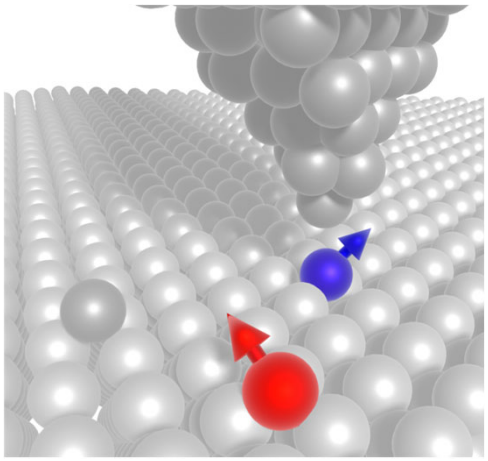
Center for Chiral Electronics

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From single-atom magnetism to Kondo lattices

Katharina Franke

Fachbereich Physik and
Halle-Berlin-Regensburg Cluster of Excellence CCE
Freie Universität Berlin

Thank you!

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Sergey Trishin

Now at UC Berkeley



Carmen Rubio Verdu

Now at ICFO Barcelona



Felix von Oppen

Verena Caspari
Florian Faaber
Caroline Firschke
Melvin Grumser
Margarete Huisinga
Christian Lotze
Bharti Mahendru
Vibhuti Rai
Carmen Rubio Verdu
Junyoung Sim
Rahel Specht
Sergey Trishin
Huan Wang
Werner van Weerdenburg
Paul Wiechers

Center for Chiral Electronics

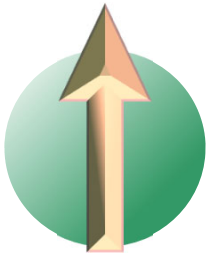
Single magnetic atoms

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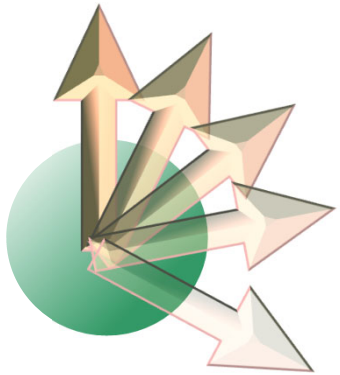
Classical magnet



„Classical“ single-atom spin



Quantum spin



Magnetic atoms on surfaces:

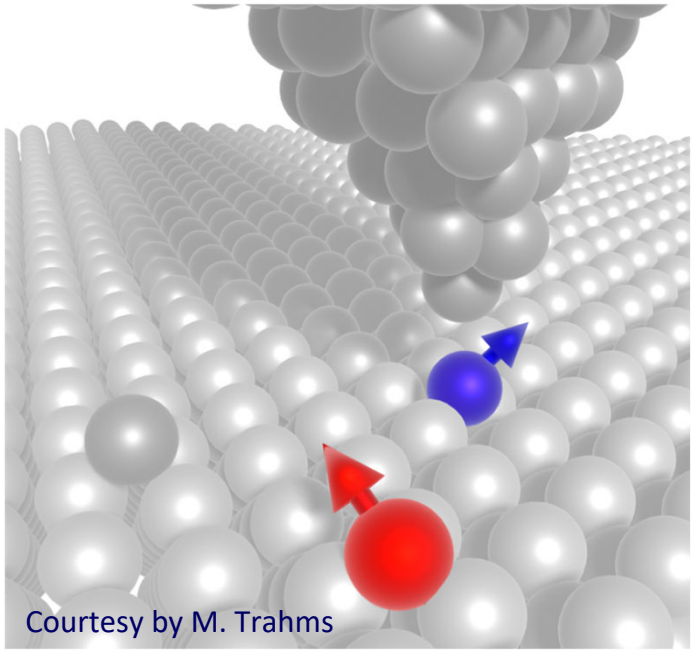
- Exchange scattering with substrate electrons

Tuning of exchange interaction on the single atom scale?

Interaction of many quantum spins?

Single-atom magnetism on surfaces

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Courtesy by M. Trahms

Magnetic atoms on surfaces:

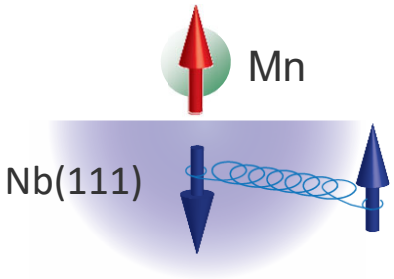
- Need of single-atom measurements
  - Low-temperature scanning tunneling microscopy

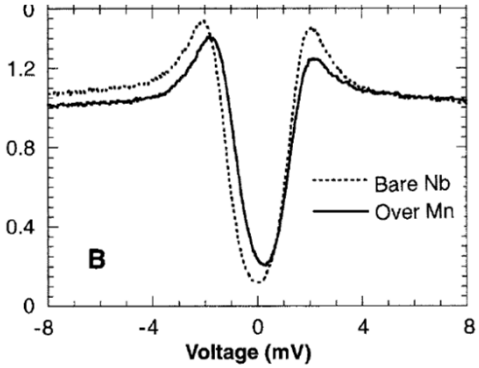
Single-atom magnetism on surfaces

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On superconductors:

Yu-Shiba-Rusinov states

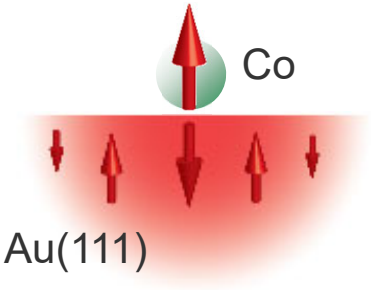


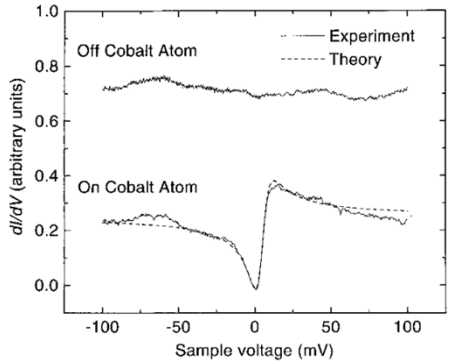


Yazdani et al., Science (1997)

On metals:

- Kondo effect

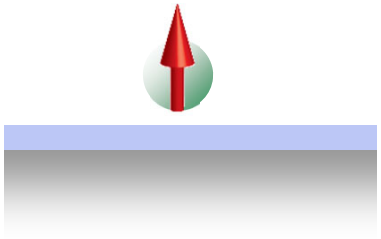


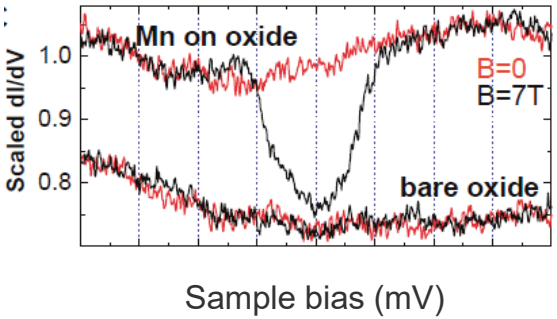


Madhavan et al., Science (1998)
Li et al., Phys. Rev. Lett. (1998)

On thin insulators:

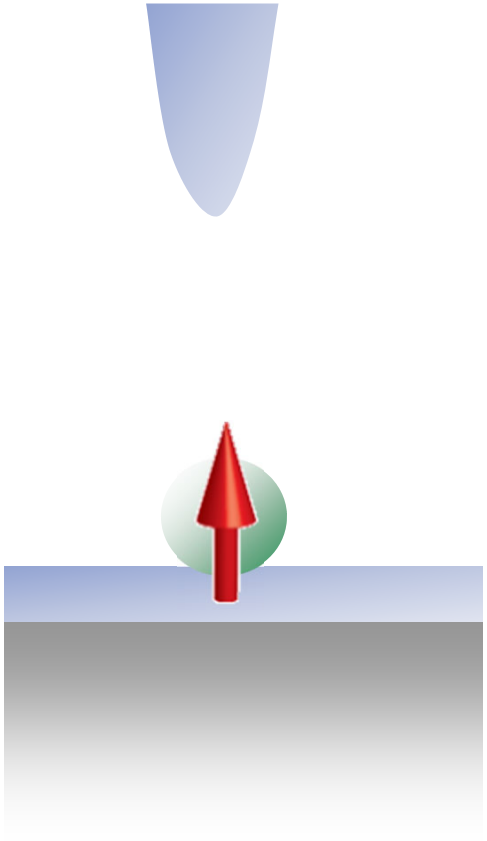
- Inelastic spin excitations

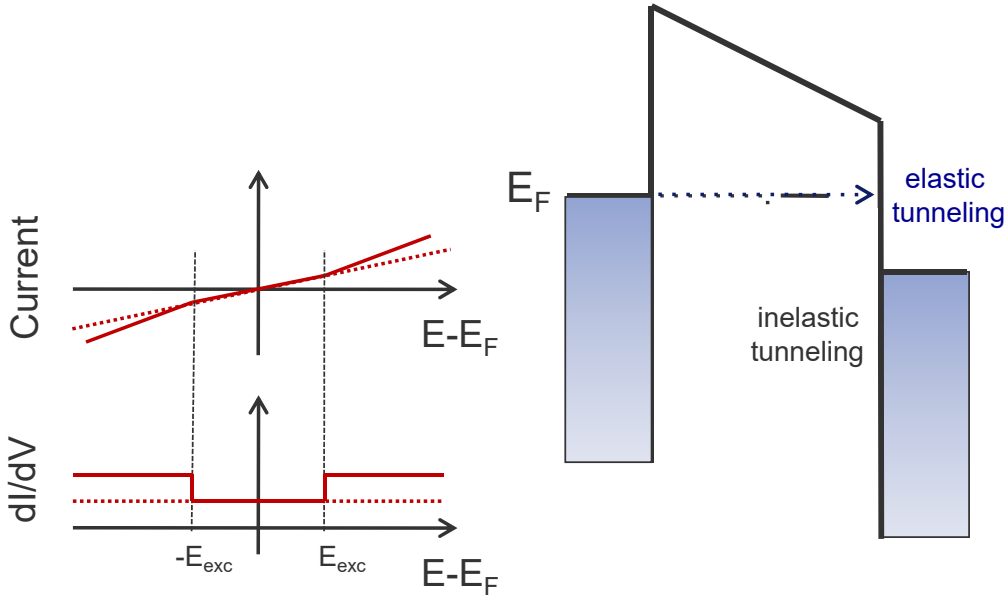




Heinrich et al., Science (2004)

Inelastic electron tunneling spectroscopy - IETS





- excitation of vibrations* or spins
- threshold spectroscopy: opening of inelastic channel at ± E_{exc}
- steps in dI/dV spectra

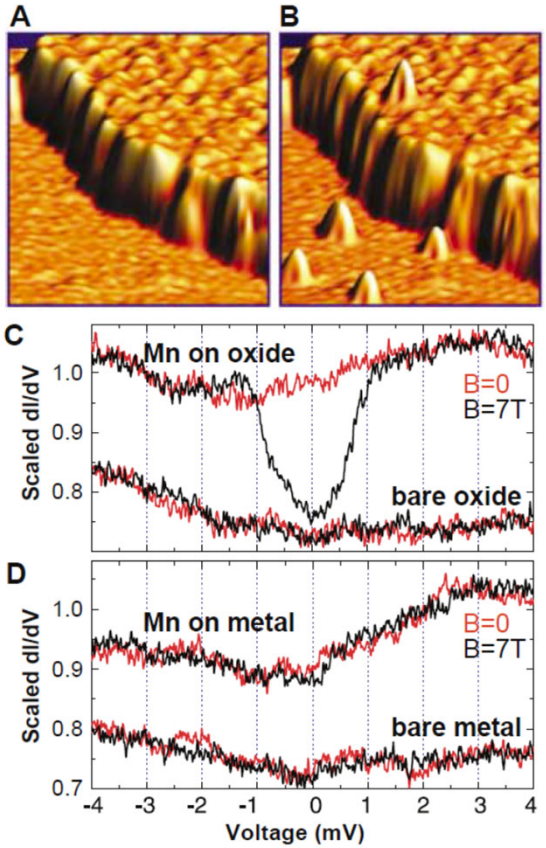
*B.C. Stipe *et al.*, Science **279**, 1907 (1998)

The first single-atom spin excitation

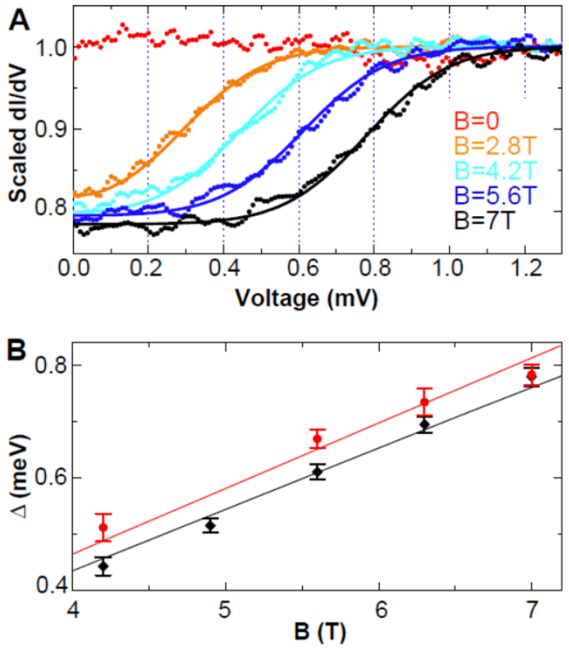
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Single Mn atoms:

- Inelastic excitation in magnetic field when lying on aluminum oxide

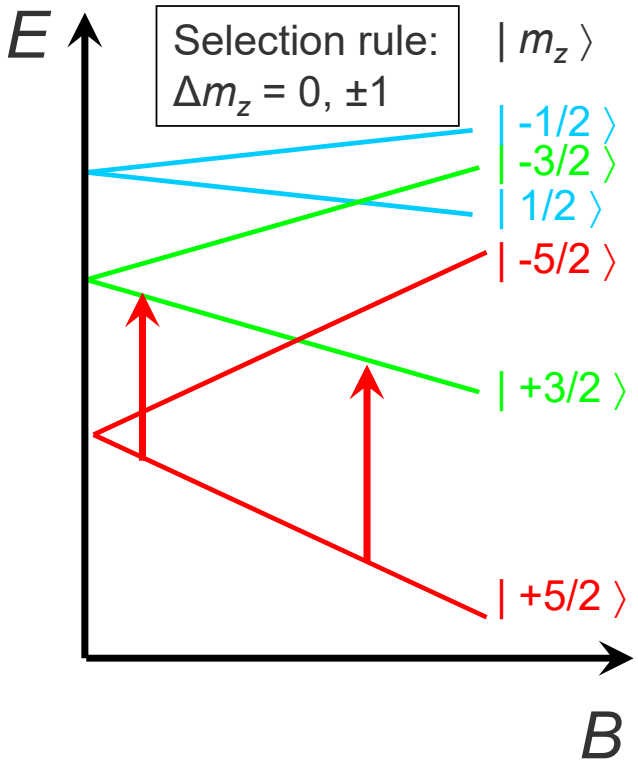


- Inelastic excitations shift in energy with magnetic field
- Agreement with Zeeman effect $\Delta = g\mu_B B$

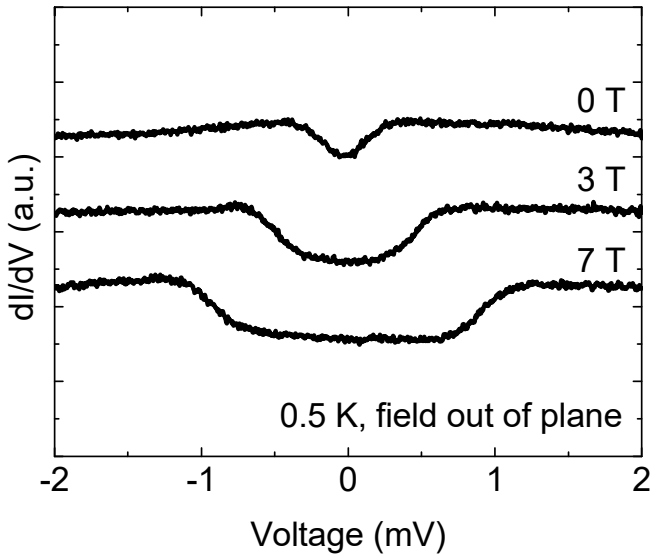


A.J. Heinrich, J.A. Gupta, C.P. Lutz, D.M. Eigler, Science **306**, 466 (2004)

Deviation from free spin: Mn on CuN



$$H = -g\mu_B \vec{B} \cdot \vec{S} + DS_z^2$$

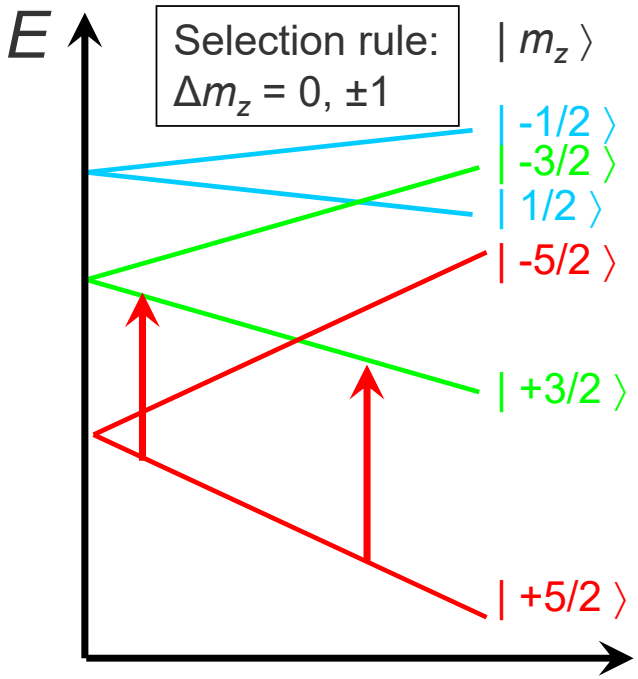


Single Mn atoms on CuN:

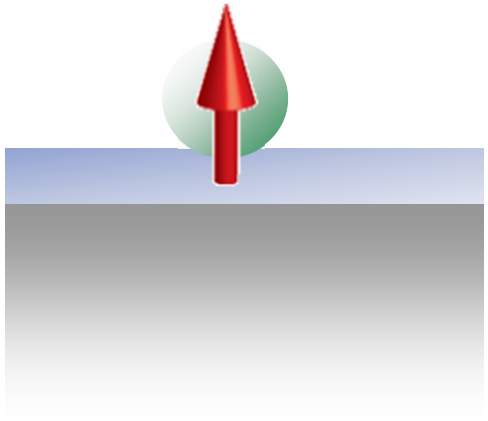
- Inelastic excitation in zero field!
- Need anisotropy term to explain the spectra

C.F. Hirjibehedin, C.-Y .Lin, A.F. Otte, M. Ternes, C.P. Lutz, B.A. Jones, A.J. Heinrich, Science **317**, 1199 (2007)

Anisotropy at a surface



$$H = -g\mu_B \vec{B} \cdot \vec{S} + DS_z^2$$

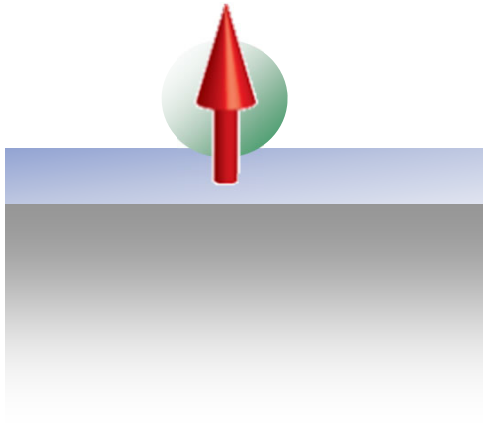


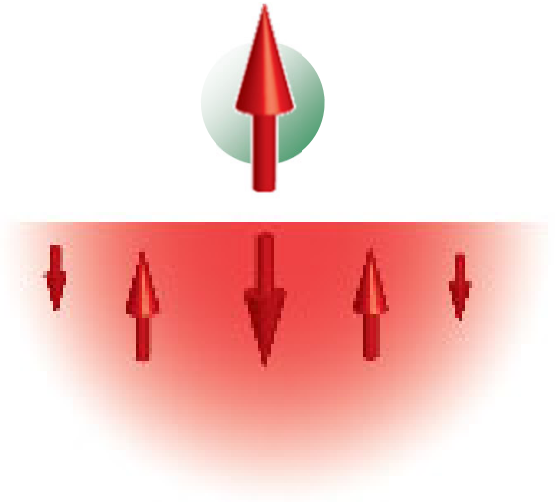
- Loss of rotational symmetry breaks degeneracy of spin orientations.

