Experiments for double beta decay and dark matter

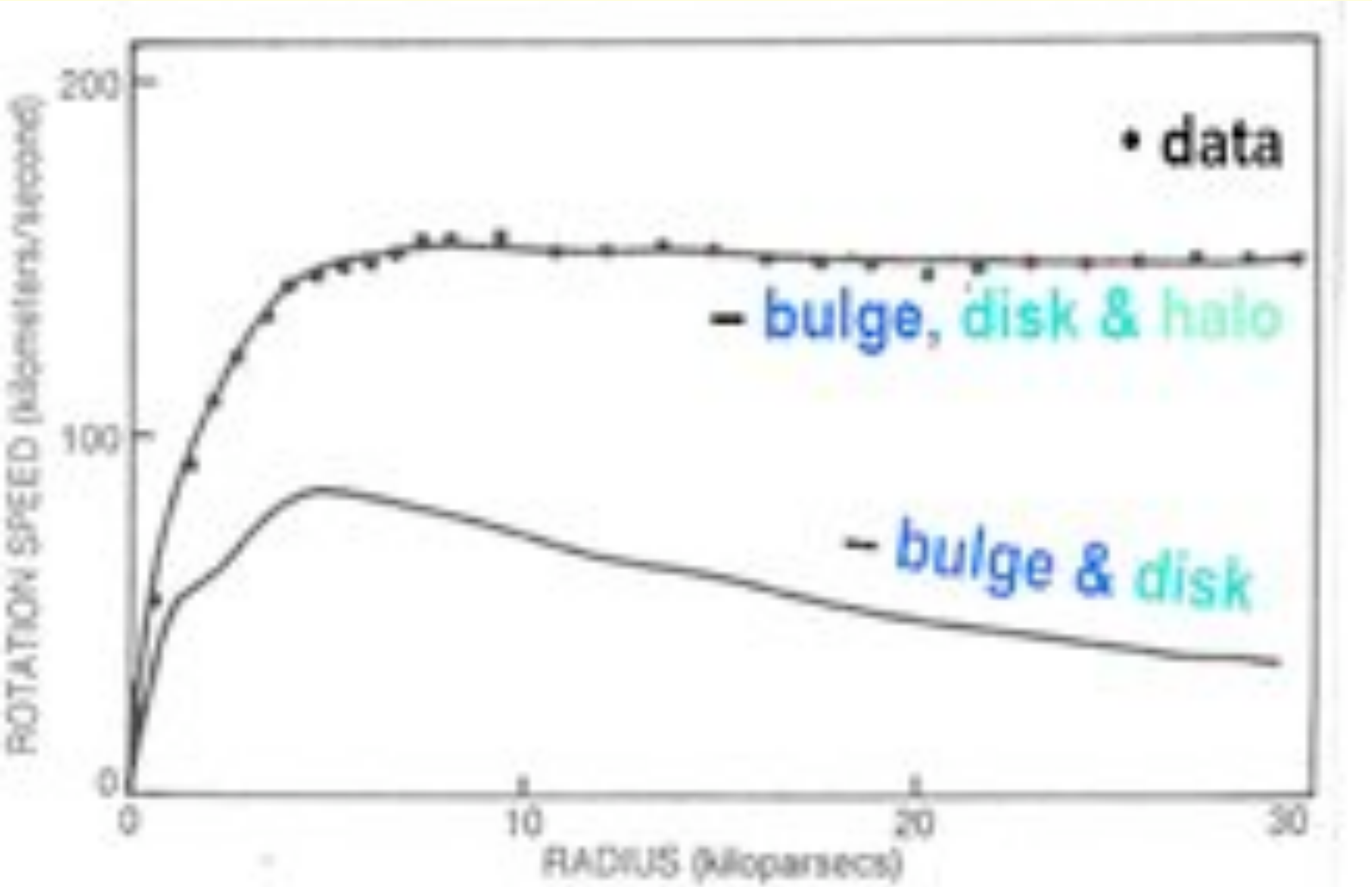
Ettore Fiorini, NDM2006, Paris September 4, 2006

Je ne loue ni blâme pas, je report seulement (Talleyrand)
I am not praising, nor blaming; I anly report

-Historically close connection both from the strictly scientific and technical point of view:

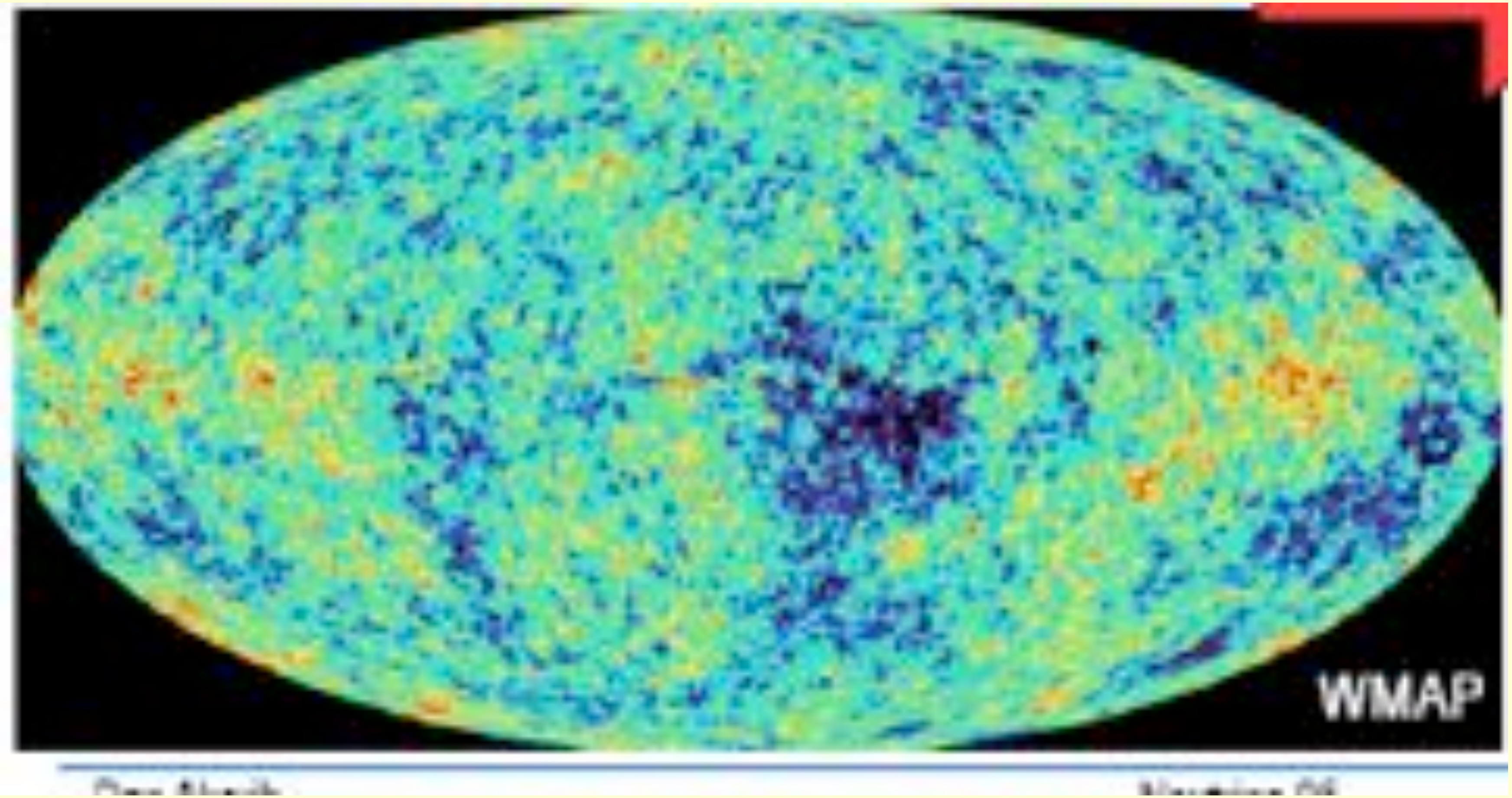
- Neutrinoless DBD => lepton number conservation => $\langle m_\nu \rangle$ and m_ν as possible component of DM
- Many experimental common problems (operation underground , reduction of the background , choice of detectors, hybrid techniques)
- Searches for WIMPs. started as a sub-product of DBD (Drukier, Avignone) Even now Synergy with $\beta\beta$ experiments

Evidence for DM in a spiral galaxy, superclusters etc



WMAP!

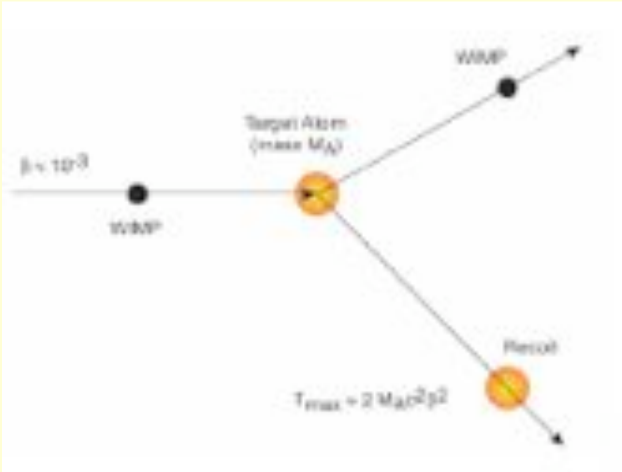
(now three years of measurements)

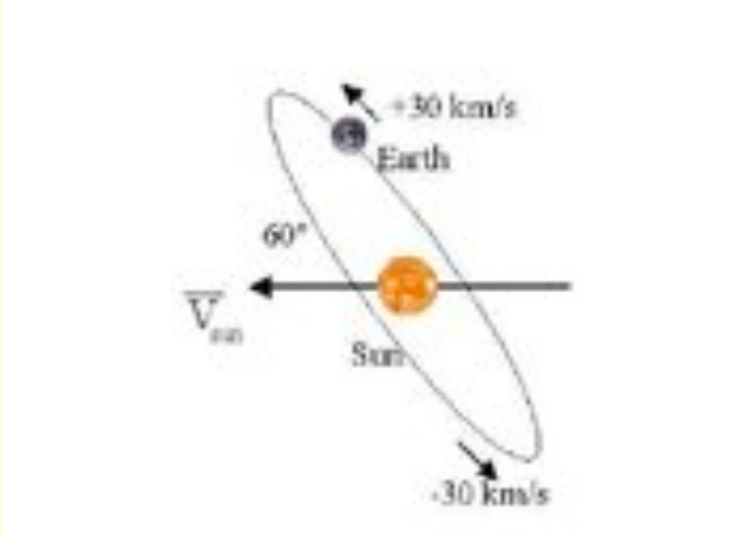


Description	Symbol	Value
Total Density	Ω_{tot}	$1.02 \pm .02$
Dark energy Density	Ω_{Λ}	$.73 \pm .04$
Baryon Density	$\Omega_{bar}h^2$	$.0224 \pm .0009$
Baryon Density	Ω_{bar}	$.044 \pm .004$
Baryon Density (cm^{-3})	N_{bar}	$(2.5 \pm .1) \times 10^{-7}$
Matter Density	$\Omega_m h^2$	$.135^{+..008}_{-.009}$
Baryon Density	Ω_m	$.27 \pm .04$
Light Neutrino Density	$\Omega_{\nu}h^2$	$< .0076 \Rightarrow \Sigma m_{\nu} < .7$ eV
CMB Temperature (K)	T_{CMB}	$2.725 \pm .002$
CMB Photon Density	N_{γ}	$410.4 \pm .9$
Baryon to Photon Ratio	η	$(6.1^{+.3}_{-.2}) \times 10^{-10}$
Hubble Constant	h	$.71^{+.04}_{-.03}$
Age of the Universe (Gy)	T_0	$13.7 \pm .2.04$
Age at Decoupling (ky)	T_{dec}	$378^{+9}_{-7}) \times 10^{-10}$

How to search for WIMPS

By rude force (reduction of the background in the energy region expected for recoils induced by WIMPs



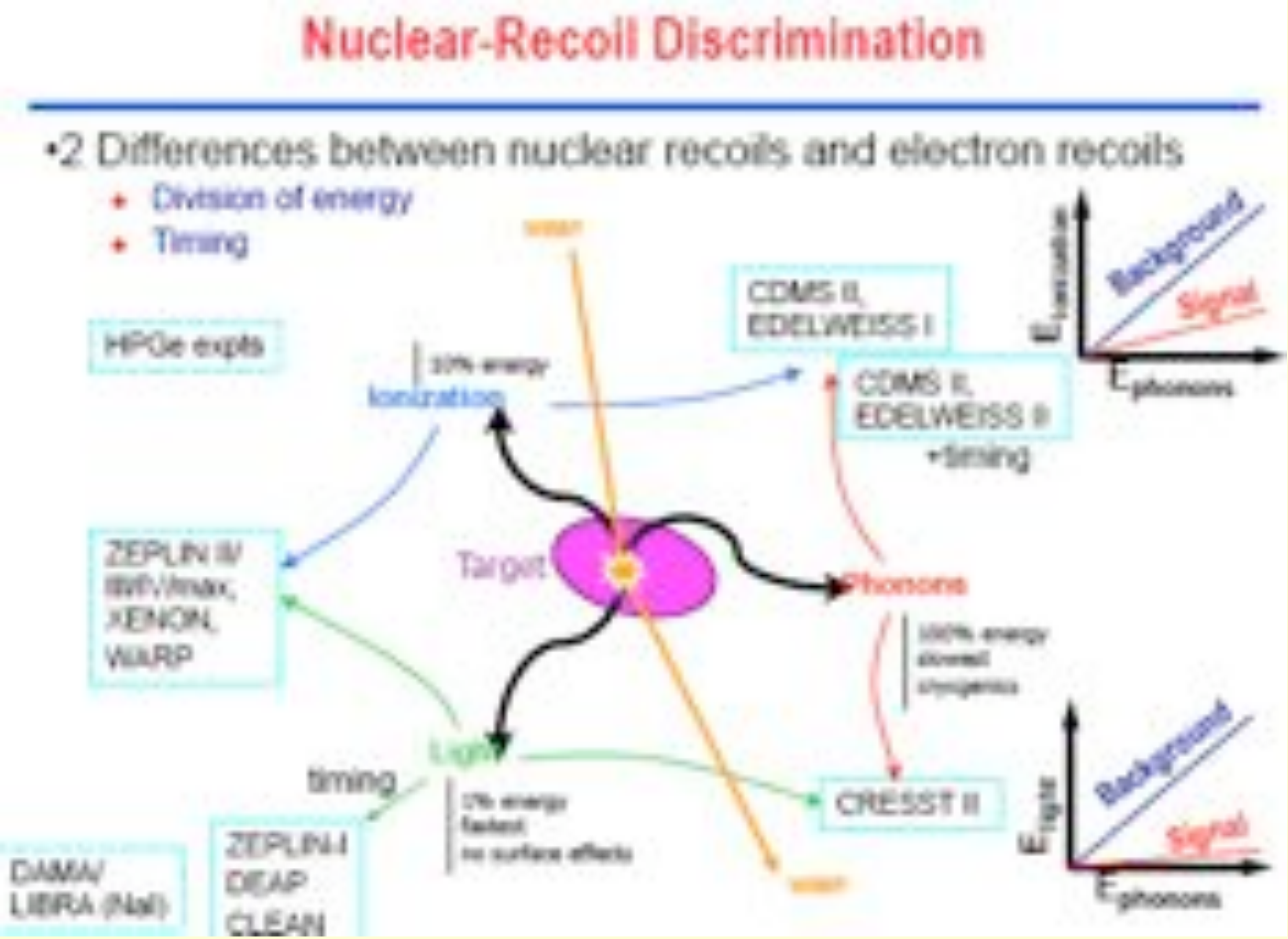


- **Seasonal modulation** due to the orbital motion of our observatory with respect to the Sun
- **Directionality**
- **Pulse shape** and time discrimination
- **Position** reconstruction
- Hybrid techniques (heat+ light or ionization)
- Double phase liquid detectors - “Bubble chambers” etc.

