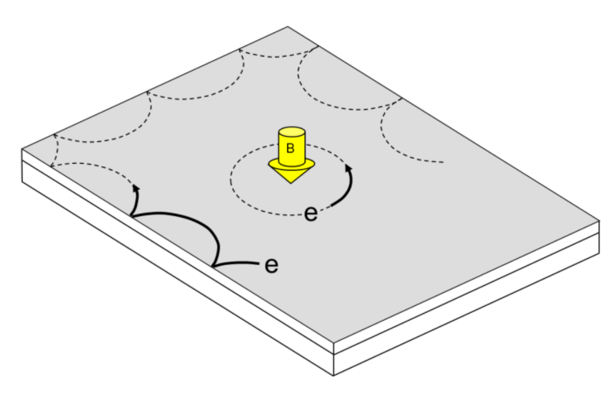
Edge Modes in QHE Regime …. their nature & use

- ‘bulk – edge’ correspondence
- interference
- thermal conductance

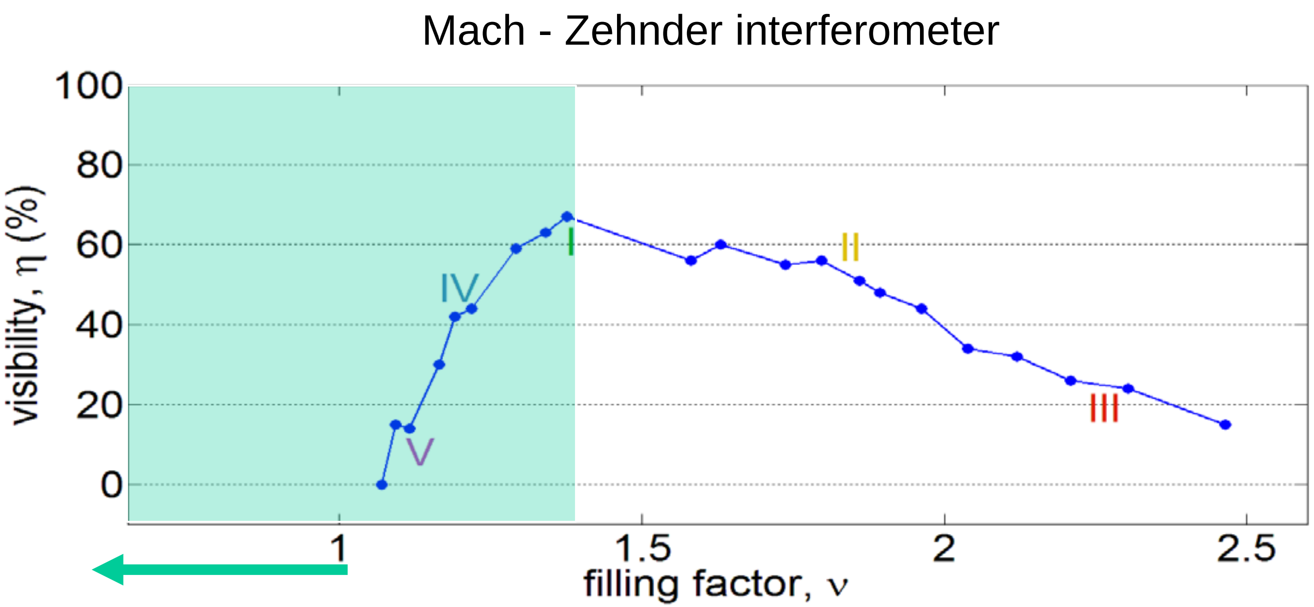
Moty Heiblum

WEIZMANN INSTITUTE OF SCIENCE



interference and dephasing

vanishing of interference ...



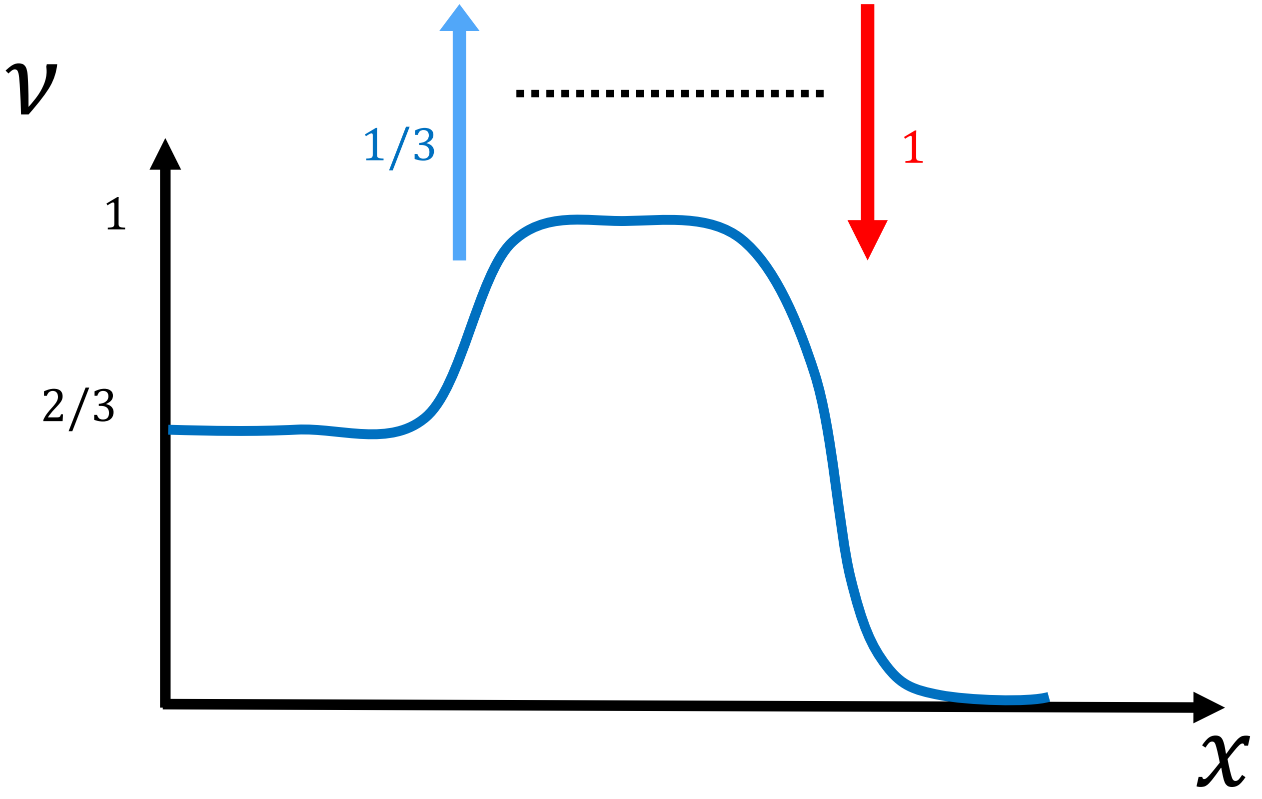
neutral modes due to edge reconstruction?

edge reconstruction

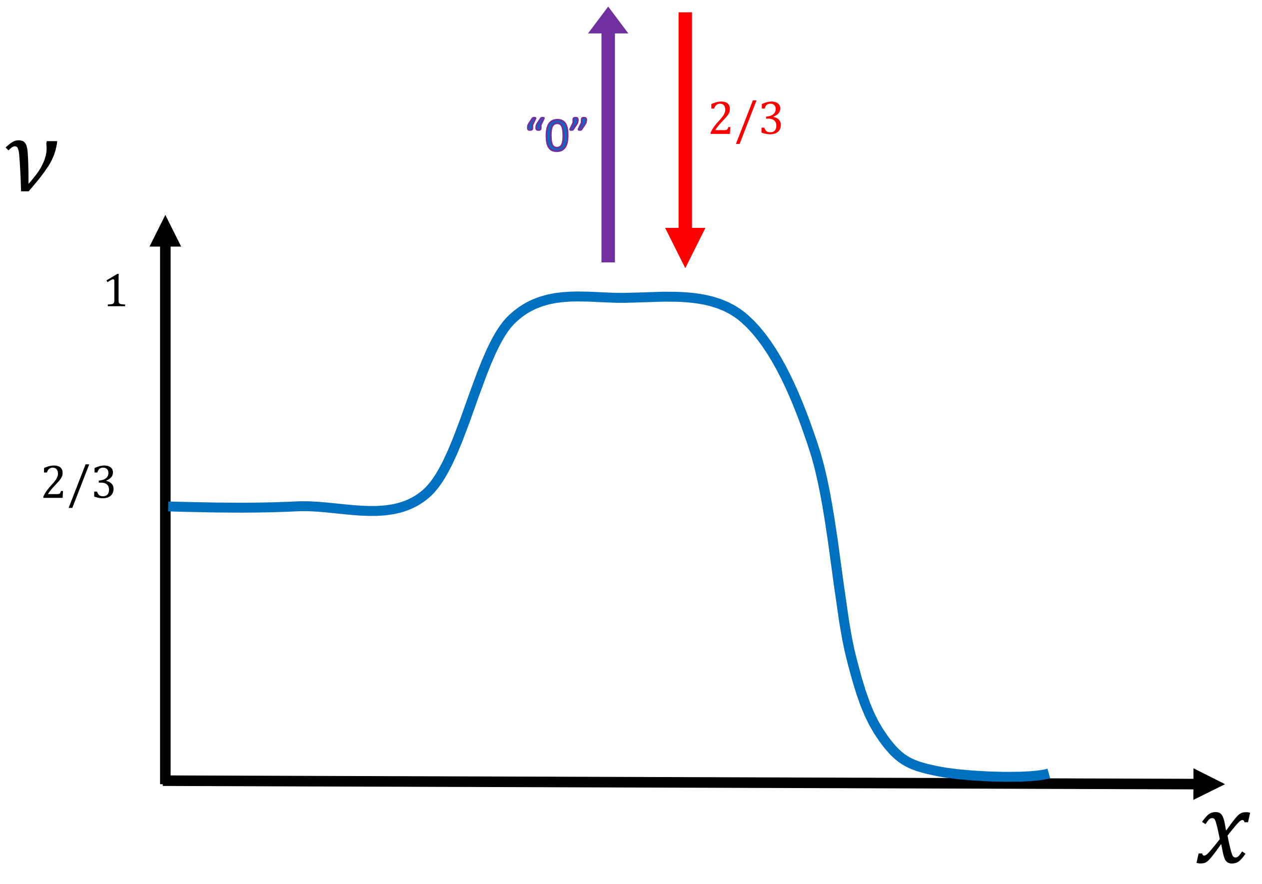
neutral modes ?

....measurements in ν=2/3 & ν=1

MacDonald **un-equilibrated**



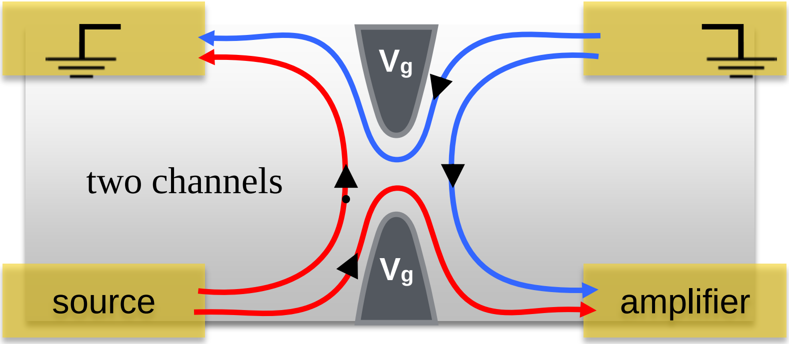
Kane Fisher Pulchinski equilibrated



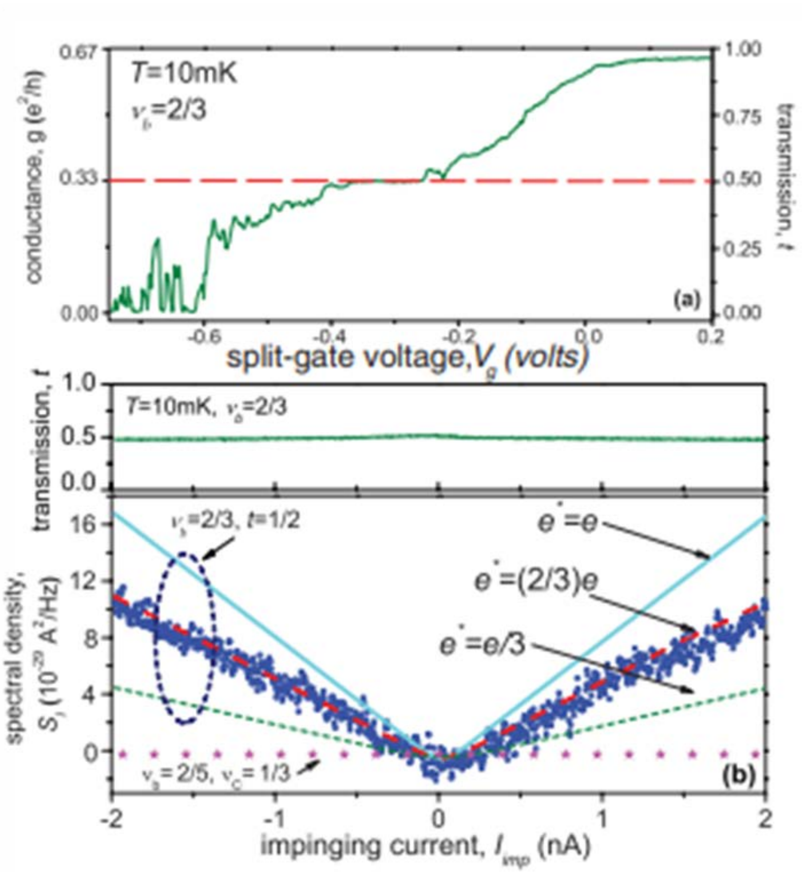
unexpected behavior in $\nu = 2/3$

un-partitioned (full) channel does not carry shot noise

can modes structure be any different?

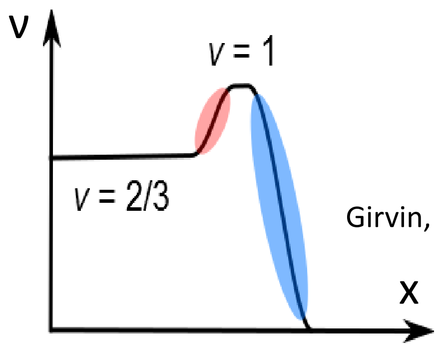


yet, shot noise on plateau



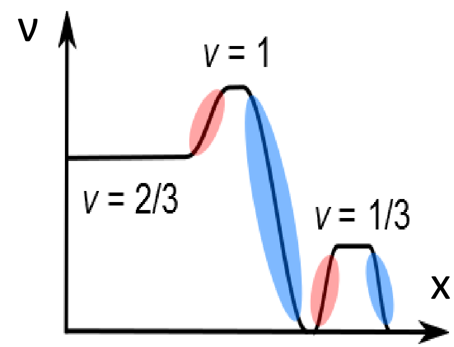
do we know the structure of $\nu = 2/3$?

sharp - smooth edge



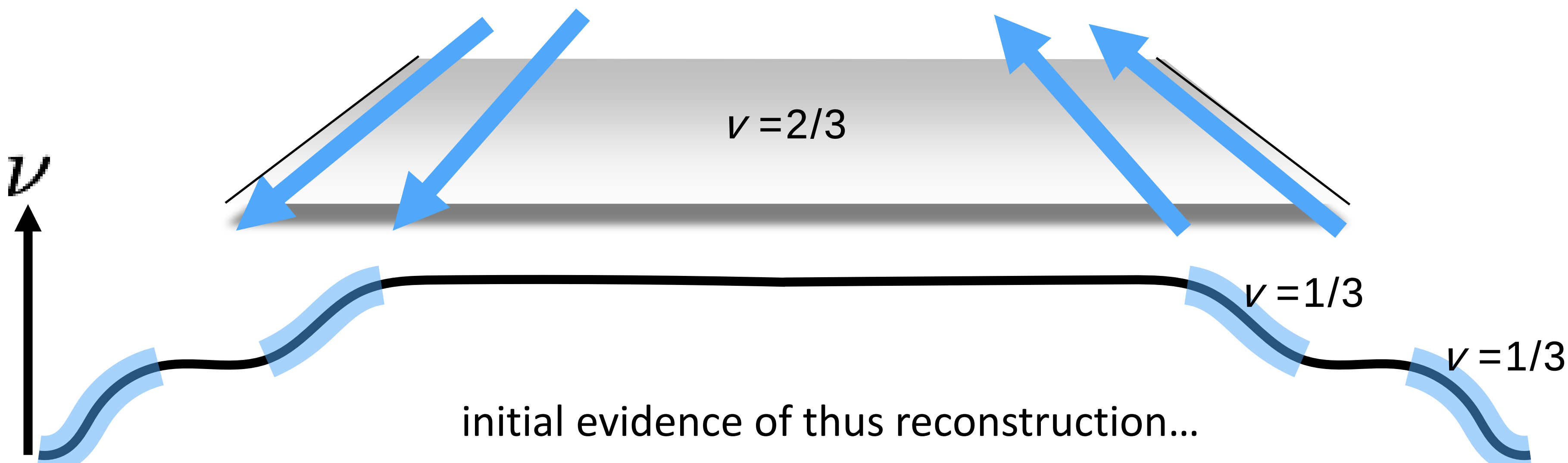
Girvin, MacDonald 1992

smoother edge ?



