LATVIJAS UNIVERSITATE
UNIVERSITY OF LATVIA

ESF EIROPAS SOCIĀLAIS FONDS

Datorzinātnes lietojumi un tās saiknes ar kvantu fiziku

Single-gate non-adiabatic quantized charge pumps

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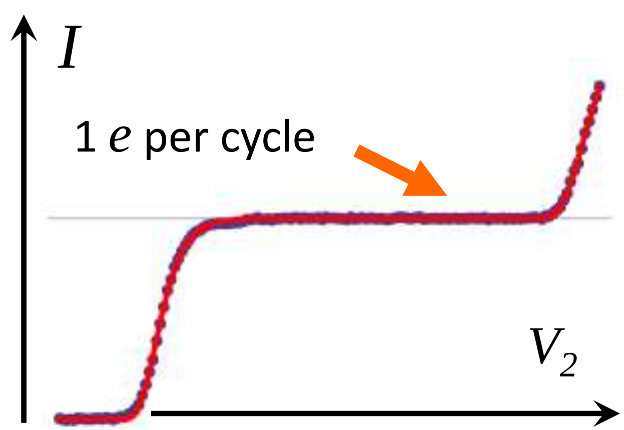
Single-gate pumps in metrology context

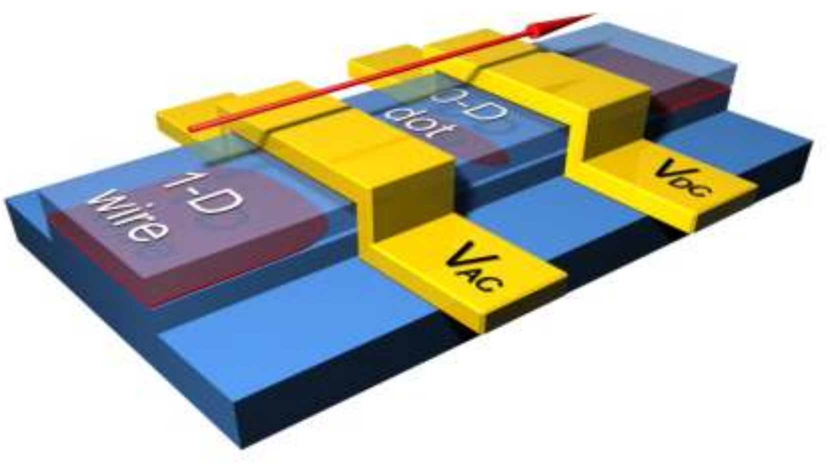
- A particular class of "quantized pumps"
- Aim at low, predictable error rate
- Motivated by…
  - metrology needs
  - basic physics

$$I = e\,f$$

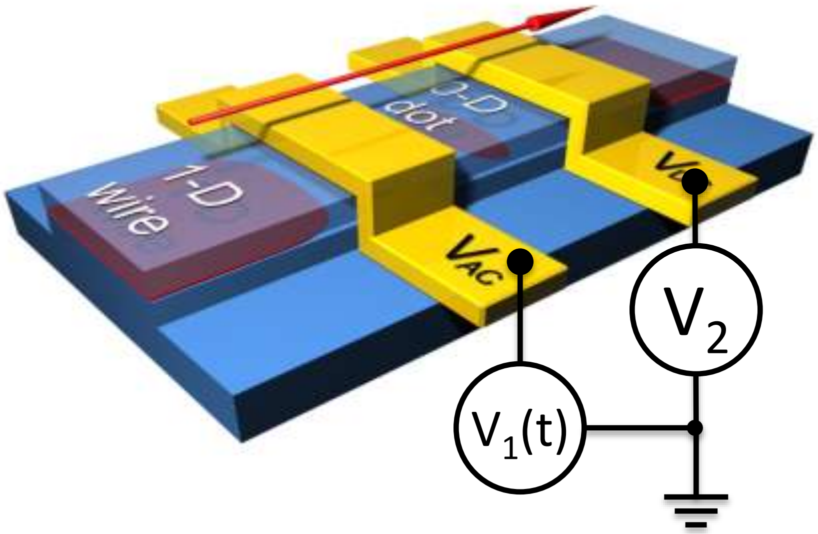


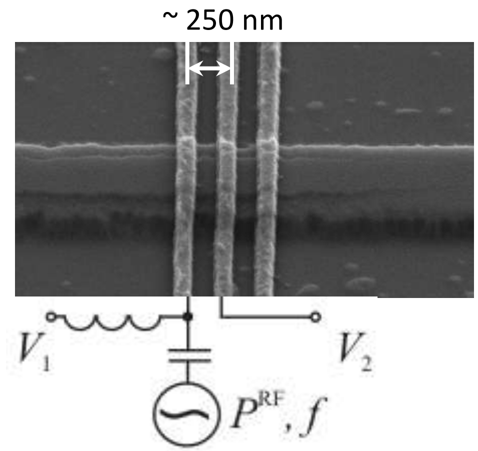
Outline

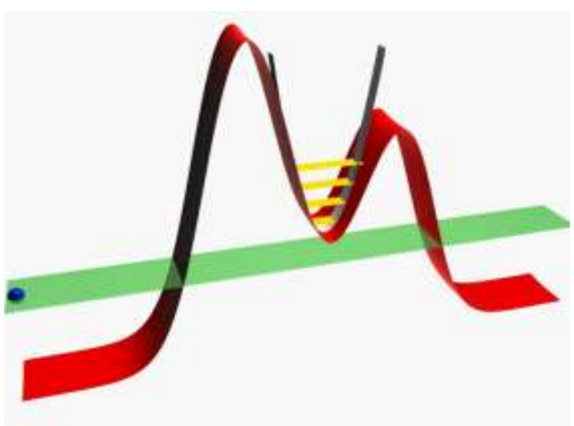
- Introduction (phenomenological)
- Message I: constructive non-adiabaticity
- Message II: universality of decay cascade
- Outlook for metrological applications



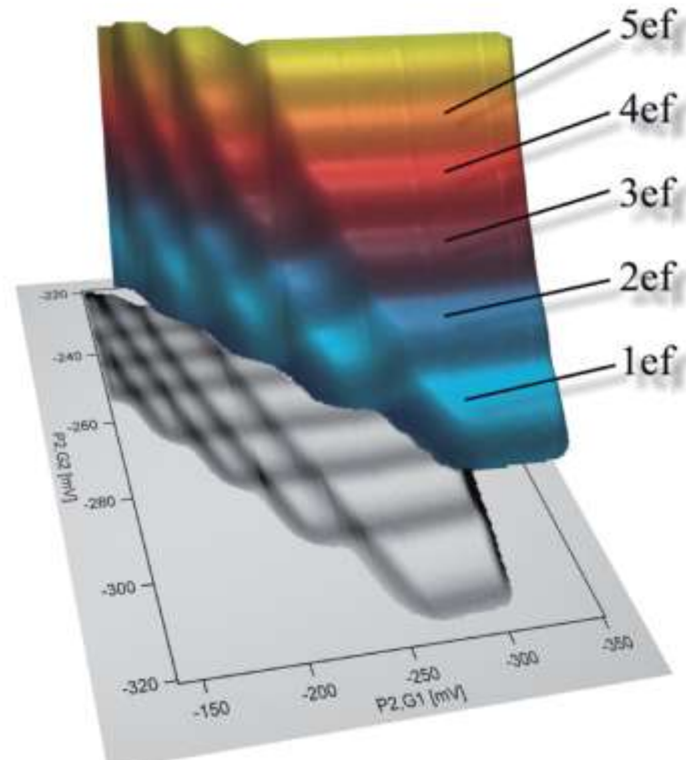
$$V_1(t) = V_1^{DC} + V_1^{AC} \cos \omega t$$