Events/kg/d for spin independent interaction with
m_{WIMP} = 100GeV and $\sigma = 4.0 \times 10^{-43}$ cm^2
(~10^7 ev/kg/d in an unshielded detector)

Threshold (keV)	Xe	Ge	Ar
no	.3	.05	.006
10	.03	.02	.004
20	.008	,008	.003
30	.0025	.004	.002
40	.0015	.0035	.0015
50	.0006	.0025	.001
60	.00015	.0015	.0008
70	.00006	.0008	.0006

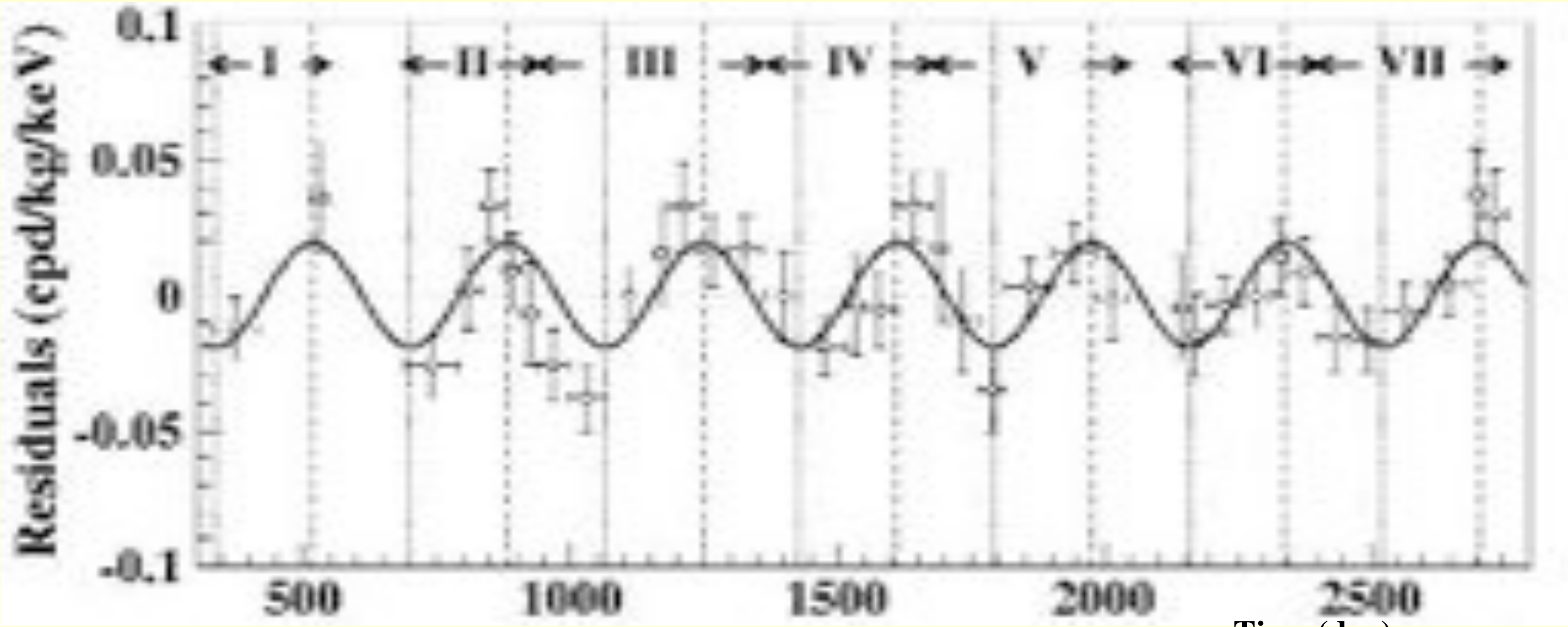
-More techniques for DM than for searches on DBD. Some adopted for both searches and more should be



From Akerib – Neutrino2006

DAMA results

107731 kg d a **6.3 σ** effect



Time (day)

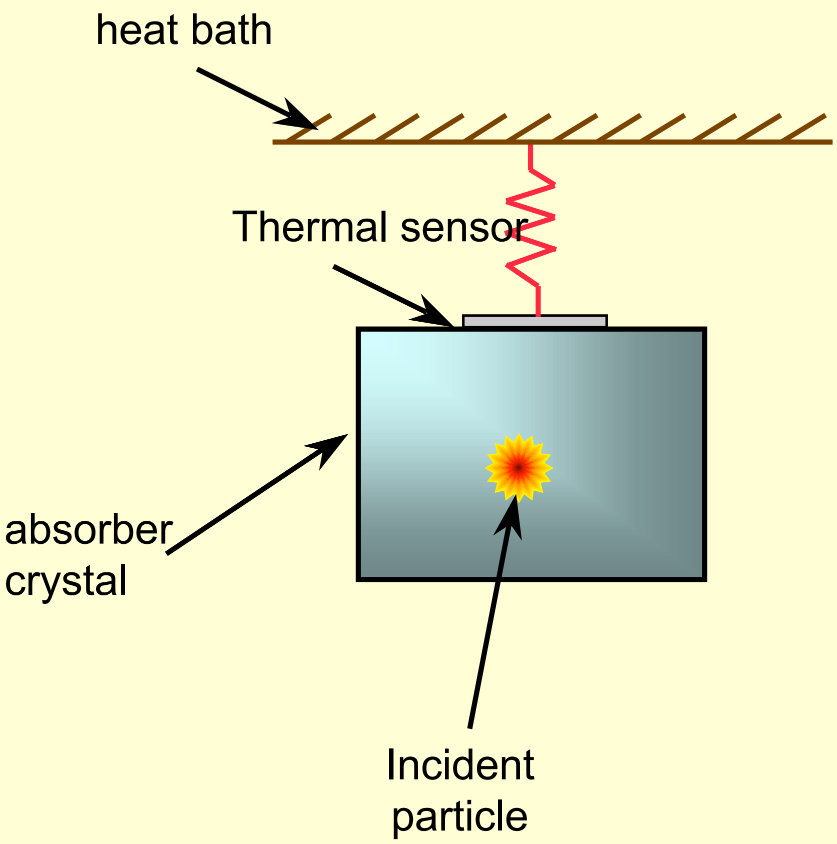
At present no running “conventional” experiment with similar mass, threshold and background , but many being planned including massive β β experiments.

New => Korea Invisible Mass Search with CsI in the place of NaI

Thermal Detectors

$$\Delta T = \frac{Q}{C_V}$$

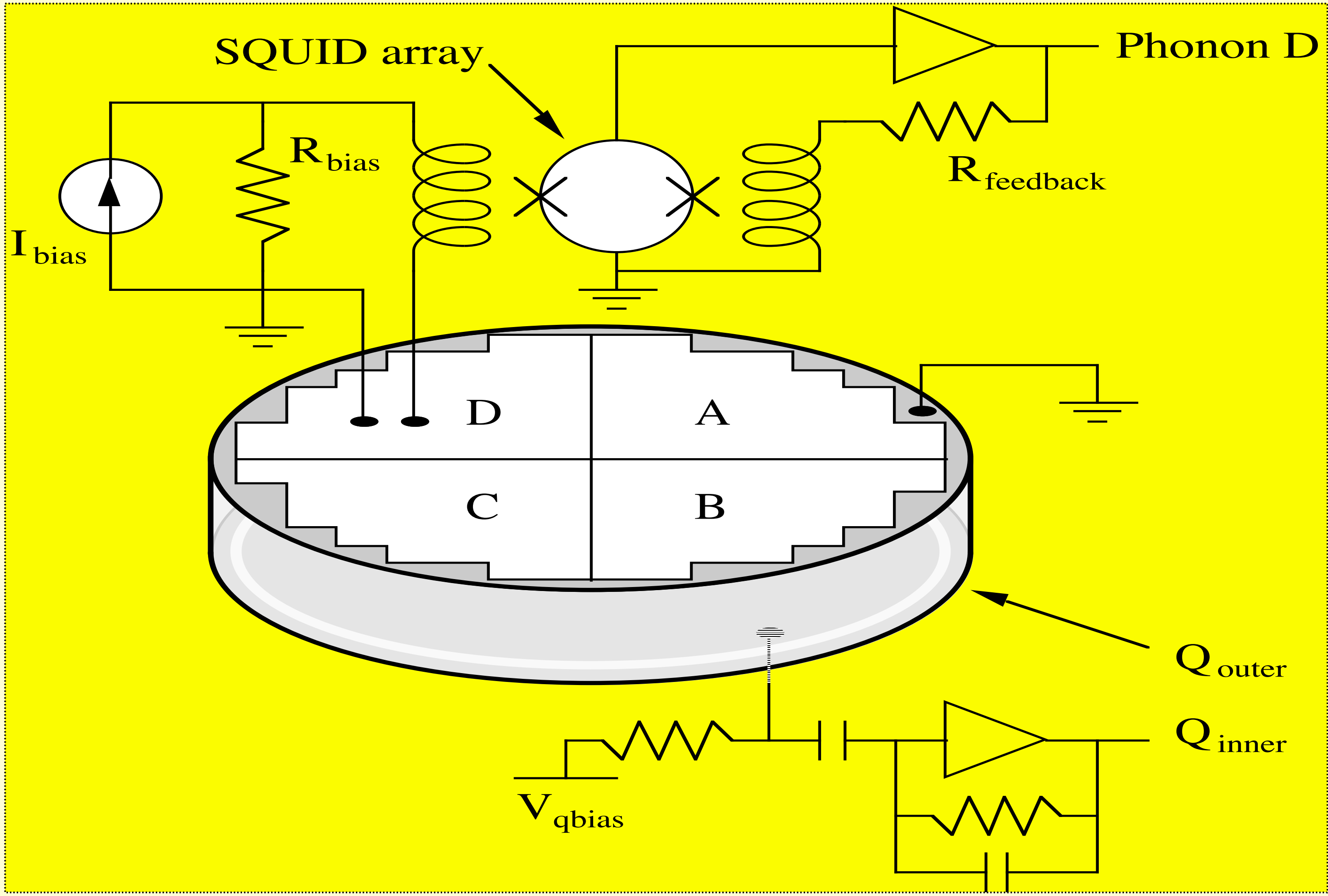
$$C_V = 1944 \frac{V}{V_m} \left(\frac{T}{\Theta}\right)^3 \text{ J/K}$$

