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Photon-assisted resonant Andreev reflections: Yu-Shiba-Rusinov and Majorana states

Felix von Oppen

Freie Universität Berlin

Acknowledgments

- Resonant Andreev reflections probed by photon-assisted tunnelling at the atomic scale
  O. Peters, N. Bogdanoff, S. Acero González, L. Melischek, J.R. Simon, G. Reecht, C.B. Winkelmann, FvO, K.J. Franke
  Nature Physics https://doi.org/10.1038/s41567-020-0972-z (2020)
- Photon-assisted resonant Andreev reflections: Yu-Shiba-Rusinov and Majorana states
  S. Acero González, L. Melischek, O. Peters, K. Flensberg, K.J. Franke, FvO
  PRB **102**, 045413 (2020)


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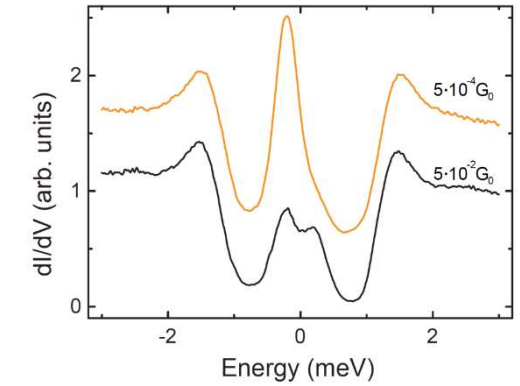
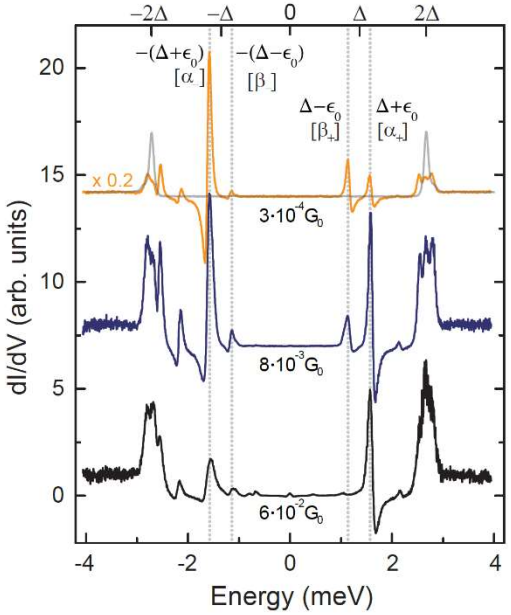
Larissa Melischek

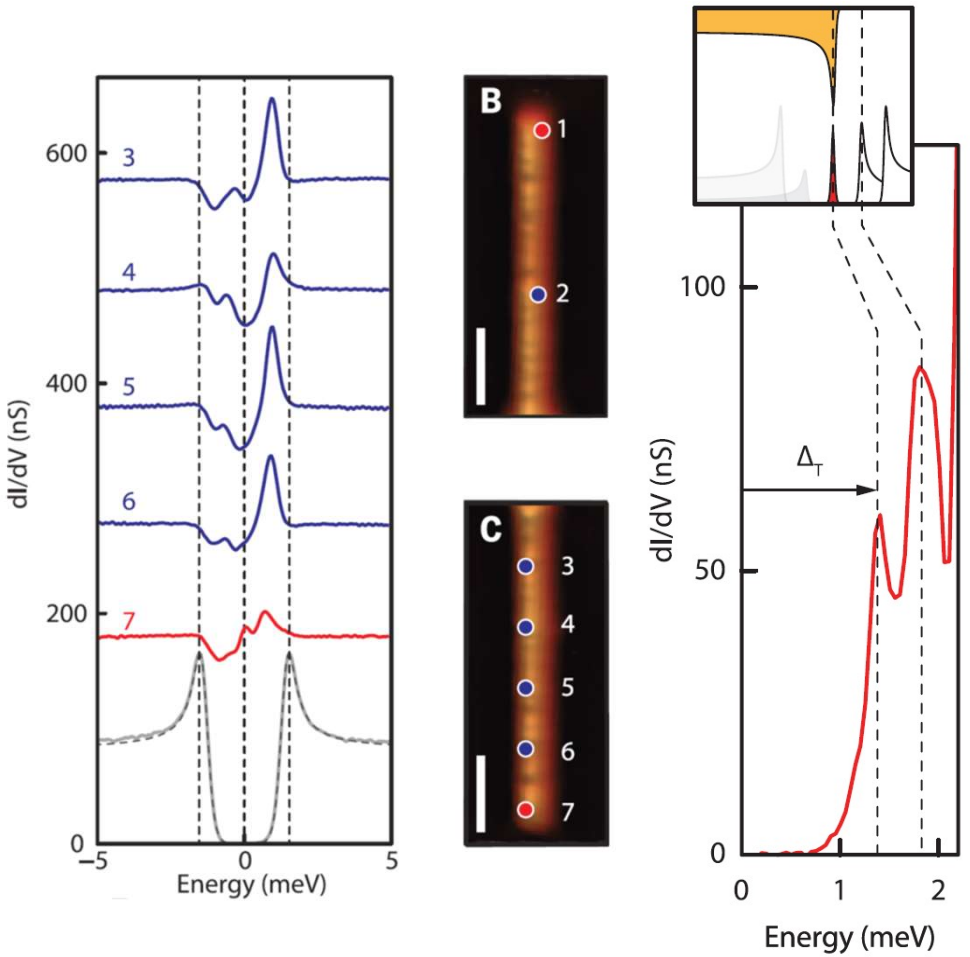

Karsten Flensberg (Copenhagen)

STM with superconducting tips



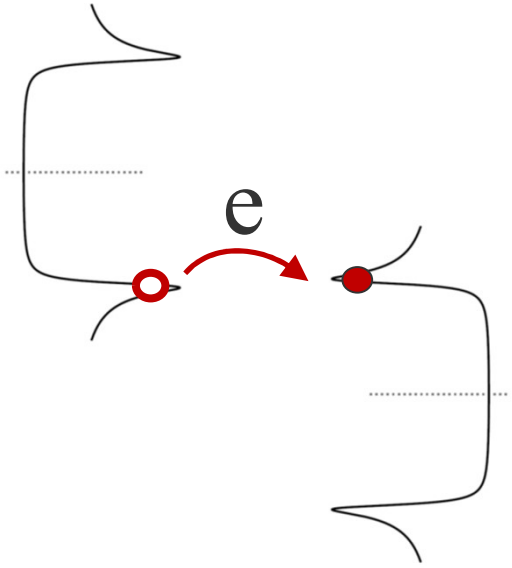


M. Ruby, …, K. Franke, PRL (2015)



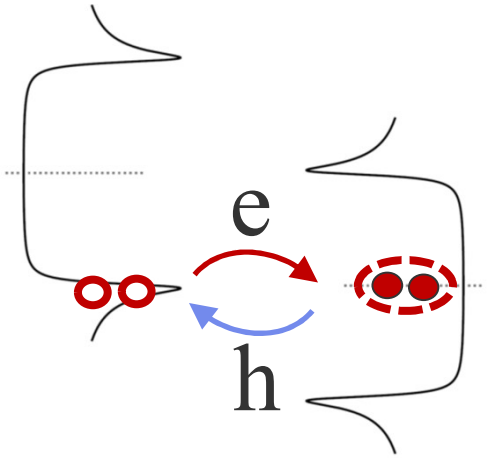
Yazdani group, Science (2014)

Tunneling between (plain) SCs



1e
quasiparticle
tunneling

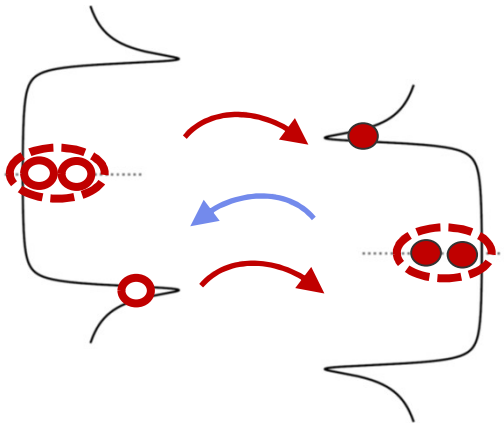
$eV = 2\Delta$



2e
Andreev
tunneling

$eV = \Delta$

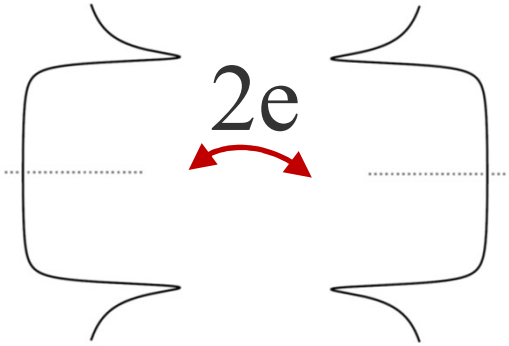
Tunneling between (plain) SCs



.....

