Development of scintillation detectors for rare events searches

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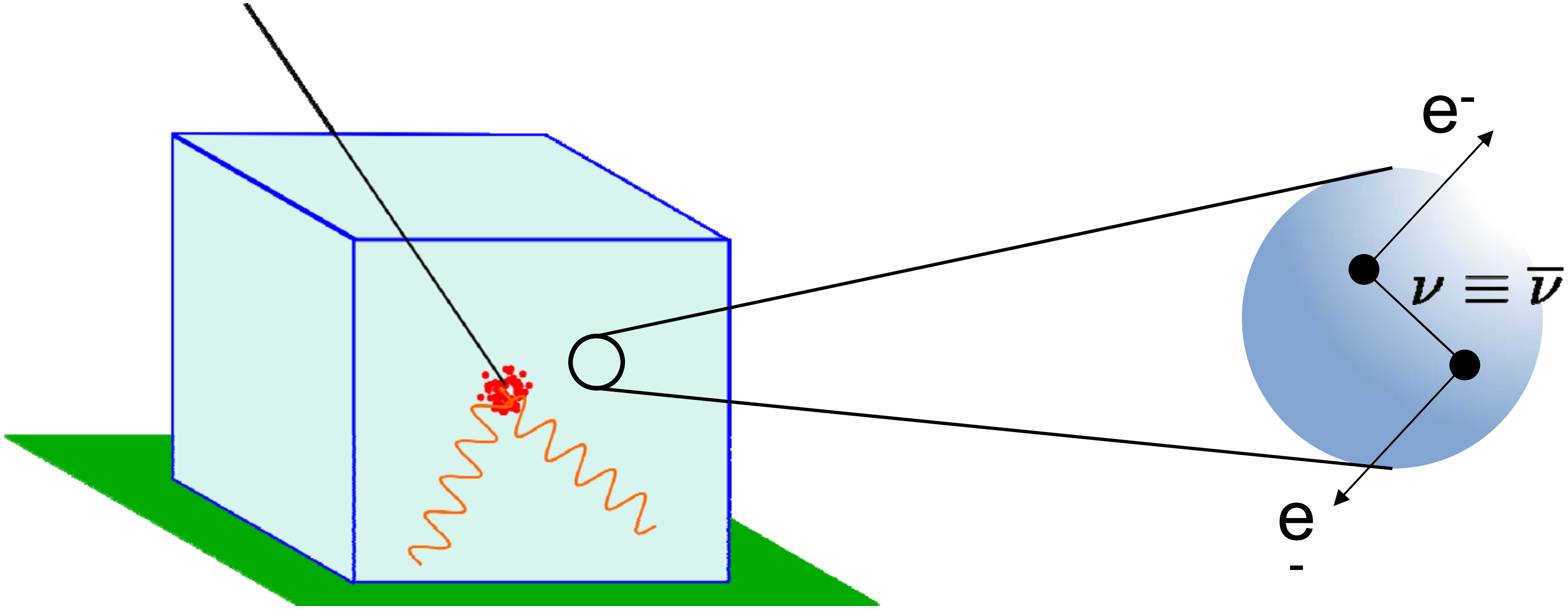
The project

Scintillation detectors for **neutrinoless double beta decay (0vββ) searches**

Detector:
high quality scintillating crystals, containing 0vββ candidate, optically coupled to Silicon Drift Detectors (SDDs) operated at 120 K



Prove the detector concept

to build **large mass** compact structures of **high resolving** detectors for neutrinoless double beta (0vββ) decay and other rare event searches

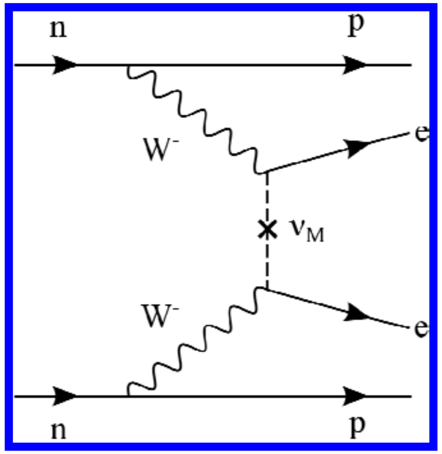
Neutrinoless double beta decay (0νββ)

0νββ: (A,Z) → (A,Z+2) + 2e-

$$m_\nu \neq 0$$

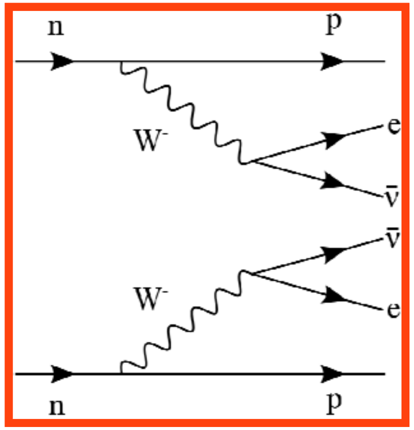
$$\nu \equiv \bar{\nu}$$

- Prohibited in the Standar Model (ΔL=2)
- Limits: $T^{0\nu}_{1/2} > 10^{24}$ -10^{25} y

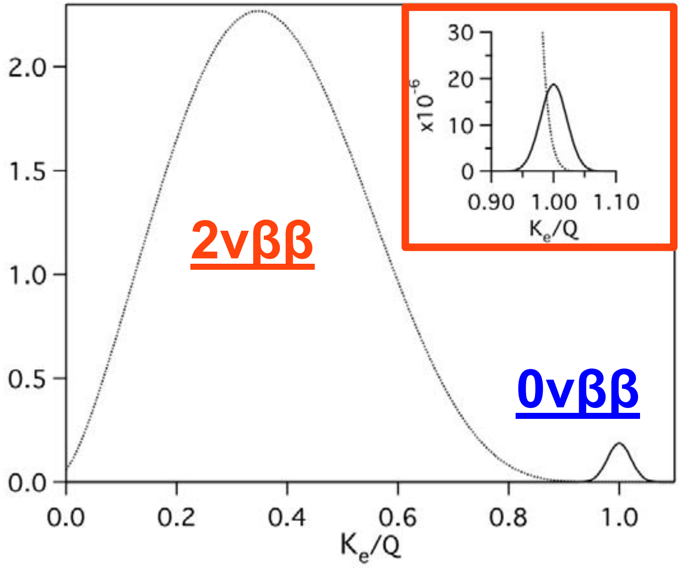


2νββ: (A,Z) → (A,Z+2) + 2e-+2v

- Predicted and detected



Measuring the two electron energy



Performing resolution

- At 2-3 MeV (Q_{value} of different isotopes)

High sensitivity

- Observing few counts above background

Experimental search for 0νββ

Experimental sensitivity
Maximum measurable half-life at a given C.L.

$$S_{0\nu} \propto \sqrt{\frac{M \cdot T}{B \cdot \Delta}}$$

Crytical experimental parameters:

- **Isotope Mass (M)**
- **FWHM energy resolution (Δ)**
- **Background (B)**

Mass scalability at low cost and **high isotopic abundance** are mandatory for next generation experiments

Δ of few % at Q_{value} mandatory to avoid **the 2νββ induced background**

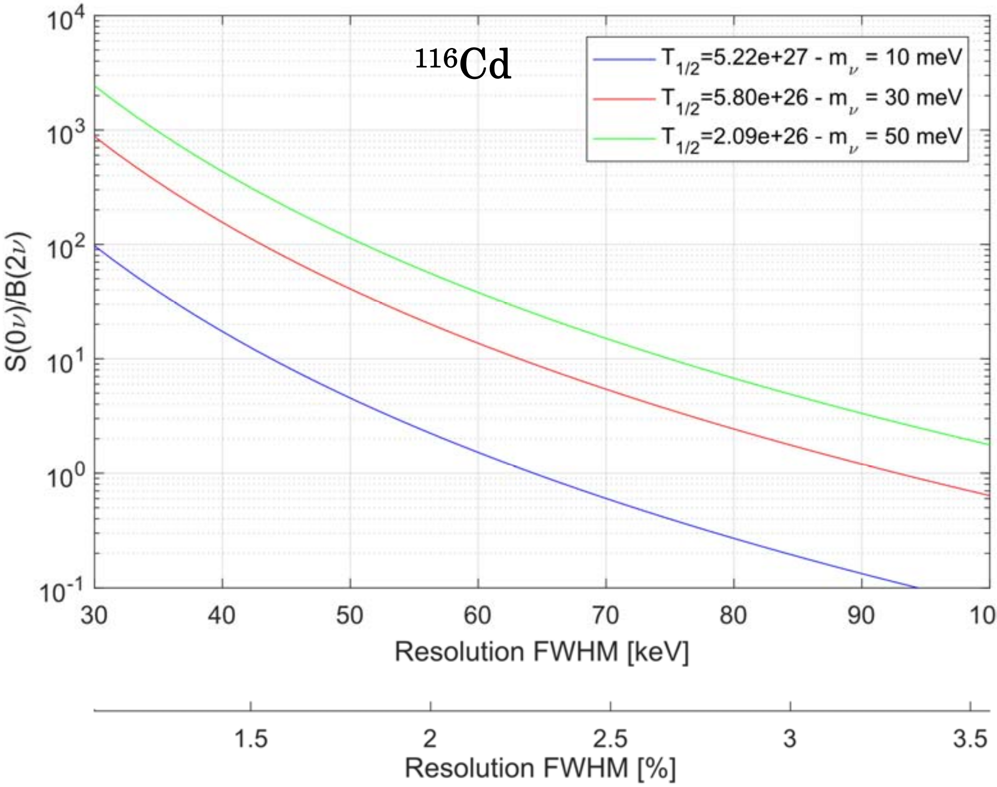
High purity materials
(< ppb radioactive contaminations)
Rejection techniques