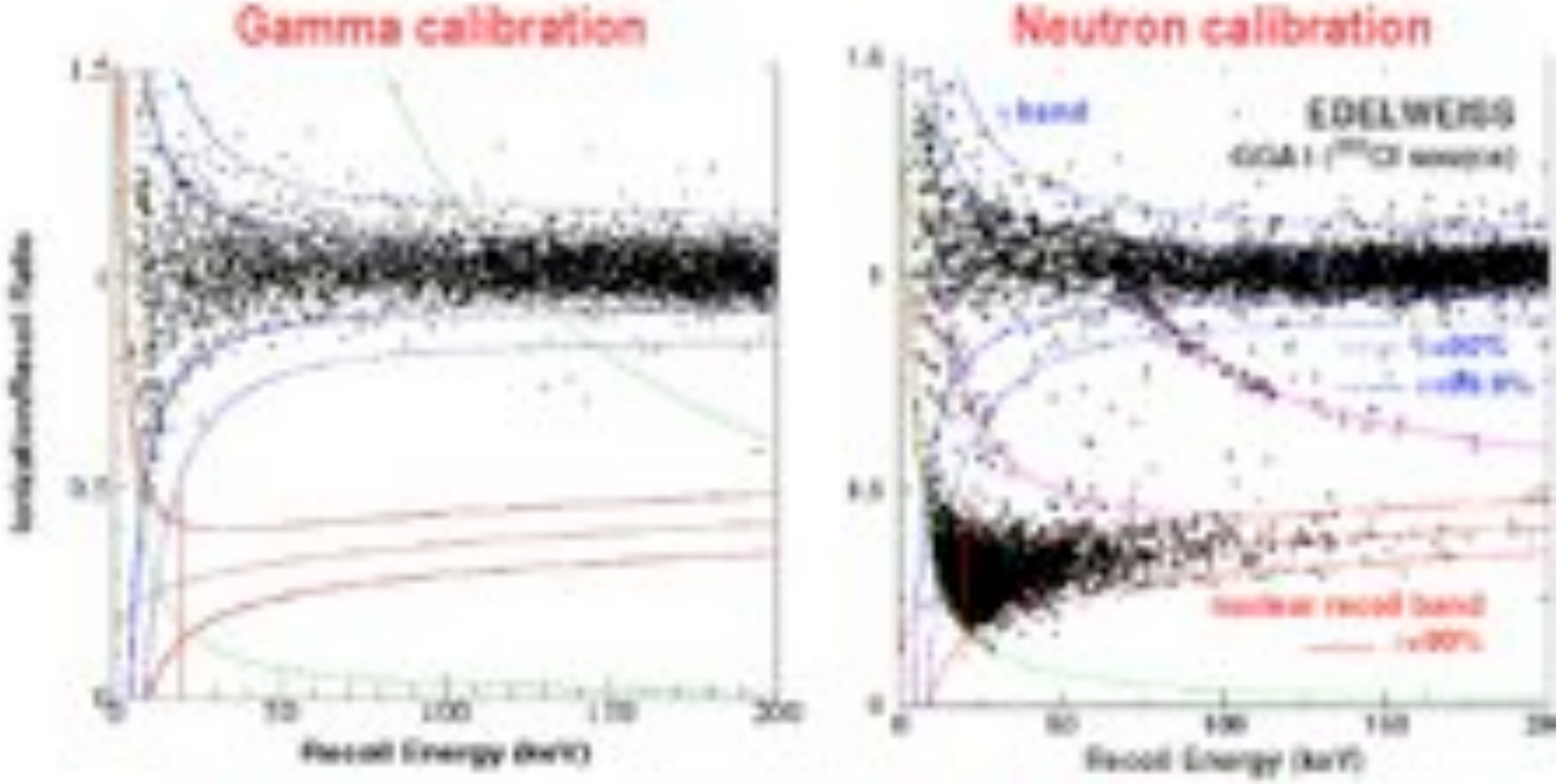


Excellent resolution <1 eV ~ 3 eV @ 6 keV
~ 10 eV $\sim$keV @ 2 MeV

Hybrid techniques

Heat + ionization or heat + scintillation

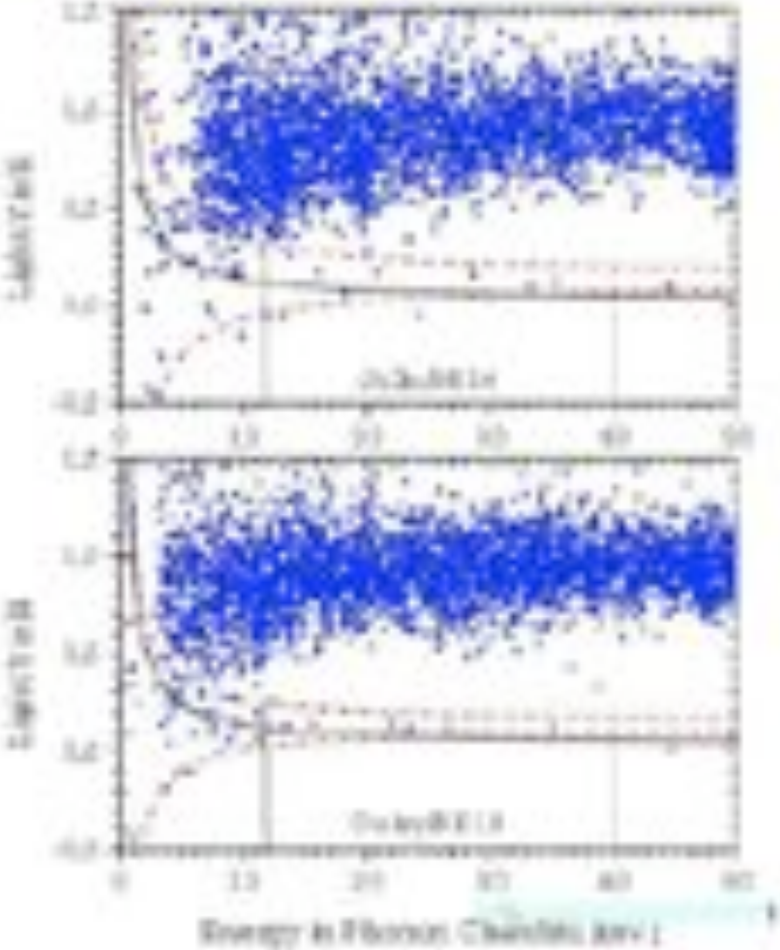




Nuclear recoil discrimination down to 20 keV threshold

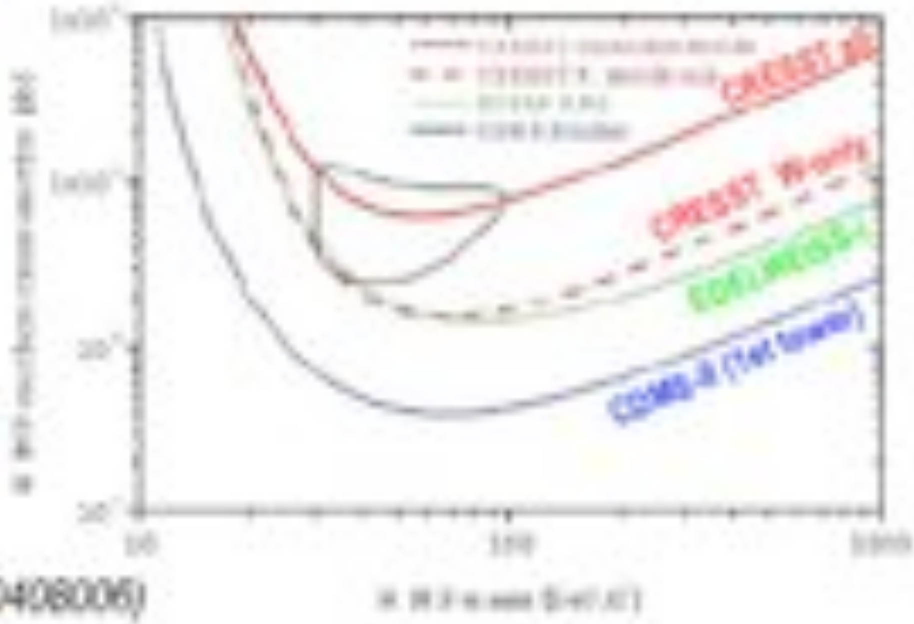
γ-ray rejection > 99.99 %

CRESST II: Phonons and Scintillation

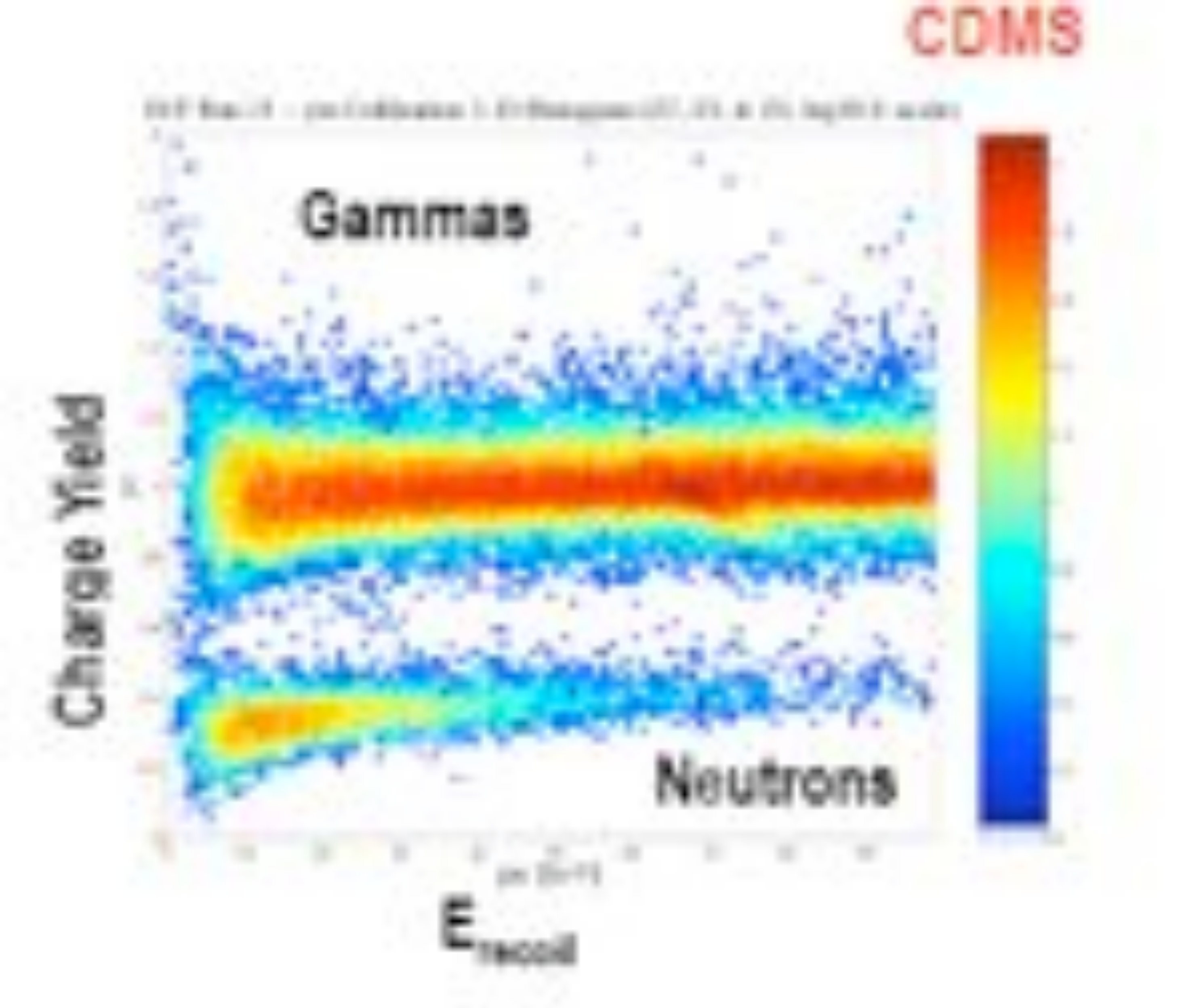


Results from 20.5 kg-d exposure of two 300-g $CaWO_4$ prototypes

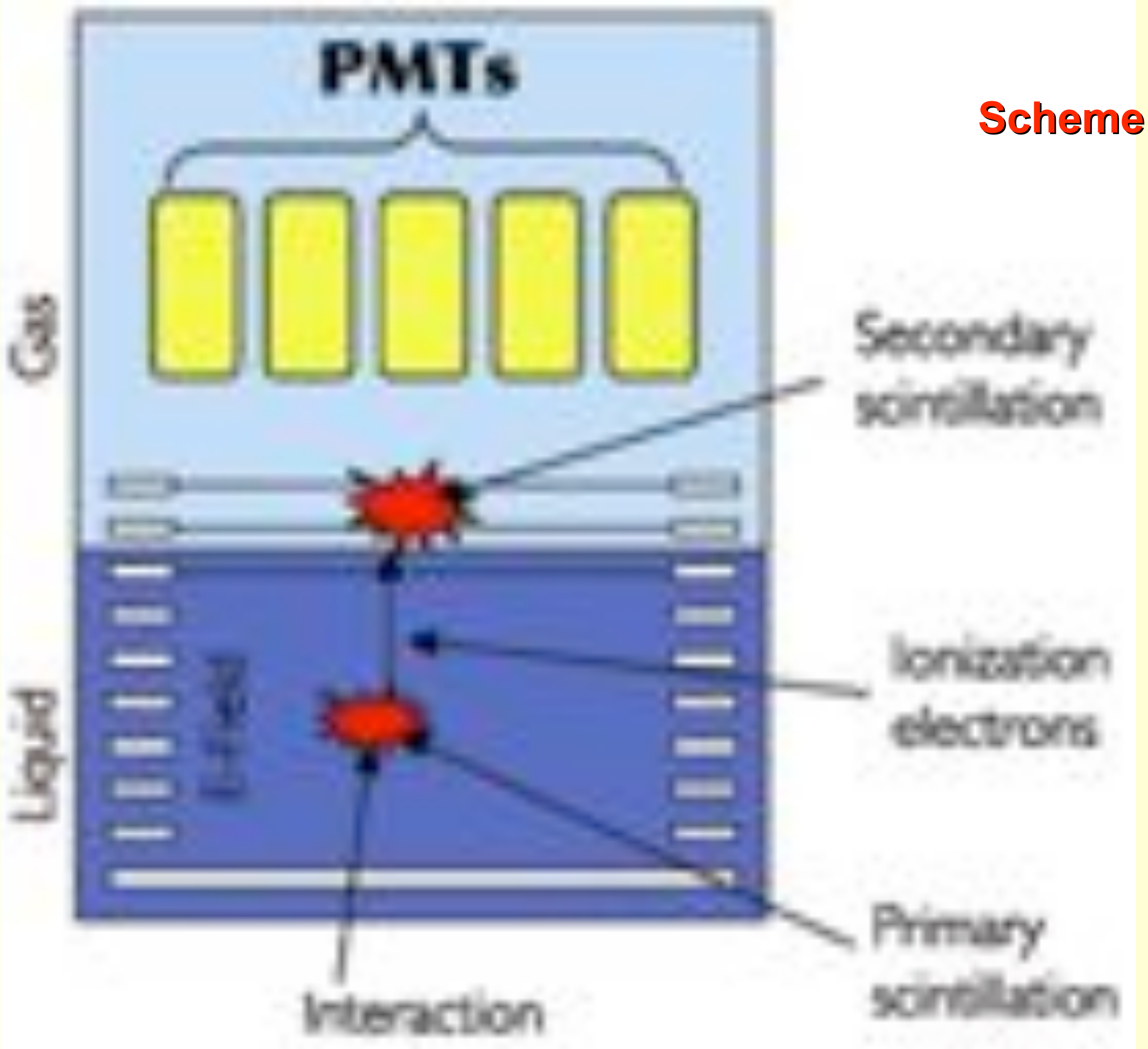
- No neutron shielding
- Observe low-yield events consistent with neutron rates and oxygen cross section & light yield
- Claim no tungsten recoils in light yield region below oxygen yield (not distinct from noise)



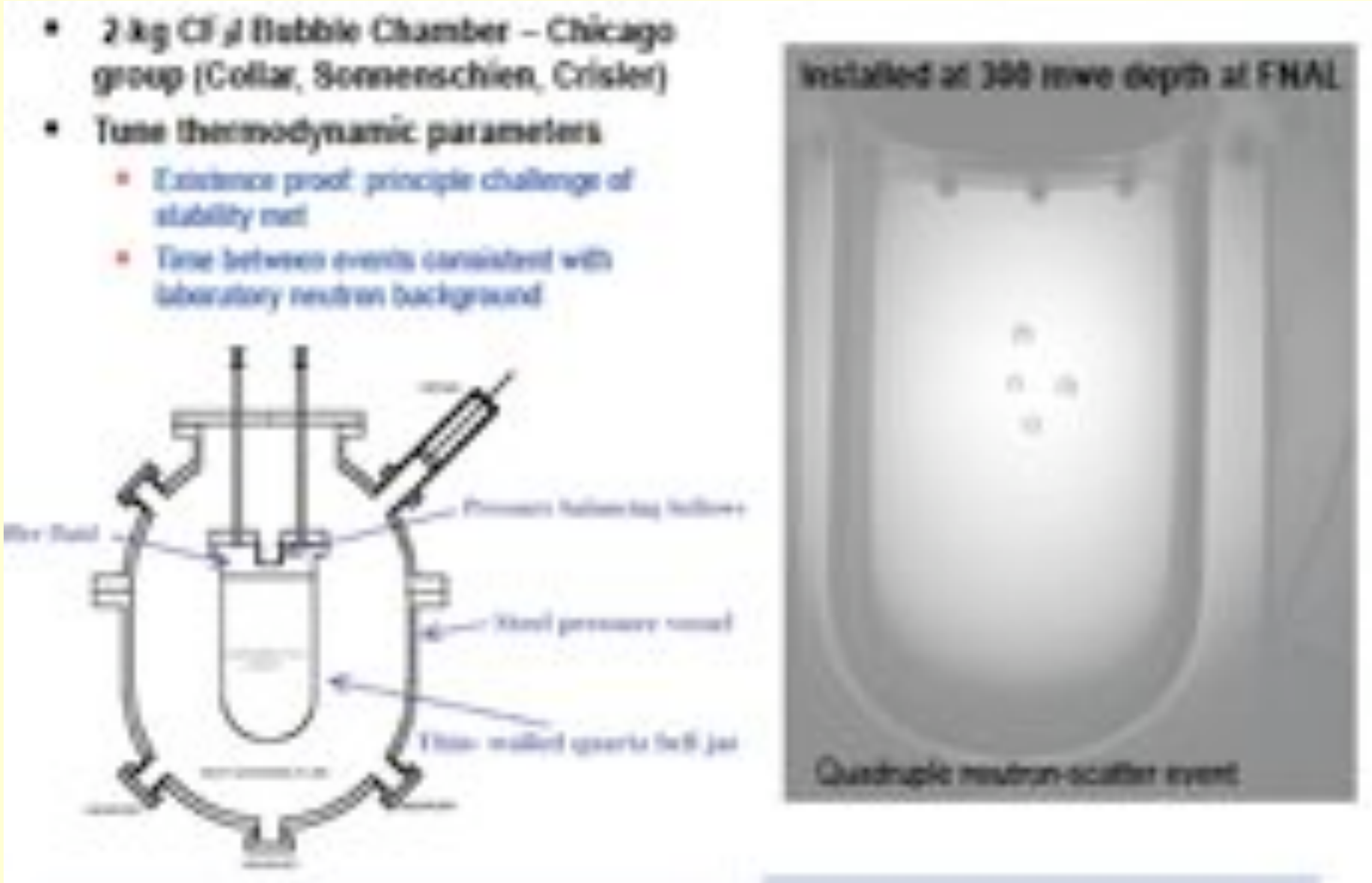
Astropart. Phys. **23**, 325-339, 2005 (astro-ph/0408006)


CDMS
Gammas
Neutrons
Charge Yield
E_recoil

Scheme of WARP



The “bubble chamber”



Future experiments for direct detection of WIMPS

Experiment	Target	Technique	Note
SuperCDMS	Ge,Si	cryogenic	Pulse shape inform.=>localization
Eureka	Ge,$CaWO_4$	cryogenic	Improved suppr.of low β backgr
Zeplin	Xe	two phase	Scintillation + ionization
Xenon	Xe	two phase	Scintillation + ionization
Warp	Ar	two phase	Scintillation + ionization
Xmass	Xe	1/2 phase	Also for ββ decay
Deap	Ar	one phase	Cryogenic scintillator
Clean	Ar,Ne	one phase	Cryogenic scintillator
Drift	CS_2	TPC	Directiona
Sign	Ne	S and I	Scintillation and ionisation in gas
COUPP	CF_3 I	Bubble Chamber	Insensitive to minimum ionizing particles

