



**Training &
Experience Hub
Berlin**

Quantum Materials: from ARPES to trARPES



16/09/2026
online

Introduction to quantum materials and their key phenomena

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Kyiv Academic University

Department of Applied Physics and Nanomaterials > <https://kau.org.ua/en/kordyuk>



G.V. Kurdyumov Institute for Metal Physics of NAS of Ukraine

Department of Superconductivity > <https://www.imp.kiev.ua/~kord>



Leibniz Institute for Solid State and Materials Research Dresden - IFW Dresden

Leibniz Lab in Kyiv > <https://gu-qumat.ifw-dresden.de>



German-Ukrainian Center for Quantum Materials

<https://kau.org.ua/gu-qumat>

Light for
Ukraine

Eastern European
Synchrotron Light Source
in Ukraine



<https://vuias.org>



National Research
Foundation of Ukraine
<https://nrfu.org.ua>



KYIV ACADEMIC UNIVERSITY
learning by doing research internationally



KAU Quantum Seminar

KAU-BITP WINTER STUDENT SCHOOL

FRONTIERS IN
CONDENSED MATTER
PHYSICS

January 11-15, 2021

Головна

Новини

Освіта

Кафедри

Наука

Випускники

Контакти

Центр дослідження даних

Центр квантових матеріалів та технологій

German-Ukrainian Lab (UKRATOR)

Науково-освітній центр KAY-Risen (KRREC)

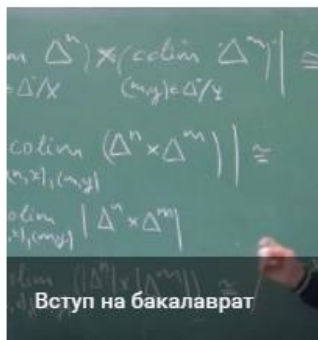
Інноваційний центр

Лабораторія електронного приладобудування

Проект Багатозонність



Малий академічний університет



Вступ на бакалаврат

Останні новини

Анонси

Семінари

Школи, конференції

Новини науки

- 27.05.2021 "Інноваційні рішення в енергетиці: можливі науки та бізнесу"
- Стартувала реєстрація на ЄВІ/ЄФВВ для вступу до магістратури
- 05.05.2021. Квантовий семінар KAU: Д.Якименко, Огляд проблем теорії квантових обчислень

27.05.2021 "Інноваційні рішення в енергетиці: можливі науки та бізнесу"



Quantum Materials Group

Design of smart quantum materials for quantum technologies of the superconducting order parameters. Search for new superconductors.



Alexander Kordyuk



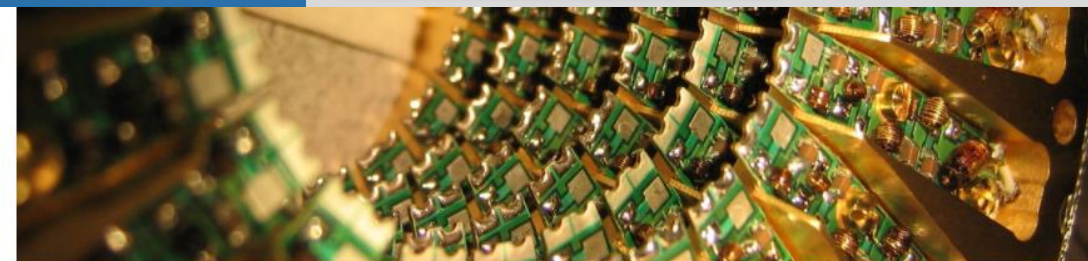
Alexander Plyushchay



Volodymyr Bezguba

The Center is focused on synergy of deep understanding of quantum materials and quantum devices design for emerging quantum technologies

KAU Research Center for Quantum Materials and Quantum Technologies (Q²RC)



27-28 July 2022

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Quantum Research and Education in Europe and in Ukraine

<http://kau.org.ua>

<http://kau.org.ua/centers/qmtech>



KYIV ACADEMIC UNIVERSITY
learning by doing research internationally

Aimed at
attracting students to scientific research
through the synergy of education, research,
and innovation

Learning by doing **cutting-edge** research

- Quantum Materials + Quantum Technologies
- ML for Research: Condmat, Astrophys, Bio, Math
- RI Development (Synchrotron Research)

**International
Collaboration**

**Students and
Young Scientists**

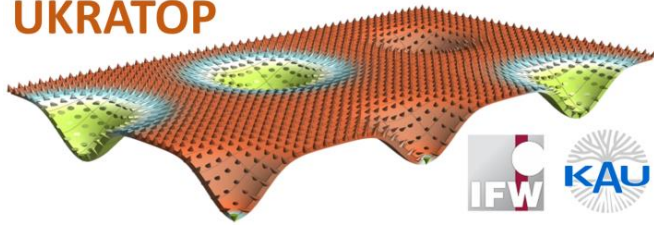
**Research
Infrastructure**

UKRATOP – a research⁺ bilateral project on Topological Quantum Materials

KAU+IFW & TU Dresden: 1 000 000 EUR/4 years

<https://kau.org.ua/ukratop>

UKRATOP



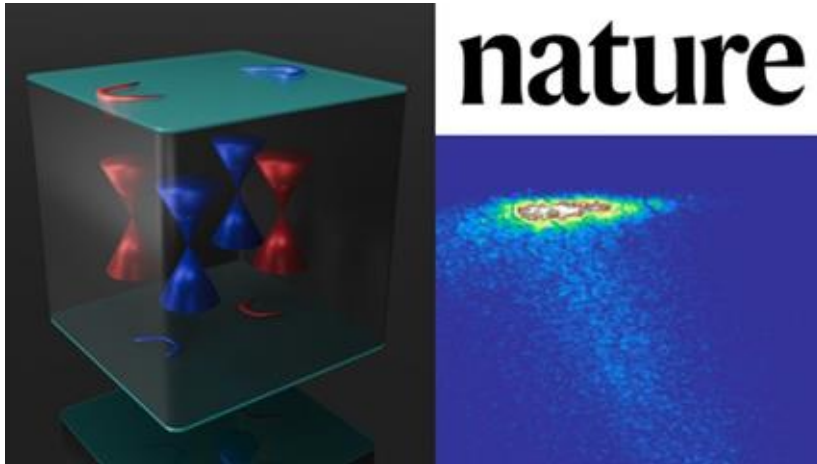
Scholarships: 21 MSc students;
2 PhD students; 5 PostDocs.

Experience in highest level research
and communication, strengthening p2p collaboration

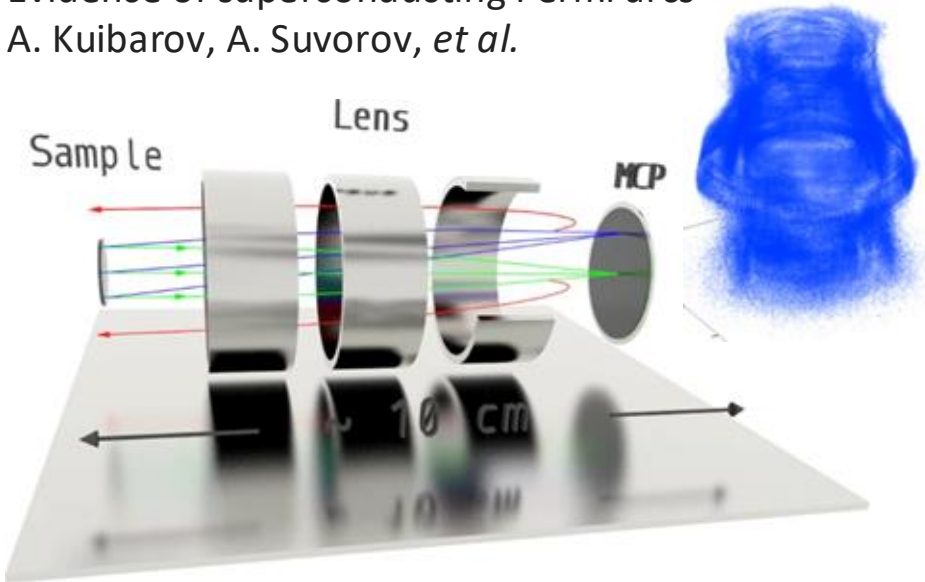
All MSc and PhD students defended their degrees in Ukraine

Exp. equipment from IFW Dresden installed in Kyiv





Evidence of superconducting Fermi arcs
A. Kuibarov, A. Suvorov, *et al.*



NATURE COMMUNICATIONS S. Borisenko *et al.*
Fermi surface tomography.

Scientific Output

2024

[Nature 626, 294 \(2024\)](#)

2023

[J. Cryst. Growth 619, 127332 \(2023\)](#)

[Phys. Rev. B 107, 165141 \(2023\)](#)

[Phys. Rev. Materials 7, 033405 \(2023\)](#)

[Phys. Rev. B 107, 035158 \(2023\)](#)

[Phys. Rev. Materials 7, 014003 \(2023\)](#)

[Phys. Rev. Materials 7, 014003 \(2023\)](#)

2022

[Phys. Rev. B 106, 085401 \(2022\)](#)

[Phys. Rev. Lett. 129, 227203 \(2022\)](#)

[Phys. Rev. B 106, 174426 \(2022\)](#)

[J. Phys. D: Appl. Phys. 55, 445003 \(2022\)](#)

[J. Solid State Chem. 314, 123416 \(2022\)](#)

[Nature Comm. 13, 4132 \(2022\)](#)

[Crystals 12, 998 \(2022\)](#)

[Phys. Rev. B 105, 235112 \(2022\)](#)

[Phys. Rev. Lett. 128, 036402 \(2022\)](#)

[Phys. Rev. B. 105, 024410 \(2022\)](#)

[Comput. Mater. Sci. 203, 111089 \(2022\)](#)

[Small 18, 2105219 \(2022\)](#)

2021

[Phys. Rev. Lett. 127, 045701 \(2021\)](#)

[SciPost Phys. 10, 004 \(2021\)](#)

[Dalton Transactions 51, 361 \(2021\)](#)

[Crystals 11,500 \(2021\)](#)

[Cryst. Growth Des. 21, 3063\(2021\)](#)

[J. Cryst. Growth 562, 126082 \(2021\)](#)

[J. Alloys Compds. 855, 157334 \(2021\)](#)

[Ukr. J. Phys. 66, 333 \(2021\)](#)

2020

[SciPost Phys. 9, 043 \(2020\)](#)

[Nano Lett. 2020, 20, 11, 8157 \(2020\)](#)

[Appl. Phys. Lett. 116, 222406 \(2020\)](#)

[Phys. Rev. Materials 4, 124202 \(2020\)](#)

[npj Quantum Materials 5, 67 \(2020\)](#)

[Phys. Rev. B 102, 220408\(R\) \(2020\)](#)

[npj Quantum Materials 5, 22 \(2020\)](#)

2019

[SciPost Phys. 7, 035 \(2019\)](#)

[Phys. Rev. B 99, 014404 \(2019\)](#)

[Phys. Rev. B 99, 184429 \(2019\)](#)

[Phys. Rev. B 100, 140407\(R\) \(2019\)](#)

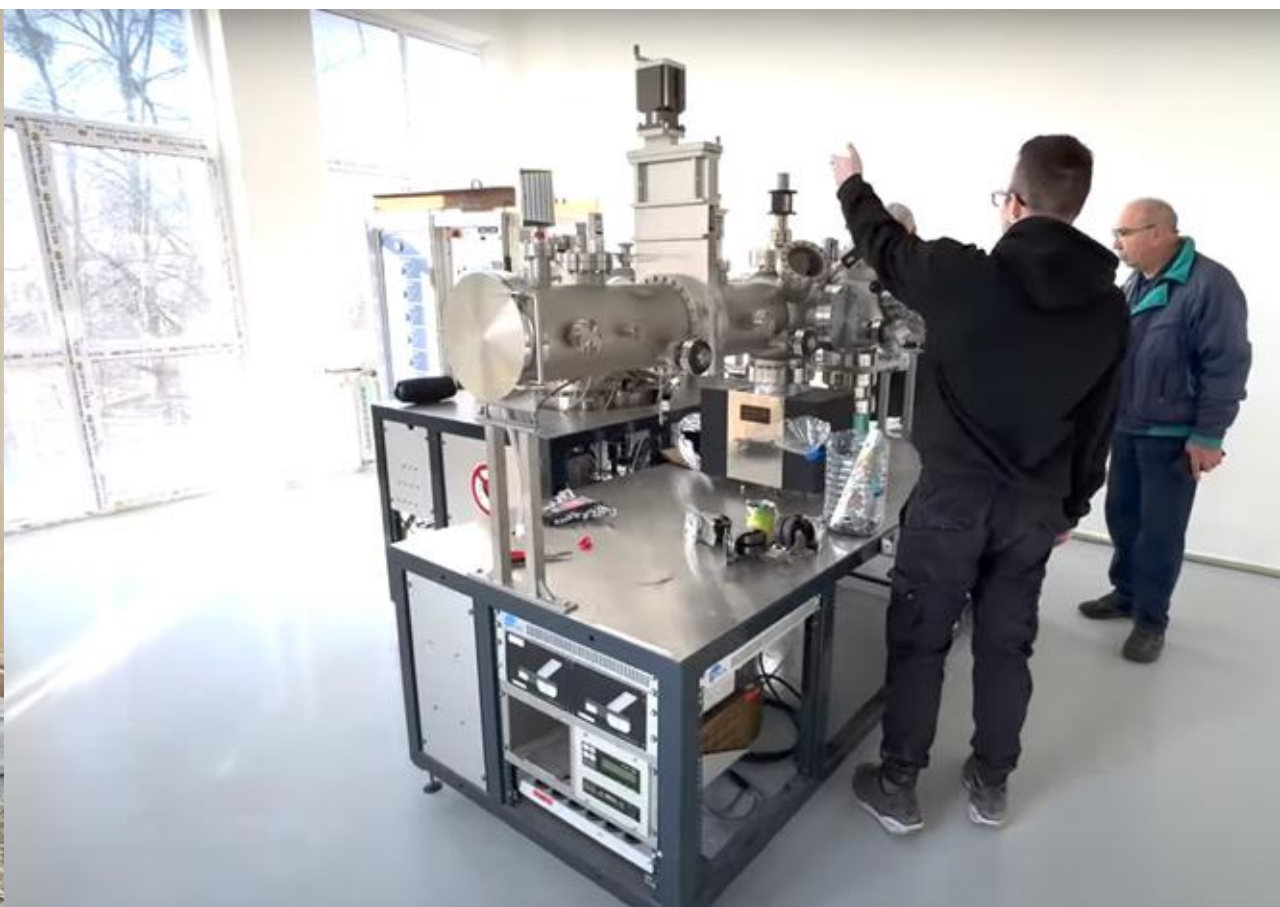
[Mater. Res. Express 6, 106319 \(2019\)](#)

[APL Materials 7, 121106 \(2019\)](#)

[Low Temperature Physics 45, 1172 \(2019\)](#)

German-Ukrainian Center for Quantum Materials

aiming in the theory assisted search for new quantum materials





“Quantum materials”



Semiclassics



Strong correlations

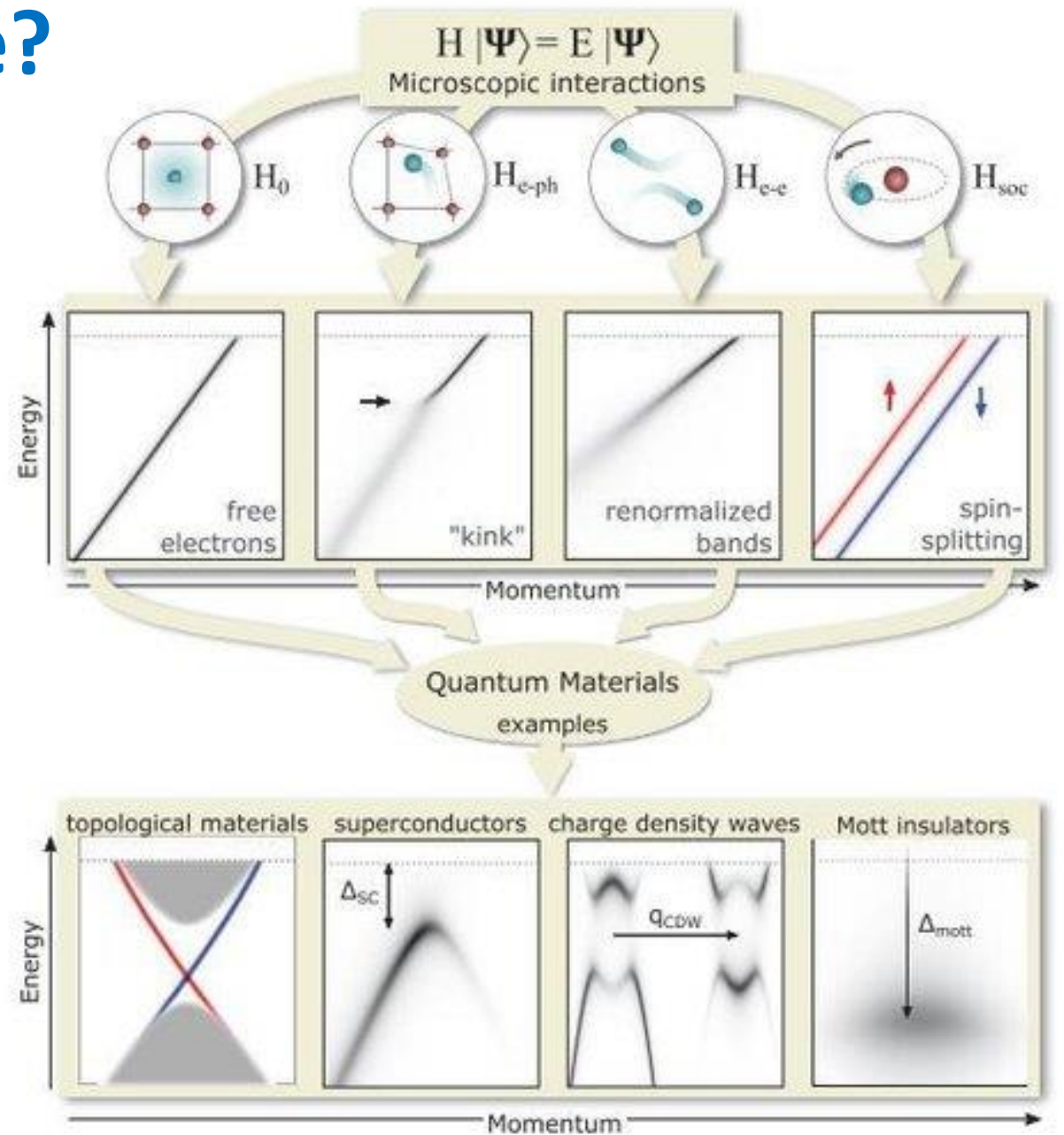
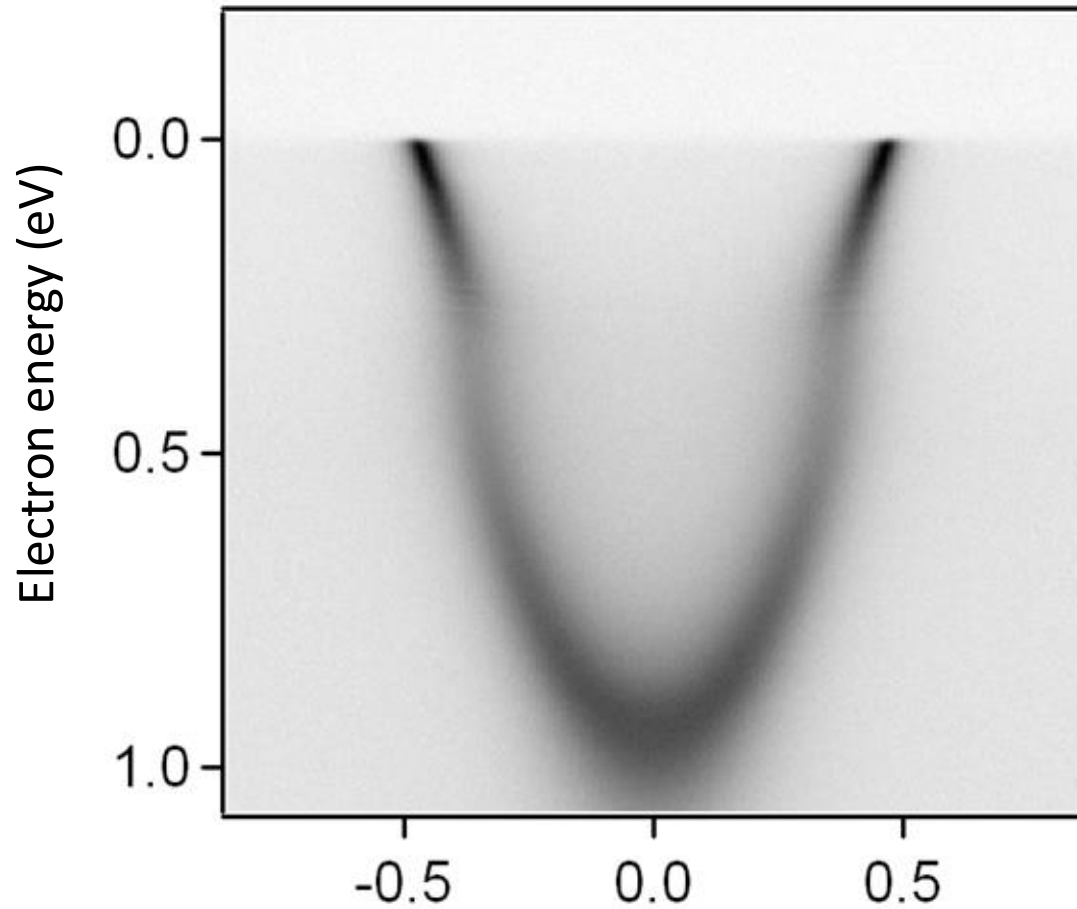


Emergence

Quantum technology

- Robert Cava *et al.* - Introduction: Quantum Materials. *Chemical Reviews* **121**, 2777 (2021)
- The rise of quantum materials. *Nature Physics* **12**, 105 (2016)

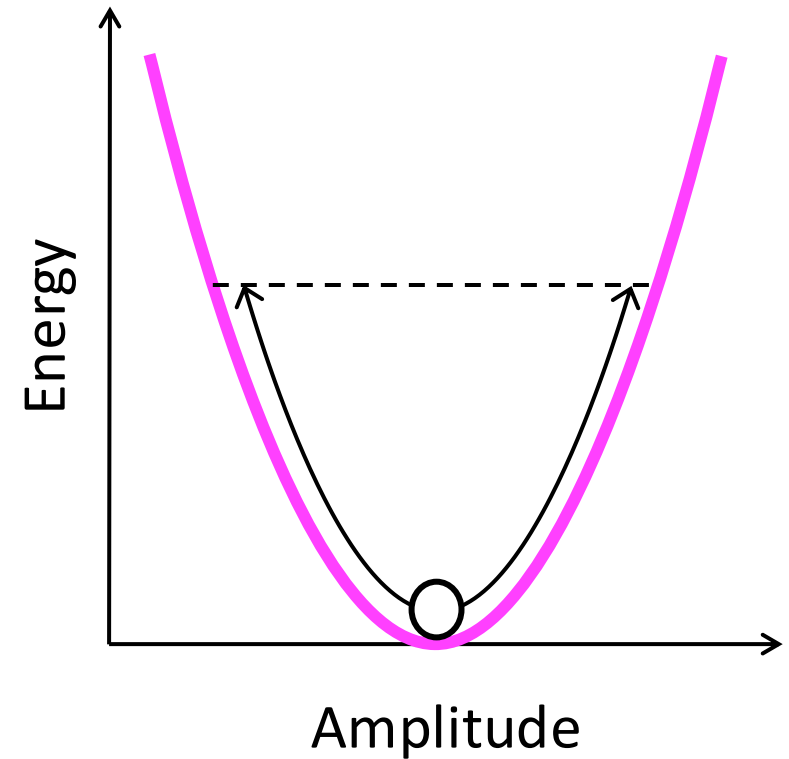
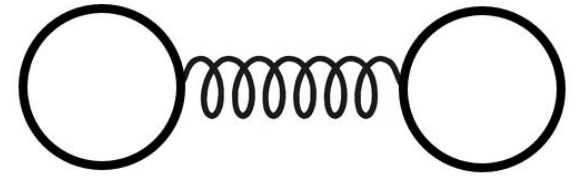
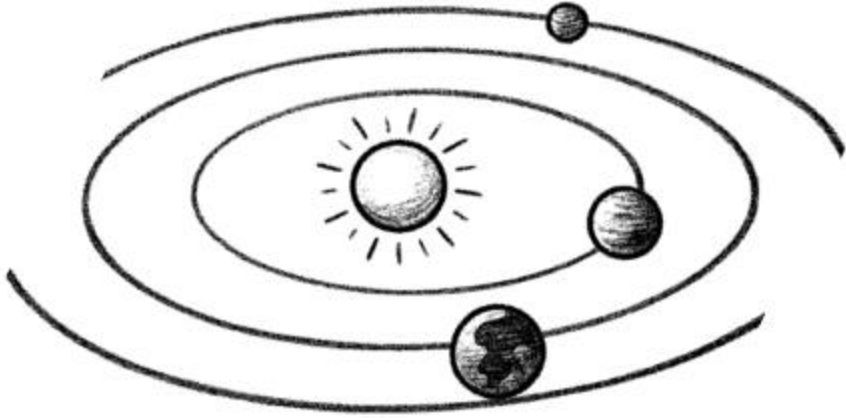
Measure for Emergence?



