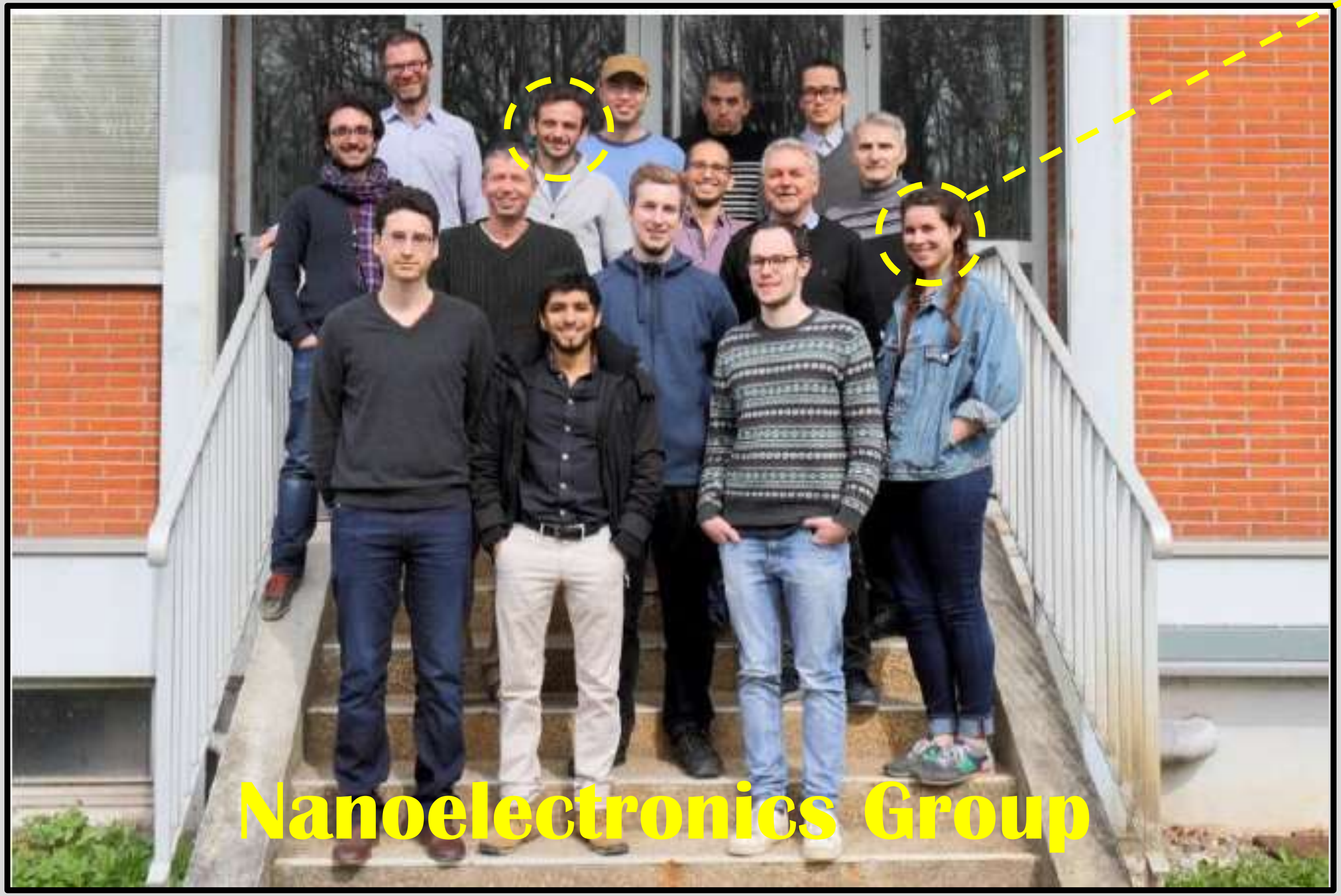
Periodic driving of e/3 and e/5 Anyons in the FQHE Regime

D. Christian Glattli



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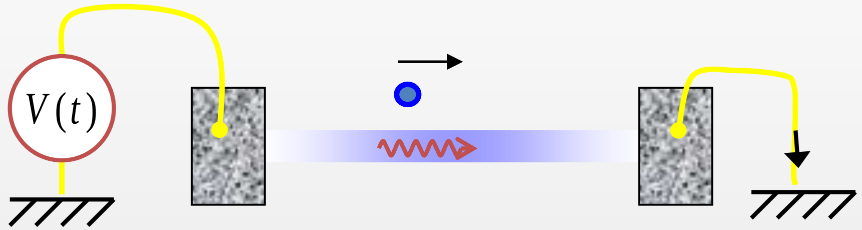
OPEN POSITION
for 18-24 months
Post-doct.

AGENCE NATIONALE DE LA RECHERCHE ANR

Science Cite as: M. Kapfer *et al.*, *Science* 10.1126/science.aau3539 (2019).

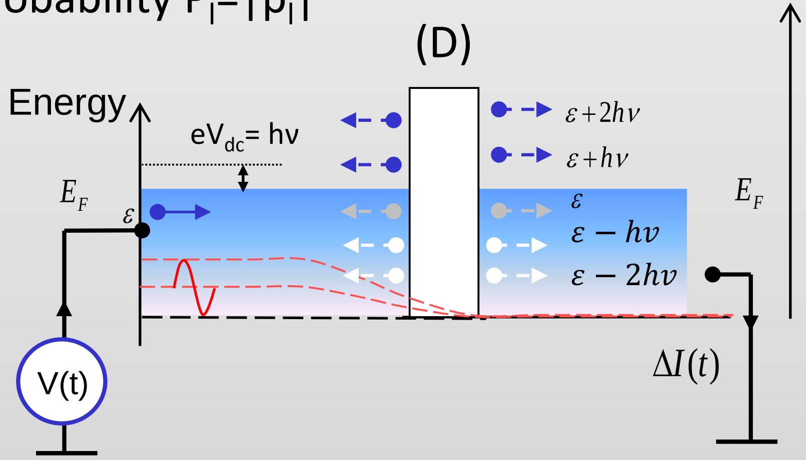
Motivation

PERIODIC DRIVING of a mesoscopic conductor



- Brings new information on electron time-scales:
  quantum inductance ~ $(h/e^2)\tau$, quantum capacitance ~ $(e^2/h)\tau$, charge relaxation (or Büttiker's) resistance $h/2e^2$
- Can provide interesting comparison between quantum systems and cycle-operated thermodynamic engines
- Can be simply described by the photo-absorption (l>0) or emission (l<0) Floquet probability $P_l=|p_l|^2$

For voltage pulses on a contact $V(t)=V_{dc}+V_{ac}(t)$: $p_l=\frac{1}{T}\int_0^T dt\, e^{-i\phi(t)}\, e^{il2\pi\nu t}$



$$O^{P.A.}(V_{dc})=P_0\,O_{D.C}(V_{dc})+P_1\,O_{D.C.}(V_{dc}+h\nu/q)+P_{-1}\,O_{D.C.}(V_{dc}-h\nu/q)+$$
$$+P_2\,O_{D.C.}(V_{dc}+2h\nu/q)+....$$

O : current, heat, current noise, heat noise, ….

- An interesting regime is when the A.C. voltage amplitude is small, typically eV_{ac} ~ hν → single-electron transport

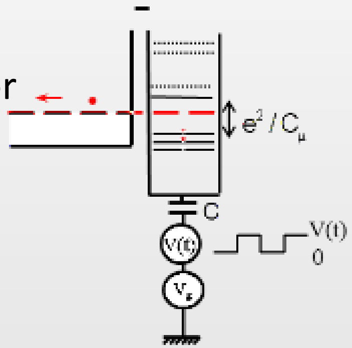
Current $I(t)=v_F\,|\psi(t)|^2$

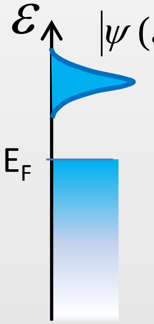
Heat current $I^Q(t)=v_F\hbar\,\mathrm{Im}\left[\frac{d\psi(t)^*}{dt}\psi(t)\right]$

M. Moskalets, G. Haack - physica status solidi (b), (2017)
M.F. Ludovico, J. S. Lim, M. Moskalets, L. Arrachea, D. Sanchez (2014)

coherent single electron sources

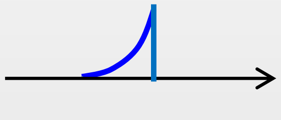
quantum capacitor electron source





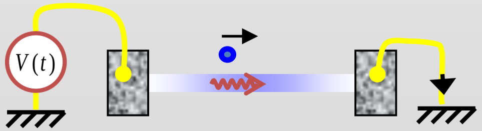
$$|\psi(\varepsilon)|^2 \propto \frac{1}{(\varepsilon-\varepsilon_0)^2+\Gamma^2}$$

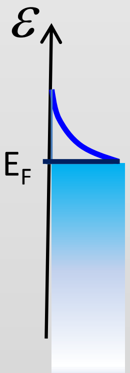
$$\psi(t) \propto e^{-\Gamma t}$$



G. Fève, A. Mahé, J.-M. Berroir, T. Kontos, B. Plaçais, and D. C. Glattli, B. Etienne, Y. Jin, , Science 316, 1169 (2007)

voltage pulse source:

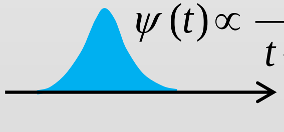




$$|\psi(\varepsilon)|^2 \propto e^{-\varepsilon.w}$$

leviton

$$\psi(t) \propto \frac{1}{t+iw}$$



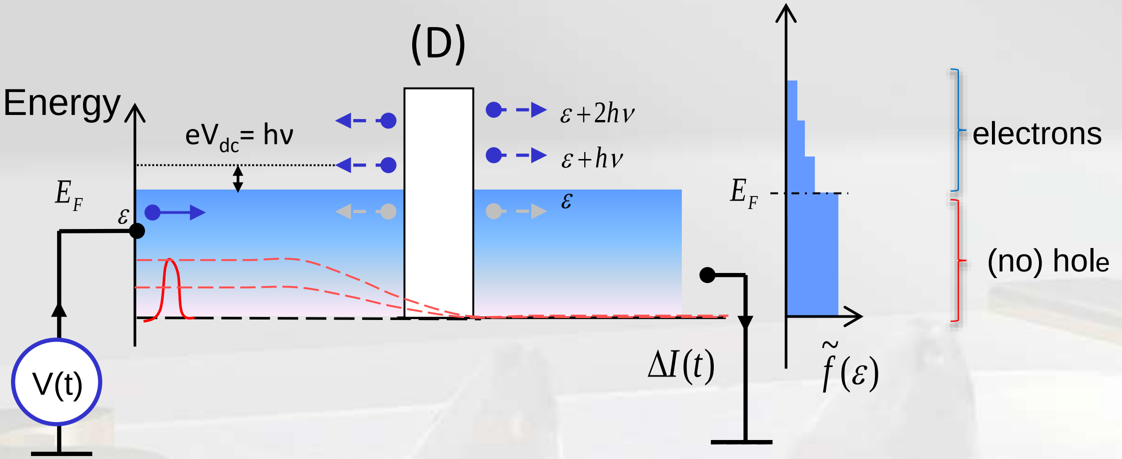
J. Dubois, T. Jullien,P. Roulleau, F. Portier,P. Roche, Y. Jin, W. Wegscheider, and D.C. Glattli , NATURE 502, 659 (2013)

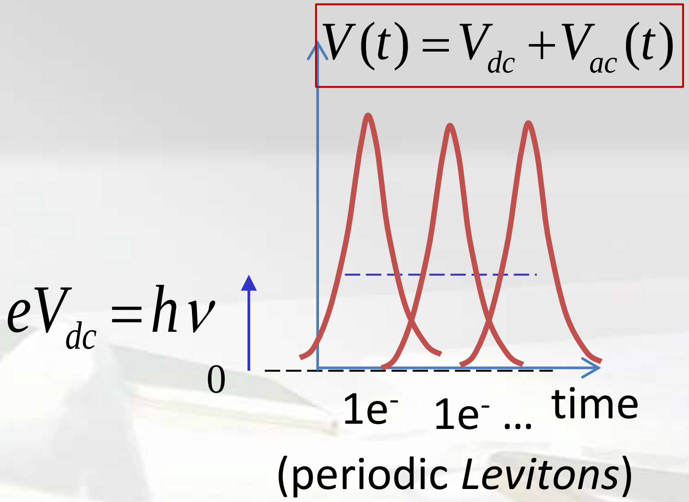
- simple: voltage pulse on a contact
- Lorentzian pulses create **minimal excitation states** (levitons) *Levitov, Lee,Lesovik, J. Math. Phys.(1996) Keeling, Klich and Levitov PRL 97, 116403 (2006)*
- time resolved (no quantum jitter)
- long lifetime
- Minimal heat production: *Dashti, Misiorny, Kheradsoud, Samuelsson, and Splettstoesser, PRB 100, 035405 (2019)*

Periodic single electron sources

Lorentzian Pulses

$l \geq 0$ only



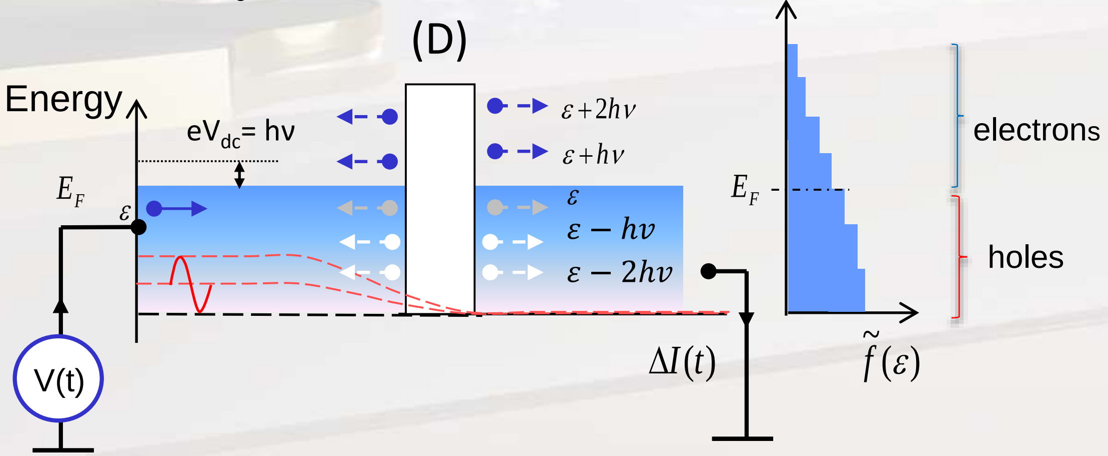


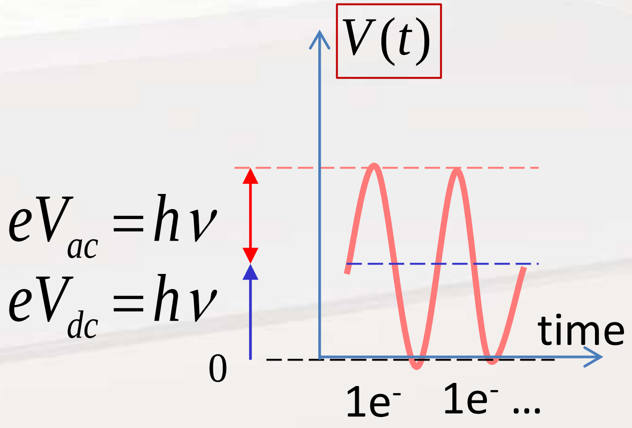
$$p_l = \frac{1}{T}\int_0^T dt\, e^{-i\phi(t)}\, e^{il2\pi\nu t} \qquad \phi(t) = \frac{e}{h}\int^t V_{ac}(t')\, dt'$$

Sine Pulses

$l \geq 0$ and

$l < 0$

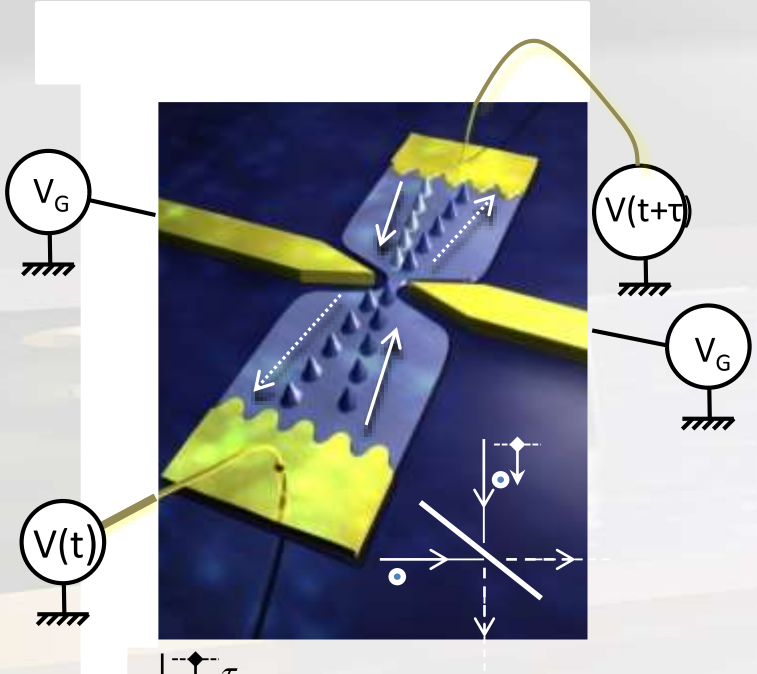


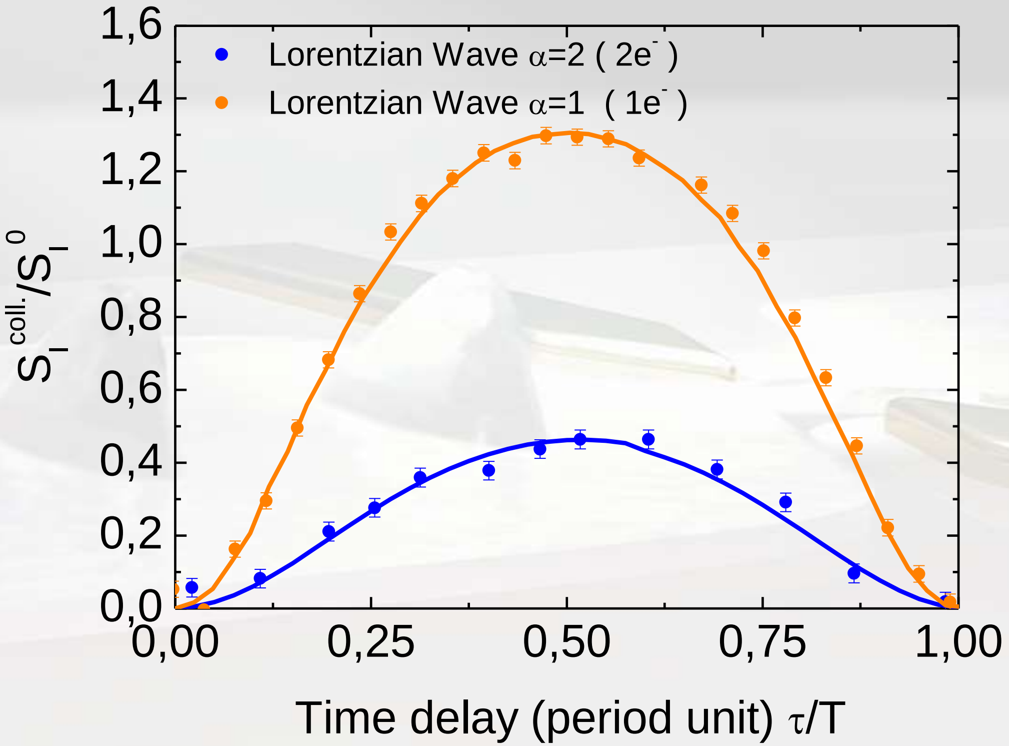


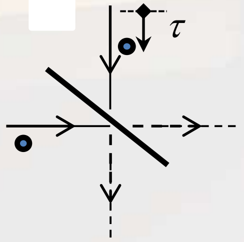
Periodic electron injection is well described by Photo-Assisted process

NEW Quantum physics with on-demand electrons

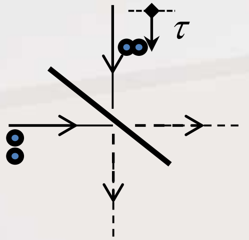
Electronic Hong Ou Mandel correlation:







$$S_I^{HOM}(1e) \propto 1 - \left|\langle \psi_1(0) | \psi_1(\tau) \rangle\right|^2$$



$$S_I^{HOM}(2e) \propto 2 - \left|\langle \psi_1(0) | \psi_1(\tau) \rangle\right|^2 - \left|\langle \psi_2(0) | \psi_2(\tau) \rangle\right|^2$$

D. C. Glattli, P. Roulleau (2017)
DOI 10.1002/pssb.201600650

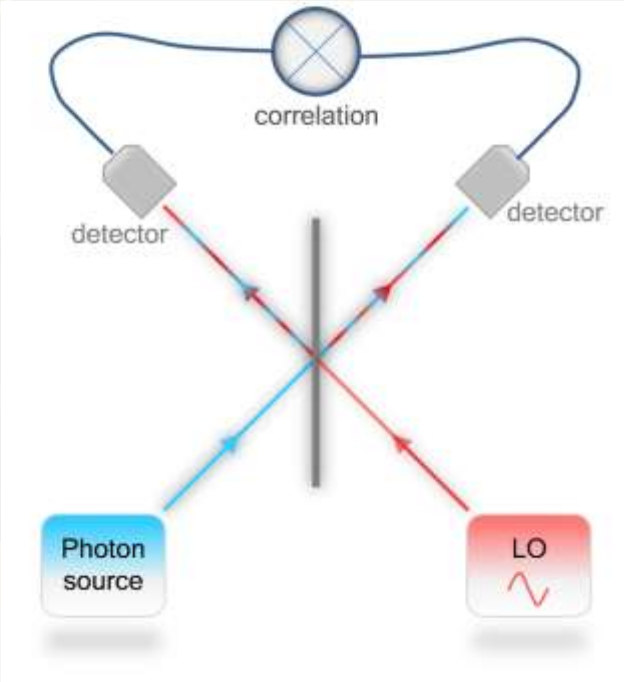
J. Dubois et al., Nature 502, 659–663 (2013)

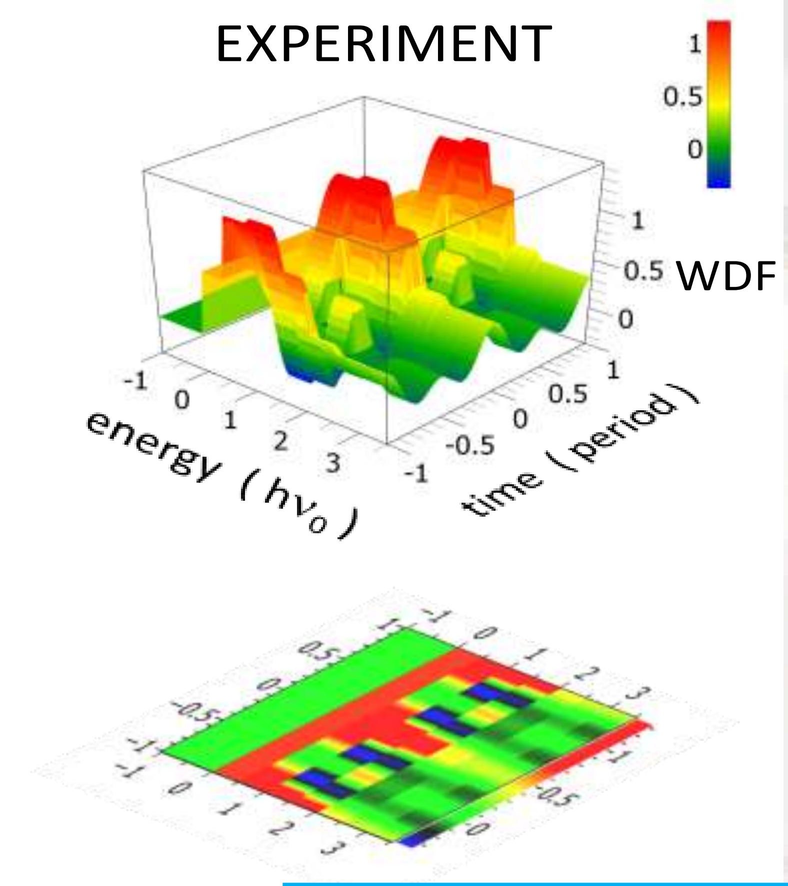
E. Bocquillon et al., Science 339, 1054–1057 (2013)

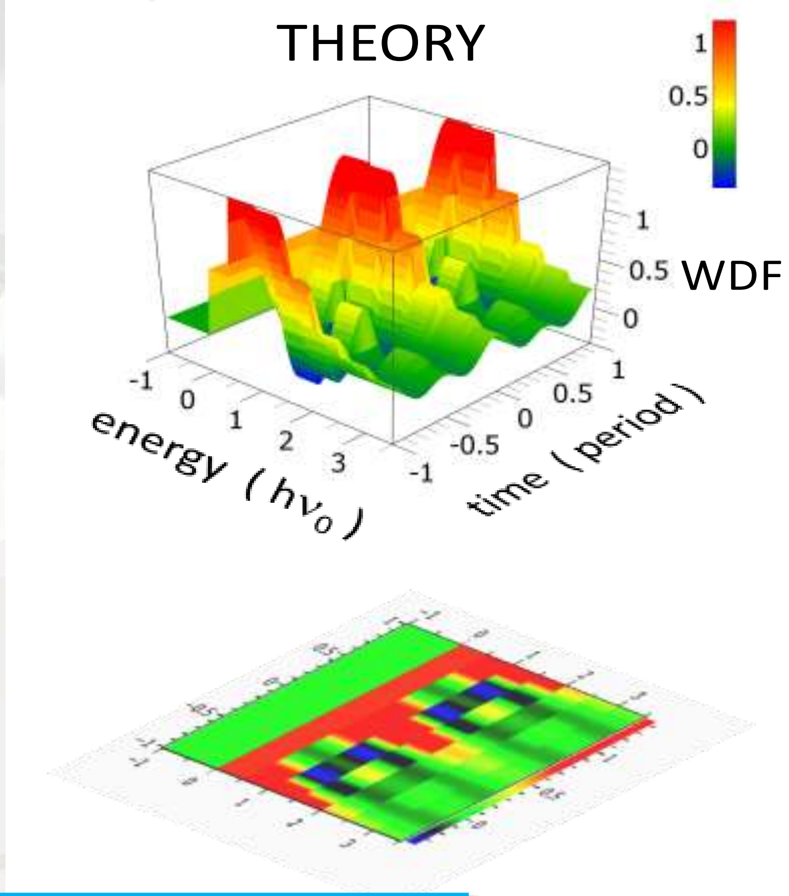
(many particle HOM experiments open a new field of quantum investigations)

NEW Quantum physics with on-demand electrons

Wigner Function of (periodic) levitons







Wigner function
(quasi-probability)

$$W(\bar{t},\varepsilon)=\int_{-\infty}^{+\infty}\left\langle\psi^{+}(\varepsilon+\delta/2)\psi\ (\varepsilon-\delta/2)\right\rangle e^{-i\delta\bar{t}/\hbar}\, d\delta$$

NEGATIVE PARTS (blue) reflect Quantum Coherence)

T. Jullien, P. Roulleau, B. Roche and D. C. Glattli **Nature**, 514 603-607 (2014)
C. Grenier et al., New J. Phys. 13, 093007 (2011))

This TALK:

- First step to realize a single anyon source

- Shows that FQHE abelian anyons with charge e*=e/3 and e/5 can be manipulated with microwave by well-defined Photon-Assisted processes.

- Validates the possibility to realize on-demand single anyon sources for time domain anyon braiding.

