Università degli Studi di Milano - Bicocca
INFN di Milano - Bicocca

The FLARES project: an innovative detector technology for rare events searches

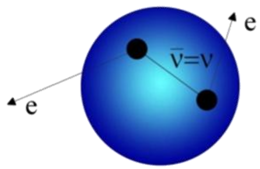
L. Gironi on behalf of the FLARES collaboration

14th Vienna Conference on Instrumentation
Vienna, Feb 15 - 19, 2016

Neutrinoless Double Beta Decay (0νDBD)

0νDBD

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



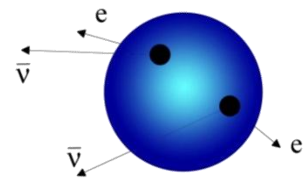
- Not allowed in Standard Model (ΔL=2)
- The decay occurs only if neutrinos are Majorana particles
- Requires neutrino is a massive particle
- The decay rate depends on the "effective Majorana mass"

$$\left(T_{1/2}^{0\nu}\right)^{-1} = F_N \frac{\left|\left\langle m_{\beta\beta}\right\rangle\right|^2}{m_e^2}$$

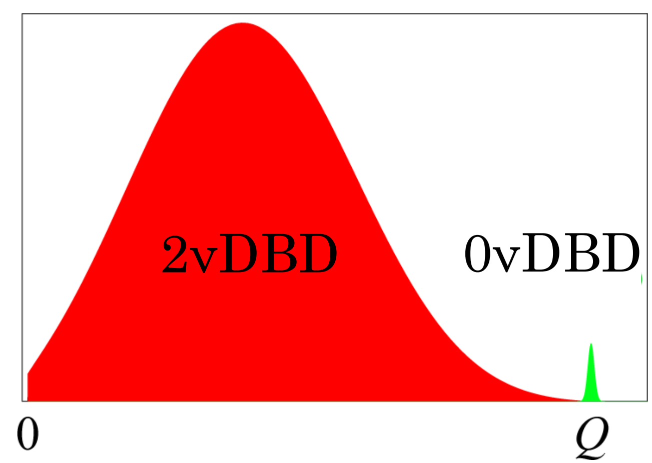
Nuclear factor of merit

2νDBD

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



- Allowed in Standard Model
- Already observed for several nuclei (half-lives of the order $10^{18} - 10^{21}$ y)



Neutrinoless Double Beta Decay (0νDBD)

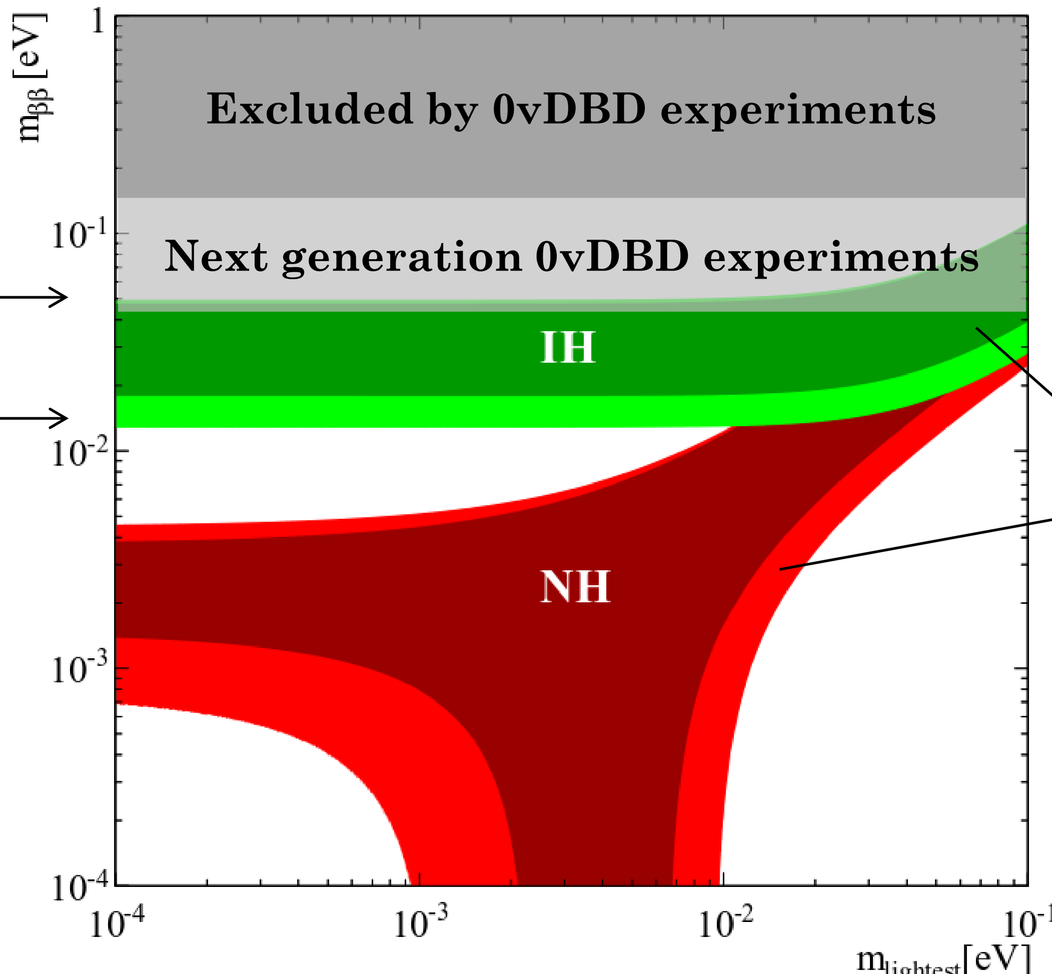
- Possible for ~35 nuclei, only ~10 really interesting
- Extremely rare process ($T^{0\nu}_{1/2} > 10^{24}$ - 10^{25} y)

$T^{0v} \sim 10^{26}$-10^{27}y →

$T^{0v} \sim 10^{27}$-10^{28}y →

↓

Experiments able of measuring such low rate are a technological challenge!!!



Neutrino oscillations constrains

Detector sensitivity for rare events searches

Sensitivity: the process half-life corresponding to the maximum signal that could be observed (over the background fluctuations) at a given statistical C.L..

$$S = \ln 2 \cdot N_{\beta\beta}^{eff} \cdot \frac{T}{n}$$

n = confidence level
$N_{\beta\beta}^{eff} = N_{\beta\beta} \cdot \varepsilon$
$N_{\beta\beta}$ = number of nuclei
ε = detector efficiency

$$N_{\beta\beta} = \frac{N_A \cdot M \cdot x \cdot \eta}{A}$$

T = live time [y]
M = detector mass [kg]
B = background [c/keV/kg/y]
Δ = energy resolution [keV]
A = atomic mass
x = isotopic ab.
η = $N_{\beta\beta}$ per molecule

'Zero' background experiments

$$M \cdot T \cdot B \cdot \Delta \approx 0$$

$$\downarrow$$

$$n = 2.8 \quad (68\% \ \text{C.L.})$$

$$S_{0B} = \ln 2 \cdot N_{\beta\beta}^{eff} \cdot \frac{T}{2.8} \propto M \cdot T$$

Experiments with background

$$M \cdot T \cdot B \cdot \Delta >> 0$$

$$\downarrow$$

$$n = \sqrt{M \cdot T \cdot B \cdot \Delta} \quad (68\% \ \text{C.L.})$$

Assumption: B∝M

$$S_B = \ln 2 \cdot N_{\beta\beta}^{eff} \cdot \sqrt{\frac{T}{M \cdot B \cdot \Delta}} \propto \sqrt{\frac{M \cdot T}{B \cdot \Delta}}$$

Critical experimental parameters: M, T, B, Δ

Live Time and Mass

Live Time

• It could be considered a **constant** since commonly live time of **5-10 y** are used (it is hard to think to data taking much longer)

• The duty cycle must be optimized in order to have live time ≈ data taking.

Mass

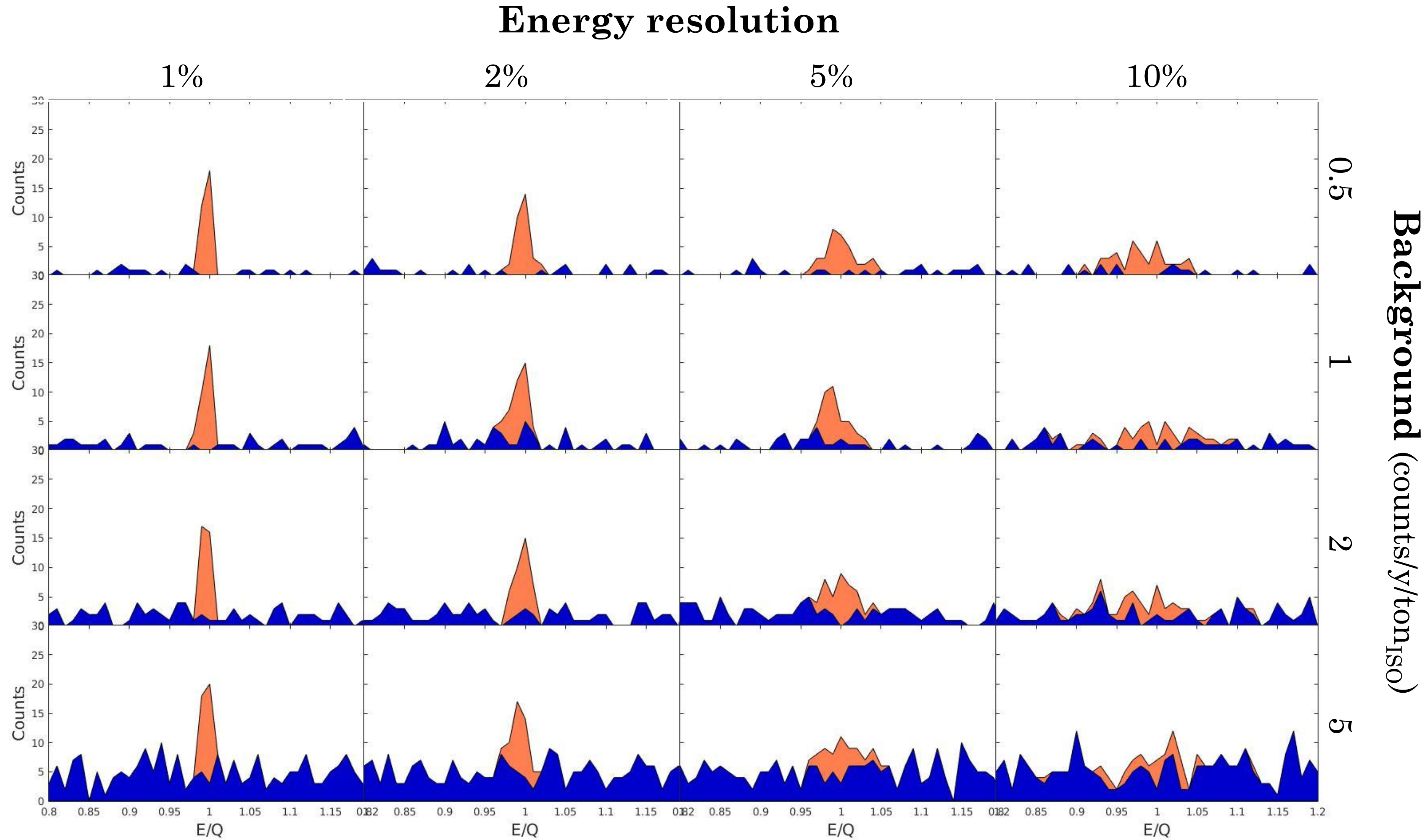
Since the live time is fixed (e.g. 5 y), the maximum sensitivity reachable (i.e. zero background experiments) depends only on the number of isotope nuclei:

$$M_{ISO} \approx 10^{2}\, kg \quad \rightarrow \quad N_{\beta\beta}^{eff} \approx 5 \cdot 10^{26} \quad \rightarrow \quad S_{0B} = \ln 2 \cdot N_{\beta\beta}^{eff} \cdot \frac{T}{2.8} \approx 5 \cdot 10^{26}\, y$$

Low cost mass scalability and high isotopic abundances are mandatory for future experiments!!!!

Selection of isotopes with high natural abundance and enrichment.

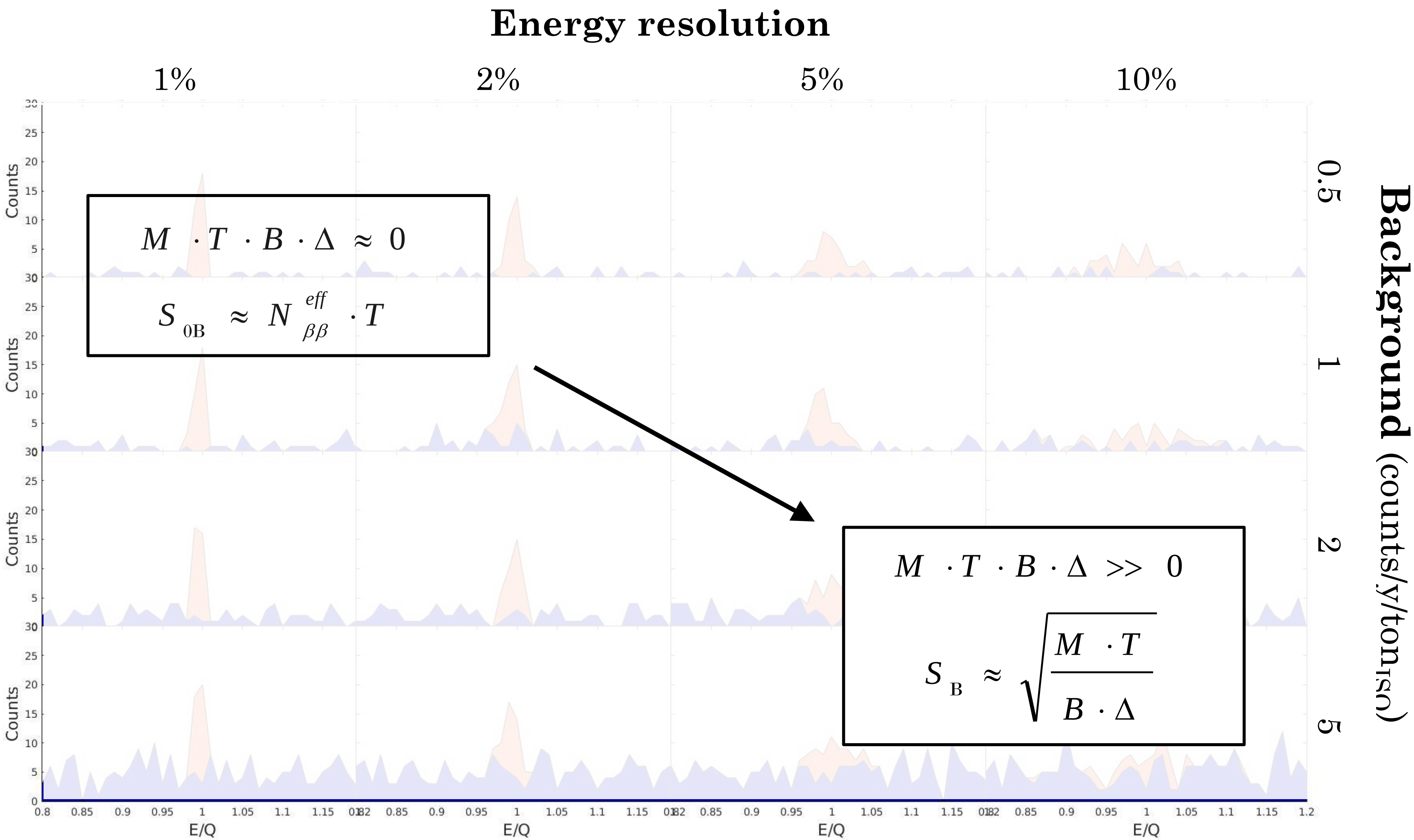
Energy resolution and background – Toy MC



Toy MC assumptions:

- Isotope mass = 10^3 kg
- $T^{0\nu} = 10^{27}$ y
- Live Time = 5y
- Detector efficiency = 1

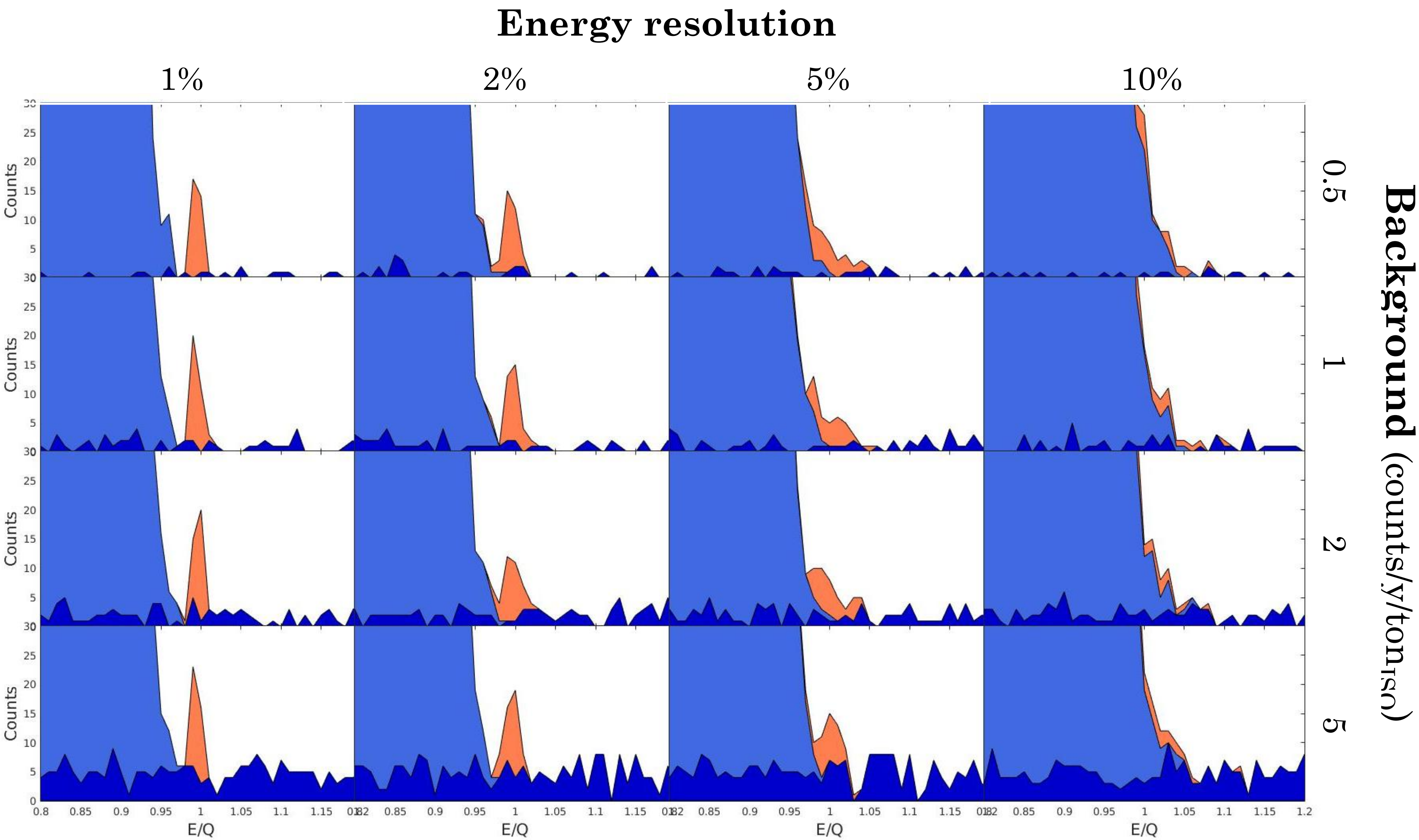
Energy resolution and background – Toy MC



Toy MC assumptions:

- Isotope mass = 10^3 kg
- $T^{0\nu} = 10^{27}$ y
- Live Time = 5y
- Detector efficiency = 1

