Universal fermi liquid crossover and quantum criticality in a mesoscopic system

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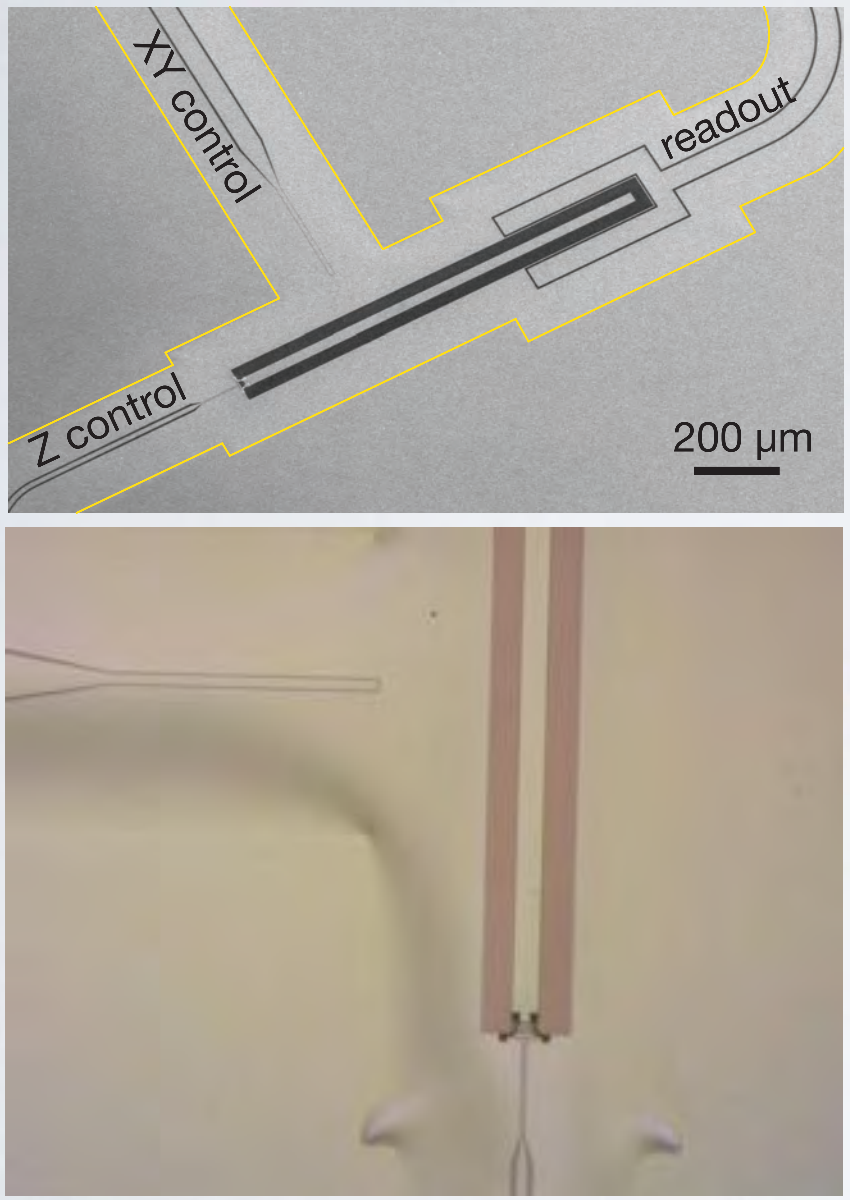
SPICE Quantum Thermodynamics and Transport

May 8, 2018

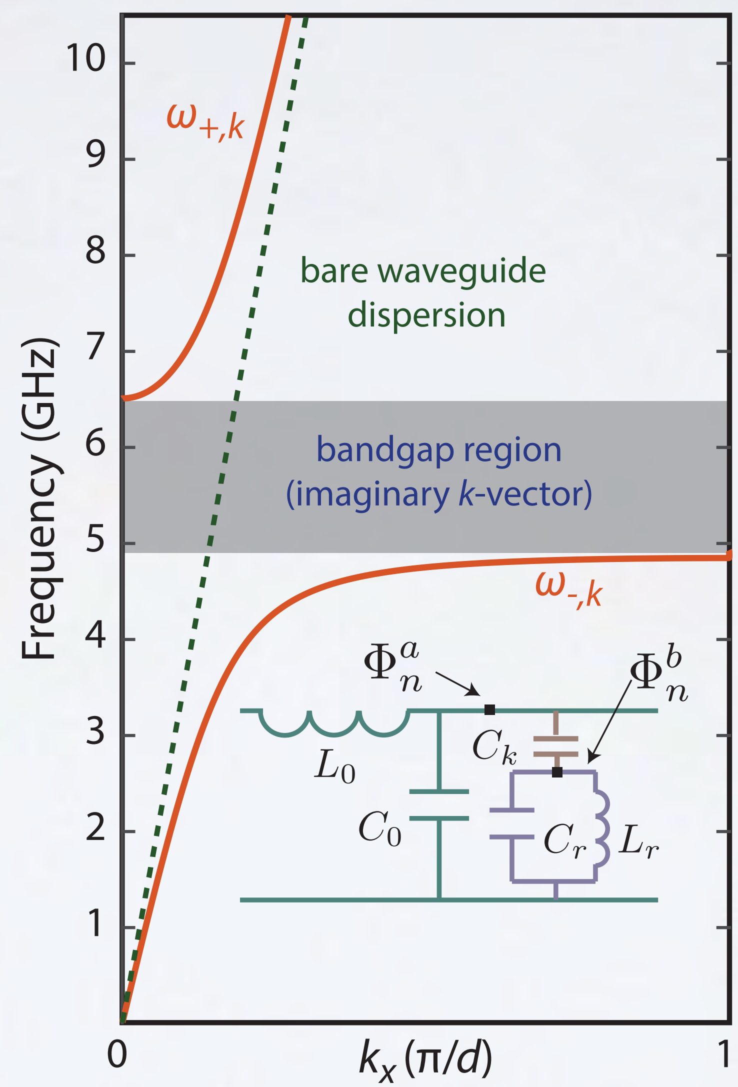
Hybrid quantum systems on silicon platforms

Transmon qubits on silicon membranes



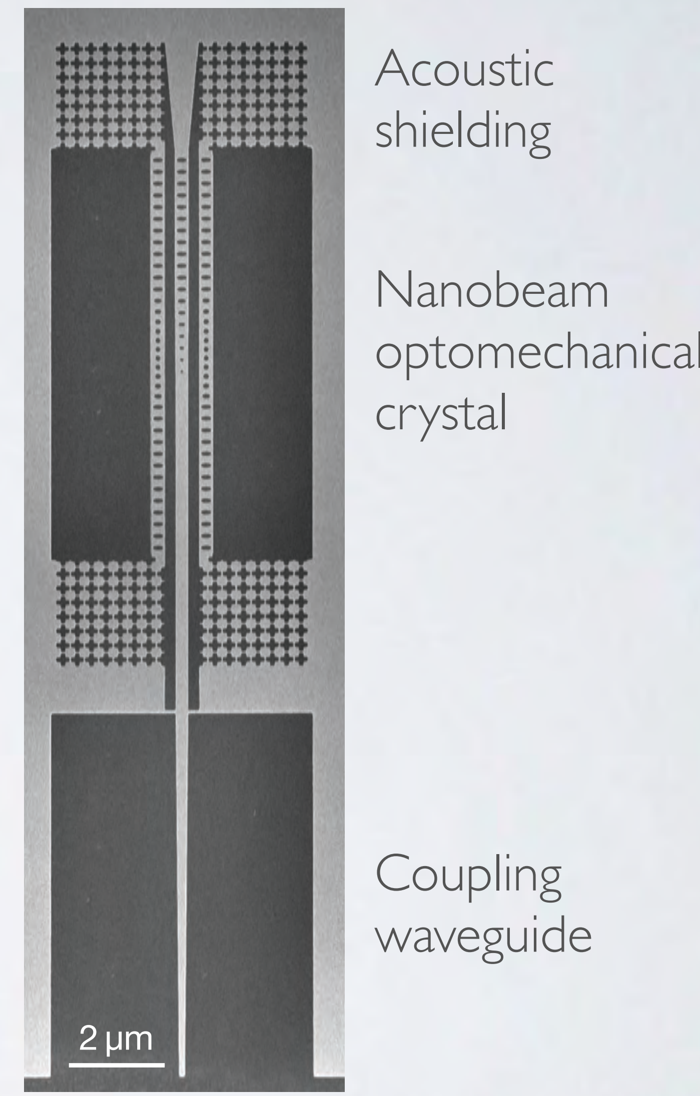
A. J. Keller, *et al.*, APL 111, 042603 (2017)

Superconducting metamaterials



M. Mirhosseini, *et al.*, arXiv:1802.01708 (2018)

Optomechanics and high-Q acoustic cavities



G. MacCabe, *et al.*, forthcoming

Hybrid quantum systems on silicon platforms

Transmon q… on silicon mem…

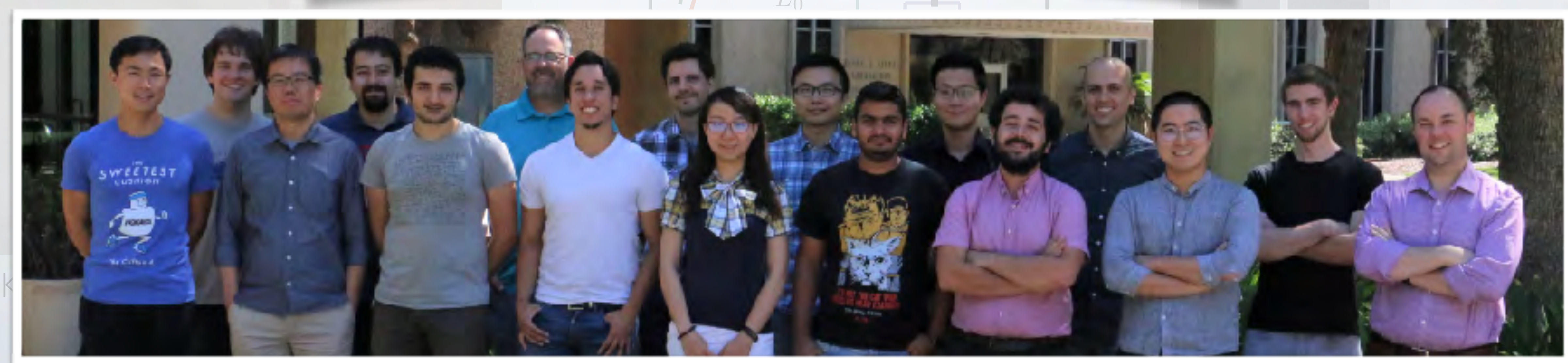
…tomechanics and …-Q acoustic cavities

Some Painter group research directions:

- Hybrid circuit quantum electrodynamics / acoustodynamics
- Superconducting metamaterials
- Information scrambling, measuring out-of-time-ordered correlators
- Waveguide QED

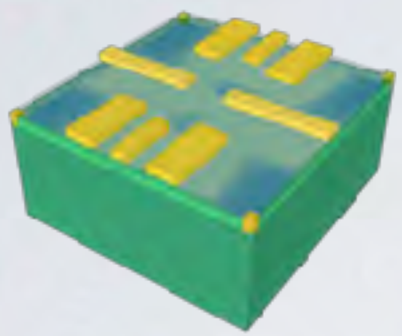
Acoustic shielding

Nanobeam optomechanical crystal

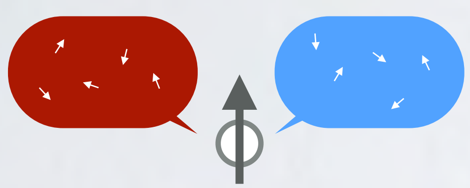


A. J. K… …ng

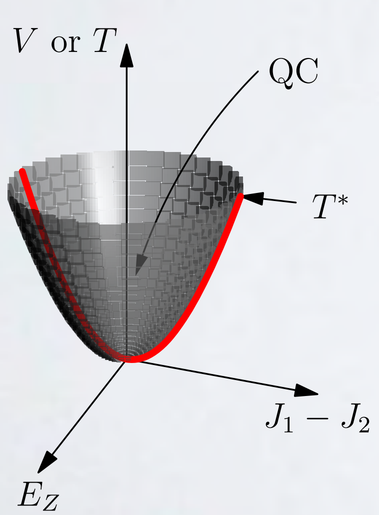
Outline



- **The Kondo effect, quantum phase transitions, and tunable quantum dot systems**



- The two-channel Kondo effect: a prototypical non-Fermi liquid state

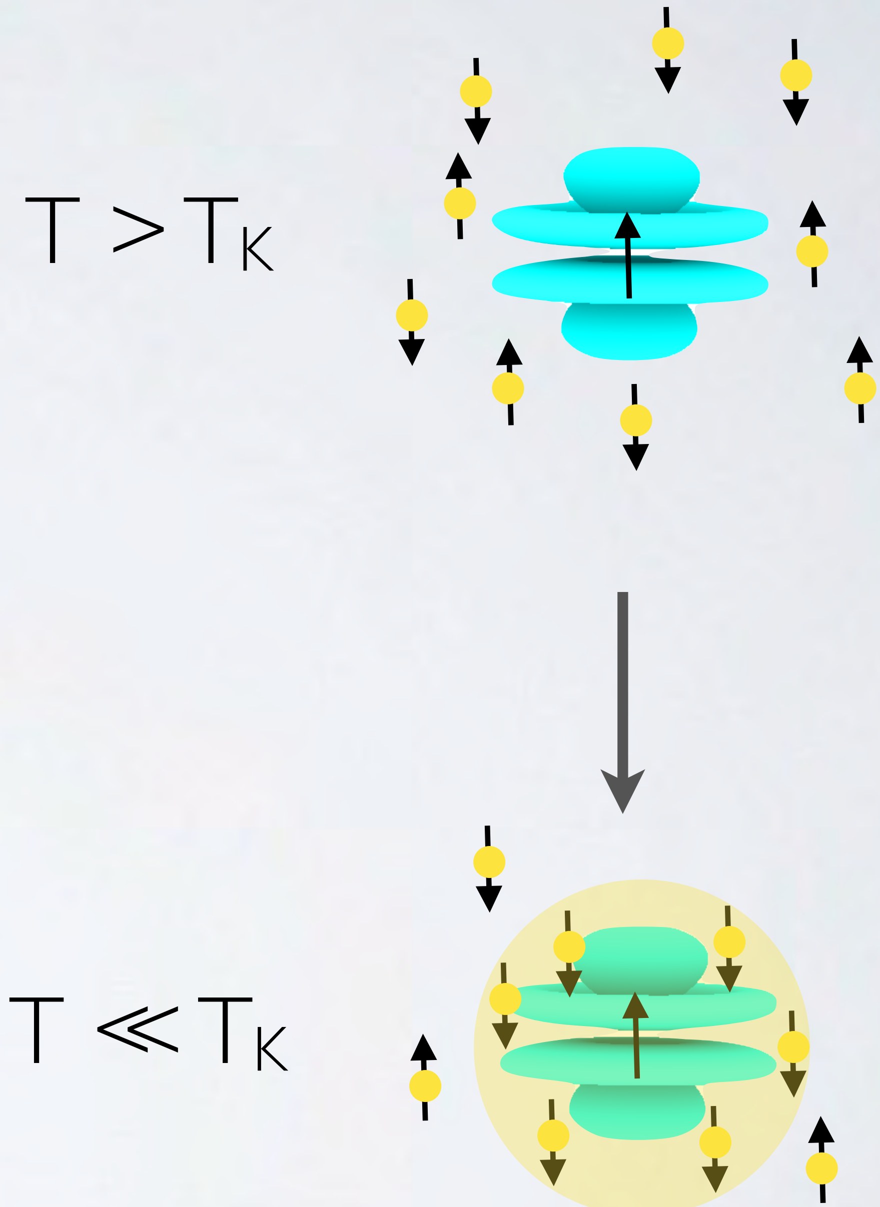


- Mapping the universal crossover between quantum critical and Fermi liquid states (Nature 526, 237 (2015))
- Future directions in using devices to explore quantum phase transitions

Kondo effect

$$H = J\hat{S} \cdot \hat{s}$$

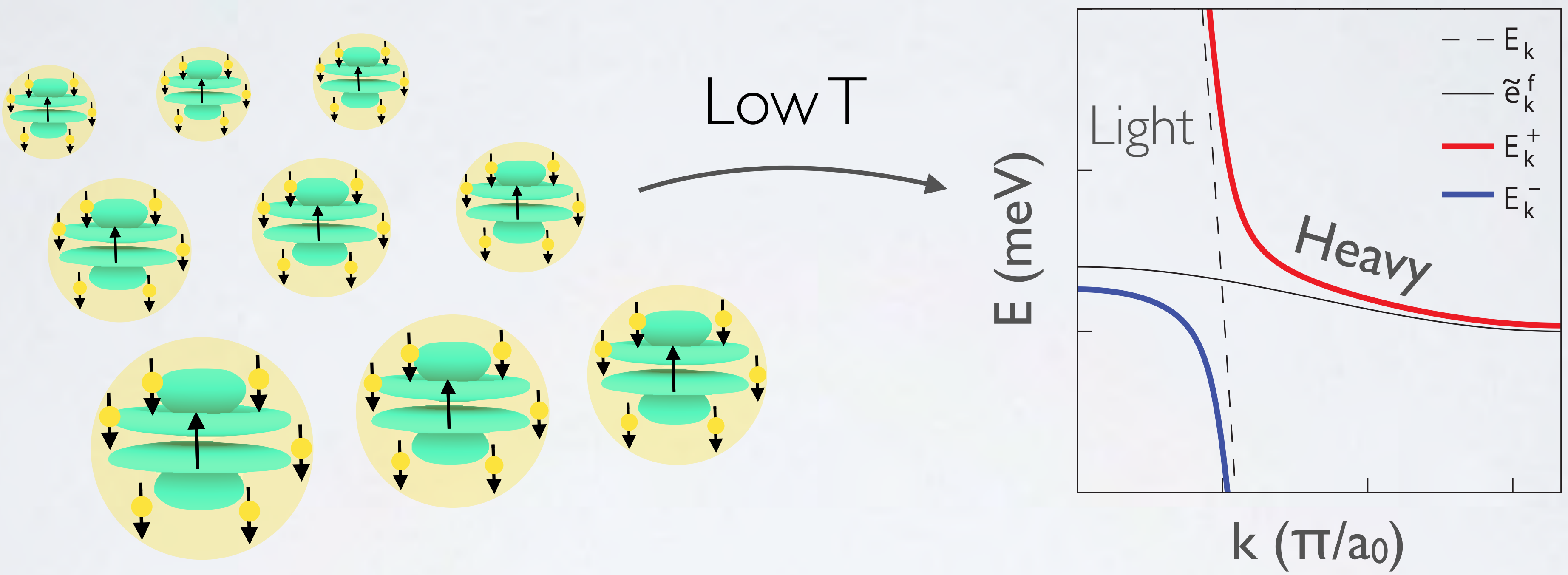
- Itinerant electrons screen a local moment
- Emergence of a dynamical energy scale, the Kondo temperature T_K
- Formation of a many-body singlet when $T << T_K$
- Describes low-energy physics of Anderson impurity model



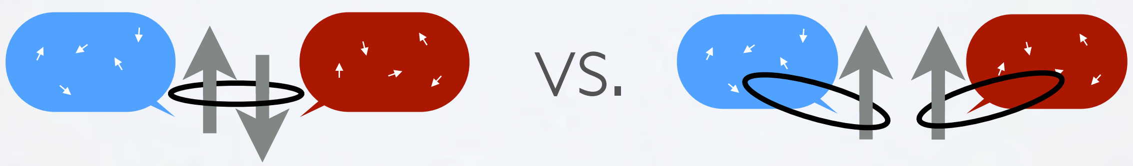
Many Kondo impurities

Heavy fermion systems

Diagrams adapted from M. H. Hamidian, PNAS 108, 18233 (2011).

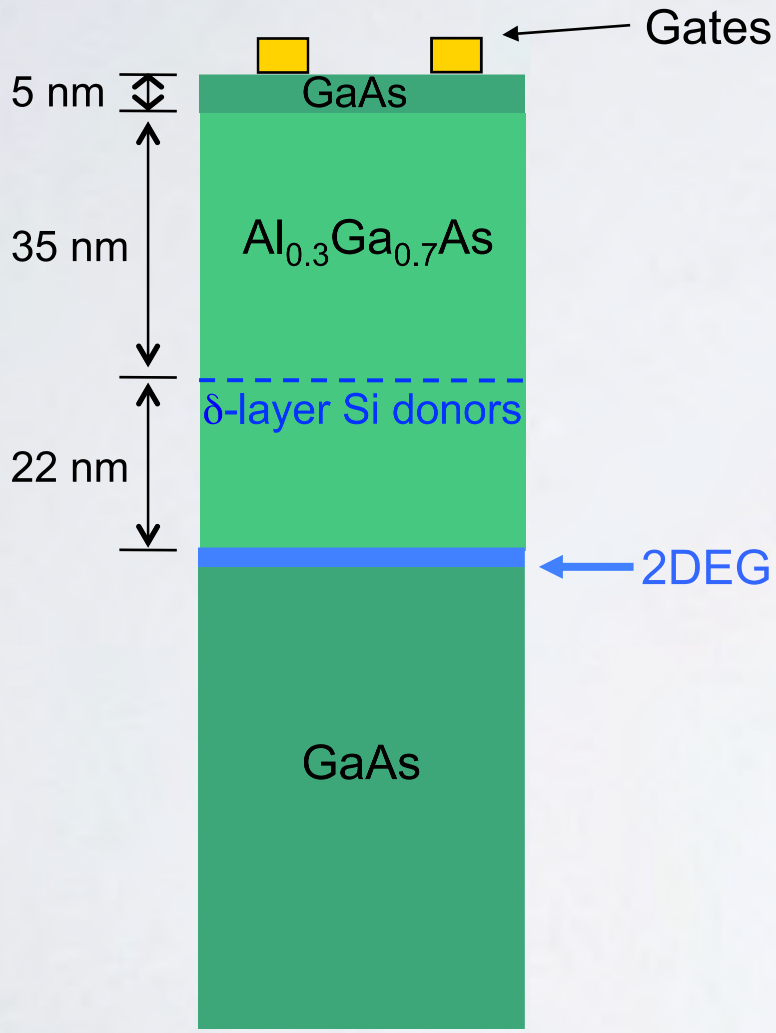


Two-impurity Kondo effect

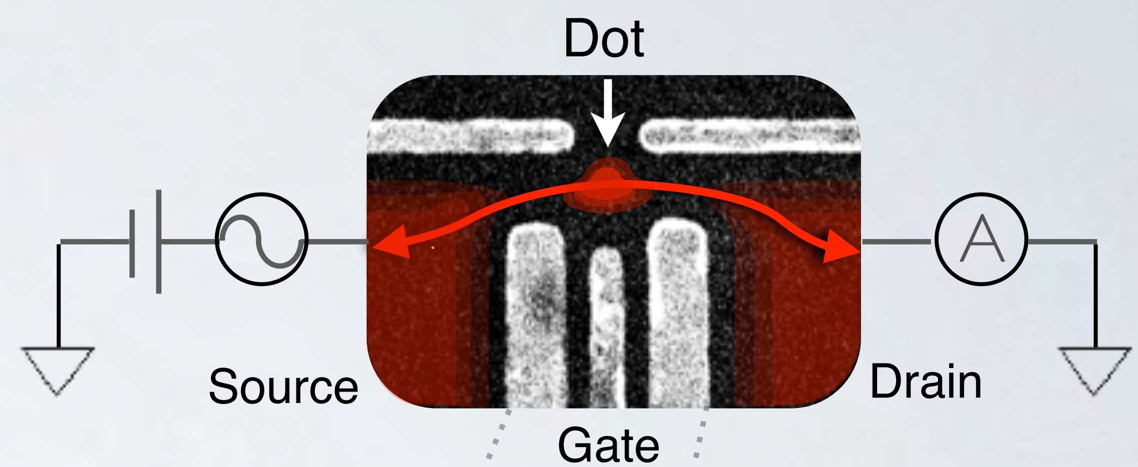


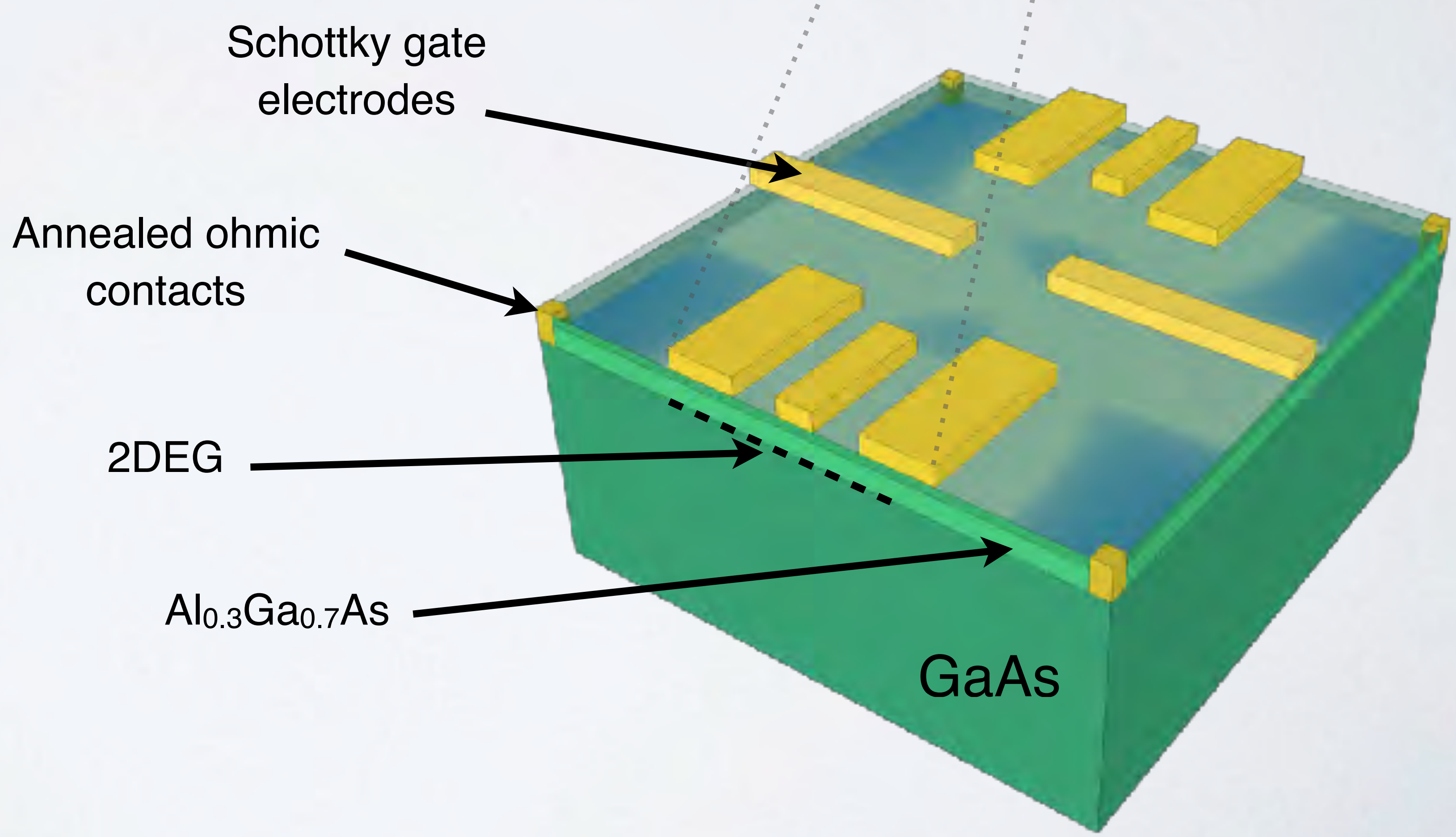
Quantum dots

in GaAs/AlGaAs heterostructures



Measure G = dI/dV at ~ 20 mK





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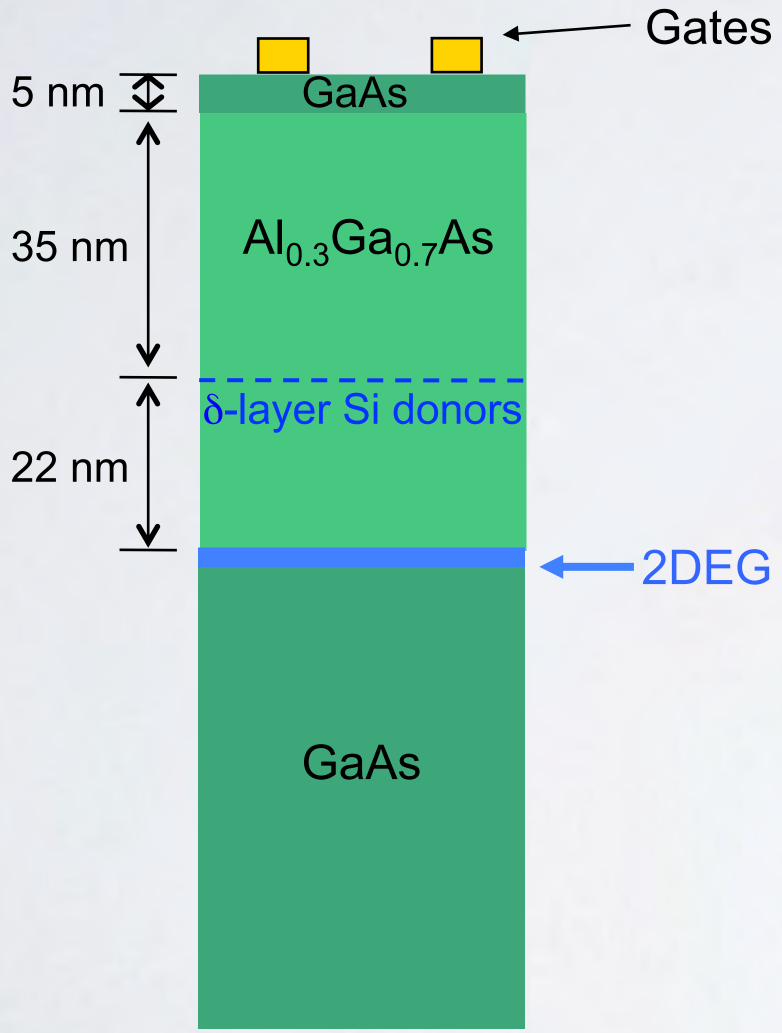

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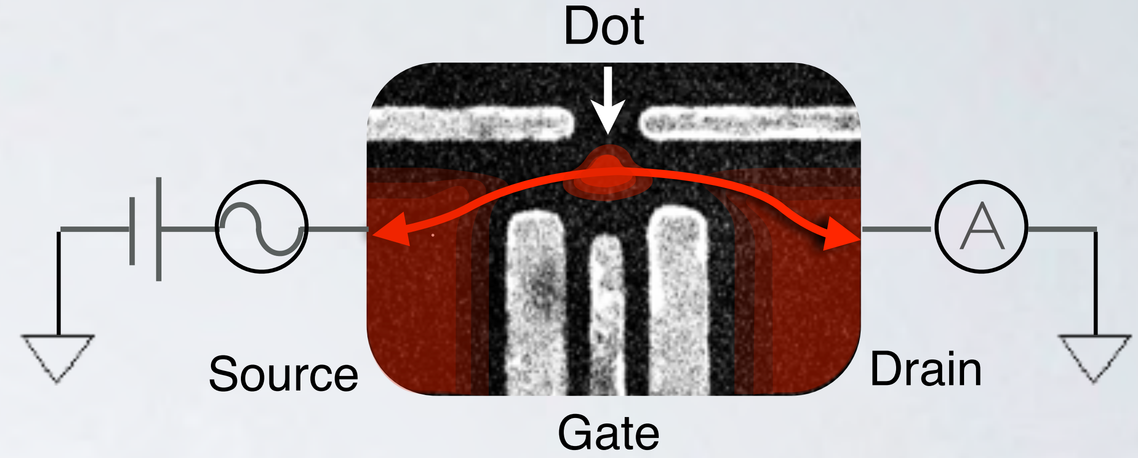
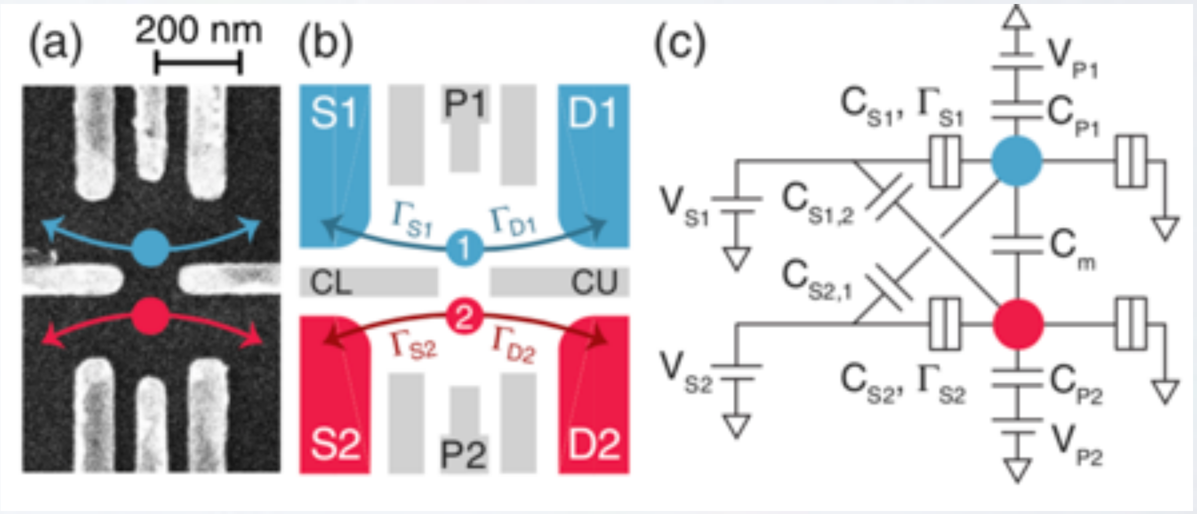


