Exotic physics induced by by magnetic moments in a superconductor

Pascal Simon
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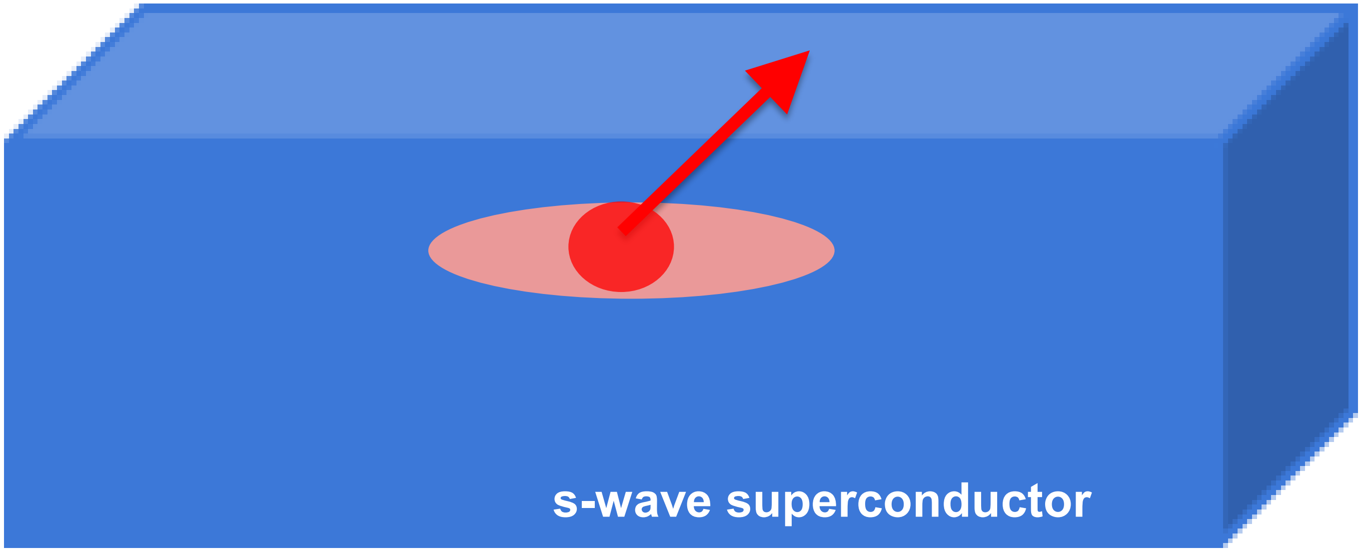
Why studying magnetic impurities in a superconductor ?

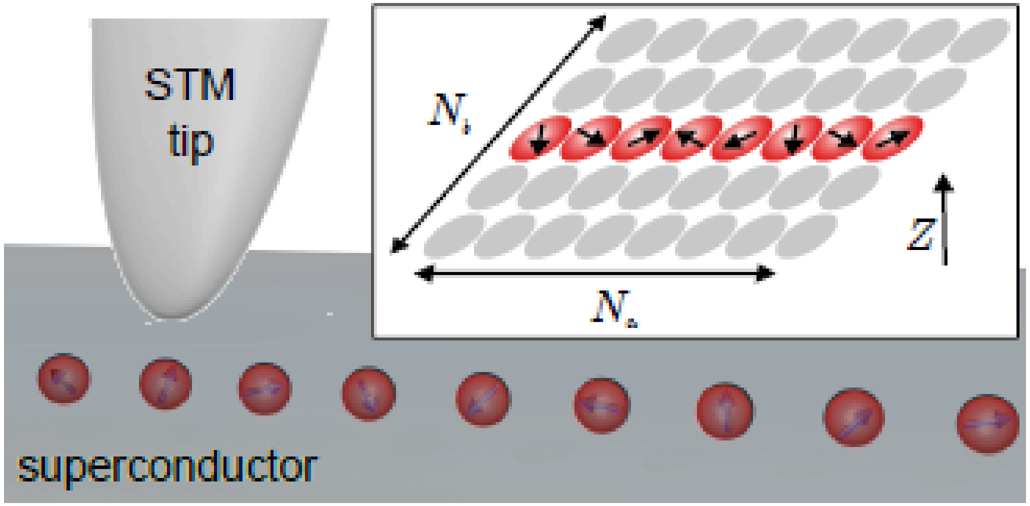
Atom with a magnetic moment:
Fe, Co, Mn



An old solved problem ?

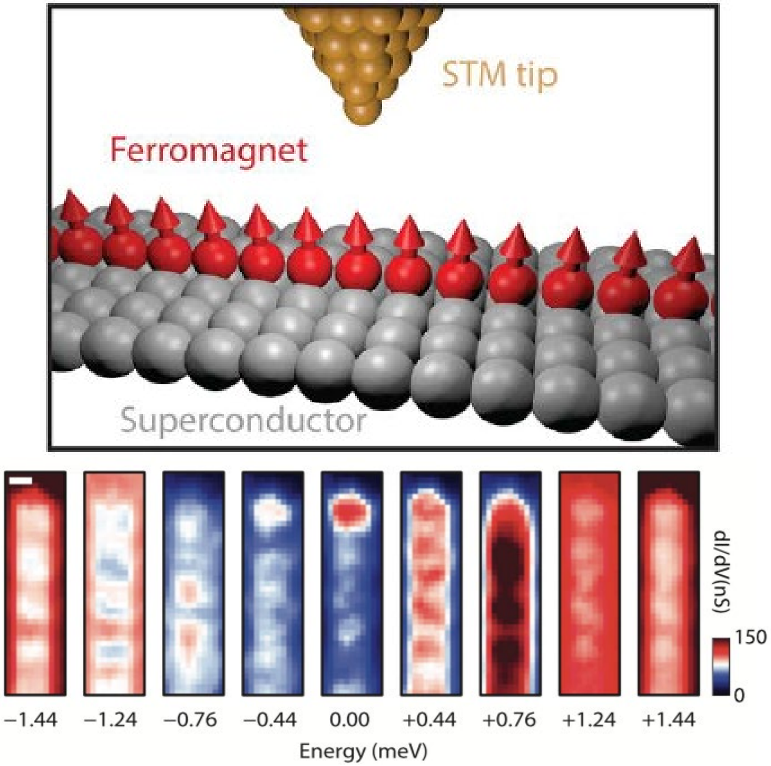
Why studying magnetic impurities in a superconductor ?

- Chains of magnetic atoms on a superconductor: a new platform for Majorana physics ?

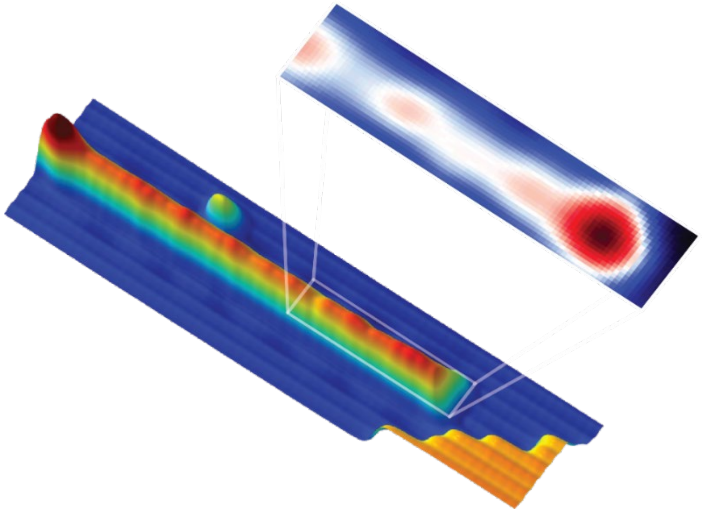


Nadj-Perge, Drozdov, Bernevig, Yazdani, PRB (2013)

Majorana end states in magnetic chains : Fe/Pb(110)



Zero-bias anomaly localized on the last atoms of the Fe chain, almost no extension into the Pb substrate



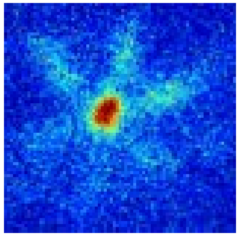
S. Nadj-Perge et al., Science **346,** 6209 (2014)
B. E. Feldman et al., Nature Physics (2016)
S. Jeon et al., Science (2017) **(Princeton)**

see also

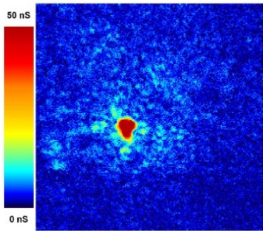
M. Ruby et al., PRL 2015 **(Berlin)**
R. Pawlak et al., NPJ QI (2016) **(Basel)**
H. Kim et al. Science Advances (2018) **(Hamburg)**

Outline

I) Shiba states in a 2D superconductor:
large real space extent



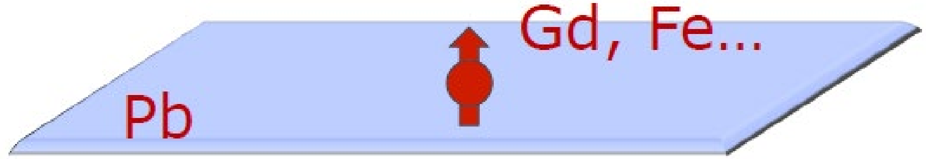
II) Odd-frequency pairing around a magnetic
impurity in a superconductor



III) Shot noise tomography of bound states
in (topological) superconductors

I) Shiba state in a 2D superconductor: Large real space extent

A magnetic impurity in a superconductor



Bogoliubov-de Gennes Ham. $\mathcal{H}_0 = \xi_p \tau_z + \Delta \tau_x$

Assumes Δ constant
(homogeneous)

$$\mathcal{H}_{\rm imp} = -J\mathbf{S}\cdot\boldsymbol{\sigma}\;\delta(\mathbf{r})$$

$$\Rightarrow \quad \mathcal{H}_{\rm imp} = -JS\sigma^z\;\delta(\vec{r})$$

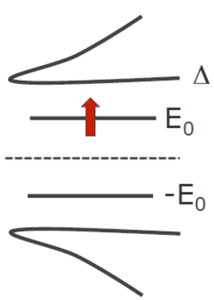
Like a local magnetic field

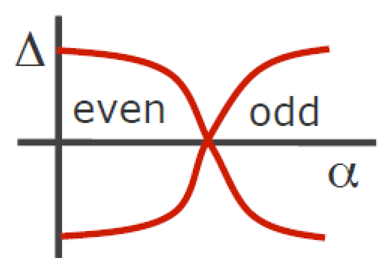
It creates an attractive potential

Shiba bound state

$$E_0 = \Delta \frac{1-\alpha^2}{1+\alpha^2}$$

$$\alpha = \pi \nu_0 J S$$





Yu Lu (1965), Shiba (1968), Rusinov (1969)

Asymptotics of the Shiba wave-function

Convenient paramatrization $E = \Delta \cos(\delta^+ - \delta^-)$

$$\tan \delta^\pm = V\nu_0 \pm \pi \nu_0 J S$$

Rusinov (1969)

Potential scattering term ($V\nu_0$)

Asymptotics of the Shiba wave

In 3D

$$\psi_\pm(r) \approx \frac{1}{\sqrt{\mathcal{N}}} \frac{\sin\left(k_F r + \delta^\pm\right)}{k_F r} e^{-\Delta \sin(\delta^+ - \delta^-) r / \hbar v_F}$$

Rusinov (1969)

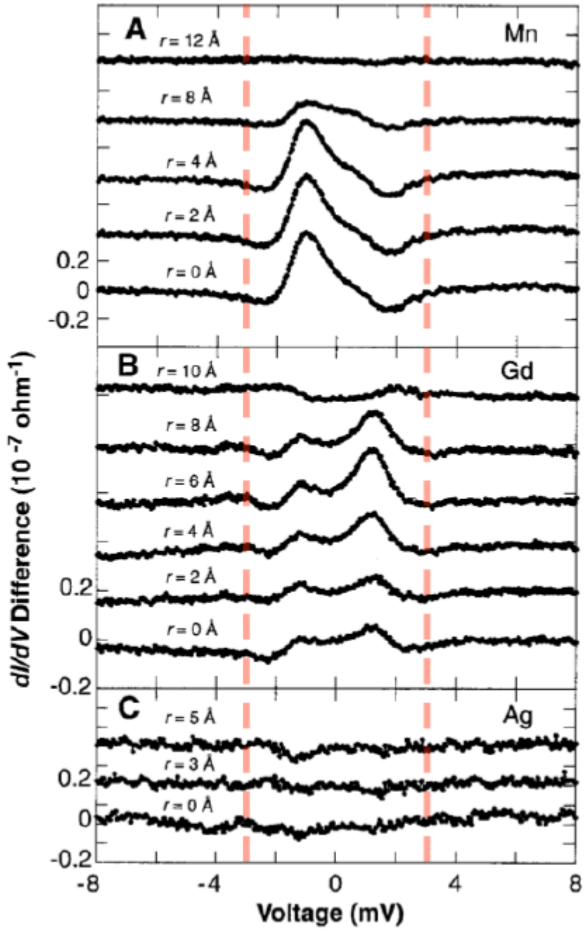
In 2D

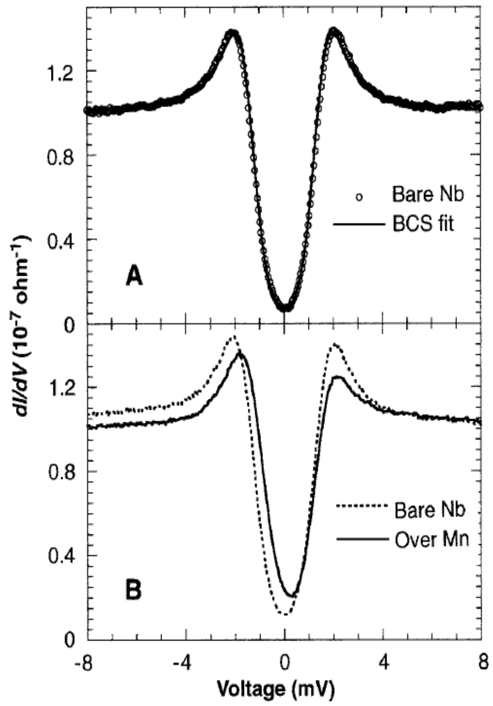
$$\psi_\pm(r) \approx \frac{1}{\sqrt{\mathcal{N}}} \frac{\sin(k_F r - \frac{\pi}{4} + \delta^\pm)}{\sqrt{\pi k_F r}} e^{-\Delta \sin(\delta^+ - \delta^-) r / \hbar v_F}$$

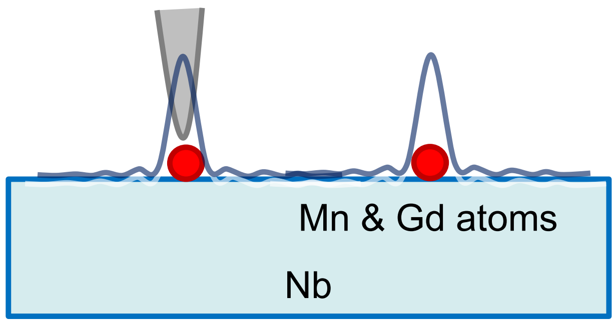
Can we test these predictions experimentally ?