Spin independent

DAMA

IGEX

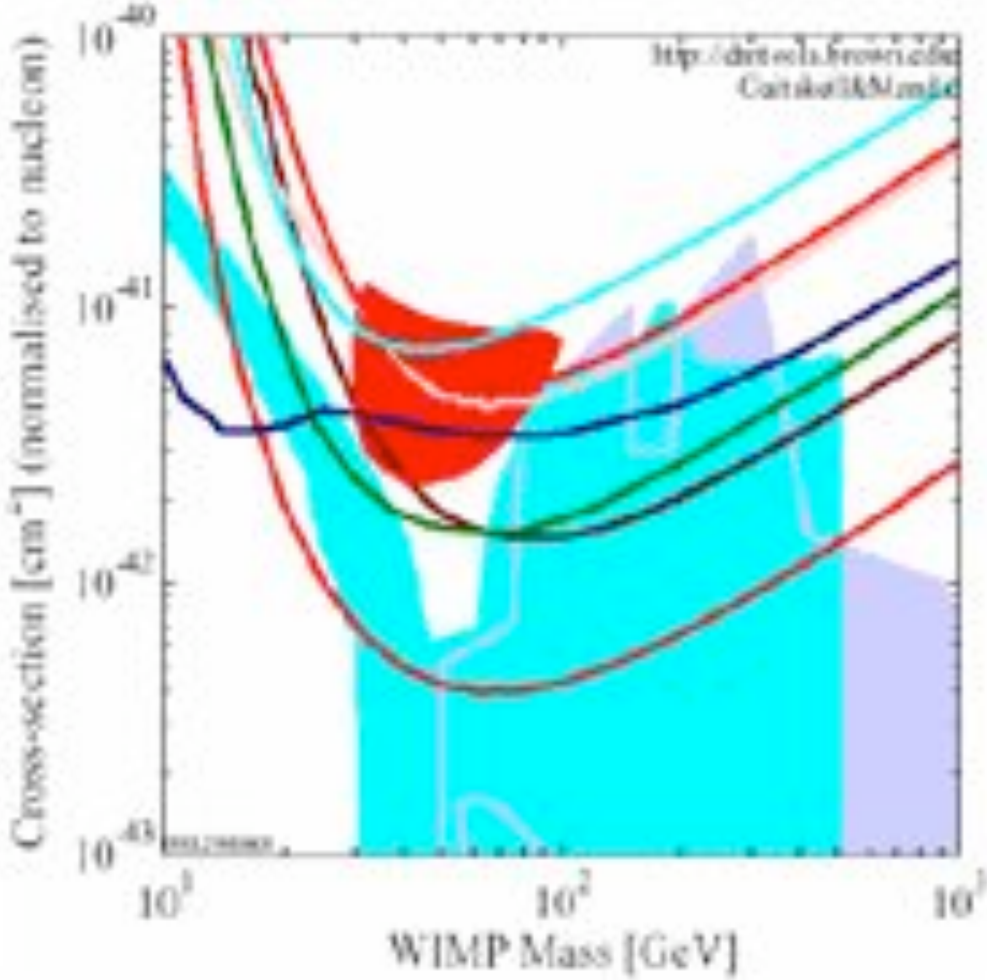
CRESST II

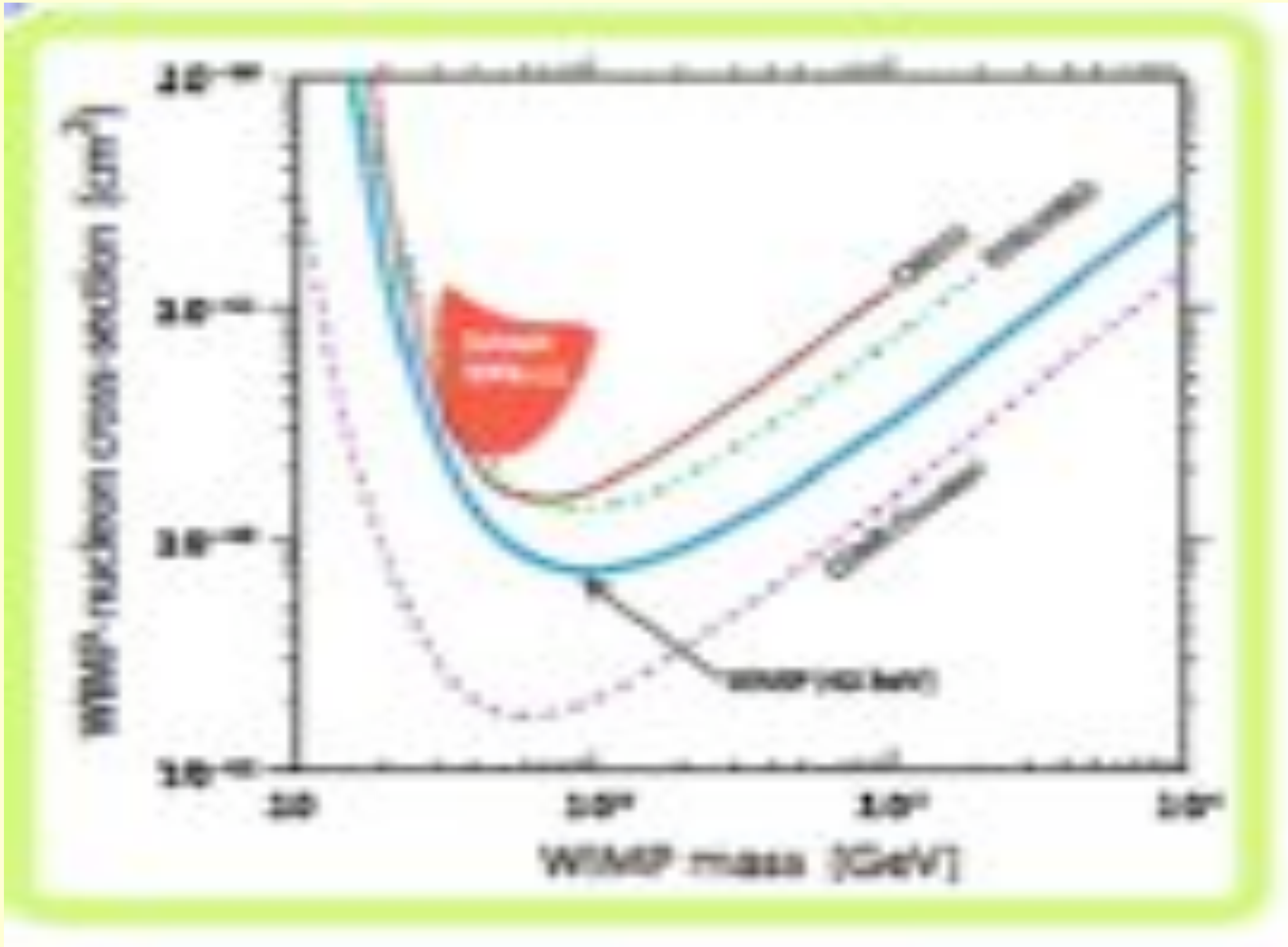
CDMS I

EDELWEISS

ZEPLIN I

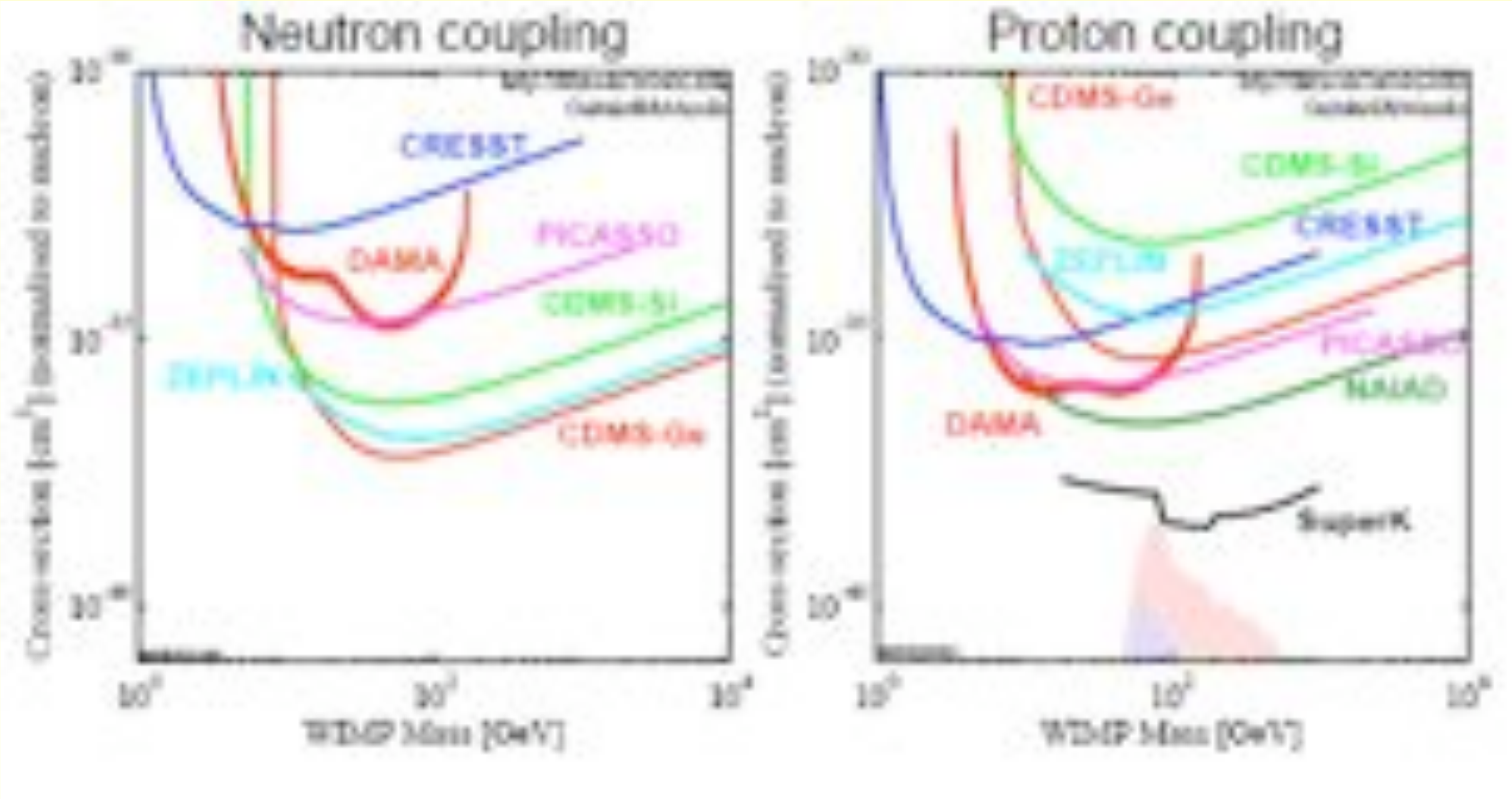
CDMS II





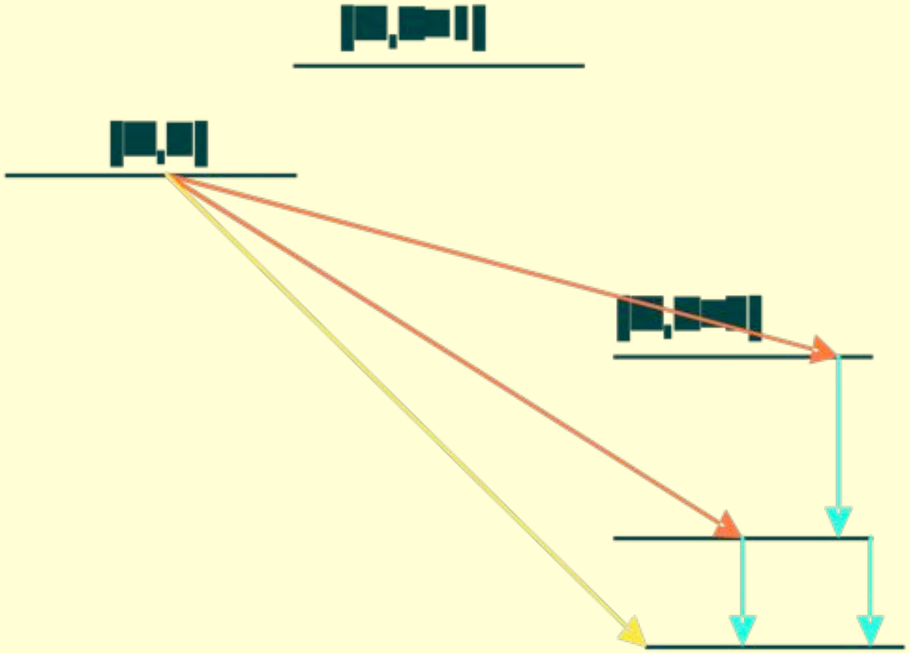
Many attempts (not only by DAMA) to reconcile DAMA with exclusion plots => **annual modulation of spin dependent interaction on Na, anisotropic galactic halos, steams of WIMPS etc.,, many uncertain astrophysical and nuclear parameters**

Spin dependent



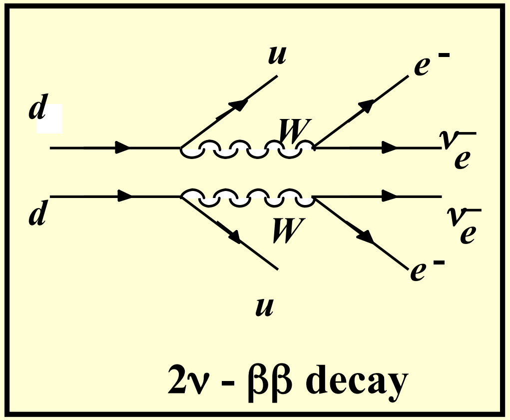
DOUBLE BETA DECAY

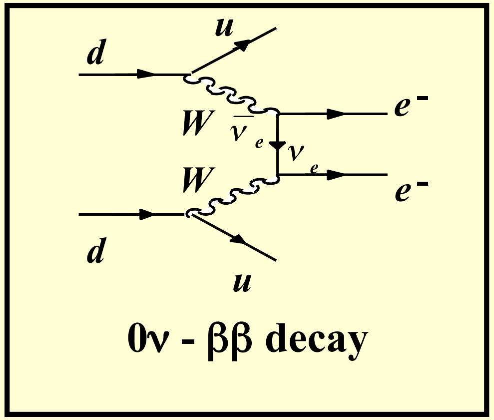
1. $(A,Z) \Rightarrow (A,Z+2) + 2\,e^- + 2\,\bar{\nu}_e$
2. **$(A,Z) \Rightarrow (A,Z+2) + 2\,e^- + \chi$ $(\ldots 2,3\,\chi)$**
3. **$(A,Z) \Rightarrow (A,Z+2) + 2\,e^-$**