Cotunneling Drag Effect in Coulomb Coupled Quantum Dots
A. Keller, J. S. Lim, D. Sánchez, R. López, et al., PRL 117, 066602 (2016)



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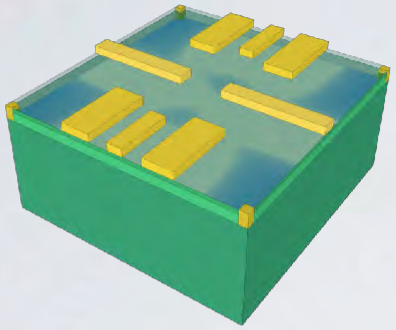

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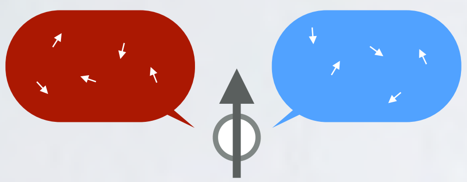
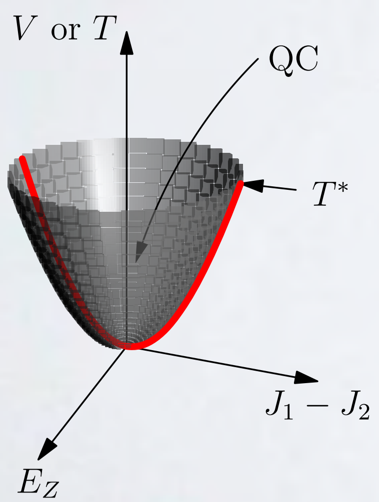


- **The two-channel Kondo effect: a prototypical non-Fermi liquid state**

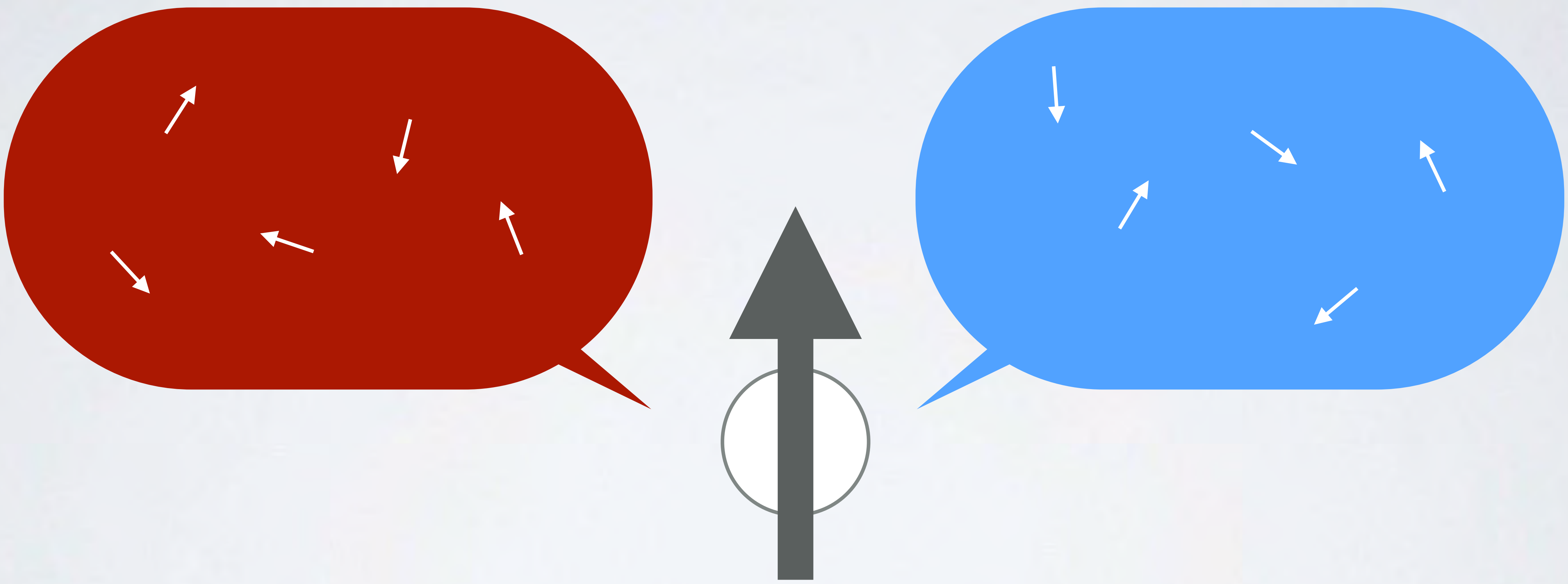


- Mapping the universal crossover between quantum critical and Fermi liquid states (Nature 526, 237 (2015))

- Future directions in using devices to explore quantum phase transitions

Two-channel Kondo effect

A model quantum phase transition

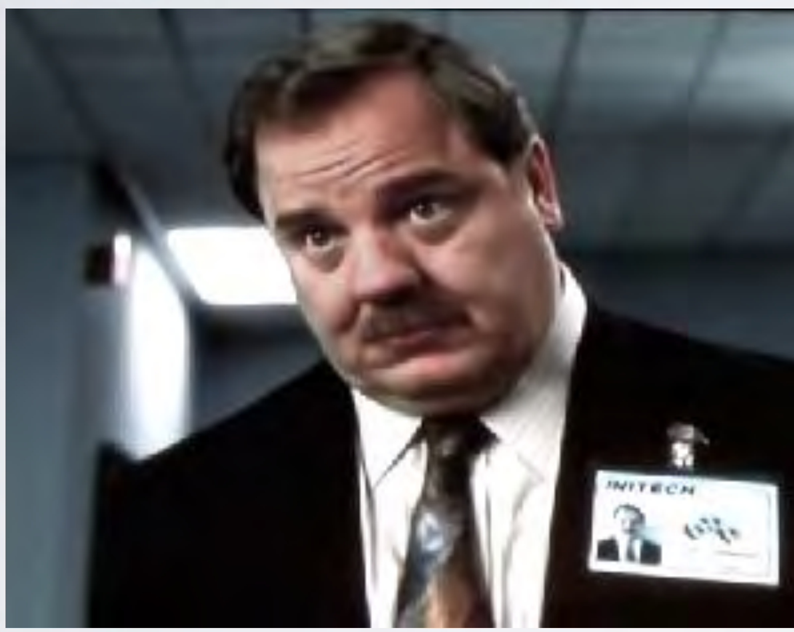


First discussed theoretically by Nozières, and Blandin,
J. Physique (Paris), 41, 193–211 (1980).

Two-channel Kondo effect

An analogy

Boss #1



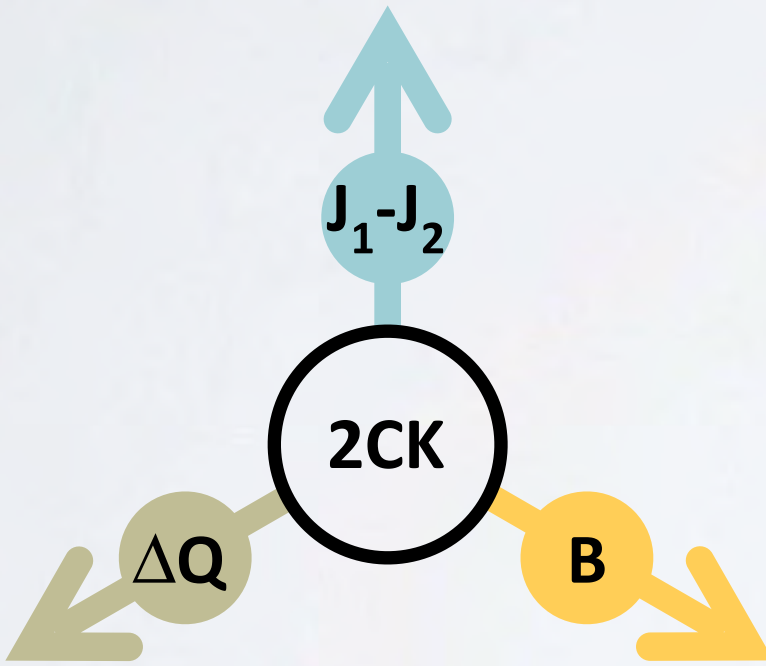
Boss #2

Employee

Two-channel Kondo effect

Hamiltonian and relevant perturbations

$$H_{2\mathrm{CK}} = \sum_{\alpha,k} \epsilon_k c^\dagger_{k\sigma\alpha} c_{k\sigma\alpha} + J\vec{S}\cdot(\vec{s}_L + \vec{s}_R) + \delta H_{2\mathrm{CK}}$$



Graphic courtesy L. Peeters

Exchange coupling detuning

Charge transfer between channels

Magnetic field

Mitchell & Sela, Physical Review B 85 235127 (2012).

Two-channel Kondo effect

Peculiar properties anticipated at the quantum critical point

- Free Majorana fermion local to the impurity site

  A. K. Mitchell, *et al.*, PRL 116, 157202 (2016); many others, but this paper says it straightforwardly

- Impurity zero-point entropy = 1/2 log 2 (infinite system size)

  N. Andrei & C. Destri, PRL 52, 364 (1984)

- 2CK fixed point is identical to the 2IK fixed point, up to potential scattering

  J. M. Maldacena & A. W. W. Ludwig, Nucl. Phys. B 506, 565–588 (1997)

  A. K. Mitchell, *et al.,* PRL 108, 086405 (2012)

- Incoming electrons scatter off the impurity into collective excitations only

  J. M. Maldacena & A. W. W. Ludwig, Nucl. Phys. B 506, 565–588 (1997)

  L. Borda, *et al.*, PRB 75, 235112 (2007)

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$$\delta H_{2\mathrm{CK}} = \sum_{l=x,y,z} \Delta_l \sum_{\alpha\beta,\sigma\sigma',kk'} c^\dagger_{k\sigma\alpha}\left(\frac{1}{2}\vec{\sigma}_{\sigma\sigma'}\tau^l_{\alpha\beta}\right) c_{k'\sigma'\beta}\cdot\vec{S} + \vec{B}\cdot\vec{S}$$

Two-channel Kondo effect

Detuning exchange couplings

$$H_{2\mathrm{CK}} = \sum_{\alpha,k} \epsilon_k c^\dagger_{k\sigma\alpha} c_{k\sigma\alpha} + J\vec{S}\cdot(\vec{s}_L + \vec{s}_R) + \delta H_{2\mathrm{CK}}$$

$$\delta H_{2\mathrm{CK}} = \Delta_z(\vec{s}_L - \vec{s}_R)\cdot\vec{S}$$

Two-channel Kondo effect

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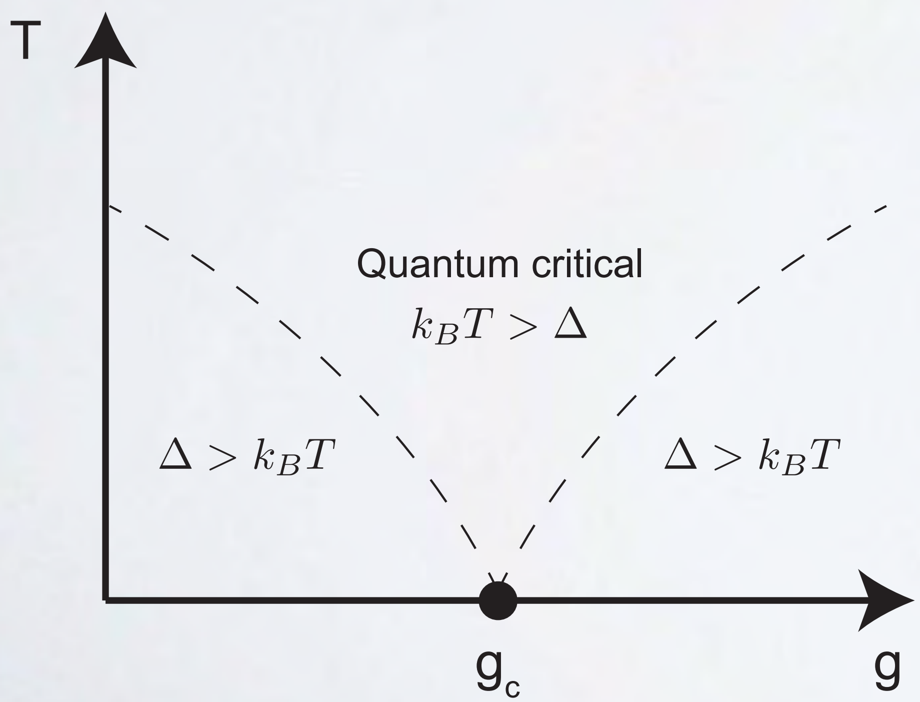

$$\Delta \sim J|g - g_c|^{z\nu}$$

$$\xi^{-1} \sim \Lambda|g - g_c|^{\nu}$$

$$\Delta \sim \xi^{-z}$$

S. Sachdev, *Quantum Phase Transitions, 2nd ed. (2011).*

Two-channel Kondo effect

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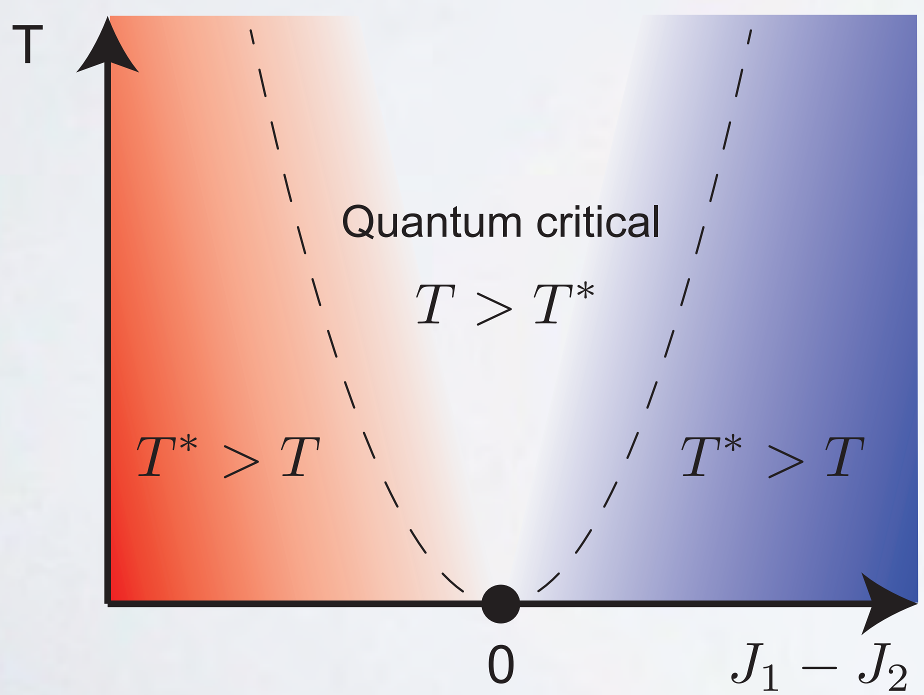


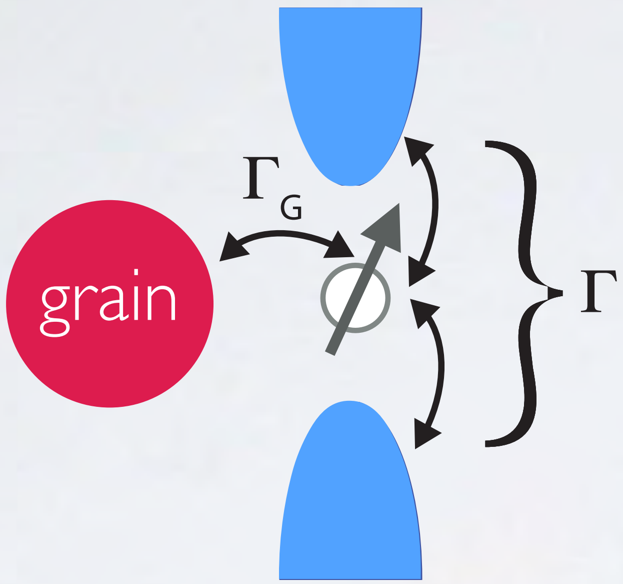
$$T^* \sim (J_1 - J_2)^2 \qquad z\nu = 2$$

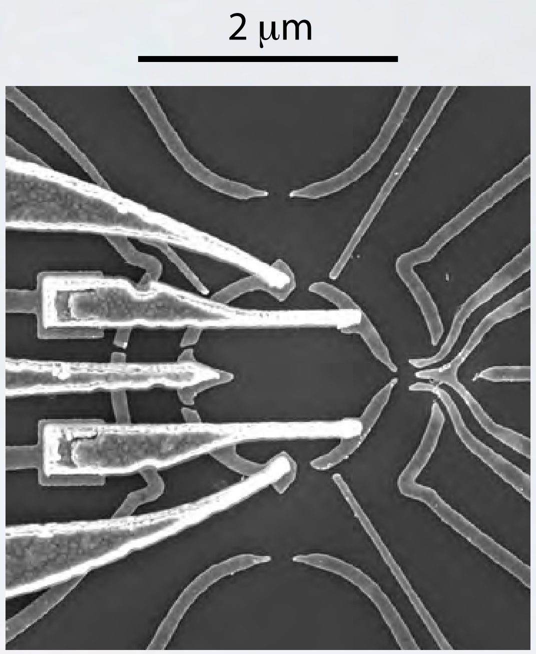
$$\xi^{-1} \sim (J_1 - J_2)^2 \qquad \nu = 2$$

$$T^* \sim \xi^{-1} \qquad z = 1$$

Mitchell, Becker, Bulla, Physical Review B 84, 115120 (2011).

How can we implement 2CK?





Quantum dot tunnel coupled to a "metallic grain"

Small enough that grain charging energy $E_C \gg k_B T$

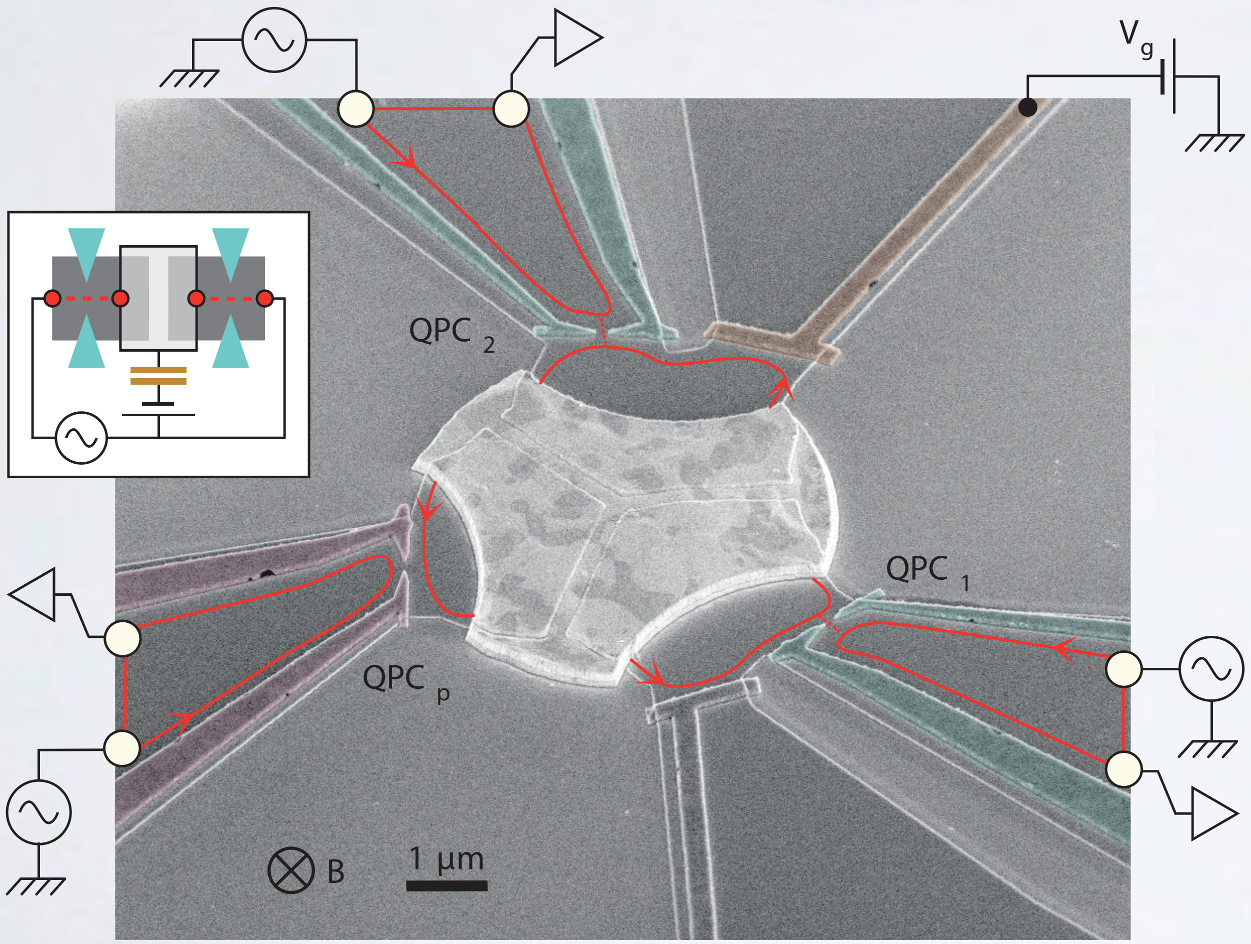
Large enough that level spacing $\Delta \lesssim k_B T$

Y. Oreg & D. Goldhaber-Gordon, PRL 90, 136602 (2003)

How can we implement 2CK?

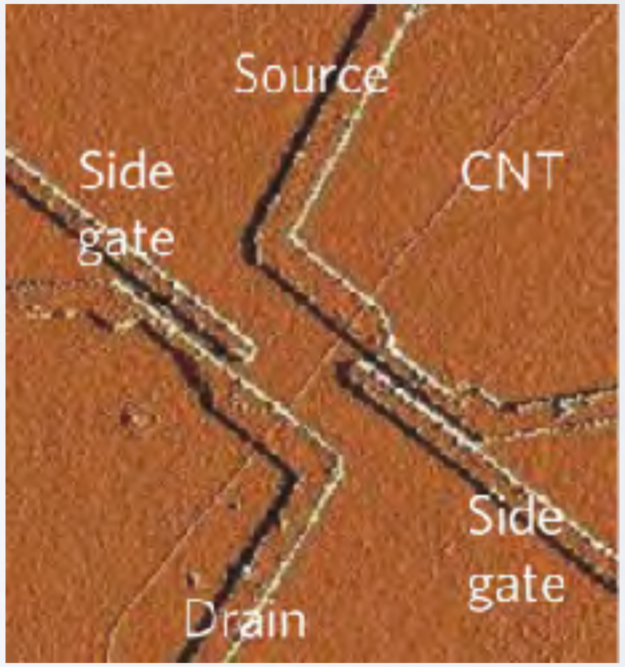
Charge 2CK

Z. Iftikhar, et al., Nature 526, 233 (2015)

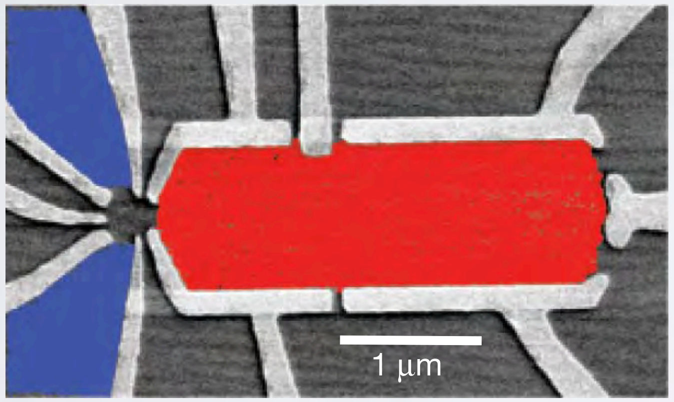


Related QPT in a nanowire

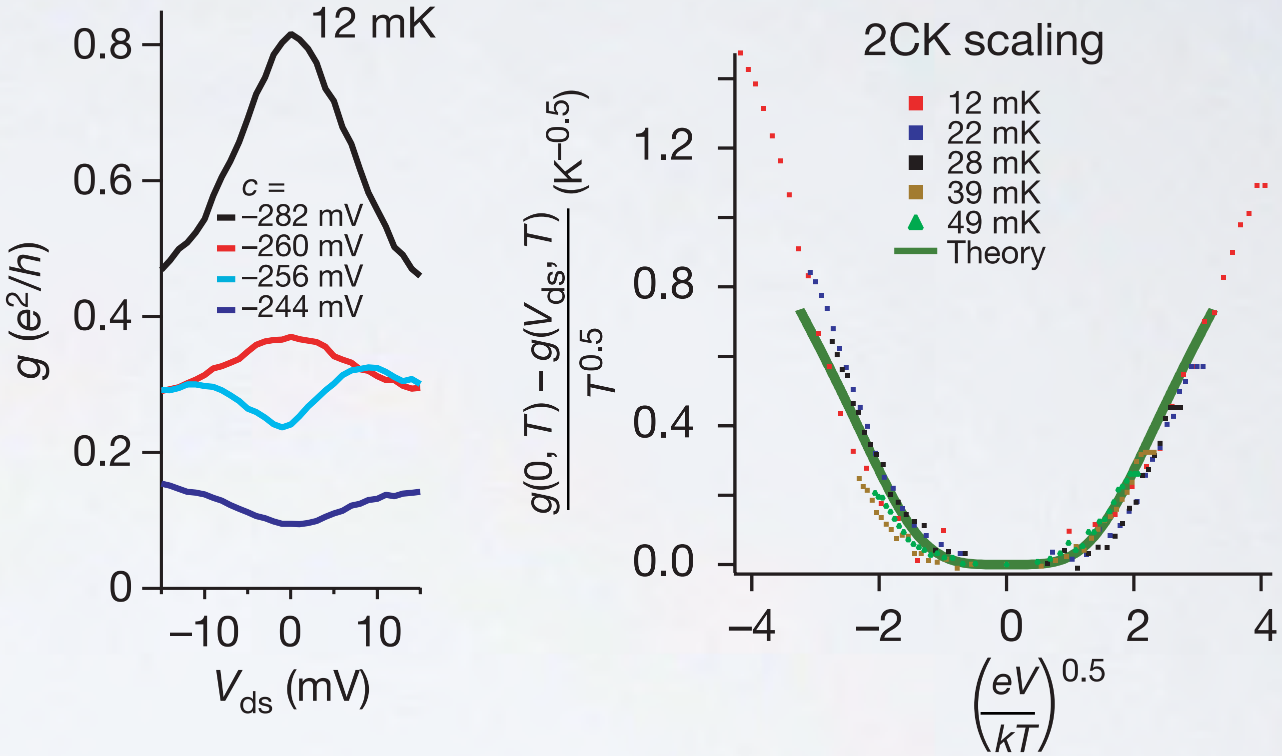
H.T. Mebrahtu, et al.,
Nature Physics 9, 9 (2013).



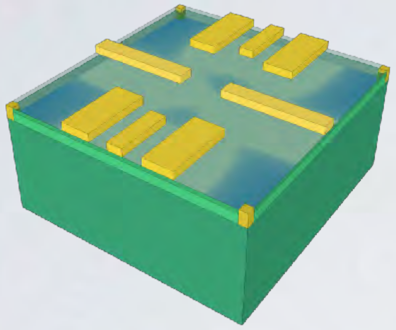
Quantum critical scaling



Potok, et al., Nature 446, 167–71 (2007)



Outline



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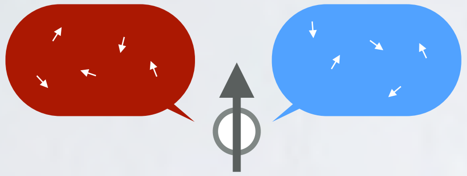

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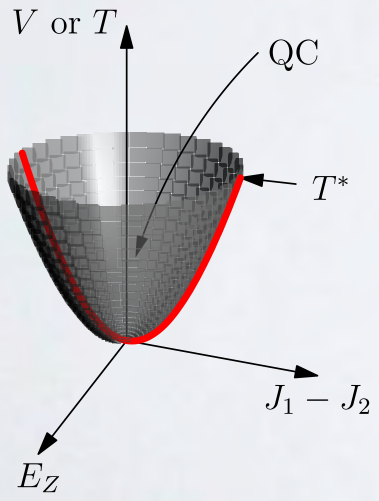
- **Mapping the universal crossover between quantum critical and Fermi liquid states** (Nature 526, 237 (2015))



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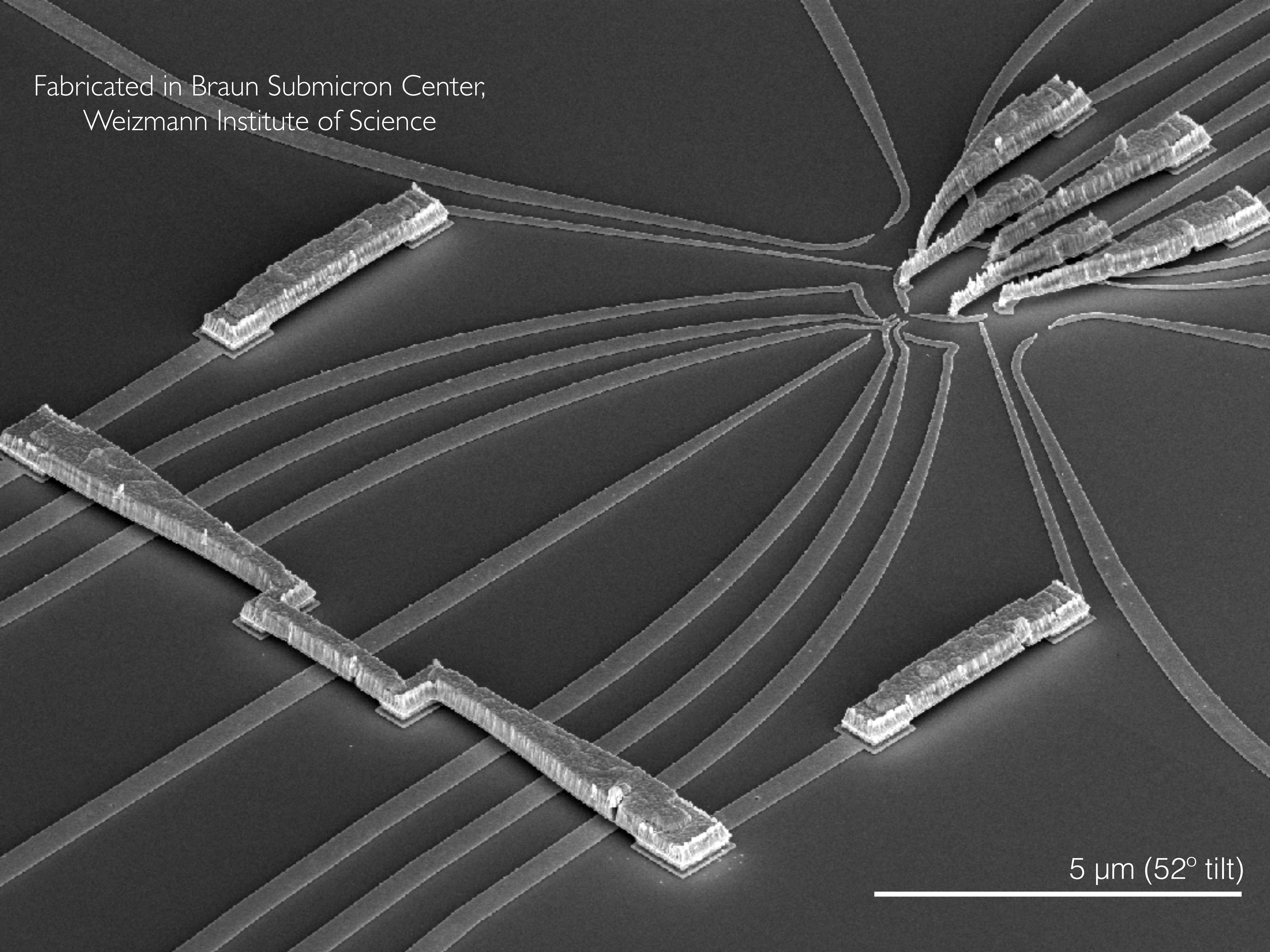
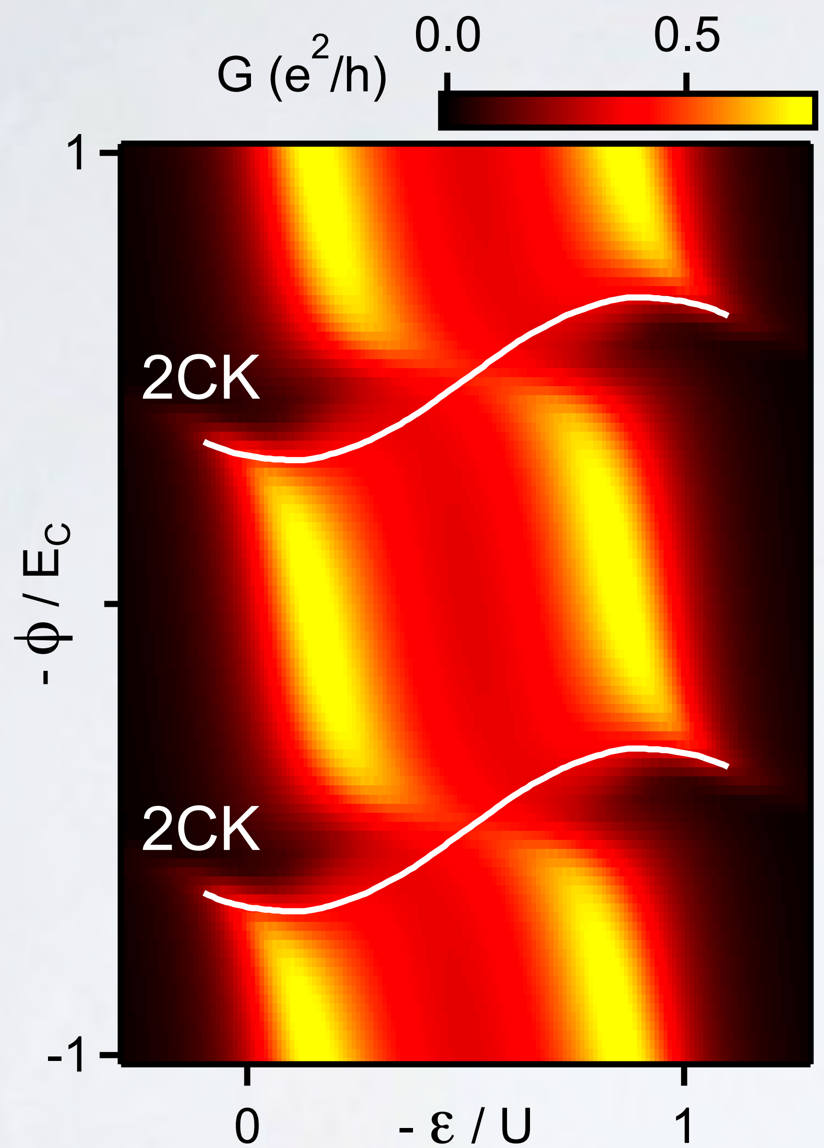

