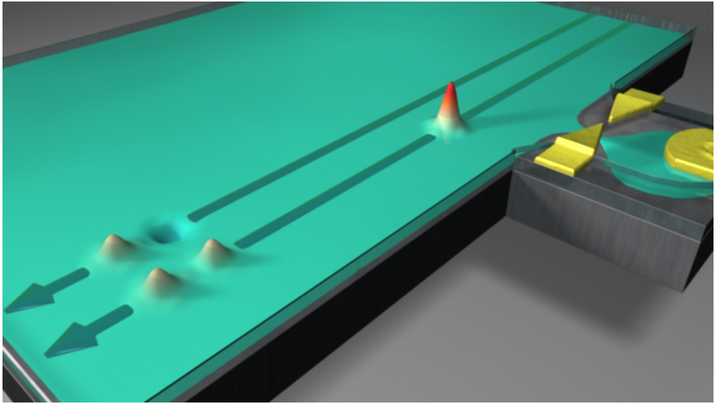
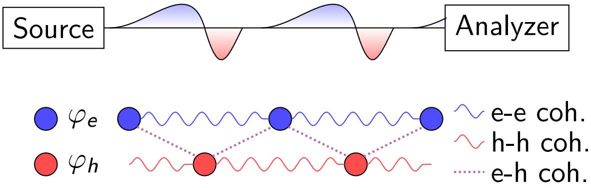
# Electron quantum optics



**Reviews:**
E. Bocquillon *et al*, Ann. Phys.-Berlin **526**, 1 (2014)
A. Marguerite *et al*, Phys. Status Solidi B **254**, 1600618 (2017)

# Wavefunctions in a quantum current

## How to find electronic wavefunctions contained in a quantum current?

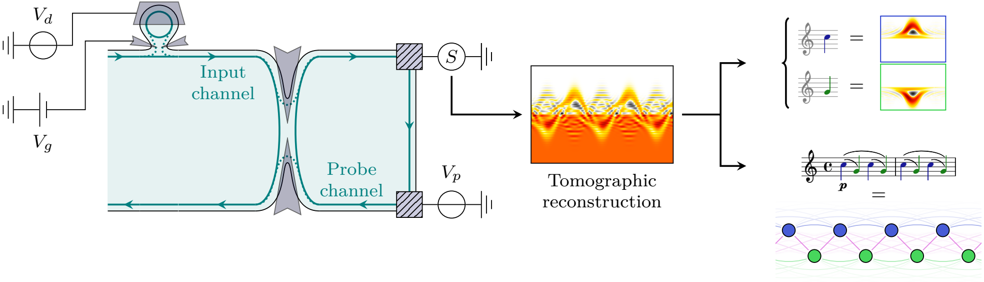


R. Bisognin *et al*, Nature Comm **10**, 3379 (2019)
B. Roussel *et al*, PRX Quantum **2**, 020314 (2021)

# Wavefunctions in a quantum current

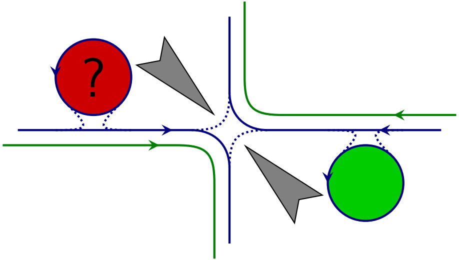
## How to find electronic wavefunctions contained in a quantum current?

### Quantum electric current analyzer



R. Bisognin *et al*, Nature Comm **10**, 3379 (2019)
B. Roussel *et al*, PRX Quantum **2**, 020314 (2021)

# Basic idea for tomography

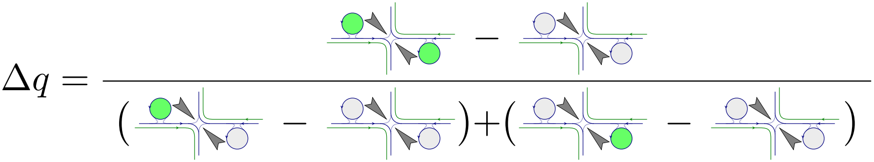


$$\Delta q = 1 - \alpha \int \frac{\mathrm{d}\omega}{2\pi} \overline{\Delta W_S^{(e)}(t,\omega) \Delta W_P^{(e)}(t,\omega)}^{t}$$

# Link with experiments

We define

$$\Delta q = \frac{\Delta S_{33}}{\Delta S_{\mathrm{HBT}}}$$



And we have:

$$\Delta q = 1 - \alpha \int \overline{\Delta\mathcal{W}_1^{(e)}(t,\omega)\Delta\mathcal{W}_2^{(e)}(t,\omega)}^{t} \frac{\mathrm{d}\omega}{2\pi}$$

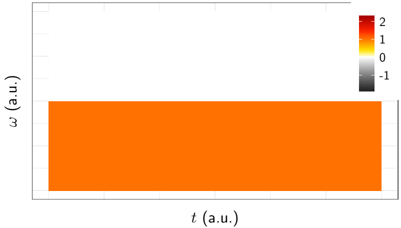
D. Ferraro *et al*, Phys. Rev. B **88**, 205303 (2013)

# Theoretical proposal

We use an AC+DC voltage drive at specific frequencies, and vary the DC part.

