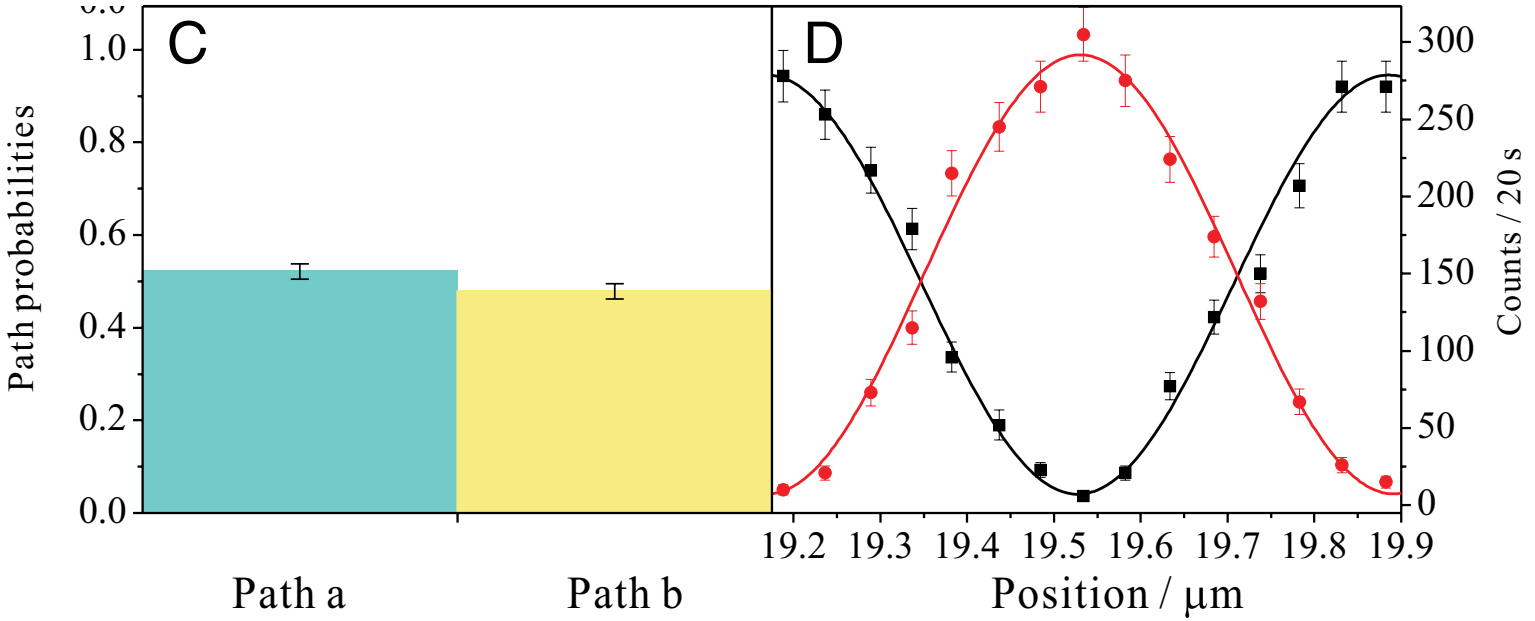
$$|\Psi_{\text{hybrid}}\rangle_{se} = \frac{1}{2\sqrt{2}}\left[(|a\rangle_s + |b\rangle_s)|L\rangle_e + (|a\rangle_s - i|b\rangle_s)|R\rangle_e\right]$$

$$|L\rangle = (|H\rangle - i|V\rangle)/\sqrt{2}$$

$$|R\rangle = (|H\rangle + i|V\rangle)/\sqrt{2}$$

L,R measurement basis doesn't give WP information

Conditional probability



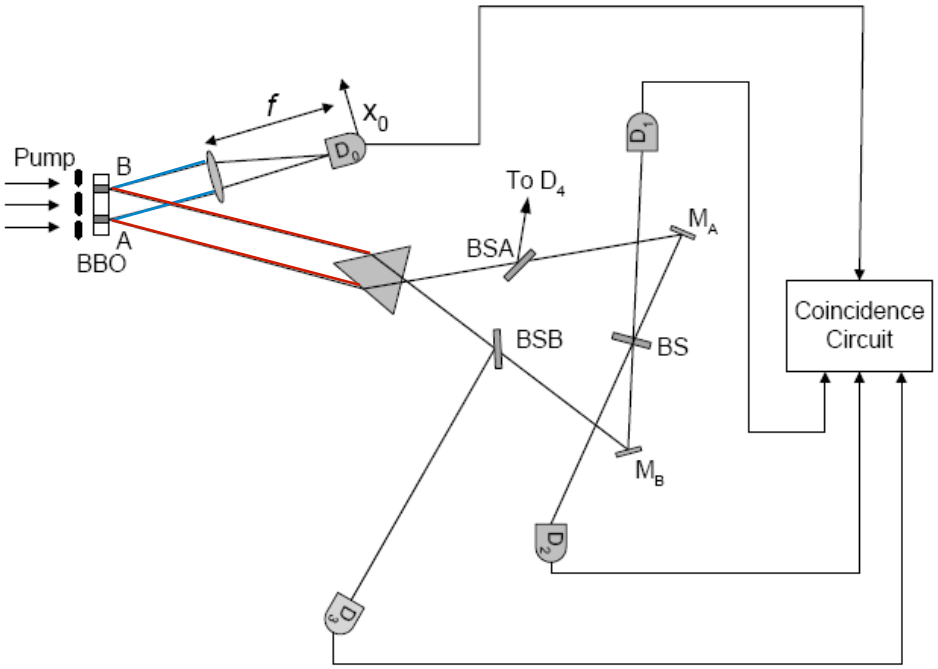
When environment photon is detected in the state $|R\rangle_e$ ⟶ interference

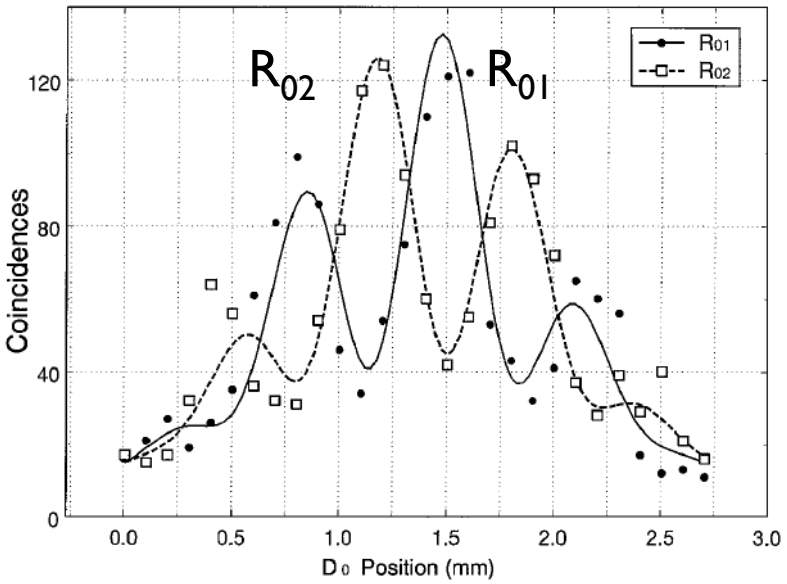
(L,R : measurement basis)

$$D = \left|P\left(a\middle|R\right) - P\left(b\middle|R\right)\right| \approx 0 \qquad V \approx 1$$

$$D^2 + V^2 \leq 1 \quad : \text{complementarity}$$

Quantum eraser -Delayed choice with photon





Y.H. Kim *et al.*, PRL **84**,1 (2000)

can interference be recovered ?

