CUPID-0

…a step forward exploring the inverted hierarchy region of the neutrino mass

Maria Martinez (U. La Sapienza, Rome)
on behalf of the CUPID-0 collaboration

28th Rencontres de Blois, May 29 - June 03 (2016)

Outline

- Bolometers for neutrinoless double beta decay ($0\nu\beta\beta$): CUORE
- CUPID: Cuore Upgrade with Particle IDentification
- Scintillating bolometers for $0\nu\beta\beta$: LUCIFER & CUPID
- CUPID-0: The first demonstrator
- Conclusions

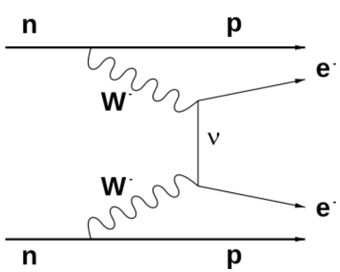
Experimental search for $0\nu\beta\beta$

WHAT WE ARE LOOKING FOR

2νββ: $(A,Z) \rightarrow (A,Z+2) + 2e^- + 2\bar{\nu}_e$

- allowed in the SM and already observed with $T_{1/2} > 10^{18}$ y

0νββ: $(A,Z) \rightarrow (A,Z+2) + 2e^-$



- not allowed in the SM
- expected with $T_{1/2} > 10^{25}$ y

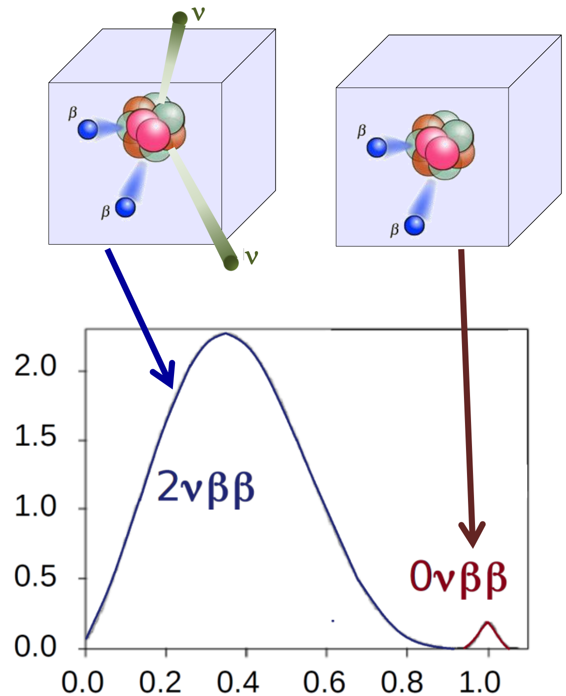
If observed:

- lepton number violation
- neutrinos are Majorana particles
- measures effective electron neutrino mass

$$m_{\beta\beta} \equiv |e^{i\alpha_1}|U_{ei}^2|m_1 + e^{i\alpha_2}|U_{e2}^2|m_2 + |U_{e3}^2|m_3|$$

EXPERIMENTAL SIGNATURE

Approach:
SOURCE = DETECTOR



Main signature:
Peak at Q-value over 2νββ tail enlarged only by detector resolution

EXPERIMENTAL SENSITIVITY

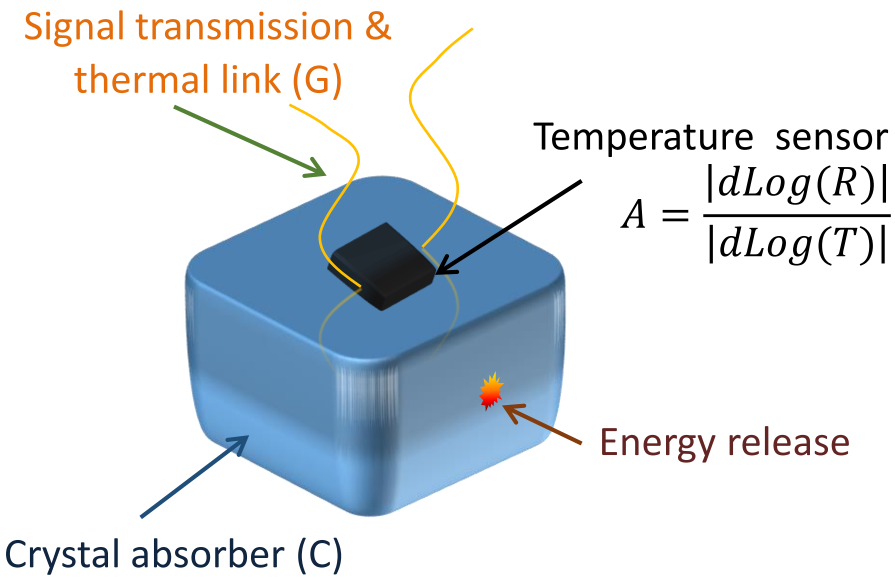
Lifetime corresponding to the minimum detectable number of events over background at a given C.L.:

$$S^{0\nu} \propto \epsilon\, i.a. \sqrt{\frac{MT}{b\Delta E}} \qquad b \neq 0$$

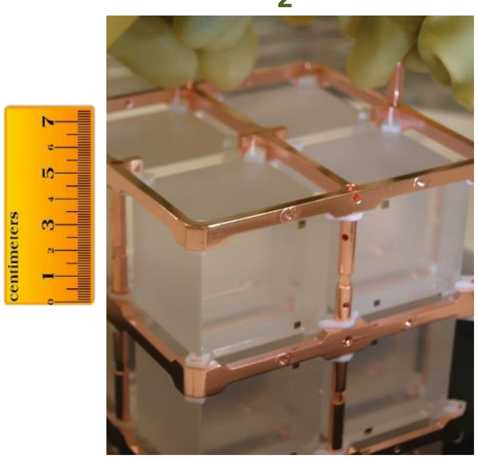
$$S^{0\nu} \propto \epsilon\, i.a. MT \qquad b = 0$$

- M: Total active mass in kg
- ϵ: Detector efficiency
- $i.a.$: Isotopic abundance
- b: Background in c/keV/kg/y
- ΔE: Detector resolution @ ROI in keV
- T: Exposure time in y

Bolometers as particle detectors



CUORE TeO_2 bolometers:

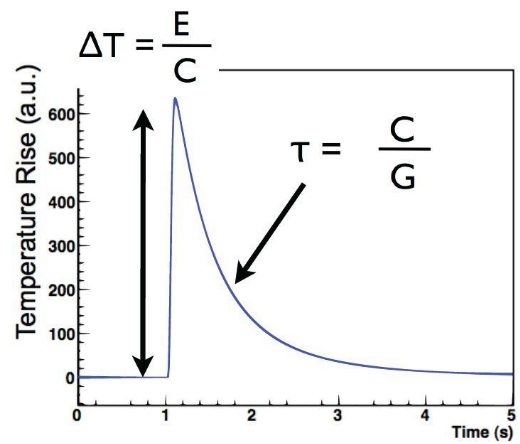


T ~ 10 mK
M ~ 0.75 kg
C ~ 2 x 10^{-9} J/K
ΔT/ΔE ~ 100 µK/MeV
ΔV/ΔE ~ 300 µV/MeV
G ~ 2 x 10^{-9} W/K
t = C/G ~ 1 s

- The energy release originates a temperature rise:

$$\Delta T = \frac{E}{C(T)}$$

- The temperature sensor converts the temperature rise in an electric signal:



- **Excellent energy resolution!**

CUORE ~ 5 keV FWHM

Evolution of TeO_2 bolometric experiments

MiDBD
6.8 kg TeO_2
(1.8 kg ^{130}Te)

1997-2001
$T^{0\nu}_{1/2} > 2.1 \times 10^{23} yr$ [1]

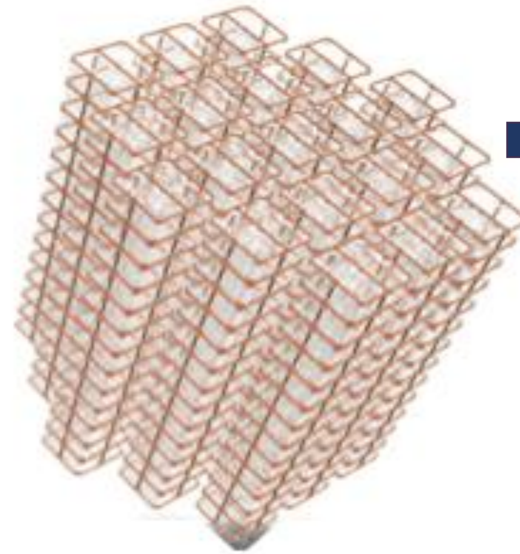
Cuoricino
40.7 kg TeO_2
(11.3 kg ^{130}Te)

2003-2008
$T^{0\nu}_{1/2} > 2.8 \times 10^{24} yr$ [2]

CUORE-0
39 kg TeO_2
(11 kg ^{130}Te)

2013-2015
$T^{0\nu}_{1/2} > 4 \times 10^{24} yr$ [3]
(combined with Cuoricino)

CUORE
741 kg TeO_2
(206 kg ^{130}Te)



2016...

