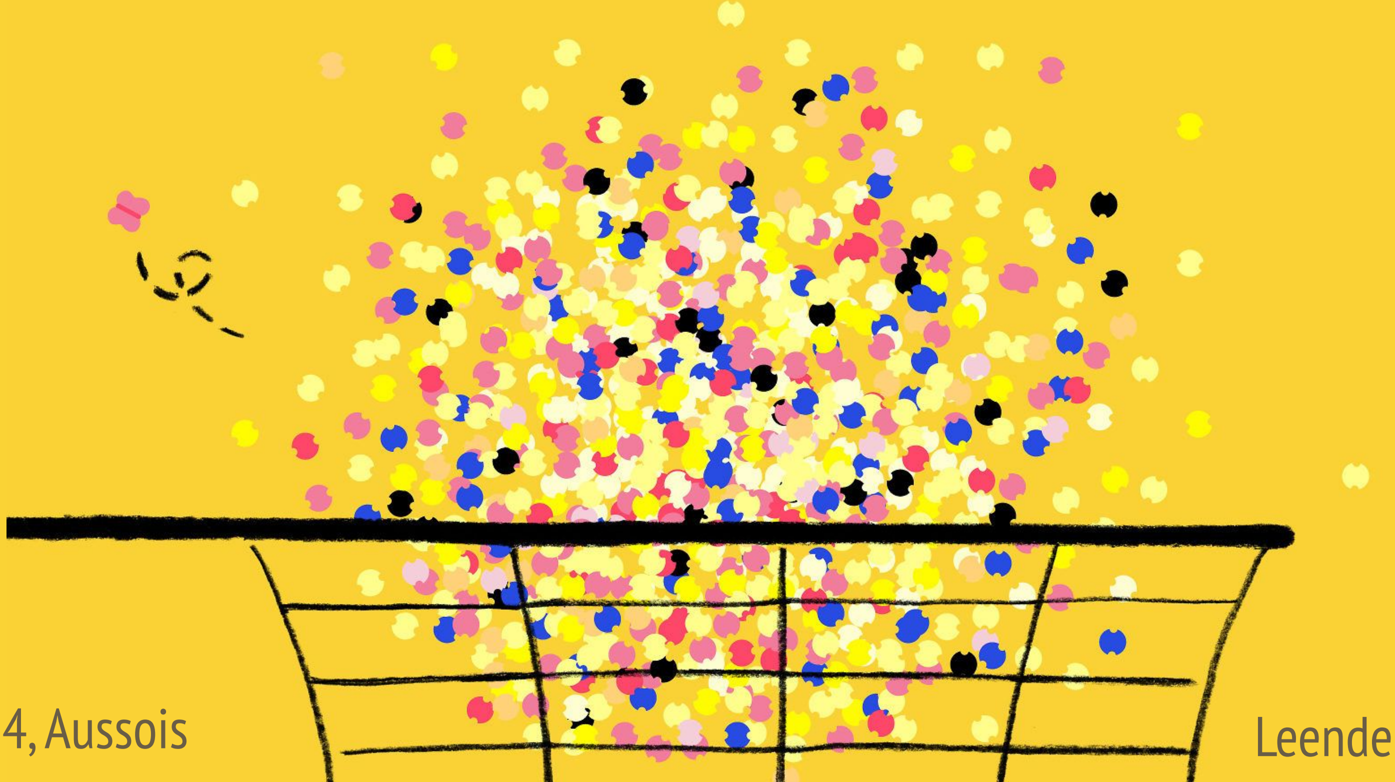
Quantum Sensors



PhyNuBe4, Aussois

Leendert Hayen

Why Quantum Sensors

The future is at low energy

Major open questions in physics right now:

- What is the neutrino mass, and *what is* the neutrino?
- What is dark matter, and where is it?
- Is the Standard Model Electroweak model complete?
- …

Some are **inherently low energy,** others have untapped low energy potential

Neutrinos and their mass

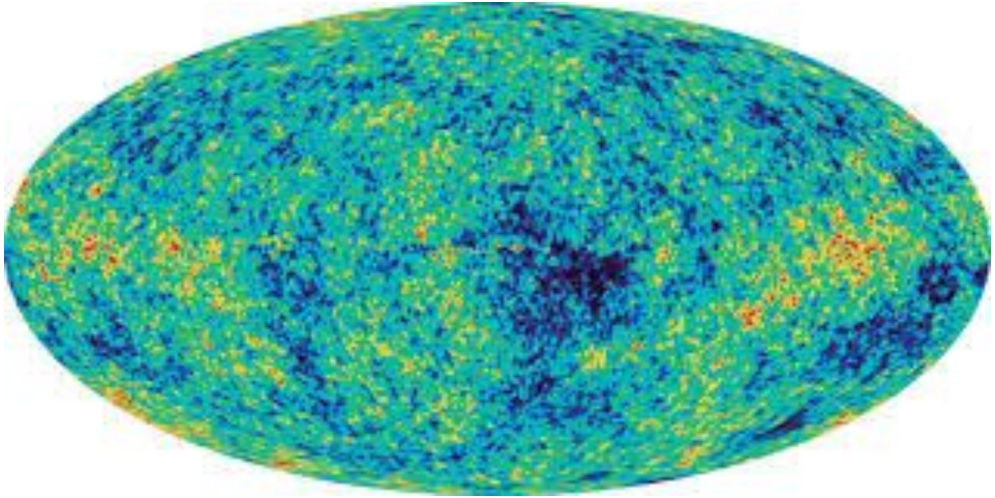
Neutrino mass discovered late 90s/early 2000s: 2015 Nobel

Undeniable **Beyond Standard Model** physics: in SM $m_\nu = 0!$

Cosmological bounds, direct searches & 0vbb: **(below) eV-scale**!

Dark matter searches

Have long known we needed dark matter, most recent from Cosmic Microwave Background ($\Omega_m h^2 \sim 0.14 >> \Omega_b h^2 \sim 0.02$)

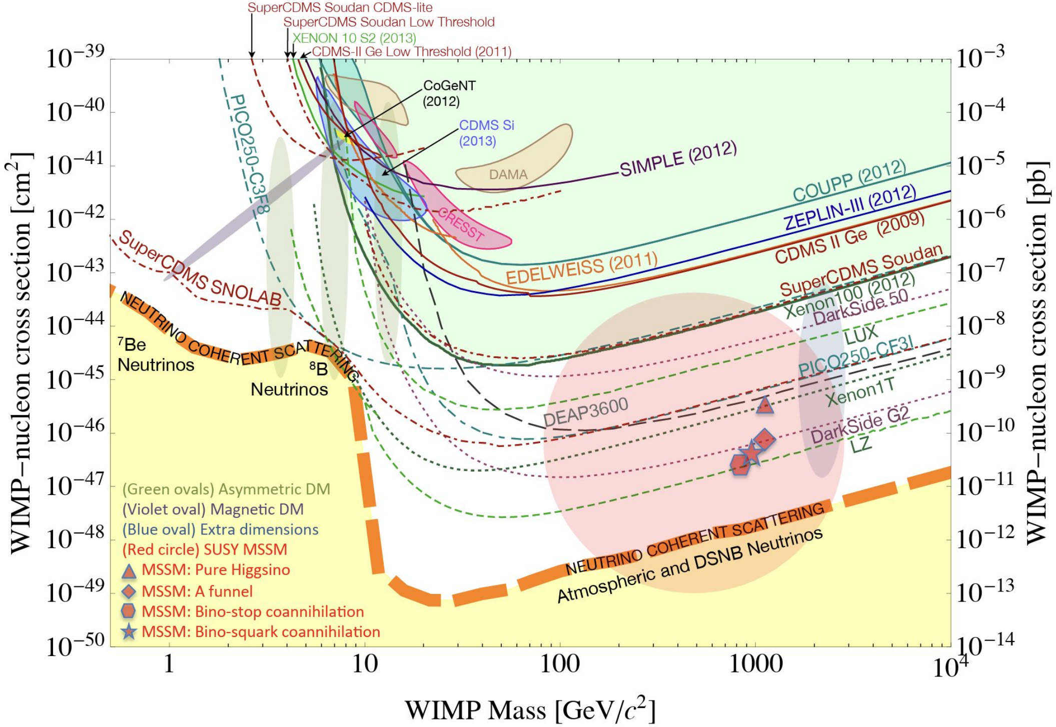


Dark matter searches

In 1980s: WIMP Miracle

decades-long search, but not found

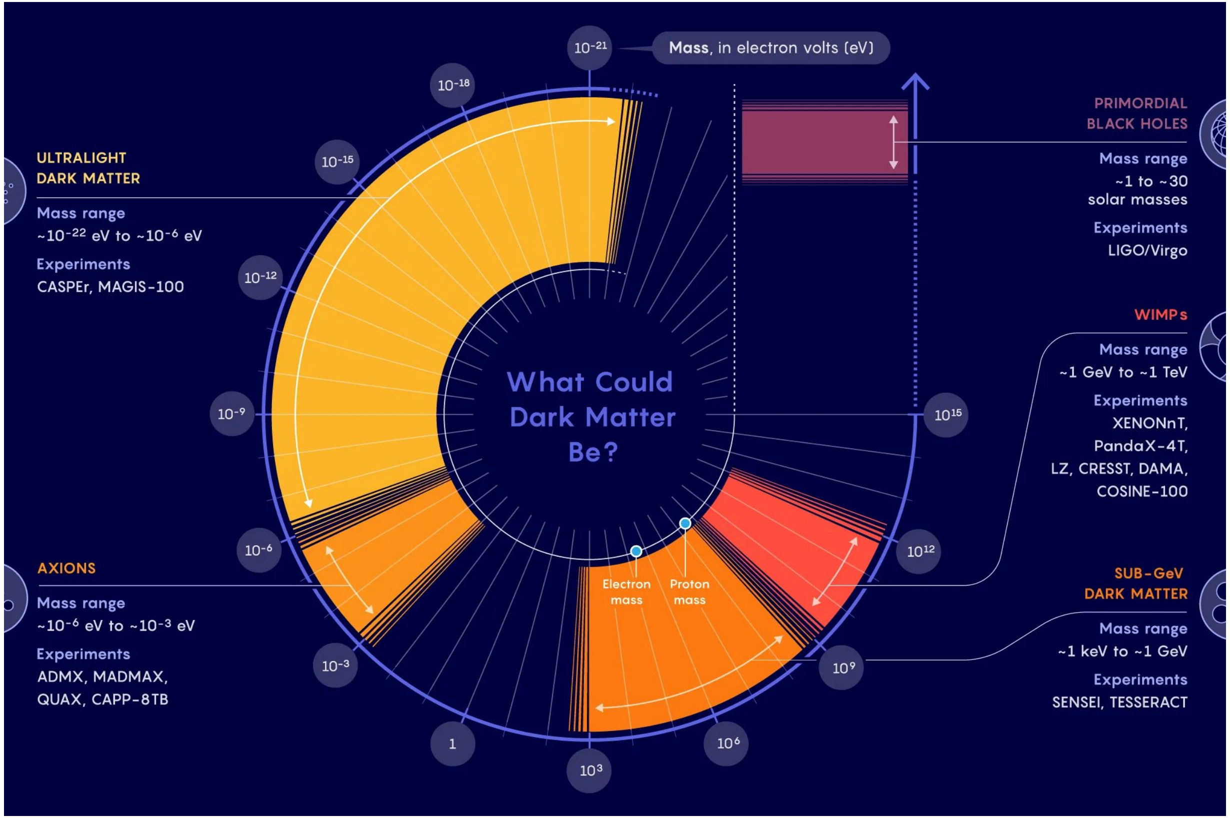
original theory motivations largely gone



Dark matter searches

Much research ongoing for **light** degrees of freedom

- Axion-like particles
- Sterile neutrinos
- …

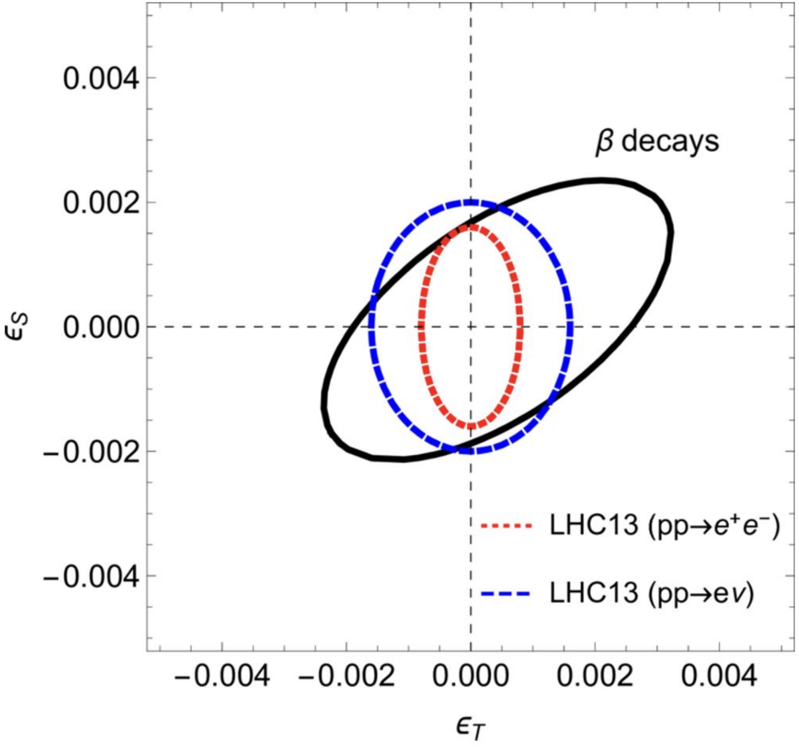


Electroweak incompleteness

Weak interaction is 100% parity-violating (Mme Wu, only left-handed particles):

Is this **fundamental?**

What about deviations from V-A?

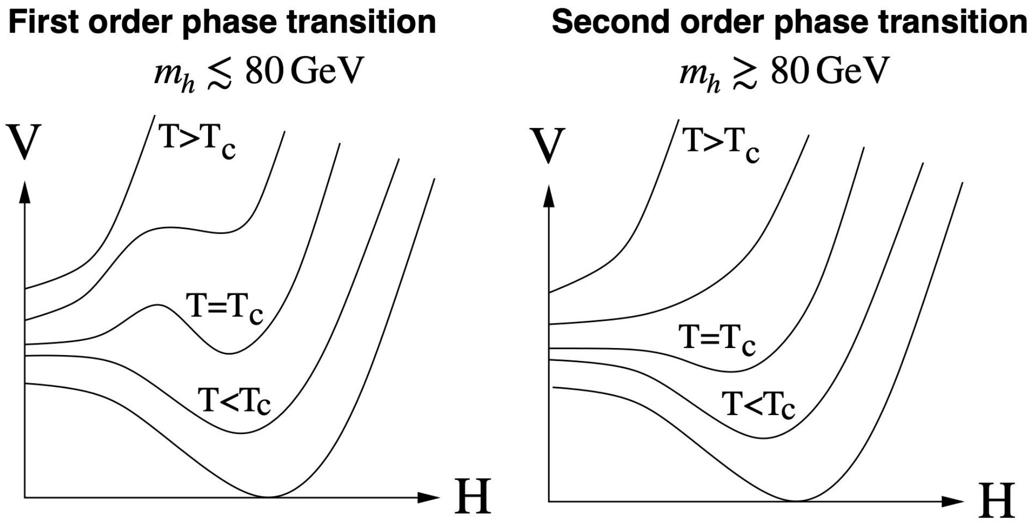


Electroweak incompleteness

Standard Model electroweak sector cannot explain **matter-antimatter asymmetry**

Sakharov conditions

- C and CP violation
- B violation
- Out of equilibrium


First order phase transition

$m_h \lesssim 80\,\mathrm{GeV}$

Second order phase transition

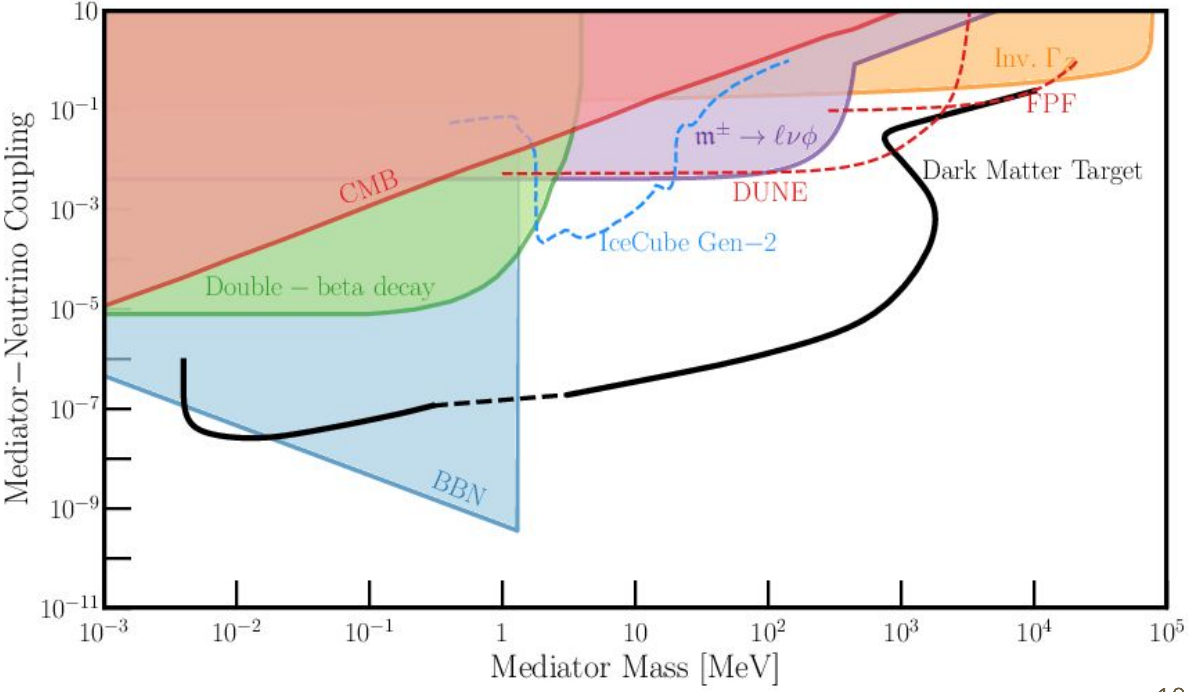
$m_h \gtrsim 80\,\mathrm{GeV}$

Higgs is too light, even if/when we find new CPV

Electroweak incompleteness

Neutrino (self-)couplings are **poorly constrained**

largely open sector with significant cosmological implications



The energy frontier.. but opposite

Traditional detector technologies are limited by the ***lowest*** energy measurable

- Solid/Liquid Scintillator: tens of keV
- Semiconductor: ~keV
- Gaseous detectors: tens of keV

Intrinsic to used technology

Traditional detection limitations

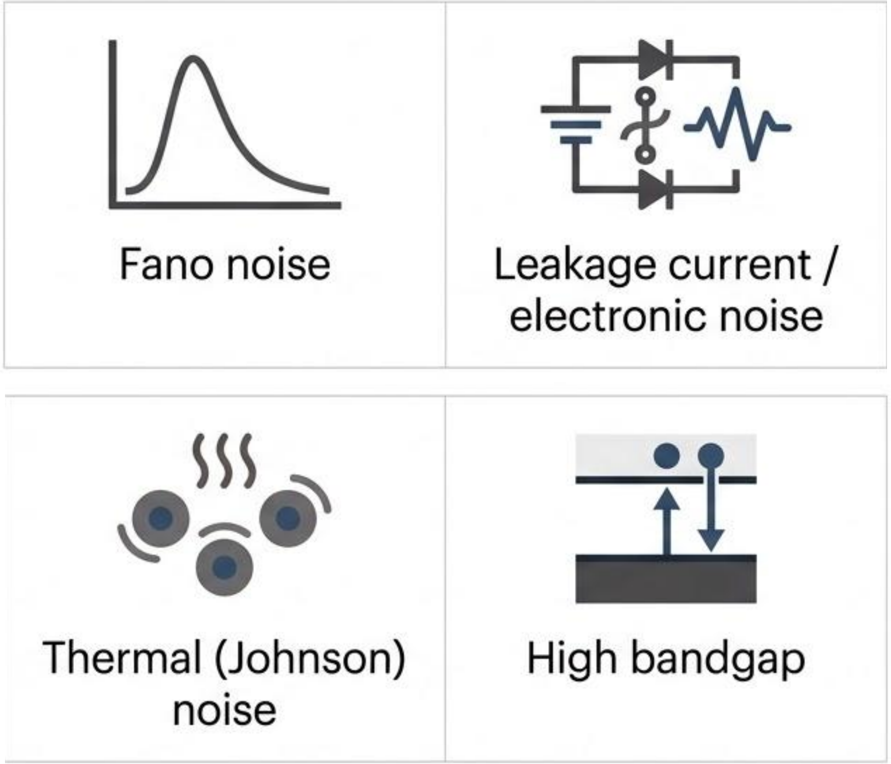
Resolution can be written as

$$\delta_E = \sqrt{F \cdot E + \delta_{elec} + c \cdot E^2}$$

so limitations are obvious

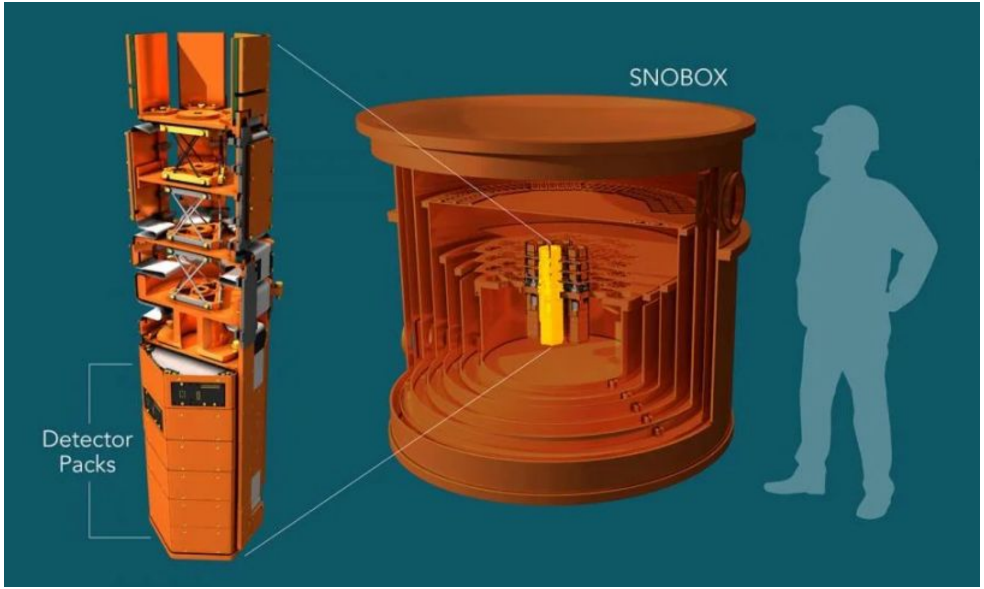
- Fano noise
- Leakage current/electronic noise
- Thermal (Johnson) noise
- High bandgap

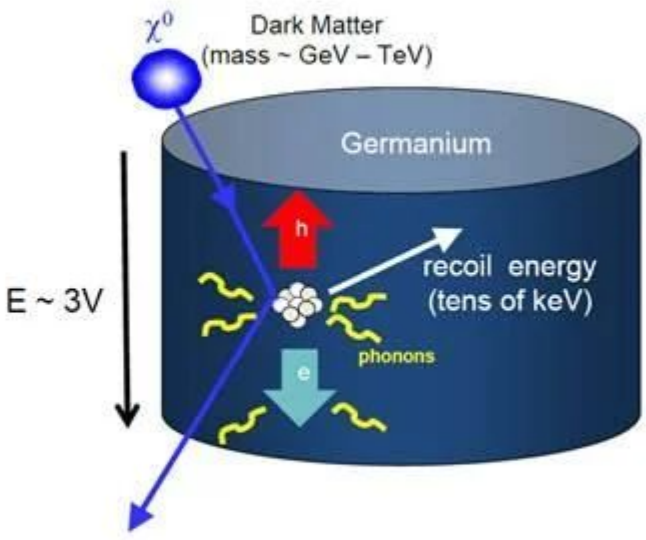
need to go **cold**



Well-known experiments

Cryogenic Dark Matter Search (SuperCDMS)



