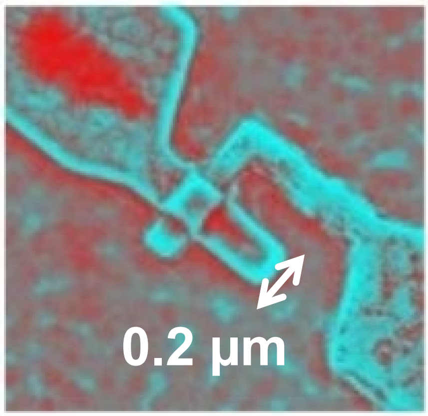
Superconducting Quantum Hardware: Materials, Fabrication and Noise



Spring School on Superconducting Qubit Technology

2023, Apr 11 -- Apr 21

Organizers:
David López-Núñez (IFAE, Barcelona)
Fabian Zwiehoff (IFAE, Barcelona)
Pol Forn-Díaz (IFAE, Barcelona)

Ioan M. Pop

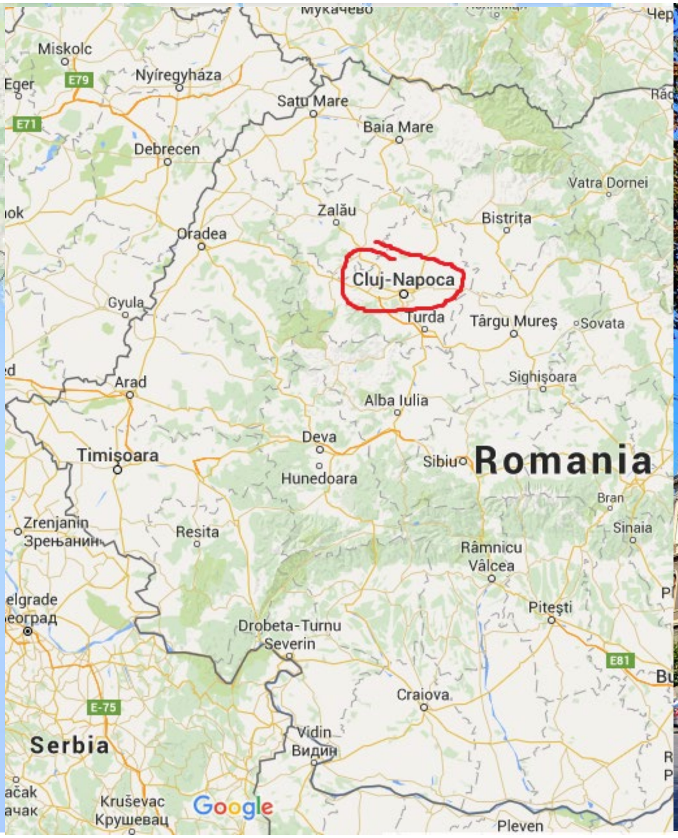
KIT

An older example: post-apprentice in the baker's guild

MUSEUM DER BROTKULTUR ULM *1955

By the rules of the guild, before settling down and opening a shop, a young baker had to travel for several years to learn new recipes and techniques.

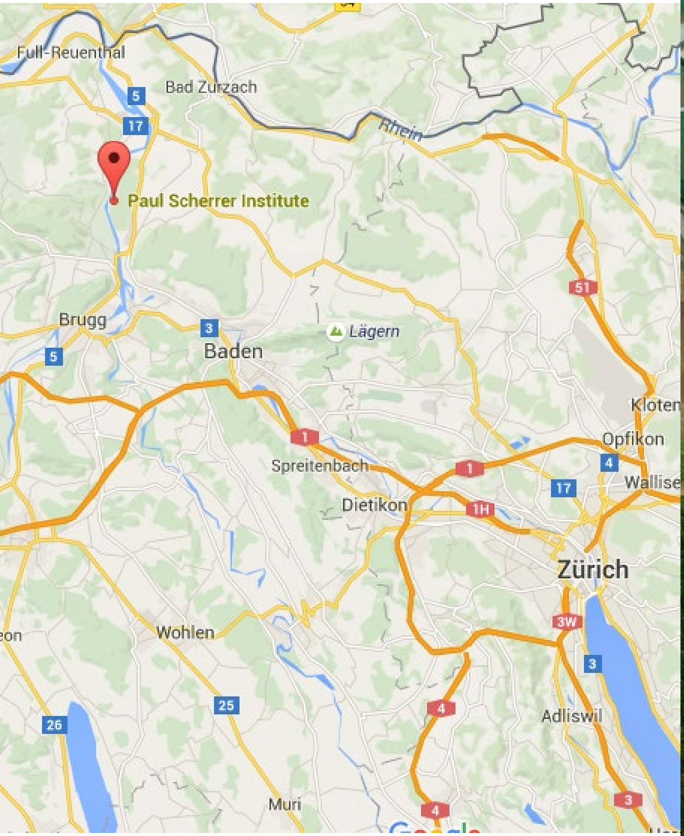
My initiation journey



Undergraduate at Babes-Bolyai University, Bachelor in Physics

(2002-2006)

My initiation journey

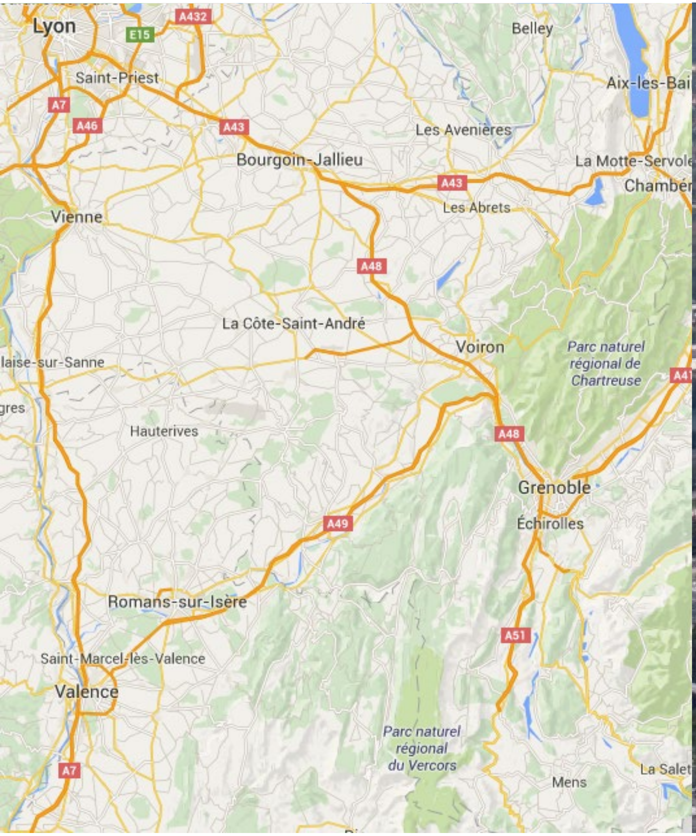


PAUL SCHERRER INSTITUT
PSI

Research Internships at Paul Scherer Institute (PSI)

(2005 and 2006)

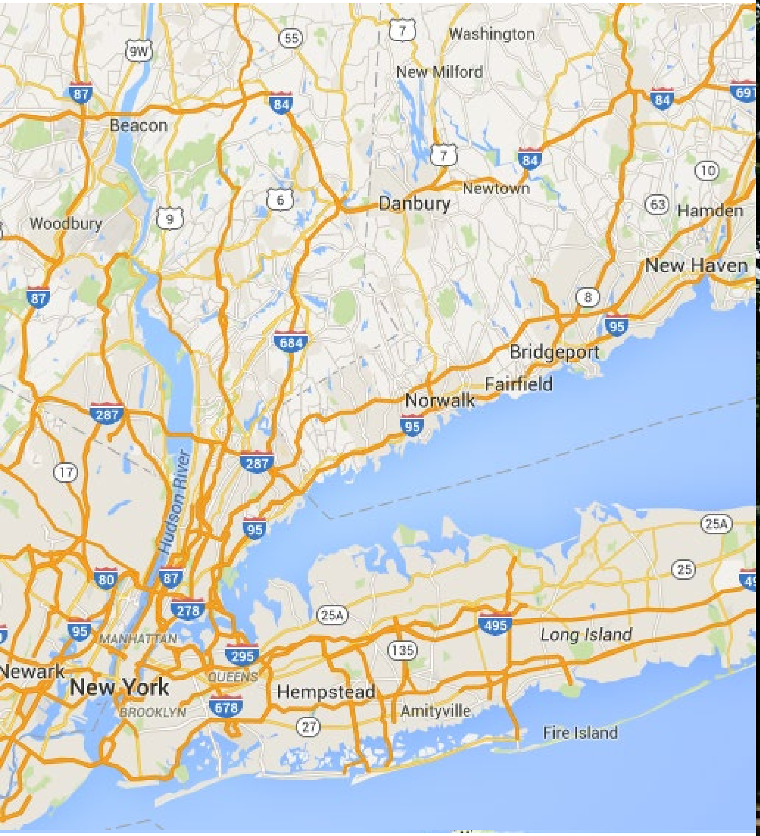
My initiation journey

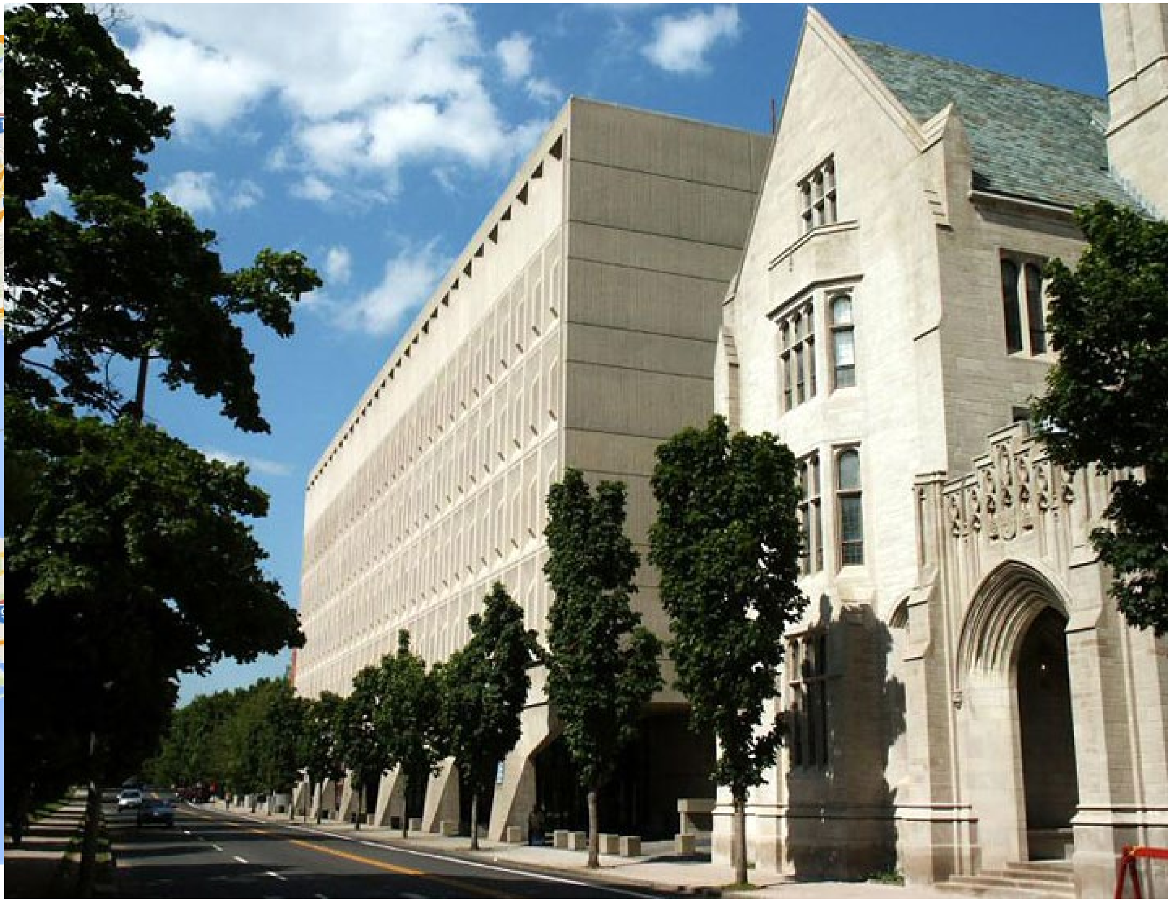


Master and PhD, in CNRS and University of Grenoble

(2006-2011)

