Unexpected Pairing in the IQHE Regime

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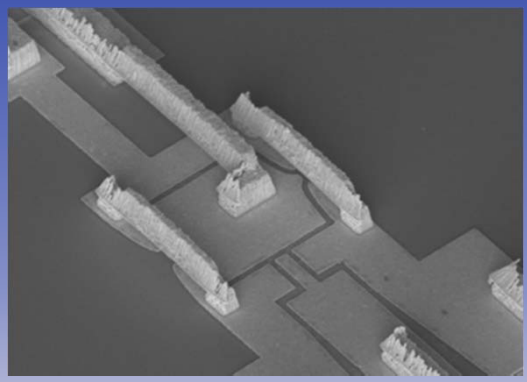


during the process of looking

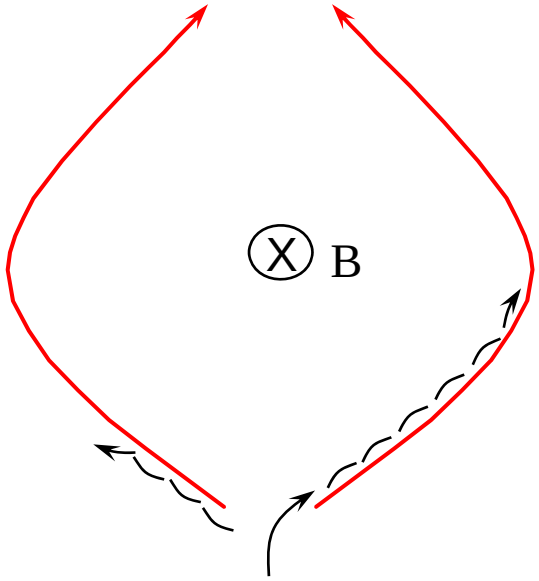
for interference of fractional charges

we stumbled upon...

unexpected interference phenomenon in IQHE

.... start with interferometers in the QHE regime

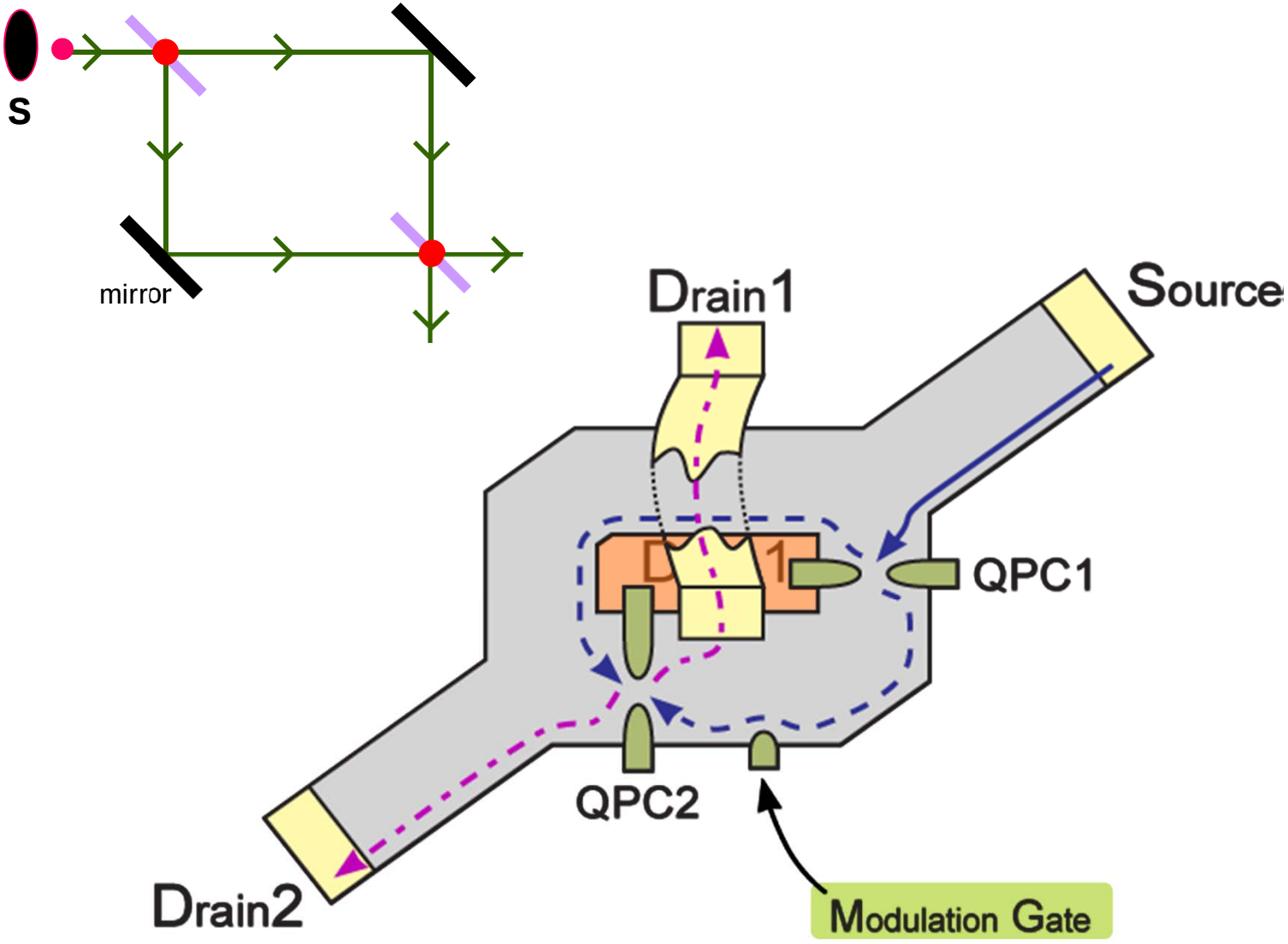
interfering edge channels



two-path Mach-Zehnder & many-path Fabry-Perot

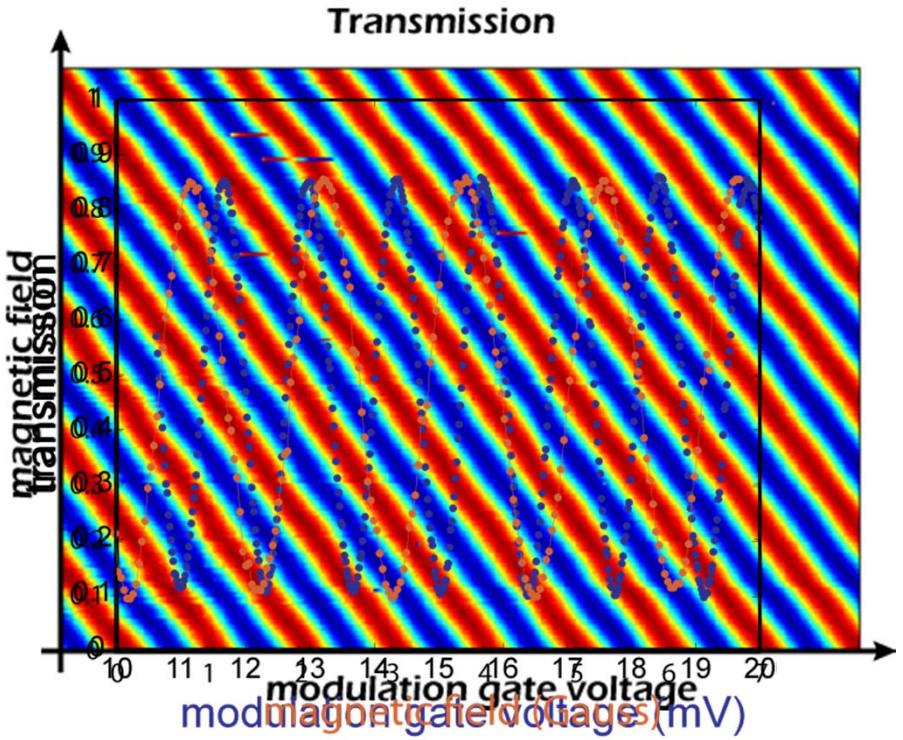
electronic MZI

two path interference



modulation of phase

Aharonov-Bohm phase



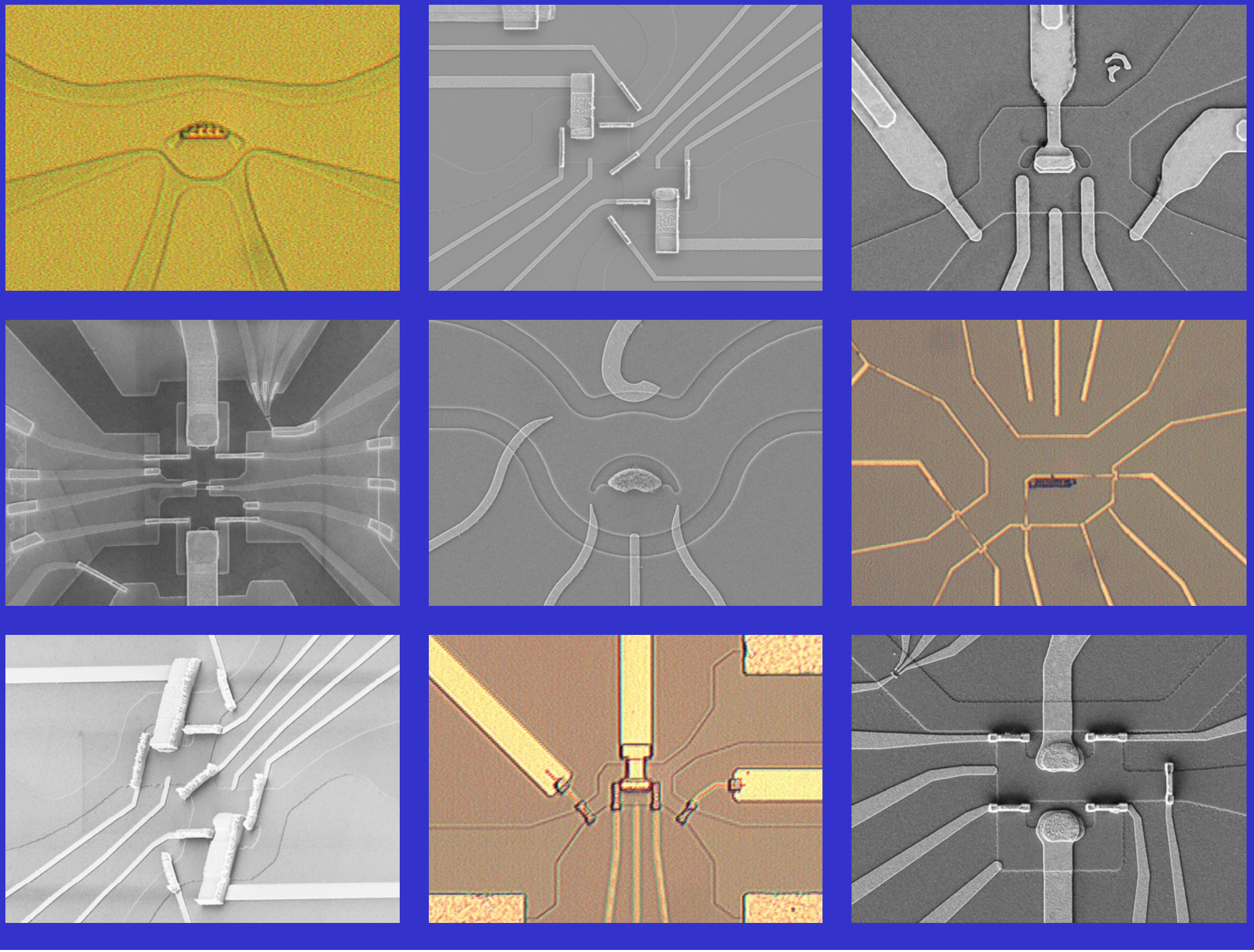
$$\Delta\varphi = 2\pi \frac{\Delta\Phi}{\phi_0}$$

$$\Delta\Phi = B \cdot \Delta A + A \cdot \Delta B$$

mind the slope...

