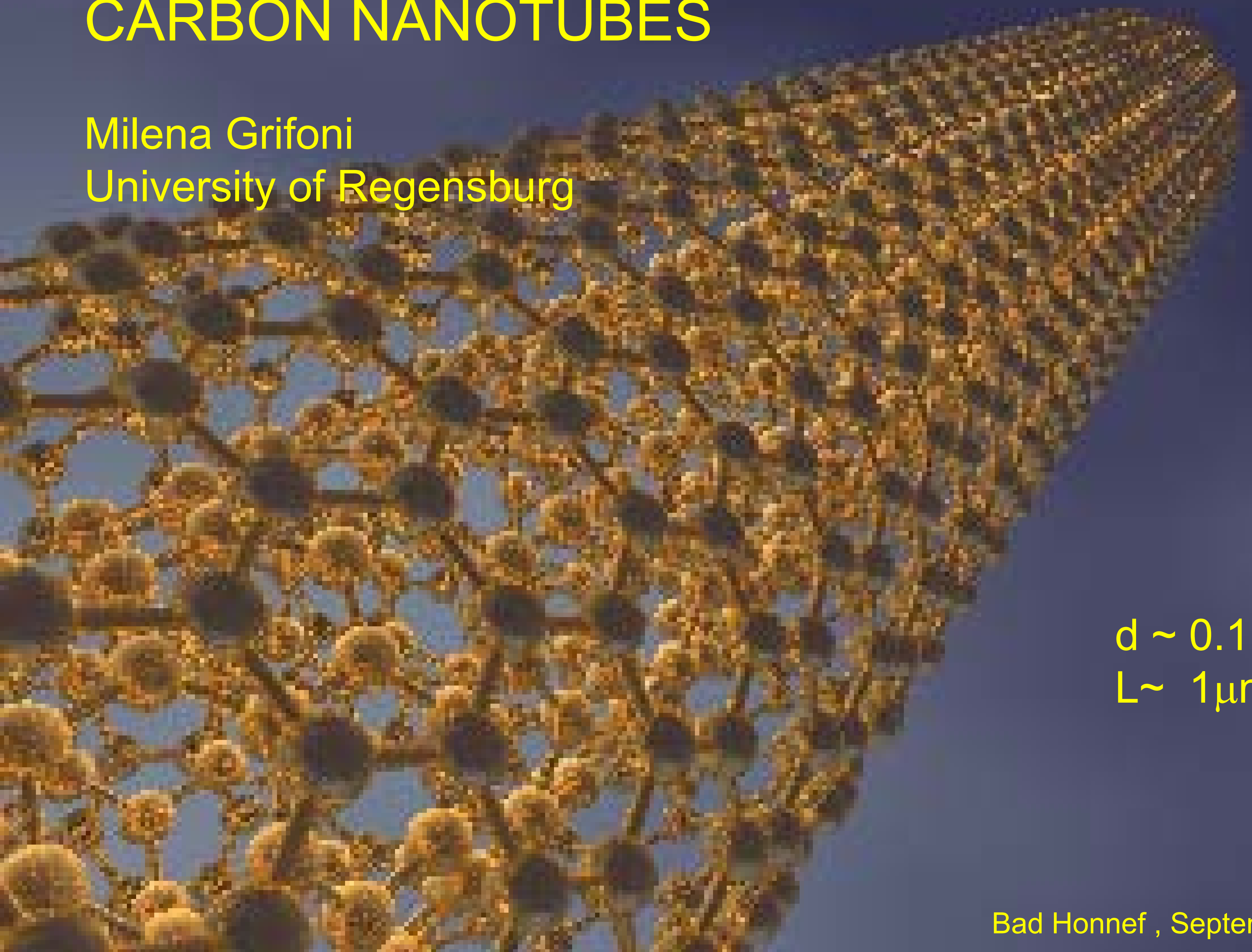
QUANTUM TRANSPORT WITH CARBON NANOTUBES

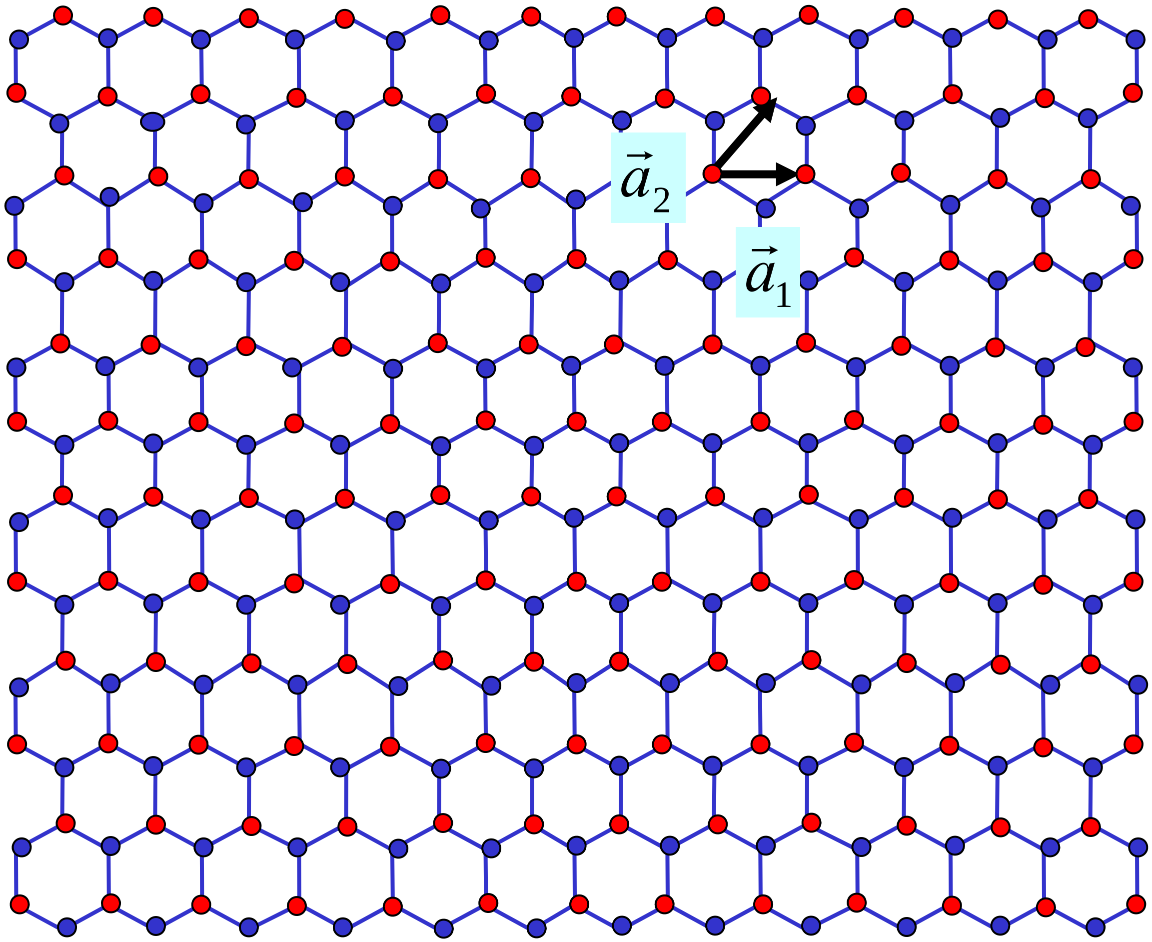
Milena Grifoni
University of Regensburg



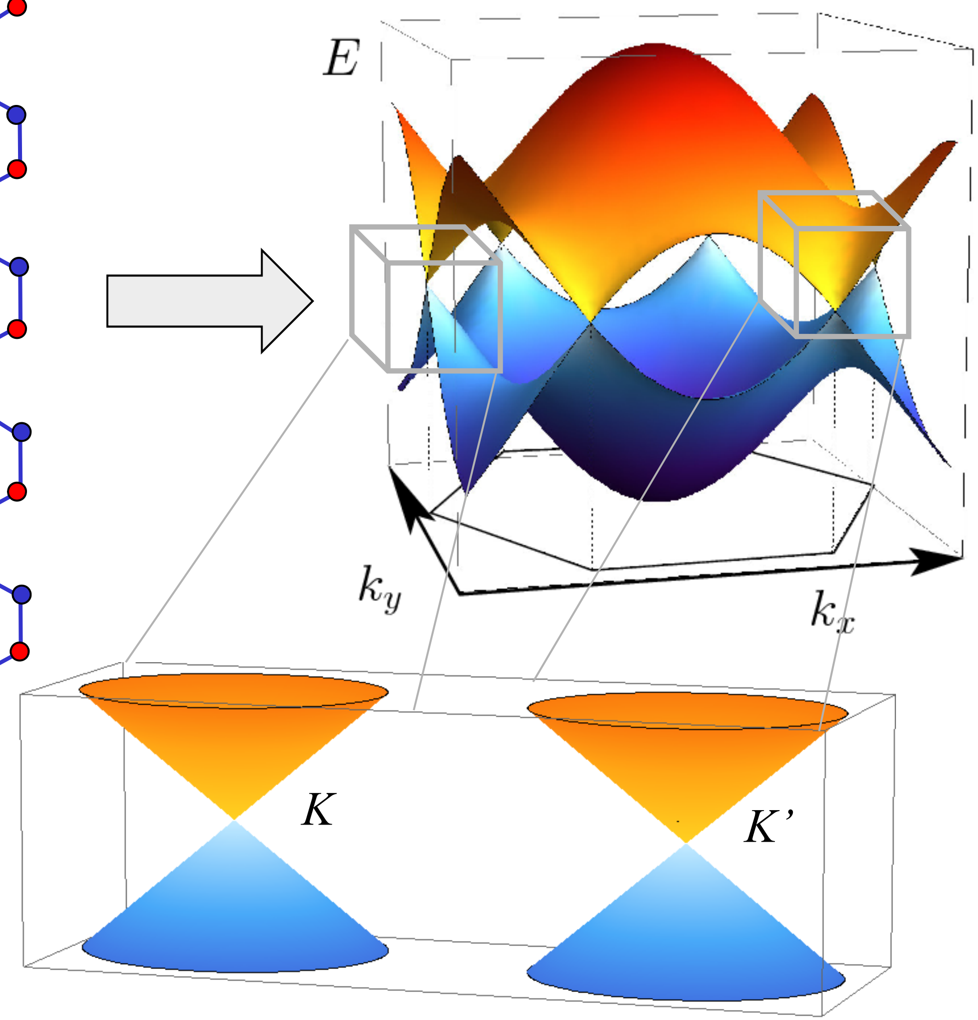
$d \sim 0.1$ nm
$L \sim 1 \mu m$

Bad Honnef , September 22, 2016

GRAPHENE



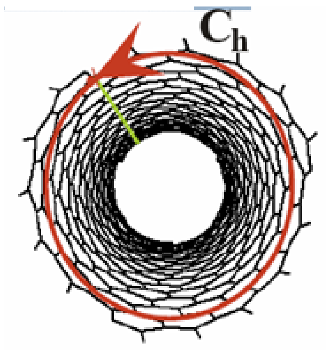
$|\vec{a}_1| = |\vec{a}_2| = a,$ a = 2.4 A°

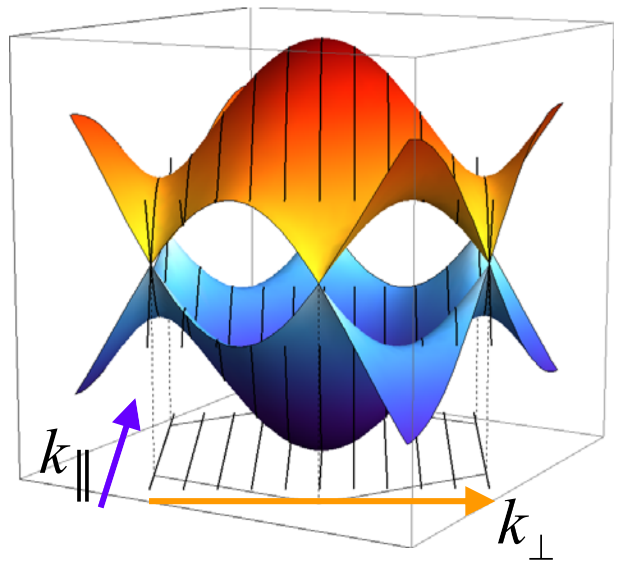


Dirac cones

TRANSVERSE CONFINEMENT

Quantization of $k_{\perp}$:



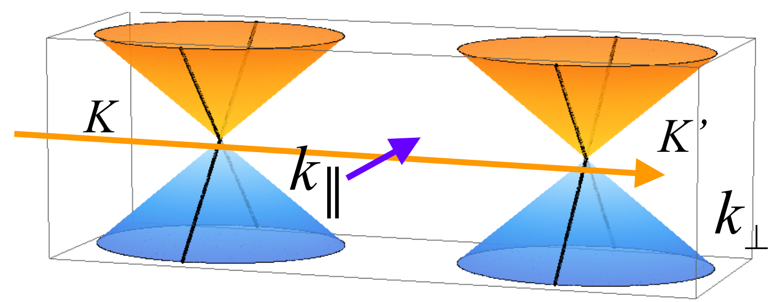


boundary condition

$C_h \cdot k_{\perp} = 2\pi l$

$\tau = +1, -1$

$\mathbf{K}' = -\mathbf{K}$



1D system with extra pseudospin degree of freedom τ

MODEL HAMILTONIAN

Rolled up Graphene

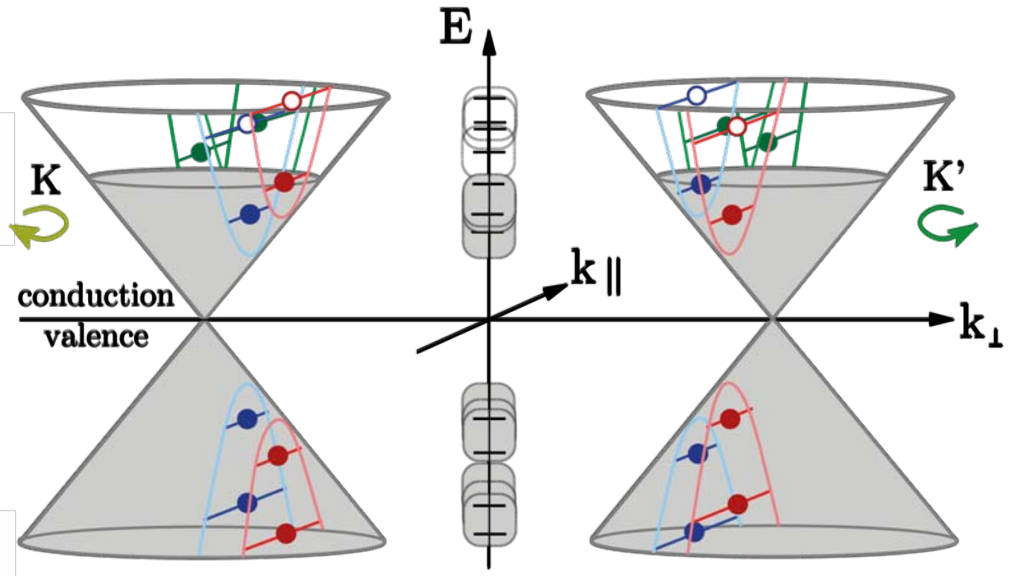
- Only lowest transverse band matters

Finite length

- Longitudinal quantization

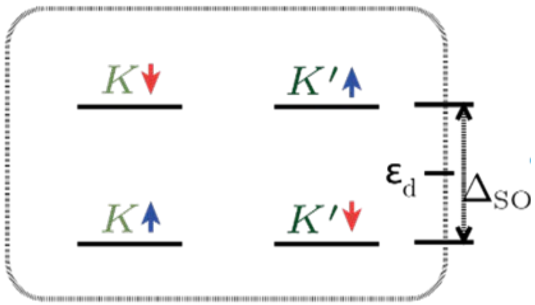
Effects of curvature

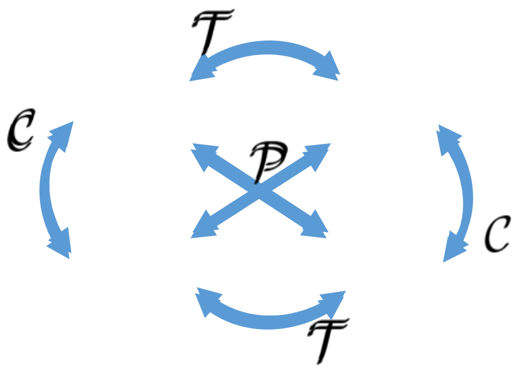
- Curvature shift and spin-orbit coupling (SOC)