$$V_P(t) = V_{\rm dc}$$

Coherence
(Wigner representation)



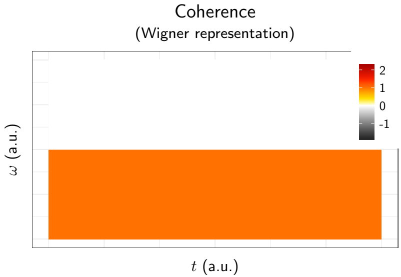
$$\Delta q = 1 - \alpha \int \overline{\Delta W_S^{(e)}(t,\omega)\Delta W_P^{(e)}(t,\omega)}^{\,t} \frac{\mathrm{d}\omega}{2\pi}$$

C. Grenier *et al*, New Journal of Physics **13**, 093007 (2011)

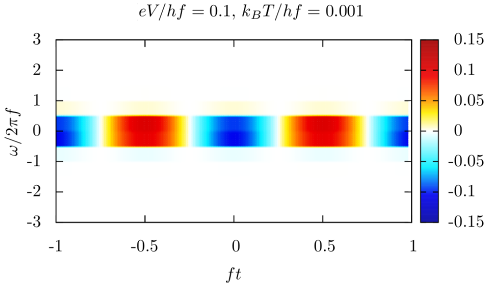
# Theoretical proposal

We use an AC+DC voltage drive at specific frequencies, and vary the DC part.

$$V_P(t) = V_{\mathrm{dc}} + V_0 \cos(\omega t + \phi)$$



Coherence
(Wigner representation)



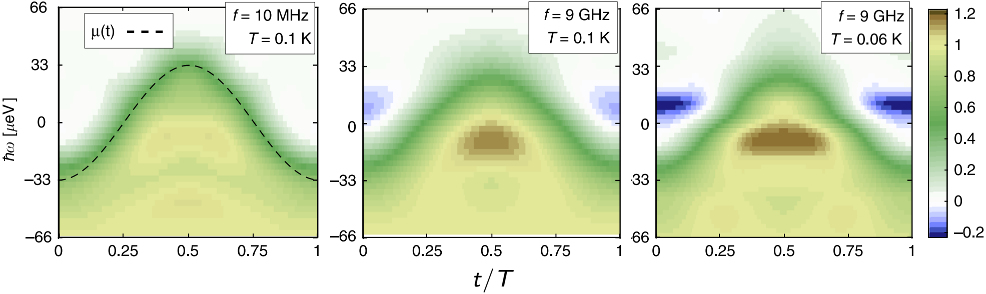
$$\Delta q = 1 - \alpha \int \overline{\Delta W_S^{(e)}(t,\omega)\Delta W_P^{(e)}(t,\omega)}^{t} \frac{\mathrm{d}\omega}{2\pi}$$

C. Grenier *et al*, New Journal of Physics **13**, 093007 (2011)

# Tomography of a sine drive: classical to quantum regime

Low amplitude sine drive (no interactions)

$V = 32\,\mu\text{V}$



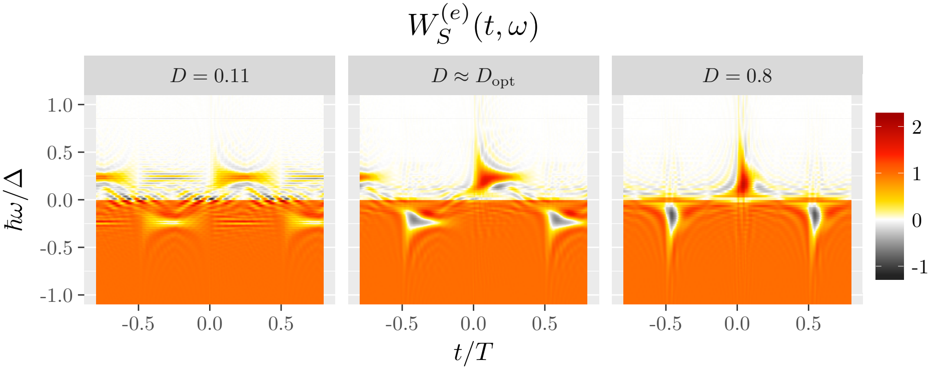
R. Bisognin *et al*, Nature Comm **10**, 3379 (2019)

**See also:**

T. Jullien *et al*, Nature **514** (2014), 603

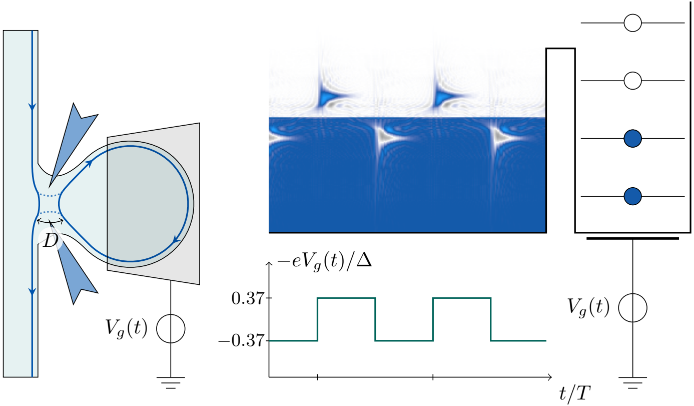
# From first-order coherence to wavefunctions