Single magnetic impurities observed by STM

- Bound states for magnetic impurities (Mn & Gd) on Nb
- No bound states for non magnetic Ag adatoms on Nb







The wave function of the bound states is localized at less than 10 Å from the impurities

Yazdani et al. Science **275**, 1767 (1997)

Single magnetic impurities observed by STM: Angular momentum dependence

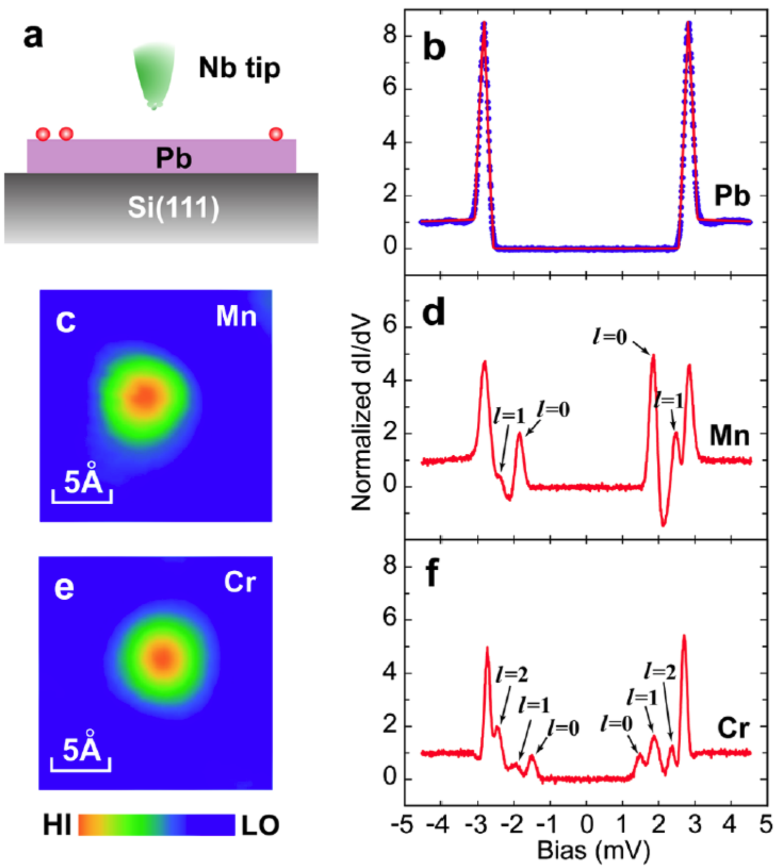
The number of Shiba peaks depends on the atom nature

$$Mn \rightarrow l = 0,1$$

$$Cr \rightarrow l = 0,1,2$$

Every peak may correspond to a different angular momentum scattering channels for the superconducting electrons.

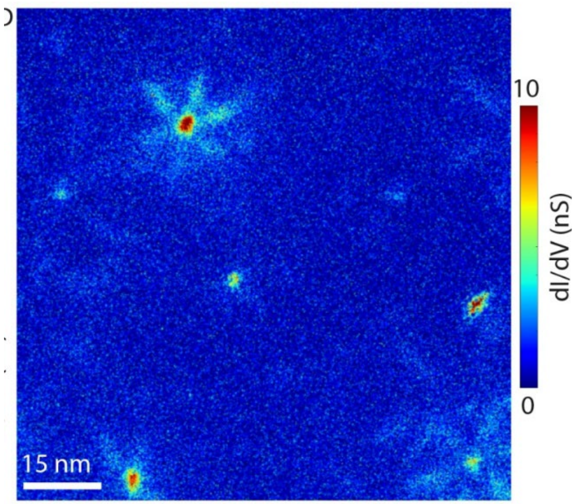
Extremely local effect of the impurities (a few Å)



Shuai-Hua Ji et al. *PRL* **100**, 226801 (2008)

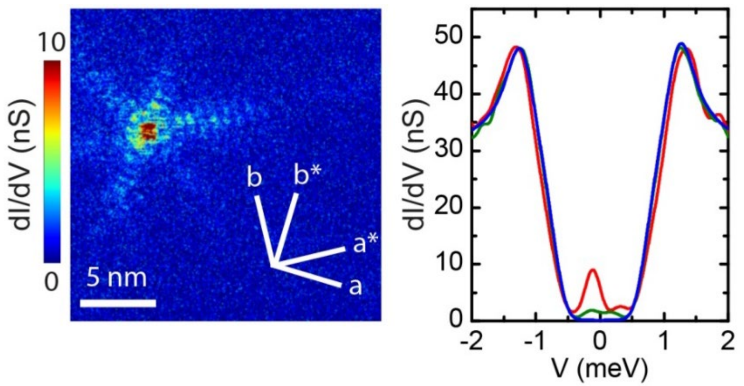
See also N. Hatter et al., Nature Commun. (2015)

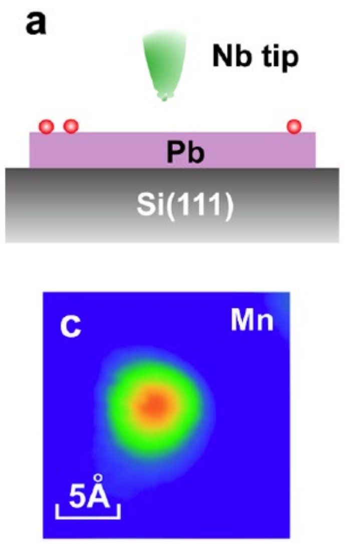
Observation of bound states around magnetic impurities in 2H-$NbSe_2$



Nb used for the crystal growth contains magnetic impurities :

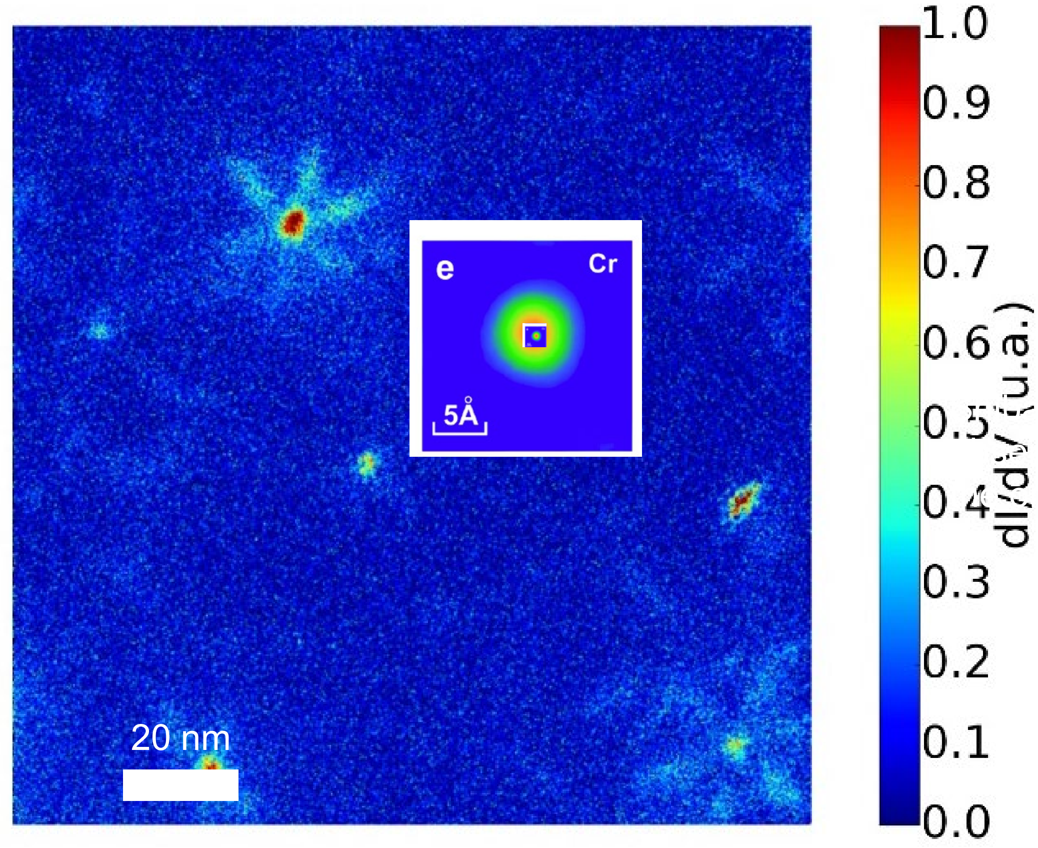
- 175 ppm of Fe
- 54 ppm of Cr
- 22 ppm of Mn