3e
multiple
Andreev
tunneling

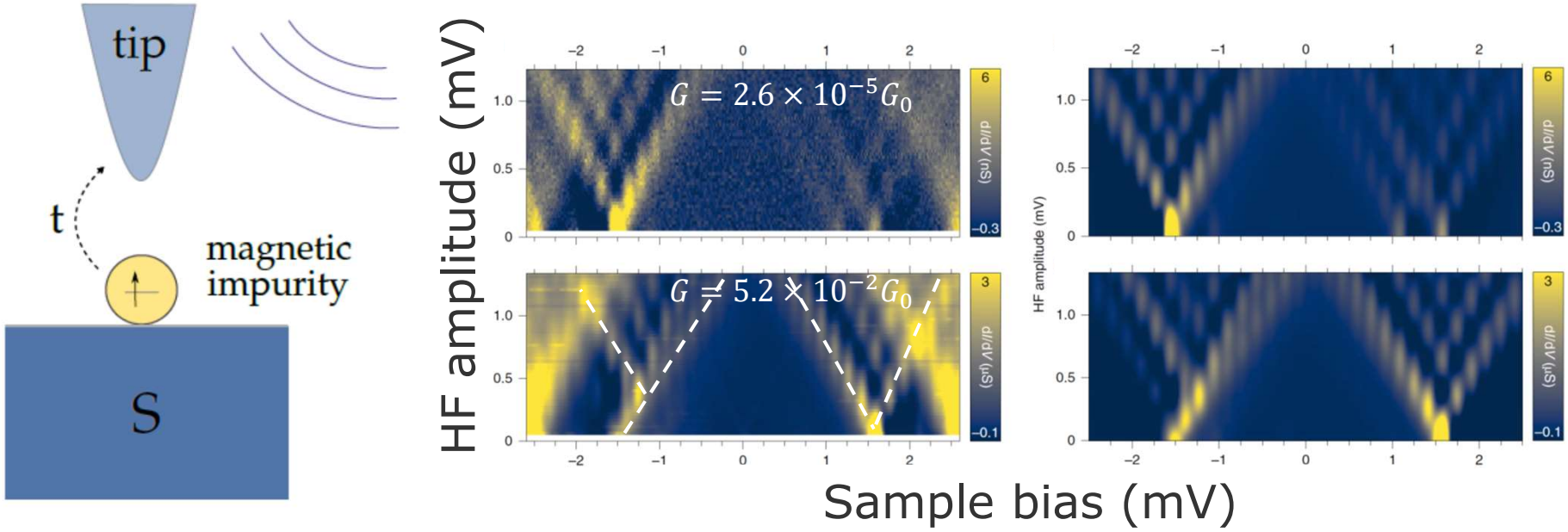
$$eV = \frac{2\Delta}{3}$$



Josephson
coupling
of
Cooper pairs

$$eV \approx 0$$

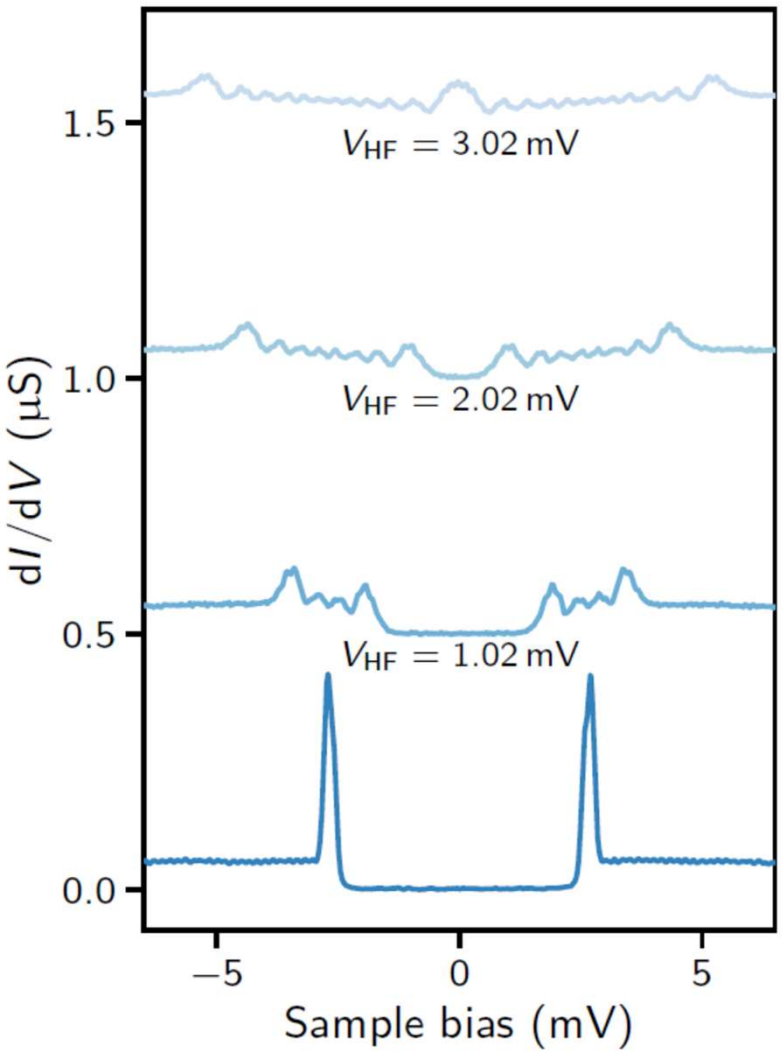
Resolving the tunneling processes

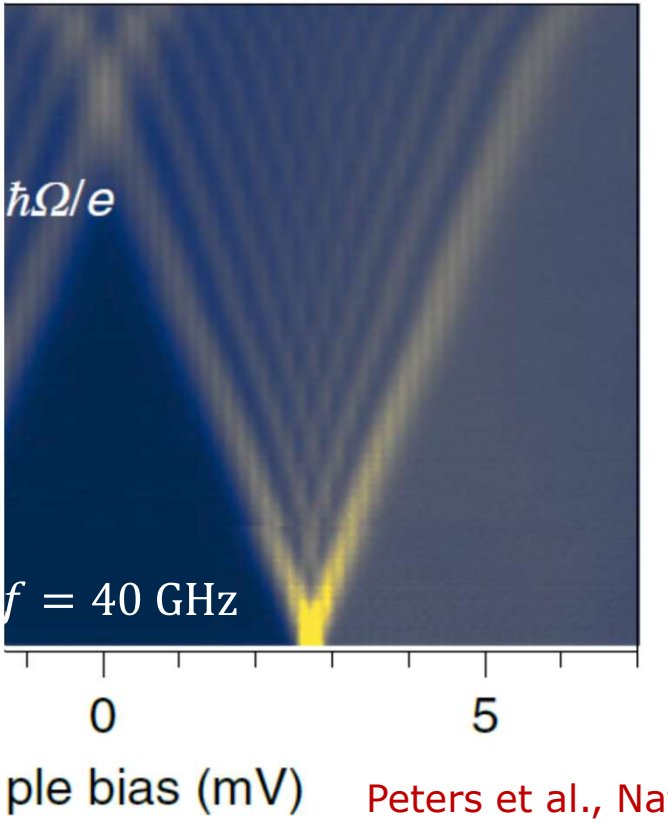


Mn on Pb(111)
w/ Pb tip

Peters et al., Nature Phys. (2020)

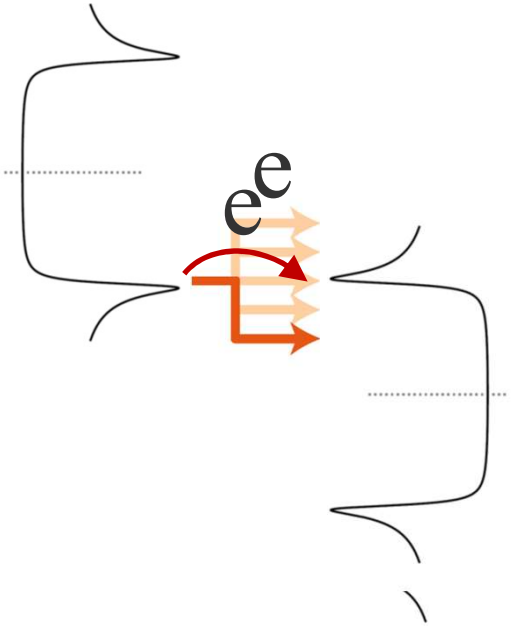
Photon-assisted tunneling



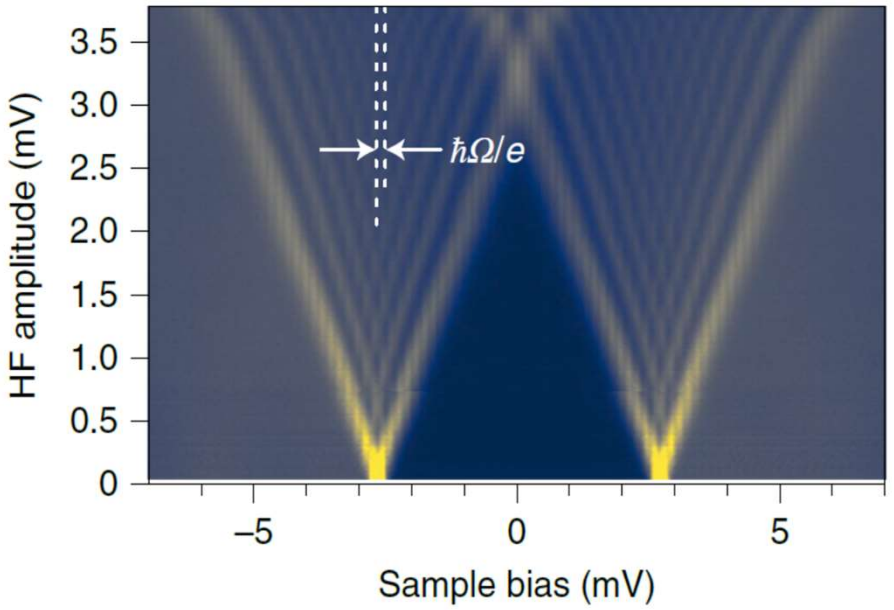


Peters et al., Nature Phys. (2020)
[see also Kot et al., *ibid.* (2020)]

Coherence peaks



Peters et al., Nature Phys. (2020)