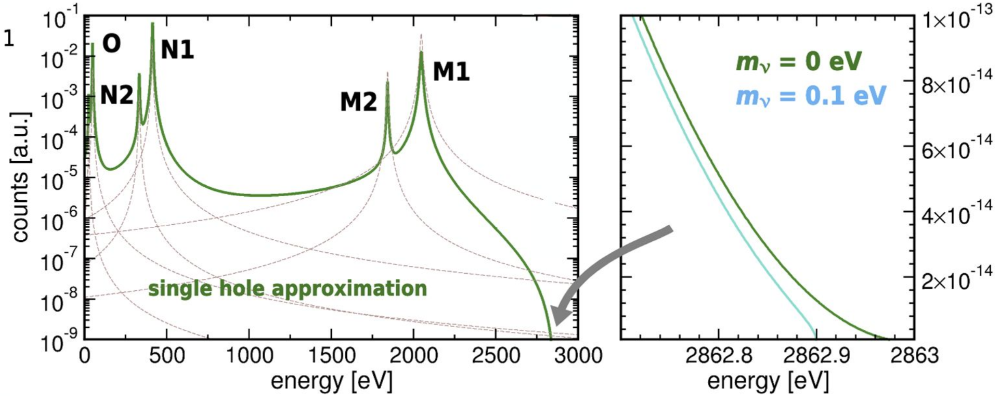


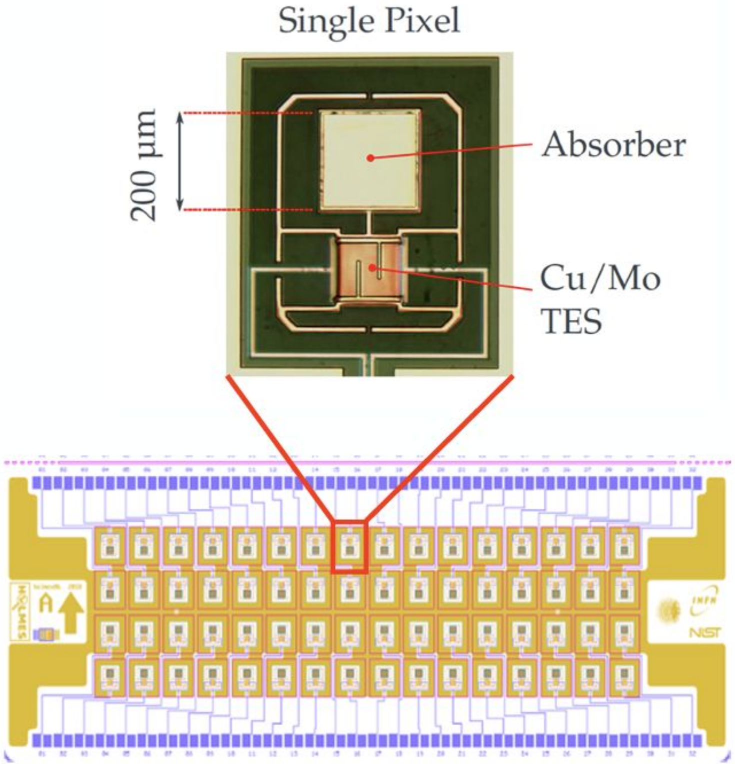
Well-known experiments

HOLMES aims to measure

neutrino mass with 163Ho EC

1



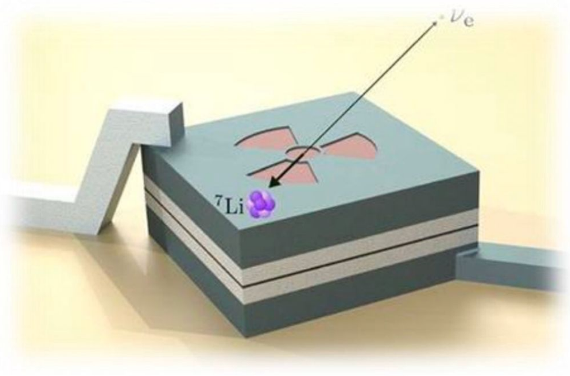


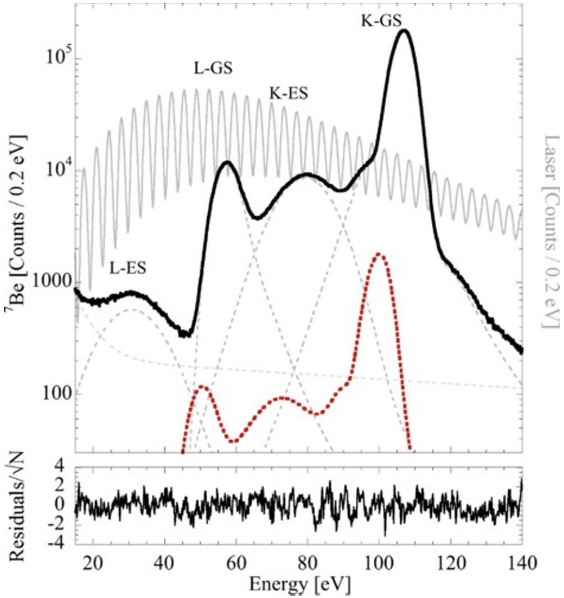
64 chs array

7

Well-known experiments

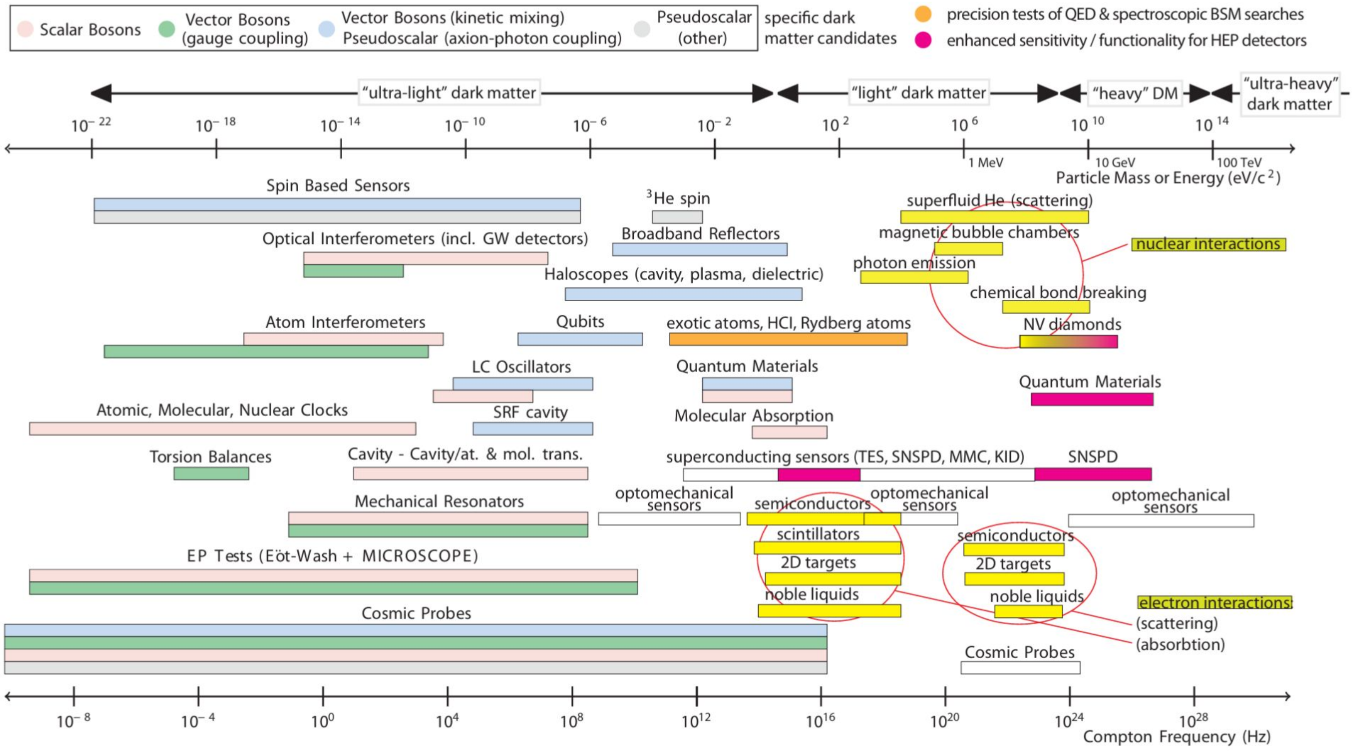
uses 7Be EC for sterile neutrino searches using superconducting tunnel junctions



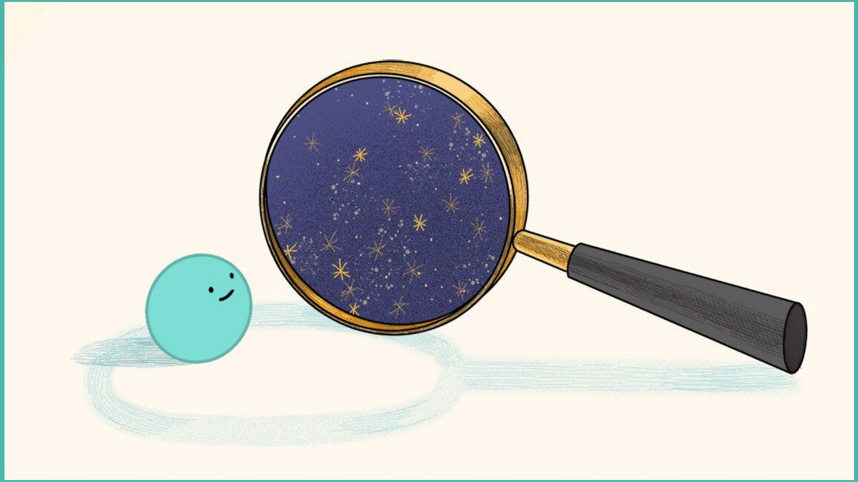


Physics cases

Ranges of applicability of different quantum sensor techniques to searches for BSM physics



What are quantum sensors



What do we mean?

A detector exploiting one or more

- Quantum coherence
- Superconductivity
- Quantized excitations
- Quantum-limited amplification

to achieve better than classical resolution or sensitivity

What do we mean?

A detector exploiting one or more

- Quantum coherence
- Superconductivity
- Quantized excitations
- Quantum-limited amplification

to achieve **better** than classical resolution or sensitivity

A classical-quantum comparison

Classical	Quantum
Ionization	Quasiparticle breaking
Thermal noise dominated	Quantum noise dominated
Large band gap	meV-scale gap
Room temperature	(tens of) mK
Charge collection	Phonon/quasiparticle counting

Coherence

Shows up everywhere, both fundamental and applied

Phase (difference) between states in superposition is maintained

Allows for

- Interferometry
- Superconductivity
- Qubits for quantum computing
- …

General properties

Usually **low-gap** materials and/or **interference** devices

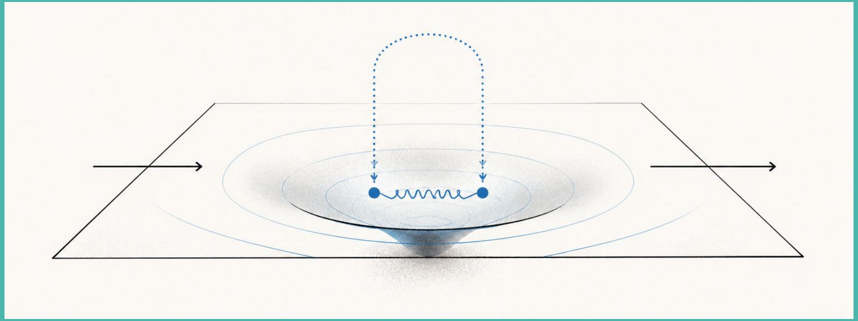
Central idea:

$$N_{qp} = \frac{E}{\Delta}$$

If Δ is small, significantly increase resolution

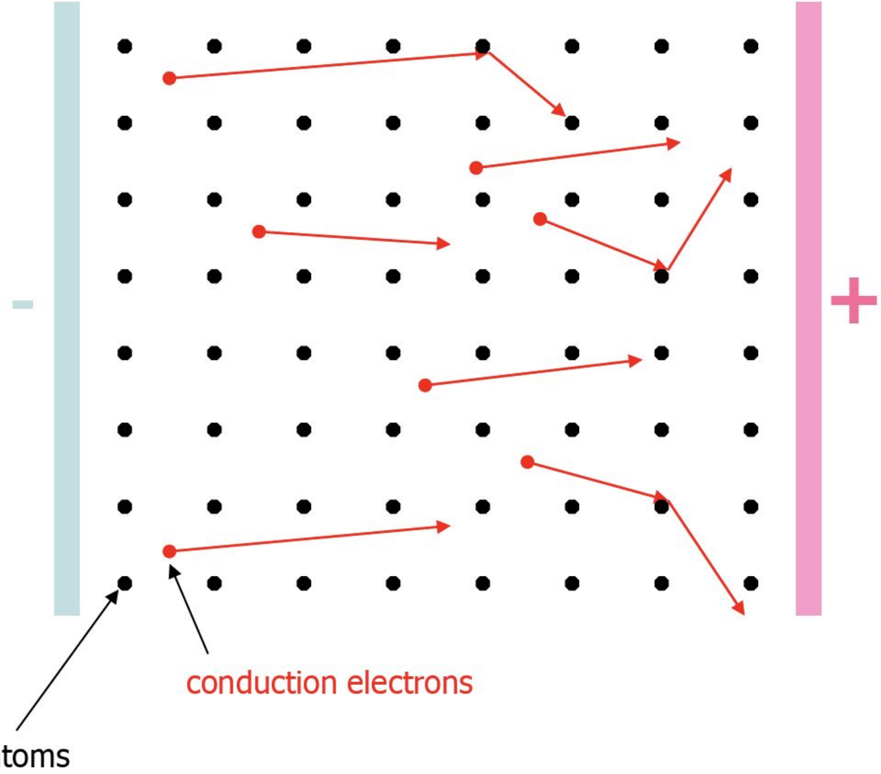
Most commonly used: **superconductivity** with Δ ~ meV → more than **30x better than semiconductor**

Intro to superconductivity



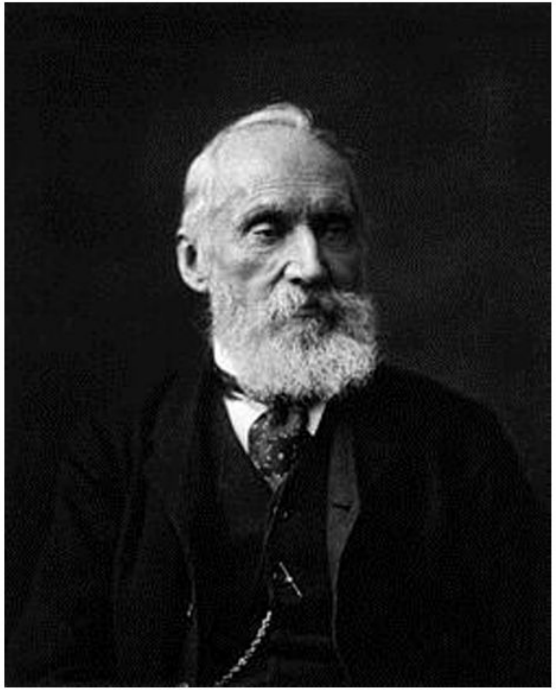
Drude's model of conductivity

Paul Drude

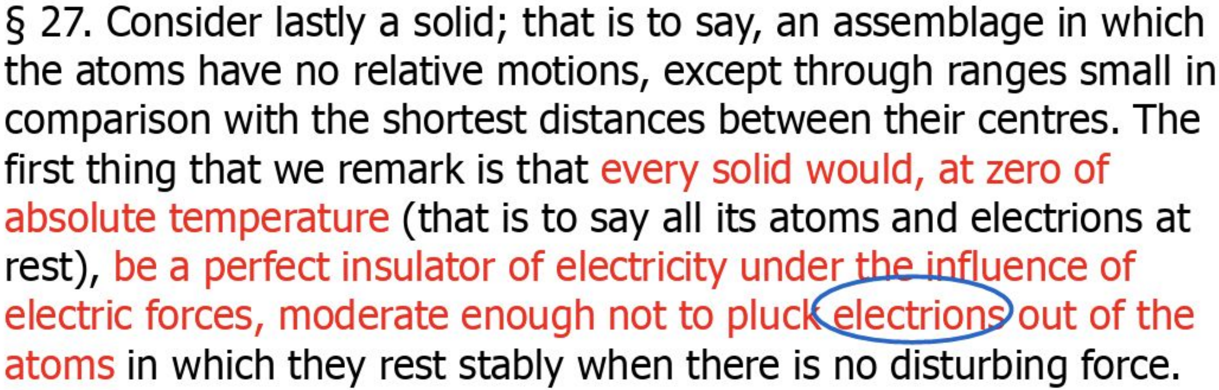


Resistivity is due to scattering off of lattice, which increases with T

Kelvin's view on resistivity

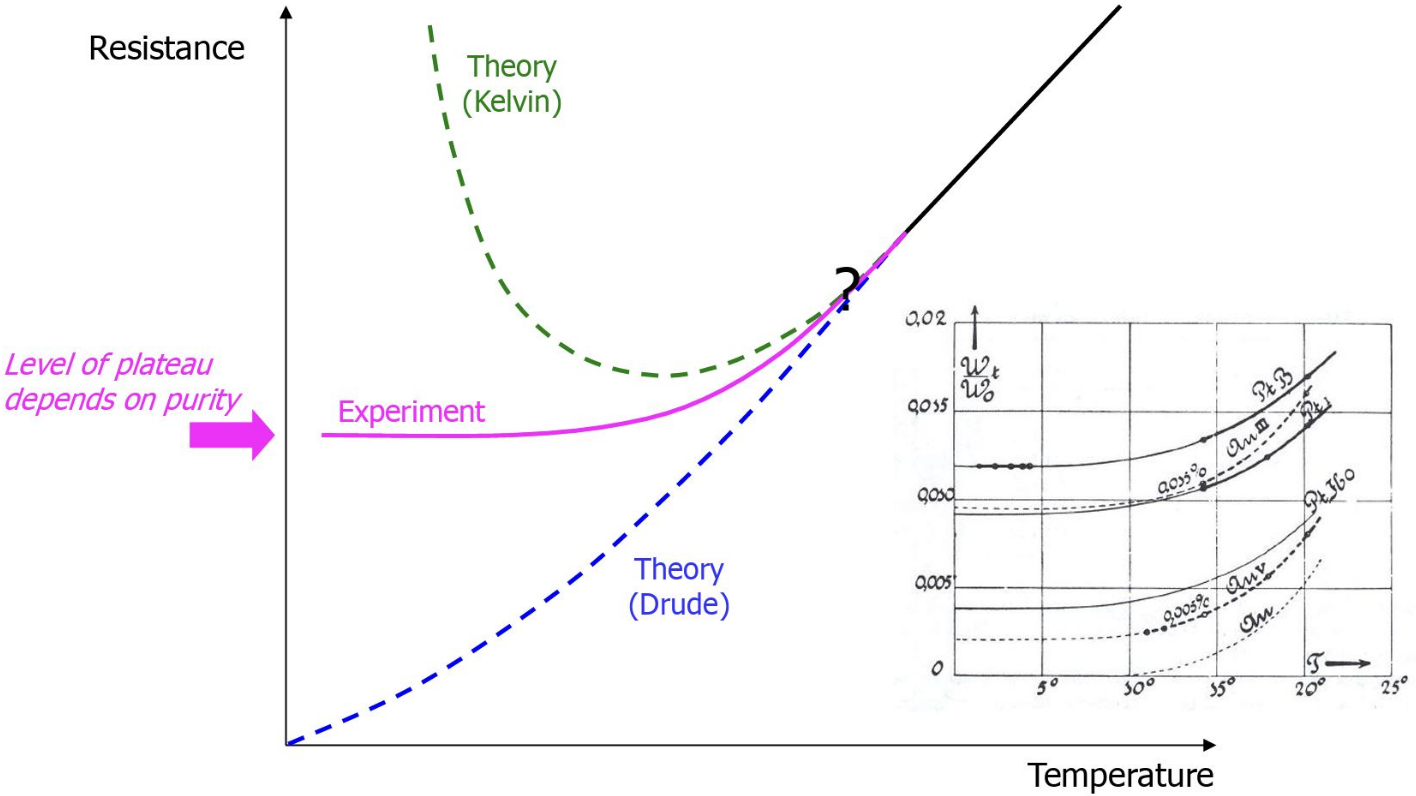


At T=0, electrons would “condense” onto atoms



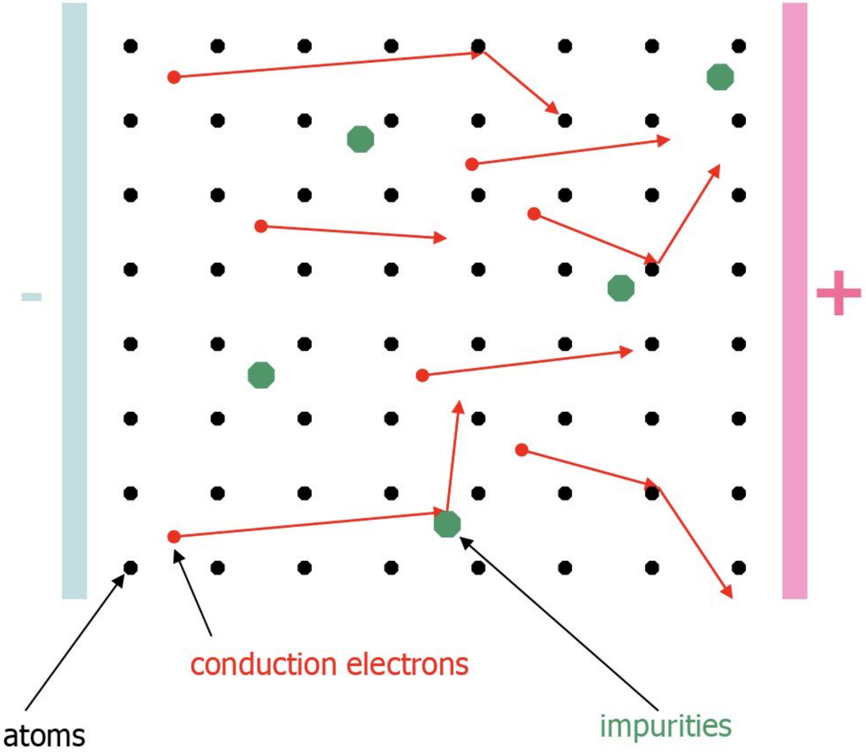
§ 27. Consider lastly a solid; that is to say, an assemblage in which the atoms have no relative motions, except through ranges small in comparison with the shortest distances between their centres. The first thing that we remark is that every solid would, at zero of absolute temperature (that is to say all its atoms and electrons at rest), be a perfect insulator of electricity under the influence of electric forces, moderate enough not to pluck electrions out of the atoms in which they rest stably when there is no disturbing force.

Confrontation with experiment

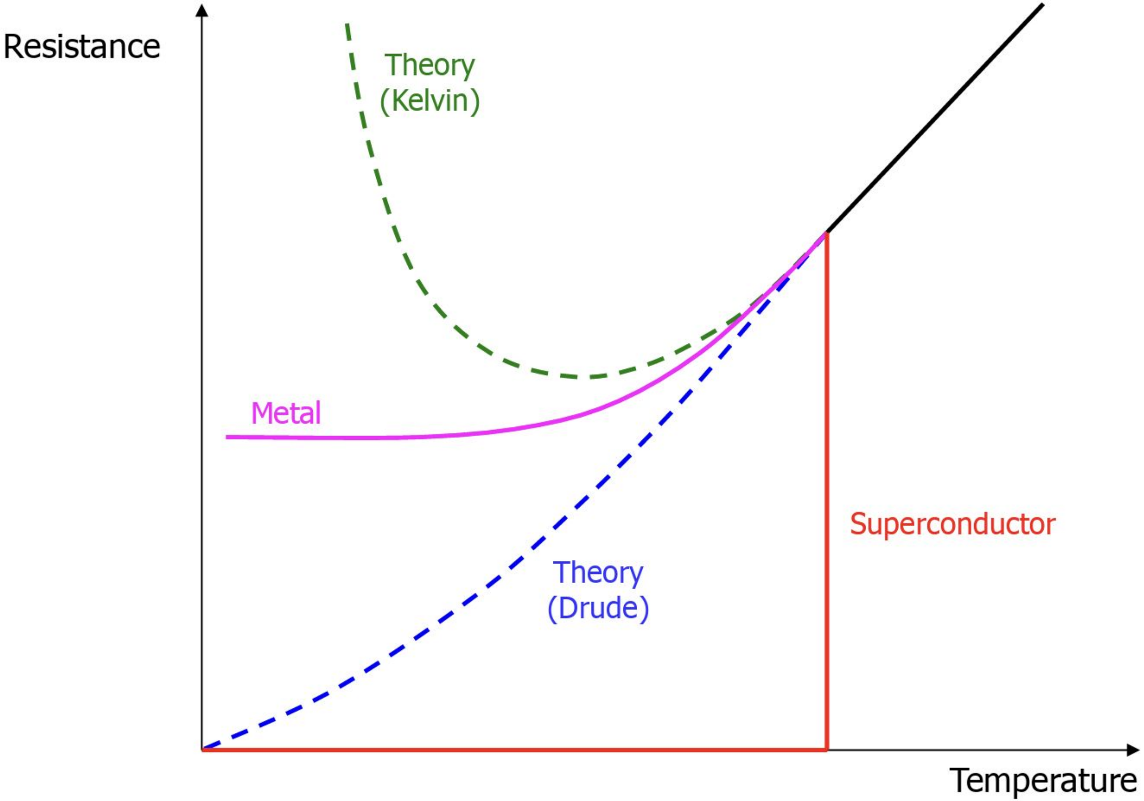


Drude's modified model - impurity scattering

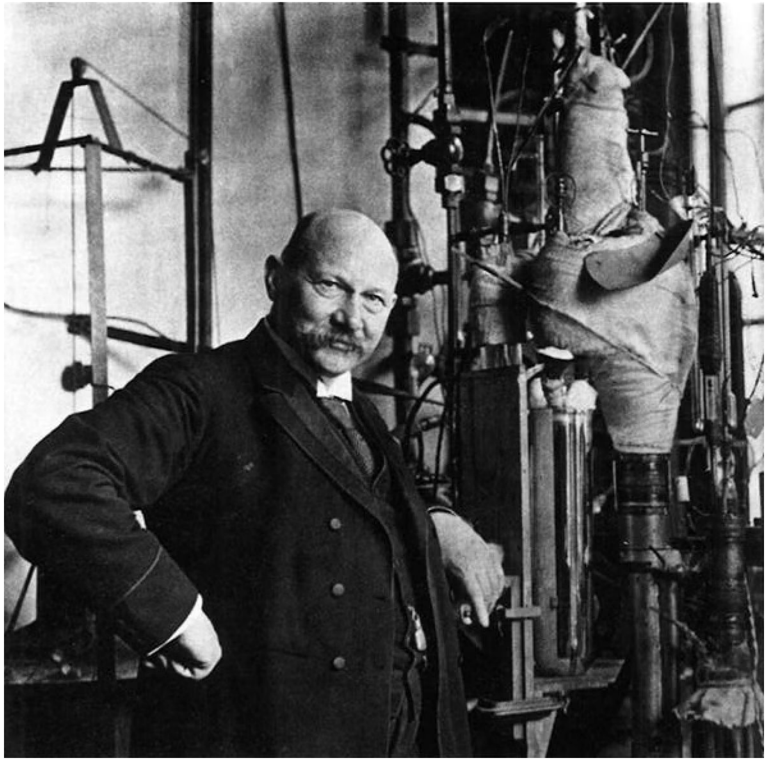
Paul Drude



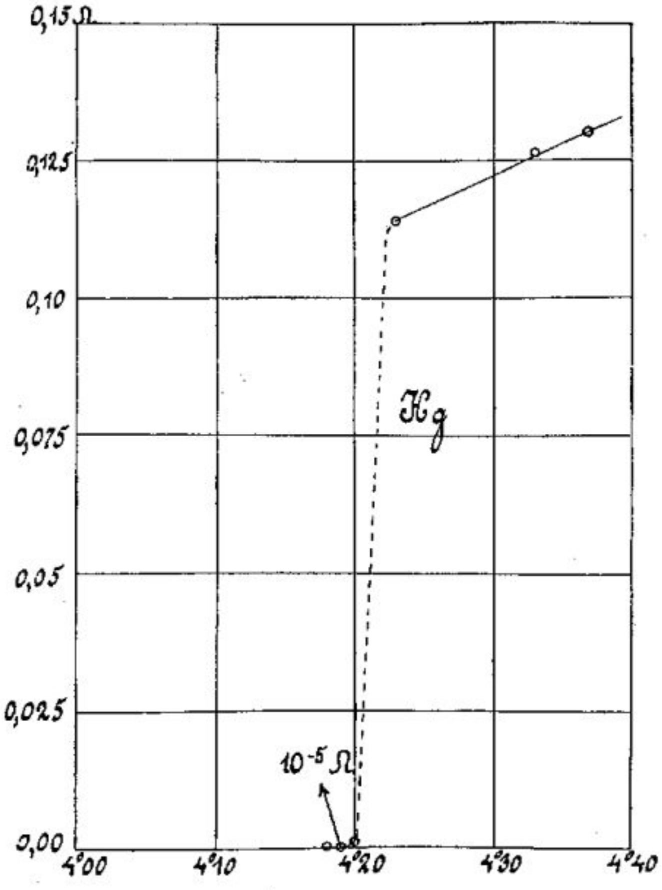
What about superconductivity?