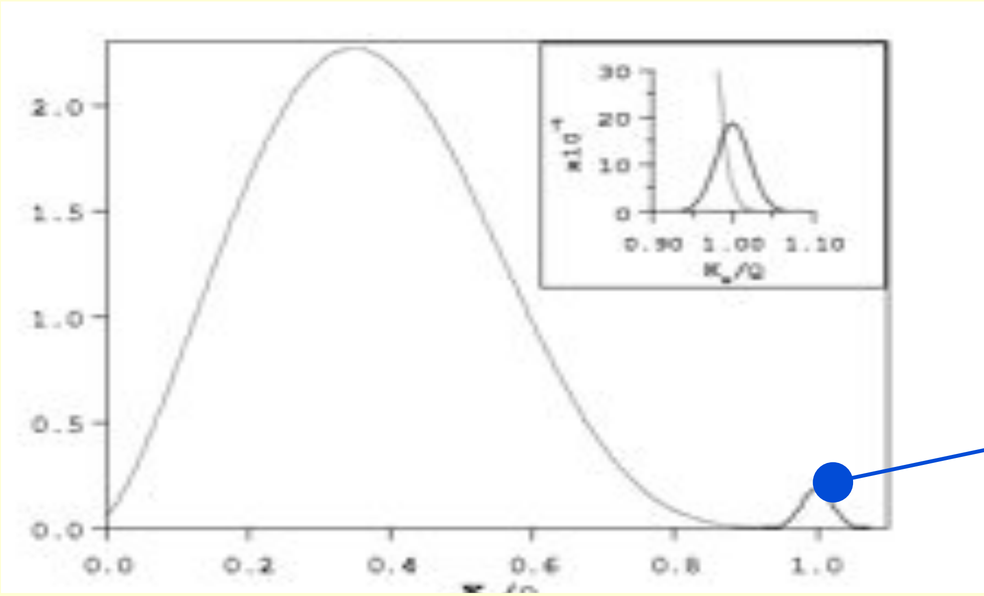


Oscillations have been found in solar, atmospheric and reactor neutrino experiments,but only only indicate that $\Delta m_\nu^{\,2} \neq 0$

to determine $< m_\nu >$ => neutrinoless double beta decay







Neutrinoless ββ decay

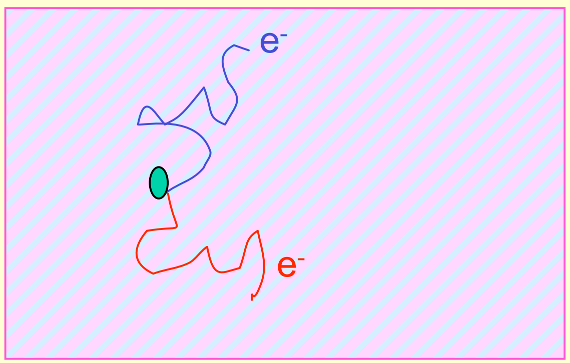
Two neutrino ββ decay has been detected in ten nuclei also into exited states rate of DDB-0ν — Phase space — Nuclear matrix elements — EffectiveMajorana neutrino mass

$$1/\tau = G(Q,Z)\,|M_{nucl}|^2 \langle m_\nu \rangle^2$$

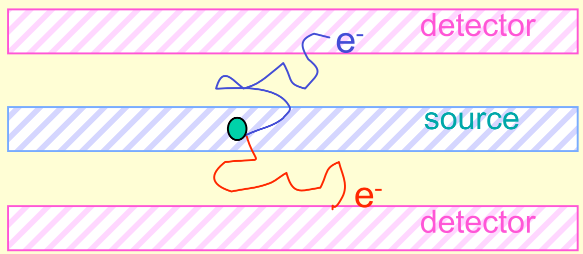
Need to search for neutrinoless DBD in **various nuclei**

A pick could be due to some unforeseen background peak

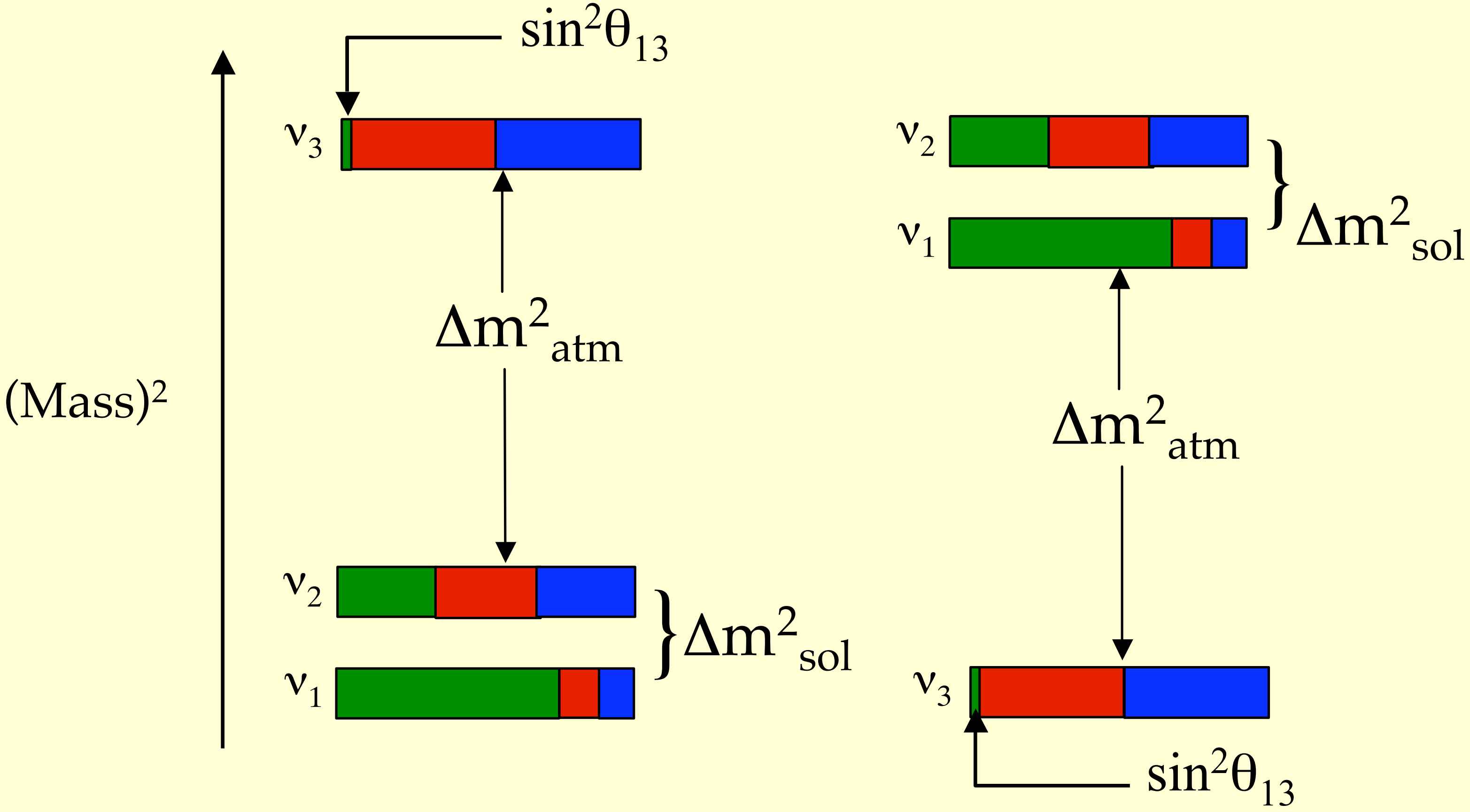
Source = detector (calorimetric)



Source ≠ detector

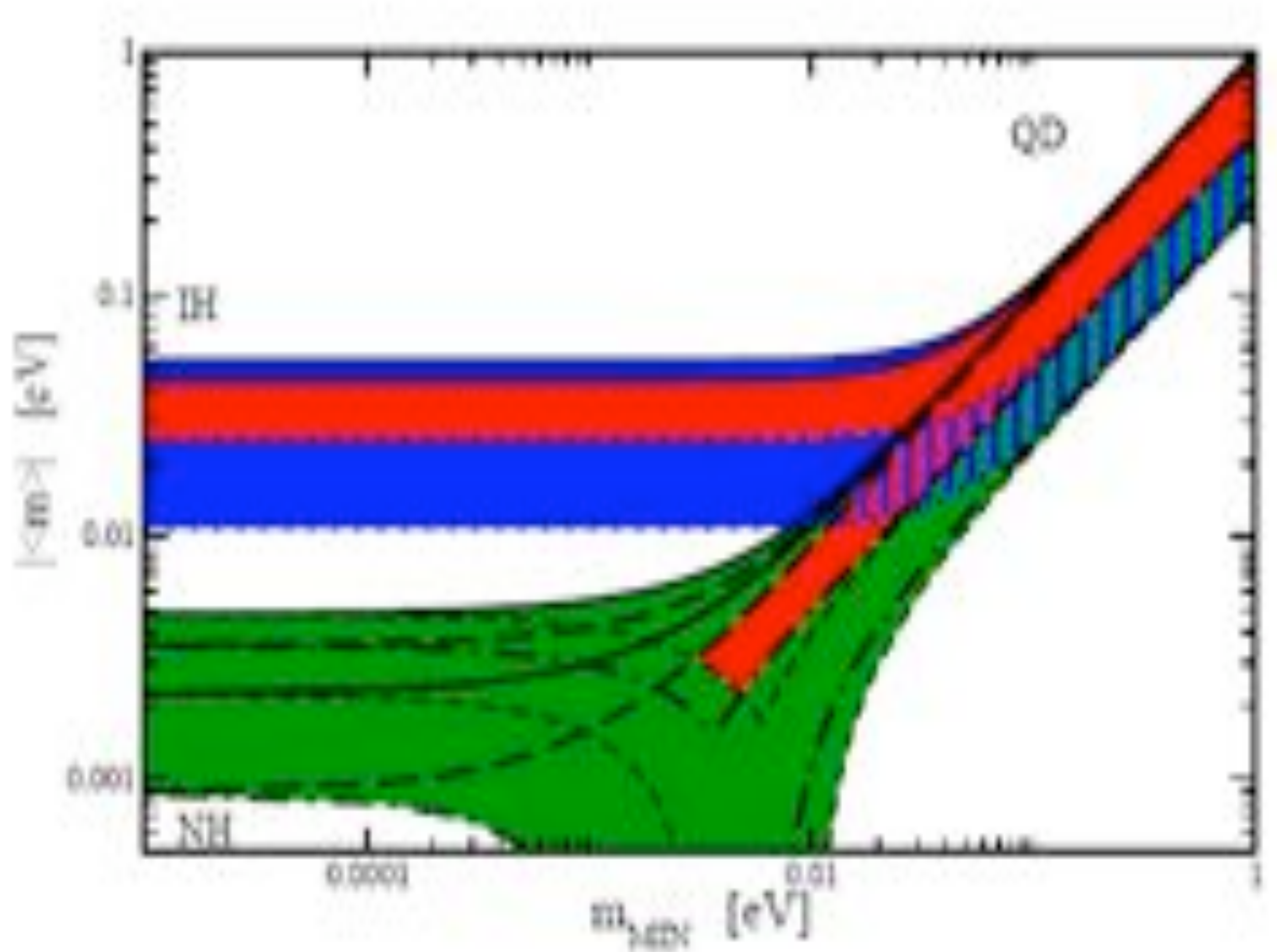


Normal　　　　Inverse



$m_{low} \approx$ Quasi-degenerate: $m_{low}^2 \gg \Delta m^2_{atm} \gg \Delta m^2_{sol}$

Recent calculation by S. Pascoli and S.T. Petkov



Present experimental situation

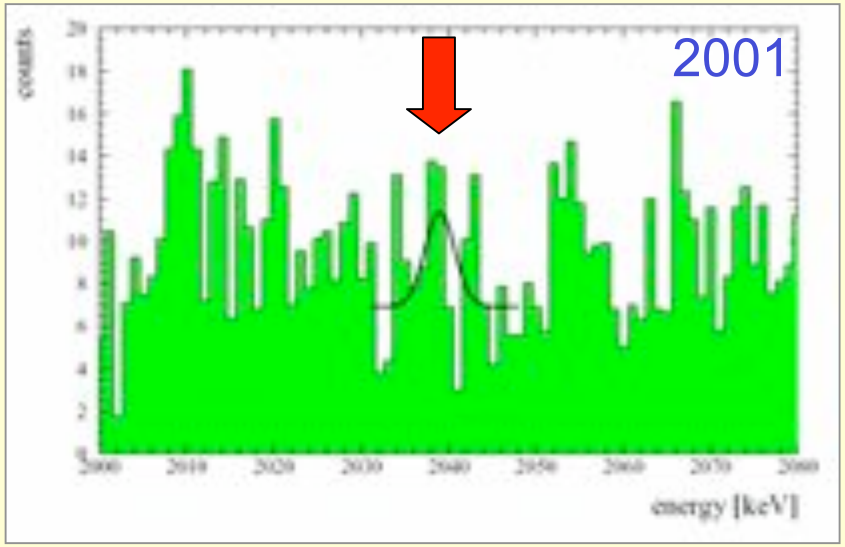
Nucleus	Experiment	%	$Q_{\beta\beta}$	Enr	Technique	$T_{0\nu}$ (y)	$<m_\nu)$
^{48}Ca	Elegant IV	0.19	4271		scintillator	$>1.4x10^{22}$	7-45
^{76}Ge	Heidelberg-Moscow	7.8	2039	87	ionization	$>1.9x10^{25}$	.12 - 1
^{76}Ge	IGEX	7.8	2039	87	Ionization	$>1.6x10^{25}$	.14 – 1.2
^{76}Ge	Klapdor et al	7.8	2039	87	ionization	$1.2x10^{25}$	.44
^{82}Se	NEMO 3	9.2	2995	97	tracking	$>1.x10^{23}$	1.8-4.9
^{100}Mo	NEMO 3	9.6	3034	95-99	tracking	$>4.6x10^{23}$	.7-2.8
^{116}Cd	Solotvina	7.5	3034	83	scintillator	$>1.7x10^{23}$	1.7 - ?
^{128}Te	Bernatovitz	34	2529		geochem	$>7.7 \times 10^{24}$	.1-4
^{130}Te	Cuoricino	33.8	2529		bolometric	$>2.4x10^{24}$	.2-1.
^{136}Xe	DAMA	8.9	2476	69	scintillator	$>1.2x10^{24}$	1.1 -2.9
^{150}Nd	Irvine	5.6	3367	91	tracking	$>1.2x10^{21}$	3 - ?

HM collaboration subset (KDHK): claim of evidence of 0ν-DBD

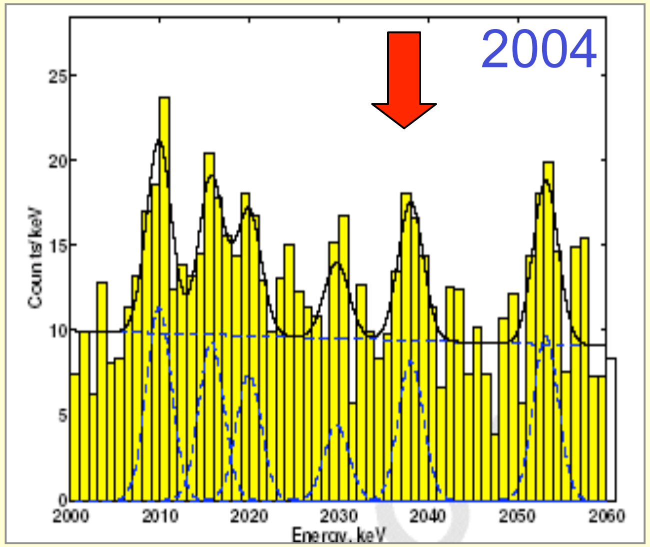
In December 2001, 4 authors (**KDHK**) of the HM collaboration announce the **discovery of neutrinoless DBD**

$\tau_{1/2}^{0\nu}$ (y) = (0.8 – 18.3) × 10^{25} y (1 × 10^{25} y b.v.)

$\langle M_{\beta\beta} \rangle$ = 0.05 - 0.84 eV (95% c.l.)



