Scintillating Bolometers for Double Beta Decay

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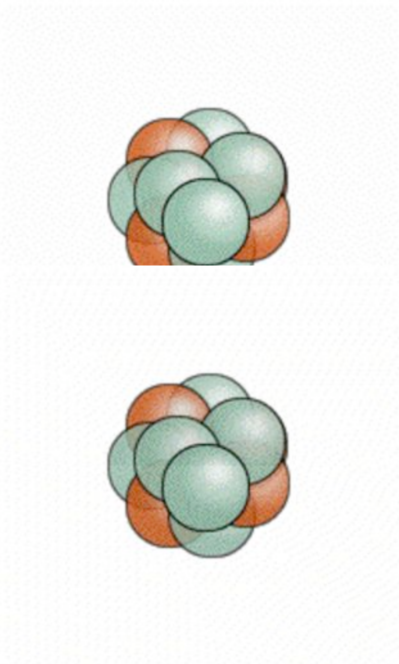
- Double Beta Decay
- Thermal detectors
- Cuoricino
- New bolometric techniques
- Conclusions

ILIAS 4th annual meeting - Chambery, 28 February 2007

Decay modes for Double Beta Decay

Two decay modes are usually discussed:

① $(A,Z) \rightarrow (A,Z+2) + 2e^- + 2\bar{\nu}_e$ ← al

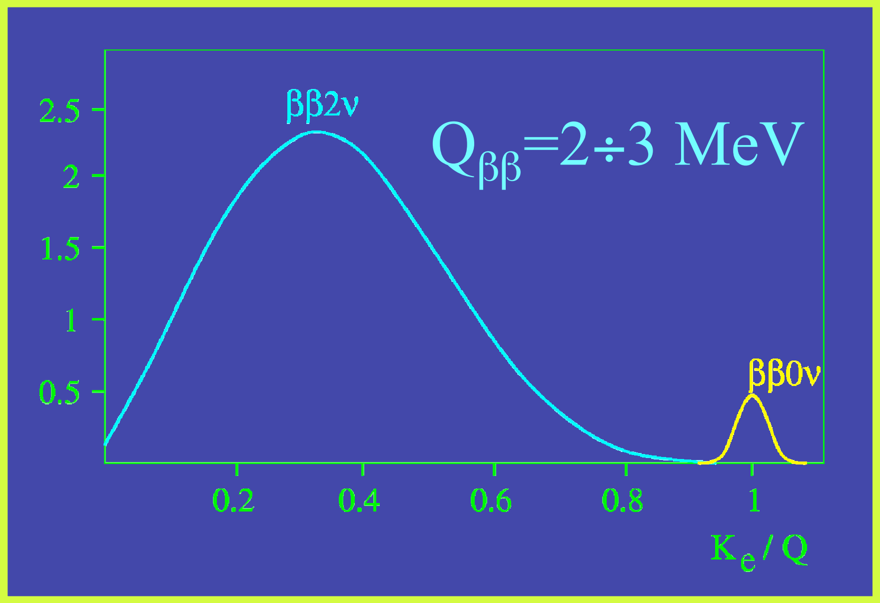


ecay
rd Model
10^{17} y

② $(A,Z) \rightarrow (A,Z+2) + 2e^-$ ← neutrin ecay (0n-DBD)
never o scussed claim)

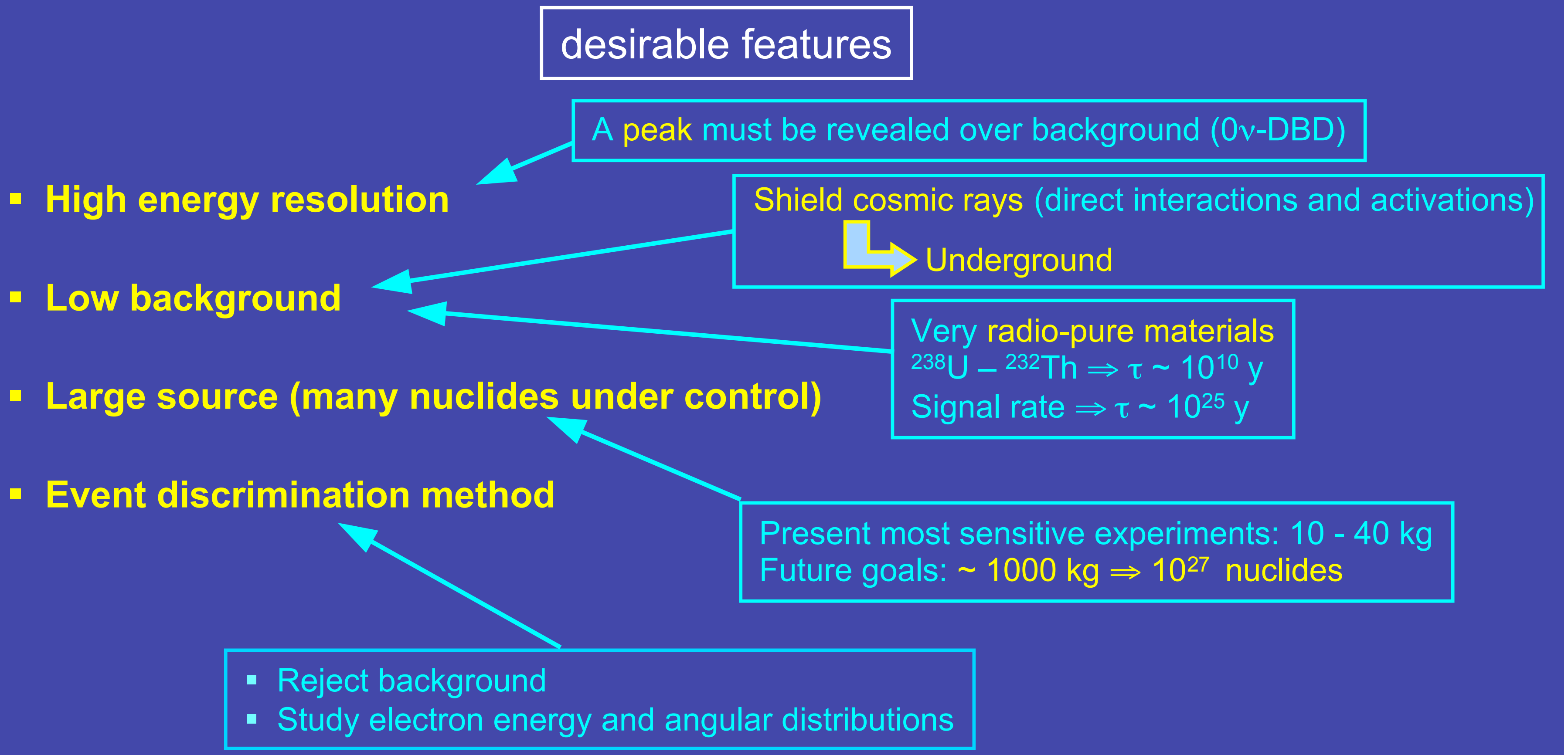
Process ② would imply <u>new physics</u> beyond t

violation of lepton number conservation



Experimental strategies

Detect the two electrons with a proper nuclear detector (direct search)



desirable features

- **High energy resolution**
- **Low background**
- **Large source (many nuclides under control)**
- **Event discrimination method**

A peak must be revealed over background (0ν-DBD)

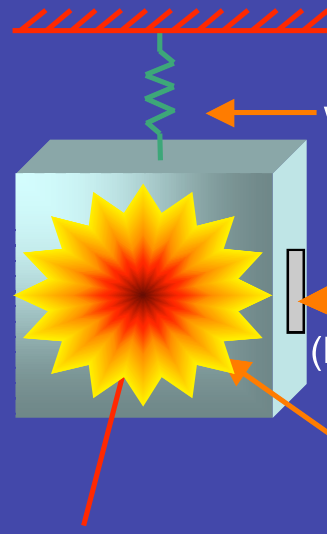
Shield cosmic rays (direct interactions and activations)
Underground

Very radio-pure materials
^{238}U – ^{232}Th $\Rightarrow \tau \sim 10^{10}$ y
Signal rate $\Rightarrow \tau \sim 10^{25}$ y

Present most sensitive experiments: 10 - 40 kg
Future goals: ~ 1000 kg $\Rightarrow 10^{27}$ nuclides

- Reject background
- Study electron energy and angular distributions

Thermal Detectors



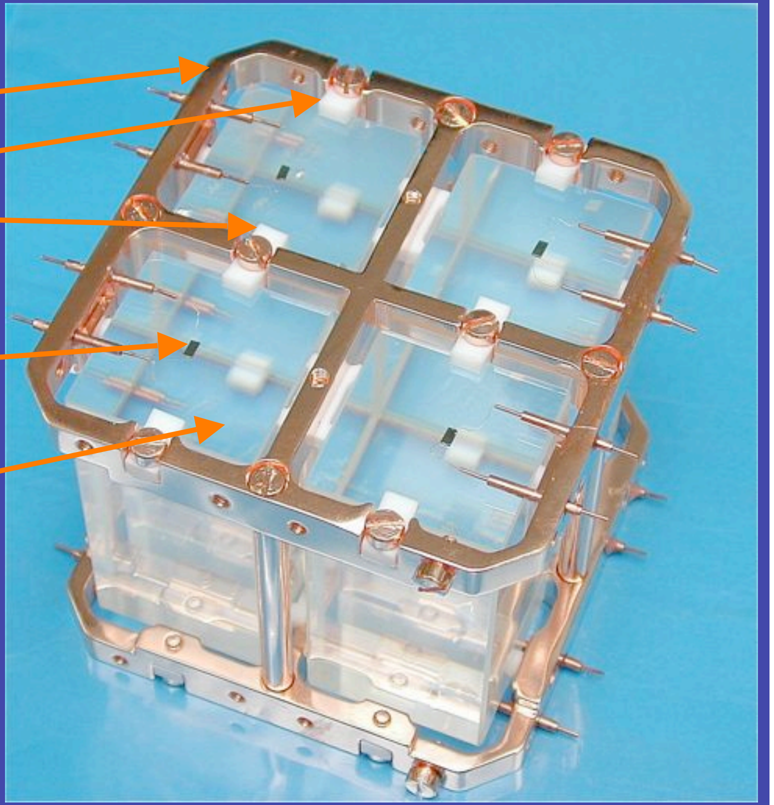
heat sink (≈ 9 mK)

weak thermal coupling
(~ 4 pW/mK)

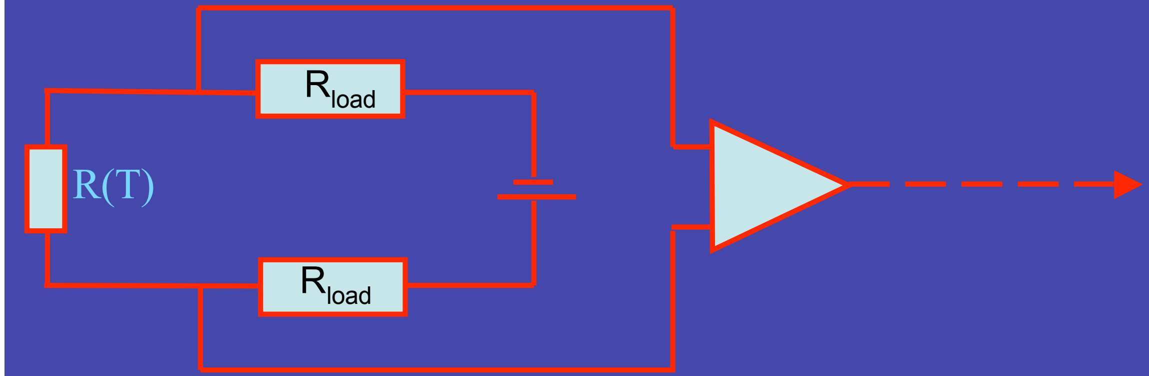
thermometer
(NTD Ge, R ≈ 100 MΩ I ≈ 50 pA)

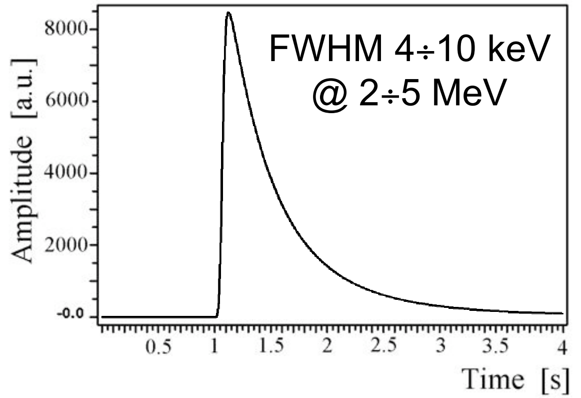
Crystal absorber
(TeO_2)

incident particle



$dR/dE \approx 20\ k\Omega/keV$





Experimental strategies

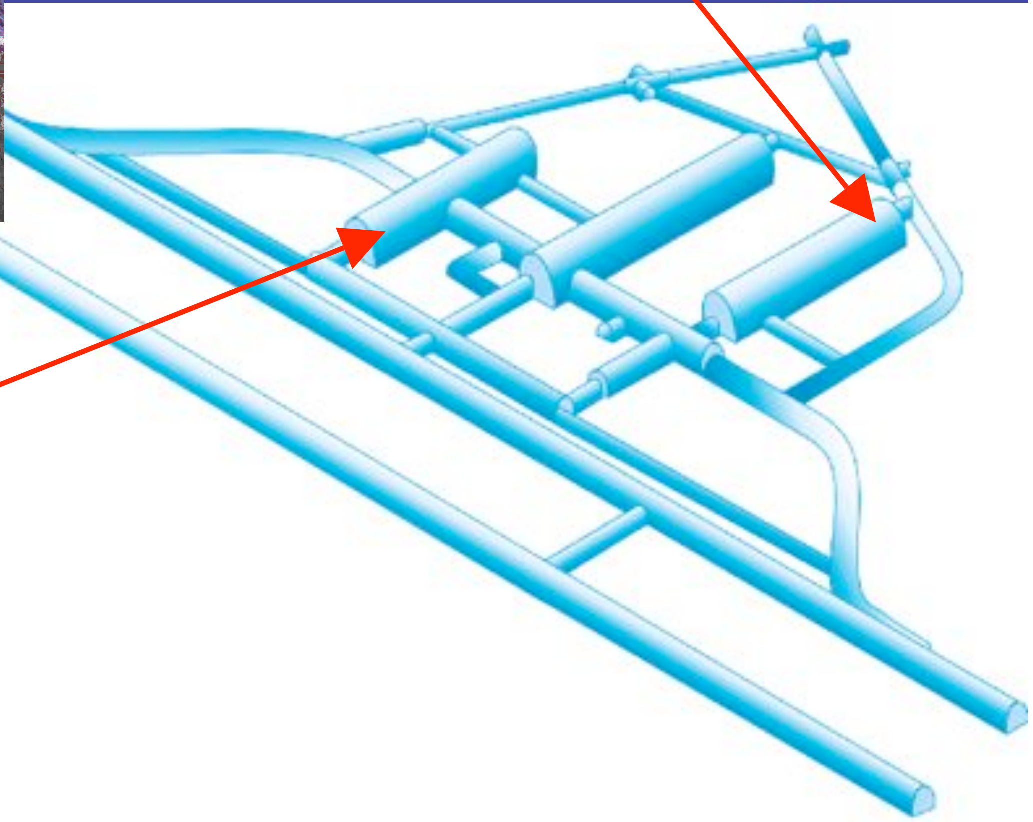
Detect the two electrons with a proper nuclear detector (direct search)

desirable features

- **High energy resolution** — Bolometers are comparable with Ge detectors
- **Low background** — It is a problem for all the detectors…
- **Large source (many nuclides under control)** — The bolometer is made off a ββ emitter
- **Event discrimination method** → This is the purpose of this talk…..

