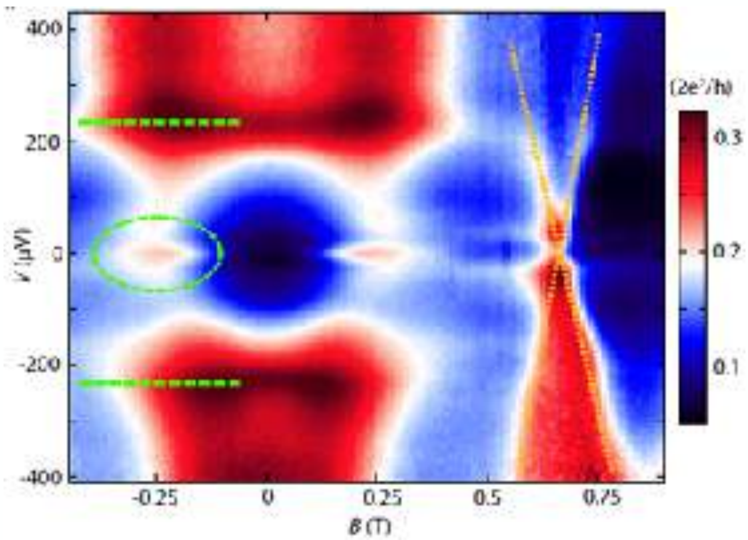
RECENT EXPERIMENTAL DEVELOPMENTS IN MAJORANA NANOWIRES: EPITAXIAL DEVICES

2012 (Kouwenhoven, Delft)
Science **336,** 1003, 2012.



- Since 2012, new fabrication developments have allowed to produce much improved samples, very good semiconductor/superconductor contacts and much cleaner data (hard gaps, etc).

- Zero bias anomalies are extremely robust.

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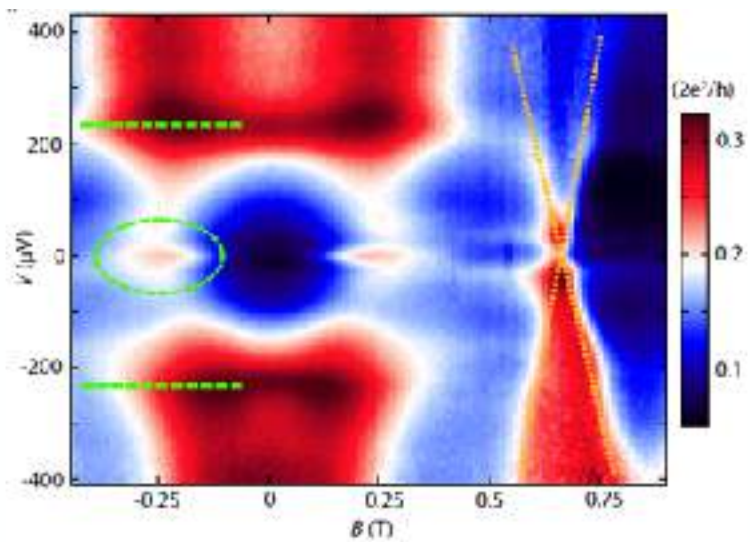
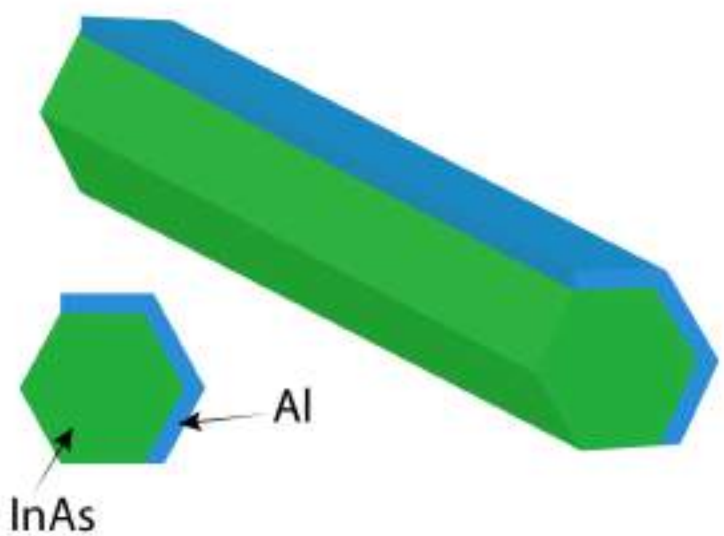
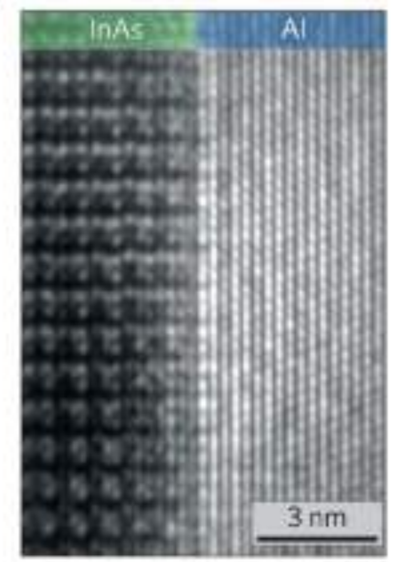
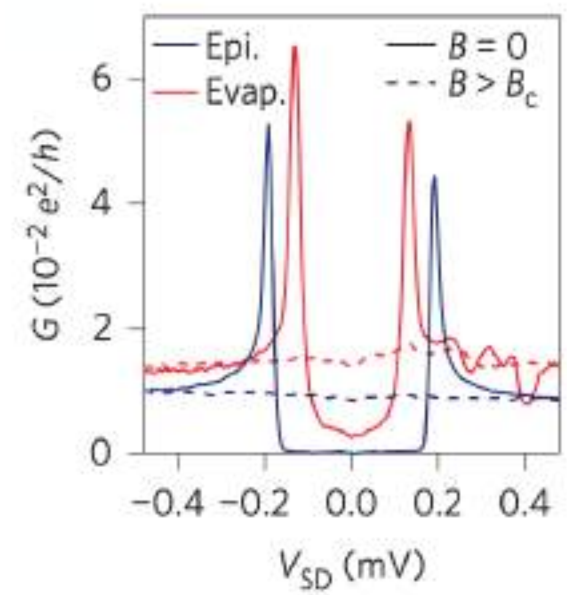
Breakthrough epitaxial Al-InAs wires 2015 (Peter Krogstrup, Jesper Nygard, Charlie Marcus @Copenhagen)









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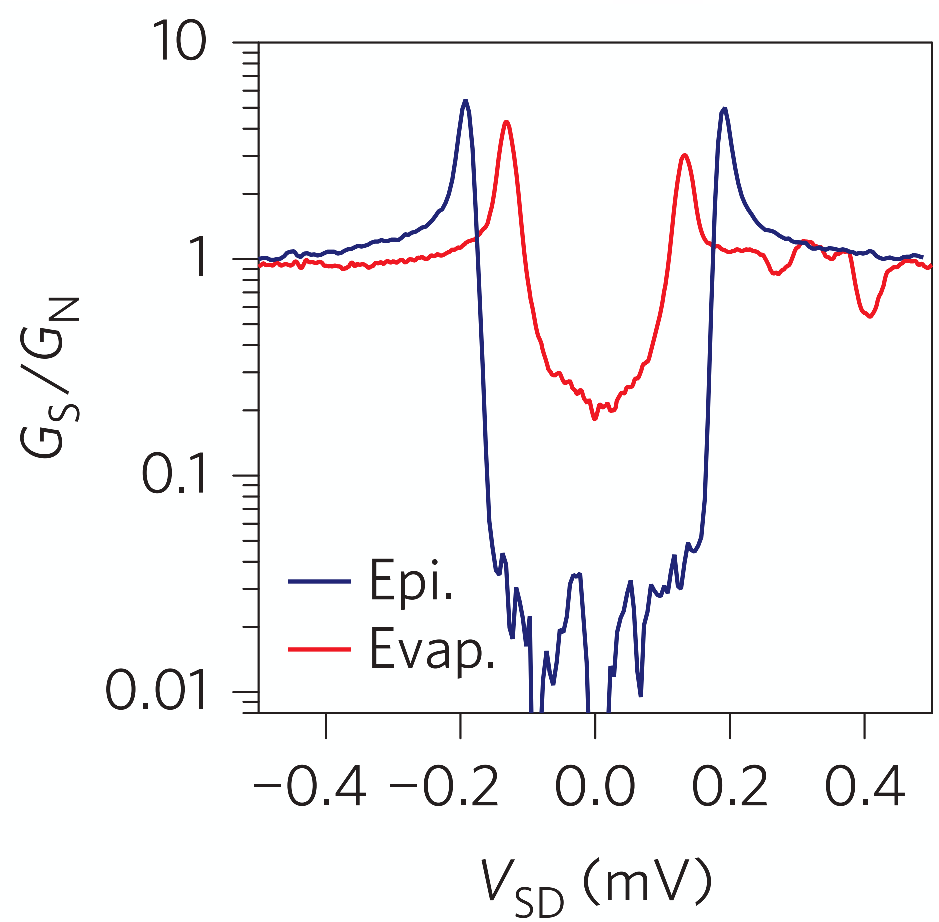

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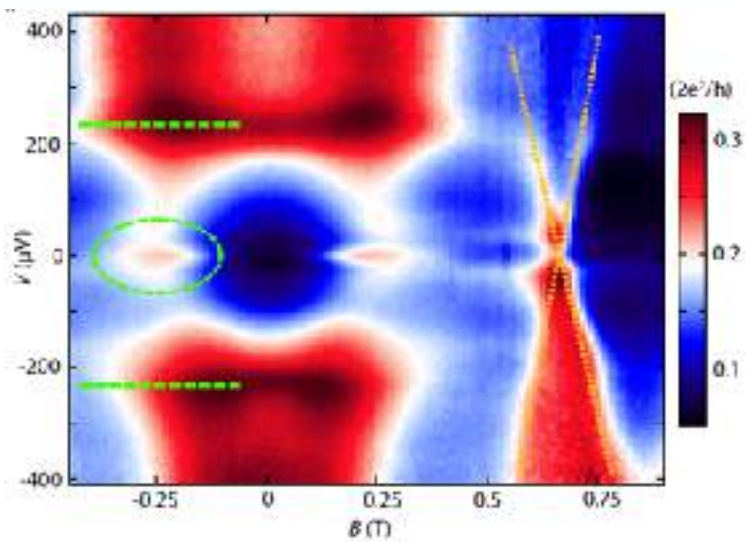

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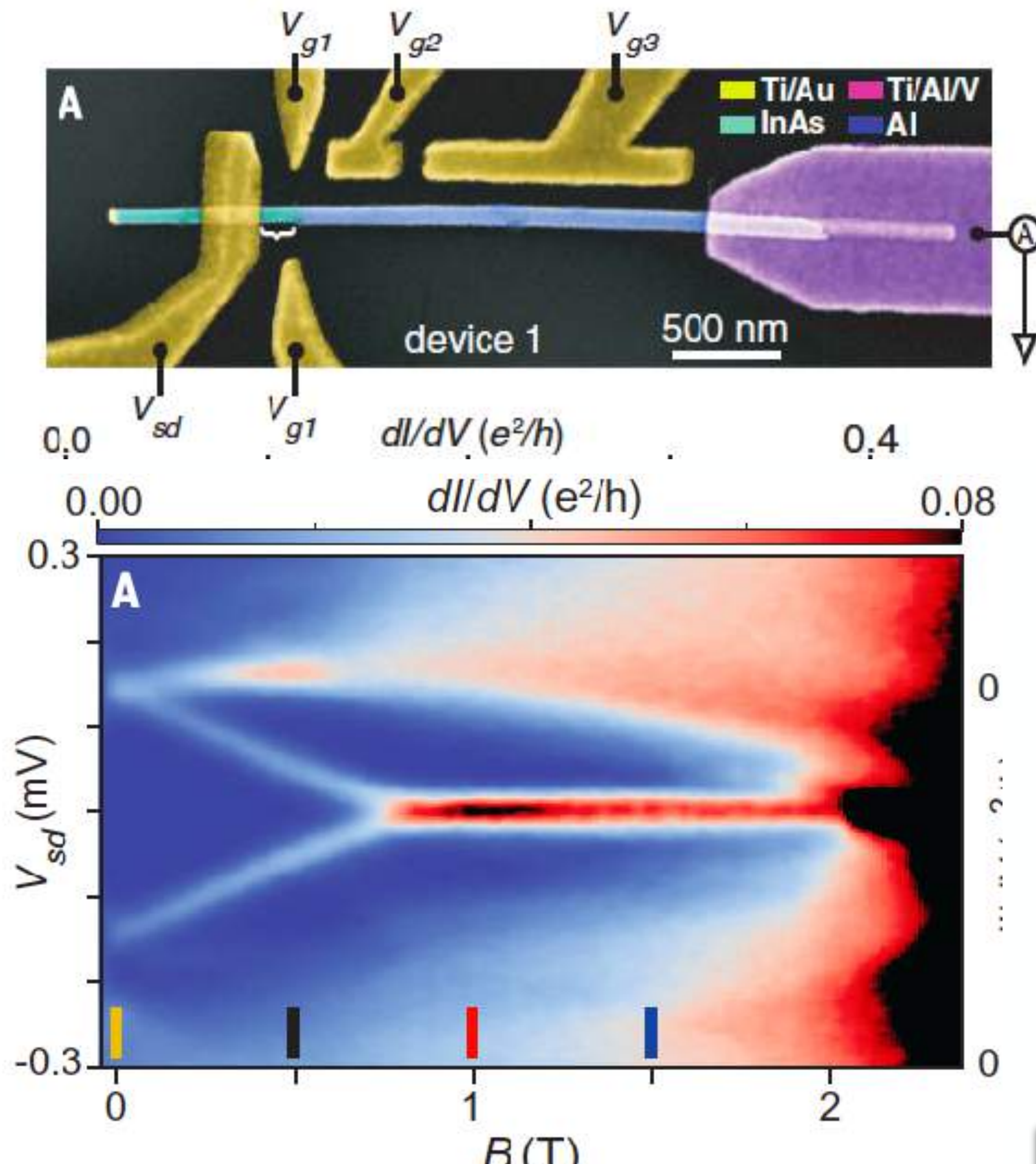

Science **354,** 1557, 2016.

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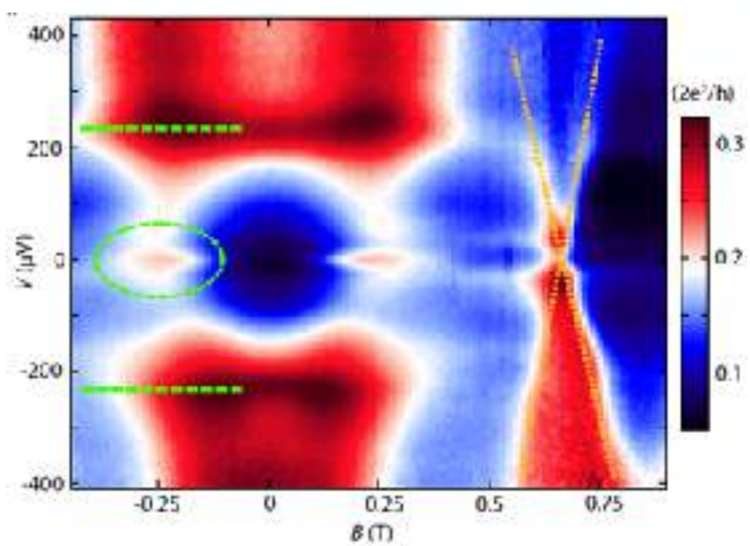
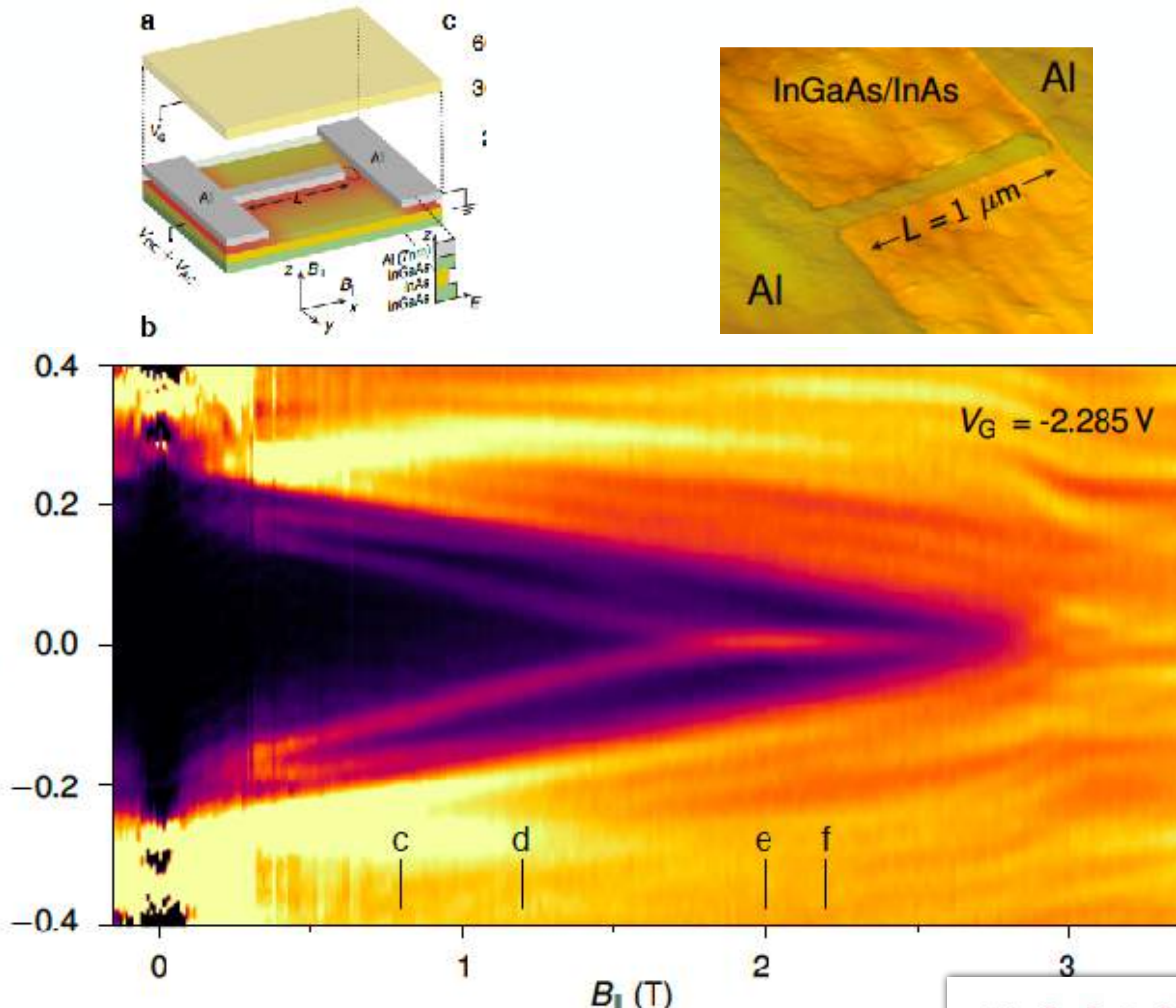


epitaxial Al-InAs heterostructure 2016 (Marcus, Copenhagen)
Phys. Rev. Lett. 119, 176805 (2017)



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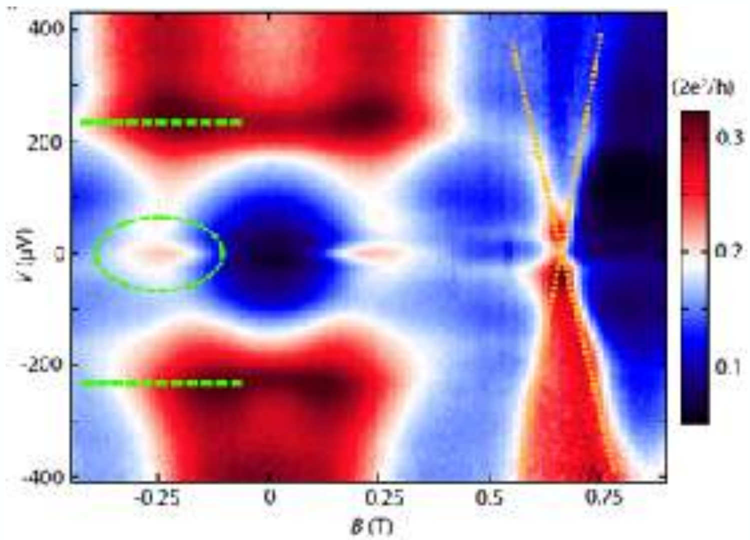