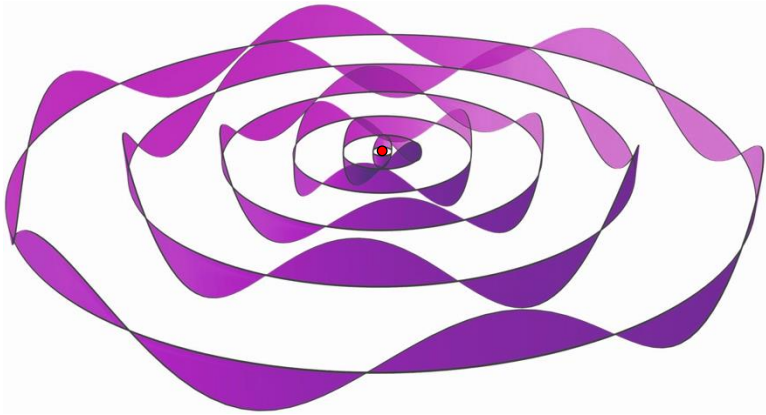
Introduction to quantum materials (QM) and their key phenomena

- All the materials are quantum
- Electronic structure is a key
- Emergent phenomena
- Why Superconductors are QM^N
- Other examples:
 - TMD's and Topological Insulators
 - QM^{N+1}

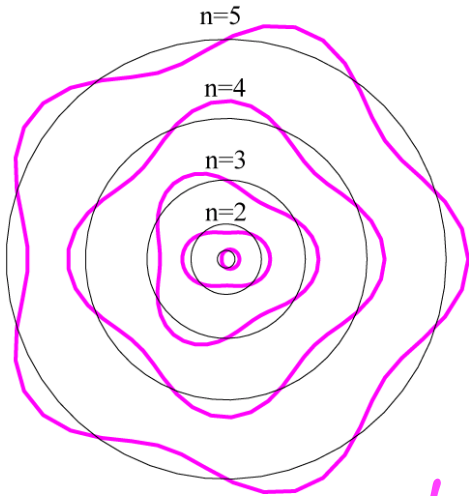
Classical oscillator $\rightarrow$ quantum oscillator



Wave → Interference → Quantization

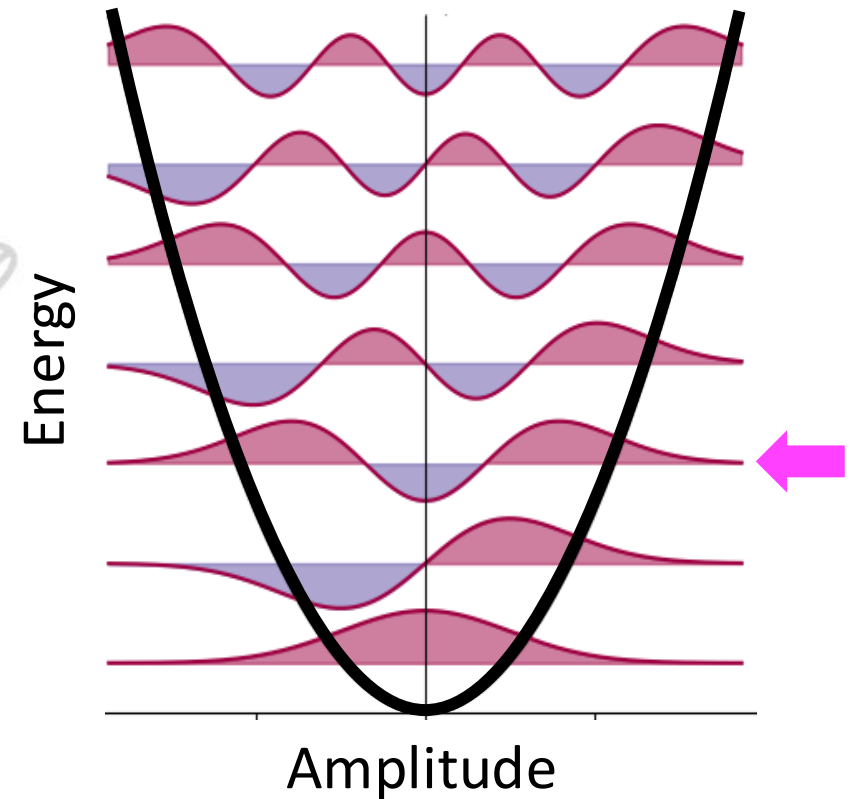


Bohr atom



$$p = mv = \hbar k = \frac{h}{\lambda}$$

de Broglie wave

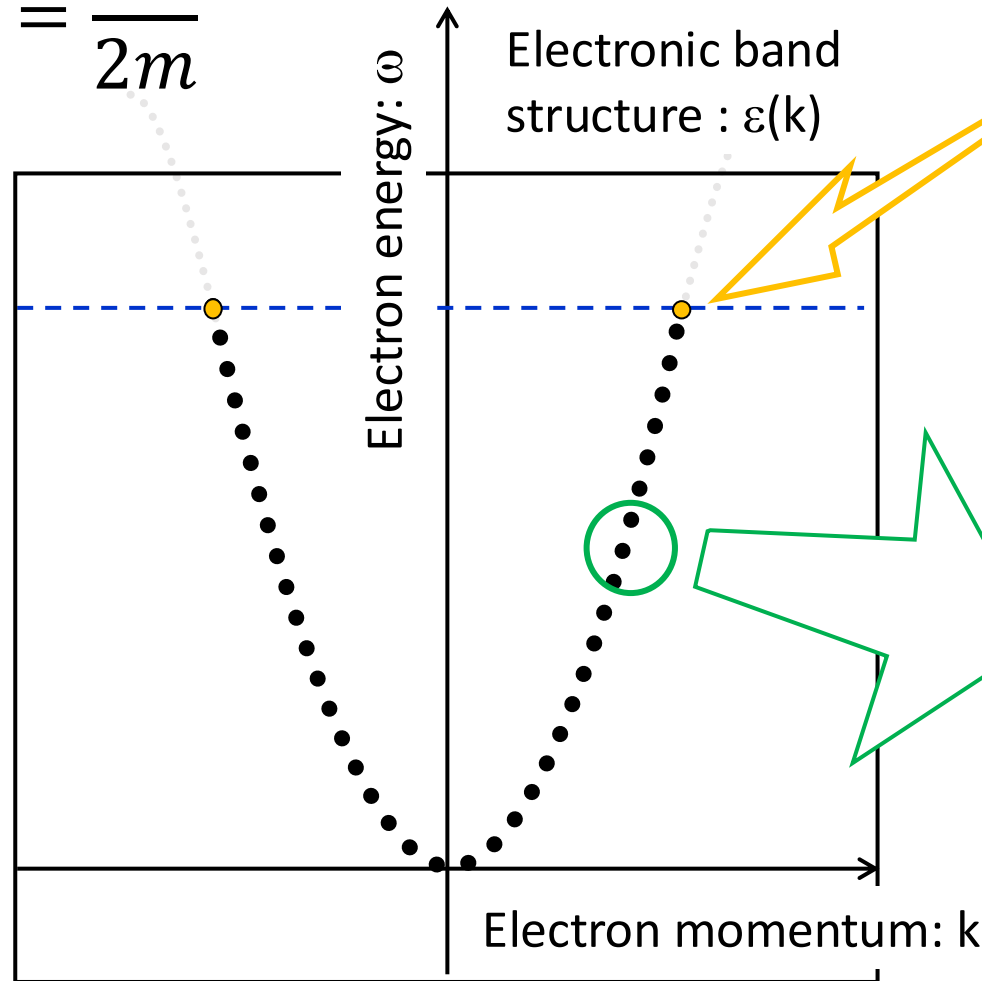


Electronic structure under the ARPES microscope:
electron states are quantized

(Heisenberg and Pauli)

$$E_k = \frac{mv^2}{2} = \frac{p^2}{2m}$$

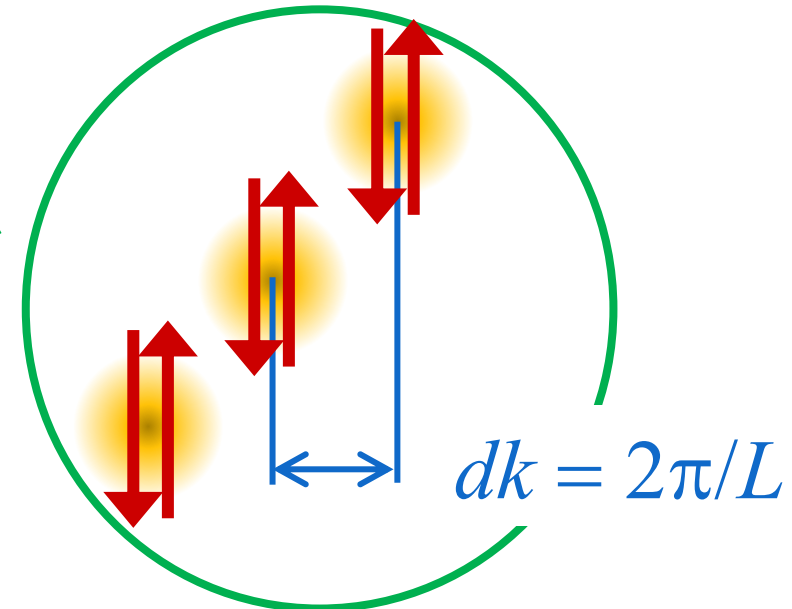
$$p = \hbar k$$



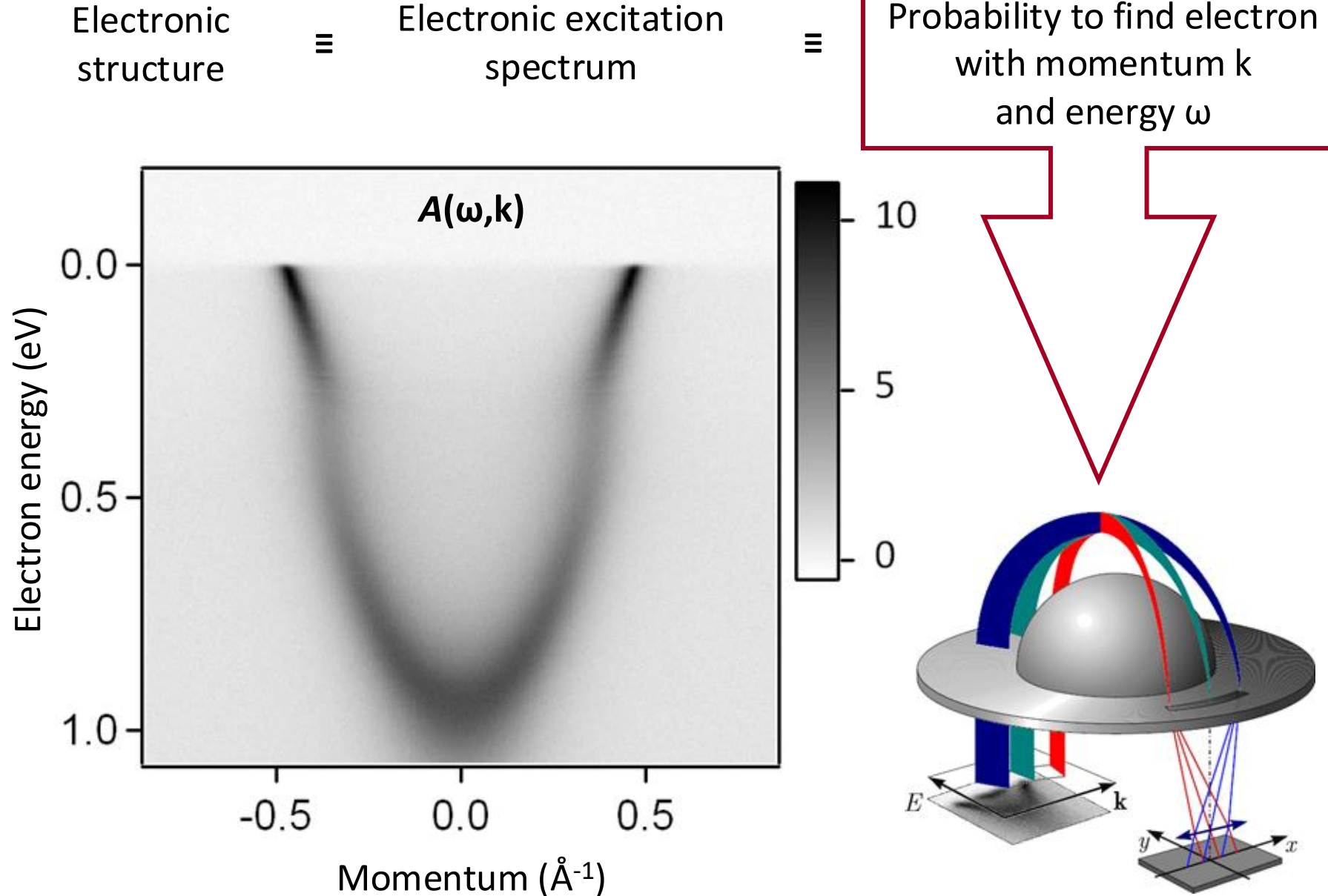
Fermi surface



$$\Delta x \Delta p \geq \frac{\hbar}{2}$$



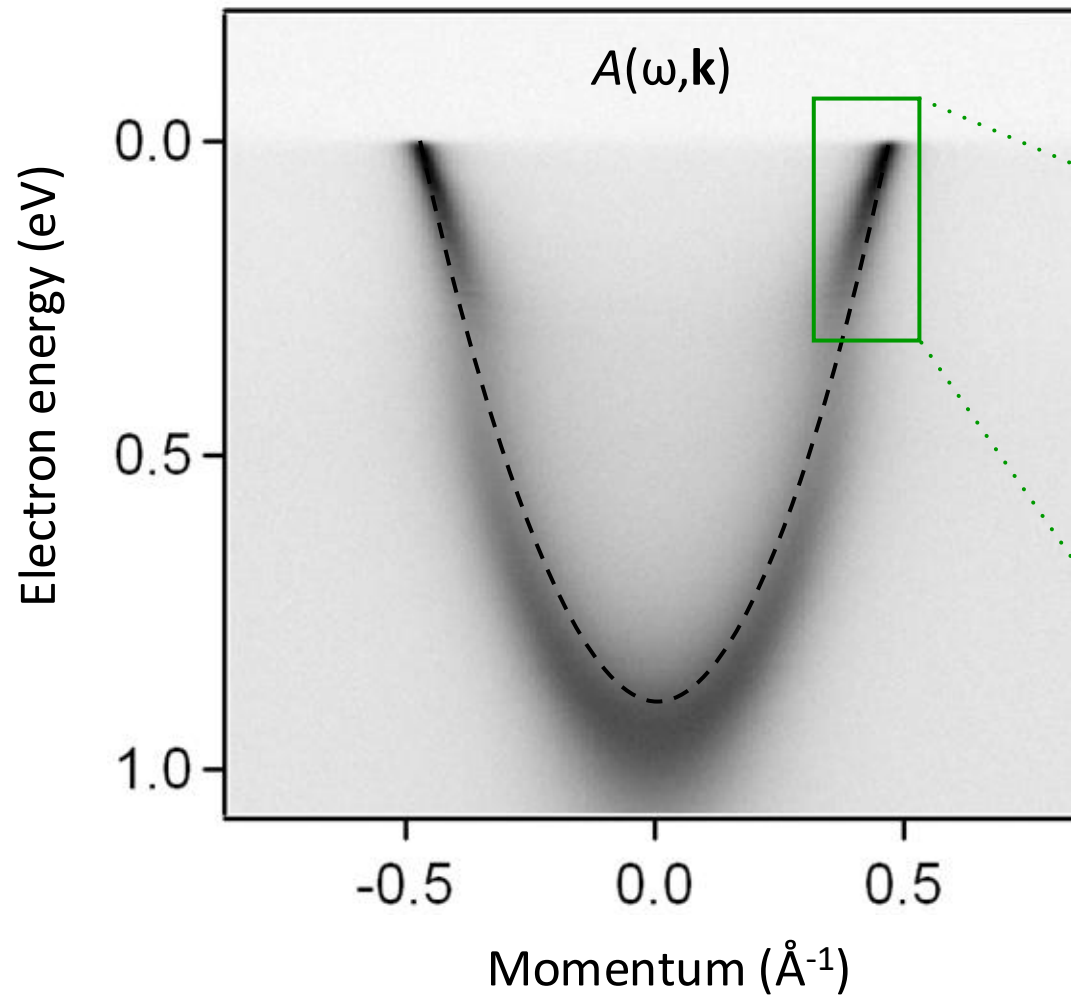
Photoemission spectrum



Structure of electronic spectrum

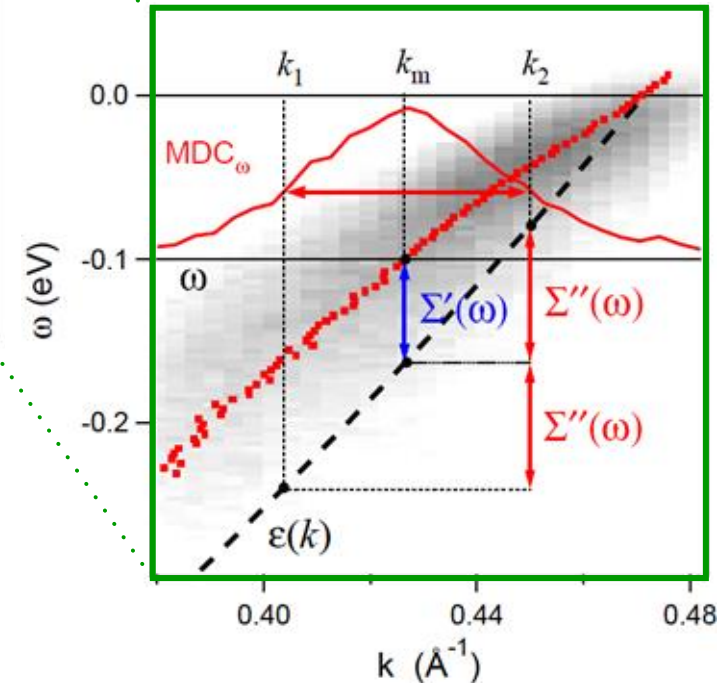
Spectral
function

$$A(\omega, \mathbf{k}) = -\frac{1}{\pi} \frac{\Sigma''(\omega)}{(\omega - \varepsilon(\mathbf{k}) - \Sigma'(\omega))^2 + \Sigma''(\omega)^2}$$

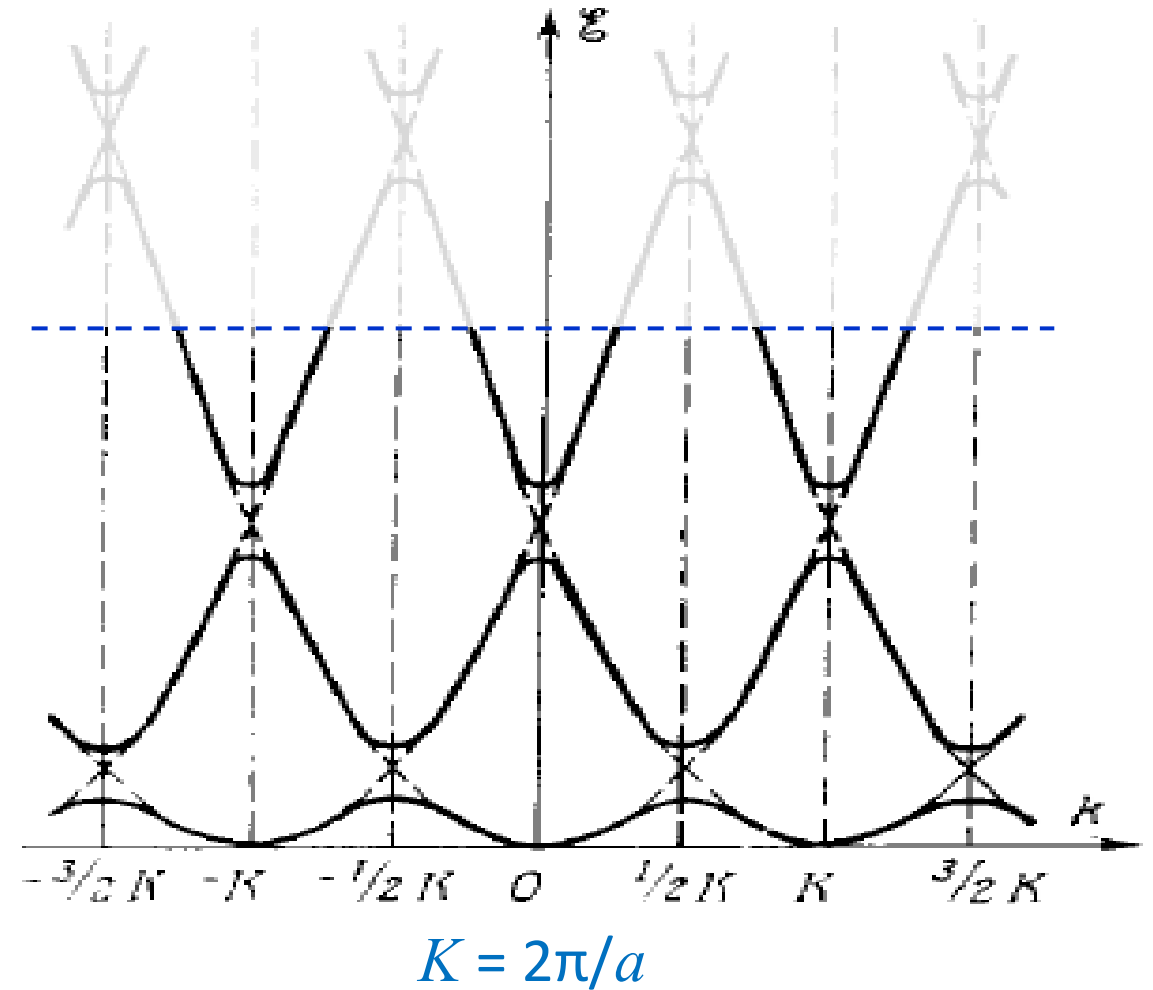
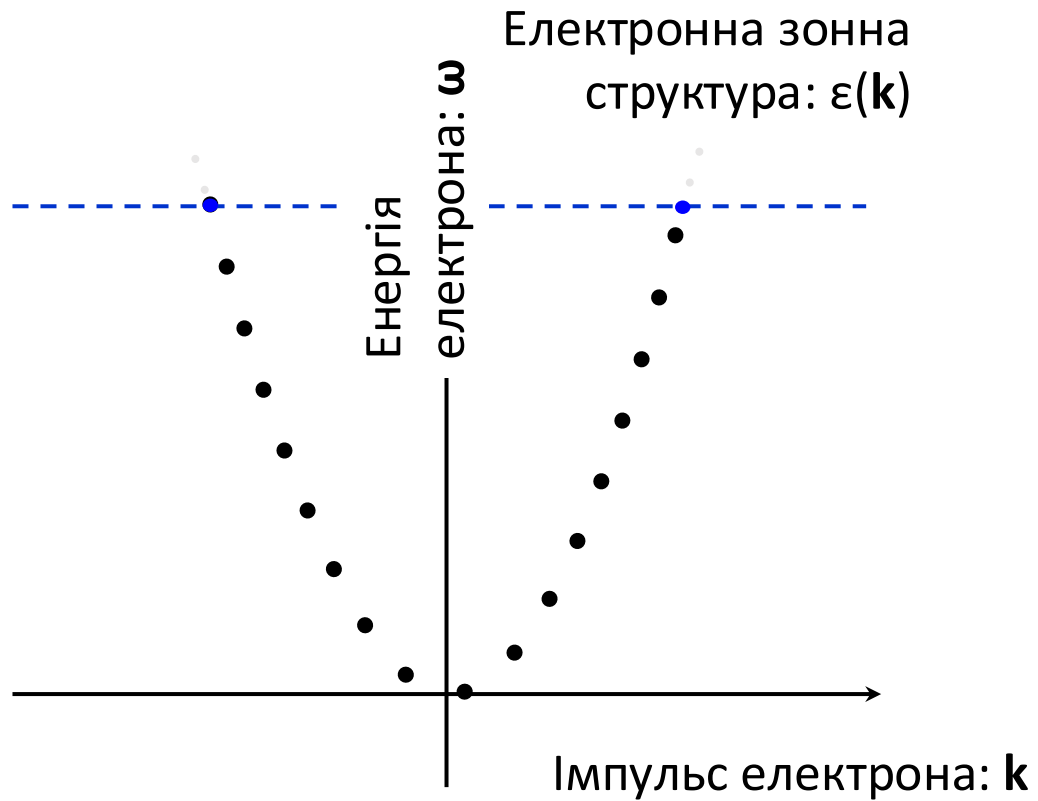
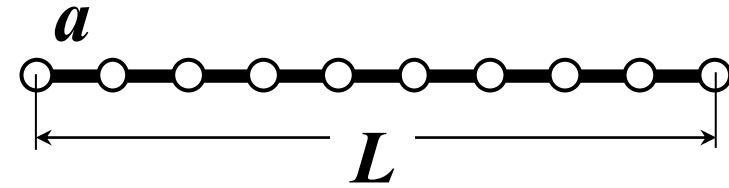