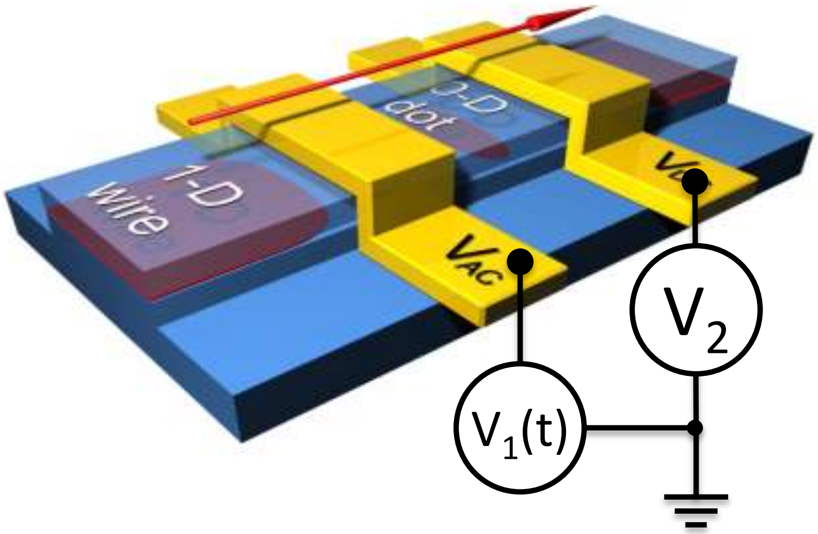


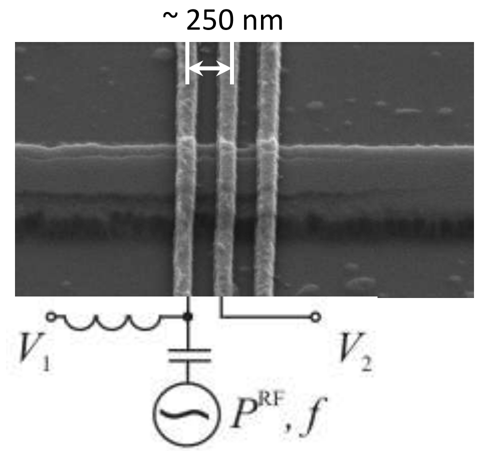
Animation: A. Müller

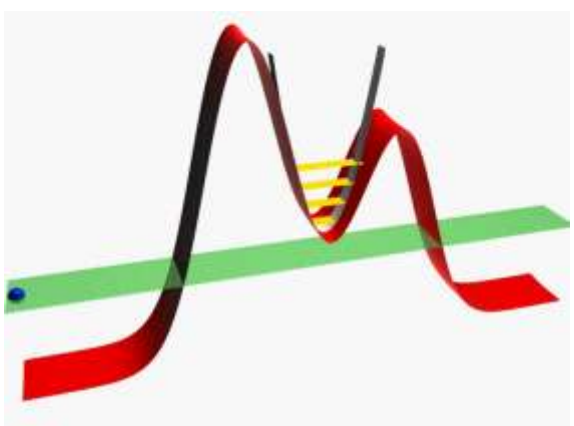


Data: F. Luckas (U.of Hannover)

$V_1(t) = V_1^{DC} + V_1^{AC} \cos \omega t$







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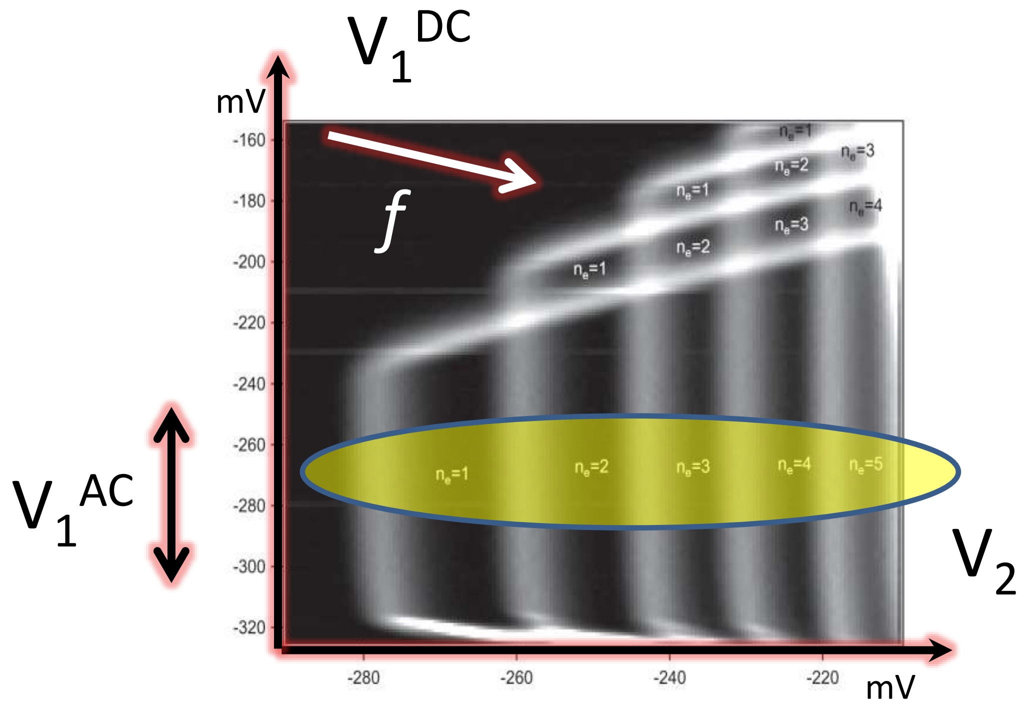