Meir 1994

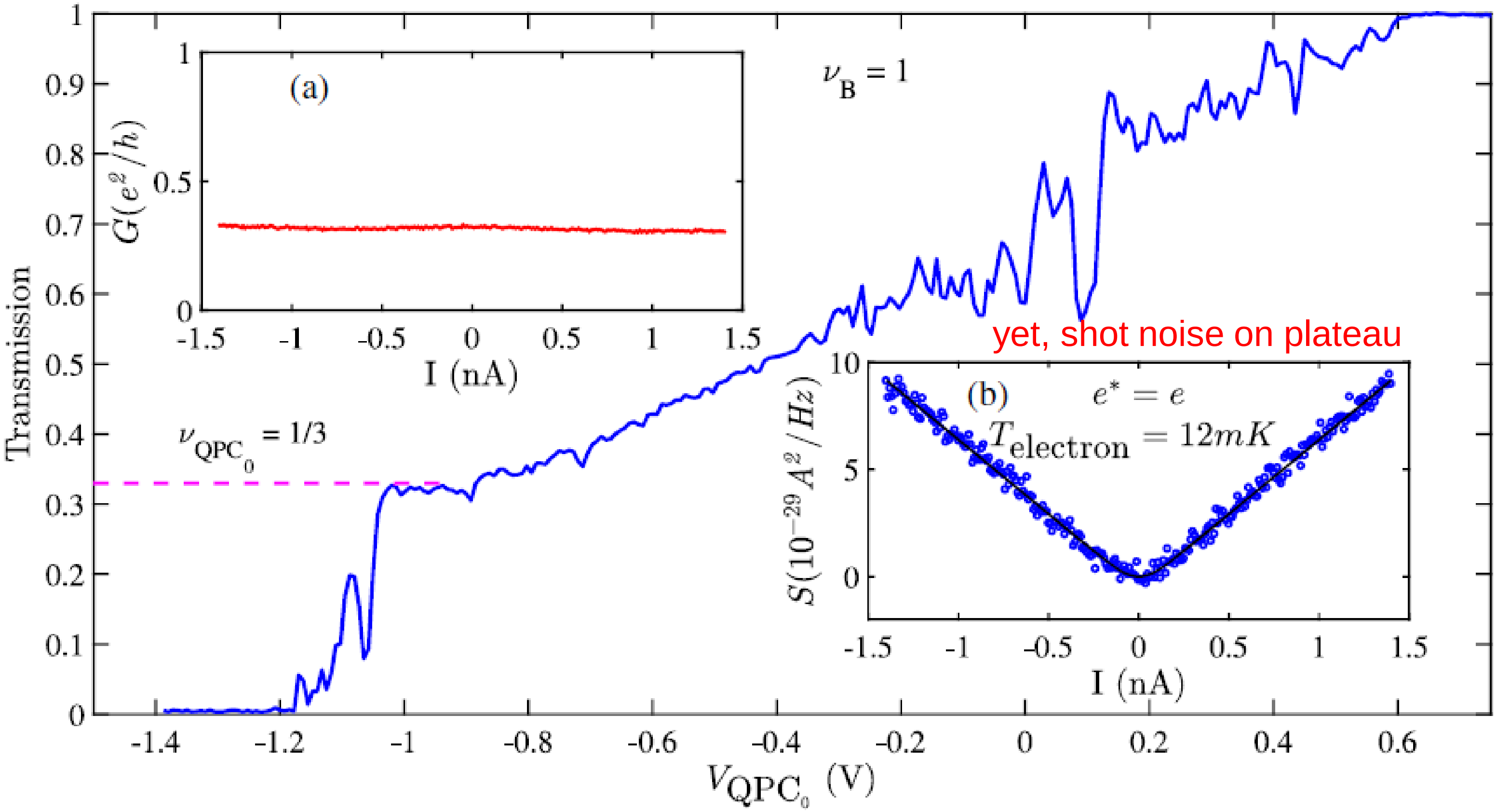
or, could it be ?



initial evidence of thus reconstruction…

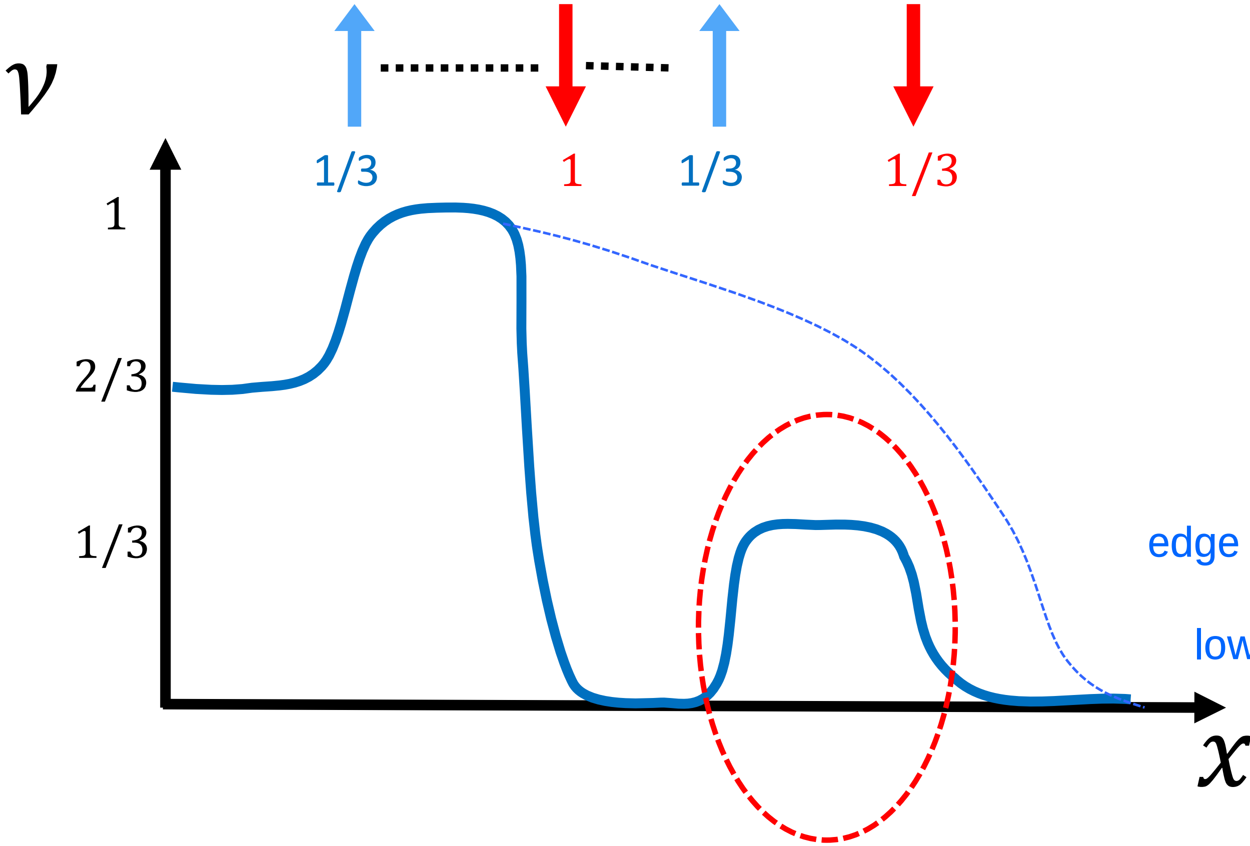
unexpected behavior in $\nu = 1$

un-partitioned (full) channel does not carry shot noise



Bhattachryya 2019

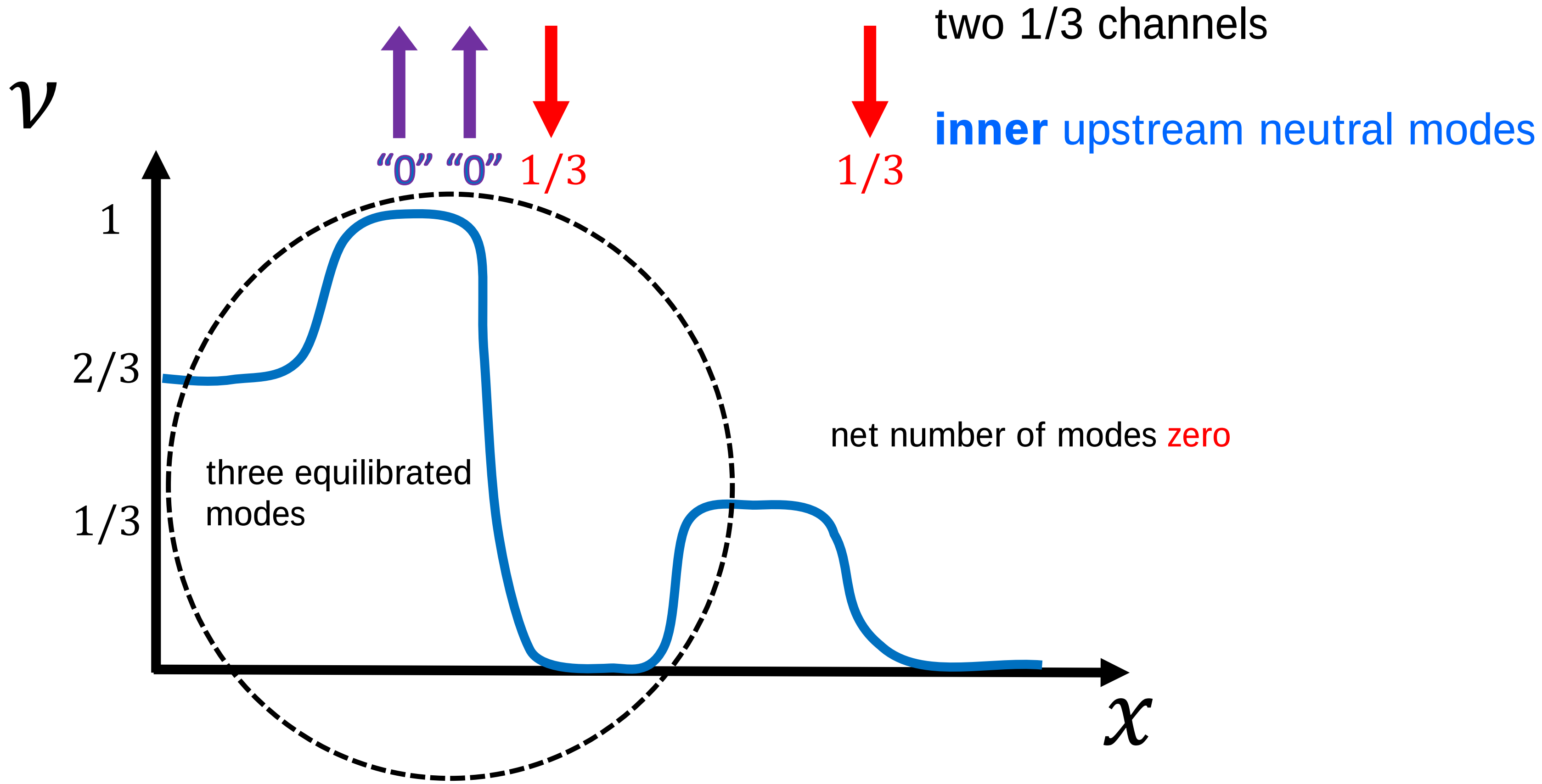
Meir , Gefen **un-equilibrated**



edge reconstructed of *soft edge*

lowering the kinetic energy

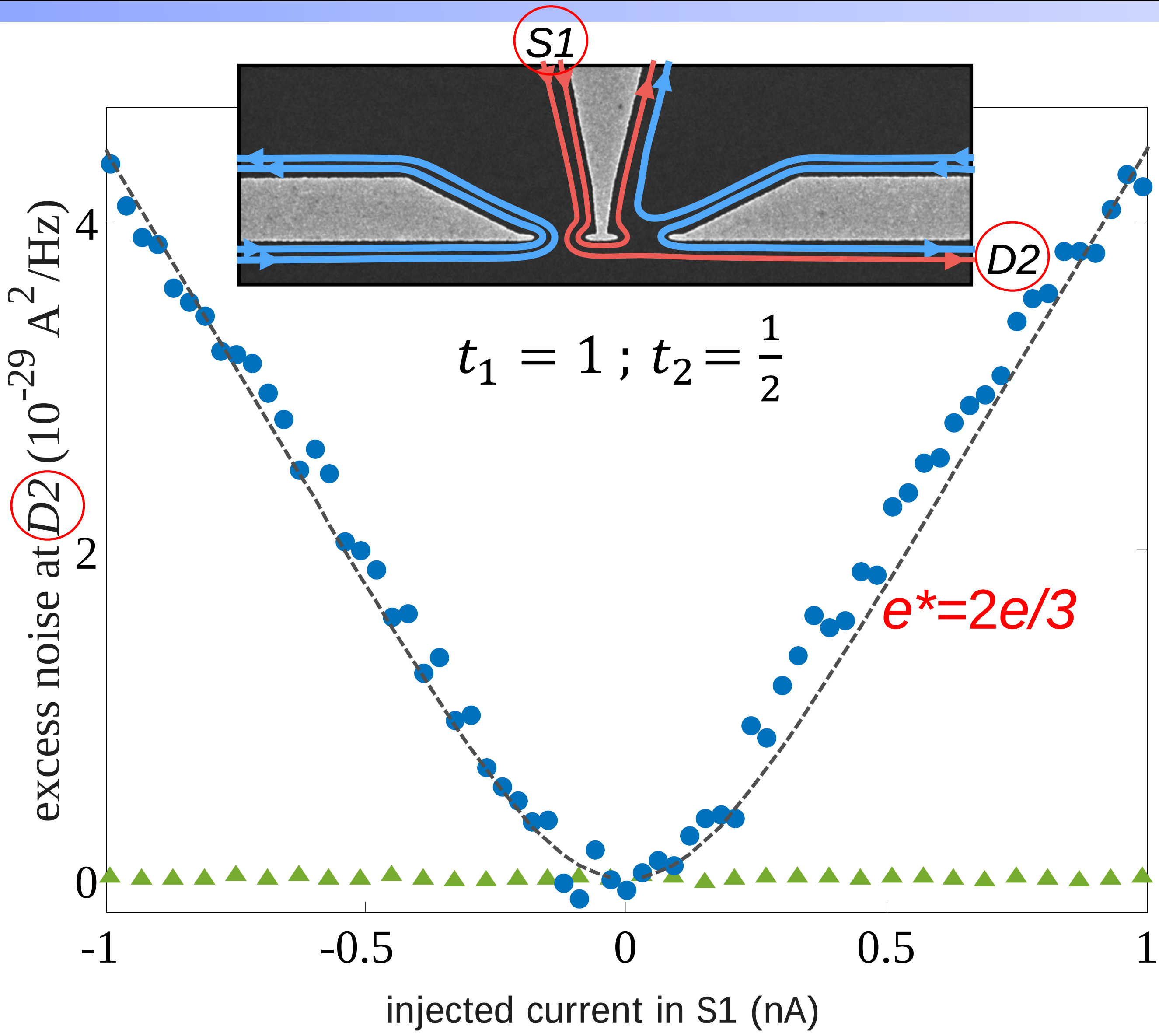
Meir , Gefen - equilibrated



why shot noise?

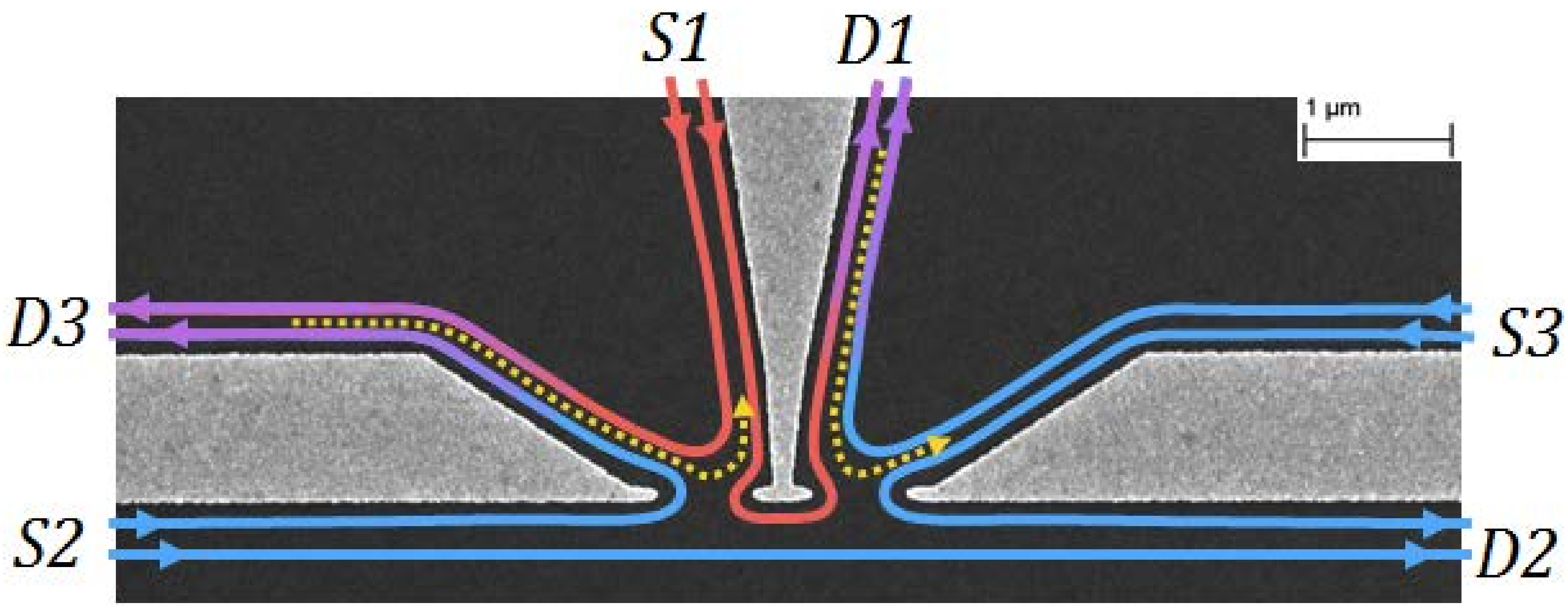
upstream neutral modes...