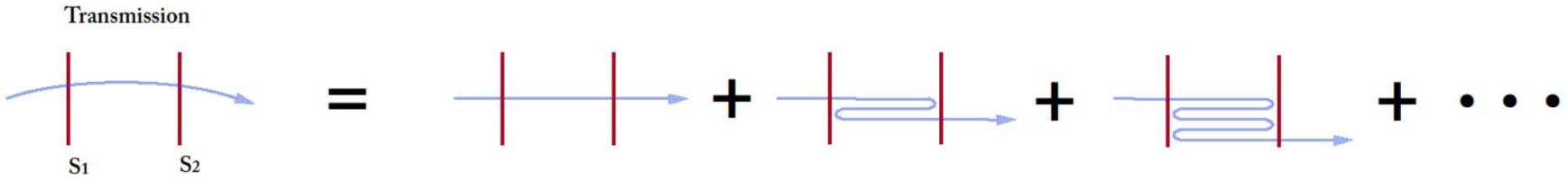
true AB interference

AB area = geometrical area



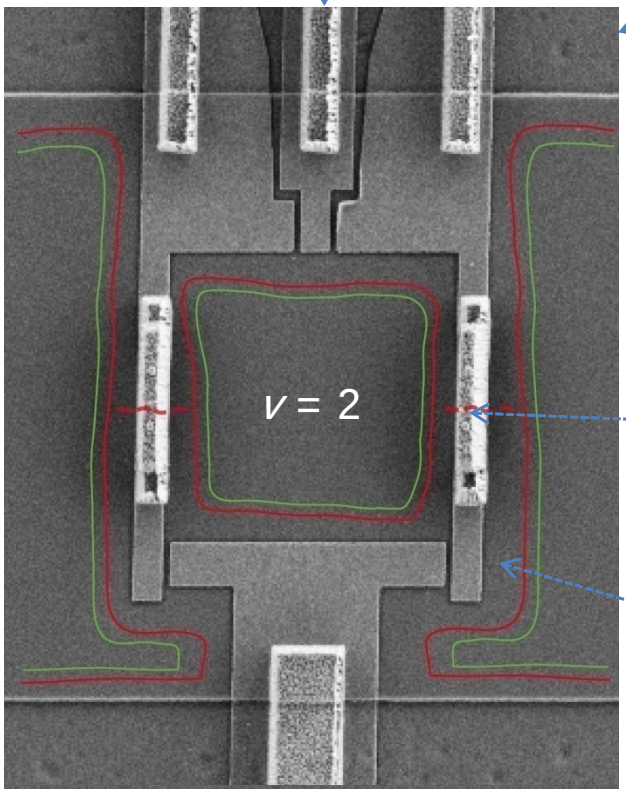
electronic FPI

many-path interference

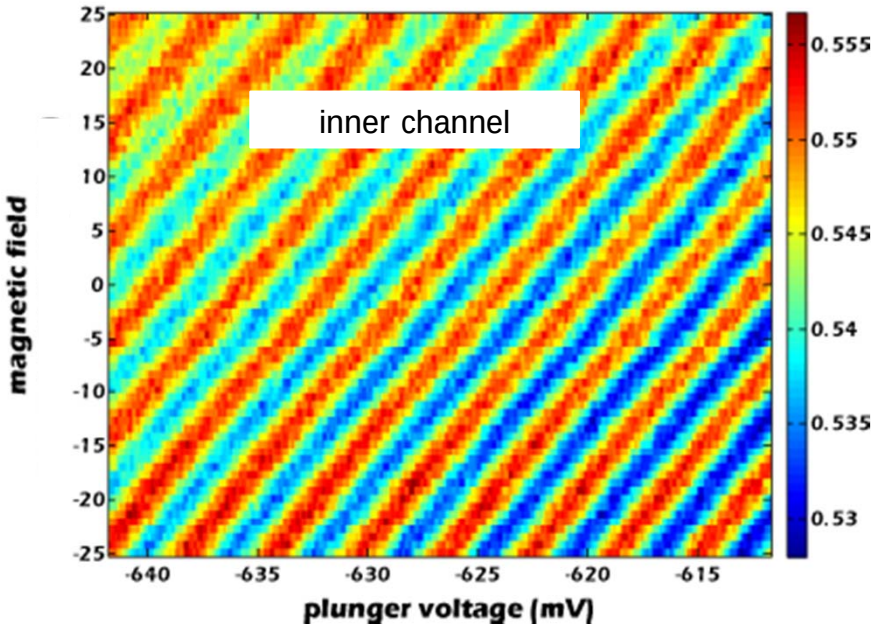


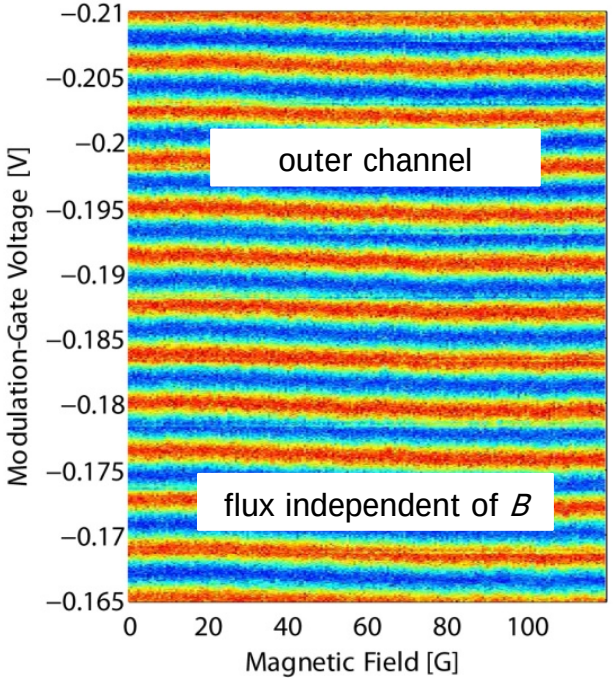
actual realization

2DEG in GaAs-AlGaAs

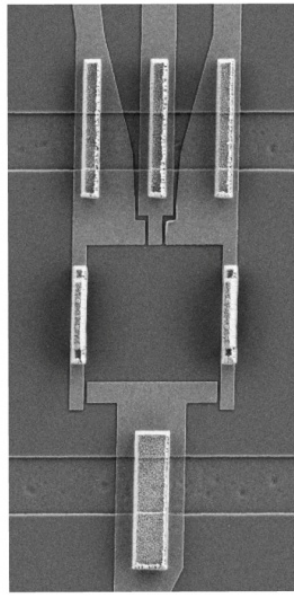


however, Coulomb interactions → dominate





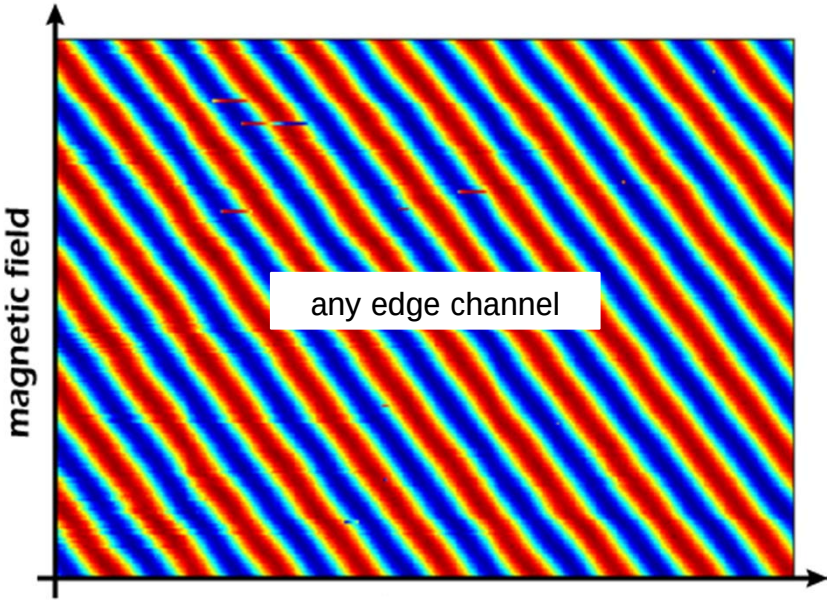
bare FPI

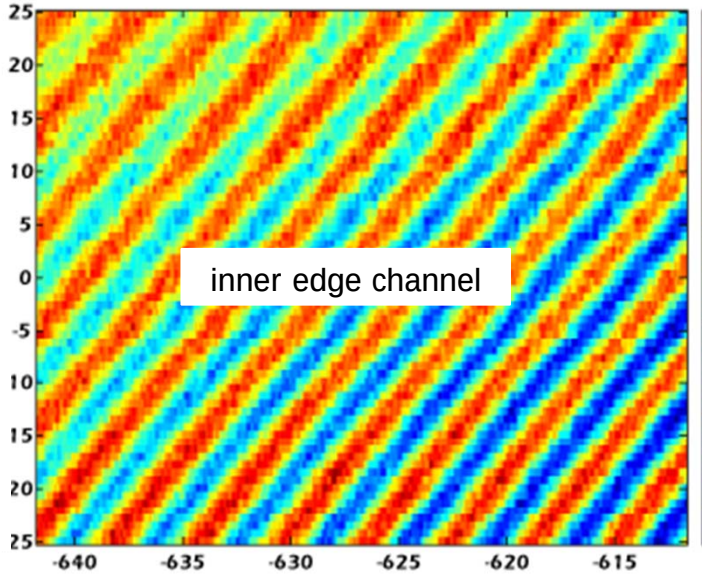


MZI integers only **FPI**

AB interference

Coulomb dominated

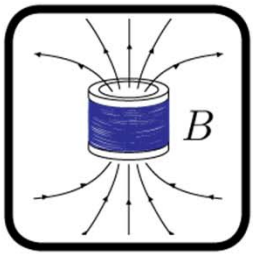




increasing area →

area shrinks with increasing *B*

experiments w / FPI



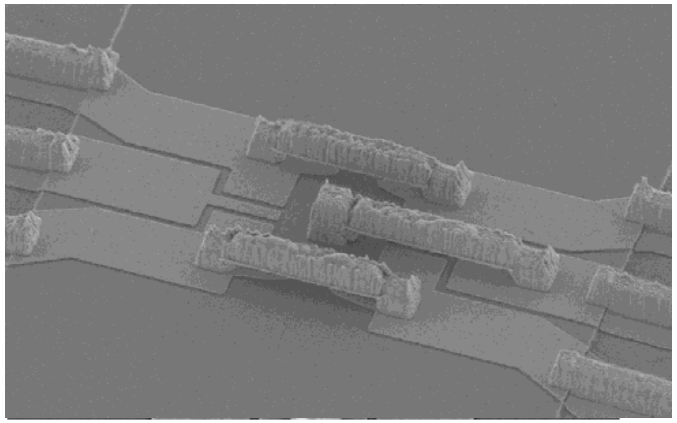
B = 2-9 T

T =20-30 mK

n_e =1-2.5 x 10^{11} cm^{-2}

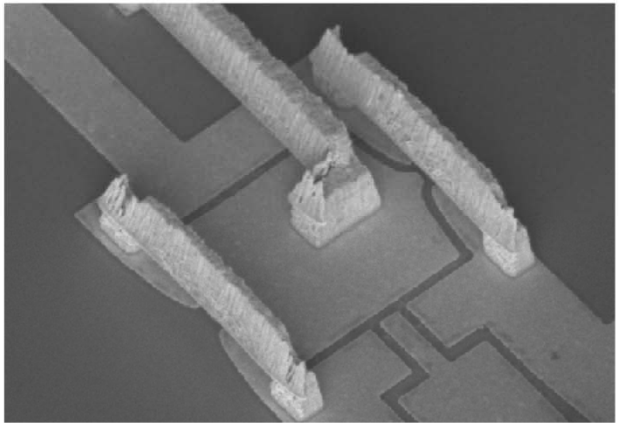
screening Coulomb interaction in FPI

Fabry-Perot with ohmic-contact



effective screening, AB all sizes

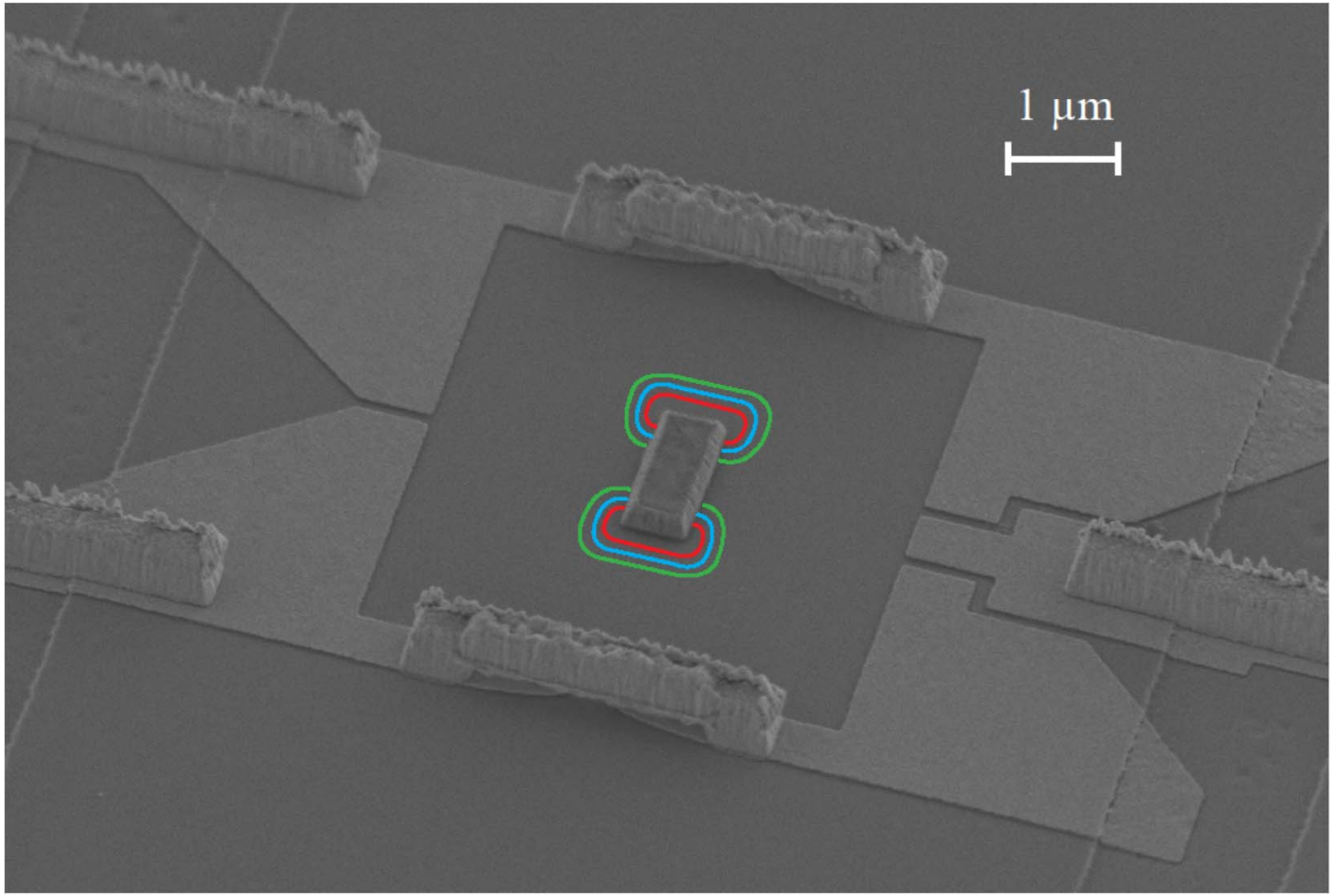
Fabry-Perot with top-gate



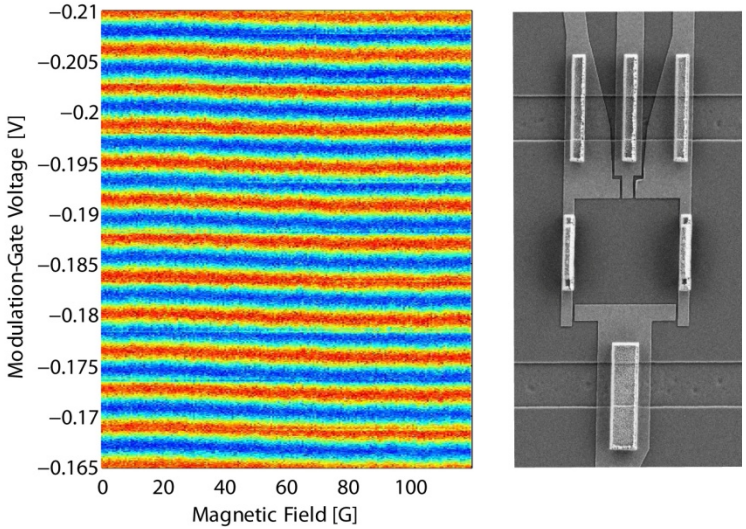
effective screening, AB >~4 μm^2

tested FPI areas.....2 – 16 μm^2

ohmic in center of incompressible bulk

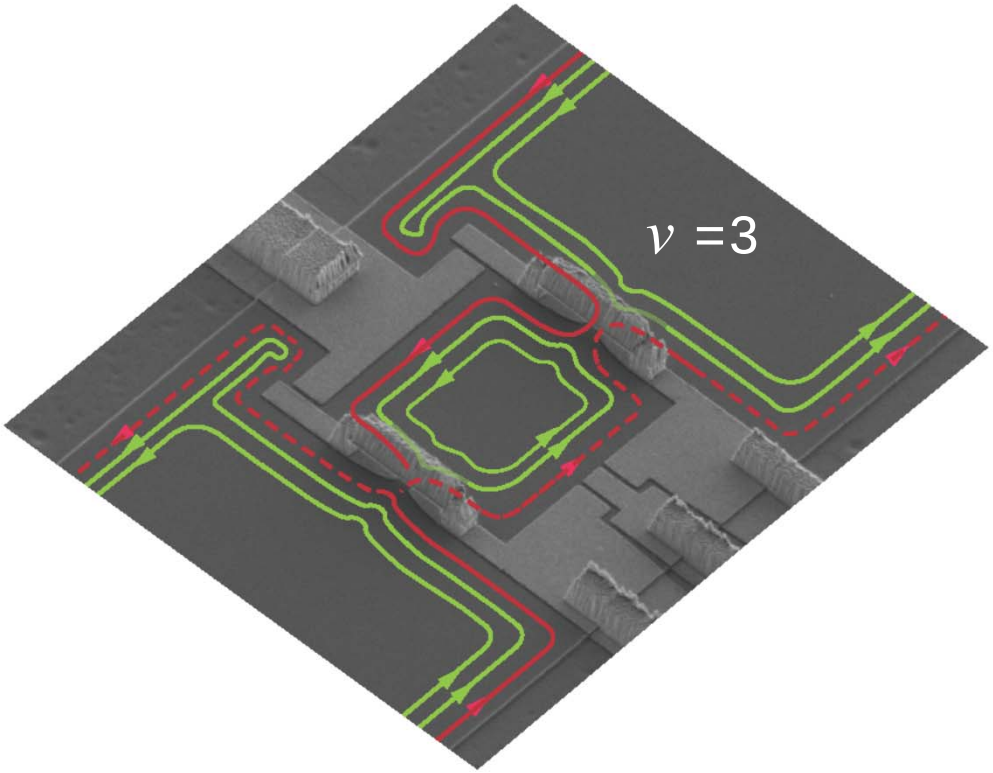


Coulomb dominated

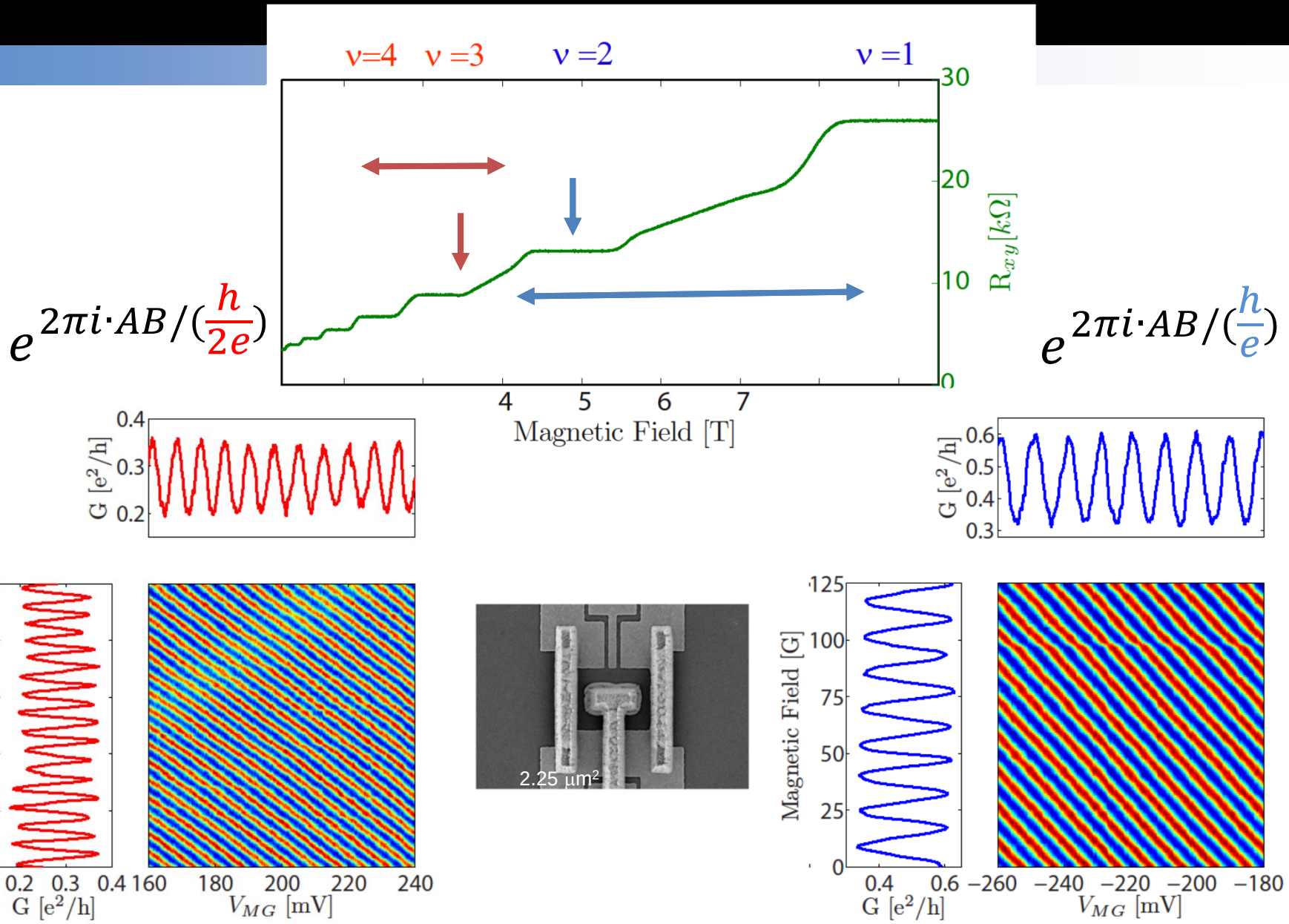


our experiments:

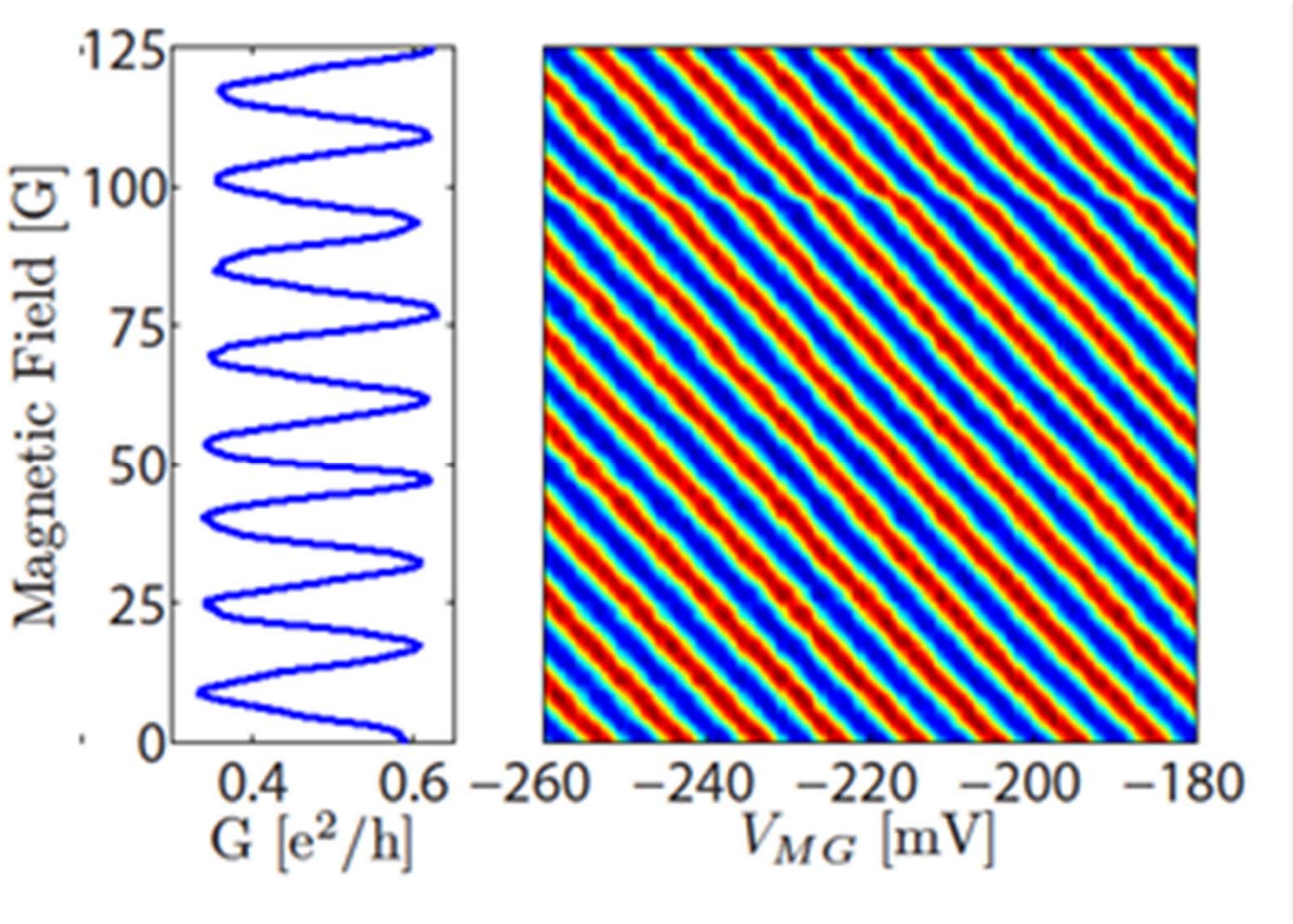
interference of *outer* edge channel



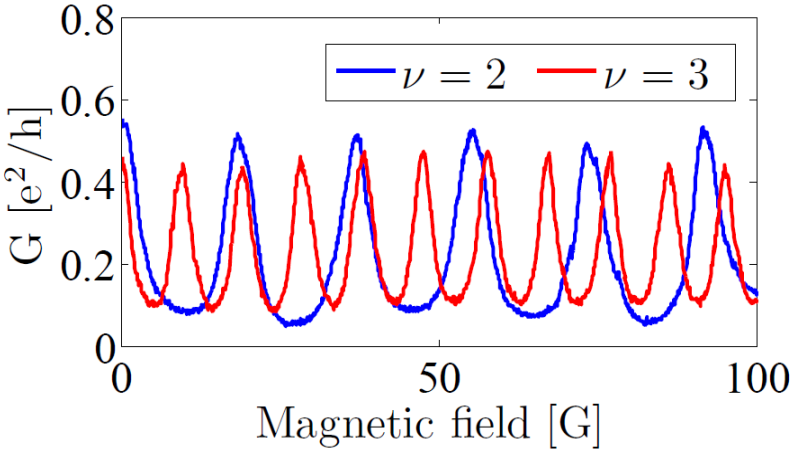
AB interference

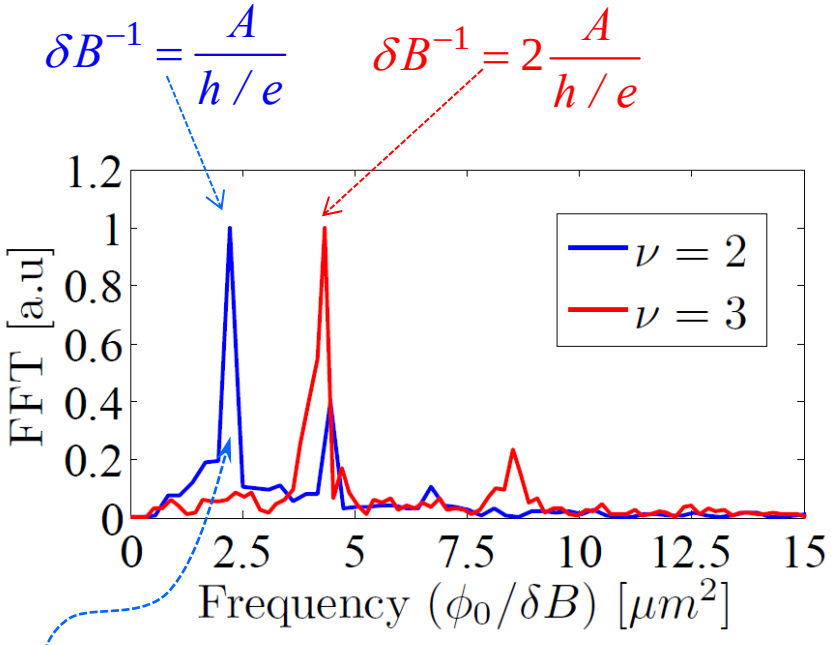


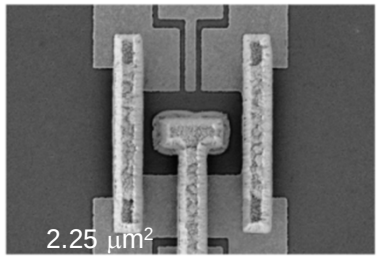
periodicity in *B*



periodicity in *B*

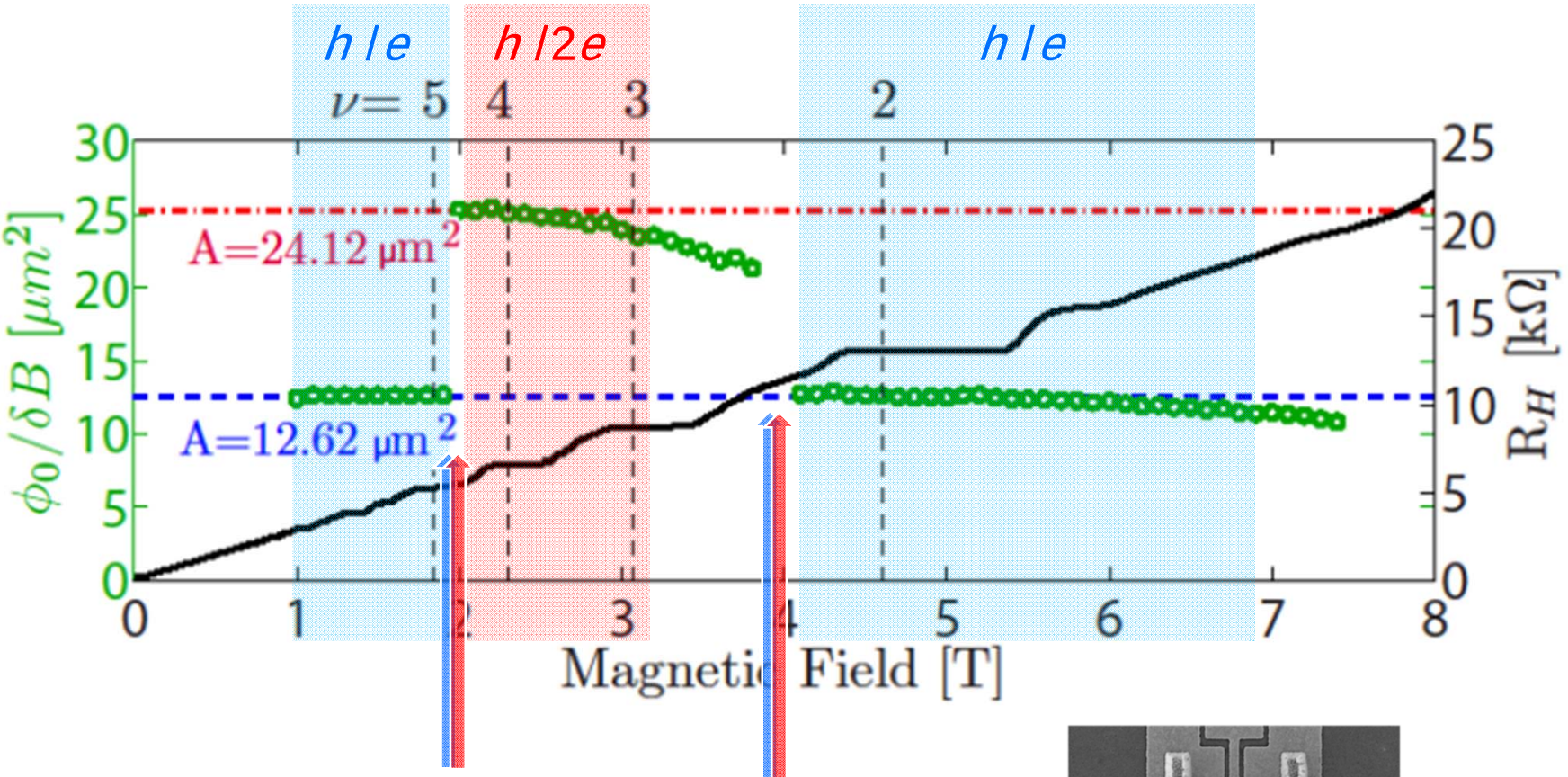






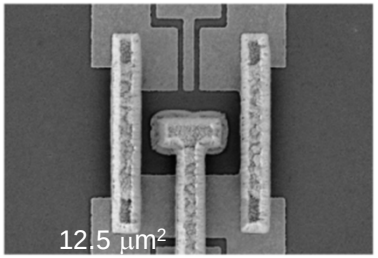
universality of results...

periodicity in *B* …. large FPI 12.5μm

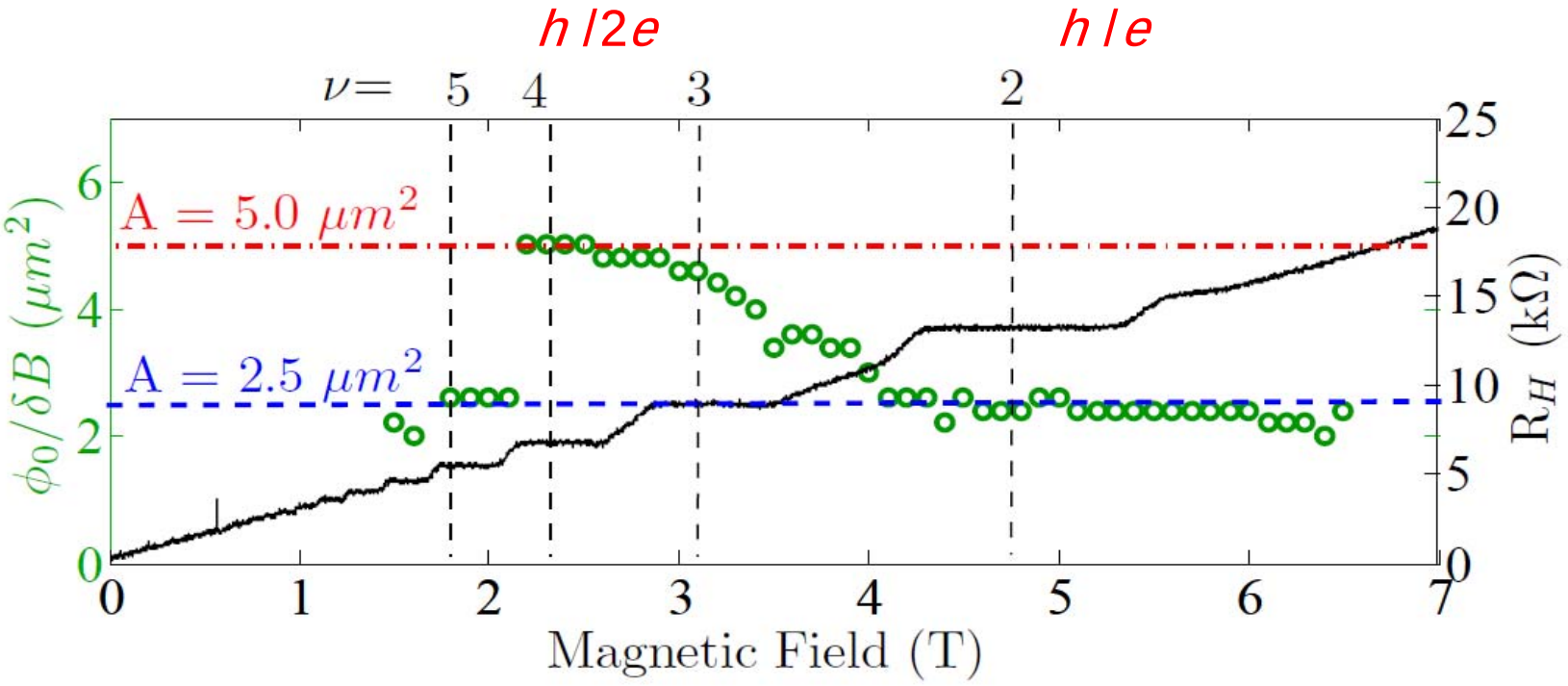


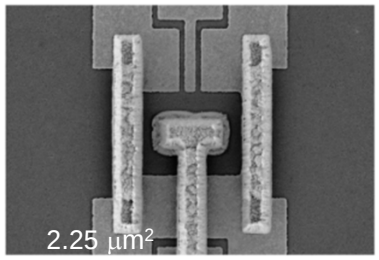