Discovery of superconductivity

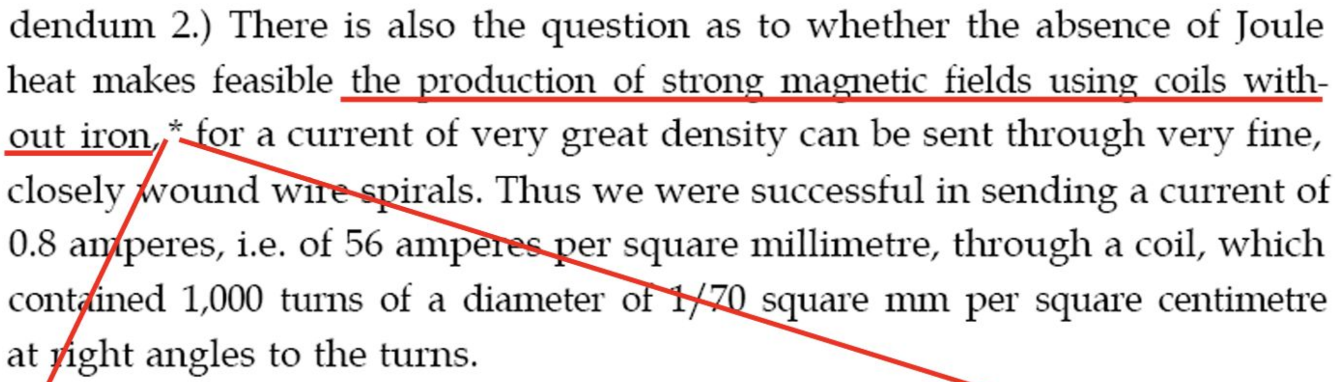


Leiden, NL, 1911



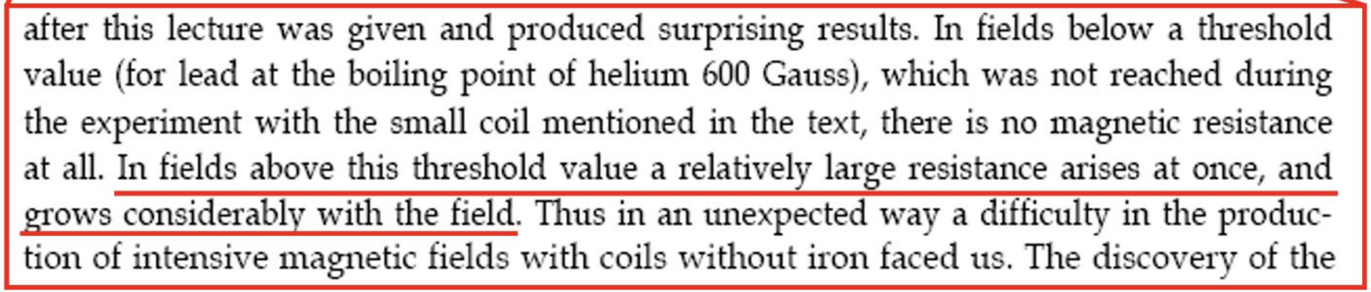
Electrical resistivity of Hg drops below 4.2K

Big magnetic fields?



dendum 2.) There is also the question as to whether the absence of Joule heat makes feasible the production of strong magnetic fields using coils without iron,* for a current of very great density can be sent through very fine, closely wound wire spirals. Thus we were successful in sending a current of 0.8 amperes, i.e. of 56 amperes per square millimetre, through a coil, which contained 1,000 turns of a diameter of 1/70 square mm per square centimetre at right angles to the turns.

…but stumbles upon their « critical field »!



after this lecture was given and produced surprising results. In fields below a threshold value (for lead at the boiling point of helium 600 Gauss), which was not reached during the experiment with the small coil mentioned in the text, there is no magnetic resistance at all. In fields above this threshold value a relatively large resistance arises at once, and grows considerably with the field. Thus in an unexpected way a difficulty in the production of intensive magnetic fields with coils without iron faced us. The discovery of the

Superconducting wiring

No resistance = no losses

No losses → high current density

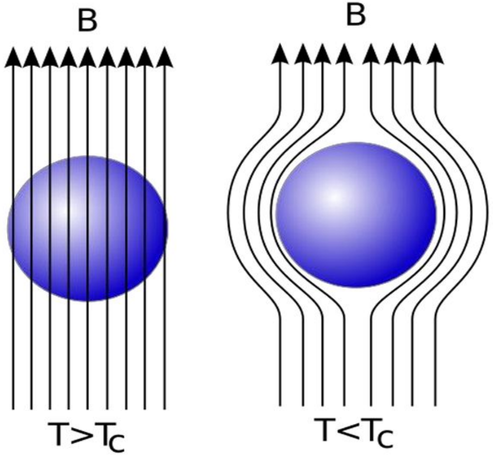
In absence of losses, superconductors do not heat, so that higher currents can be transported in the same cross-section of material

- Copper: ~ A/mm^2
- Superconductor: ~ kA/mm^2

⇒ *factor 1000*

The Meissner effect

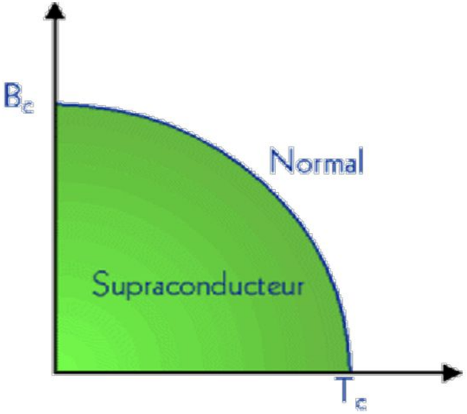
Walther Meissner



A superconductor excludes magnetic field from its interior

Application of a magnetic field above a limit value B_c destroys superconductivity

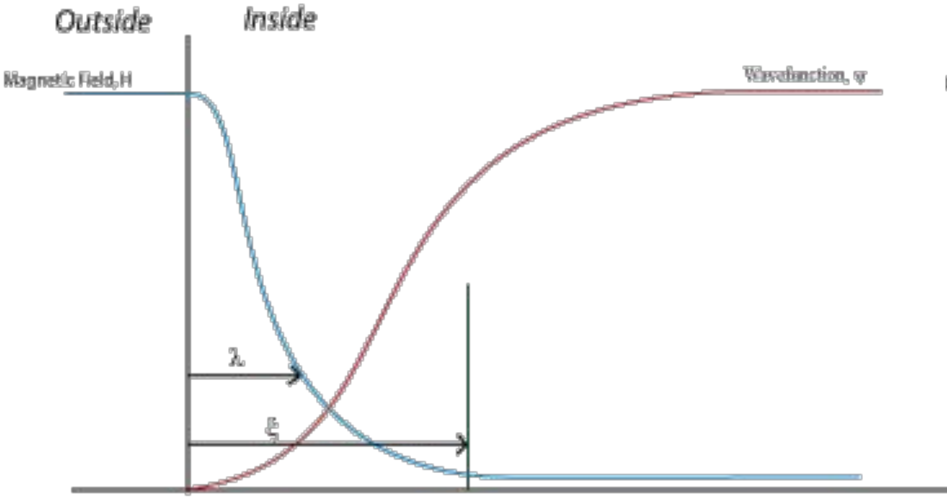
The superconducting state only exists in a limited domain of temperature and magnetic field



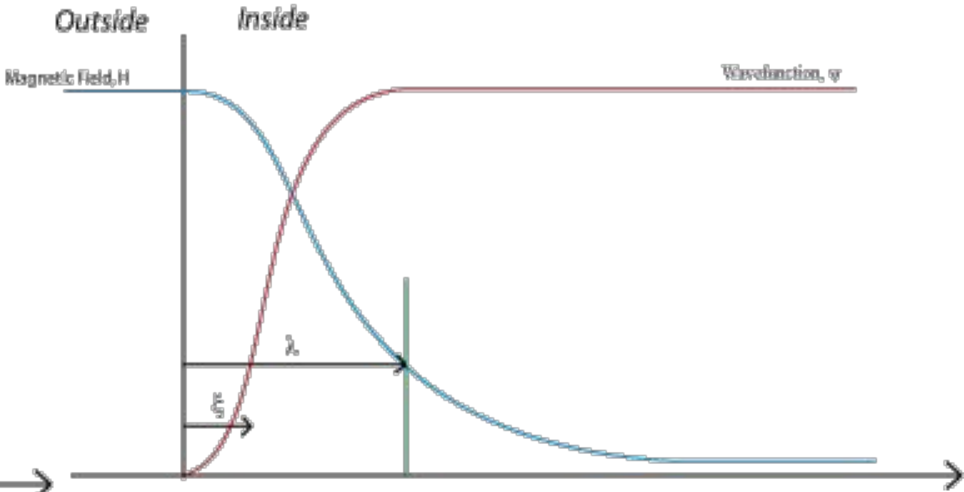
Type-I or Type-II?

Characterized by penetration depth (λ) and coherence length (ξ)

Type I

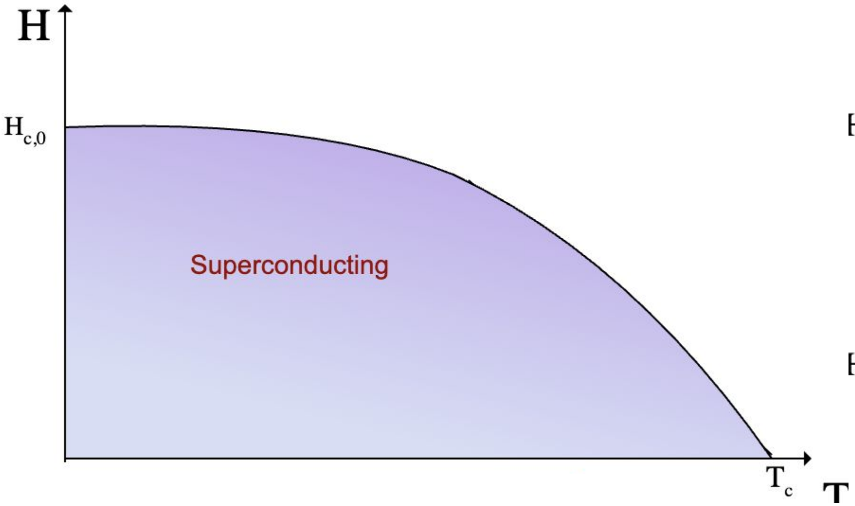


Type II

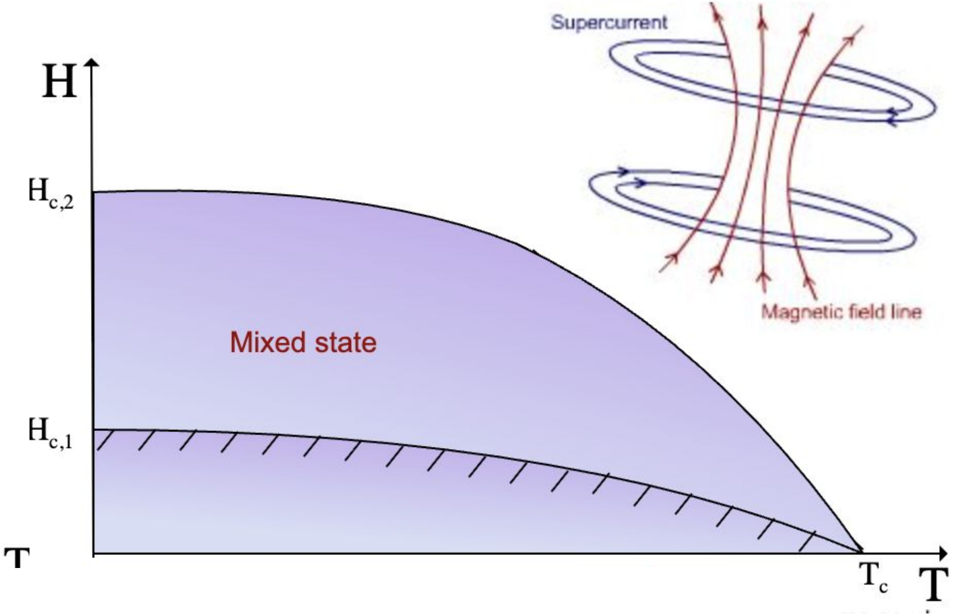


Type-I or Type-II?

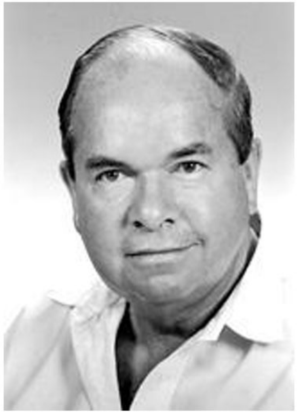
Type I



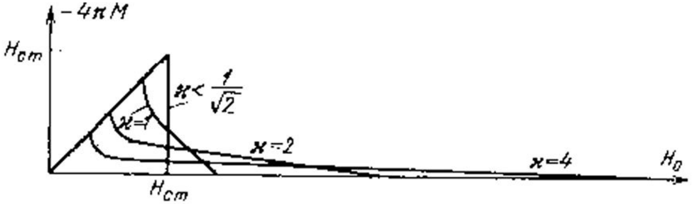
Type II

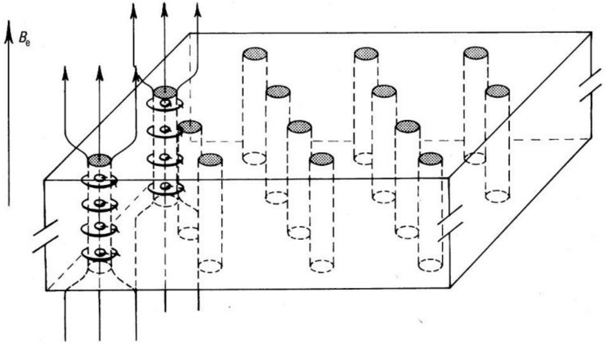


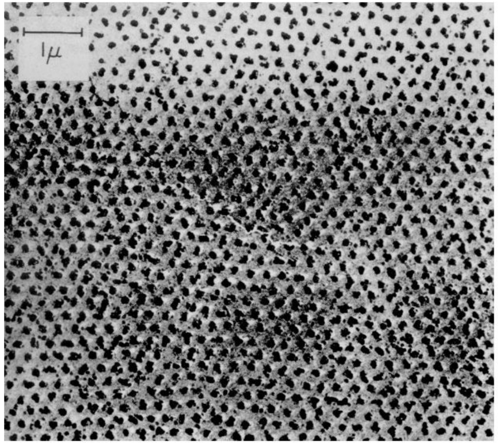
Vortices - flux trapping



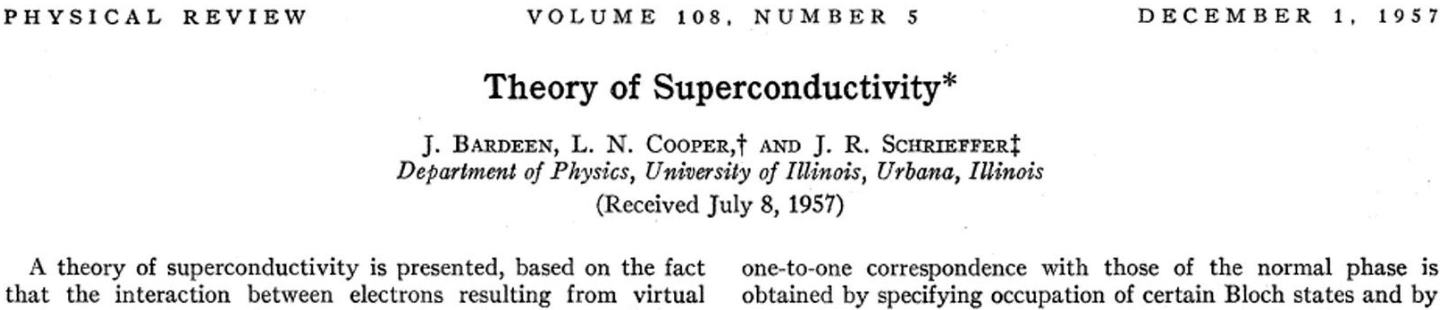
Alexei Abrikosov







Microscopic theory of superconductivity



PHYSICAL REVIEW VOLUME 108, NUMBER 5 DECEMBER 1, 1957

Theory of Superconductivity*

J. BARDEEN, L. N. COOPER,† AND J. R. SCHRIEFFER‡
Department of Physics, University of Illinois, Urbana, Illinois
(Received July 8, 1957)

A theory of superconductivity is presented, based on the fact
that the interaction between electrons resulting from virtual
exchange of the energ
between the less than
energy, $\hbar\omega$. I conducting
this attracti he repulsi
Coulomb inte described l
individual-pa te of a sup
formed from nal state c
in which elec pairs of c
and moment n the norm
amount prop $)^2$, consiste
isotope effec et of excit

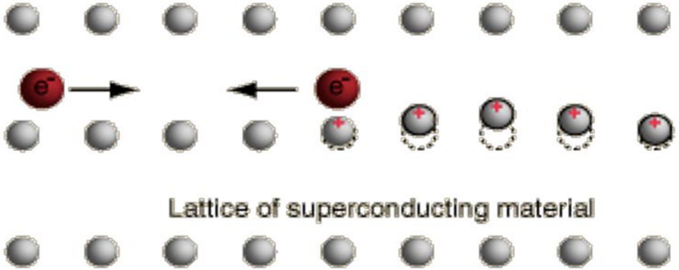
one-to-one correspondence with those of the normal phase is
obtained by specifying occupation of certain Bloch states and by
t to form a al pair con-
he theory y nsition and
ffect in the Calculated
cific heats a heir temper-
n are in g nt. There is
for indivi h decreases
$.5kT_c$ at T s of matrix
single-parti xcited-state
ing wave f tion expan-
culations of given.

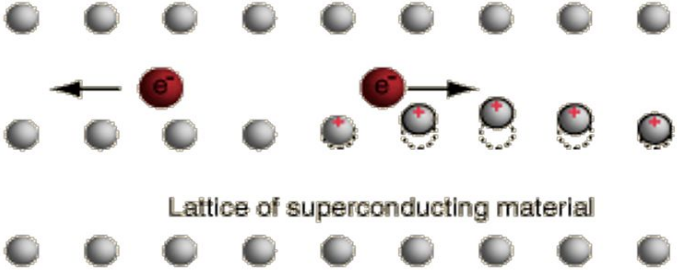
John Bardeen

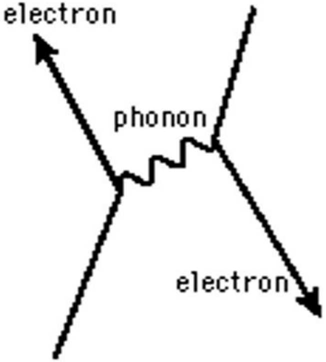
Leon Neil Cooper

John Robert Schrieffer

Cooper pairs







Electrons (fermions) get coupled by the lattice vibrations (so-called « phonons ») thus constituting « Cooper pairs », thus behaving as bosons

The current carriers in a superconductor are the Cooper pairs

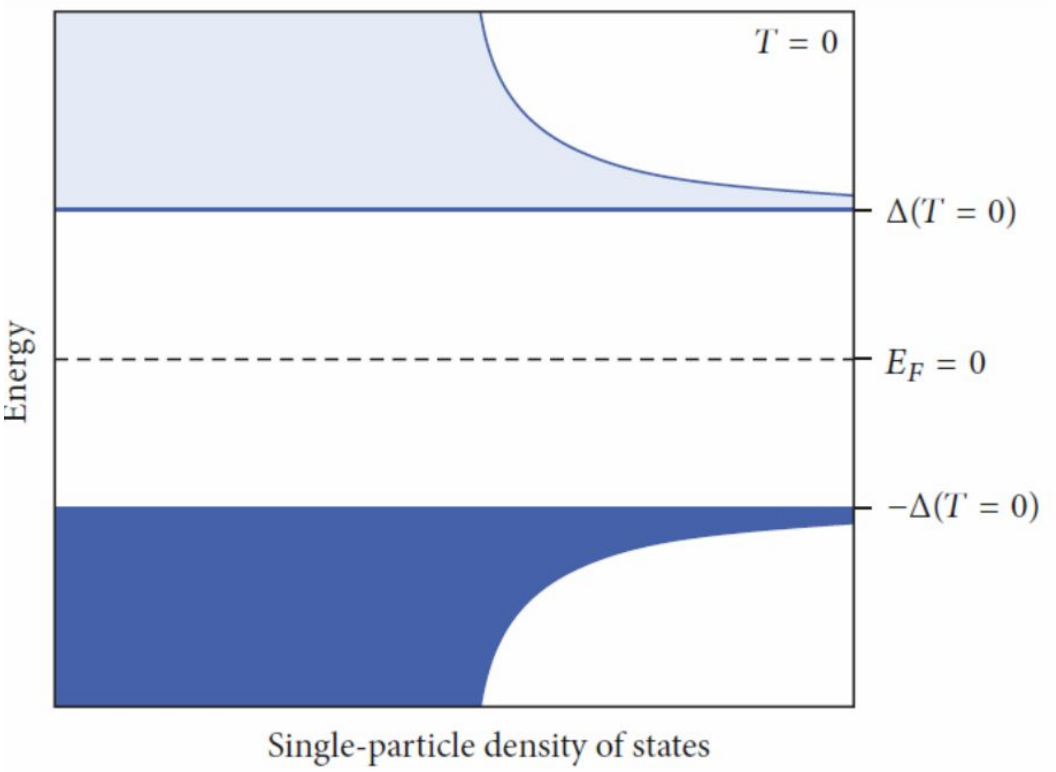
Superconducting gap

Electron binding creates a **gap** in the density of states

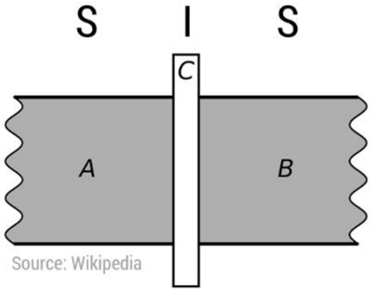
Crucial equation

$$2\Delta(0) \approx 3.53 k_B T_C$$

excited **quasiparticles** downscatter to the gap



Josephson junction: the basic element



Source: Wikipedia

$$\psi_A = \sqrt{n_A}e^{i\phi_A} \qquad \psi_B = \sqrt{n_B}e^{i\phi_B}$$

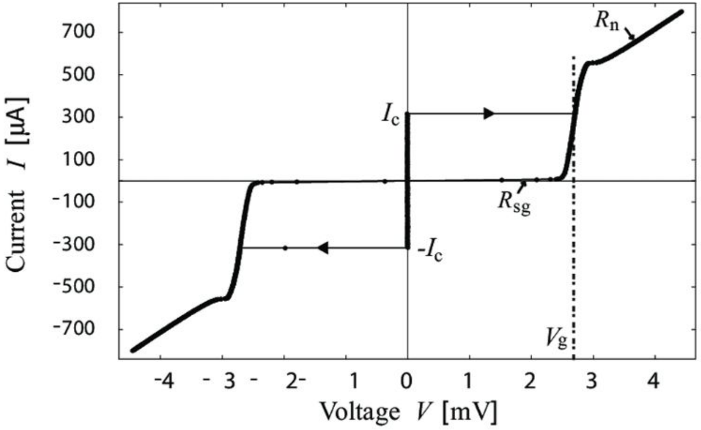
$$\varphi \equiv \phi_B - \phi_A$$

Josephson equations

$$I(t) = I_c \sin\big(\varphi(t)\big)$$

$$\frac{\partial\varphi}{\partial t} = \frac{2e\,V(t)}{\hbar}$$

$$\mathrm{V} = \frac{\Phi_0}{2\pi \cdot I_c \cdot cos\varphi} \cdot \frac{\mathrm{d}I}{\mathrm{d}t} = L_J(\varphi) \cdot \frac{\mathrm{d}I}{\mathrm{d}t}$$

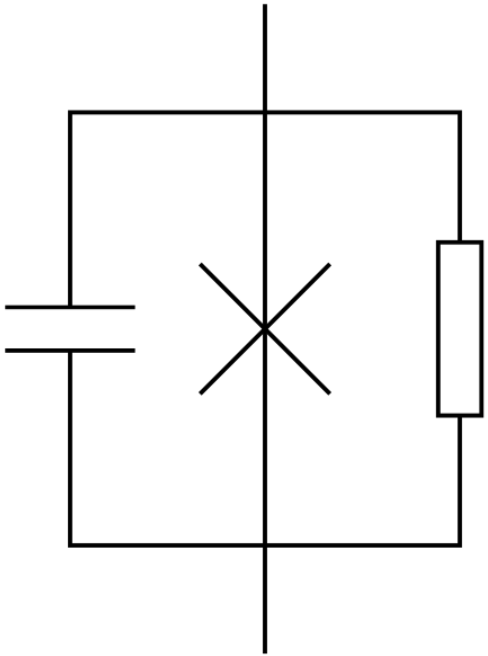


Josephson junction: the basic element

Non-linear circuit element with some

- capacitance (pF-nF)
- dynamic resistance (up to kΩ)

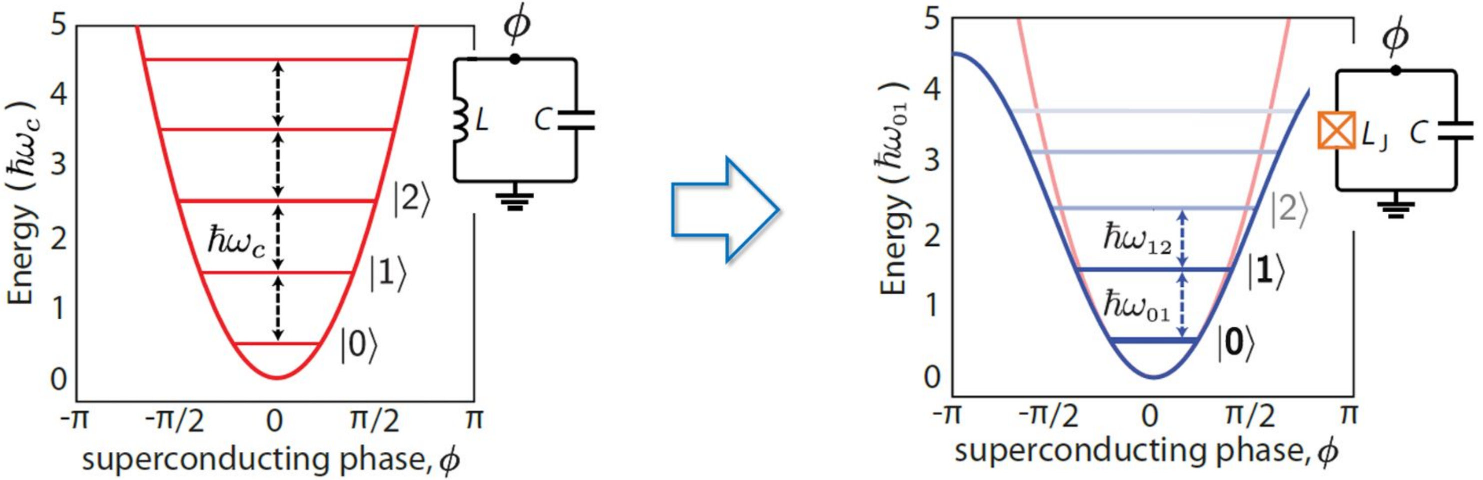
DC and AC Josephson effect can be suppressed with bias and magnetic field



Superconducting qubits

$$H = 4E_C N^2 + \frac{E_L}{2}\varphi^2$$

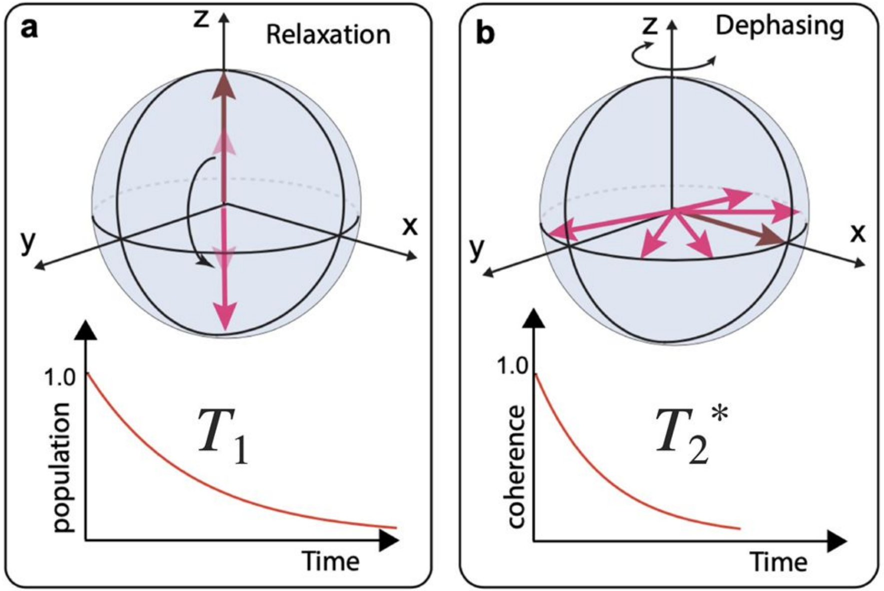
$$H = 4E_C N^2 - E_J \cos\varphi$$



Josephson junction!