54.98 kg•y   2.2 σ

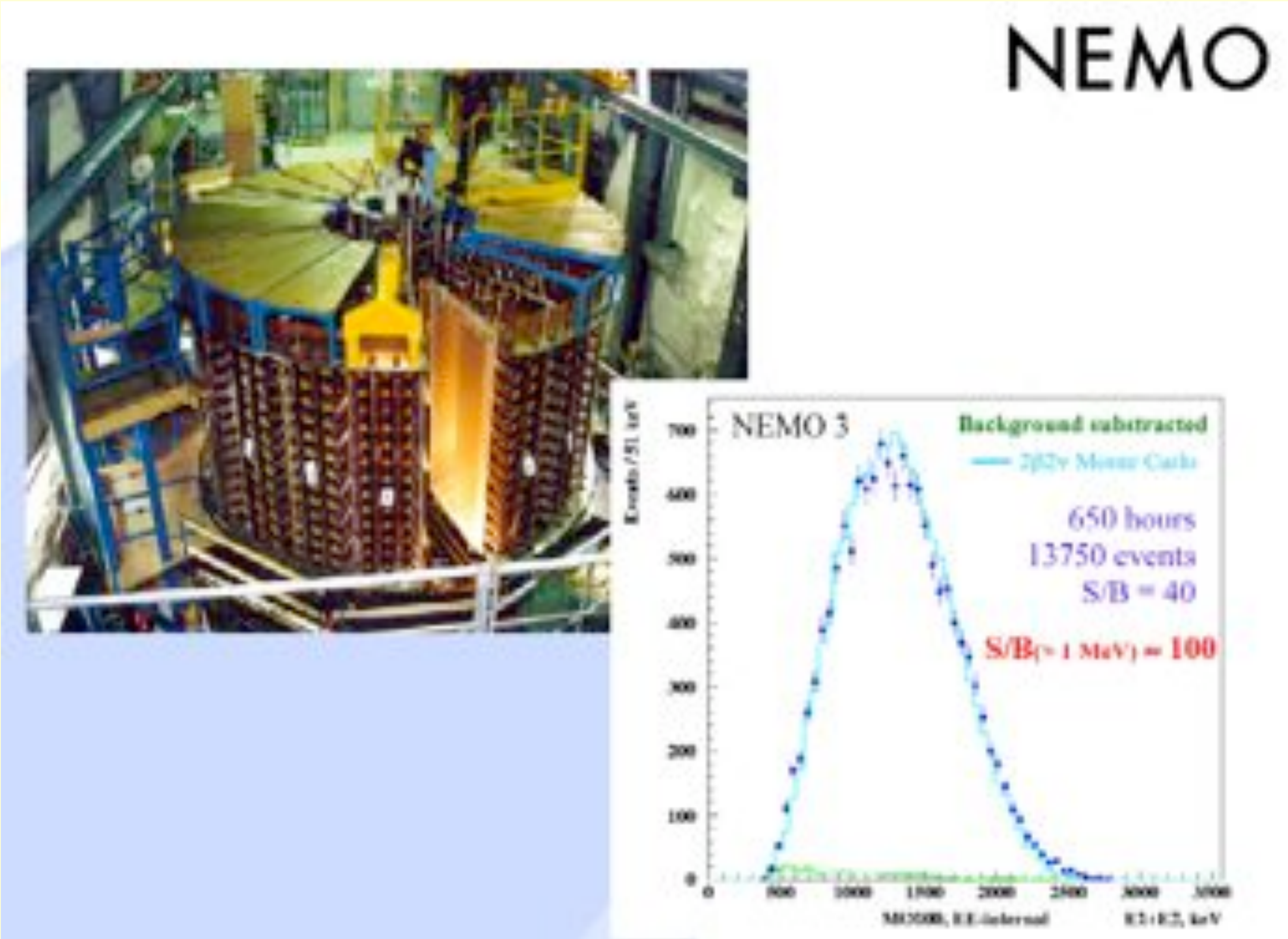


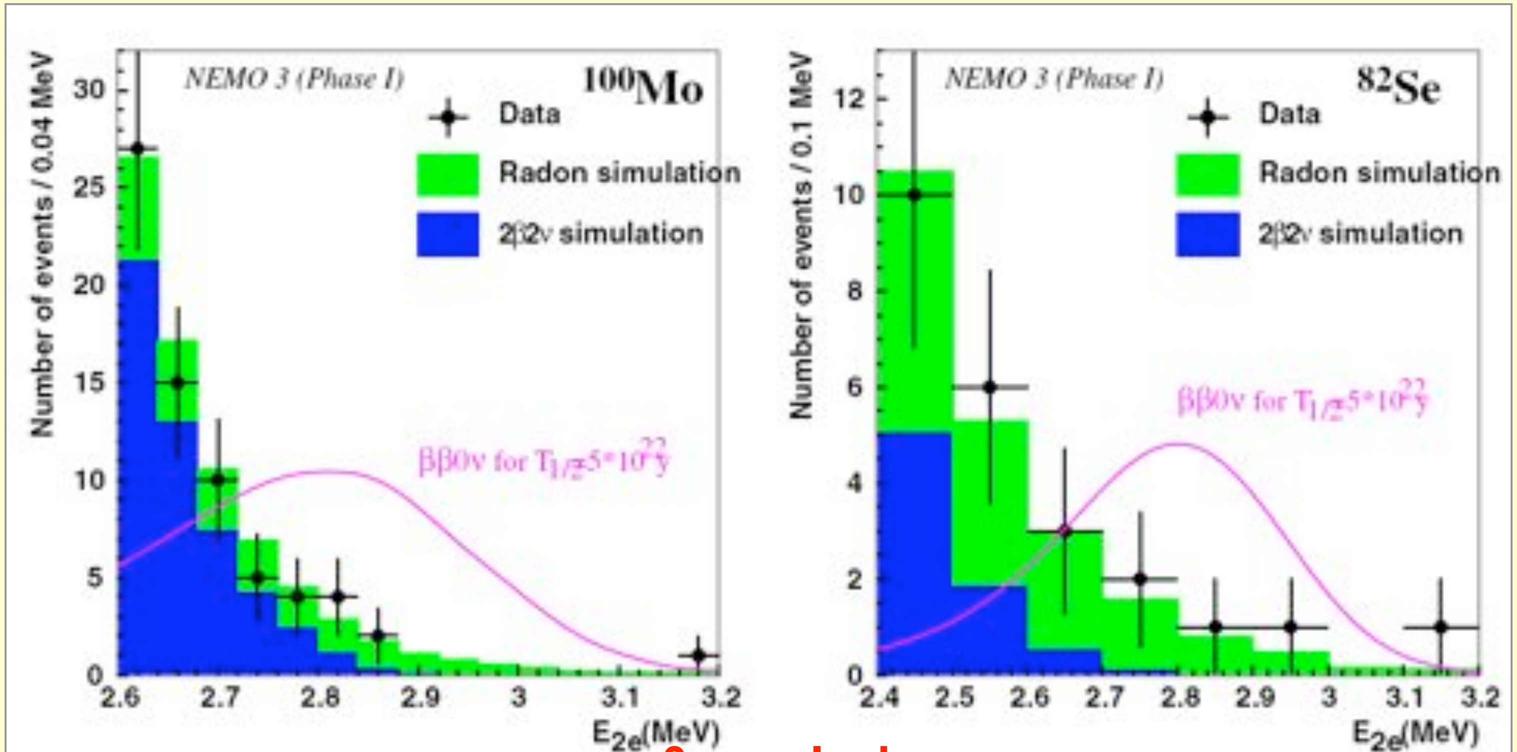
71.7 kg•y   4 σ

skepticism in DBD community in 2001

better results in 2004

Two new experiments NEMO III e CUORICINO

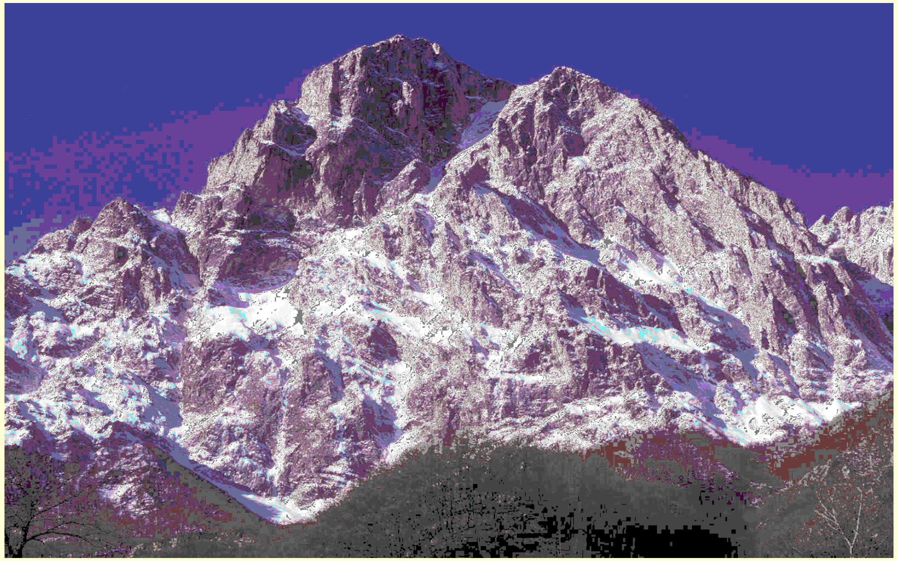




0ν analysis

^{100}Mo $\Rightarrow \tau_{1/2}^{0\nu}$ (y) $> 4.6 \times 10^{23}$ $\langle M_{\beta\beta} \rangle < 0.7 - 2.8$ eV (90% c.l.)

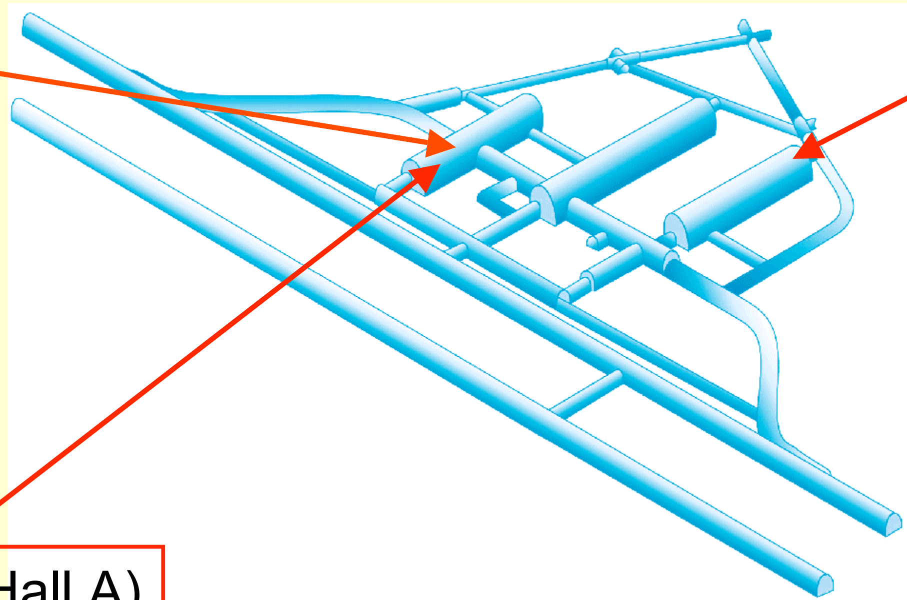
^{82}Se $\Rightarrow \tau_{1/2}^{0\nu}$ (y) $> 1.0 \times 10^{23}$ $\langle M_{\beta\beta} \rangle < 1.7 - 4.9$ eV (90% c.l.)



Searches with thermal detectors

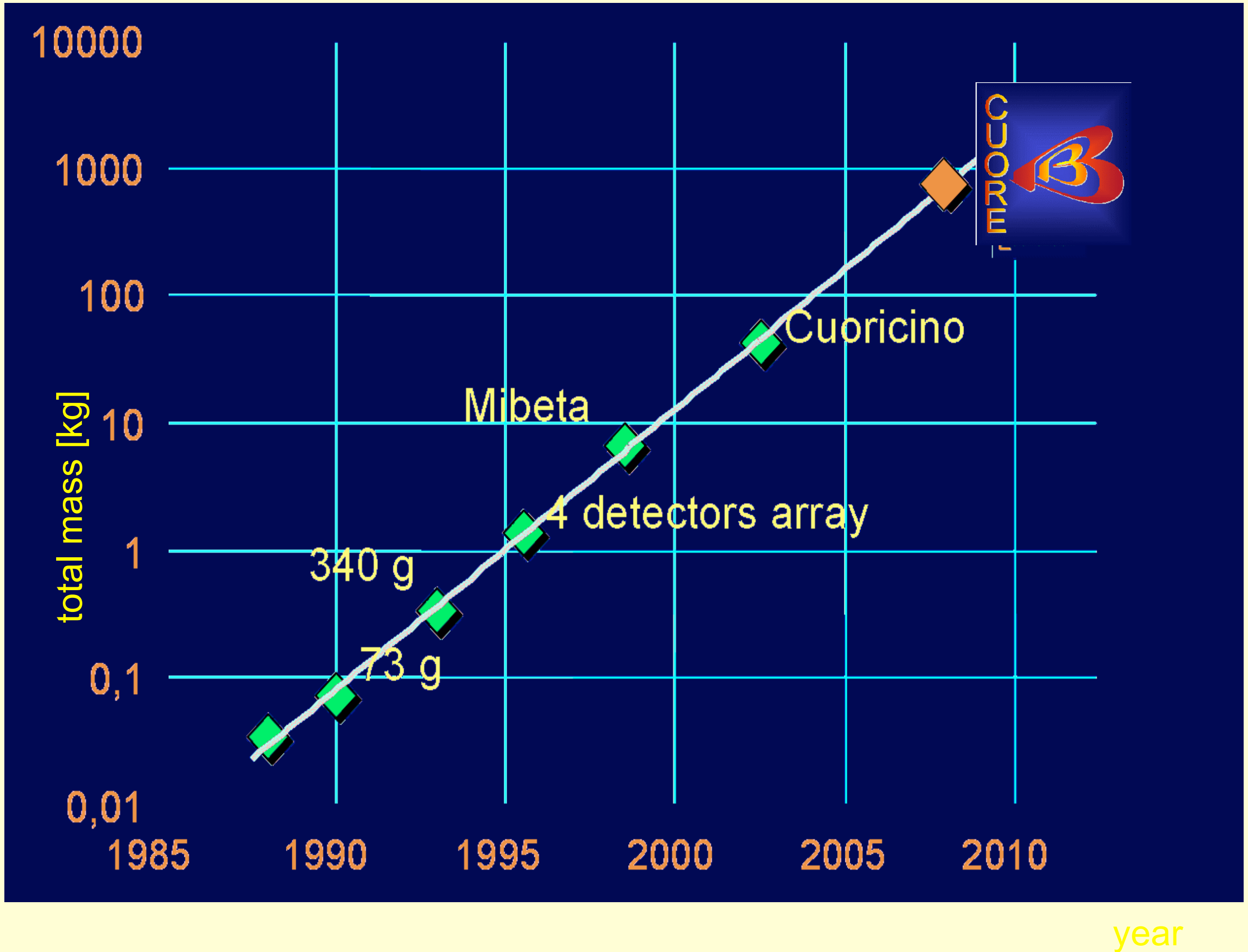
CUORE R&D (Hall C)

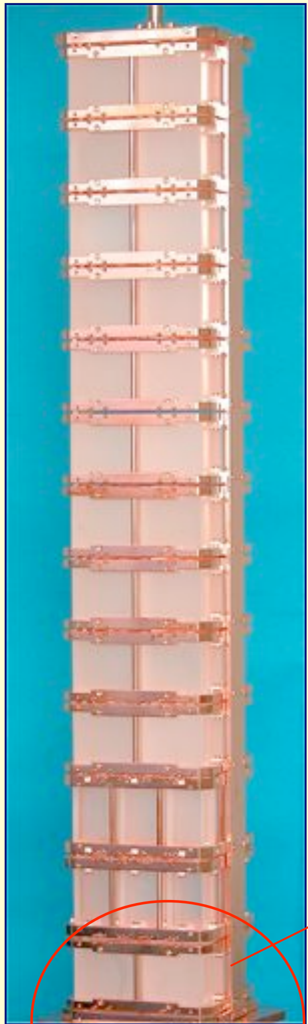
CUORE (Hall A)



Cuoricino (Hall A)