coexistence *h*/*e* & *h*/2*e*

zero visibility

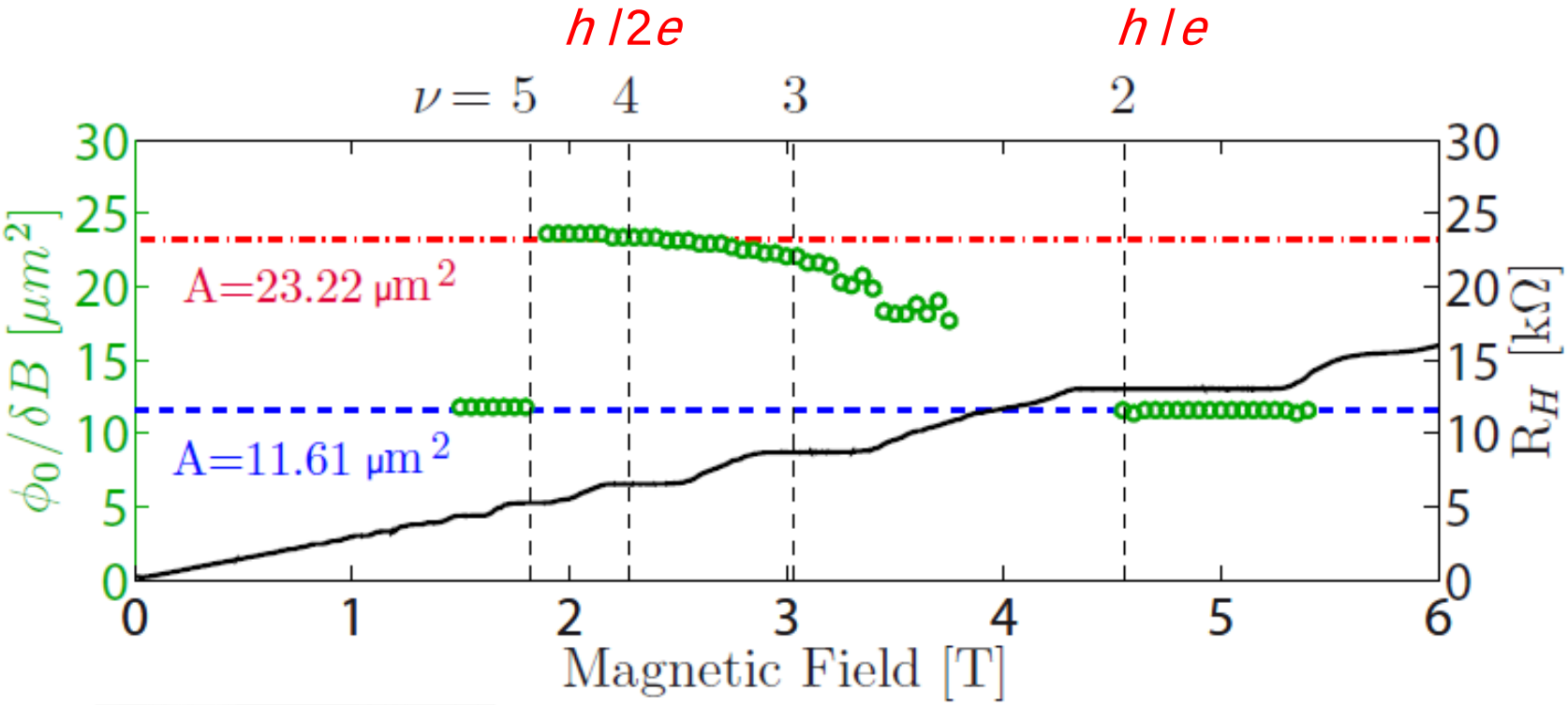


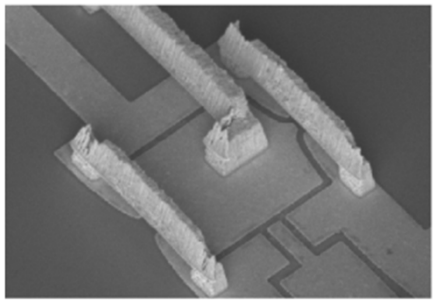
periodicity in *B* …. small 2.5μm



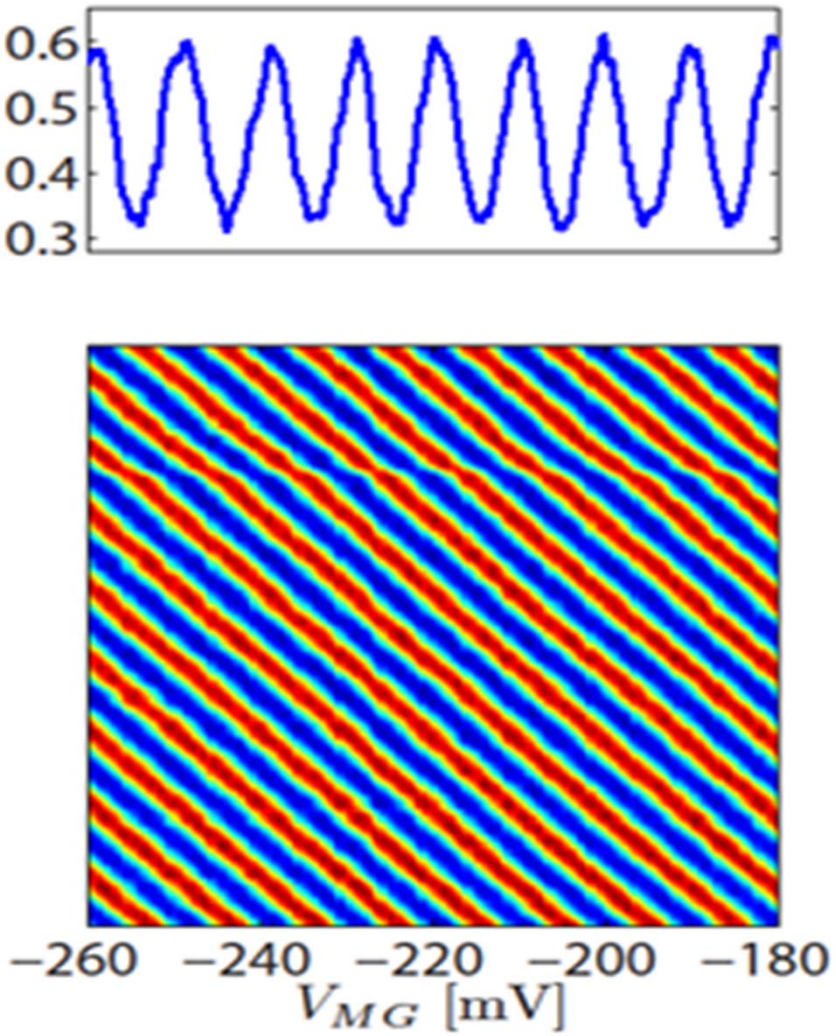


periodicity in *B* …. large 12μm





periodicity in V_{MG}



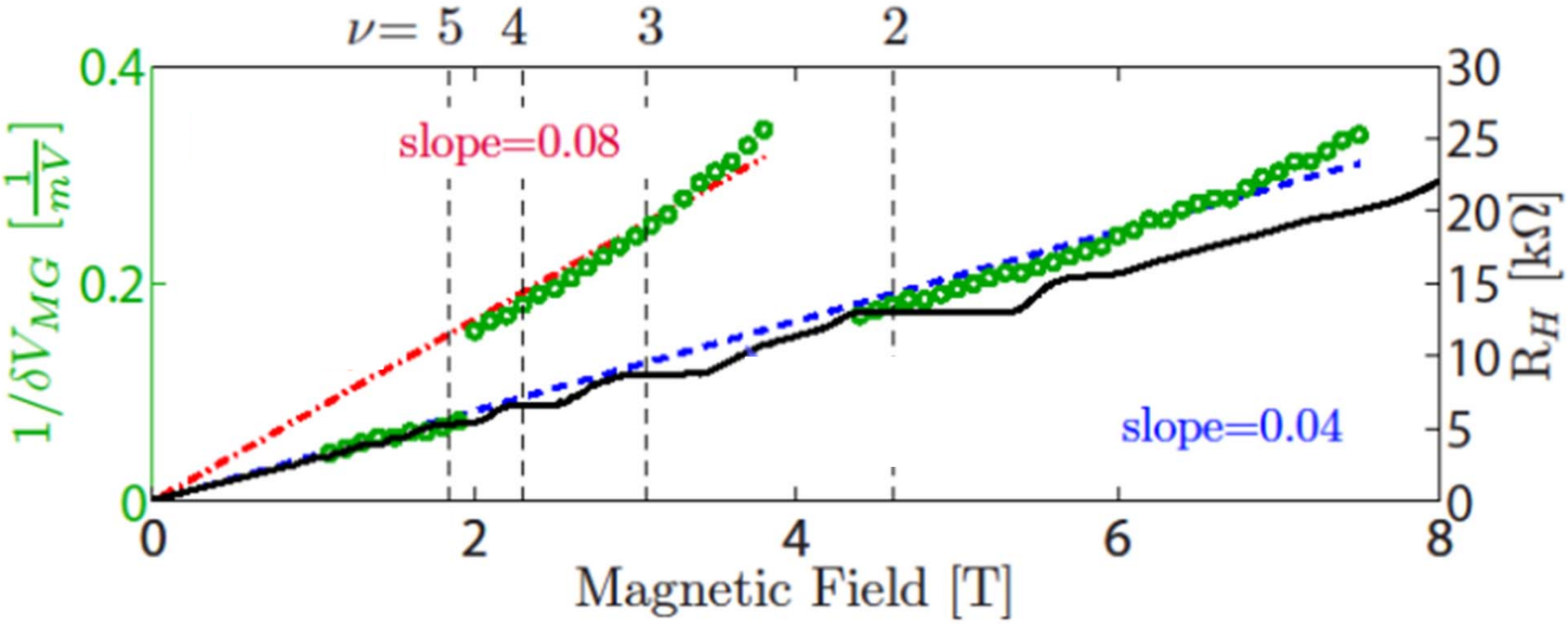
periodicity in V_{MG}

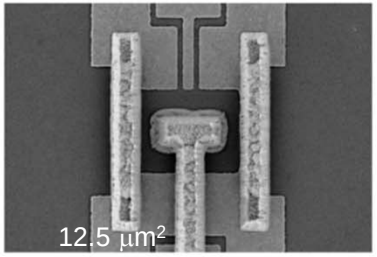
$$\delta Q = C_{MG} \times \delta V_{MG}$$ assumed constant capacitance to outer channel

