Model Many-body Systems Based on Quantum Dots

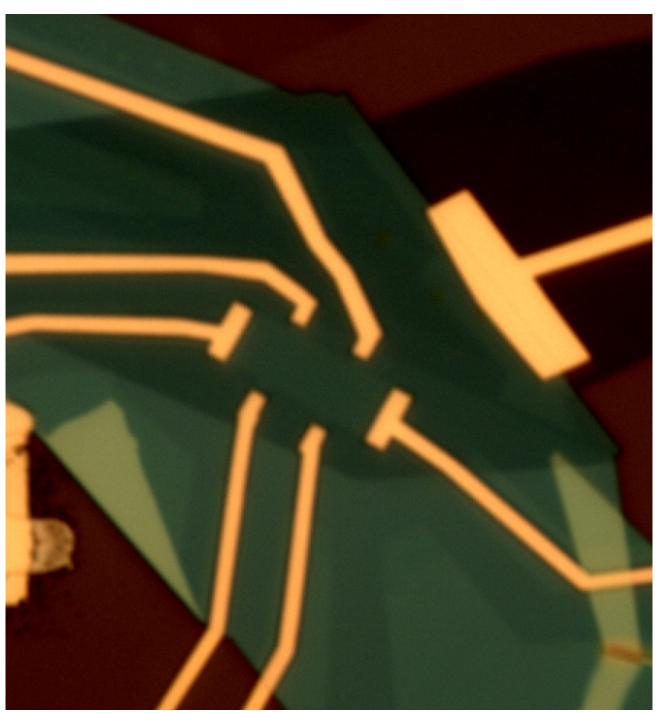
David Goldhaber-Gordon
Stanford University

KITP SYNQUANT Workshop
November 1, 2016

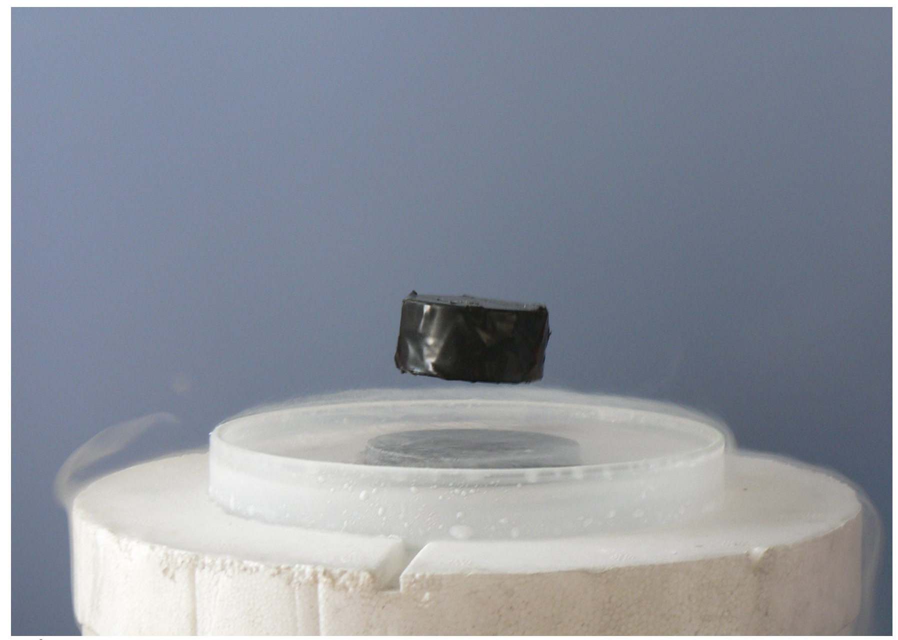
How to beat Ohm’s Law

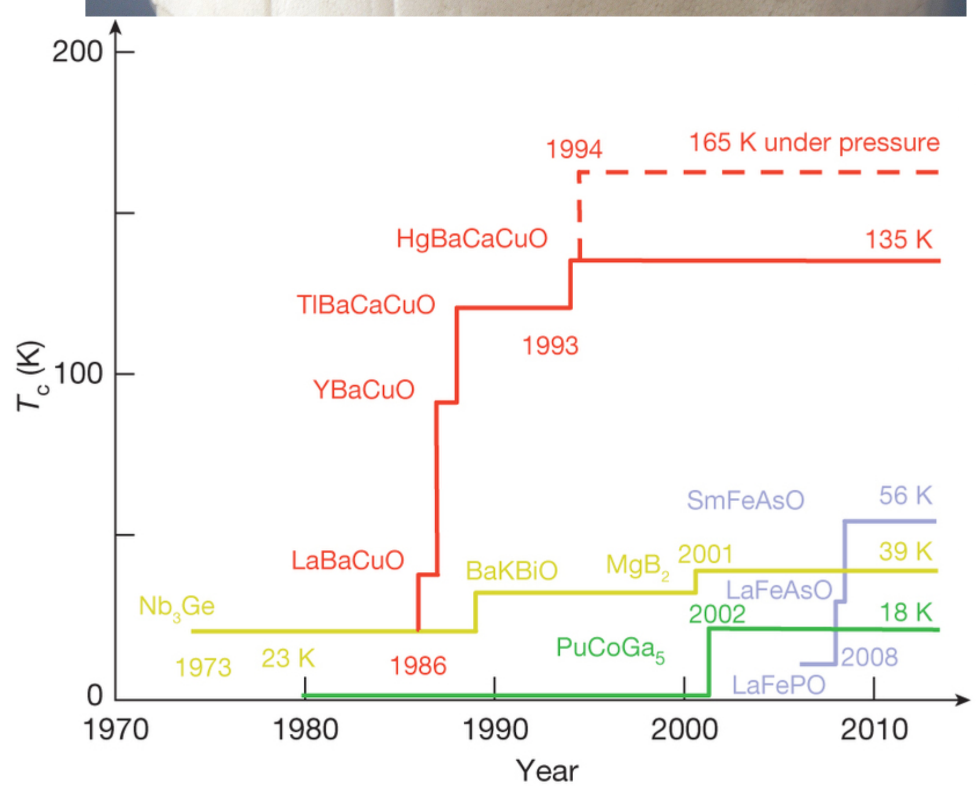
Three possible approaches.

Make the best conductor



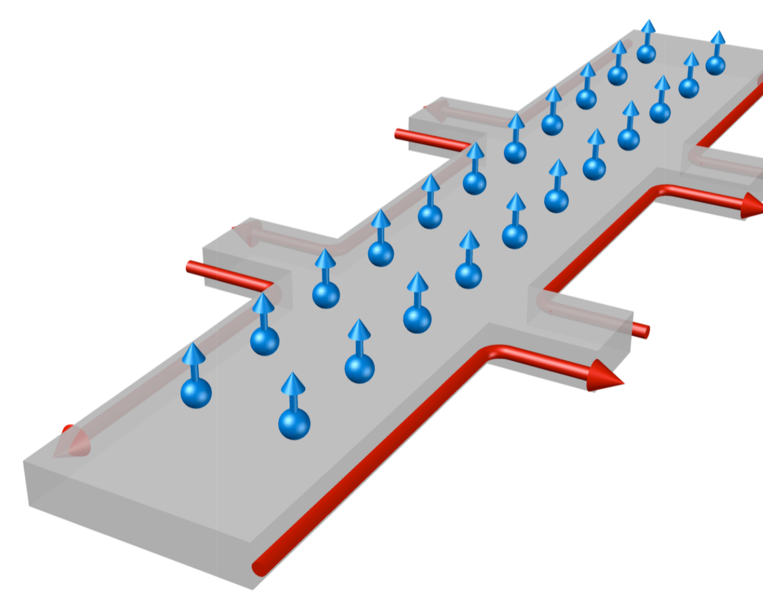
Make a superconductor





B. Keimer *et al.*, Nature, 2015

Set some rules



Outline

- **Symmetry and renormalization**
- Quantum dots and the Kondo effect
- Emergent SU(4)-symmetric Kondo effect in a double quantum dot
- Universal crossover between quantum critical and Fermi liquid states in a quantum dot coupled to a “metallic grain”

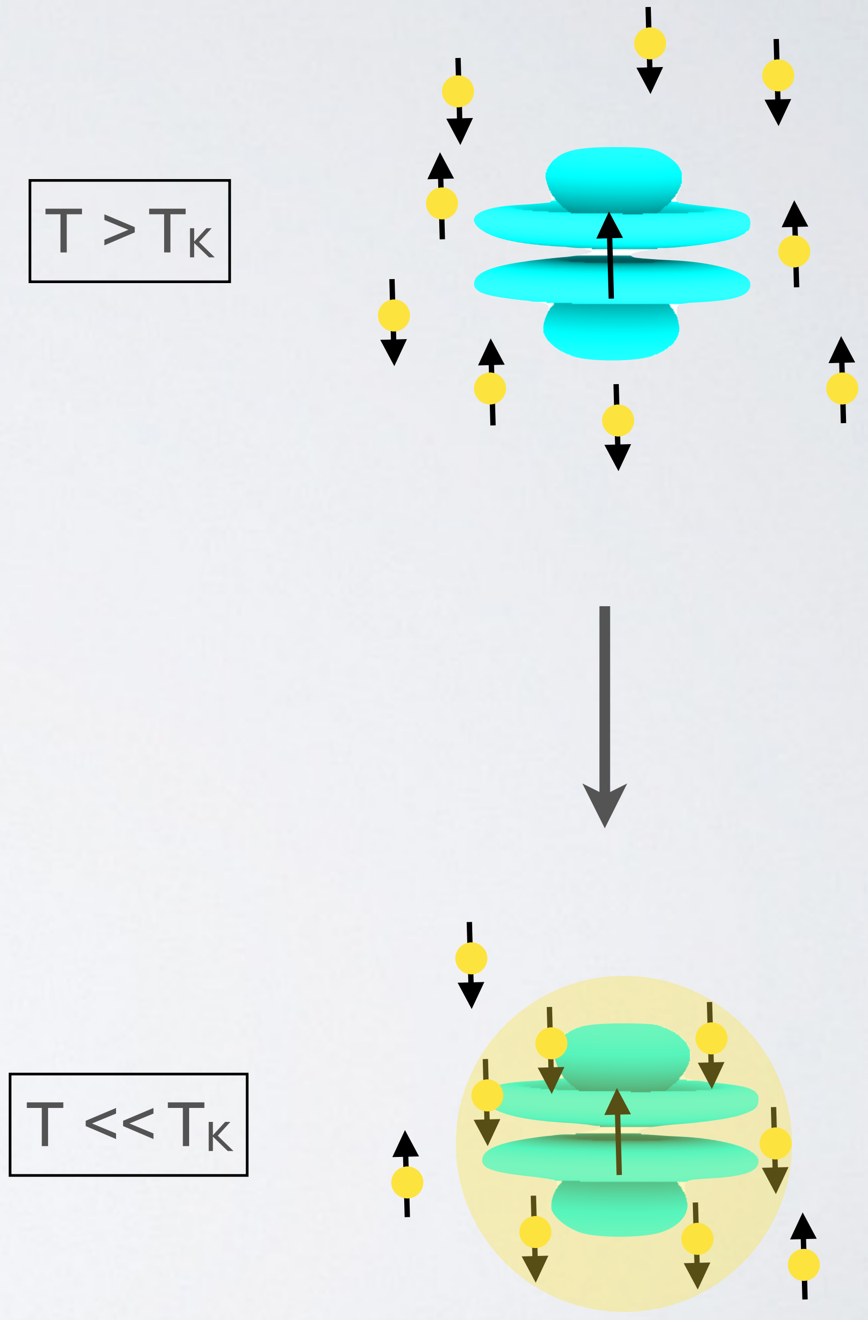
Calculations in this talk by G. Zaránd, C. P. Moca, I. Weymann

Outline

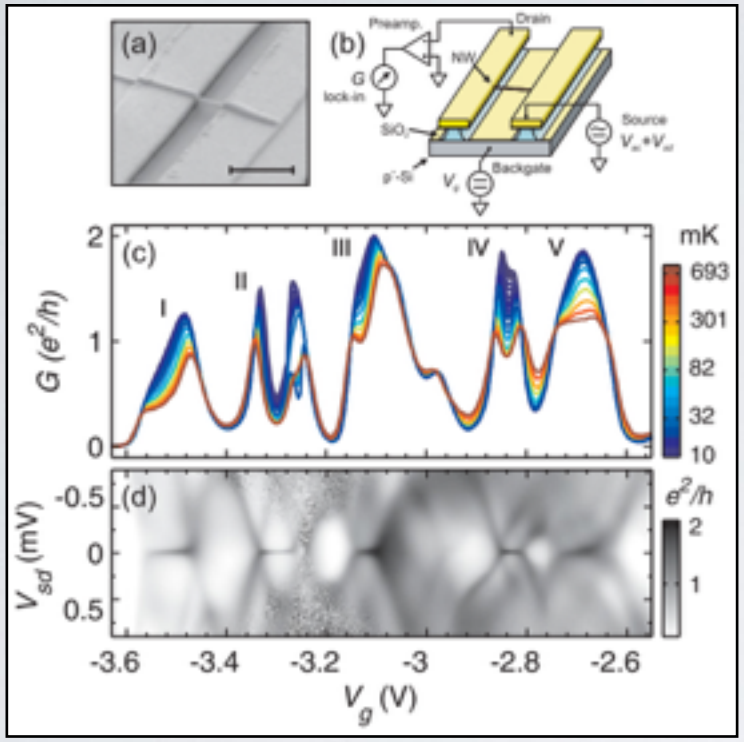
- Symmetries in physics
- **Quantum dots and the Kondo effect**
- Emergent SU(4)-symmetric Kondo effect in a double quantum dot
- Universal crossover between quantum critical and Fermi liquid states in a quantum dot coupled to a “metallic grain”

Kondo effect

- Itinerant electrons screen a localized 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

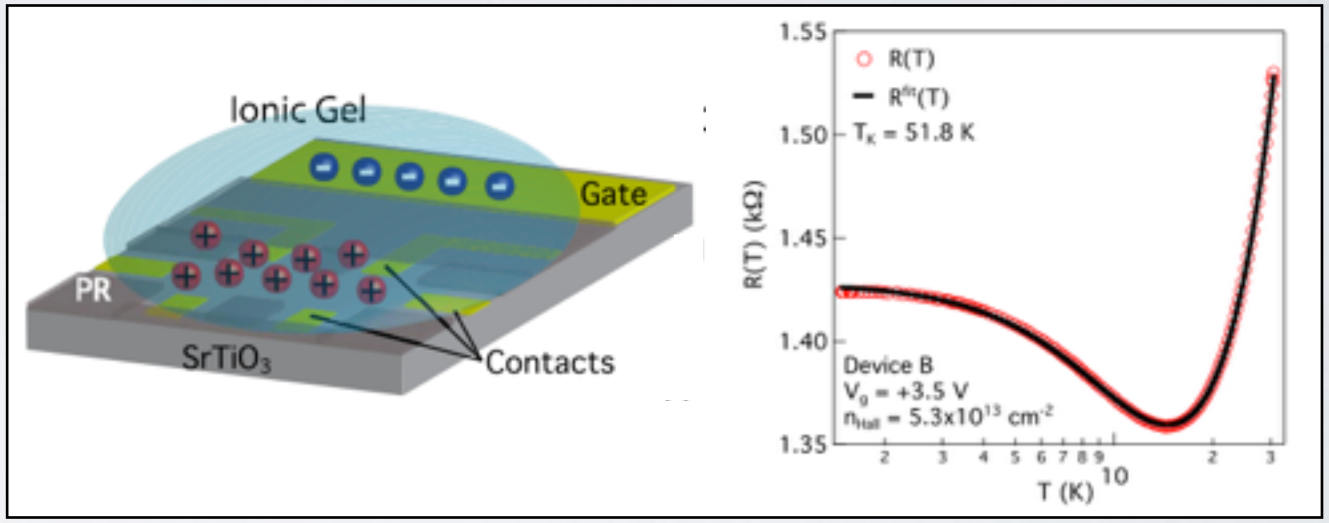


Kondo effect



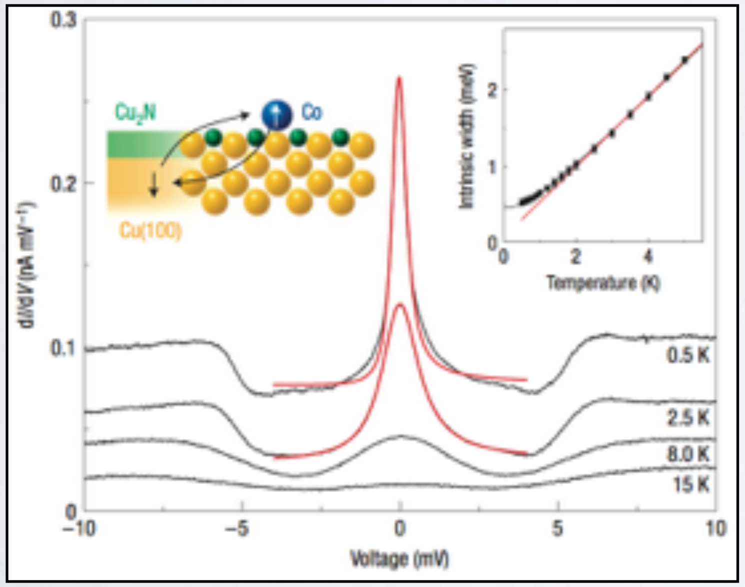
InAs nanowires

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



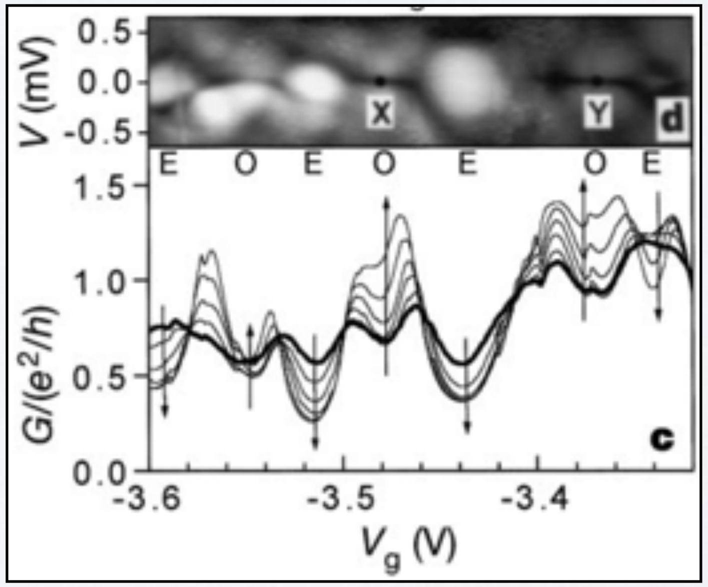
Electrolyte gate controlled SrTiO$_3$

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



Magnetic adatoms on surfaces

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

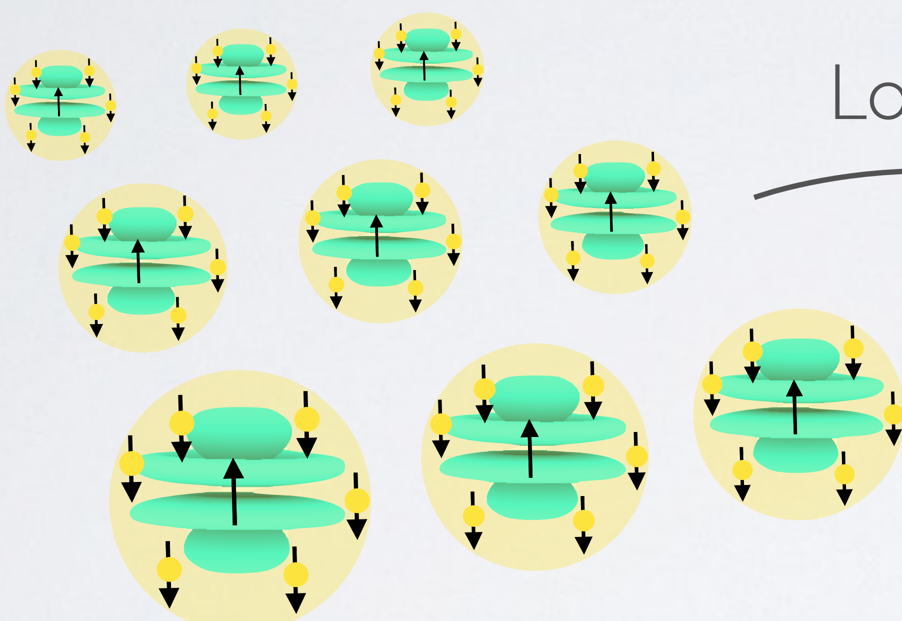


Carbon nanotubes

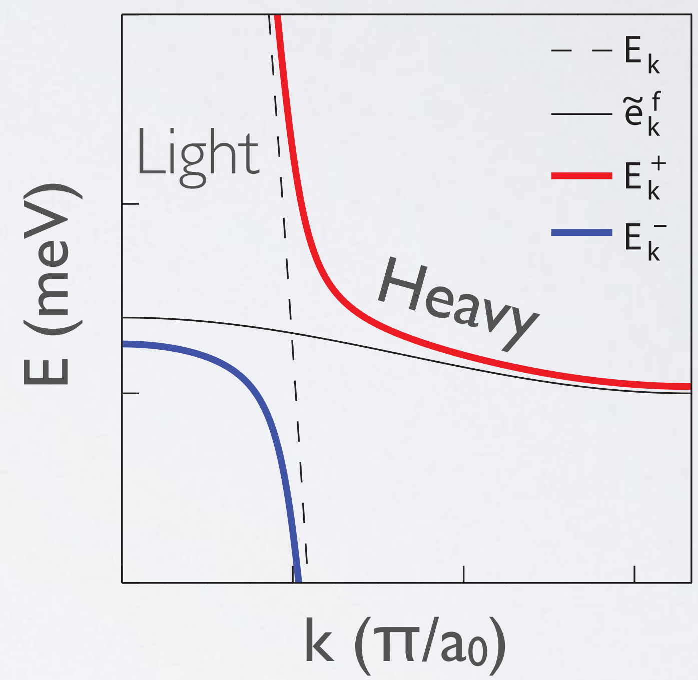
Nygård, J., et al, *Nature* 408 (2000)

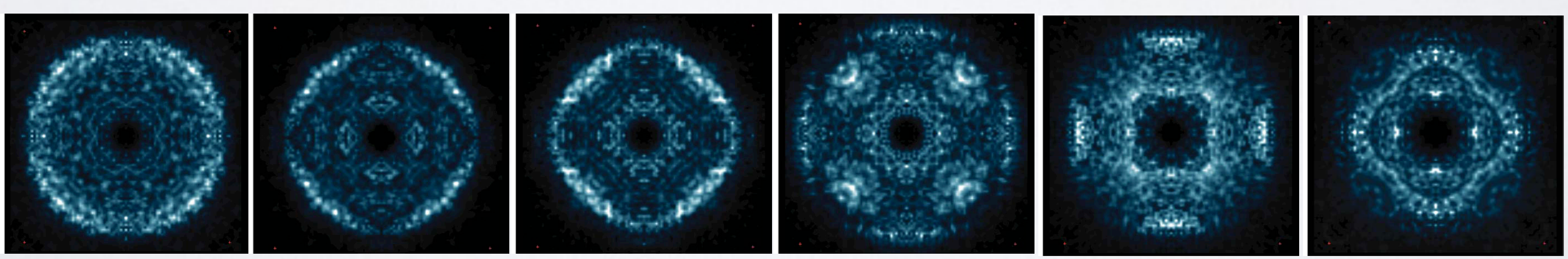
Adding more local spins

Heavy fermion systems



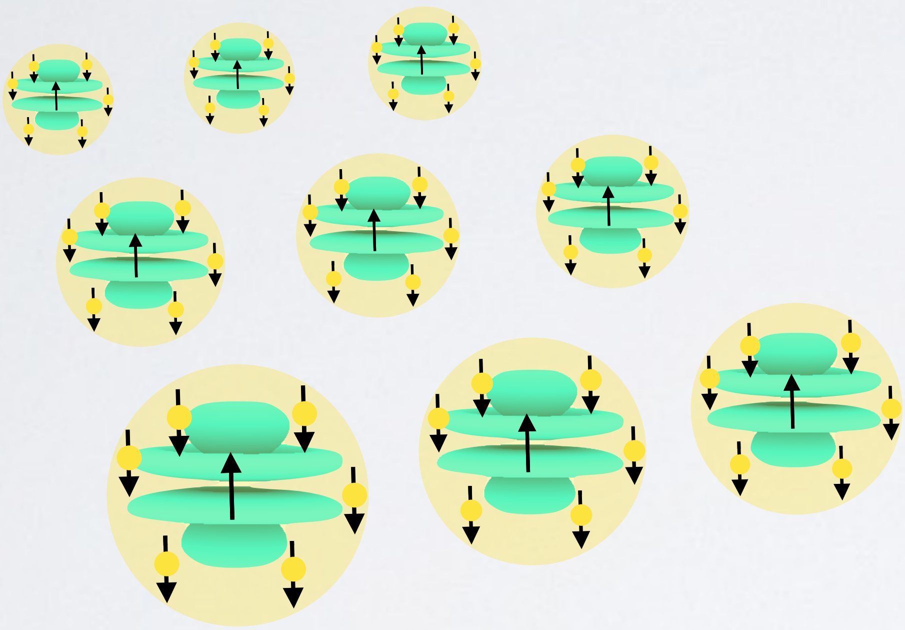
Low T





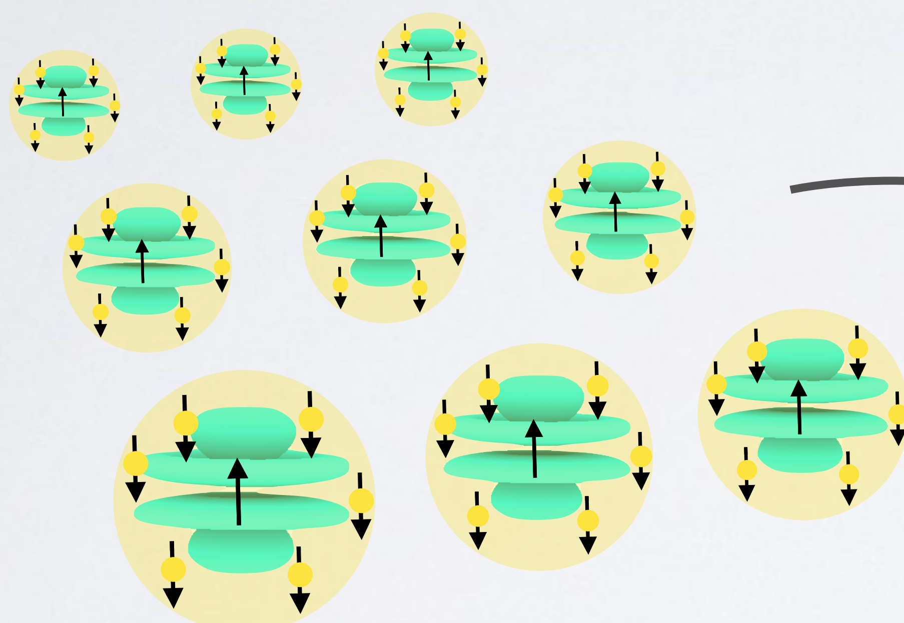
A. R. Schmidt, *et al.*, Nature 465, 570 (2010)

Adding more local spins

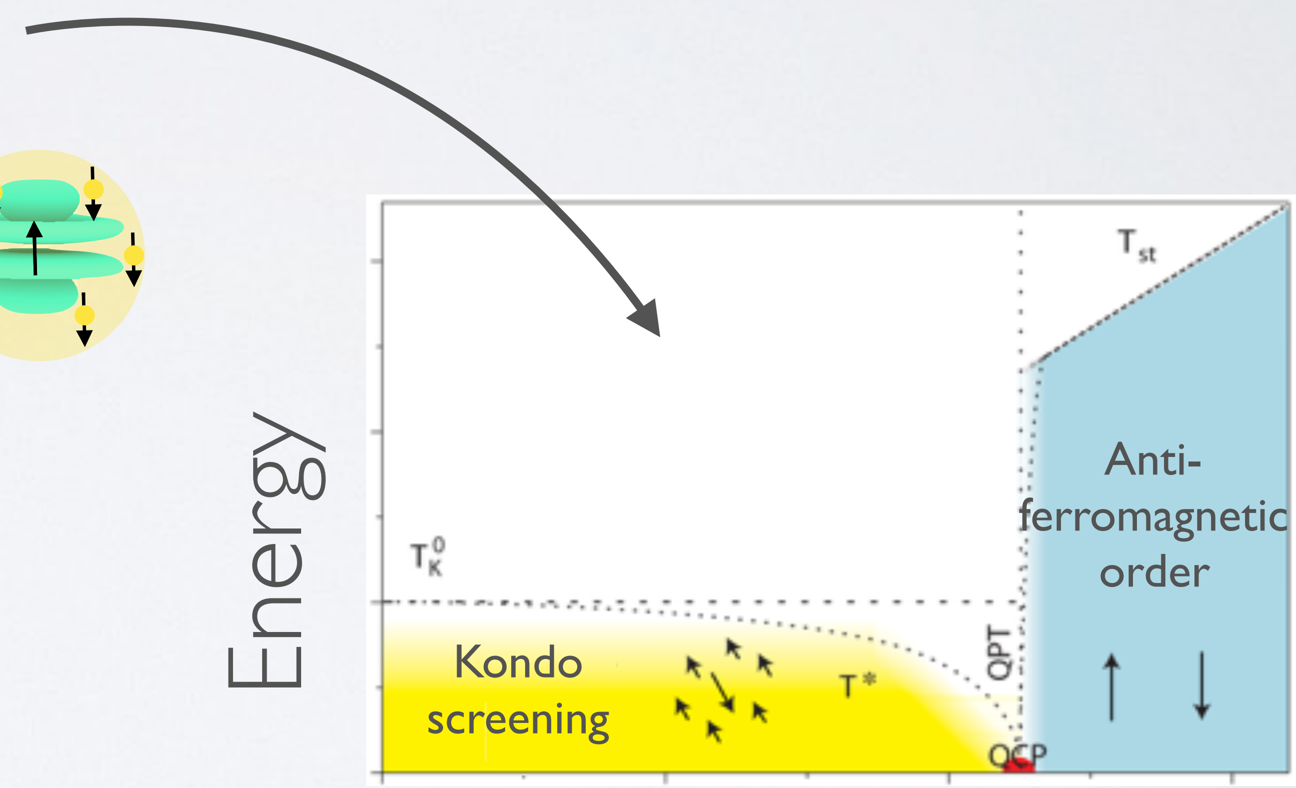


Adding more local spins

Quantum critical points?