Hamiltonian of one shell

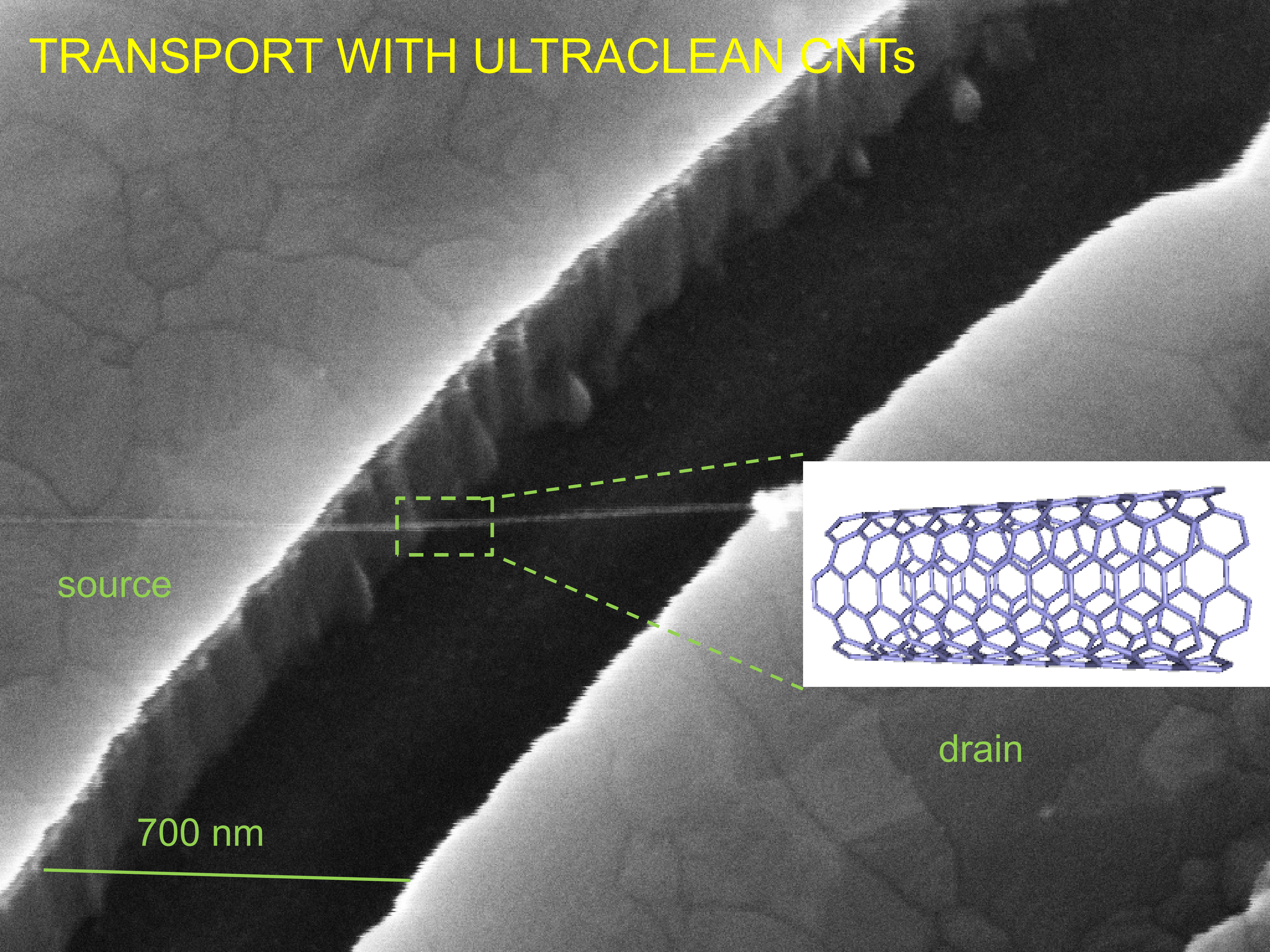
$$\hat{H}_{\mathrm{CNT}} = \hat{H}_{\mathrm{d}} + \hat{H}_{\mathrm{SO}} + \hat{H}_{\mathrm{KK'}} + \hat{H}_{B} + \hat{H}_{U} + \hat{H}_{J}$$



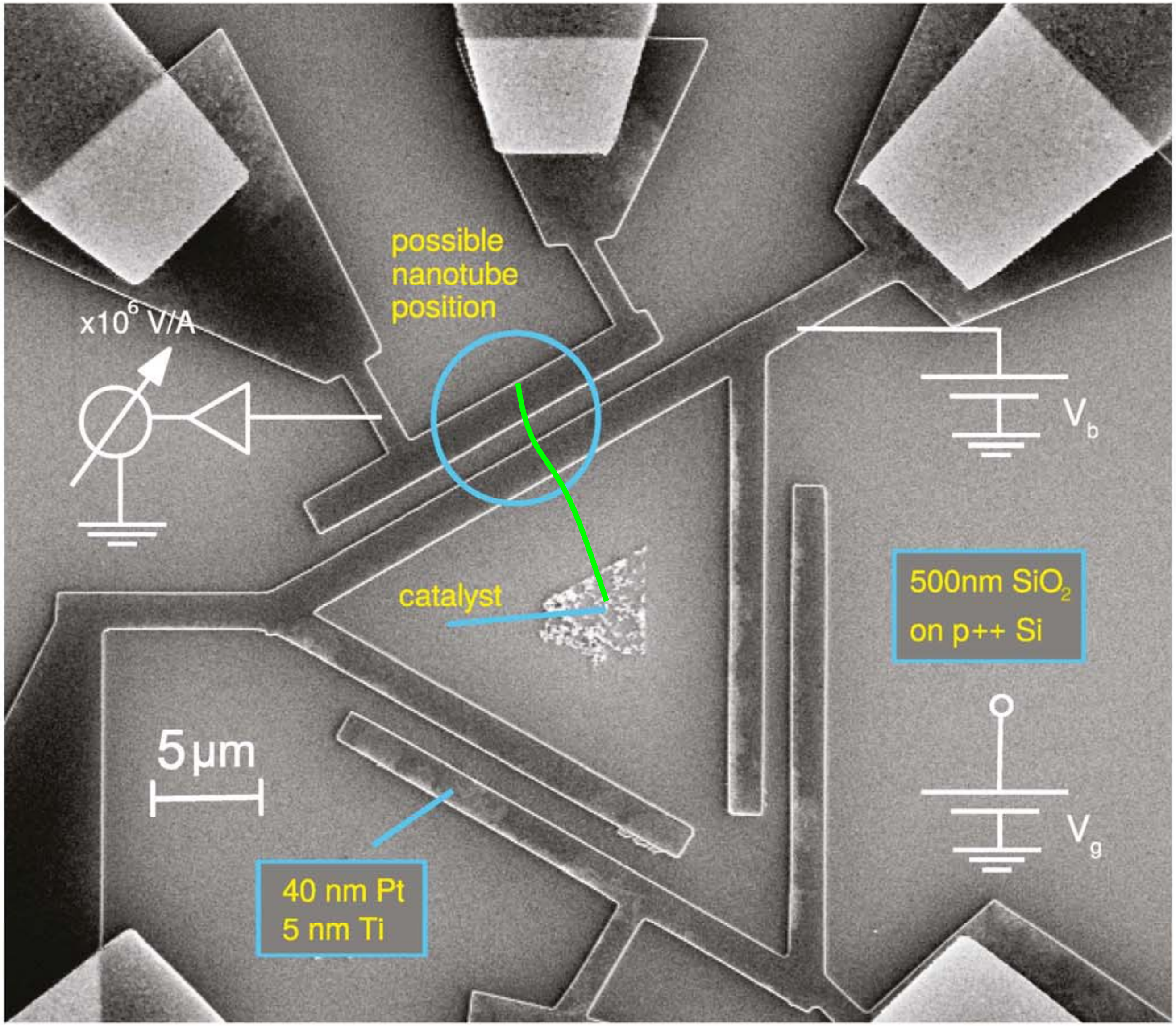


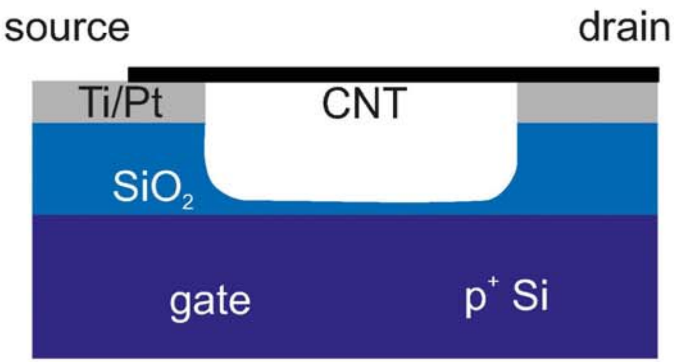
$$= \sqrt{\Delta_{\mathrm{SO}}^2 + \Delta_{\mathrm{KK'}}^2}$$

TRANSPORT WITH ULTRACLEAN CNTs



FABRICATION OF ULTRACLEAN CNTs

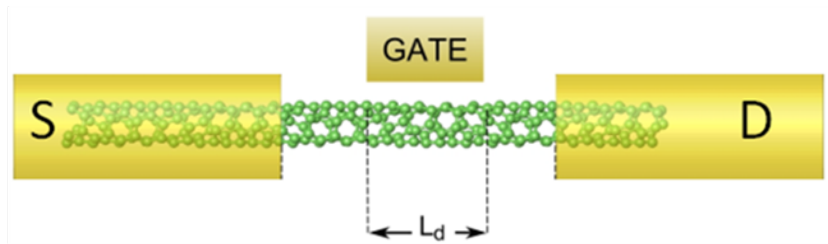




- CVD overgrowth as last step of fabrication
- working samples identified only by electrical measurements
- ballistic transport

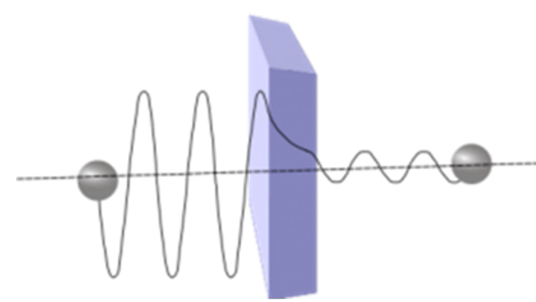
Courtesy of C. Strunk and A. Hüttel, UR

TRANSPORT IN CARBON NANOTUBES



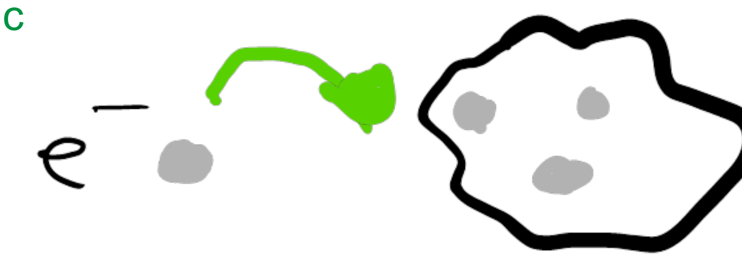
Transport regimes determined by three energy scales:

