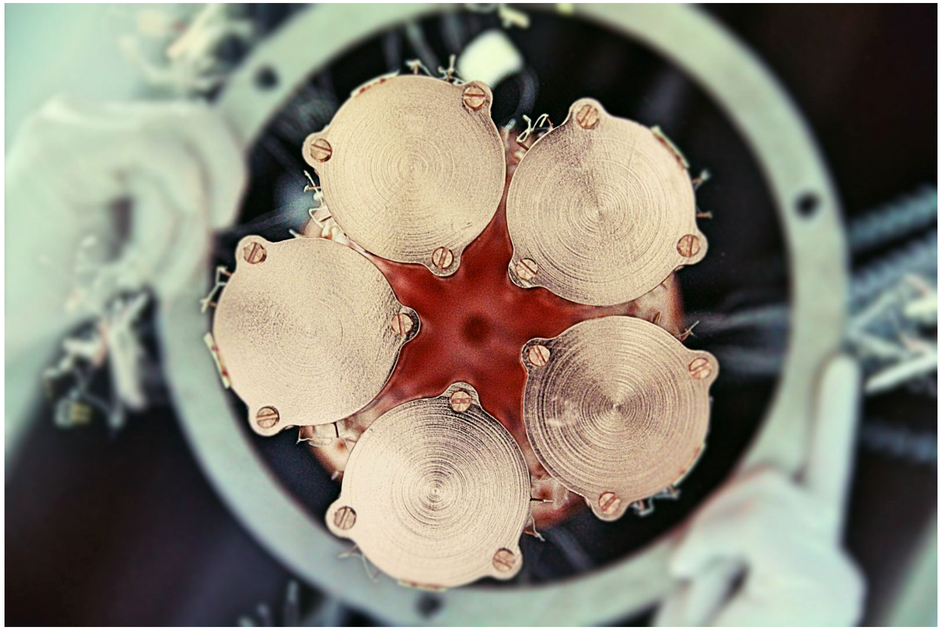
Cryogenic Calorimeters to search for Double Beta Decay



Laura Cardani

15/05/2017

INFN Istituto Nazionale di Fisica Nucleare

Physics Motivation

- Definitive evidences for **massive neutrinos**
- How do we incorporate these masses in the SM?
- Being neutral, neutrinos could be **the only fermion that could be its own anti-particle**

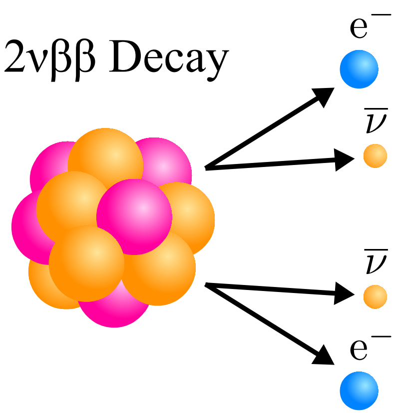
Neutrinos would be **Majorana particles** (as opposed to all the other fermions)

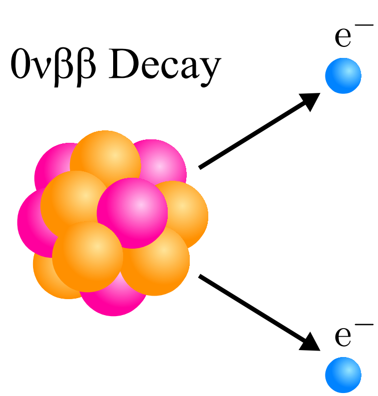
A Majorana mass term:

- Implies **violation of lepton number** conservation
- Crucial for theories explaining the **dominance of matter over antimatter** in the Universe

Neutrinoless Double Beta Decay

- How do we probe the Majorana nature of neutrinos?
- **Neutrino-less Double Beta Decay (0nDBD)**





Hypothesized (never observed) nuclear transition:

- Can occur **only if ν is a Majorana** particle
- Forbidden by SM: it **violates L** (actually B-L) conservation
- It **creates matter** (no anti-matter balancing)
- Majorana phases: **other sources of CPV**?
- If observed, insights on the neutrino mass

Neutrino (Majorana) Mass

The observable of the process $T_{1/2}$ is related to $m_{\beta\beta}$

$$(T^{0\nu}_{1/2})^{-1} = G^{0\nu}(Q, Z)\,|M^{0\nu}|^2 \left(\frac{\langle m_{\beta\beta}\rangle}{m_e}\right)^2$$

Phase Space Factor

Nuclear Matrix Element

$$m_{\beta\beta} = |m_1 c_{12}^2 c_{13}^2 + m_2 s_{12}^2 c_{13}^2 e^{i\alpha_{21}} + m_3 s_{13}^2 e^{i(\alpha_{31}-\delta)}|$$

- **m_1, m_2, m_3** particle neutrino **mass eigenstates**
- **c_{12}, c_{13}… mixing angles** parametrizing the PMNS matrix (transform mass to flavor bases)
- **α_{21}, α_{31}: Majorana phases**

Neutrino (Majorana) Mass

The observable of the process $T_{1/2}$ is related to $m_{\beta\beta}$

$$(T^{0\nu}_{1/2})^{-1} = G^{0\nu}(Q,Z)\,|M^{0\nu}|^2 \left(\frac{\langle m_{\beta\beta}\rangle}{m_e}\right)^2$$

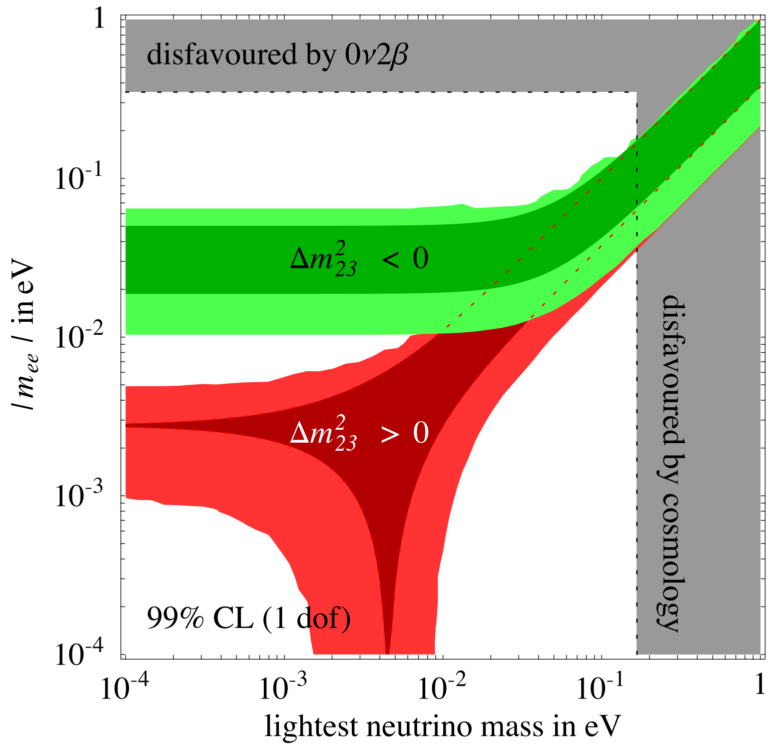
Phase Space Factor

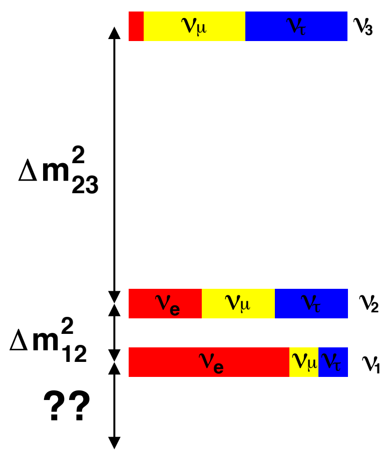
Nuclear Matrix Element

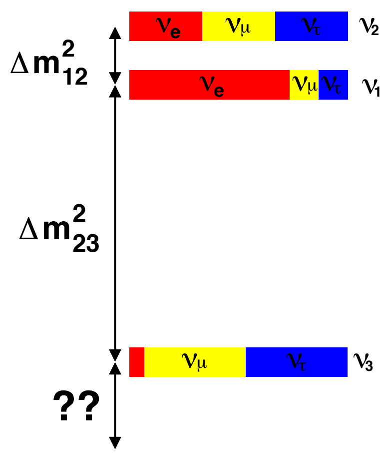
$$m_{\beta\beta} = |m_1 c_{12}^2 c_{13}^2 + m_2 s_{12}^2 c_{13}^2 e^{i\alpha_{21}} + m_3 s_{13}^2 e^{i(\alpha_{31}-\delta)}|$$

- **m_1, m_2, m_3** particle neutrino **mass eigenstates don't know the absolute values**
- **c_{12}, c_{13}… mixing angles** parametrizing the PMNS matrix (transform mass to flavor bases) **known from oscillations**
- **α_{21}, α_{31}: Majorana phases no idea**

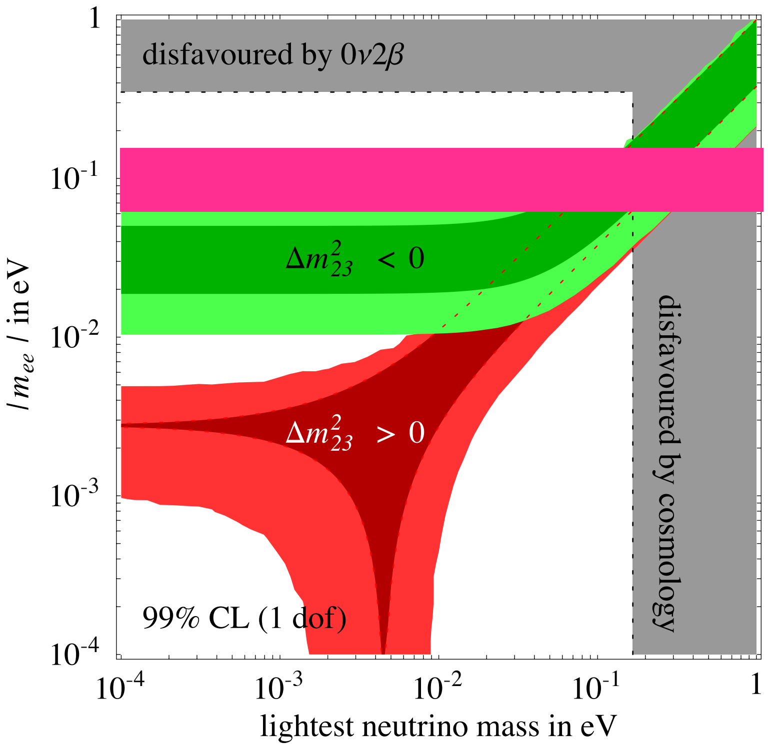
Neutrino (Majorana) Mass

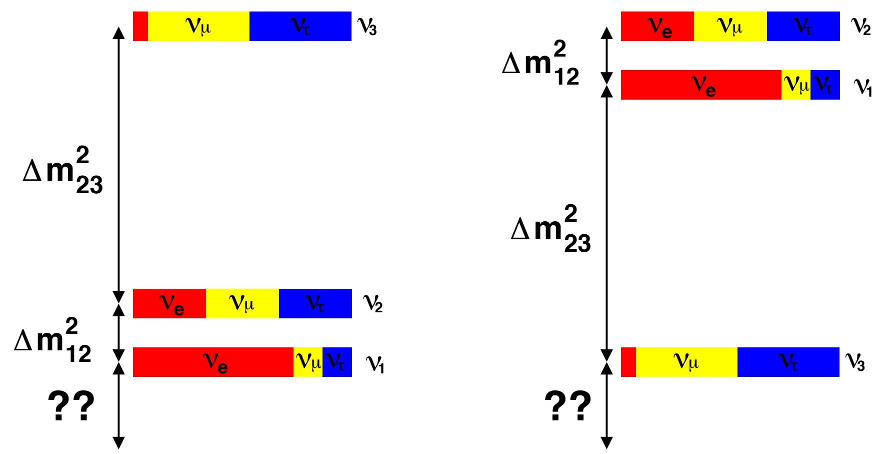






Neutrino (Majorana) Mass





Current best limits: $m_{\beta\beta}$ < 61-165 meV @ 90% CL

Touch the inverted hierarchy region

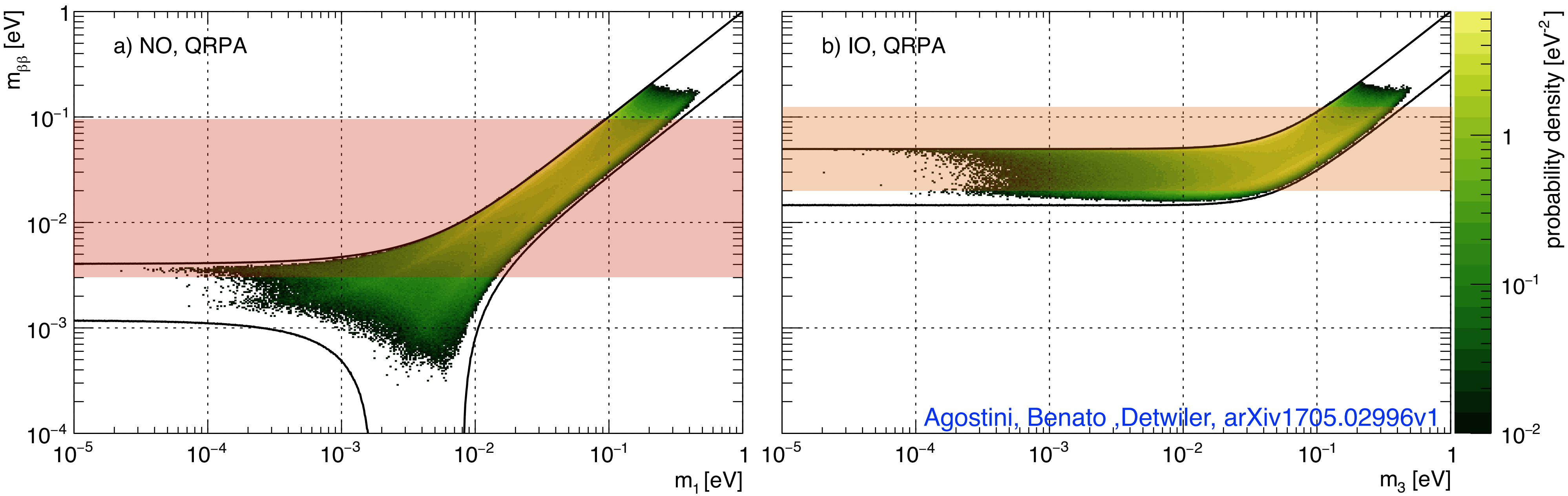
$$(T^{0\nu}_{1/2})^{-1} = G^{0\nu}(Q,Z)\,\left|M^{0\nu}\right|^2 \left(\frac{\langle m_{\beta\beta}\rangle}{m_e}\right)^2$$

Increasing the sensitivity on $T_{1/2}$ by a factor 10 = increasing the sensitivity on $m_{\beta\beta}$ by ~ 3

Neutrino (Majorana) Mass

Maybe the situation is more optimistic that we thought

$$m_{\beta\beta} = |m_1 c_{12}^2 c_{13}^2 + m_2 s_{12}^2 c_{13}^2 e^{i\alpha_{21}} + m_3 s_{13}^2 e^{i(\alpha_{31}-\delta)}|$$

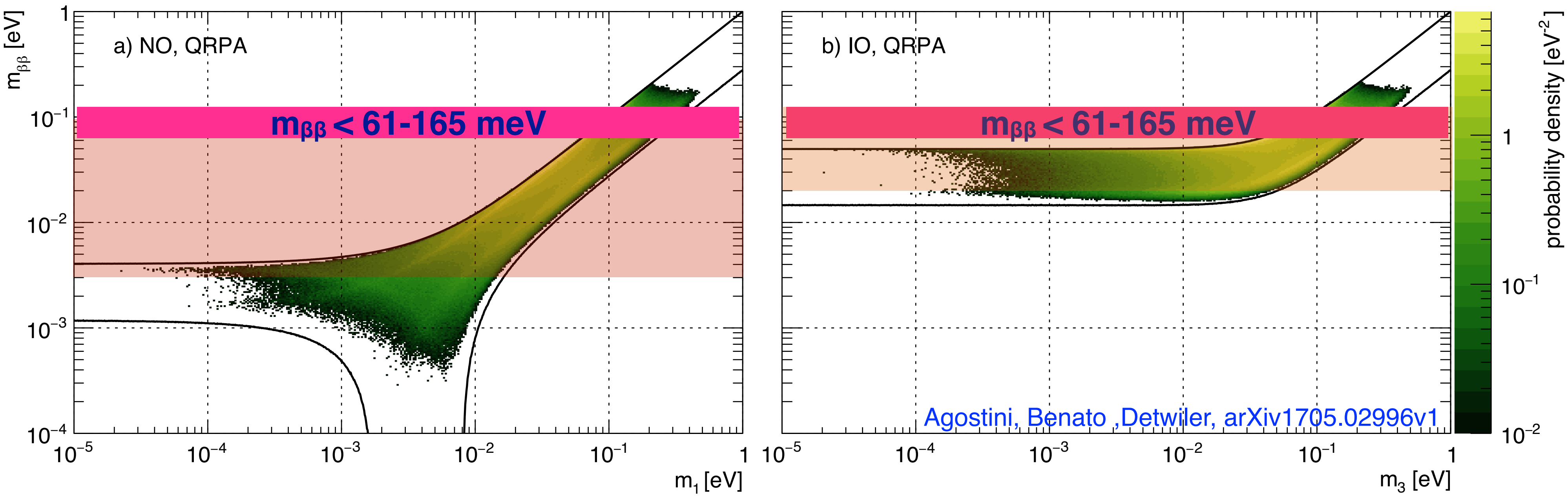


- **Normal** hierarchy: the 90% probability central interval for $m_{\beta\beta}$ is **3-104 meV**
- **Inverted** hierarchy: the 90% probability central interval for $m_{\beta\beta}$ is **20-119 meV**

Neutrino (Majorana) Mass

Maybe the situation is more optimistic that we thought

$$m_{\beta\beta} = |m_1 c_{12}^2 c_{13}^2 + m_2 s_{12}^2 c_{13}^2 e^{i\alpha_{21}} + m_3 s_{13}^2 e^{i(\alpha_{31}-\delta)}|$$