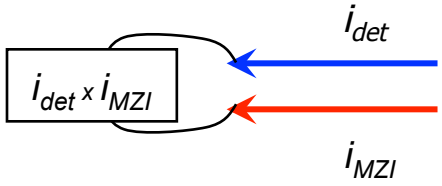
event #1: $0e$ in detector ..... $\varphi_{MZI} = \varphi_{AB} + 0$

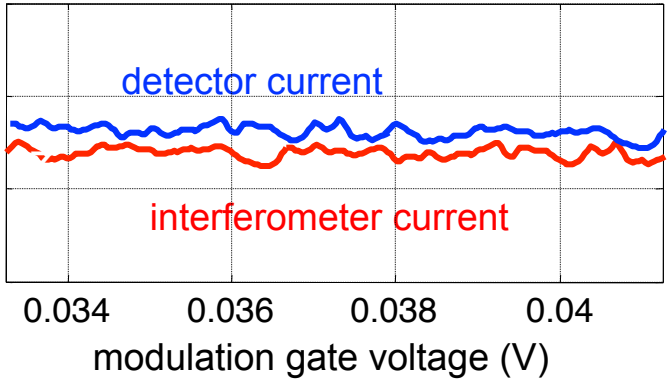
event #2: $1e$ in detector ..... $\varphi_{MZI} = \varphi_{AB} - \pi$

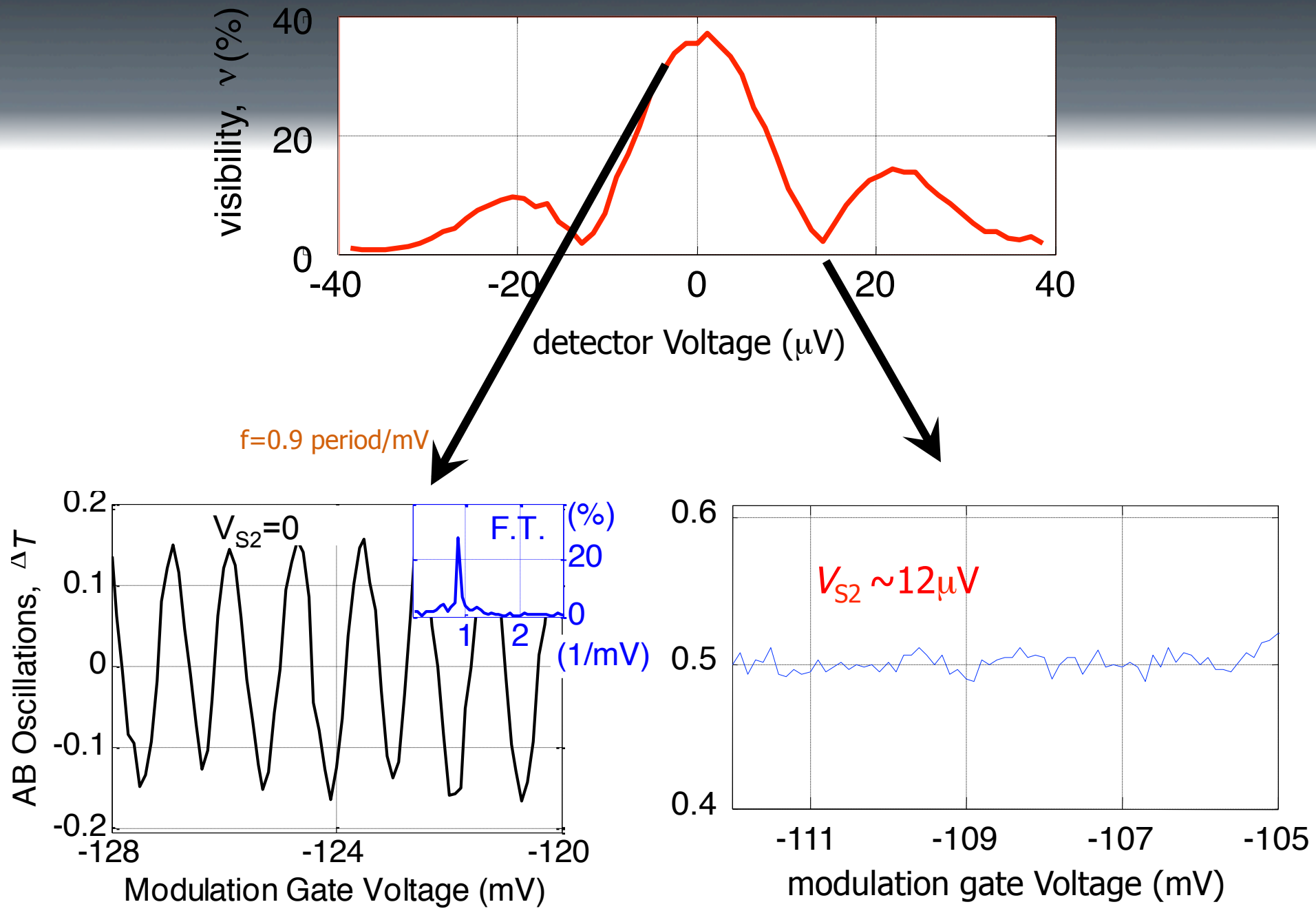
post select $1e_{\,detector} - 1e_{\,MZI} \rightarrow$ deterministic φ_{AB}-π

multiplying current fluctuations

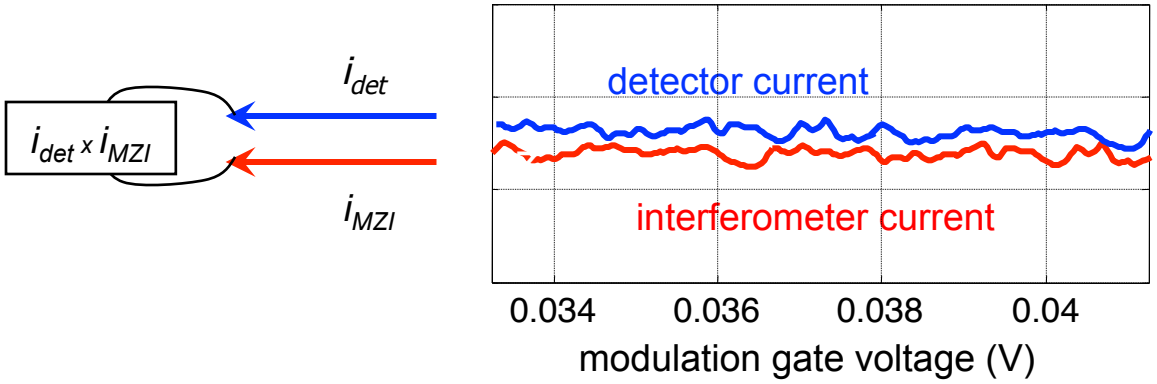
$$\left\langle n_{MZI} \cdot n_{detector} \right\rangle_{11}$$