Energy resolution and background + 2vDBD – Toy MC



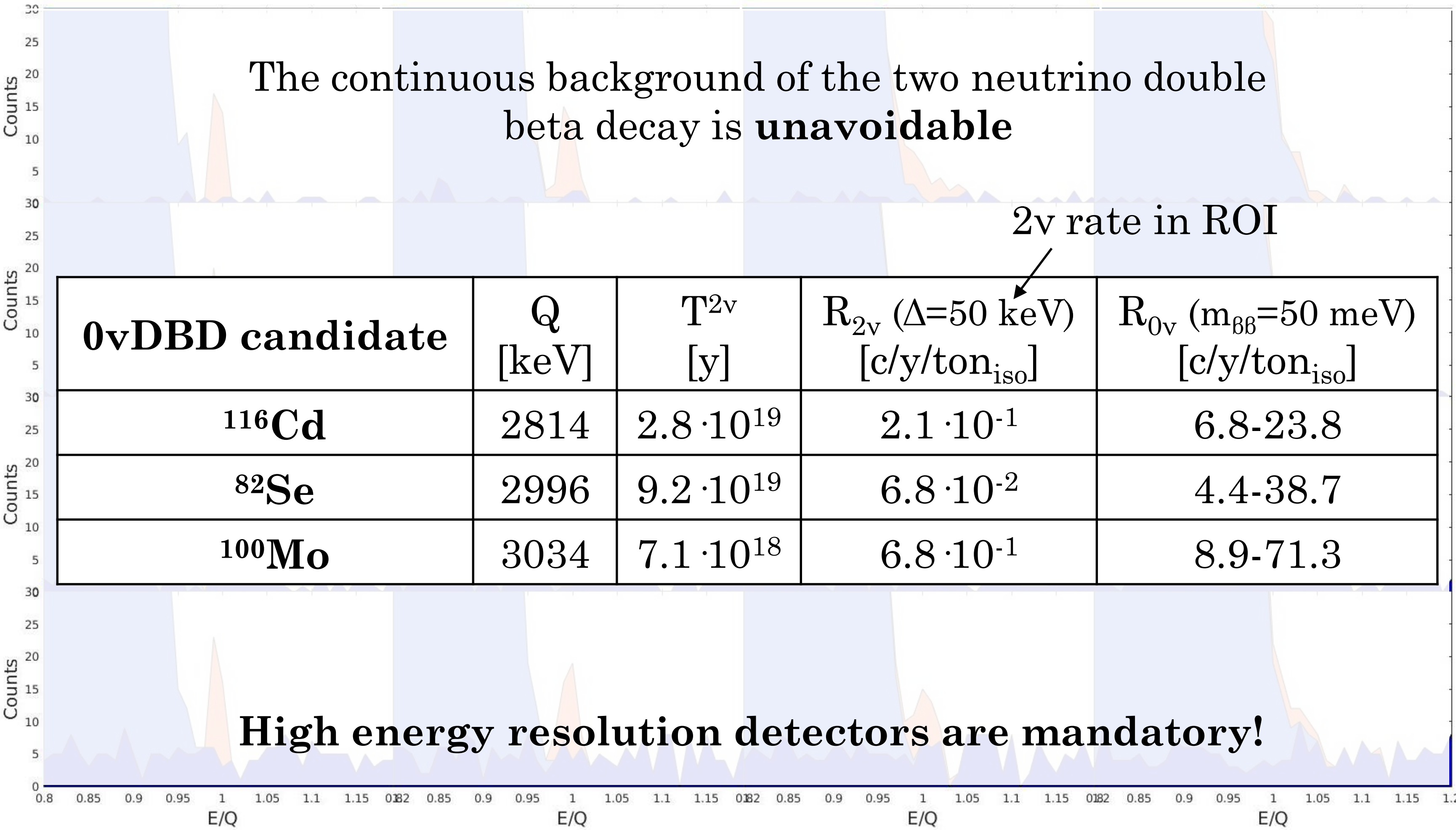
Toy MC assumptions:

- Isotope mass = 10^3 kg
- $T^{0\nu} = 10^{27}$ y
- Live Time = 5y
- Detector efficiency = 1
- $T^{2\nu} = 10^{21}$ y

Energy resolution and background + 2vDBD – Toy MC

Energy resolution

1% 2% 5% 10%



Background (counts/y/ton$_{iso}$)

0.5 1 2 5

The continuous background of the two neutrino double beta decay is **unavoidable**

2v rate in ROI

0vDBD candidate	Q [keV]	T^{2v} [y]	R_{2v} (Δ=50 keV) [c/y/ton$_{iso}$]	R_{0v} ($m_{\beta\beta}$=50 meV) [c/y/ton$_{iso}$]
^{116}**Cd**	2814	$2.8 \cdot 10^{19}$	$2.1 \cdot 10^{-1}$	6.8-23.8
^{82}**Se**	2996	$9.2 \cdot 10^{19}$	$6.8 \cdot 10^{-2}$	4.4-38.7
^{100}**Mo**	3034	$7.1 \cdot 10^{18}$	$6.8 \cdot 10^{-1}$	8.9-71.3

High energy resolution detectors are mandatory!

0vDBD experimental sensitivity - Inorganic scintillator

M	• Flexibility in the choice of the 0vDBD candidate (optimization of the isotopic abundance) • Very high detection efficiency (source=detector) • Mass scalability
T	• High duty cycles (~100%)

B	• Flexibility in the choice of the 0vDBD candidate (Q-value in a low background region)
	• Alpha background reduction thanks to
	  • pulse shape discrimination
	  • scintillation quenching factor for alpha particles as low as 0.2
	• Can be grown with high intrinsic radiopurity

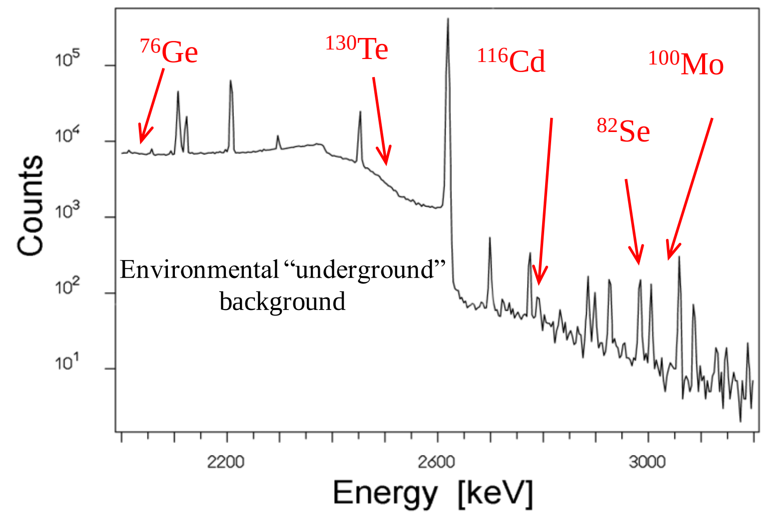
Δ	• So far the limiting factor for the use of this technique for the 0vDBD searches

The main challenge for FLARES is to demonstrate to be able to reach energy resolution of ~1-2%

The choice of the compound

0vDBD candidates with good isotopic abundances (>5%) and transition energy above most intense γ line from natural radioactivity (2615 keV, ^{208}Tl)

Candidates	Q [keV]	i.a. [%]
^{116}Cd	2814	7.5
^{82}Se	2996	8.7
^{100}Mo	3034	9.6

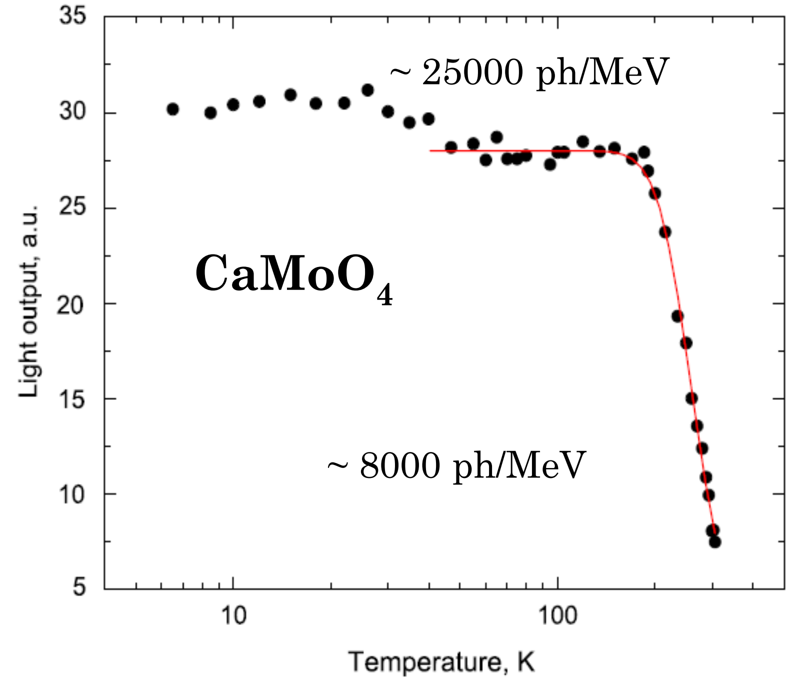


Isotope	Available scintillating crystals
^{116}Cd	$CdWO_4$, $CdMoO_4$
^{82}Se	ZnSe
^{100}Mo	$CaMoO_4$, $ZnMoO_4$

Inorganic scintillating crystals

Many scintillating crystals show a light yield increase as the temperature is lowered

V.B. Mikhailik et al., NIM A 583 (2007) 350



	$CaMoO_4$		$CdWO_4$	
	300 K	120 K	300 K	120 K
Density [g/cm3]	~4.3		~7.9	
Emission maximum [nm]	520		480	
Light yield [ph/MeV]	~8900	~25000	~18500	~33500
Scintillation decay time [μs]	18	190	13	22

Potential energy resolution with scintillators

Assuming a light yield of 20000 ph/MeV at 120 K,
a reasonable value for many scintillators,
at the Q value of many interesting 0vDBD candidates (3 MeV):

$$R_{stat} = \frac{2.355}{\sqrt{3 \cdot 20000}} = 0.96\ \% \equiv 29\ \mathbf{keV}\quad \mathbf{(FWHM)}$$

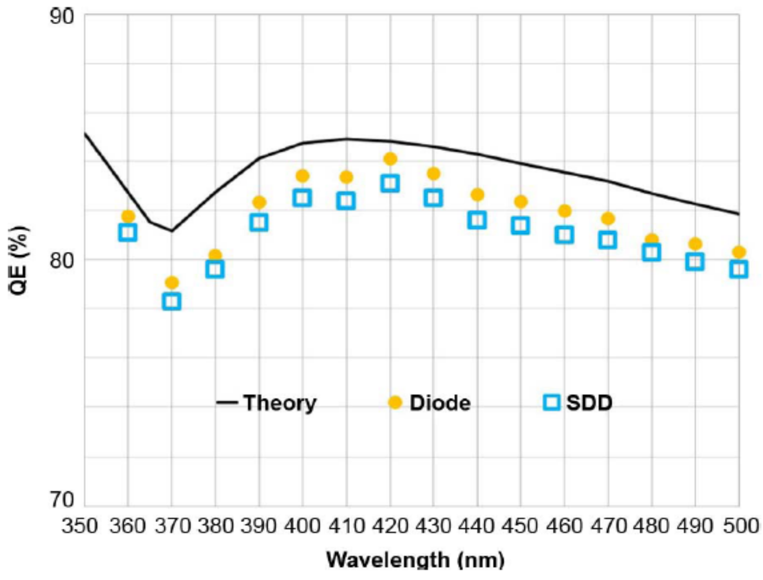
⬇

Not limited by statistics
if all scintillation photons are detected!