Anharmonic spacing means we can probe single states, necessary for a qubit!

Superconducting qubit



Mahdi Naghiloo, (2019) [arXiv:1904.09291]

Decoherence – loss of the set up state in the qubit (relaxation/dephasing)

- Bad for QIS
- Good for Detecting Low Energy Depositions

T_1: Relaxation Time
timescale for loss of the energy of the qubit state (1 to 0)
T_2*: Dephasing Time
timescale for loss of the coherence of the qubit state

Technology overview

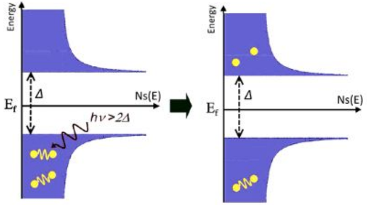
Superconductivity for detection

Small energy gap of Cooper pairs

⇩

$$\Delta_0 = 1.76 k_B T_c$$

$$\boldsymbol{\Delta_0}\left(T_c^{\mathrm{NbN}} = 16.5\ \mathrm{K}\right) = \mathbf{2.5\ meV}$$



Credits: 10.1088/1742-6596/664/8/082007

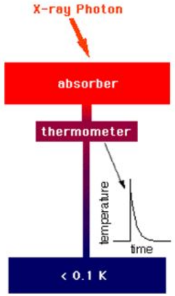
Small heat capacity

$$C_e \propto T$$

⇩

Sensitive **calorimeters**

$$\Delta T = E/C$$



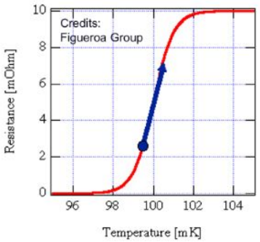
Credits: NASA

Sharp **superconducting transition**

⇩

Sensitive **thermometer**

$$\mathrm{d}R/\mathrm{d}T$$



Credits: Figueroa Group

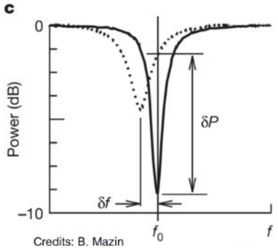
Change of **kinetic inductance**

$$L_k \propto 1/n_S$$

⇩

Detection using LC **resonator**

$$f_R = 1/(2\pi\sqrt{LC})$$



Credits: B. Mazin

SQUIDs

Superconducting

QUantum

Interference

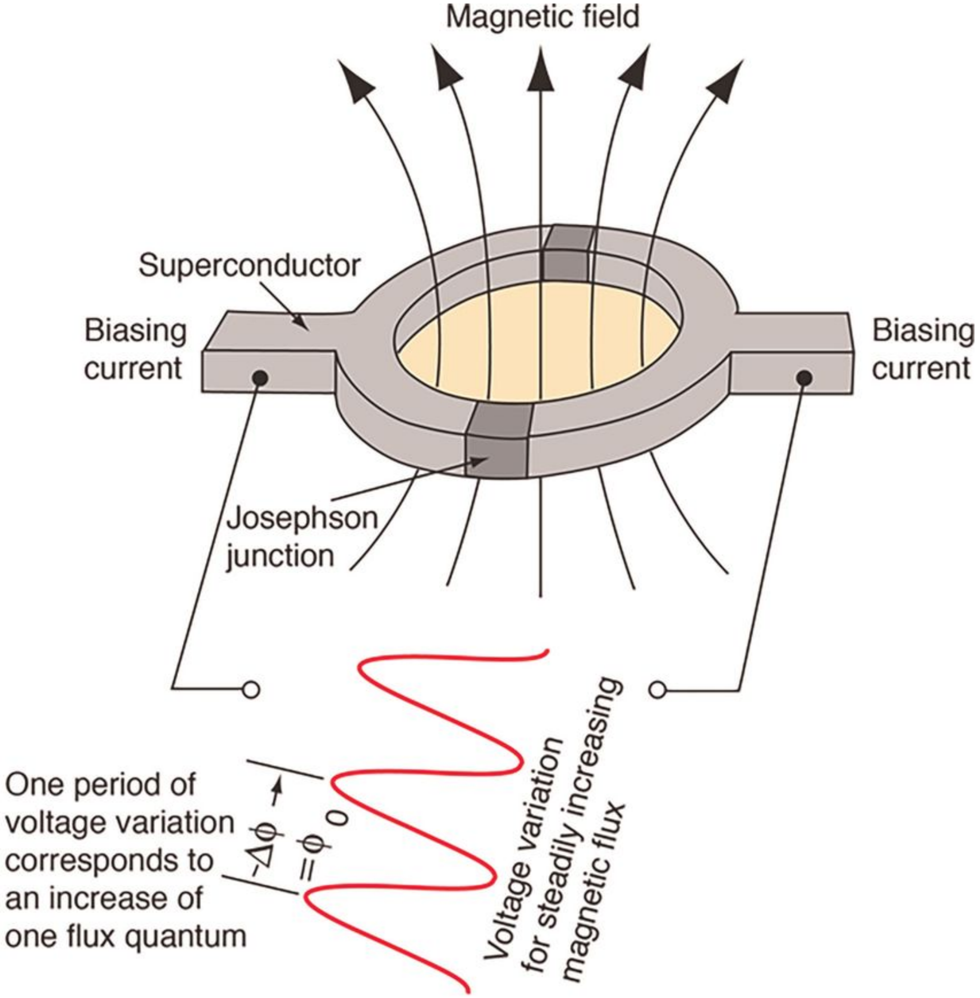
Devices

extremely precise

magnetometry (down to 10^{-18} T)

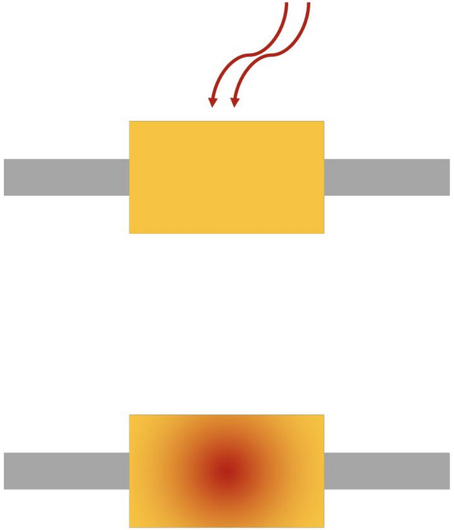
central component of

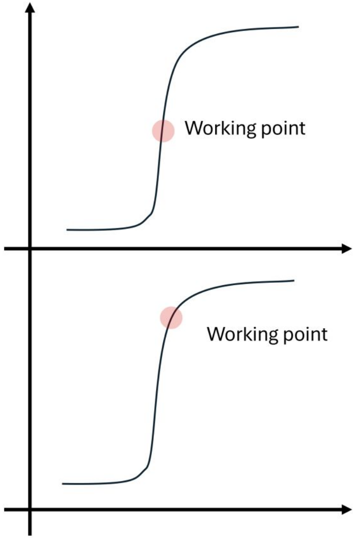
microcalorimetry

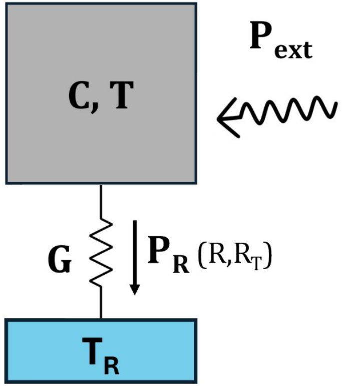


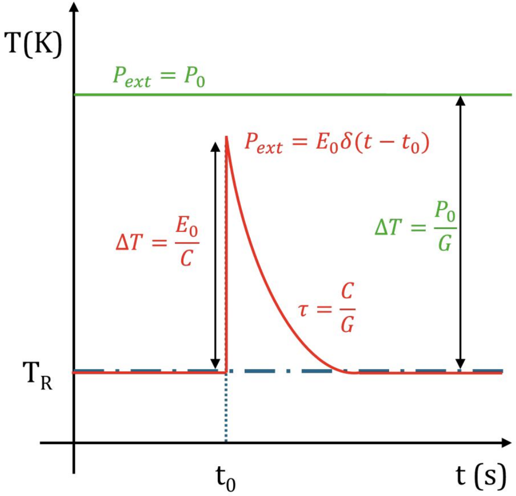
Transition Edge Sensor

Operate detector at the superconducting transition





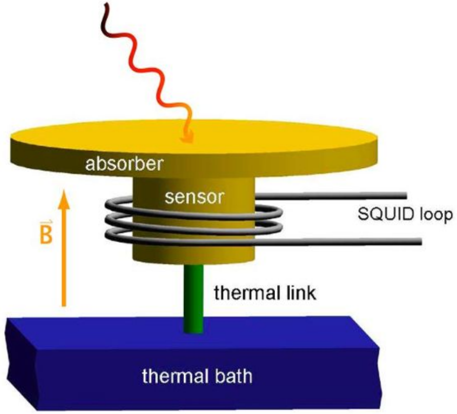




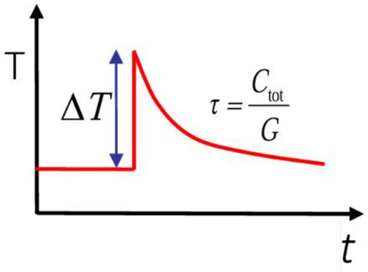
Good energy resolution but thermal recovery → **slow (ms)**

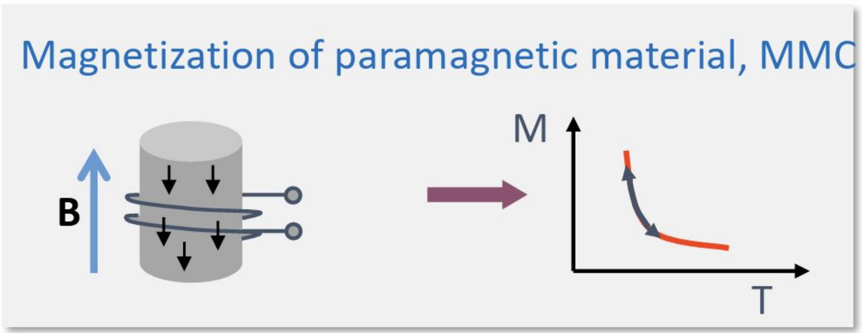
+ **saturation** for large signals

Metallic Magnetic Calorimeter



$$\Delta T \cong \frac{E}{C_{\text{tot}}} \xrightarrow{\text{MMC}} \Delta\Phi_S \propto \frac{\partial M}{\partial T}\Delta T \rightarrow \Delta\Phi_S \propto \frac{\partial M}{\partial T}\frac{E}{C_{\text{tot}}}$$




Magnetization of paramagnetic material, MMC

Good energy resolution but thermal recovery → **slow (ms)**

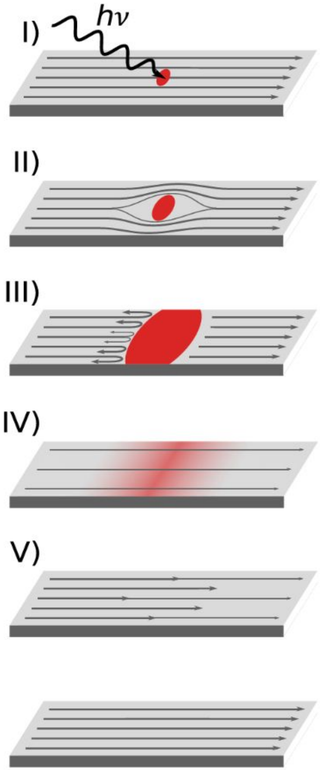
Superconducting Nanowire Single Photon Detector

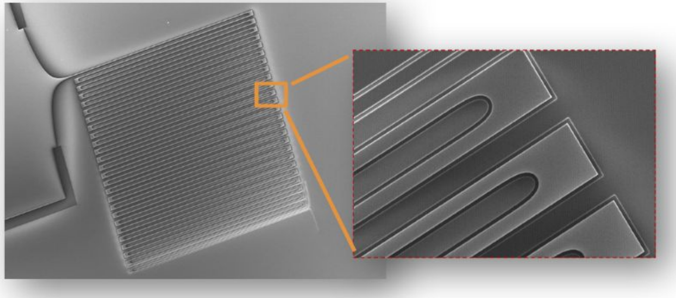
Superconducting circuit (wire) or pads (chicane)

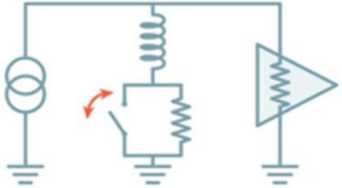
- Absorbed photos create non-superconducting region
- Extremely low energy threshold, extremely fast
- Applications for quantum pixels, ultra-sensitive tracking, milli-charged particles

Recent advances

- Higher temperature operation (1-4 K)
- Demonstrated to work for micron size (optical lithography possible)
- Commercial devices available - quantum communication

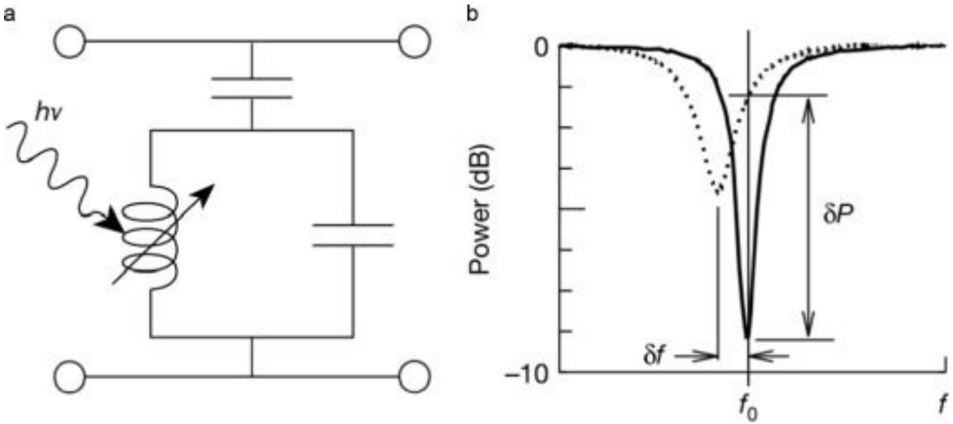






Kinetic Inductance Detector

Microwave resonator through LC oscillator circuit

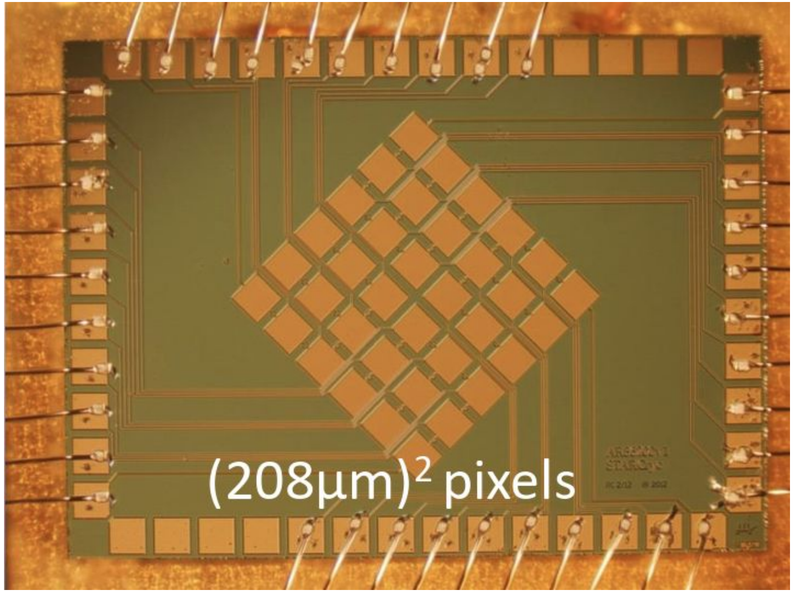


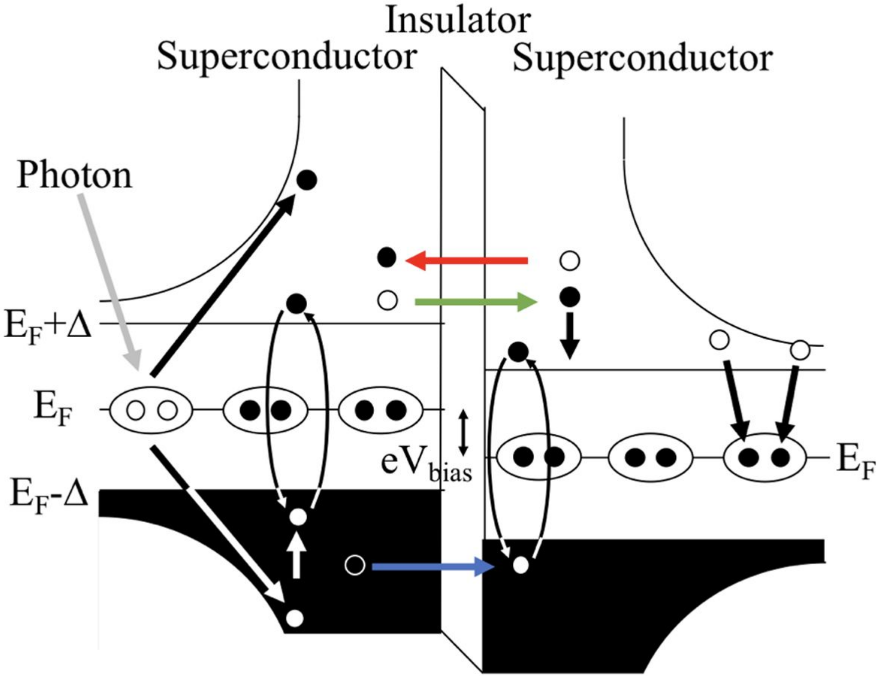
Kinetic inductance is inversely proportional to quasiparticle density

Energy absorption changes frequency, very easily multiplexed!

Superconducting Tunnel Junction

Biased Josephson junction



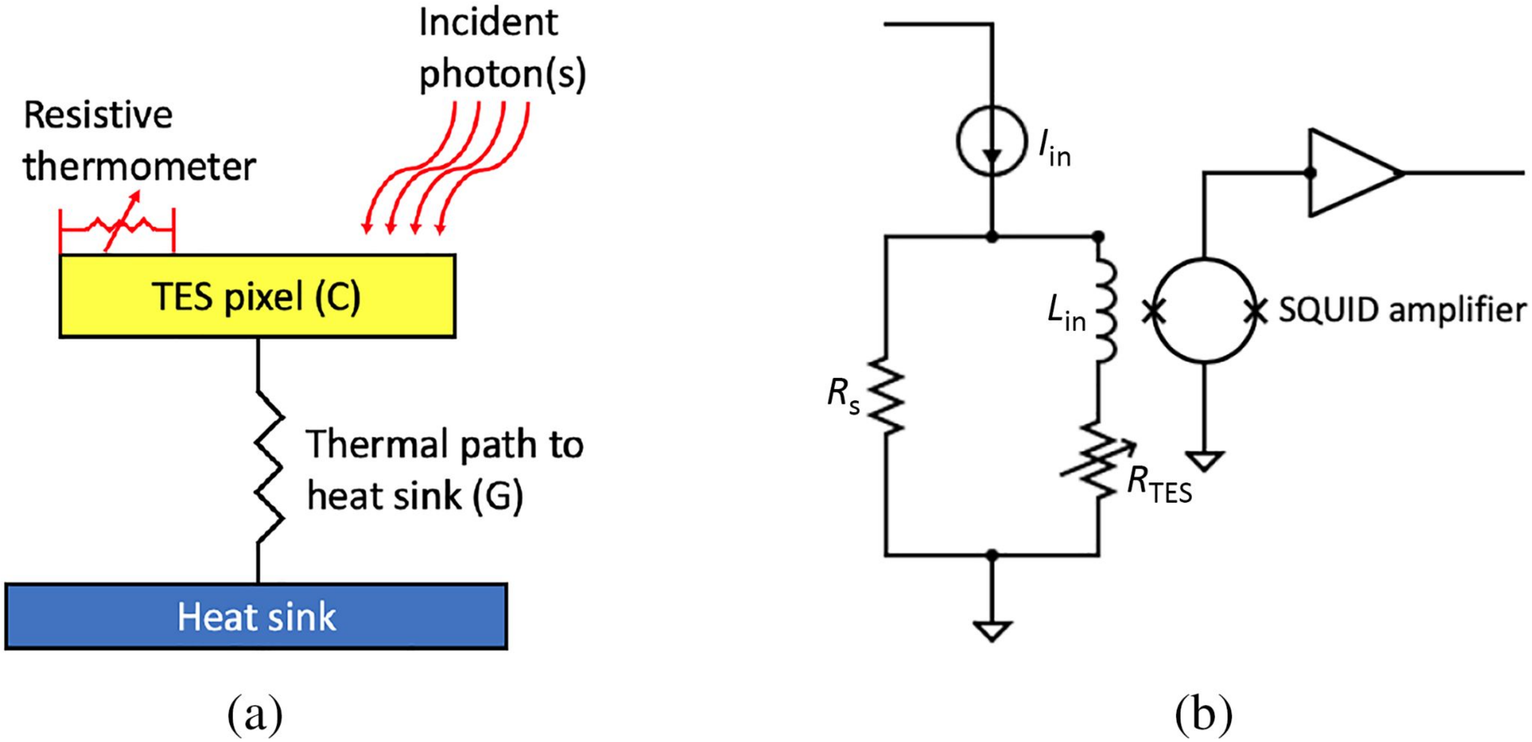


Summary

Detector	**Microwave** 3cm - 3mm 10-100 GHz 0.04-0.4 meV	**Submillimeter** 3mm - 300µm 100 GHz - 1 THz 0.4-4 meV	**Far infrared** 300 – 30 µm 1 – 10 THz 4-40 meV	**Optical** 2 µm - 300 nm 2-37 eV	**High Energy** UV, X-Ray
Transition Edge Sensors (TES)	🟡	🟢	🟢	🟢	🟢
Kinetic Inductance Detectors (KID)	🟡	🟢	🟢	🟢	
Superconducting Nanowire Single-Photon Detector (SNSPD)			🟡	🟢	
Hot-Electron Bolometer (HEB)			🟢		
Cold-Electron Bolometer (CEB)		🟢			
Superconductor-Insulator-Superconductor (SIS)		🟢	🟢	🟢	🟢
Travelling Wave Parametric Amplifier (TWPA)	🟢	🟡			
Josephson Junction Parametric Amplifiers (JJPA)	🟢				

Transition Edge Sensors

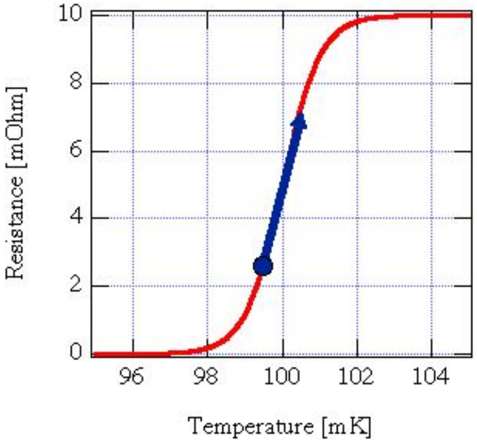
Transition Edge Sensor



Operating characteristics

Took long time to get popular (~1995) because of

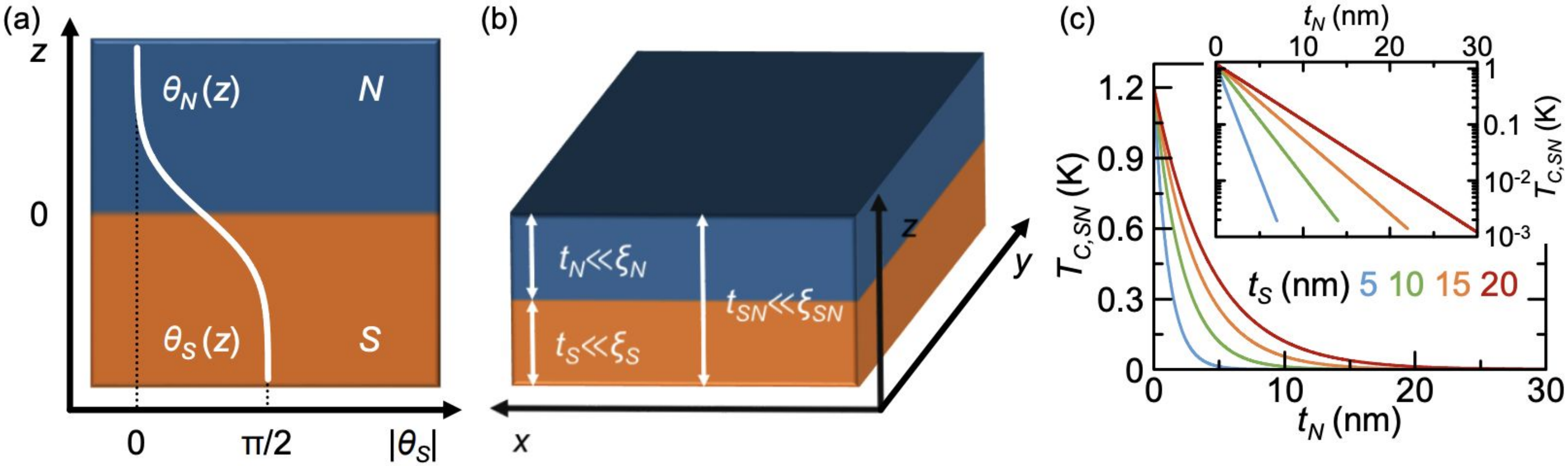
- Low impedance
- High Tc of regular metals
- Inhomogeneous response
- Self heating, thermal runaway
- …



widespread use when successful voltage-biasing (instead of current) was demonstrated + multilayer Tc engineering