C.F. Hirjibehedin, C.-Y .Lin, A.F. Otte, M. Ternes, C.P. Lutz, B.A. Jones, A.J. Heinrich, Science **317**, 1199 (2007)

From „quasi-free“ spin to exchange-coupled spin

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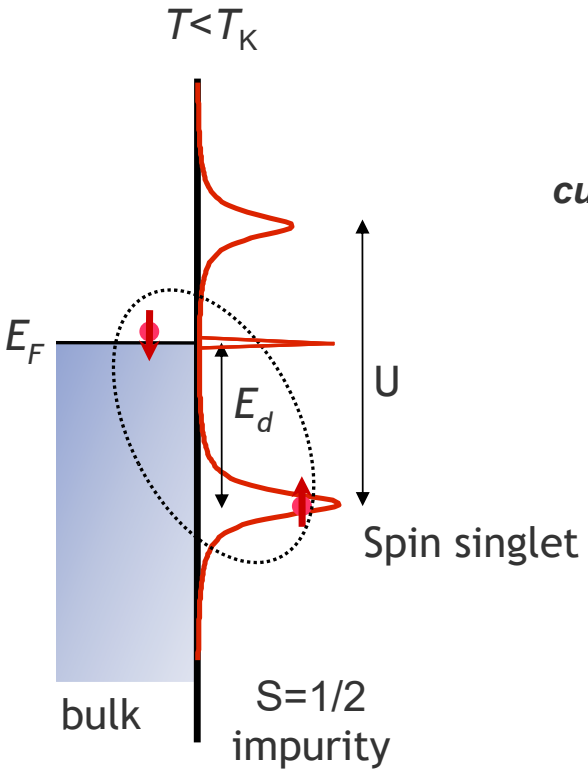


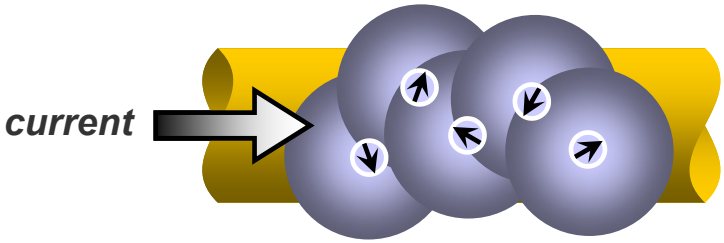


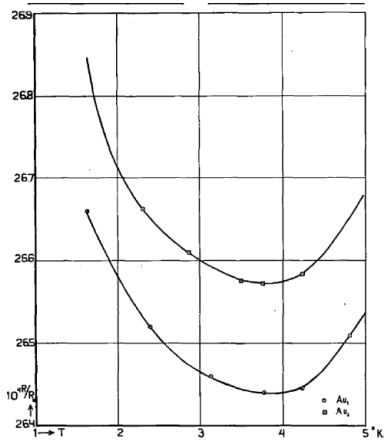
- atomic spin decoupled from the substrate
  - Inelastic spin excitations

- atomic spin exchange- decoupled to substrate
  - Kondo resonance

The Kondo effect





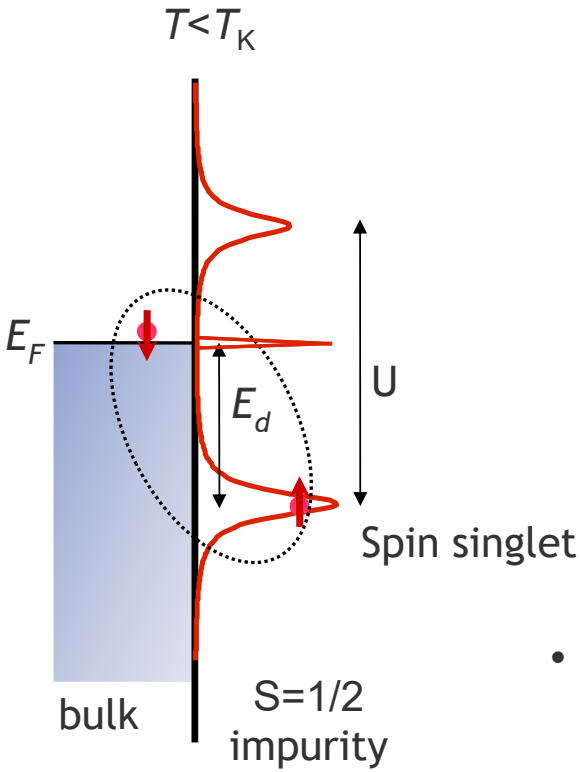

Fig. 1. Resistance of Au between 1°K. and 5°K.

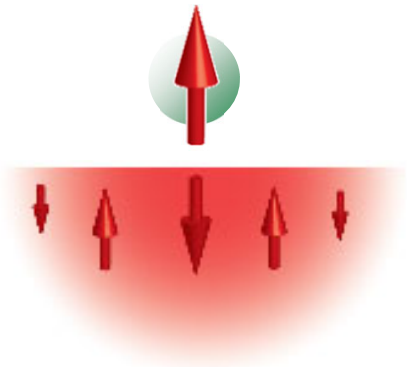
- High T: resistance arises from scattering with phonons
- Low T: Increase in resistance?!?

P. W. Anderson, *Phys. Rev.* **124**, 61 (1961)
J. Kondo , *Prog. Theor. Phys.* **32**, 37 (1964)
J. Kondo , *Phys. Rev.* **169**, 437 (1968)

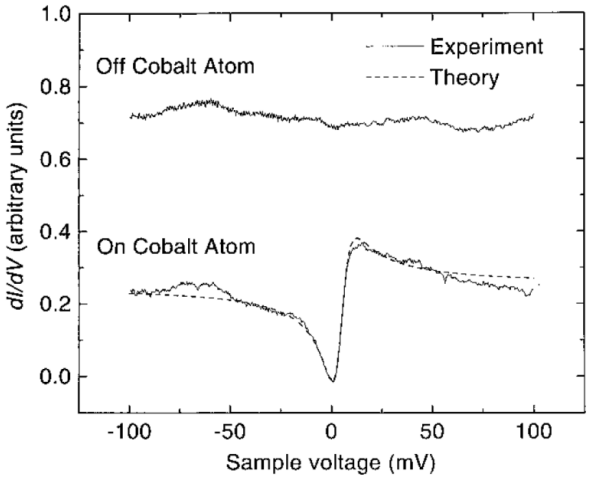
W. J. de Haas, *Physica* **34**, 1115 (1934)
W. Meissner, *Ann. d. Phys.* **7**, 761 (1930)

Kondo effect on the surface

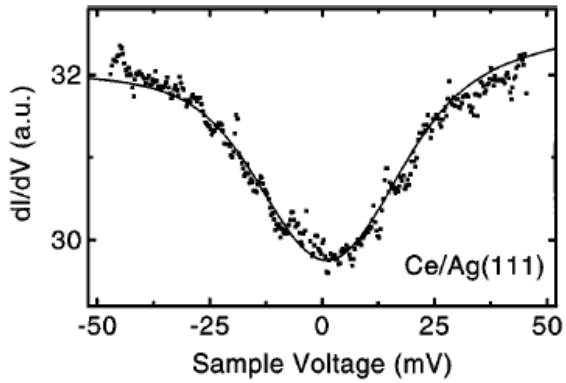




- zero-bias anomaly in tunneling spectra
- Fano line shape due to interference of different tunneling paths



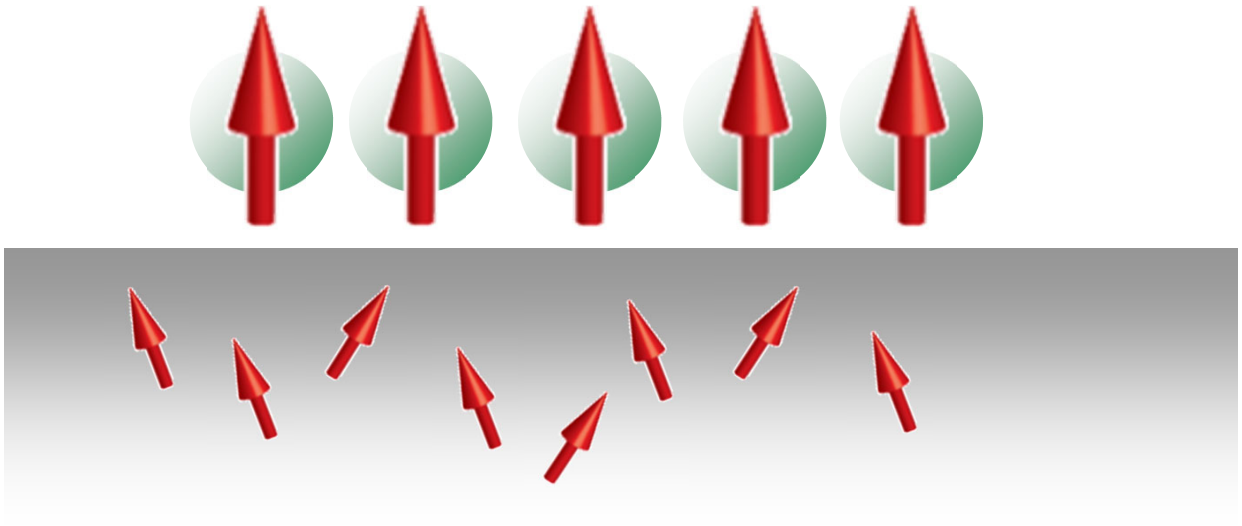
Madhavan *et al.,* Science **280** (1998)



Li *et al.,* Phys. Rev. Lett. **80** (1998)

Interaction of magnetic adatoms

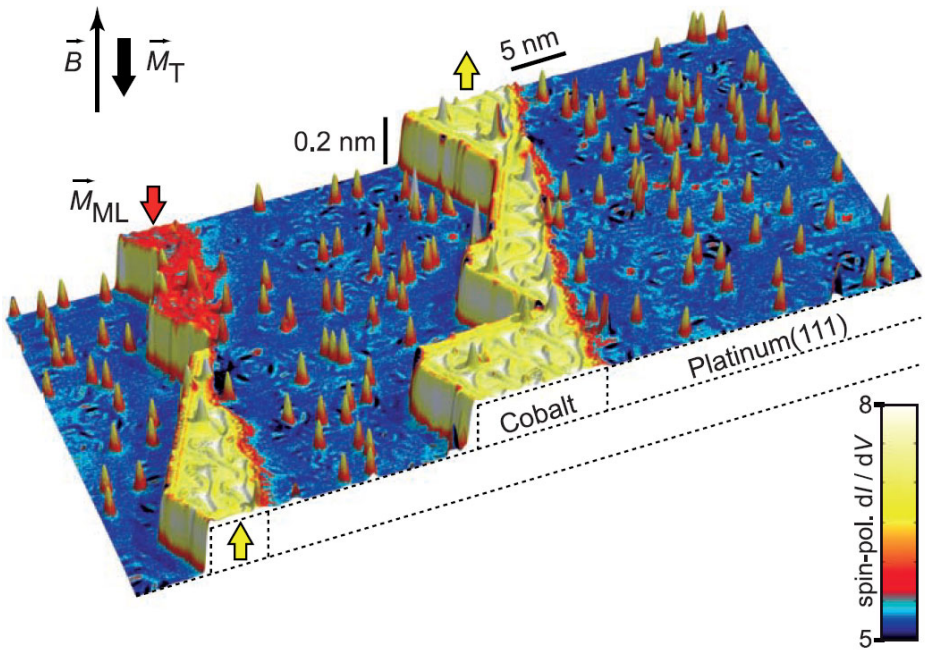
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Role of substrate electrons?

Competing interactions?

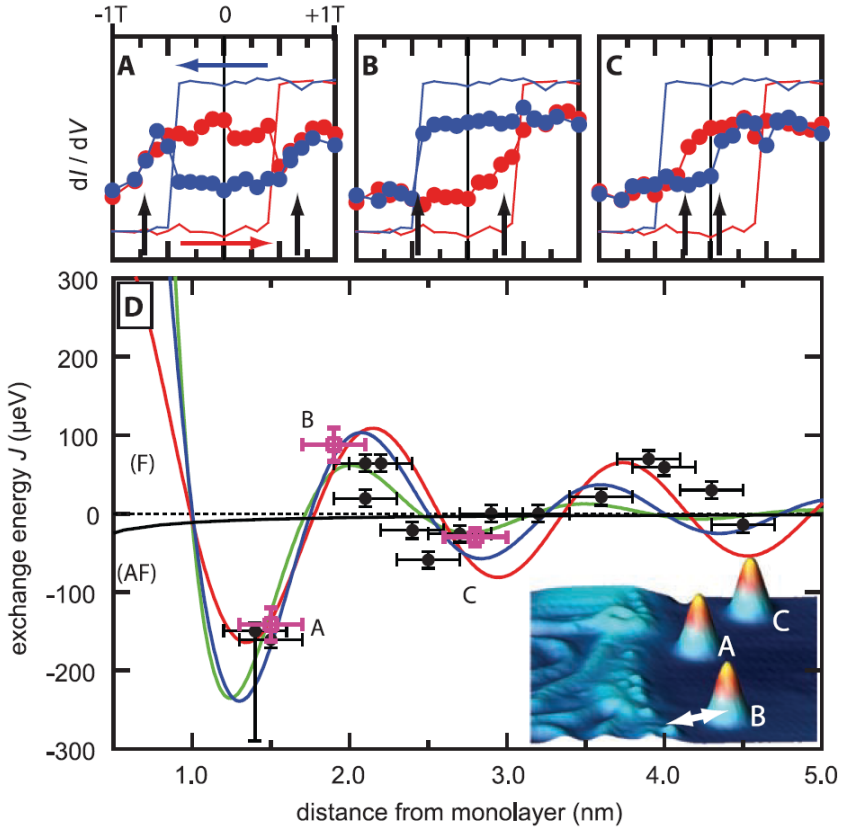
Coupling of magnetic atoms via the substrate



- Co islands and Co adatoms on Pt(111)
- Measured with spin-polarized tip

F. Meier, L. Zhou, J. Wiebe, R. Wiesendanger, Science 320, 82 (2008)

Coupling of magnetic atoms via the substrate

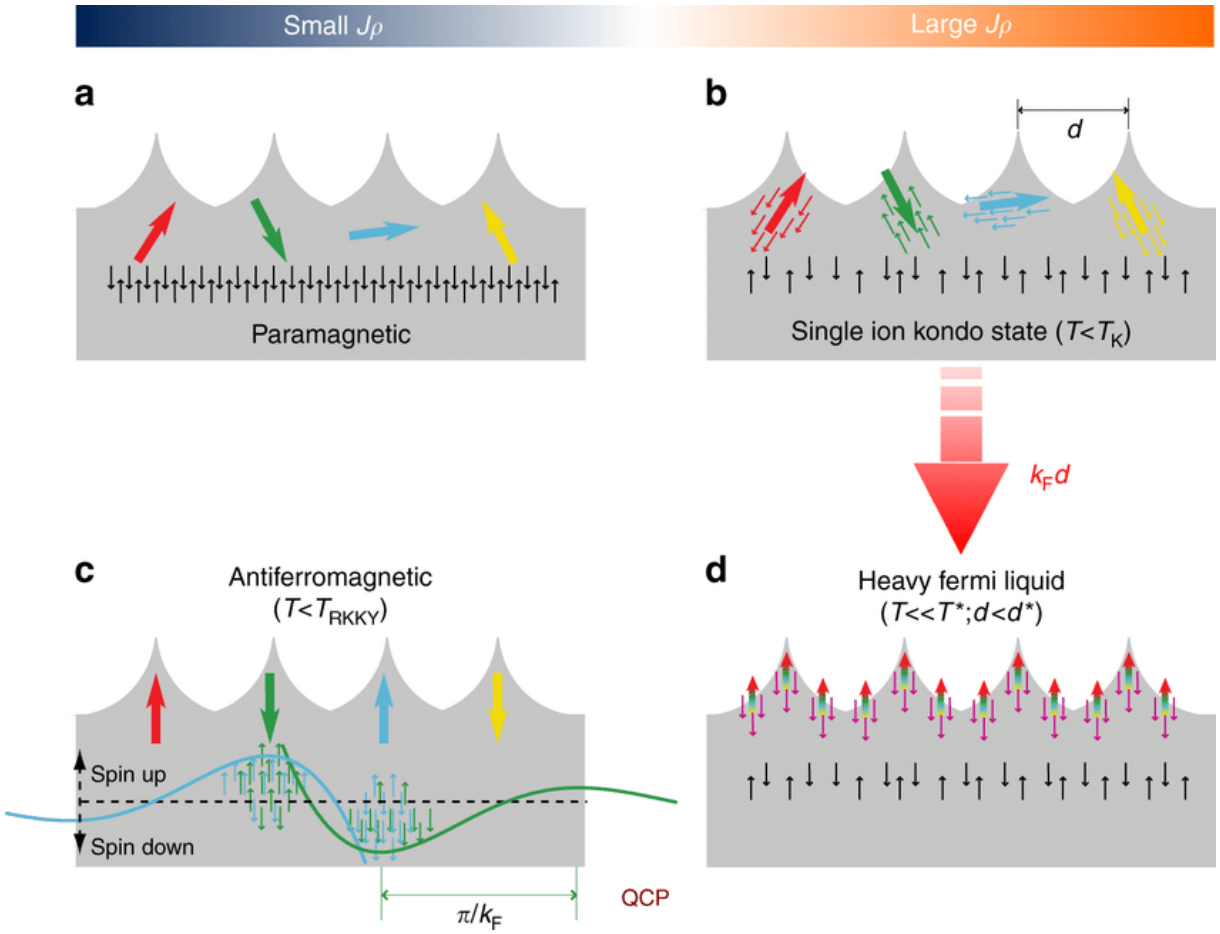


- Co atoms show remanence
- „stabilization“ of magnetic moment
- stabilization by exchange coupling to island
- distance dependence shows oscillatory behaviour
- RKKY (Ruderman-Kittel-Kasuya-Yosida) coupling through surface state electrons