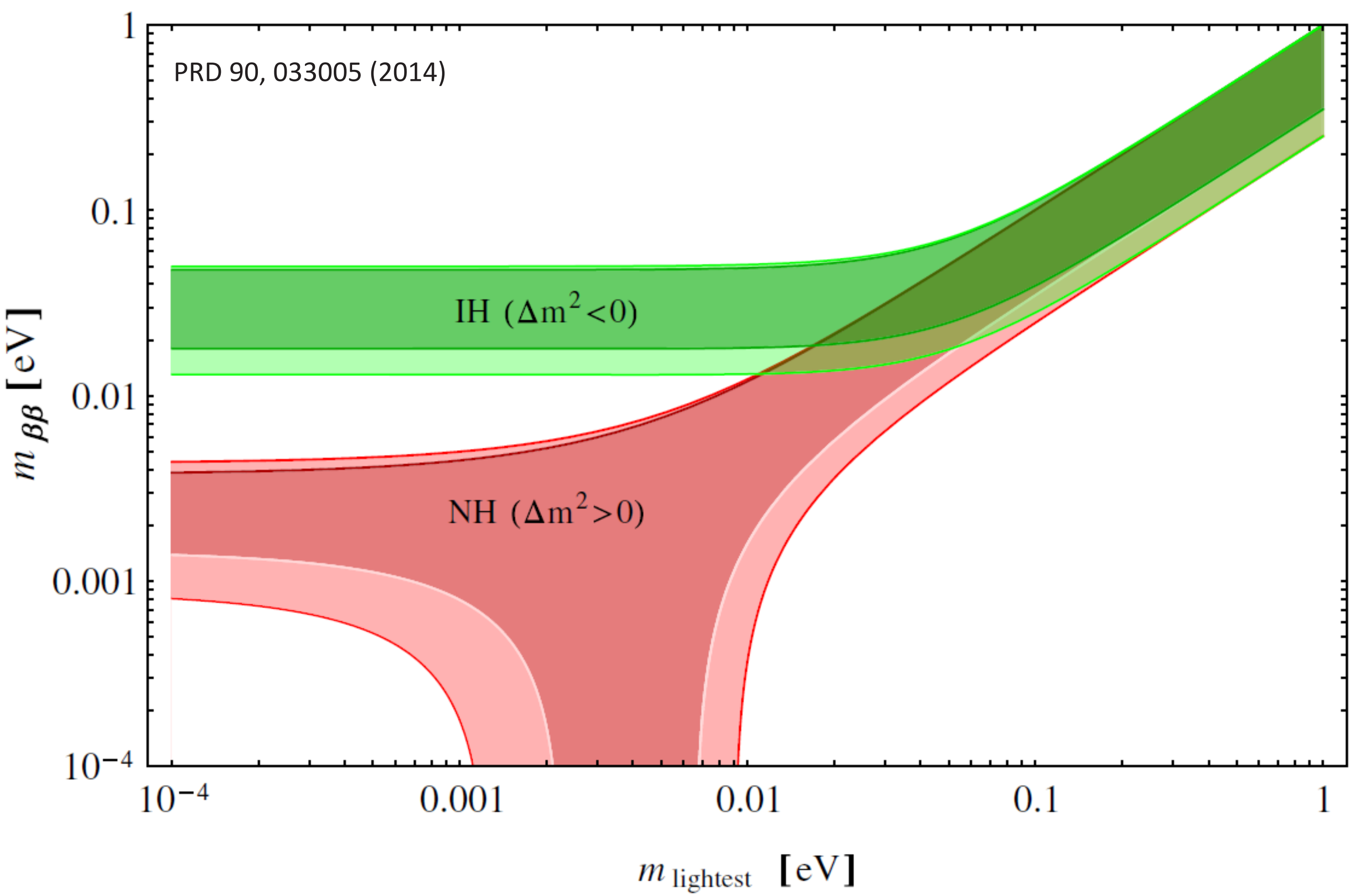
[1] Phys. Lett. B 557 (2003) 167
[2] Astrop. Phys. 34 (2011) 822
[3] PRL 115, 102502 (2015)

$0\nu\beta\beta$ sensitivity

$$Rate_{0\nu} \propto \frac{1}{T_{1/2}^{0\nu}} = G^{0\nu}(Q,Z)|M^{0\nu}|^2 |\langle m_{\beta\beta}\rangle|^2$$

nuclear matrix element estimates

IBM-2 Phys. Rev. C 91, 034304 (2015)
QRPA-TU Phys. Rev. C 87, 045501 (2013)
pnQRPA Phys. Rev. C 91, 024613 (2015)
ISM Nucl. Phys. A 818, 139 (2009)
EDF Phys. Rev. Lett. 105, 252503 (2010)