Ratio 0νββ signal/2νββ background

$$\frac{S^{0\nu}}{B^{2\nu}} \propto \frac{Q^5_{value}}{\Delta^6} = \frac{1}{Q_{value} \cdot \delta^6}$$

$$\delta = \frac{\Delta}{Q_{value}}$$

Percentage FWHM resolution



Scintillation Detectors: a possible solution

Different possible choices for detector material

Best 0νββ candidate

	Q [keV]	i.a. [%]	Available Crystals
^{116}Cd	2814	7.5	$CdWO_4$, $CdMoO_4$
^{82}Se	2996	8.7	ZnSe
^{100}Mo	3034	9.6	$CaMoO_4$, $PbMoO_4$

Good Scintillator

Improved with detector setup

Mass

Buildable in large arrays

Background

Different particle have different scintillation mechanism

High purity material selection

Resolution

Main limiting factor for this application

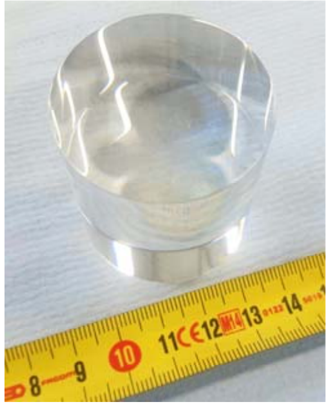
Different effects contribute in spoiling the scintillators resolution

FLARES project

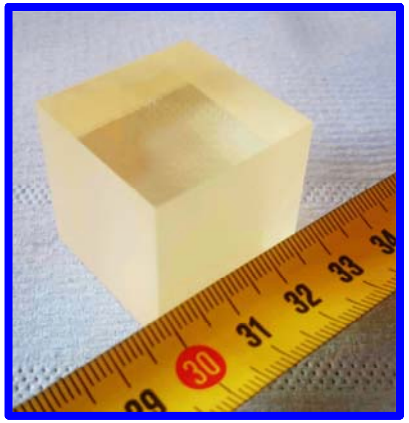
Flexible scintillation Light Apparatus for Rare Events Search

@120K

Selected crystals



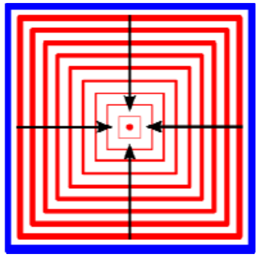
$Ca^{100}MoO_4$



$^{116}CdWO_4$

	ρ [g/cm³]	LY [ph/keV]		τ [μs]	
		300K	120K	300K	120K
$CdWO_4$	7,9	18.5	33.5	13	22
$CaMoO_4$	4,3	8.9	25	18	190

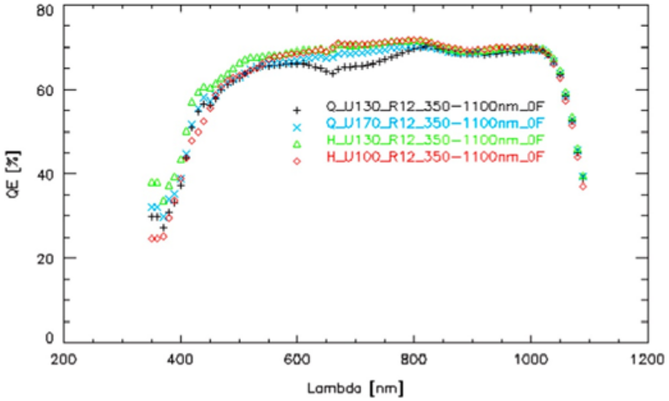
SDD: Silicon Drift Detectors



Electron drift through decreasing negative voltage rings

Central anode collection, Capacitance ~ fF

~80% QE over many wavelengths



Low electronic noise: < 20 rms electrons

LY increase and characterization

Device characterization

Low temperature are optimal

LY increases at lower temperature

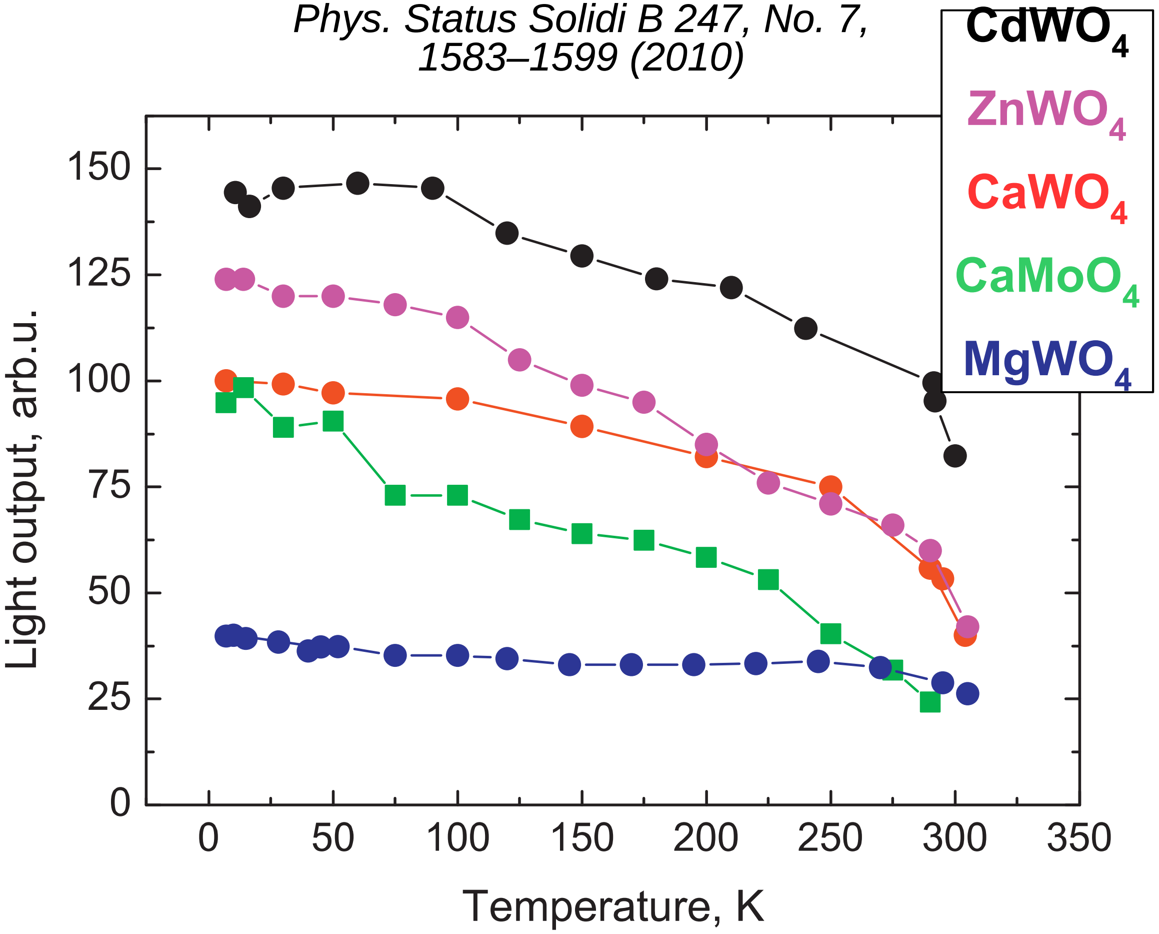
Less phonon scattering

Needs to be quantified to select crystal and operation conditions

↓

Lower T, better resolution

Phys. Status Solidi B 247, No. 7, 1583–1599 (2010)



Extremely low temperature are not needed for all crystals

Easy operational conditions

	LY [ph/MeV]	
	300K	120K
CdWO4	18500	33500
CaMoO4	8900	25000
PbMoO4	-	6000

Non proportionality is limiting

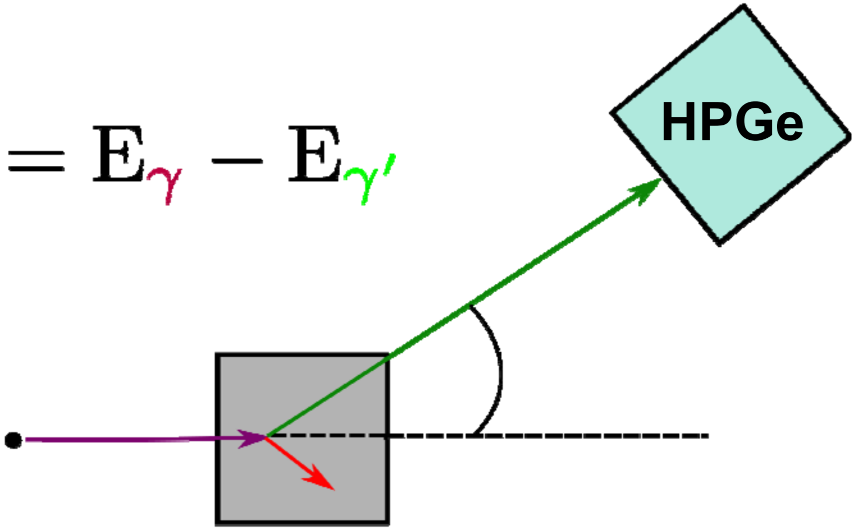
- Lack of proportionality between energy deposited in the crystal and light output
  - No correct energy determination → **resolution spoiling**

$$R_{LY} = \frac{LY(E)}{LY(662keV)}$$

Relative light yield

- **CCT:** exploiting Compton effect to create **electrons** of known energy inside the crystal