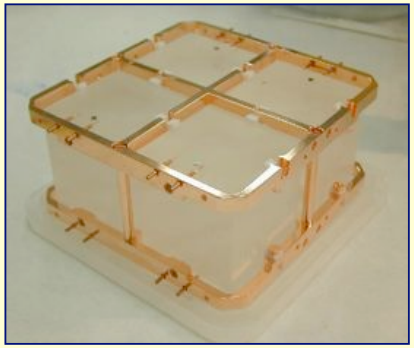
Mass increase of bolometers





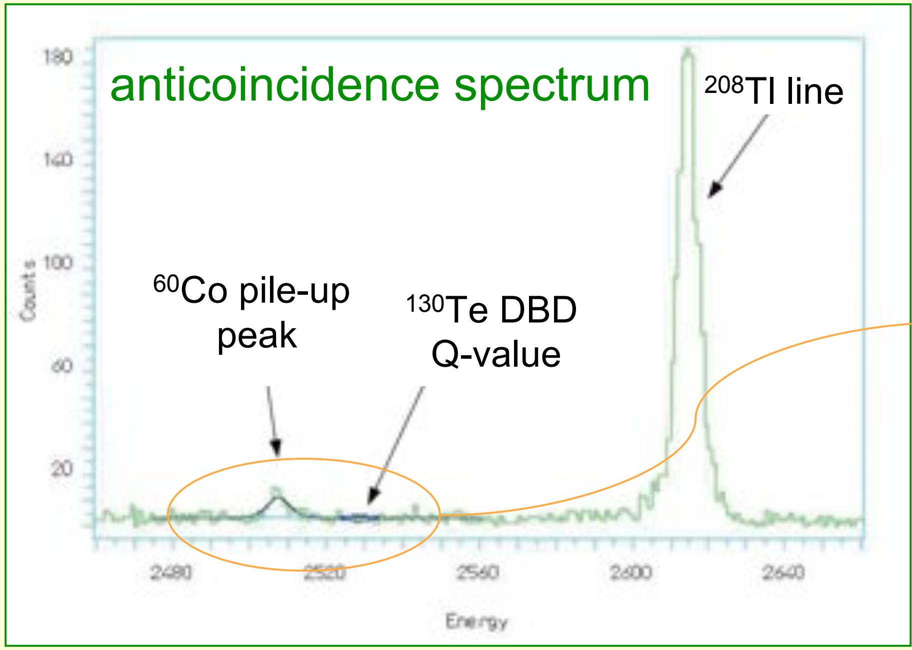
- ✓ Search for the $2\beta|_{0\nu}$ in ^{130}Te (Q=2529 keV) and other rare events
- ✓ At Hall A in the Laboratori Nazionali del Gran Sasso (LNGS)
- ✓18 crystals 3x3x6 cm3 + 44 crystals 5x5x5 cm3 = 40.7 kg of TeO2
- ✓Operation started in the beginning of 2003 => ~ 4 months
- ✓**Background .18±.01 c /kev/ kg/ a**
- ✓ **$T_{1/2}^{0\nu}$ (^{130}Te) > 2.4x 10^{24} y** **$\langle m_\nu \rangle$ .19 -1.**

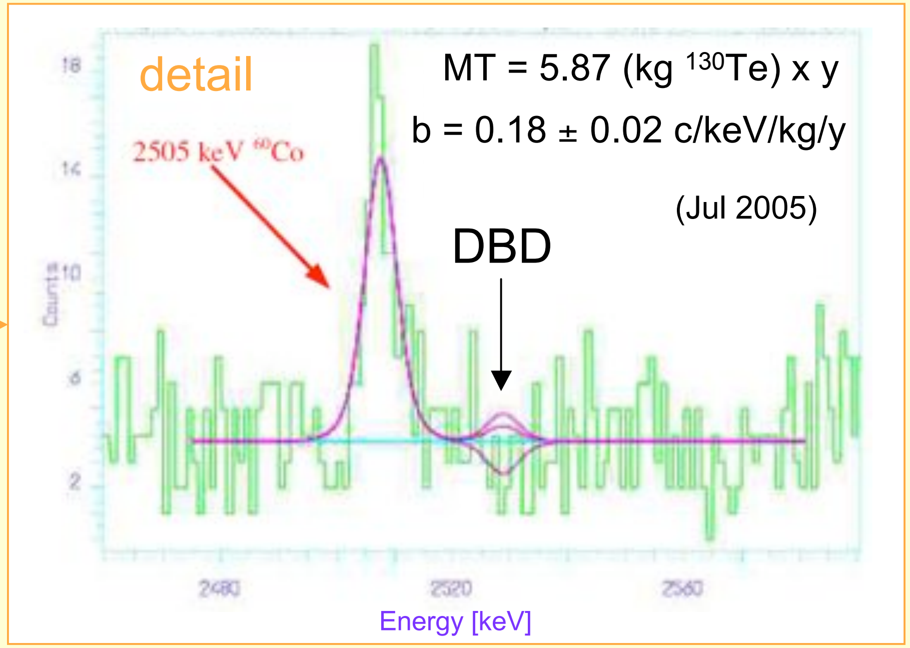
Klapdor 0.1 – 0.9



2 modules, 9 detector each,
crystal dimension 3x3x6 cm^3
crystal mass 330 g
9 x 2 x 0.33 = 5.94 kg of TeO_2

11 modules, 4 detector each,
crystal dimension 5x5x5 cm^3
crystal mass 790 g
4 x 11 x 0.79 = 34.76 kg of TeO_2





*PRL. **95**, 142501 (2005)*

$\tau_{1/2}^{0\nu}$ (y) > 2.4×10^{24} y

$\langle M_{\beta\beta} \rangle$ < 0.2 – 1.0 eV (90% c.l.)

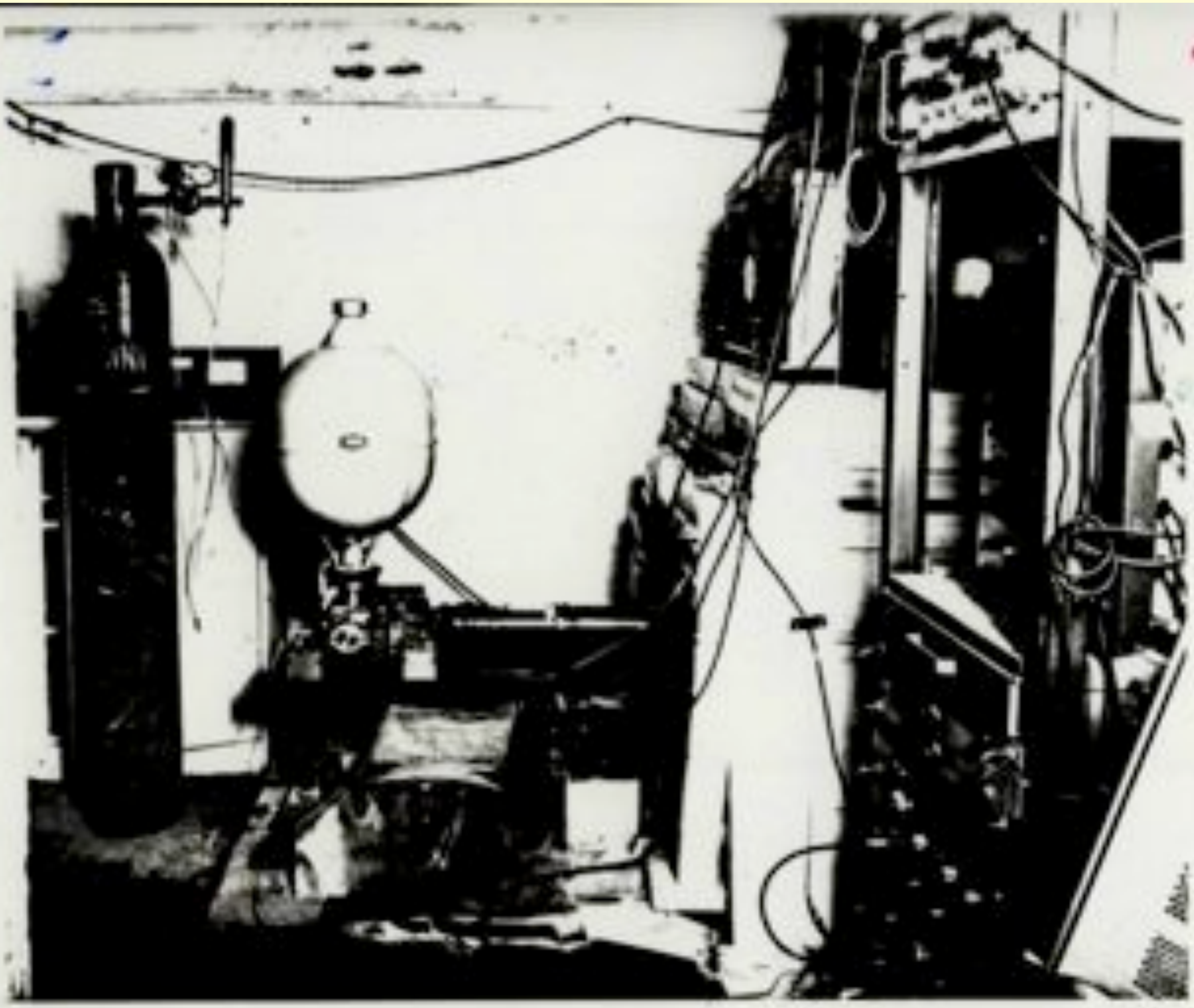
5 y sensitivity (with present performance):
5×10^{24} y
$\langle M_{\beta\beta} \rangle$ < 0.12 – 0.65 eV

← Powerful test of KDHK

Next generation experiments

Name		%	$Q_{\beta\beta}$	% E	B c/y	T (year)	Tech	<m>
CUORE	^{130}Te	34	2533	90	3.5	1.8×10^{27}	Bolometric	9-57
GERDA	^{76}Ge	7.8	2039	90	3.85	2×10^{27}	Ionization	29-94
Majorana	^{76}Ge	7.8	2039	90	.6	4×10^{27}	Ionization	21-67
GENIUS	^{76}Ge	7.8	2039	90	.4	1×10^{28}	Ionization	13-42
Supernemo	^{82}Se	8.7	2995	90	1	210^{26}	Tracking	54-167
EXO	^{136}Xe	8.9	2476	65	.55	1.3×10^{28}	Tracking	12-31
Moon-3	^{100}Mo	9.6	3034	85	3.8	1.7×10^{27}	Tracking	13-48
DCBA-2	^{150}Nd	5.6	3367	80		1×10^{26}	Tracking	16-22
Candles	^{48}Ca	.19	4271	-	.35	3×10^{27}	Scintillation	29-54
CARVEL	^{48}Ca	.19	4271	-		3×10^{27}	Scintillation	50-94
GSO	^{160}Gd	22	1730	-	200	1×10^{26}	Scintillation	65-?
COBRA	^{115}Cd	7.5	2805				Ionization	
SNOLAB+	^{150}Nd	5.6	3367				Scintillation	

FQ



$\tau_{\beta\beta} > 5\times10^{21}$ $\langle m_\nu \rangle < \underline{30}$

i.a. 12

mass $\sqrt{1000}$

t $\sqrt{3}$

ΔE $\sqrt{2}$

Back $\sqrt{15}$

↓

3600

↓

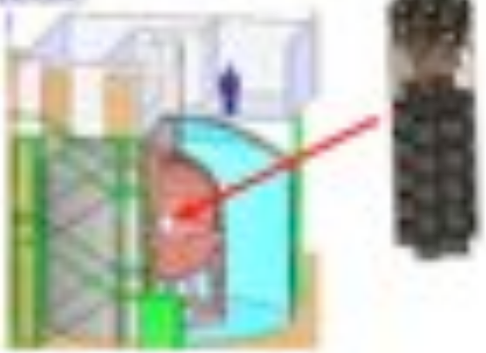
1.8×10^{15}

↓

$\langle m_\nu \rangle < .3$

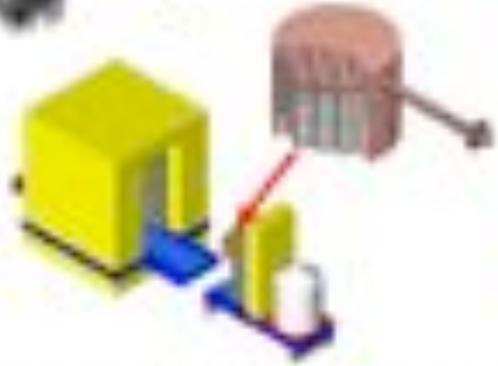
Two new ^{76}Ge Projects:

GERDA



- 'Bare' ^{enr}Ge array in liquid argon (nitrogen)
- Shield: high-purity liquid Argon (N) / H_2O
- Phase I: ~18 kg (HdM/IGEX diodes)
- Phase II: add ~20 kg new enr. Detectors; total ~40 kg

Majorana



- Array(s) of ^{enr}Ge housed in high-purity electroformed copper cryostat
- Shield: electroformed copper / lead
- Staged approach based on 60 kg arrays (60/120/180 kg)

Physics goals: degenerate mass range
Technology: study of bgds. and exp. techniques

LoI
- open exchange of knowledge & technologies (e.g. MaGe MC)
- consider to merge for O(1 ton) exp. (inv. Hierarchy)

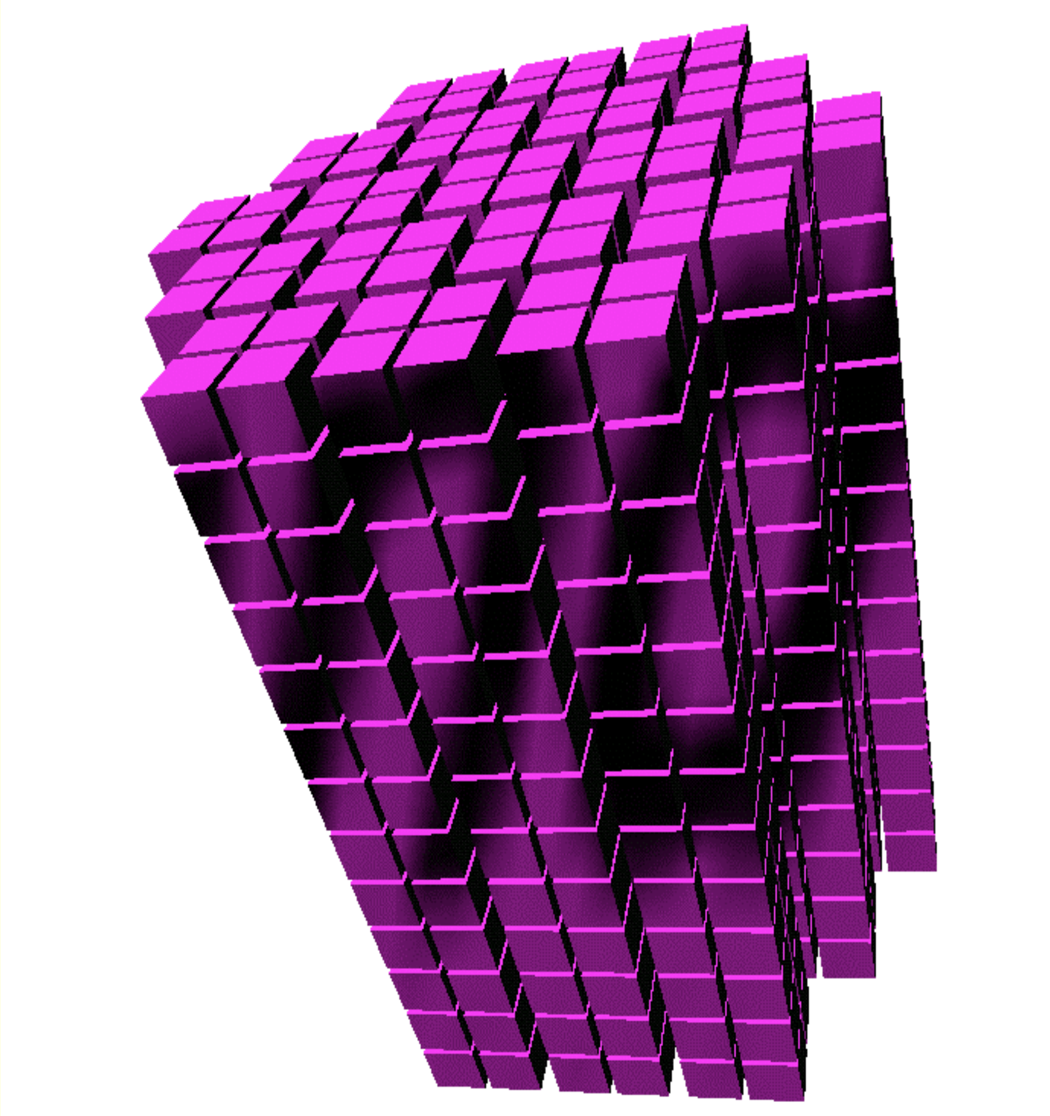
The CUORE project

(approved by the S.C. of Gran Sasso Laboratory and by INFN)