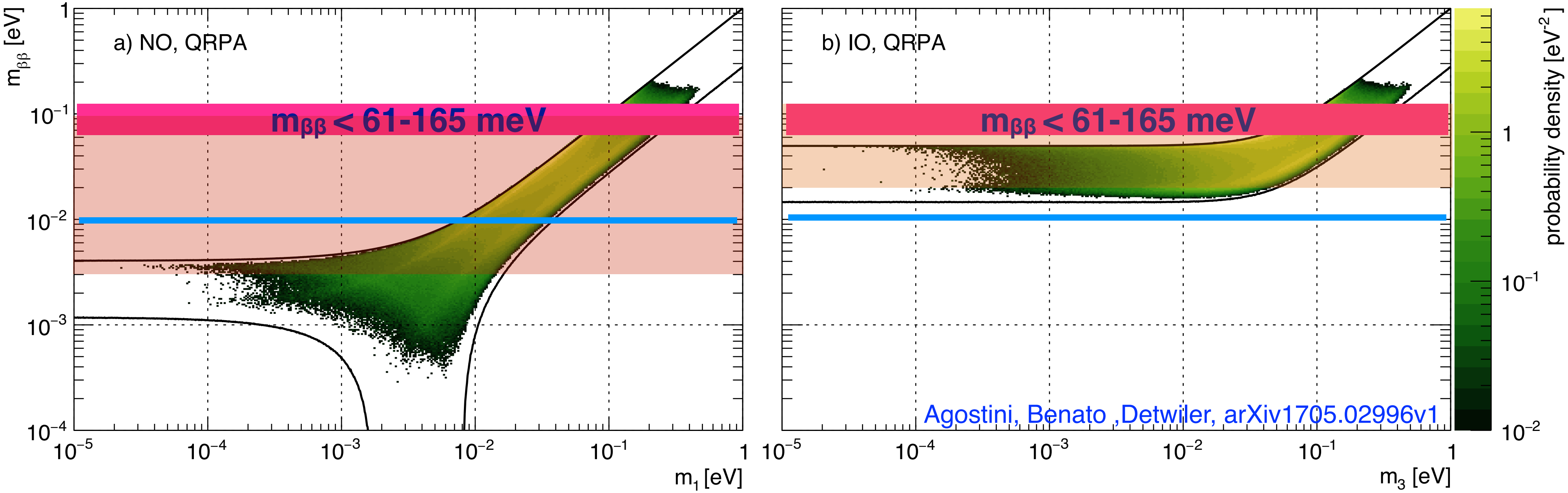


- **Normal** hierarchy: the 90% probability central interval for $m_{\beta\beta}$ is **3-104 meV**
- **Inverted** hierarchy: the 90% probability central interval for $m_{\beta\beta}$ is **20-119 meV**

Neutrino (Majorana) Mass

Maybe the situation is more optimistic that we thought

$$m_{\beta\beta} = |m_1 c_{12}^2 c_{13}^2 + m_2 s_{12}^2 c_{13}^2 e^{i\alpha_{21}} + m_3 s_{13}^2 e^{i(\alpha_{31}-\delta)}|$$

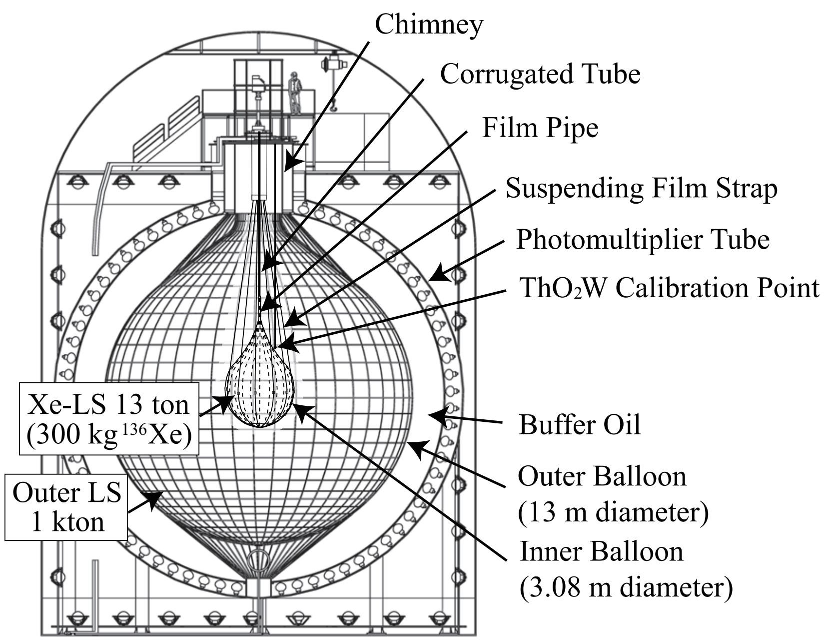


- With a **discovery sensitivity of 10-20 meV** we can cover the true value of $m_{\beta\beta}$
- with **more than 95%** probability assuming **Inverted** hierarchy
- with **more than 50%** probability assuming **normal** hierarchy (to reach ~90% need 5 meV)

How do we reach 10 meV

Status:

- Current best limits: **$m_{\beta\beta}$ < 61-165 meV** @ 90% CL
- This corresponds to **$T_{1/2}(^{136}Xe)$ >1.07x10^{26} years**

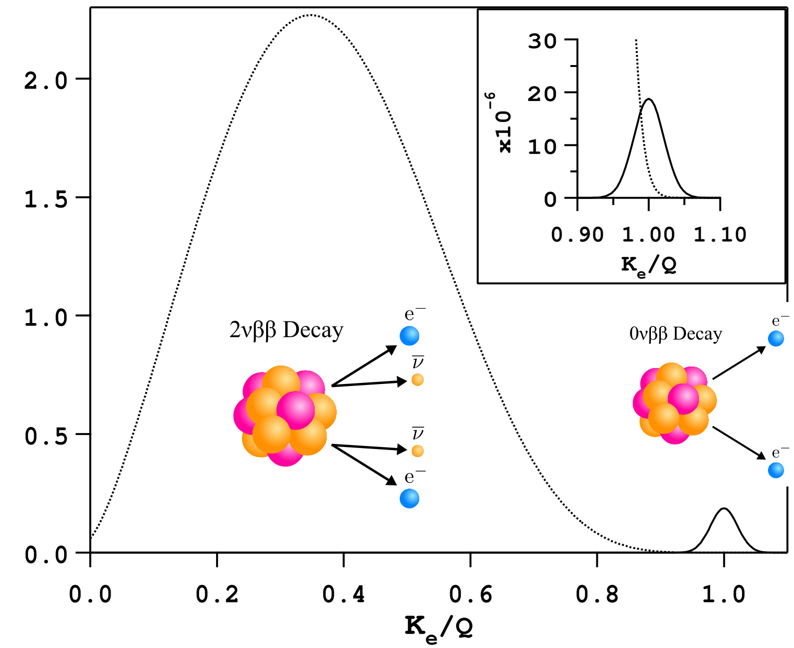


10^{27} nuclei: Hundreds of kg of source

How do we reach 10 meV

Status:

- Current best limits: **$m_{\beta\beta}$ < 61-165 meV** @ 90% CL
- This corresponds to **$T_{1/2}(^{136}Xe)$ >1.07×10^{26} years**
- Clear signature



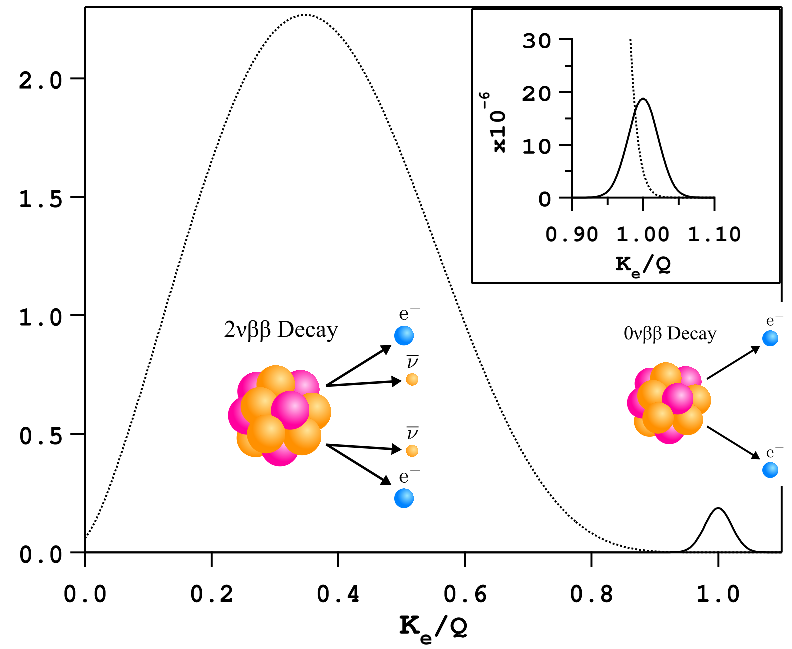
10^{27} nuclei: Hundreds of kg of source

Good Energy Resolution

How do we reach 10 meV

Status:

- Current best limits: $m_{\beta\beta}$ < 61-165 meV @ 90% CL
- This corresponds to $T_{1/2}(^{136}Xe) > 1.07 \times 10^{26}$ years
- Clear signature
- $T_{1/2}(^{238}U - ^{232}Th) = 10^9 - 10^{10}$ years

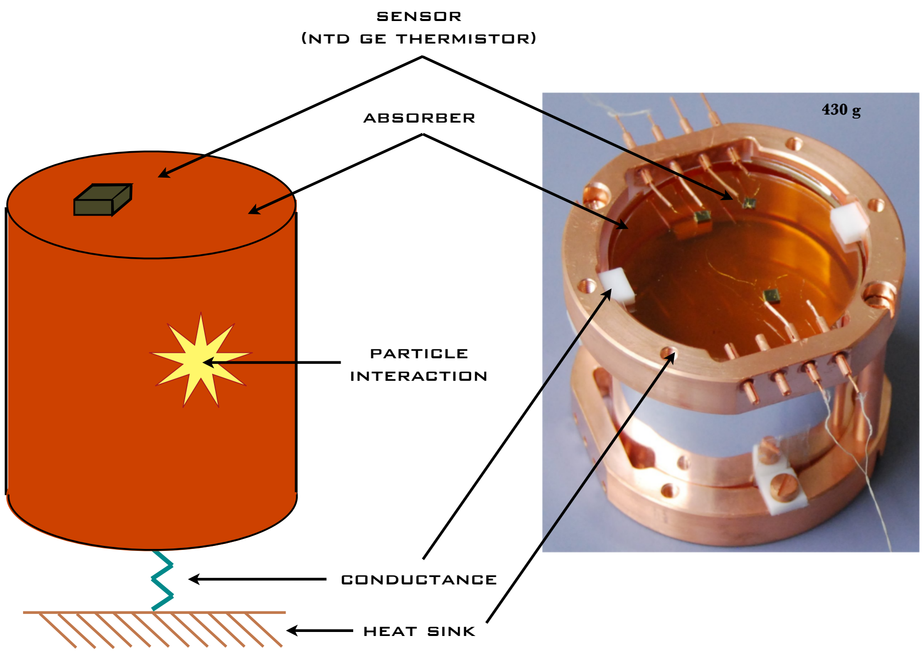


10^{27} nuclei: Hundreds of kg of source

Good Energy Resolution

Background free detectors

Cryogenic Calorimeters



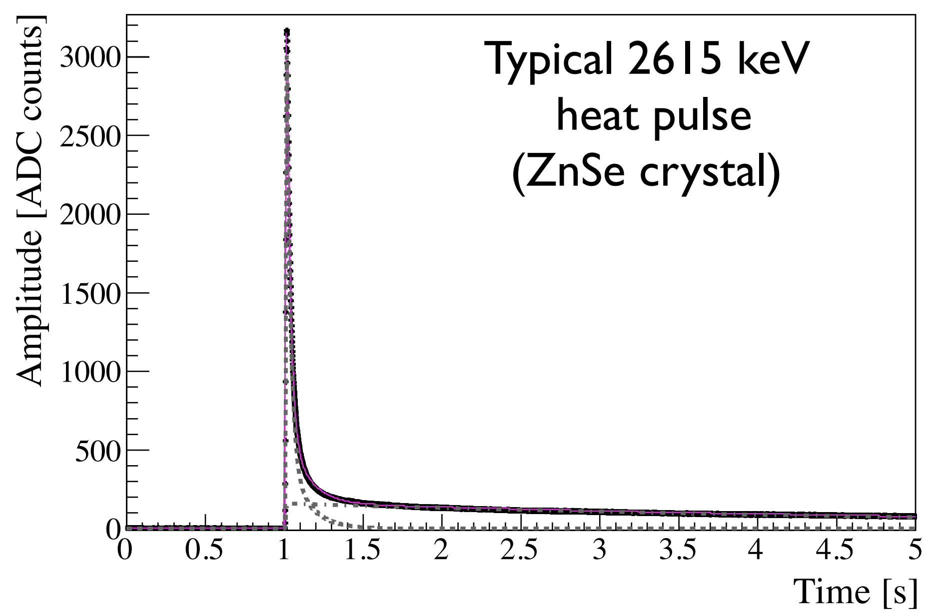
Wednesday, September 4, 13

Crystal operated as calorimeter at **~10 mK**

Particle interaction ➪ E deposit ➪ T increase

Dedicated sensor to convert ΔT in a voltage pulse

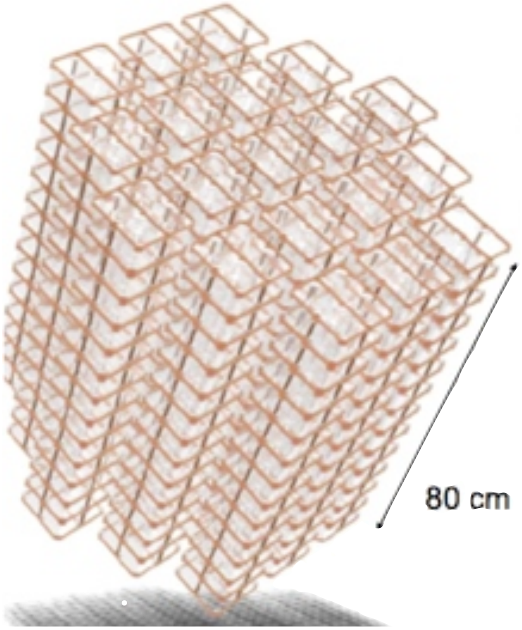
- Grown from 0νββ emitter ➪ **ε > 80%**
- Possibility to test **different 0νββ emitters**
- Excellent **energy resolution** (5-20 keV FWHM at 2615 keV)
- Scalability ➪ large **source mass**

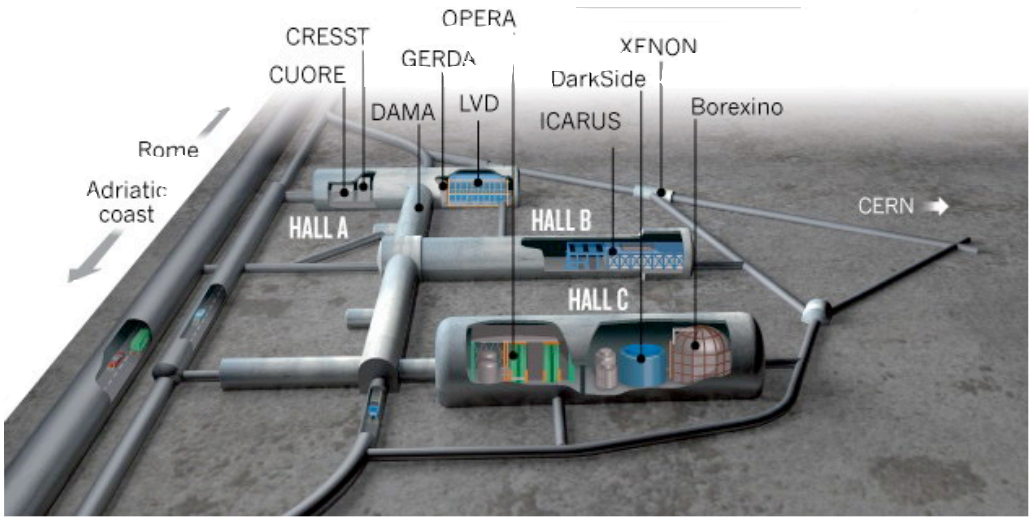


CUORE

Goal: study of the ^{130}Te $0\nu\beta\beta$ with sensitivity of ~ 10^{26} y

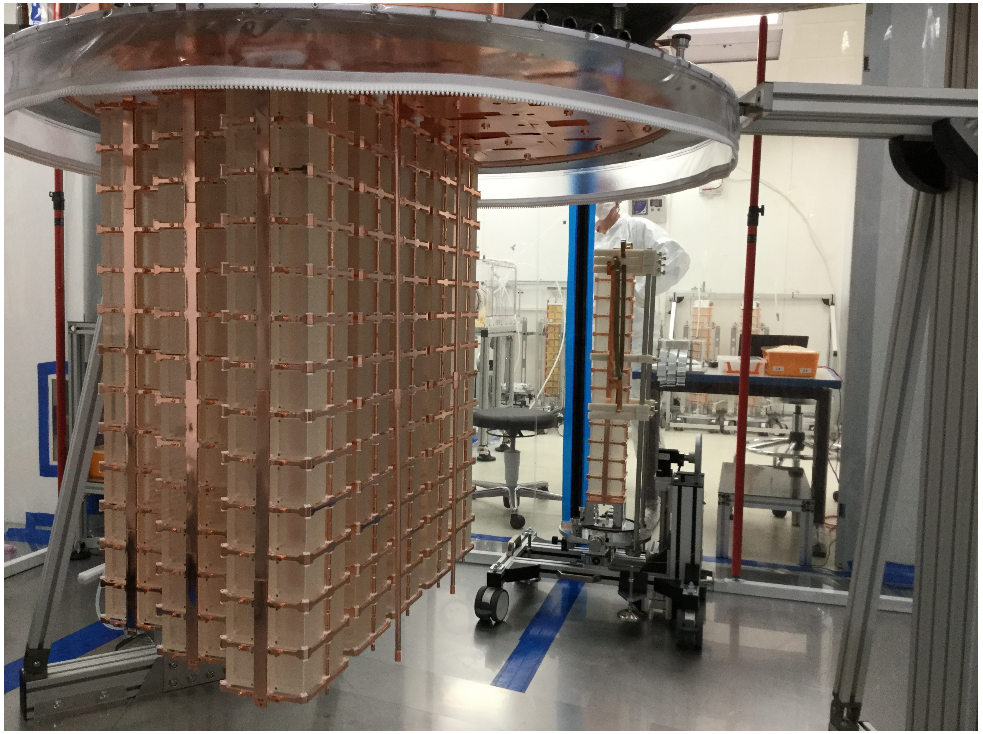
- **988 TeO_2** crystals for a **total mass of ~1 ton**
- 206 kg of ^{130}Te
- Background goal: **200 counts in the ROI** (far from zero)
- In data taking at Laboratori Nazionali del Gran Sasso
→ mountain suppresses the cosmic rays interactions of ~10^6

