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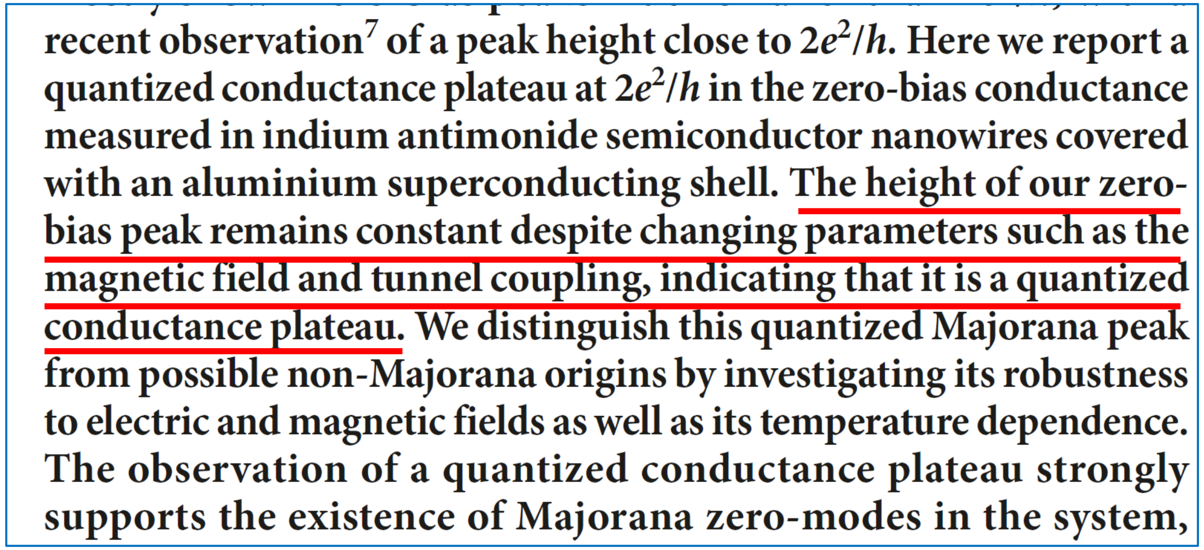
Data manipulation and omission in **'Quantized Majorana conductance', Zhang et al, Nature 2018**

On November 24th 2019 we received from one of the authors of the now retracted 'Quantized Majorana Conductance' paper in Nature a pdf file with experimental notebook-quality data. Within this pdf file, we found data that appear to contradict the central claim of the paper. We have found that the original source experimental data may have been manipulated, namely cut, as well as cut out and pasted together. Furthermore, entire datasets that contradict the central claim of the Nature paper were suppressed. Our analysis was carried out between December 2019 and March 2020. We are able to publish our analysis now, in March 2021, after the authors of the Nature paper have finalized their retraction and deposited data from their experiment in full on Zenodo.

Central claim from the bold paragraph of the Nature paper:

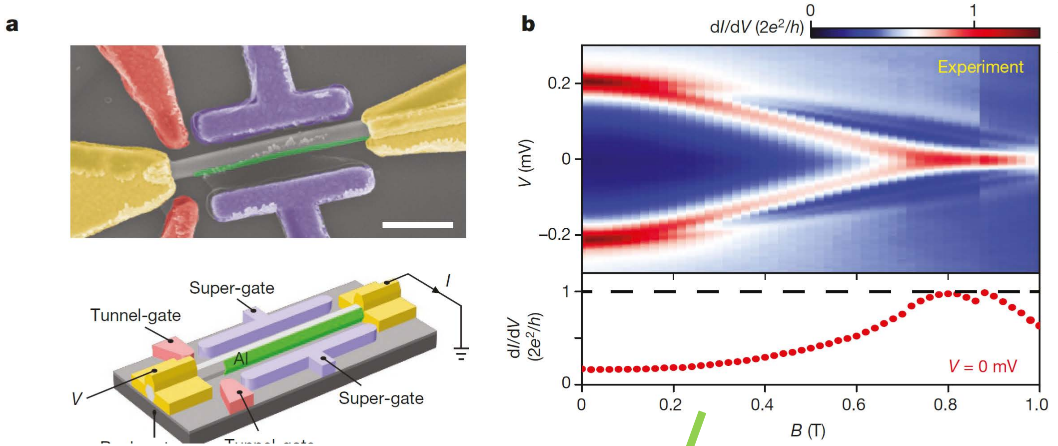


recent observation[7] of a peak height close to $2e^2/h$. Here we report a quantized conductance plateau at $2e^2/h$ in the zero-bias conductance measured in indium antimonide semiconductor nanowires covered with an aluminium superconducting shell. The height of our zero-bias peak remains constant despite 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,

These slides originally prepared in Jan-Mar 2020
Edited to preserve privacy of communications Mar 2021

Figure 1

Device A:



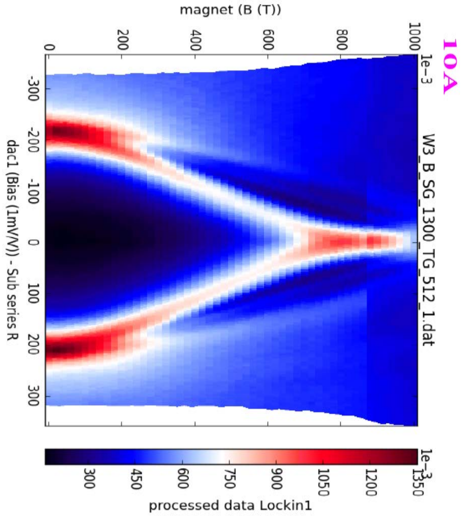
We were only shown two magnetic-field dependence datasets where ZBCP peaks near 2e^2/h

One of them is used for Fig 1b.

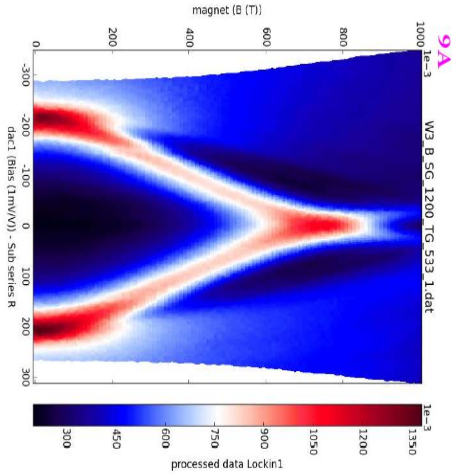
The second one is at a slightly different super-gate and tunnel-gate settings. But this one makes clear the transient nature of ZBCP formed by a crossing of two resonances.

Data at a nearby super-gate setting show a very similar crossing reaching above 2e^2/h

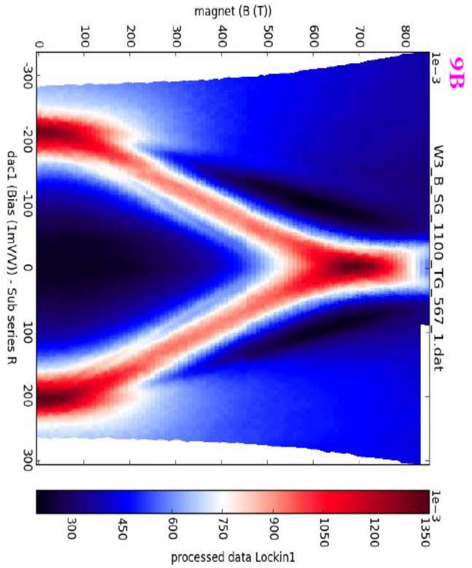
Figure 1b source data
super-gate = -6.5 V



super-gate = - 6.0 V
Peak appears transient and splits at higher field



super-gate = - 5.5 V
Peak reaches > 1.3*2e^2/h

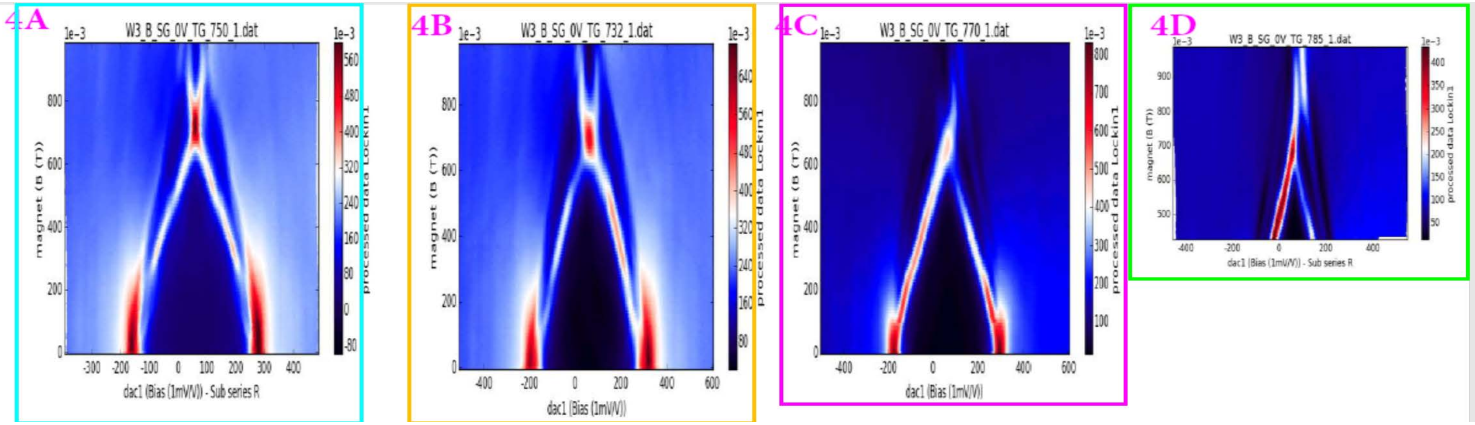


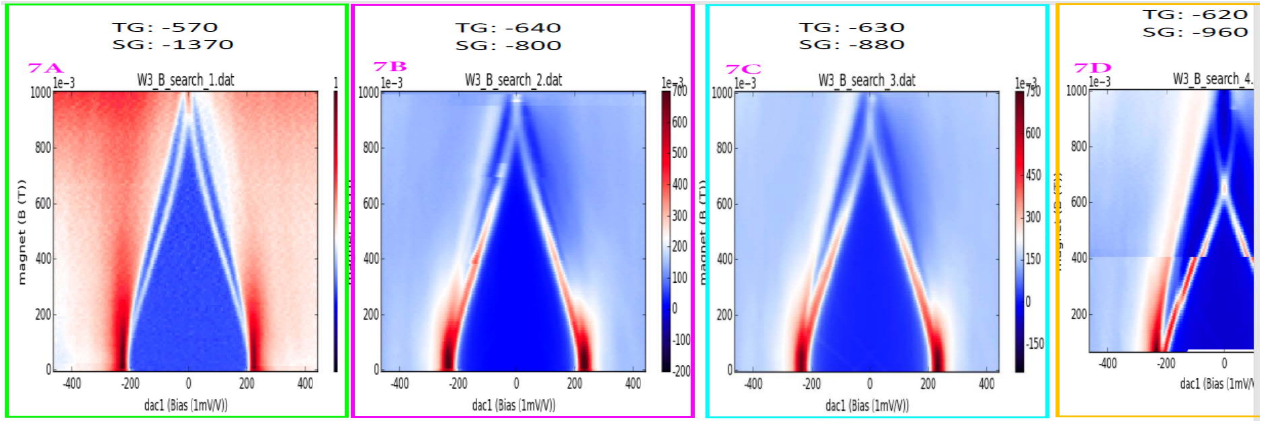
Super-gate within ‘Majorana regime’ according to Fig 3a.
Tunnel-gate is adjusted here, but likely also in Fig. 3a.

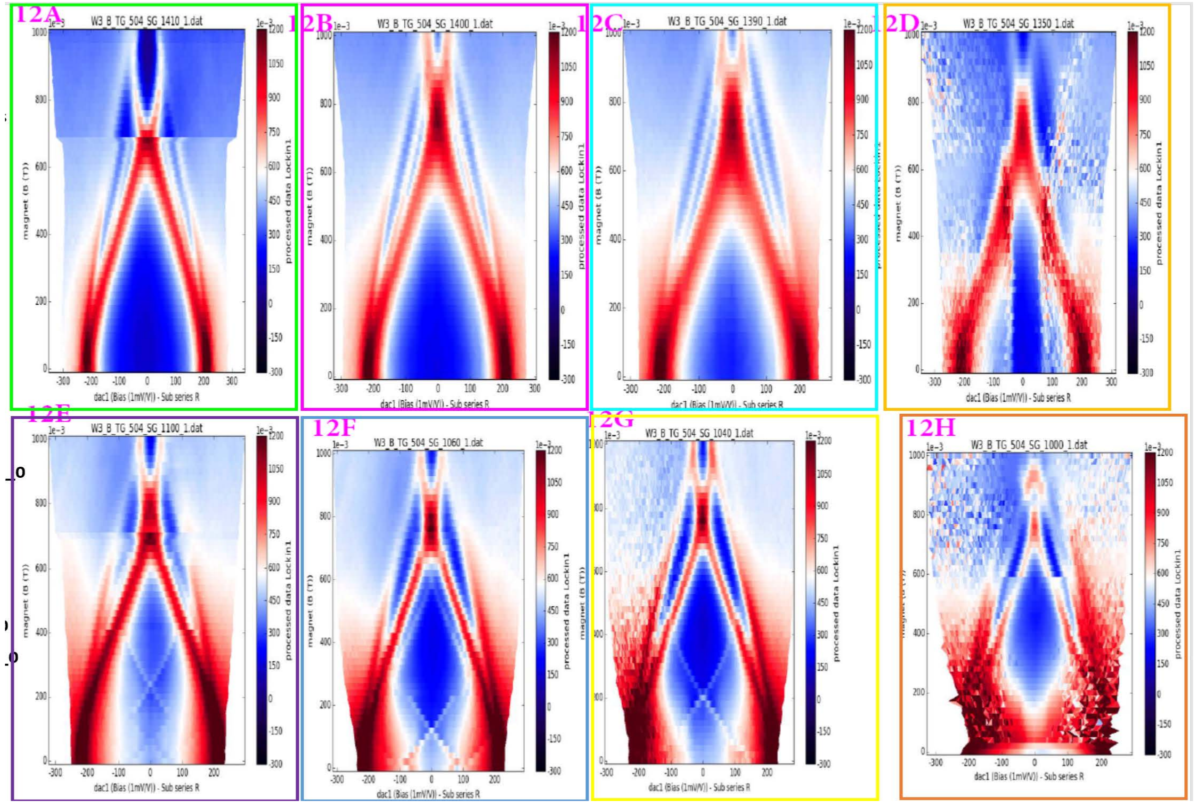
Data omission: Many magnetic field sweeps – only two near the quantized value – others above or below!

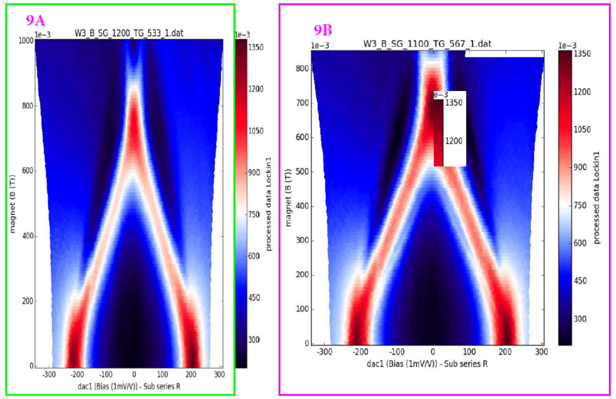
All patterns of merging resonances are consistent with trivial Andreev bound states crossing zero bias. The presence of a somewhat extended zero bias peak at very high field is a well known phenomenon caused by level repulsion from the closing superconducting gap.

Figure 1 is a rare example where conductance reaches the desired value. 19 other data sets from the same device were not revealed. No reason is given why the one shown is expected to be Majorana other than due to conductance.









