# Solid-state devices for particle and radiation detection

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**IJCLab, Orsay**

*with*
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Pôle: Astroparticles, Astrophysics, Cosmology (A2C), Ingénierie

*Atelier « Technologies quantiques des deux infinis », CPPM Marseille*
*1 July, 2021*

# Outline

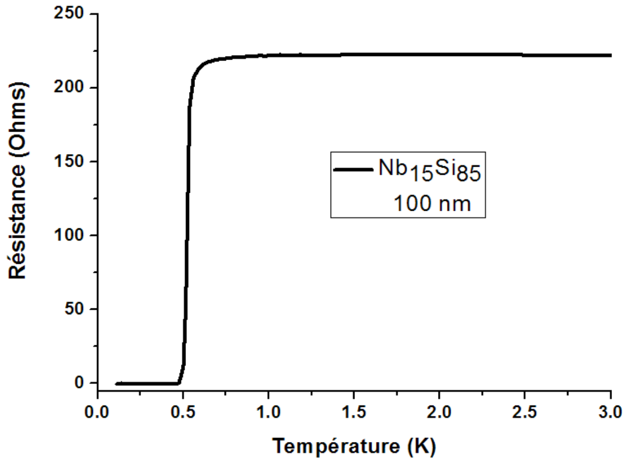
**Physics of superconductors**

**Application to detectors**

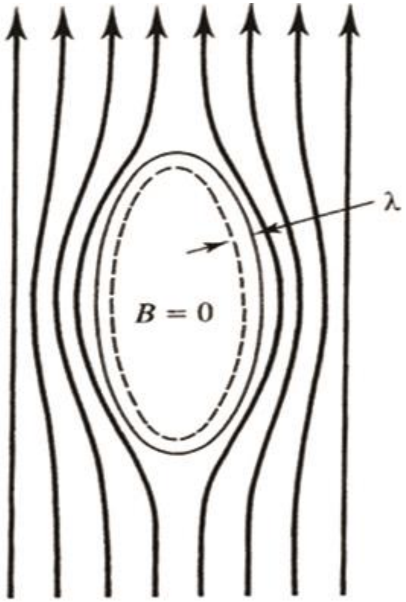
**Future prospects**

# Superconductivity

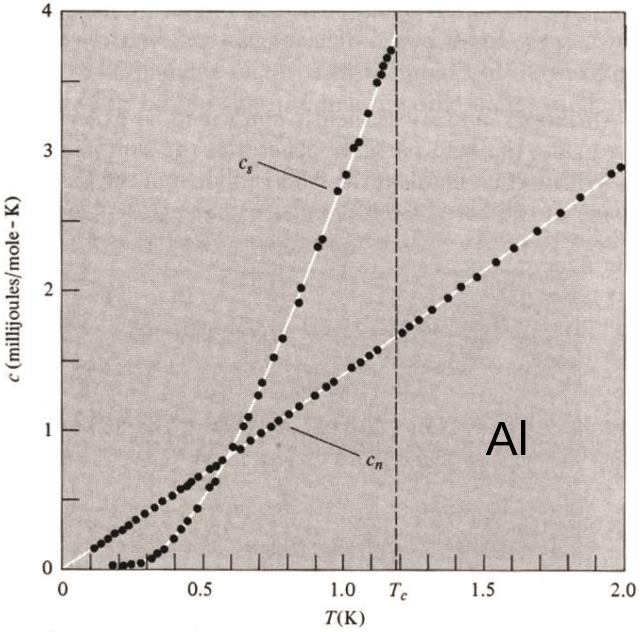
**Quantum phenomenon + Collective phenomenon**