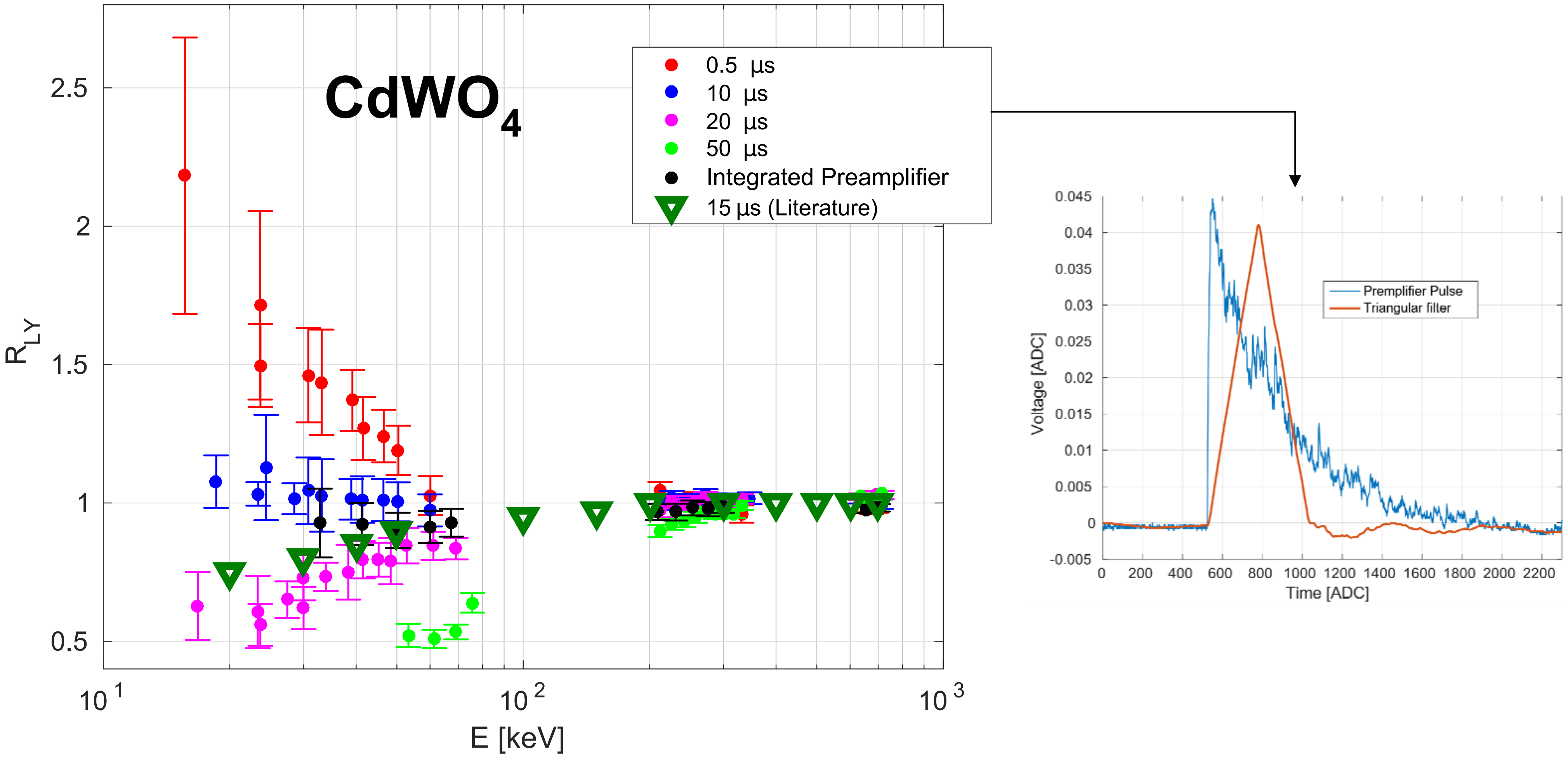
$$E_e = E_\gamma - E_{\gamma'}$$



Scintillator +PMT

- Coincident detectors
- HPGe allows precise energy determination

Result: $CdWO_4$ dependence on shaping



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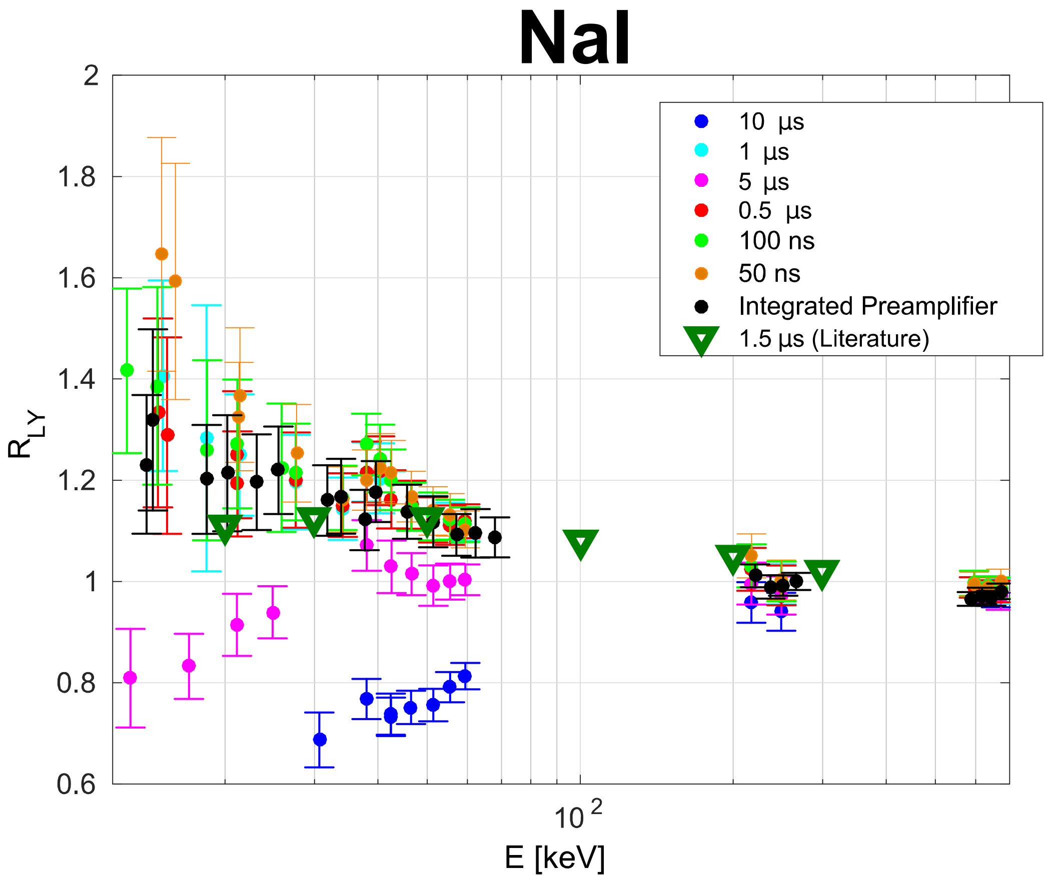
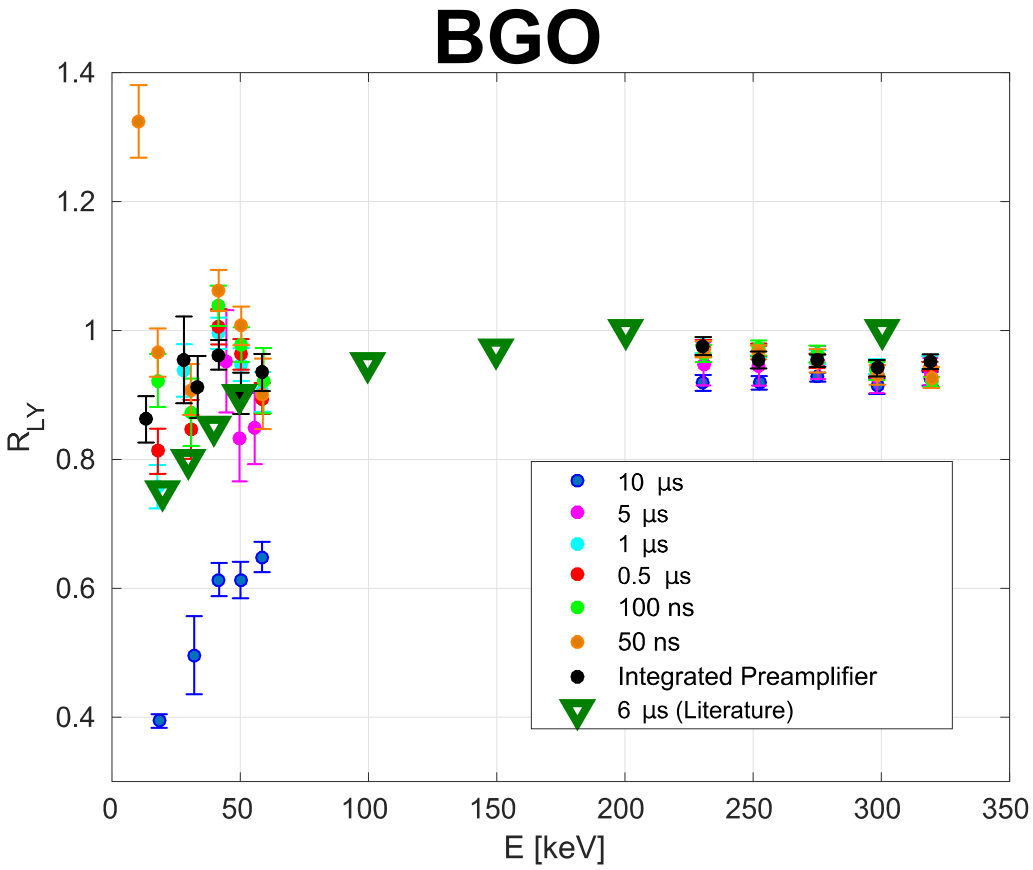
Significant dependence on the ST