Fabricated in Braun Submicron Center,
Weizmann Institute of Science
5 μm (52° tilt)

Identifying a 2CK state

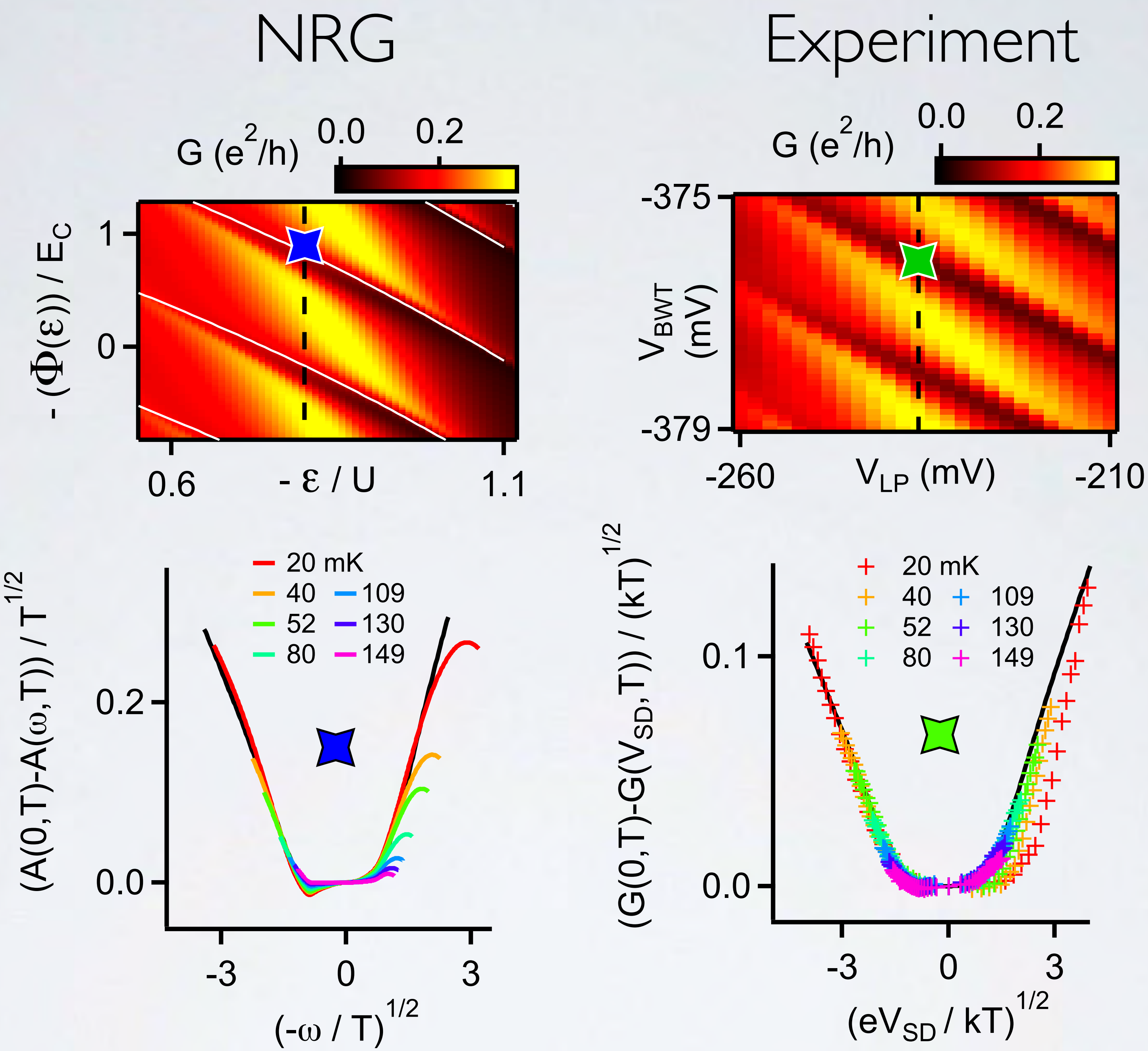


DM-NRG calculation

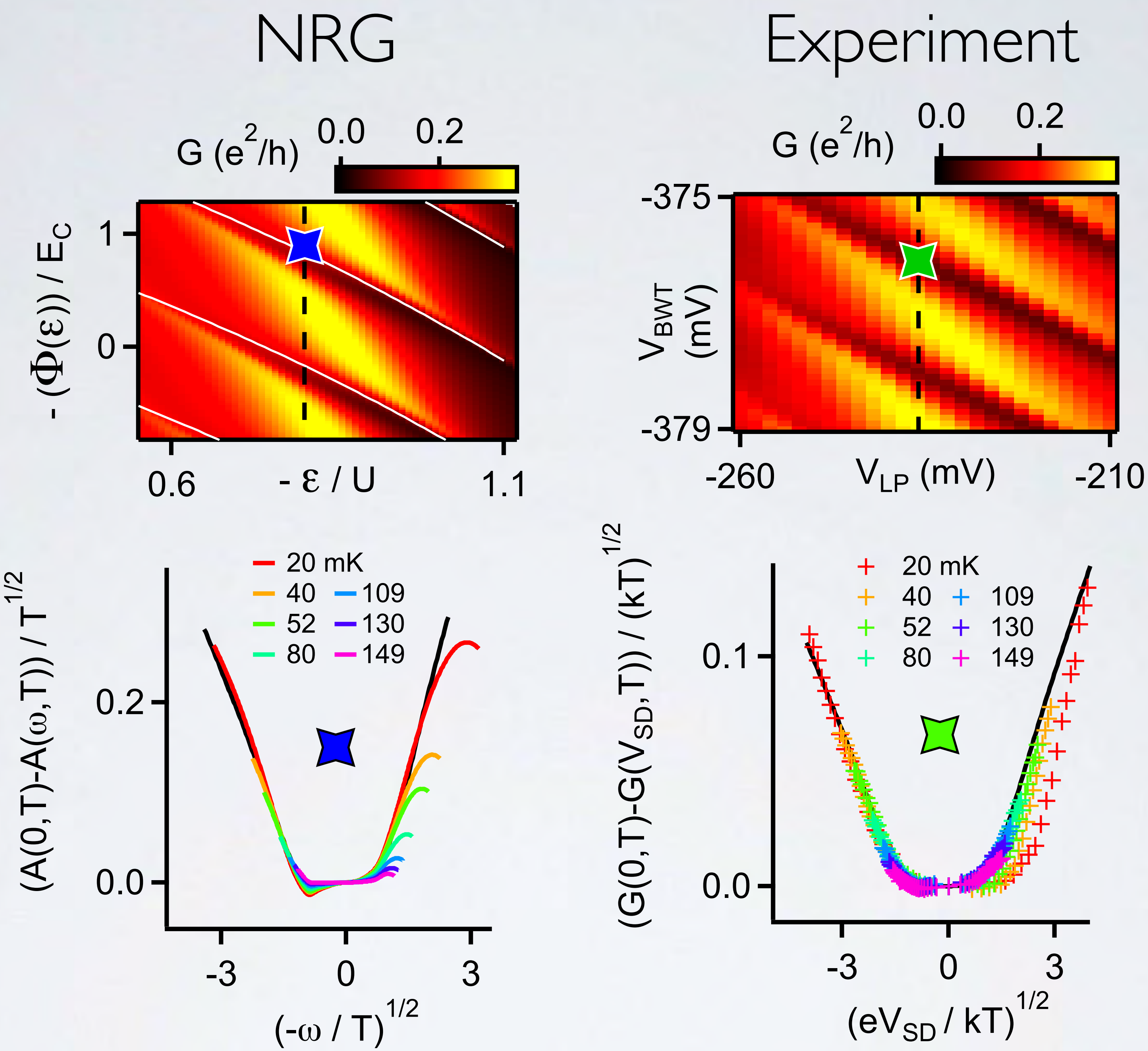
<u>Theory collaborators:</u>

G. Zaránd & C. P. Moca
(Budapest U. of
Technology and
Economics),

I. Weymann
(Adam Mickiewicz U.)



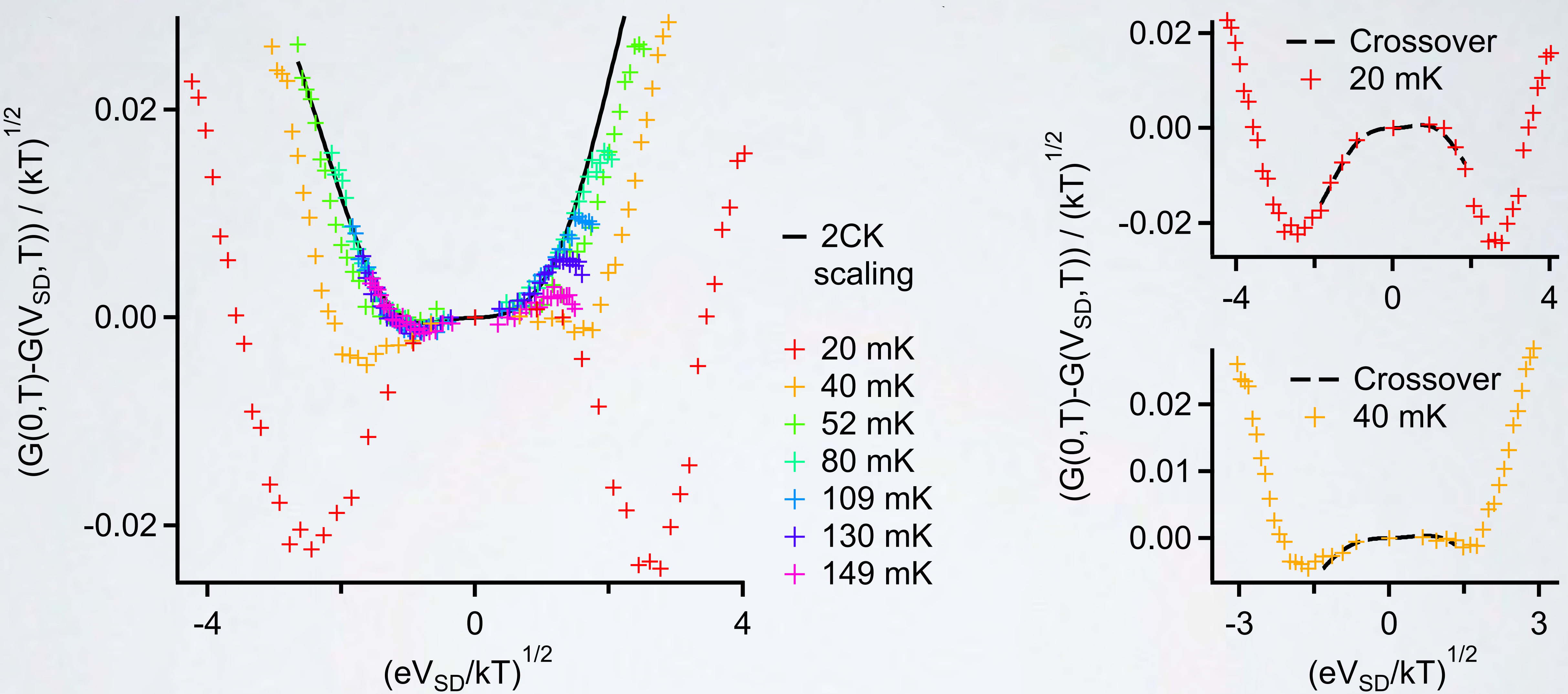
NRG
Experiment
G (e^2/h)
0.0
0.2
1
0
- (Φ(ε)) / E_C
0.6
- ε / U
1.1
-375
-379
V_BWT (mV)
-260
V_LP (mV)
-210
20 mK
40
52
80
109
130
149
0.2
0.0
(A(0,T)-A(ω,T)) / T^1/2
-3
0
3
(-ω / T)^1/2
0.1
0.0
(G(0,T)-G(V_SD,T)) / (kT)^1/2
(eV_SD / kT)^1/2



$$\Sigma^R(\omega) = -\frac{in_i}{2\pi\nu}\left\{[1-e^{2i\delta_P}S_{(1)}] - e^{2i\delta_P}N\lambda\left(\frac{2\pi}{\beta}\right)^{\Delta} 2\sin(\pi\Delta)\int_0^1 du\left[u^{-i\beta\omega/2\pi}u^{-1/2}(1-u)^{\Delta}F(u) - \frac{\Gamma(1+2\Delta)}{\Gamma^2(1+\Delta)}u^{(\Delta-1)}(1-u)^{-(1+\Delta)}\right]\right\}$$

Affleck and Ludwig, PRB 48, 7297 (1993)

The Fermi liquid crossover



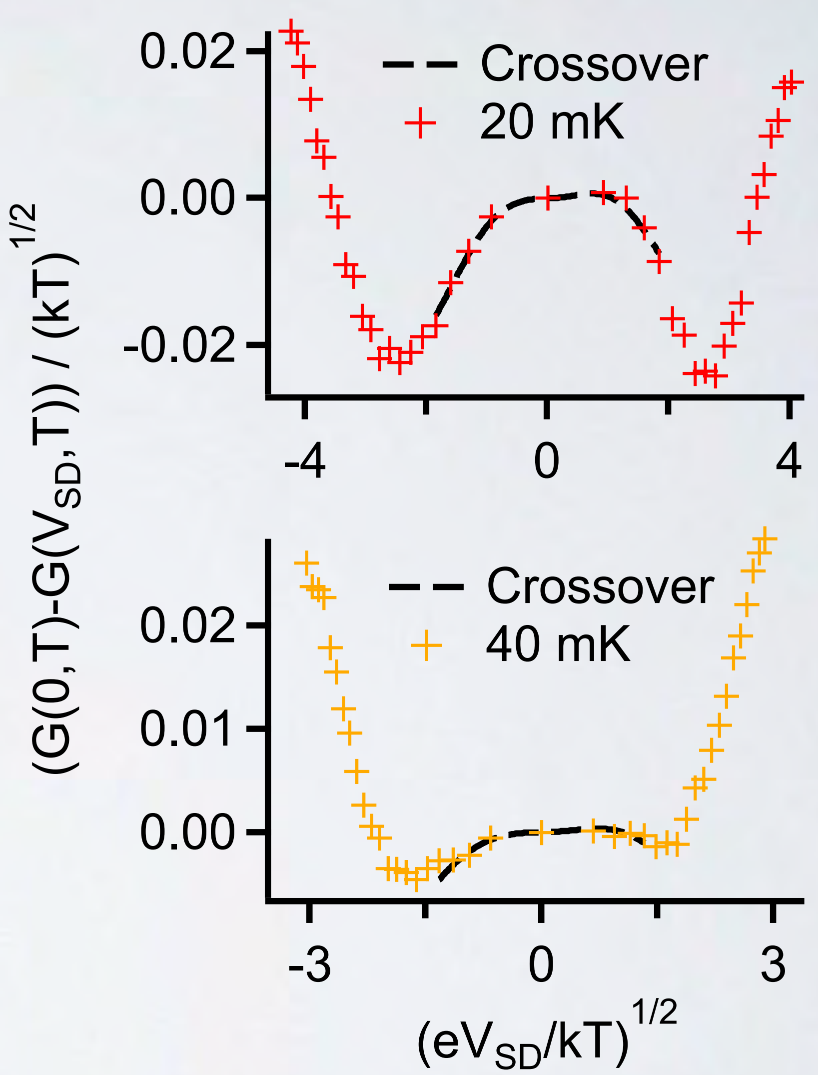
The Fermi liquid crossover

$$2\pi i\nu \mathcal{T}_{\sigma\alpha,\sigma'\alpha'}(\omega,T) = \delta_{\sigma\sigma'}\delta_{\alpha\alpha'} - S_{\sigma\alpha,\sigma'\alpha'}\mathcal{G}\left(\frac{\omega}{T^*},\frac{T}{T^*}\right)$$

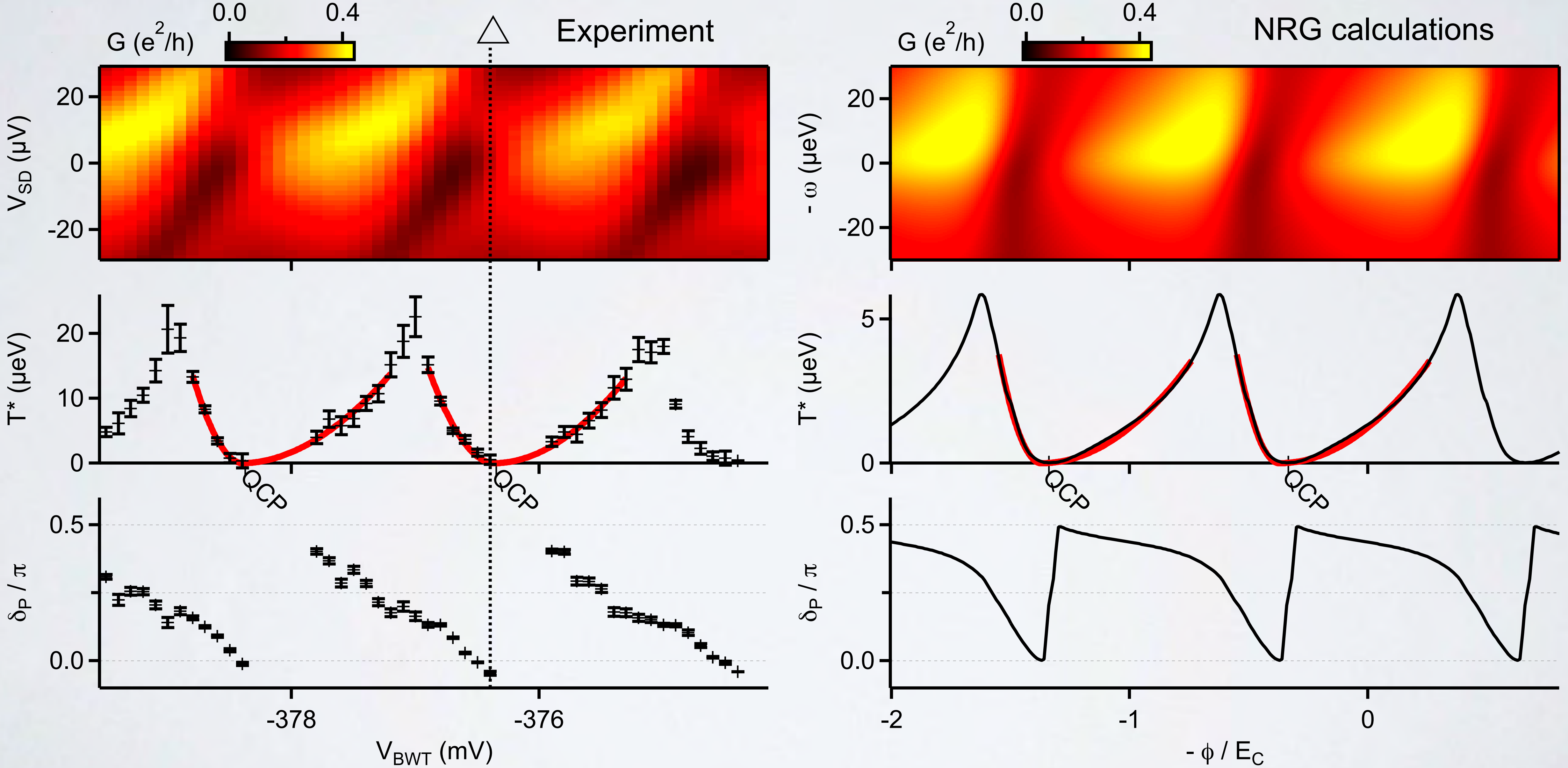
$$\mathcal{G}\left(\tilde{\omega},\tilde{T}\right) = \frac{\frac{-i}{\sqrt{2\pi^3\tilde{T}}}}{\tanh\frac{\tilde{\omega}}{2\tilde{T}}}\frac{\Gamma\left(\frac{1}{2}+\frac{1}{2\pi\tilde{T}}\right)}{\Gamma\left(1+\frac{1}{2\pi\tilde{T}}\right)}\times$$

$$\int_{-\infty}^{\infty}dx\frac{e^{\frac{ix\tilde{\omega}}{\pi\tilde{T}}}}{\sinh x}\mathrm{Re}\left[{}_2F_1\left(\frac{1}{2},\frac{1}{2};1+\frac{1}{2\pi\tilde{T}},\frac{1-\coth x}{2}\right)\right]$$

Mitchell and Sela, PRB 85, 235127 (2012)



Critical exponents



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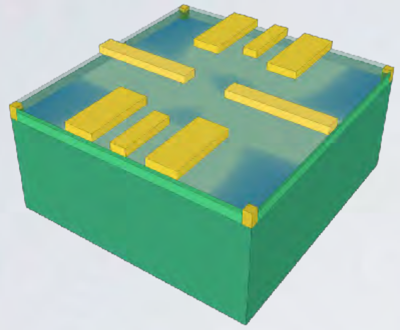

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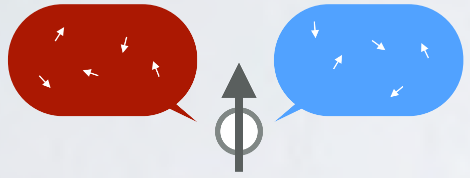

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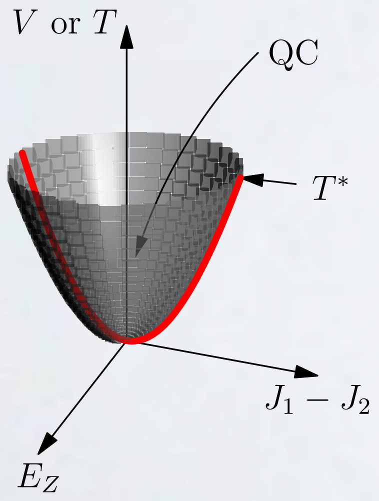

- Mapping the universal crossover between quantum critical and Fermi liquid states (Nature 526, 237 (2015))
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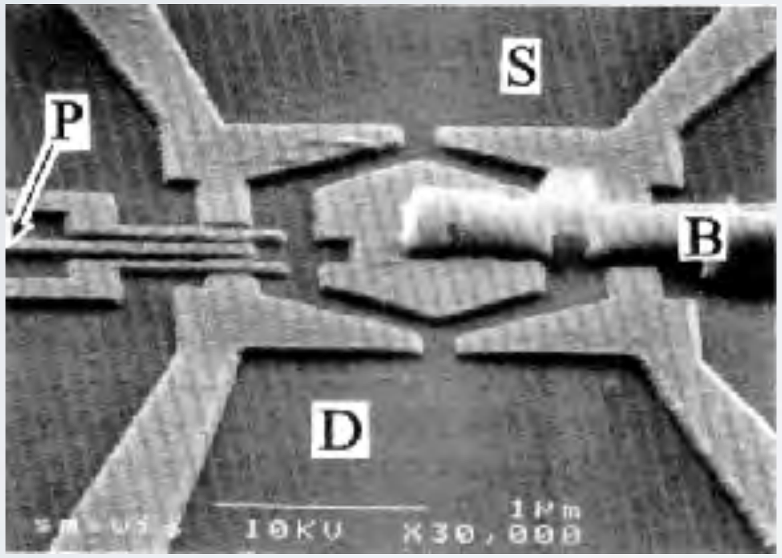
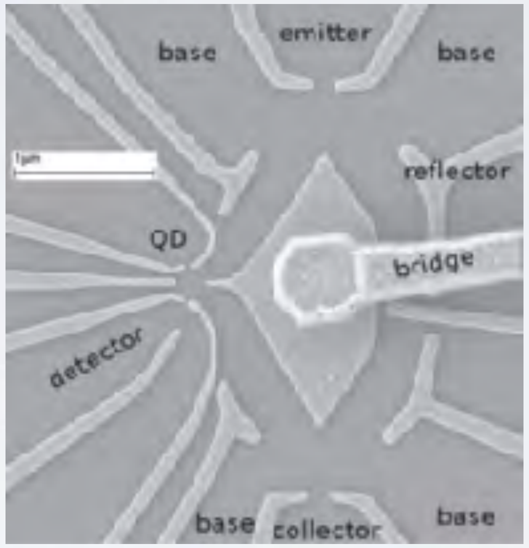
Phase-sensitive probes of non-Fermi liquids

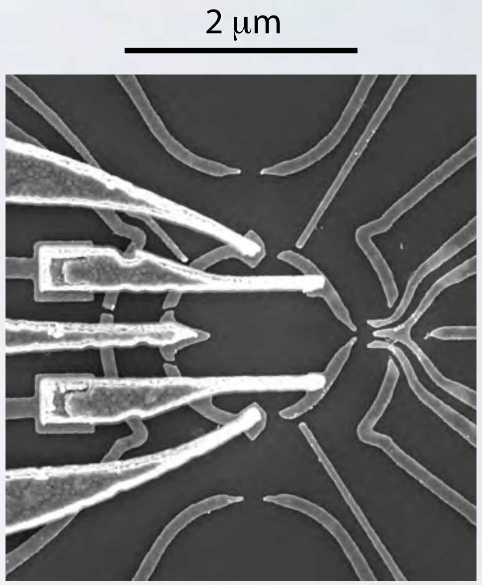
Aharonov-Bohm effect: $\varphi = \frac{e}{h}\int_P \mathbf{A}\cdot d\mathbf{x}$



A. Yacoby, et al.,
PRL 74, 4047 (1995)



M. Zaffalon, et al.,
PRL 100, 226601 (2008)



Related theory: A. Carmi, *et al.*, PRB 86, 115129 (2012).

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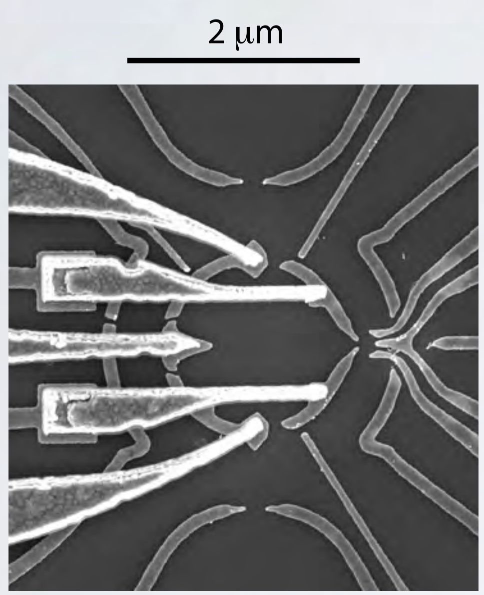
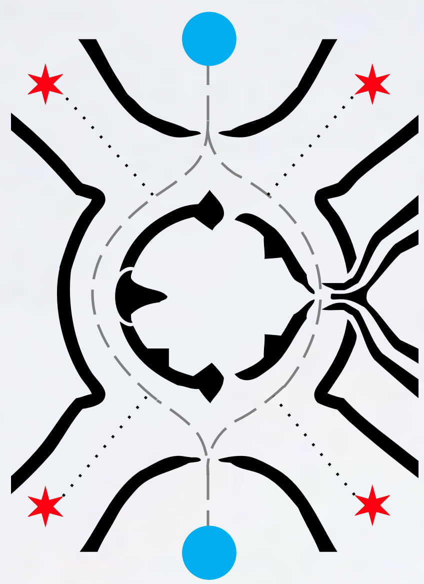
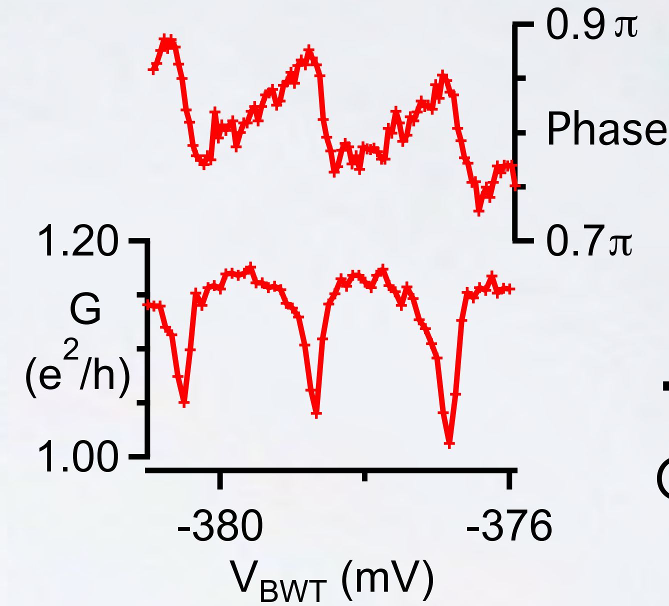
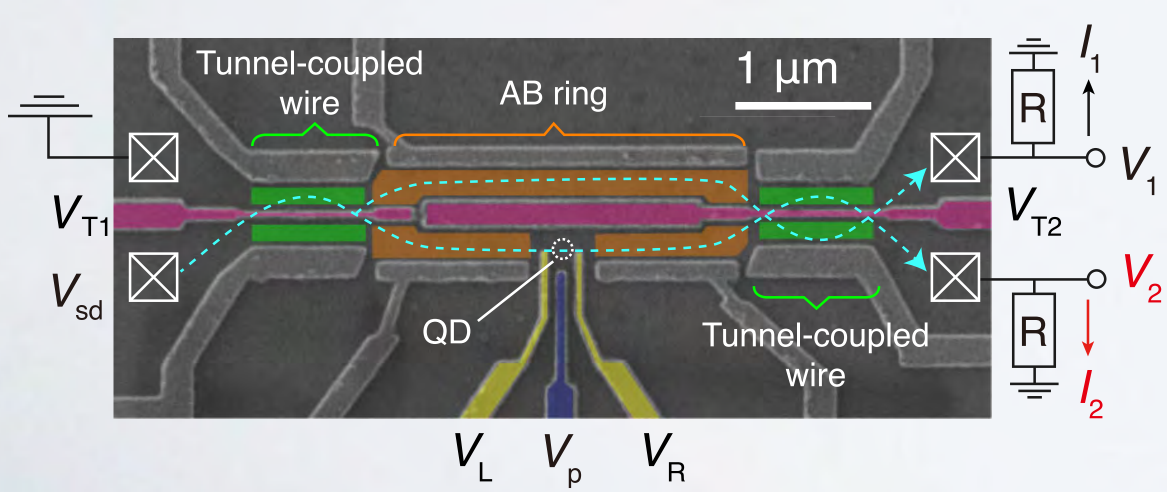






… but visibility of interference is unreliable

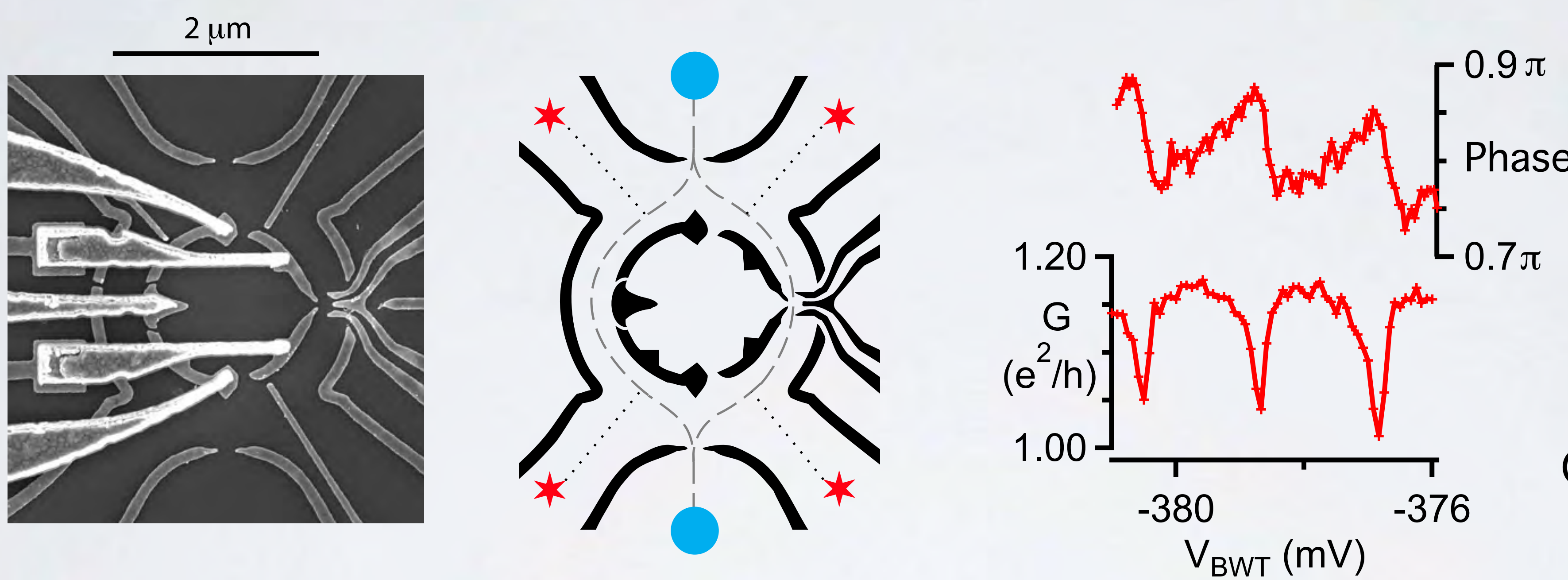


What experiment will show directly the exotic properties of the quantum critical state? (Majoranas, collective excitations)

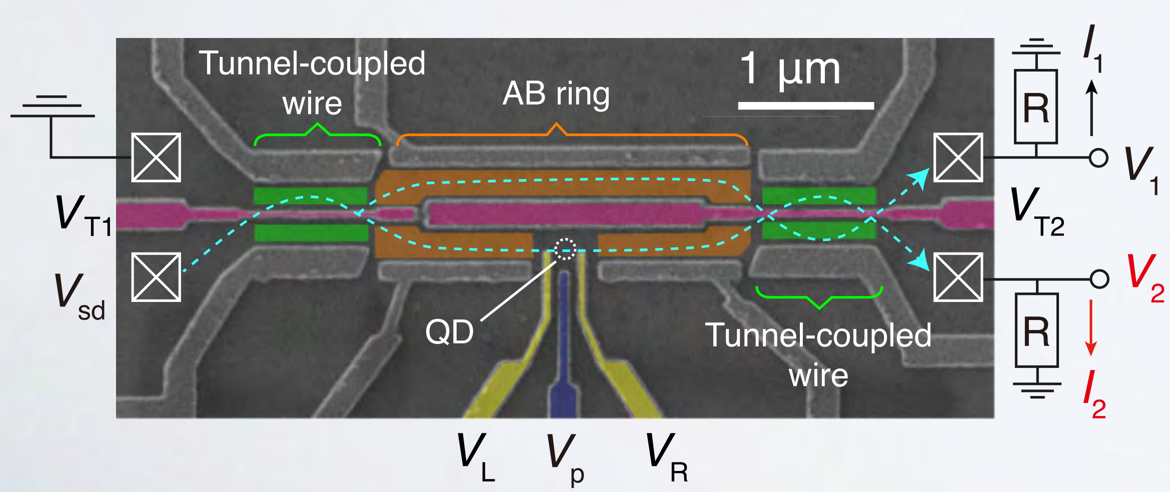
Takada, et al., PRL 113, 126601 (2014).