⬇

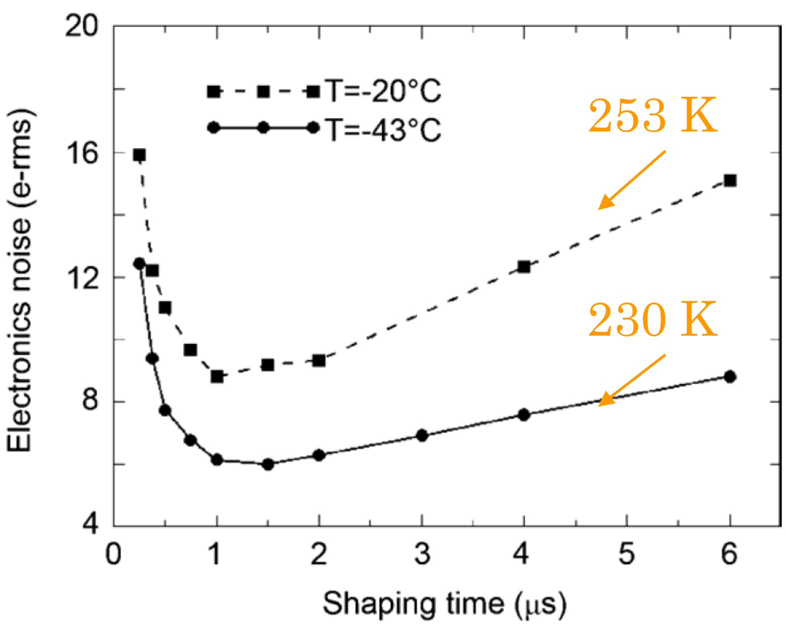
The key point: avoid resolution degradation when the crystal is coupled to a proper photodetector

Silicon Drift Detectors (SDDs) as photodetectors



Quantum efficiency of commercial phototubes ~ 35%

SDDs show high quantum efficiency (~80%) and, at the same time, low electronic noise (especially at low temperature)



$ENC_e = 3.1\ e^-$ r.m.s.

by calculating the ENC for 1 cm² SDD operated at 120 K

C. Fiorini et al., IEEE Transaction on Nuclear Science 60 (2013)

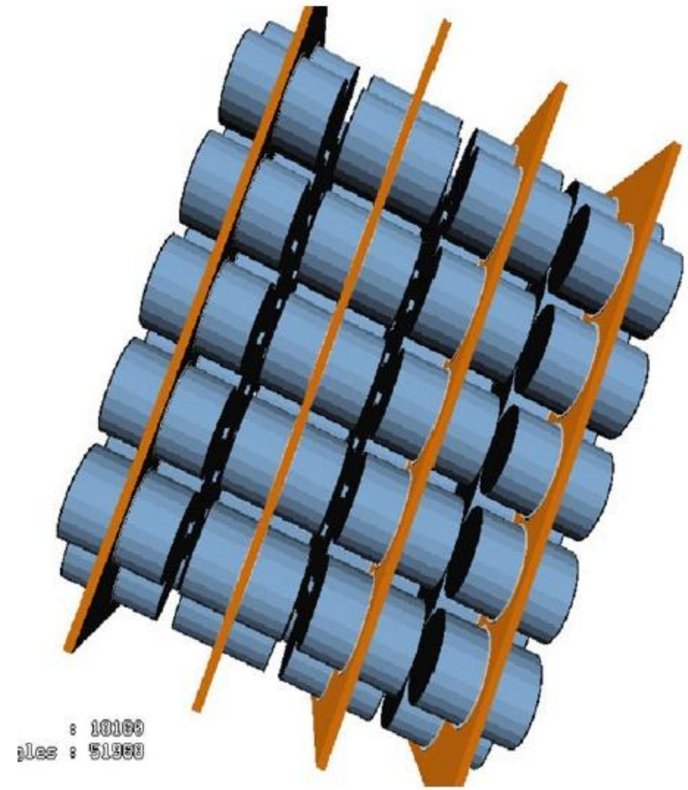
Expected energy resolution: $CaMoO_4$ case

$$R(FWHM) = \sqrt{R_{stat}^2 + R_{noise}^2} \cong 2.355 \sqrt{\frac{1}{\alpha_{ph} N_{ph} \varepsilon_Q} + \frac{N_{SDD} ENC_e^2}{\alpha_{ph}^2 N_{ph}^2 \varepsilon_Q^2}} = 1.15\ \%$$

N_{ph} = 75000 (for 3 MeV for $CaMoO_4$ @ 120K)
α_{ph} = 70% (collection efficiency from MC simulation)
ε_Q = 80% (SDD quantum efficiency)
N_{SDD} = 40 (number of 1 cm^2 SDDs for a Ø 5 cm crystal)
ENC_e = 3.1 e^- r.m.s. (noise of a single 1 cm^2 SDD)

at 3 MeV: ΔE (FWHM) = 35 keV

for one $CaMoO_4$ crystal coupled to an array of 40 SDDs (1 cm^2 each) operated at 120 K



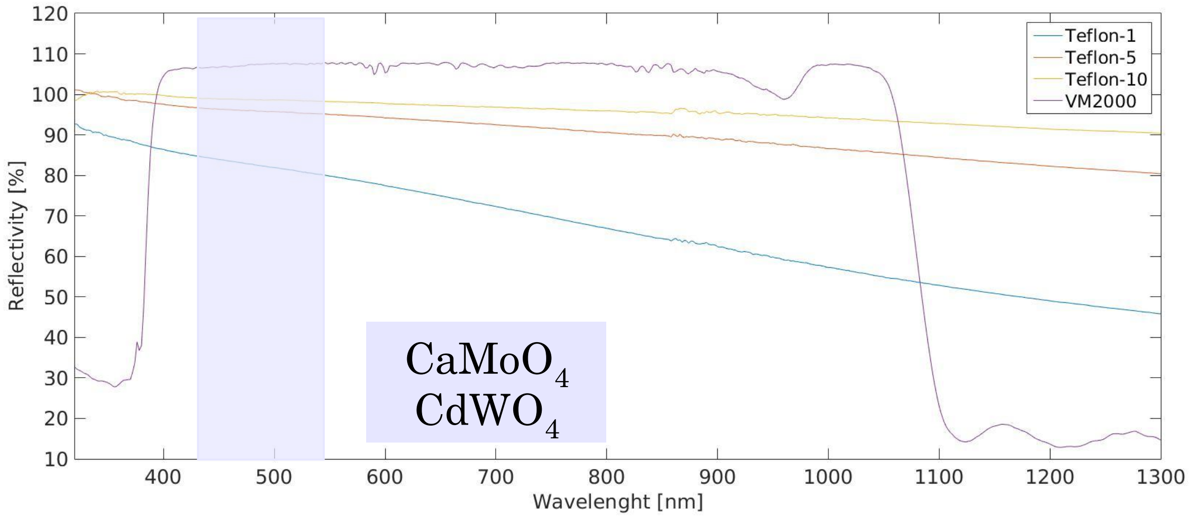
With this detector concept it would be possible to build large mass compact structures of high performing detectors

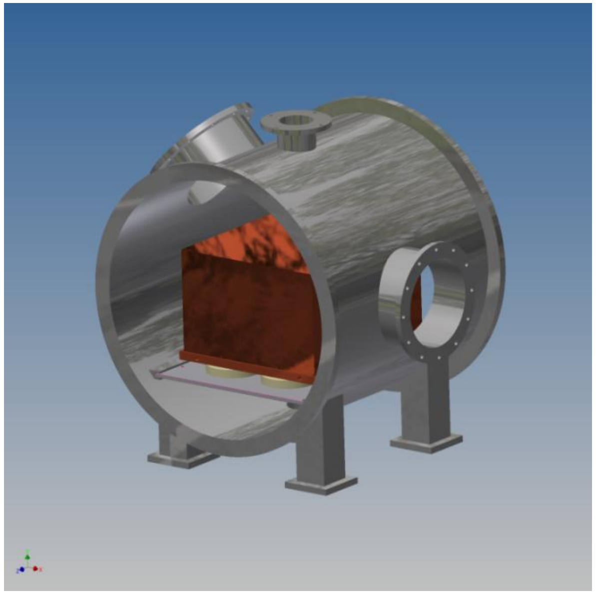
Scintillating crystals for single detector module

We are currently working on:

- Selection of a producer of high quality crystals: $CaMoO_4$ and $CdWO_4$
- Study of radioactive background within the chosen crystals
- Low temperature (~100K) measurements
- Optimization of the light collection efficiency

$CaMoO_4$
330g (Ø=45mm, h=50mm)



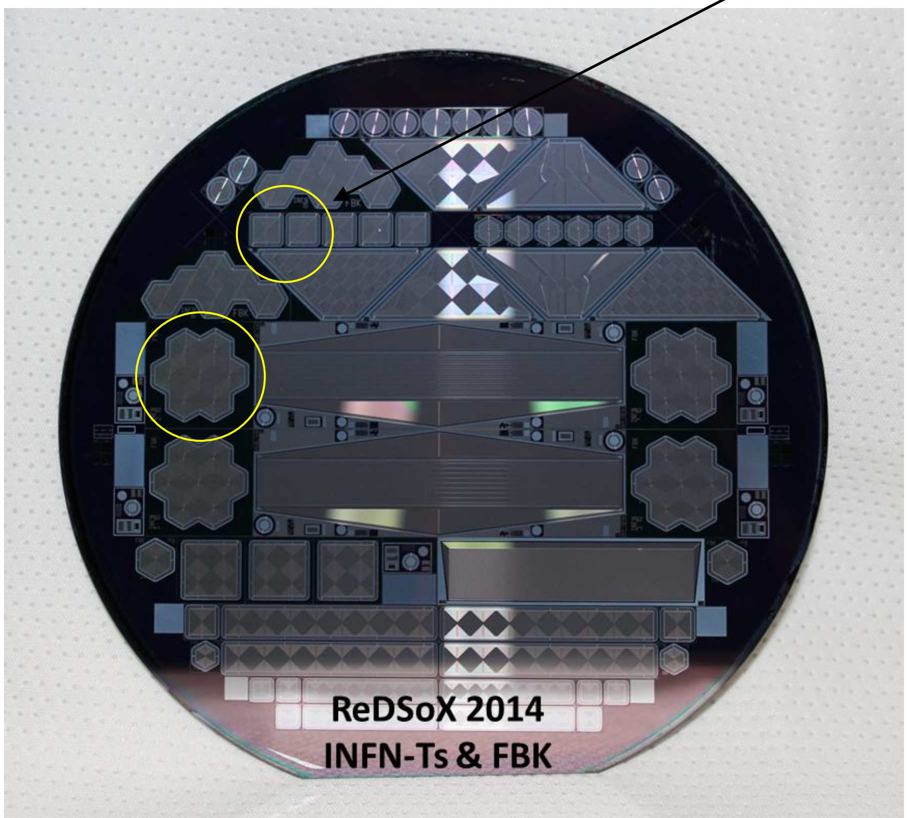


Relative light collection gain ($CdWO_4$ + PMT + ^{137}Cs)