- Digitally applied: trapezoidal shaping
- Changes non proportionality slope → different from **literature**
- **Can be exploited to avoid non-proportionality**

Even on more known crystal



NaI



BGO

- “Same” behavior of $CdWO_4$
  - Different behavior at same shaping time
    - Link with the different scintillation time constant (τ_{scint})
  - **Always possible to reduce the non proportionality effect**

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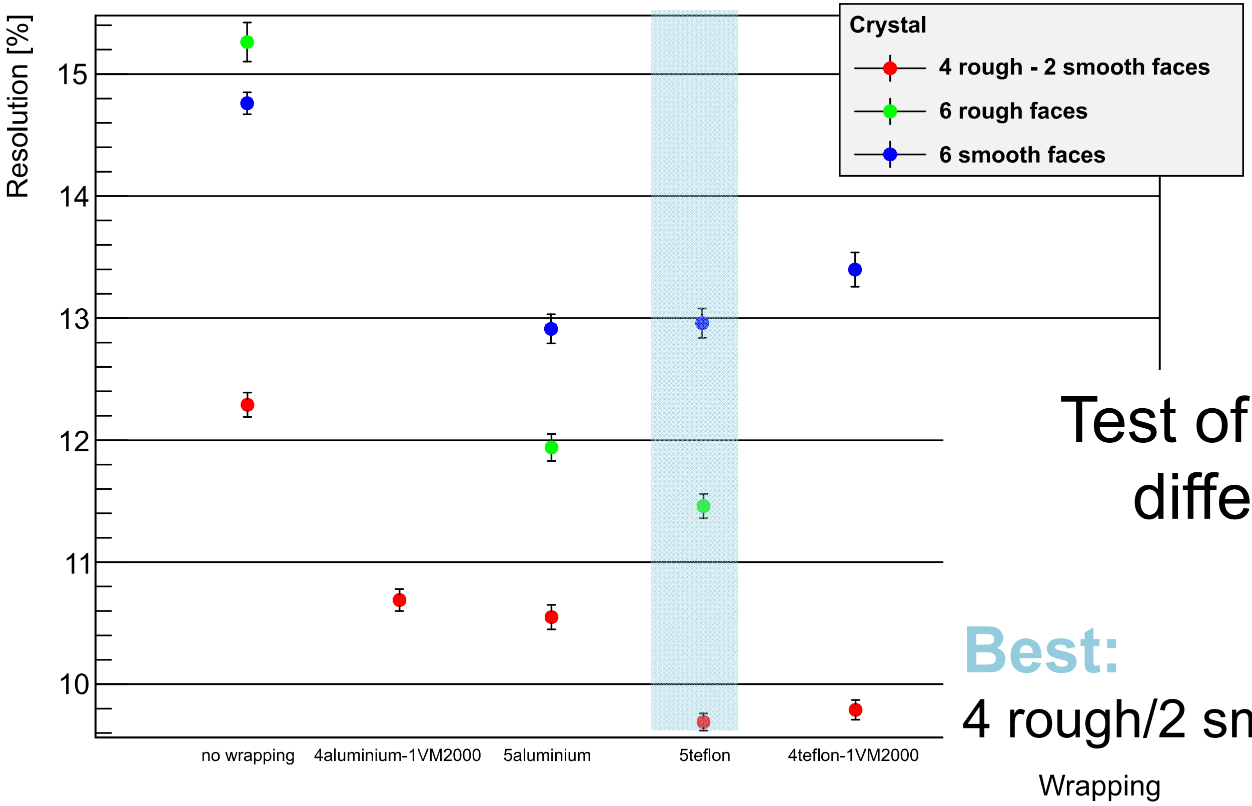
Wrapping: Increase of light collection efficiency

Increasing the chance of redirecting a photon toward the photodetector

$$\mathrm{N_{ph}} = \mathrm{E_{Dep}} \cdot \mathrm{LY} \cdot \epsilon_{\mathrm{Q}} \cdot \boxed{\alpha_{\mathrm{ph}}}$$

Wrapping: reflective/diffusive material around the crystal

Resolution as a function of crystal wrapping

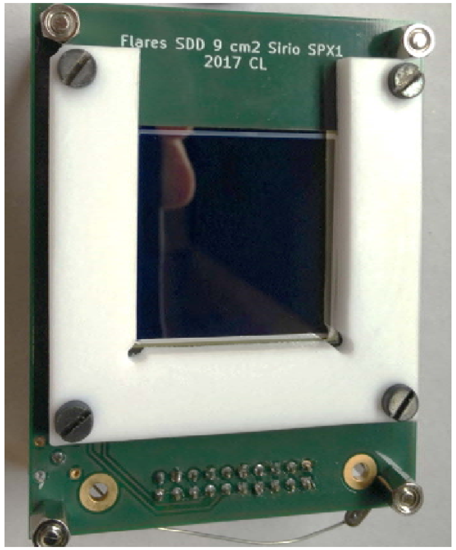


Resolution @511 keV
$CdWO_4$ + PMT

Test of different materials and different crystal surfaces

Best:
4 rough/2 smooth + Teflon

SDD characterization

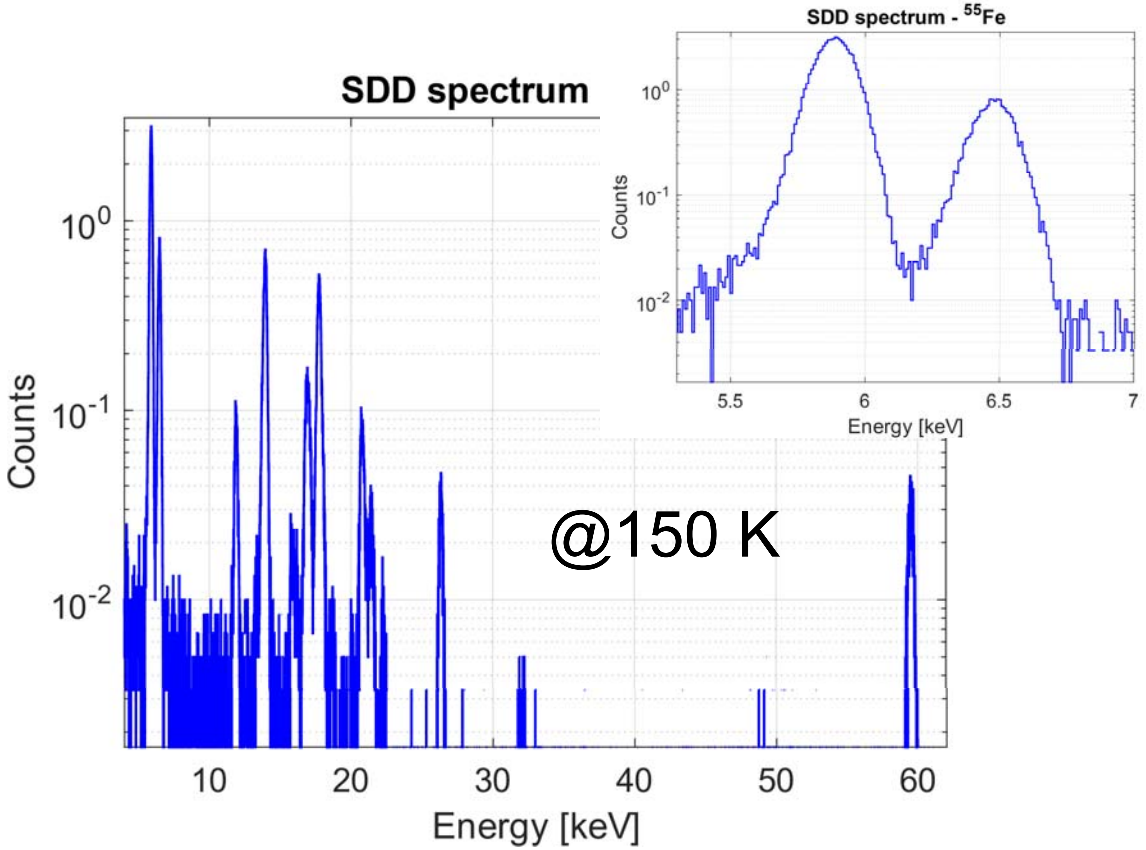


New large area detectors

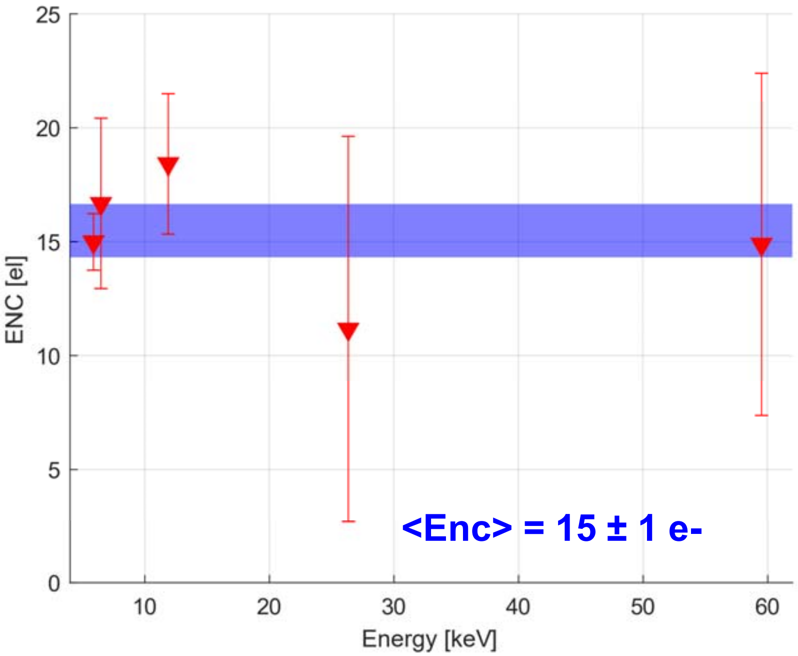
- 9cm^2 of active area

Characterization ongoing

- X-ray measurement: electronic noise evaluation
  - o Detector working correcly
  - o **15 RMS electrons @150K**