- Based on Photon-Assisted Shot Noise (PASN) measurements

- Photon-Assisted process revealed by the anyonic Josephson relation $e^*V/h=f$

(*X. G. Wen (1991)*)

Anyons

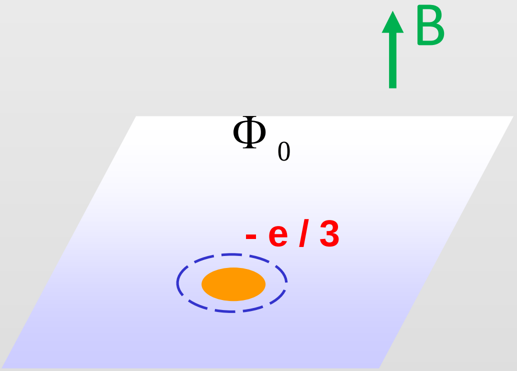
$$|\psi(a,b)\rangle = e^{i\theta_S}\,|\psi(b,a)\rangle$$

(Leynaas+Mirrheim 1977, Wilczek 1982)

expected for Fractional Quantum Hall effect (FQHE) quasiparticles (Arovas, Schrieffer, Wilczek 1984)

<u>Example</u>: for filling factor **ν** = 1/3 (= 1 electron/3 quantum states)

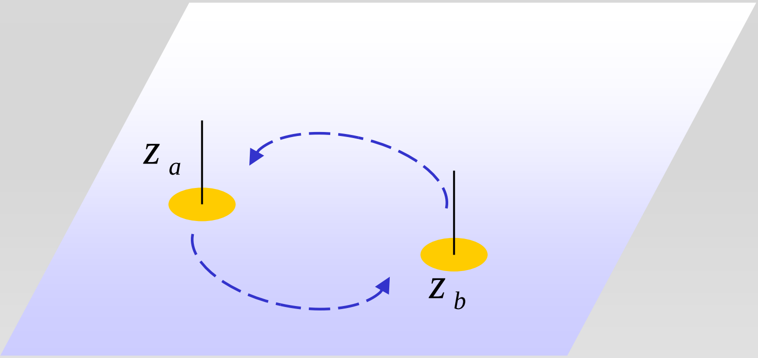
a quasi-hole particle has a charge e*=-e/3 (Laughlin 1983)



$$\Delta = \frac{e^2}{\varepsilon\, l_C}$$

$$\Psi^{2-holes}(z_a, z_b) = \exp\left(i\frac{\pi}{3}\right)\Psi^{2-holes}(z_b, z_a)$$

Berry phase

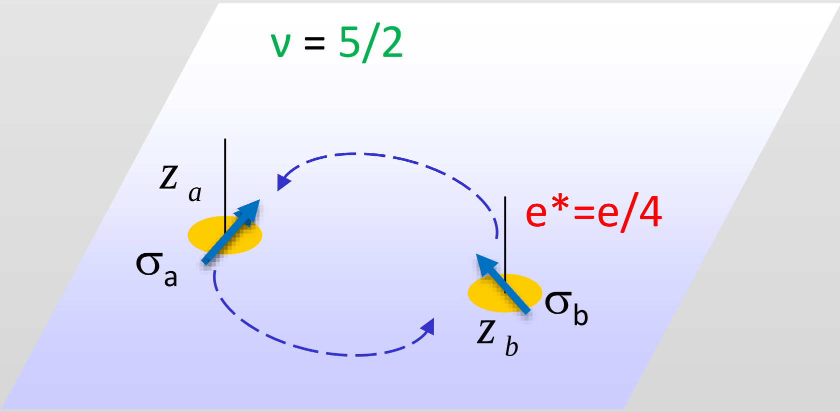


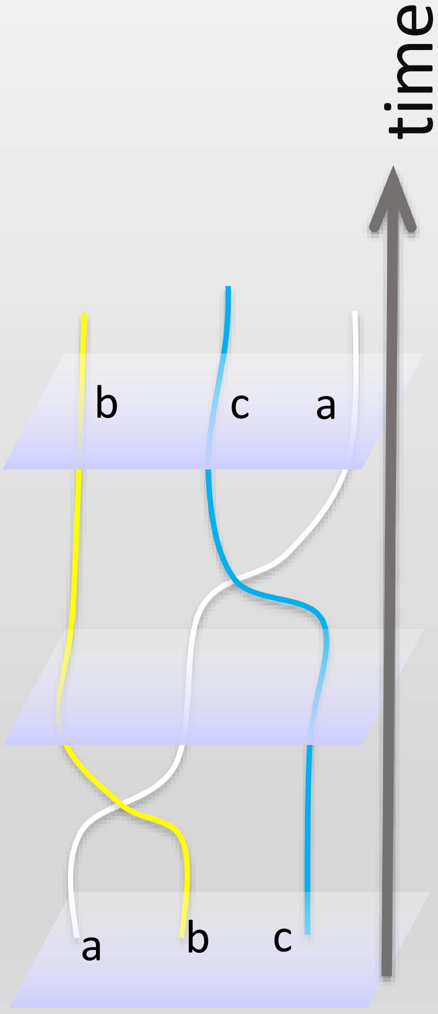
Anyons

$$|\psi(a,b)\rangle = e^{i\theta_S}|\psi(b,a)\rangle$$ *abelian* ν = 1/3;1/5,2/5,3/7, …

$$|\psi_{\sigma_a,\sigma_b}(a,b)\rangle = \widehat{U}|\psi_{\sigma_b,\sigma_a}(b,a)\rangle$$ *non-abelian* ν = 5/2, 7/2, …
Majorana

(Moore, Read 1991, Wen 1991)





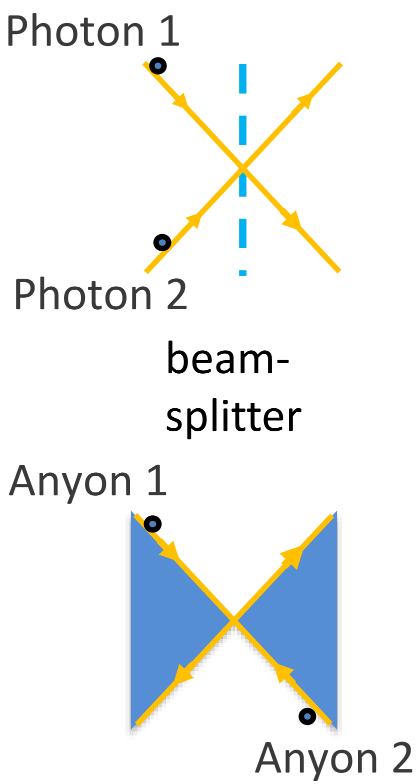
Non-abelian anyons should allow topological quantum computation (Freedman, Kitaev 2002)

To date: no convincing experimental observation of anyons

BRAIDING

Our approach: Hong Ou Mandel Braiding Interference

Hong, Ou, & Mandel (1987)



$$S_{B.S.} = \begin{pmatrix} ir & t \\ t & ir \end{pmatrix}$$

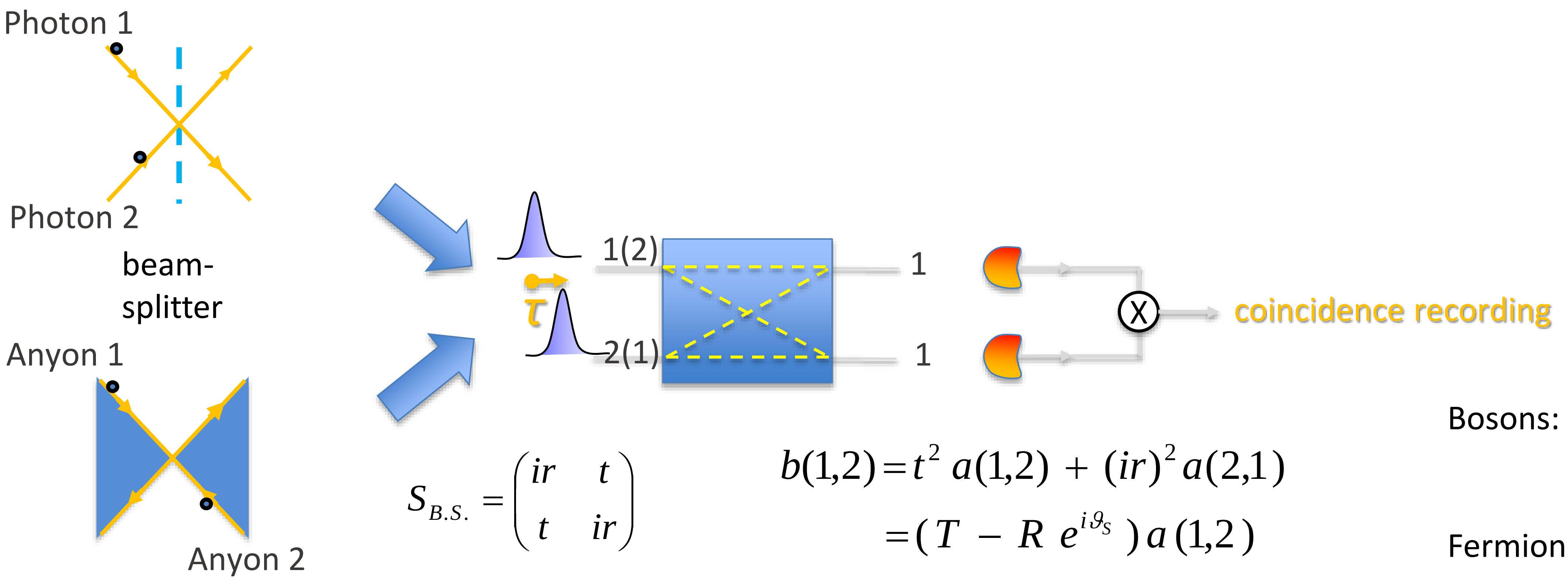
$$b(1,2) = t^2\, a(1,2) + (ir)^2\, a(2,1)$$
$$= (T - R\, e^{i\vartheta_S})\, a(1,2)$$

Bosons: $\theta_S = 0$

Fermions: $\theta_S = \pi$

$$P(1,2) = (1 - \cos\theta_s)/2$$

Hong Ou Mandel Braiding Interference



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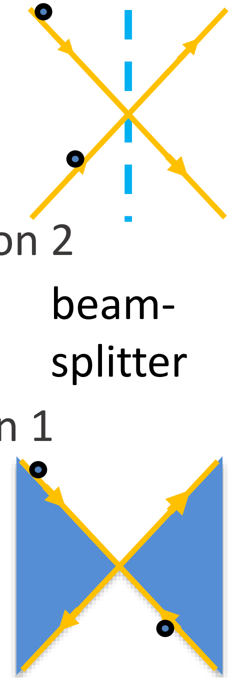
$$b(1,2) = t^2\, a(1,2) + (ir)^2 a(2,1)$$
$$= (T - R\, e^{i\vartheta_S})\, a(1,2)$$

Bosons: $\theta_S = 0$

Fermions: $\theta_S = \pi$

$$P(1,2) = (1 - g_2(\tau)\cos\theta_S)/2$$

Hong Ou Mandel Braiding Interference



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$$= (T - R\, e^{i\vartheta_S})\, a(1,2)$$

Bosons: $\theta_S = 0$

Fermions: $\theta_S = \pi$

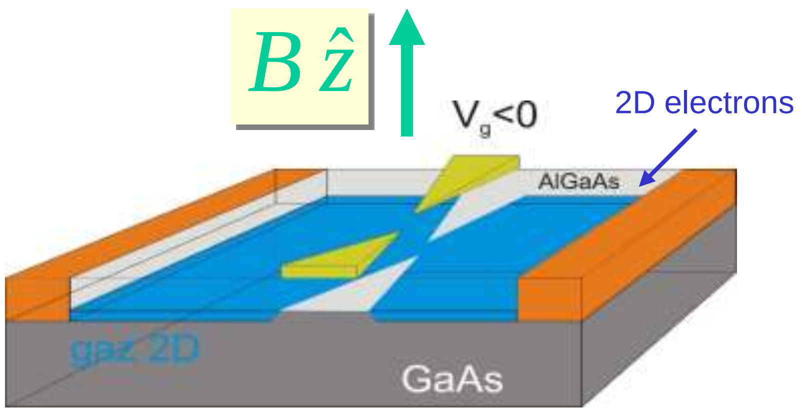
$$P(1,2) = (1 - g_2(\tau)\cos\theta_S)/2$$

Statistical measurements: Current noise $S_I = 2\,(e^*)^2\, \nu\, (1 - P(1,2)) = (e^*)^2\, \nu\, (1 + g_2(\tau)\cos\theta_S)$

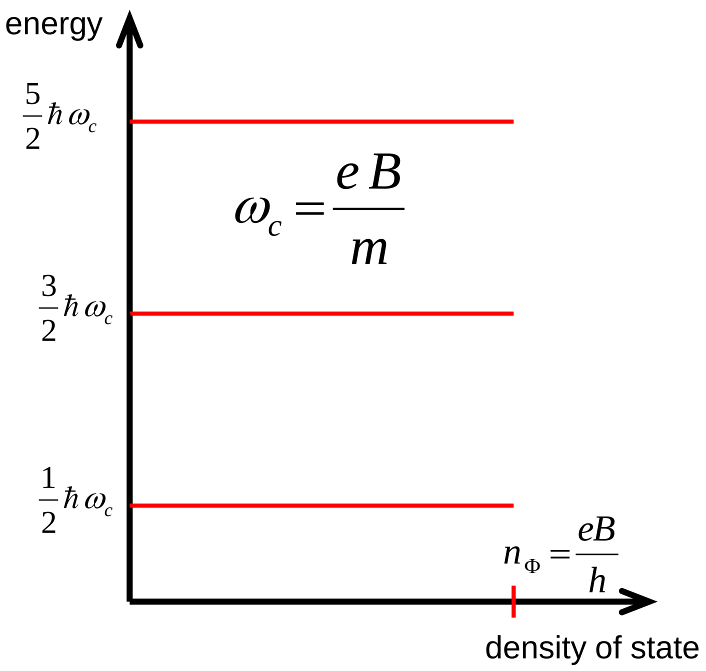
OUTLINE

- EDGE STATE and DC SHOT NOISE in FQHE
- PHOTON-ASSISTED TRANSPORT
    - Photon-assisted processes
    - A JOSEPHSON Relation for Photon Assisted Shot Noise (PASN)
- Experimental Results
    - $e^*=e/3$
    - $e^*=e/5$
- CONCLUSION and PERSPECTIVES

QHE and EDGE STATES



III-V semi-conductor heterojunction GaAs/GaAlAs

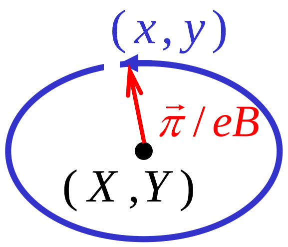


$$H=\frac{1}{2m}\left(\vec{p}+e\vec{A}\right)^2=\frac{\vec{\pi}^2}{2m}$$

$$\left[\pi_x,\pi_y\right]=-i\hbar eB \longrightarrow E_n=\hbar\omega_c\left(n+\frac{1}{2}\right)$$

$$X=x-\frac{\pi_y}{eB}$$

$$Y=y+\frac{\pi_x}{eB}$$



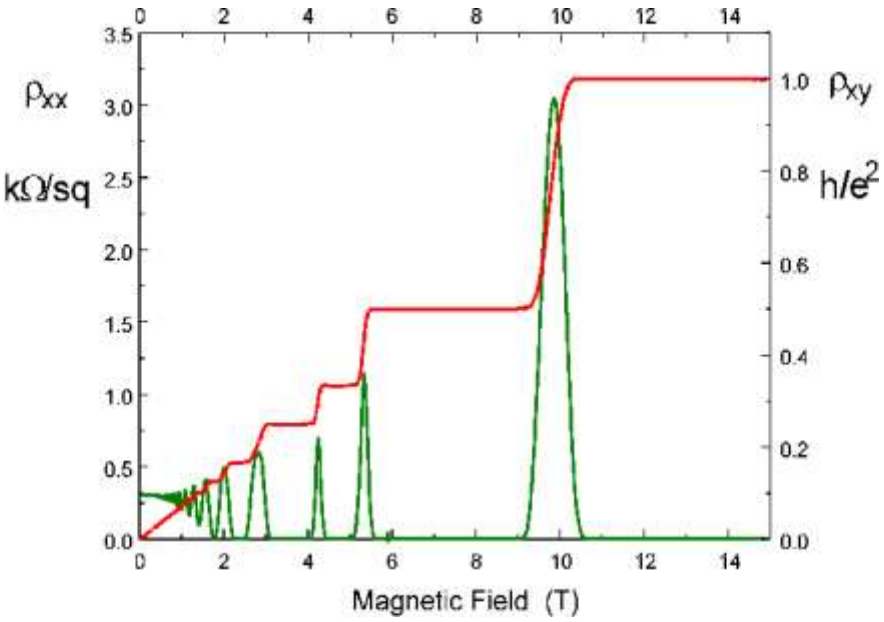
cyclotron motion

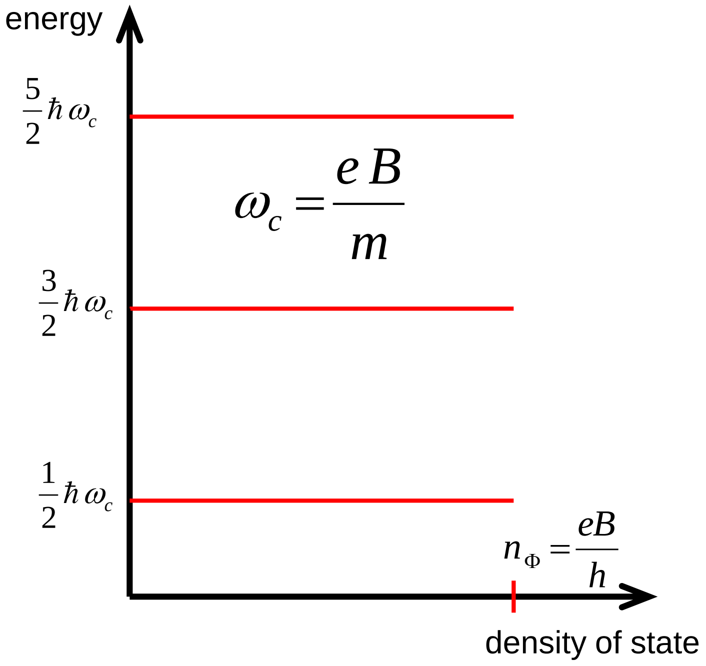
$$\left[X,Y\right]=-i\frac{\hbar}{eB} \longrightarrow B\,\Delta X.\Delta Y=\frac{h}{e}$$

cyclotron motion is frozen → 1D dynamics

Integer Quantum Hall Effect (IQHE)

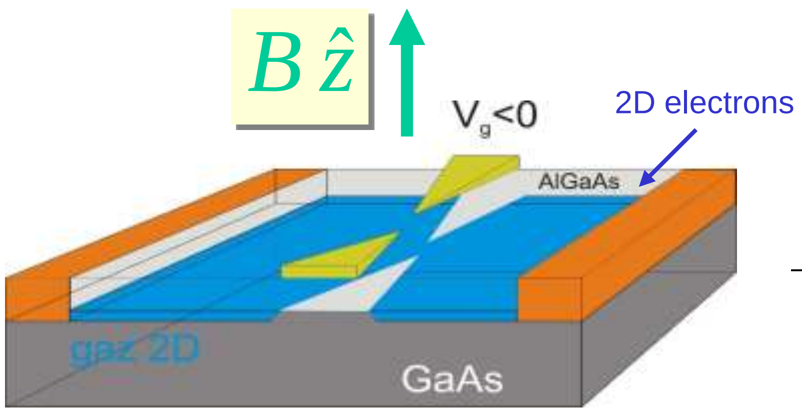
$R_{hall}=(h/e^2)1/\nu \quad \nu=1,2,3, \ldots$





$$R_{Hall} = \frac{B}{e\,n_s} = \frac{h}{e^2}\frac{1}{(\nu = k)}$$

QHE and EDGE STATES



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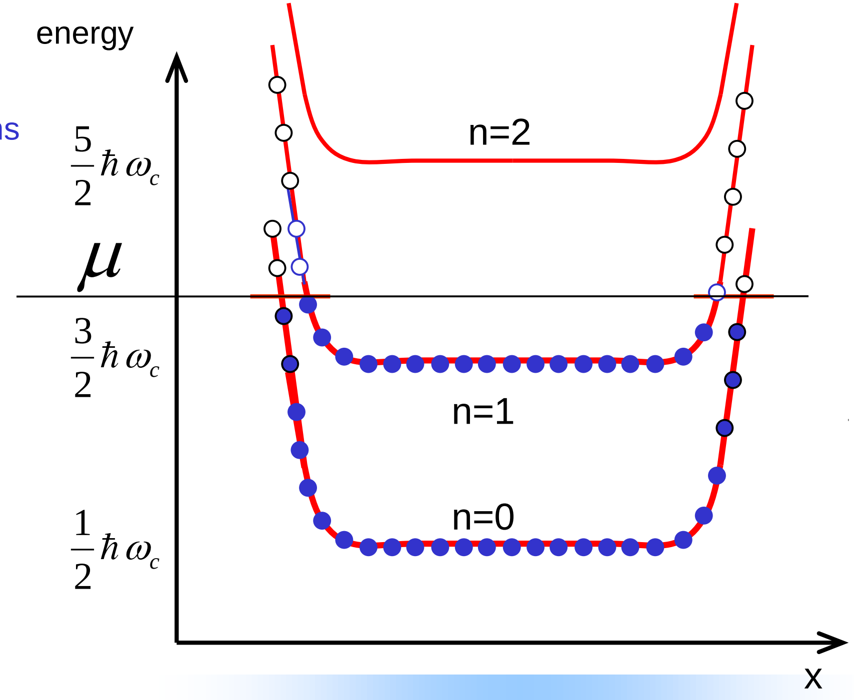
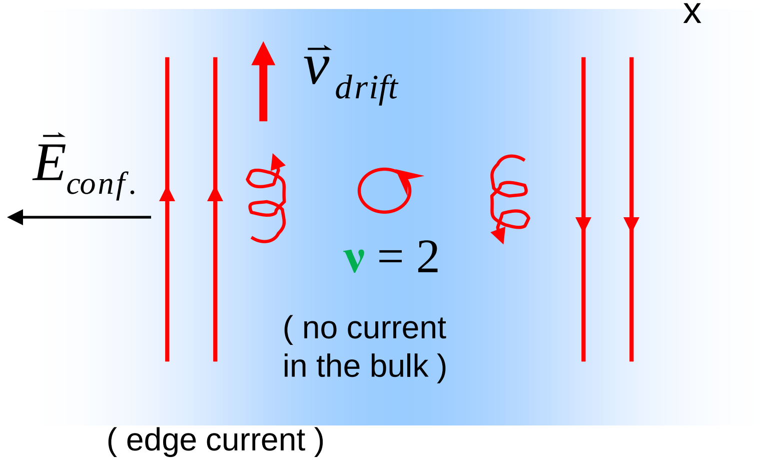


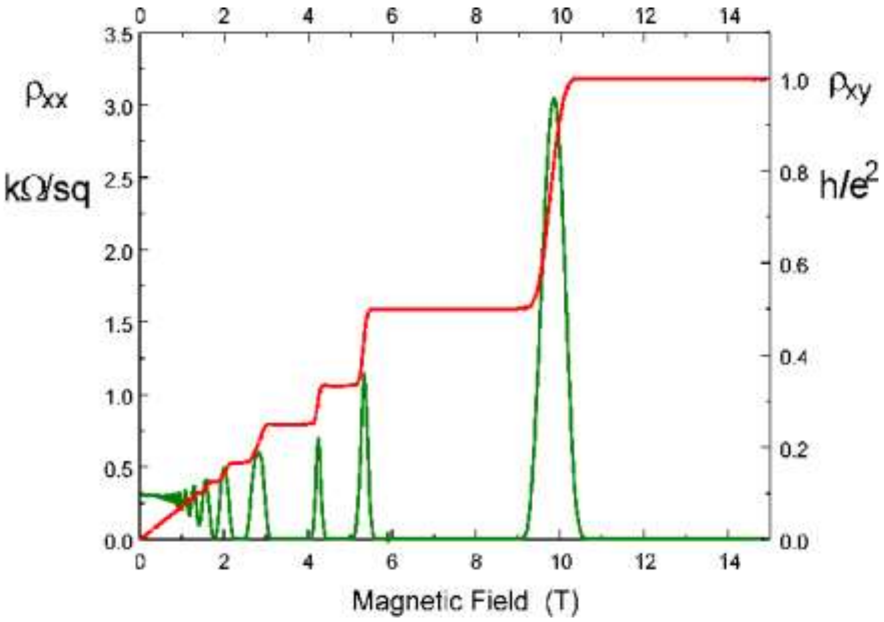


$$\vec{v}_{drift} = \frac{\vec{E}_{conf.}}{B} \times \hat{z}$$

cyclotron motion drift → chiral 1D EDGE CHANNELS

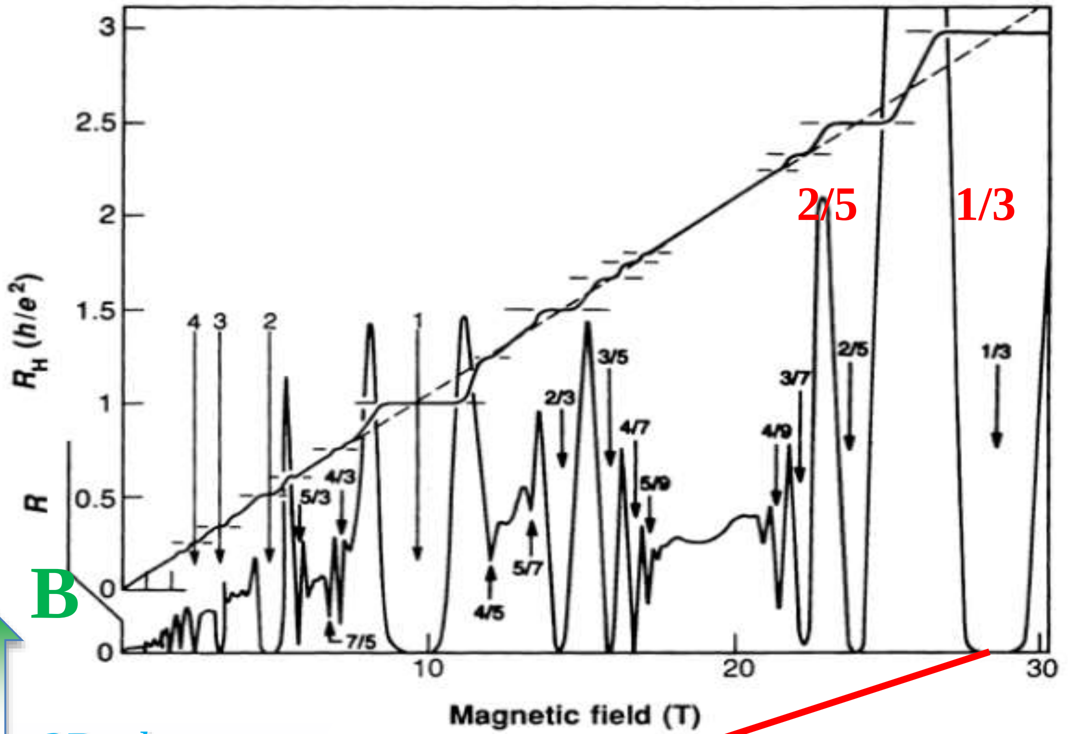
Integer Quantum Hall Effect (IQHE)

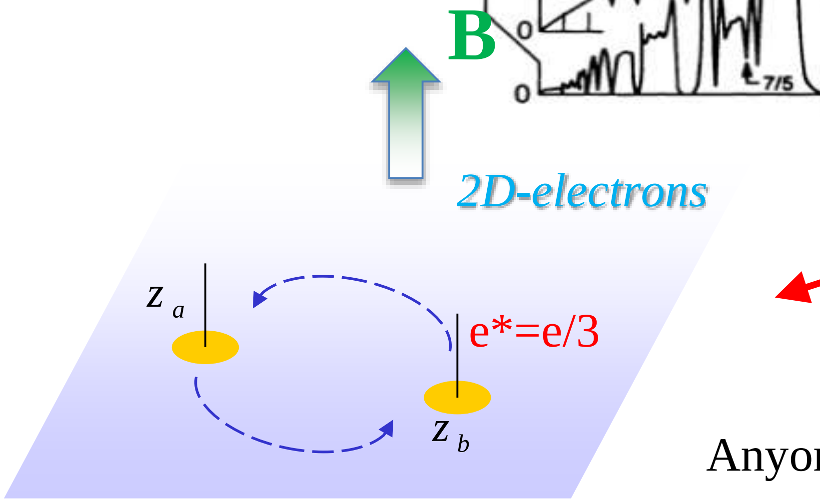
$R_{hall}=(h/e^2)1/\nu \quad \nu=1,2,3, \ldots$



Fractional Quantum Hall Effect (FQHE)

$R_{hall}=(h/e^2)1/\nu \quad \nu=1/3,2/5,3/7, \ldots 2/3, 3/5, 4/7, \ldots$

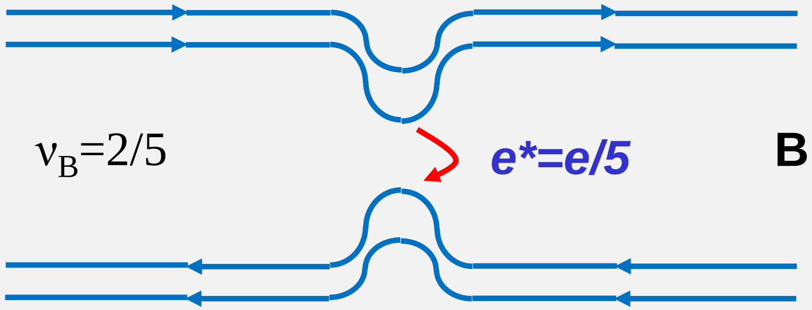




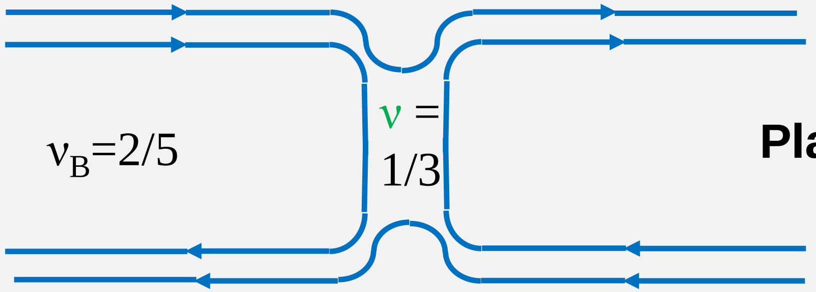
Anyons $\Psi(a,b)=e^{i\theta}\,\Psi(b,a) \quad \theta=\pi/3$

Tunneling through a ν=2/5 Jain FQHE state

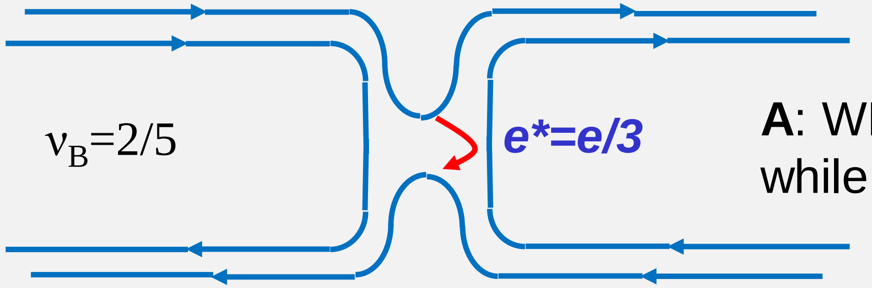
FQHE	→	C-F. IQHE
$\nu = 1/3$	→	$\nu=1$
$\nu = 2/5$	→	$\nu=2$
$\nu = 3/7$	→	$\nu=3$
….	→	….