Phase-sensitive probes of non-Fermi liquids

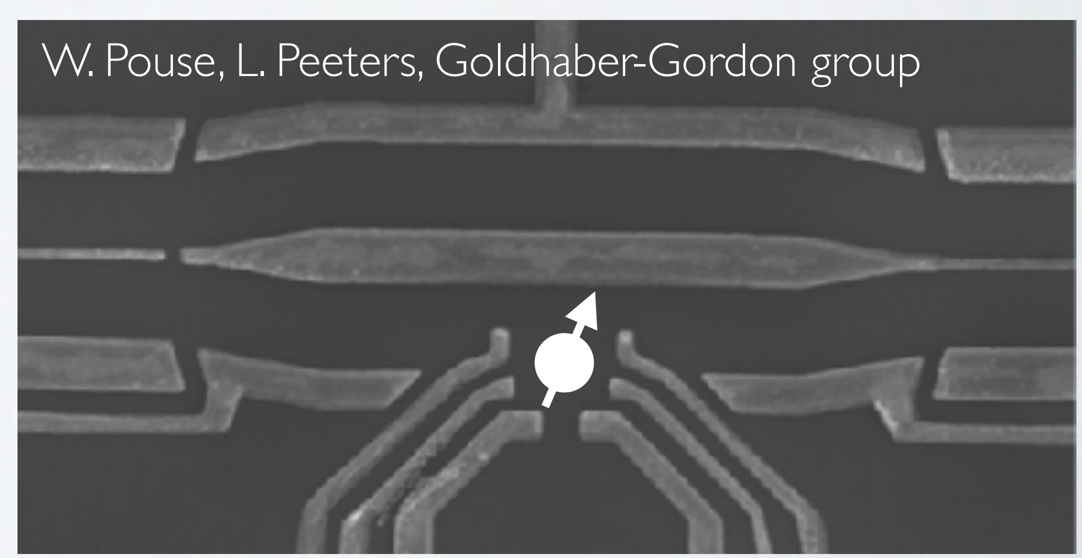
Aharonov-Bohm effect: $\varphi = \frac{e}{h} \int_P \mathbf{A} \cdot d\mathbf{x}$



… but visibility of interference is unreliable



Takada, et al., PRL 113, 126601 (2014).



Acknowledgments

Thank you for listening
and thanks to the organizers!

<u>Principal investigator</u>
David Goldhaber-Gordon

<u>Quantum dots subgroup</u>
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Sami Amasha
Ileana Rau

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J. A. Katine (HGST),

J. MacArthur (Harvard),

Y. Chung (Pusan National U.)

BSF United States - Israel Binational Science Foundation

NSF

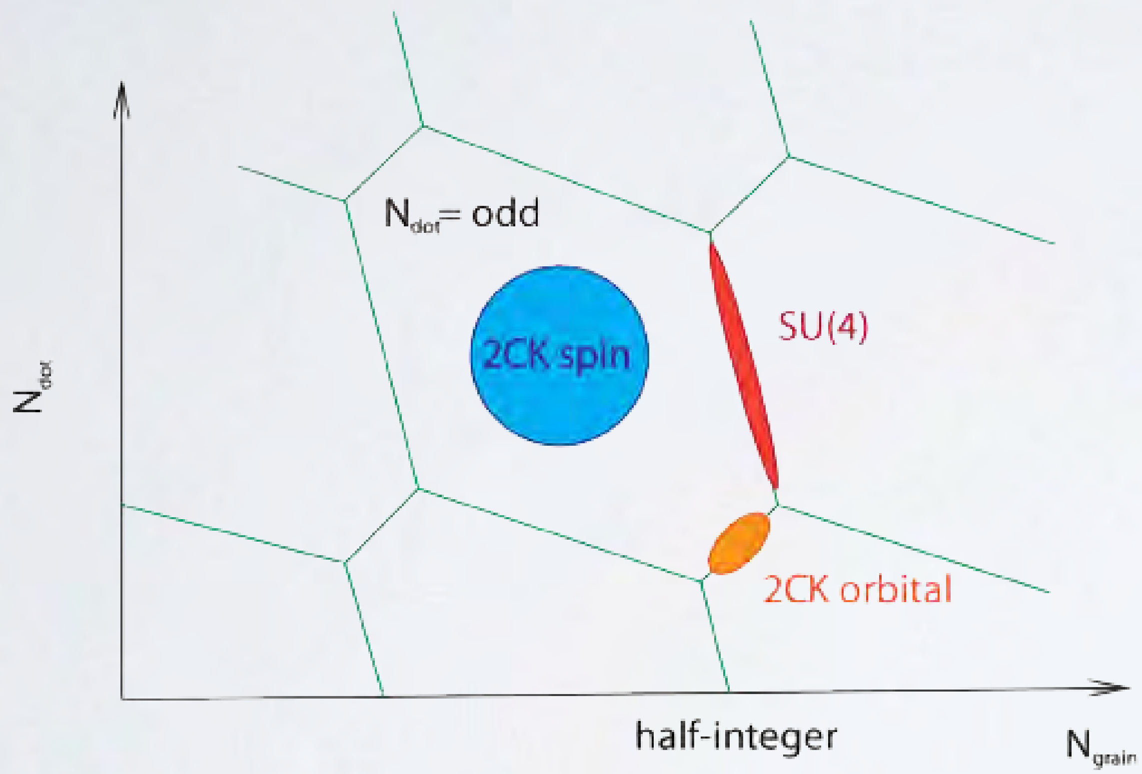
SGF

GORDON AND BETTY MOORE FOUNDATION

Backup slides

Exotic phases in the dot-grain structure

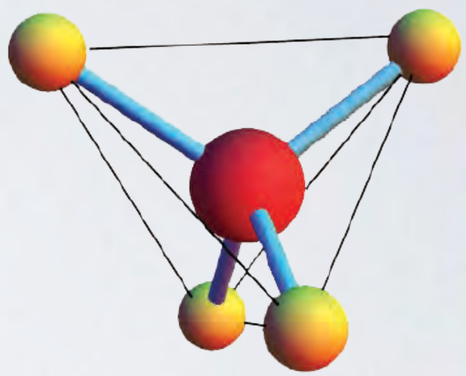
Theoretical; few experiments

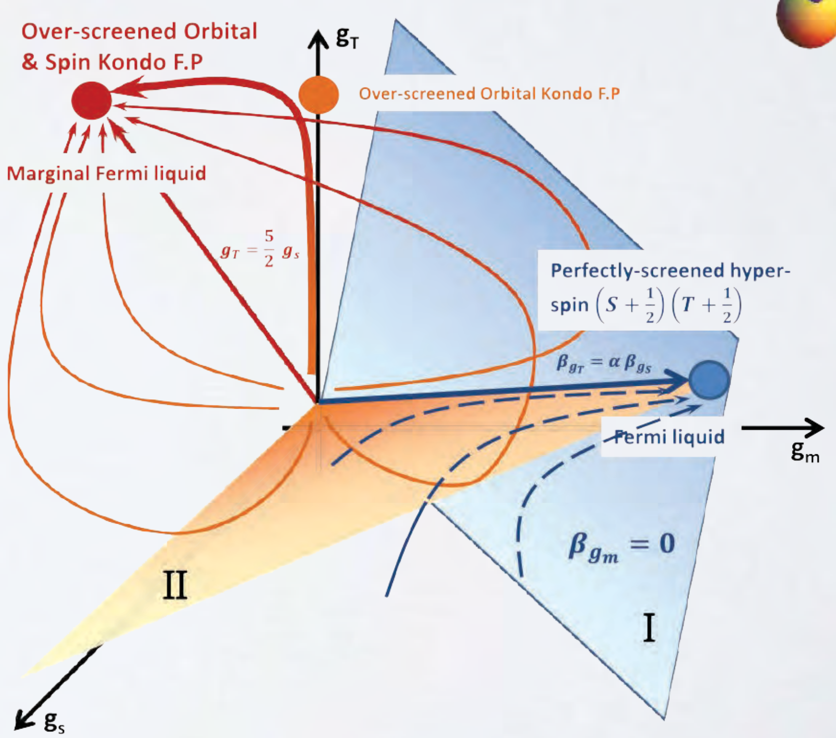


Le Hur, K. *et al.* PRB 75, 035332 (2007)

Observed phases appear in the context of real materials

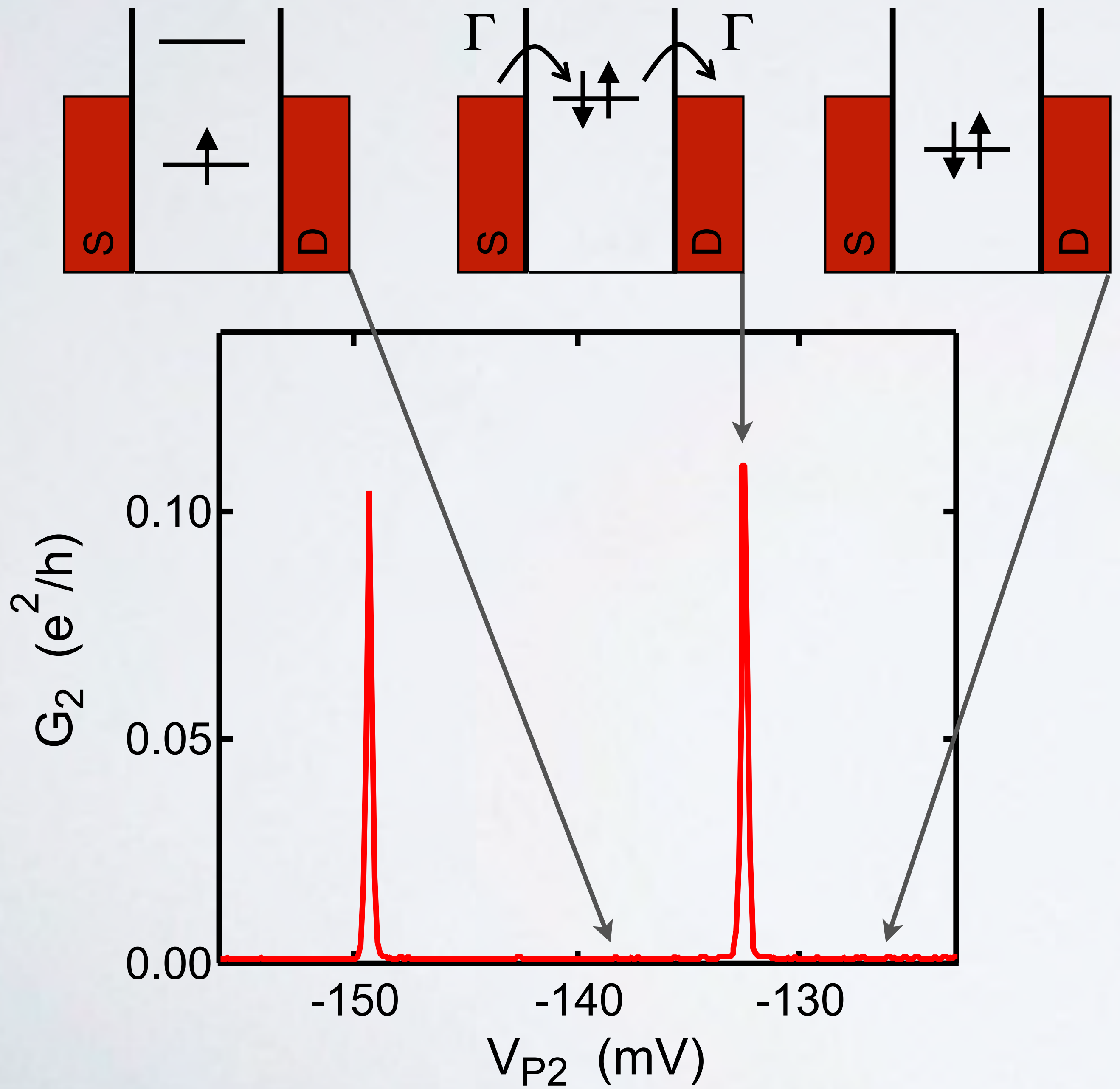
Tzen Ong and Coleman, PRL 108, 107201 (2012).

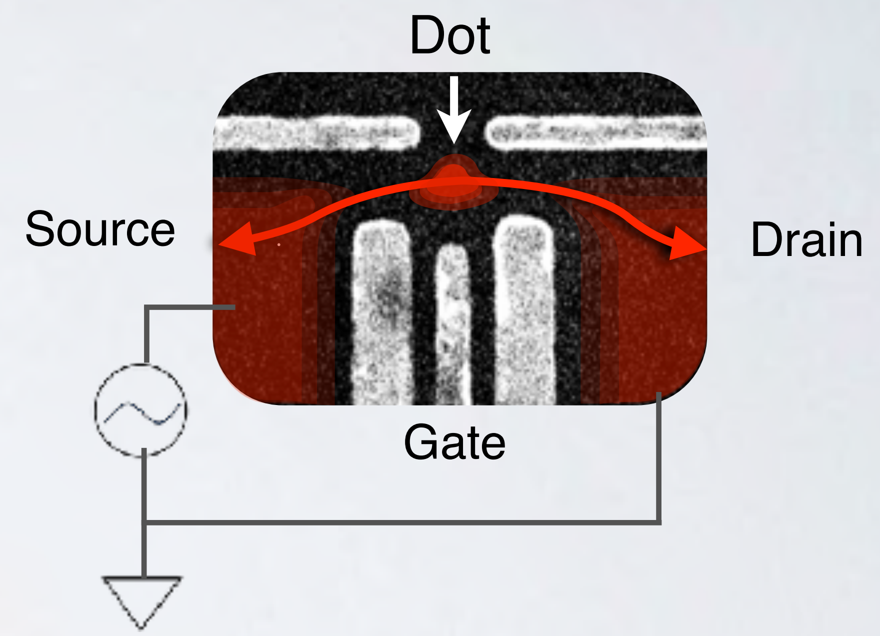




Transport through quantum dots

Coulomb blockade





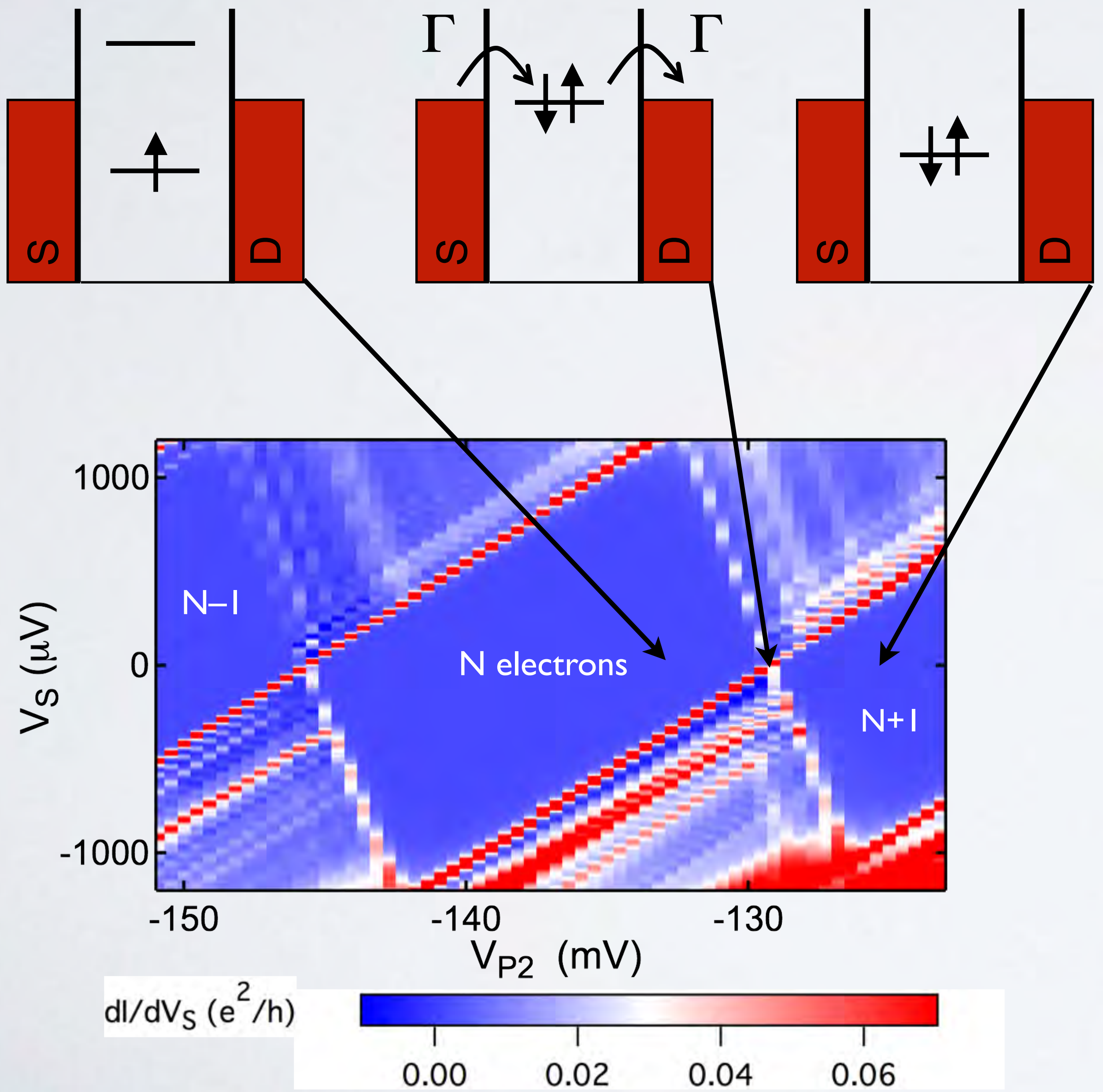
Charging energy: U

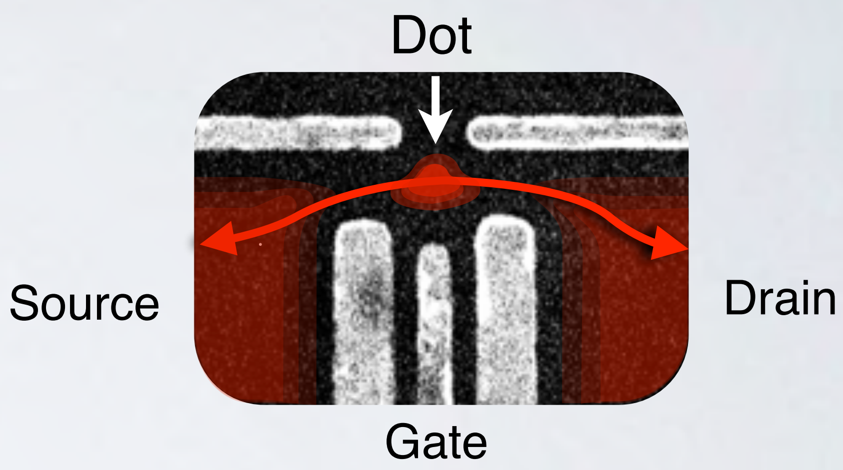
Dot-lead tunnel rate: Γ

$\Gamma/U << 1$

Transport through quantum dots

Coulomb blockade

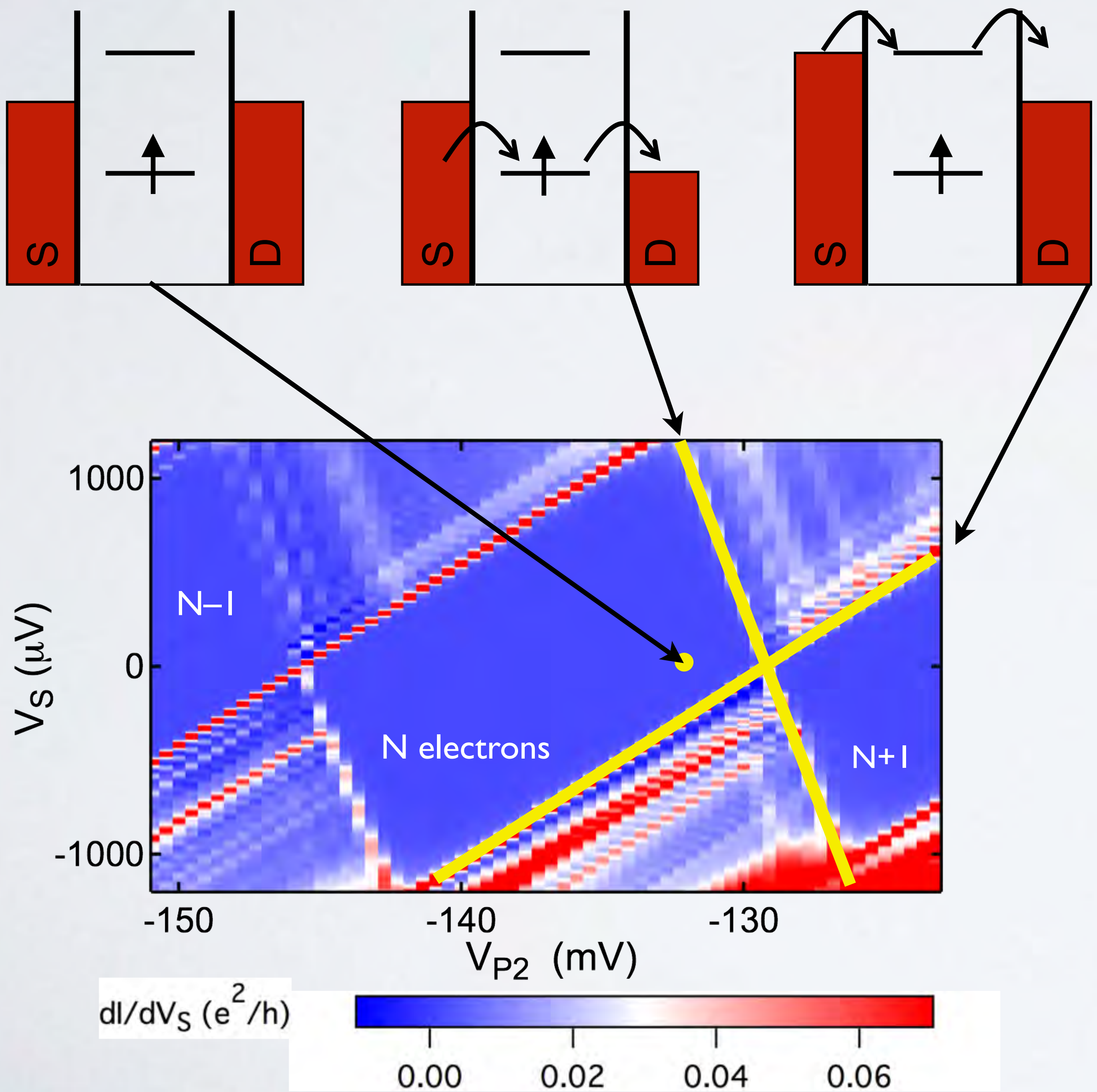


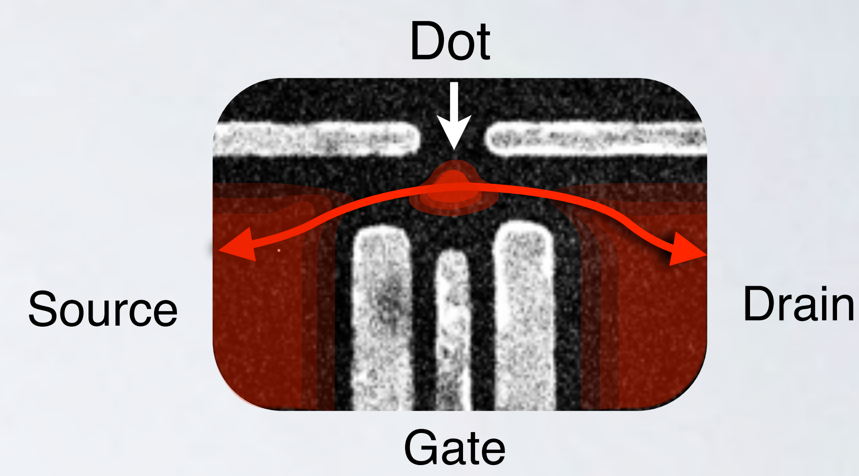


Diamonds give constant electron occupation in bias spectroscopy

Transport through quantum dots

Coulomb blockade





Diamonds give constant electron occupation in bias spectroscopy

Transport through quantum dots

Kondo effect

Interacting level coupled to a lead

$$H = \sum_{k\sigma} \epsilon_k c^\dagger_{k\sigma} c_{k\sigma} + \sum_{\sigma} \epsilon_d d^\dagger_\sigma d_\sigma + U n_{d\uparrow} n_{d\downarrow} + \sum_{k\sigma} \left(V_k d^\dagger_\sigma c_{k\sigma} + \mathrm{h.c.} \right)$$

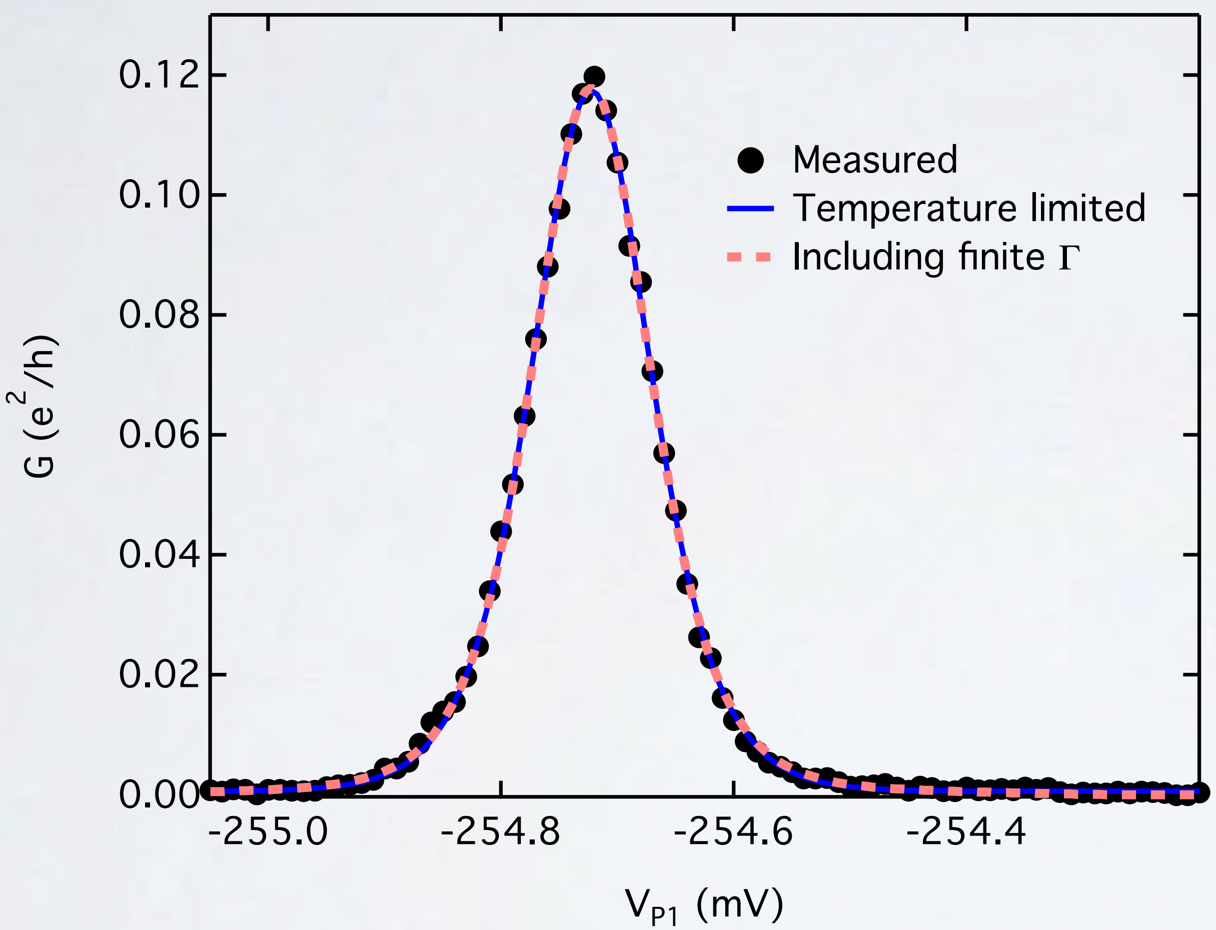
Dot spin operator

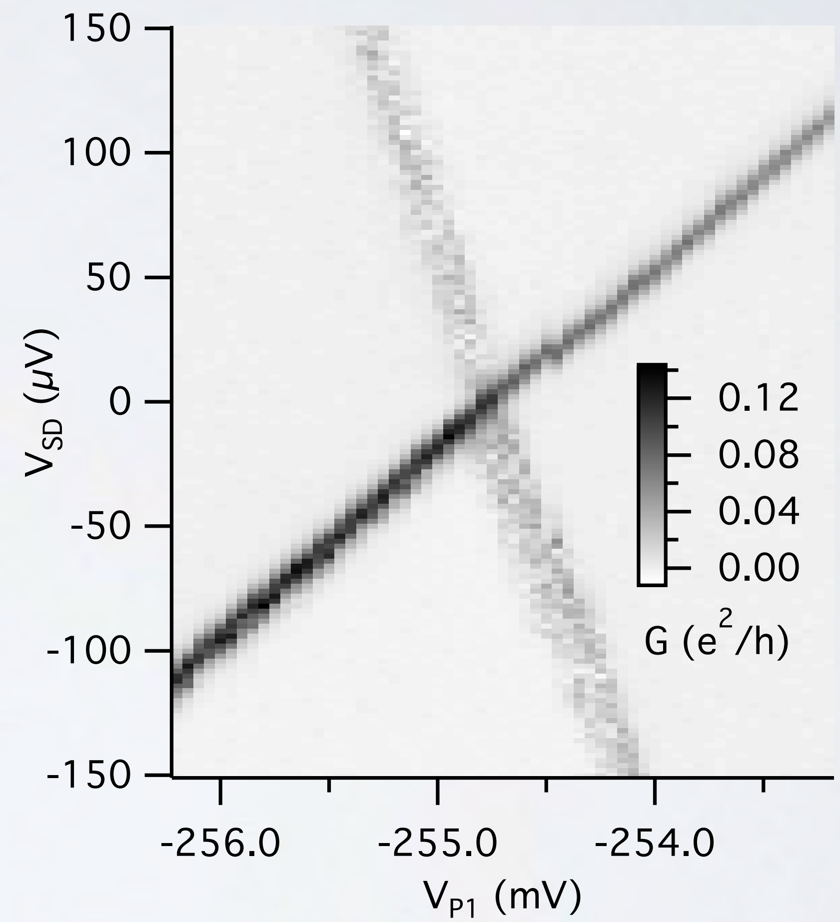
$$\vec{S}_d = \frac{1}{2} \sum_{\sigma\sigma'} d^\dagger_\sigma \vec{\sigma}_{\sigma\sigma'} d_{\sigma'}$$