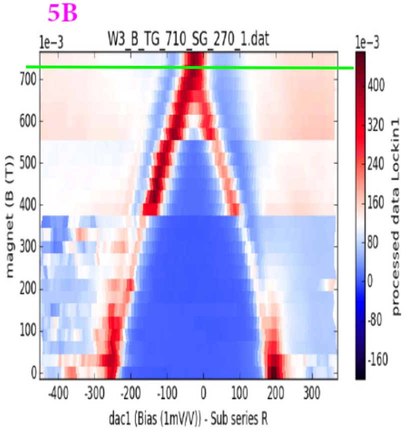
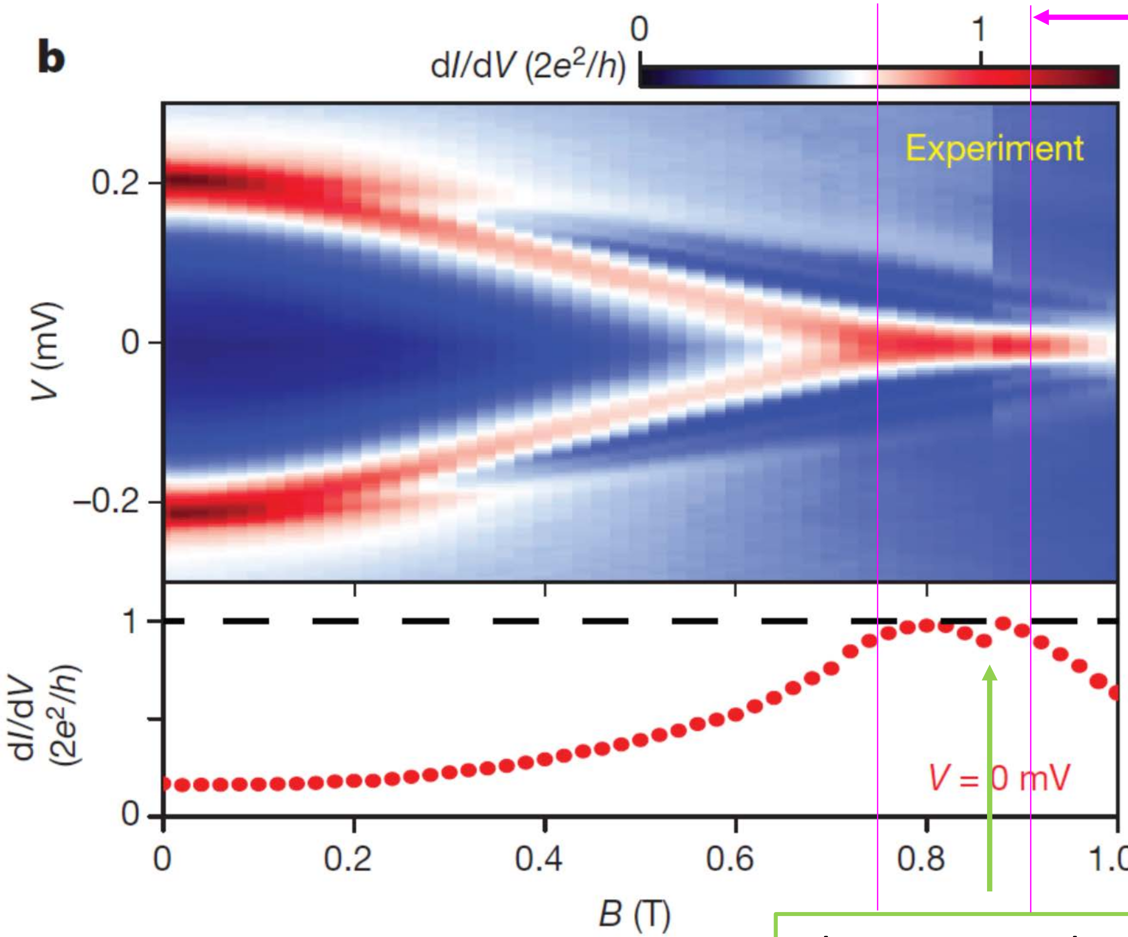


Figure 1b: effect of a single charge switch



ΔB quoted in text

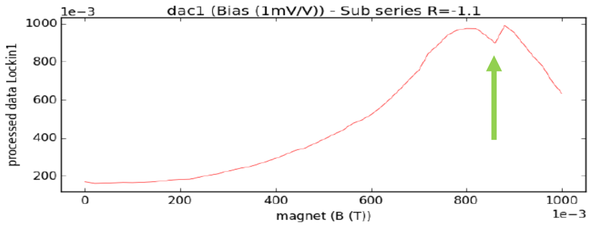
Main text claim (from the Nature paper):

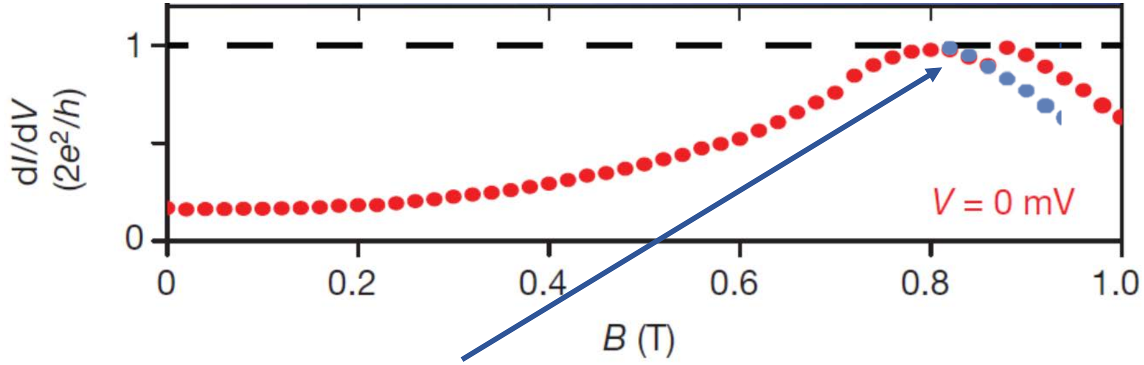
‘The line-cut at zero bias in the lower panel of Fig. 1b shows that the ZBP height remains close to 2e2/h over a sizable range in B field (0.75–0.92 T).’

Range indicated in figure with pink lines, note it includes a sudden jump. The influence of this jump on the above claim is not discussed in main text or figure caption. Not including this jump makes it very difficult to use this dataset as evidence for a plateau at zero bias voltage as a function of B, see below.

Charge jump that affects the zero bias conductance peak.

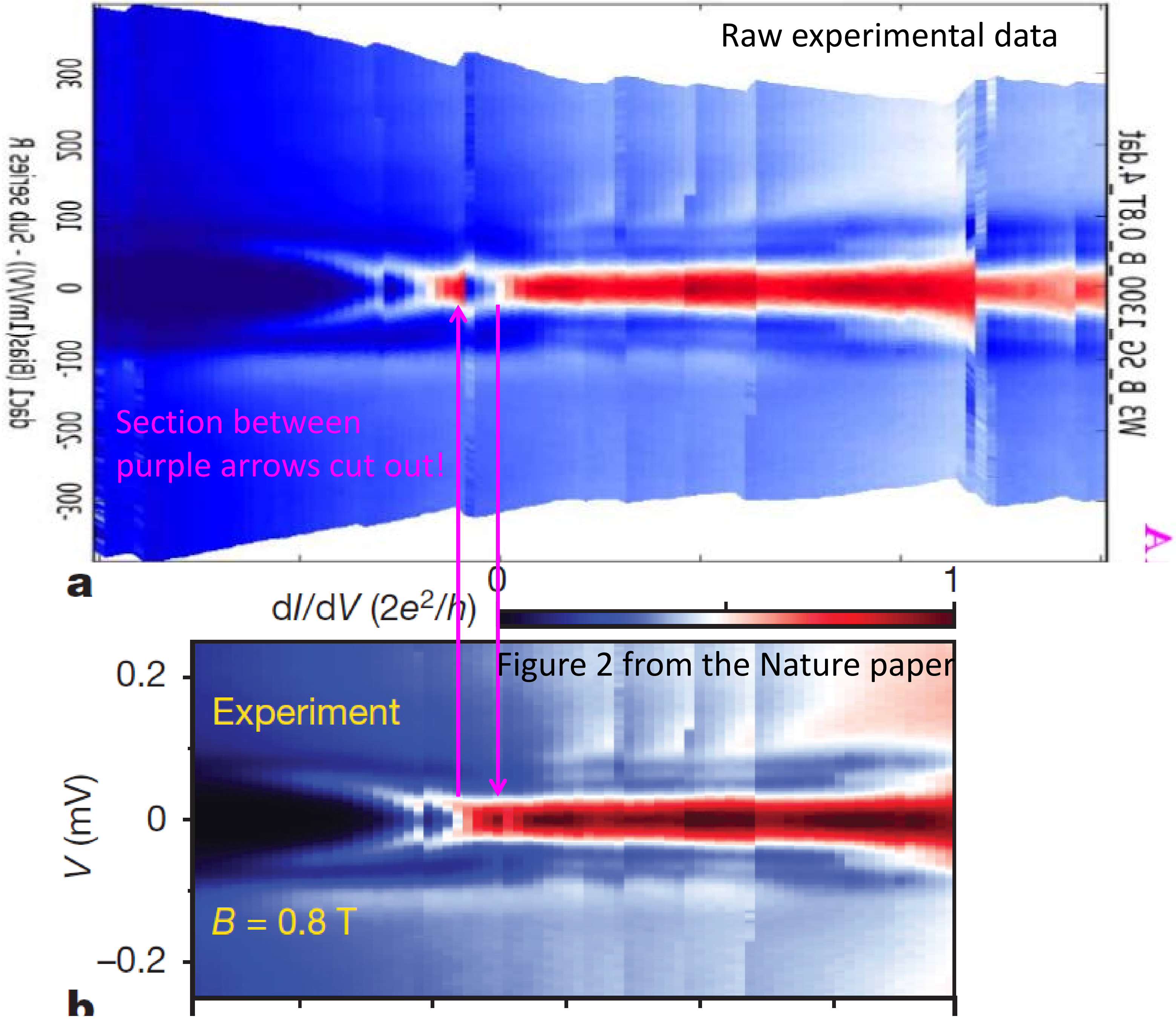
switch more clear in line plot:





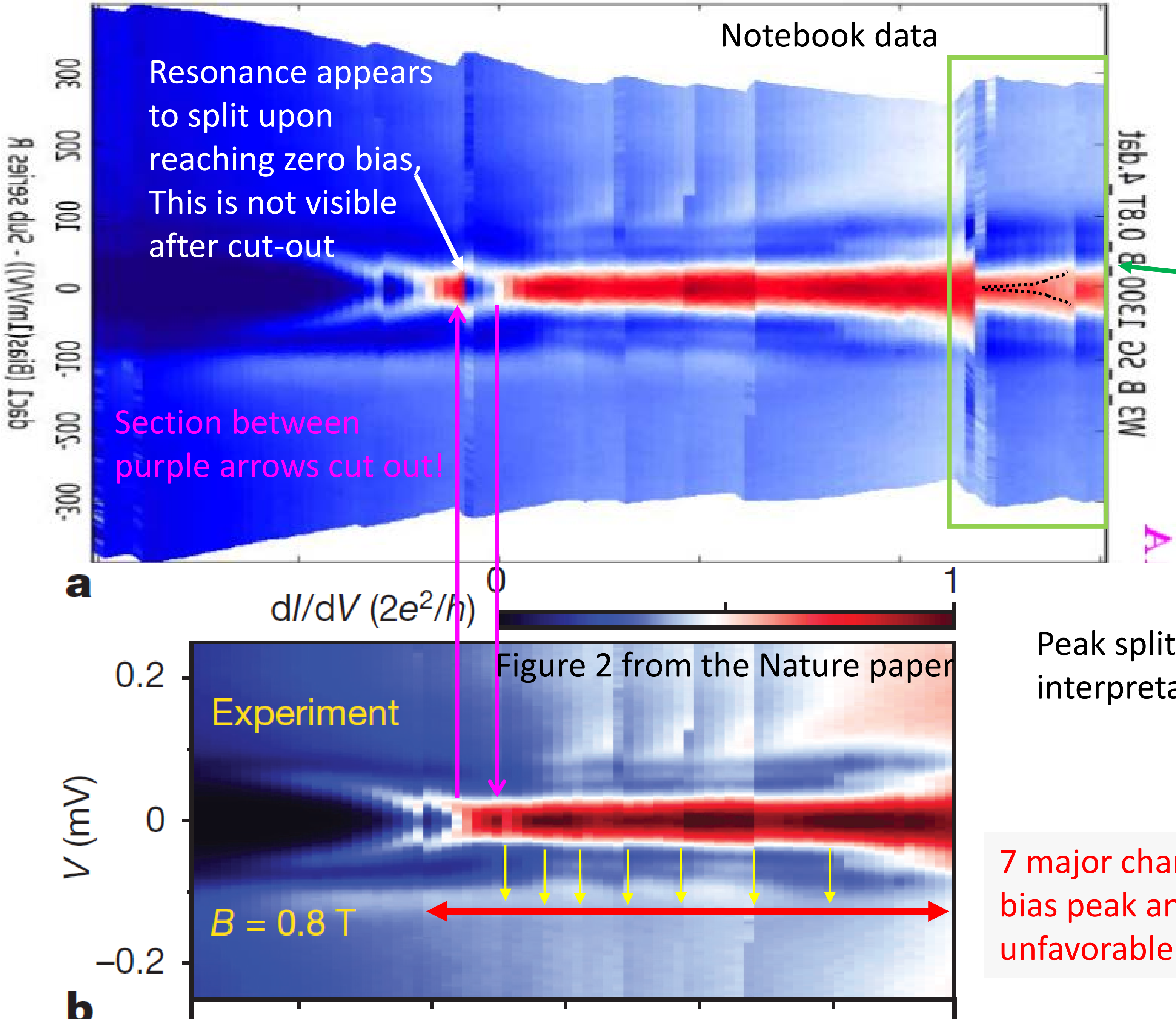
While it is inappropriate to shift data in this fashion, we show in blue dots, as an exercise, data shifted back in B to imagine how zero-bias conductance could have evolved without a jump. **There is now no plateau in B**!

Figure 2 – cut-out



We have identified a cut-out of 4 columns from raw data (purple arrows). The data left of the cutout were simply shifted right, so they do not correspond to horizontal axis values (gate voltages) at which they were obtained. The gate axis in Figure 2 is not adjusted accordingly, nor is this procedure disclosed in the manuscript.

Figure 2 – splittings cut, plateau generated by charge jumps



Notebook data

Resonance appears to split upon reaching zero bias, This is not visible after cut-out

Section between purple arrows cut out!

Figure 2 from the Nature paper

Experiment

$B = 0.8$ T

Zero-bias peak continues, but dramatic charge switches and peak splitting cropped.

A segment on the far right of raw data has been cut (green rectangle). It contains zero bias peaks below quantized value and a peak splitting.

Peak splitting favors trivial Andreev bound state interpretation and goes against ‘robust plateau’ claim

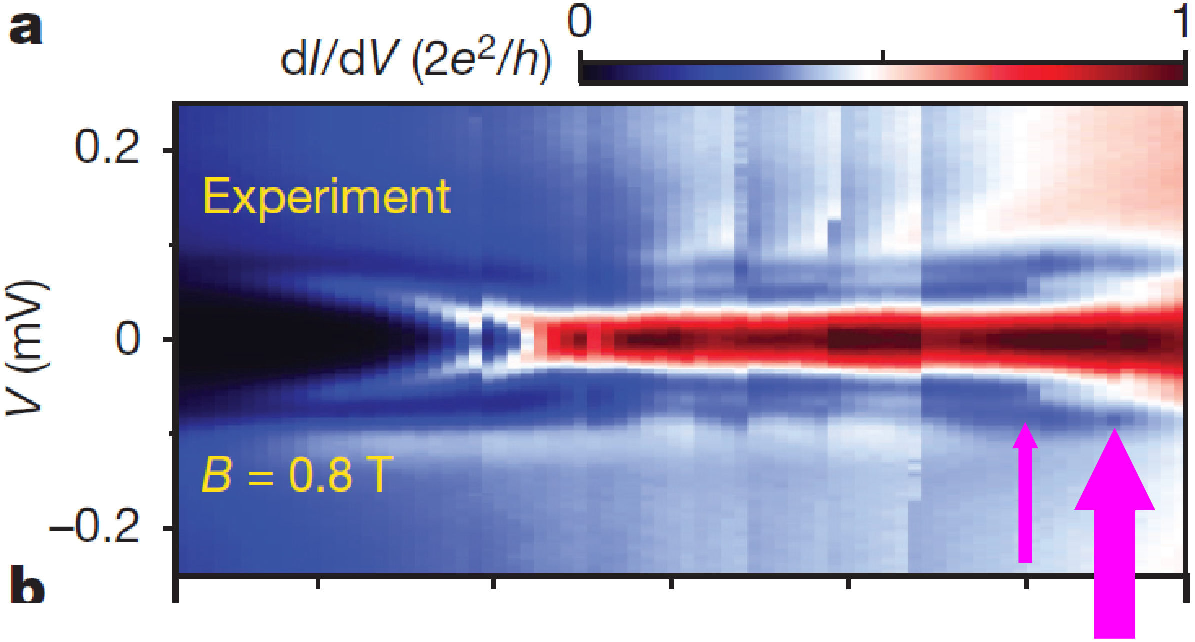
7 major charge jumps are left uncut to extend zero bias peak and generate an apparent ‘**plateau**’, while unfavorable charge jumps were cut.