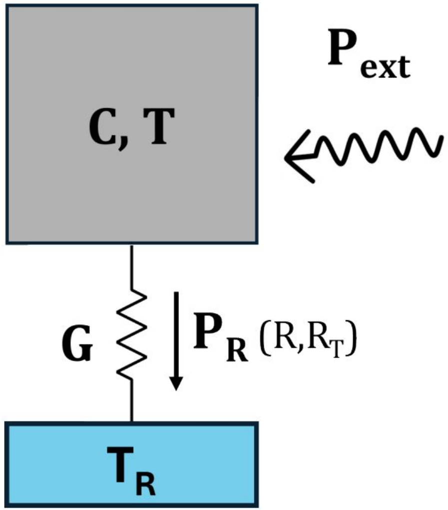
Multilayer engineering

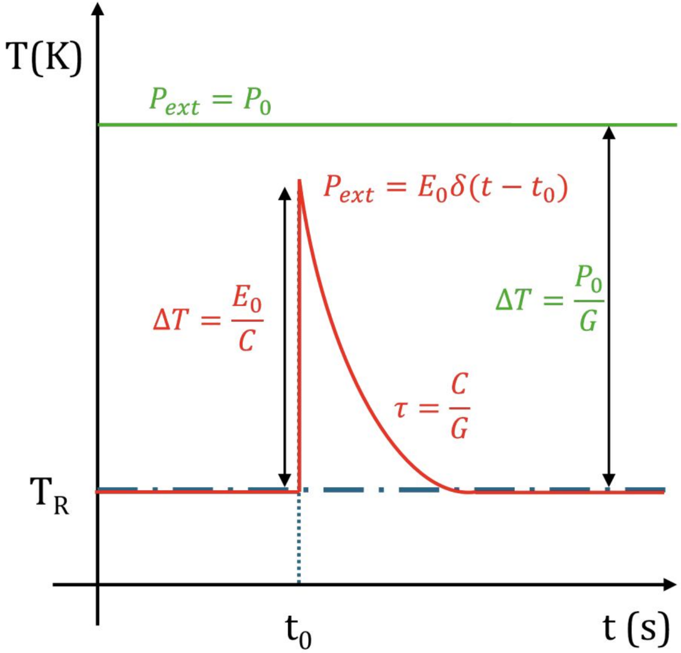
Tc can be modified through proximity effect



Allows for lower Tc for better noise behaviour

Simple TES picture





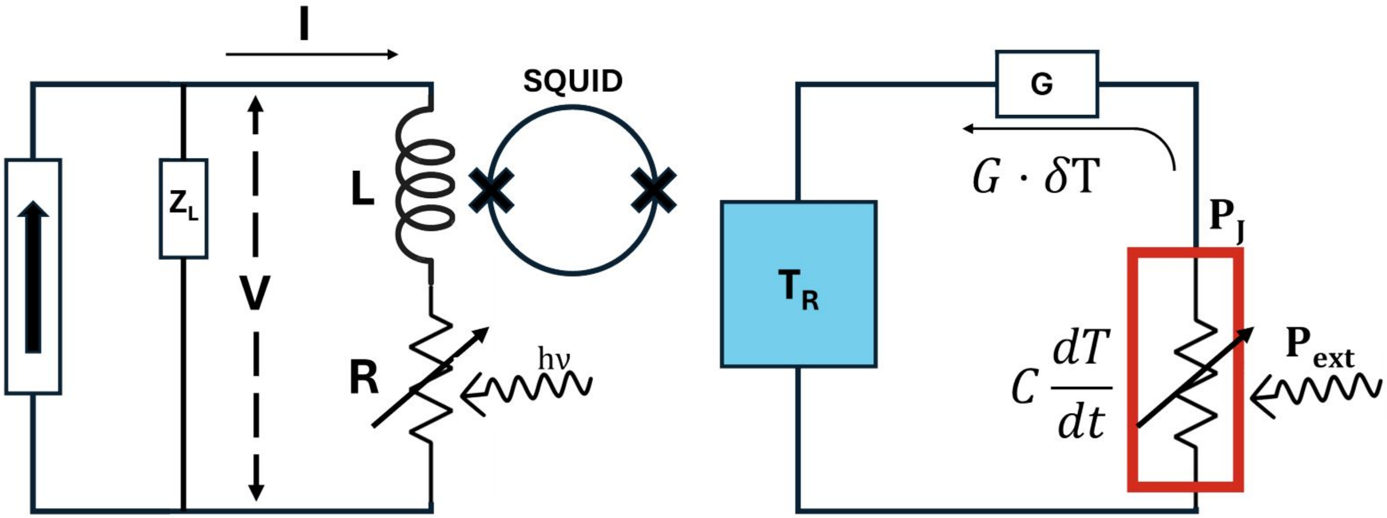
Response defined by

$$P_{ext} = G(T - T_R) + C\frac{dT}{dt}$$

Can get very good resolution, but **slow**

Negative electro-thermal feedback

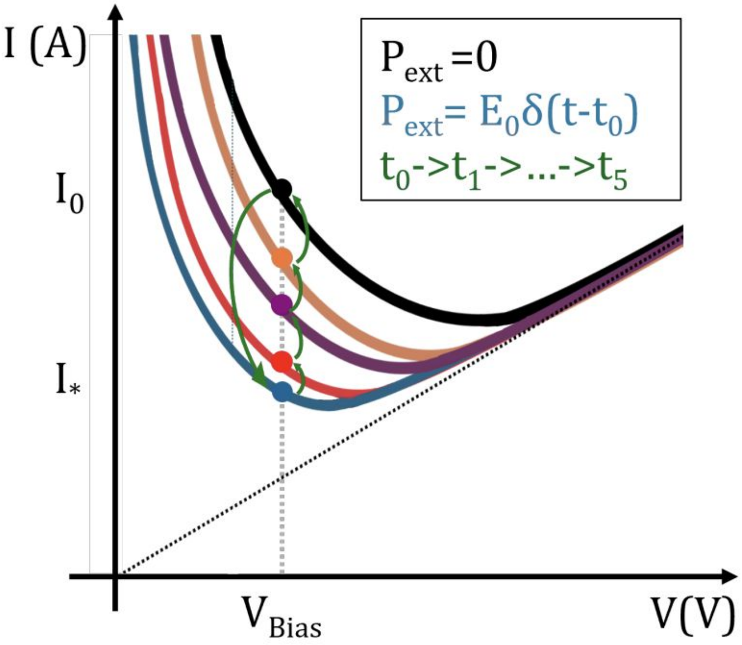
Initially very difficult to keep TESs stable → fixed with voltage biasing (additional shunt resistor contributing Joule heating)

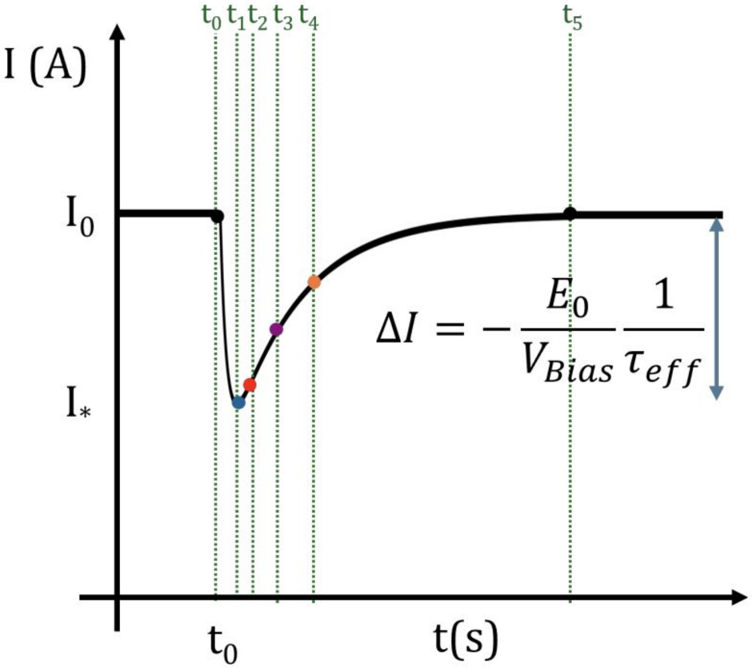


Electrical

Thermal

TES I-V curves



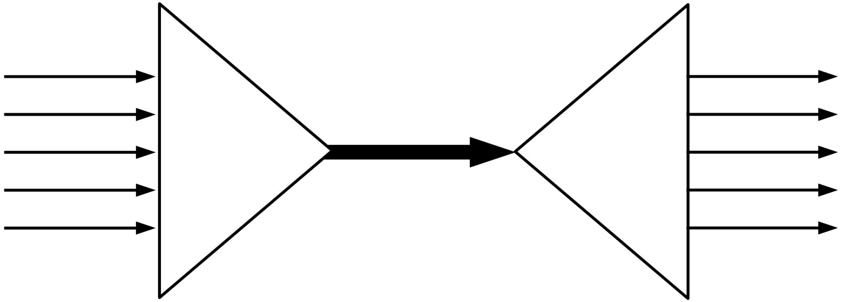


Multiplexing

Central idea: detectors are slow, but maybe put a lot of them together?

Immediate problems: too many cables, too much heating

Solution: Multiplexing

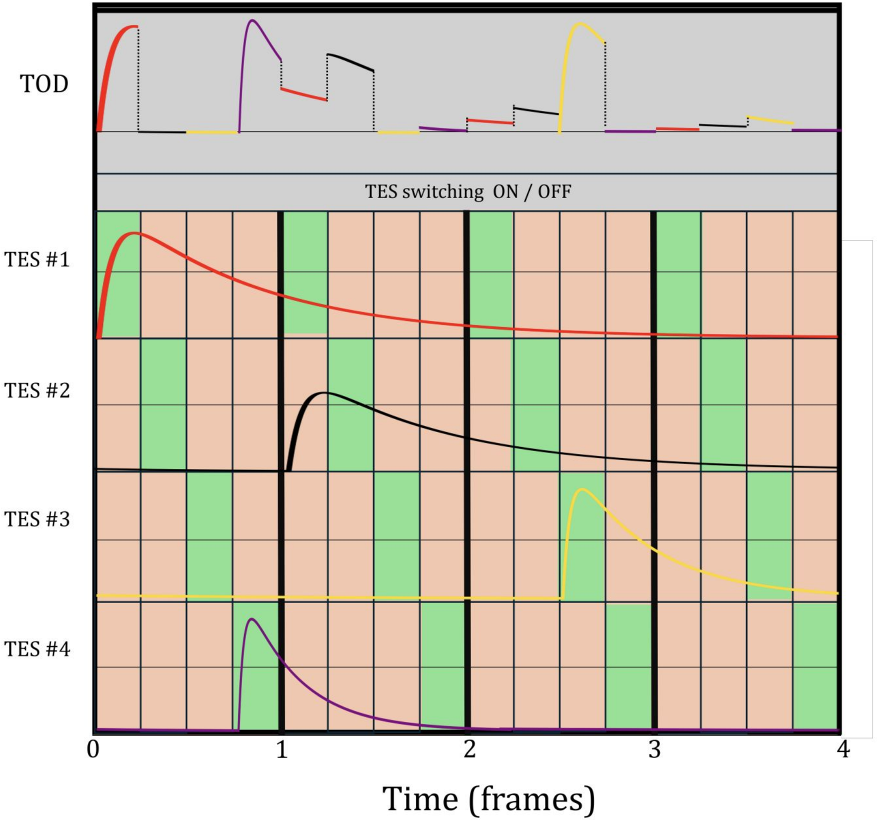


Multiplexing: Time Division Multiplexing

Signals being slow helps!

Simply switch the readout from sensor to sensor

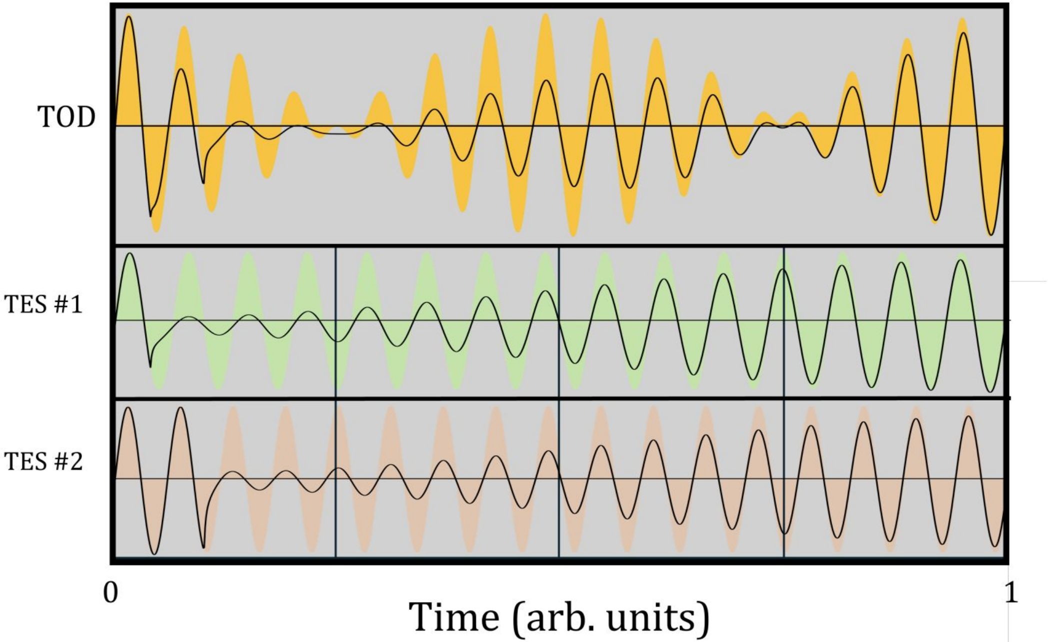
Interpolate between data taking



Multiplexing: Frequency Division Multiplexing

Very similar as radio technology, with similar downsides

- Cross talk
- Finite bandwidth
- Signal loss
- Low multiplexing factor

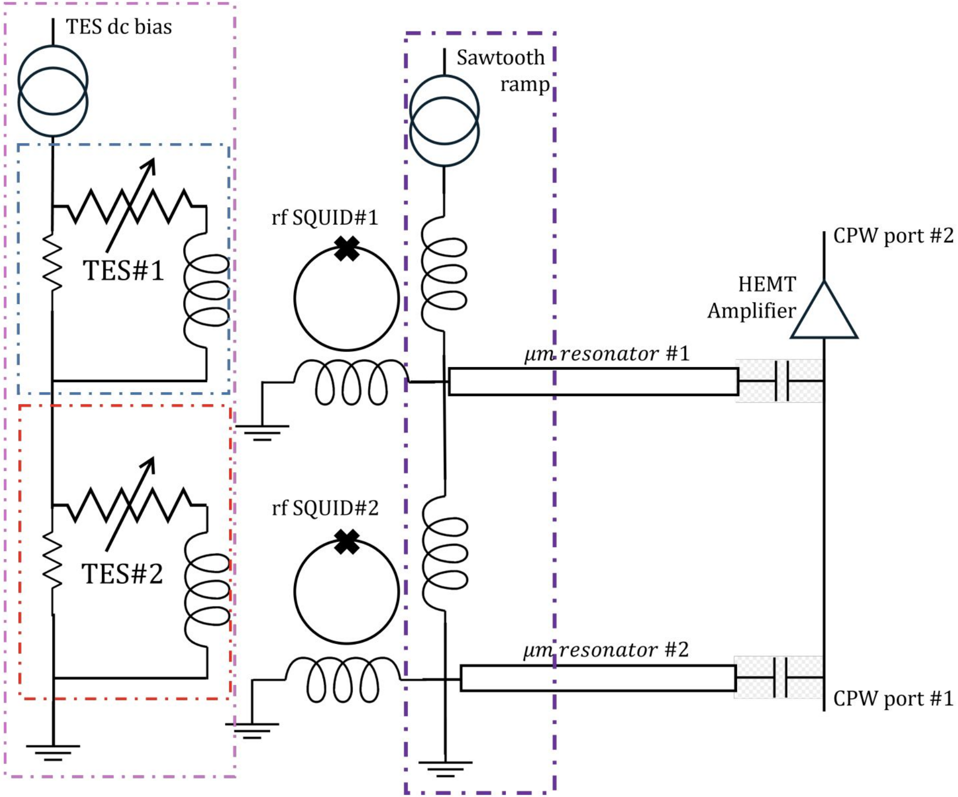


Multiplexing: Microwave

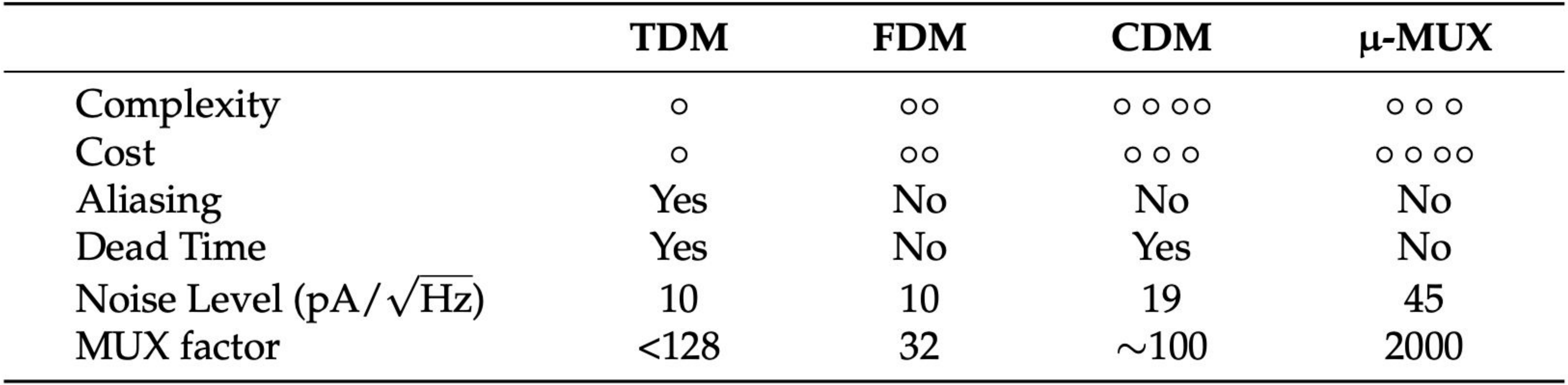
One RF-SQUID per TES to modulate

Can achieve very high multiplexing factors

Increased complexity..



Multiplexing: Comparison

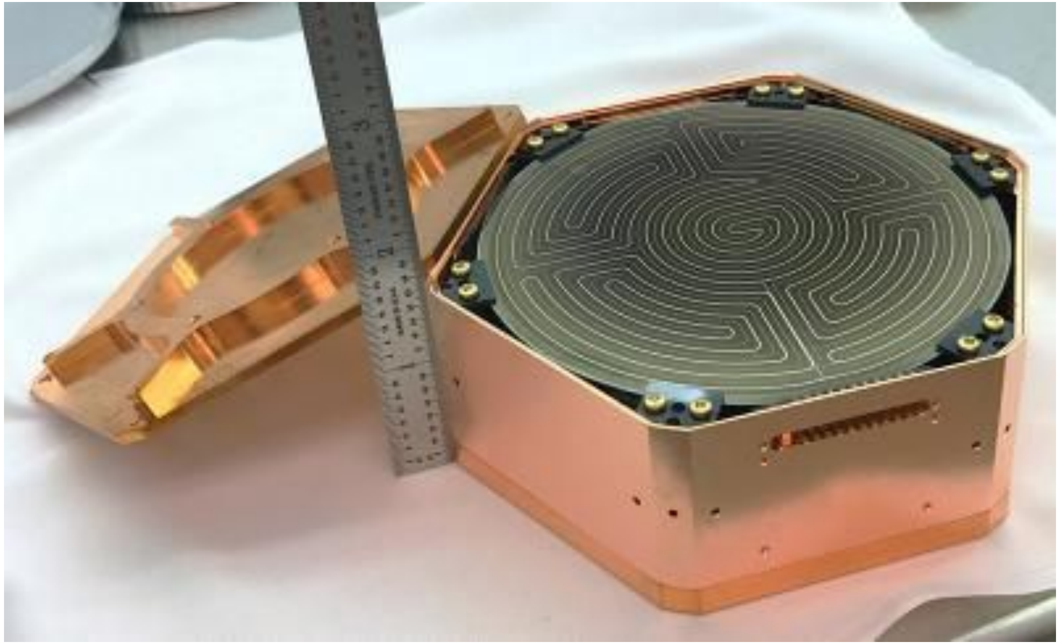


	TDM	**FDM**	**CDM**	**μ-MUX**
Complexity	○	○○	○ ○ ○○	○ ○ ○
Cost	○	○○	○ ○ ○	○ ○ ○○
Aliasing	Yes	No	No	No
Dead Time	Yes	No	Yes	No
Noise Level ($\mathrm{pA}/\sqrt{\mathrm{Hz}}$)	10	10	19	45
MUX factor	<128	32	∼100	2000

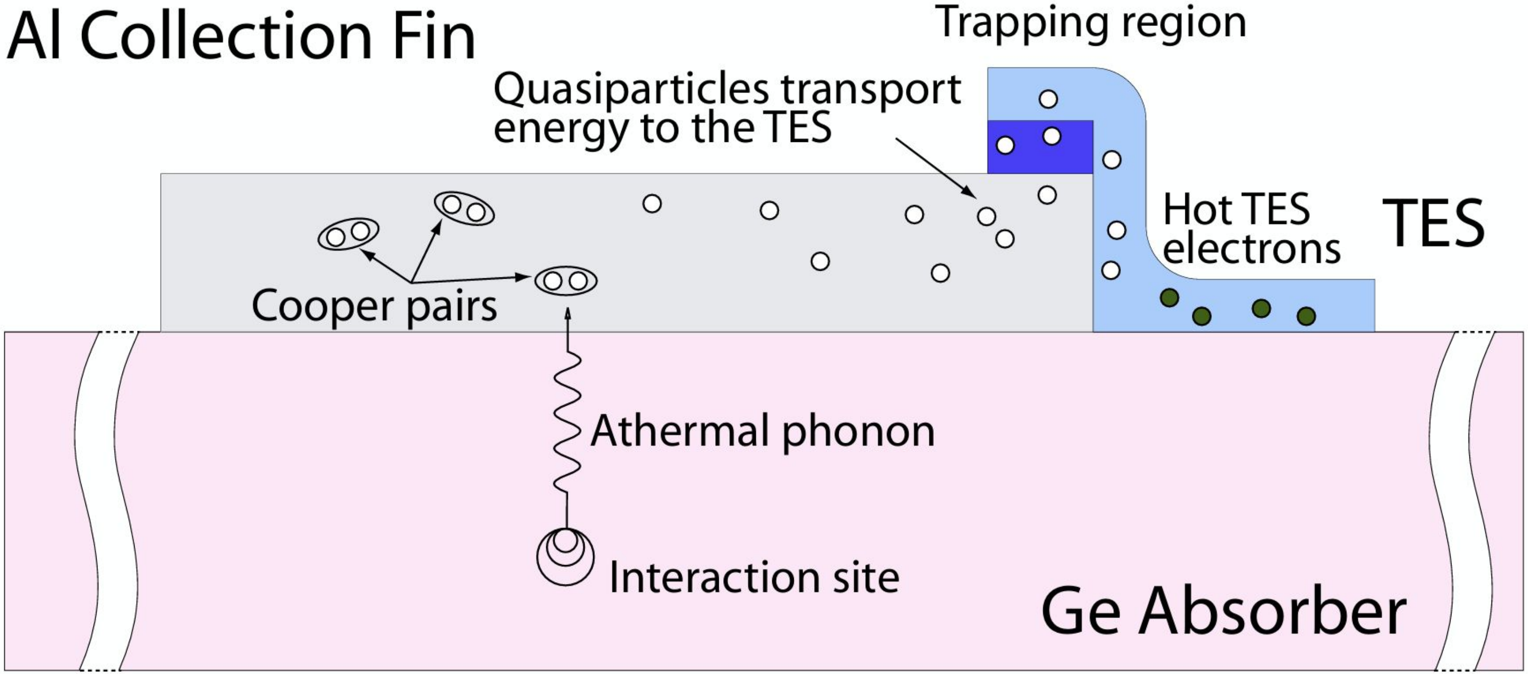
Actual devices

SuperCDMS collaboration has done major developments

Usually combination of absorber material and quasiparticle trap



TES as a quasiparticle trap



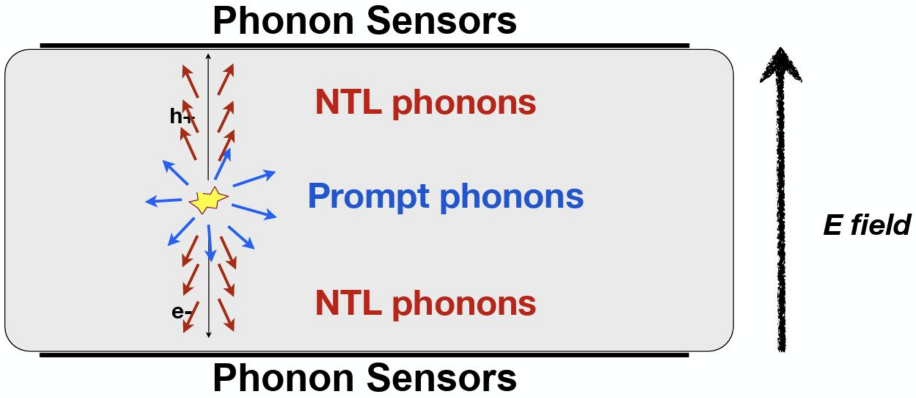
HVeV detectors

Combine E field and phonon detection

Phonon multiplication through NTL mechanism

can achieve O(10) eV resolution

Phonon sensors measure amount of charge produced: Phonon-based charge amplification!



$$\text{Phonon energy} = E_{\text{recoil}} + E_{\text{NTL}}$$
$$= E_{\text{recoil}} + n_{eh}\, e^{-} V$$