1. Zero resistance for T<Tc



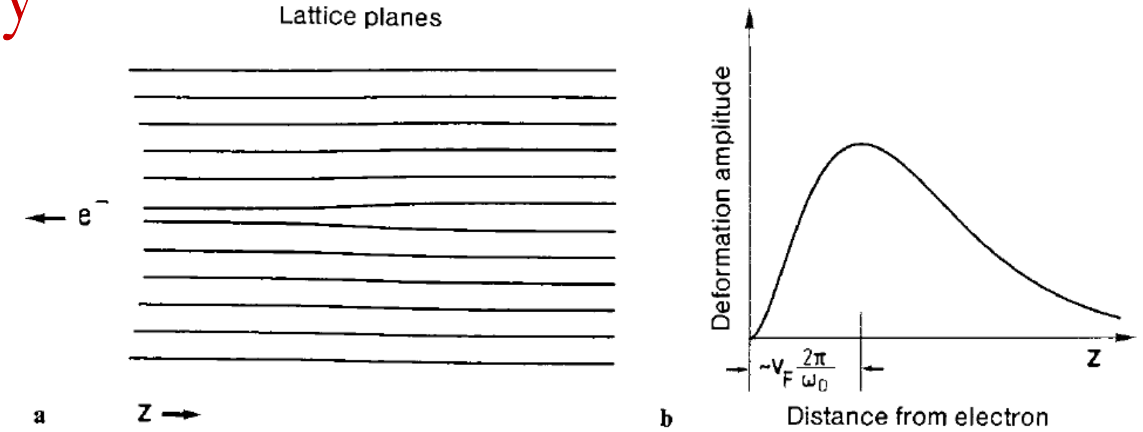
2. Exclusion of magnetic field

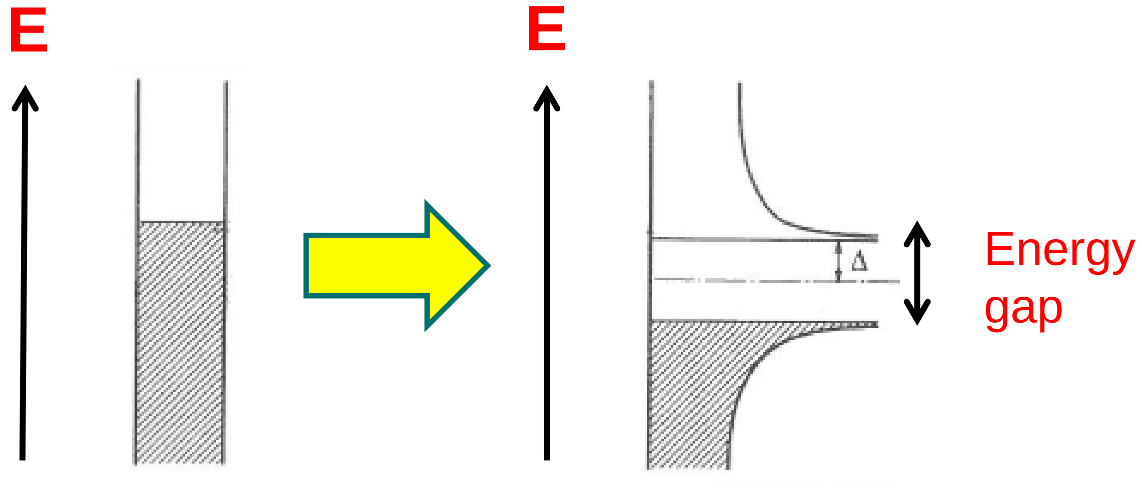


3. Strong decrease of specific heat

# Superconductivity

Microscopic pairing mechanism:
Cooper pairs





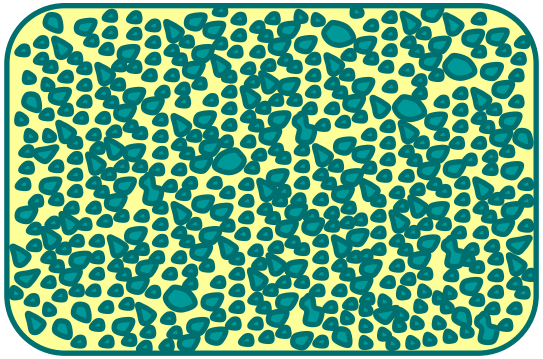
**Normal Metal** **Superconductor**

**Δ = strength of the superconductivity**

$$\Delta \propto k_B T_c$$

$$\xi = \frac{\hbar v_F}{k_B T_c}$$

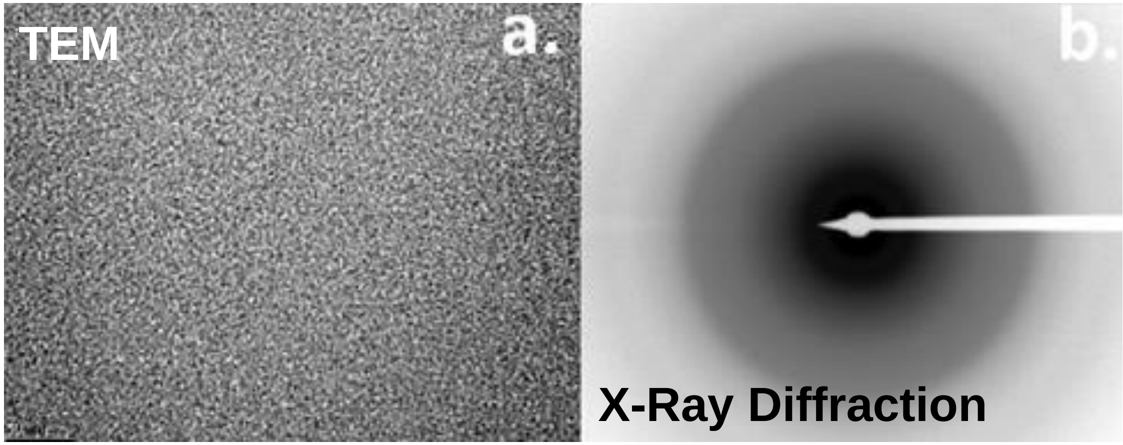
# Disordered materials



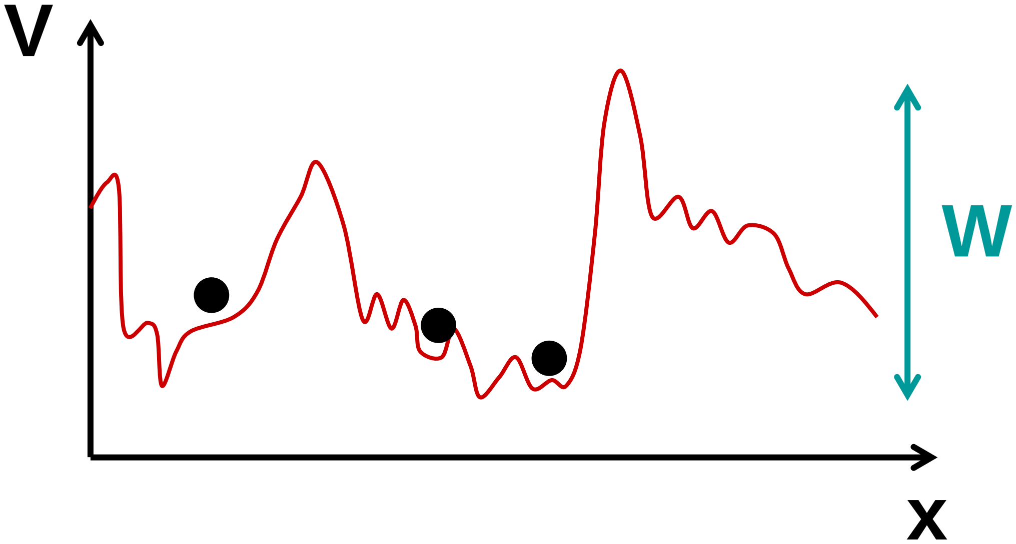
**Limit :**
**grain size = atomic scale**

**Amorphous**

**NbSi samples**



# Disordered materials



**Disorder potential (random)**

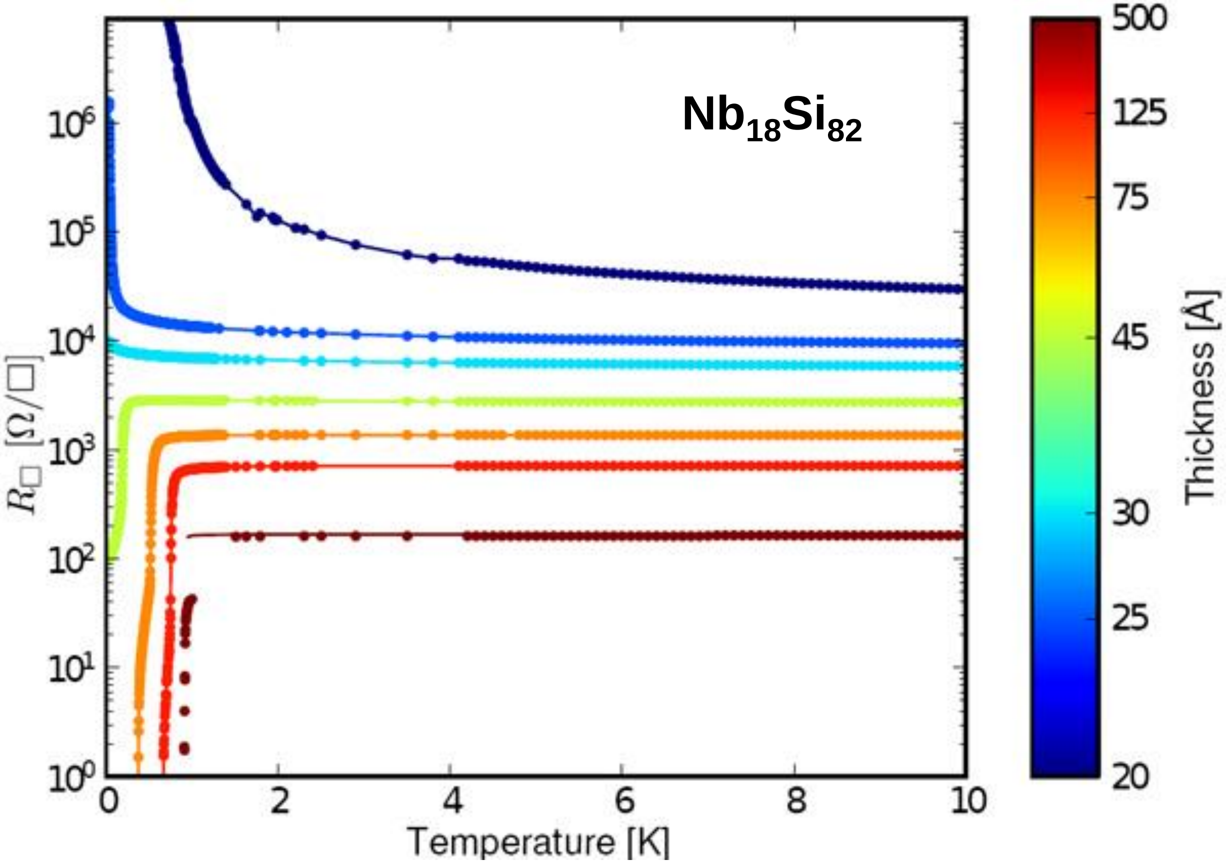
**Disorder enhances Coulomb interaction**

*The physics of superconducitivity in disordered materials deals with the interplay of electron localization effects, Coulomb interactions and Cooper pair formation.*

*Different types of novel electronic phenomena are expected, e.g. Cooper pair insulators, many-body-localization etc.*