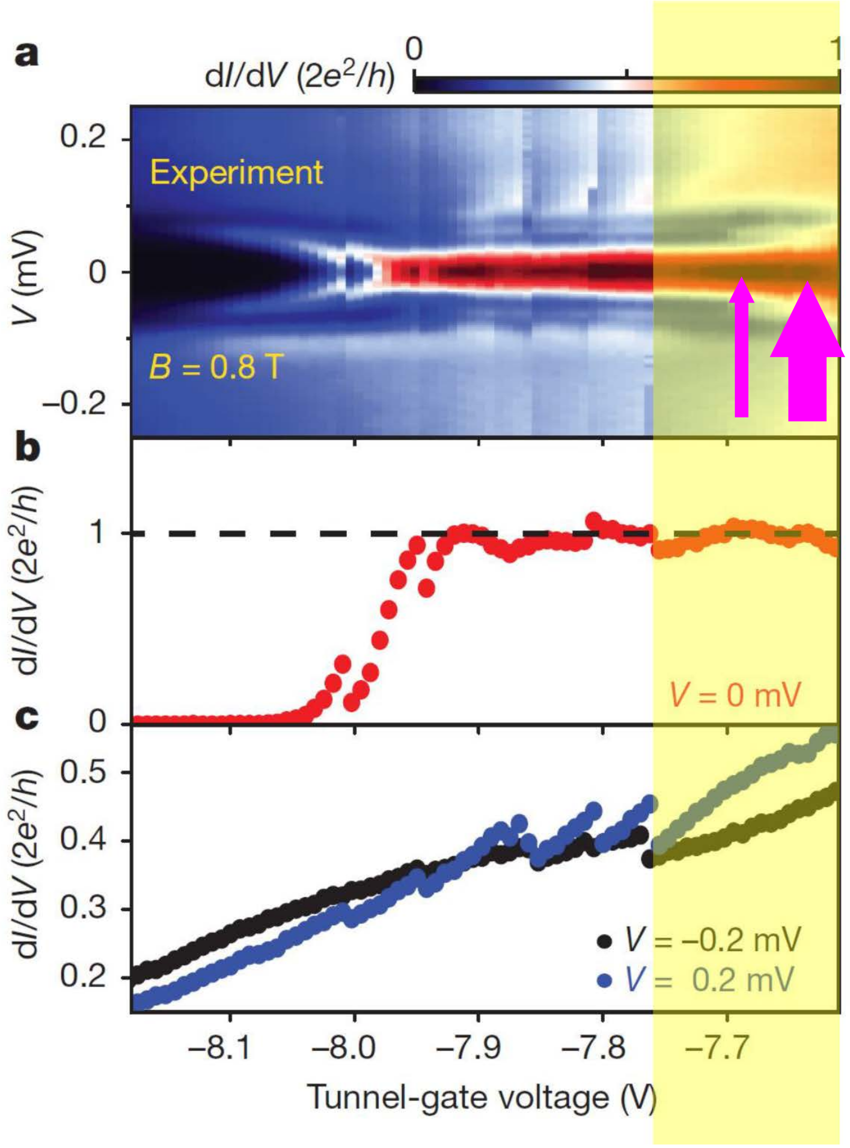
A discussion took place where the authors suggested that It is enough to consider the gate voltage range in yellow as a plateau

SF and VM found that:

There is a charge jump about three-quarters through the yellow shaded region, and another one is visible half-way through the 'yellow shadow region' (see pink arrows below). There are other jumps visible in that region.

It is not possible to support plateau claims based on the yellow region.



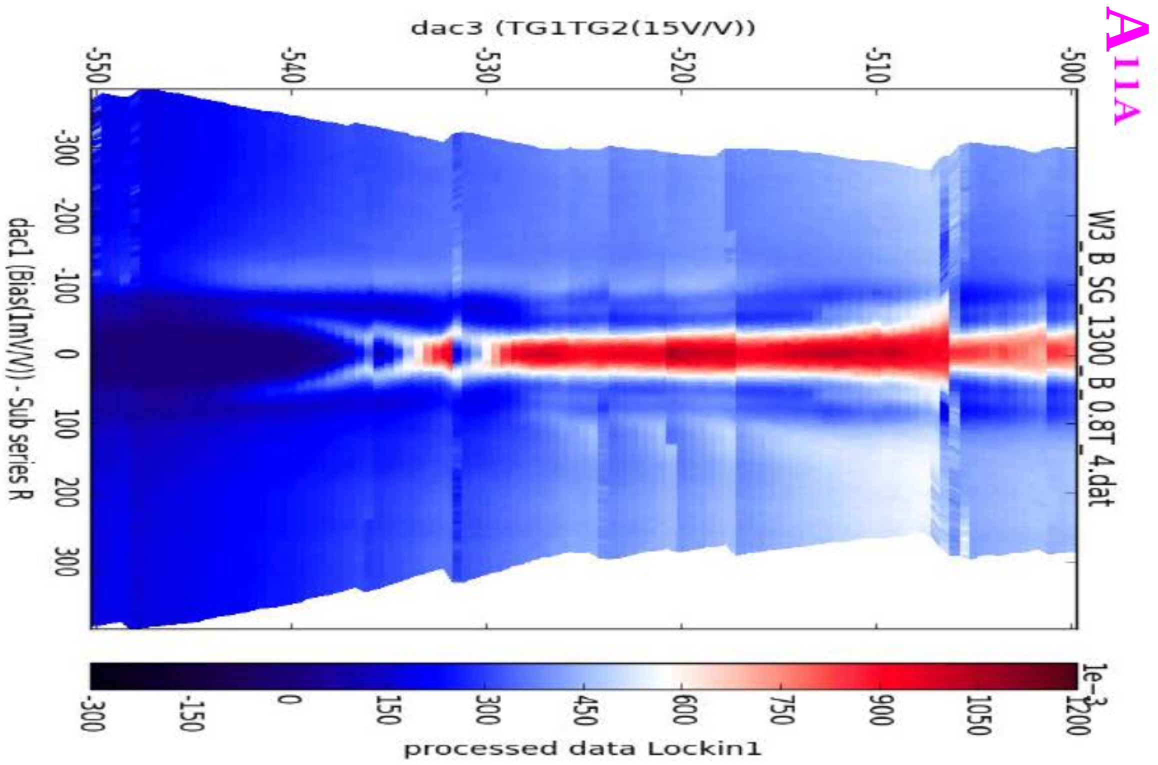


Data omission:

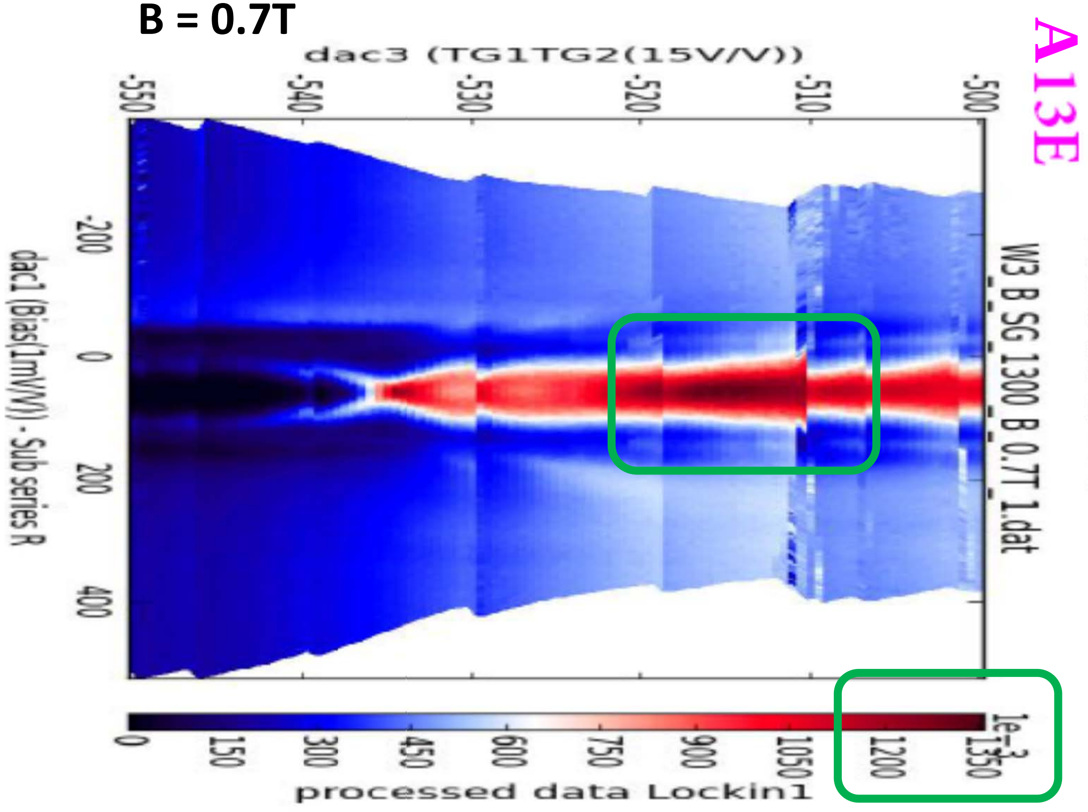
Data used for Figure 2:
“quantized plateau”

Data not presented:
Conductance reaches above $2e^2/h$ (see green boxes)
Over the same gate range at a lower magnetic field:
Inconsistent with paper claim and with Majorana.

B = 0.8T



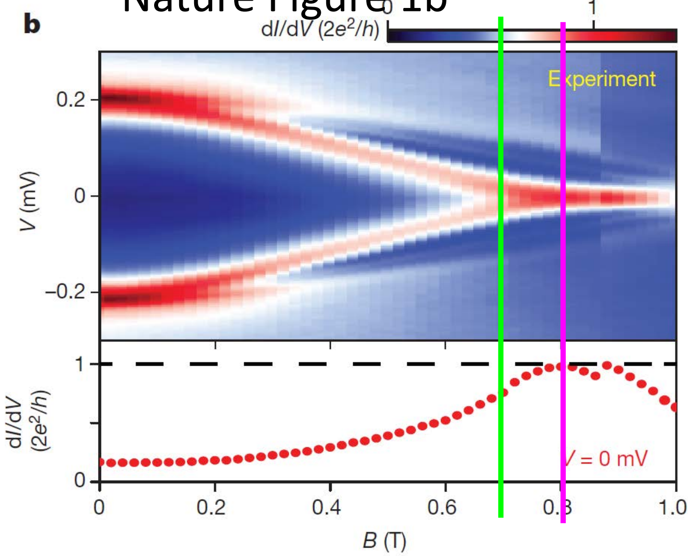
B = 0.7T



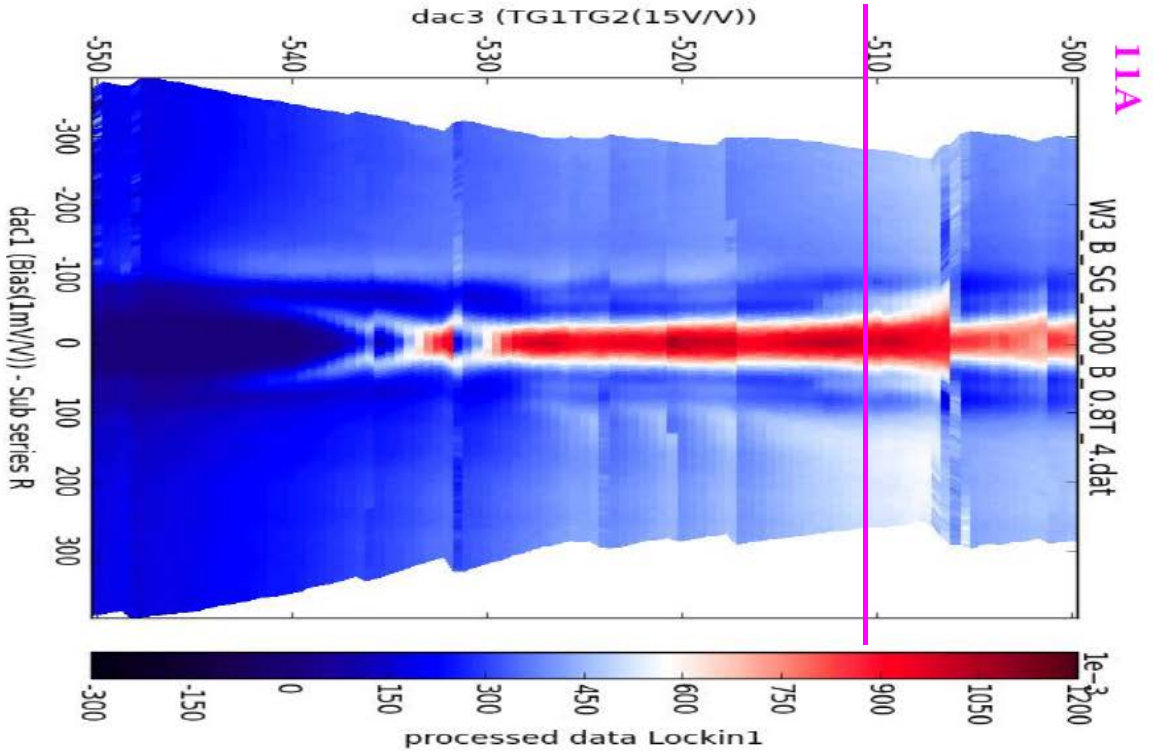
Which data to show?

The green and purple lines in these plots correspond to the same gate and field settings. Purple lines are in approximate agreement. Green lines are in complete disagreement. The tall peak at 0.7T with a height of 1.3* $2e^2/h$ is not visible in Figure 1. Measuring at the same settings some time apart yielded very different results, some of which directly contradict the paper's conclusion. The favorable combination was chosen for the paper while unfavorable data were not included.