My initiation journey

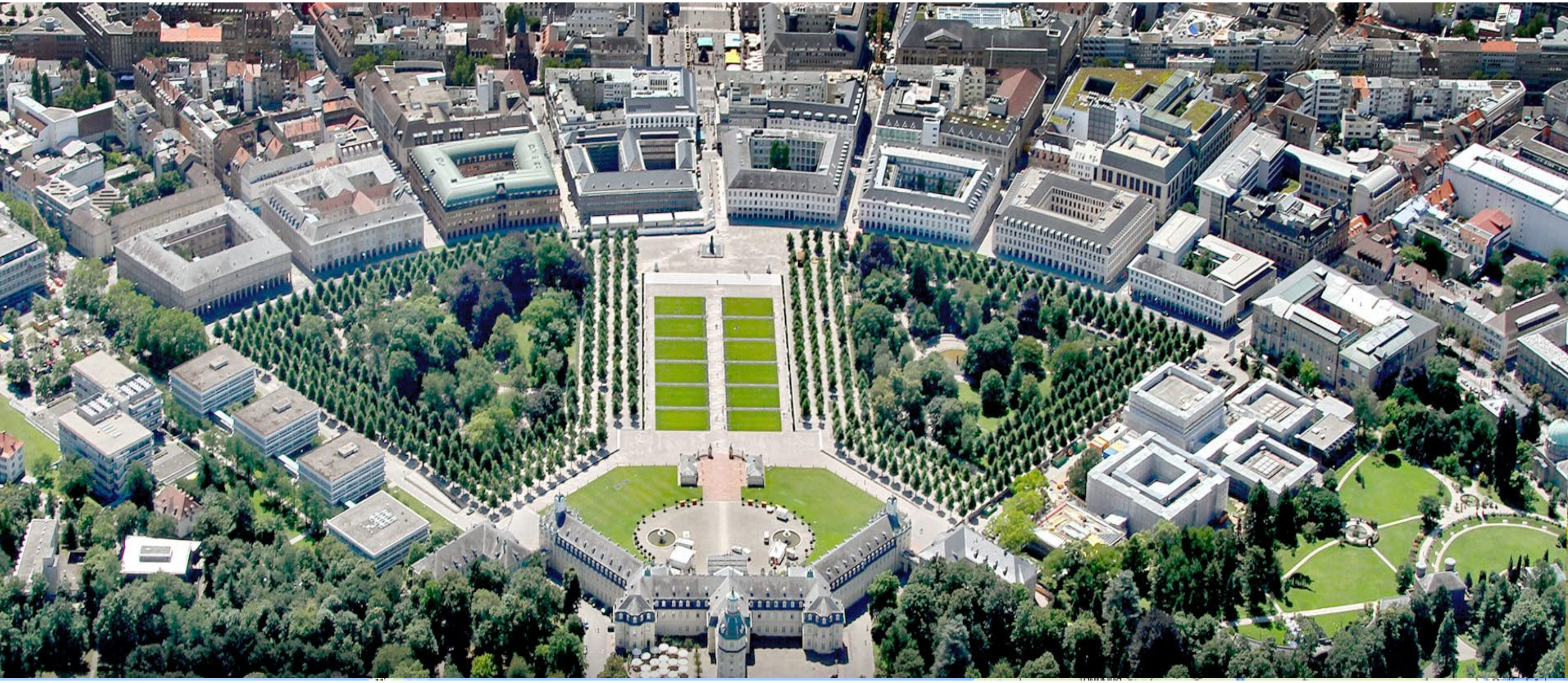




Postdoctoral research in Yale University

(2011-2015)

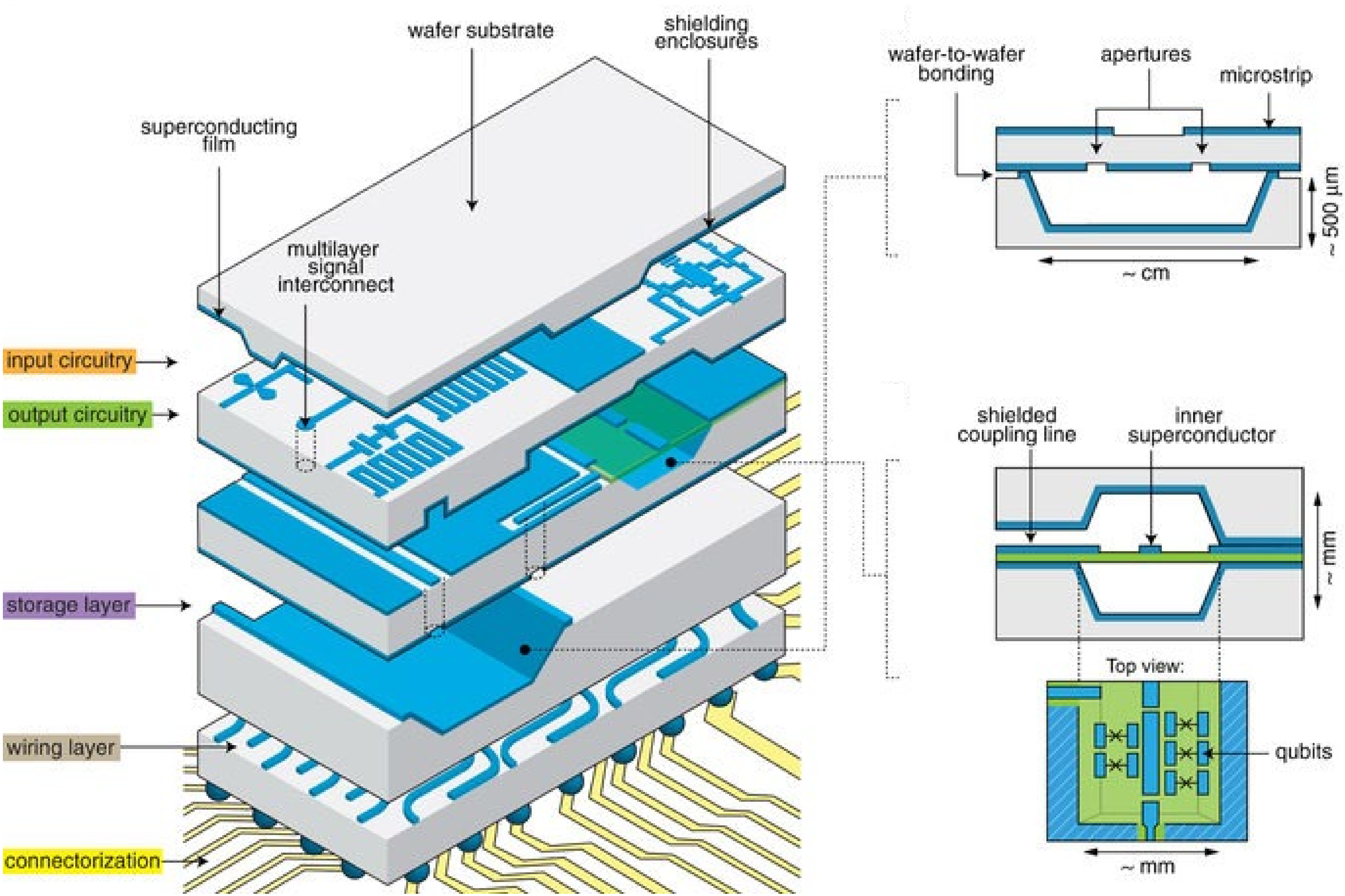
My initiation journey



Back in Europe!

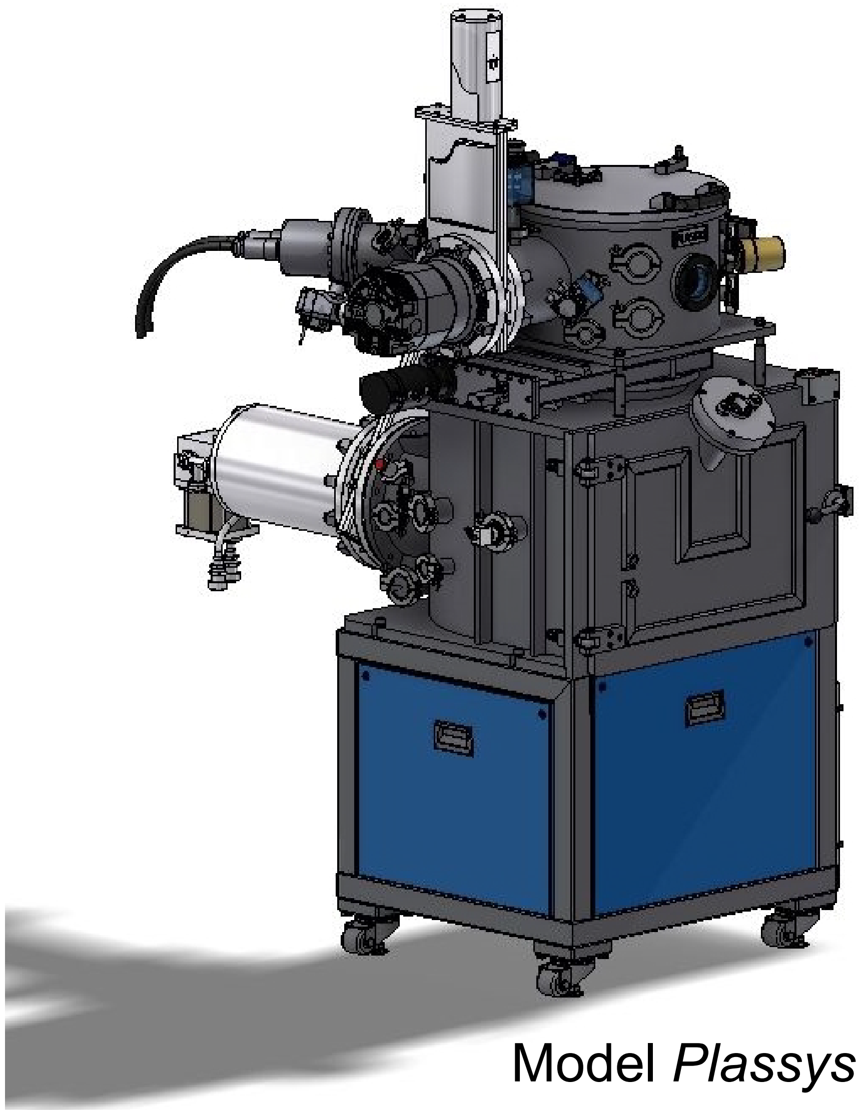
Thanks to the Humboldt Foundation


BLACK FOREST QUANTUM
Thomas
Ameya
Immanuel
Nico Z.
Denis
Ritika
Fabian
Markus
Nico G.
Dennis
Simon I.
Martin
Mathieu
Simon II.
Patrick
Sören
Mahya
Ioan
autumn 2022



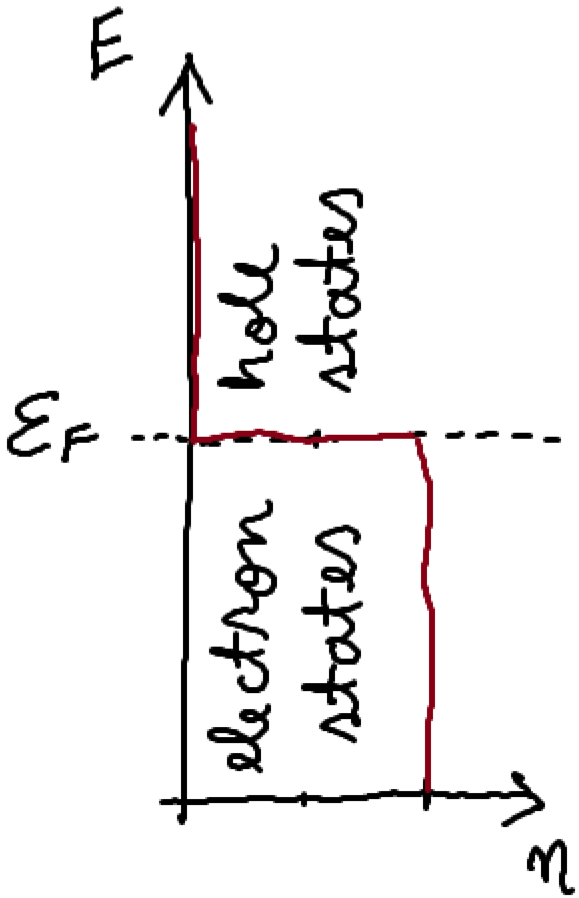
Brecht et al. , *Multilayer Microwave Integrated Quantum Circuits for Scalable Quantum Computing,* NPJ Quantum Information (2016)