QPCs separation 400nm

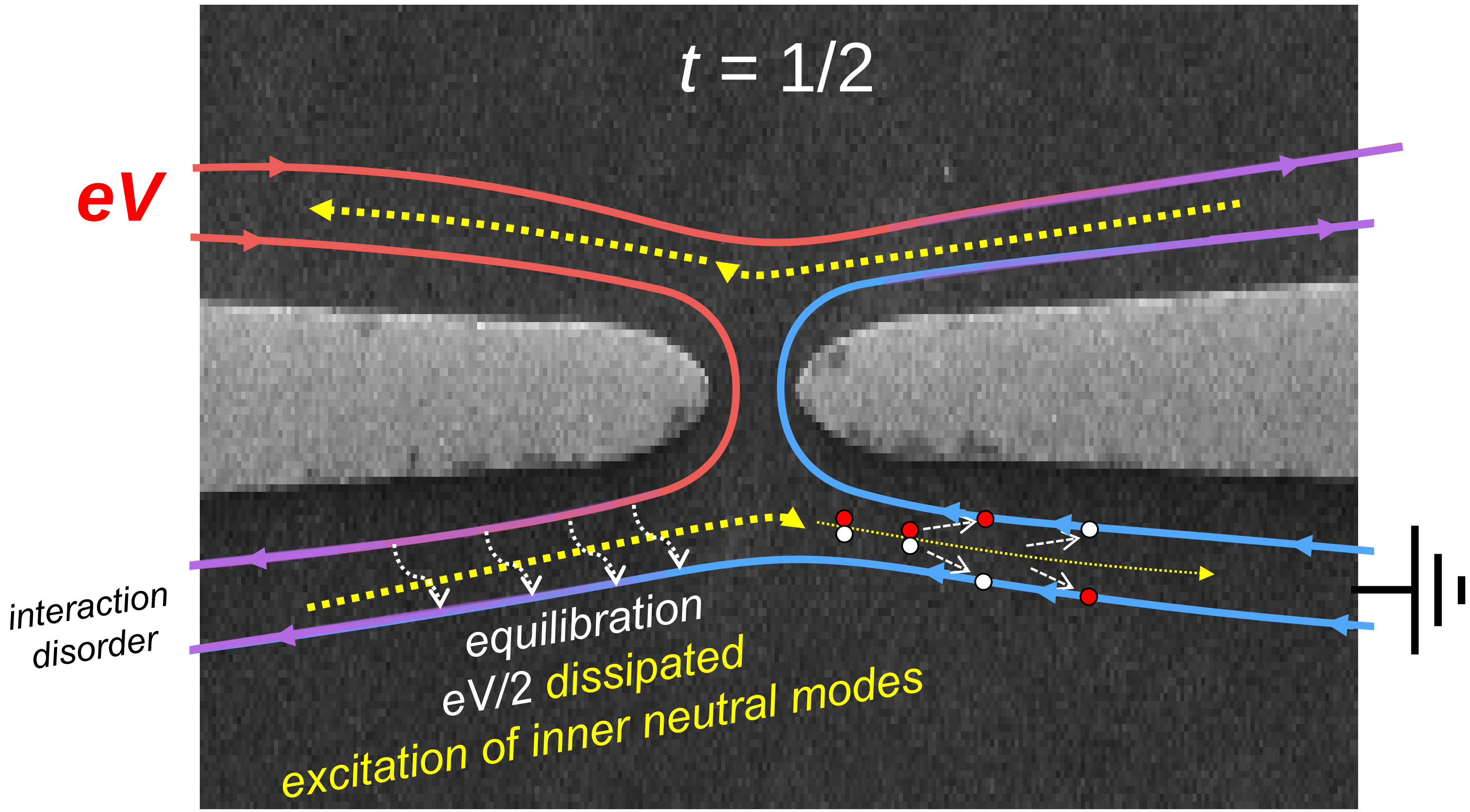


proposed mechanism of noise **two-QPC**

$$t_1 = \frac{1}{2}\ ;\ \ t_2 = \frac{1}{2}$$



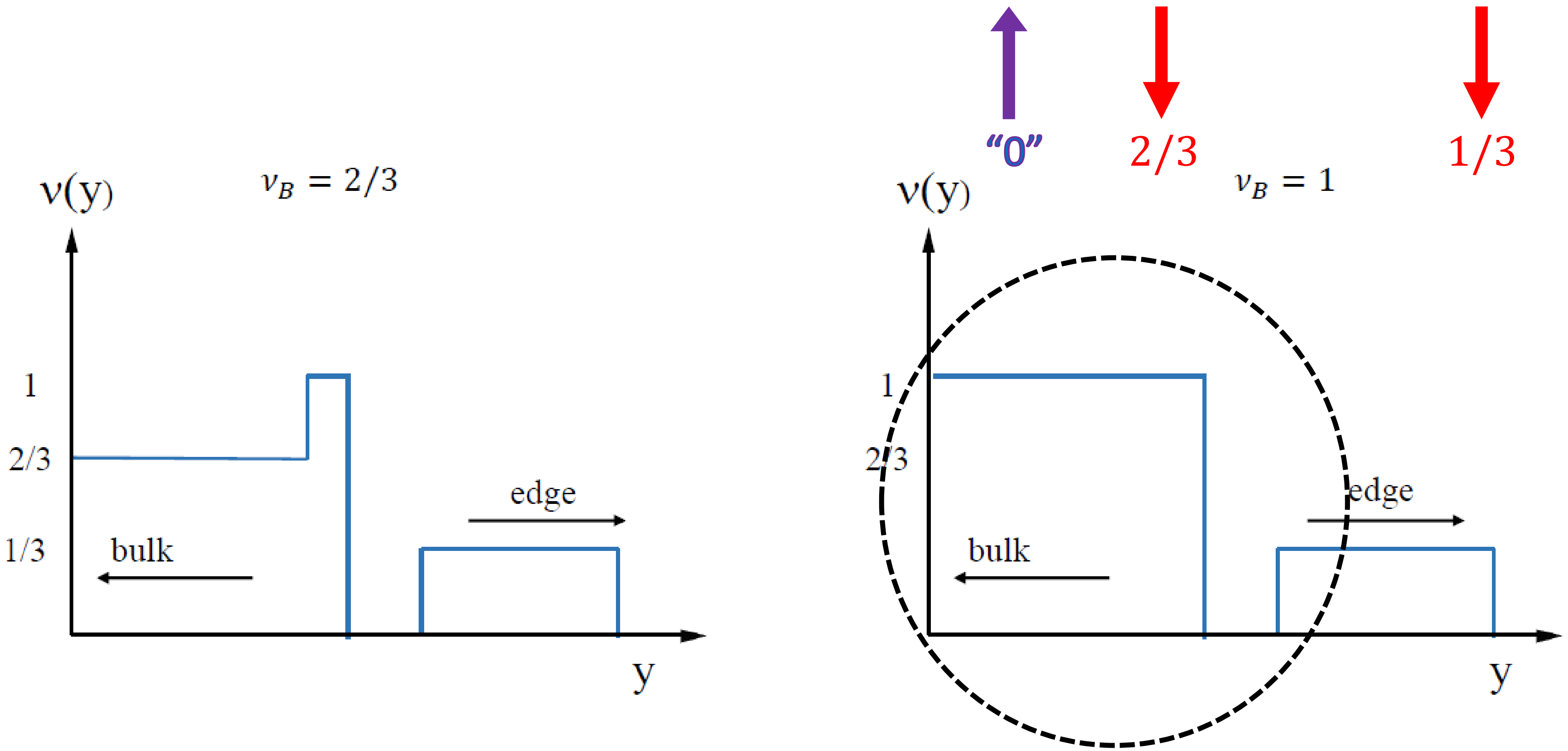
proposed mechanism of noise single QPC

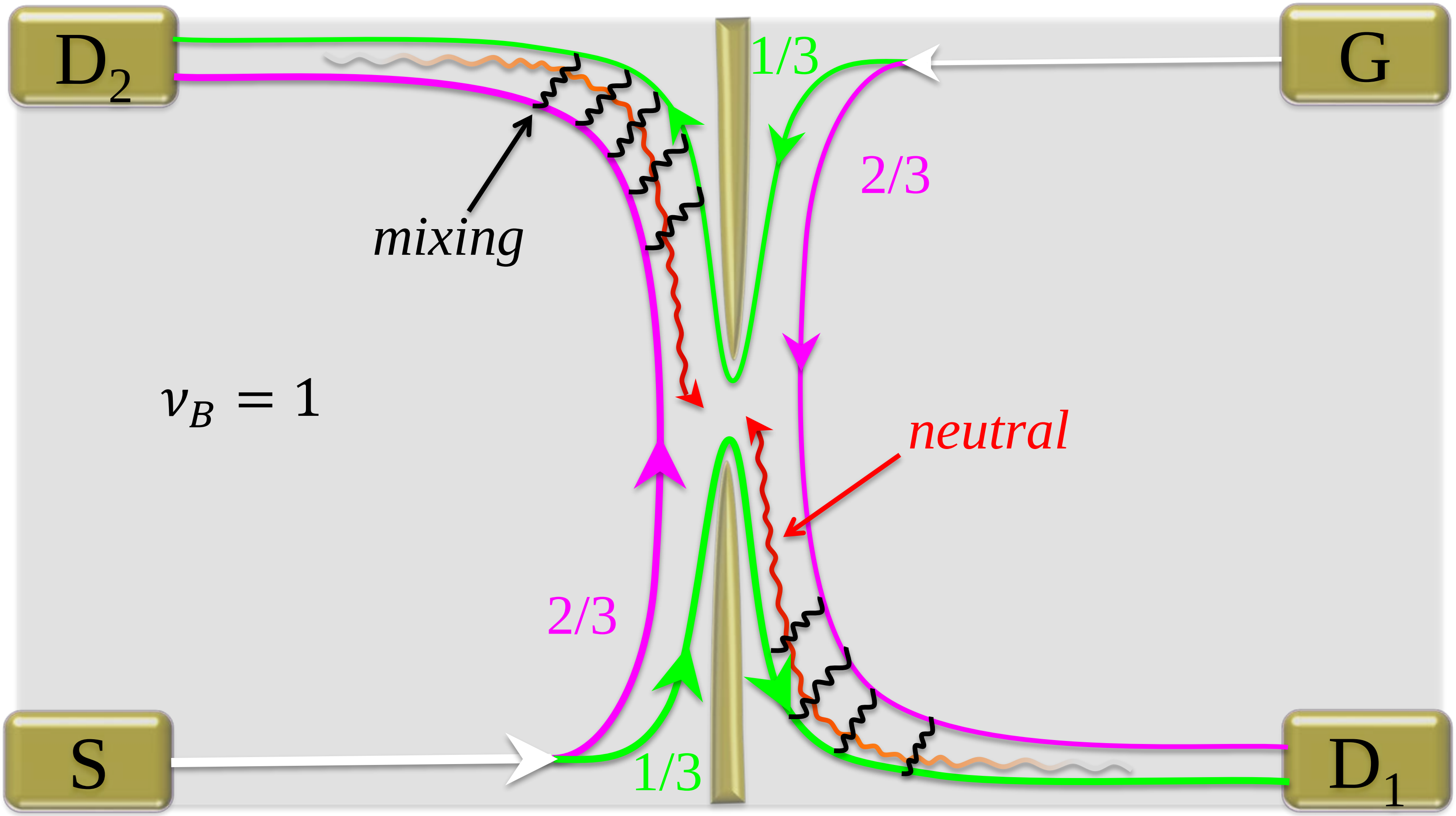


noise is quantized $e^{*}=2e/3$

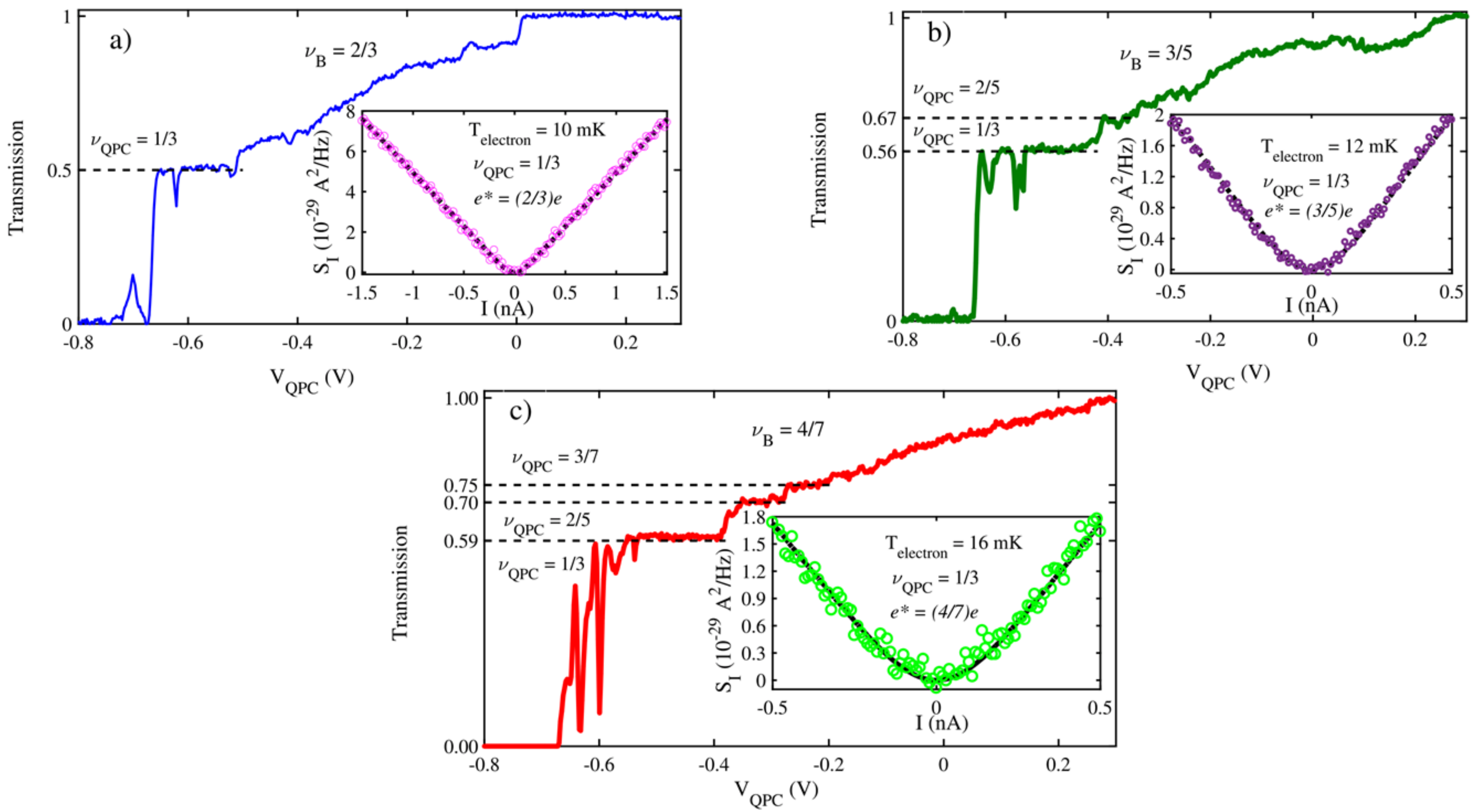
similar edge reconstructions...

net one *downstream* mode

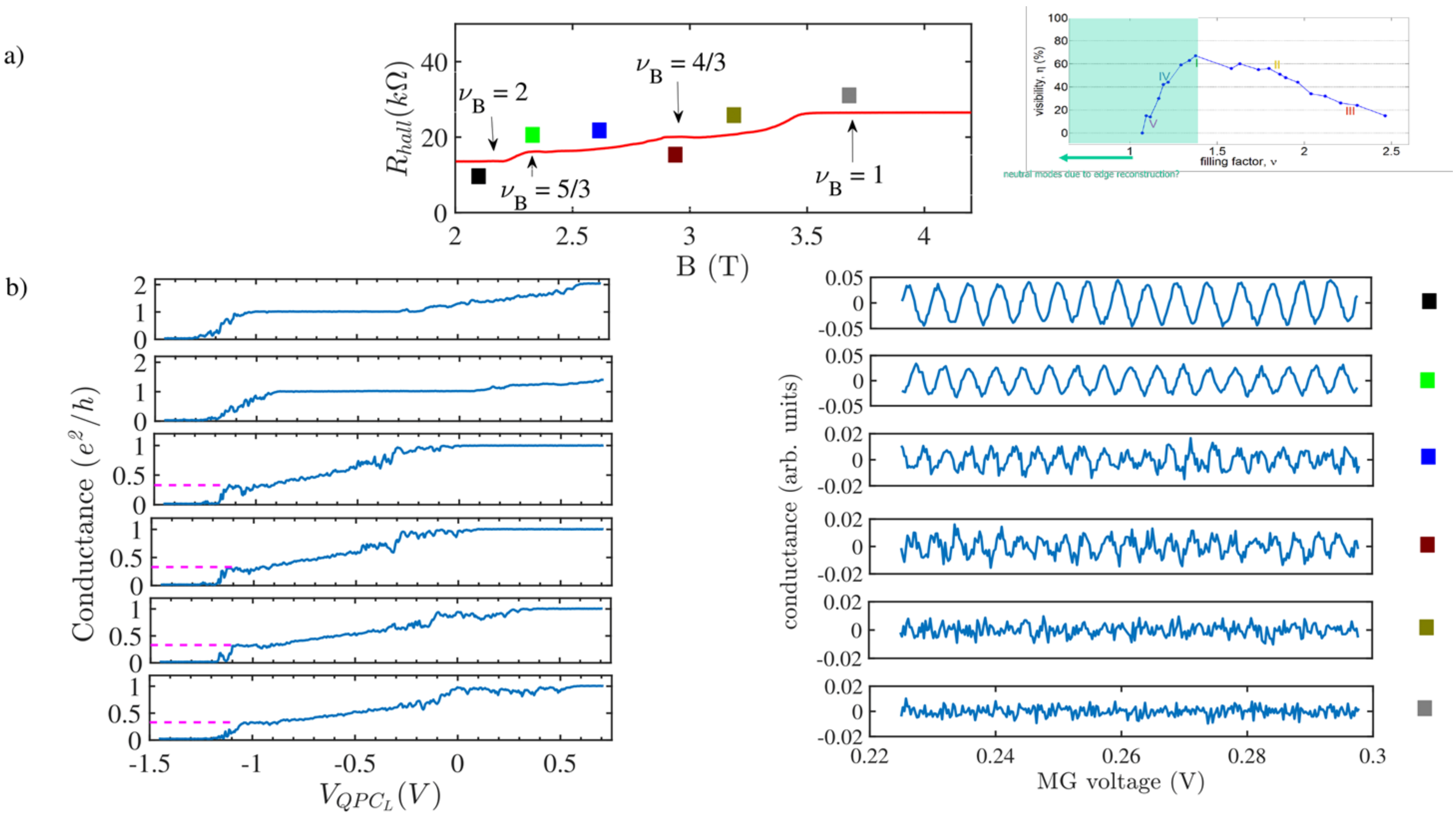



D2
G
1/3
2/3
mixing
$\nu_B = 1$
neutral
2/3
1/3
S
D1

all hole-conjugate states suffer from edge reconstruction with added fractional modes and neutral modes

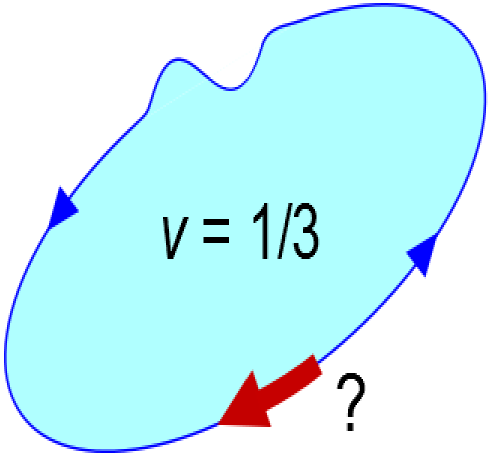


concomitant of noisy plateau and dephasing

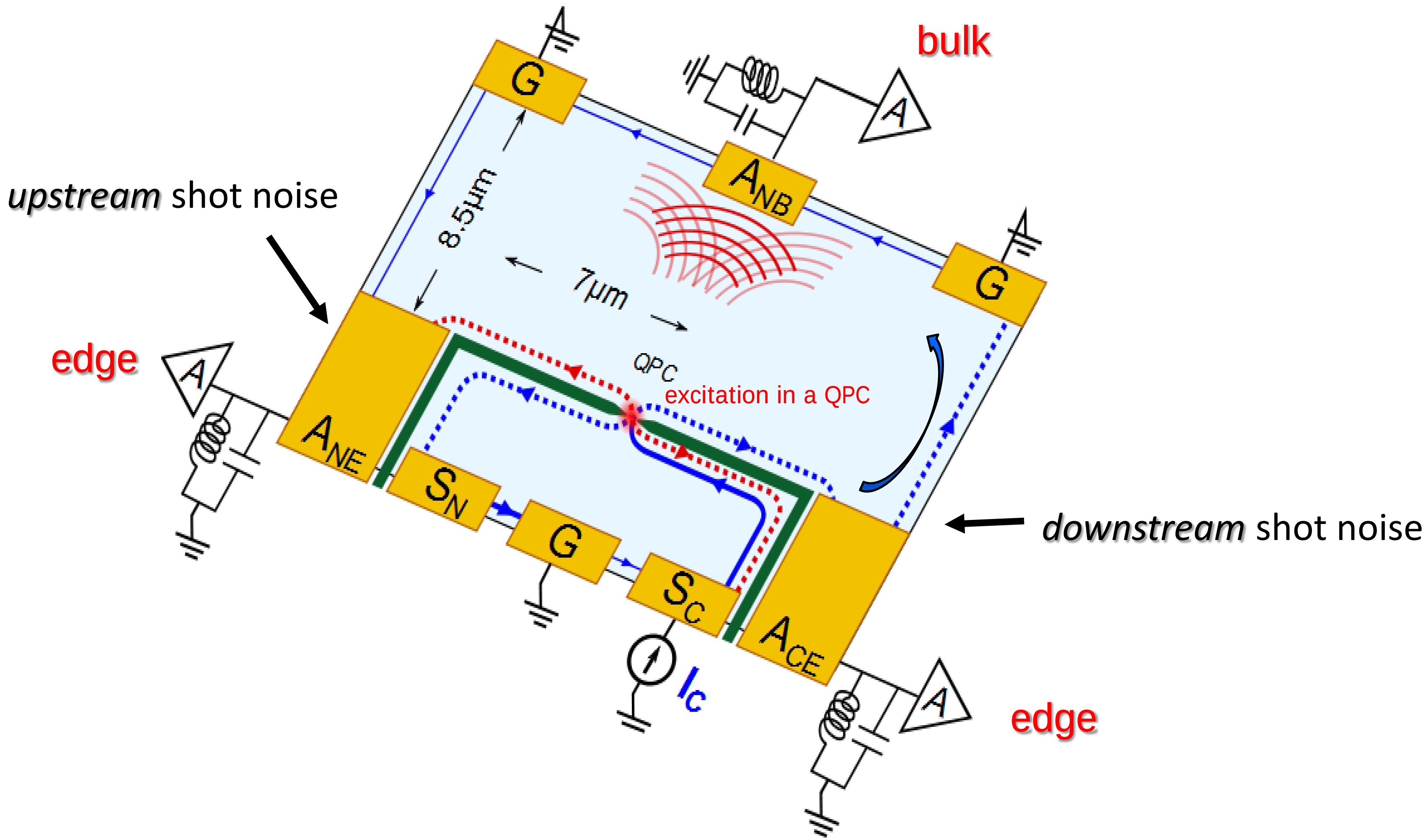


BUT, why no interference in $\nu = 1/3$...

are particle-like states also support neutral edge modes?