Nature Figure 1b



B = 0.8T



B = 0.7T

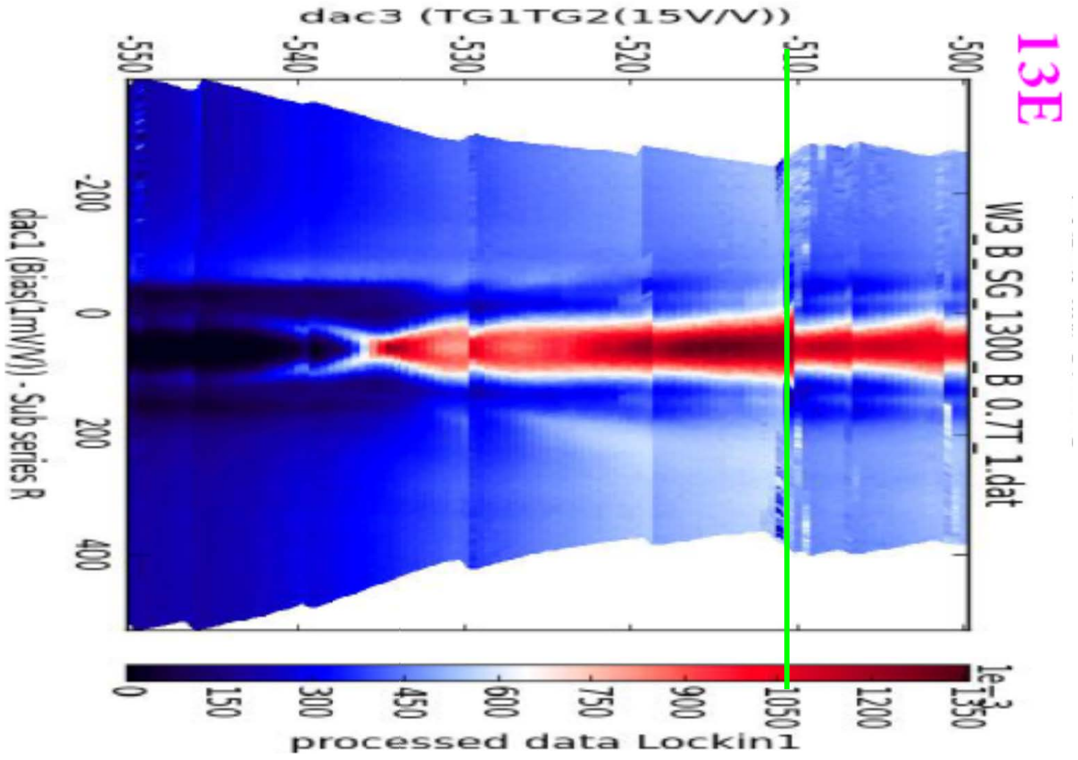
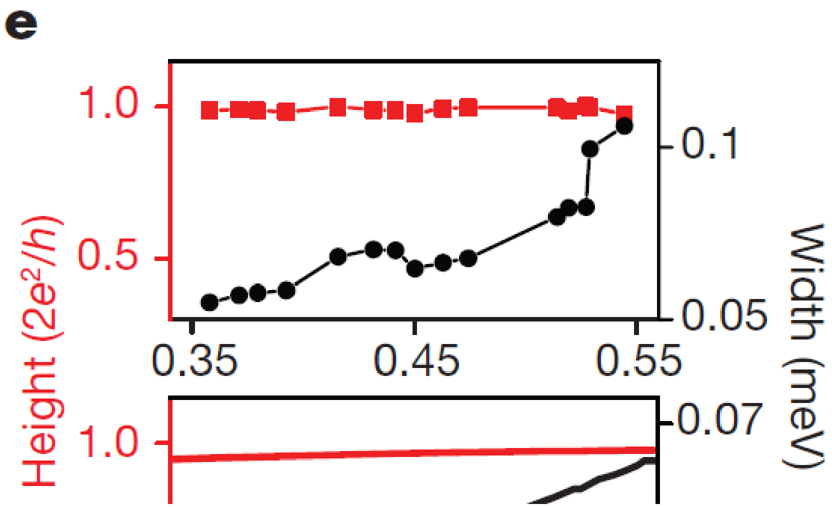
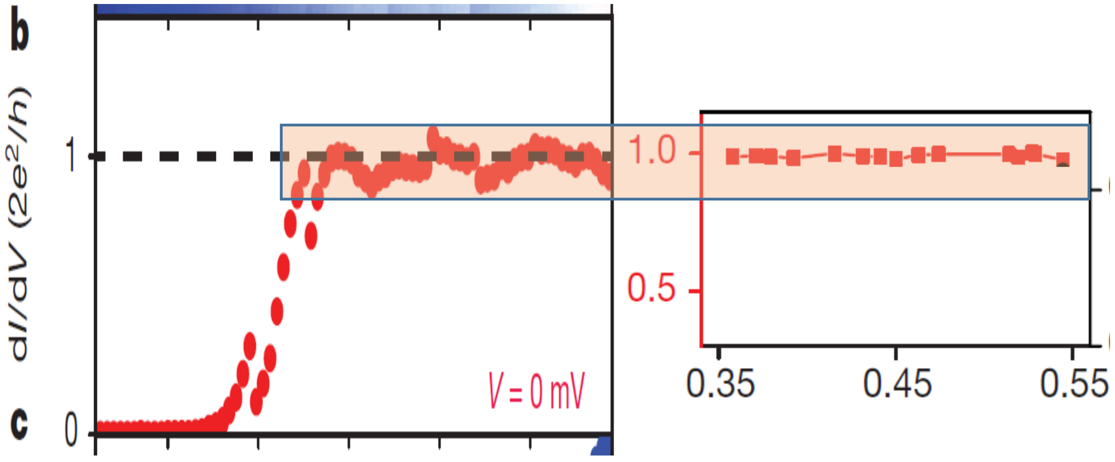


Figure 2e



This is a relatively small panel located in the center of Figure 2.
It shows a less common way of extracting data from a set such as Fig. 2a.
Namely, using red squares conductance at zero bias (vertical axis) is plotted vs. conductance at finite bias (horizontal axis).
Black circles are the zero bias peak widths.

On the left we show Fig 2b side-by-side with Fig 2e where the vertical axes are stretched to align conductance values. Black circles are hidden by us for clarity.



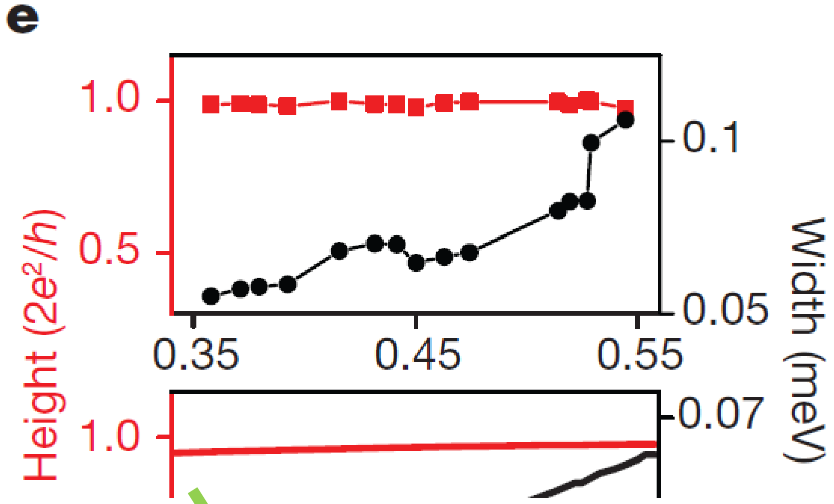
46 data points within the box in 2b, 15 in 2e…
70% of data were excluded

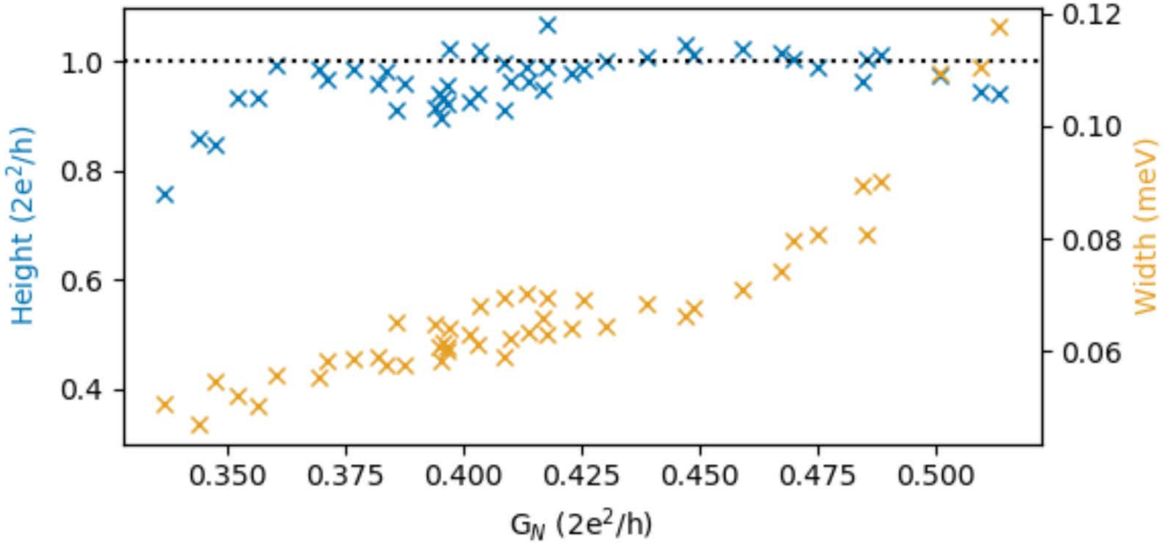
It appears that data in 2b within the orange box have a significantly larger deviation from 1*2e^2/h than in panel 2e. We infer that the data points for panel 2e were selected based on the criterion that they have conductance as close as possible to 1. This unusual data selection method is not stated in the Nature paper.

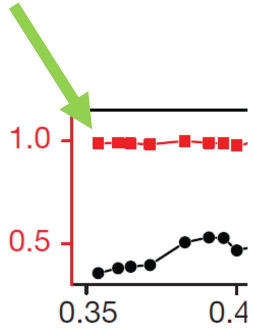
How would panel 2e look if all of the data from unmanipulated original source dataset were plotted?

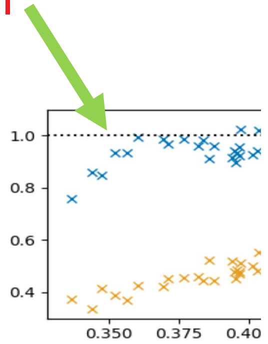
Figure 2e (contd.)

The authors provided a plot that should have been Figure 2e, where as they state they used the uncut version of the source data. The scatter of blue points now exceeds scatter of red points in Figure 2e. Overlapping points are a manifestation of charge jumps. For the same value of GN (horizontal axis), the full dataset contains many different peak heights (blue points). This is especially clear around GN = 0.400. What this means is that upon charge jumps the device shifted to different states that corresponded to different peak height and different peak width. Plotting a subset of such data connected by red and black lines in Figure 2e is inappropriate, because it suggests a continuous evolution of parameters.
In the uncut version, the range of GN over which GS ~ 1 is closer to being (0.375;0.475) than (0.35;0.55),
i.e. half of what was shown in the paper. Does the claim that ‘peak remains quantized while tunnel rate increases’ still stand?









There is an apparent discrepancy between Fig 2e and data as replotted by the authors around GN = 0.350. The replotted version does not show any points at GS = 1, while Fig 2e does show a couple there. There is a similar discrepancy in the range GN (0.50 to 0.55). We return to this aspect later.

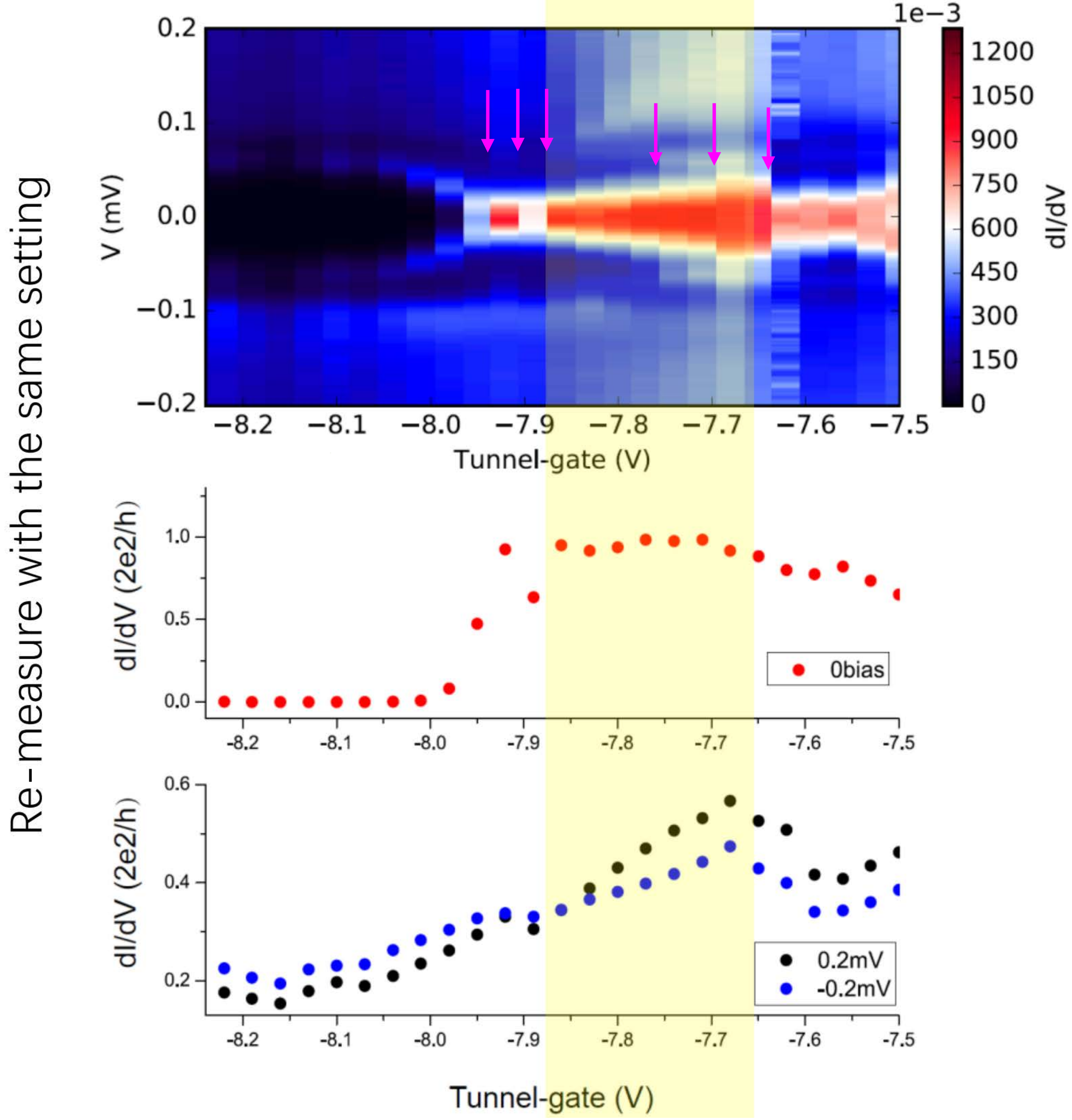
New Dataset

On Feb 8 the authors provided a single additional low-resolution dataset. It is from the same regime as Fig 2. The low resolution (few data points along the tunnel-gate direction) makes it difficult to seriously argue about this dataset.

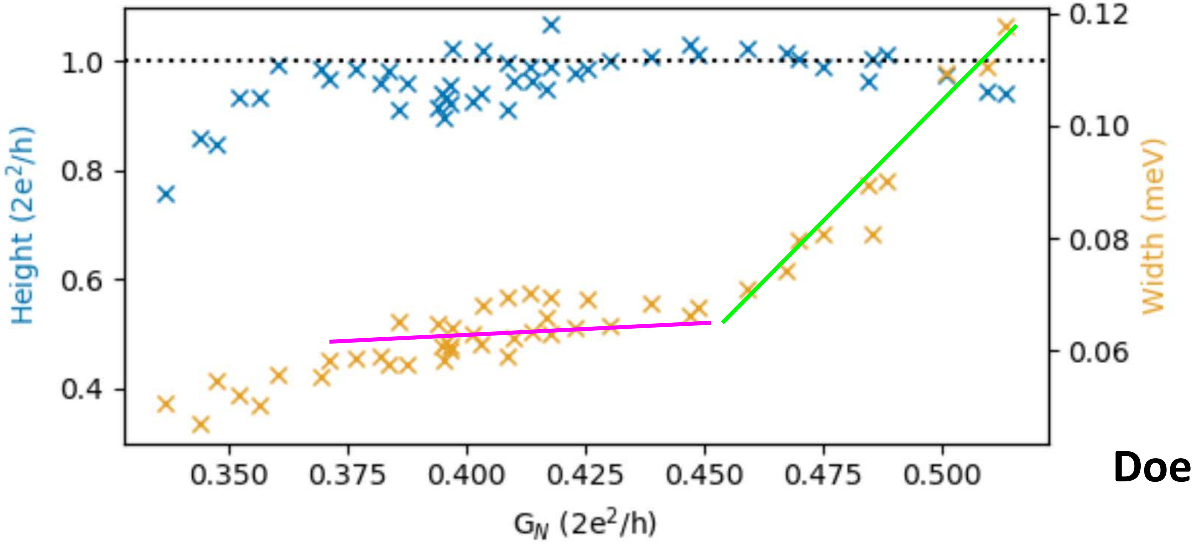
This set shows some of the same artefacts (charge jumps) as Fig 2, which we indicated with purple arrows.