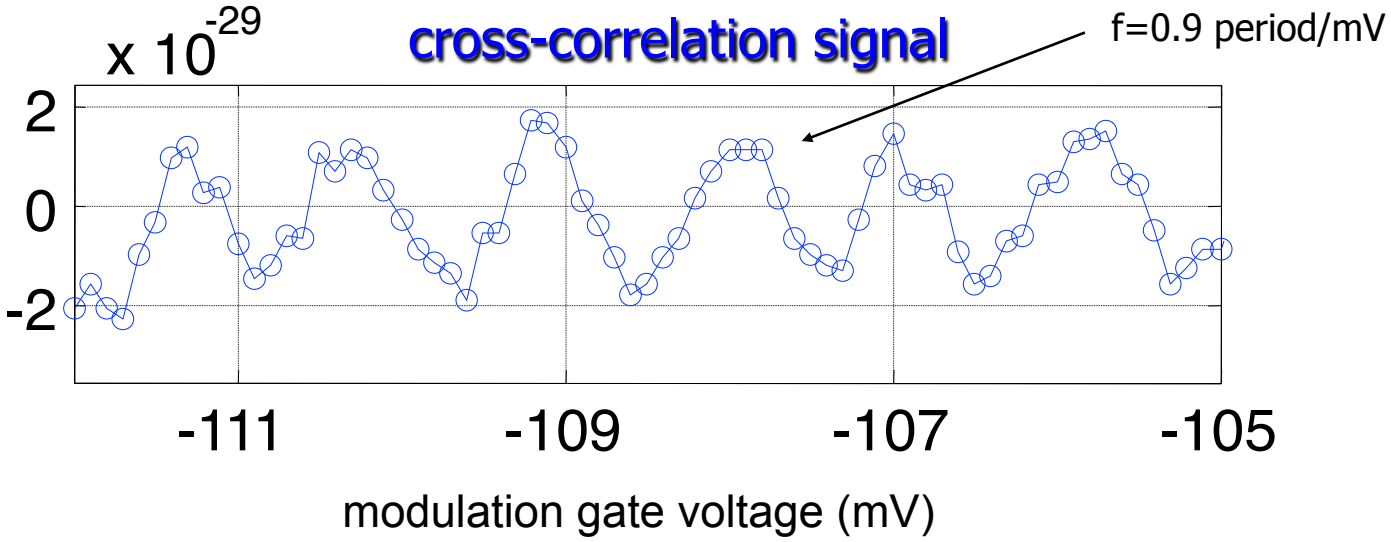

visibility, ν (%)
40
20
0
-40
-20
0
20
40
detector Voltage (μV)
f=0.9 period/mV
0.2
0.1
0
-0.1
-0.2
AB Oscillations, ΔT
V_S2=0
F.T.
(%)
20
0
1
2
(1/mV)
-128
-124
-120
Modulation Gate Voltage (mV)
0.6
0.5
0.4
V_S2 ~12μV
-111
-109
-107
-105
modulation gate Voltage (mV)

cross-correlation MZI ⊗ detector

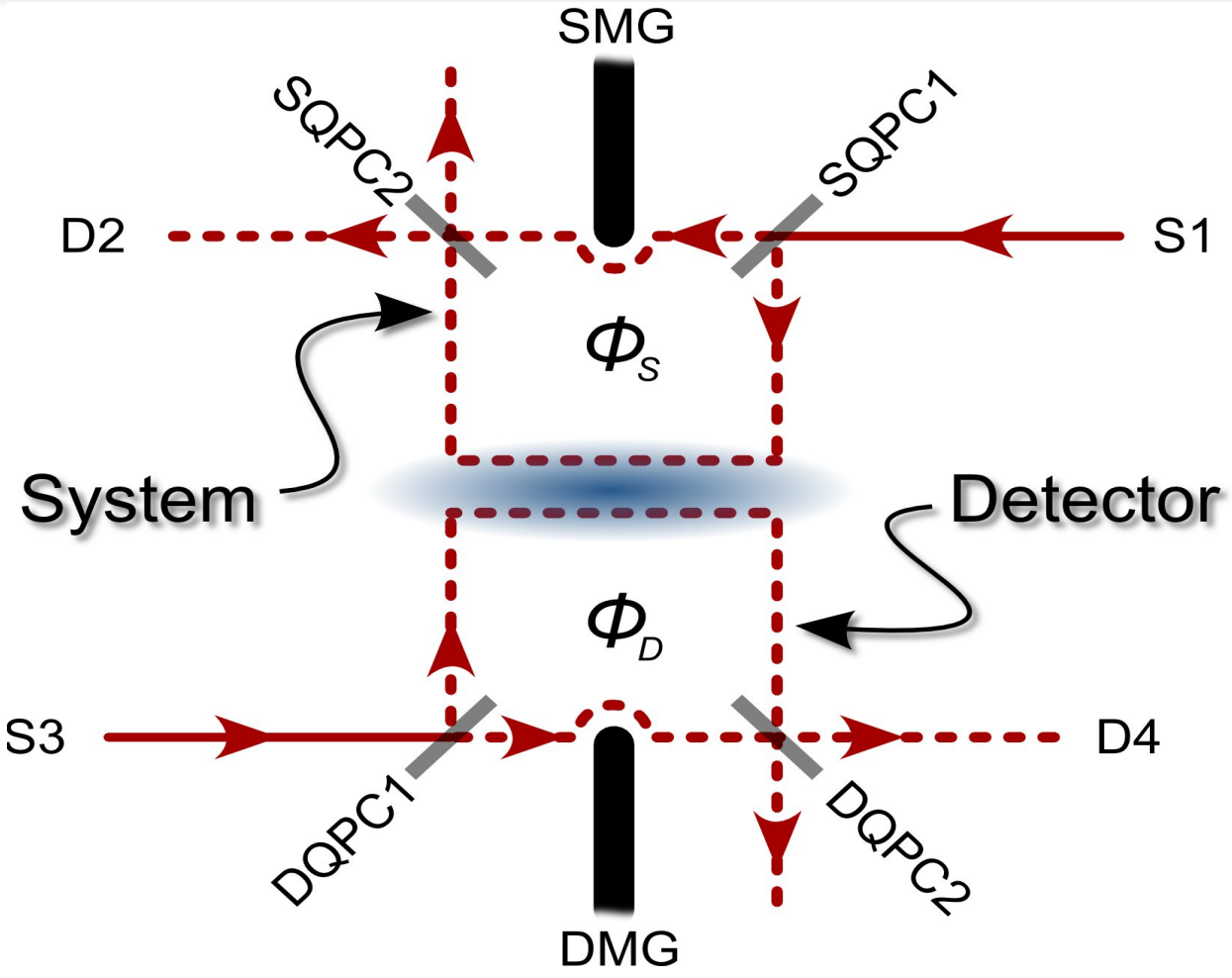


- $V_{S1} = V_{S2} = 12\mu V$; electron temperature 10mK
- ~1 electron in detector and in MZI ……. 10 μm
- measure fluctuations at 0.8 MHz and bandwidth 60 kHz
  integrating 30,000 electrons