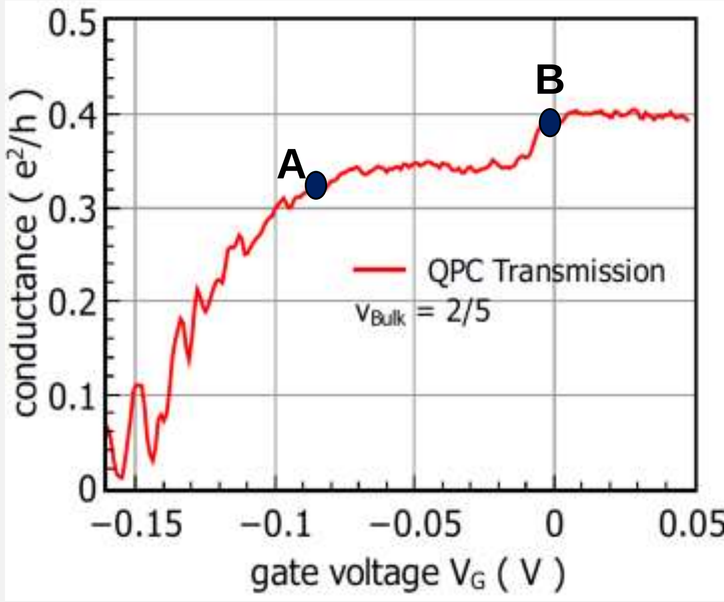
B: WB in 2/5

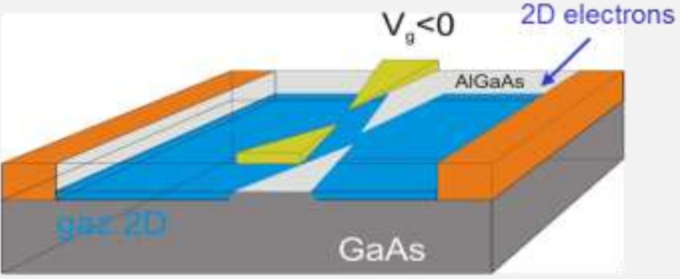


Plateau 1/3



A: WB in 1/3
while 2/5 reflected





III-V semi-conductor heterojunction GaAs/GaAlAs

J. K. Jain *Composite-fermion approach for the fractional quantum Hall effect*. Phys. Rev. Lett. 63, 199-202 (1989)

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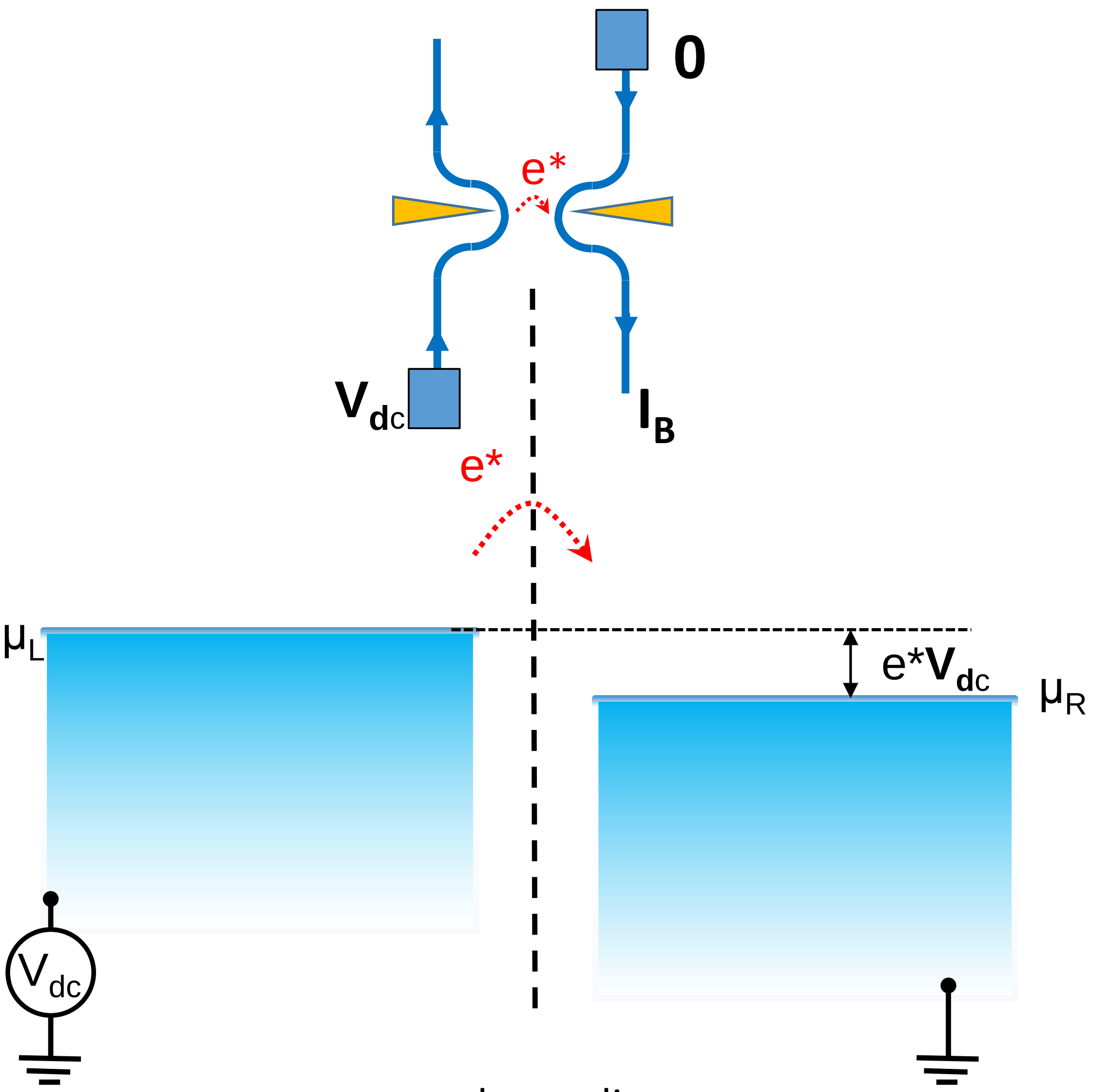
DC SHOT NOISE (weak coupling)

DC Transport

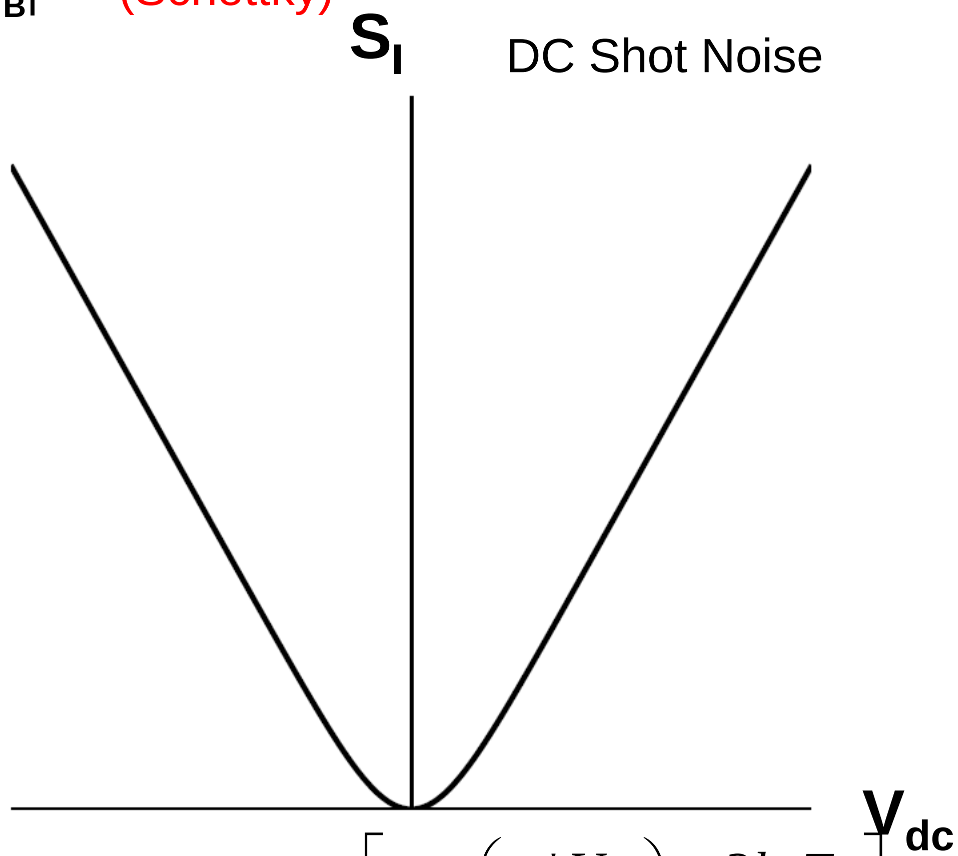


weak coupling limit

$\mu_R - \mu_L = e^*V_{dc}$

$I_B(V_{dc})$

$S_I^{DC} = 2e^* |I_B|$ (Schottky)



$$S_I^{DC} = 2e^* I_B \left[\coth\left(\frac{e^* V_{dc}}{2k_B T} \right) - \frac{2k_B T}{e^* V_{dc}} \right]$$

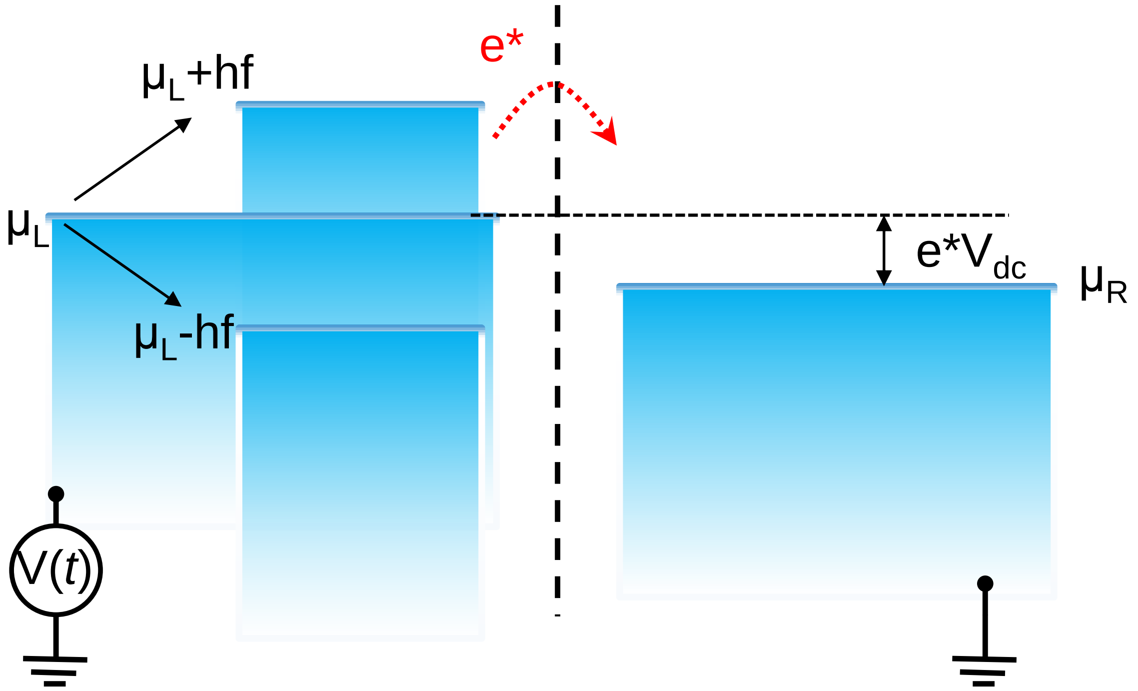
Photon-Assisted Shot Noise (PASN)

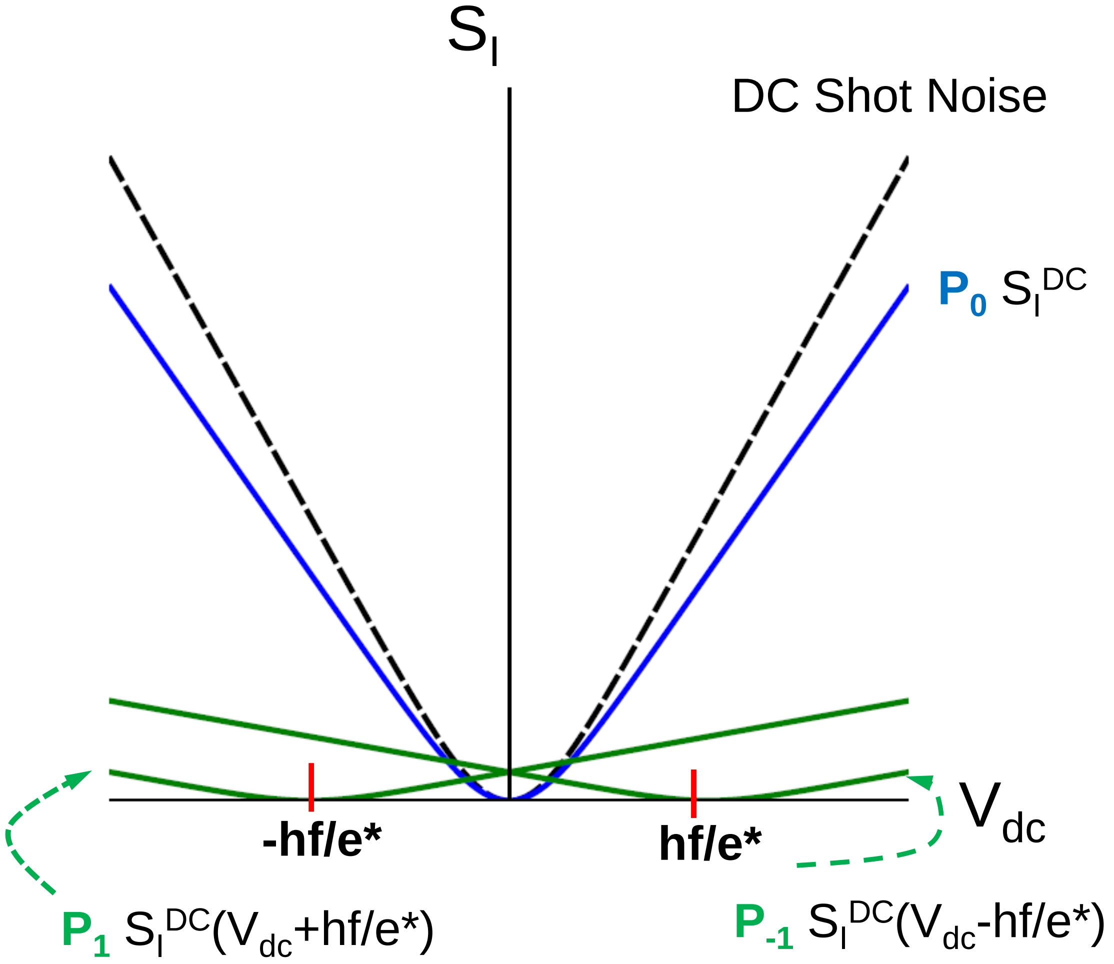
$V(t) = V_{dc} + V_{ac}\cos(2\pi f t)$

P_l : probability to absorb (emit) $l > 0$ (< 0) Photons

$$S_I^{PASN} = P_0\, S_I^{DC}(V_{dc}) + P_1\, S_I^{DC}(V_{dc} + hf/e^*) + P_{-1}\, S_I^{DC}(V_{dc} - hf/e^*) + \ldots$$

Lesovik and Levitov (1994)
C. de C. Chamon, D. E. Freed, X. G. Wen (1995)
A. Crépieux, P. Devillard, T. Martin (2004)





Photon-Assisted Shot Noise (PASN)

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$$S_I^{PASN} = P_0\, S_I^{DC}(V_{dc}) + P_1\, S_I^{DC}(V_{dc}+hf/e^*) + P_{-1}\, S_I^{DC}(V_{dc}-hf/e^*)+\ldots$$

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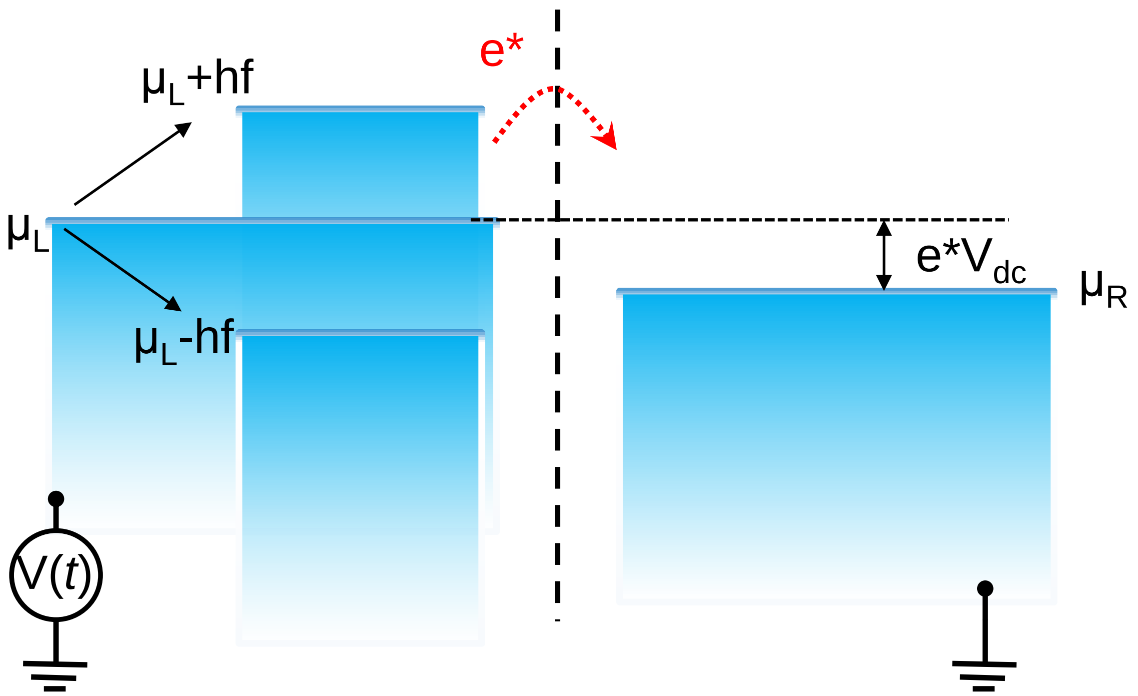
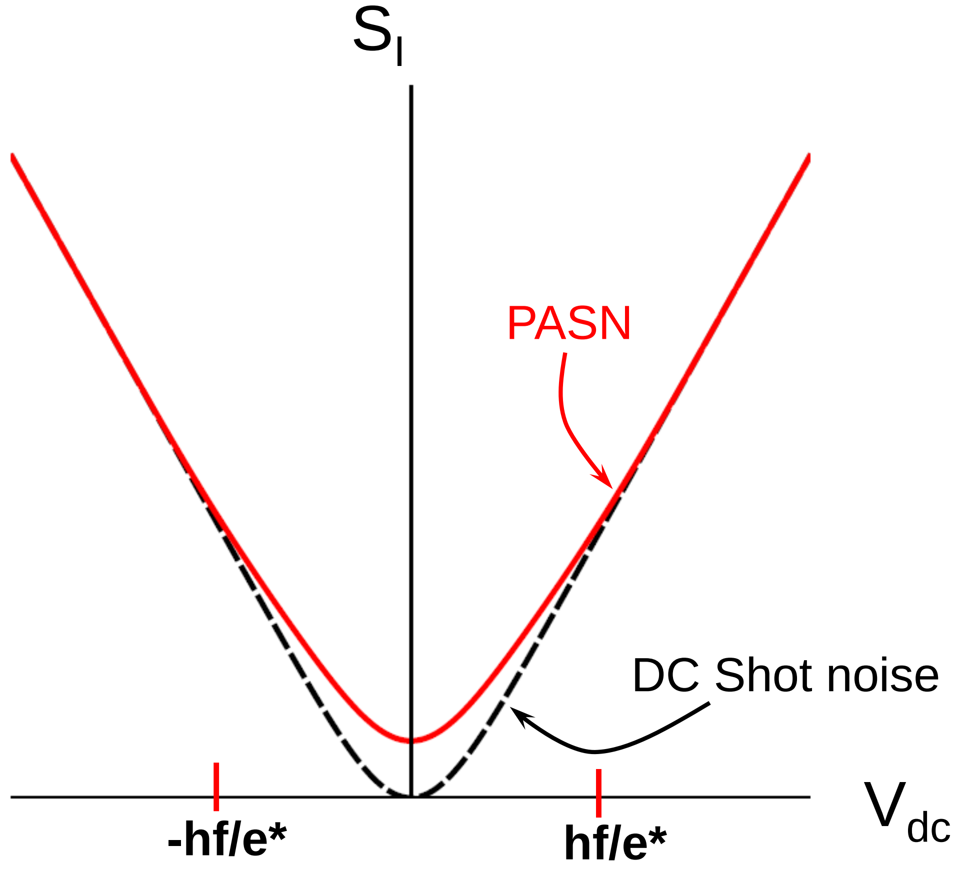
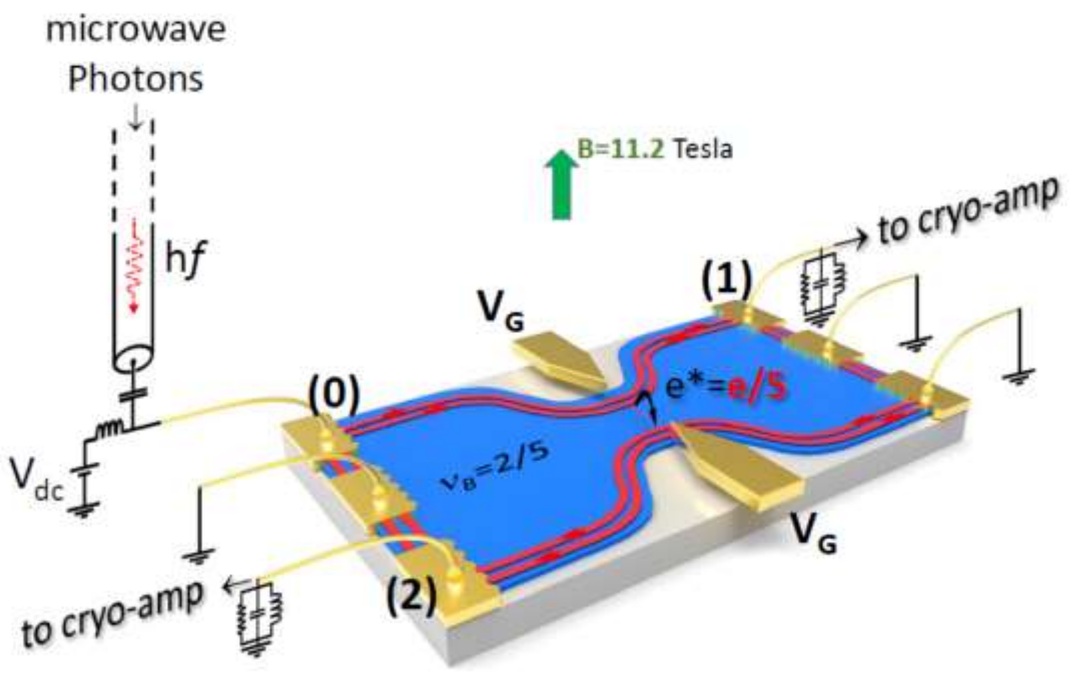
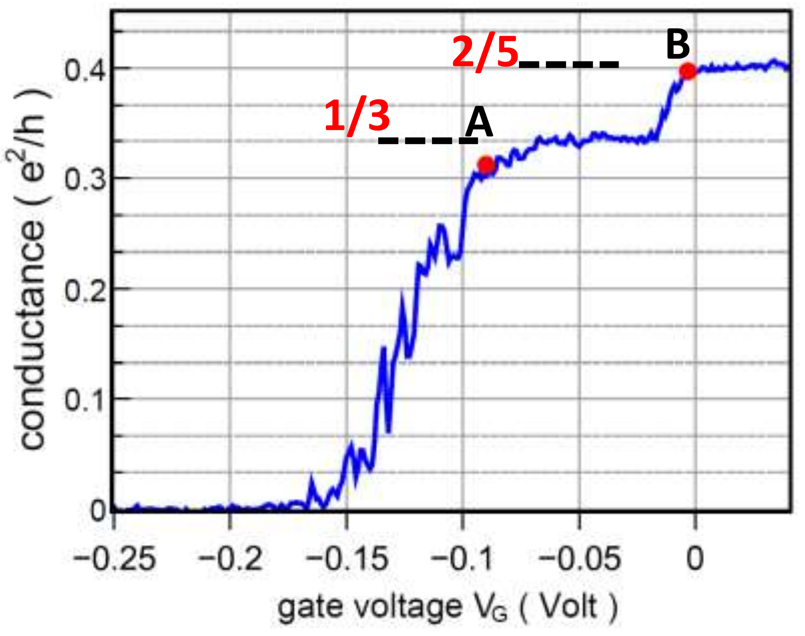
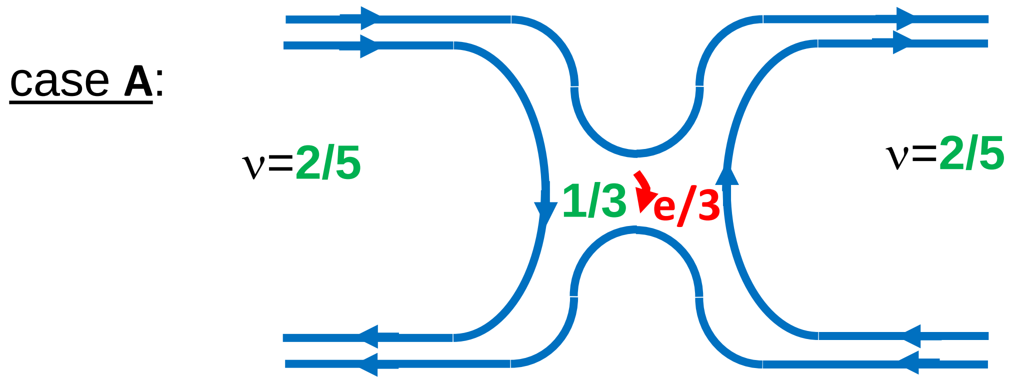
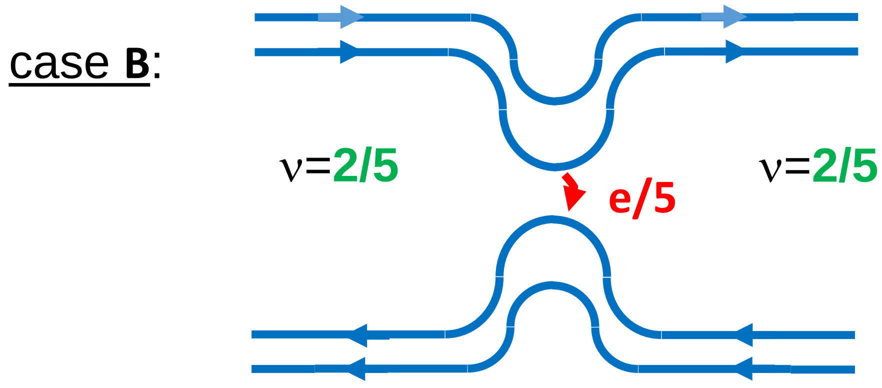





microwave
Photons
hf
B=11.2 Tesla
to cryo-amp
(1)
V_G
(0)
$e^*=e/5$
V_{dc}
$\nu_B=2/5$
V_G
to cryo-amp
(2)