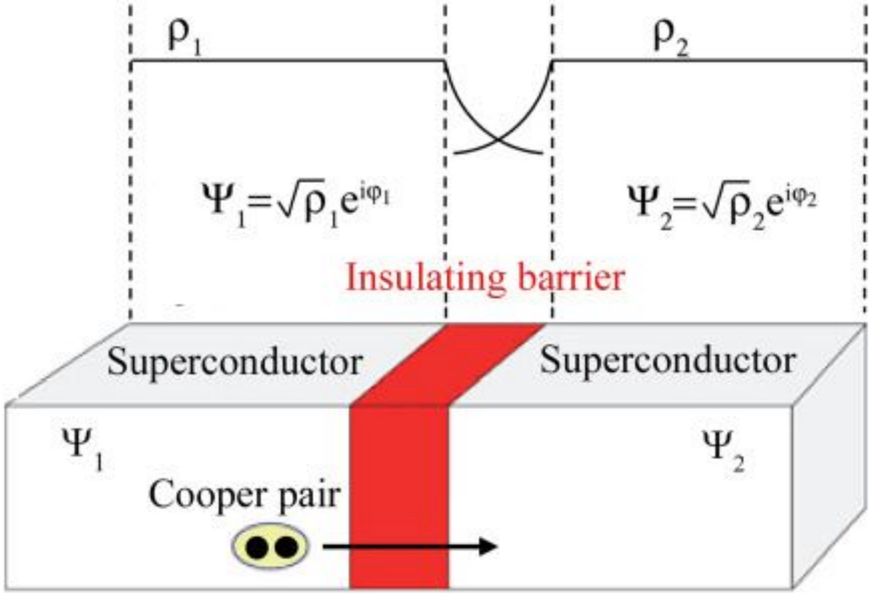
Superconducting Tunnel Junctions

Superconducting Tunnel Junction

Biased Josephson junction,

but don't want AC/DC Josephson

Instead, calorimeter operation requires special care

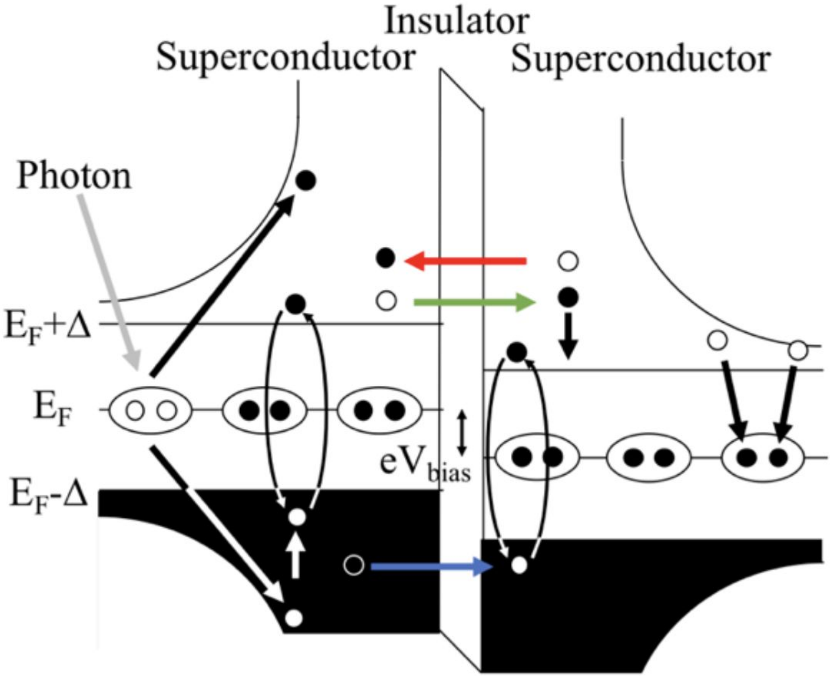


Superconducting Tunnel Junction: Principle

Applied voltage (typically 100μV) determines preferential direction

Quasiparticles contain both electron- and hole-like behaviour: *back-tunneling*

Each qp does multiple tunnelings

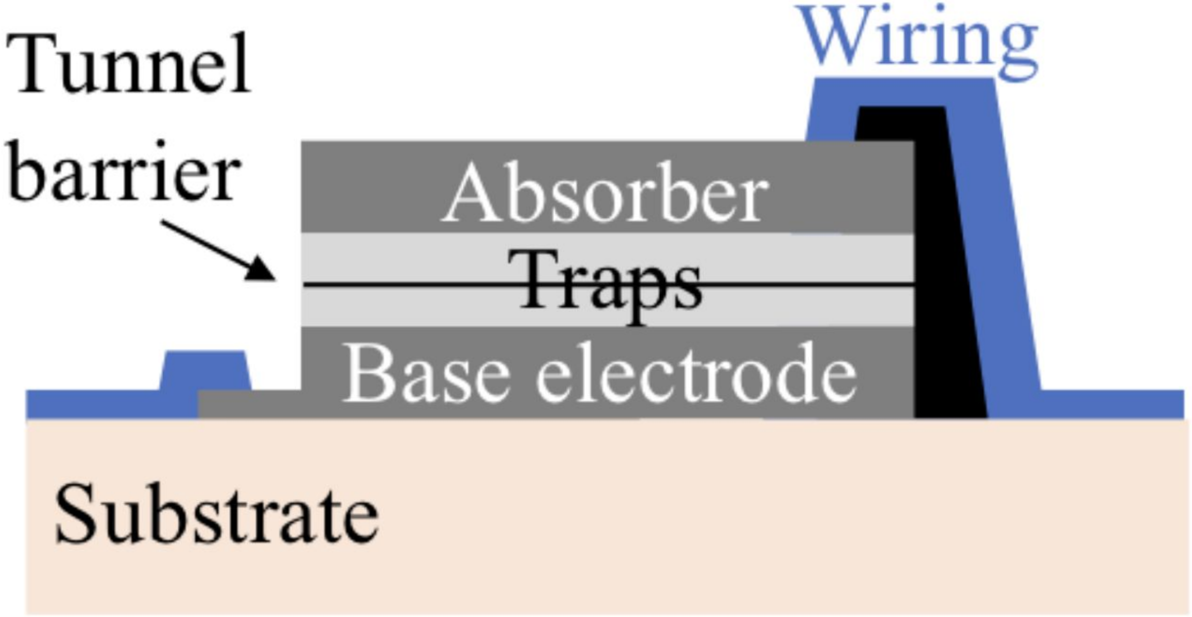


Superconducting Tunnel Junction: Construction

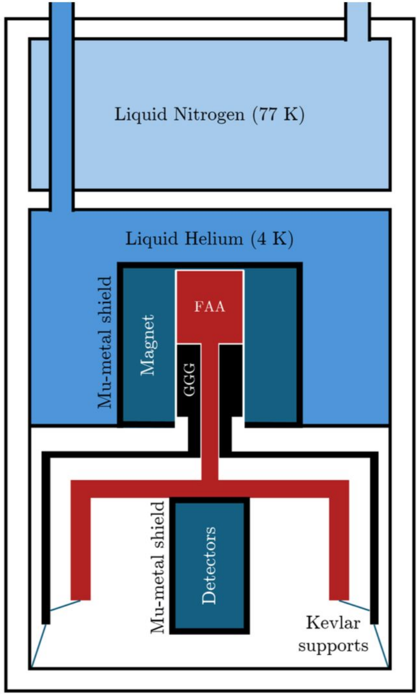
Often 5-layer

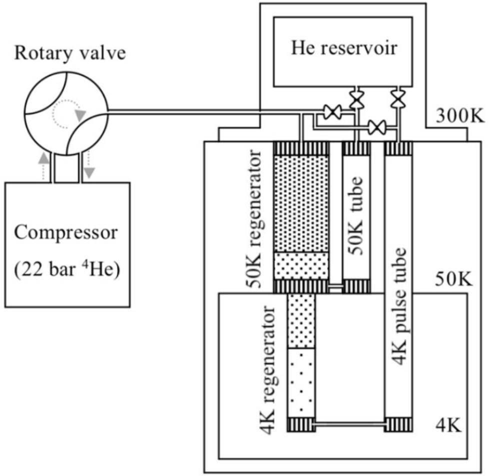
Absorber layer for high photon absorption, usually used in synchrotron

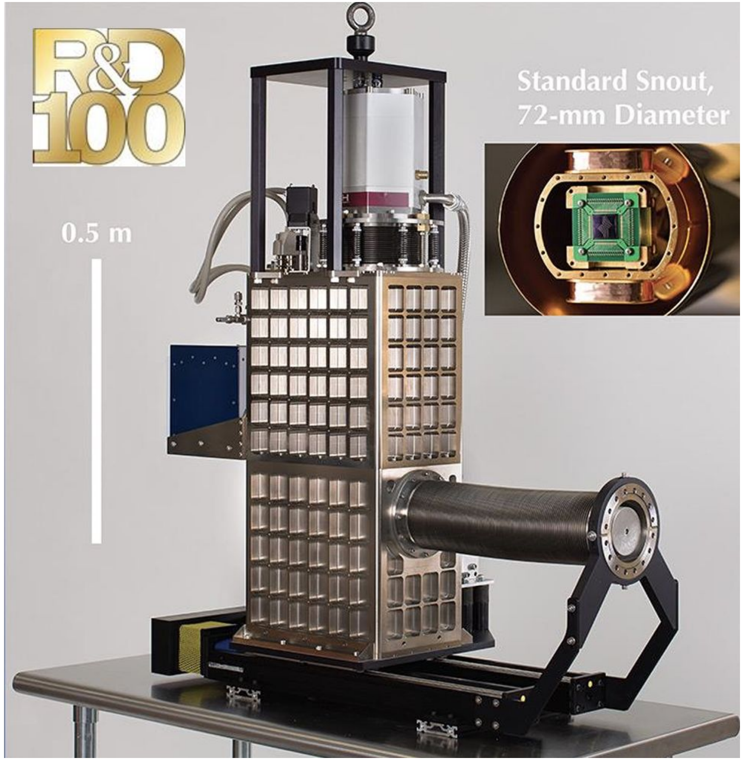
Inner layer acts as qp trap



Adiabatic Diamagnetization Cooling





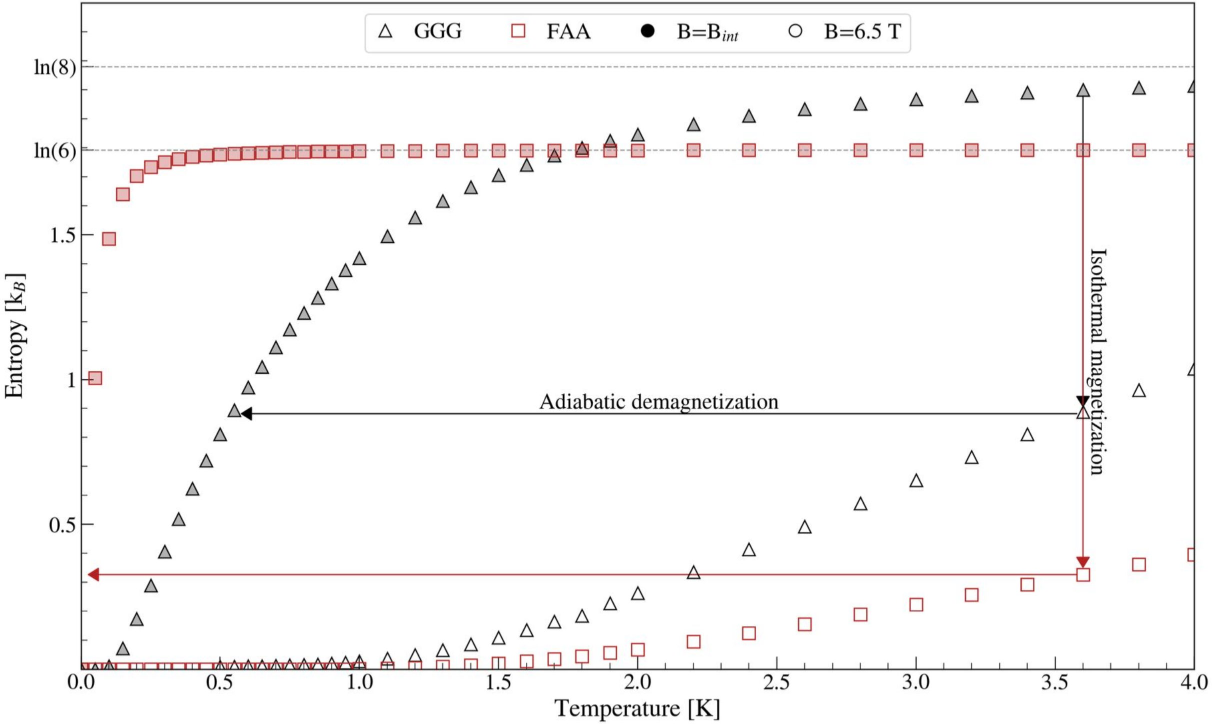


Adiabatic Diamagnetization Cooling

Three-part cycle

1. Connected to heat bath, increase B field, decrease S
2. Disconnect from heat bath, stabilize
3. Ramp down B field

Final T ~ 40 mK



STJ: I-V curve

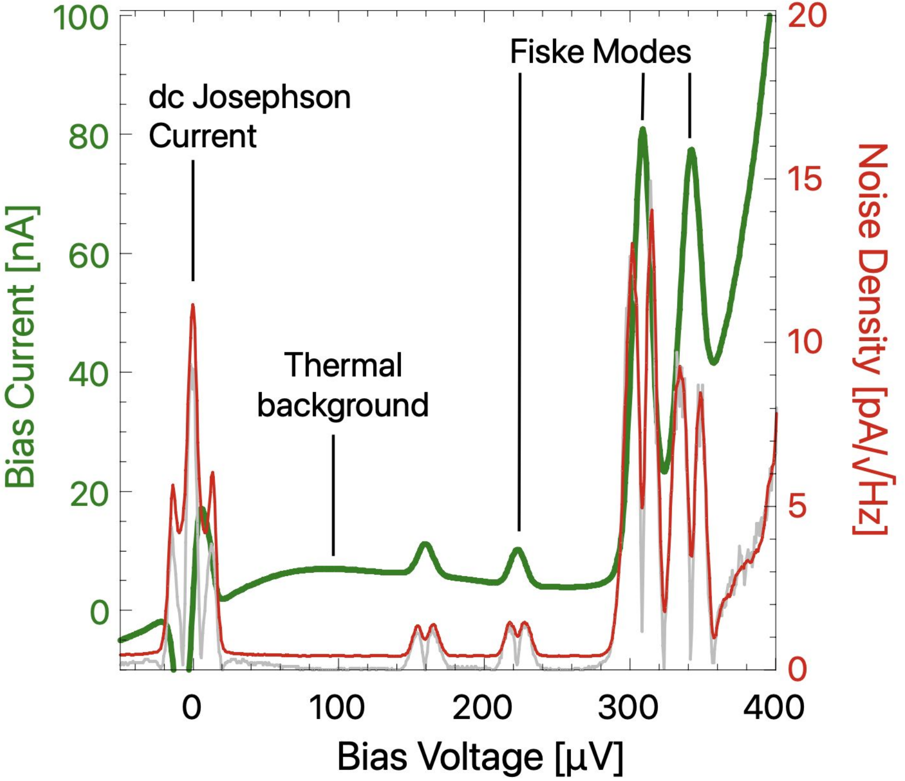
Real sensors show deviation from ideal behaviour

Finite leakage current: dynamic resistance in kΩ range

Fiske modes: geometric resonator resonances

B field ‖ detector plane → suppress

DC Josephson & Fiske modes



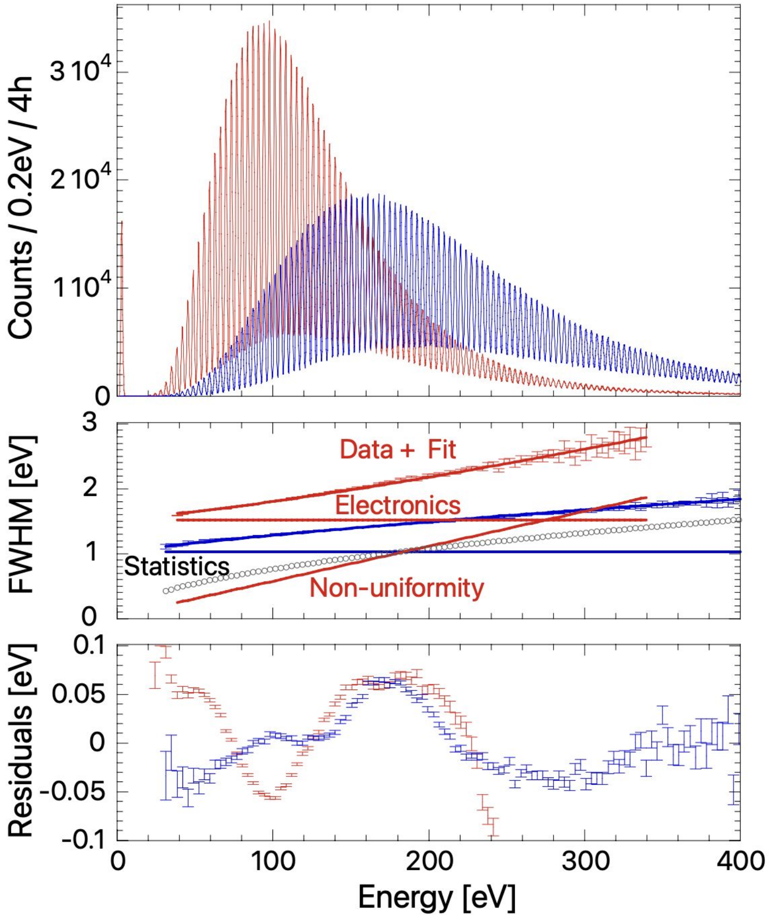
STJ: Calibration

Single-photon sensitivity

eV-scale resolution & threshold

Allows to see non-linearity of ADC

Centroid determination at <meV level



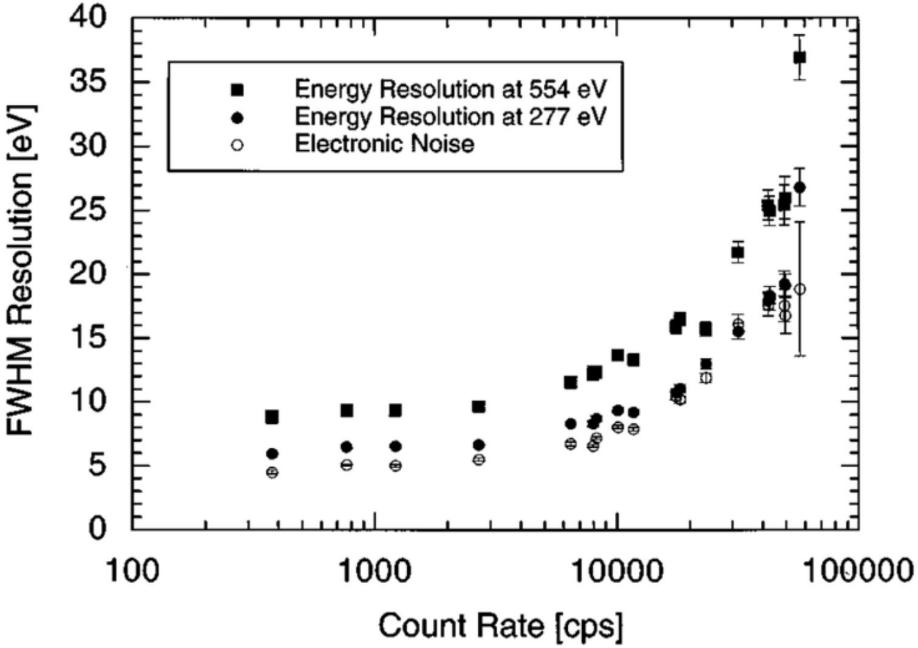
STJ: Speed

Not a thermal sensor

Measure tunneling current

→ directly proportional to qp density

Recombination times ~ **tens of us**



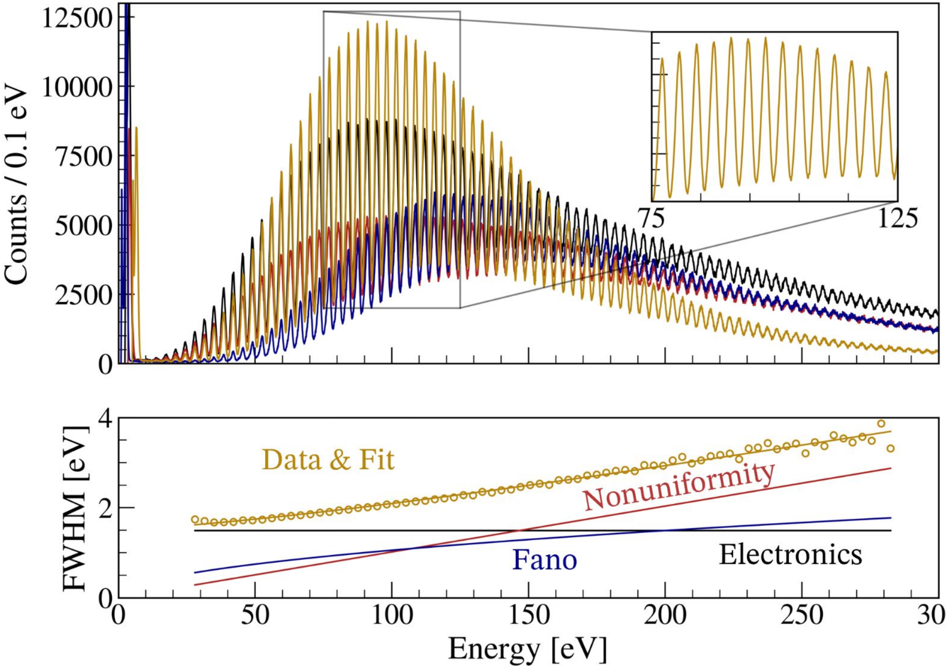
STJ: Resolution

Resolution goes like

$$\sqrt{(F + 1 + \langle n \rangle^{-1})\epsilon E + f^2 E^2 + \delta_{elec})}$$

F ~0.2, multiple tunneling of each qp causes additional fluctuation

In reality, usually dominated by room-temperature electronics or non-uniformity



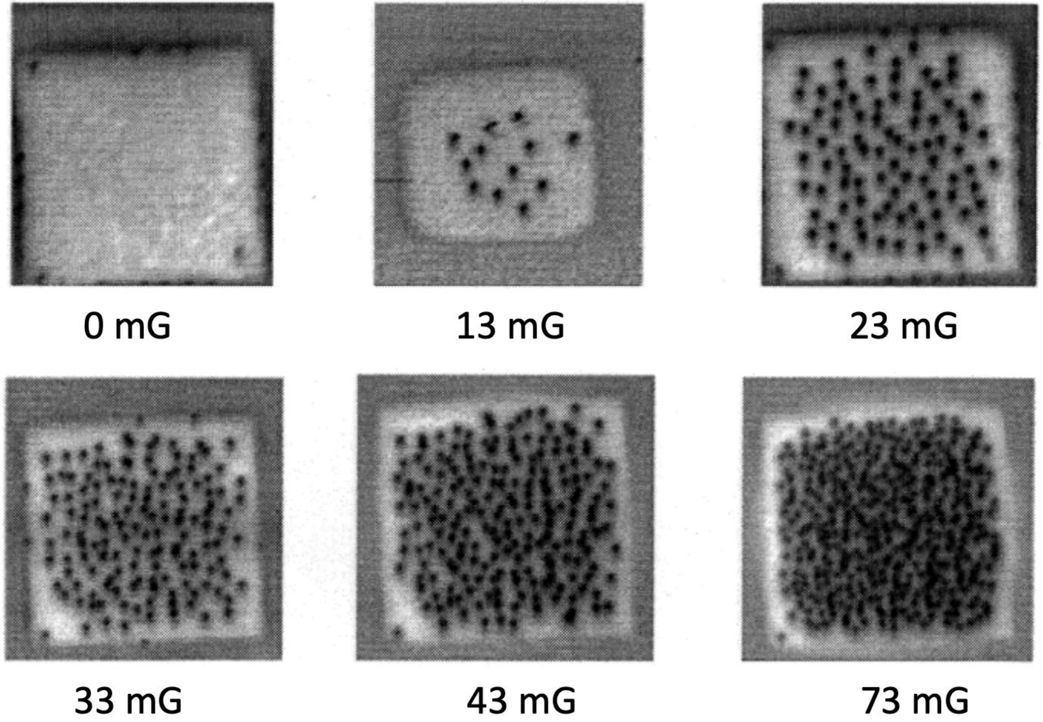
Flux trapping

Thin films are always Type-II

B field matters a lot when going through T_c

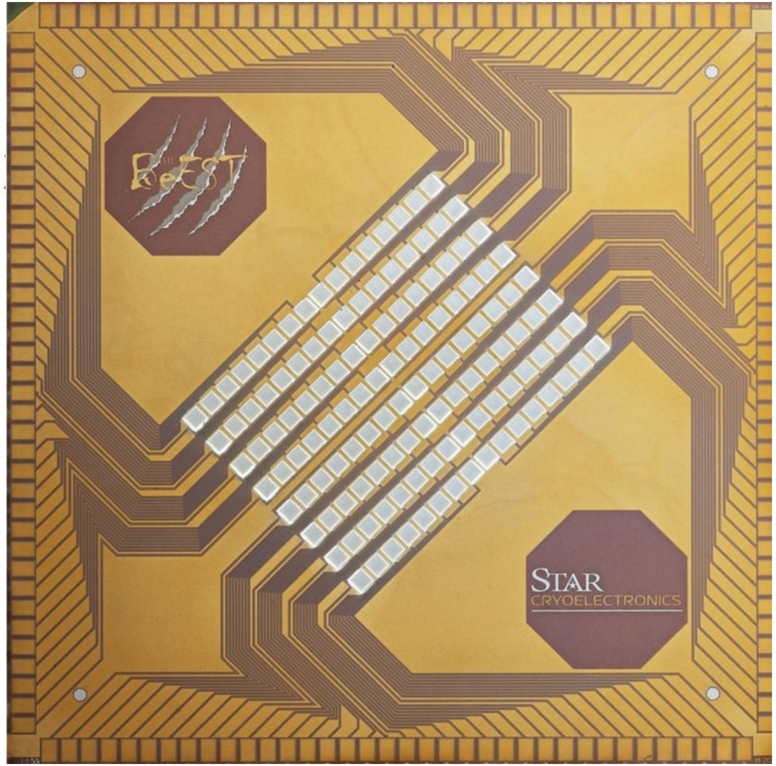
Flux trapping (Abrikosov vortices) cause qp loss

→ decrease of resolution



Superconducting Tunnel Junctions: BeEST

Josephson junction, measure tunneling current of broken cooper pairs ($\Delta \sim 1$ meV)

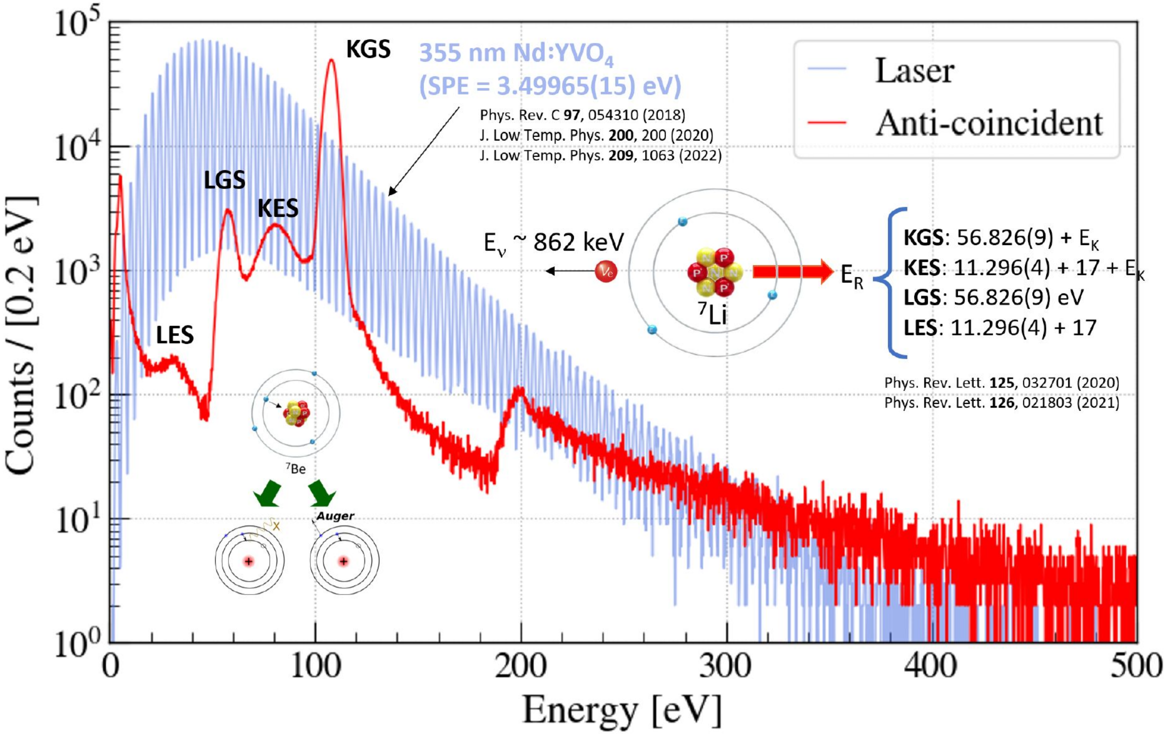


Unique properties:

- High resolution (~ 2 eV)
- Low threshold (~ 1 eV)
- Fast (up to kHz)

ideal for measurement of **short-lived radioactivity**

The BeEST experiment



355 nm Nd:YVO$_4$ (SPE = 3.49965(15) eV)

Phys. Rev. C **97**, 054310 (2018)
J. Low Temp. Phys. **200**, 200 (2020)
J. Low Temp. Phys. **209**, 1063 (2022)

KGS: 56.826(9) + E_K
KES: 11.296(4) + 17 + E_K
LGS: 56.826(9) eV
LES: 11.296(4) + 17

Phys. Rev. Lett. **125**, 032701 (2020)
Phys. Rev. Lett. **126**, 021803 (2021)

PRL 126 (2021) 021803; PRL 125 (2020), 032701

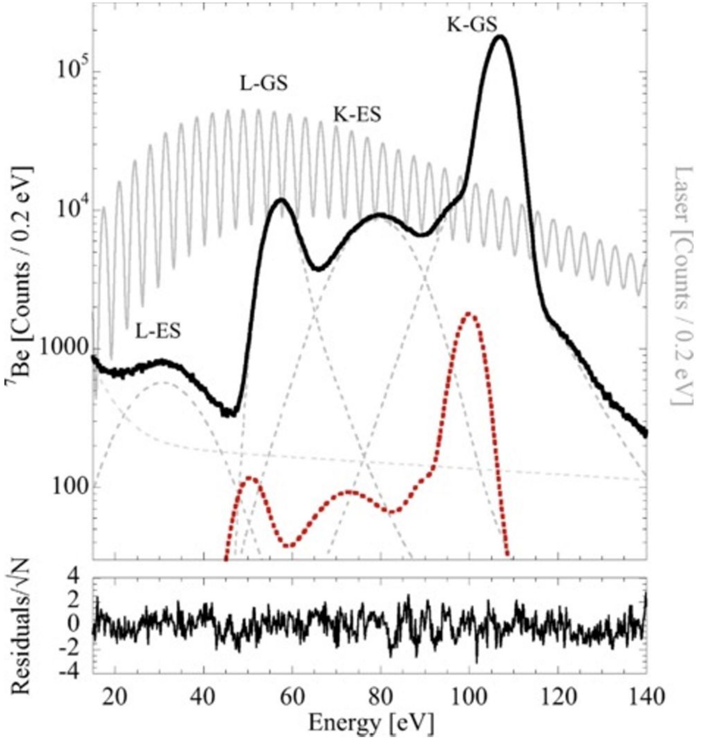
First spectroscopy of ^{7}Be recoil + cascade

Competitive sterile neutrino searches

Tests of quantum mechanics!