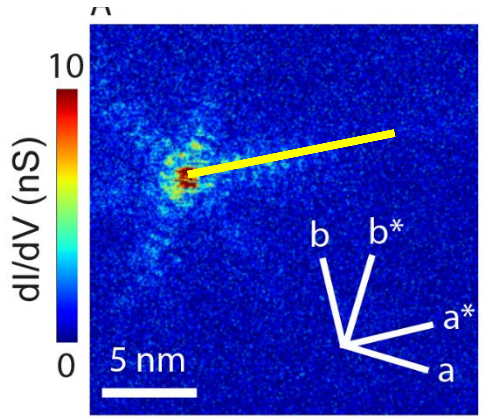
G. Ménard et al., Nature Physics 2015

Observation of bound states around magnetic impurities in 2H-$NbSe_2$



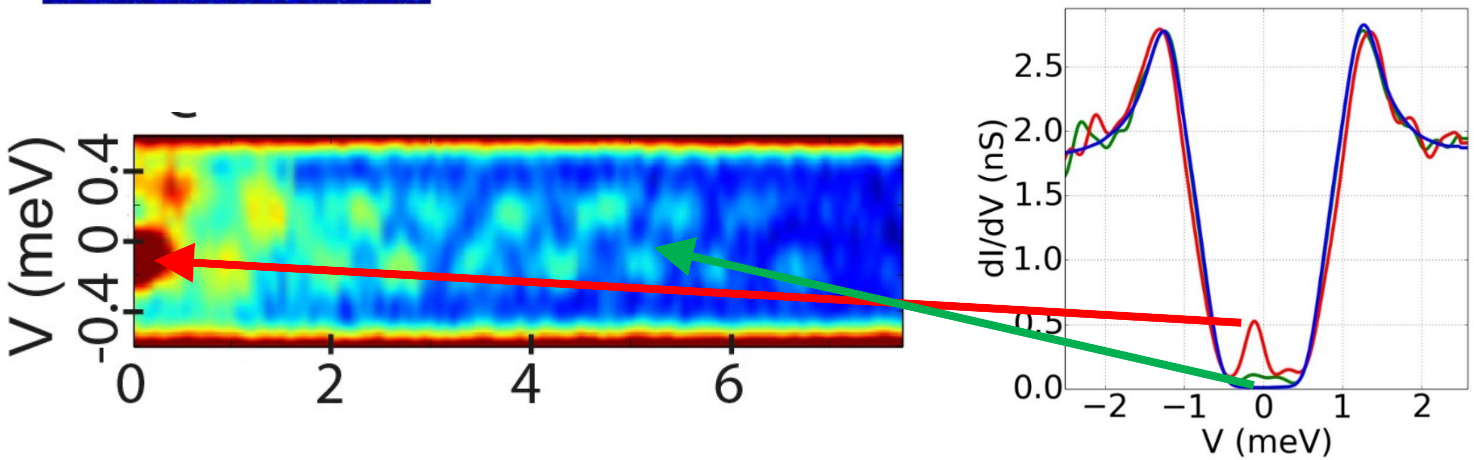
G. Ménard et al., Nature Physics 2015

Spatial oscillation of Shiba bound states
Electron-hole asymmetry



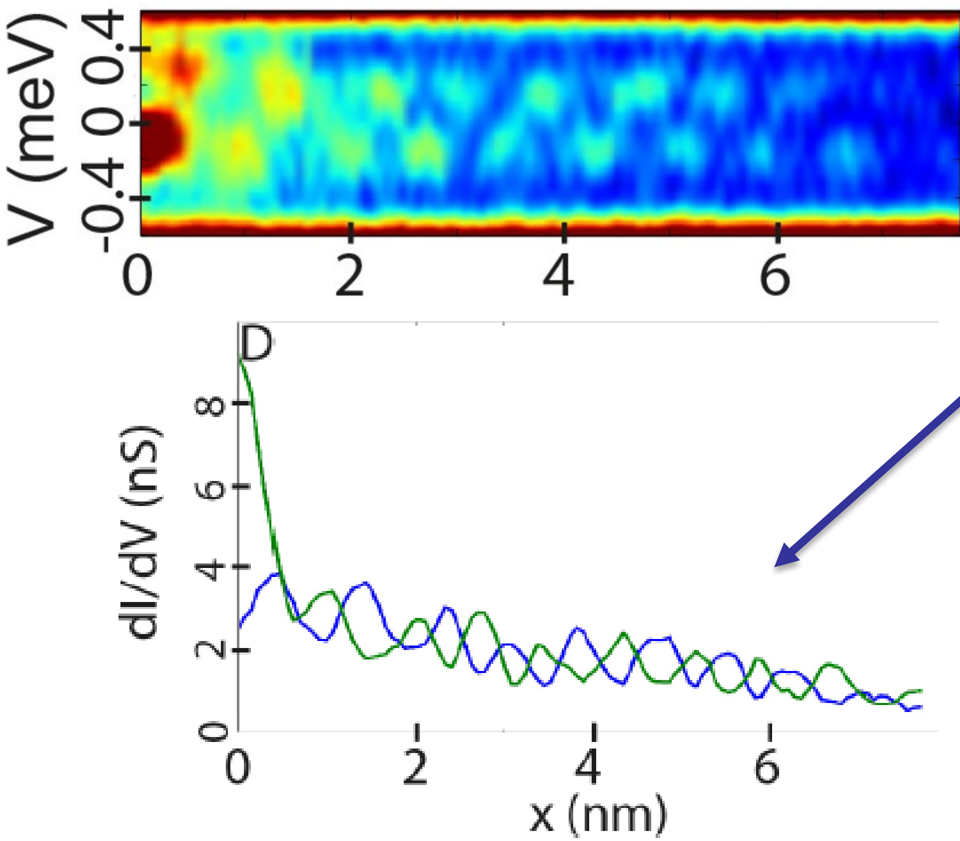
•Oscillations of the local density of states with a phase opposition between positive and negative energy states

•Decrease of the Shiba bound states on a size of the order of the coherence length ξ



G. Ménard et al., Nature Physics 2015

Spatial oscillations and electron-hole asymmetry



Good agreement with theoretical calculations for Shiba state in a **2D** SC in the asymptotic limit.

$$\psi_{\pm}(r) = \frac{1}{\sqrt{N\pi k_F r}} \sin\left(k_F r - \frac{\pi}{4} + \delta^{\pm}\right) e^{-\Delta \sin(\delta^+ - \delta^-) r/\hbar v_F}$$

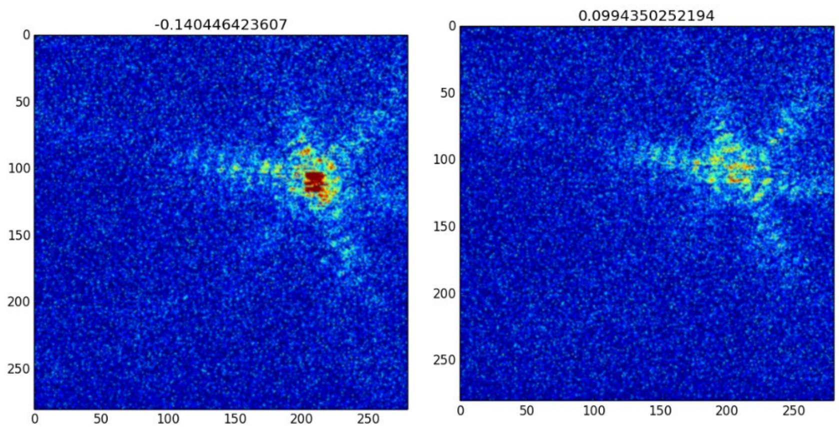
$$E = \Delta \cos(\delta^+ - \delta^-)$$

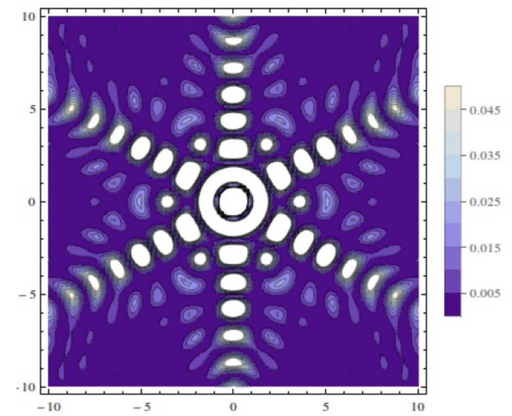
$$\tan \delta^{\pm} = (K\nu_0 \pm \nu_0 JS/2)$$

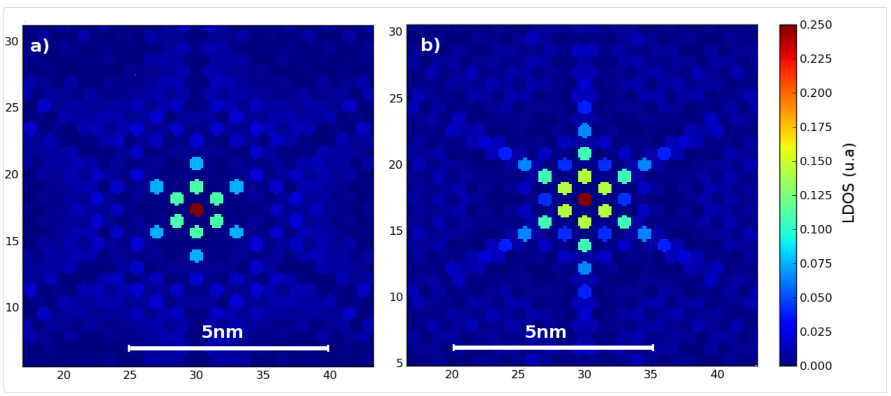
The Shiba peaks **position relatively to the gap** is directly related to the phase shift.

Theoretical modelling

numerical resolution of the Shiba equation using a
a Bogoliubov-de Gennes tight-binding model extracted from ARPES







Continuous asymptotic model

The star shape comes from the anisotropy of the Fermi surface

Anisotropy of Yu-Shiba-Rusinov states

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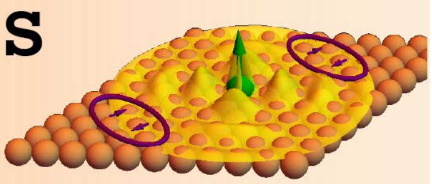


II) Odd-frequency pairing around a magnetic impurity

Even/odd-frequency pairing

Key quantity: the pairing correlation is defined by:

$$F_{\alpha,\beta}(\boldsymbol{r}_1 t_1, \boldsymbol{r}_2 t_2) = -i \left\langle \mathsf{T} \psi_\alpha(\boldsymbol{r}_1 t_1) \psi_\beta(\boldsymbol{r}_2 t_2) \right\rangle$$

Under exchange of time:

Conventional even-frequency pairing:

$$F_{\alpha,\beta}(\boldsymbol{r}_1 t_1, \boldsymbol{r}_2 t_2) = F_{\alpha,\beta}(\boldsymbol{r}_1 t_2, \boldsymbol{r}_2 t_1)$$

odd-frequency pairing :

$$\boxed{F_{\alpha,\beta}(\boldsymbol{r}_1 t_1, \boldsymbol{r}_2 t_2) = -F_{\alpha,\beta}(\boldsymbol{r}_1 t_2, \boldsymbol{r}_2 t_1)}$$

V. L. Berezinskii, *JETP Lett.* 20, 287 (1974)

Symmetry of the pairing function

Orbital ⊗ Spin ⊗ Frequency = Odd

Several options

	Frequency (time)	Spin	Orbital	Total	
ESE	+(even)	− (singlet)	+(even)	−	BCS; cuprates
ETO	+(even)	+ (triplet)	−(odd)	−	P-wave SC => Majoranas
OTE	−(odd)	+ (triplet)	+(even)	−	
OSO	−(odd)	− (singlet)	−(odd)	−	

See e.g. Y. Tanaka, M. Sato, N. Nagaosa, J. Phys. Soc. Jpn. 81, 011013 (2012)
J. Linder, A. V. Balatsky, Rev. Mod. Phys. 91, 045005 (2019)

A long history….

Odd-frequency pairing was proposed

- First by Berezinskii in 74' (superfluid He)

- As a purely intrinsic electronic mechanism to generate bulk odd-ω spin triplet pairing

Belitz, Kirkpatrick, 91',92'
Balatsky, Abrahams, 91',92', etc.

- In the Kondo lattice and heavy fermions

Zachar, Emery, Kivelson, 96',
Coleman, Miranda, Tsvelik, 97'; etc.

- In hybrid SF junctions, odd-ω pair amplitudes are induced in a ferromagnet in contact with a spin-singlet s-wave superconductor

Bergeret, Efetov, Volkov, 01'

See e.g. **Y. Tanaka, M. Sato, N. Nagaosa, J. Phys. Soc. Jpn. 81, 011013 (2012)**

J. Linder, A. V. Balatsky, Rev. Mod. Phys. 91, 045005 (2019)

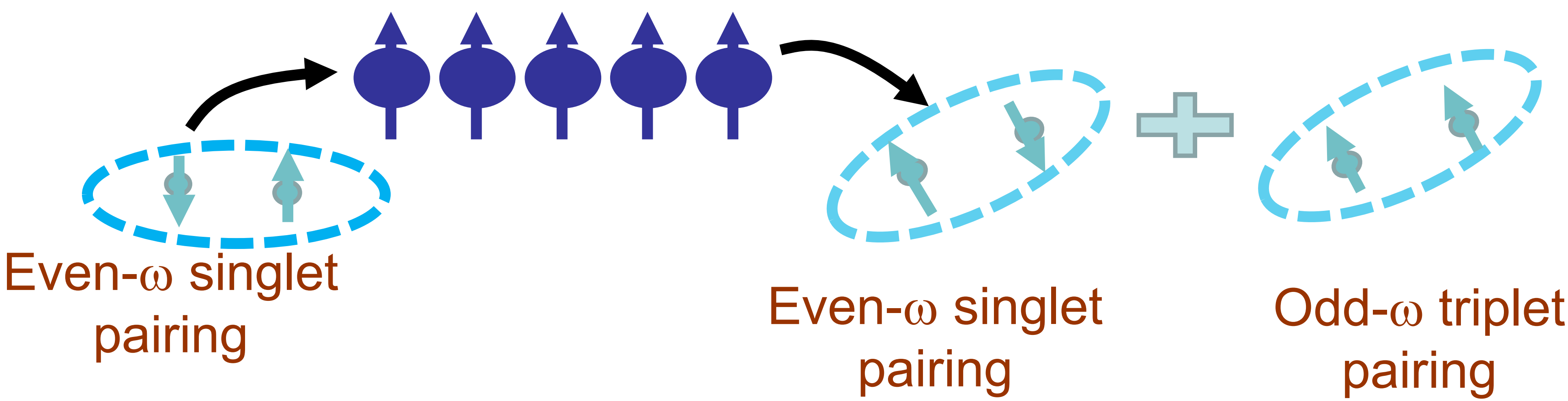
1D case: **J. Cayao, C. Triola, A. M Black-Schaffer, The European Physical Journal Special Topics, 229, 545 (2020)**

Where to find it ?

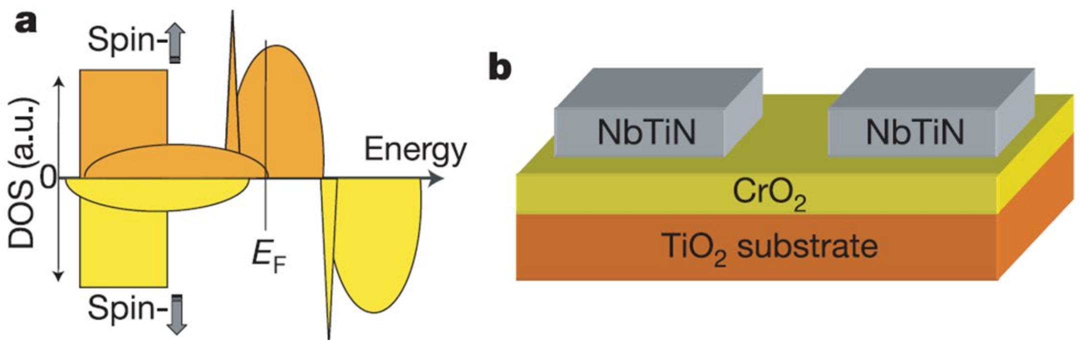
Actually, odd-ω pairing state is rather ubiquitous:

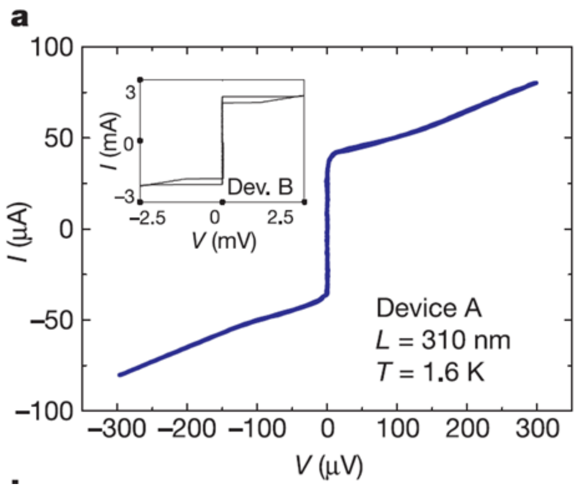
Starting from conventional s-wave even-ω superconductivity, any system with broken spin rotational symmetry OR broken translation symmetry can induce odd-ω pairing states.