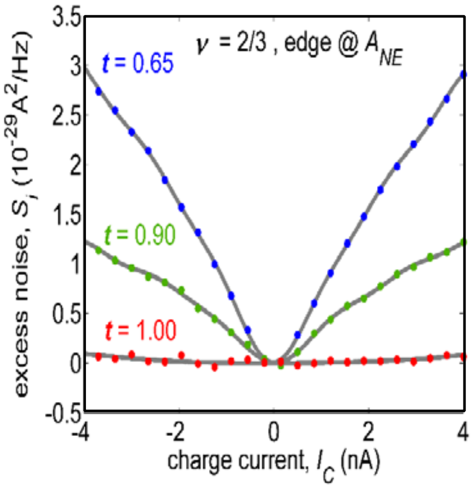
neutral modes in short distance relevant to interferometers



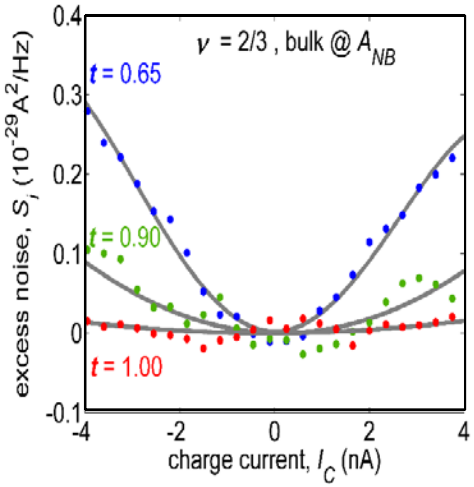
ν = 2/3 25mK

$10^{-29}A^2/Hz \rightarrow$ 7mK

edge



bulk

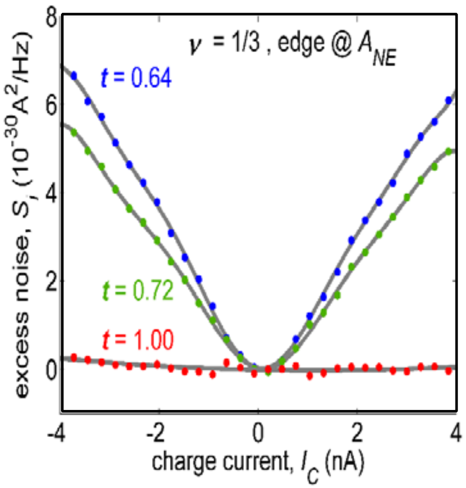


energy also propagates through the incompressible bulk !

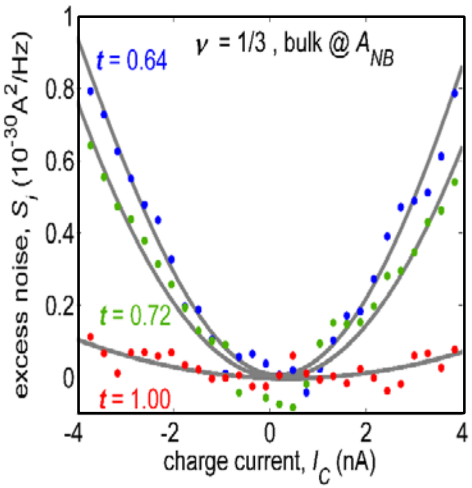
however, most energy is carried by chiral upstream edge modes

ν = 1/3 25mK

edge



bulk

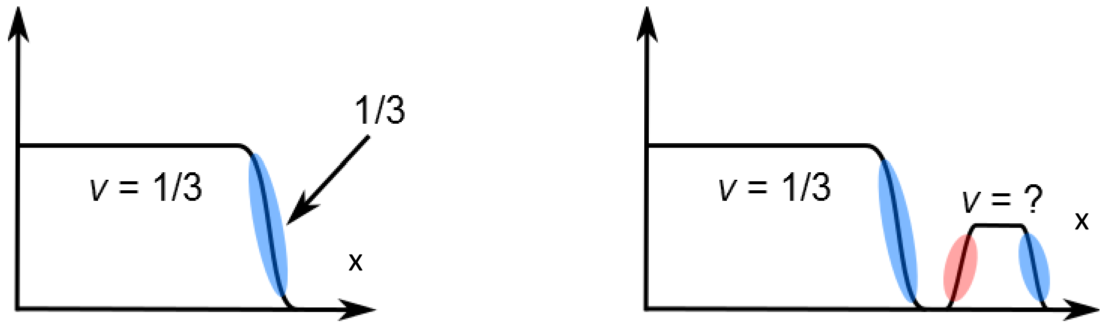


$10^{-30}A^2/Hz$ = 1.4mK

weaker than ν =2/3

qualitatively similar results obtained in ν = 2/5, 4/3

unexpected reconstruction $\nu=1/3$...



interference

interference with edge modes

- electrons directed along definite paths

  flexible design

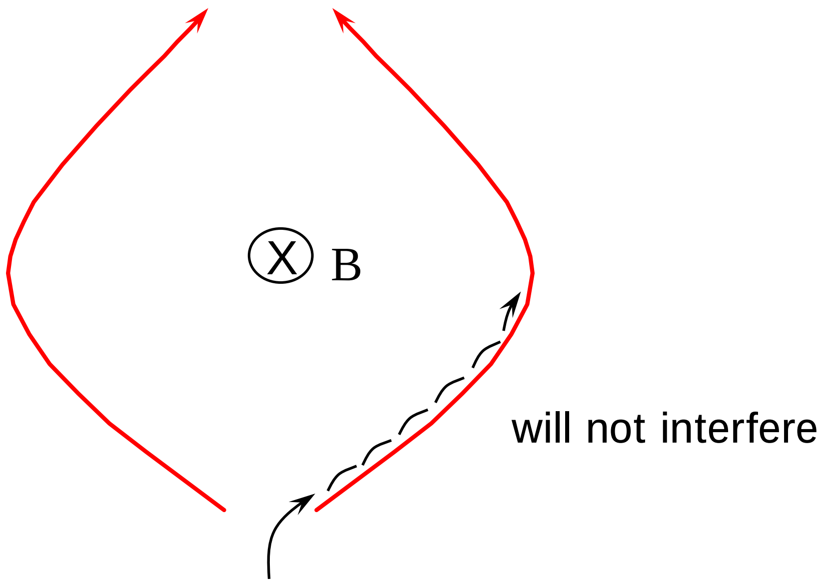
- edge modes enclose a definite area

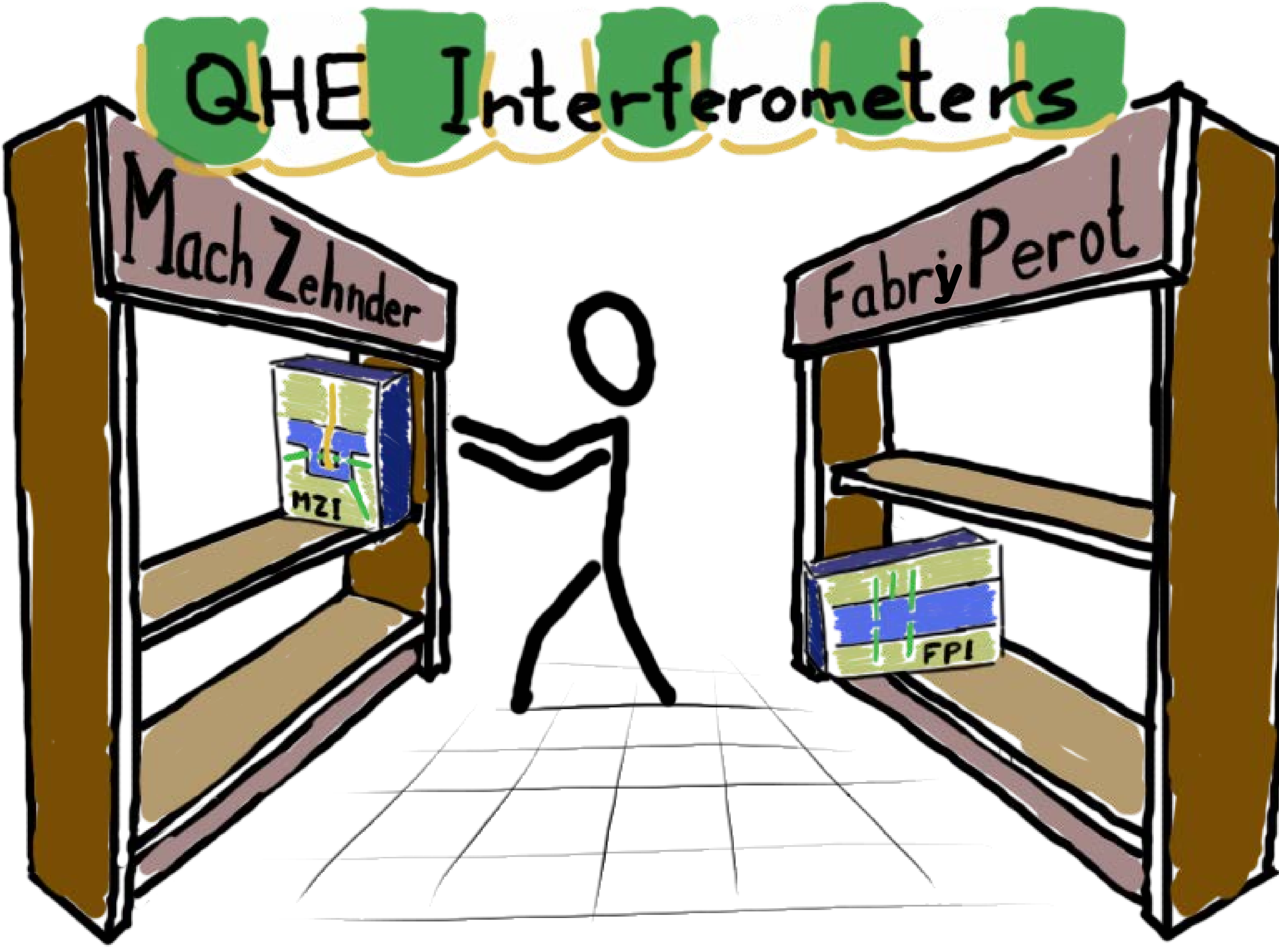
  minimizes phase averaging, high visibility fringes

- no back-scattering

  insensitive to impurities

how to fool edge channels to interfere ?



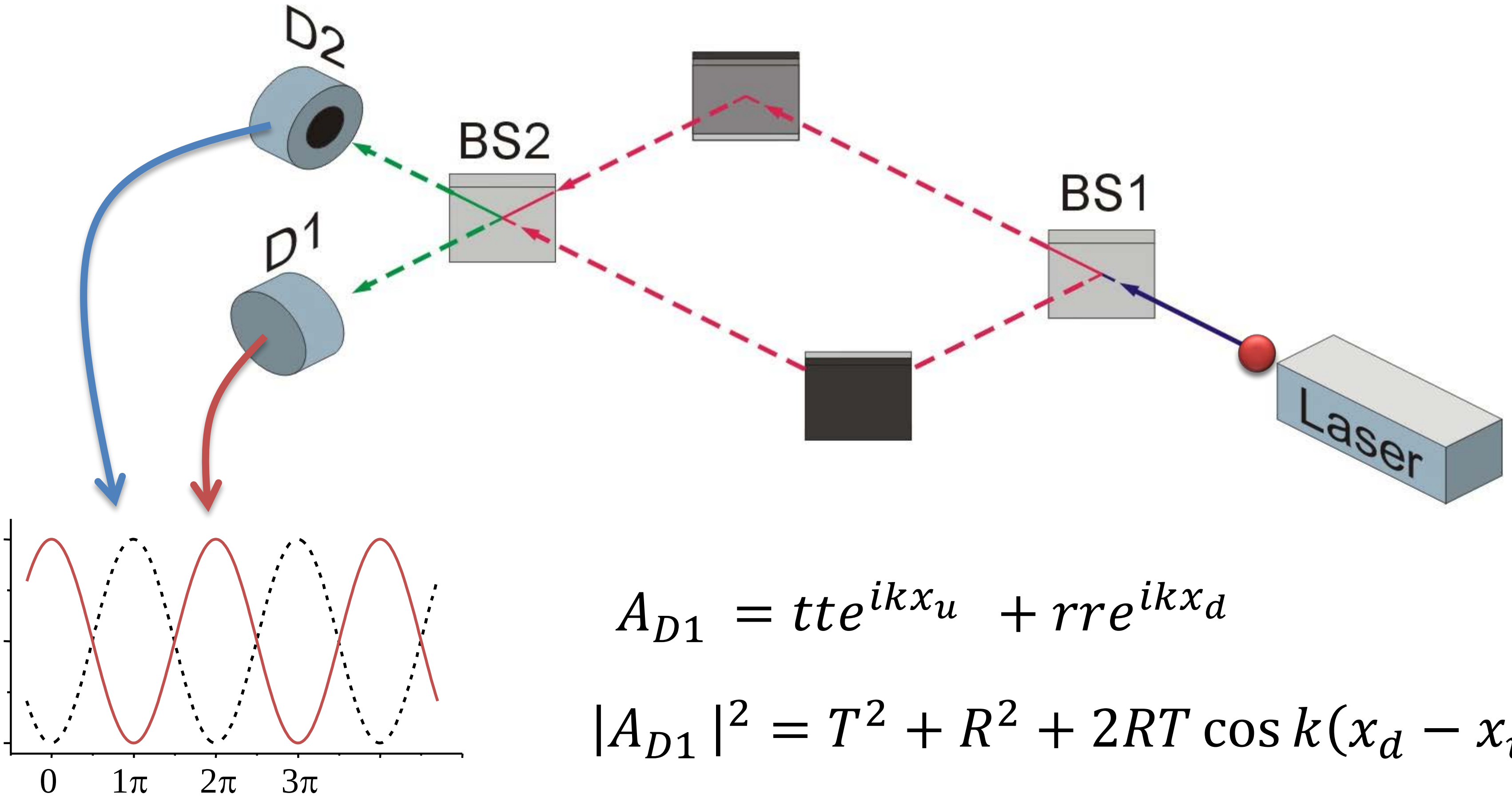


QHE Interferometers
Mach Zehnder
Fabry Perot
MZI
FPI

Mach - Zehnder

optical MZI

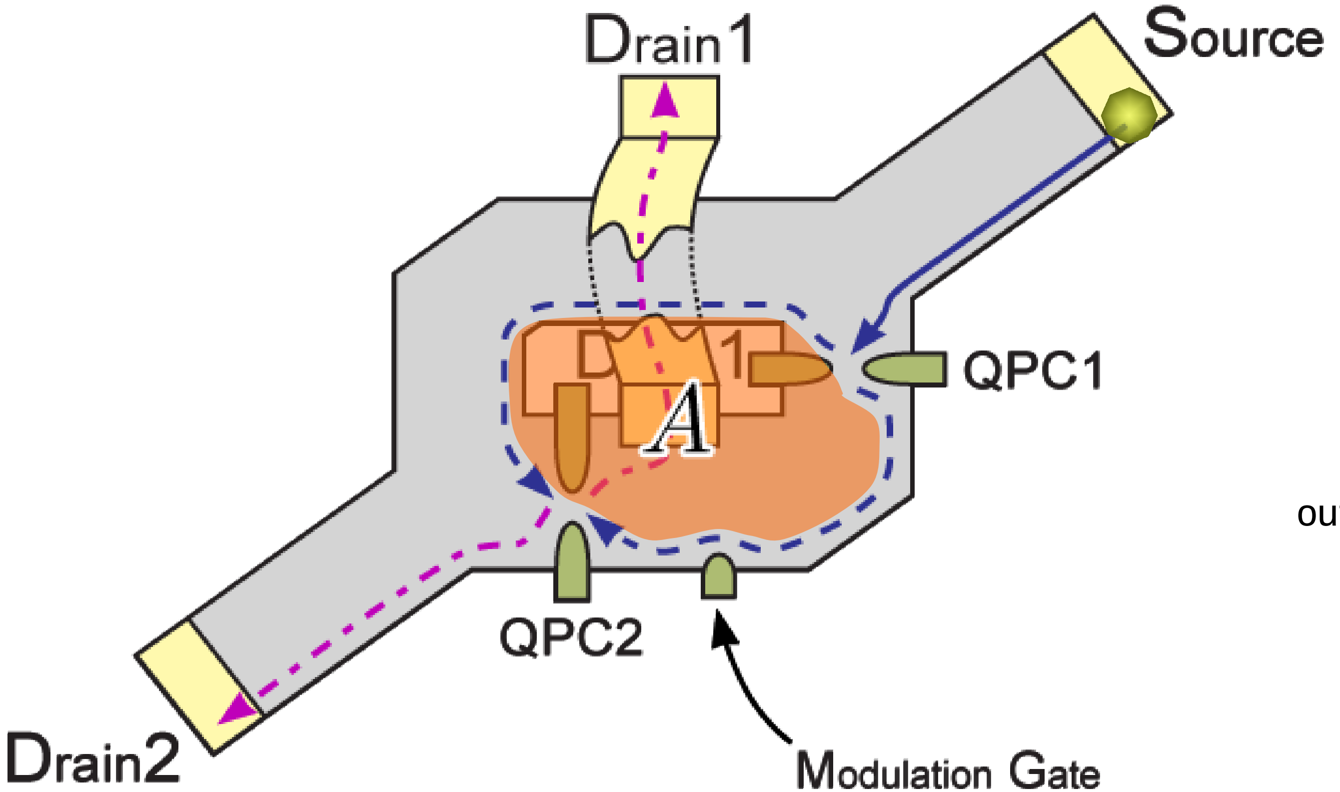
interference observed as function of the path difference

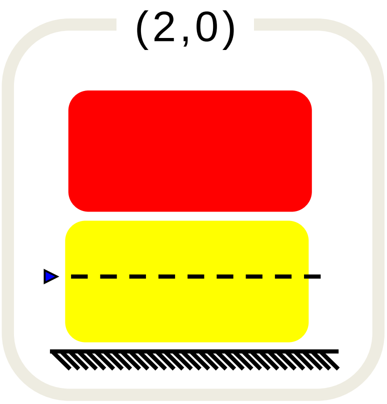


$$A_{D1} = tte^{ikx_u} + rre^{ikx_d}$$

$$|A_{D1}|^2 = T^2 + R^2 + 2RT\cos k(x_d - x_u)$$

electronic MZI



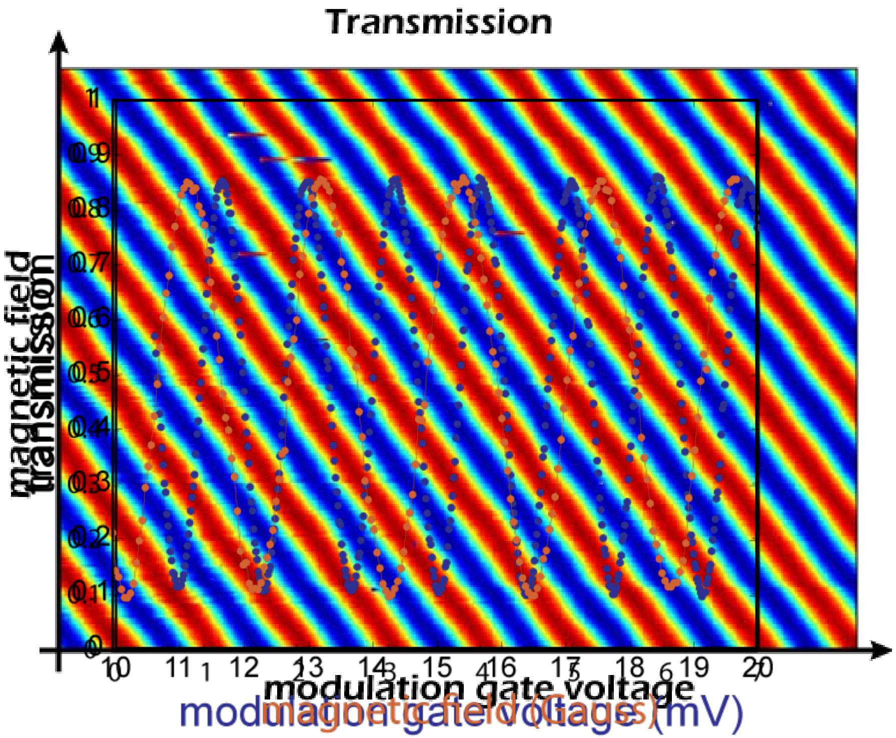


outer-most mode interferes

$$A_{D1} = tt \quad + rre^{i2\pi AB}$$

$$|A_{D1}|^2 = T^2 + R^2 + 2RT\cos(2\pi AB/\Phi_0)$$

Aharonov – Bohm interference (AB)



$$\Delta\varphi = 2\pi \frac{\Delta\Phi}{\Phi_0}$$

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

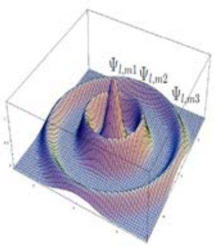
$\Delta B\ (\Phi_0) \sim 1\text{gauss}$

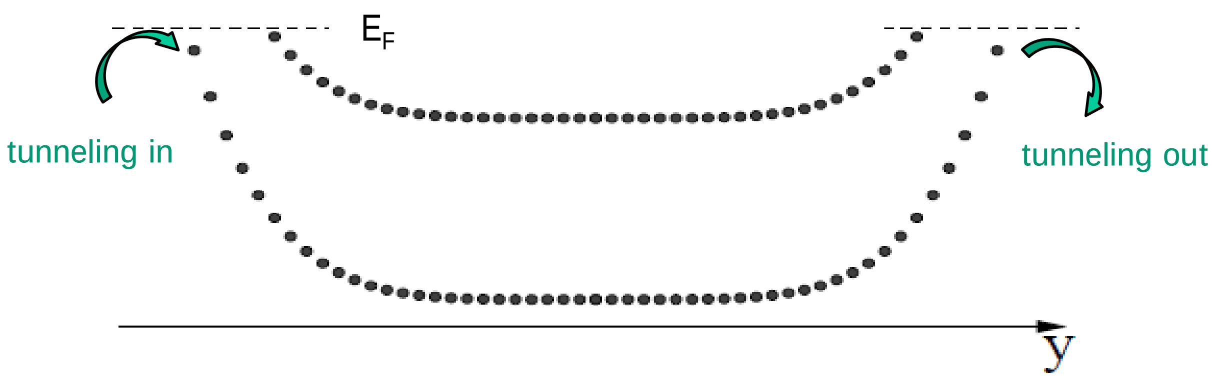
mind the slope...