Metal evaporator



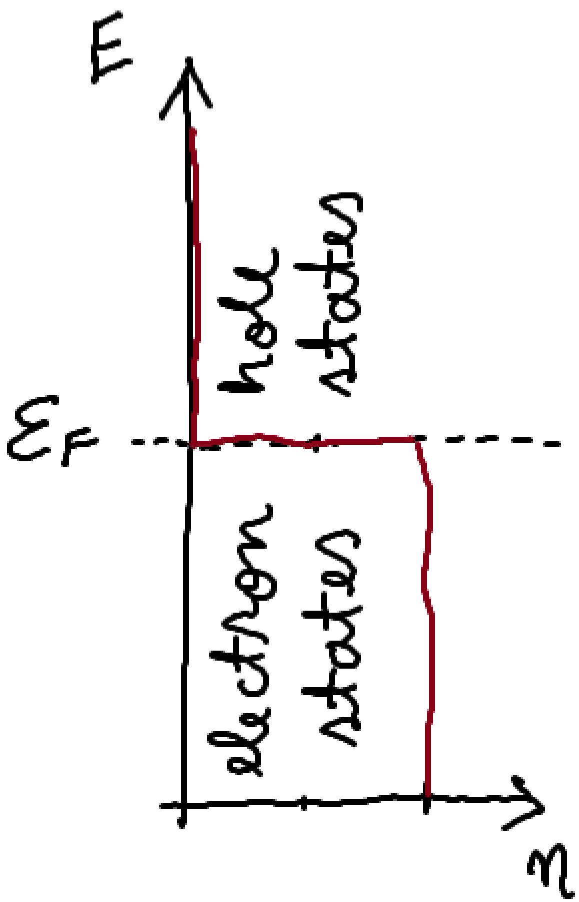
Model *Plassys MEB550*

Why Superconductors?



T=0

Why Superconductors?



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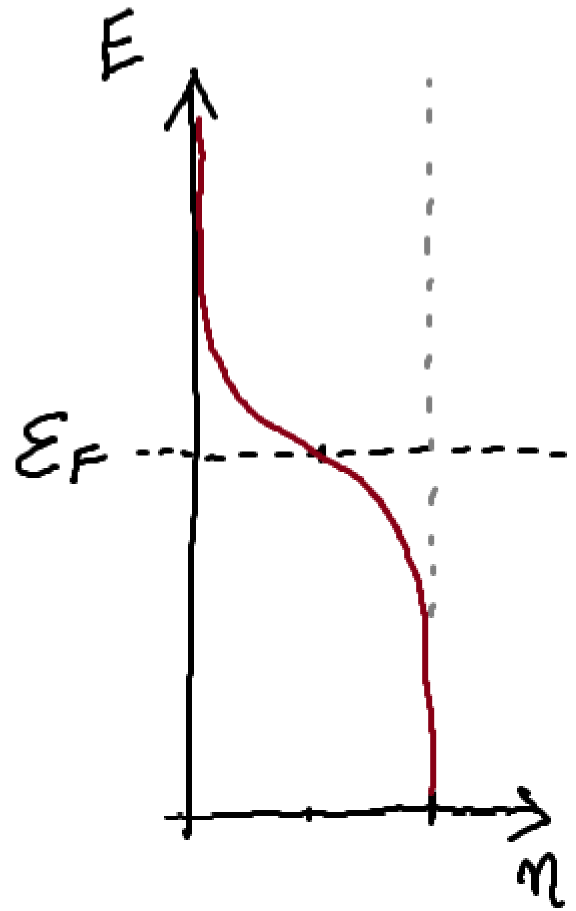
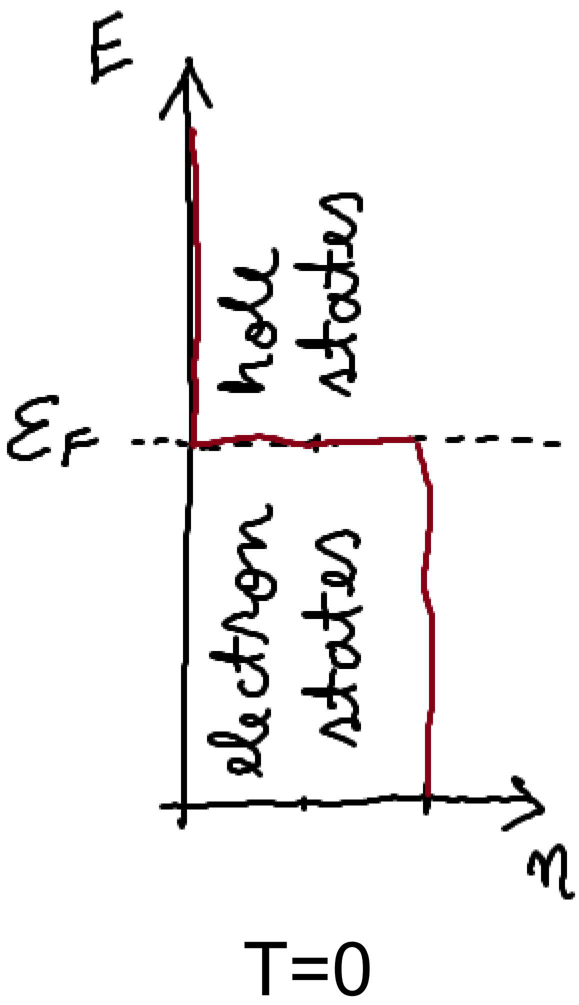
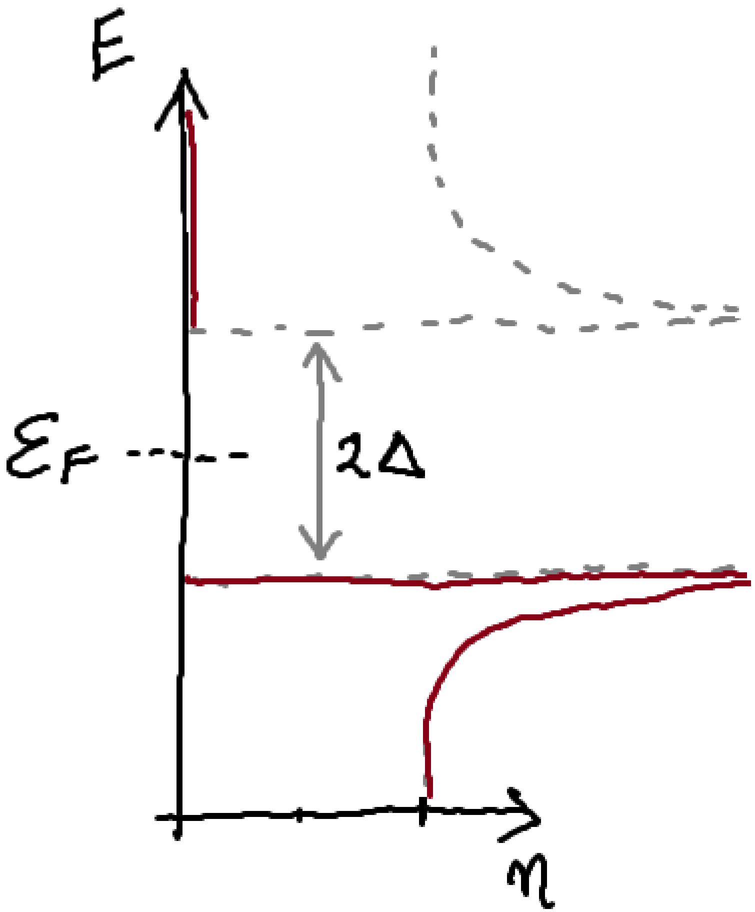


T>0

Why Superconductors?

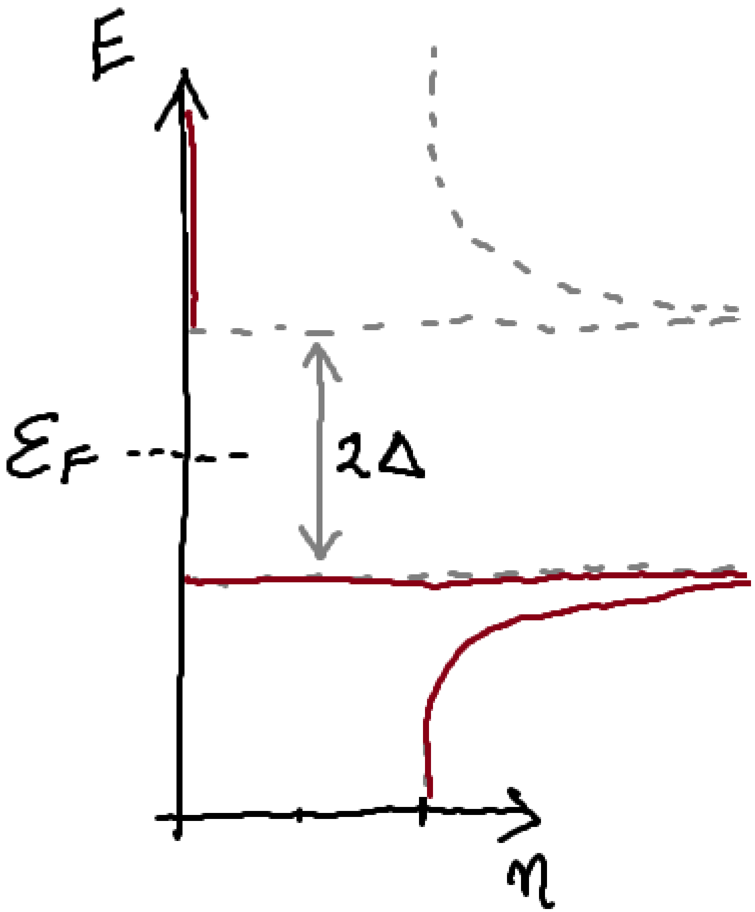


Why Superconductors?

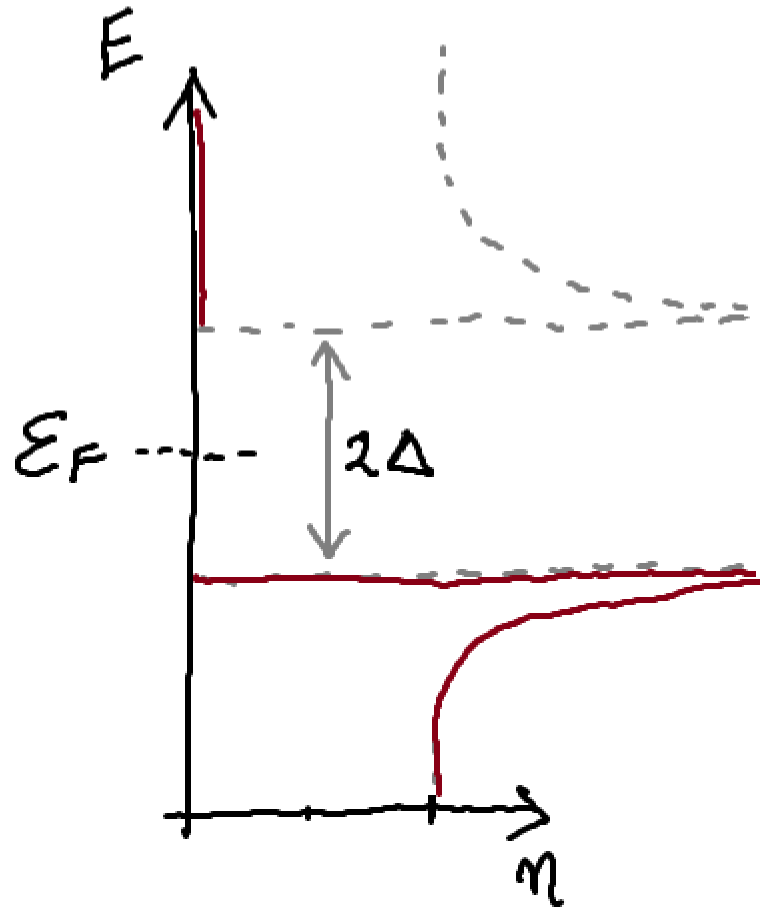


T=0

Why Superconductors?