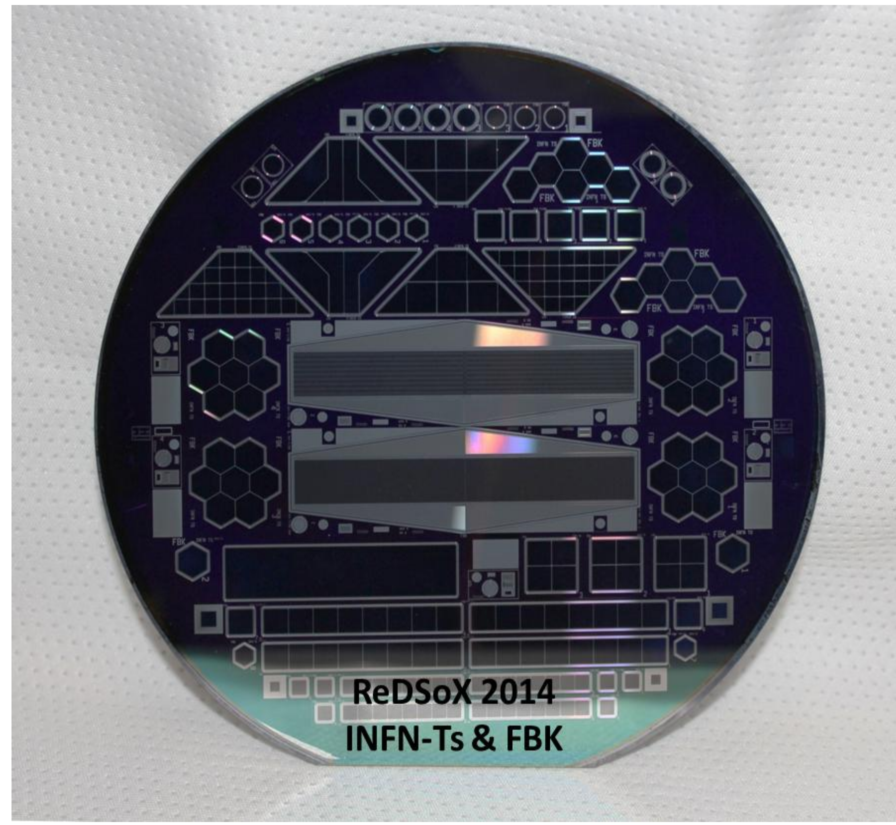
Teflon-1 + VM2000	1.31	Teflon-5	1.37
Teflon-5 + VM2000	1.35	Teflon-10	1.41

SDD geometries

We are testing the performance of some SDDs produced at FBK in Trento - in collaboration with INFN-Ts - for the ReDSoX project (not optimized for FLARES)

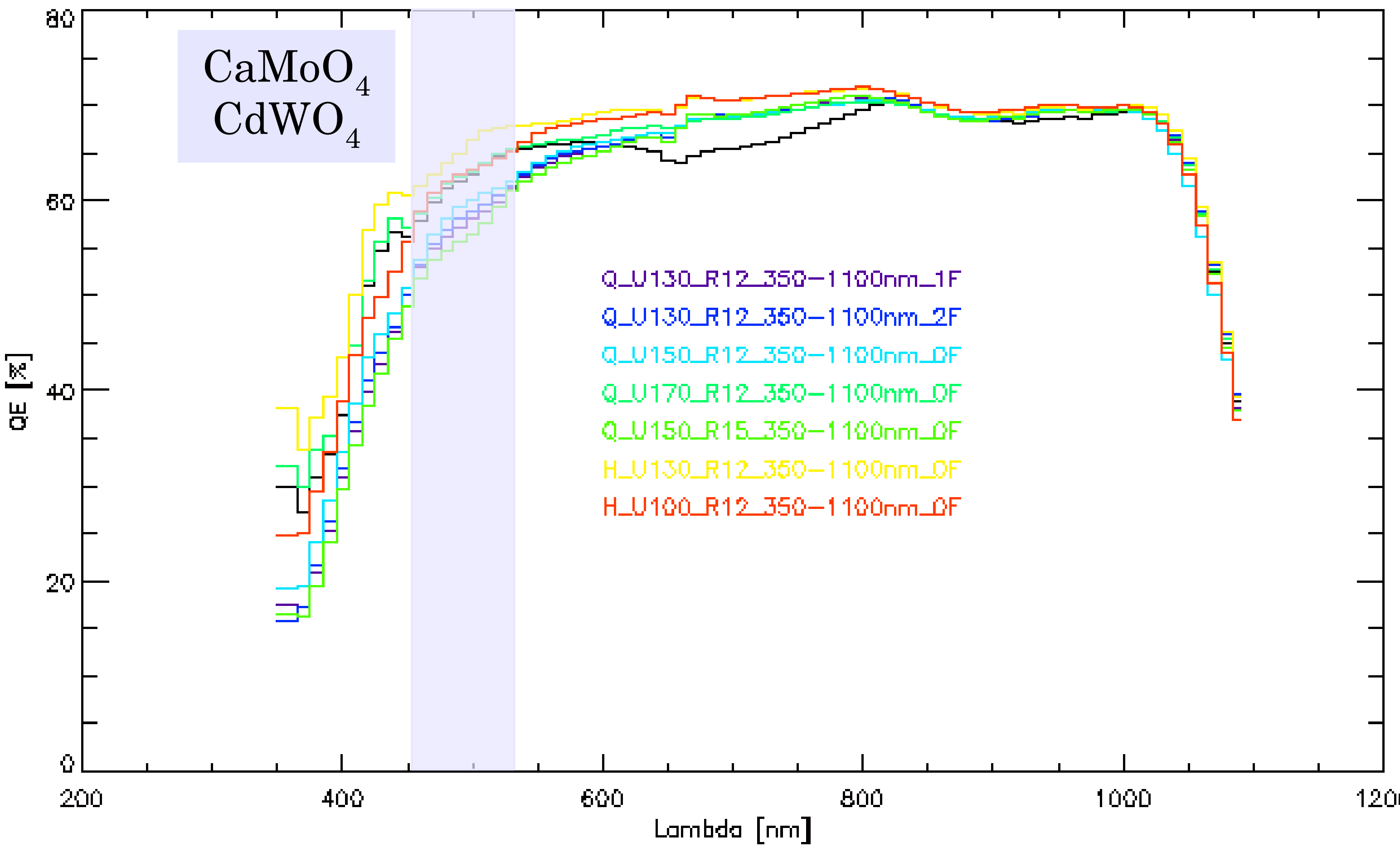


n side



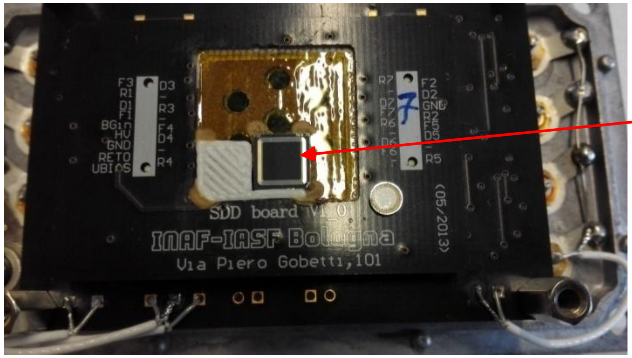
p side

Measured SDD Quantum Efficiency



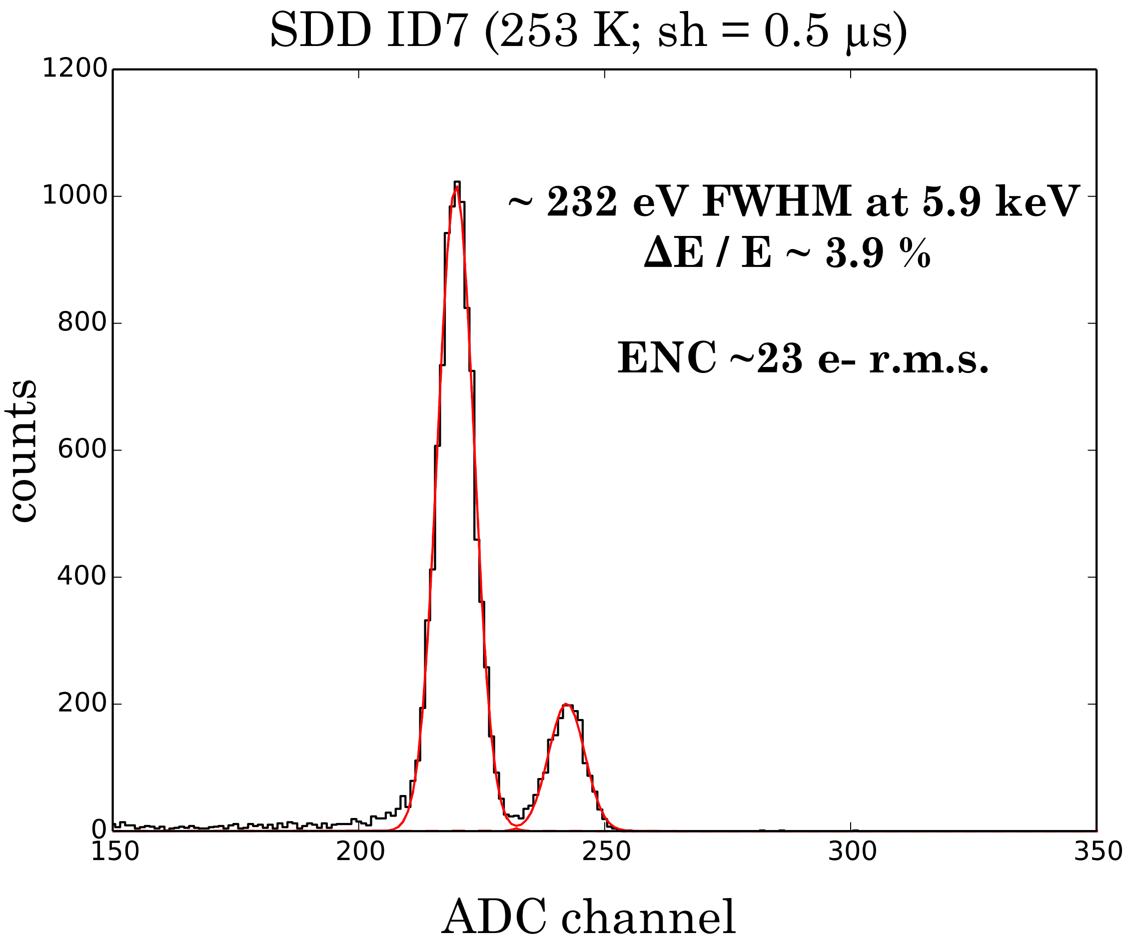
A new SDD run with thin entrance window has been produced for ReDSox: should show improved quantum efficiency at the λs of interest for FLARES.
Next run: anti-reflecting coating will be added.

