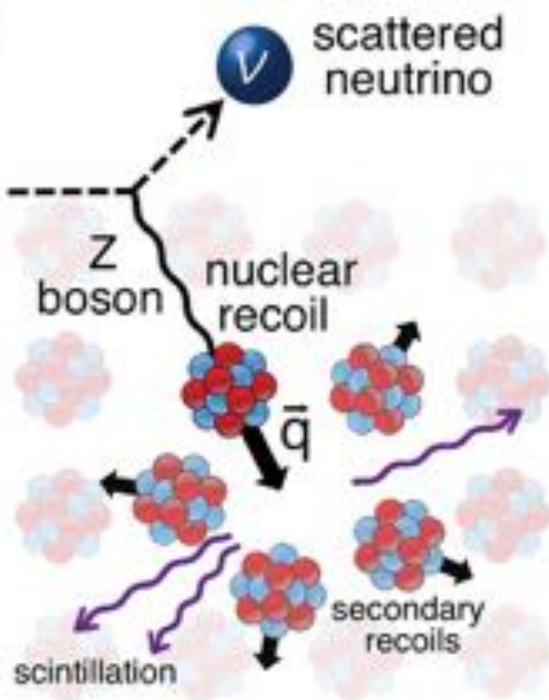
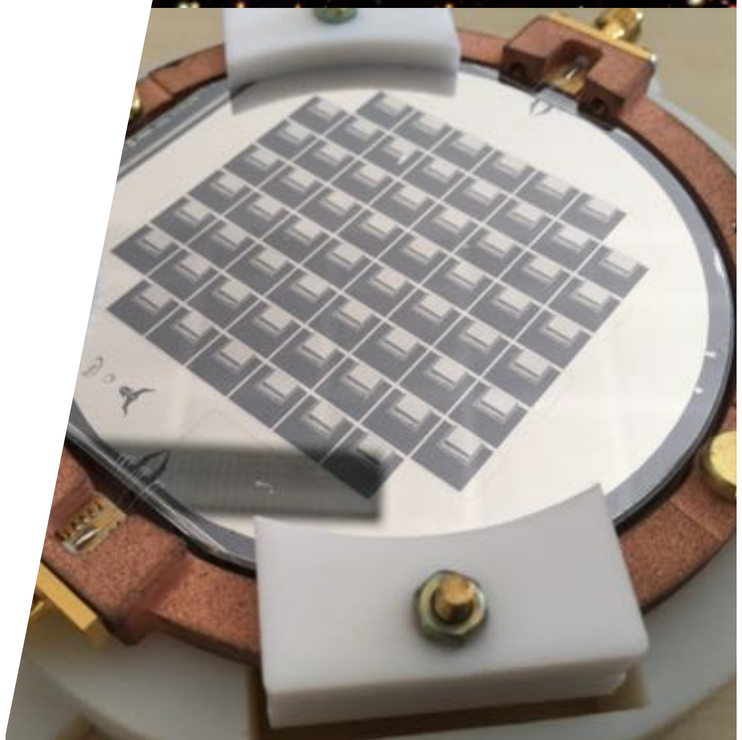
SAPIENZA
UNIVERSITÀ DI ROMA

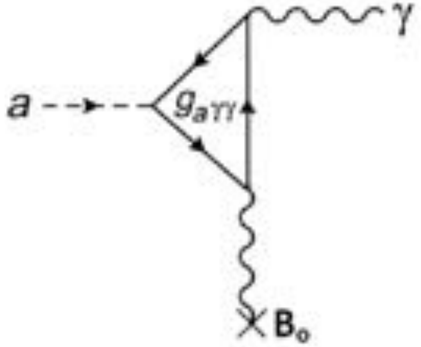
INFN
Istituto Nazionale di Fisica Nucleare

Kinetic inductance detectors for Low-mass Dark Matter Low-energy neutrinos

Marco Vignati - 23 July 2022
Snowmass

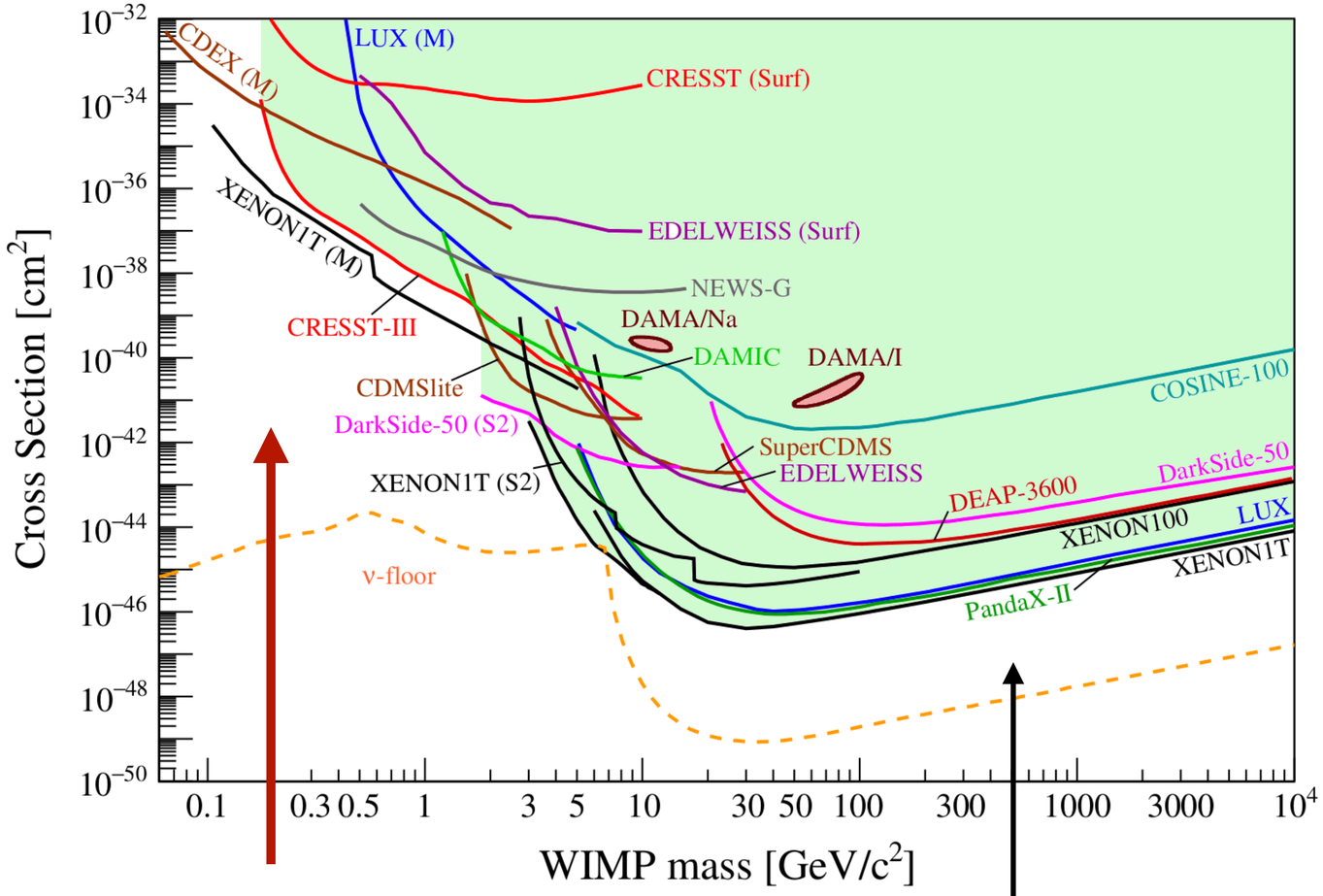


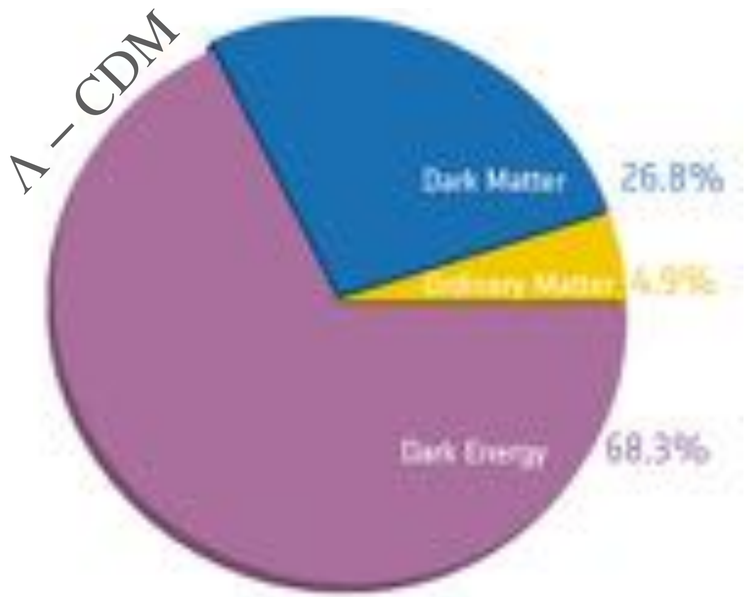




Dark Matter - direct search

J. Billard, et al, Direct Detection of Dark Matter – APPEC Committee Report, arXiv:2104.07634





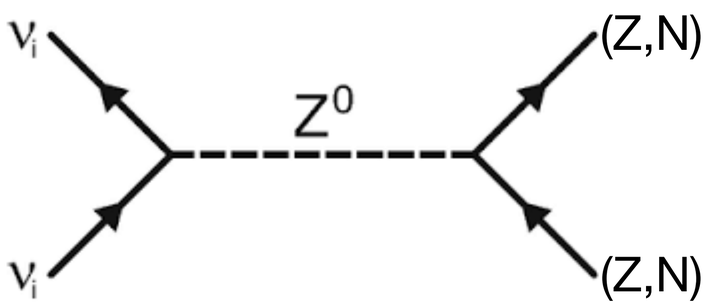
What is the Dark Matter made of?

- primordial black holes?
- μeV/c² - eV/c² axion-like waves?
- MeV/c² - TeV/c² WIMP-like particles?

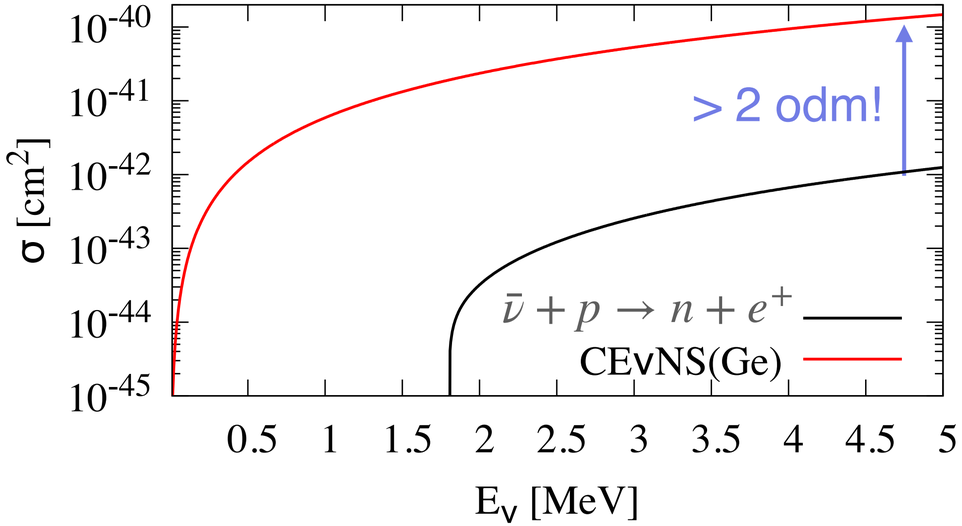
kg-scale solid-state phonon detectors (this talk)

Multi-ton liquid scintillators

Coherent elastic neutrino-nucleus scattering (CEνNS)



