laboratoire pierre aigrain
électronique et photonique quantiques

Spin-charge separation in chiral edge channels

Experiments LPA

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Theory, ENS Lyon

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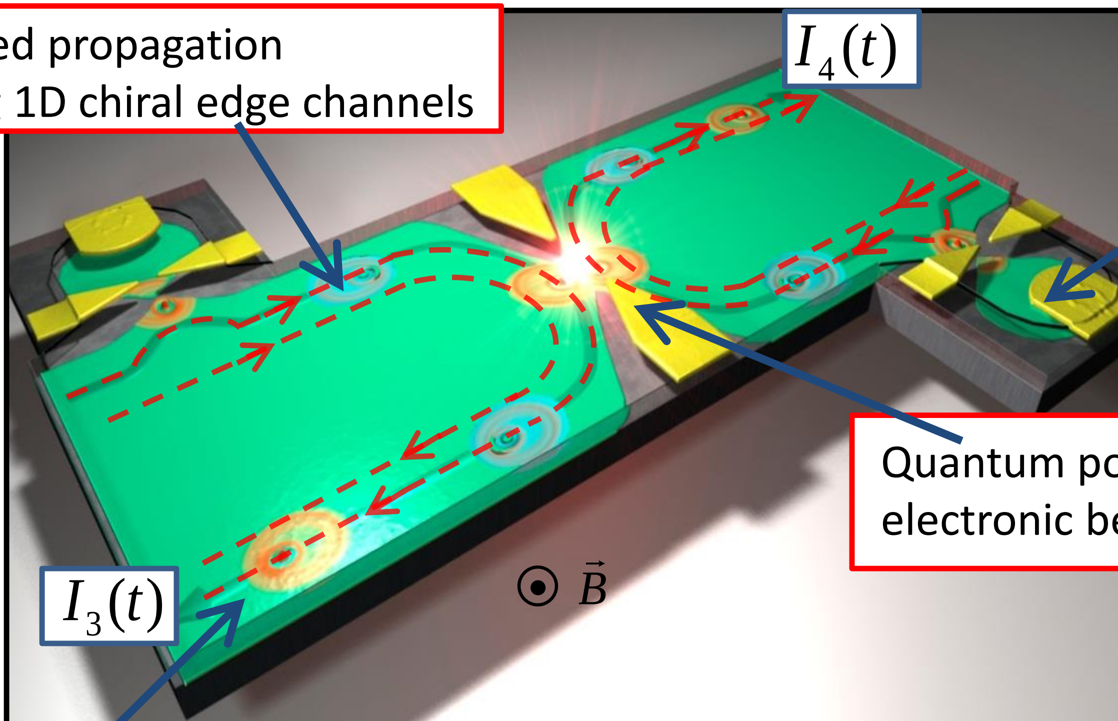
Theory, CPT Marseille

T. Martin, T. Jonckheere, J. Rech, C. Wahl

Electron optics in chiral edge channels

Guided propagation along 1D chiral edge channels



Single electron emitter

T~ 30 mK

Quantum point contact used as electronic beam-splitter

Measurement of current and output current correlations

$$\langle I_3(t) \rangle$$

$$S_{34}(t,t') = \langle \delta I_3(t) \delta I_4(t') \rangle$$

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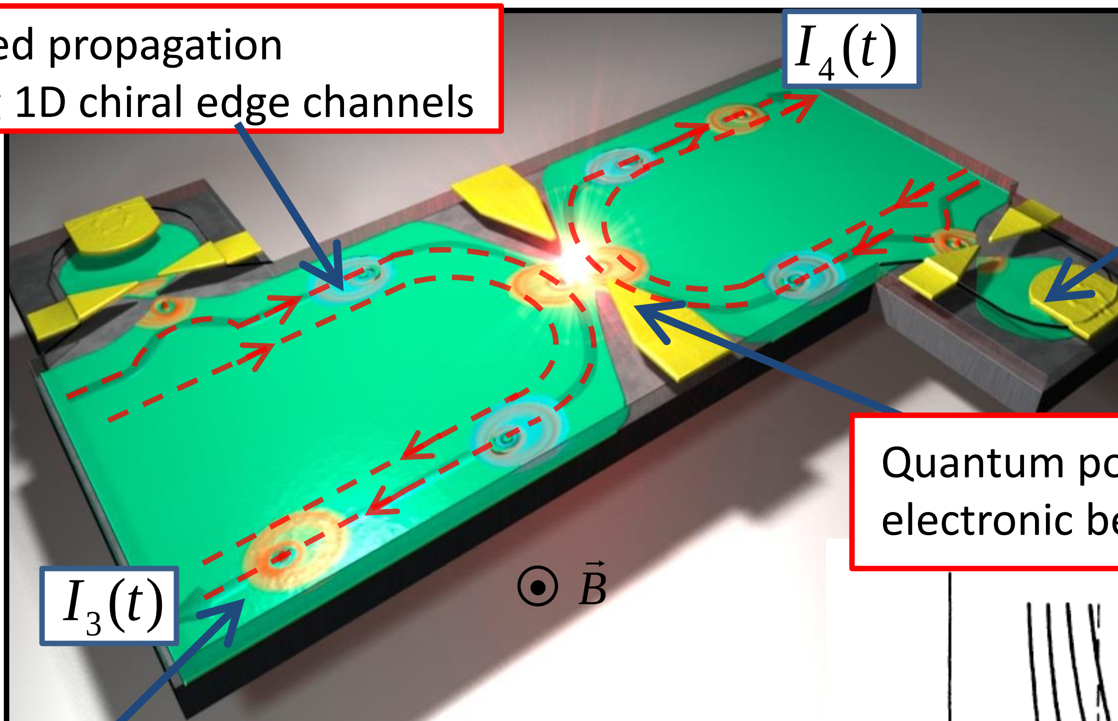

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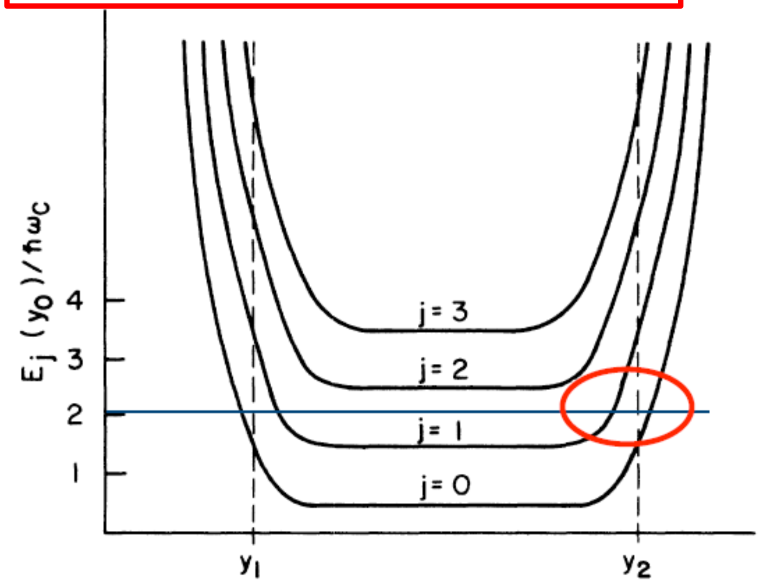

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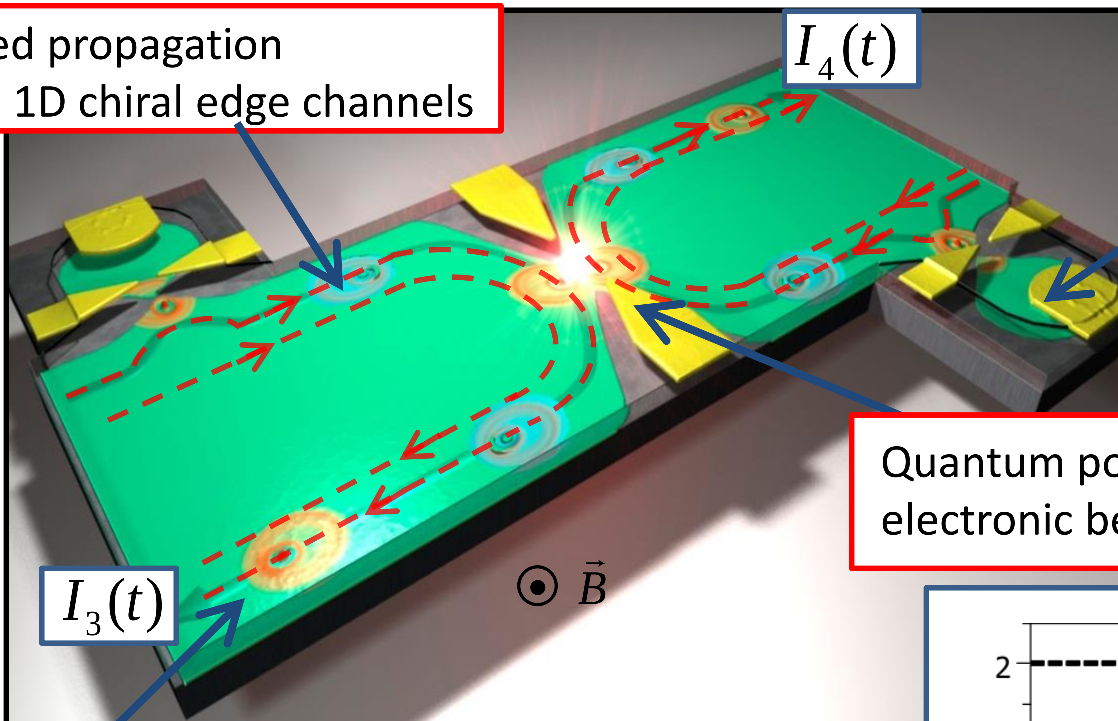

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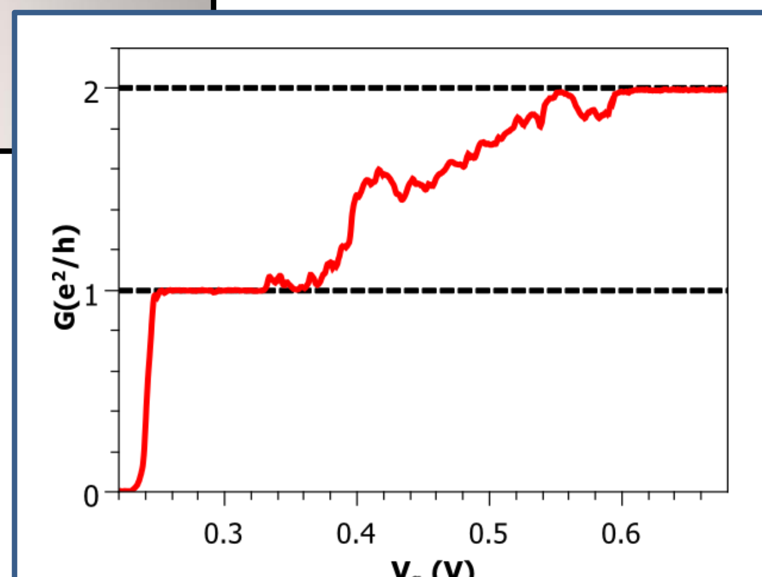