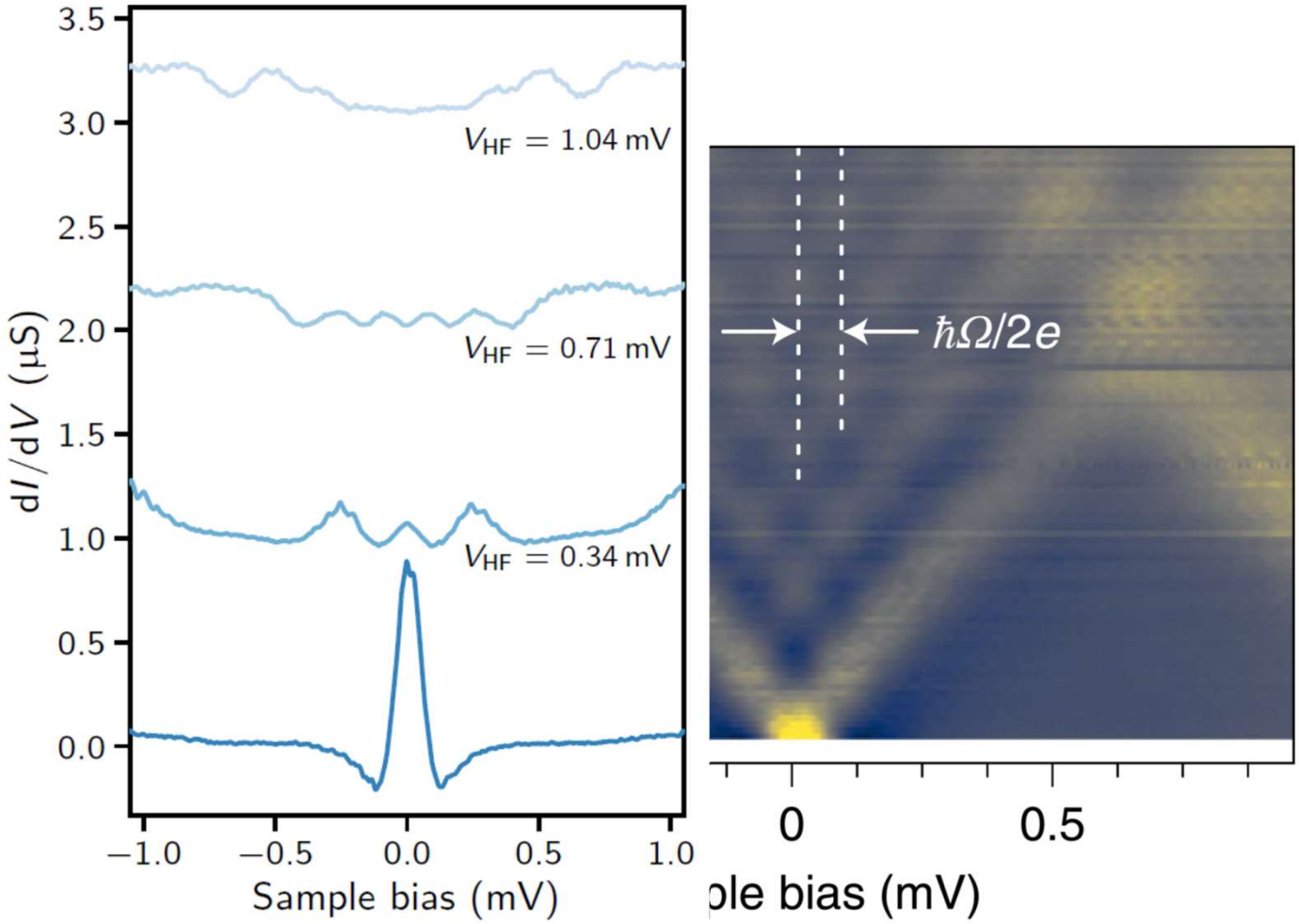
$$eV \pm n\hbar\Omega = 2\Delta$$

$$n\hbar\Omega < eV_{HF}$$

$$G(V) = \sum_n J_n^2\left(\frac{eV_{HF}}{\hbar\Omega}\right) G^{(0)}\left(V + \frac{n\hbar\Omega}{e}\right)$$

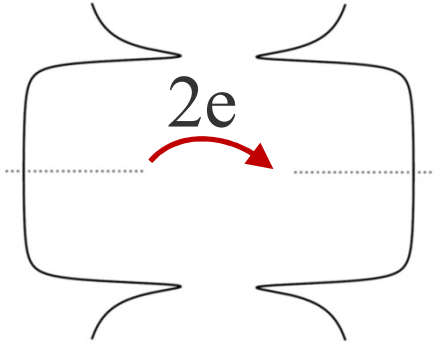
Tien & Gordon, PRB **129**, 647 (1963).

Josephson peak

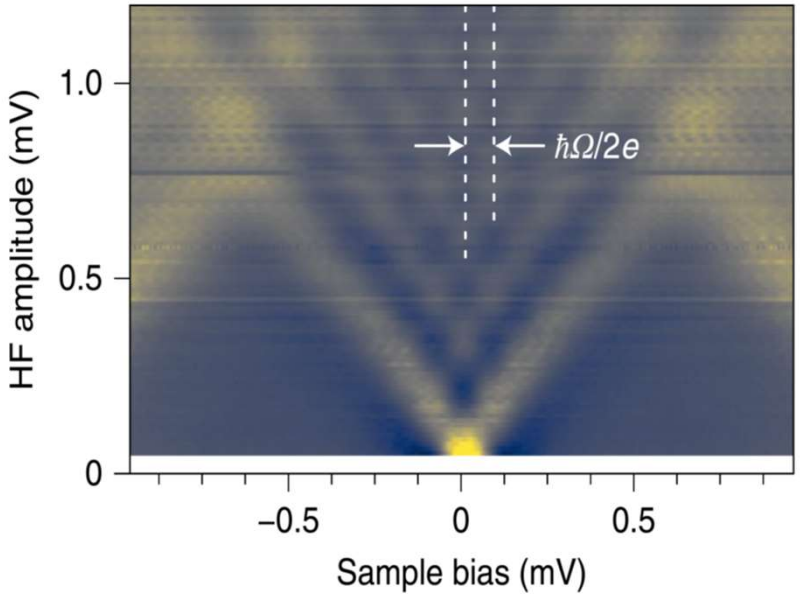


Peters et al., Nature Phys. (2020)
[see also Kot et al., *ibid.* (2020)]

Josephson peak



Peters et al., Nature Phys. (2020)



$$2eV \pm n\hbar\Omega = 0$$

$$n\hbar\Omega < eV_{HF}$$

$$G(V) = \sum_n J_n^2\left(\frac{keV_{HF}}{\hbar\Omega}\right) G^{(0)}\left(V + \frac{n\hbar\Omega}{ke}\right)$$

Cooper pairs: $k = 2$

Generalized Tien-Gordon approach

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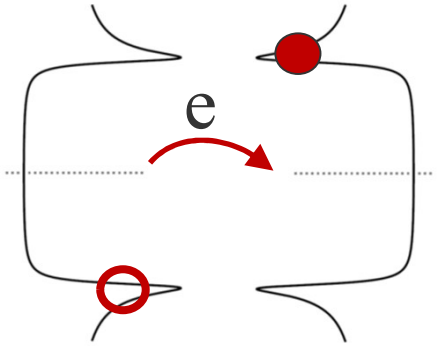
$$T = H_T + H_T G_0 H_T + \cdots$$

$$\begin{cases} H_T = t e^{i\phi(\tau)} c_{\text{tip}}^{+} c_{\text{sub}} + H.c. \\ \phi(\tau) = \int_0^{\tau} d\tau' \left[eV + eV_{HF}(\tau') \right] \end{cases}$$

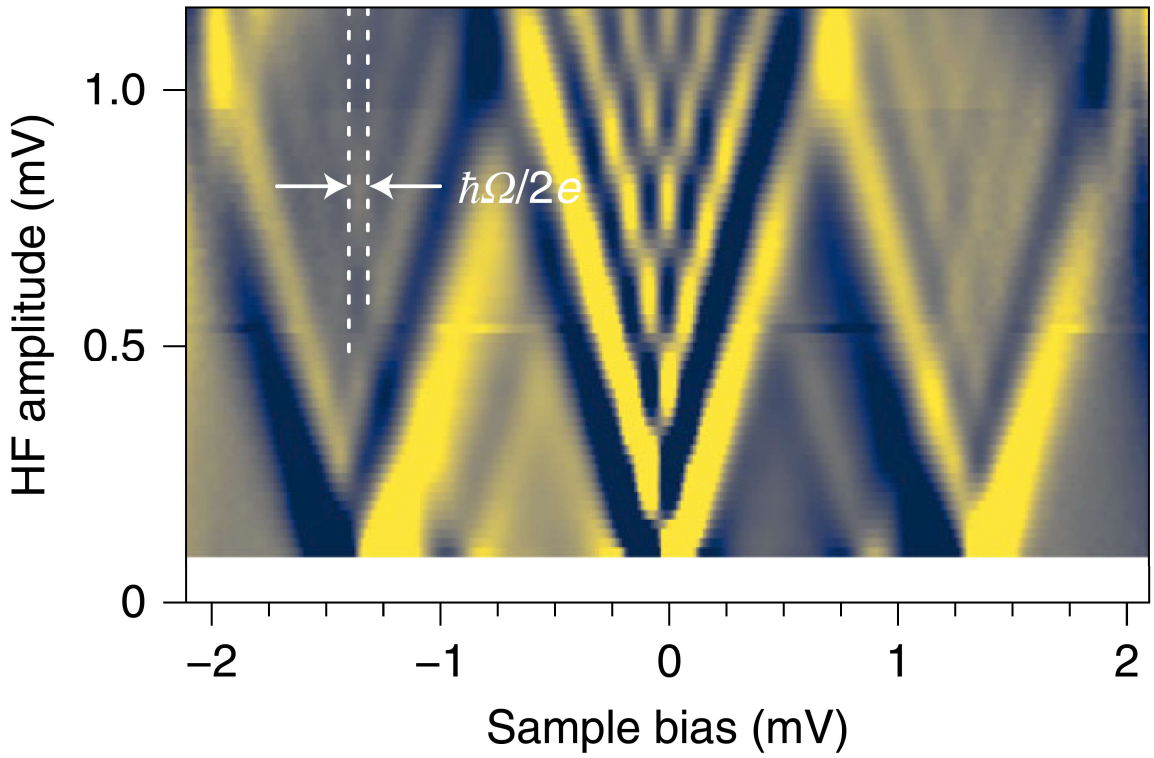


$$H_T G_0 H_T \propto t_{\text{eff}} e^{i2\phi(\tau)}$$

$$G_0(\omega) \approx \frac{1}{eV - 2\Delta}$$

$$G(V) = \sum_n J_n^2 \left(\frac{keV_{HF}}{\hbar\Omega} \right) G^{(0)} \left(V + \frac{n\hbar\Omega}{ke} \right)$$