interference recovered



Electronic Double MZI for QE



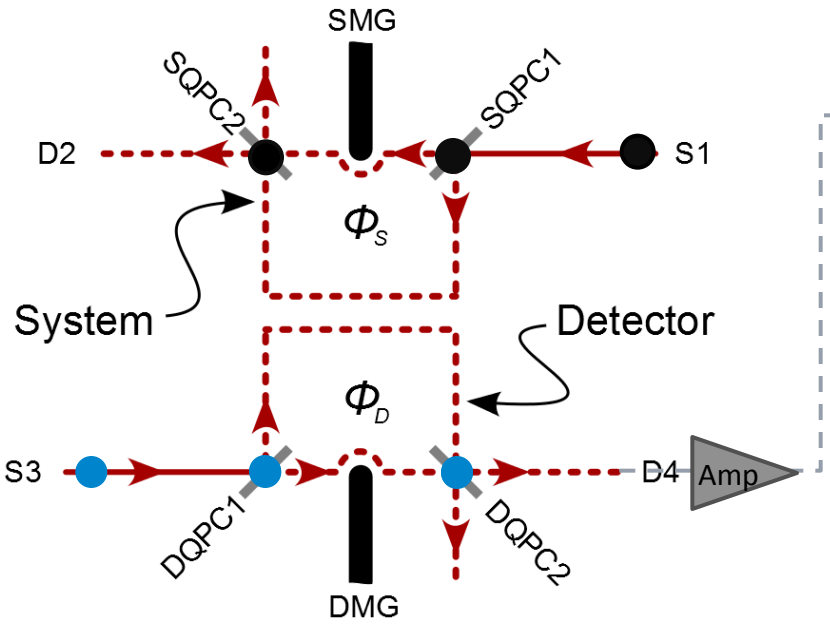
$$\left|\Psi_{total}\right\rangle = \left|\uparrow_S\right\rangle \otimes \left|D^{\uparrow}\right\rangle + \left|\downarrow_S\right\rangle \otimes \left|D^{\downarrow}\right\rangle$$

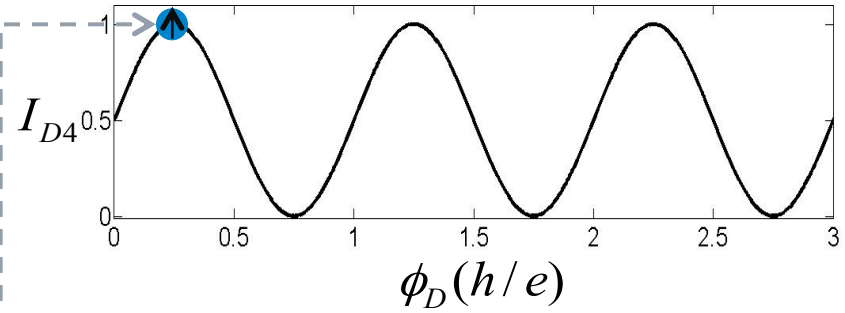
How to erase which path information

What is measurement on to Detector in Electronic QE?