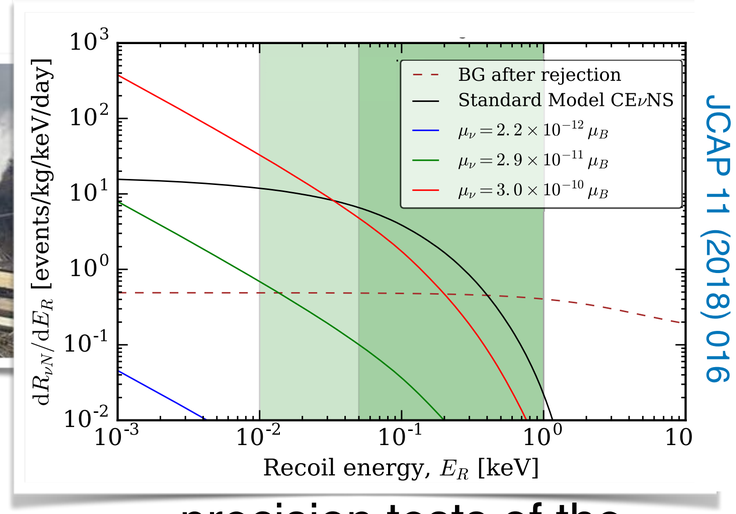
$$\sigma_{\mathrm{CE}\nu\mathrm{NS}} \simeq \frac{G_F^2}{4\pi} E_\nu^2 N^2$$



Predicted in 1977, first observed in 2017

COHERENT Coll., Science 357 (2017) 1123)

reactor and nuclear waste monitoring



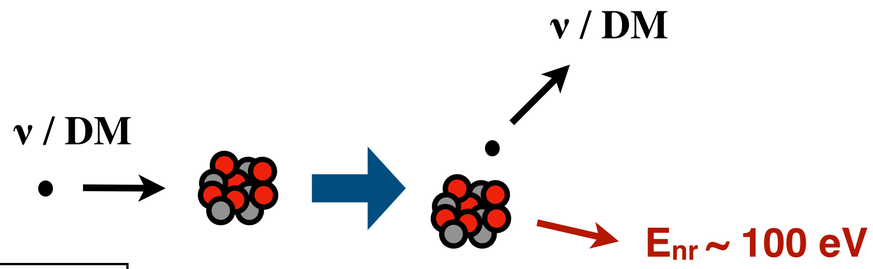
Billard, Johnston and Kannavagh, JCAP 11 (2018) 016

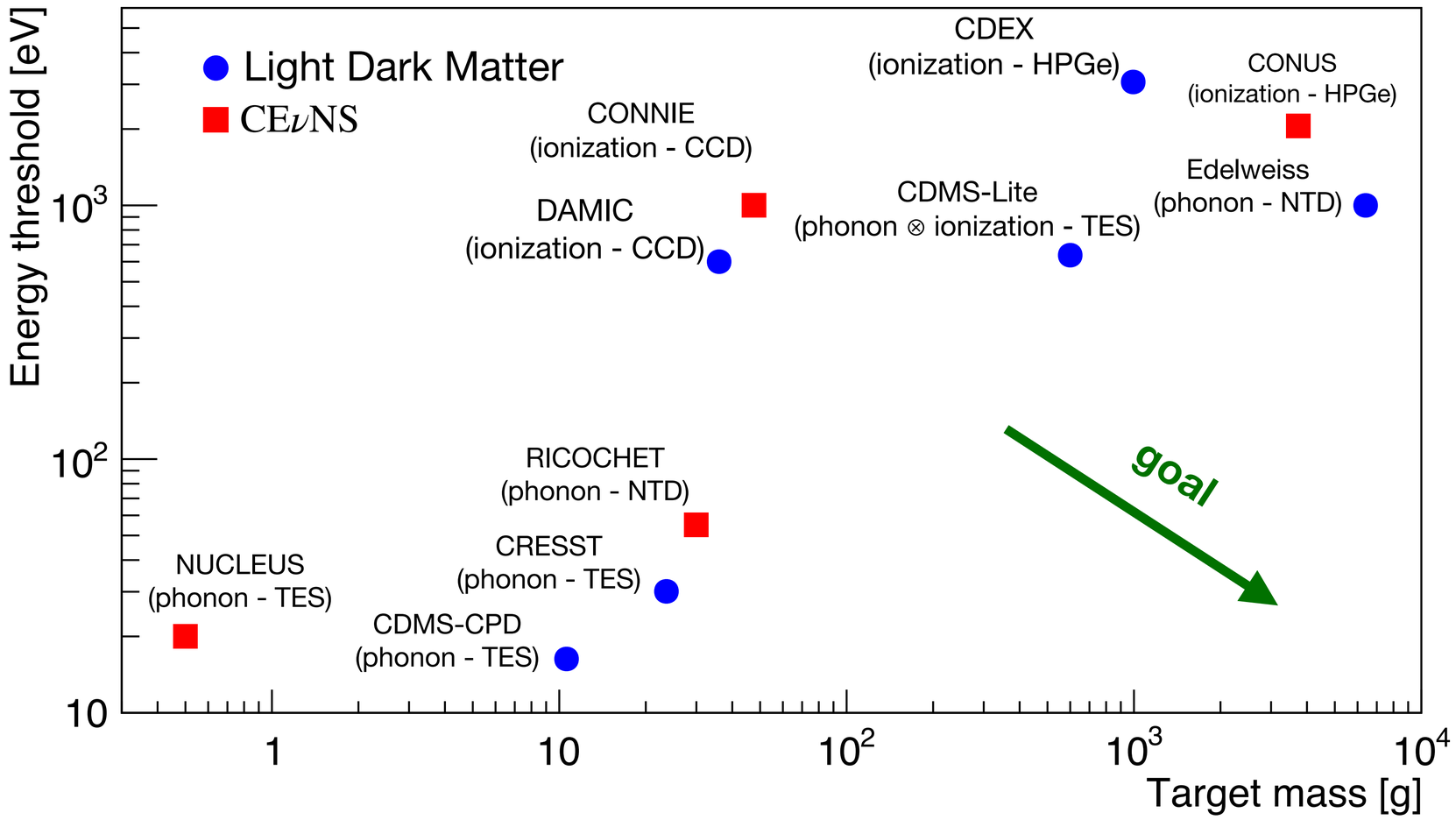
precision tests of the Standard Model $(\mathrm{NSI}, \mu_\nu, \sin^2\theta_W, \ldots)$

The current 15% precision on $\sigma_{\mathrm{CE}\nu\mathrm{NS}}$ limits its application

Need to reach a few % precision or better

State of the art





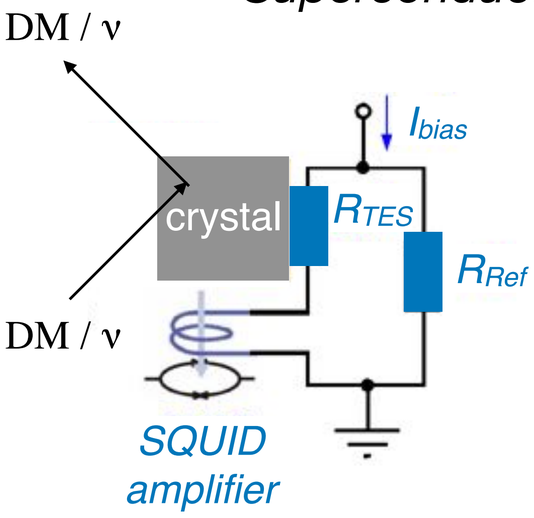
Lighter Dark Matter
Lower-energy νs

Smaller Dark Matter cross section,
Higher precision on CEνNS

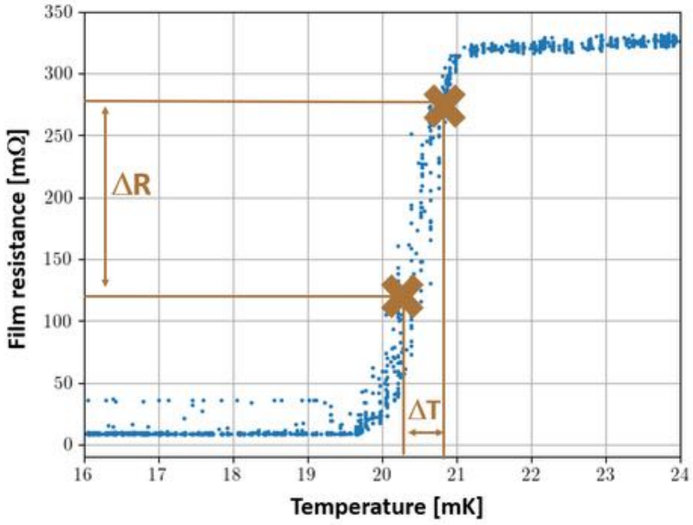
Thermal phonon detection

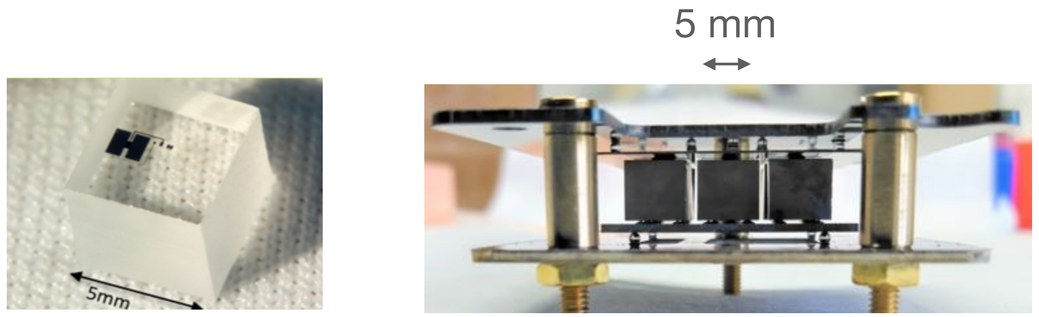
e.g. CRESST and NUCLEUS experiments

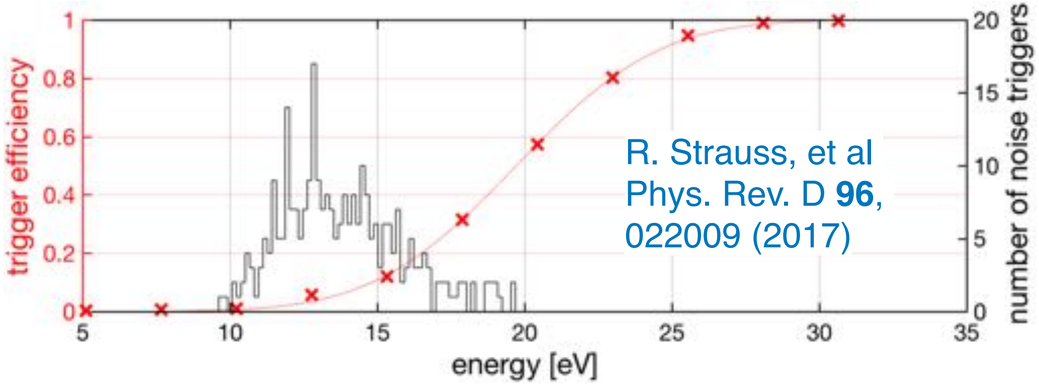
Superconducting thermometers (TES)



Transition of W-TES







Limitation: individual readout

Pro: record-low energy threshold ~ 20 eV

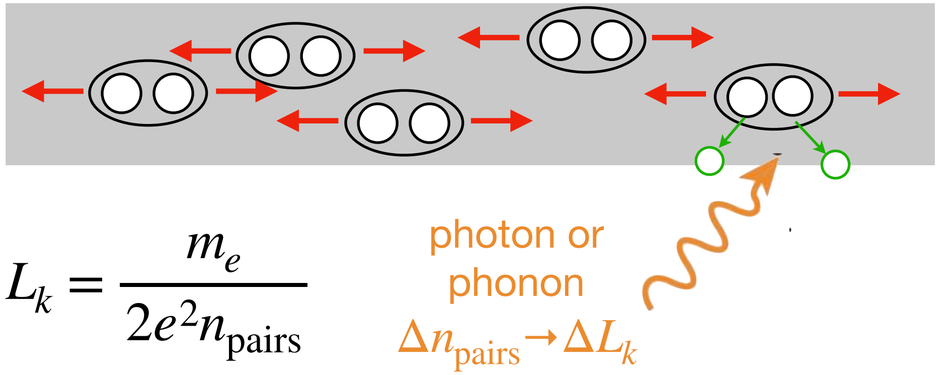
Future experiments need kg target (~1000 crystals) challenging with this technology