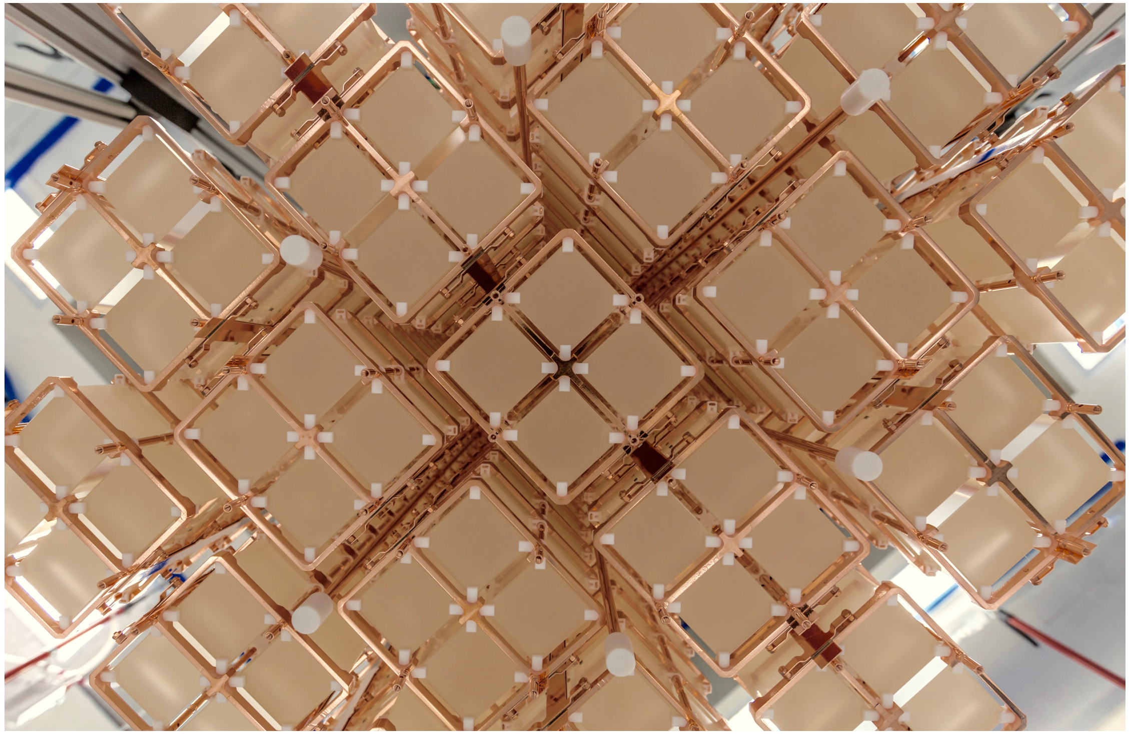




CUORE

Assembly completed in August 2016





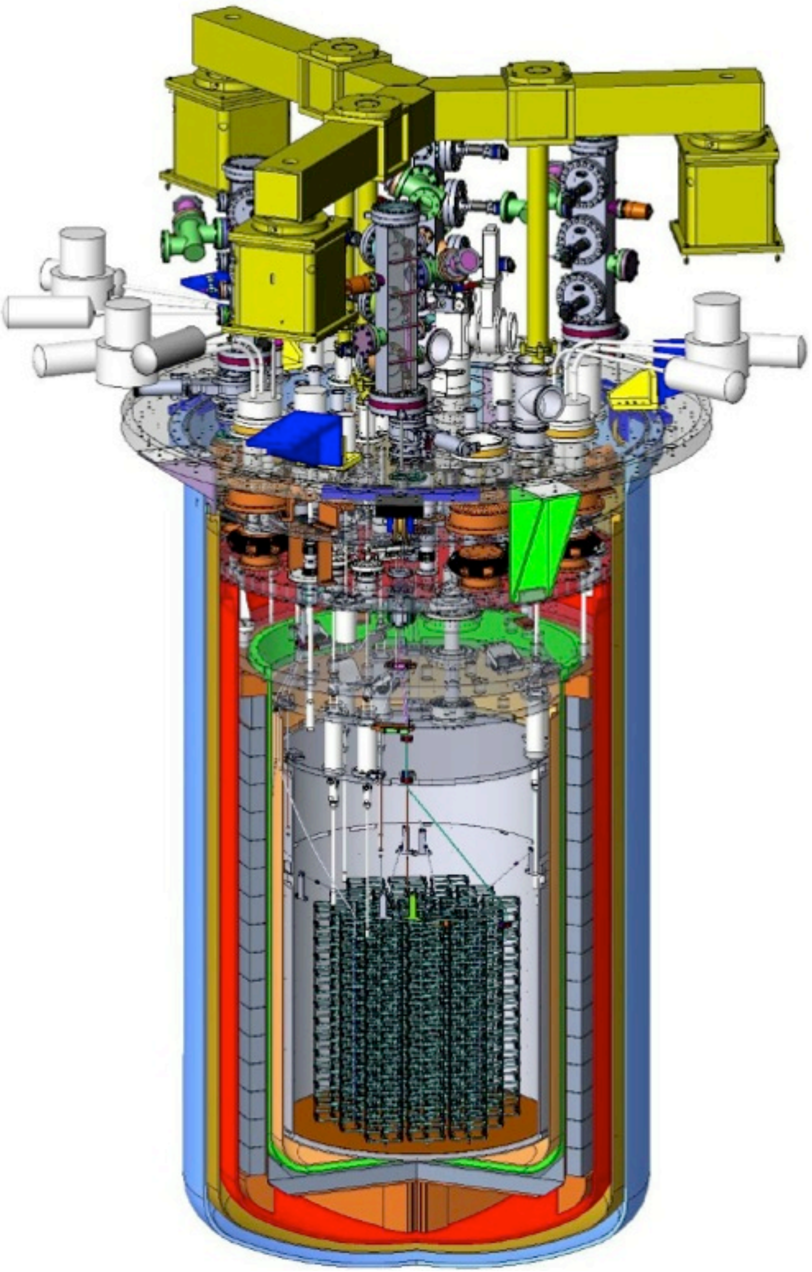
CUORE

10 mK shield

Roman Pb radiation shield (4K)

Thermal shields,
radiation shields,
and electronics
installed
Sep – Nov, 2016

CUORE



3 tons of crystals and copper at **10 mK**

~20 tons at different temperature stages

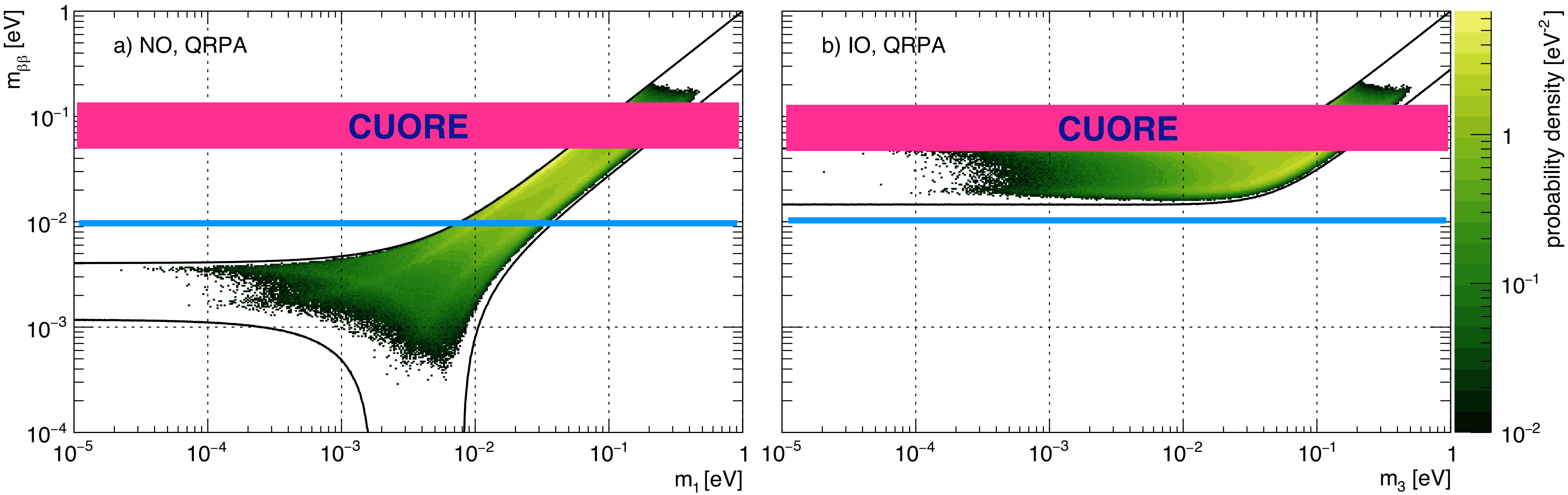
January 2017: base temperature **(10 mK) reached**

Today: commissioning completed, in **data taking**!

The success of CUORE is fundamental for future bolometric experiments

From CUORE to CUPID

Goal: study of the ^{130}Te $0\nu\beta\beta$ with sensitivity of $T_{1/2} \sim 10^{26}$ y
CUORE will probe the region of **$m_{\beta\beta}$ 50-130 meV**

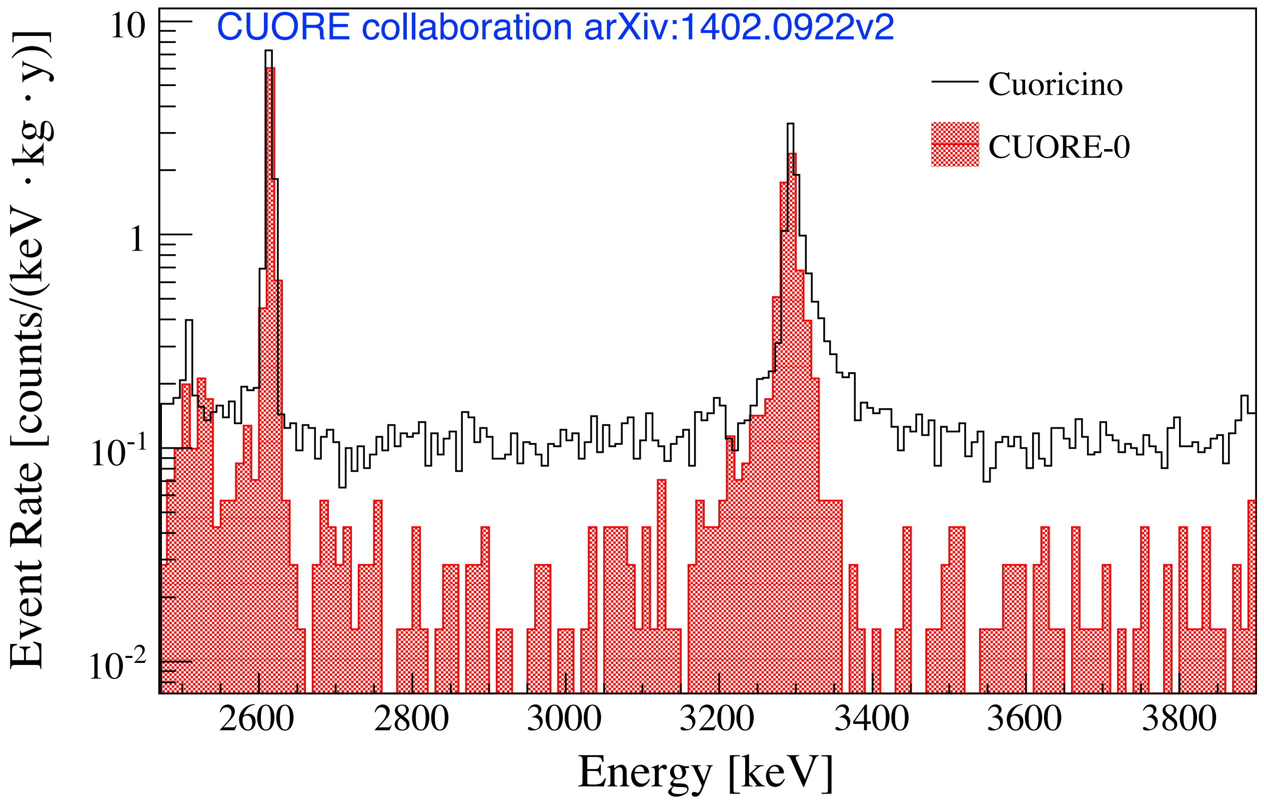


Next generation projects are targeting a discovery potential as low as **10 meV.**

CUPID
CUORE Upgrade with Particle Identification

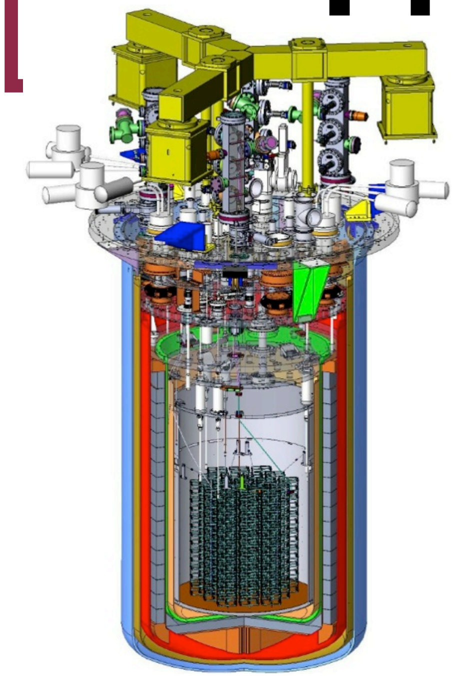
G. Wang arXiv:1504.03599
G. Wang arXiv:1504.03612

Background Study: CUORE-0

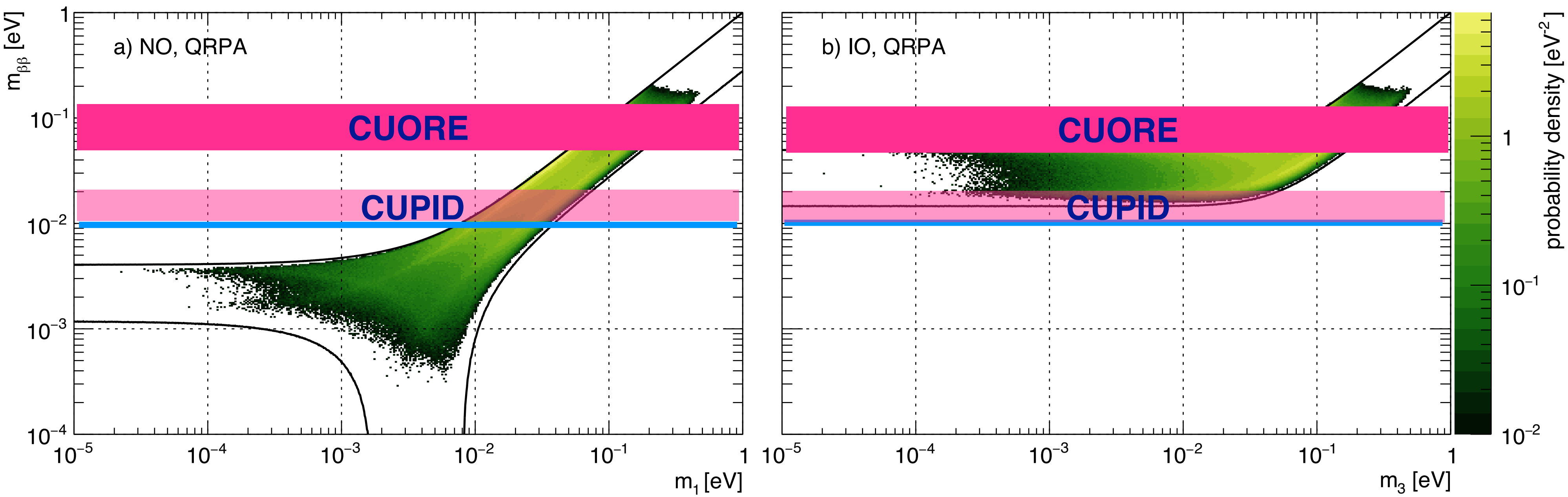


- Background: **α-decaying isotopes** on copper/crystals
- Further improvement of cleaning? Not realistic
- Novel technologies: **particle identification**

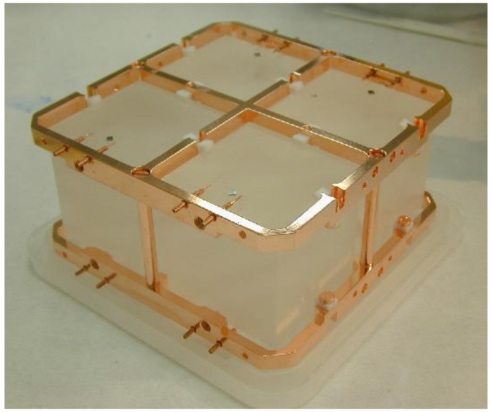
From CUORE to CUPID

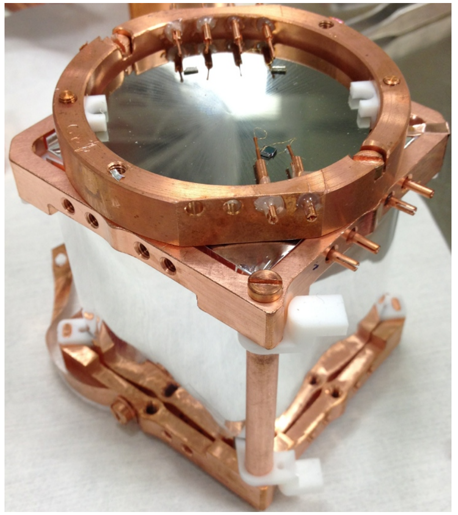


- **CUORE cryostat** (ultimate limit in the detector mass)
- Same **energy resolution 0.1%**
- **Particle identification** to distinguish electrons (possible 0nDBD) from α (dominant background): **light output**



Particle Identification





TeO_2

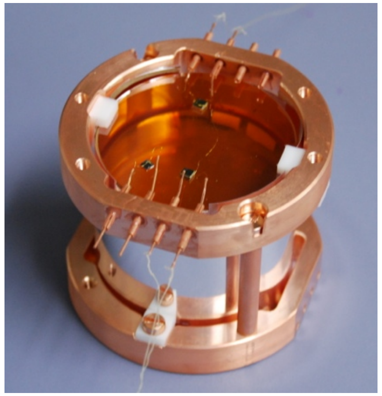
CHERENKOV LIGHT DETECTION

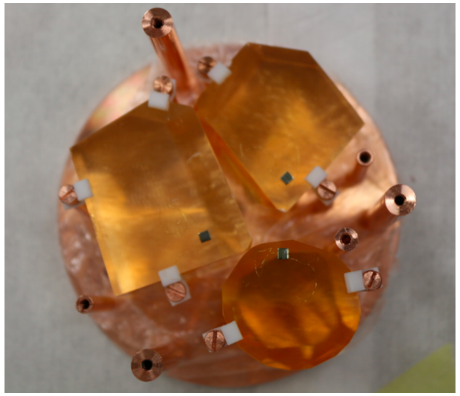
- Ge + Luke effect
- TES
- MMC
- KIDs

SURFACE EFFECTS

- Al films

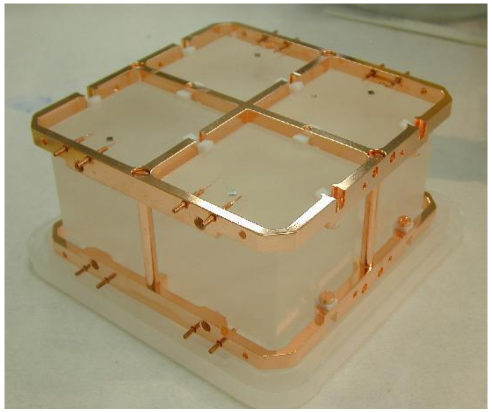
Other emitters/crystals

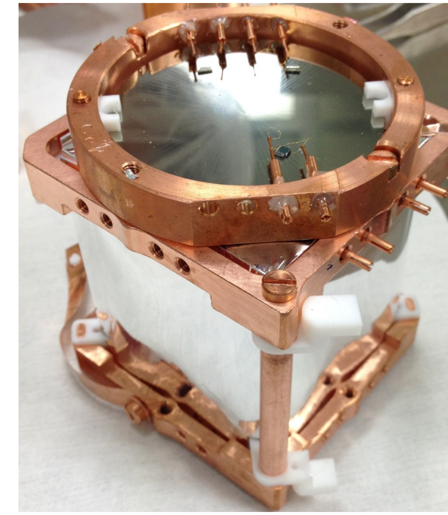




- ZnSe (^{82}Se)
- $ZnMoO_4$ (^{100}Mo)
- $CdWO_4$ (^{116}Cd)