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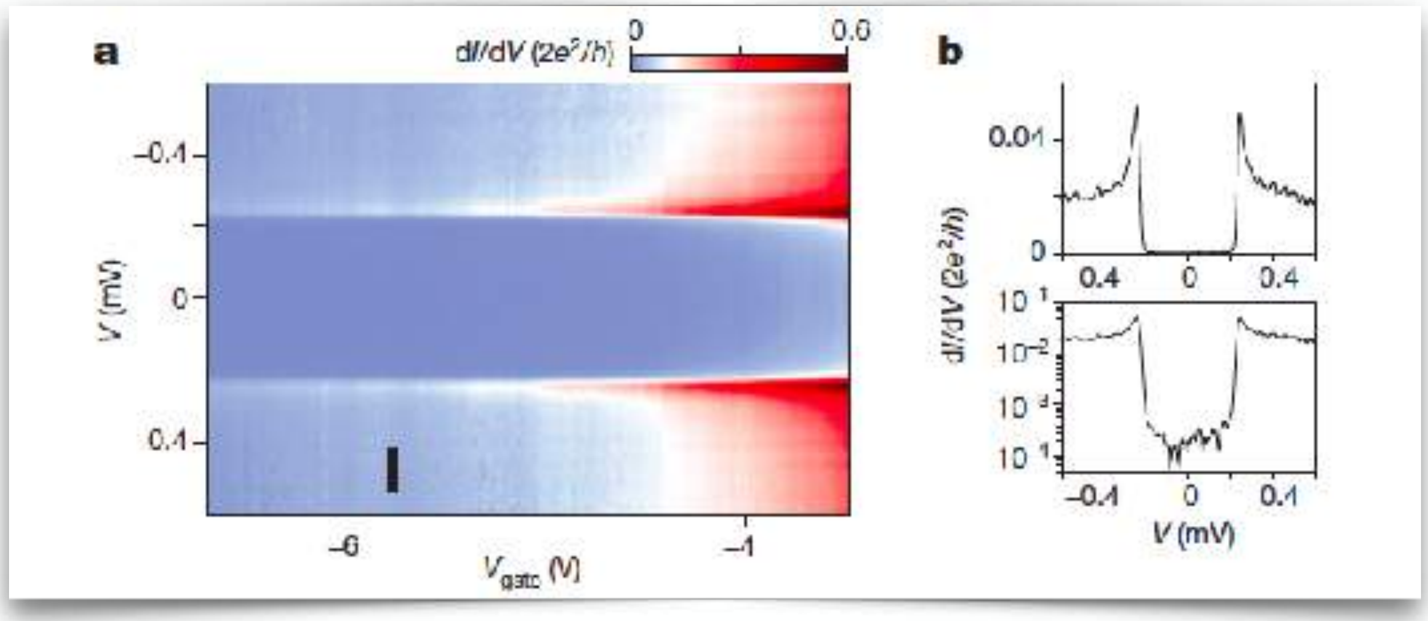
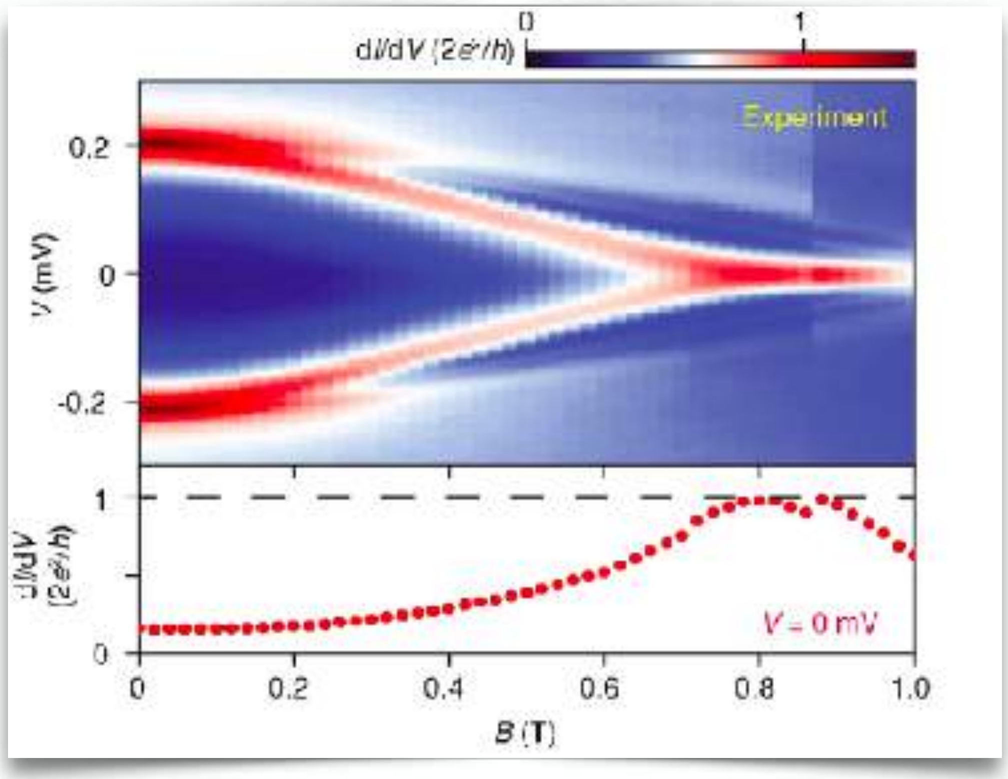
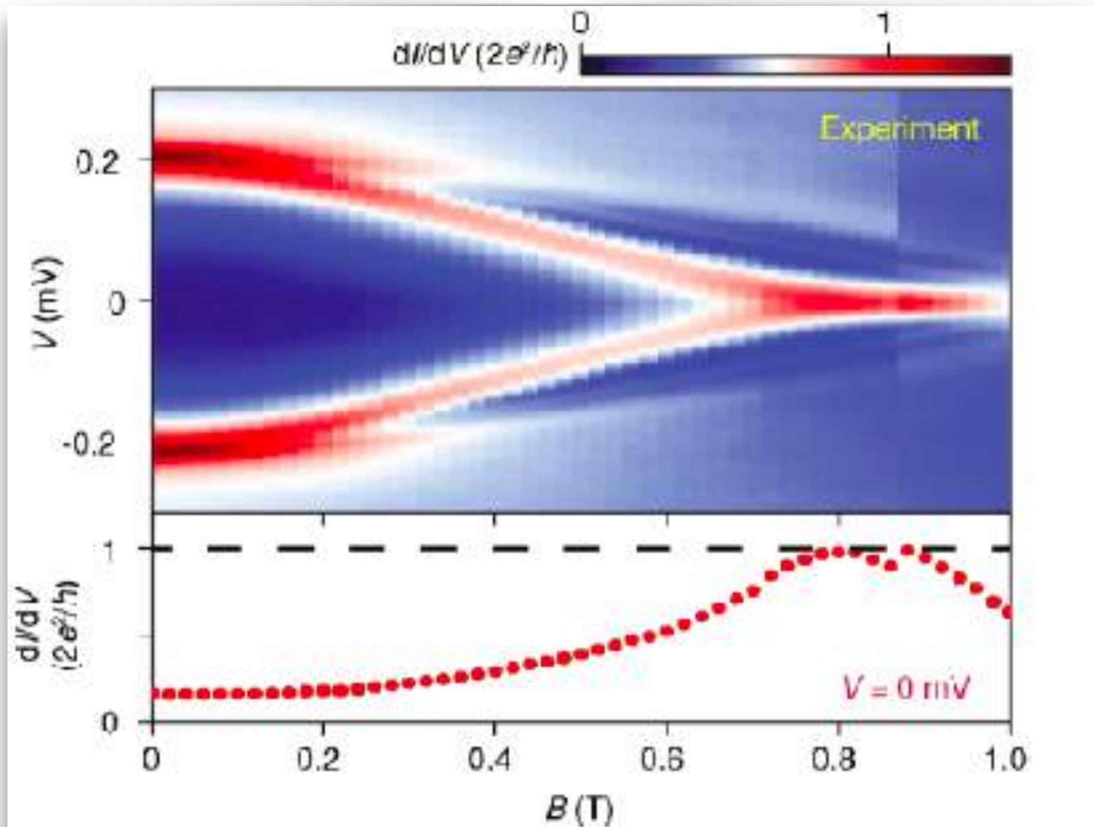
epitaxial Al-InSb wires (Kouwenhoven, Delft)
Nature 548 434 (2017)



These wires also show very good Andreev enhancement and $2e^2/h$ ZBAs were claimed (Hao Zhang et al, Nature March 2018)



Retraction two years later
(in March 2020)



doi:10.1038/nature26142

Quantized Majorana conductance

Hao Zhang[1*], Chun-Xiao Liu[2*], Sasa Gazibegovic[3*], Di Xu[1], John A. Logan[4], Guanzhong Wang[1], Nick van Loo[1], Jouri D. S. Bommer[1], Michiel W. A. de Moor[1], Diana Car[3], Roy L. M. Op het Veld[3], Petrus J. van Veldhoven[3], Sebastian Koelling[3], Marcel A. Verheijen[3,5], Mihir Pendharkar[6], Daniel J. Pennachio[4], Borzoyeh Shojaei[4,7], Joon Sue Lee[7], Chris J. Palmstrøm[4,6,7], Erik P. A. M. Bakkers[3], S. Das Sarma[2] & Leo P. Kouwenhoven[1,8]

Majorana zero-modes—a type of localized quasiparticle—hold great promise for topological quantum computing[1]. Tunnelling spectroscopy in electrical transport is the primary tool for identifying the presence of Majorana zero-modes, for instance as a zero-bias peak in differential conductance[2]. The height of the Majorana zero-bias peak is predicted to be quantized at the universal conductance value of $2e^2/h$ at zero temperature[3] (where e is the charge of an electron and h is the Planck constant), as a direct consequence of the famous Majorana symmetry in which a particle is its own antiparticle. The Majorana symmetry protects the quantization against disorder, interactions and variations in the tunnel coupling[3–5]. Previous experiments[6], however, have mostly shown zero-bias peaks much smaller than $2e^2/h$, with a recent observation[7] of a peak height close to $2e^2/h$. Here we report a quantized conductance plateau at $2e^2/h$ in the zero-bias conductance measured in indium antimonide semiconductor nanowires covered with an aluminium superconducting shell. The height of our zero-bias peak remains constant despite changing parameters such as the magnetic field and tunnel coupling, indicating that it is a quantized conductance plateau. We distinguish this quantized Majorana peak from possible non-Majorana origins by investigating its robustness to electric and magnetic fields as well as its temperature dependence. The observation of a quantized conductance plateau strongly supports the existence of Majorana zero-modes in the system, consequently paving the way for future braiding experiments that could lead to topological quantum computing.

A semiconductor nanowire coupled to a superconductor can be tuned into a topological superconductor with two Majorana zero-modes localized at the wire ends[1,8,9]. Tunnelling into a Majorana mode will show a zero-energy state in the tunnelling density-of-states, that is, a zero-bias peak (ZBP) in the differential conductance (dI/dV)[2,6]. This tunnelling process is an 'Andreev reflection', in which an incoming electron is reflected as a hole. Particle–hole symmetry dictates that the zero-energy tunnelling amplitudes of electrons and holes are equal, resulting in a perfect resonant transmission with a ZBP height quantized at $2e^2/h$ (refs 3, 4, 10), irrespective of the precise tunnelling strength[3–5]. The Majorana nature of this perfect Andreev reflection is a direct result of the well-known Majorana symmetry property 'particle equals antiparticle'[11,12].

This predicted robust conductance quantization has not yet been observed[7,13,14]. Instead, most of the ZBPs have a height considerably less than $2e^2/h$. This discrepancy was first explained by thermal averaging[15–18], but that explanation does not hold when the peak width exceeds the thermal broadening (about $3.5k_BT$)[13,14]. In that case, other averaging mechanisms, such as dissipation[19], have been invoked. The main source of dissipation is a finite quasiparticle density-of-states within the superconducting gap, often referred to as a 'soft gap'. Substantial advances have been achieved in 'hardening' the gap by improving the quality of materials, eliminating disorder and interface roughness[20,21], and better controlling device processing[22,23], all guided by a more detailed theoretical understanding[24]. We have recently solved all these dissipation and disorder issues[21], and here we report the resulting improvements in electrical transport leading to the elusive quantization of the Majorana ZBP.

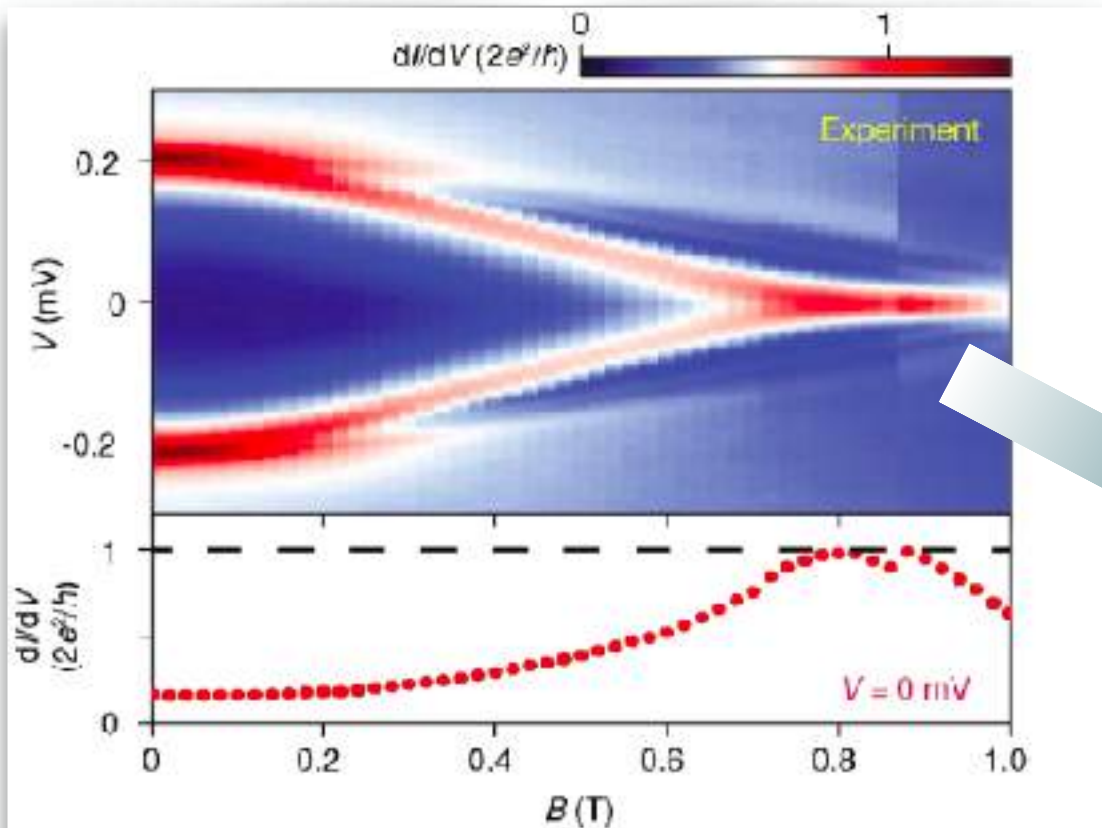
Figure 1a shows a micrograph of a fabricated device and schematics of the measurement set-up. An InSb nanowire (grey) is partially covered (two out of six facets) by a thin superconducting aluminium shell (green)[21]. The 'tunnel gates' (coral red) are used to induce a tunnel barrier in the non-covered segment between the left electrical contact (yellow) and the Al shell. The right contact is used to drain the current to ground. The chemical potential in the segment covered with Al can be tuned by applying voltages to the two long 'super-gates' (purple).

Transport spectroscopy is shown in Fig. 1b, which displays dI/dV as a function of voltage bias V and magnetic field B (aligned with the nanowire axis), while fixed voltages are applied to the tunnel- and super-gates. As B increases, two levels detach from the gap edge (at about 0.2 meV), merge at zero bias and form a robust ZBP. This is consistent with the Majorana theory: a ZBP is formed after the Zeeman energy closes the trivial superconducting gap and re-opens a topological gap[8,9]. The gap re-opening is not visible in a measurement of the local density-of-states because the tunnel coupling to these bulk states is small[25]. Moreover, the finite length (about 1.2 μm) of the proximitized segment (that is, the part that is superconducting because of the proximity effect from the superconducting Al coating) results in discrete energy states, turning the trivial-to-topological phase transition into a smooth crossover[26]. Figure 1c shows two line-cuts from Fig. 1b extracted at 0 T and 0.88 T. Importantly, the height of the ZBP reaches the quantized value of $2e^2/h$. The line-cut at zero bias in the lower panel of Fig. 1b shows that the ZBP height remains close to $2e^2/h$ over a sizable range in B field (0.75–0.92 T). Beyond this range, the height drops, most probably because of a closure of the superconducting gap in the bulk Al shell.

We note that the sub-gap conductance at $B = 0$ (black curve, left panel, Fig. 1c) is not completely suppressed down to zero, reminiscent of a soft gap. In this case, however, this finite sub-gap conductance does not reflect any finite sub-gap density-of-states in the proximitized wire. It arises from Andreev reflection (that is, transport by dissipationless Cooper pairs) due to a high tunnelling transmission, which is evident from the above-gap conductance (dI/dV for $V > 0.2$ mV) being larger than e^2/h. As this softness does not result from dissipation, the Majorana peak height should still reach the quantized value[27]. In Extended Data Fig. 1, we show that this device tuned into a low-transmission regime,

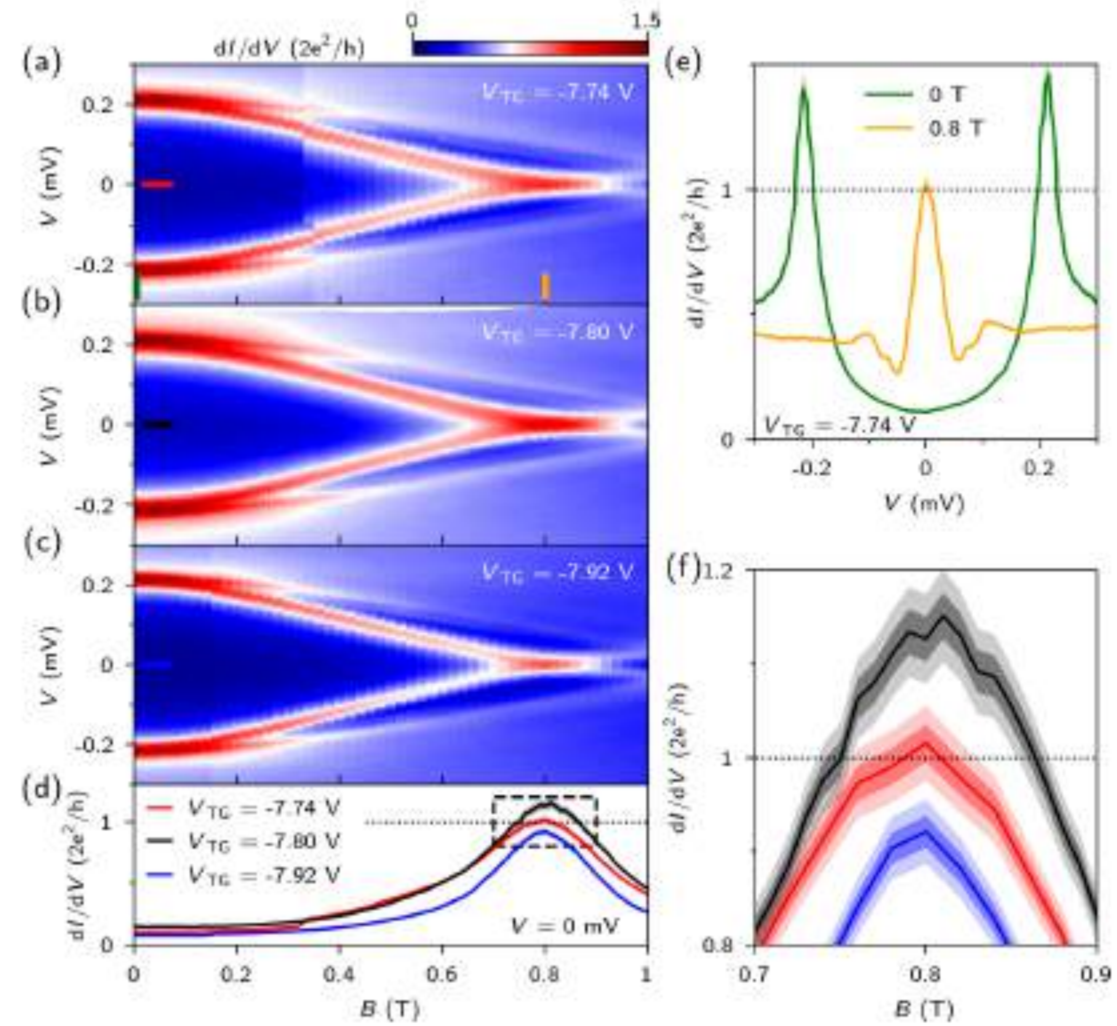
[1]QuTech and Kavli Institute of NanoScience, Delft University of Technology, 2600 GA Delft, The Netherlands. [2]Condensed Matter Theory Center and Joint Quantum Institute, Department of Physics, University of Maryland, College Park, Maryland 20742, USA. [3]Department of Applied Physics, Eindhoven University of Technology, 5600 MB Eindhoven, The Netherlands. [4]Materials Engineering, University of California Santa Barbara, Santa Barbara, California 93106, USA. [5]Philips Innovation Services Eindhoven, High Tech Campus 11, 5656AE Eindhoven, The Netherlands. [6]Electrical and Computer Engineering, University of California Santa Barbara, Santa Barbara, California 93106, USA. [7]California NanoSystems Institute, University of California Santa Barbara, Santa Barbara, California 93106, USA. [8]Microsoft Station Q Delft, 2600 GA Delft, The Netherlands.
*These authors contributed equally to this work.

Retraction two years later (in March 2020)



Large zero-bias peaks in InSb-Al hybrid semiconductor-superconductor nanowire devices

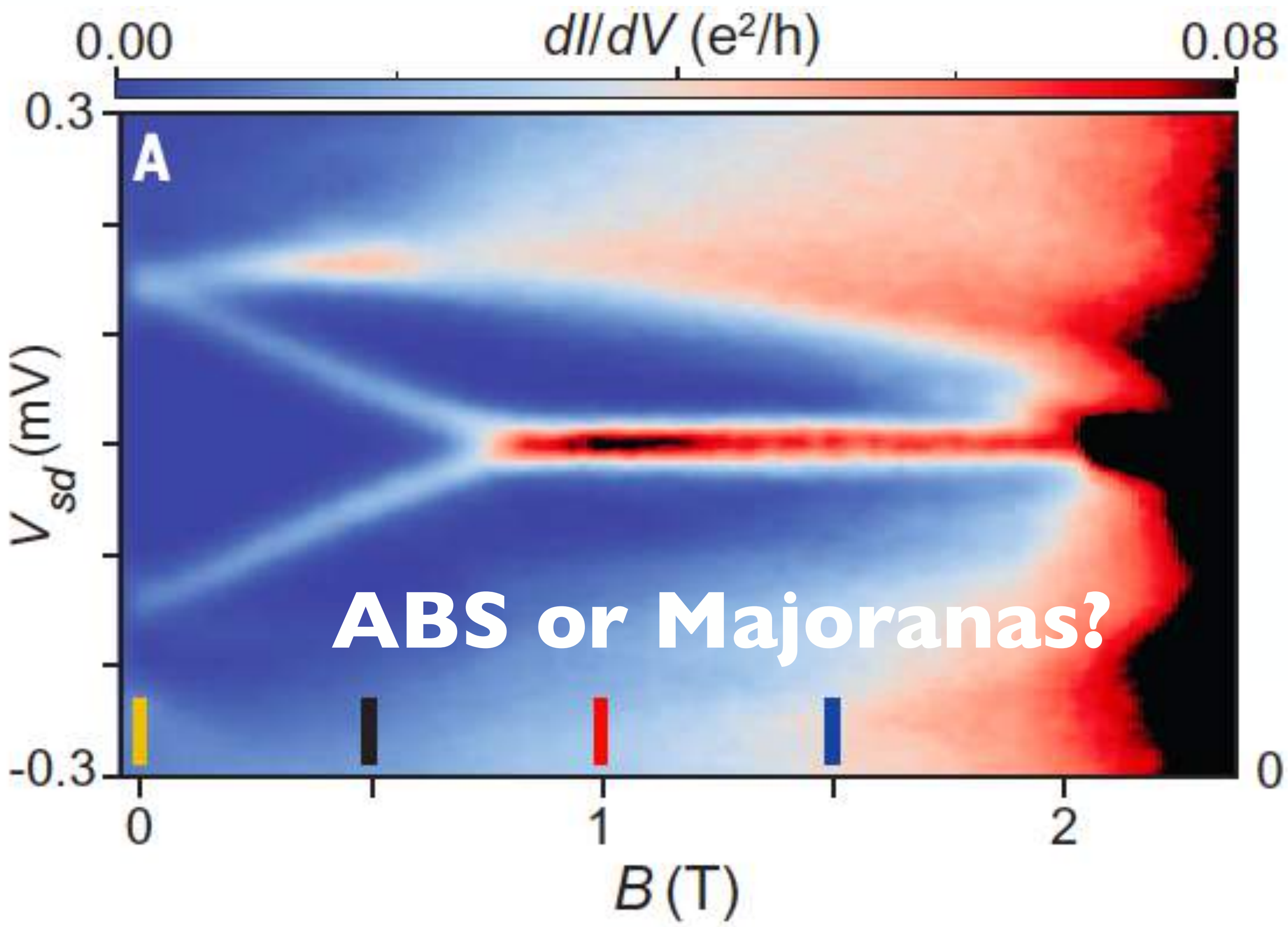
Hao Zhang*,[1, 2, 3] Michiel W.A. de Moor*,[1, 2] Jouri D.S. Bommer*,[1, 2] Di Xu,[1, 2] Guanzhong Wang,[1, 2] Nick van Loo,[1, 2] Chun-Xiao Liu,[1, 2, 4] Sasa Gazibegovic,[5] John A. Logan,[6] Diana Car,[5] Roy L. M. Op het Veld,[5] Petrus J. van Veldhoven,[5] Sebastian Koelling[a],[5] Marcel A. Verheijen,[5] Mihir Pendharkar,[7] Daniel J. Pennachio,[6] Borzoyeh Shojaei,[6, 8] Joon Sue Lee[b],[8] Chris J. Palmstrøm,[6, 7, 8] Erik P.A.M. Bakkers,[5] S. Das Sarma,[4] Leo P. Kouwenhoven[1, 2, 9†]



Zero energy crossings of Andreev levels and/or smooth confinement can mimic this behavior (reported theoretically many years before the retraction).