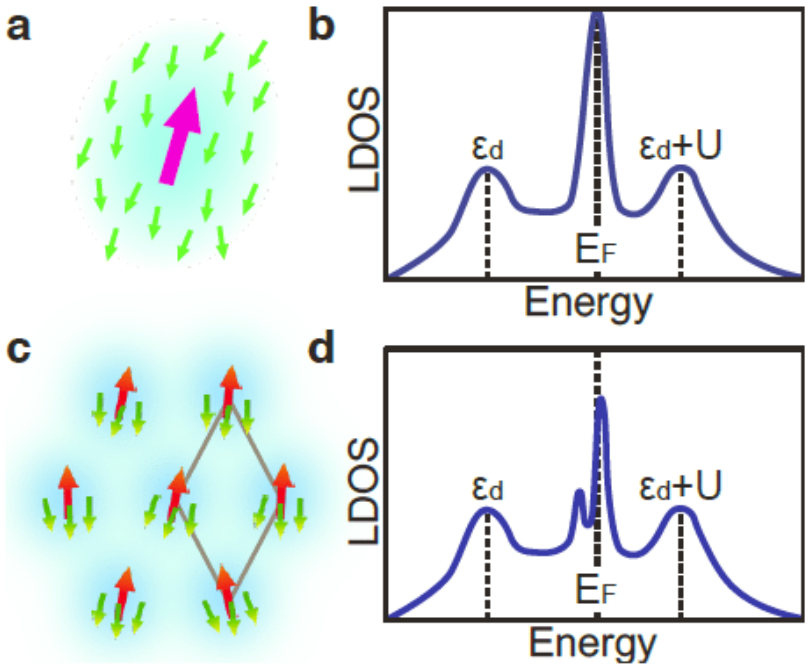
F. Meier, L. Zhou, J. Wiebe, R. Wiesendanger, Science 320, 82 (2008)

„Phase diagram of exchange coupled atoms on surfaces



M. Moro-Lagares, R. Korytár, M. Piantek, R. Robles, N. Lorente, J. I. Pascual, M. Ricardo Ibarra, D. Serrate, Nature Commun. 10, 2211 (2018)

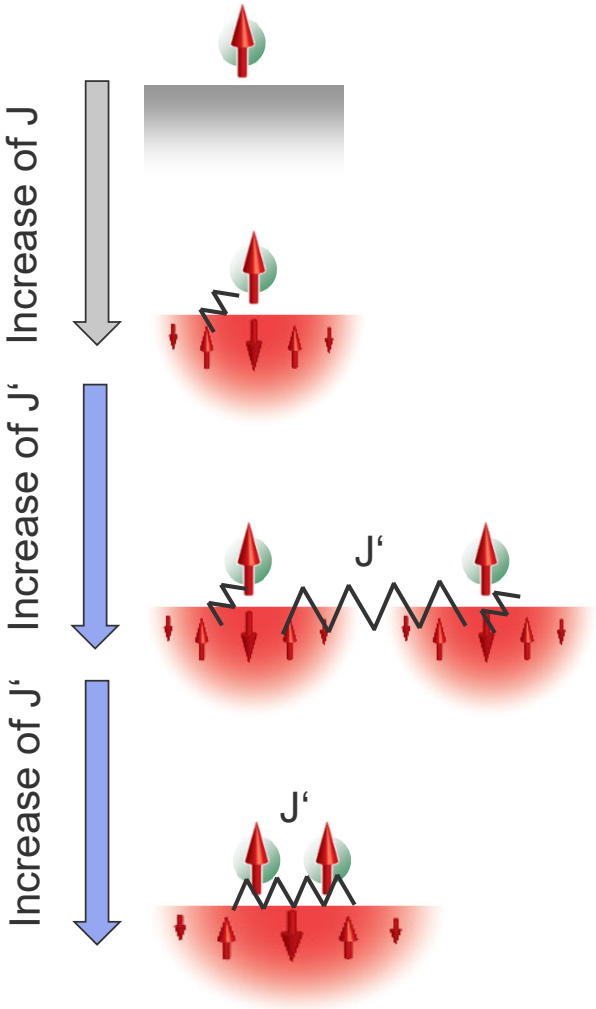
Signature of Kondo lattice



- Opening of hybridization gap on top of Kondo resonance

C. G. Ayani, M. Pisarra, I. M. Ibarburu, M. Garnica, R. Miranda, F. Calleja, F. Martín, A. L. Vázquez de Parga, Small 20, 2303275 (2024)

Exchange-coupled nanostructures on surfaces



Free spin:

- Inelastic spin excitations

Screened spin:

- Kondo resonance

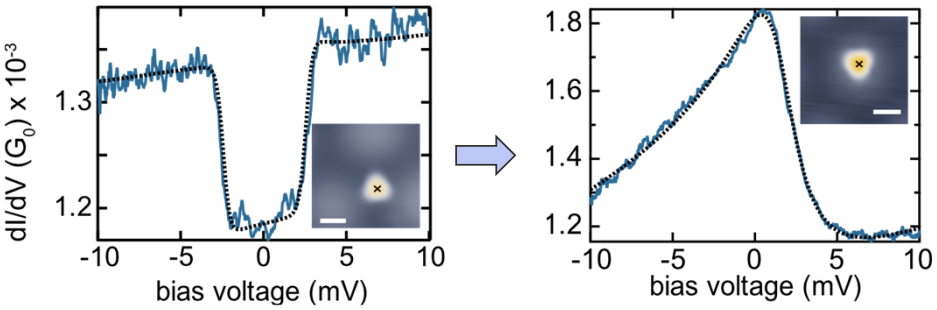
Exchange interaction:

- Zeeman-split Kondo resonance

Coherently screened spin:

- Kondo lattice: Hybridization gap of Kondo resonance

Exchange-coupled nanostructures on surfaces

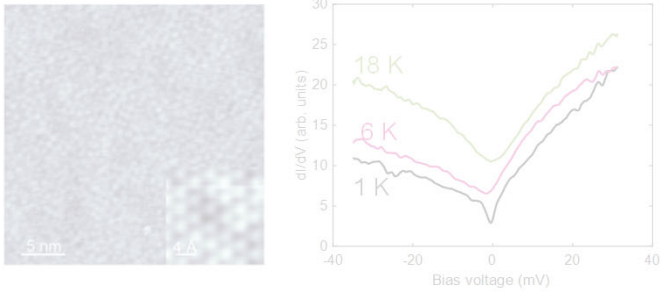


Fe atoms on MoS_2/Au(111)

- Spin excitations of single atoms
- Exchange coupling to substrate

Mn dimers on MoS_2/Au(111)

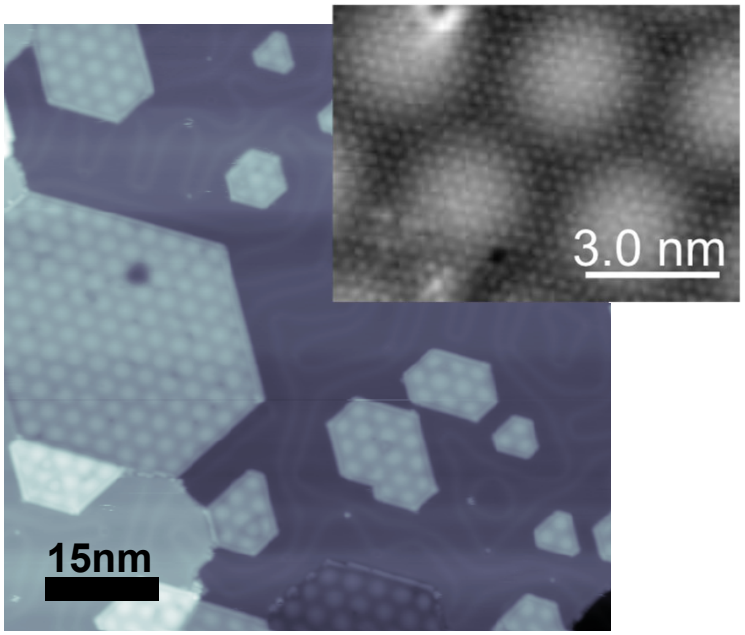
- Coupling of magnetic atoms
- Exchange coupling of dimers to substrate

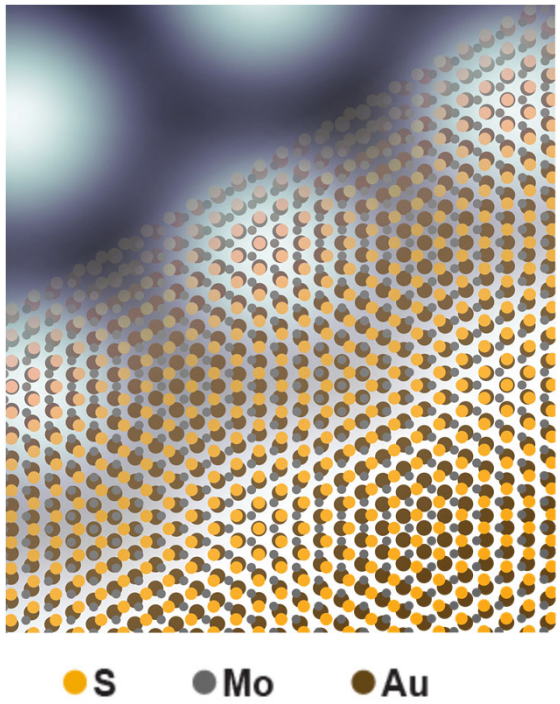


Fe_3GeTe_2:

- Kondo resonances on Fe_3GeTe_2
- Interaction with magnetic adatoms

Moiré structure of MoS_2 on Au(111)





In-situ growth of MoS_2 [1]:

- deposition of Mo on Au(111) and annealing in H_2S

[1] Sorensen, et al., ACS Nano 8, 6788-6796 2014

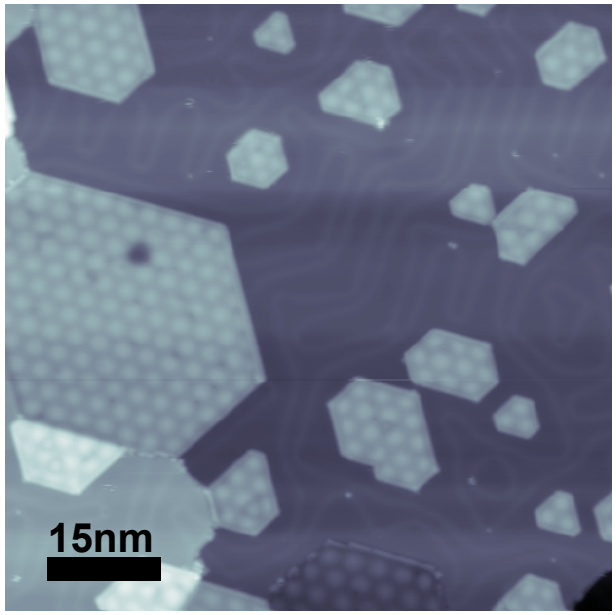
Monolayer-islands on Au(111):

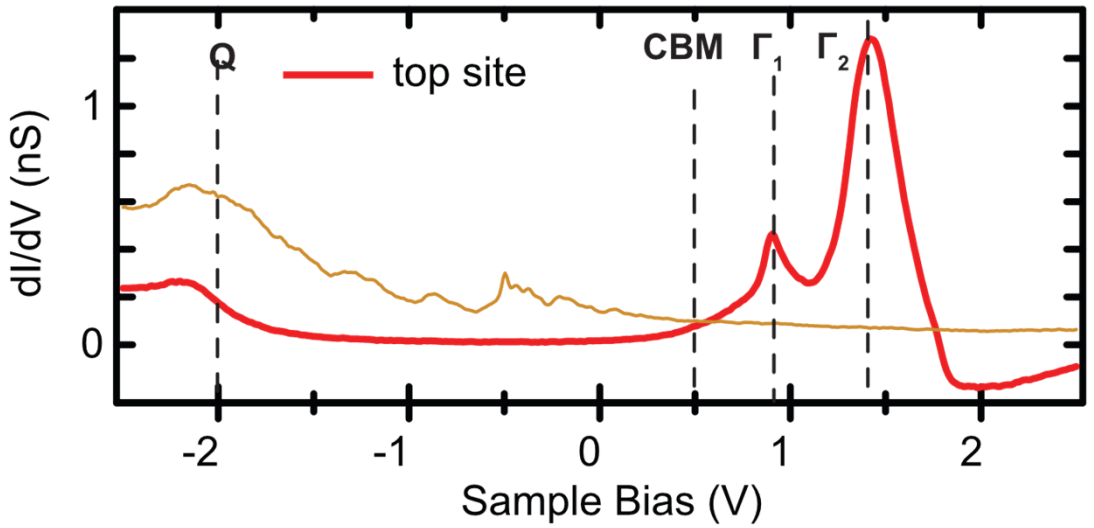
- Hexagonal modulation
- Moiré structure due to lattice mismatch

N. Krane, C. Lotze, KJF, Surf. Sci. 678, 136 (2018)

Electronic structure of MoS_2: STS

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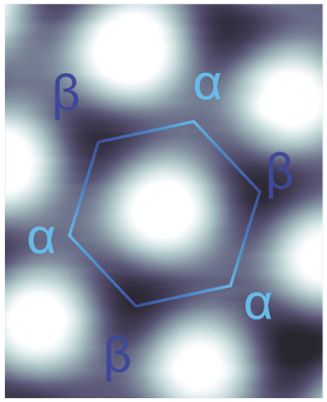


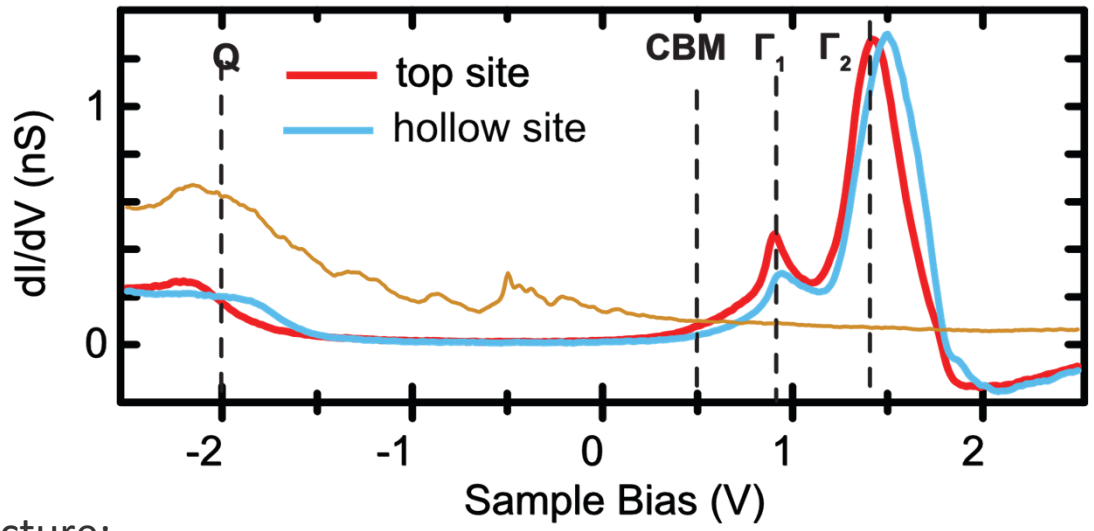


- Electronic band gap of MoS_2/Au(111)
- Broadened gap edges due to hybridization with Au states

Bruix et al, Phys. Rev. B **93**, 165422 (2016)

Electronic structure modulated by moiré





Electronic structure:

- Electronic band gap of MoS_2/Au(111)
- Shift of bands along moiré structure

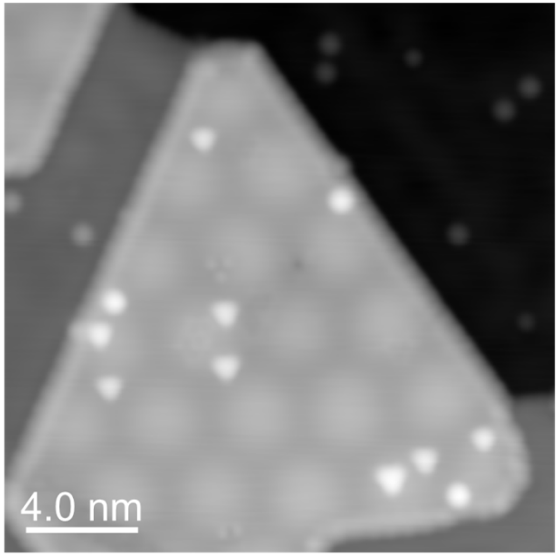
Template for adsorption properties?