Measurement of current and output current correlations

$$\langle I_3(t) \rangle$$

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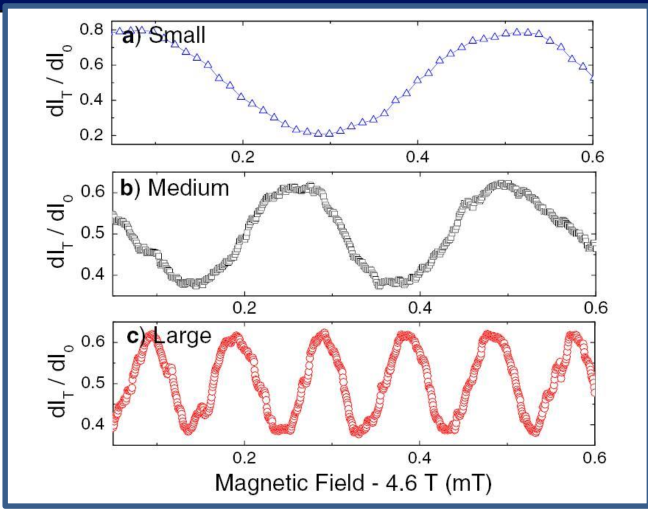
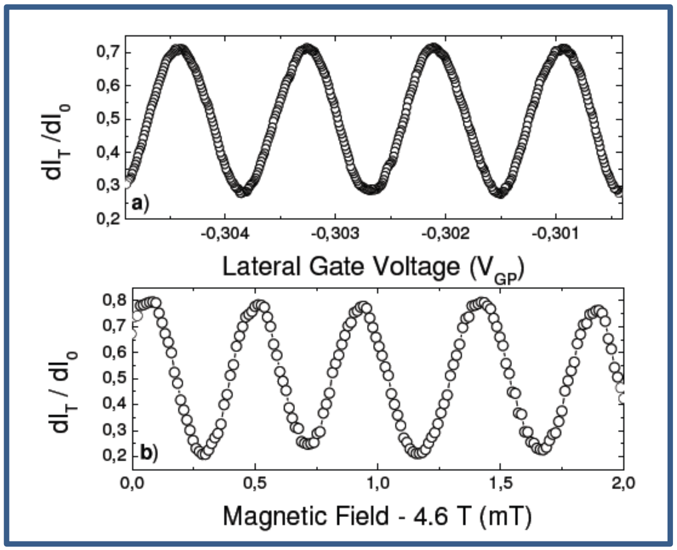
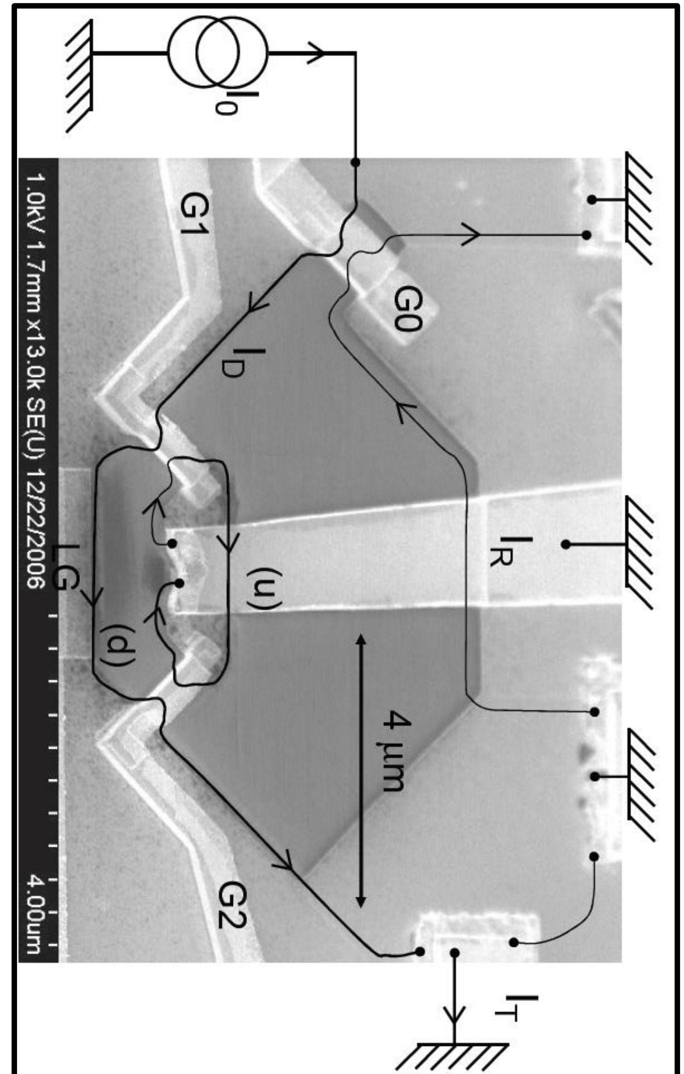
Electron optics: the Mach-Zehnder interferometer







P. Roulleau et al. Phys. Rev. Lett. **100,** 126802 (2008)

Electron optics in chiral edge channels

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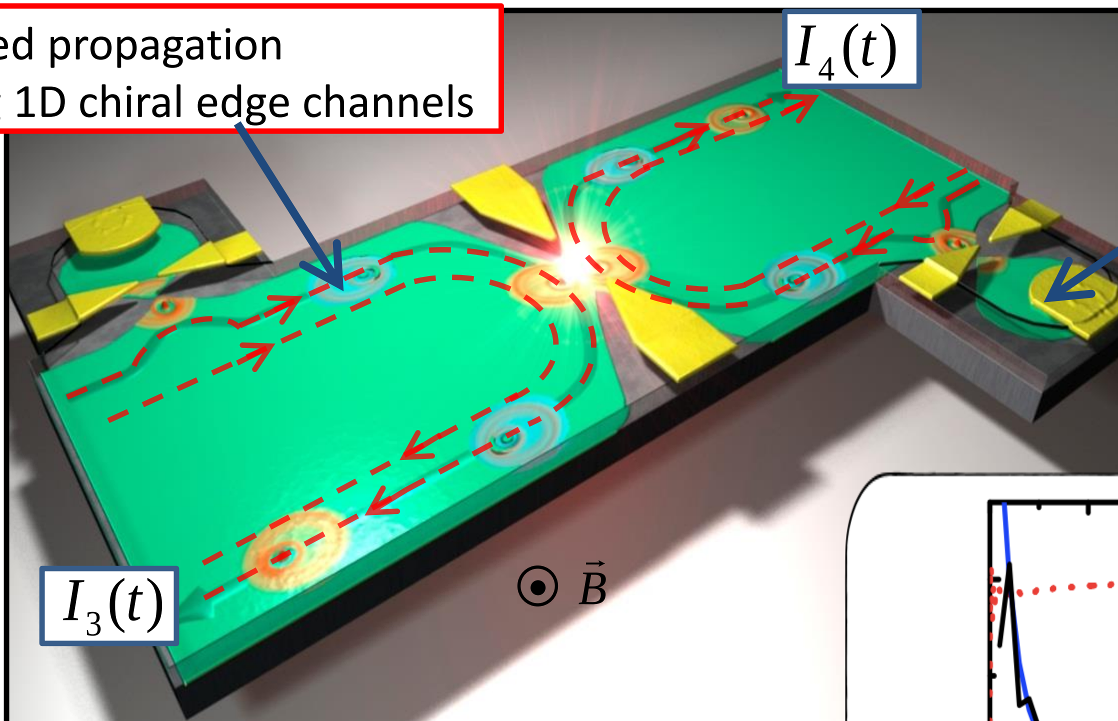