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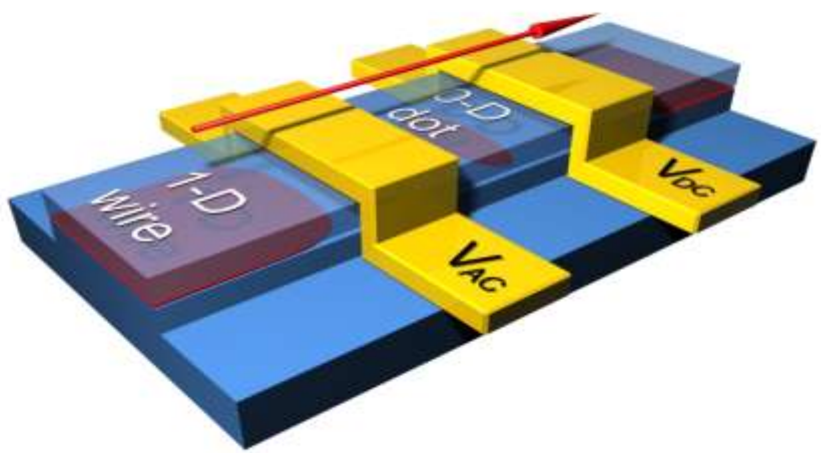
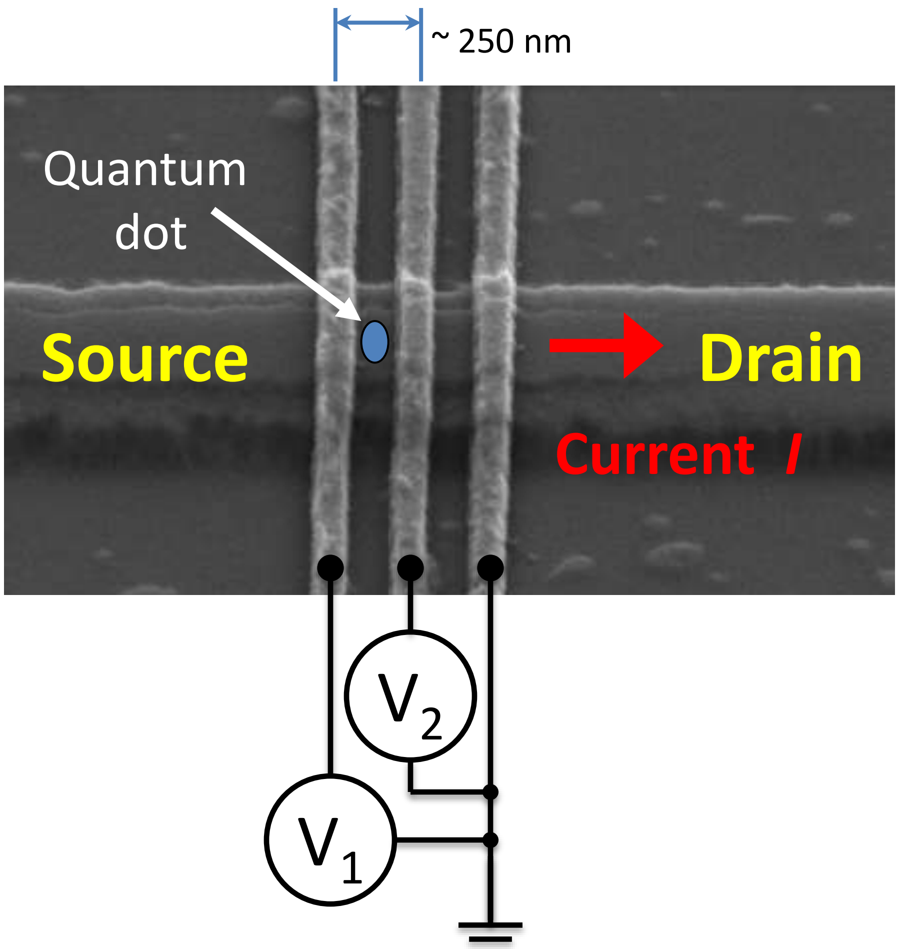
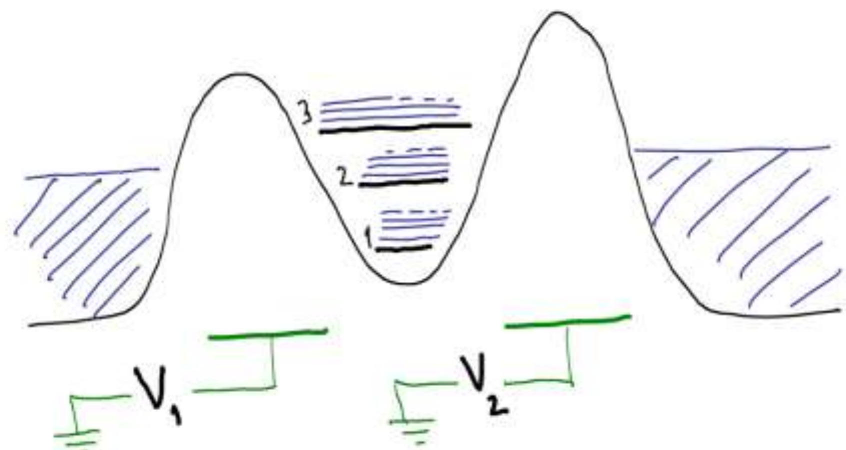
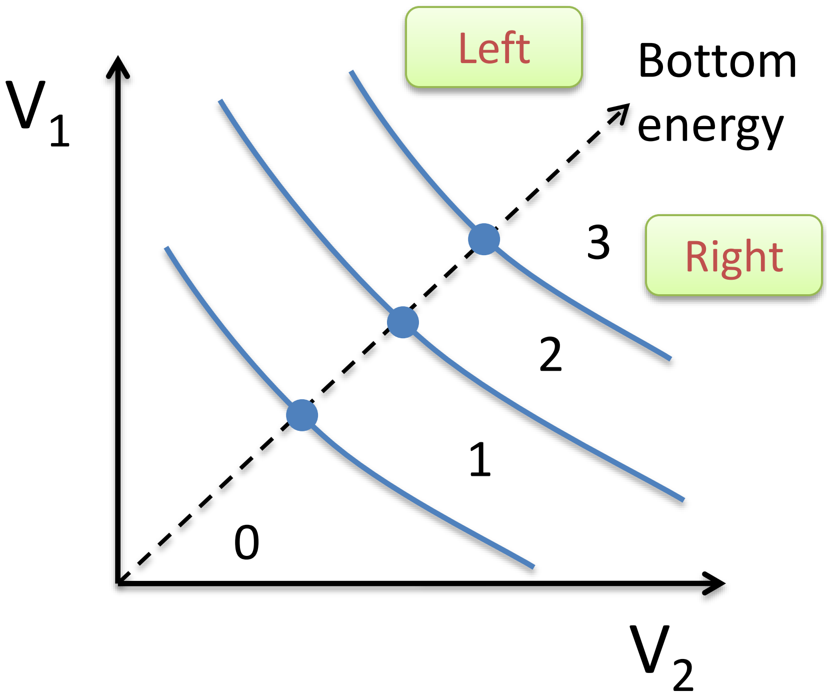