This involves inhomogeneous systems, S-F junctions, hybrid systems….



Odd-w pairing in ferromagnet-superconductor hybrid systems





Long range proximity effect in a S-F-S junction as a direct manifestation of odd triplet s-wave pairing

R. S. Keizer et al., Nature 439, 825 (2006)

Odd-Frequency Pairing on the impurity site

$$\hat{G}^R(t,t') = -i\theta(t-t')\langle\Psi(\mathbf{0},t)\Psi^\dagger(\mathbf{0},t')\rangle$$
$$= \begin{bmatrix} G^R_\uparrow(t-t') & F^R_{\uparrow,\downarrow}(t-t') \\ -F^R_{\downarrow,\uparrow}(t-t')^* & -G^R_\downarrow(t-t')^* \end{bmatrix}$$

Retarded Green function in Nambu space

Dyson equation : $$[\hat{G}^R]^{-1}(\omega) = [g^R(\omega)]^{-1} - \Sigma$$

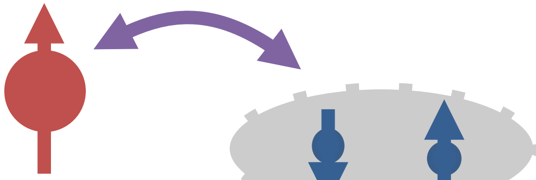
Width of the bound state

$$g^R(\omega) = \begin{bmatrix} g^R_\uparrow(\omega) & f^R_{\uparrow,\downarrow}(\omega) \\ f^R_{\uparrow,\downarrow}(\omega) & -(g^R_\downarrow(-\omega))^* \end{bmatrix} \qquad \hat{\Sigma} = \begin{bmatrix} V-J-i\Gamma & 0 \\ 0 & -(V+J)-i\Gamma \end{bmatrix}$$

Two possibilities:

1. $F^R_{\uparrow,\downarrow}(\omega) = F^{R*}_{\uparrow,\downarrow}(-\omega)$ Even ω; spin singlet,

2. $F^R_{\uparrow,\downarrow}(\omega) = -F^{R*}_{\uparrow,\downarrow}(-\omega)$ Odd ω; spin triplet.



Odd-Frequency Pairing on the impurity site

Local density of states on the impurity:

$$\rho_{\mathrm{even/odd}}(\omega) = [\rho(\omega) \pm \rho(-\omega)]/2$$

$$|\omega| < \Delta$$

$$\rho_{\mathrm{even/odd}}(\omega) = C_{e/o}(E_0) \times \Im F^R_{\mathrm{odd/even}}(\omega)$$

General proportionality relation between LDOS and the odd-ω pairing fuction

Odd-Frequency Pairing on the impurity site

Local density of states on the impurity:

$$\rho_{\mathrm{even/odd}}(\omega) = [\rho(\omega) \pm \rho(-\omega)]/2$$

$$|\omega| < \Delta$$

$$\rho_{\mathrm{even/odd}}(\omega) = C_{e/o}(E_0) \times \Im F^R_{\mathrm{odd/even}}(\omega)$$

Shiba bound state:

$$E_0 = \Delta \frac{1 - \alpha^2 + \beta^2}{\sqrt{(1 - \alpha^2 + \beta^2)^2 + 4\alpha^2}}$$

$$\alpha = \pi \nu_0 J$$
$$\beta = \pi \nu_0 V$$

$$C_e(E_0) = -\frac{2}{\Delta}[E_0 + \pi J \nu_0 \sqrt{\Delta^2 - E_0^2}]$$
$$= -\frac{2}{\pi} \frac{1 + \beta^2 + \alpha^2}{\sqrt{(1 - \alpha^2 + \beta^2)^2 + 4\alpha^2}}$$

Concrete protocol to extract the odd-ω pairing

Assuming a constant DOS in the normal regime

$$\hat{G}(\omega) = \frac{1}{\omega - E_0 + i\Lambda} \begin{bmatrix} u^2 & uv \\ uv & v^2 \end{bmatrix} \qquad u^2, v^2 = 2\pi\alpha\nu_0\Delta \frac{1 + (\alpha \pm \beta)^2}{((1 - \alpha^2 + \beta^2)^2 + 4\alpha^2)^{3/2}}$$

$$\Rightarrow \quad \rho(\omega) = \frac{\Lambda u^2/\pi}{(\omega - E_0)^2 + \Lambda^2} + \frac{\Lambda v^2/\pi}{(\omega + E_0)^2 + \Lambda^2}$$

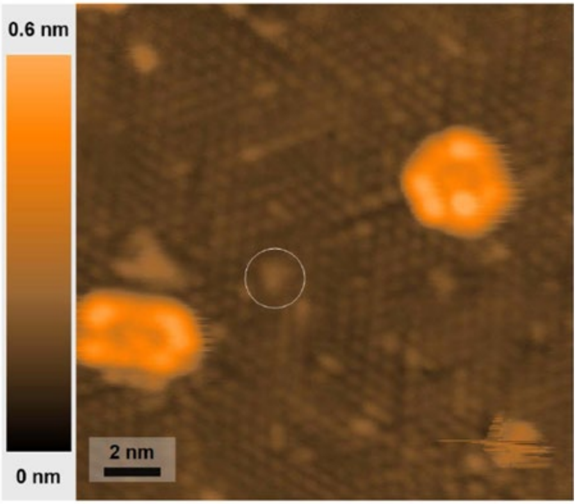
M. Ruby et al., Phys. Rev. Lett. 115, 087001(2015)

$$\Rightarrow \quad C_e(E_0) = -\frac{u^2 + v^2}{\pi uv}$$

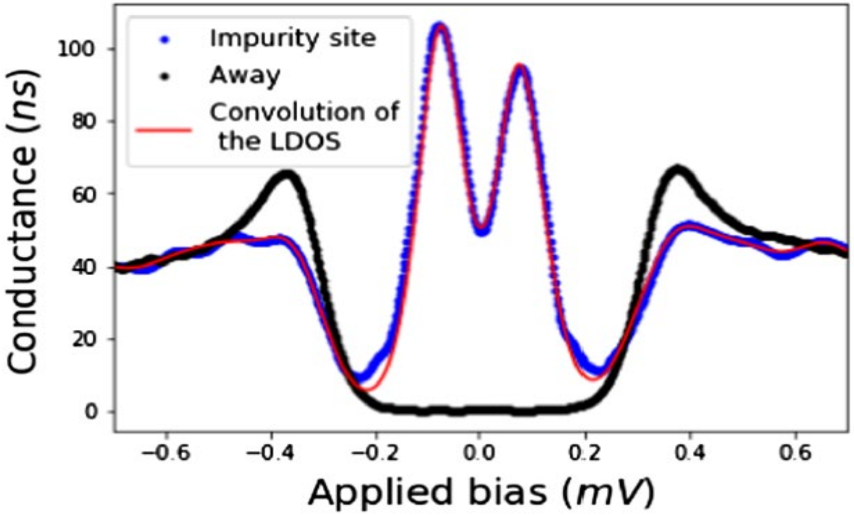
E_0, u, v **funtions of** $J, V, \Delta \ldots$ ⇒ Extracted from the measured deconvoluted LDoS

$$\Im F^R_{odd}(\omega) \; = \; \rho_{even}(\omega)/C_e(E_0)$$

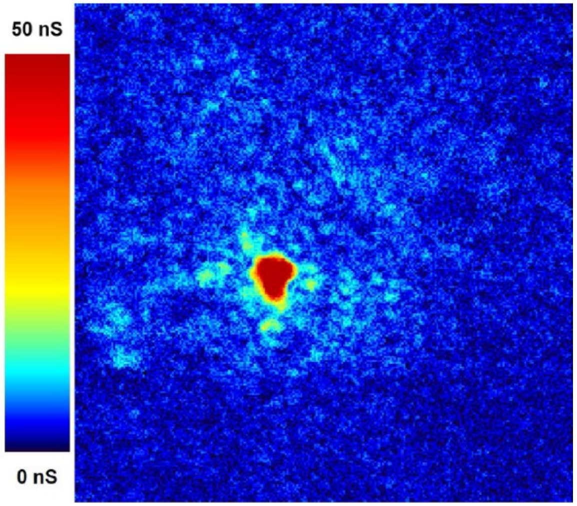
Odd-Frequency Pairing on the impurity site



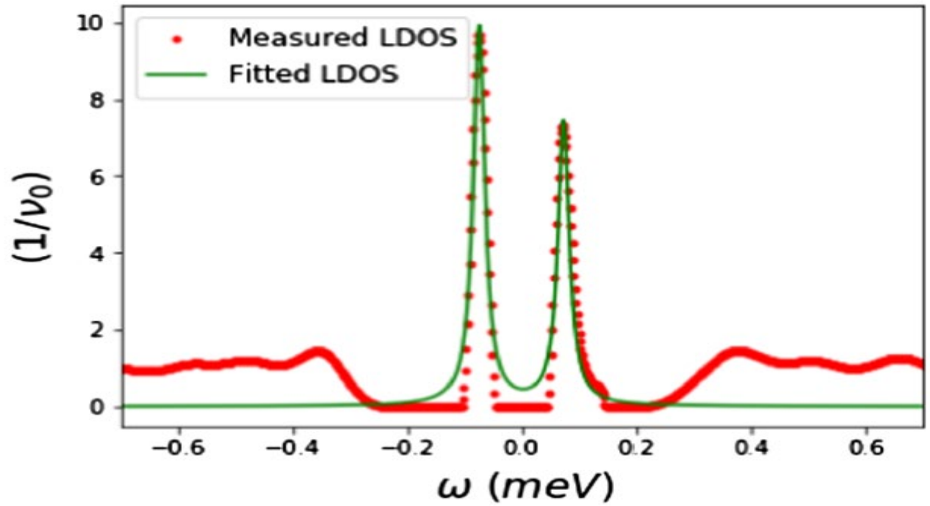
Pb/Si(111) monolayer



Conductance on top of the impurity



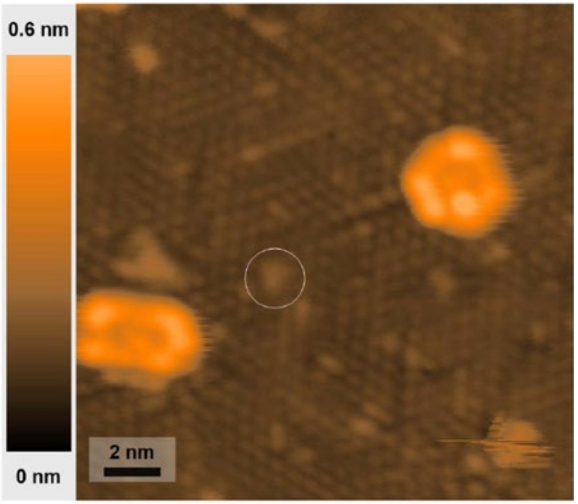
Conductance map at E_F



Deconvoluted LDOS on top of the impurity

V. Perrin et al., Phys. Rev. Lett. 125, 117003 (2020)

Odd-Frequency Pairing on the impurity site



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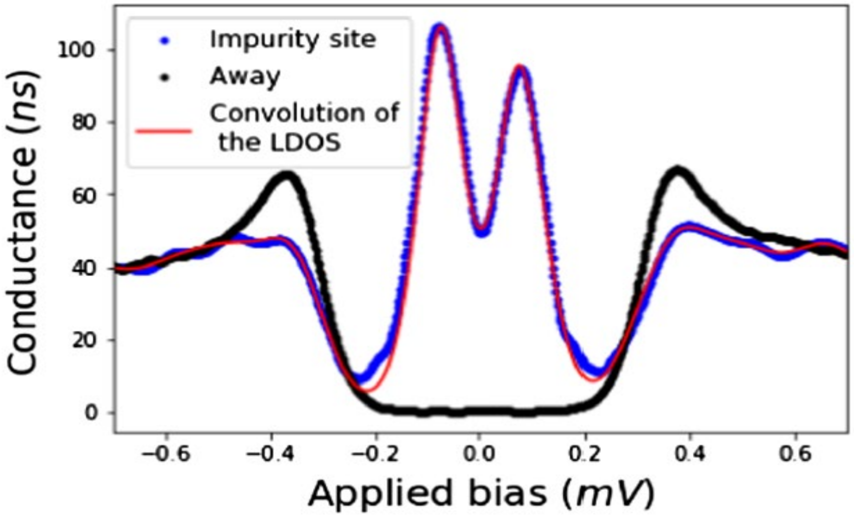
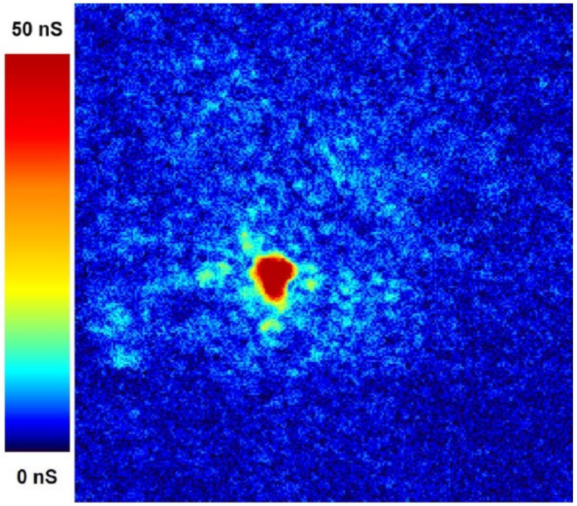