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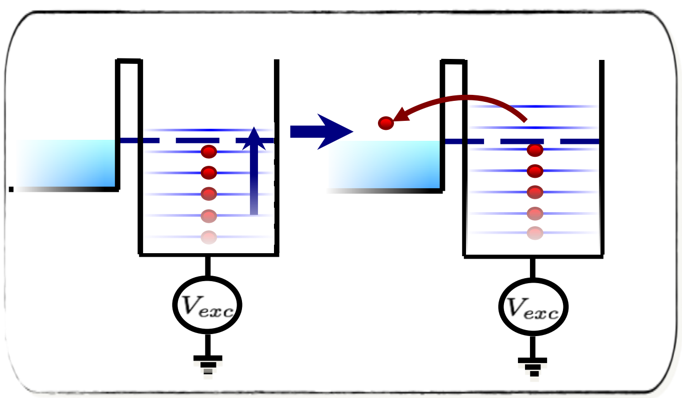
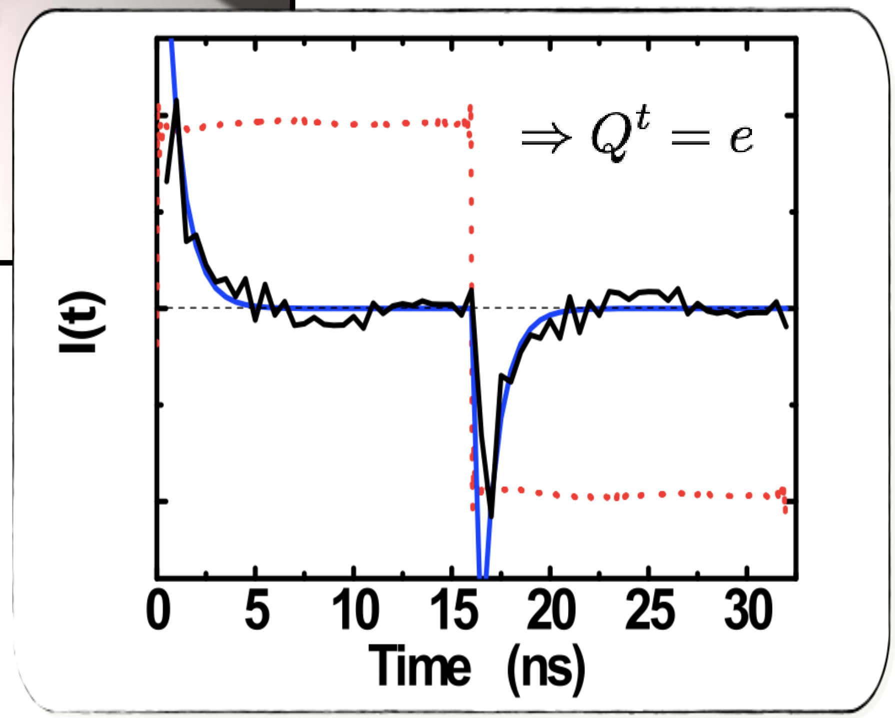
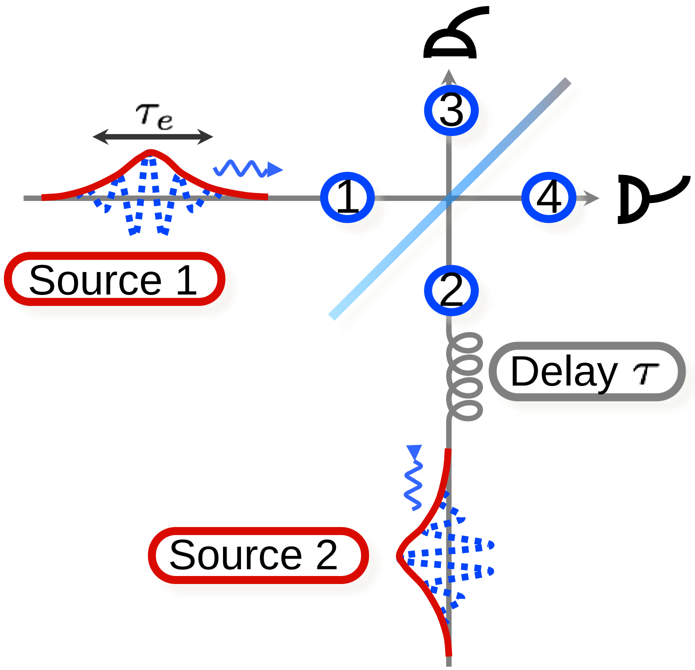
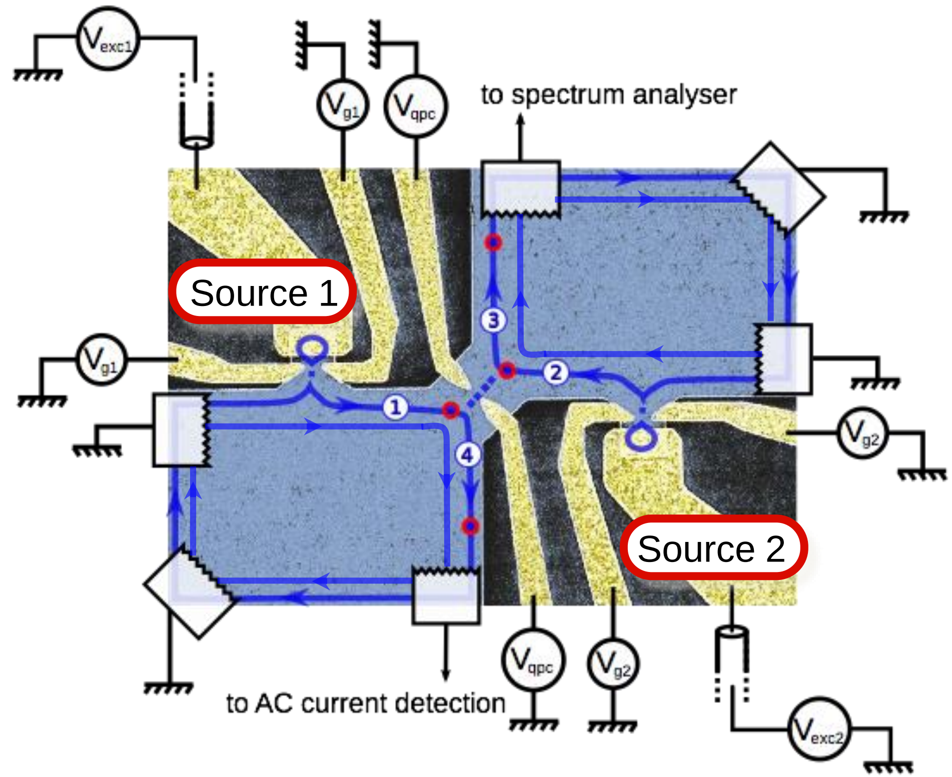
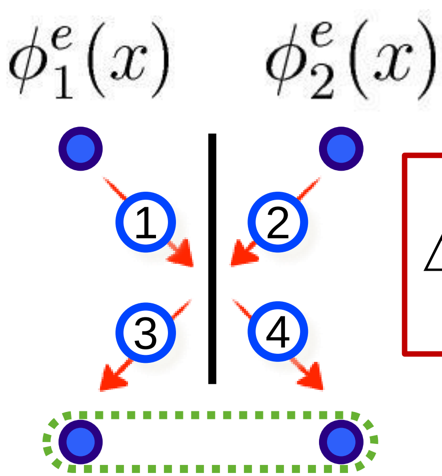




Interferences with single electrons: electronic HOM







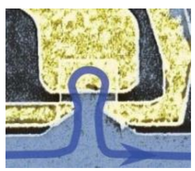
$$\Delta q = \frac{S_{HOM}}{S_{part}} = 1 - \left| \int dt\, \varphi_1(t+\tau)\varphi_2^*(t) \right|^2 = 1 - e^{-|\tau|/\tau_e}$$

S. Ol'khovskaya et al., PRL 101, 166802 (2008)

The electronic HOM dip

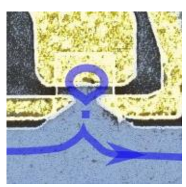
$$\Delta q = \frac{S_{HOM}}{S_{HBT}} = 1 - \gamma e^{-|\tau|/\tau_e}$$

- D=1: $\tau_e \to 0$

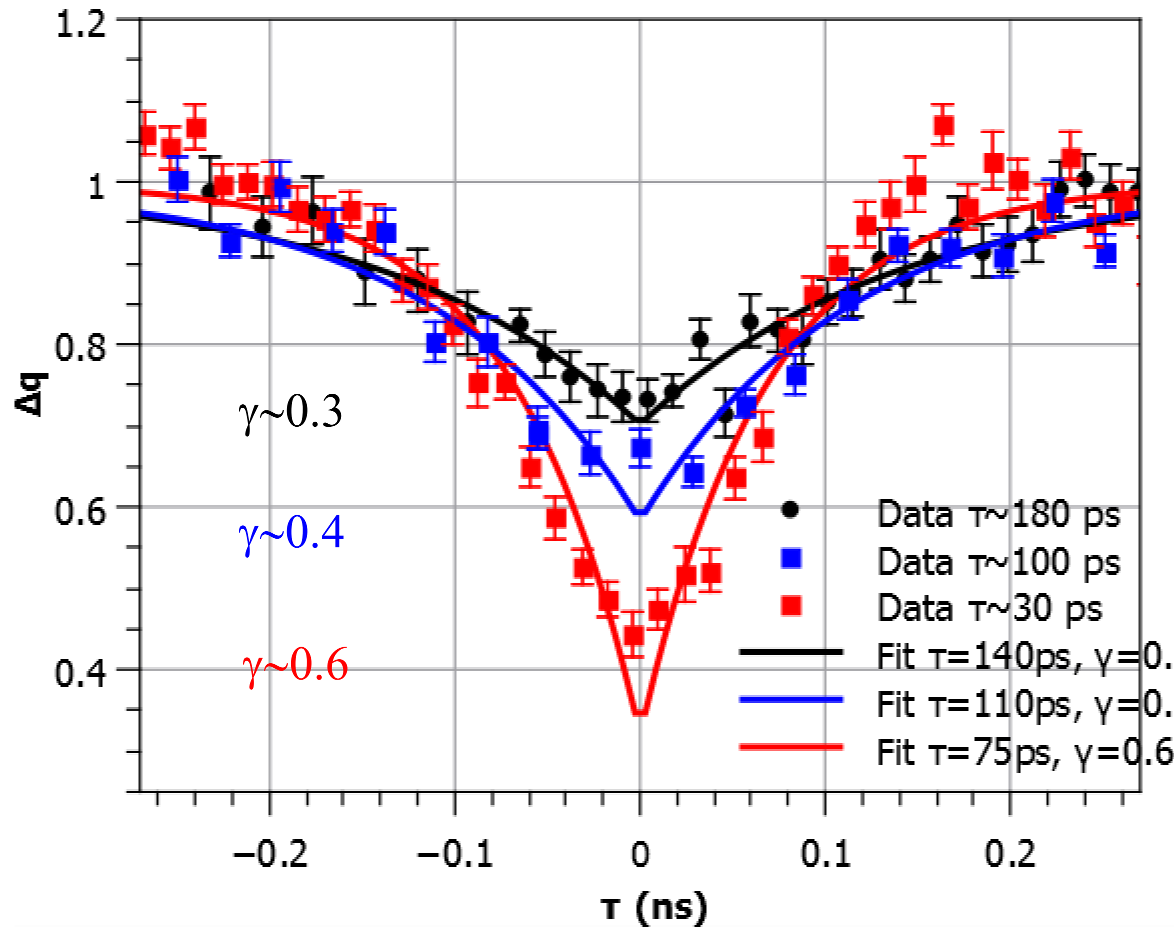


$\gamma \to 1$

- D<<1 : $\tau_e \nearrow$



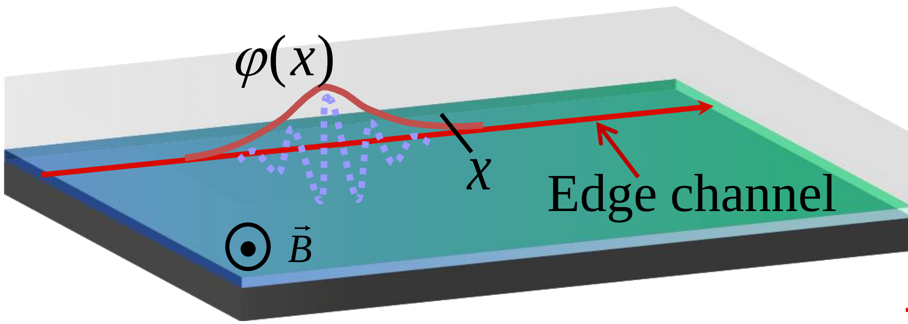
$\gamma \to 0$



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

A. Marguerite et al., PRB **94**, 115311 (2016).

Electron quantum optics: first order coherence of Fermion field



- analogies $\Psi^+(t) \leftrightarrow E^-(t)$

- electrical current/ light intensity

$$I(t) = e\Psi^+(t)\Psi(t) \leftrightarrow I_{ph}(t) \propto E^-(t)E^+(t)$$

- first order coherence

$$G^{(1)}(t,t') = \langle \Psi^+(t)\Psi(t') \rangle$$

G. Haack et al., Phys. Rev. B **84**, 081303 (2011).

C. Grenier et al., New J. Phys. **13**, 093007 (2011)

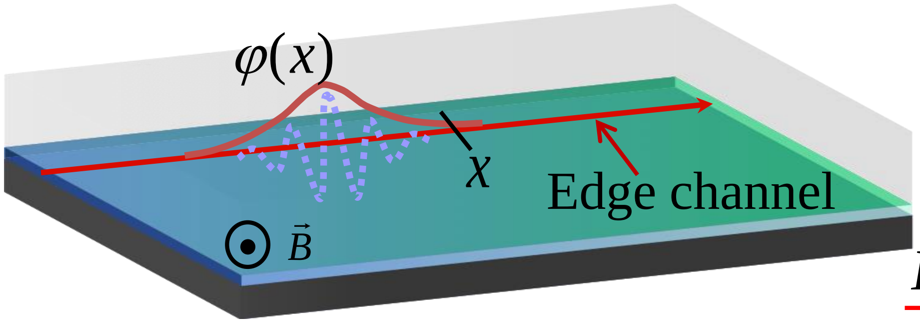
- single electron state

$$\Psi^+[\varphi] | F \rangle = \int dx\, \varphi(x)\, \Psi^+(x) | F \rangle$$

$$G^{(1)}(t,t') = G_F^{(1)}(t,t') + \varphi(t)\varphi^*(t')$$

$\Delta G^{(1)}$

Electron quantum optics: first order coherence of Fermion field



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$\Delta G^{(1)}$

•Hong-Ou-Mandel interferometer:

$$\langle \Delta N^2 \rangle = \langle \Delta N_{class}^2 \rangle - 4e^2 f\, D(1-D) \int dt dt' \Delta G_1^{(1)}(t,t')\, \Delta G_2^{(1)}(t',t)$$