Superconducting resonators - KIDs

AC superconductivity

- Electrons bound into Cooper pairs (no dissipation)
- High quality factors (Q ~ 10^4 - 10^6)
- Inertia from the mass of pairs (*kinetic inductance, L_k*)

superconductor under AC field $\overrightarrow{E_{AC}}$

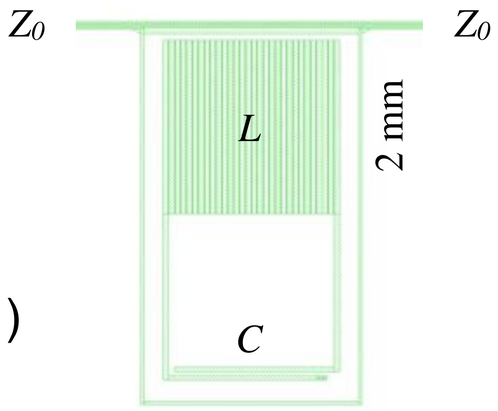


$$L_k = \frac{m_e}{2e^2 n_{\text{pairs}}}$$

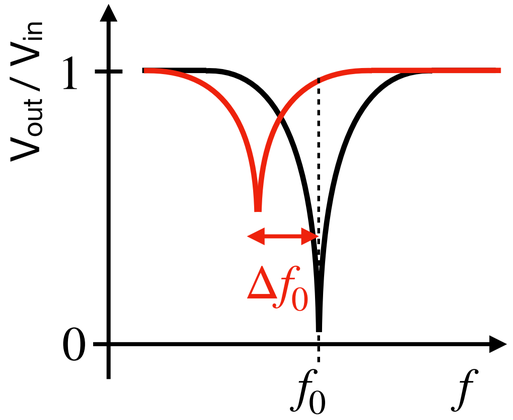
Kinetic Inductance Detector (KID):

- Superconductor at T < 200 mK
- Resonant circuit ($f_0 = 1/\sqrt{LC}$)
- Energy release → Cooper-pair breaking ($\Delta L_k \rightarrow \Delta f_0$)

LC resonator



frequency response

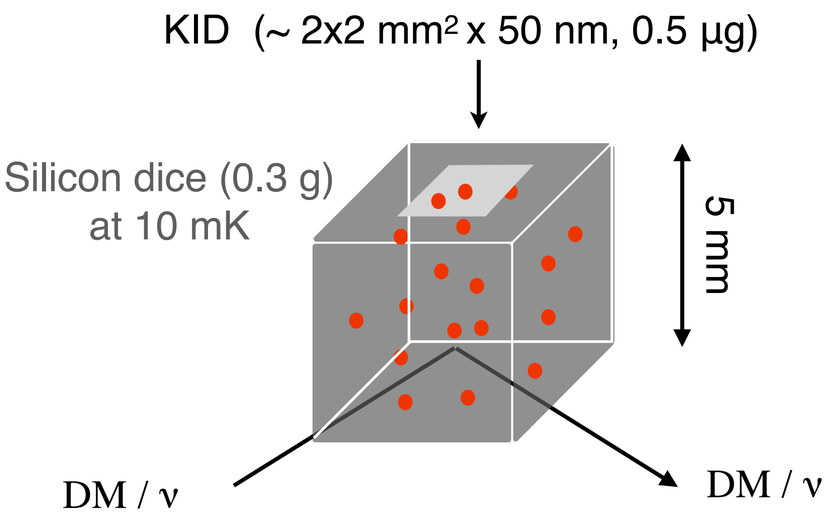


KIDs Invented by J. Zmuidzinas and his group at Caltech in 2003 for astrophysical applications

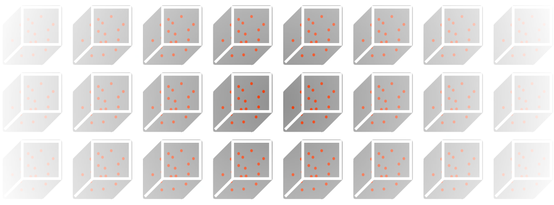
Large mass: phonons and multiplexing

Phonon mediation

detect phonons created by nuclear recoils in a silicon dice

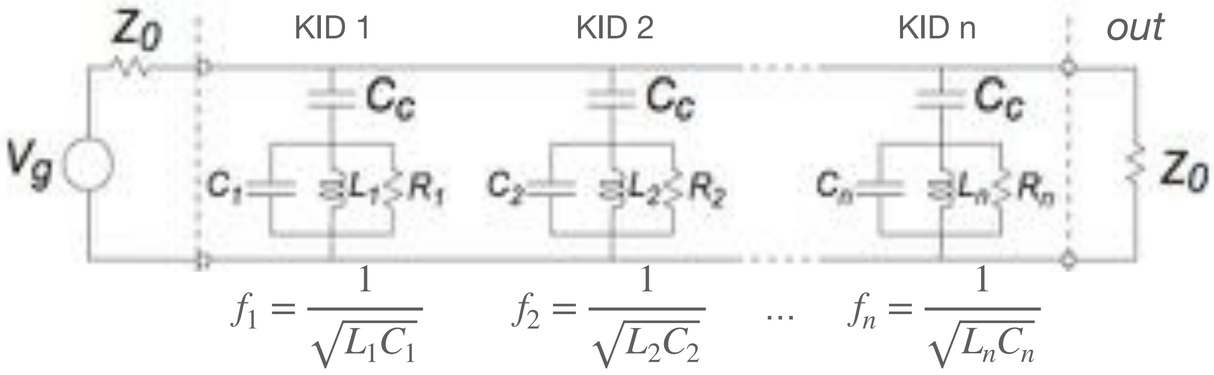


kg mass: array of Si-dices / KIDs



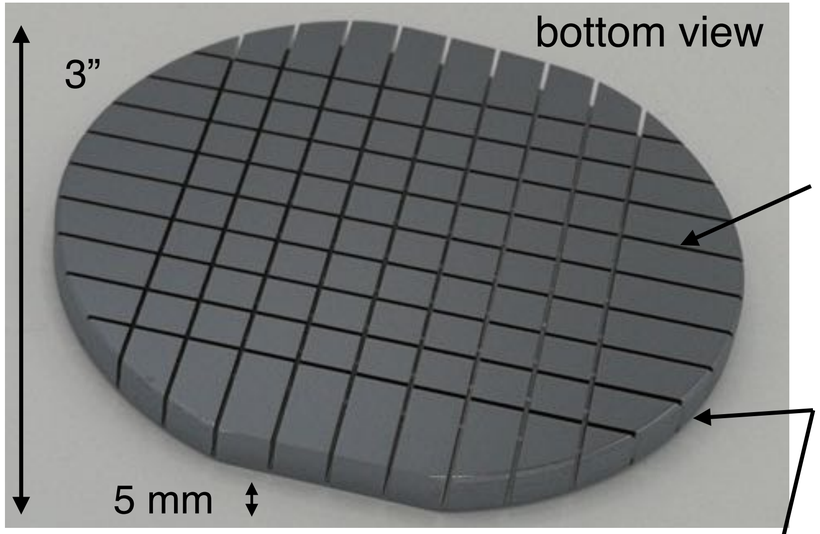
unique feature of KIDs: multiplexed readout

several KIDs coupled to the same feedline at different frequencies



Large number of targets: BULLKID

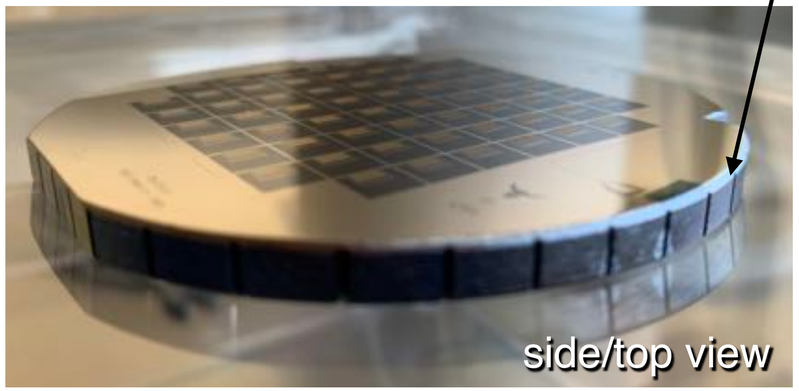
1. carving of dices in a thick silicon wafer



4.5 mm deep grooves
- 5.5 mm pitch
- chemical etching

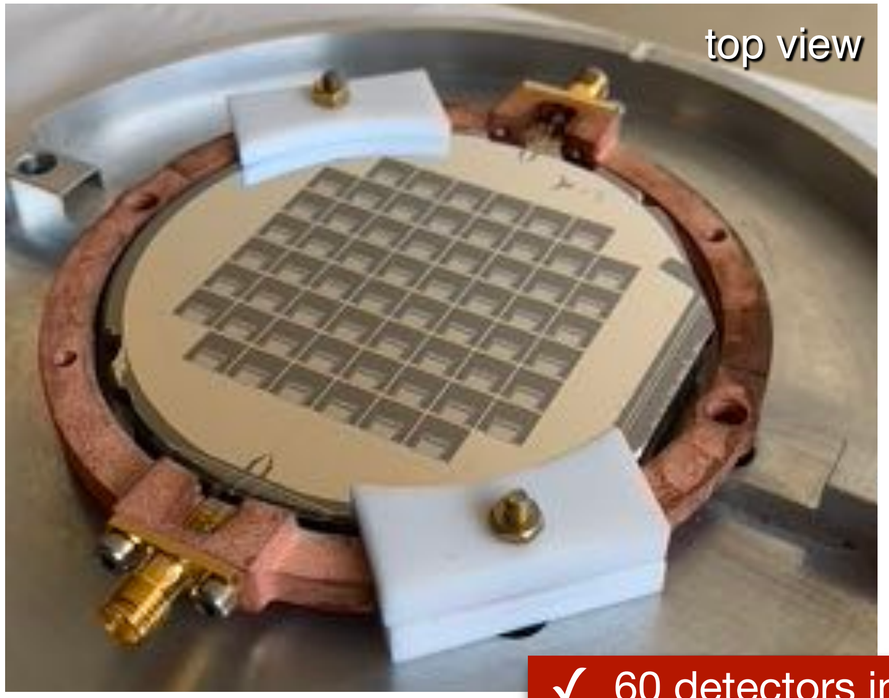
0.5 mm thick surface:
- holds the structure
- hosts the KIDs