Degenerate hierarchy
~100 events/ton/yr

Inverted hierarchy
~1 events/ton/yr

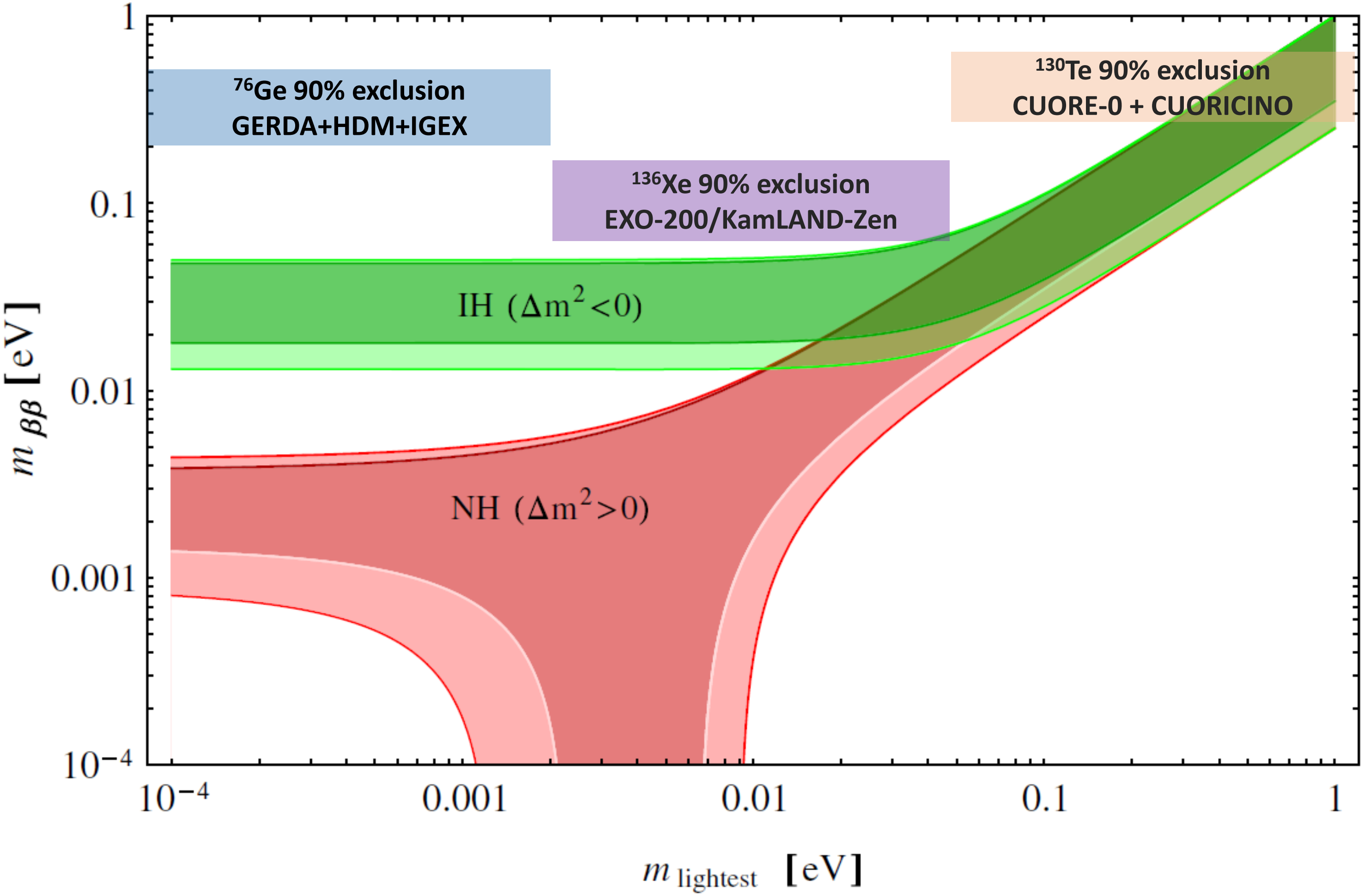
Normal hierarchy
< 0.01events/ton/yr

$0\nu\beta\beta$ sensitivity: where we are

nuclear matrix element estimates

IBM-2 Phys. Rev. C 91, 034304 (2015)
QRPA-TU Phys. Rev. C 87, 045501 (2013)
pnQRPA Phys. Rev. C 91, 024613 (2015)
ISM Nucl. Phys. A 818, 139 (2009)
EDF Phys. Rev. Lett. 105, 252503 (2010)

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



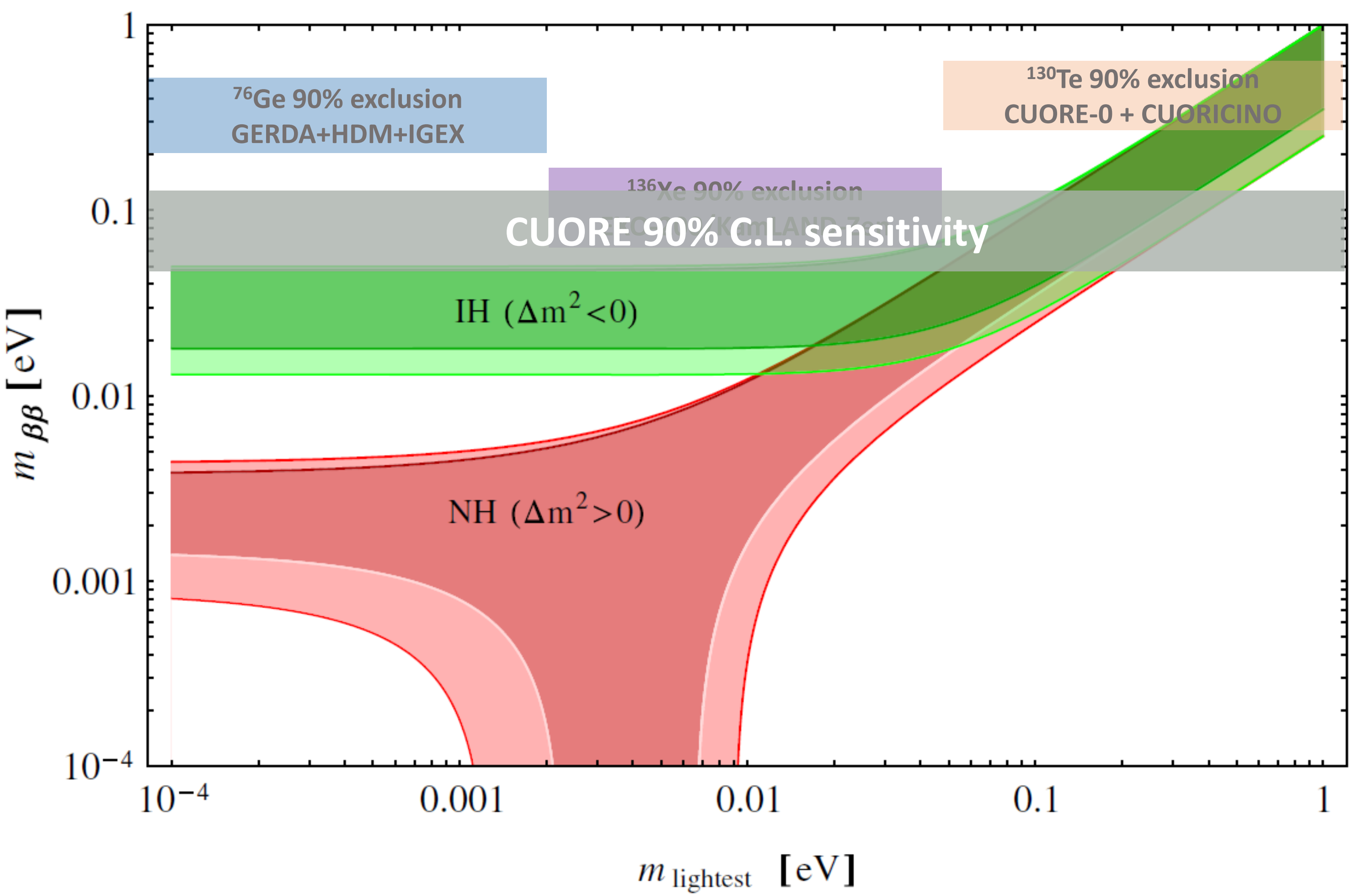
Degenerate hierarchy
~100 events/ton/yr

CUORE projection

nuclear matrix element estimates

IBM-2 Phys. Rev. C 91, 034304 (2015)
QRPA-TU Phys. Rev. C 87, 045501 (2013)
pnQRPA Phys. Rev. C 91, 024613 (2015)
ISM Nucl. Phys. A 818, 139 (2009)
EDF Phys. Rev. Lett. 105, 252503 (2010)