First tests: square SDD



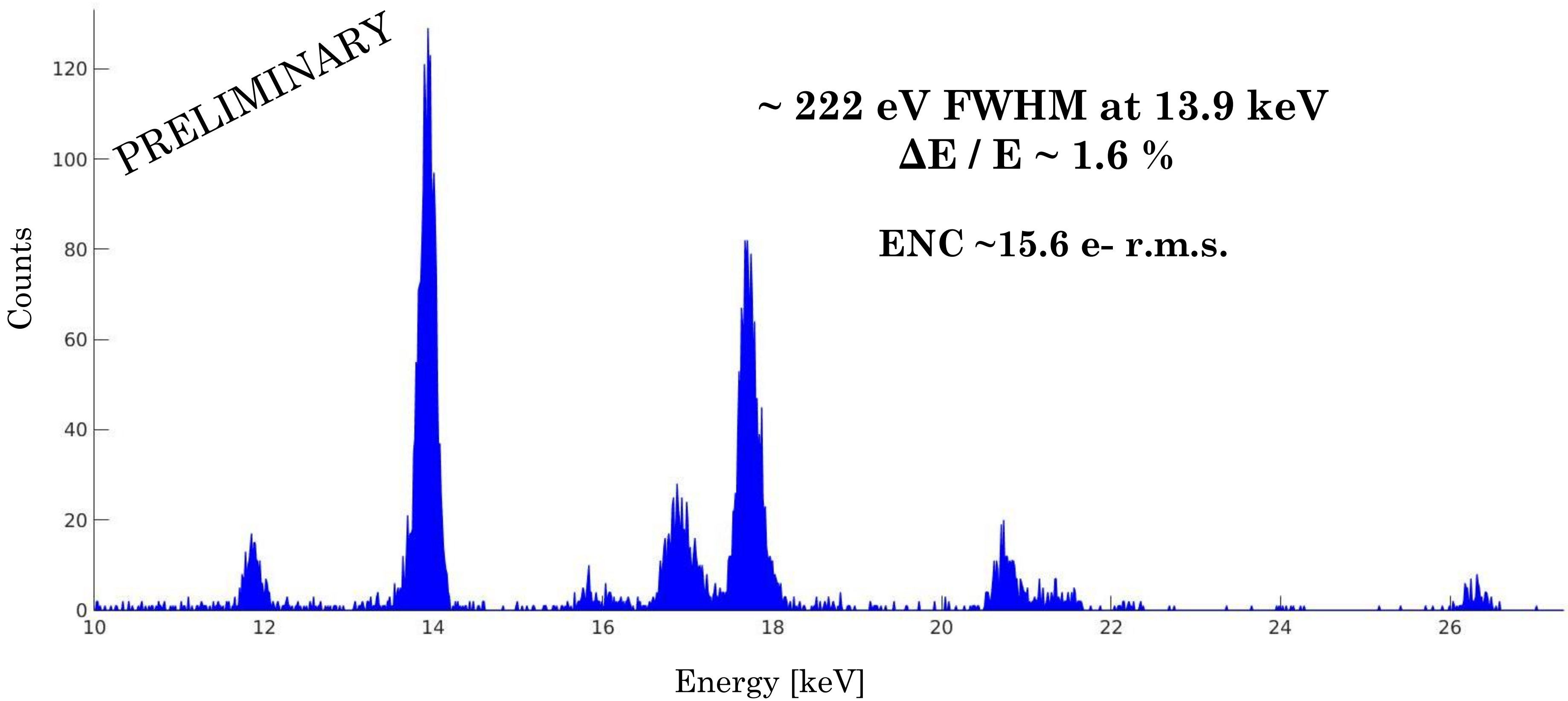
square cell of 25 mm^2 area

^{55}Fe source irradiating the SDD cell directly



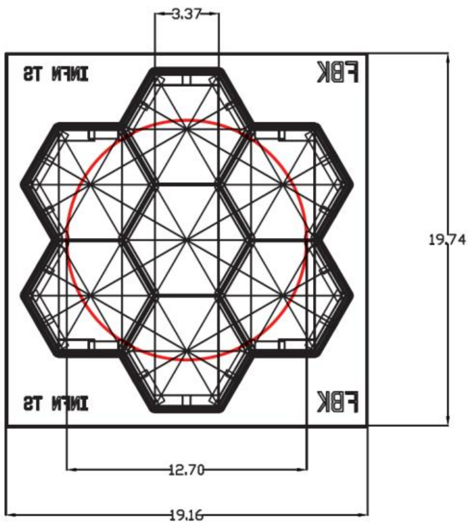
First ‘cold’ tests: square SDD at ~150 K

Square cell of 25 mm^2 area (^{241}Am source)



System not optimized

First tests: hexagonal SDD

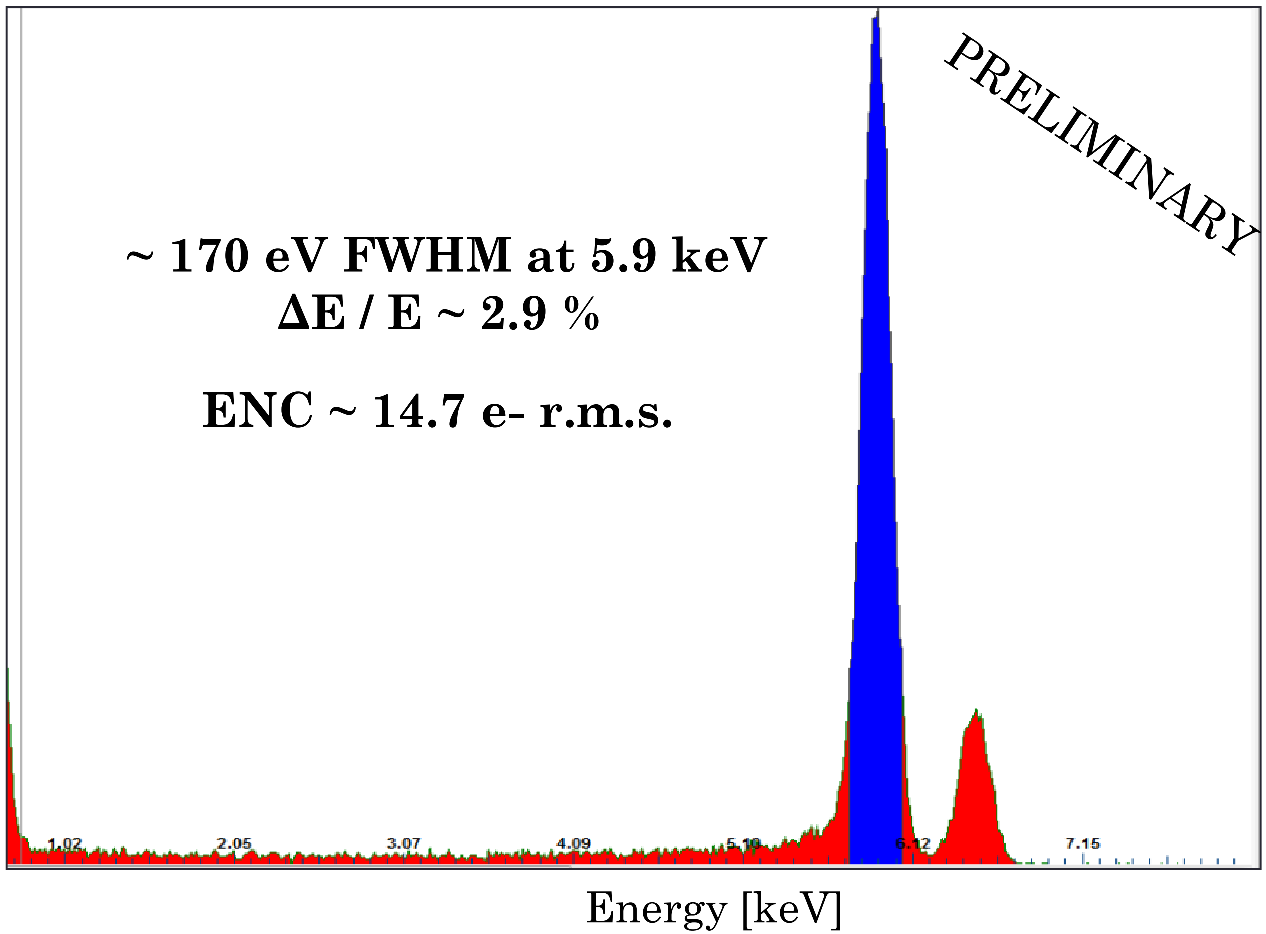


7 hexagonal cell array ("margherita")

^{55}Fe source directly facing a single SDD cell

Not yet measured at lower temperature

^{55}Fe (T= 253K; sh = 1μs)