(Multiple) Andreev reflections



$$meV \pm n\hbar\Omega = 2\Delta \qquad \Rightarrow \qquad eV = \frac{2\Delta}{m} \pm n\frac{\hbar\Omega}{m}$$

Peters et al., Nature Phys. (2020)
[see also Kot et al., *ibid.* (2020)]

Photon-assisted tunneling at the atomic scale

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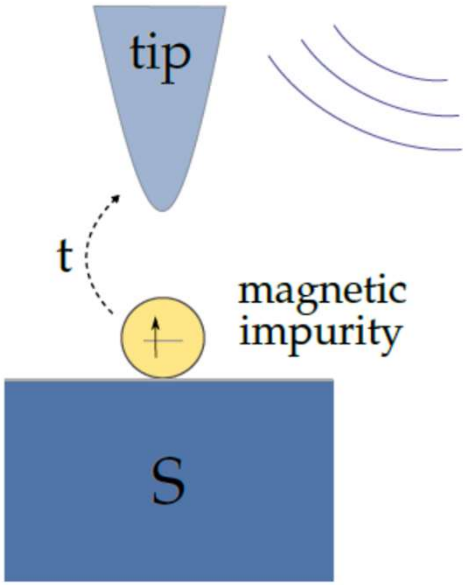
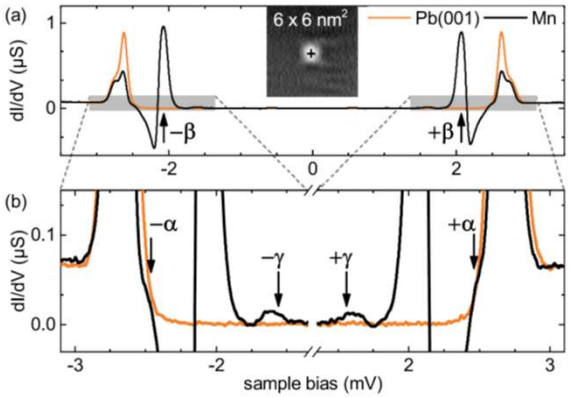


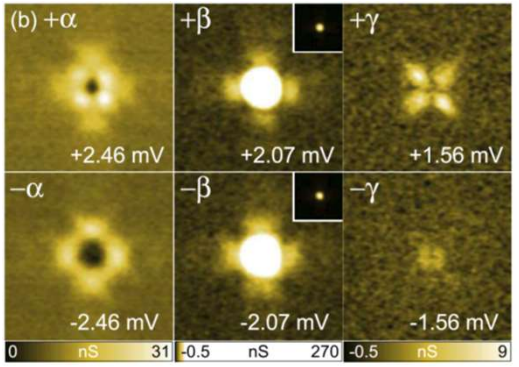
Yu-Shiba-Rusinov states:

$$\mathcal{H} = \xi_{\mathbf{p}}\tau_z + \Delta\tau_x + V\delta(\mathbf{r})\tau_z - J\mathbf{S}\cdot\boldsymbol{\sigma}\delta(\mathbf{r})$$

$$\psi \sim \frac{\cos(k_F r - \delta)}{k_F r} e^{-r/\xi_E}$$

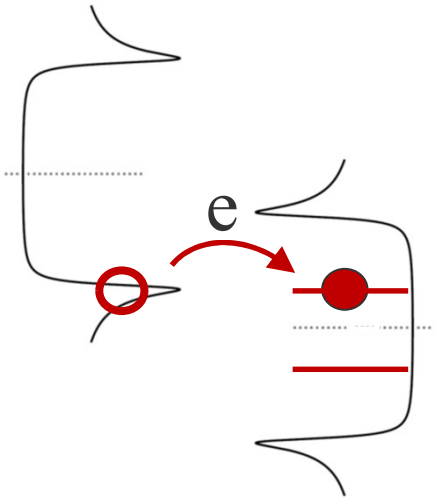
$$\xi_E \sim \frac{\hbar v_F}{\sqrt{\Delta^2 - E^2}}$$