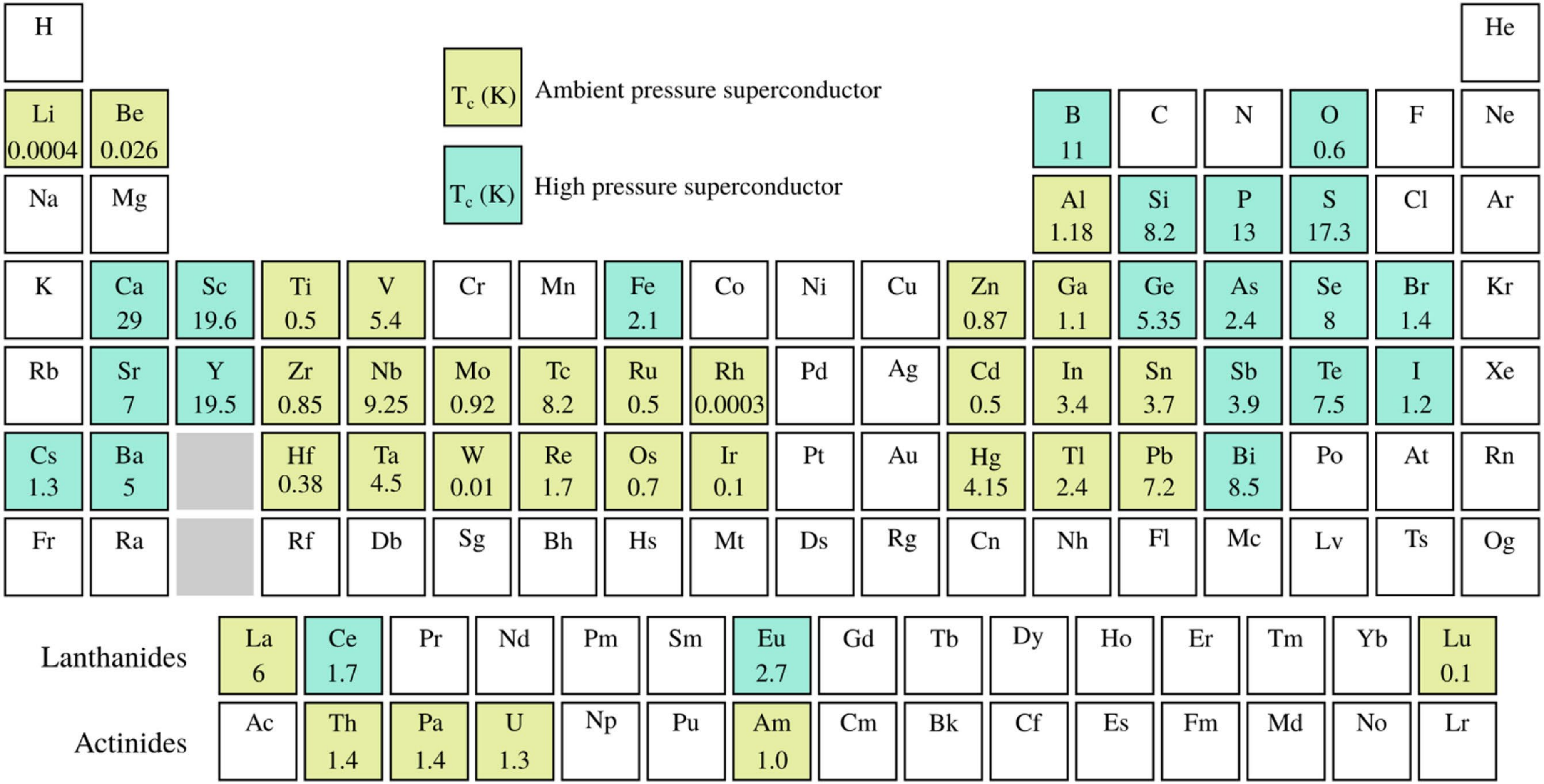
T=0



0<T<<2Δ

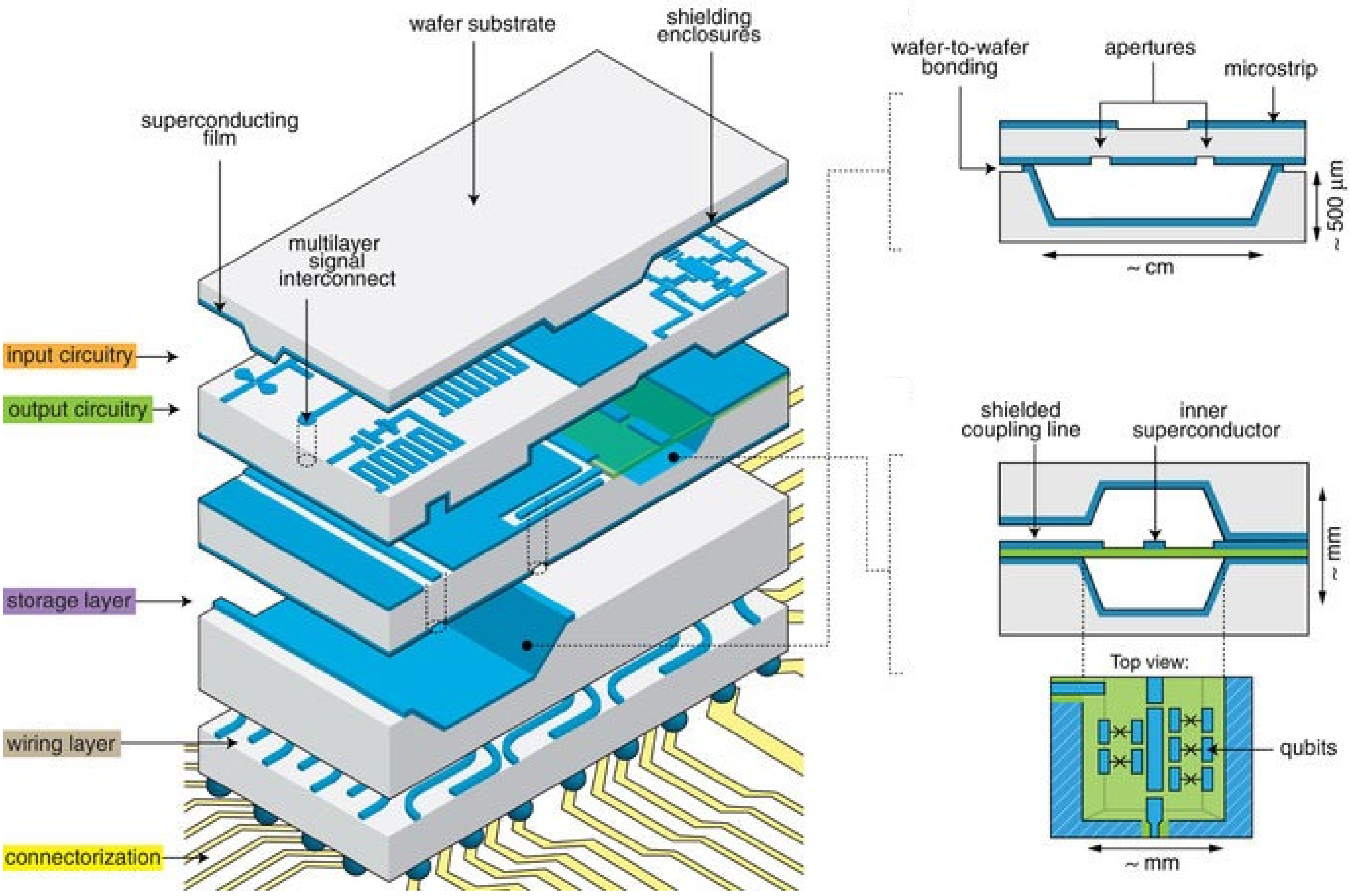
Which Superconductors?

Periodic table of superconductivity



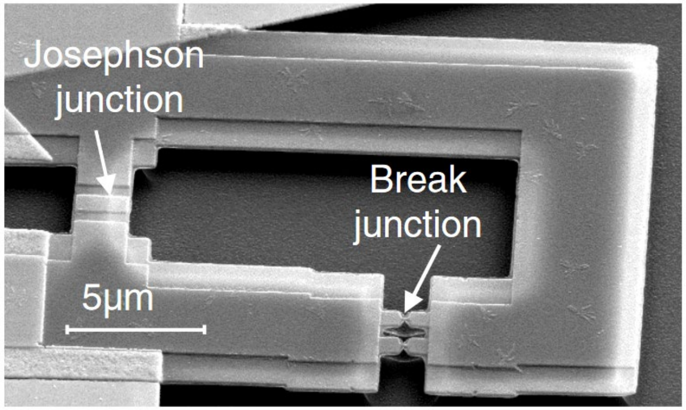
Flores-Livas et al. Phys. Rep. 856 (2020)

How about the junctions?

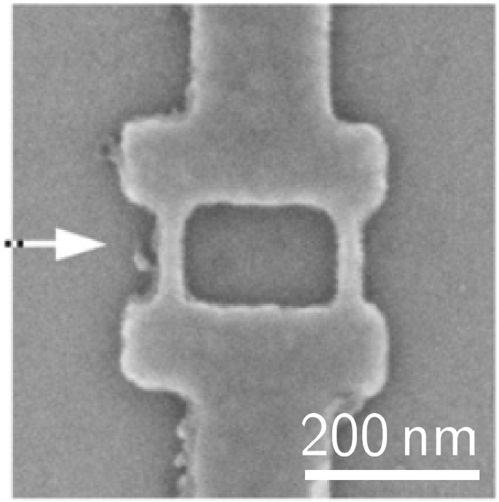


What should we chose?

Point Contact



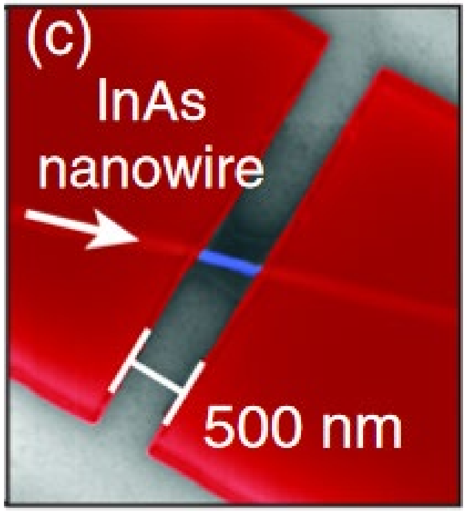
Rocca et al., PRL **99** (2007)



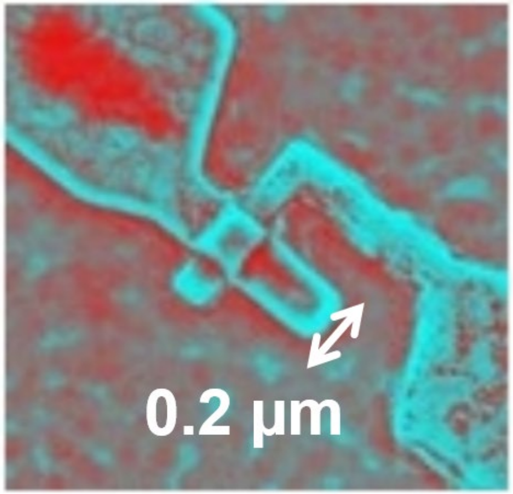
Constriction

Wernsdorfer, Supercond. Sci. Technol. 22 (2009)

Semiconductor Junction



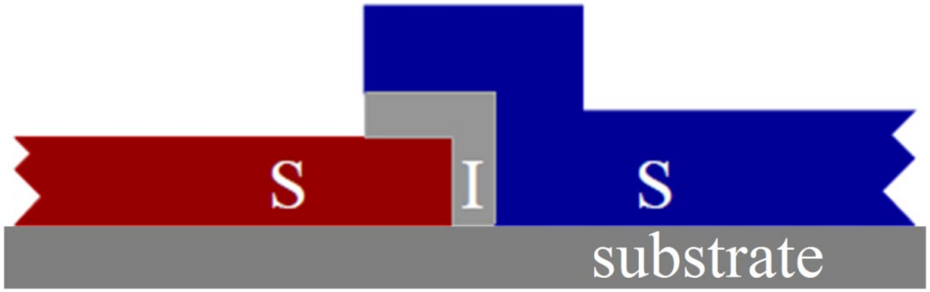
Lange et al., PRL **115** (2015)