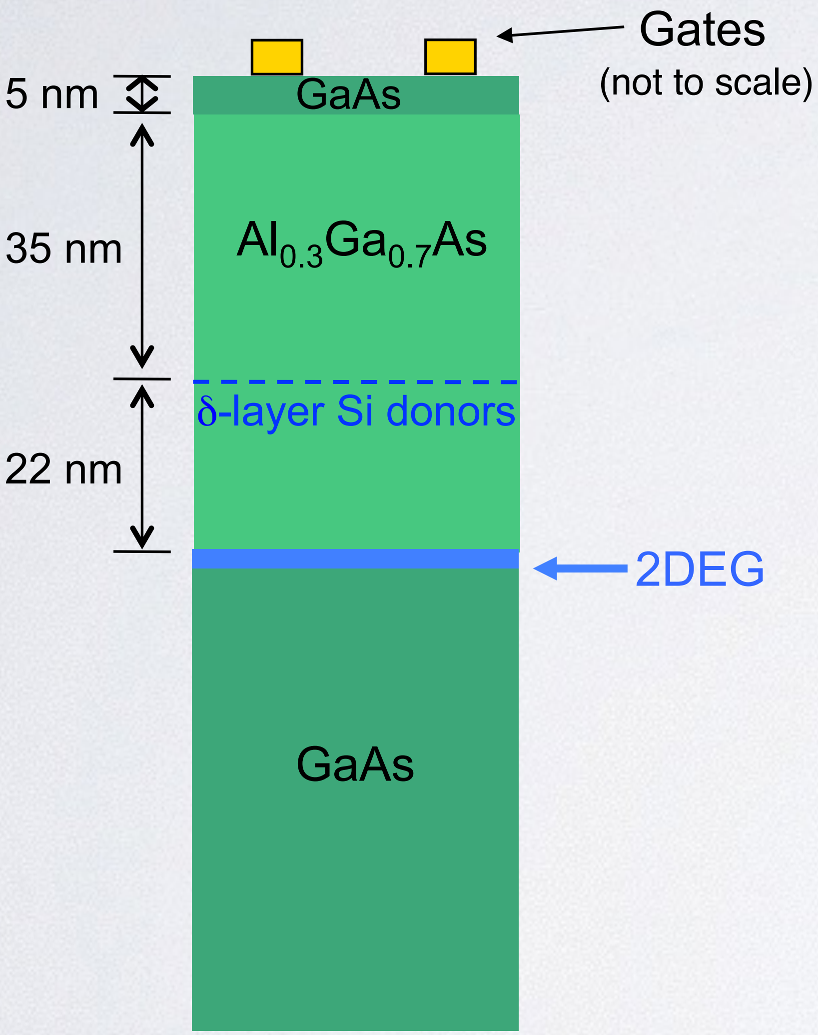


+ RKKY interaction



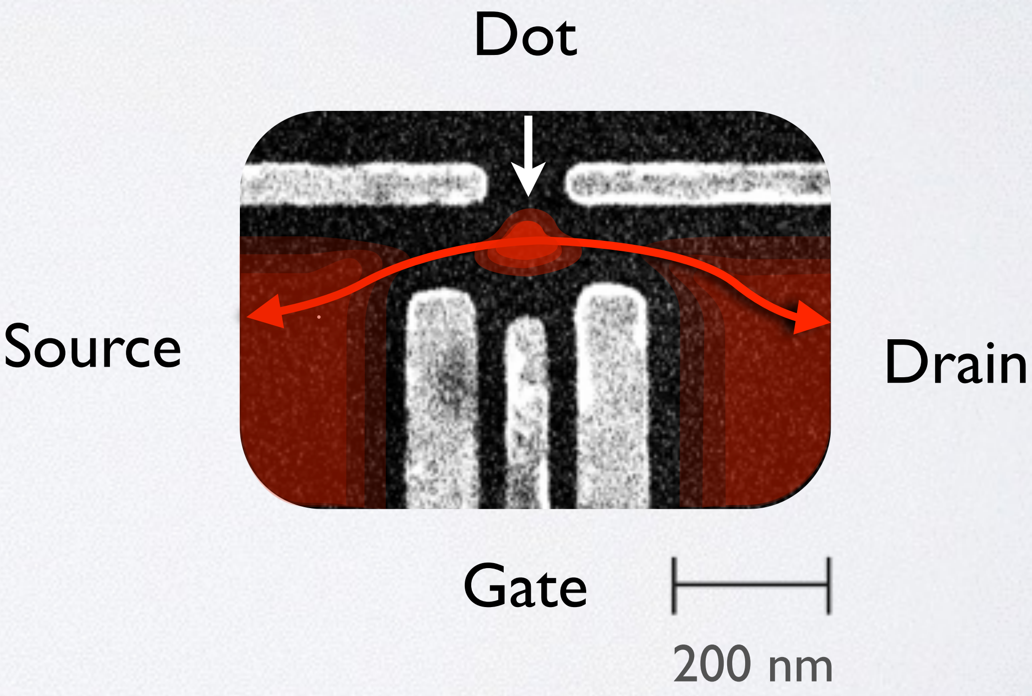
Adapted from Bork, *et al.*, Nature Physics 7, 11 (2011).

Quantum dots



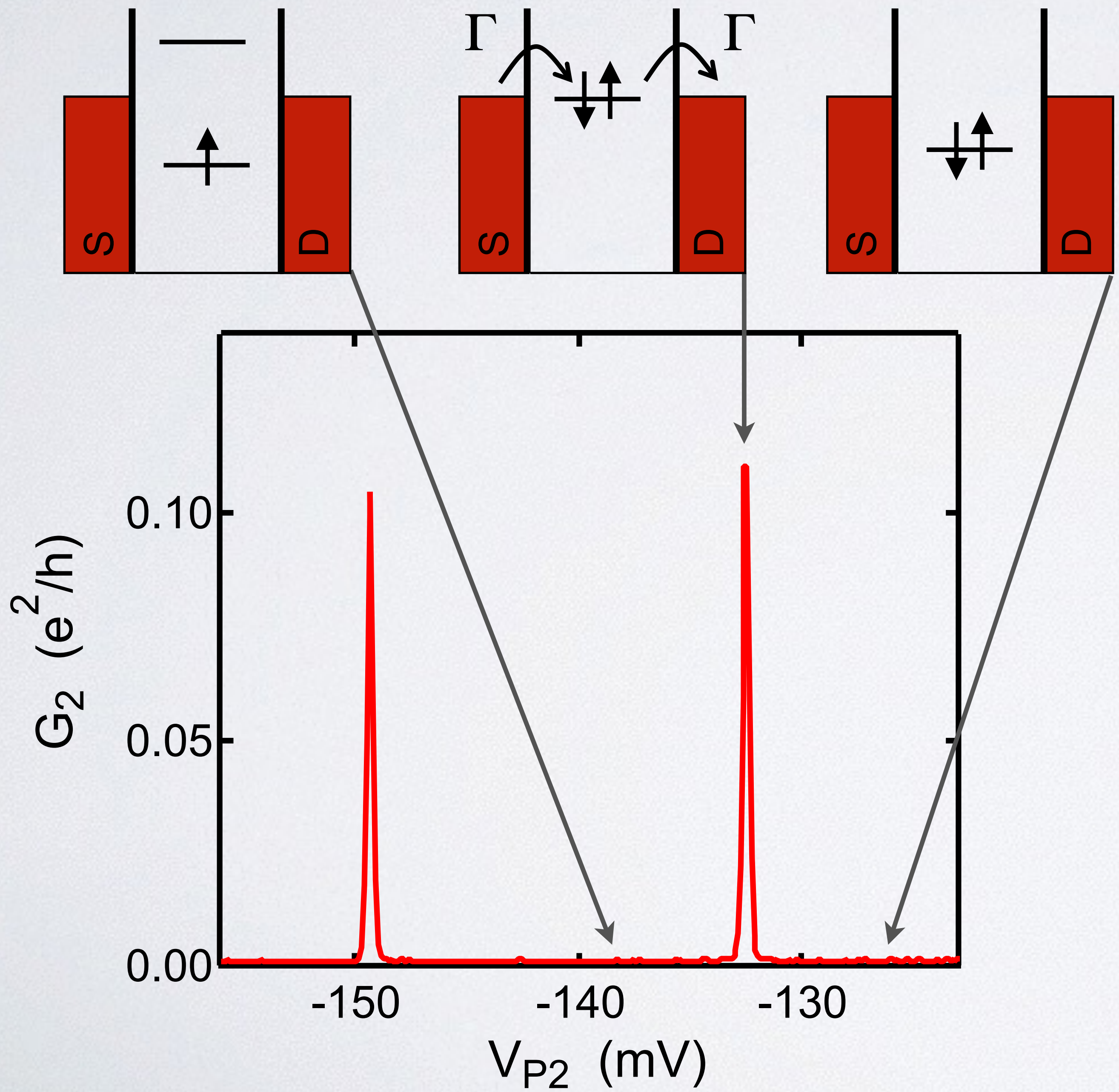
$$H = \sum_{k\sigma} \epsilon_k c^\dagger_{k\sigma} c_{k\sigma} + \sum_\sigma \epsilon_d d^\dagger_\sigma d_\sigma + U n_{d\uparrow} n_{d\downarrow}$$

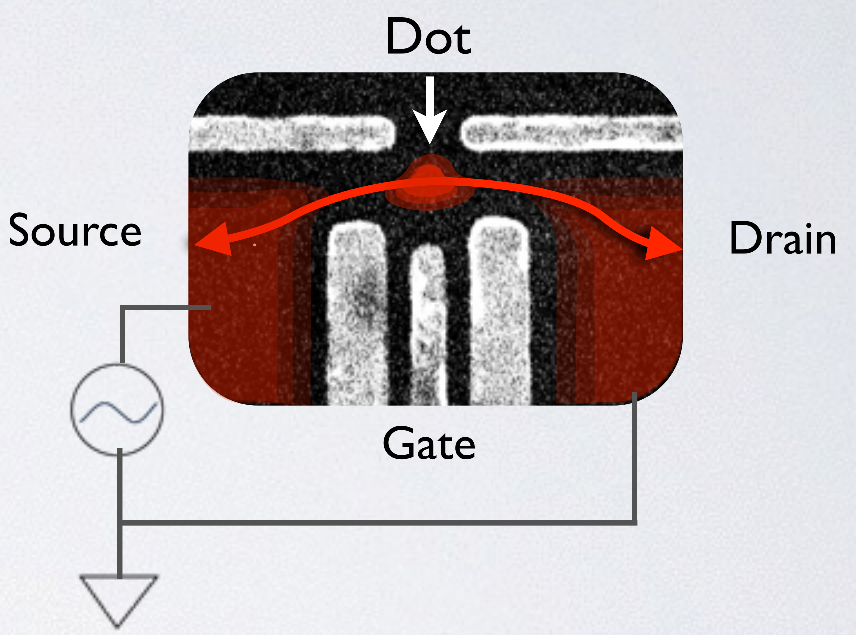
$$+ \sum_{k\sigma} \left(V_k d^\dagger_\sigma c_{k\sigma} + \mathrm{h.c.} \right)$$



Transport through quantum dots

Coulomb blockade





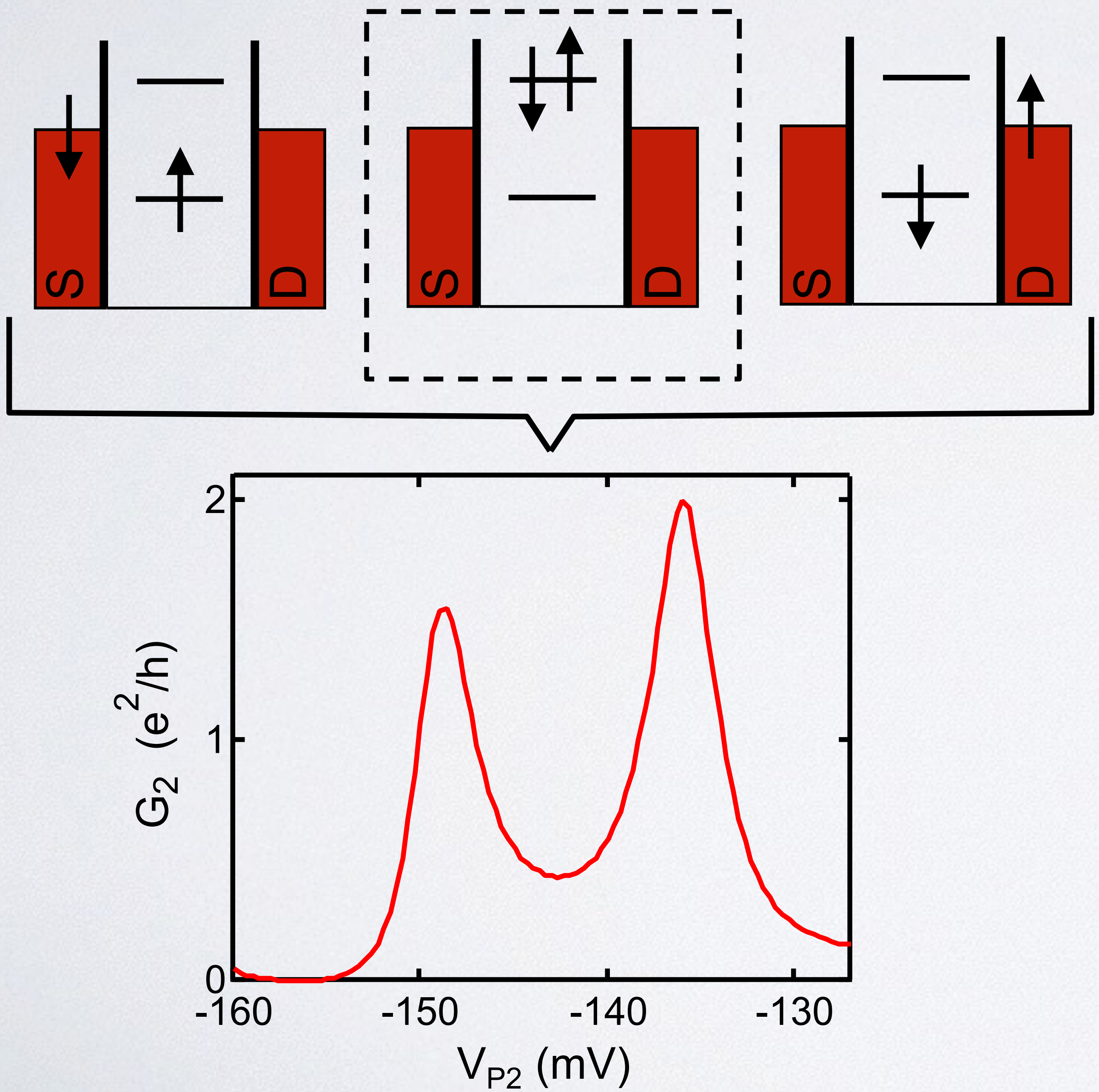
Charging energy: U

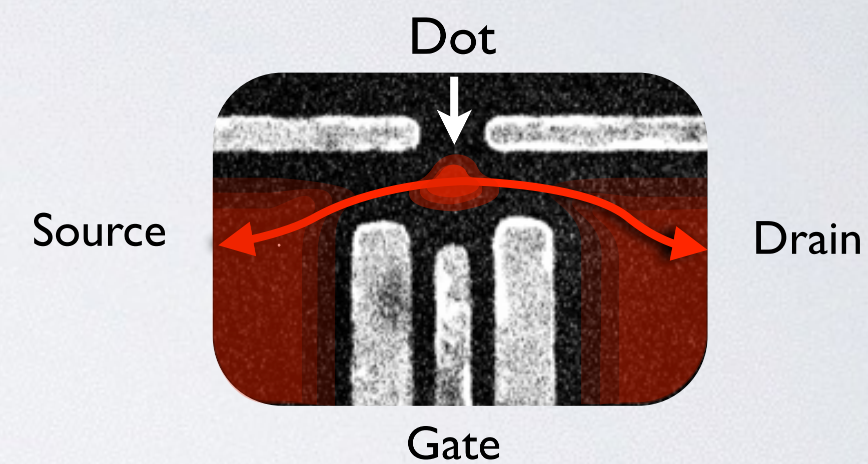
Dot-lead tunnel rate: Γ

$\Gamma/U << 1$

Transport through quantum dots

Kondo effect





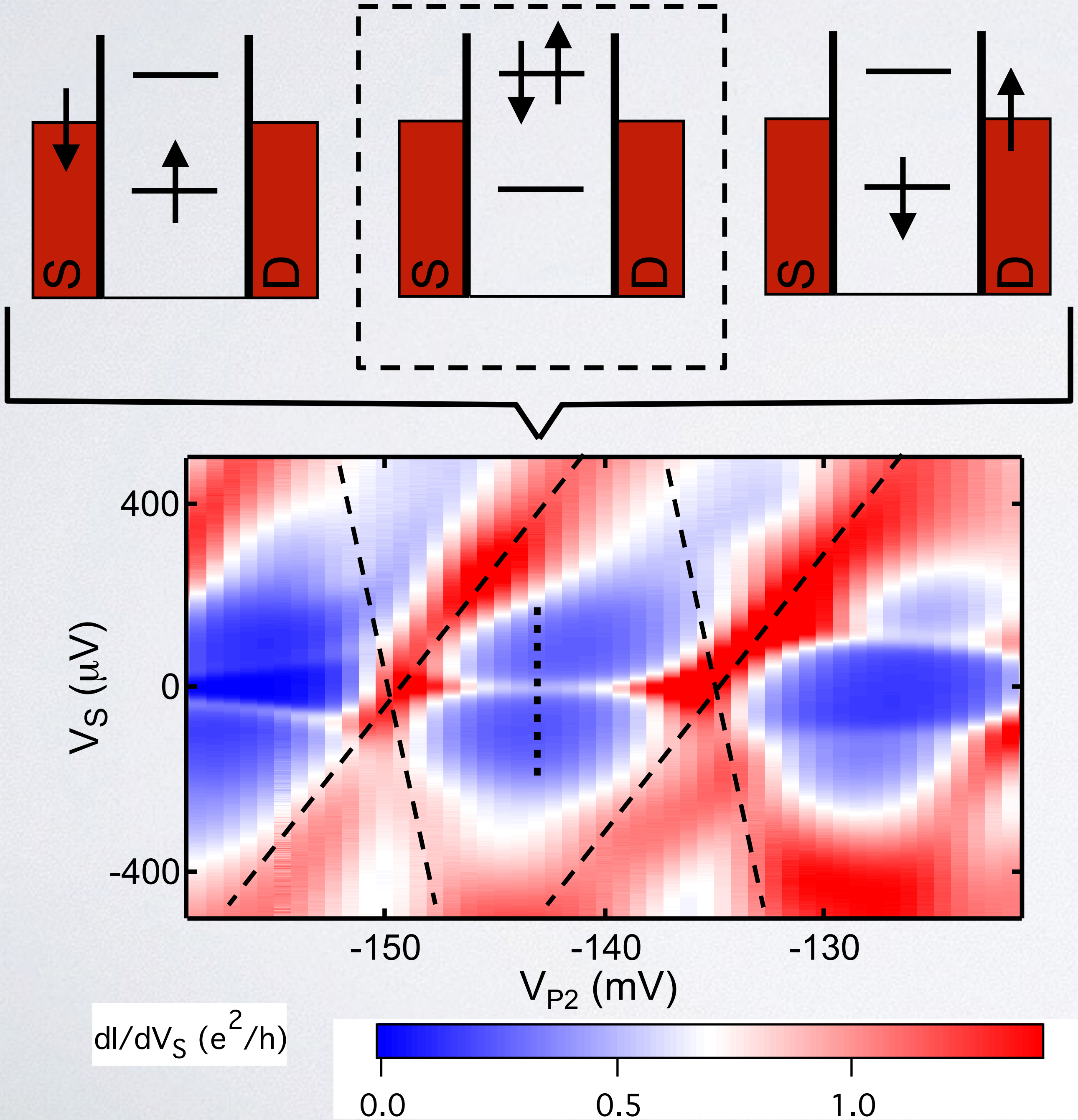
Charging energy: U

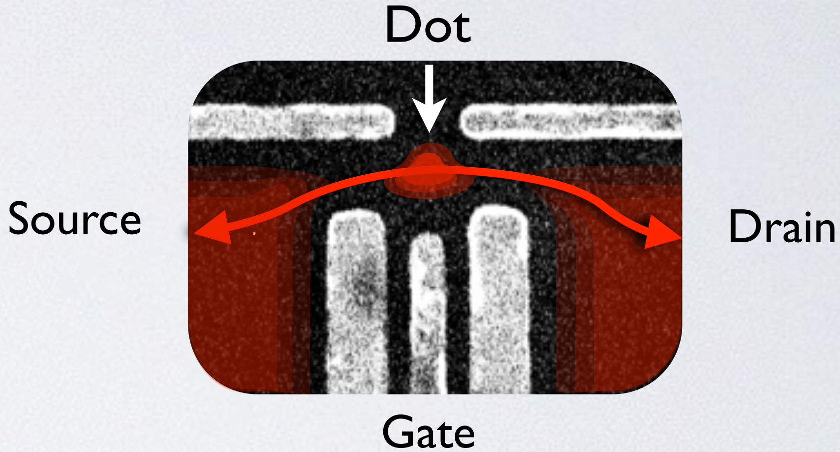
Dot-lead tunnel rate: Γ

$\Gamma/U \sim 0.2$ to 0.3

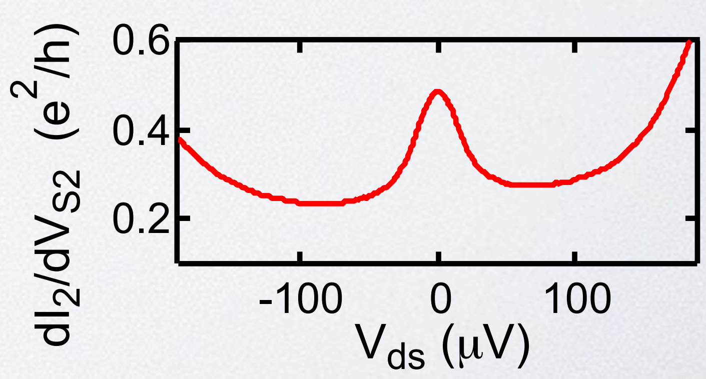
Transport through quantum dots

Kondo effect





Zero-bias conductance enhancement implies Kondo



Challenge

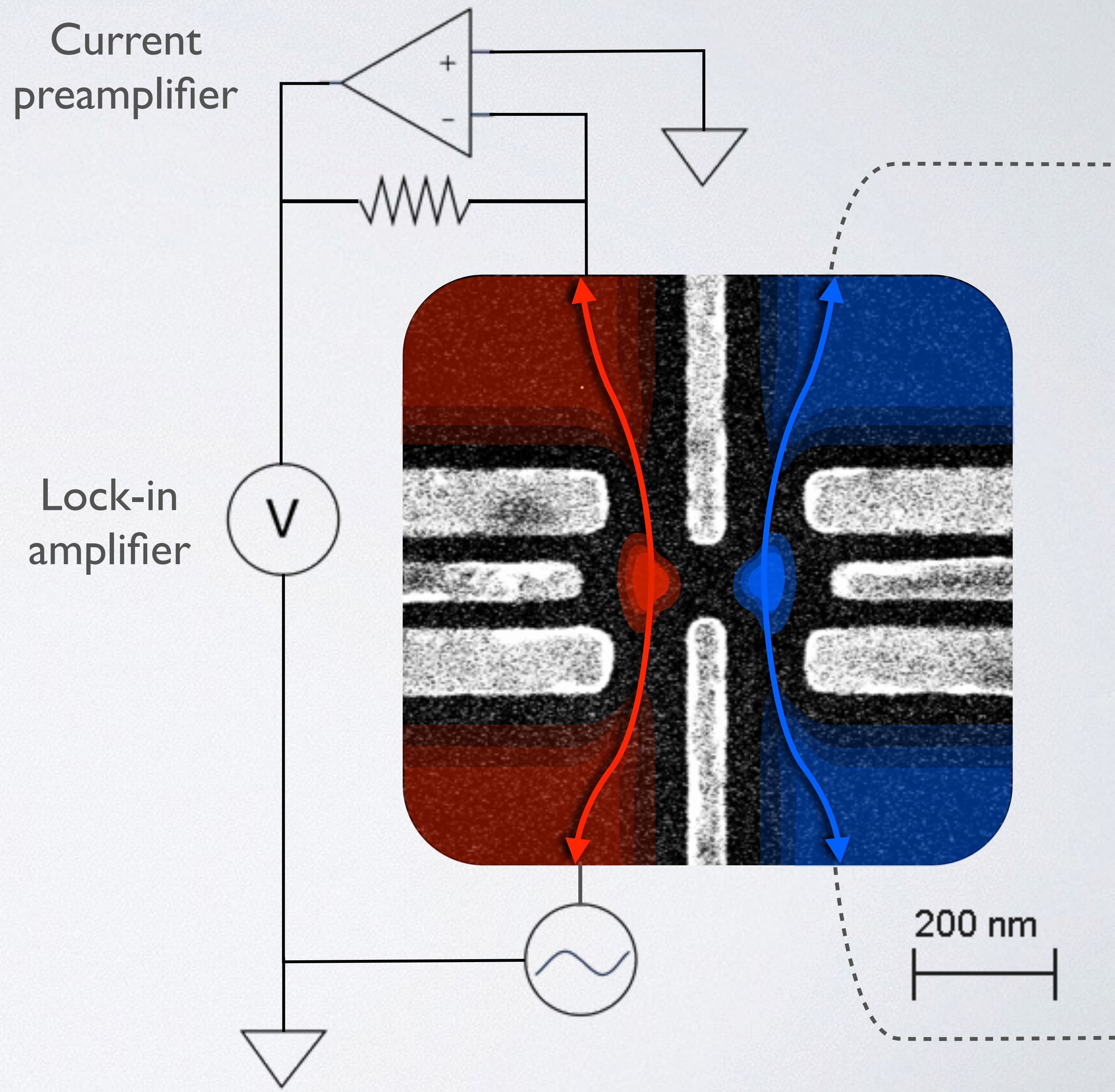
- Can we realize more complicated Kondo effects to address the physics of exotic material systems?

Outline

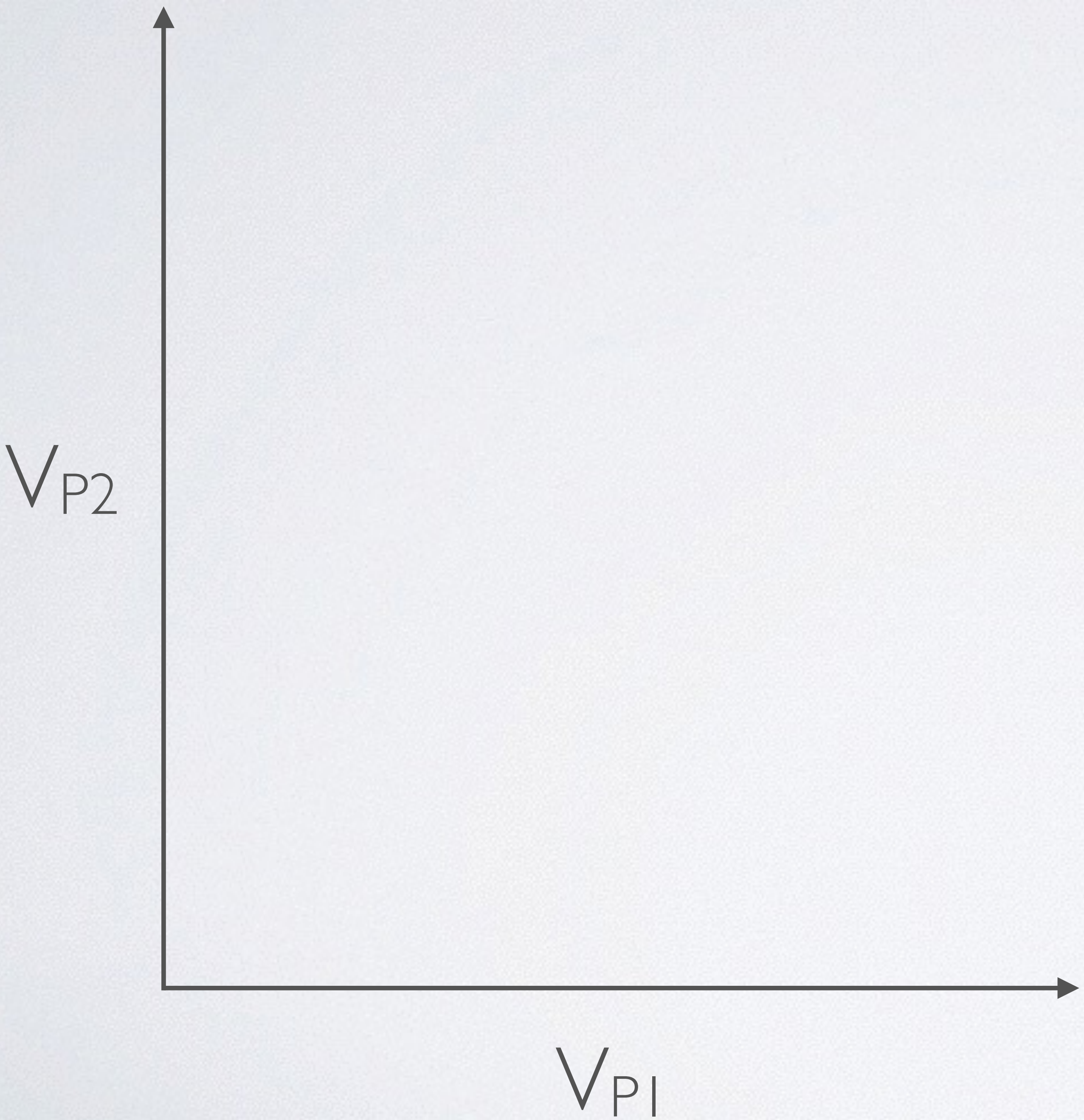
- Symmetries in physics
- Quantum dots and the Kondo effect
- **Emergent SU(4)-symmetric Kondo effect in a double quantum dot**
- Universal crossover between quantum critical and Fermi liquid states in a quantum dot coupled to a "metallic grain"