Classical random partitioning

-sign for fermions

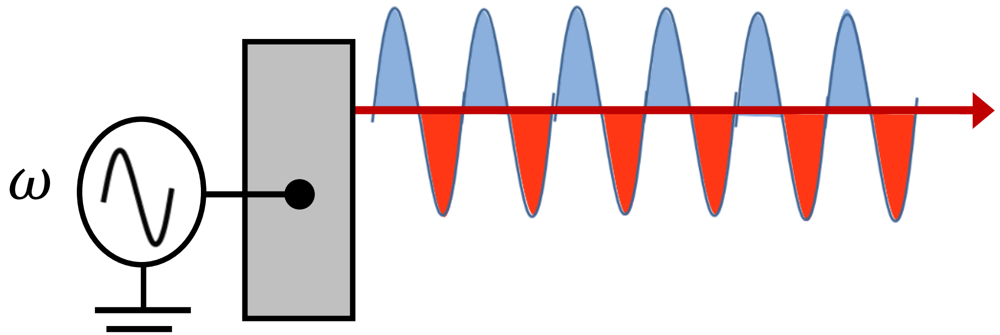
Generalized overlap between sources

Bosonic representation

a.c. regime

charge density waves,
edge magnetoplasmons

$$\rho_{\omega,i}(x,t) = \rho_{0,i} e^{i\omega(\frac{x}{v} - t)}$$



Bosonic field $\phi(x,t)$ related to charge density: $:\Psi^{+}(x,t)\Psi(x,t) := \rho(x,t) = \frac{1}{\sqrt{2\pi}}\partial_x \phi$

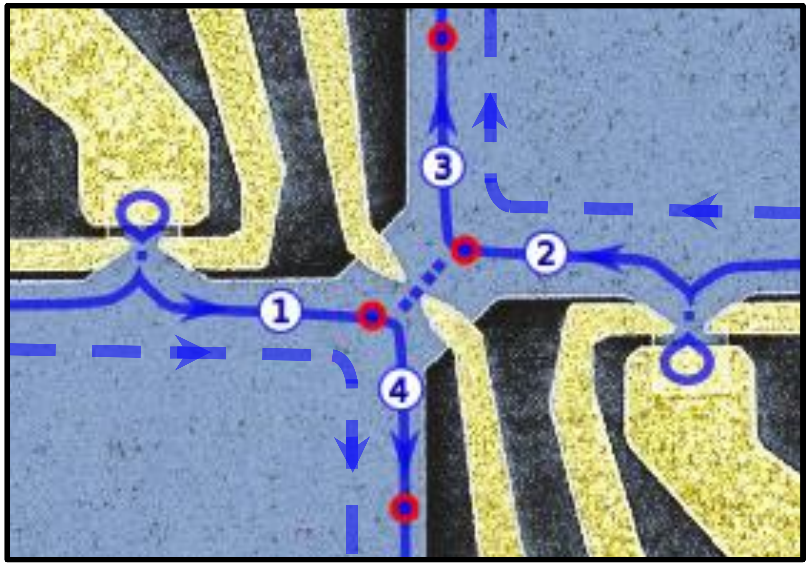
Without interactions, the propagation speed is the fermi velocity (drift velocity)

$$\phi_{\omega,i}(x,t) = A_i e^{i\omega(\frac{x}{v_D} - t)}$$

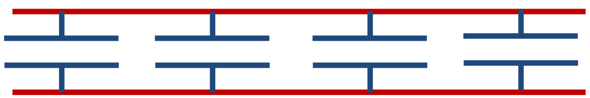
Interactions: the ν=2 case

Coulomb interaction

$$H_{\text{int}} = \frac{e^2}{2}\sum_{i,j}\int dx dy \rho_i(x) V_{ij}(x,y)\rho_j(y)$$



Short range interaction: $V_{ij}(x,y) = (C^{-1})_{ij}\,\delta(x-y)$



$$H_{\text{intra}} = e^2 \sum_i \frac{C_{ii}^{-1}}{2}\int dx\, \rho_i(x)\rho_i(x)$$

$$H_{\text{inter}} = e^2 \sum_{i\neq j} \frac{C_{ij}^{-1}}{2}\int dx\, \rho_i(x)\rho_j(x)$$

Interactions: the ν=2 case

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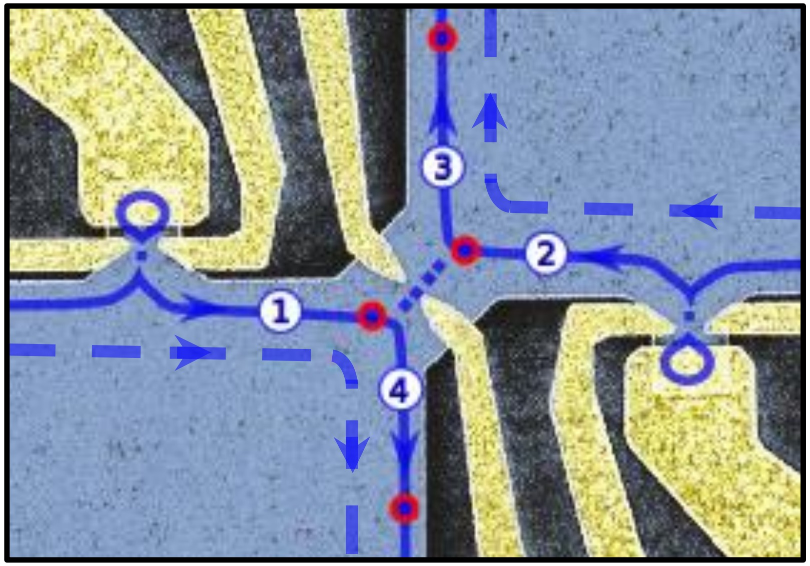

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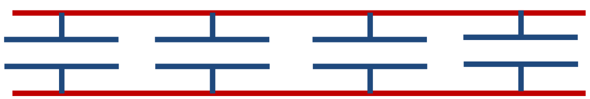


Bosonic representation: chiral Lüttinger liquid

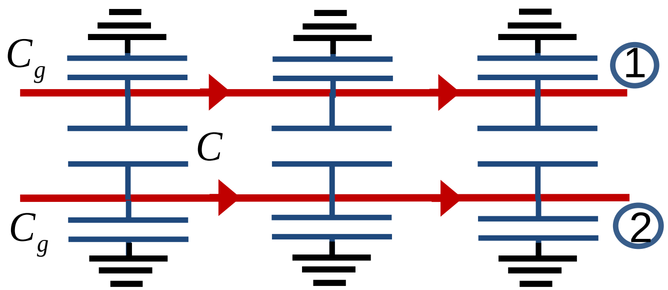
$$H_0 = \hbar v_D \sum_i \int dx\, \left(\partial_x \phi_i(x)\right)^2 \qquad H_{\text{int}} = \frac{e^2}{2\pi}\sum_{i,j}(C^{-1})_{ij}\int dx\ \partial_x\phi_i \partial_x\phi_j$$

Spin-charge separation at filling factor ν=2

$$H = \hbar \sum_{i,j} \int dx\, \partial_x \phi_i \, v_{ij} \, \partial_x \phi_j$$

Velocity matrix renormalized by interactions

$$v_{ij} = v_D \delta_{ij} + (C^{-1})_{ij}$$

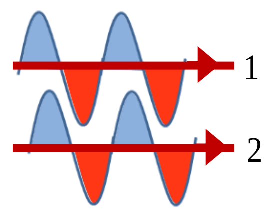


$$[C] = \begin{bmatrix} C_g + C & -C \\ -C & C_g + C \end{bmatrix}$$

Symmetric charge mode

$$\varphi_{\rho,\omega}(l,t) = e^{i\omega l / v_\rho} \varphi_{\rho,\omega}(0,t)$$

$$\varphi_{\rho,\omega} = \begin{bmatrix} 1 \\ 1 \end{bmatrix}$$



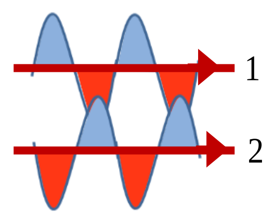
fast $\quad v_\rho = v_D + \dfrac{e^2}{hC_g}$

$(C >> C_g)$

Antisymmetric neutral mode

$$\varphi_{n,\omega}(l,t) = e^{i\omega l / v_n} \varphi_{n,\omega}(0,t)$$

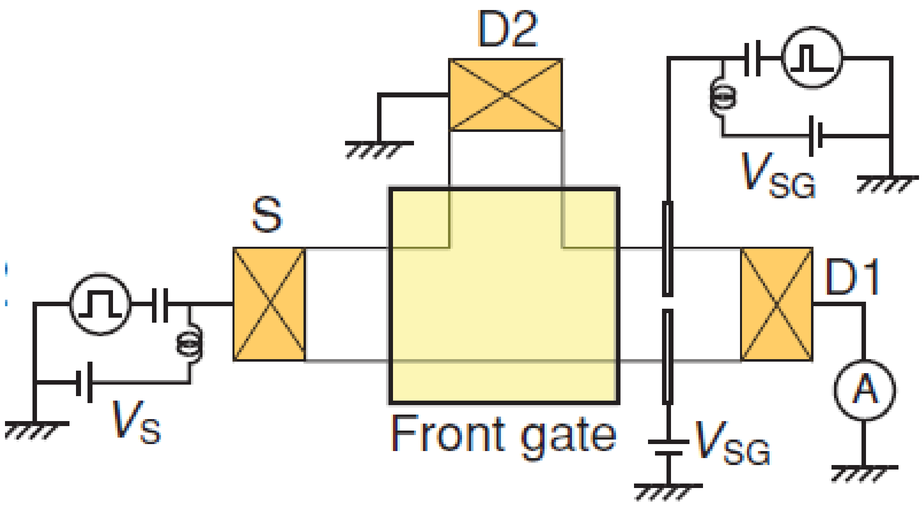
$$\varphi_{n,\omega} = \begin{bmatrix} 1 \\ -1 \end{bmatrix}$$