**How can we extract wavefunctions from electron coherence?**



# Theoretical example: quantum dot source

## Energy-resolved source



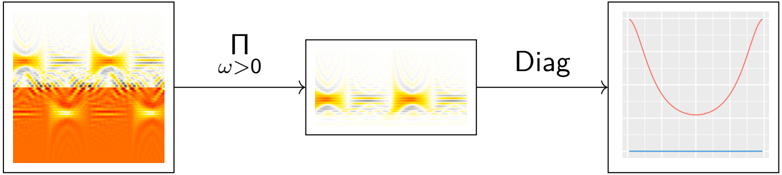
G. Fève *et al*, Science **316** (2007)

# Extracting waves

**Full coherence** (theory/experiment)

**Electronic part of the coherence**

**Spectrum** and eigenmodes



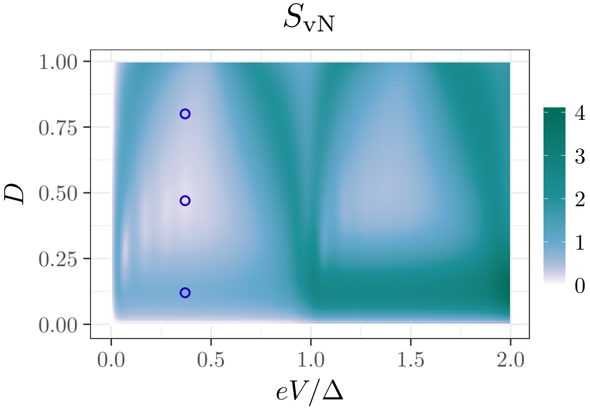
| | **Bloch theory** | | **Electron quantum optics** |
|---|---|---|---|
| $a$ | cell size | $T$ | period |
| $k$ | quasi-momentum | $\nu$ | quasi-pulsation |
| $\vert\psi_n(k)\rangle$ | Bloch waves | $\vert\psi_n(\nu)\rangle$ | eigenmodes |
| $E_n(k)$ | energy spectrum | $p_n(\nu)$ | probability spectrum |

# Entropy

**Non-interacting case, $T = 0\,\mathrm{K}$**

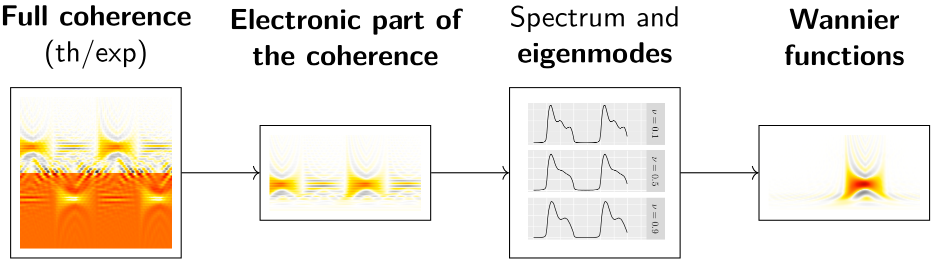
spectrum
$\updownarrow$
entanglement spectrum

von Neumann entropy ($S_{\mathrm{vN}}$)
measures
electron-hole entanglement



**Informational criterion of the purity of the source**

# Extracting wavefunctions



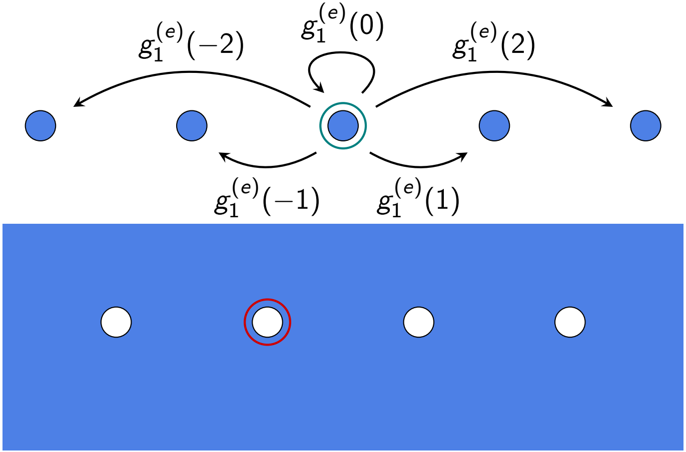
**Full coherence** (th/exp) → **Electronic part of the coherence** → Spectrum and **eigenmodes** → **Wannier functions**

Basis analoguous to Wannier functions:

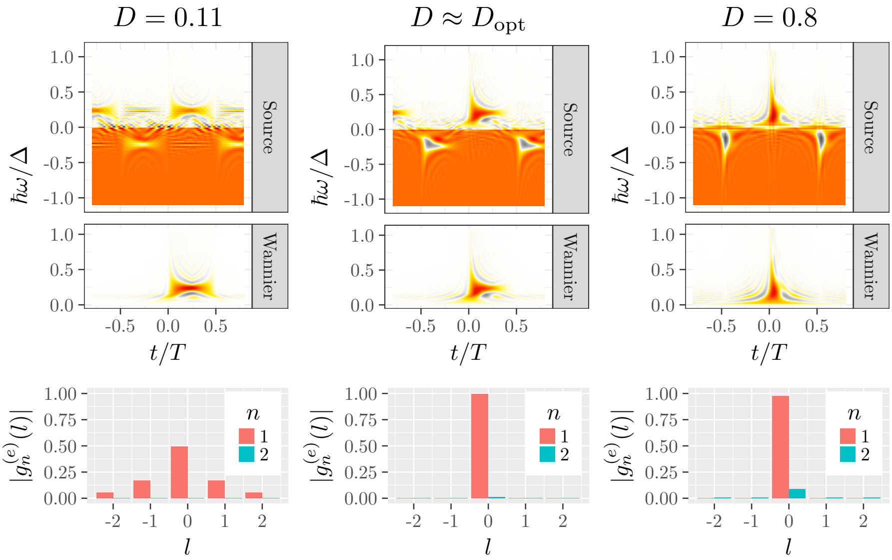
- For each band of the spectrum, time-translated Wannier functions
- Coherences from one period to the other in the same band ($g_n^{(e)}(l)$)

**On Wannier wavefunction ambiguity:**
N. Marzari *et al*, Rev. Mod. Phys. **84**, 1419 (2012)

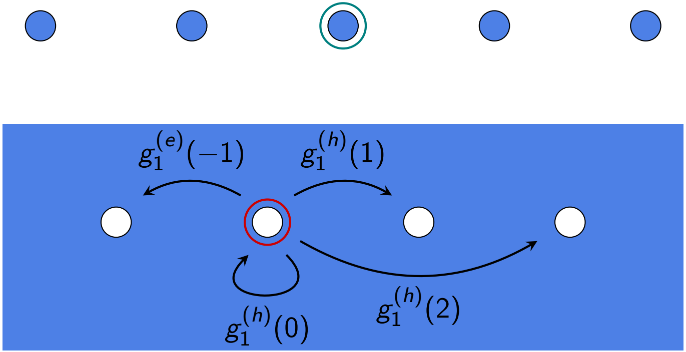
# Coherences between Wannier functions



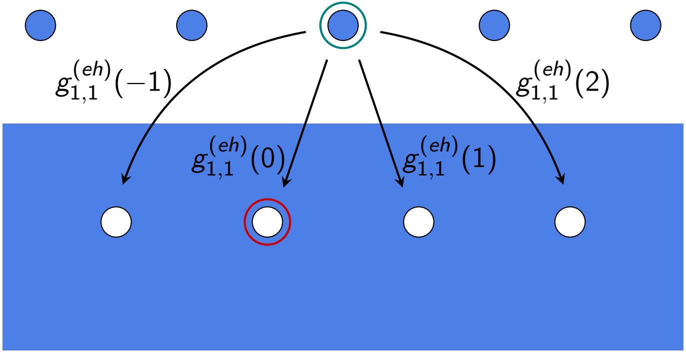
# Wannier functions



# Coherences between Wannier functions

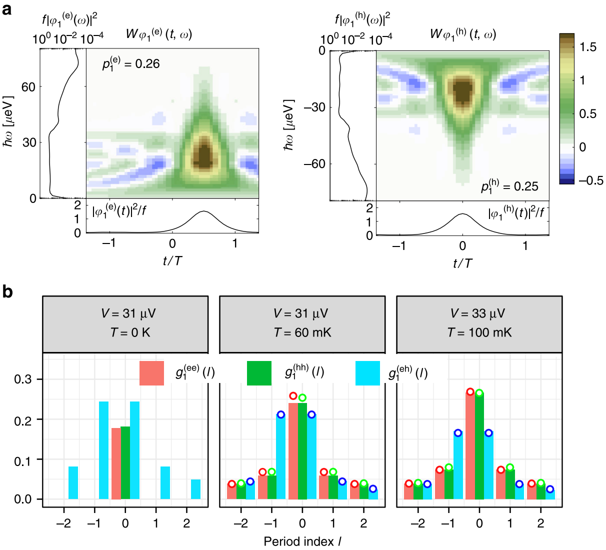


# Coherences between Wannier functions



# Wavefunctions in a quantum sine drive

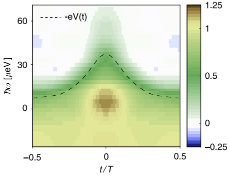
## $f = 9\,\mathrm{GHz}$, $V = 32\,\mu\mathrm{V}$

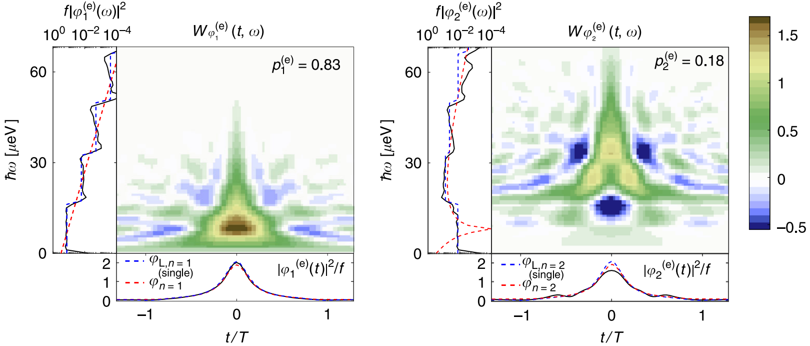


# Wavefunctions for a Leviton drive

$f = 4\,\mathrm{GHz}$, $V = 32\,\mu\mathrm{V}$, $\tau = 42\,\mathrm{ps}$, $q = -e$, $T = 50\,\mathrm{mK}$