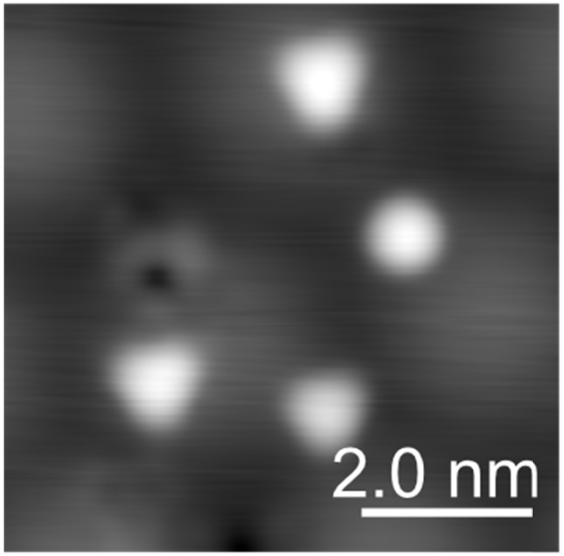
N. Krane, C. Lotze, KJF, Surf. Sci. 678, 136 (2018)

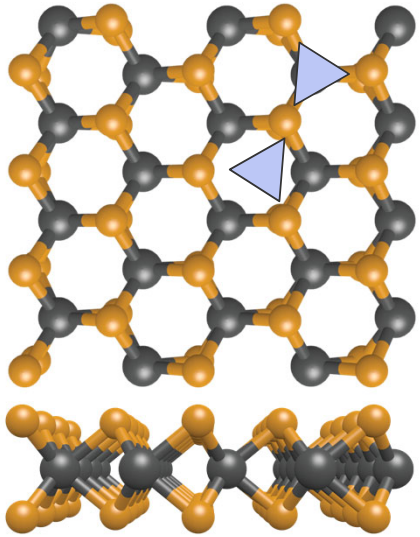
Fe atoms on MoS_2/Au(111)



Sergey Trishin



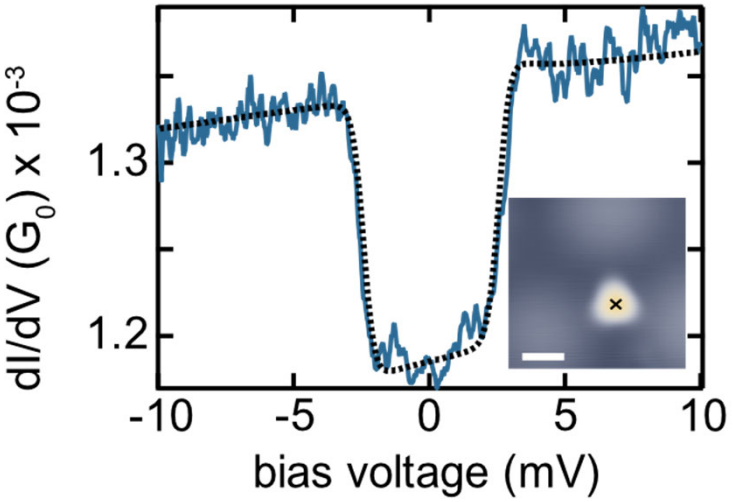


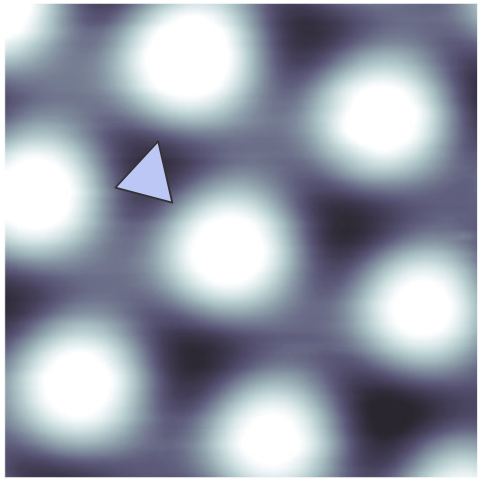


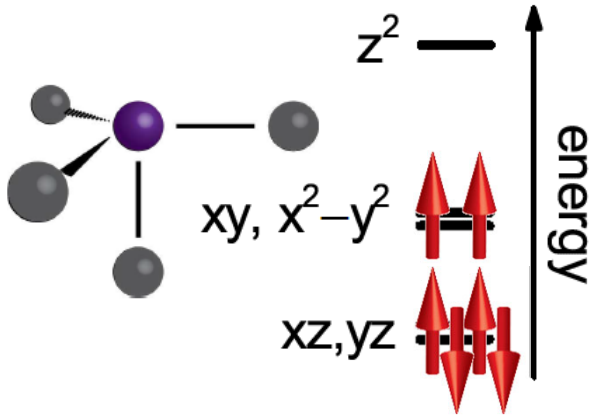
- Single Fe atoms appear with triangular shape
- All triangles point in same direction
- Equivalent hollow adsorption site

S. Trishin, C. Lotze, N. Bogdanoff, F. von Oppen, KJF, Phys. Rev. Lett. 127, 236801 (2021)

Magnetic properties: Fe on moiré minimum







Fe atom on minimum of moiré:

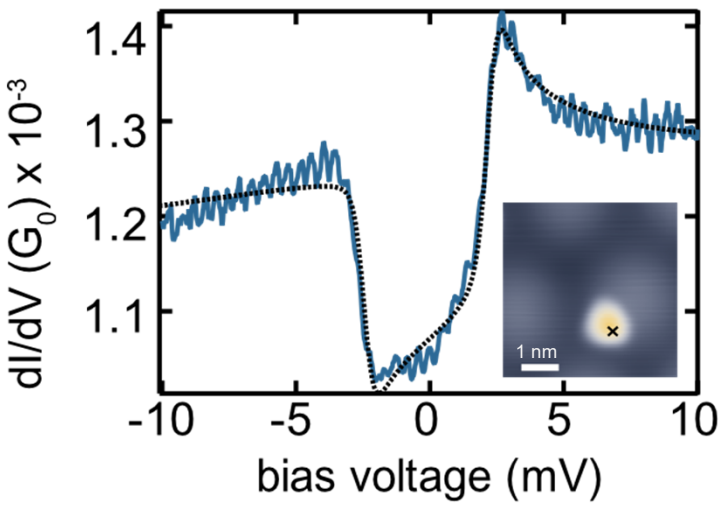
- Inelastic spin excitations
- Compatible with S=1
- Lifetime > 1 ps

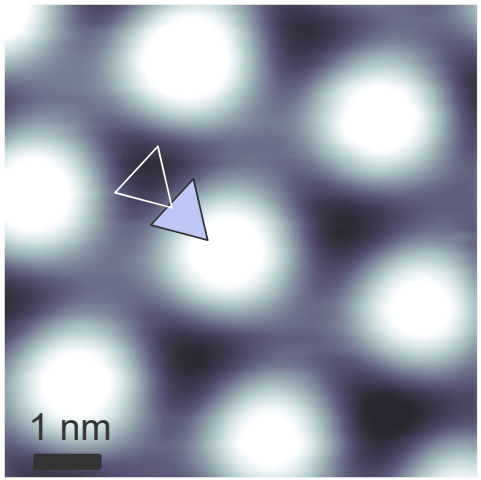
$$H = DS^2$$



S. Trishin, C. Lotze, N. Bogdanoff, F. von Oppen, KJF, Phys. Rev. Lett. 127, 236801 (2021)

Magnetic properties: Fe close to moiré minimum



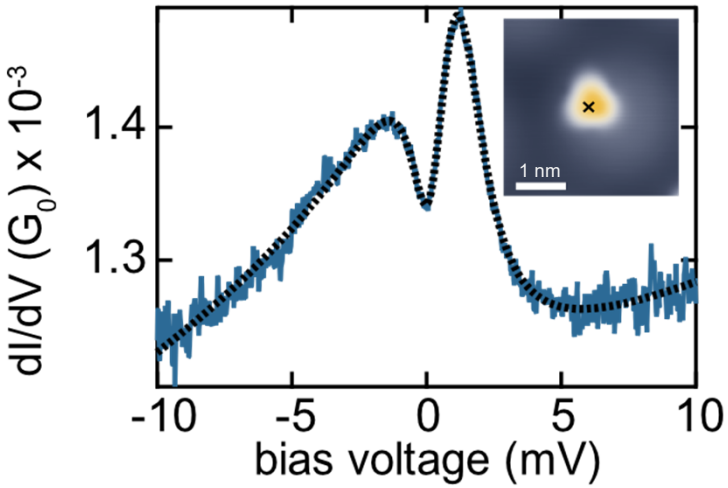


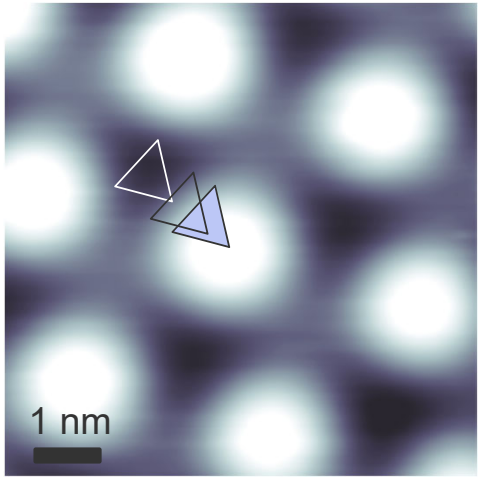
Fe atom close to minimum of moiré:

- Inelastic spin excitations
- Compatible with S=1
- Additional Kondo correlations manifested in conductance overshoots

M. Ternes, New J. Phys.17, 063016 (2015)

Magnetic properties: Fe close to moiré maximum

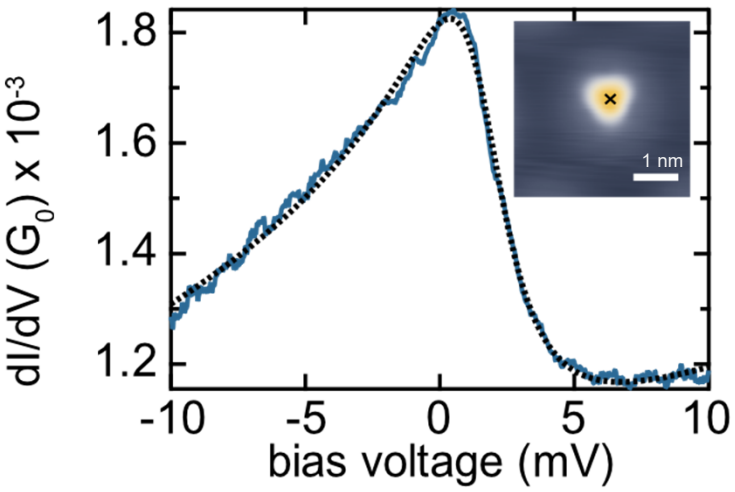


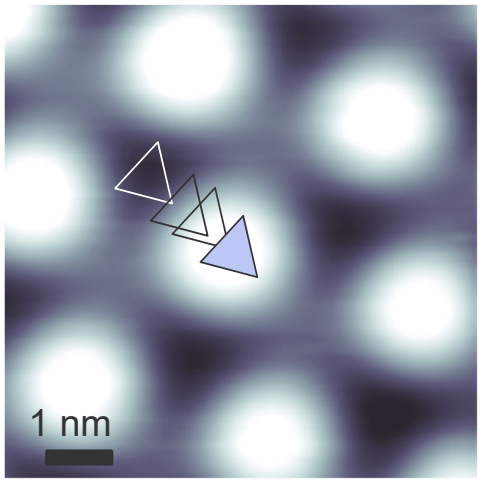


Fe atom close to maximum of moiré:

- Kondo peak and inelastic excitations

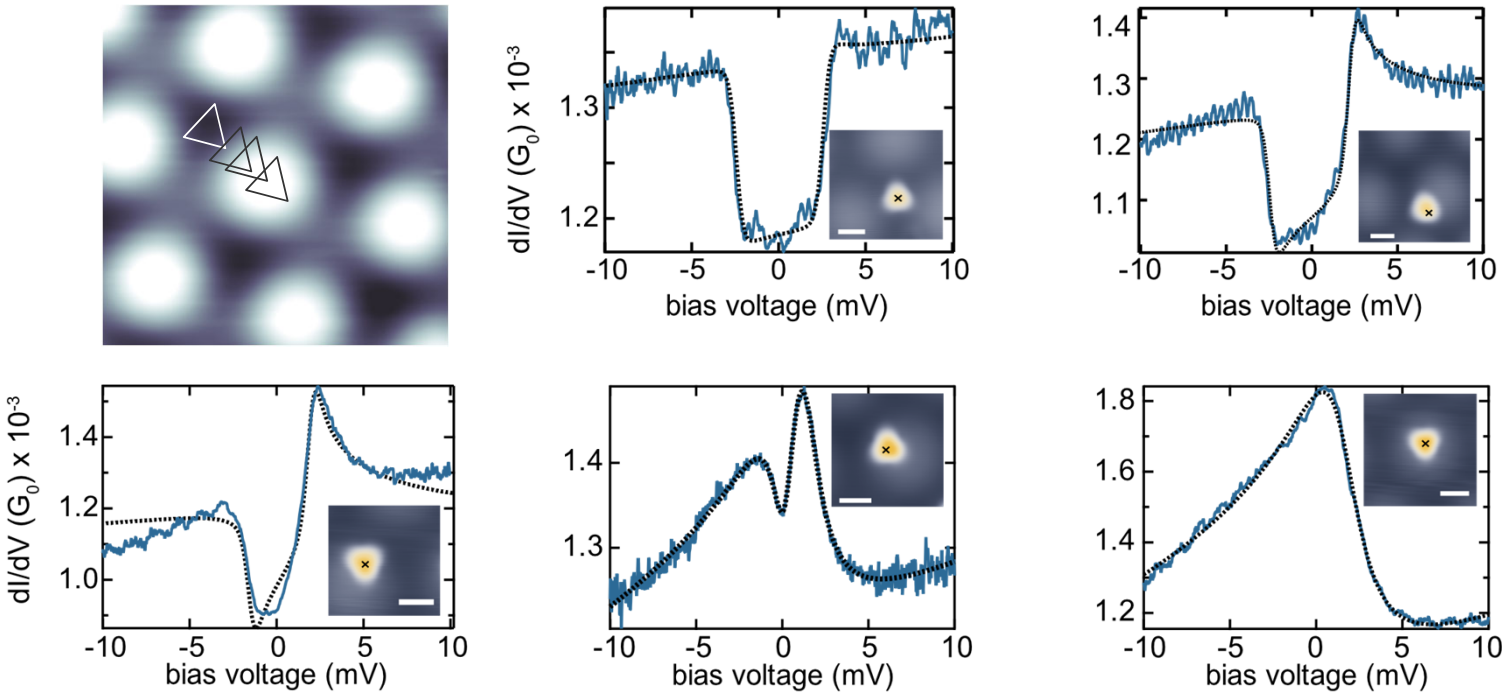
Magnetic properties: Fe on moiré maximum





- Fe atom close on maximum of moiré:
- Fully developed Kondo peak

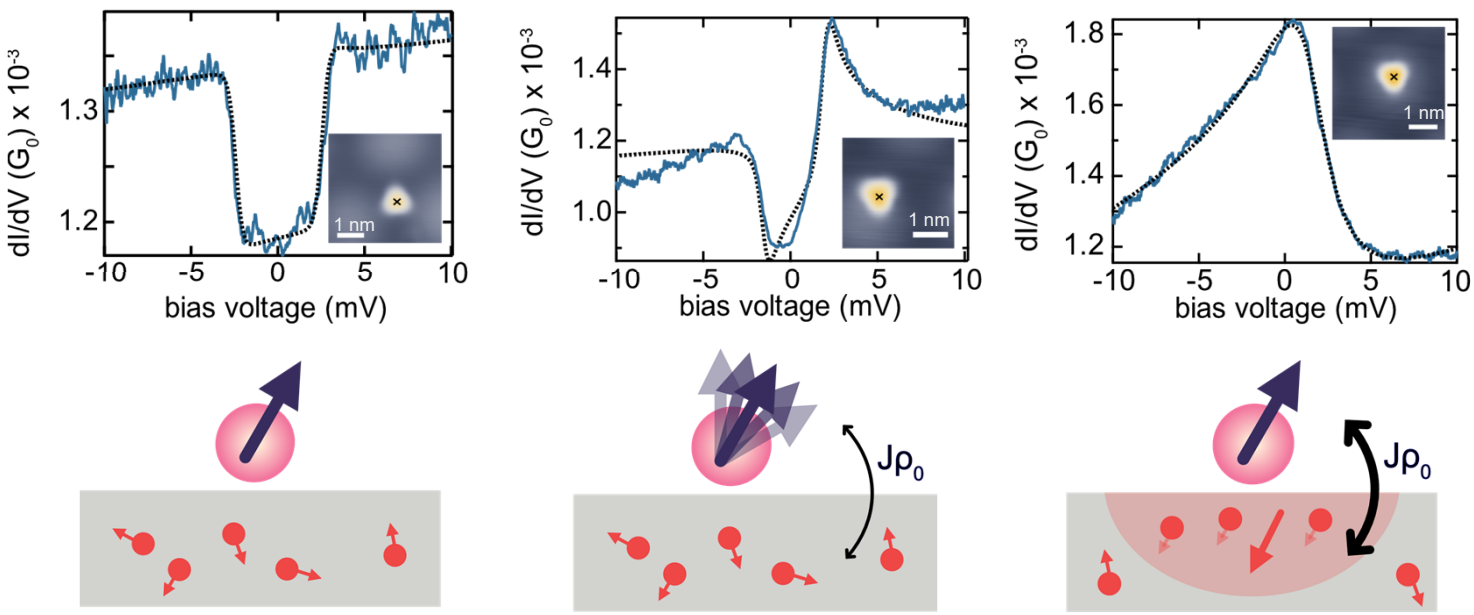
Magnetic properties along moiré: Fe atoms



- Continuous evolution of exchange coupling to substrate along moiré
- From pure spin excitations to fully developed Kondo correlations
- Concomitant decrease of anisotropy