Particle Identification





TeO_2

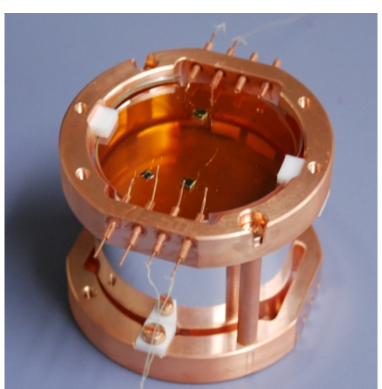
CHERENKOV LIGHT DETECTION

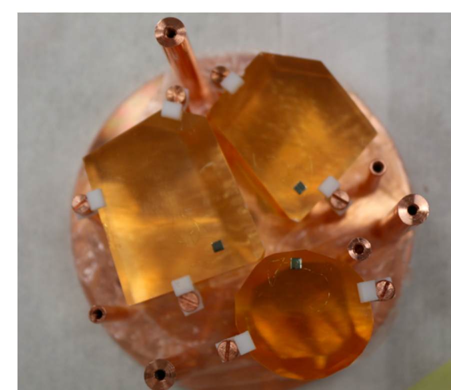
- Ge + Luke effect
- TES
- MMC
- KIDs

SURFACE EFFECTS

- Al films

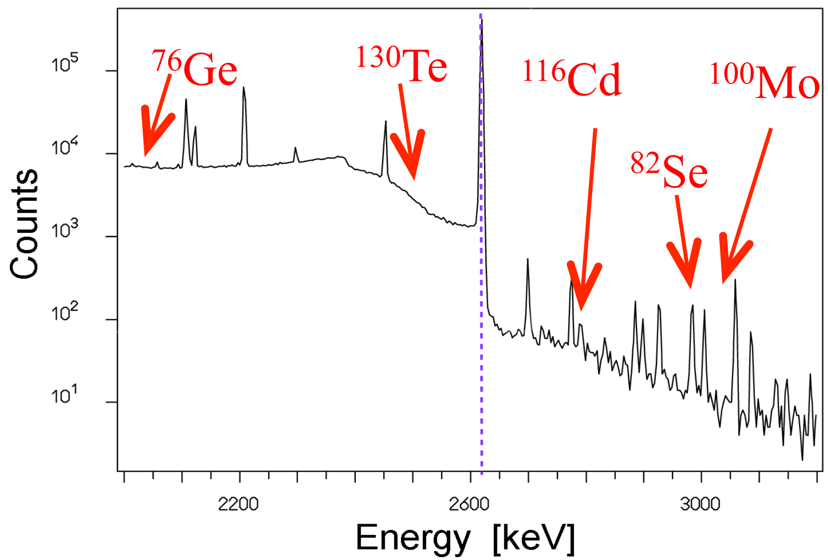
Other emitters/crystals





- ZnSe (^{82}Se)
- $ZnMoO_4$ (^{100}Mo)
- $CdWO_4$ (^{116}Cd)

Other emitters: Se



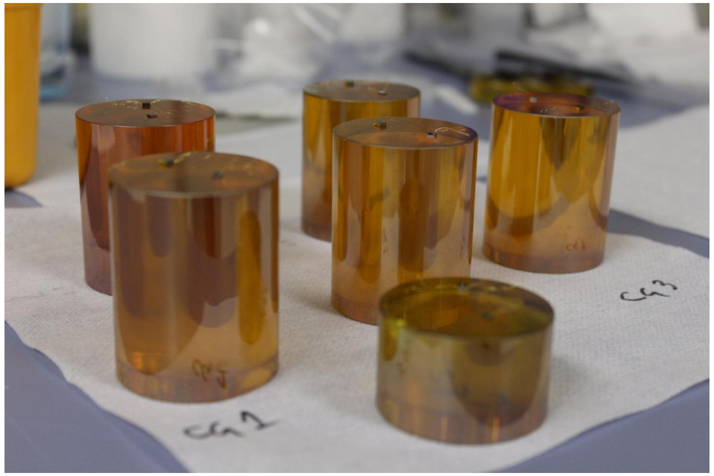
Isotopes with large Q-value

➪ we **suppress also γ background**

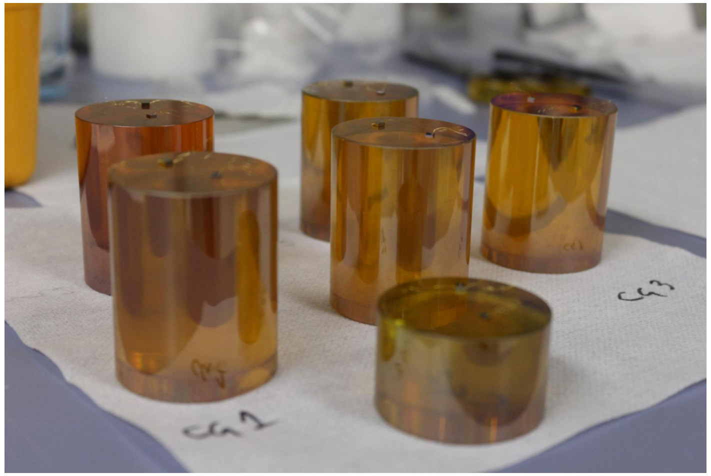
➪ approach **zero background!**

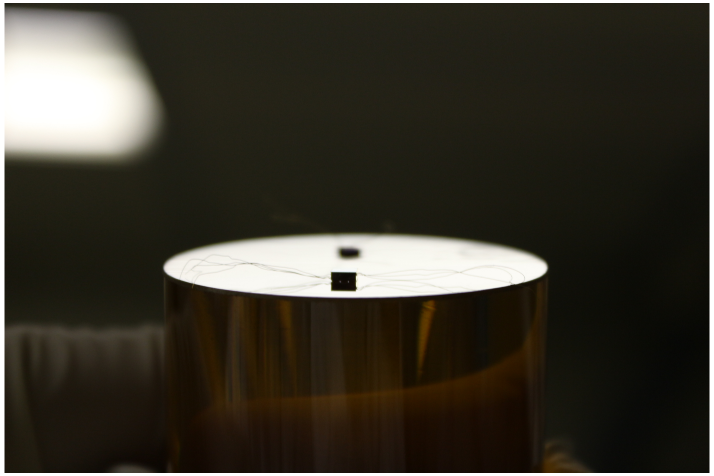
Which isotope? Years of R&D, many possibilities

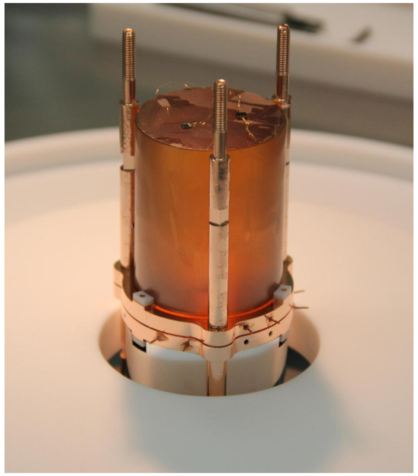
- **^{82}Se**: high **Q-value ~2998 keV**
- Enrich in ^{82}Se from 8.7% to **96.3%** (arXiv:1702.05877)
- ^{82}Se embedded in **Zn^{82}Se crystals** to be operated as **cryogenic calorimeters**

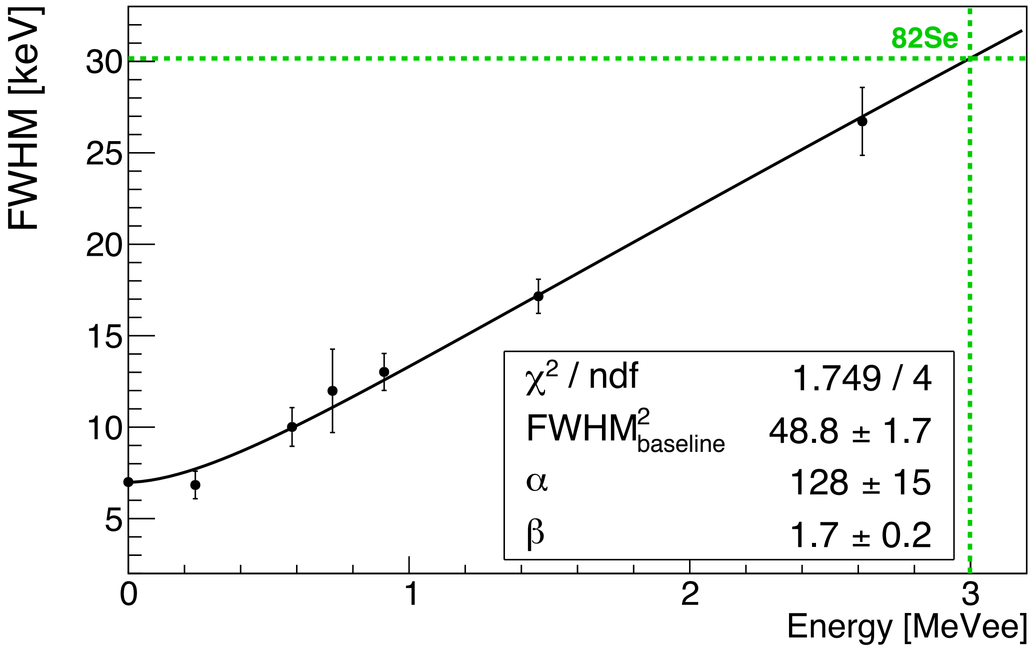


ZnSe scintillating calorimeters



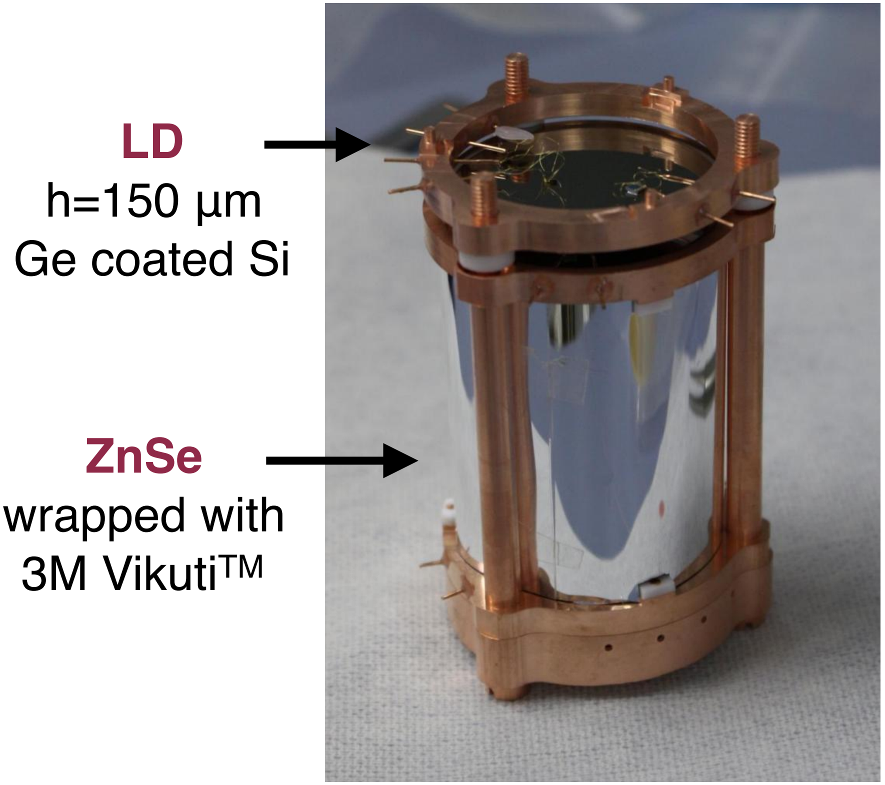




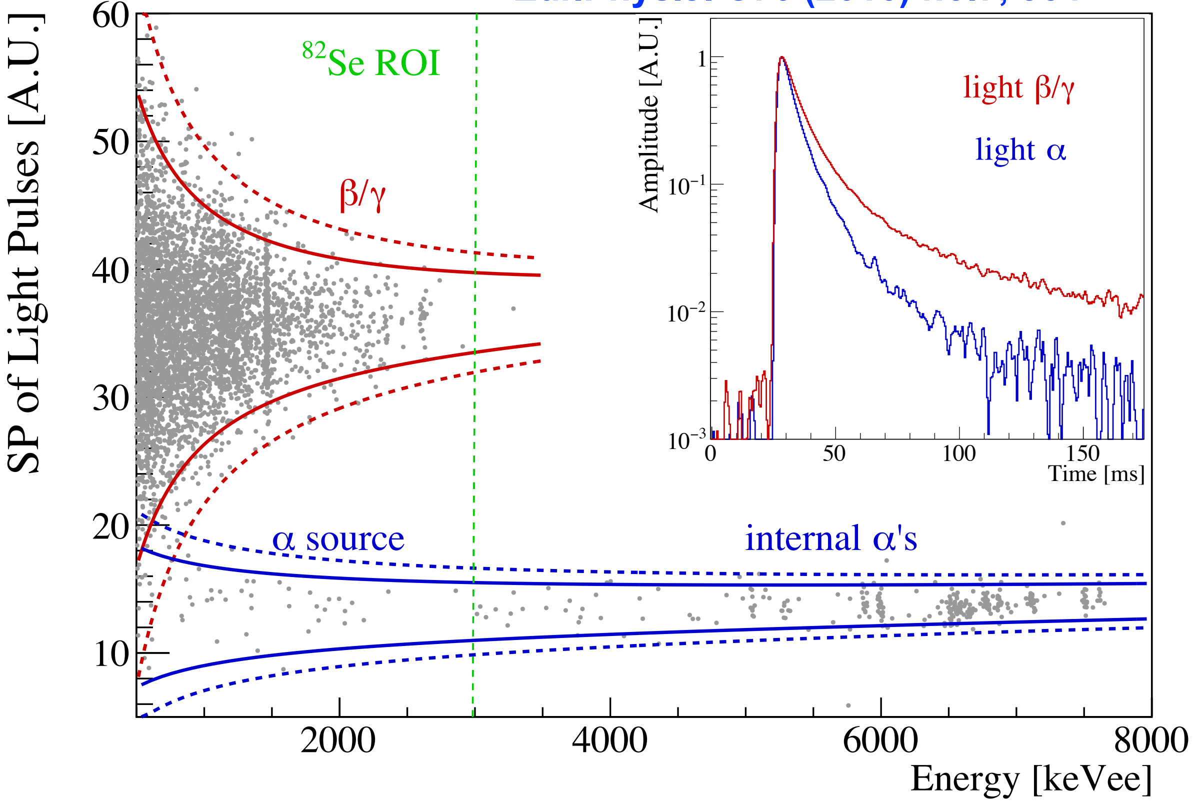


- Containment **efficiency >80%**
- Energy resolution **30 keV at 3 MeV** (1%)
- Reasonable intrinsic background

Potential of Particle ID



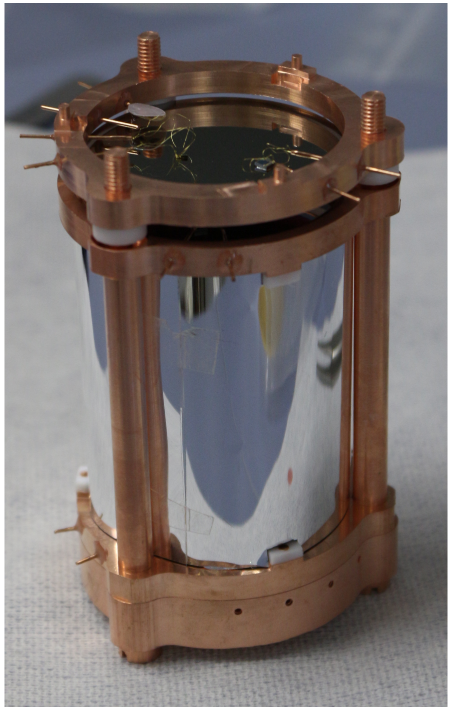
Eur.Phys.J. C76 (2016) no.7, 364

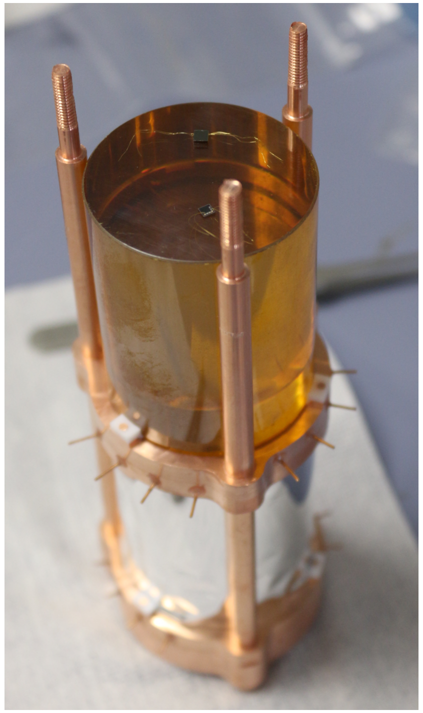


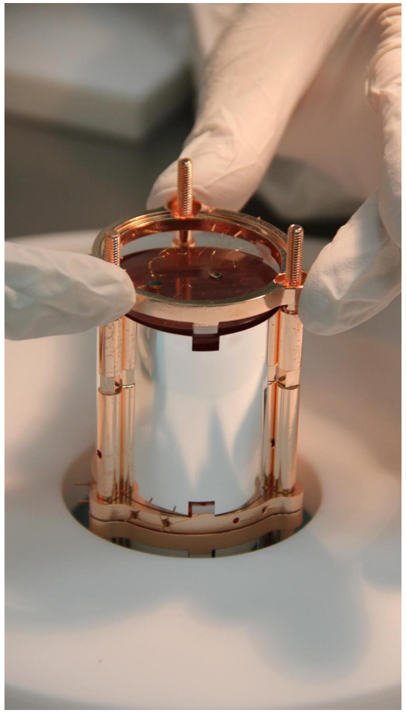
- Containment **efficiency >80%**
- Energy resolution **30 keV at 3 MeV** (1%)
- Reasonable intrinsic background