Project onto one electron subspace —> s-d Hamiltonian

$$H = \sum_{k\sigma} \epsilon_k c^\dagger_{k\sigma} c_{k\sigma} + \sum_{kk'} \left[2 J_{kk'} \vec{s}_{kk'} \cdot \vec{S}_d + K_{kk'} \sum_{\sigma} c^\dagger_{k\sigma} c_{k'\sigma} \right]$$

Coulomb blockade thermometry





Order parameters for impurity QPTs

They are not obvious…

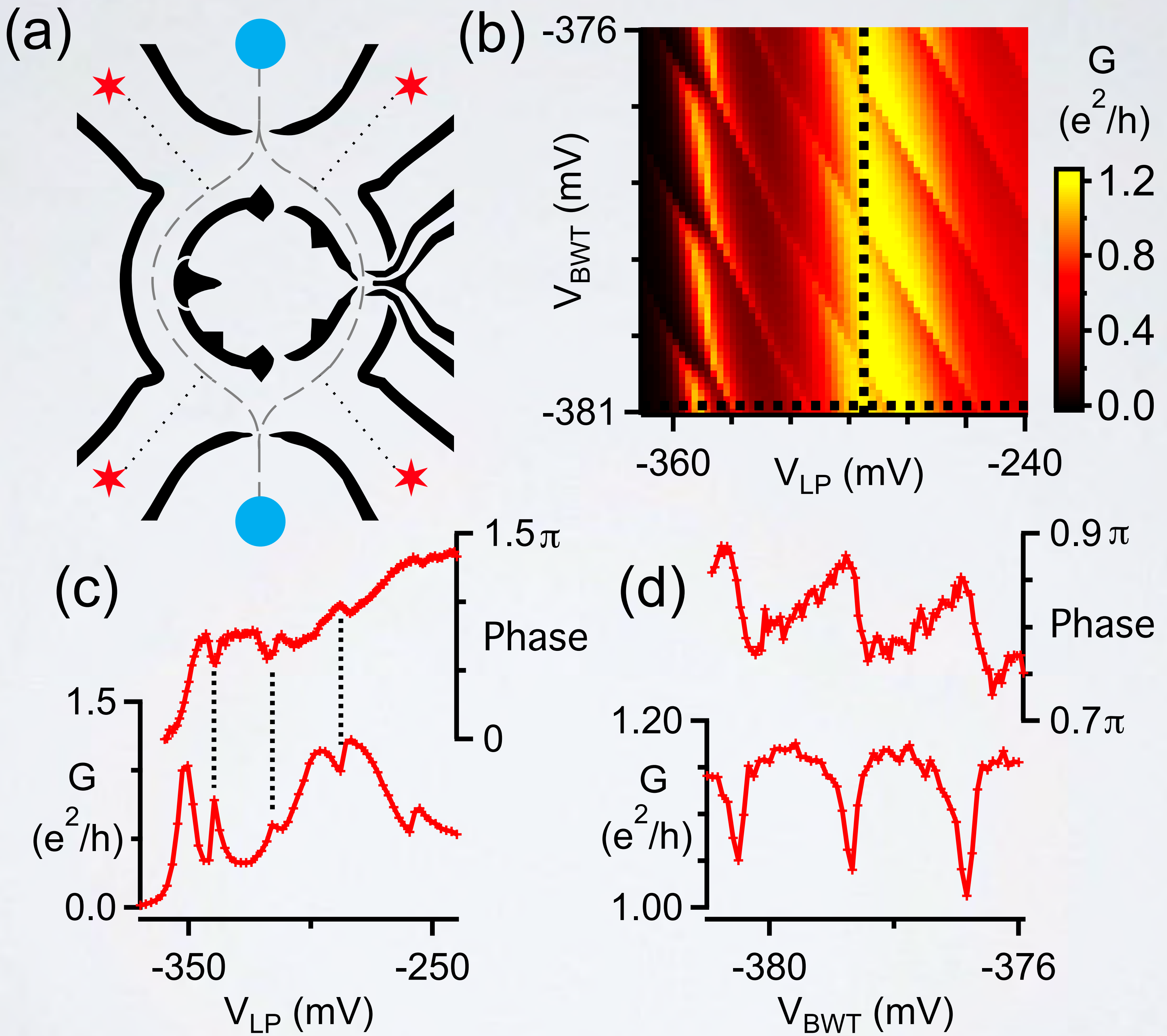
G. De Chiara, *et al.*, PRL 109, 237208 (2012).

A. Bayat, *et al.*, Nat. Commun. 5, 3784 (2014).

Alkurtass, *et al.* PRB 93, 081106(R) (2016).

Schmidt gap. Another key quantity, related to the entanglement spectrum, is the Schmidt gap Δ_S. Given a bipartitioning of the system, it is defined by $\Delta_S = \lambda_1 - \lambda_2$, where $\lambda_1 \geqslant \lambda_2$ are the two largest eigenvalues of the reduced density matrix of any of the two subsystems. It was recently shown that the Schmidt gap can serve as an order parameter across quantum phase transitions [37,38]. For the 2CK model close to $\Gamma = 1$, and choosing a bipartition as shown in Fig. 1(c) for two complementary left and right blocks, the Schmidt gap is found to obey finite-size scaling with the same critical exponents as the negativity. Figure 3(d) shows the Schmidt gap data collapse for three different system sizes, confirming it as an alternative order parameter to the negativity in the 2CK model.

Phase-sensitive probes of non-Fermi liquids

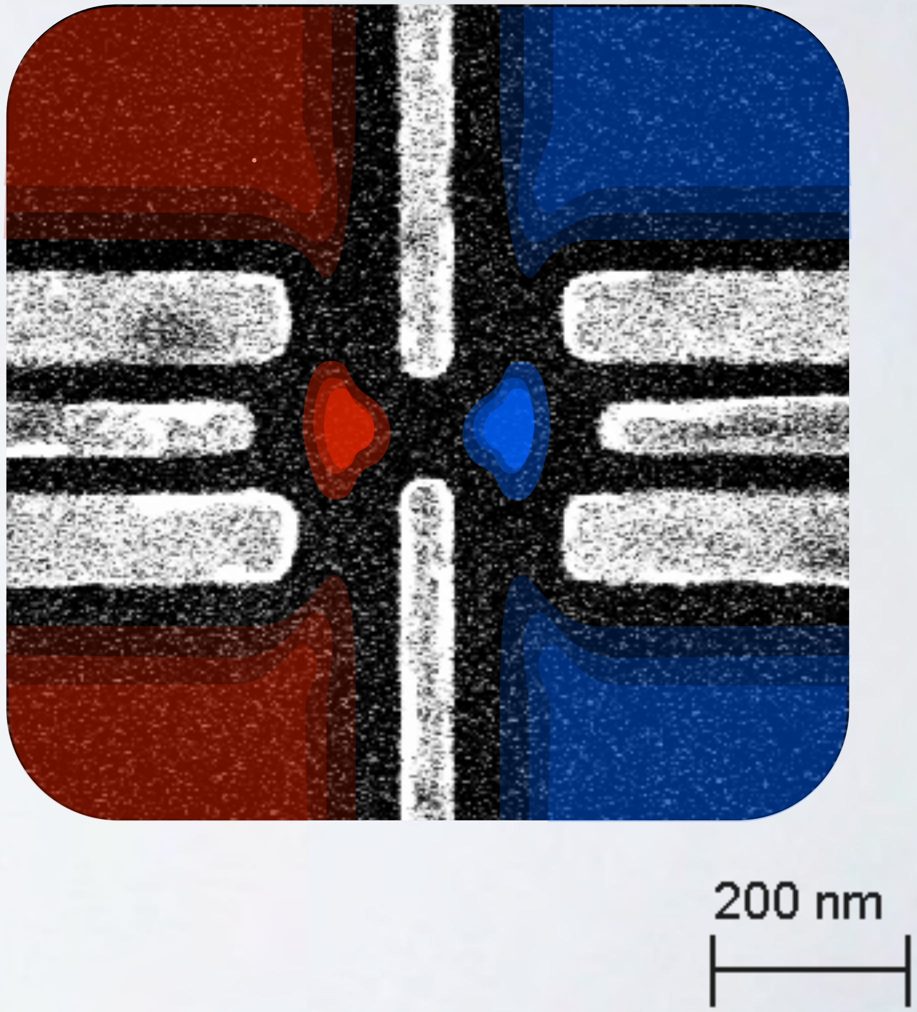


The simplest double QD

Capacitively coupled with **no inter-dot tunneling**

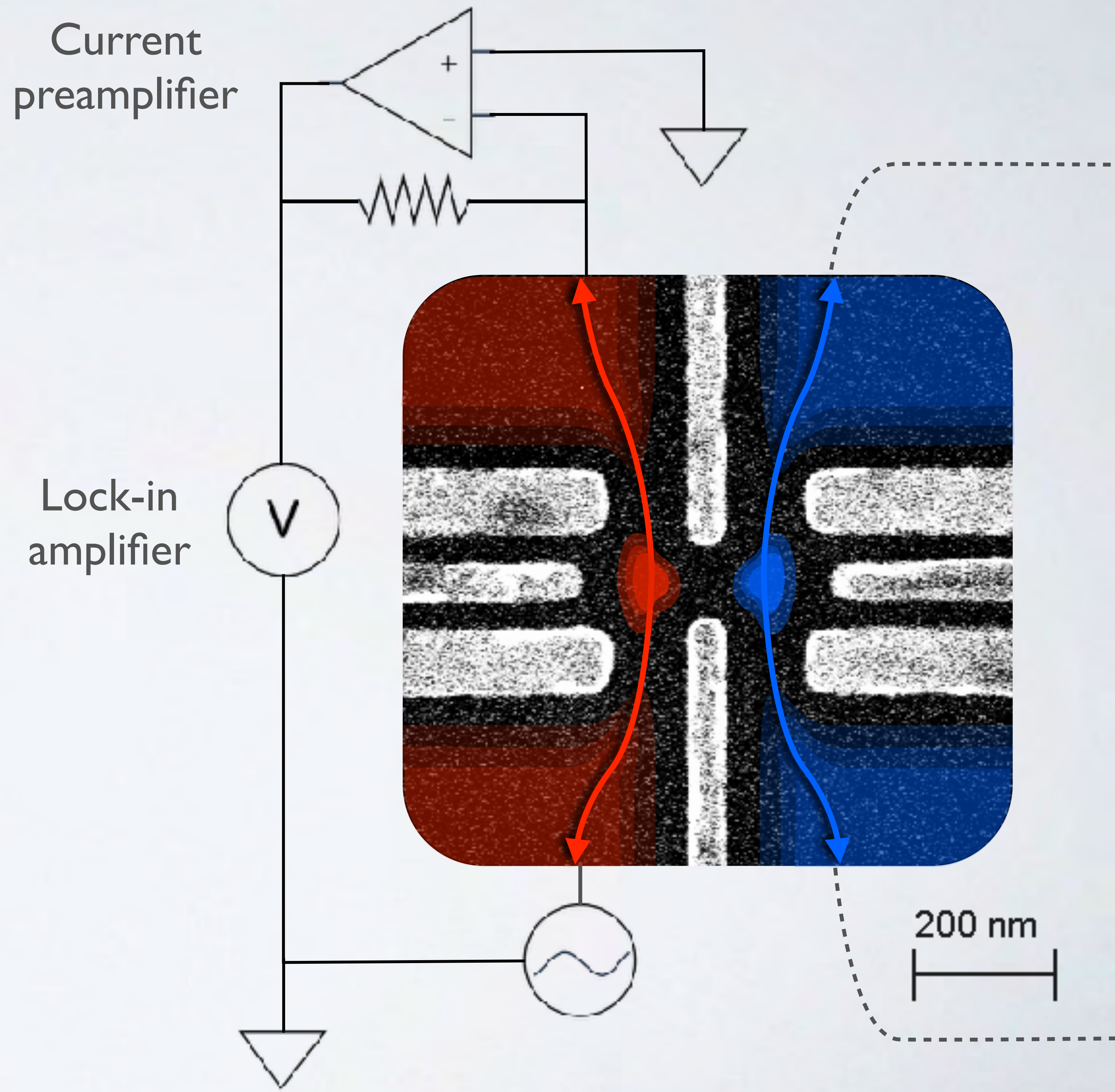
$$\left(\sum_{k\sigma} \epsilon_k c^\dagger_{k\sigma} c_{k\sigma} + \sum_{\sigma} \epsilon_d d^\dagger_\sigma d_\sigma + U n_{d\uparrow} n_{d\downarrow} + \sum_{k\sigma} \left(V_k d^\dagger_\sigma c_{k\sigma} + \mathrm{h.c.} \right) \right) \times 2$$

$$+U' n_1 n_2$$

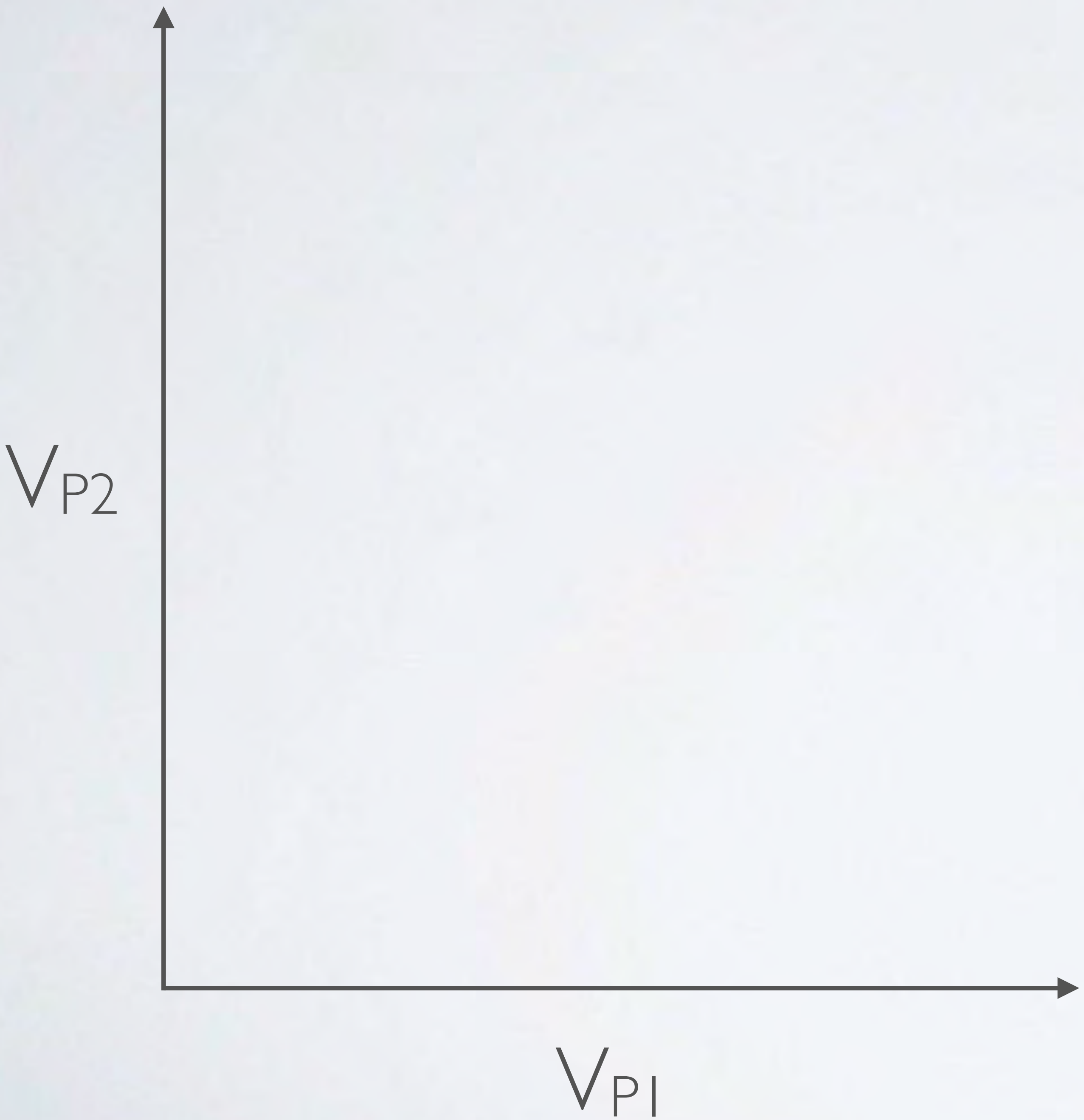


Measurement scheme

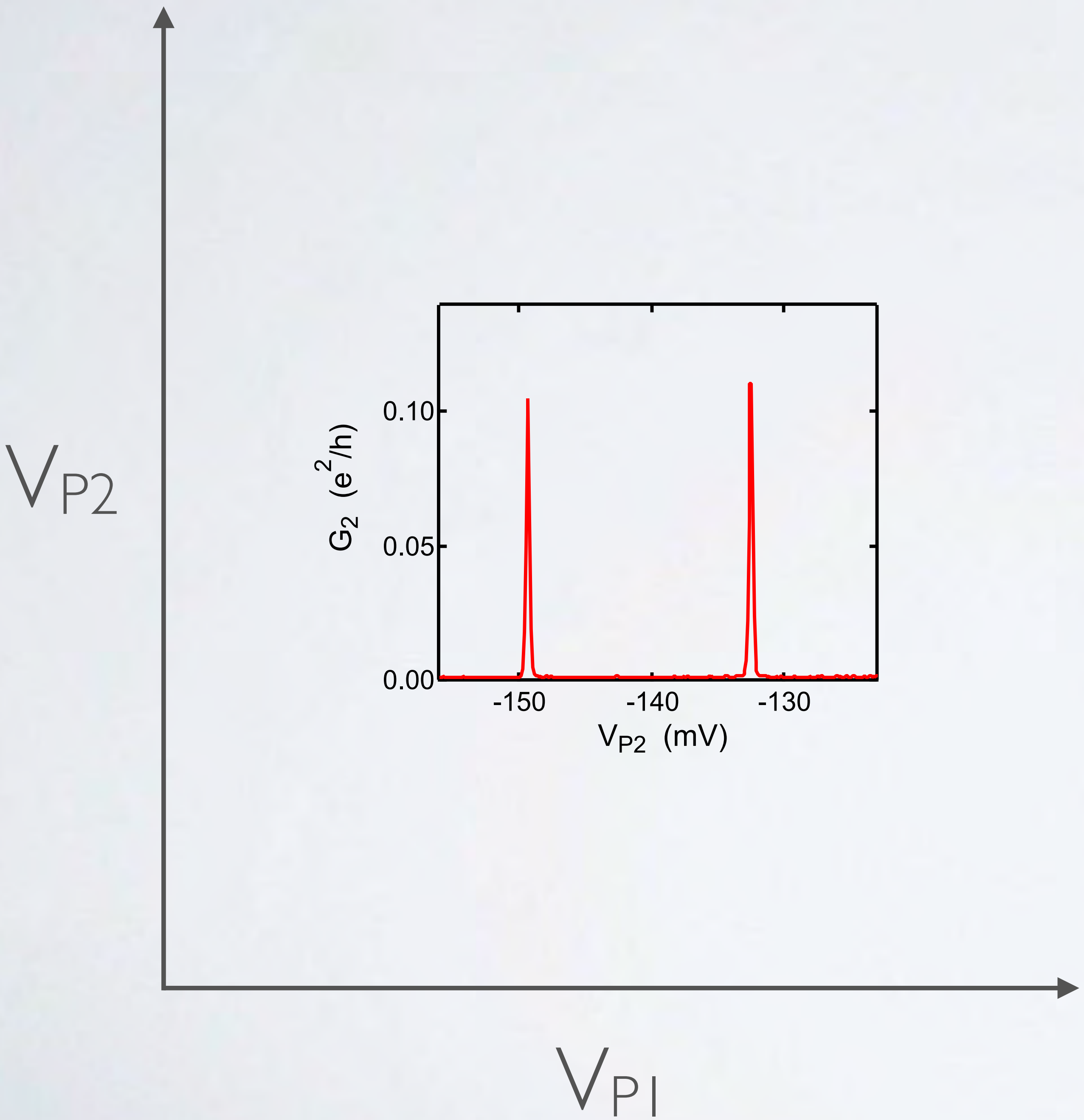
- Provide AC excitation and measure $G=dI/dV\,|_{V=0}$
- Can simultaneously measure through each dot in parallel