via modulation gate **MG**

AB area = geometrical area

different look at AB.... **tunneling to edge** every Φ_0





increasing *B*

states slide downhill inwards

tunneling of electrons into empty states crossing E_F

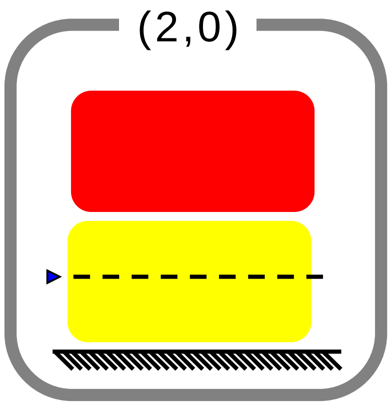
area remains ~constant (added charges empty via inner drain)

Fabry - Perot

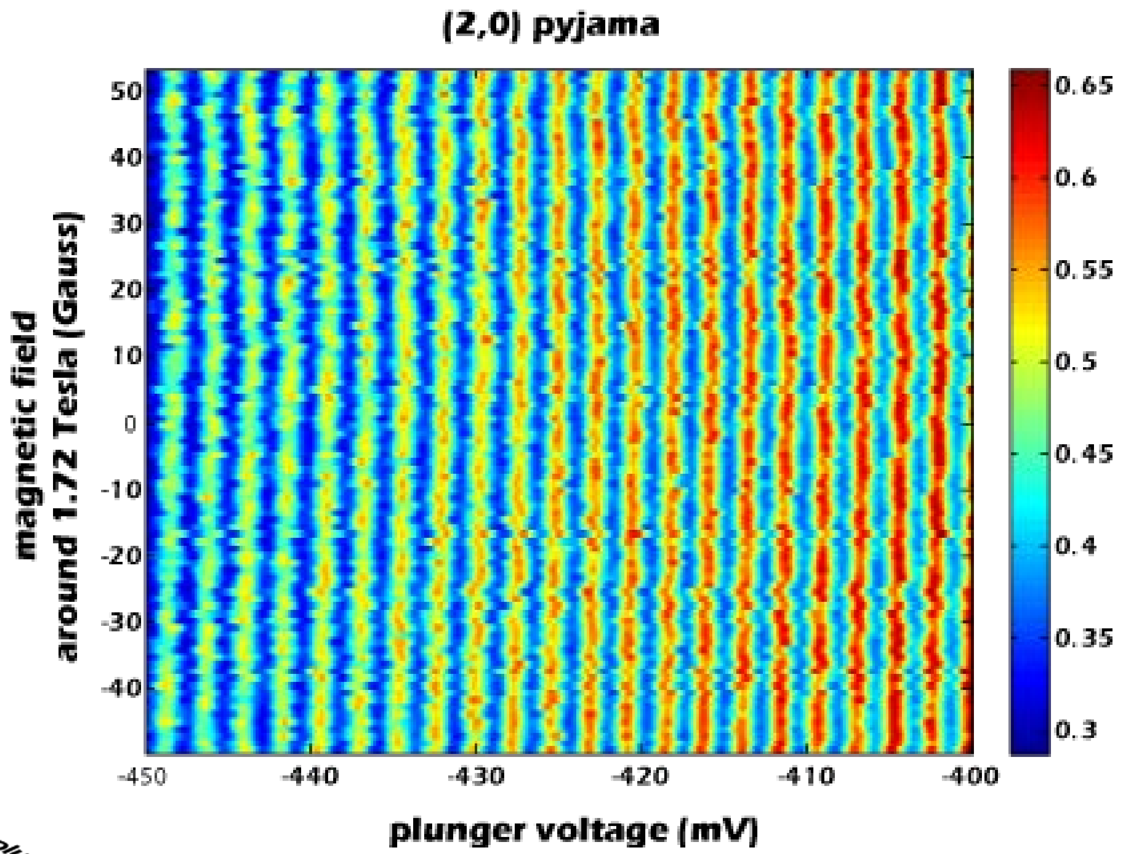
electronic FPI

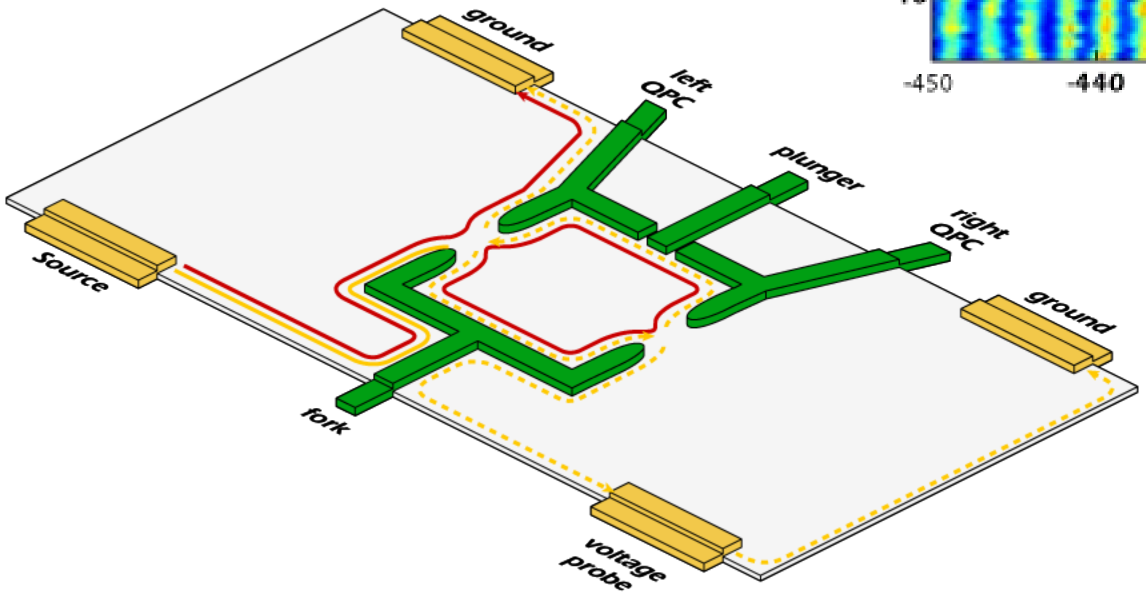
in the limit of only two-path interference

bare FPI – Coulomb dominated (CD)



interfering the lowest Landau level

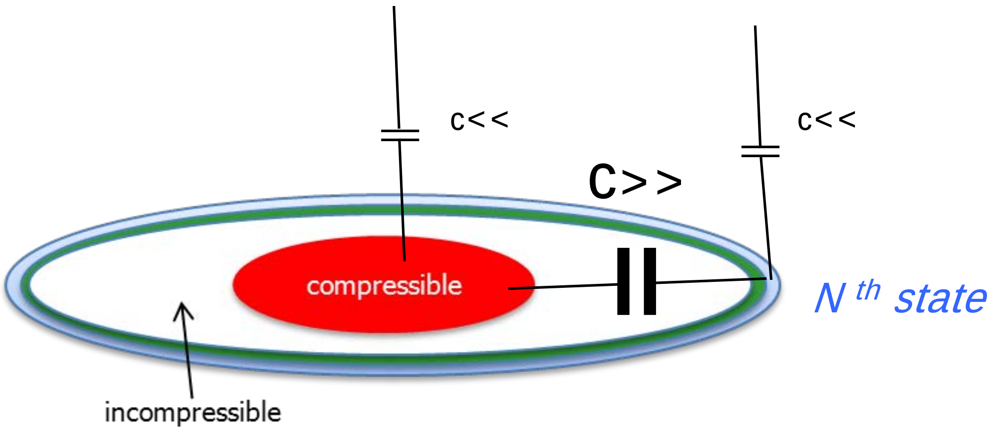




no B dependence

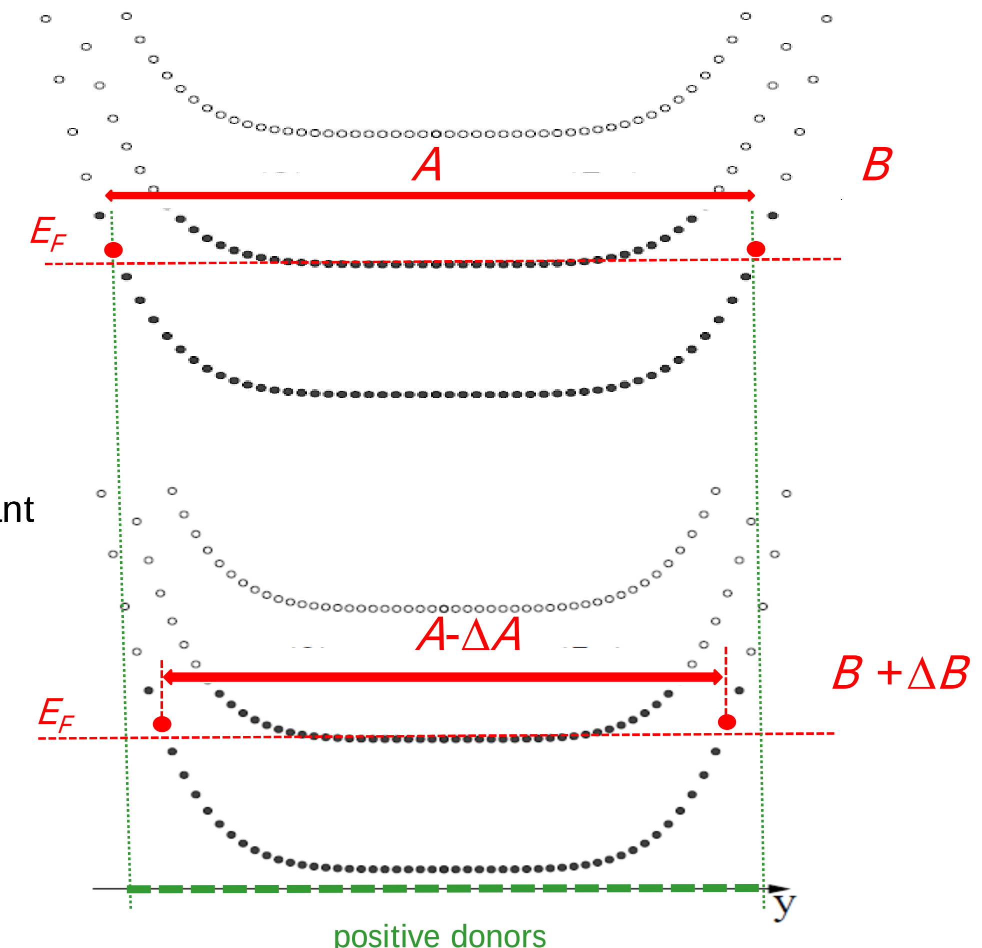
flux remains constant

CD dominated



large charging energy needed to add an electron to the leads

FPI in CD regime – insufficient screening



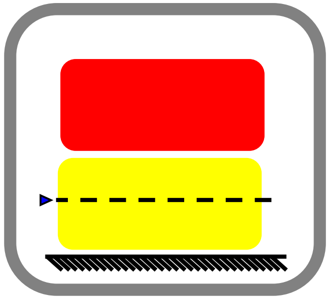
- electrons cannot be added from the leads
- number of electrons in outer state = constant
- hence, all states shrink
- $(A-\Delta A)(B+\Delta B) = constant$
- after Φ_0 a new qp added in the lowest LL
- electron is added to outer state from bulk