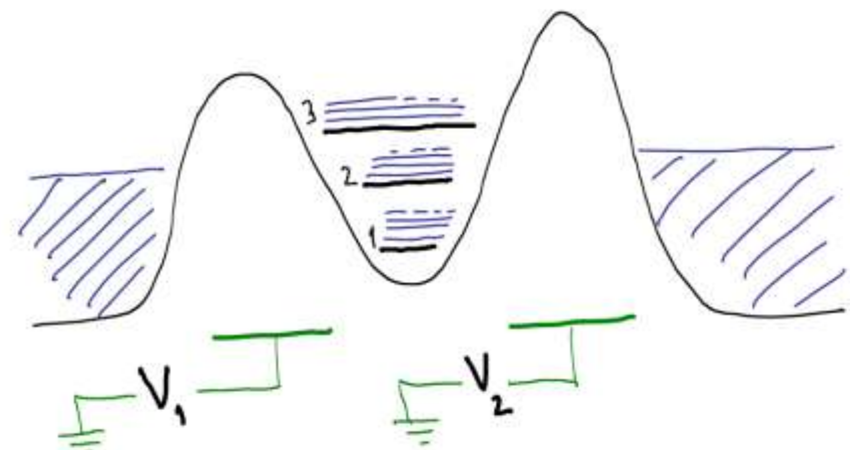
Double-barrier quantum dot

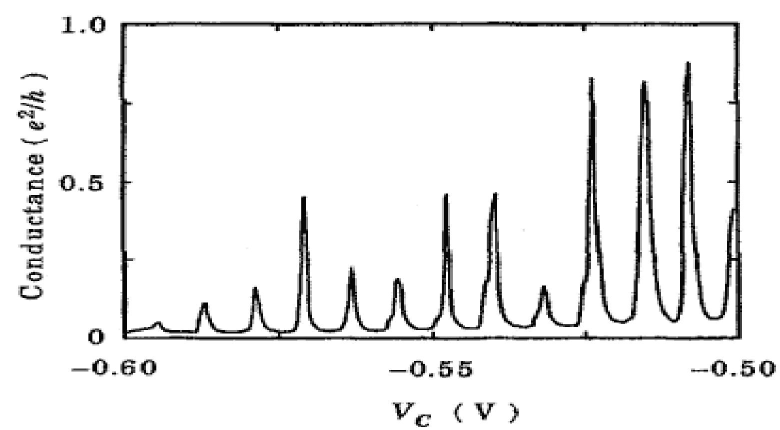




Charge stability diagram

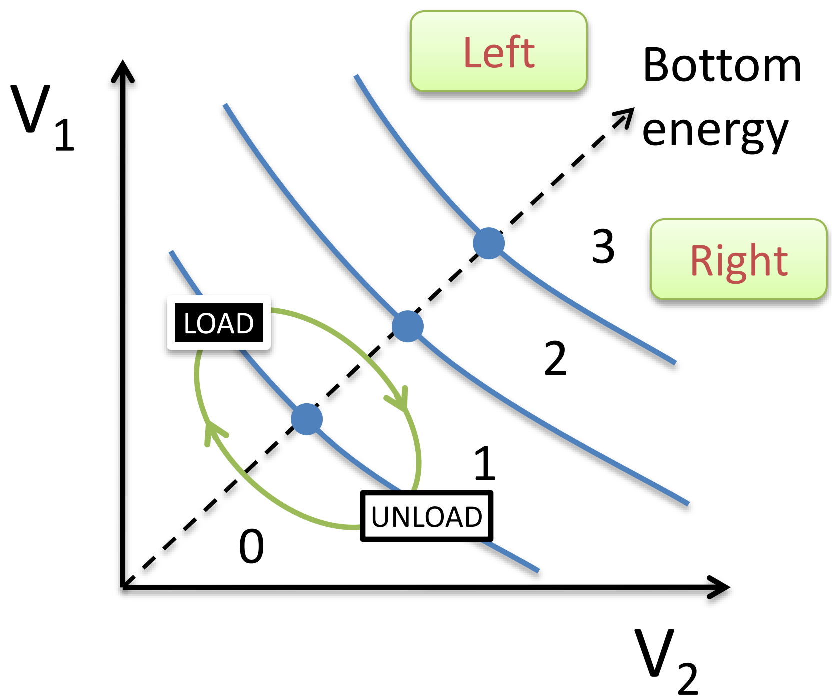






- Coulomb blockade for $kT, \hbar\Gamma < E_c$
- Resonance lines

Adiabatic paradigm for pumps



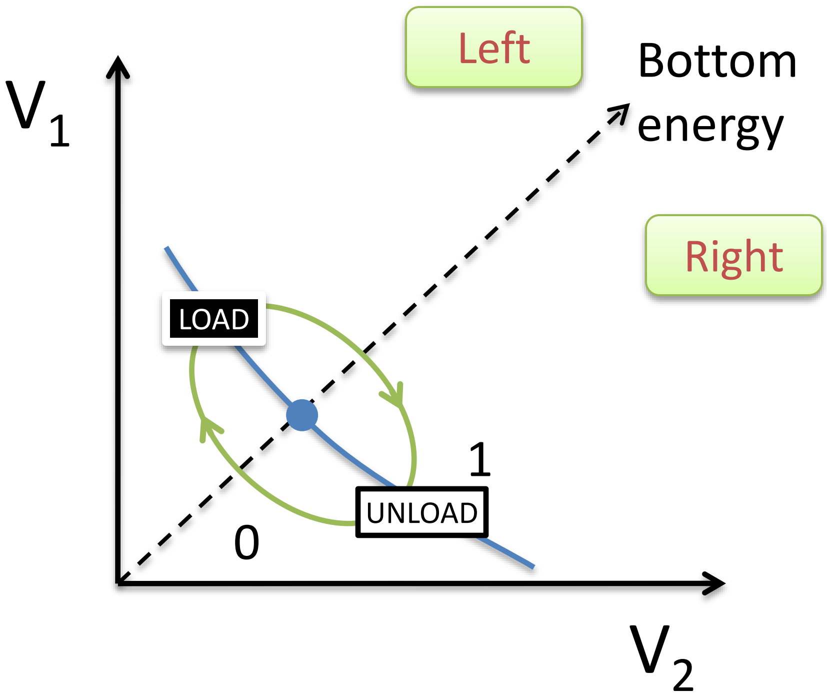
- Stay close to equilibrium
- Well-established SET technology
- At least **two** phase-shifted parameters
- Increasing frequency **increases** error rate

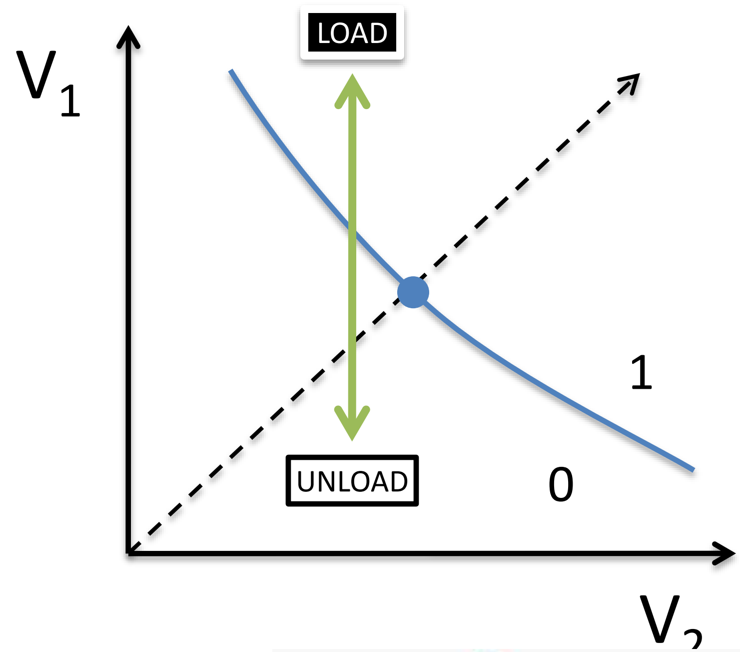
First quantized pump: Pothier et al, *Eur.Phys.Lett.*, **17**, 249 (1992)

"Electron counting capacitance standard", Keller et al, *Science* **285**, 1706 (1999)

Mapping of charge carrier type: Buitelaar, VK et al, *Phys. Rev. Lett*. **101**, 126803 (2008)

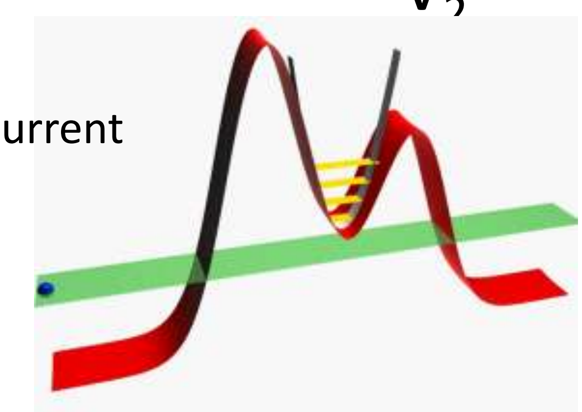
Adiabatic vs single-gate pumping





Moskalets-Büttiker (2002) “no-go theorem” :
adiabatic single-parameter modulation **cannot** produce current

Blumenthal *et al*, *Nature Physics* **3**, 343 (2007)
Kaestner, VK *et al*, *Phys. Rev. B* **77**, 153301 (2008)