The Nature paper authors added a yellow rectangle to show what they believe is a ‘plateau’ in this set. But there are charge jumps within the yellow rectangle. Same issues apply when characterizing this as a ‘plateau’ as in Figure 2.

In this dataset ZBCP in the yellow region looks like the beginning of a peak splitting. See next slide.



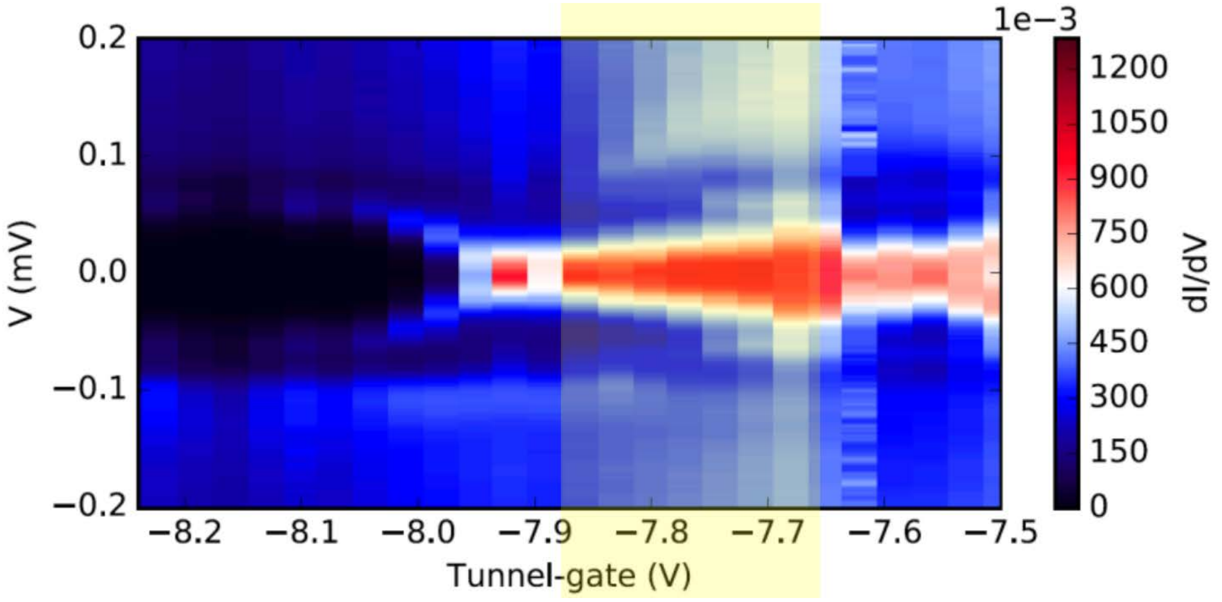
Peak broadening or peak splitting?



We added pink and green lines to suggest that the peak width exhibits two regimes:

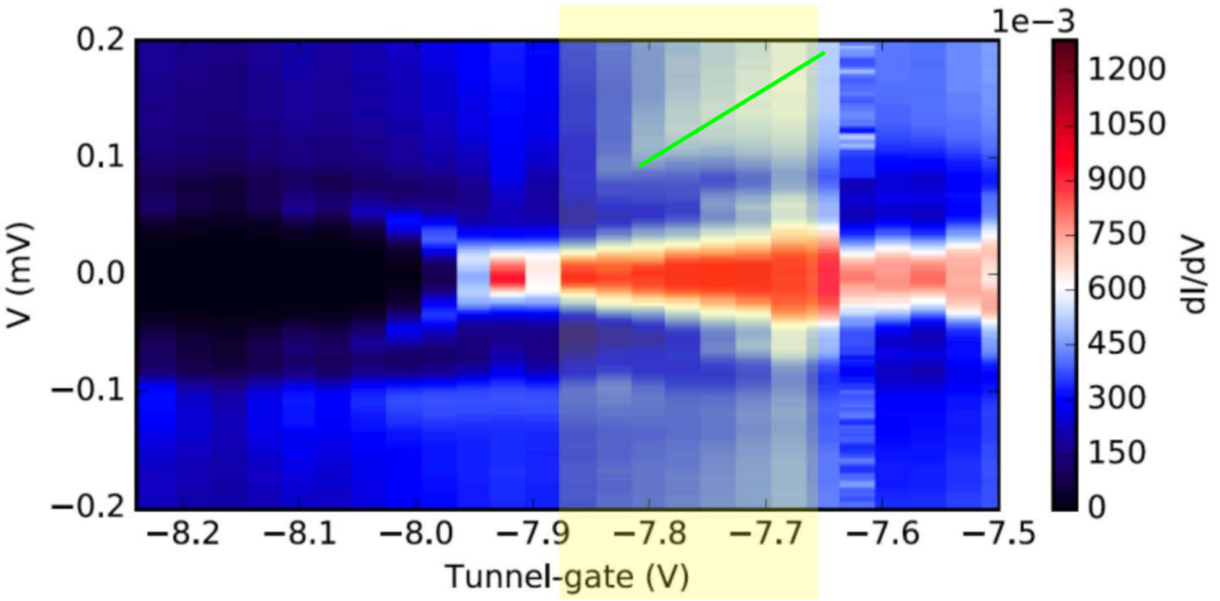
1) Between GN = 0.375 and 0.450 the peak width is near constant
2) Between GN = 0.450 and 0.525 the peak width grows

Does the peak broaden or does it begin to split into two peaks?

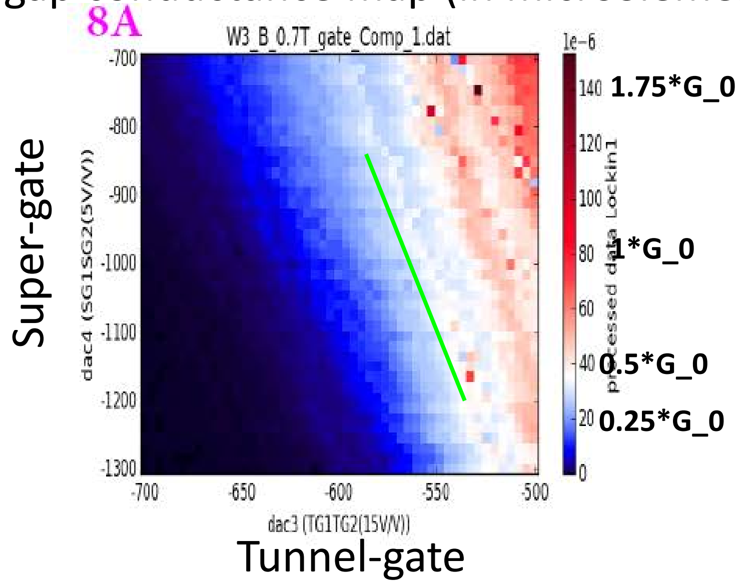


The additional dataset shows more clearly than Fig 2 the splitting of resonances upon touching zero. This is a well-known behavior of trivial Andreev bound states living in a quantum dot. The Andreev crossing is stretched on the right side due to charge switches which create the illusion of a ‘plateau’. See green lines.

Above-gap resonance



Above-gap conductance map (in microSiemens):



Datasets used for Figure 2 and obtained under similar settings exhibit a rapidly enhanced conductance as a function of tunnel gate or super-gate.

It is difficult to see this because of the limited source-drain bias range and numerous charge jumps, but in our experience this is due to an above-gap resonance that is transient through zero bias. Such resonances are observed in super-vs-tunnel gate map of above gap conductance (green line).

The true tunnel barrier conductance increases on a much larger scale of tunnel-gate voltage (volts), whiles above-gap conductance in Fig 2 and the new dataset grows over tunnel gate change of 0.2 V.

Two points are related to the transient above-gap resonance:

1) It is not meaningful to plot GS vs GN like in Figure 2e because GS does not correspond to tunneling rate but to a resonance.
2) Transient above-gap resonances are typically found in quantum dots and they generate trivial Andreev bound states at lower subgap bias voltages.

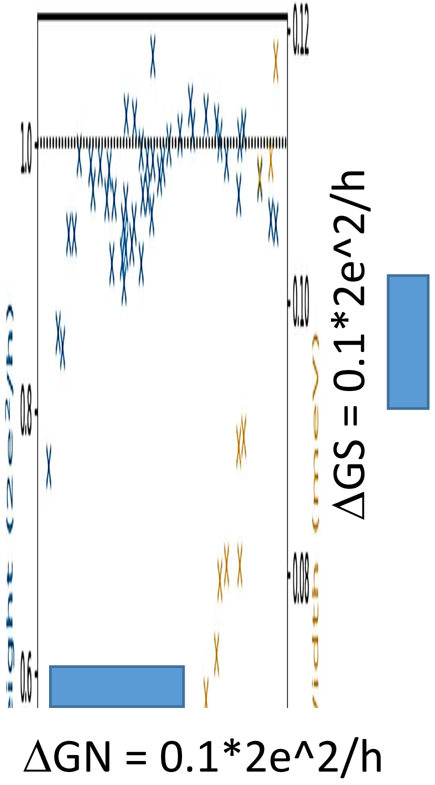
Can we just ignore charge jumps and look at GS vs GN?

Figure 2e is very important to the authors. The authors argued to us several times that, despite the imperfect quantization, charge jumps, and even despite the data manipulation, the data nevertheless show a quantized conductance plateau.

They point to Figure 2e when they do this. The say that while GN (above the gap conductance) increases, GS (zero bias conductance) 'stays constant'. As if transmission of the tunnel barrier changed but not the peak height.

In previous slides we already described how charge jumps, peak splitting, a transient resonance, cut into these claims. But suppose someone is still inclined to believe them.

We re-size the GS vs GN figure so that the vertical and horizontal axis are more equivalent. Now, a change of 0.1 in GN is the same number of pixels as 0.1 in GS.



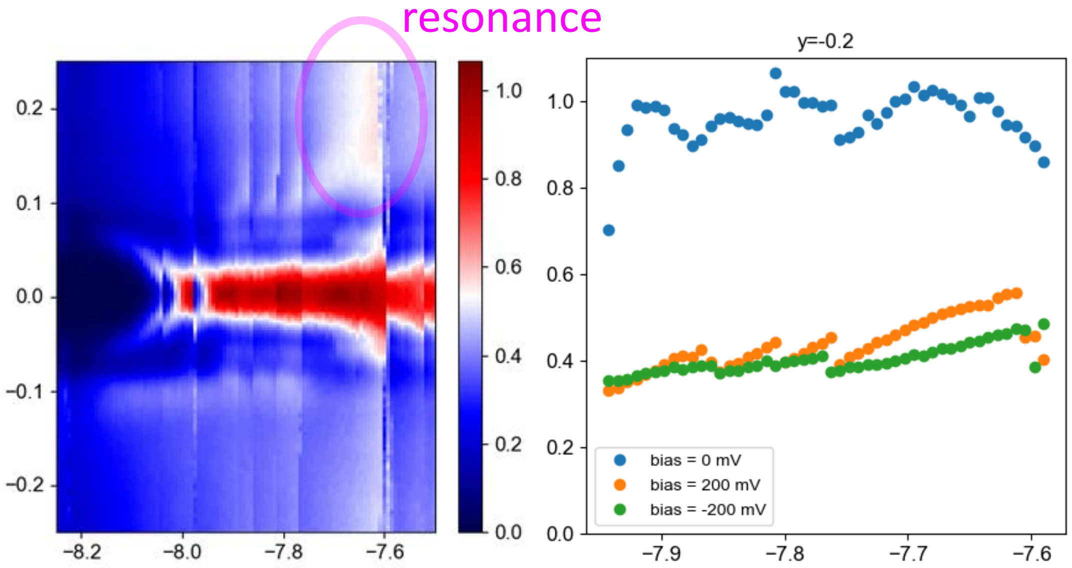
From the Nature paper:

The extracted height and width are plotted in Fig. 2e (upper panel) as a function of above-gap conductance GN= T× e2 /h where T is the transmission probability for a spin-resolved channel. Although the ZBP width does change with GN, the quantized height remains unaffected. [...] The robustness of the ZBP quantization to a variation in the tunnel barrier is an important finding of our work.

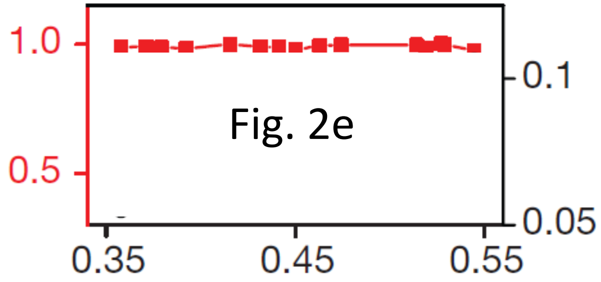
When presented like this,
Is there evidence of
constant GS when GN is varied?

Over 0.2 change in GN, GS changes by 0.2

We plotted the plateau data ourselves…



<- zero bias conductance

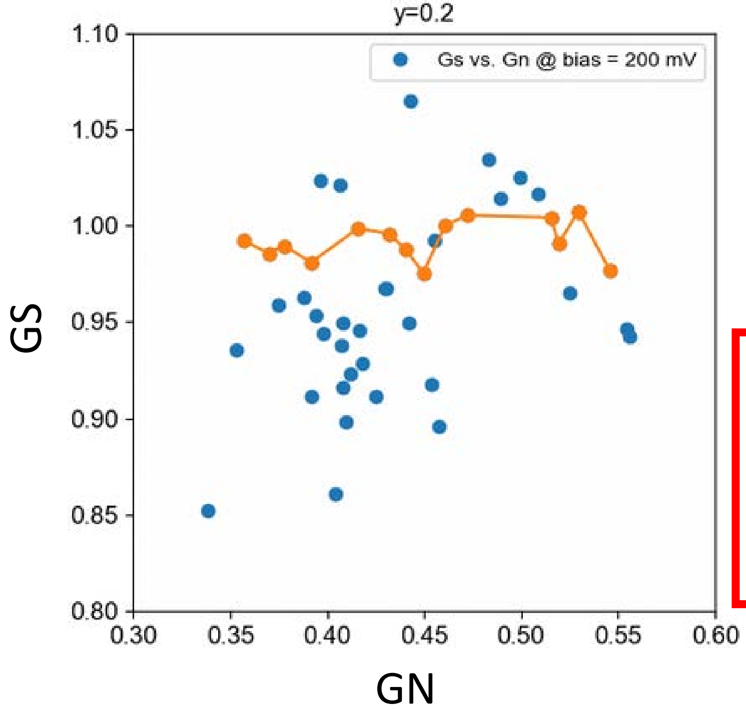


Finite bias conductance.
Has the same change as variation in the zero-bias conductance.
Orange trace goes over a resonance at positive bias, hence larger change.
Different sized axes in Fig. 2b,c create false impression of larger increase.

GS (at zero bias) vs GN,
Our version of Fig 2e ->

Vertical and horizontal axes cover an identical change in conductance for a fair comparison.

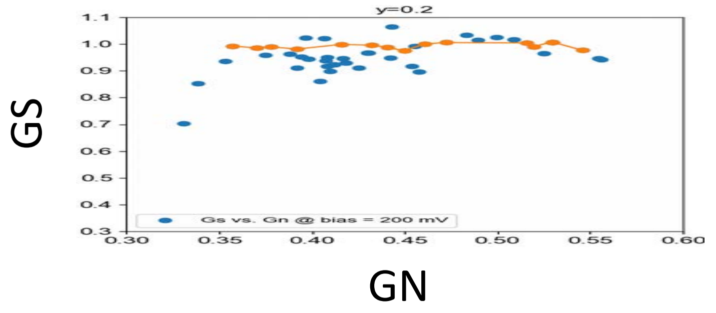
Yellow dots are data used in Fig. 2e, blue dots are the remaining points in this range of GN.