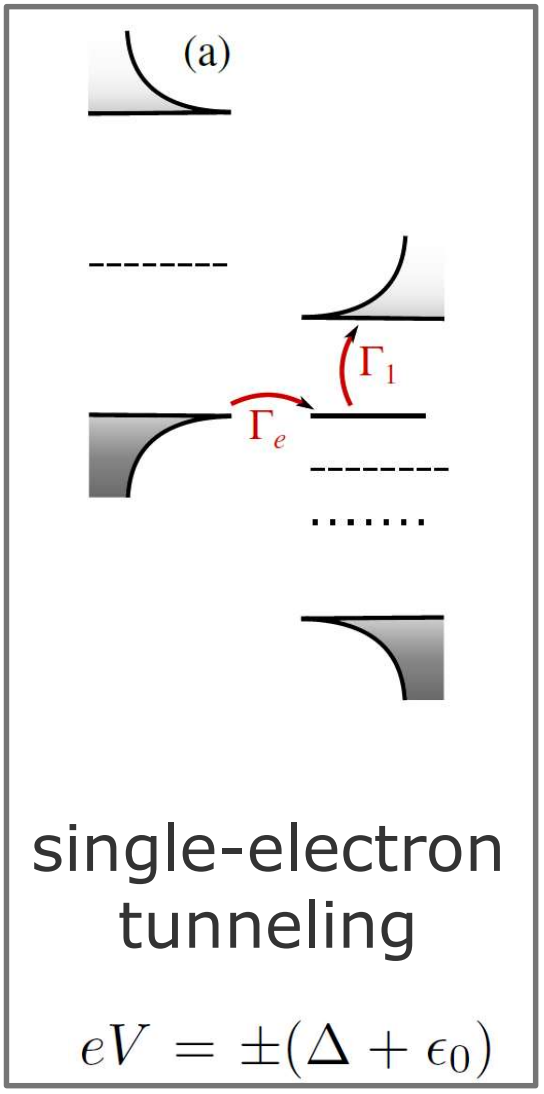


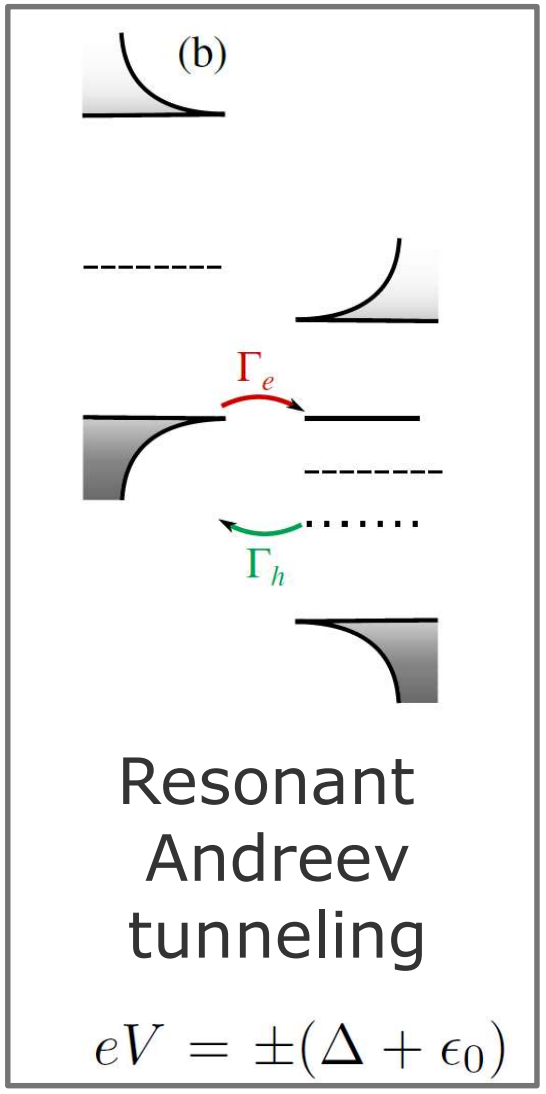


M. Ruby, Y. Peng, FvO, B. Heinrich, K. Franke, PRL (2016)

Tunneling via subgap states

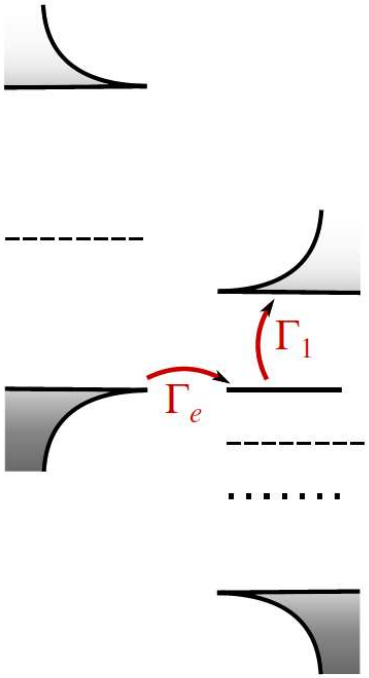


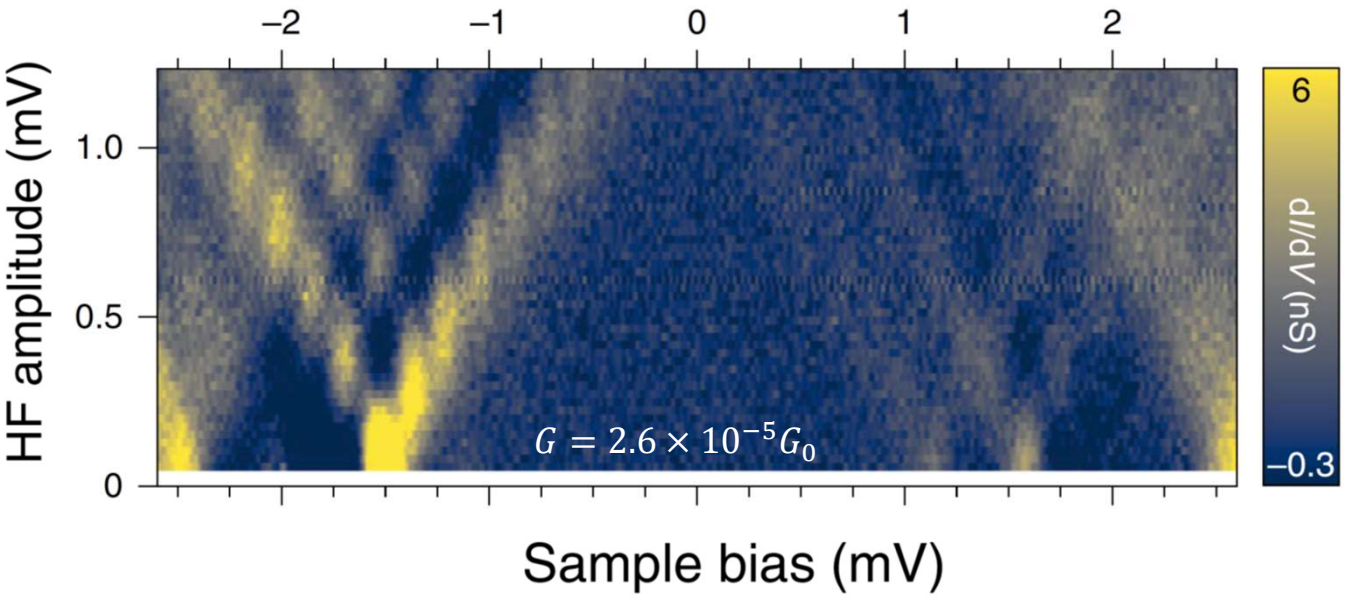




M. Ruby, F. Pientka, Y. Peng, FvO, B. Heinrich, K. Franke, PRL **115**, 087001 (2015)

Low tunneling conductance

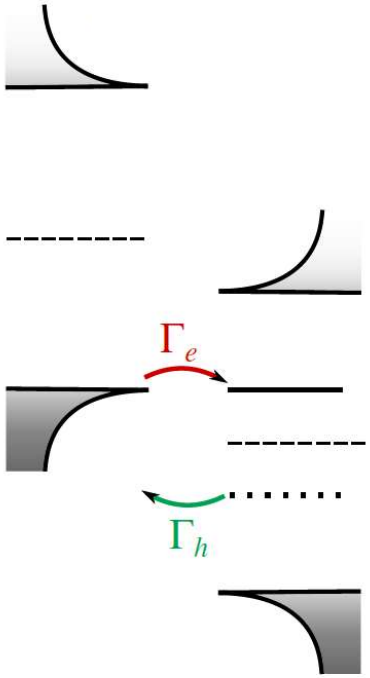


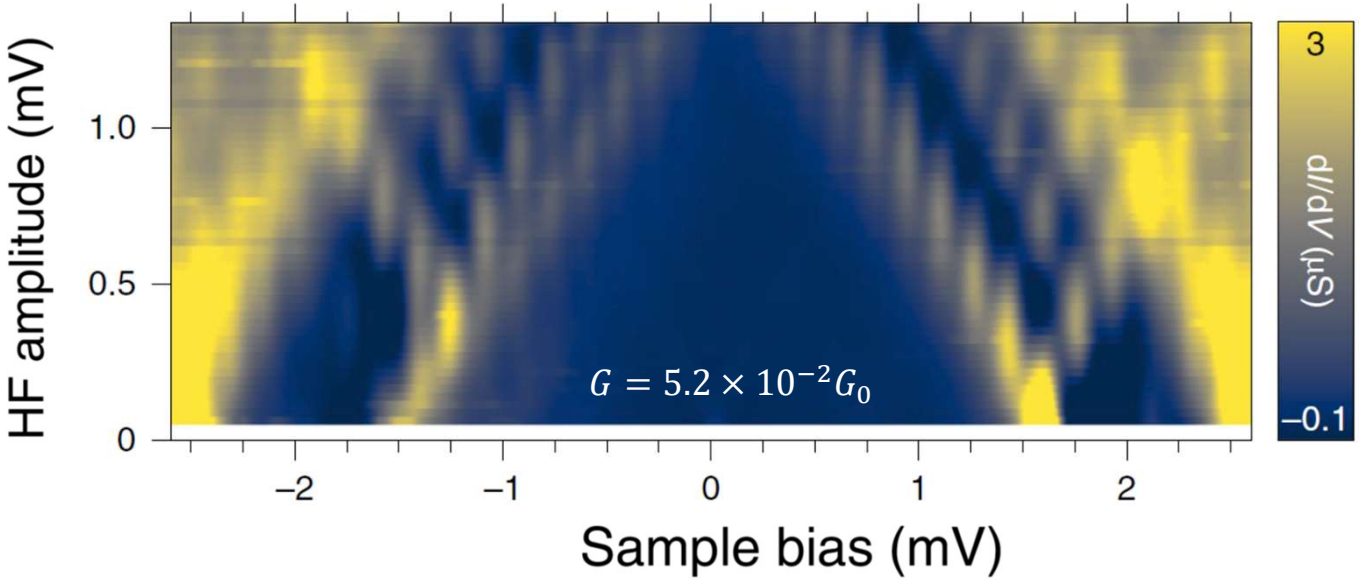


- sideband spacing: $\hbar\Omega/e$

  $\Rightarrow$ single-electron tunneling
- standard V-shape

High tunneling conductance



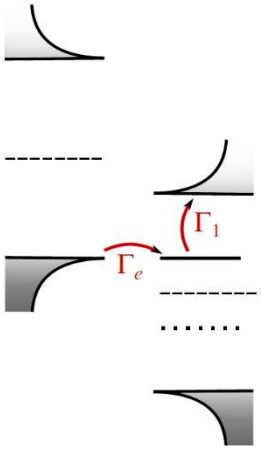


- sideband spacing: $\hbar\Omega/e$

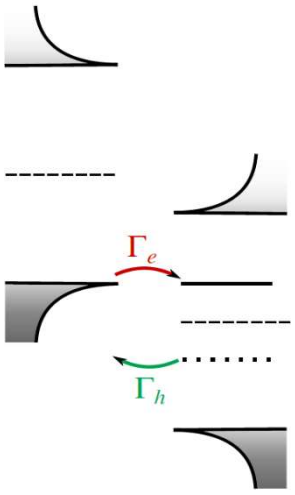
  $\Rightarrow$ single-electron tunneling??

- Y-shape??

A little (Keldysh) calculation …



$$I(\tau) = e \int d\tau' \, \mathrm{Tr}\Big\{\tau_z\Big[G_R^<(\tau,\tau')\Sigma_R^a(\tau',\tau) + G_R^r(\tau,\tau')\Sigma_R^<(\tau',\tau) - \Sigma_R^<(\tau,\tau')G_R^a(\tau',\tau) - \Sigma_R^r(\tau,\tau')G_R^<(\tau',\tau)\Big]\Big\}.$$



$$\Sigma_R(\tau,\tau') = |t|^2 \sum_{n,m} J_n\left(\frac{eV_{\mathrm{HF}}}{\Omega}\right) J_m\left(\frac{eV_{\mathrm{HF}}}{\Omega}\right) e^{-i(eV+n\Omega)\tau\tau_z} \times g_L(\tau-\tau') e^{i(eV+m\Omega)\tau'\tau_z}$$

- single electron tunneling & resonant Andreev reflections
- diagonal approximation

Acero González, Melischek et al., PRB (2020)

… gives a simple result

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$$I = 2e \int \frac{d\omega}{2\pi} \sum_{n,m} J_n^2(eV_{\mathrm{HF}}/\Omega) J_m^2(eV_{\mathrm{HF}}/\Omega)$$

$$\times \frac{\Gamma_e(\omega - (eV + n\Omega))\Gamma_h(\omega + (eV + m\Omega))}{[\omega - \epsilon_0 - \Lambda(\omega)]^2 + \frac{1}{4}\Gamma^2(\omega)}$$

$$\times [n_F(\omega - (eV + n\Omega)) - n_F(\omega + (eV + m\Omega))]$$

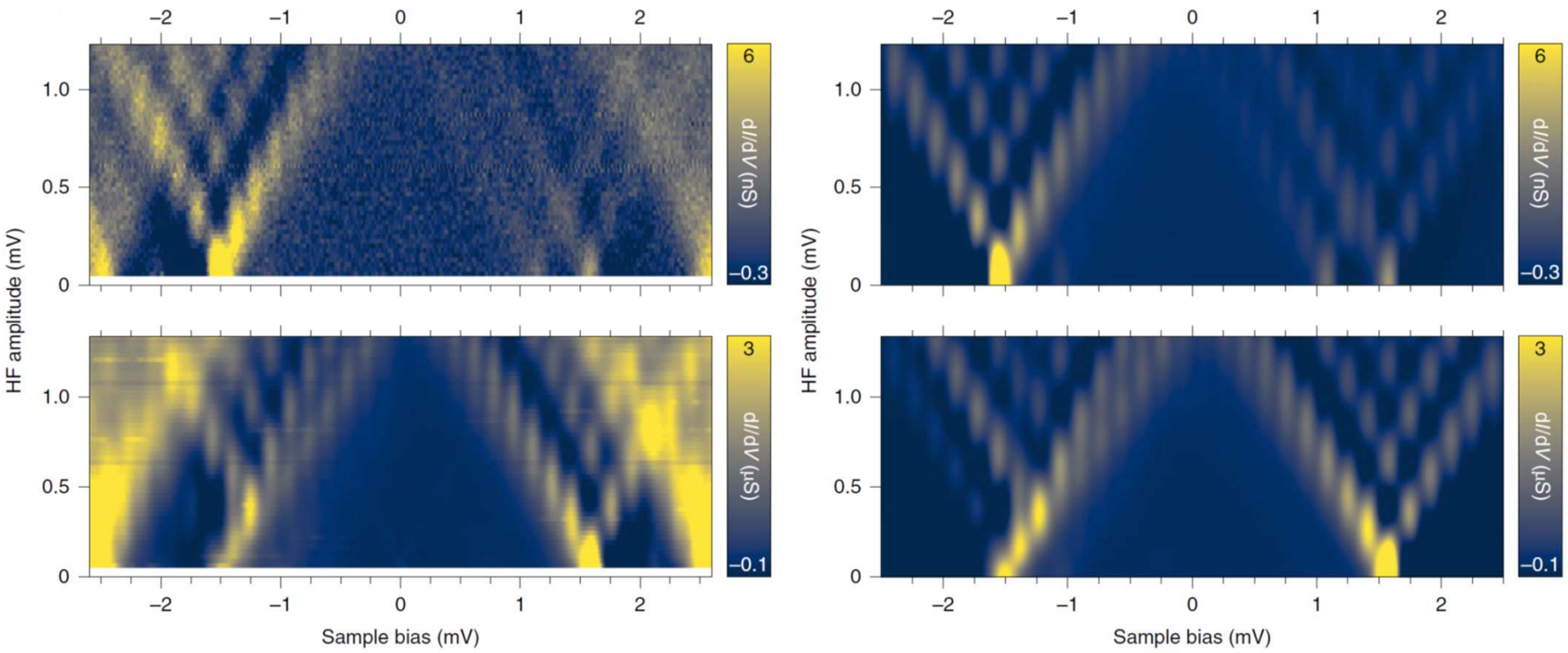
$$\Gamma(\omega) = \sum_n J_n^2(eV_{\mathrm{HF}}/\Omega)[\Gamma_e(\omega - (eV + n\Omega)) + \Gamma_h(\omega + (eV + n\Omega))]$$