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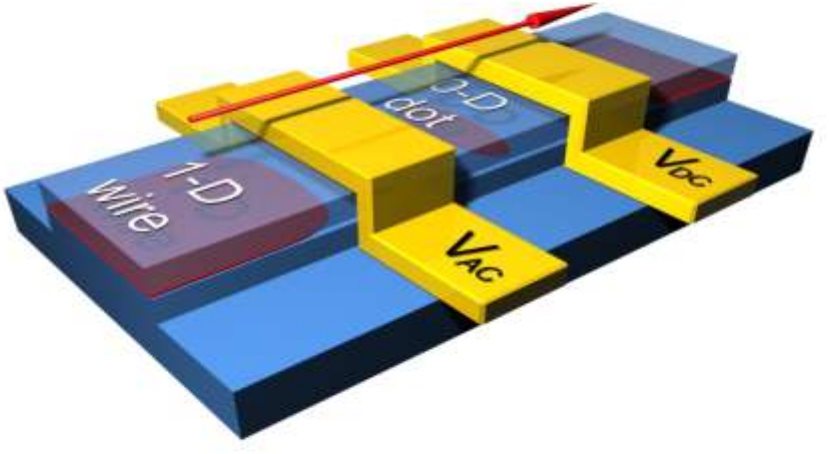
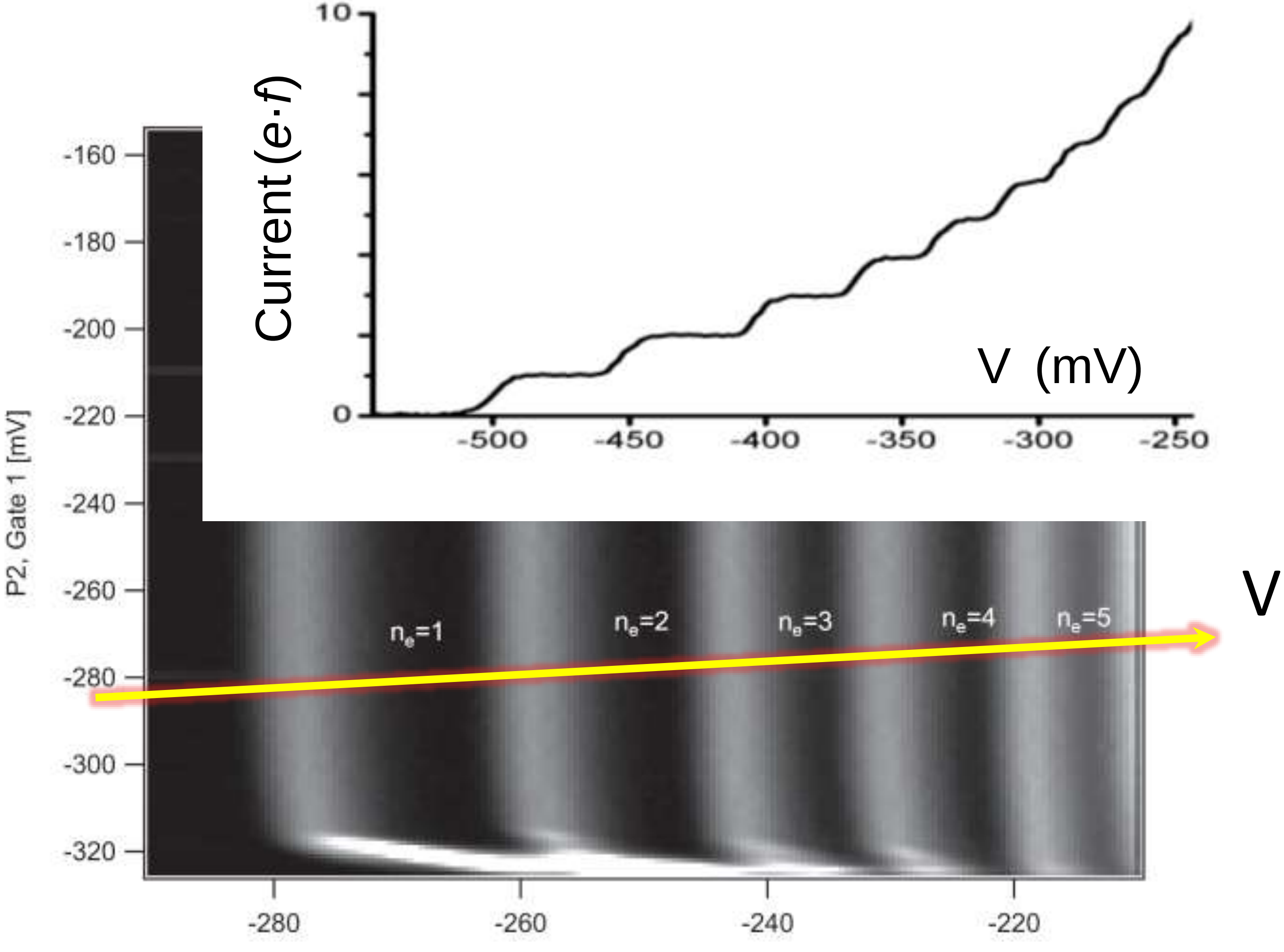
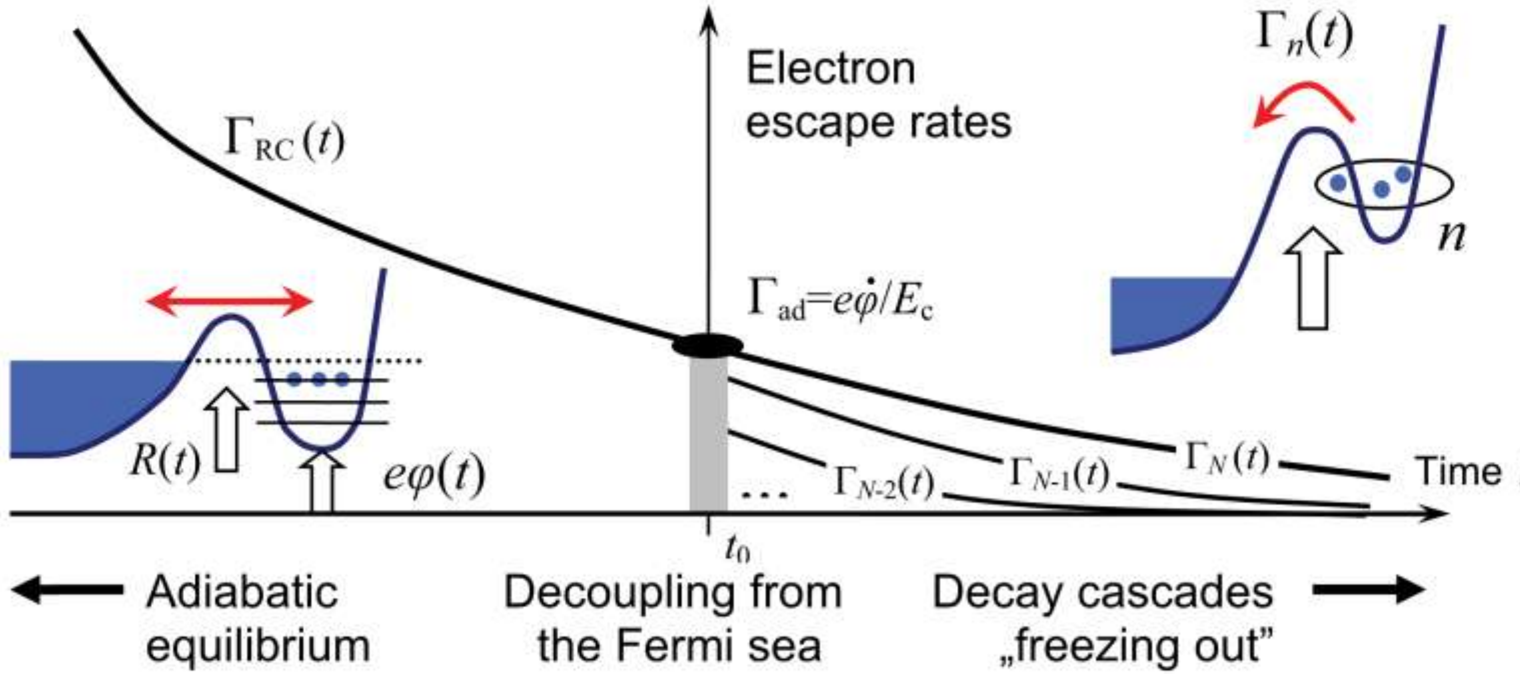


Universal limit: decay cascade regime



VK and B.Kaestner, *Phys. Rev. Lett.* **104**, 186805 (2010)

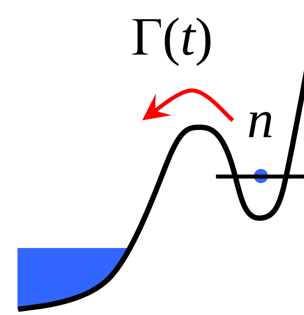


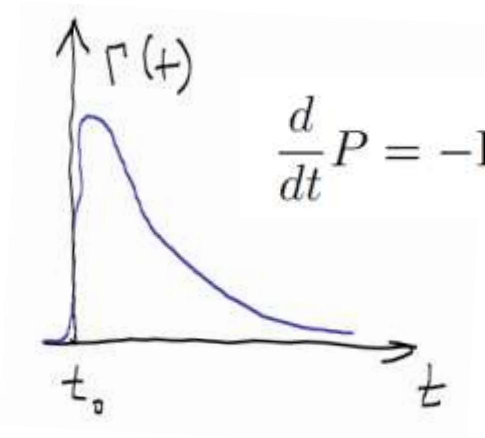
- $\Gamma(t) = \Gamma_0 e^{-\beta t}$ decreasing escape rate
- $\Gamma_{\text{ad}} \equiv e\dot{\varphi}/E_c$ escape rate to maintain equilibrium
- $\Gamma_{\text{ad}} = \Gamma(t_0)$ essential non-equilibrium for $t > t_0$
- If $\Gamma_{\text{ad}} \gg \beta$ then the initial condition is forgotten!

Raise faster than decouple!