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



Degenerate hierarchy
~100 events/ton/yr

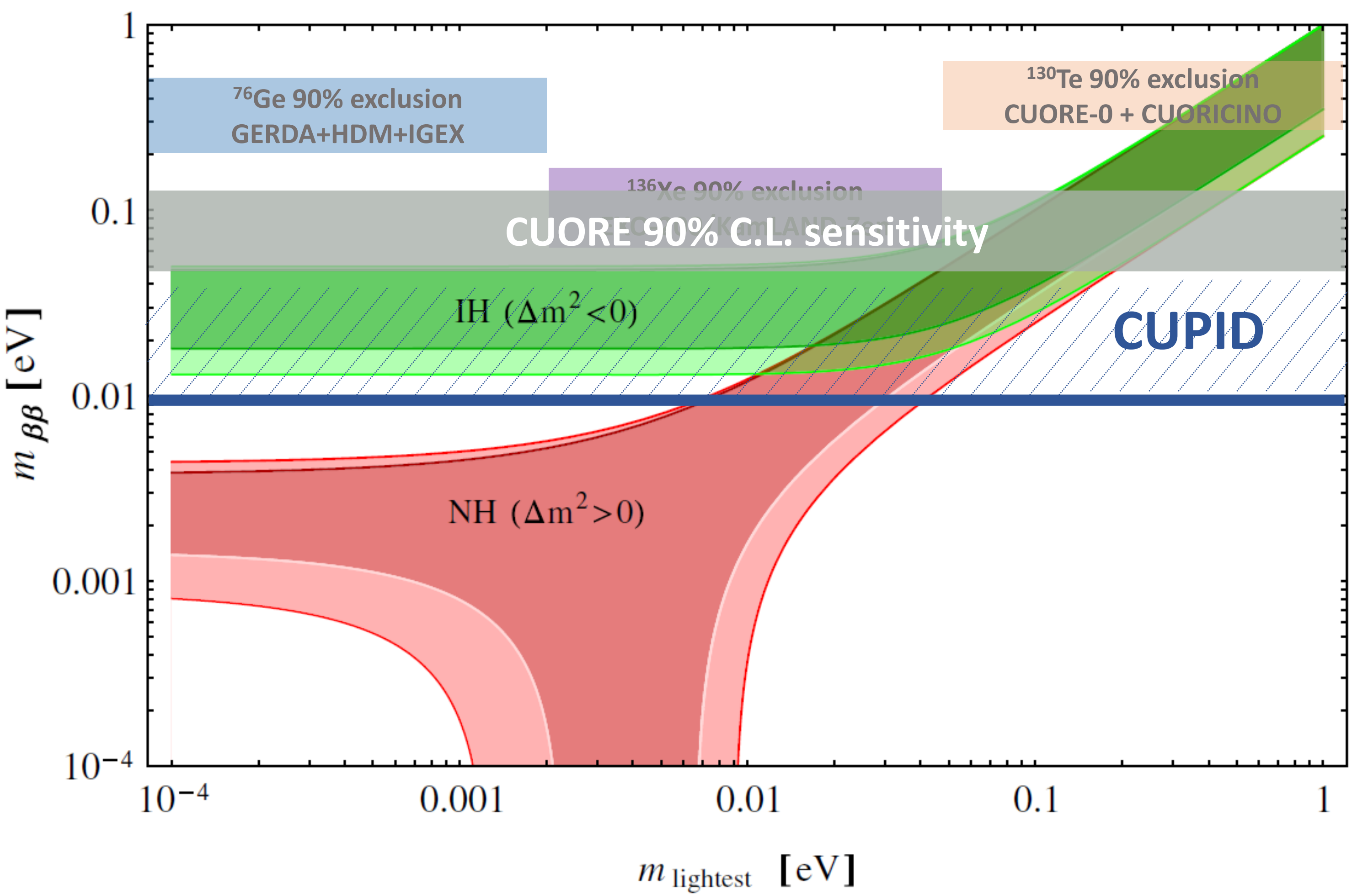
Reaching
Inverted hierarchy
~10 events/ton/yr

CUPID GOAL: 10 meV ($m_{\beta\beta}$)

nuclear matrix element estimates

IBM-2 Phys. Rev. C 91, 034304 (2015)
QRPA-TU Phys. Rev. C 87, 045501 (2013)
pnQRPA Phys. Rev. C 91, 024613 (2015)
ISM Nucl. Phys. A 818, 139 (2009)
EDF Phys. Rev. Lett. 105, 252503 (2010)

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



Degenerate hierarchy
~100 events/ton/yr

Completely explore Inverted hierarchy
~0.1 events/ton/yr

↑ **number of $\beta\beta$ emitters**

↓ **Background**

CUPID

CUORE UPGRAGE WITH PARTICLE IDENTIFICATION

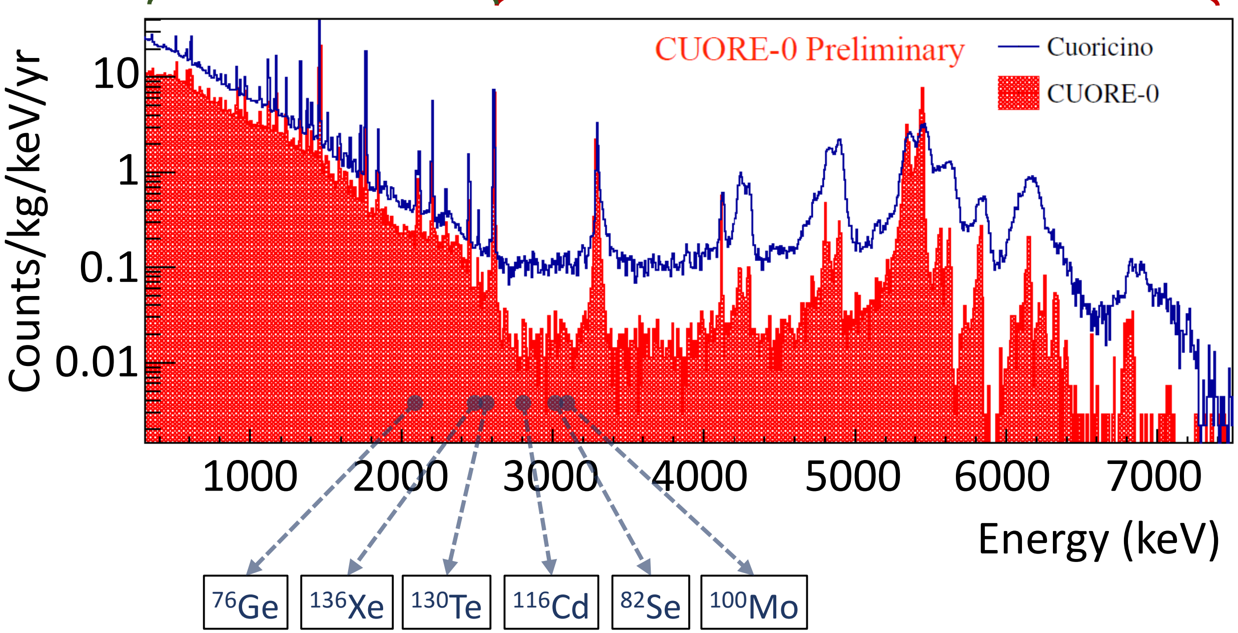
CUPID Interest Group: 32 institutions

White papers:
arXiv: 1504.03599
arXiv:1504.03612

CUORE infrastructure
+ isotope enrichment
+ particle identification to get
$\sim$0 bkg at ton scale

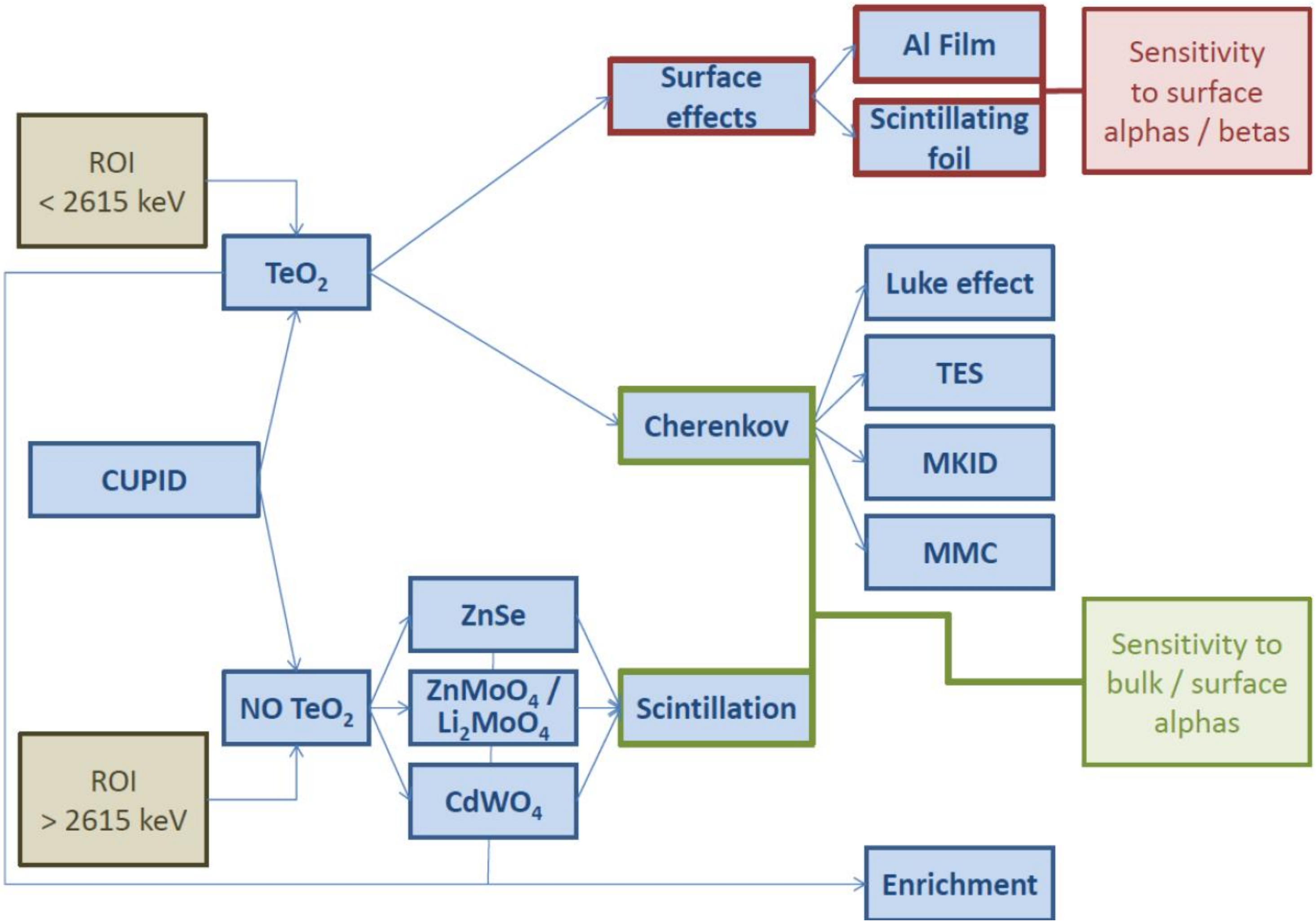
β/γ background (CUORICINO CRYOSTAT)