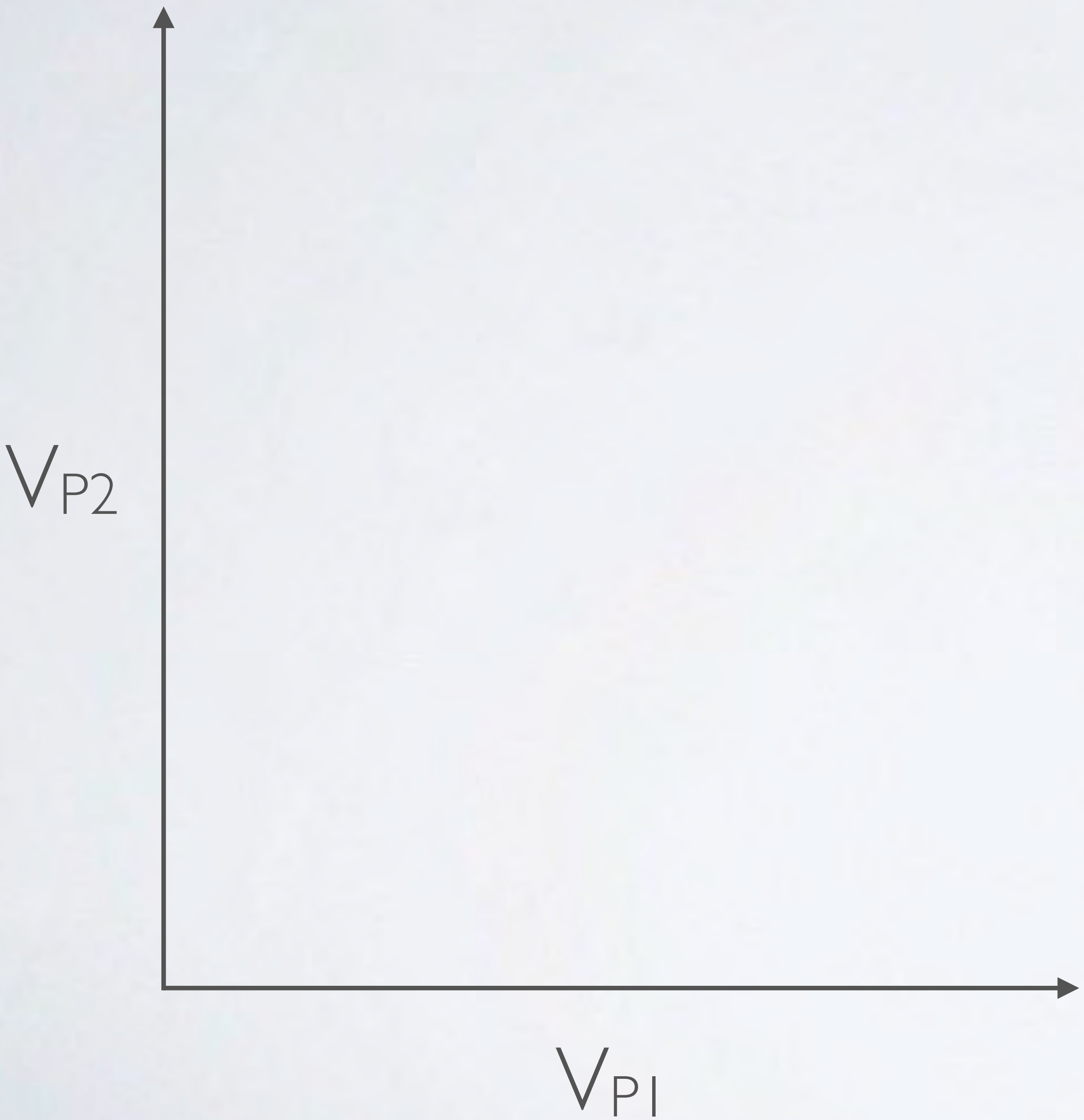
Charge stability diagram



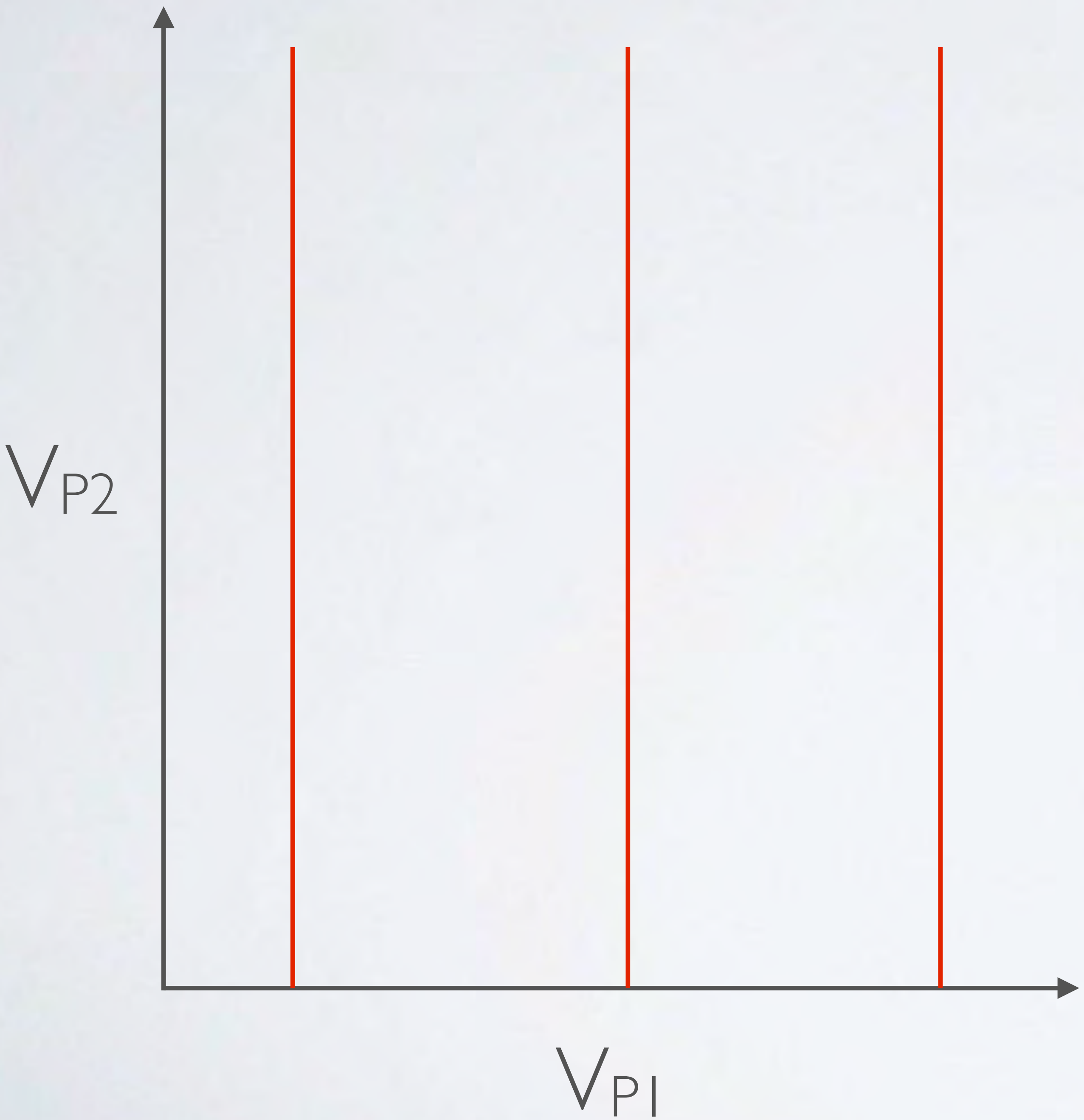
Charge stability diagram



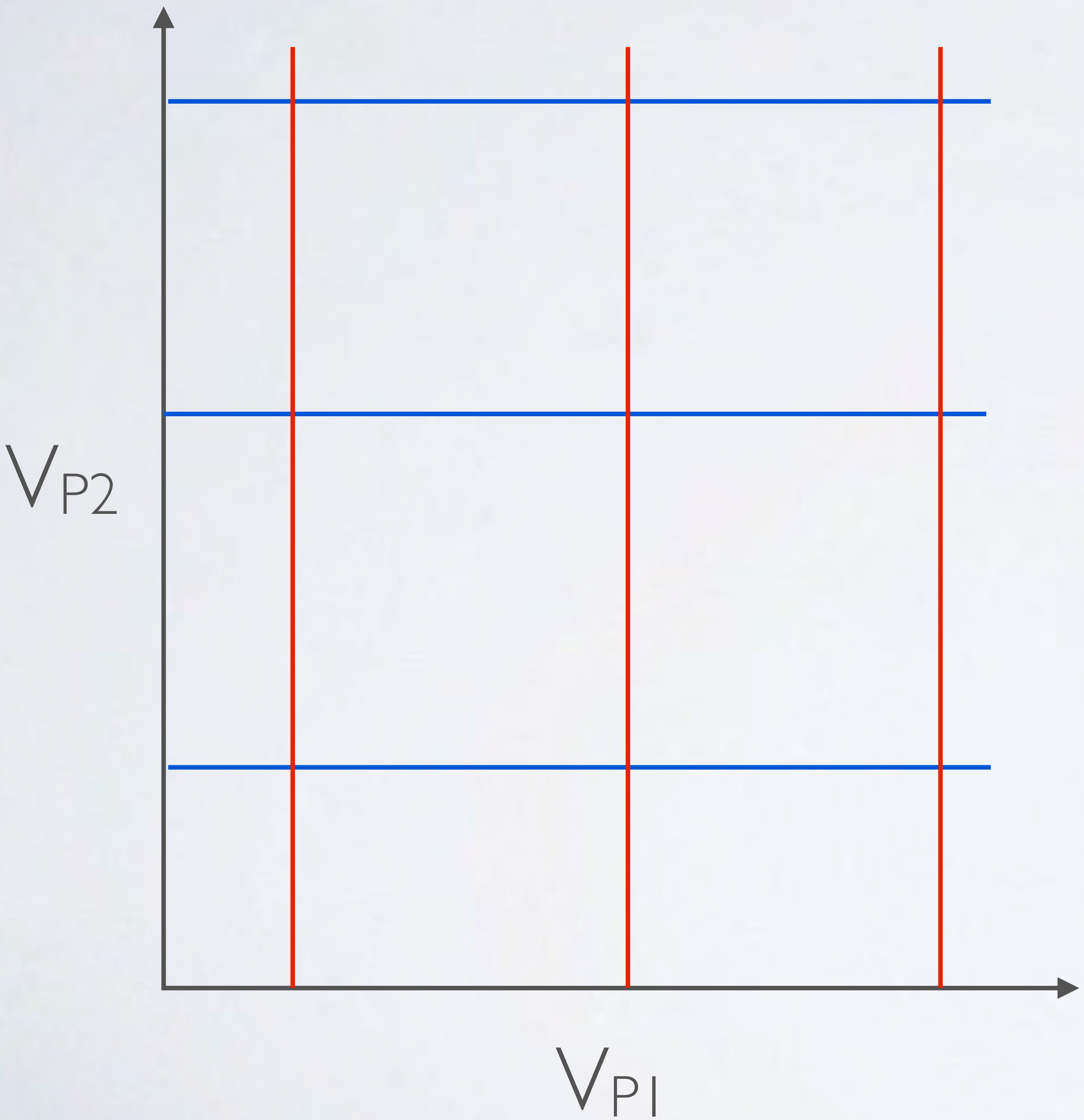
Charge stability diagram



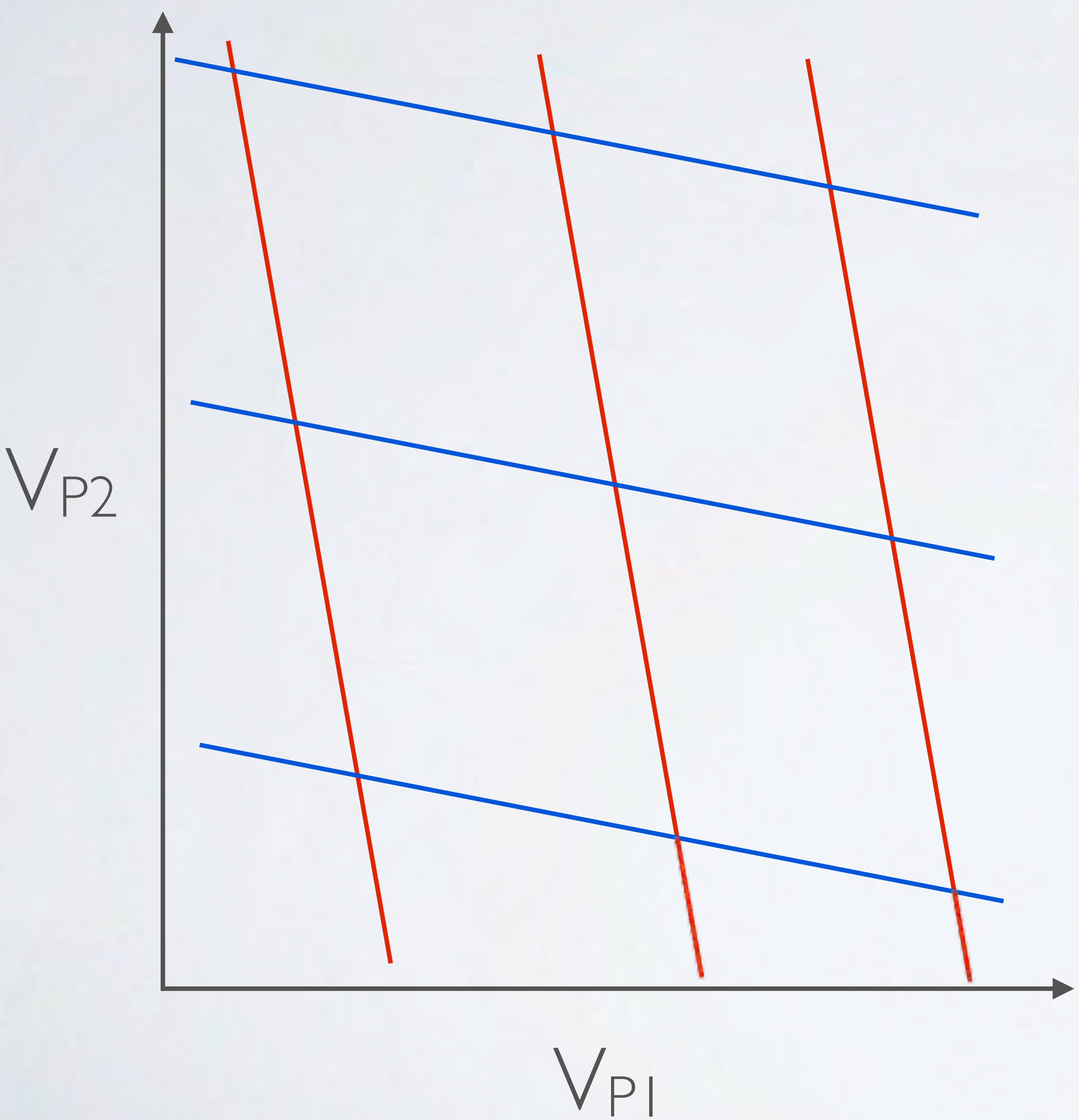
Charge stability diagram



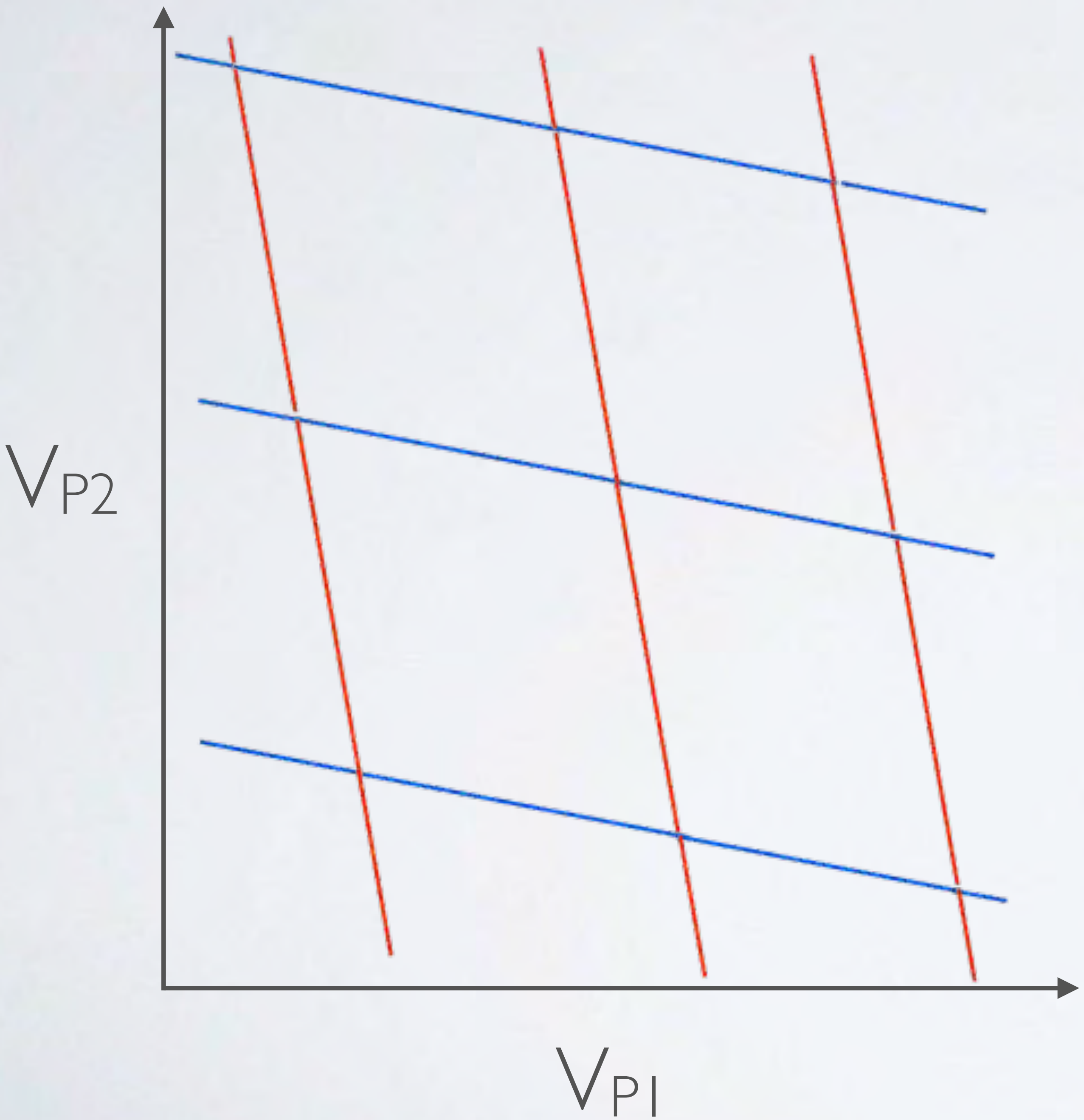
Charge stability diagram



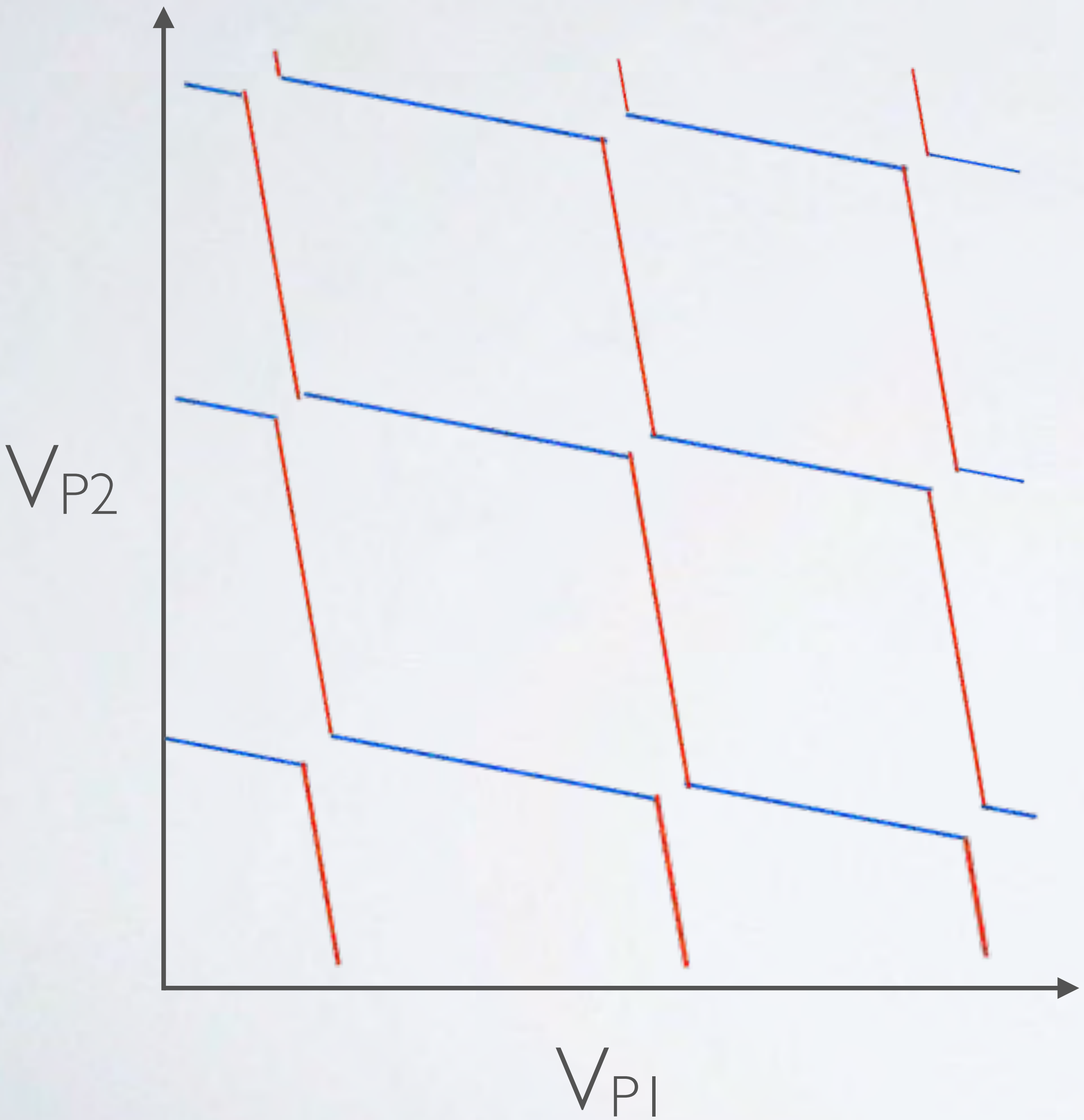
Charge stability diagram



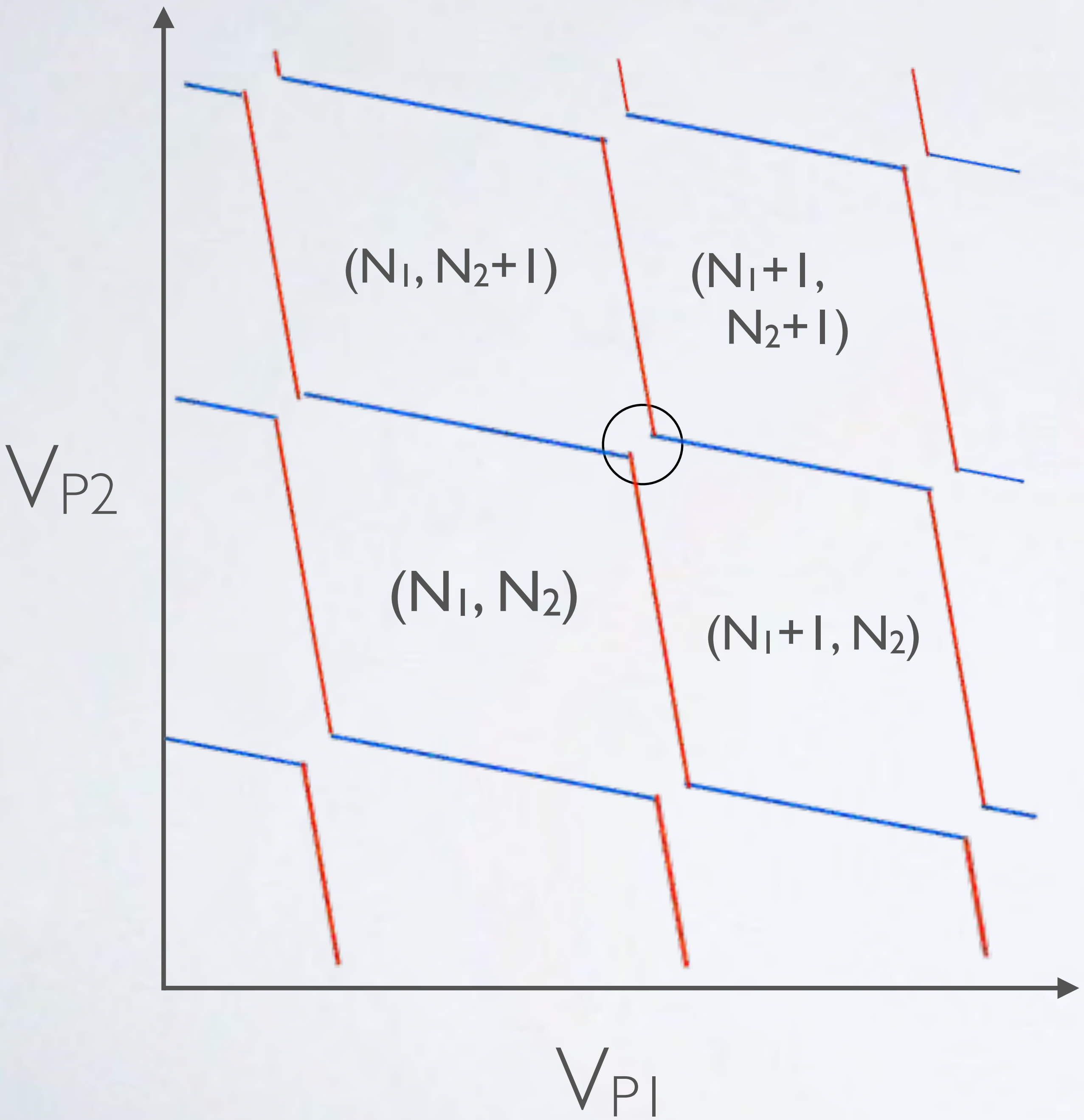
Charge stability diagram

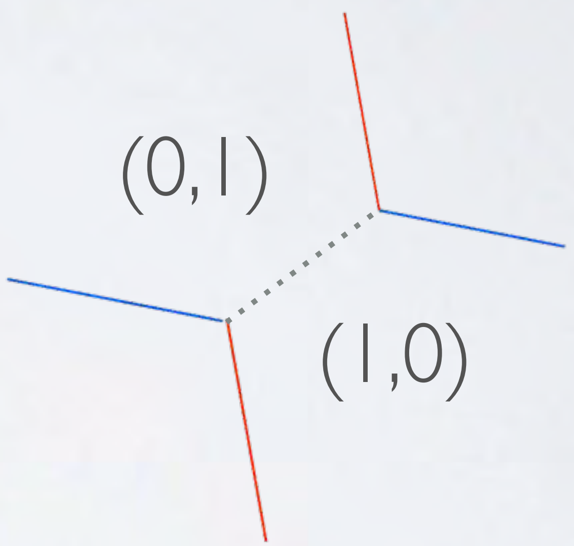


Charge stability diagram

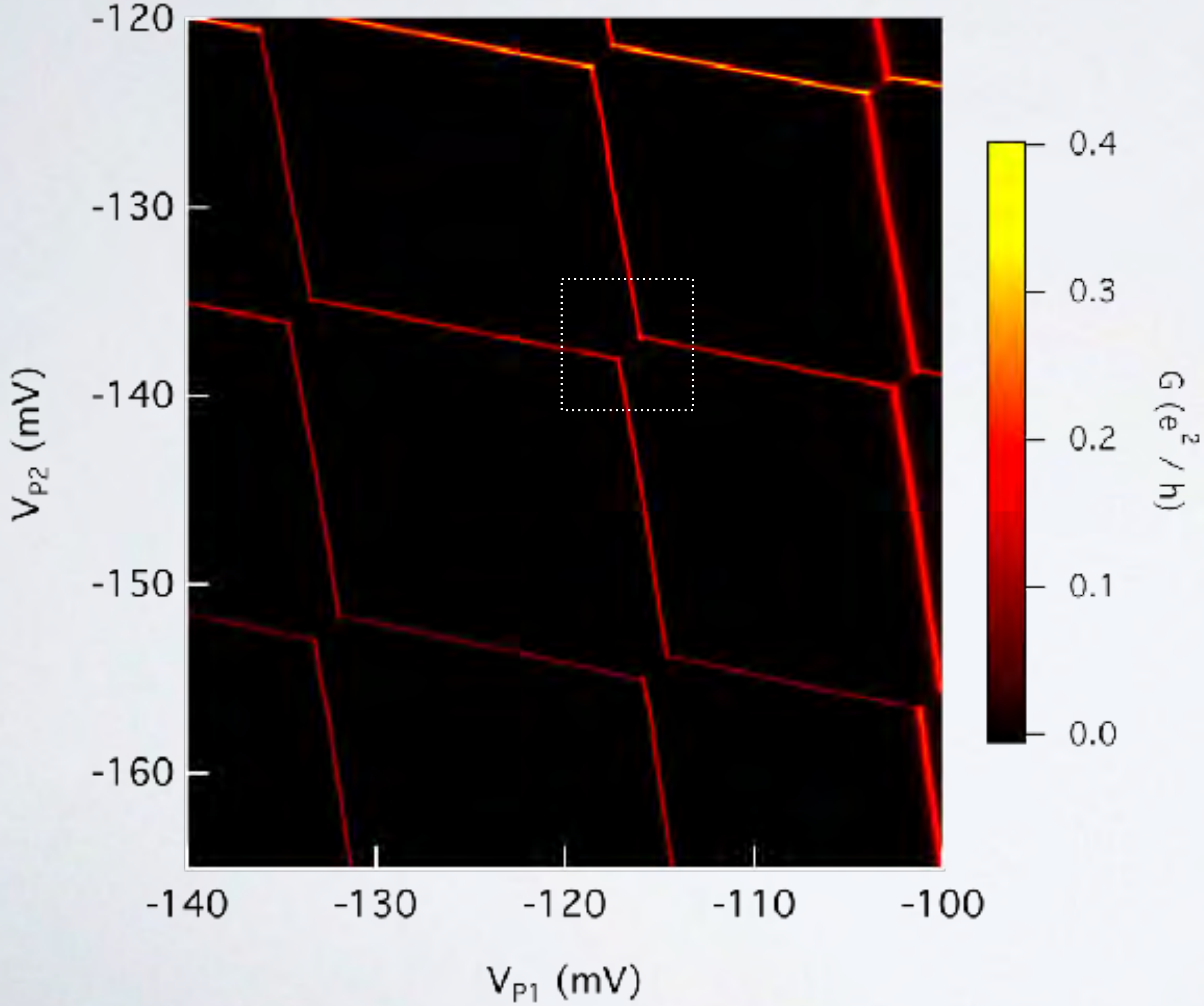


Charge stability diagram





Charge stability diagram

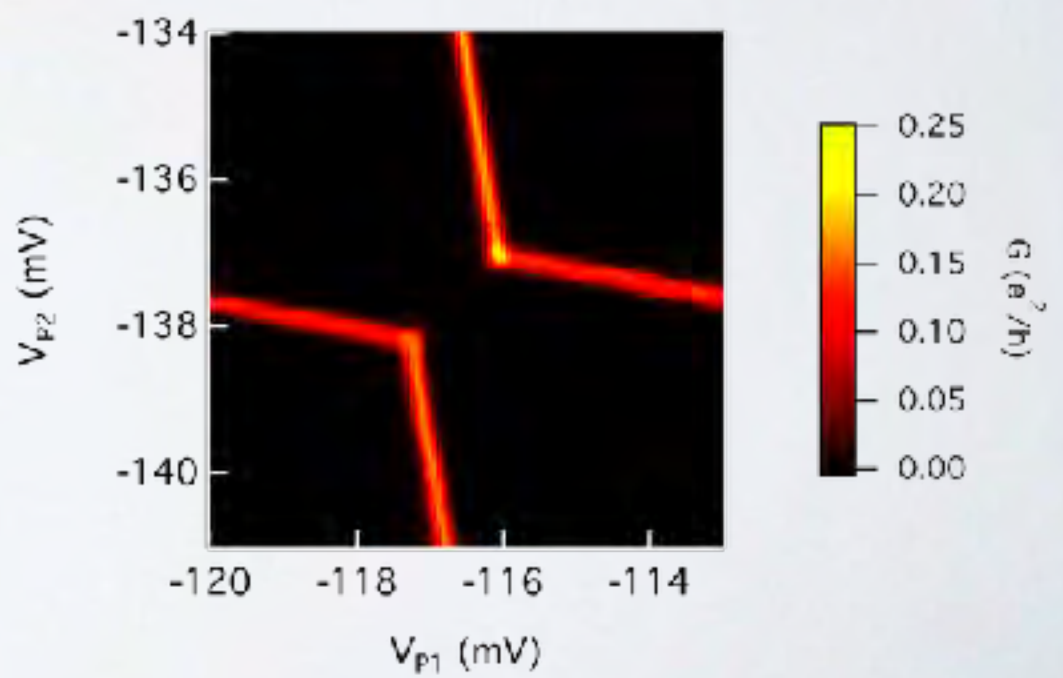


T_e = 1.7 μeV (20 mK)

$\Gamma_1 \sim \Gamma_2 \sim$ 20 μeV

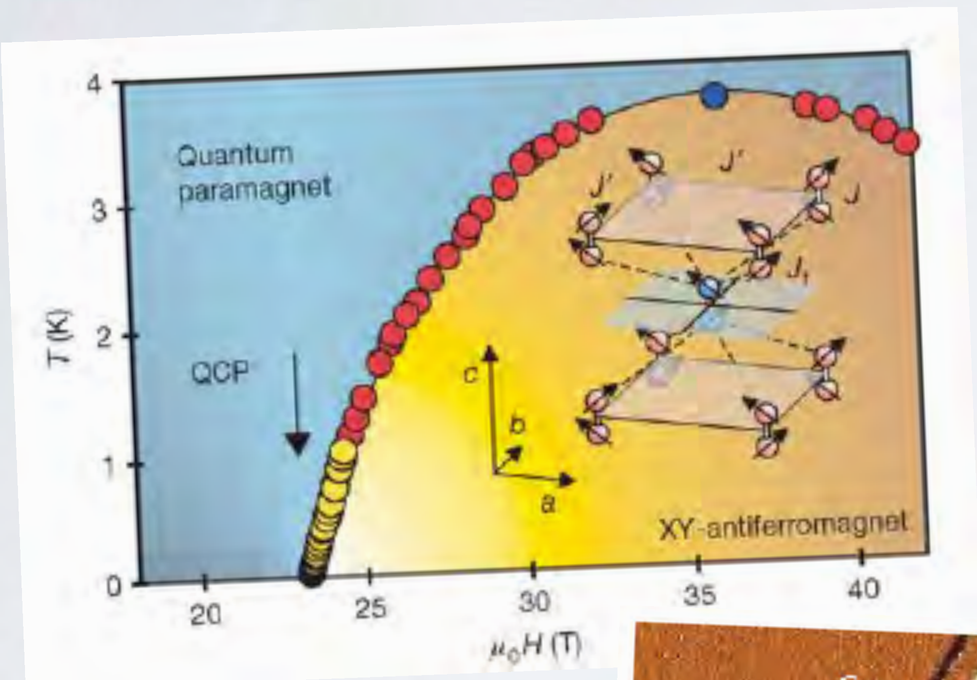
U' ~ 100 μeV

U ~ 1 meV

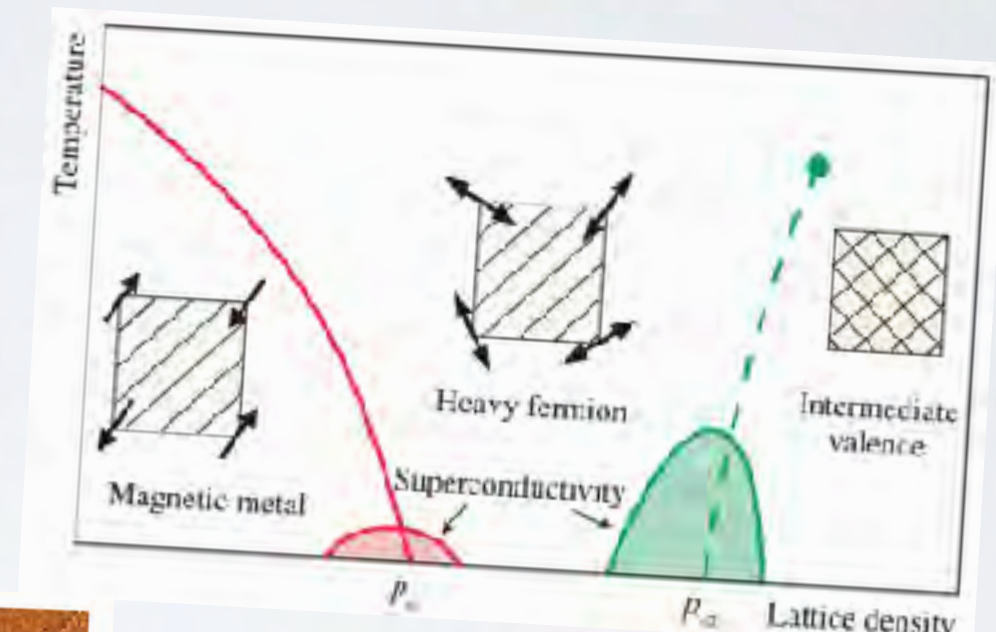


Quantum criticality

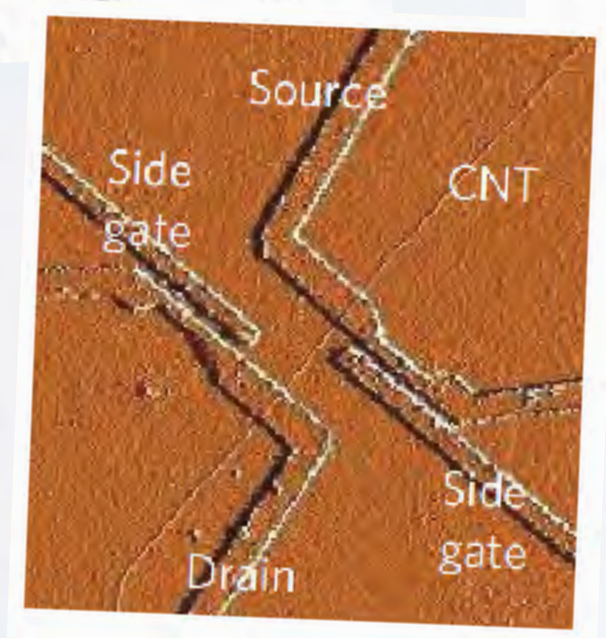
Materials design and device design as complementary approaches



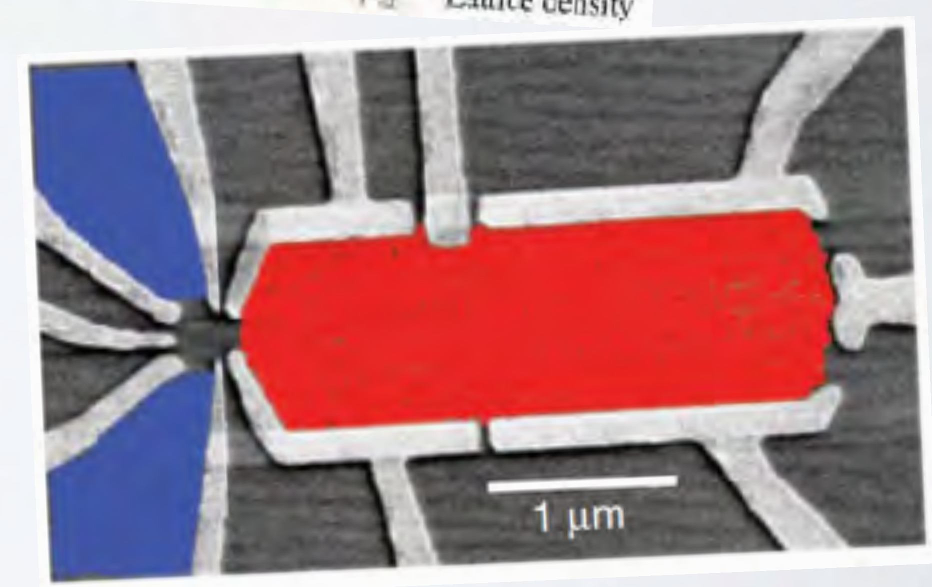
S. E. Sebastian *et al.*,
Nature **441**, 617 (2006).