How to control measurement basis

Double MZI

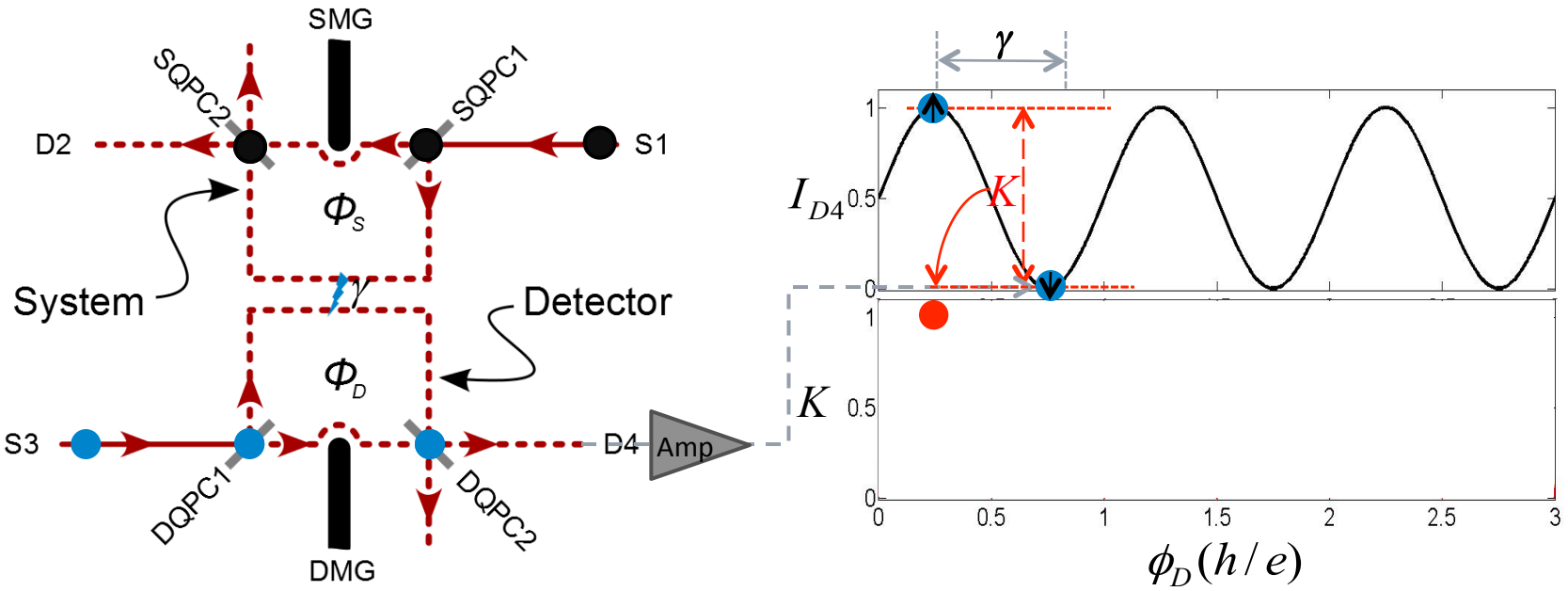




When System electron pass through upper path

Detector current : $P(\mathrm{D4}\,|\uparrow_{\mathrm{S}})$

Double MZI



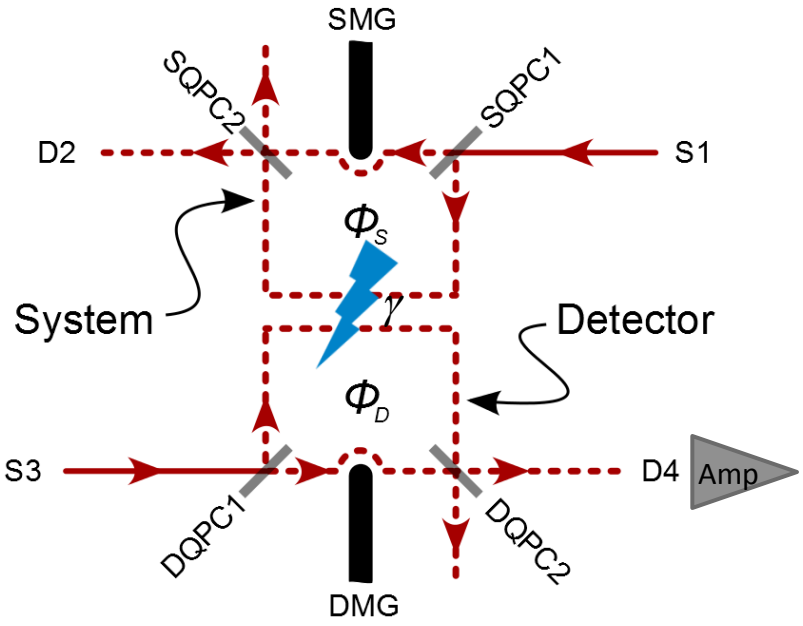
When System electron pass through lower path

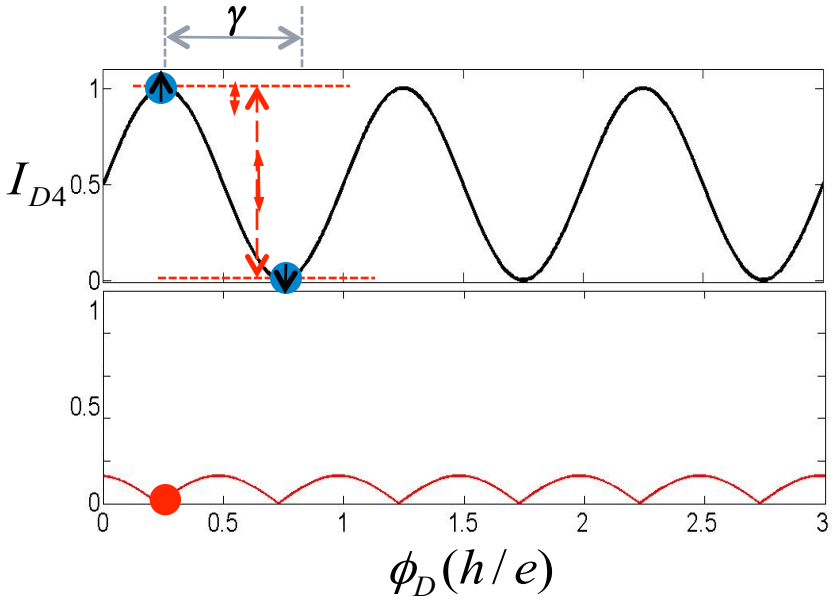
Measured which-path information K:

Detector current : $P(\mathrm{D4}|_{\mathrm{S}})$ here, $\gamma=\pi$.

$$K(\phi_D) \equiv \left| P(\mathrm{D4}|\uparrow_{\mathrm{S}}) - P(\mathrm{D4}|\downarrow_{\mathrm{S}}) \right| \propto \left| \sin(\phi_D) \right|$$