Temperature, T

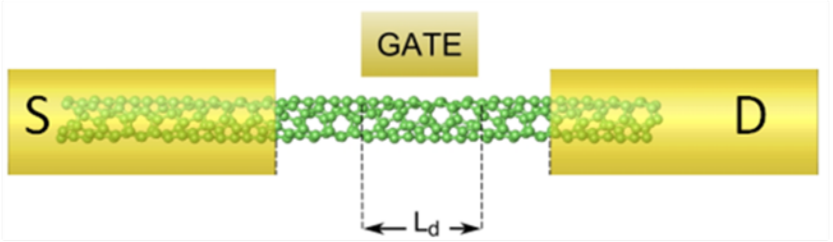


Tunnel coupling, Γ

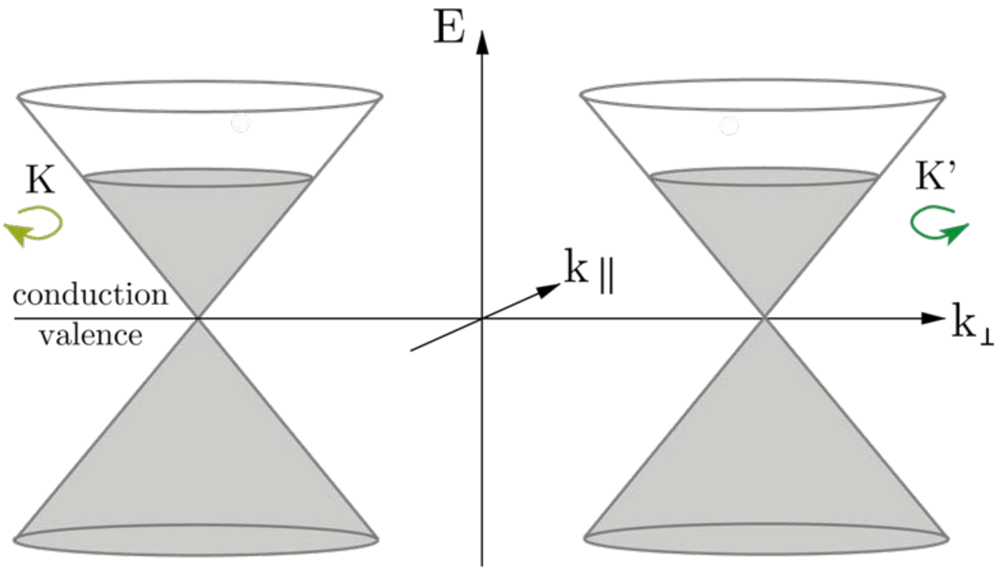
Charging energy, E_c



TRANSPORT IN CARBON NANOTUBES

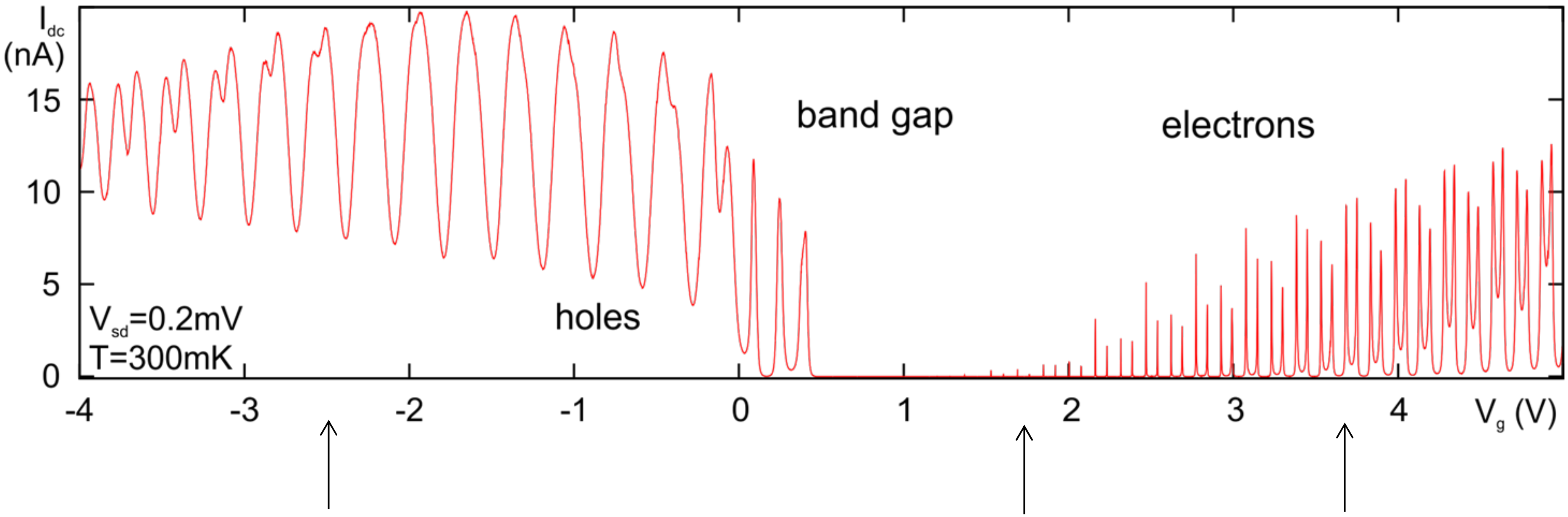


The gate voltage determines the electronic density in the CNT:



It changes the electrostatic profile and hence $E_c(V_g)$

TRANSPORT IN CARBON NANOTUBES



Fabry-Perot

$E_c, T \ll \Gamma$

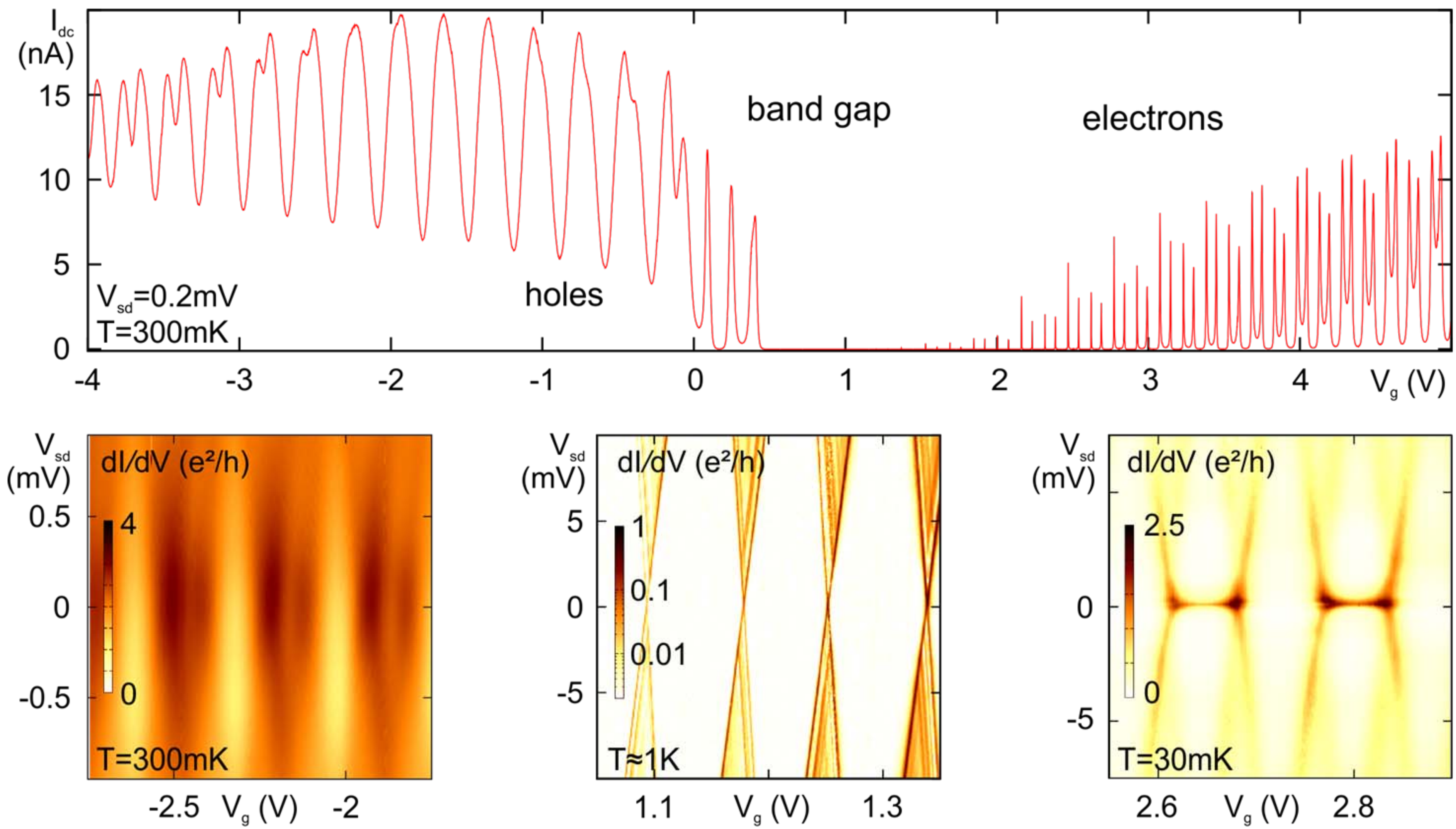
Coulomb blockade

$\Gamma < T \ll E_c$

Kondo

$T < \Gamma \ll E_c$

TRANSPORT IN CARBON NANOTUBES

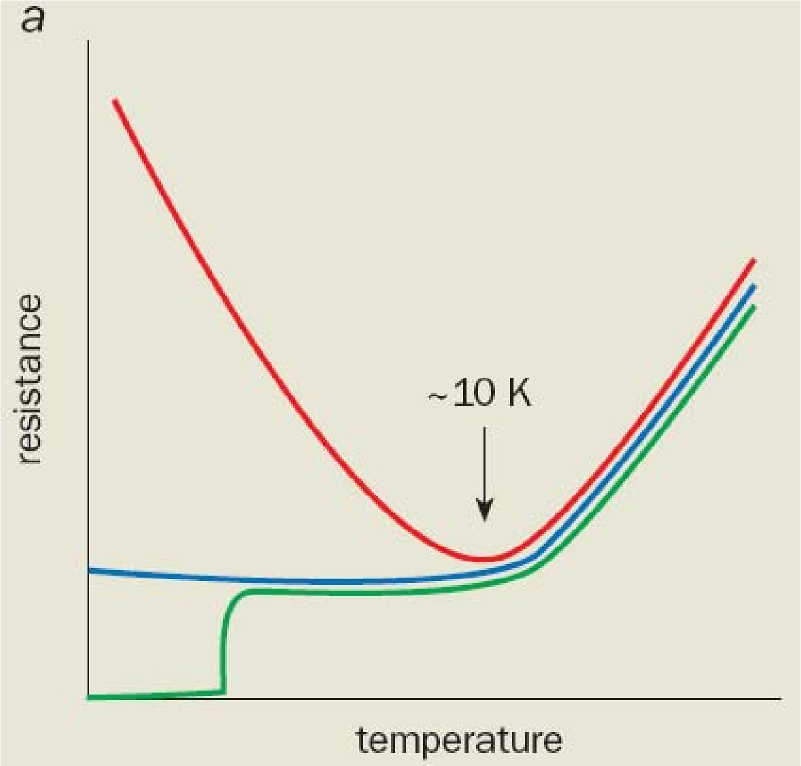


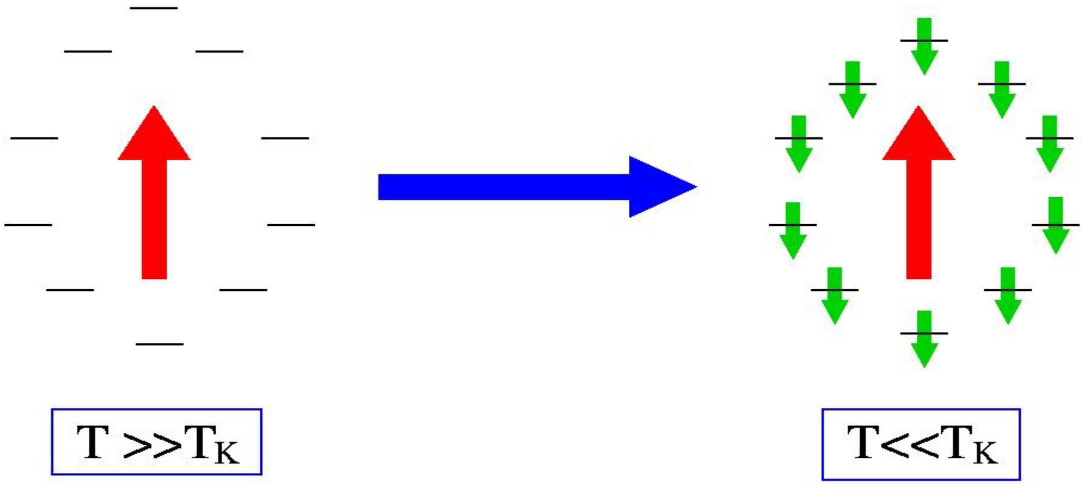
Fabry-Perot | Coulomb blockade | Kondo

$E_c, T \ll \Gamma$ | $\Gamma < T \ll E_c$ | $T < \Gamma \ll E_c$

KONDO EFFECT

Anomalous resistance of metals with magnetic impurities

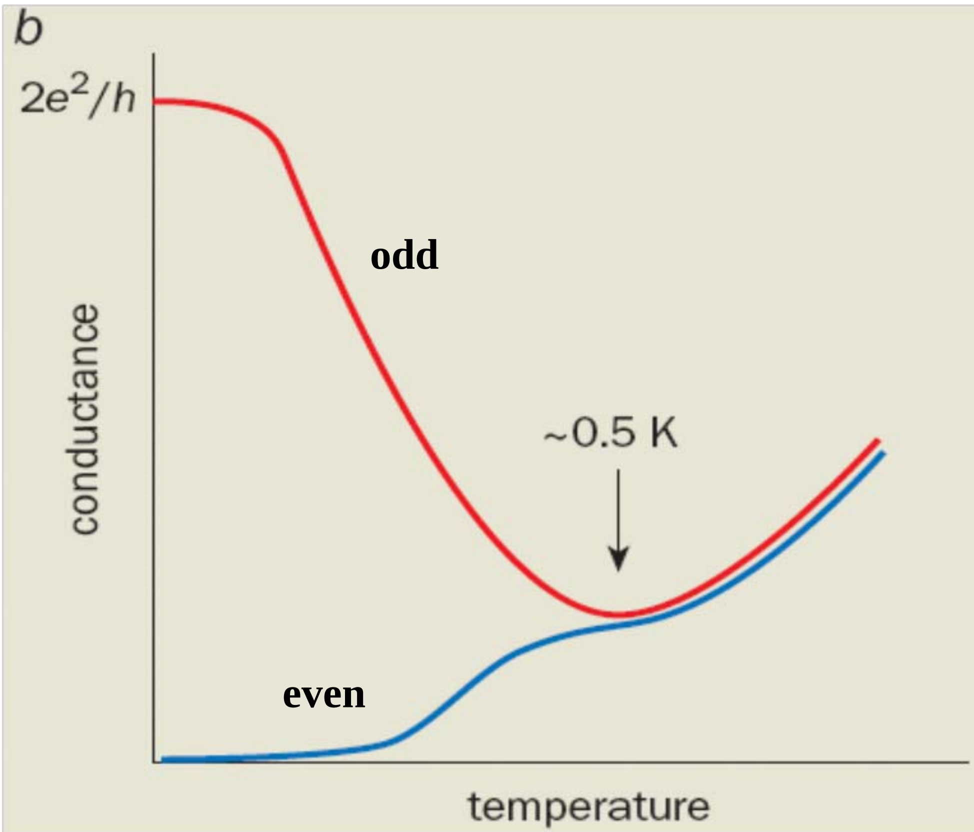


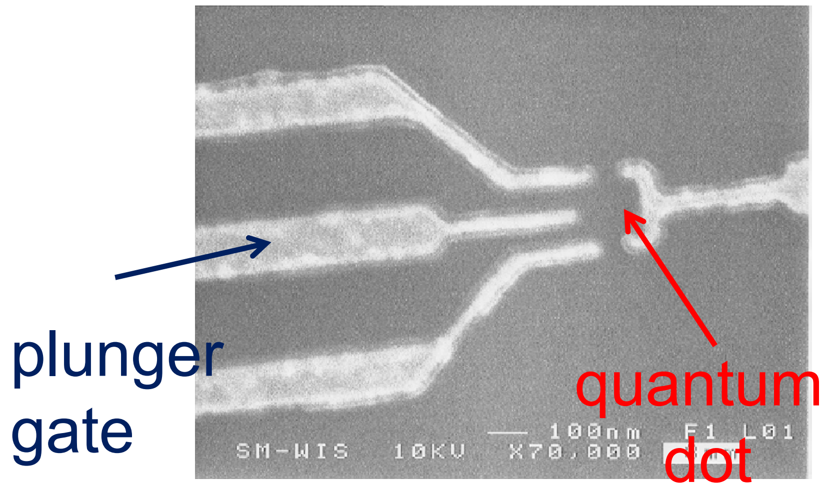


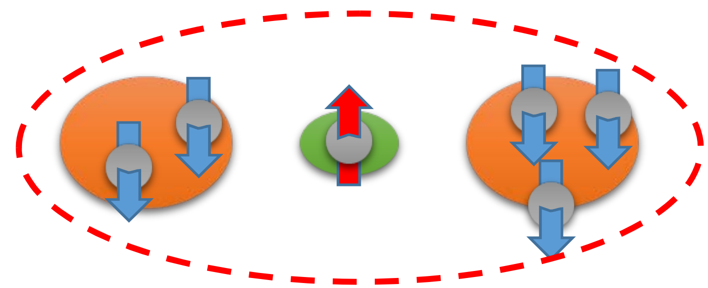
- Below T_K impurity spin is progressively screened
- Universal scaling with T/T_K for $T<T_K$

