Frontier Detectors for Frontier Physics
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FLARES: a flexible scintillation light apparatus for rare event searches

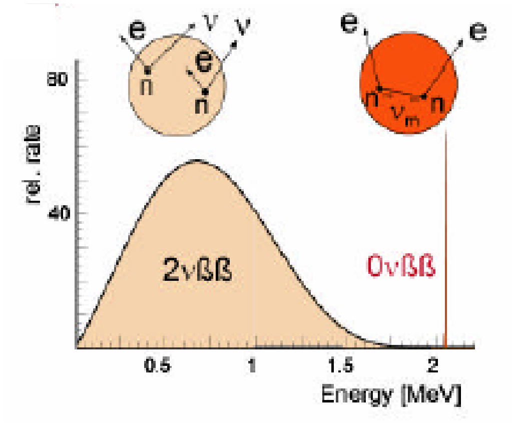
Monica Sisti
Università and INFN – Milano Bicocca

on behalf of the FLARES collaboration

Neutrinoless double beta decay

ββ-0ν: $(A, Z) \rightarrow (A, Z+2) + 2e^{-}$

- not allowed in Standard Model ($\Delta L=2$)
- expected $\tau_{1/2} > 10^{25}$ years



✔ The decay occurs only if neutrinos are **Majorana** particles

✔ The decay rate depends on the "**effective Majorana mass**"

$$\beta\beta\text{-}0\nu \Leftrightarrow \begin{cases} m_\nu \neq 0 \\ \nu \equiv \bar{\nu} \end{cases}$$

light Majorana ν mediated ββ-0ν decay rate:

$$\frac{1}{\tau_{1/2}^{0\nu}} = \frac{|m_{\beta\beta}|^2}{m_e^2} \cdot F_N$$

nuclear factor of merit
(contains nuclear physics details)

Next generation experiments will give informations on:

✔ neutrino mass scale

✔ neutrino mass hierarchy

ββ0ν experimental sensitivity

$$S^{0\nu}(\tau_{1/2}) \propto \epsilon \cdot \frac{i.a.}{A}\sqrt{\frac{M\,t_{meas}}{\Delta E \cdot bkg}} \qquad bkg \neq 0$$

ε	detector efficiency	**ΔE**	FWHM resolution
i.a.	ββ0ν isotope abundance	**M**	total active mass
A	atomic mass	**t_{meas}**	measuring time
bkg	background @ ROI in counts/keV/kg/y		

For bkg = 0:

$$S^{0\nu}(\tau_{1/2}) \propto \frac{\epsilon\, i.a.}{A} M\, t_{meas}$$

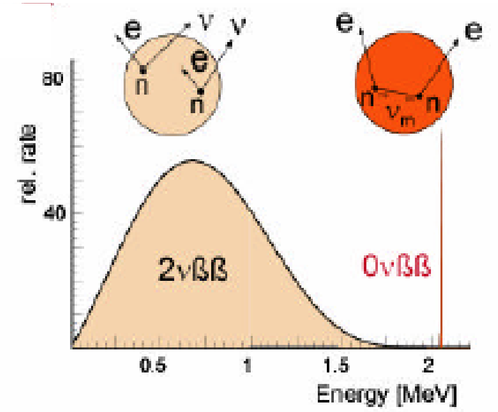
$$m_{\beta\beta} \propto \sqrt{1/\tau^{0\nu}_{1/2}}$$

Main properties of most common techniques for neutrinoless double beta decay searches, taking into account also actual feasibility and cost:

Experimental approach	FWHM <2% in the ROI	Mass scalability	ββ0ν isotope flexibility	Background reduction
Ge diodes	✓			γ vs. α/β (event topology by PSD)
Bolometers	✓		✓	β/γ vs. α (PSD and/or light/heat)
Organic scintillators		✓	✓	
Liquid noble gas TPC		✓		β/γ vs. α (light/charge), γ vs. β (topology)
Noble gas TPC	✓			ββ vs. α/β/γ (event topology)
Inorganic scintillators	✓	✓	✓	β/γ vs. α (PSD), γ vs. α/β (topology)

ββ2ν: the ultimate background

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



2ν rate in ROI

Isotope	$Q_{\beta\beta}$ [keV]	η [%]	$T^{2\nu}_{1/2}$ [y]	$R_{2\nu}(50\,\mathrm{keV})$ [c/y/ton_iso]	$R_{0\nu}(m_{\beta\beta} = 50\,\mathrm{meV})$ [c/y/ton_iso]	$R_{0\nu}(m_{\beta\beta} = 10\,\mathrm{meV})$ [c/y/ton_iso]
^{48}Ca	4274	0.2	4.4×10^{19}	4.0×10^{-2}	1.4–23.1	0.1–0.9
^{76}Ge	2039	7.6	1.8×10^{21}	2.5×10^{-2}	1.2–12.2	0.05–0.5
^{82}Se	2996	8.7	9.2×10^{19}	6.8×10^{-2}	4.4–38.7	0.2–1.5
^{96}Zr	3348	2.8	2.3×10^{19}	1.3×10^{-1}	3.9–50.7	0.2–2.0
^{100}Mo	3034	9.6	7.1×10^{18}	6.8×10^{-1}	8.9–71.3	0.4–2.9
^{116}Cd	2814	7.5	2.8×10^{19}	2.1×10^{-1}	6.8–23.8	0.3–1.0
^{130}Te	2528	34.2	6.8×10^{20}	1.3×10^{-2}	3.6–24.9	0.1–1.0
^{136}Xe	2458	8.9	2.1×10^{21}	4.8×10^{-3}	2.5–14.0	0.1–0.6
^{150}Nd	3368	5.6	8.2×10^{18}	2.3×10^{-1}	9.1–42.7	0.4–1.7

High energy resolution detectors are mandatory!

A possible solution: scintillation

Inorganic scintillating crystals:

- ✔ can be grown with high intrinsic radiopurity
- ✔ offer flexibility in the choice of the ββ0ν candidate
- ✔ show quenching factors for α particles as small as 0.2
- ✔ have intrinsic α/β pulse shape discrimination ability

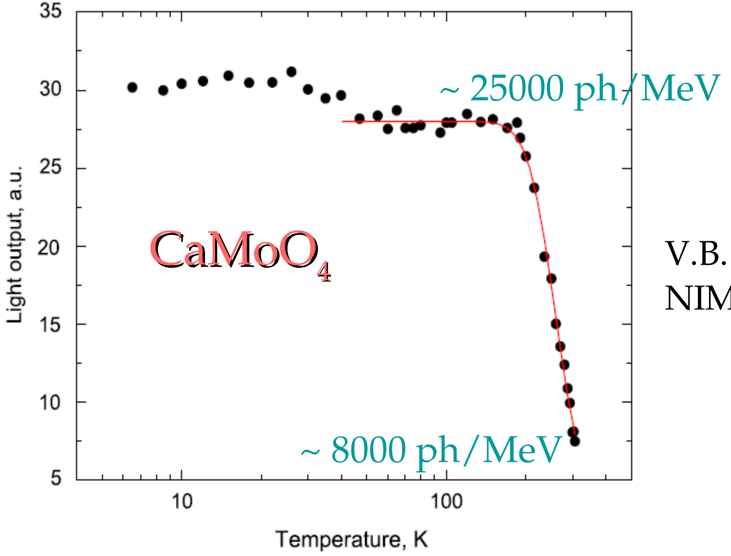
ββ0ν candidate	Q [keV]	i.a. [%]
$^{48}Ca \rightarrow ^{48}Ti$	4274	0.2
$^{136}Xe \rightarrow ^{136}Ba$	2458	8.9
$^{130}Te \rightarrow ^{130}Xe$	2528	34.2
$^{124}Sn \rightarrow ^{124}Te$	2228	5.64
$^{116}Cd \rightarrow ^{116}Sn$	2814	7.5
$^{110}Pd \rightarrow ^{110}Cd$	2013	11.8
$^{100}Mo \rightarrow ^{100}Ru$	3034	9.6
$^{96}Zr \rightarrow ^{96}Mo$	3348	2.8
$^{82}Se \rightarrow ^{82}Kr$	2996	8.7
$^{76}Ge \rightarrow ^{76}Se$	2039	7.6
$^{150}Nd \rightarrow ^{150}Sm$	3367	5.6