2. lithography of multiplexed KID array



KID array
- 60 nm aluminum film
- 60 KIDs lithography

3. assembly

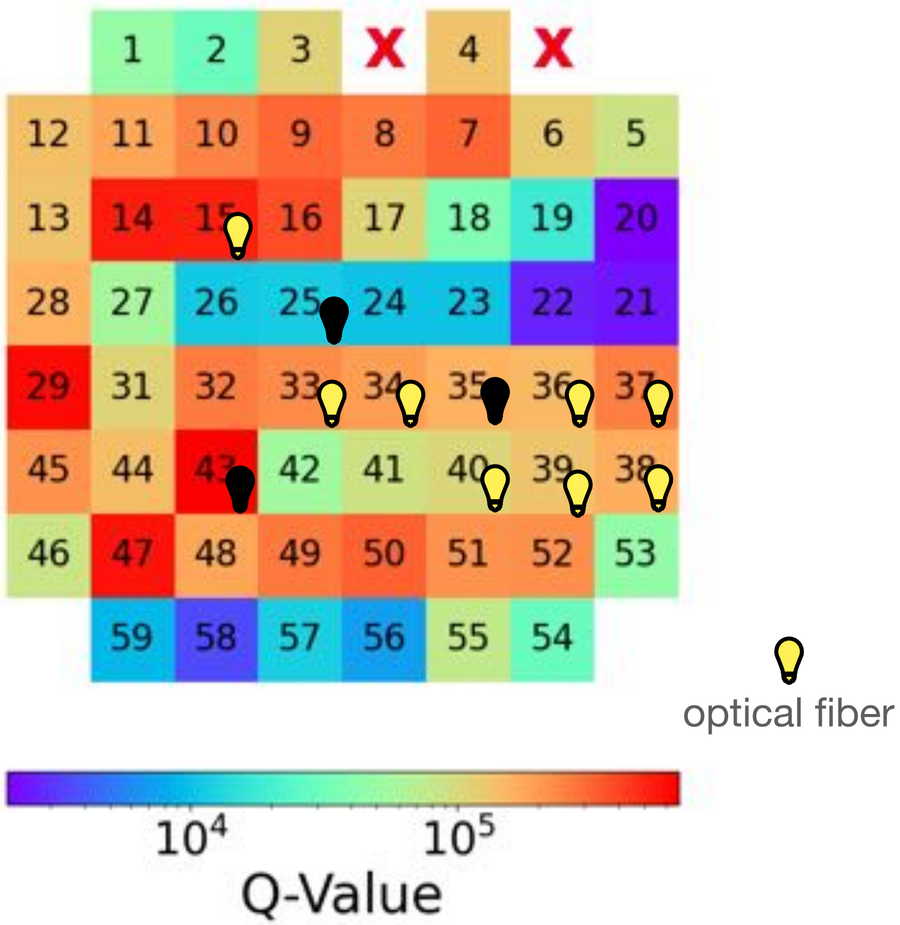


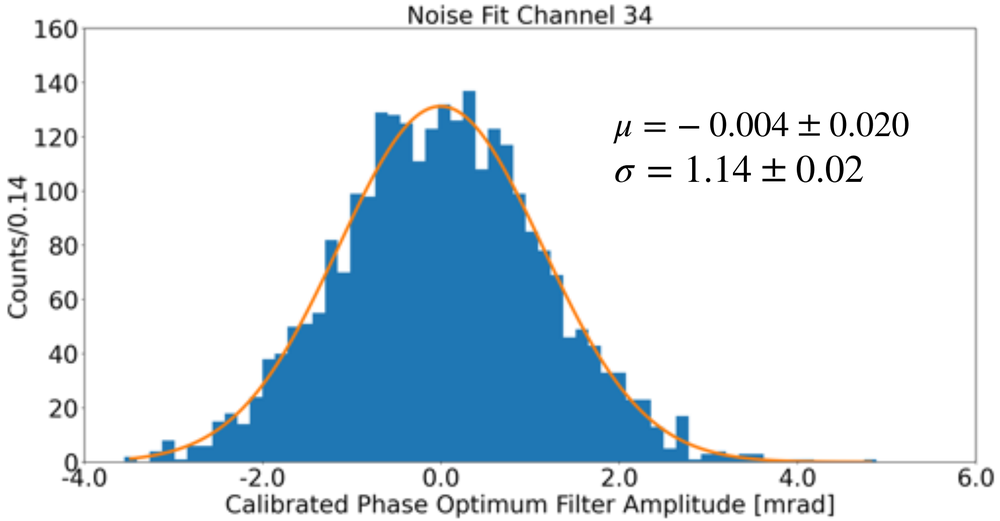
✓ 60 detectors in 1

Design and assembly
- 3D-printed Cu holder
- Aluminum case

60 dices 0.3 g each
1 readout line

Preliminary results





KID	σ_0 [mrad]	σ_0 [eV]
15	3.4±0.1	*25.0±1.2*
33	1.78±0.03	*22.9±0.8*
34	1.14±0.02	*25.4±0.5*
36	1.02±0.01	*23.8±0.7*
37	1.03±0.01	*23.7±0.7*
38	1.34±0.02	*24.4±1.0*
39	0.90±0.01	*19.4±0.7*
40	0.73±0.01	*20.6±0.9*
	average:	***23±2***

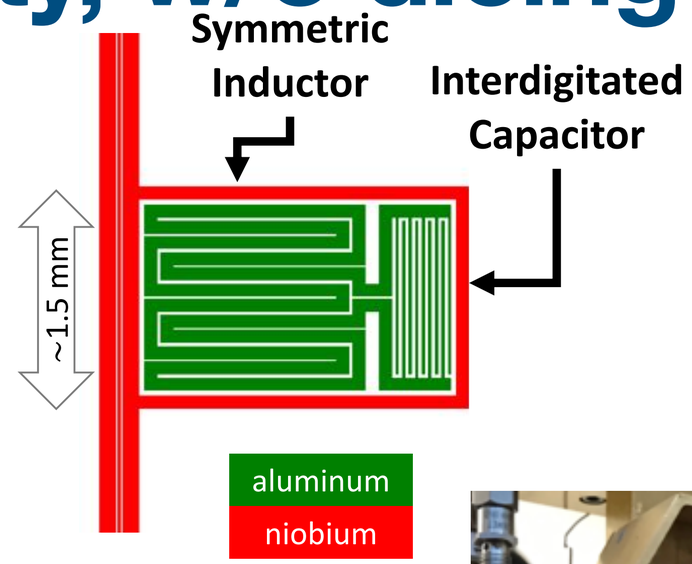
optical cal

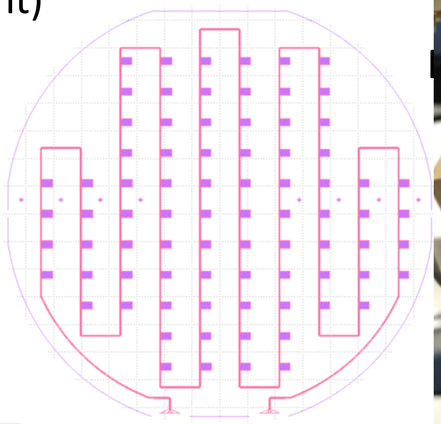
threshold 100 - 120 *eV*

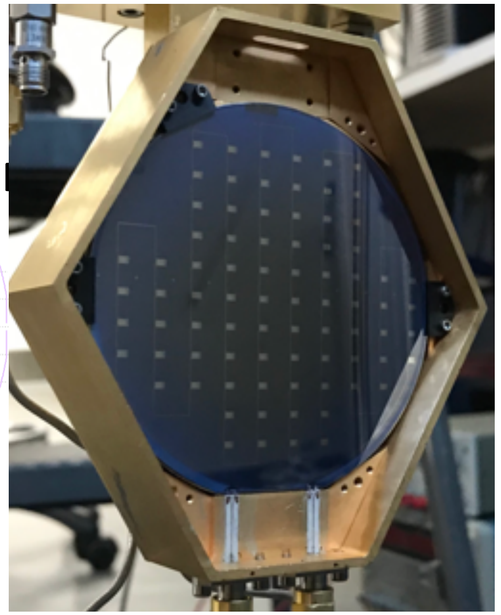
@Caltech - high sensitivity, w/o dicing

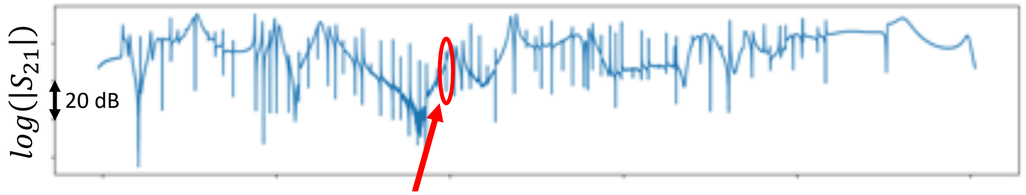
Design

- 80 MKIDs coupled to 1 coplanar waveguide feedline
  - KIDs are aluminum
    - $\Delta_{Al} \approx 0.2$ meV
  - Feedline is niobium
    - $\Delta_{Nb} \approx 1.5$ meV
    - Want phonon energy to be absorbed by KIDs, not feedline
    - $< 1\%$ of phonons are above $2\Delta_{\mathrm{Nb}}$ (for NTL phonons) **[1]**
  - $3.0\ GHz \leq f_r \leq 3.5\ GHz$
    - For CASPER ROACH readout (potential large-scale deployment)
  - Overcoupled KIDs
    - $Q_c \ll Q_i$
    - $Q_r \ll Q_i$
    - Need bandwidth > 30 kHz to preserve phonon rise time
- High-resistivity silicon substrate
  - 75 mm diameter
  - 1 mm thick







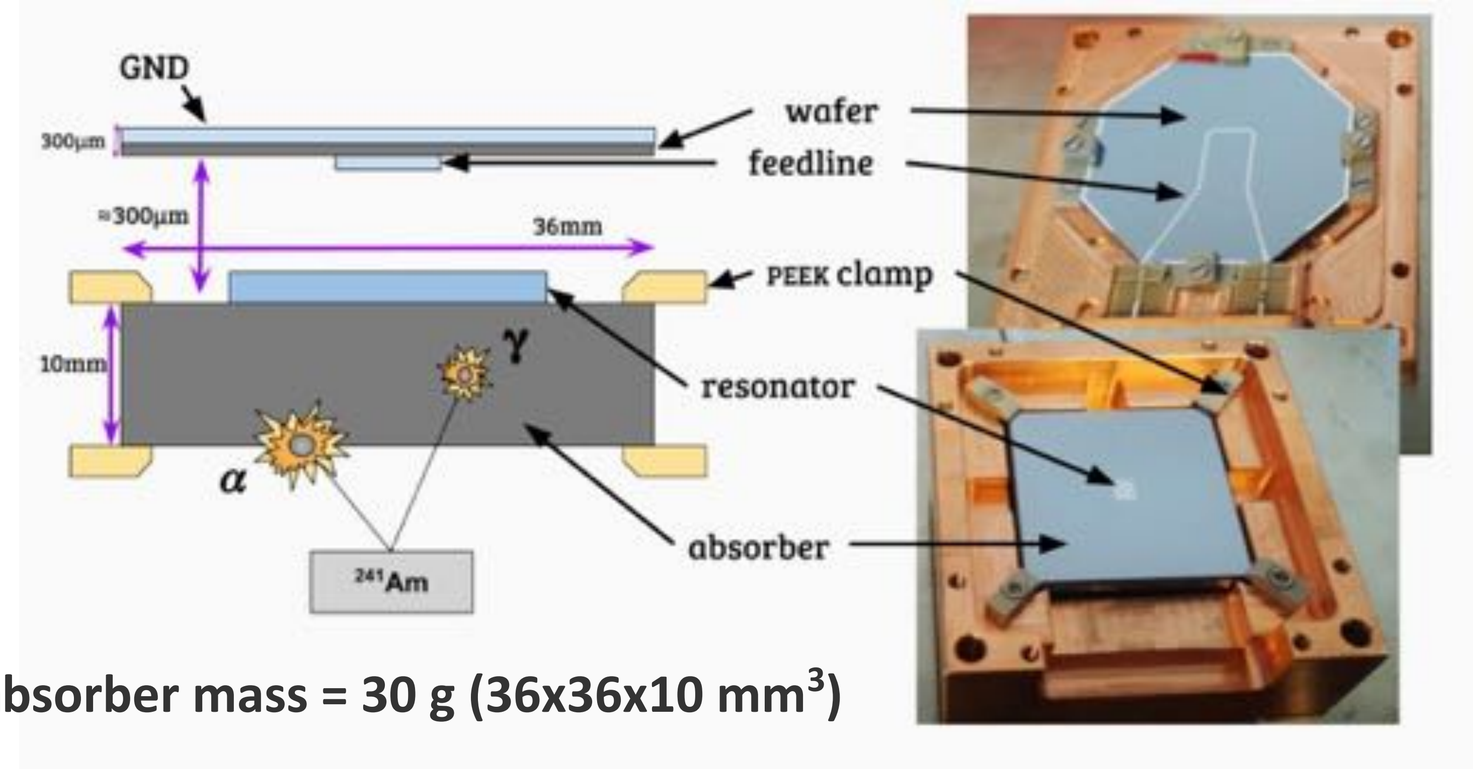


@Grenoble: WiFi KIDs

Developed in the framework of **RICOCHET** project (R&D, backup)