Kouwenhoven and Glazman, Physics World (2001)

KONDO EFFECT IN QUANTUM DOTS





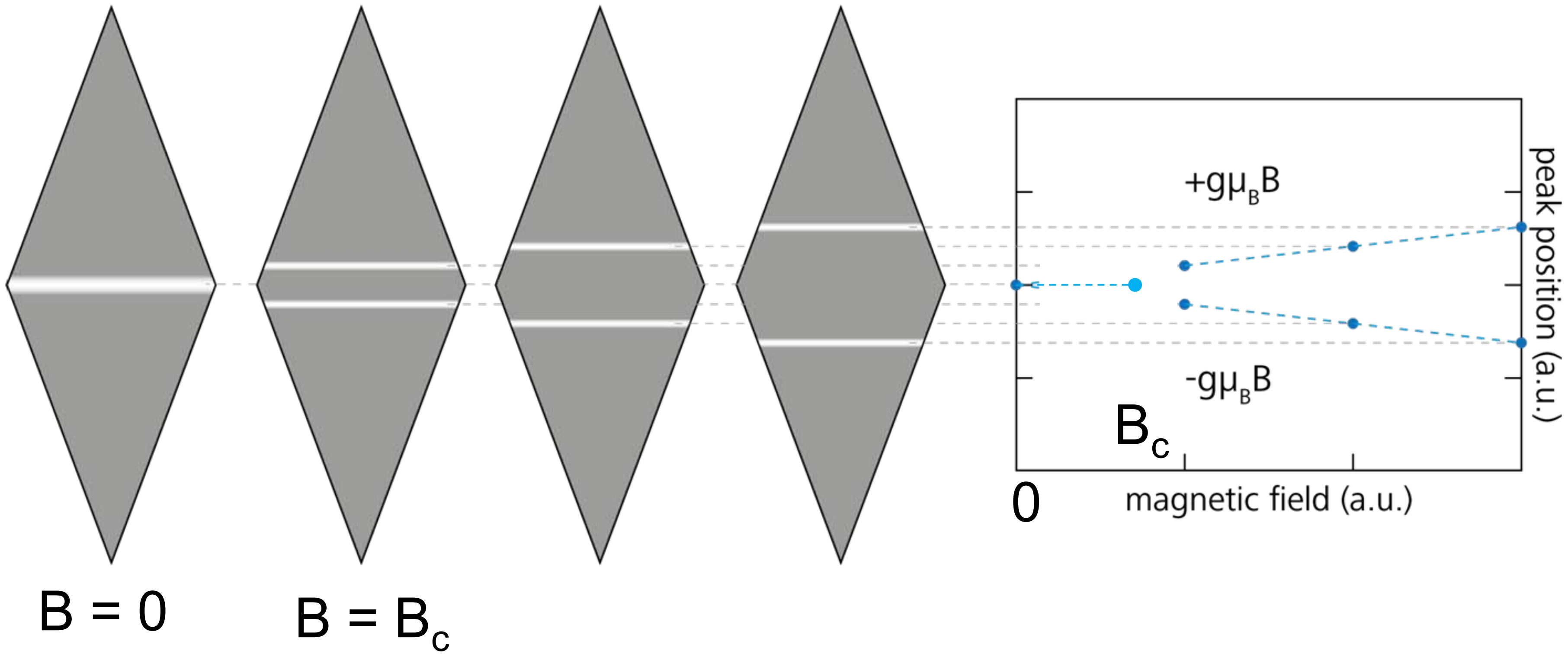


SINGLET GROUNDSTATE

Kouwenhoven and Glazman, Physics World (2001)

$$[H, S] = 0$$

MAGNETOSPECTROSCOPY



see e.g. Kretinin et al., PRB **85**, 201301 (2012)

- spin degeneracy of state on the QD lifted by Zeeman energy
- central resonance peak splits above B_c
  with linear split at large fields
- absence of elastic line signals that GS is a singlet !!!

KONDO EFFECT s=1/2 LEVEL

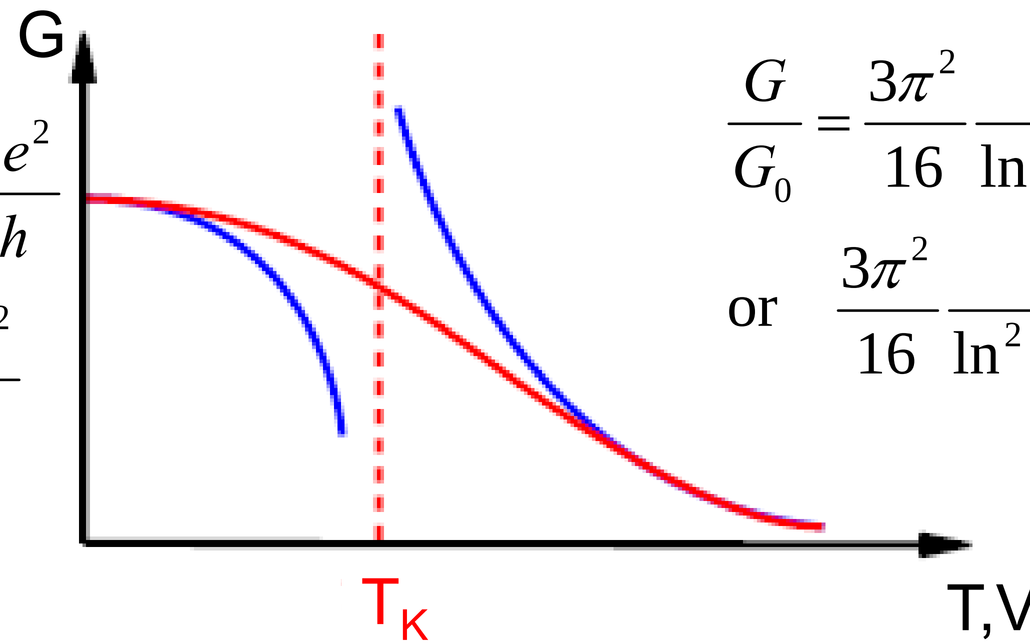
Low T, V

Fermi liquid behavior
(Nozieres, Yosida and Yamada)

$$G_0 = \frac{2e^2}{h}$$

$$\frac{G}{G_0} = 1 - \frac{c_T T^2 + c_V (eV/k)^2}{T_K^2}$$

universal c_V/c_T



High T ,V

Perturbative regime
(Anderson, Hamann)

$$\frac{G}{G_0} = \frac{3\pi^2}{16} \frac{1}{\ln^2(T/T_K)}$$

or $$\frac{3\pi^2}{16} \frac{1}{\ln^2(eV/kT_K)}$$

Keldysh effective action (KEA) theory
→ analytic tunneling DOS in the whole regime of parameters

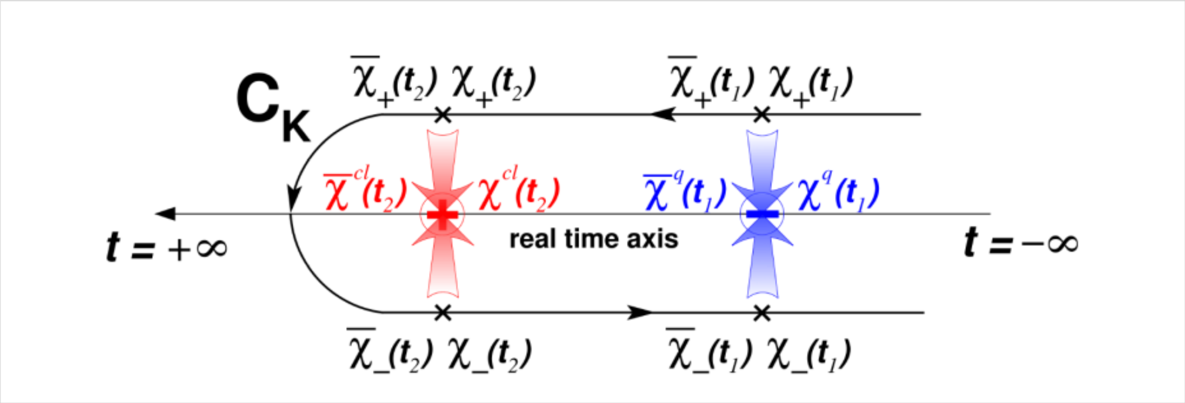
Smirnov and Grifoni, PRB **87**, R121302 (2013)

KEA METHOD

- Consider very large U → single occupancy
- Perform slave-boson transformation to diagonalize H_{CNT} (but not H_T):

$$d_i = b^+ p_i, \quad d_i^+ = b p_i^+$$

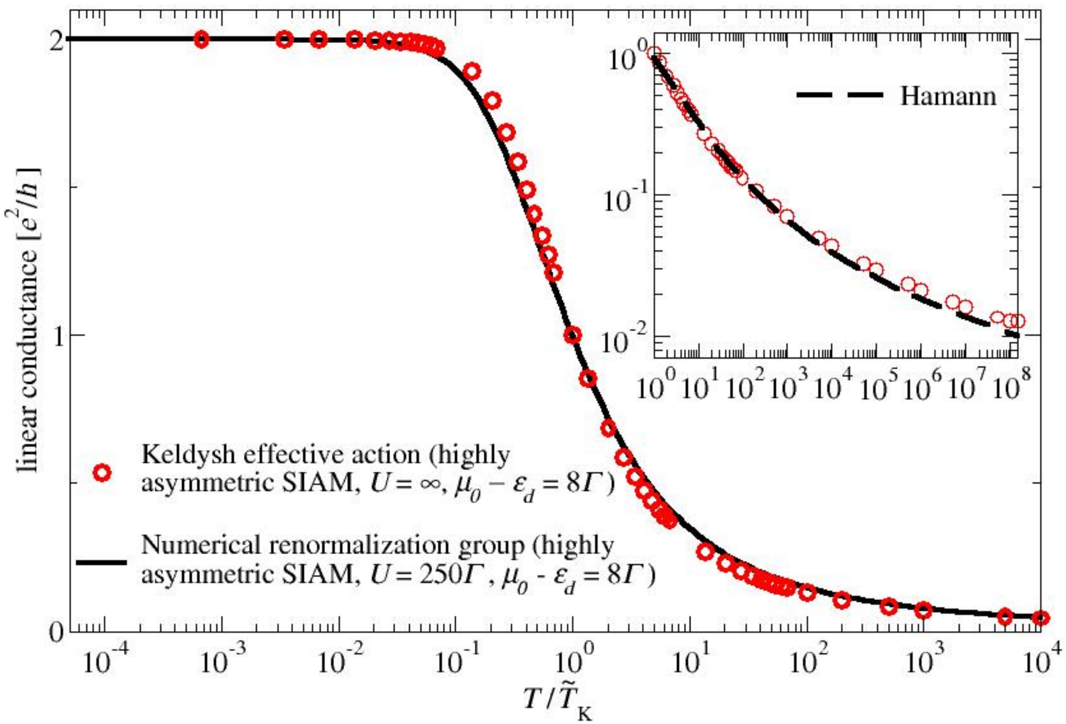
- Use field-integral representation of H to evaluate the expectation value of any observable $O=F(d^+,d)$ on C_K

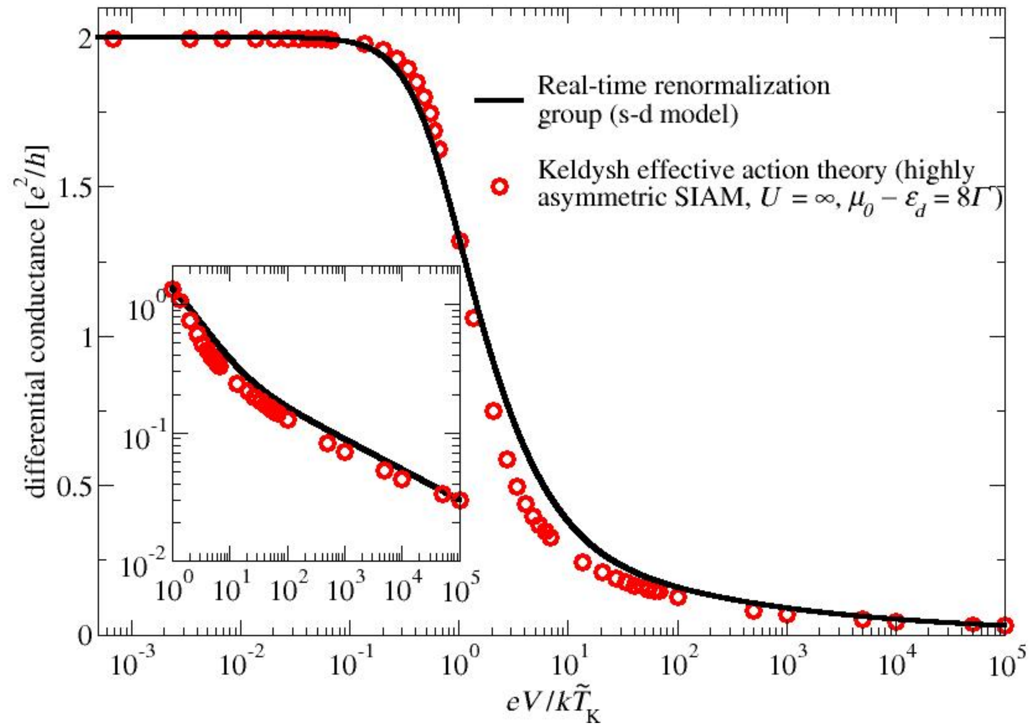


$$\langle O \rangle(t) = \frac{1}{N} \lim_{\mu\to\infty} e^{\beta\mu} \int D[\overline{\chi}, \chi] e^{\frac{i}{\hbar} S_{eff}[\overline{\chi}^{cl,q}, \chi^{cl,q}]} F[\overline{\chi}^{cl,q}, \chi^{cl,q}]$$