CUORICINO

INFN- Laboratori Nazionali del Gran Sasso



CUORE R&D (Hall C)

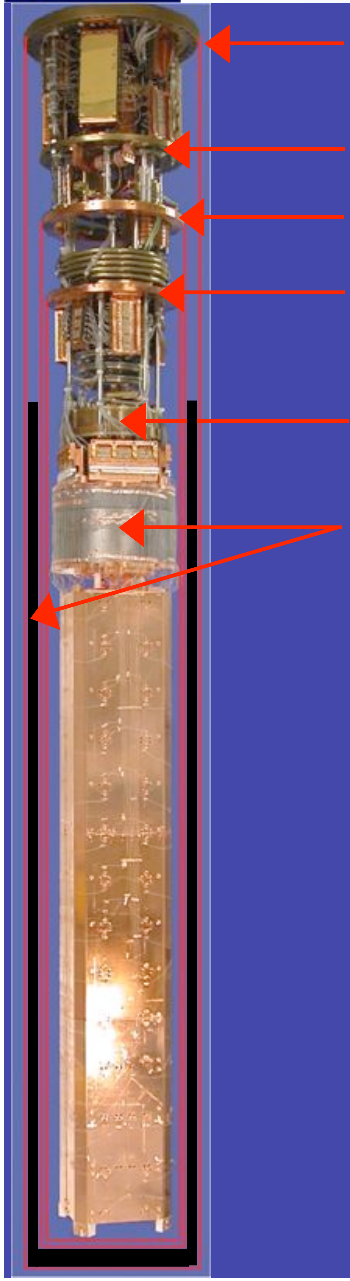
Cuoricino (Hall A)

Assembling Detectors….

Almost all the operations done in nitrogen atmosphere

Assembling the Tower...

Overall Layout



4.2 K Plate (+ vacuum shield)

1.2 K Plate

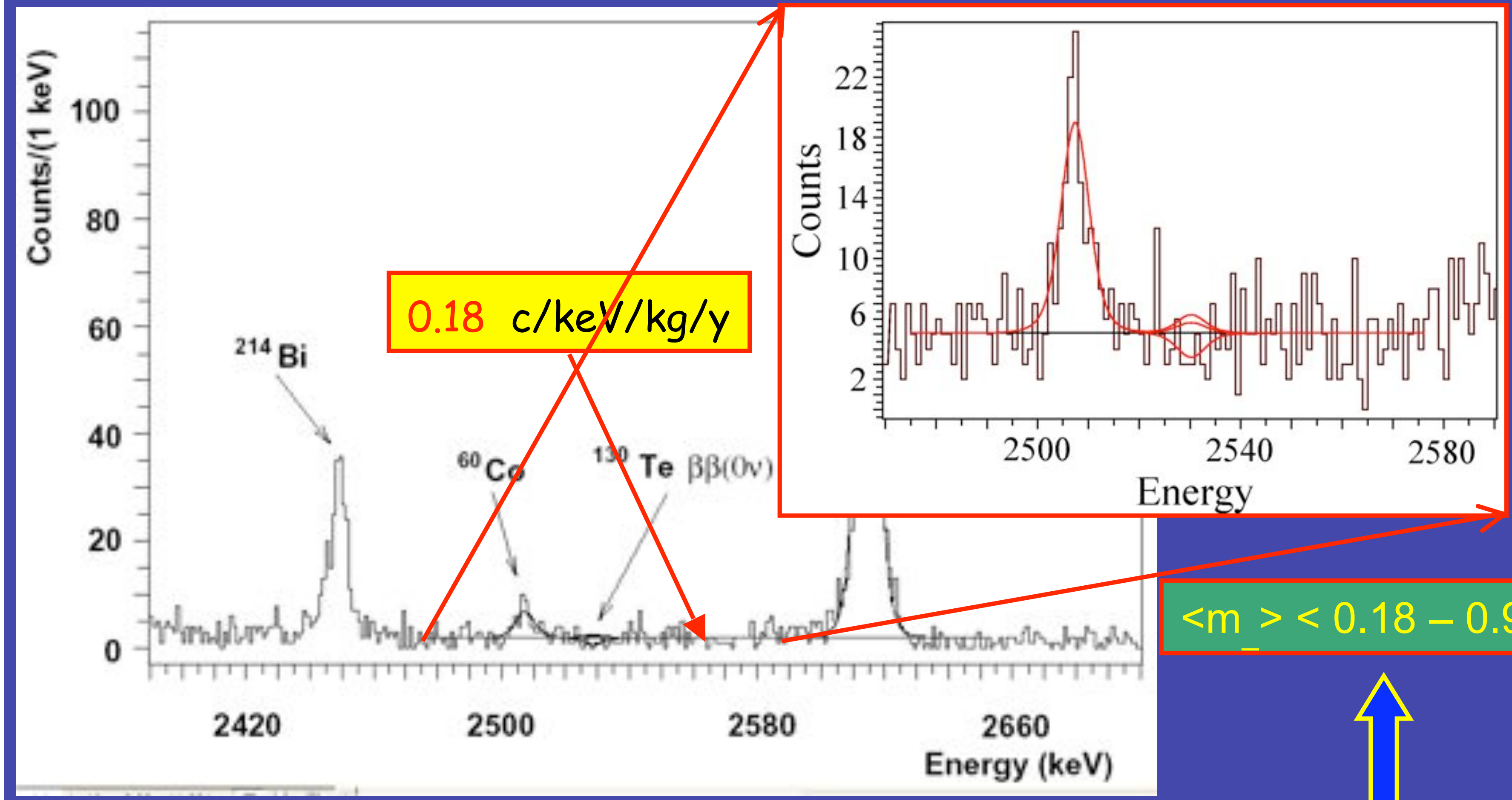
0.6 K Plate (+ IR shield)

0.05 K Plate (+ IR shield)

0.007 K (Mixing Chamber)

Roman Lead

Results on ^{130}Te bb-ov decay



0.18 c/keV/kg/y

<m_ > < 0.18 – 0.94 eV

Statistic collected: 8.38 kg (^{130}Te) x y
(3.9·10^{25} atoms x y)

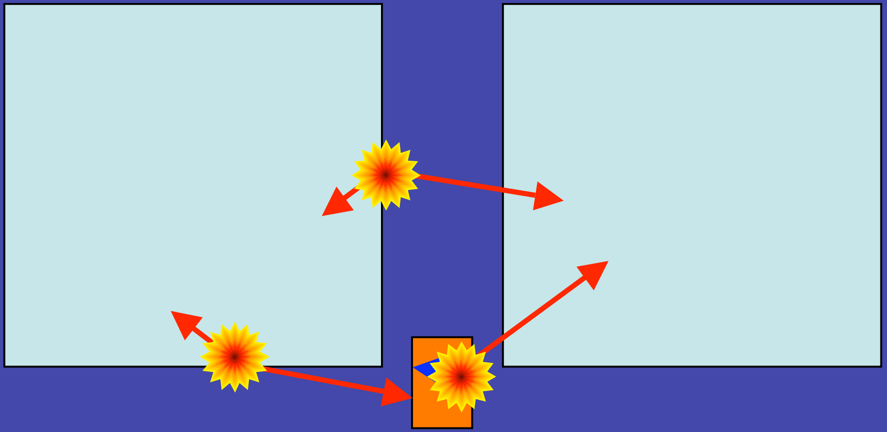
$$\tau^{0\nu}_{1/2} \geq 2.4\cdot10^{24}\ y \quad (90\%\ CL)$$

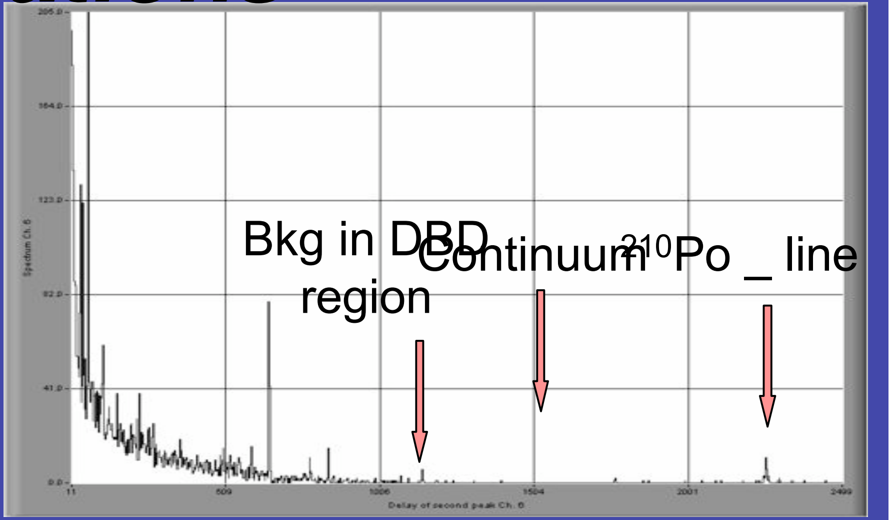
Sources of background

There are three main sources of background

- Internal contaminations — $Q > E_{\beta\beta}$ * — * tagged with delayed anticoincidence cuts with calorimetric technique (^{232}Th & ^{238}U)
- External contaminations — $E_{\gamma} > E_{\beta\beta}$
- Surface contaminations — *Smeared* α-particles
- μ - spallation — High energy neutrons
- low energy neutrons — (n, γ) — Can be avoided (at least in principle) with appropriate shielding