Conductance on top of the impurity



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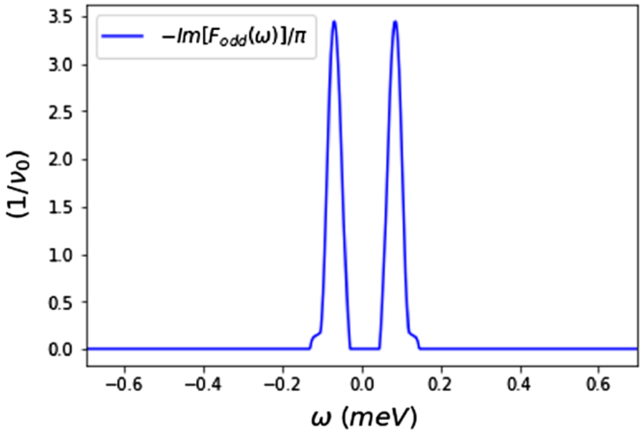
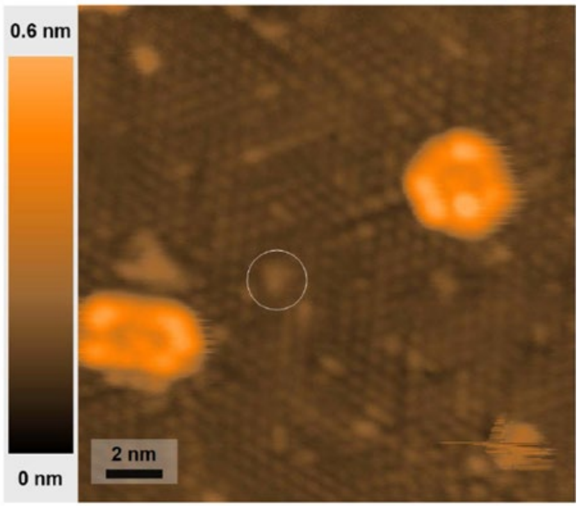
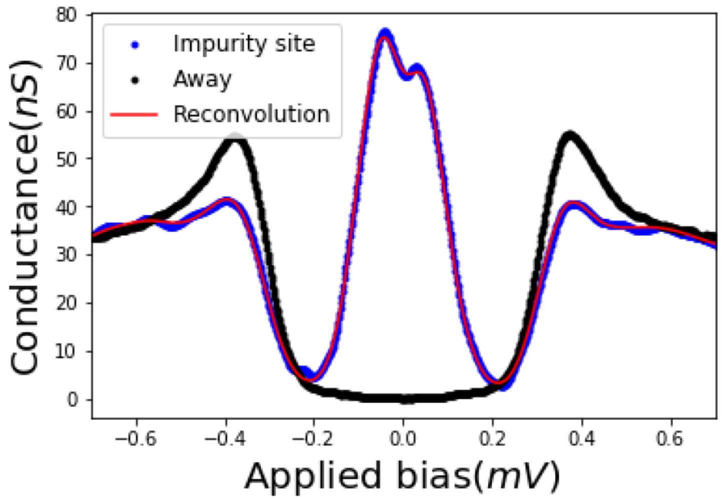


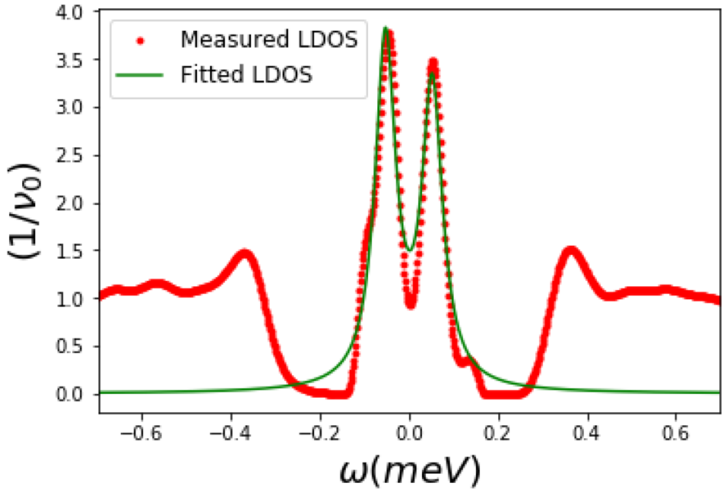
Odd-triplet correlations on top of the impurity

V. Perrin et al., Phys. Rev. Lett. 125, 117003 (2020)

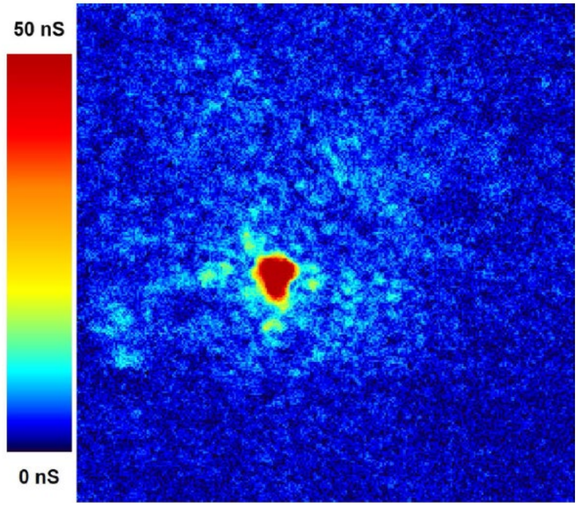
Another magnetic impurity



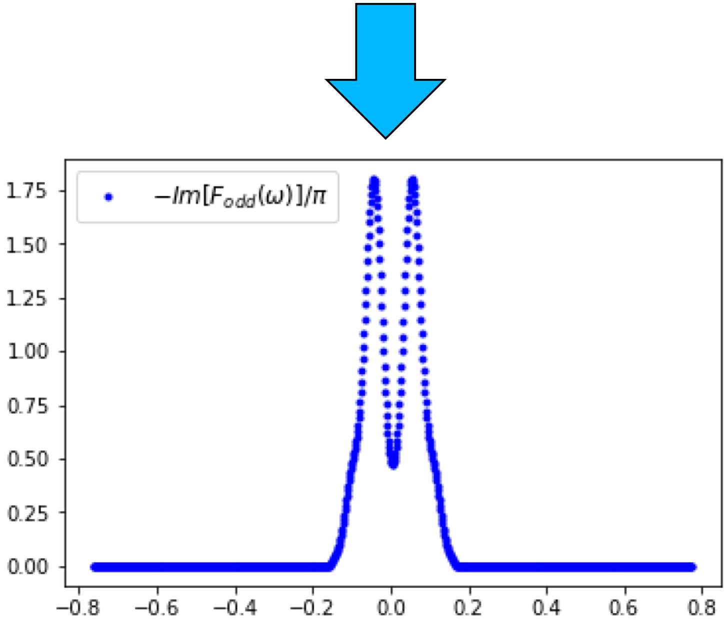




Pb/Si(111) monolayer



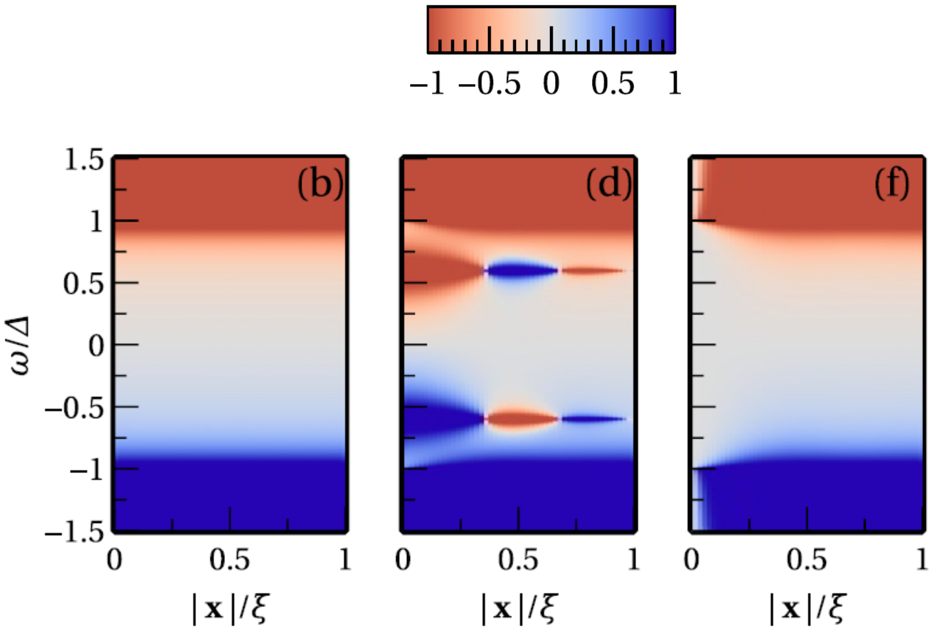
Conductance map at E_F

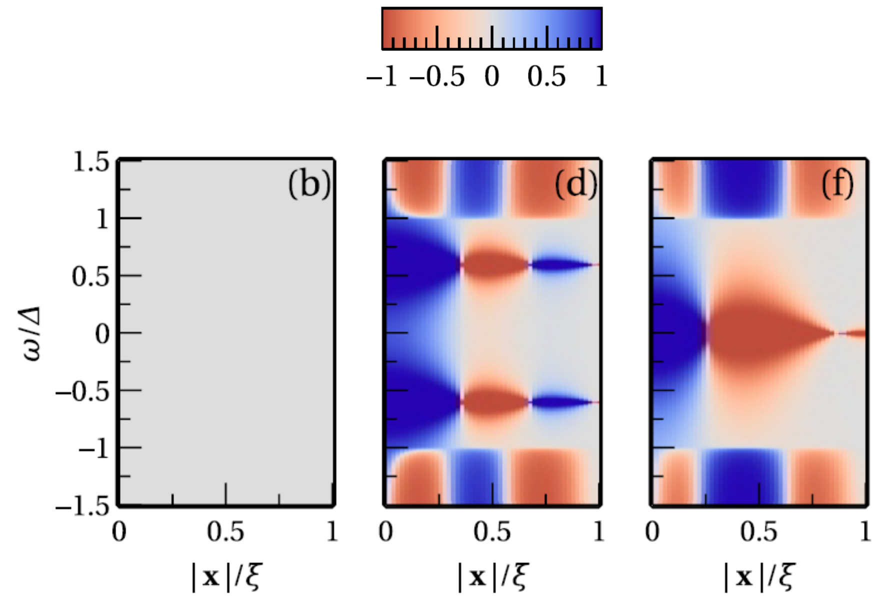


A macroscopic fraction of the LDOS !