$\varepsilon(\mathbf{k})$ – “bare” electronic
band structure

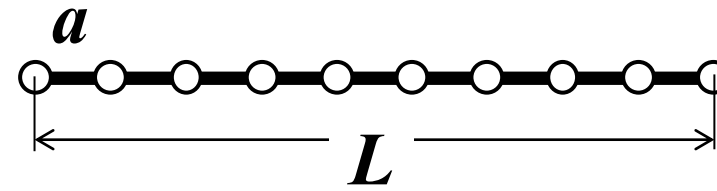
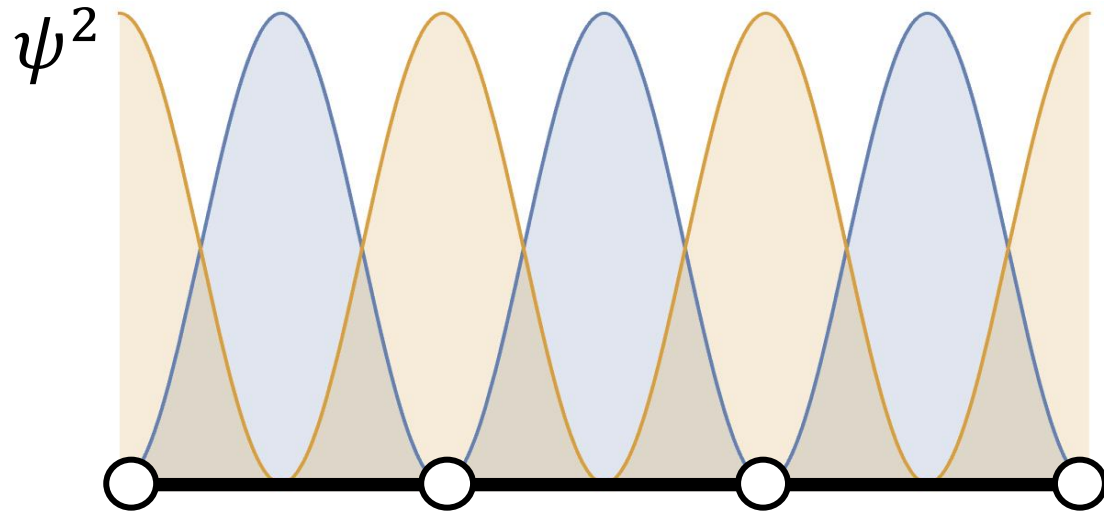
$\Sigma(\omega, \mathbf{k})$ – self-energy



From plane waves to Bloch waves



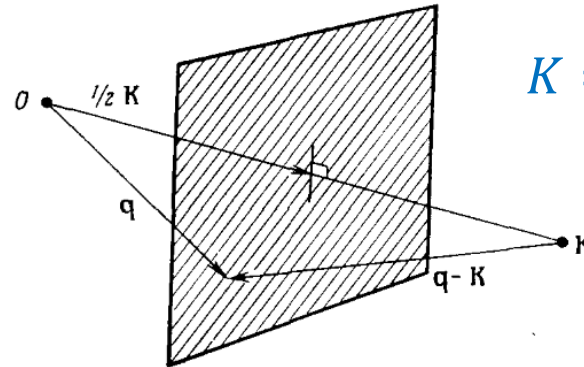
Electrons in a Weak Periodic Potential: Band Gaps



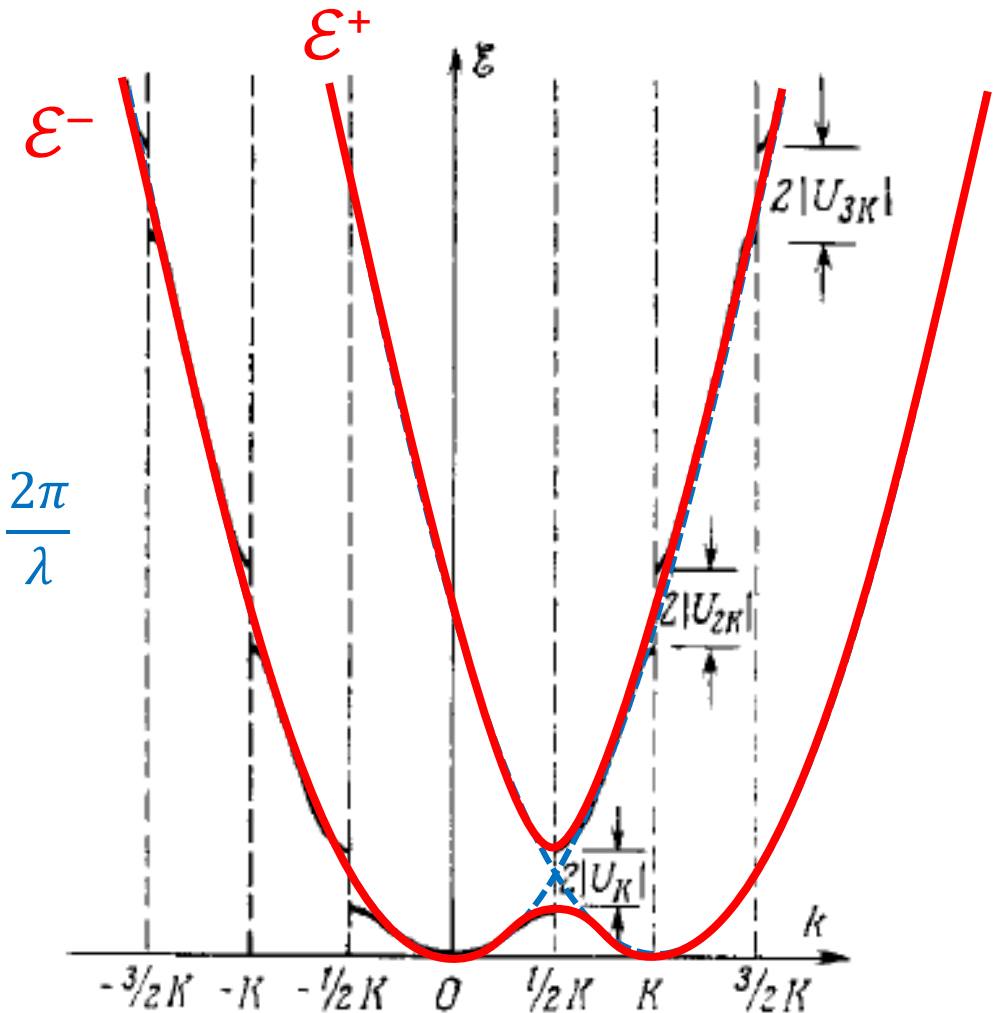
$$\begin{vmatrix} \mathcal{E} - \mathcal{E}_q^0 & -U_K \\ -U_K^* & \mathcal{E} - \mathcal{E}_{q-K}^0 \end{vmatrix} = 0$$

$$(\mathcal{E} - \mathcal{E}_q^0)(\mathcal{E} - \mathcal{E}_{q-K}^0) = |U_K|^2$$

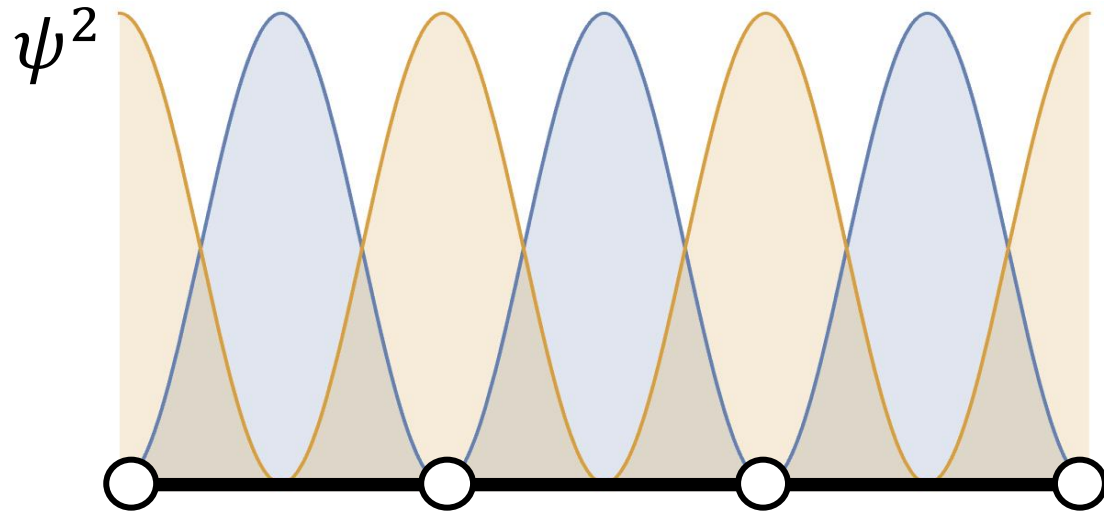
$$\mathcal{E} = \frac{1}{2} (\mathcal{E}_q^0 + \mathcal{E}_{q-K}^0) \pm \left[\left(\frac{\mathcal{E}_q^0 - \mathcal{E}_{q-K}^0}{2} \right)^2 + |U_K|^2 \right]^{1/2}$$



$$K = \frac{2\pi}{a} = \frac{2\pi}{\lambda}$$



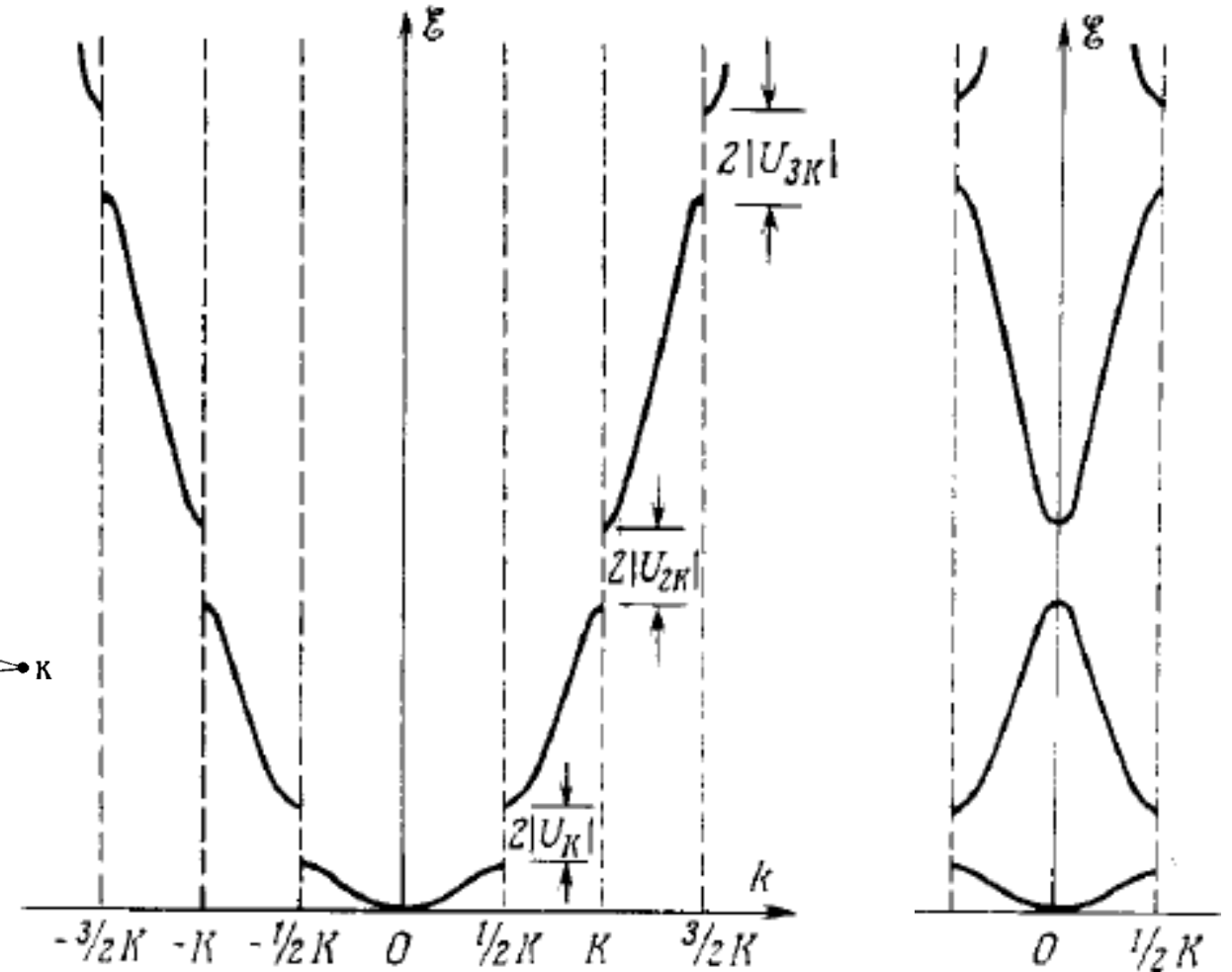
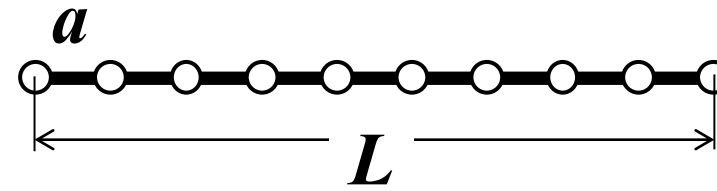
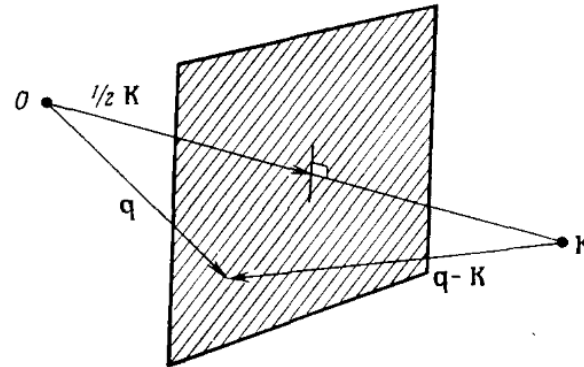
Electrons in a Weak Periodic Potential: Band Gaps



$$\begin{vmatrix} \mathcal{E} - \mathcal{E}_q^0 & -U_K \\ -U_K^* & \mathcal{E} - \mathcal{E}_{q-K}^0 \end{vmatrix} = 0$$

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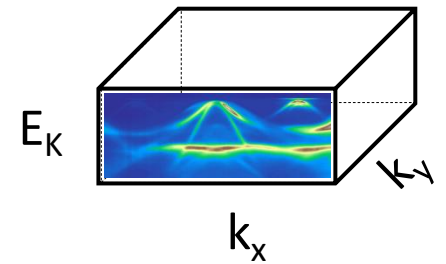
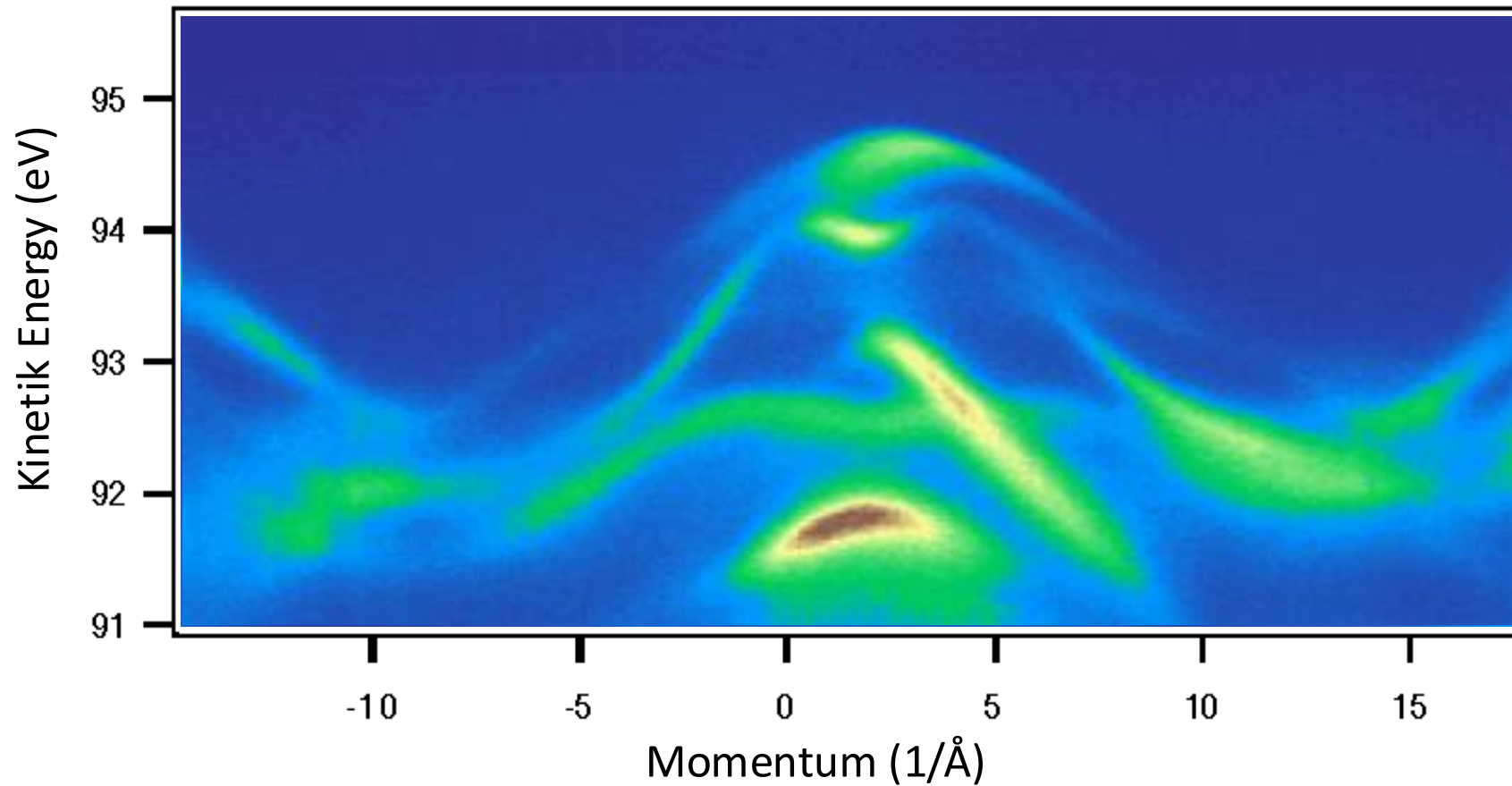
$$\mathcal{E} = \frac{1}{2} (\mathcal{E}_q^0 + \mathcal{E}_{q-K}^0) \pm \left[\left(\frac{\mathcal{E}_q^0 - \mathcal{E}_{q-K}^0}{2} \right)^2 + |U_K|^2 \right]^{1/2}$$



$$K = 2\pi/a$$

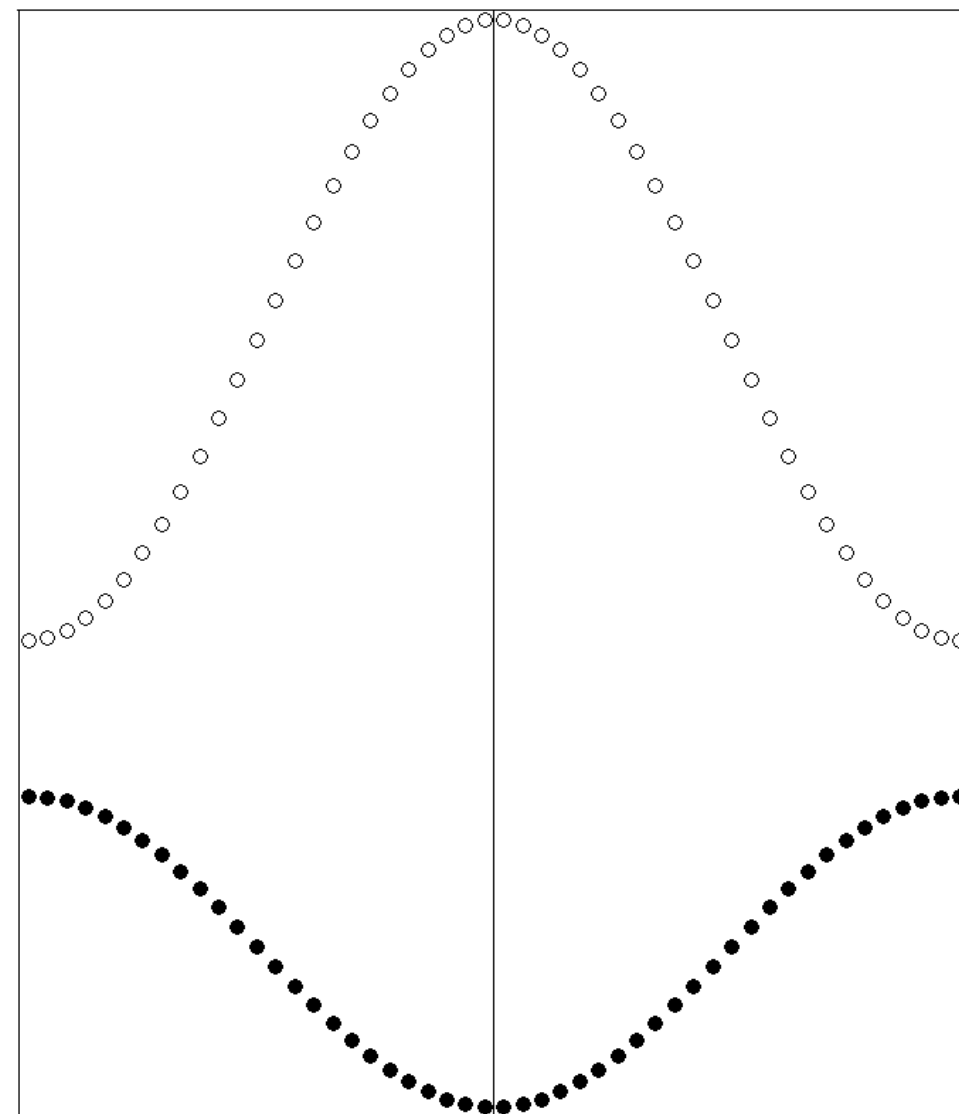
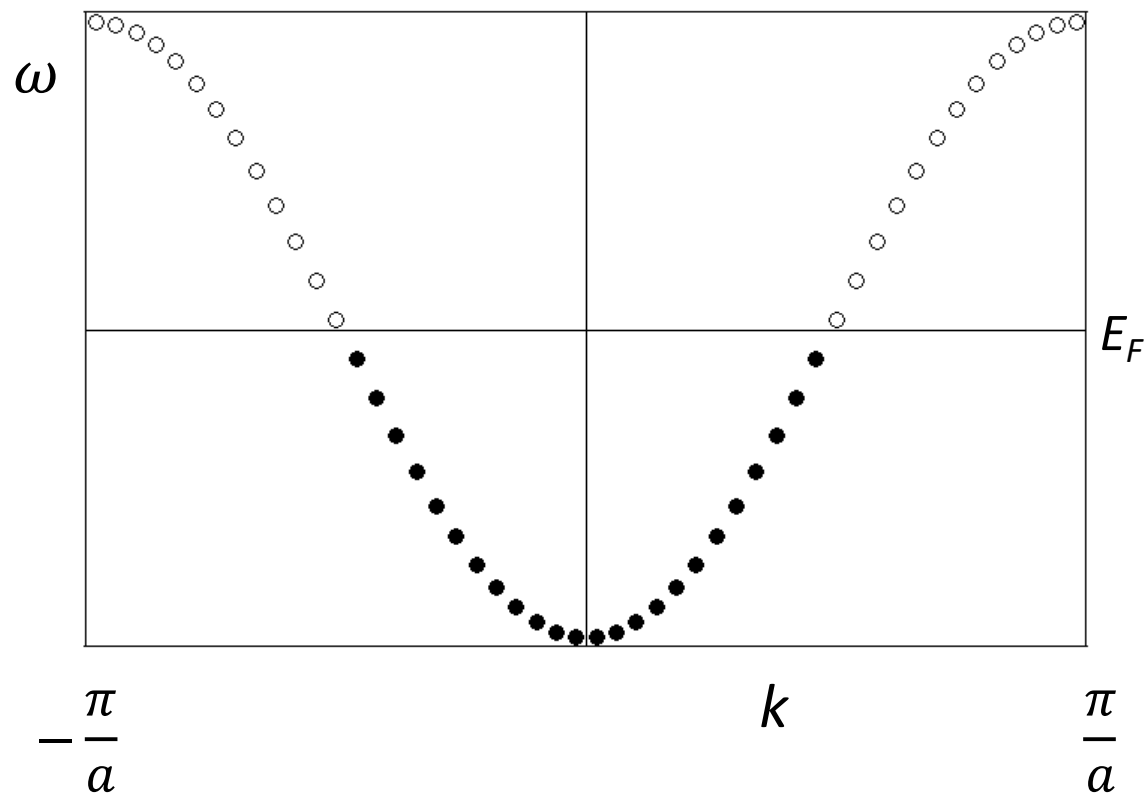
The electronic spectrum in the momentum-energy 3D space