Double MZI

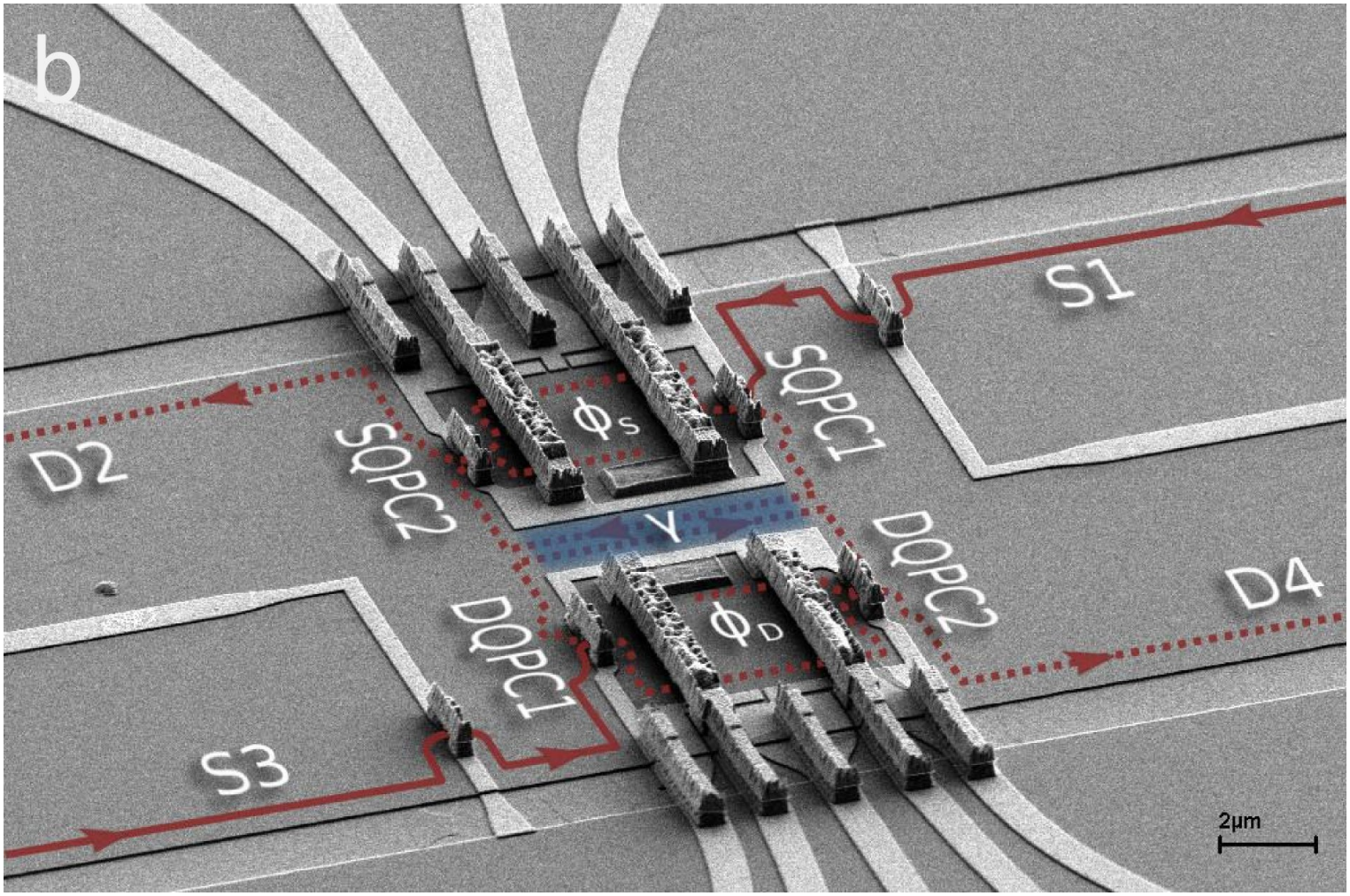




When $\gamma\ (\sim \pi/12) << \pi$

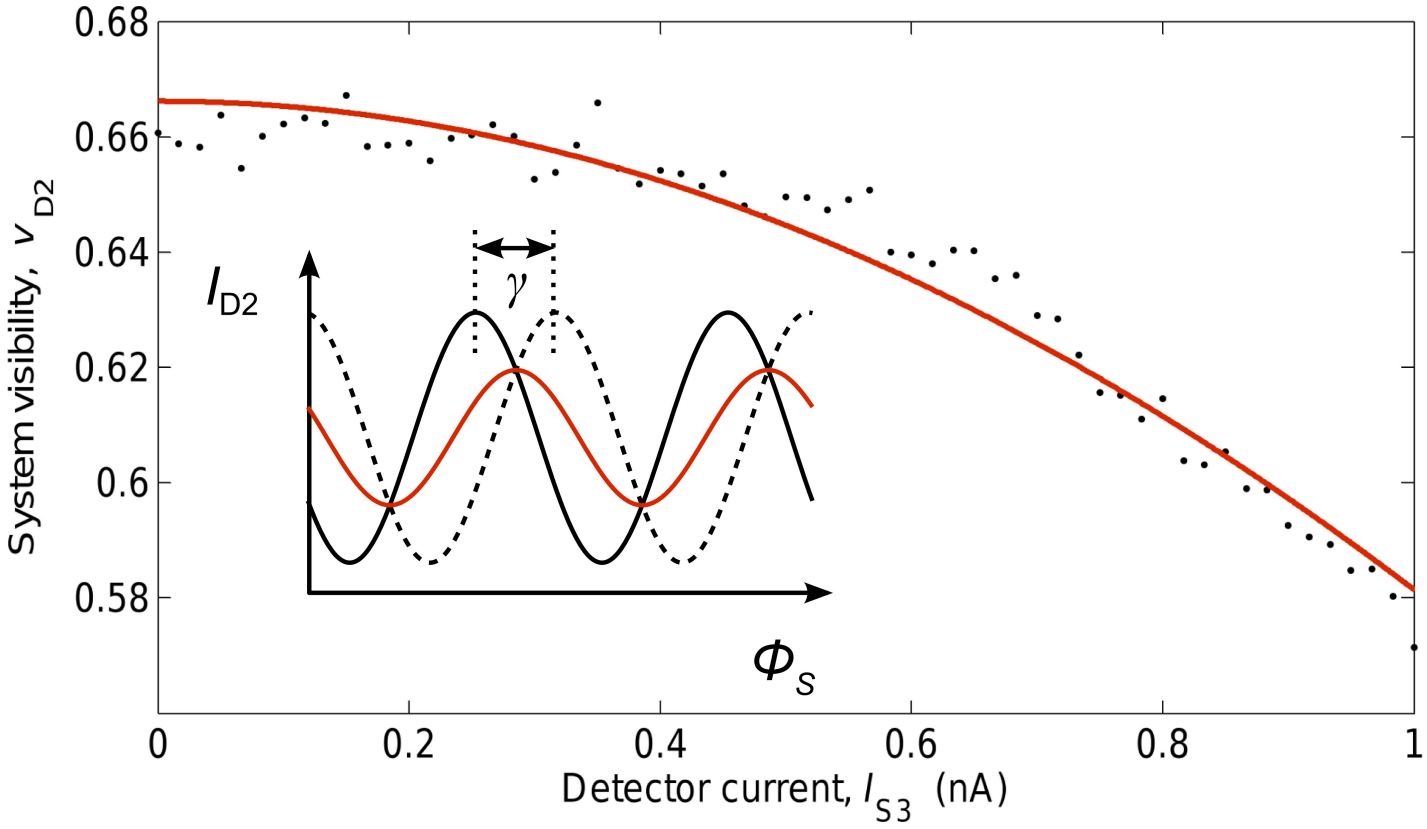
$$K(\phi_D) \equiv \left| P(\mathrm{D4}\,|\uparrow_S) - P(\mathrm{D4}\,|\downarrow_S) \right| \approx \left| \gamma \frac{\delta I_{D4}}{\delta \varphi_D} \right|$$

Realization of Double MZI



H. K. Choi, E. Weisz *et al.*, Science **344**, 1363 (2014)

Dephasing


0.68
0.66
0.64
0.62
0.6
0.58
System visibility, v_{D2}
I_{D2}
γ
Φ_S
0
0.2
0.4
0.6
0.8
1
Detector current, I_{S3} (nA)

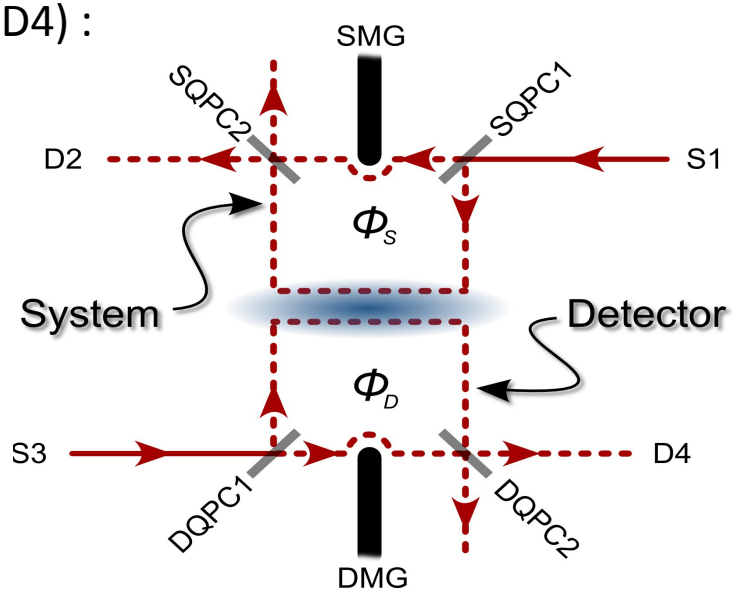
How to measure

Joint probability at system drain (D2) and detector drain (D4) :