S. Trishin, C. Lotze, N. Bogdanoff, F. von Oppen, KJF, Phys. Rev. Lett. 127, 236801 (2021)

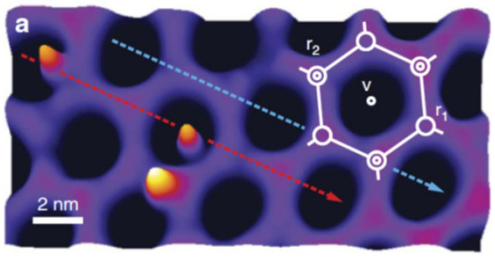
Magnetic properties along moiré

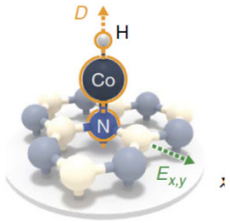


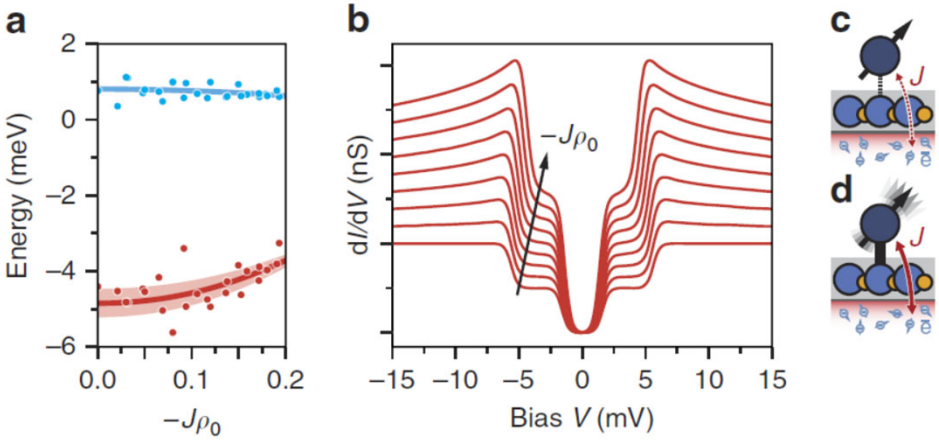
- Increasing Kondo correlation towards the moiré maxima leads to:
  - Reduced lifetime of the spin excitations
  - Renormalisation of the anisotropy energy

S. Trishin, C. Lotze, N. Bogdanoff, F. von Oppen, KJF, Phys. Rev. Lett. 127, 236801 (2021)

Comparison to other 2D materials





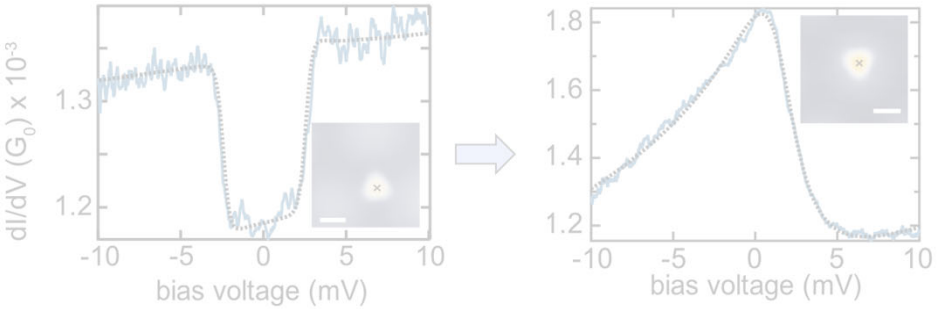


Co-H on hexagonal BN:

- Scaling of anisotropy with exchange coupling

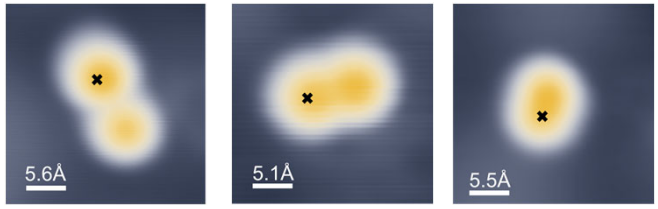
P. Jacobsen, et al., Nature Commun. 6, 8536 (2015)

Exchange-coupled nanostructures on surfaces



Fe atoms on MoS_2/Au(111)

- Spin excitations of single atoms
- Exchange coupling to substrate



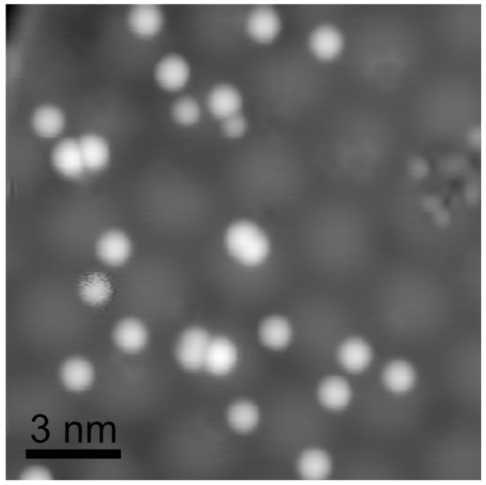
Mn dimers on MoS_2/Au(111)

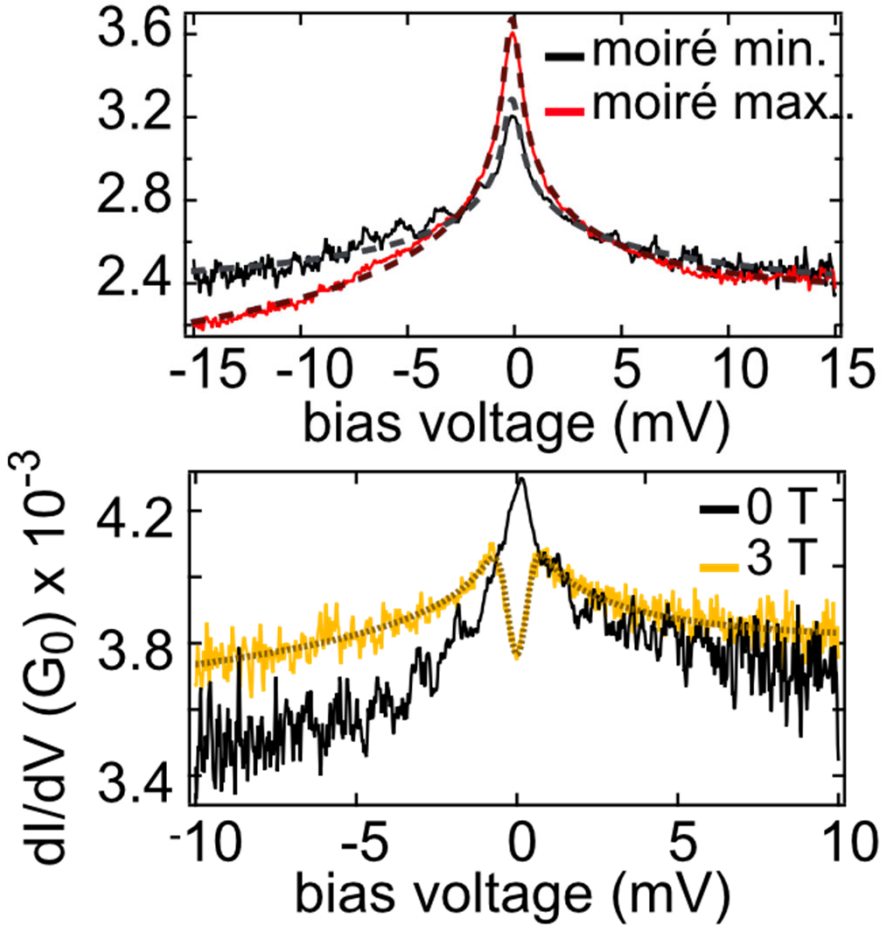
- Coupling of magnetic atoms
- Exchange coupling of dimers to substrate

Fe_3GeTe_2:

- Kondo resonances on Fe_3GeTe_2
- Interaction with magnetic adatoms

Mn atoms on MoS_2/Au(111)



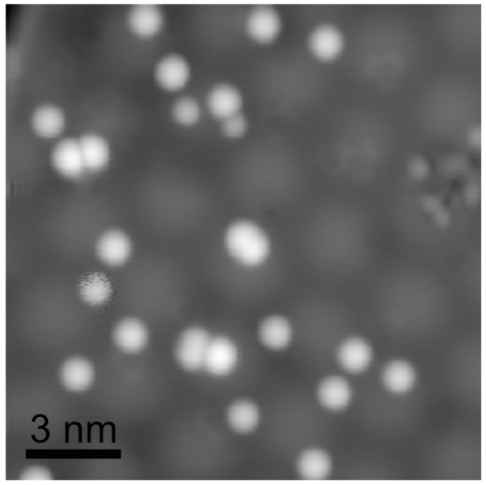


Single Mn atoms:

- Thermally broadened logarithmic peak at zero bias
- Peaks splits in B field
- Weakly coupled Kondo

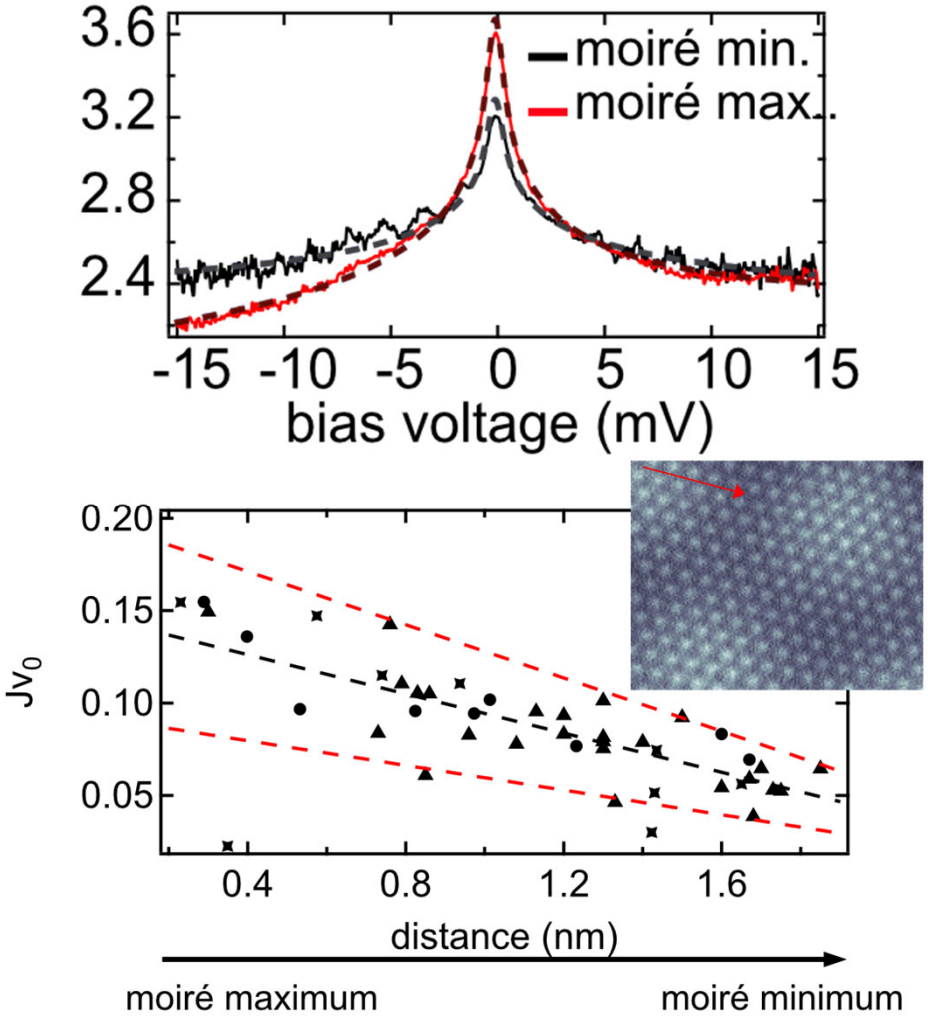
S. Trishin, C. Lotze, F .Lohss, G. Franceschi, L. I. Glazmann, F. von Oppen, KJF, Phys. Rev. Lett. 130, 176201 (2023)

Variation of Kondo resonance on moiré: Mn atoms



Single Mn atoms:

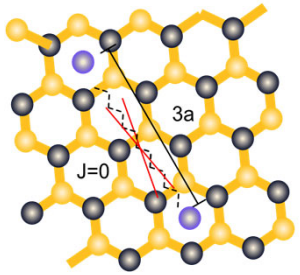
- Thermally broadened logarithmic peak at zero bias
- Peaks splits in B field
- Weakly coupled Kondo

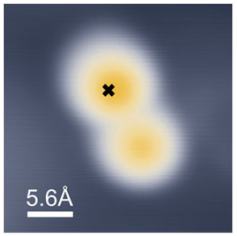


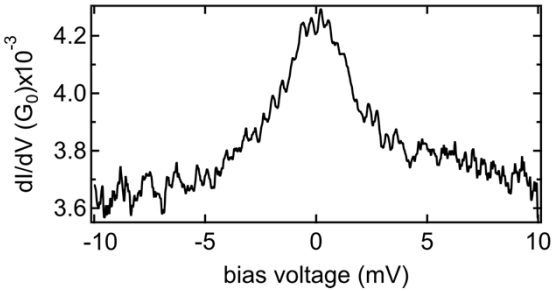
Mn dimers: distance-dependent coupling

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Separation 3 lattice sites

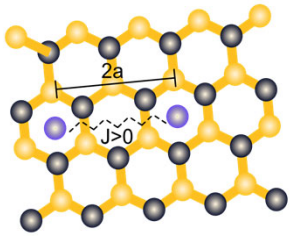


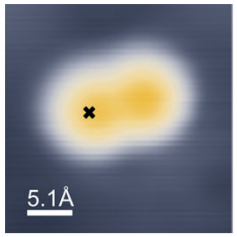


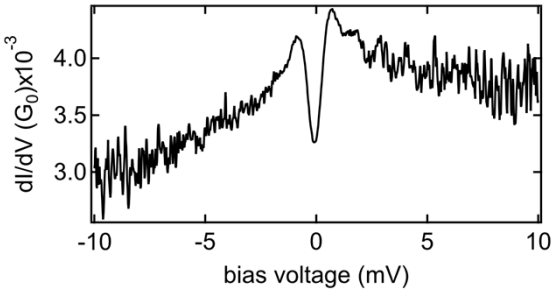


Unperturbed Kondo

Separation 2 lattice sites

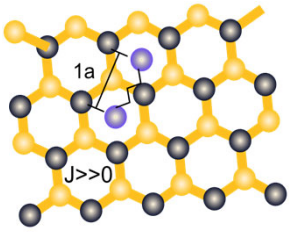


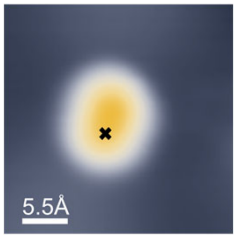


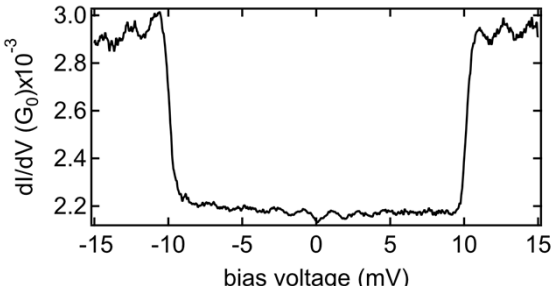


Split Kondo: RKKY coupling

Separation 1 lattice site

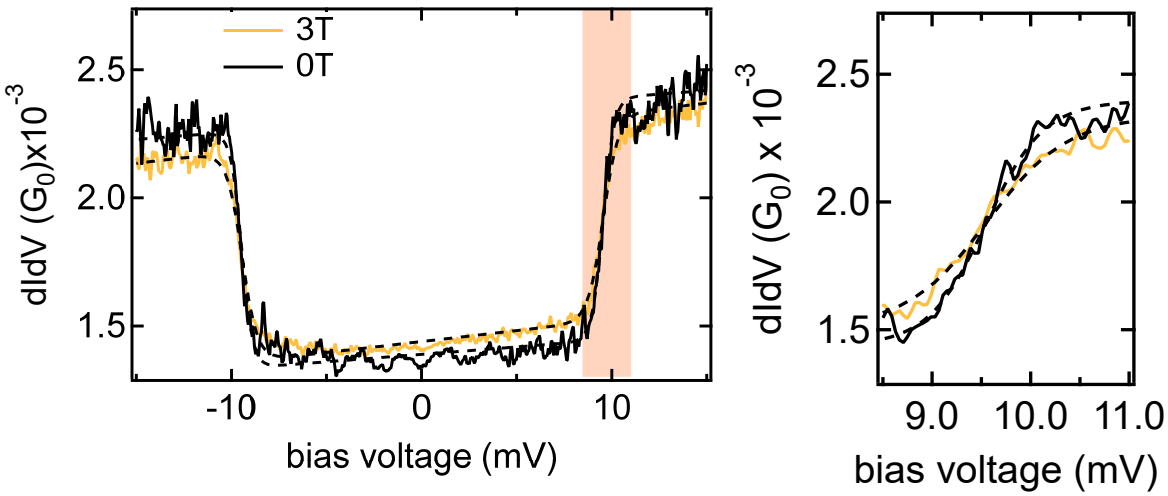


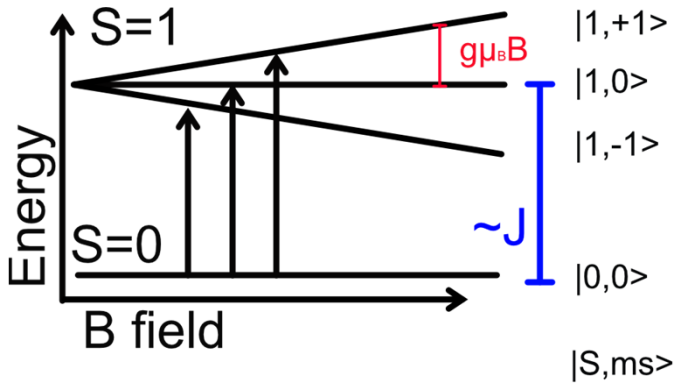




Inelastic excitation

Singlet-Triplet excitation in B field

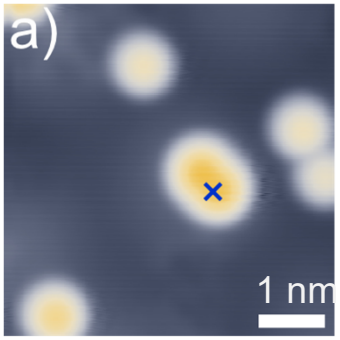




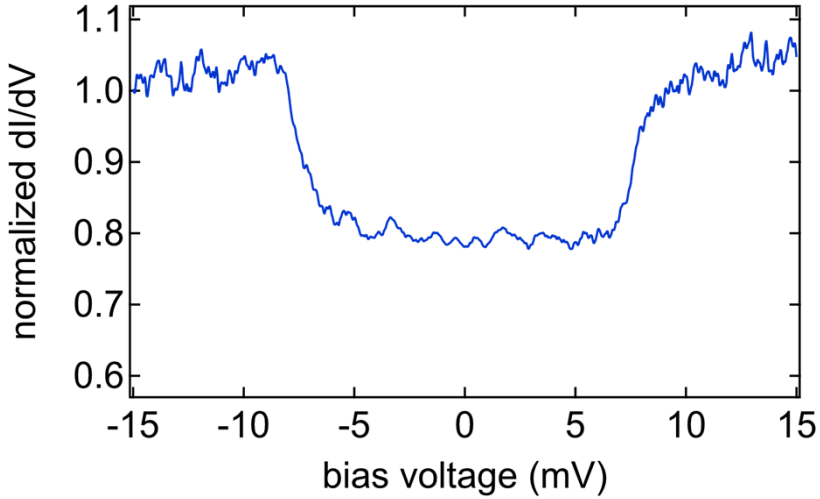
- Broadening of step in B field
- Compatible with singlet-triplet transition