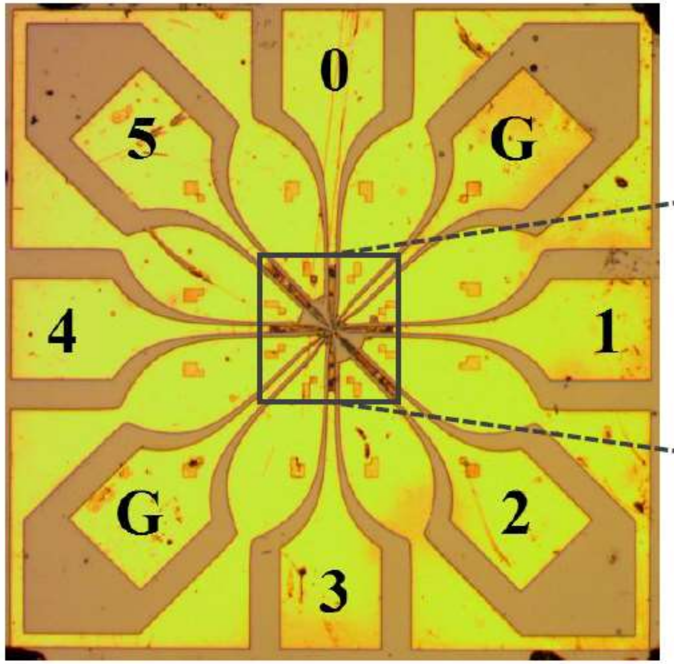

2/5
B
1/3
A
conductance (e^2/h)
0.4
0.3
0.2
0.1
0
−0.25
−0.2
−0.15
−0.1
−0.05
0
gate voltage V_G (Volt)

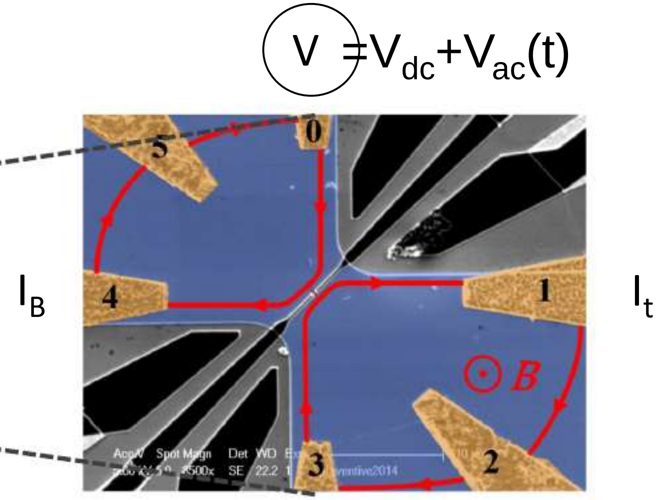

case **A**:
ν=2/5
1/3
e/3
ν=2/5


case **B**:
ν=2/5
e/5
ν=2/5

Experimental Set-up and samples

Samples: n_s =1.07 10^{11} cm^{-2} μ=3 10^6 $cm^2V^{-1}s^{-1}$ (from I. Farrer, D. Ritchie, Cambridge UK)

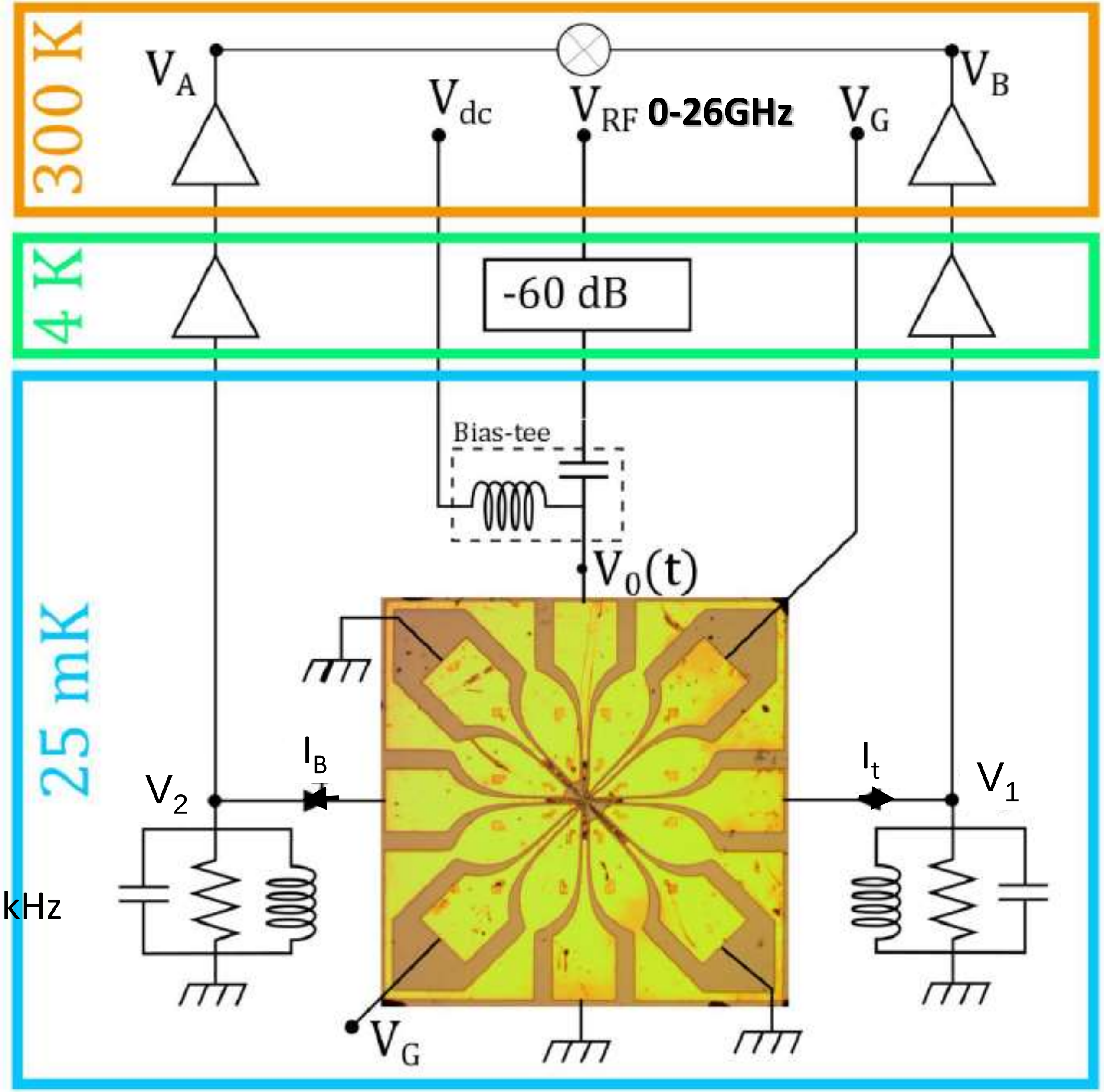




S.E.M. view
Nanolithography at SPEC (M. Kapfer)

Experimental Set-up and samples

CROSS-SPECTRUM



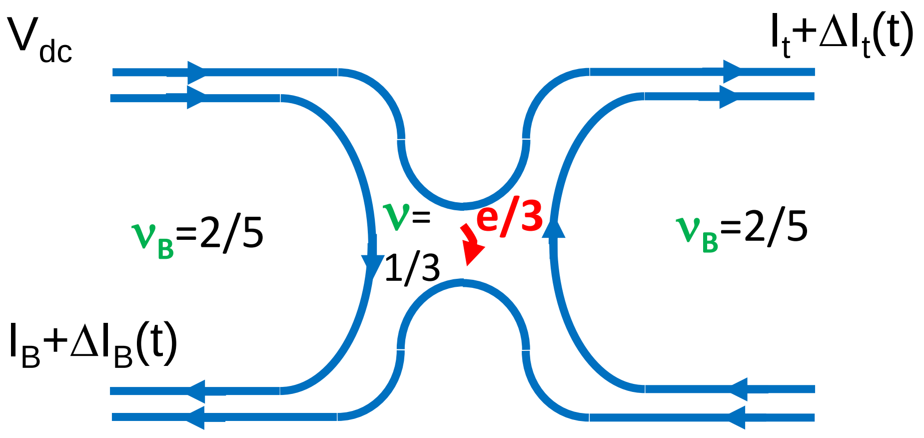
Home-made Cryo-amp. ($\mathbf{0.22nV}$)^2/Hz

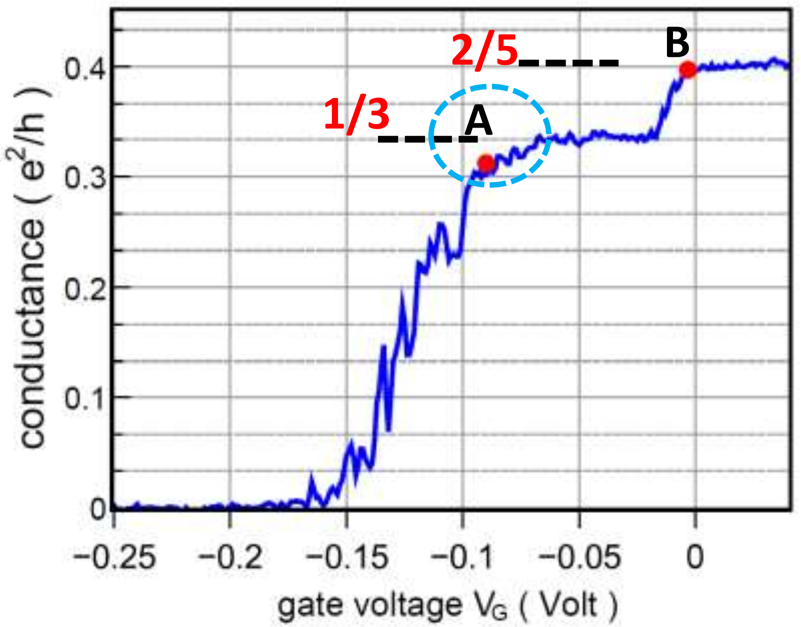
2.2 MHz
Δf=~150kHz

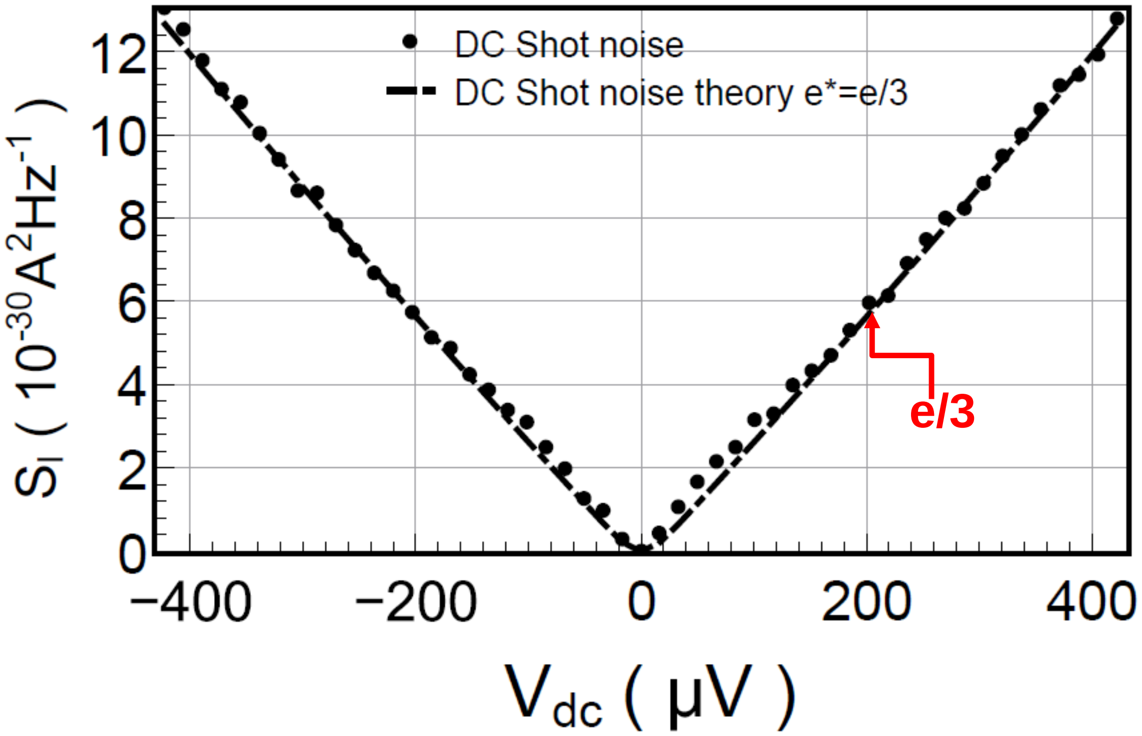
Helium-free Cryoconcept® crysostat

14 Tesla Dry Magnet
13mK base temperature

DC Shot noise for the 1/3-FQHE state





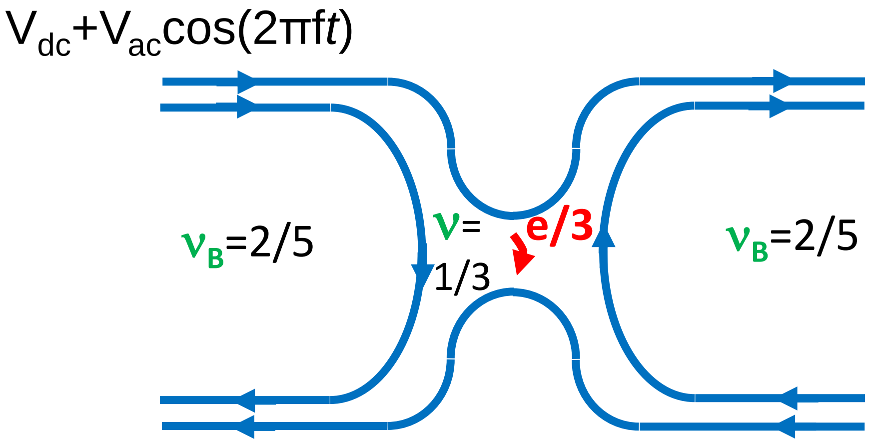


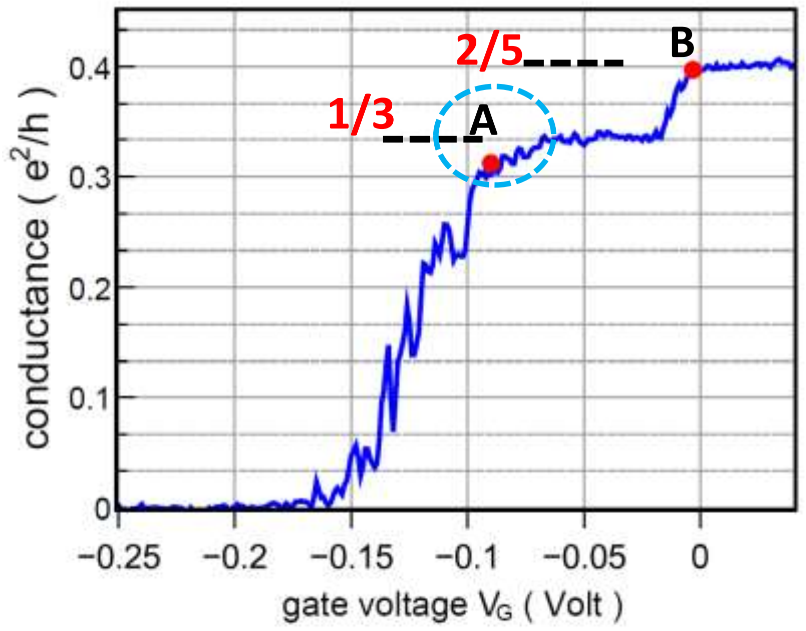
$$S_I^{DC} = 2e^* I_B\left[\coth\left(\frac{e^* V_{dc}}{2k_B T}\right) - \frac{2k_B T}{e^* V_{dc}}\right]$$

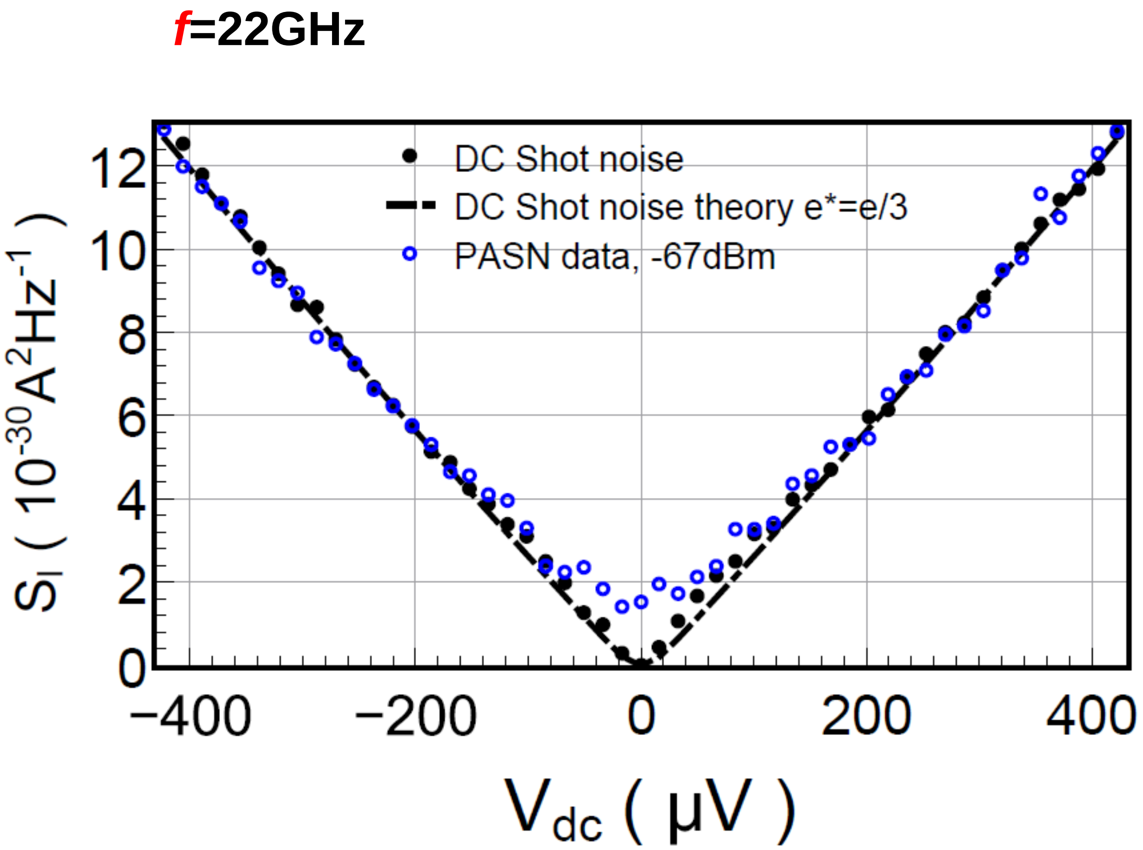
e*= e/3 ! confirms '97-'98 experiments

(Saclay PRL 97, Weizmann Nat. 97 and 99)