THE NAGGING QUESTION:

IS THIS ZERO MODE A MAJORANA OR IS IT AN ANDREEV LEVEL?



Science 354, 1557, 2016 (Marcus' lab)

THE NAGGING QUESTION:

IS THIS ZERO MODE A MAJORANA OR IS IT AN ANDREEV LEVEL?

Chi l'ha visto?

Ettore Majorana, ordinario di fisica teorica all' Università di Napoli, è misteriosamente scomparso dagli ultimi di marzo. Di anni 31, alto metri 1,70, snello, con capelli neri, occhi scuri, una lunga cicatrice sul dorso di una mano. Chi ne sapesse qualcosa è pregato di scrivere al R. P. E. Marianecci, Viale Regina Margherita 66 - Roma.

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NATURE REVIEWS | PHYSICS

From Andreev to Majorana bound states in hybrid superconductor–semiconductor nanowires

Elsa Prada[1] ✉, Pablo San-Jose[2], Michiel W. A. de Moor[3], Attila Geresdi[3], Eduardo J. H. Lee[1], Jelena Klinovaja[4], Daniel Loss[4], Jesper Nygård[5], Ramón Aguado[2] and Leo P. Kouwenhoven[3,6]

Abstract | Inhomogeneous superconductors can host electronic excitations, known as Andreev bound states (ABSs), below the superconducting energy gap. With the advent of topological superconductivity, a new kind of zero-energy ABS with exotic qualities, known as a Majorana bound state (MBS), has been discovered. A special property of MBS wavefunctions is their non-locality, which, together with non-Abelian braiding, is the key to their promise in topological quantum computation. We focus on hybrid superconductor–semiconductor nanowires as a flexible and promising experimental platform to realize one-dimensional topological superconductivity and MBSs. We review the main properties of ABSs and MBSs, state-of-the-art techniques for their detection and theoretical progress beyond minimal models, including different types of robust zero modes that may emerge without a band-topological transition.

*Nature Reviews Physics volume **2**, pages 575–594 (2020)*

THERE IS A NAGGING DEBATE ABOUT MAJORANAS IN HYBRID NANOWIRES

icmm csic

NATURE REVIEWS | PHYSICS volume 2, pages 575–594 (2020)

From Andreev to Majorana bound states in hybrid superconductor–semiconductor nanowires

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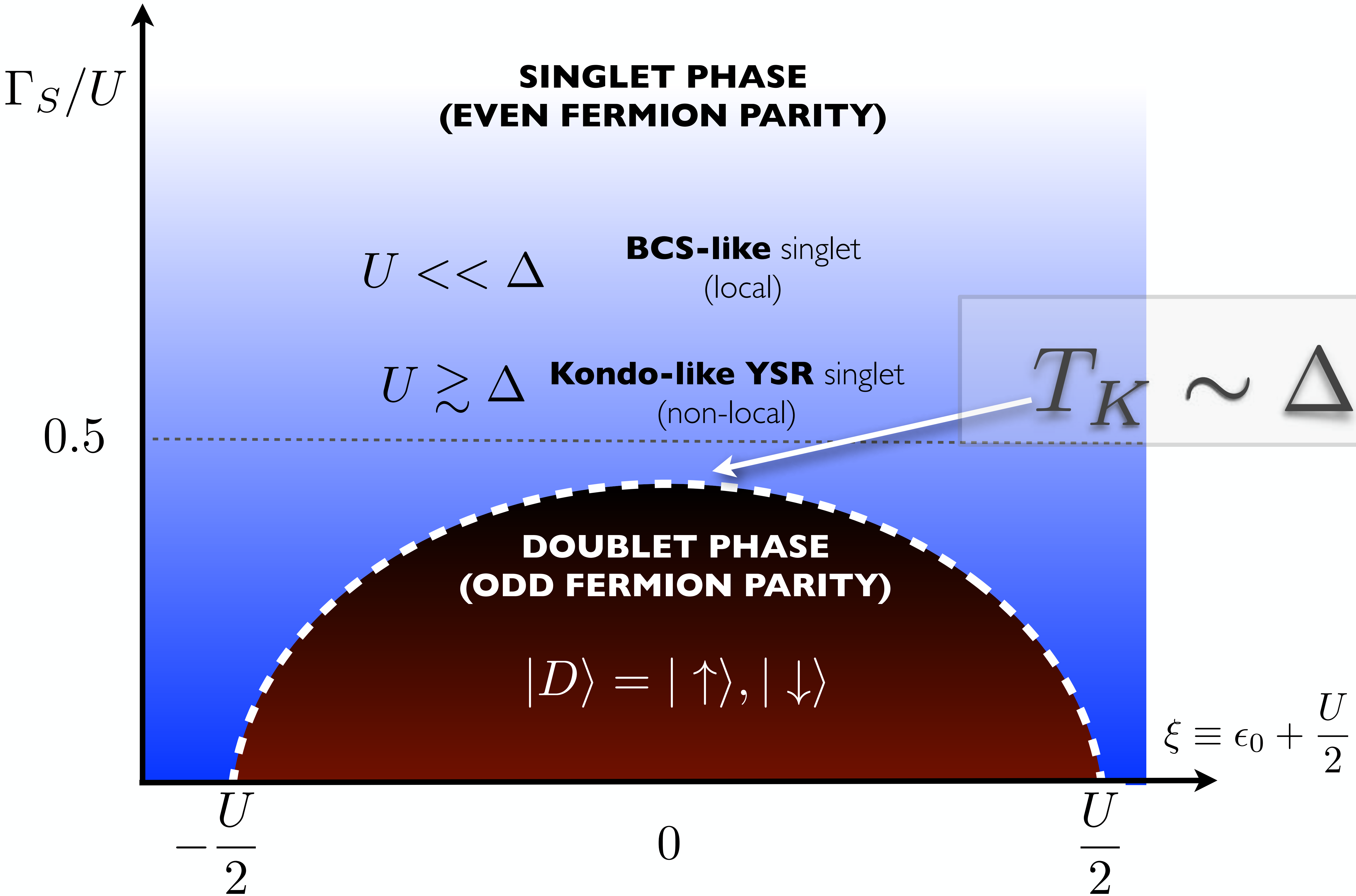
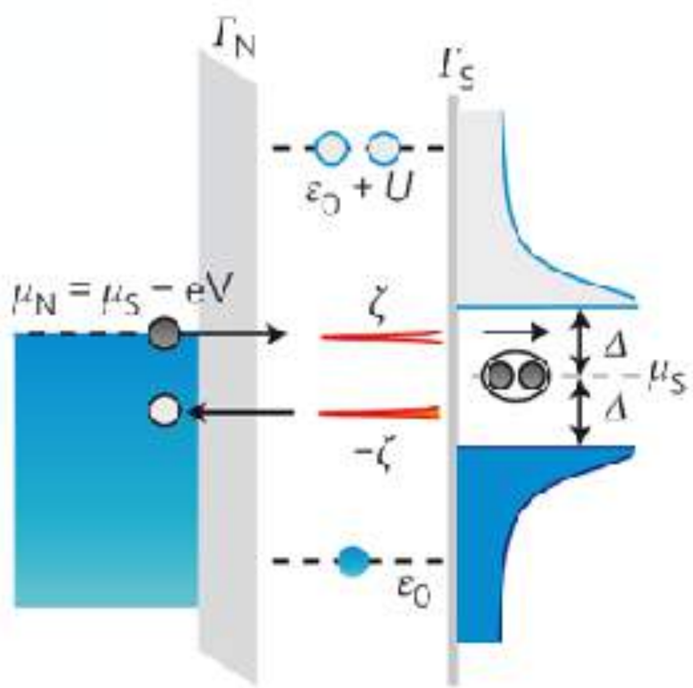
Type	Subtype	Bulk topology	Spatial Overlap of Majorana components	Spatial extension of Majorana components	Zero energy pinning	Non-Abelian braiding
ABSs	**Standard: SO=0, V_Z=0**	trivial	complete	spread across junction/ normal region	no	no
	SO≠0, V_Z<V_Z^c	trivial	partial	spread across junction/ normal region	no	no
	strong SO, V_Z<V_Z^c	trivial	partial	spread across junction/ normal region	only vs. V_Z, rest fine-tuned	no
	coupled multiband + short-range inhomogeneity	trivial	high	spread across inhomogeneity	approximate	no
	Shiba state	trivial	complete	localized to impurity	no	no
MBSs	**Long (L≫ξ_M, V_Z>V_Z^c)**	nontrivial	exponentially suppressed	localized to edges	yes	yes
	Short (L≲ξ_M, V_Z>V_Z^c)	nontrivial	partial	localized to edges but overlapping	no (Majorana oscillations)	no
Smooth zero modes	**Smoothly confined S**	trivial	partial	localized to smooth edge	yes	yes (parametric)
	Smooth S'S/NS junction (nontopological MBS/ps-MBS/ quasi-MBS/EP-MBS)	trivial	partial	localized to smooth junction	yes	yes (parametric)

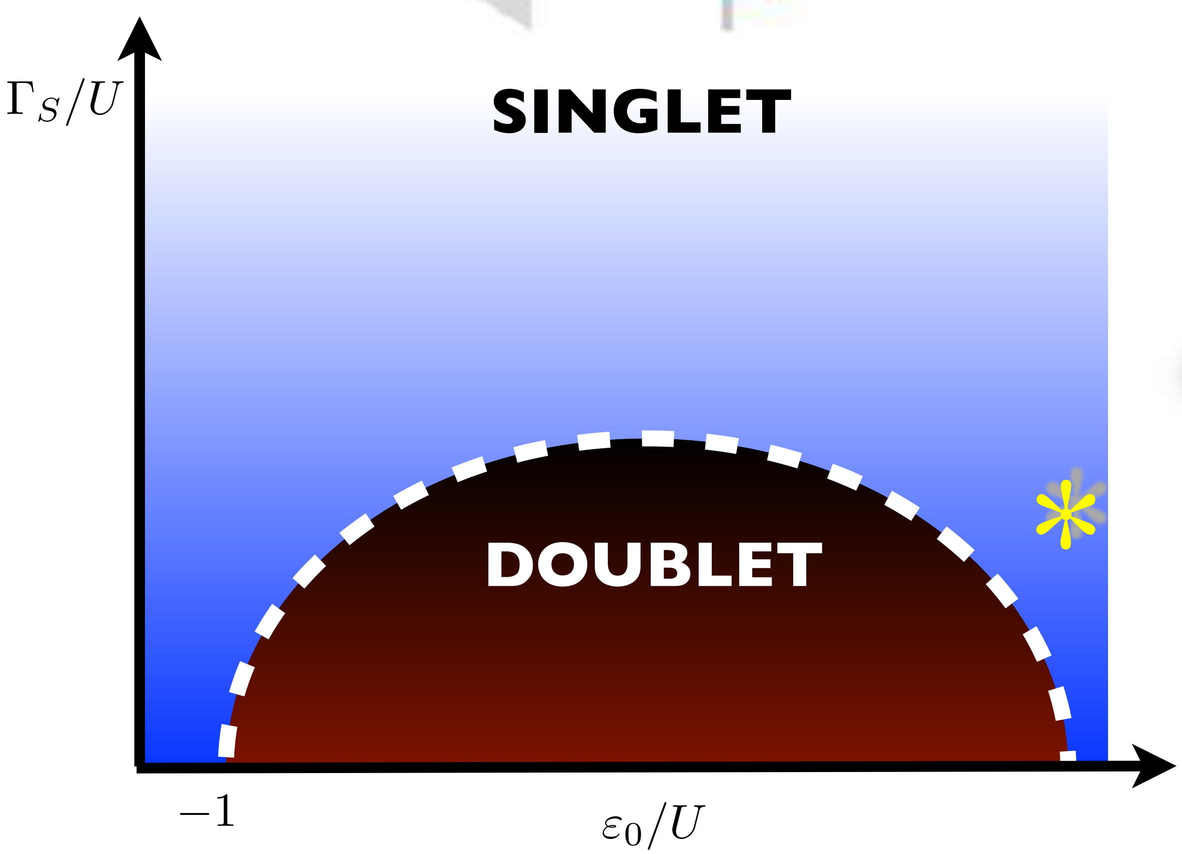
Finite Δ: quasiparticle excitations above the gap induce Kondo correlations

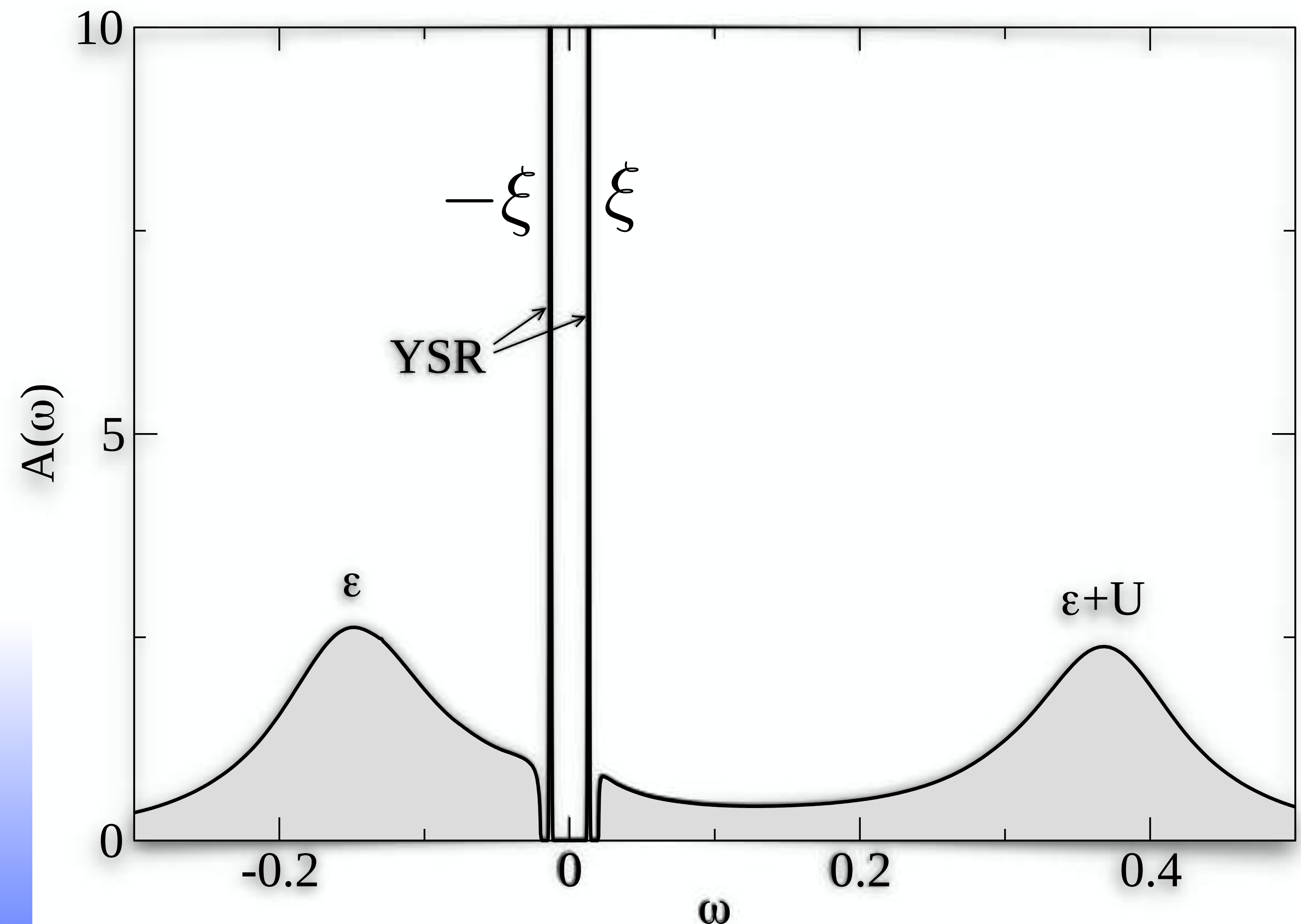


TWO KEY CONCEPTS:

- PEAKS IN ANDREEV CONDUCTANCE dI/dV MEASURE SUBGAP EXCITATIONS
- CHANGES IN THE GROUND STATE ARE SIGNALED AS ZERO-ENERGY CROSSINGS OF SUCH SUBGAP STATES







NRG calculation

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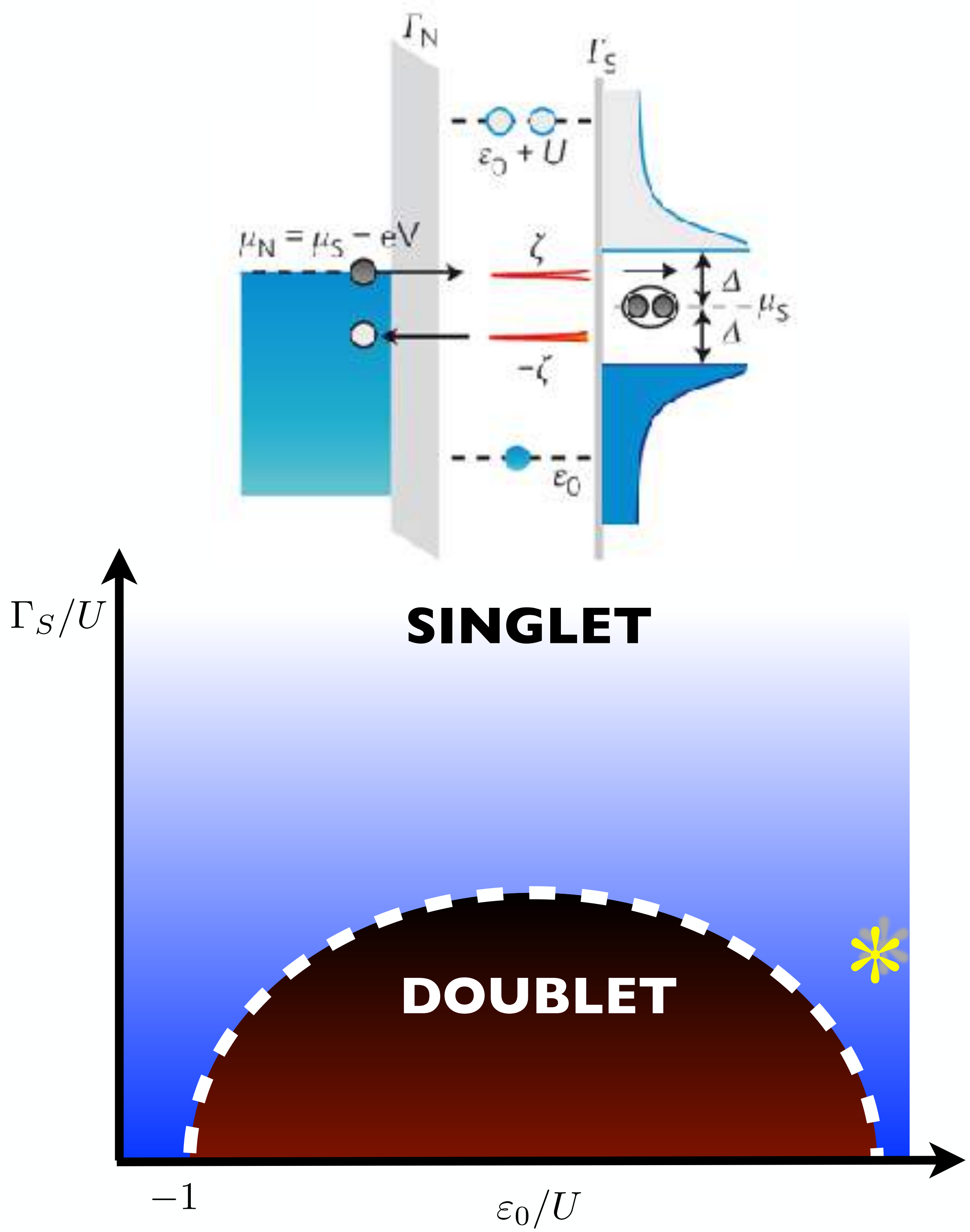
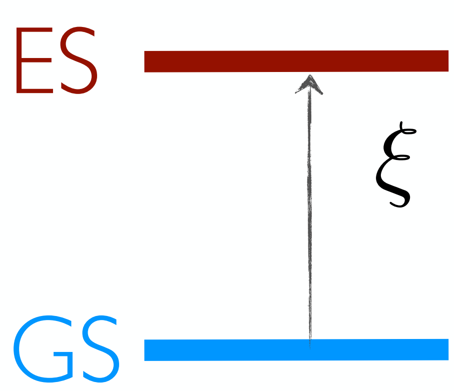


ES=excited state

GS=ground state



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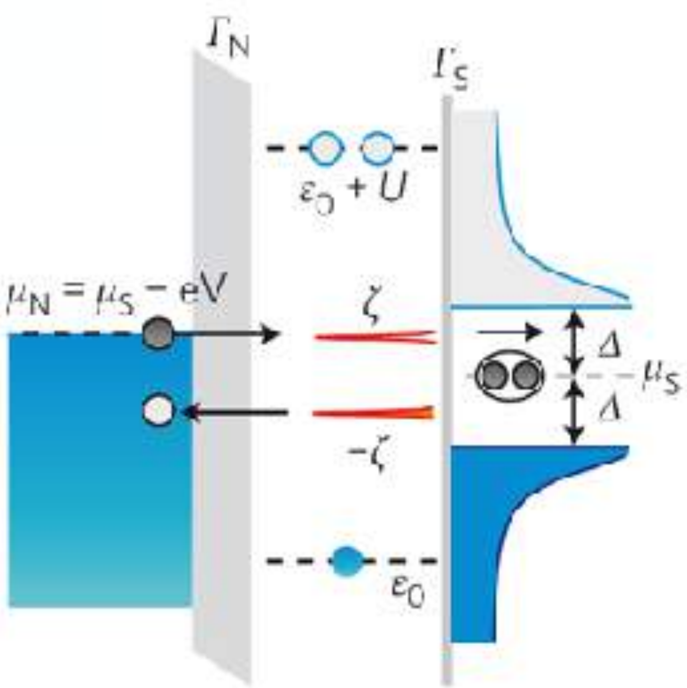