Tunnel Junction

The building blocks of superconducting circuits: SIS Josephson junctions

Side view



Qubit Fabrication : Dolan bridge technique

Spin the PMMA resist

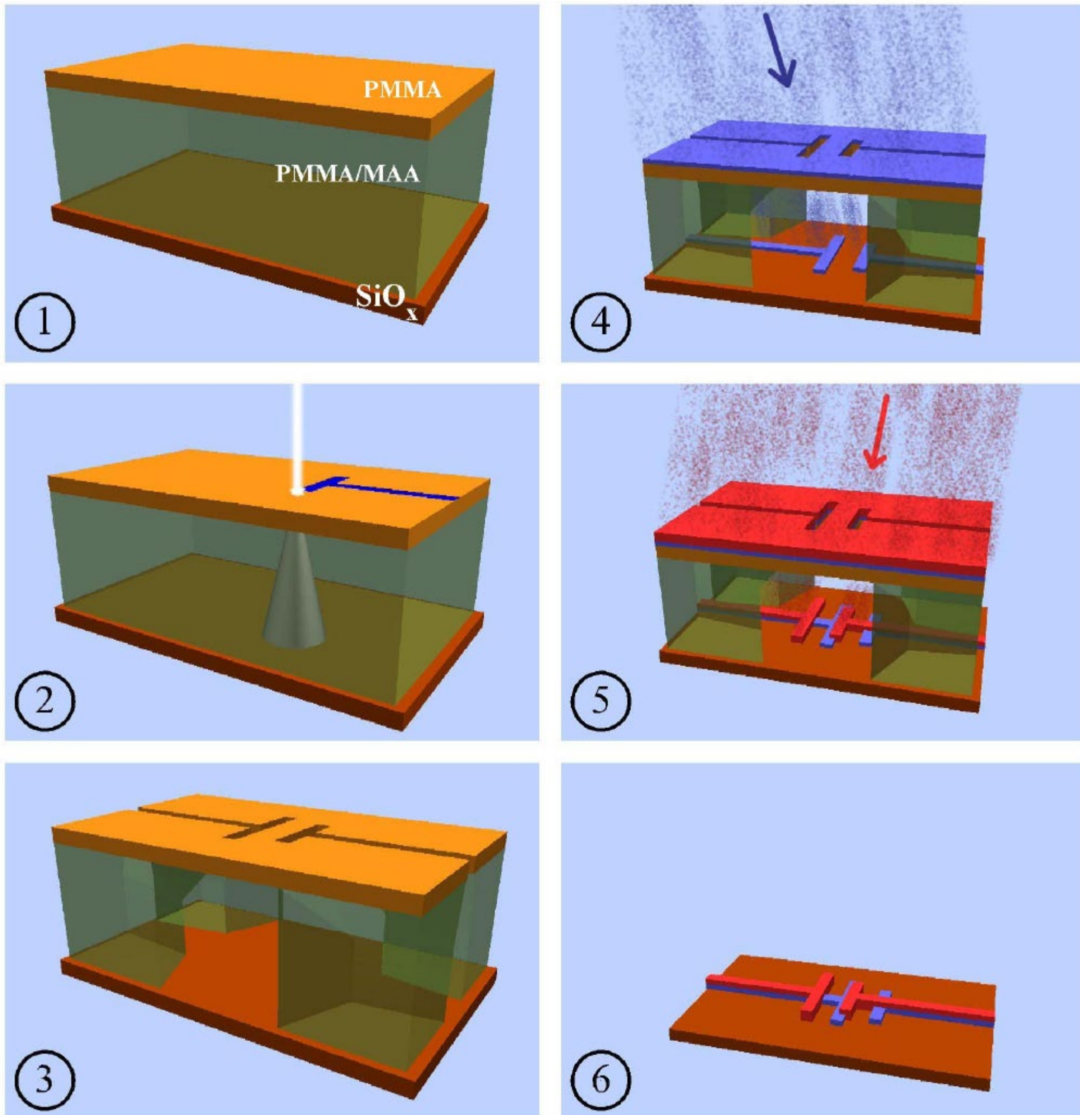
Electron beam exposure

Development

1’st deposition

2’nd deposition

Lift off



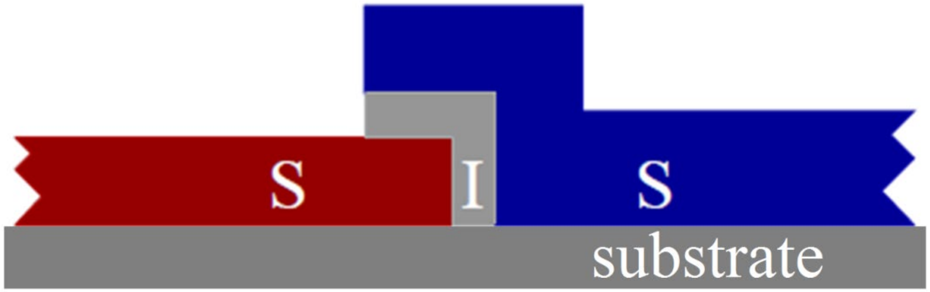
An intuition about our junctions with AlO_x

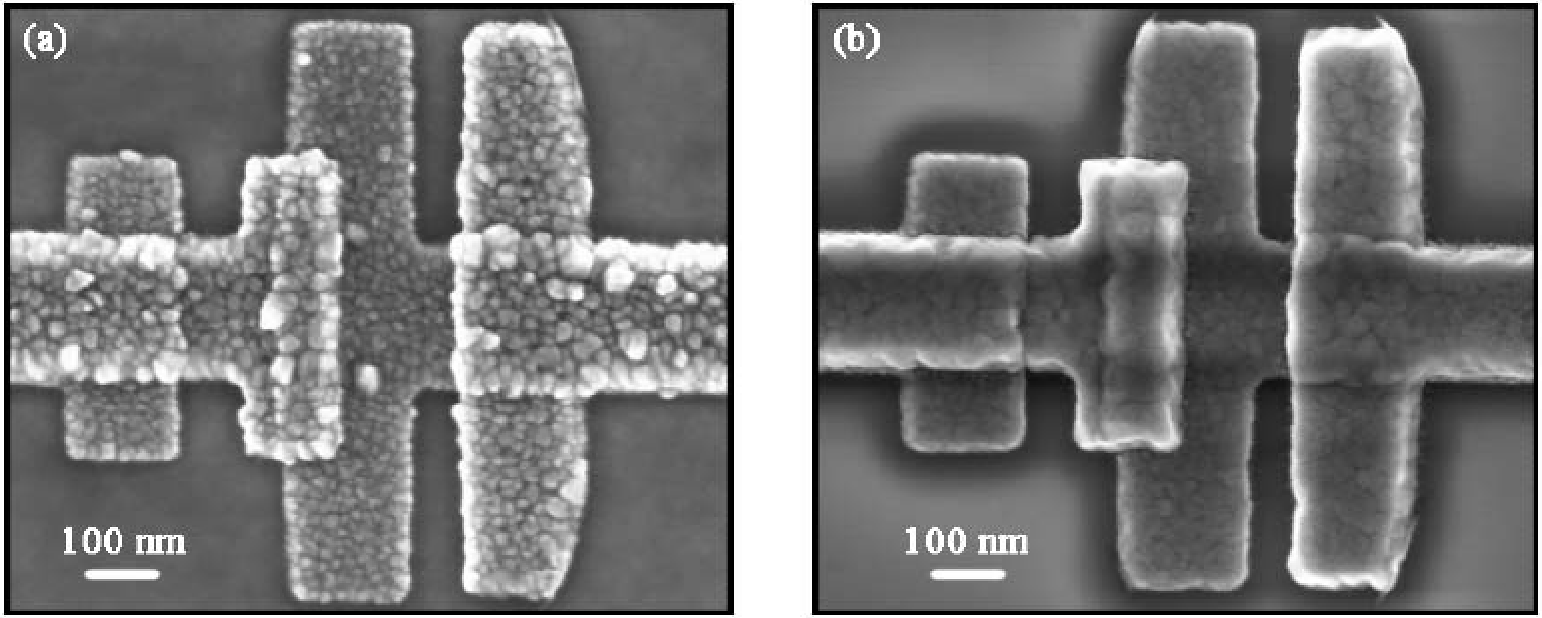
Death Valley

Red Rock Canyon

The building blocks of superconducting circuits: SIS Josephson junctions

Side view

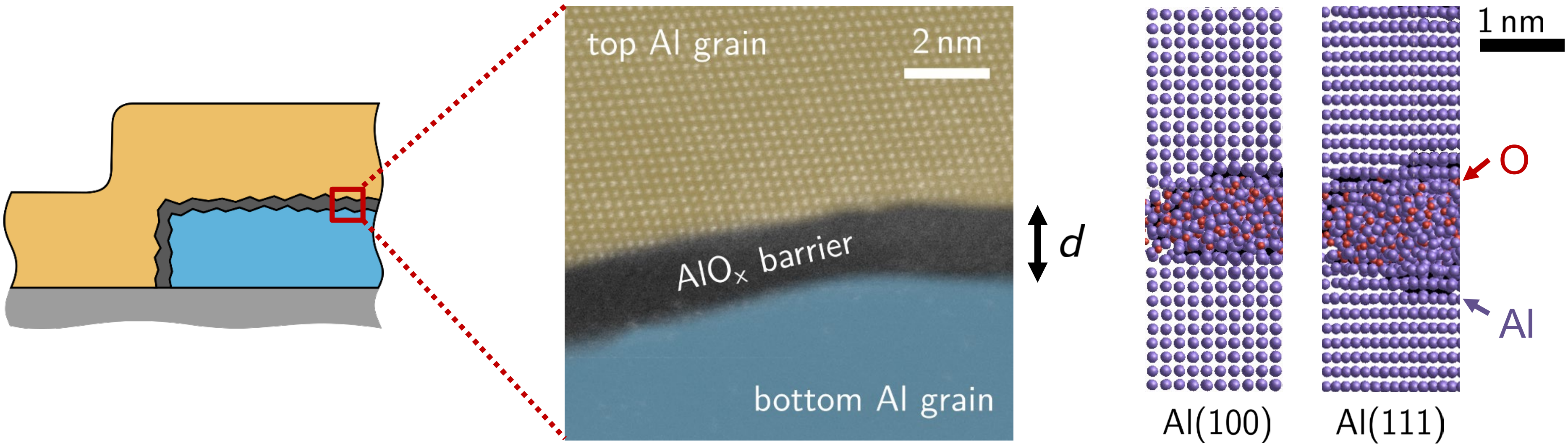




Slow deposition: 0.1 nm/s

Fast deposition: 1 nm/s

Transmission Electron Microscopy and Molecular Dynamics reveal AlO_x barrier inhomogeneity



Schüffelgen Group, FZ Jülich

ITIM Group, Cluj, Romania

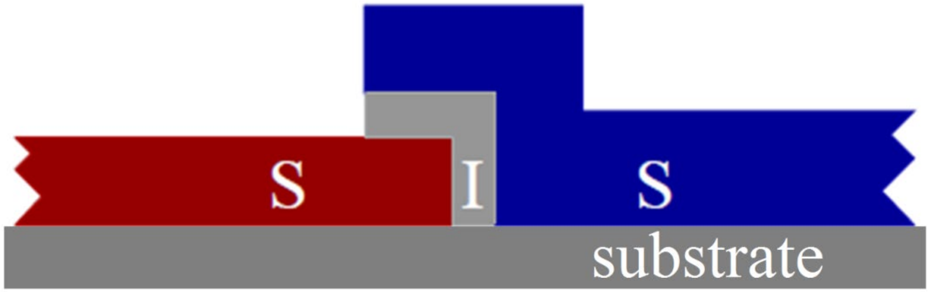
Gaussian thickness distribution → few % of $\sin 2\varphi$

Gianluigi Catelani, FZ Jülich

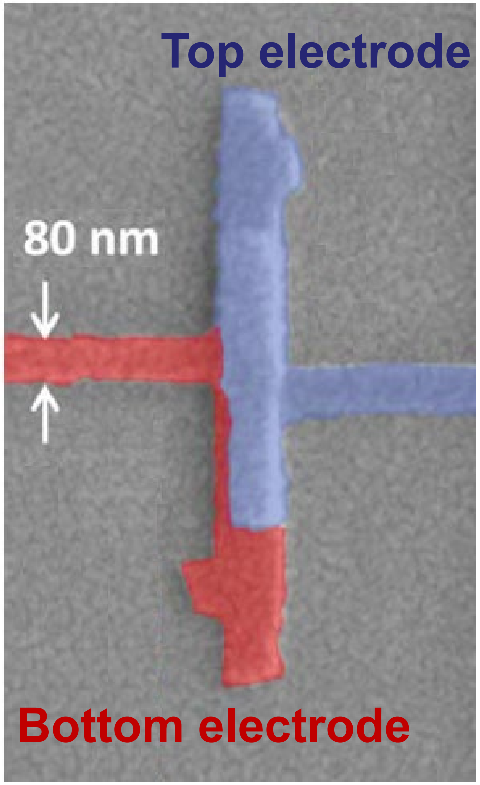
Willsch & Rieger et al. arXiv:2302.09192