- Expand the tunneling part of S_{eff} to second order around expansion points γ_i and δ_i

KONDO EFFECT s=1/2 LEVEL





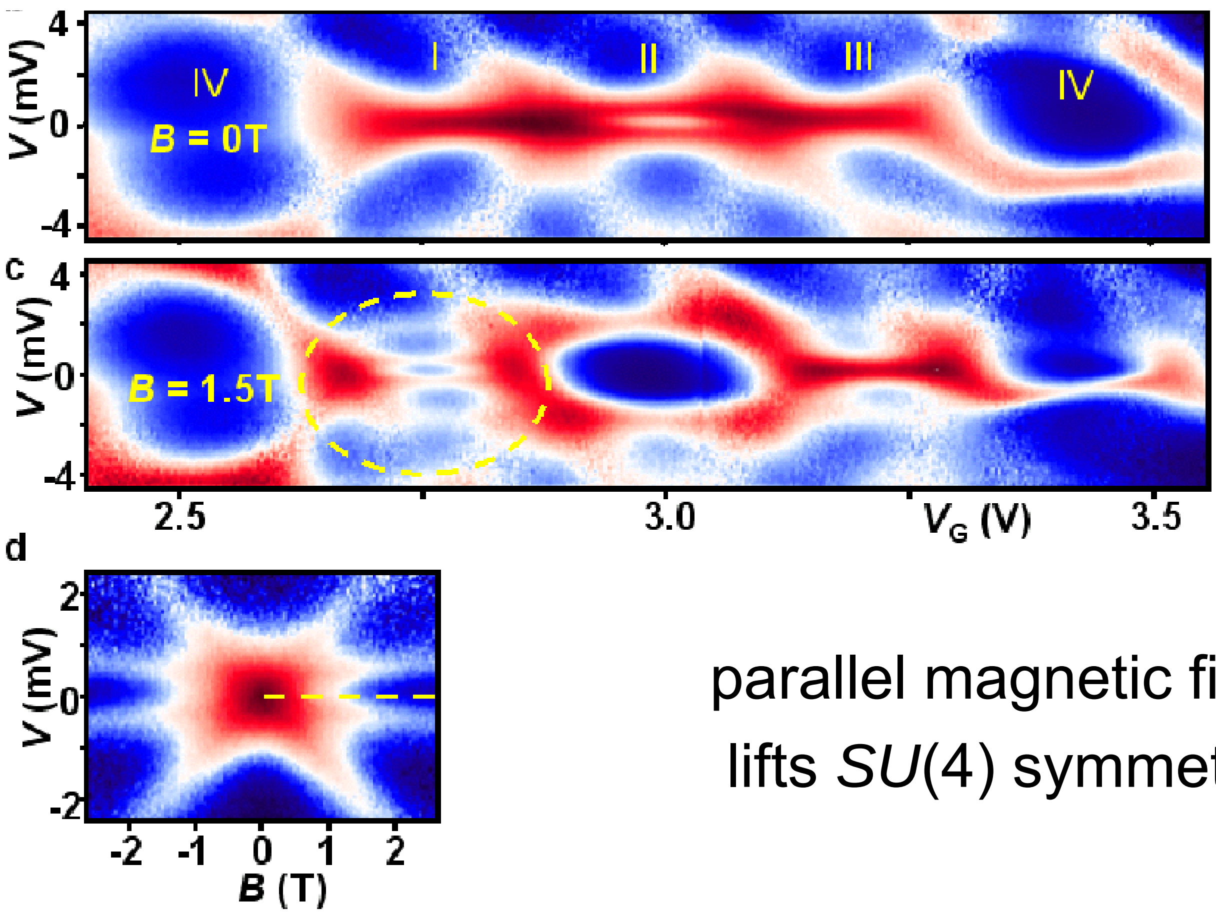
Keldysh effective action theory

→ analytic tunneling DOS in the whole regime of parameters

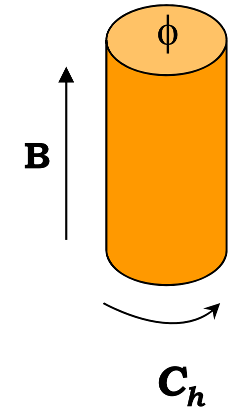
Smirnov and Grifoni, PRB **87**, R121302 (2013)

SU(4) KONDO PHENOMENA IN CNTs

four-fold nature of CNT shells allows for *SU*(4) Kondo when $T_K >> \Delta$



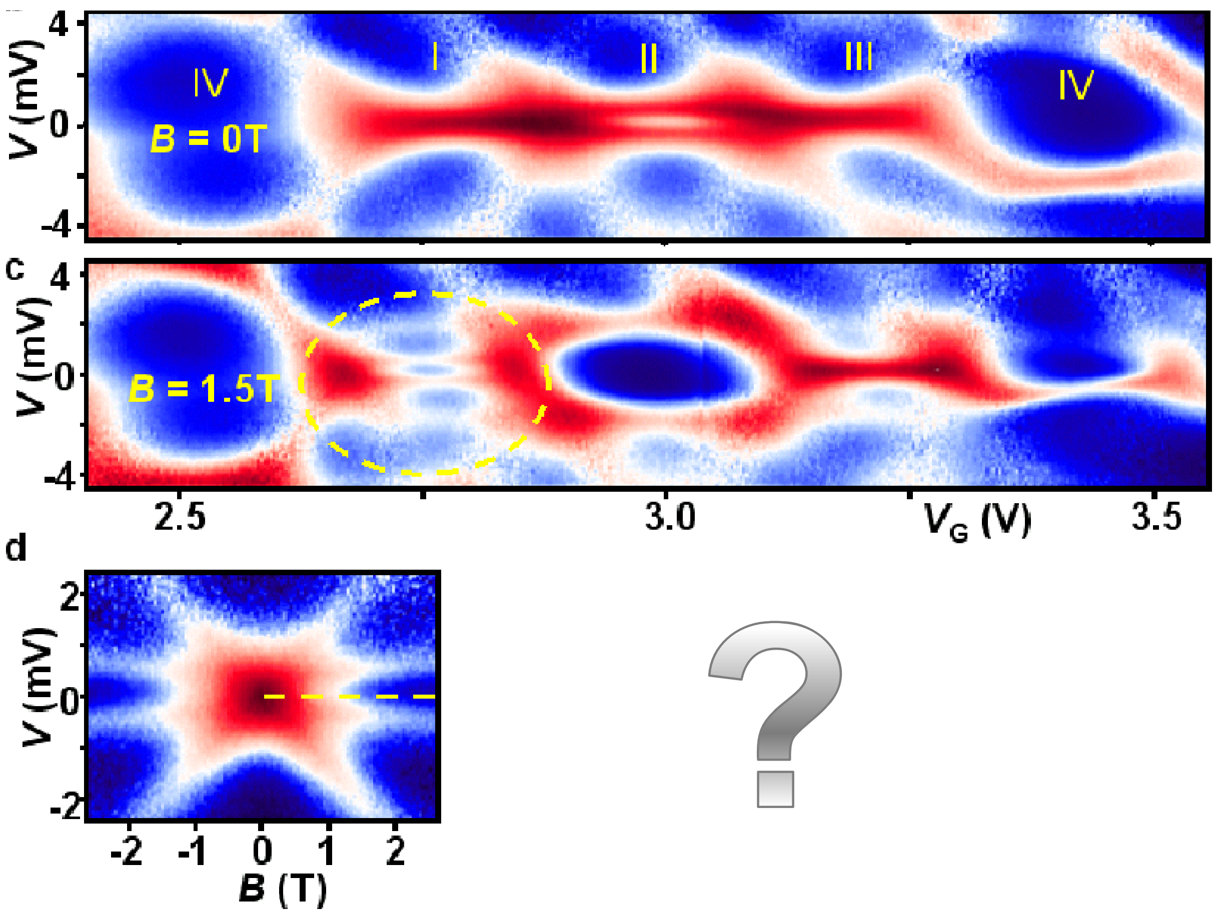
parallel magnetic field
lifts *SU*(4) symmetry

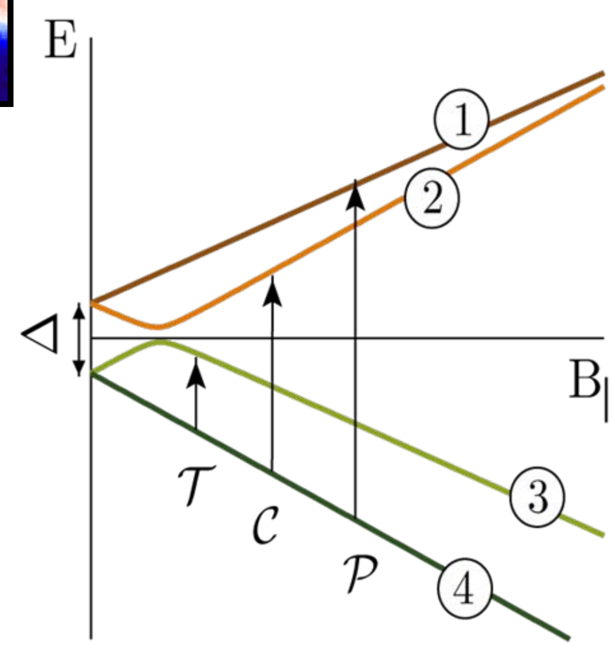


Jarillo-Herrero et al. Nature **434**, 484 (2005)

SU(4) KONDO PHENOMENA IN CNTs

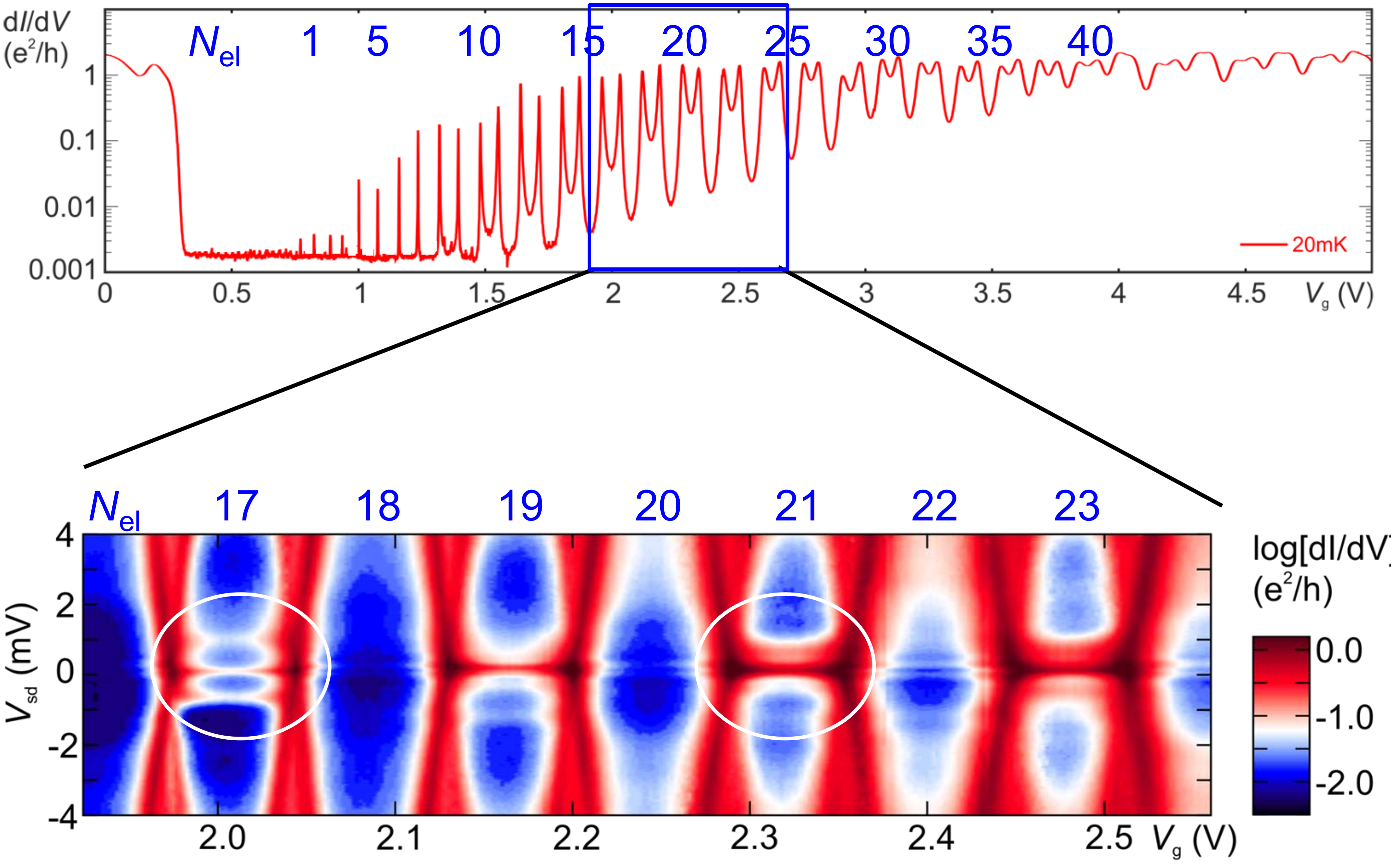
four-fold degeneracy of CNT shells allows for *SU*(4) Kondo when $T_K >> \Delta$





Jarillo-Herrero et al. Nature **434**, 484 (2005)