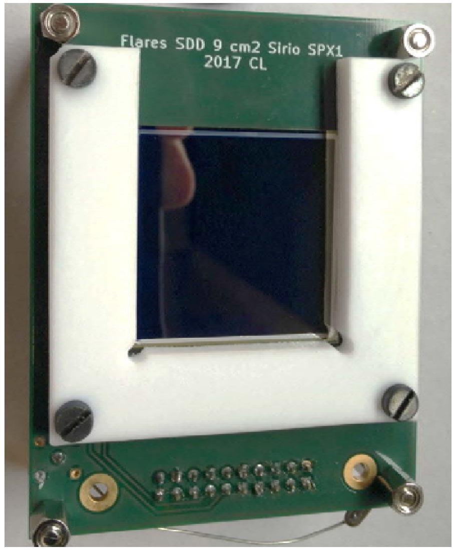


@150 K



<Enc> = 15 ± 1 e-

SDD characterization



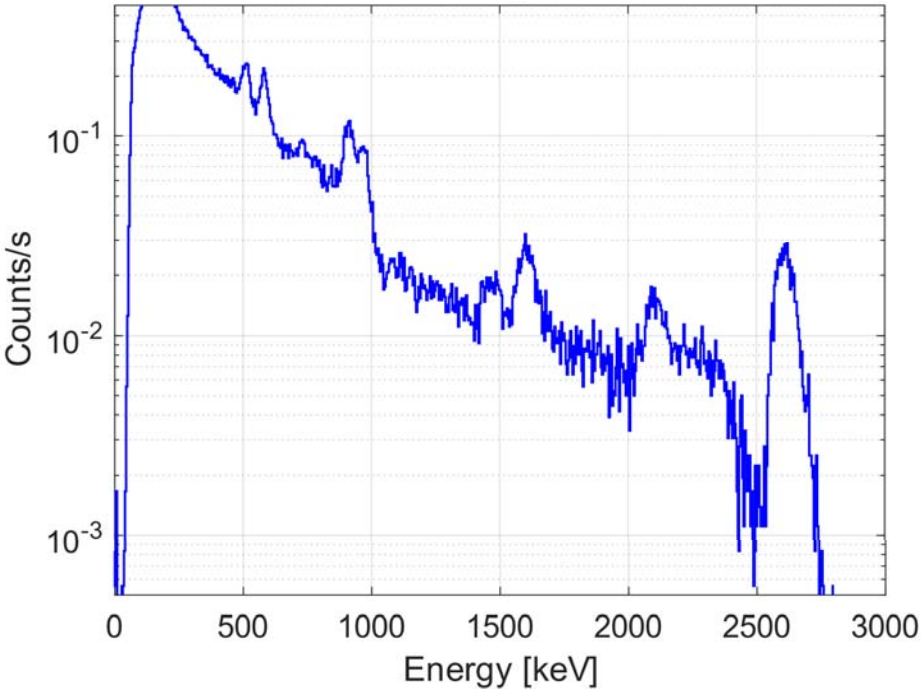
New large area detectors

- 9cm^2 of active area

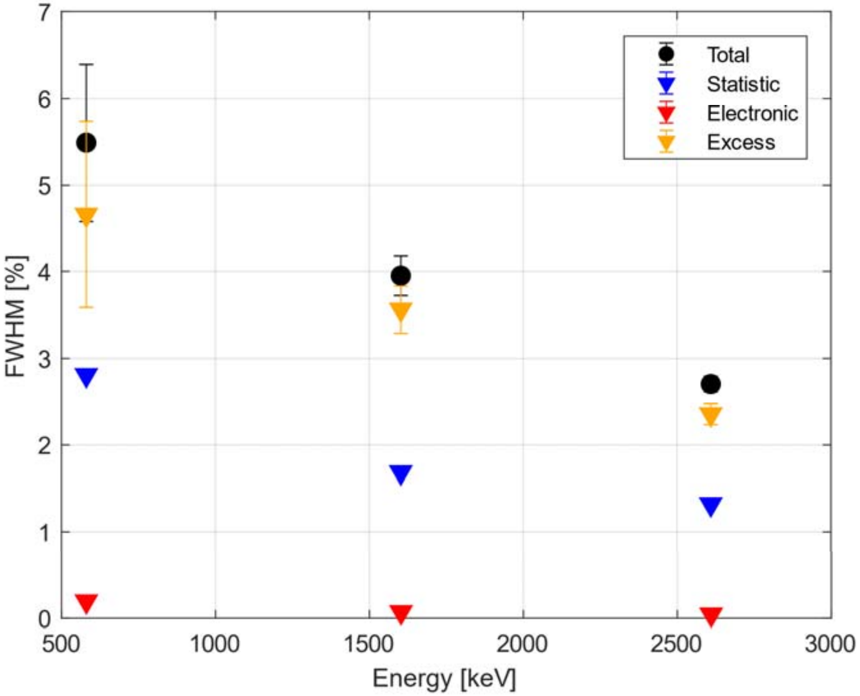
Characterization ongoing

- γ-ray measurement: SDD+CdWO$_4$
  - R=2.6% @ 2615 keV → **ok with concept**
  - **Resolution limited by non uniform detection efficiency**

SDD Calibrated Spectrum – ^{232}Th



Relative FWHM at different energies



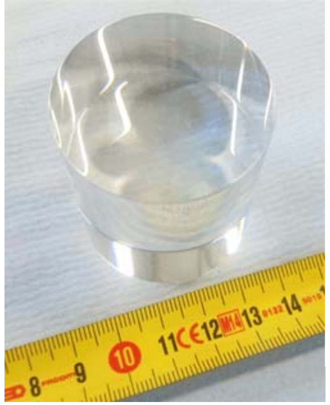
Summarizing

Development of a scintillator **with good energy resolution** and **good mass scalability**.

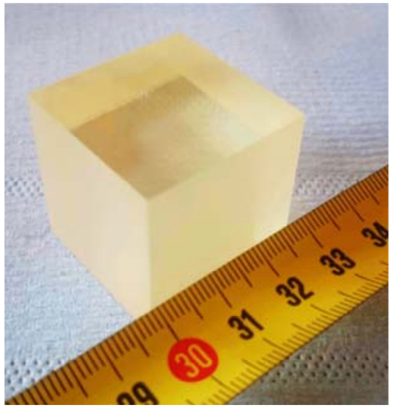
High quality scintillators containinf 0νββ candidate and high performance light detectors with large area (SDD)

Crystal R&D

- Different characterization performed
  - Selection of the best operational configuration
  - Understanding of light emission non-proportionality



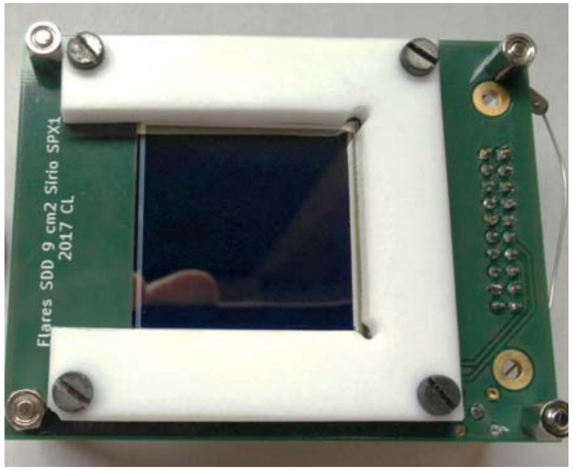
Ca^{100}**Mo**O$_4$



^{116}**Cd**WO$_4$

Sensor R&D

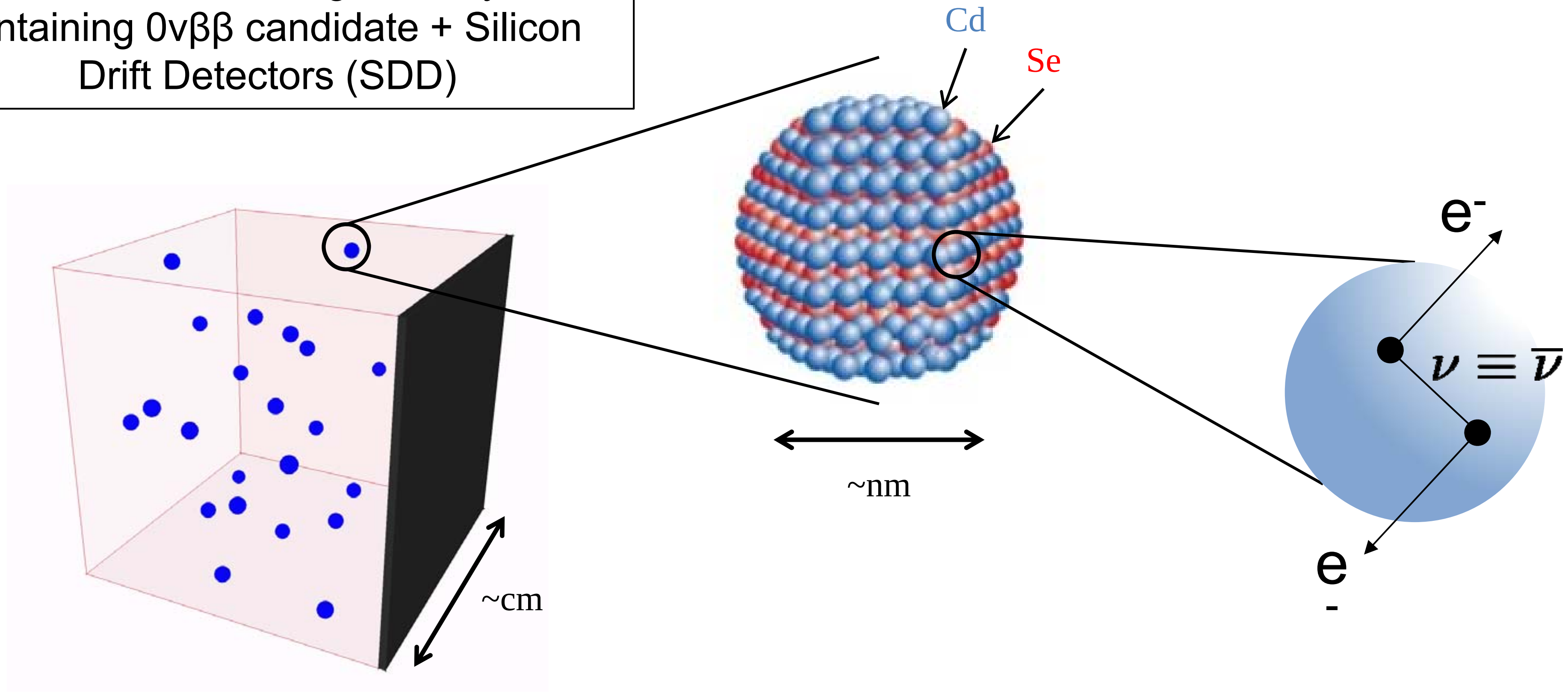
- 9 cm^2 SDDs are the largest devices ever produced. Their noise performance are good and are not the limiting factor.
- Achieved energy resolutions are slightly worse than expected, but our measurements show that the non uniform detection efficiency is the main limitation