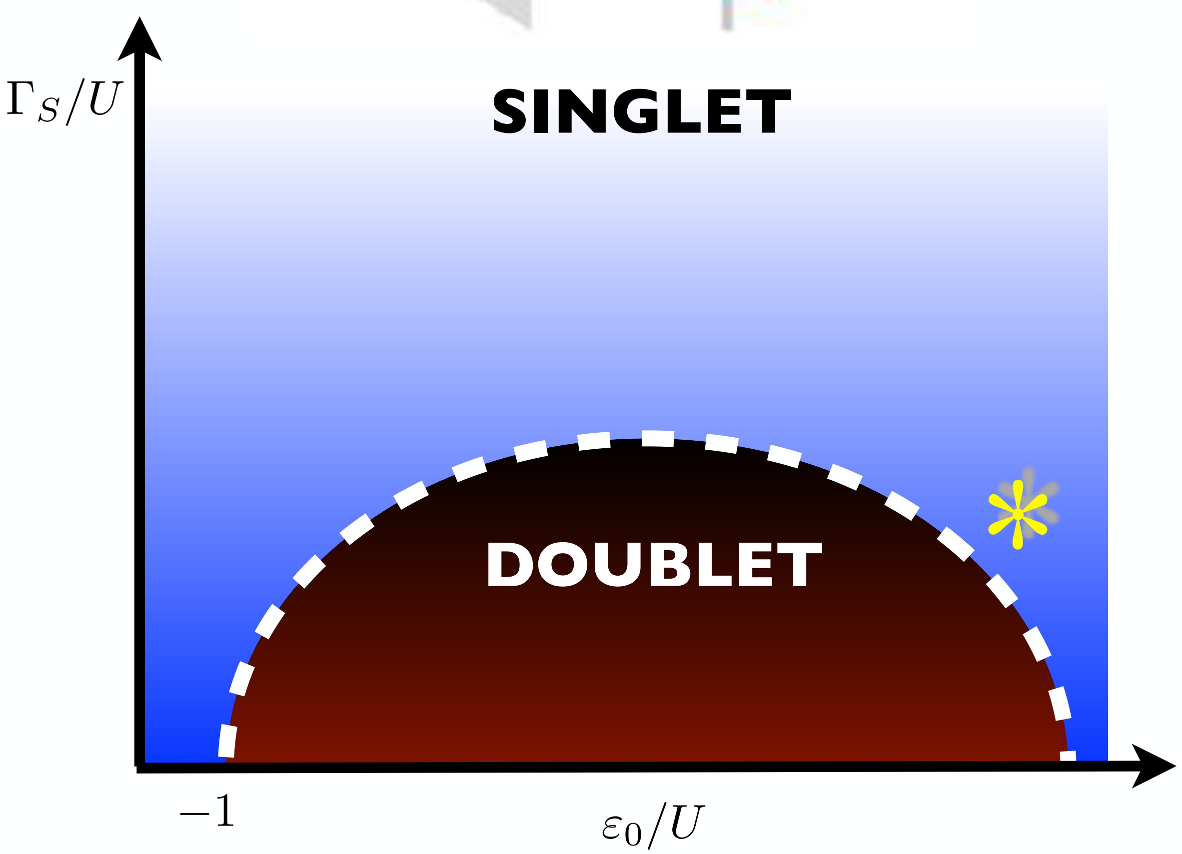

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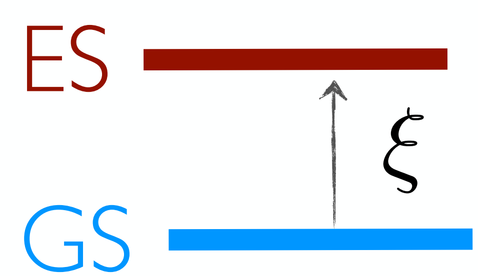

The energy of the subgap state (transition) **decreases** as we move towards the boundary by varying some external parameter (here the QD level position)

TWO KEY CONCEPTS:

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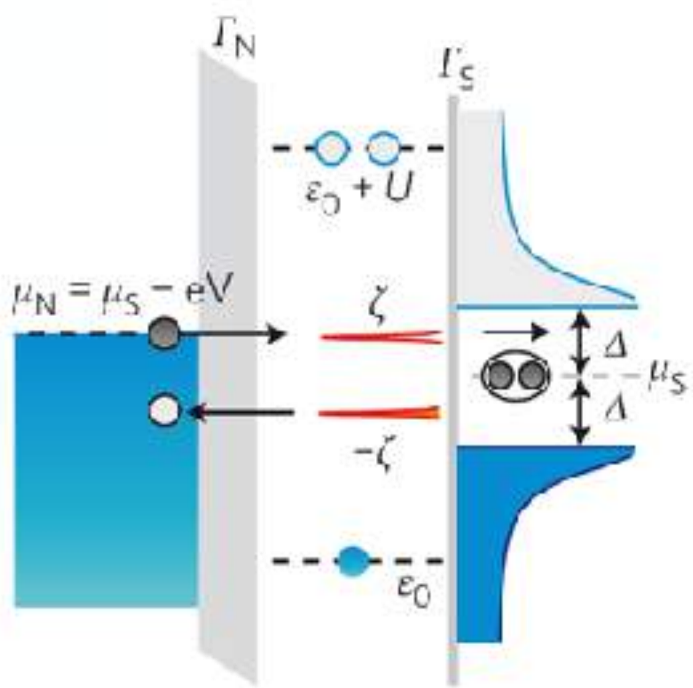

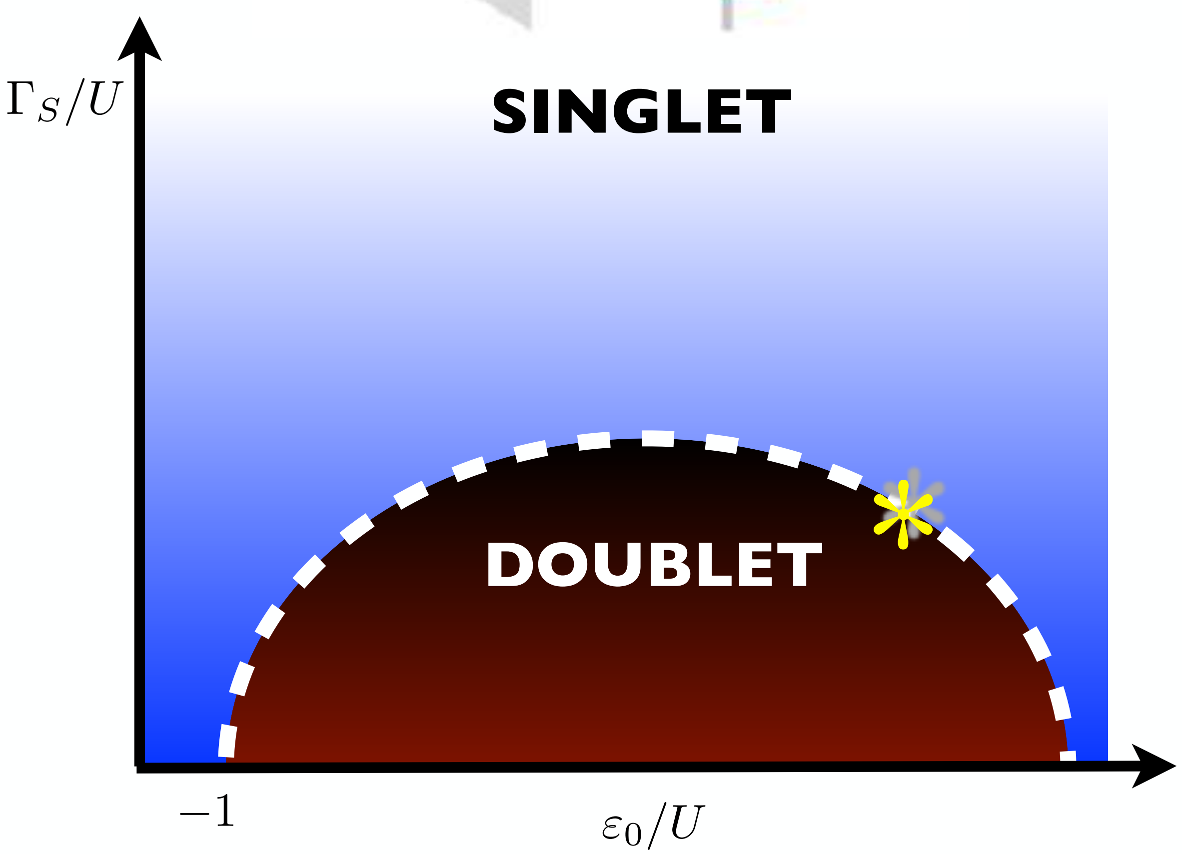

ES=excited state

GS=ground state

ES GS $\xi = 0$

Eventually it reaches zero at the boundary: **zero energy crossing**

TWO KEY CONCEPTS:

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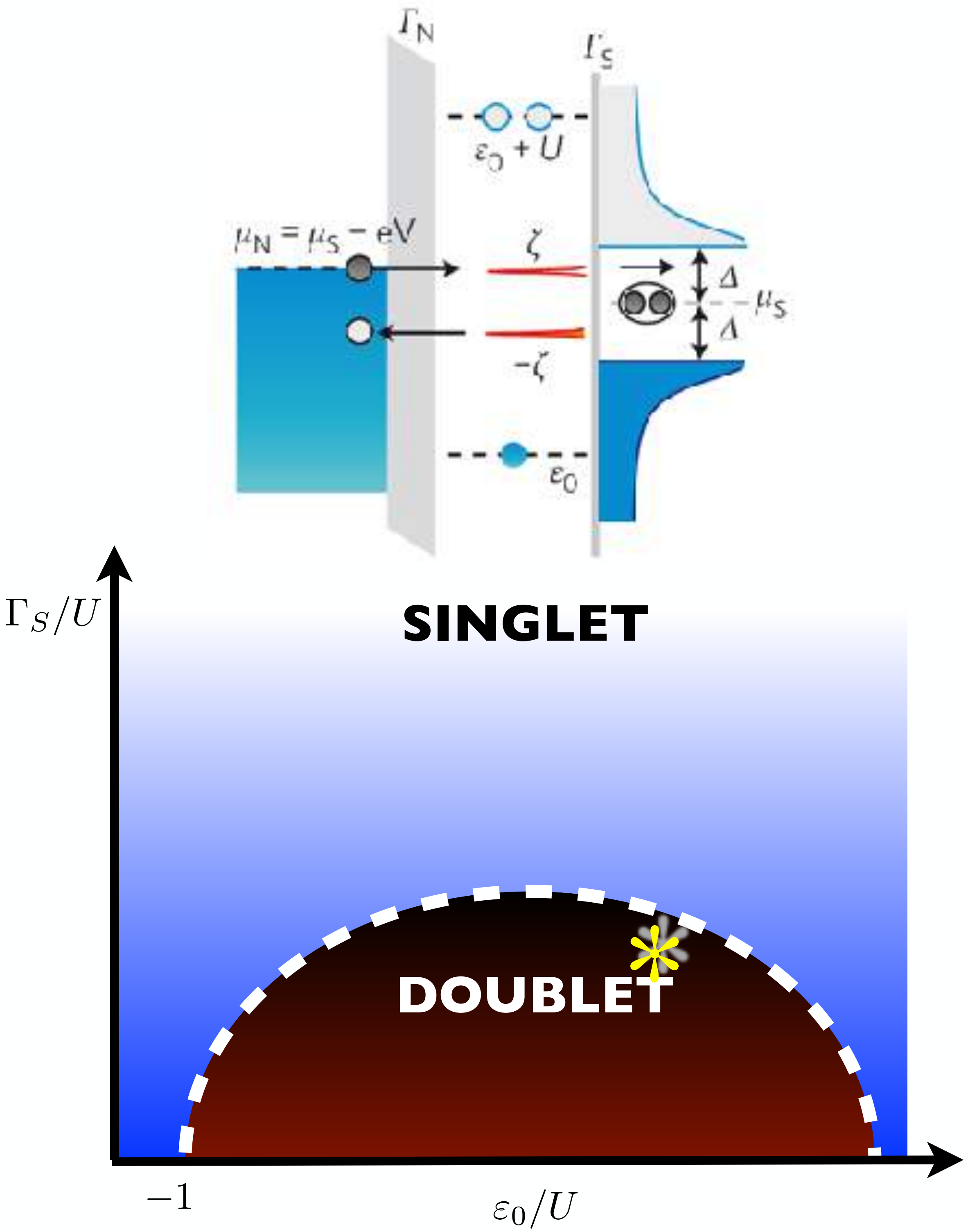

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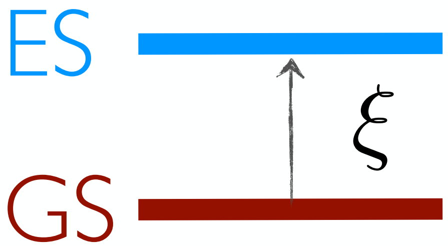
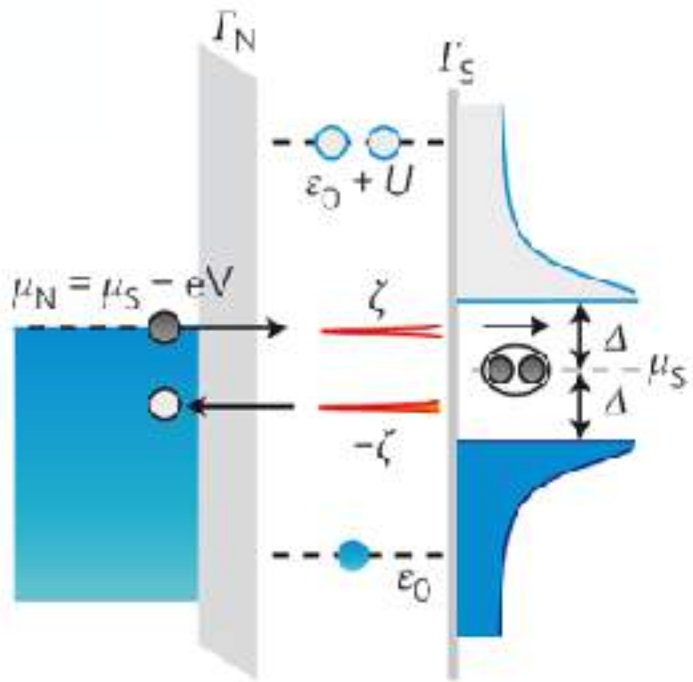


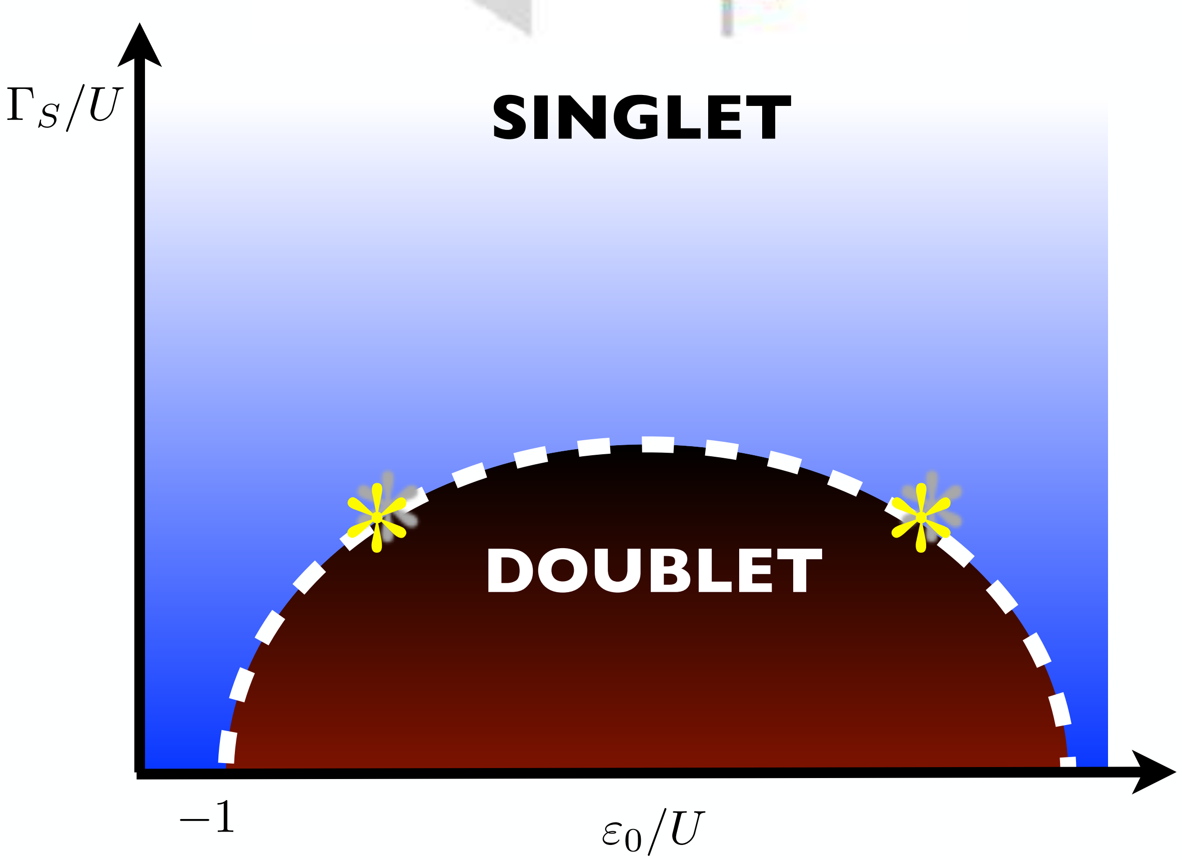
The ground state **has changed**

nature nanotechnology | ARTICLES
PUBLISHED ONLINE: 15 DECEMBER 2013 | DOI: 10.1038/NNANO.2013.267

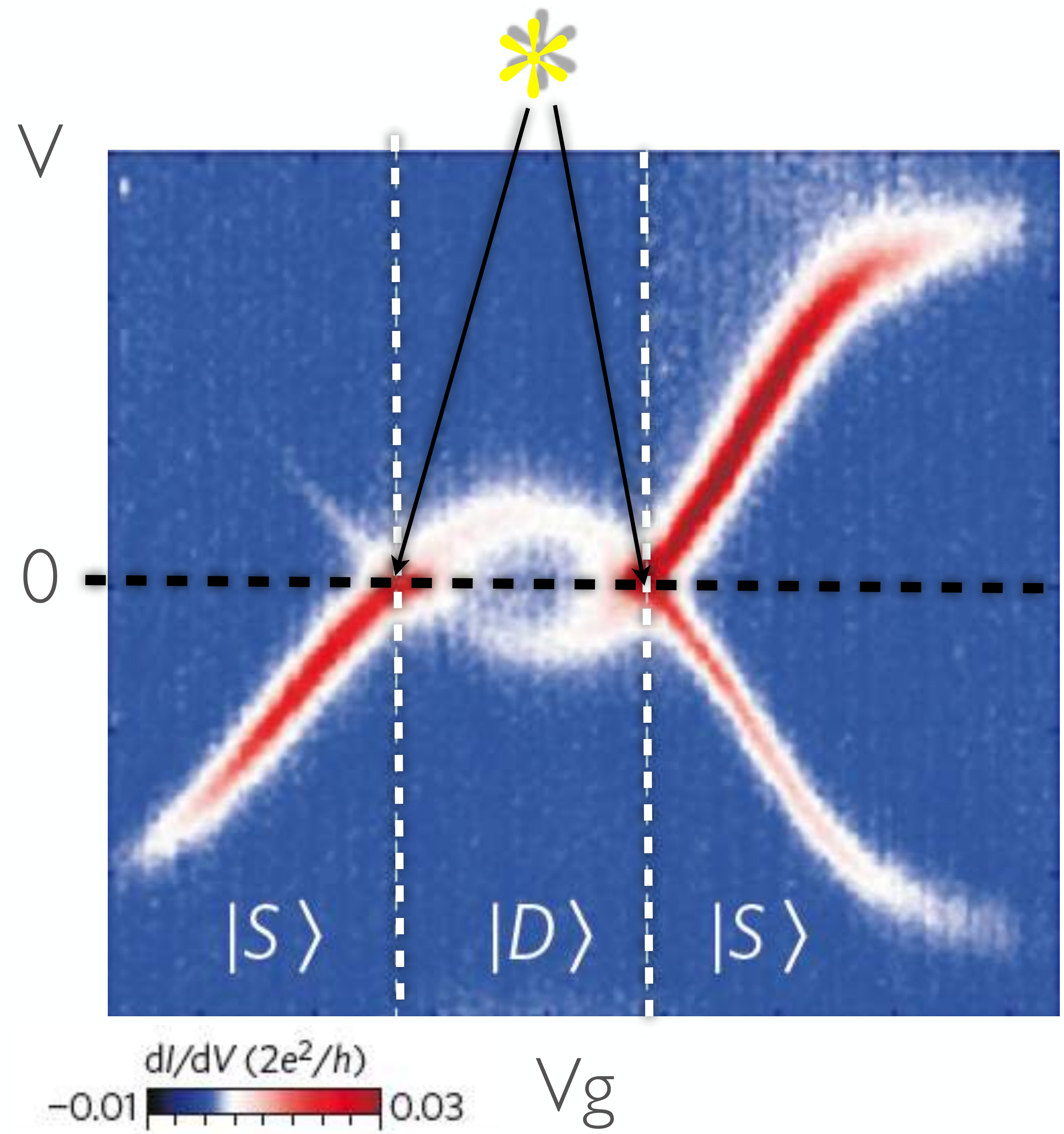
Spin-resolved Andreev levels and parity crossings in hybrid superconductor–semiconductor nanostructures

Eduardo J. H. Lee[1], Xiaocheng Jiang[2], Manuel Houzet[1], Ramón Aguado[3], Charles M. Lieber[2] and Silvano De Franceschi[1]*





Experimentally, this is seen as resonates in Andreev conductance (red lines) that **cross zero voltage**



Quantum phase transition: when the **subgap states cross zero energy**, the ground state changes parity

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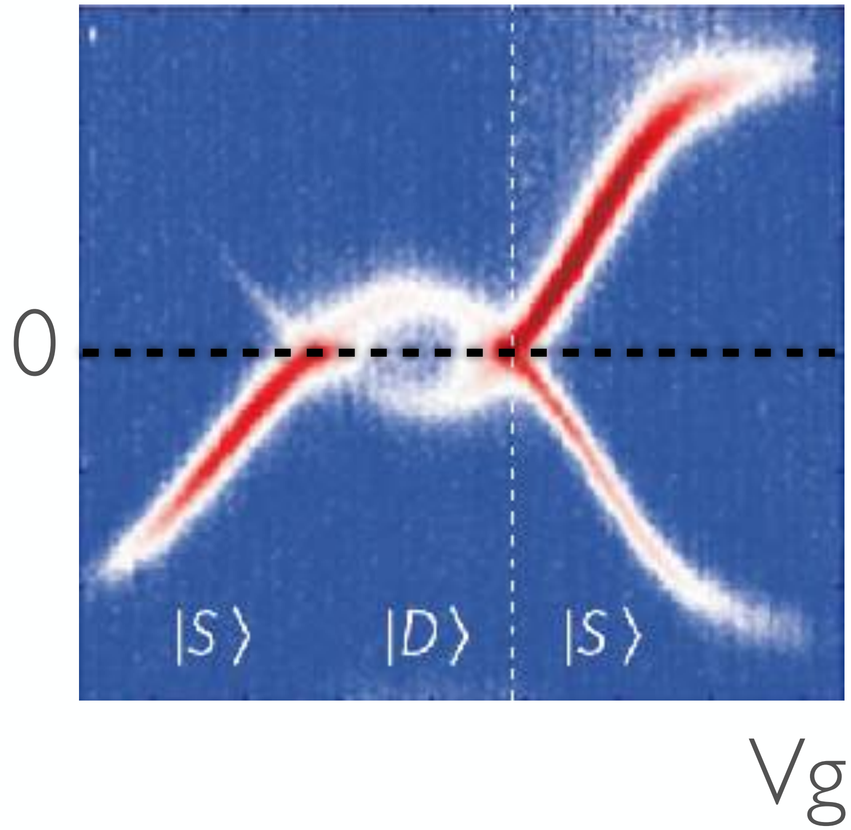
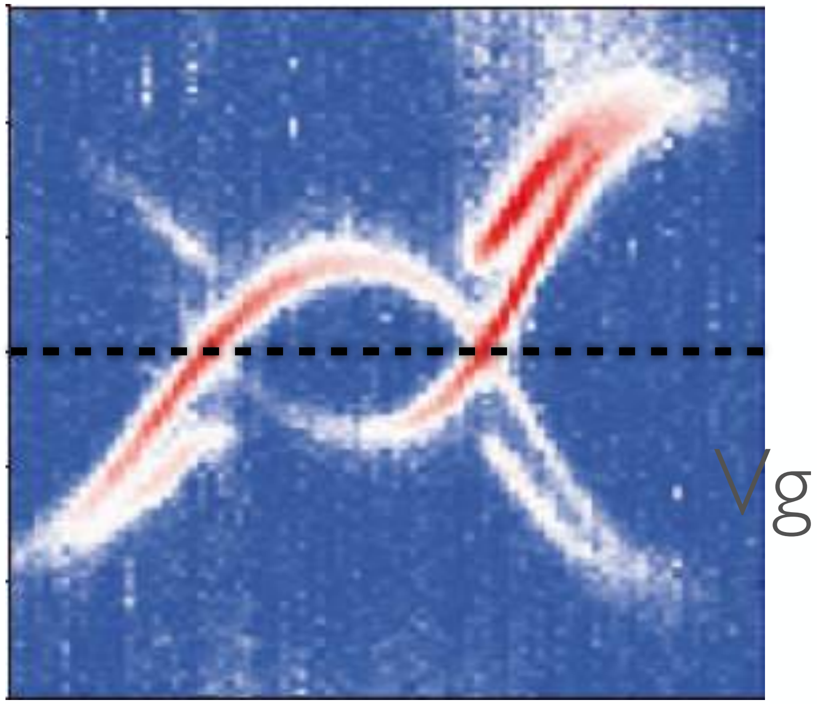
- PEAKS IN ANDREEV CONDUCTANCE dI/dV MEASURE THESE SUBGAP EXCITATIONS