Photon-Assisted Shot Noise for the 1/3-FQHE state



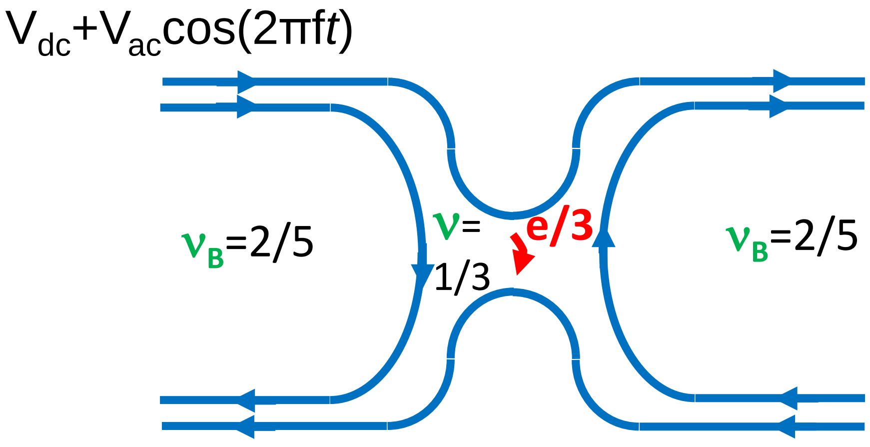


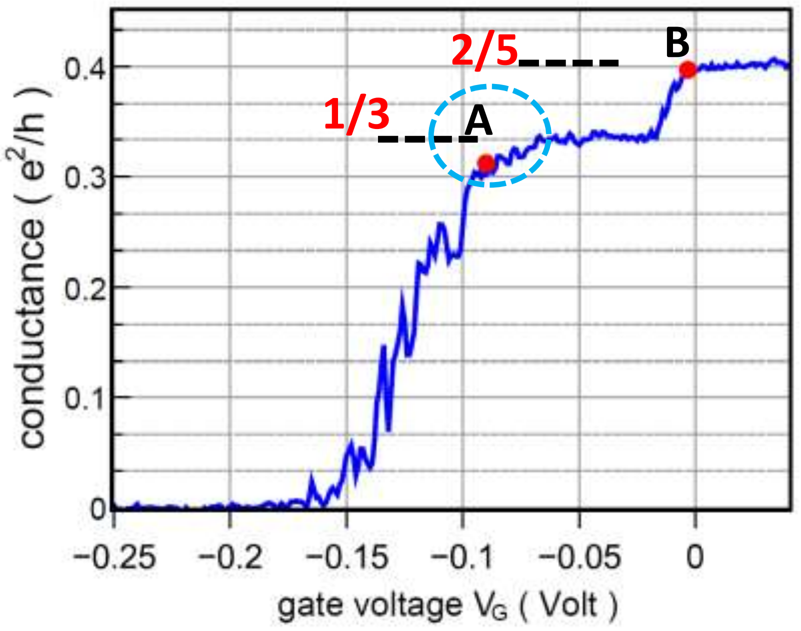


$$V(t) = V_{dc} + V_{ac}\cos(2\pi f t)$$

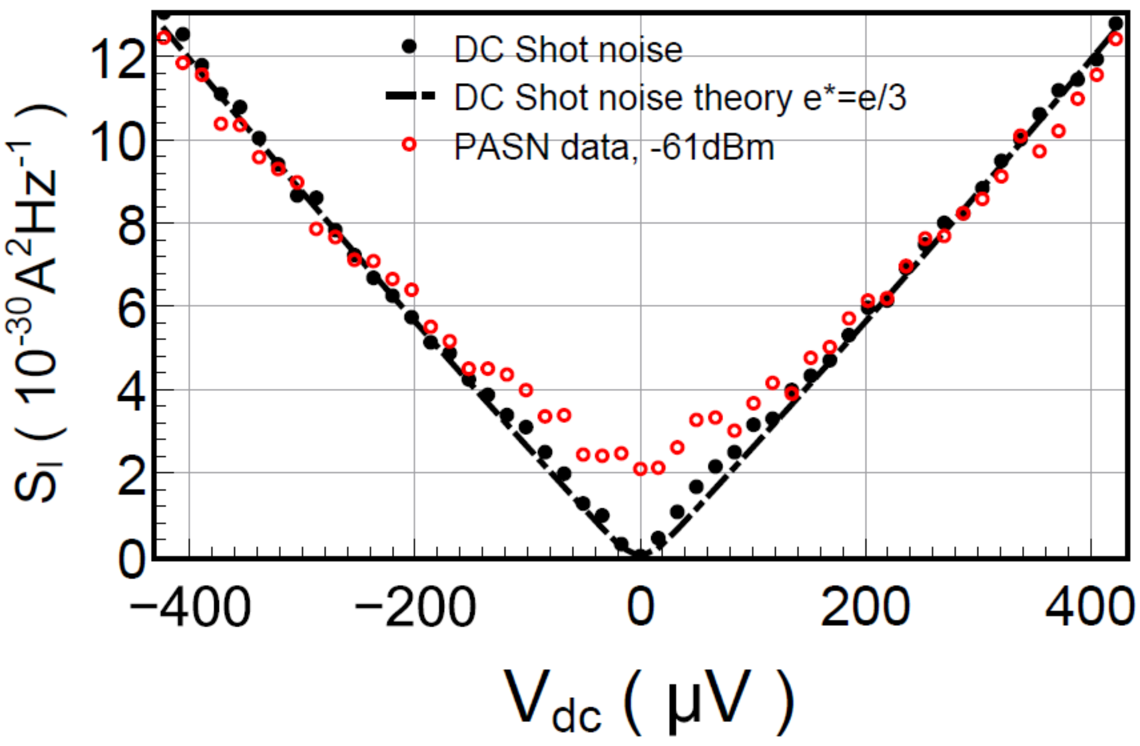
$V_{ac} \approx$ 100 μV for -67dBm

Photon-Assisted Shot Noise for the 1/3-FQHE state





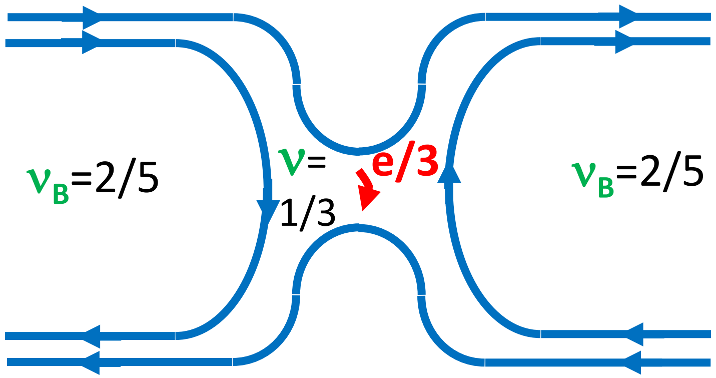
f=22GHz

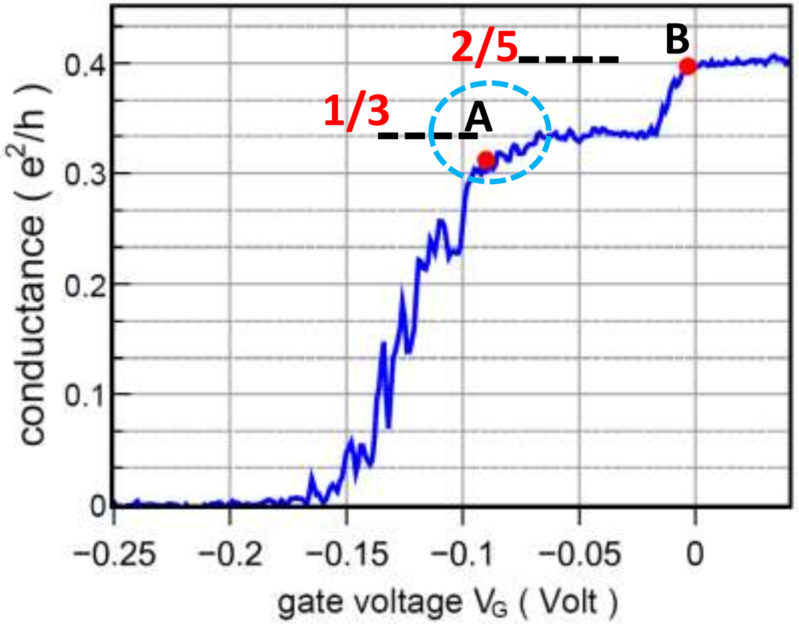


$$V(t) = V_{dc} + V_{ac}\cos(2\pi f t)$$

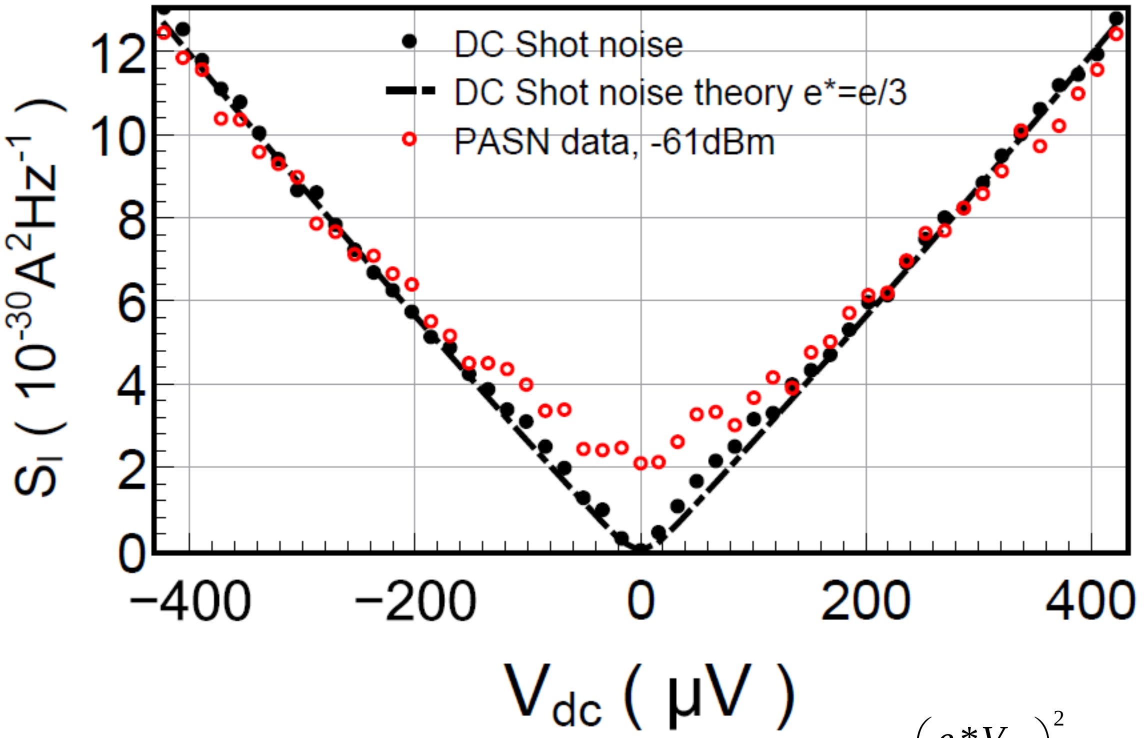
$V_{ac} \approx 200$ µV for -61dBm

Photon-Assisted Shot Noise for the 1/3-FQHE state





***f*=22GHz**



$$V(t) = V_{dc} + V_{ac}\cos(2\pi f t)$$

$$P_0 = J_0\left(\frac{e^* V_{ac}}{hf}\right)^2$$

$V_{ac} \approx 200\ \mu V$ for -61dBm

$$P_1 = P_{-1} = J_1\left(\frac{e^* V_{ac}}{hf}\right)^2$$

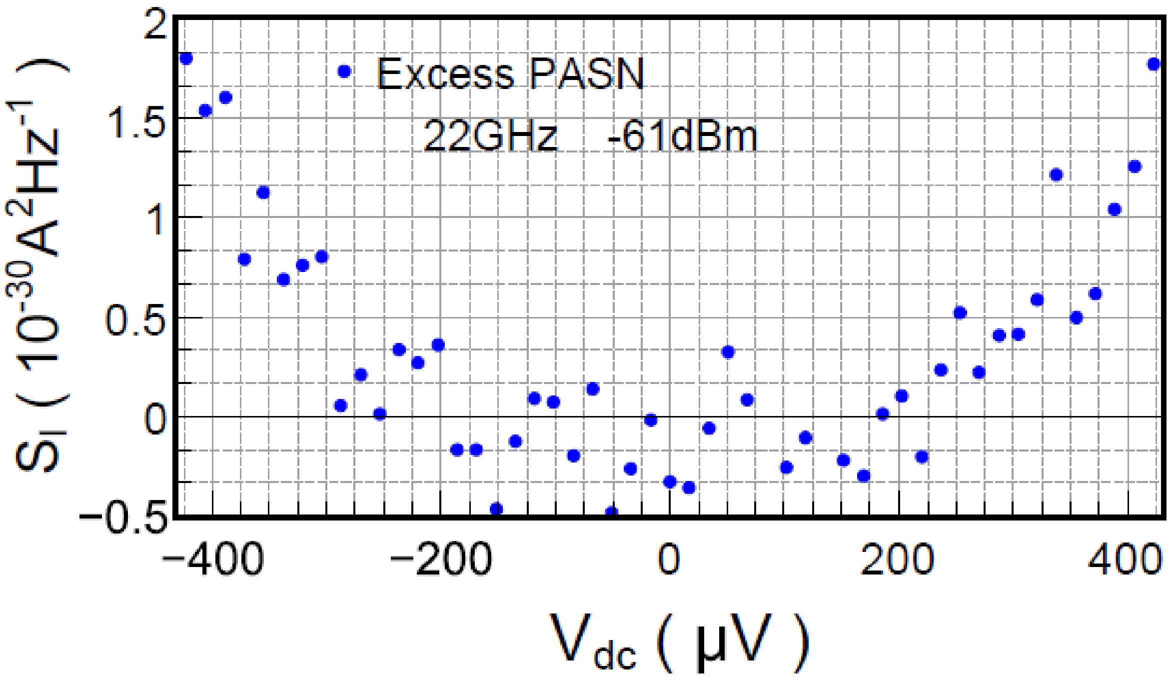
$$S_I^{PASN}(V_{dc}) \ ?=? \ P_0\, S_I^{DC}(V_{dc}) + P_1\left[S_I^{DC}(V_{dc} - hf/e^*) + S_I^{DC}(V_{dc} + hf/e^*)\right]$$

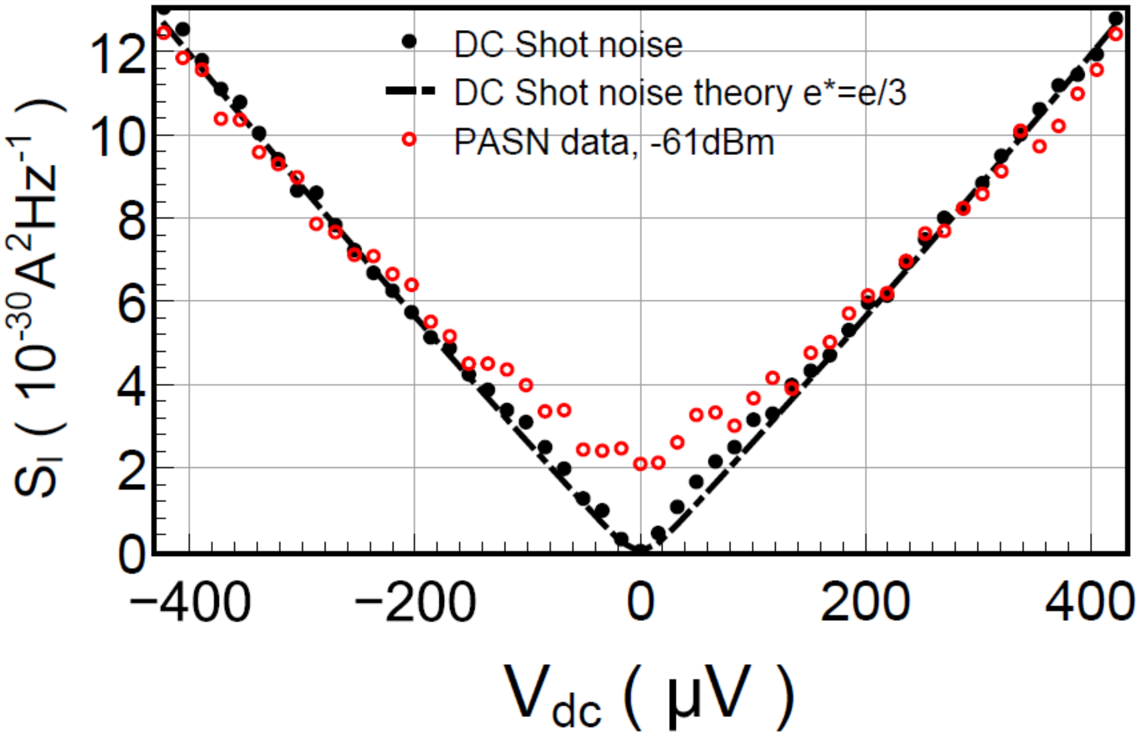
Excess PASN for the 1/3-FQHE state

Killing the non photon-assisted part !

Excess PASN:

$$\Delta S_I = S_I^{PASN}(V_{dc}) - P_0\, S_I^{DC}(V_{dc})$$
$$= P_1 \left[S_I^{DC}(V_{dc} - hf/e^*) + S_I^{DC}(V_{dc} + hf/e^*) \right]$$





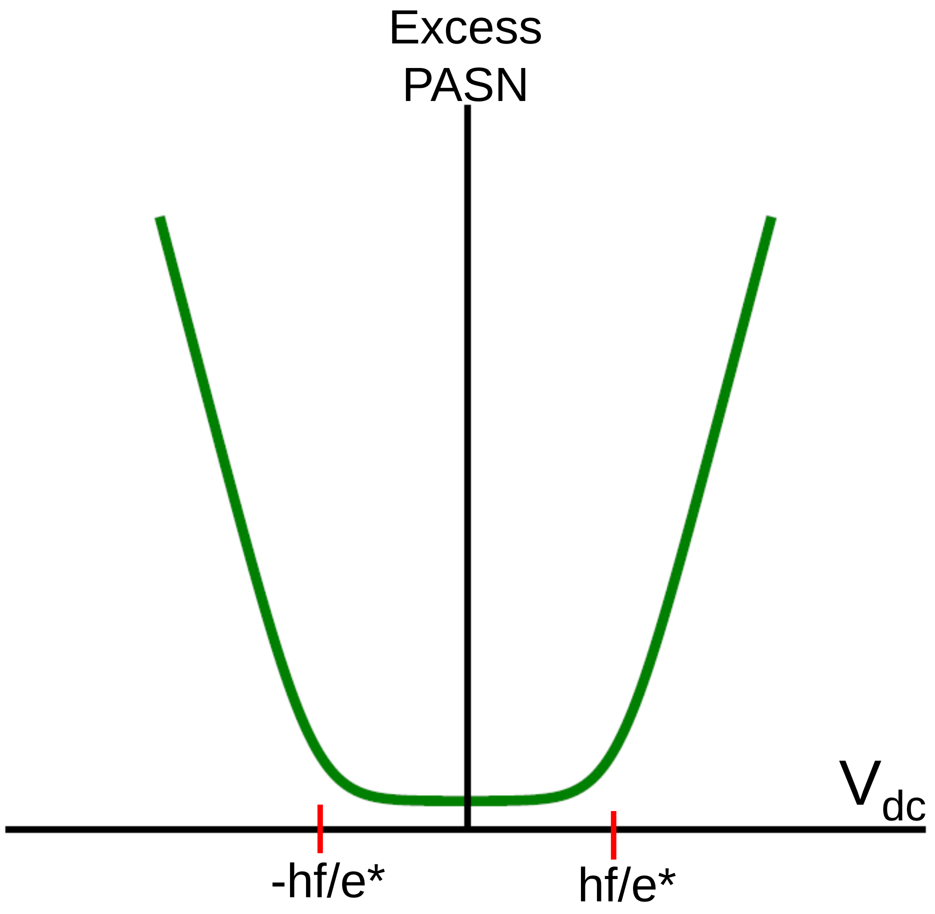
Finding *a flat variation* for the low $|V_{dc}|$ range provides a determination of P_0

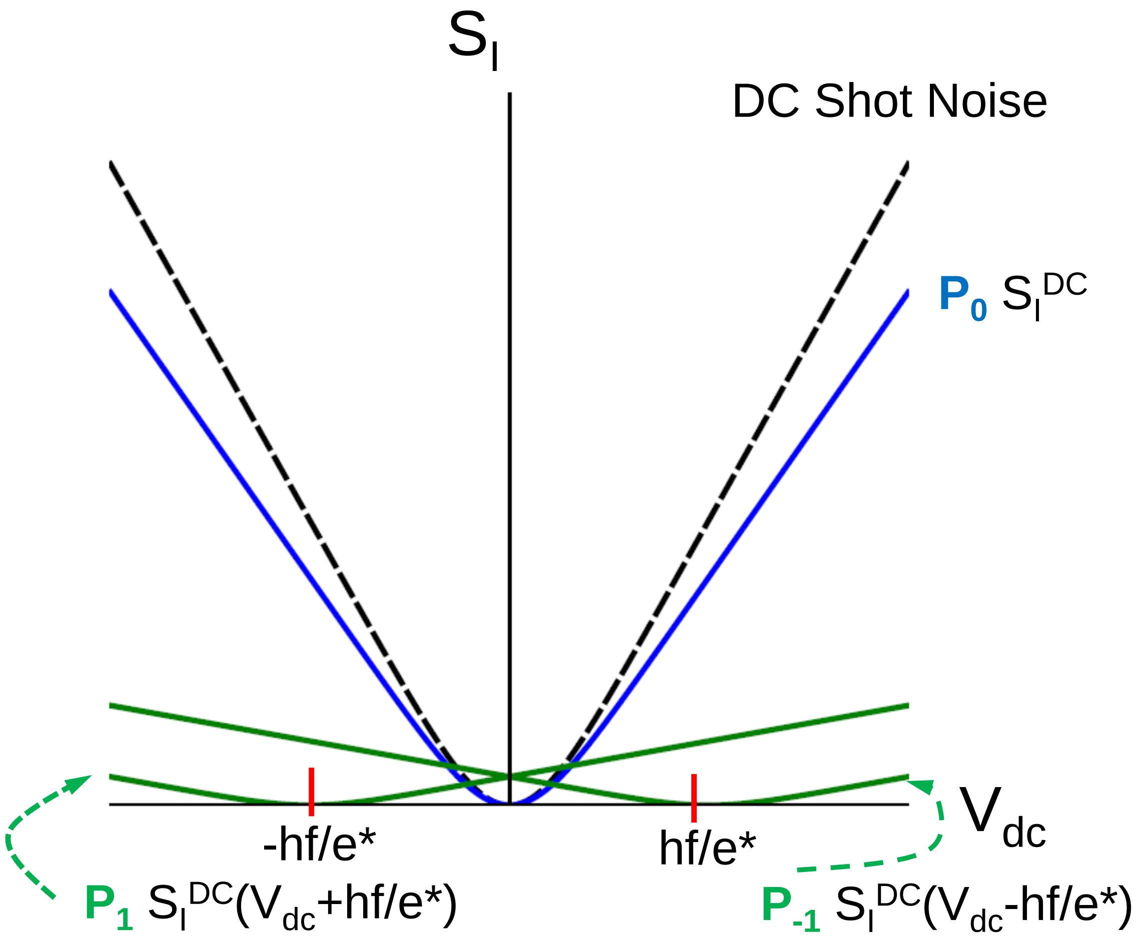
Excess PASN for the 1/3-FQHE state

WHY a FLAT VARIATION?

$$\Delta S_I = S_I^{PASN}(V_{dc}) - P_0\, S_I^{DC}(V_{dc})$$

$$= P_1 \left[S_I^{DC}(V_{dc} - hf/e^*) + S_I^{DC}(V_{dc} + hf/e^*) \right]$$





Excess PASN for the 1/3-FQHE state

Killing the non photon-assisted part !

Excess PASN:

$$\Delta S_I = S_I^{PASN}(V_{dc}) - P_0\, S_I^{DC}(V_{dc})$$
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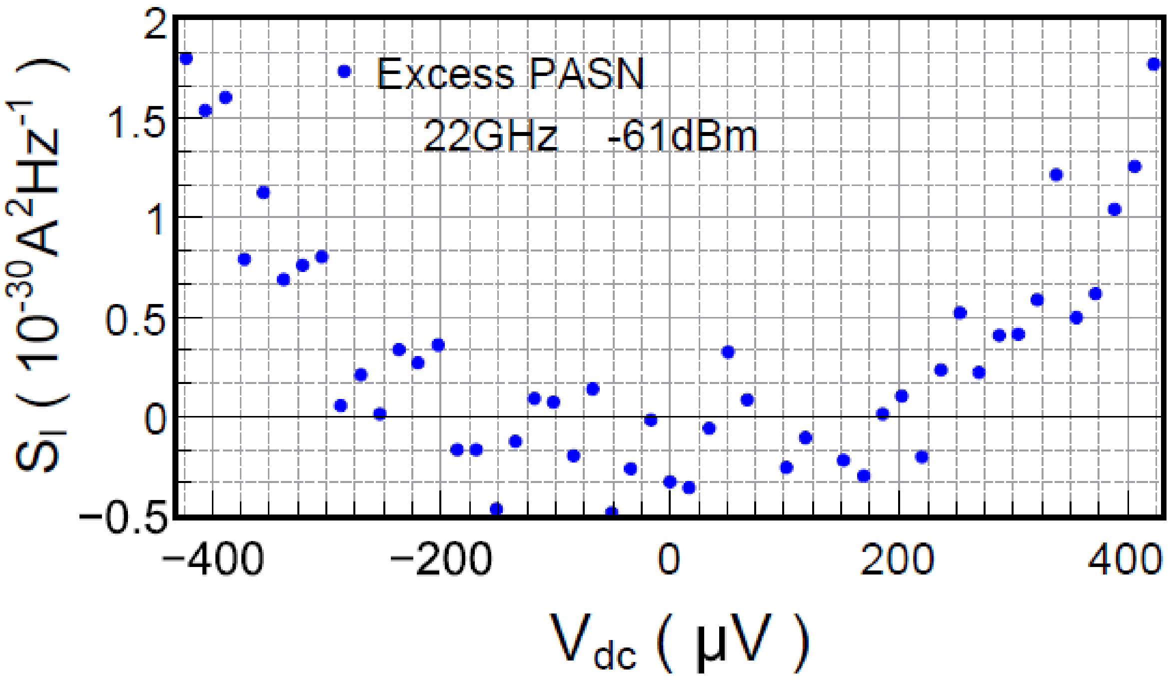

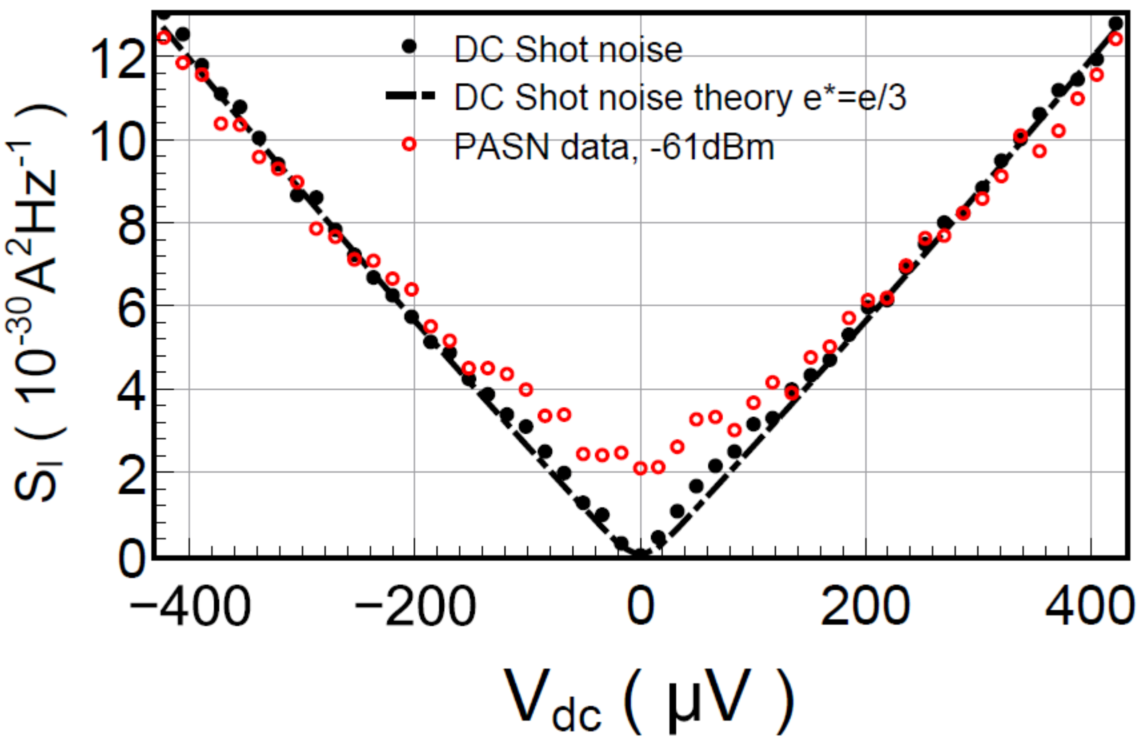

Finding a flat variation for the low $|V_{dc}|$ range provides a determination of $|p_0|^2$

as: $P_0 + 2\,P_1 \approx 1$, this gives P_1

Excess PASN for the 1/3-FQHE state

Killing the non photon-assisted part !

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$$\Delta S_I = S_I^{PASN}(V_{dc}) - P_0\, S_I^{DC}(V_{dc})$$
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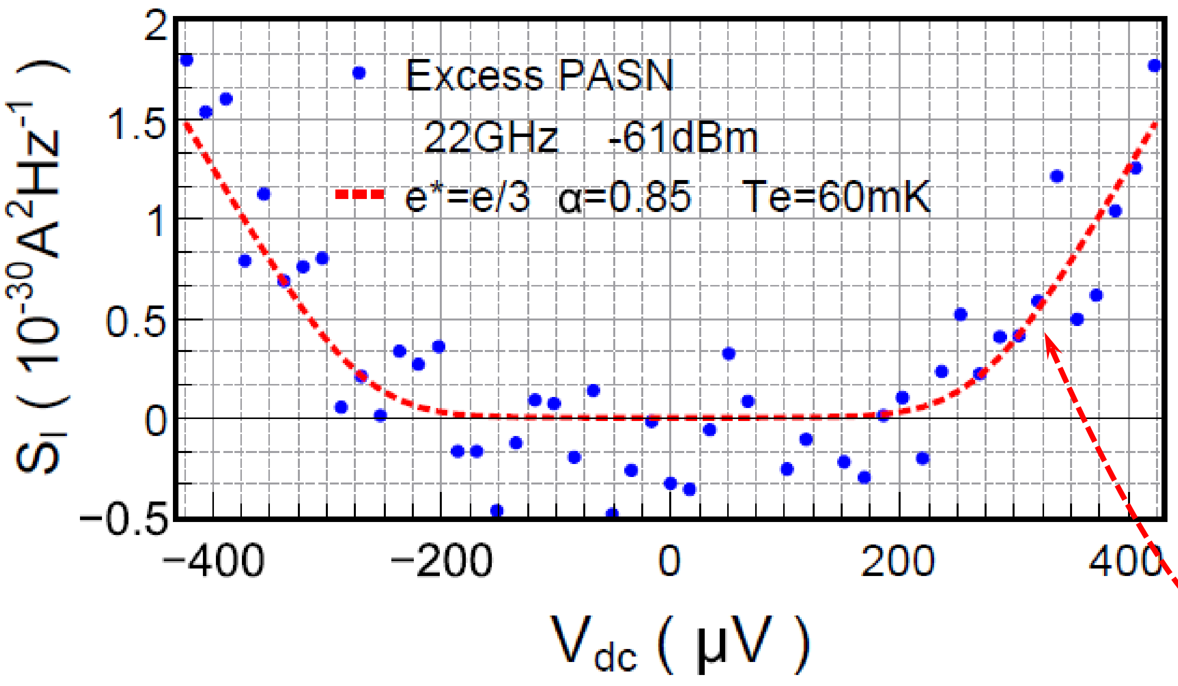
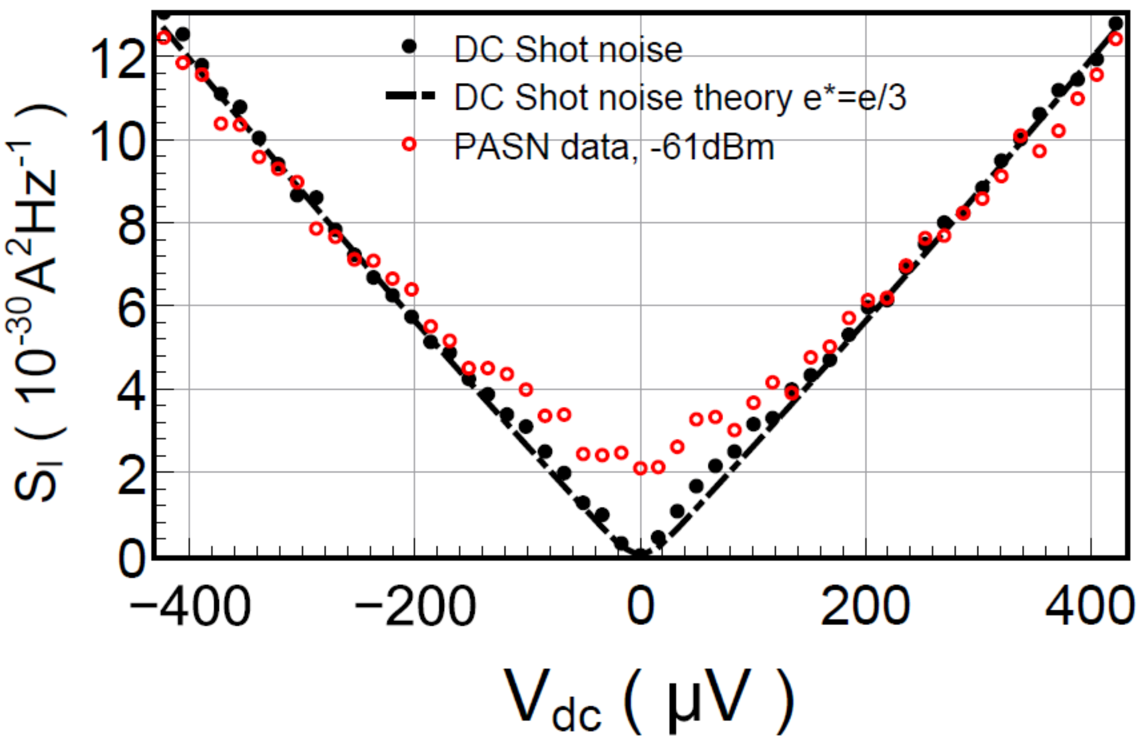




Finding a flat variation for the low $|V_{dc}|$ range provides a determination of $|p_0|^2$

as: $P_0 + 2\,P_1 \approx 1$, this gives P_1

comparison using $f_{Josephson} = e^*V_{dc}/h$ with $e^*=e/3$

New Measurement of e* for the 1/3-FQHE State

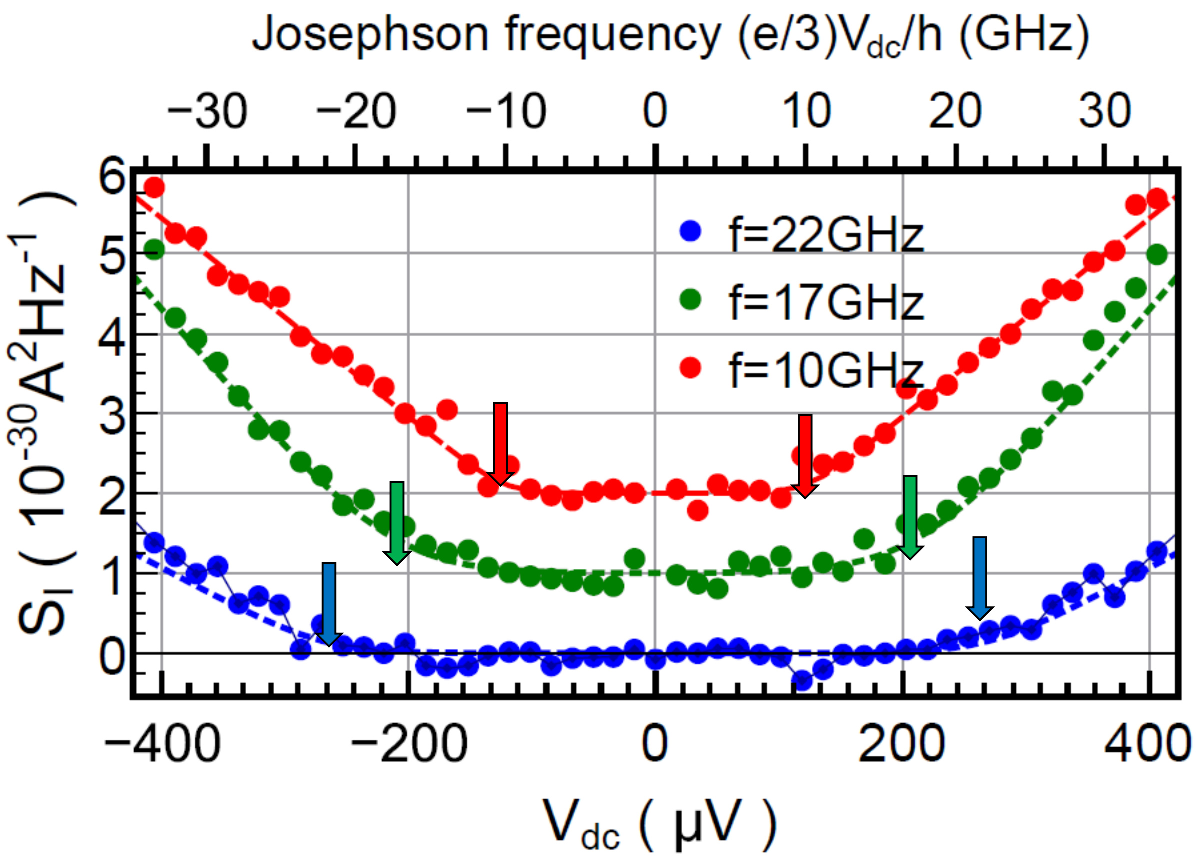
MEASURING e* from Excess PASN:

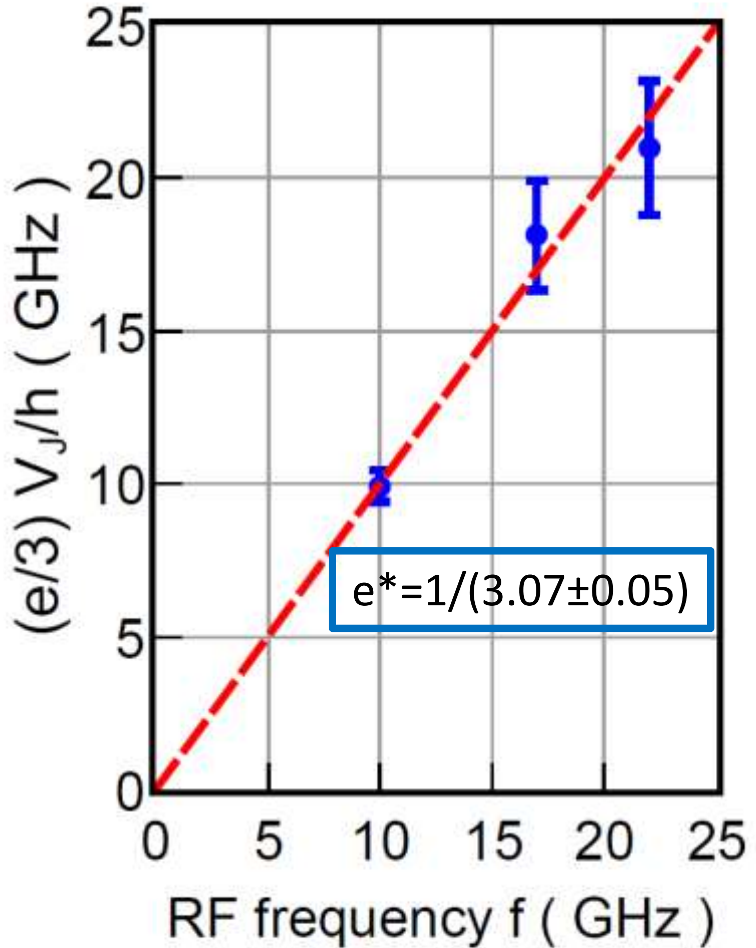
M. Kapfer et al. SCIENCE, Vol. 363 pp. 846-849 (2019)

$$\Delta S_I = S_I^{PASN}(V_{dc}) - P_0\, S_I^{DC}(V_{dc})$$
$$= P_1\left[S_I^{DC}(V_{dc} - hf/e^*) + S_I^{DC}(V_{dc} + hf/e^*)\right]$$

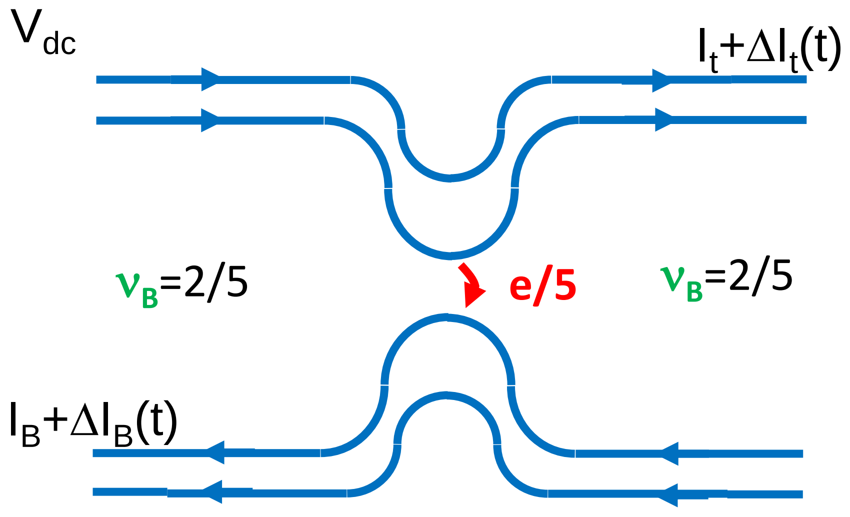
threshold voltage : $V_J = hf/e^*$ scales with frequency!