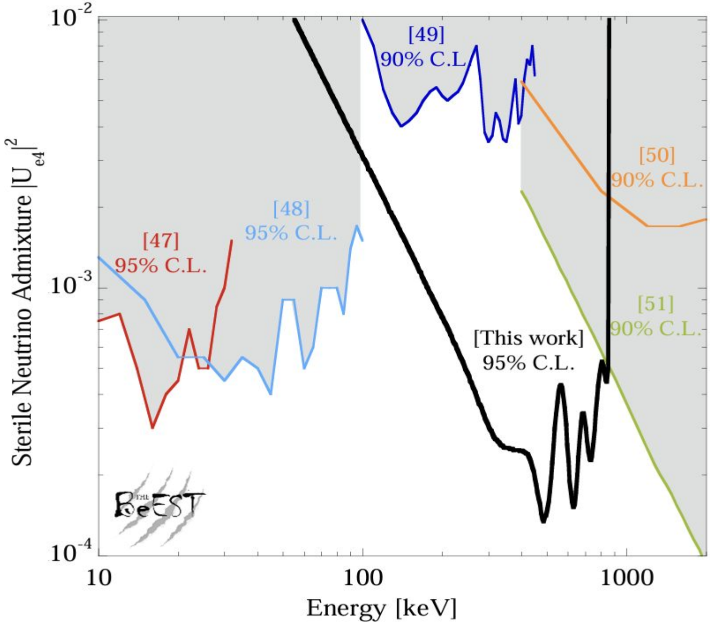
Nature 638 (2025) 640

BeEST: Sterile neutrino search



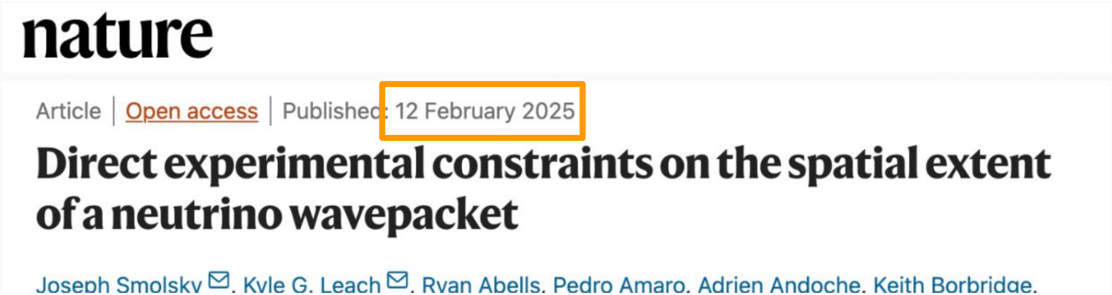
Emission of keV-scale sterile neutrino:

same spectrum, shifted down



Immediate high impact: ‘low hanging fruit’ with BeEST

Recoil nucleus is broadened due to $\sigma_x\sigma_p \geq \hbar/2 \longrightarrow$ get σ_x^{ν}



nature

Article | Open access | Published: 12 February 2025

Direct experimental constraints on the spatial extent of a neutrino wavepacket

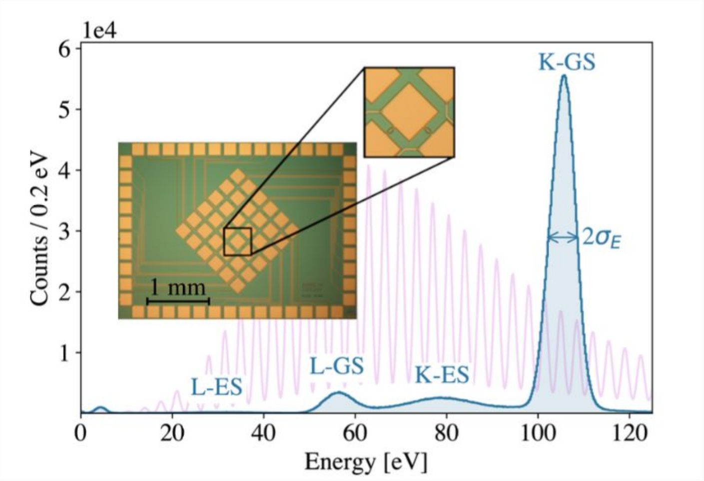
Joseph Smolsky, Kyle G. Leach, Ryan Abells, Pedro Amaro, Adrien Andoche, Keith Borbridge,

Une expérience évalue avec une précision inédite l'espace occupé par...

Une expérience évalue avec une précision inédite l’espace occupé par un neutrino

18 février 2025

RÉSULTATS SCIENTIFIQUES PHYSIQUE DES NEUTRINOS



See also PRD 111 (2025) 052010

Experimental opportunities with recoil spectroscopy

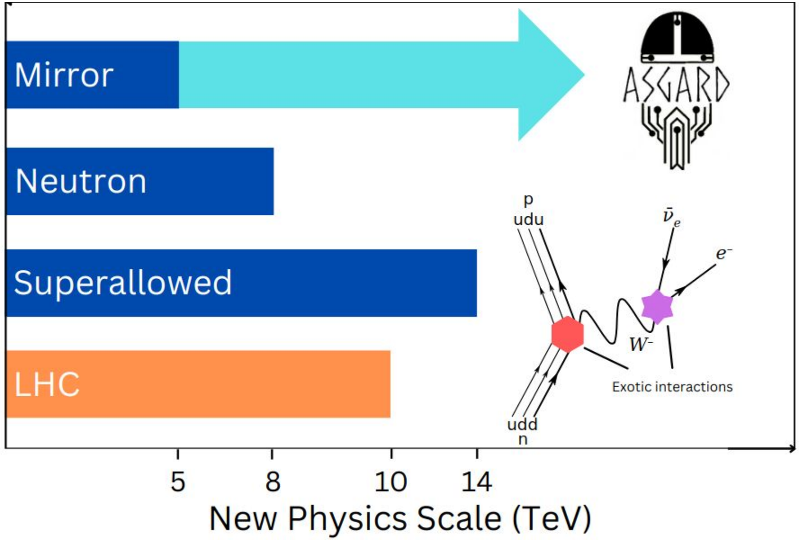
Competitive with LHC $(1/\Lambda^2_{BSM})$

- TeV-scale new currents
- Extra flavour components

but **plateau** due to **systematics**

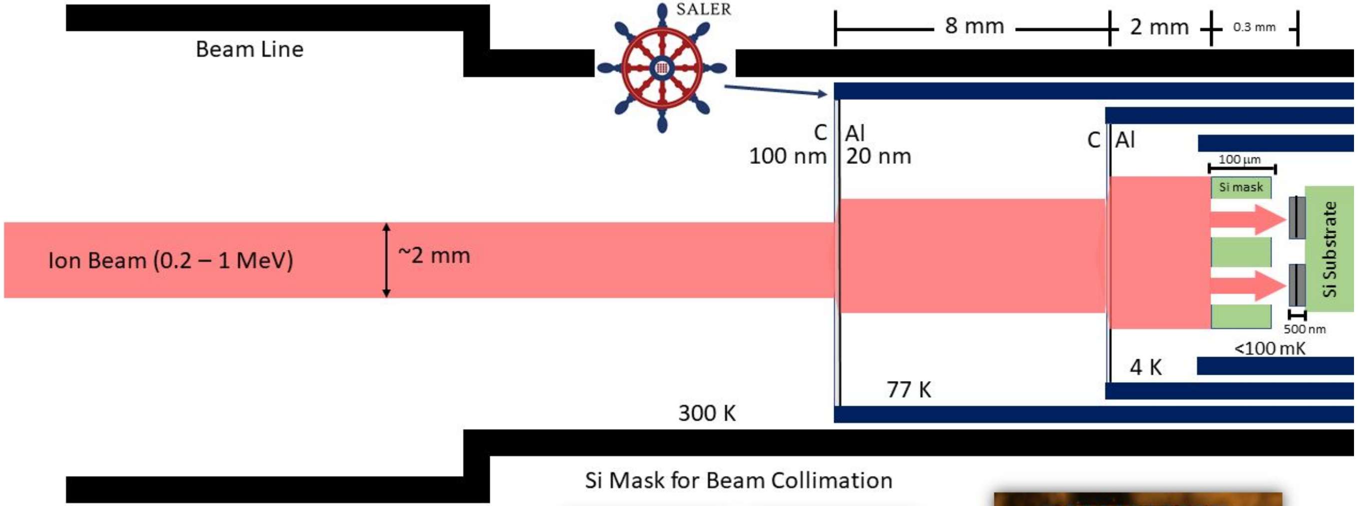
Recoiling ion has wealth of information, but **technologically inaccessible** and requires **broad theory understanding**

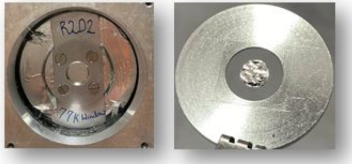
High precision at *low energy* probes new physics at *high energy*



LH, *ARNPS* 74 (2024) 497
LH et al., *RMP* 90 (2018) 015008

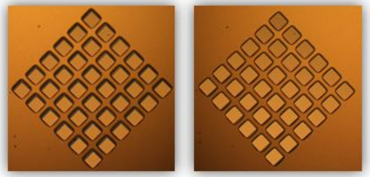
SALER: First short-lived measurements at FRIB



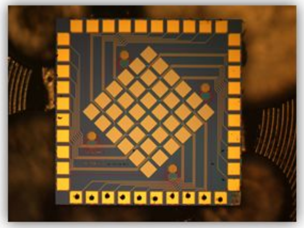


Ultra-Thin (120 nm)
Thermal windows

Si Mask for Beam Collimation



Before Alignment After Alignment



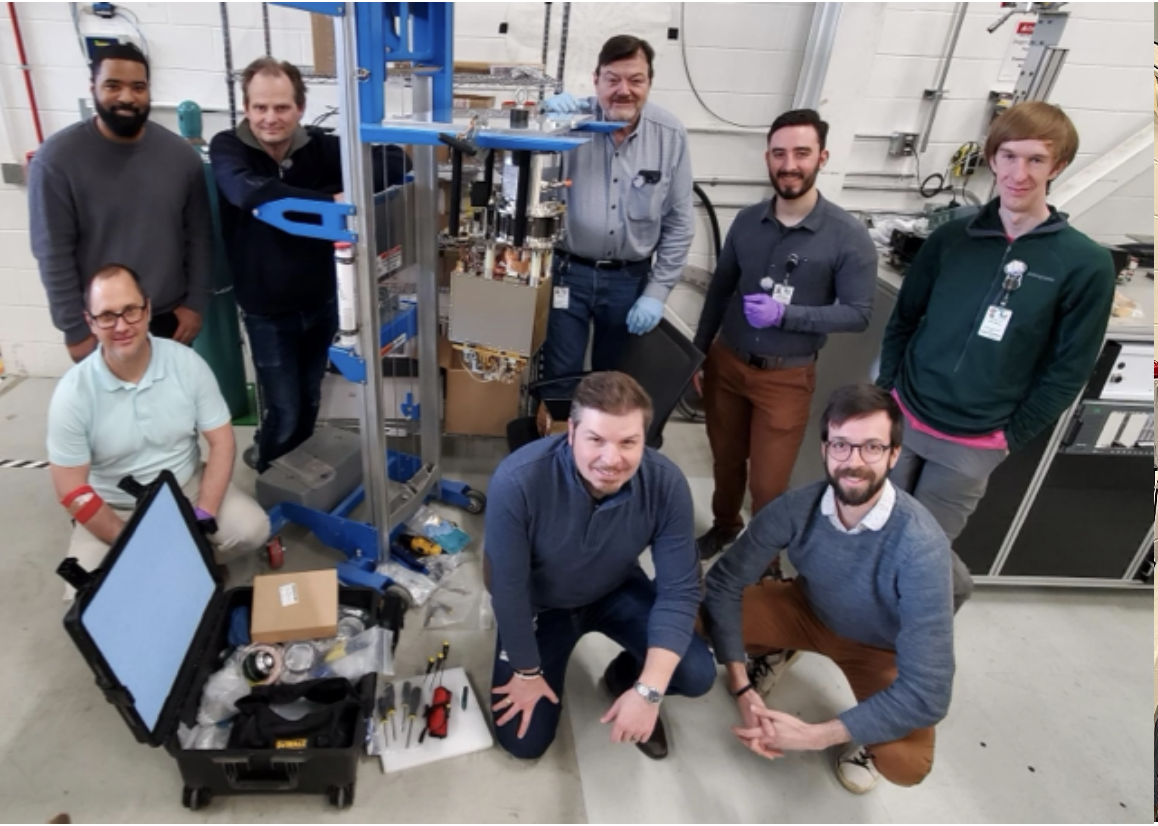
Mounted 36-Pixel Nb STJ Array

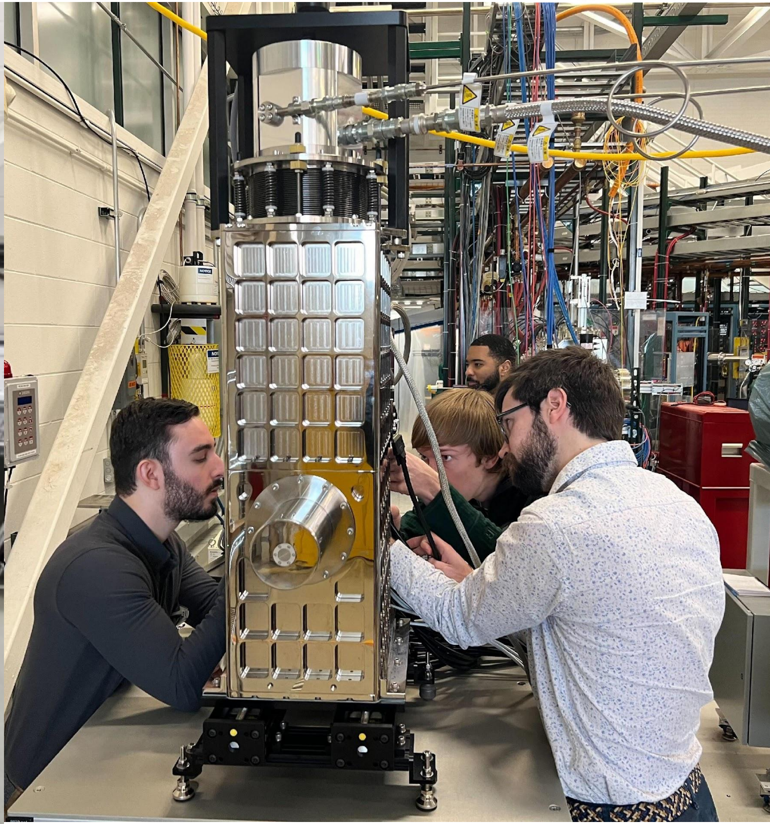
First-of-its-kind

but

- closed fridge
- significant scattering
- no precise implantation
- limited isotopes

SALER commissioning: First light April 2024



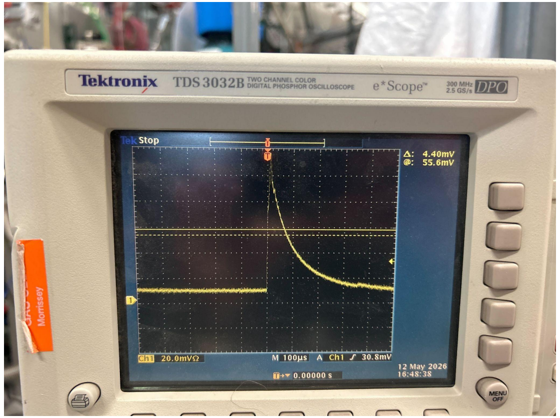


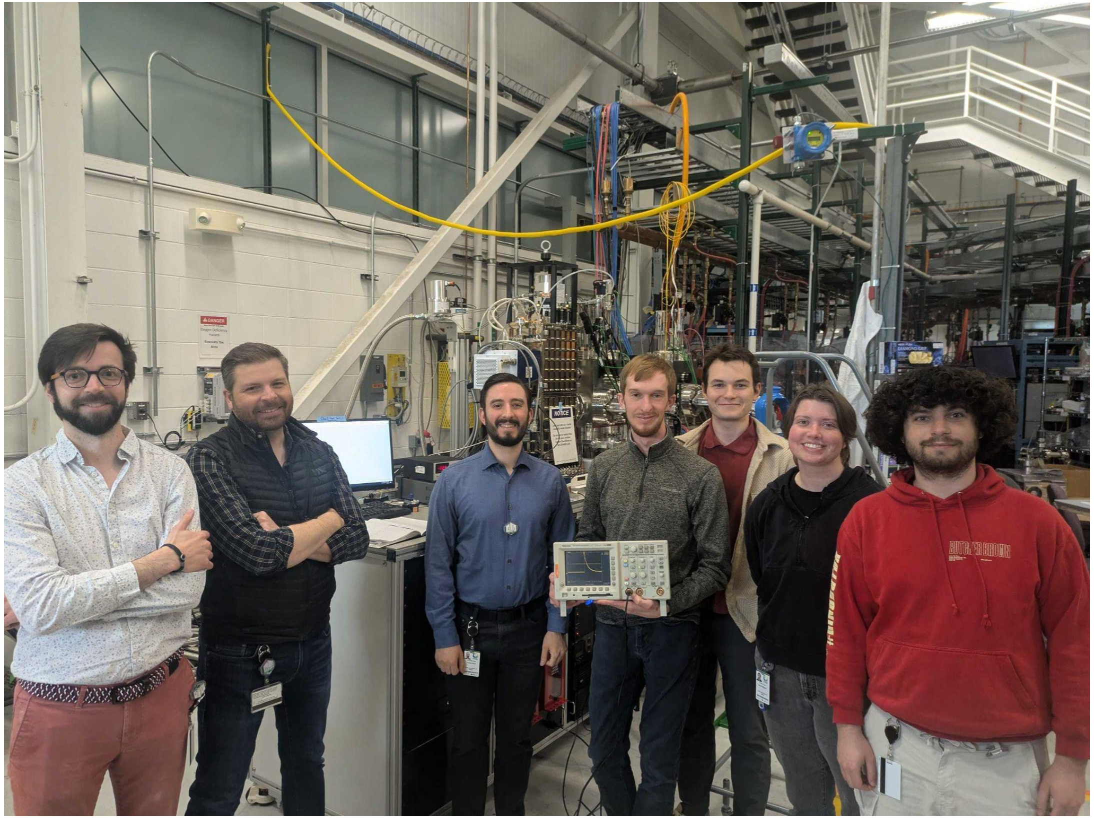
SALER: First online commissioning May 2026

Poster Driss GUILLET

First light with ^{14}N beam

Radioactive late 26/early 27





Recoil spectroscopy: broader scope

Out of *thousands of known* radioactive transitions,

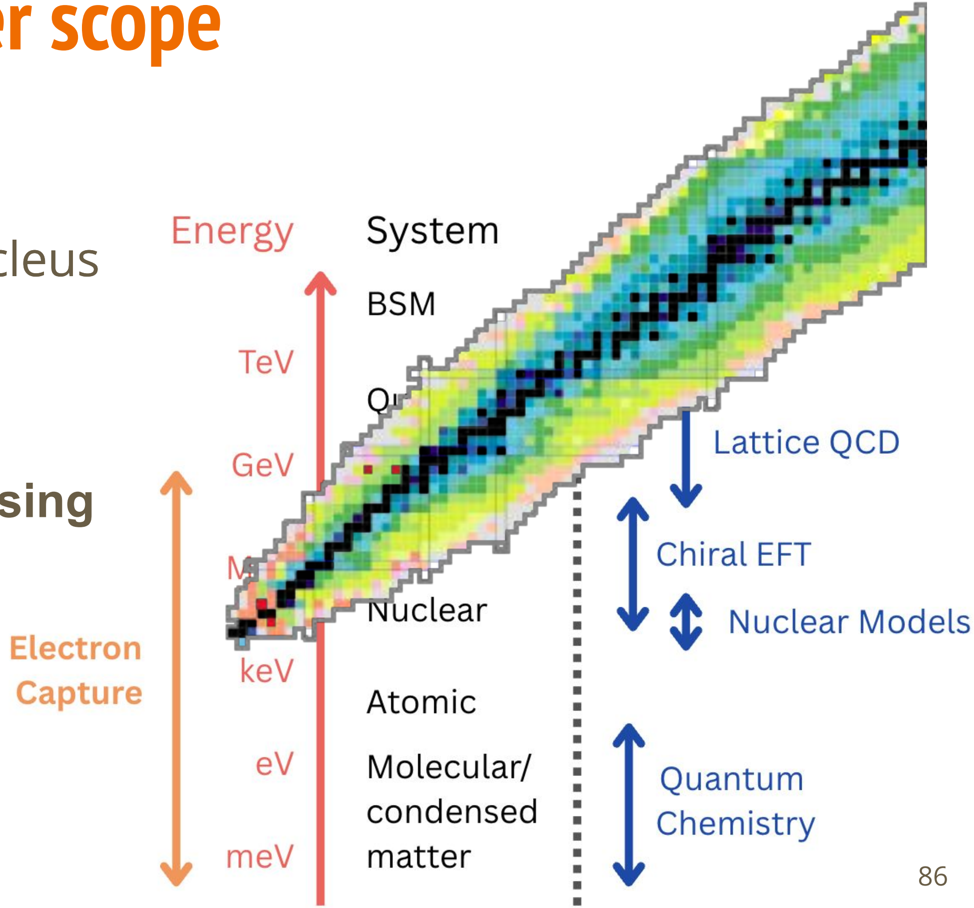
only handful measured recoiling nucleus

Coherent multi-scale framework

(QCD → Chemistry) is **crucial**, but **missing**

Recoil: Access to electron capture &

electronic environment



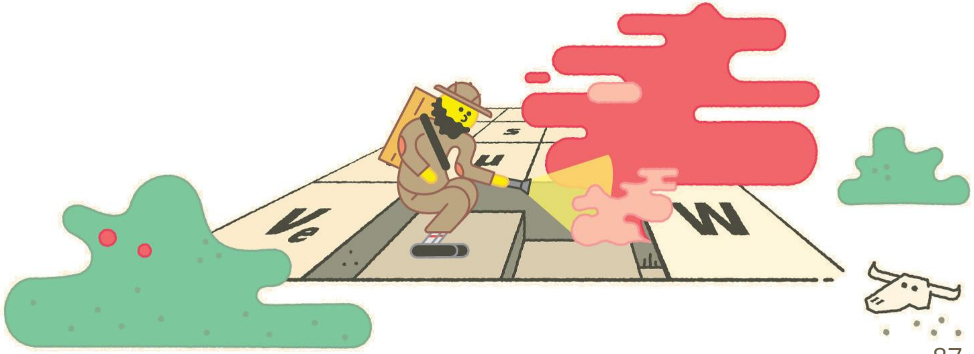
ASGARD: Tabletop experiment for particle physics

ASGARD will perform precise **eV-scale spectroscopy** on **short-lived isotopes** with **superconducting quantum sensors**