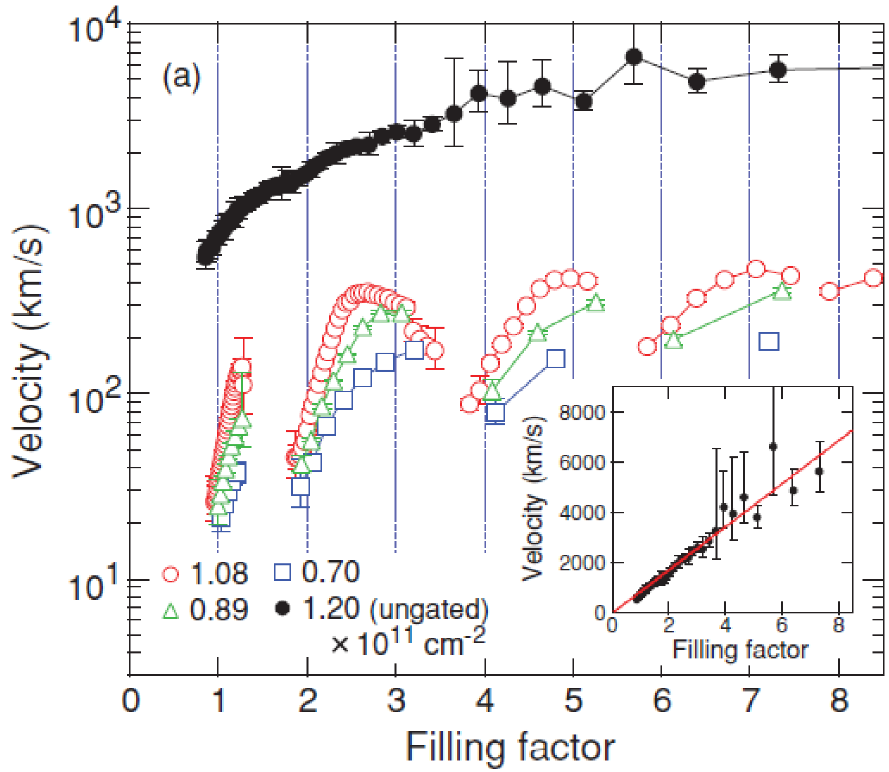


v_n

slow $\quad v_n = v_D + \dfrac{e^2}{2hC}$

Charge mode propagation

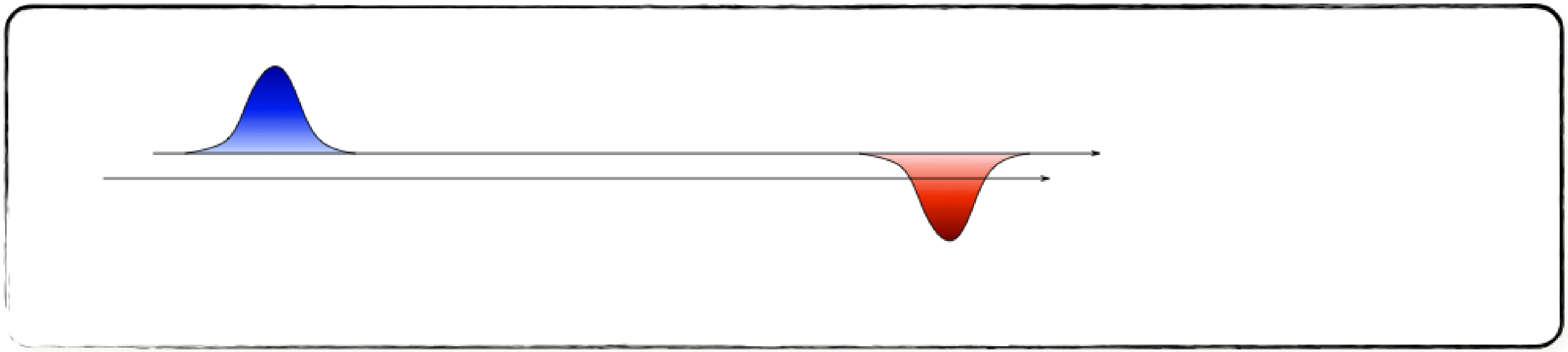




$$v_\rho = v_D + \frac{e^2}{hC_g}$$

N. Kumada et al., Phys. Rev. B **84**, 045314 (2011)

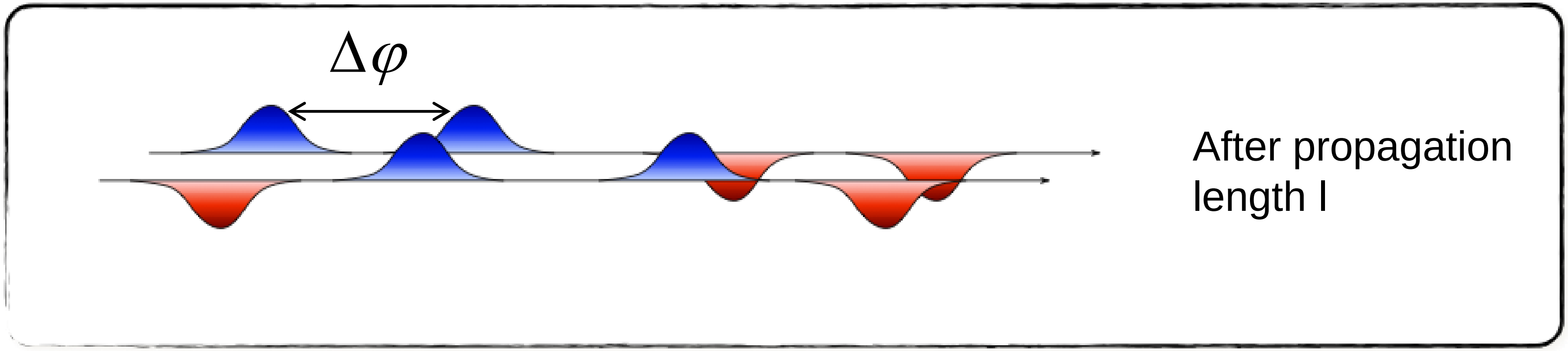
Interchannel coupling in the frequency domain



In the "frequency domain": charge oscillations

- Sine wave induced in outer edge channel

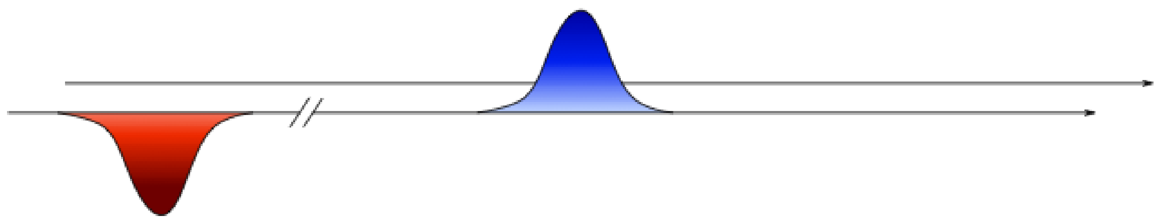
Interchannel coupling in the frequency domain



In the "frequency domain": charge oscillations

- Sine wave induced in outer edge channel
- Phase shift between both modes: $\Delta\varphi = \omega l(\frac{1}{v_n} - \frac{1}{v_\rho}) \simeq \frac{\omega l}{v_n}$

Interchannel coupling in the frequency domain



$$\Delta\varphi \approx \frac{\omega l}{v_n} = \pi$$

$$l = \lambda_n / 2$$

$$\omega \sim 1 - 10\,\mathrm{GHz}$$

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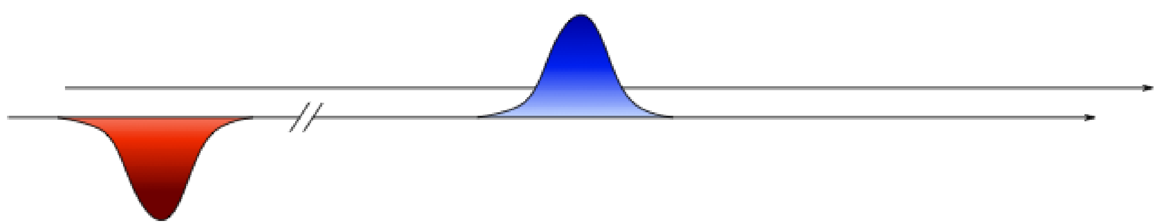


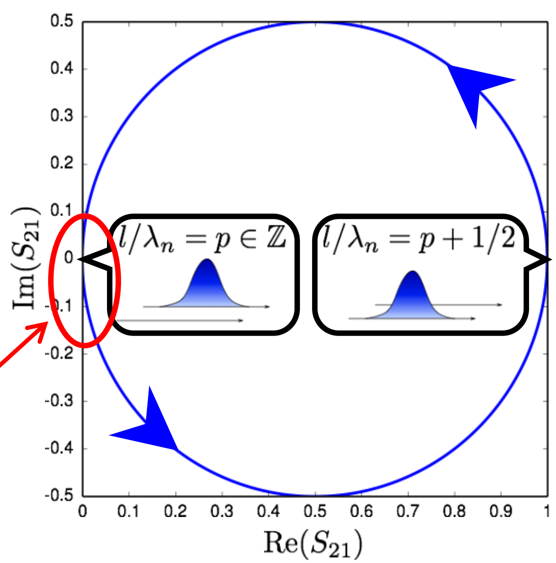
$$\Delta\varphi \approx \frac{\omega l}{v_n} = \pi$$