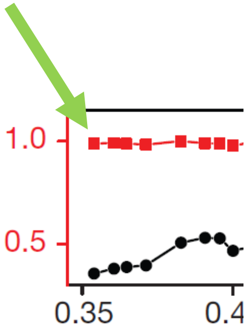
Change of GS and GN are both 0.2*G_0 based on blue points.

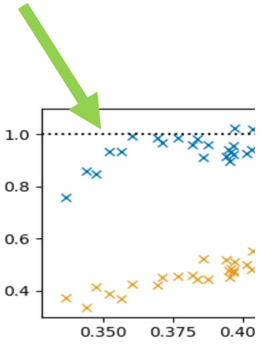
There is no evidence for constant GS when GN is changed.

Of course, these data can be plotted using a rescaled plot in an attempt to make the yellow dots appear similar to Fig. 2e:



Discrepancy between Fig. 2e and new plot from authors





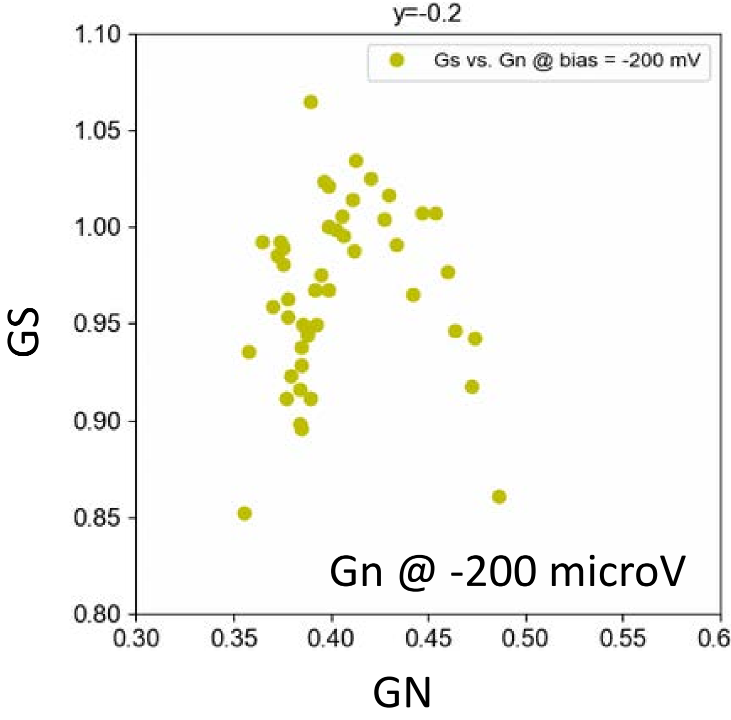
We pointed out before that datapoints present in Fig. 2e are not present in the subsequent plot provided to us by the authors. This is surprising at first sight, as the authors assured this new plot covered the full dataset.

One cause of this could be another undisclosed type of data processing or manipulation. Alternatively, the bias voltage at which GN was chosen might have been slightly different. To illustrate this effect we show two examples.

The right plot contains the data used in Fig. 2e, based on a GN trace at + 200 microV cutting through a transient resonance.

The left plot is generated using GN at -200 microV. Because the transient resonance is absent at negative bias, now the change in GN is 50% smaller compared to the positive bias axis! No regime of constant GS is present.

GS vs GN plot is very sensitive to the bias voltage at which GN is chosen. The GN trace for Fig. 2e was chosen to stretch the GN axis, and then all points not at 2e^2/h were removed.



Yellow dots used in Fig. 2e

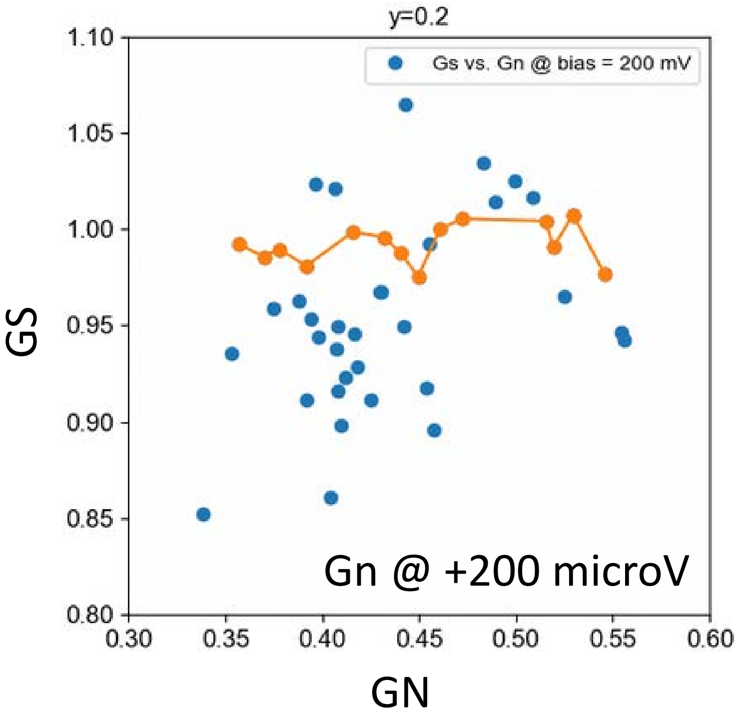
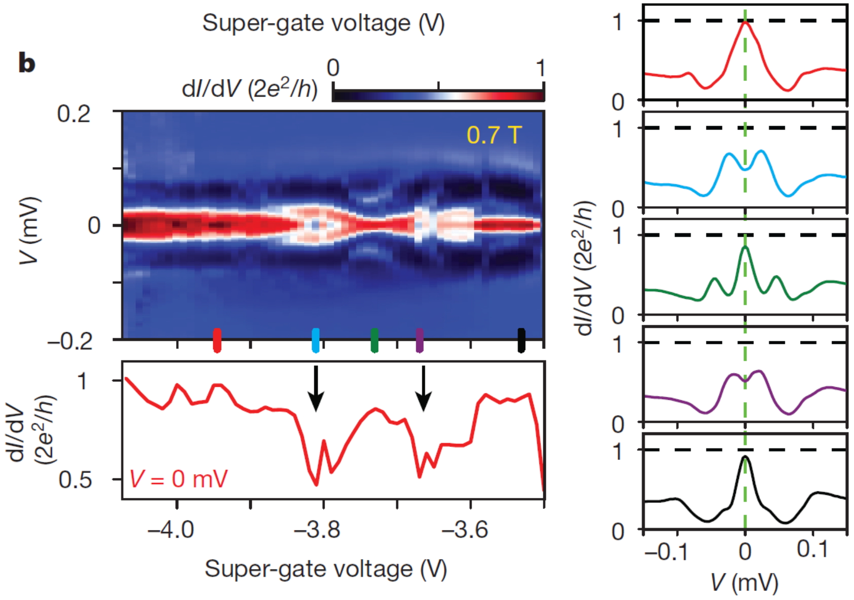


Figure 3 : peak reaches above $2e^2/h$

From the Nature paper discussion of Fig 3b:

Notably, the ZBP height comes back up to the quantized value and <u>does not cross through it</u>.

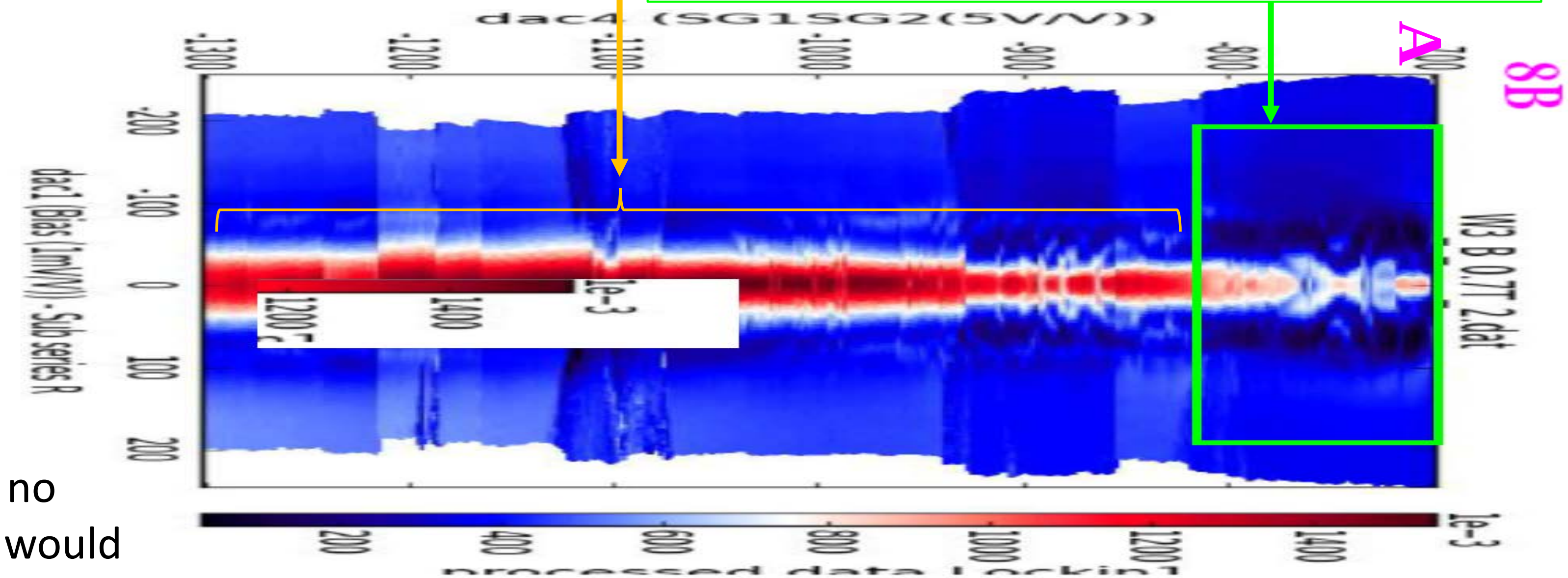
Nature paper Figure 3



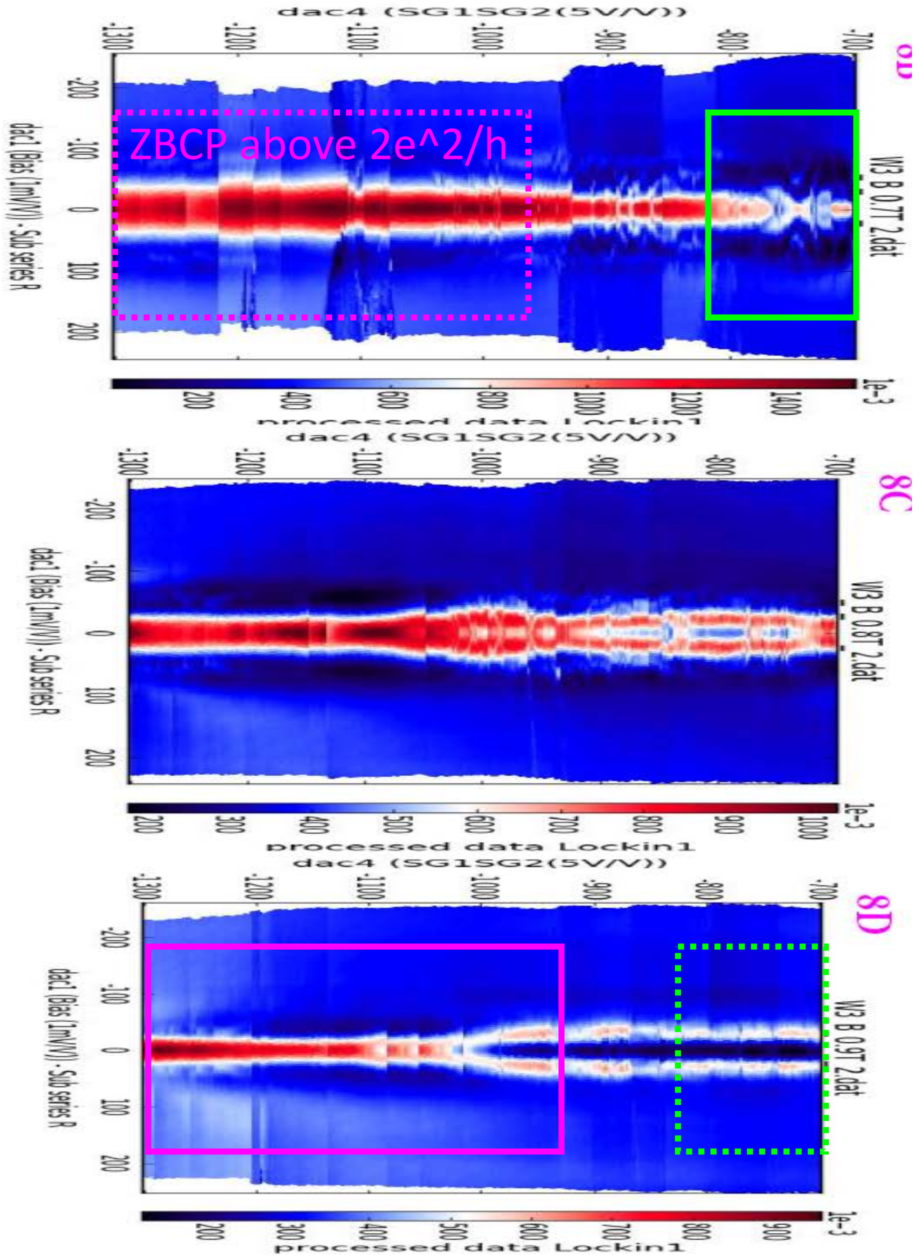
Zero-bias peak taller than the quantized value presents a problem for the Majorana interpretation. This directly contradicts the paper's claim shown above. There is also no widely known and simple way in which ZBCP would continuously evolve from 'topological' to 'trivial'.

Figure 3 was cropped at the exact point where the zero bias peak goes above $2e^2/h$ (the quantized value). The zero-bias peak remains pinned to zero bias over a super-gate range that is 5 times larger in Figure 3. The conductance of the zero-bias peak increases **significantly above** $2e^2/h$ for more negative super gate. immediately adjacent to the cropped range shown in Figure 3.

Green frame corresponds to Nature Figure 3



The ‘Majorana regime’ is wherever ZBCP is of a desired value…

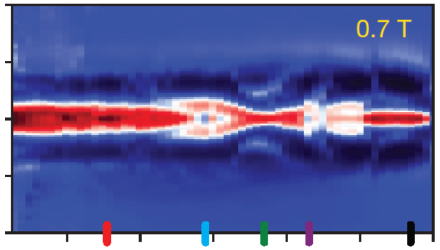


Same super-gate range in 3 panels….

Three data sets presented together on page 8 of the notebook we received in November 2019.
This appears to be a study of a B-field evolution of super-gate dependence.
The settings of tunnel-gate are not specified, presumed the same.

B = 0.7 T

Segment within the green box used for Figure 3b
So, the Majorana regime is on the right?

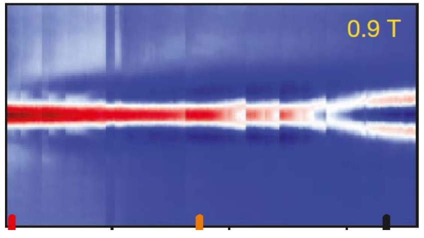


B = 0.8 T

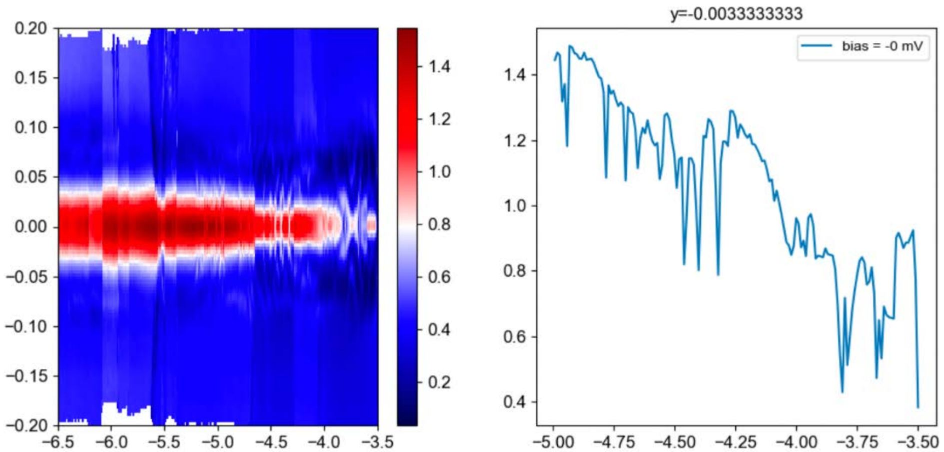
Not shown in the Nature paper

B = 0.9 T

Segment in the pink box used for Figure 3a
So, the Majorana regime is on the left?