H. Q. Yuan *et al.*,
Science **302**, 2104 (2003).

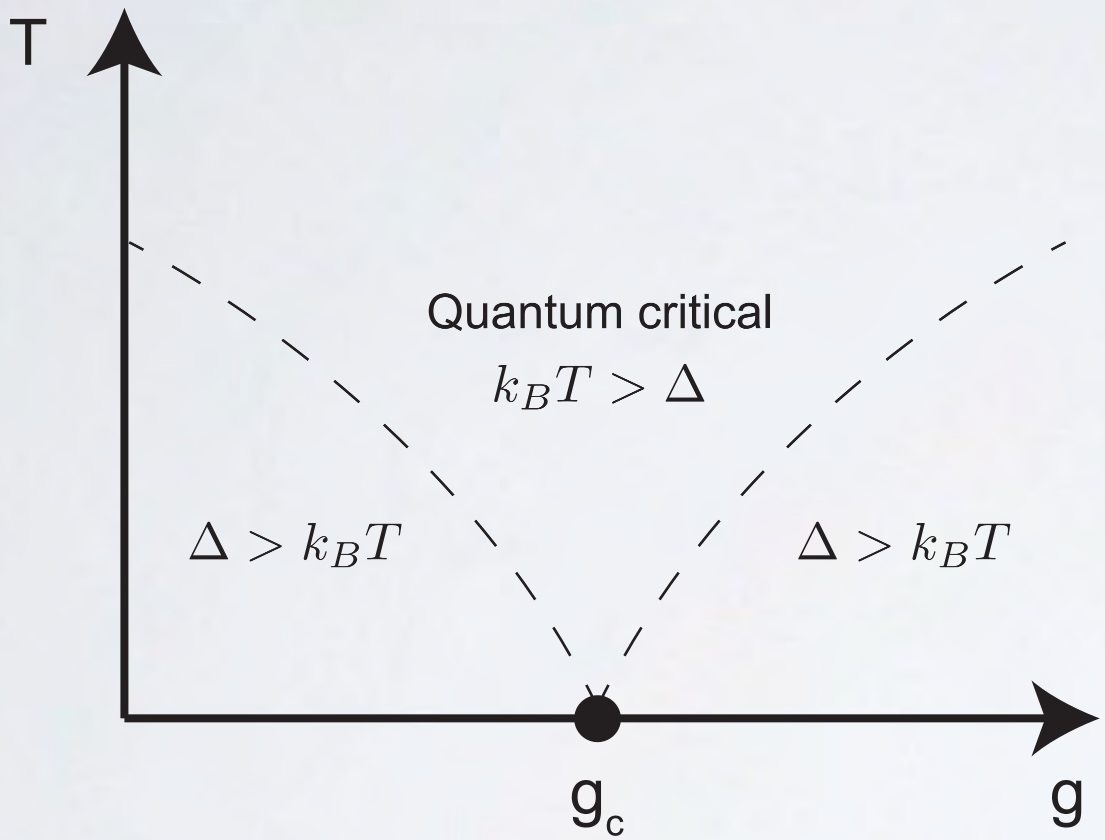


H. Mebrahtu *et al.*,
Nature Phys. **9**, 732 (2013).



R. Potok *et al.*, Nature **446**, 167 (2007).

Quantum criticality



S. Sachdev, *Quantum Phase Transitions* 2nd ed. (2011)

At T=0:

$$\Delta \sim J|g - g_c|^{z\nu}$$

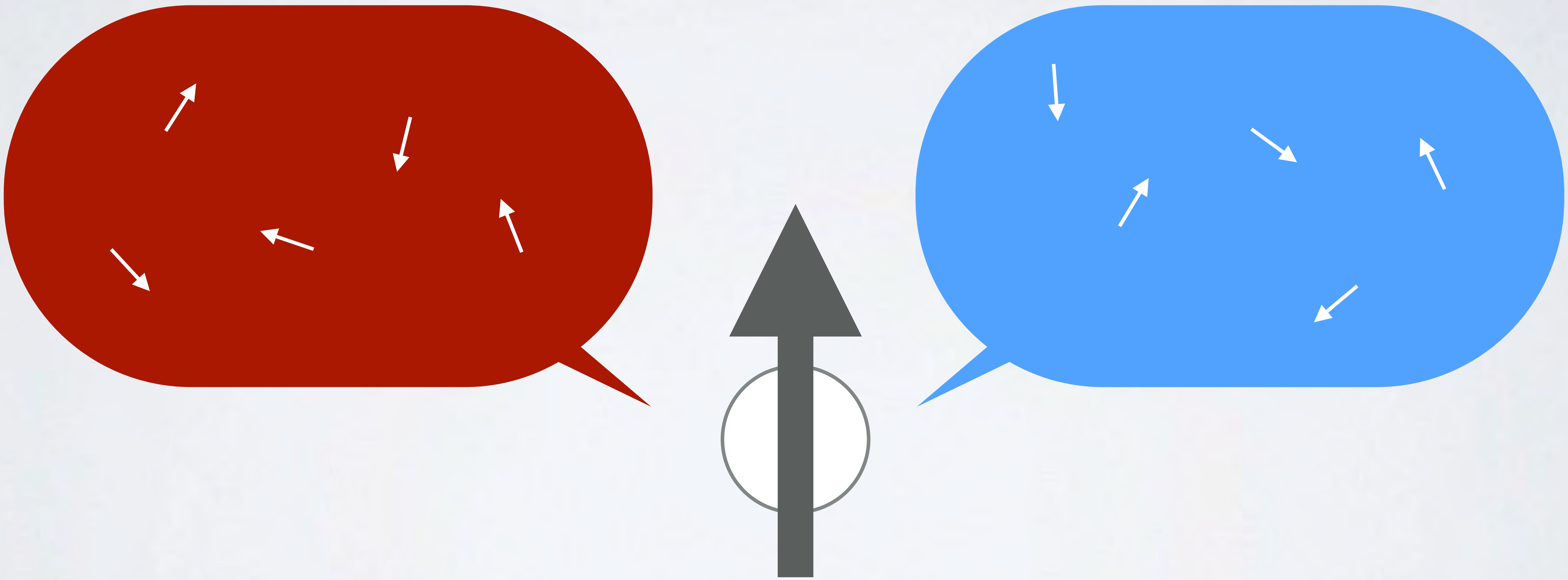
$$\xi^{-1} \sim \Lambda|g - g_c|^{\nu}$$

$$\Delta \sim \xi^{-z}$$

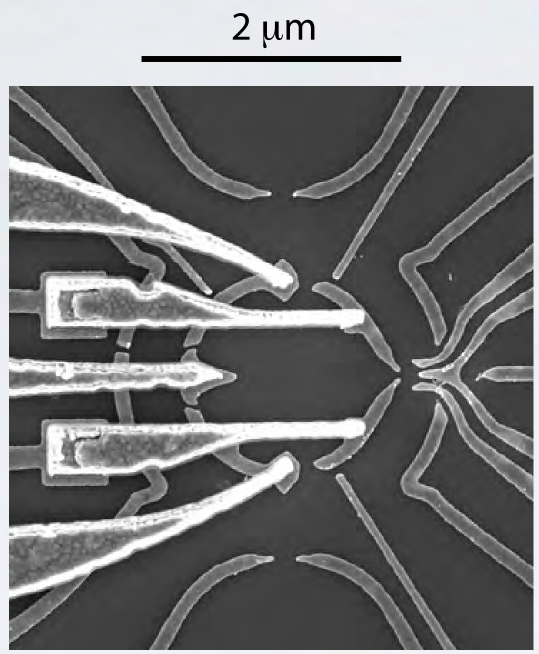
Same exponents on either side of the QCP, but different non-universal amplitudes

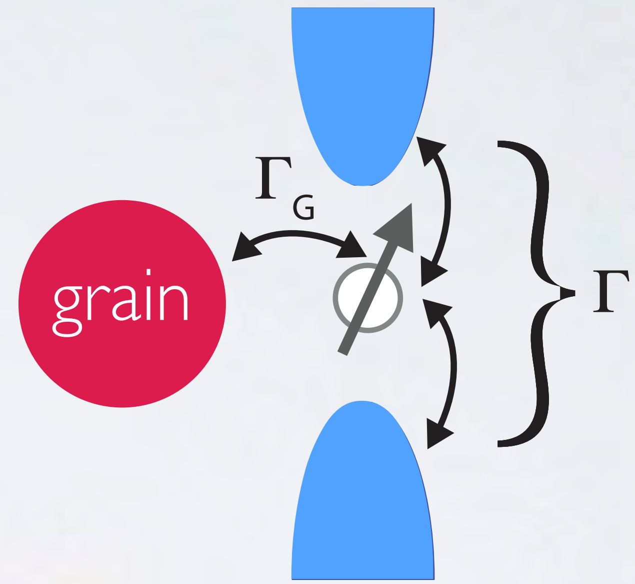
Two-channel Kondo effect

A model quantum phase transition



How do we implement this?





$$H_{\text{dot}} = \sum_{\sigma} \varepsilon \, d_\sigma^\dagger d_\sigma + U \hat{n}_\uparrow \hat{n}_\downarrow$$

$$H_{\text{grain}} = \sum_{p,\sigma} \varepsilon_p a_{p\sigma}^\dagger a_{p\sigma} + \frac{E_C}{2} \hat{n}_g^2 + \phi \hat{n}_g$$

$$H_{\text{leads}} = \sum_{\alpha=\{U,L\}} \sum_{k,\sigma} \varepsilon_{\alpha k} c_{\alpha k\sigma}^\dagger c_{\alpha k\sigma}$$

$$H_{\text{tunneling}} = t_G \sum_{p,\sigma} \left(a_{p\sigma}^\dagger d_\sigma + d_\sigma^\dagger a_{p\sigma}\right) + \sum_{\alpha=\{U,L\}} \sum_{k,\sigma} t_\alpha \left(c_{\alpha k\sigma}^\dagger d_\sigma + d_\sigma^\dagger c_{\alpha k\sigma}\right)$$

Crossover physics

$$H_{2\mathrm{CK}} = H_0 + J\vec{S}\cdot(\vec{s}_{0L} + \vec{s}_{0R}) + \delta H_{2\mathrm{CK}}$$

$$\delta H_{2\mathrm{CK}} = \sum_{l=x,y,z} \Delta_l \sum_{\alpha\beta,\sigma\sigma',kk'} c^\dagger_{k\sigma\alpha}\left(\frac{1}{2}\vec{\sigma}_{\sigma\sigma'}\tau^l_{\alpha\beta}\right) c_{k'\sigma'\beta}\cdot\vec{S} + \vec{B}\cdot\vec{S}$$

$$2\pi i\nu\mathcal{T}_{\sigma\alpha,\sigma'\alpha'}(\omega,T) = \delta_{\sigma\sigma'}\delta_{\alpha\alpha'} - S_{\sigma\alpha,\sigma'\alpha'}\mathcal{G}\left(\frac{\omega}{T^*},\frac{T}{T^*}\right)$$

$$\mathcal{G}(\tilde{\omega},\tilde{T}) = \frac{\frac{-i}{\sqrt{2\pi^3\tilde{T}}}}{\tanh\frac{\tilde{\omega}}{2\tilde{T}}}\frac{\Gamma\left(\frac{1}{2}+\frac{1}{2\pi\tilde{T}}\right)}{\Gamma\left(1+\frac{1}{2\pi\tilde{T}}\right)}\int_{-\infty}^{\infty} dx\,\frac{e^{\frac{ix\tilde{\omega}}{\pi\tilde{T}}}}{\sinh x} \times \mathrm{Re}\left[{}_2F_1\left(\frac{1}{2},\frac{1}{2};1+\frac{1}{2\pi\tilde{T}},\frac{1-\coth x}{2}\right)\right]$$

$$\tilde{\omega} = \omega/T^* \qquad \tilde{T} = T/T^*$$

$$S^{2\mathrm{CK}}_{\sigma\alpha,\sigma'\alpha'} = [-\delta_{\sigma\sigma'}(\vec{\lambda}_f\cdot\vec{\tau}_{\alpha\alpha'}) + i(\vec{\lambda}_B\cdot\vec{\sigma}_{\sigma\sigma'})\delta_{\alpha\alpha'}]/\lambda$$

λ_i	2CK model	
λ_1	$c_1\nu\Delta_z\sqrt{T_K}$	channel asymmetry
λ_2	$c_1\nu\Delta_x\sqrt{T_K}$	charge transfer
λ_3	$c_1\nu\Delta_y\sqrt{T_K}$	charge transfer
$\vec{\lambda}_B$	$c_B\vec{B}/\sqrt{T_K}$	magnetic field

$$T^* = \lambda^2$$

Add potential scattering:

$$2\pi\nu\mathcal{T}_{\sigma\alpha,\sigma\alpha}(\omega,\delta_P) = e^{2i\delta_P}[2\pi\nu\mathcal{T}_{\sigma\alpha,\sigma\alpha}(\omega) + i] - i$$

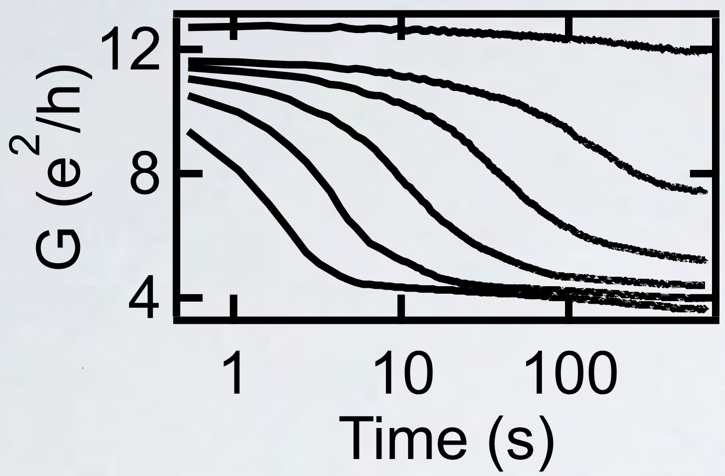
$$dI/dV \propto \sum_{\sigma=\uparrow,\downarrow}[-\pi\nu\,\mathrm{Im}T_{L\sigma}(eV)]$$

(although we also incorporate thermal broadening)

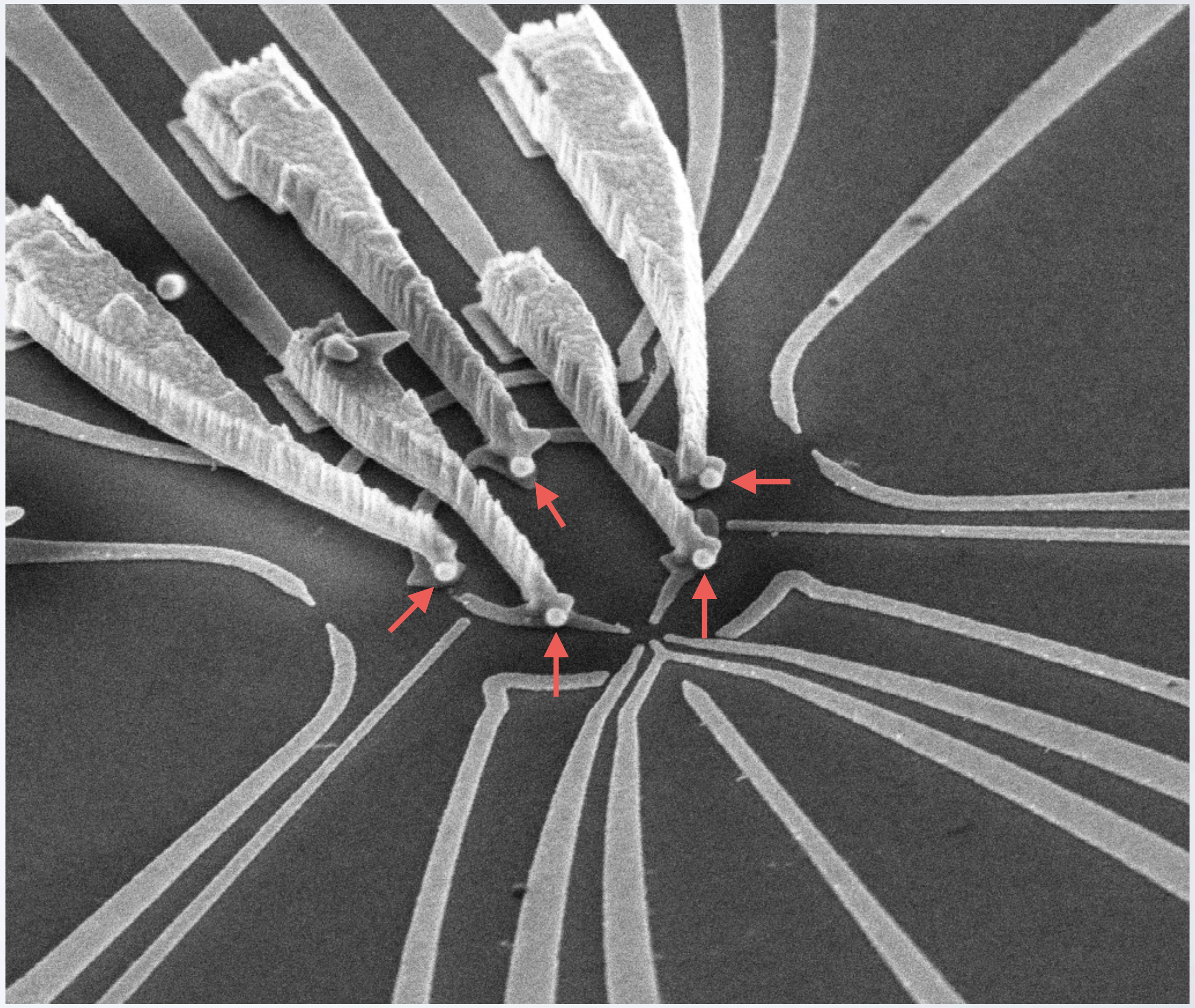
Sela, E., Mitchell, A., & Fritz, L.
PRL 106, 147202 (2011).

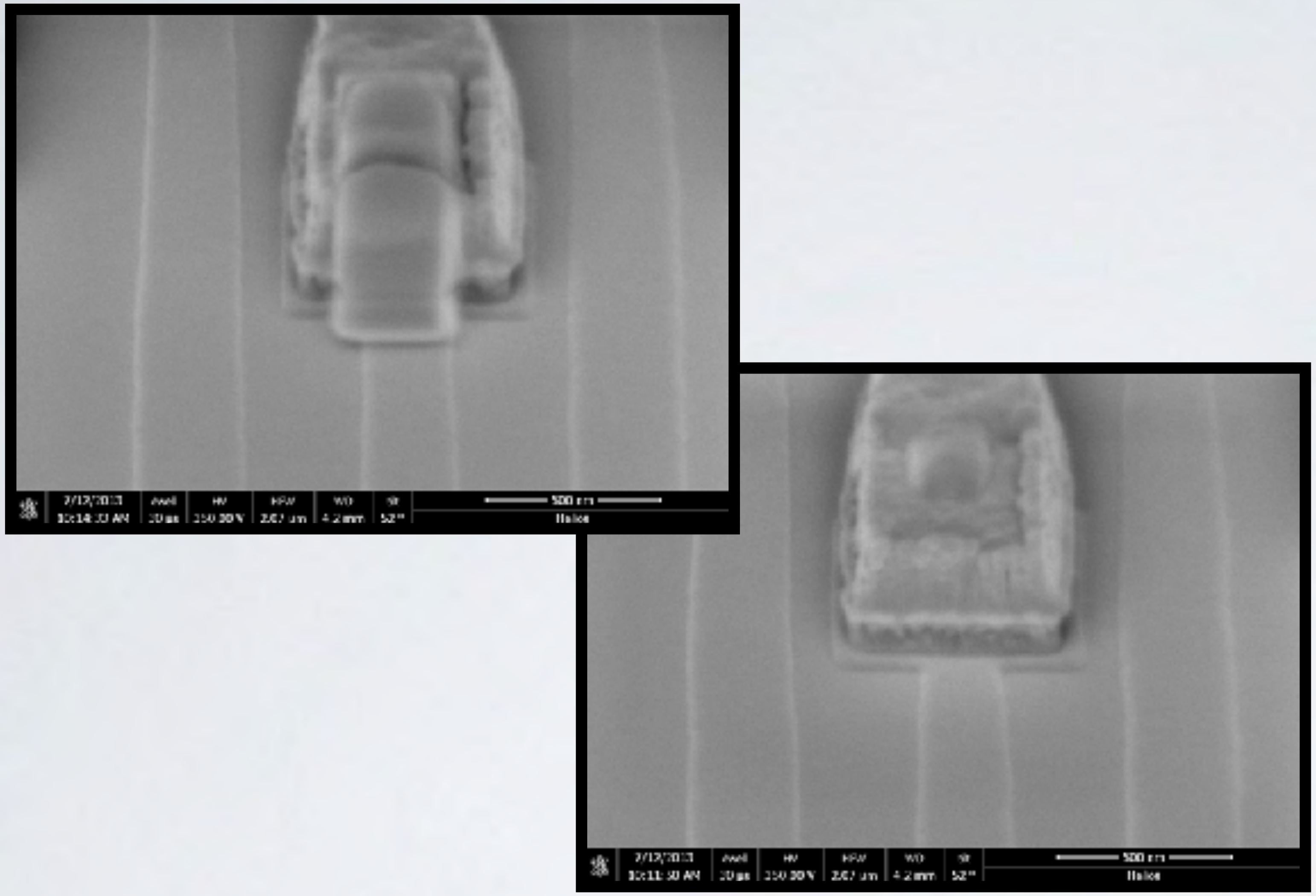
Mitchell, A. K., & Sela, E.
PRB 85, 235127 (2012).

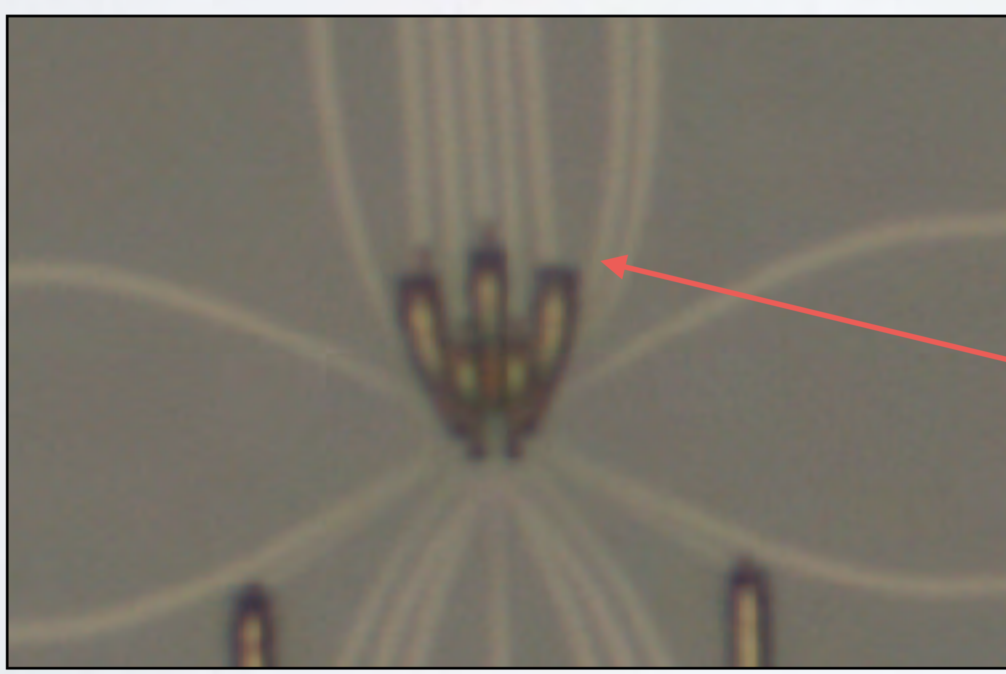
Problem: bridged gates are poorly contacted, leading to drifty behavior.

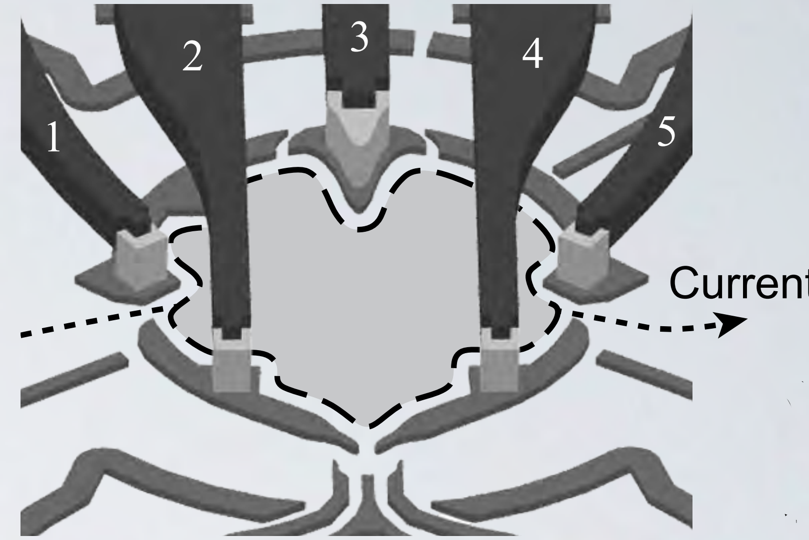


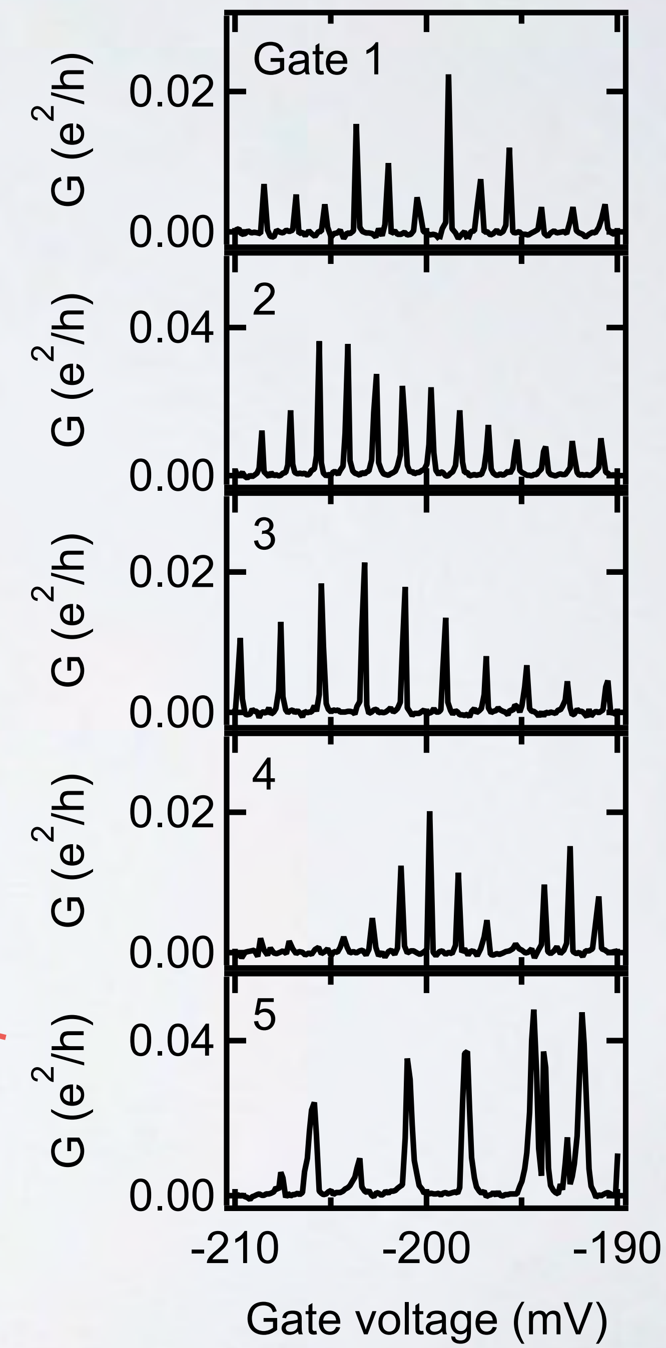
Solution: EBID platinum?





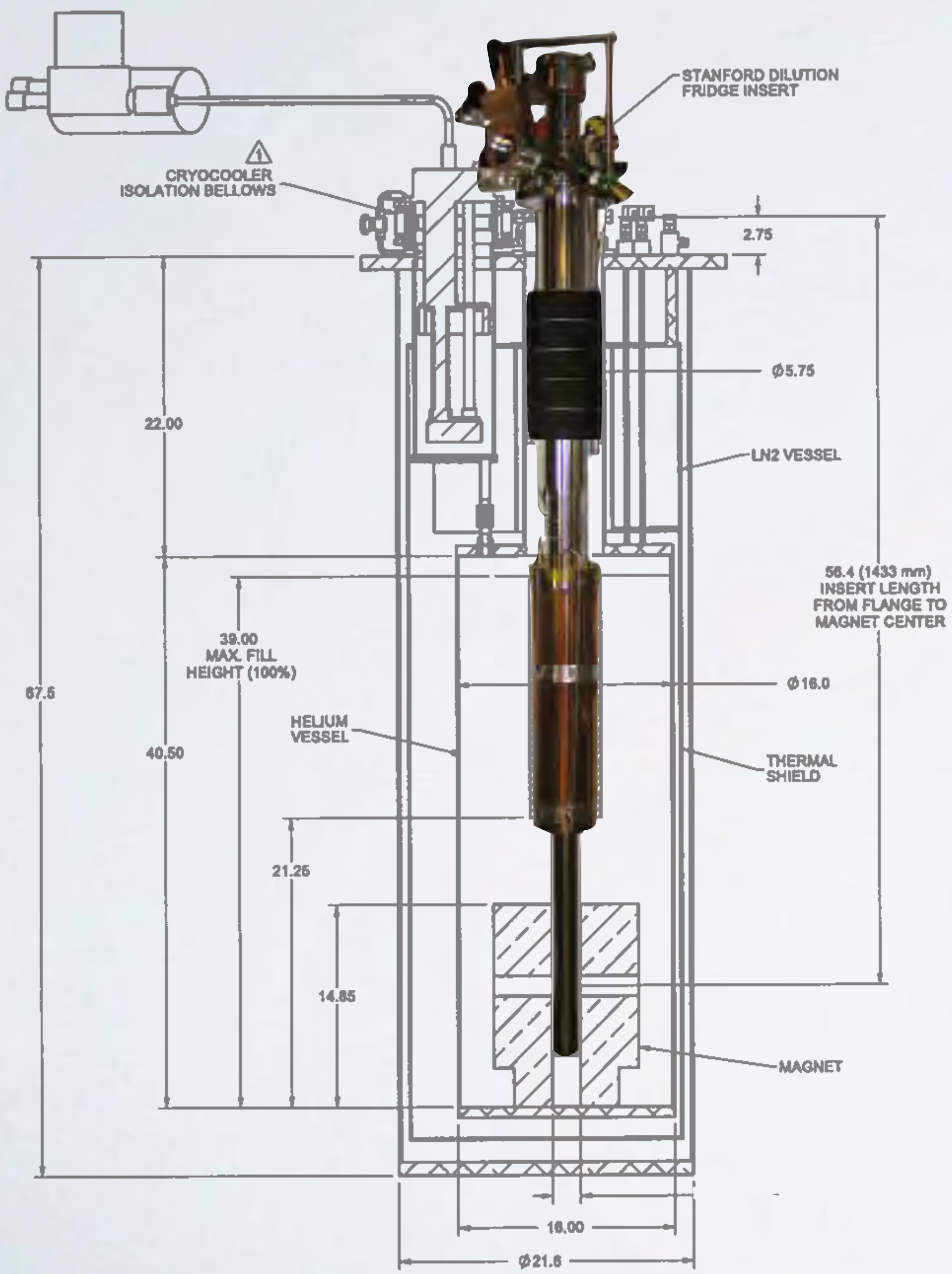



1
2
3
4
5
Current

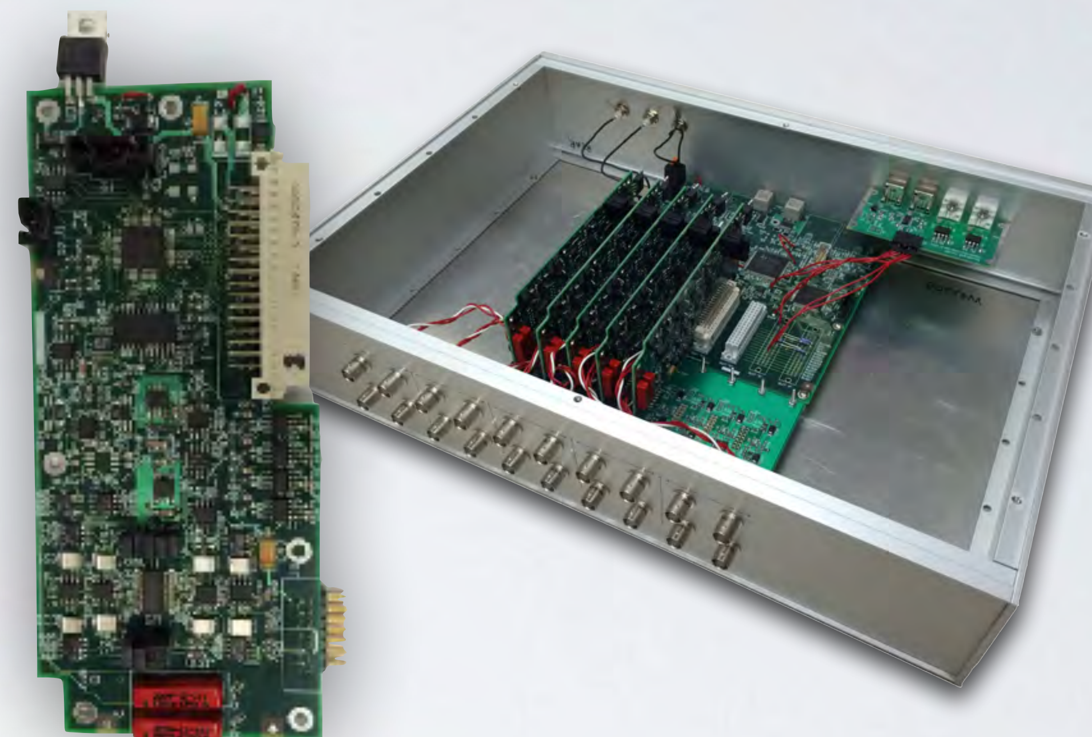

Gate 1
2
3
4
5
G (e^2/h)
0.00
0.02
0.04
-210
-200
-190
Gate voltage (mV)