A serious problem : Surface contaminations

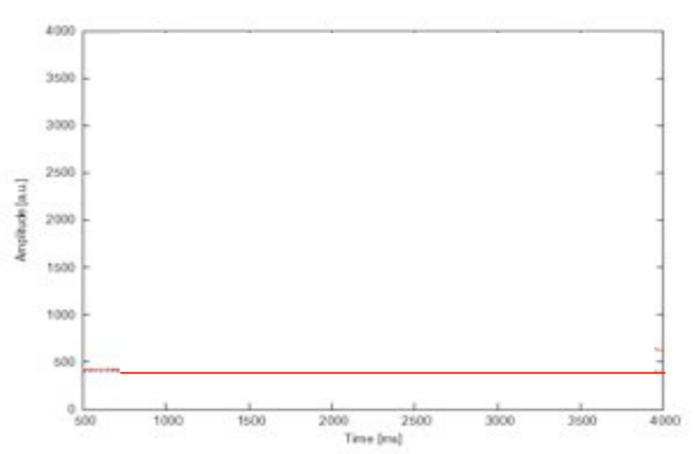


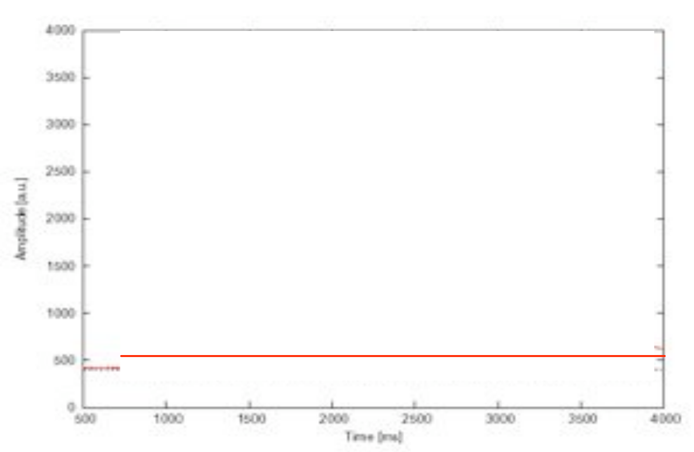


Bkg in DBD region

Continuum

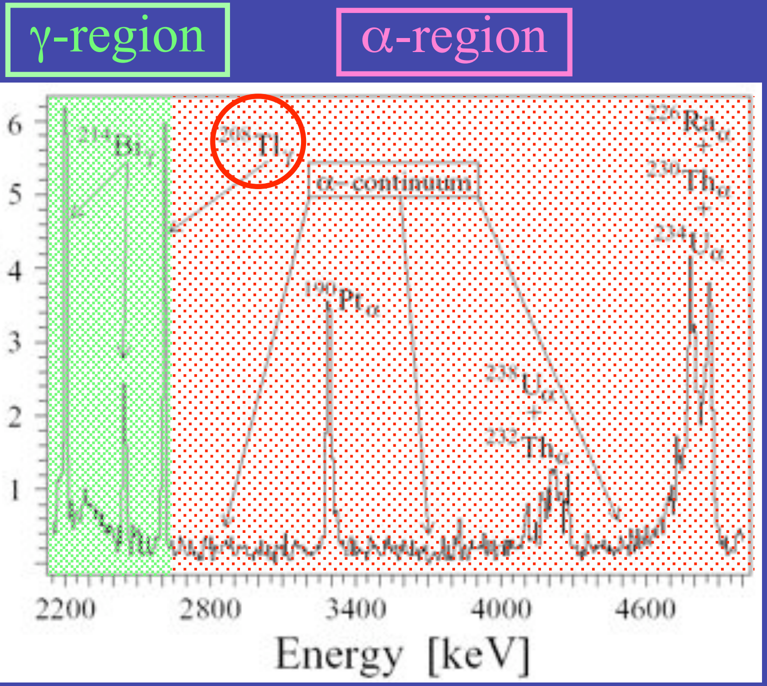
^{210}Po _ line



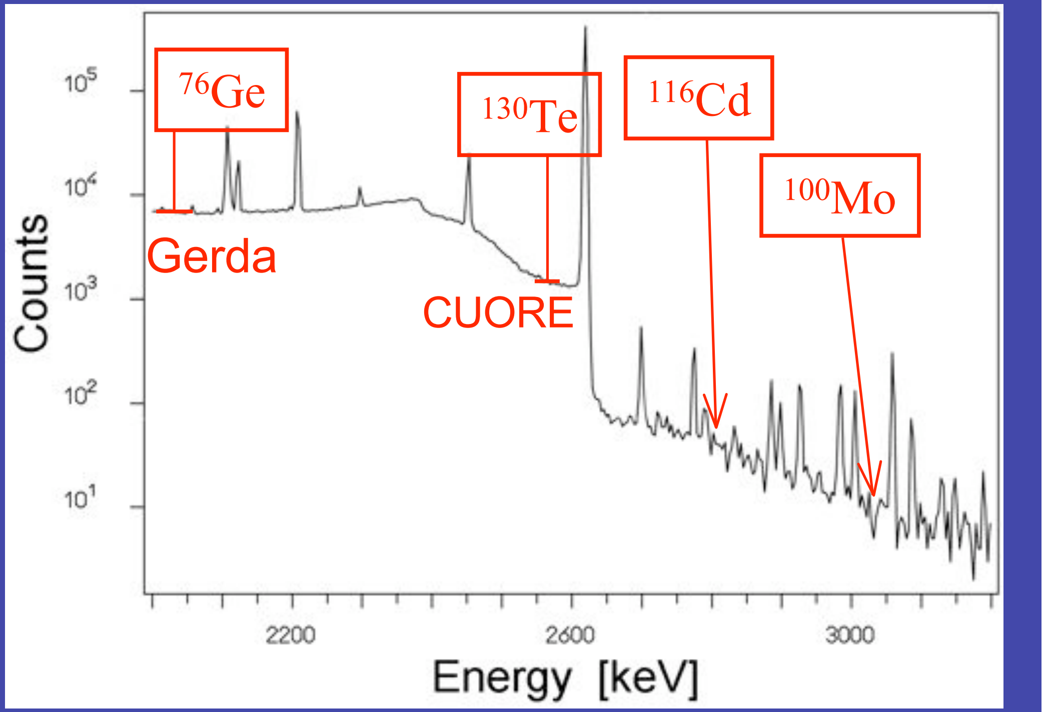


Sum energy: 2530 keV

Surface & Bulk Contaminations : Experimental spectra



CUORICINO Background



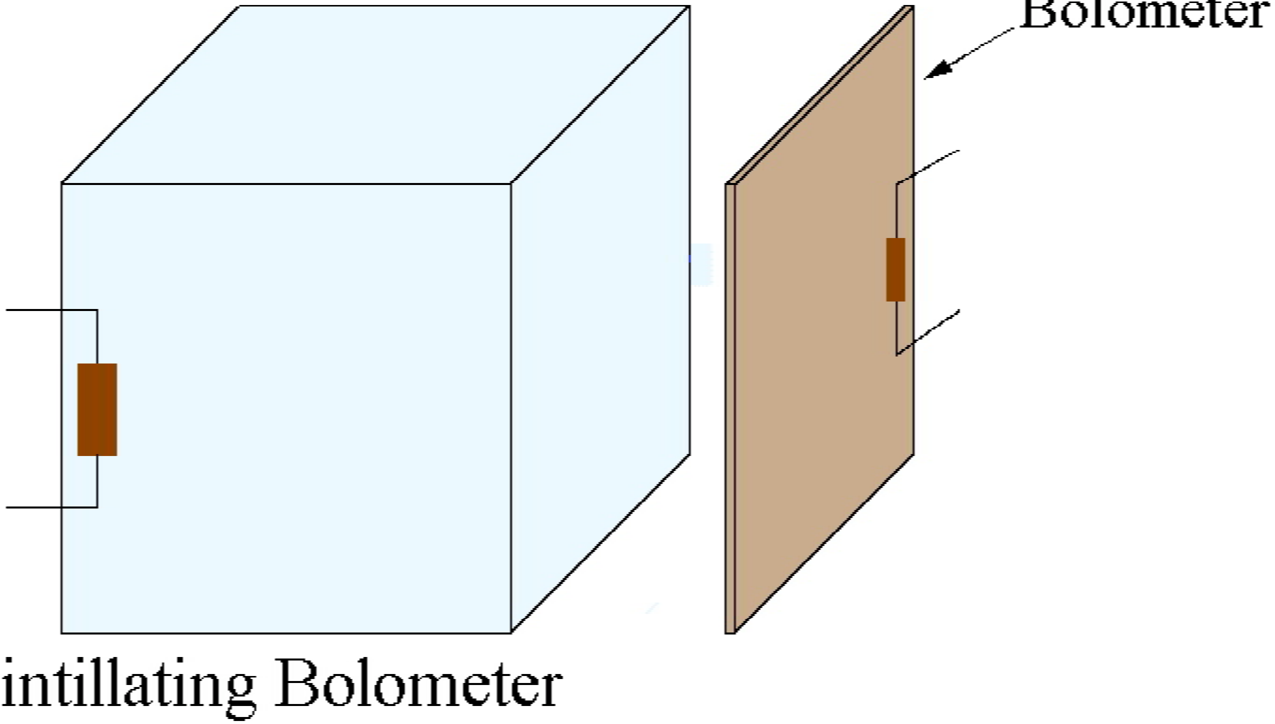
Environmental "underground" Background: ^{238}U and ^{232}Th trace contaminations

Furthermore a not negligible part of the background can arise from high energy neutrons from μ-spallation

Scintillating bolometers: Principles of operation

$\tau = C/G$

$\Delta T = \Delta E/C$



α/n - background suppression : Light-detection

A powerful tool in order to discriminate α particles is the scintillation light

The idea is to use a scintillating crystal as bolometer and to measure ***both*** (heat+light) channels

Thanks to the different Quenching Factor α ,β/γ, and **neutrons** can be easily identified

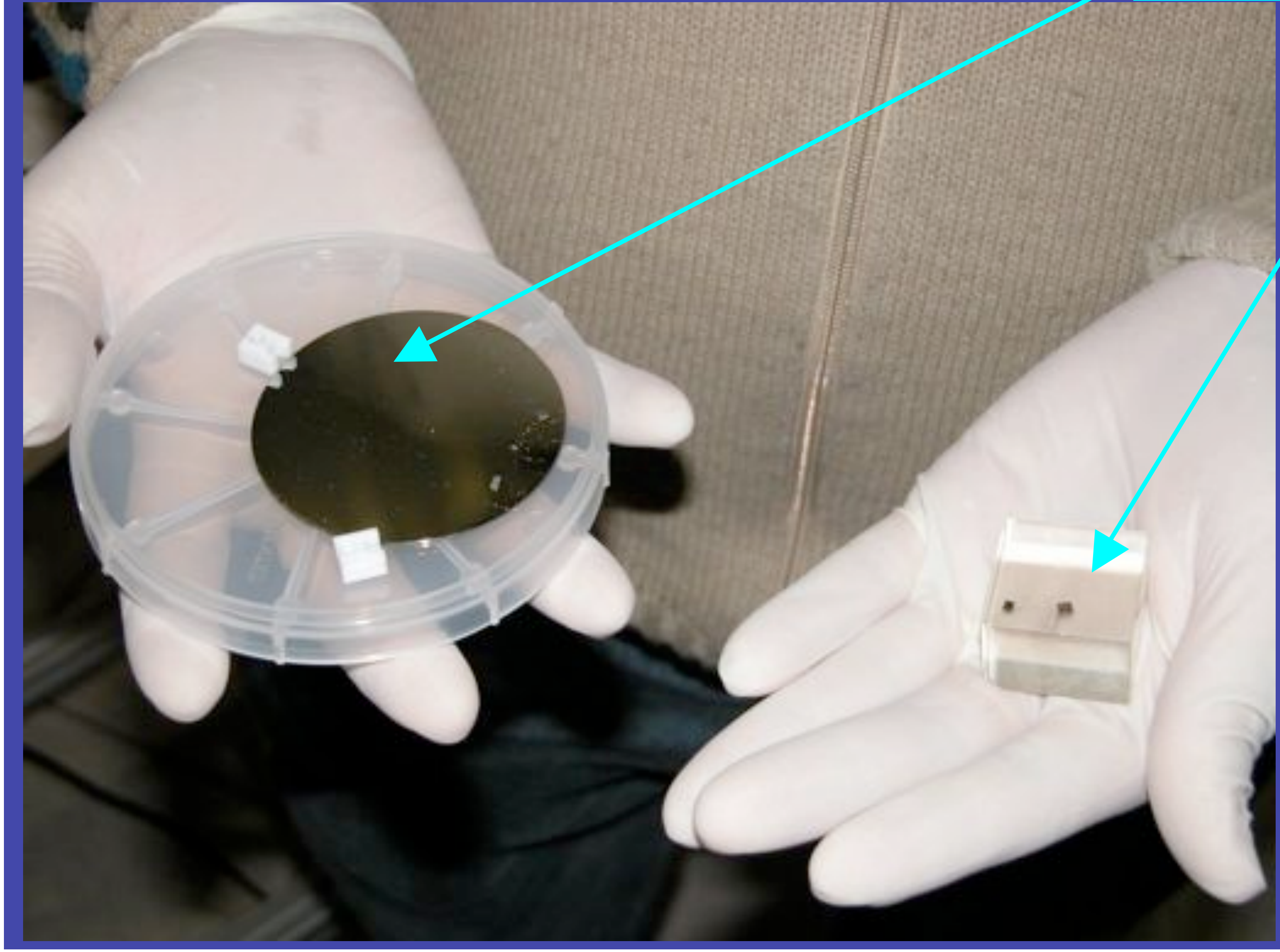
However, for a large and competitive experiment, some points need to be addressed

Feasible light detectors setup →
- *It has to work in the mK range*
- *Low radioactive contaminations*

"good" scintillation yield → *> 0.5 %*

Large $Q_{\beta\beta}$ value → *> 2615 keV* (^{208}Tl, *from* ^{232}Th)