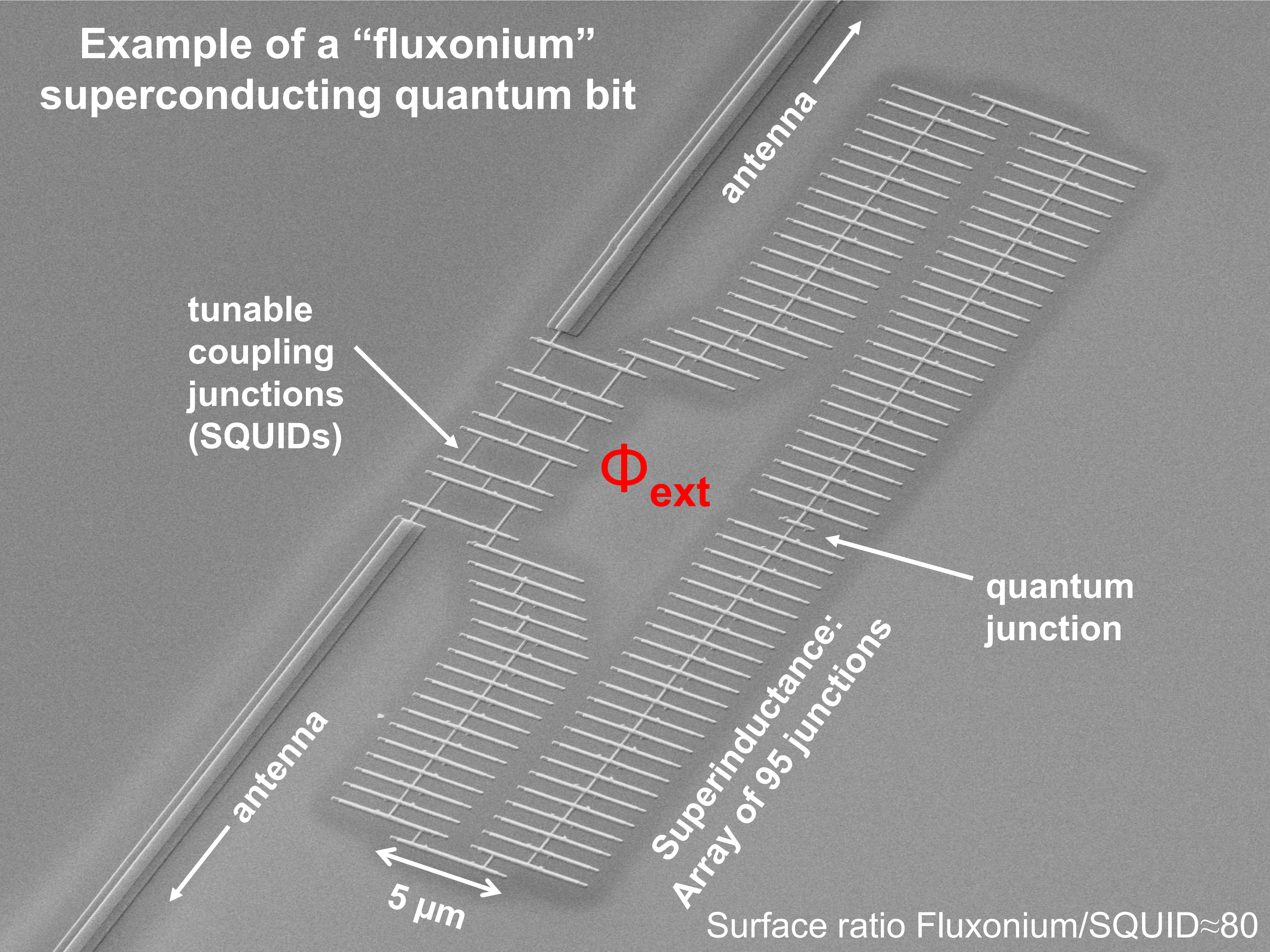
The building blocks of superconducting circuits: SIS Josephson junctions

Side view



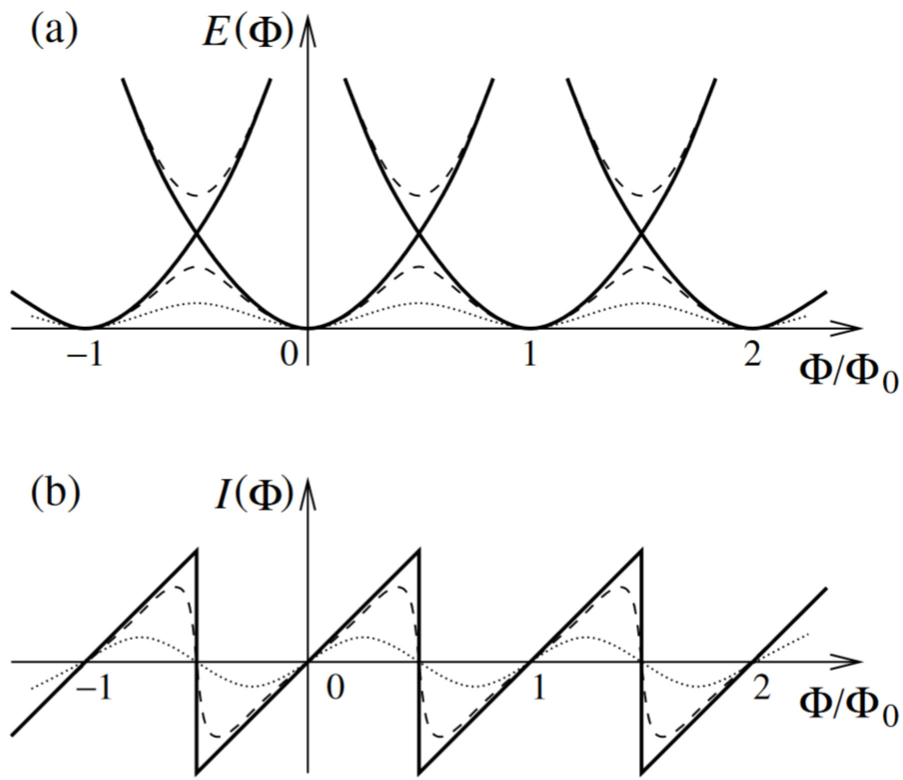
Top view




Example of a "fluxonium" superconducting quantum bit
antenna
tunable coupling junctions (SQUIDs)
Φ_{ext}
quantum junction
Superinductance: Array of 95 junctions
antenna
5 µm
Surface ratio Fluxonium/SQUID≈80

Persistent Current in Superconducting Nanorings

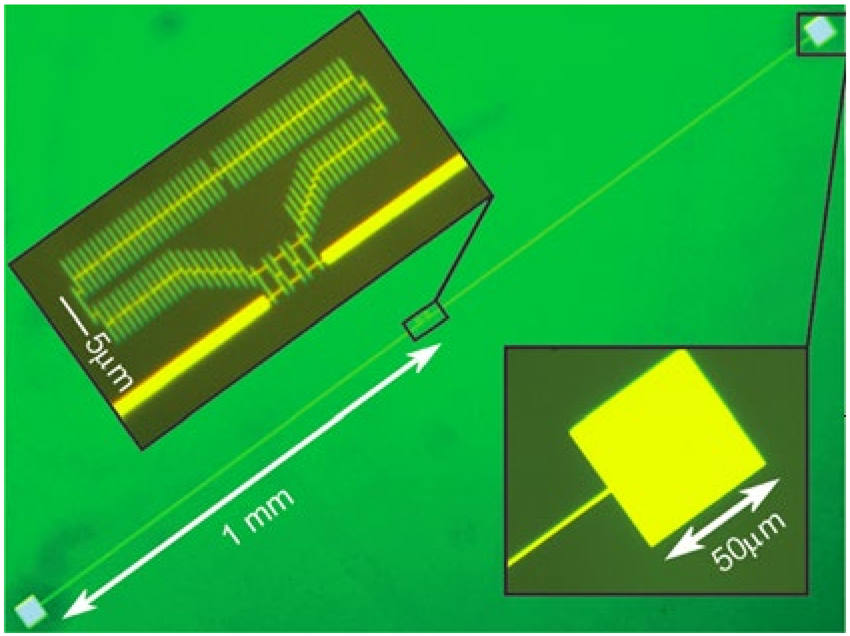
K. A. Matveev,[1] A. I. Larkin,[2,3] and L. I. Glazman[2]



$$\upsilon = \frac{4}{\sqrt{\pi}}(E_J^3 E_C)^{1/4} \exp\left(-8\sqrt{\frac{E_J}{E_C}}\right)$$

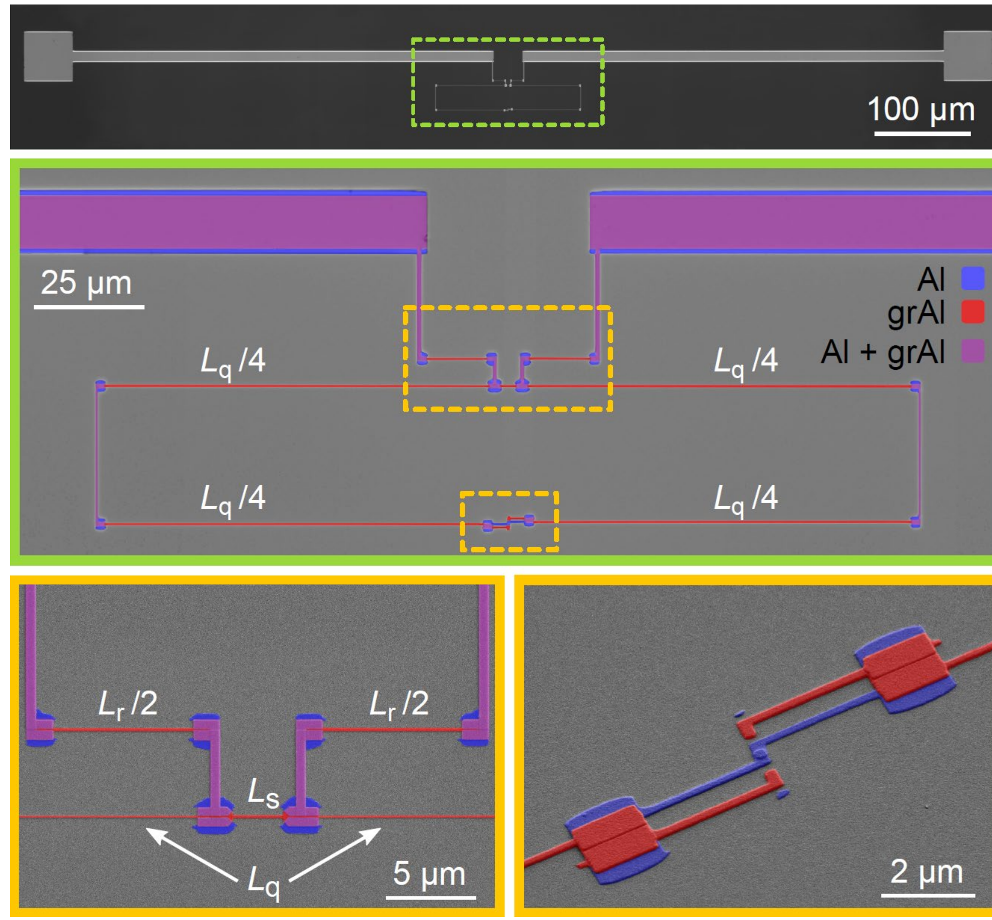
Fluxonium with granular Aluminum (grAl) and one SIS phase-slip junction