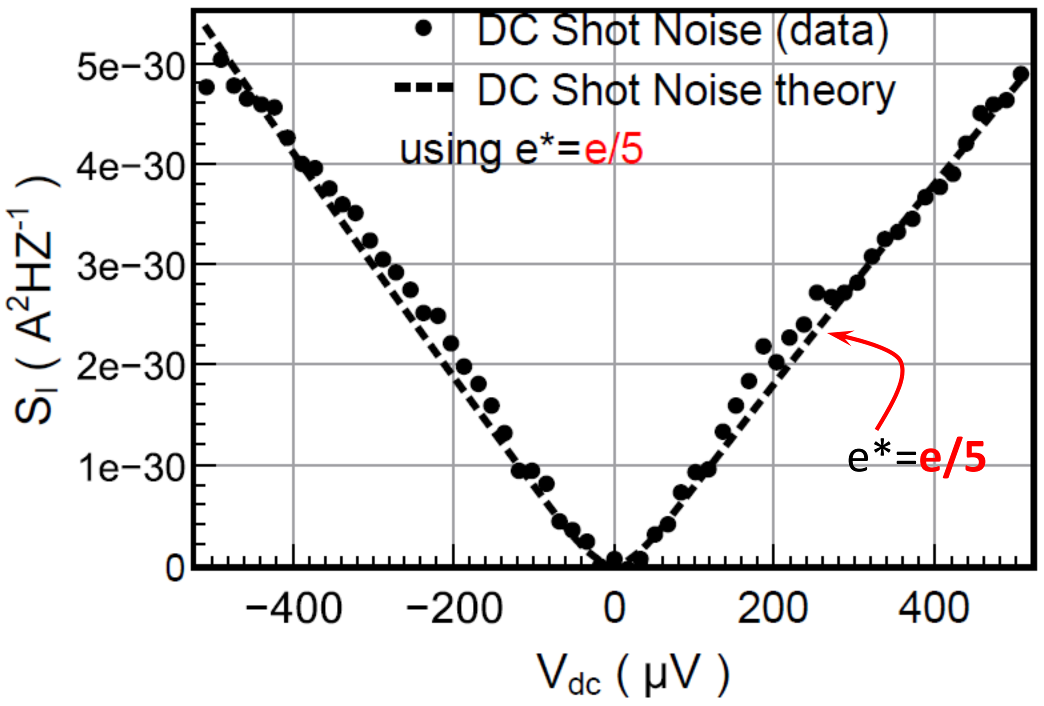
Best fit of data with e* free parameter

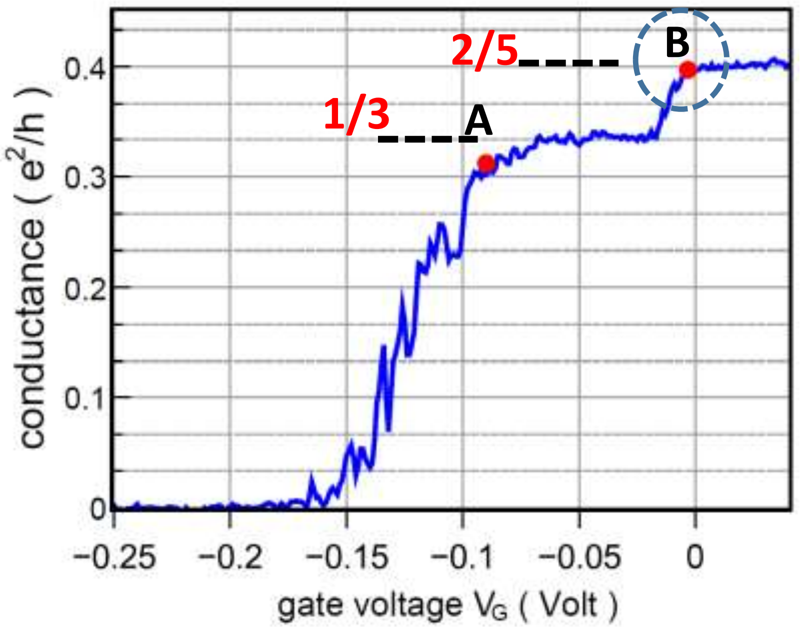




DC Shot noise for the 2/5-FQHE state







$$S_I^{DC} = 2e^* I_B \left[\coth\left(\frac{e^* V_{dc}}{2k_B T} \right) - \frac{2k_B T}{e^* V_{dc}} \right] \propto - \langle \Delta I_B \Delta I_t \rangle$$

e*= e/5 !

confirms Weizmann results (Reznikov 1999) on 2/5

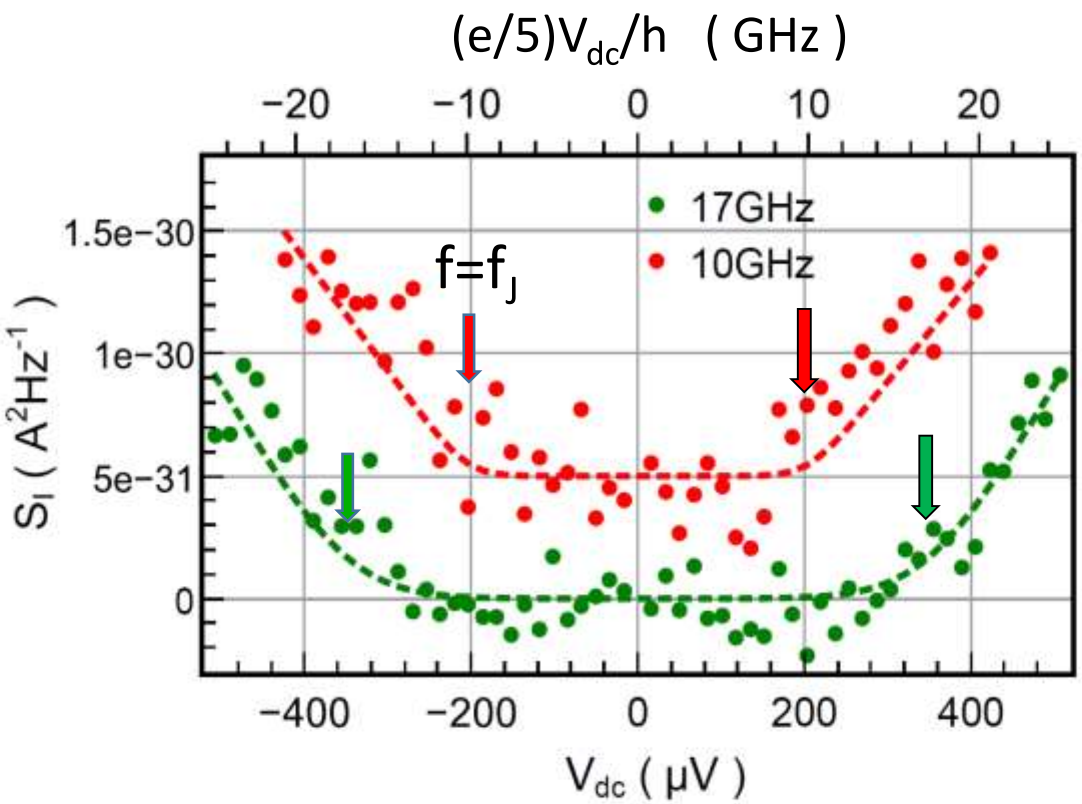
New Measurement of e* for the 2/5-FQHE State

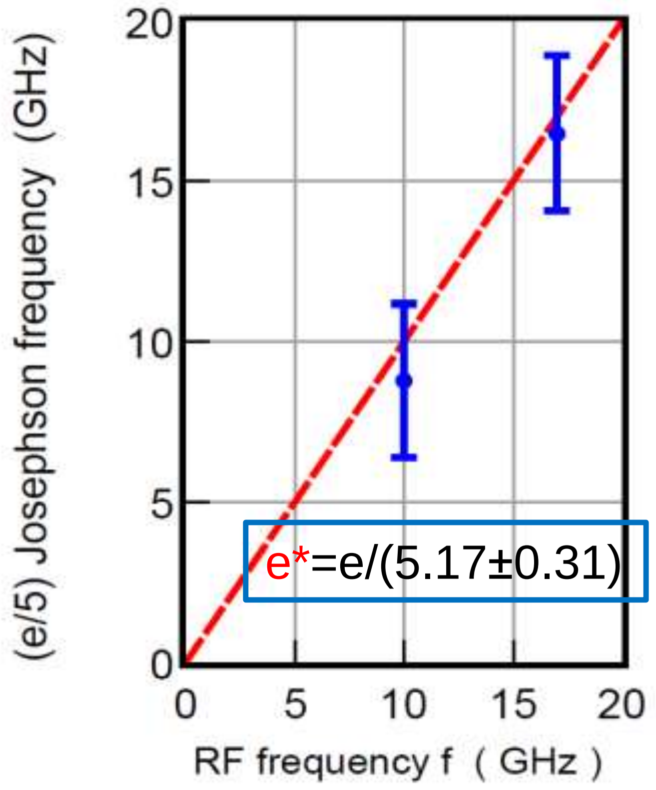
MEASURING e* from Excess PASN:

$$\Delta S_I = S_I^{PASN}(V_{dc}) - P_0\, S_I^{DC}(V_{dc})$$
$$= P_1 \left[S_I^{DC}(V_{dc} - hf/e^*) + S_I^{DC}(V_{dc} + hf/e^*) \right]$$

threshold voltage : $V_J = hf/e^*$ scales with frequency!

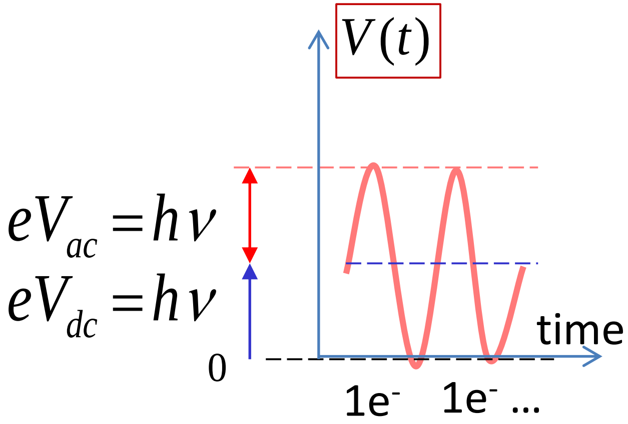
Best fit of data with e* free parameter



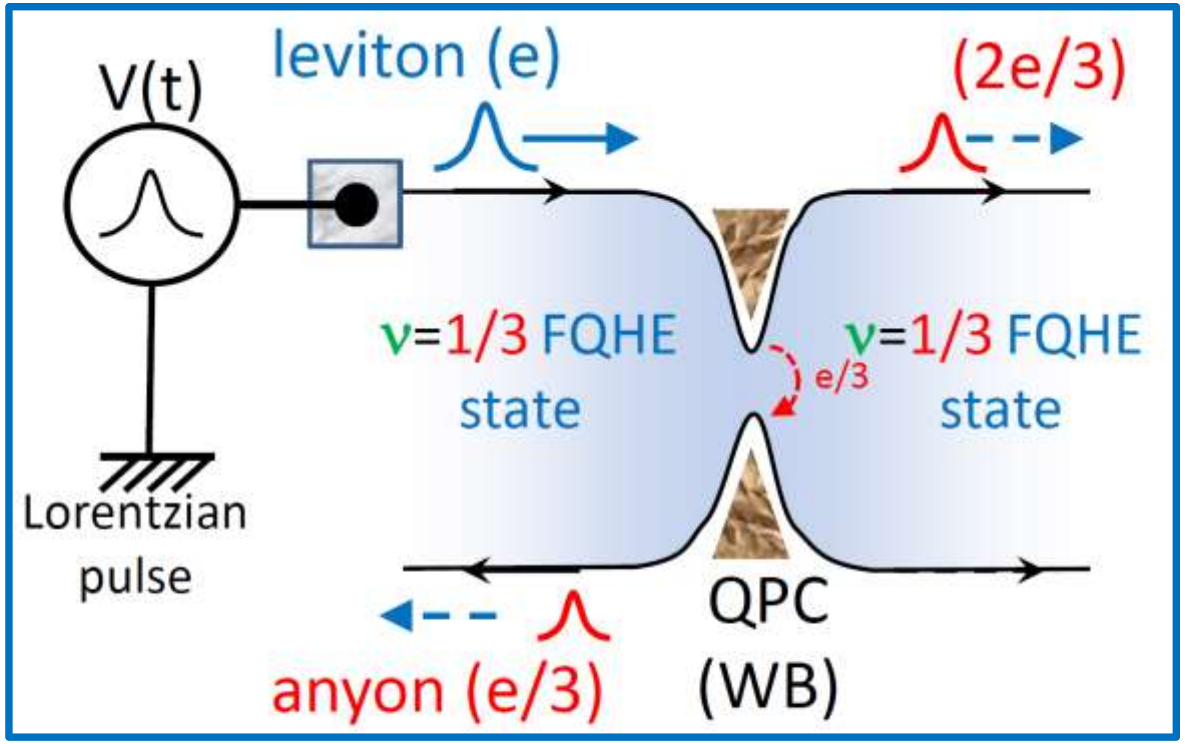


M. Kapfer et al. SCIENCE, Vol. 363 pp. 846-849 (2019)

CONCLUSION



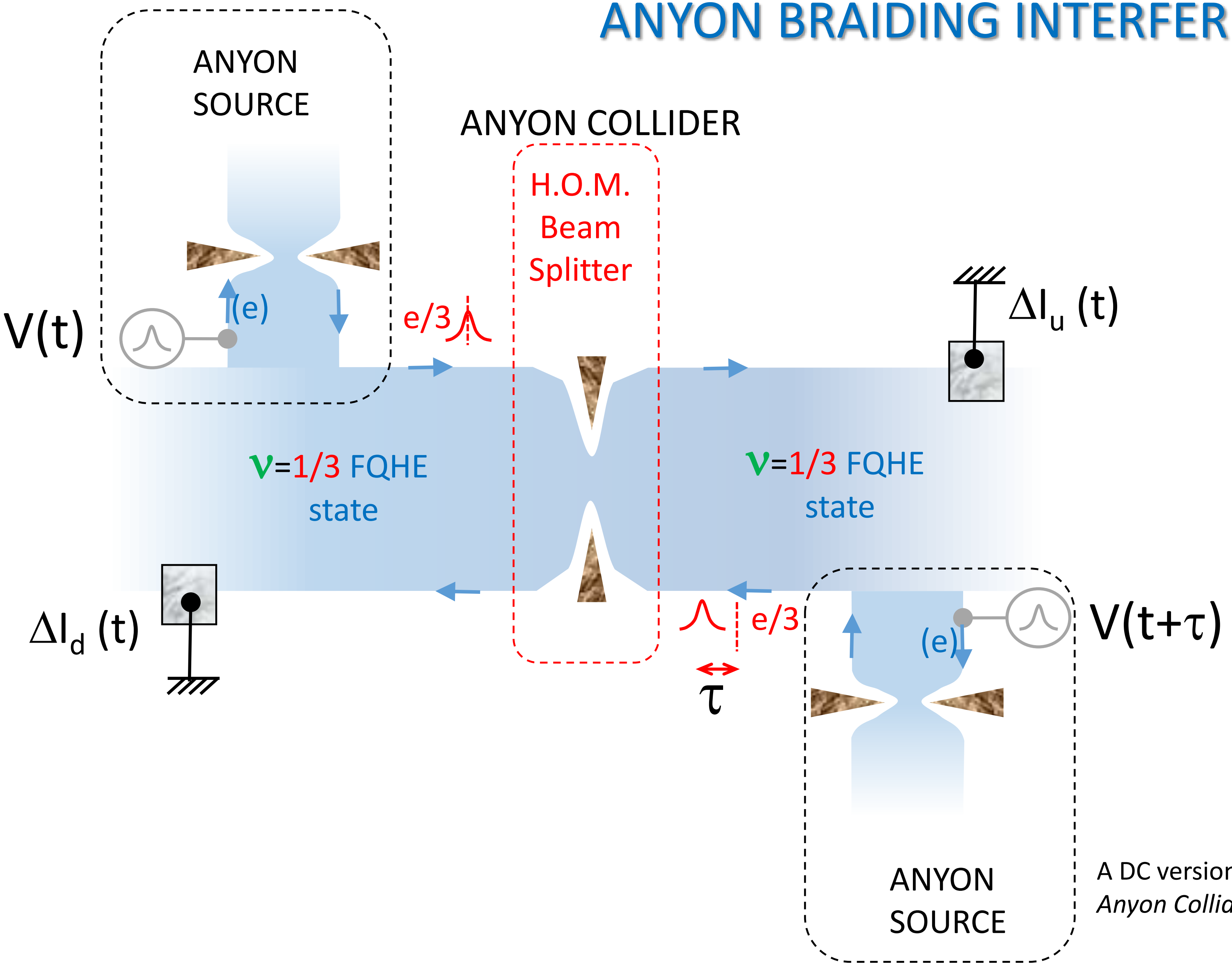
- WE HAVE SHOWN the MICROWAVE CONTROL of ANYONS is possible
- NEXT STEP : sine-wave to Lorentzian pulses.
- → TIME RESOLVED STOCHASTIC SOURCE OF ANYONS



See: theory prediction for photo-assisted current noise at ν=1/3
J. Rech, D. Ferraro, T. Jonckheere, L. Vannucci, M. Sassetti, and T. Martin, . Phys. Rev. Lett. 118, 076801 (2017)

Also heat noise at at ν=1/3
L. Vanucci;F. Ronetti, J. Rech, D. Ferraro, T. Jonckheere, T. Martin, M. Sassetti, PRB 95, 245415 (2017)

PERSPECTIVE :
ANYON BRAIDING INTERFERENCE



$$-\langle \Delta I_u \, \Delta I_d \rangle \propto 1 + g_2(\tau)\cos(\theta_{stat.})$$

A DC version can be find in: ``*Current Correlations from a Mesoscopic Anyon Collider* '' B. Rosenow, I. P. Levkivskyi, B. I. Halperin, (2016)

CONCLUSION-2

SHOT NOISE combined with Microwave **PHOTONS**

→ **2 ways** to determine **carrier charge**

SCHOTTKY (charge **granularity**)

$$S_I = 2\,e^*\,I_B$$

weak signal
but accurate

good signal
but lack of accuracy,
I_B : model dependent

OLD METHOD

PASN Josephson Relation (photon **quantum**)

$$h\,f = e^*\,V$$

very accurate

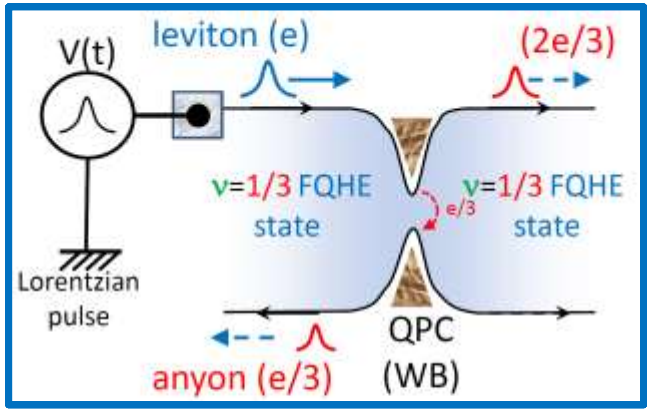
good accuracy

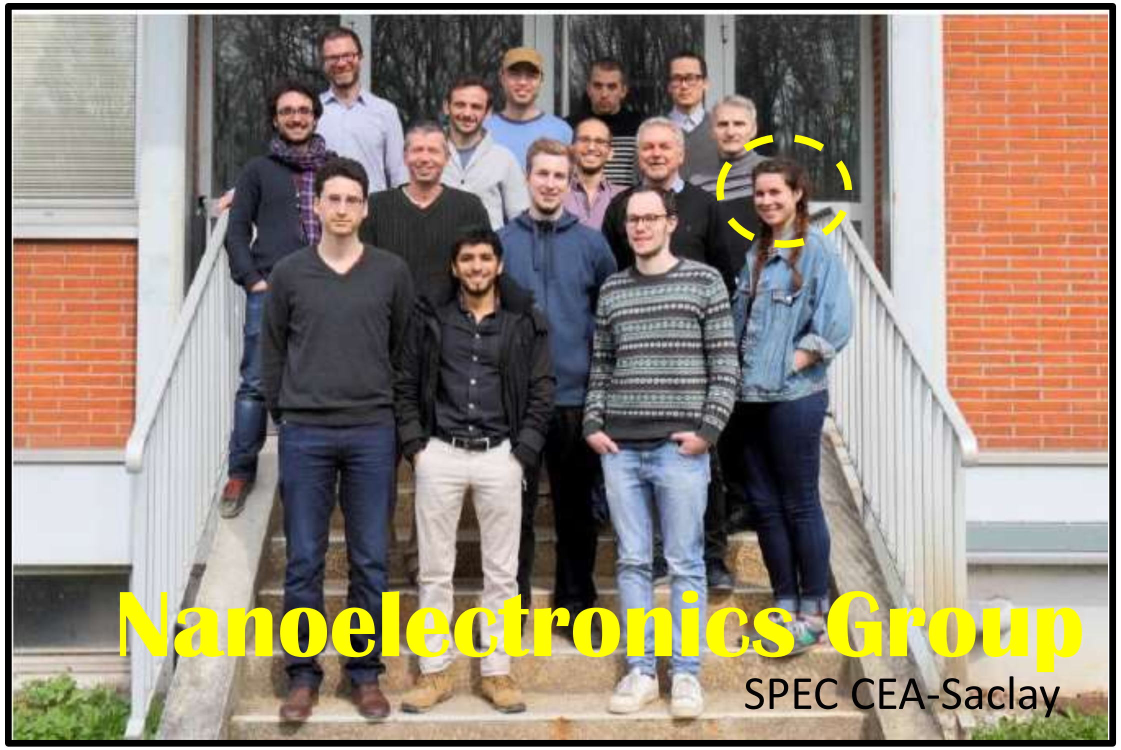
NEW METHOD

e/3 and e/5: M. Kapfer et al**. SCIENCE**, Vol. 363 pp. 846-849 (2019)
e/3 finite frequency noise, R. Bisognin et al. Nature Communications (2019)

ACKNOWLEDGEMENTS

soon coming !





X. Waintal
H. Saleur
I Safi
Th. Martin, J. Rech, T. Jonkheere
M. Freedman
All members of Nanoelectronics Group at Saclay

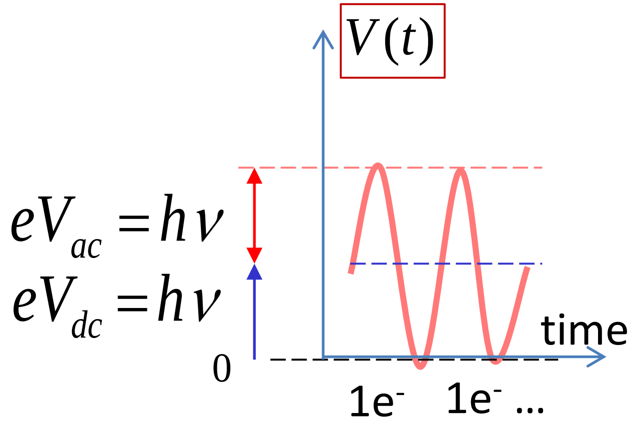
ANR FullyQuantum AAP CE30
UltraFastNano FET Open H2020.

The Josephson Frequency of fractionally charge anyons
M. Kapfer, P. Roulleau, I. Farrer, D. A. Ritchie, and D. C. Glattli,
SCIENCE, Vol. 363 pp. 846-849 (2019)

Levitons :
J. Dubois et al, **Nature** 502, 659 (2013*)*
T. Jullien et al., **Nature** 514, 603 (2014)

OPEN POSITION
for 18-24 months
Post-doct.