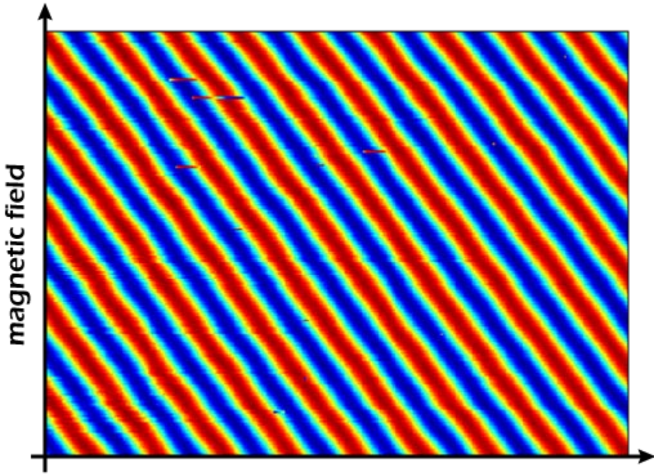
Halperin 2011

interference of outer-most edge mode

MZI

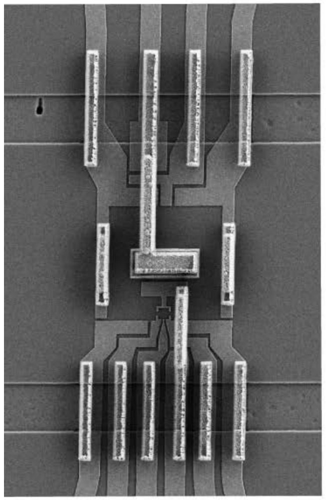
FPI

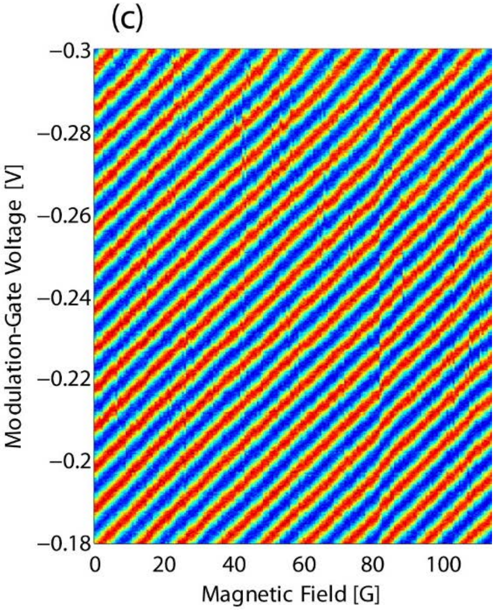


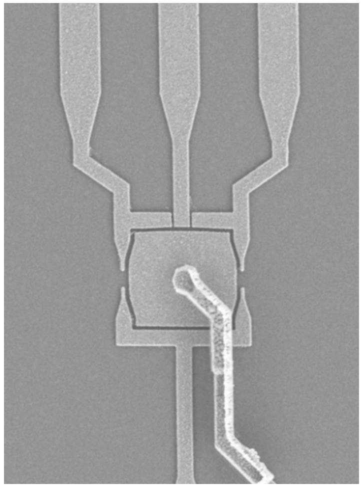


increasing area

FPI CD →→ AB



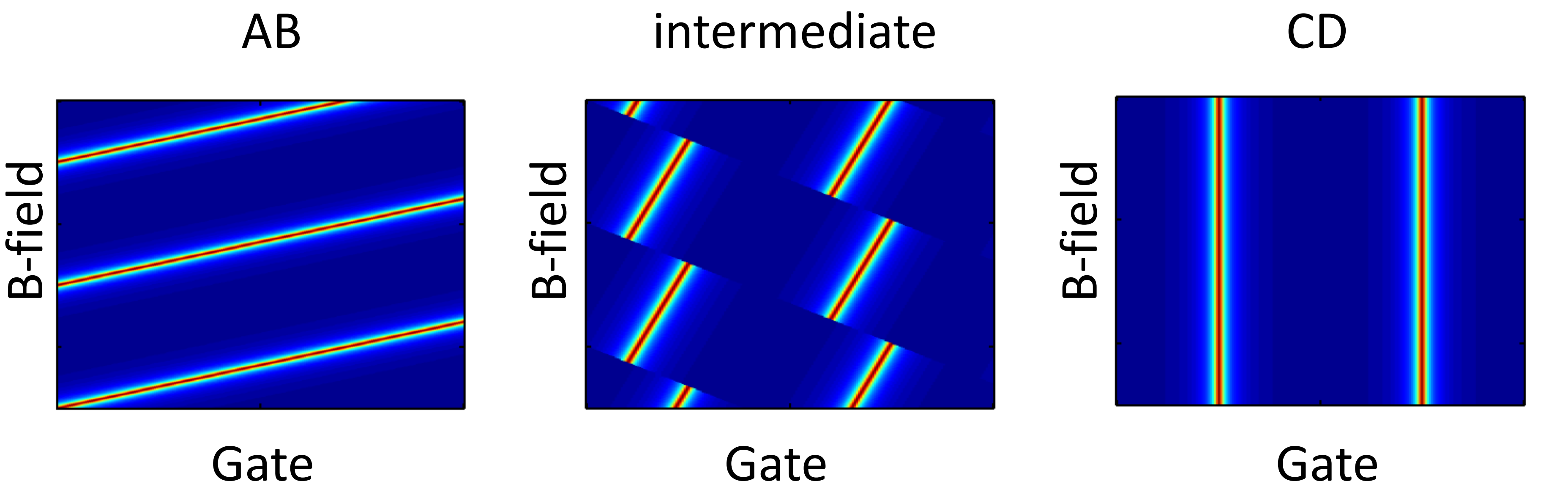




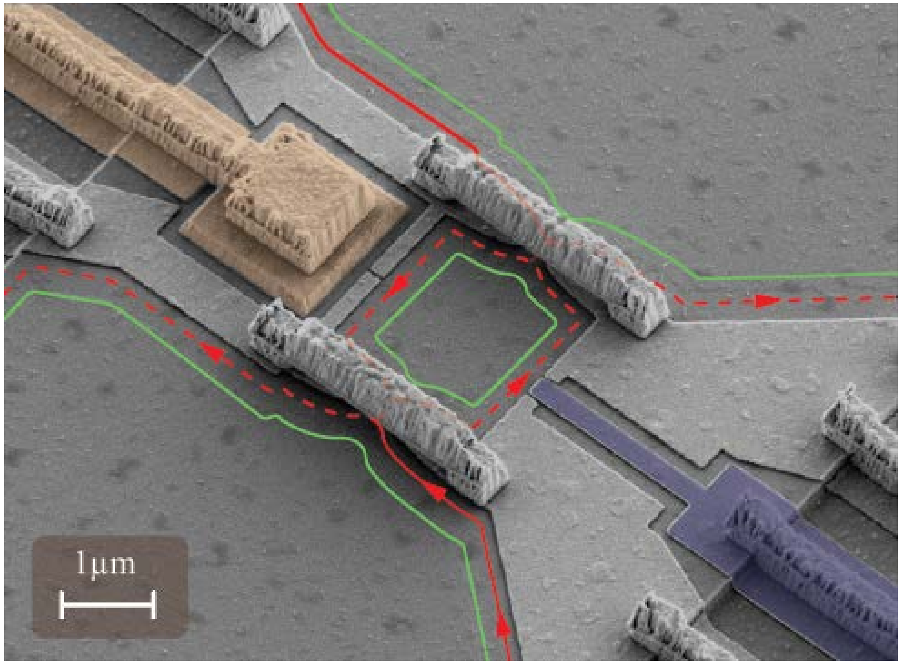
-- grounded ohmic contact

-- top gate

mixed regime ..... AB →→ CD



AB →→ CD



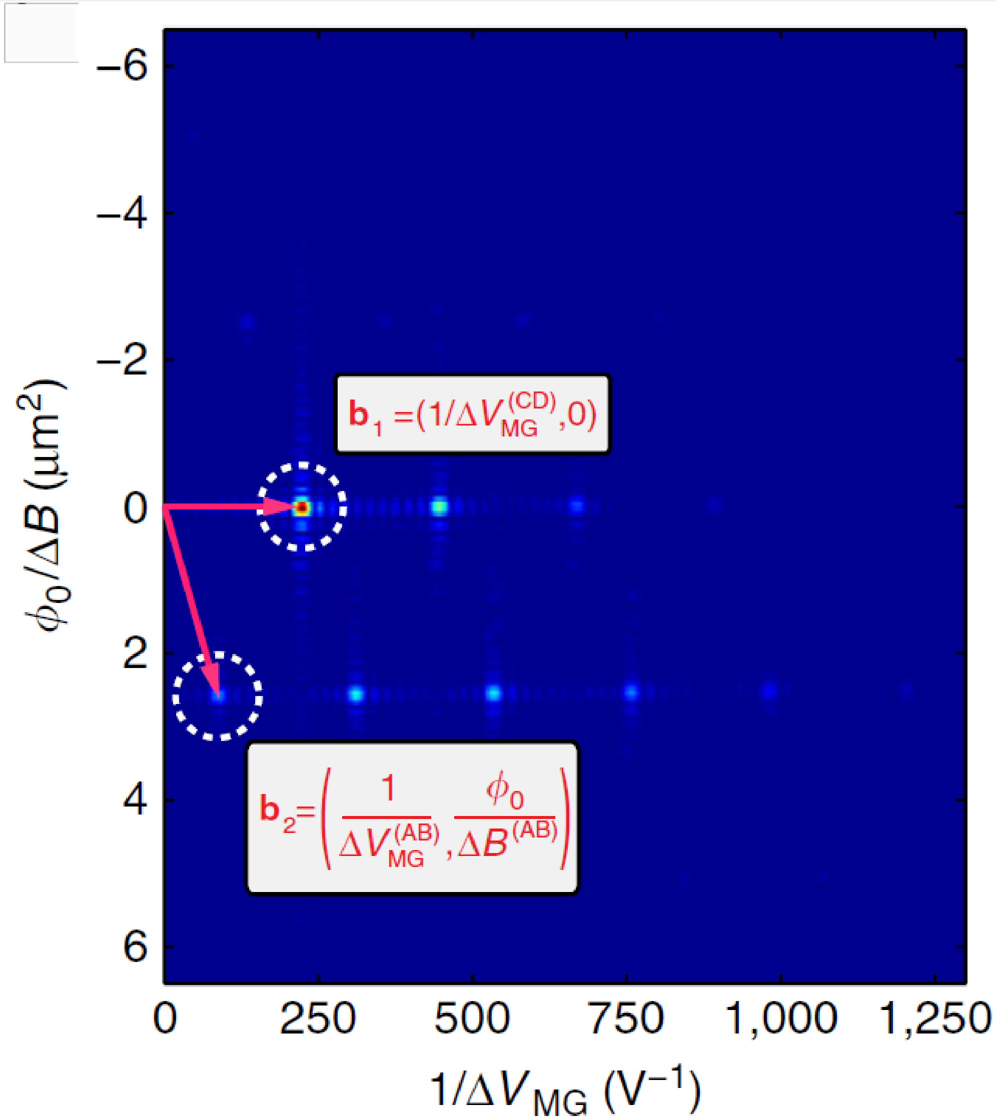
intermediate regime
controlling screening

Sivan 2016)

AB →→ CD

CD oscillations preserves hidden coherence ?

AB →→ CD



−6
−4
−2
0
2
4
6
$\phi_0/\Delta B$ (µm²)
0
250
500
750
1,000
1,250
$1/\Delta V_{MG}$ (V⁻¹)
$\mathbf{b}_1 = (1/\Delta V_{MG}^{(CD)}, 0)$
$\mathbf{b}_2 = \left(\frac{1}{\Delta V_{MG}^{(AB)}}, \frac{\phi_0}{\Delta B^{(AB)}}\right)$

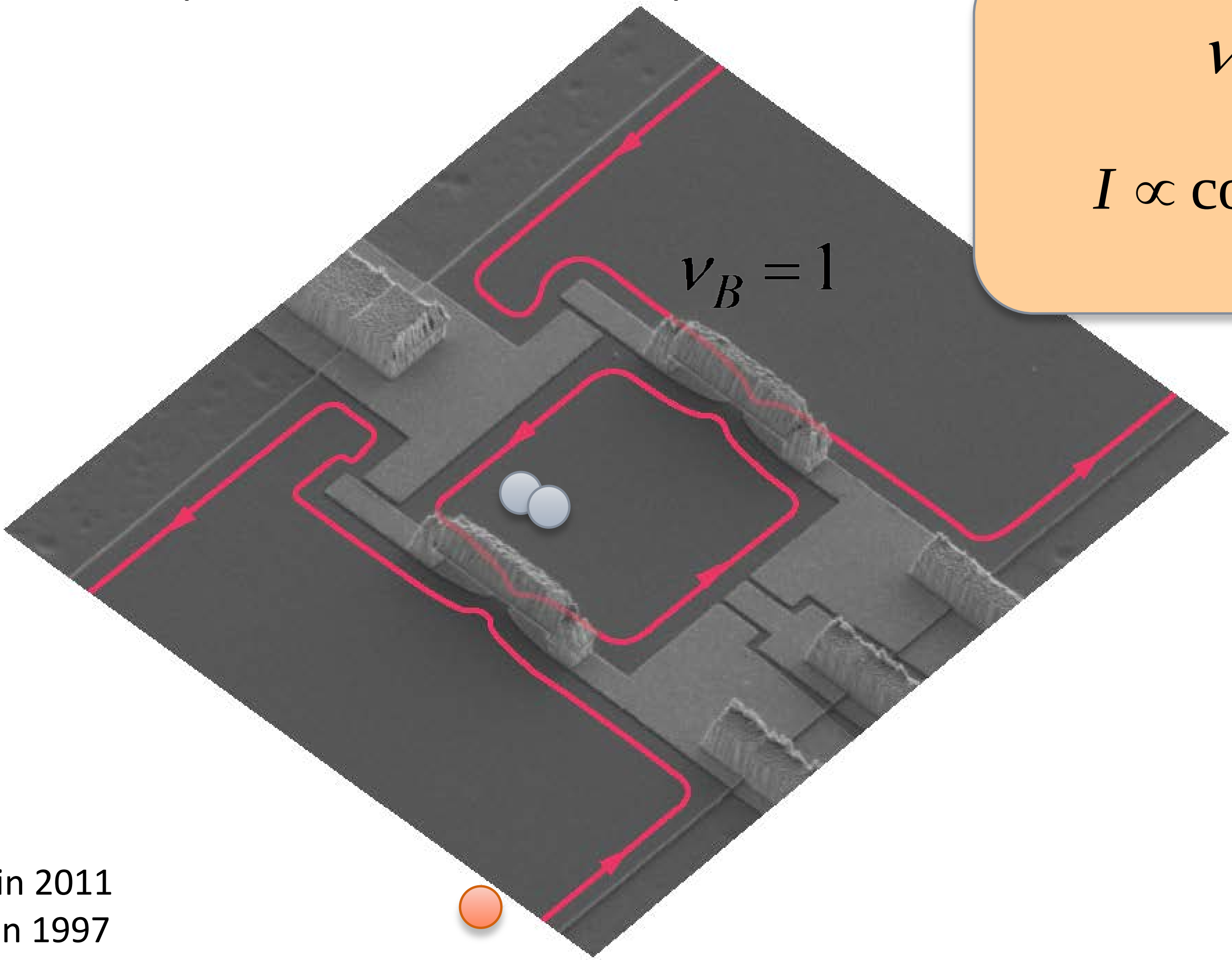
expected interference
in the fractional regime

anyonic statistics

phase is comprised of AB + statistical phases

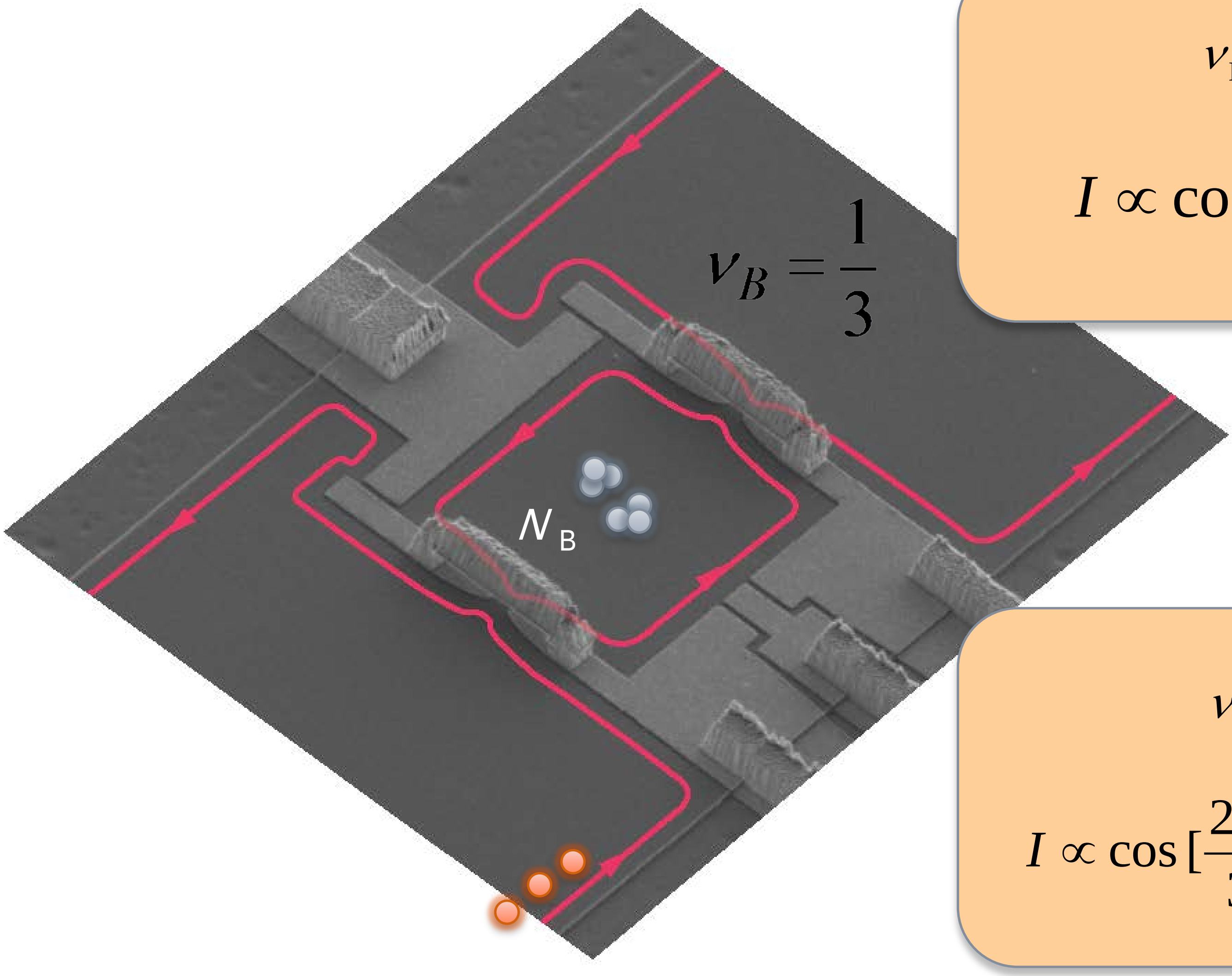
$$\nu_B = 1$$

$$I \propto \cos(2\pi \frac{AB}{\Phi_0})$$



Halperin 2011
Chamon 1997

anyonic statistics



$$\nu_B = 1$$

$$I \propto \cos(2\pi \frac{AB}{\Phi_0})$$

$$\nu_B = \frac{1}{3}$$

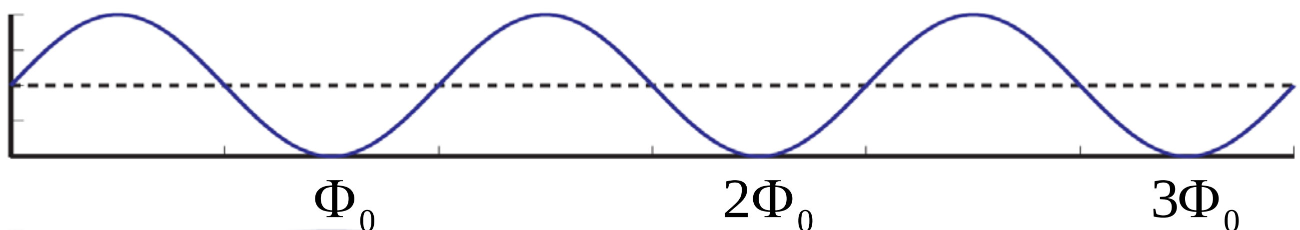
$$I \propto \cos[\frac{2\pi}{3}(\frac{AB}{\Phi_0} - N_B)]$$

anyonic statistics

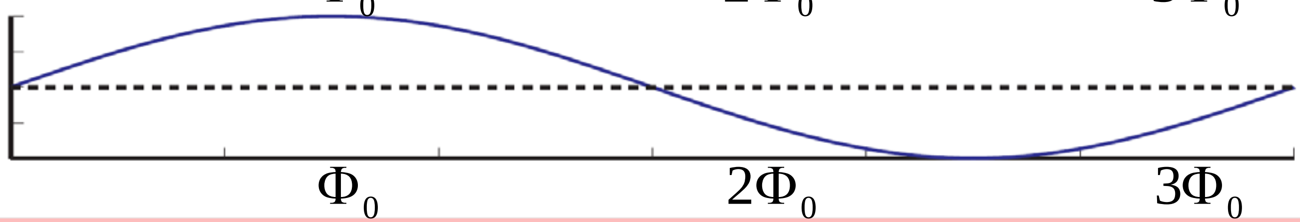
$$\nu_B = \frac{1}{3}$$

$$I \propto \cos\left[\frac{2\pi}{3}\left(\frac{AB}{\Phi_0} - N_B\right)\right]$$

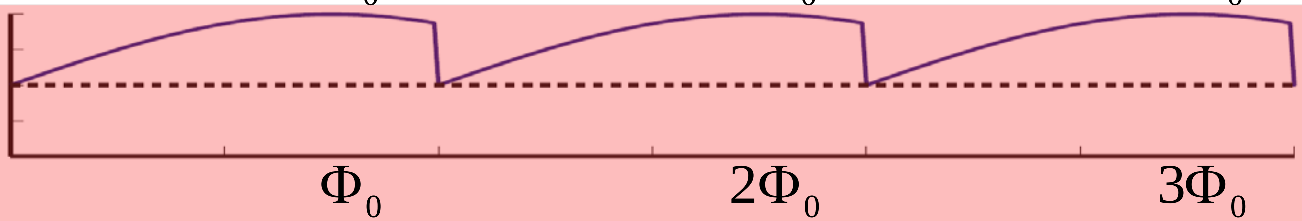
$$\nu_B = 1$$



$$\nu_B = \frac{1}{3}$$



$$\nu_B = \frac{1}{3} + stat'$$

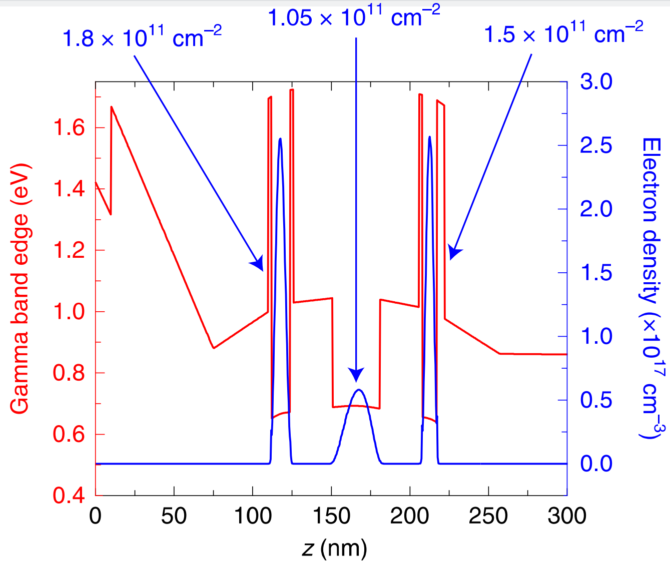


recent report on AB oscillation in *ν* =1/3

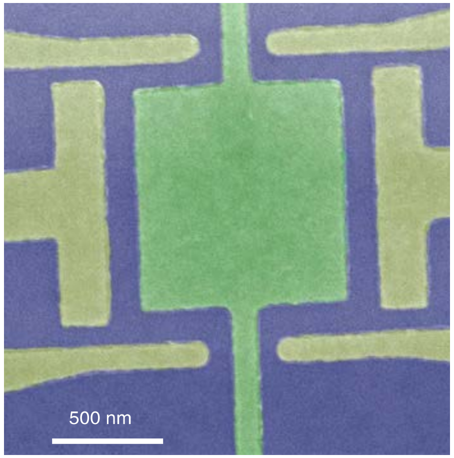
nature physics
ARTICLES
https://doi.org/10.1038/s41567-019-0441-8