**Ongoing project: ANR CP-Insulators**

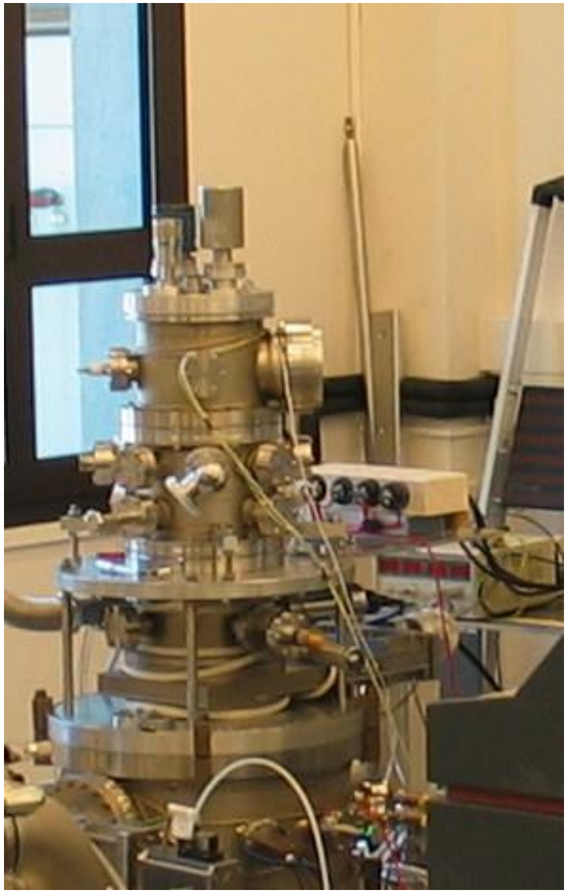
# Superconductors and insulators

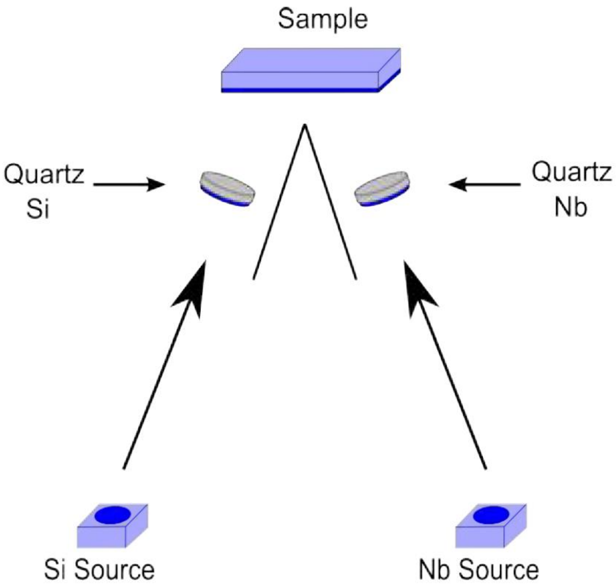


**Phase transitions between different ground states**

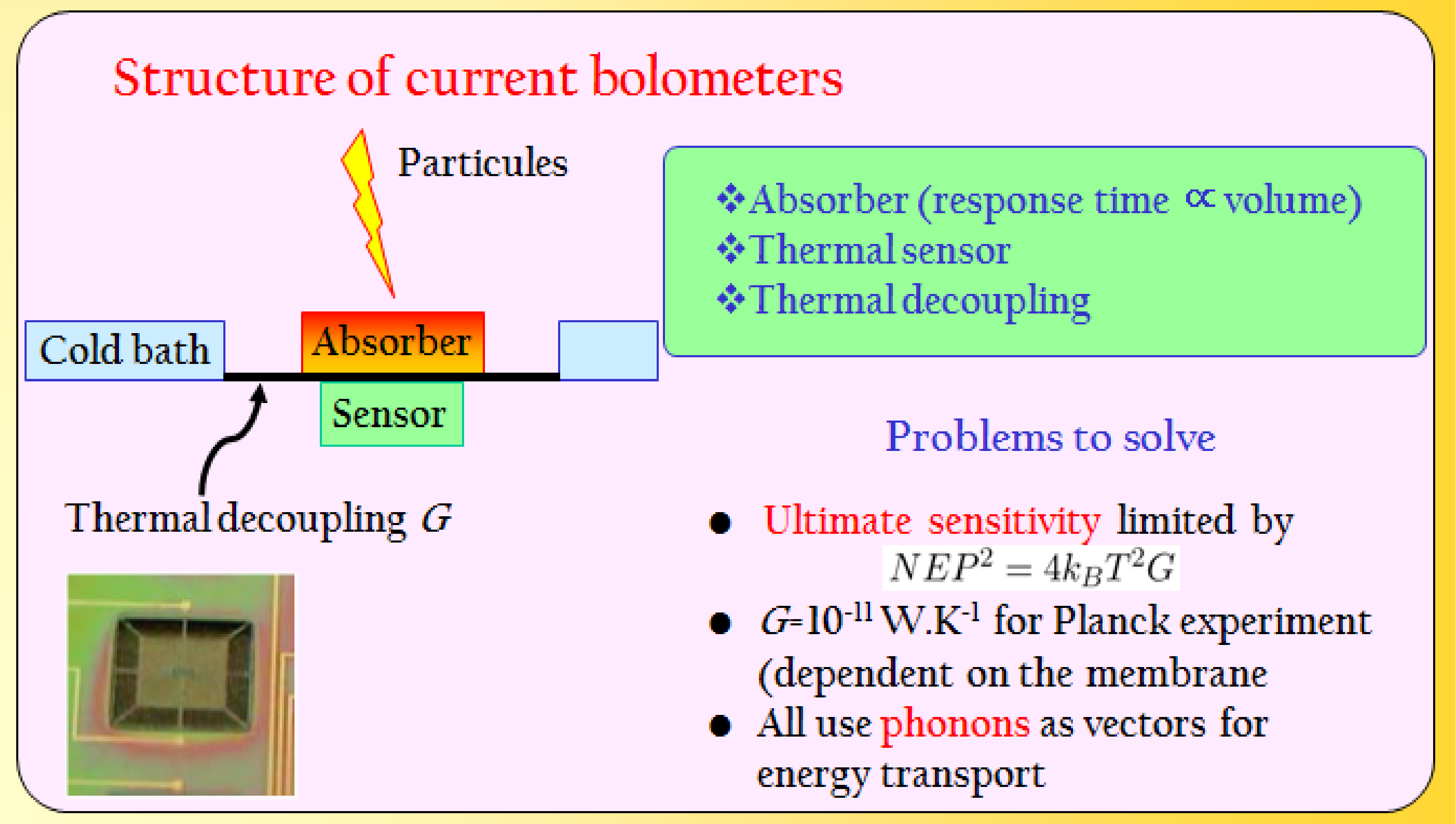
# NbSi thin films

## Synthesis





# NbSi applied to detectors



## Structure of current bolometers

Particules

Cold bath

Absorber

Sensor

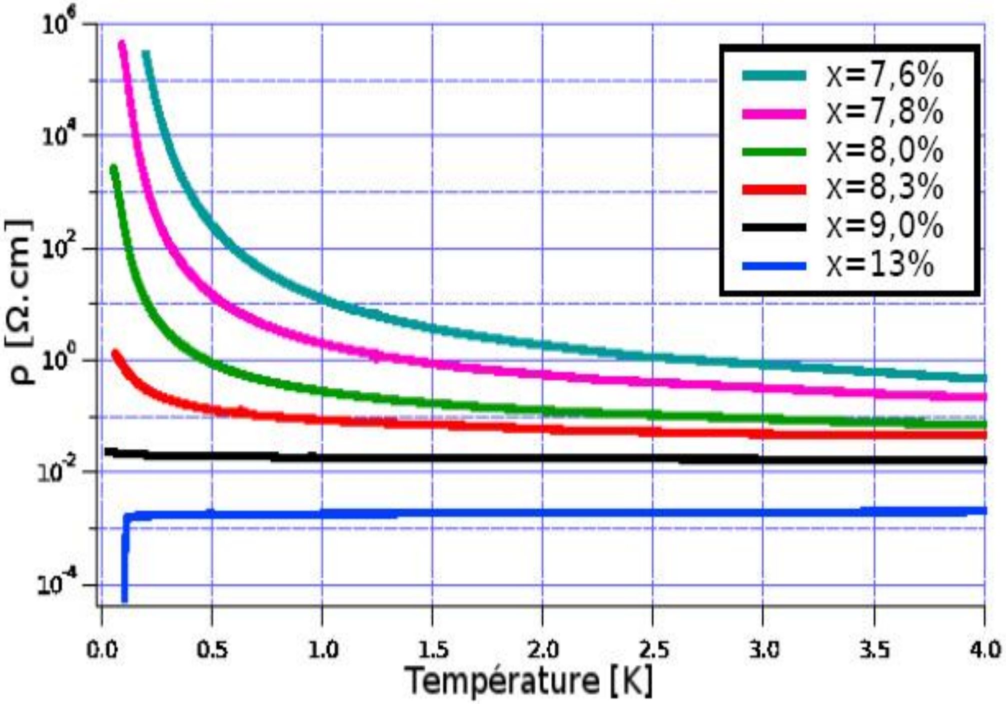
Thermal decoupling $G$

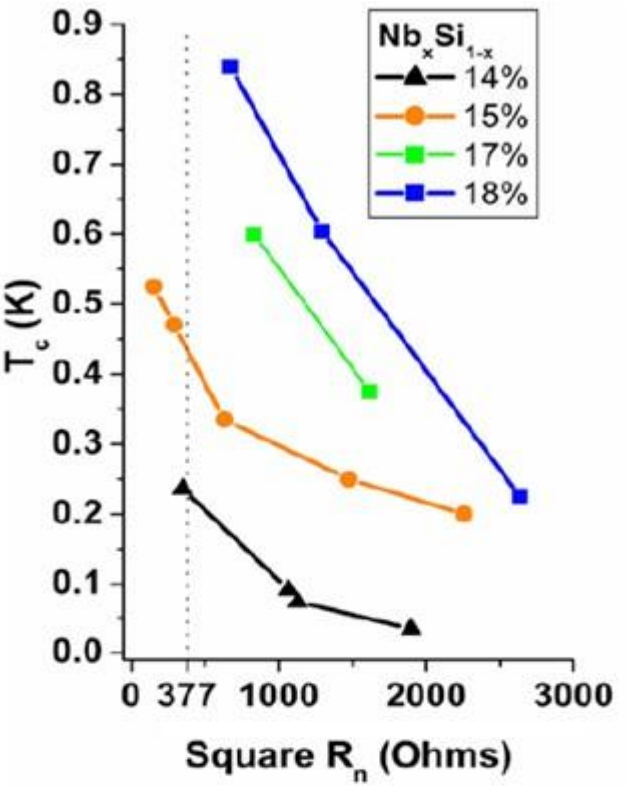
- Absorber (response time ∝ volume)
- Thermal sensor
- Thermal decoupling

### Problems to solve

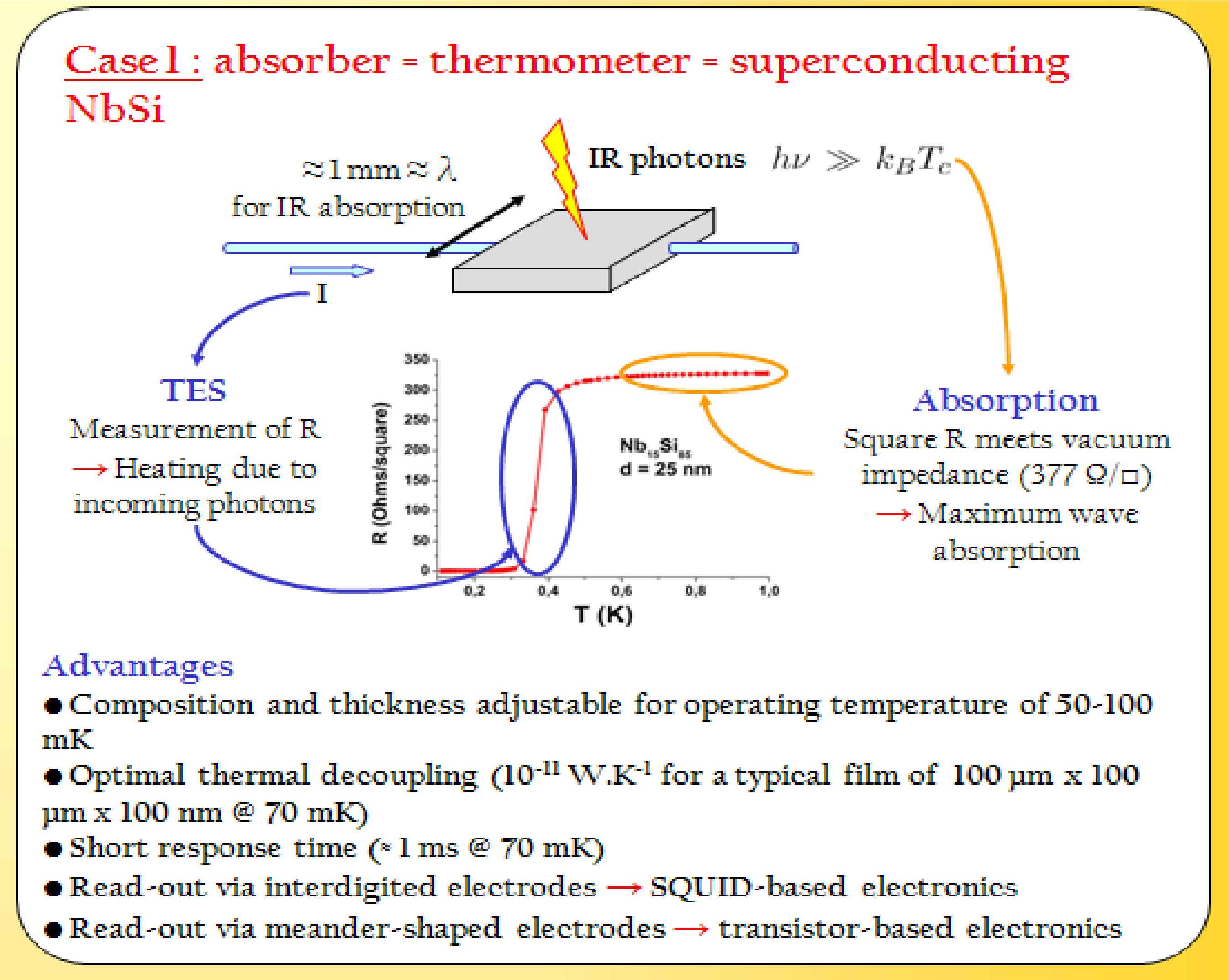
- Ultimate sensitivity limited by $NEP^2 = 4k_B T^2 G$
- $G$=$10^{-11}$ W.K$^{-1}$ for Planck experiment (dependent on the membrane
- All use phonons as vectors for energy transport