$$l = \lambda_n / 2$$

$$\omega \sim 1 - 10\,\mathrm{GHz}$$

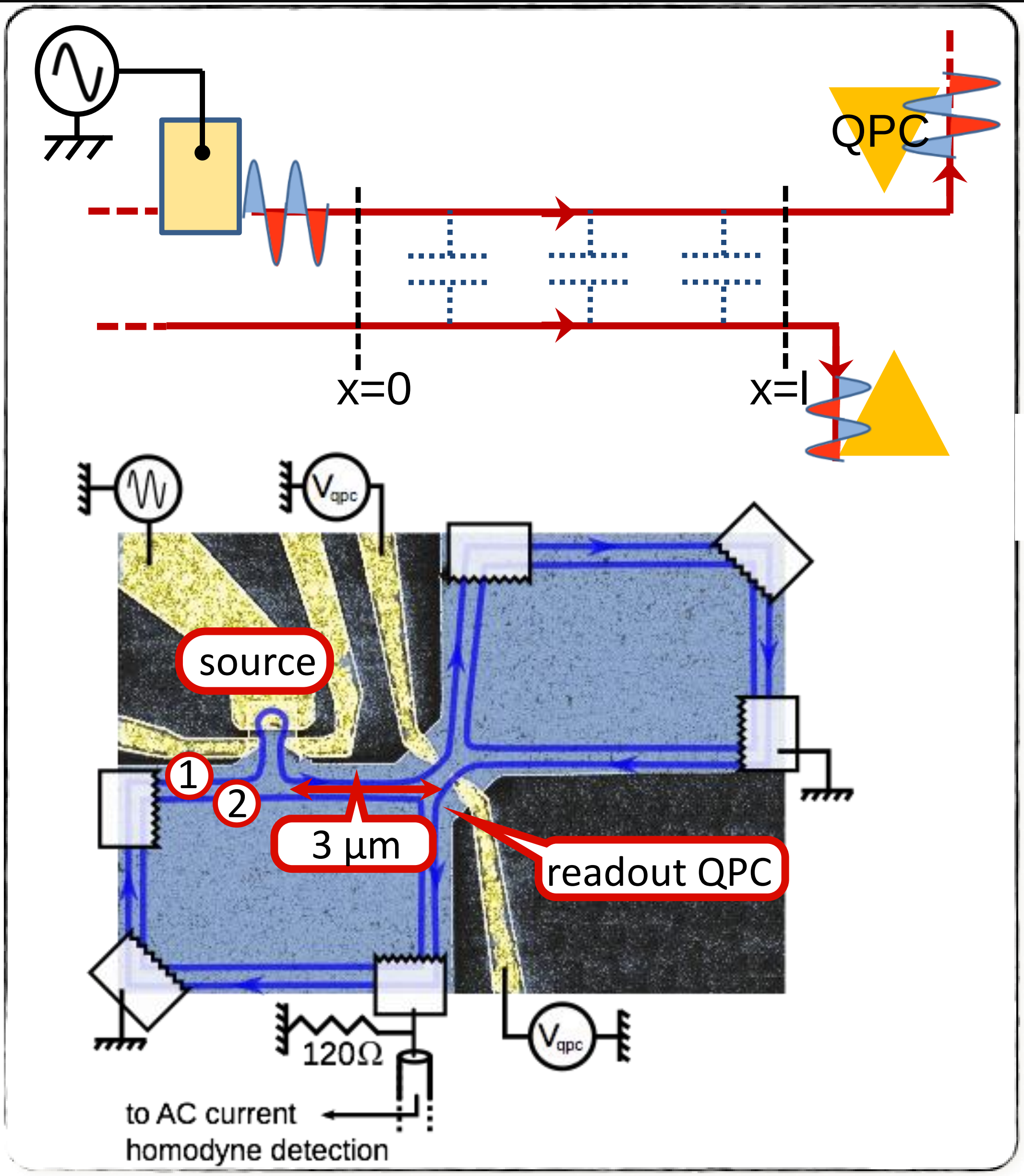
$$S_{21} = \frac{1 - e^{i\omega l / v_n}}{2} \qquad k_n(\omega) = \frac{\omega}{v_n(\omega)}$$

$$(v_n << v_\rho)$$

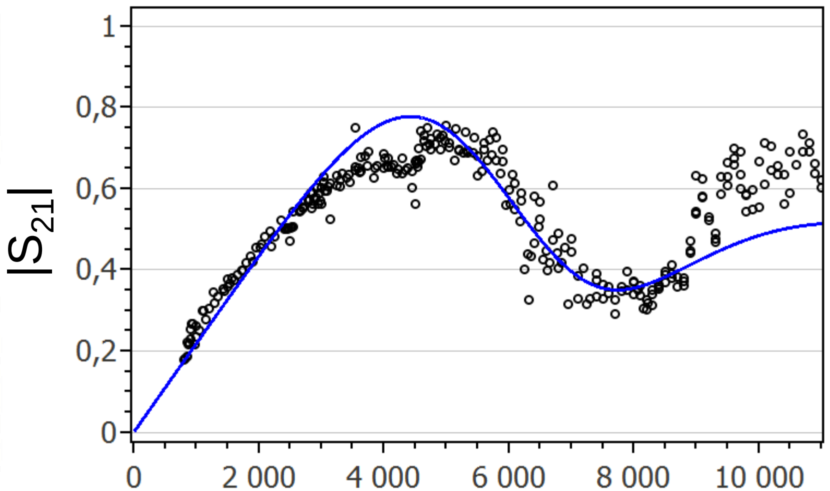


$$S_{21} \simeq -i\omega \frac{l}{2v_n}$$

Charge/neutral mode separation



E. Bocquillon et al., Nature Comm. **4**, 1839 (2013)



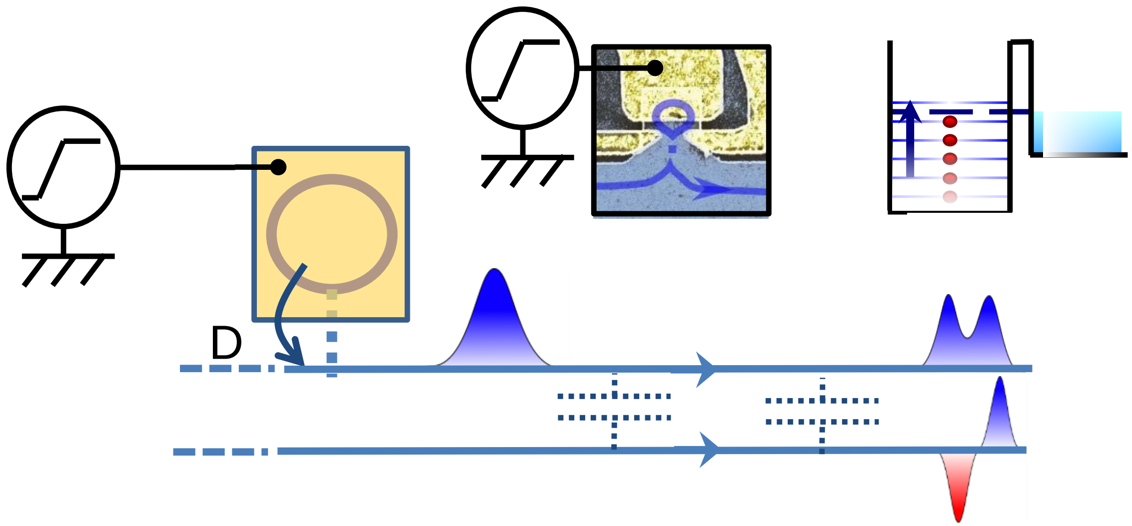
$$v_n^0 \simeq 4.6\ 10^4\,\mathrm{m.s}^{-1}$$

$$\tau_s = l / v_n = 70\,ps$$

Electron fractionalization and decoherence/relaxation

Time domain : electron fractionalization

E. Berg et al., Phys. Rev. Lett. 102, 236402 (2009)



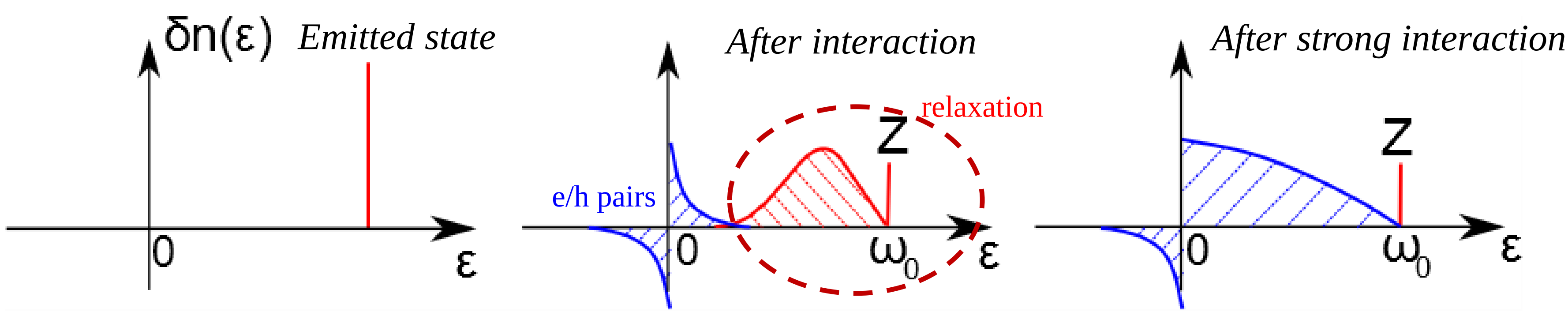
$$\Psi(x,t) \propto e^{i\sqrt{4\pi}\phi(x,t)}$$

$$|\Psi\rangle = \int dx\,\varphi_e(x)\hat{\psi}^+(x)|F\rangle$$

$$|\Psi\rangle = \int dx\,\varphi_e(x) \otimes_\omega |\lambda_\omega(x)\rangle$$