$$\delta Q = e n_e \times \delta A$$

$$B \times \delta A = \Phi_0^*$$ periodicity in *B*

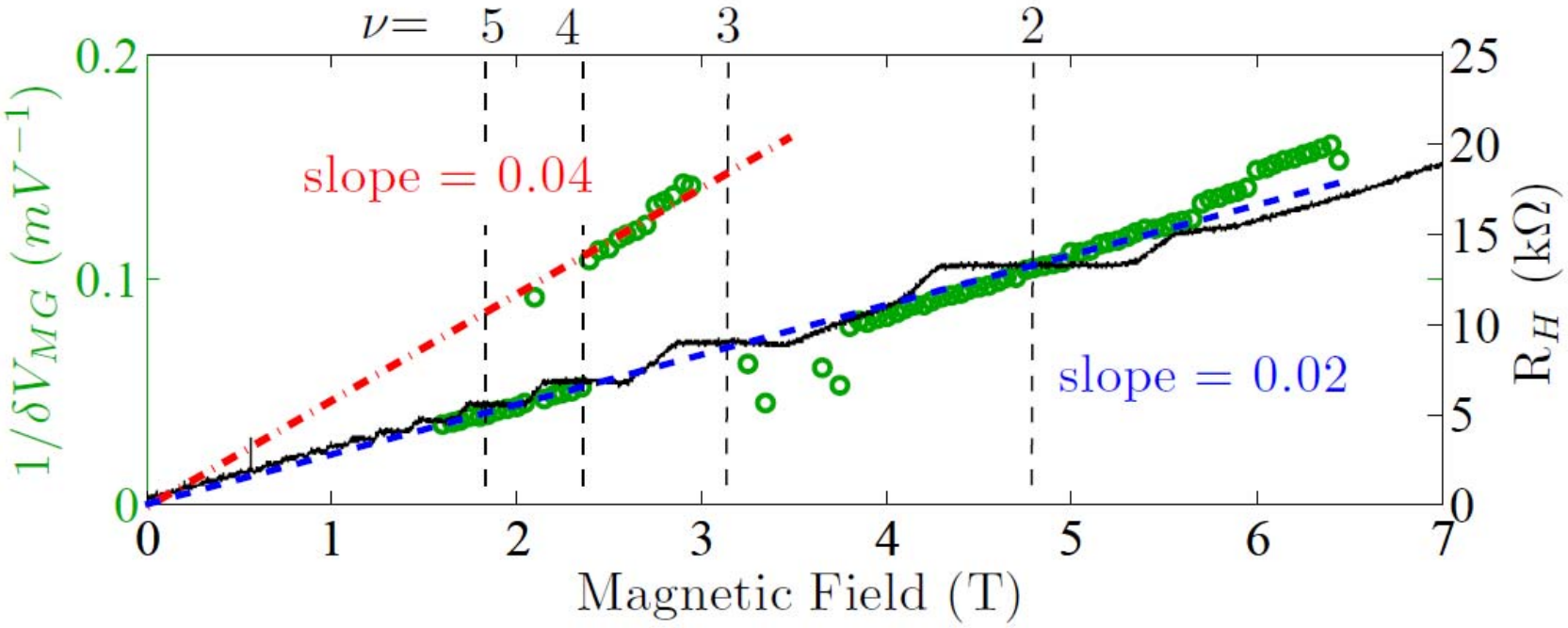
periodicity in V_{MG} .... large 12.5μm





doubled slope....$e^*=2e$

periodicity in V_{MG} .... small 2.25μm



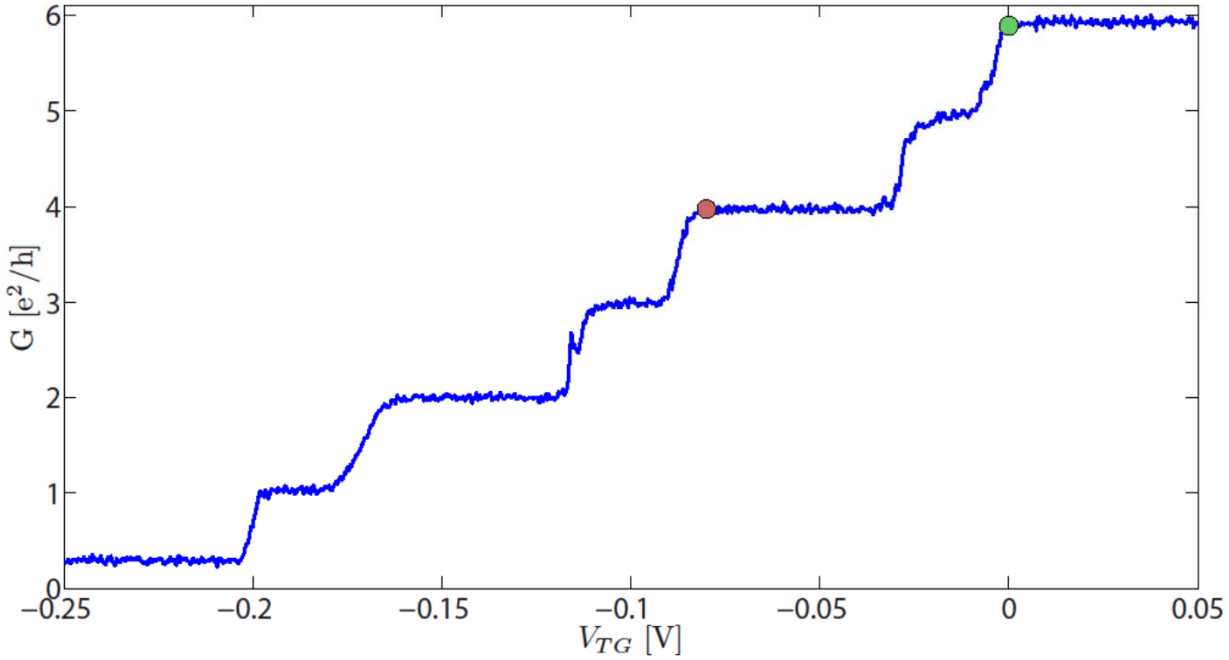
a few tests:

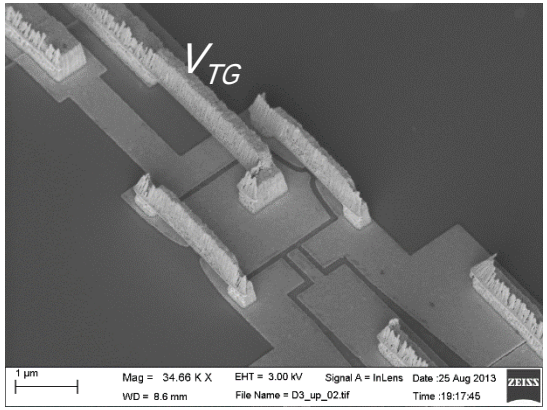
- bulk filling ν_B
- transparency of FPI
- $h/2e$ only in outer channel ?
- temperature dependence
- phase relation between h/e and $h/2e$
- tunneling between channels
- coherence and dephasing

only $ff = \nu_B$ dependence

varying density with top gate $n_e \in (1.3 - 2.4) \cdot 10^{11}\,\mathrm{cm}^{-2}$