TiSe₂ – “excitonic insulator”

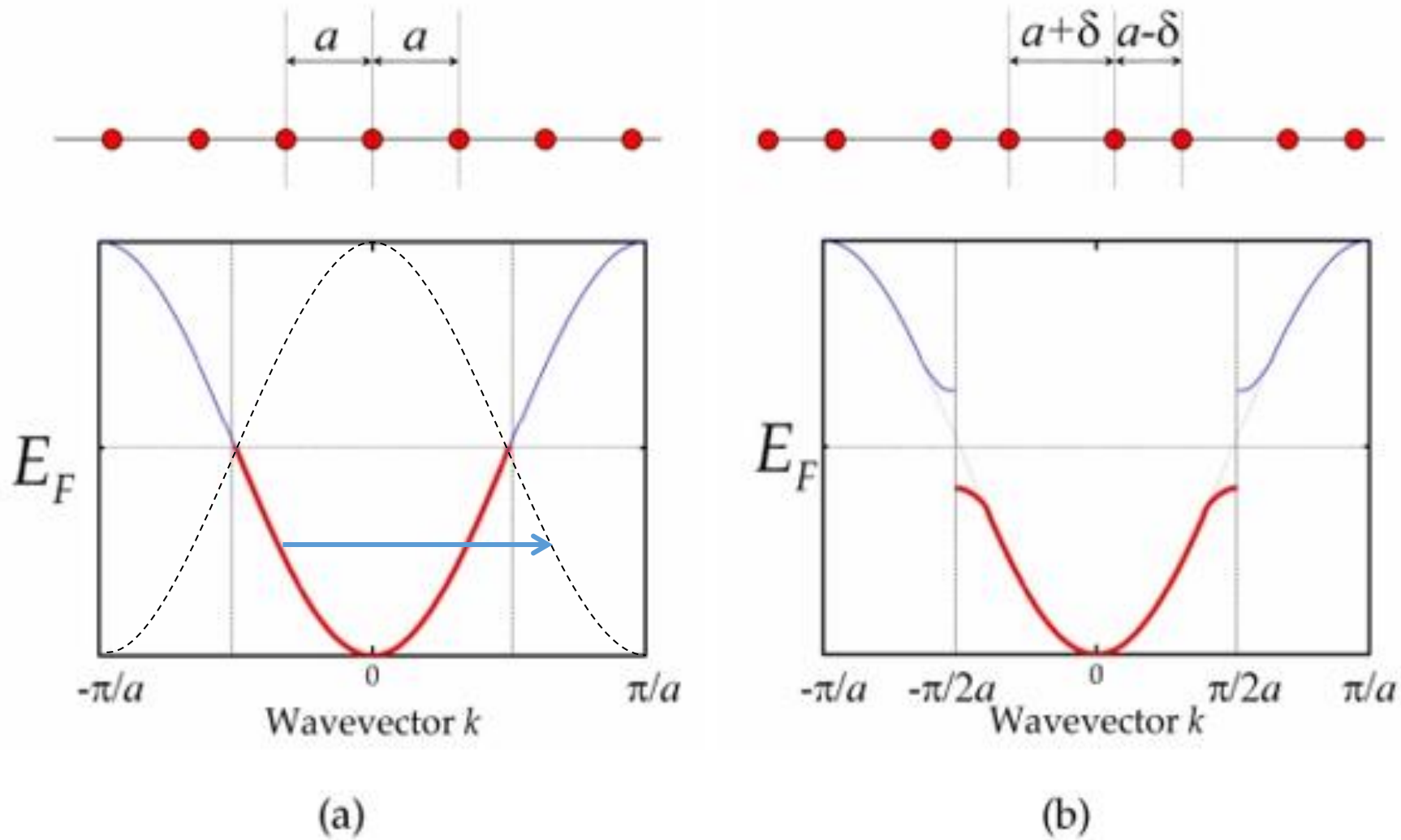


- All the materials are quantum
- Electronic structure is a key
- **Emergent phenomena**
- Why Superconductors are QM^N
- Other examples:
 - TMD's and Topological Insulators
 - QM^{N+1}

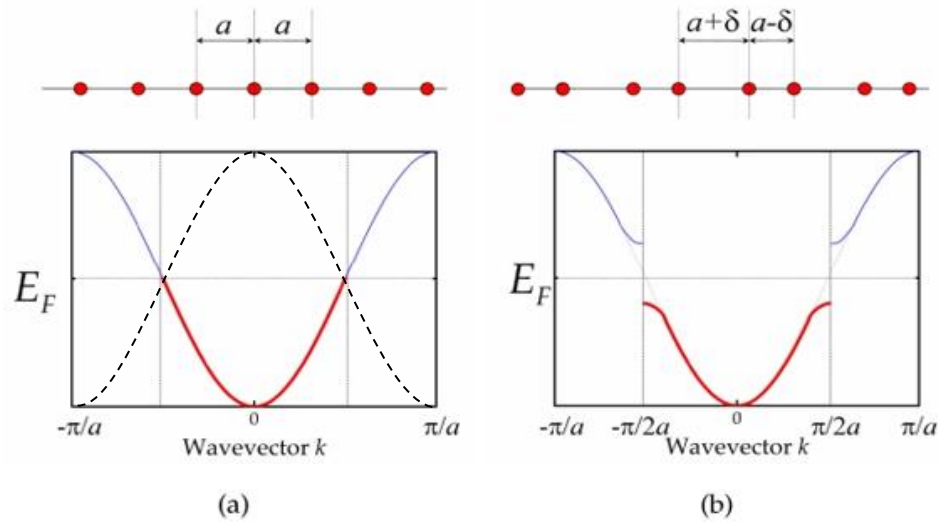
Metal vs Insulator



Peierls transition



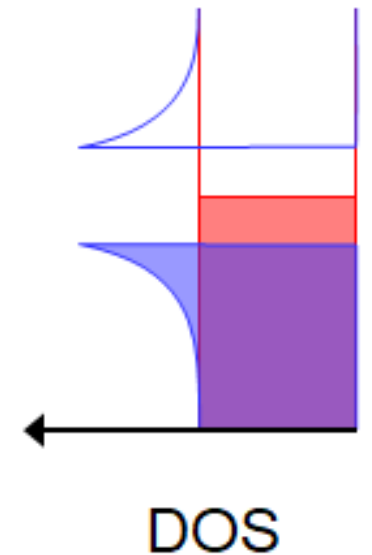
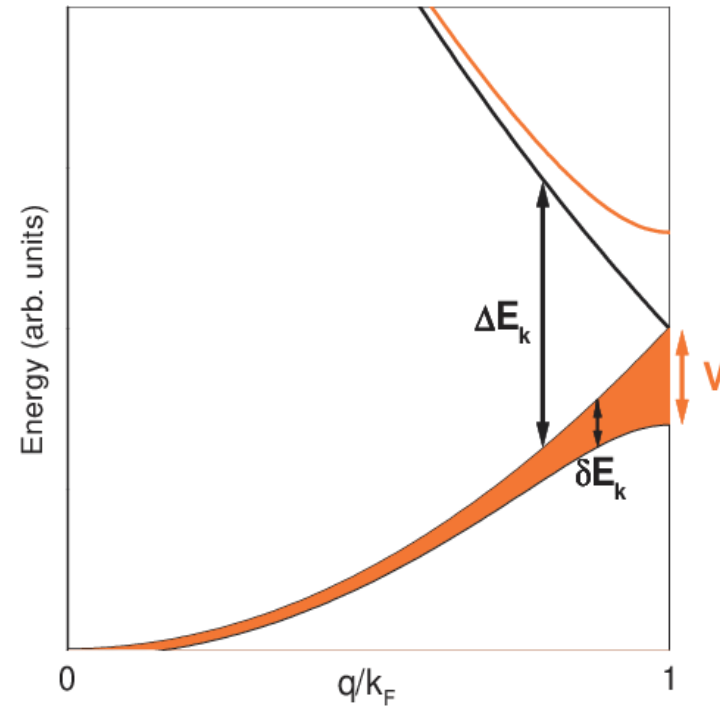
Peierls transition and Fermi surface nesting



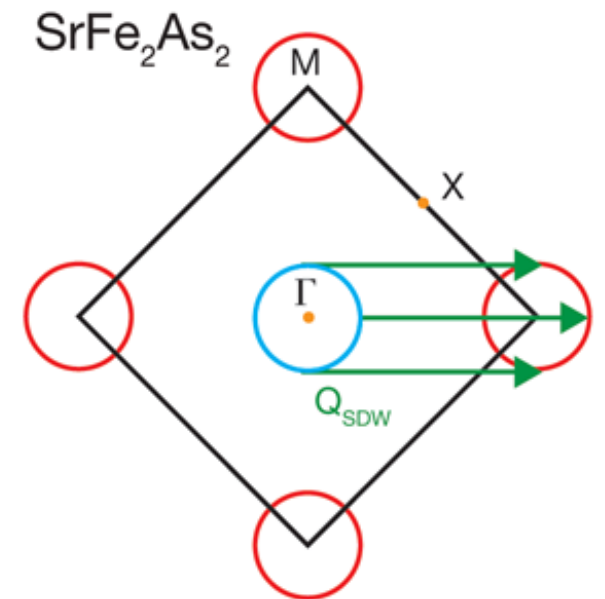
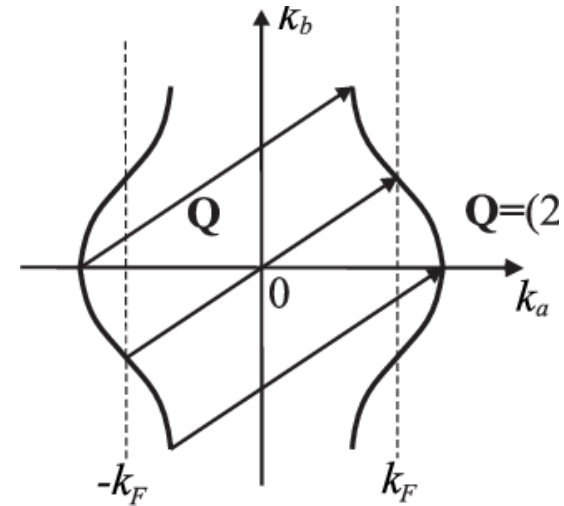
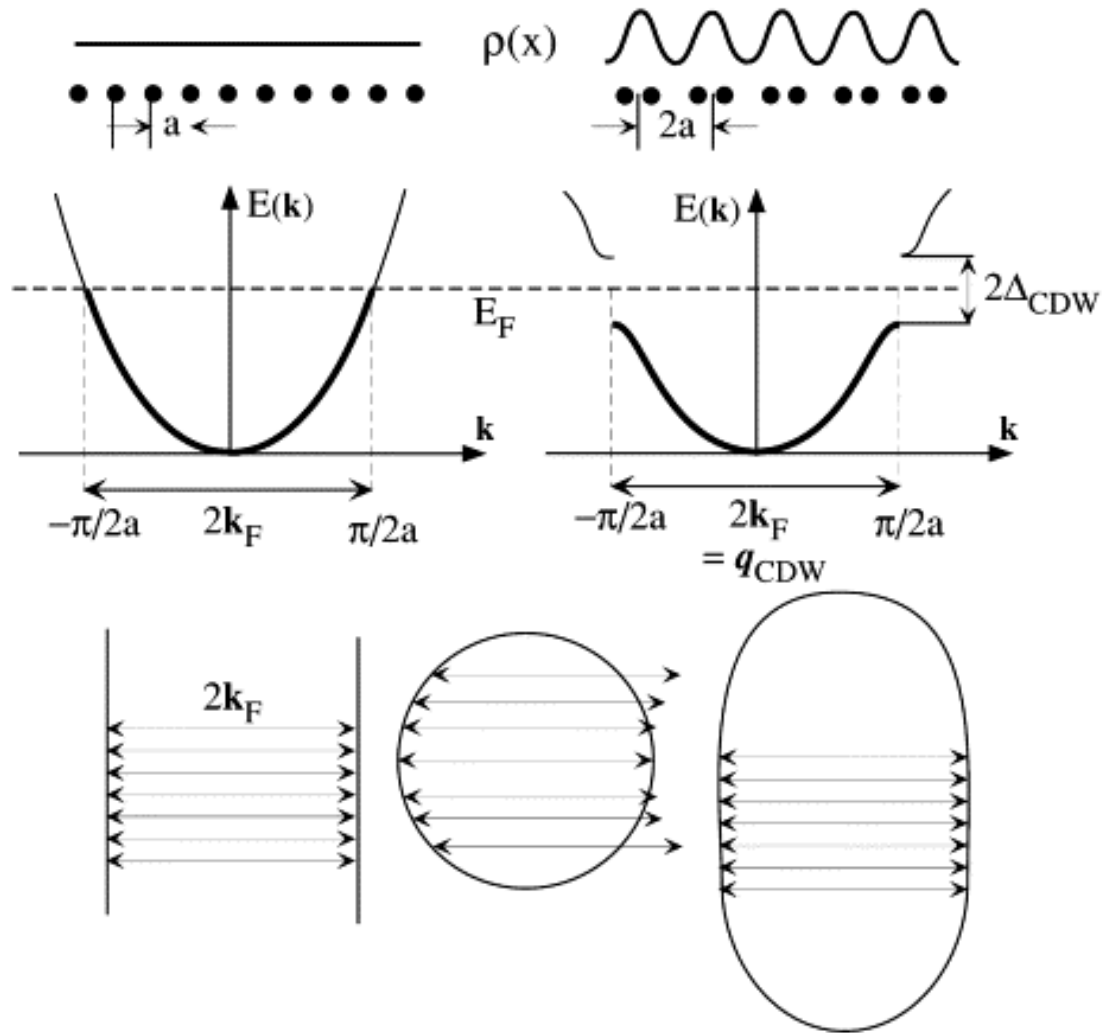
New BZ boundary crosses the dispersion at k_F



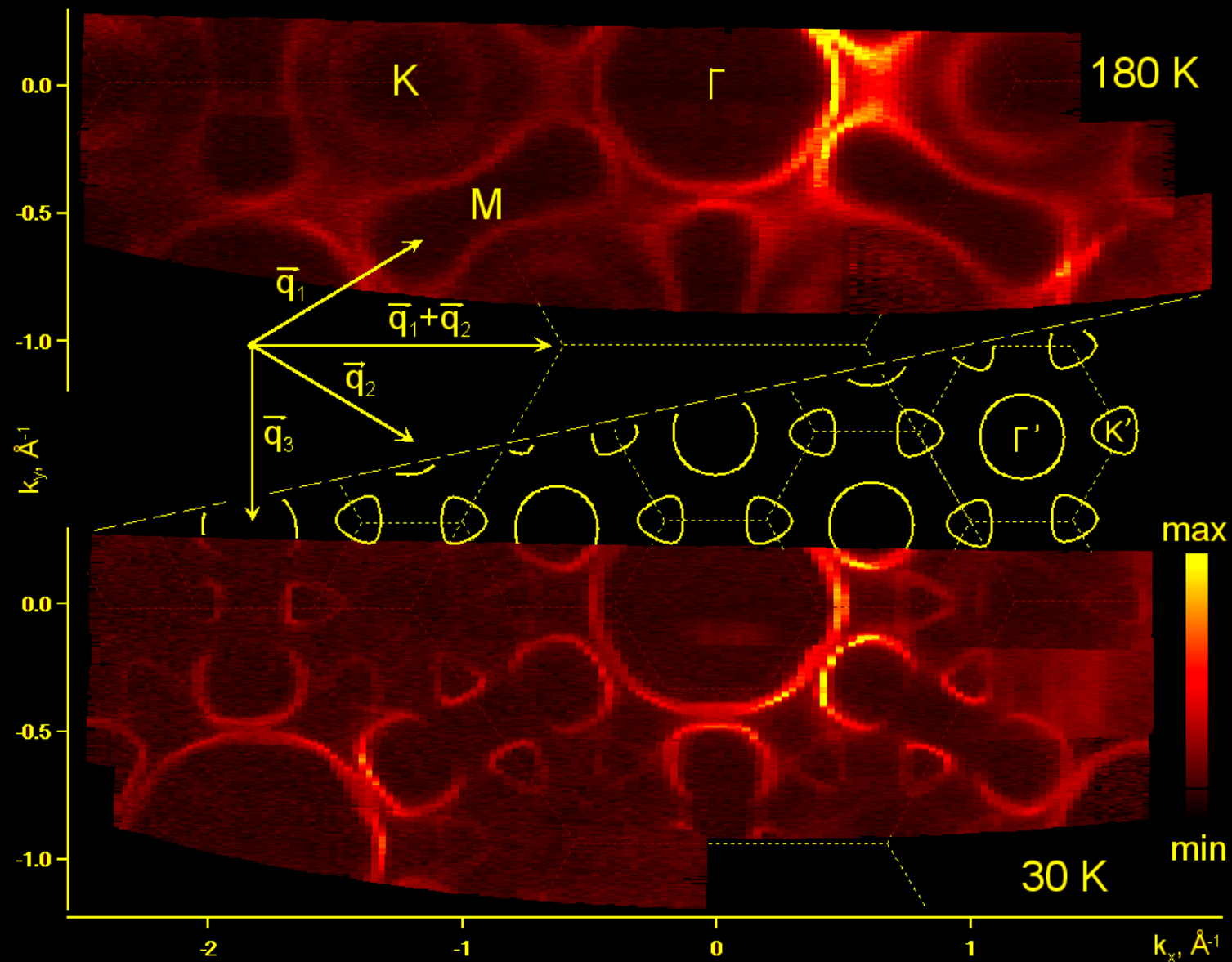
Band Gap opens at E_F



Peierls gap and Fermi surface nesting

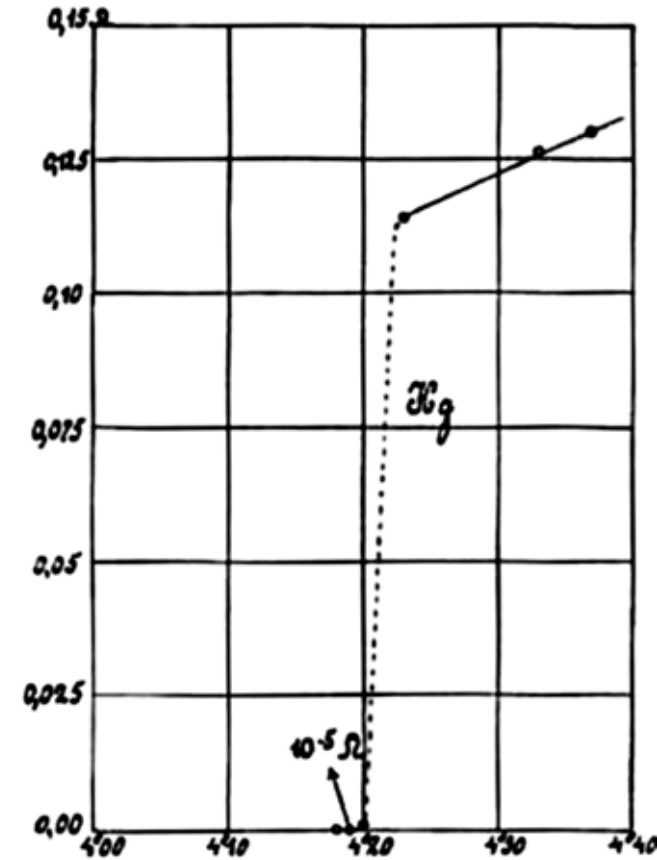
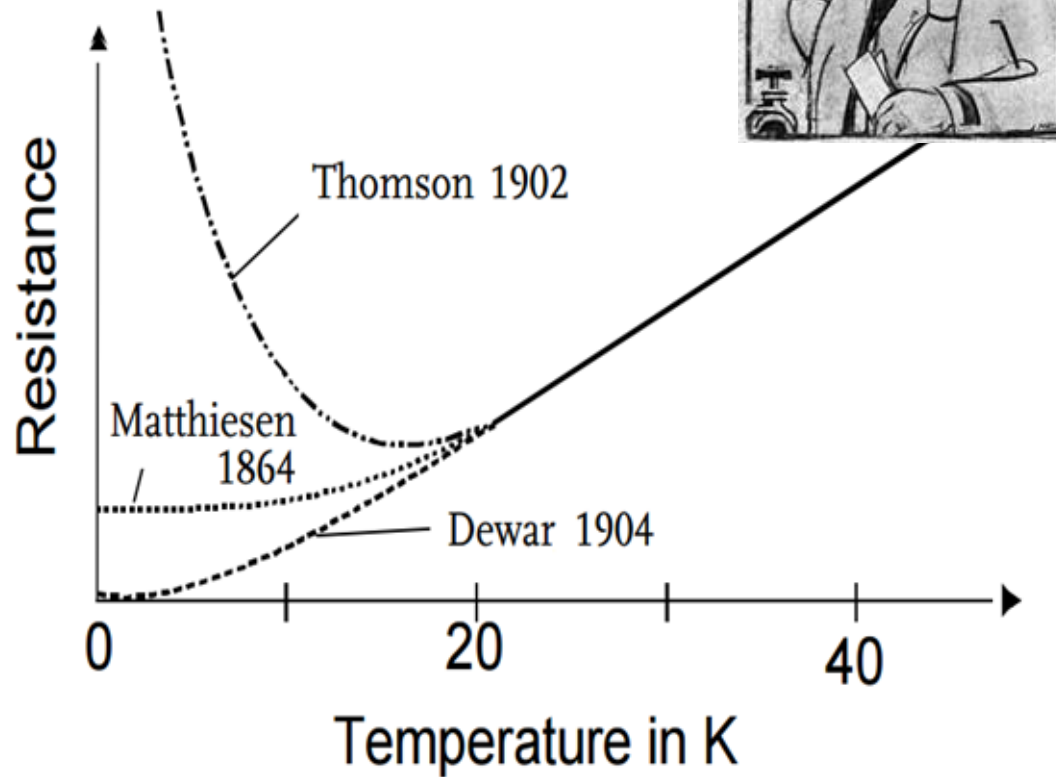


CDW in TaSe₂: commensurate CDW state



The history of superconductivity: the beginning

1911



Hg, $T_c = 4.2\text{K}$

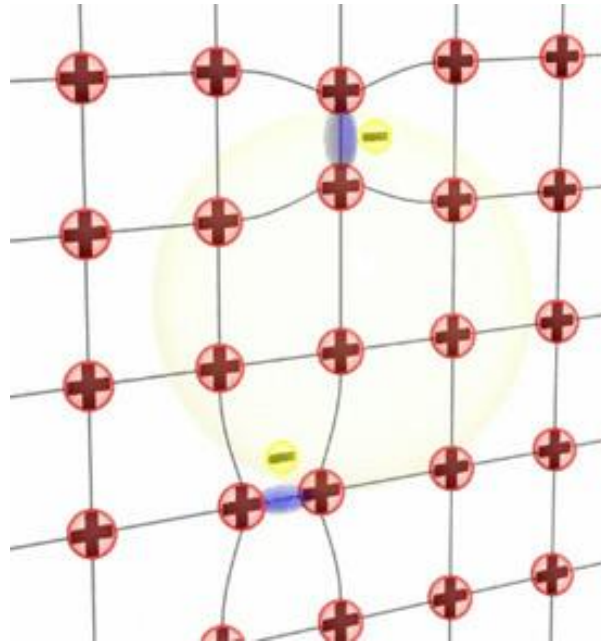
Why mercury?