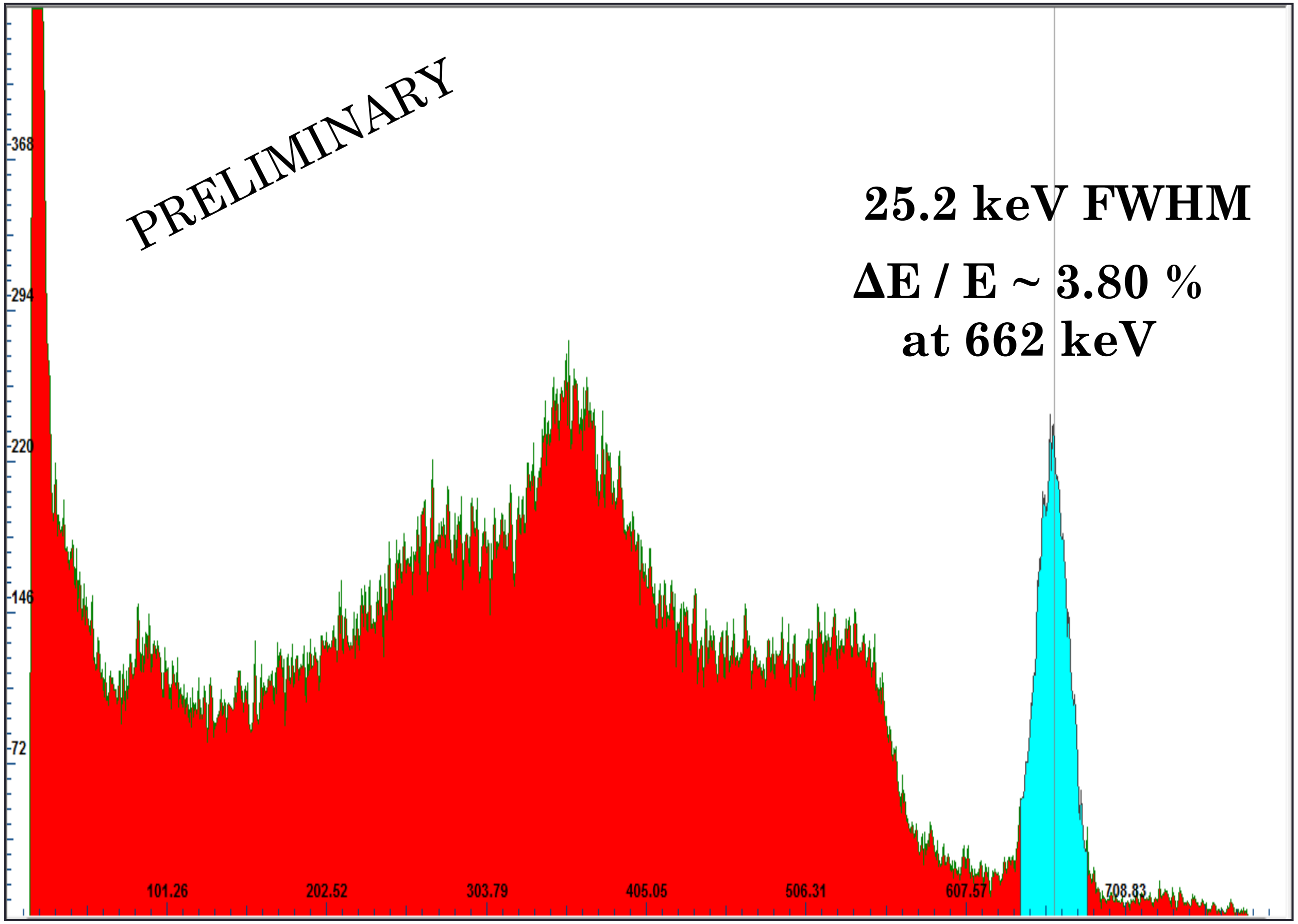


First scintillation light readout

SDD +
CsI(Tl) scintillator

^{137}Cs measurement of a single SDD cell of the exagonal array optically coupled to a very small CsI(Tl) cylindrical scintillator (3mm dia., 10mm height)

^{137}Cs (T= 253K; sh = 6 μs)



Energy [keV]

By simply scaling this result at 3 MeV energy, the 1-2% goal seems achievable!

Conclusions and perspectives

- The FLARES detector concept offers in a single device all the demanding features of an ideal 0vDBD experiment: energy resolution, low cost mass scalability, isotope choice flexibility, background suppression tools.
- The same detector concept may be applied to other physics measurements as well: Dark Matter searches, neutrino-nucleus interactions, ...
- The project has just started: preliminary results are very encouraging!

FLARES collaboration:

S. Capelli, L. Gironi, E. Previtali, M. Sisti (Università & INFN Milano-Bicocca)
C. Labanti, R. Campana, M. Marisaldi (INAF/IASF & INFN Bologna)
F. Fuschino, G. Baldazzi, L. Riganese, M. Zuffa (Università & INFN Bologna)
Y. Evangelista, M. Feroci (INAF/IASF & INFN Roma 2)
V. Bonvicini, A. Rashevsky, A. Vacchi, G. Zampa, N. Zampa (INFN Trieste)

BACK UP SLIDES

FLARES project

Approved and funded by INFN-CSN5 to prove the detector principle
Start of research activity: January 2015

Collaboration between: INFN-Milano Bicocca, INFN-Bologna, INFN-Trieste
Synergy with REDSOX experiment for SDD development

Eur. Phys. J. C (2014) 74:3151
DOI 10.1140/epjc/s10052-014-3151-5

THE EUROPEAN PHYSICAL JOURNAL C

Regular Article - Experimental Physics

A flexible scintillation light apparatus for rare event searches

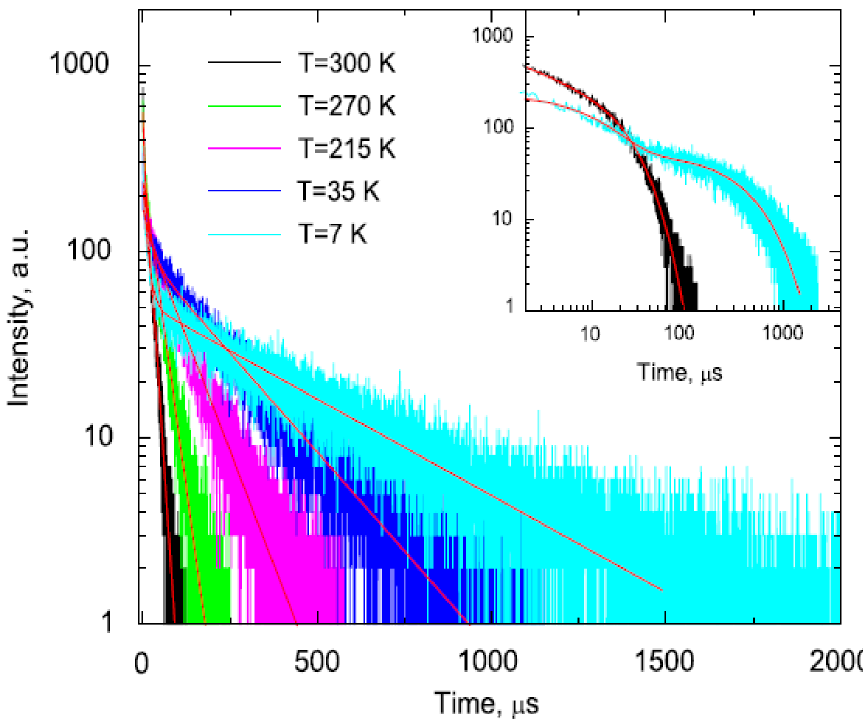
V. Bonvicini[1], S. Capelli[2,3], O. Cremonesi[3], G. Cucciati[2], L. Gironi[2,3], M. Pavan[2,3], E. Previtali[3], M. Sisti[2,3,a]

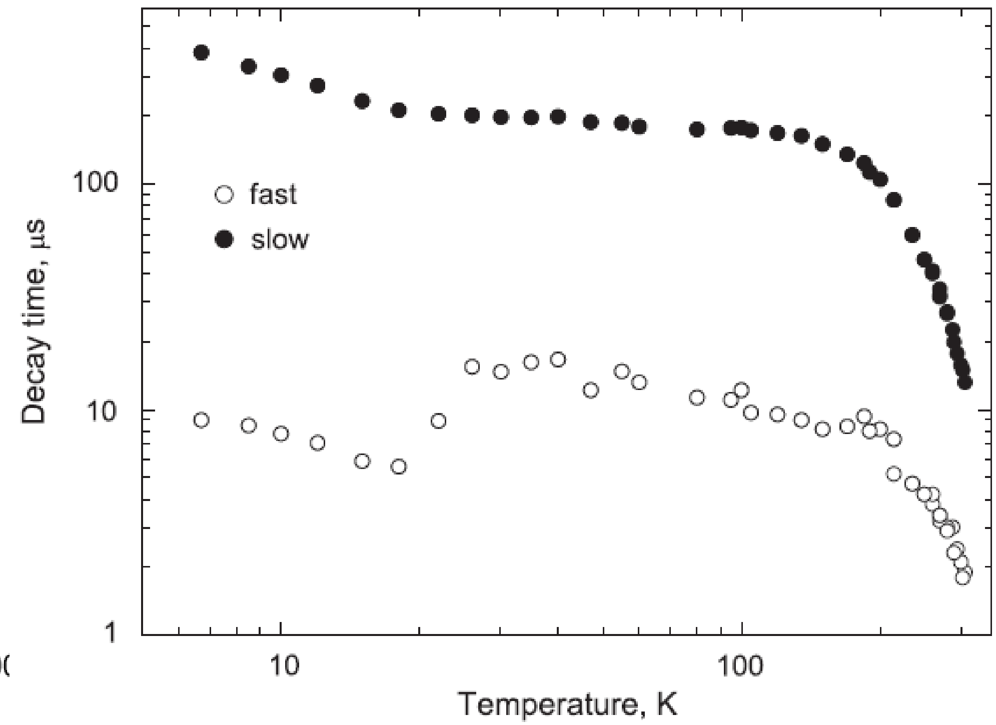
[1] INFN-Sezione di Trieste, 34149 Trieste, Italy
[2] Dipartimento di Fisica, Università di Milano-Bicocca, 20126 Milan, Italy
[3] INFN-Sezione di Milano-Bicocca, 20126 Milan, Italy

Received: 24 July 2014 / Accepted: 22 October 2014

Time response and energy resolution - $CaMoO_4$

V.B. Mikhailik et al., NIM A 583 (2007) 350





Time resolution is on the 10 ms scale
(not a problem for a rare event search)