$B = 0$

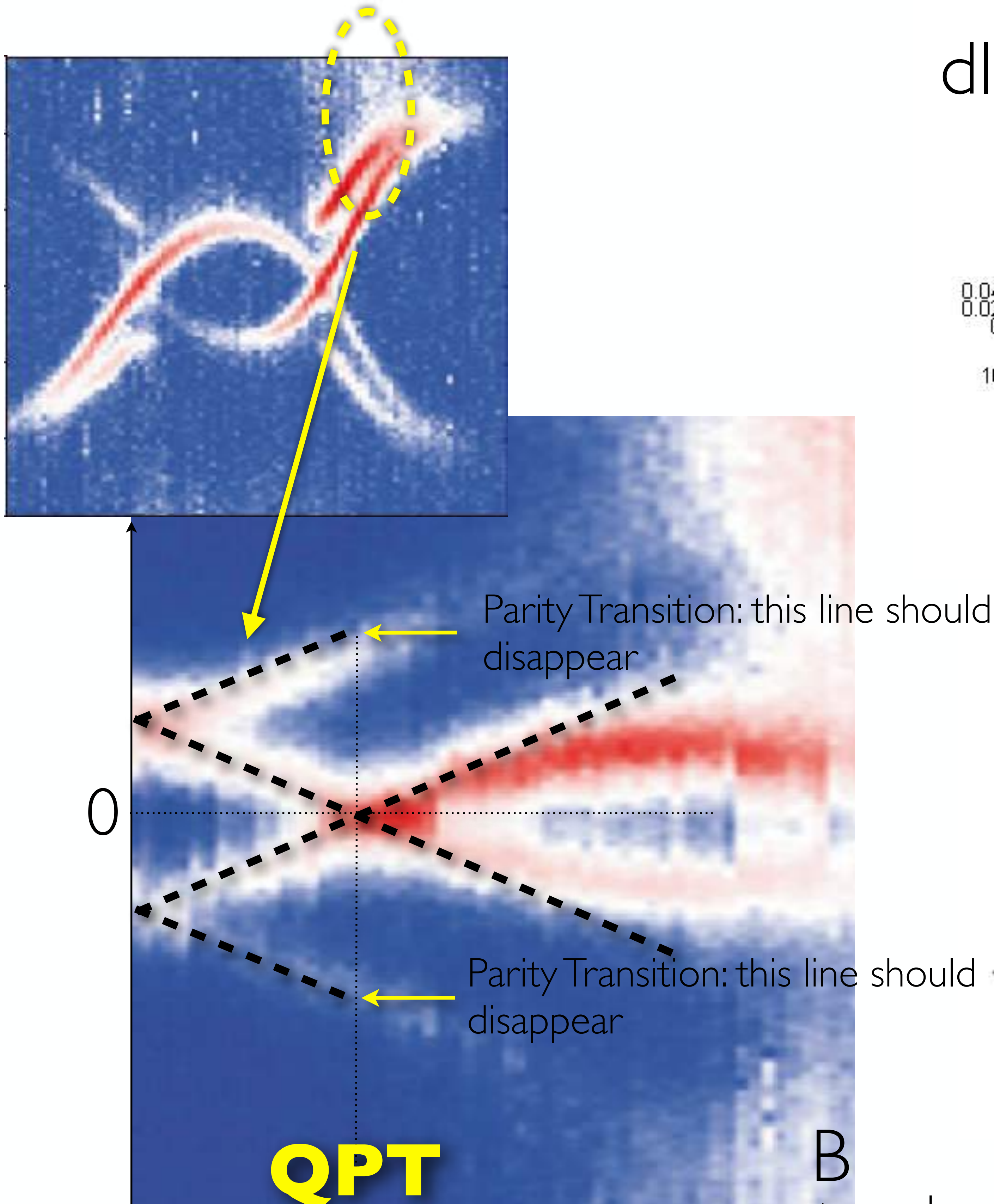


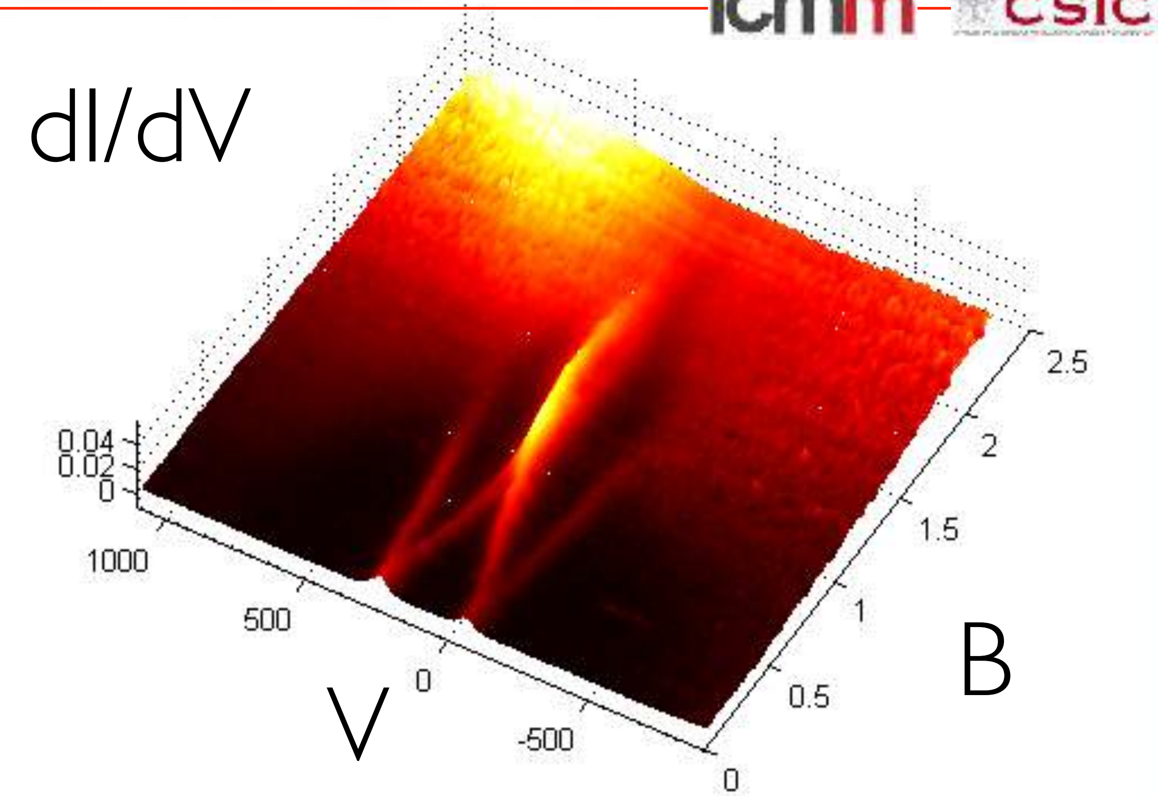
$B \neq 0$

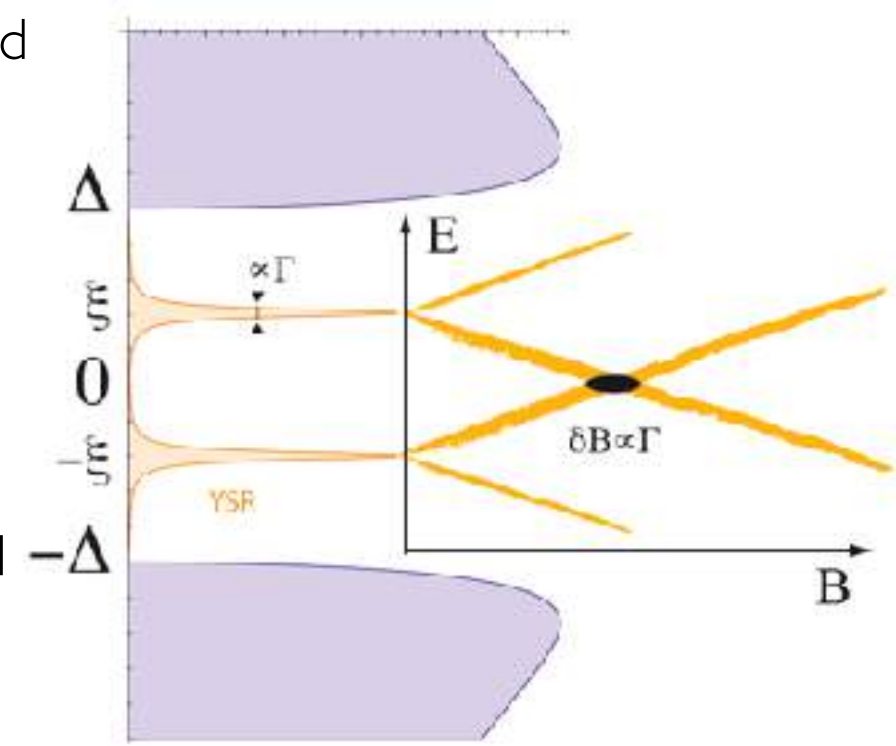


Zeeman splitting is **gate dependent**. Full agreement with theory.

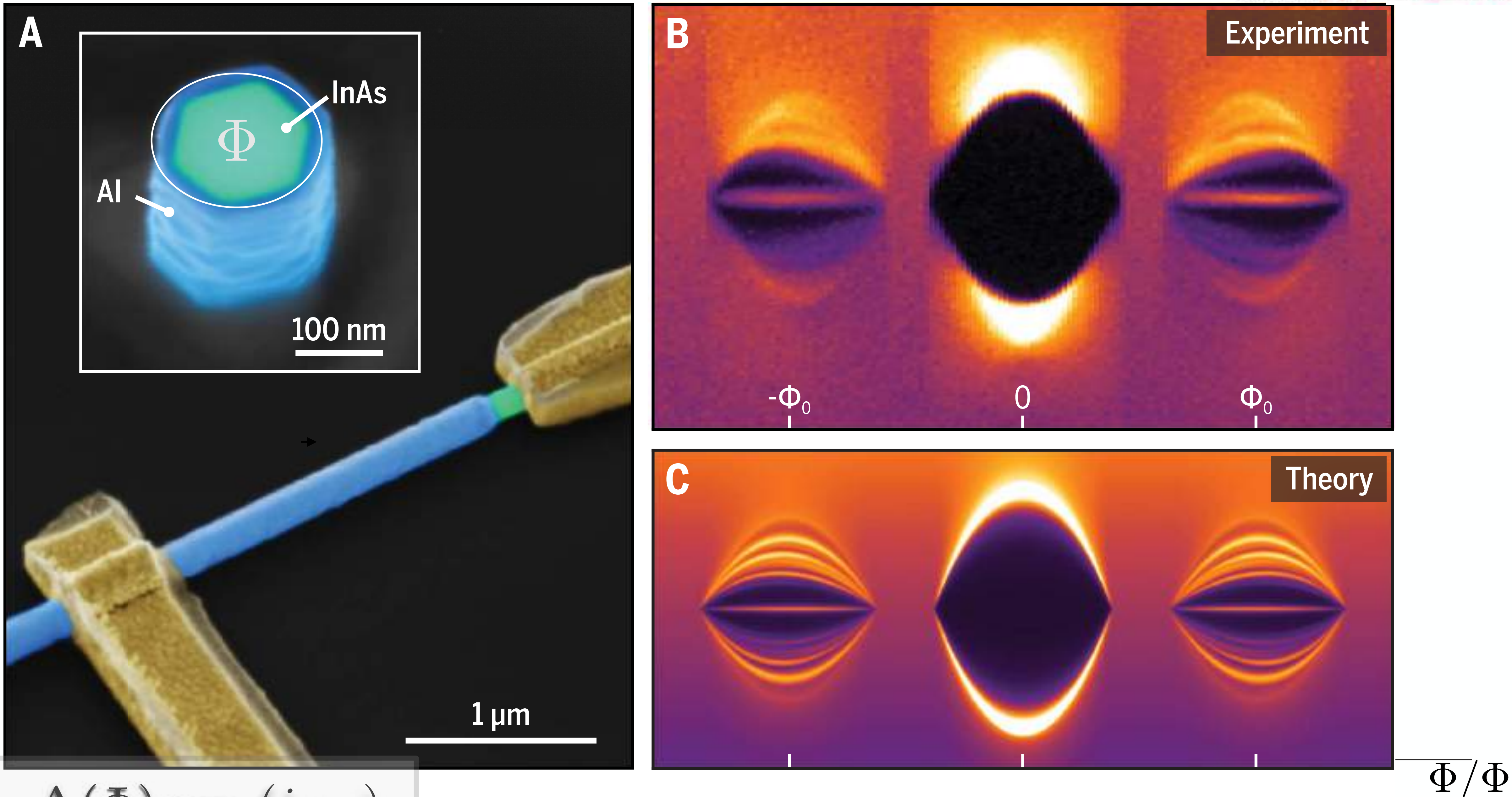
ZERO-BIAS ANOMALIES AS A FUNCTION OF MAGNETIC FIELD MIMIC MAJORANAS!







Lee, Jiang Houzet, Aguado, Lieber, De Franceschi, Nature Nano 9, 79 (2014)



$$\Delta(\varphi) = \Delta(\Phi)\exp{(in\varphi)}$$

Fluxoid

$$\frac{\hbar}{2e}\oint \partial_{\mathbf{r}}\varphi d\mathbf{r} = \Phi + \frac{m}{2e}\oint \mathbf{v}_s d\mathbf{r} = n\Phi_0$$

Little-Parks

$$v_s = \frac{\hbar}{mR}(n - \frac{\Phi}{\Phi_0})$$

RESEARCH ARTICLE

TOPOLOGICAL MATTER

Flux-induced topological superconductivity in full-shell nanowires

S. Vaitiekėnas[1], G. W. Winkler[2], B. van Heck[2], T. Karzig[2], M.-T. Deng[1], K. Flensberg[1], L. I. Glazman[3], C. Nayak[2], P. Krogstrup[1], R. M. Lutchyn[2]*, C. M. Marcus[1]*

Vaitiekėnas *et al.*, *Science* **367**, eaav3392 (2020) 27 March 2020

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Vaitiekėnas *et al.*, *Science* **367**, eaav3392 (2020)

RESEARCH ARTICLE

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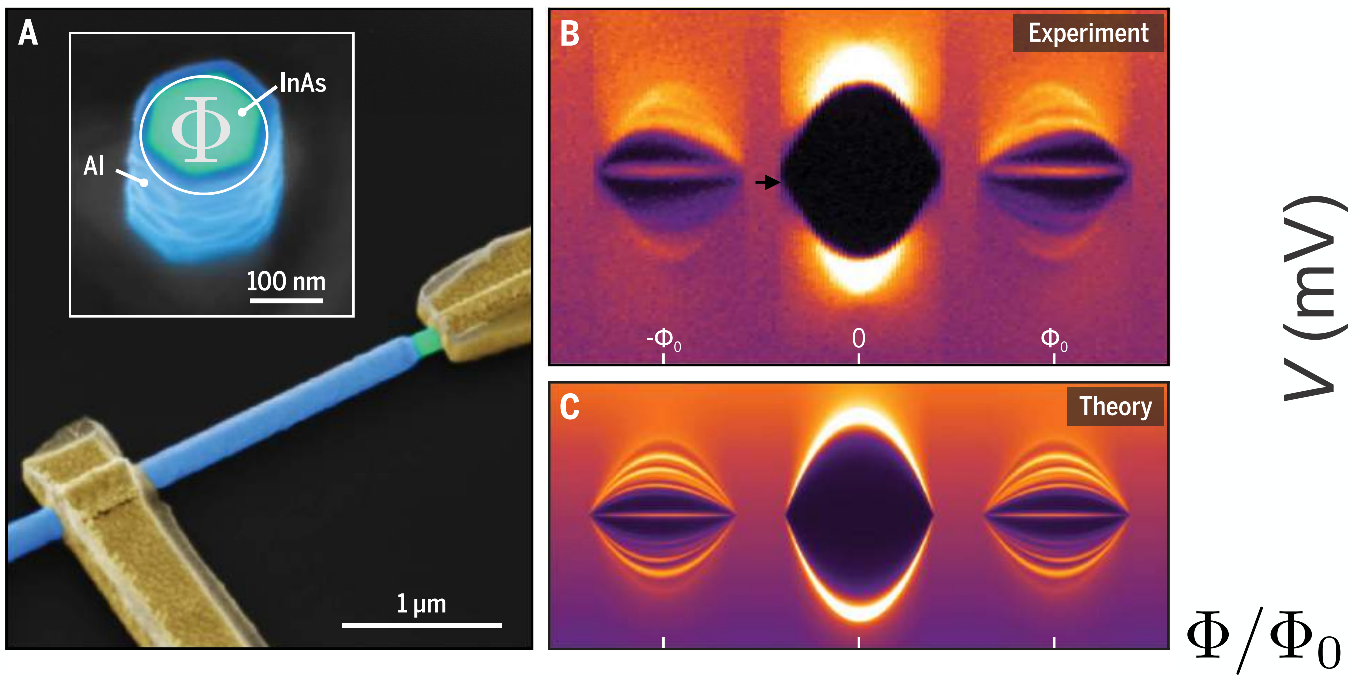
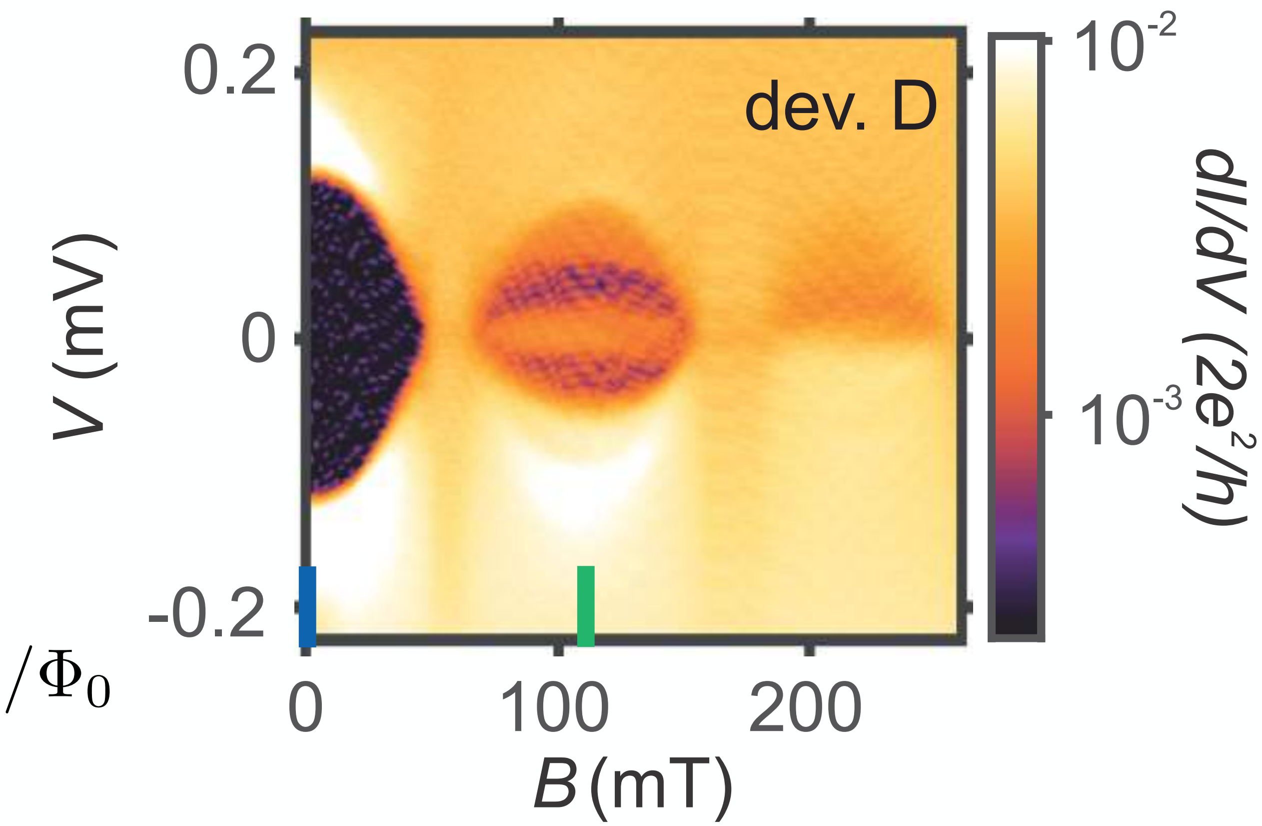


Valentini *et al.*, *Science* **373**, 82–88 (2021)

MESOSCOPIC PHYSICS

Nontopological zero-bias peaks in full-shell nanowires induced by flux-tunable Andreev states

Marco Valentini[1]*, Fernando Peñaranda[2], Andrea Hofmann[1]†, Matthias Brauns[1]‡, Robert Hauschild[1], Peter Krogstrup[3], Pablo San-Jose[2], Elsa Prada[2,4], Ramón Aguado[2]*, Georgios Katsaros[1]*



$$\Delta(\varphi) = \Delta(\Phi)\exp(in\varphi)$$

Fluxoid

$$\frac{\hbar}{2e}\oint \partial_{\mathbf{r}}\varphi d\mathbf{r} = \Phi + \frac{m}{2e}\oint \mathbf{v}_s d\mathbf{r} = n\Phi_0$$

Little-Parks

$$v_s = \frac{\hbar}{mR}\left(n - \frac{\Phi}{\Phi_0}\right)$$

442 | Nature | Vol 612 | 15 December 2022

Article

Majorana-like Coulomb spectroscopy in the absence of zero-bias peaks

https://doi.org/10.1038/s41586-022-05382-w

Received: 24 March 2022

Accepted: 22 September 2022

Marco Valentini[1,7]✉, Maksim Borovkov[1,2,7], Elsa Prada[3], Sara Martí-Sánchez[4], Marc Botifoll[4], Andrea Hofmann[1,6], Jordi Arbiol[4,5], Ramón Aguado[3], Pablo San-Jose[3]✉ & Georgios Katsaros[1]✉