# SIT in NbSi applied to detectors





# SIT in NbSi applied to detectors



Case 1 : absorber = thermometer = superconducting NbSi

$\approx 1\,\text{mm} \approx \lambda$ for IR absorption

IR photons $h\nu \gg k_B T_c$

TES

Measurement of R

→ Heating due to incoming photons

Absorption

Square R meets vacuum impedance (377 Ω/□)

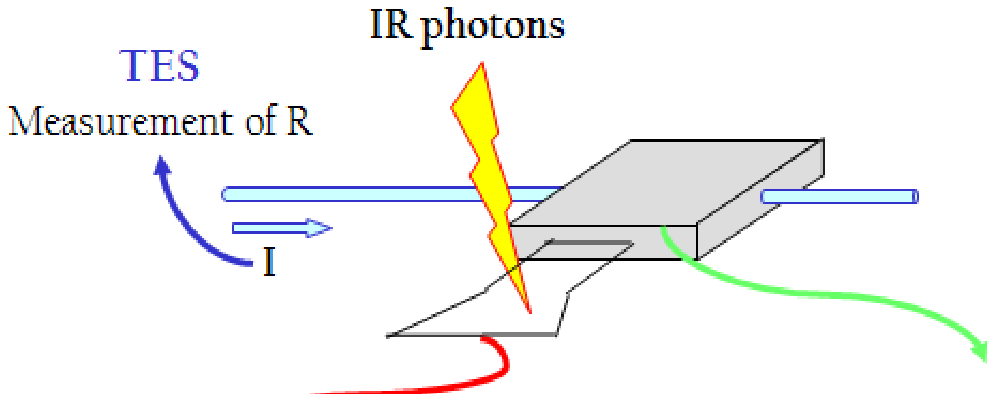
→ Maximum wave absorption

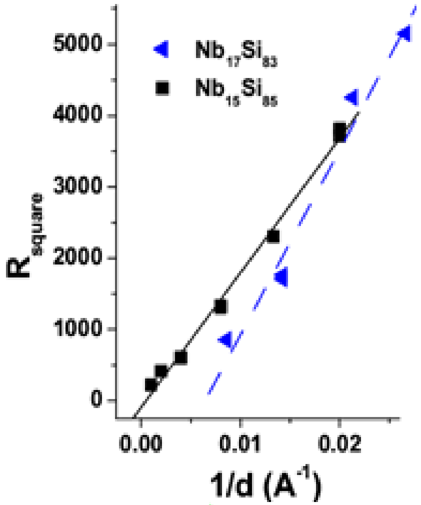
Advantages

- Composition and thickness adjustable for operating temperature of 50-100 mK
- Optimal thermal decoupling ($10^{-11}$ W.K$^{-1}$ for a typical film of 100 µm x 100 µm x 100 nm @ 70 mK)
- Short response time (≈ 1 ms @ 70 mK)
- Read-out via interdigited electrodes → SQUID-based electronics
- Read-out via meander-shaped electrodes → transistor-based electronics

# SIT in NbSi applied to detectors

## Case 2 : absorption through antennas ; thermometer = superconducting NbSi (TES)





**Antennas**

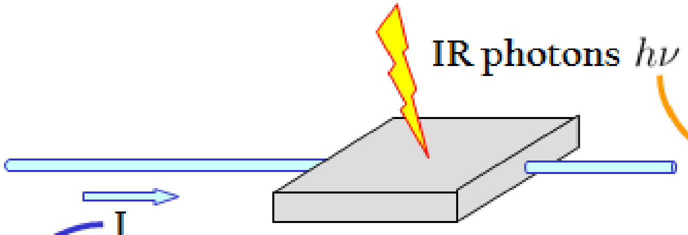
- High selectivity for the energy spectrum & polarization
- Good filling factor
- Smaller NbSi film → lower *G*

**NbSi film**

- Good matching impedance with antennas → transfer of the absorbed energy directly into TES' electrons via tunable normal R of the film

# SIT in NbSi applied to detectors

Case 3 : absorber = thermometer = Anderson insulating NbSi



Absorption

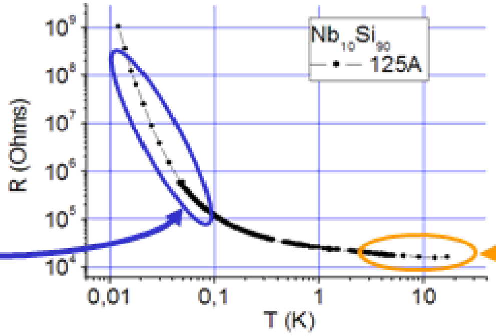
Temperature

- DC measurement of R

→ Heating due to incoming photons

- Suitable for JFET read-out

→ Square R may meet vacuum impedance (377 Ω/□) → Maximum wave absorption



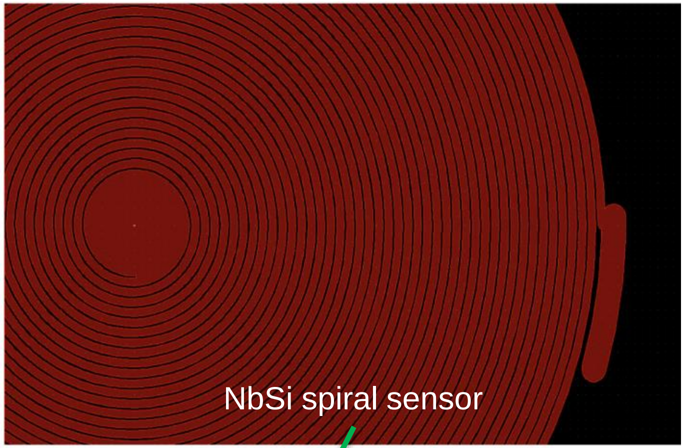
# SIT in NbSi applied to detectors

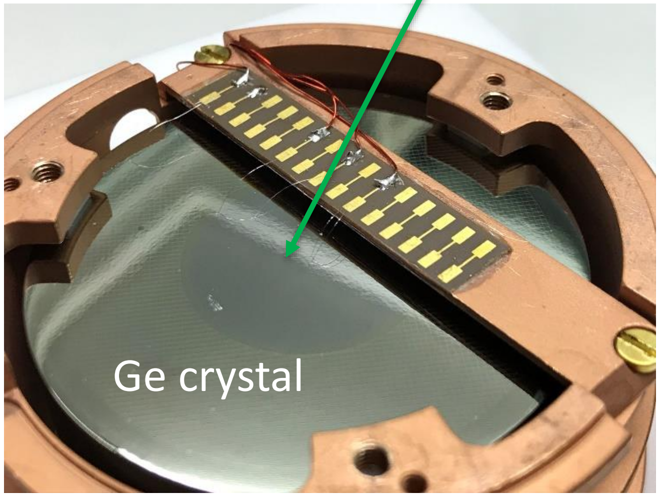
## Massive bolometers

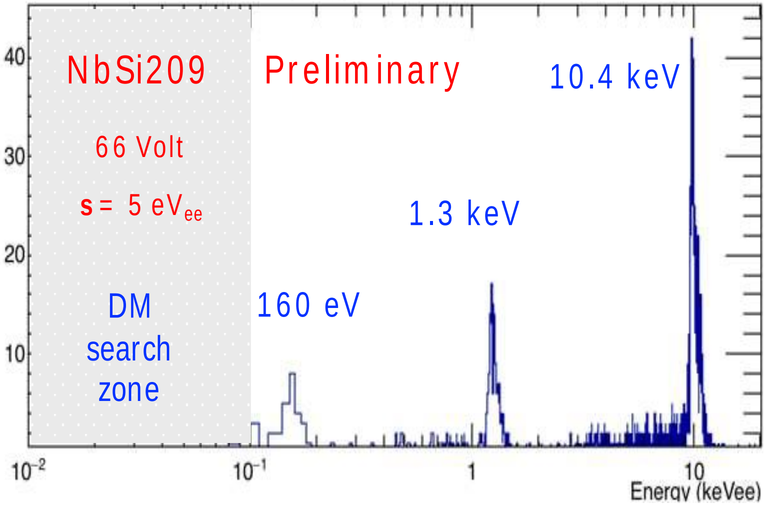
NbSi TES layers evaporated on massive crystals.

In the frame of the EDELWEISS project for dark matter research, 200 g Ge crystals combined to spiral-shaped TES were developed.

5 eV baseline resolution has been be demonstrated using “Neganov-Luke” amplification.