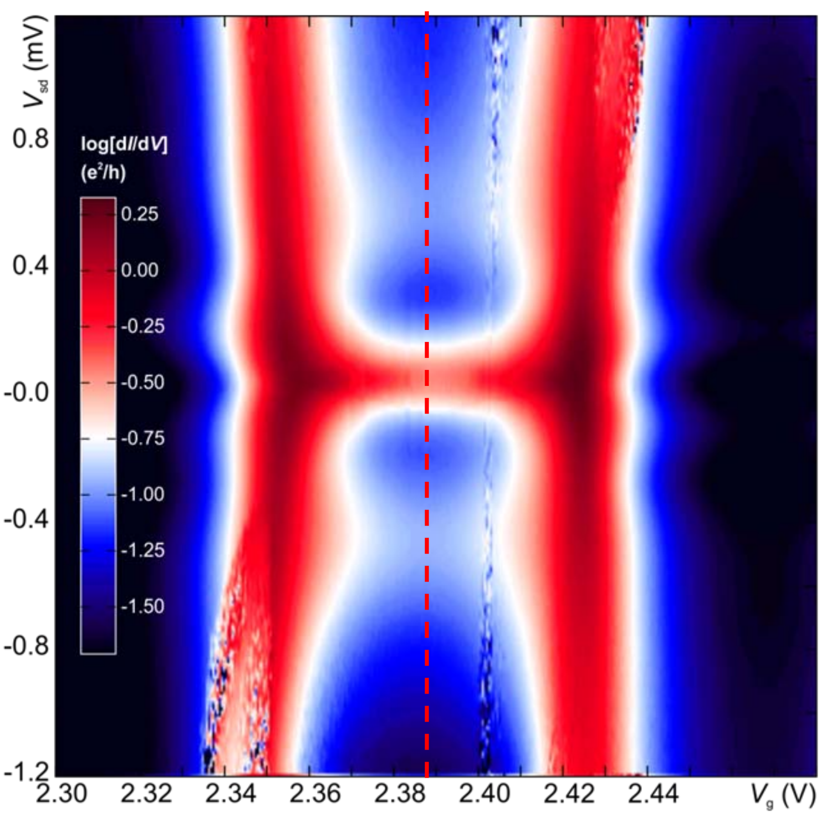
KONDO EFFECT WITH BROKEN SU(4)

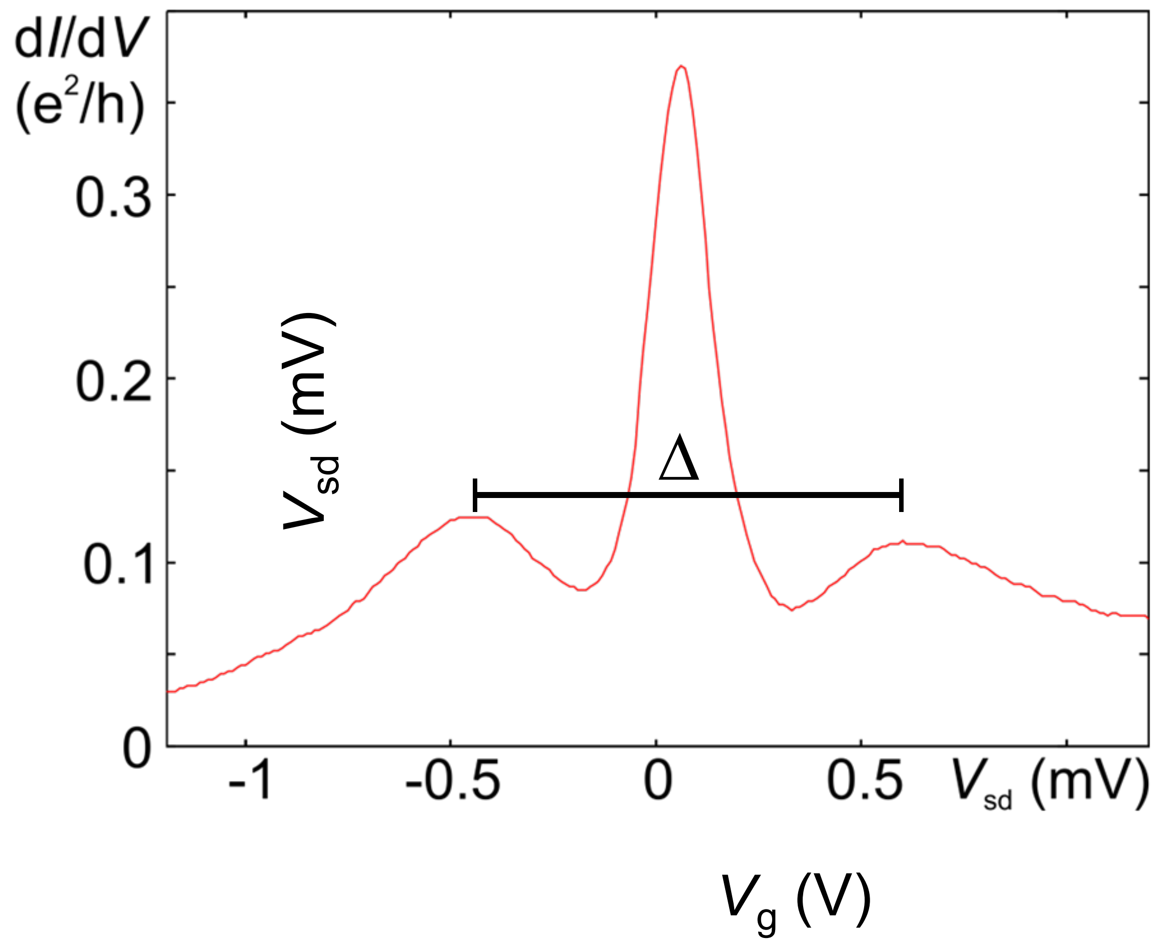


KONDO EFFECT WITH BROKEN SU(4)

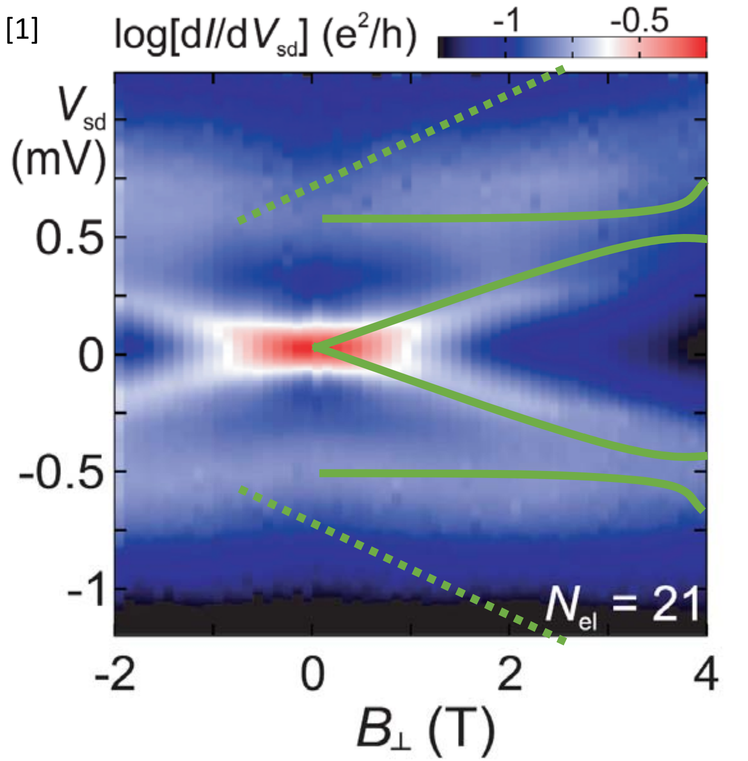
- sharp Kondo ridge at $V_{sd} \approx 0$mV
- broad satellites at $V_{sd} \approx \pm\ 0.5$mV

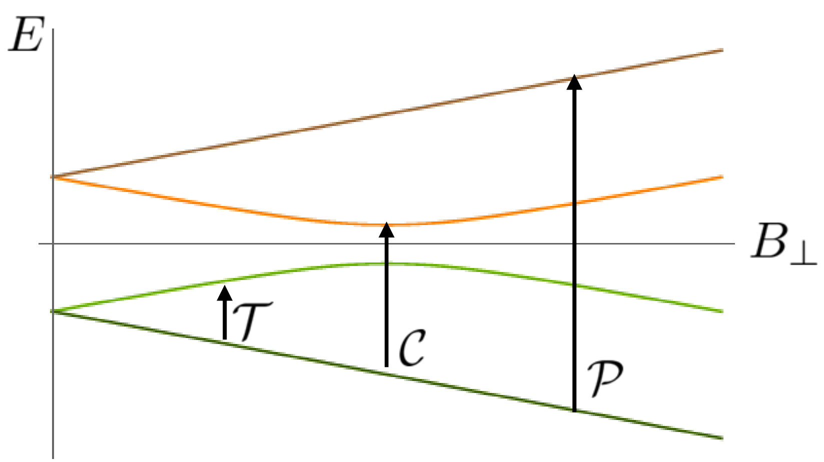
$N_{el} = 21$

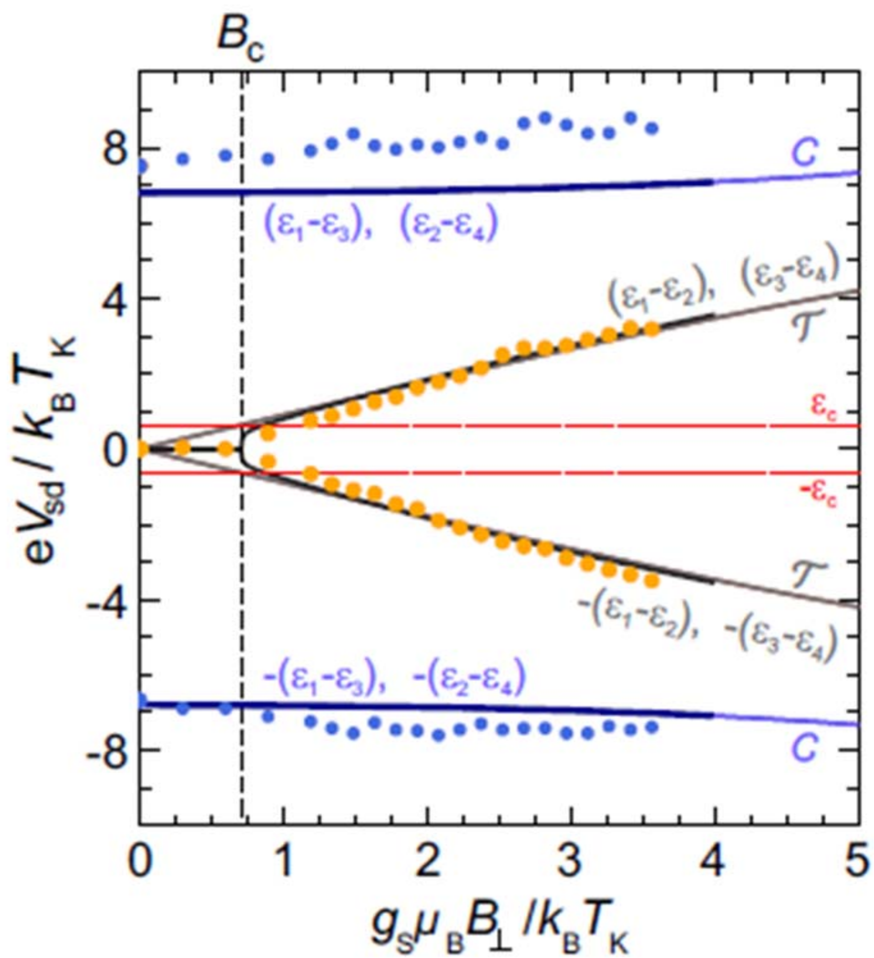




MAGNETOSPECTRUM





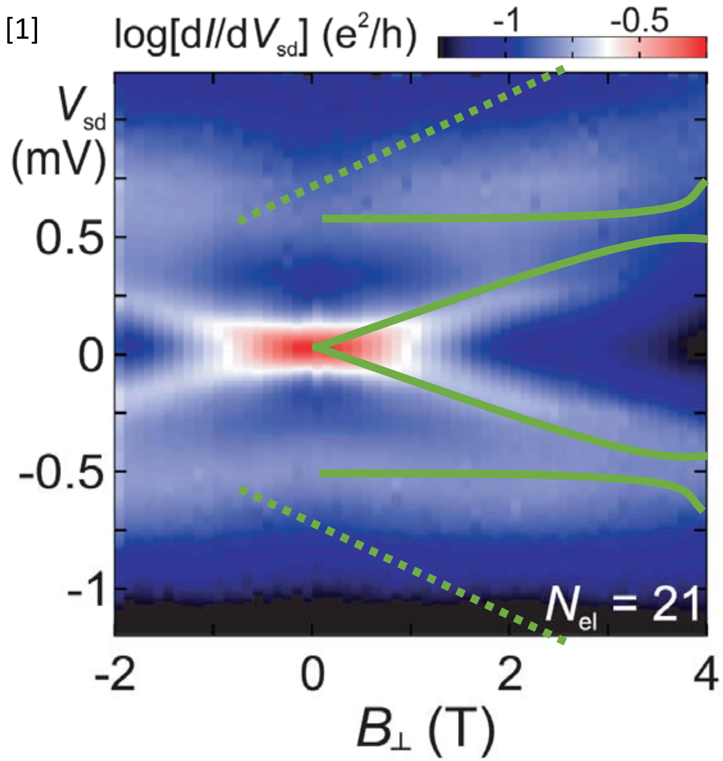


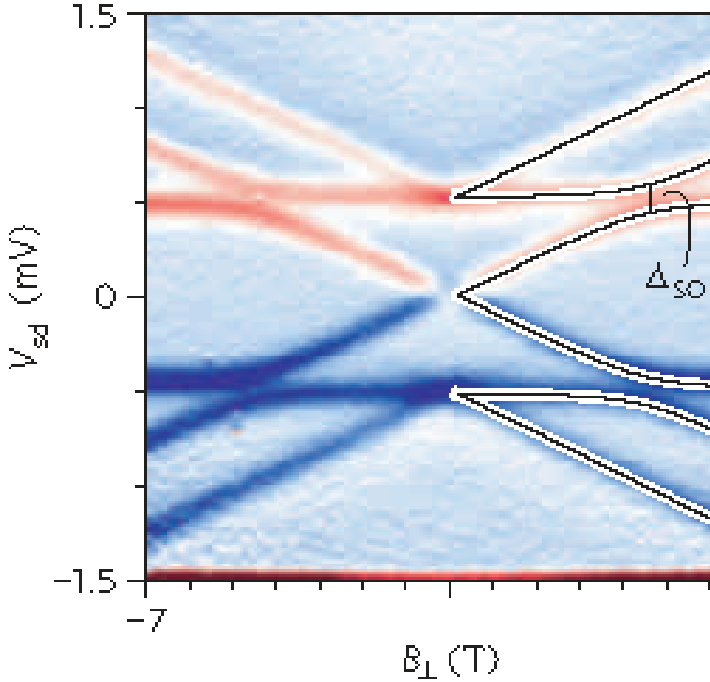
Kondo spectrum

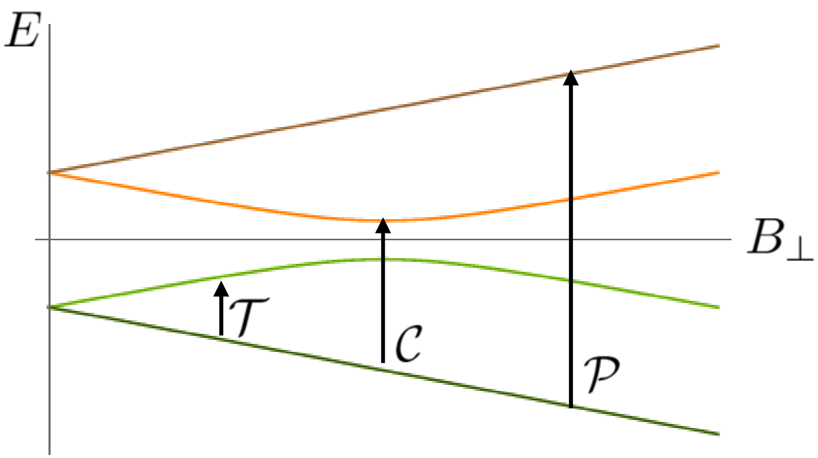
- P lines missing

[1] D. R. Schmid et al., PRB **91**, 155435 (2015)

