Real space imaging of the superconducting vortex lattice: Recent results and prospects

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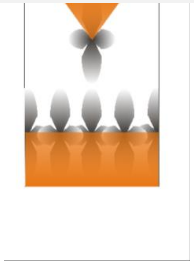
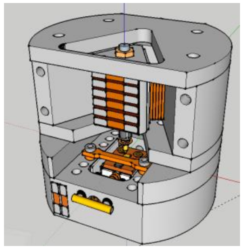
Center for Condensed Matter Physics (IFIMAC)

Universidad Autónoma de Madrid (UAM)

Real space imaging of the superconducting vortex lattice: Recent results and prospects

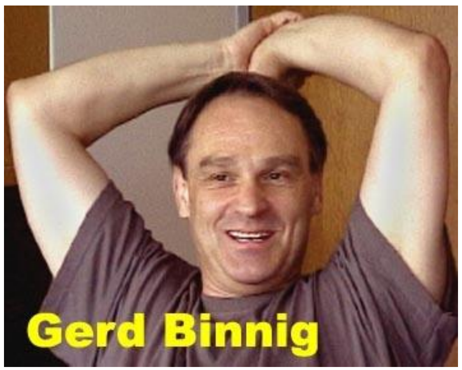


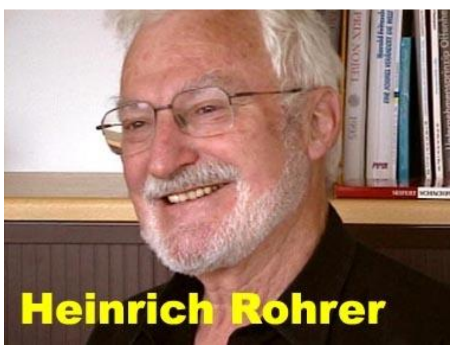
- Real space imaging and spectroscopy of the vortex lattice
- Superconducting CaKFe4As4, bandstructure, vortex core, vortex lattice and pinning
- Vortex lattice structure: interactions vs disorder
- Observation of vortex creep on cooling
- Josephson effect at atomic scale

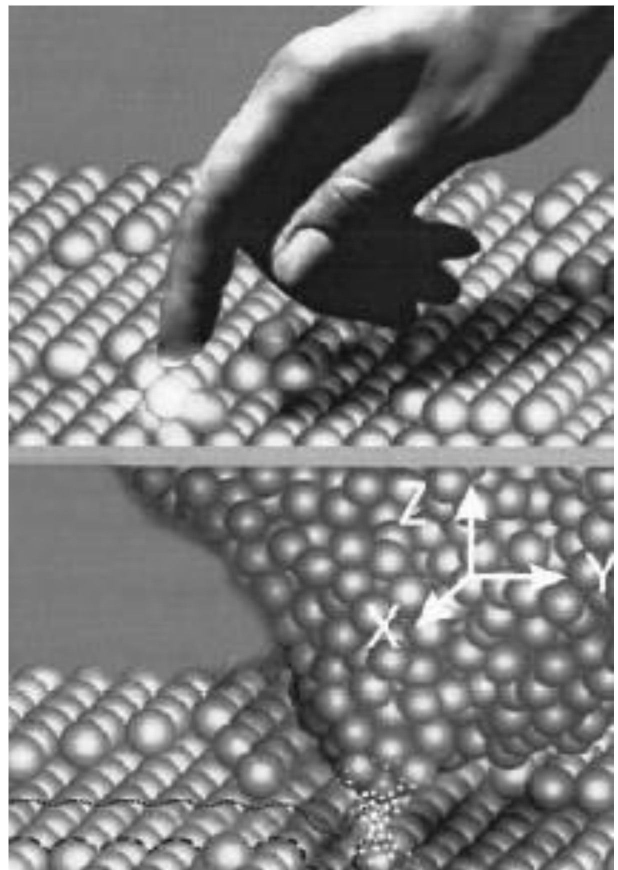


The birth of scanning probe microscopy

The invention of the scanning tunneling microscope
Gerd Binnig and Heini Rohrer, Zurich, 1982







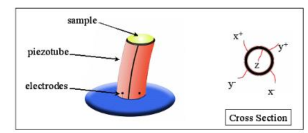


Figure 2.5. A piezotube scheme. The cross section drawing shows the inner electrode (Z) and the four outer electrodes (+X, -X, +Y, -Y).

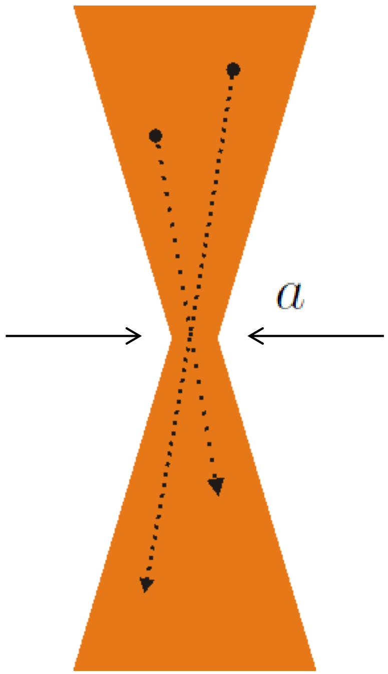
$$\Delta x, y \approx 20\,\frac{A}{V}$$

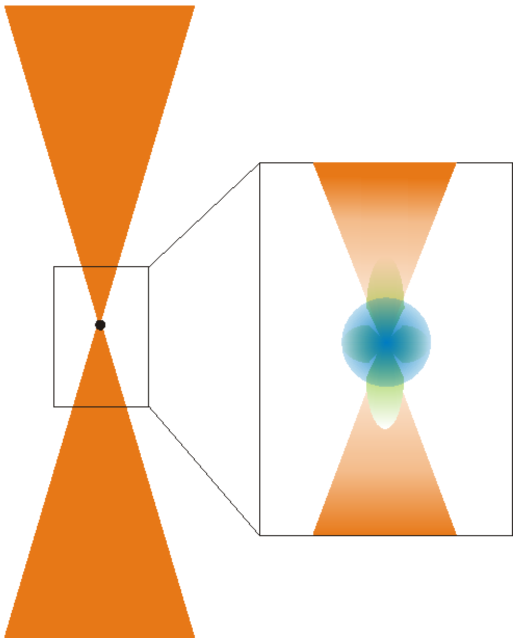
1Å ~ 250 mV

Tunneling
Piezoelectrics

Tunneling

Conduction through constrictions





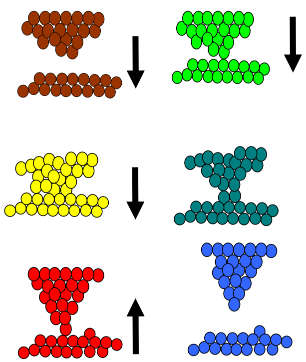
$$G = \frac{2e^2}{h}\left(\frac{k_F a}{2}\right)^2$$

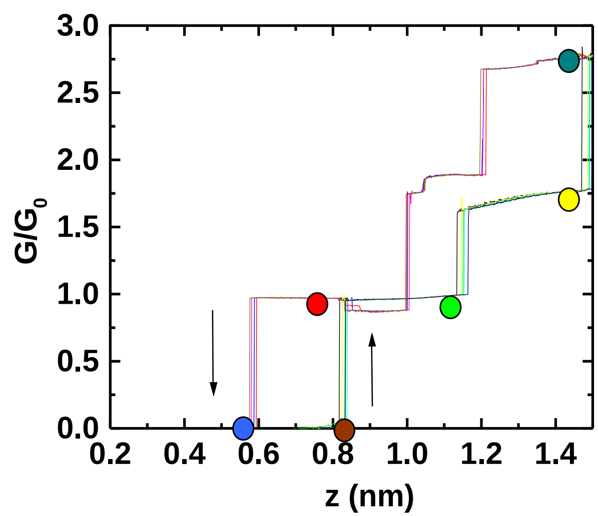
$$G = \frac{2e^2}{h}\sum_i T_i$$

Imaging superconducting vortex cores and lattices with a STM
H. Suderow, I. Guillamón, J.G. Rodrigo and S. Vieira
Superc. Sci. Techn., 27, 063001 (2014)

Tunneling

Conduction through constrictions





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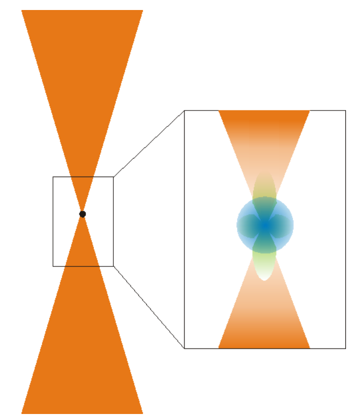
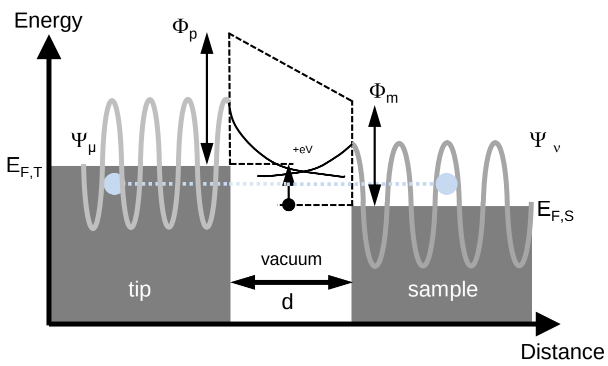


Imaging superconducting vortex cores and lattices with a STM
H. Suderow, I. Guillamón, J.G. Rodrigo and S. Vieira
Superc. Sci. Techn., 27, 063001 (2014)

Tunneling

The tunneling current: Bardeen's formalism



$$I = \frac{2\pi e}{\hbar} \sum_{\mu\nu} f(E_\mu)\left(1 - f(E_\nu + eV)\right) \left|M_{\mu\nu}\right|^2 \delta(E_\mu - E_\nu)$$

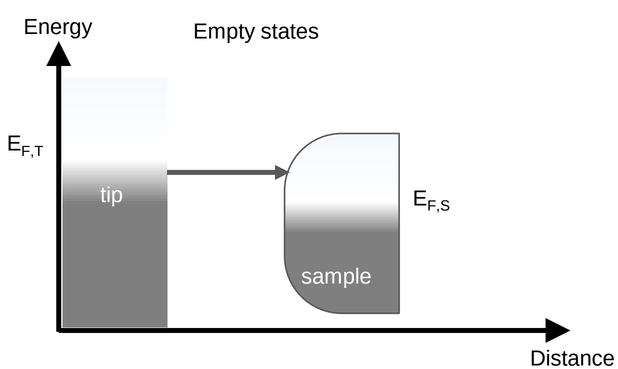
$$f(E) = \frac{1}{1 + e^{\frac{(E - E_F)}{k_B T}}}$$

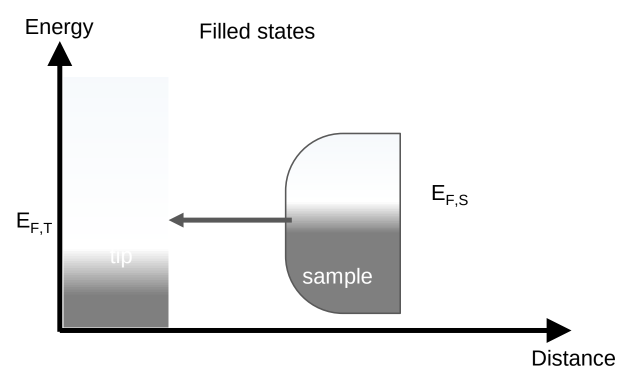
$$E_\mu ; \psi_\mu$$

$$E_\nu ; \psi_\nu$$

$$M_{\mu\nu} = \frac{\hbar^2}{2m} \int dS \left(\psi_\mu^* \nabla \psi_\nu - \psi_\nu \nabla \psi_\mu^*\right)$$

Tunnelling from a Many-Particle Point of View
J. Bardeen
PRL, 6, 57 (1961)



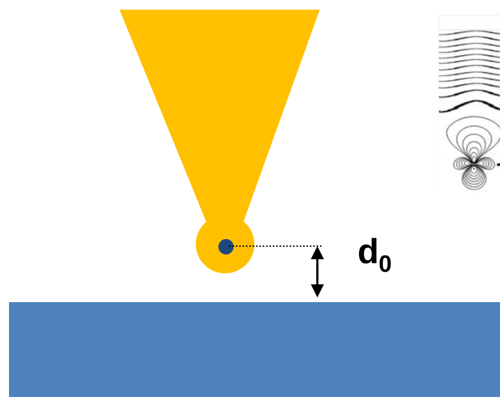


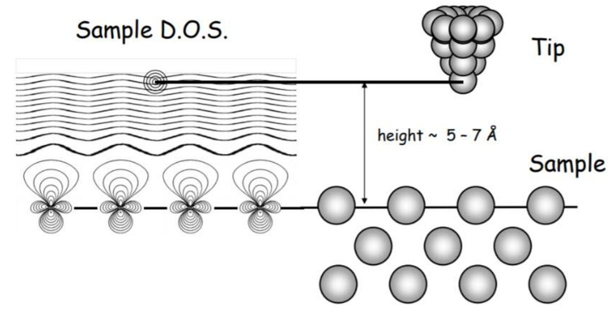
Tunneling

The tunneling current: Tersoff-Haman

Theory and Application for the Scanning Tunneling Microscope
J. Tersoff and D. R. Hamann
PRL, 50, 1998 (1983)

Ideal tip, low bias voltage (V=0) :





Rubén Pérez UAM

$$I \propto \sum_{\nu} \left|\psi_{\nu}(\mathbf{d_0})\right|^2 \delta(E_{\nu} - E_F) = \rho(\mathbf{d_0}, E_F)$$

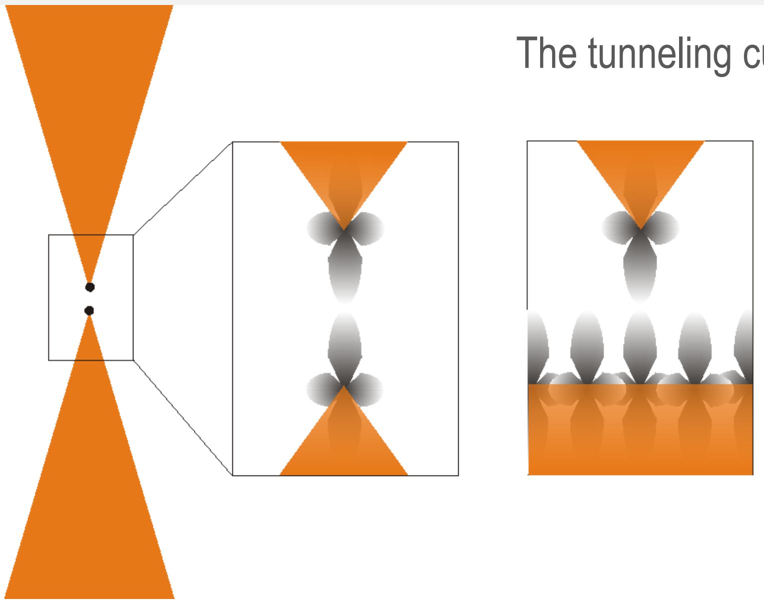
STM: Contour map of the local DOS

$$I(\mathrm{r}_0, V) \propto \int_{E_F}^{E_F + eV} dE\, \rho_S(\mathbf{d}_0, E) T(\mathbf{d}_0, E, eV)$$

Tunneling

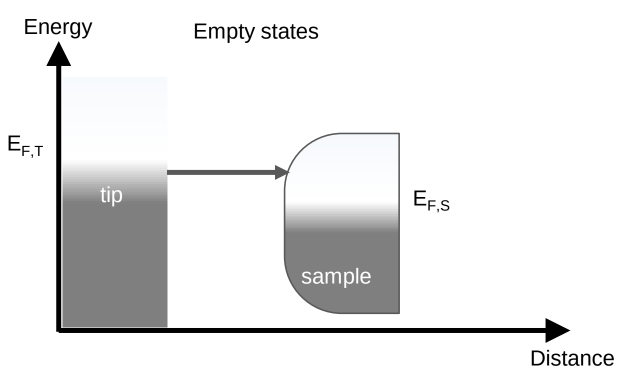
The tunneling current: Chen

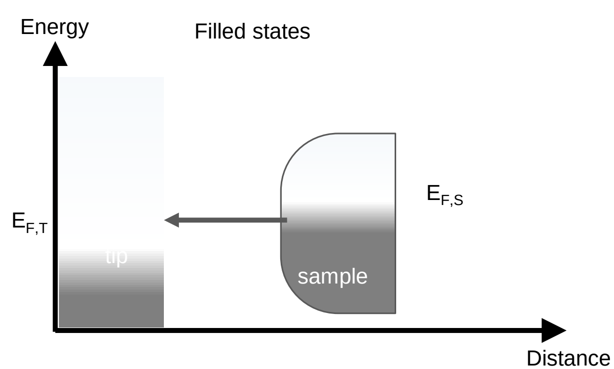
Directional tunneling



- Microscopic (C_p, κ, ρ, ...)
- Empty + filled states (ARPES, dHvA)
- Bandstructure (ARPES)
- Real space (neutrons, x-ray)

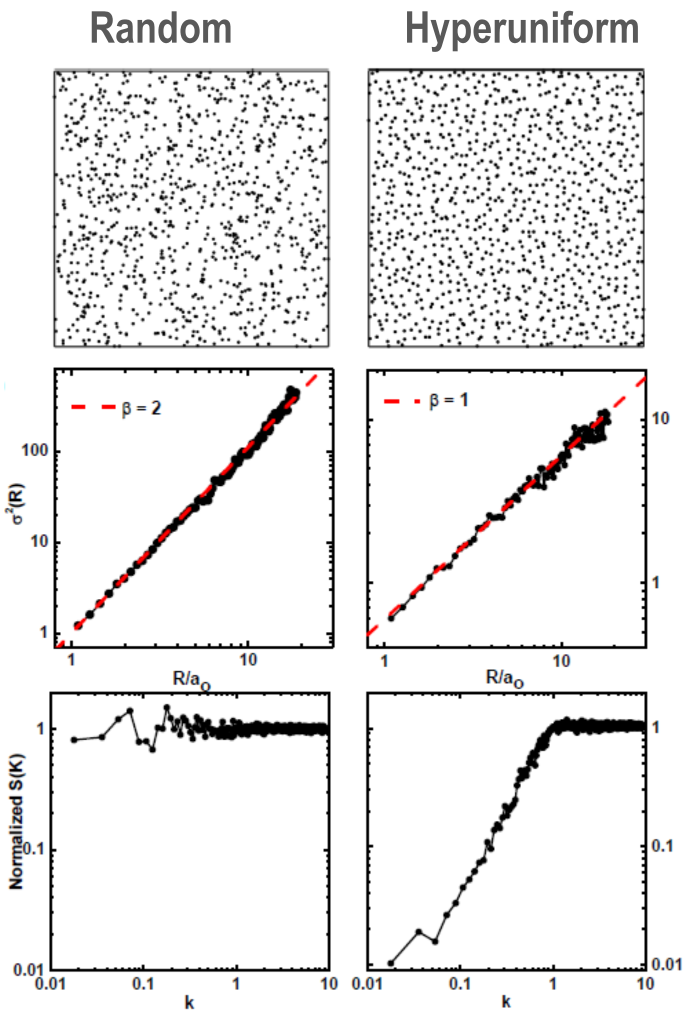
$$I(\mathrm{r}_0, V) \propto \int_{E_F}^{E_F+eV} dE\, \rho_S(\mathbf{d}_0, E)\, T(\mathbf{d}_0, E, eV)$$





Imaging

Working in real space



Vortex lattice ?