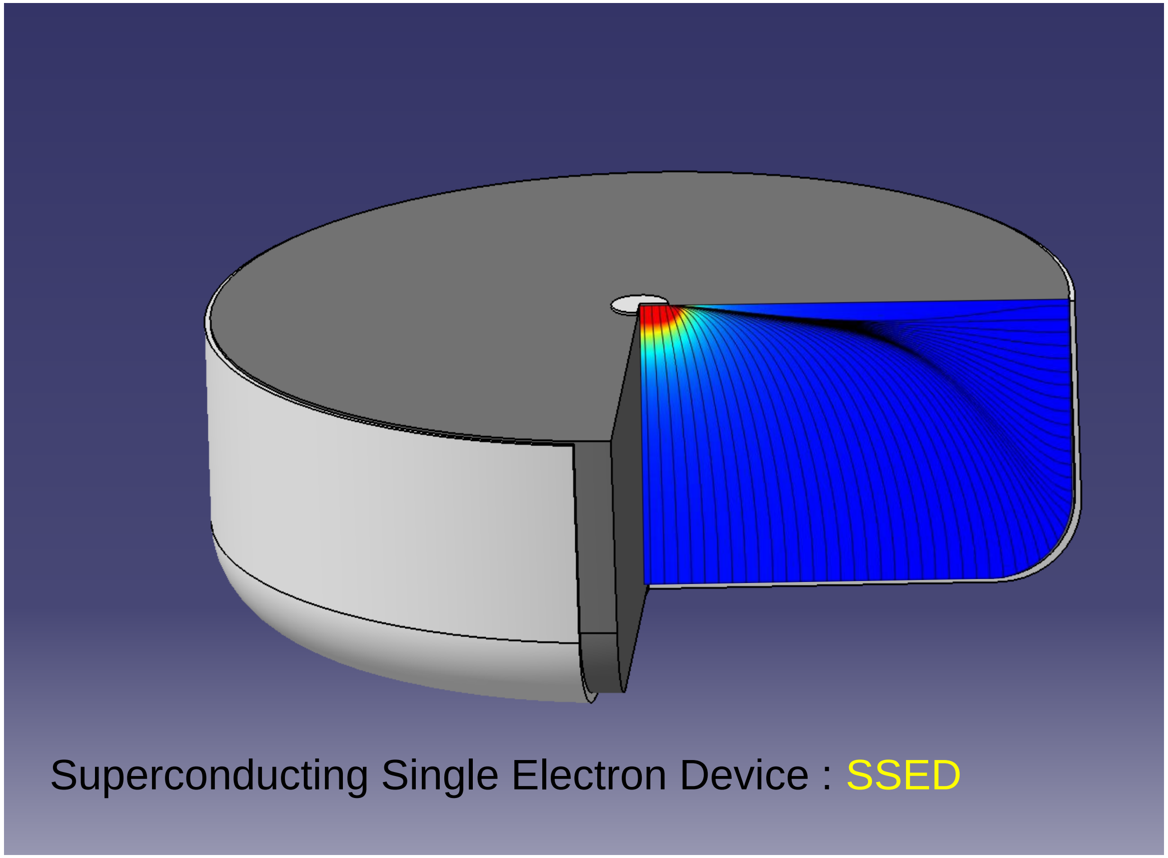




# Single-electron detection in Ge crystals

## Application to Astroparticle physics (dark matter, neutrino detection…)

Development of a detector using a sensor similar to SNSPD
Goal : Single-electron detection (instead of single-photon detection for SNSPD)


Superconducting Single Electron Device : SSED

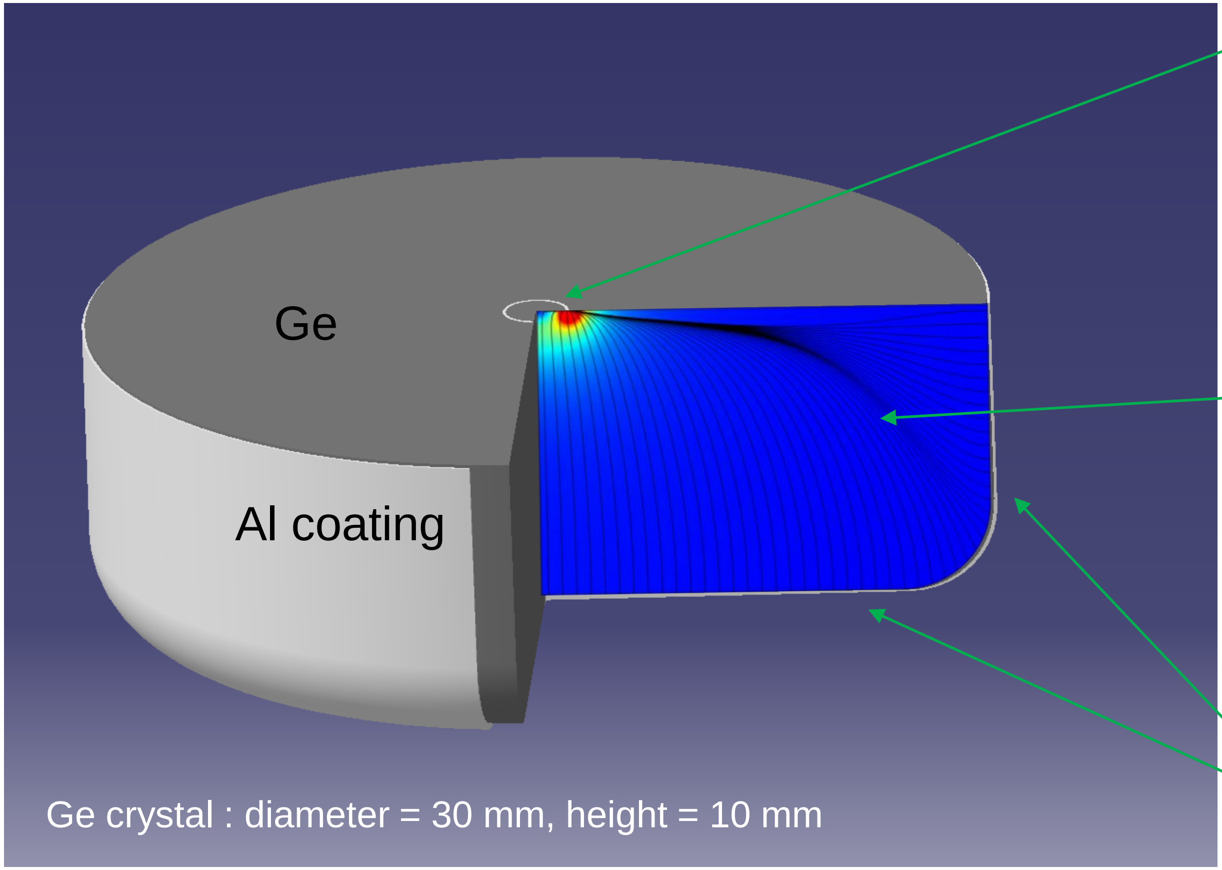
A particle or a photon interacting with a germanium target will create excited charges that can drift through the crystal

We collect and measure these charges with a “SSED” sensor

Single electron resolution on a massive Ge crystal has never been achieved worldwide.

# SSED detector design

An electric-field applied to the Ge crystal will bring the charges into the SSED



Ge crystal : diameter = 30 mm, height = 10 mm

SSED sensor & top biasing

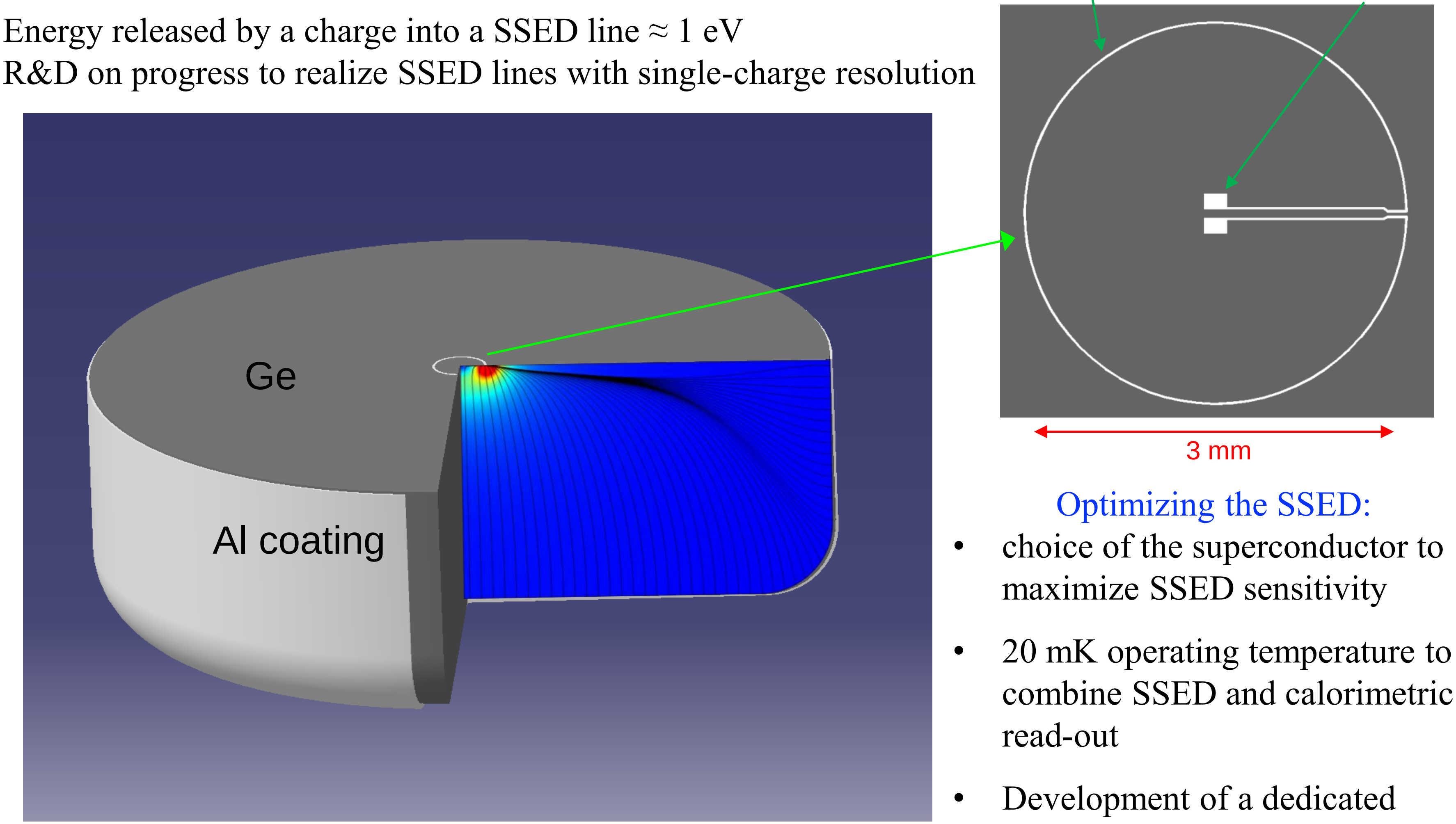
Electric-field lines into the Ge:

excited charges will drift along these lines and hit the SSED

Bottom & side biasing Al electrode

# SSED detector R&D

Energy released by a charge into a SSED line ≈ 1 eV
R&D on progress to realize SSED lines with single-charge resolution



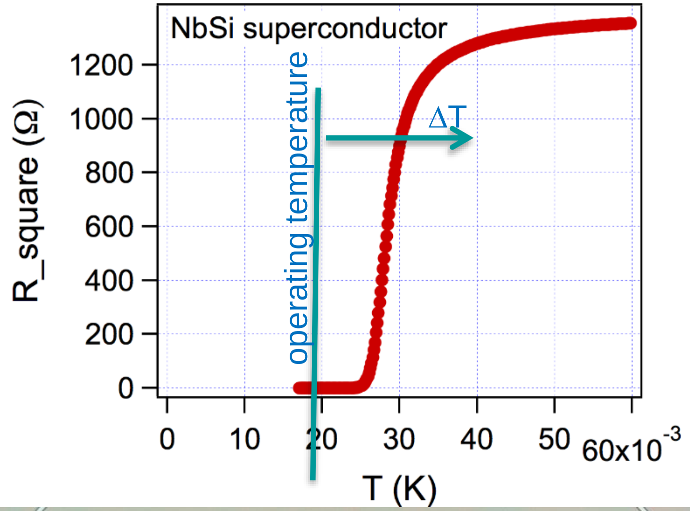
Optimizing the SSED:

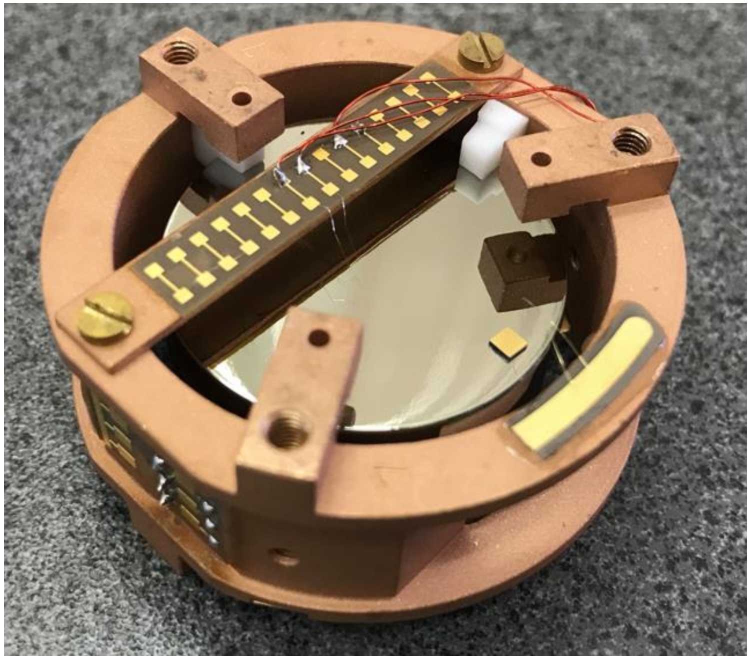
- choice of the superconductor to maximize SSED sensitivity
- 20 mK operating temperature to combine SSED and calorimetric read-out
- Development of a dedicated read-out using HEMT transistors

# SSED detector R&D

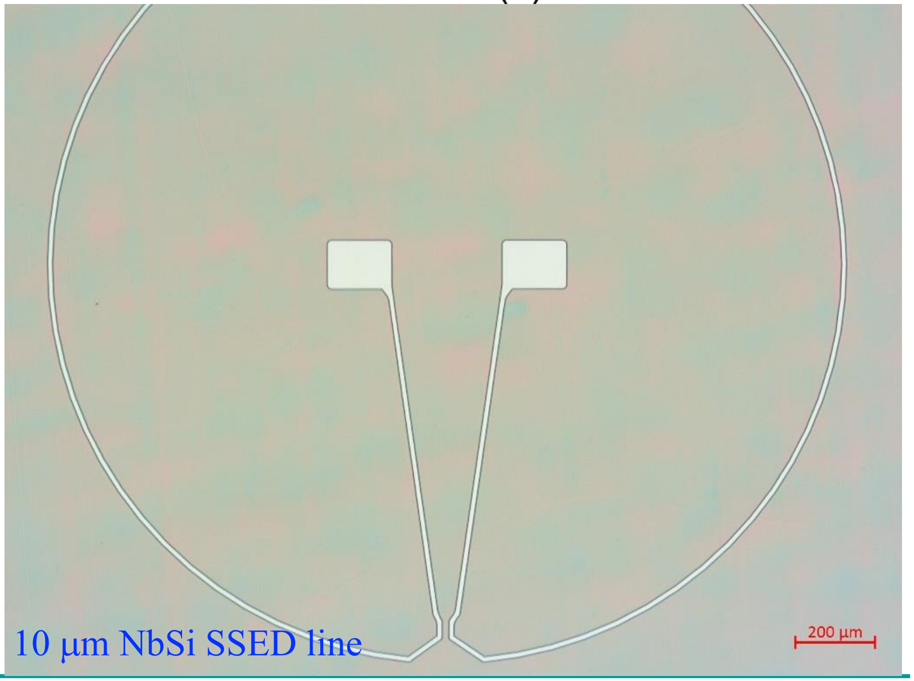
First prototypes realized recently
using NbSi superconducting SSED

10 x 10 μm$^2$ NbSi resistivity





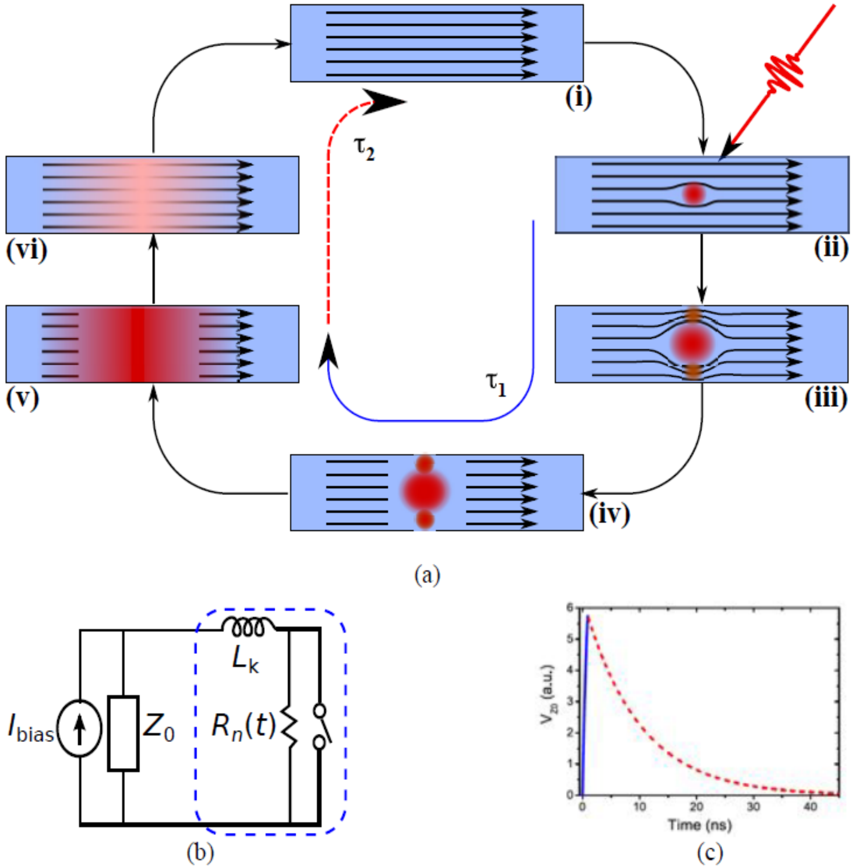
Emerging R&D…
… preliminary results expected in
the coming months