Our Setup - I



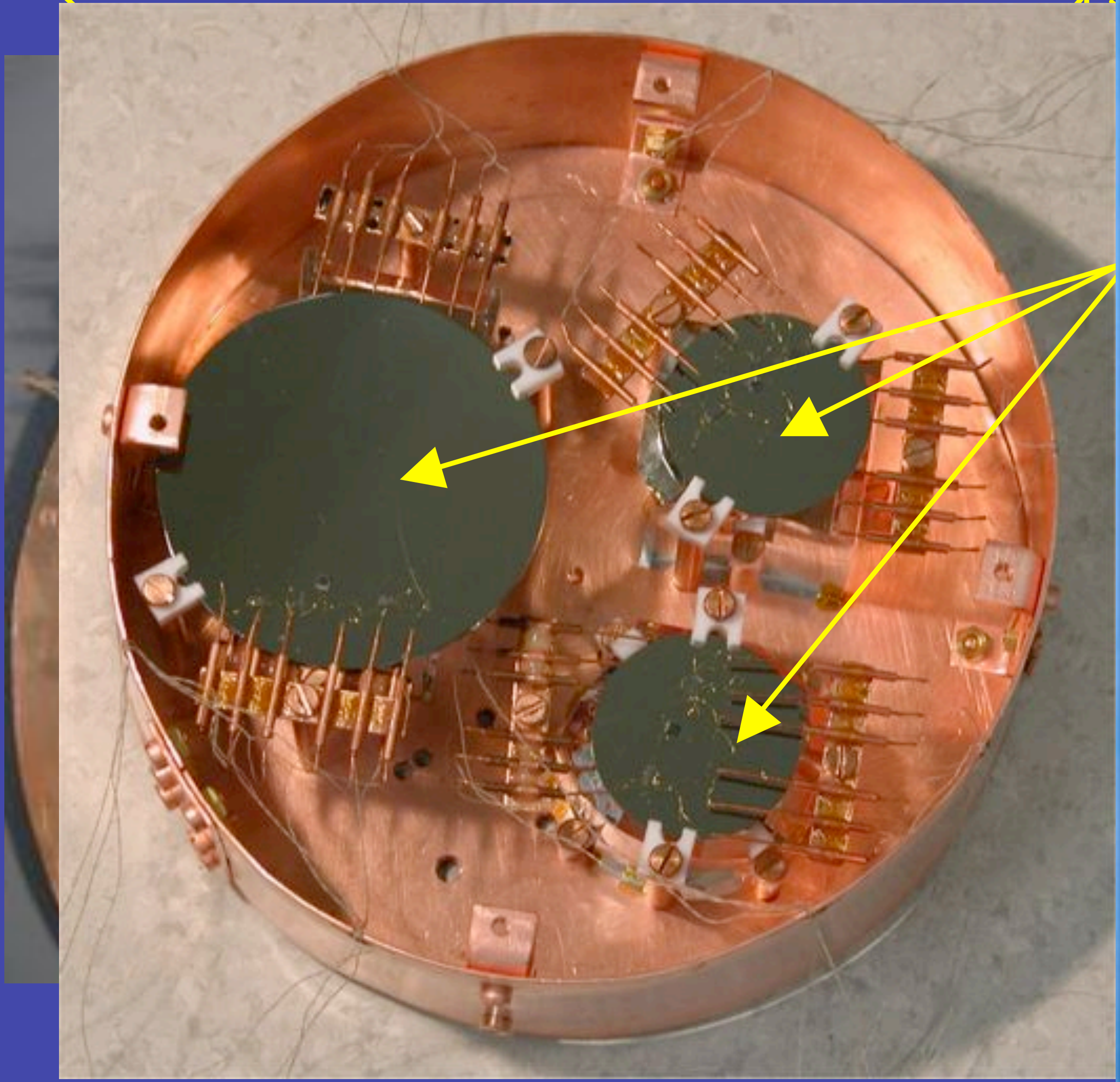
6.3 cm dia 1 mm thick Ge

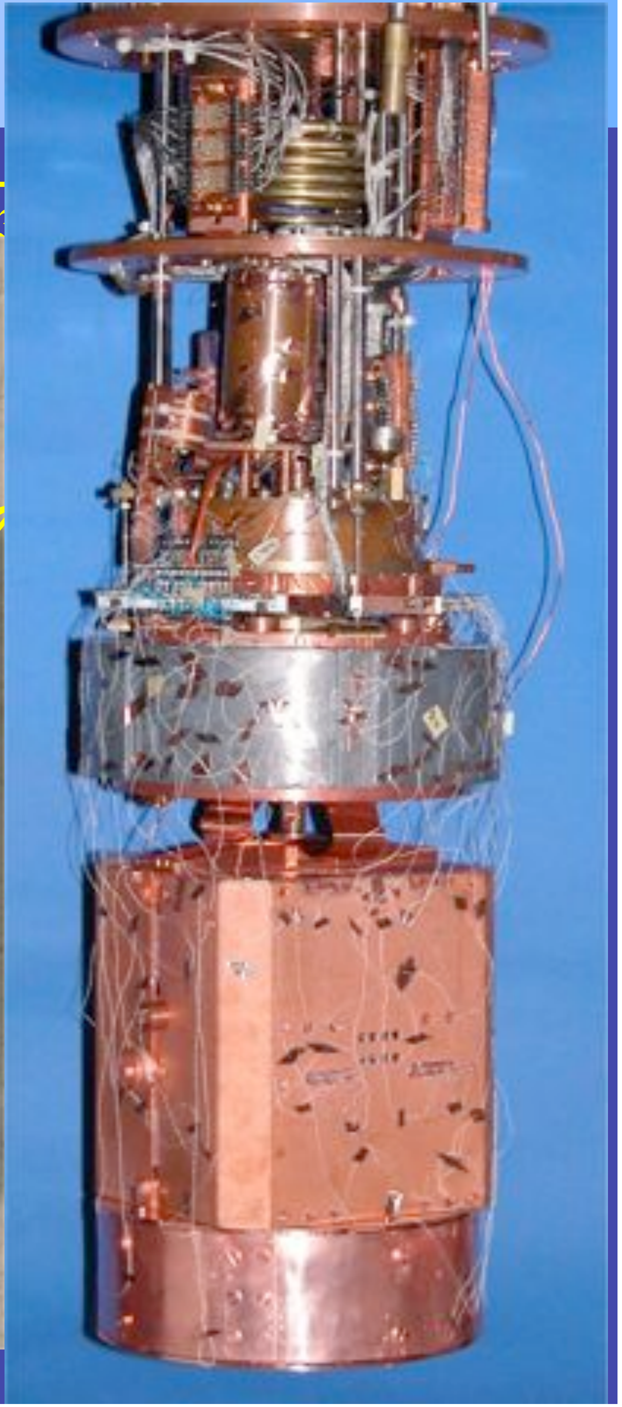
3x3x2 cm^3 $CdWO_4$ (140g)

$Q_{\beta\beta}(^{116}Cd)$=2802 keV

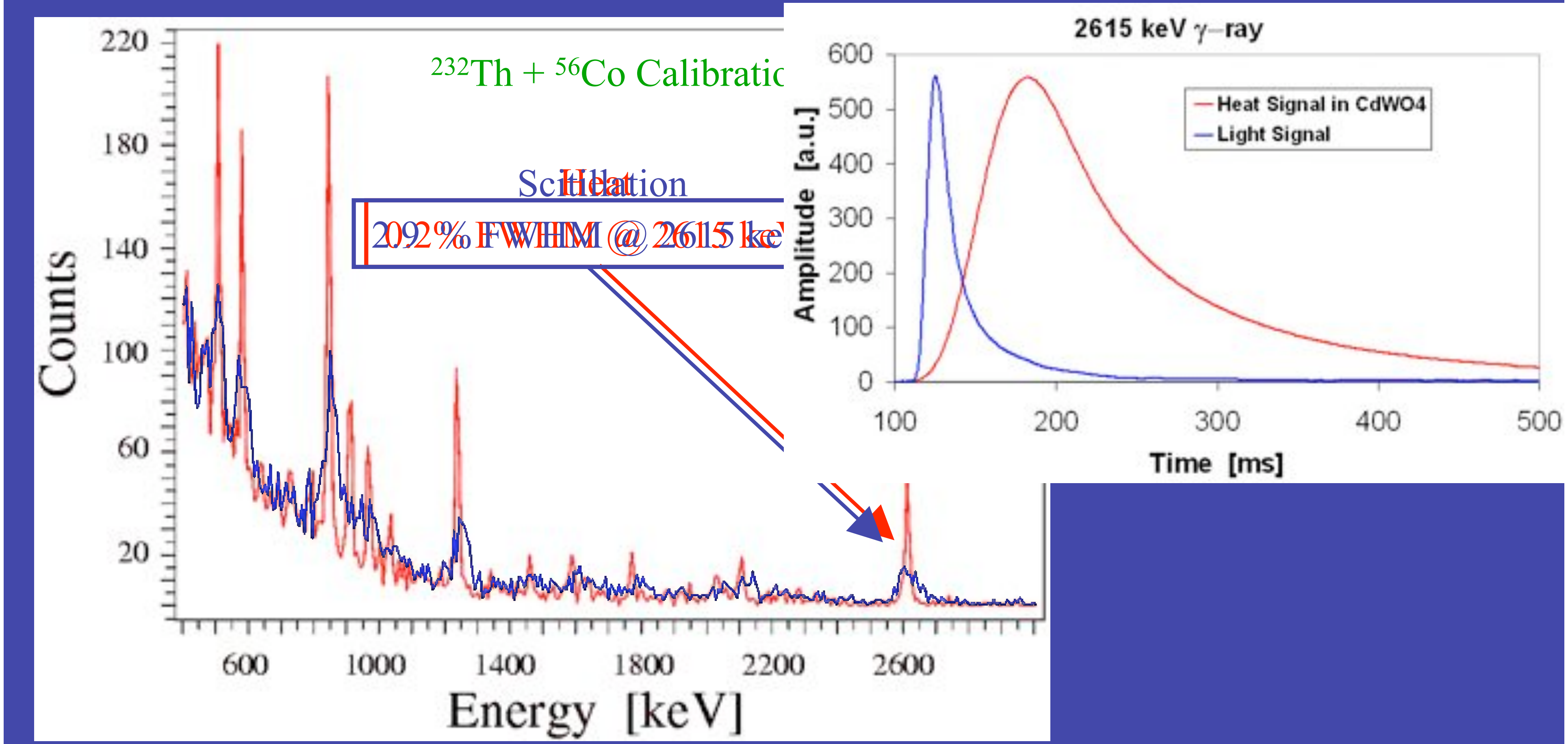
Our Setup - II

3x3x2 cm^3 CdWO$_4$





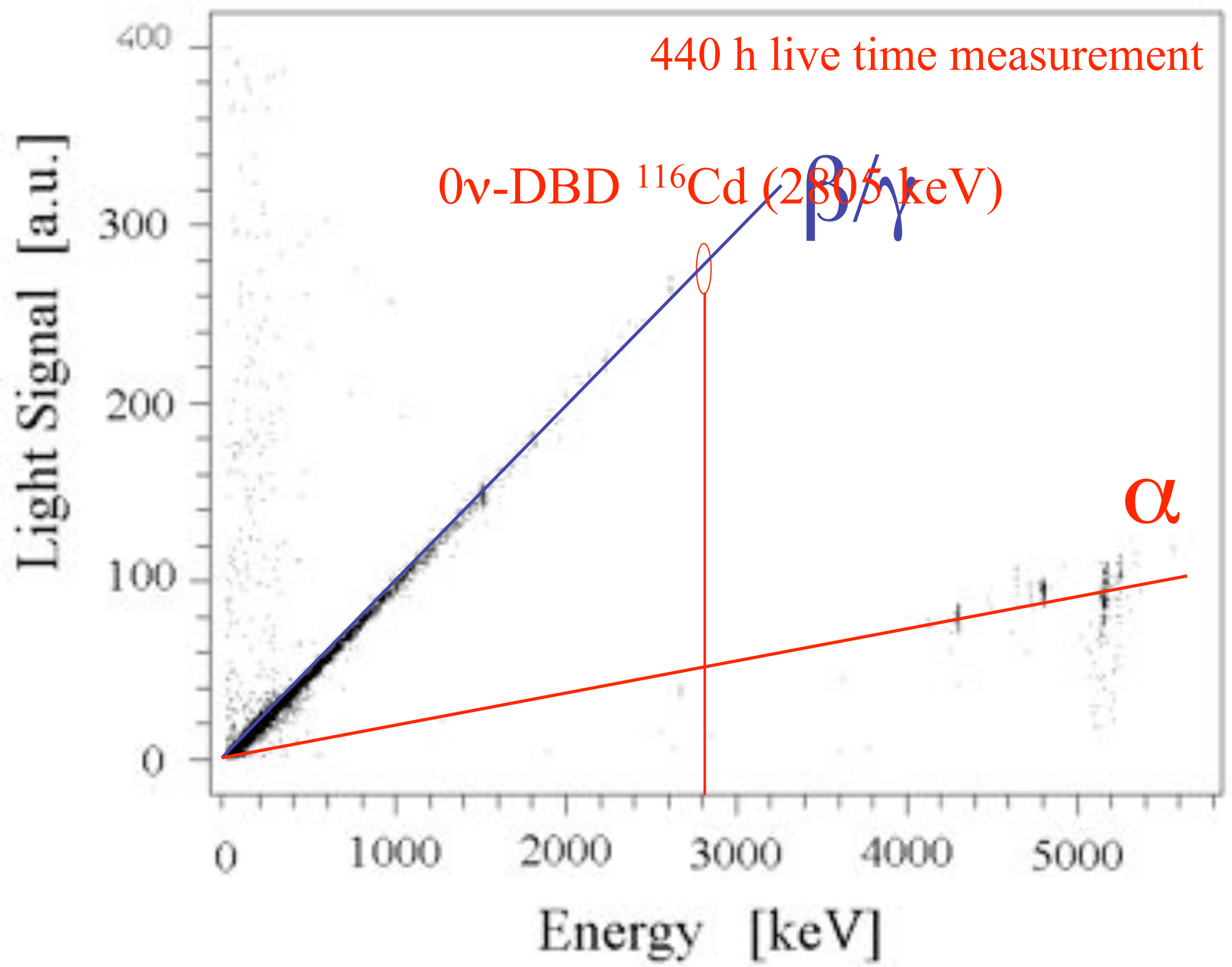
Calibration results on $CdWO_4$



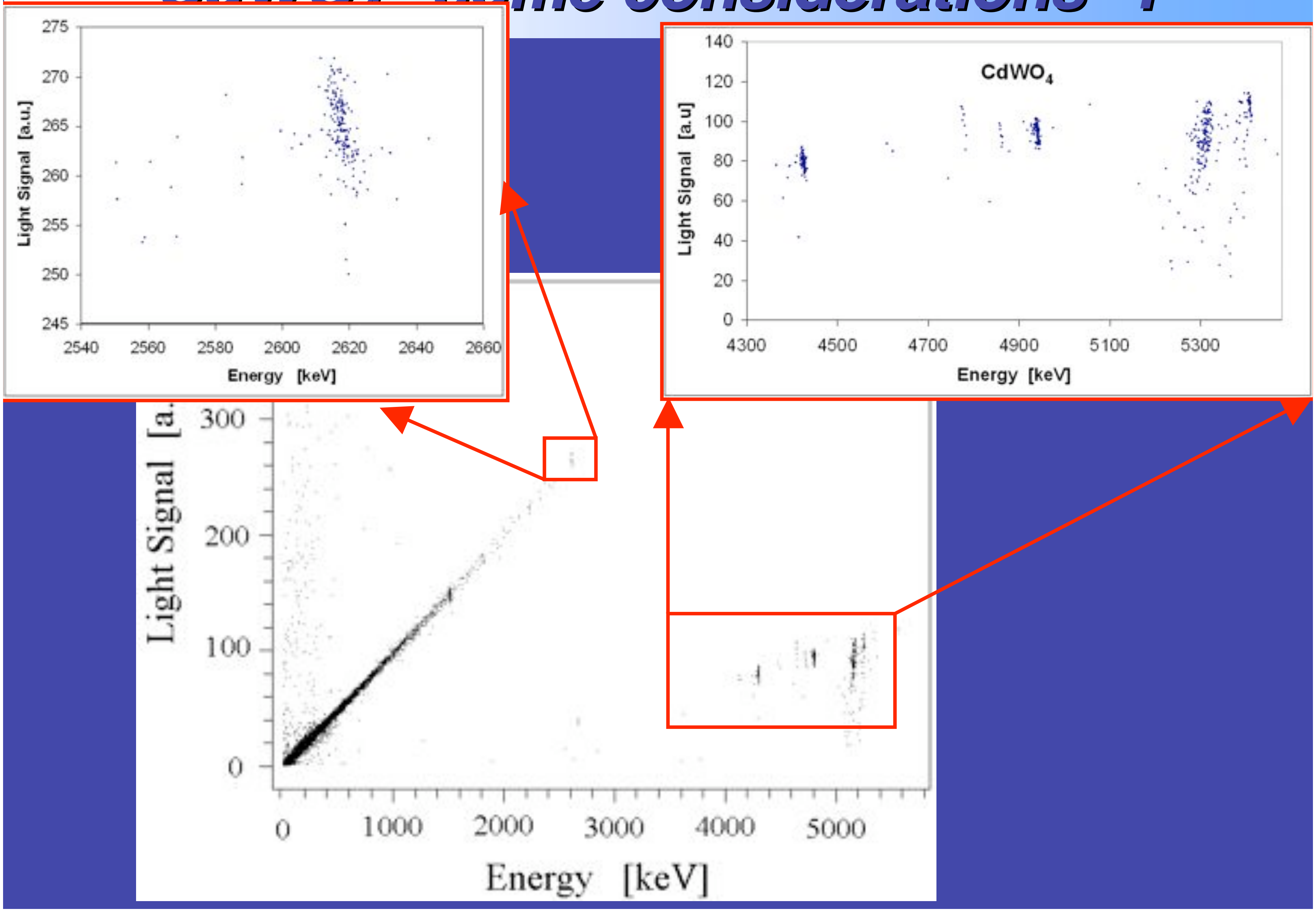
2.9% FWHM is the best result ever achieved with $CdWO_4$ as scintillator