Energy domain: electron relaxation

P. Degiovanni et al., Phys. Rev. B 80, 241307R (2009)

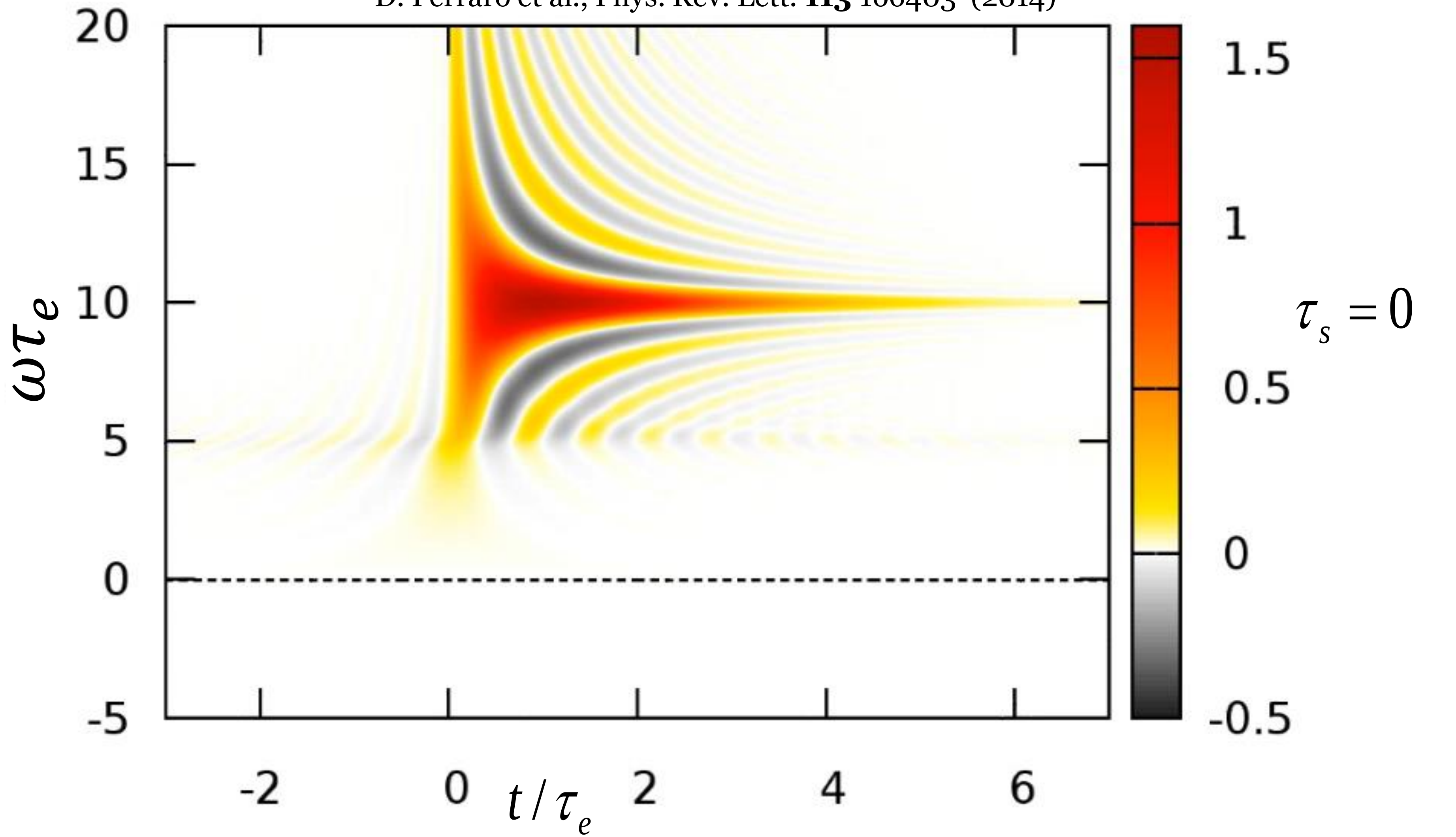


Decoherence in Wigner representation

$$\Delta W(t,\omega) = \int d\tau \Delta G^{(1)}(t+\frac{\tau}{2}, t-\frac{\tau}{2}) e^{i\omega\tau}$$

$$\varphi(t) = \theta(t) e^{i\omega_e t} e^{-t/2\tau_e}$$

D. Ferraro et al., Phys. Rev. Lett. **113** 166403 (2014)



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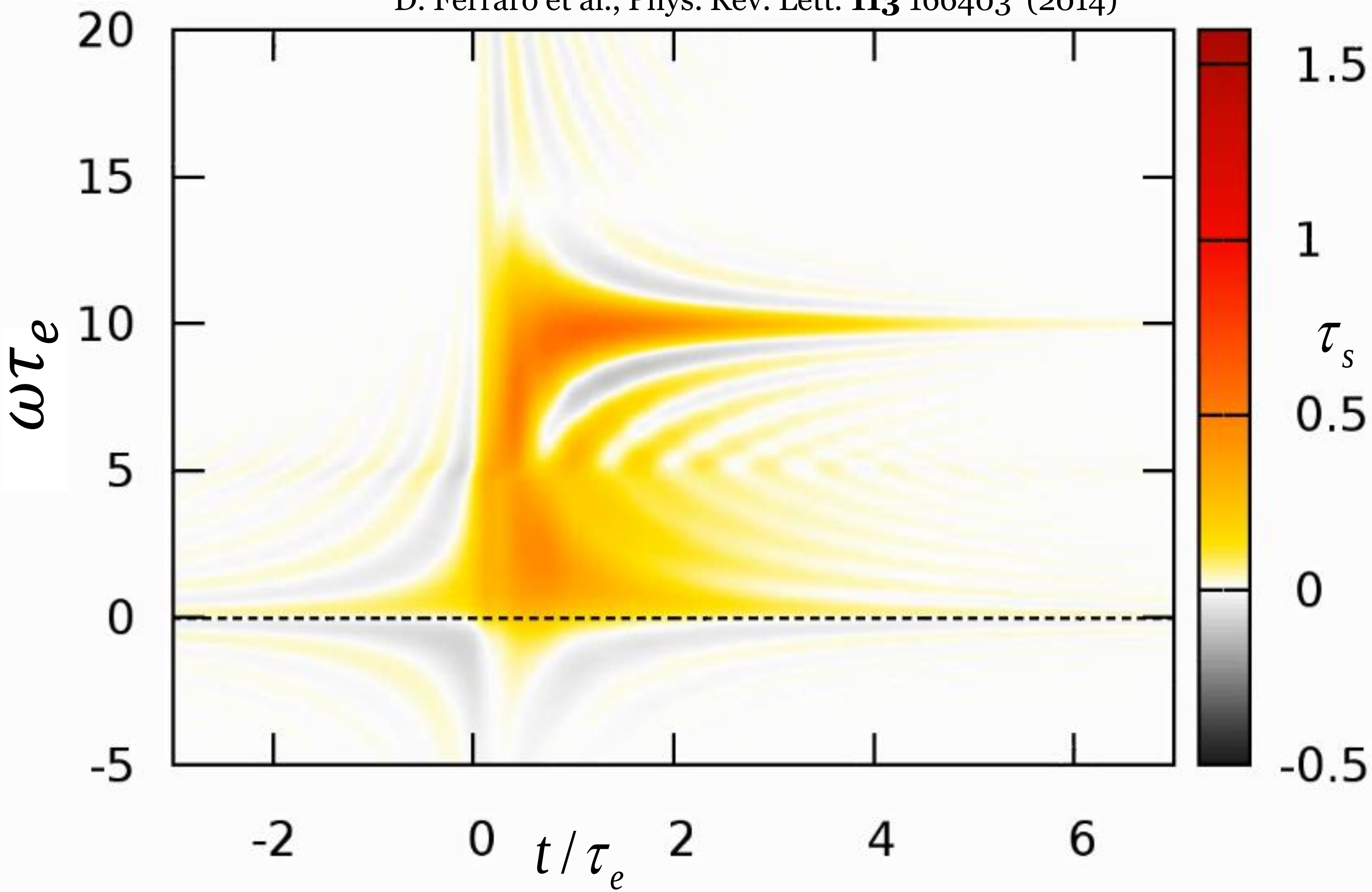

$\tau_s \approx 0.3\tau_e$

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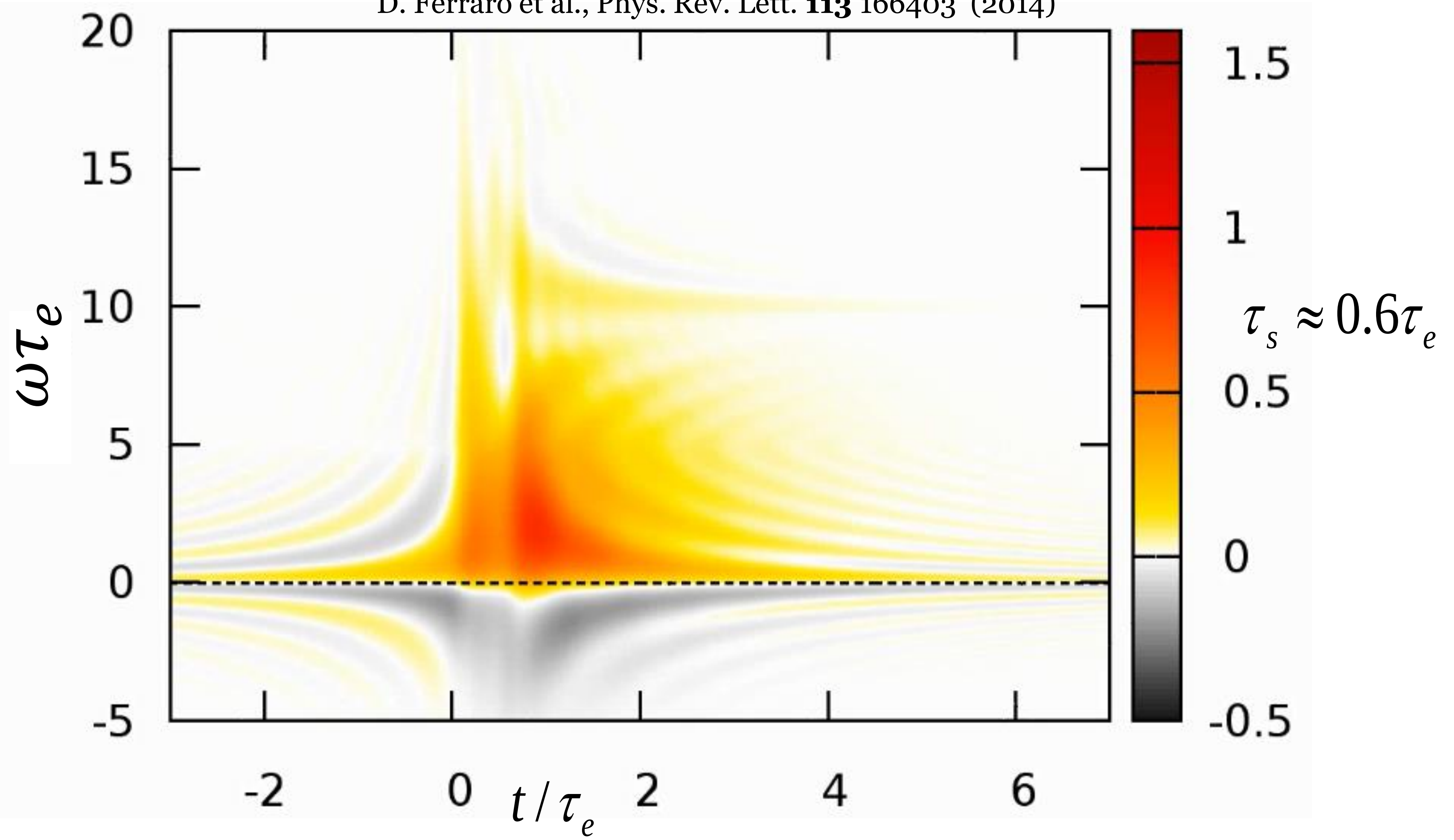