A New Approach: ESQUIRE

The goal of ESQUIRE is to apply a **new approach** in the study of rare events, such as the **Neutrinoless Double Beta decay(0vββ)**.

Detector:
Matrix with scintillating nanocrystals containing 0vββ candidate + Silicon Drift Detectors (SDD)



Main Objective:
Development of a Quantum Dots based scintillator with **good energy resolution** and **easy mass scalability**.

↓

Being a new approach, the ESQUIRE R&D can pave the way to the development **of a new class of radiation detectors**

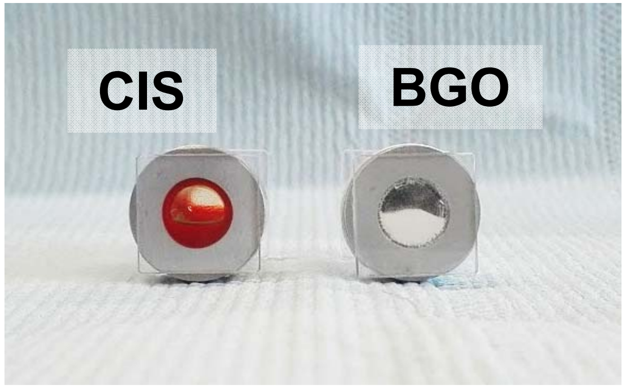
Next Steps

Production/characterization of QD

- Search for the best sample
  - High emission and concentration

Different Matrices

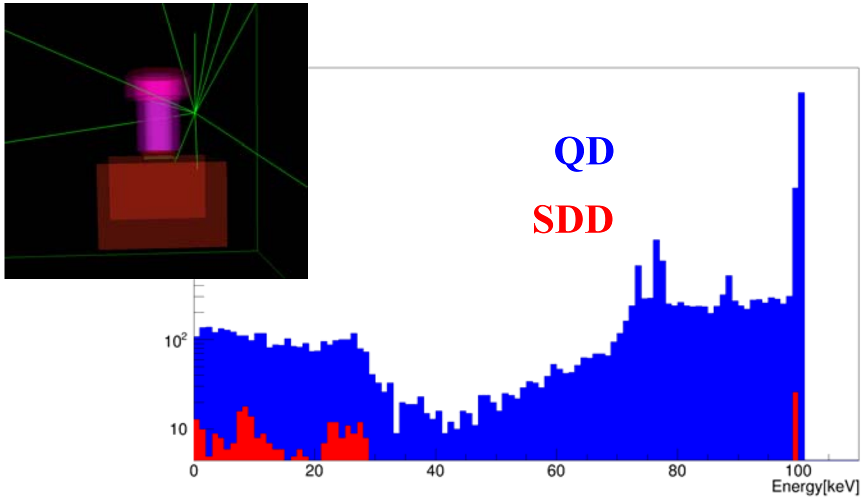
- Both liquid and solid



Optical Characterizations

Scintillation measurements

- With PMT and SDD
- Evaluation of QDs LY



MC simulation of the sample

- Detection efficiency evaluation
- Prior evaluation of the experimental condition

Thank you for your attention!

FLARES

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ESQUIRE

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BackUp Slides

0νDBD

Effective neutrino mass

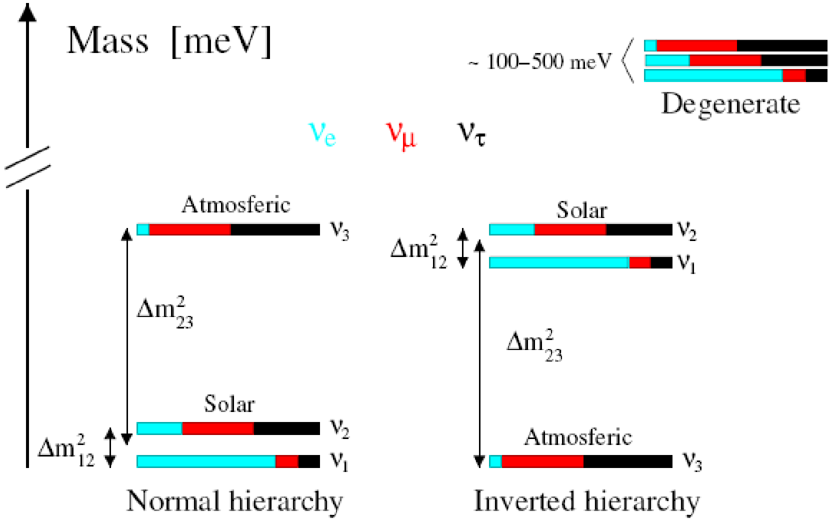
$$\left[T_{1/2}^{0\nu}\right]^{-1} = C \cdot \frac{\left\langle m_{\beta\beta} \right\rangle^{2}}{m_e^{2}}$$

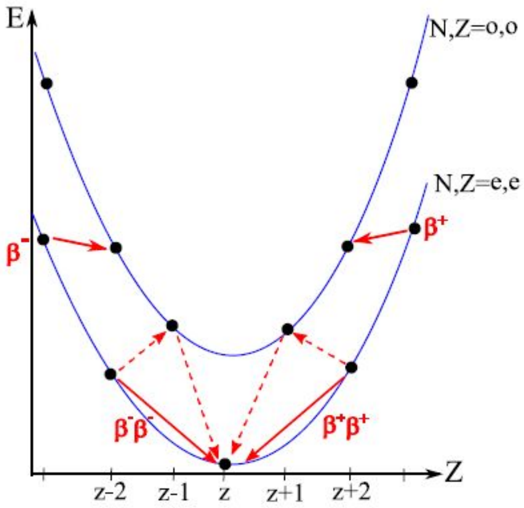
Nuclear Factor of merit

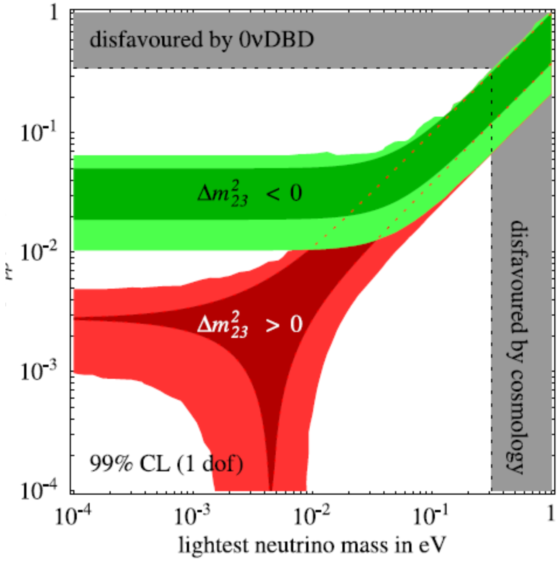
$$C = \left|M^{0\nu}\right|^{2} \cdot G^{0\nu} \qquad [y^{-1}]$$