S. Trishin, C. Lotze, F .Lohss, G. Franceschi, L. I. Glazmann, F. von Oppen, KJF, Phys. Rev. Lett. 130, 176201 (2023)

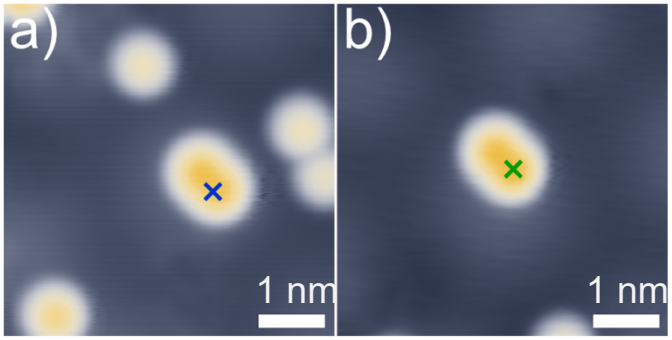
Moiré dependence of singlet-triplet excitation



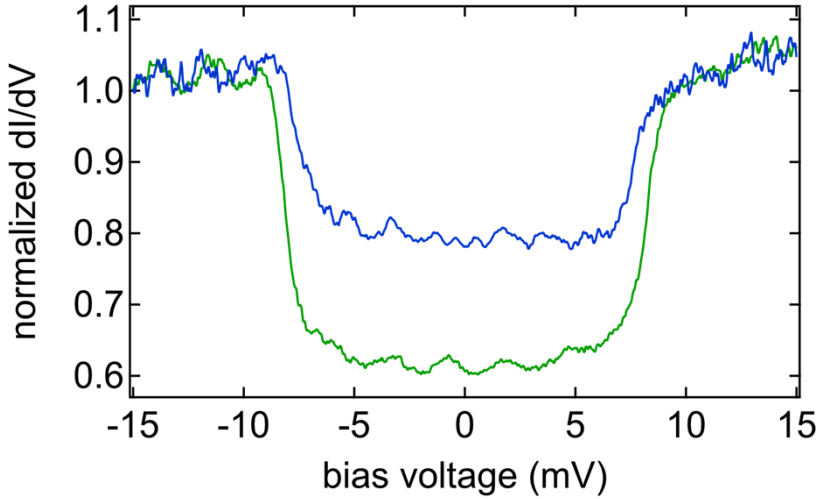
moiré maximum → moiré minimum



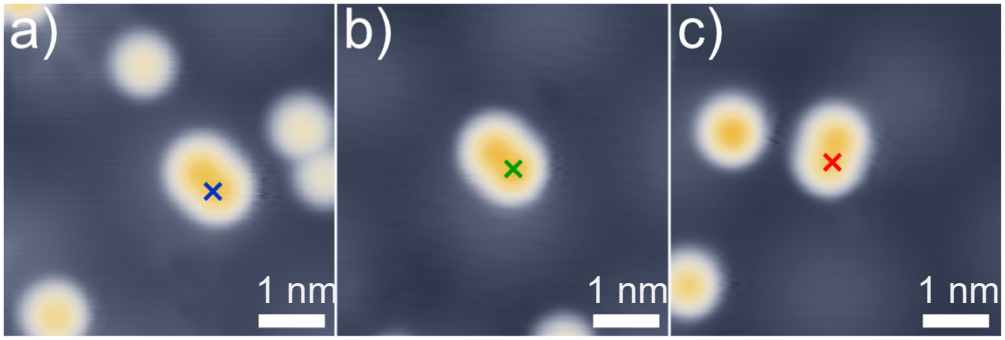
Moiré dependence of singlet-triplet excitation



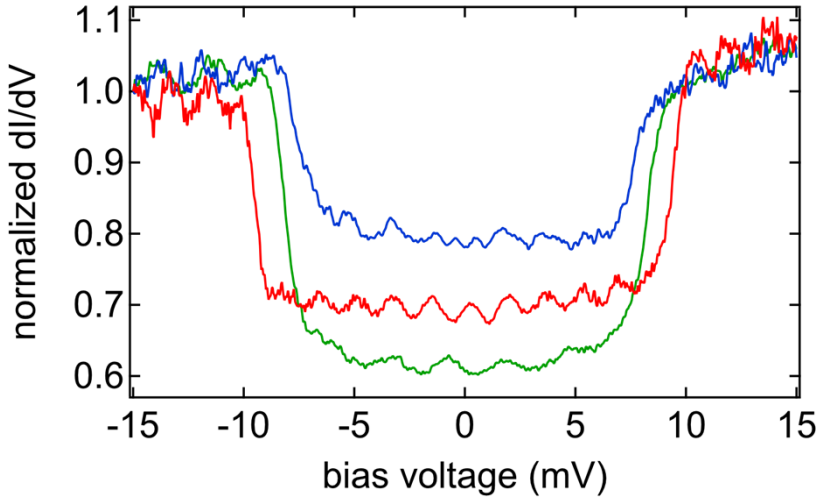
moiré maximum → moiré minimum



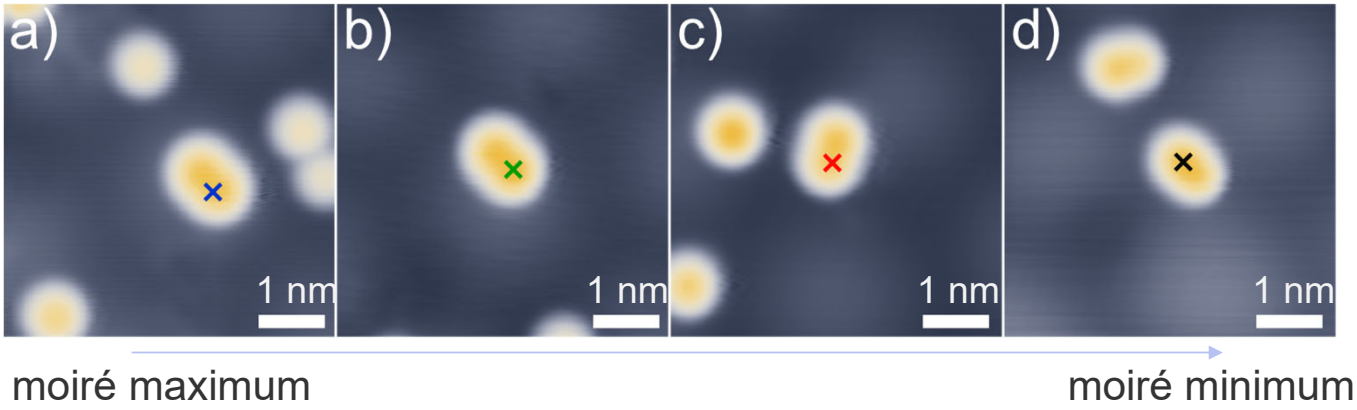
Moiré dependence of singlet-triplet excitation

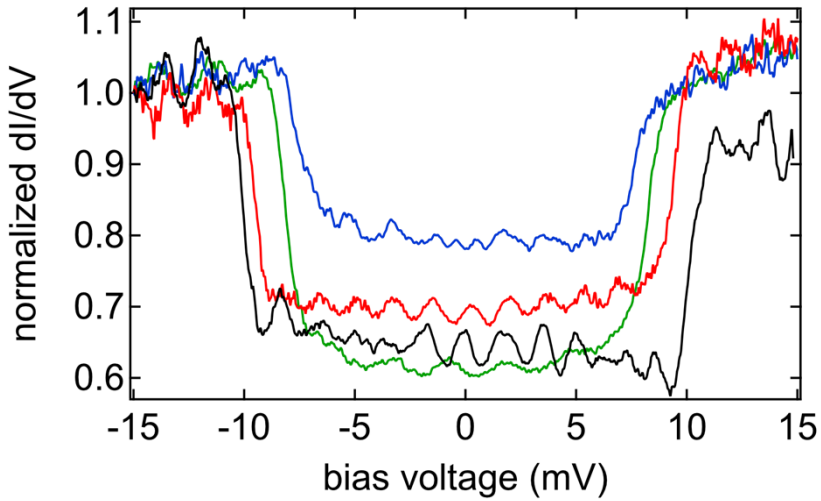


moiré maximum → moiré minimum



Moiré dependence of singlet-triplet excitation



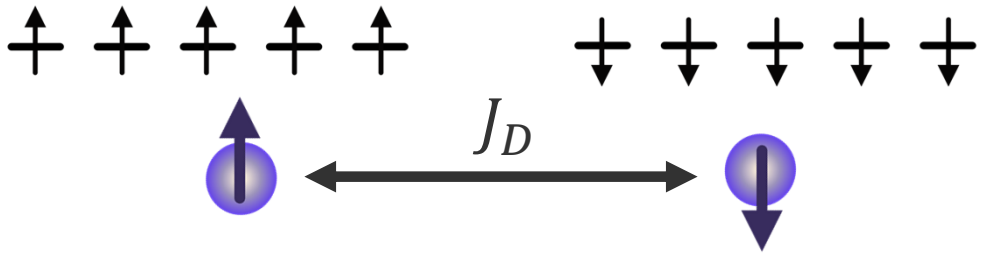


- Singlet-triplet excitation depends on moiré structure
- Excitation energy decreases with increasing exchange coupling to substrate

S. Trishin, C. Lotze, F. Lohss, G. Franceschi, L. I. Glazmann, F. von Oppen, KJF, Phys. Rev. Lett. 130, 176201 (2023)

Moiré dependence of singlet-triplet excitation

$$\Delta = E_{\mathrm{ex,t}} - E_{\mathrm{ex,s}} = J_D$$

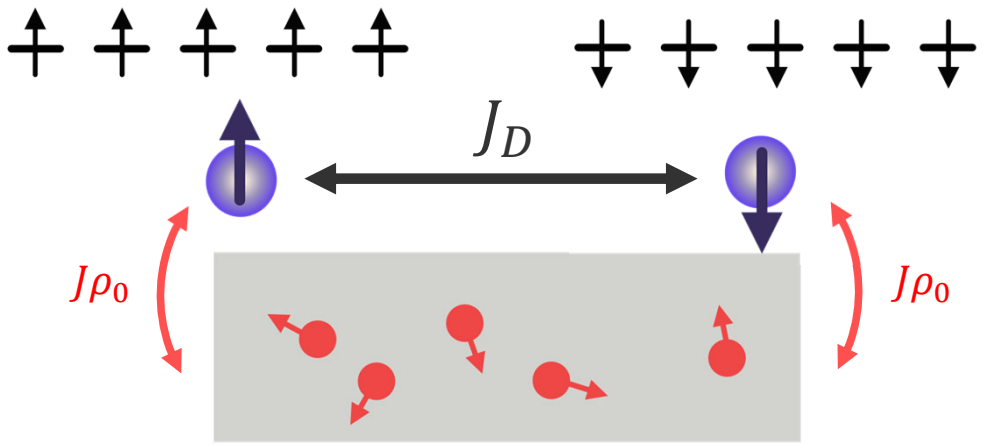


- Singlet-triplet excitation energy depends on exchange coupling to substrate

S. Trishin, C. Lotze, F. Lohss, G. Franceschi, L. I. Glazmann, F. von Oppen, KJF, Phys. Rev. Lett. 130, 176201 (2023)

Moiré dependence of singlet-triplet excitation

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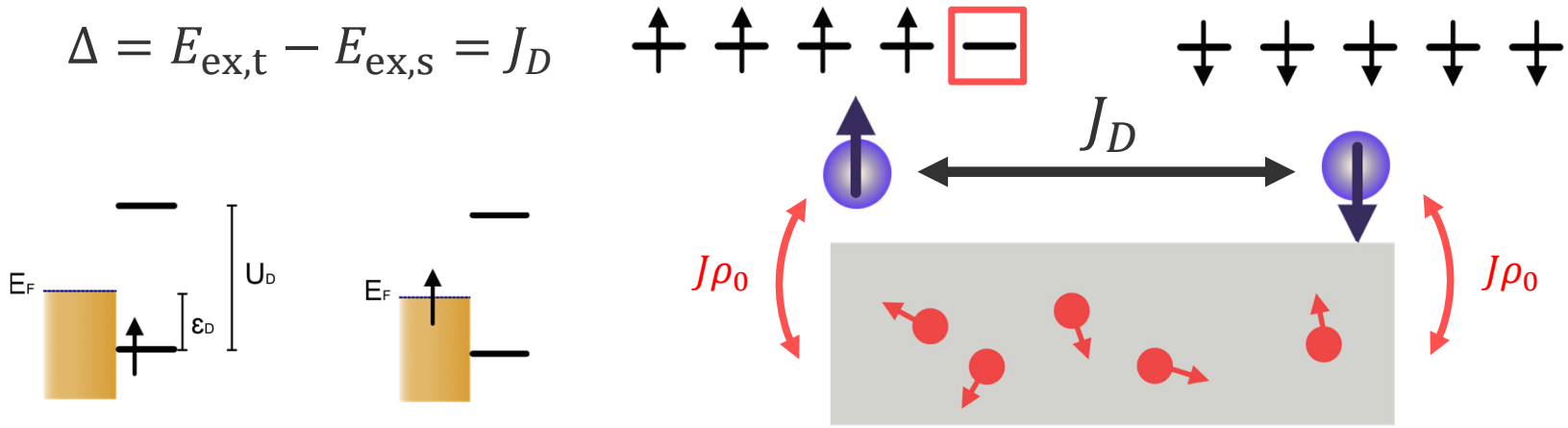


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S. Trishin, C. Lotze, F. Lohss, G. Franceschi, L. I. Glazmann, F. von Oppen, KJF, Phys. Rev. Lett. 130, 176201 (2023)

Moiré dependence of singlet-triplet excitation

$$\Delta = E_{\mathrm{ex,t}} - E_{\mathrm{ex,s}} = J_D$$



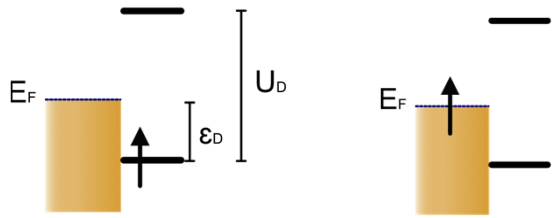
- Singlet-triplet excitation energy depends on exchange coupling to substrate
- Virtual excitation processes
- Effective reduction of adatom spin

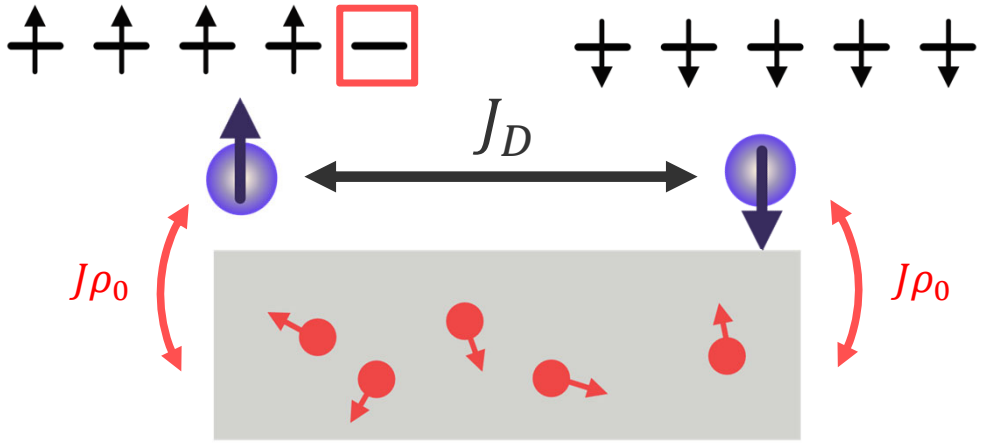
S. Trishin, C. Lotze, F. Lohss, G. Franceschi, L. I. Glazmann, F. von Oppen, KJF, Phys. Rev. Lett. 130, 176201 (2023)

Moiré dependence of singlet-triplet excitation

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$$\Delta = E_{\mathrm{ex,t}} - E_{\mathrm{ex,s}} = J_D$$



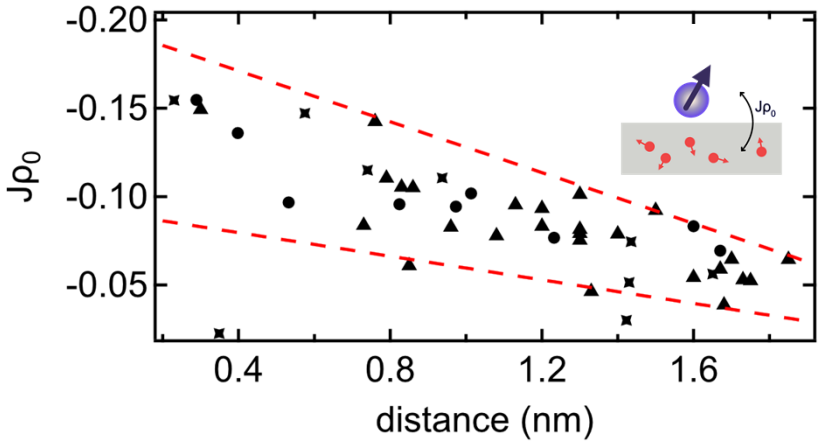


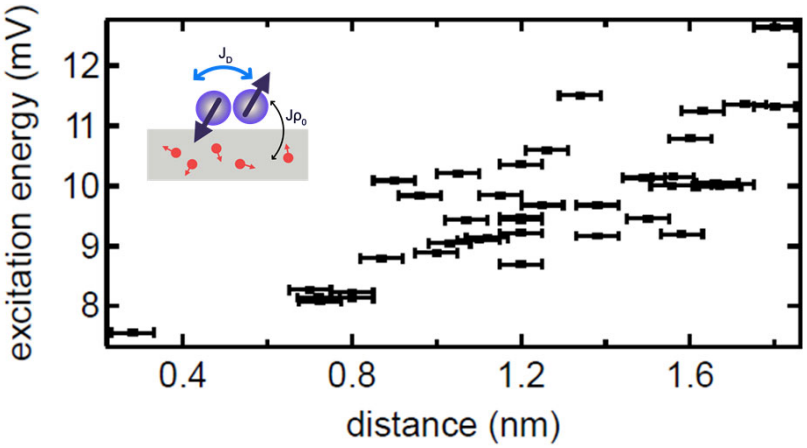
$$\Delta = J_D(1 - 2\rho_0 J)$$

- Singlet-triplet excitation energy depends on exchange coupling to substrate
- Virtual excitation processes
- Effective reduction of adatom spin