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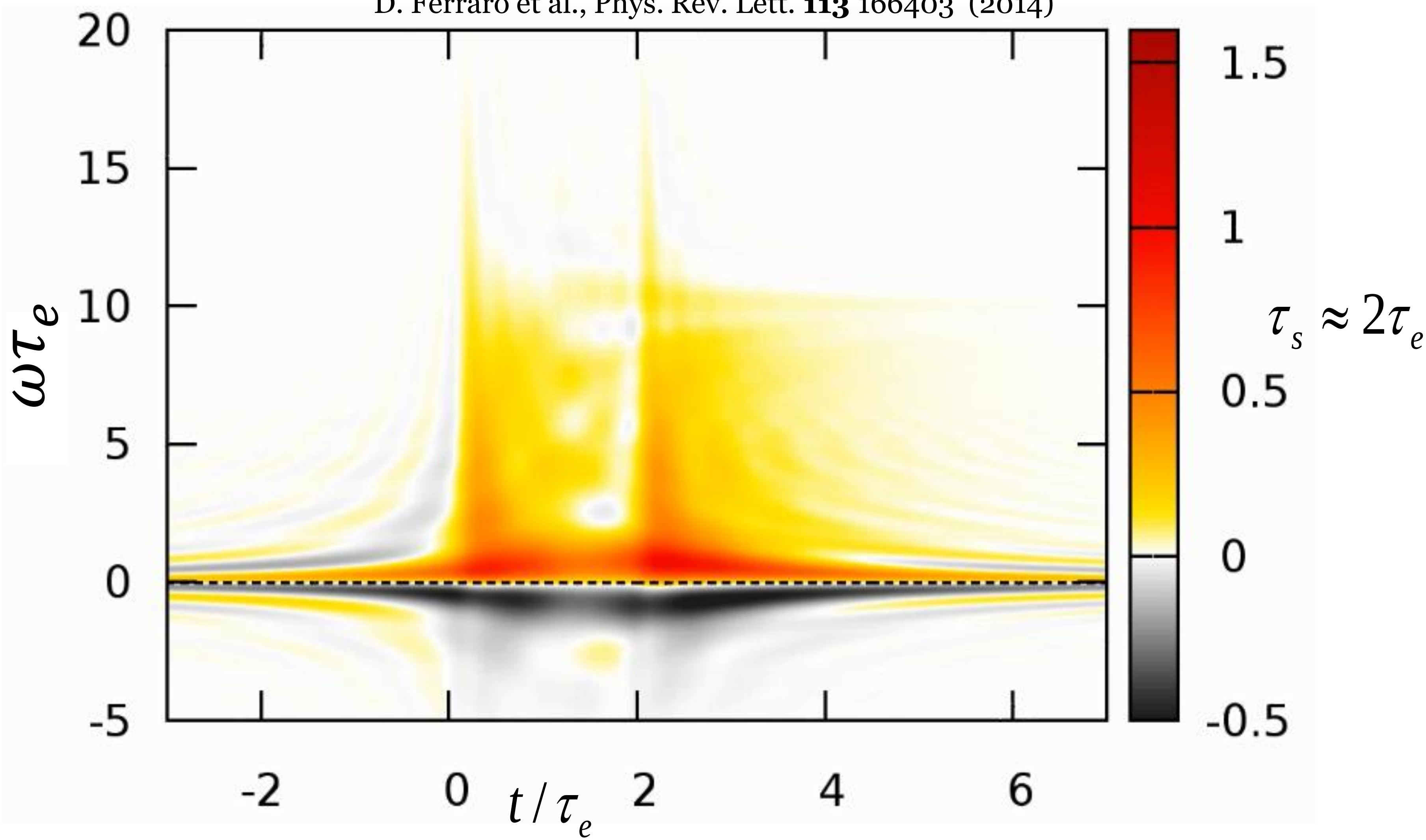

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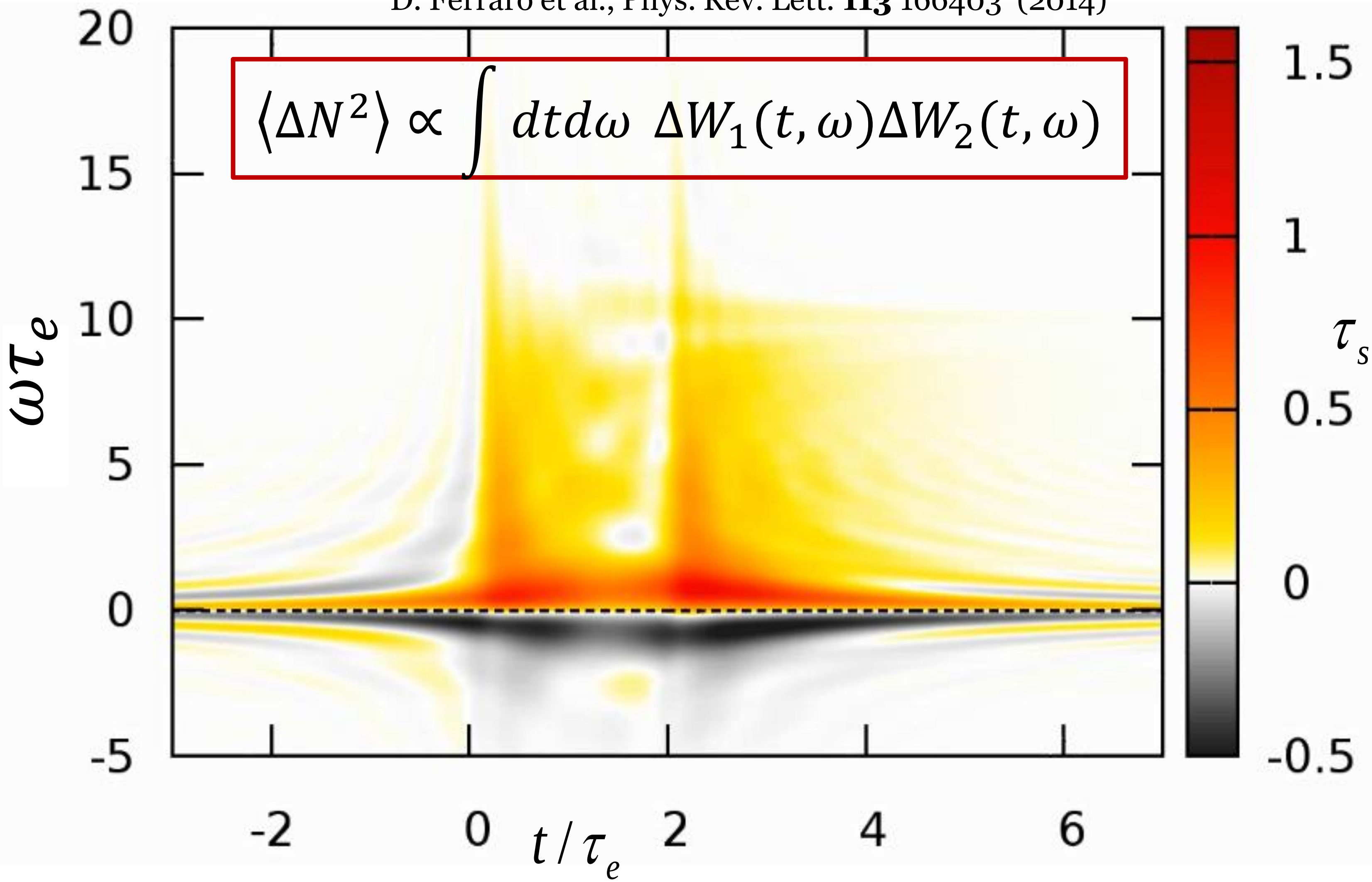


$$\langle \Delta N^2 \rangle \propto \int dt d\omega \; \Delta W_1(t,\omega) \Delta W_2(t,\omega)$$

$\tau_s \approx 2\tau_e$

Charge fractionalization and decoherence

Data / model comparison:

$$\tau_s = 70\,ps$$

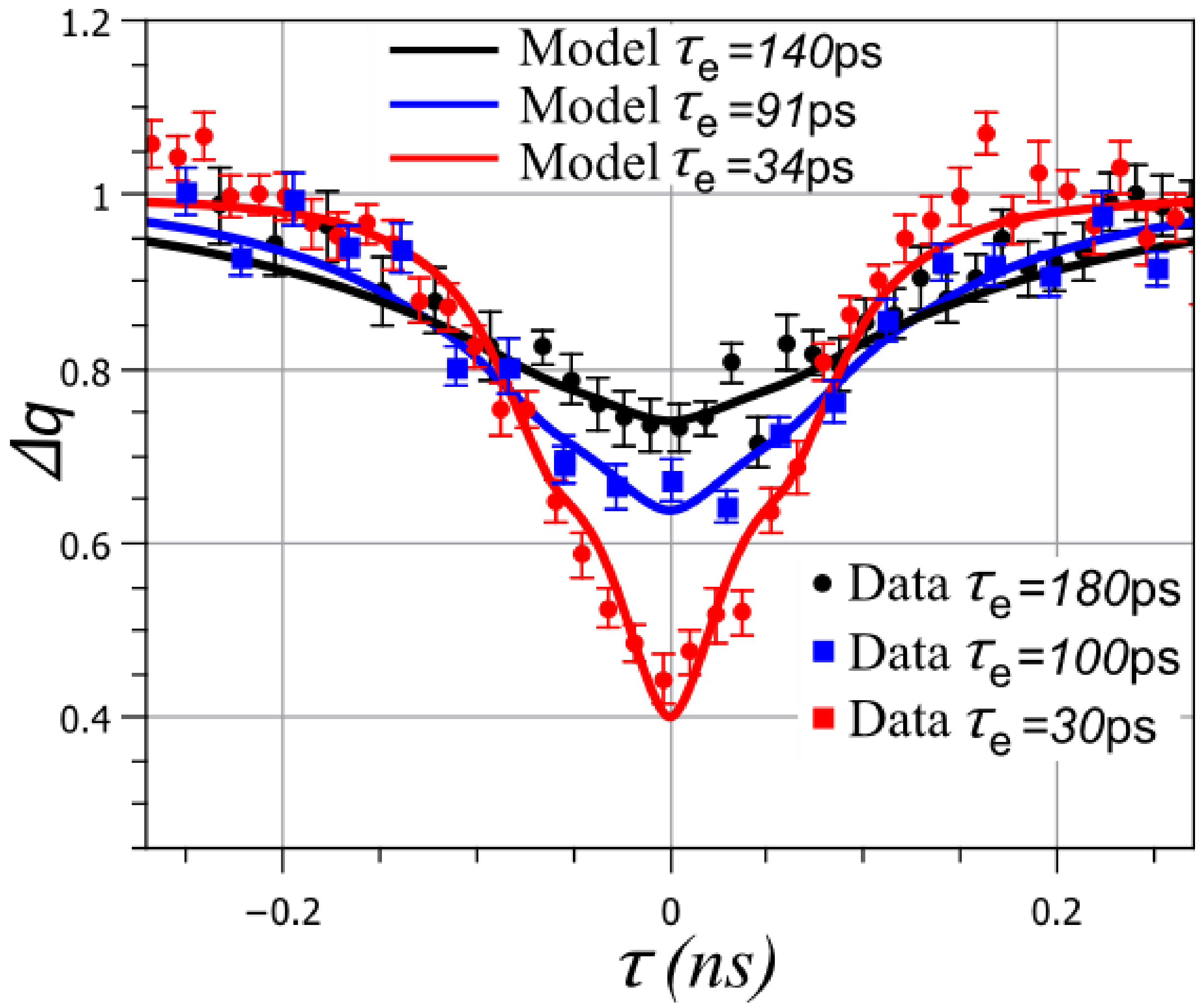
$$\varphi_1 = \varphi_2 = \theta(t)e^{i\omega_e t}e^{-t/2\tau_e}$$

$$T = 0K$$

Short range interaction

C. Wahl et al., Phys. Rev. Lett. **112**, 046802 (2014)

D. Ferraro et al., Phys. Rev. Lett. **113** 166403 (2014)



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Conclusion

- control of electronic coherence/decoherence
  → see presentation of Benjamin Roussel

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- Charge fractionalization in counter-propagating edge channels (non-chiral Lüttinger liquid)

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- Visualization of single electron/hole states using HOM interferometry
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