Tunneling

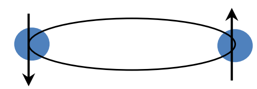
Superconductor

Microscopic theory
J. Bardeen, L. Cooper, J. Schrieffer (BCS, 1957)

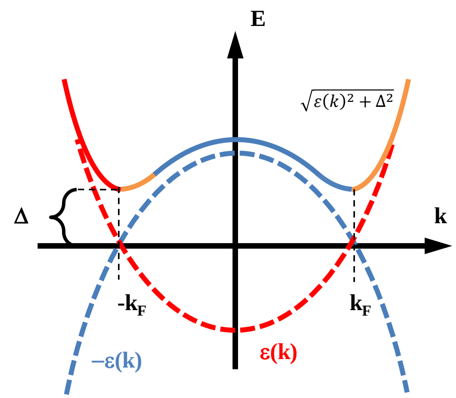
$$\psi = |\psi| e^{i\varphi}$$

Cooper pairs

S=0
L=0

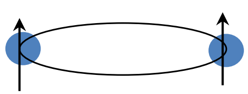


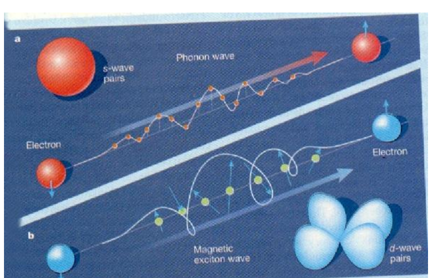
$$\Delta_k = -\sum_{k'} V_{kk'} \frac{\Delta_{k'}}{2E_{k'}}$$



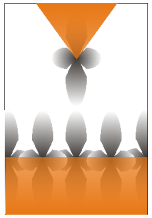
Kohn, Luttinger (1965)

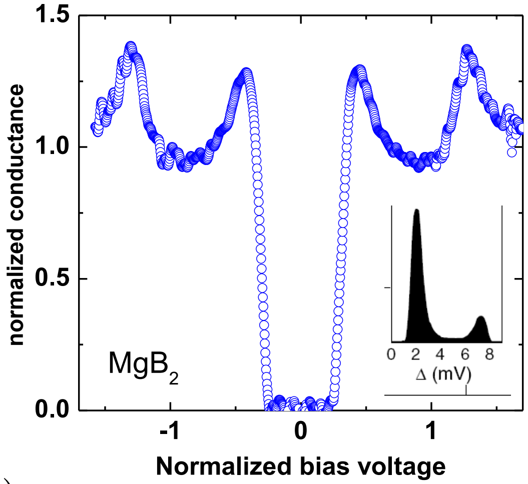
S=1
L=1





STM Tunneling





Bardeen's formalism $I \propto \sum_{\nu} |\psi_{\nu}(\mathrm{d}_0)|^2 \delta(E_{\nu} - E_F) = N(\mathrm{d}_0, E_F)$

The local density of states $\frac{dI}{dV} \propto \int N(E) \frac{\partial f(E-eV)}{\partial V} dE$

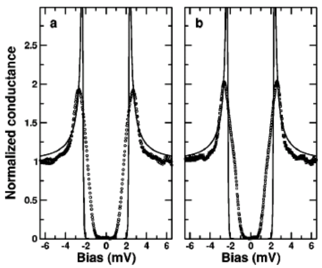
$$N_S(E) = \sum_i \gamma_i \frac{E}{\sqrt{E^2 - \Delta_i(k)^2}}$$

P. Martínez-Samper et al. Physica C 2003

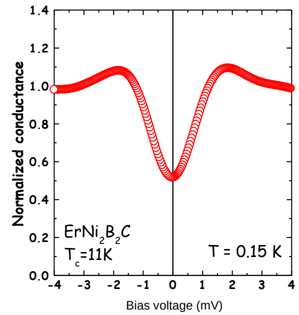
The superconducting gap through scanning tunneling spectroscopy at very low temperatures

$$\frac{dI}{dV} \propto \int N(E)\frac{\partial f(E-eV)}{\partial V}dE$$

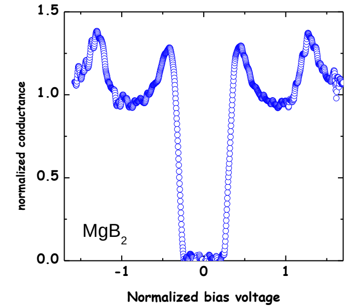
YNi_2B_2C



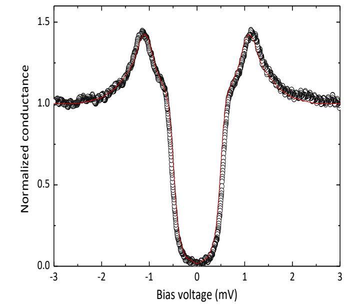
$ErNi_2B_2C$

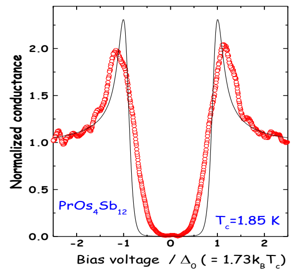


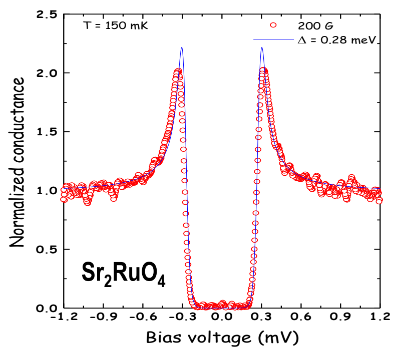
MgB_2



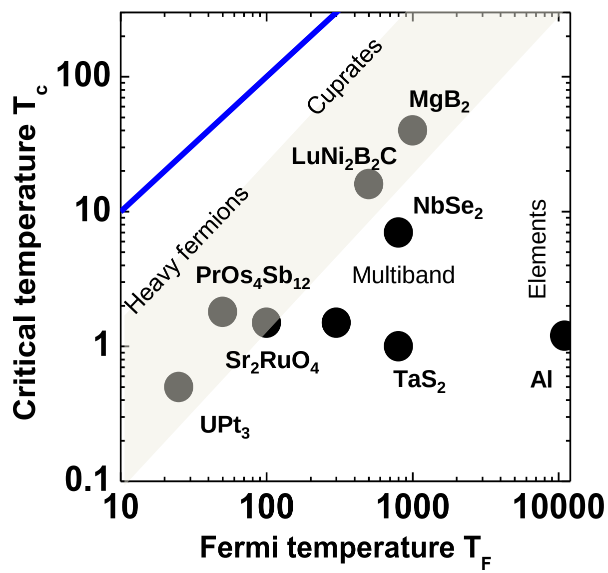
NbS_2



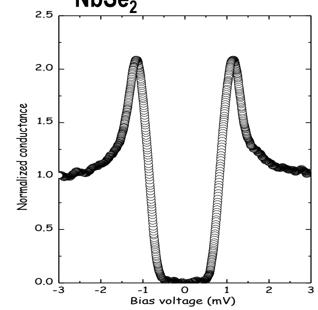




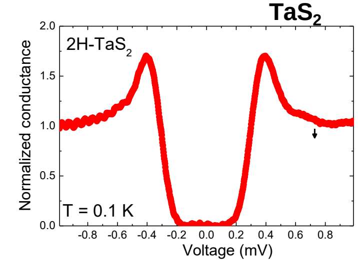
Uemura plot



$NbSe_2$



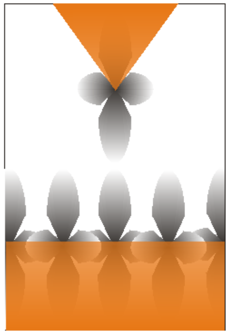
TaS_2



Madrid

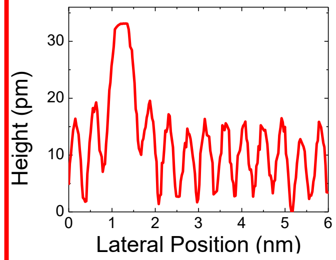
Can we find atomic resolution in a metal ?

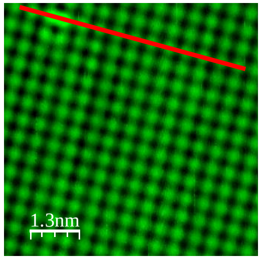
STM



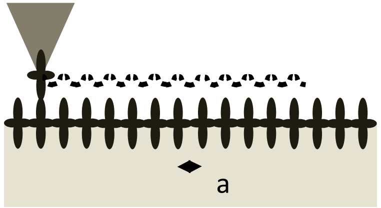
$$I \propto \sum_{\nu} |\psi_{\nu}(d_0)|^2 \delta(E_{\nu} - E_F) = N(d_0, E_F)$$

Atomic resolution





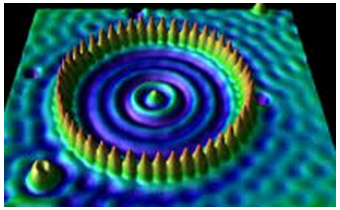
Here: URu_2Si_2 at 150 mK

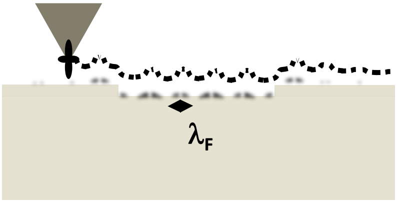


Quasiparticle interference

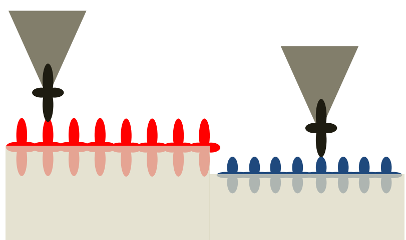
Electronic standing waves

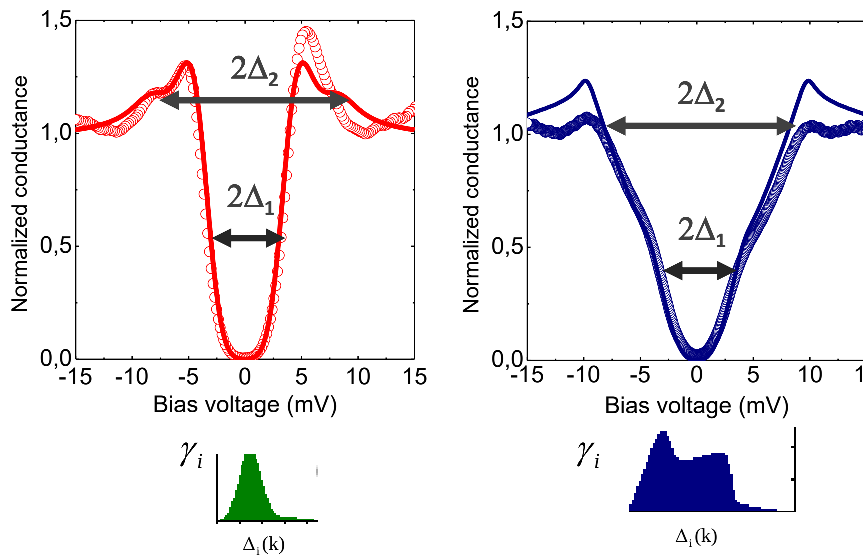
$$\rho(r) = \frac{cos(2k_F r)}{r^3}$$





Atomic resolution



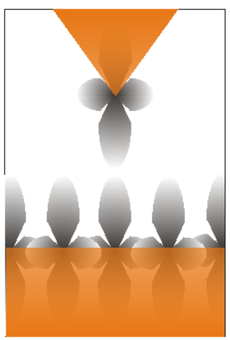


$$N_S(E) = \sum_i \gamma_i \frac{E}{\sqrt{E^2 - \Delta_i(k)^2}}$$

K. Cho et al Phys Rev B, 95, 100502(R) (2017)

Can we find atomic resolution in a metal ?

STM



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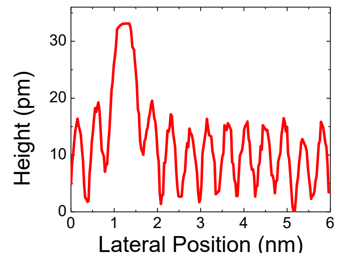
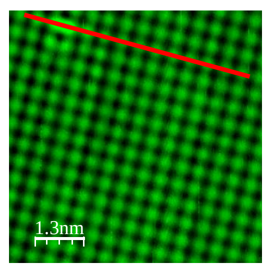
Atomic resolution





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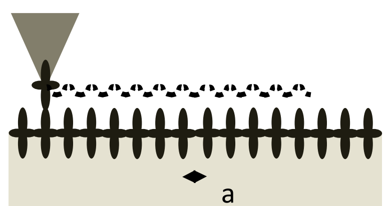

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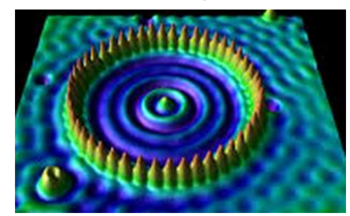
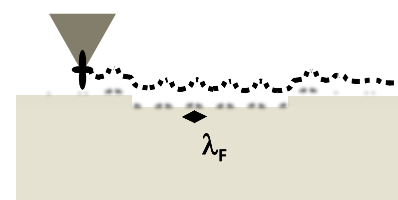
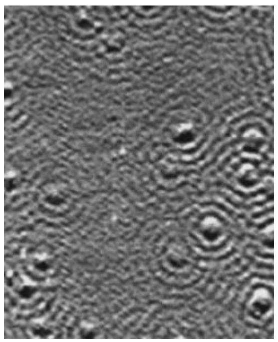




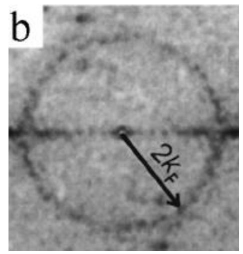
QPI

Quasiparticle interference
Bandstructure of empty and filled states

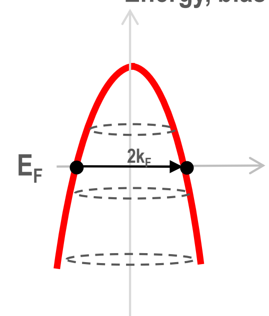
Real space conductance map



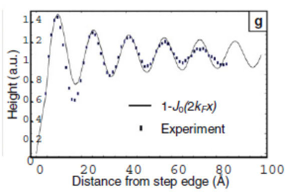
Fourier transform



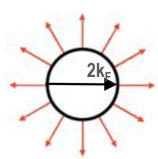
Energy, bias voltage



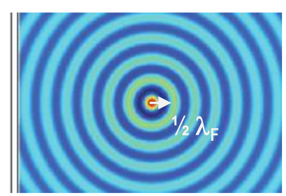
Wavevector



Fermi surface

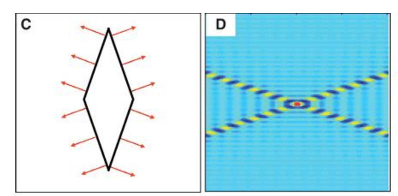


Real space DOS



Fermi surface

Real space DOS



Direct imaging of the two-dimensional Fermi contour: Fourier-transform STM
L. Petersen et al.
Phys. Rev. B, R6858, 57 (1998)
A phenomenological approach of joint density of states for the determination of bandstructure in the case of a semi-metal studied by FT-STS
L. Simon, F. Vonau and D. Aubel
J. Phys. Cond. Matt. 19 (2007) 355009

QPI

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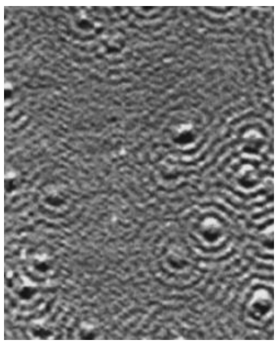
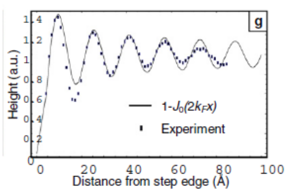
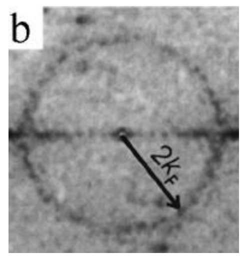
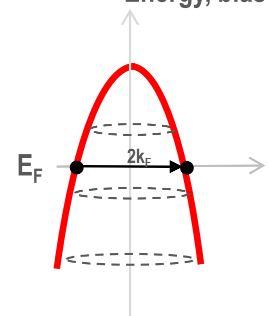




Fourier transform

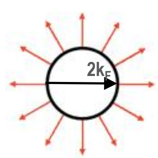


Energy, bias voltage

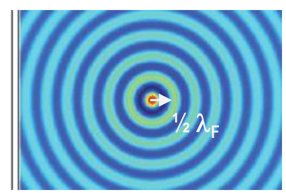


Wavevector

Fermi surface

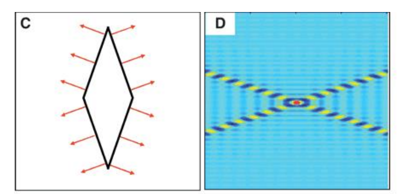


Real space DOS



Fermi surface

Real space DOS



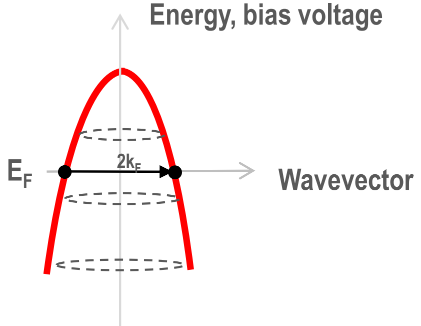
$$g(E,\vec{q}) \propto |V_s(\vec{q})|^2 J(E,\vec{q})$$

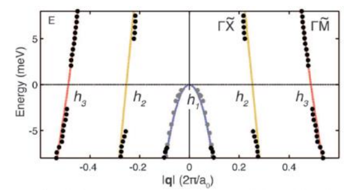
$$J(E,\vec{q}) \propto N_1(E,\overrightarrow{k_1})N_2(E,\overrightarrow{k_2})$$

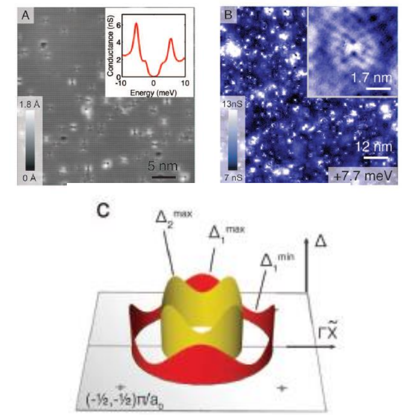
Direct imaging of the two-dimensional Fermi contour: Fourier-transform STM
L. Petersen et al.
Phys. Rev. B, R6858, 57 (1998)
A phenomenological approach of joint density of states for the determination of bandstructure in the case of a semi-metal studied by FT-STS
L. Simon, F. Vonau and D. Aubel
J. Phys. Cond. Matt. 19 (2007) 355009

QPI

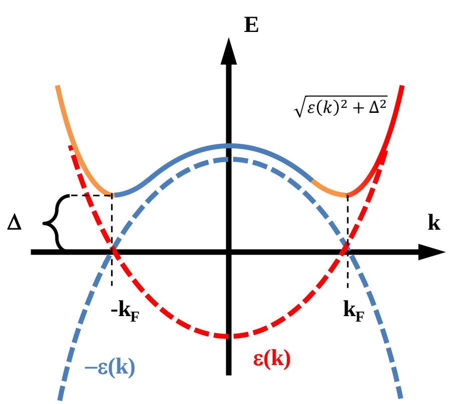
Quasiparticle interference
Superconducting gap anisotropy

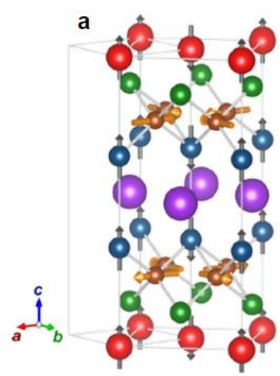


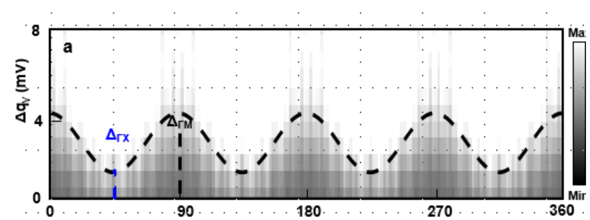




Anisotropic energy gaps of iron-based superconductivity from intraband quasiparticle scattering in LiFeAs
Science 336 (2012) 563

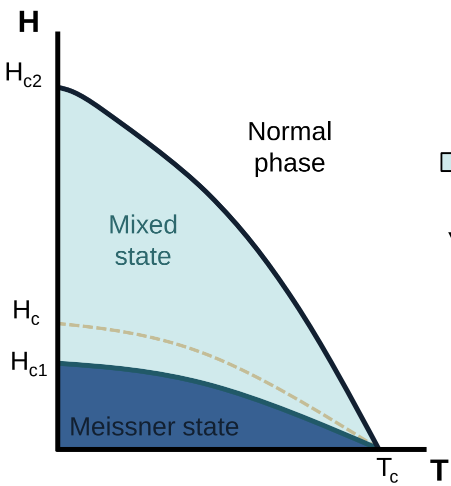


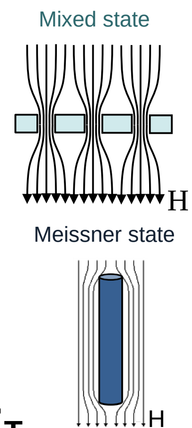




Spectroscopic scanning tunneling microscopy insights into Fe-based superconductors
J. Hoffman Rep. Prog. Phys. 74 (2011) 124103

Type II superconductors : high upper critical field + the vortex lattice

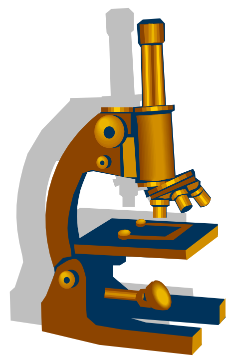


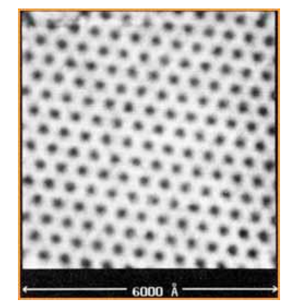


VOLUME 62, NUMBER 2 PHYSICAL REVIEW LETTERS 9 JANUARY 1989

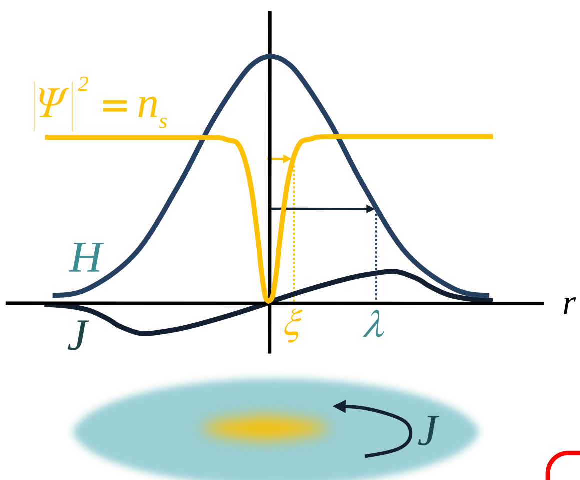
Scanning-Tunneling-Microscope Observation of the Abrikosov Flux Lattice and the Density of States near and inside a Fluxoid