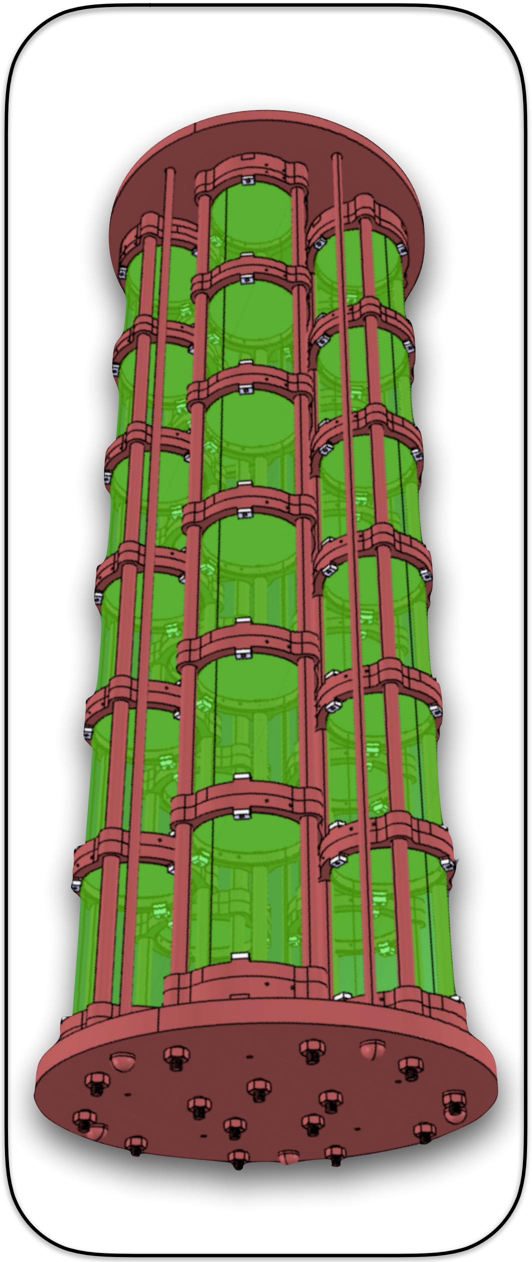
Complete rejection of the dominant alpha background

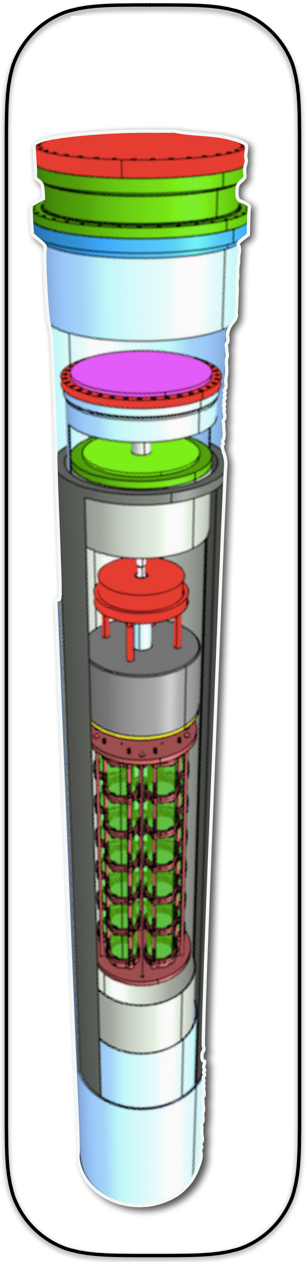
CUPID-0









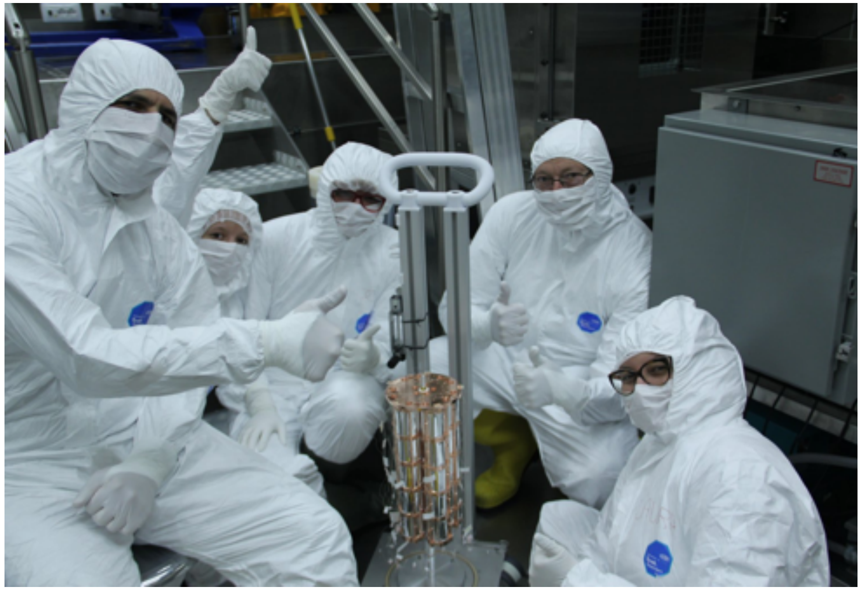


- **CUPID-0** is a modular detector **~10 kg**
- Commissioned in **early 2017**
- About 60 researcher from Italy, US and France

CUPID-0 Assembly

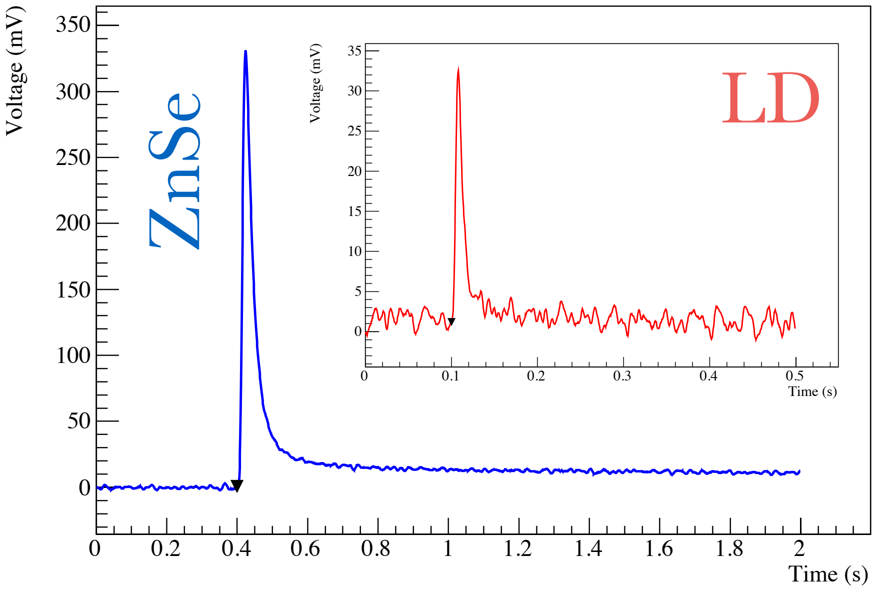
Coordinated by Nicola Casali

Invaluable help from S. Morganti, M. Iannone, V. Pettinacci, M. Capodiferro and A. Pelosi



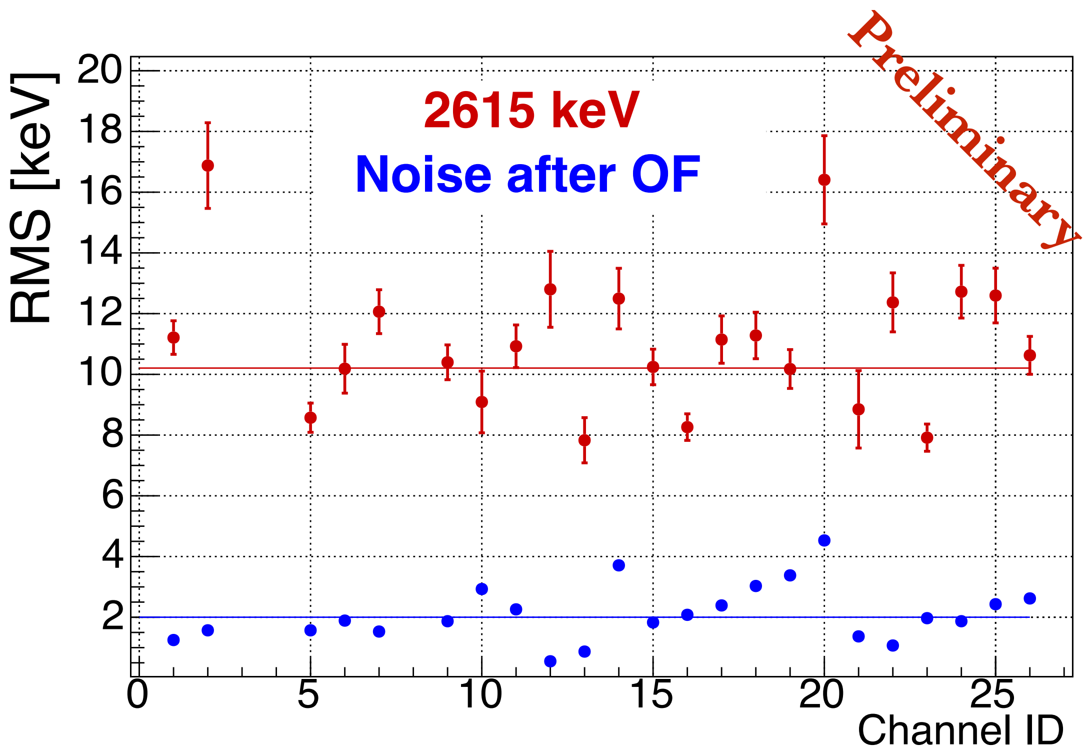
- 24 Enriched $Zn^{82}Se$ crystals + 2 natural ZnSe
- 10.5 kg ZnSe (5.17 kg of ^{82}Se)
- CUPID-0 is a demonstrator, still it features **3.8×10^{25} 0nDBD emitters**

First Data



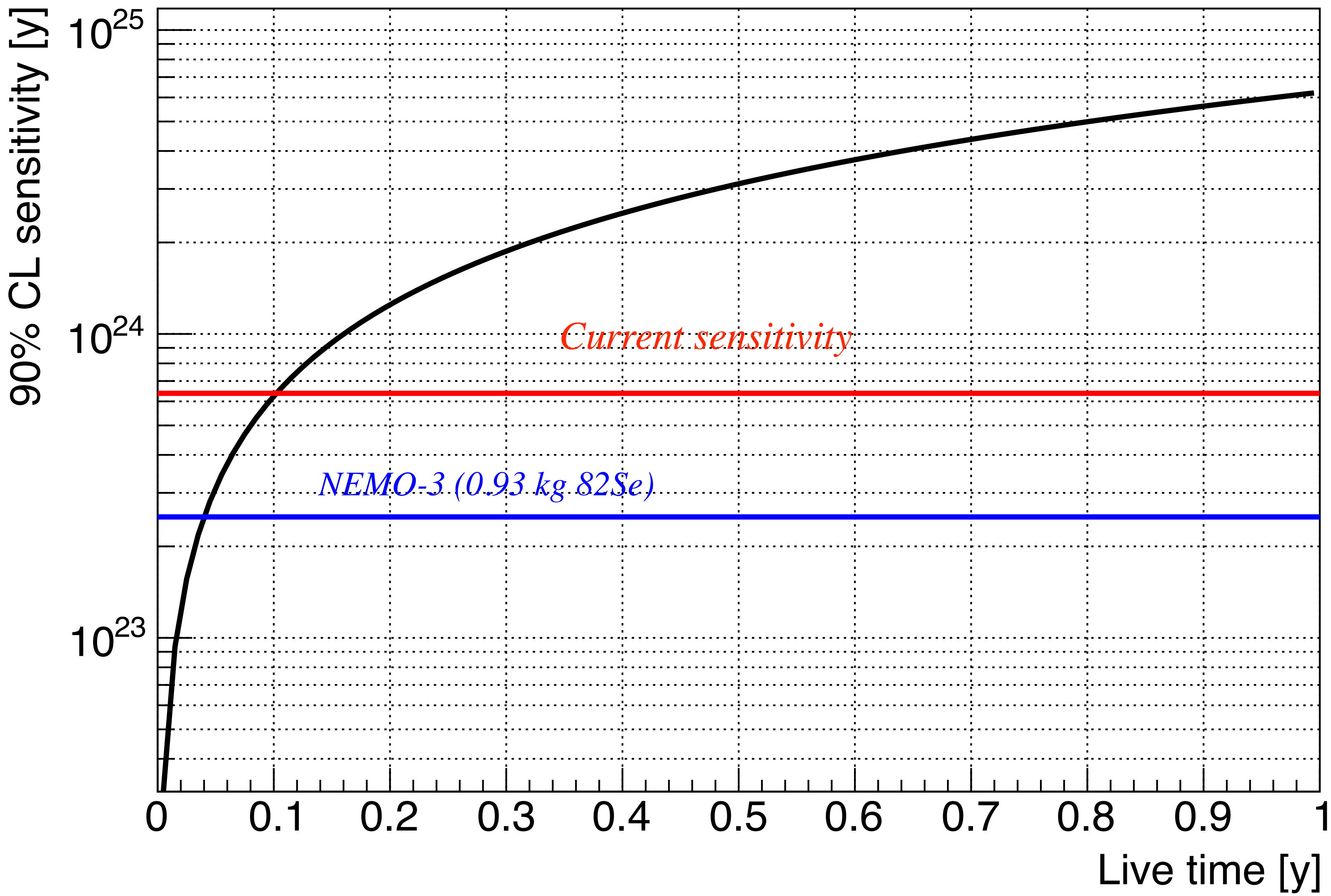
First pulses from **all** the detectors

2 channels temporarily excluded



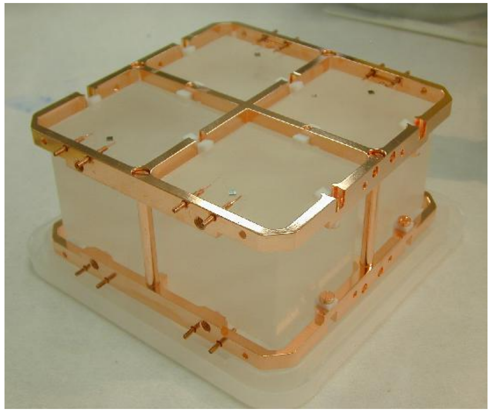
- Average **FWHM @2.6 MeV = 25.5 keV**
- Still room for improvement

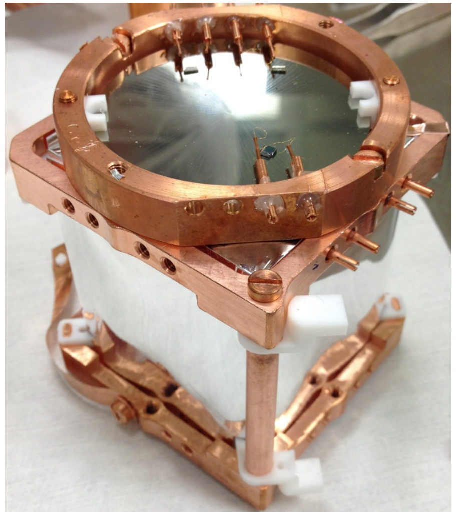
CUPID-0 Perspectives



In ~one month of operations we can already surpass current limits on 0nDBD of ^{82}Se

Many possibilities





TeO_2

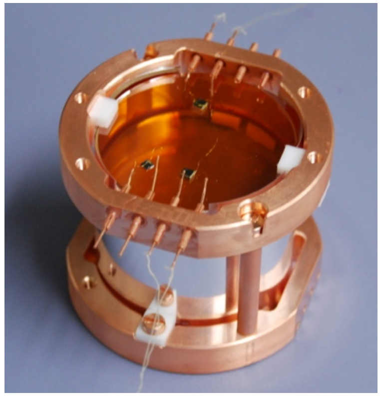
CHERENKOV LIGHT DETECTION

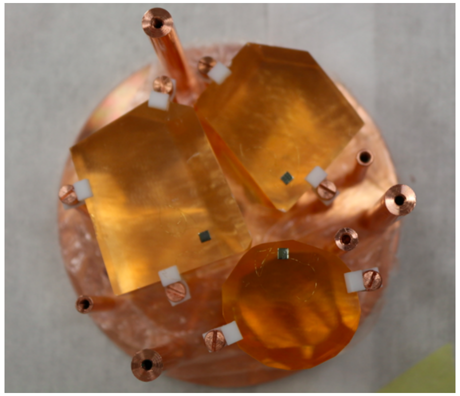
- Ge + Luke effect
- TES
- MMC
- KIDs

SURFACE EFFECTS

- Al films

Other emitters/crystals

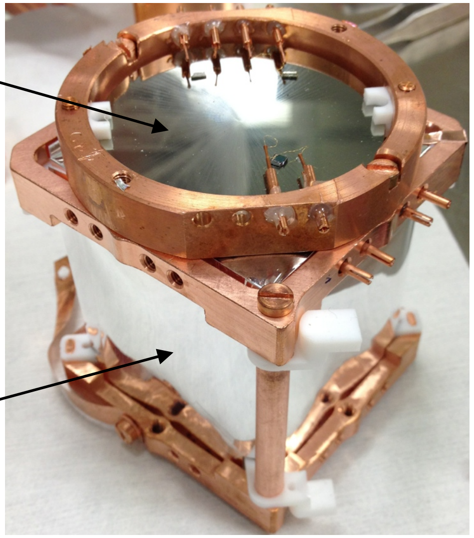




- ZnSe (^{82}Se)
- $ZnMoO_4$ (^{100}Mo)
- $CdWO_4$ (^{116}Cd)

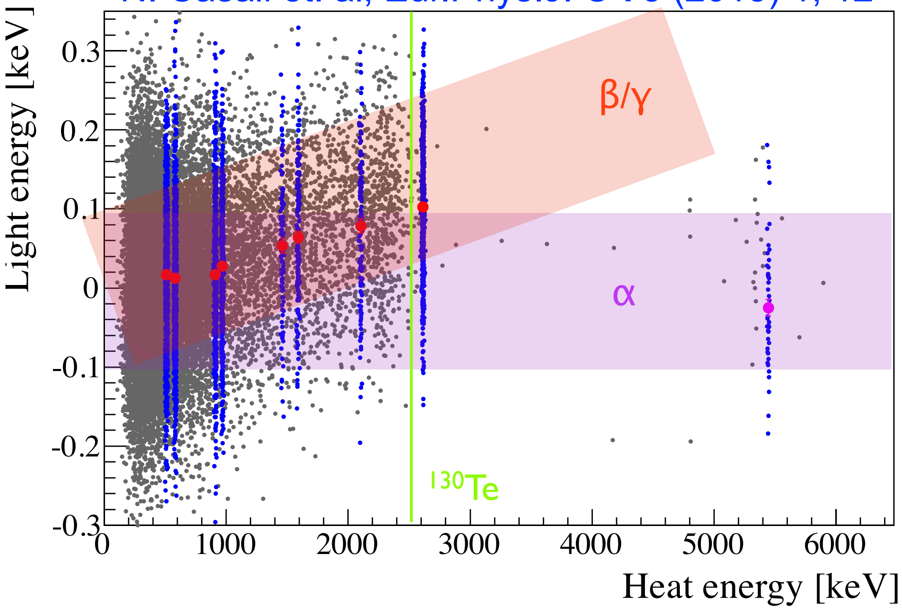
TeO_2 + Cherenkov

Light Detector



TeO_2

N. Casali et. al, Eur.Phys.J. C **75** (2015) 1, 12



CUORE TeO_2 feature **low light output** (~100 eV at 0νββ from Cherenkov emission)

Using a “standard" LD with noise of 80 eV RMS does not permit particle ID

A LD with noise **RMS < 20 eV** would allow to reject the dominant background (α)

Challenge: light detector

For a next generation project

- Baseline resolution <20 eV RMS
- Large active area (5x5 cm^2)
- High radio-purity
- Ease in fabrication/operation (~1000 channels)
    - Reproducible behavior in a rather wide temperature range (5-20 mK)
    - Low heat load for cryogenic system

Challenge: light detector

For a next generation project

- Baseline resolution <20 eV RMS
- Large active area (5x5 cm^2)
- High radio-purity
- Ease in fabrication/operation (~1000 channels)
    - Reproducible behavior in a rather wide temperature range (5-20 mK)
    - Low heat load for cryogenic system