α background



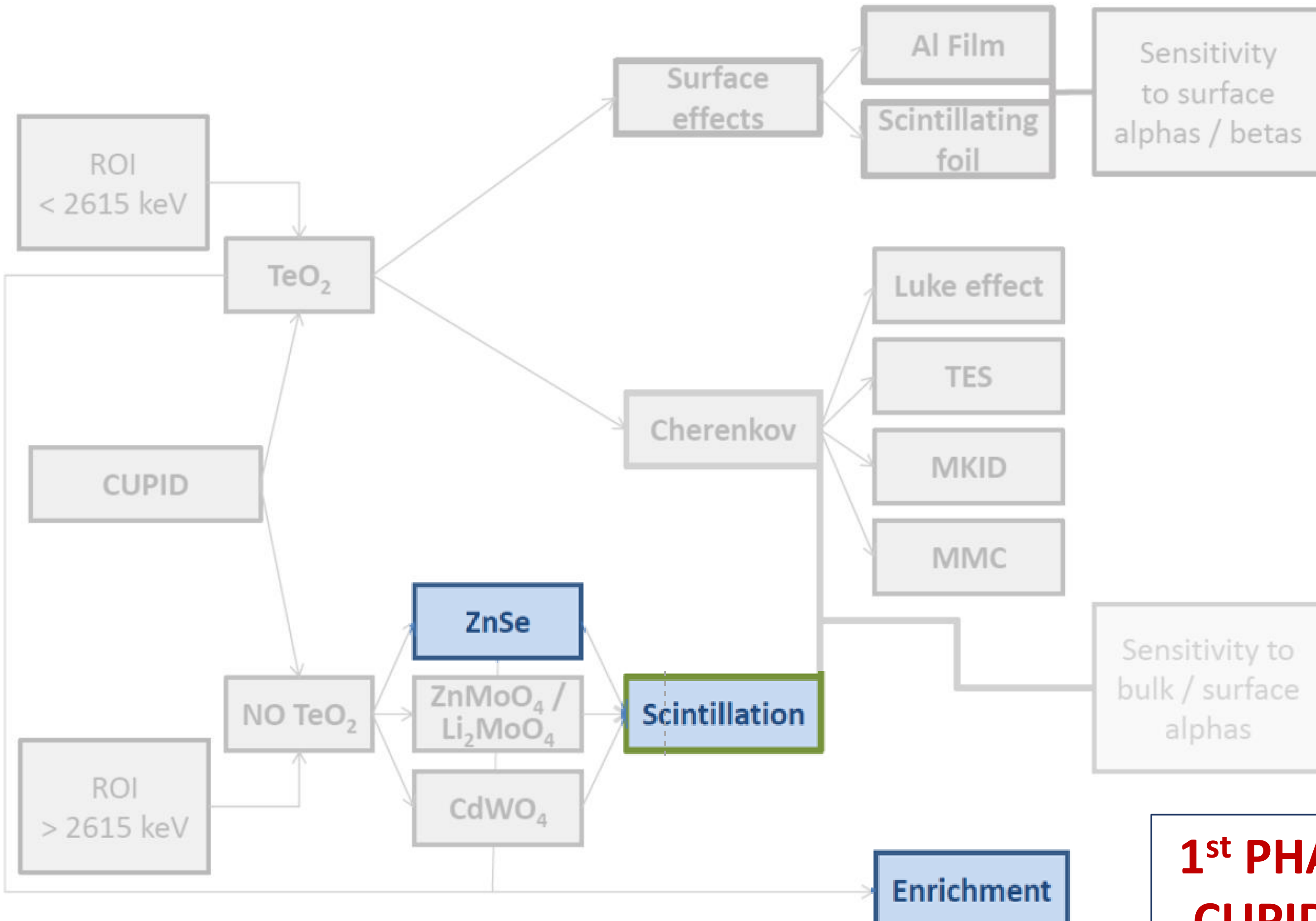
To reduce background we need α discrimination

CUPID R&D



ROI
< 2615 keV
TeO$_2$
CUPID
NO TeO$_2$
ROI
> 2615 keV
Surface effects
Al Film
Scintillating foil
Sensitivity to surface alphas / betas
Luke effect
TES
Cherenkov
MKID
MMC
ZnSe
ZnMoO$_4$ / Li$_2$MoO$_4$
CdWO$_4$
Scintillation
Sensitivity to bulk / surface alphas
Enrichment