10 µm NbSi SSED line

# Superconducting nanowires

## Superconducting nanowire single photon detector (SNSPD)

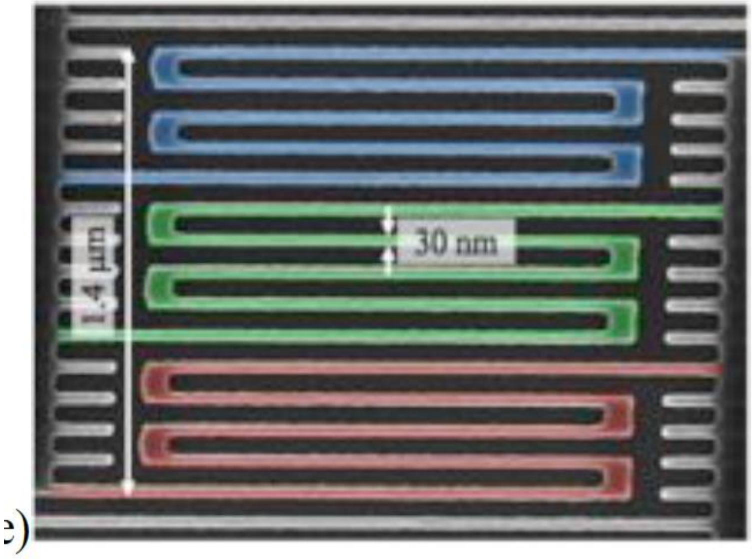


(a)

(b)

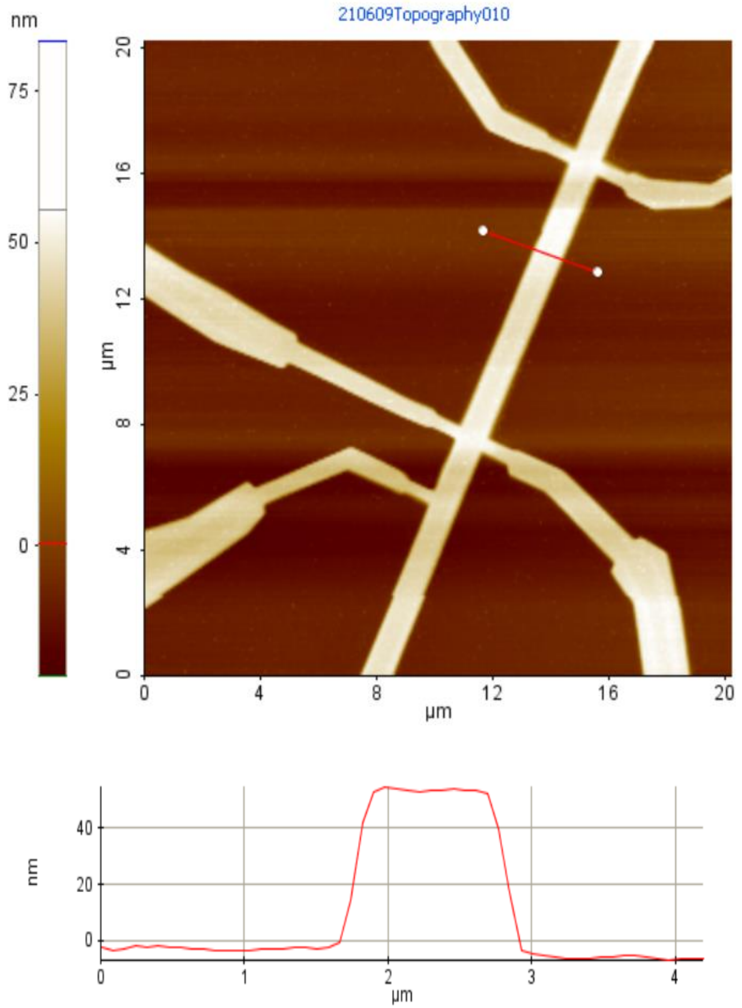
(c)

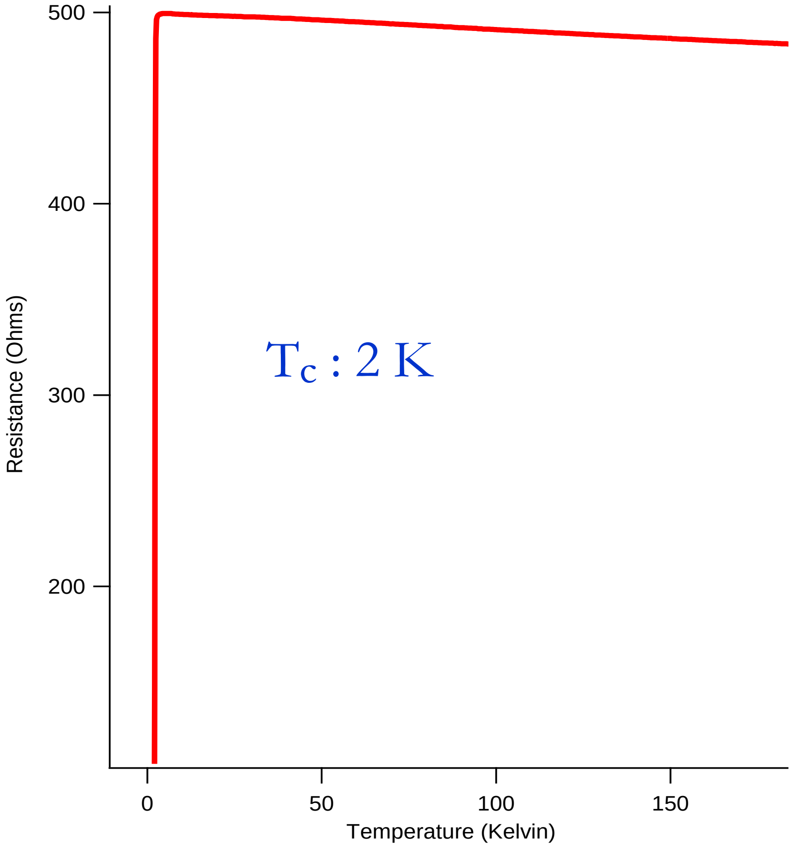
Natarajan et al., Supercond.Sci.Technol. 25 (2012)



Marsili et al., Nano Lett. 11 (2011)

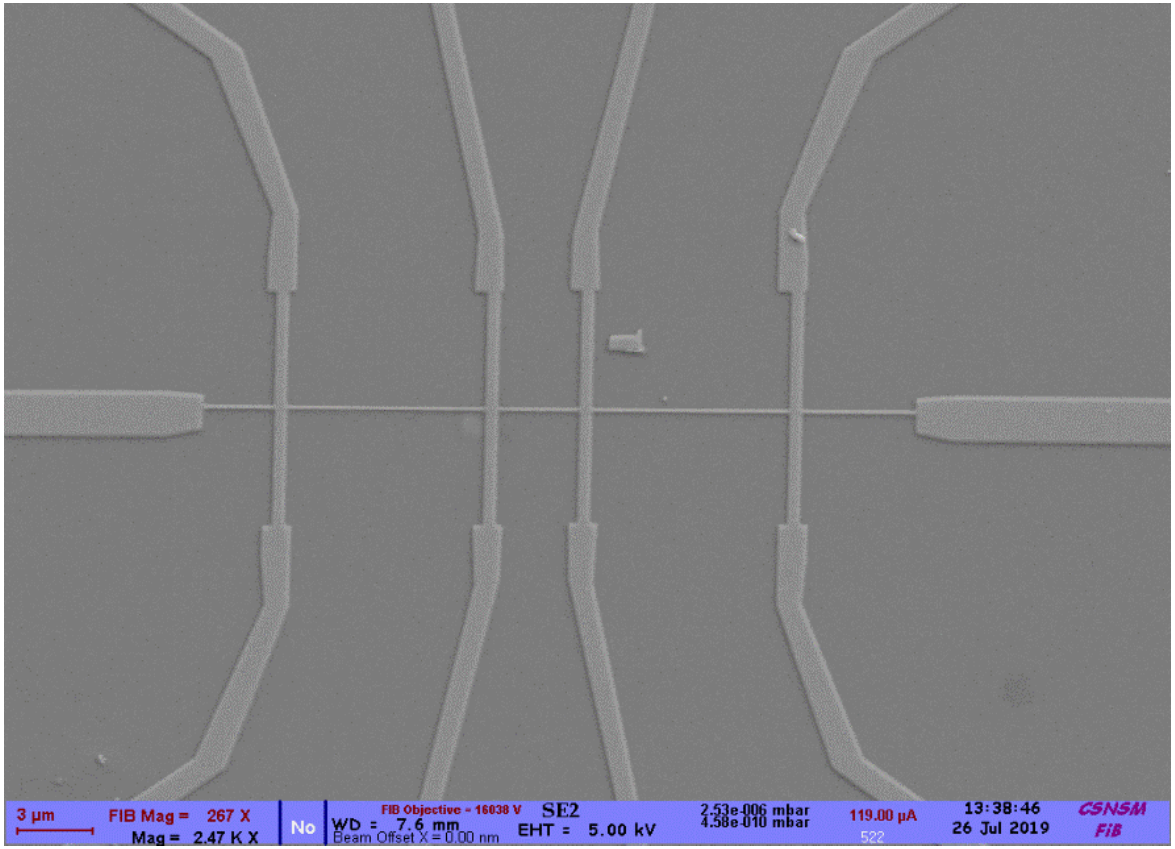
# Superconducting nanowires





$T_c$ : 2 K

# Superconducting nanowires



Nanowire with a 200 nm wide channel

# Proposals for dark matter detetction

Dark matter of MeV to GeV mass with graphene:
Sensitivity is perhaps comparable to Si and Ge targets
*Hochberg et al., Physics Letters B 772 (2017)*

Directional detection of dark matter particles in Mev rane with an array of parallel carbon nanotubes
*Cavoto et al., Physics Letters B 776 (2018)*

For sub-Mev range, superconductors can outperform electron ionization techniques.
*Hochberg et al., Phys. Rev. Lett. 116, 011301 (2016)*