CONCLUSION



- WE HAVE SHOWN the MICROWAVE CONTROL of ANYONS is possible
- NEXT STEP : sine-wave to Lorentzian pulses.
- → TIME RESOLVED STOCHASTIC SOURCE OF ANYONS

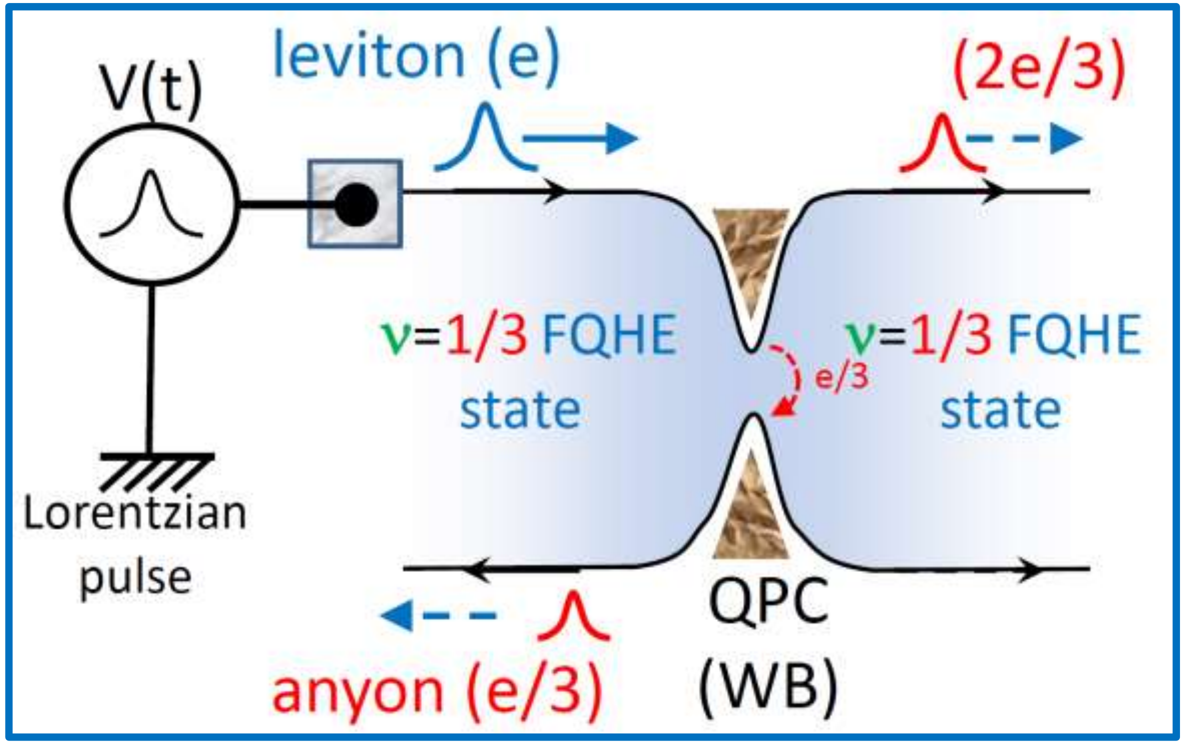
Why only charge e levitons in FQHE.

$$\Delta\phi = \frac{1}{\hbar}\int e^* V(t)dt = 2\pi$$

$$I(t) = e^* \frac{e}{h} V(t)$$

$$\int I(t)dt = e$$

See: also: Jérome Rech's Talk, Wednesday Session 3-C, and *J. Rech, D. Ferraro, T. Jonckheere, L. Vannucci, M. Sassetti, and T. Martin,* . Phys. Rev. Lett. 118, 076801 (2017)



DC SHOT NOISE: Integer QHE

$$S_I = 2eI_0\, D(1-D)$$

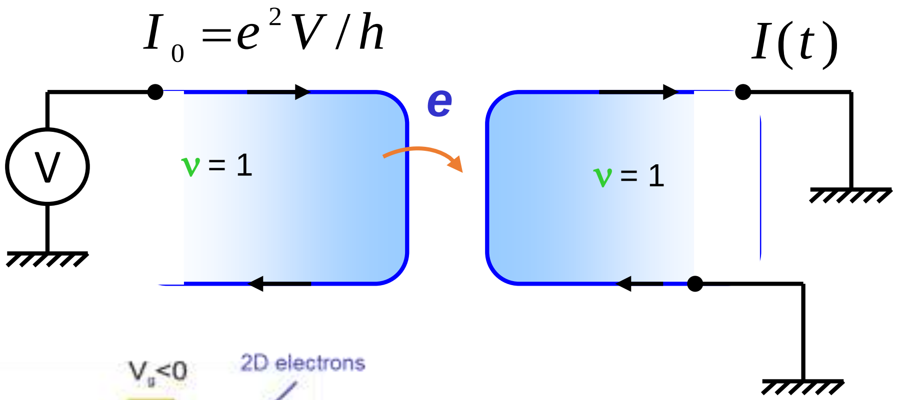
G. B. Lesovik,
JETP Letters49, 594 (1989)

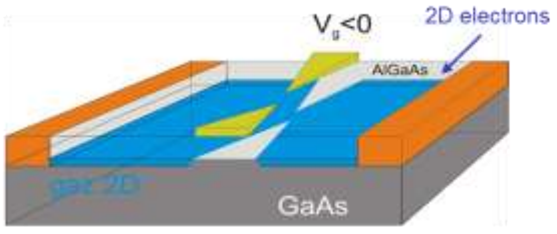
$$I_0 = e^2V/h$$

$$I_0 = I + I_B$$

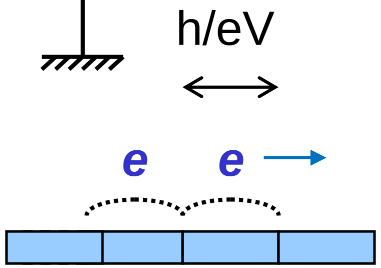
transmitted (D)   reflected (1-D)

strong barrier :





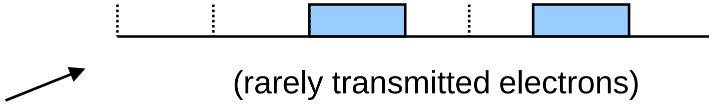
III-V semi-conductor heterojunction GaAs/GaAlAs



(incoming electrons)

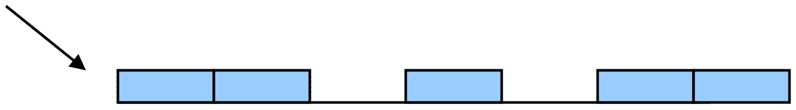
$$S_I = 2eI \qquad D \ll 1$$

Schottky (1918)



(rarely transmitted electrons)

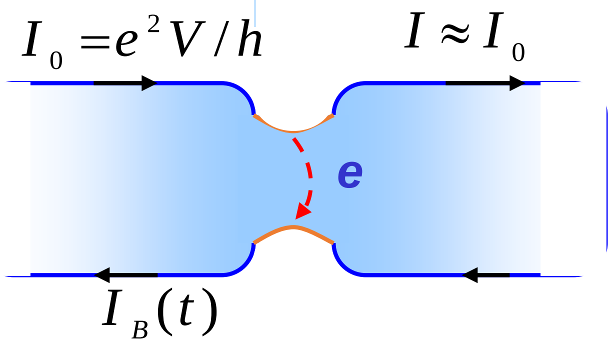
Poisson's statistics



(rarely transmitted holes)

$$S_I = 2eI_B \qquad D \approx 1$$

weak barrier :

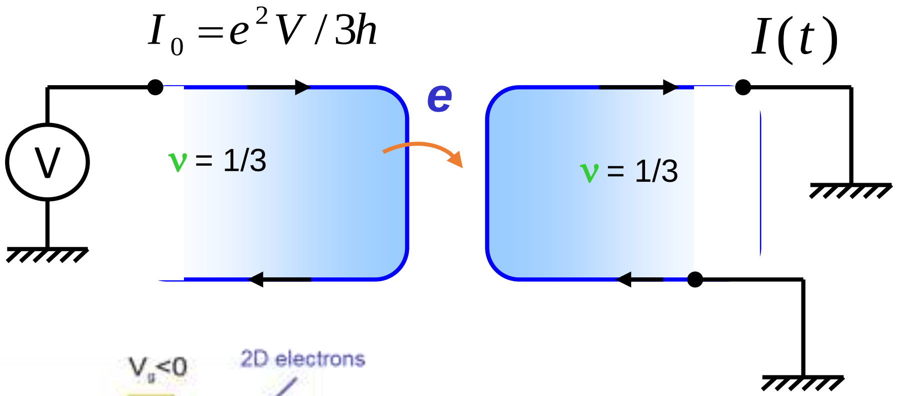


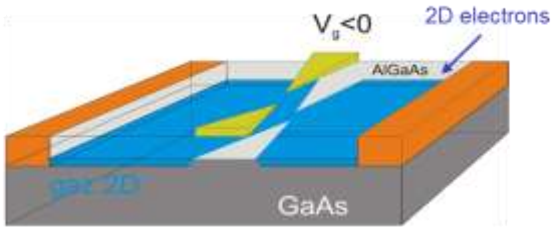
DC SHOT NOISE: FQHE

$$I_0 = e^2 V / 3h$$
$$I_0 = I + I_B$$

transmitted (D) reflected ($1-D$)

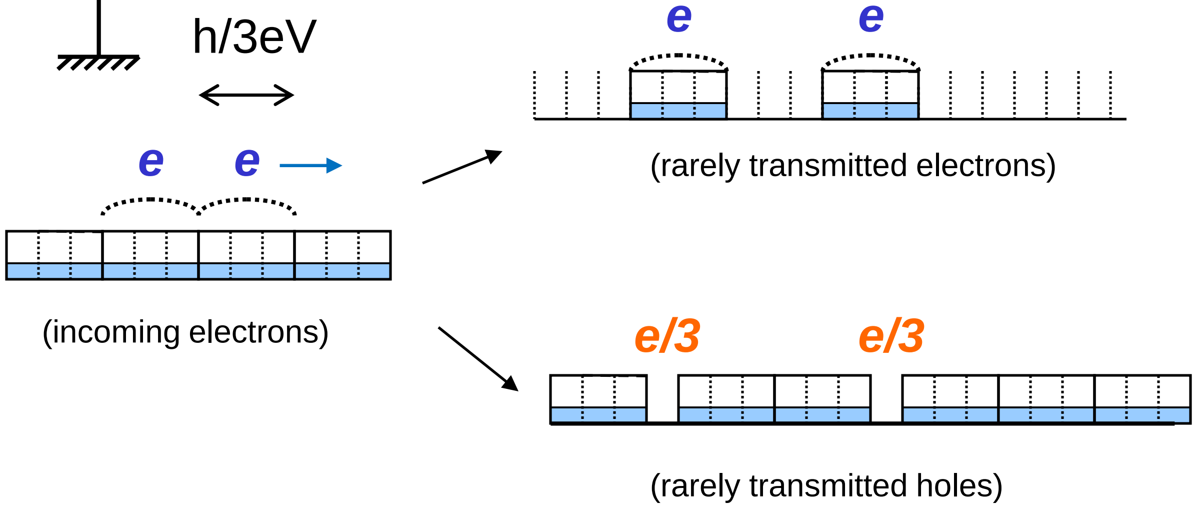
strong barrier :



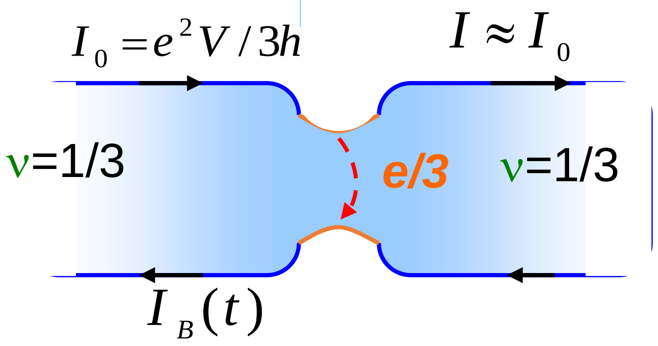


III-V semi-conductor heterojunction GaAs/GaAlAs

$$S_I = 2eI \qquad D \ll 1$$



weak barrier :



$$S_I = 2\frac{e}{3} I_B \qquad D \approx 1$$

First observation:
CEA Saclay 1997
Weizmann 1997

derived from chiral-Luttinger liquid approach
(*X.G. Wen 1995, C. Kane + M. Fisher 1994; Fendley, Ludwig + Saleur (1995)*)

Science REPORTS

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A Josephson relation for fractionally charged anyons

M. Kapfer[1], P. Roulleau[1], M. Santin[1], I. Farrer[2], D. A. Ritchie[3], D. C. Glattli[1*]

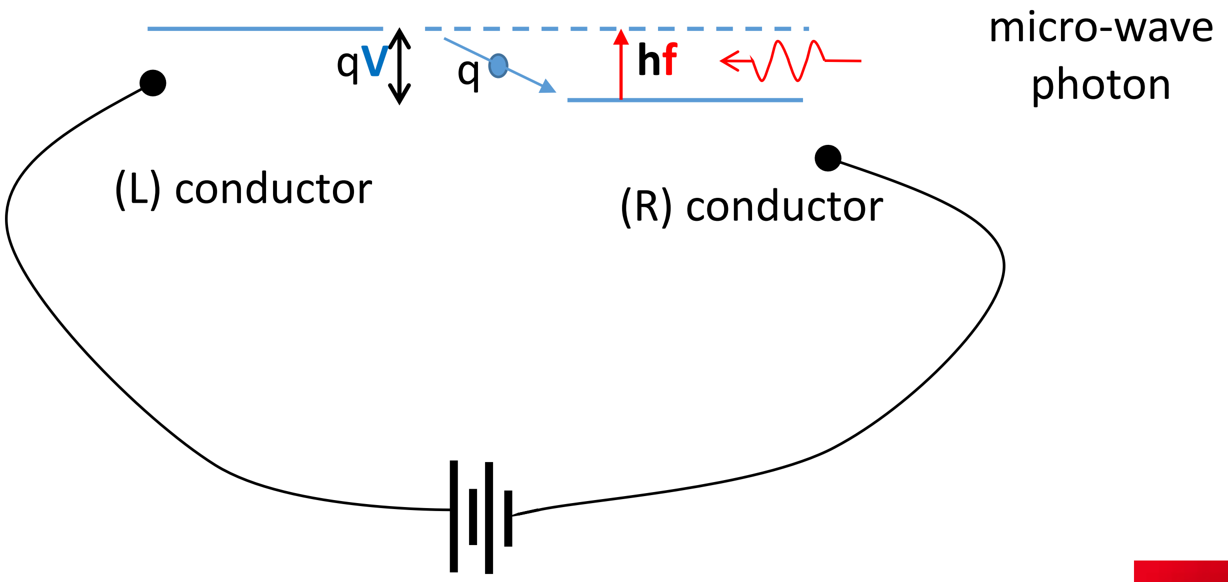
[1]Service de Physique de l'Etat Condensé, CEA, CNRS, Université Paris Saclay, CEA Saclay, 91191 Gif sur Yvette cedex, France. [2]Department of Electronic and Electrical Engineering, University of Sheffield, Mappin Street, Sheffield S1 3JD, UK. [3]Cavendish Laboratory, University of Cambridge, J. J. Thomson Avenue, Cambridge CB3 0HE, UK.

*Corresponding author. E-mail: christian.glattli@cea.fr

D. C. GLATTLI
CEA Saclay

JOSEPHSON RELATION

$$q\,V = h\,f$$



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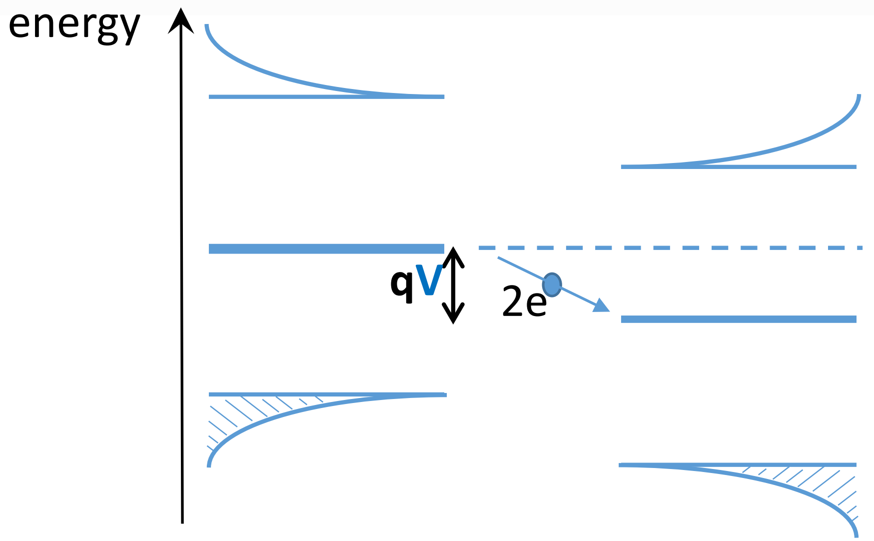
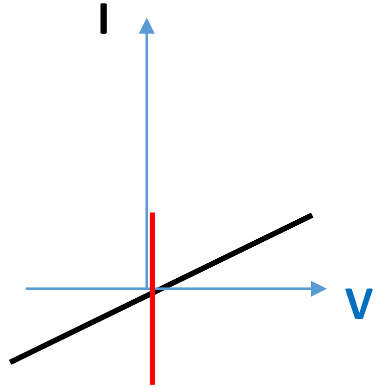
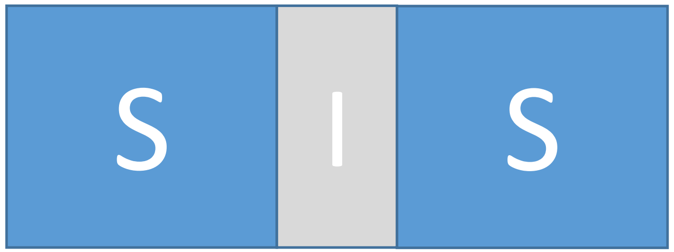


q = 2e   Inverse
AC Josephson Effect

S. Shapiro (1963)





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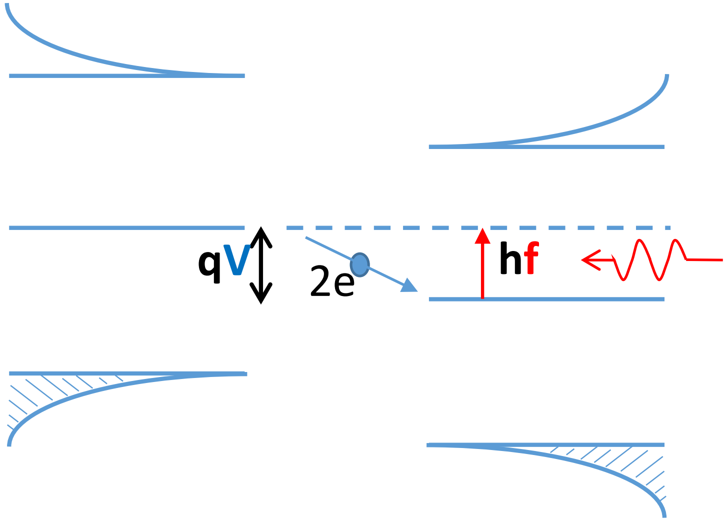
JOSEPHSON RELATION

$$q\,V = h\,f$$



q = 2e Inverse
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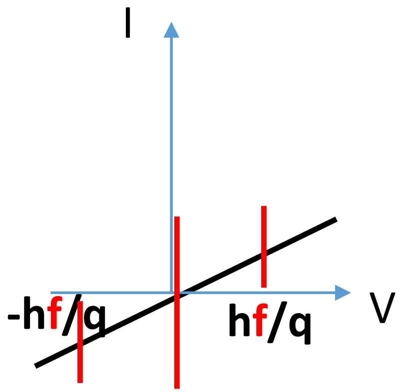

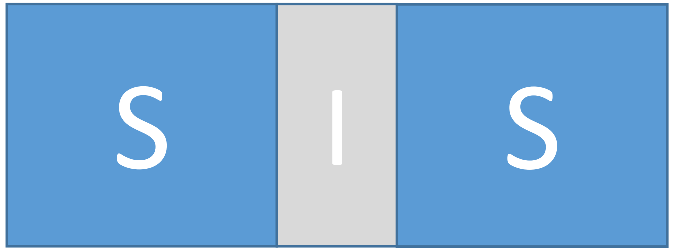

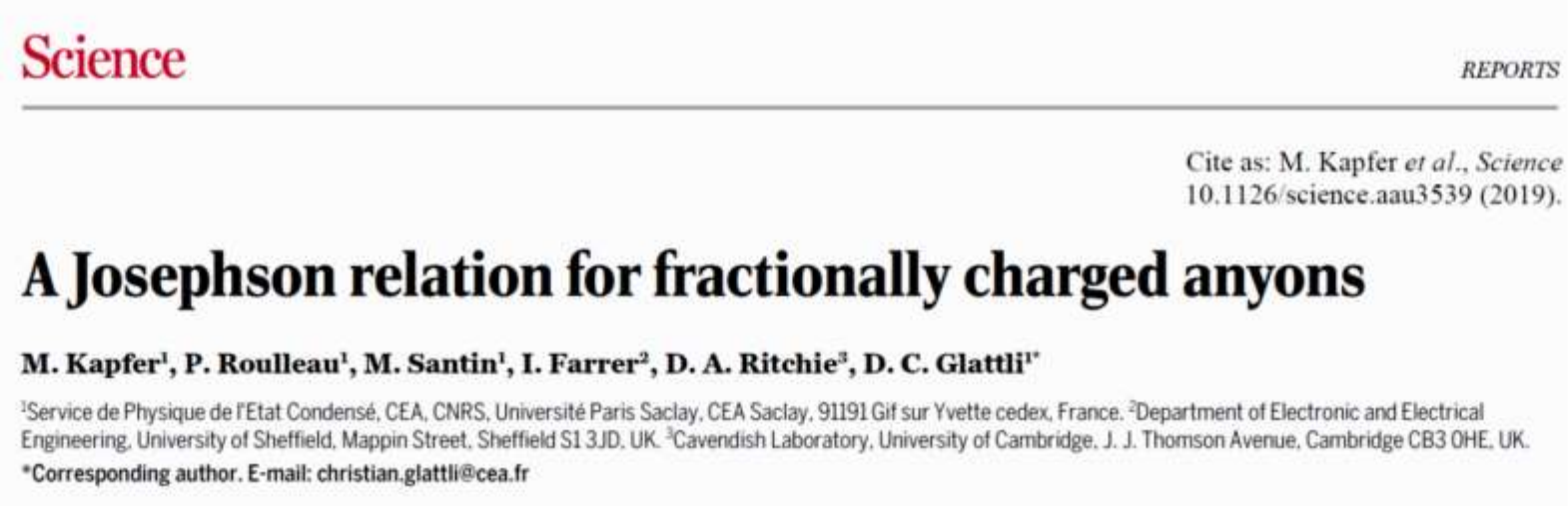

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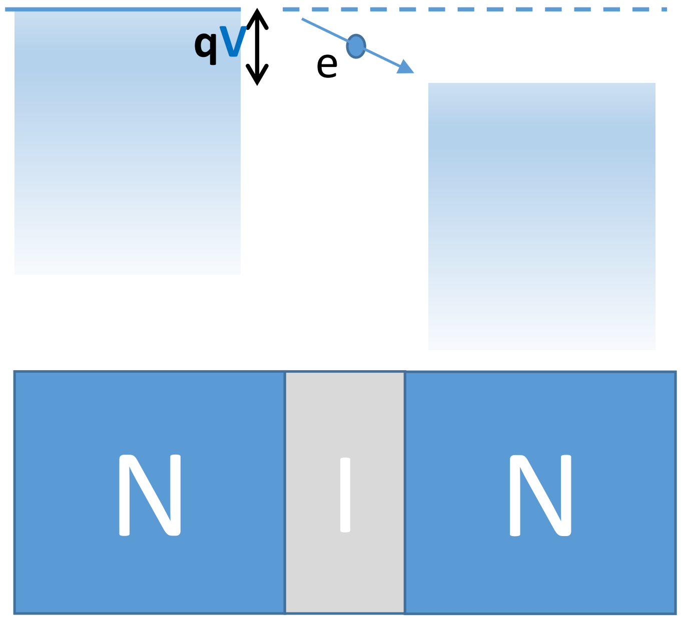
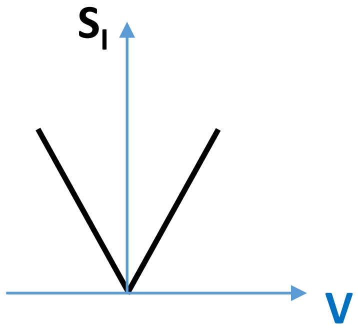


HERE: no Josephson Effect



BUT: current Shot Noise

Lesovik + Levitov (1994)

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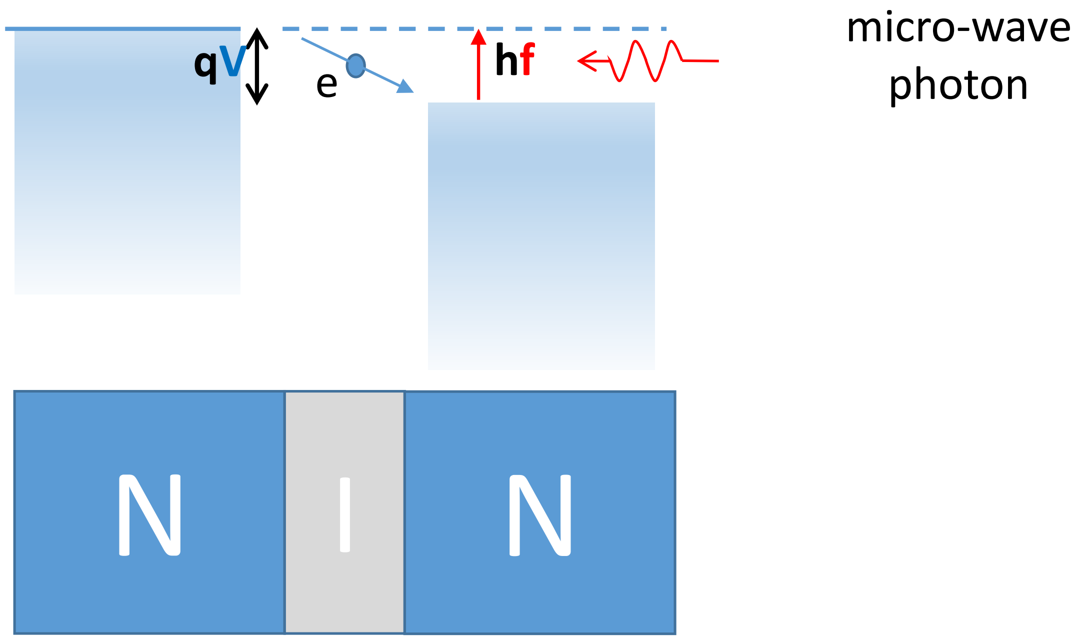
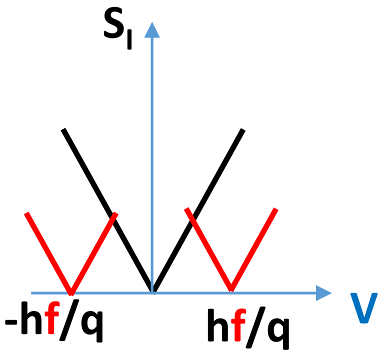
JOSEPHSON RELATION

$$q\,V = h\,f$$



HERE: no Josephson Effect

BUT: Photo-Assisted Shot Noise



Lesovik + Levitov (1994)

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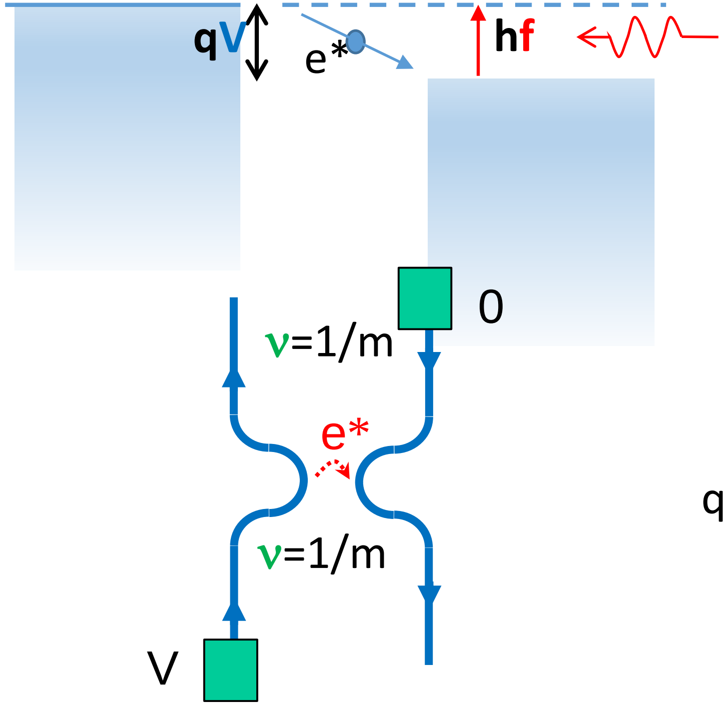
JOSEPHSON RELATION