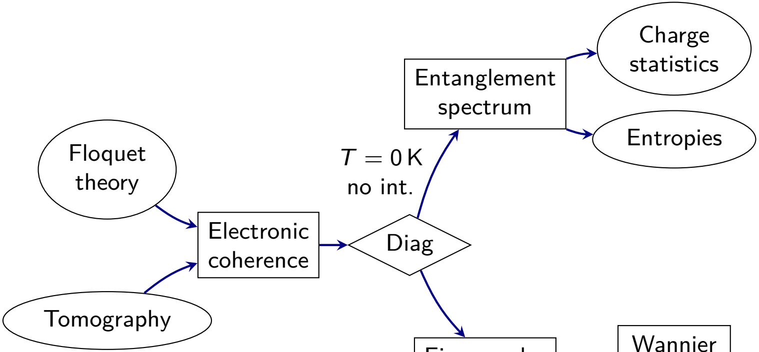
- Effect of temperature: two wavefunctions
- $p_1 \approx 83\,\%$, $p_2 \approx 18\,\%$
- Overlap with theory: 0.98 and 0.93



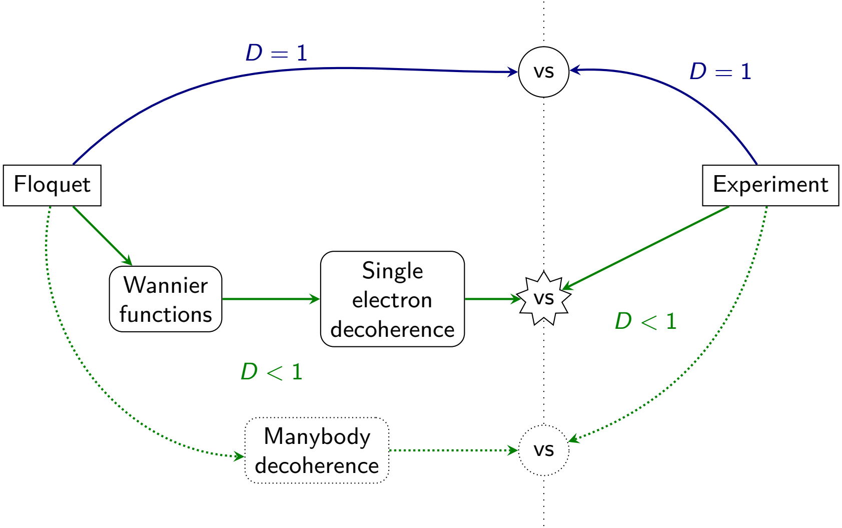


R. Bisognin *et al*, Nature Comm **10**, 3379 (2019)

# Dissecting an electrical current



# Outlook



$D = 1$

vs

$D = 1$

Floquet

Experiment

Wannier functions

Single electron decoherence

vs

$D < 1$

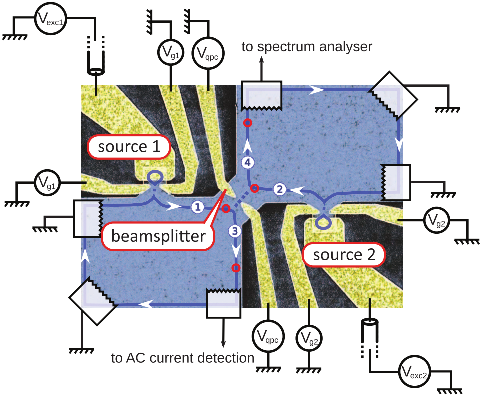
$D < 1$

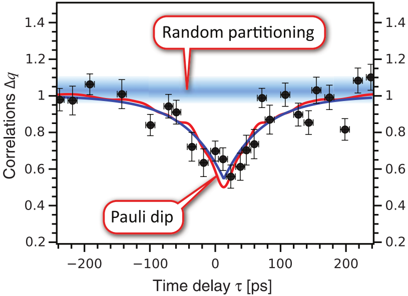
Manybody decoherence

vs

# Interactions

Interactions play a key role in electronic systems.

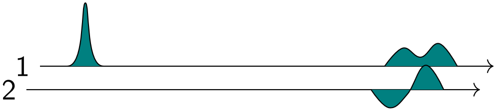




E. Bocquillon *et al*, Science **339** (2013)

# Capacitive interactions

Dominant interactions are capacitive ones. They alter classical current linearly:



$$i_{1,\text{out}}(t) = \int \mathcal{T}\left(t-t'\right) i_{1,\text{in}}(t')\,\mathrm{d}t'$$

$$i_{2,\text{out}}(t) = \int \mathcal{R}\left(t-t'\right) i_{1,\text{in}}(t')\,\mathrm{d}t'$$

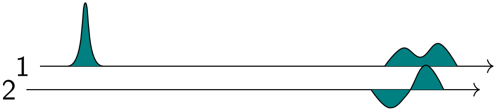
The output state is a tensor state:

$$\left|i_{1,\text{in}}\right\rangle_1 \otimes \left|0\right\rangle_2 \mapsto \left|i_{1,\text{out}}\right\rangle_1 \otimes \left|i_{2,\text{out}}\right\rangle_2$$

How to translate an emitted wavefunctions in terms of classical currents?