Mechanism of superconductivity: BCS

1957: BCS

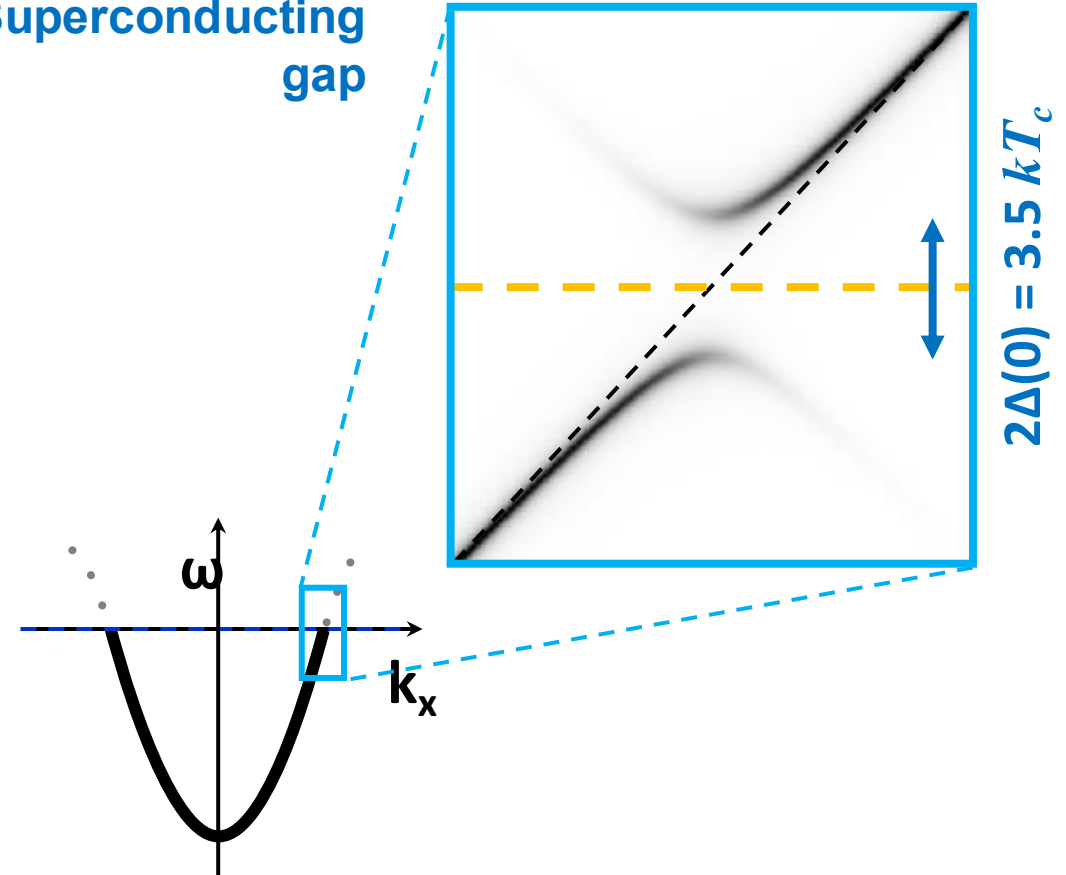


Phonons
 $T_c < 25\text{K}$



1972

Superconducting gap



$$k_B T_c = 1.13 E_D e^{-1/N(0) V}$$

$$\Delta(T = 0) = 1.764 k_B T_c$$

T_c / Δ

¹³Al 1.8 K
0.3 meV

⁴¹Nb 9.3 K
3 meV

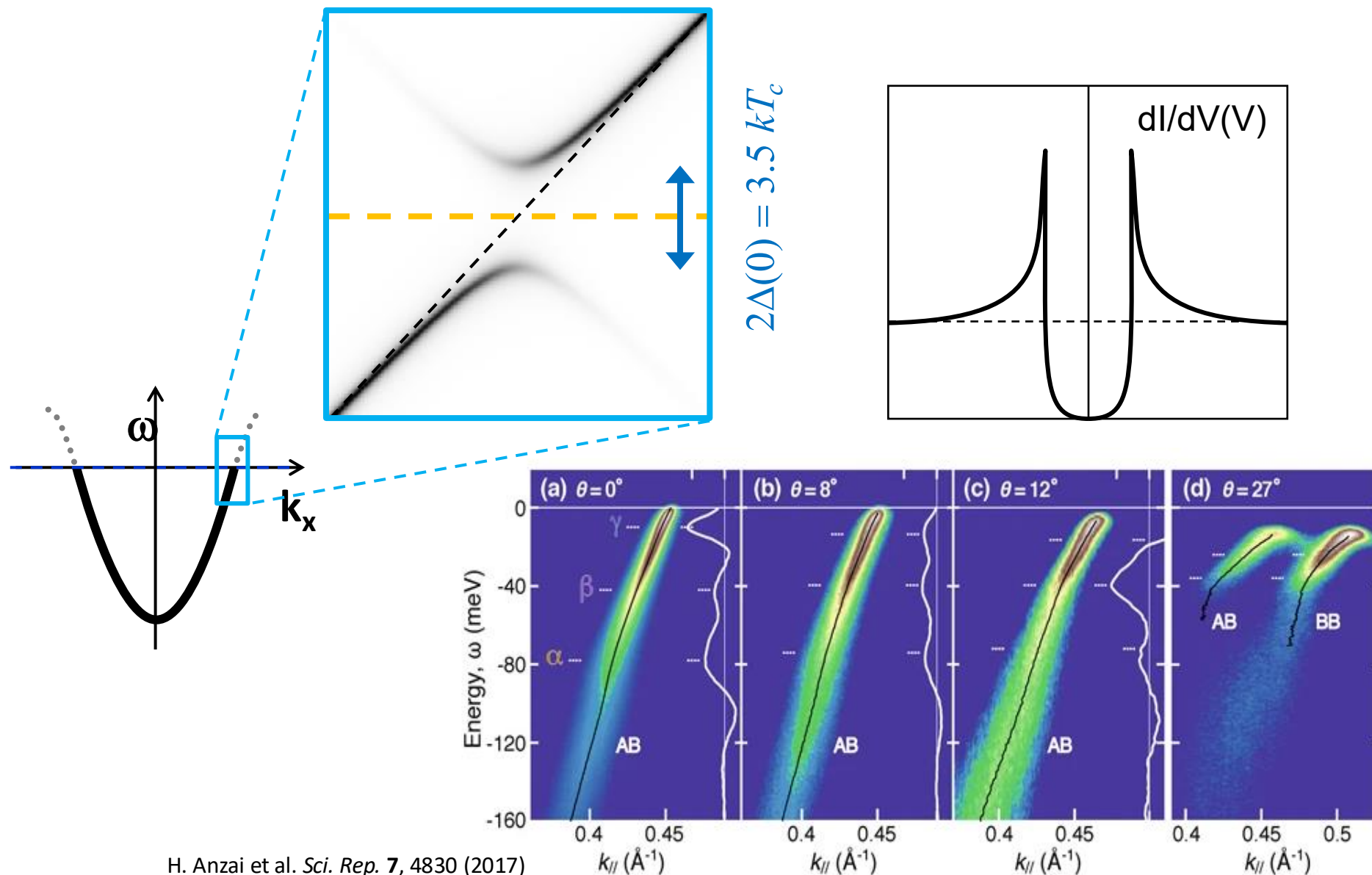
Nb₃Sn 18 K
4 & 1 meV

MgB₂ 39 K
6 & 2 meV

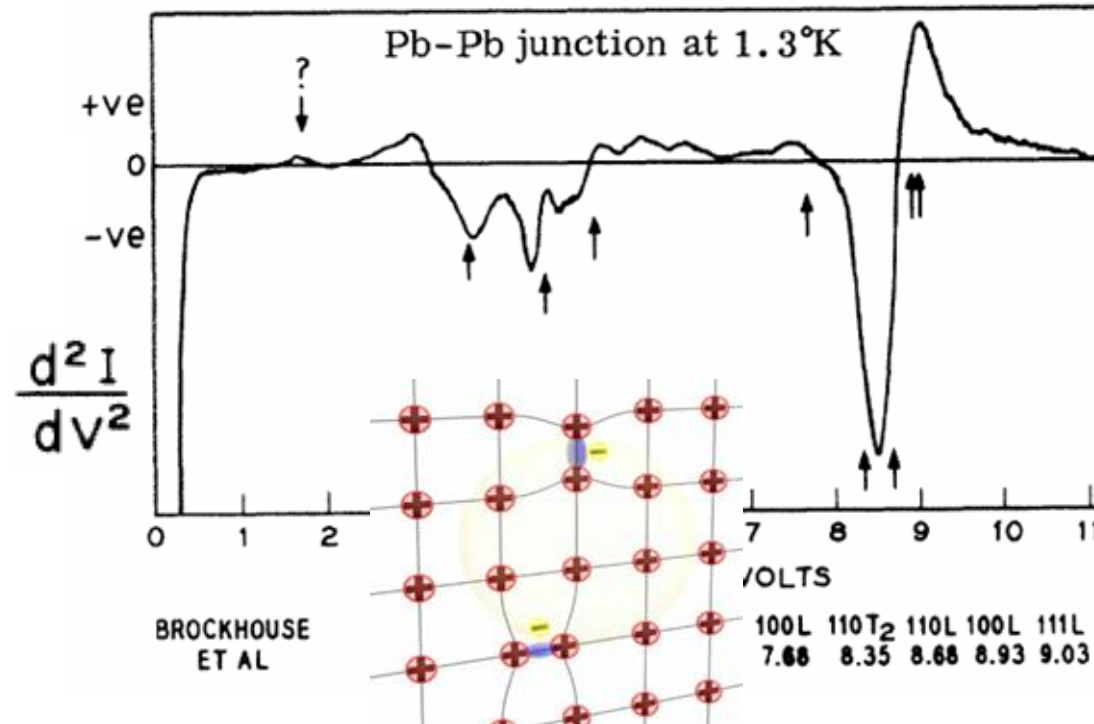
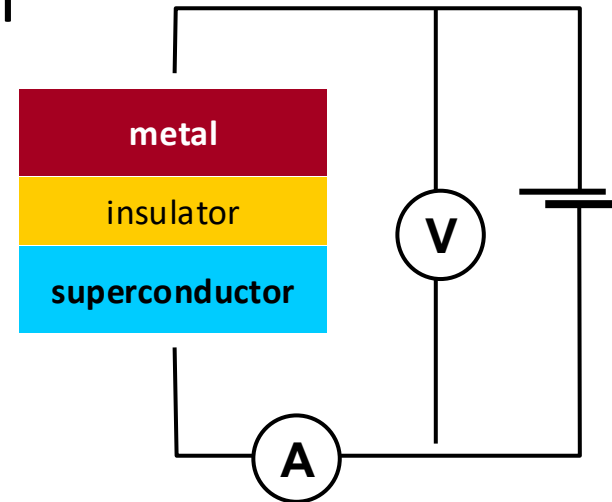
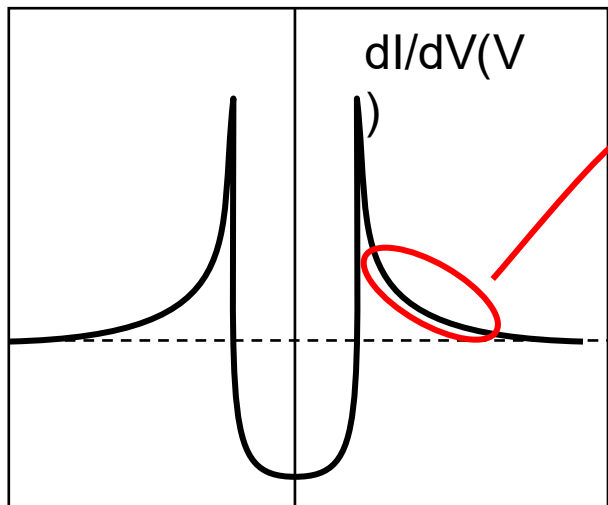
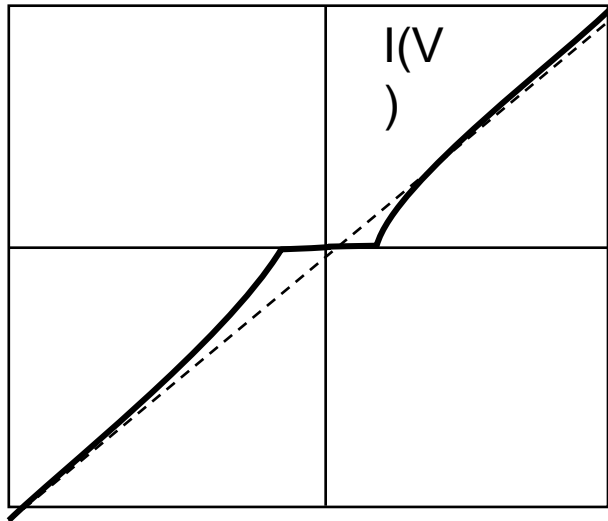
Bi-2212 90 K
20 – -20 meV

BKFA 32 K
10, 3 & -10 meV

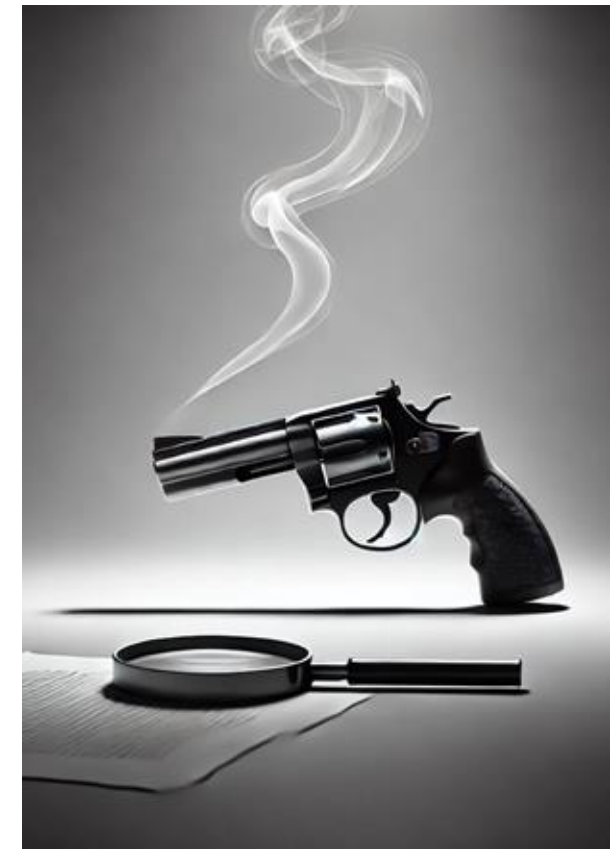
Superconducting gap



Experimental proof for the mechanism of superconductivity

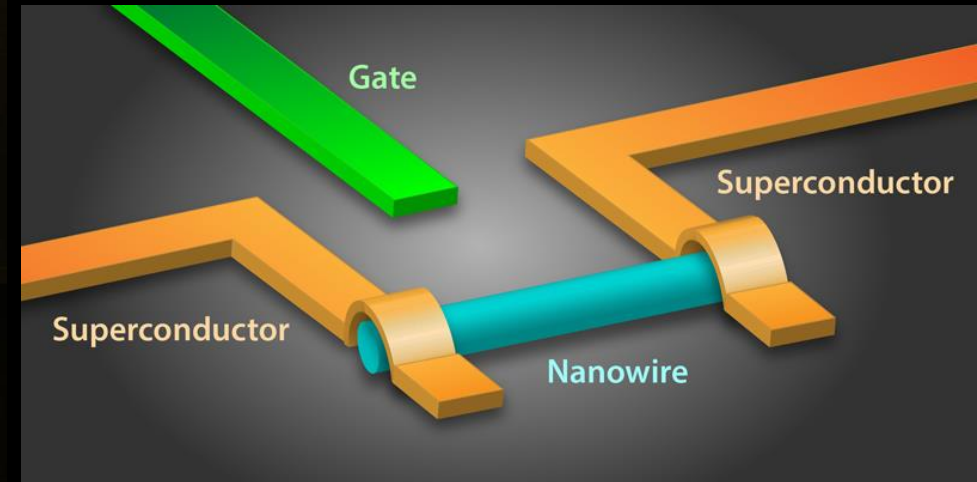
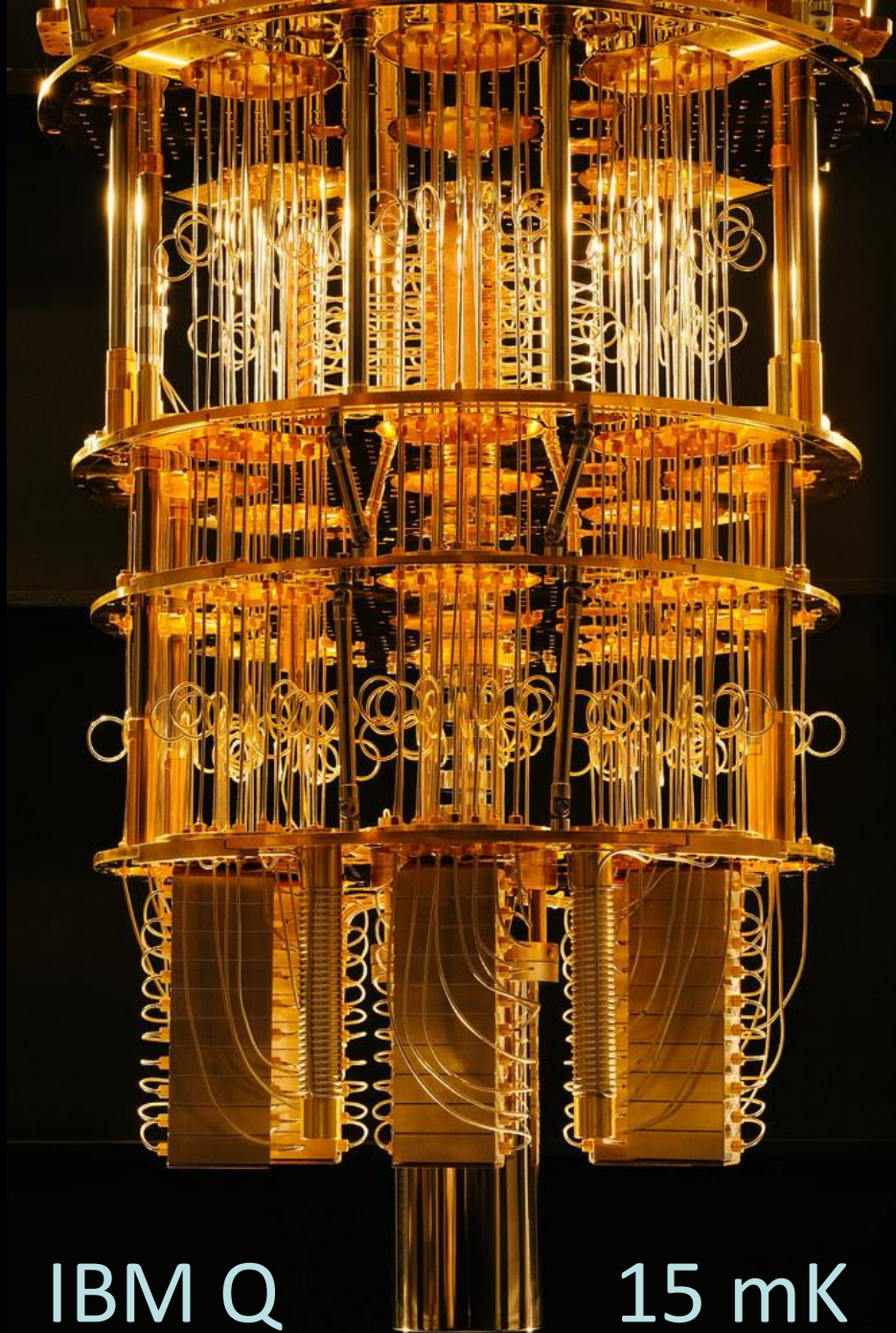


Rowell *PRL* 1963



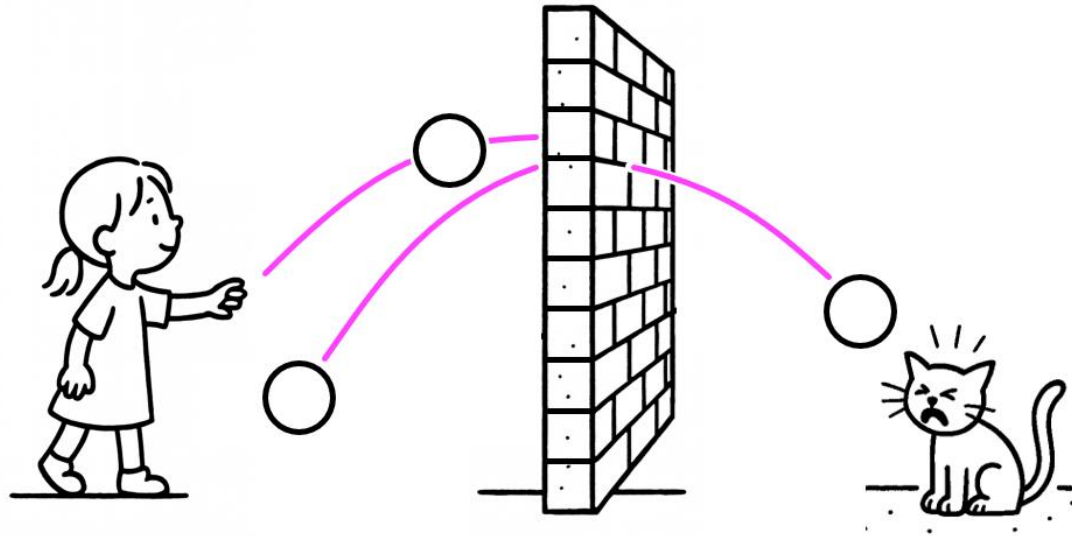
- All the materials are quantum
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Superconducting qubits

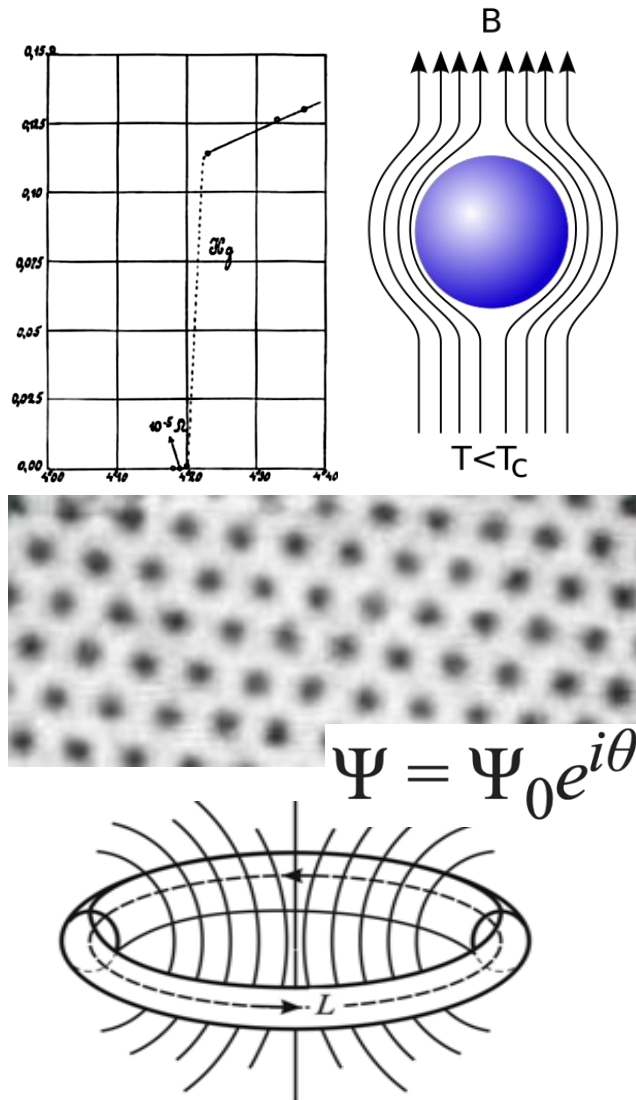


What is macroscopic quantum tunneling?