RICOCHET
A Coherent Neutrino Scattering Program

KID used with 'wireless' readout → maximized phonon sensing .. and other advantages



Si absorber mass = 30 g (36x36x10 mm^3)

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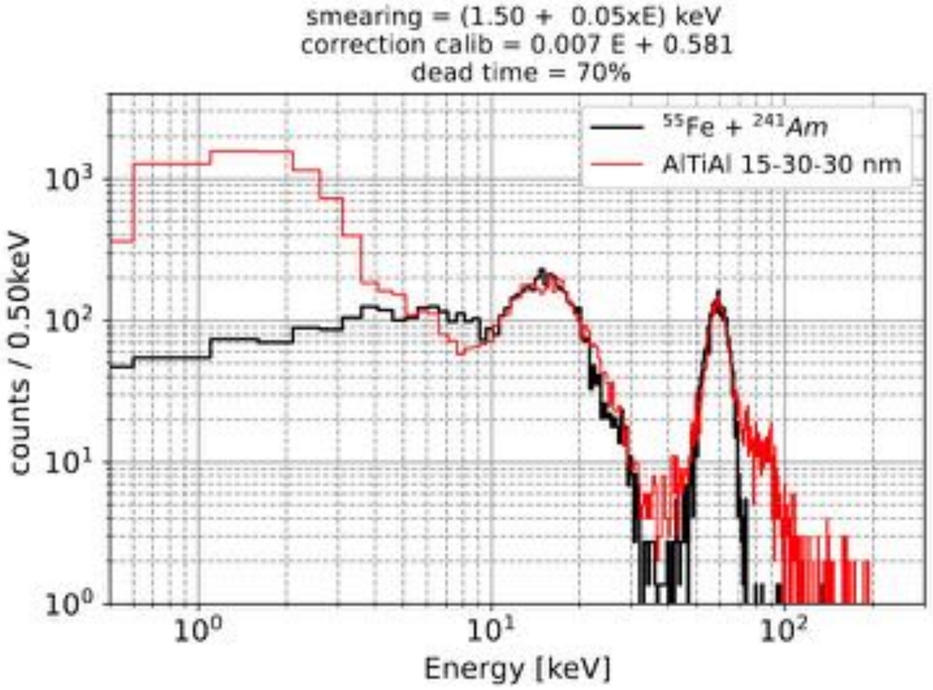
cnrs IN2P3 Les deux infinis
iP2i
Lyon 1

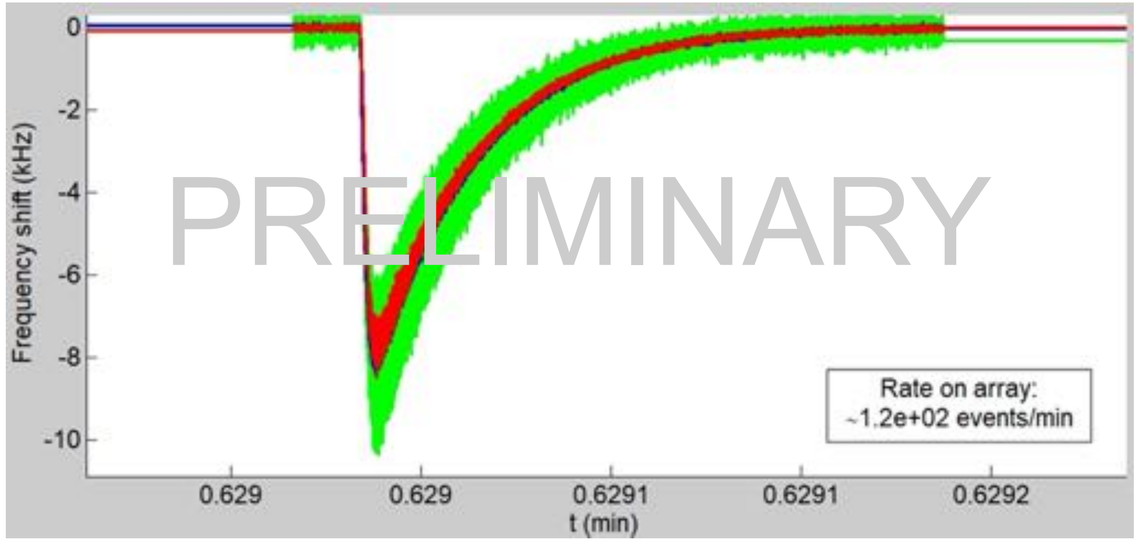
J. Goupy et al., APL 115, Issue 22, 223506 (2019)

WiFi KIDs - results

Since the first demonstration of the WiFi scheme, we have tested **Al and AlTiAl**, different **holders**, several Q_c **couplings**, two **substrate materials** (Si and Quartz) and **multi-pixel** detectors. **IN PROGRESS**



J. Colas et al., LTD19 Proceedings, in press



PRELIMINARY on multi-pixel: very same pulse (shape/amplitude) is detected on the three pixels.

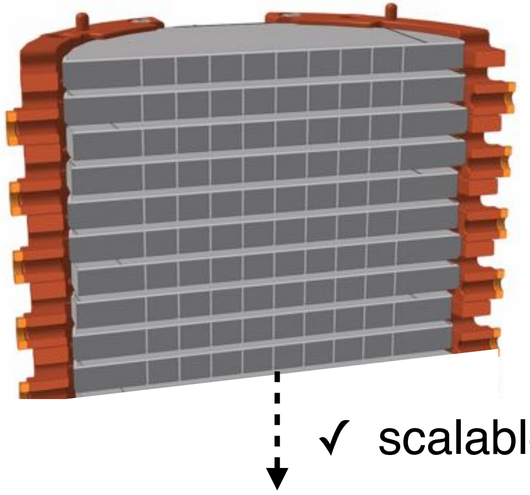
Pulse shape (versus temperature) puzzling
→ not compatible with standard interpretations

Impact

Nuclear recoil detector with:

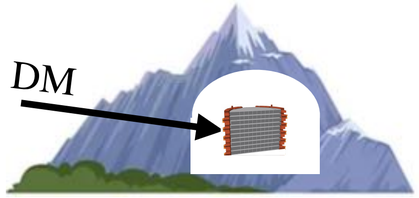
✓ 0.6 kg (Si) / 1.3 kg (Ge) target

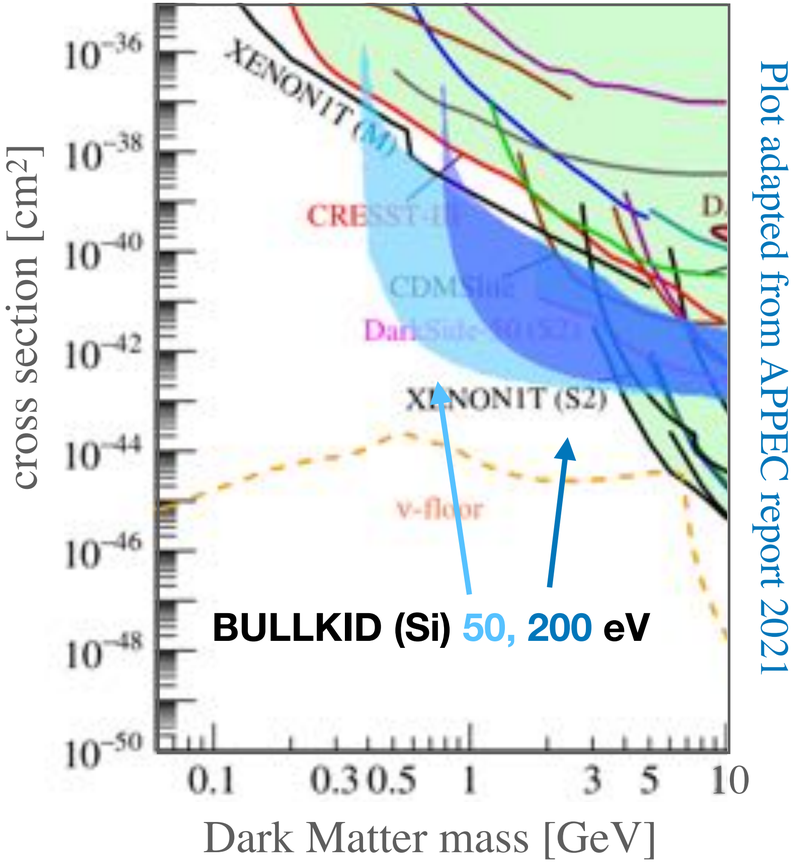
✓ 200 ÷ 50 eV threshold



✓ scalable

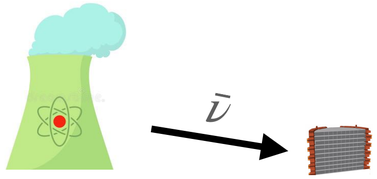
Dark Matter experiment

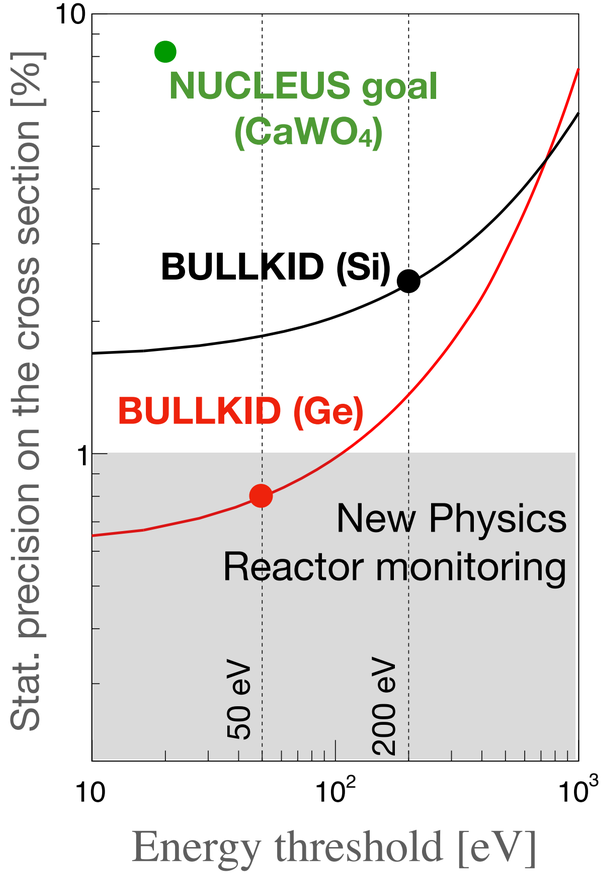




Plot adapted from APPEC report 2021

Neutrino scattering experiment





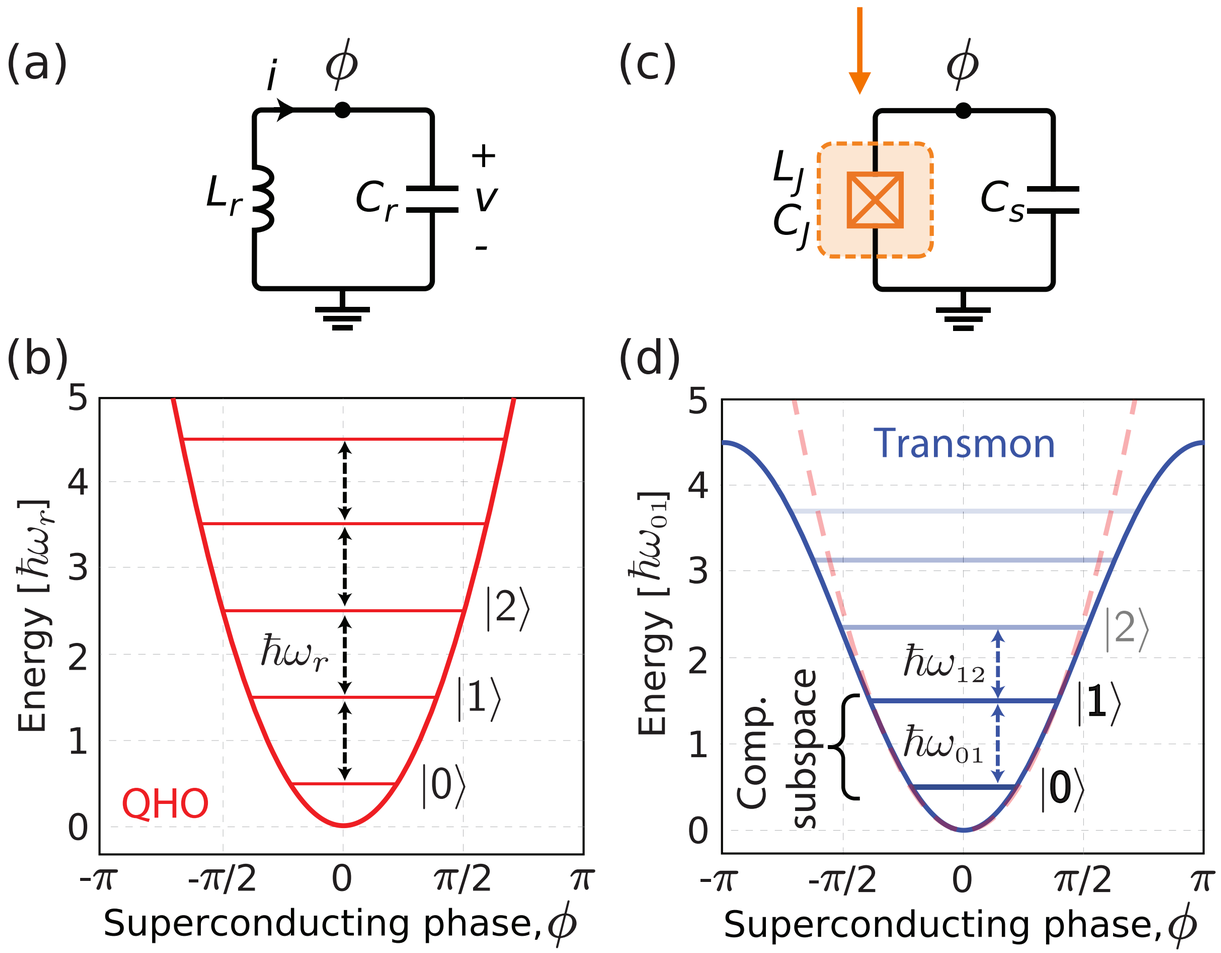
Quantum circuits

$h\nu$ (1 GHz) $= 4\ \mu eV$

Quantum harmonic oscillator

Josephson junction acting as non-linear inductor

Josephson qubit



even energy levels

uneven energy levels: isolates the 0-1 levels to create a “bit”

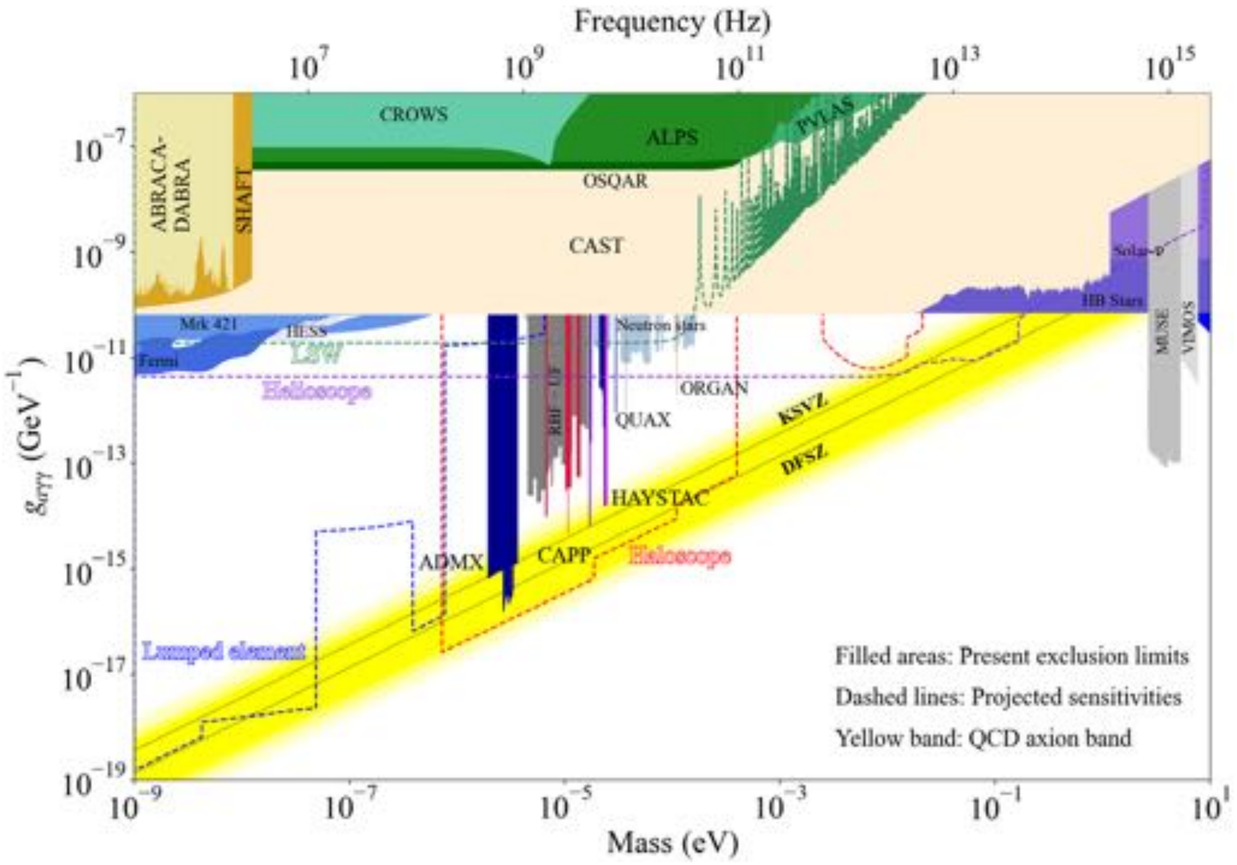
P. Krantz, et al, Applied Physics Reviews 6, (2019) 021318

Axion Dark Matter

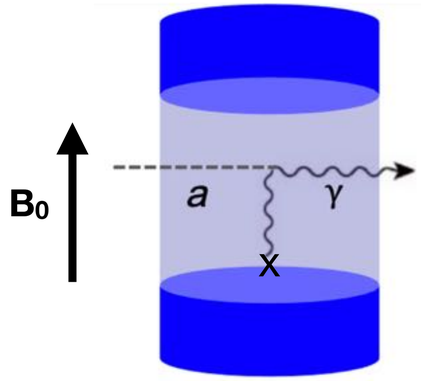
What is the Dark Matter made of?

- primordial black holes?
- μeV/c² - eV/c² axion-like waves?
- MeV/c² - TeV/c² WIMP-like particles?

Axions motivated by the strong CP problem

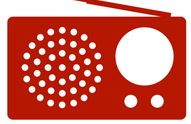


Y K. Semertzidis and S. Youn, Science Advances 8 (2022) eabm9928



accumulation cavity (ADMX)
or dielectric booster (MADMAX)

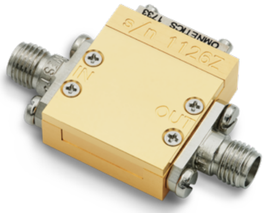
receiver $\frac{S}{N} = \frac{P_\gamma}{k_B T_N}\sqrt{\frac{t_{\text{scan}}}{\Delta f}}$



State of the art of receivers (@ 10 GHz)

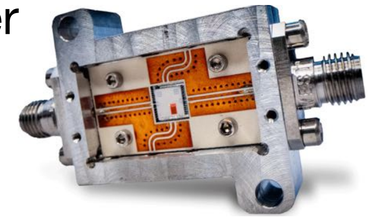
HEMT

T_{work} = LHe
T_N ~ 5 K



Parametric amplifier

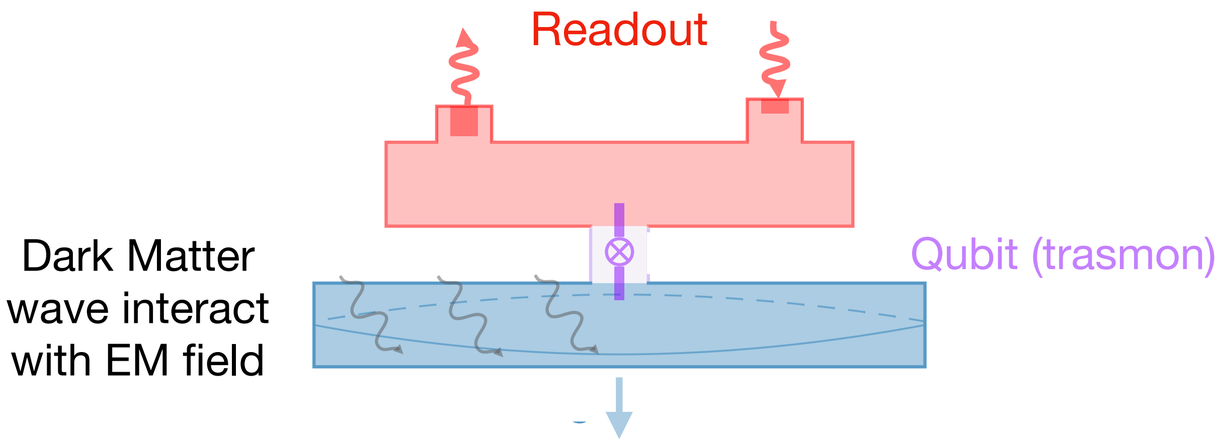
T_{work} = ^{4}He-^{3}He
$T_N = h\nu$ ~ 0.5 K
quantum limited