# Capacitive interactions

Dominant interactions are capacitive ones. They alter classical current linearly:



$$i_{1,\text{out}}(\omega) = \mathcal{T}(\omega)\, i_{1,\text{in}}(\omega)$$
$$i_{2,\text{out}}(\omega) = \mathcal{R}(\omega)\, i_{1,\text{in}}(\omega)$$

The output state is a tensor state:

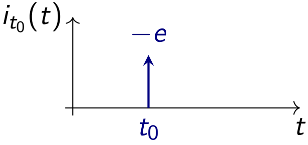
$$|i_{1,\text{in}}\rangle_1 \otimes |0\rangle_2 \mapsto |i_{1,\text{out}}\rangle_1 \otimes |i_{2,\text{out}}\rangle_2$$

How to translate an emitted wavefunctions in terms of classical currents?

# Bosonization

A time-resolved electron above the Fermi sea is nothing more than a percussional current of charge $-e$.

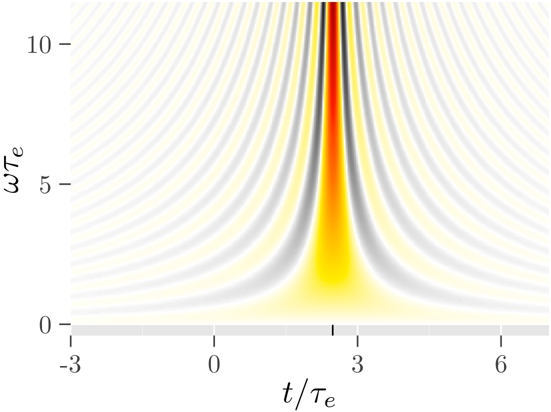
$$\psi^\dagger(t_0)\left|F\right\rangle = \left|i_{t_0}\right\rangle$$



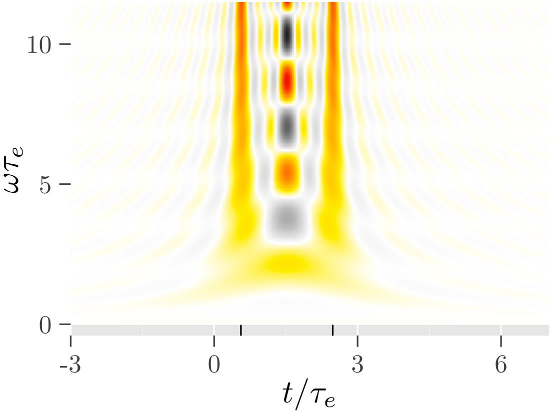
A wavepacket $\varphi$ on top of the Fermi sea is a quantum superposition of percussional currents:

$$\left|\varphi, F\right\rangle = \int \varphi(t')\psi^\dagger(t')\left|F\right\rangle \mathrm{d}t' = \int \varphi(t')\left|i_{t'}\right\rangle \mathrm{d}t'$$

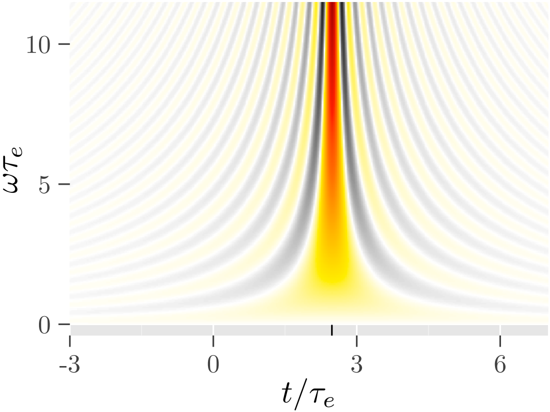
# Electrons from edge magnetoplasmons: $\psi^\dagger(t_1)$



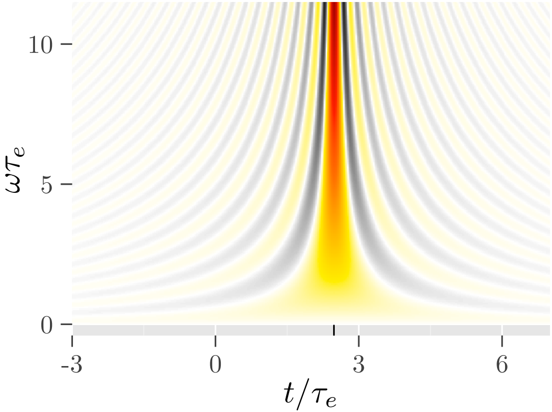
# Electrons from edge magnetoplasmons: $\frac{1}{\sqrt{2}}(\psi^\dagger(t_1) + \psi^\dagger(t_2))$



# State emitted by the SES: $\int \varphi_e(t)\psi^\dagger(t)\mathrm{d}t$



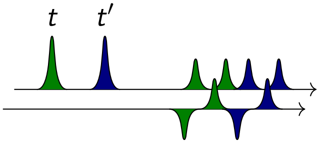
# State emitted by the SES: $\int \varphi_e(t)\psi^\dagger(t)\mathrm{d}t$