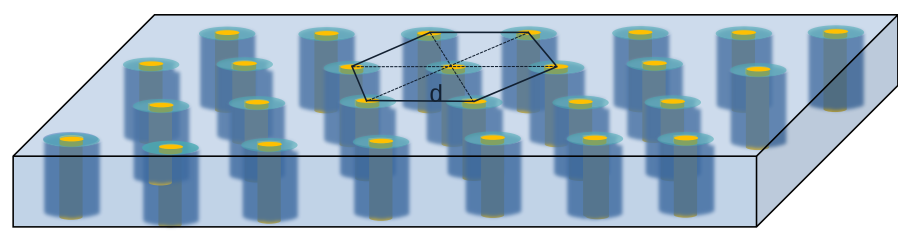
H. F. Hess, R. B. Robinson, R. C. Dynes, J. M. Valles, Jr., and J. V. Waszczak
AT&T Bell Laboratories, 600 Mountain Avenue, Murray Hill, New Jersey 07974
(Received 28 October 1988)





$$d(\mathrm{nm}) \approx 50/\sqrt{H(\mathrm{T})}$$





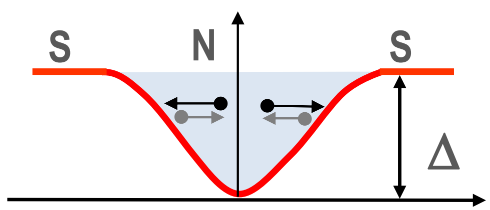
$$\psi = |\psi| e^{i\varphi}$$

$$\Delta_{\alpha\beta} \propto \langle \psi_{\vec{k},\alpha} \psi_{-\vec{k},\beta} \rangle$$

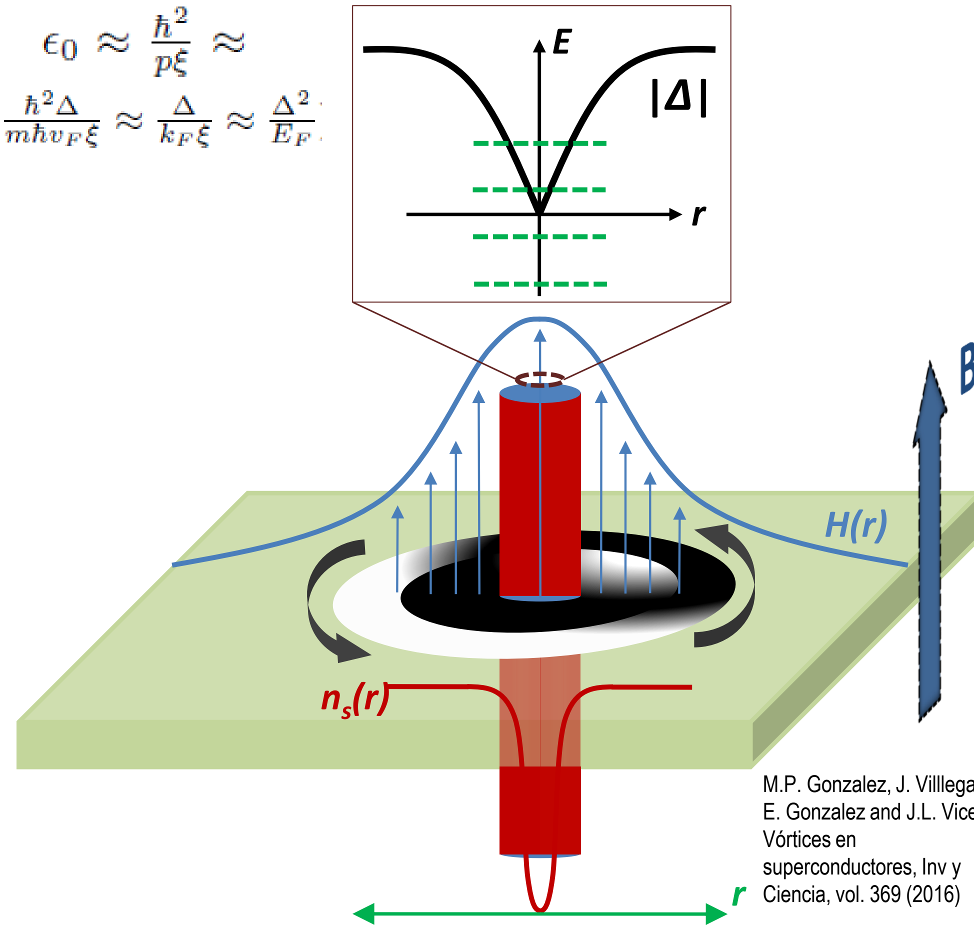
$$N(E) = \frac{E}{\sqrt{E^2 - \Delta^2}}$$

$$H_{c2} = \frac{\phi_0}{2\pi\xi^2}$$

Bound core states: Caroli-de Gennes-Matricon states



$$\epsilon_0 \approx \frac{\hbar^2}{p\xi} \approx \frac{\hbar^2\Delta}{m\hbar v_F \xi} \approx \frac{\Delta}{k_F \xi} \approx \frac{\Delta^2}{E_F}$$

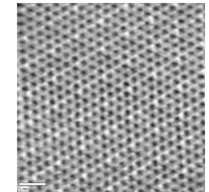


M.P. Gonzalez, J. Villlegas, E. Gonzalez and J.L. Vicent, Vórtices en superconductores, Inv y Ciencia, vol. 369 (2016)

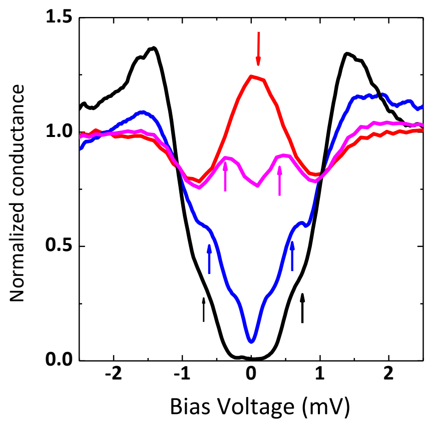
The vortex physics which comes from the vortex core
N.B. Kopnin
Physica. B, 280, 231, (2000)

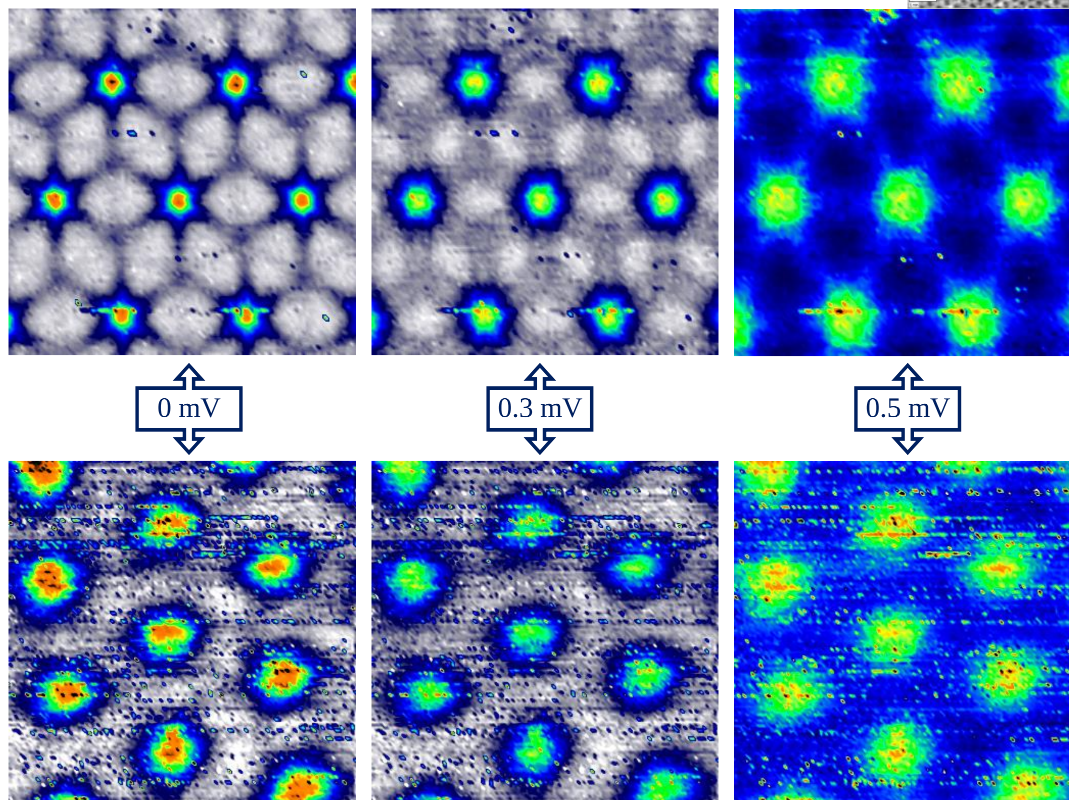
Current carried by bound states of superconducting vortices
D. Rainer, J.A. Sauls and D. Waxmann
Phys. Rev. B, 54, (1996)

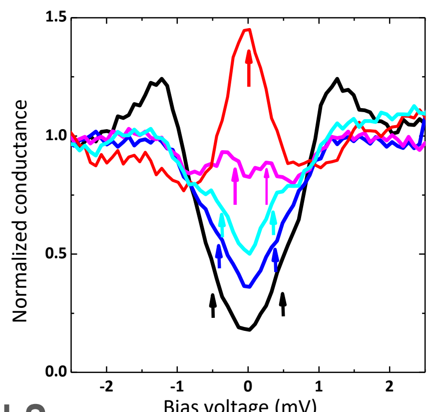
Internal electronic structure of the vortex cores: $NbSe_2$ vs. NbS_2

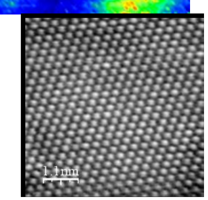


$NbSe_2$









NbS_2

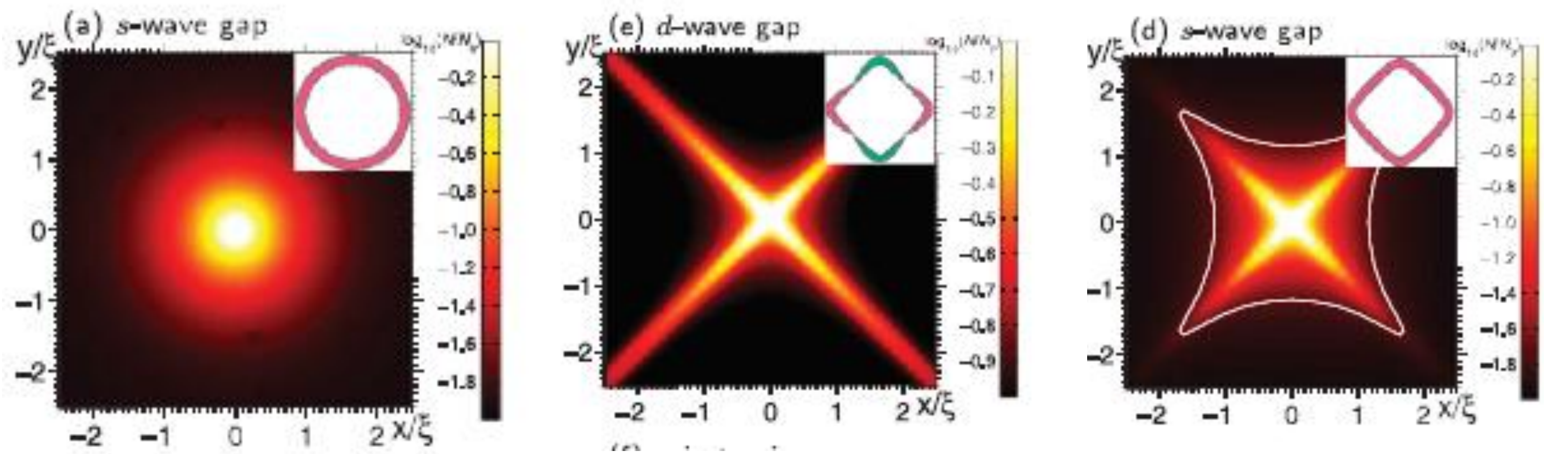
Superconducting density of states and vortex cores in NbS2
I. Guillamon, H. Suderow, S. Vieira and P. Rodiere
Phys Rev Lett, 101, 166407 (2008)

Shape of the vortex core depends on bandstructure and gap symmetry

$$\xi = \frac{\hbar v_F}{\pi \Delta}$$

$$\Delta = \Delta(\theta)$$

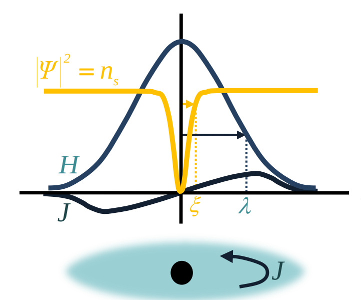
$$v_F = \langle v_F \rangle_{FS} = \int\int dz d\theta \, N(z, \theta) \, v_F$$



Angular band structure of a vortex line in a type II superconductor
F. Gygi and M. Schluter
Phys. Rev. Lett., 65, 1820 (1990)

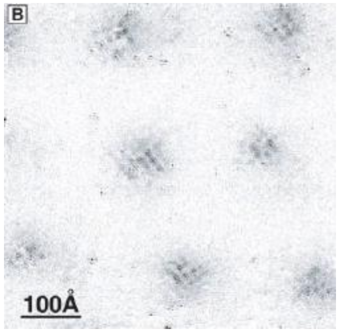
Star shaped local density of states around vortices in a type II superconductor
M. Ichioka, N. Hayashi and K. Machida
Phys. Rev. Lett. 77, 4074 (1996)

Theory of quasiparticle bound states in iron-based superconductors: application to scanning tunneling spectroscopy of LiFeAs
Y. Wang, P.J. Hirschfeld and I. Vekhter
Phys Rev B, 85, 020506(R) (2012)

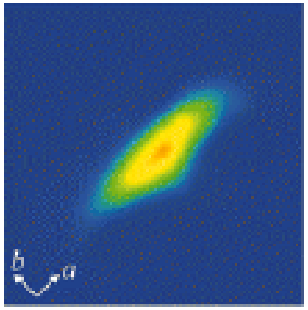


Vortex cores in perpendicular fields by STM

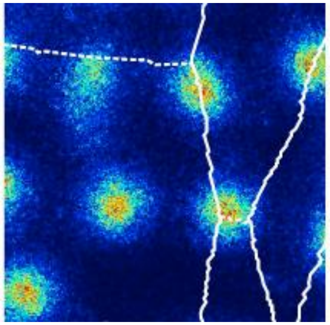
High T_c materials:
Geneva , Paris, Tokyo/Nagoya, Cornell , Princeton, …



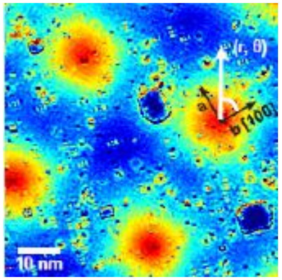
FeAs, FeSe
Beijing, Harvard, Tokyo …



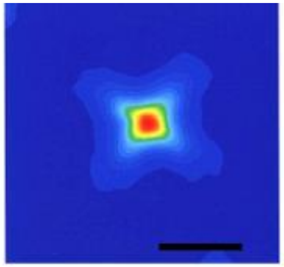
Very thin films
Paris, …



Heavy fermions
Princeton, Cornell



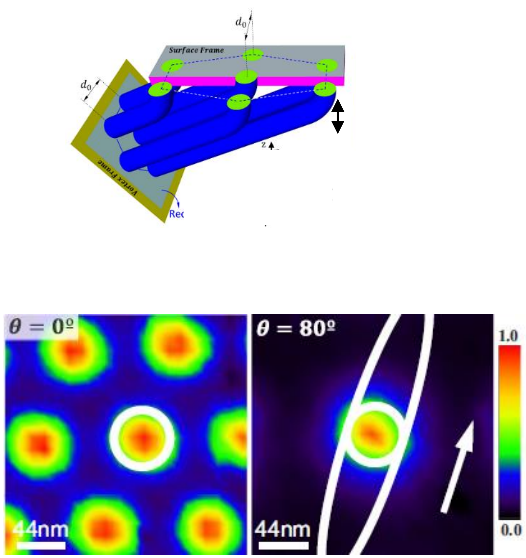
Nickel borocarbides
Tokyo/Nagoya, Argonne, Madrid

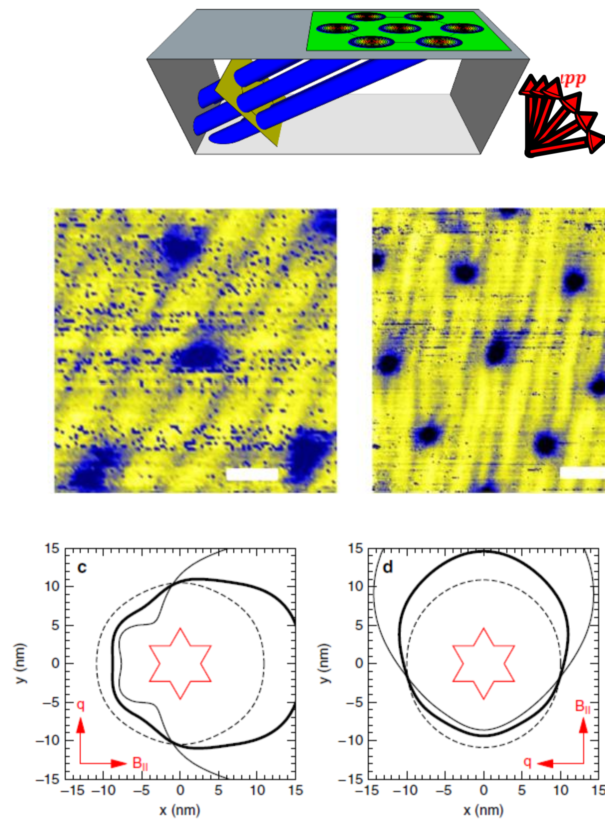


Imaging superconducting vortex cores and lattices with a STM
H. Suderow, I. Guillamón, J.G. Rodrigo and S. Vieira
Superc. Sci. Techn., 27, 063001 (2014)

Scanning tunneling spectroscopy of high-temperature superconductors
O. Fischer, M. Kugler, I. Maggio-Aprile, Ch. Berthod
Rev Mod Phys, 79, 373 (2007)

Vortex cores in tilted fields by STM



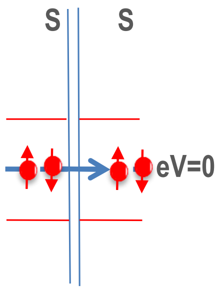


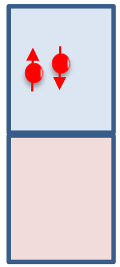
Subsurface bending and reorientation of tilted vortex lattices in bulk isotropic superconductors due to Coulomb-like repulsion at the surface
E. Herrera et al,Phys Rev B, 96, 184502 (2017)

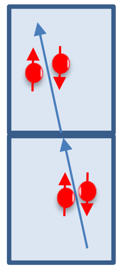
Tilted vortex cores and superconducting gap anisotropy in 2H-NbSe2
J.A. Galvis et al, Comm. Phys. 2:31 (2019)

Lateral imaging of the superconducting vortex lattice using Doppler-modulated scanning tunneling microscopy, **I. Fridman et al, Appl. Phys. Lett. 99, 192505 (2011)**

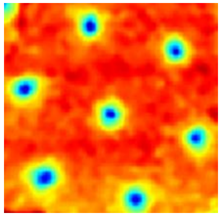
Superconducting tip: Josephson







Josephson



$$\psi = |\psi| e^{i\varphi}$$

φ_L	φ_R

$$\delta\varphi = \varphi_L - \varphi_R$$

$$I = I_0 \sin(\delta\varphi)$$

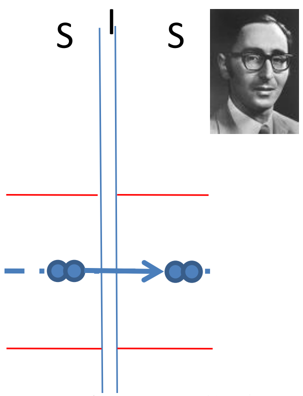
$$\frac{\partial \delta\varphi}{\partial t} = \frac{2e}{\hbar} V$$

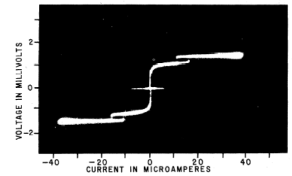
$$I = I_0 \sin(\delta\varphi)$$

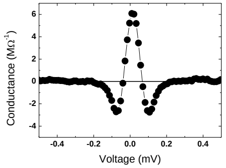
Density of Cooper pairs n_{s1} and n_{s2}

Phase ?