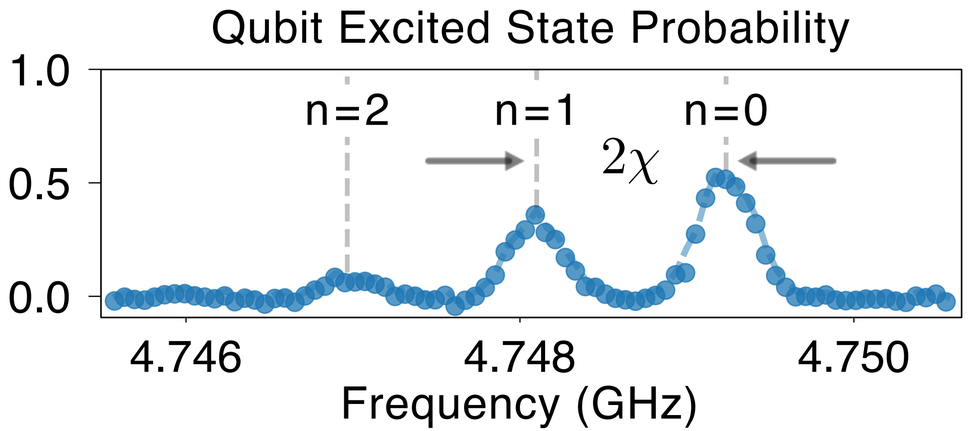
Frontier of receivers: quantum sensing

$h\nu$ (1 GHz) $= 4\ \mu eV$

Search for wave dark matter with mass ~ 10 - $100\ \mu eV$



Storage cavity (Q_c) accumulates energy from interactions



Excitation frequency of qubit depends on photons in cavity

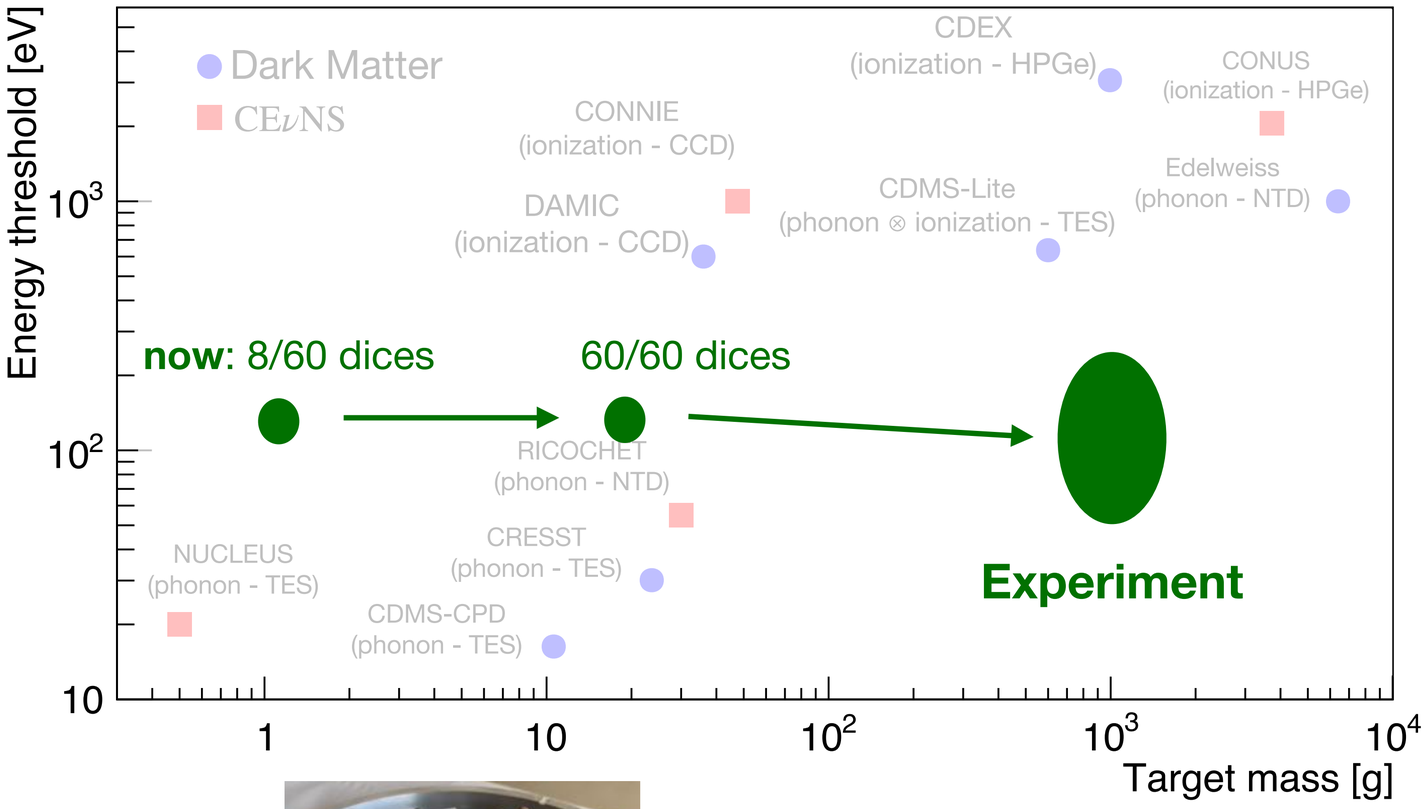
qubit as a single microwave photon counter!

T_N = 0.006 K

A. V. Dixit, et al, Phys. Rev. Lett. 126, 141302

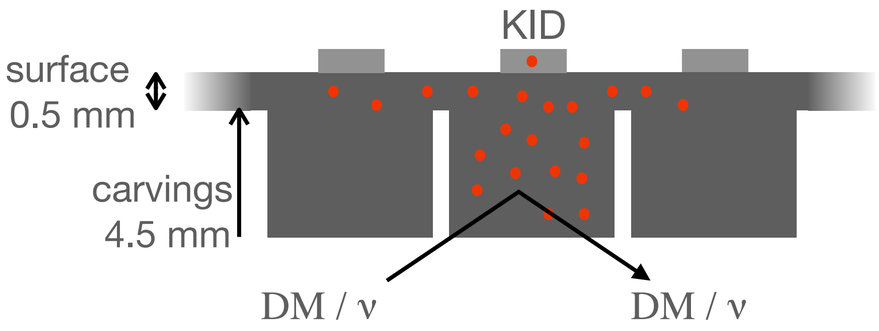
Thank you for your attention!

Towards the experiment

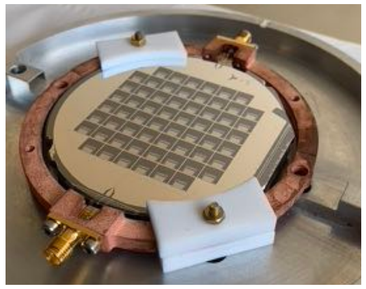


Threshold (ongoing R&D):

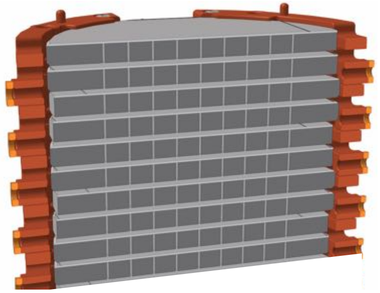
1. Replace Al with Al-Ti-Al KIDs - 5x inductance
2. Deeper carvings for higher phonon focussing



+ port the technology to Germanium wafers
(10x neutrino x-sec, does not apply to Dark Matter)

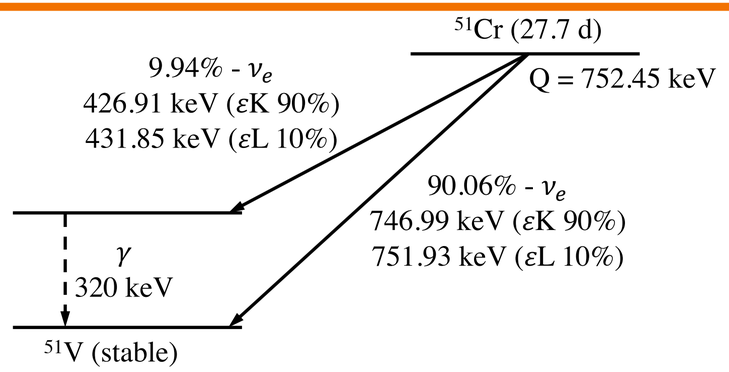


Mass:
from 3” to 4” wafers
stack of wafers

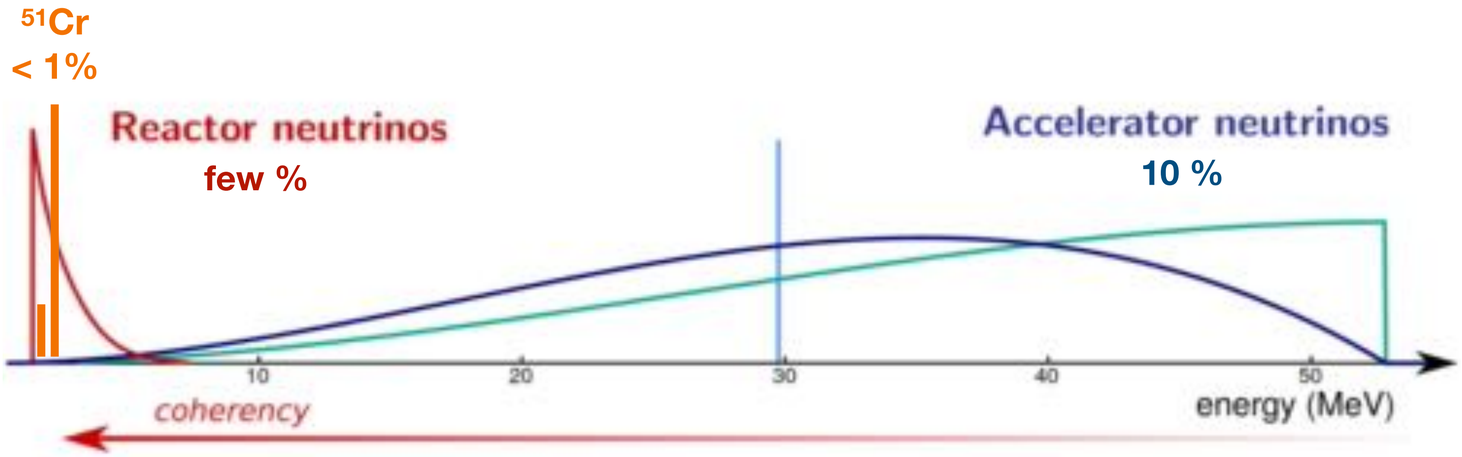


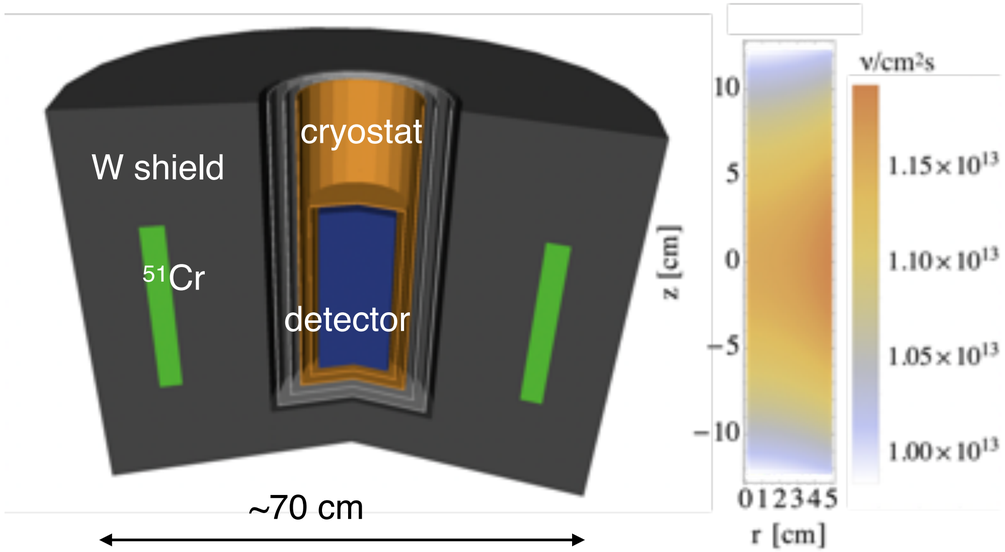
3D-printed Cu stacking prototype

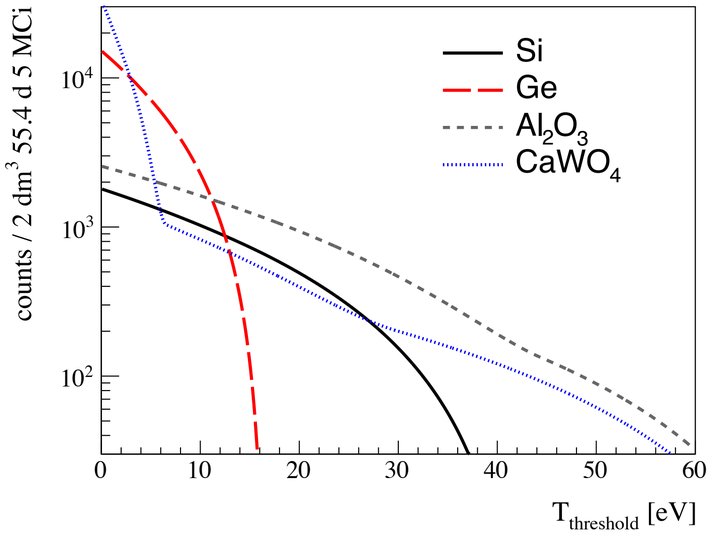
Future: precise ν source



- ✓ Activity monitored with calorimeter < 1 % precision (SOX experience)
- ✓ INFN owns a 36 kg source (GALLEX)