Background measurement on $CdWO_4$

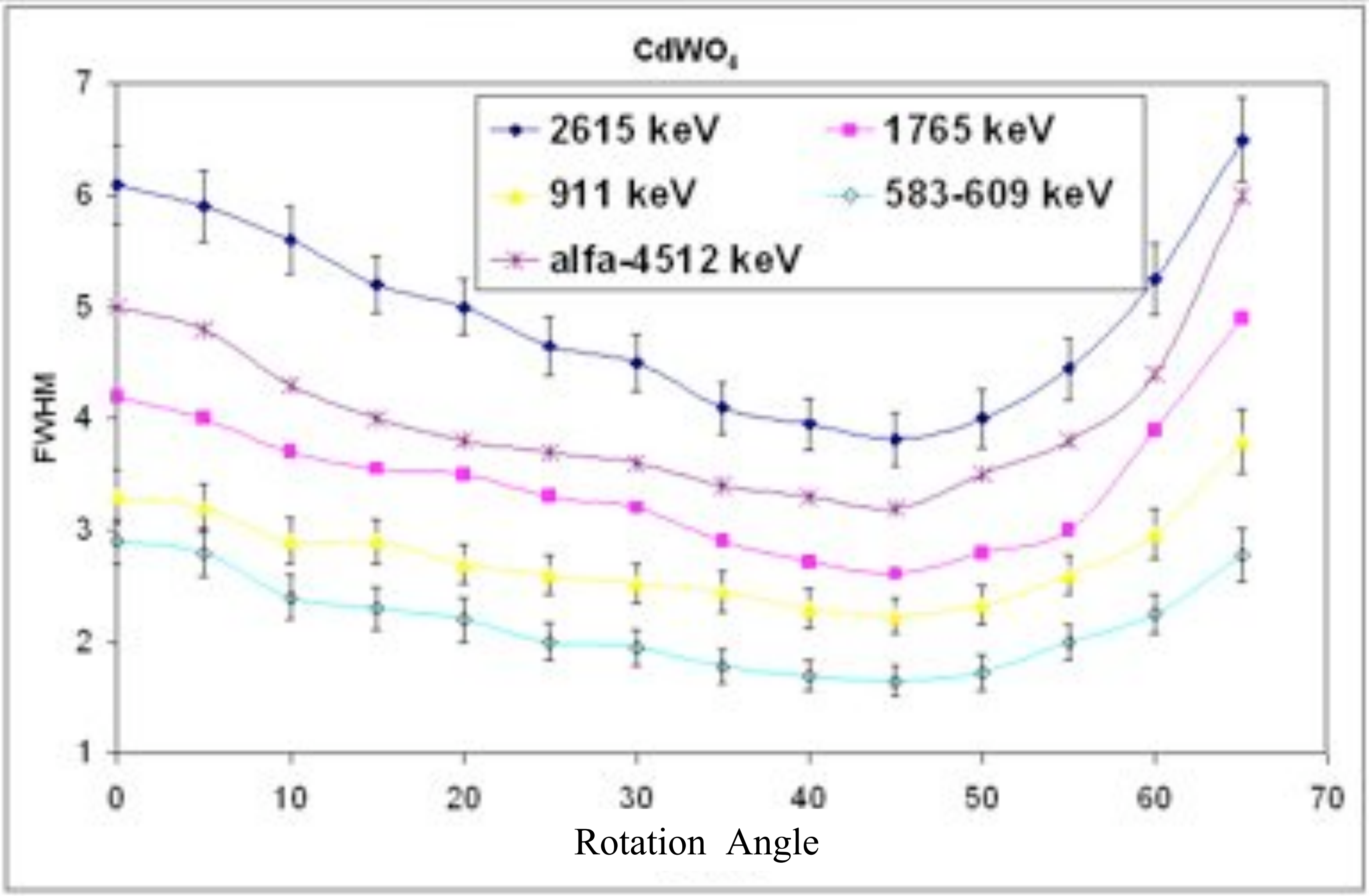
During last year a long Bg measurement was performed together with CUORE detectors



$CdWO_4$ - some considerations -1

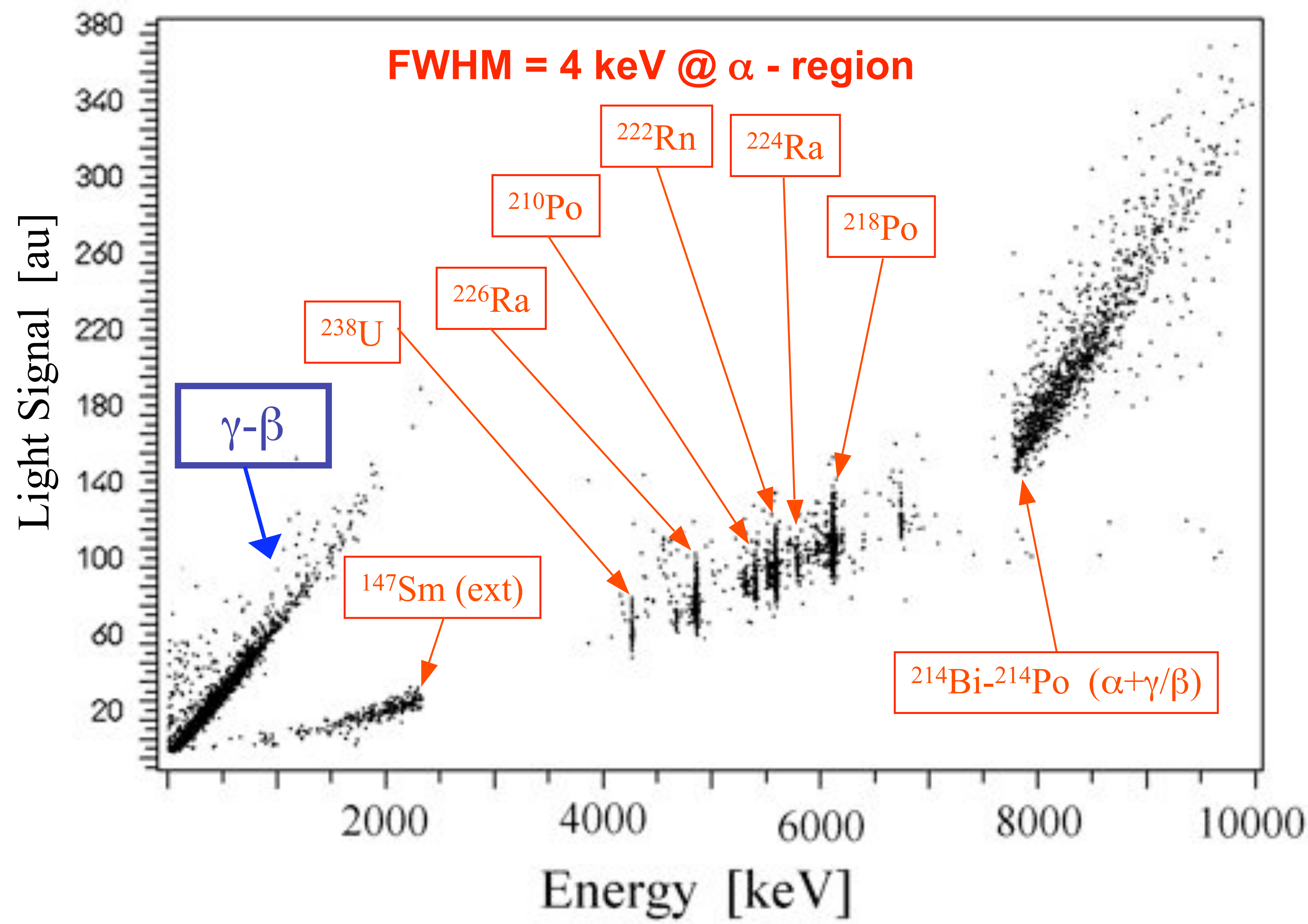


$CdWO_4$ - some considerations - 2

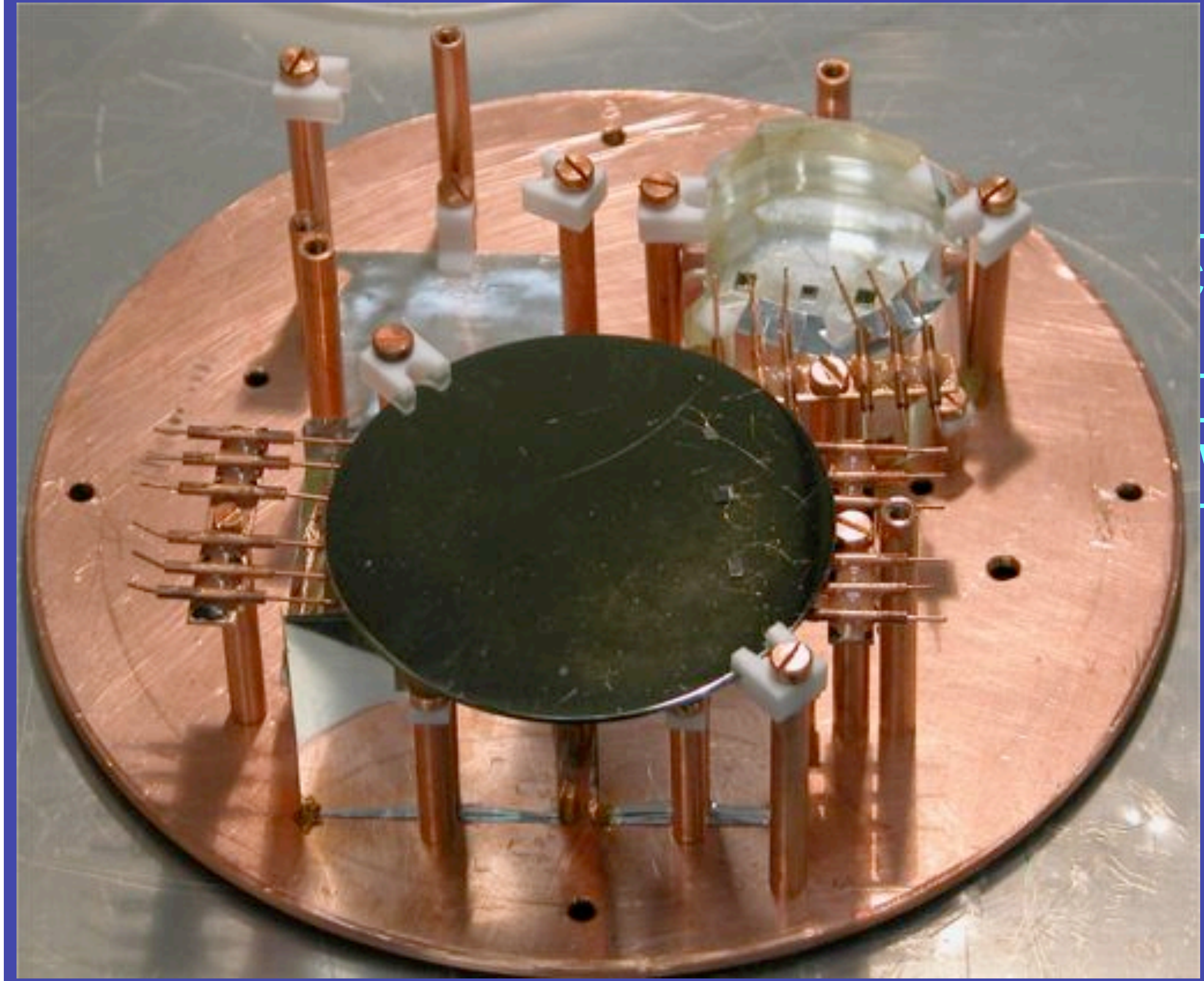


FWHM @ 2615 improves by ~ 40% !!!!!

$CaMoO_4$ -17.4 g sample



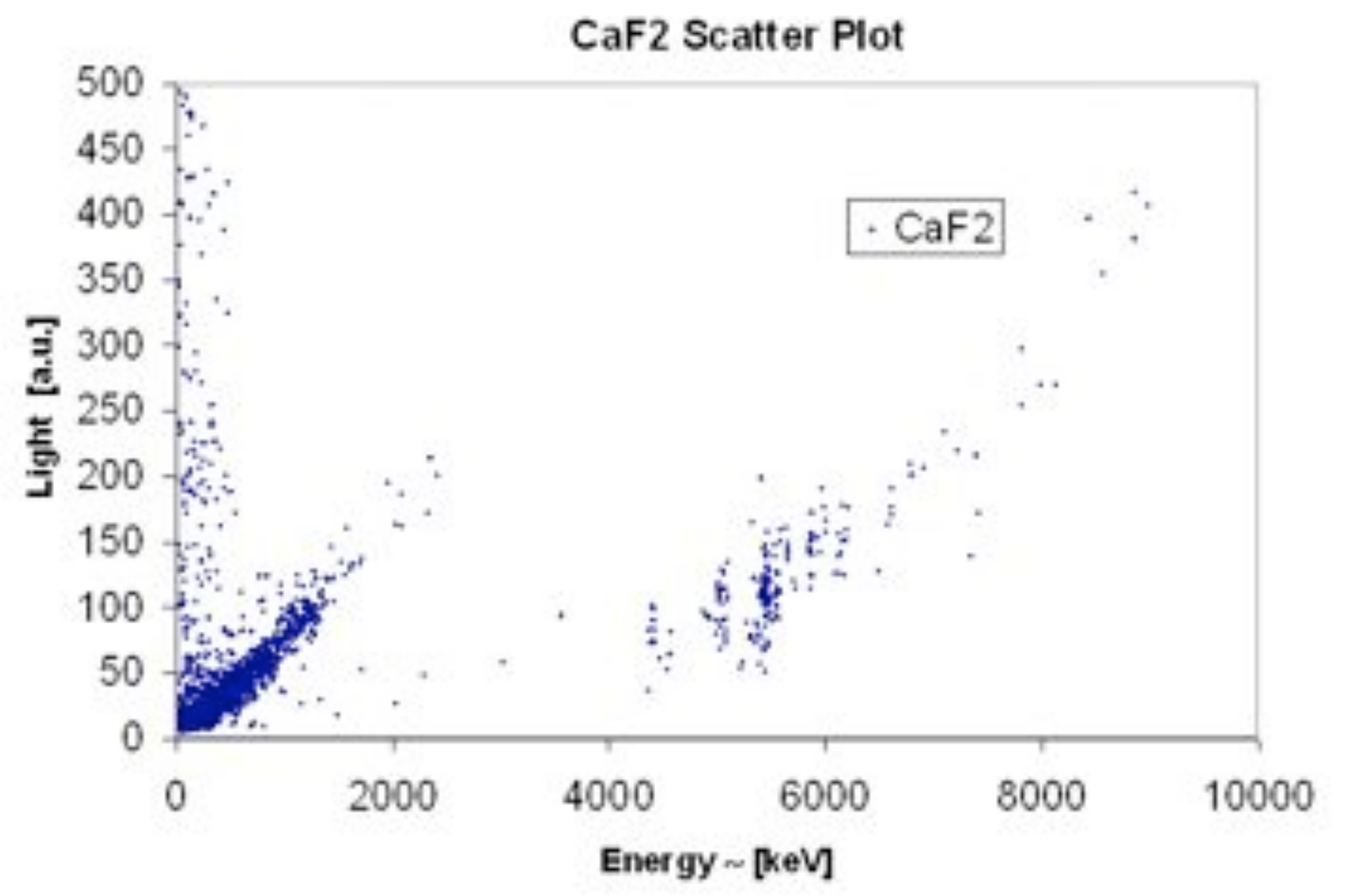
CaF2 (undoped) - 86 g Sample



aF$_2$ Sample
(3x3x3 cm^3)