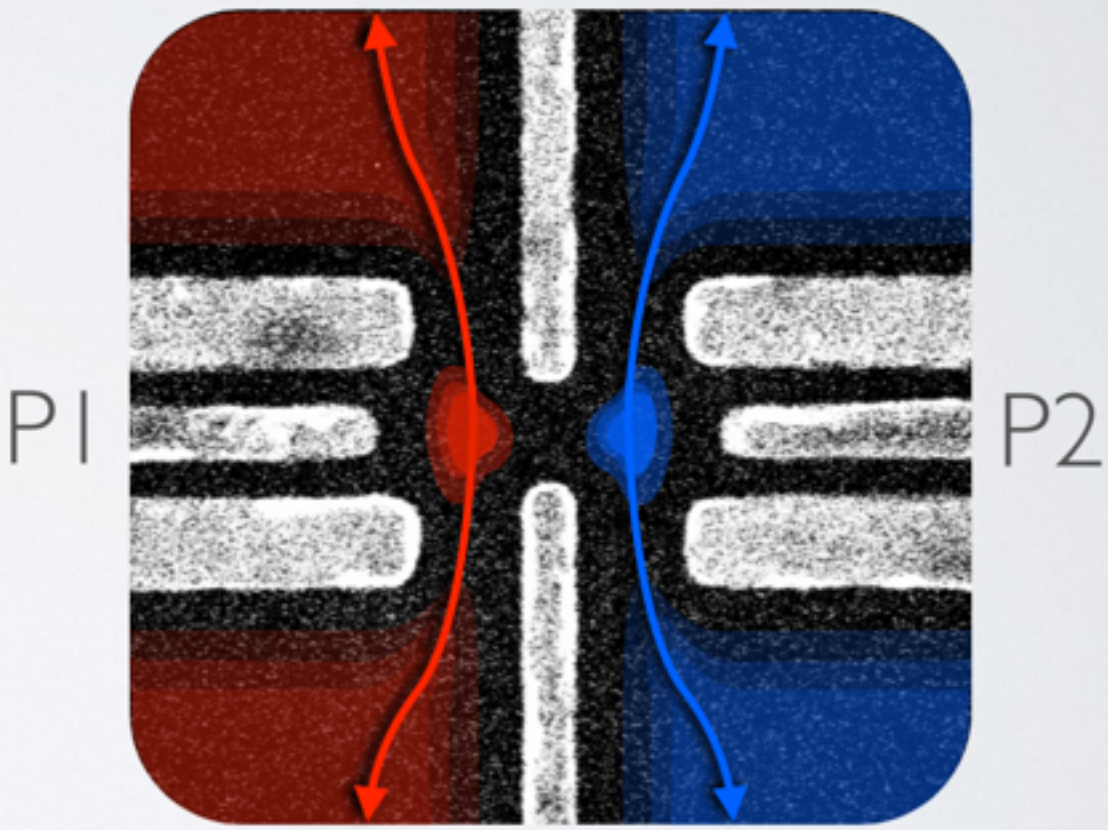
Measurement scheme

- Simultaneously measure conductance through each dot in parallel

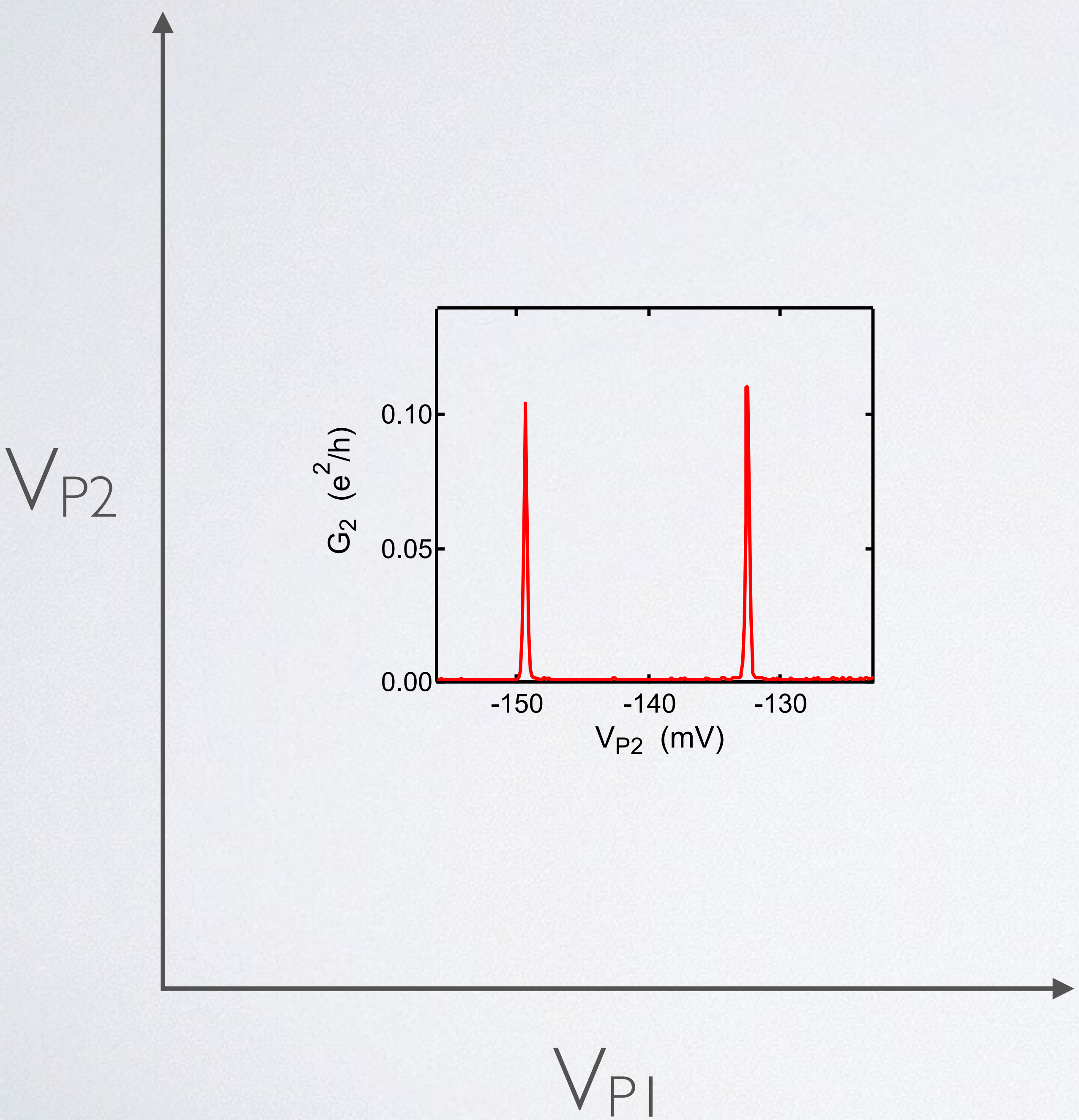


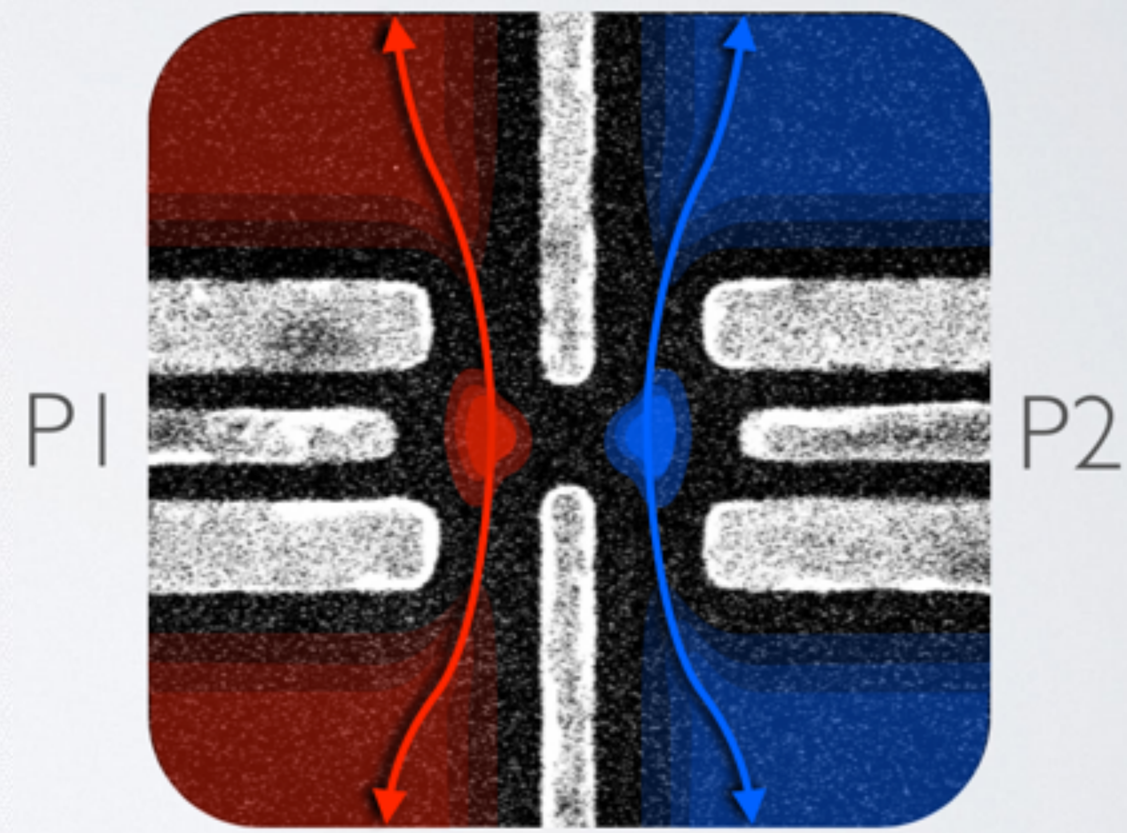
Charge stability diagram





Charge stability diagram





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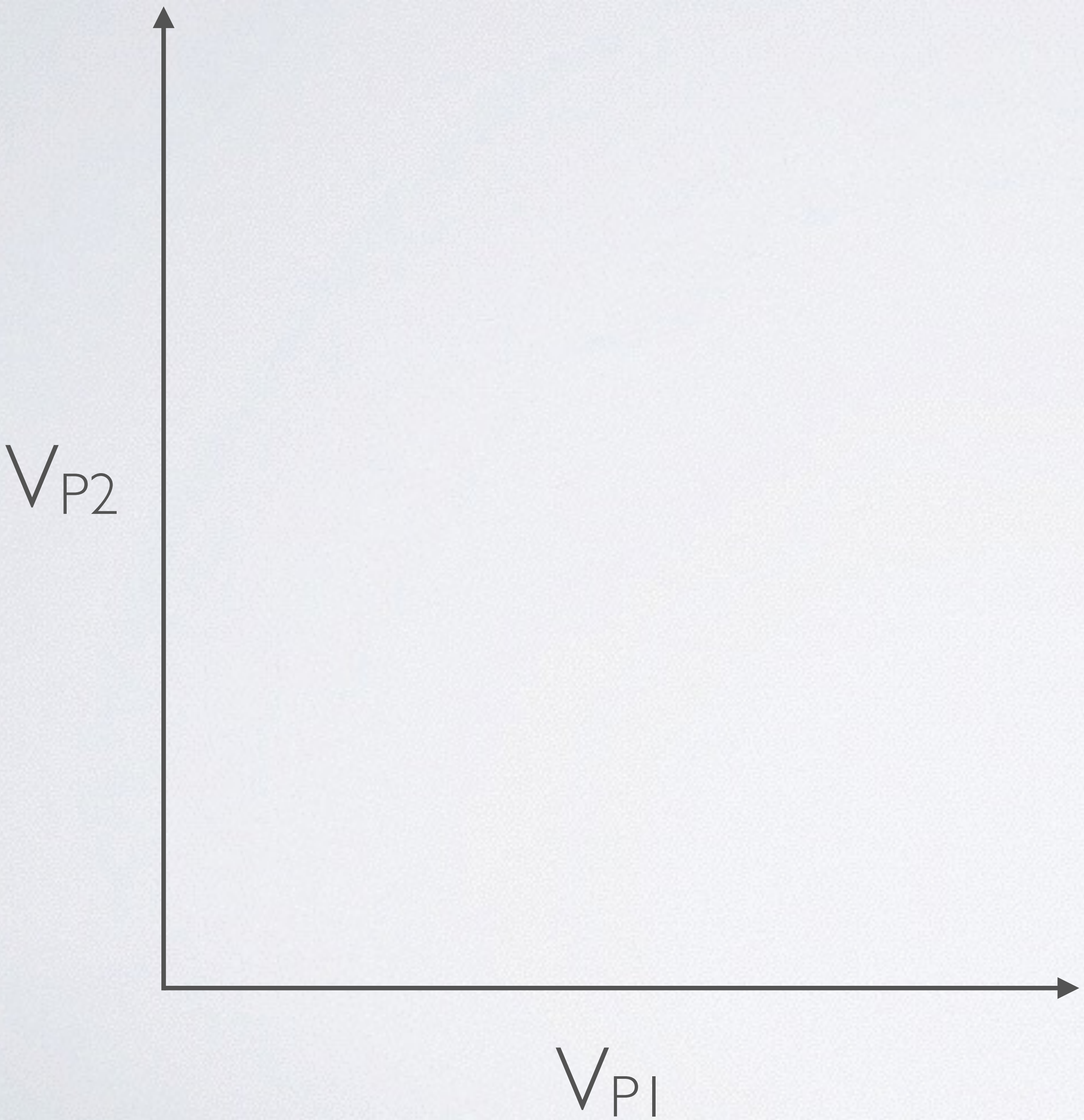

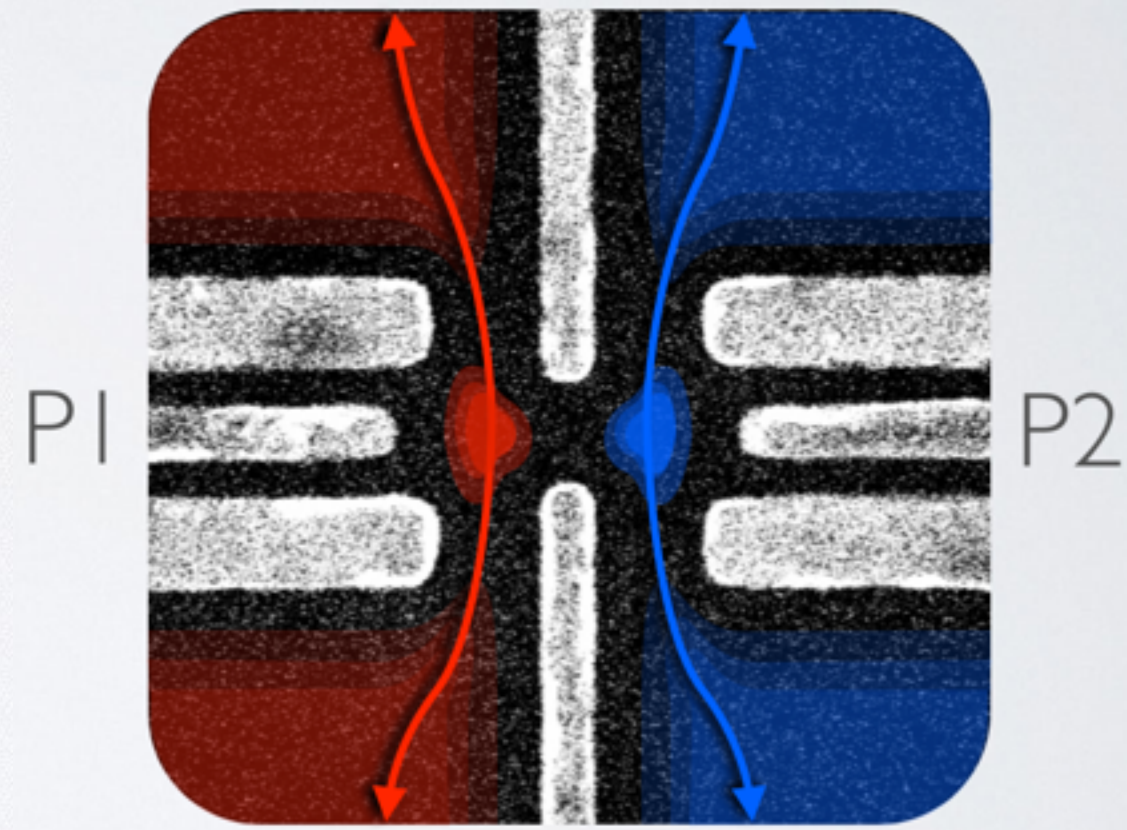

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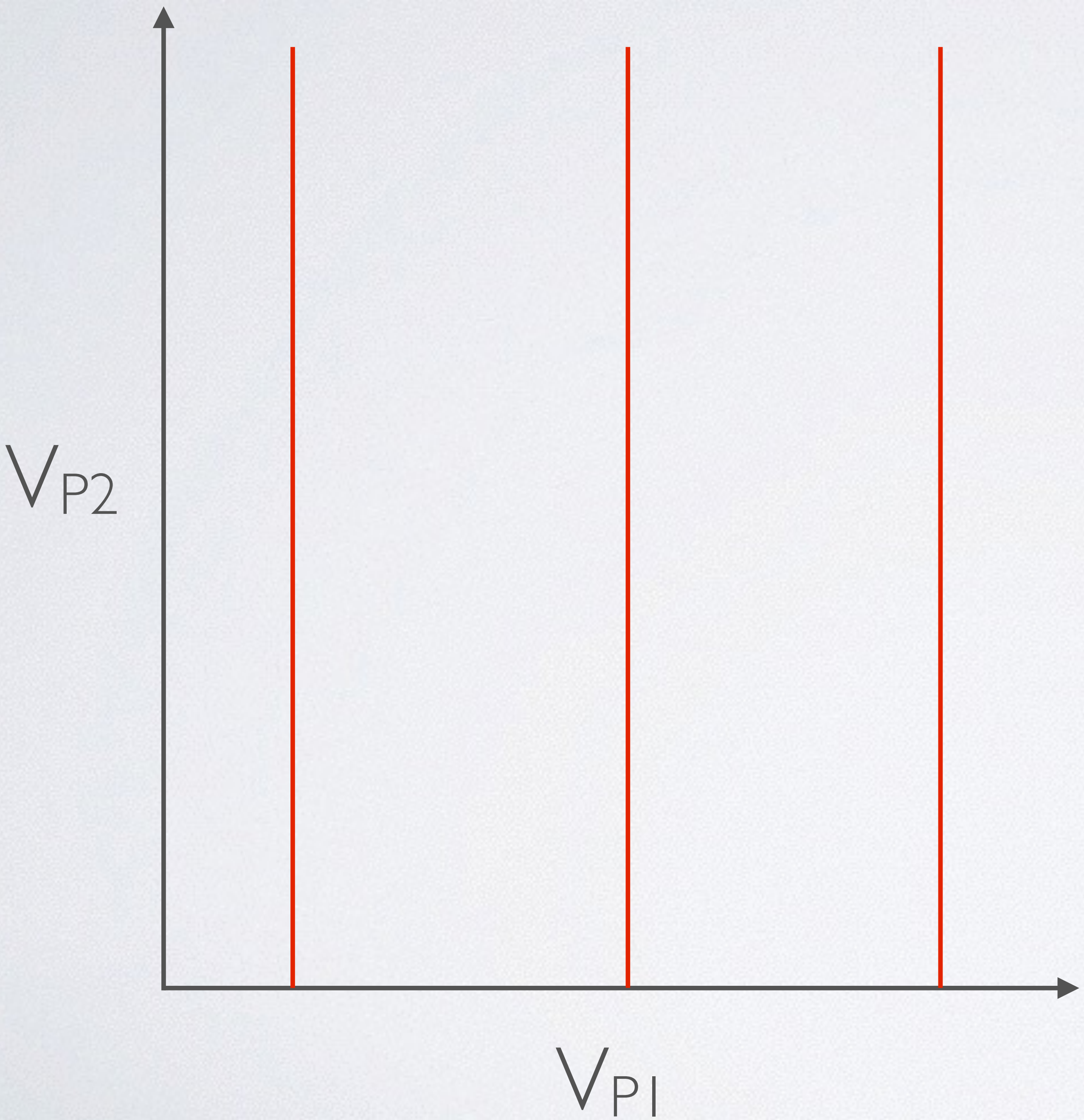

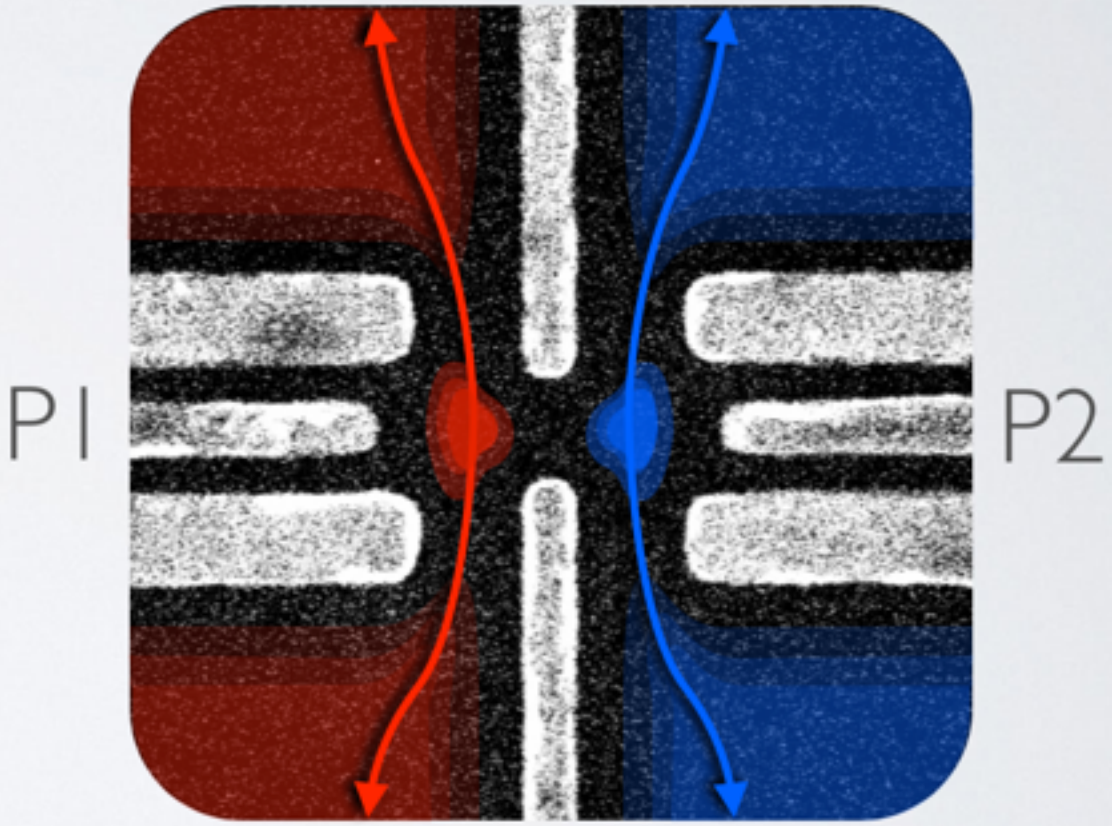

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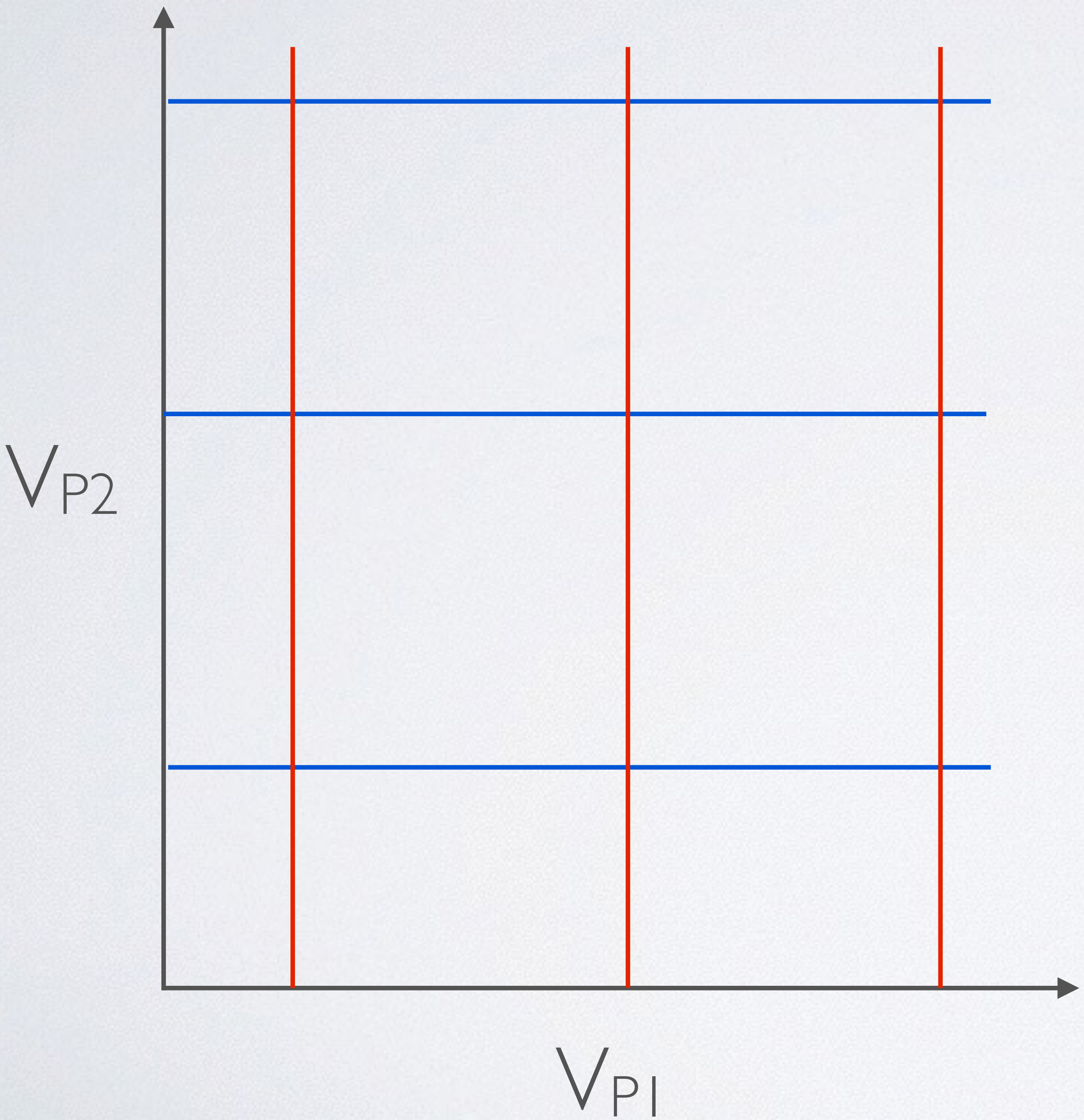

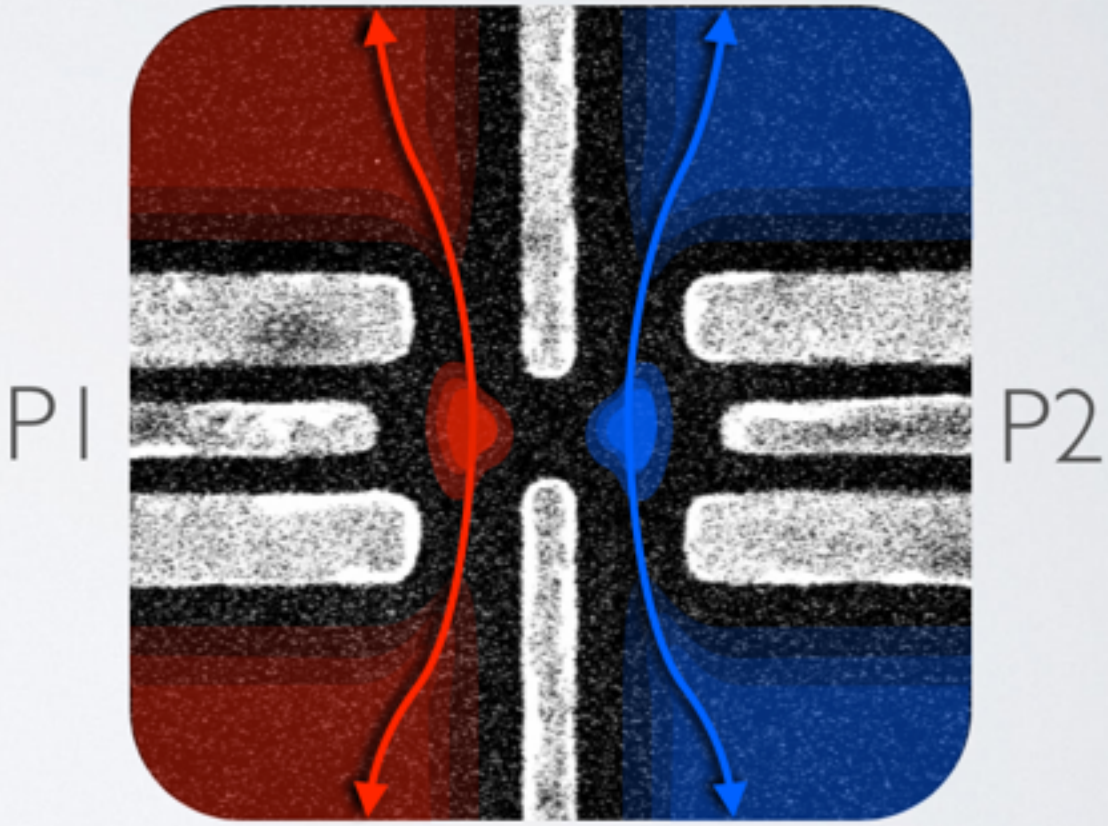

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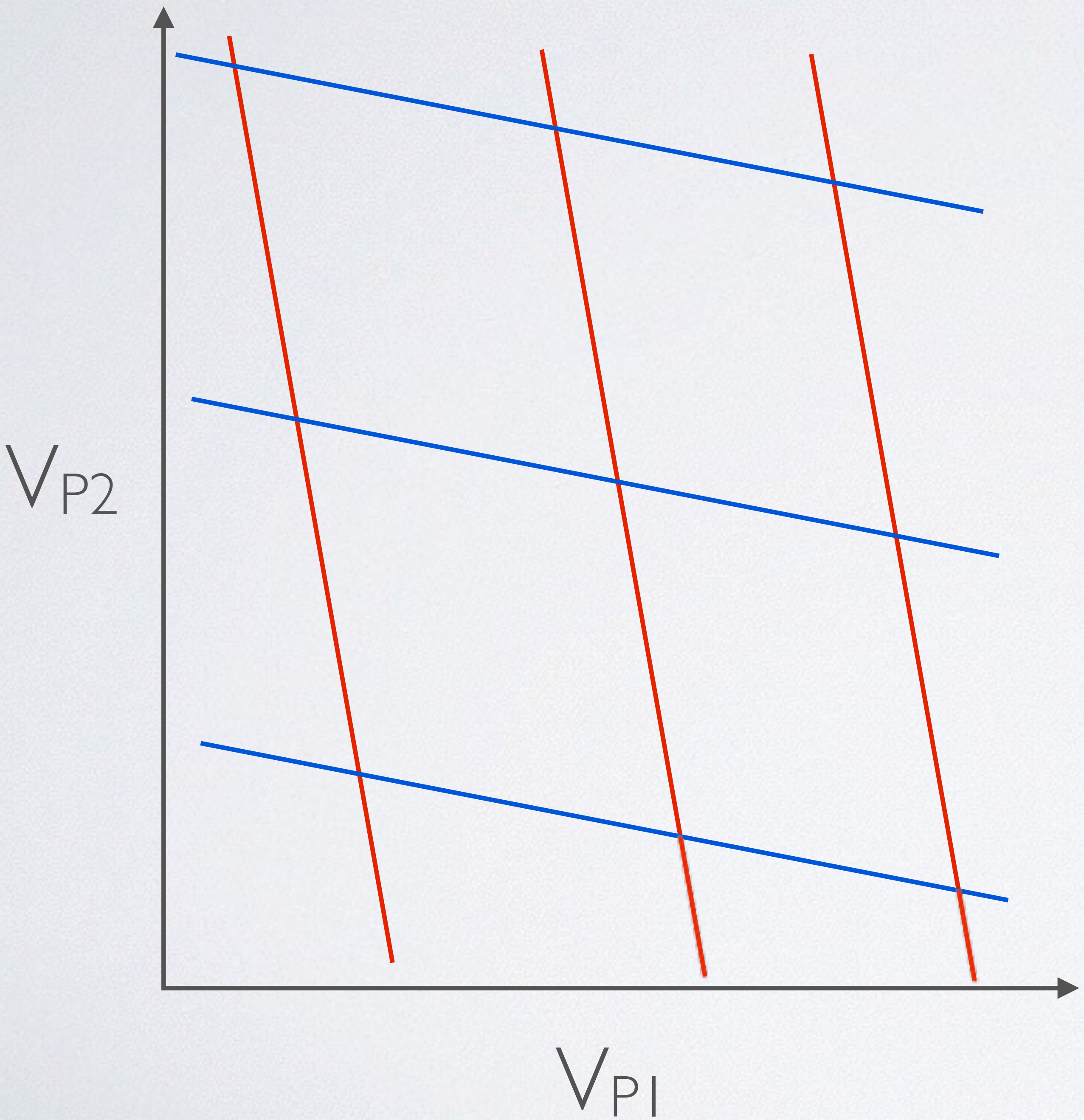