$\nu_B = 6 \rightarrow \boldsymbol{h/e}$

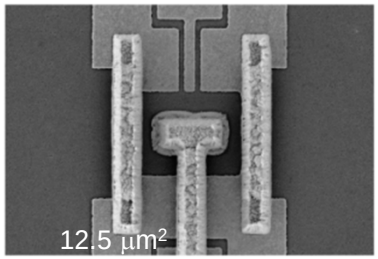




independence on transmission coefficient

large FPI

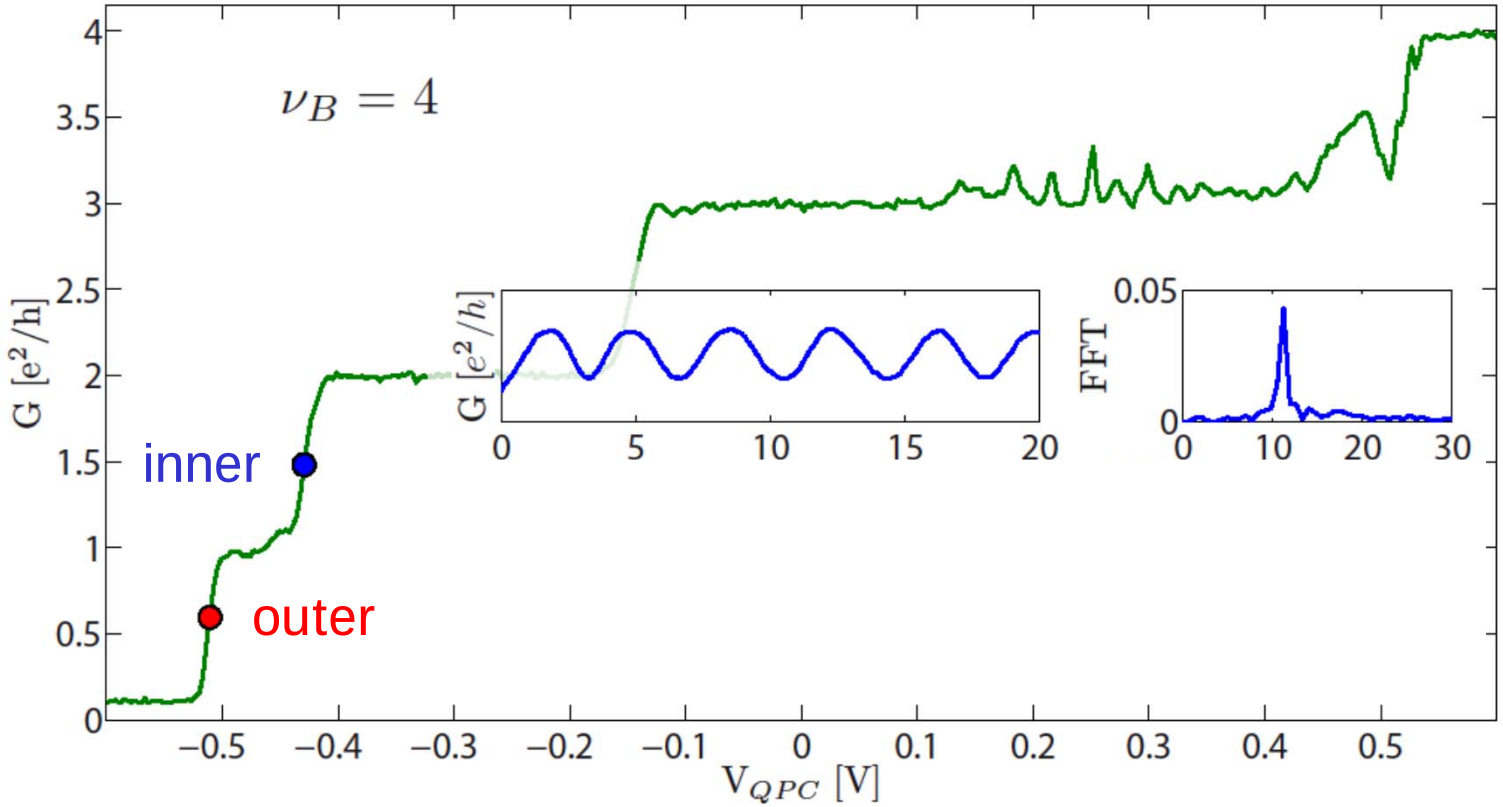
h/e regime



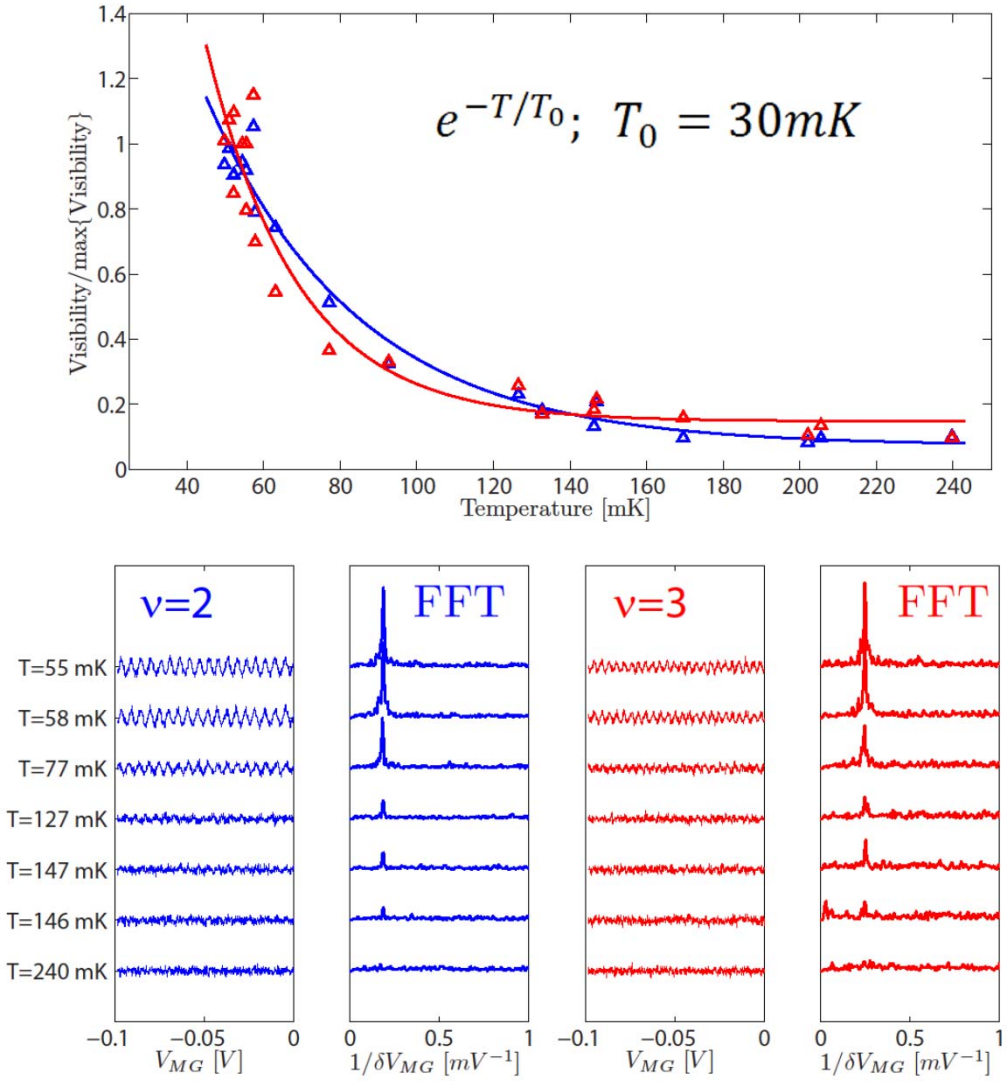
$h/2e$ regime

inner channel shows only *h / e*

LL1 @ $\nu_B \sim 4 \rightarrow h/2e$ *outer* $\rightarrow\rightarrow$ LL2 @ $\nu_B \sim 4 \rightarrow h/e$ *inner*



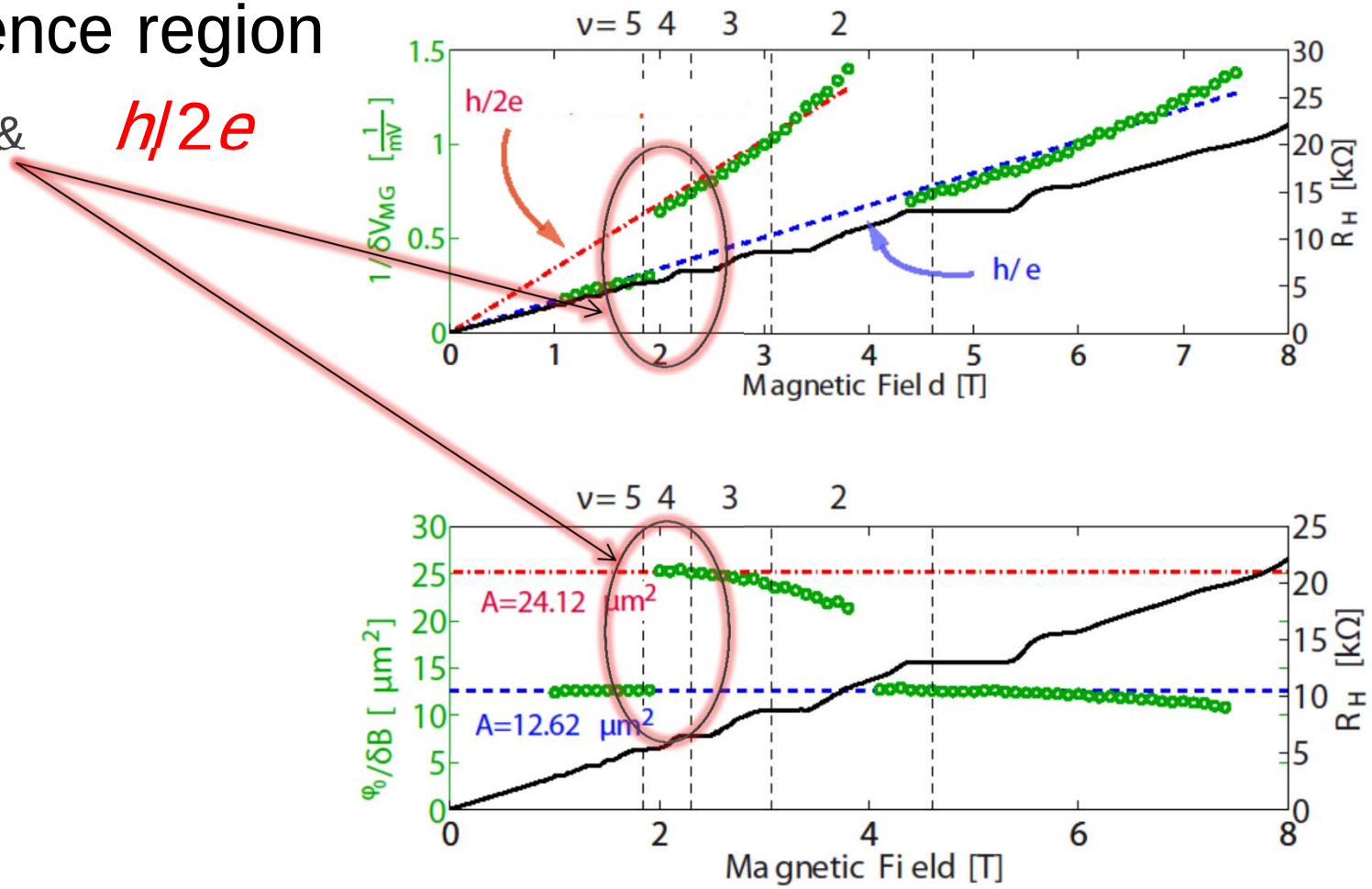
temperature dependence



coexistence of h/e & $h/2e$ ..... $\nu_B \sim 4$ - 4.5

coexistence region

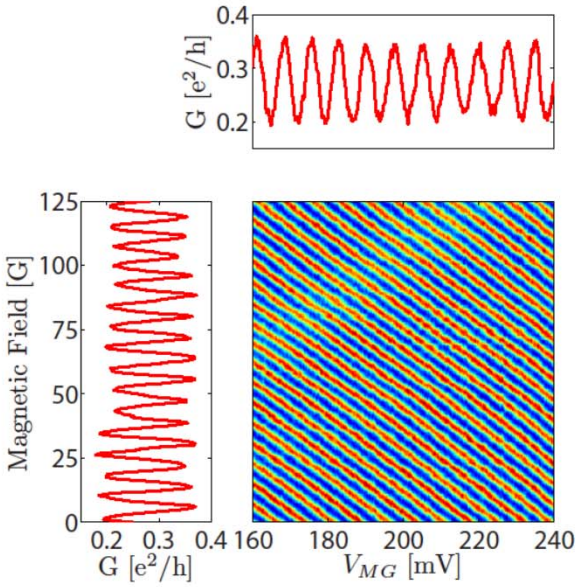
h/e & $h/2e$



unique phase relation *h/e* & *h/2e*

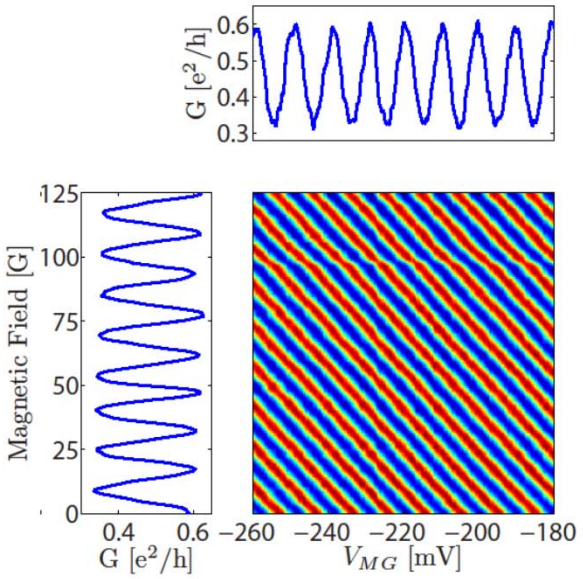
$\nu_B = 3$

$$\cos\left(2\pi i \cdot \frac{AB}{h/\mathbf{2e}}\right)$$



$\nu_B = 2$

$$\cos\left(2\pi i \cdot \frac{AB}{h/e}\right)$$



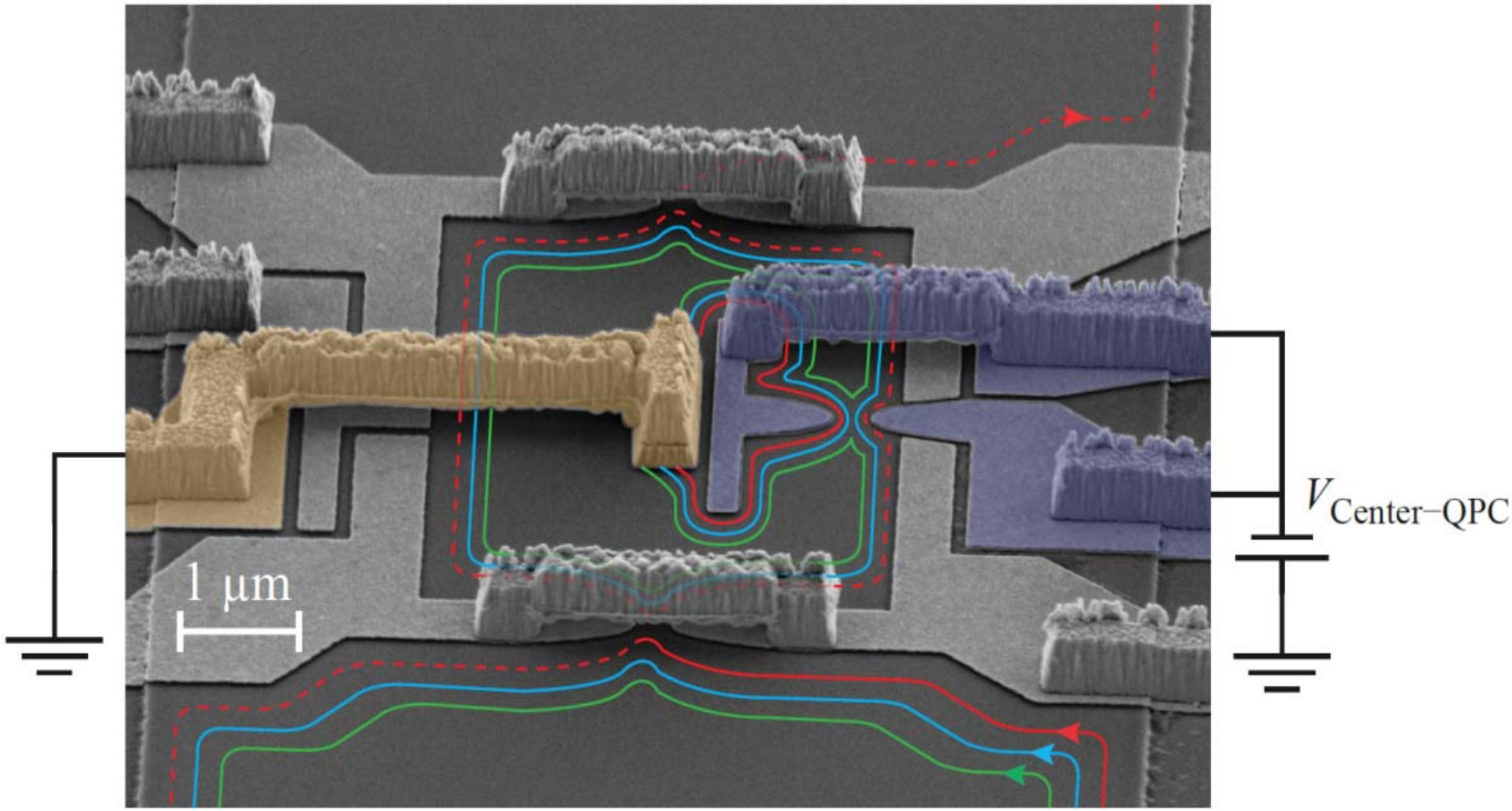
no tunneling between

edge channels

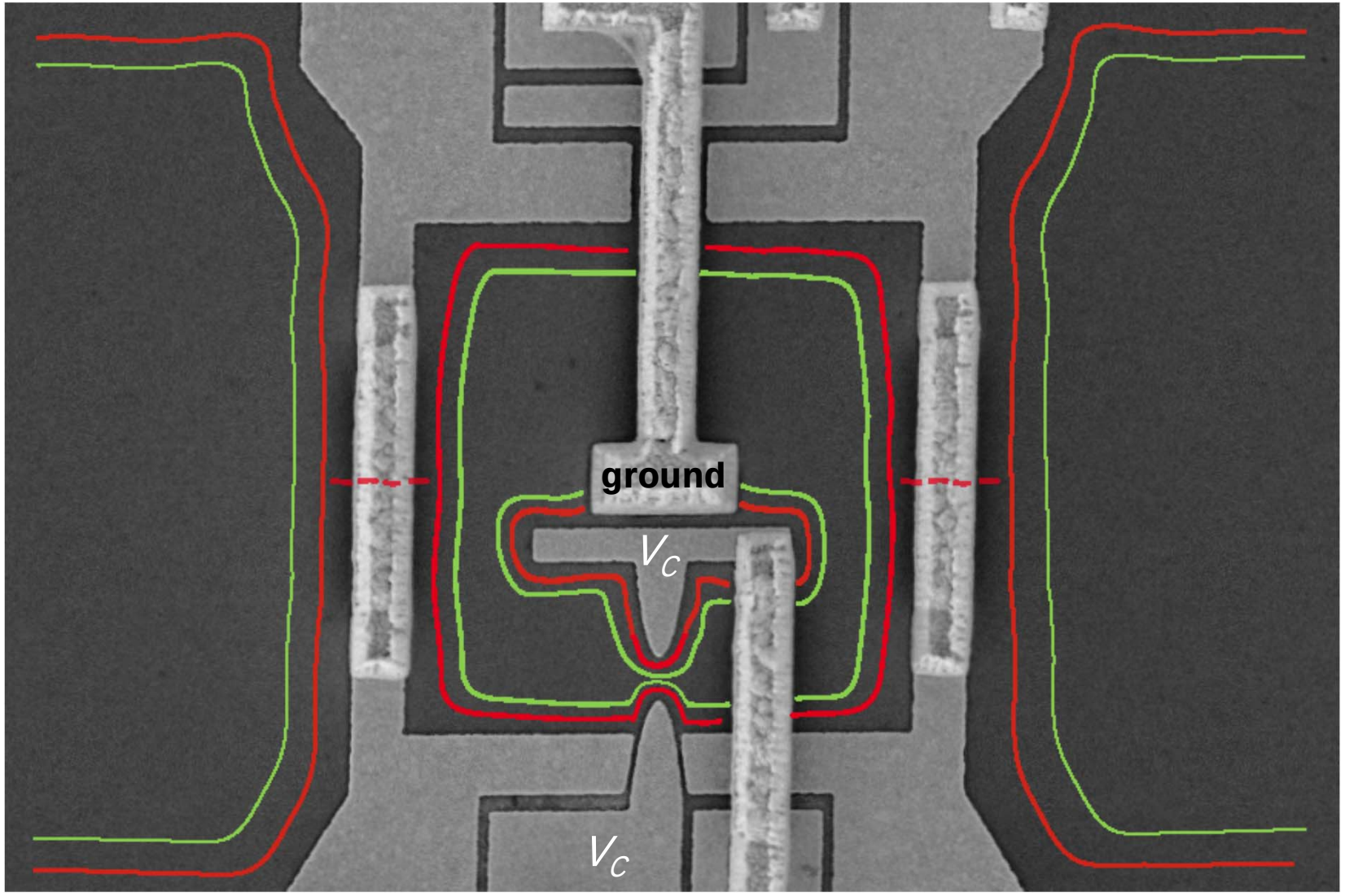
coherence and dephasing

preferential dephasing of channels

adding a ‘center QPC’