V. Perrin et al., Phys. Rev. Lett. 125, 117003 (2020)

Space dependence of odd-ω pairing





Even-singlet correlations

b) No impurity

d) Impurity with E_0 = 0.6 D

c) Impurity with E_0 = 0

Odd-triplet correlations

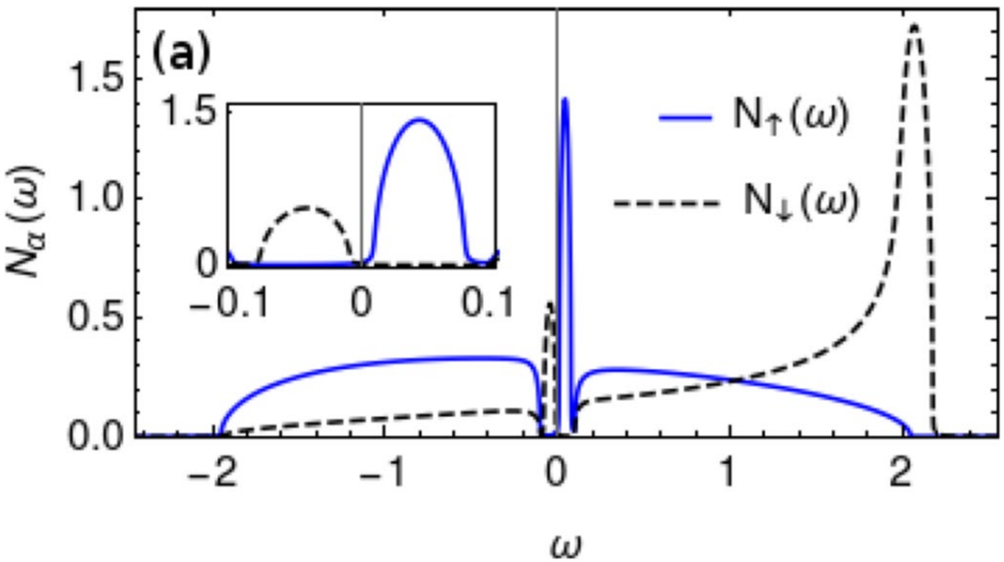
b) No impurity

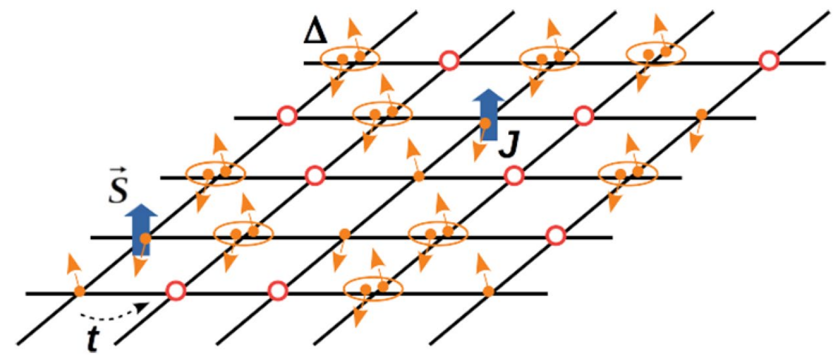
d) Impurity with E_0 = 0.6 D

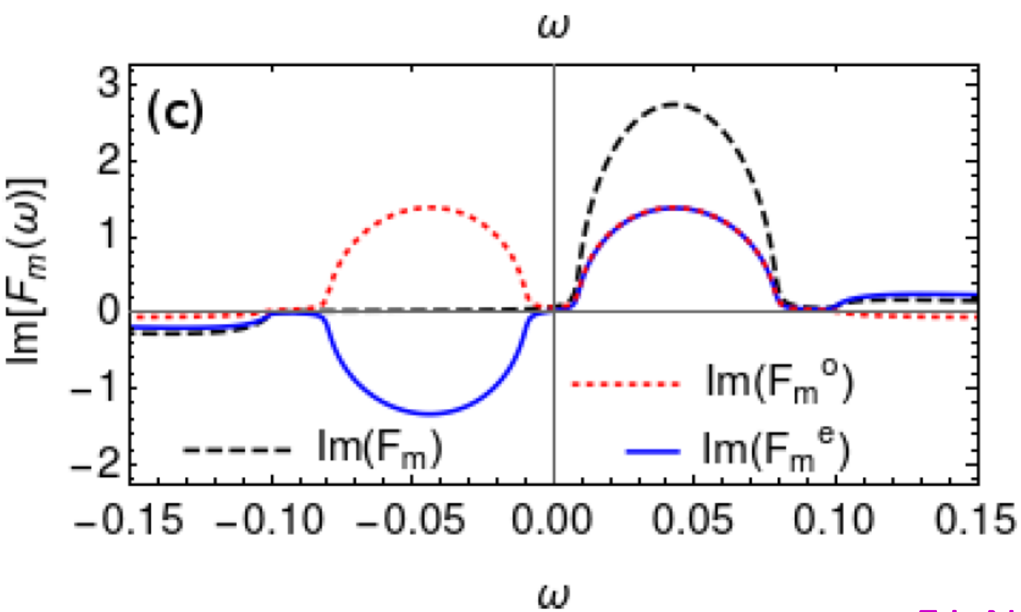
c) Impurity with E_0 = 0

Odd-frequency superconductivity near a magnetic impurity in a conventional superconductor,
D. Kuzmanovski, R. S. Souto and A. V. Balatsky, Phys. Rev. B 101, 094505 (2020)

A dilute magnetic s-wave superconductor







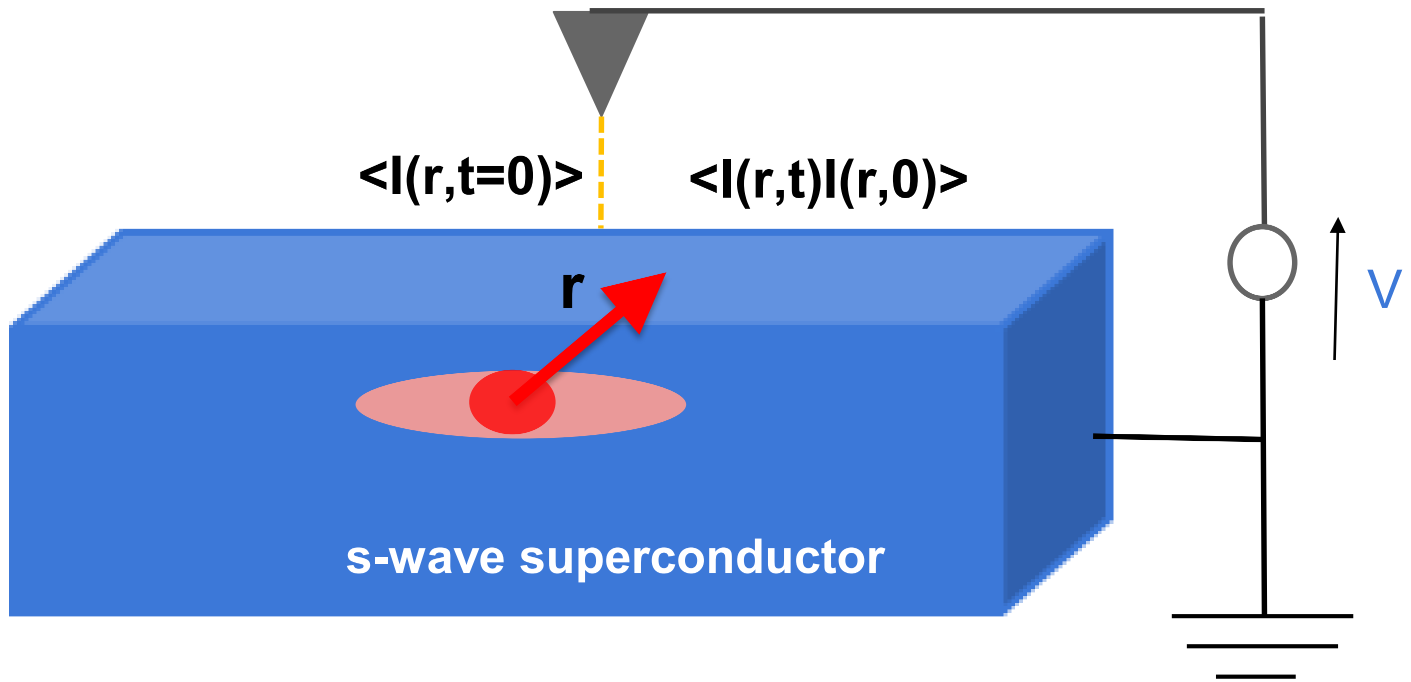
$$\mathrm{Im}[F_m^o(\omega)] = a_F\left[\frac{N_\uparrow(\omega)}{a_\uparrow} + \frac{N_\downarrow(\omega)}{a_\downarrow}\right].$$

Proportionality relations valid here too!

F.L.N. Santos et al., Phys. Rev. Res. 2, 033229 (2020)

III) Shot noise tomography of bound states in (topological) superconductors

STM noise tomography



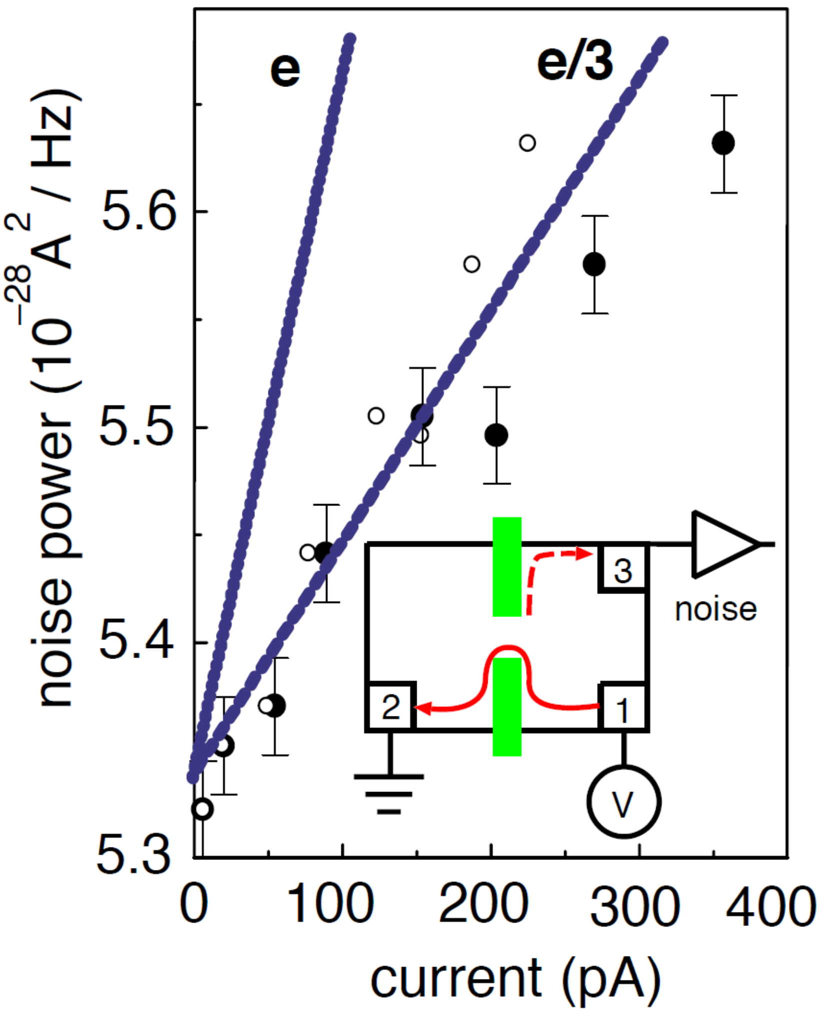
Atomically resolved noise :
$$S(\mathbf{r}) = \int dt \, \langle \delta\hat{I}(t,\mathbf{r})\delta\hat{I}(0,\mathbf{r})\rangle$$

where $\delta\hat{I}(t,\mathbf{r}) = \hat{I}(t,\mathbf{r}) - \langle\hat{I}(t,\mathbf{r})\rangle$

Atomically resolved Fano factor :
$$F(\mathbf{r}) = \frac{S(\mathbf{r})}{2e|\langle\hat{I}(\mathbf{r})\rangle|}$$

F. Massee et al., Atomic scale shot-noise using cryogenic MHz circuitry, Rev. Sci. Instrum. 89, 093708 (2018)

Fano factor: a measure of the effective transferred charge



Evidence of the fractional charge in the fractional quantum Hall effect

L. Saminadayar et al., Phys. Rev. Lett. 79, 2526 (1997)

R. De Picciotto et al., Nature 399, 238 (1999)

Application to YSR state

A simple theoretical model

Assumptions :

- Retain only YSR contributions to the transport observables
- Local tunneling of quasiparticles from tip to sample.
- Neglect direct injection of quasiparticles into the impurity's orbitals.

→ Expected to be relevant to describe STM experiments probing the tail of the YSR.

Application to YSR state

Energy of the YSR bound state

$$E_0 = \frac{1-\alpha^2+\beta^2}{\sqrt{(1-\alpha^2+\beta^2)^2+4\alpha^2}}$$

$\alpha = \pi\nu_0 J$ →Magnetic exchange

$\beta = \pi\nu_0 U$ →scalar potential

$$g^r_{SS}(\omega) \sim \frac{1}{\omega - E_0 + i\Lambda/2}\begin{bmatrix} u^2 & uv \\ uv & v^2 \end{bmatrix}$$

$$u^2, v^2 = 2\pi\alpha\nu_0\Delta\frac{1+(\alpha\pm\beta)^2}{((1-\alpha^2+\beta^2)^2+4\alpha^2)^{3/2}}$$

$\tau = \hbar/\Lambda$ Intrinsic YSR lifetime due to dissipation

(4 parameters and T= temperature)

Current and shot-noise in YSR state

Exact expressions :

$$I = \frac{e}{h}\int d\omega 2\frac{\Gamma_e\Gamma_h}{(\omega-E_0)^2+\Gamma_t^2/4}[f(\omega^-)-f(\omega^+)]$$

→ Andreev Current

$$+\frac{\Gamma_e\Lambda}{(\omega-E_0)^2+\Gamma_t^2/4}[f(\omega^-)-f(\omega)]$$

$$+\frac{\Gamma_h\Lambda}{(\omega-E_0)^2+\Gamma_t^2/4}[f(\omega)-f(\omega^+)].$$

→ Quasiparticle Current (incoherent)

$$\omega^{\pm} = \omega \pm eV$$

$$S = \frac{2e^2}{h}\int d\omega \frac{4\Gamma_e\Gamma_h\{(\omega-E_0)^2+(\Gamma_e-\Gamma_h)^2/4\}}{\{(\omega-E_0)^2+\Gamma_t^2/4\}^2}[f(\omega^-)f(-\omega^+)+f(\omega^+)f(-\omega^-)]$$

→ Andreev-like contribution

$$+\frac{\Gamma_e\Lambda\{(\omega-E_0)^2+(3\Gamma_h-\Gamma_e)^2/4\}}{\{(\omega-E_0)^2+\Gamma_t^2/4\}^2}[f(\omega^-)f(-\omega)+f(-\omega^-)f(\omega)]$$

$$+\frac{\Gamma_h\Lambda\{(\omega-E_0)^2+(3\Gamma_e-\Gamma_h)^2/4\}}{\{(\omega-E_0)^2+\Gamma_t^2/4\}^2}[f(\omega)f(-\omega^+)+f(-\omega)f(\omega^+)]$$