How does Nobel Prize 2025 differs from previous Nobel Prizes for superconductivity, and how is it related to the development of quantum computers?



Superconductivity and quantization

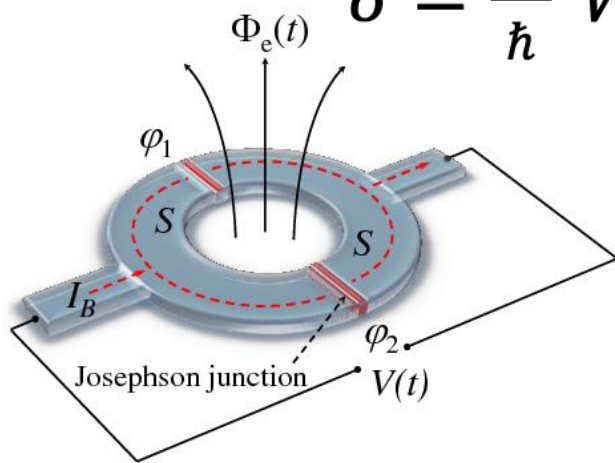


1911	Discovery of superconductivity (sudden disappearance of electrical resistance)	Heike Kamerlingh Onnes	1913	
1933	Meissner effect (expulsion of the magnetic field)	W. Meissner, R. Ochsenfeld	—	
1935 – 1950	London theory (London equations)	F. & H. London	—	
1950	Ginzburg–Landau theory (phenomenological)	V. Ginzburg, L. Landau	2003 (Ginzburg, Landau)	
1957	BCS theory — microscopic theory of superconductivity	Bardeen, Cooper, Schrieffer	1972	
1957	Discovery of type-II superconductors and Abrikosov vortice	A. Abrikosov	2003	
1961	Magnetic flux quantization in a superconducting ring	Deaver & Fairbank; Doll & Näbauer	—	

Superconductivity and quantum tunneling

$$I = I_0 \sin \delta$$

$$\dot{\delta} = \frac{2e}{\hbar} V$$

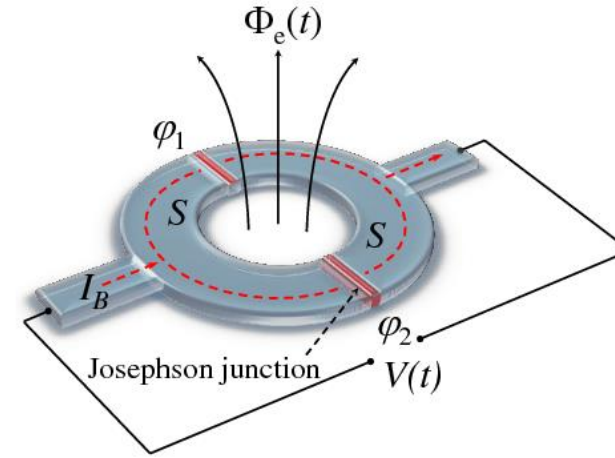


1962	Josephson effect (tunneling of Cooper pairs)	Brian Josephson	1973
1962–63	SQUID — an ultrasensitive superconducting interferometer	J. Clarke, J. Zimmermann	2025
1973	Tunneling spectroscopy of superconductors → Δ	Ivar Giaever	1973
1980- π	Theory of fluctuations in 2D; Berezinskii–Kosterlitz–Thouless vortices	Berezinskii, Kosterlitz, Thouless	2016
1986	Discovery of high-temperature superconductivity in cuprates	J. G. Bednorz & K. A. Müller	1987
1985-87	Macroscopic quantum tunneling	John Clarke, Michel Devoret, John Martinis	2025





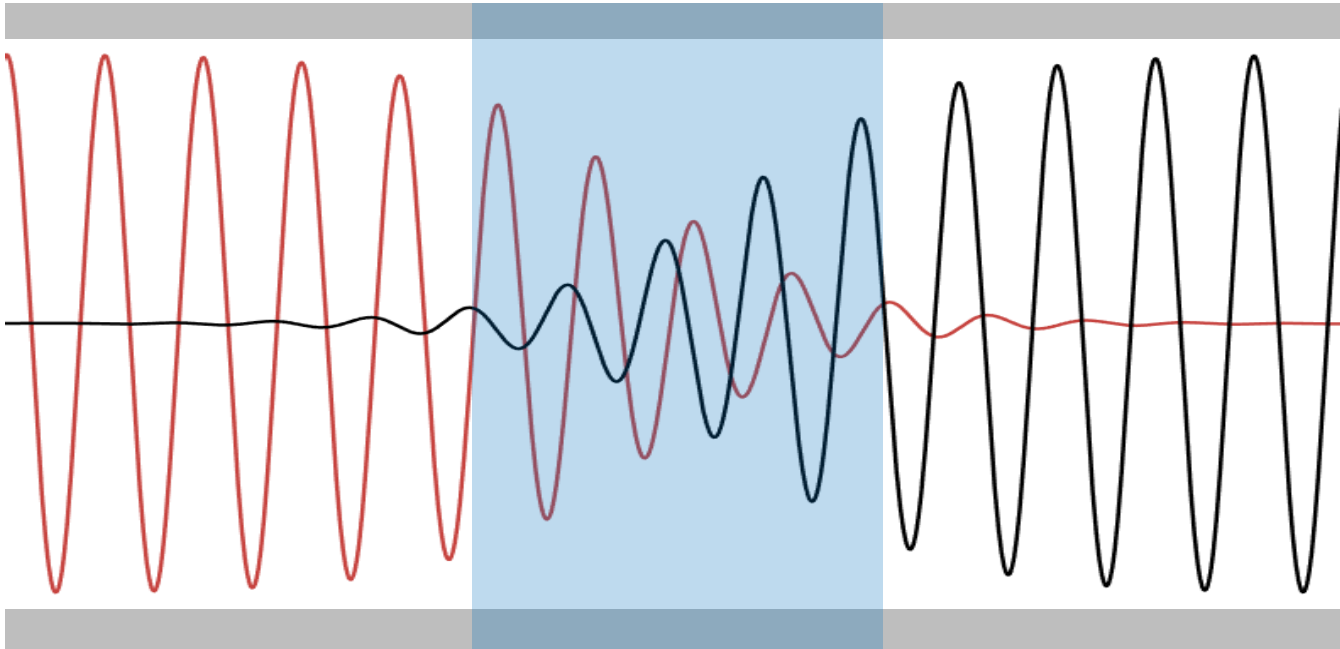
Josephson Effects



$$\psi_L \propto e^{i\theta_L}$$

$$\psi_R \propto e^{i\theta_R}$$

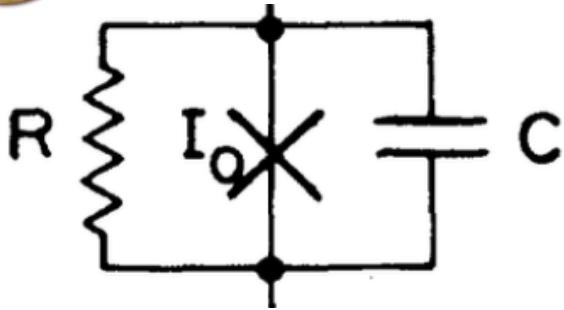
$$\delta = \theta_R - \theta_L$$



$$I = I_0 \sin \delta$$

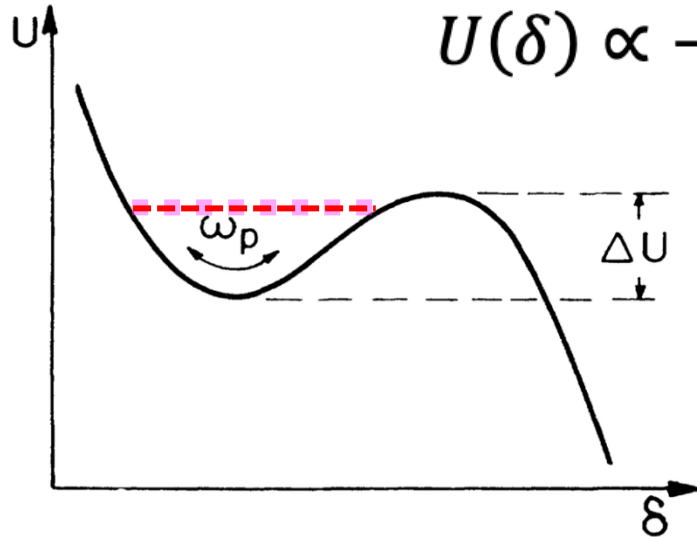
$$\dot{\delta} = \frac{2e}{\hbar} V$$

Macroscopic quantum tunnelling



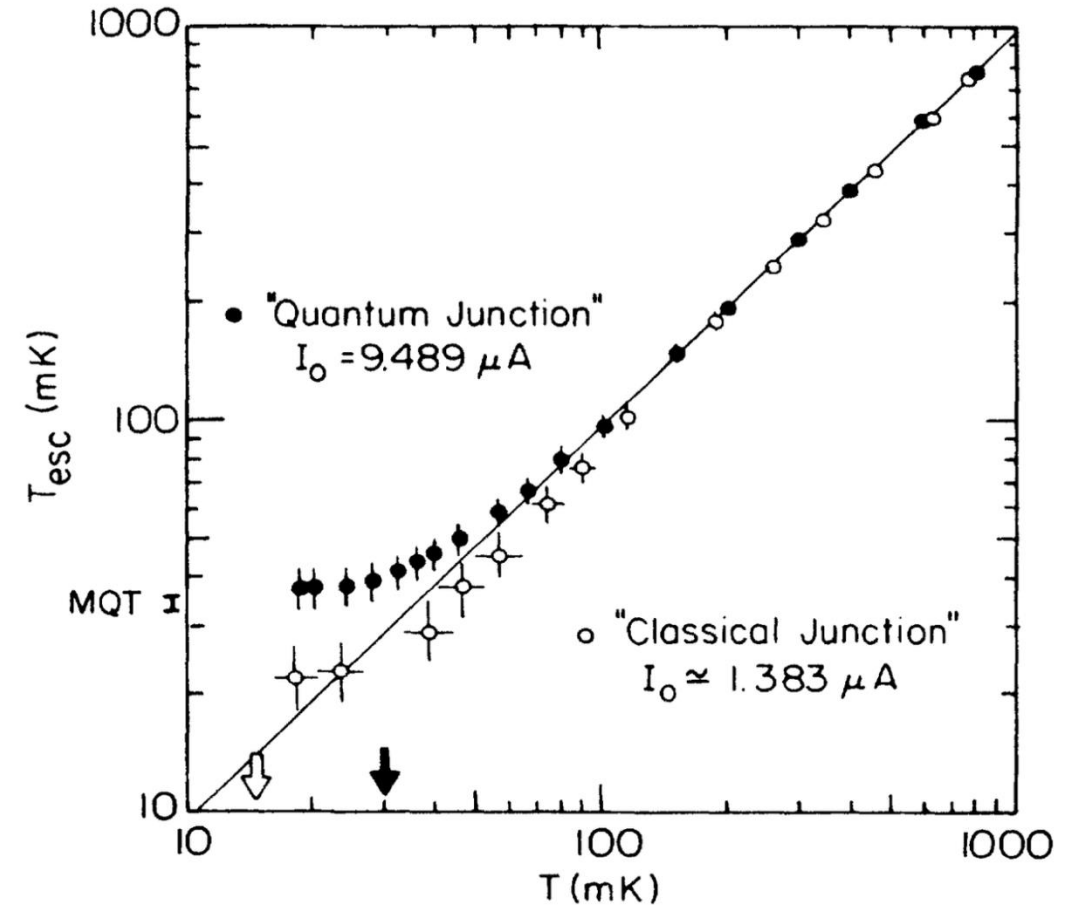
$$I = I_0 \sin \delta + \frac{\hbar}{2e} C \ddot{\delta}$$

$$U(\delta) \propto -\left[\cos \delta + \left(\frac{I}{I_0}\right) \delta\right]$$

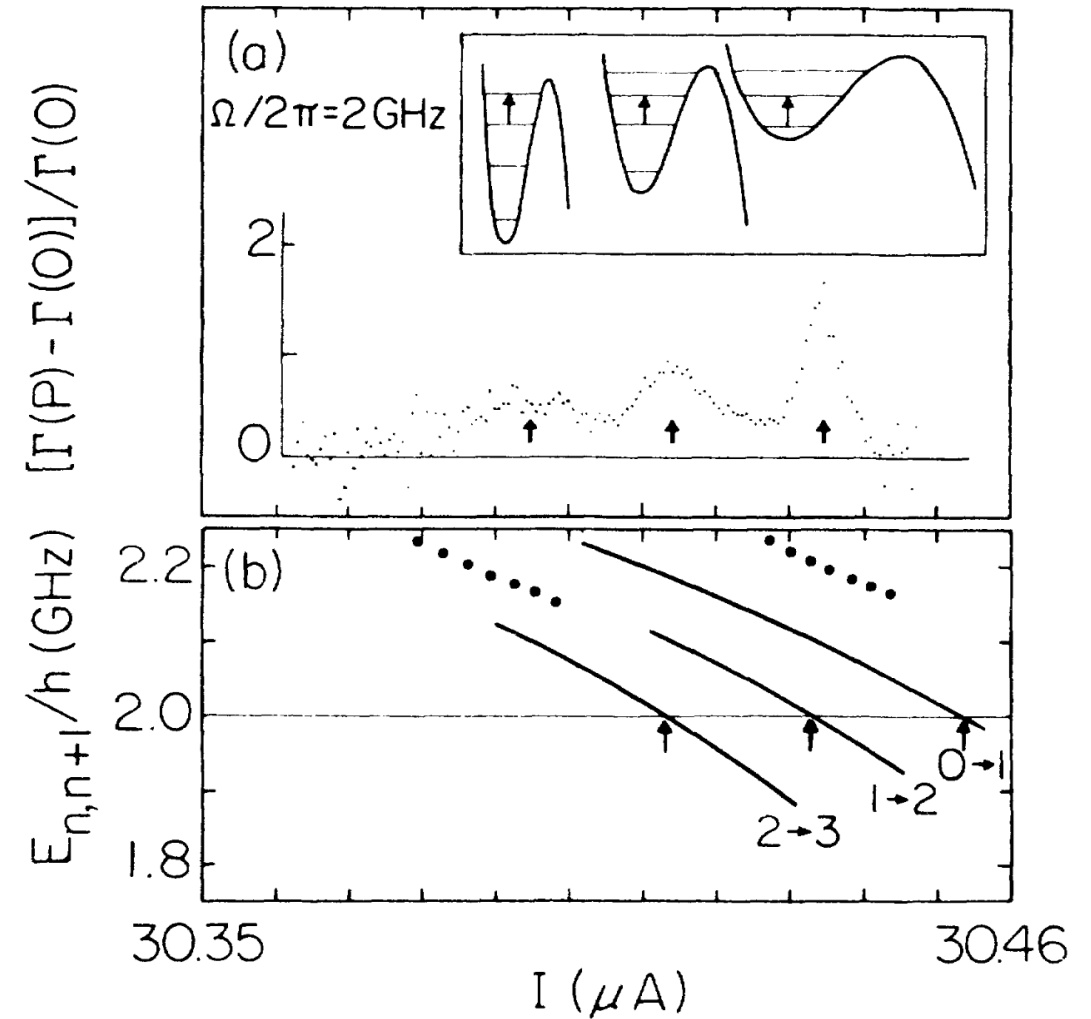
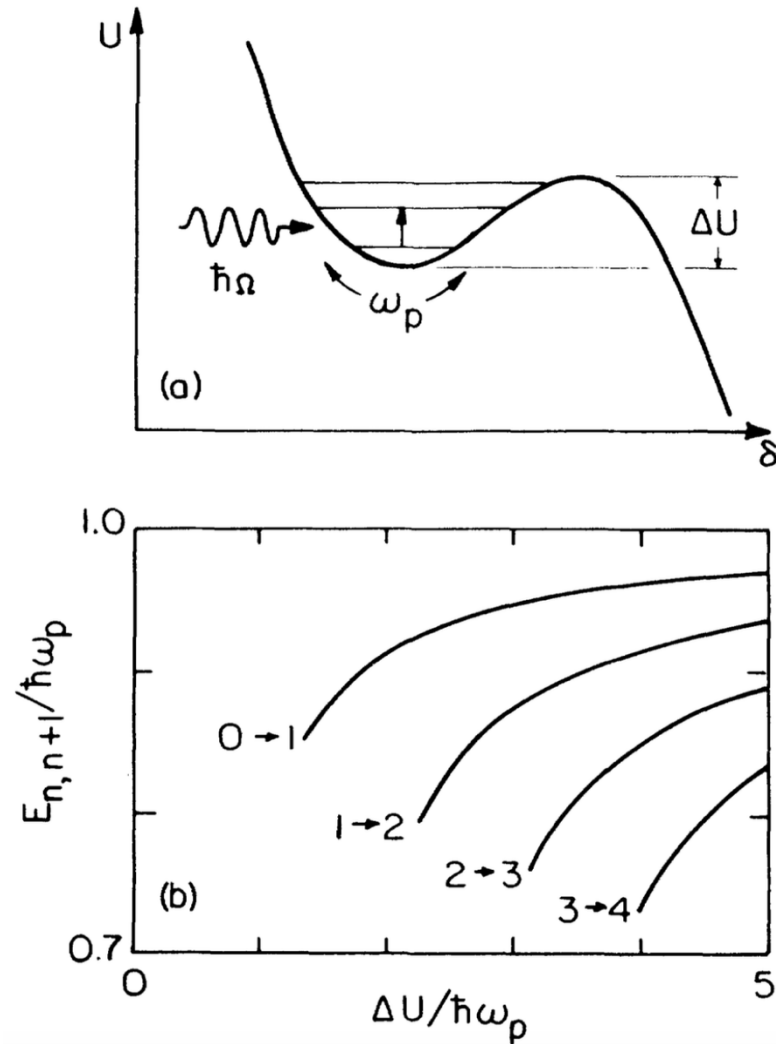


Escape rate

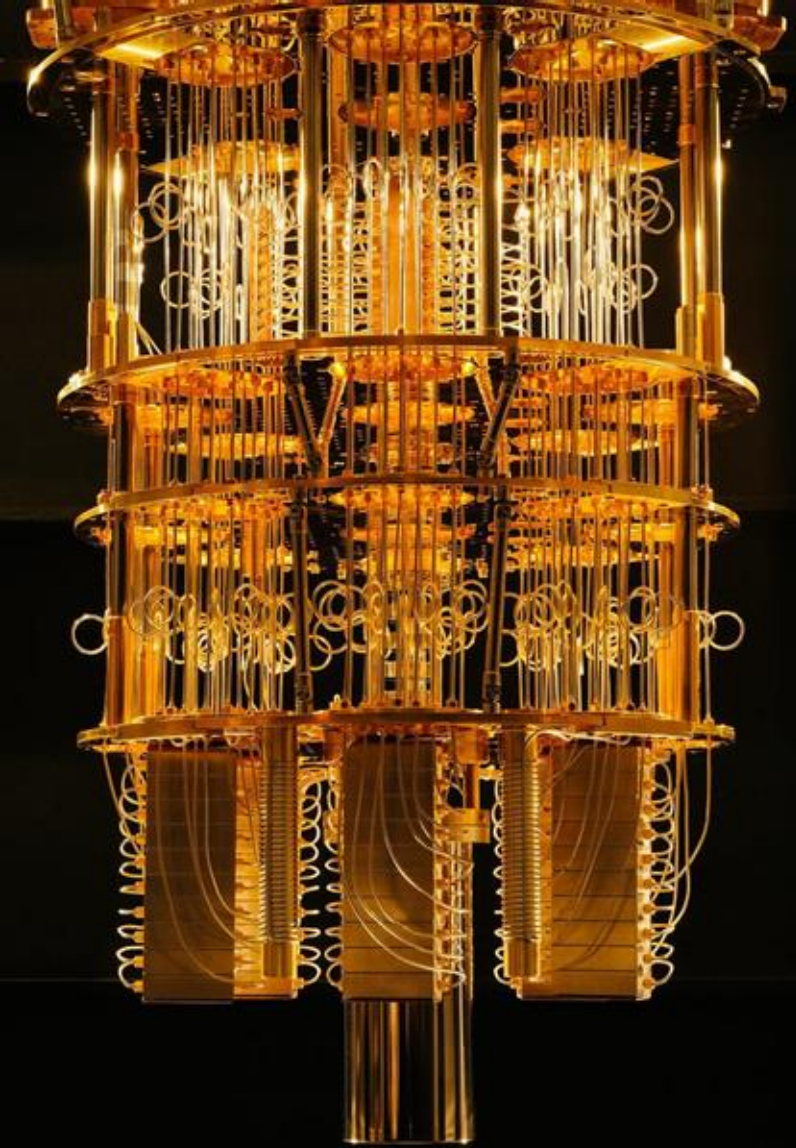
$$\Gamma = (\omega_p / 2\pi) \exp(-\Delta U / k_B T_{\text{esc}})$$



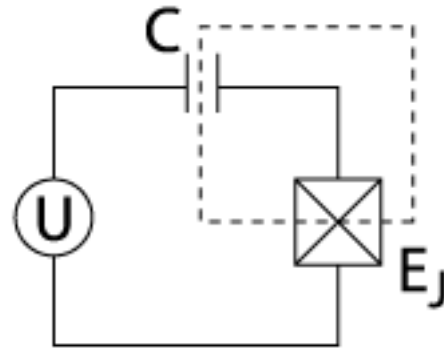
Macroscopic quantum tunnelling



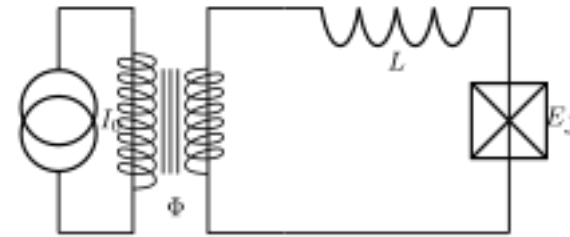
Superconducting qubits



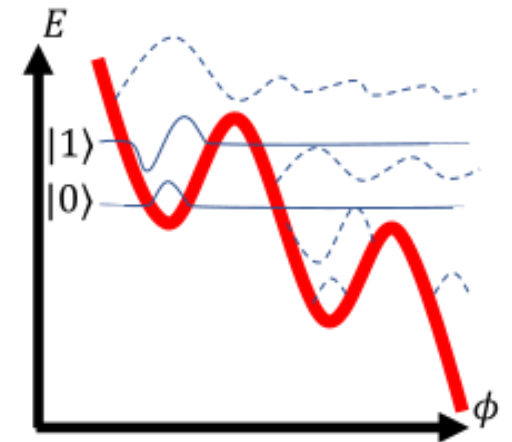
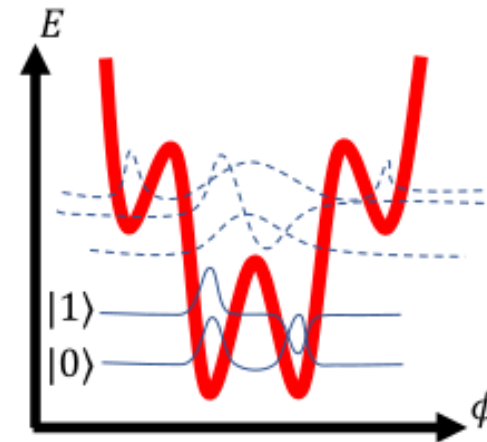
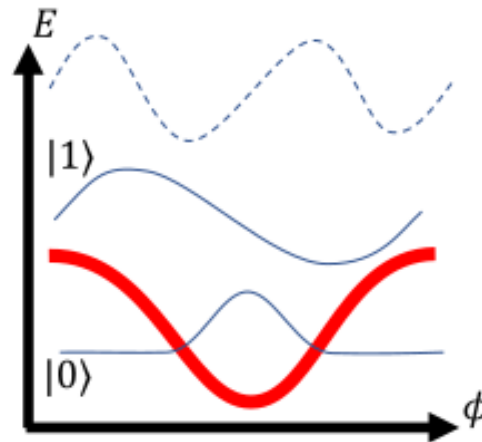
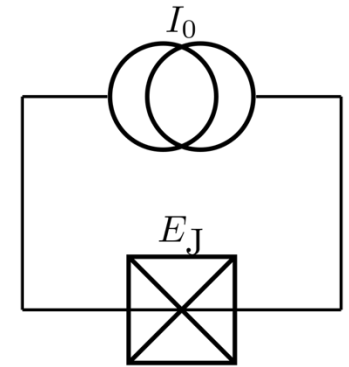
Charge qubit