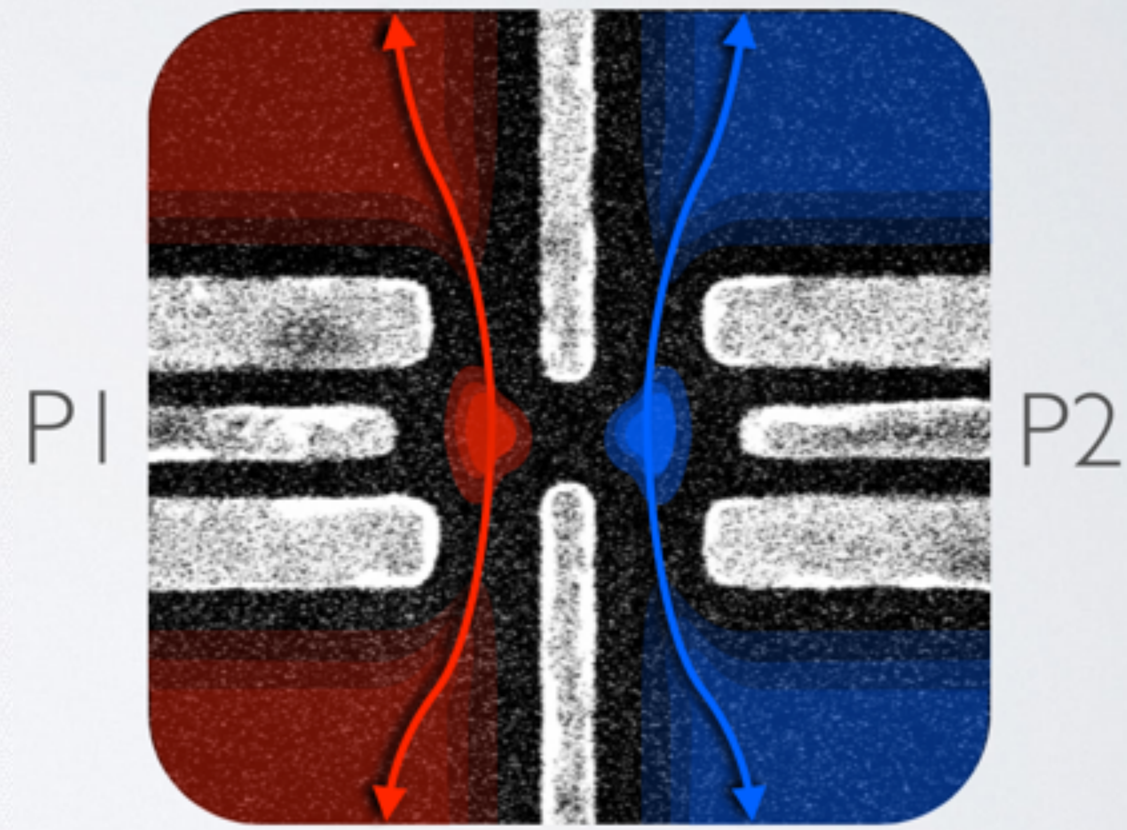

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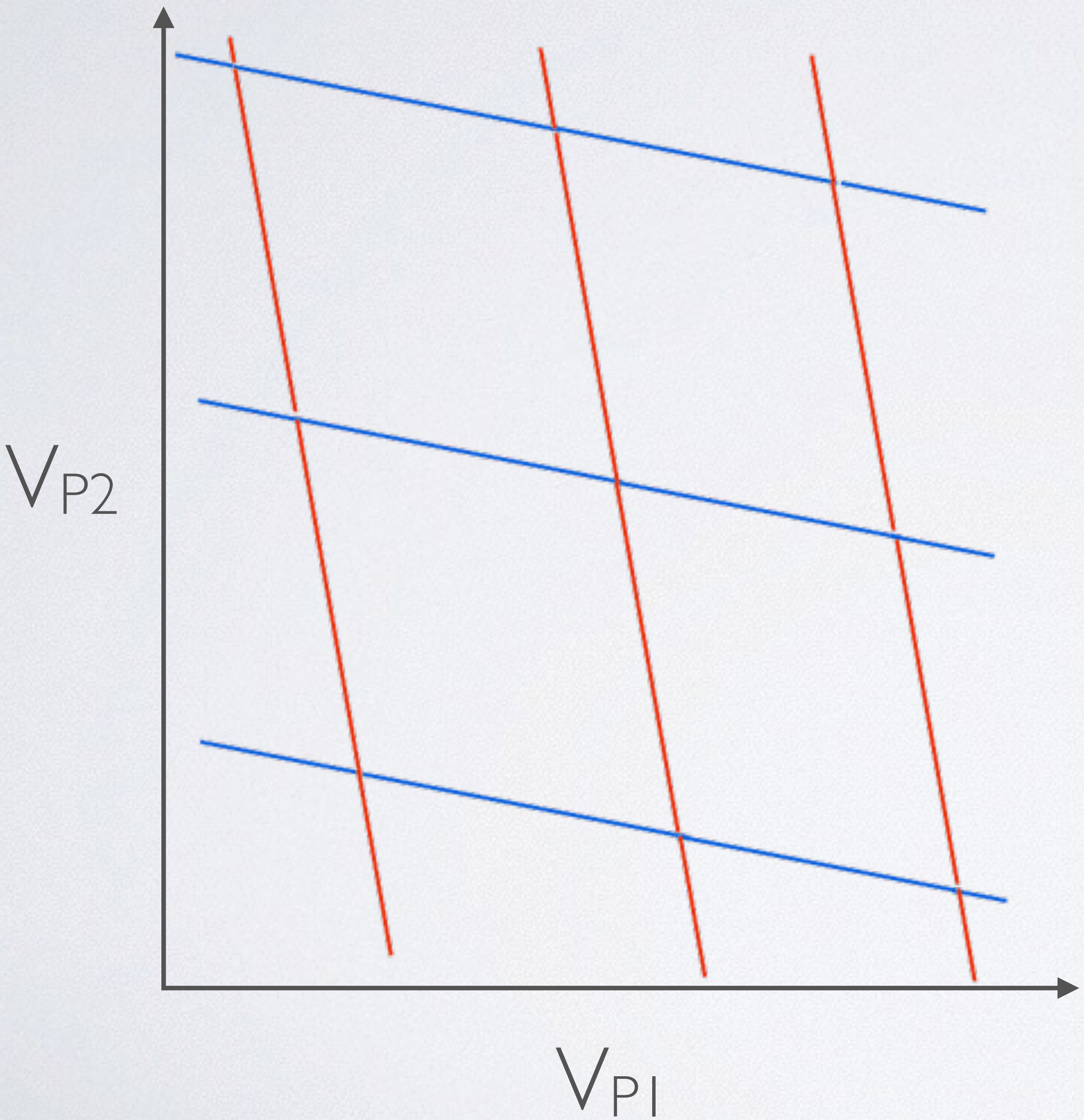

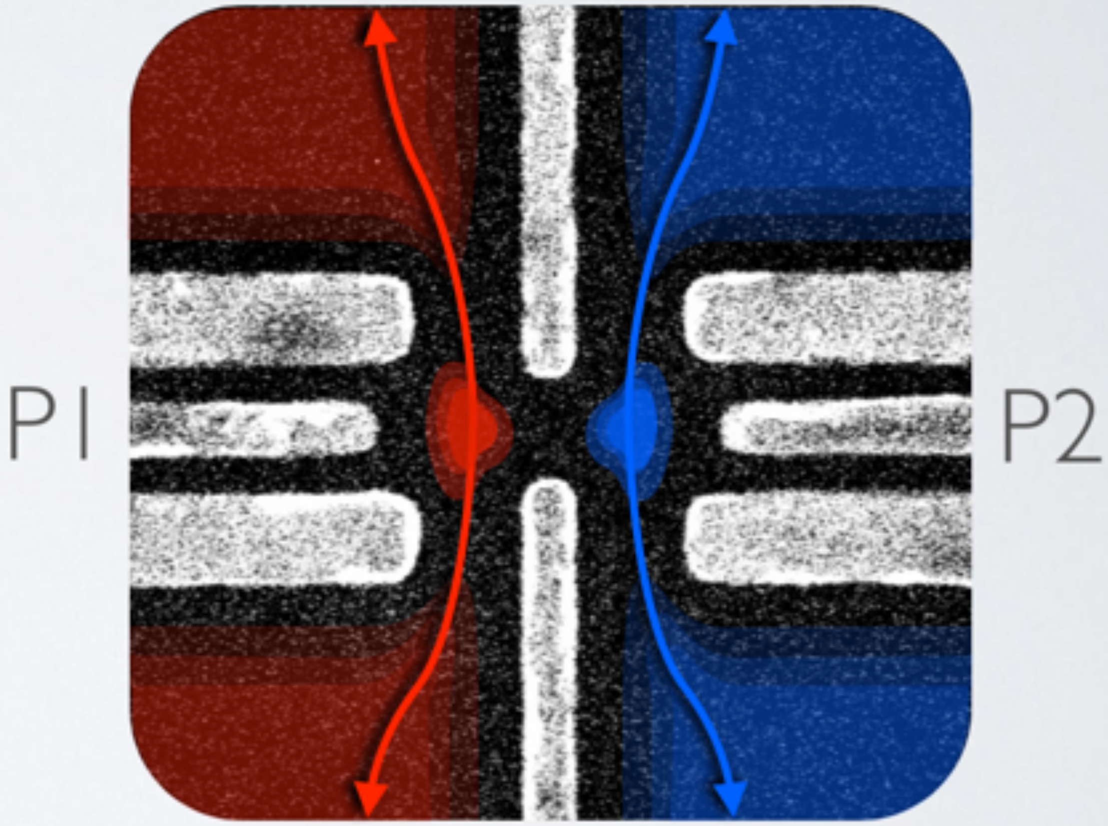

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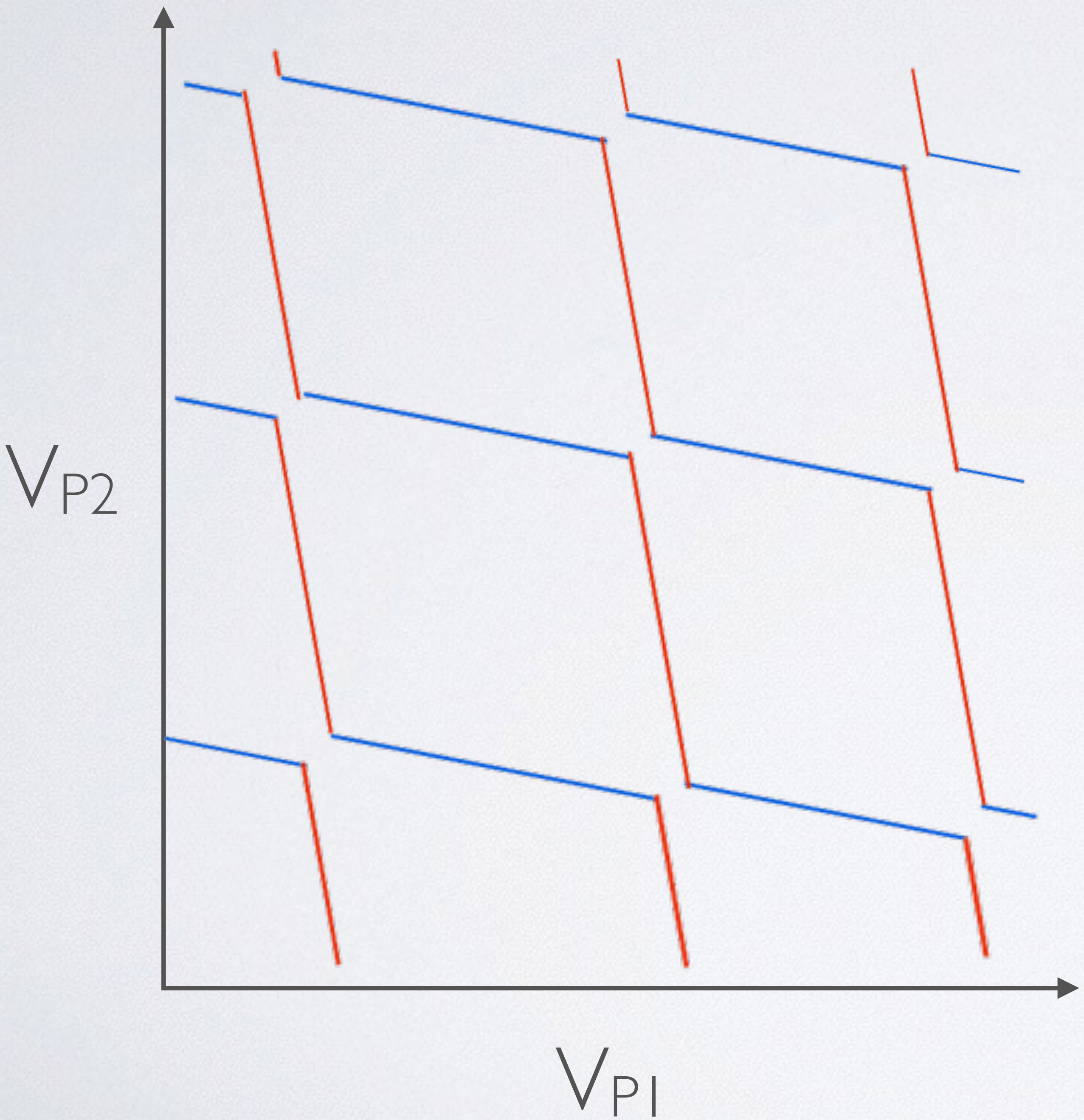

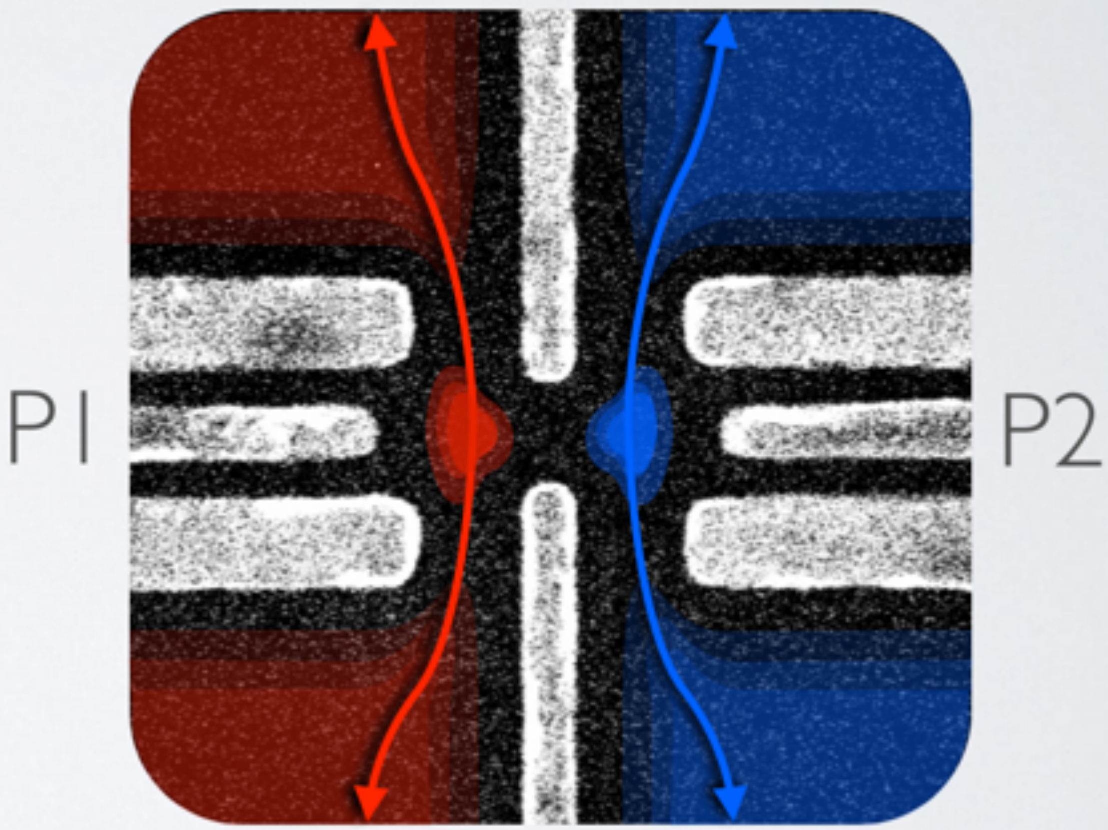

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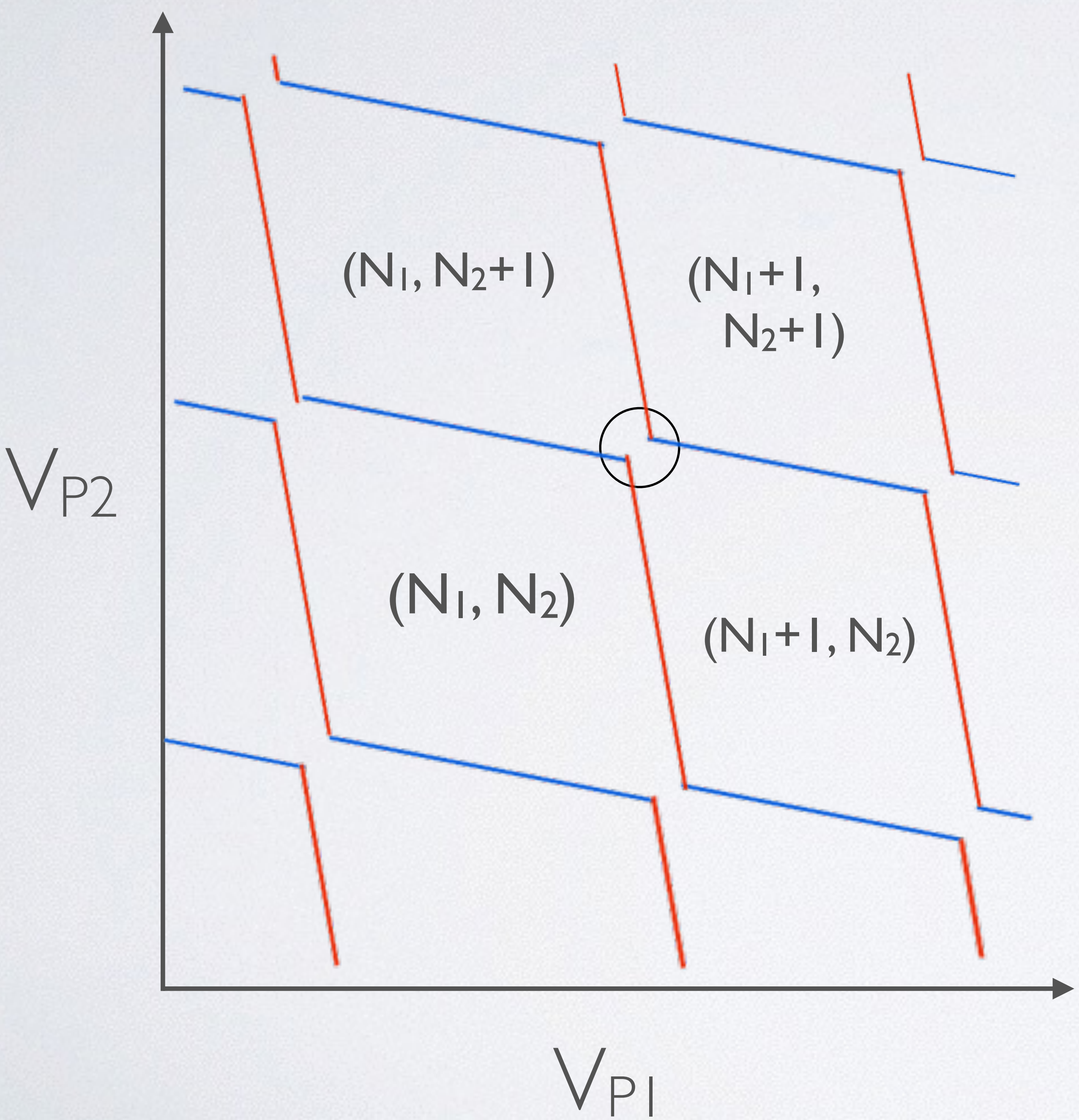

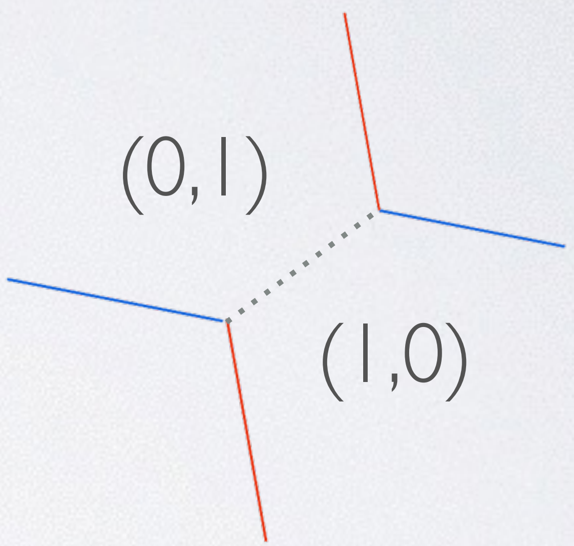

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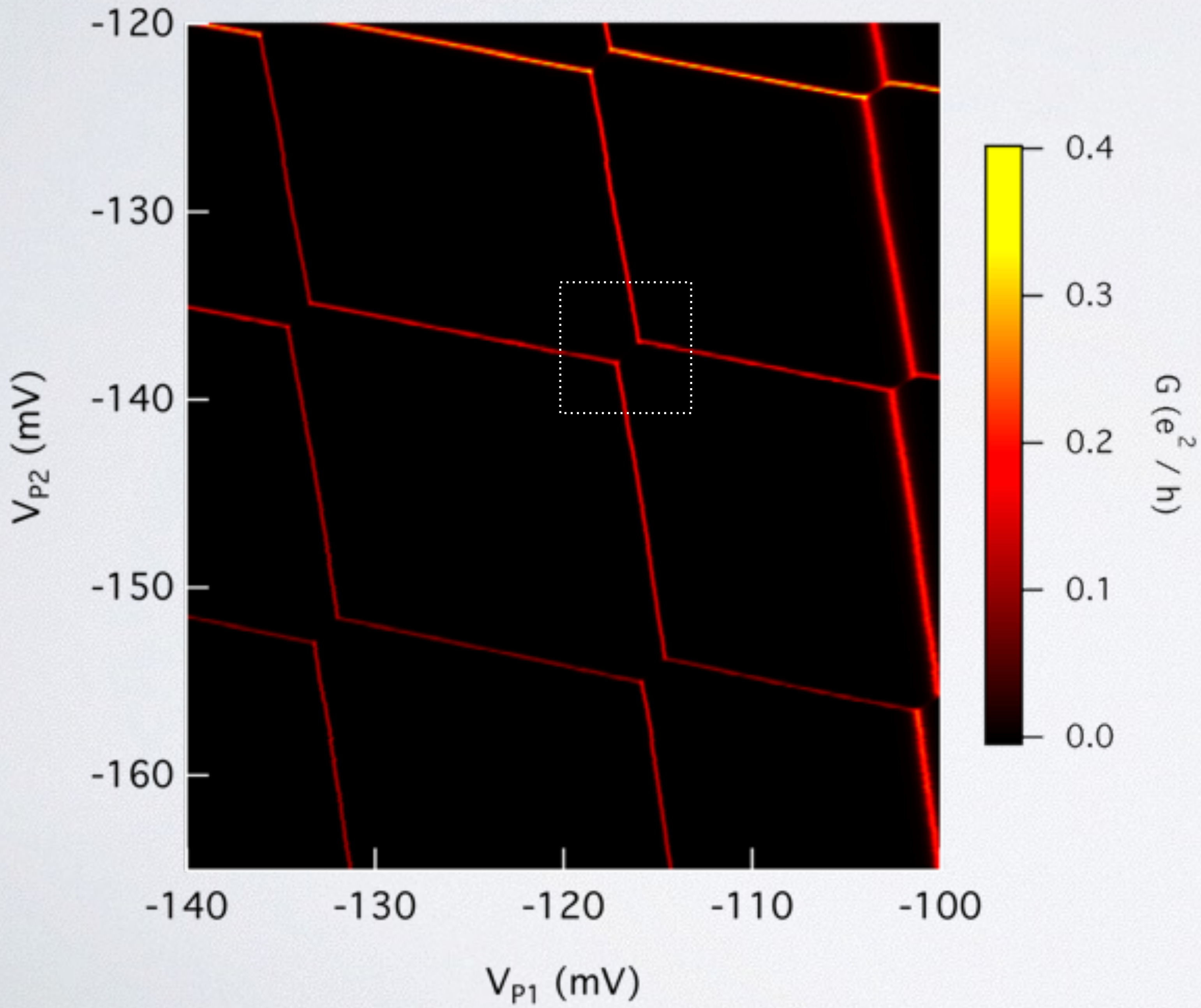
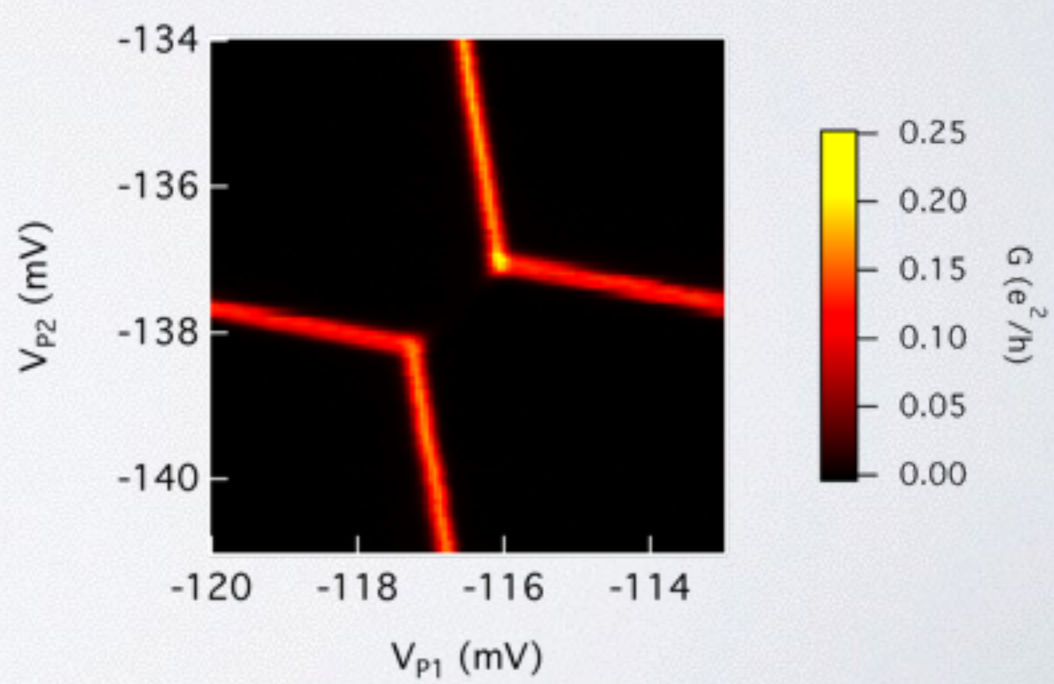


T_e = 1.7 μeV (20 mK)

$\Gamma_1 \sim \Gamma_2 \sim$ 20 μeV

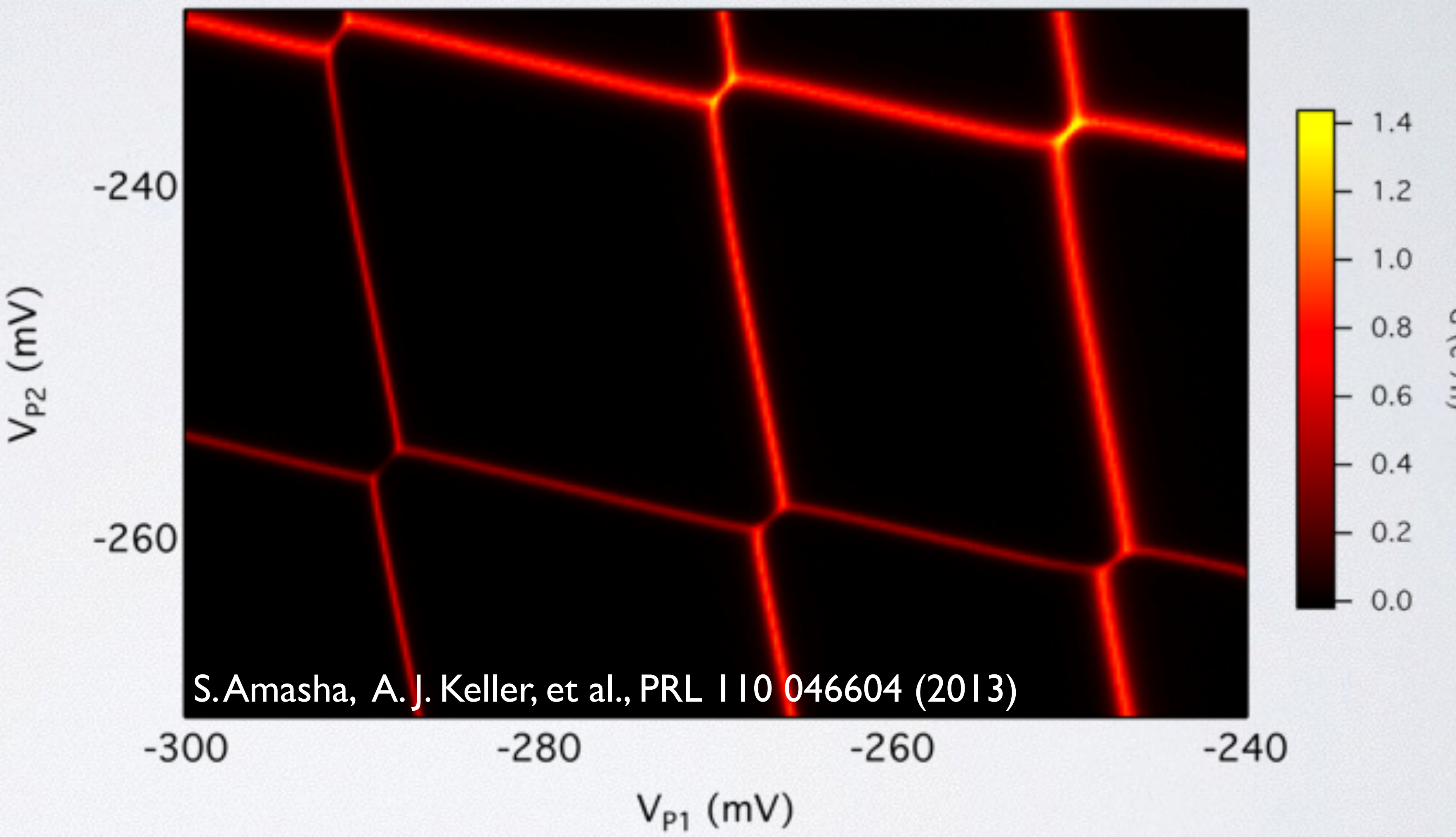
U' ~ 100 μeV

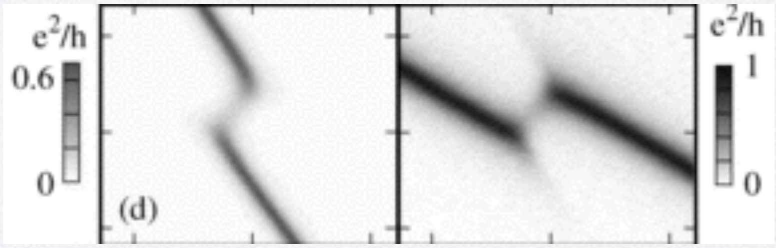
U ~ 1 meV



A Kondo effect between triple points?