Nuclear matrix element

Space phase factor







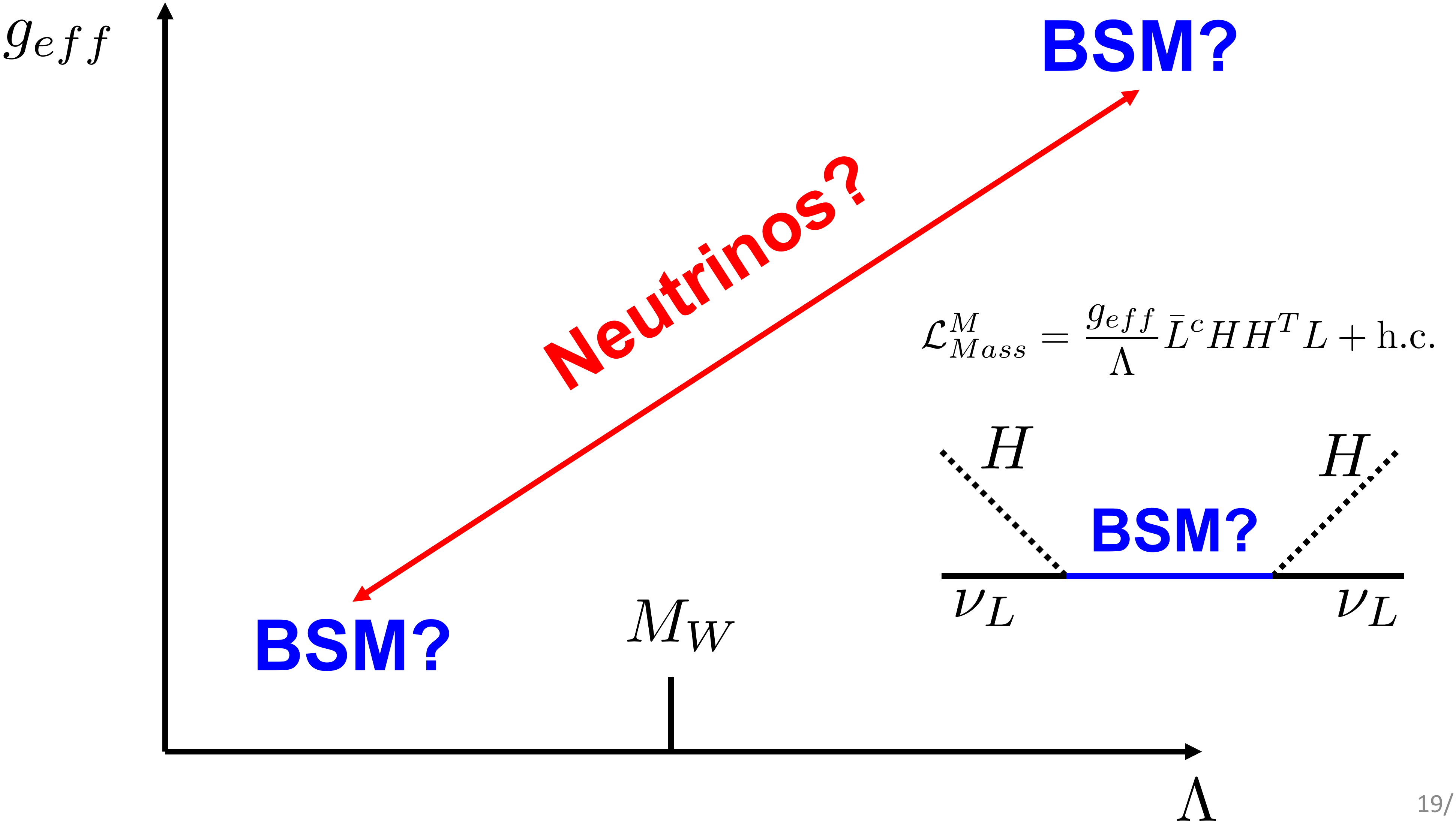
$$N_{Ev} = M\frac{\chi \cdot N_{Av}}{M_{mol}}\eta\frac{T}{\tau^{0\nu}}$$

χ = coefficiente stechiometrico
η = abbondanza isotopica

Theoretical importance of 0νββ searches

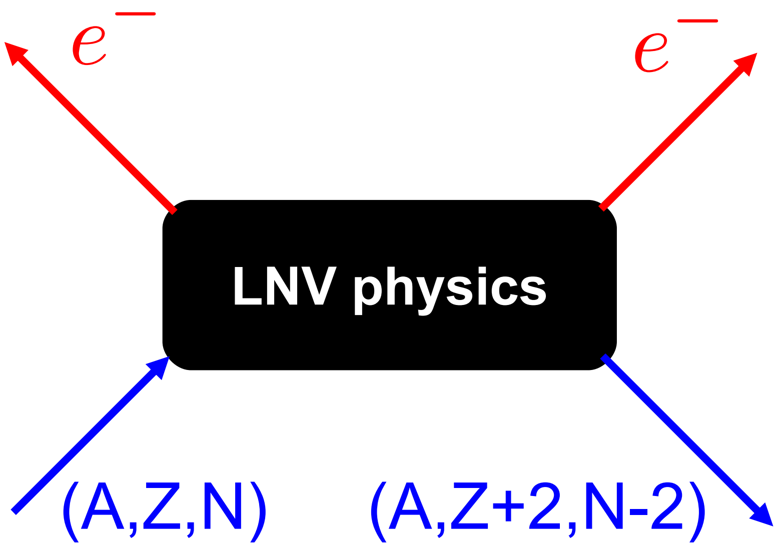
Different possible generator masses and couplings to neutrinos

- All BSM features → **new phenomenologies**



$$\mathcal{L}^{M}_{Mass} = \frac{g_{eff}}{\Lambda}\bar{L}^{c}HH^{T}L + \text{h.c.}$$

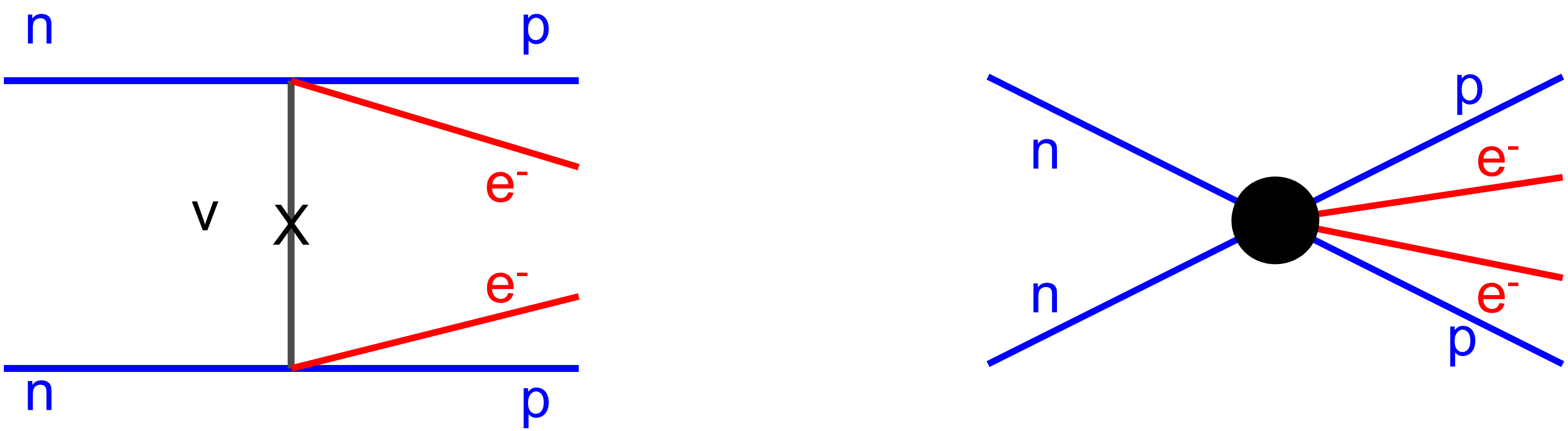
Theoretical importance of 0νββ searches



Black Box

- Unpacked differently by different mass models
- <u>Indipendent by the model chosen</u>

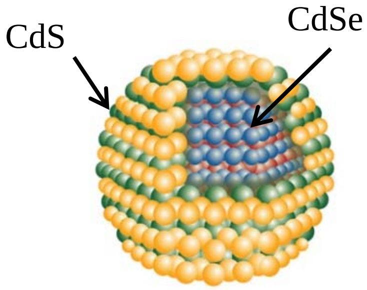
- Each model leads to **different predictions** with respect to the physics of 0νββ
- Two different main scenarios:

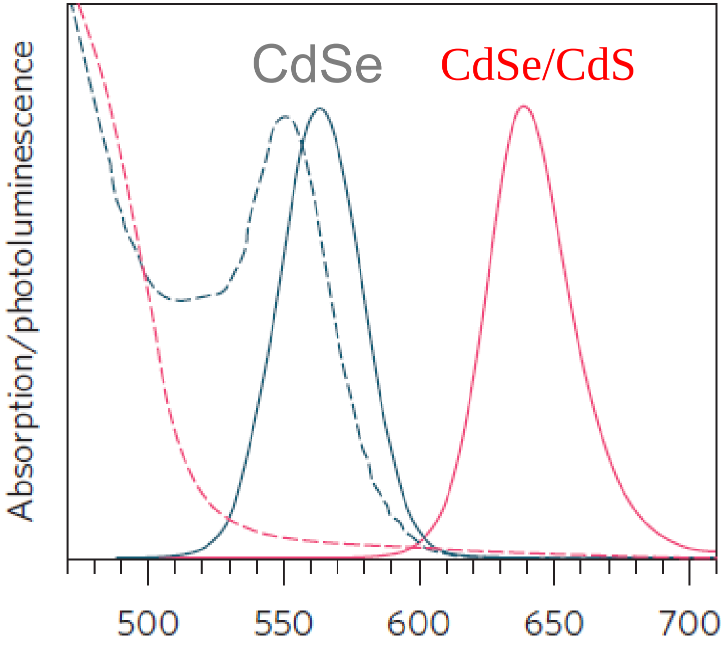


Most Interesting QDs

Core/shell Quantum Dots, for example **CdSe/CdS e CuInSe$_2$**

- High **Stokes shift** (low self-absorbance)
- Small probability for Auger non radiative recombination
- Photo stability
- Preliminary indication of high light yield after X and γ interaction





Stokes shift

- Decoupling of absorption/emission bands

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High luminous emission even with high concentration

^{116}Cd e ^{82}Se are two of the most interesting 0νββ candidate isotopes, given their Q$_{valore}$ end isotopic abundance

Resolution issue for scintillation detectors

Scintillation light detectors suffer from non optimal **energy resolution**

$$\delta = \sqrt{\mathrm{R}_{\mathrm{Stat}}^2 + \mathrm{R}_{\mathrm{El}}^2 + \boxed{\mathrm{R}_{\mathrm{Int}}^2}}$$