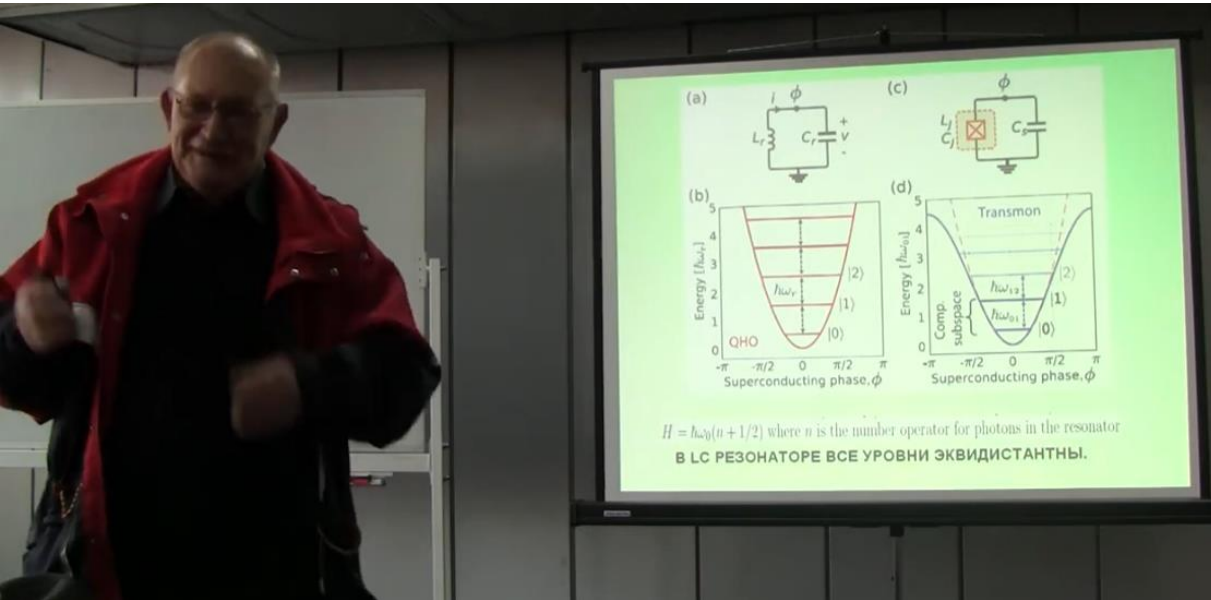
RF-SQUID qubit (Flux Qubit)



Phase qubit



Macroscopic quantum tunnelling in Ukraine



J. M. Martinis, M. H. Devoret, & J. Clarke, Experimental tests for the quantum behavior of a macroscopic degree of freedom: The phase difference across a Josephson junction, *Physical Review B*, 35(10), 4682 (1987).

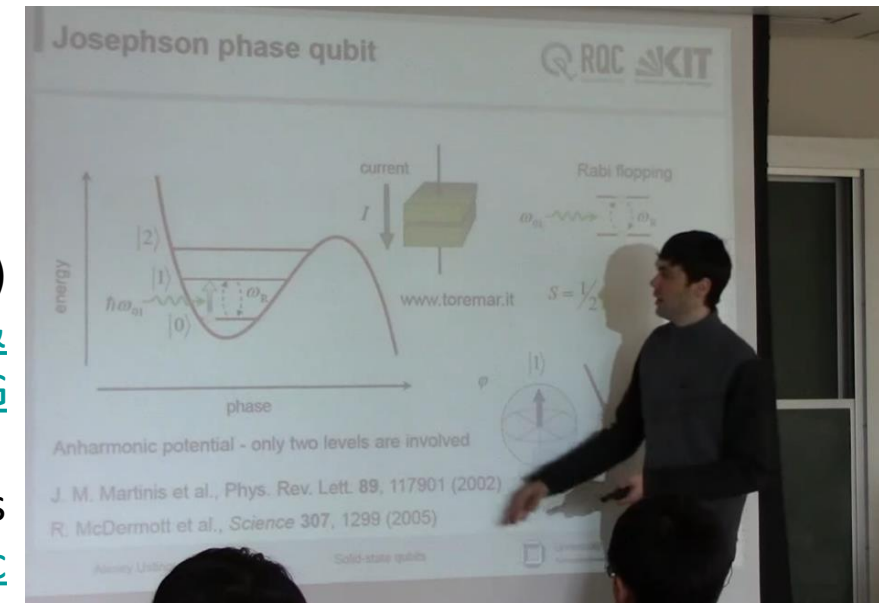
Yu. M. Ivanchenko and L. A. Zilberman, *Zh. Eksp. Teor. Fiz.* 55, 2395 (1968) [*Sov. Phys.—JETP* 28, 1272 (1969)].

I. M. Dmitrenko, V. A. Khlus, G. M. Tsoi, and V. I. Shnyrkov, *Fiz. Nizk. Temp.* 11, 146 (1985) [*Sov. J. Low. Temp. Phys.* 11, 77 (1985)].

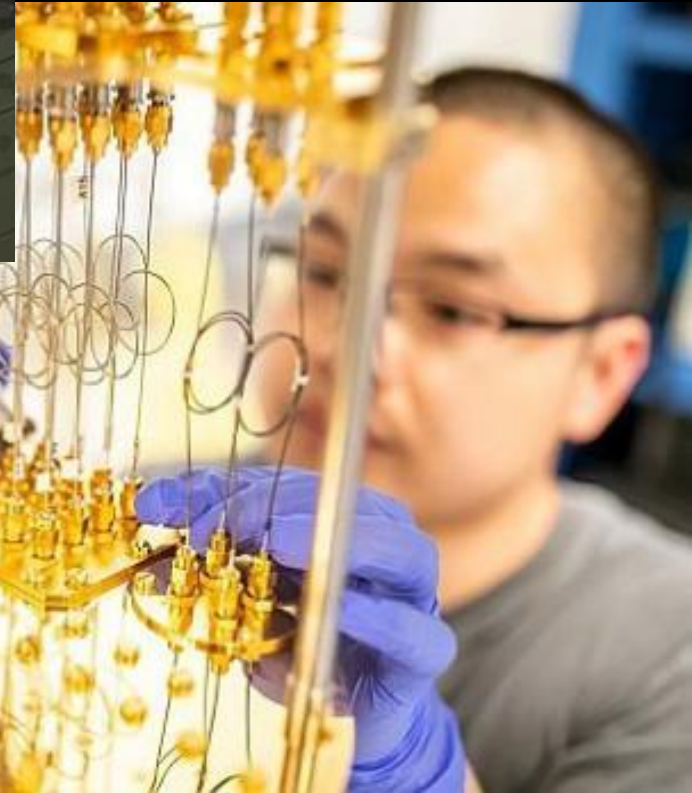
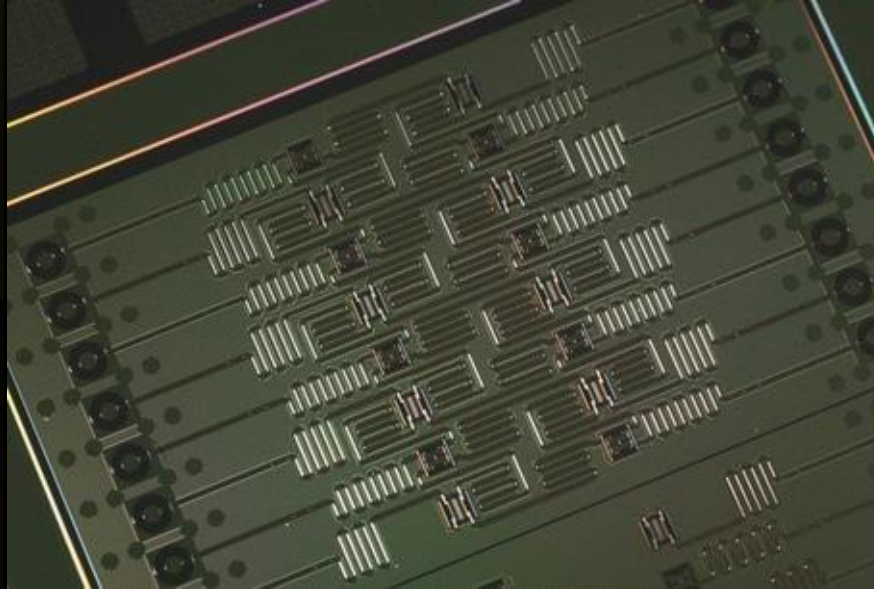
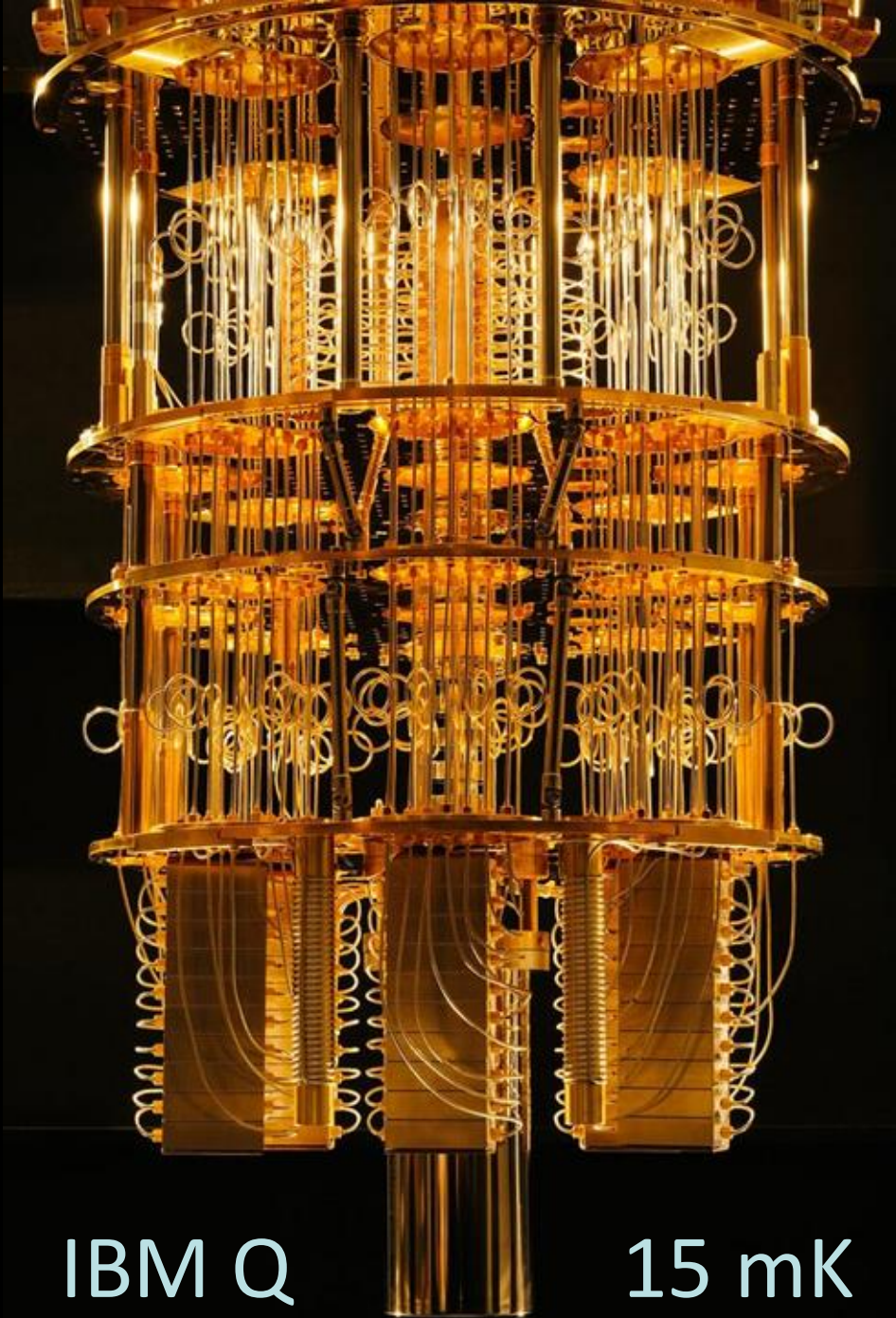
Single MW photon detector by Vladimir Shnyrkov
https://youtu.be/PgExRoI29a8?si=_oJH_8wGQev_9GRN

Sergey Frolov. *Quantum Transport* (2013)
https://youtube.com/playlist?list=PLtTPtV8SRcxjedfIXwNPSI_fxvxwUCjsd&si=3rCtkfwokxyHwW0G

Lecture 16: Superconducting qubits
https://youtu.be/Kz6mhh1A_mU?si=A1uFPwfch1rMWufc



Superconducting qubits



IBM Q

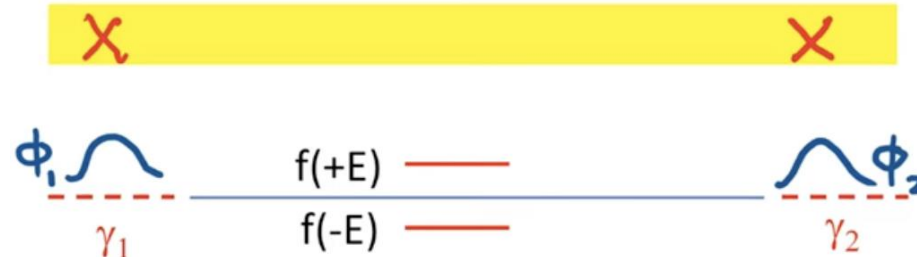
15 mK

Decoherence Is a Problem for Quantum Computing, but ...

The very thing quantum computers are battling is allowing the field of quantum measurements to blossom

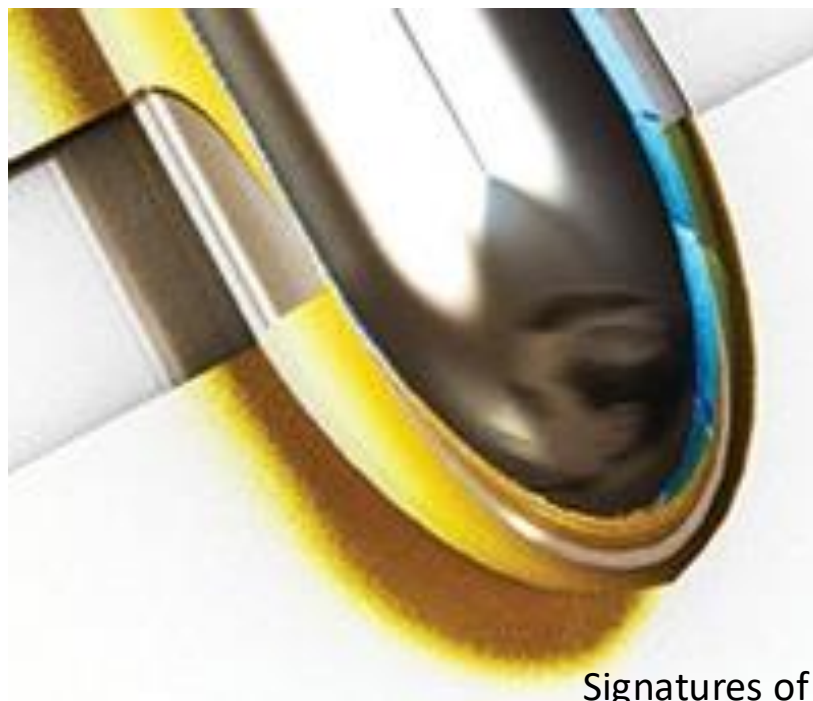
Science

25 May 2012 | \$10



Patrick Lee (MIT): Majorana Zero Modes: What, Why, Where and When

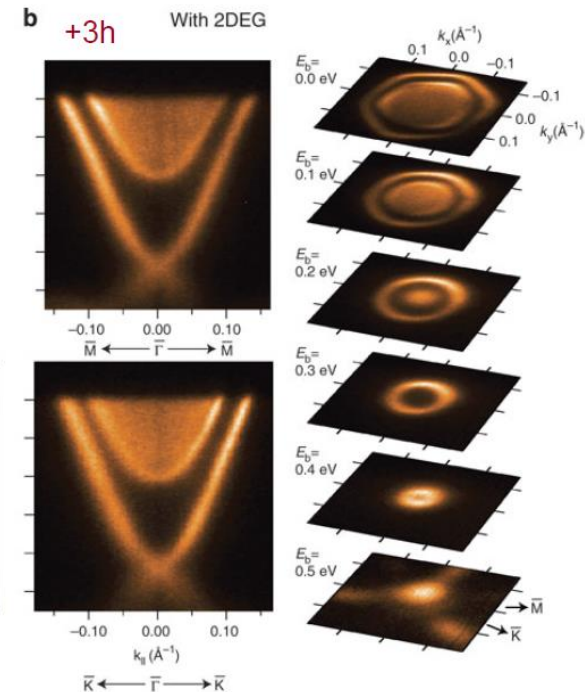
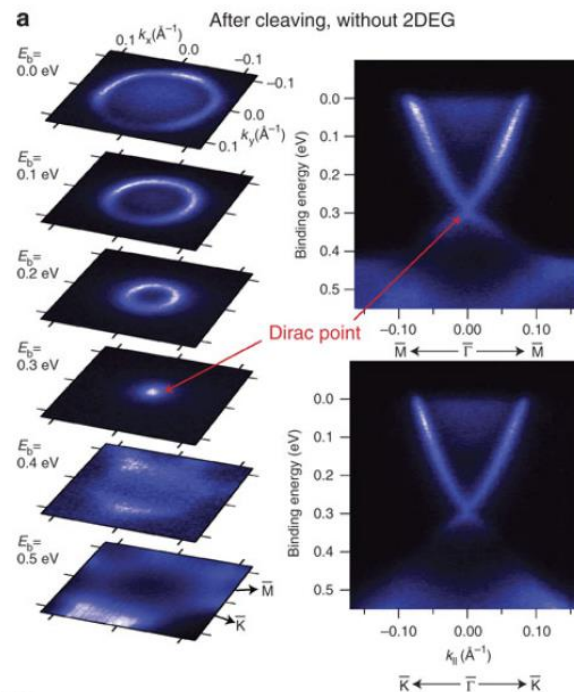
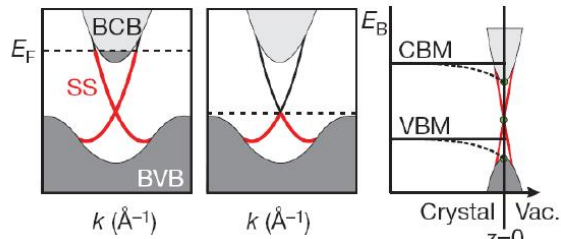
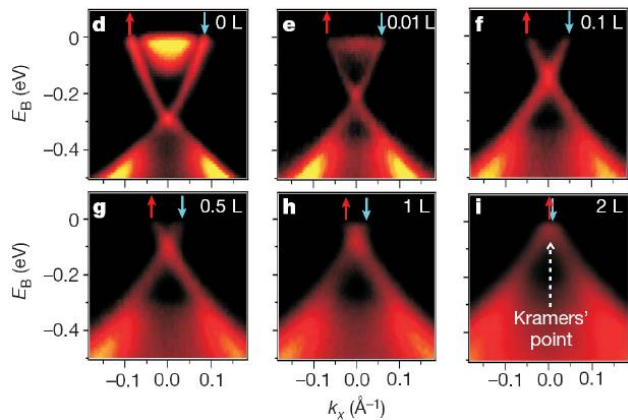
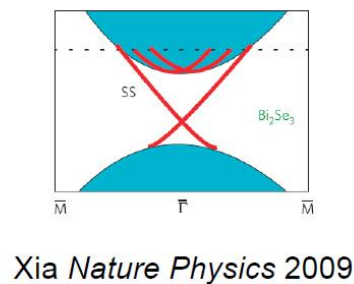
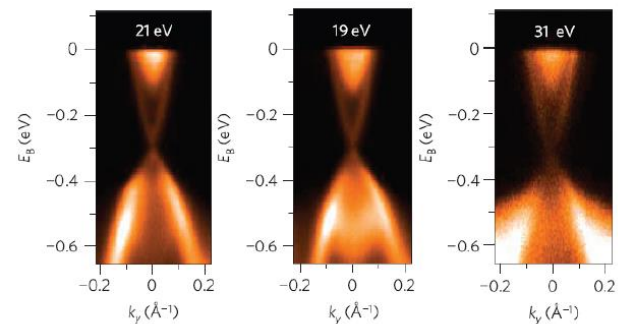
<https://youtu.be/RewClmgP8RY?t=1219>



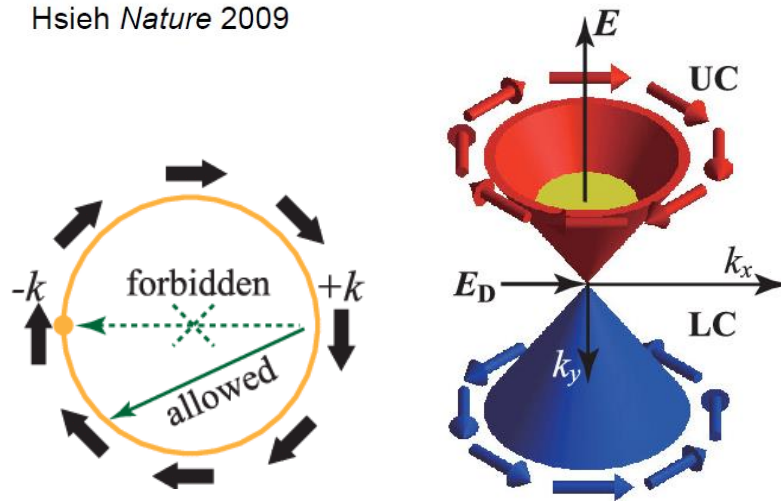
Signatures of Majorana Fermions in Hybrid
Superconductor-Semiconductor Nanowire Devices
V. Mourik et al. *Science* **336** 1003 (2012)

- All the materials are quantum
- Electronic structure is a key
- Emergent phenomena
- Why Superconductors are QM^N
- **Other examples:**
 - **TMD's and Topological Insulators**
 - **QM^{N+1}**