Isotope	$T^{0\nu}_{1/2}(10\,\mathrm{meV})$ [10^{27} years]	Available scintillating crystals
^{48}Ca	7–100	CaF_2, $CaWO_4$, $CaMoO_4$
^{100}Mo	1–9	$CaMoO_4$, $ZnMoO_4$
^{116}Cd	3–10	$CdWO_4$, $CdMoO_4$

Transition energy above most intense
γ lines from natural radioactivity

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

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		7.9		3.2	
Melting point [°C]	~1445		1271		1418	
Lattice structure	Scheelite		Wolframite		Fluorite	
Energy gap E_g [eV]	4.0		4.2			
Emission maximum λ_{max} [nm]	520	~530	480	480	435	
Light yield [ph/MeV]	~8900	~25000	~18500	~33500	24000	~26400
Scintillation decay time [µs]	~18	~190	13	~22	0.9	
Refractive index	1.98		2.2–2.3		1.44	
Absorption length [cm]	~60		~ 60			

Potential energy resolution with scintillators

Assuming a light yield of 10000 ph/MeV @ 120 K
(a reasonable value for many scintillators):

$$R_{stat}=\frac{2.355}{\sqrt{3\cdot 10000}}=1.36\,\%\equiv 41\,keV\,(FWHM)$$

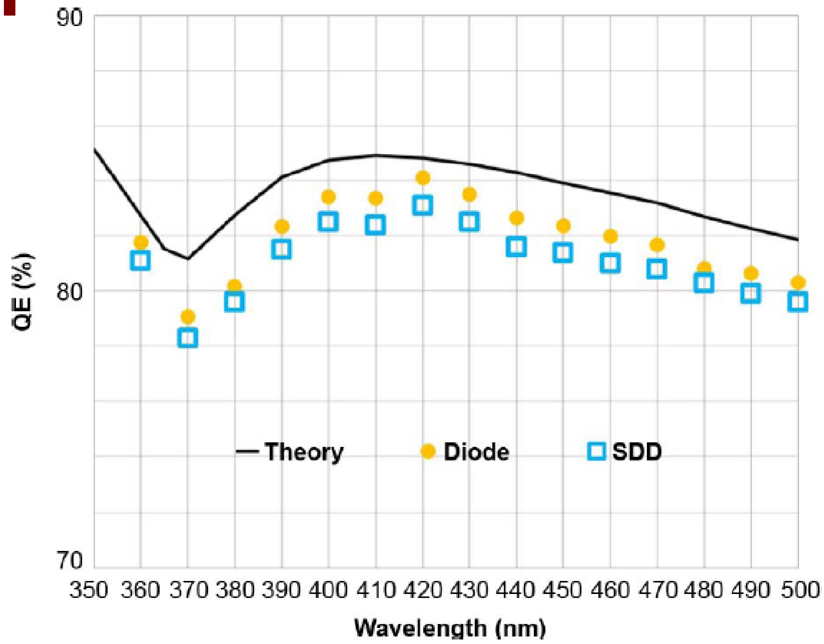
@ 3 MeV

(Q value of many ββ0ν candidates)

not limited by statistics
if all scintillation photons are detected!

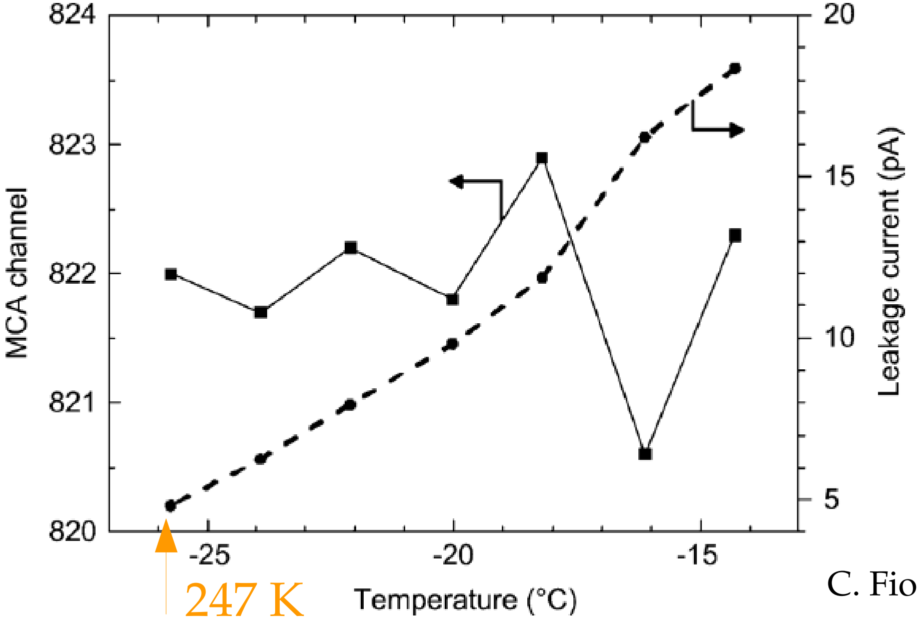
The key point: avoid resolution degradation when the crystal is coupled to a proper photodetector