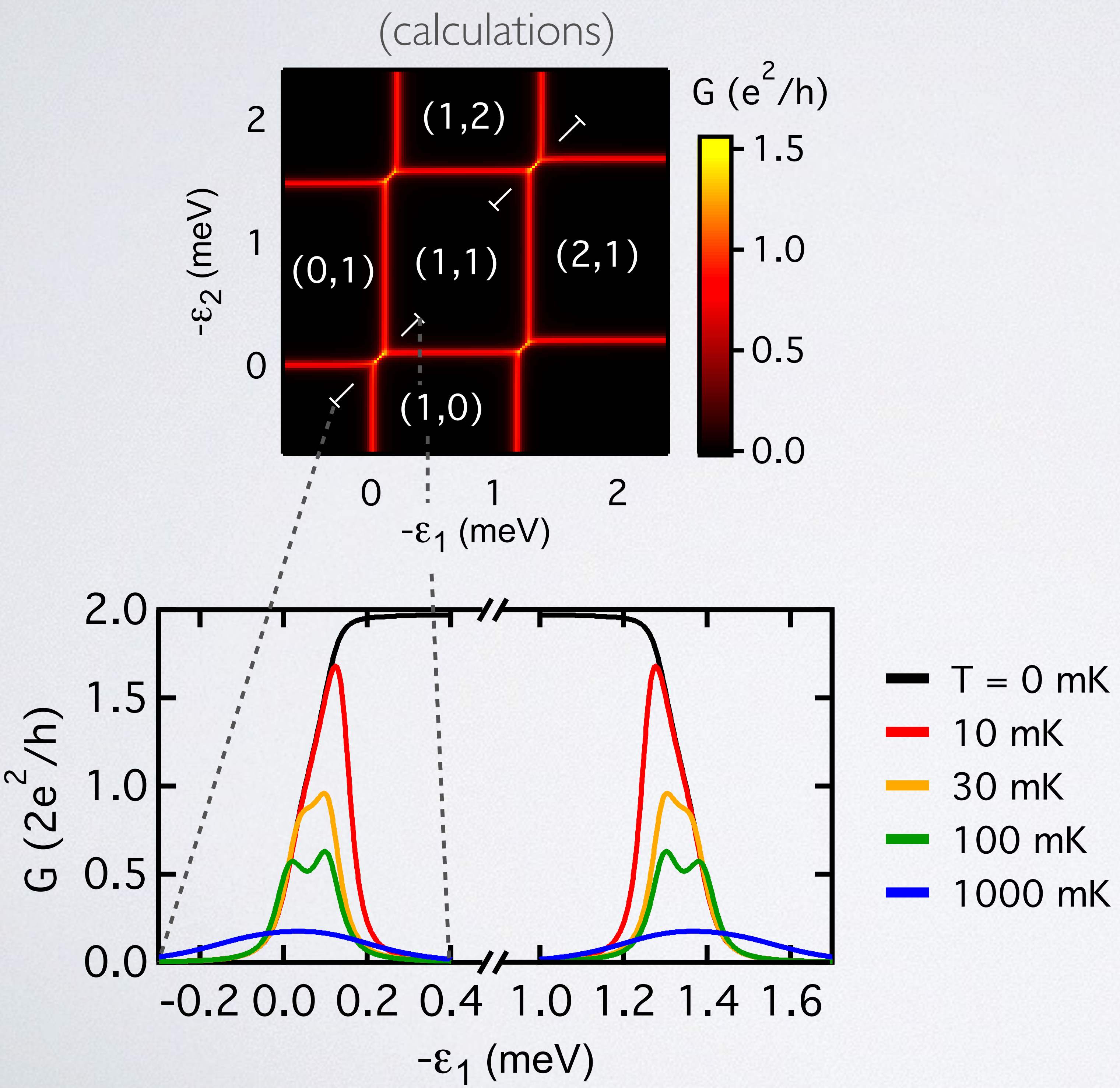
Increasing Γ





First observed by Hübel, et al, PRL 101 186804 (2004).

A four-fold degenerate state



Degeneracies

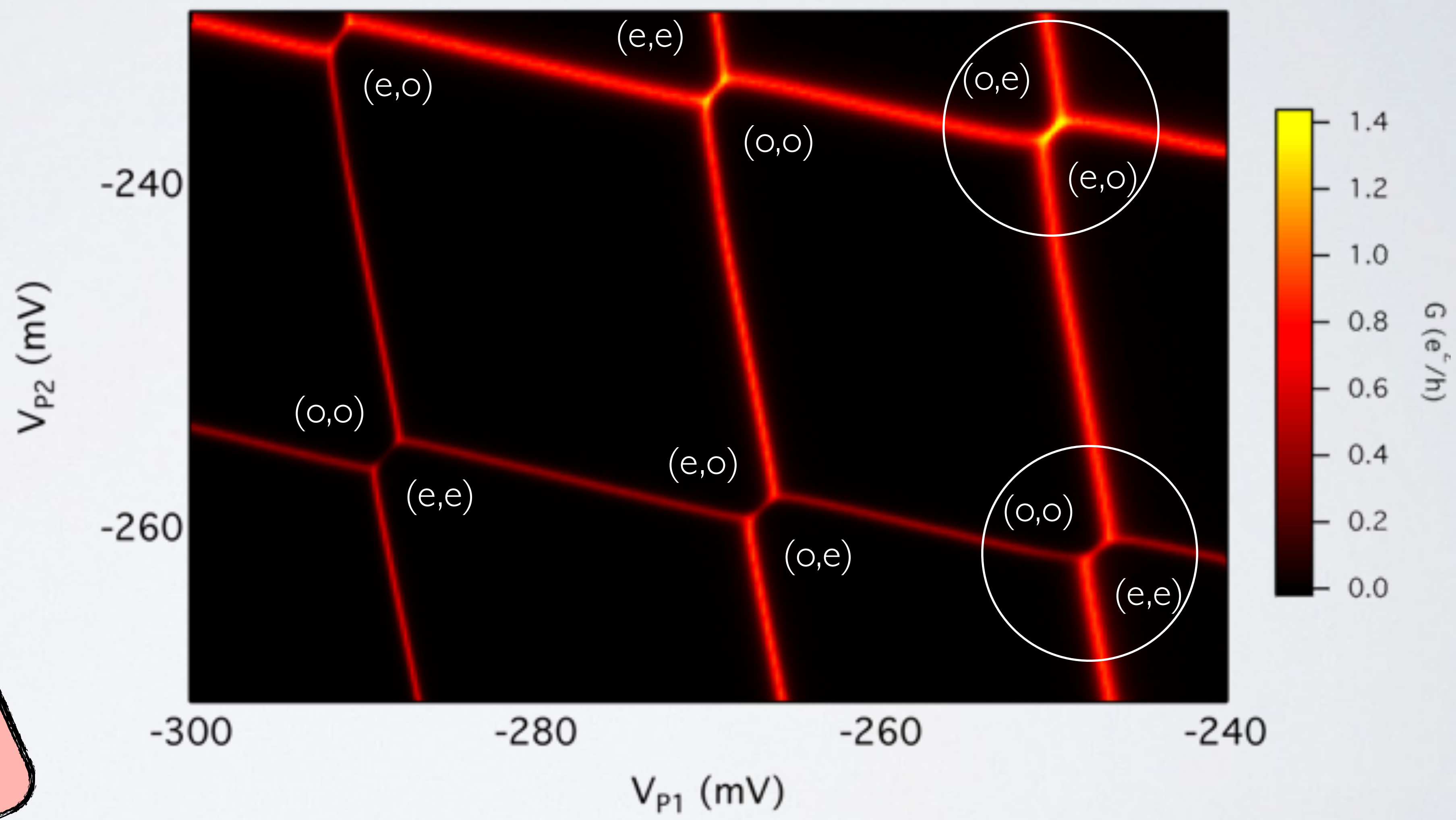
(o,e)–(e,o)
degeneracies:

(↑,0) (↓,0)
(0,↑) (0,↓)

(o,o)–(e,e)
degeneracies:

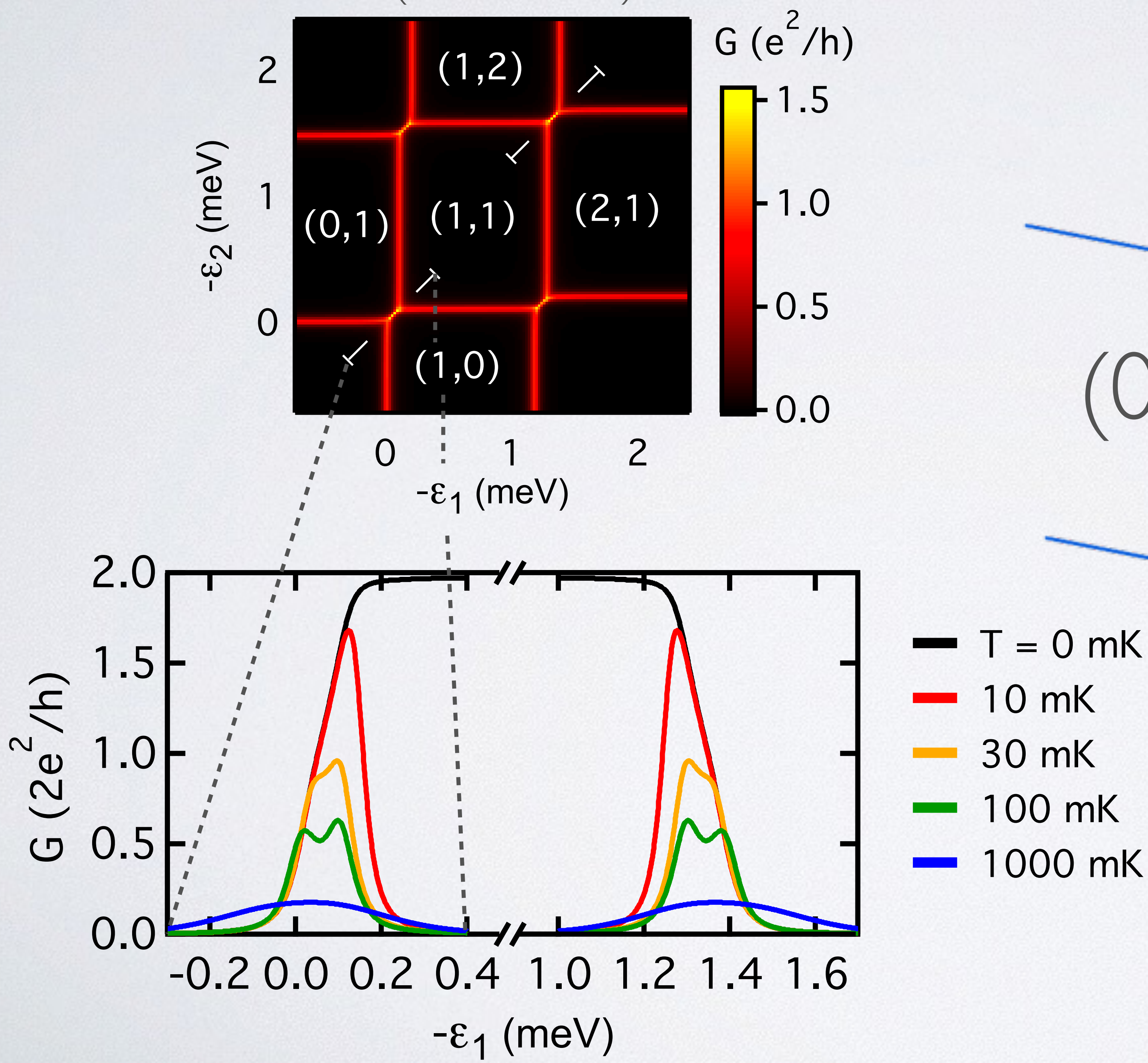
(↑,↑) (↓,↑)
(↑,↓) (↓,↓)

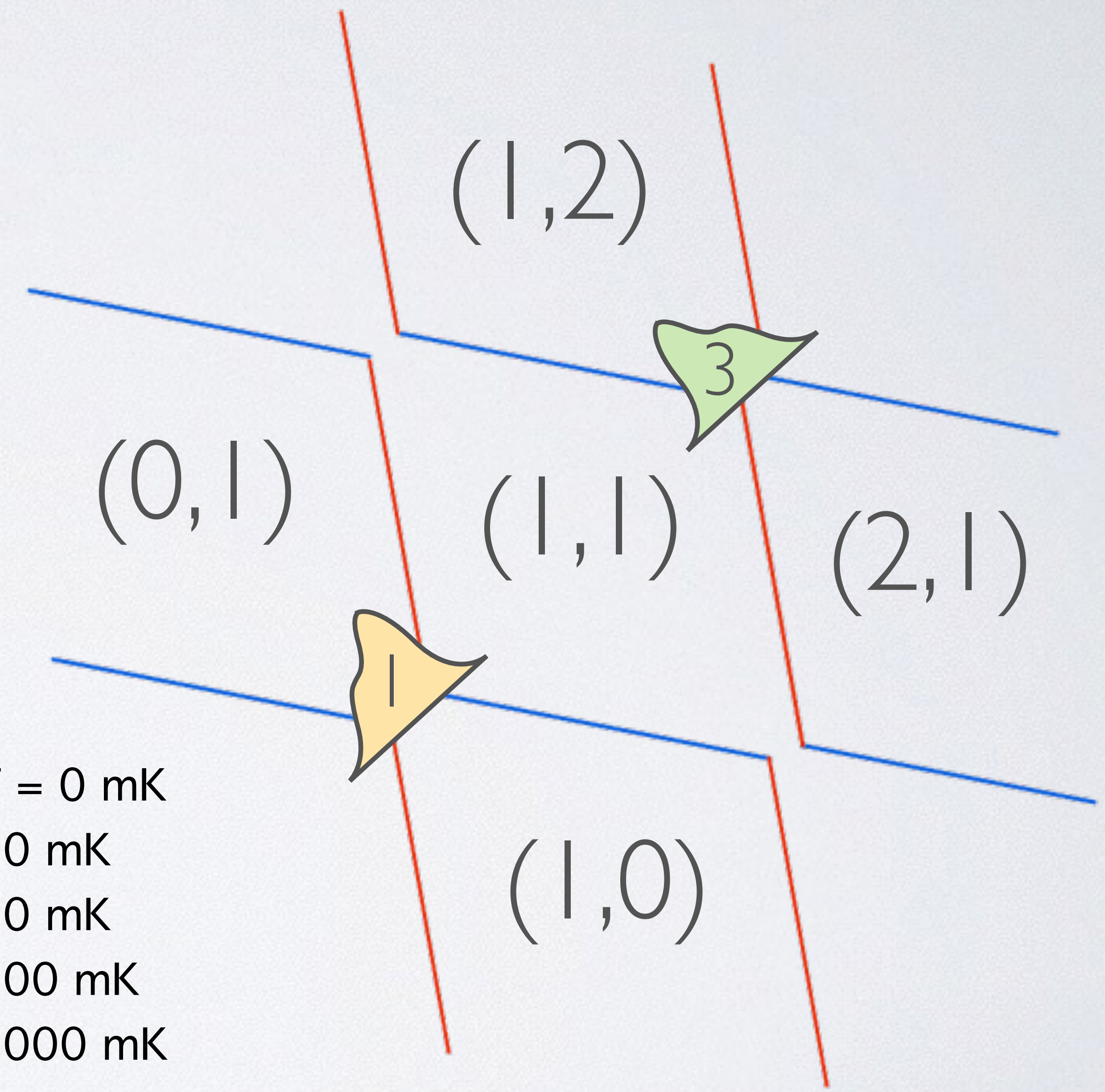
and (0,2)



A four-fold degenerate state

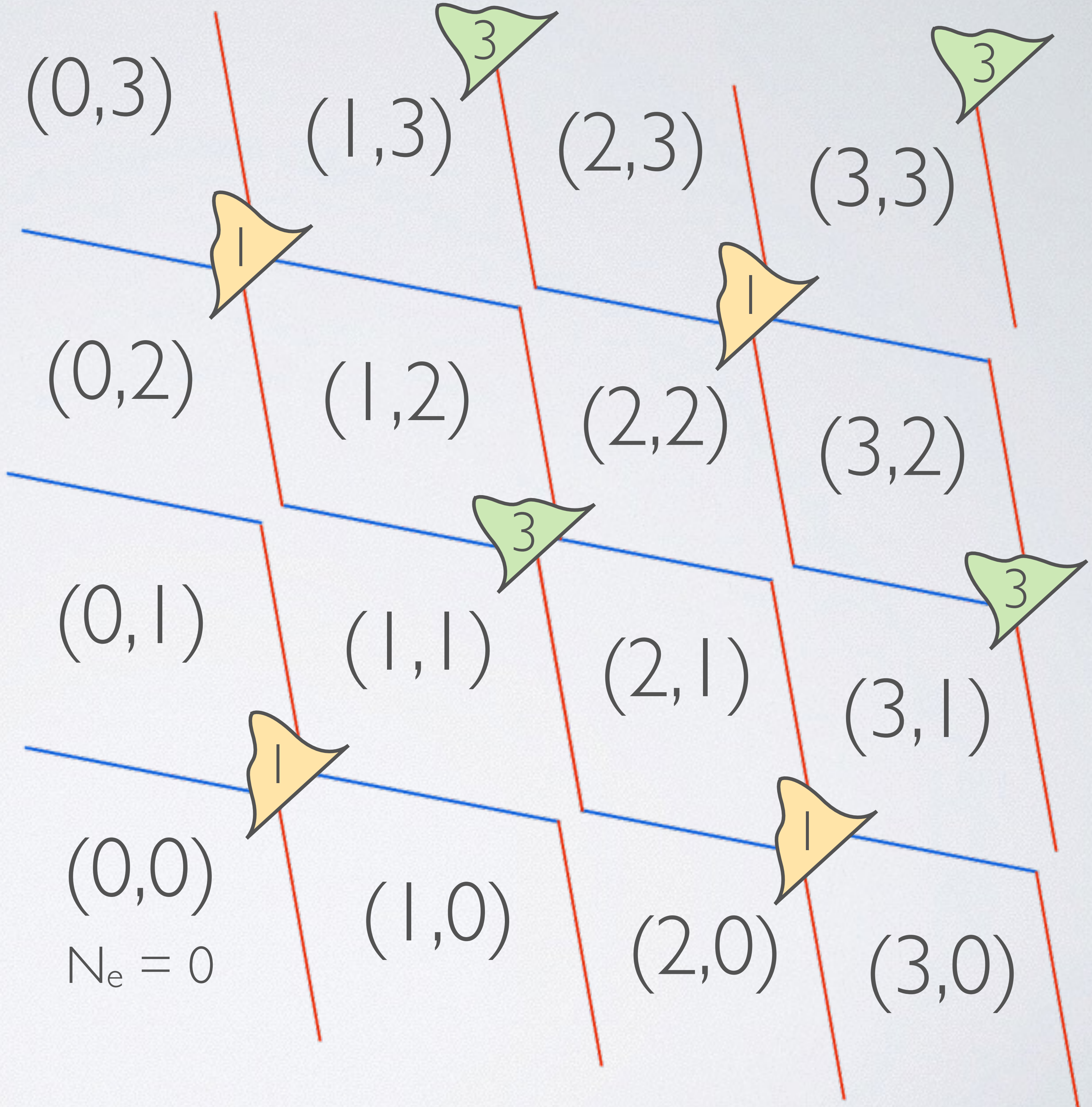
(calculations)

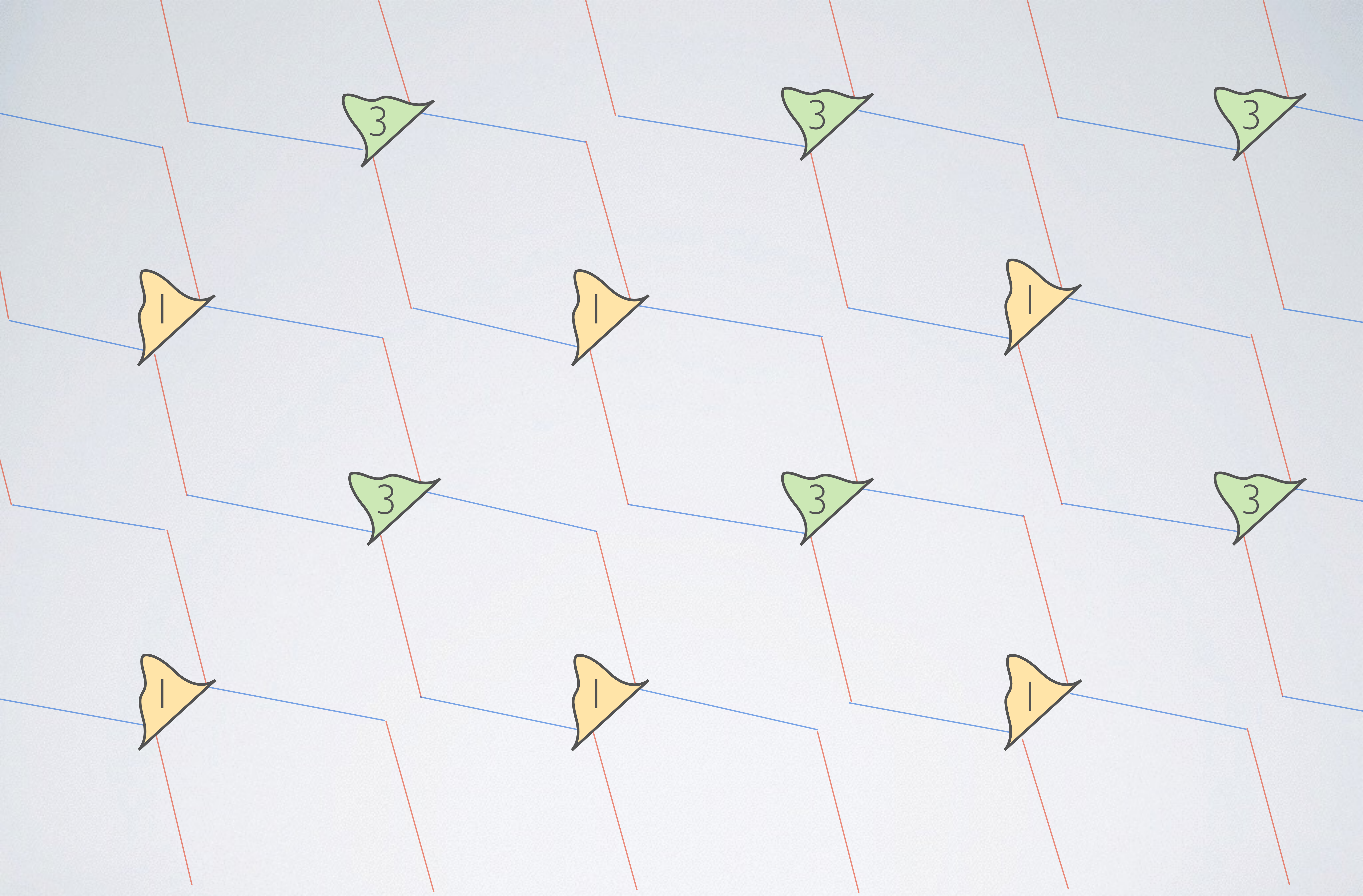


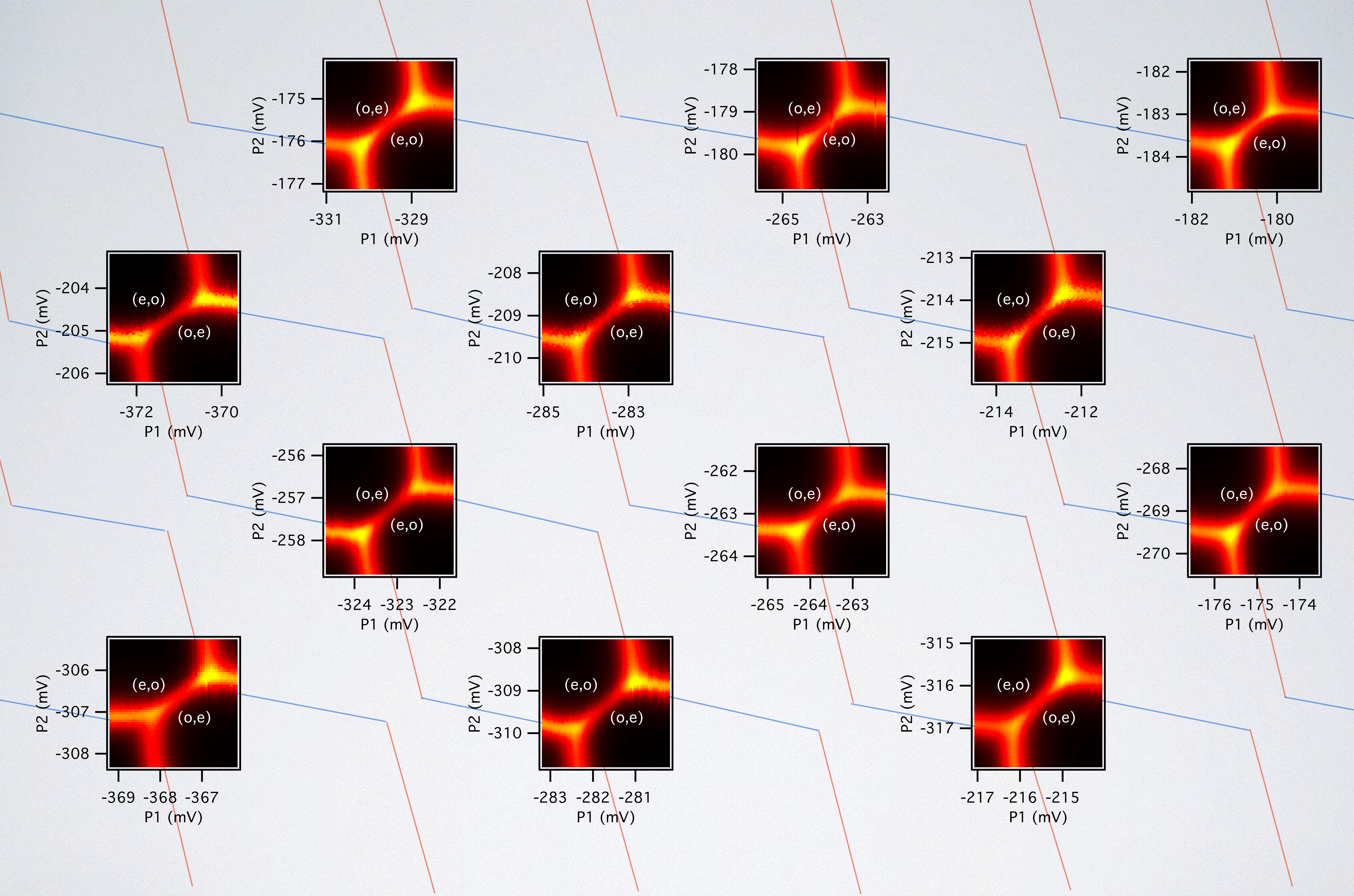


Adding two electrons to either dot should not change the physics

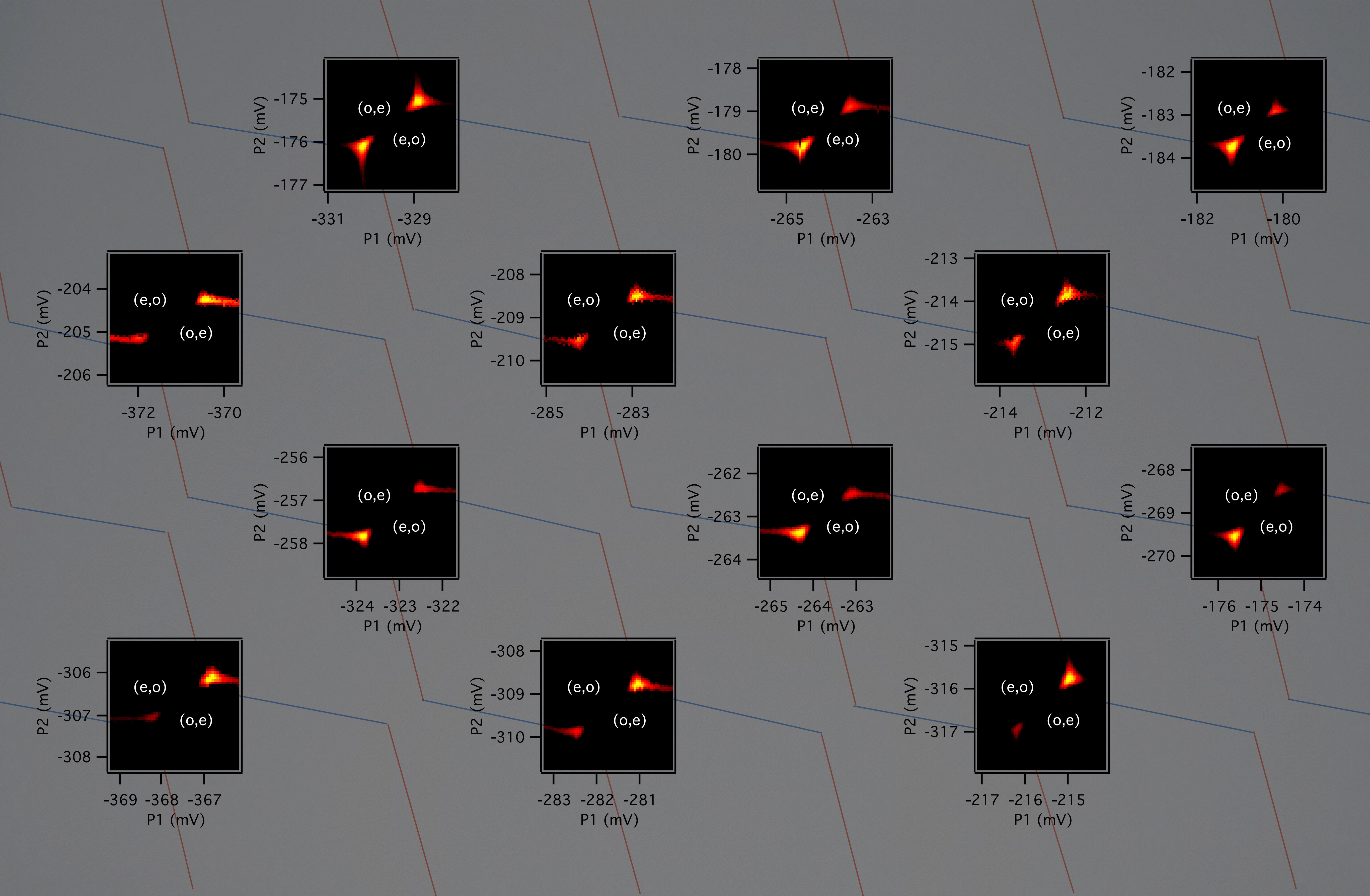
Conductance should always "point to" the (odd, odd) hexagon