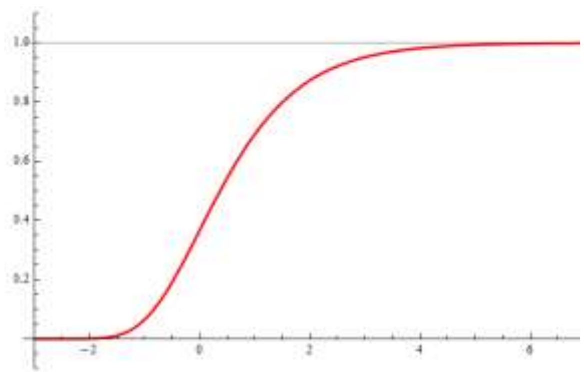
$$\frac{d}{dt}P_n = -\Gamma_n(t)P_n + \Gamma_{n+1}(t)P_{n+1}$$

1-step line shape





$$\frac{d}{dt}P = -\Gamma(t)P$$



- Backtunneling to empty space
- Survival probability:

$$P(t\rightarrow\infty) = e^{-X}\,, \text{ with } X \equiv \int_{t_0}^{\infty} \Gamma(t)\,dt$$

- Escape rate ansatz:

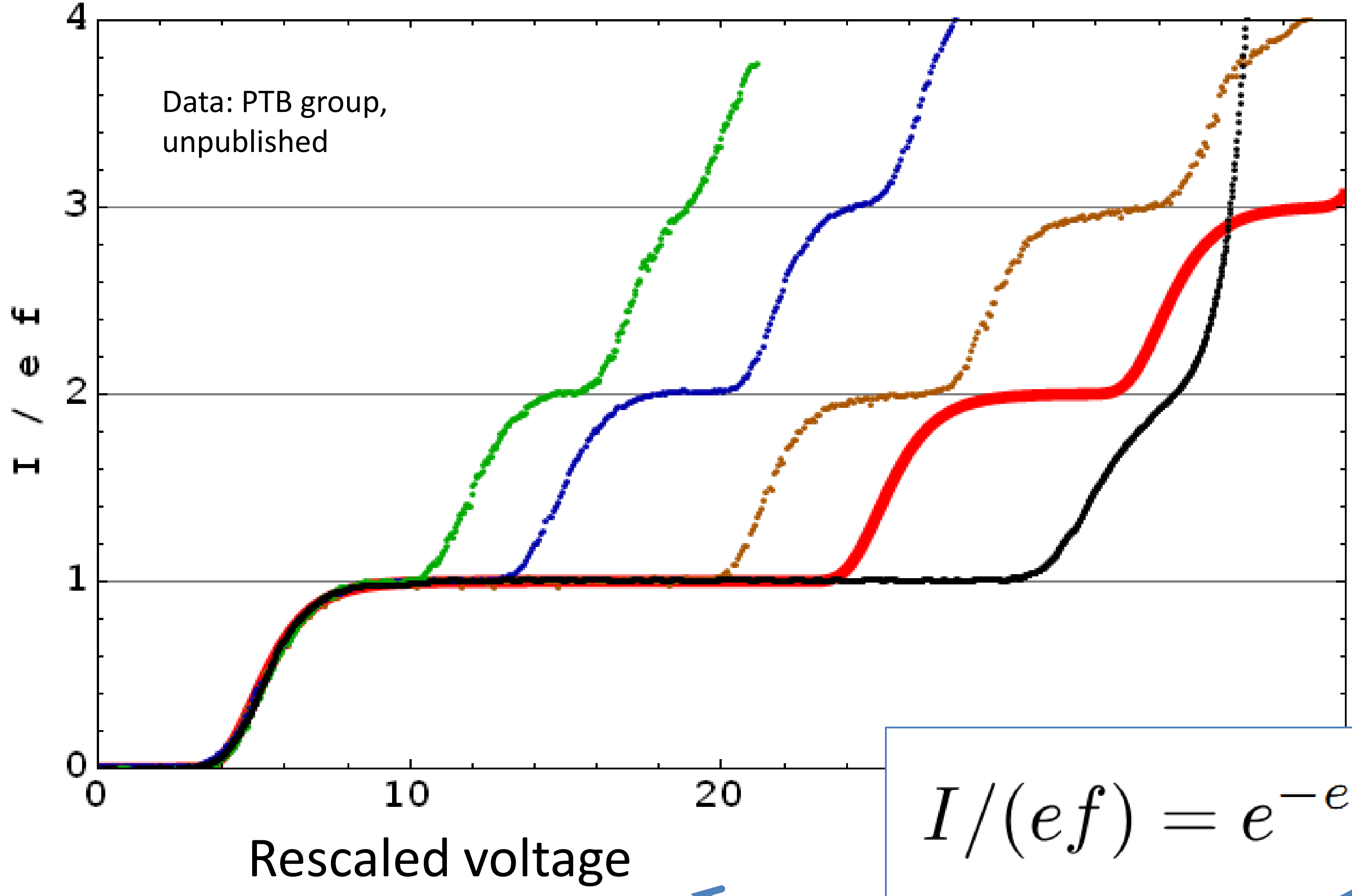
$$X \propto e^{-\alpha V}$$

$$I/(ef) = e^{-e^{-\alpha V + \delta_1}}$$

Fujiwara et al. Appl.Phys.Lett. **92**, 042102 (2008)

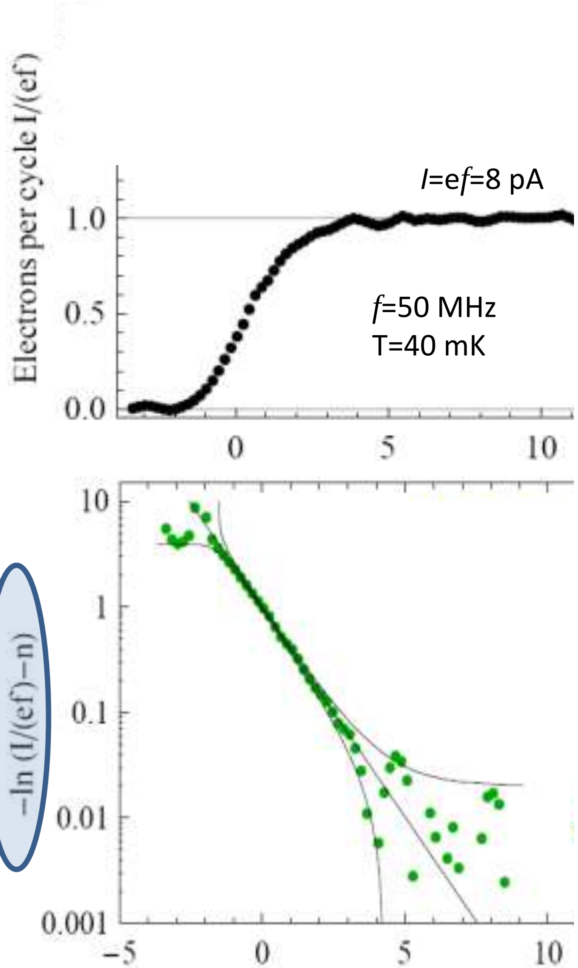
Kaestner *et al*,Appl. Phys. Lett. **94**, 012106 (2009)

Universal shape in rescaled coordinates



$$I/(ef) = e^{-e^{-\alpha V + \delta_1}}$$

Single-step fitting



Data from B.Kaestner *et al*,
Appl. Phys. Lett. **94**, 012106 (2009)