Silicon Drift Detectors (SDDs) as photodetectors

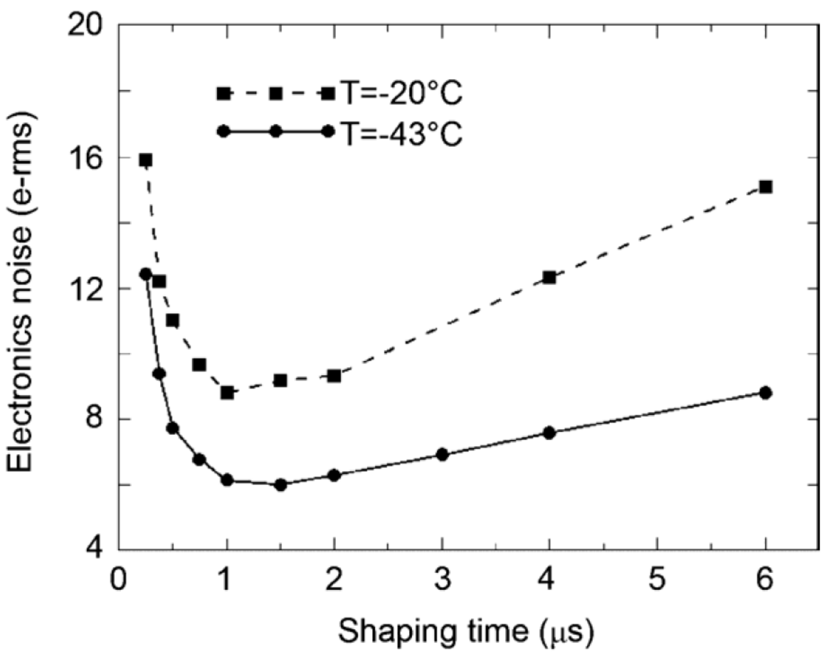


Quantum efficiency of commercial phototubes ~ 35%

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



247 K



253 K

230 K

C. Fiorini et al., IEEE Transaction on Nuclear Science,Vol. 60, NO. 4, August 2013

SDD electronic noise

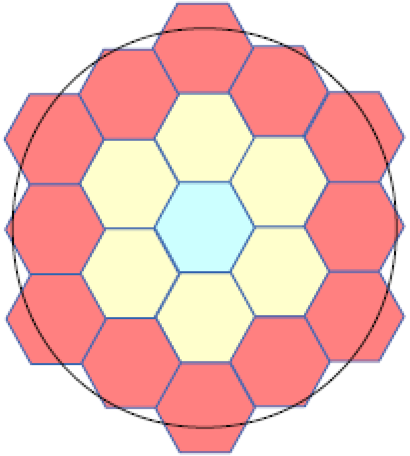
$$\mathrm{ENC} = \left[\frac{k_1 \cdot \langle e_w^2 \rangle \cdot (C_d + C_i + C_p)^2}{\tau} + k_3 A_{1/f} (C_d + C_i + C_p)^2 + 2k_2 q I_l \tau \right]^{1/2}$$

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 (negletable 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



Expected energy resolution: $CaMoO_4$ case

$$R(\mathtt{FWHM}) = \sqrt{R^2_{\mathtt{int}} + R^2_{\mathtt{stat}} + R^2_{\mathtt{noise}}} \simeq 2.355\sqrt{\frac{1}{\alpha_{ph}N_{ph}\epsilon_Q} + \frac{N_{\mathrm{SDD}}\mathrm{ENC}_e^2}{\alpha_{ph}^2 N_{ph}^2 \epsilon_Q^2}} = 1.15\,\%$$

N_{ph} = 75000 (for 3 MeV for $CaMoO_4$ @ 120K)

α_{ph} = 70% (collection efficiency from MC simulation)

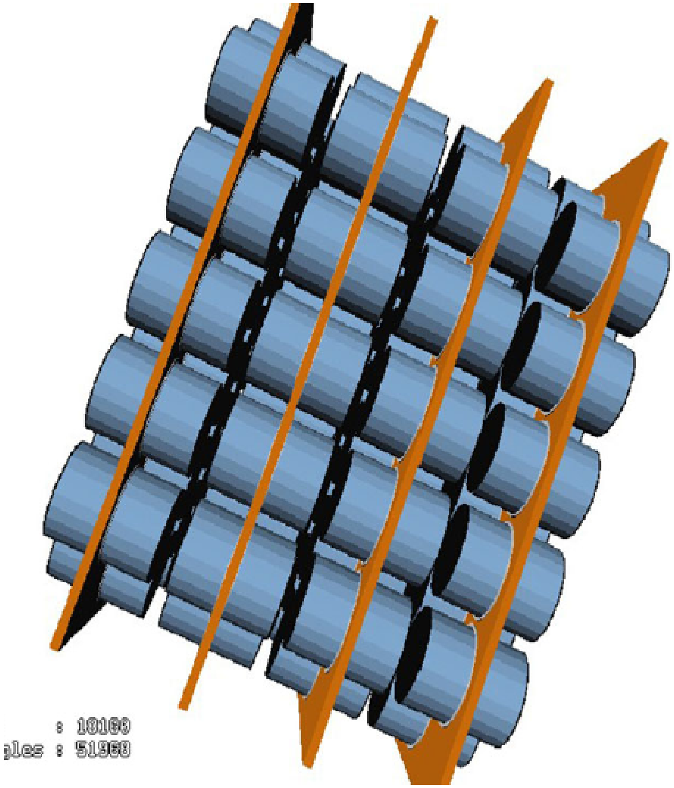
ε_Q = 80% (SDD quantum efficiency)

N_{SDD} = 40 (number of 1 cm² SDDs for a Ø 5 cm crystal)

ENC_e = 3.1 e⁻ r.m.s. (noise of a single 1 cm² SDD)

@ 3 MeV: ΔE (FWHM) = 37 keV

for one $CaMoO_4$ crystal coupled to an array of 40 SDDs (1 cm² each) operated at 120 K

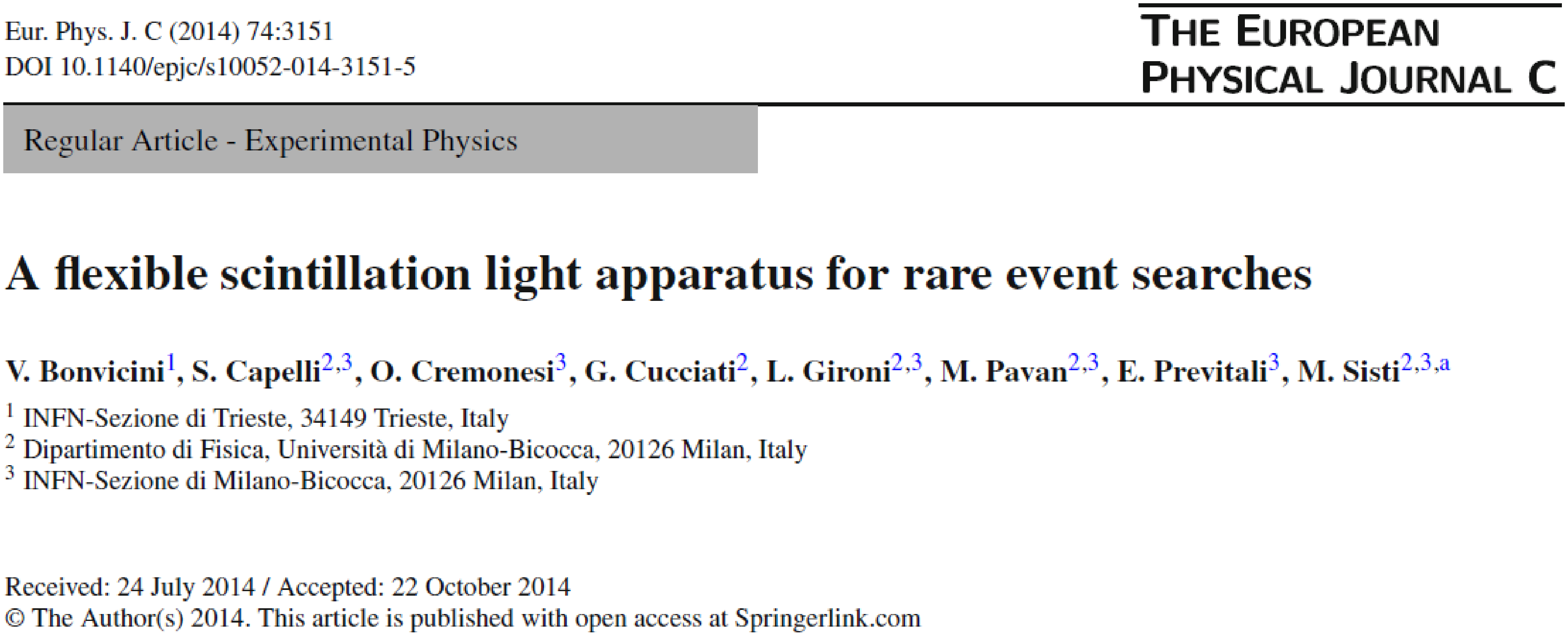


With this detector concept it would be possible to build large mass compact structures of high performing detectors