3
3
3
1
1
1
3
3
3
1
1
1



-175 -176 -177
P2 (mV)
(o,e)
(e,o)
-331 -329
P1 (mV)
-178 -179 -180
P2 (mV)
(o,e)
(e,o)
-265 -263
P1 (mV)
-182 -183 -184
P2 (mV)
(o,e)
(e,o)
-182 -180
P1 (mV)
-204 -205 -206
P2 (mV)
(e,o)
(o,e)
-372 -370
P1 (mV)
-208 -209 -210
P2 (mV)
(e,o)
(o,e)
-285 -283
P1 (mV)
-213 -214 -215
P2 (mV)
(e,o)
(o,e)
-214 -212
P1 (mV)
-256 -257 -258
P2 (mV)
(o,e)
(e,o)
-324 -323 -322
P1 (mV)
-262 -263 -264
P2 (mV)
(o,e)
(e,o)
-265 -264 -263
P1 (mV)
-268 -269 -270
P2 (mV)
(o,e)
(e,o)
-176 -175 -174
P1 (mV)
-306 -307 -308
P2 (mV)
(e,o)
(o,e)
-369 -368 -367
P1 (mV)
-308 -309 -310
P2 (mV)
(e,o)
(o,e)
-283 -282 -281
P1 (mV)
-315 -316 -317
P2 (mV)
(e,o)
(o,e)
-217 -216 -215
P1 (mV)


(o,e)
(e,o)
P2 (mV)
P1 (mV)
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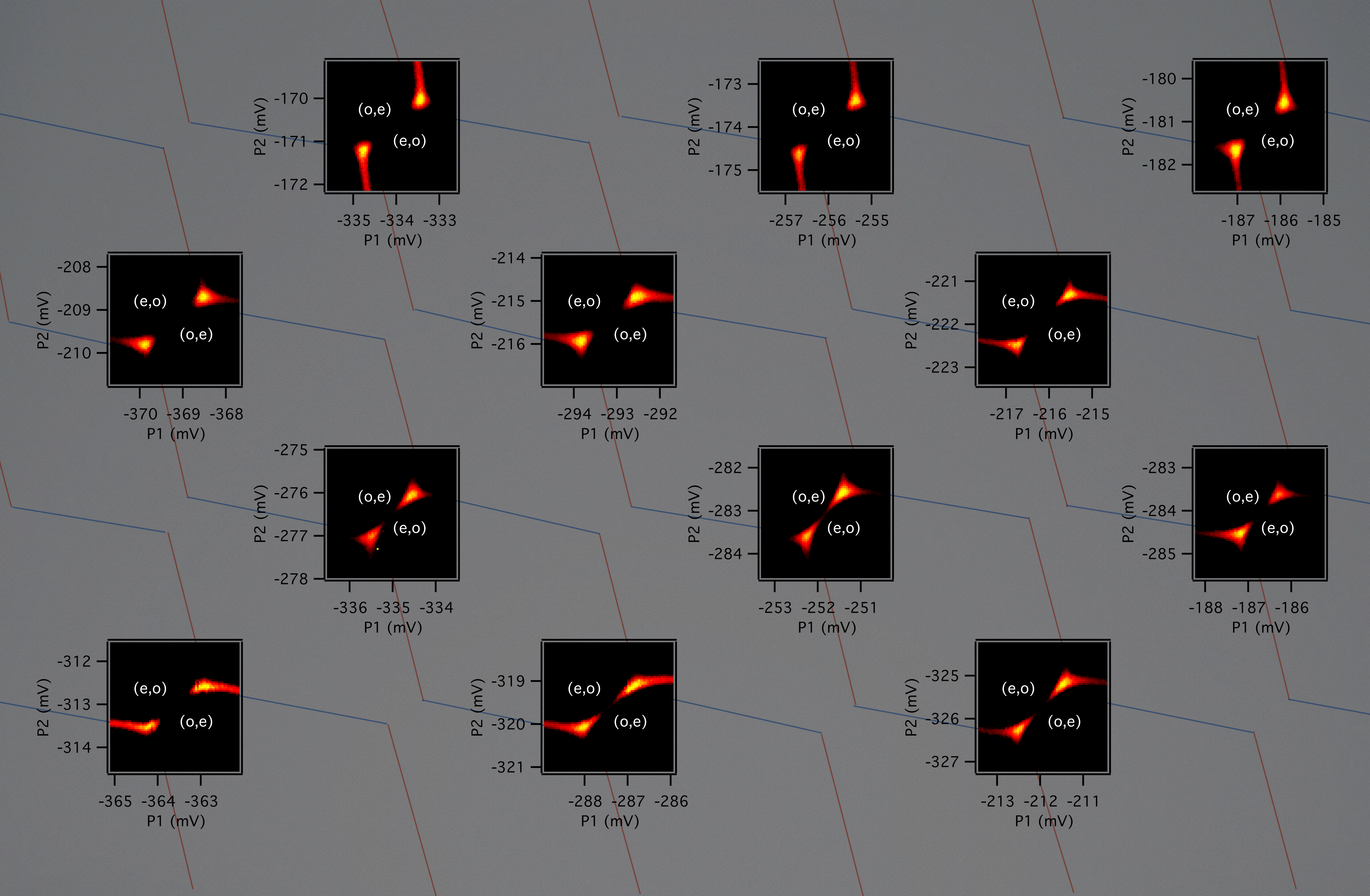


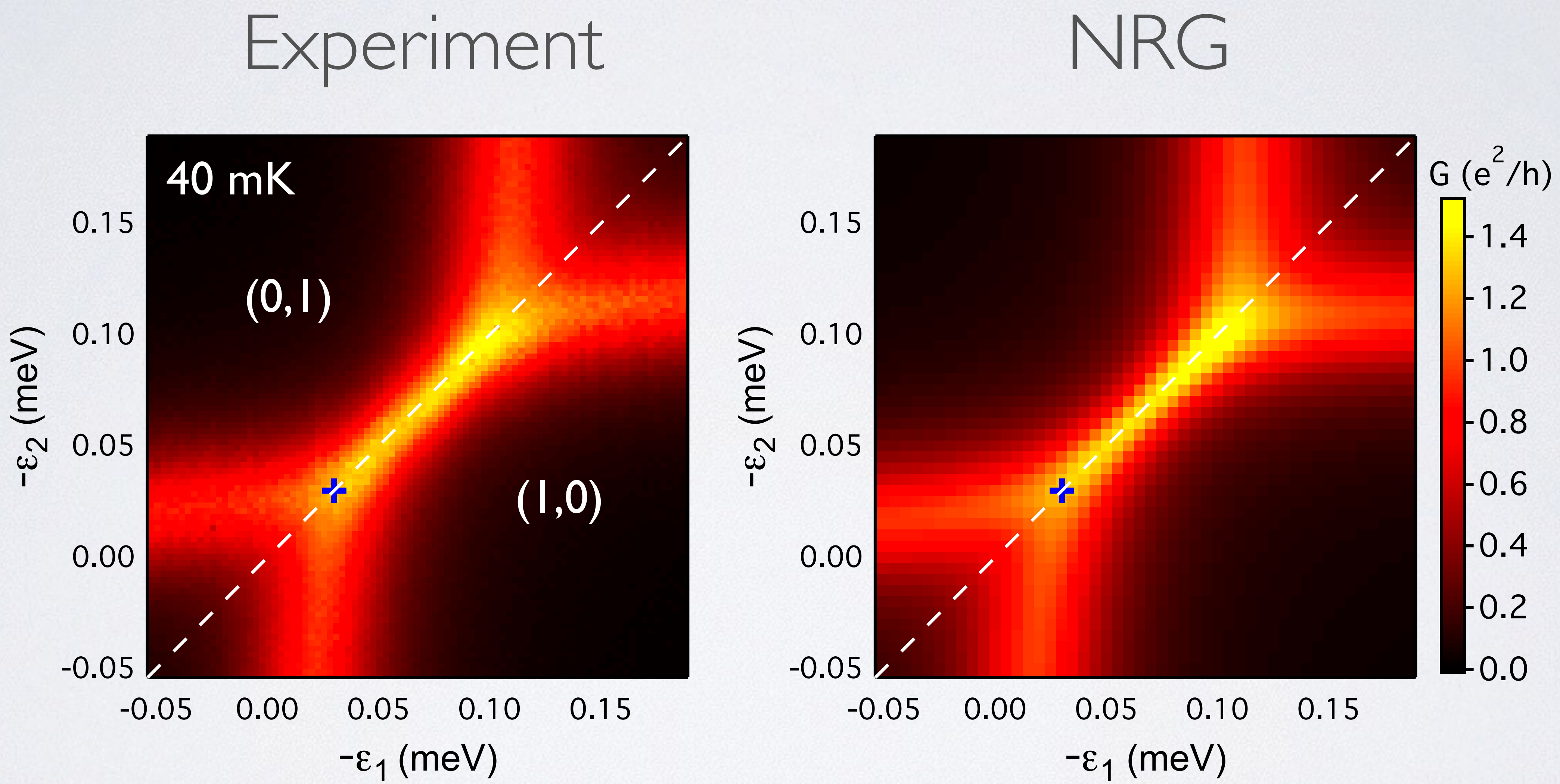
2 Tesla magnetic field

Establishing a correspondence between experiment and theory

- Agreement between simple theoretical models and experiments gives confidence in the interpretation of experimental data

- This correspondence helps us compare experimental data to the prediction of universal models

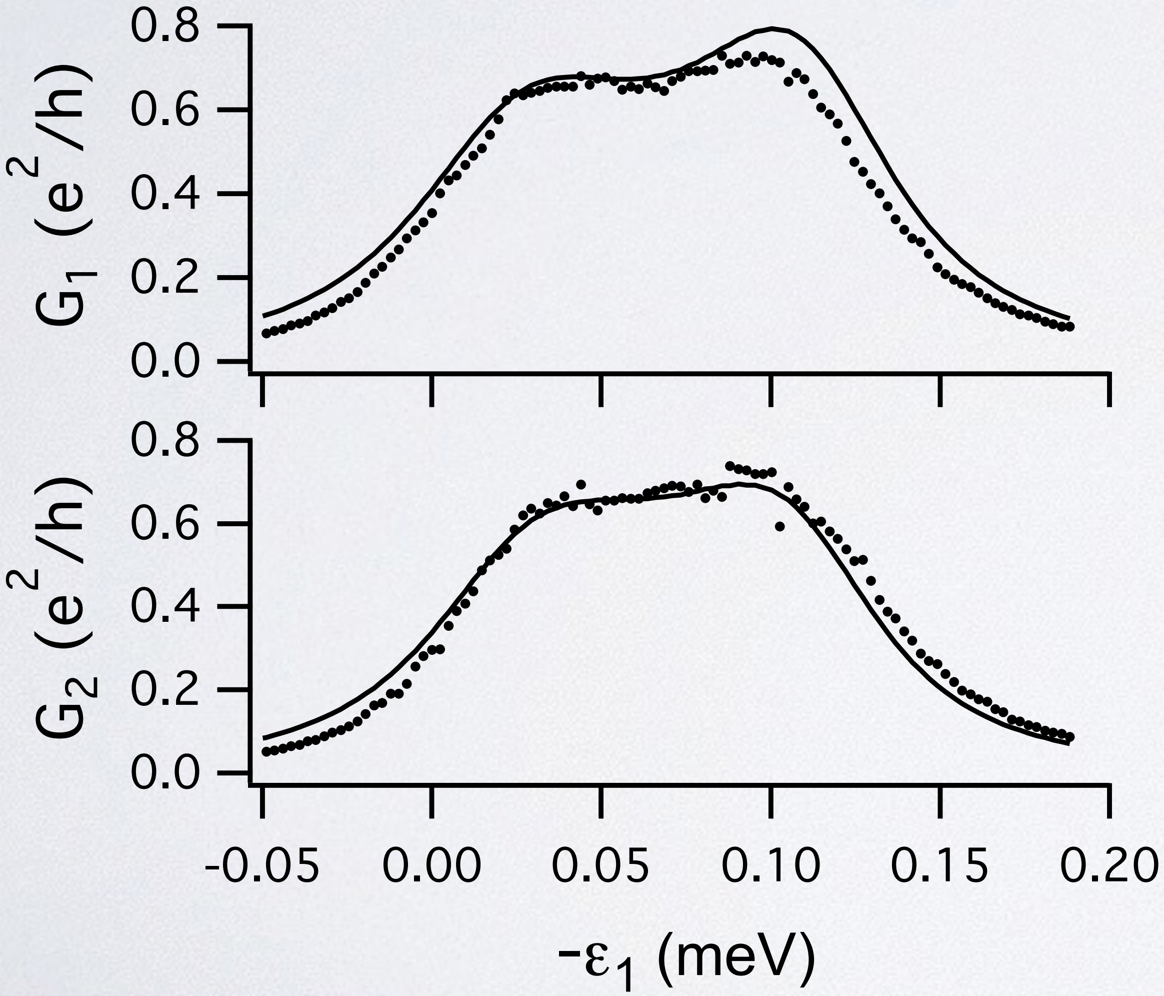
Establishing a correspondence between experiment and theory



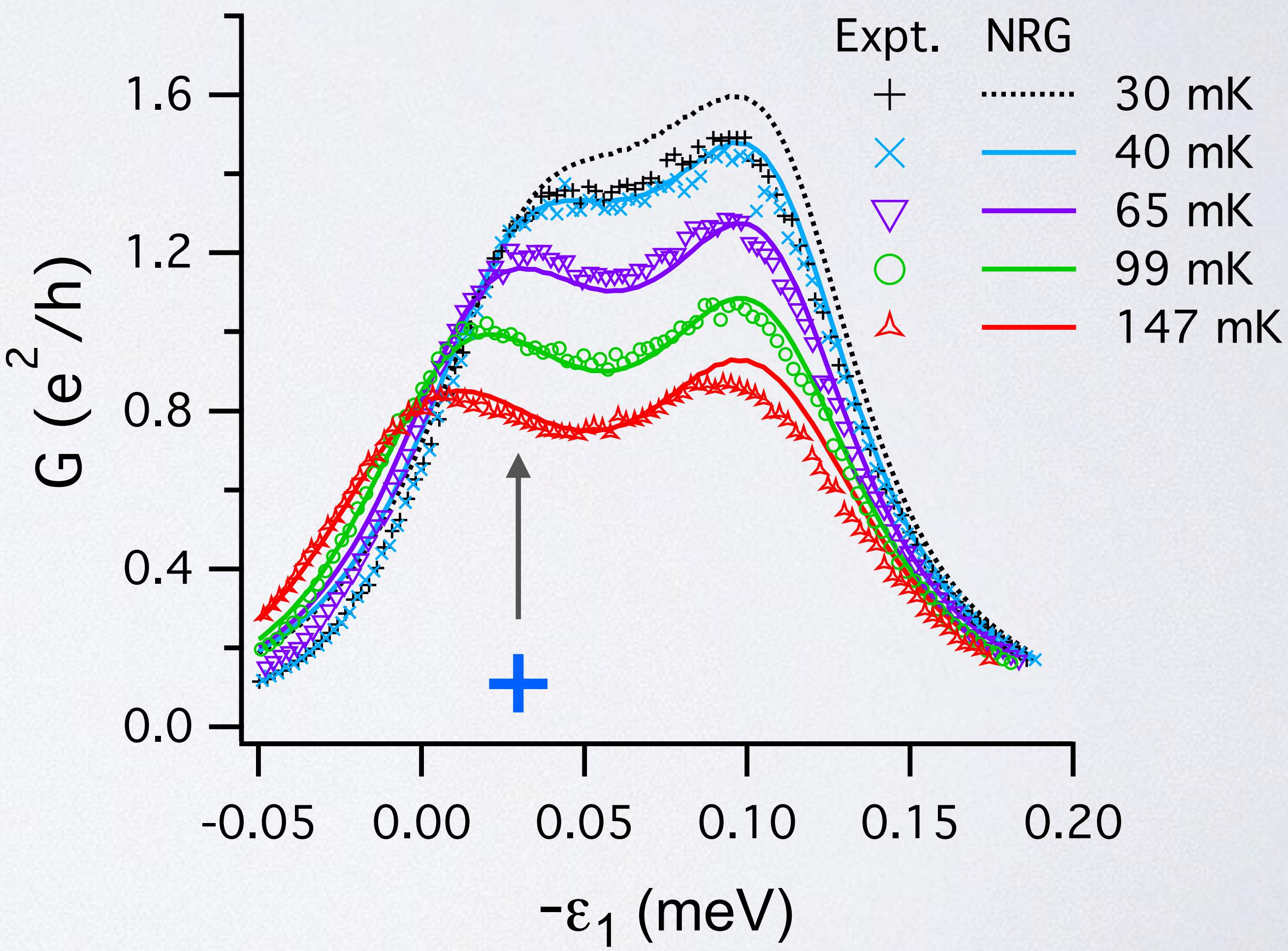
N = 1 LBTP

Establishing a correspondence between experiment and theory

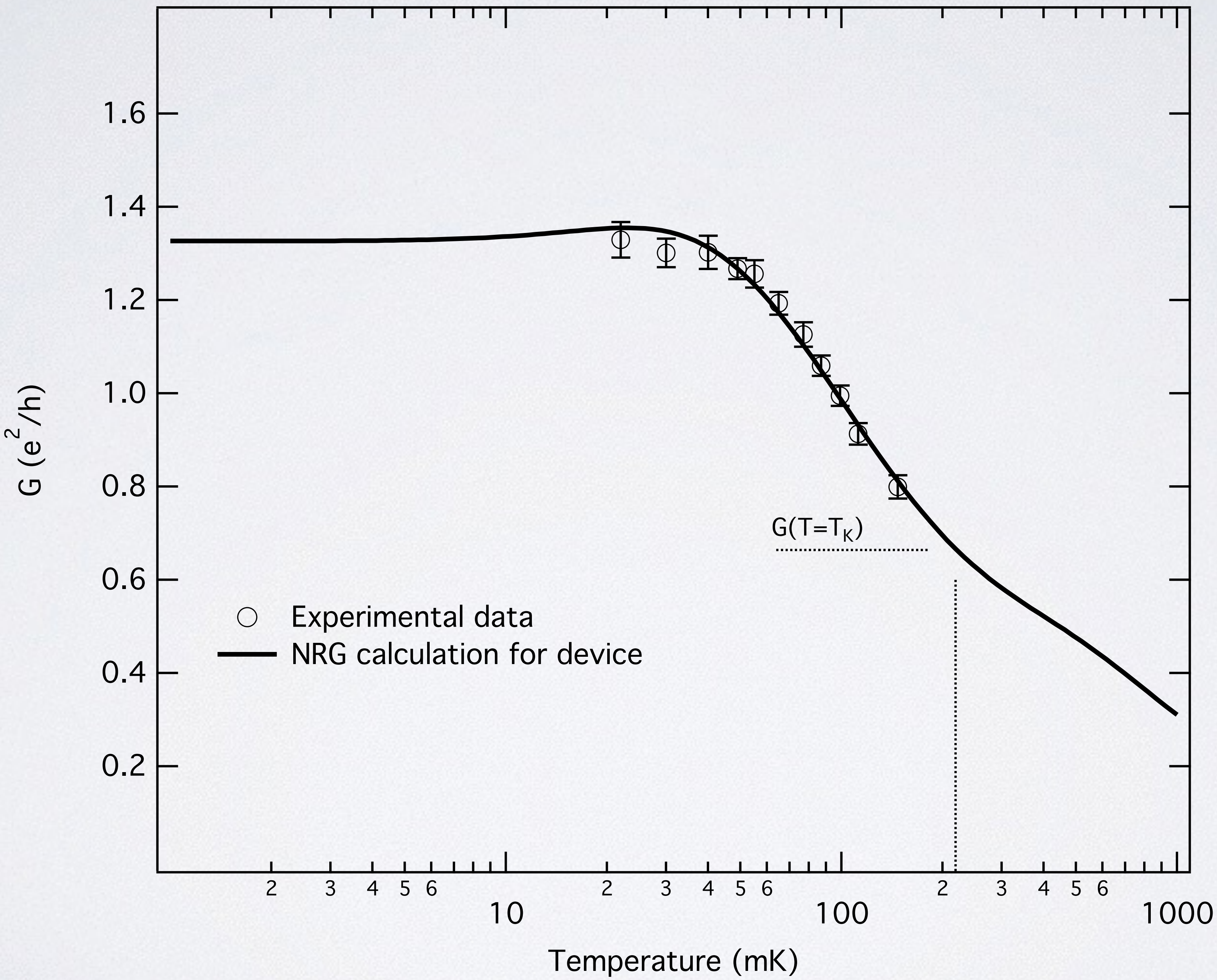
Orbital state-resolved conductances at 40 mK



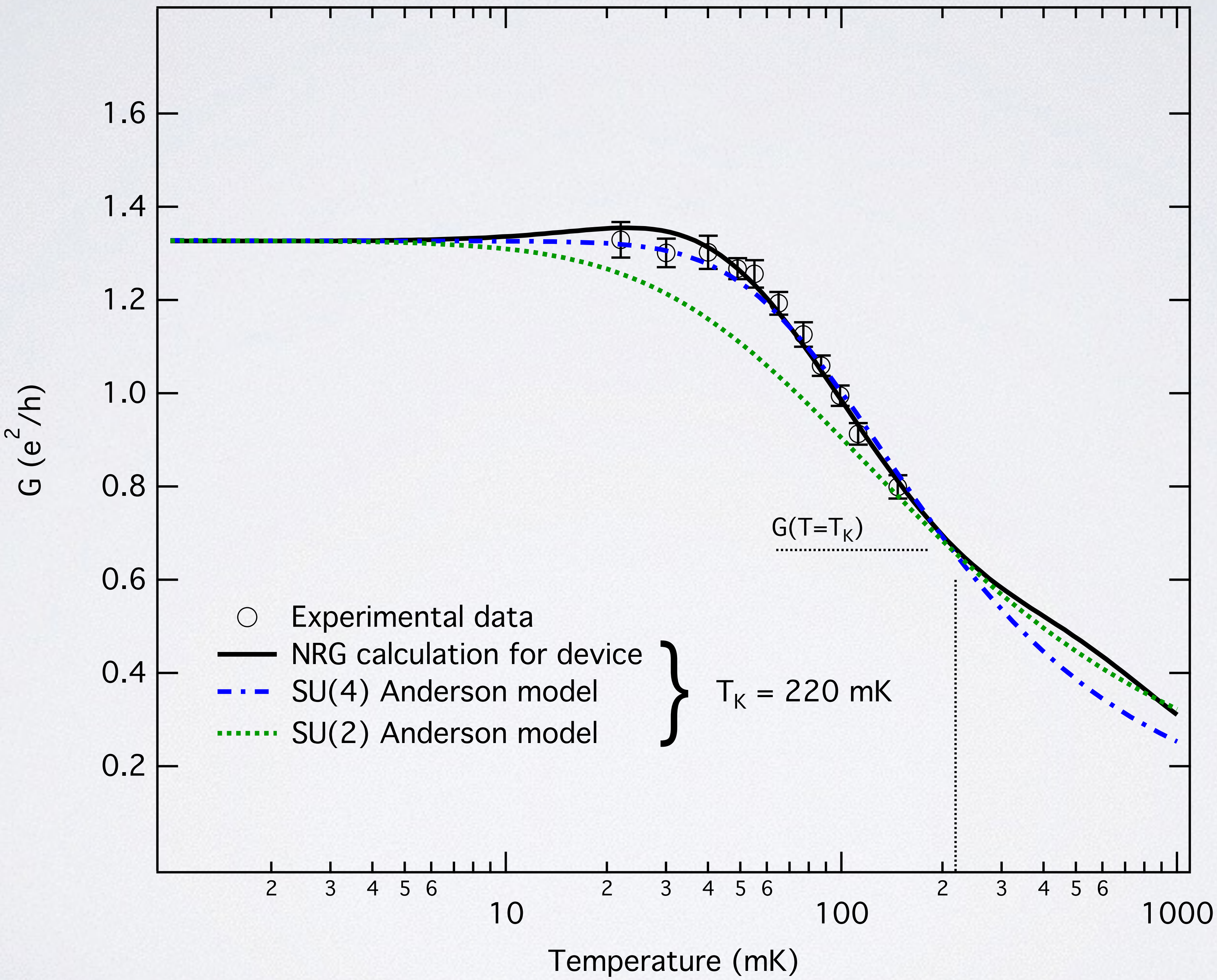
Temperature dependent conductances



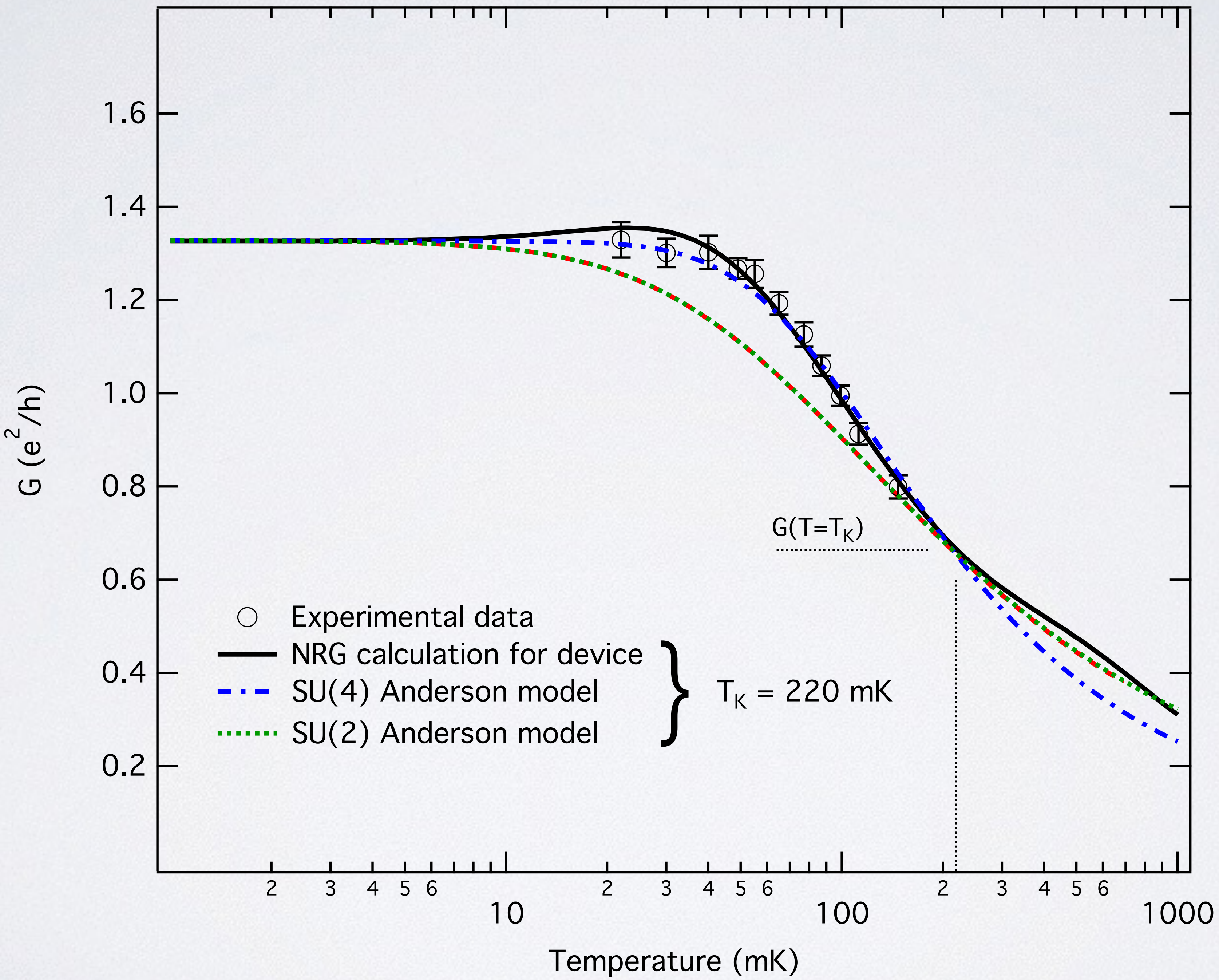
Comparing to universal models



Comparing to universal models



Comparing to universal models

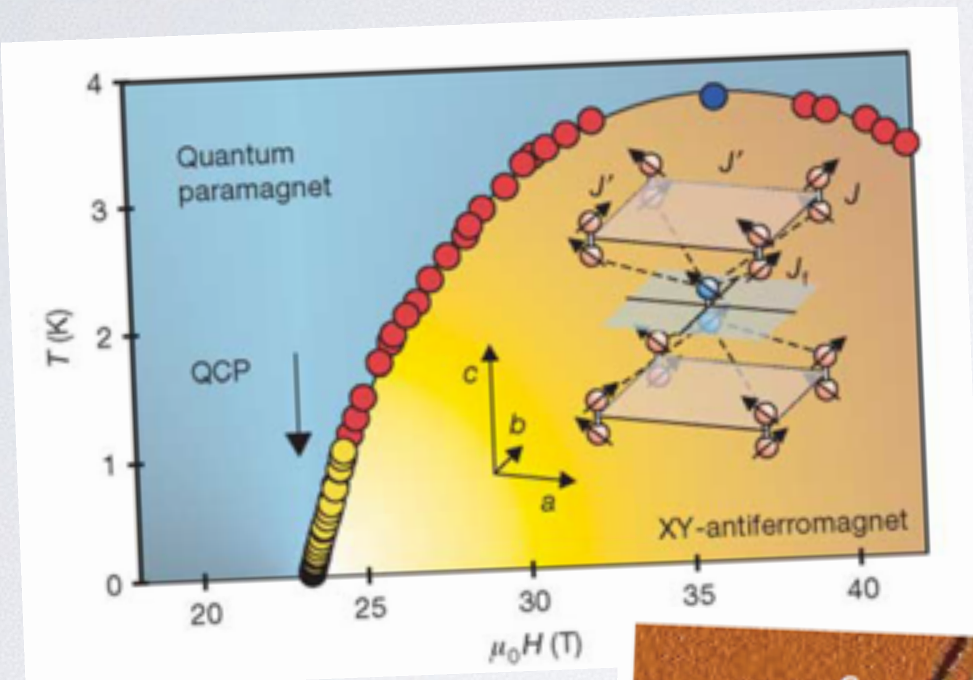


Outline

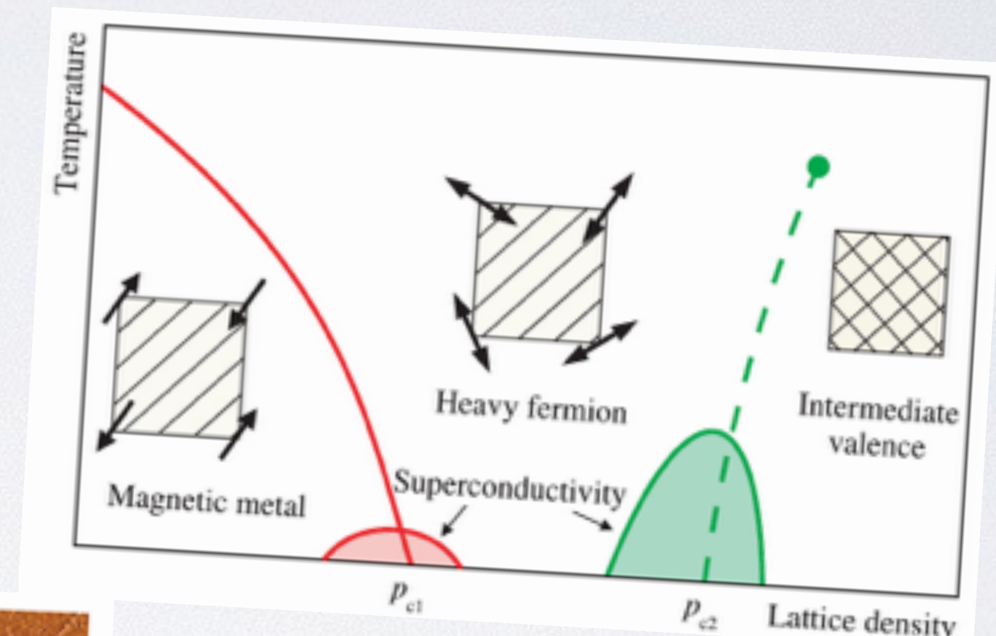
- Symmetries in physics
- Quantum dots and the Kondo effect
- Emergent SU(4)-symmetric Kondo effect in a double quantum dot
- **Universal crossover between quantum critical and Fermi liquid states in a quantum dot coupled to a “metallic grain”**