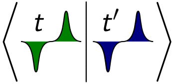
# Two faces of decoherence

## Extrinsic decoherence

Between two channels

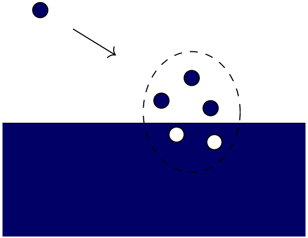


$\mathcal{D}_{\text{ext}}(t-t') =$



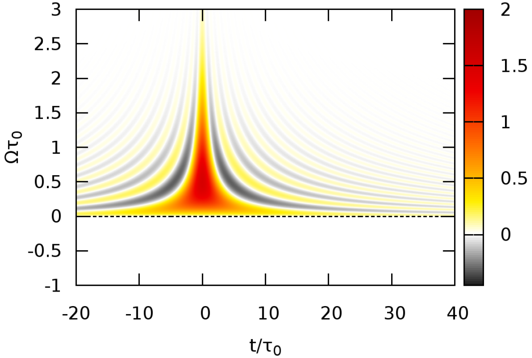
## Intrinsic decoherence

Inside one channel

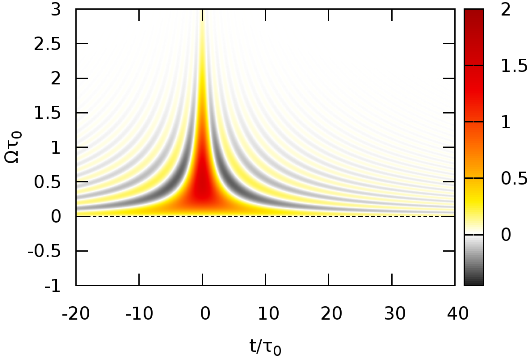


Many-body correlations induce single-body decoherence

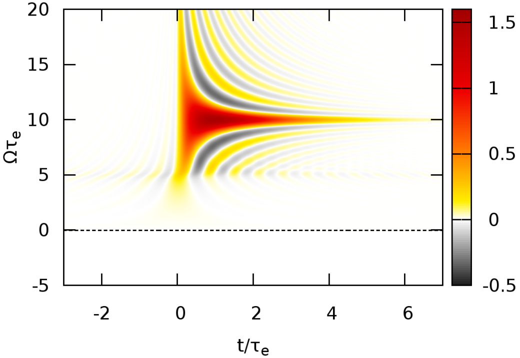
P. Degiovanni, C. Grenier, G. Fève, Phys. Rev. B **80**, 241307



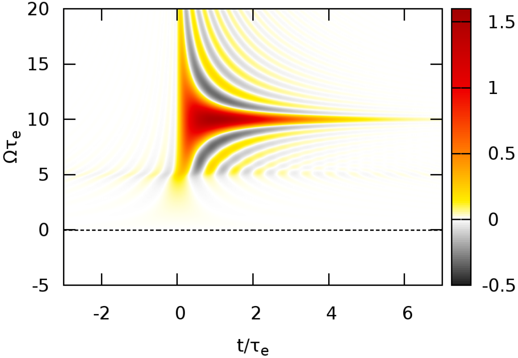
D. Ferraro *et al*, Phys. Rev. Lett. **113** (2014)



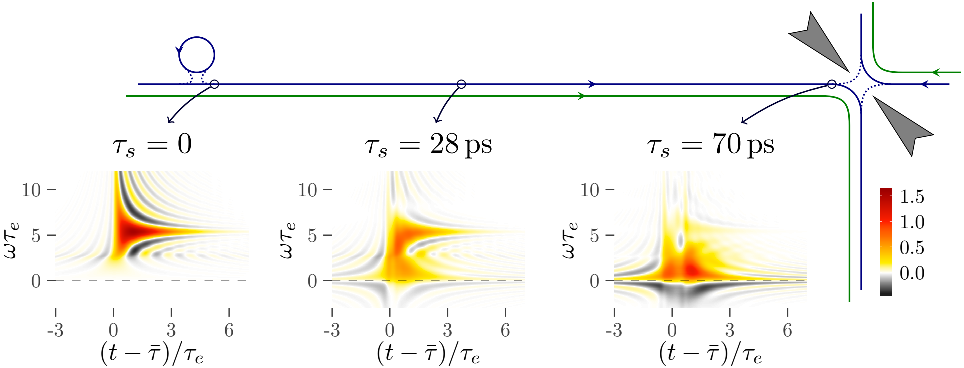
D. Ferraro *et al*, Phys. Rev. Lett. **113** (2014)