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



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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

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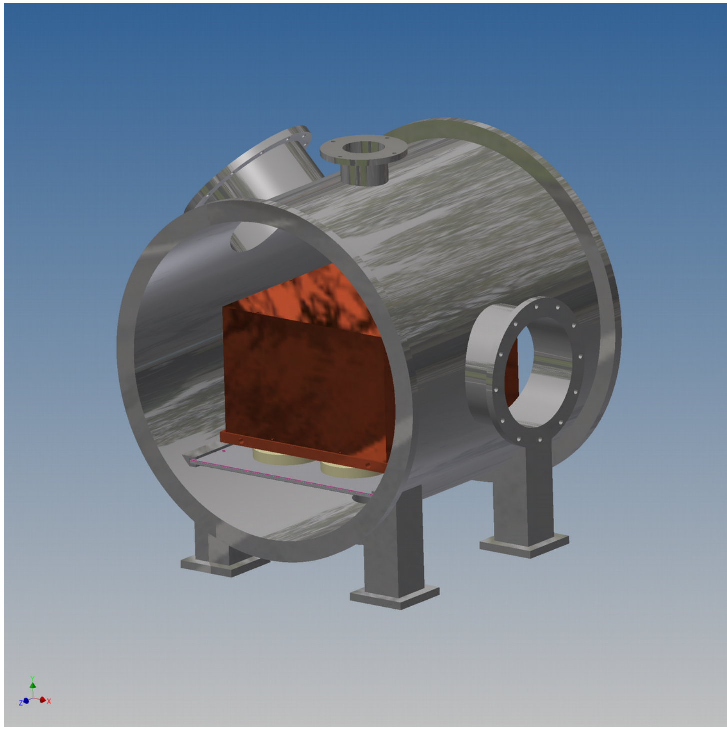
Scintillating crystals for single detector module

We are currently working on:

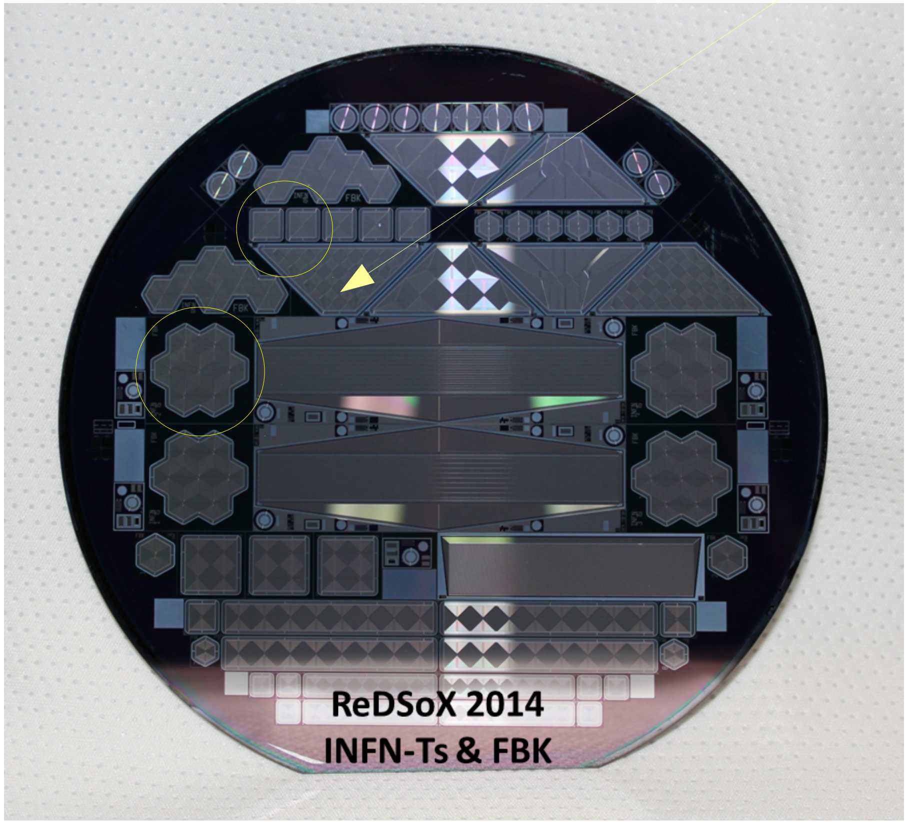
- Selection of a producer of high quality crystals: $CaMoO_4$ ($CdWO_4$)
- Study of radioactive background within the chosen crystals
- Low temperature measurements to optimize light collection efficiency

All the above points are closely interconnected…

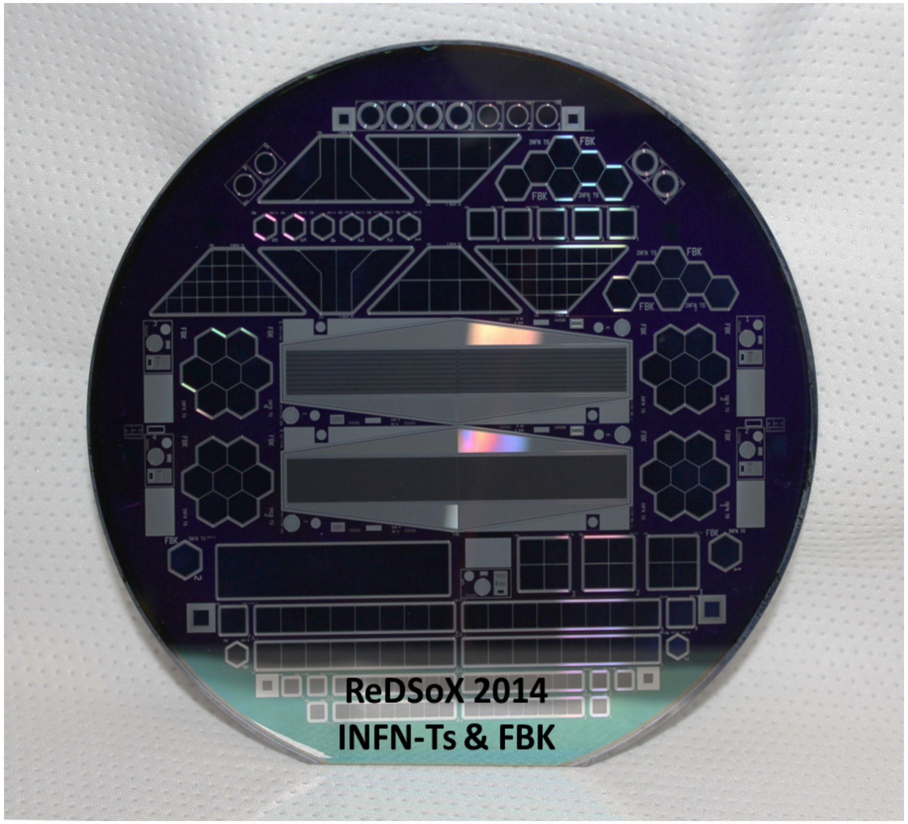


SDD geometries

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)