$$P(D2D4)$$

If events at the drains are independent:

$$P(D2D4) = P(D2)P(D4)$$



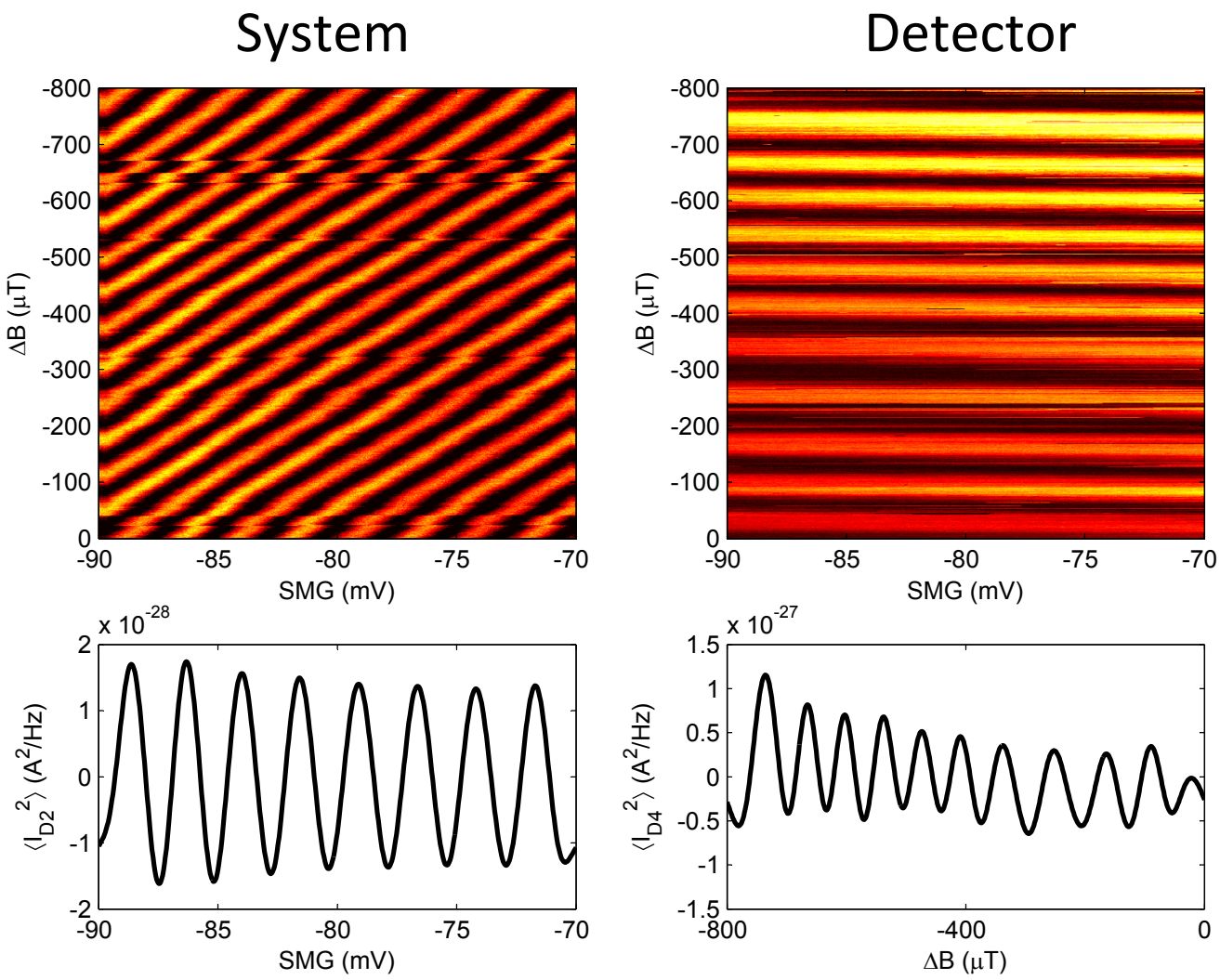
Reduced joint probability: non-trivial correlation

$$P(\delta D2\delta D4) = P(D2D4) - P(D2)P(D4)$$

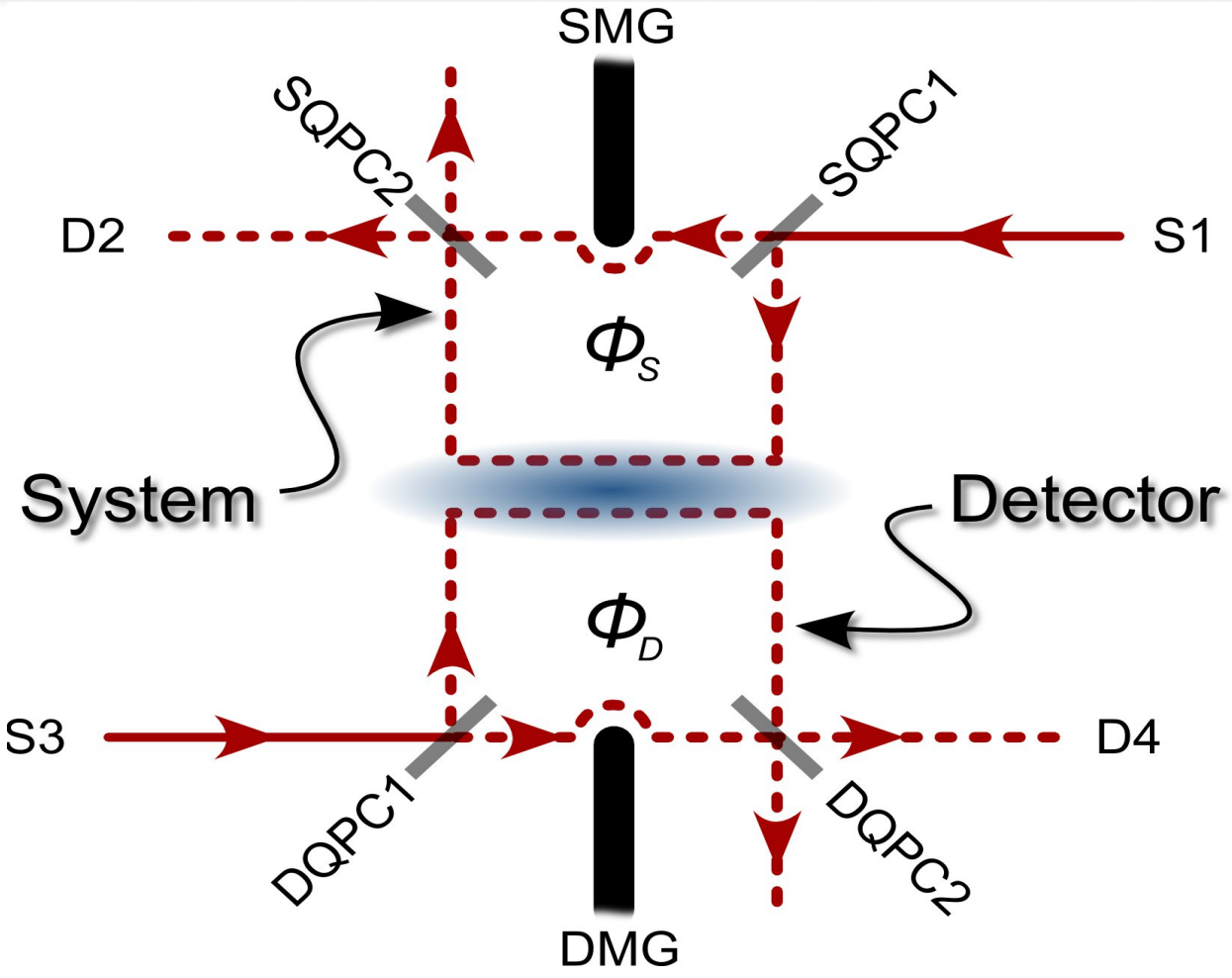
$$\propto \left\langle \delta I_{D2}\delta I_{D4} \right\rangle$$