Cooper pair tunneling







Quantum phase as a measurable quantity: DC and AC Josephson effect

$$\Psi_1 = \psi_{0,1} e^{i\varphi_1} \qquad \Psi_2 = \psi_{0,2} e^{i\varphi_2}$$

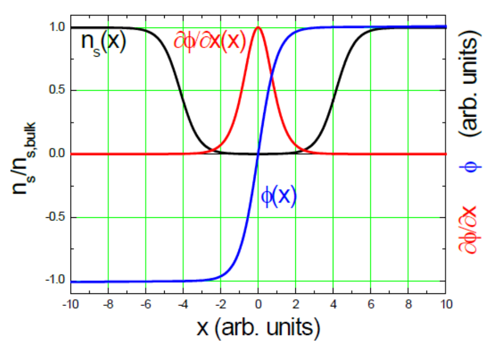
$$n_{S1} = \left|\psi_{0,1}\right|^2 \qquad n_{S2} = \left|\psi_{0,2}\right|^2$$

$$j_S = 2en_s \mathrm{v}_S = \tfrac{\hbar e}{m} n_s \nabla\phi$$

$$j_S \; \alpha \; n_s \nabla\phi$$

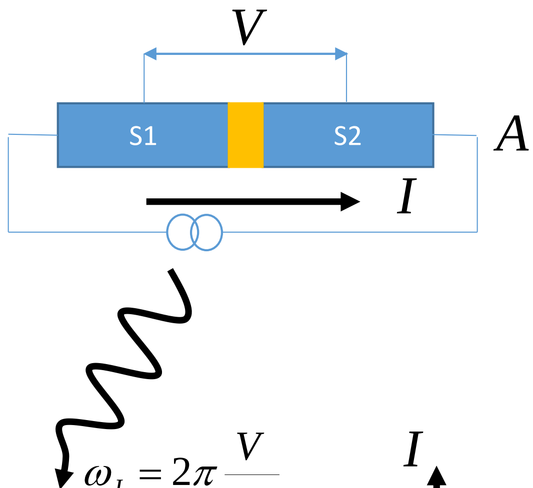
$$j_S = \frac{\mathrm{I}}{\mathrm{A}} = cte$$

$$n_s \frac{\partial\phi(x)}{\partial x} = cte$$



https://nanocohybri.inc.uam.es/wp-content/uploads/2019/01/Koelle_1.pdf

Quantum phase as a measurable quantity: DC and AC Josephson effect



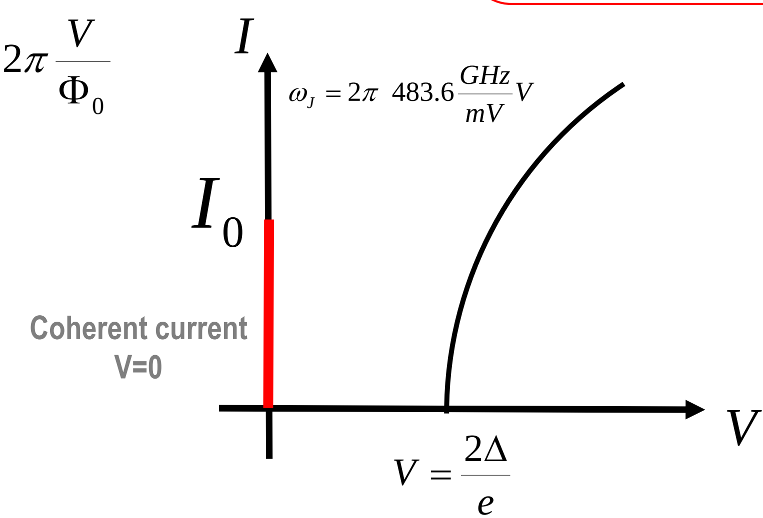
$$\omega_J = 2\pi \frac{V}{\Phi_0}$$

$$I = I_0 \sin(\delta)$$

First Josephson equation

$$\frac{\partial \delta}{\partial t} = \frac{2e}{\hbar} V$$

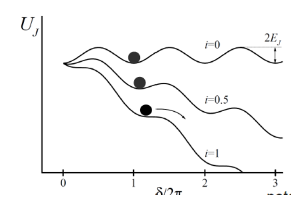
Second Josephson equation



$$\delta(t) = \delta_0 + 2\pi \frac{V}{\Phi_0} t$$

$$I = I_0 \sin(\delta_0 + 2\pi \frac{V}{\Phi_0} t)$$

$$I + I_n(t) = I_0 \sin\delta + \frac{\Phi_0}{2\pi R}\dot{\delta} + \frac{\Phi_0 C}{2\pi}\ddot{\delta}$$



Josephson effect at atomic level

Eur. Phys. J. B 40, 483–488 (2004)
DOI: 10.1140/epjb/e2004-00273-y

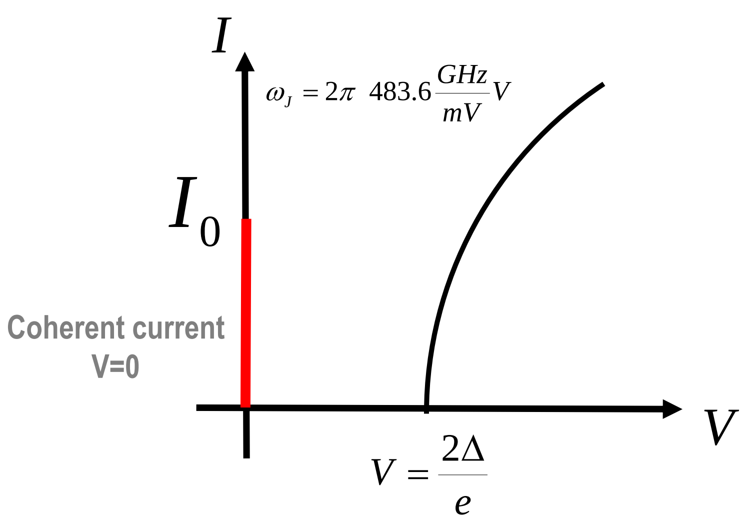
THE EUROPEAN PHYSICAL JOURNAL B

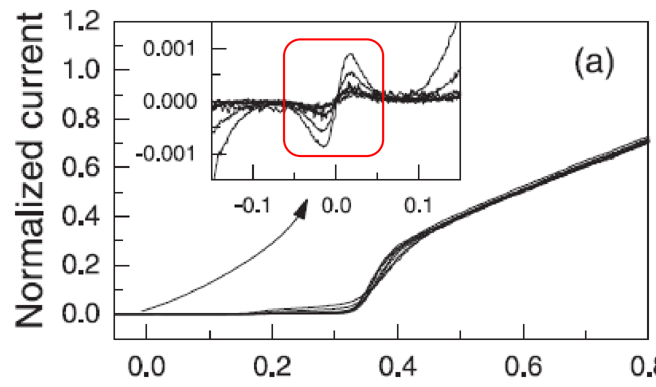
On the use of STM superconducting tips at very low temperatures

E_J -> *Junction resistance*

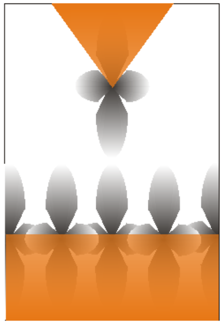
<<

k_BT about 0.1 K

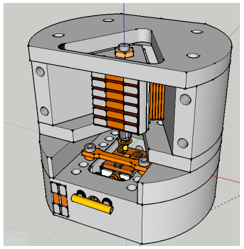




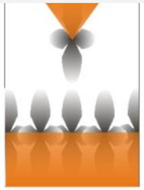
Real space visualization of electronic correlations



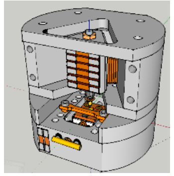
- **Real space imaging and spectroscopy**
  - **Atomic structure**
  - **Electronic bandstructure**
  - *Superconducting gap structure*
  - *Vortex lattice structure*
  - *Josephson effect (phase)*
  - **Pairing interaction**
  - **Electronic correlations (Coulomb, Kondo)**



Real space imaging of the superconducting vortex lattice: Recent results and prospects

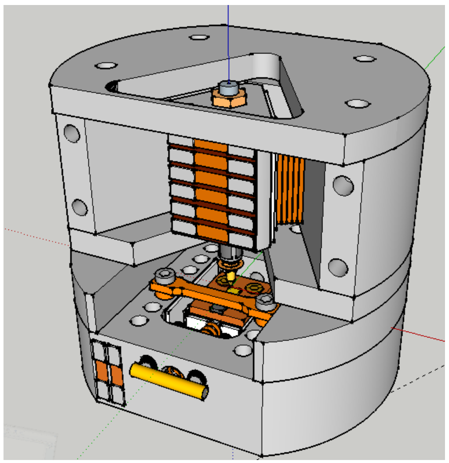


- Real space imaging and spectroscopy of the vortex lattice
- Superconducting $CaKFe_4As_4$, bandstructure, vortex core, vortex lattice and pinning
- Vortex lattice structure: interactions vs disorder
- Observation of vortex creep on cooling
- Josephson effect at atomic scale

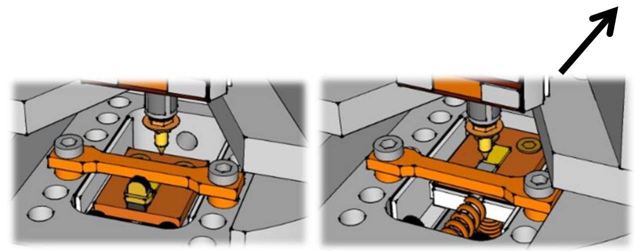


Small compact dil fridge STM/S

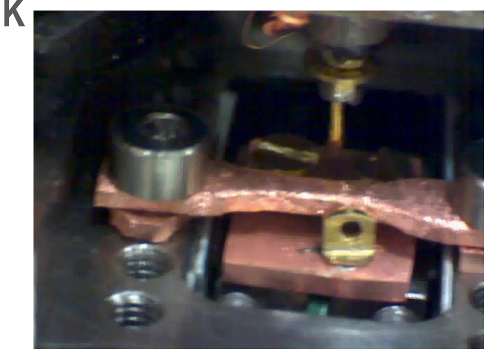
Tip and sample preparation and scanning window

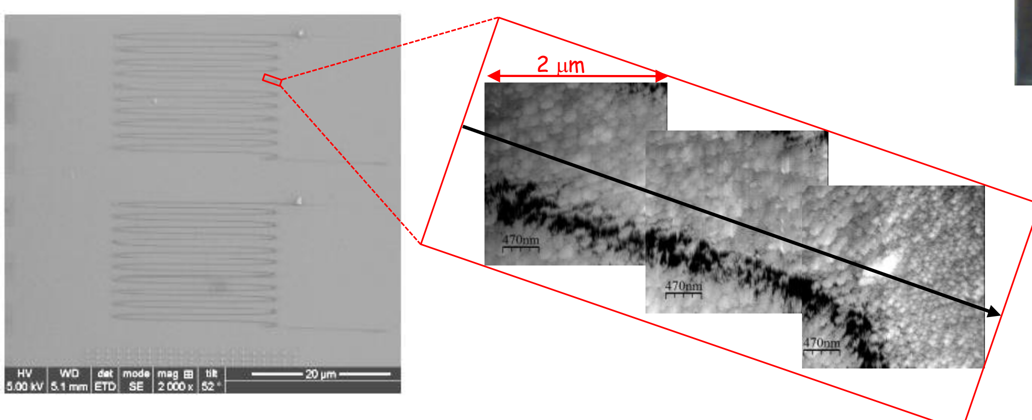


100 mK
13 μeV



100mK, 50 mK, 10 mK, 30 mK





REVIEW OF SCIENTIFIC INSTRUMENTS 82, 033711 (2011)

Compact very low temperature scanning tunneling microscope with mechanically driven horizontal linear positioning stage

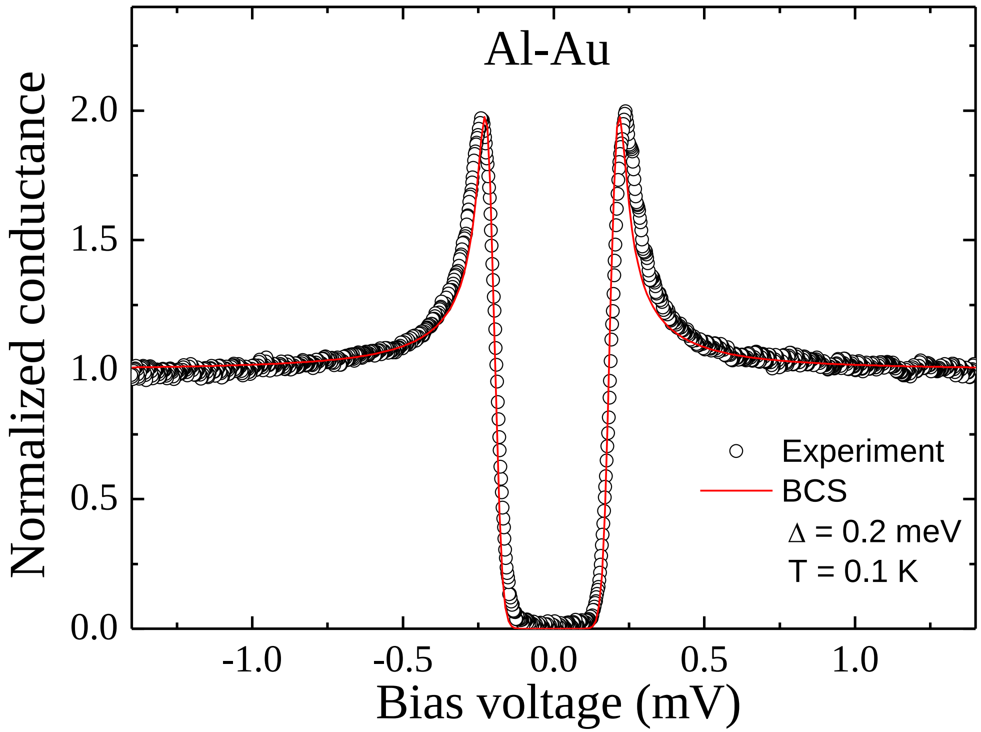
H. Suderow,[a)] I. Guillamon, and S. Vieira
Laboratorio de Bajas Temperaturas, Departamento de Física de la Materia Condensada Instituto de Ciencia de Materiales Nicolás Cabrera, Facultad de Ciencias Universidad Autónoma de Madrid, 28049 Madrid, Spain

(Received 3 December 2010; accepted 19 February 2011; published online 23 March 2011)

Patente

Temperature

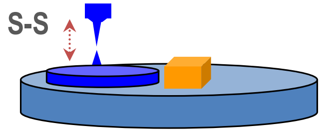
$$\frac{dI}{dV} \propto \int N_S(E) \frac{\partial f(E-eV)}{\partial V} dE$$



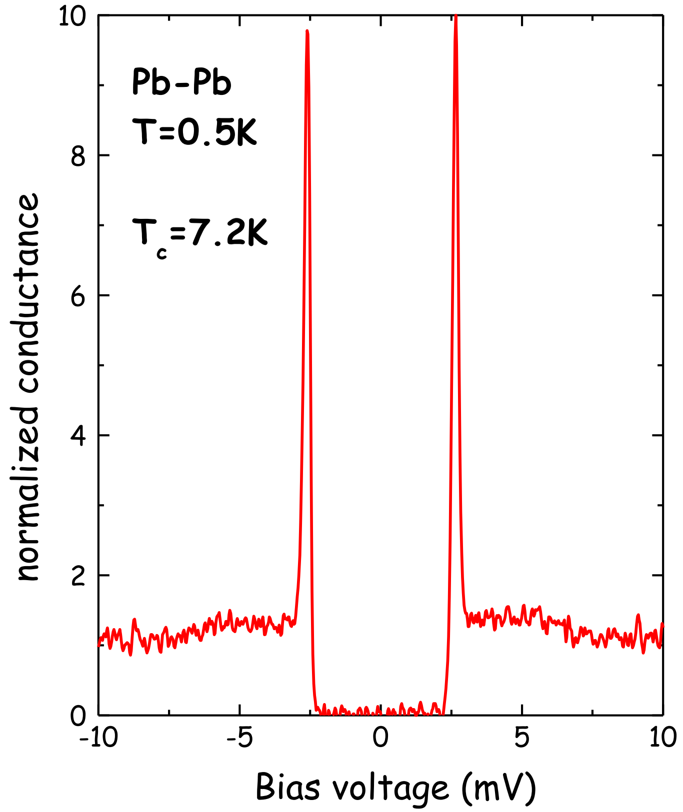
15μeV

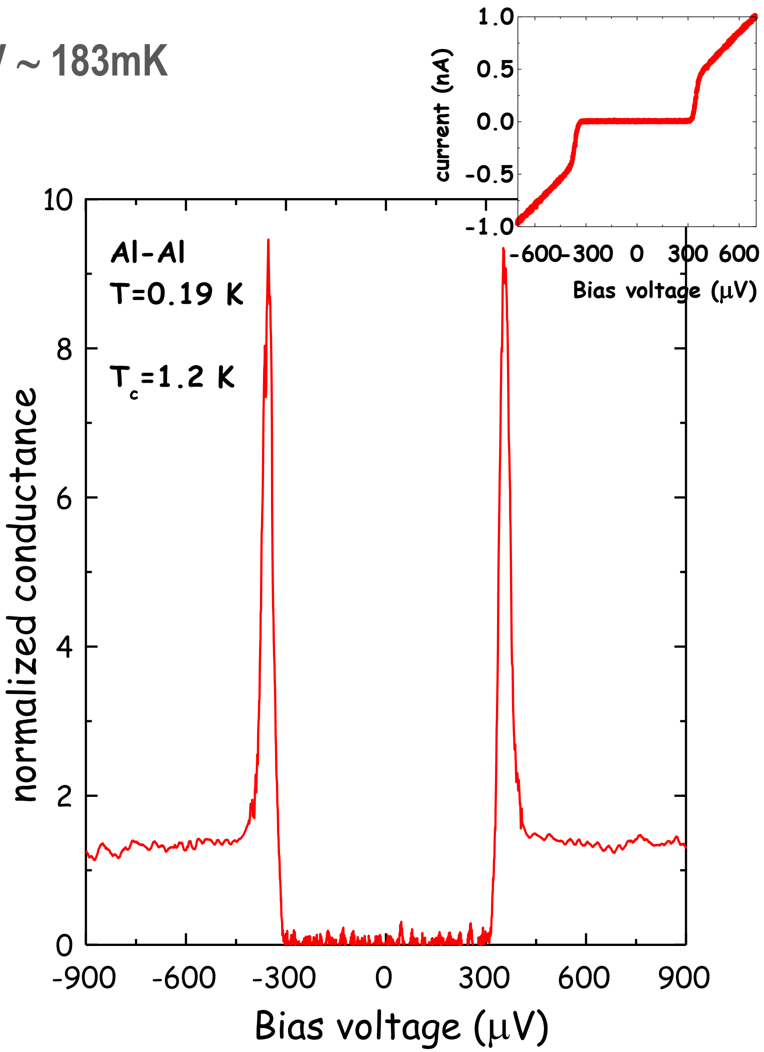
$$N_S(E; x, y)$$

Energy resolution

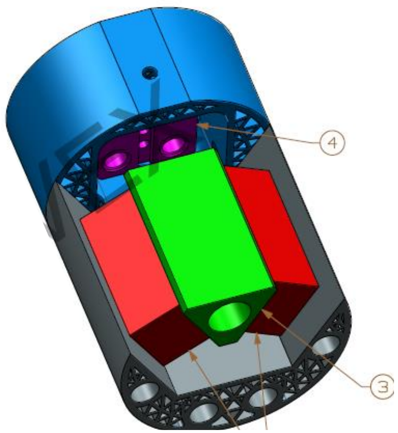


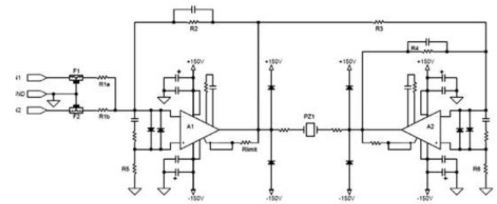
15 μV ~ 183mK



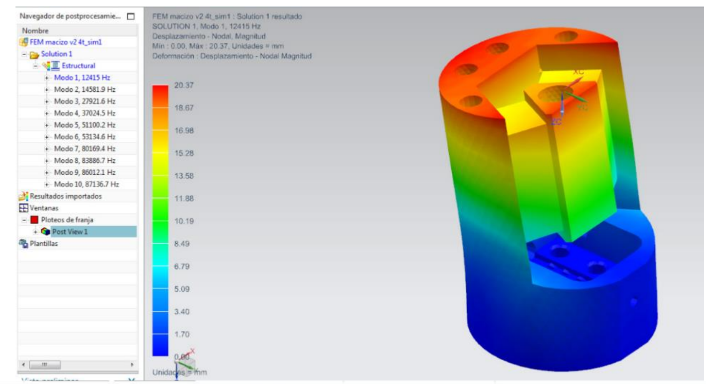


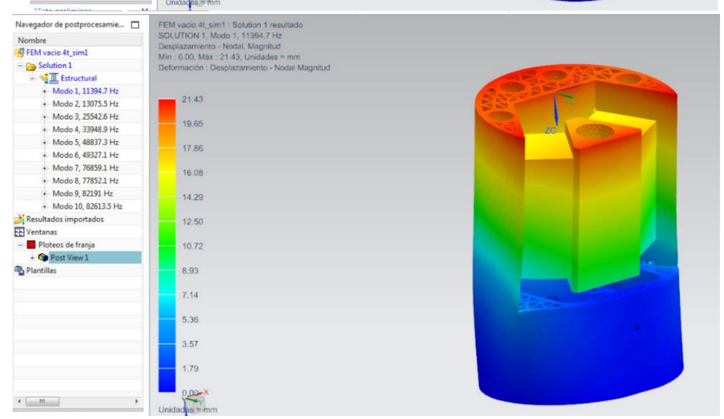
New smaller STM/S





3D printed in grade 5 Titanium alloy





REVIEW OF SCIENTIFIC INSTRUMENTS 82, 033711 (2011)