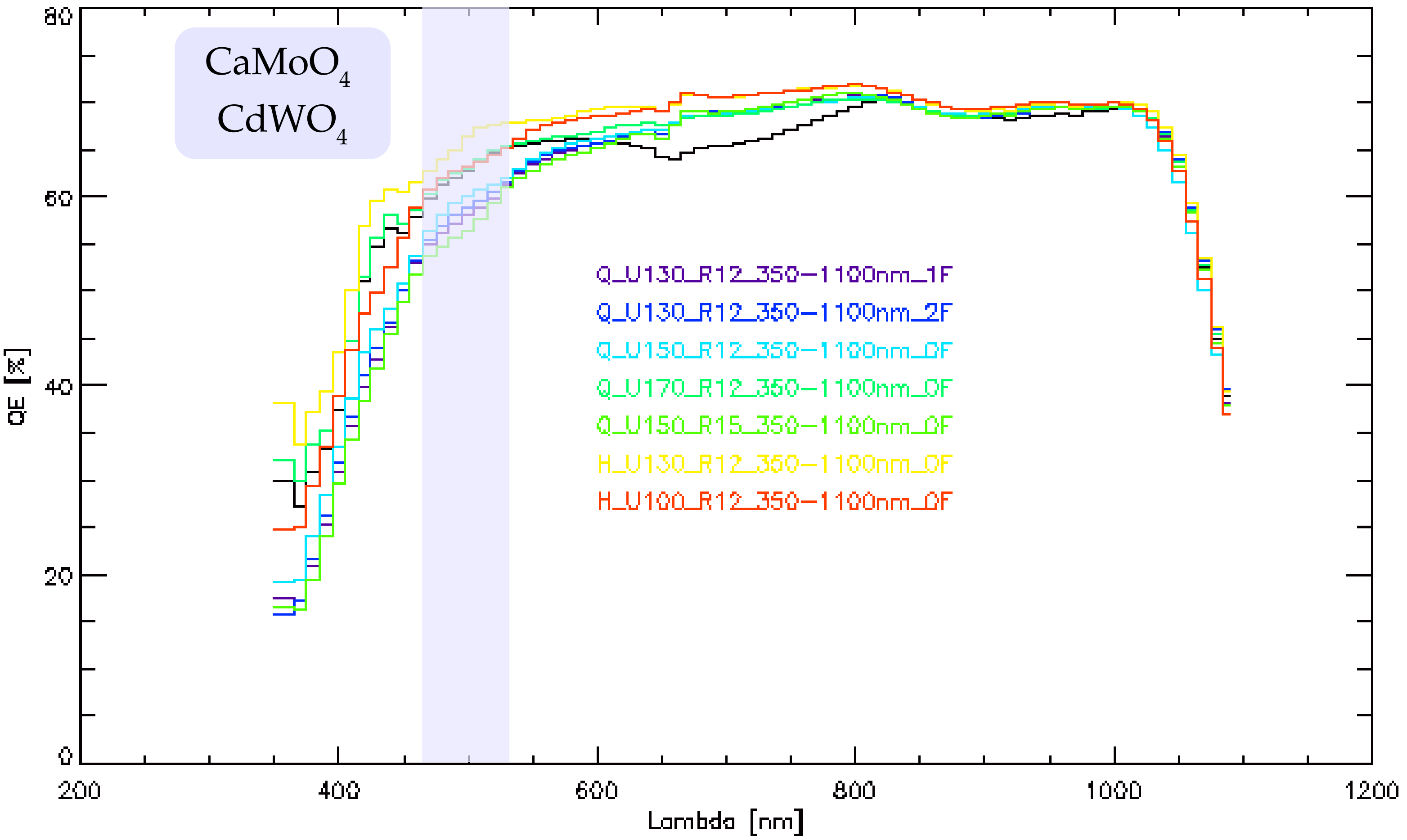


n side



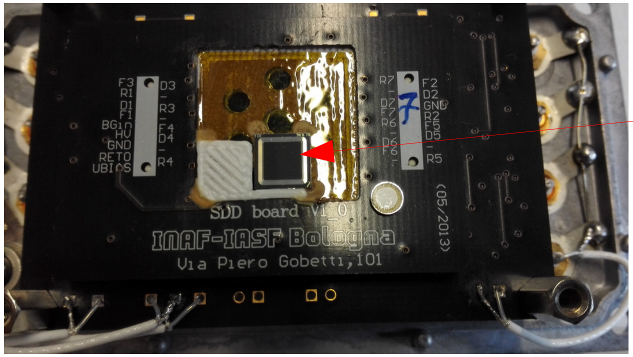
p side

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.