WO$_4$ Sample

CaF2 Preliminary results



There is a lack of an actual calibration due to the "lightness" of the compound

Other small–size crystal tested

Other small size DBD crystals were tested within in the last 2 years

Good Scintillation light

- $PbMoO_4$
- $ZnSe$
- $CdMoO_4$
- $SrMoO_4$
- $CdWO_4$
- CaF_2

Poor Scintillation light

- ZrO_2
- $LiMoO_4$

No Scintillation light

- $MgMoO_4$
- TeO_2

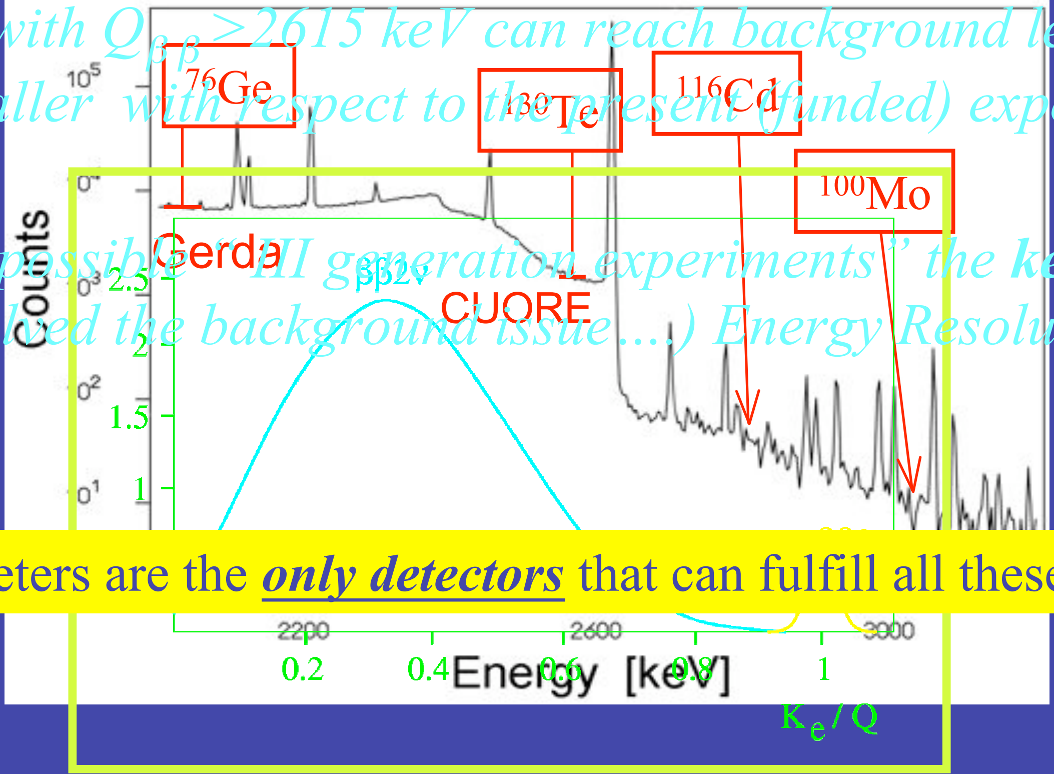
Other types of Molybdates are “ongoing”

Conclusions

$$(T^{0\nu}_{1/2}) = G(Q,Z)M^2\langle m_\nu \rangle^2 \propto K\sqrt{\frac{M \cdot t}{B \cdot \Delta E}}$$

Different nuclei HAVE to be investigated by DBD experiments

DBD Detectors with $Q_{\beta\beta} \geq 2615$ keV can reach background levels ~ 2 orders of magnitude smaller with respect to the present (funded) experiments



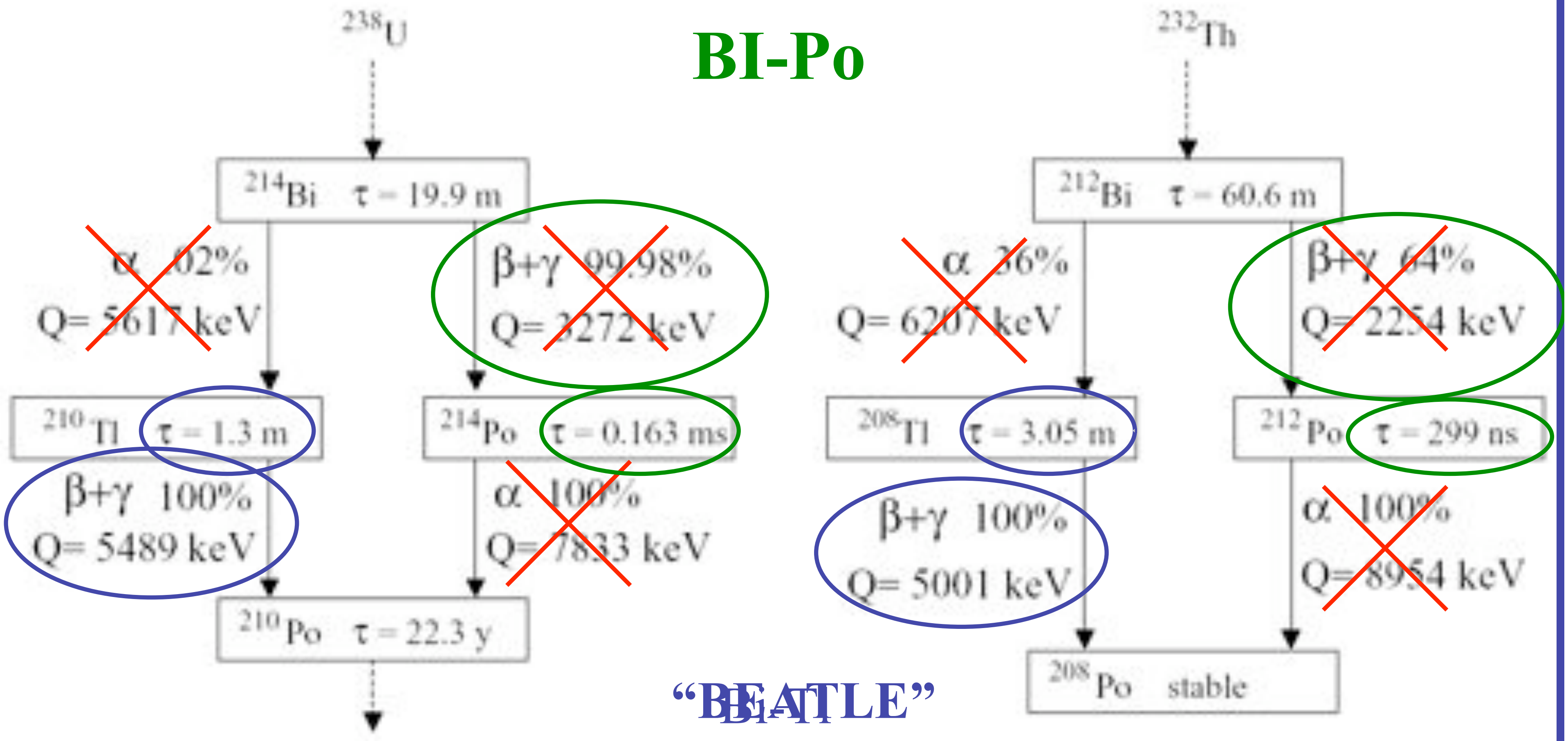
If we think about possible "III generation experiments" the ***key point*** *will be (if we consider solved the background issue ....) Energy Resolution (≈ 1 %)*

Scintillating Bolometers are the ***only detectors*** that can fulfill all these 3 requirements

People interested : Cryoscint 07 – Lyon 23 April 2007

Backups

Background Suppression : Bulk contaminations

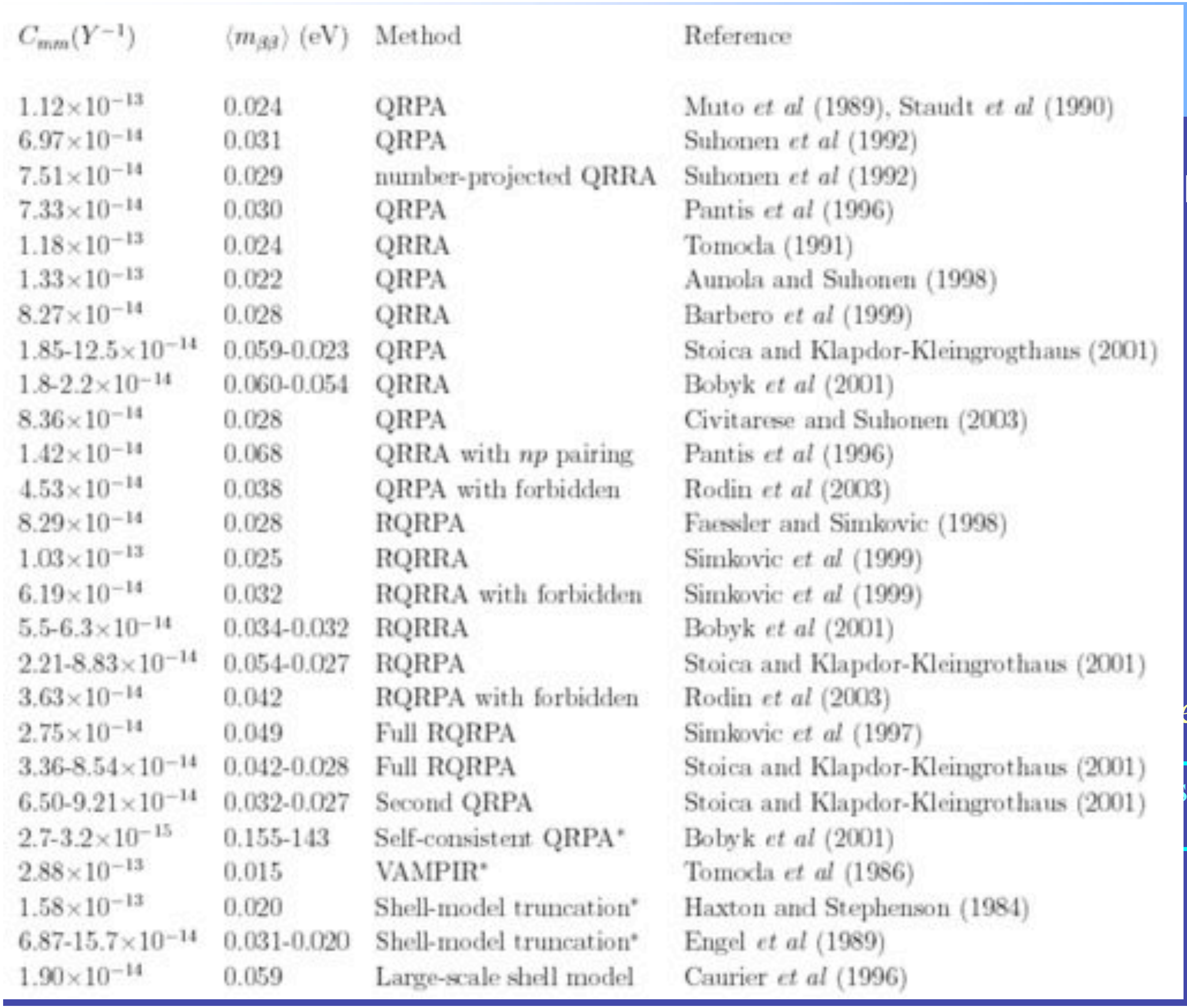


BI-Po

“BEATLE”

Thanks to Bi-Po’s and Beatles internal contaminations do not play a significant role

Does not hold for ^{234}Pa (Q=2195 keV)



$C_{mm}(Y^{-1})$	$\langle m_{\beta\beta}\rangle$ (eV)	Method	Reference
1.12×10^{-13}	0.024	QRPA	Muto *et al* (1989), Staudt *et al* (1990)
6.97×10^{-14}	0.031	QRPA	Suhonen *et al* (1992)
7.51×10^{-14}	0.029	number-projected QRRA	Suhonen *et al* (1992)
7.33×10^{-14}	0.030	QRPA	Pantis *et al* (1996)
1.18×10^{-13}	0.024	QRRA	Tomoda (1991)
1.33×10^{-13}	0.022	QRPA	Aunola and Suhonen (1998)
8.27×10^{-14}	0.028	QRRA	Barbero *et al* (1999)
$1.85\text{-}12.5\times10^{-14}$	0.059-0.023	QRPA	Stoica and Klapdor-Kleingrogthaus (2001)
$1.8\text{-}2.2\times10^{-14}$	0.060-0.054	QRRA	Bobyk *et al* (2001)
8.36×10^{-14}	0.028	QRPA	Civitarese and Suhonen (2003)
1.42×10^{-14}	0.068	QRRA with *np* pairing	Pantis *et al* (1996)
4.53×10^{-14}	0.038	QRPA with forbidden	Rodin *et al* (2003)
8.29×10^{-14}	0.028	RQRPA	Faessler and Simkovic (1998)
1.03×10^{-13}	0.025	RQRRA	Simkovic *et al* (1999)
6.19×10^{-14}	0.032	RQRRA with forbidden	Simkovic *et al* (1999)
$5.5\text{-}6.3\times10^{-14}$	0.034-0.032	RQRRA	Bobyk *et al* (2001)
$2.21\text{-}8.83\times10^{-14}$	0.054-0.027	RQRPA	Stoica and Klapdor-Kleingrothaus (2001)
3.63×10^{-14}	0.042	RQRPA with forbidden	Rodin *et al* (2003)
2.75×10^{-14}	0.049	Full RQRPA	Simkovic *et al* (1997)
$3.36\text{-}8.54\times10^{-14}$	0.042-0.028	Full RQRPA	Stoica and Klapdor-Kleingrothaus (2001)
$6.50\text{-}9.21\times10^{-14}$	0.032-0.027	Second QRPA	Stoica and Klapdor-Kleingrothaus (2001)
$2.7\text{-}3.2\times10^{-15}$	0.155-143	Self-consistent QRPA*	Bobyk *et al* (2001)
2.88×10^{-13}	0.015	VAMPIR*	Tomoda *et al* (1986)
1.58×10^{-13}	0.020	Shell-model truncation*	Haxton and Stephenson (1984)
$6.87\text{-}15.7\times10^{-14}$	0.031-0.020	Shell-model truncation*	Engel *et al* (1989)
1.90×10^{-14}	0.059	Large-scale shell model	Caurier *et al* (1996)

N(A,Z+2)

e mass

es

Predictions on the Majorana mass….