About 100 JJ typically required for a fluxonium qubit



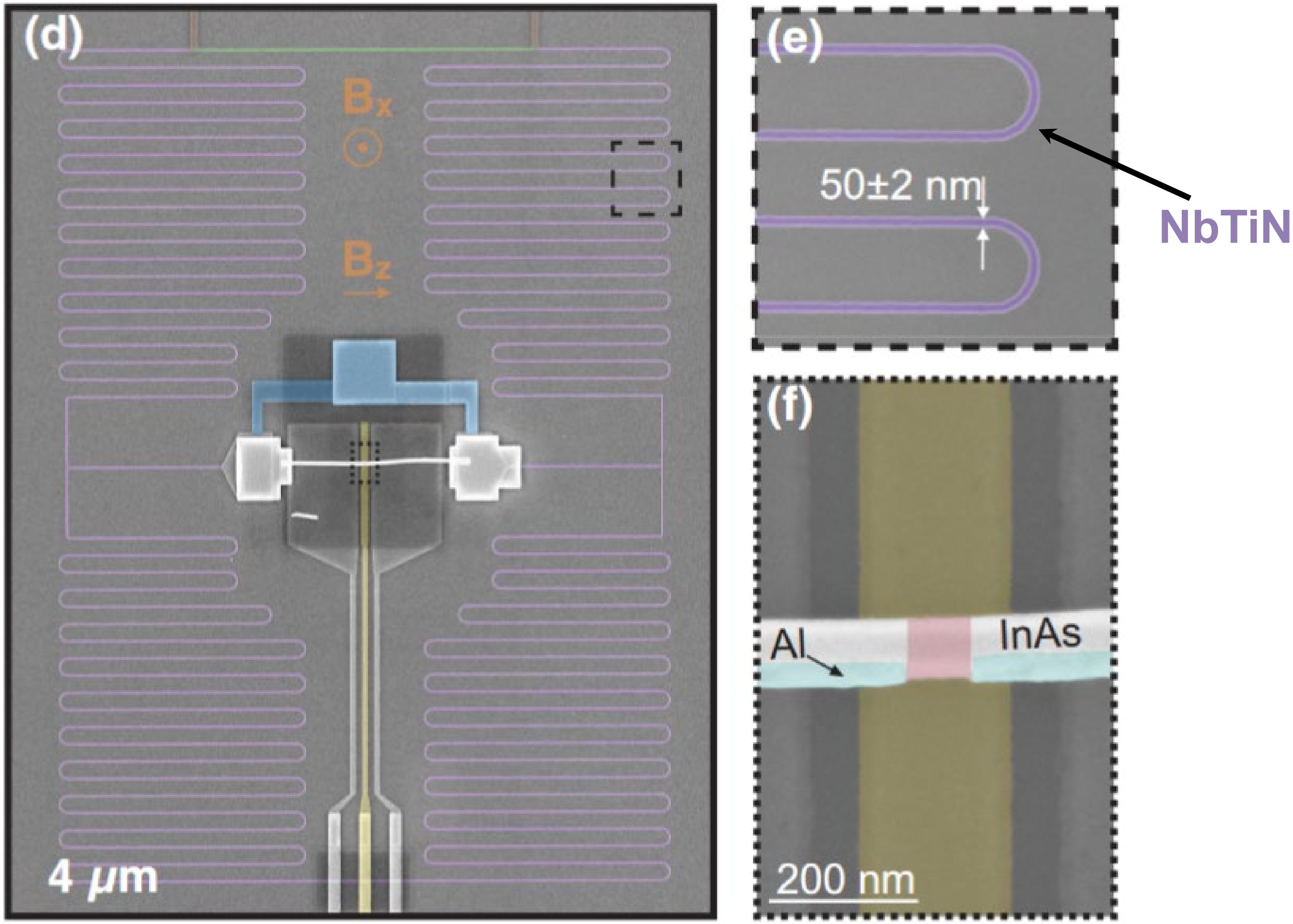
Vool, Pop et al.
Phys Rev. Lett. 113 (2014)

Now how about a 99% discount?



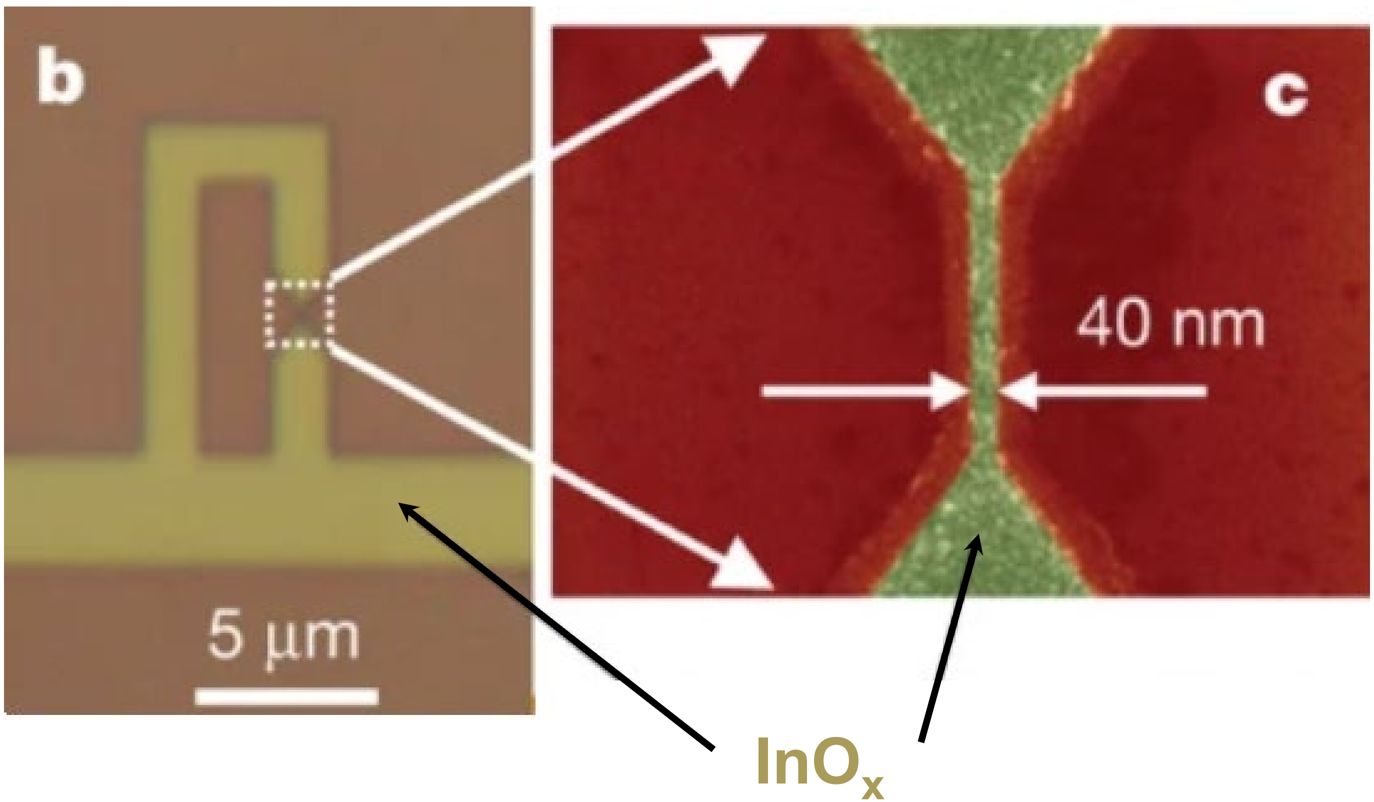
Grünhaupt & Spiecker et al., *Nature Materials* **18**, 816 (2019)

Semiconducting nanowire fluxonium



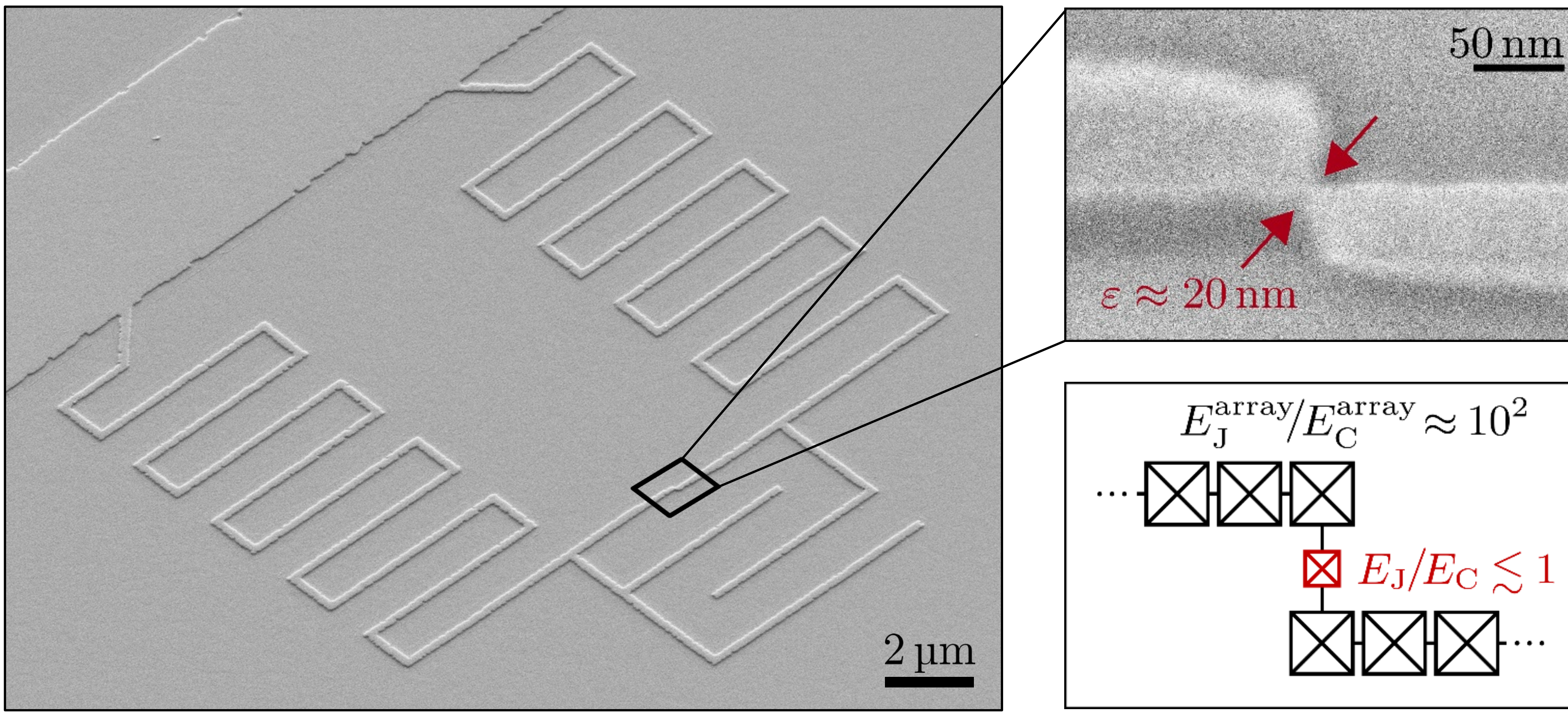
Pita-Vidal et al. *Phys. Rev. App.* **14** (2020)

Indium oxide nanowire fluxonium



Astafiev et al. *Nature* **484** (2012)