# Dark matter detectors using superconductors

PHYSICAL REVIEW LETTERS **123,** 151802 (2019)

## Detecting Sub-GeV Dark Matter with Superconducting Nanowires

Yonit Hochberg,[1,*] Ilya Charaev,[2,†] Sae-Woo Nam,[3,‡] Varun Verma,[3,§] Marco Colangelo,[2,‖] and Karl K. Berggren[2,¶]
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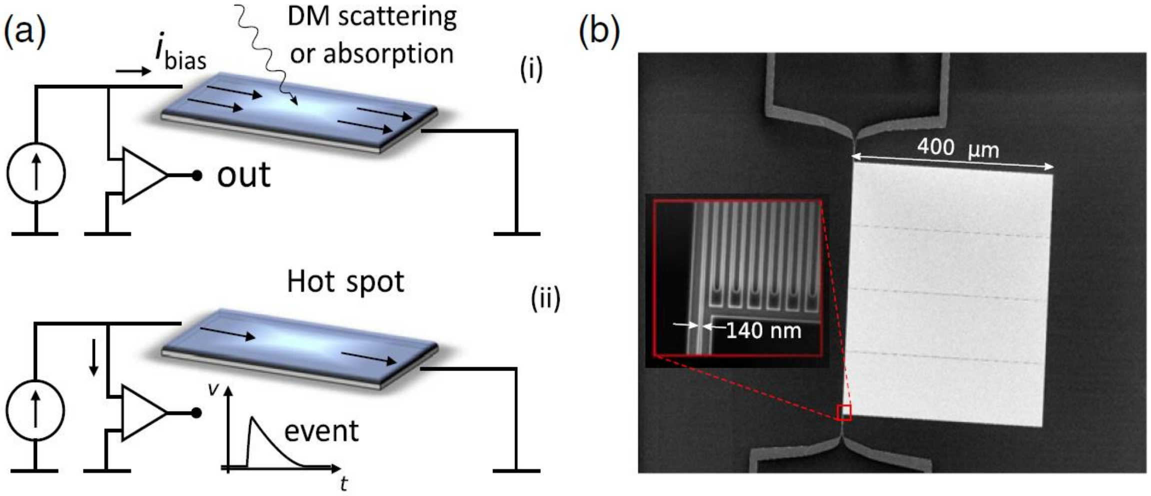
[2]*Department of Electrical Engineering and Computer Science, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA*
[3]*National Institute of Standards and Technology, Boulder, Colorado 80309, USA*



WSi superconductor nanowire

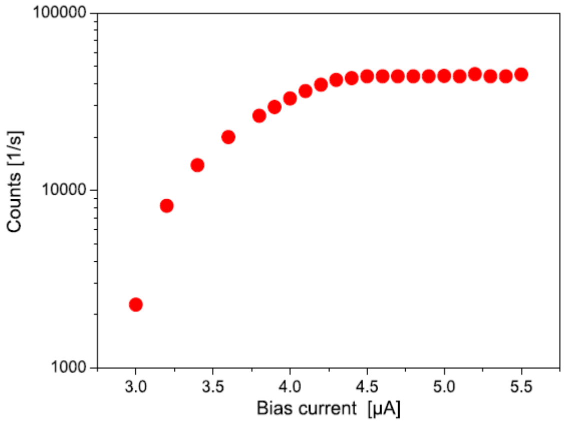
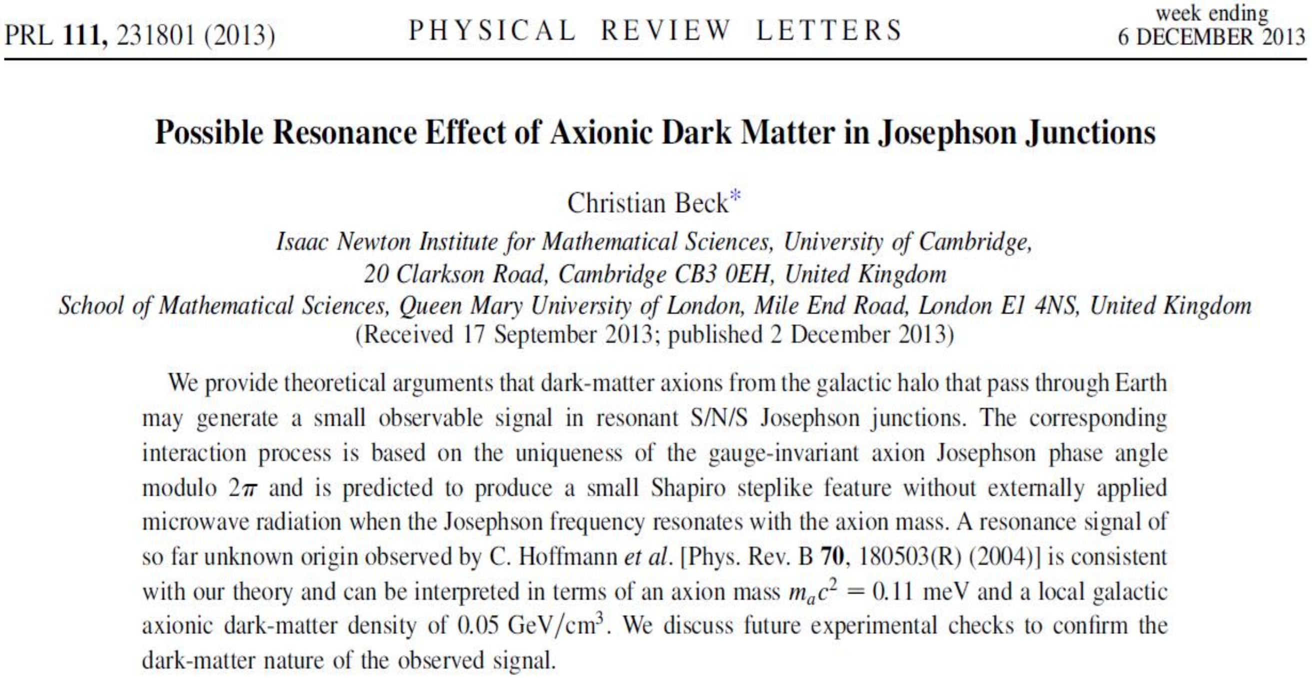


FIG. 2. The photon counts as a function of the absolute bias current, exhibited by the prototype WSi device tested in a fiber-coupled package at 300 mK.

1550 nm wavelength, ~0.8 eV

# Josephson junctions



PRL **111,** 231801 (2013) PHYSICAL REVIEW LETTERS week ending 6 DECEMBER 2013

## Possible Resonance Effect of Axionic Dark Matter in Josephson Junctions

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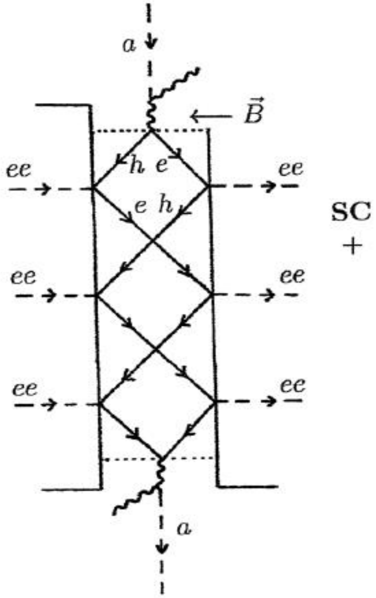
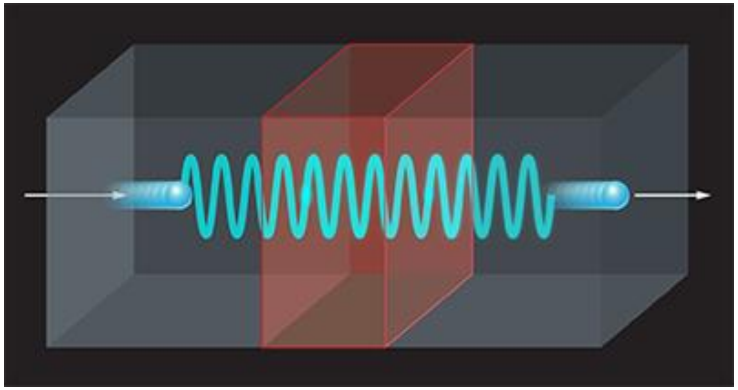
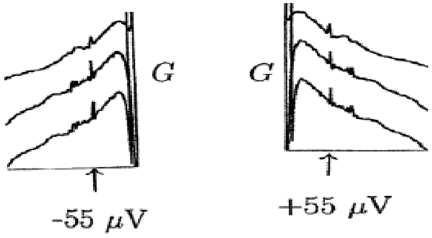
(Received 17 September 2013; published 2 December 2013)

We provide theoretical arguments that dark-matter axions from the galactic halo that pass through Earth may generate a small observable signal in resonant S/N/S Josephson junctions. The corresponding interaction process is based on the uniqueness of the gauge-invariant axion Josephson phase angle modulo $2\pi$ and is predicted to produce a small Shapiro steplike feature without externally applied microwave radiation when the Josephson frequency resonates with the axion mass. A resonance signal of so far unknown origin observed by C. Hoffmann *et al*. [Phys. Rev. B **70**, 180503(R) (2004)] is consistent with our theory and can be interpreted in terms of an axion mass $m_a c^2 = 0.11$ meV and a local galactic axionic dark-matter density of 0.05 GeV/cm$^3$. We discuss future experimental checks to confirm the dark-matter nature of the observed signal.





Axions can transform into photons
In the barrier and re-emerge as
axions.



# Conclusion

Superconductors have various applications in detection of matter and radiation.

The main questions are:
***Which materials are interesting? What geometry of device is appropriate for a given application? What are the energy scales required?***