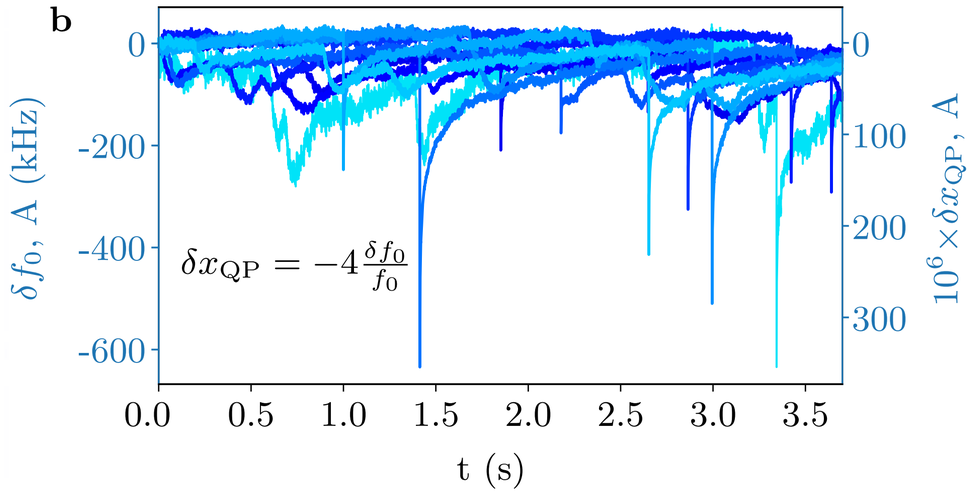
Challenges:

- activation up to 5 MCi
- lower threshold than reactors

👍 1% precision in 2 months with a 10 kg Ge target

C. Bellenghi et. al, EPJC 79 (2019) 727

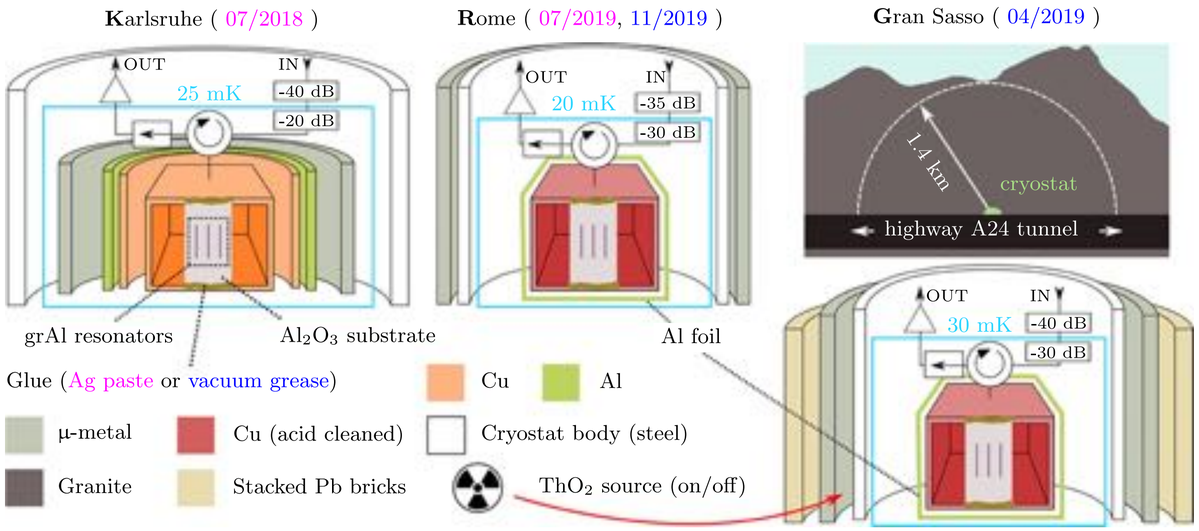
Bridging communities: effect of radioactivity

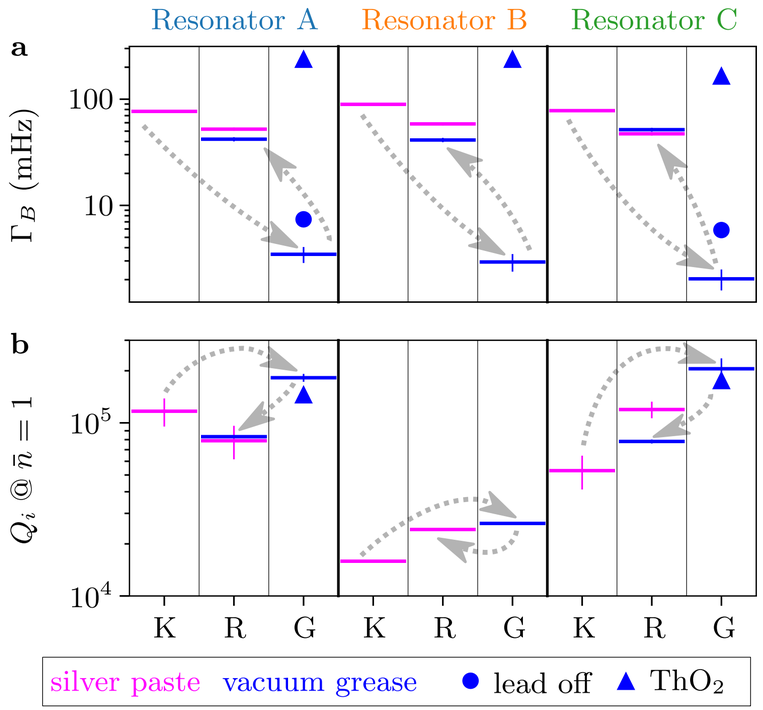


Radioactivity interactions:

→ Cooper pair breaking → dissipation

→ Q lowering→ Limits coherence time

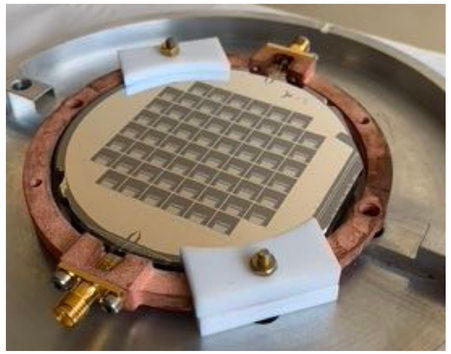


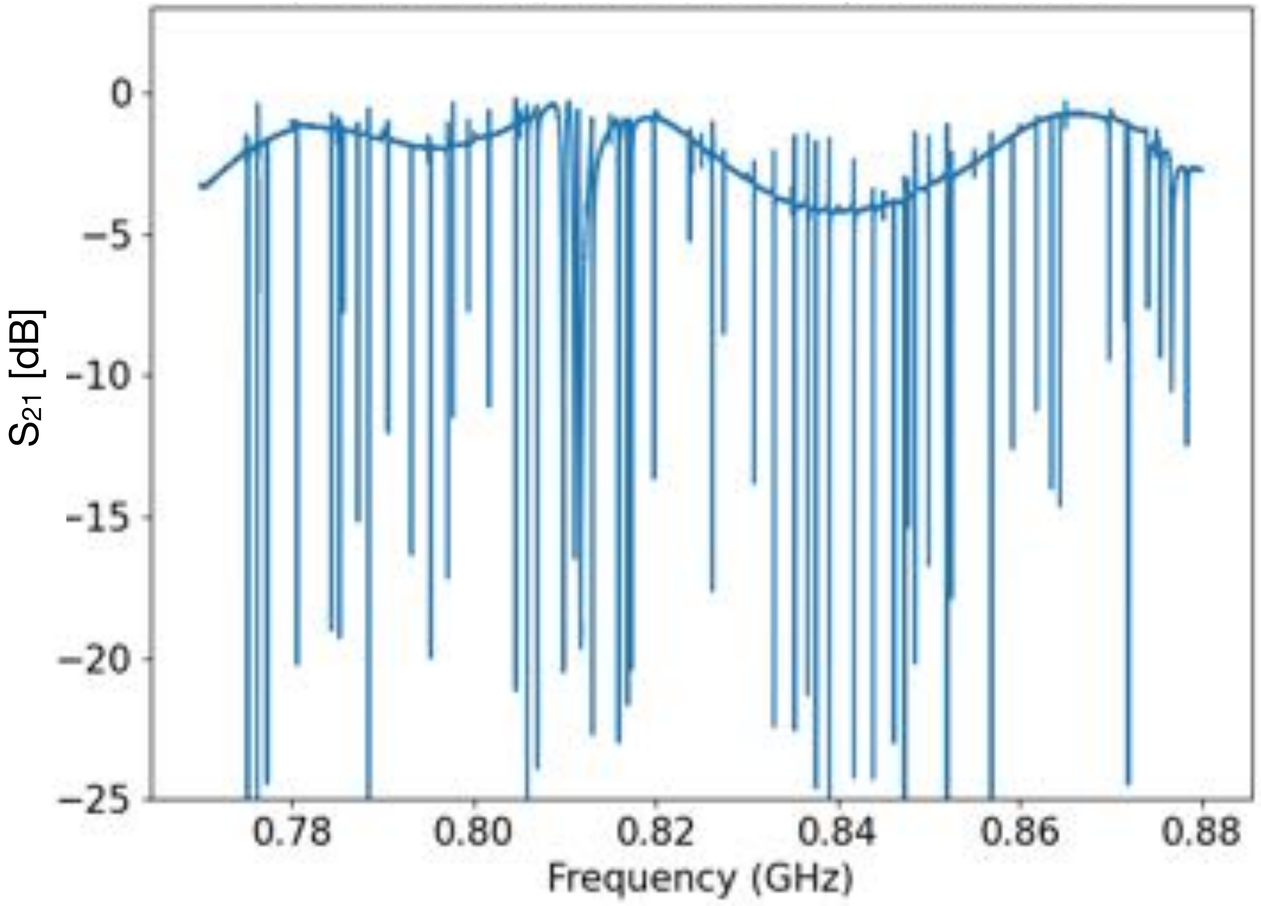


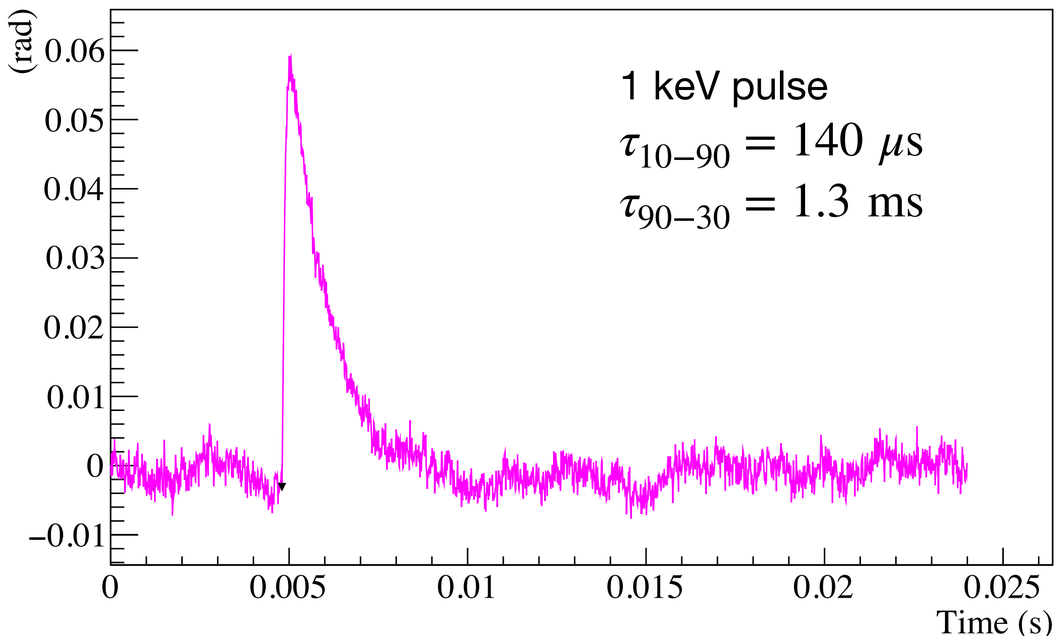
indication of Q increase

L. Cardani, et al Nat. Commun. 12 (2021) 2733

Latest prototype (5/2022)







58/60 resonators responding