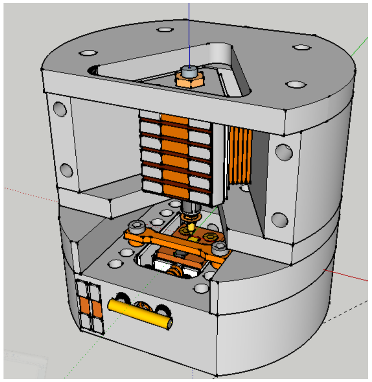
Compact very low temperature scanning tunneling microscope with mechanically driven horizontal linear positioning stage

H. Suderow,[a] I. Guillamon, and S. Vieira
Laboratorio de Bajas Temperaturas, Departamento de Física de la Materia Condensada Instituto de Ciencia de Materiales Nicolás Cabrera, Facultad de Ciencias Universidad Autónoma de Madrid, 28049 Madrid, Spain

(Received 3 December 2010; accepted 19 February 2011; published online 23 March 2011)

STM/S in Madrid

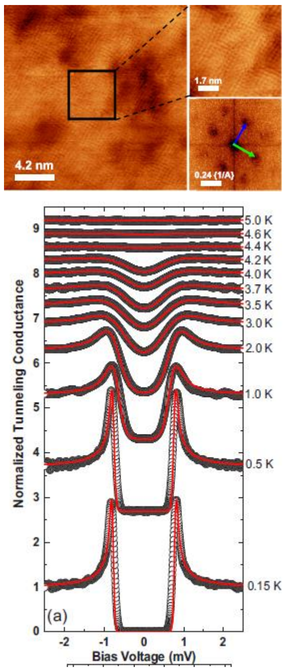
22 T superconducting coil, hundreds of field ramps and no single quench in Madrid

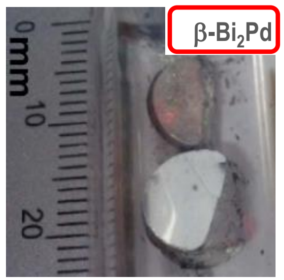


Very high magnetic field STM (22 T), Isabel Guillamón

Isabel.guillamon@uam.es

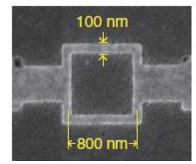
QUAMaterials





Superconductivity at 5.4 K in β-Bi_2Pd
Y. Imai JPSJ 81, 113708

Full gap superconductivity in spin-polarised surface states of topological semimetal β-Bi_2Pd
K. Iwaya Nat Comm, 8, 976 (2017)

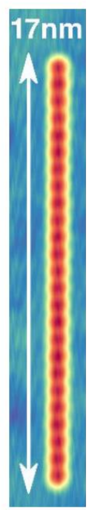


RESEARCH

SUPERCONDUCTIVITY

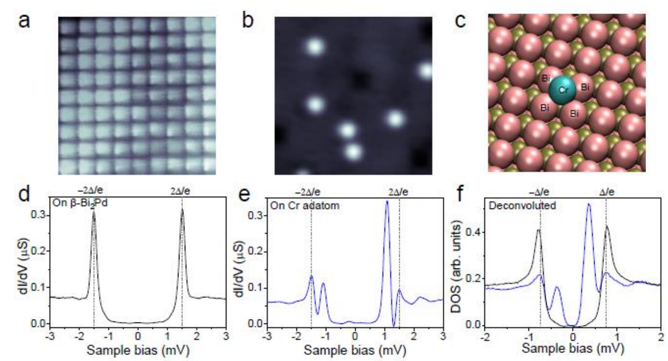
Observation of half-quantum flux in the unconventional superconductor β-Bi_2Pd

Yufan Li[1*†], Xiaoying Xu[1*], M.-H. Lee[2], M.-W. Chu[2], C. L. Chien[1,3,4†]



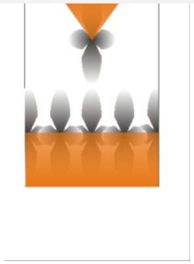
J. Zaldivar, J.I. Pascual

Shiba states on Cr adatoms

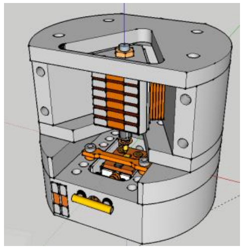


Influence of Magnetic Ordering between Cr Adatoms on the Yu-Shiba-Rusinov States of the β-Bi_2Pd Superconductor
DJ Choi et al PRL 120 (2018) 167001

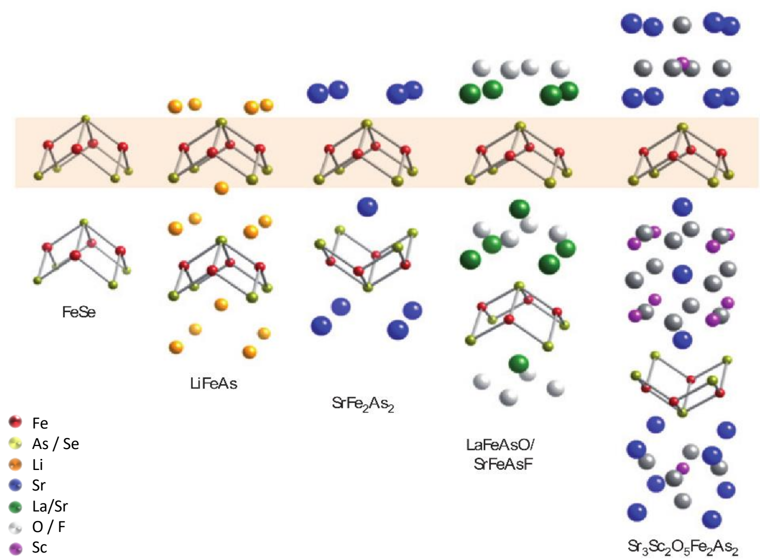
Real space imaging of the superconducting vortex lattice: Recent results and prospects

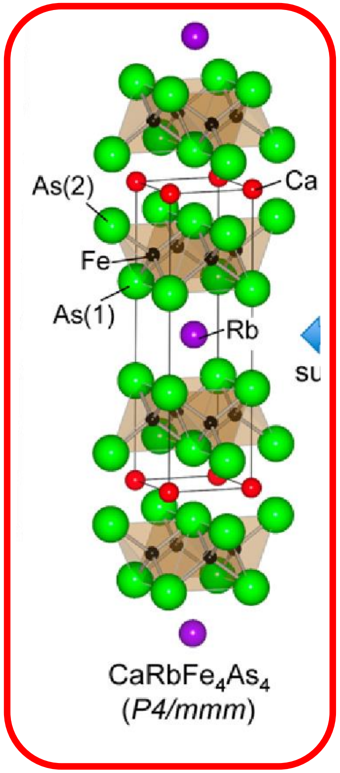


- Real space imaging and spectroscopy of the vortex lattice
- Superconducting CaKFe4As4, bandstructure, vortex core, vortex lattice and pinning
- Vortex lattice structure: interactions vs disorder
- Observation of vortex creep on cooling
- Josephson effect at atomic scale

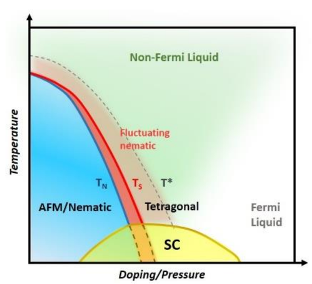


Crystal structures in the iron pnictides

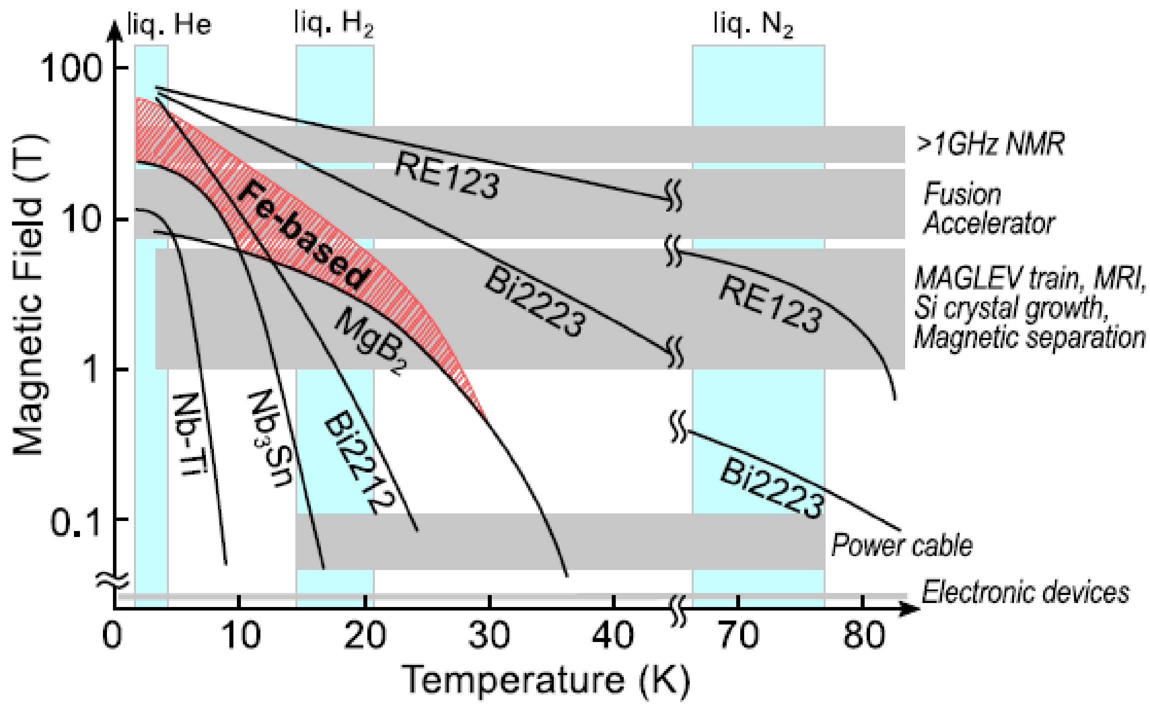




New-Structure-Type Fe-Based Superconductors: $CaAFe_4As_4$ (A = K, Rb, Cs) and $SrAFe_4As_4$ (A = Rb, Cs)

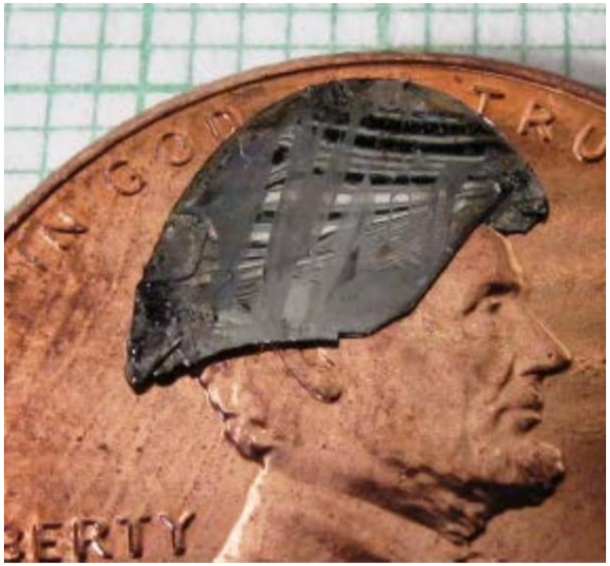


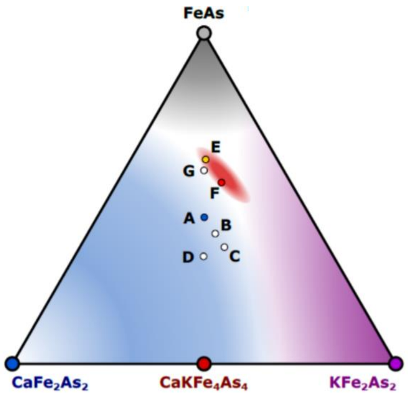
Critical temperature and magnetic field



Potentials of iron-based superconducting alloys for practical future materials
J.I. Shimoyama
Superc. Sci. Tech., 044002, 27 (2014)

The $CaKFe_4As_4$ system

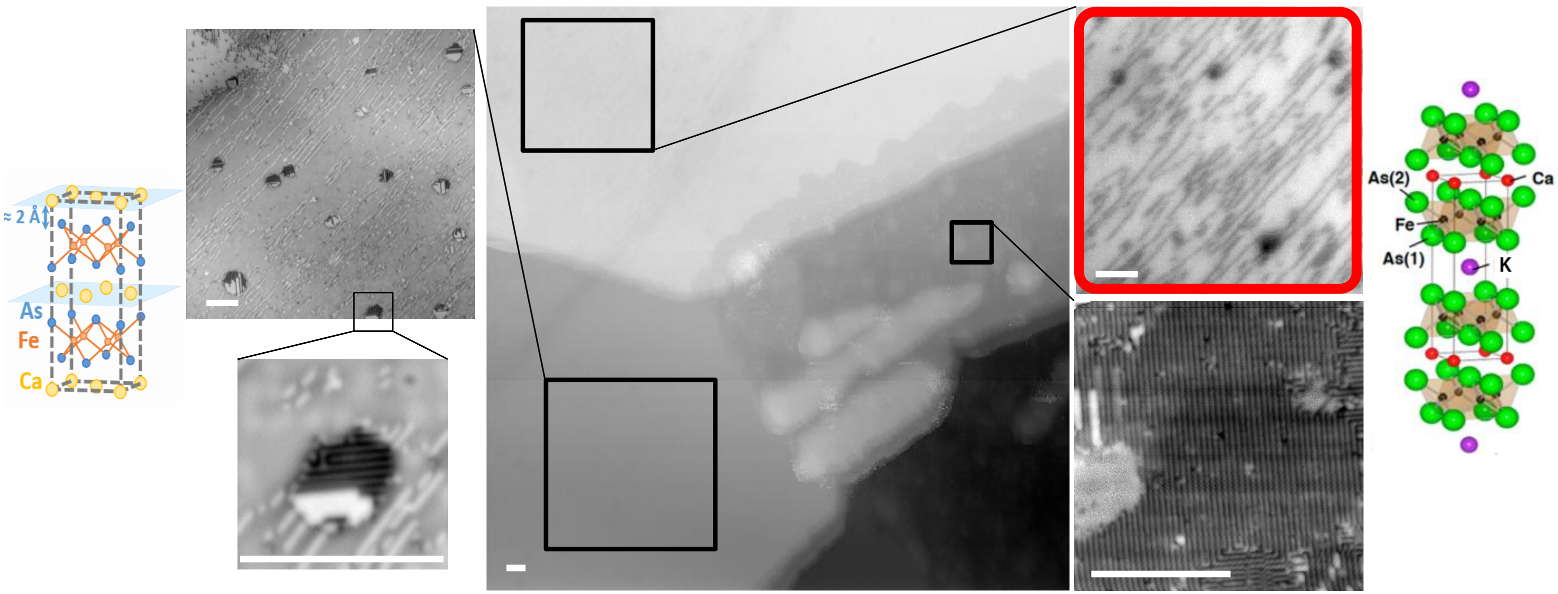




Wed. Afternoon
PC5-4, Unique defect structure and advantageous vortex pinning properties in CaKFe4As4, Ishida
PC5-5, Critical current density and its enhancement by particle irradiation in CaK2Fe4As4F2, Tamegai

The $CaKFe_4As_4$ system

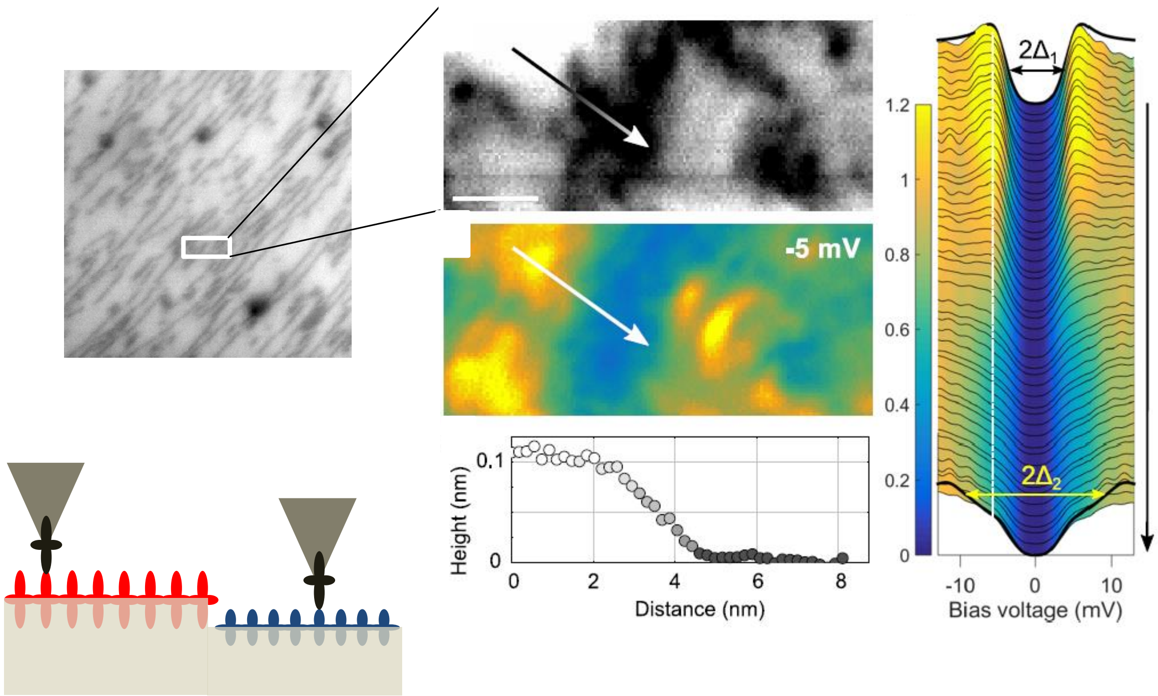
Topography of $CaKFe_4As_4$: No surface reconstruction
Ca-K surface with stripes

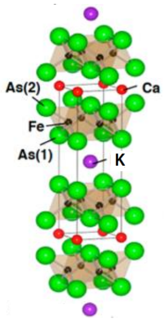


White scale bar: 20 nm

The $CaKFe_4As_4$ system

Two gap superconductivity in $CaKFe_4As_4$, T_c = 35 K
Stripes





The $CaKFe_4As_4$ system

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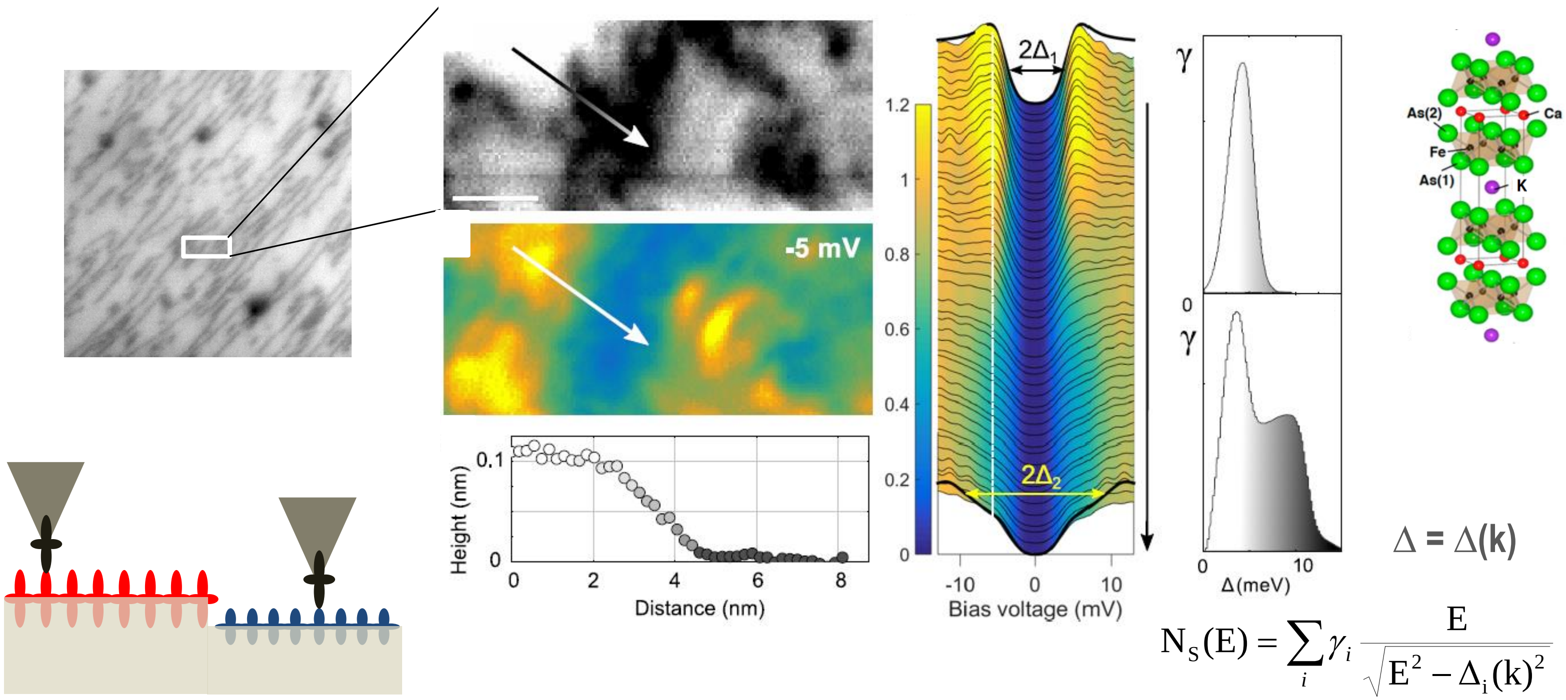
Stripes