From the neutrino oscillations → U_{e1} U_{e2} U_{e3} Δm^2_{sun} Δm^2_{atm}

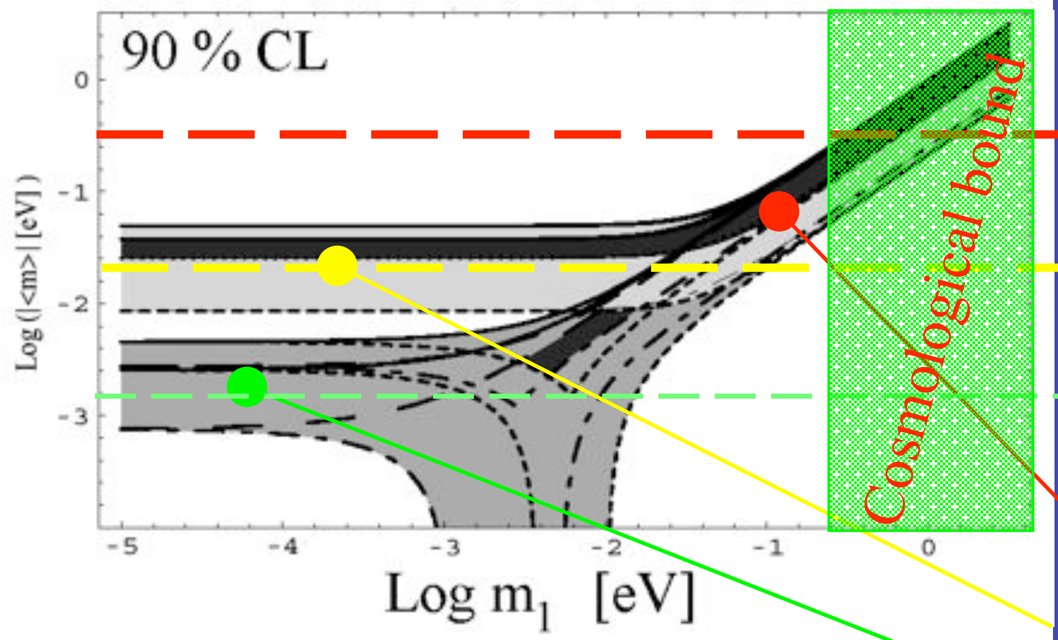
Parameterising

$$m_2 = \sqrt{\Delta m^2_{sun} + m_1^2}$$

$$m_3 = \sqrt{\Delta m^2_{atm} + m_1^2}$$

$$\Rightarrow \quad |< m^{\nu}_{ee} >| = f(const, m_1)$$

Represent the absolute scale mass



A.Lewis, S. Bridle, 2002

present limit m<0.35 eV $\tau > 10^{24} \div 10^{25}$ *y*

$\tau \approx 10^{26} \div 10^{27}\ y$

$\tau \approx 10^{28} \div 10^{29}\ y$

Quasi-degenenerate $m_1 \approx m_2 \approx m_3$

Inverse hierarchy $m_1 > m_2 > m_3$

Normal hierarchy $m_1 < m_2 < m_3$

Pascoli S. Petcov S.T. hep-ph/0310003

Strumia A. , Vissani F. hep-ph/0606054

DBD & Sensitivity

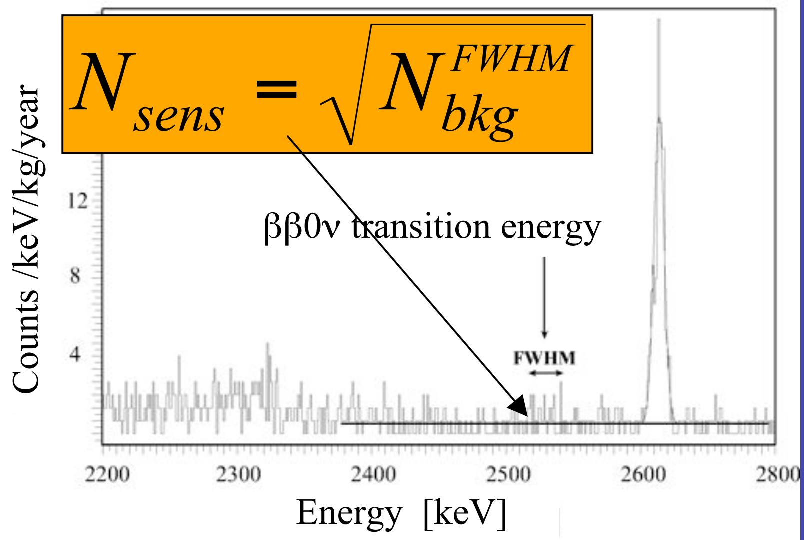
$$T_{1/2} = \ln 2 \cdot N_a \cdot t / N_d \qquad (T_{1/2} >> t)$$

N_a = *number of atoms* → $N_A \frac{M}{A} a.i.$

t = *measure time*

N_d = *number of observed decays*

The sensitivity is defined as the decay time corresponding to the detection of a minimum amount of decays above background, with respect to a defined CL



$$N_{sens} = \sqrt{N_{bkg}^{FWHM}}$$

$$N_{bkg}^{FWHM} = B_{[c/keV/t]}\, \Delta E_{[keV]}\, t$$

$$S = \ln 2\, N_A \frac{M}{A}\, i.a.\, \varepsilon \sqrt{\frac{t}{B\, \Delta E}}$$

If $bkg \propto M$

$$S = \ln 2\, N_A \frac{i.a}{A}\, \varepsilon \sqrt{\frac{M\, t}{B\, \Delta E}}$$

$[F] = c\, [E]^{-1} [M]^{-1} [t]^{-1}$

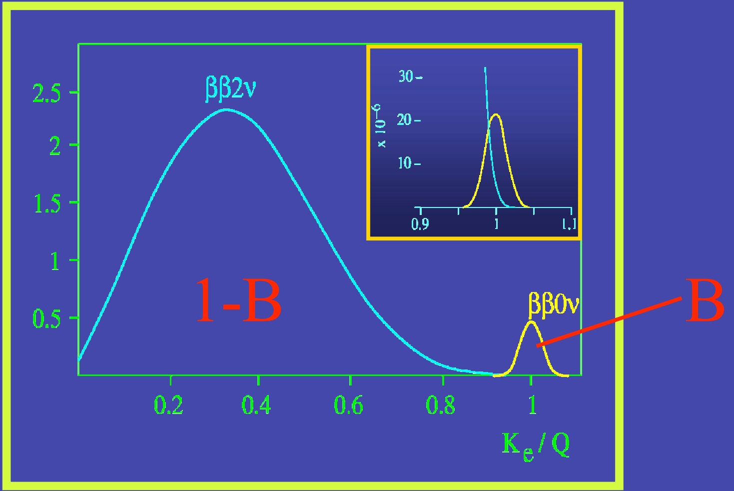
ε=*detection efficency*

Linear dependence

The energy resolution

The 2n decay mode as background for the 0n channel

$$A = \begin{cases} 8.5 \quad \mathrm{DE}/\mathrm{E}_{\mathrm{FWHM}} = 1\ \% \\ 7 \quad \mathrm{DE}/\mathrm{E}_{\mathrm{FWHM}} = 5\ \% \\ 5 \quad \mathrm{DE}/\mathrm{E}_{\mathrm{FWHM}} = 10\% \end{cases}$$



$$\boxed{B = A\,\frac{Q\,\delta^7}{m_e}}$$

$d = \mathrm{DE}_{\mathrm{FWHM}}/Q$

$$\boxed{\frac{S_{0\nu}}{B_{2\nu}} = \frac{m_e}{A\,Q\,\delta^7}\,\frac{\Gamma_{0\nu}}{\Gamma_{2\nu}} = \frac{m_e}{A\,Q\,\delta^7}\,\frac{T^{2\nu}_{1/2}}{T^{0\nu}_{1/2}}}$$

$\mathrm{DE}/\mathrm{E}_{\mathrm{FWHM}} = 10\%$

S/B=1

^{100}Mo $\xrightarrow{B \sim 3\ 10^{-6}}$ $T^{0n} < 3\,10^{24}$ $\langle m_n \rangle \sim 0.3$ ∏ 0.7 eV (0.1 ∏ 0.25)*

^{150}Nd $\xrightarrow{B \sim 3\ 10^{-6}}$ $T^{0n} < 2\ 10^{24}$ $\langle m_n \rangle \sim 0.16$ ∏ 0.11 eV (0.04 ∏ 0.06)*

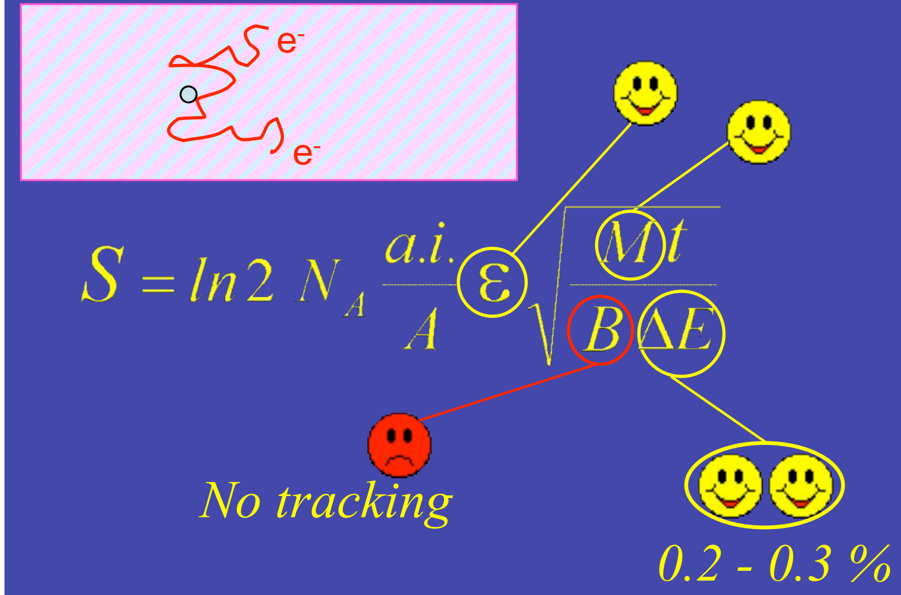
For Ge diodes and bolometers B ~10^{-16}

* choosing an asimmetric window Q < E < Q + DE/2 S/F gain ~ 8

DBD: Experimental approach

2 different strategies to detect the 2 e

Source ∫ detector
(calorimetric technique)



$$S = \ln 2 \, N_A \frac{a.i.}{A} \varepsilon \sqrt{\frac{M t}{B \Delta E}}$$

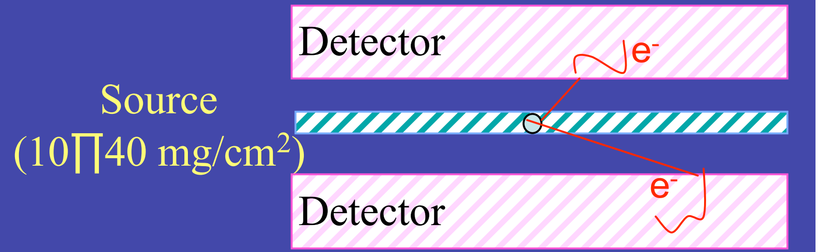
No tracking

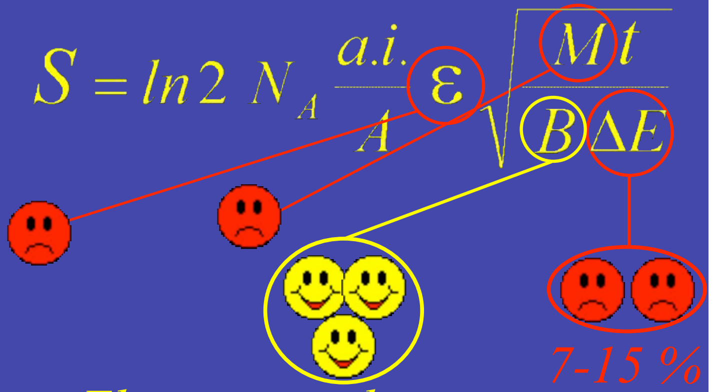
0.2 - 0.3 %

Germanium diodes ^{76}Ge

Bolometers ^{130}Te

Source π Detector





$$S = \ln 2 \, N_A \frac{a.i.}{A} \varepsilon \sqrt{\frac{M t}{B \Delta E}}$$

7-15 %

Electron tracking

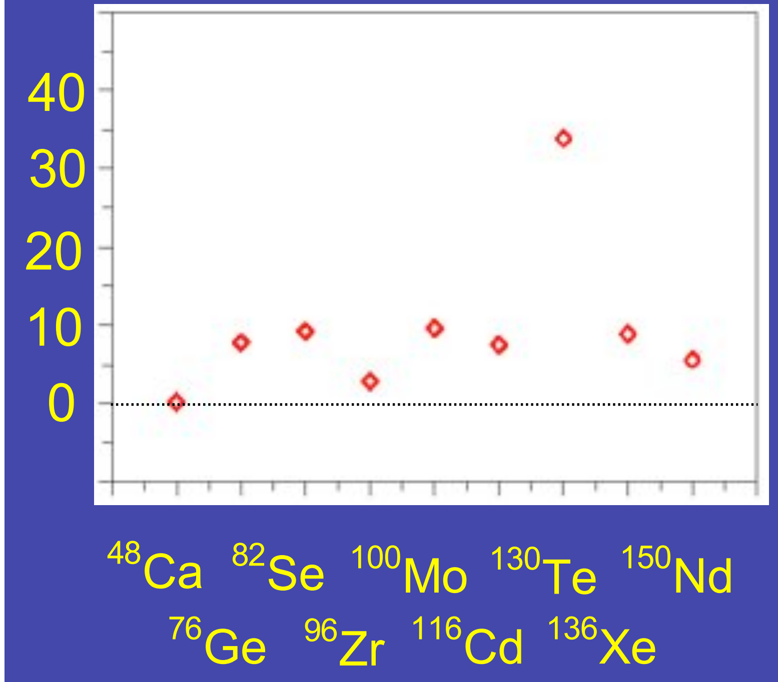
Tracking chambers DC,TPC
- ^{82}Se
- ^{100}Mo
- ^{96}Zr
- ...