- Novel TeV-scale new physics searches
- New directions in nuclear physics

ASGARD will be a precision device

at DESIR@GANIL



Artwork by Sandbox Studio, Chicago

ASGARD: Principle

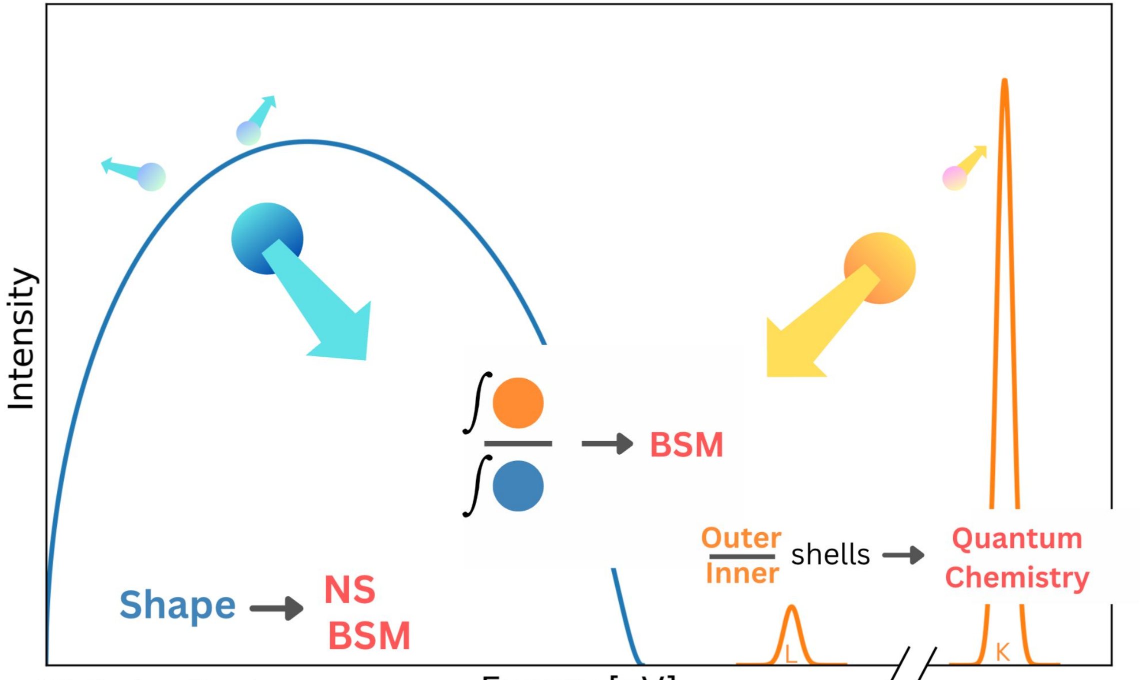
Perform full spectroscopy of **short-lived isotopes** with **quantum sensors**

Two novel measurement schemes:

- I: EC/B+ Branching ratio
- II: B+ shape

probe new physics at tens of TeV in completely new way

Direct beta decay & electron capture measurement

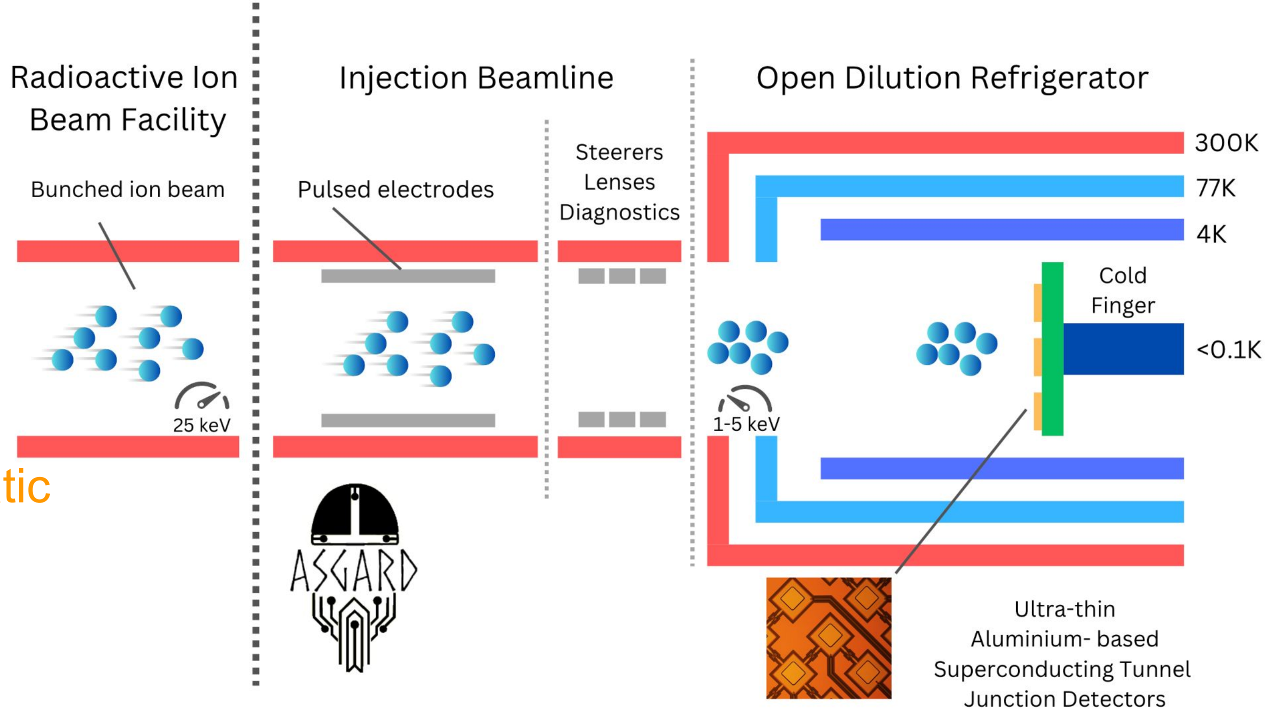


NS: Nuclear Structure
BSM: Beyond Standard Model

ASGARD: Methodology

Combination of **expertise** in beta decay and technical innovations

Orders of magnitude improvement in systematic effects and efficiency



ASGARD: Methodology

Key #1: Windowless dilution fridge

→ Full access to nuclear chart

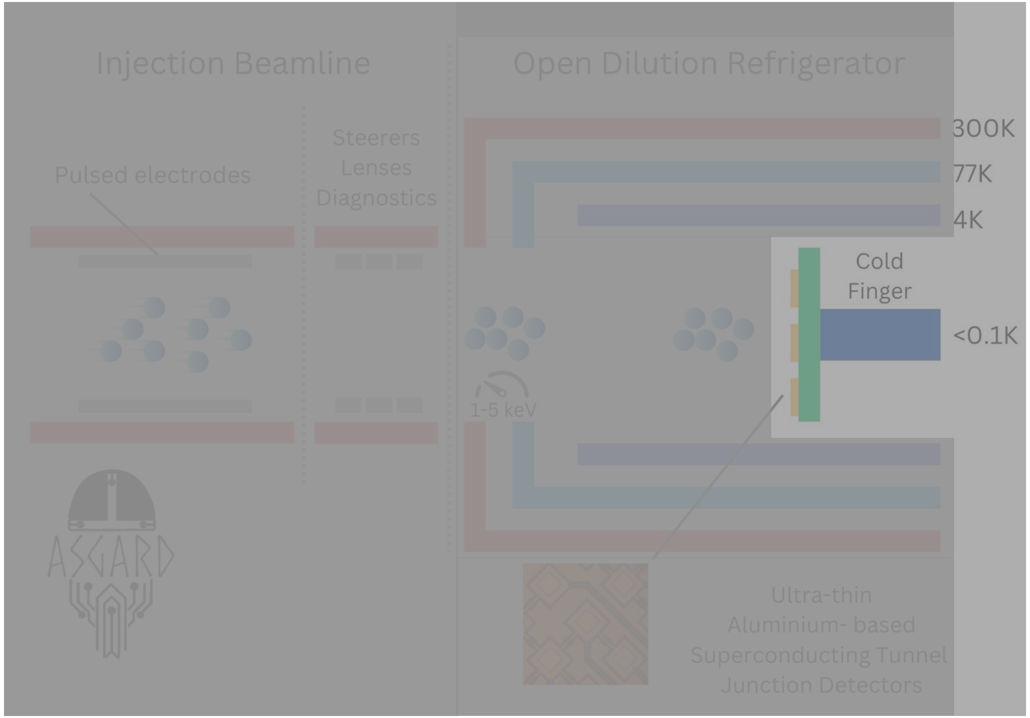
Key #2: Ultrathin Al-STJs

→ x100 reduced scattering

Key #3: Injection beam line

→ Extremely precise implantation

Together world-first precision device



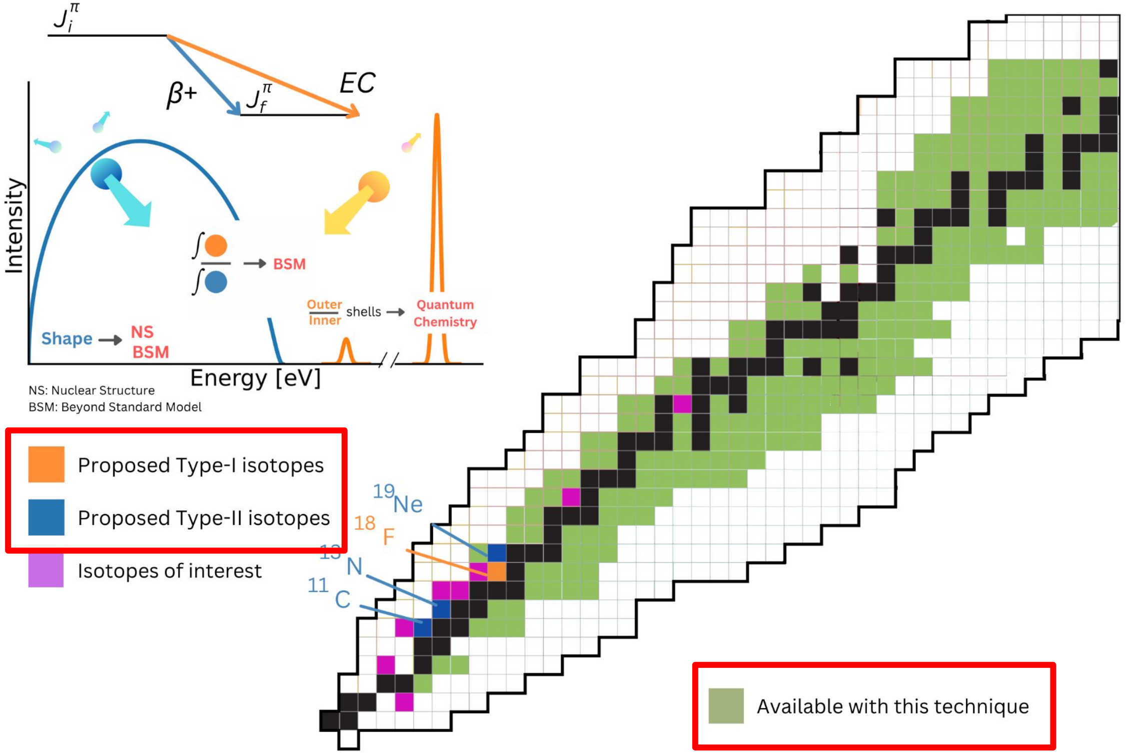
ASGARD: Reach

Complementary high-impact isotopes for BSM

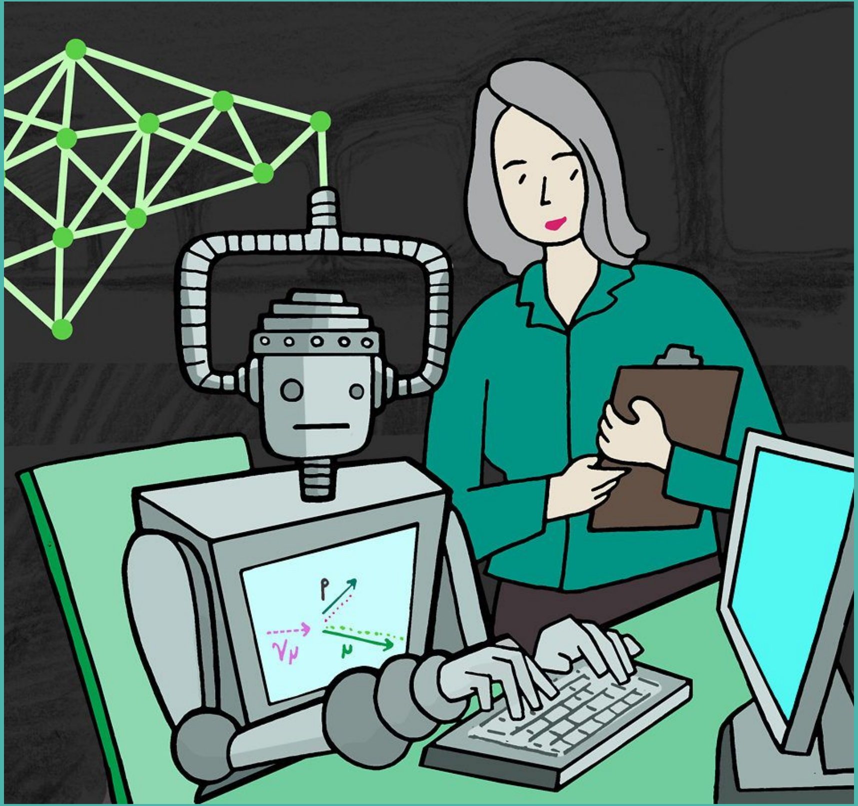
Unlock **hundreds of isotopes** for study

- Nuclear structure
- Auger spectroscopy

Completely unexplored variable



Detector Simulation



Simulation needs

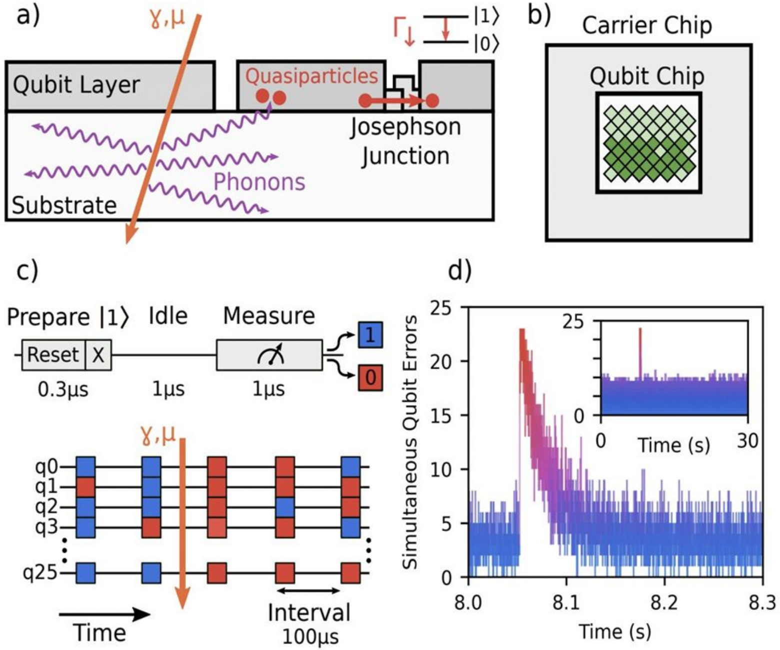
Completely different regime from usual ‘Geant4’ domain

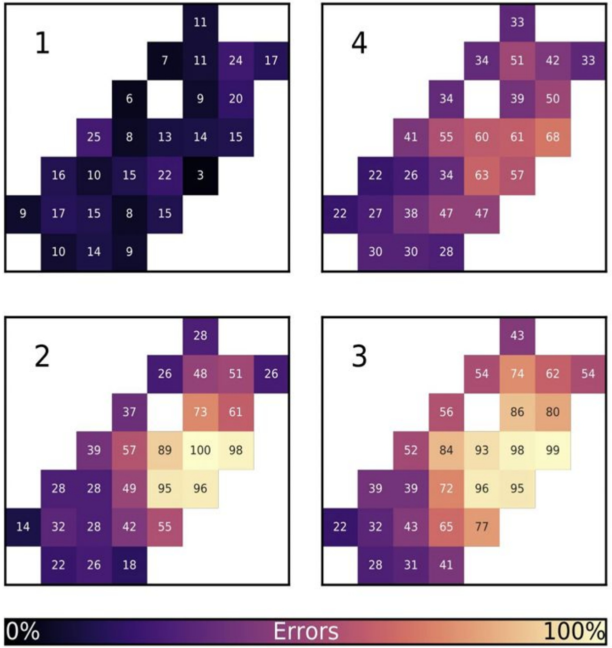
- phonon propagation
- quasiparticles
- superconducting materials
- …

why do people care?

Qubit degradation due to cosmic rays: Google saw it first

Nature Physics 18, 107-111





1

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		25	8	13	14	15	
	16	10	15	22	3		
9	17	15	8	15			
	10	14	9				

4

					33		
				34	51	42	33
			34		39	50	
		41	55	60	61	68	
	22	26	34	63	57		
22	27	38	47	47			
	30	30	28				

2

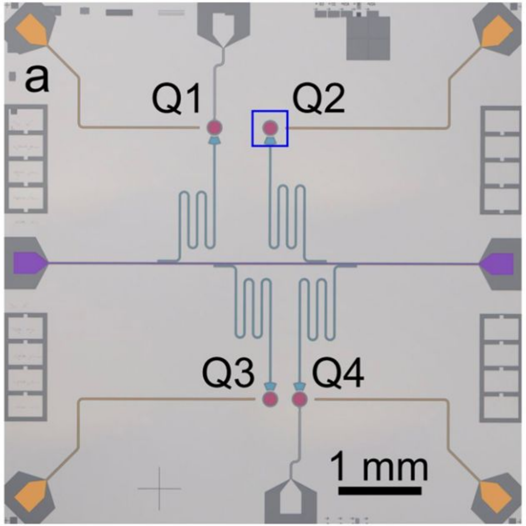
					28		
				26	48	51	26
			37		73	61	
		39	57	89	100	98	
	28	28	49	95	96		
14	32	28	42	55			
	22	26	18				

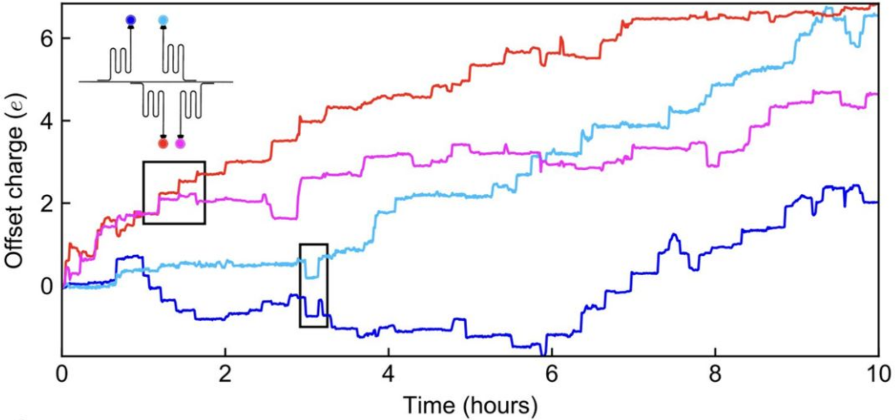
3

					43		
				54	74	62	54
			56		86	80	
		52	84	93	98	99	
	39	39	72	96	95		
22	32	43	65	77			
	28	31	41				

Qubit degradation due to cosmics

Nature 594, 369--373 (2021)

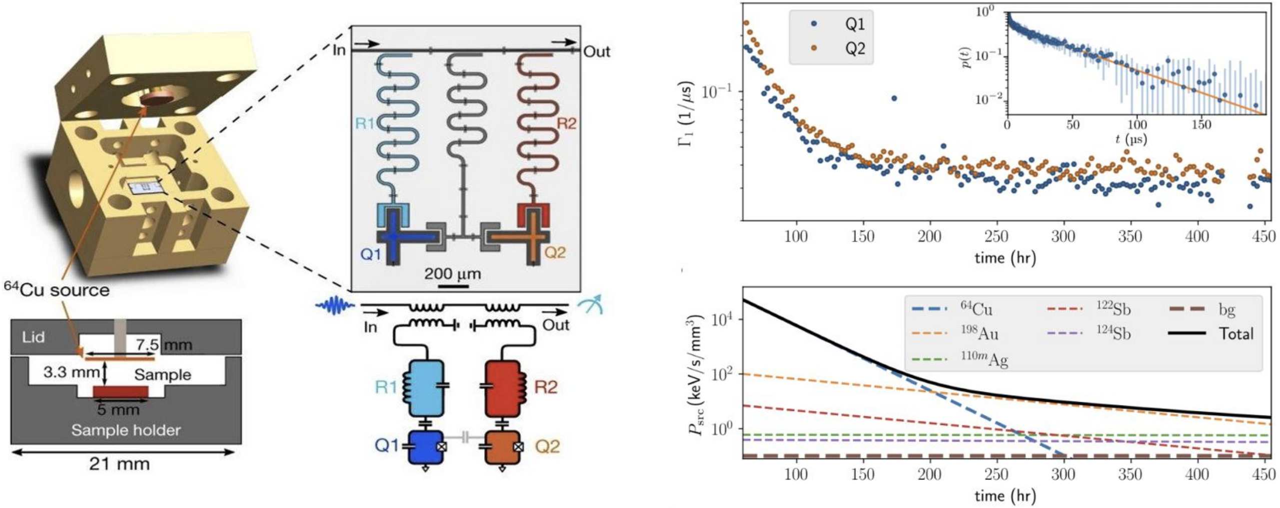




“Discrete charge jumps in qubits, induced by phonon-mediated quasiparticle poisoning associated with absorption of gamma rays and cosmic-ray muons in the qubit substrate”

Decoherence due to radioactivity

Nature 584, 551-556 (2020)



Measurements of decoherence relaxation rates ($1/T_1$) in the presence of a ^{64}Cu source. Strong evidence that quasiparticle poisoning due to radiation breaking Cooper pairs is a limiting factor in superconducting qubits for QIS.

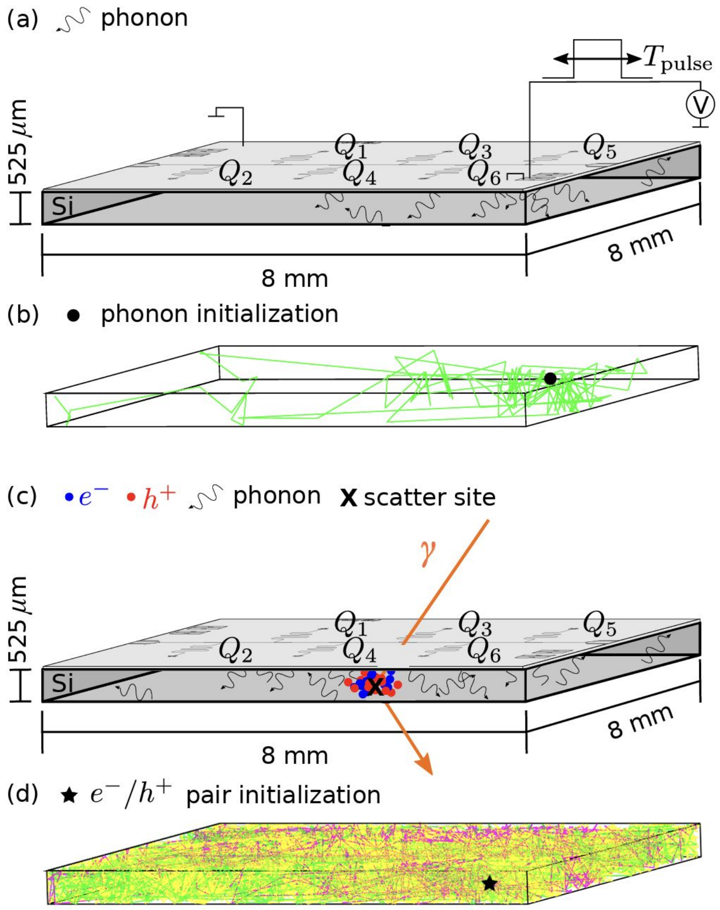
Monte Carlo simulation

SuperCDMS started Geant4 Condensed Matter Physics

G4CMP

Explicit phonon propagation

Successful agreement with TES-like data

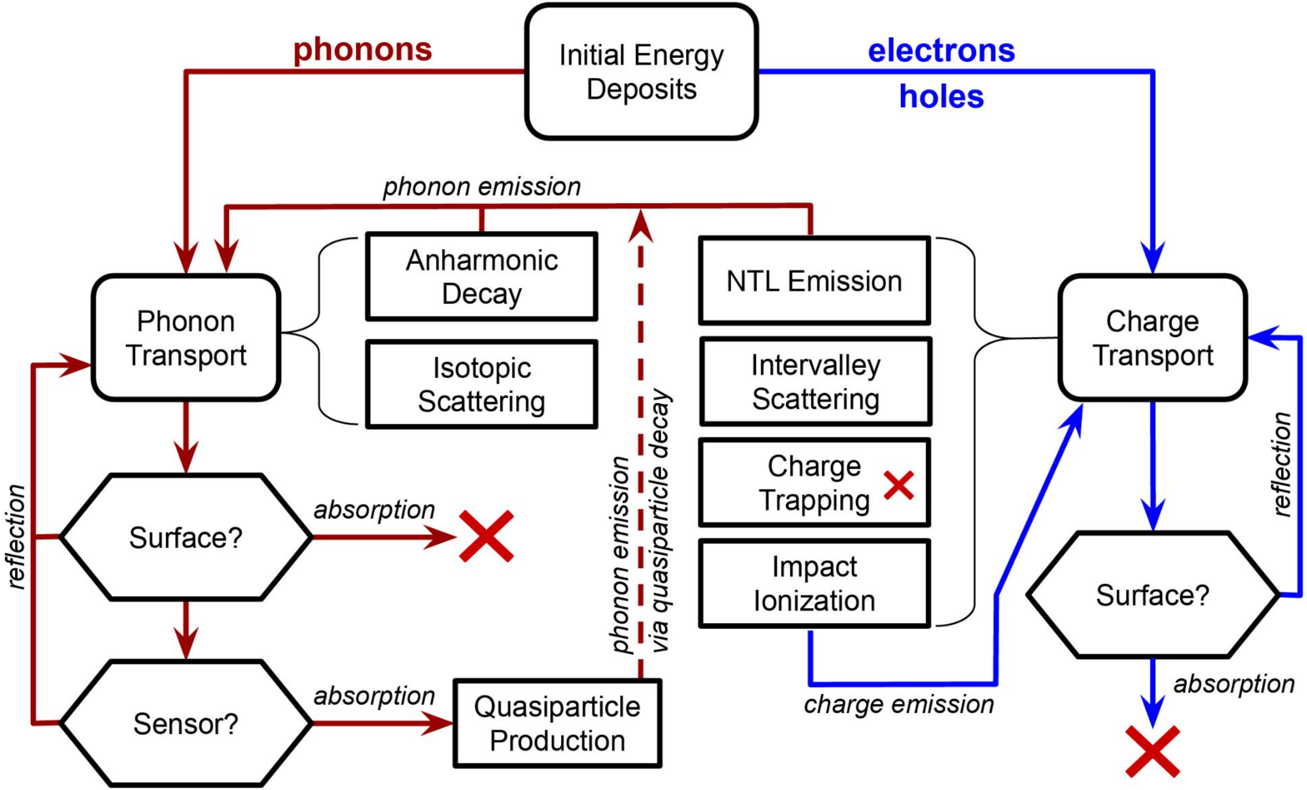


G4CMP

Crucial for new developments

Many improvements in progress

Dedicated community



Outlook

A race to the bottom.. in energy

Both ‘old’ tech with new applications and completely new tech

Orders of magnitude lower energy resolution opens new doors (dark matter, recoil, medical applications → **Poster Safa HELAL**)

Field **at the interface,** and material science gives a lot of knobs to tune

Next decade will be interesting..