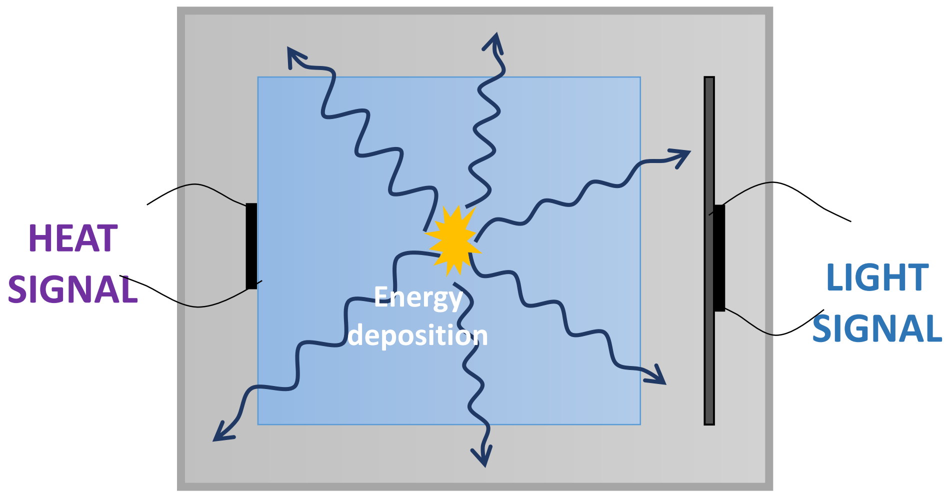
CUPID R&D

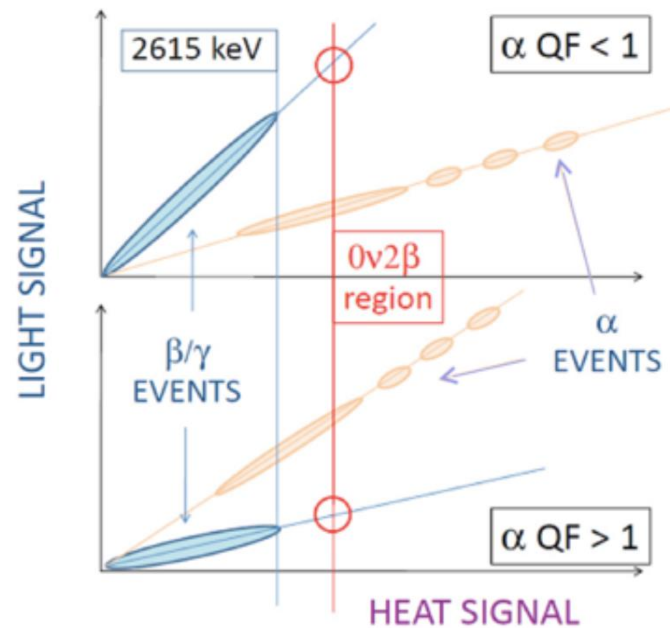


1st PHASE
CUPID-0

Scintillating bolometers for $0\nu\beta\beta$

Simultaneous measurement of heat and light





The light yield depends on the ionizing power of the particle

Particle discrimination by the ratio HEAT/LIGHT

Scintillating bolometers for $0\nu\beta\beta$: LUCIFER & CUPID

LUCIFER

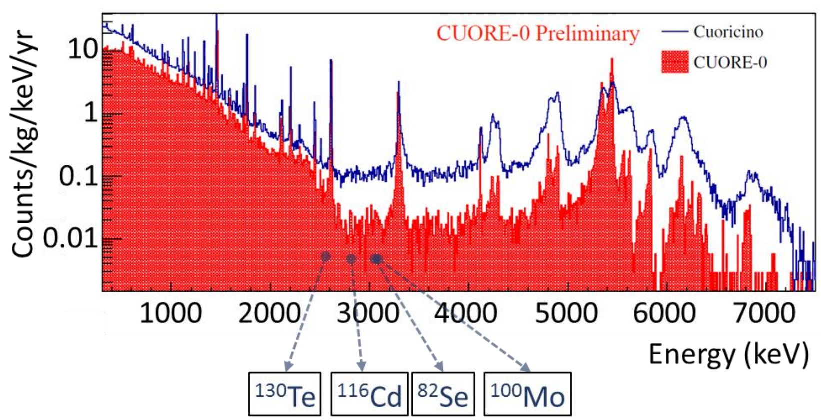
Low-background **U**nderground **C**ryogenics **I**nstallation **F**or **E**lusive **R**ates

- **ERC Advanced Grant**
- **From March 2010 – March 2016**

→ **CUPID-0**

Characterization of scintillating crystals interesting for $0\nu\beta\beta$

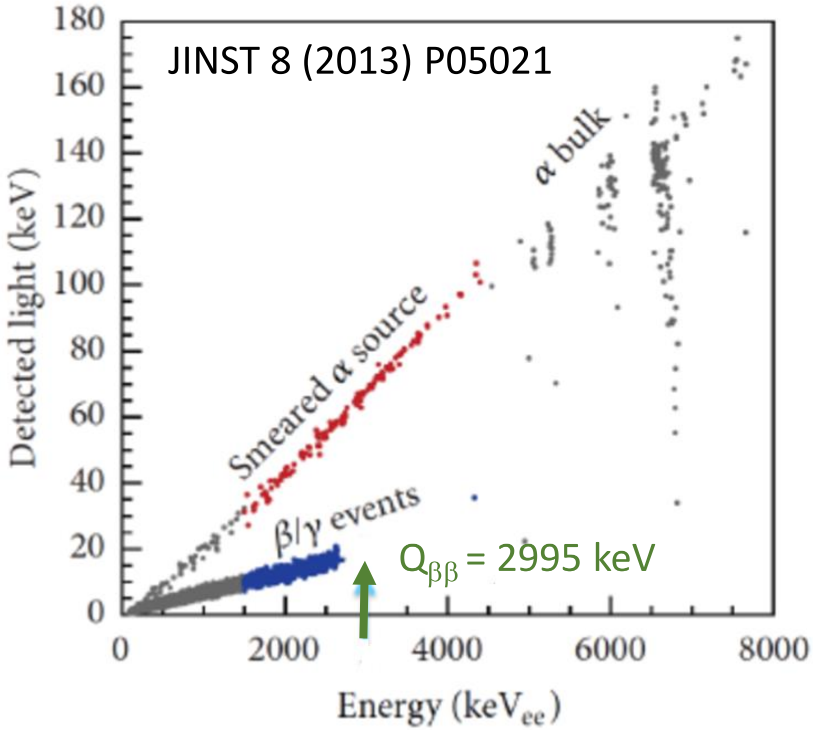
- $Zn^{82}Se$
- $Zn^{100}MoO4$
- $^{116}CdWO4$



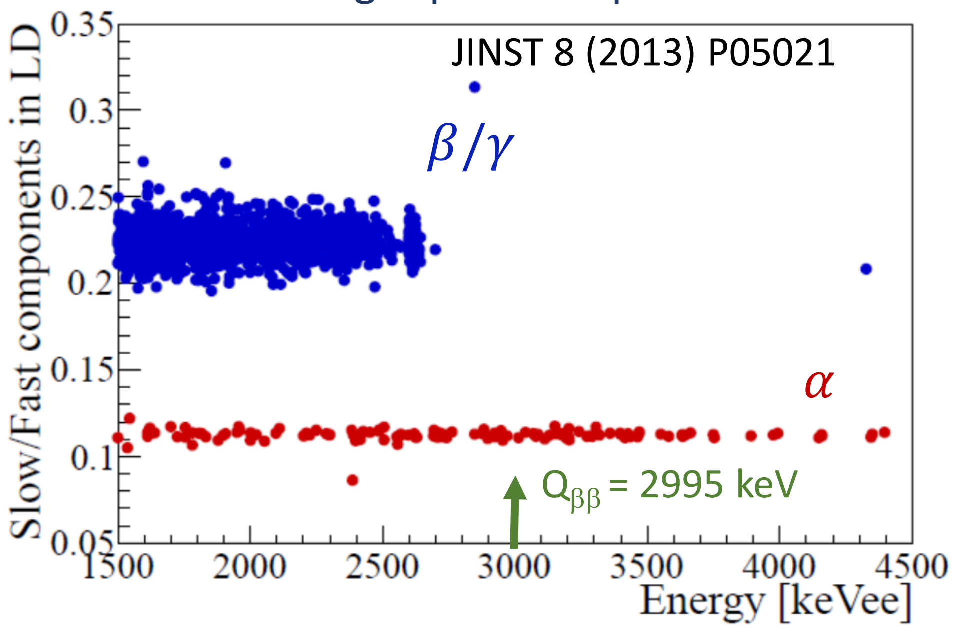
ZnSe detectors for $0\nu\beta\beta$ of ^{82}Se

- Excellent particle discrimination light/heat (α light yield > β/γ → inverted behaviour respect to the usual one not well understood)
- Excellent discrimination based on the shape of the light pulse!