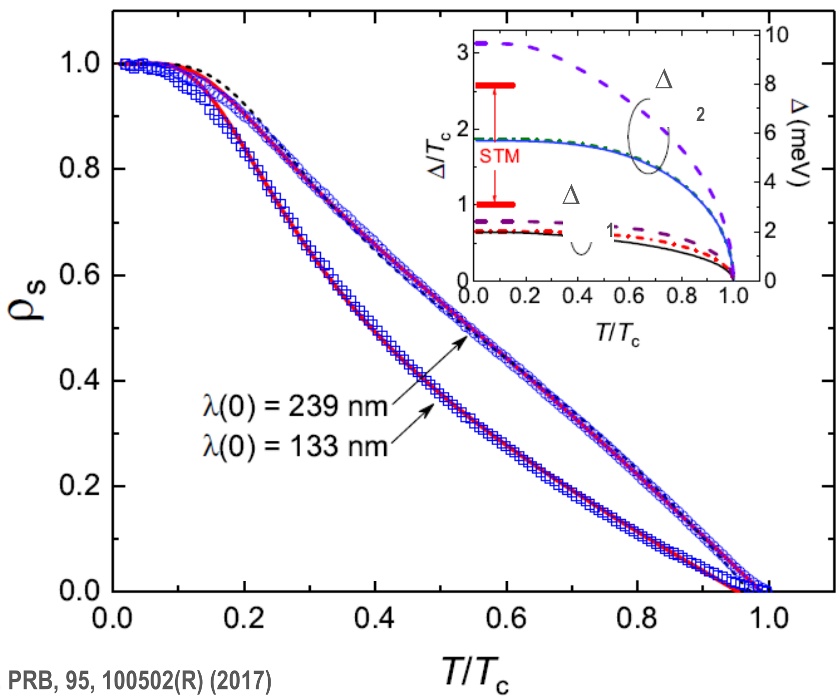


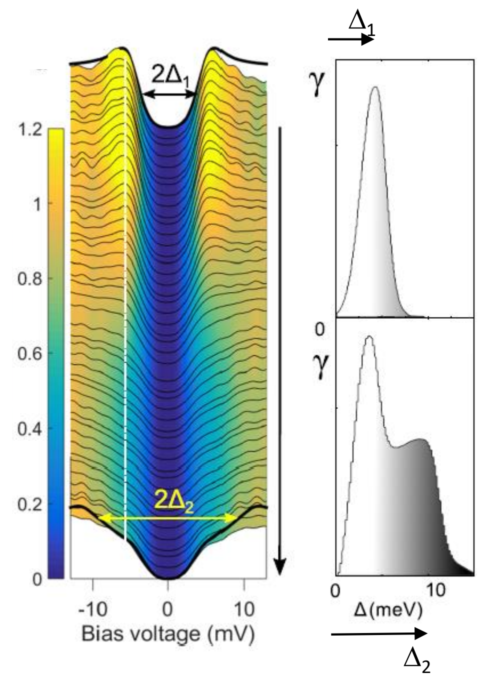
$\Delta = \Delta(\mathbf{k})$

$$N_S(E) = \sum_i \gamma_i \frac{E}{\sqrt{E^2 - \Delta_i(k)^2}}$$

The $CaKFe_4As_4$ system

Two gap superconductivity in $CaKFe_4As_4$, T_c = 35 K
London penetration depth, R. Prozorov et al

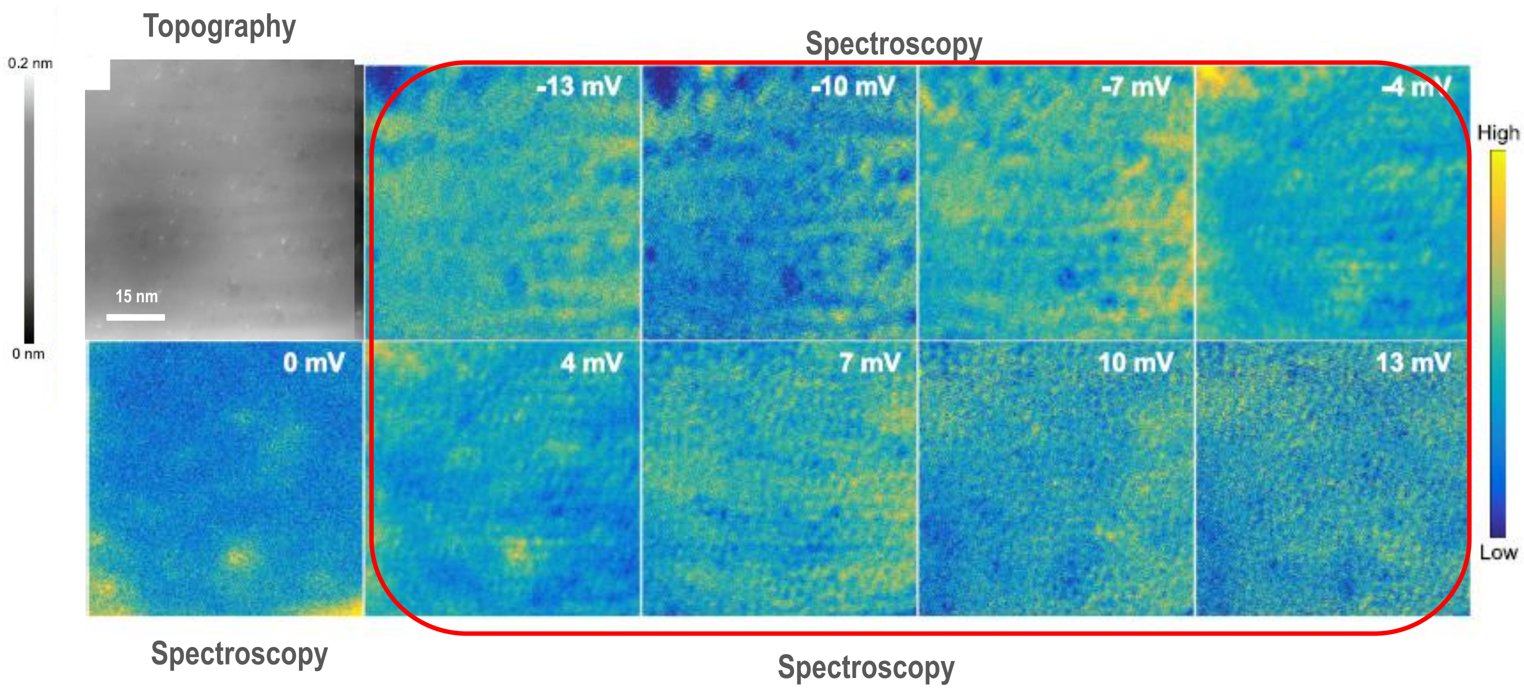




K. Cho et al, PRB, 95, 100502(R) (2017)

The $CaKFe_4As_4$ system

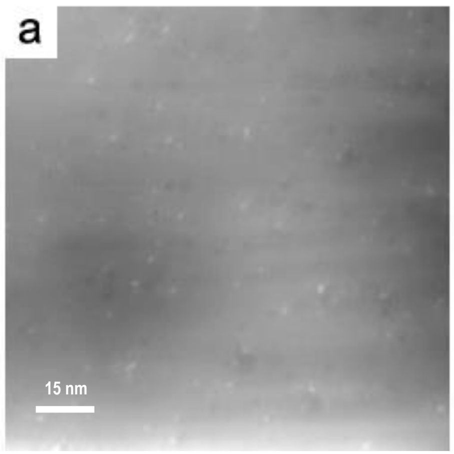
Quasiparticle interference scattering



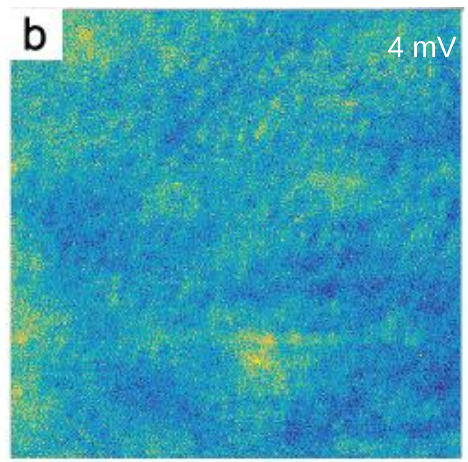
The $CaKFe_4As_4$ system

Quasiparticle interference scattering

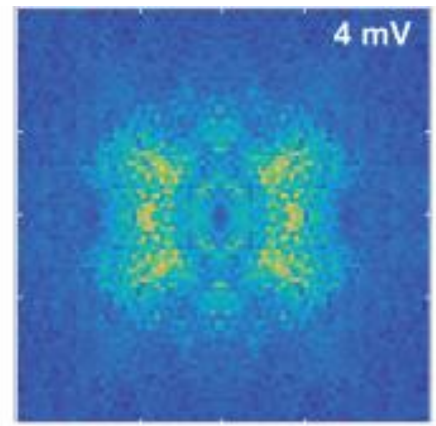
Topography



Spectroscopy

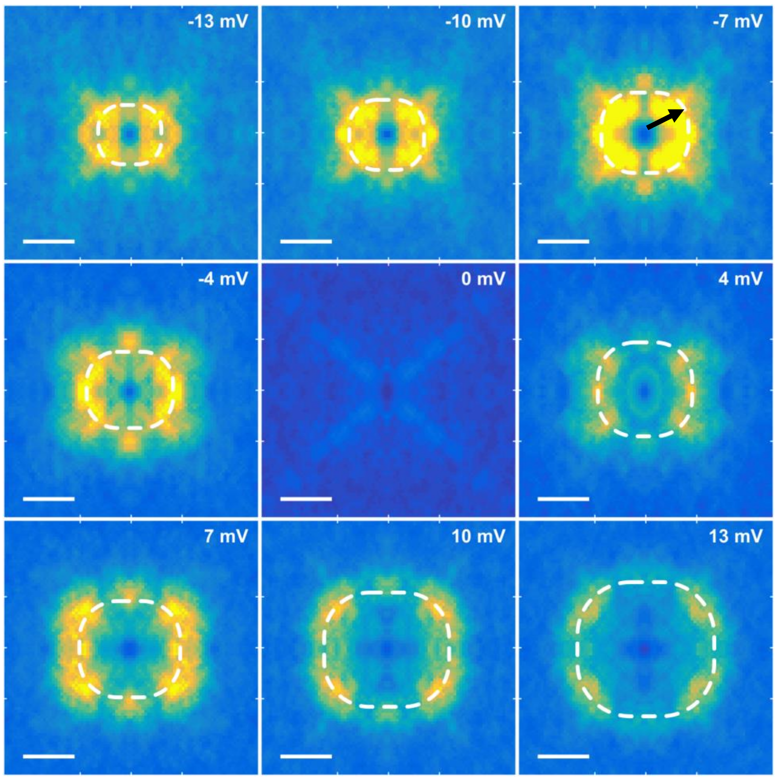


Fourier transform of the spectroscopy



The $CaKFe_4As_4$ system

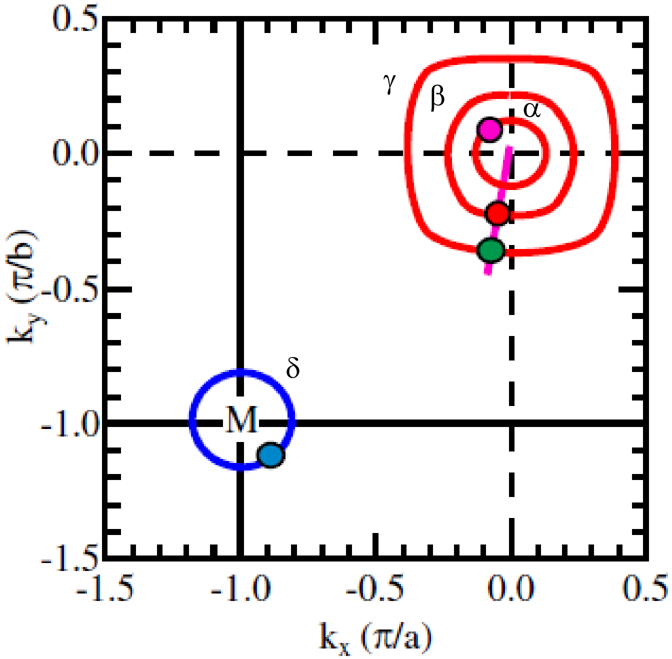
Fourier transform of the spectroscopy

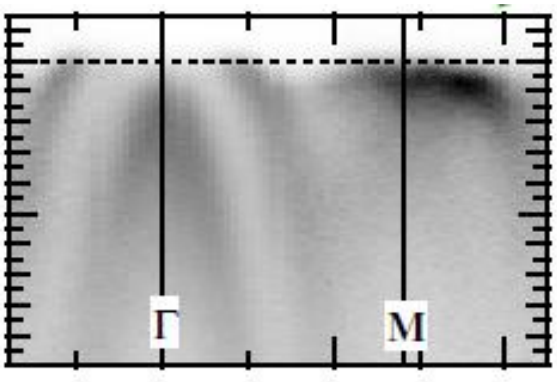


- One main scattering wavevector whose size increases with energy
- No scattering below about 4 mV

The $CaKFe_4As_4$ system

ARPES

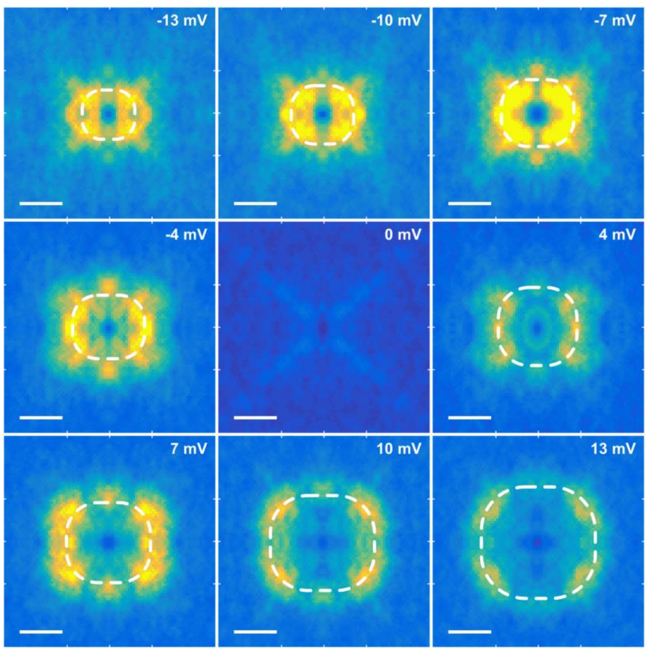


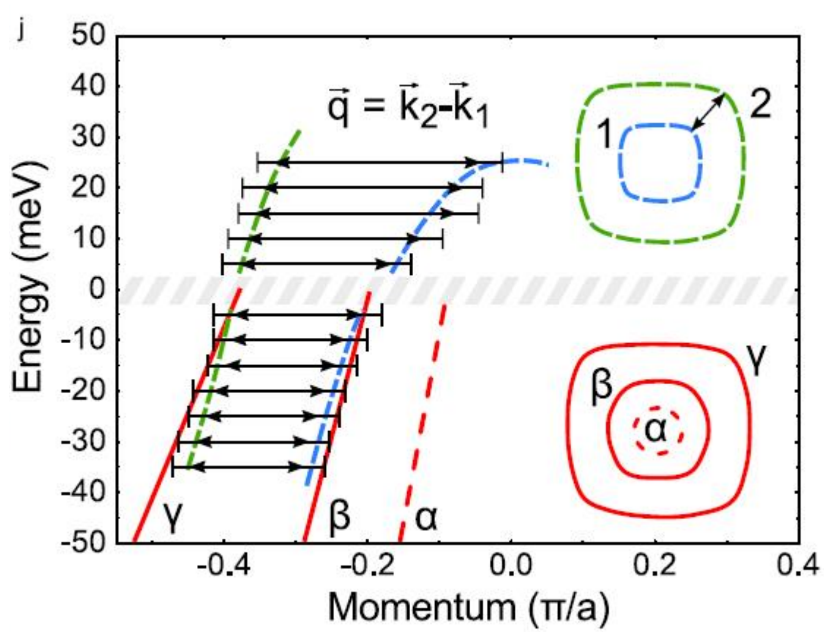


Mou et al., PRL 117 277001 (2016)

The $CaKFe_4As_4$ system

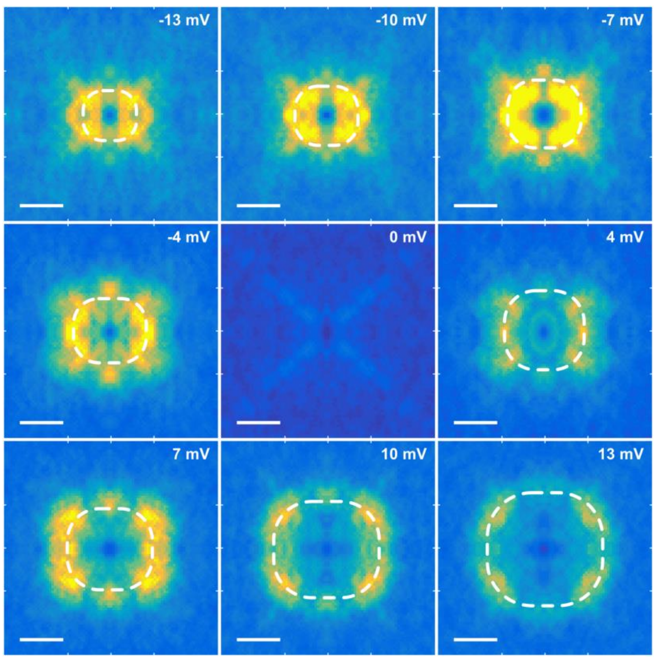
Electron dispersion relation from quasiparticle interference scattering
Empty and full states.
Innermost pocket closes a few mV above E_F

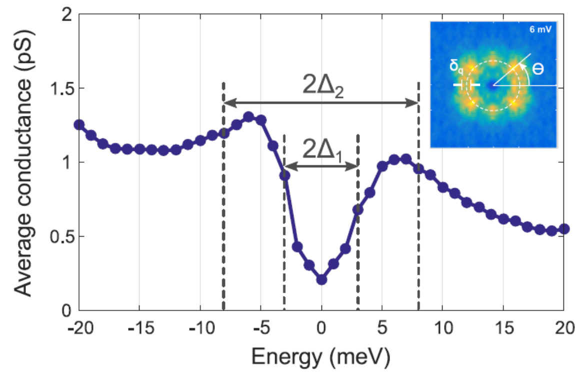


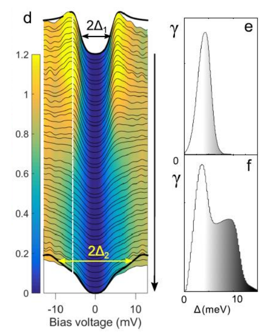


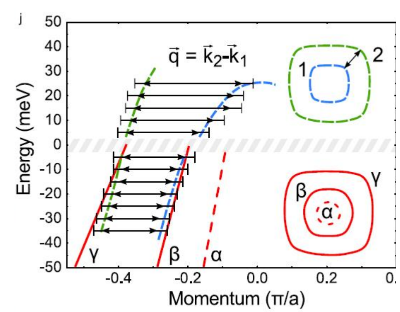
The $CaKFe_4As_4$ system

Superconducting gap opening from quasiparticle interference scattering
Isotropic gap opening in the hole sheets



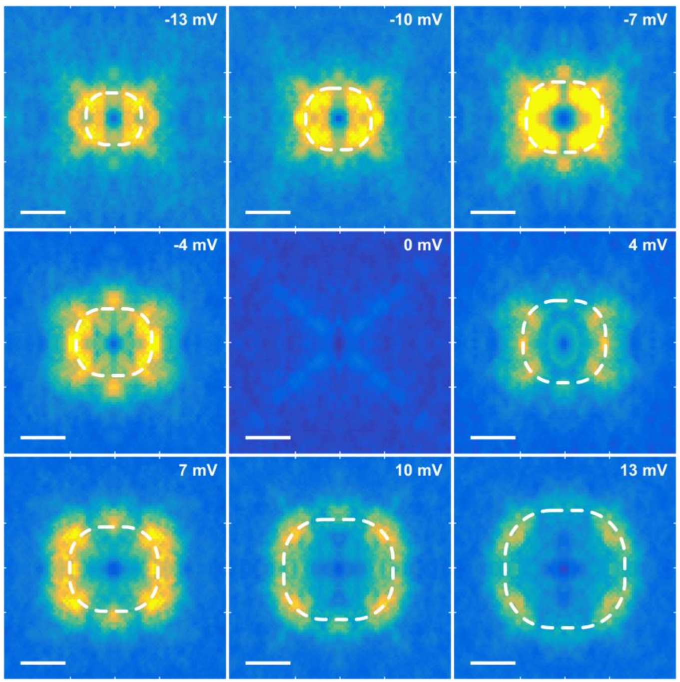


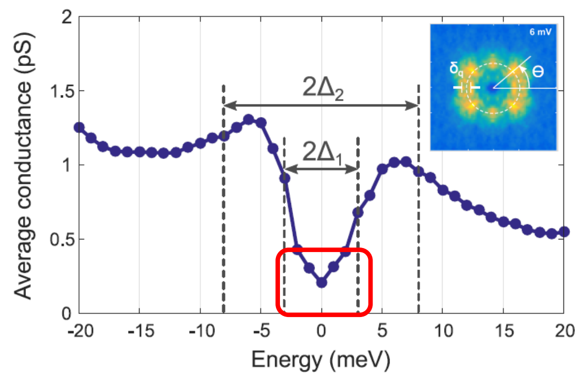


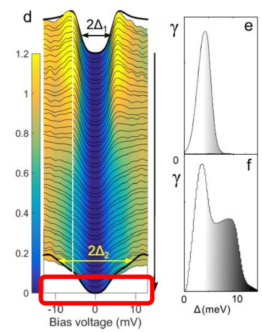


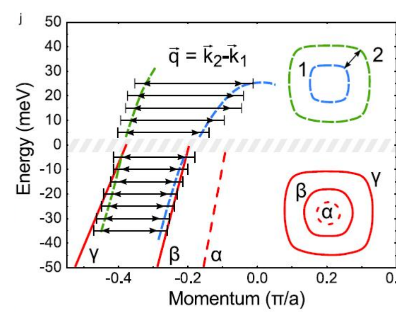
The $CaKFe_4As_4$ system

Superconducting gap opening from quasiparticle interference scattering
Zero bias DOS ??