Article **442** | Nature | Vol 612 | 15 December 2022

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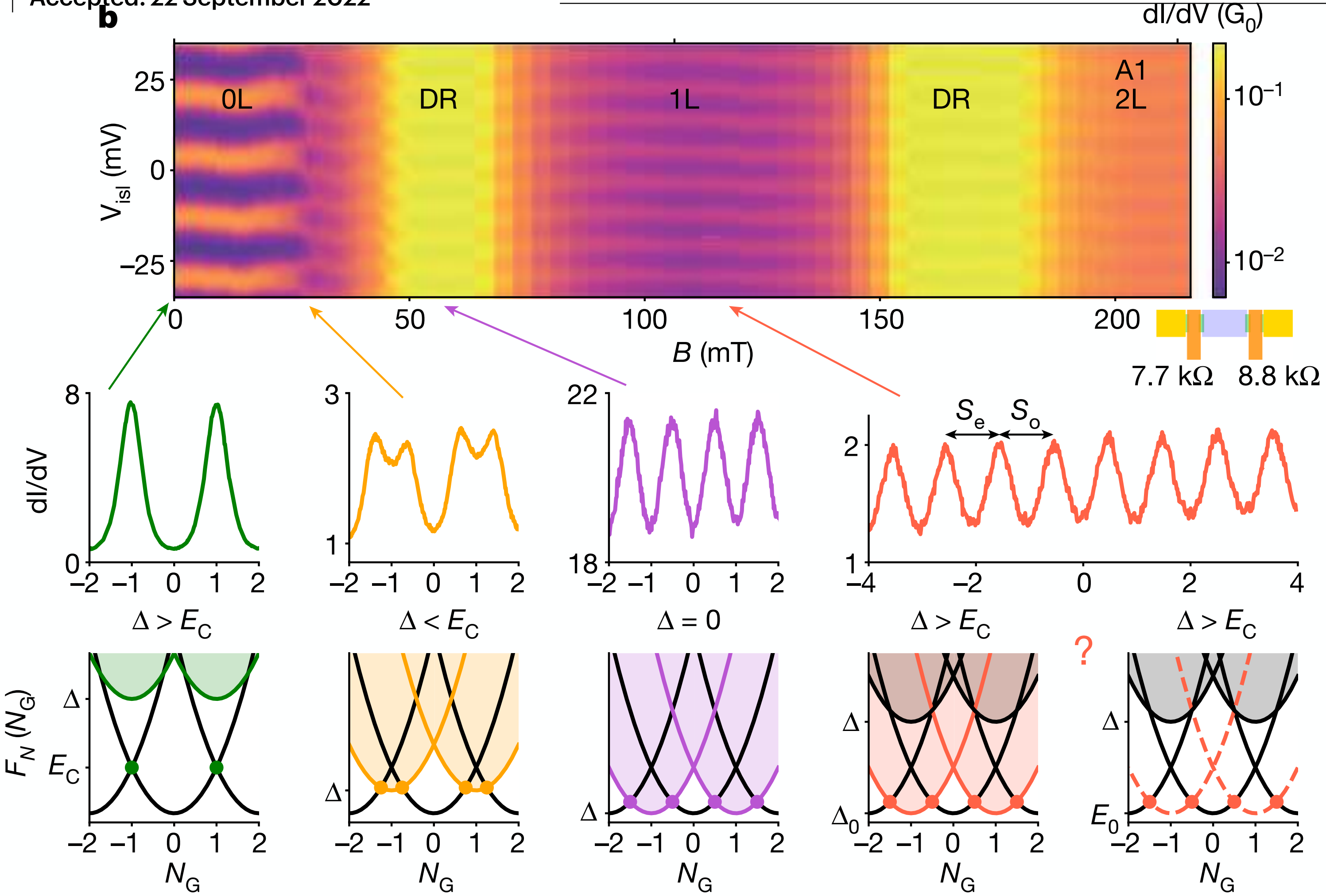
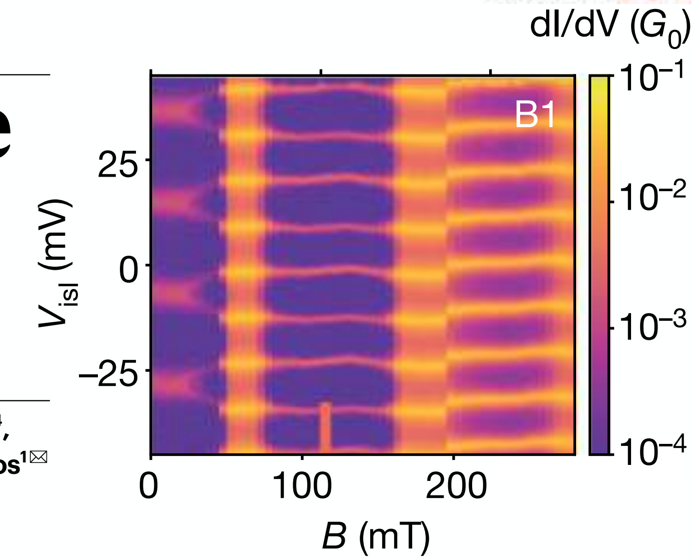
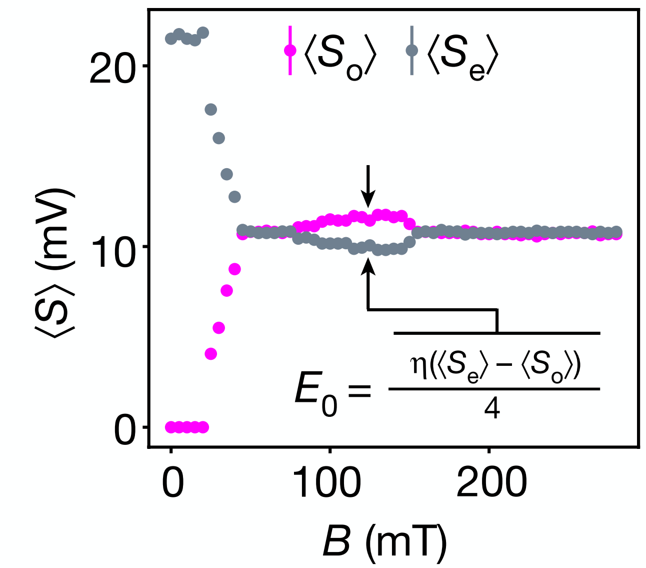
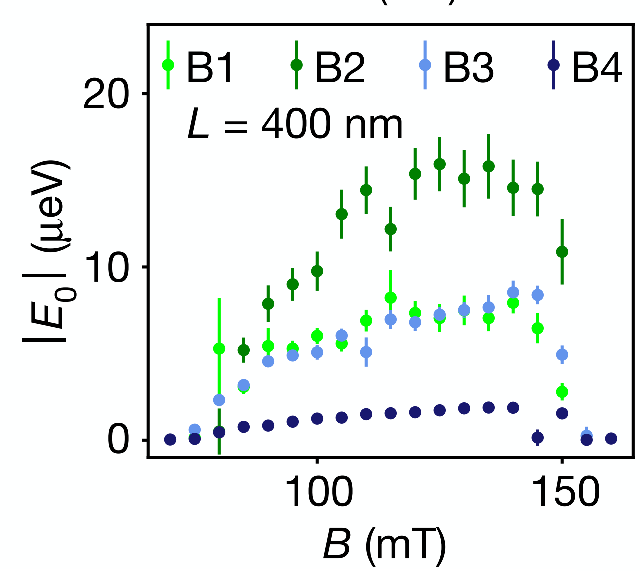








Andreev subgap levels can also mimic Majoranas in Coulomb blockade spectroscopy of floating nanowire islands with finite charging energy.

TAKE HOME MESSAGE I

- Distinguishing Majorana bound states from other subgap states from non-topological origin (Andreev,Shiba) in current spectroscopy experiments is probably hopeless.

- "Zero bias anomaly" endless controversy….


Chi l'ha visto ?

Ettore Majorana, ordinario di fisica teorica all' Università di Napoli, è misteriosamente scomparso dagli ultimi di marzo. Di anni 31, alto metri 1,70, snello, con capelli neri, occhi scuri, una lunga cicatrice sul dorso di una mano. Chi ne sapesse qualcosa è pregato di scrivere al R. P. E. Marianecci, Viale Regina Margherita 66 - Roma.

- So far, only "bad news" in the talk: Andreev/Shiba subgap levels can mimic Majoranas and it's almost impossible to unambiguously discern them using transport spectroscopy.

Good News, while figuring out how to create and detect Majoranas we got two very important outputs:

- Amazing improvement in material growth of semi-super hybrids
- Very good understanding of the physics of NS junctions, superconducting quantum dots, and their subgap physics in these hybrids

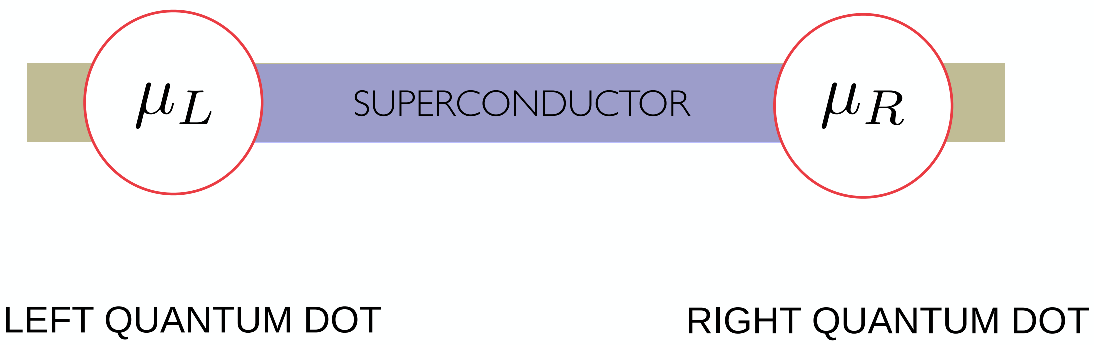
We can use this progress to explore novel qubits using these hybrid platforms: NEXT

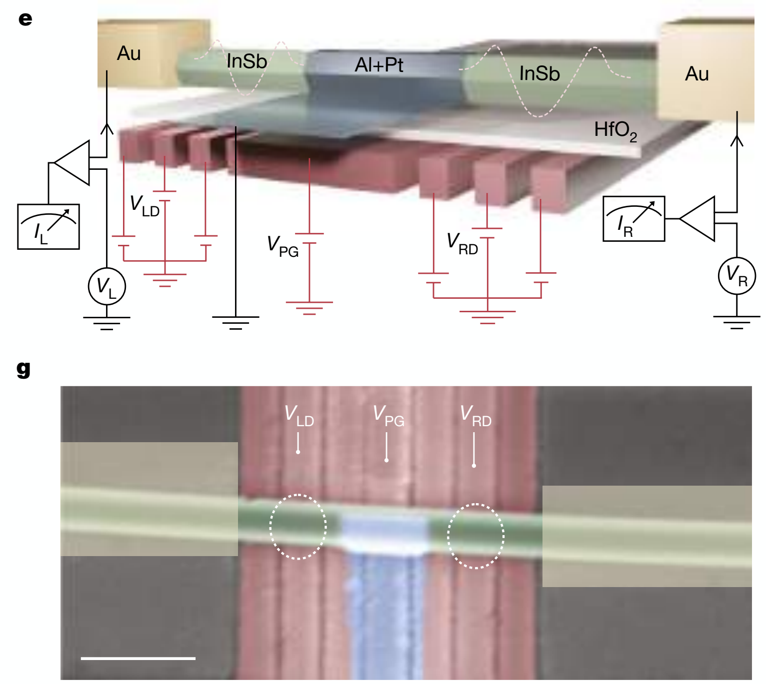
Nature | Vol 614 | 16 February 2023 | 445

Article

Realization of a minimal Kitaev chain in coupled quantum dots

Tom Dvir[1,2,4]✉, Guanzhong Wang[1,2,4], Nick van Loo[1,2,4], Chun-Xiao Liu[1,2], Grzegorz P. Mazur[1,2], Alberto Bordin[1,2], Sebastiaan L. D. ten Haaf[1,2], Ji-Yin Wang[1,2], David van Driel[1,2], Francesco Zatelli[1,2], Xiang Li[1,2], Filip K. Malinowski[1,2], Sasa Gazibegovic[3], Ghada Badawy[3], Erik P. A. M. Bakkers[3], Michael Wimmer[1,2] & Leo P. Kouwenhoven[1,2]✉





BACK TO MAJORANAS!

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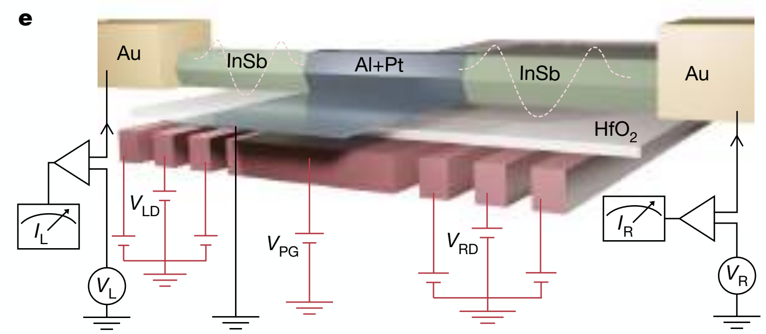
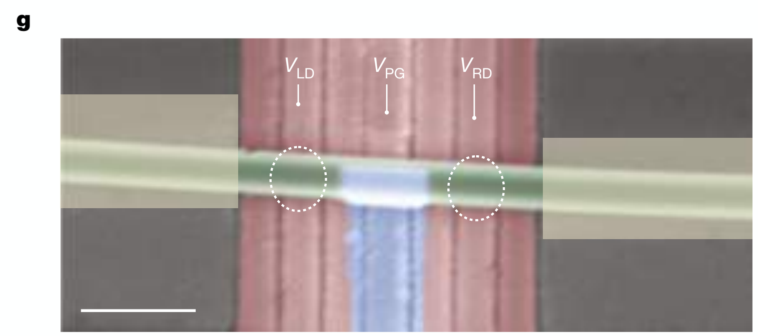
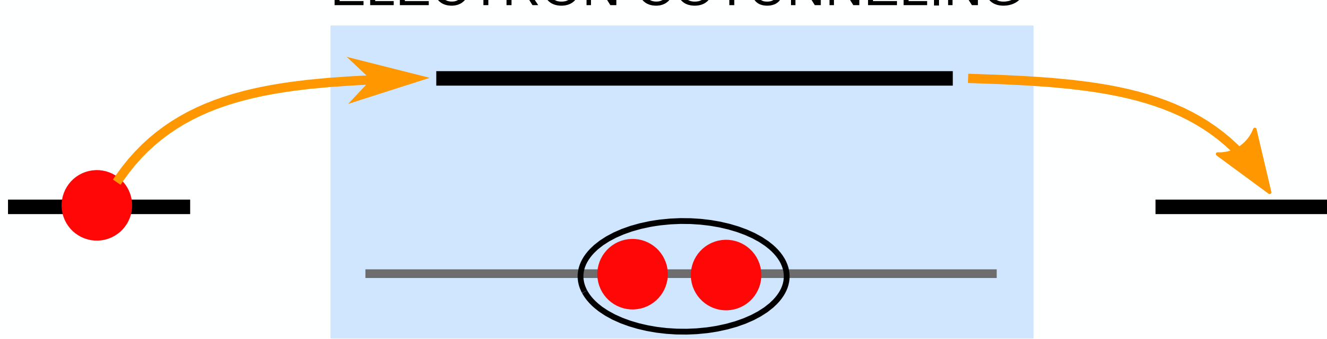


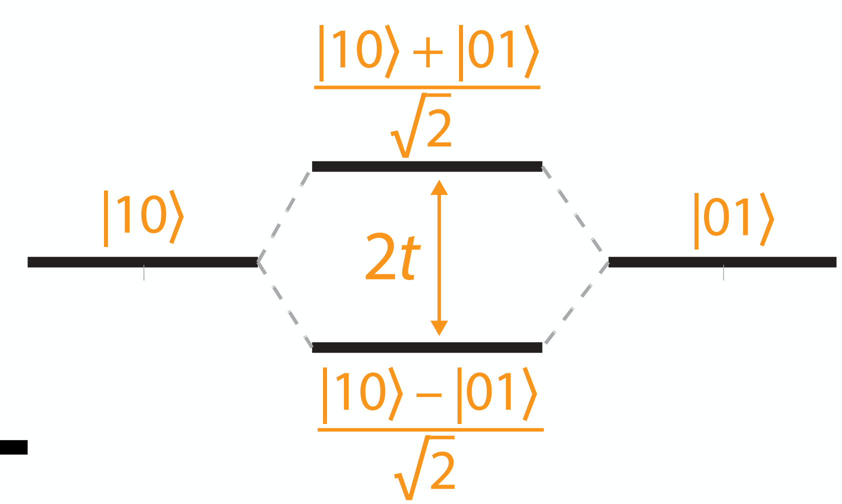


LEFT QUANTUM DOT

RIGHT QUANTUM DOT

ELECTRON COTUNNELING





ODD STATES

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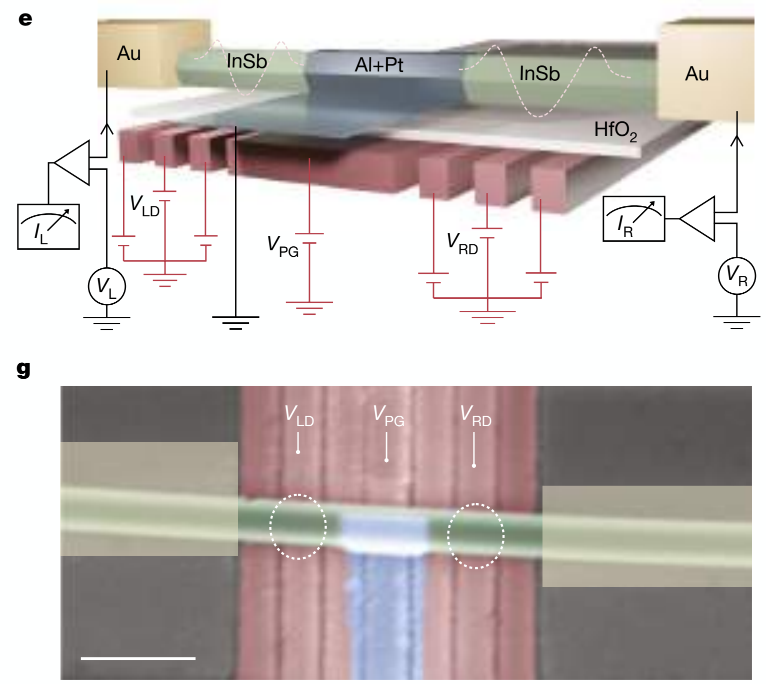
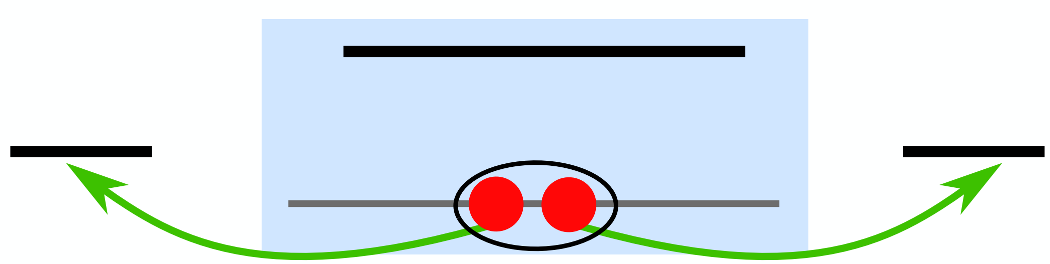
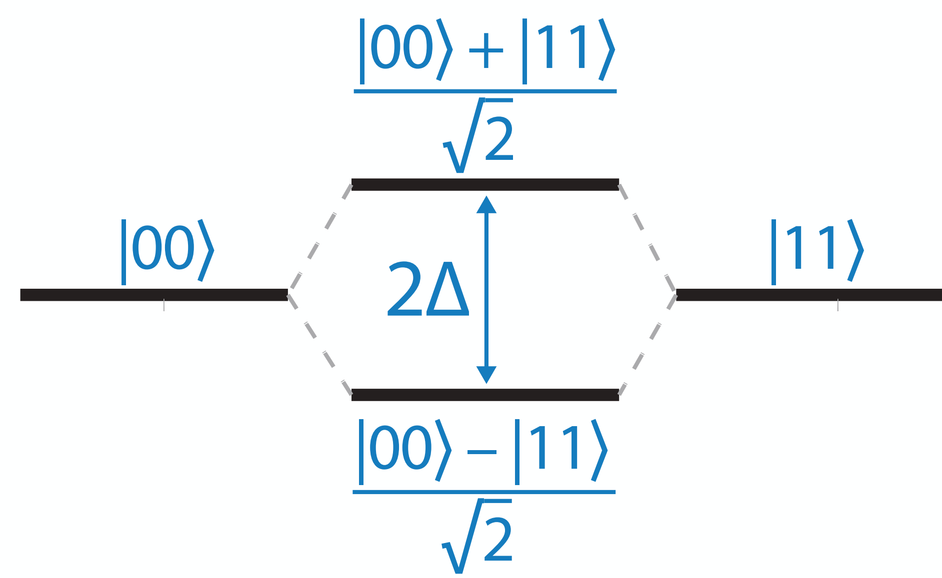
LEFT QUANTUM DOT

RIGHT QUANTUM DOT



COOPER PAIR SPLITTING





EVEN STATES

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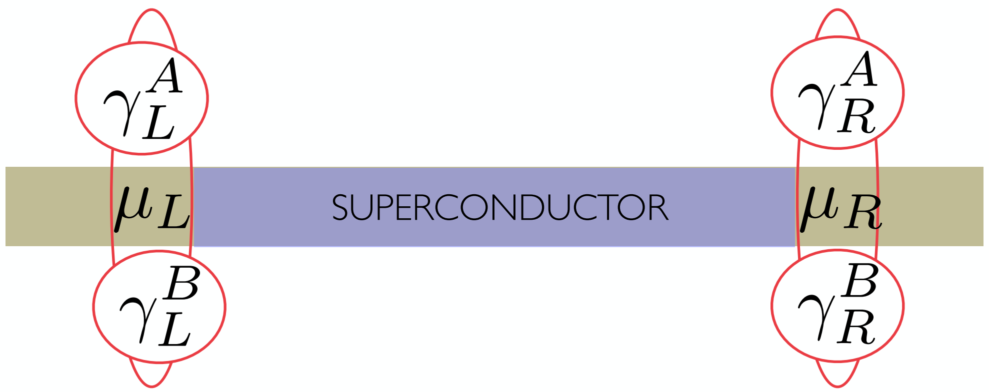