STRONG vs. WEAK COUPLING







[2] T. S. Jespersen et al., Nature Physics **7**, 348 (2011)

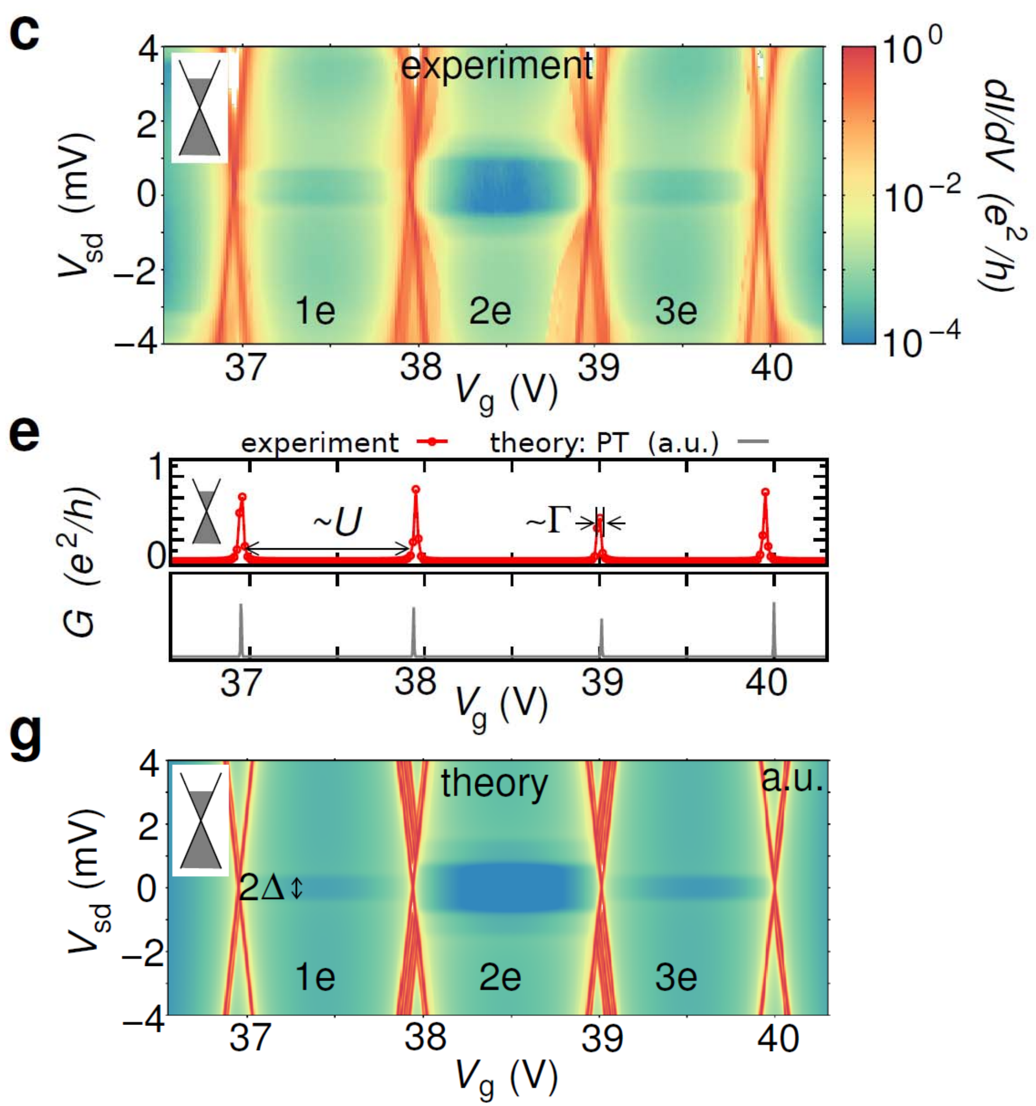
Cotunneling spectrum

- All expected lines appear ???

[1] D. R. Schmid et al., PRB **91**, 155435 (2015)

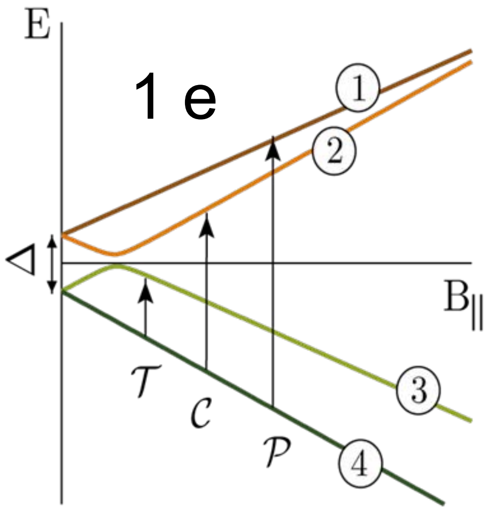
COTUNNELING vs. KONDO

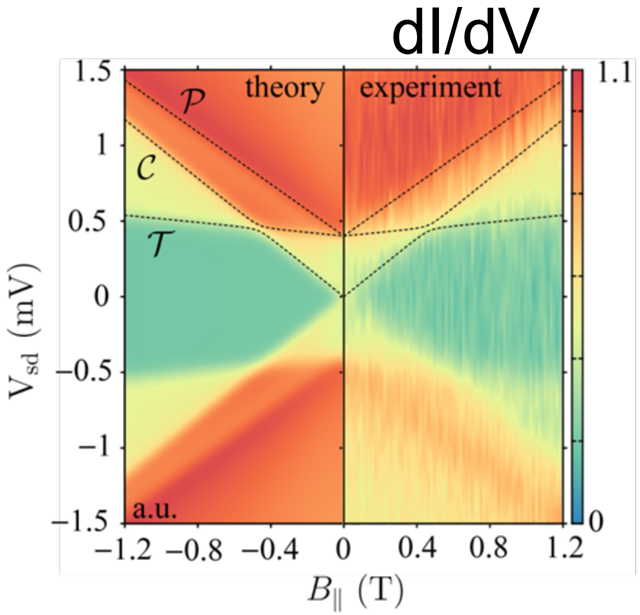
Check the two regimes on the same CNT …

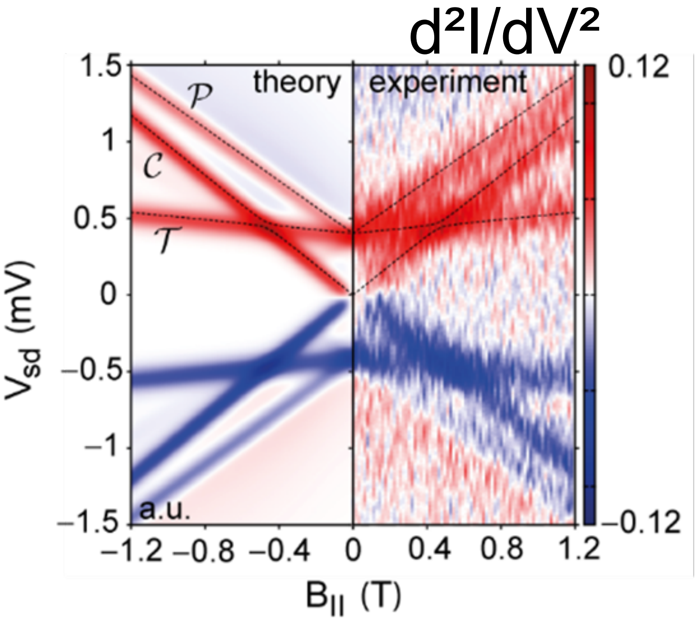


with Jean-Pierre Cleuziou @CEA Grenoble

COTUNNELING





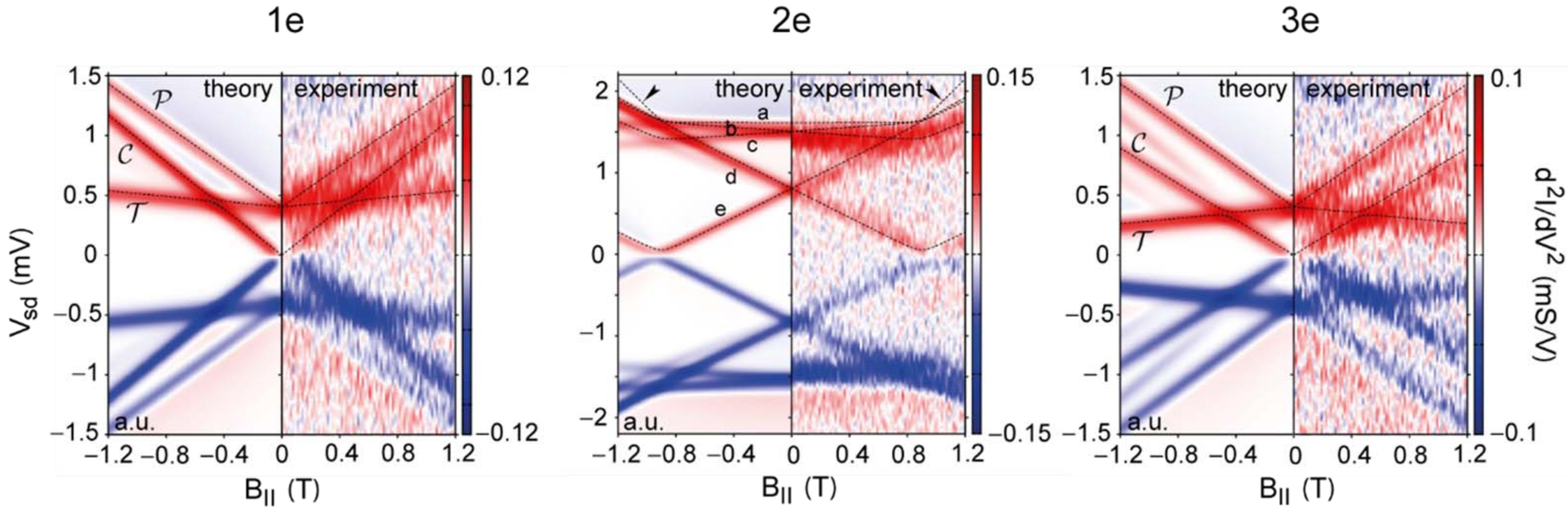


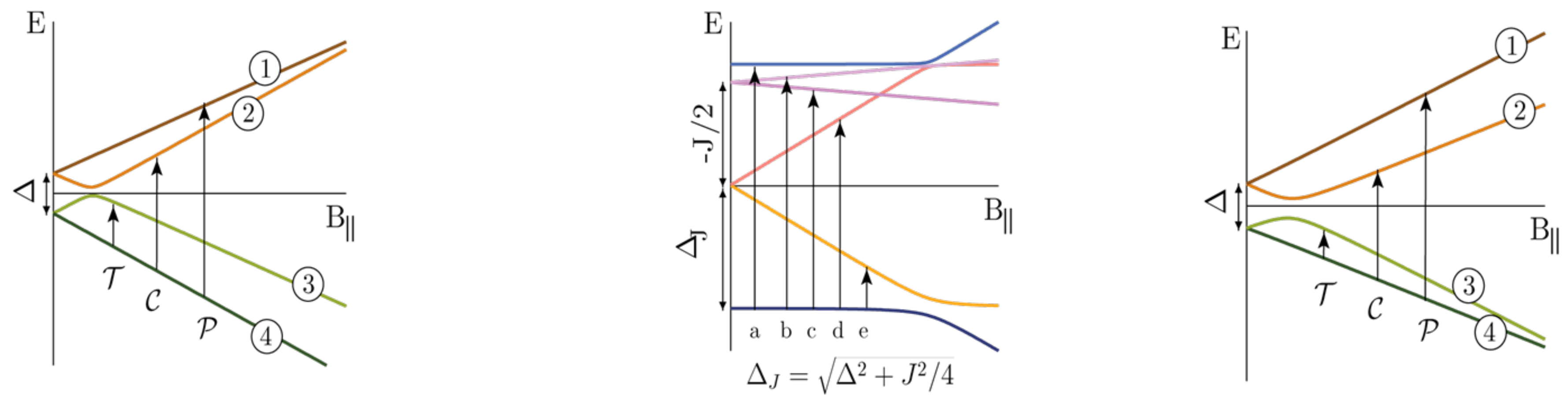
All transition lines appear in the cotunneling excitation spectrum

Method: PT up to second order in Γ [1]

[1] Koller, S. et al., Phys. Rev. B **82**, 235307 (2010)