$$\Gamma_e(\omega) = 2\pi |u|^2 |t|^2 \nu(\omega)$$

$$\Gamma_h(\omega) = 2\pi |v|^2 |t|^2 \nu(\omega)$$

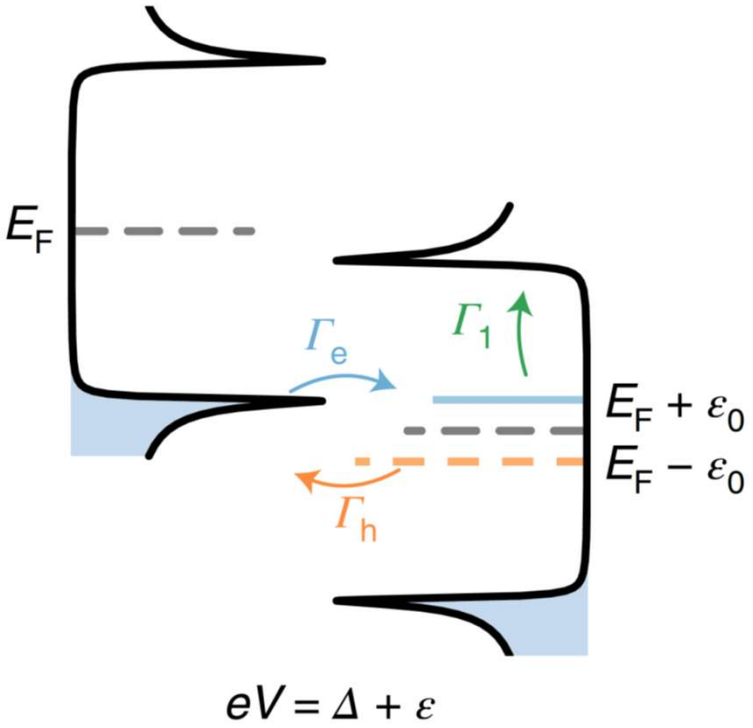
Acero González, Melischek et al., PRB (2020)

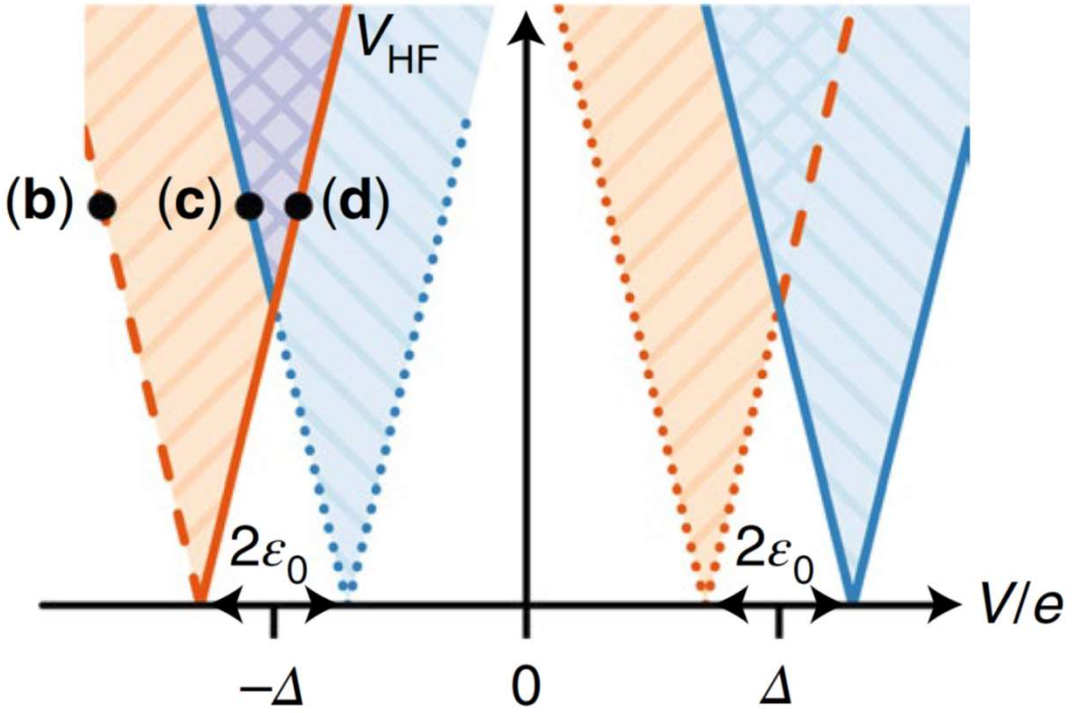
… which works



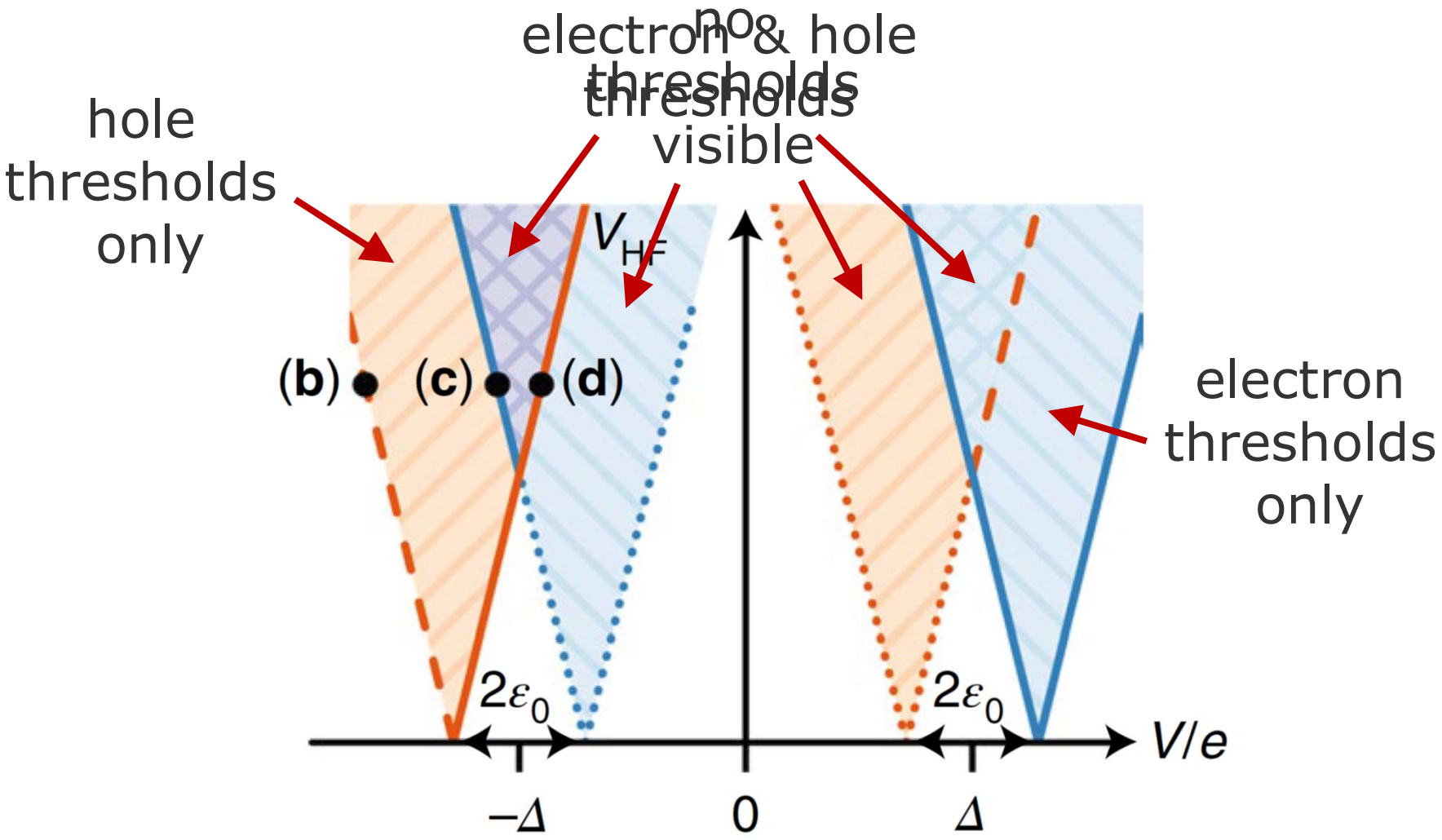
Peters et al., Nature Phys. (2020)