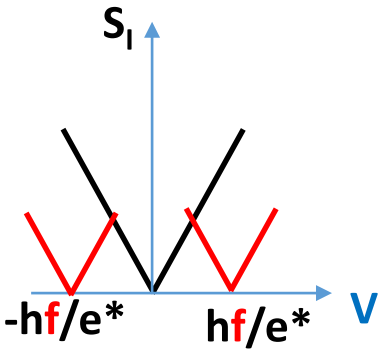
$$e^*V = h\,f$$



HERE: Fractional QH Effect

and Photo-Assisted Shot Noise

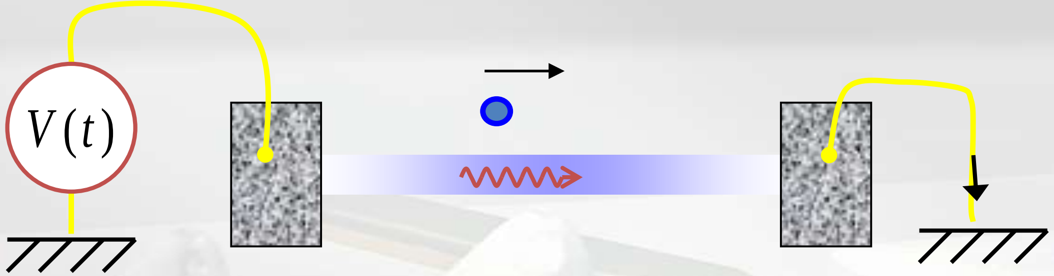
Lesovik + Levitov (1994) ***X.G. Wen*** *(1995)*

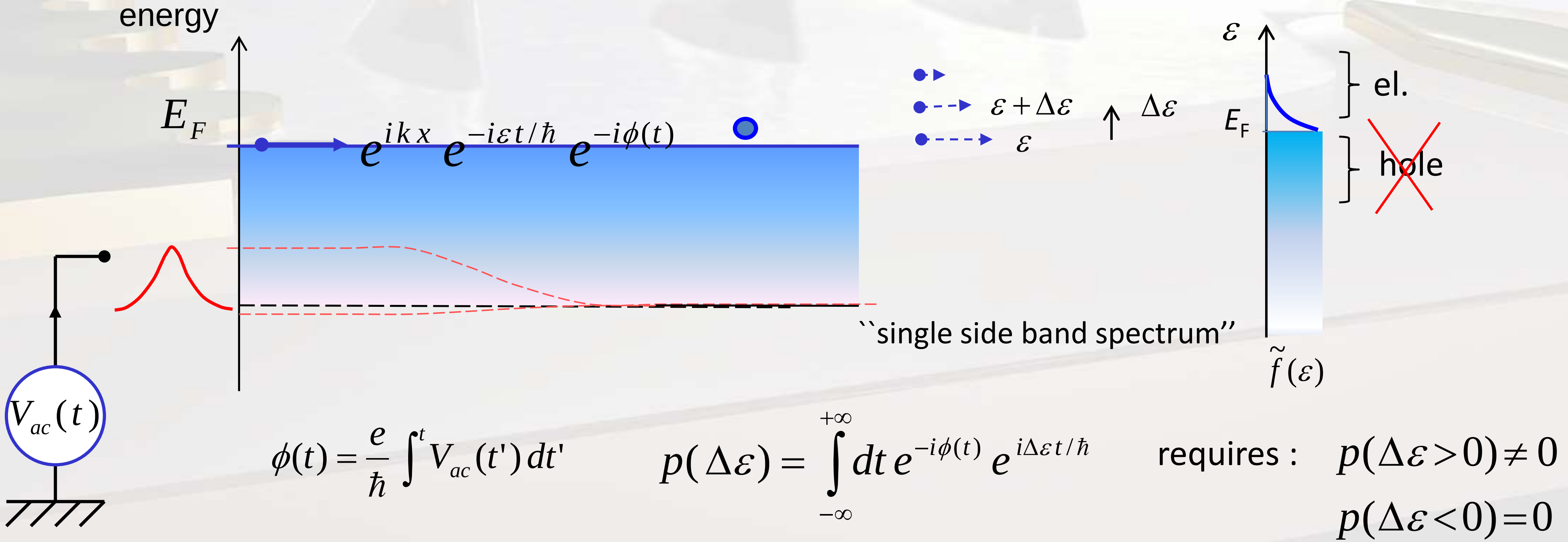


$q = e^* = e/m$

LEVITONS : a wave property + Fermi statistics

Lorentzian pulse





$$\phi(t) = \frac{e}{\hbar}\int^{t} V_{ac}(t')\,dt'$$

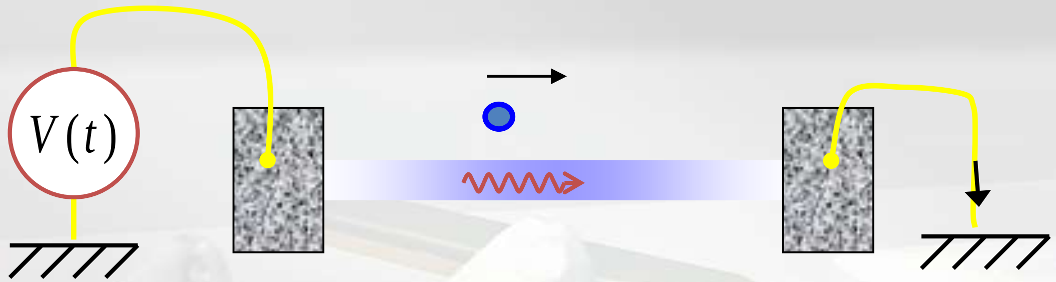
$$p(\Delta\varepsilon) = \int_{-\infty}^{+\infty} dt\, e^{-i\phi(t)}\, e^{i\Delta\varepsilon t/\hbar}$$

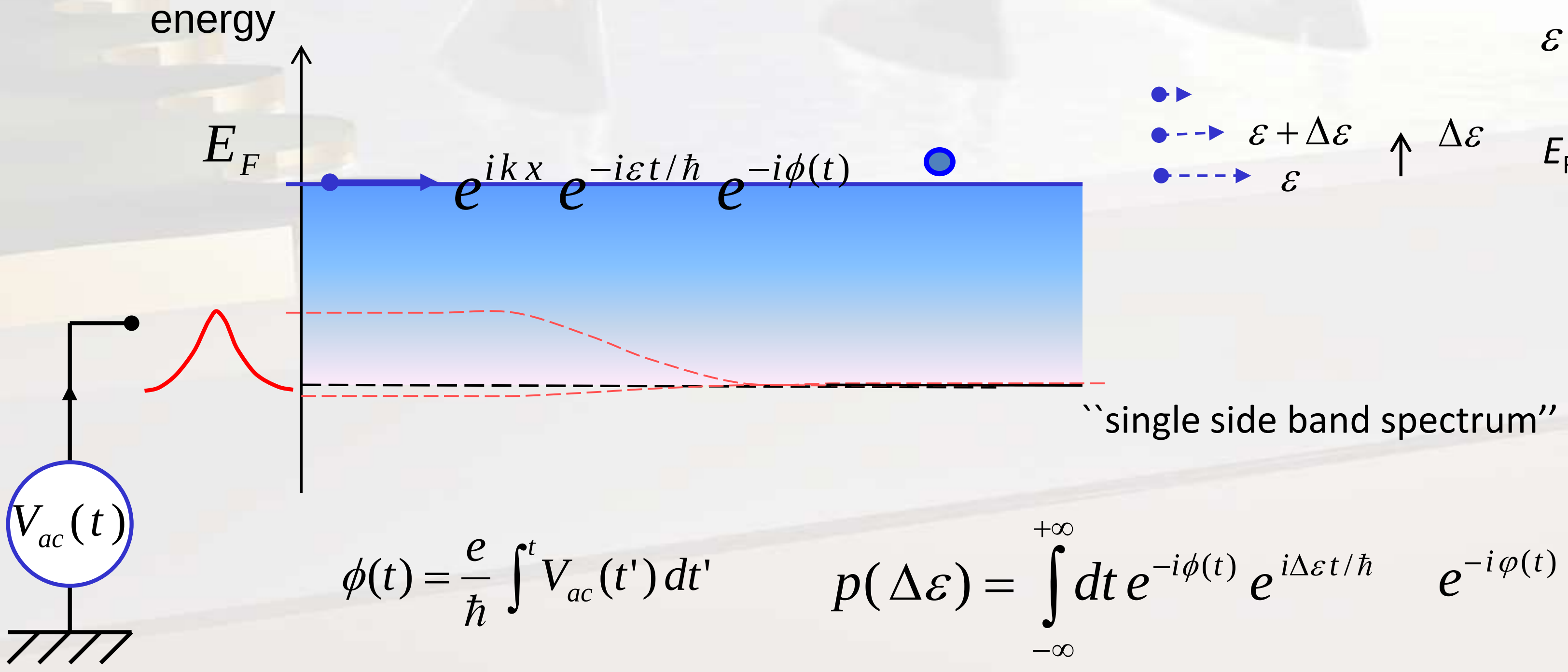
requires : $p(\Delta\varepsilon > 0) \neq 0$

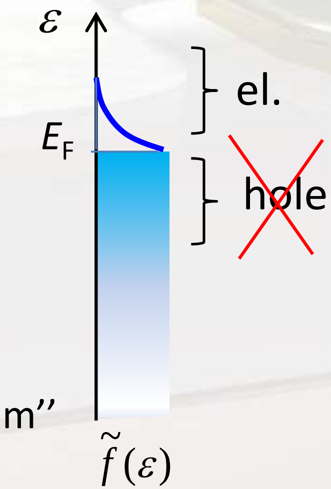
$p(\Delta\varepsilon < 0) = 0$

LEVITONS : a wave property + Fermi statistics

Lorentzian pulse



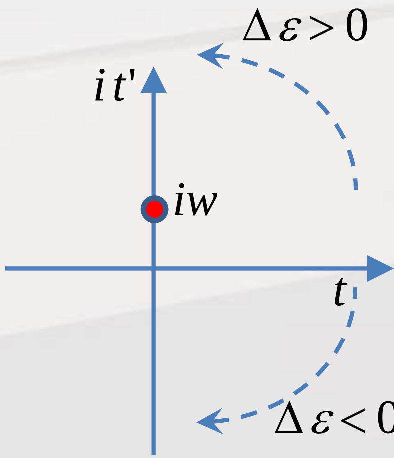




$$\phi(t)=\frac{e}{\hbar}\int^{t} V_{ac}(t')\,dt'$$

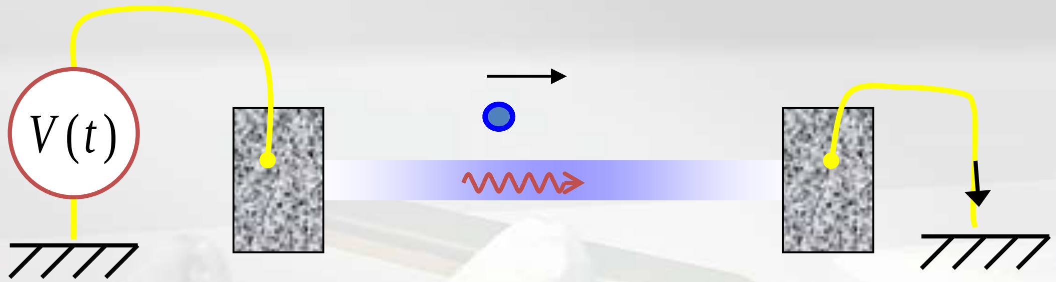
$$p(\Delta\varepsilon)=\int_{-\infty}^{+\infty} dt\, e^{-i\phi(t)}\, e^{i\Delta\varepsilon t/\hbar}$$

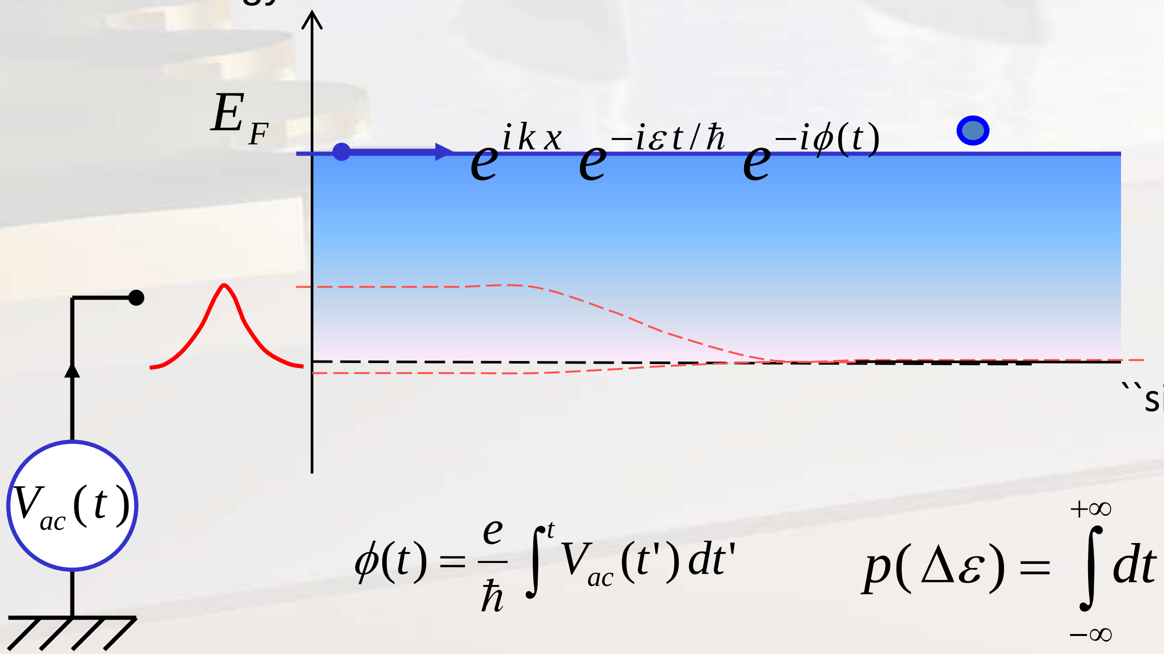
$$e^{-i\varphi(t)}=\frac{(\;\dots\;)}{t-iw}$$

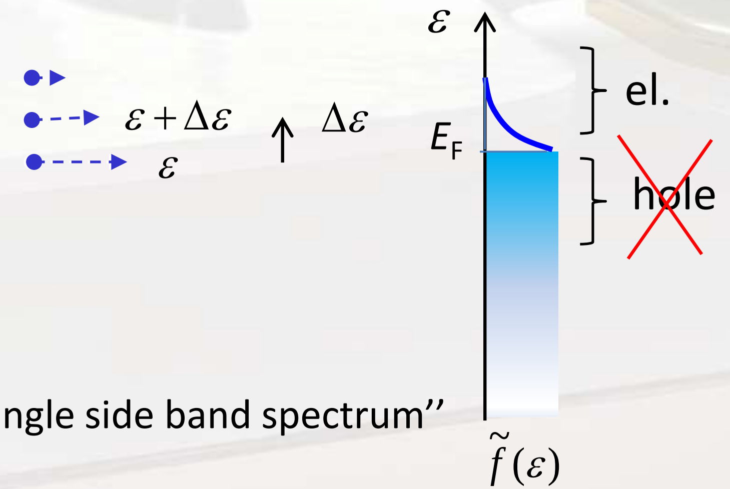


LEVITONS : a wave property + Fermi statistics

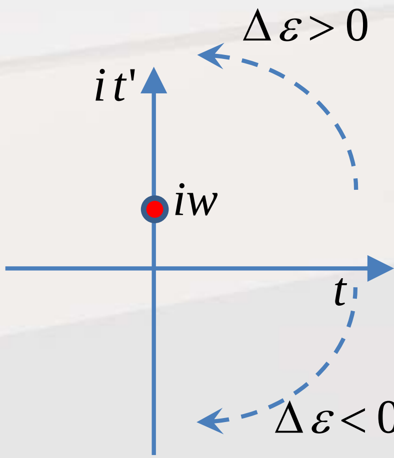
Lorentzian pulse







``single side band spectrum''



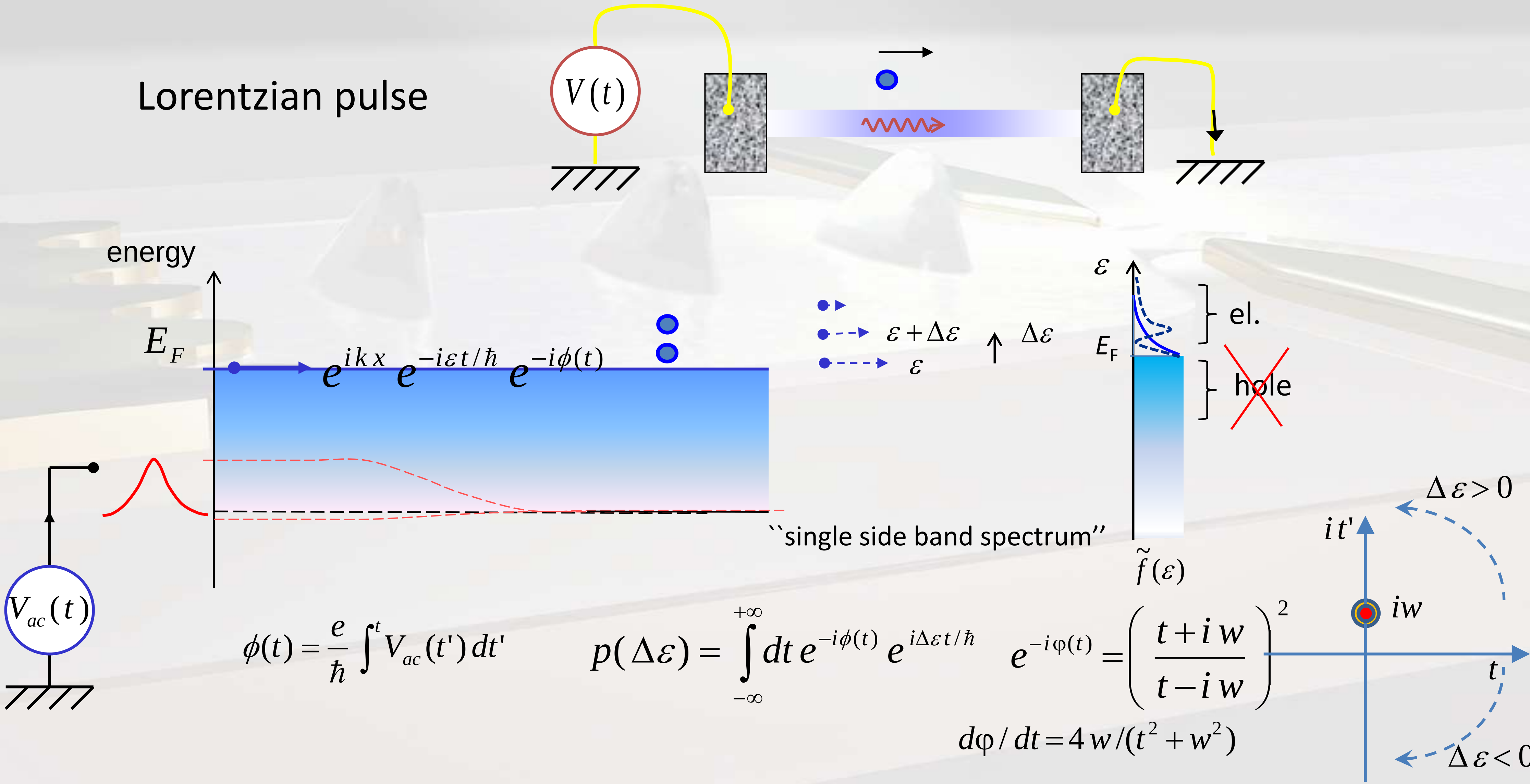
$$\phi(t)=\frac{e}{\hbar}\int^{t} V_{ac}(t')\,dt'$$

$$p(\Delta\varepsilon)=\int_{-\infty}^{+\infty} dt\, e^{-i\phi(t)}\, e^{i\Delta\varepsilon t/\hbar}$$

$$e^{-i\varphi(t)}=\frac{t+iw}{t-iw}$$

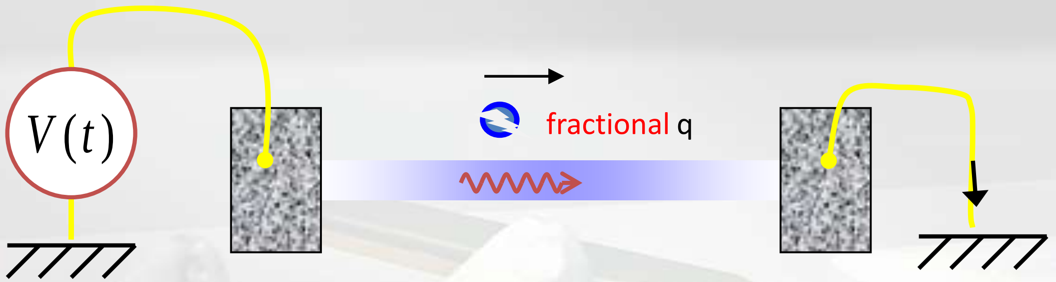
$$d\varphi/dt=2w/(t^2+w^2)$$

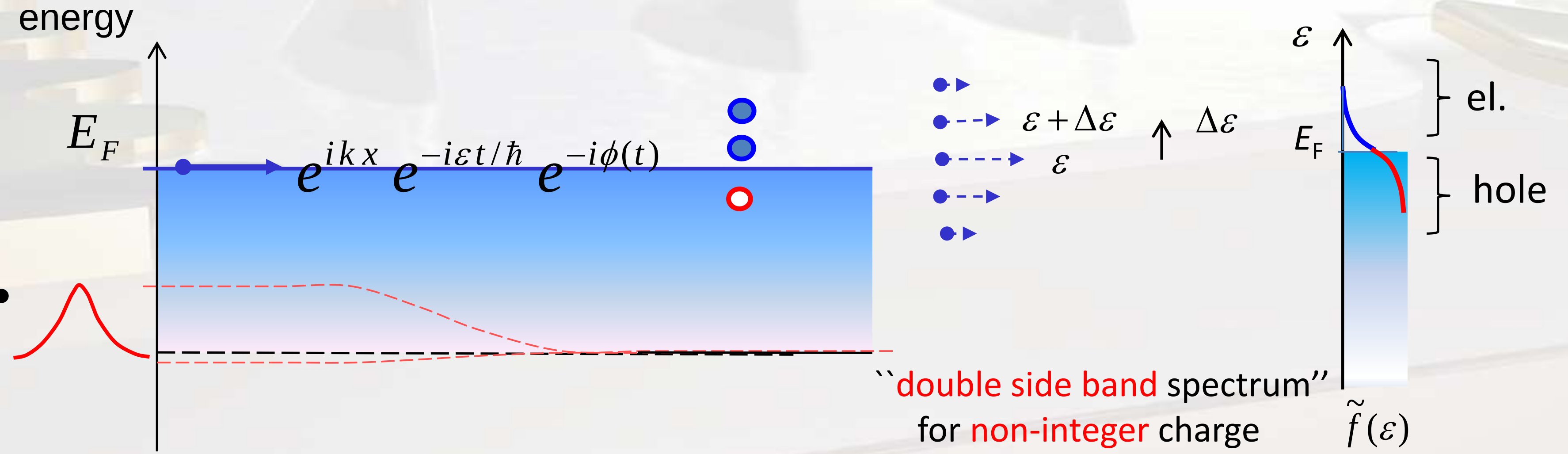
LEVITONS : a wave property + Fermi statistics

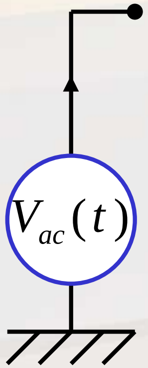


LEVITONS : a wave property + Fermi statistics

Lorentzian pulse







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$$p(\Delta\varepsilon) = \int_{-\infty}^{+\infty} dt\, e^{-i\phi(t)}\, e^{i\Delta\varepsilon t/\hbar}$$

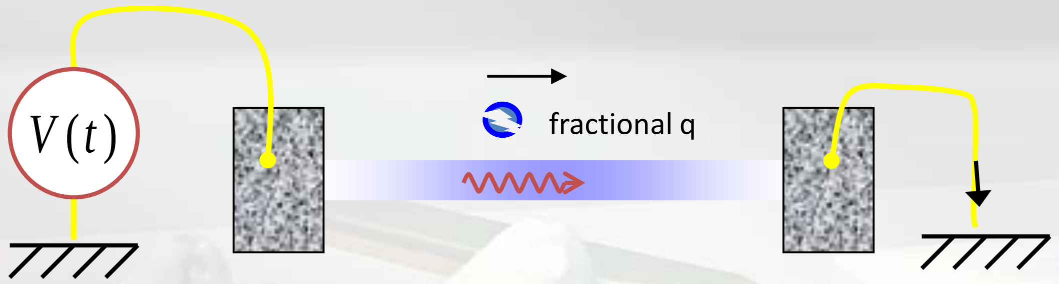
$$e^{-i\varphi(t)} = \left(\frac{t+iw}{t-iw}\right)^{q/e}$$

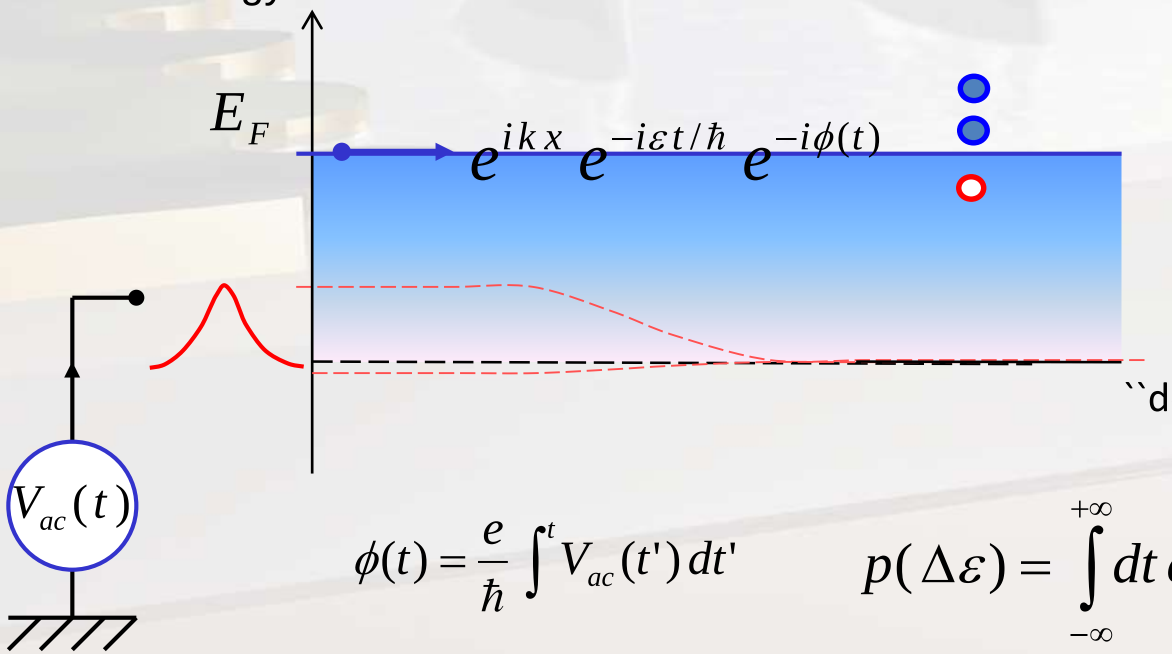
$$d\varphi/dt = \frac{q}{e}\,2w/(t^2+w^2)$$

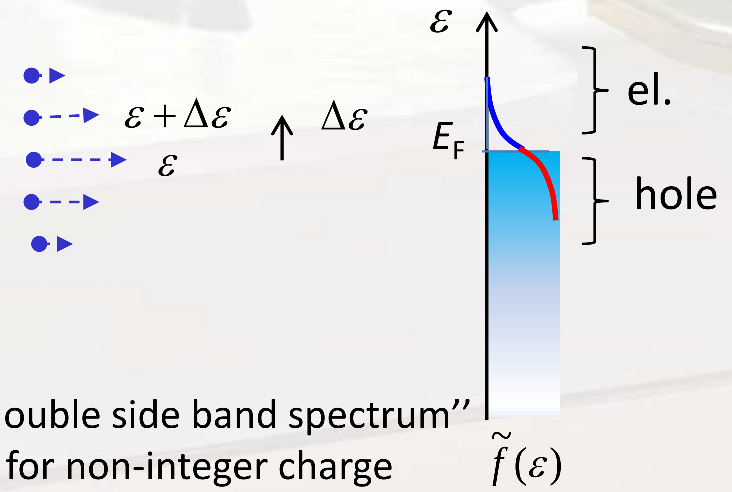
« Dynamical orthogonality catastrophe » *Levitov 1995*

LEVITONS : a wave property + Fermi statistics

Lorentzian pulse







``double side band spectrum'' for non-integer charge

$$\phi(t) = \frac{e}{\hbar}\int^{t} V_{ac}(t')\,dt'$$

$$p(\Delta\varepsilon) = \int_{-\infty}^{+\infty} dt\, e^{-i\phi(t)}\, e^{i\Delta\varepsilon t/\hbar}$$

$$e^{-i\varphi(t)} = \left(\frac{t+iw}{t-iw}\right)^{q/e}$$

$$d\varphi/dt = \frac{q}{e}\,2w/(t^2+w^2)$$

minimal excitation states (levitons) for **integer** charge only