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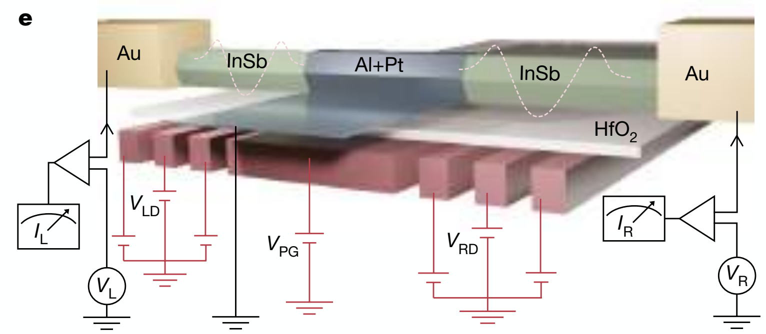

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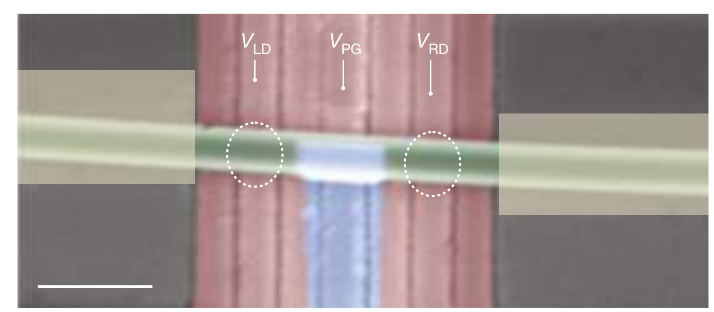

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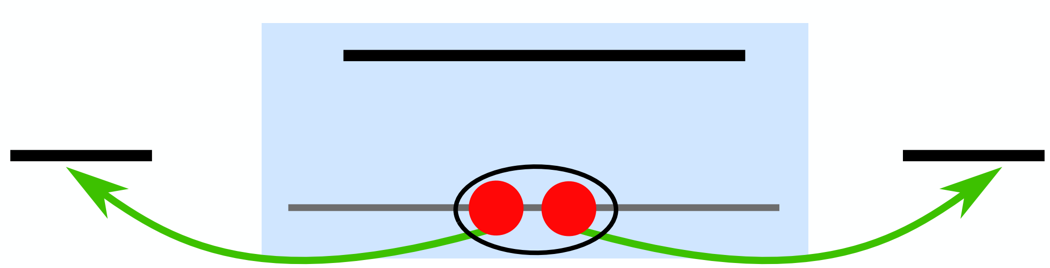

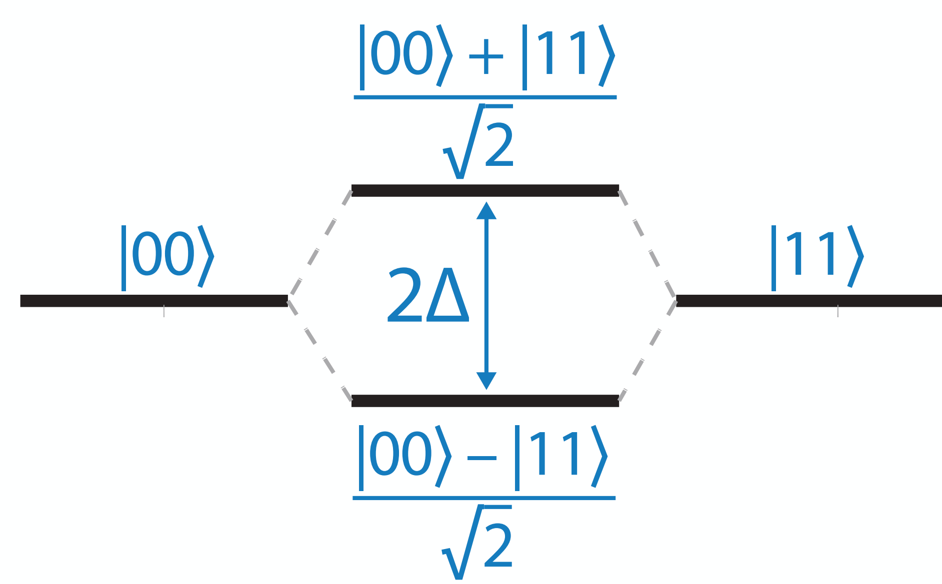

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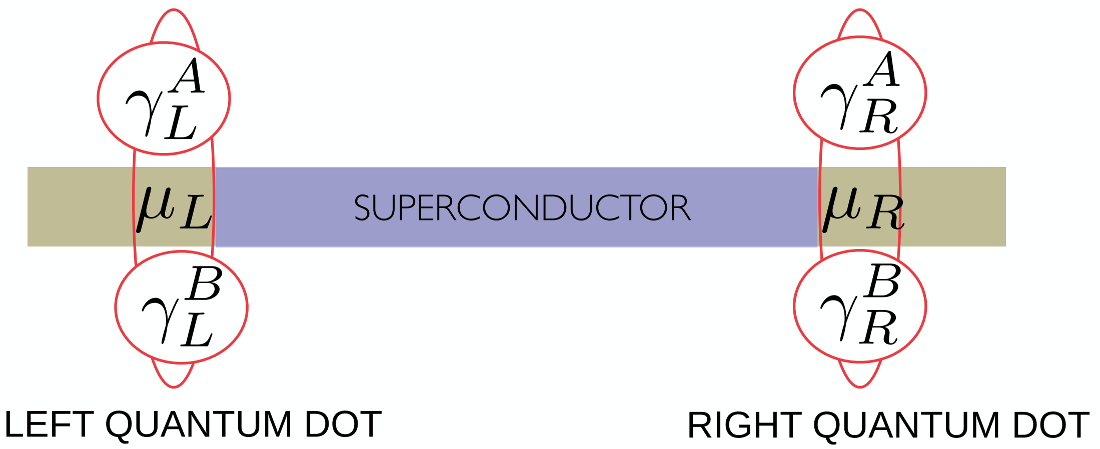
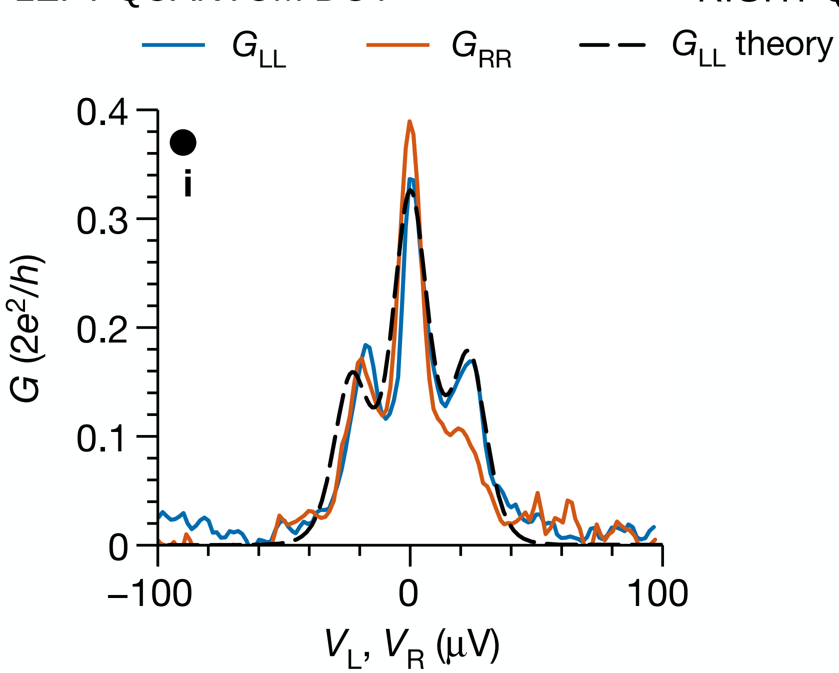
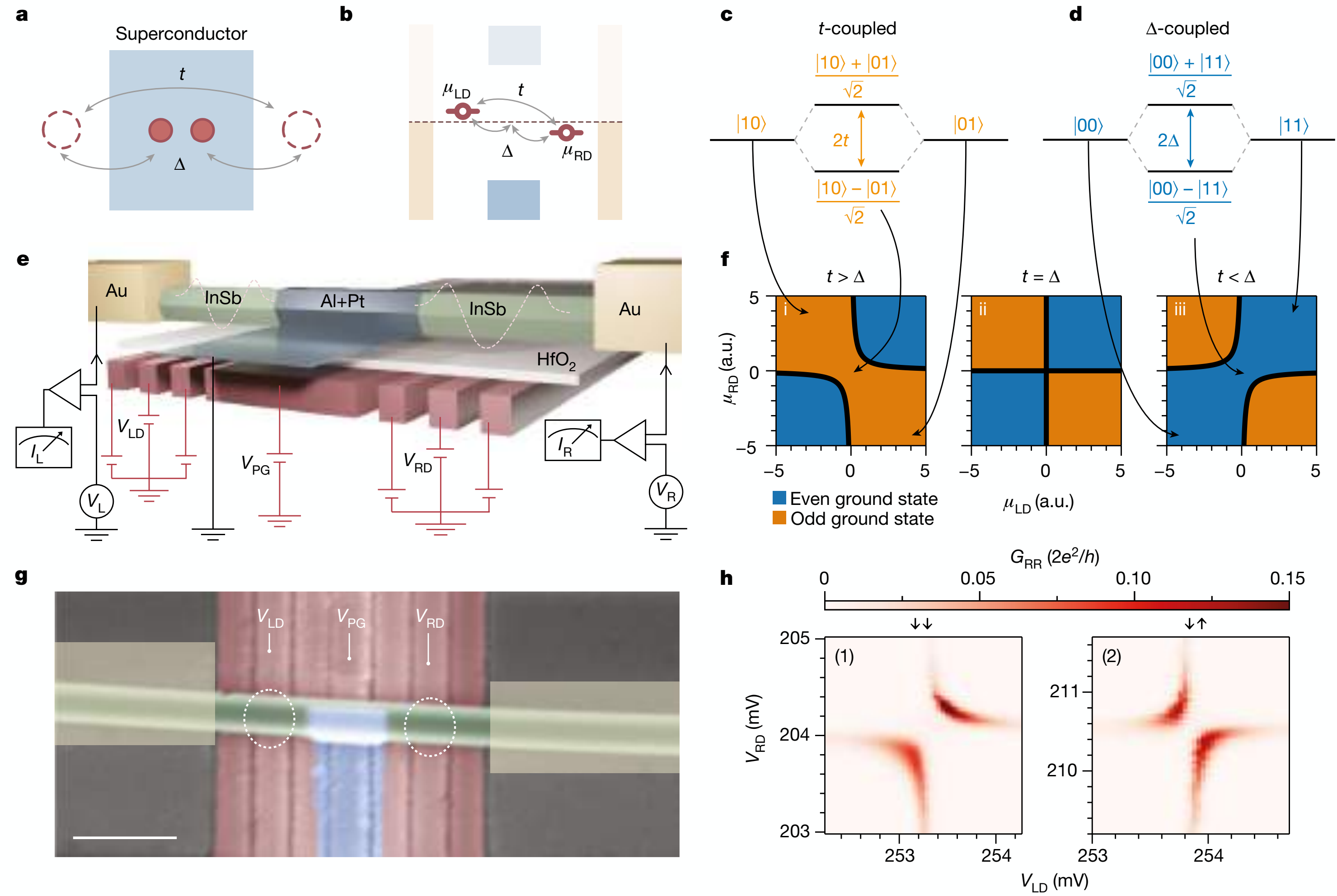






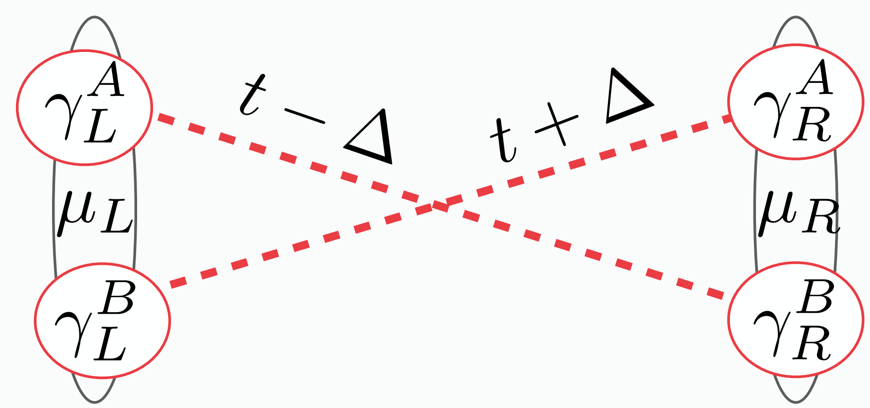
First theoretical proposal

PHYSICAL REVIEW B **86**, 134528 (2012)

Parity qubits and poor man's Majorana bound states in double quantum dots

Martin Leijnse and Karsten Flensberg

$$H_K = \mu_L c_L^\dagger c_L + \mu_R c_R^\dagger c_R + (t c_L^\dagger c_R + \Delta c_L c_R + \text{H.c.})$$



TWO-SITE KITAEV CHAIN USING A DOUBLE QUANTUM DOT SYSTEM

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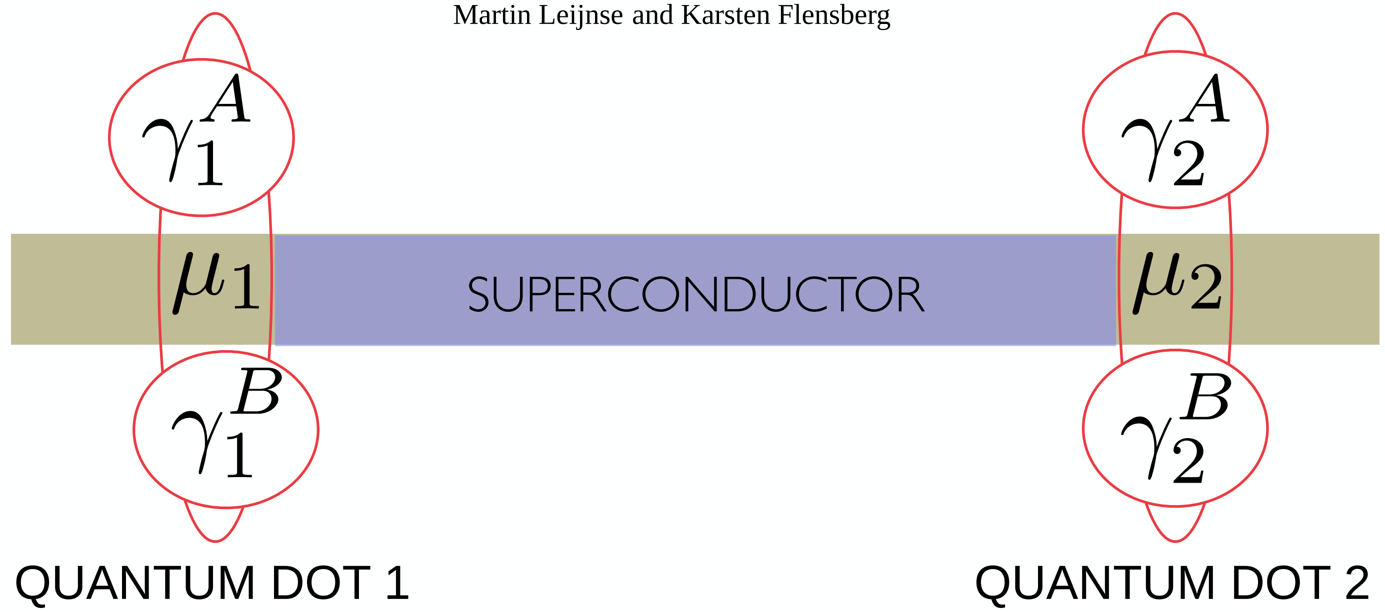

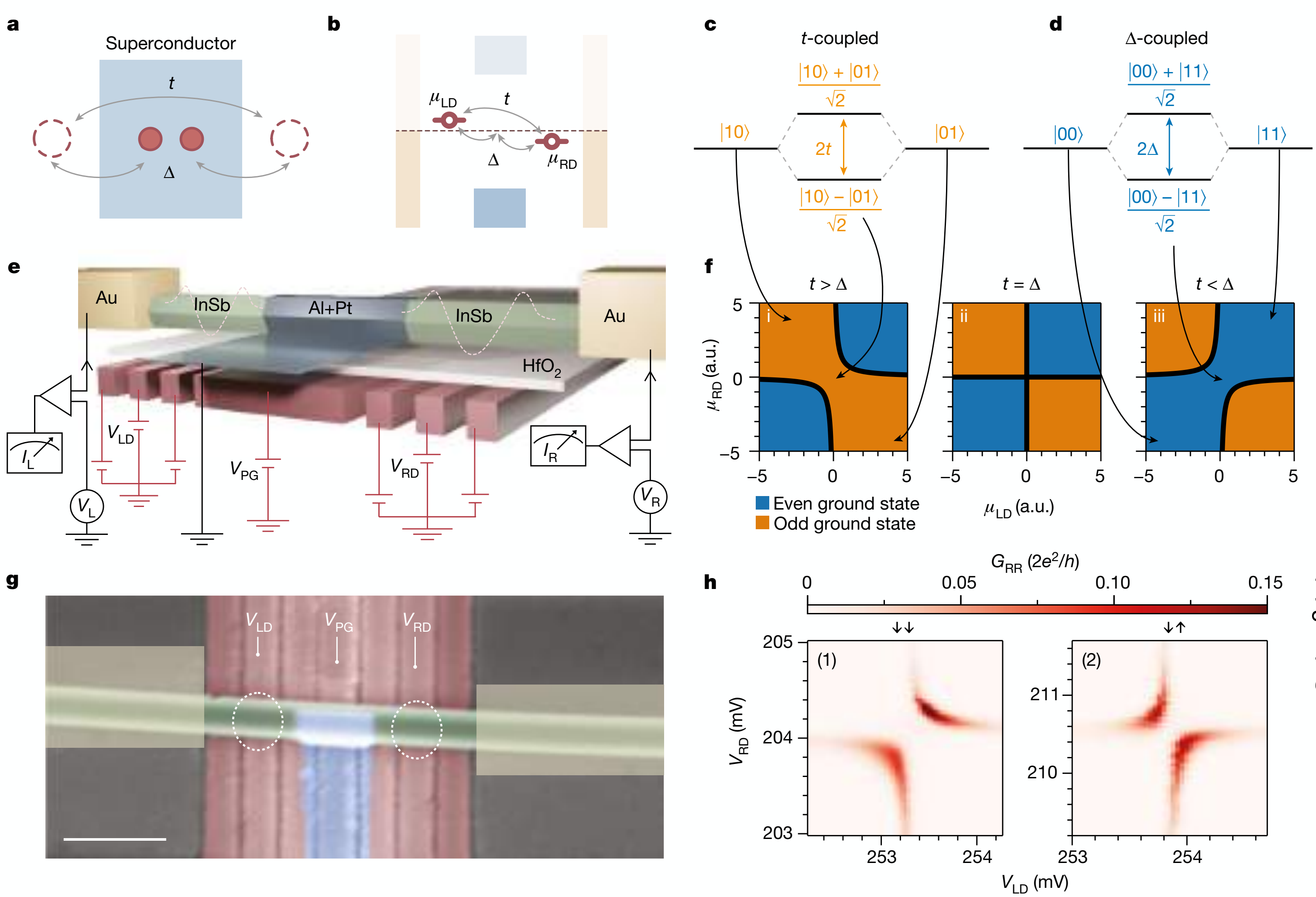

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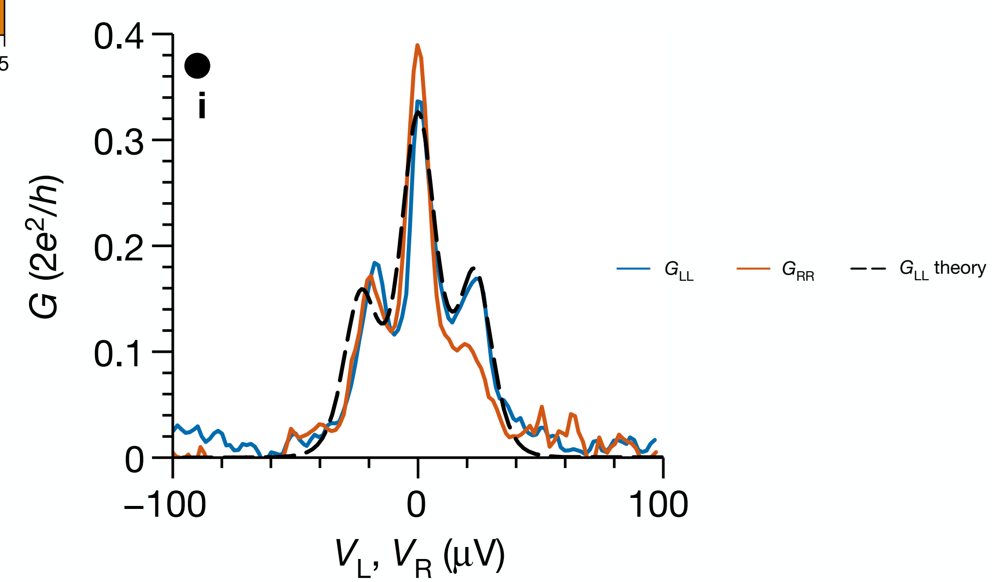
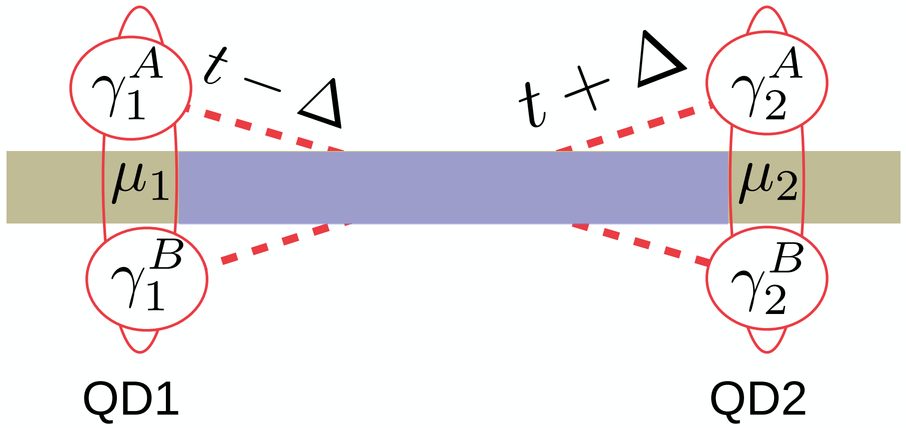
Nature | Vol 614 | 16 February 2023 | 445





$$H_K = \mu_1 c_1^\dagger c_1 + \mu_2 c_2^\dagger c_2 + (t c_1^\dagger c_2 + \Delta c_1 c_2 + \text{H.c.})$$

Single particle basis $$H_K = \frac{1}{2}\Psi^\dagger h_K \Psi$$

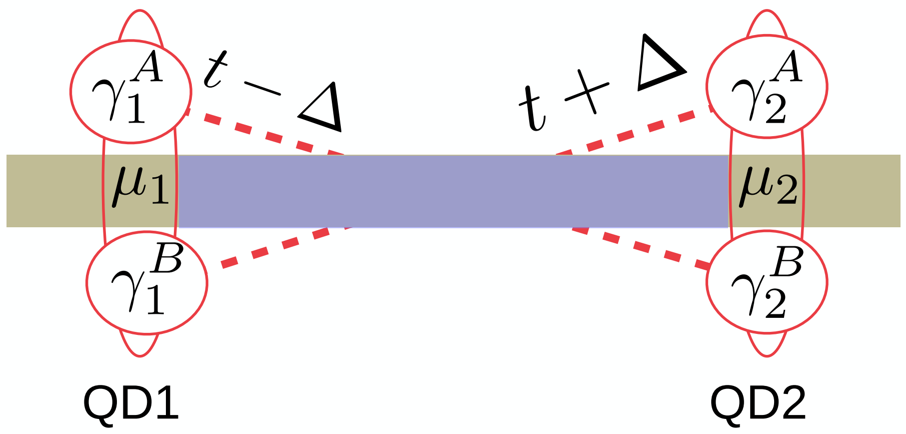
$$\Psi = (c_1, c_2, c_1^\dagger, c_2^\dagger)$$

$$h_K = \begin{pmatrix} \mu_1 & t & 0 & \Delta \\ t & \mu_2 & -\Delta & 0 \\ 0 & -\Delta & -\mu_1 & -t \\ \Delta & 0 & -t & -\mu_2 \end{pmatrix}$$