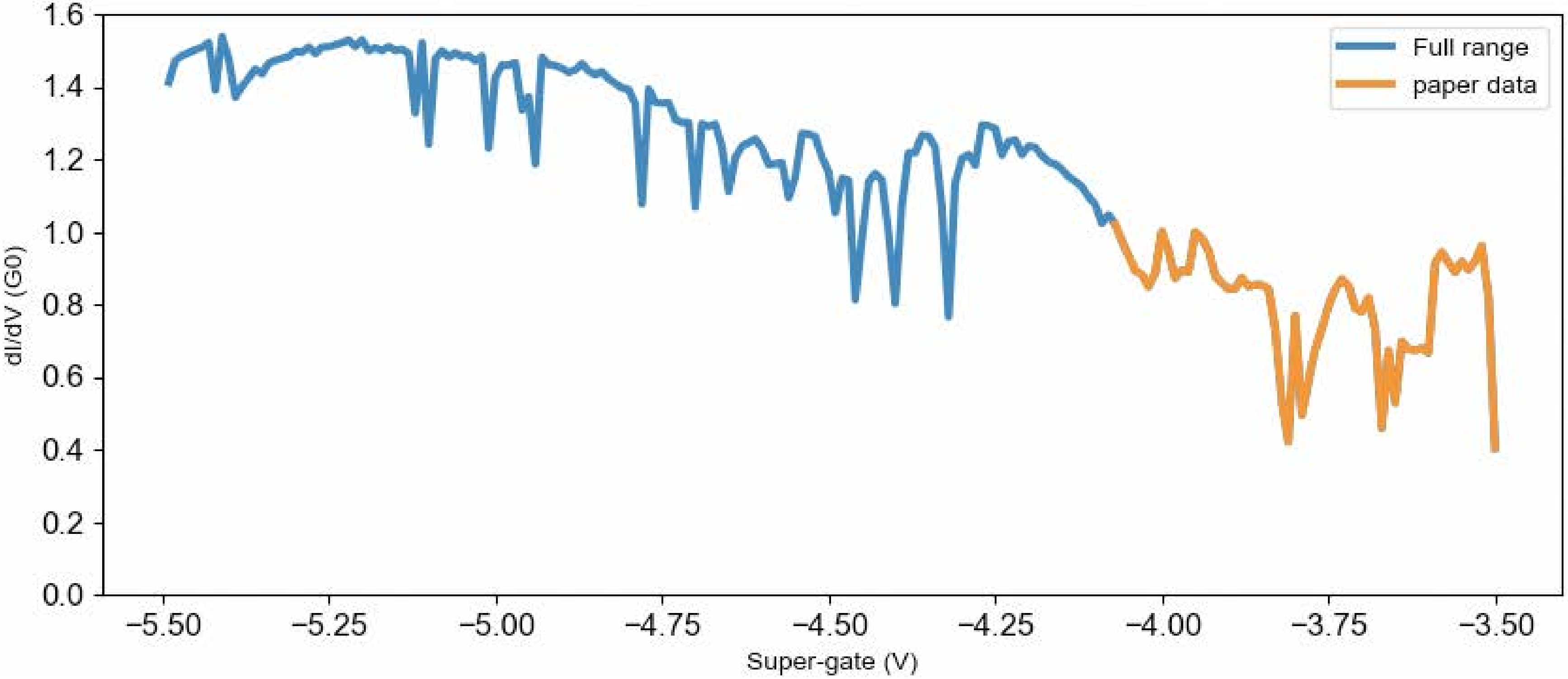
We plotted source data for Fig 3b ourselves…



Zero-bias conductance in orange was what was shown in the paper

In blue, conductance goes above 2e^2/h continuously.

Zero-bias conductance



Comments on other devices studied in the Nature paper

At this stage, no lab notebook type data have been presented to us from Device B and Device C that are shown in figures 4 and 5 of the Nature paper.

Device B is relevant, as the paper claims it reproduces the quantized peak. It would be interesting in the future to examine the full dataset from this device to see if similar issues surround Device B. The first author has stated that data from device B are presented in a separate paper (New Journal of Physics 20 (2018)103049, Fig.4) and that those data contain what he described as 'trivial peaks'. We became aware that in preparation of Figure 4 (showing device B), the authors labelled a graph where 'super-gate' was swept as 'tunnel gate'. They also cut out 7 IV traces from the figure.

Device C is relevant, as the paper claims it exhibits non-quantized zero bias conductance peaks. We believe this is deceptive, as we found widespread evidence in Device A for non-quantized zero bias conductance peaks as well. Showing this for Device C, but not for Device A creates the wrong impression that Device A is a special device with a special zero bias conductance peak.

Figure 4: device B

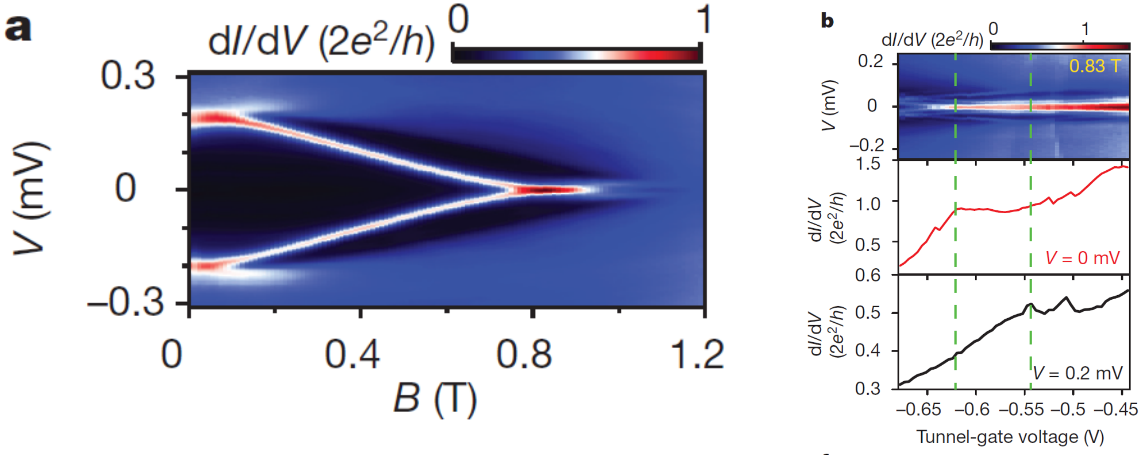
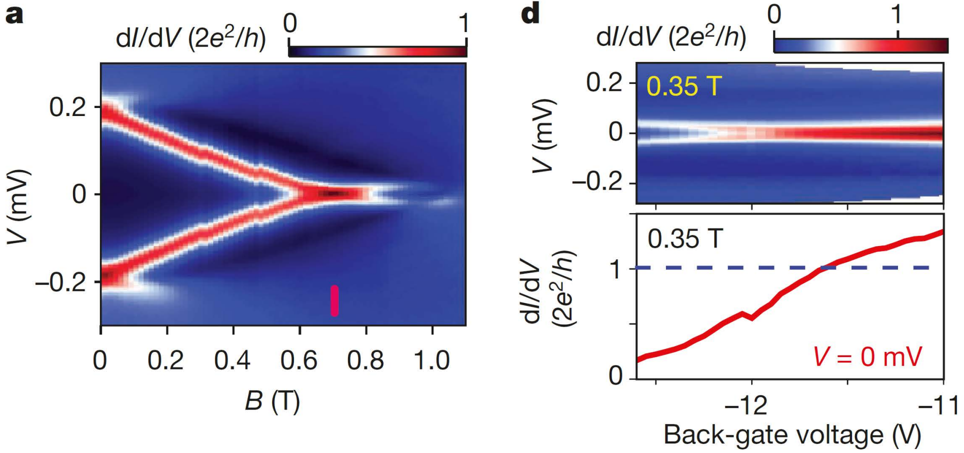


Figure 5: device C



Conclusions :

Panel after panel, figures 1-4 are manipulated and composed with the aim to emphasize the desired conductance value and conceal deviations from this value.

The role of charge switches in extending gate and magnetic field ranges of the desired zero bias conductance is not laid out in the Nature paper.

Panels in Figs. 2, 3 and 4 contain cut data. Apparent peak splittings are removed from raw data. Such splittings go against the claim of a ‘Majorana conductance plateau’.

Repeat measurements at the same settings contradict claims or point at an alternative explanation but these irreproducibilities are not disclosed.

The Nature paper omits large parameter ranges in device A in which apparently similar physical states yield zero-bias peaks that reach heights well above $2e^2/h$. Such ranges are much larger than the range studied and are directly adjacent to the presented data.

Taking the Nature paper and the additional data together, **no evidence of zero-bias conductance quantization exists in this work**.

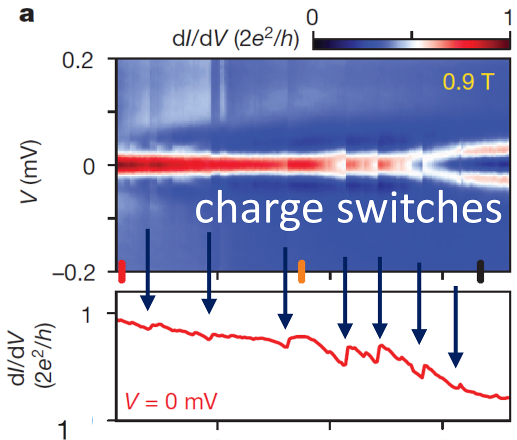
Supplementary slides:

1) The nature of charge switches
2) Andreev bound states
3) Conductance renormalization

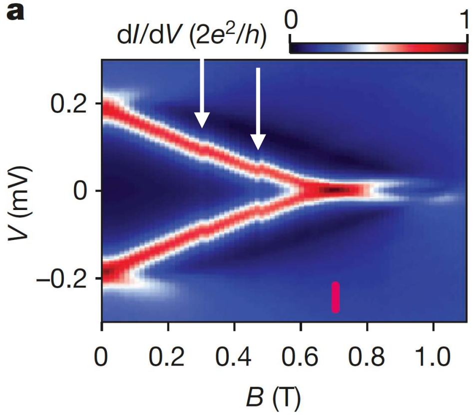
1) The nature of charge switches

Charge instabilities (switches) in devices from the Nature paper

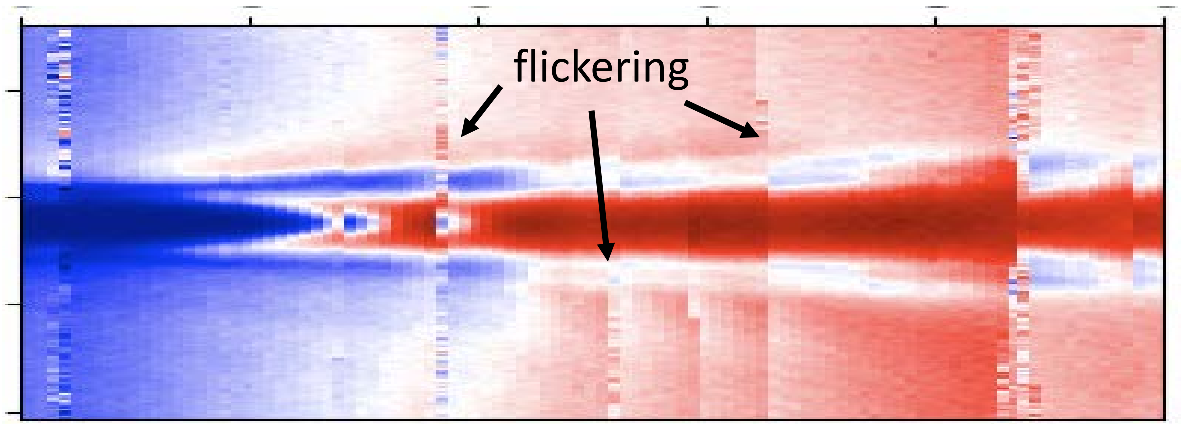
Device A exhibits many sudden discontinuities in conductance. An experimentalist working in the field may call device A ‘very switchy’. Switches have the effect of violating the correspondence between the measured value such as conductance and externally controlled parameters such as source-drain bias, gate voltage and magnetic fields. During the precise moments of time that a voltage applied to a gate is changed continuously in a certain range, e.g. from -5 V to -6 V, the device occupies 7 - 10 different states distinguished by arrangements of locally trapped charges within and around the device. Fig. 3a offers an example ->



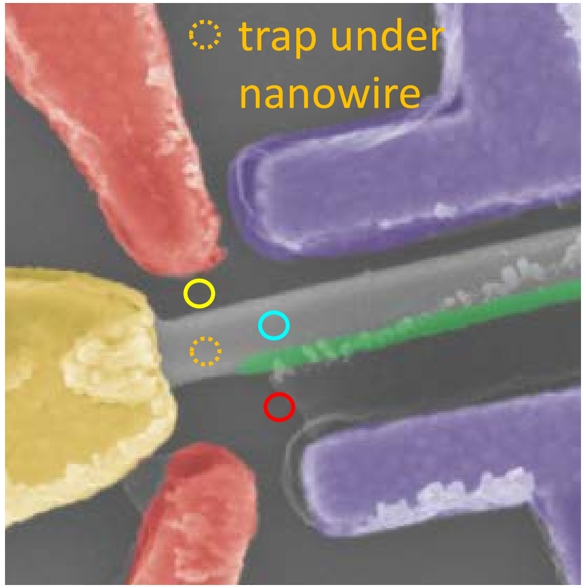
The discontinuities that manifest in magnetic field may seem counter-intuitive. However, a magnetic field sweep may easily contain a time-dependent stochastic rearrangement of charges and record a discontinuity if the field axis is simply thought of as time axis. Other devices shown are also switchy: see an example in Fig. 5a ->



Change switches can be very fast, when a trap is rapidly occupied and deoccupied. Our replot of Fig 2a from raw data shows hundreds of individual switches. Some of them appear as flickering signal with each consecutive data point corresponding to a different state of a device. After periods of flickering dynamics the device settles, sometimes in the same state but often into a different state.



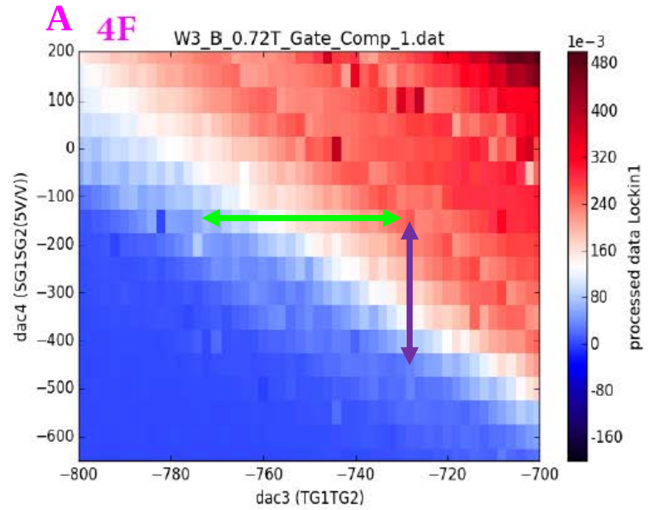
The effect of switches is local in nature because they are caused by individual charge traps hosted by defects (circles on the right). One wire can be surrounded by many charge traps. They don’t need to coincide in position with gate electrodes. When a device is highly sensitive to electric fields, these time-dependent stochastic charge rearrangements in the vicinity of the device have a major effect. They affect not just the magnitude of conductance but also the energies of various quantum levels, and the shapes, couplings of the bound state wavefunctions.



A naive capacitive coupling model would treat switches as shifts in gate potential. However, this is not the case. Electric fields emanating from traps are not identical to electric fields from gates. Thus charge traps affect the nanowire in a way that is generically different from the effect of gates. And different charge traps have different effects. A charge jump is not equivalent to a gate shift.