Light vs heat

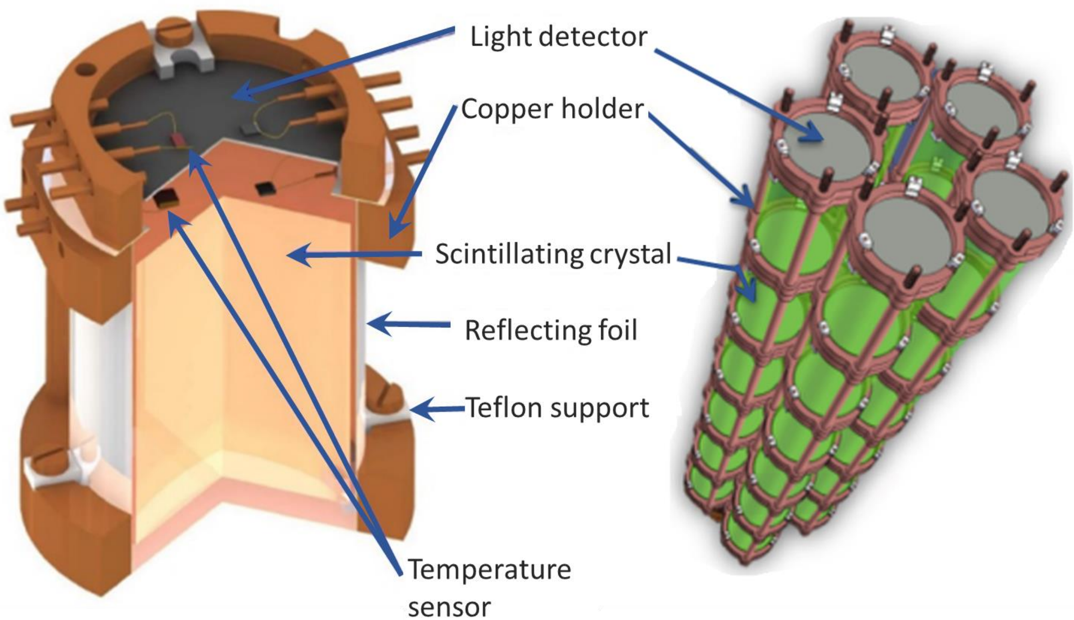


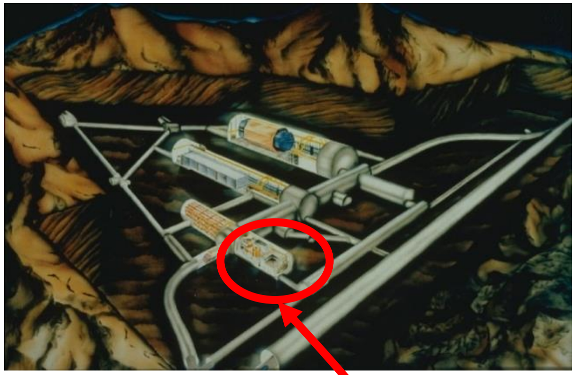
Light pulse shape

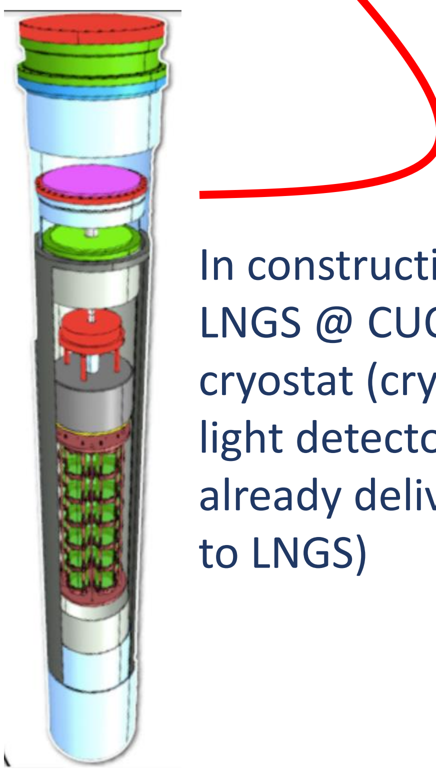


CUPID-0

- 30 $Zn^{82}Se$ bolometers ~440 g each @ 95% enrichment
- Bolometers arranged in 5 towers. Central bolometers faced to two Ge light detectors
- Total mass: 13.2 kg (7 kg ^{82}Se)
- Expected bkg @ ROI 10^{-3} c/keV/kg/y
- Expected FWHM @ ROI: 10 keV
- **START DATA TAKING WITHIN 2016**







In construction at LNGS @ CUORE-0 cryostat (crystals & light detectors already delivered to LNGS)

High purity enriched $Zn^{82}Se$

- Se powder 96.3% enriched at URENCO Stable Isotope Group (Netherlands)
- $Zn^{82}Se$ synthesis and growth at ISMA (Ukraine).
  Final enrichment: 95.4%
- Crystals already delivered to LNGS
- Cutting and polishing @ LNGS
- Final dimensions: ϕ = 4.3 cm
  h = 5.5 cm
  weight ≈ 440 g

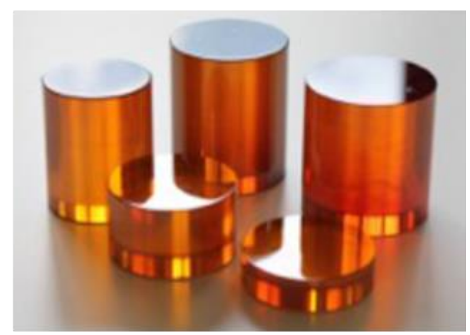
Enriched powder activity (HP-Ge)	
Isotope	Upper limit 90% CL (μBq/kg)
^{232}Th	<61
^{238}U	<110
^{235}U	<74

Metal Zn

Enriched Se powder

$Zn^{82}Se$ powder

Grown crystals

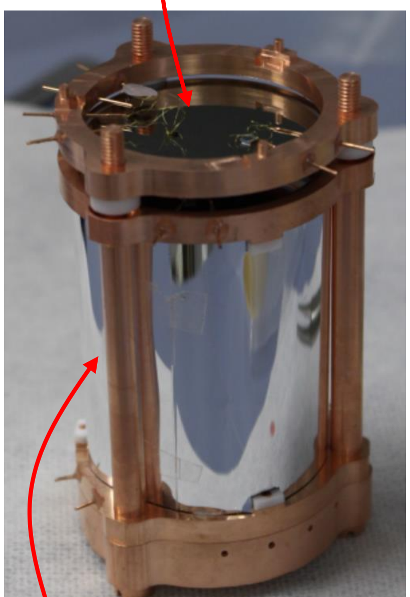


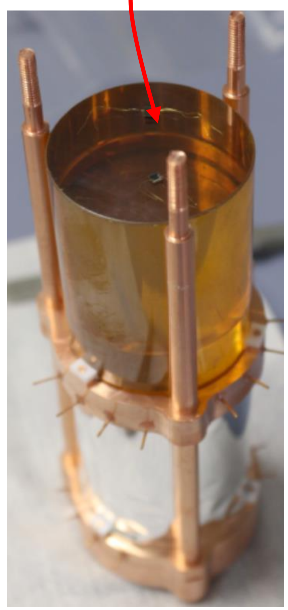
First test run with CUPID-0 crystals

- 3 $Zn_{82}Se$ crystals in a single tower (total mass 1.32 kg) + 4 Ge light detectors with antireflective SiO coating
- α source ^{147}Sm (Q_{value} = 2.3 MeV) to determine α rejection power
- R&D cryostat @ LNGS Hall C reached a T ~ 20 mK (Not optimized conditions!)

Ge light detector

$Zn_{82}Se$





VM2002 (reflectant foil)