Cross correlation
of current fluctuation

Auto correlation in MZI

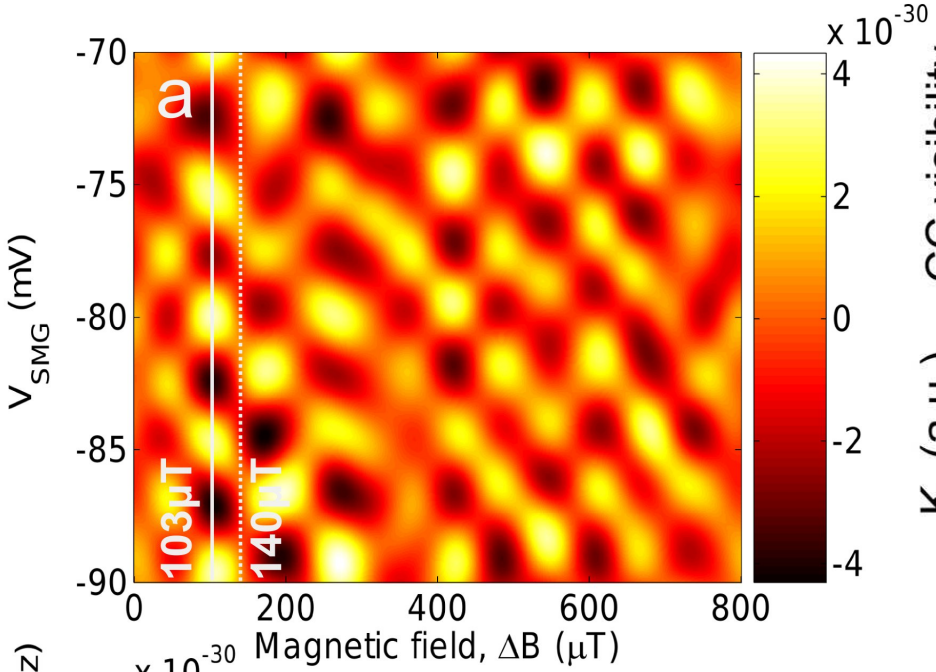


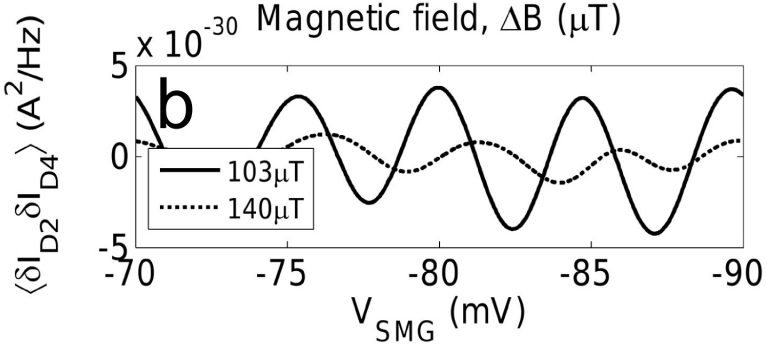
Electronic Double MZI for QE

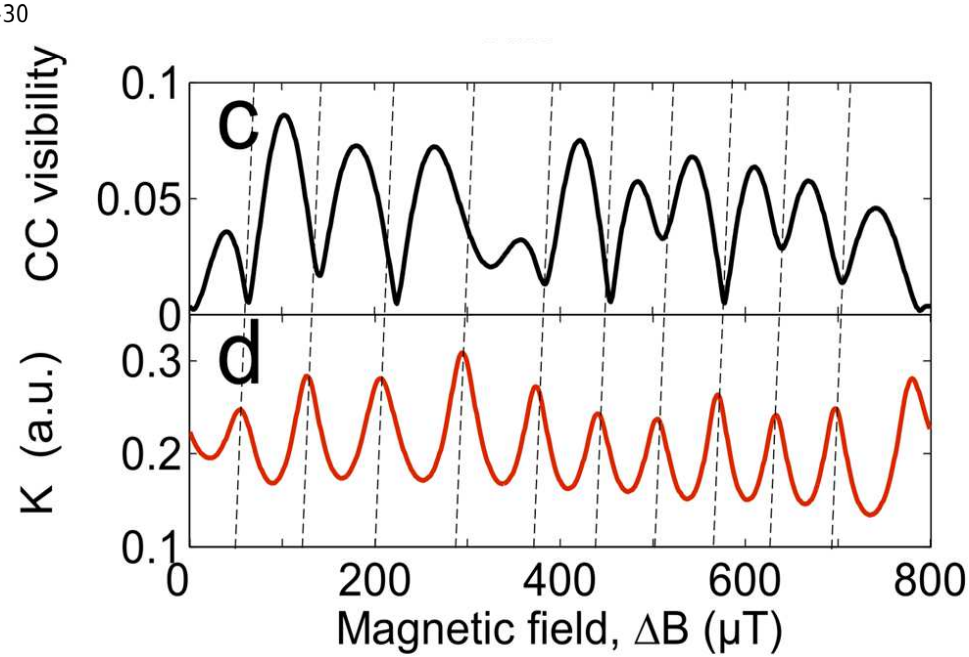


$$\left|\Psi_{total}\right\rangle = \left|\uparrow_S\right\rangle \otimes \left|D^{\uparrow}\right\rangle + \left|\downarrow_S\right\rangle \otimes \left|D^{\downarrow}\right\rangle$$

Electronic Quantum eraser







Anti-correlation

Summary 2

First realization of quantum eraser in electronic system

Control of both entanglement strength and detectability

Can controlled quantum eraser be proof of complementarity?

This setup can be good platform to explore weak-values or the Bell inequality