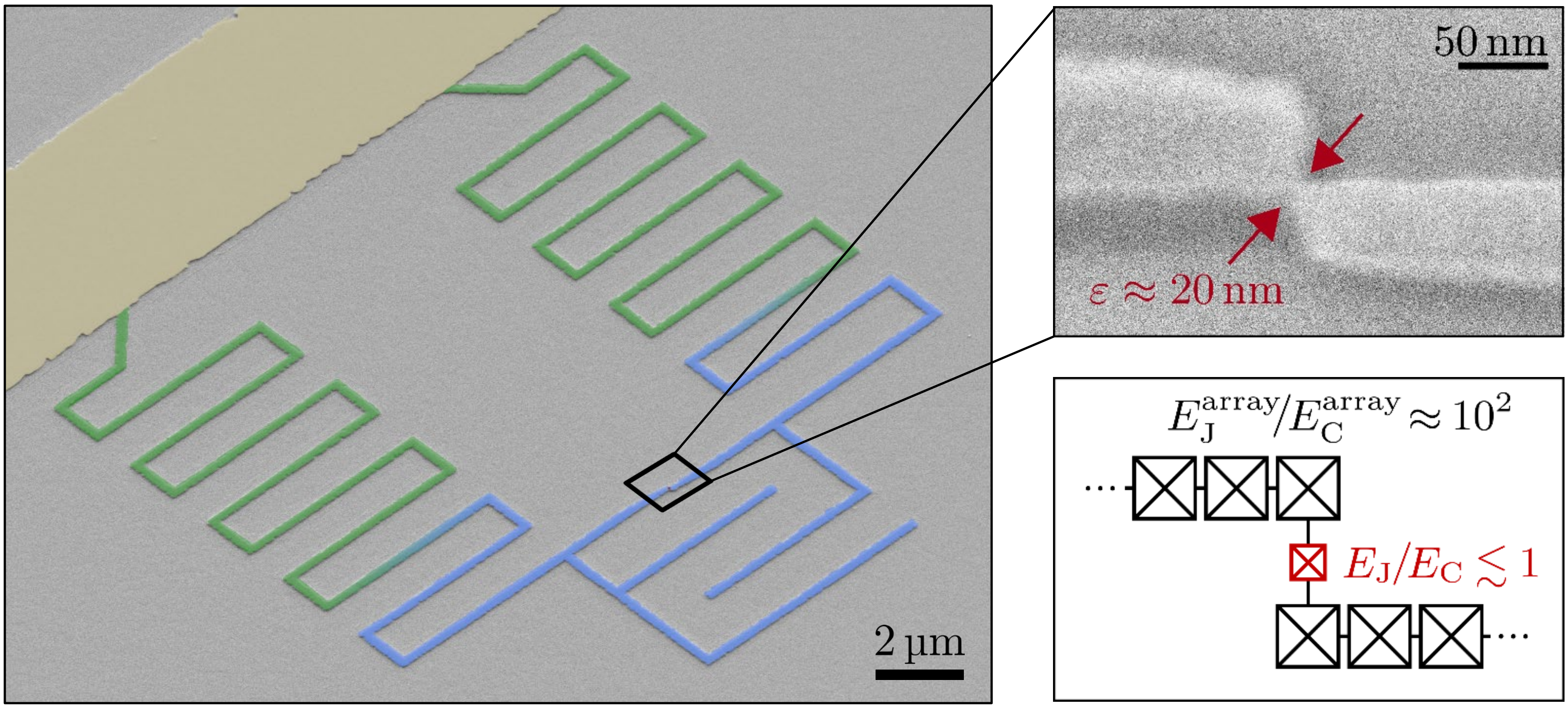
The Gralmonium Circuit & the GrAl Nano-Junction



Rieger & Günzler et al. *Nature Materials* **22** (2023)

The Gralmonium Circuit & the GrAl Nano-Junction

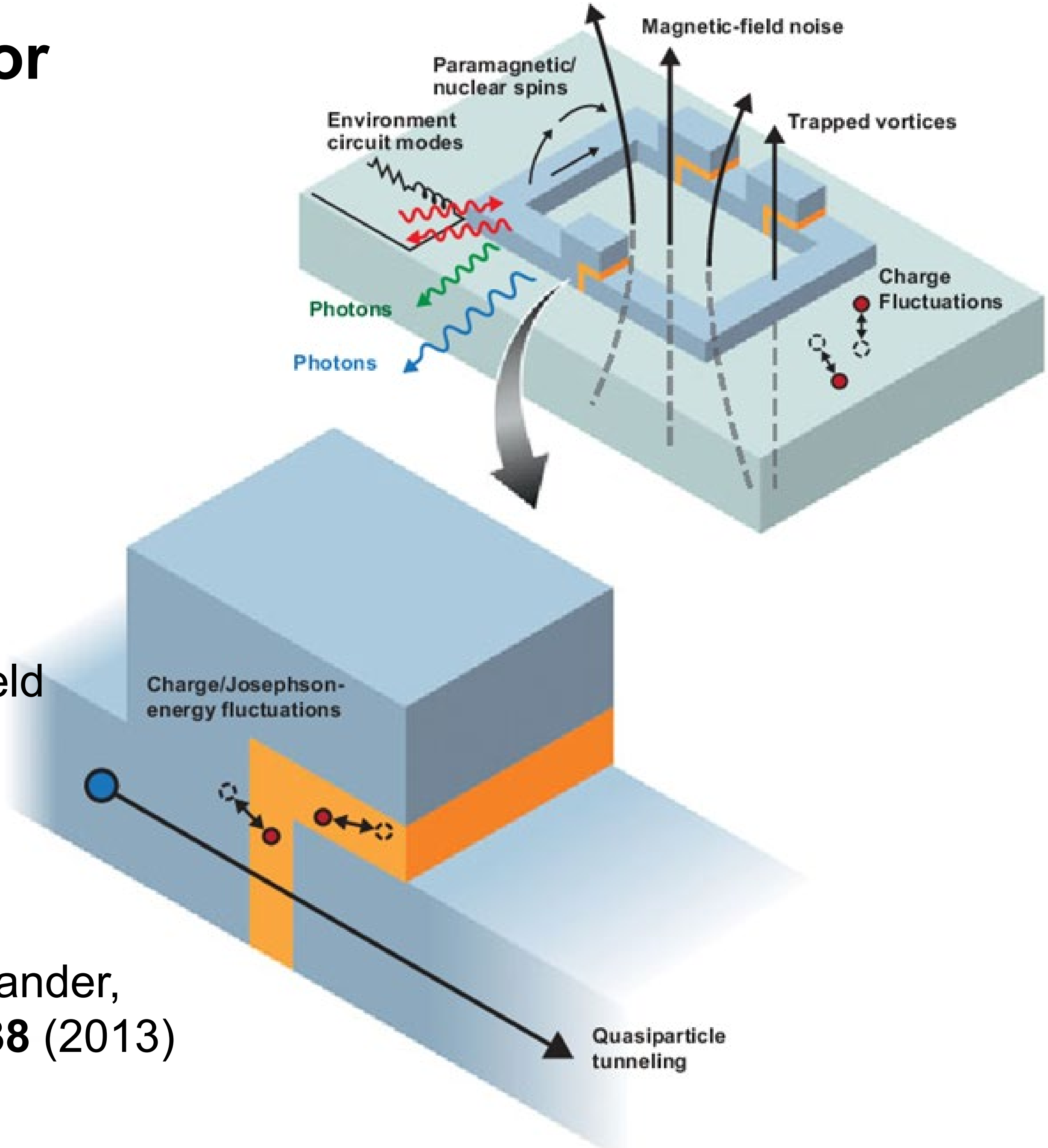
$$H = \frac{1}{2}E_{\mathrm{L}}\left(\varphi - 2\pi\frac{\Phi_{\mathrm{ext}}}{\Phi_0}\right)^2 + 4E_{\mathrm{C}}^{\Sigma}n^2 - E_{\mathrm{J}}\cos\varphi$$



Rieger & Günzler et al. *Nature Materials* **22** (2023)

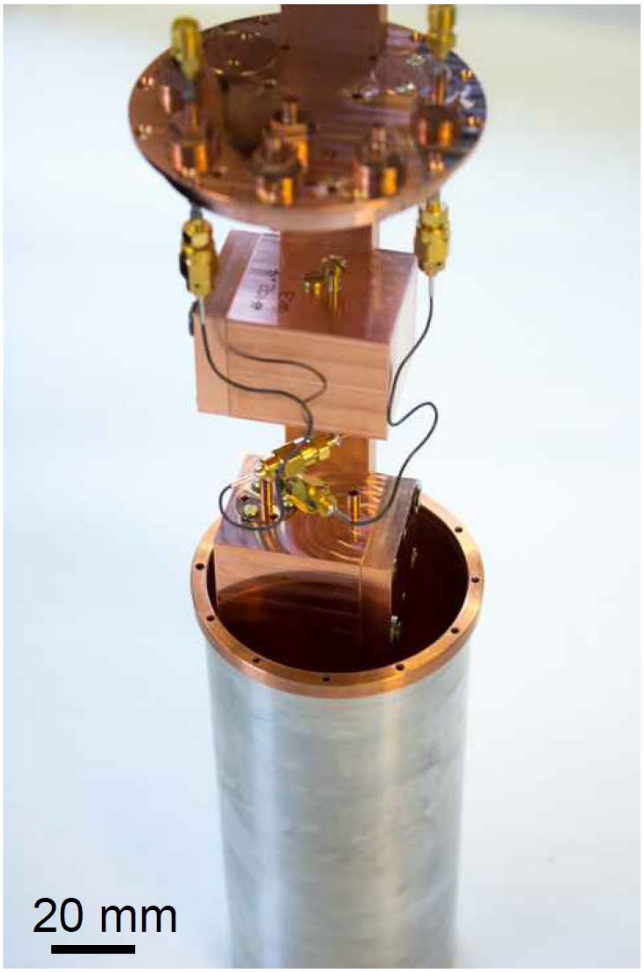
Achilles' heel for SC hardware: Decoherence

- Surface spins
- Dangling bonds
- Surface charges
- Parasitic uW modes
- Stray photons
- Stray phonons
- Trapped magnetic field
- Broken Cooper pairs
- etc.



Oliver and Welander, MRS bulletin, **38** (2013)

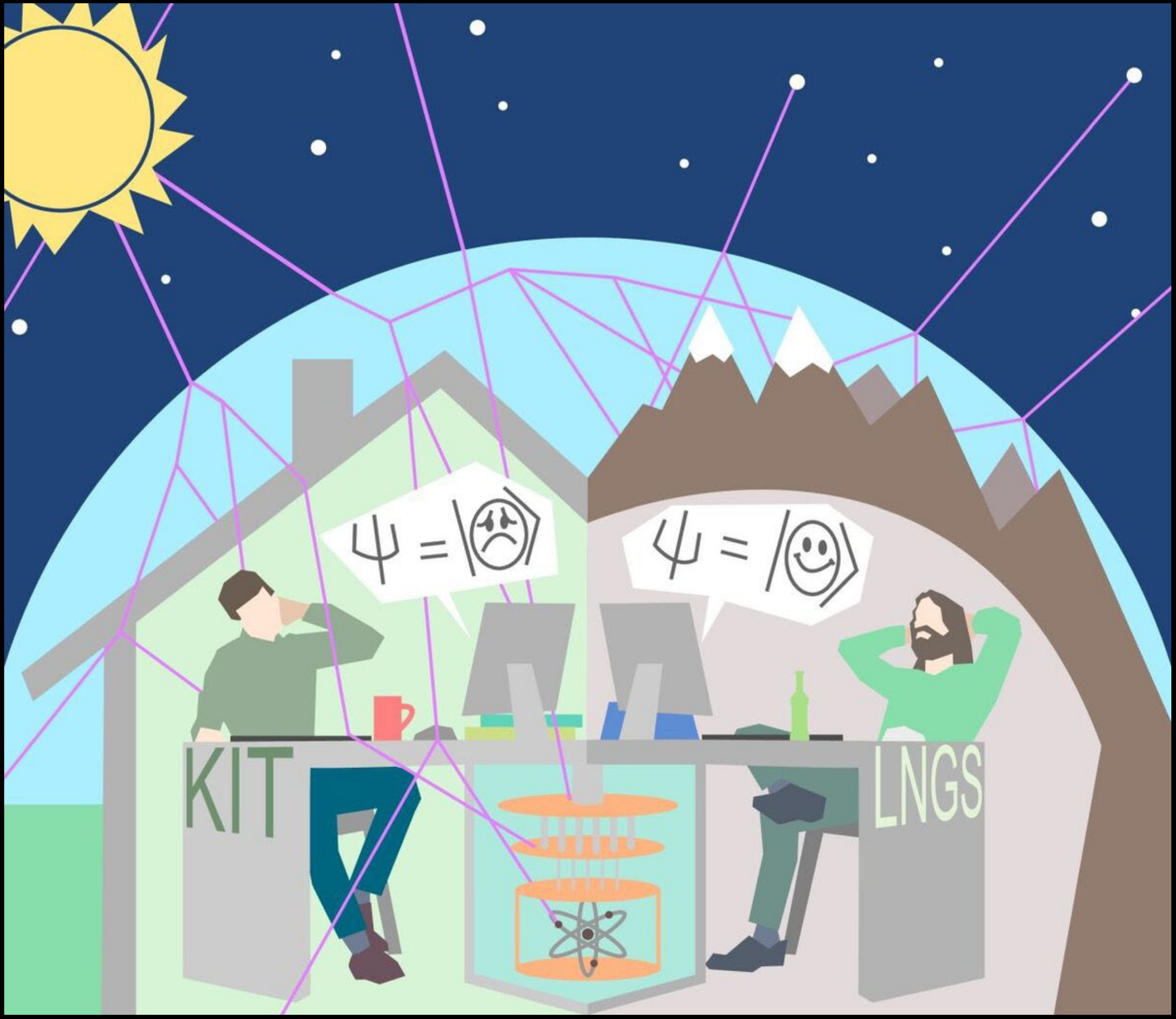
Sample shielding



For details see: Grünhaupt et al., *Appl. Phys. Lett.* **111**, 072601 (2017)

The ultimate shielding

Quantum Computers: A Future Underground?



Cardani, Valenti et al. *Nature Comm.* **12**, 2733 (2021)