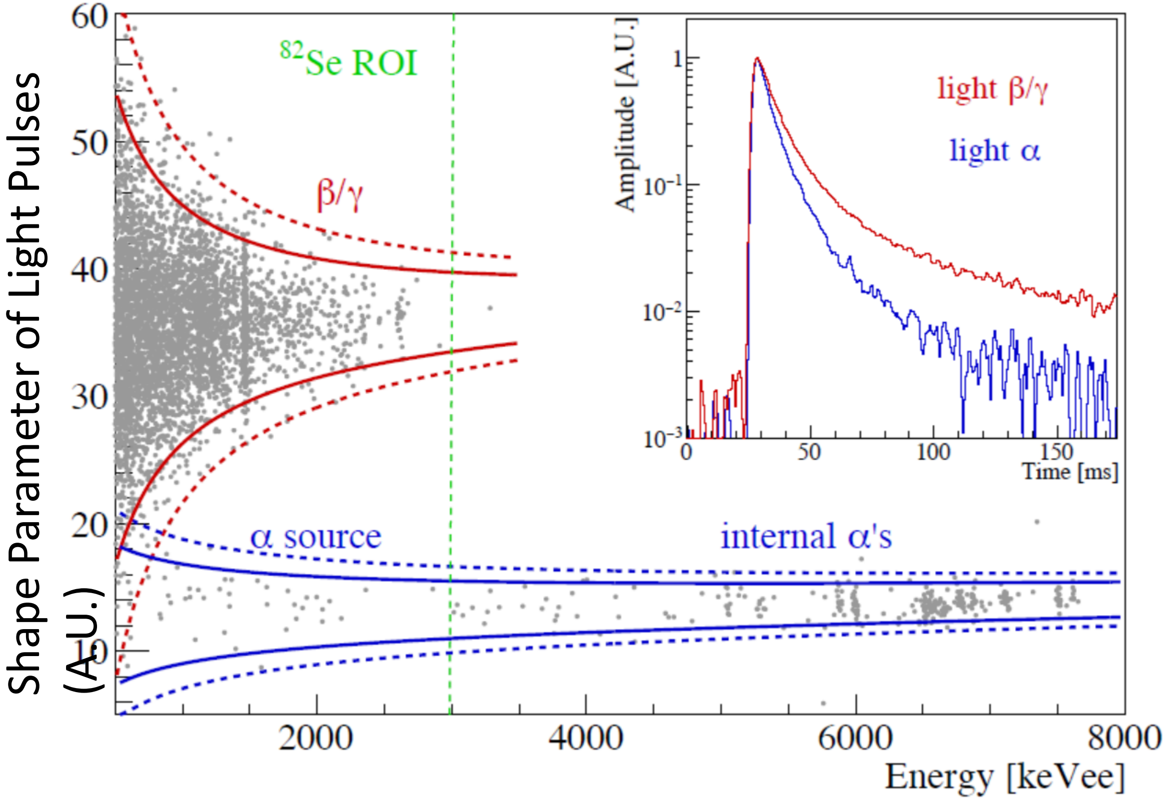
Crystal	Extrapolated FWHM @ Q_{value} (from γ calibration)
ZnSe-1	30.1 ± 1.7 keV
ZnSe-2	29.7 ± 1.4 keV
ZnSe-3	30.2 ± 1.7 keV

× 3 larger values that those expected for CUPID-0 (not optimal T) but enough for the experimental goals

arXiv:1605.05934

First test run with CUPID-0 crystals: α discrimination power

β/γ light pulses slower than α



Discrimination power:

$$DP(E) = \frac{|\mu_\alpha(E) - \mu_{\beta\gamma}(E)|}{\sqrt{\sigma_\alpha^2(E) + \sigma_{\beta\gamma}^2(E)}}$$

Crystal	$DP(Q_{\beta\beta})$
ZnSe-1	12
ZnSe-2	11
ZnSe-3	10

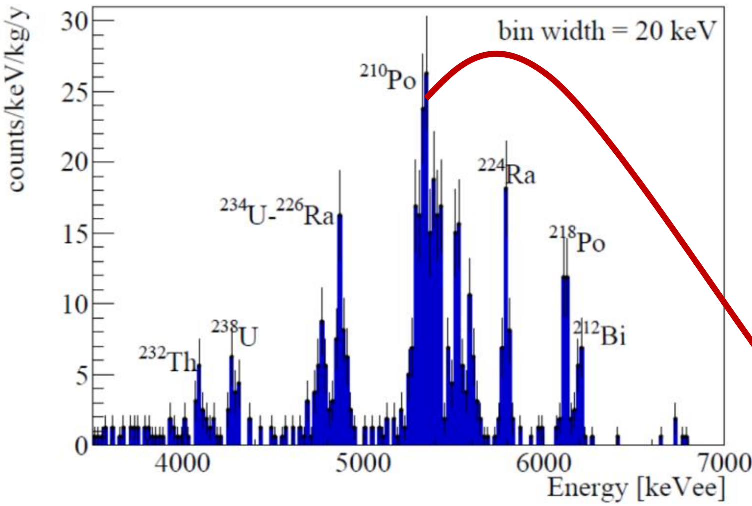
EXCELLENT DISCRIMINATION POWER!

arXiv:1605.05934

First test run with CUPID-0 crystals

- Internal contamination

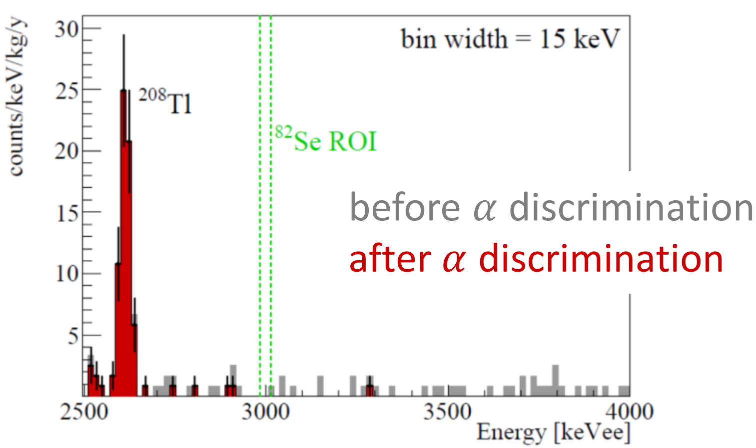
Except from ^{210}Pb, contaminations in bulk or deep in surface (>0.1μm)



	$Zn^{82}Se$-1 [μBq/kg]	$Zn^{82}Se$-2 [μBq/kg]	$Zn^{82}Se$-3 [μBq/kg]	Array [μBq/kg]
^{232}**Th**	13 ± 4	13 ± 4	<5	7 ± 2
^{228}**Th**	32 ± 7	30 ± 6	22 ± 4	26 ± 2
^{224}Ra	29 ± 6	26 ± 5	23 ± 5	27 ± 3
^{212}Bi	31 ± 6	31 ± 6	23 ± 5	29 ± 3
^{238}**U**	17 ± 4	20 ± 5	<10	10 ± 2
^{234}**U**+^{226}**Ra**	42 ± 7	30 ± 6	23 ± 5	33 ± 4
^{230}**Th**	18 ± 5	19 ± 5	17 ± 4	18 ± 3
^{218}Po	20 ± 5	24 ± 5	21 ± 5	21 ± 2
^{210}**Pb**	100 ± 11	250 ± 17	100 ± 12	150 ± 8

^{210}Pb is the larger value, but not dangerous for $\beta\beta$

- Background:



530 h → no events in ROI after discrimination

Even better results are expected for CUPID-0

- better anti-Rn shield
- Surface treatment
- cosmogenic isotopes depleted (mainly ^{56}Co, Q_{value}=4566 keV, $T_{1/2}$= 79 d)
- Better energy resolution (lower T)

arXiv:1605.05934

CUPID-0 prospects

arXiv:1605.05934

From MC simulation of internal contaminants:

- contamination in bulk
- DP = 12
- FWHM = 30keV

Background at ^{82}Se $Q_{\beta\beta}$ (counts/keV/kg/y)	
after α discrimination	4×10^{-3}
coincidences rejection	2.3×10^{-3}
^{208}Tl – ^{212}Bi time delay rejection	1×10^{-3}
+ cryostat γ contamination	$< 1.5 \times 10^{-3}$

$T_{1/2} = 9.3 \times 10^{24}$ yr (90% CL) (1 yr data-taking, 0 bkg approx.)

And next…

2nd PHASE:

- Li_2MoO_4 — MoU between INFN, IN2P3 and ITEP
- TeO_2 CHERENKOV

Conclusions

- Completely exploring the inverted hierarchy region of neutrino masses will require a detector with $\sim$1 ton isotopic mass and background level at the order of 0.1 counts/ton/yr.
- CUPID (Cuore Upgrade with Particle Identificiation) is pursuing this goal through several strategies, one of them being using scintillating bolometers.
- LUCIFER ZnSe crystals and Ge-light detectors fulfill the project requirements both in terms of α background rejection and energy resolution.
- CUPID-0, the first CUPID demonstrator with $Zn^{82}Se$ will start data-taking LNGS within 2016. A second phase with $Li_2{}^{100}MoO_4$ and/or TeO_2/Cherenkov will follow.

Thanks for your attention!