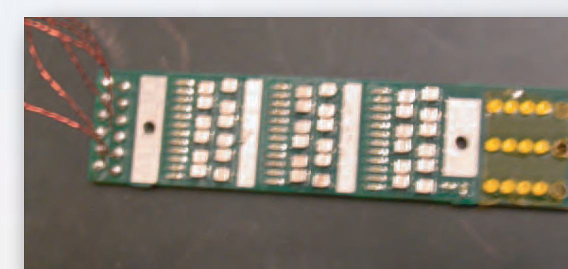
Keeping electrons cold and stable

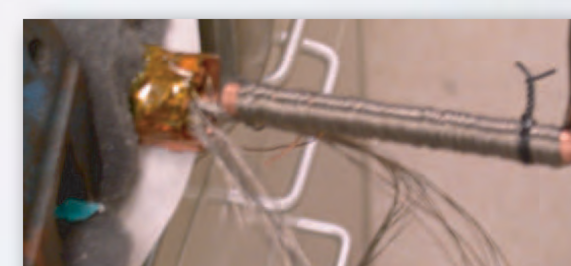
Recondensing helium dewar



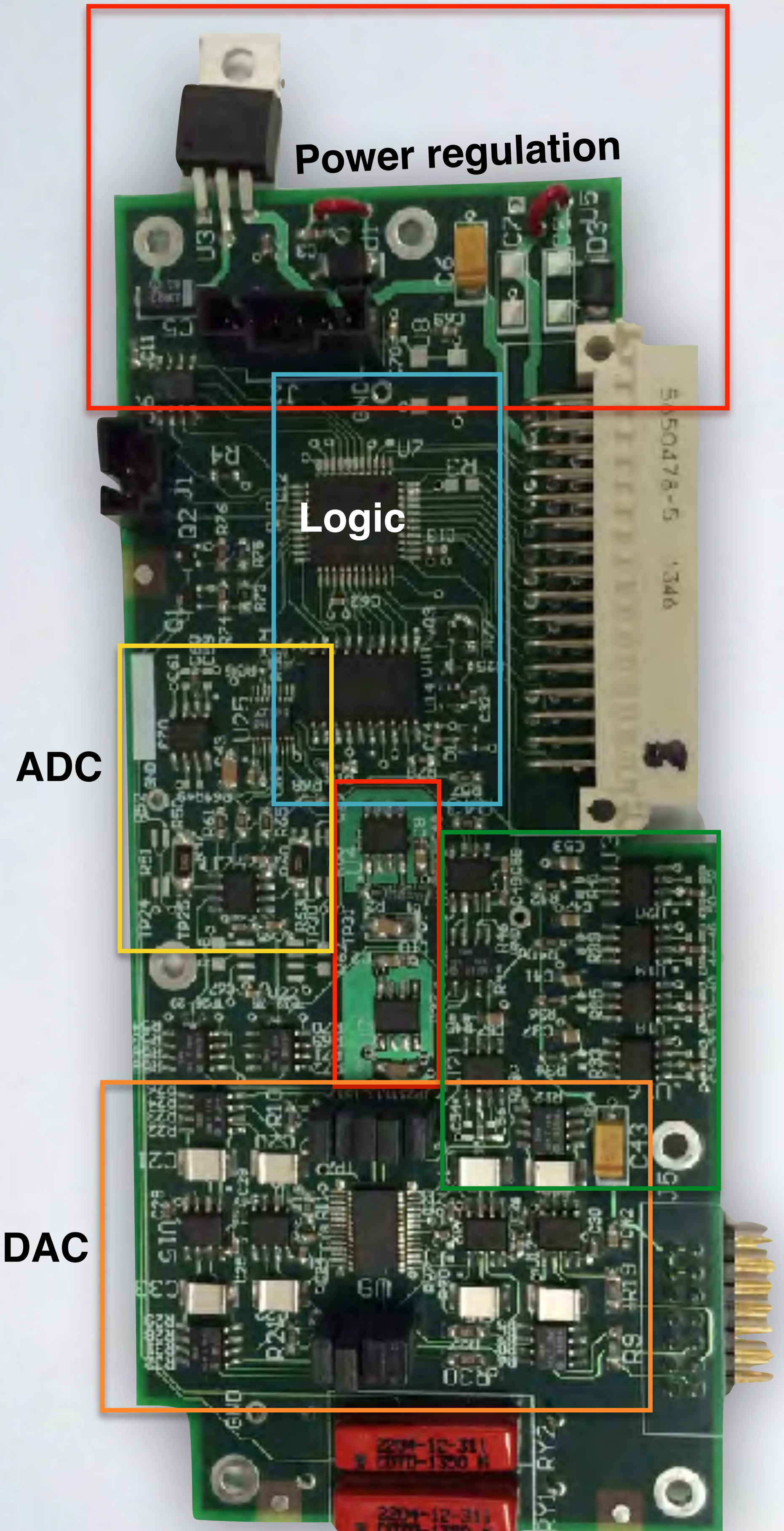
Custom electronics and filtering

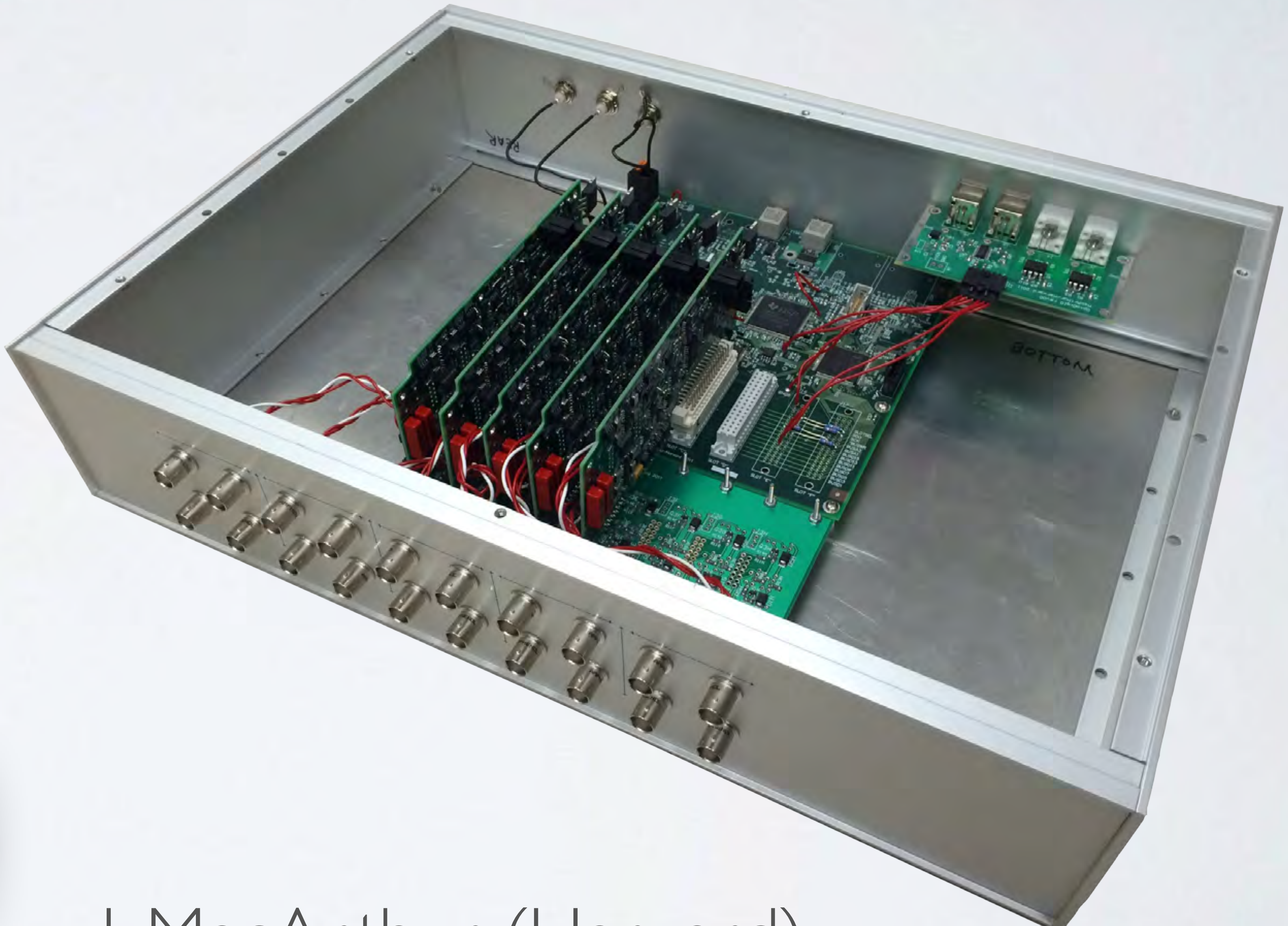






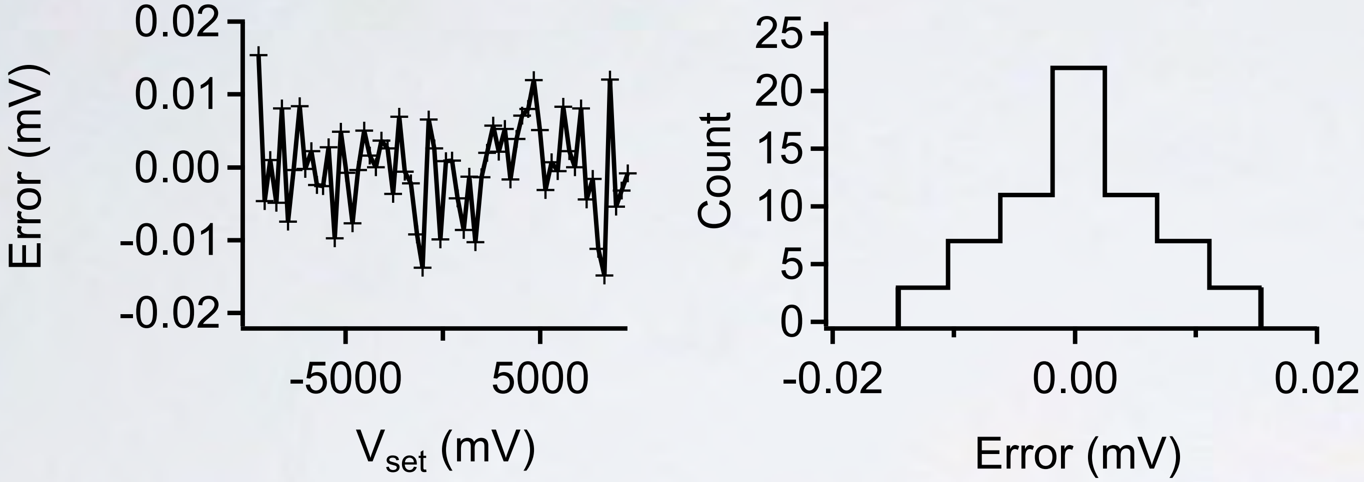
Building a high-precision voltage source

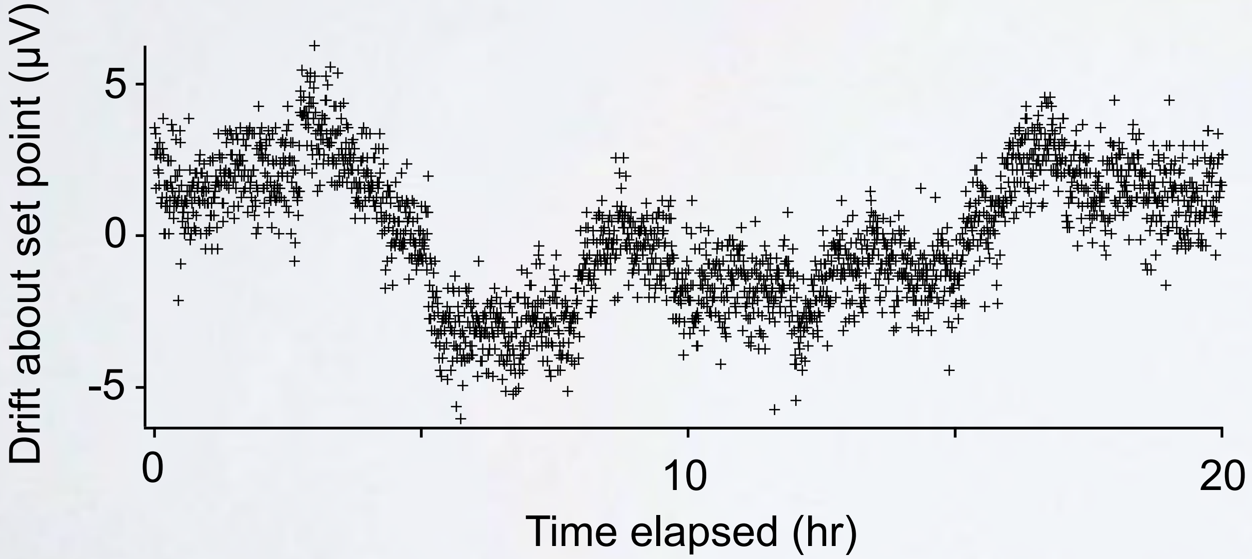




J. MacArthur (Harvard)

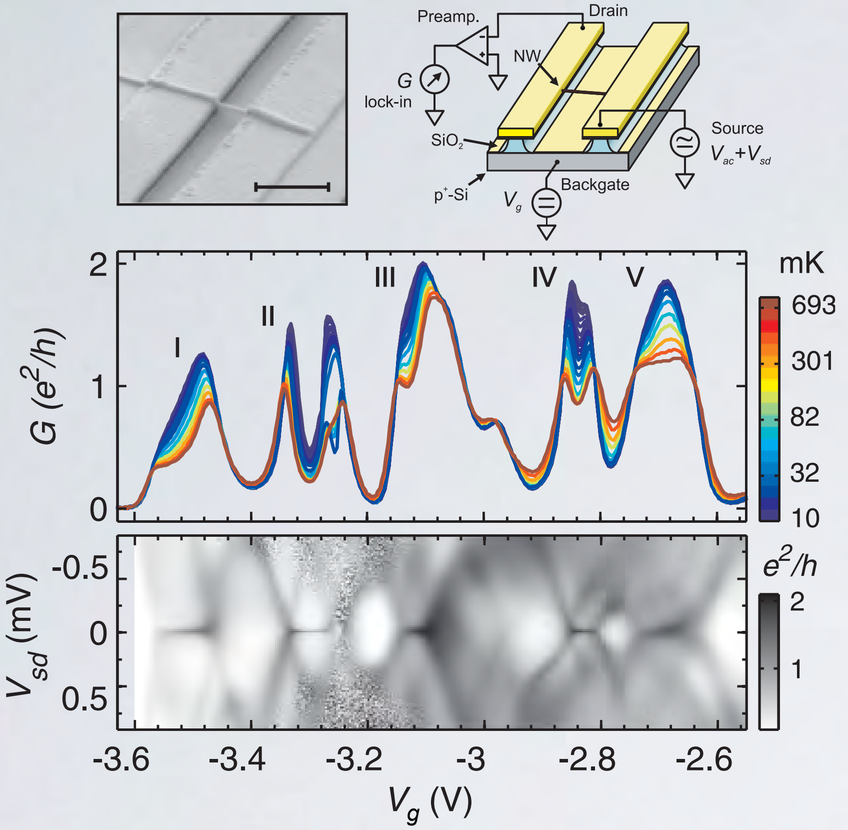
Building a high-precision voltage source





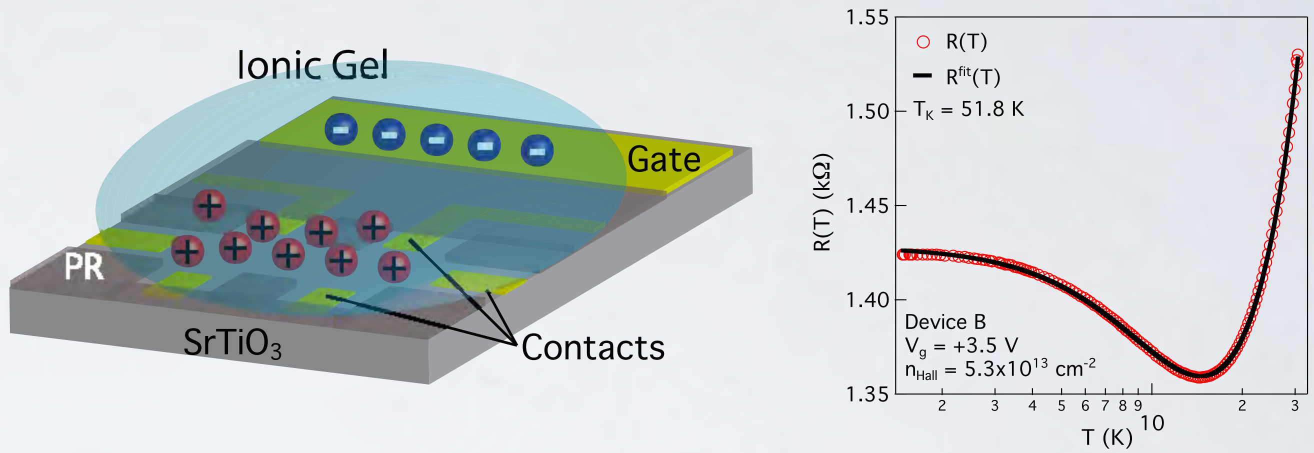
10 channels, low drift, nearly ppm accuracy

Kondo effect



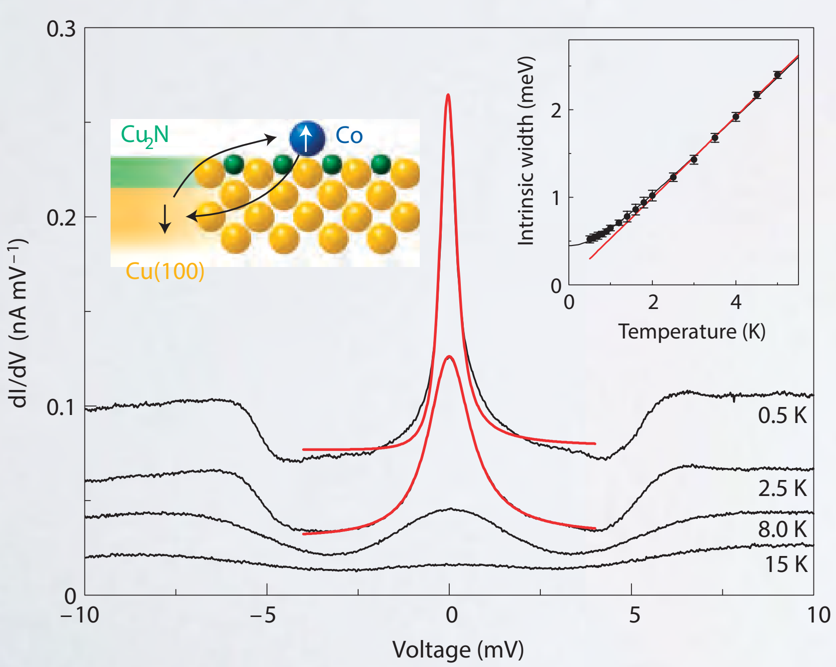
InAs nanowires

Kretinin, A.V., et al, *PRB* 84, 245316 (2011)



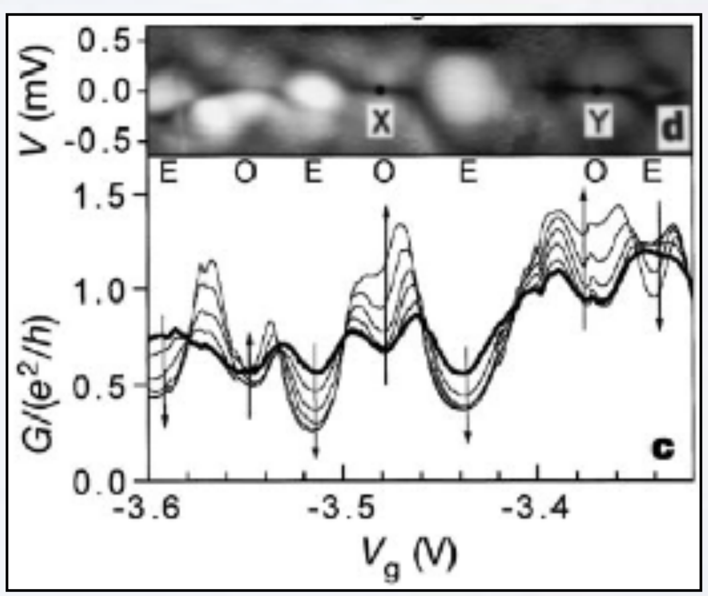
Electrolyte gate controlled $SrTiO_3$

Lee, M., et al, *PRL* 107, 256601 (2011)



Magnetic adatoms on surfaces

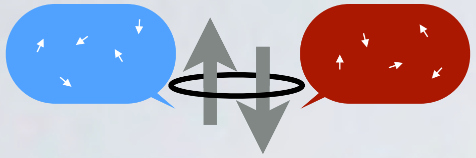
Otte, A. F., et al, *Nat. Phys.* 4 (2008)



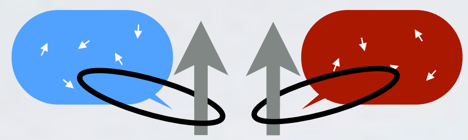
Carbon nanotubes

Nygård, J., et al, *Nature* 408 (2000)

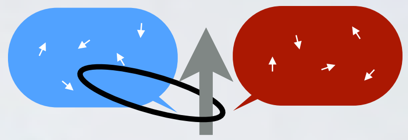
Two-impurity Kondo effect



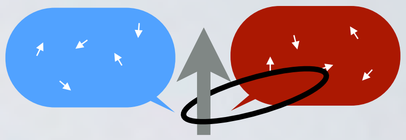
vs.



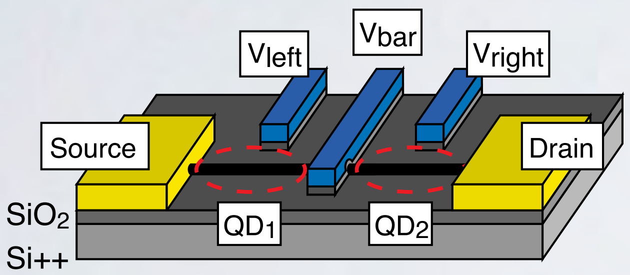
Two-channel Kondo effect



vs.

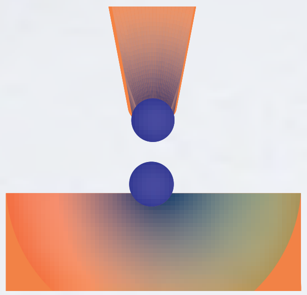


Nanotubes



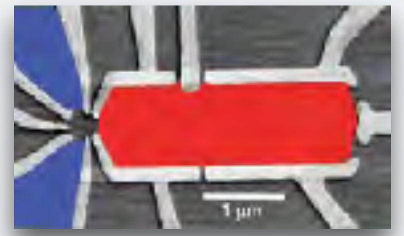
Chorley, et al., PRL 109, 156804 (2012)

STM

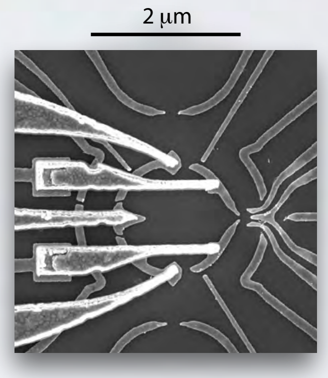


Bork, et al., Nature Phys. 7, 901–906 (2011)

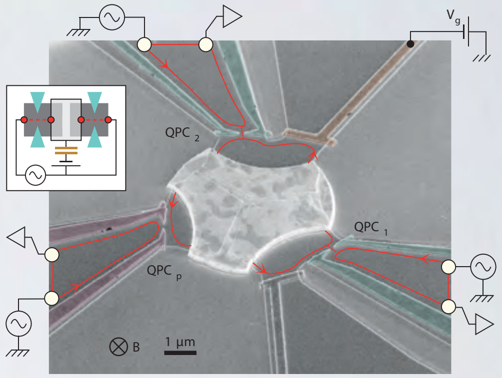
GaAs/AlGaAs heterostructures



Potok, et al., Nature 446, 167–71 (2007)



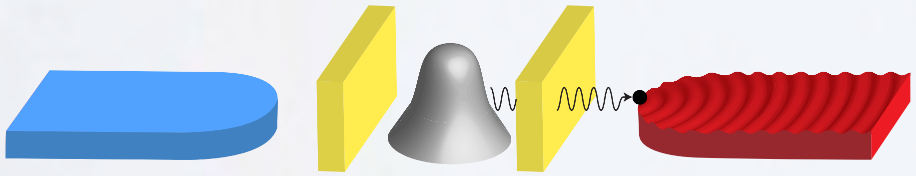
Keller, et al., Nature 526, 237–240 (2015)



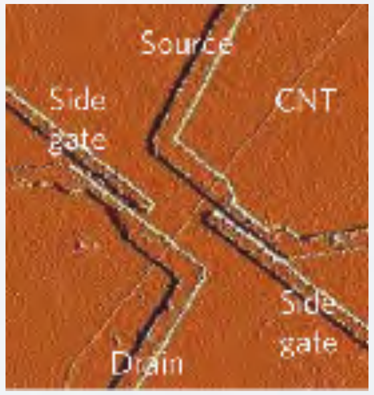
Iftikhar, et al., Nature 526, 233–236 (2015)

Majorana QPTs

Nanotube with dissipative leads



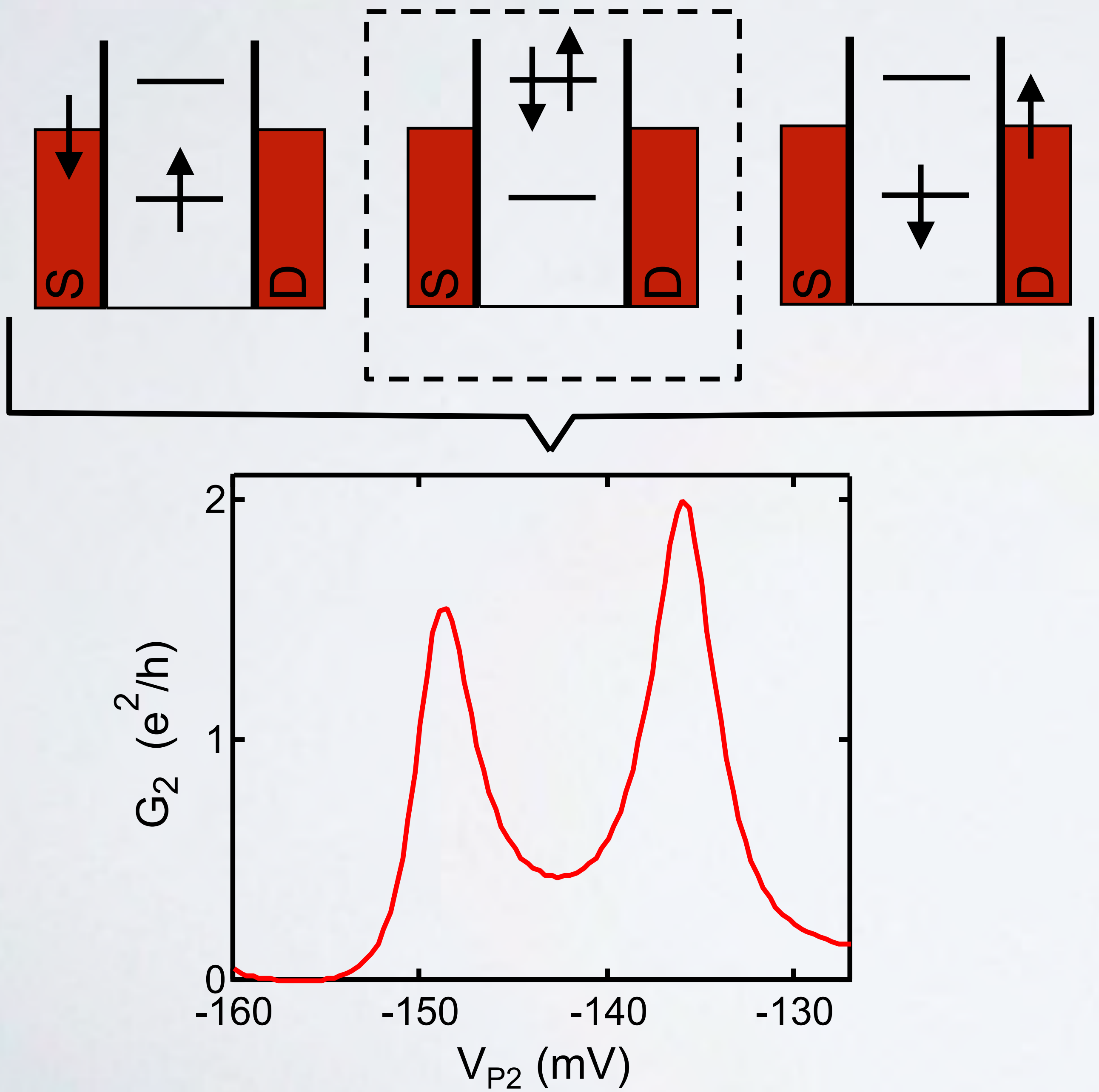
Graphic adapted from Peeters and Goldhaber-Gordon, Nature Phys. 9, 695–696 (2013).

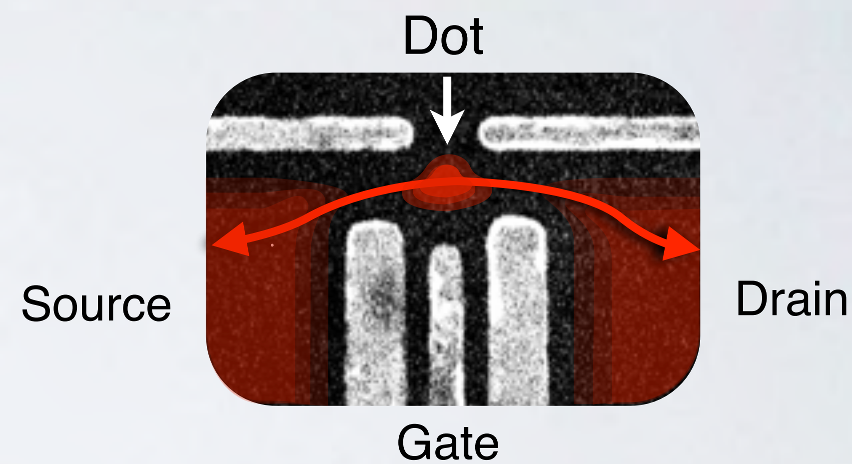


Mebrahtu, *et al.*, Nature 488, 61–4 (2012), Nature Phys. 9, 1–6 (2013)

Transport through quantum dots

Kondo effect





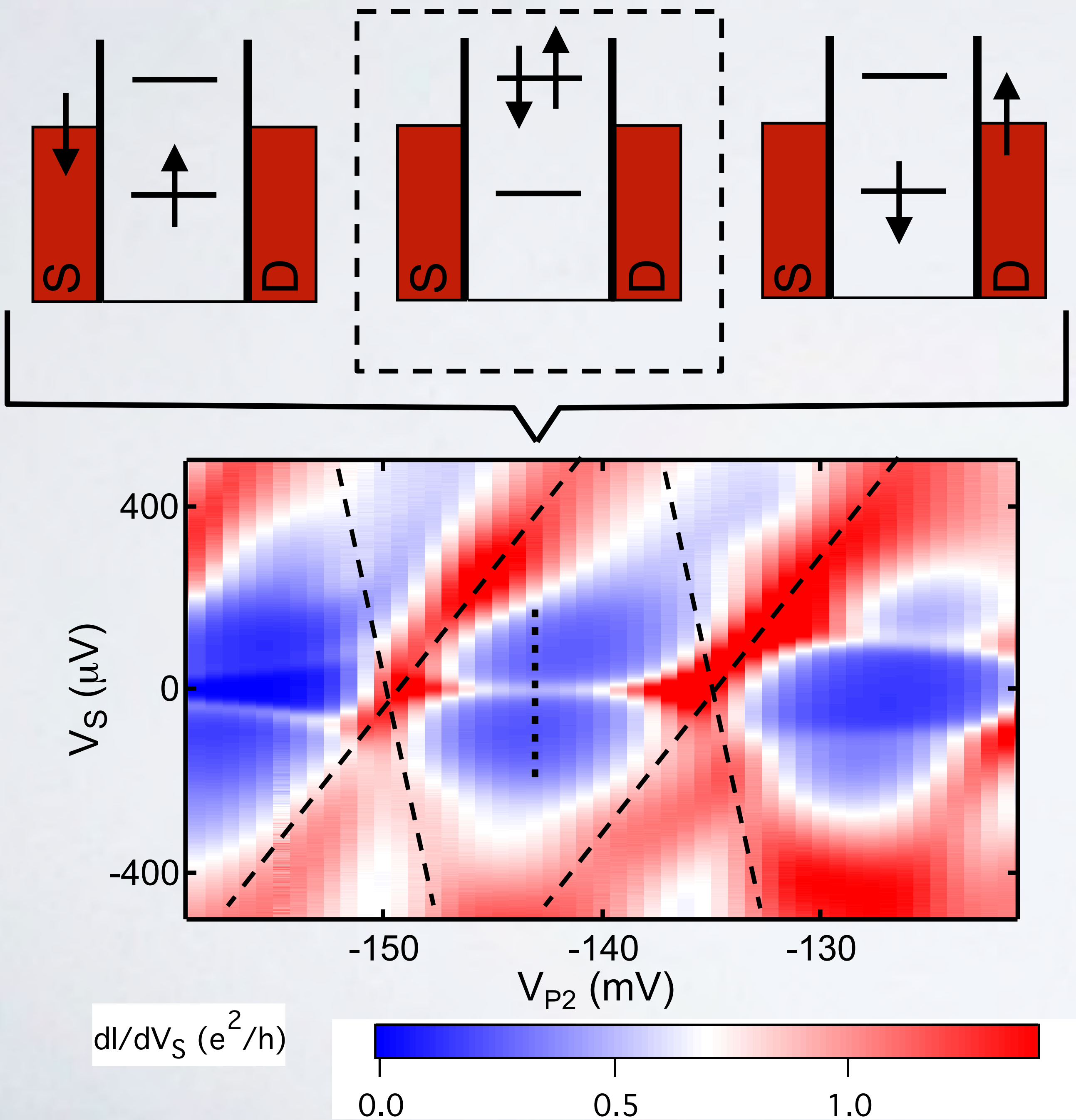
Charging energy: U

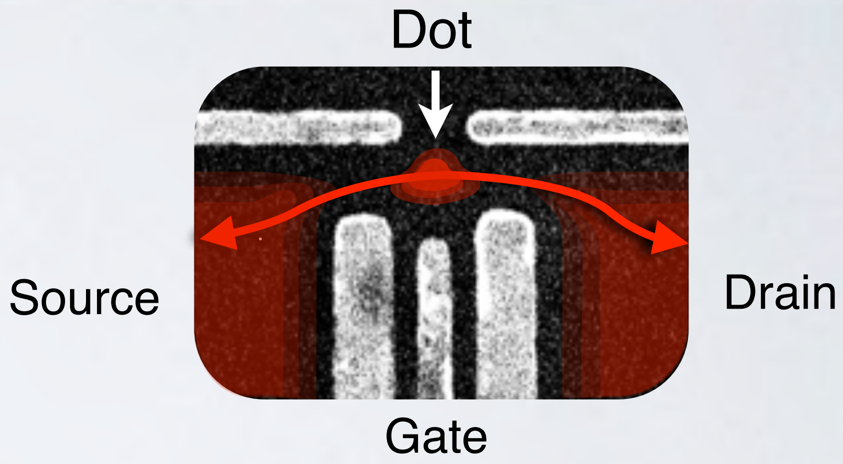
Dot-lead tunnel rate: Γ

$\Gamma/U \sim 0.2$ to 0.3

Transport through quantum dots

Kondo effect





Zero-bias conductance enhancement → Kondo effect