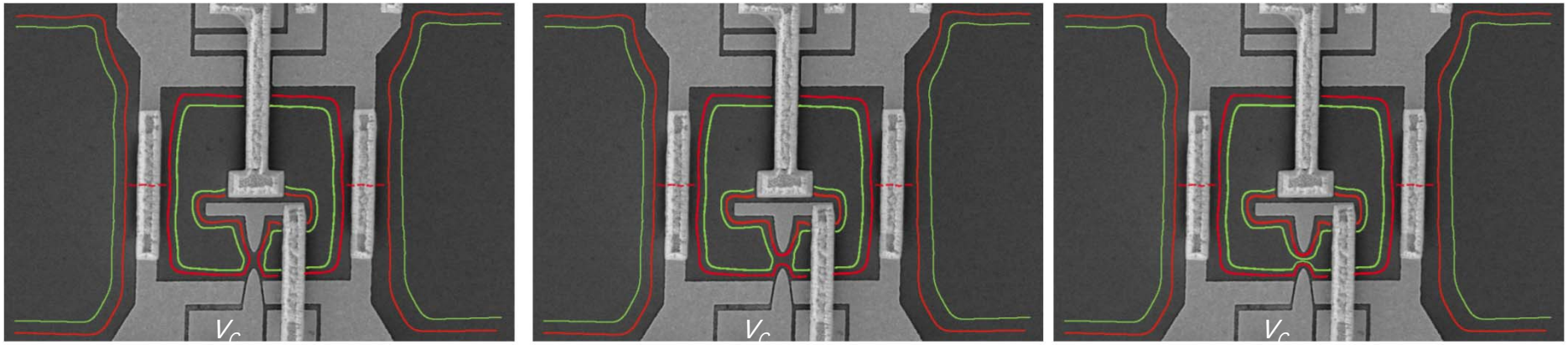


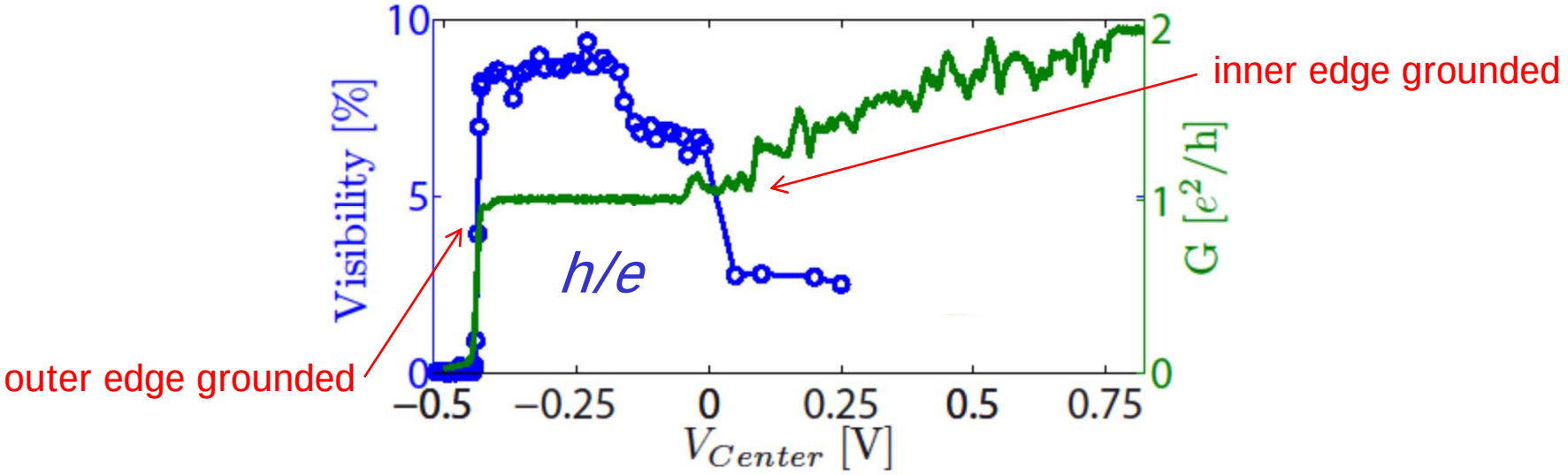
preferential dephasing of channels



role of second channel @ $\nu_B = 2$

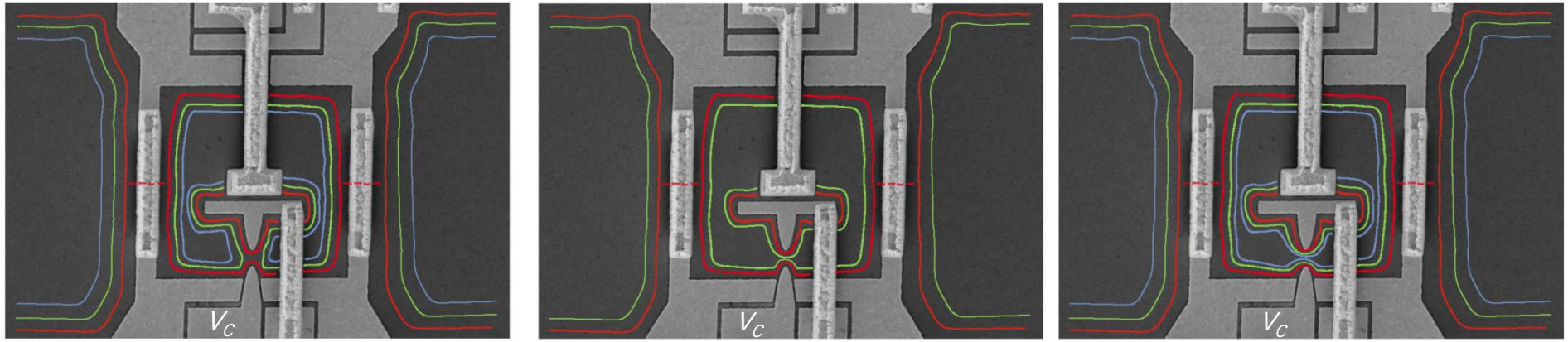
dephasing of second channel is irrelevant





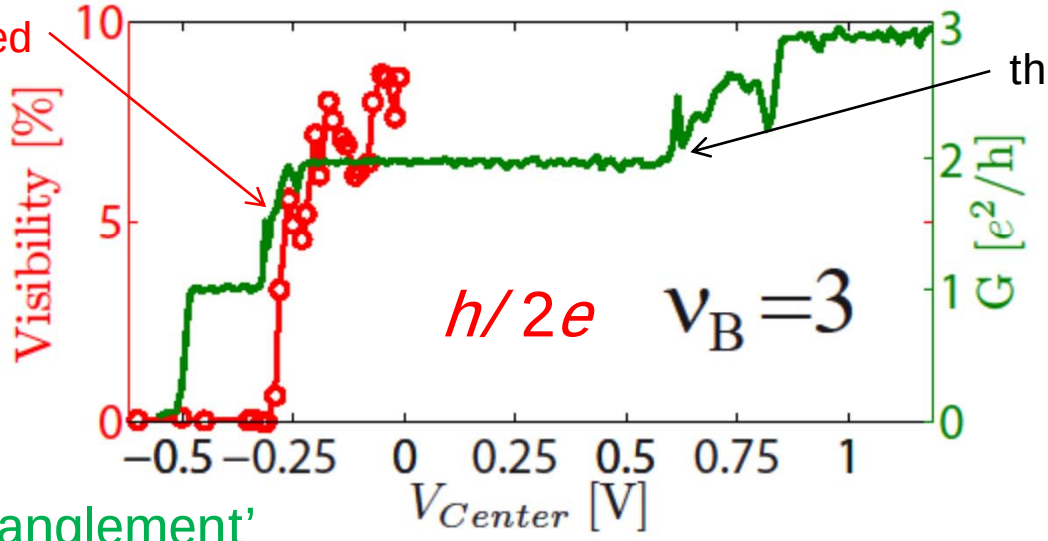
role of second channel @ ν_B =3

dephasing of second channel fully dephases the outer channel



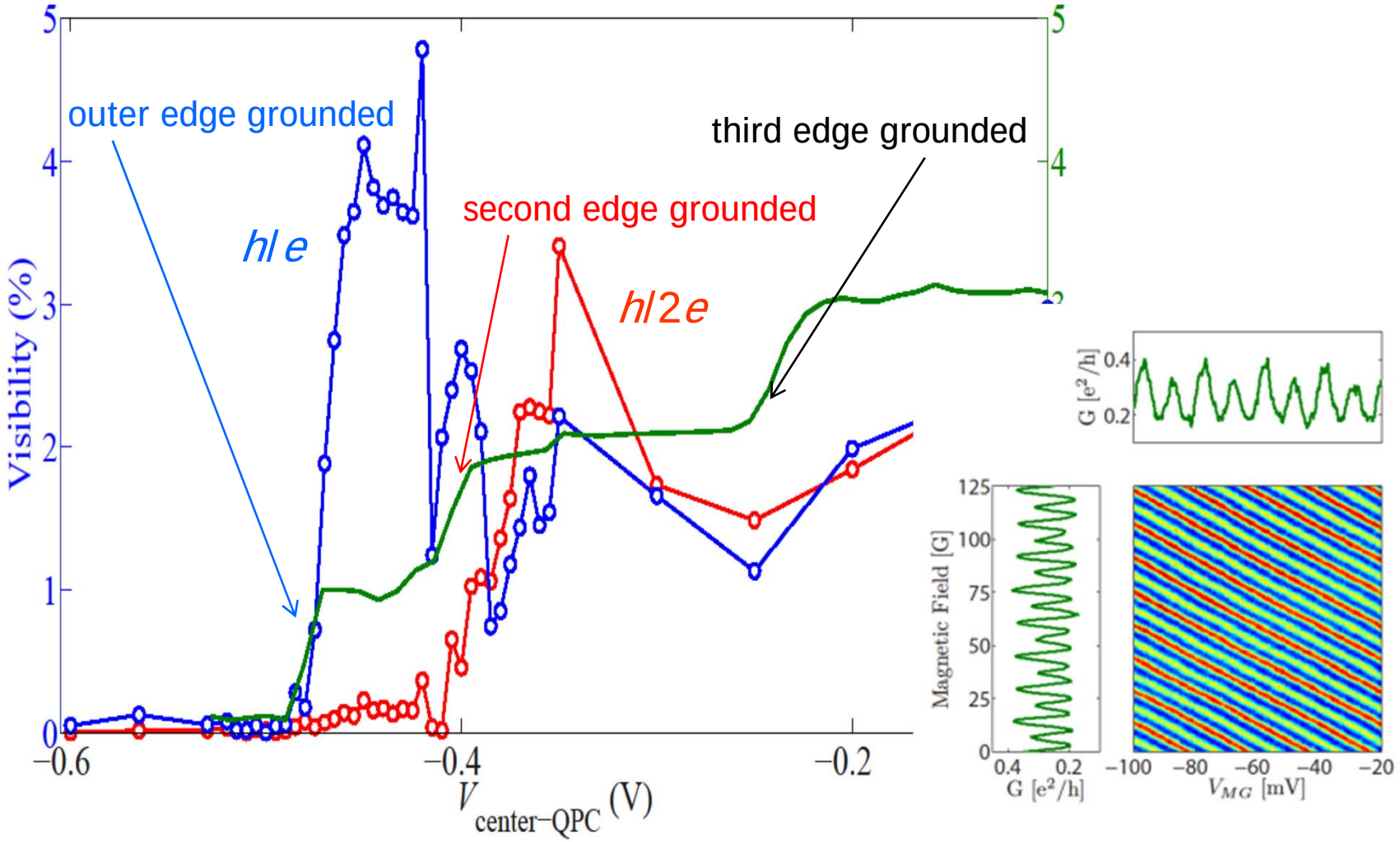
second edge grounded

third edge grounded



'two-channel entanglement'

dephasing $h/2e$ @ $\nu_B = 4.5$ coexistence regime



preference of even windings

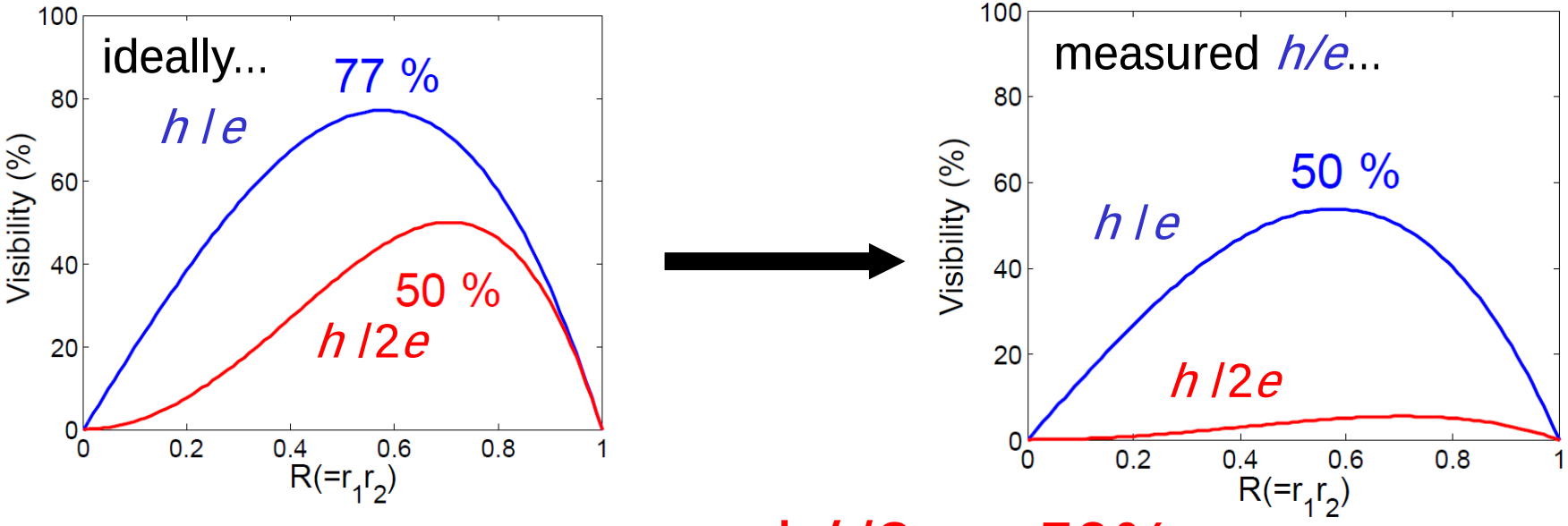
can it be excluded ?