Electron & hole thresholds

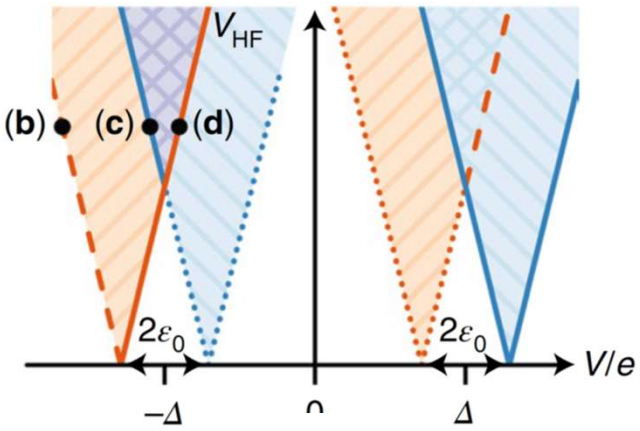


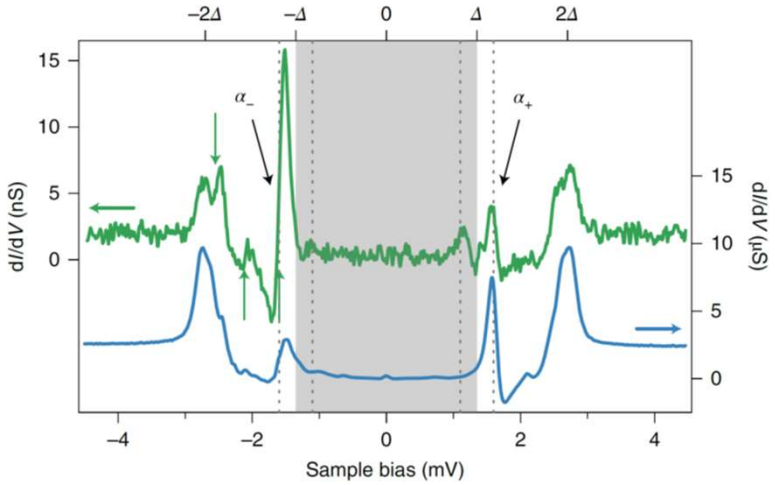


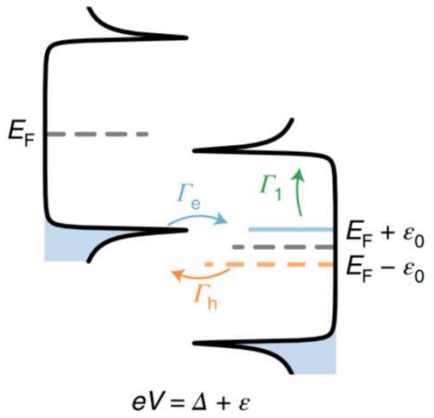
Thresholds

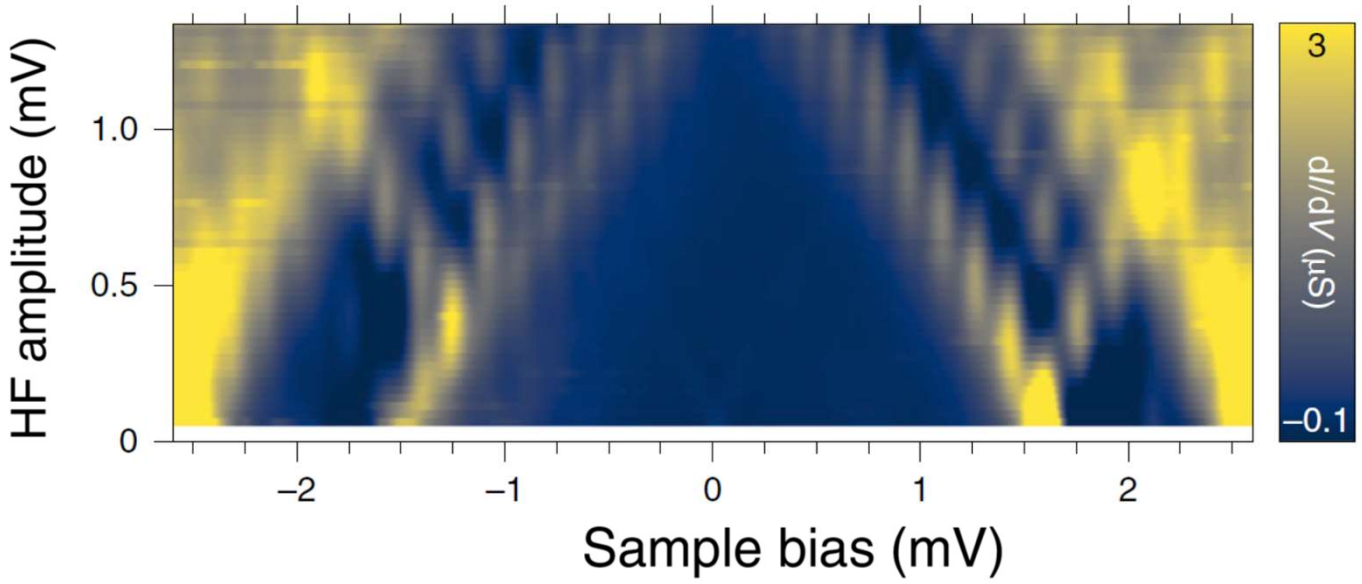

hole thresholds only
no electron & hole thresholds
thresholds visible
V_{HF}
(b)
(c)
(d)
$2\varepsilon_0$
$2\varepsilon_0$
V/e
$-\Delta$
0
Δ
electron thresholds only

Y-shape

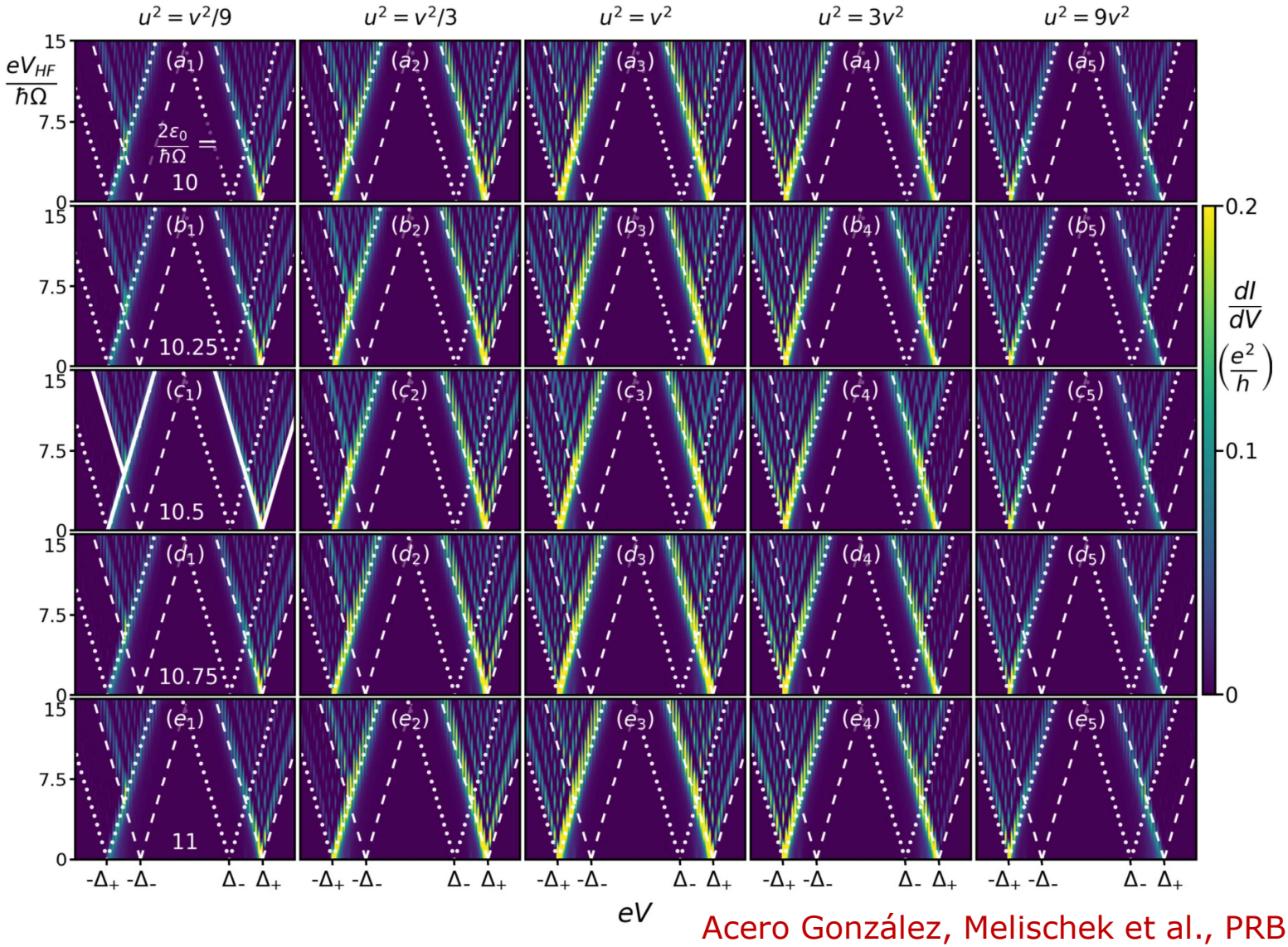

V_{HF}
(b)
(c)
(d)
$2\varepsilon_0$
$2\varepsilon_0$
V/e
$-\Delta$
0
Δ


-2Δ
$-\Delta$
0
Δ
2Δ
α_-
α_+
dI/dV (nS)
$(S^{nl})\ \Lambda p//p$
Sample bias (mV)


E_F
Γ_e
Γ_1
$E_F + \varepsilon_0$
$E_F - \varepsilon_0$
Γ_h
$eV = \Delta + \varepsilon$