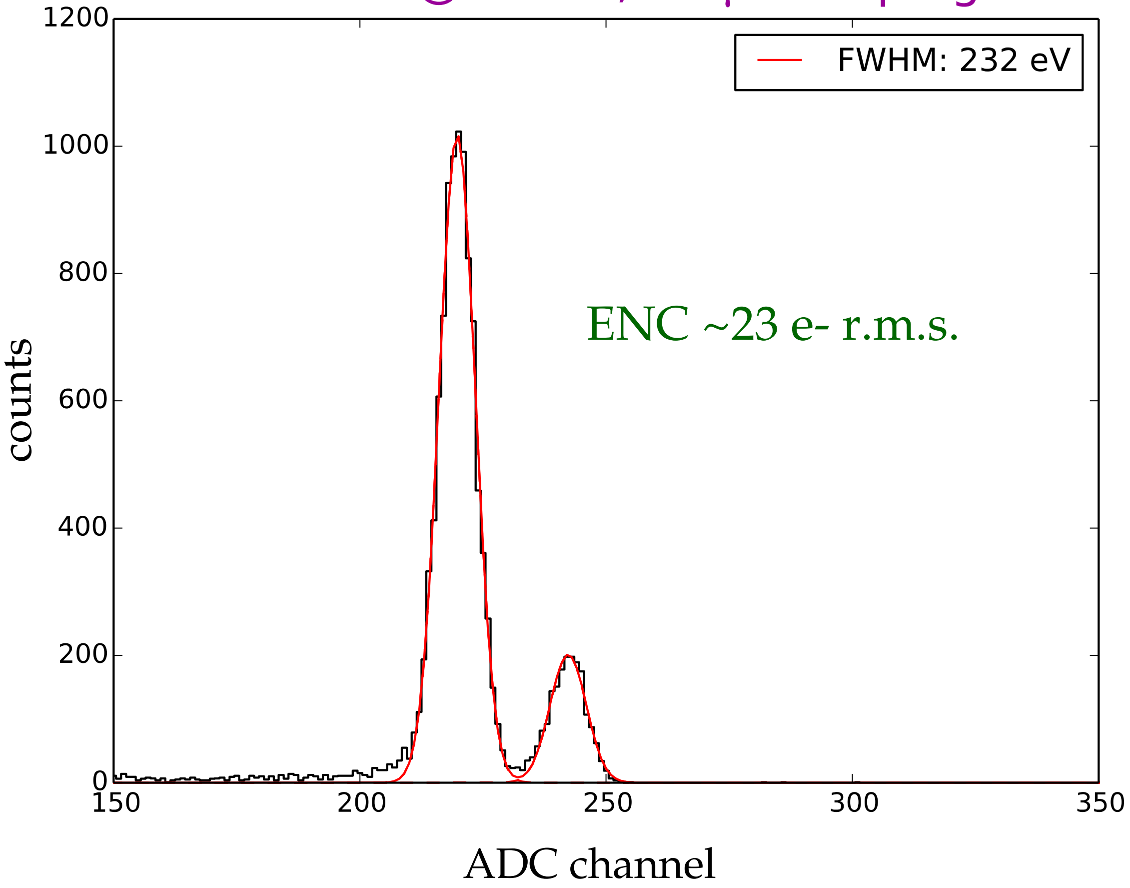
First tests: square SDD



square cell of 25 mm^2 area

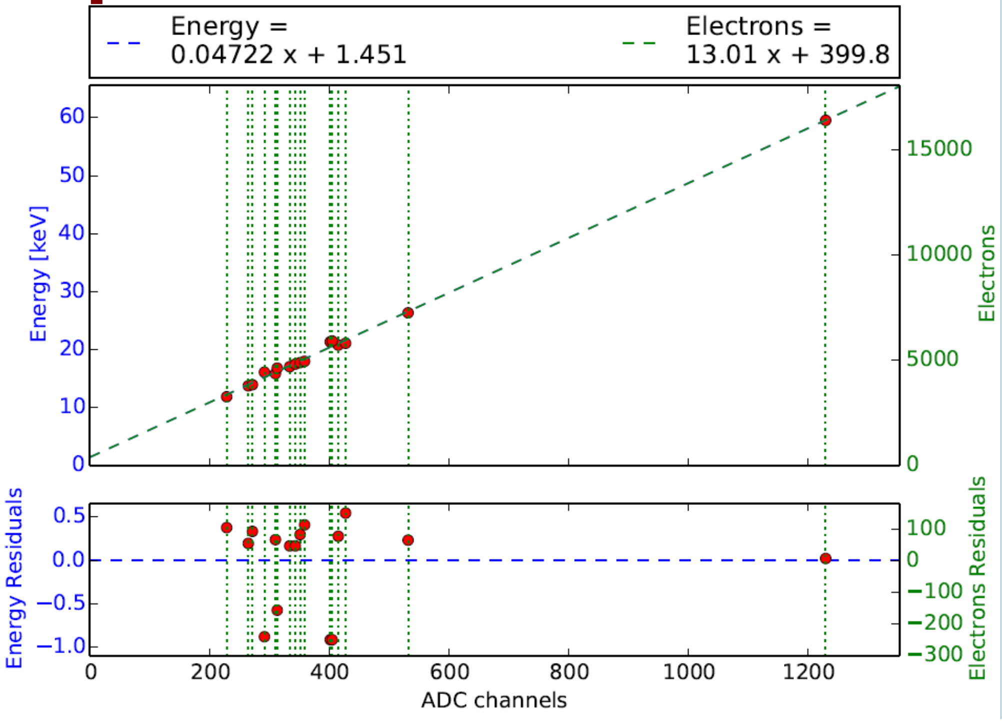
^{55}Fe source irradiating the SDD cell directly

SDD ID7 @ 253 K; 0.5μs shaping



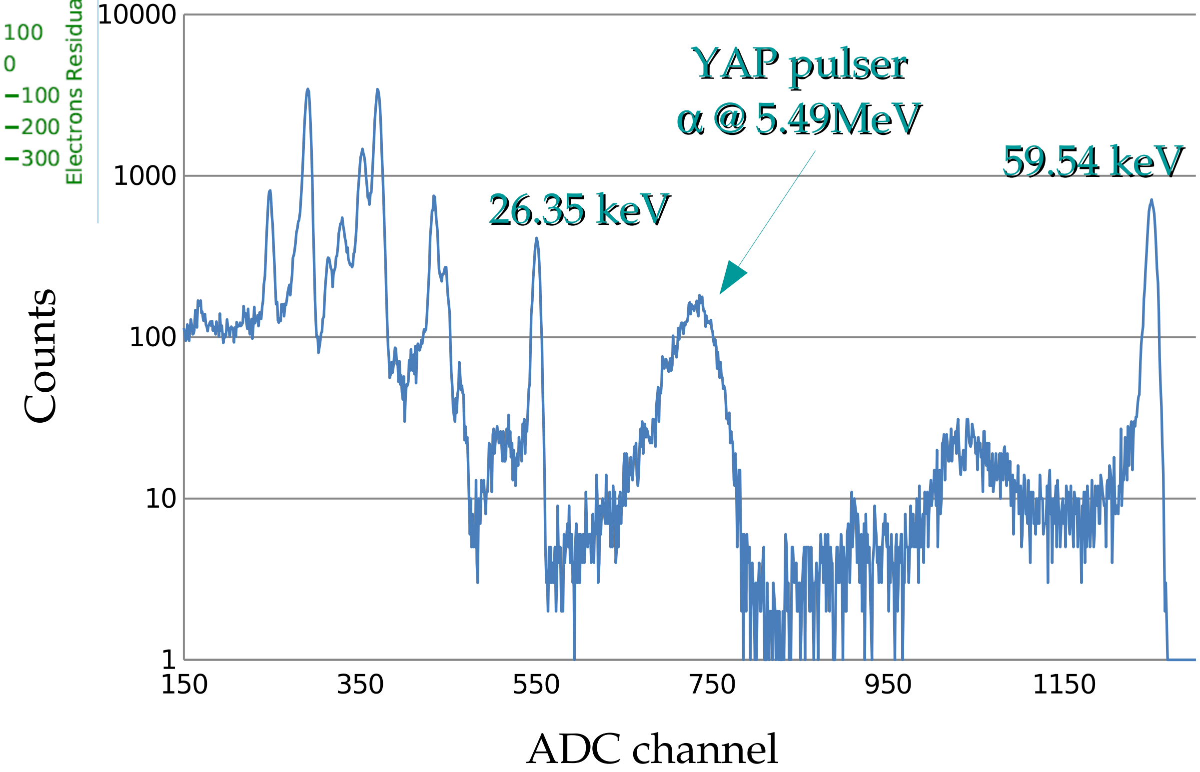
ENC ~23 e- r.m.s.