A lot of interest…

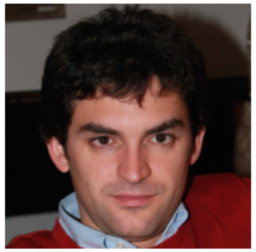
L.Gironi et al. arXiv:1603.08049 (2016)
L.Pattavina et al., Journal of Low Temp Phys 1-6 (2015)
M. Biassoni et al., Eur.Phys.J. C75 (2015) 10, 480
K.Schaeffner et. al, Astropart.Phys. 69 (2015) 30-36
M. Willers et al., JINST 10 P03003 (2015)
and many others

But none of the existing technologies fulfills **all** these requirements (yet)

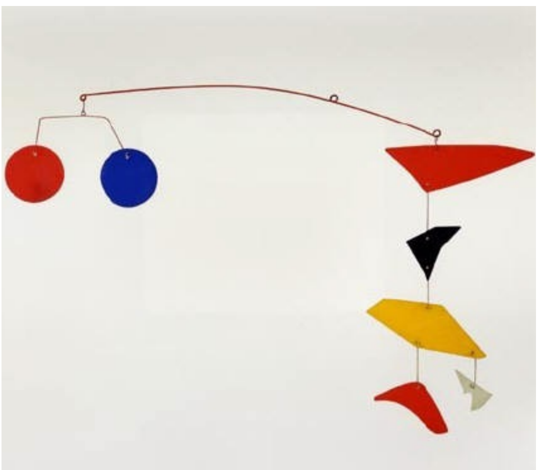
↓

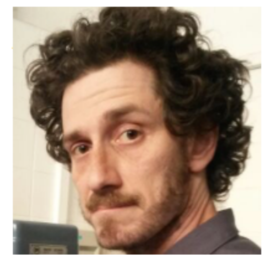
We propose a new technology

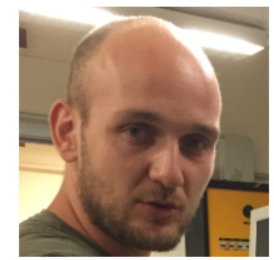
CALDER collaboration



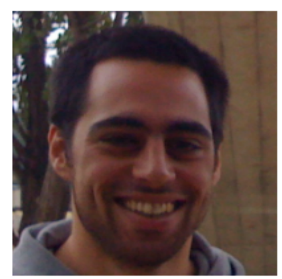




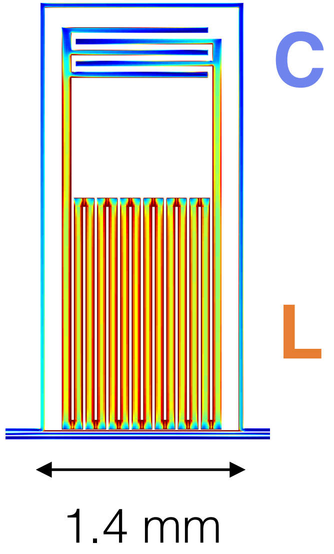
CALDER public webpage:
http://www.roma1.infn.it/exp/calder/

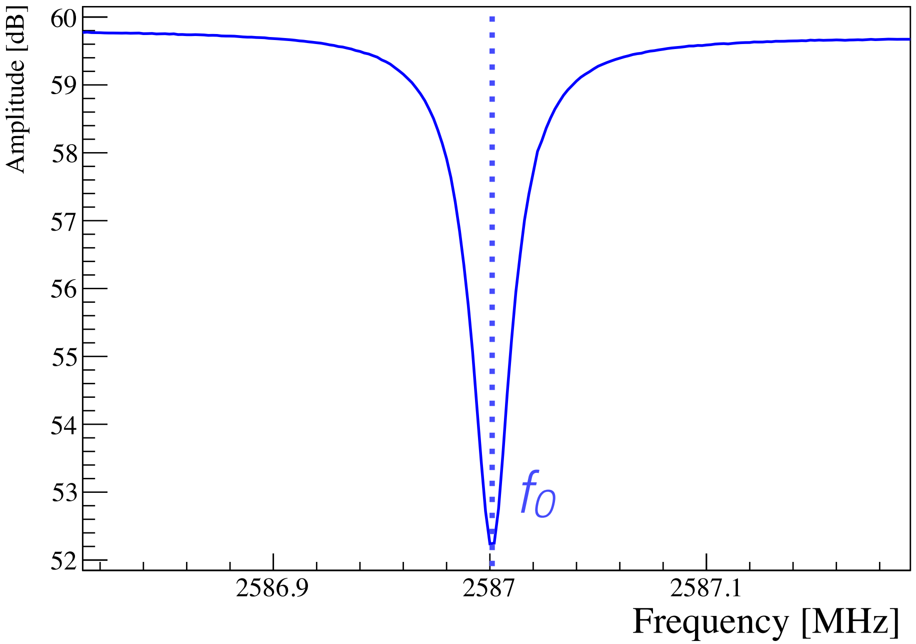

Mostly from INFN-Roma and Sapienza, coming from rare events searches sector
KIDs, cryogenic and electronics experts from astrophysics and SQUID
Other collaborators from Italian and (now) France institutions

Kinetic Inductance Detectors

- Superconductors below Tc → Cooper Pairs + Quasi-particles
- AC current bias → Cooper Pairs acquire **kinetic inductance** L
- Insert in high merit factor RLC circuit (Q ~ 10^4-10^5)

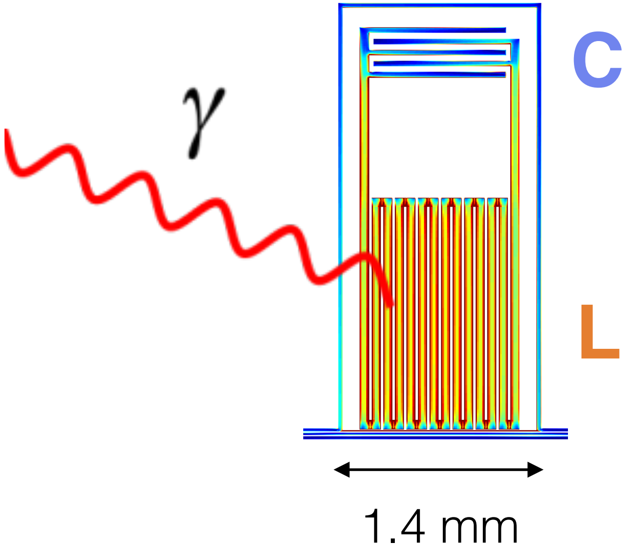


$$f_0 = \frac{1}{2\pi\sqrt{LC}}$$

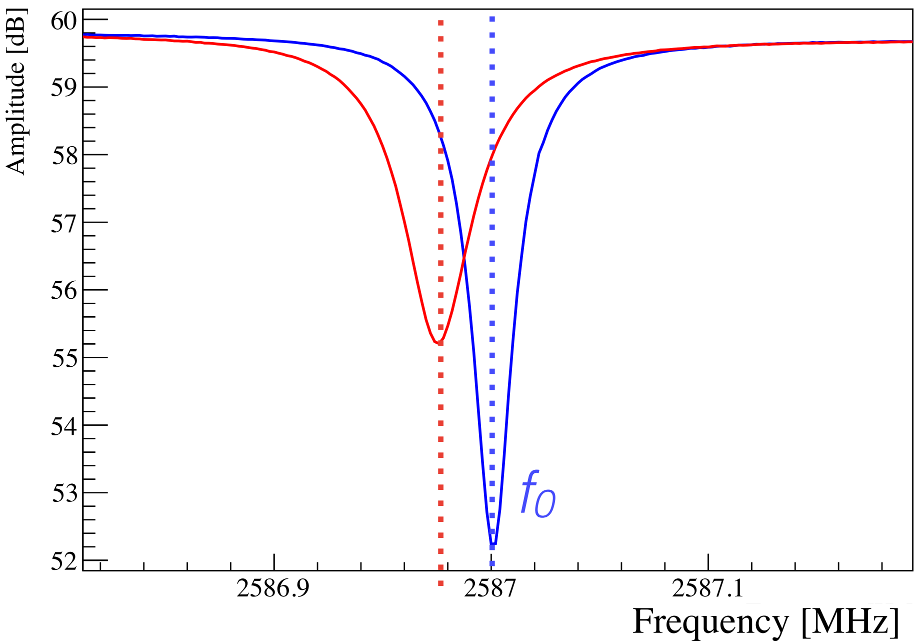


Kinetic Inductance Detectors

- The **photon** interaction breaks Cooper pairs
- The inductance **L changes**
- The resonance **shape and frequency change**



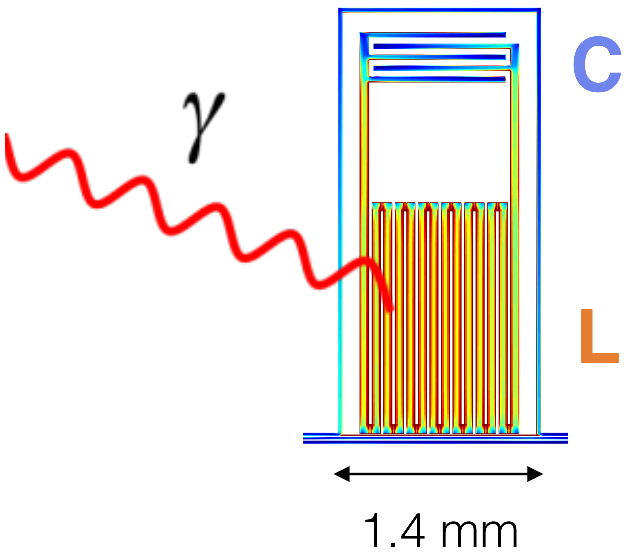
$$f_0 = \frac{1}{2\pi\sqrt{LC}}$$



Kinetic Inductance Detectors

Main advantages:

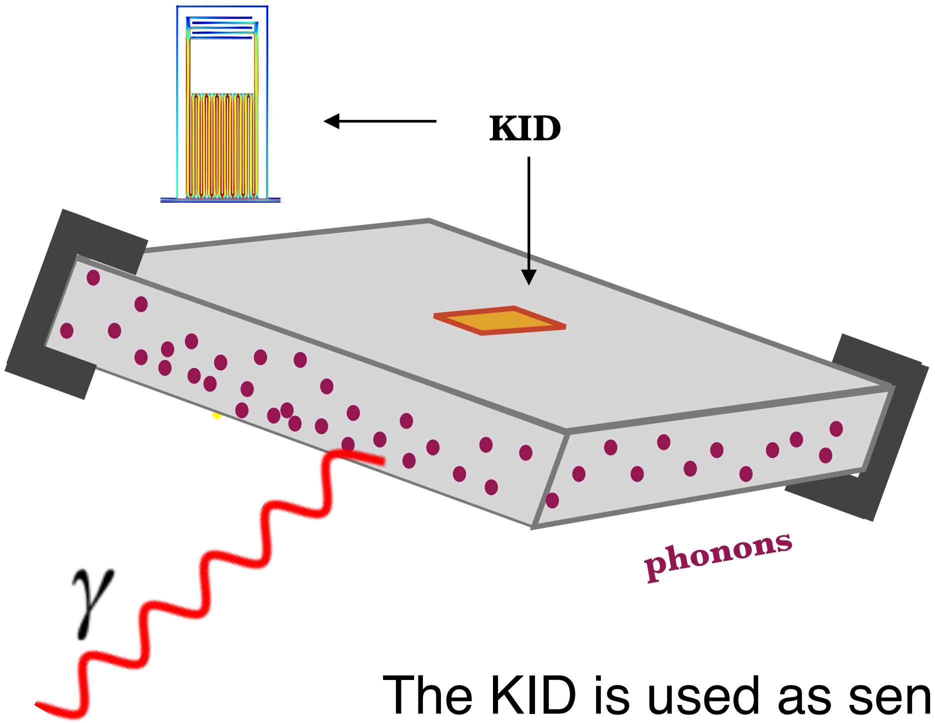
- Excellent sensitivity (baseline resolution **~eV**) (<20 eV)
- Natural **multiplexing** in frequency domain
- **Stable** behavior if operated well below T_C

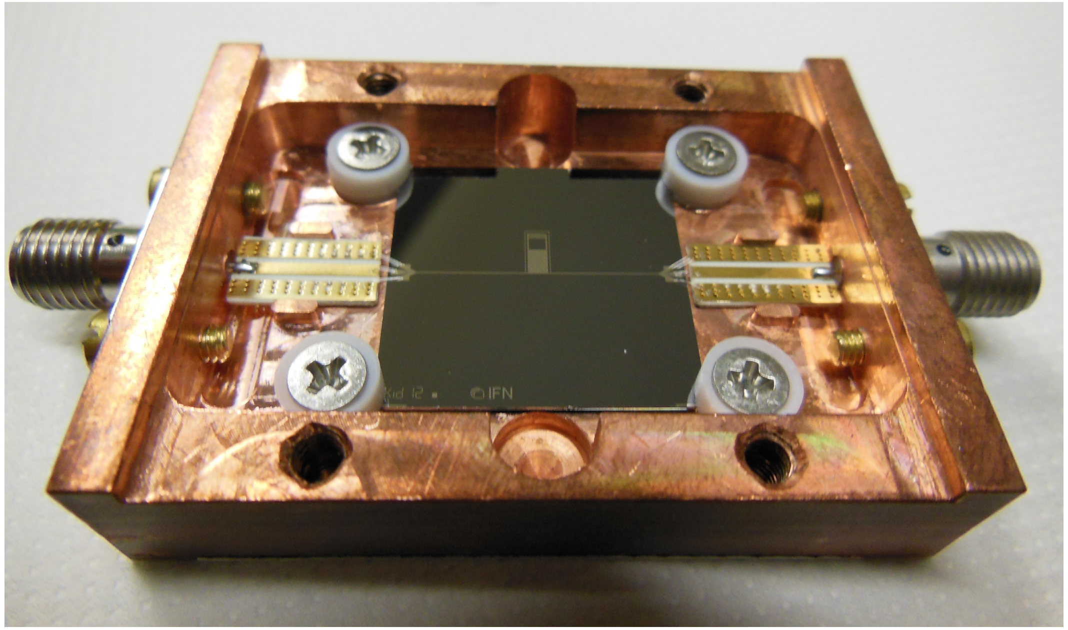


BUT **poor active surface** (a few mm^2)

TARGET: $5x5 cm^2$

Phonon Mediation





The KID is used as sensor on an insulating (Si) substrate

Photon interacts in substrate producing phonons, that can travel until they are absorbed by the KID.

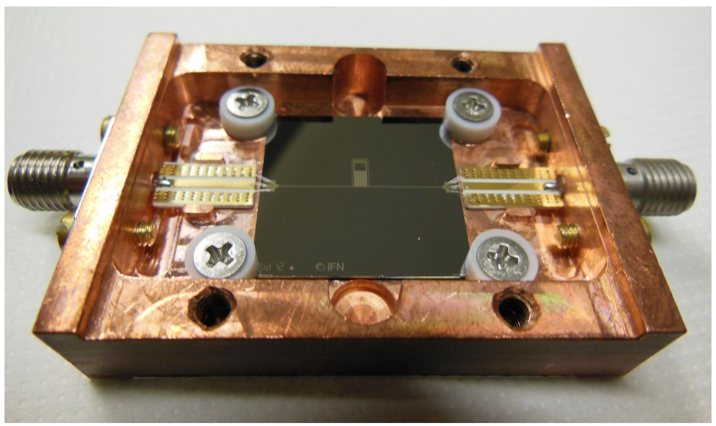
The **CALDER** project is developing a light detector based on this technology.

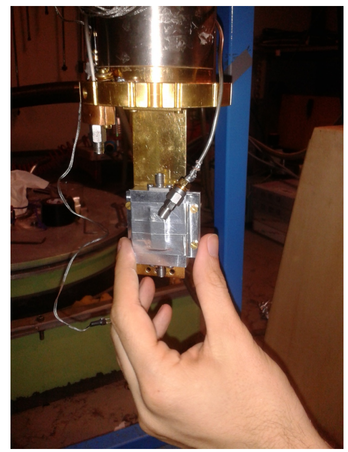
E.S Battistelli et. al, Eur.Phys.J. C75 (2015) 8, 353

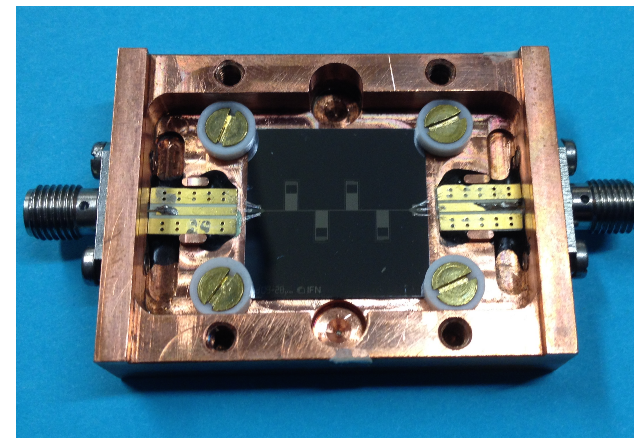
CALDER

Cryogenic Wide-**A**rea **L**ight **D**etector with **E**xcellent **R**esolution

supported by an ERC Starting Grant, started in March 2014







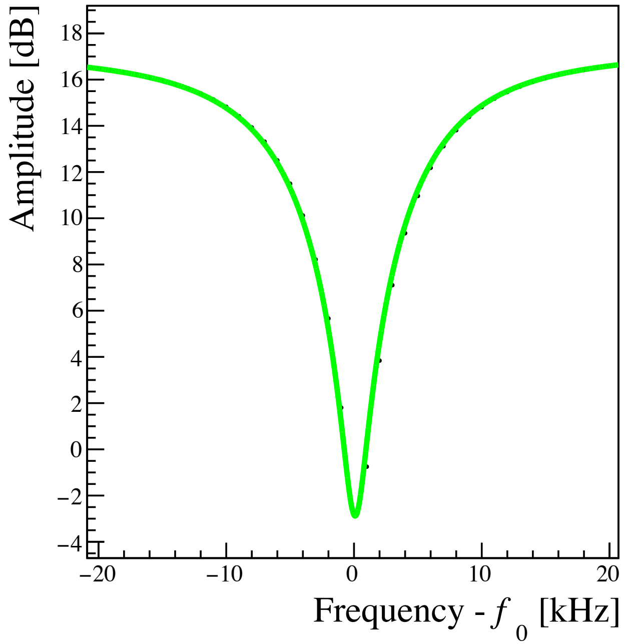
3 main project phases

1) Read-out and analysis, optimize detector geometry, using Aluminum → 80 eV

2) Move to more sensitive superconductors (TiAl, TiN..) → <20 eV

3) Large-scale test of our light detectors on TeO_2 array at LNGS (Italy)