→ Quasiparticle-like contribution

$$+\frac{\Gamma_e^2(\Lambda+2\Gamma_h)^2 f(\omega^-)f(-\omega^-)+\Gamma_h^2(\Lambda+2\Gamma_h)^2 f(\omega^+)f(-\omega^+)}{((\omega-E_0)^2+\Gamma_t^2/4)^2}$$

$$+\frac{\Lambda^2(\Gamma_e-\Gamma_h)^2 f(\omega)f(-\omega)}{((\omega-E_0)^2+\Gamma_t^2/4)^2}.$$

→ Thermal contributions

$$\Gamma_e = u^2\Gamma \qquad \Gamma_h = v^2\Gamma \qquad \Gamma_t = \Gamma_e + \Gamma_h + \Lambda$$

Current and shot-noise in YSR state

Simplifications: $E_0 \gg k_B T \gg u^2\Gamma, v^2\Gamma$

$$I \simeq \frac{e}{\hbar}\left\{\frac{2\Gamma_e\Gamma_h}{\Gamma_t}[f(E_0^-) - f(E_0^+)] + \frac{\Gamma_e\Lambda}{\Gamma_t}[f(E_0^-)] - \frac{\Gamma_h\Lambda}{\Gamma_t}[f(E_0^+)]\right\}$$

$$S \simeq \frac{e^2}{\hbar}\{4\Gamma_e\Gamma_h\frac{(\Gamma_e-\Gamma_h)^2+\Gamma_t^2}{\Gamma_t^3}[f(E_0^-)f(-E_0^+) + f(E_0^+)f(-E_0^-)]$$
$$+\Gamma_e\Lambda\frac{(3\Gamma_h-\Gamma_e+\Lambda)^2+\Gamma_t^2}{\Gamma_t^3}[f(E_0^-)] + \Gamma_h\Lambda\frac{(3\Gamma_e-\Gamma_h+\Lambda)^2+\Gamma_t^2}{\Gamma_t^3}[f(E_0^+)]$$
$$+4\frac{\Gamma_e^2(\Lambda+2\Gamma_h)^2 f(E_0^-)f(-E_0^-)}{\Gamma_t^3} + 4\frac{\Gamma_h^2(\Lambda+2\Gamma_h)^2 f(E_0^+)f(-E_0^+)}{\Gamma_t^3}\}.$$

- Extract E_0, T
- Extract $\Gamma\pi\nu_0$ from the normal conductance
- Extract u^2, v^2 from the height of the peaks

Λ only left parameter → **NEXT TALK By Freek Massee**

Can we use shot noise tomography as a signature of Majorana zero modes ?

Spectral identification of Majorana fermions

BdG Formalism

$$\mathcal{H} = \frac{1}{2}\sum_{j,j'} \psi_j^\dagger H_{BdG}^{j,j'} \psi_{j'}$$

$$\psi_j = (c_{j\uparrow}, c_{j\downarrow}, c_{j\downarrow}^\dagger, -c_{j\uparrow}^\dagger)^T$$

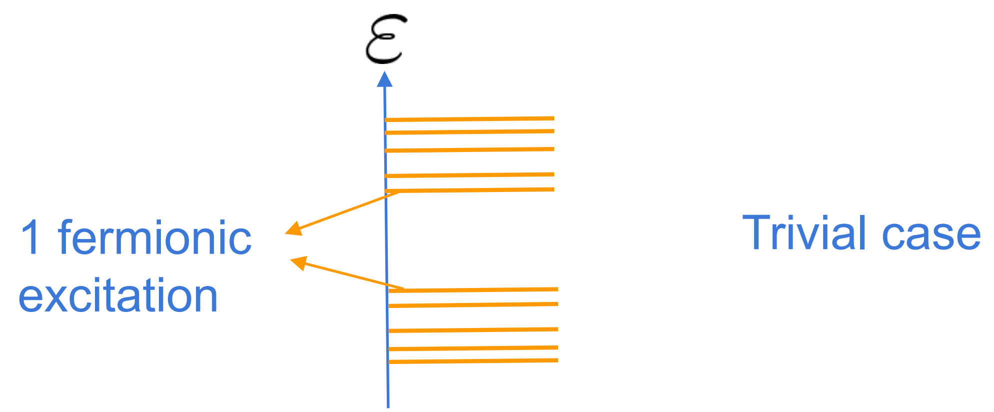
Redundant description : P-H “symmetry”

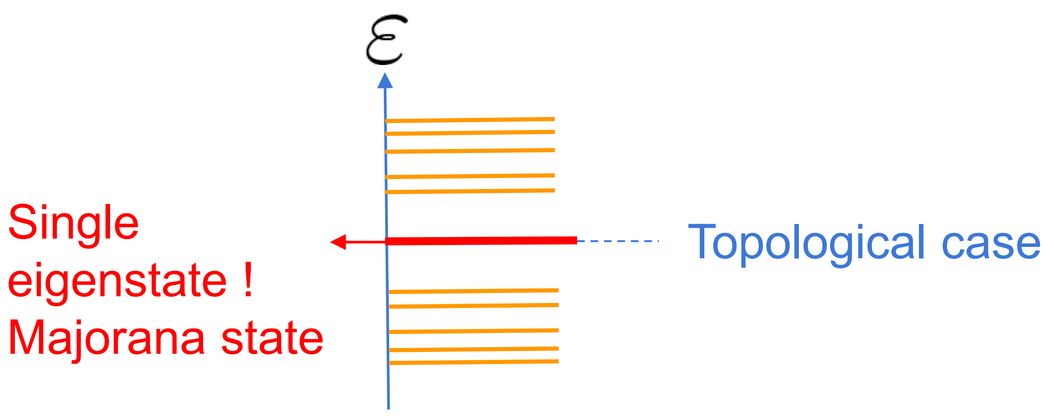
$$C H_{BdG} C^{-1} = -H_{BdG}$$

$$C = \sigma_y \tau_y \mathcal{K}$$

Symmetric spectrum around 0
1 fermionic excitation = 2 eigenstates
with eigenvalues $\pm\mathcal{E}$

Spectrum of a 1D topological SC **in semi-infinite** geometry





$$C\phi_M = \phi_M$$

⇒ **SELF-CONJUGATE**

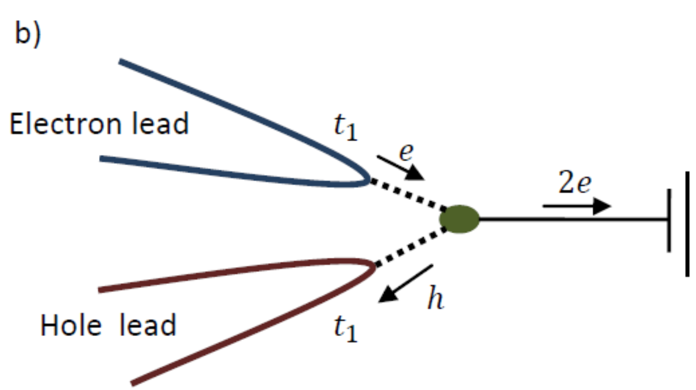
Expected signatures in local transport

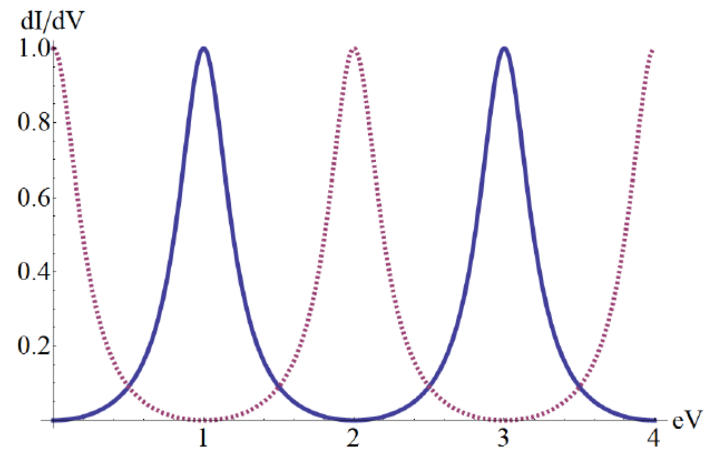
PRL **103,** 237001 (2009) PHYSICAL REVIEW LETTERS week ending 4 DECEMBER 2009

Majorana Fermion Induced Resonant Andreev Reflection

K. T. Law,[1,2] Patrick A. Lee,[2] and T. K. Ng[3]

We describe experimental signatures of Majorana fermion edge states, which form at the interface between a superconductor and the surface of a topological insulator. If a lead couples to the Majorana fermions through electron tunneling, the Majorana fermions induce *resonant* Andreev reflections from the lead to the grounded superconductor. The linear tunneling conductance is 0 ($2e^2/h$) if there is an even (odd) number of vortices in the superconductor. Similar resonance occurs for tunneling into the zero mode in the vortex core. We also study the current and noise of a two-lead device.





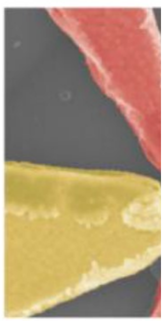
- A perfect zero-bias quantized peak
- Fano factor F=1 for a single-contact lead

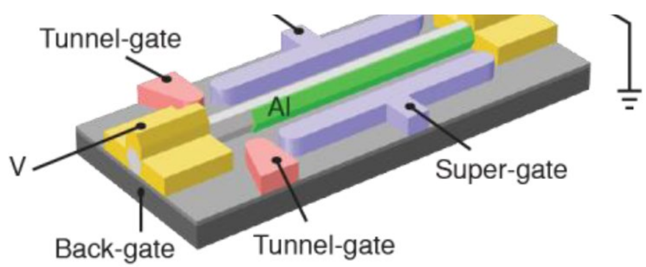
Experimental evidences

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[3,7], Mihir Pendharkar[5], Daniel J. Pennachio[4], Borzoyeh Shojaei[4,6], Joon Sue Lee[6], Chris J. Palmstrøm[4,5,6],

RETRACTED ARTICLE





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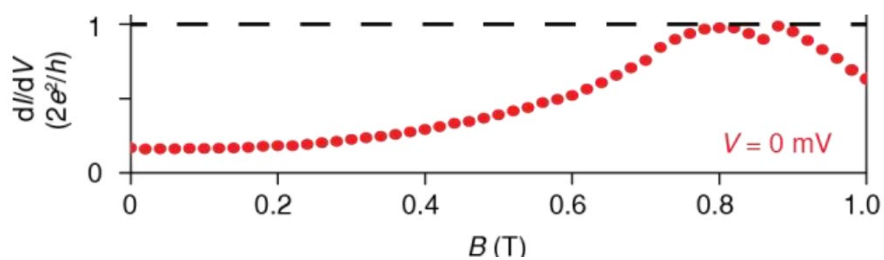


Experimental evidences

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†]

Corrected version, arXiv:2101.11456

MAIN CONCLUSION:

Our work, presented here, along with the recent theoretical developments involving quasi-Majoranas and disorder, should serve as a strong cautionary message for all Majorana experiments in all platforms, clearly emphasizing that the experimental observations of zero-bias conductance peaks, no matter how compelling, should be considered only as necessary and by no means sufficient conditions for the existence of topological MZMs.

Shot-noise signatures ?

PRL **98,** 237002 (2007) PHYSICAL REVIEW LETTERS week ending 8 JUNE 2007

Observing Majorana bound States in *p*-Wave Superconductors Using Noise Measurements in Tunneling Experiments

C. J. Bolech[1,2] and Eugene Demler[1]

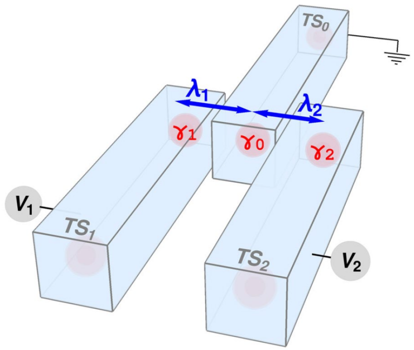
$$F_{\alpha\beta} \equiv \lim_{V/T\to\infty} \frac{S_{\alpha\beta}(\omega = 0)}{e(I_\alpha + I_\beta)} = \delta_{\alpha\beta} \qquad \alpha,\ \beta = \{L, R\} = \pm 1$$

PRL **114,** 166406 (2015) PHYSICAL REVIEW LETTERS week ending 24 APRIL 2015

Signatures of Majorana Zero Modes in Spin-Resolved Current Correlations

Arbel Haim,[1] Erez Berg,[1] Felix von Oppen,[2] and Yuval Oreg[1]

PHYSICAL REVIEW LETTERS **122,** 097003 (2019)