S. Trishin, C. Lotze, F. Lohss, G. Franceschi, L. I. Glazmann, F. von Oppen, KJF, Phys. Rev. Lett. 130, 176201 (2023)

Moiré dependence of singlet-triplet excitation





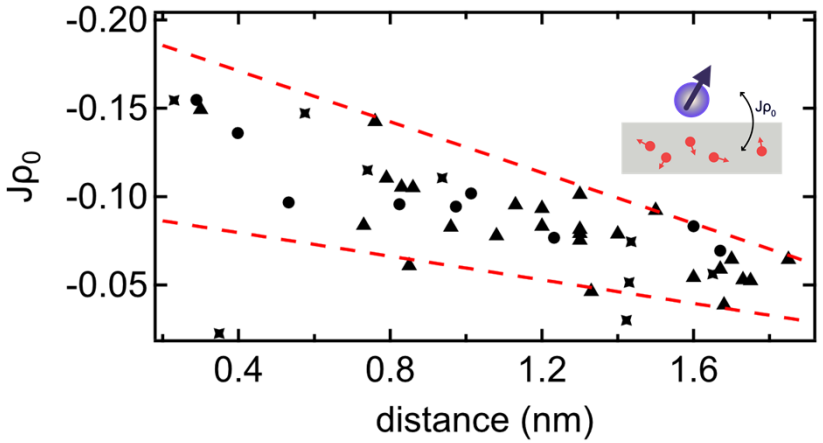
→ up to 10 % variation expected for one channel

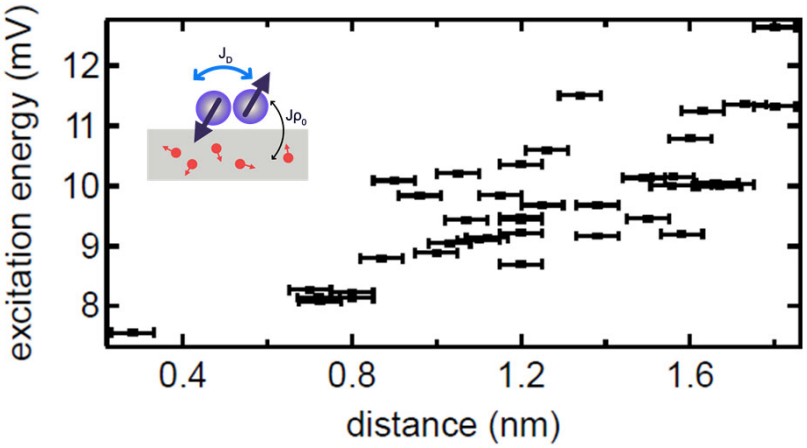
up to 40 % variation

$$\Delta = J_D(1 - 2\rho_0 J)$$

S. Trishin, C. Lotze, F. Lohss, G. Franceschi, L. I. Glazmann, F. von Oppen, KJF, Phys. Rev. Lett. 130, 176201 (2023)

Moiré dependence of singlet-triplet excitation

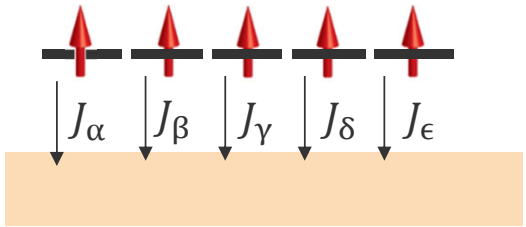




→ up to 10 % variation expected for one channel

up to 40 % variation

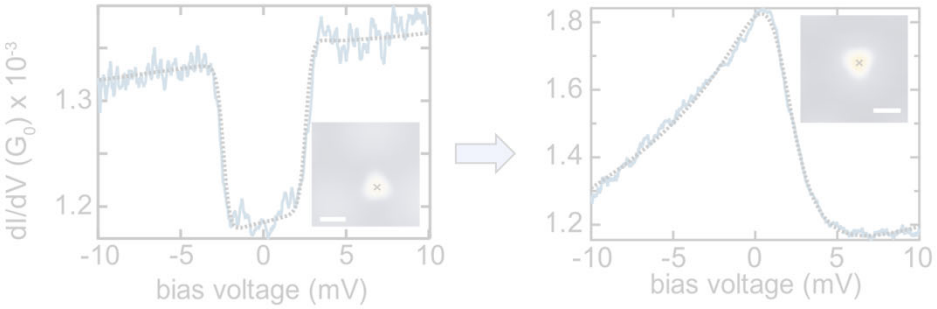
$$\Delta = J_D(1 - 2\sum_m \rho_0 J_m)$$



- Several spin channels involved

S. Trishin, C. Lotze, F. Lohss, G. Franceschi, L. I. Glazmann, F. von Oppen, KJF, Phys. Rev. Lett. 130, 176201 (2023)

Exchange-coupled nanostructures on surfaces



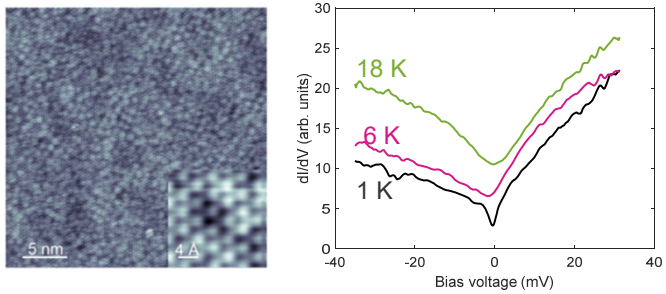
Fe atoms on MoS_2/Au(111)

- Spin excitations of single atoms
- Exchange coupling to substrate



Mn dimers on MoS_2/Au(111)

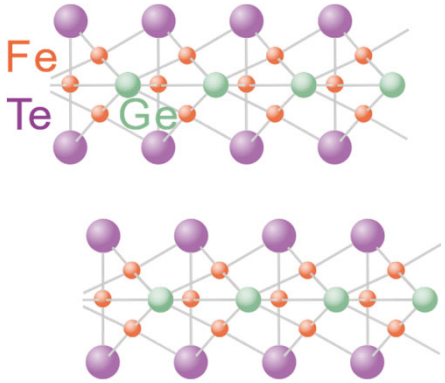
- Coupling of magnetic atoms
- Exchange coupling of dimers to substrate

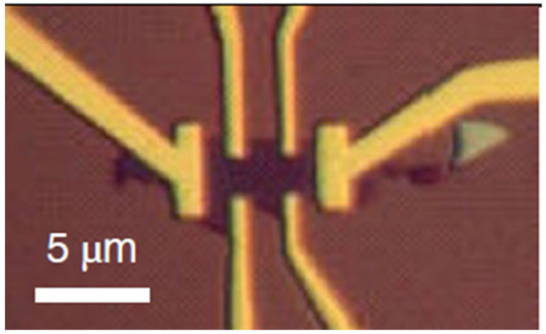


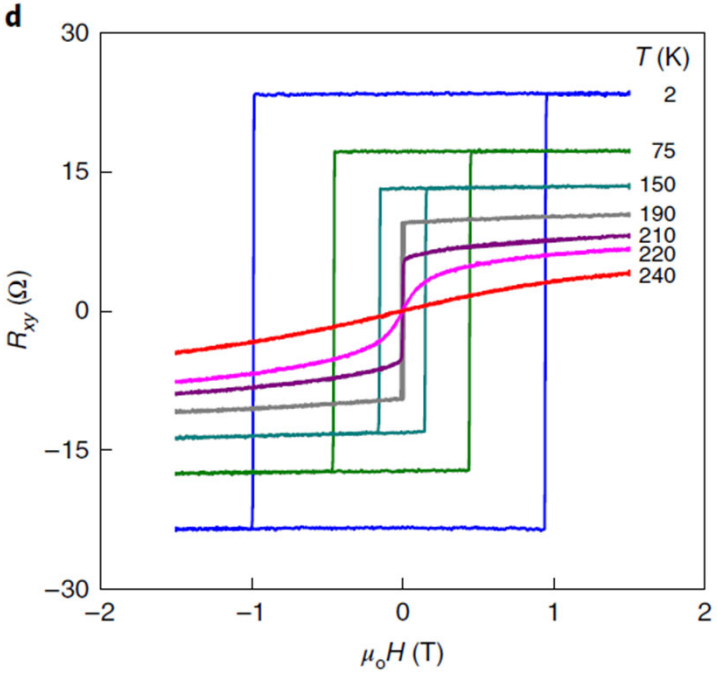
Fe_3GeTe_2:

- Kondo resonances on Fe_3GeTe_2
- Interaction with magnetic adatoms

A magnetic 2D material: Fe_3GeTe_2





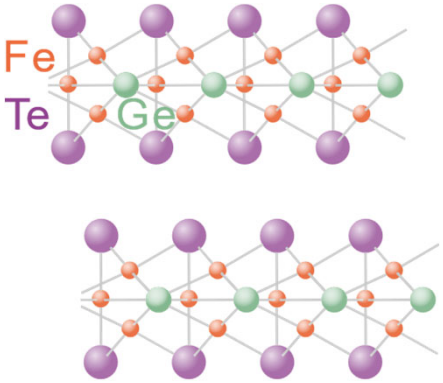


Fei *et al,* Nature Materials **17**, 778 (2018)

- 2D ferromagnet with T_c= 210 K
- Controversies about nature of FM: local vs. itinerant magnetism
  - Possible origin of both observations: two different types of Fe atoms

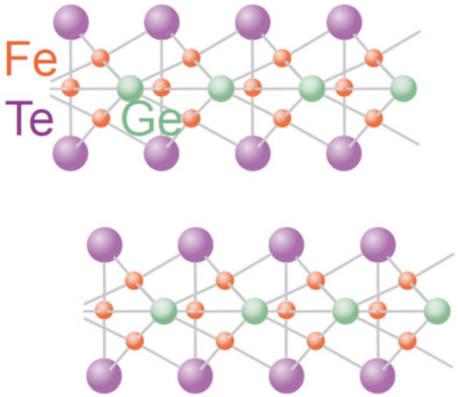
Different fingerprints of magnetism in Fe_3GeTe_2

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- Itinerant FM
  Xu *et al.,* PRB **101**, 201104 (2020)
- Interplay between local moments and itinerant electrons
  Bao *et al.,* PRX **12**, 011022 (2022)
- Kondo lattice
  Zhang *et al.*, Sci. Adv. (2018)
  Zhao *et al.,* Nano Lett., **21**, 6117 (2021)
- Anderson localization and multifractality
  Mathimalar *et al.,* arXiv:2503.04367
- Spin Glass
  Pal *et al.,* Science 392, 624 (2026)
- Magnons
  Li *et al.,* Nature Commun. 17 , 5461 (2026)

Fe_3GeTe_2: structure

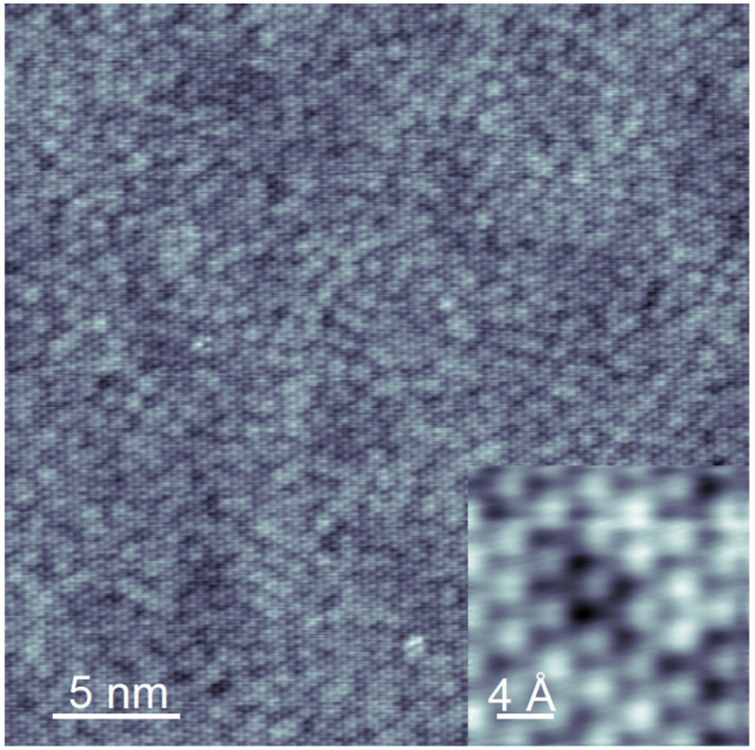


Fei et al., *Nature Materials* **17**, 778 (2018)

- Cleaved in UHV
- Atomically clean
- Electronic modulation of surface
- Most likely Fe II vacancies



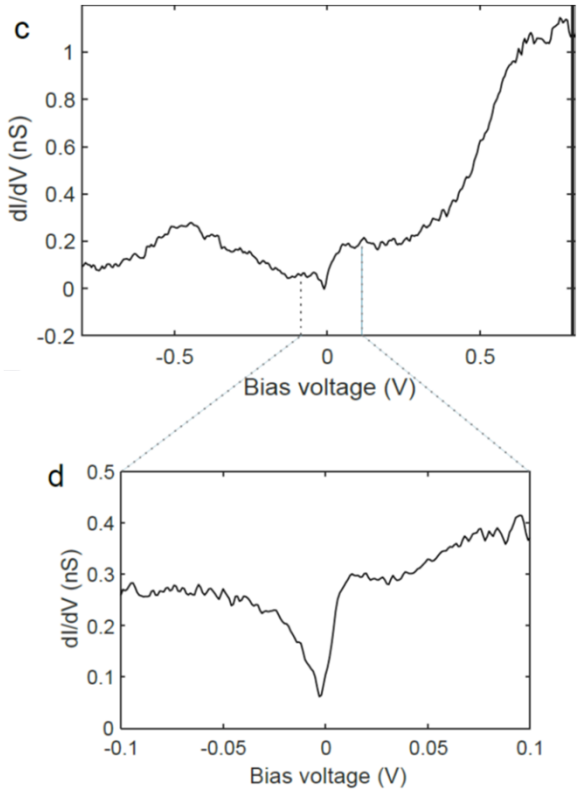
Carmen Rubio Verdu

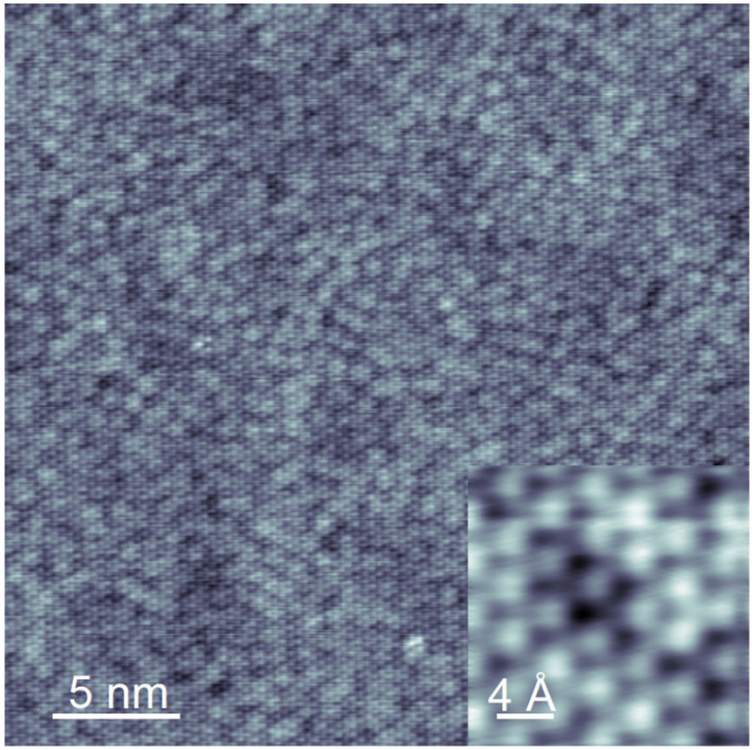


Fe_3GeTe_2: electronic properties

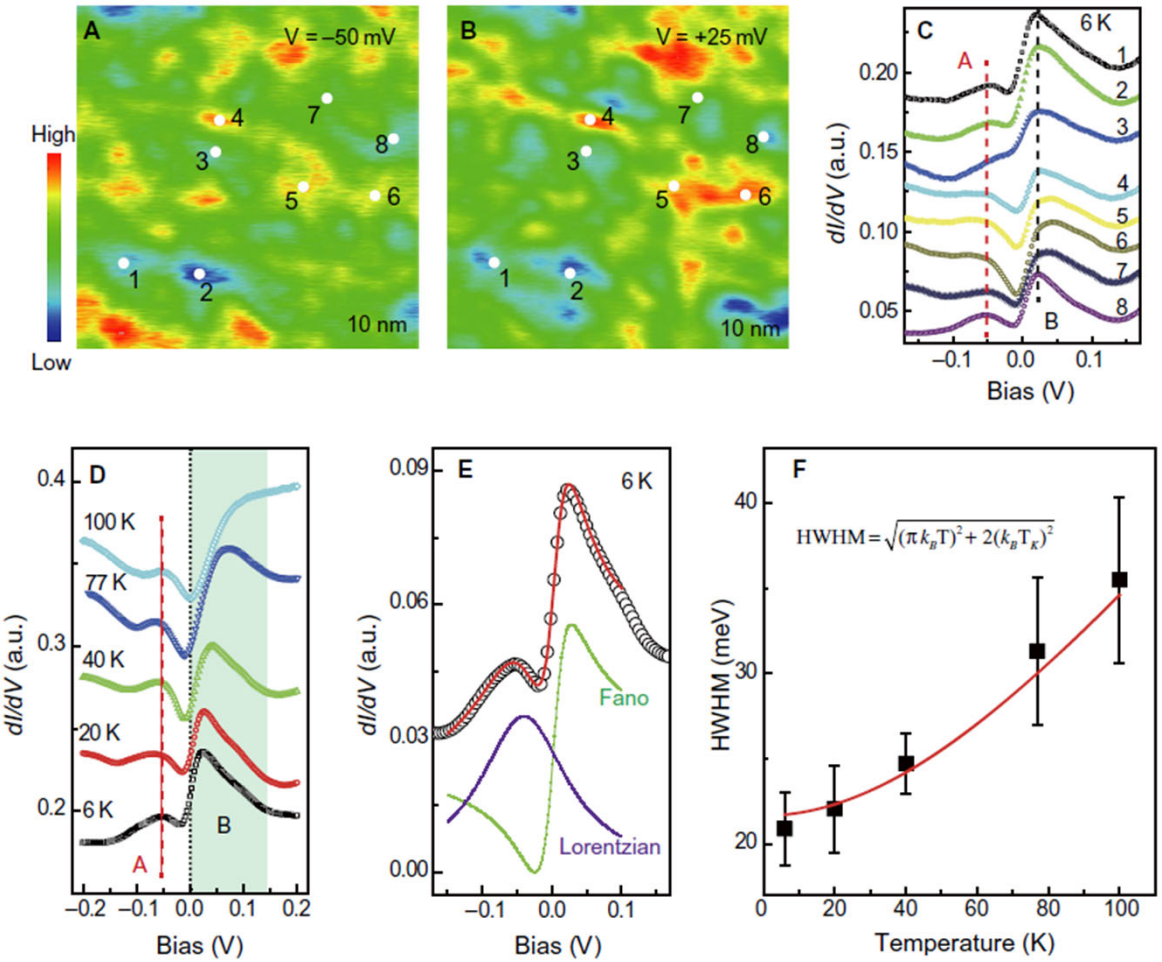
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- Dip at Fermi level