scintillators ^{48}Ca, ^{116}Cd, ^{160}Gd, ^{136}Xe (liquids)

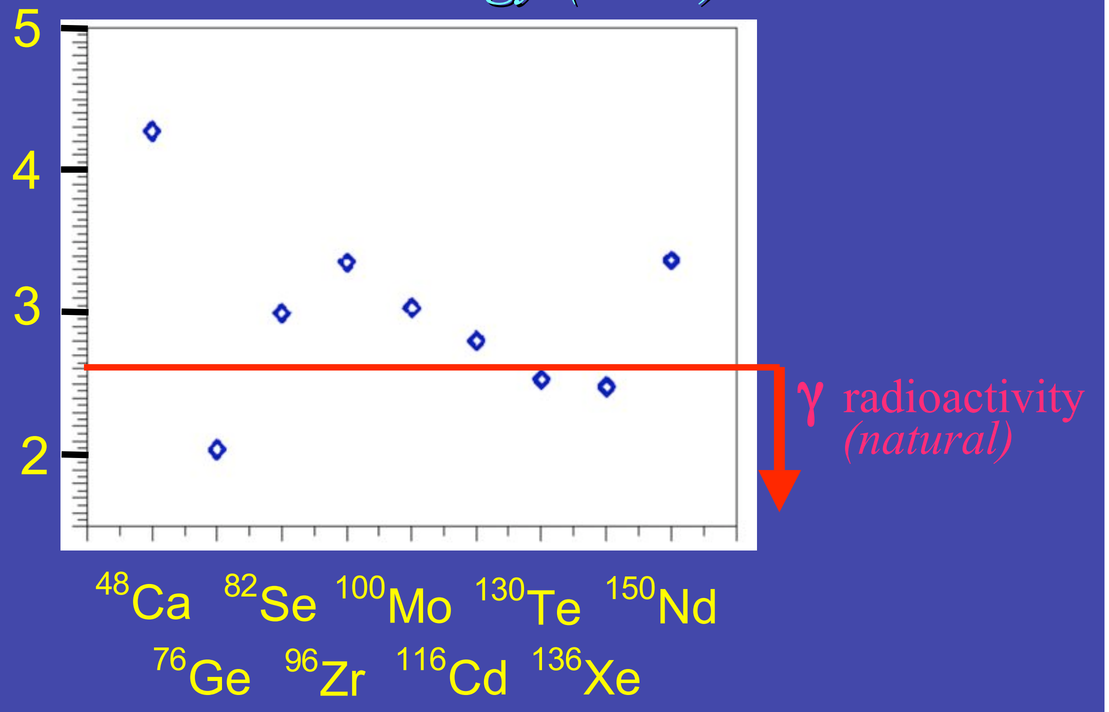
Choice of the Isotope

$$S = \ln 2 \; N_A \frac{a.i.}{A} \, \varepsilon \sqrt{\frac{M\,t}{B\,\Delta E}}$$

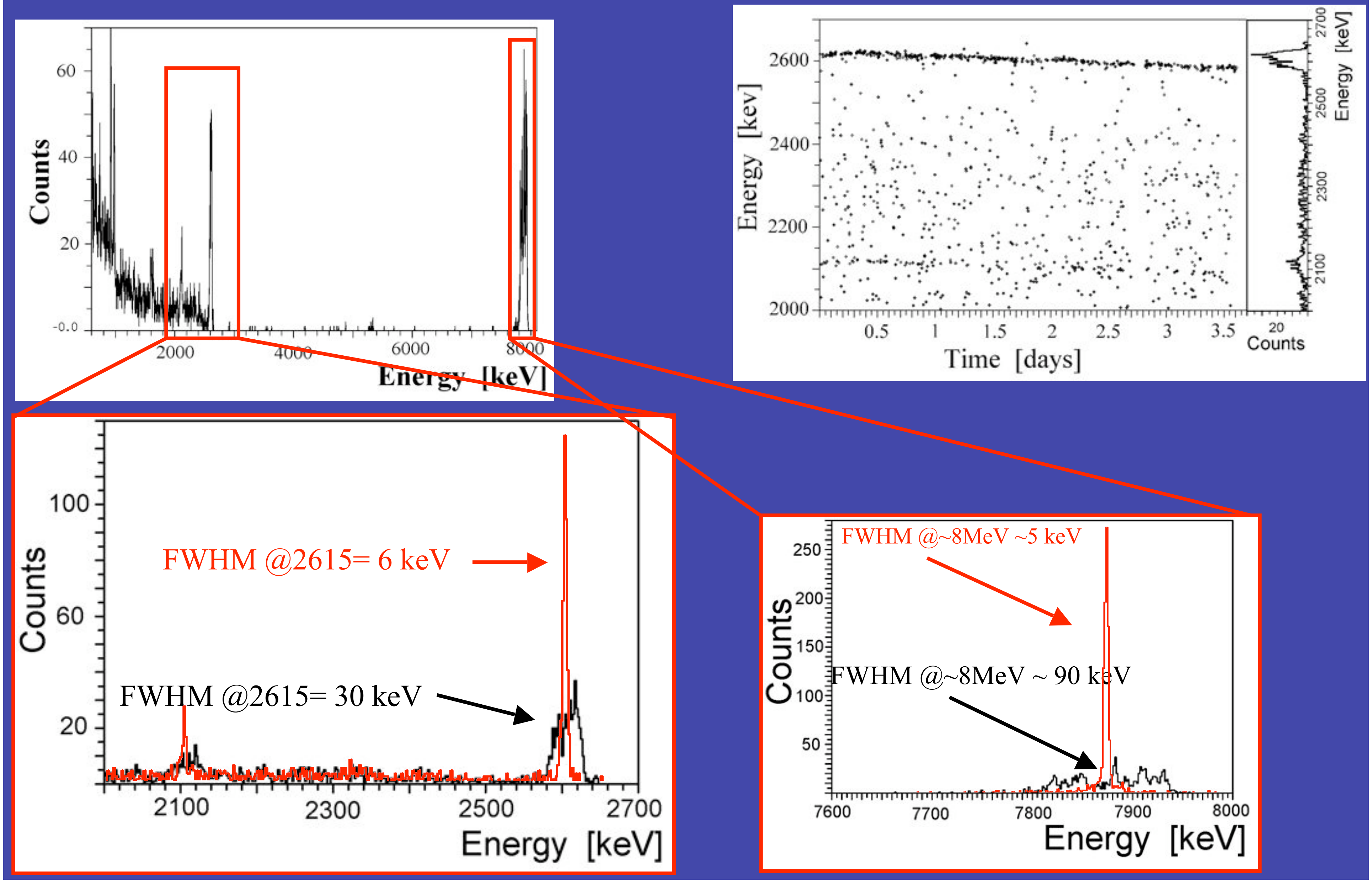
Isotopic abundance (%)



Transition Energy (MeV)



Thermal Detectors-stability



FWHM @2615= 6 keV

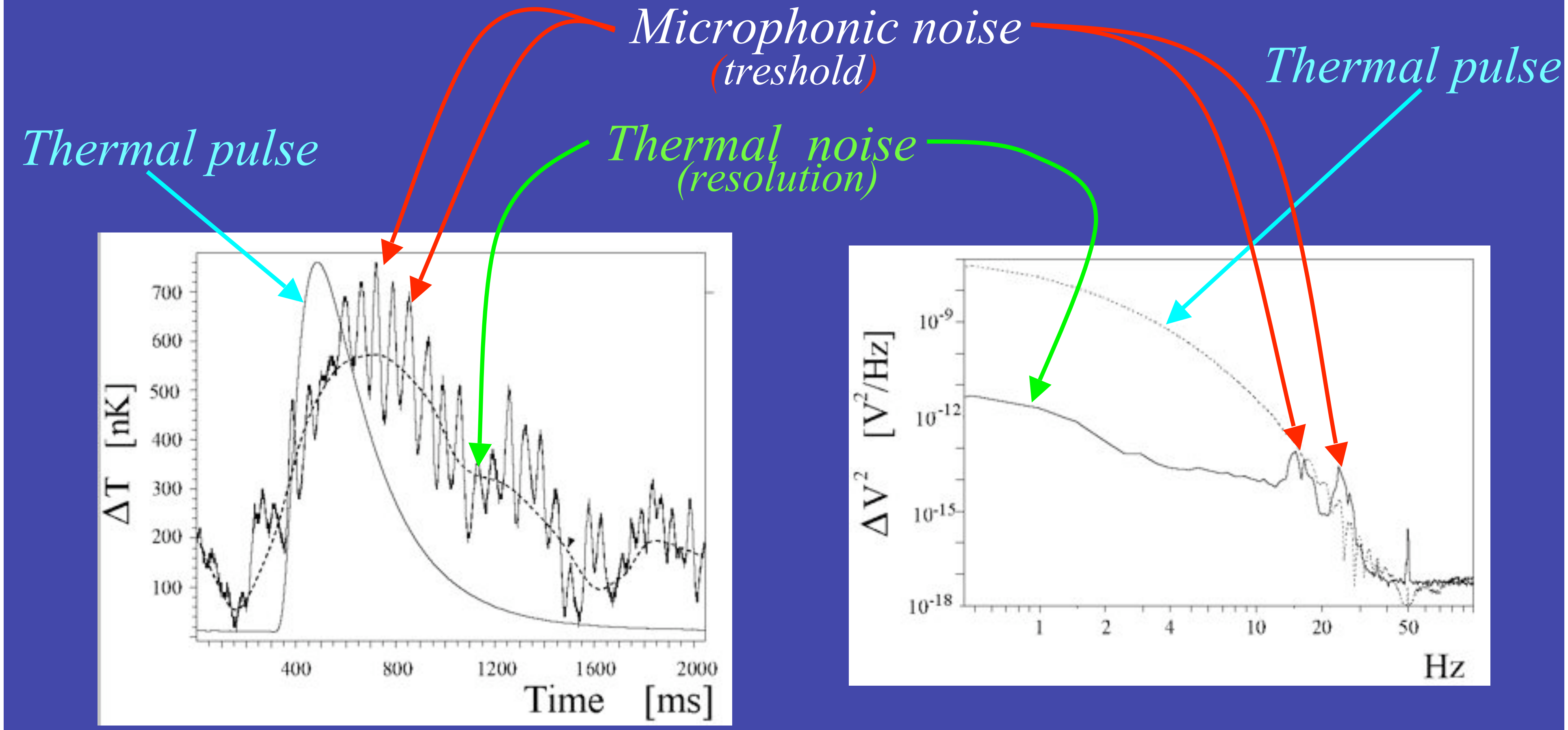
FWHM @2615= 30 keV

FWHM @~8MeV ~5 keV

FWHM @~8MeV ~ 90 keV

Thermal Detectors: Noise

Bolometers are extremely sensitive to vibrations



Microphonic noise
(treshold)

Thermal pulse

Thermal noise
(resolution)

Thermal pulse

A fundamental issue is to reduce vibrations (damping)

CUORICINO TO CUORE

CUORICINO proved the feasibility of a large bolometric array with the tower-like structure

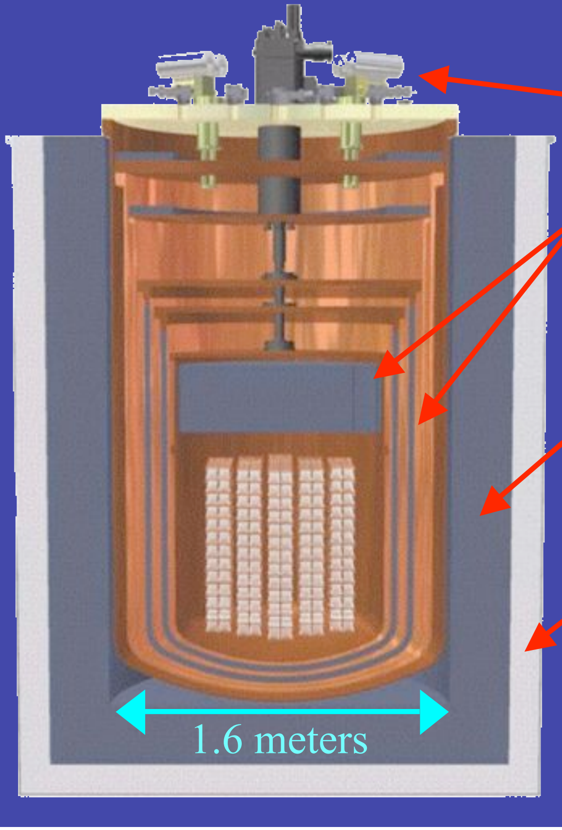
Detector performances are not affected by the increase in crystal size (from 340 g to 760 g)

Criogenic **U**nderground **O**bservatory(for) **R**are **E**vents

Array of 988 detect

19 towers - 13 modules/tower - 4

M = 0.75 to



Pulse Tubes

Internal lead shielding

External lead shielding

PET shielding