First tests: square SDD



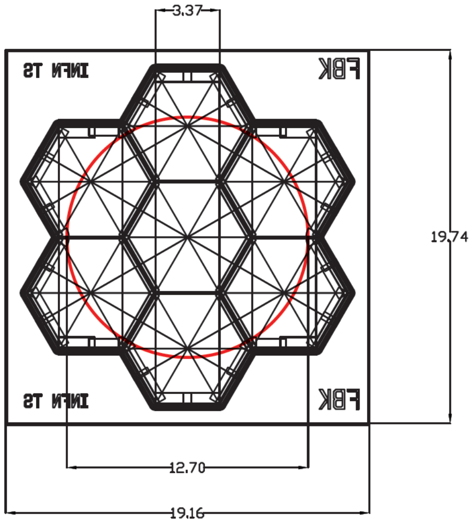
Electron calibration

SDD ID7 @ 253 K; 0.5µs shaping



^{241}Am source
+ YAP:Ce(Am) light pulser
simultaneous measurement

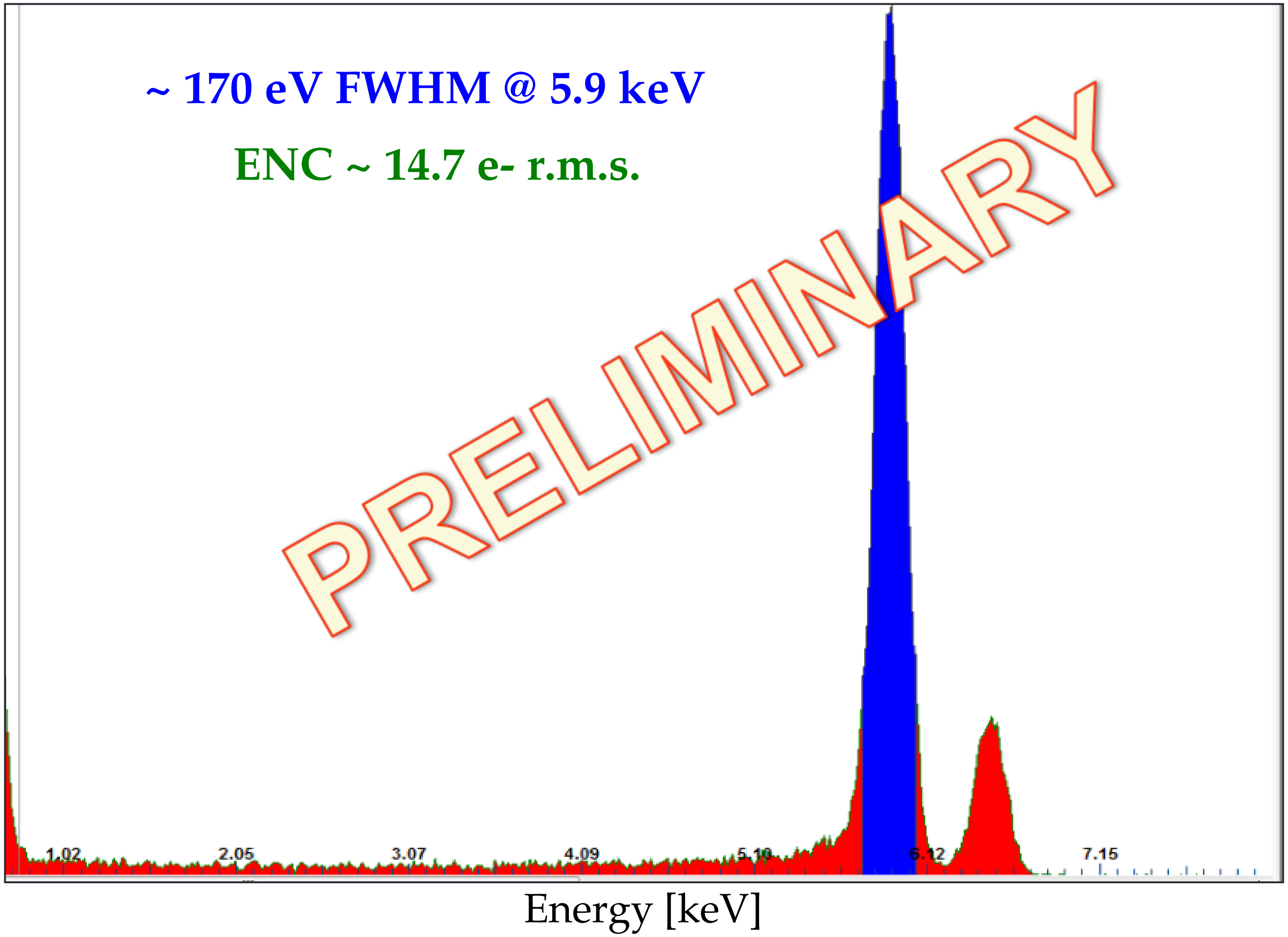
First tests: hexagonal SDD



7 hexagonal cell array (“margherita”)

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

^{55}Fe @ IAPS labs (T= 253K; sh = 1μs)



~ 170 eV FWHM @ 5.9 keV

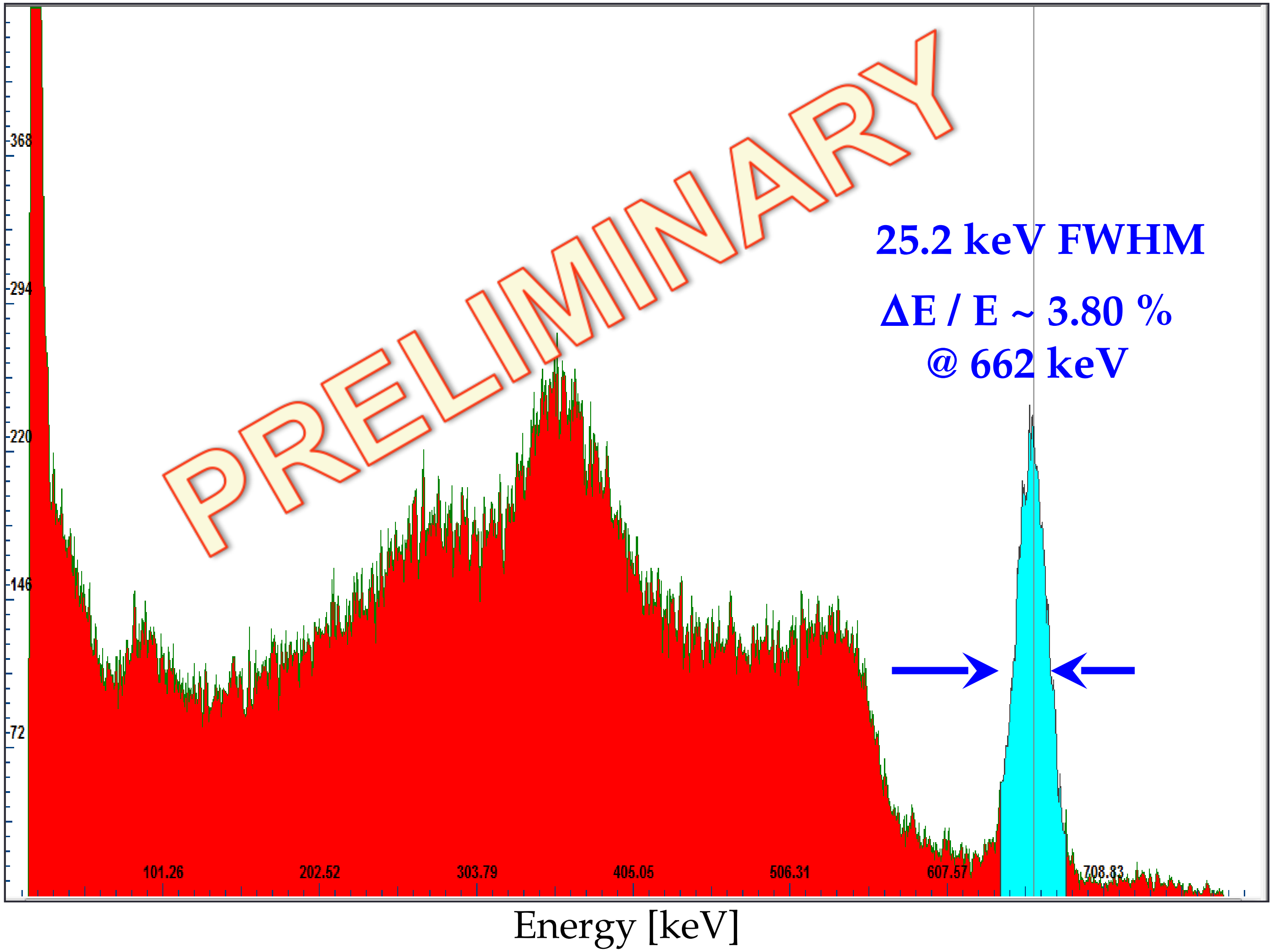
ENC ~ 14.7 e- r.m.s.