can it be related to even windings ?

transmission...

$$|A|^2 = A_0 + A_1 \cos(2\pi \cdot AB/\phi_0) + A_2 \cos(2\pi \cdot 2AB/\phi_0) + \cdots$$

4x4μm²



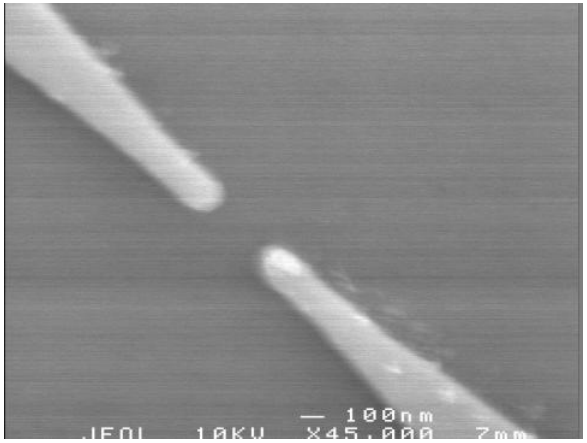
measured $h/2e$ ~ 50%

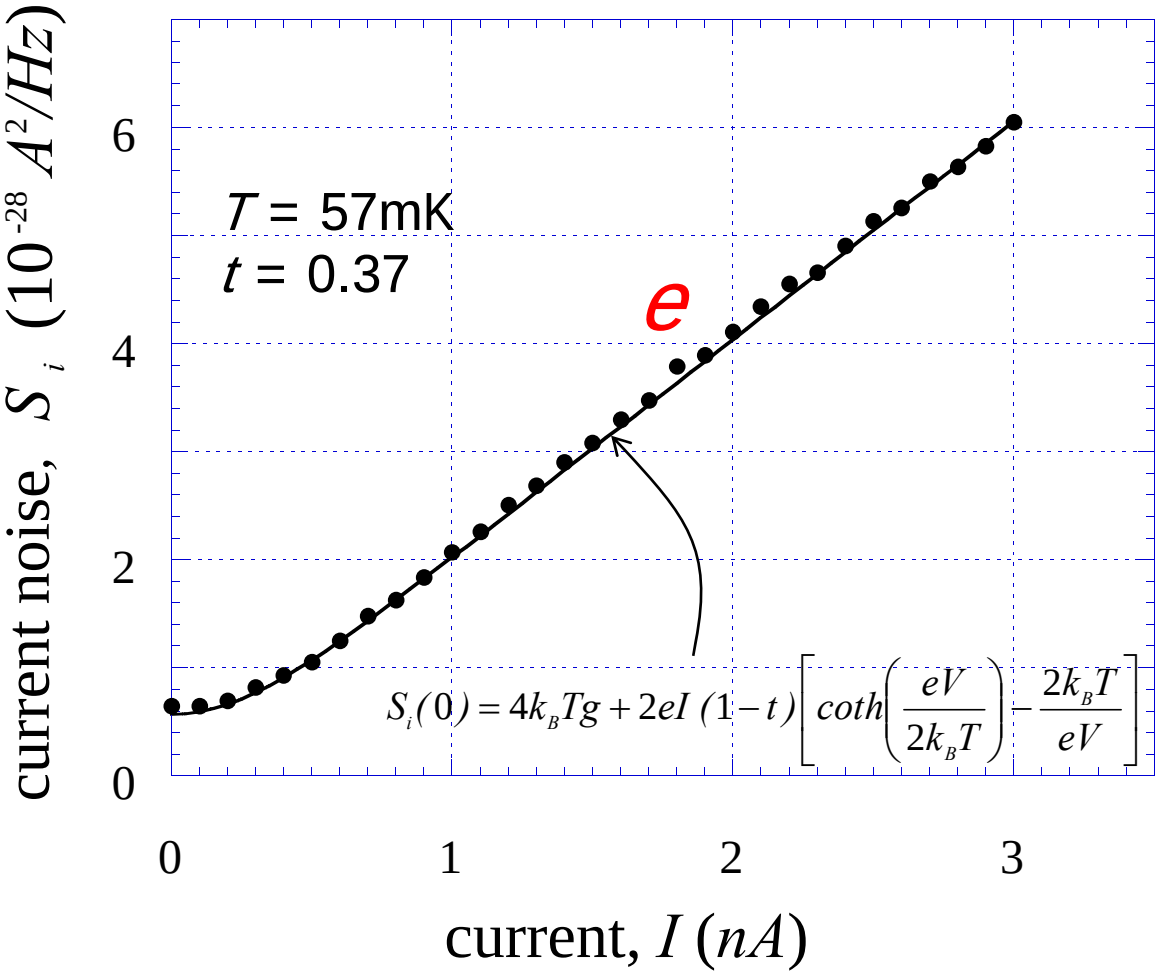
unlikely two windings

hence, do $2e$ charges interfere ?

shot noise

shot noise in QPC

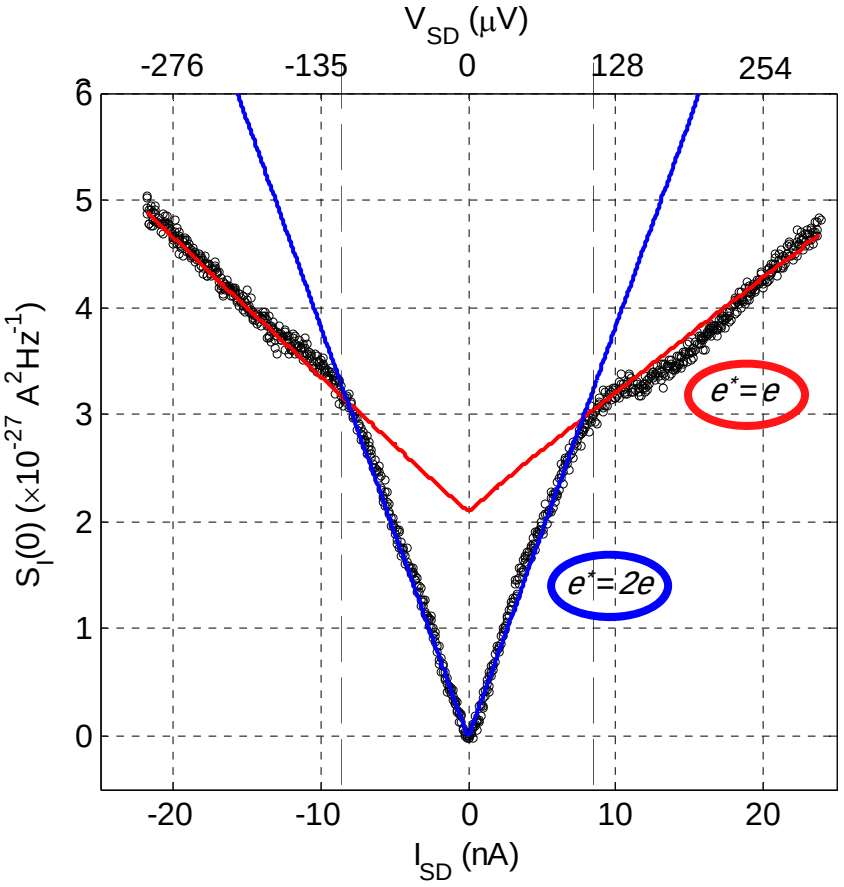




Reznikov *et al*. PRL 1995

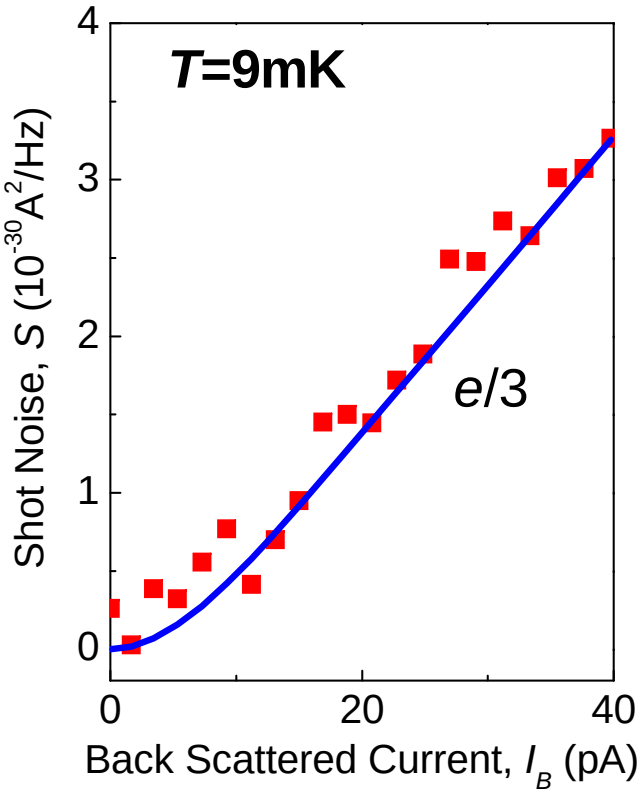
shot noise in a superconductor

Cooper pairs



Das *et al.*, Nature Comm. 2012

fractional charge

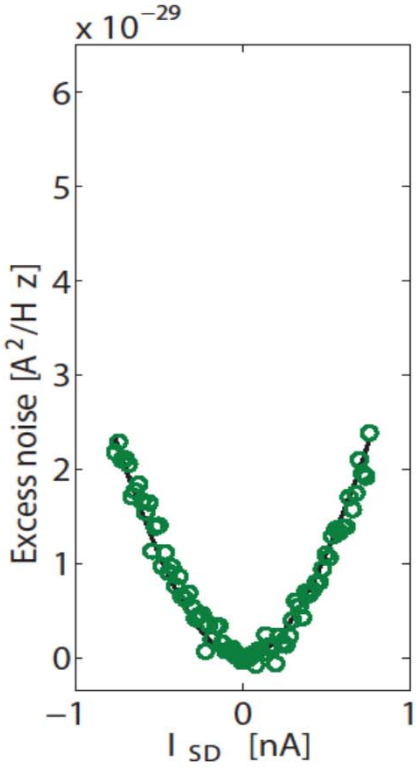


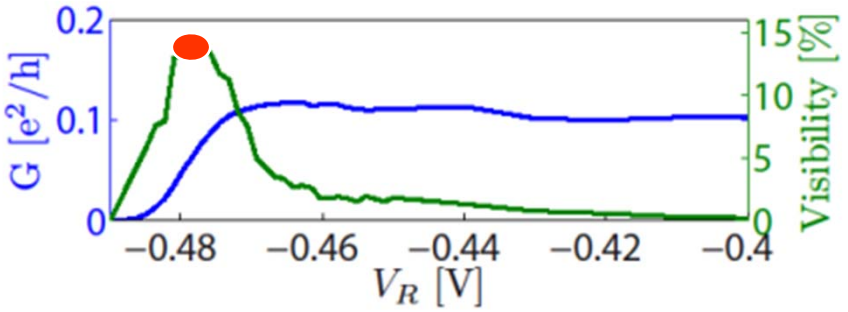
Chung *et. al.* PRL 2003

shot noise of FPI

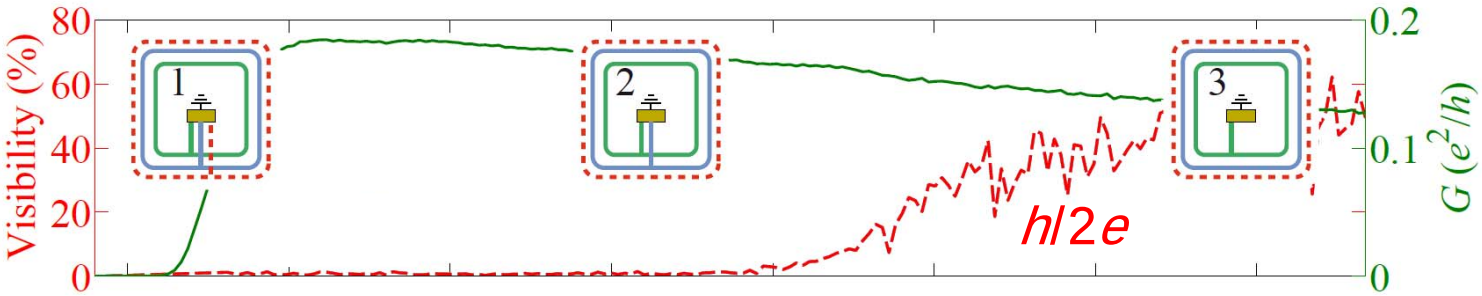
QPC

$e^* = e$





charge: dephasing *h*/2*e* @ V_B=3 ..... 2*e* → *e*



summarizing..

- screened FPI in the AB regime
- AB periodicity ν_B =1 - 2.5 ..... $\phi_o^* = \frac{h}{e}$
  - *quasi-particles charge: $e^* \sim e$*
- AB periodicity: ν_B =3 - 4.5 ..... $\phi_o^* = \frac{h}{2e}$
  - *quasi-particles charge: $e^* \sim 2e$*
- two edge-channels entanglement

screening ‘global’ Coulomb domination

revealed inter-channel interaction

leading to unexpected pairing of electrons