Quantum criticality

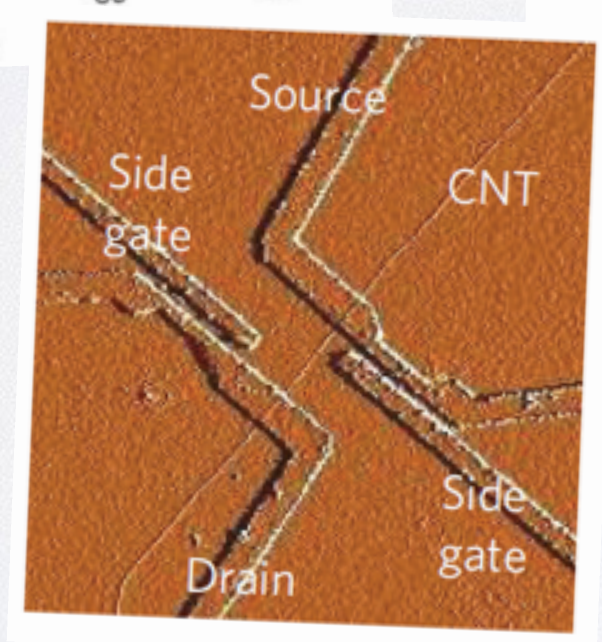
Materials design and device design as complementary approaches



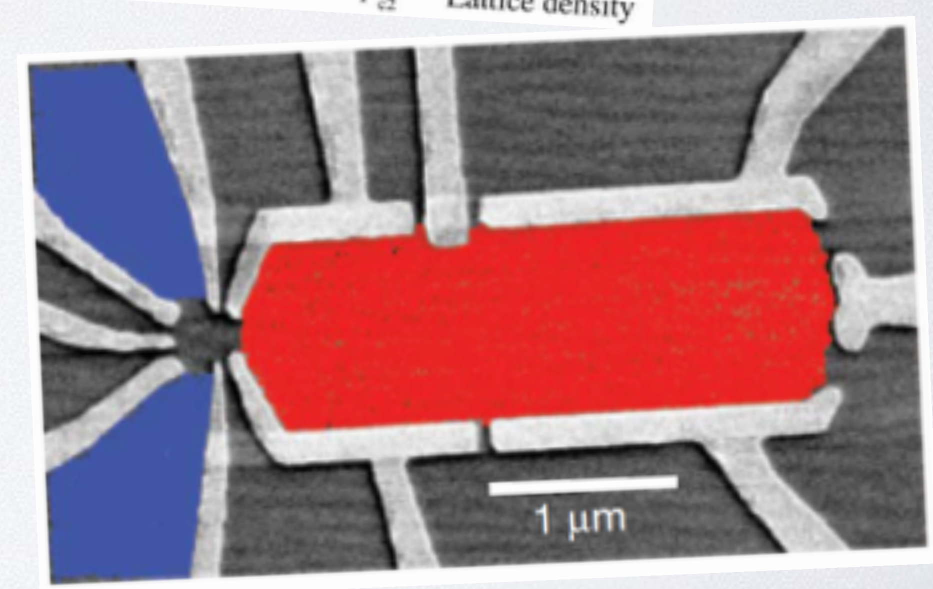
S. E. Sebastian *et al.*,
Nature **441**, 617 (2006).



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

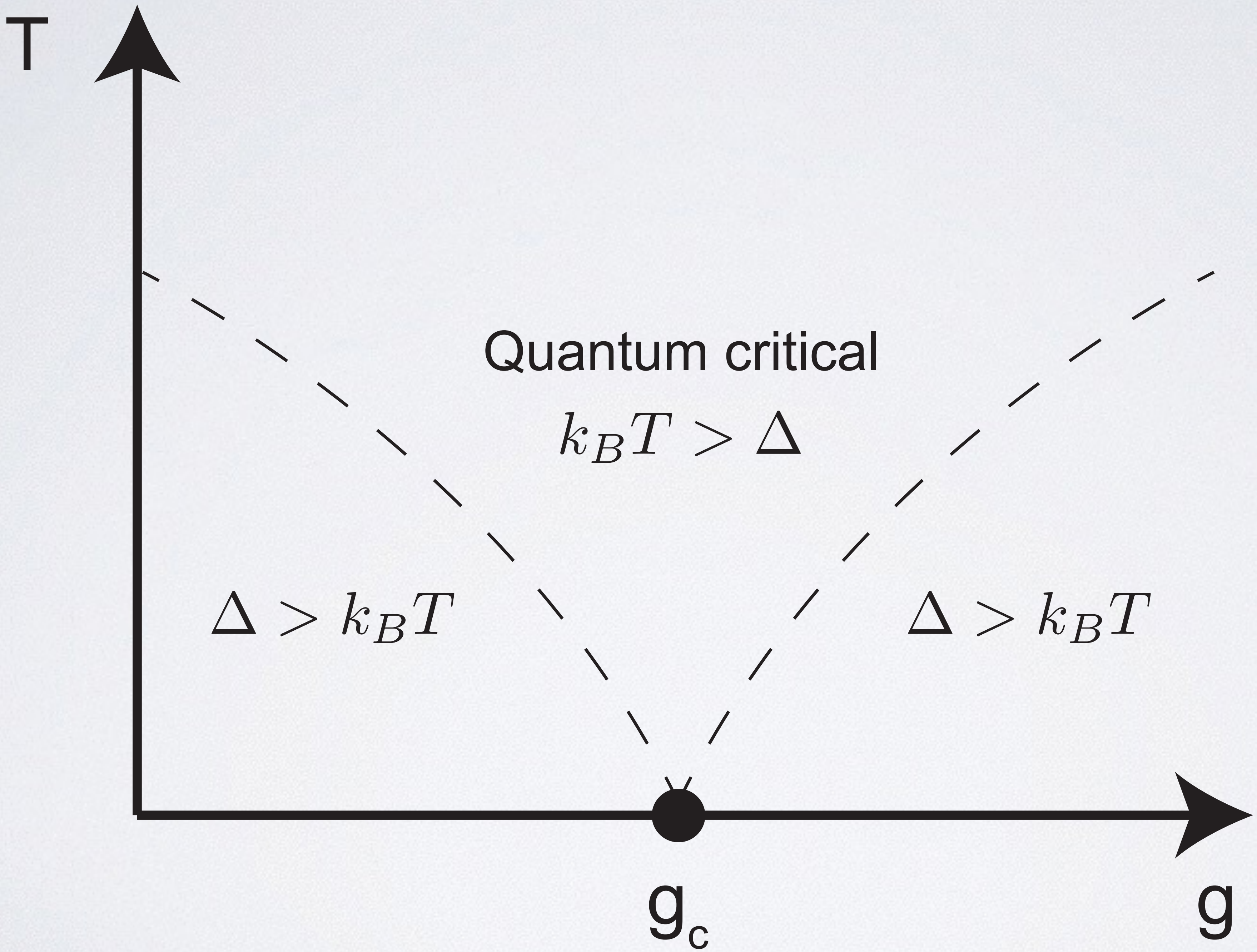


H. Mebrahtu *et al.*,
Nature Phys. **9**, 732 (2013).



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

Quantum criticality

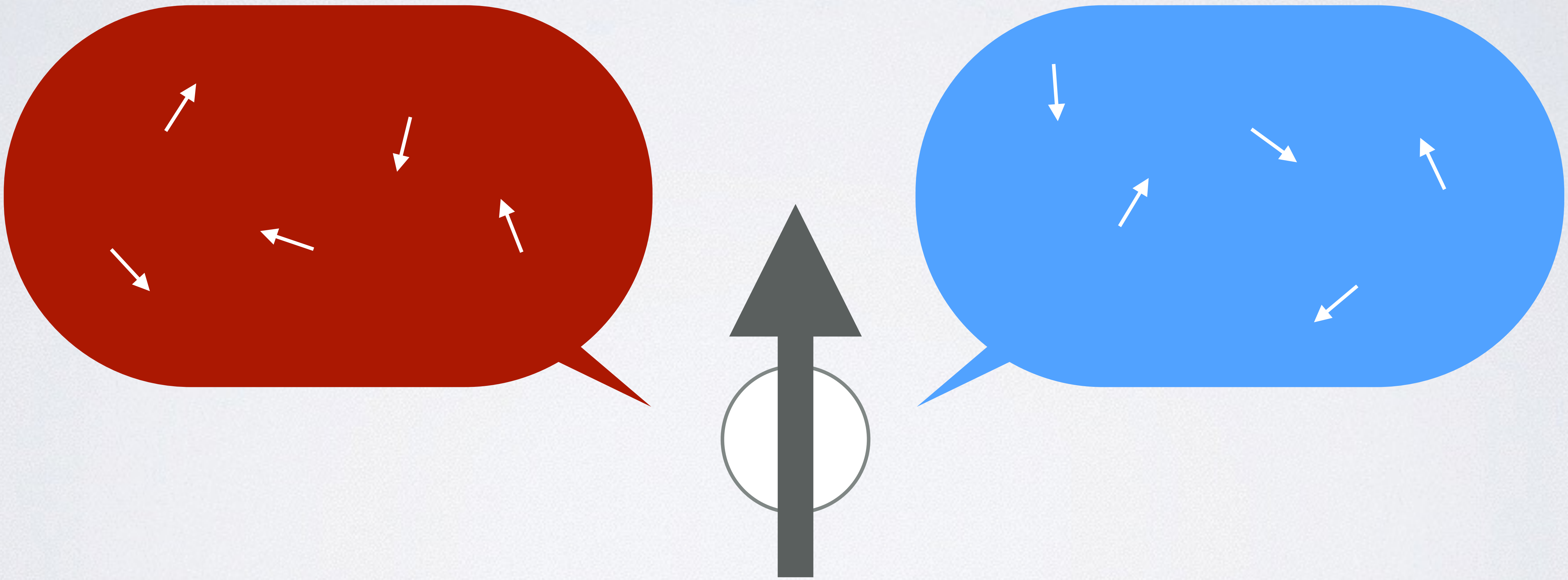


Chakravarty, Halperin, Nelson 1989

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

Two-channel Kondo effect

A model quantum phase transition



Two-channel Kondo effect,

by way of *Office Space (1999)*

Boss #1

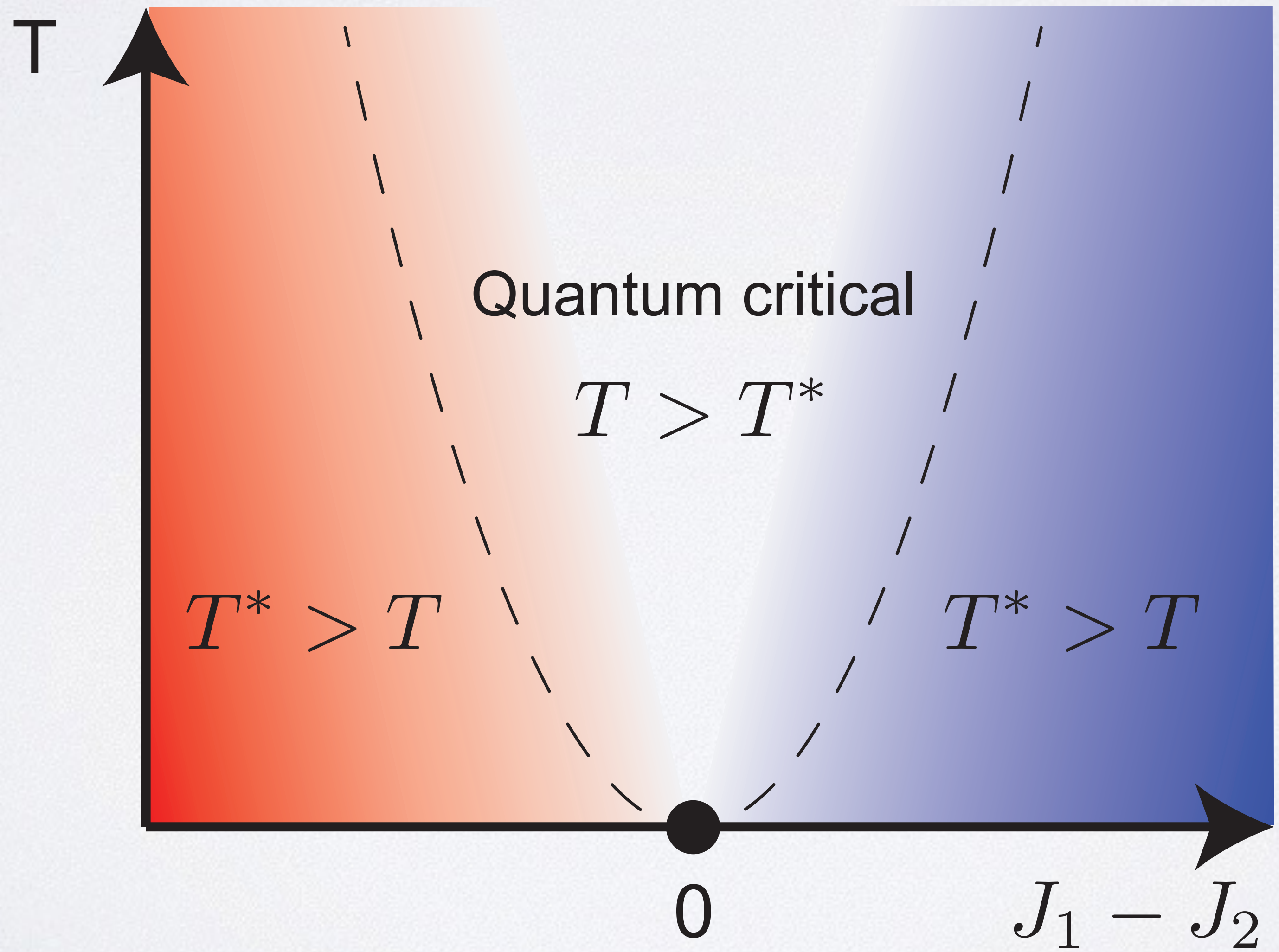
Employee

Boss #2

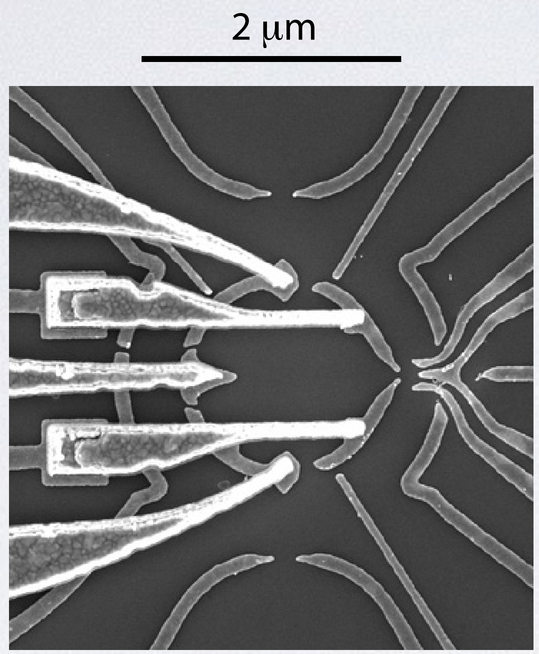
Two-channel Kondo effect

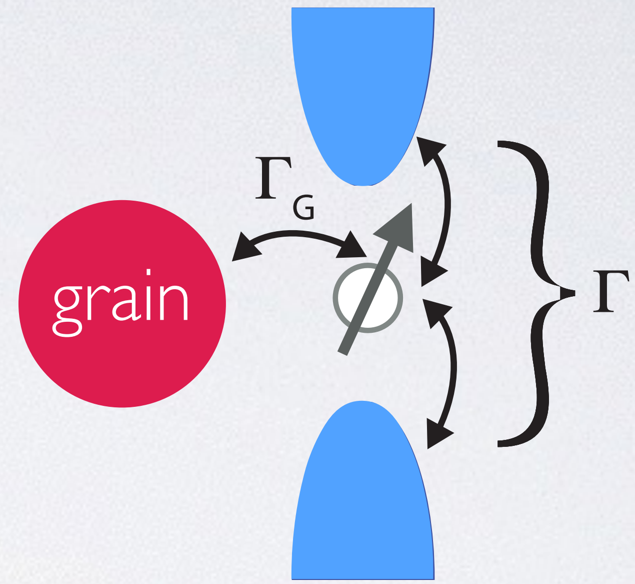
A model quantum phase transition

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



How do we implement this?

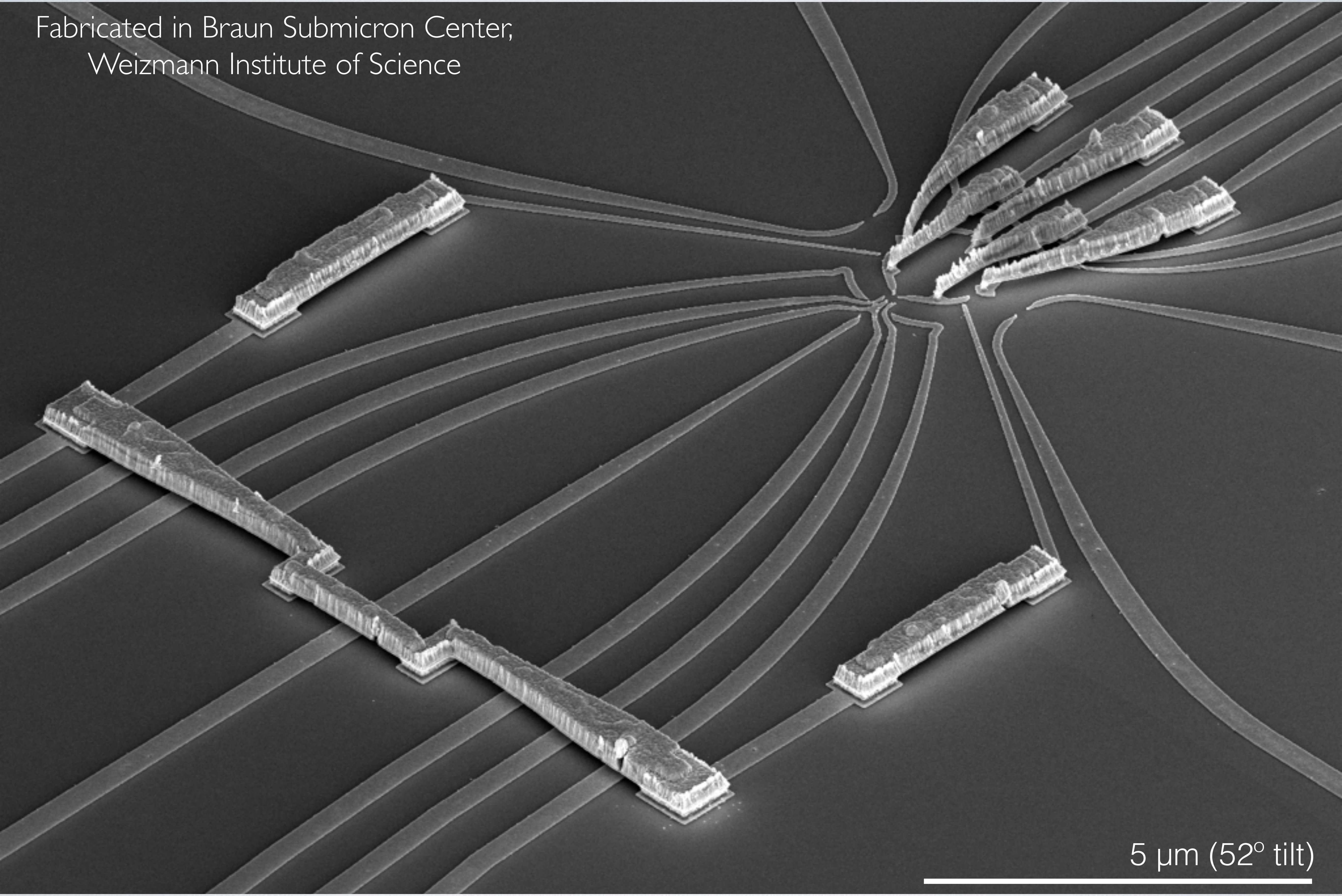




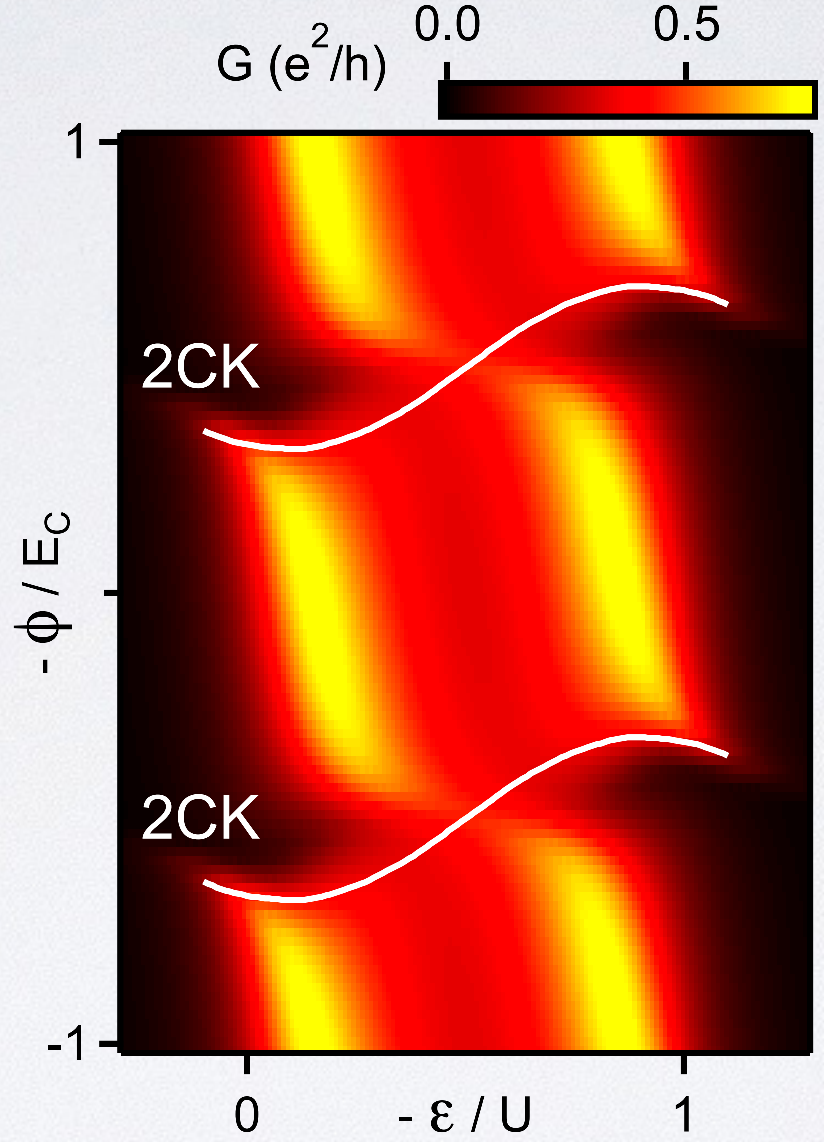
Quantum dot tunnel coupled to a "metallic grain"

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

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

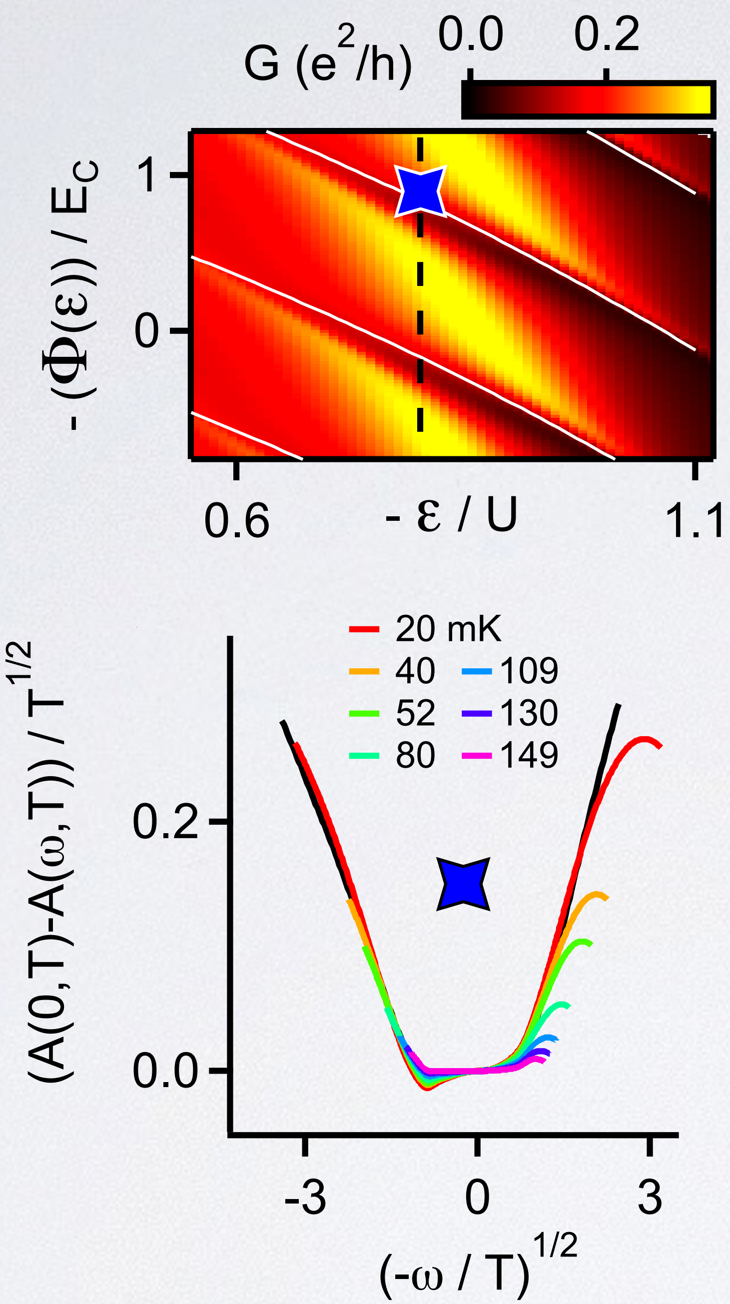

Fabricated in Braun Submicron Center,
Weizmann Institute of Science
5 µm (52° tilt)

Identifying a 2CK state

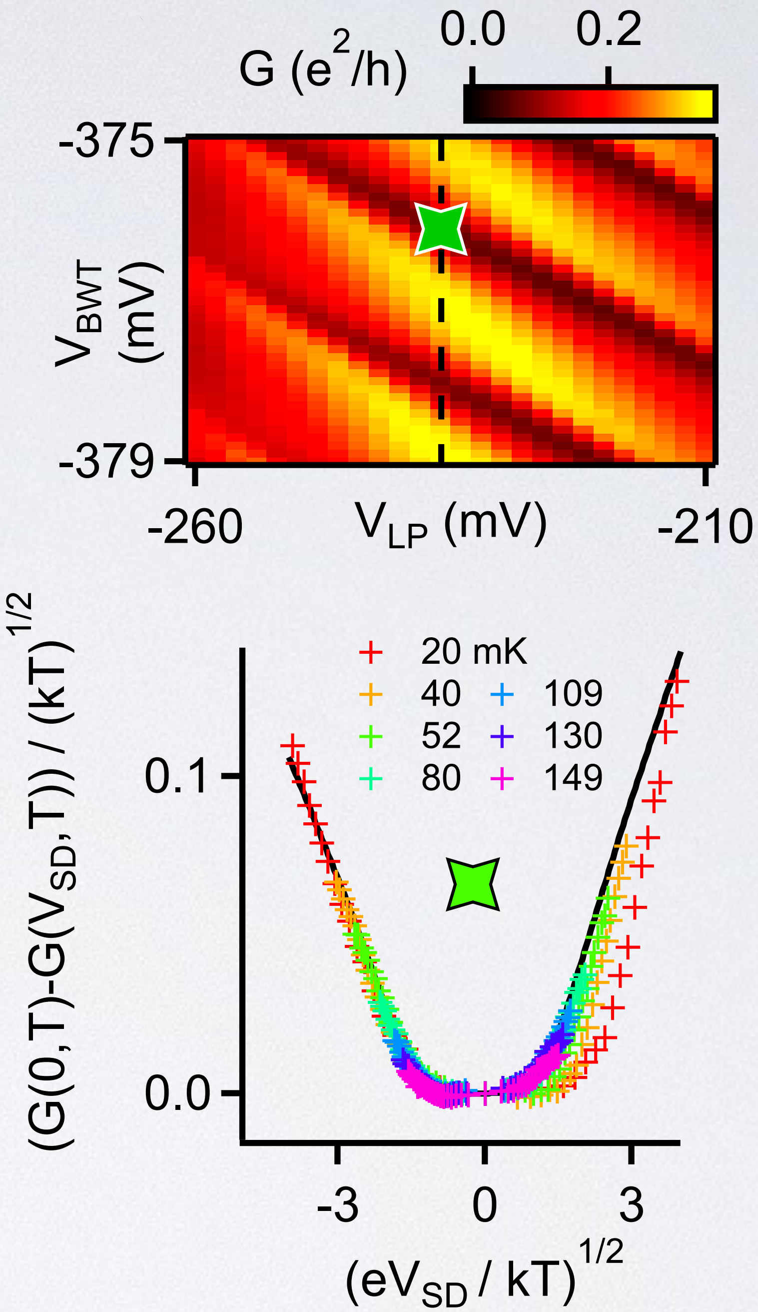


(NRG calculation)