Zero energy solutions

$$\psi_1 = \frac{1}{\sqrt{2}}(1,0,1,0) \to \gamma_1^A = \frac{1}{\sqrt{2}}(c_1 + c_1^\dagger)$$

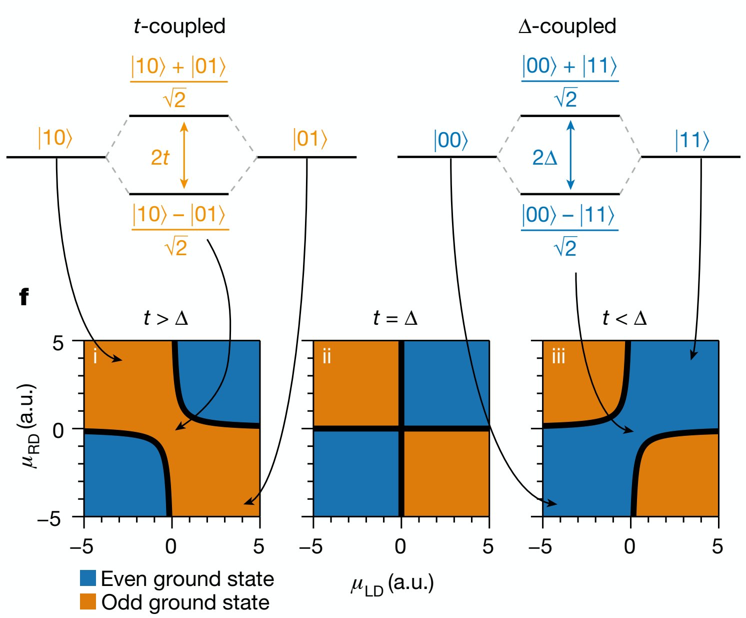
$$\psi_2 = \frac{i}{\sqrt{2}}(0,1,0,-1) \to \gamma_2^B = \frac{i}{\sqrt{2}}(c_2 - c_2^\dagger)$$



$$H_{\mathrm{K}} = \mu_1 c_1^\dagger c_1 + \mu_2 c_2^\dagger c_2 + (t c_1^\dagger c_2 + \Delta c_1 c_2 + \mathrm{H.c.})$$

Many body basis

$$|10\rangle, |01\rangle, |00\rangle, |11\rangle$$



$$H_K = \begin{pmatrix} \mu_1 & t & 0 & 0 \\ t & \mu_2 & 0 & 0 \\ 0 & 0 & 0 & \Delta \\ 0 & 0 & \Delta & \mu_1+\mu_2 \end{pmatrix}$$

$$\mu = \frac{(\mu_1+\mu_2)}{2} \qquad \delta = \frac{(\mu_1-\mu_2)}{2}$$

Odd

$$\epsilon_O^{\pm} = -\mu \pm \sqrt{t^2+\delta^2}$$

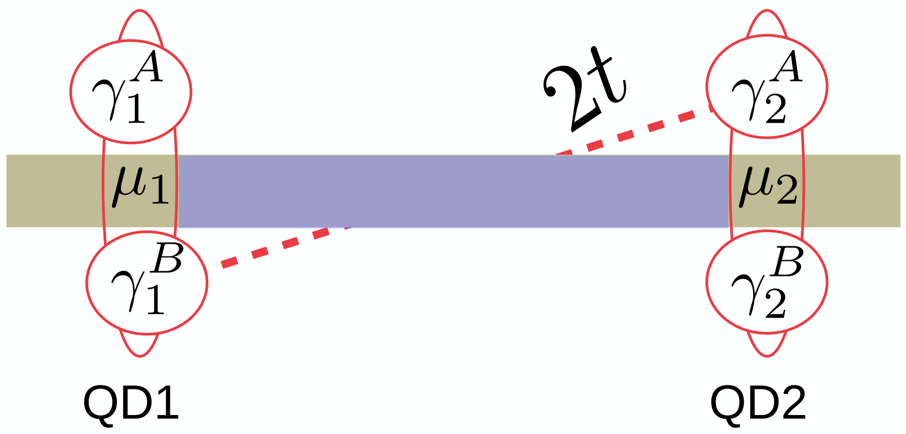
$$|O\pm\rangle = \frac{1}{2}(|10\rangle \pm |01\rangle)$$

Even

$$\epsilon_E^{\pm} = -\mu \pm \sqrt{\Delta^2+\mu^2}$$

$$|E\pm\rangle = \frac{1}{2}(|00\rangle \pm |11\rangle)$$

TWO-SITE KITAEV CHAIN USING A DOUBLE QUANTUM DOT SYSTEM

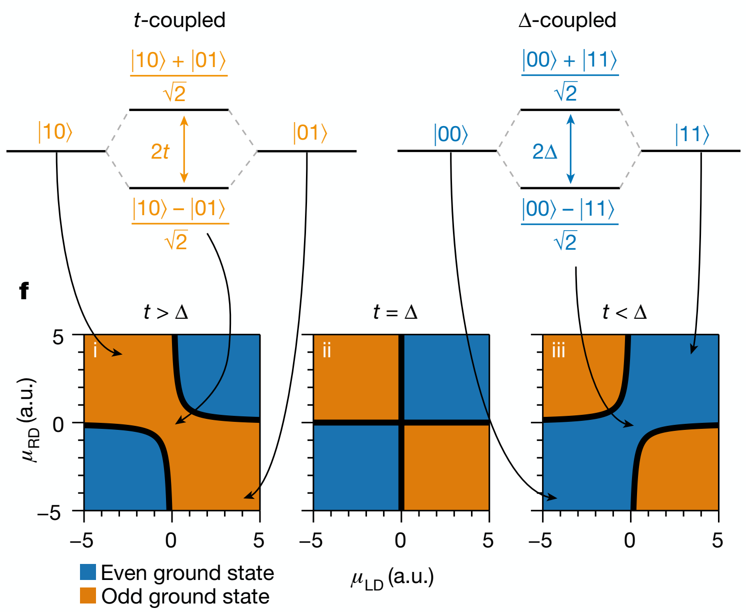


$$H_K = \mu_1 c_1^\dagger c_1 + \mu_2 c_2^\dagger c_2 + (t c_1^\dagger c_2 + \Delta c_1 c_2 + \text{H.c.})$$

Sweet spot

$$\mu_1 = \mu_2 = 0 \qquad \Delta = t$$

$$\epsilon_O^\pm = \epsilon_E^\pm = \pm t = \pm \Delta$$



$$\mu = \frac{(\mu_1 + \mu_2)}{2} \qquad \delta = \frac{(\mu_1 - \mu_2)}{2}$$

Degenerate even/odd with Majorana zero energy excitations

$$f = \frac{(\gamma_1^A - i\gamma_2^B)}{2} \qquad n = f^\dagger f = (1 - i\gamma_1^A\gamma_2^B)/2$$

$$n|O\pm\rangle = |O\pm\rangle \qquad \gamma_1^A|E\pm\rangle = |O\pm\rangle$$

$$n|E\pm\rangle = 0$$

Odd

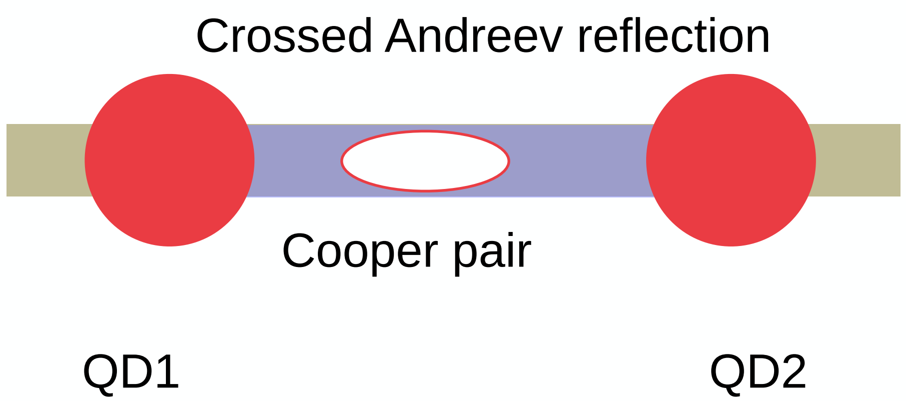
$$\epsilon_O^\pm = -\mu \pm \sqrt{t^2 + \delta^2}$$

$$|O\pm\rangle = \frac{1}{2}(|10\rangle \pm |01\rangle)$$

Even

$$\epsilon_E^\pm = -\mu \pm \sqrt{\Delta^2 + \mu^2}$$

$$|E\pm\rangle = \frac{1}{2}(|00\rangle \pm |11\rangle)$$



$$H_{\mathrm{K}} = \mu_1 c_1^\dagger c_1 + \mu_2 c_2^\dagger c_2 + (t c_1^\dagger c_2 + \Delta c_1 c_2 + \mathrm{H.c.})$$

Many body basis

$$|10\rangle, |01\rangle, |00\rangle, |11\rangle$$

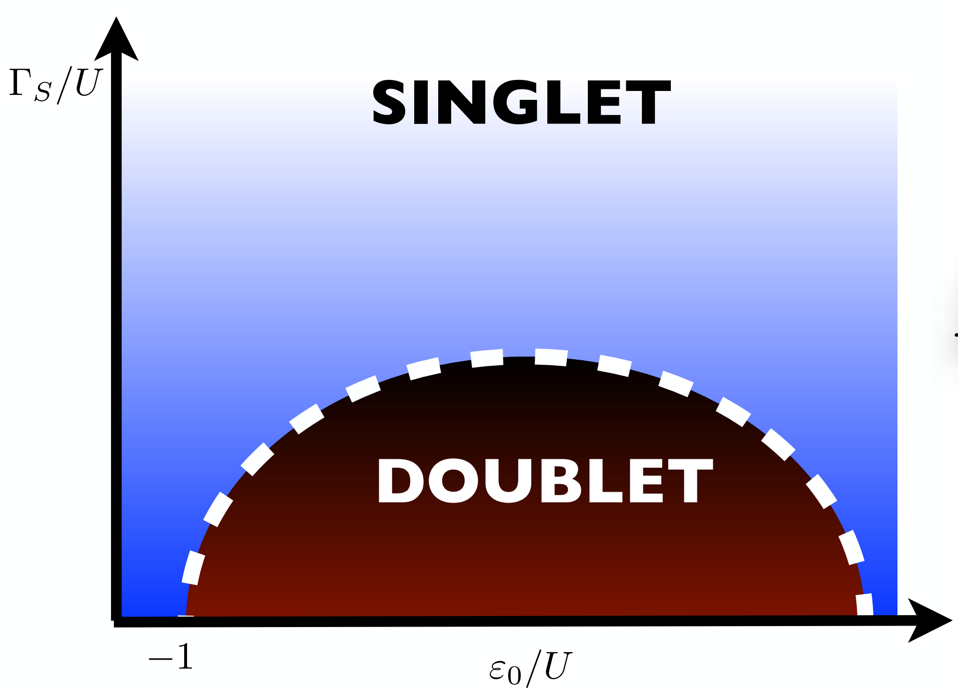
Analogy between a local spin qubit and a nonlocal charge qubit based on DQDs in the language of the large gap superconducting Anderson model

$$H_K = \begin{pmatrix} \mu_1 & t & 0 & 0 \\ t & \mu_2 & 0 & 0 \\ 0 & 0 & 0 & \Delta \\ 0 & 0 & \Delta & \mu_1 + \mu_2 \end{pmatrix}$$

Doublet

$$H_D = \begin{pmatrix} \epsilon_\uparrow & 0 & 0 & 0 \\ 0 & \epsilon_\downarrow & 0 & 0 \\ 0 & 0 & 0 & \Gamma_S \\ 0 & 0 & \Gamma_S & \epsilon_\uparrow + \epsilon_\downarrow + U \end{pmatrix}$$

Singlet



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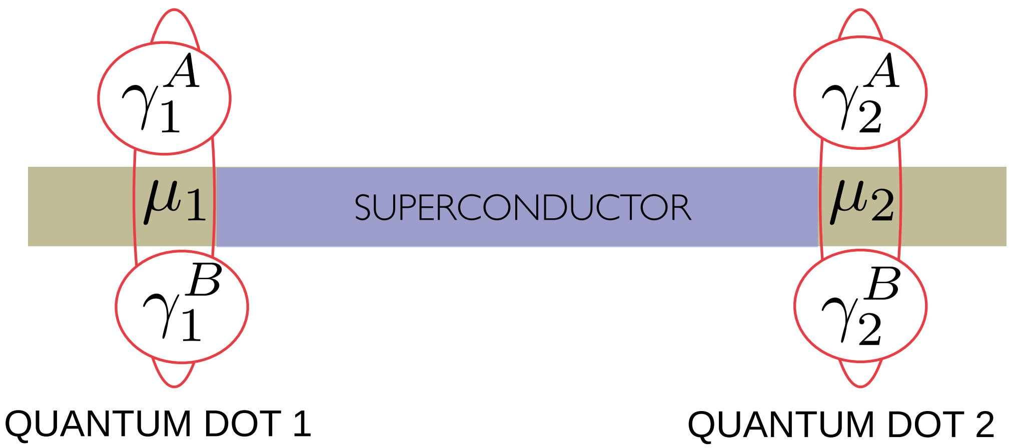
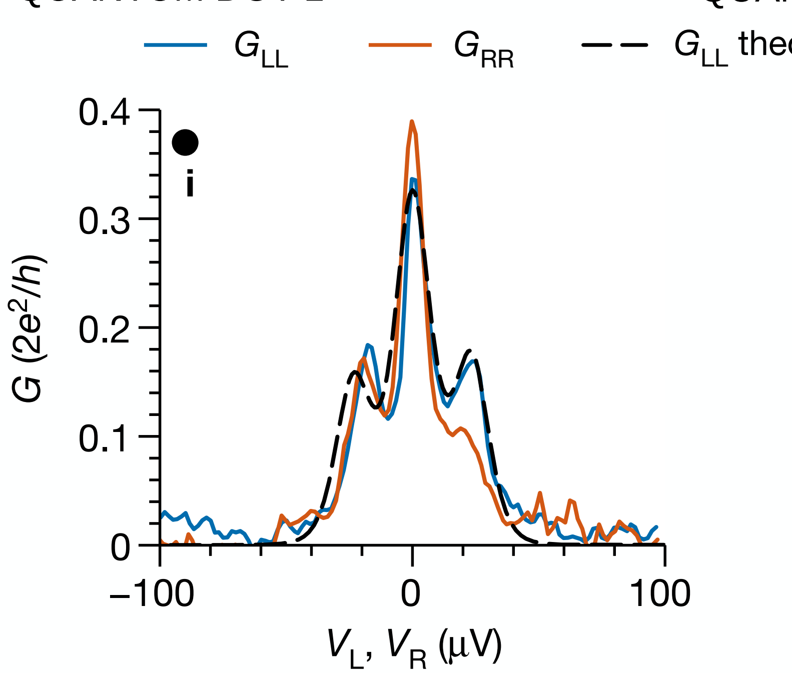
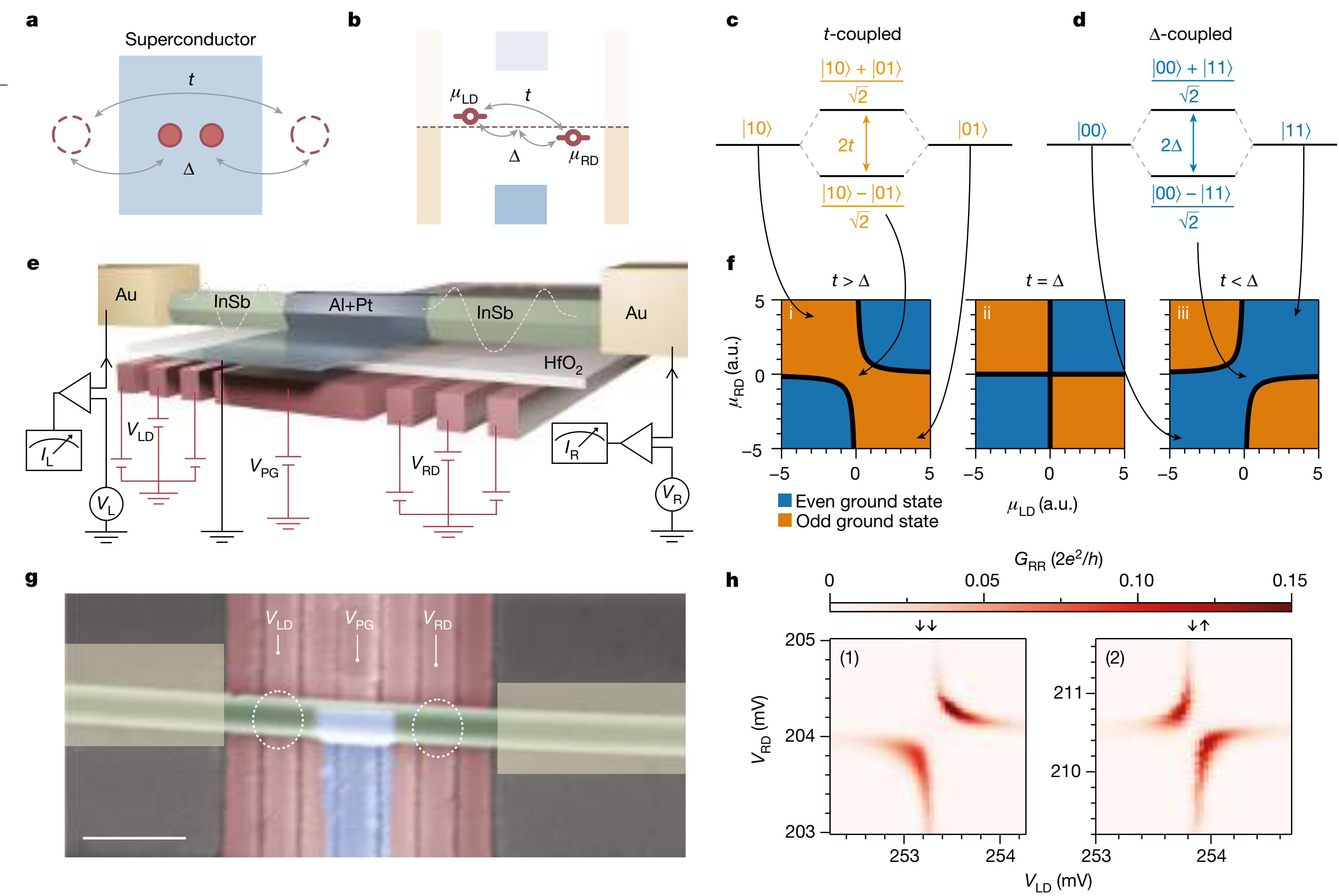
Article

Realization of a minimal Kitaev chain in coupled quantum dots

Tom Dvir[1,2,4]✉, Guanzhong Wang[1,2,4], Nick van Loo[1,2,4], Chun-Xiao Liu[1,2], Grzegorz P. Mazur[1,2], Alberto Bordin[1,2], Sebastiaan L. D. ten Haaf[1,2], Ji-Yin Wang[1,2], David van Driel[1,2], Francesco Zatelli[1,2], Xiang Li[1,2], Filip K. Malinowski[1,2], Sasa Gazibegovic[3], Ghada Badawy[3], Erik P. A. M. Bakkers[3], Michael Wimmer[1,2] & Leo P. Kouwenhoven[1,2]✉







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Article

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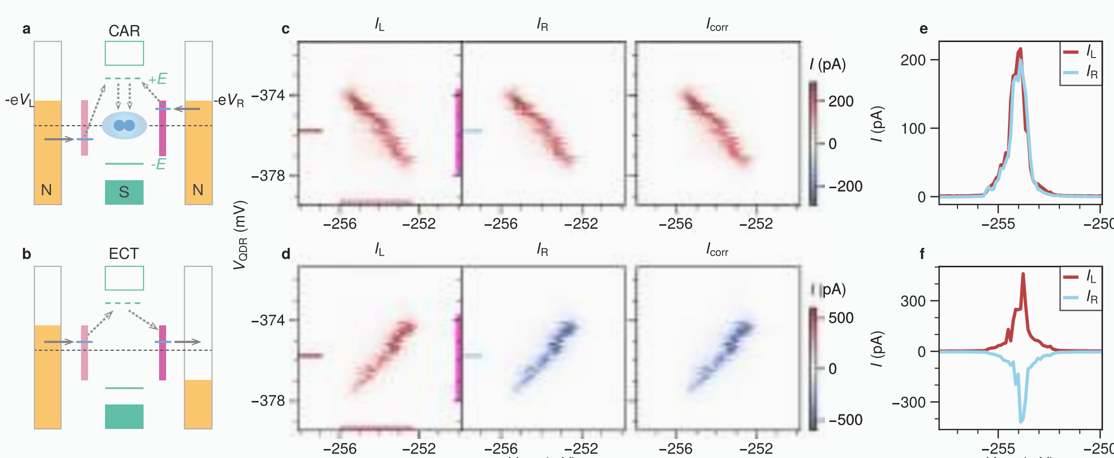
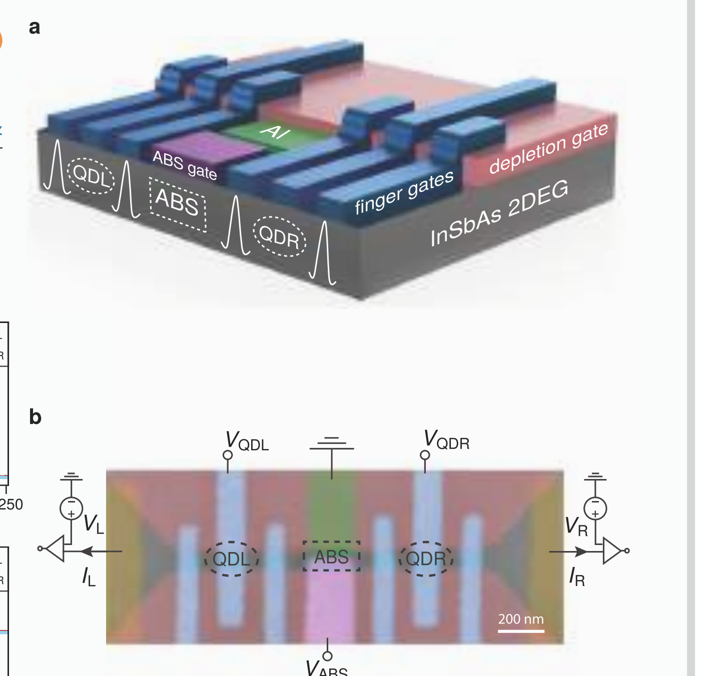
Triplet correlations in Cooper pair splitters realized in a two-dimensional electron gas





Invited talk by Srijit Goswami in Minicolloquium 54