Inorganic scintillating crystals

Property	$CaMoO_4$		$CdWO_4$		CaF_2(Eu)	
	300 K	120 K	300 K	120 K	300 K	200 K
Atomic mass [g/mol]	200		360		78	
Density [g/cm^3]	~4.3 [42]		7.9 [37]		3.2 [26]	
Melting point [°C]	~1445 [42]		1271 [37]		1418 [38]	
Lattice structure	Scheelite		Wolframite		Fluorite	
Energy gap E_g [eV]	4.0 [26]		4.2 [26]			
Emission maximum λ_{max} [nm]	520 [42]	~530 [36]	480 [37]	480 [26]	435 [38]	
Light yield [ph/MeV]	~8900 [36]	~25000 [36]	~18500 [26]	~33500 [26]	24000 [39]	~26400 [40]
Scintillation decay time [µs]	~18 [36]	~190 [36]	13 [37]	~22 [26]	0.9 [39]	
Refractive index	1.98 [36]		2.2–2.3 [37]		1.44 [39]	
Absorption length [cm]	~60		~ 60			

SDD electronic noise

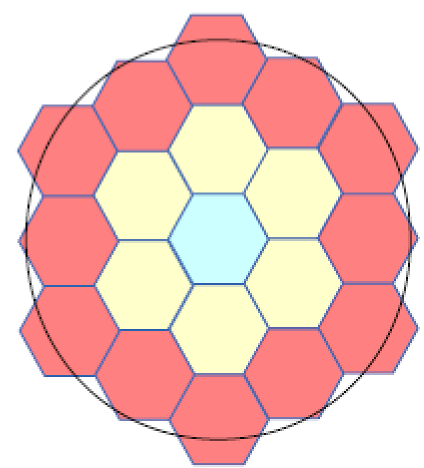
$$\mathrm{ENC} = \left[\frac{k_1 \cdot \langle e_w^2 \rangle \cdot (C_d + C_i + C_p)^2}{\tau} + k_3 A_{1/f} (C_d + C_i + C_p)^2 + 2 k_2 q I_l \tau \right]^{1/2}$$

C_d = 0.5 pF (1 cm^2 SDD)
C_i = 1.0 pF (FET)
C_P = 0.5 pF (parasitic)
$\langle e_w{}^2 \rangle = 10^{-18}\ V^2/Hz$ (FET @ 120K)
$A_{1/f}$ = 0 (neglectable for JFET)
$I_l = 10^{-14}$ A (SDD and JFET @ 120K)

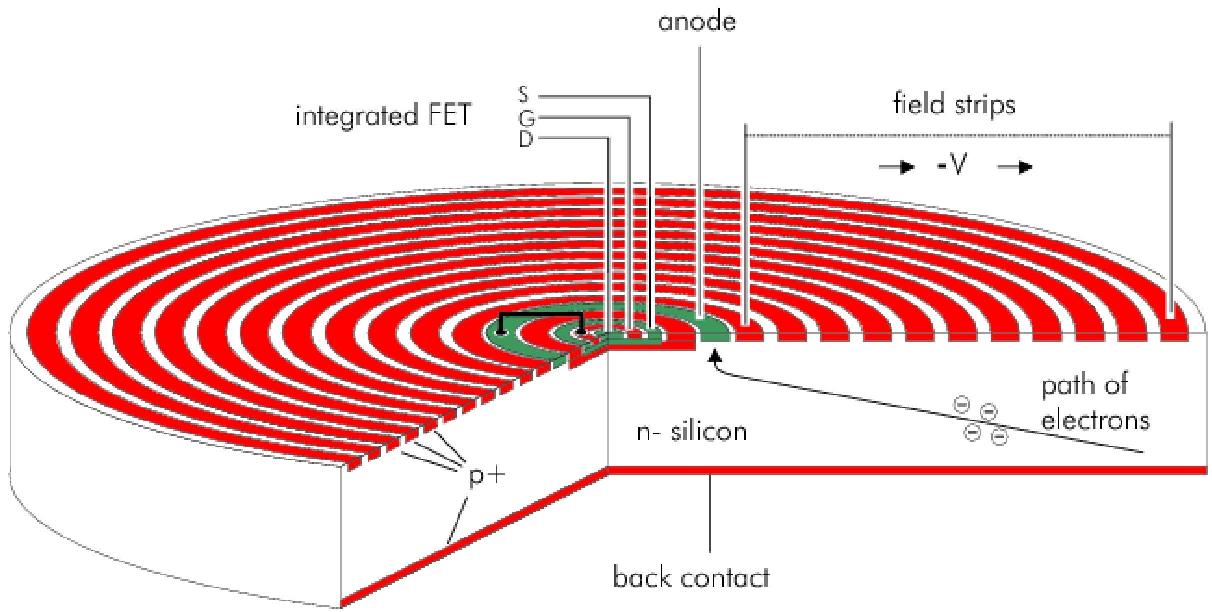
ENC_e = 3.1 e^- r.m.s.

for 1 cm^2 SDD operated at 120 K

Hypothesis:
one cylindrical crystal of 5 cm diameter and 5 cm height: the two circular surfaces are covered with ~20 SDD cells of ~1 cm^2 of area each



SDD

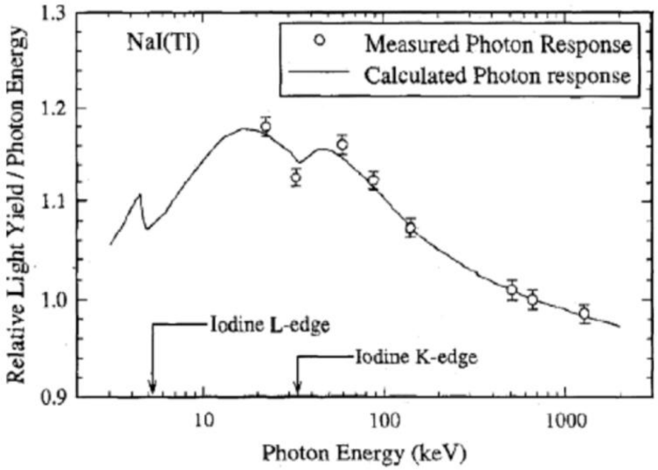


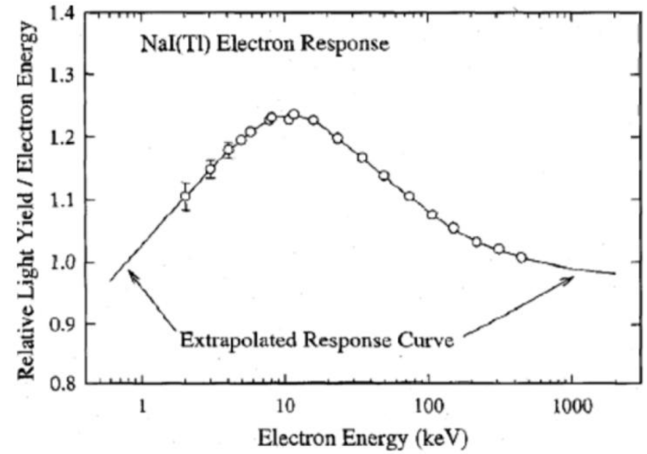
SDD:

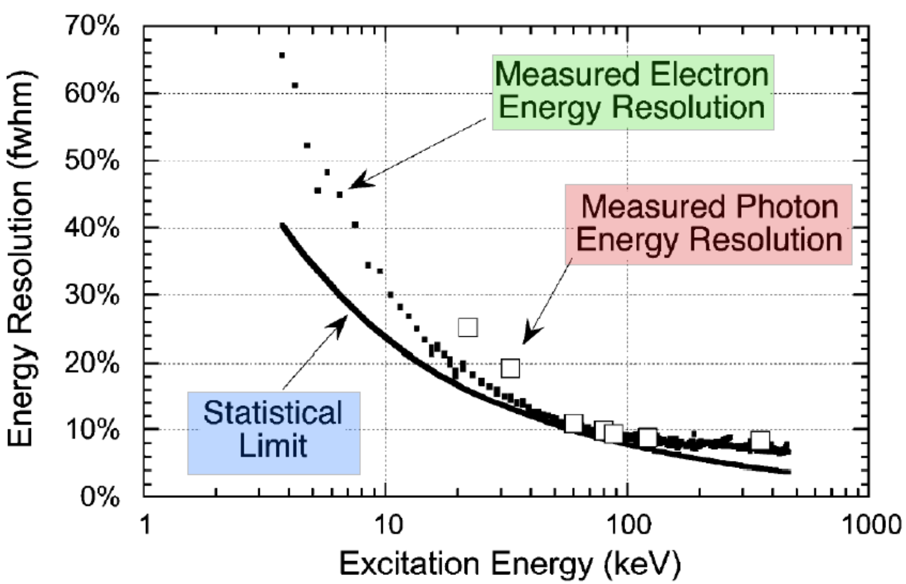
• very low capacitance at the electrode collecting the signal charge, which is independent of the active area of the device → • low electronic noise

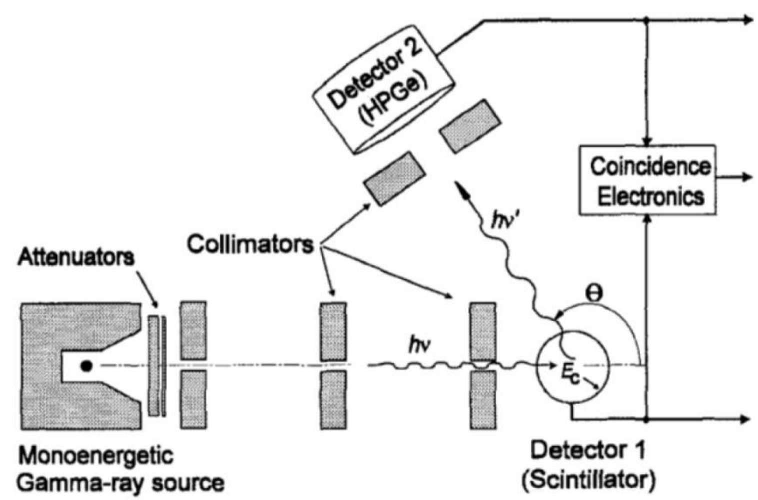
• no multiplication mechanism → • avoid statistical spread of the signal
• high dynamic range

Photon and electron response in NaI crystals









Photon and electron response in $CdWO_4$ crystals