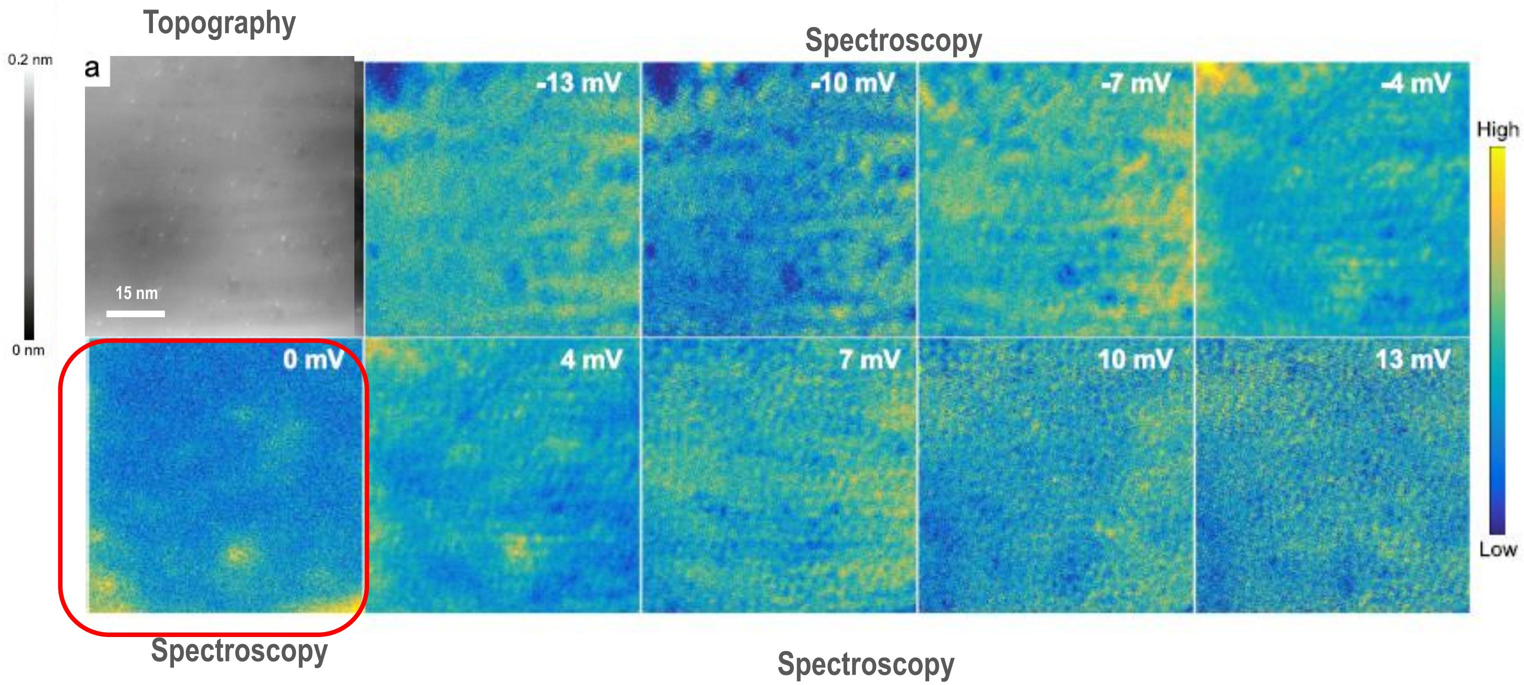






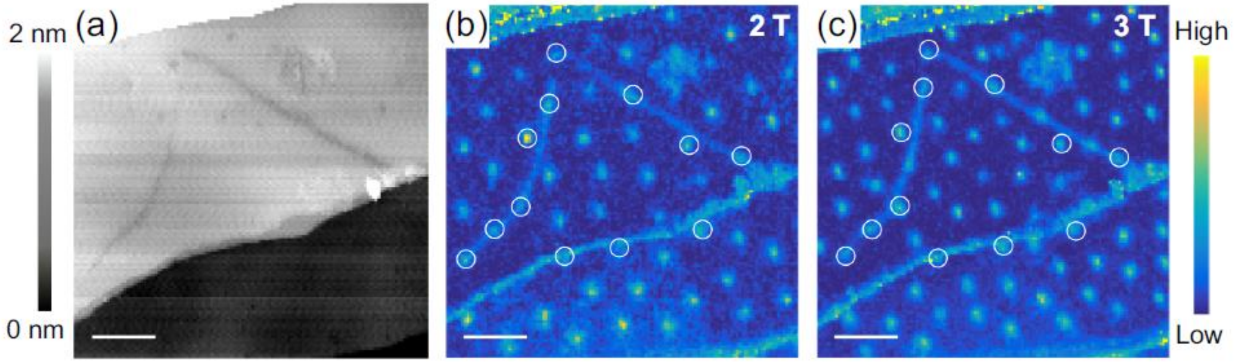
The $CaKFe_4As_4$ system

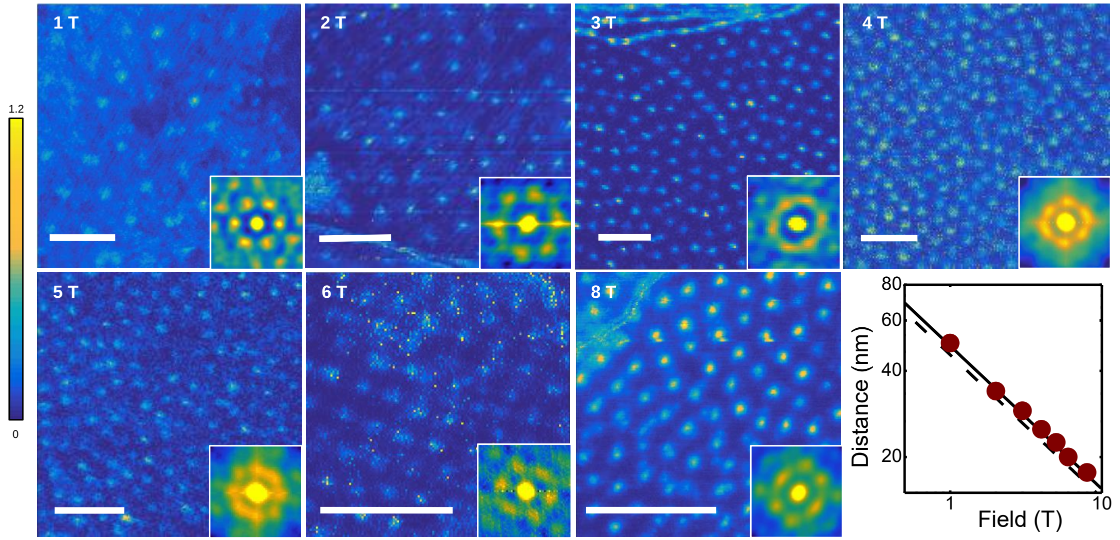
Quasiparticle interference scattering at zero bias within the superconducting gap



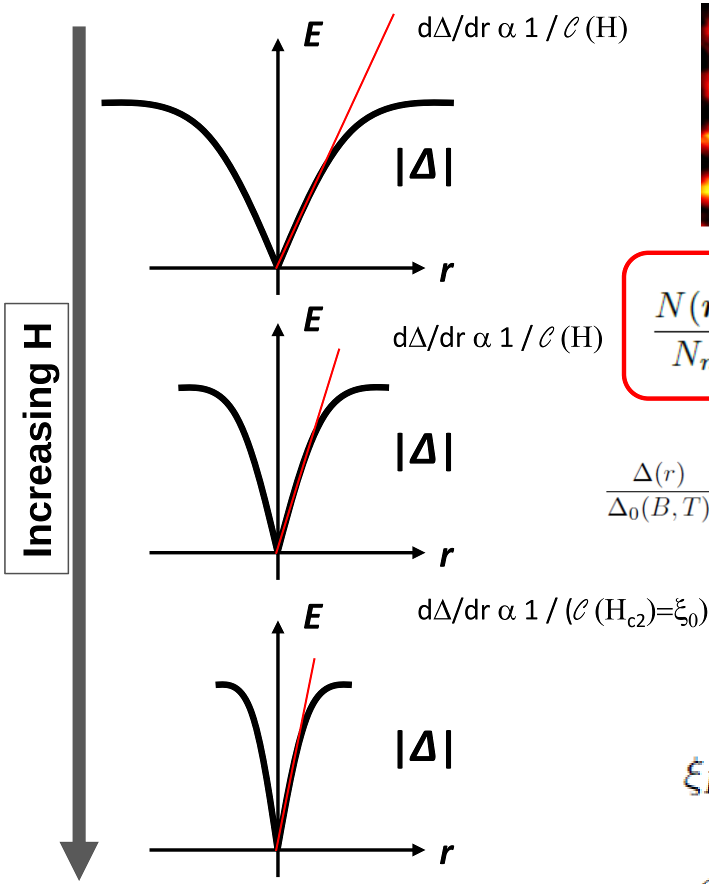
The $CaKFe_4As_4$ system

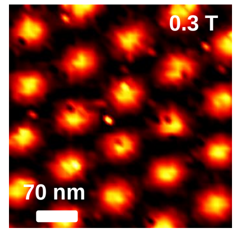
Zero bias states and pinning

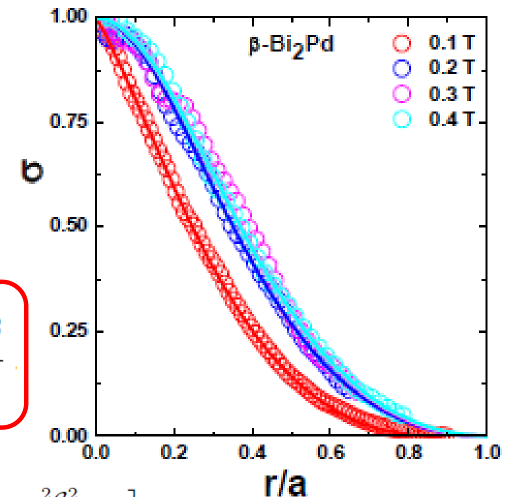




Using de Gennes relation to understand N(r) in a vortex core





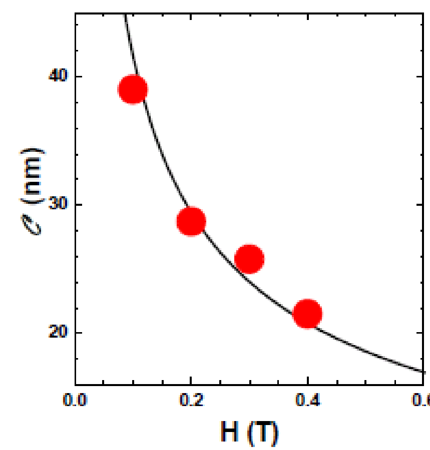


$$\frac{N(\boldsymbol{r})}{N_n} = 1 - \frac{|\Delta(\boldsymbol{r})|^2}{\Delta_0^2}$$

$$\frac{\Delta(r)}{\Delta_0(B,T)} = \frac{r}{\sqrt{r^2+\mathcal{C}^2}} \exp\left[-\frac{r^2\mathcal{C}^2}{2a^2(\mathcal{C}^2+a^2)}\right]$$

$$\xi_H = \sqrt{\phi_0/2\pi H}$$

$$\mathcal{C} = \eta a = \eta\sqrt{\frac{\phi_0}{\pi H}}$$

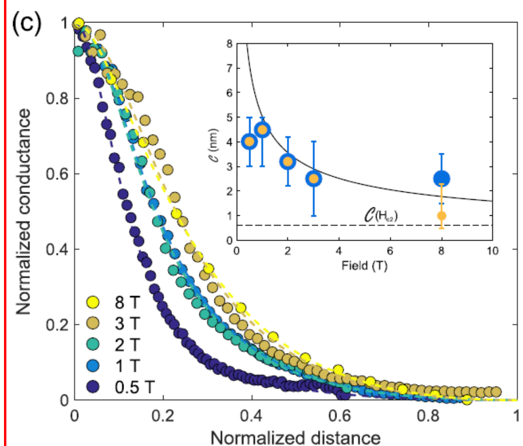


$$\mathcal{C} = \eta a = \eta\sqrt{\frac{\phi_0}{\pi H}} = \eta\sqrt{2}\,\xi_H$$

Field dependence of the vortex core size
V.G. Kogan and N.V. Zhelezina,
Phys. Rev. B, 71, 134505 (2005).

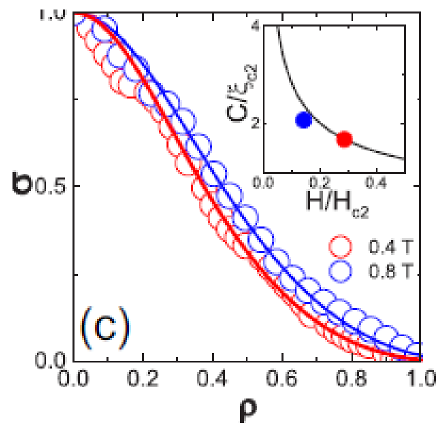
Applied to different superconductors

$CaKFe_4As_4$



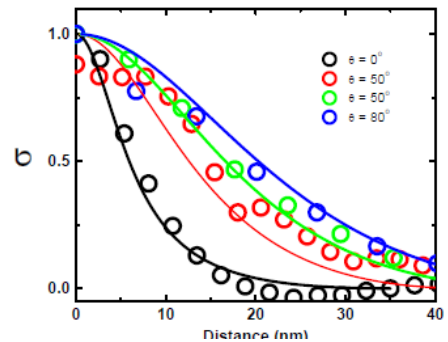
PRB 97, 134501 (2018)

$Rh_4In_4S_4$



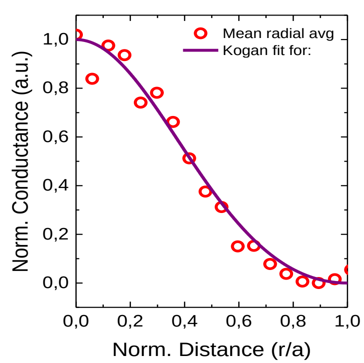
PRB 95, 134505 (2017)

$NbSe_2$



Comm. Phys. (2018) 1:30

$NbSe_{1.2}S_{0.8}$



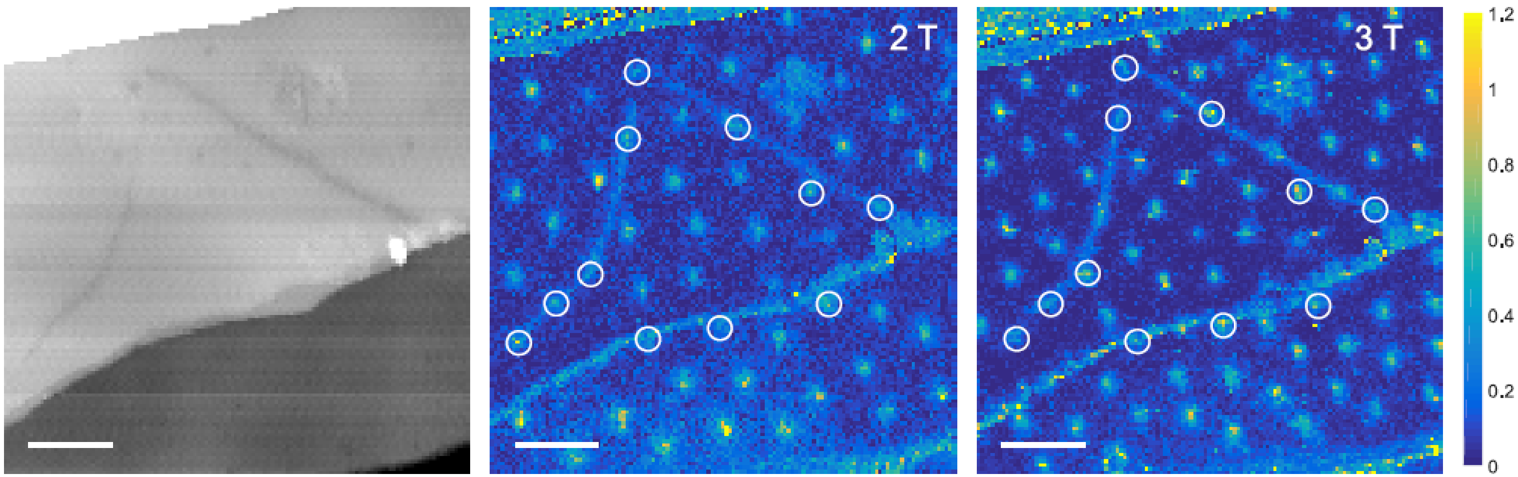
$$\frac{N(\boldsymbol{r})}{N_n} = 1 - \frac{|\Delta(\boldsymbol{r})|^2}{\Delta_0^2}$$

$$\frac{\Delta(r)}{\Delta_0(B,T)} = \frac{r}{\sqrt{r^2+\mathcal{C}^2}} \exp\left[-\frac{r^2\mathcal{C}^2}{2a^2(\mathcal{C}^2+a^2)}\right]$$

Field dependence of the vortex core size probed by STM
A. Fente et al, Phys. Rev. B, 94, 014517 (2016)

The $CaKFe_4As_4$ system

Pair breaking and vortex pinning in $CaKFe_4As_4$

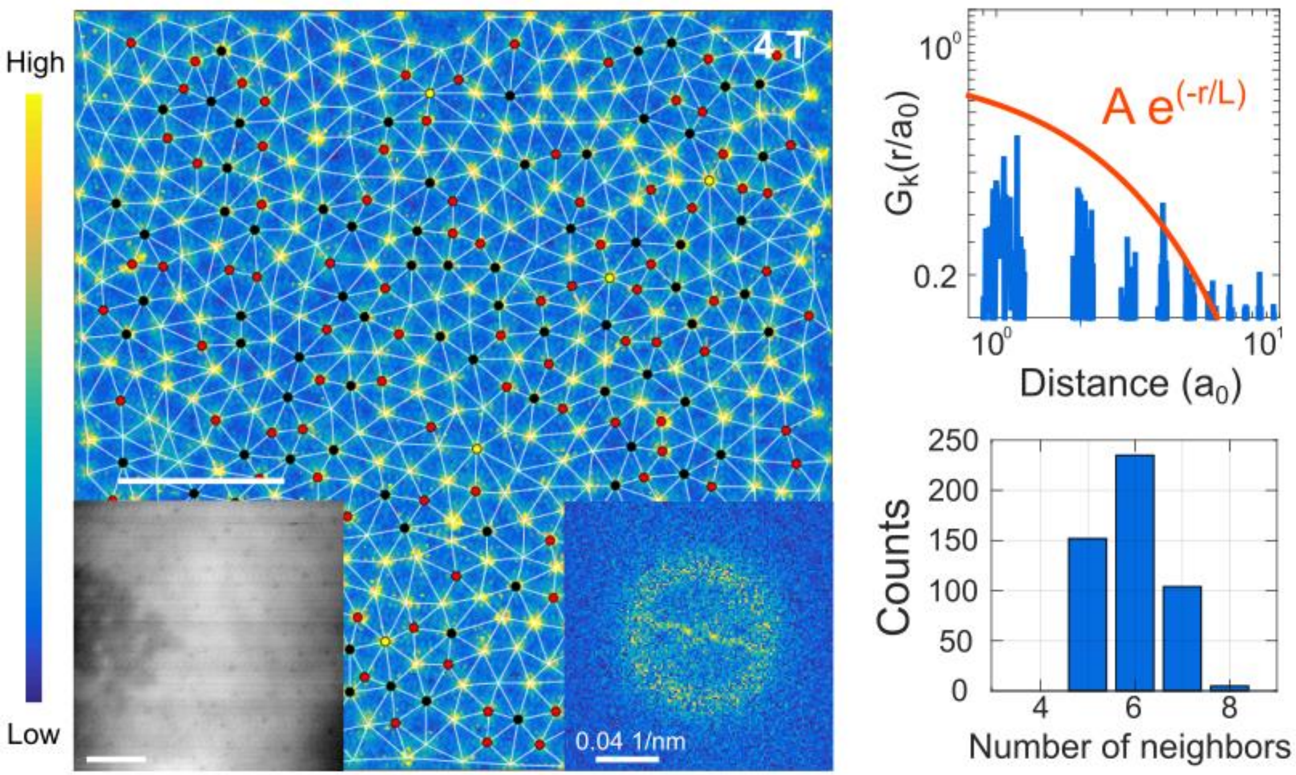


Core size $\mathcal{C}$ <-> size of pair breaking features

Single vortex pinning

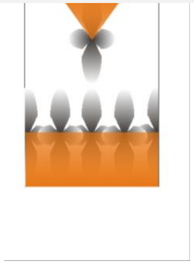
Field dependence of the vortex core size probed by STM
A. Fente et al, Phys. Rev. B, 94, 014517 (2016)