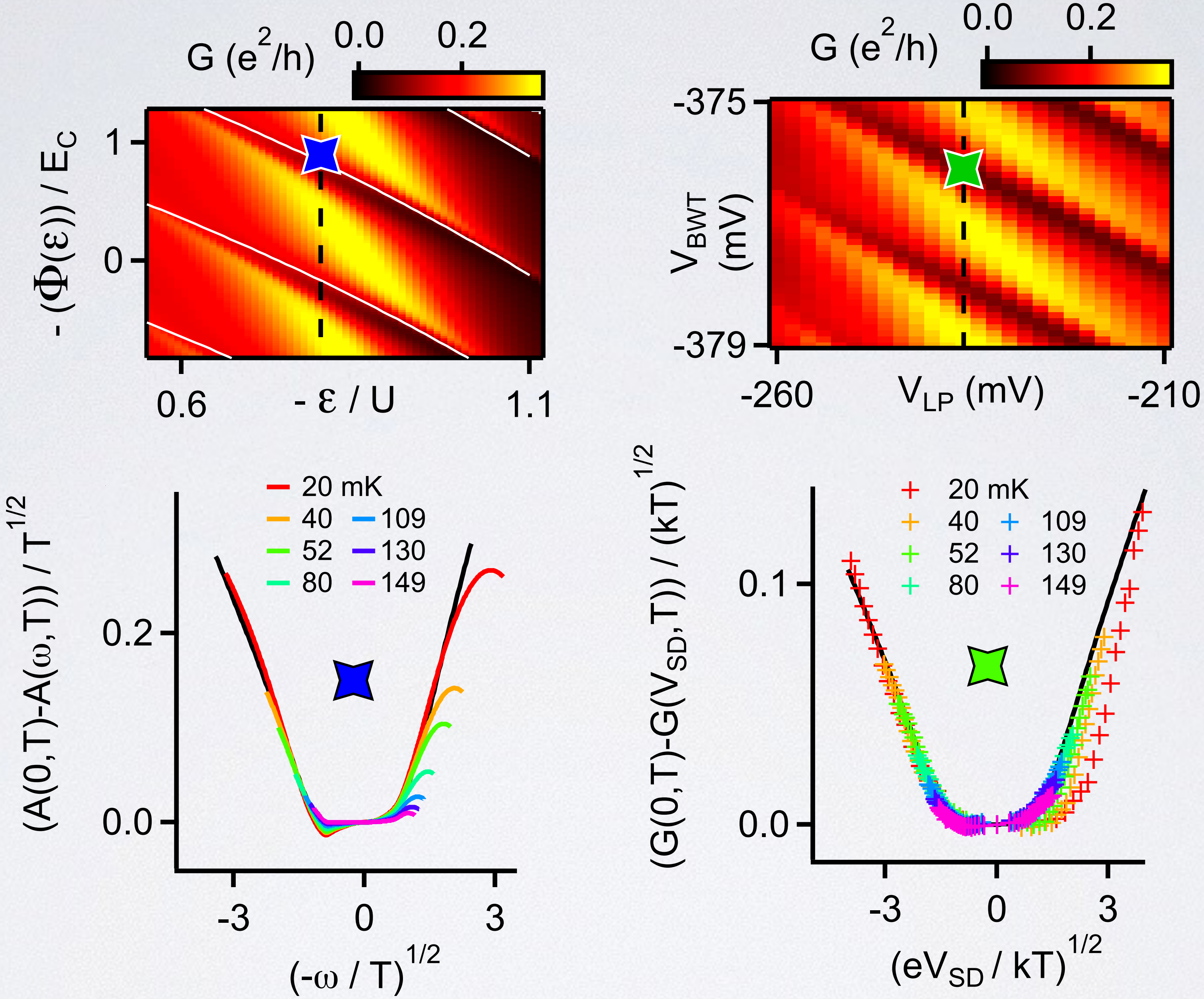
NRG



Experiment



NRG Experiment



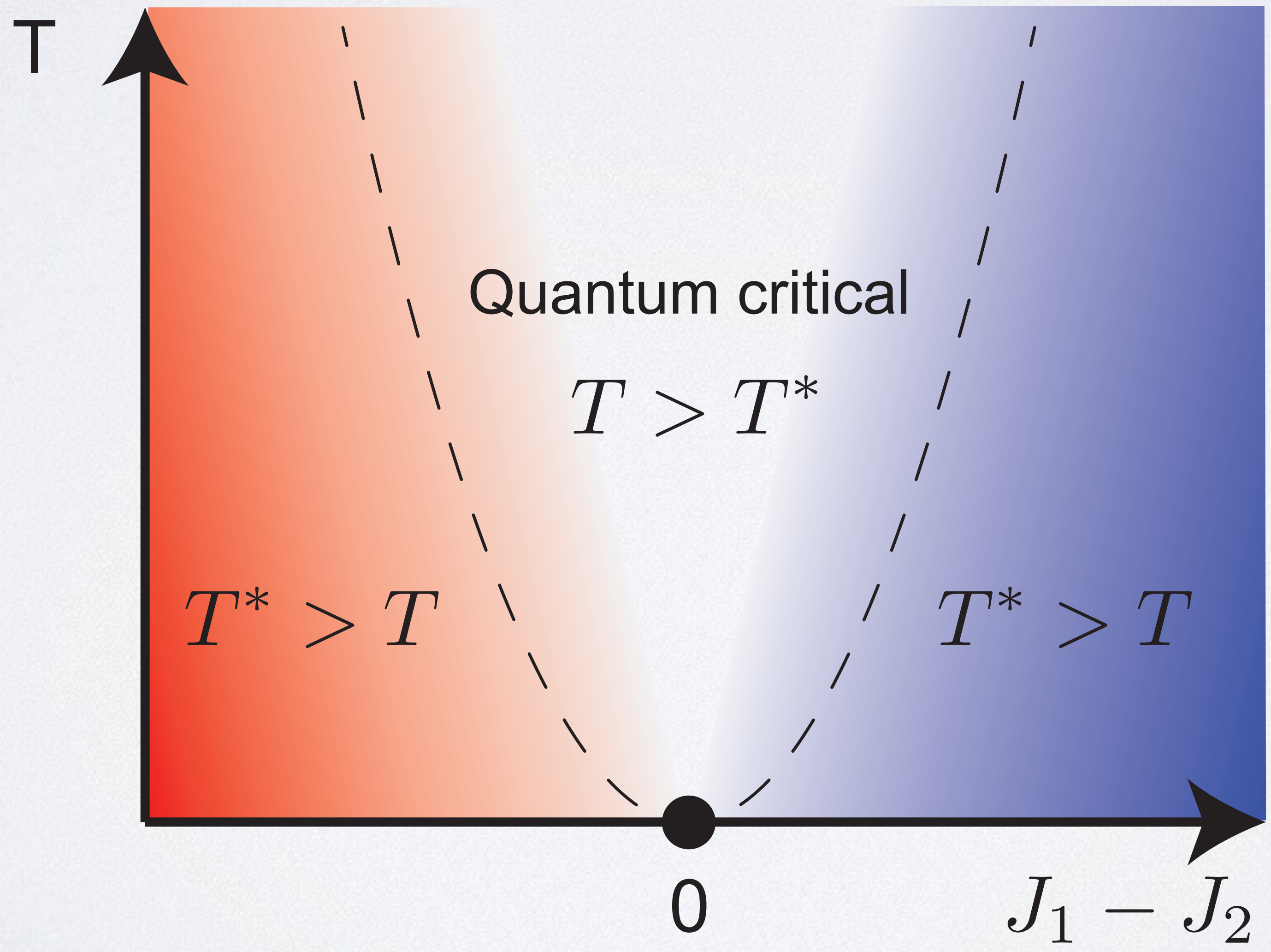
$$\Sigma^R(\omega) = -\frac{i n_i}{2\pi\nu}\left\{[1 - e^{2i\delta_P}S_{(1)}] - e^{2i\delta_P} N\lambda \left(\frac{2\pi}{\beta}\right)^{\Delta} 2\sin(\pi\Delta)\int_0^1 du\left[u^{-i\beta\omega/2\pi}u^{-1/2}(1-u)^{\Delta}F(u) - \frac{\Gamma(1+2\Delta)}{\Gamma^2(1+\Delta)}u^{(\Delta-1)}(1-u)^{-(1+\Delta)}\right]\right\}.$$

Affleck and Ludwig, PRB 48, 7297 (1993)

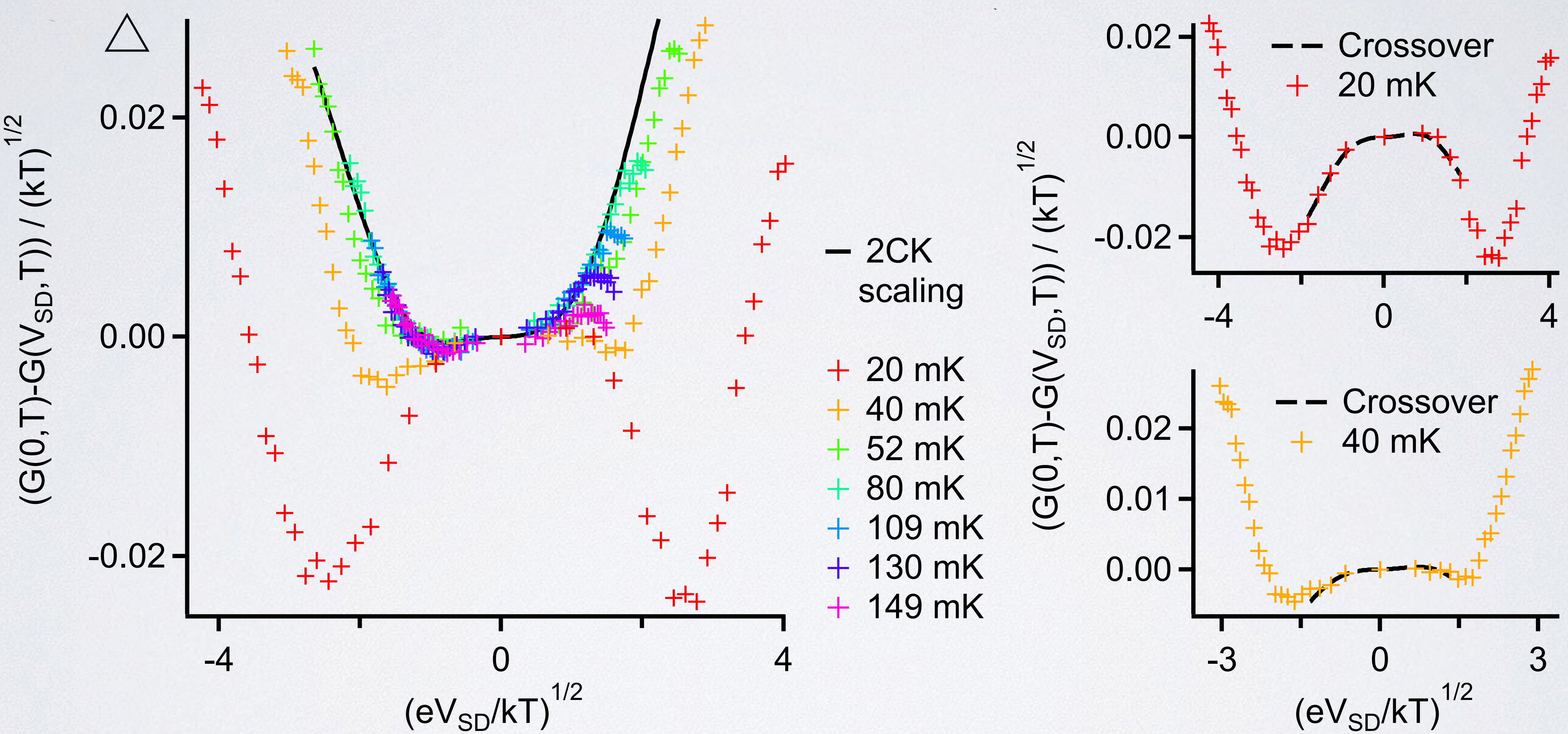
Two-channel Kondo effect

A model quantum phase transition

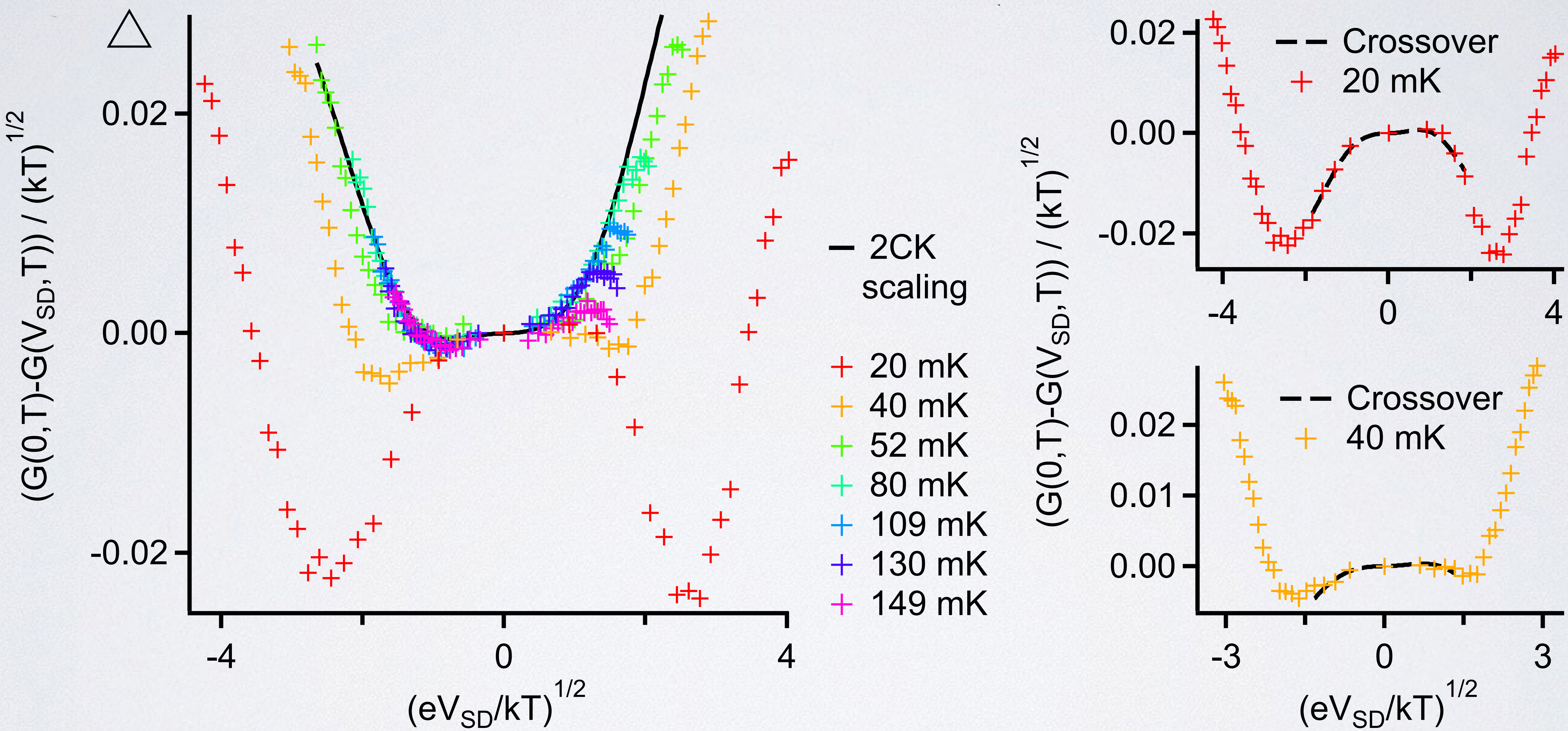
$$H_{2\mathrm{CK}} = \sum_{\alpha,k} \epsilon_k c^\dagger_{k\sigma\alpha} c_{k\sigma\alpha} + J\vec{S}\cdot(\vec{s}_L + \vec{s}_R) + \delta H_{2\mathrm{CK}}$$



The Fermi liquid crossover: near but not at the critical point



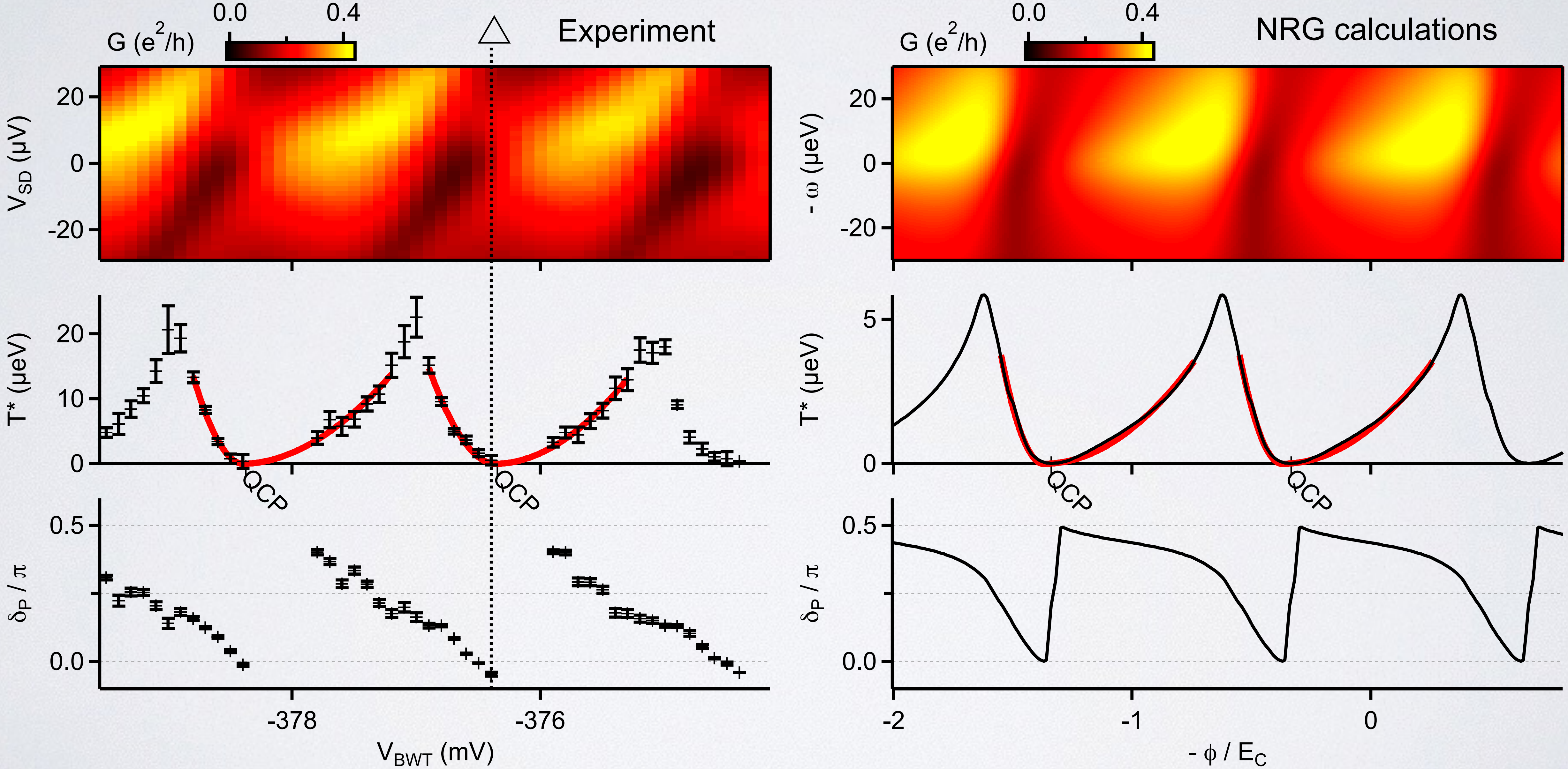
The Fermi liquid crossover



Mitchell and Sela, PRB 85, 235127 (2012)

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

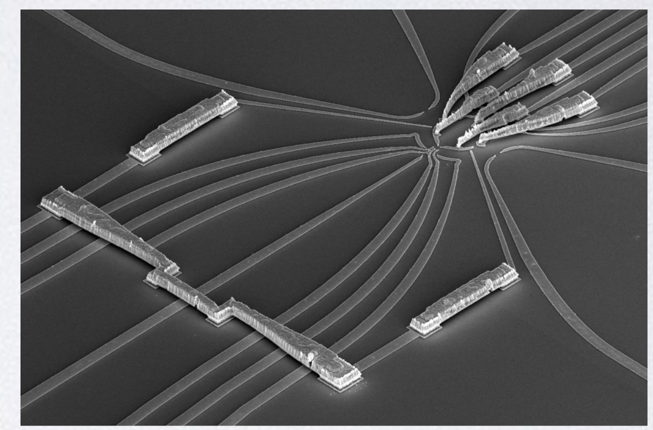
Boundary of critical regime

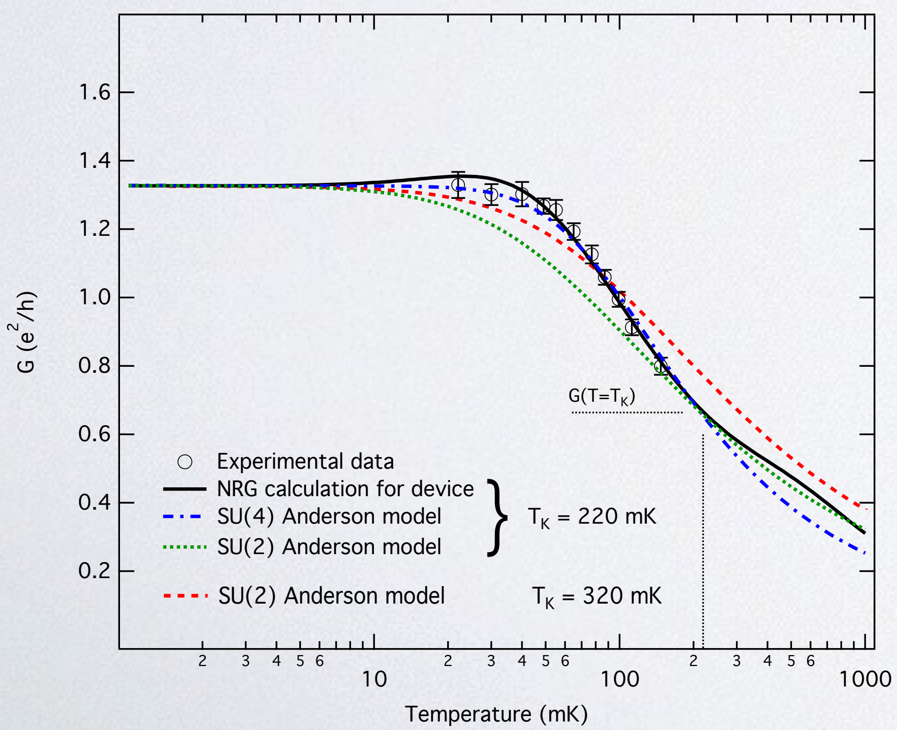


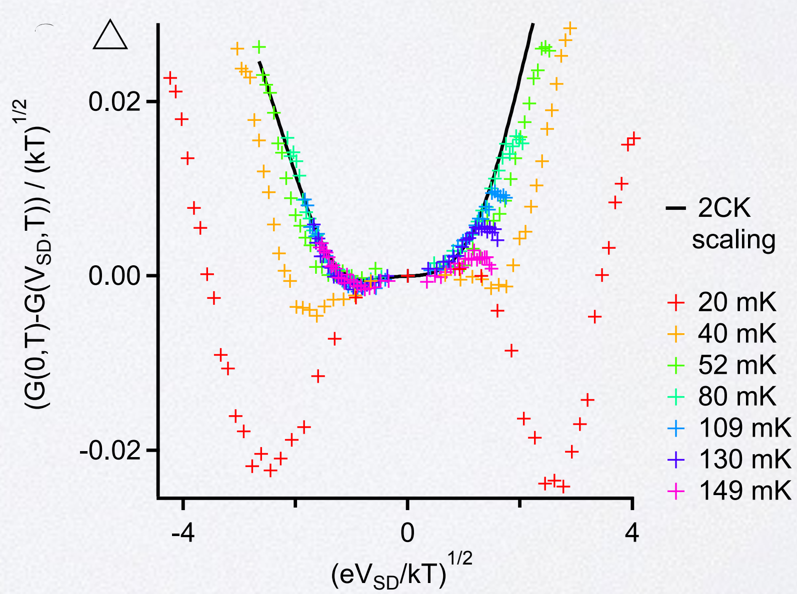
To summarize…

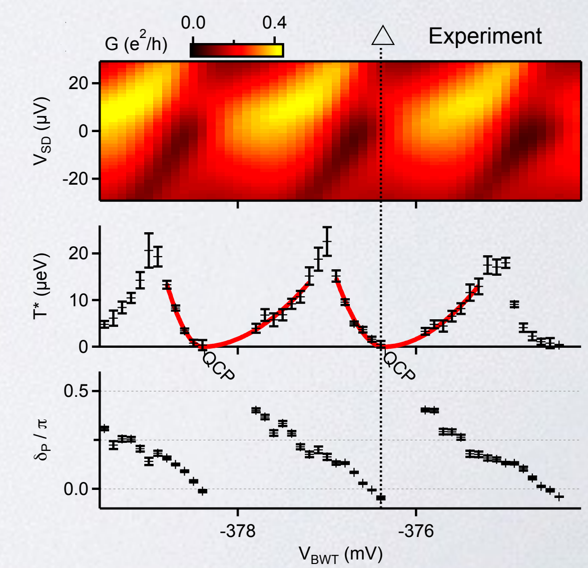
We've seen signatures of emergent symmetry in a double quantum dot

We've closely tested ideas of quantum phase transitions in a model system









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Collaborators:

G. Zaránd, C. P. Moca (Budapest University of Technology and Economics), I. Weymann (Adam Mickiewicz University), V. Umansky, H. Shtrikman, D. Mahalu, H.-K. Choi, Y. Oreg, A. Carmi, (Weizmann Institute of Science), J. A. Katine (HGST), J. MacArthur (Harvard), Y. Chung (Pusan National U.)

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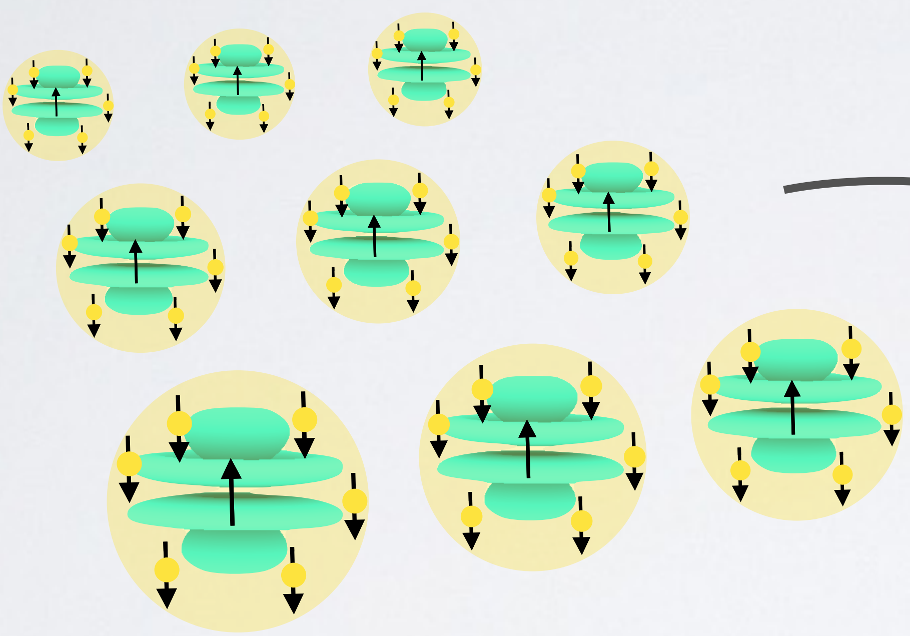
NSF

SGF

GORDON AND BETTY MOORE FOUNDATION

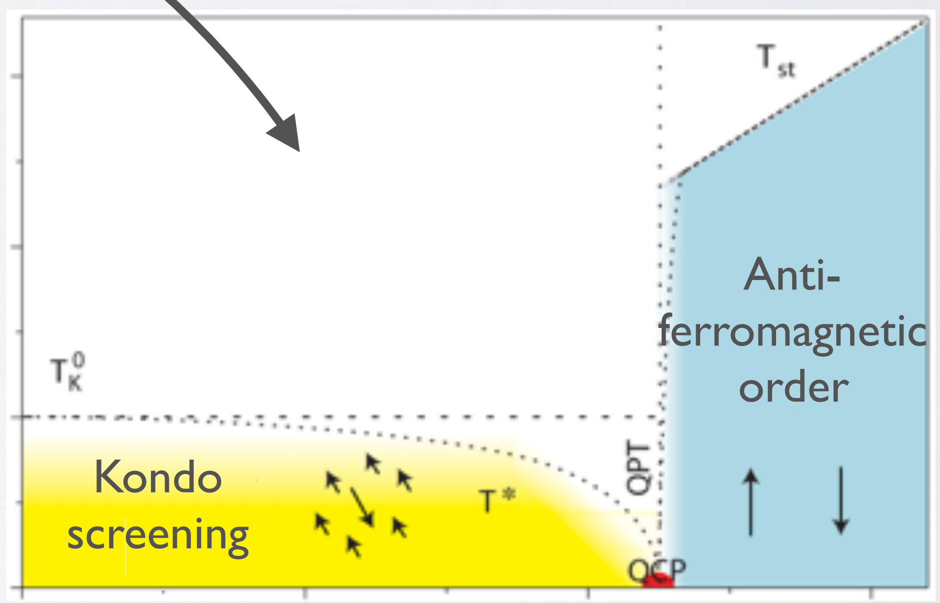
From here?

Coupling of model spins, to understand bulk materials



+ RKKY interaction

Energy



Interaction strength

Adapted from Bork, *et al.*, Nature Physics 7, 11 (2011).

To summarize…

We've seen signatures of emergent symmetry in a double quantum dot

We've closely tested ideas of quantum phase transitions in a model system