Aharonov–Bohm interference of fractional quantum Hall edge modes

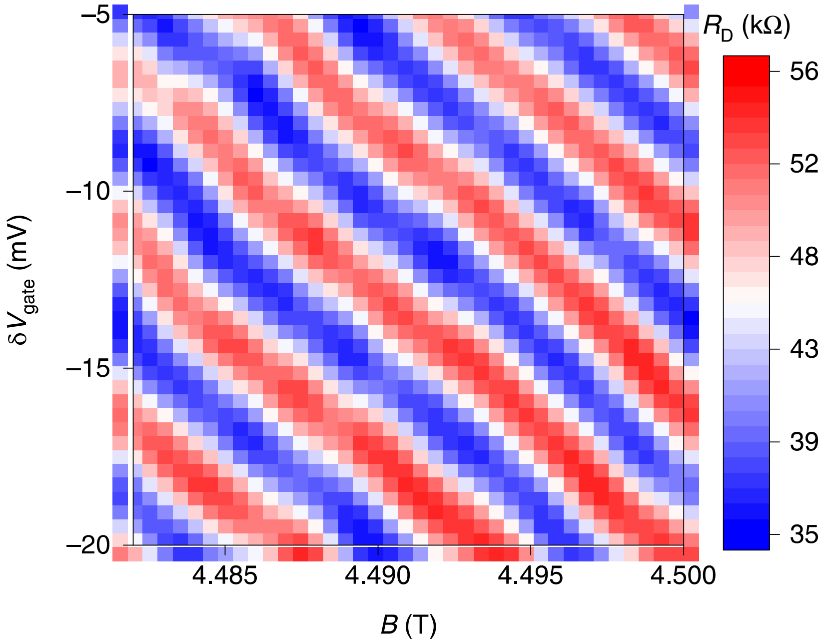
J. Nakamura[1,2], S. Fallahi[1,2], H. Sahasrabudhe[1], R. Rahman[3], S. Liang[1,2], G. C. Gardner[2,4] and M. J. Manfra[1,2,3,4,5*]



two additional 2DEGs used as screening layers

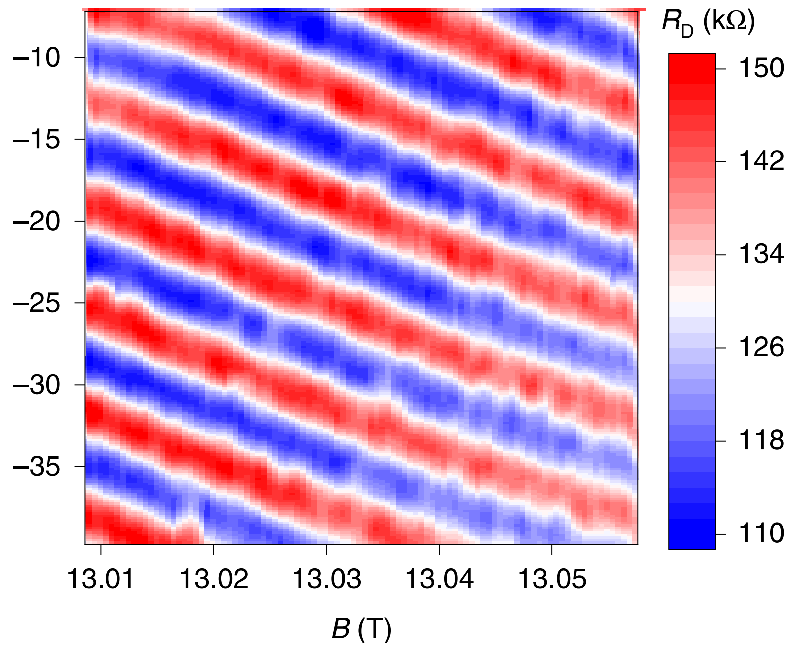


$\nu_{bulk} = 1$



$\Delta B = 5.7\ mT, \Delta V_{gate} = 5.8\ mV$

$\nu_{bulk} = \frac{1}{3}$



$\Delta B = 22.2\ mT, \Delta V_{gate} = 6.1\ mV$

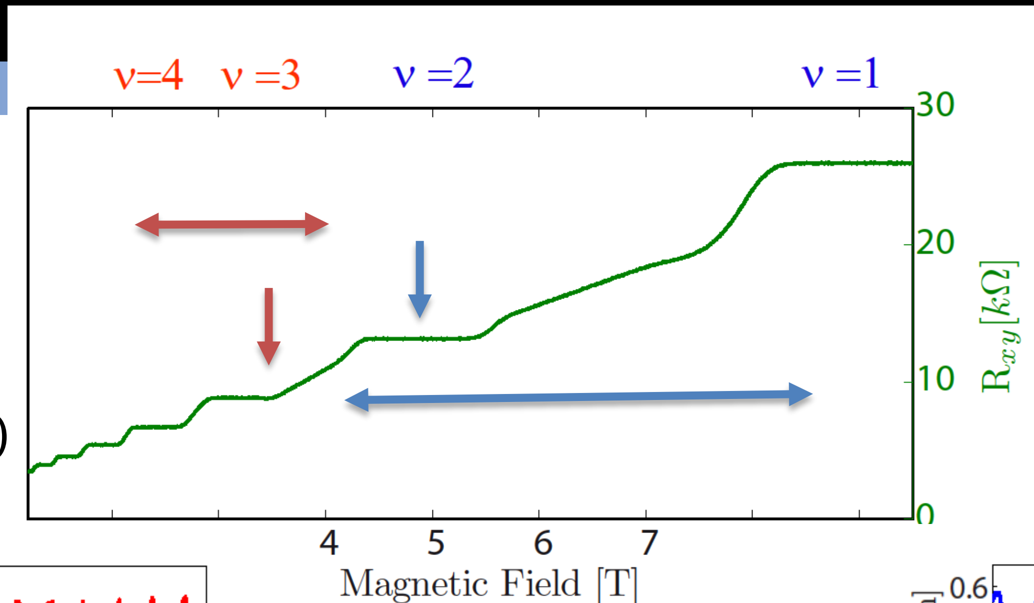
$\Delta B(1/3) \sim 3.9\ \Delta B(1)$

- $\sim 3\Phi_0$
- or Φ_0 since much smaller area
- what is e^* in the QPC
- statistical phase not observed

do we understand the integer regime?

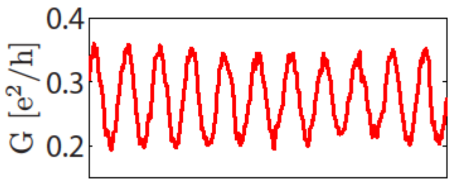
FPI in AB regime

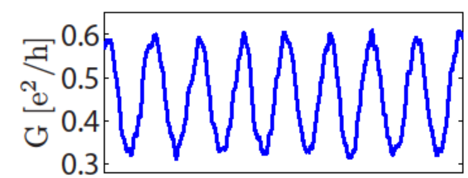
AB interference

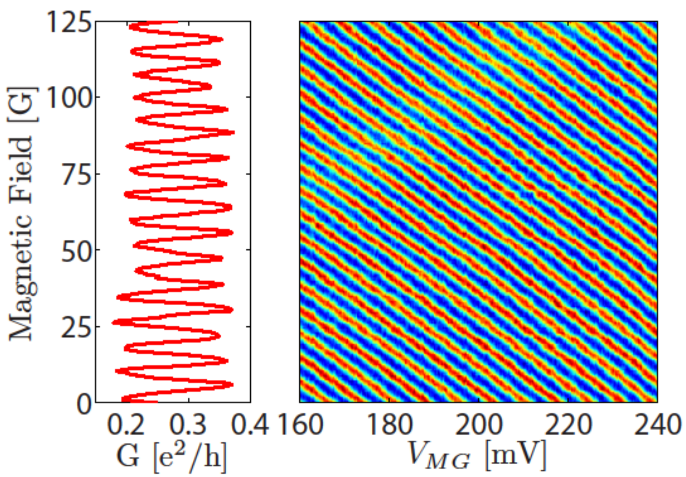


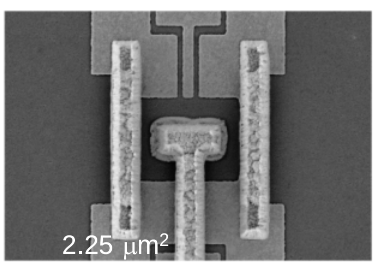
$$e^{2\pi i \cdot AB/(\frac{h}{2e})}$$

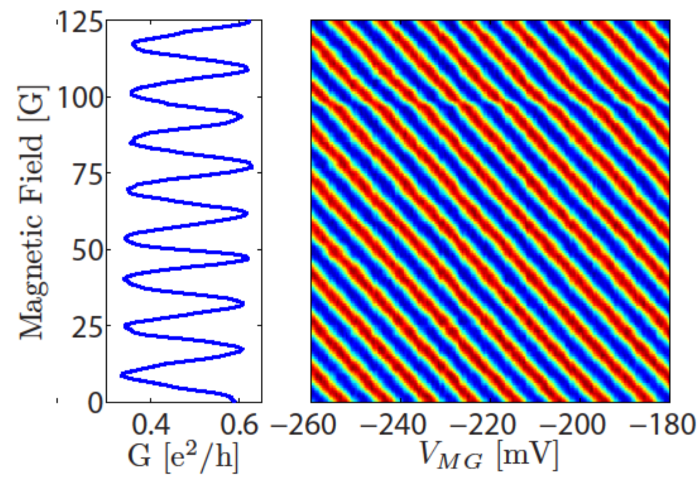
$$e^{2\pi i \cdot AB/(\frac{h}{e})}$$



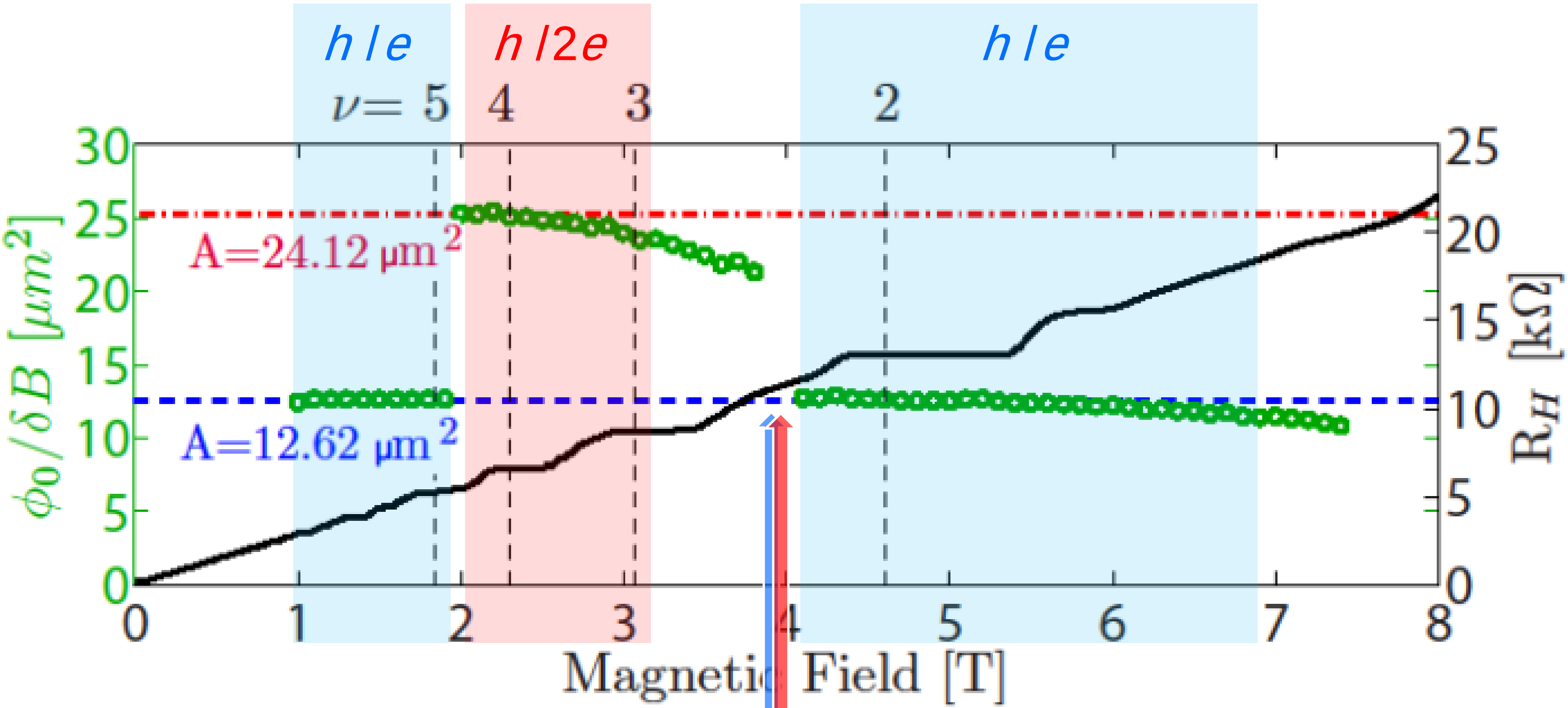




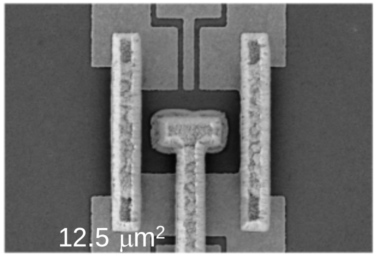




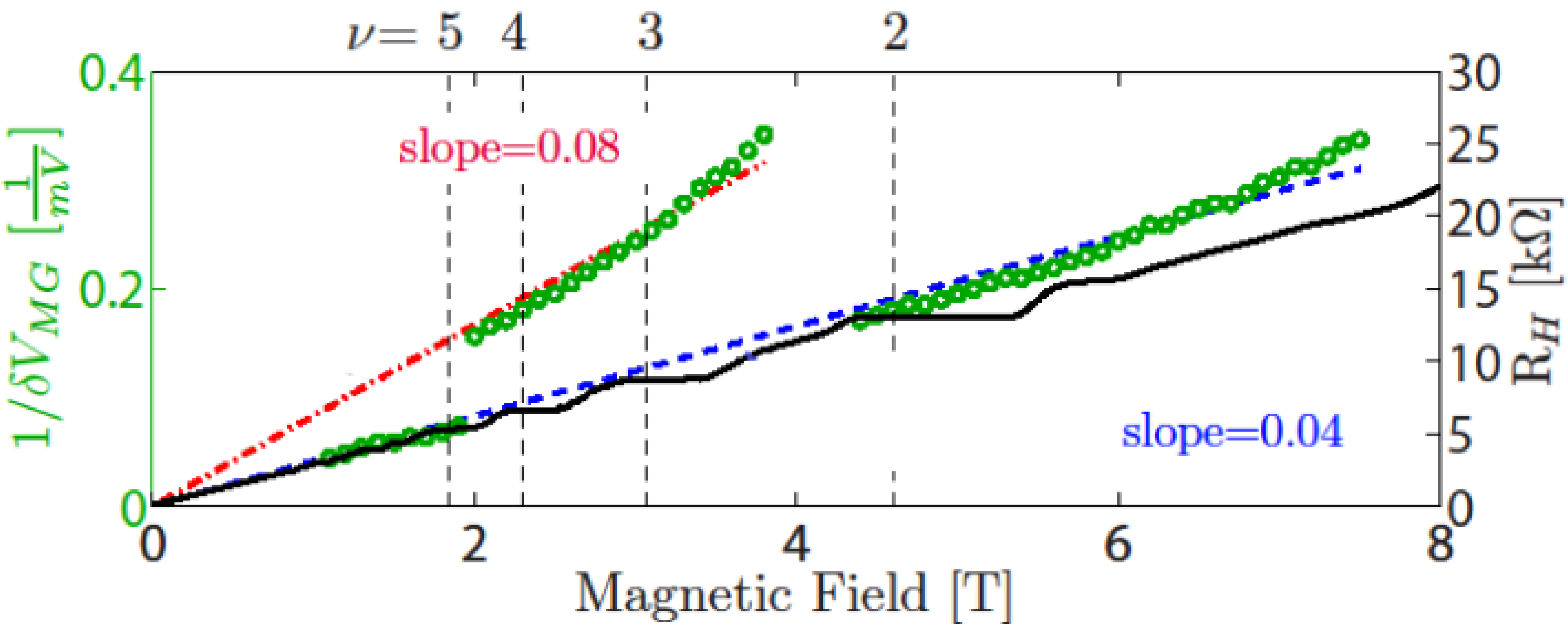
periodicity in *B* …. large 12.5μm FPI

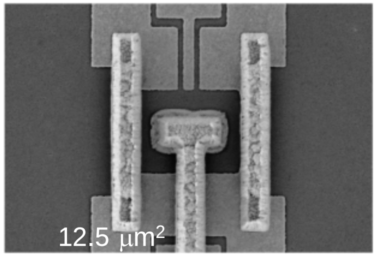


zero visibility



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



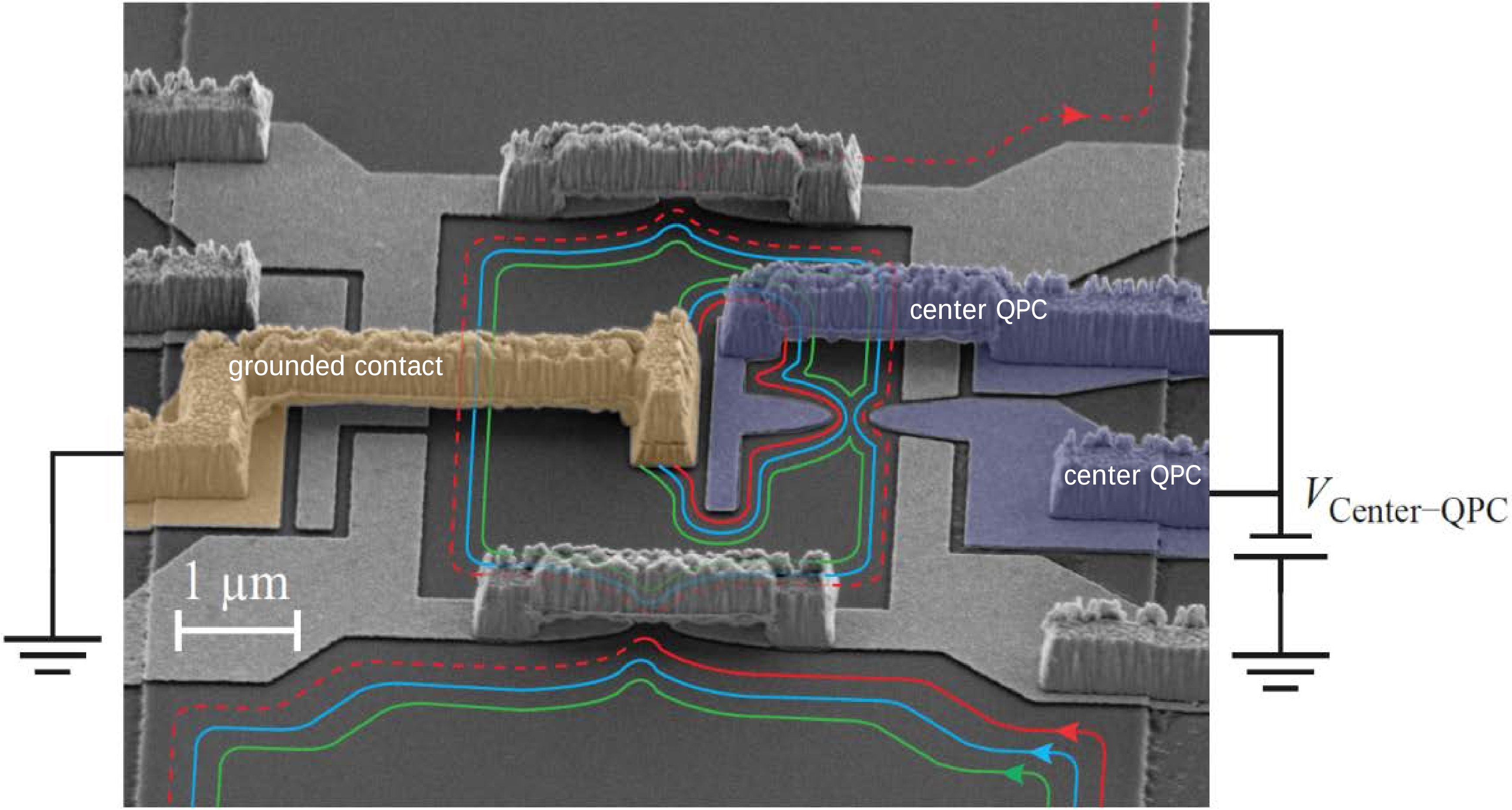


$$\Delta V_{MG} = \alpha\ \Phi_0^*$$

doubled slope…. $\Phi_0^* = h/2e$

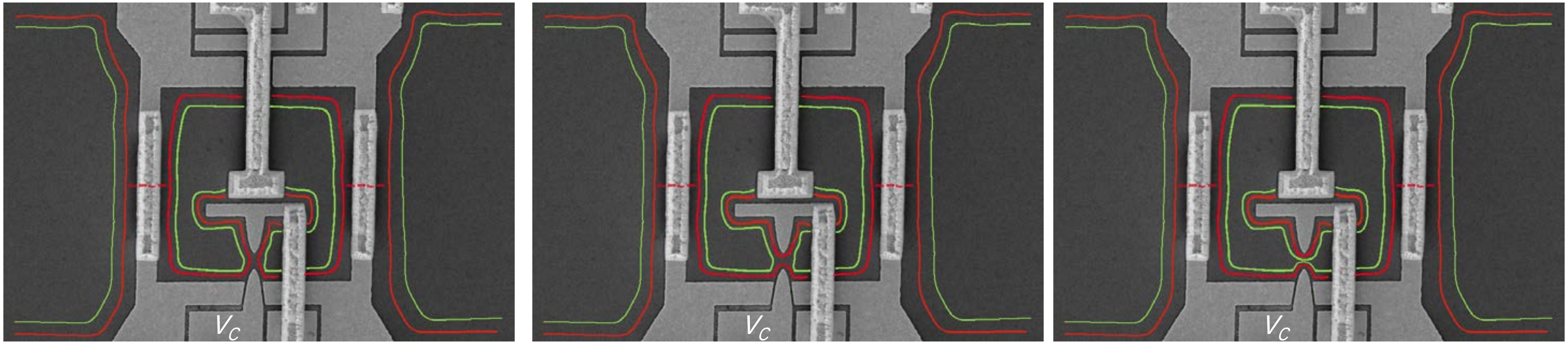
preferential dephasing of channels

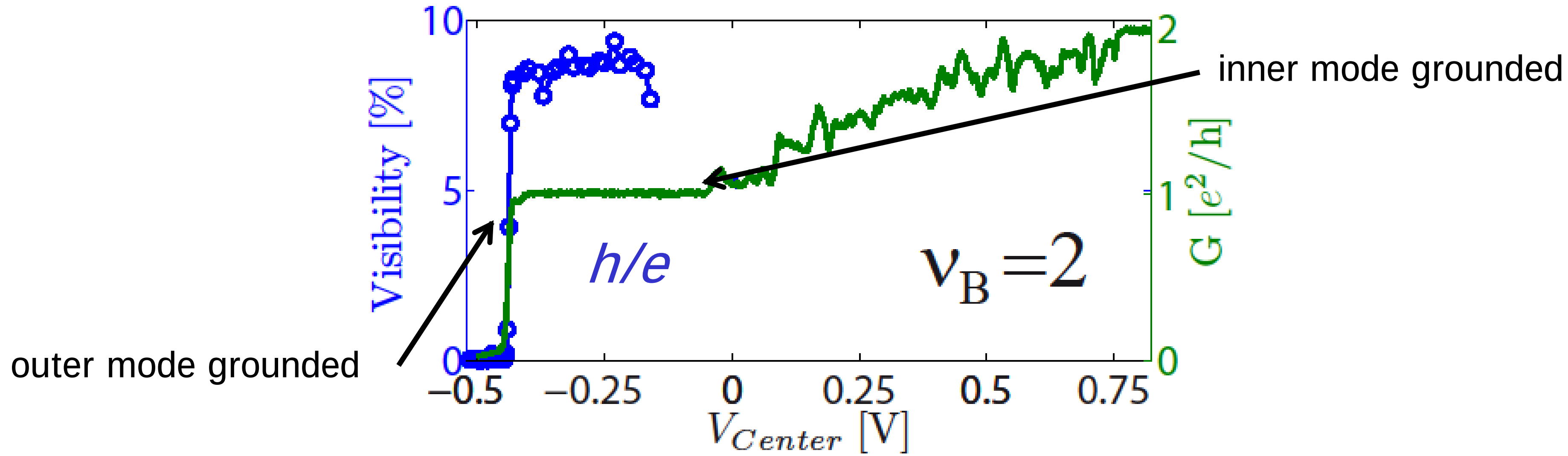
adding a ‘center QPC’