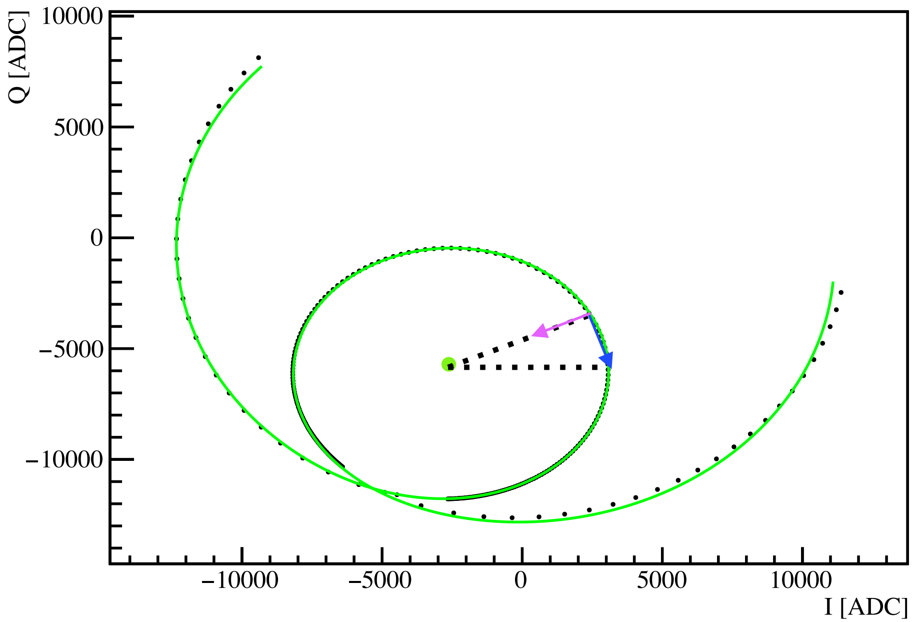
Photon Interaction

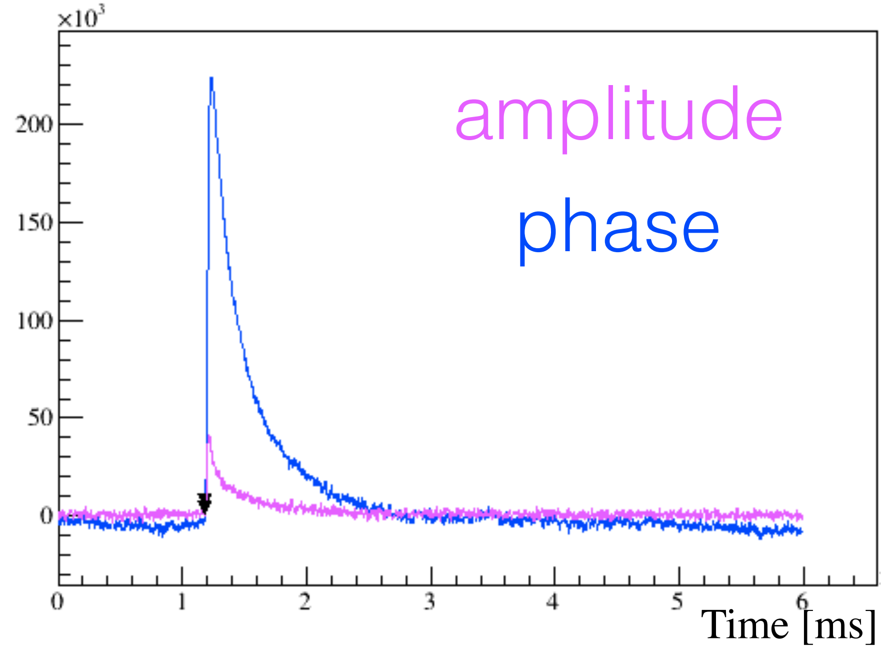


Frequency sweep to measure the transmission S_{21} past the resonator:

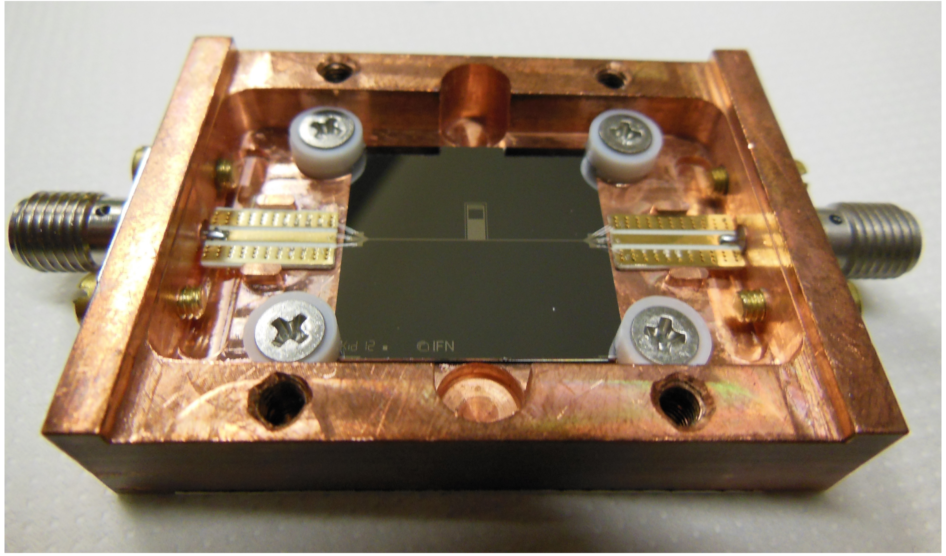
$$S_{21} = I + jQ$$

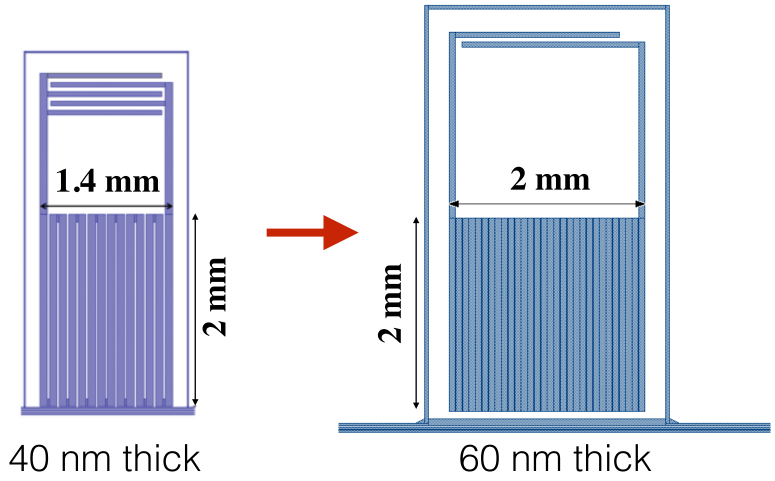
Sitting in the center of the resonance loop, we can monitor variations in I and Q (or amplitude/phase) produced by interactions

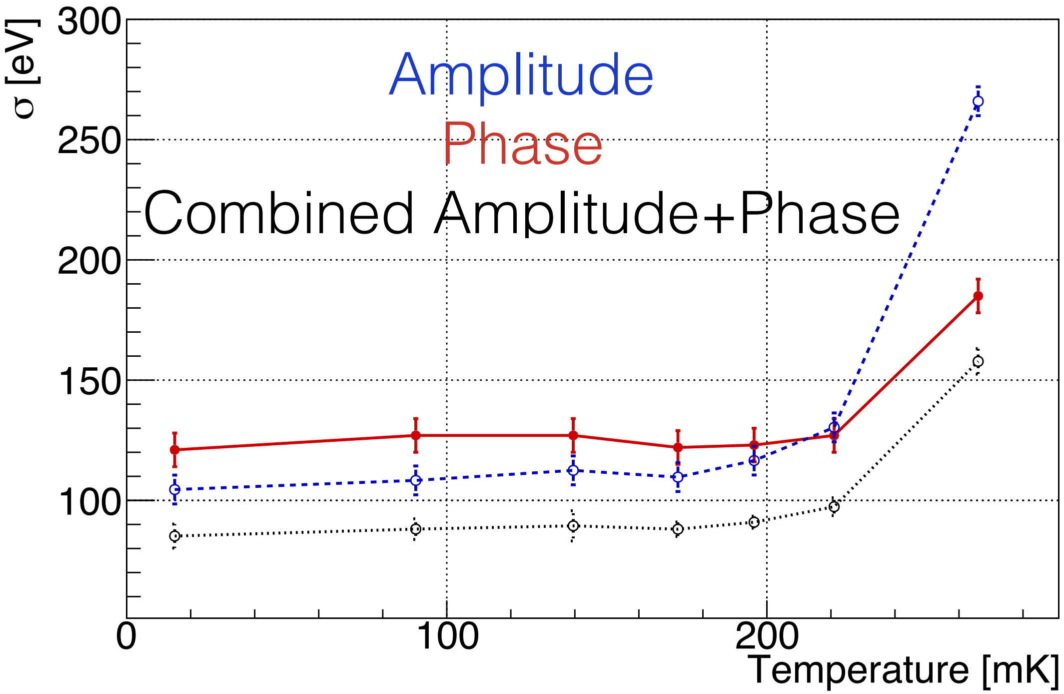




Detector Optimization







- Baseline resolution of **82 eV RMS**
- Resolution **constant up to 200 mK**

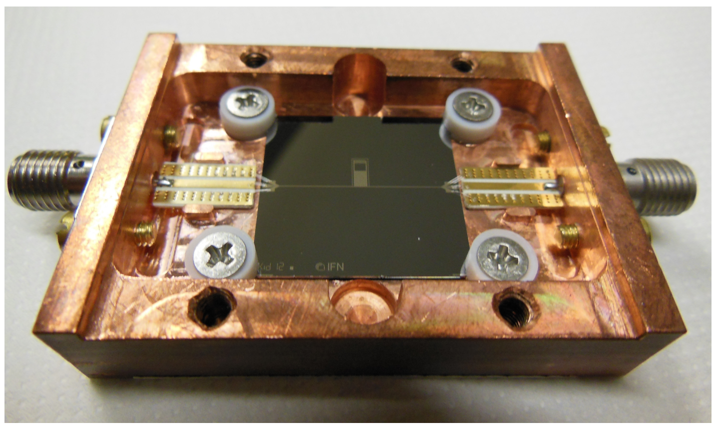
L. Cardani et al, Appl.Phys.Lett. 107 (2015) 093508

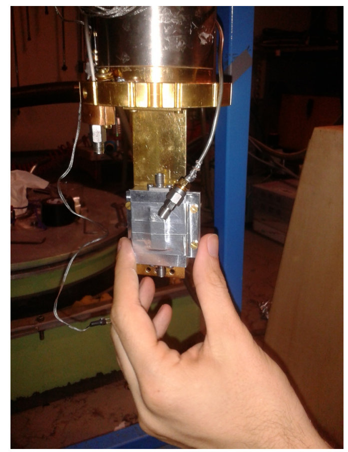
L. Cardani et al, Appl.Phys.Lett. 110 (2017) 033504

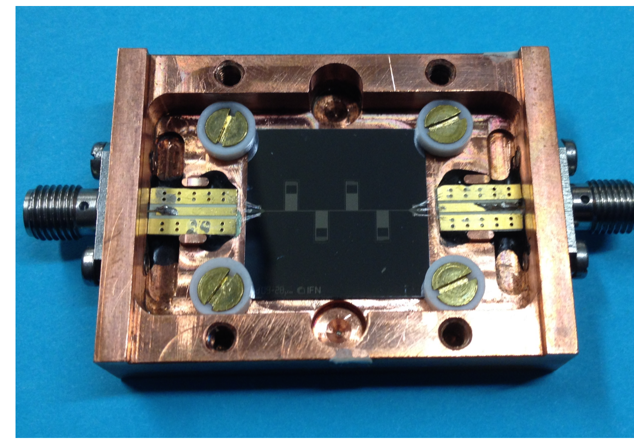
CALDER

Cryogenic Wide-**A**rea **L**ight **D**etector with **E**xcellent **R**esolution

supported by an ERC Starting Grant, started in March 2014







3 main project phases

1) ~~Optimize detector geometry, read-out and analysis using Aluminum → 80 eV~~

2) Move to more sensitive superconductors (TiAl, TiN..) → <20 eV

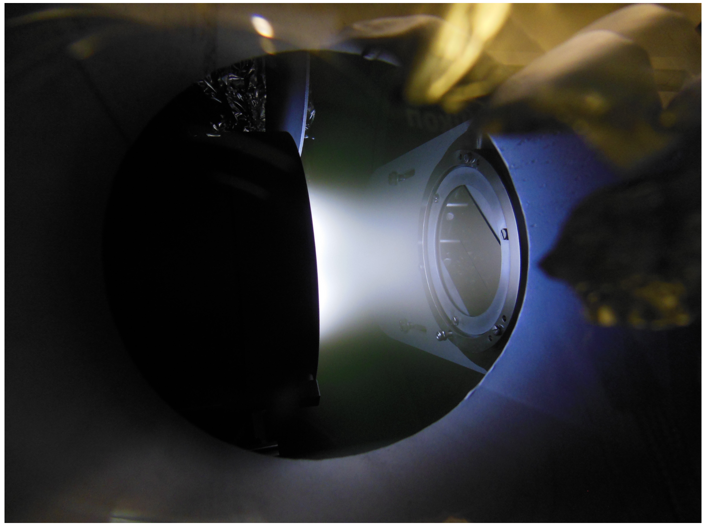
3) Large-scale test of our light detectors on TeO_2 array at LNGS (Italy)

Other Superconductors

Al does not allow to achieve the necessary sensitivity → other superconductors

$$\Delta E \propto \frac{T_C}{\epsilon\sqrt{QL}}$$

	Al	TiN sub- stoic.	Ti+TiN	TiAl
Tc [K]	1.2	0.5	0.5-0.8	0.6-0.9
L [pH/ square]	0.5	up to 50	6	1



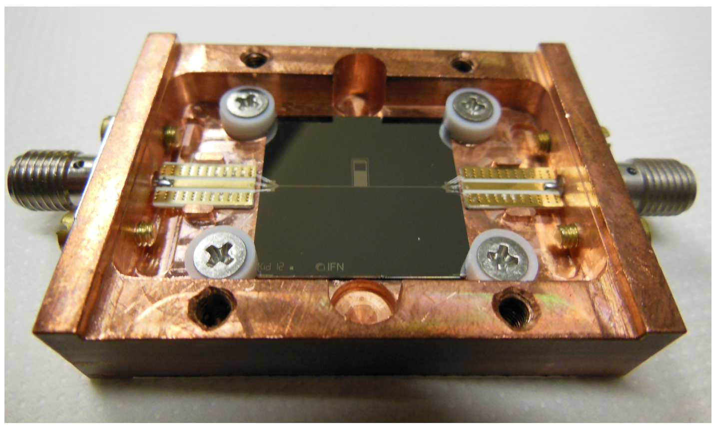
First tests on Ti-Al prototypes in collaboration with CSNSM (Orsay, France) and Institut Néel, CNRS (Grenoble, France)

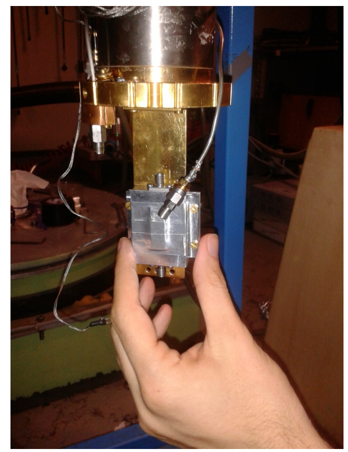
Encouraging results: **30 eV RMS** reached (paper in preparation)