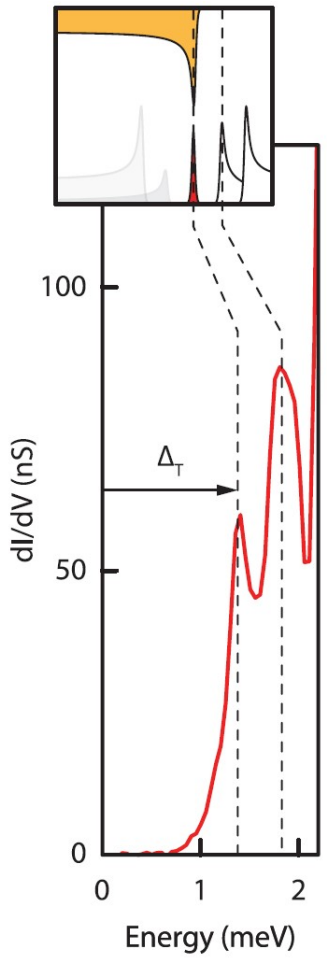

HF amplitude (mV)
Sample bias (mV)
3
$(S^{nl})\ \Lambda p//p$
−0.1

Theoretical results

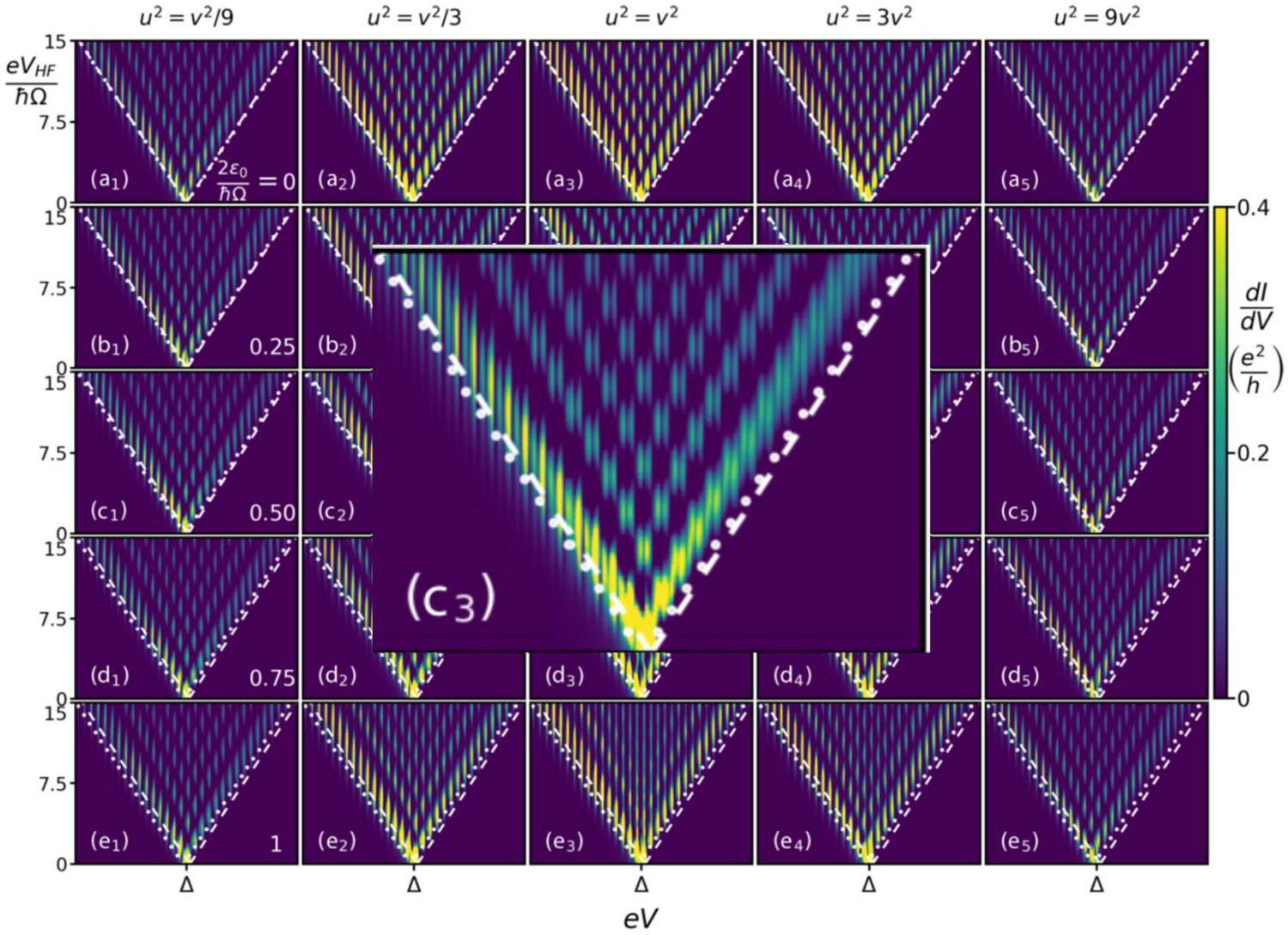


Acero González, Melischek et al., PRB (2020)

Majorana?

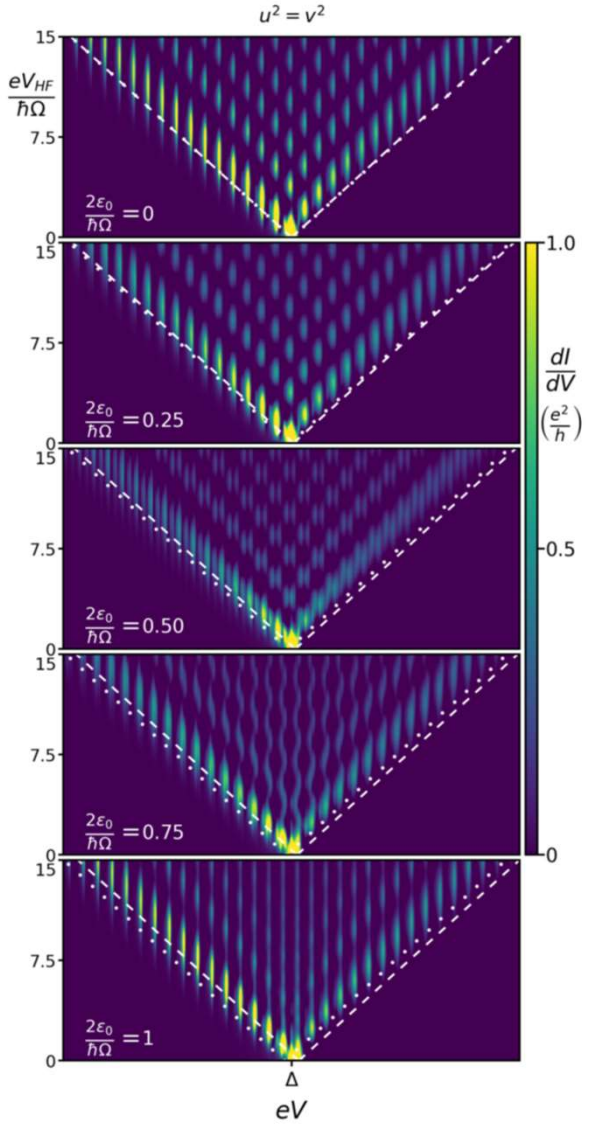


Yazdani group (2014)



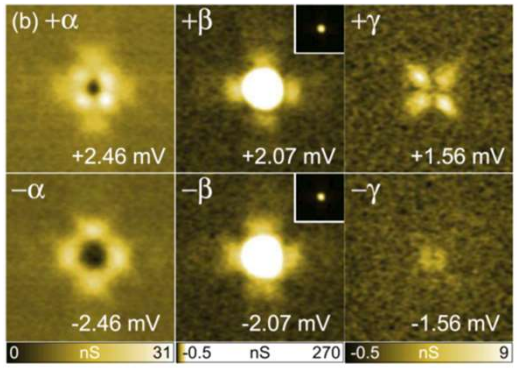
Acero González, Melischek et al., PRB (2020)

Almost-zero-energy subgap states



- Small subgap energies appear directly as line splitting
- Majoranas: $|u(\mathbf{r})|^2 = |v(\mathbf{r})|^2$
- Accidental $E \approx 0$ subgap state:

$$|u(\mathbf{r})|^2 \neq |v(\mathbf{r})|^2$$



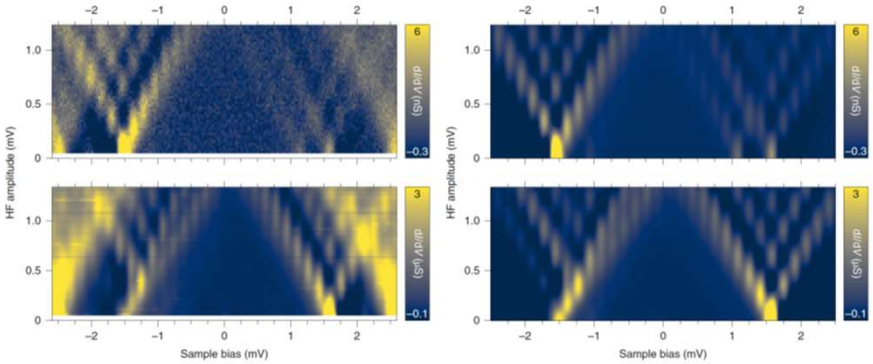
Ruby et al. (2016)

Acero González, Melischek et al., PRB (2020)

Conclusions

- Photon-assisted tunneling reveals tunneling processes in superconducting STM junctions
- Theory of PAT through subgap states beyond a simple Tien-Gordon approach.
- PAT provides a sharp probe of Majoranas.

- Photon-assisted resonant Andreev reflections: Yu-Shiba-Rusinov and Majorana states
  S. Acero González, L. Melischek, O. Peters, K. Flensberg, K. Franke, FvO
  PRB **102**, 045413 (2020)



- Resonant Andreev reflections probed by photon-assisted tunnelling at the atomic scale
  O. Peters, N. Bogdanoff, S. Acero González, L. Melischek, J. Simon, G. Reecht, C. Winkelmann, FvO, K. Franke
  Nature Physics https://doi.org/10.1038/s41567-020-0972-z (2020)