It is not valid to argue that because the conductance value is the same before and after a charge jump it means the device returned to the same state. This can be illustrated with a tunnelgate vs supergate dataset on the right. Both gates tune the magnitude of conductance. But two charge switches, along green and purple arrows, cannot be distinguished because both result in the same change in conductance from red to blue and back.

Two super-gates (purple gates)

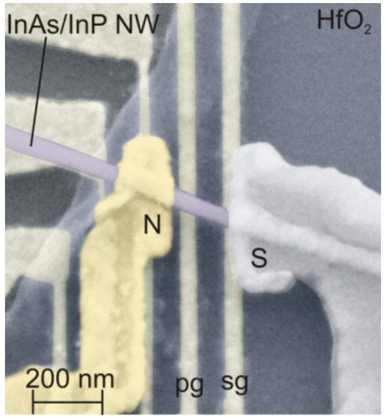


Two tunnel-gates (red gates) swept together

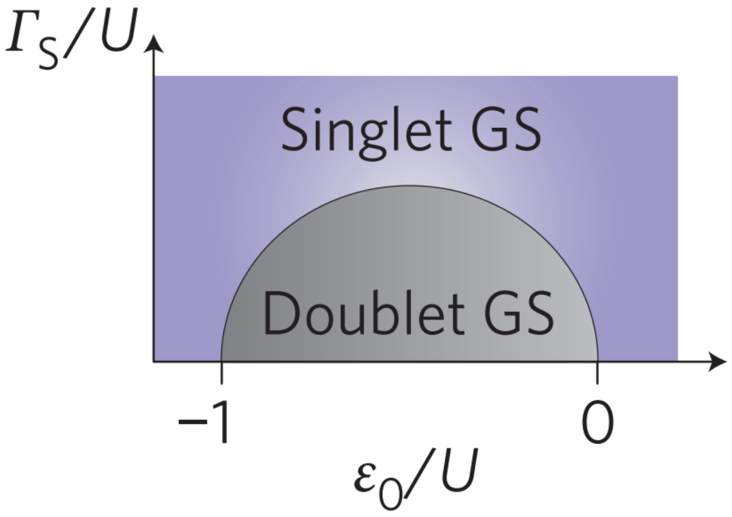
It is not only inappropriate to cut out charge jumps without disclosure.
It is furthermore scientifically unjustified to claim that features spanning across charge switches pertain to the same quantum state in a device.

2) Andreev bound states

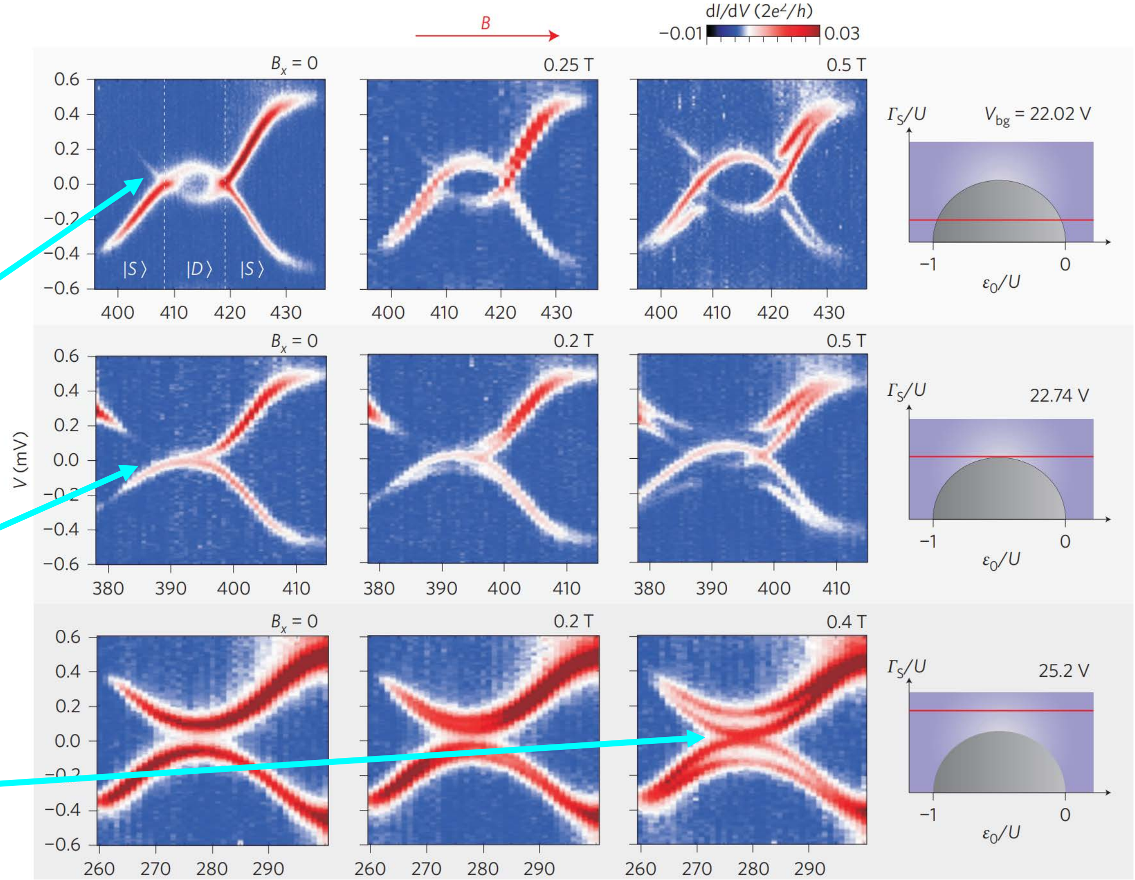
Andreev bound states primer, based on Lee et al. Nature Nanotechnology 2014



This paper studied a similar N-nanowire-S device, but focused on a quantum dot between N and S



The physics of Andreev bound states is captured by the phase diagram of singlet and doublet Andreev ground states. **Whenever the doublet-singlet boundary is crossed, a ZBCP appears.**

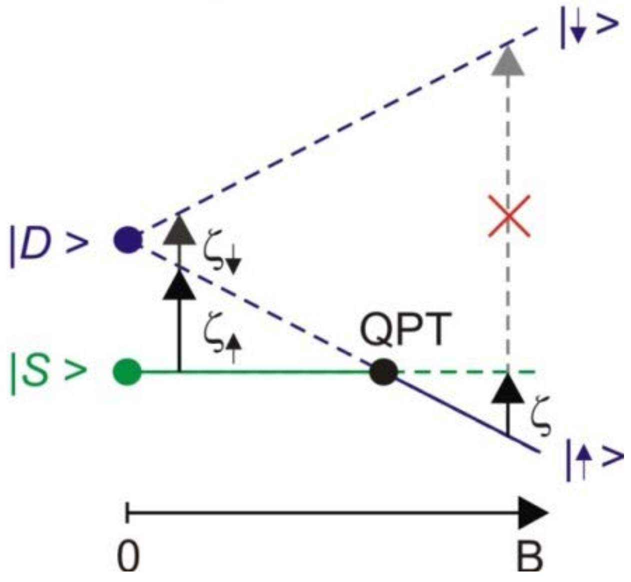


Trivial ZBCP may be transient

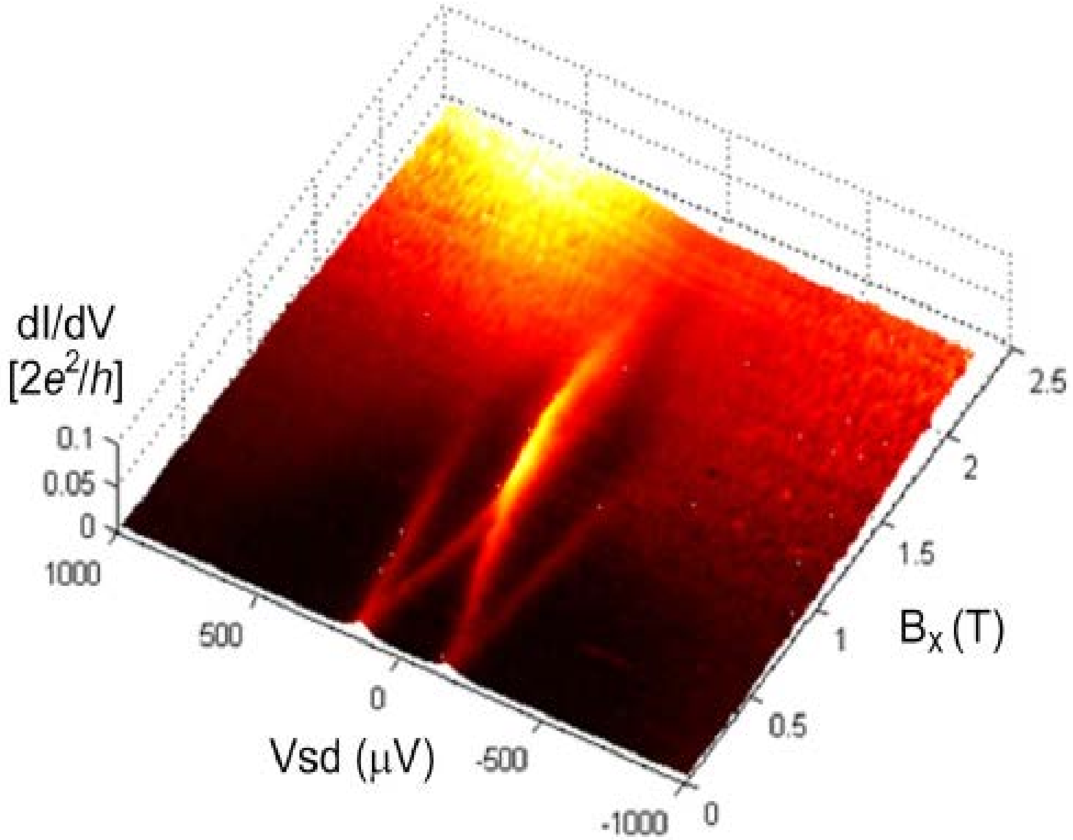
Trivial ZBCP may linger near zero bias for different settings of a gate voltage at zero B field

Trivial ZBCP may linger in gate voltage also at finite field

Andreev bound states primer, based on Lee et al. Nature Nanotechnology 2014



When magnetic field is applied, the “spin-up” state from the doublet shifts to lower chemical potential. At a finite field, a quantum phase transition (QPT) from a singlet to a doublet ground state is observed. A singlet-doublet boundary is crossed in magnetic field. At the crossing point a ZBCP appears.



When the QPT point appears at large B-field, where superconductivity in the S-lead itself is suppressed by the magnetic field, the ZBCP can persist in magnetic field.

This is because the collapsing superconducting gap pushes the singlet-doublet energy difference to zero.

3) Conductance renormalization

Note: the next slide was prepared before it became known that the authors had a systematic error leading to an underestimation of conductance by 10% in all data. Conductance normalization procedure was not described in the Nature paper. This allowed this systematic error and other issues we describe here go unnoticed.

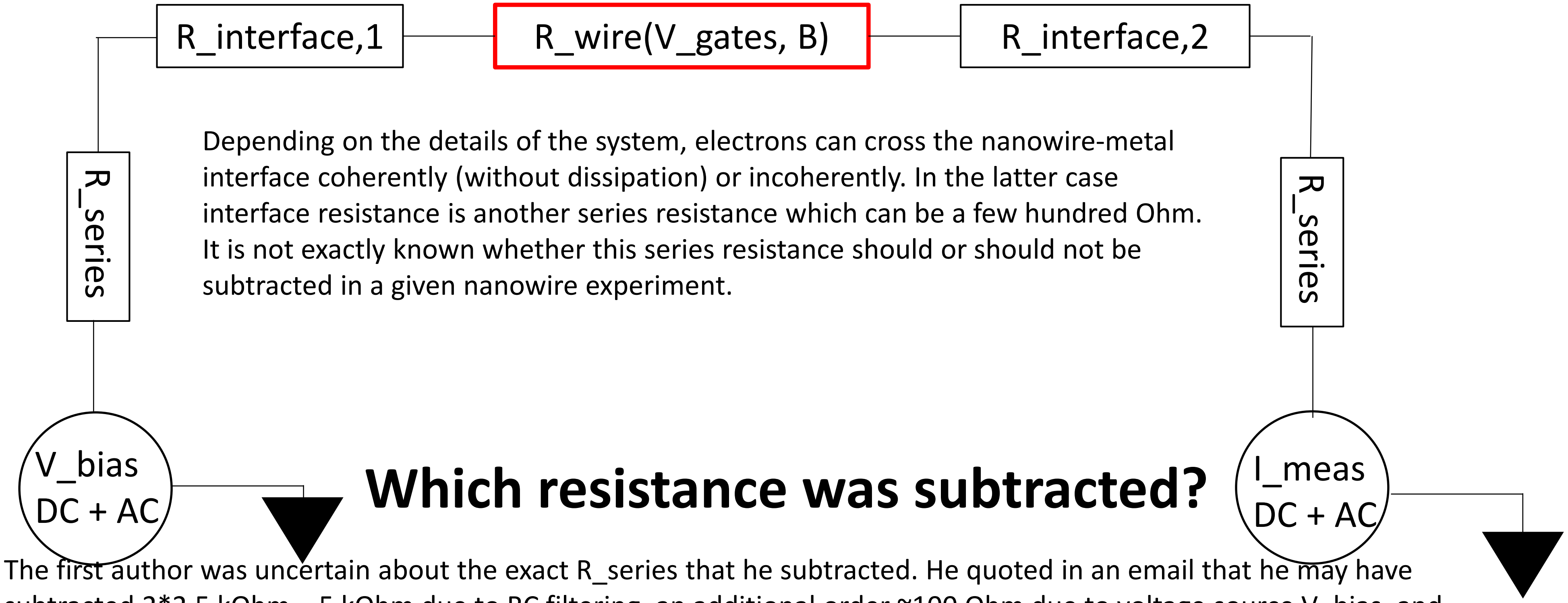
Device R_wire is in the few kOhm to few hundred kOhm regime, with the interesting regime being of order 10 kOhm (1/(2e^2/h)).

R_series includes line and filtering resistance, and should be of similar magnitude for all lines, but can easily vary by a few percent. The current amplifier typically has an input impedance not negligible to the device resistance in the more transparent regime, and that needs to be accounted for.

Careful possibilities for data presentation when the exact conductance value is of paramount importance include:

1. Present raw data
2. Pre-calibrate specific lines and the amplifier used, and correct both the voltage bias and the measured current accordingly.
3. Measure the actual voltage drop across the device in the four-point measurement configuration, and use this as the actual voltage bias axis and to rescale measured current. If done with lock-in, differential conductance can be measured directly by dividing I_meas AC by V_meas AC.

According to the first author, the following measurement scheme was used. Though it is a standard scheme, it is not the only possible scheme. For example, a 4-point measurement could have been used. This was not disclosed in the Nature paper.



Depending on the details of the system, electrons can cross the nanowire-metal interface coherently (without dissipation) or incoherently. In the latter case interface resistance is another series resistance which can be a few hundred Ohm. It is not exactly known whether this series resistance should or should not be subtracted in a given nanowire experiment.

Which resistance was subtracted?

The first author was uncertain about the exact R_series that he subtracted. He quoted in an email that he may have subtracted 2*2.5 kOhm = 5 kOhm due to RC filtering, an additional order ~100 Ohm due to voltage source V_bias, and depending on the setting of the current amplifier I_meas, 3 or 12 kOhm (not specified what setting was used in a particular scan). That adds up to either ~8 kOhm or ~17.8 kOhm series resistances, a value comparable to 1/(e2^2/h). The authors have informed now that 17.8 kOhm was subtracted from all figures, but we were not able to verify this so far Because we had no access to the original raw data.

Allowing for few percent uncertainty in these values, and considering an additional order hundred ohms interface resistance, the total uncertainty in the series resistance is of order a few hundred ohms.
Ultimately, this implies that there is a few percent uncertainty in the conductance, plausibly of order 5%. Bear in mind that interface resistances should lead to a lower value of conductance, rather than a true uncertainty that could contribute either way.