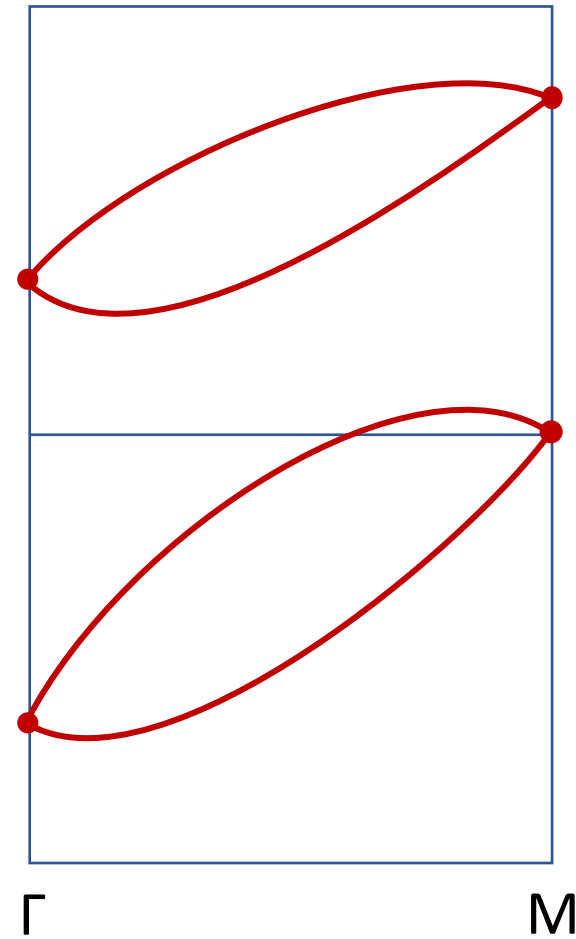
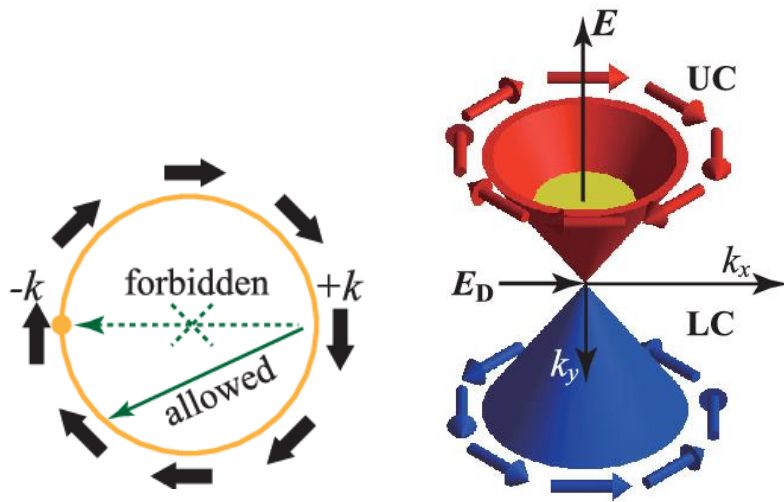
ARPES on Bi_2Se_3



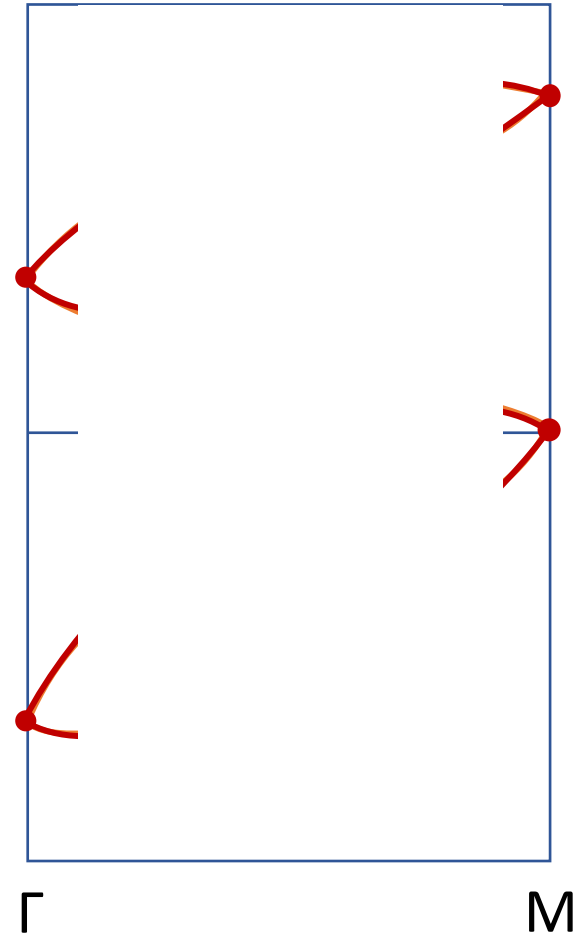
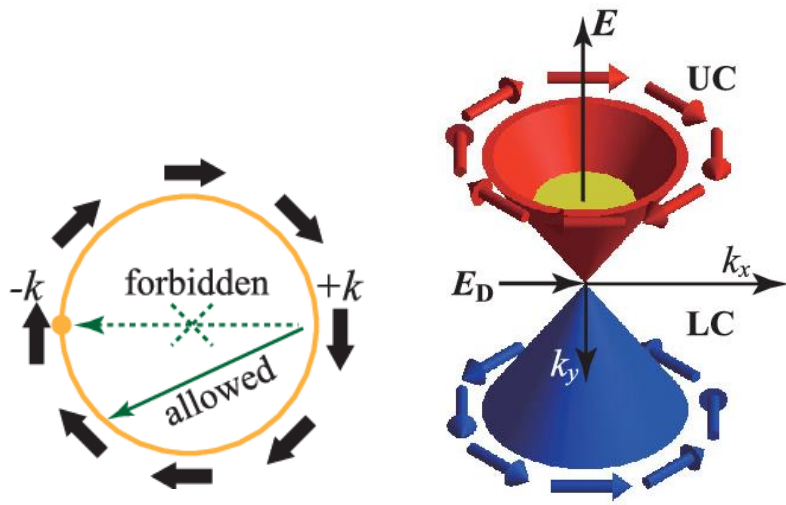
Bianchi *Nature Commun.* 2010



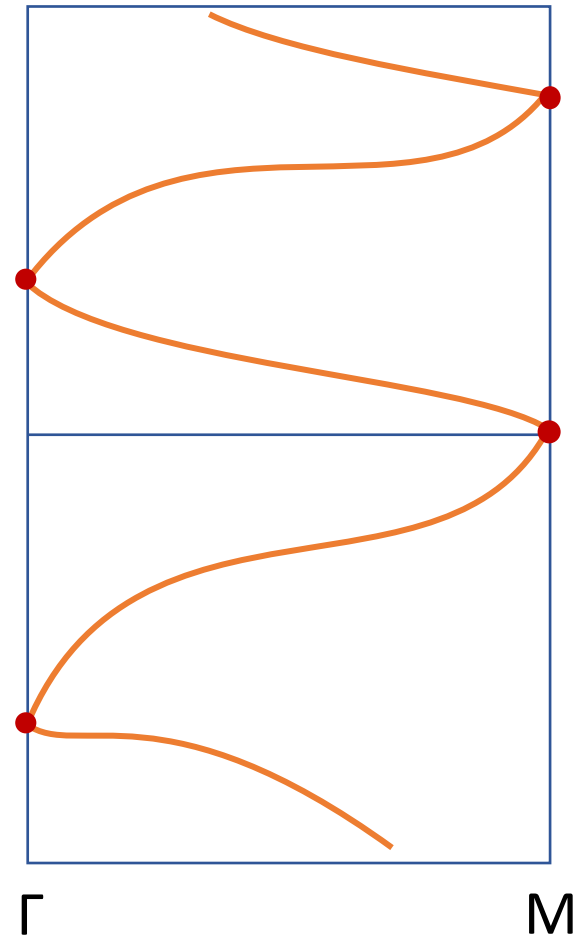
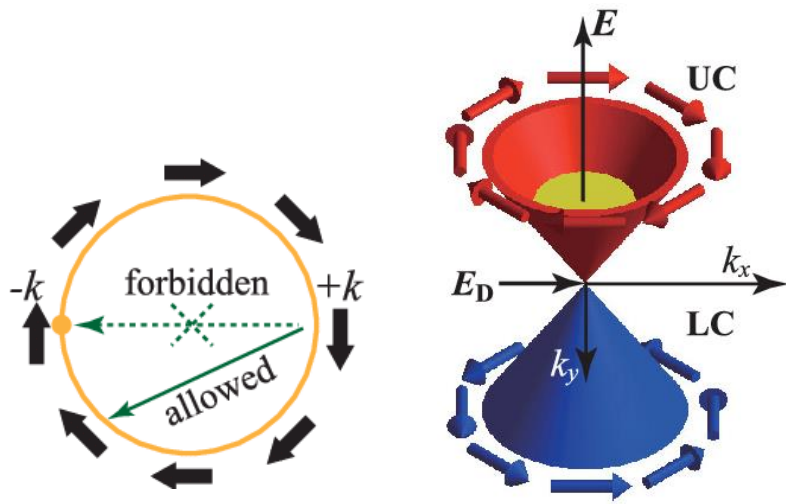
Topological protection



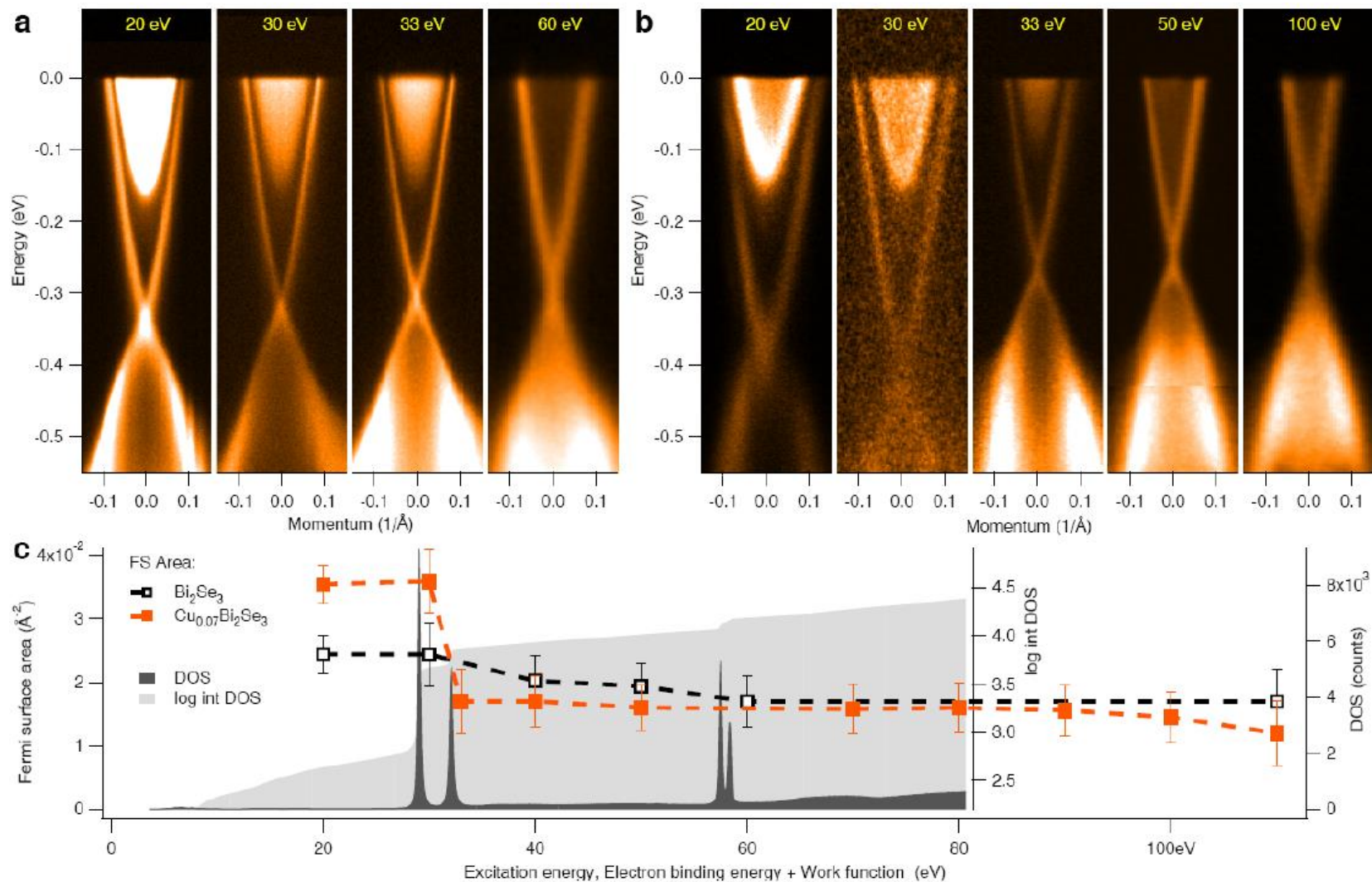
Topological protection



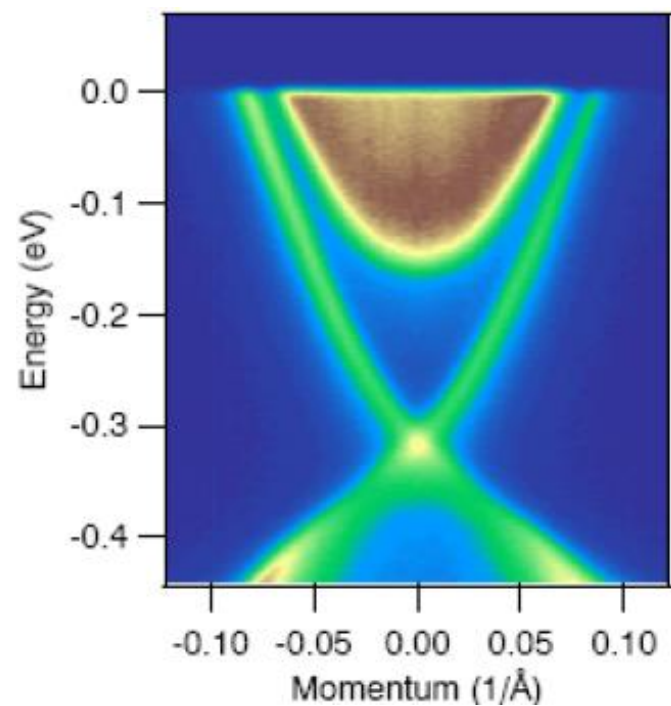
Topological protection



ARPES on Bi_2Se_3



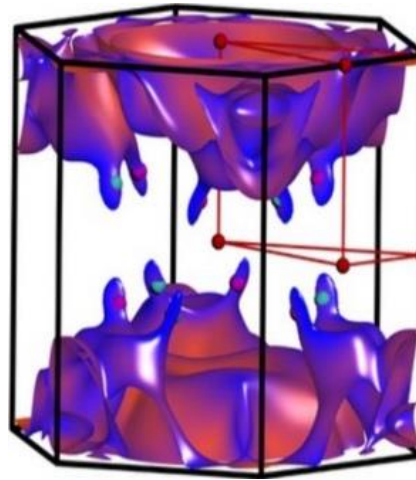
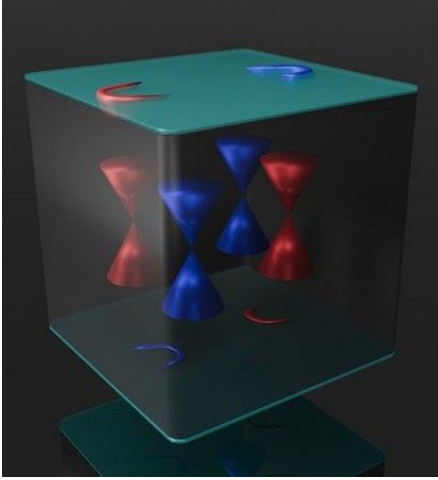
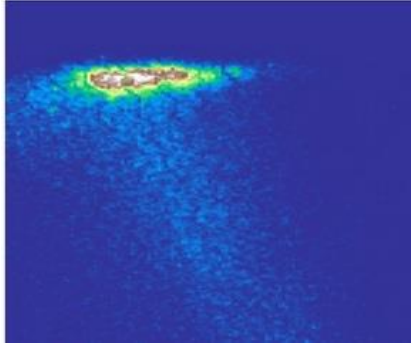
$5d_{5/2}$ and $5d_{3/2}$



Kordyuk *PRB* 2011, *PRB* 2012

Topological superconductivity in PtBi₂

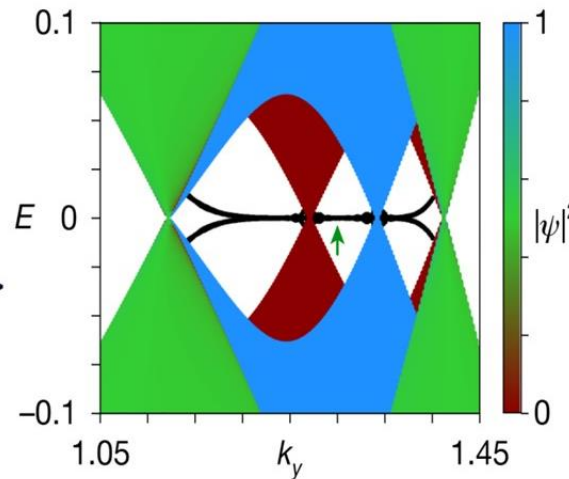
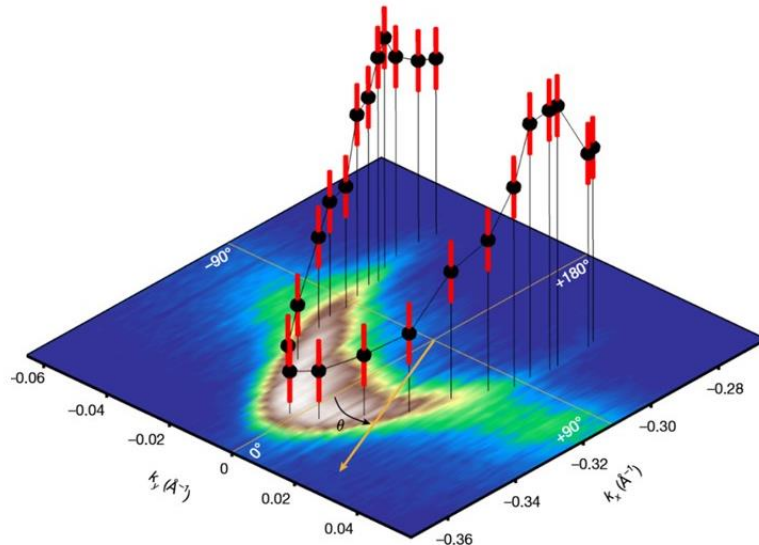
nature



Observation of superconducting “Fermi arcs” as a manifestation of topological superconductivity

Kuibarov, A., Suvorov, O., *et al.*
Evidence of superconducting Fermi arcs.
Nature **626**, 294–299 (2024).
<https://doi.org/10.1038/s41586-023-06977-7>

Topological nodal *i*-wave superconductivity in PtBi₂

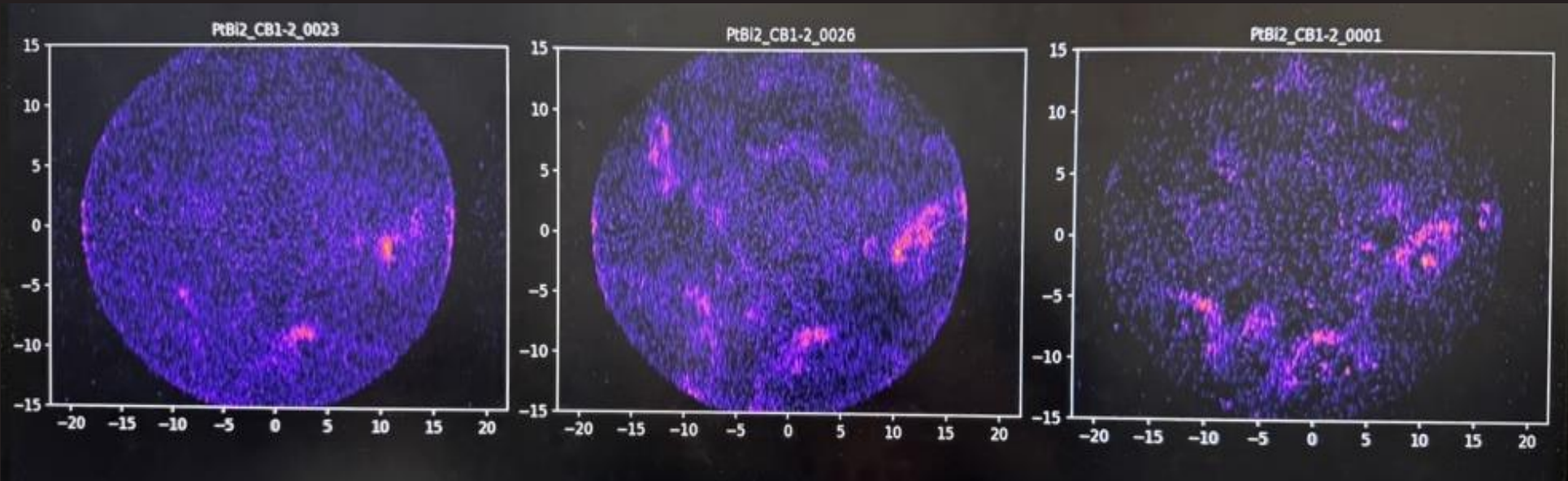
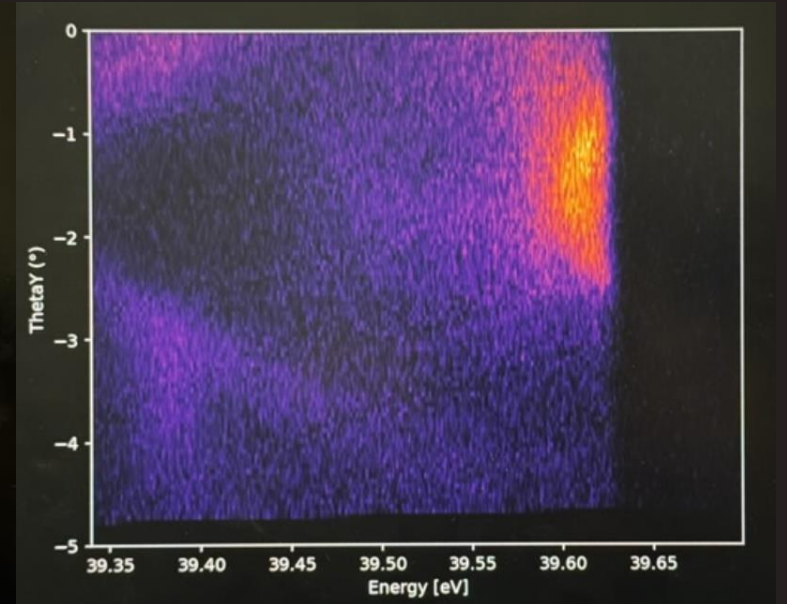
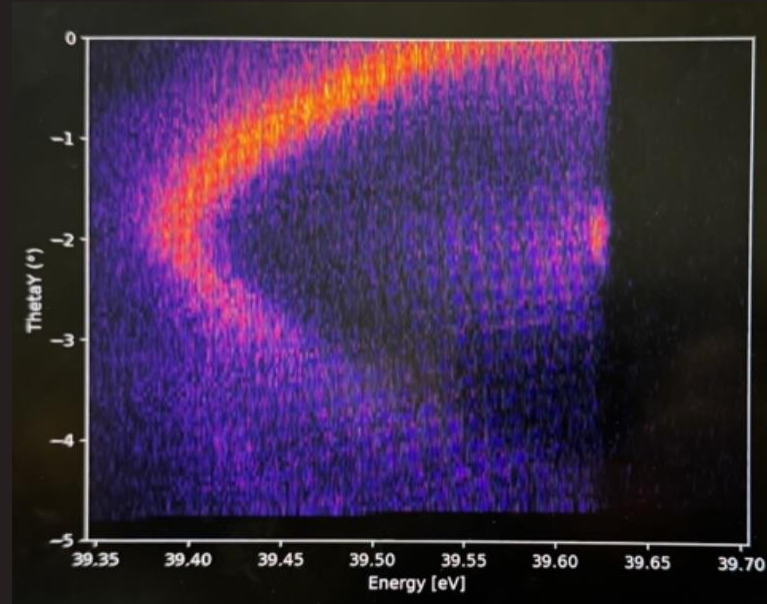


Using ARPES, superconducting gap nodes were observed on the topological Fermi arcs of PtBi₂, indicating unconventional *i*-wave pairing and topologically protected Majorana cones.

Changdar, S., Suvorov, O., Kuibarov, A. et al.
Topological nodal *i*-wave superconductivity in PtBi₂.
Nature **647**, 613–618 (2025).
<https://doi.org/10.1038/s41586-025-09712-6>

Manipulation of topological surface states

05.2025, SOLARIS:
Evolution of the
Fermi arcs with
Rb evaporation
on the surface





SOLARIS

Thank You!