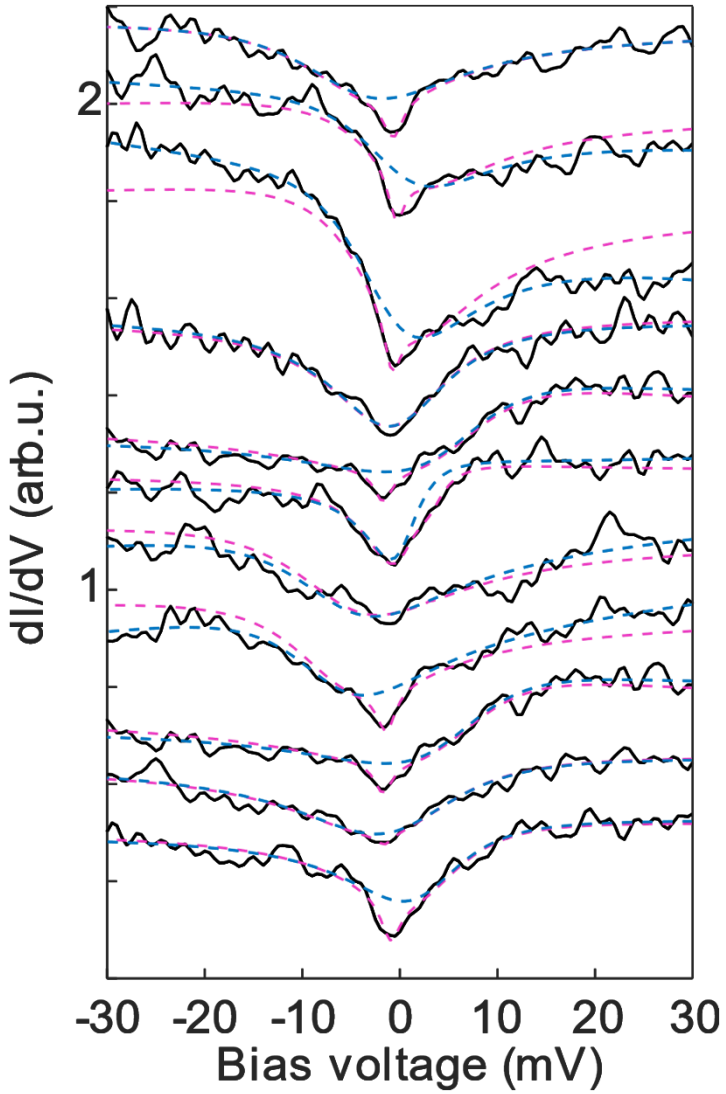
Previous observation of Kondo resonance



- Variation of lineshape along surface
- Temperature broadening in agreement with Kondo effect
- Interpretation as Kondo lattice from complementary transport and ARPES measurements

Zhang et al., *Sci. Adv.* (2018)

Lineshape analysis



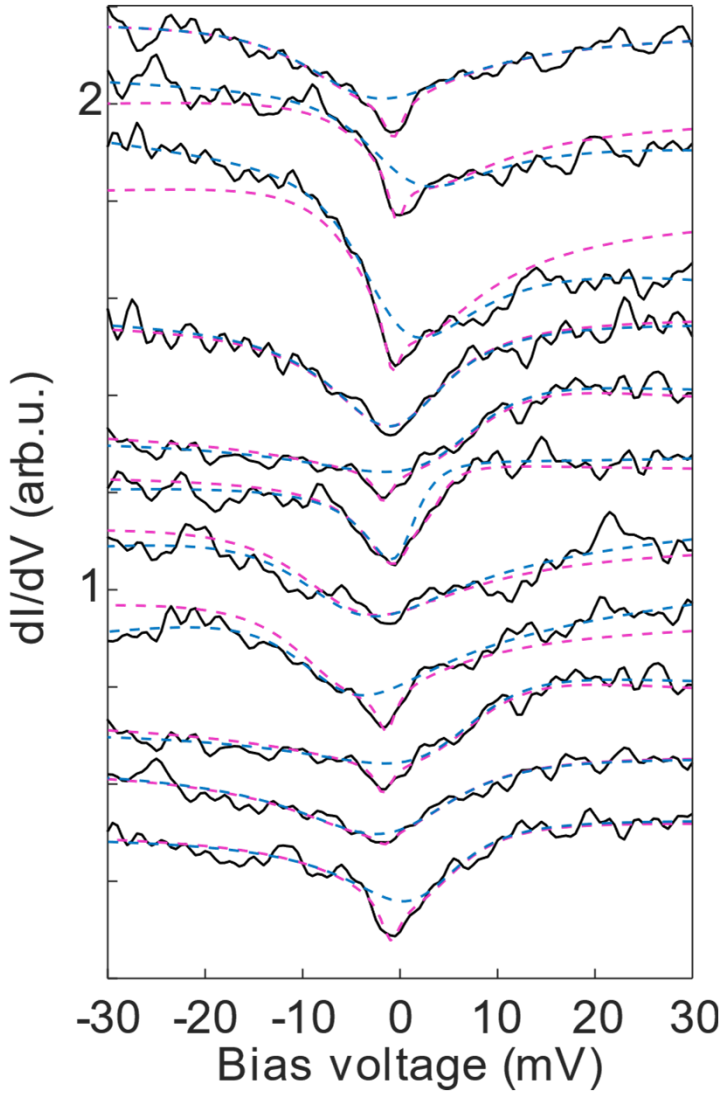
Fano lineshape

$$\sigma = A \cdot \frac{(\epsilon + q)2}{(1 + \epsilon^2)}$$

$\epsilon = (eV - ER)/(\Gamma_R/2)$

Fano + gap

Lineshape analysis



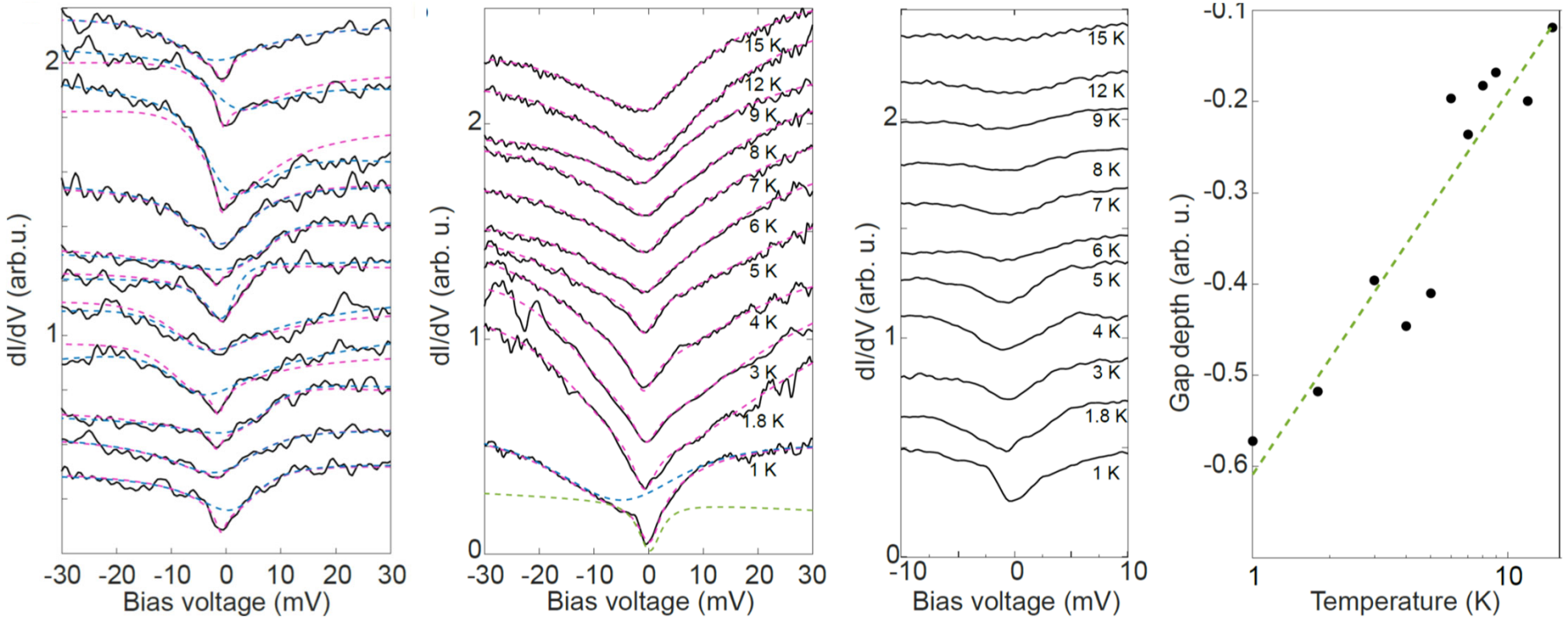
Fano lineshape

$$\sigma = A \cdot \frac{(\epsilon + q)2}{(1 + \epsilon^2)}$$

$\epsilon = (eV - ER)/(\Gamma_R/2)$

Fano + gap

Kondo lineshape

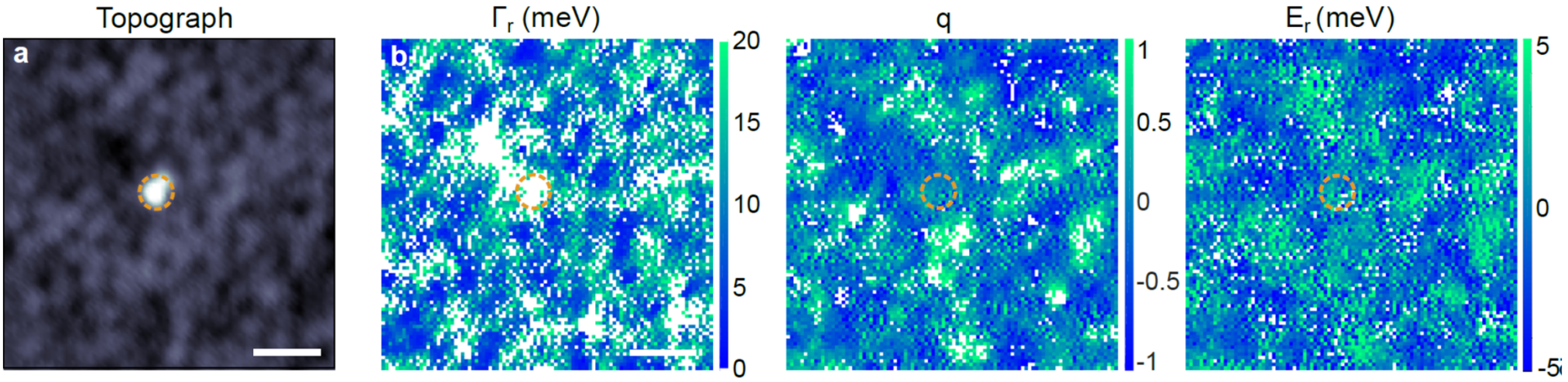


- Fano lineshape plus gap
- Fast closing of small gap

Signature of Kondo lattice

C. Rubio Verdu, KJF, Phys. Rev. B 113, 235410 (2026)

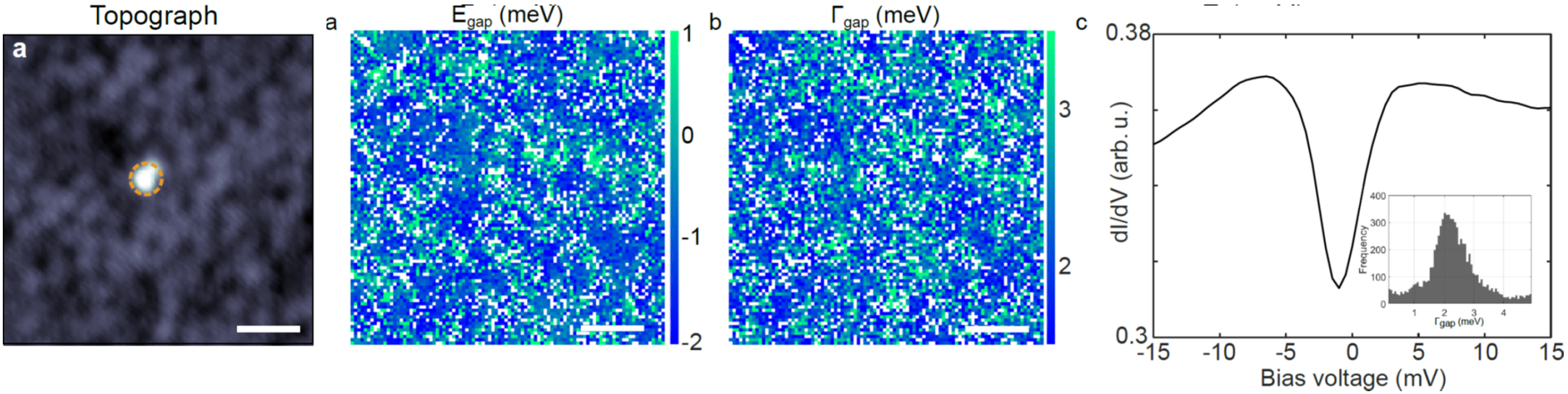
Influence of Fe adatoms on Kondo lineshape



- Some variations of Kondo parameters along surface
- Fe atom does not affect Kondo parameters significantly

C. Rubio Verdu, KJF, Phys. Rev. B 113, 235410 (2026)

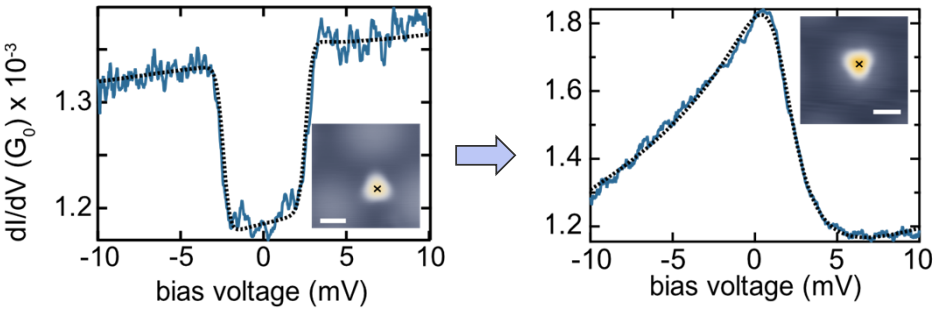
Influence of Fe adatom on hybridization gap



- Some variations of Kondo parameters along surface
- Fe atom does not affect hybridization gap
- Weak coupling of Fe atom to substrate

C. Rubio Verdu, KJF, Phys. Rev. B 113, 235410 (2026)

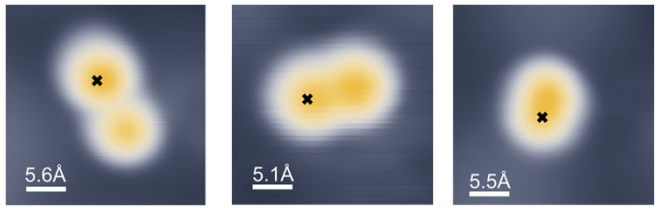
Conclusions



Moiré structure of MoS_2 on Au(111):

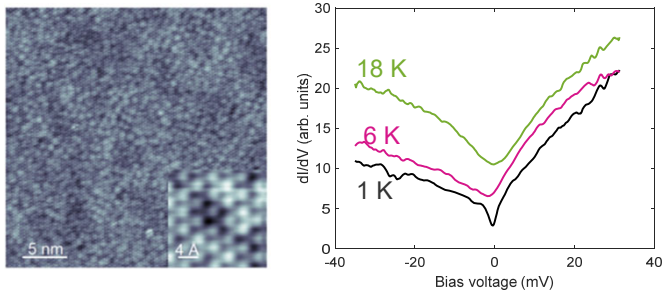
- Strong variation of exhcange coupling of adatoms to surface due to moiré structure

S. Trishin, et al., Phys. Rev. Lett. 127, 236801 (2021)



- Coupling of magnetic atoms depending on distance
- Singlet - triplet excitations renormalized by exchange coupling to substrate

S. Trishin, et al, Phys. Rev. Lett. 130, 176201 (2023)



- Kondo resonance along Fe_3GeTe_2
- Hybridization gap indicating a Kondo lattice
- No perturbation by magnetic adatoms

C. Rubio Verdu, KJF, Phys. Rev. B 113, 235410 (2026)

Thank you!

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Now at UC Berkeley



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