Statistical, electronic and intrinsic components

$$\mathrm{R}_{\mathrm{Stat}} = \frac{1}{\sqrt{\mathrm{N}_{\mathrm{ph}}}}$$

$$\mathrm{N}_{\mathrm{ph}} = \mathrm{E}_{\mathrm{Dep}} \cdot \boxed{\mathrm{LY}} \cdot \epsilon_{\mathrm{Q}} \cdot \boxed{\alpha_{\mathrm{ph}}}$$

Different parameters to be explored to optimize the resolution

Light Yield increase

Light Yield non proportionality

Light Detection efficiency

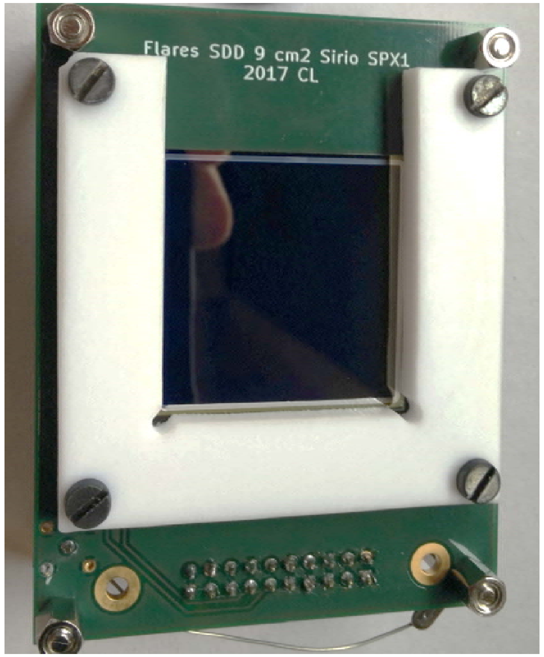
Current status and future plans

Scintillation detectors investigation

- Scintillation mechanism
- Background rejection efficiency
- Crystal study, LY at low T (130K)

FLARES technical R&D

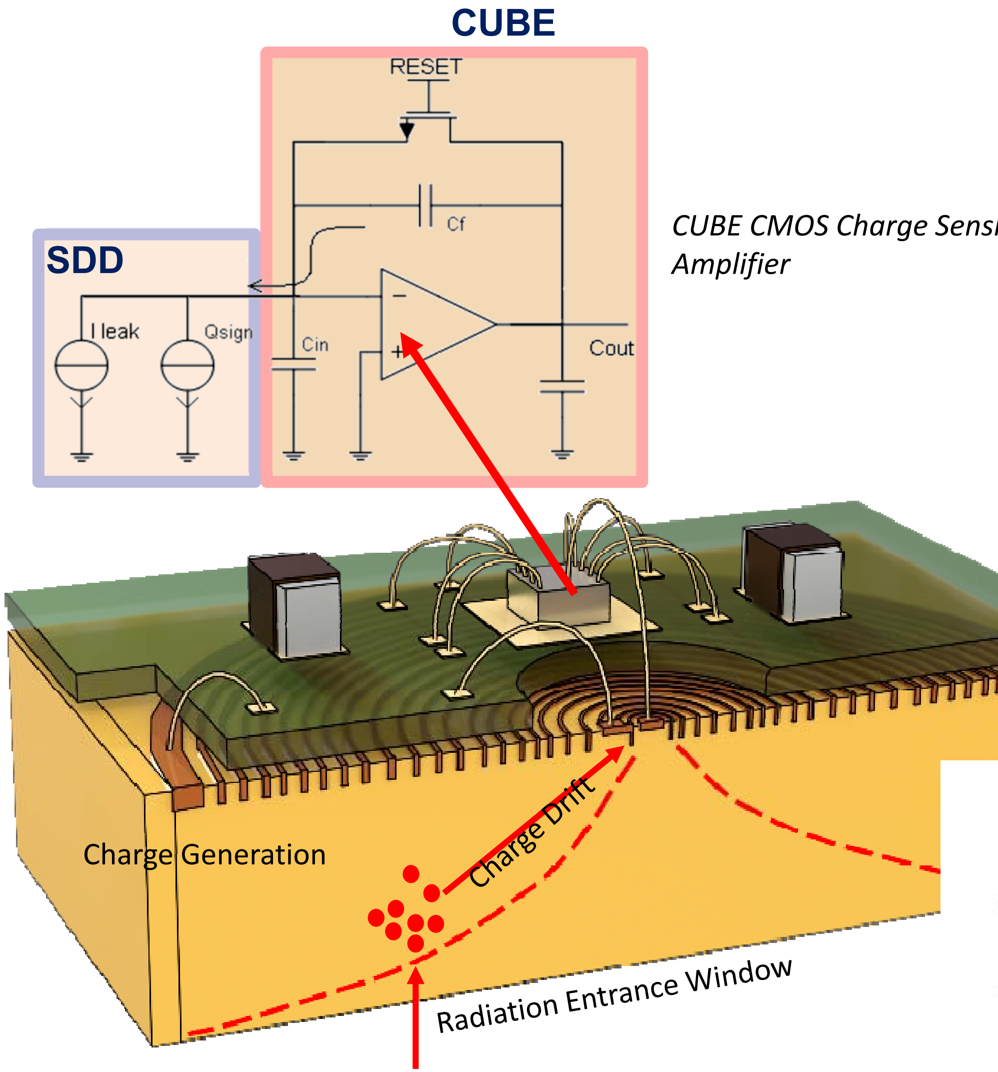
- SDD measurements and further testing



New large area detectors

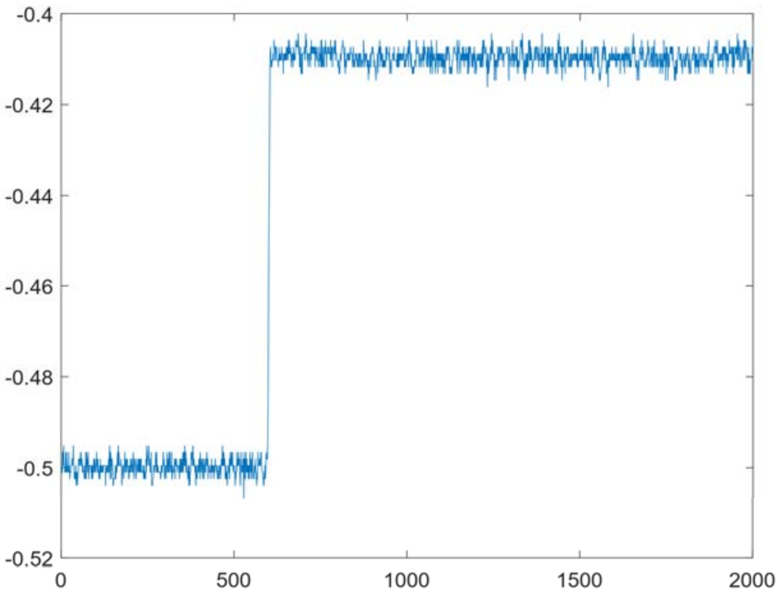
- 9cm^2 of active area
- Characterization ongoing

CUBE preamplifier



CUBE CMOS Charge Sensitive Amplifier

- CMOS technology
- Designed for high rate (10ms risetime)
- Optimized for SDD
  - Low capacitance
  - Bonded directly to the anode
  - No $R_{feedback}$ → reduced impact of leakage current noise and no offset



Typical pulse

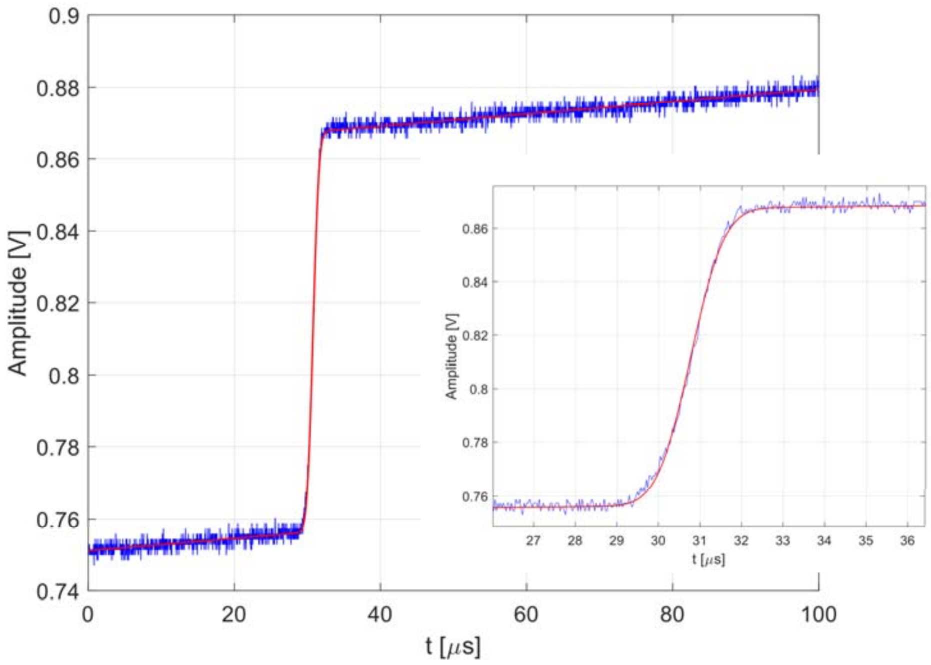
New Pulse fit for X-ray

$$A(t) = A_{Fit} \int_0^t e^{-\left(\frac{x-\mu}{\sigma}\right)^2} dx + \underline{mt + q}$$

Step Amplitude

Diffusion

Ramp



X-ray waveform @233K

- No Baseline subtraction
- Allows the investigation of imperfect charge collection
  - Bigger σ → Longer drift times
- Good modellization of pulse shape → χ2 cuts