- Plot on double-log scale
- Look for straight line

$$X \propto e^{-\alpha V}$$

$$I/(ef) = e^{-e^{-\alpha V + \delta_1}}$$

Many-step line shape

- Define (dimensionless):

$$X_n \equiv \int_{t_0}^{+\infty} \Gamma_n(t)\, dt$$

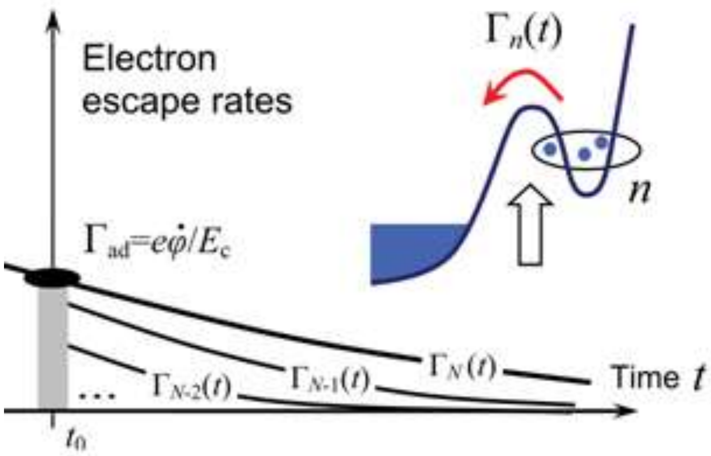
- If there is scale separation…

$$\ldots \gg X_{n+1} \gg X_n \gg X_{n-1} \gg \ldots$$

- …then the solution is

$$P_n(t \to \infty) = e^{-X_n} - e^{-X_{n+1}}$$

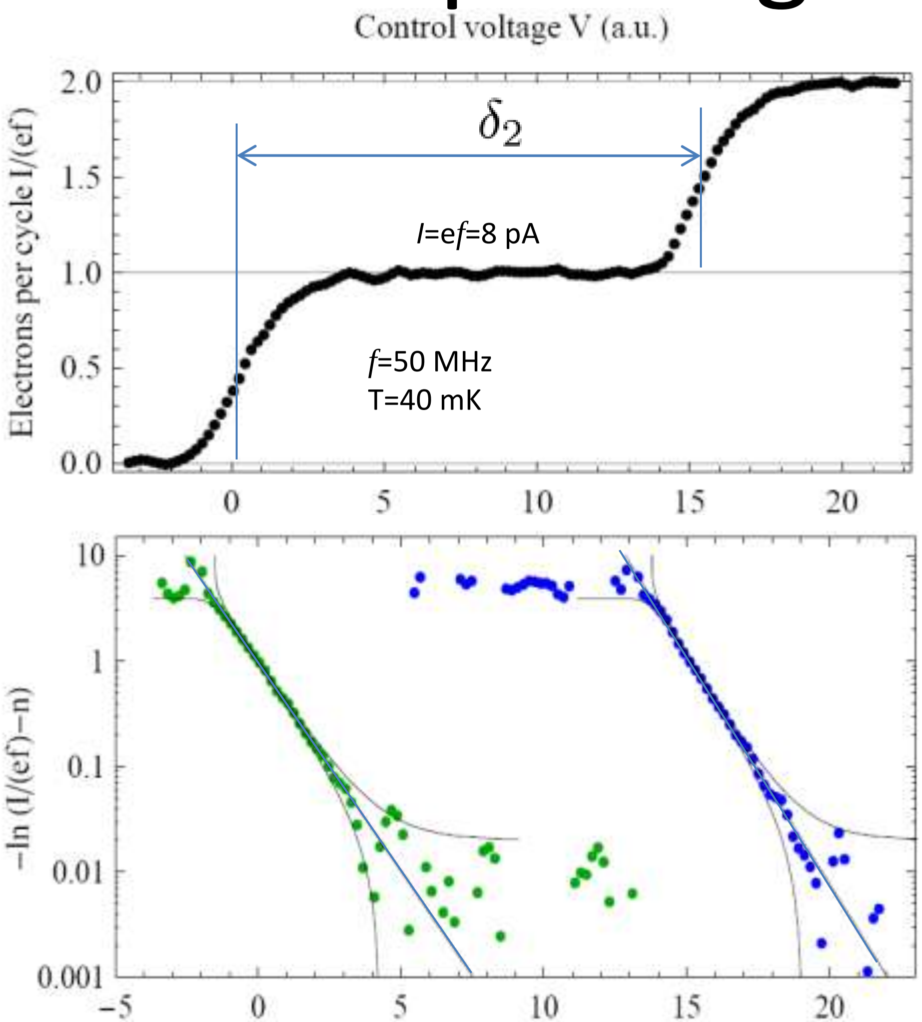
$$\langle n \rangle = \sum_m e^{-X_m}$$



$$\ln X_1 = -\alpha_1 V_g + \delta_1$$
$$\ln X_2 = -\alpha_2 V_g + \delta_1 + \delta_2$$

$$\frac{d}{dt} P_n = -\Gamma_n(t) P_n + \Gamma_{n+1}(t) P_{n+1}$$

Two-step fitting



δ_2 is the figure of merit

Fitting parameters!

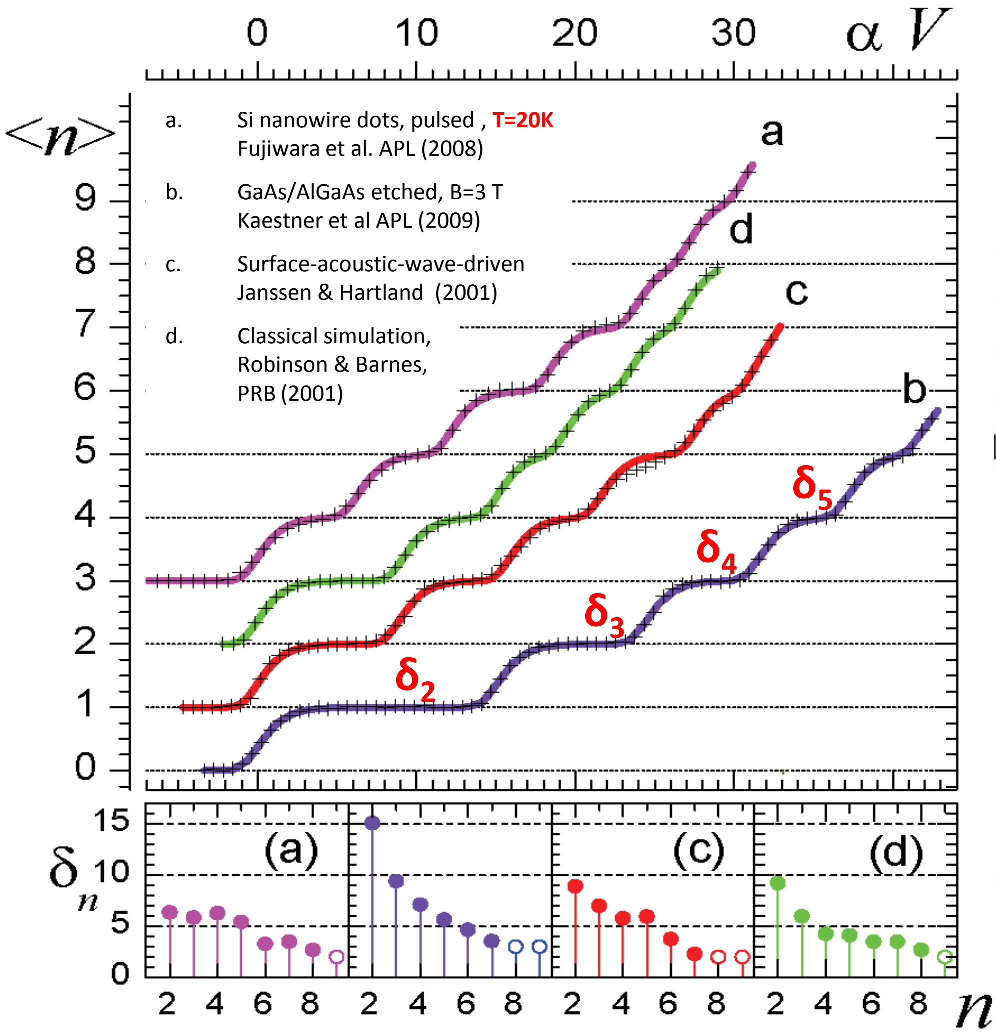
$$\approx \alpha$$

$$\ln X_1 = -\alpha_1 V_g + \delta_1$$
$$\ln X_2 = -\alpha_2 V_g + \delta_1 + \delta_2$$