role of first inner mode @ ν_B =2

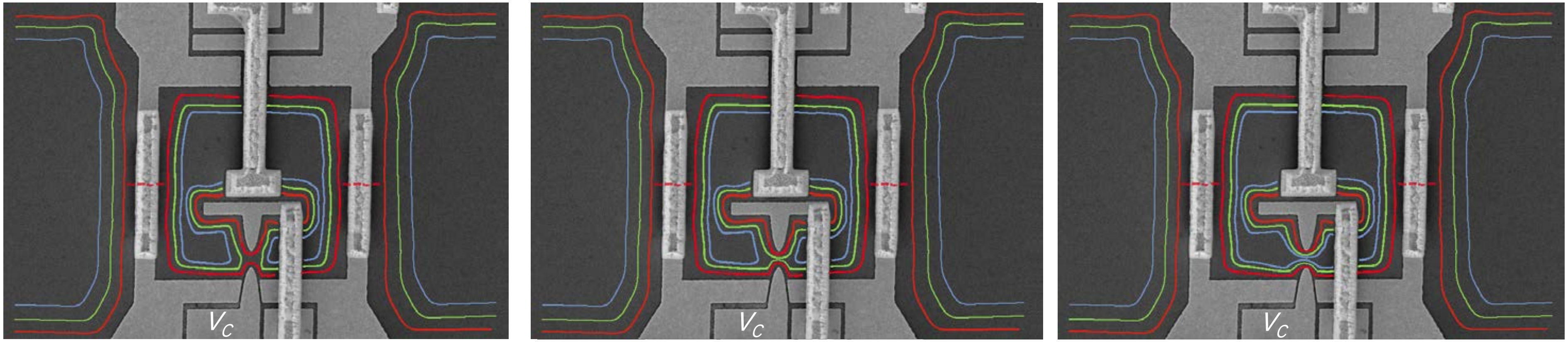
dephasing first inner mode is irrelevant

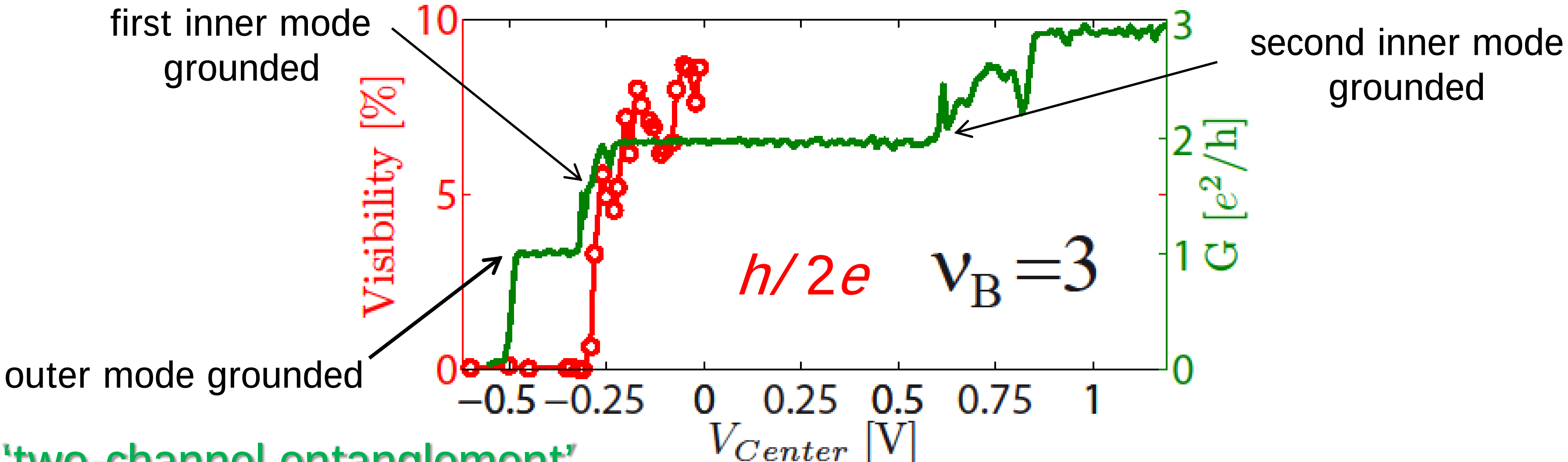




role of first inner mode @ ν_B =3

dephasing first inner mode fully dephases the outer channel





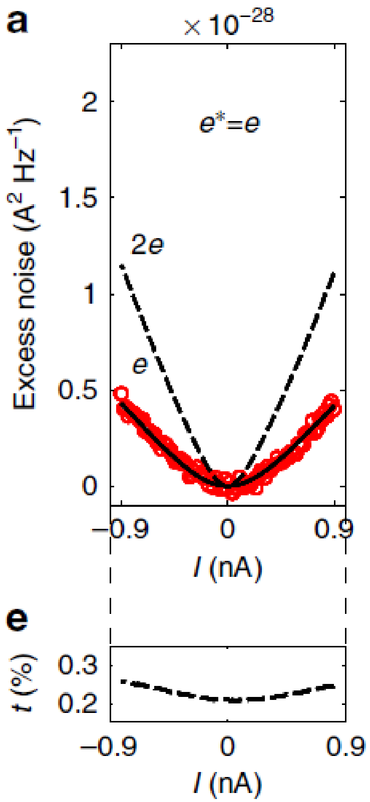
'two-channel entanglement'

is $e^{*}=2e$ charge interfere ?

do shot noise measurements

shot noise most outer channel interfering

QPC @ $\nu_B = 2$



at ν=3

finite visibility necessary for

$e \longrightarrow 2e$

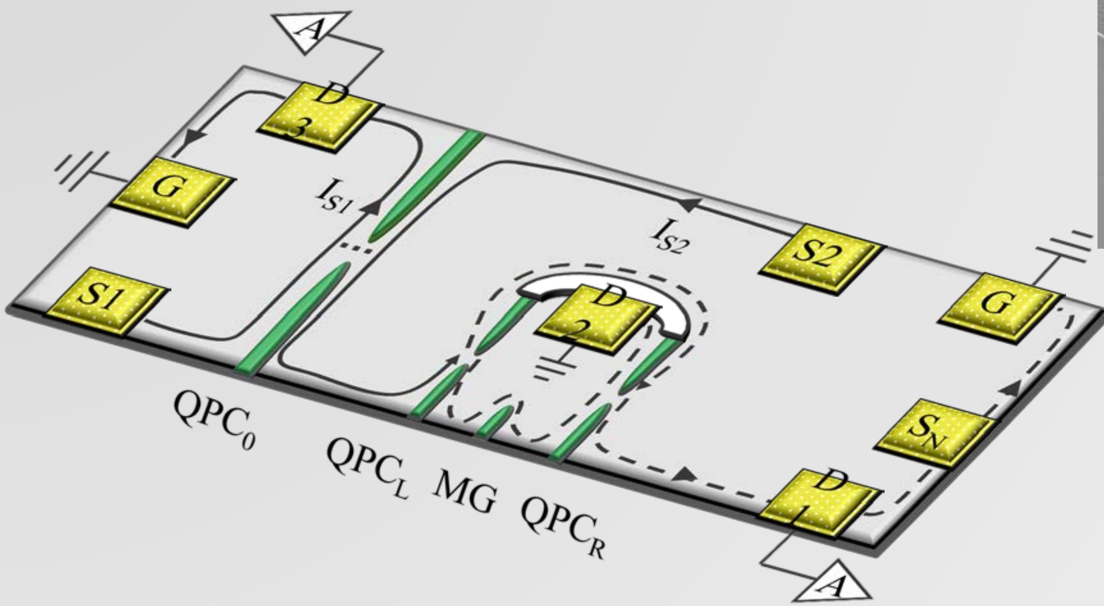
- independent of transparency of FPI
- $h/2e$ only in outer mode
- temperature dependence of h/e and $h/2e$ similar
- no tunneling between channels
- coherence and dephasing

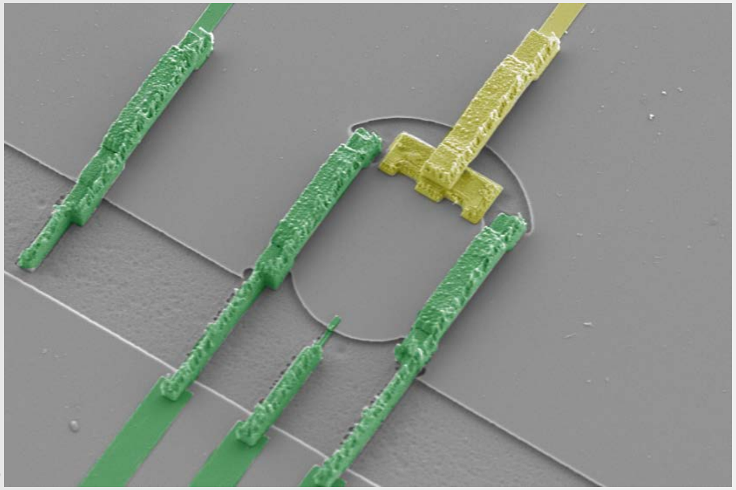
FPI in AB regime

revealed inter-channel interaction

leading to unexpected pairing of electrons

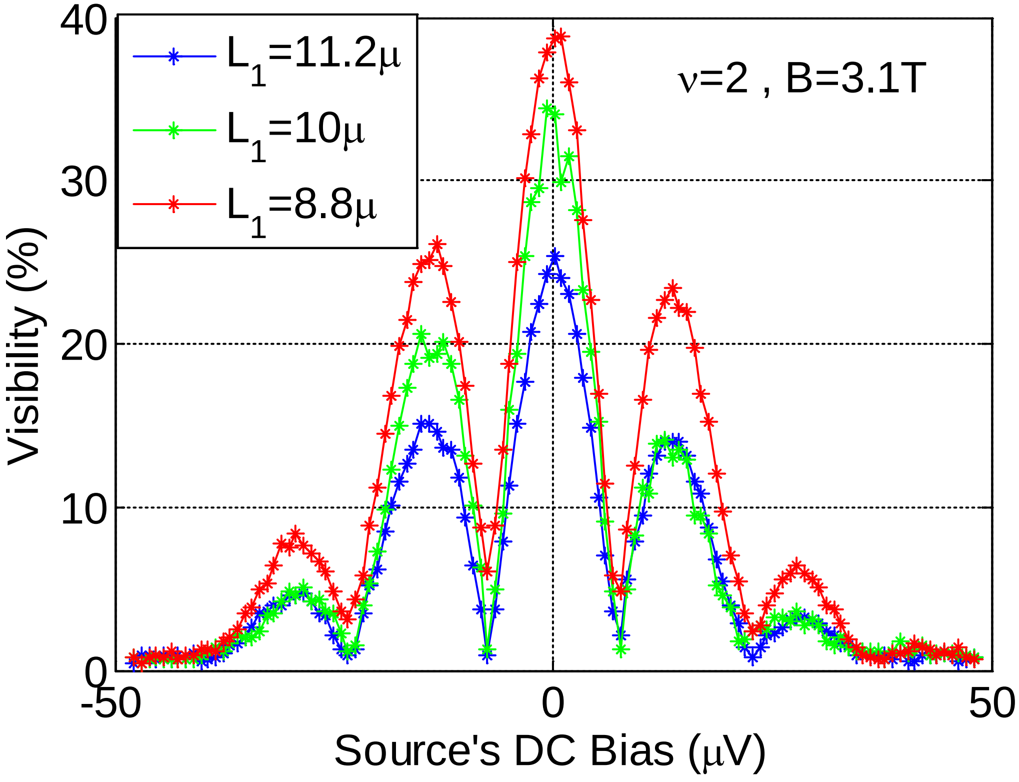
again, **MZI**





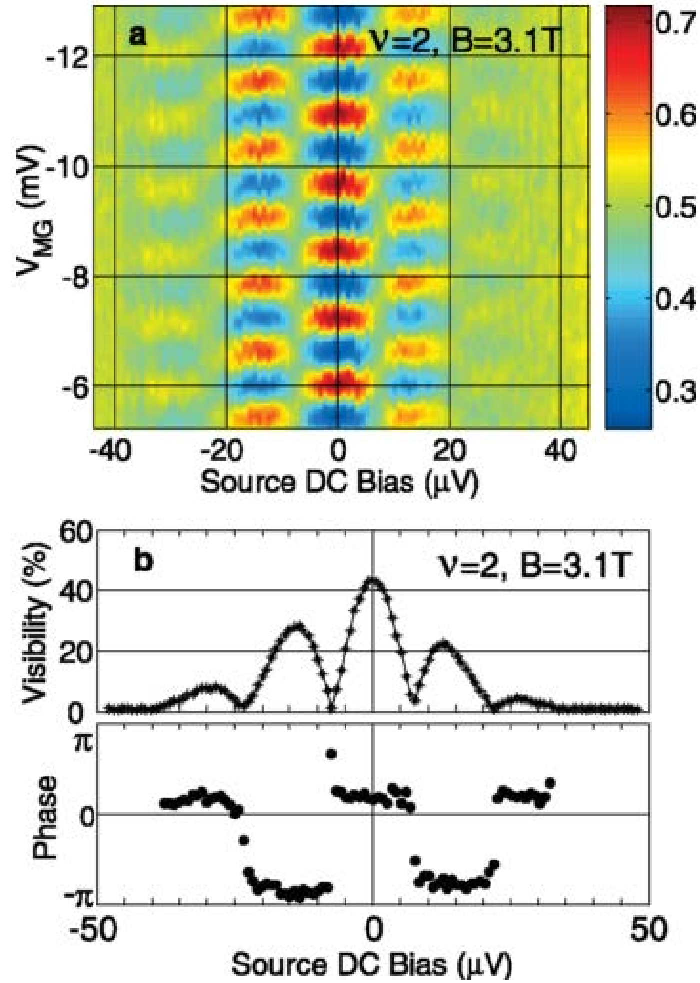
lobe structure

non-linear regime   adding V_{DC} to to the small v_{AC}



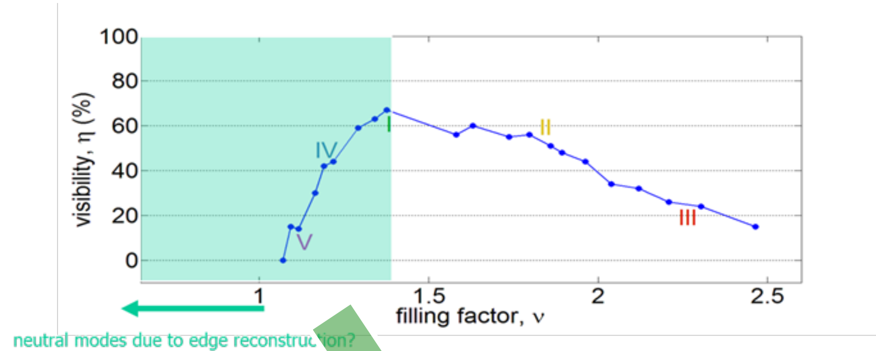
Neder et al. PRL 2006

unexpected lobe structure



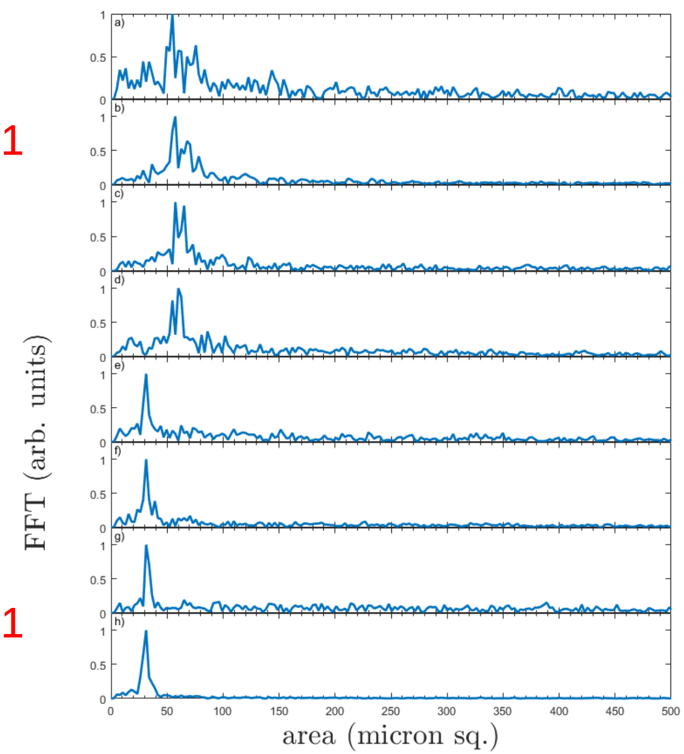
Neder et al. PRL 2006

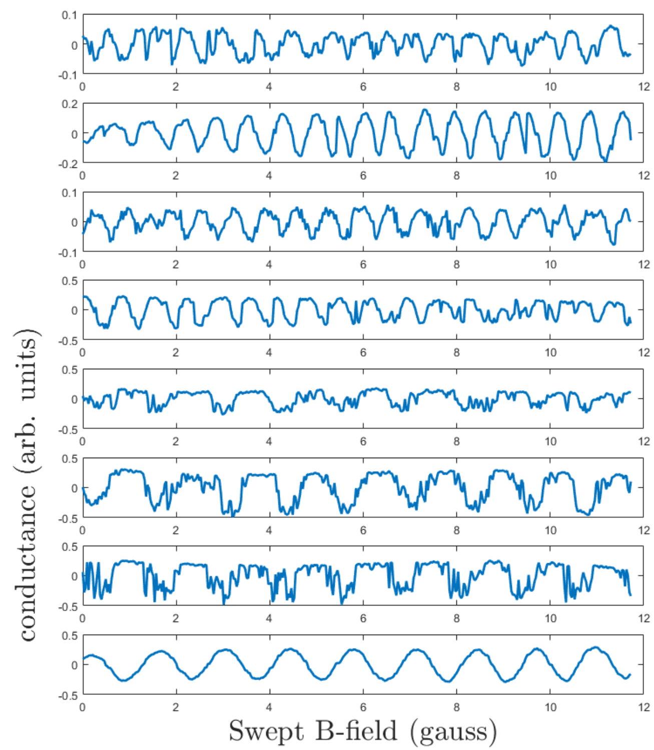
one more.....



$\nu<1$

$\nu>1$





abrupt transition from Φ_0 to $\Phi_0/2$