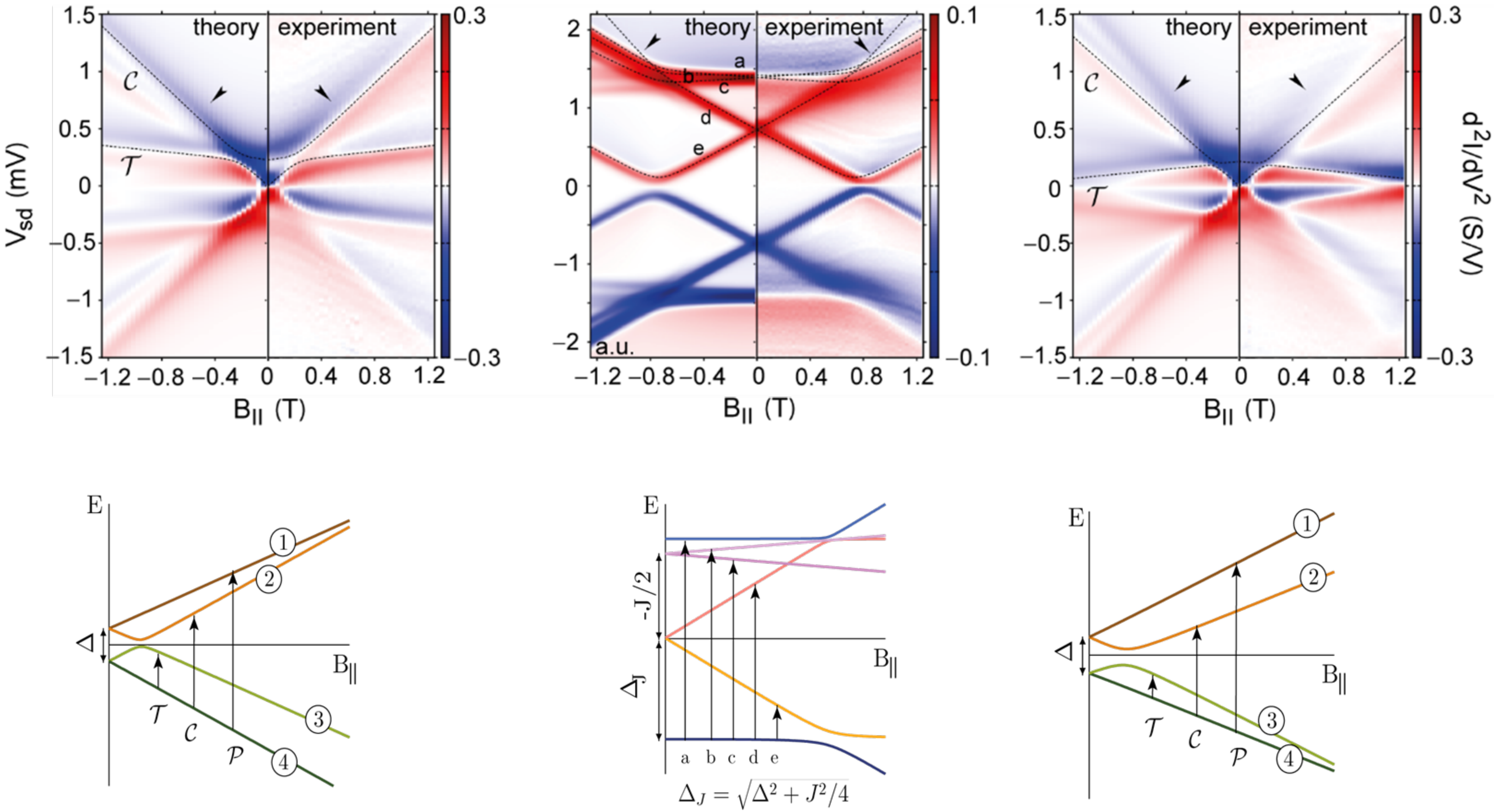
COTUNNELING





KONDO

3h 2h 1h



Only T,C lines appear in the Kondo excitation spectrum

KRAMERS PSEUDOSPINS

Extend the single level Anderson model to the CNT model:
Define charge- and spin like operators for CNT (and leads)

$$\hat{Q}_\kappa = \frac{1}{2}\sum_{j\in\kappa}(\hat{n}_j - \frac{1}{2})$$

Charge conservation in each Kramers pair

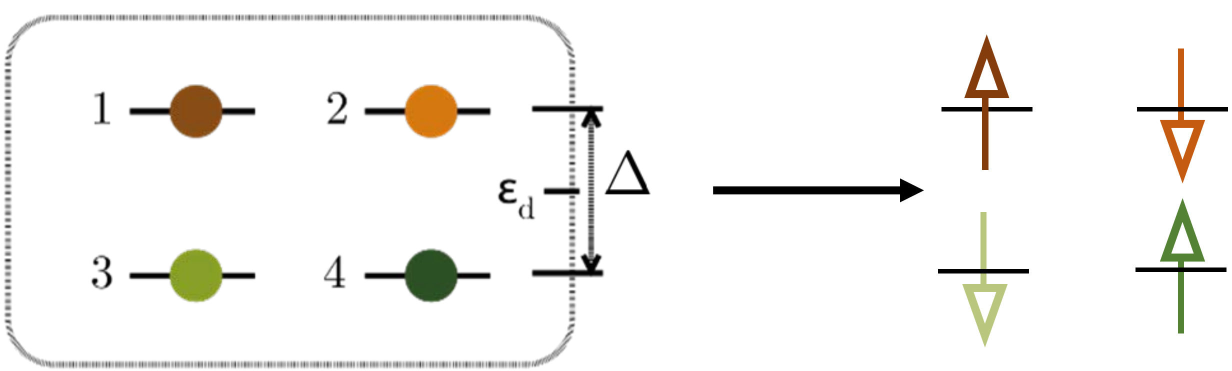
$$\kappa \in u, d$$

$$\hat{\vec{J}}_\kappa = \frac{1}{2}\sum_{jj'\in\kappa} \hat{d}_j^\dagger \vec{\sigma}_{jj'} \hat{d}_{j'}$$

e.g. charge unbalance within a Kramers pair

$$\hat{J}_d^z = \frac{1}{2}(\hat{n}_4 - \hat{n}_3)$$

Kramers pseudo spin

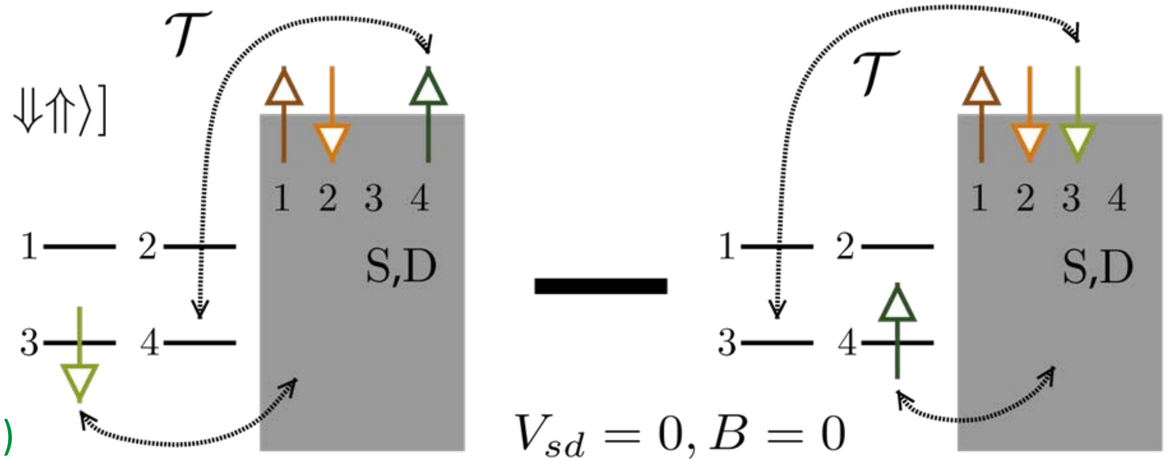


KRAMERS PSEUDOSPINS

- Use DM-NRG to compute ground state → singlet!

$$\frac{1}{\sqrt{2}}\left[|\Uparrow,-\rangle \otimes |\Downarrow;\Downarrow\Uparrow\rangle - |\Downarrow,-\rangle \otimes |\Uparrow;\Downarrow\Uparrow\rangle\right]$$

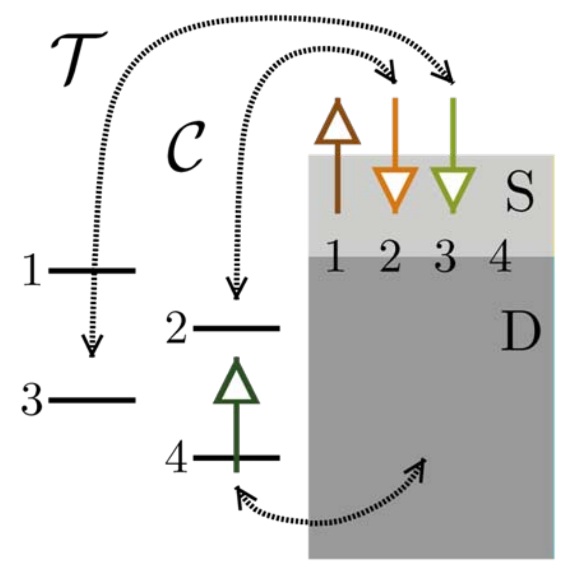
CNT LEADS



[1] Toth, A. et al., Phys. Rev. B **78**, 245109 (2008)
[2] Mantelli, D. et al., Physica E **77**, 180 (2016)

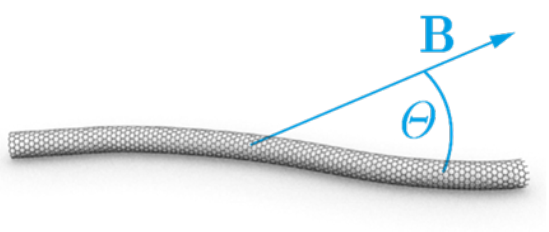
- Antiferromagnetic correlations persist at $V_{sd}\neq 0, B\neq 0$

Antiferromagnetic correlations:
only inelastic transitions which
flip the pseudospin are expected:
$\mathcal{T}$ and $\mathcal{C}$



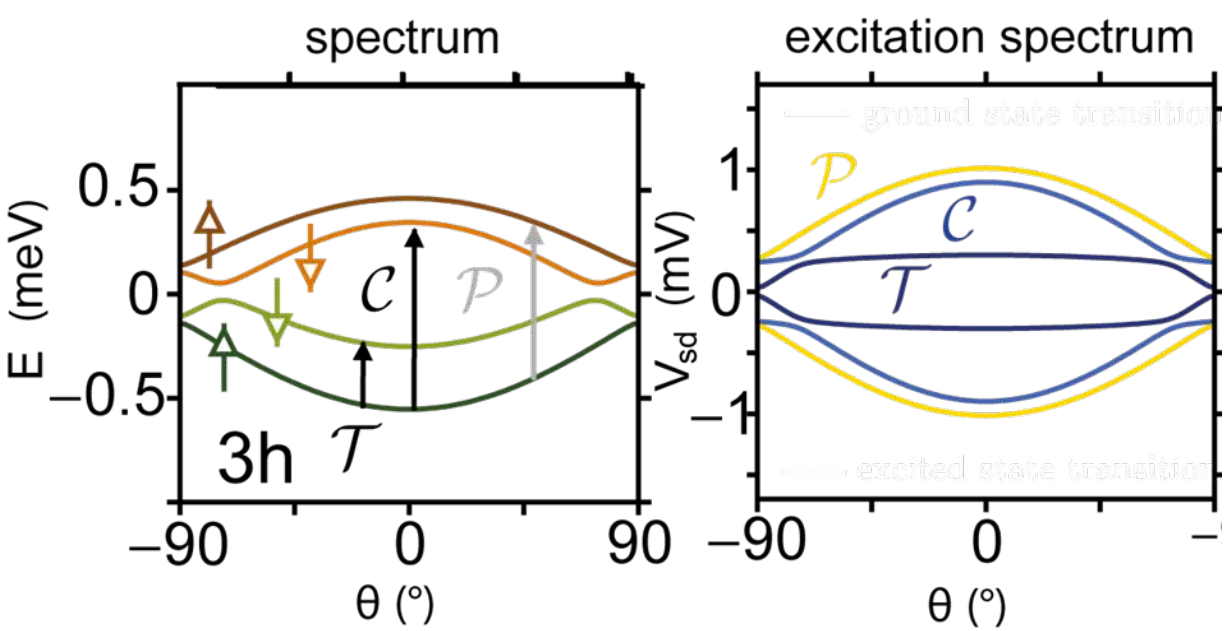
[3] Niklas et al. Nature Communications, 7:12442 (2016)

ANGULAR DEPENDENCE



- ✓ Spin and valley are mixed and no longer good quantum numbers, only pseudospin
- ✓ The three discrete $\mathcal{T}$, $\mathcal{C}$ and $\mathcal{P}$ operations still enable us to identify the transitions

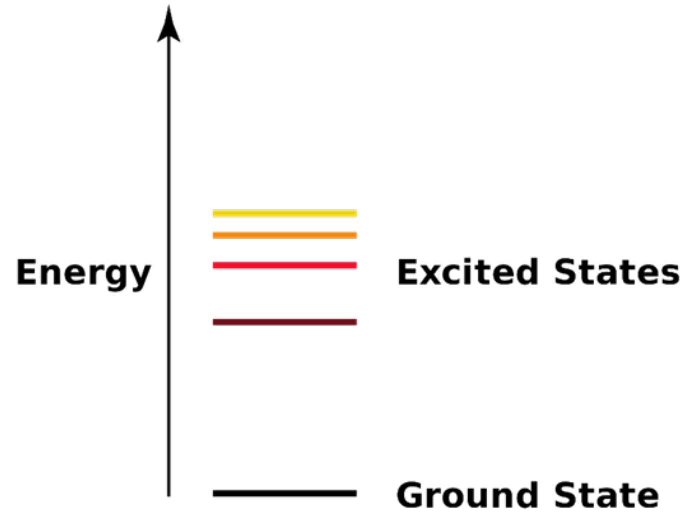
$\mathcal{P}$ transition is still missing ➡ pseudospin is screened, not electron spin!



M. Niklas et al. Nature Communication, 7:12422 (2016)

FAZIT: RELEVANT INGREDIENTS

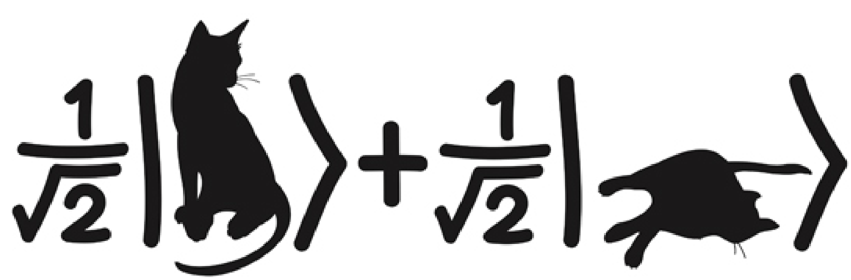
- Quantum confinement



- Symmetries

$$[H, \Upsilon] = 0$$

- Quantum correlations



Thank you!

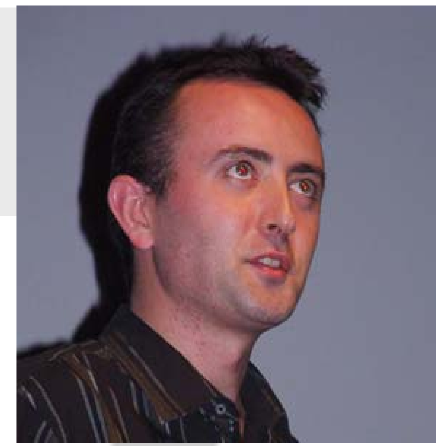
GRK 1570

SFB 689

Andreas Hüttel

AND THANKS TO

Davide Mantellli



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