Disordered vortex lattice



Red: Vortex with five nearest neighbors
Black: Vortex with seven nearest neighbors

Real space imaging of the superconducting vortex lattice: Recent results and prospects



- Real space imaging and spectroscopy of the vortex lattice
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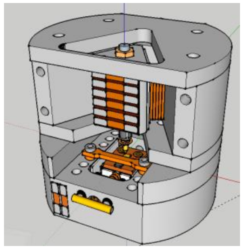
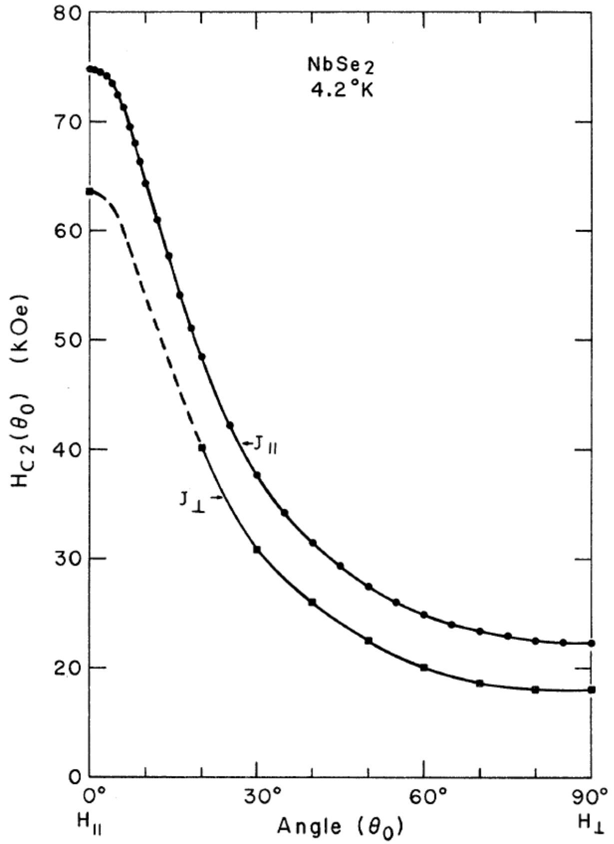


Upper critical field of the anisotropic superconductor 2H-$NbSe_2$

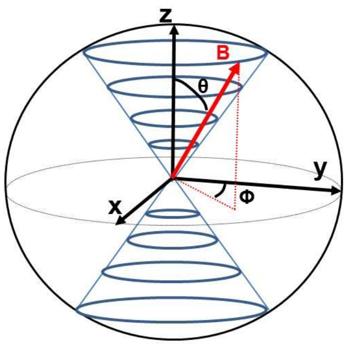
T_C = 7.2 K

$$H_{C2\perp} = 4.2T$$

$$H_{C2\parallel} = 12.7T$$



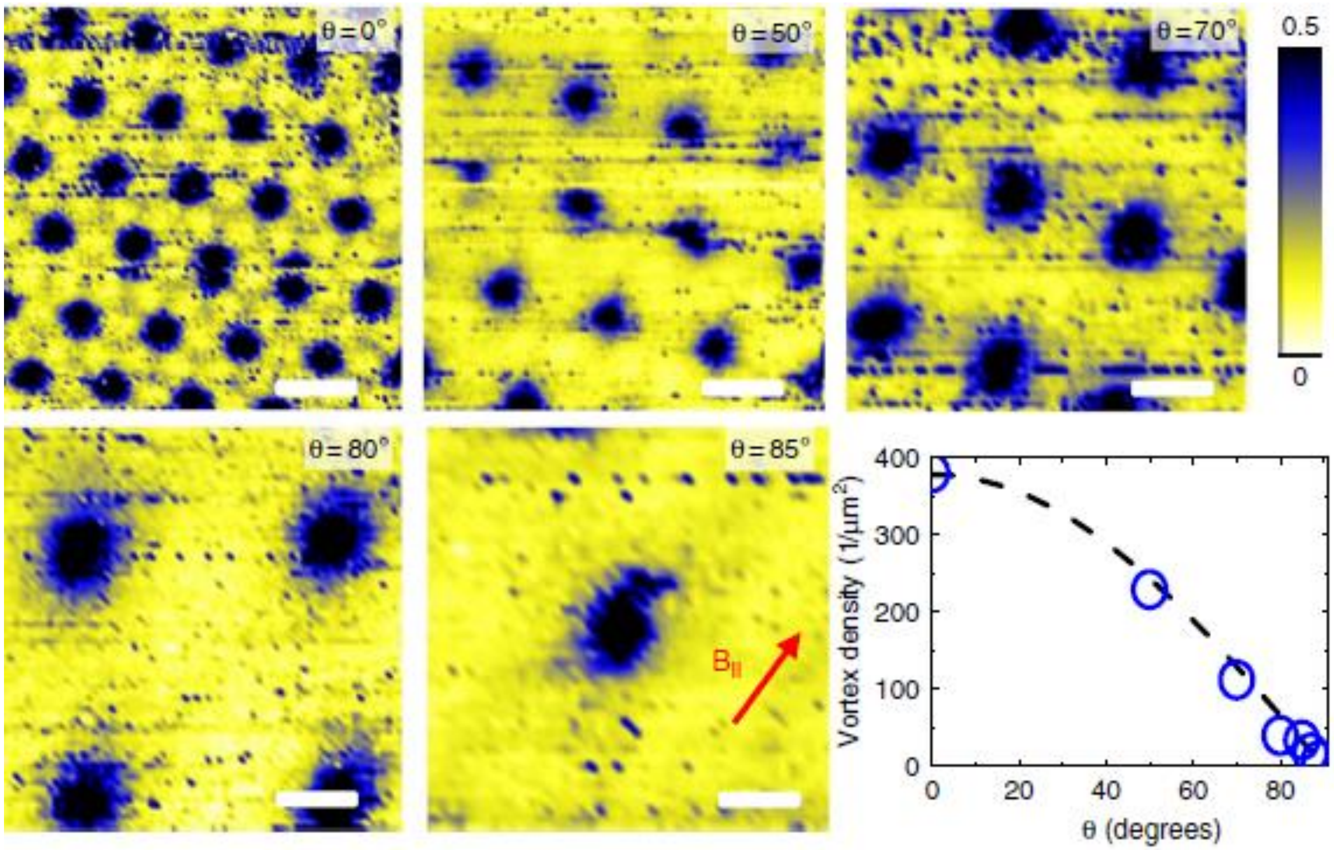
$$\Gamma = \frac{H_{C2\parallel}}{H_{C2\perp}} = \frac{\xi_{\parallel}}{\xi_{\perp}} \approx 3$$



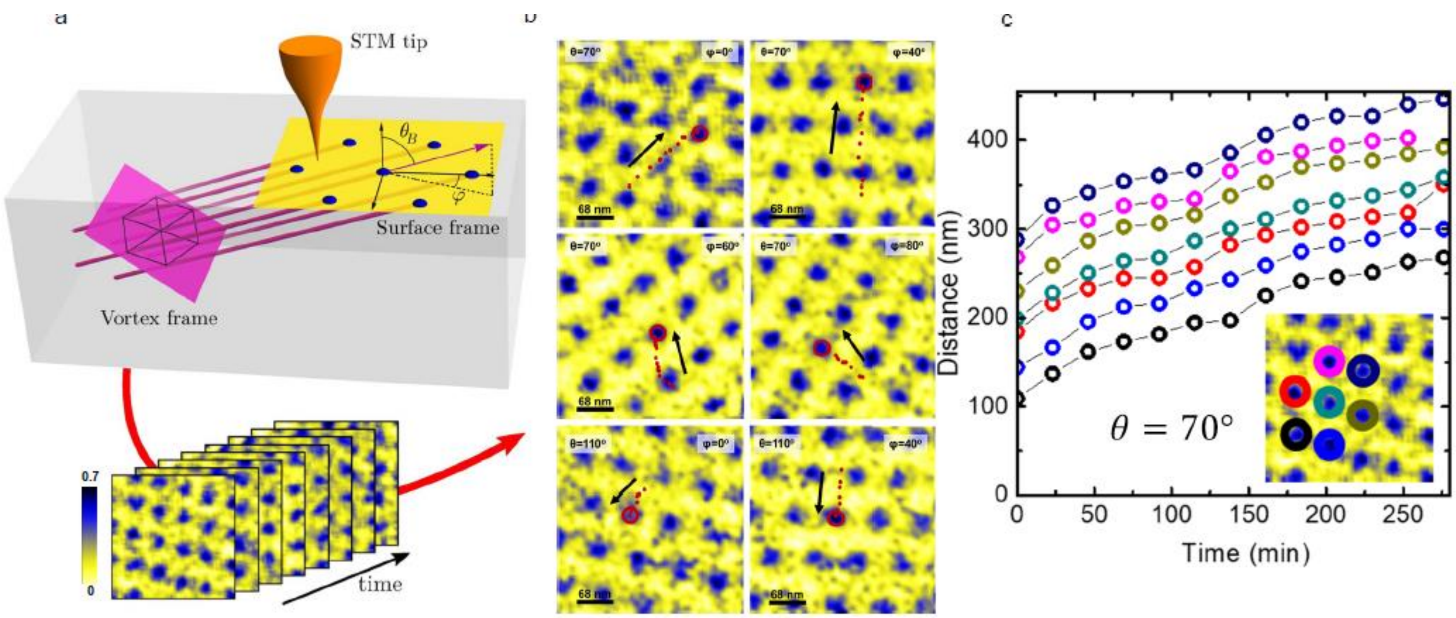
T. Janssen et al. Phys. Rev. B. 57, 11698 (1998)

R. C. Morriset al. Phys. Rev. B. 5, 895 (1972)

2H-$NbSe_2$: Vortex lattice in tilted magnetic fields

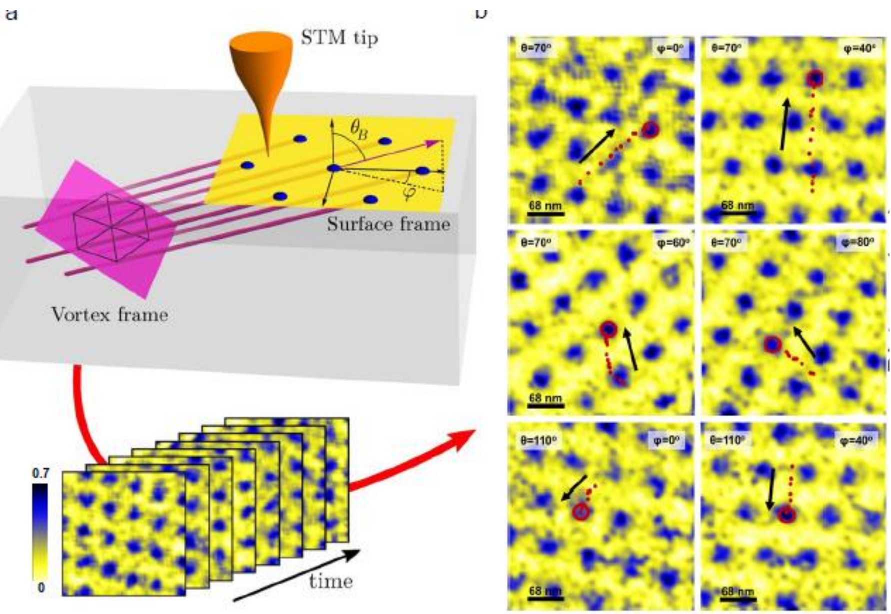


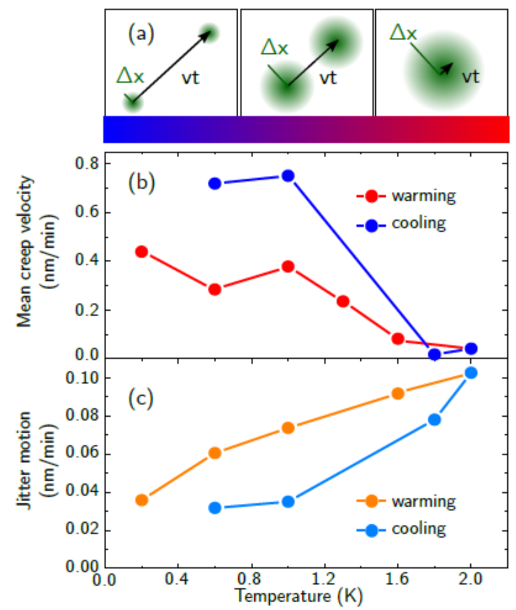
2H-$NbSe_2$: Vortex lattices spontaneously move sometimes in tilted magnetic fields



Slow vortex creep
Washboard potential

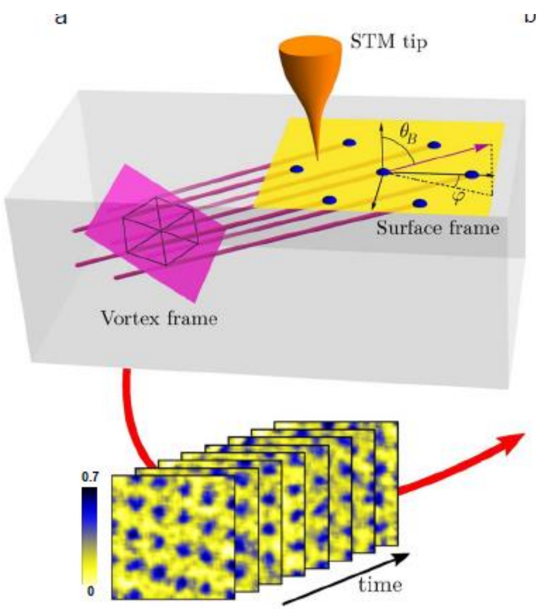
Creeping lattices when cooling

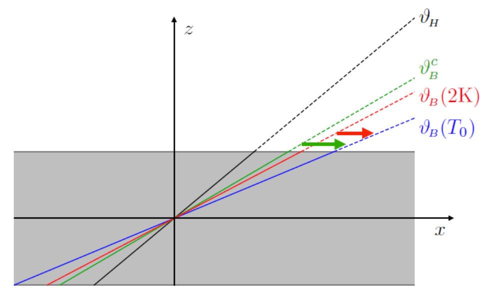


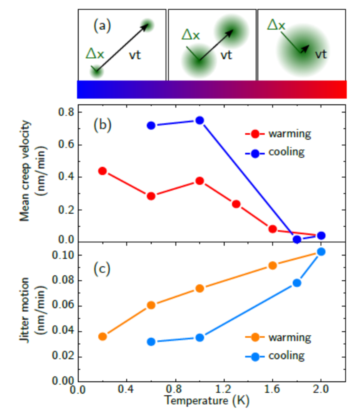


Increasing temperature stops creep
Decreasing temperature again -> creep restarts

Creeping lattices when cooling







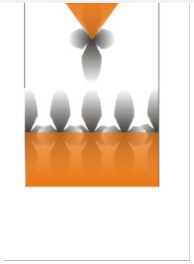
$$\sin(\theta_B - \theta_H) = \frac{H_{c1}}{H}\frac{(1-\varepsilon^2)\sin\theta_B\cos\theta_B}{(\varepsilon^2\sin^2\theta_B+\cos^2\theta_B)^{1/2}}$$

R. Willa
(Wednesday, 10h30, PC3-1)

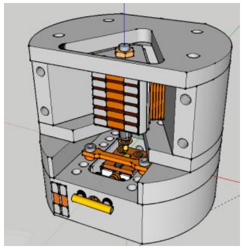
Increasing temperature stops creep
Decreasing temperature again -> creep restarts

Thermal creep emerging from cooling a tilted vortex lattice in uniaxial superconductor
R. Willa et al, arxiv 1906.06294

Real space imaging of the superconducting vortex lattice: Recent results and prospects



- Real space imaging and spectroscopy of the vortex lattice
- Superconducting $CaKFe_4As_4$, bandstructure, vortex core, vortex lattice and pinning
- Vortex lattice structure: interactions vs disorder
- Observation of vortex creep on cooling
- Josephson effect at atomic scale



Thank you very much for your attention

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E. Herrera, J. Benito
B. Wu
J.G. Rodrigo, S. Vieira

I. Guillamón

erc

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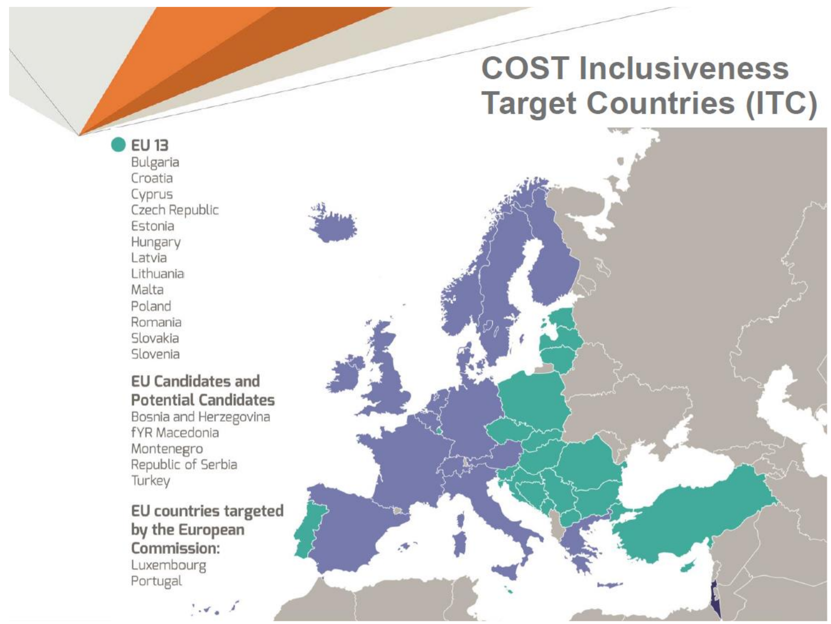

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Dimitri Roditchev and Brigitte Leridon, March 2018

School on quantum materials and workshop on vortex behavior in unconventional superconductors

7-12 October, 2018

Probing Coherent Superconducting Hybrids at the Nanoscale, 17-20 February 2019

13th November 2018 Meetings

Program and schedule The final schedule and abstract book are now available. Important dates February 17th: arrival in Eilat for dinner (around...

Yony Anahory and Beena Kalisky, February 2019

MolSpin NANOSCALE COHERENT HYBRID DEVICES FOR SUPERCONDUCTING QUANTUM TECHNOLOGIES

Joint workshop between MOLSPIN and NANOCOHYBRI – Superconductivity meets Molecular Spins – 20-22 March 2019

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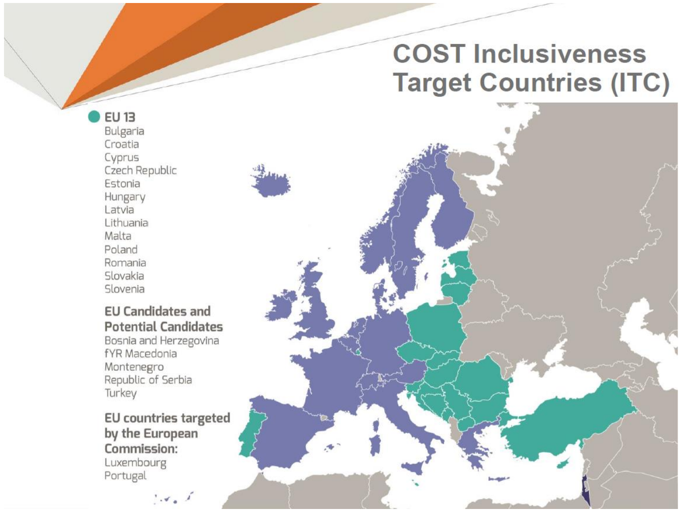

- *Open network*
- *Meetings (2/year)*
- *Short term stays*

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Short term stays

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Karazin Kharkov National University

COST International Partner Countries

Institution Name
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Ames Laboratory
National Institute for Materials Science
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