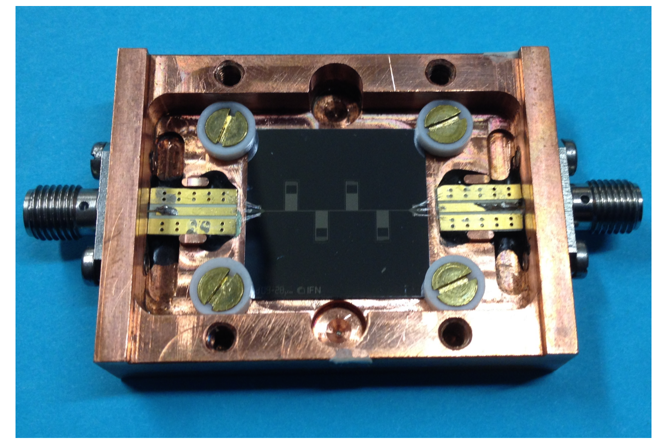
CALDER

Cryogenic Wide-**A**rea **L**ight **D**etector with **E**xcellent **R**esolution

supported by an ERC Starting Grant, started in March 2014







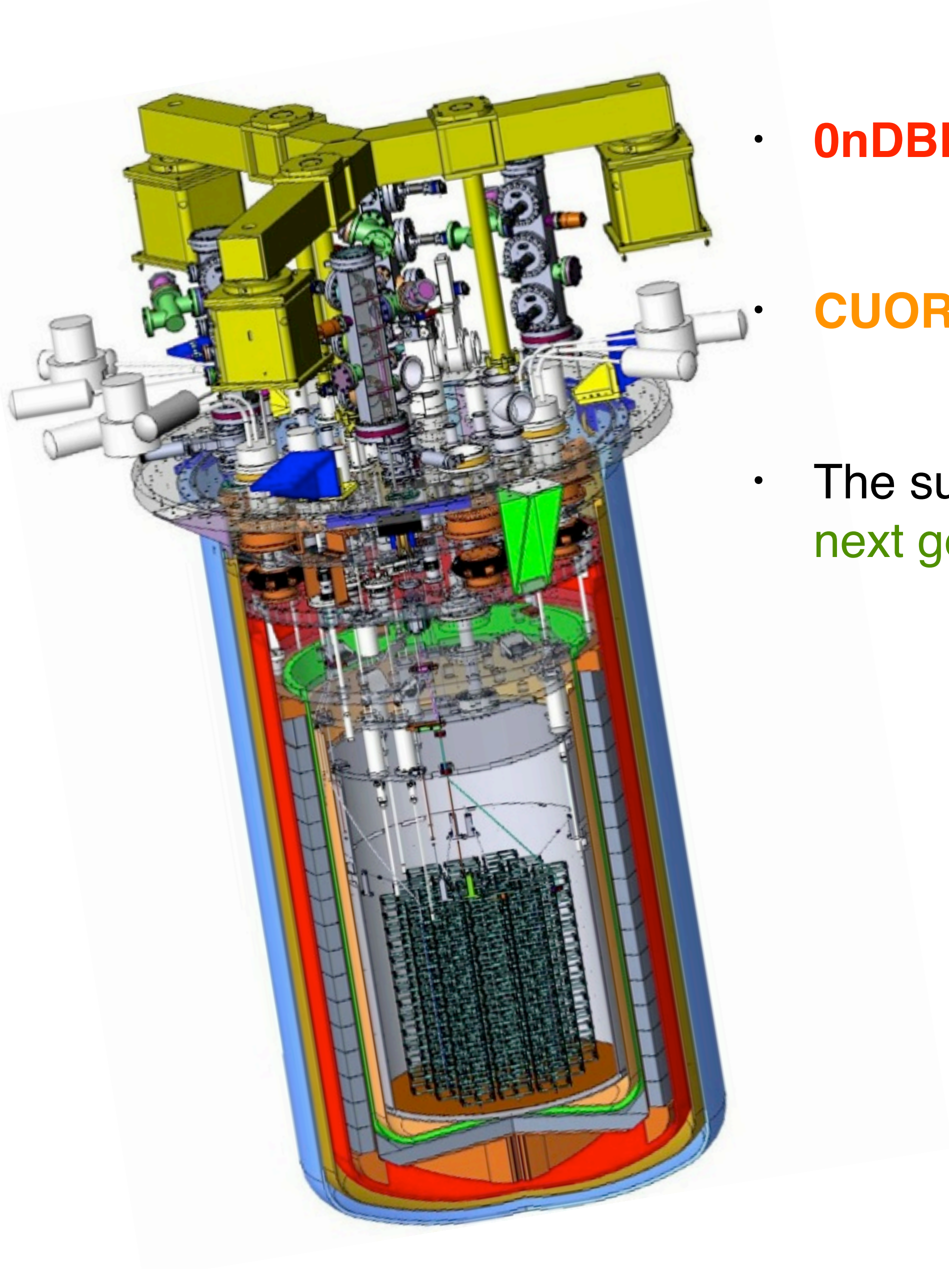
3 main project phases

1) ~~Optimize detector geometry, read-out and analysis using Aluminum → 80 eV~~

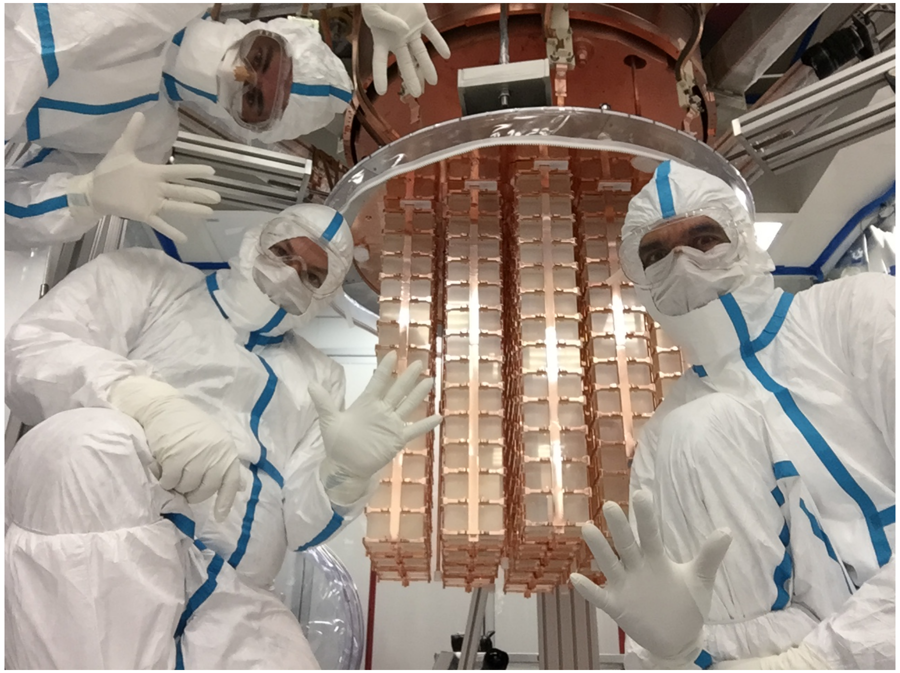
2) Move to more sensitive superconductors (TiAl, TiN..) → <20 eV

3) Large-scale test of our light detectors on TeO_2 array at LNGS (Italy)

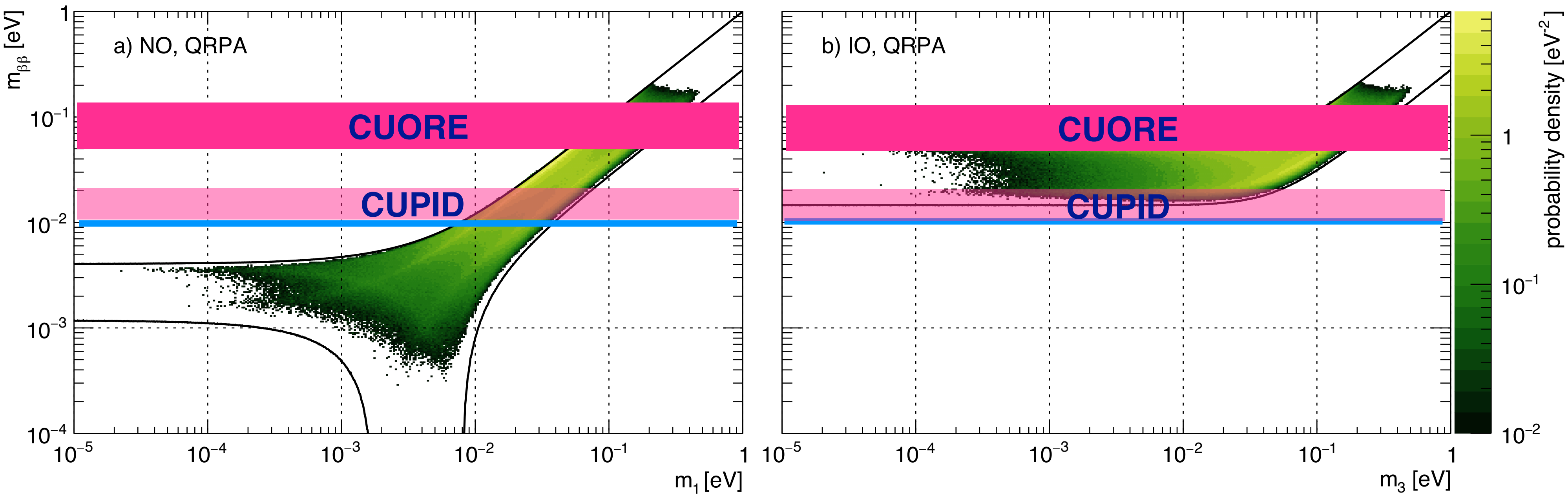
Summary and Conclusions



- **0nDBD** can be the key for **new physics** searches
- **CUORE** started data taking with 1 ton detector
- The success of this experiment is fundamental for all the next generation projects



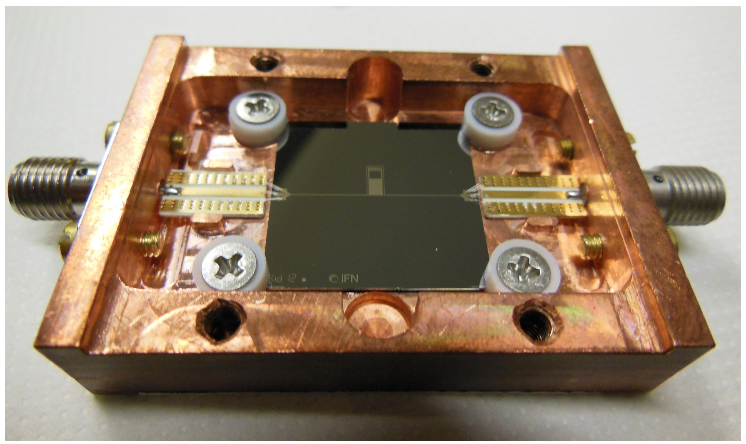
Summary and Conclusions

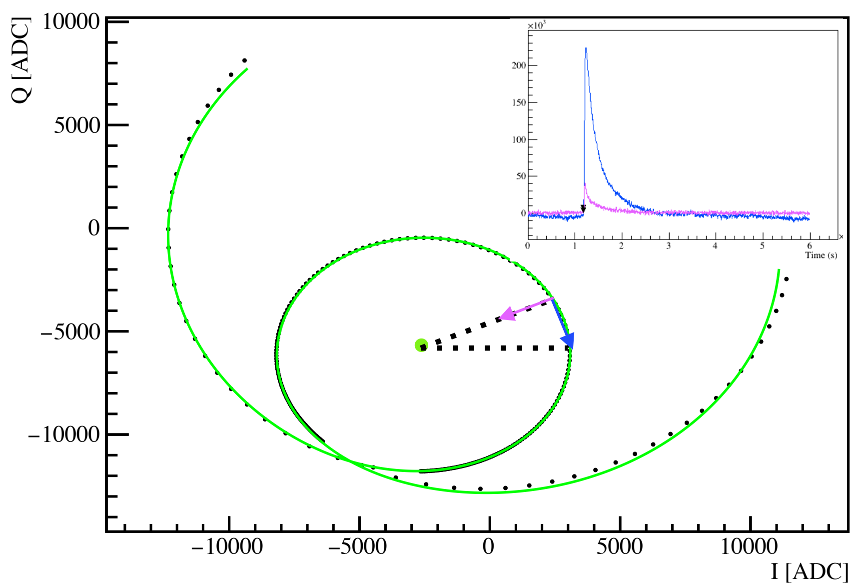


- CUPID will upgrade CUORE exploiting Particle Identification
- >95% discovery in the inverted hierarchy
- >50% discovery in the normal hierarchy region

Summary and Conclusions

CALDER: TeO_2 + new light detectors



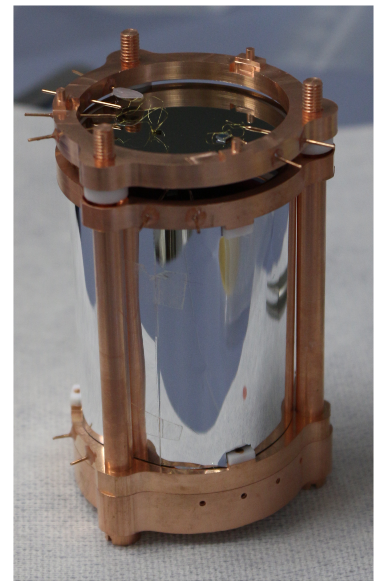


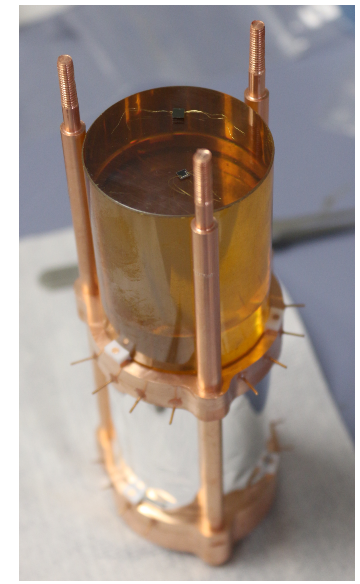
- Use **same CUORE detectors** (enriched in ^{130}Te)
- **Light Detectors** with energy resolution < 20 eV RMS
- With CALDER 30 eV RMS reached using small light detectors
- Scale up the light detector size and final tuning of the resolution

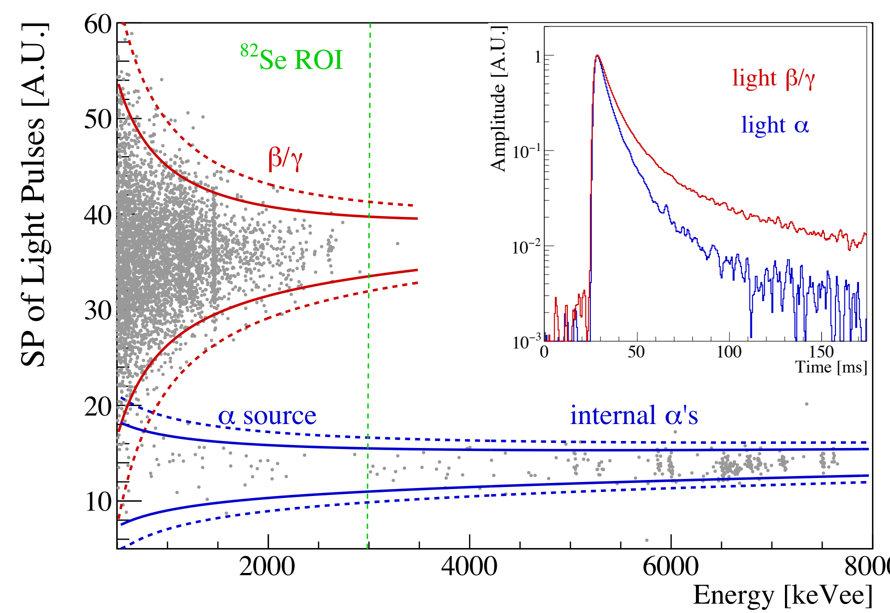
Summary and Conclusions

CUPID-0: ZnSe + “std” light detectors

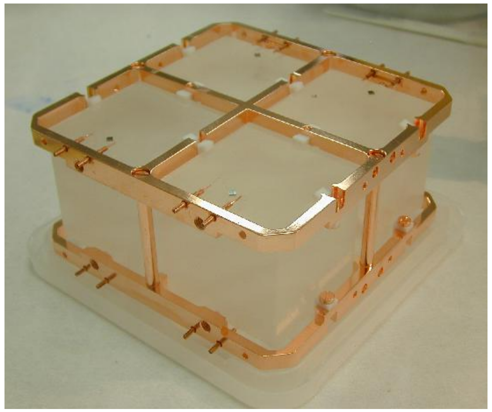
- Abandon TeO_2 in favor of **scintillating crystals** with **high Q-value** emitters
- Prove that this technology allows to **suppress the background** and reach high sensitivity
- First medium scale prototype 10 kg **ZnSe: CUPID-0**

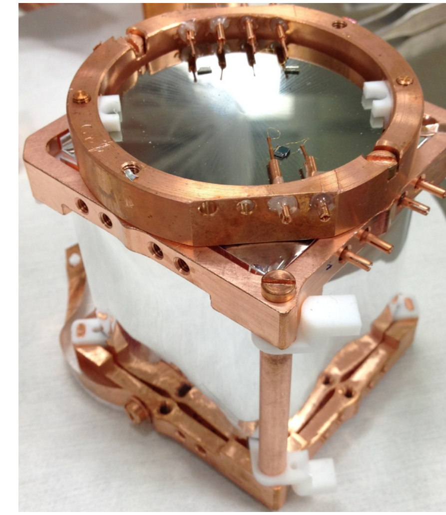






Soon a down selection

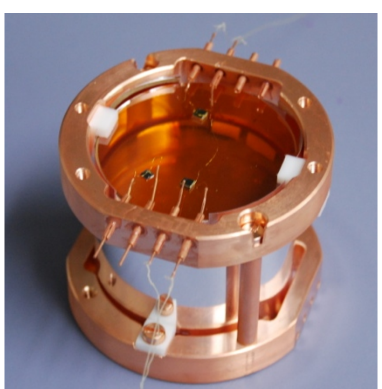


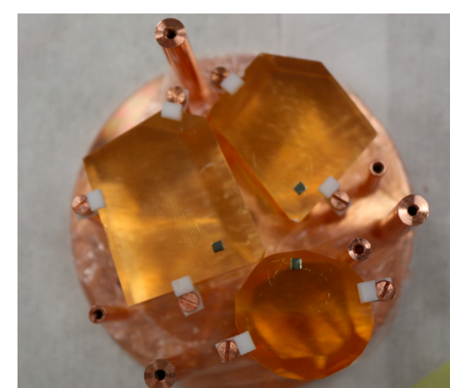


TeO_2

- CHERENKOV LIGHT DETECTION
  - Ge + Luke effect
  - TES
  - MMC
  - KIDs
- SURFACE EFFECTS
  - Al films

Other emitters/crystals





- ZnSe (^{82}Se)
- $ZnMoO_4$ (^{100}Mo)
- $CdWO_4$ (^{116}Cd)

Zero Background Approach

$$S^{bkg} \propto \varepsilon \frac{i.a.}{A} \sqrt{\frac{MT}{B\Delta E}} \quad [y]$$

the detection technique:

- ε = detector efficiency
- M = detector mass [kg]
- T = measurement time [y]
- ΔE = energy resolution [keV]
- B = background [counts/keV/kg/y]

the 0νββ emitter:

- i.a. = isotopic abundance
- A = mass number
- B = background [counts/keV/kg/y]

Zero Background Approach

$$S^{bkg} \propto \varepsilon \frac{i.a.}{A} \sqrt{\frac{MT}{B\Delta E}} \quad [y] \quad \Rightarrow \quad S^{0bkg} \propto \varepsilon \frac{i.a.}{A} MT \quad [y]$$

the detection technique:

- ε = detector efficiency
- M = detector mass [kg]
- T = measurement time [y]
- ΔE = energy resolution [keV]
- B = background [counts/keV/kg/y]

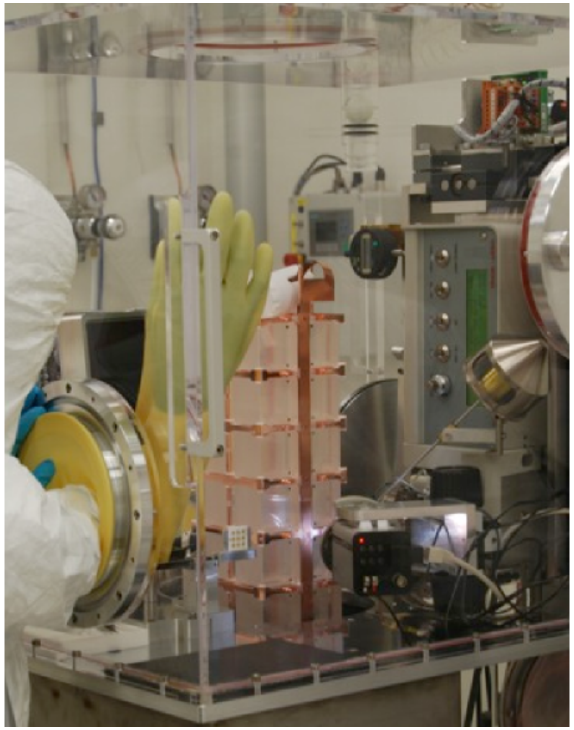
the 0νββ emitter:

- i.a. = isotopic abundance
- A = mass number
- B = background [counts/keV/kg/y]

S increases **linearly** with MT

Background Study: CUORE-0

During CUORE construction, we run a CUORE-like tower: CUORE-0



Result of an R&D activity of several years to **suppress the background**

Proved that CUORE can reach the background and resolution target

But still far from the zero background: **200 counts/ROI** expected

Background suppression

Nowadays, all the detectors devoted to rare events searches are located in deep underground facilities

All the detectors described in the next slides were measured in the
LNGS
(Laboratori Nazionali del Gran Sasso, Italy)
3650 m.w.e.

muon flux: $(2.58 \pm 0.3) \times 10^{-8}$ μ/(s cm^2)
Mei and Hime, Phys. Rev. D 73, 053004, 2006 [astro-ph 0512125]
neutron flux [<10MeV] : $\approx 4 \times 10^{-6}$ n/(s cm^2)
F. Arneodo et al., Il Nuovo Cim. 112A, 819, 1999
gamma flux: ≈ 0.73 γ/(s cm^2)
C. Bucci et al., Eur. Phys. J. A, 41, 155-168, 2009

- detectors equipped with proper shields (water, lead...) and vetoes

➜ the ultimate limit to the background suppression may become the *detector* itself

Crystal choice

The 1σ sensitivity on $\langle m_{\beta\beta} \rangle$ was calculated with the Feldman Cousins approach for 5 y live time with a background of 10^{-3} counts/keV/kg/y and an energy resolution of 5 keV.

Emitter	Bolometer	Active mass	Active mass [kg]	1σ sensitivity on $m_{\beta\beta}$
^{82}Se	ZnSe	56%	17.3	52-65
^{100}Mo	$ZnMoO_4$	44%	11.3	67-73
^{116}Cd	$CdWO_4$	32%	15.1	65-80

↓

Assuming a total experimental volume of 6000 cm^3 and an isotopic enrichment of 95%.

⇩

ZnSe as baseline choice

R&D on $ZnMoO_4$ as possible alternative