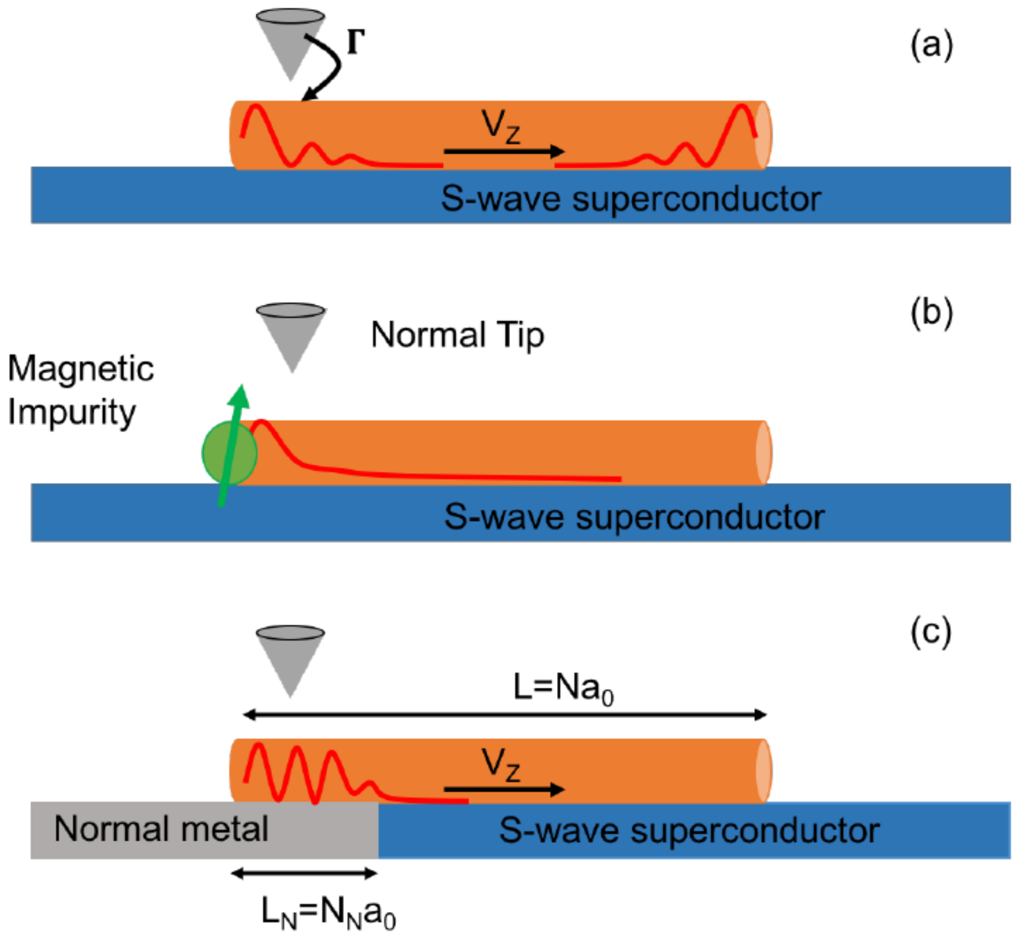


Giant Shot Noise from Majorana Zero Modes in Topological Trijunctions

T. Jonckheere,[1] J. Rech,[1] A. Zazunov,[2] R. Egger,[2] A. Levy Yeyati,[3] and T. Martin[1]

Shot-noise tomography for zero-energy states

Advantage: test the full spatial extent of the bound state wave function (non-local)

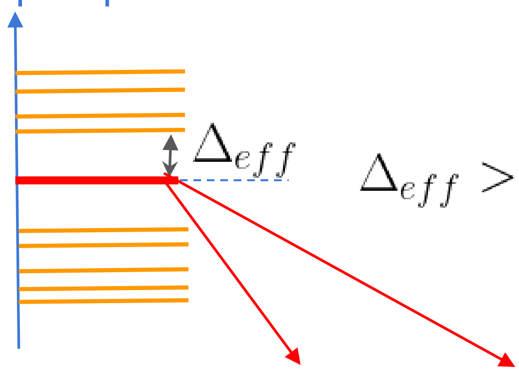


Low-energy analytical results

Fano factor tomography of zero-energy fermions : Low-energy model

Assumptions :

Sample spectrum



$\Delta_{eff} > eV \gg k_B T$

$\Gamma \equiv 2\pi \nu_T t^2$

$\Gamma \sum_\sigma (u_\sigma(j)^2 + v_\sigma(j)^2) \gg \Lambda$

coherent transport regime

Γ_j : Tip induced linewidth

Λ : dissipative linewidth

Low-energy model : $\psi_S(j,t) \sim \phi_+(j)\gamma_0 + \phi_-(j)\gamma_0^\dagger$

$\phi_+(j) = (u_\uparrow(j), u_\downarrow(j), v_\downarrow(j), -v_\downarrow(j))^T$ $\qquad$ $\phi_-(j) = C\phi_+(j))$

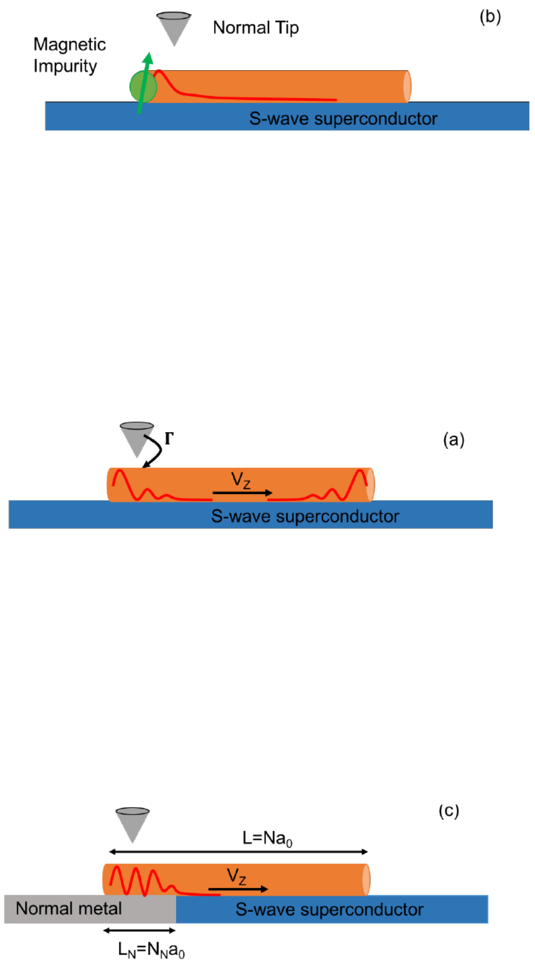
Simple analytical limit : $eV \gg \Gamma_j$

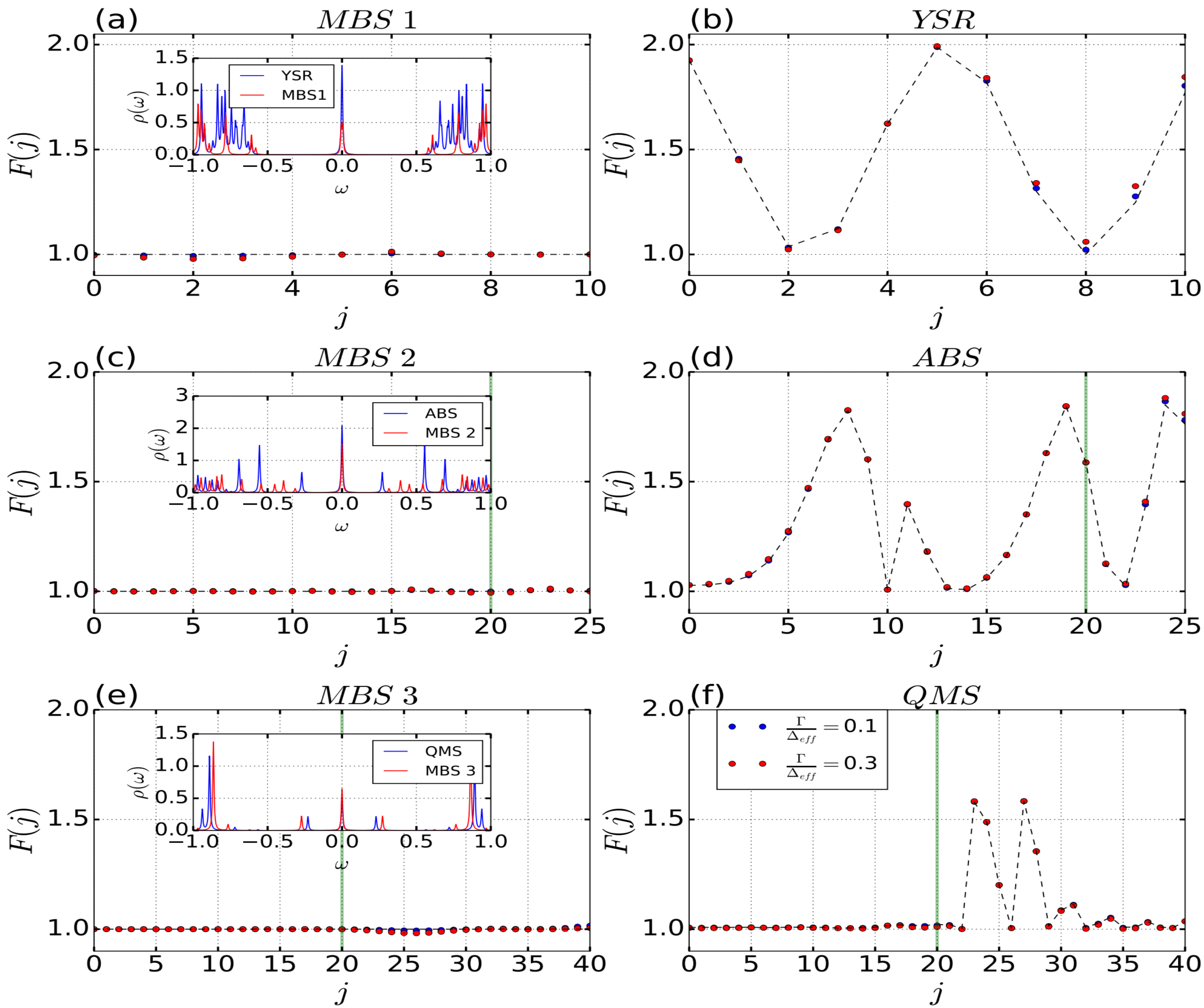
Local BCS charge , vanishes for isolated Majorana !

$$F(j) \simeq 1 + \left(\frac{\sum_\sigma (u_\sigma^2 - v_\sigma^2)}{\sum_\sigma (u_\sigma^2 + v_\sigma^2)}\right)^2 = 1 + \delta_{\text{ph}}^2(j)$$

V. Perrin et al., Phys. Rev. B 104, L121406 (2021)

Results from tight-binding simulations



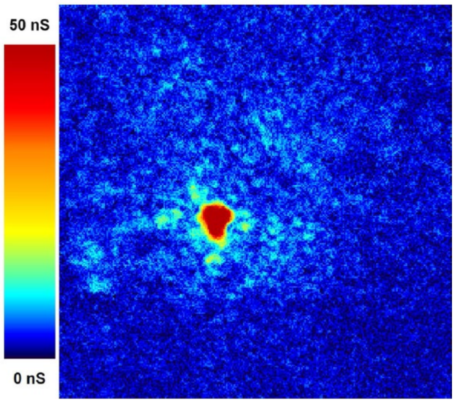


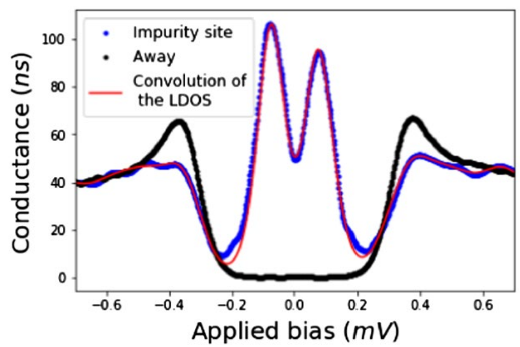
1. Key distinct features differenciating MBS from trivial ZBP
2. Quantitative agreement between low-energy effective theory (dashed line) and exact numerics (dots)
3. Sensitivity to Majorana overlap through BCS charge

V. Perrin et al., Phys. Rev. B 104, L121406 (2021)

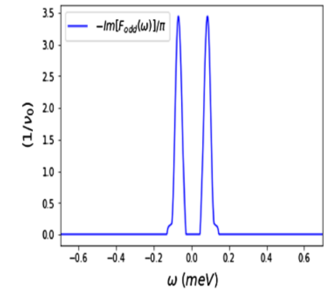
Conclusions

Odd-w frequency triplet pairing around a magnetic impurity





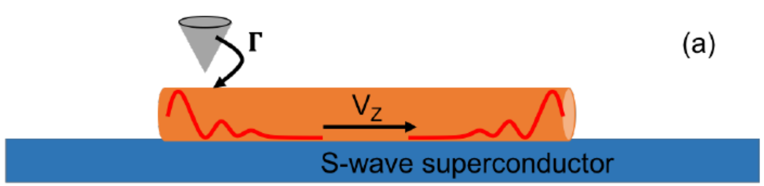
Conductance on top of the impurity

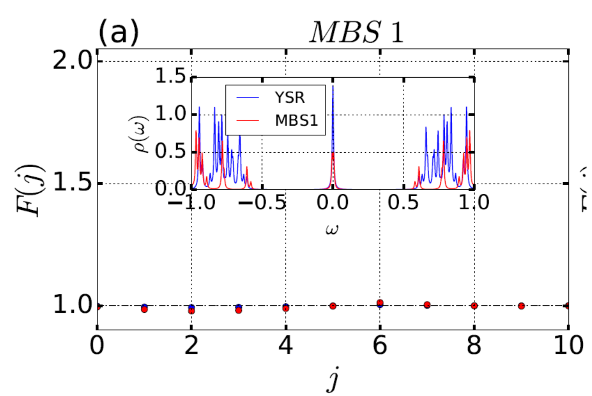


Odd-triplet correlations on top of the impurity

V. Perrin et al., Phys. Rev. Lett. 125, 117003 (2020)

A uniform Fano factor F=1 as a signature of Majorana zero mode





V. Perrin et al., Phys. Rev. B 104, L121406 (2021)

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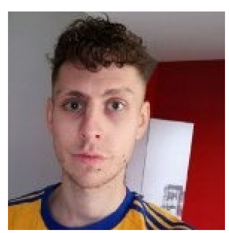

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IMN

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Thanks for your attention !