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 @ IAPS labs (T= 253K; sh = 6 μs)



25.2 keV FWHM

ΔE / E ~ 3.80 %
@ 662 keV

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

Conclusions and perspectives

- The FLARES detector concept offers in a single device all the demanding features of an ideal ββ0ν experiment:
  energy resolution, low cost mass scalability, isotope choice flexibility, background suppression means.
- 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:

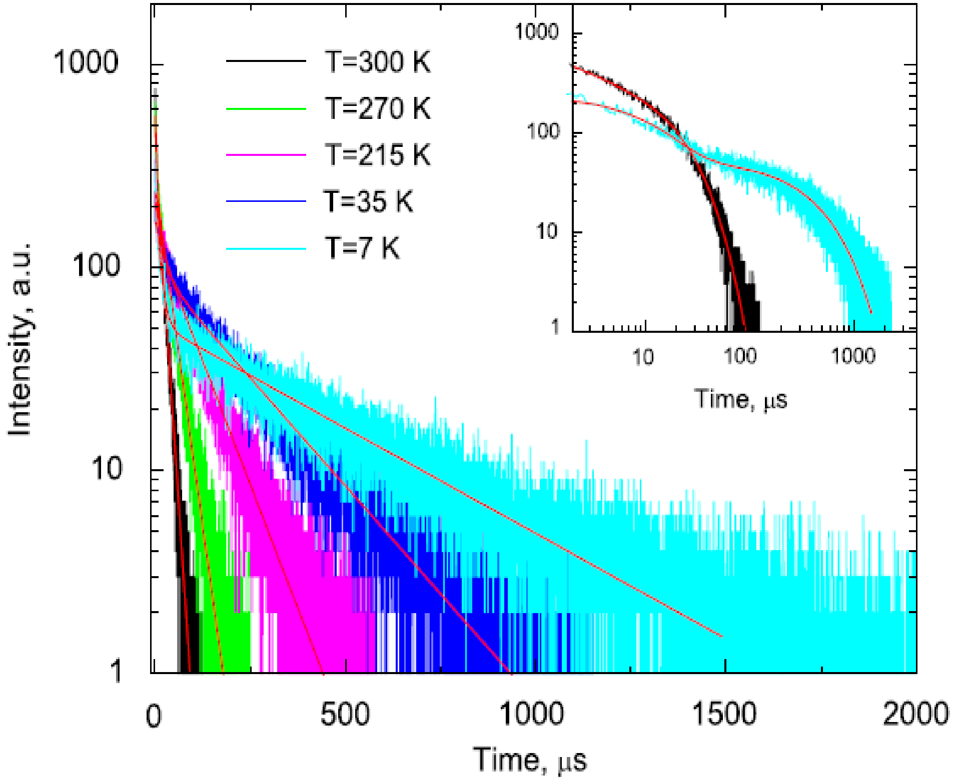
S. Capelli, L. Gironi, E. Previtali, M. Sisti (Università & INFN Milano-Bicocca)
C. Labanti, R. Campana, M. Marisaldi (INAF/IASF & INFN Bologna)
F. Fuschino, G. Baldazzi, L. Riganese, M. Zuffa (Università & INFN Bologna)
Y. Evangelista, M. Feroci (INAF/IASF & INFN Roma 2)
V. Bonvicini, A. Rashevsky,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

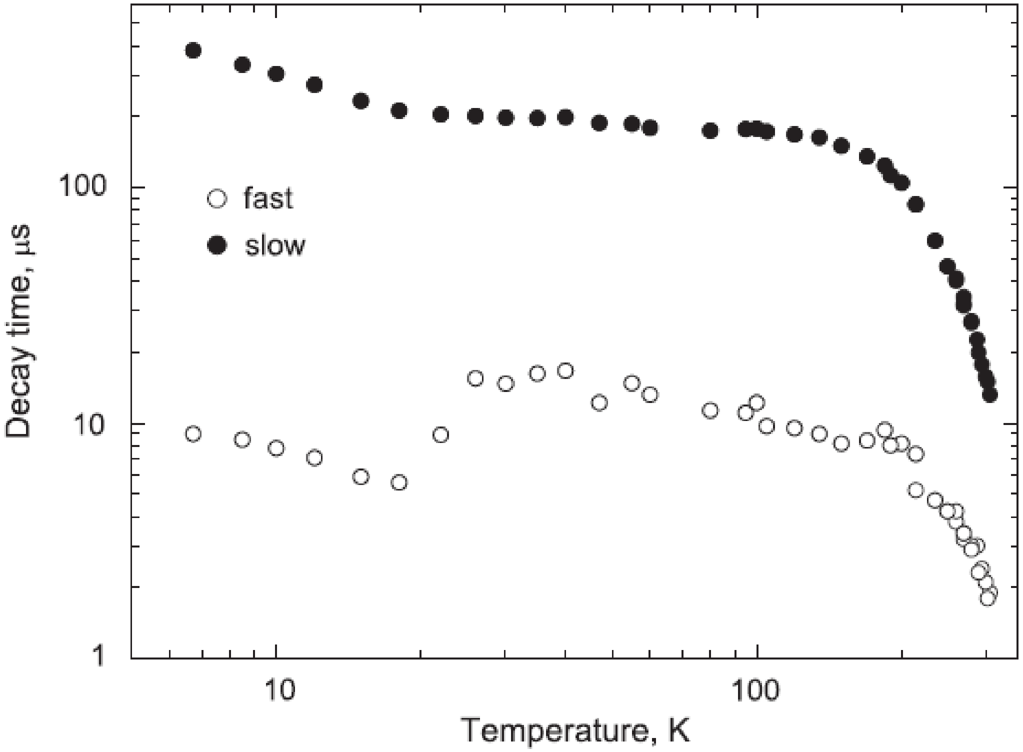
BACK UP SLIDES

Time response and energy resolution

$CaMoO_4$:

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





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