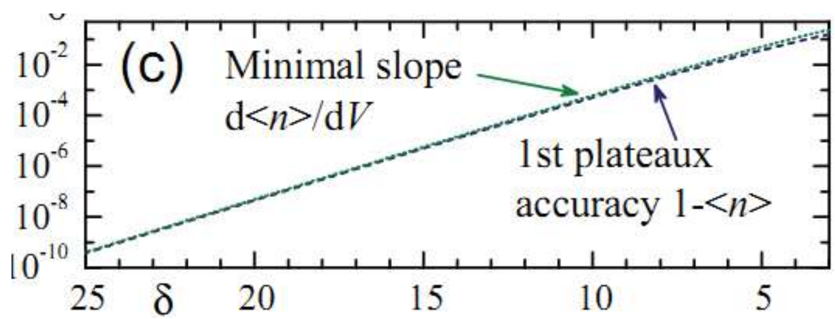
$$\langle n \rangle = \sum_m e^{-X_m}$$

Data from B.Kaestner *et al*,Appl. Phys. Lett. **94**, 012106 (2009)

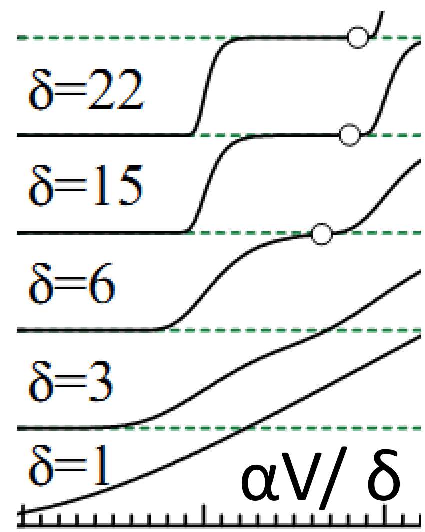
Universality of the decay cascade



δ_2 is the figure of merit



Theory prediction:



Device "fingerprint"

VK and B.Kaestner, arXiv (2009); *PRL* (2010)

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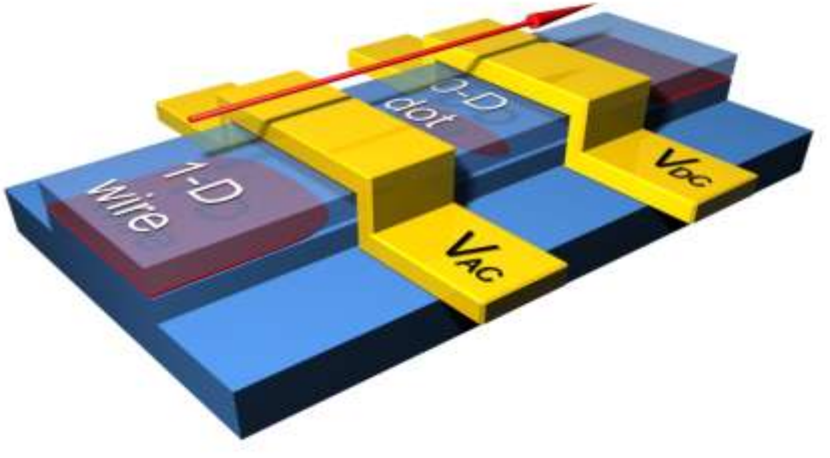
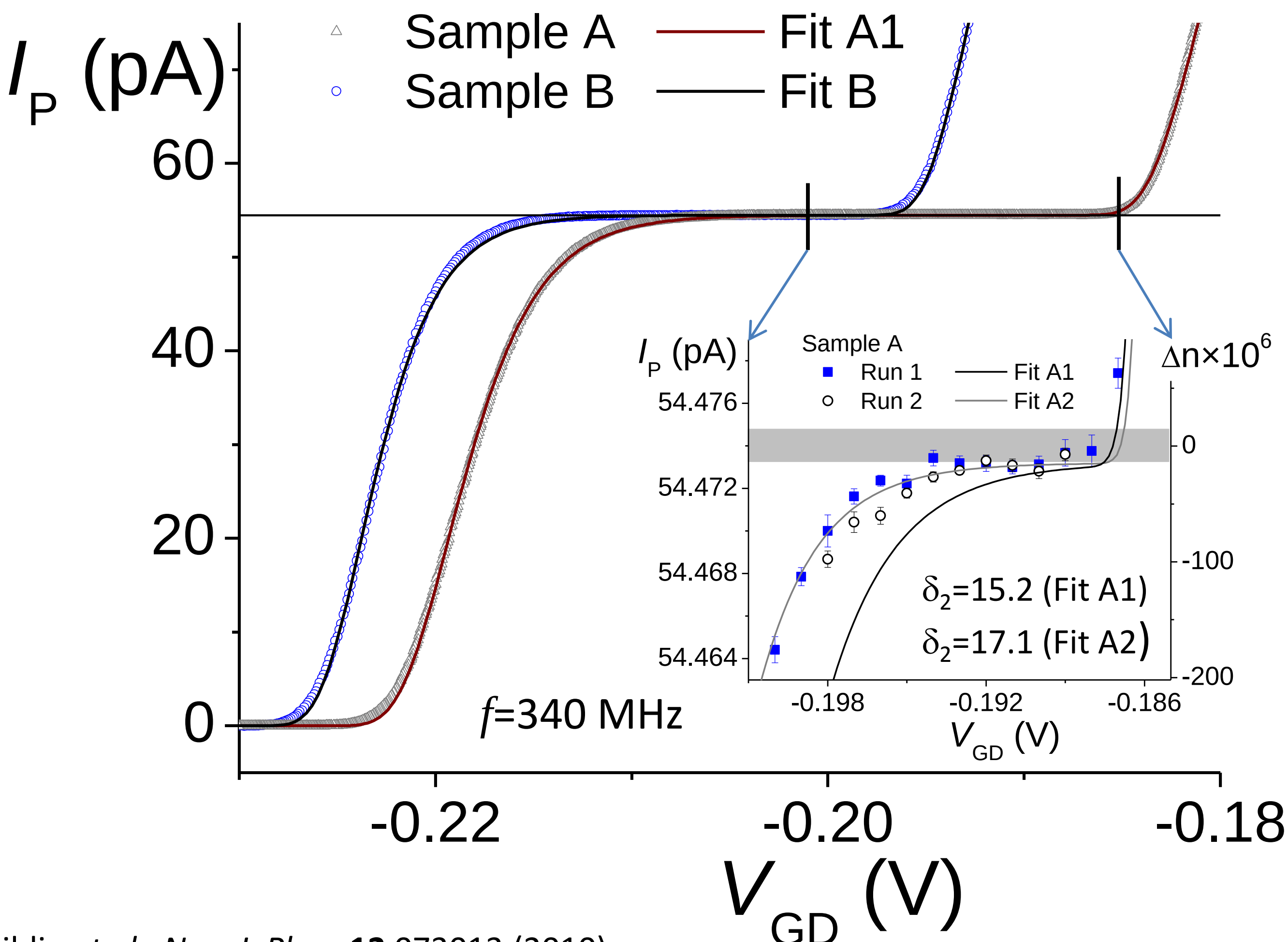
- **Outlook for metrological applications**



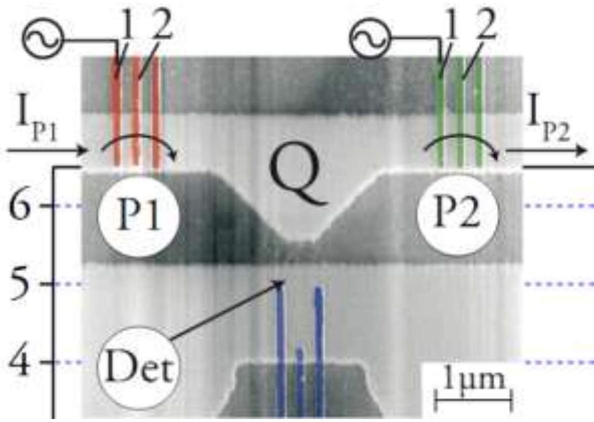
Traceable measurement (NPL)



S.Giblin *et al.*, *New J. Phys.* **12** 073013 (2010)

Outlook for metrological applications

- Advantages:
  - Optimal frequencies in 100 MHz ÷ 1 GHz range
  - Stability against voltage bias ⇒ negligible leakage
  - Single ac driving signal ⇒ parallelization
  - Robustness ⇒ one gate per pump to tune
- Optimization directions:
  - barrier selectivity optimization
  - serial operation with error detection and correction (Wulf & Zorin, arXiv:0811.3927)



L.Fricke *et al*., PRB (2011)

Thank you!