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

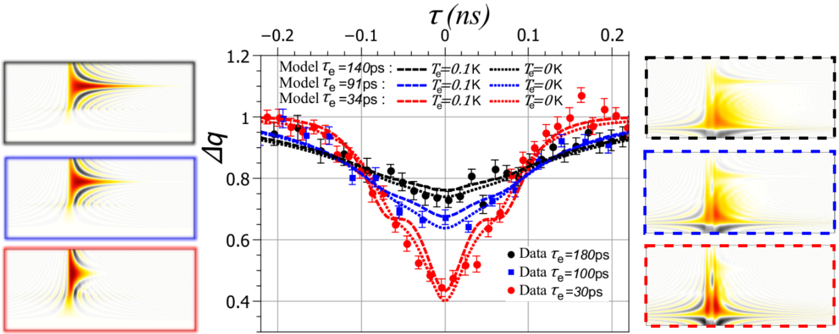


D. Ferraro *et al*, Phys. Rev. Lett. **113** (2014)



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

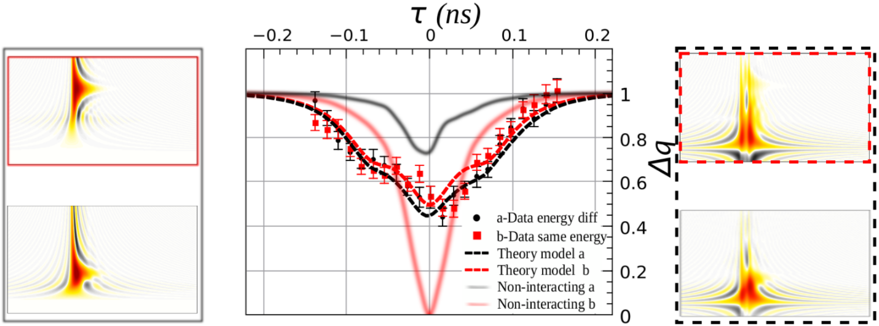
# HOM for different $\tau_e$



A. Marguerite *et al*, Phys. Rev. B **94** (2016)

**See also:**
C. Wahl *et al*, Phys. Rev. Lett. **112** (2014)
D. Ferraro *et al*, Phys. Rev. Lett. **113** (2014)

# Creating indiscernability through decoherence



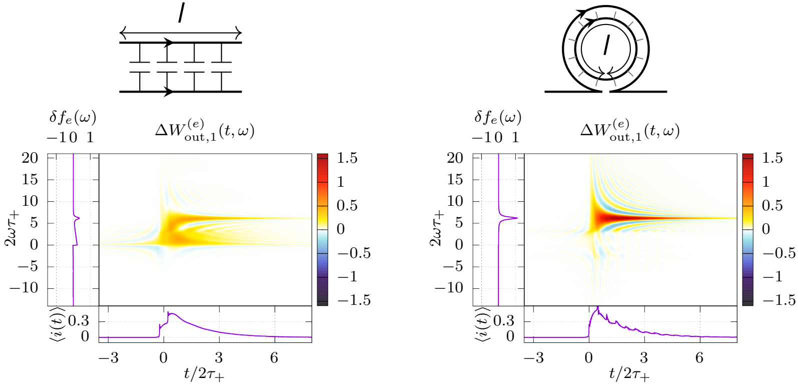
A. Marguerite *et al*, Phys. Rev. B **94** (2016)

**See also:**

C. Wahl *et al*, Phys. Rev. Lett. **112** (2014)
D. Ferraro *et al*, Phys. Rev. Lett. **113** (2014)

# Interactions

## Protection from decoherence



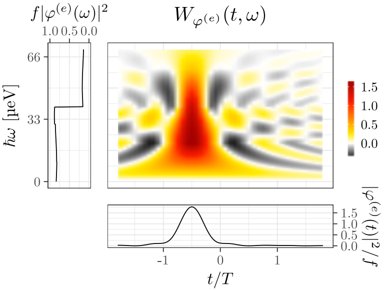
C. Cabart *et al*, Phys. Rev. B **98**, 155302 (2018)

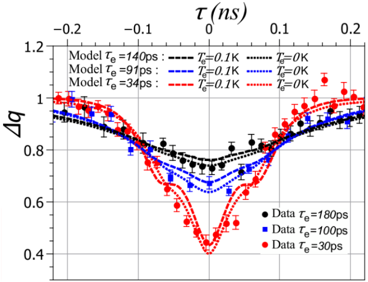
**Past experimental works (DC-regime):**

C. Altimiras *et al*, Phys. Rev. Lett. **105** (2010)

P-A. Huynh *et al*, Phys. Rev. Lett. **108** (2012)

# Summary


$f|\varphi^{(e)}(\omega)|^2$
1.0 0.5 0.0
$W_{\varphi^{(e)}}(t,\omega)$
$\hbar\omega$ [μeV]
66
33
0
1.5
1.0
0.5
0.0
$|\varphi^{(e)}(t)|^2/f$
1.5
1.0
0.5
0.0
-1
0
1
$t/T$


$\tau\,(ns)$
−0.2
−0.1
0
0.1
0.2
$\Delta q$
1.2
1
0.8
0.6
0.4
Model $\tau_e$ =140ps : $T_e$=0.1K $T_e$=0K
Model $\tau_e$ =91ps : $T_e$=0.1K $T_e$=0K
Model $\tau_e$ =34ps : $T_e$=0.1K $T_e$=0K
Data $\tau_e$=180ps
Data $\tau_e$=100ps
Data $\tau_e$=30ps

# Outlook

## Electronic transport

### Past

- Stationary states
- Average current and current noise
- Full counting statistics

### Present

- Single electron, single hole states
- Single electron wavefunctions measurement
- Decoherence control
- Probing mesoscopic physics with SES

### Future

- Engineering single electron states
- Engineering photonic states
- Metrology
- Superconductivity