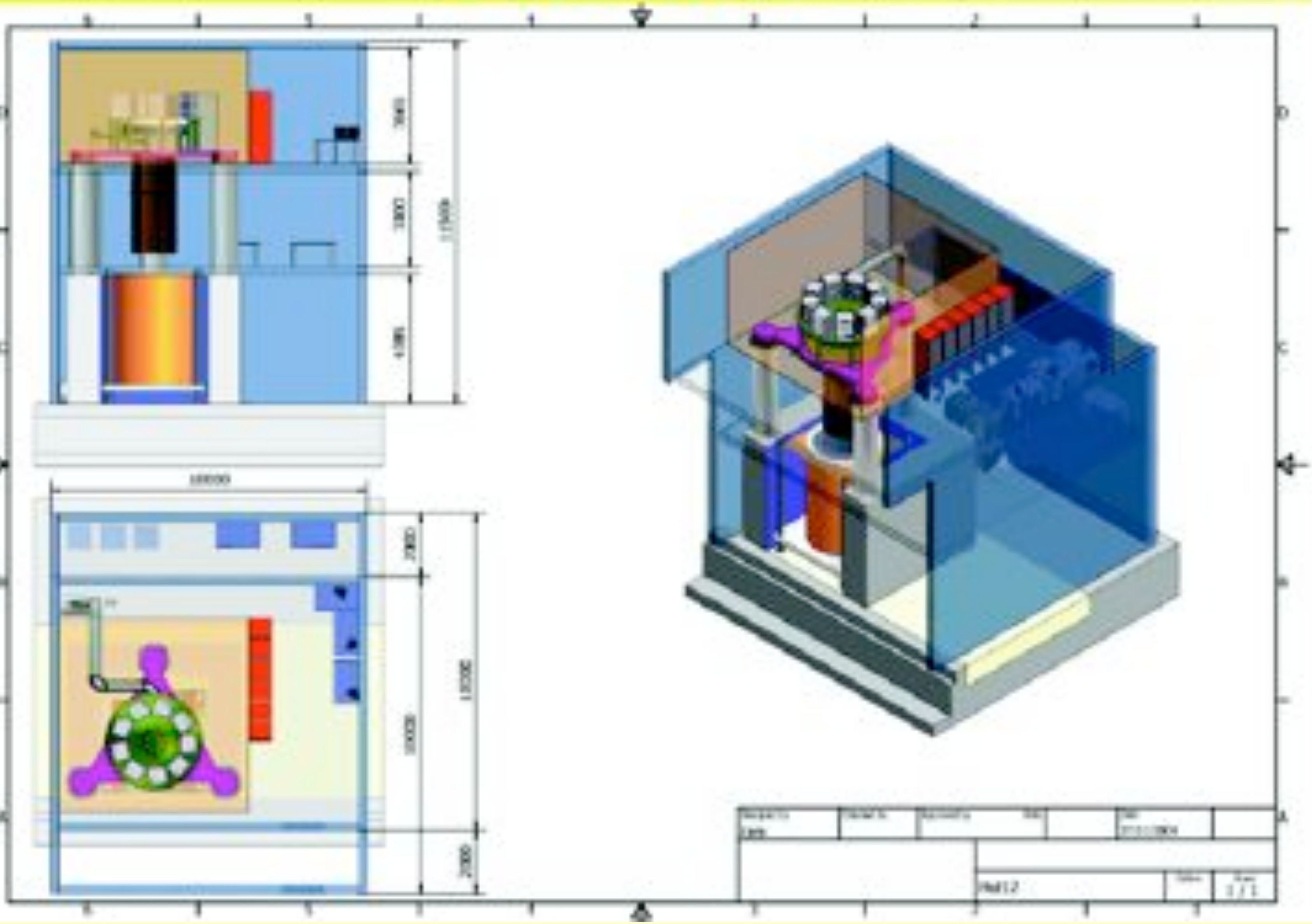
CUORE is an array of **988** bolometers grouped in **19** colums with **13** flours of **4** crystals

750 kg TeO_2 => 600 kg Te
=> **203 kg ^{130}Te**

Crystals are separated by a few mm, only, with little material among them



CUORE hut

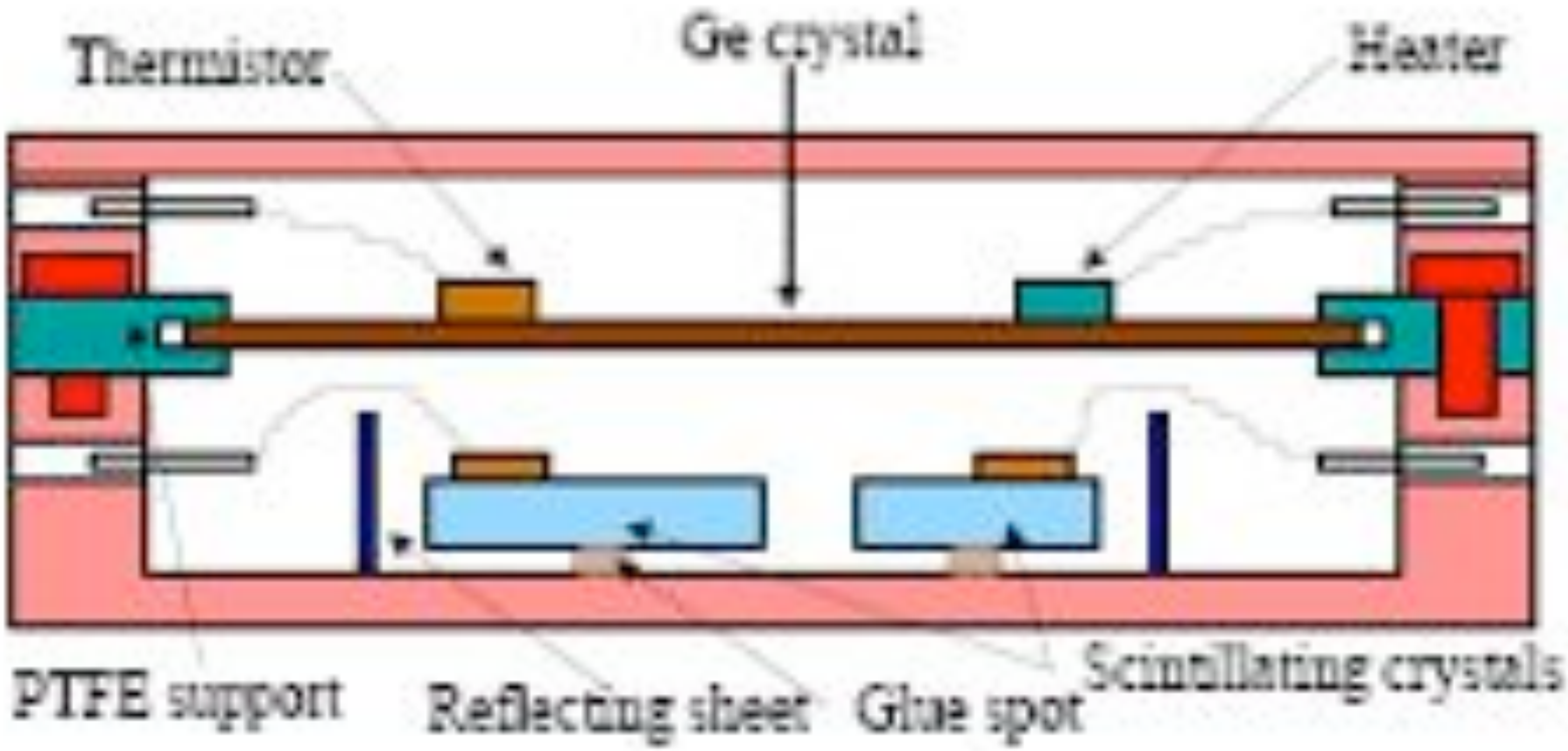


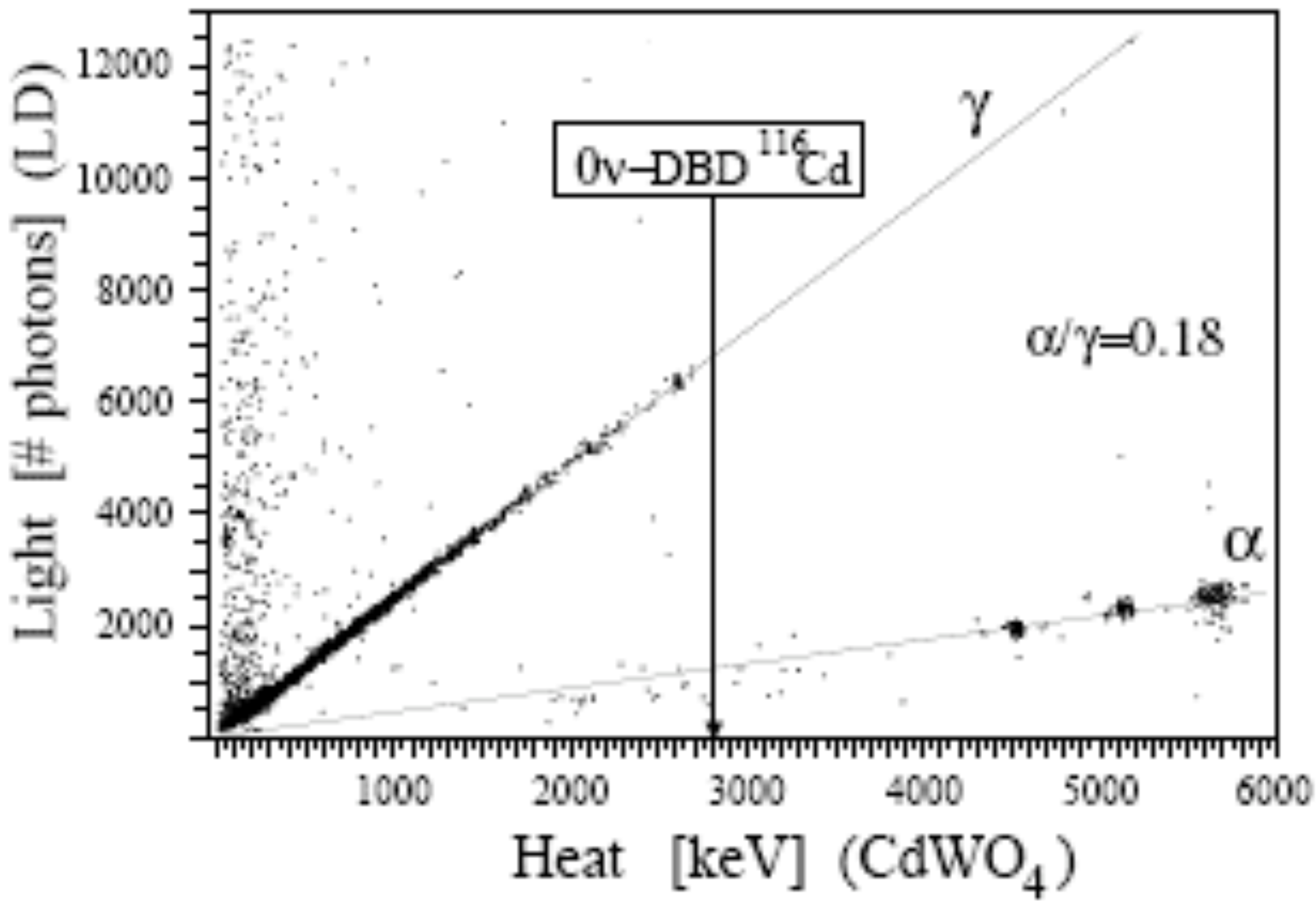
Other possible candidates for neutrinoless DBD

Compound	Isotopic abundance	Transition energy
$^{48}CaF_2$	.0187 %	4272 keV
^{76}Ge	7.44 "	2038.7 "
$^{100}MoPbO_4$	9.63 "	3034 "
$^{116}CdWO_4$	7.49 "	2804 "
$^{130}TeO_2$	34 "	2528 "
$^{150}NdF_3$ $^{150}NdGaO_3$	5.64 "	3368 "

- 130Te has high transition energy and 34% isotopic abundance => enrichment non needed and/or very cheap. Any future extensions are possible
- Performance of CUORE, amply tested with CUORICINO
- - CUORE has been approved and has already an underground location Dilution refrigerator already funded

Recent results obtained with scintillating crystals of Cd WO4





Light [# photons] (LD)
12000
10000
8000
6000
4000
2000
1000
2000
3000
4000
5000
6000
Heat [keV] (CdWO4)
0ν–DBD 116Cd
γ
α/γ=0.18
α

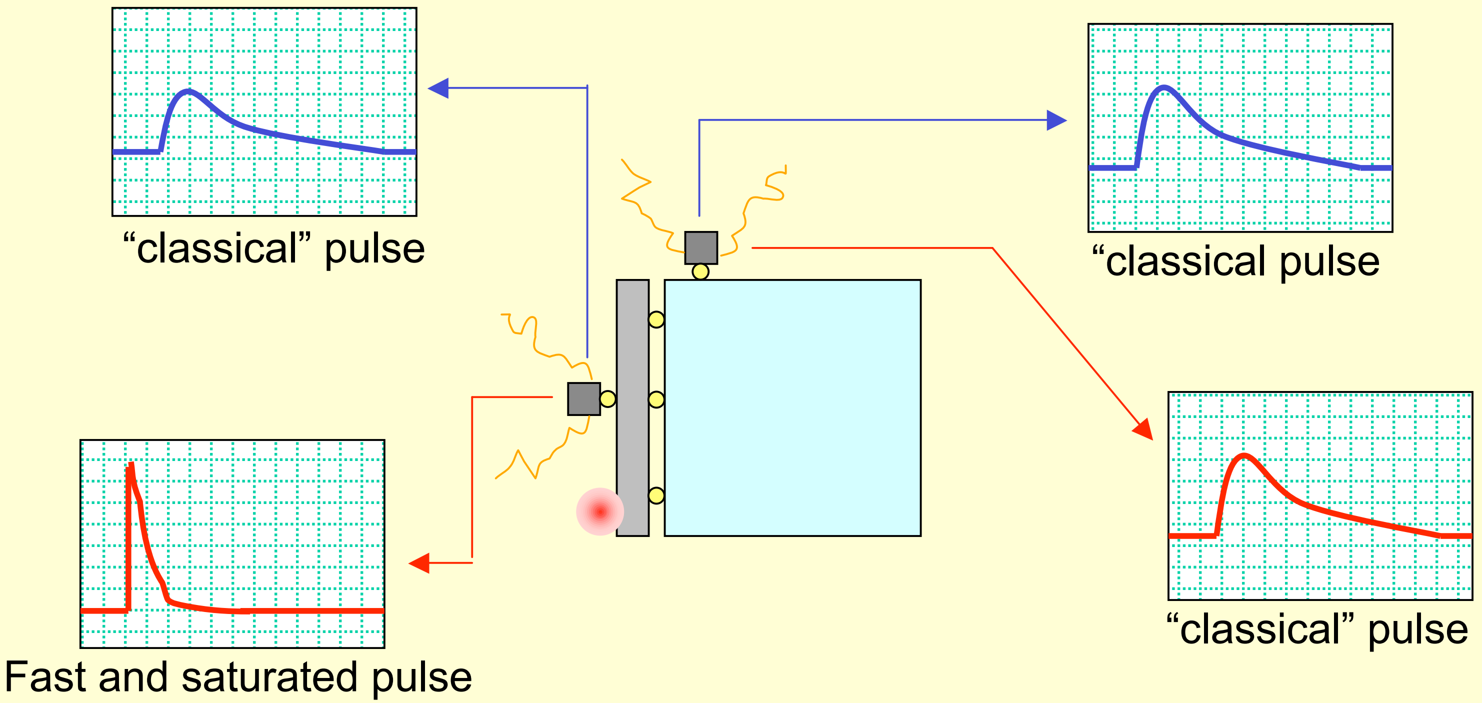
Background: in DM => ionizing particles

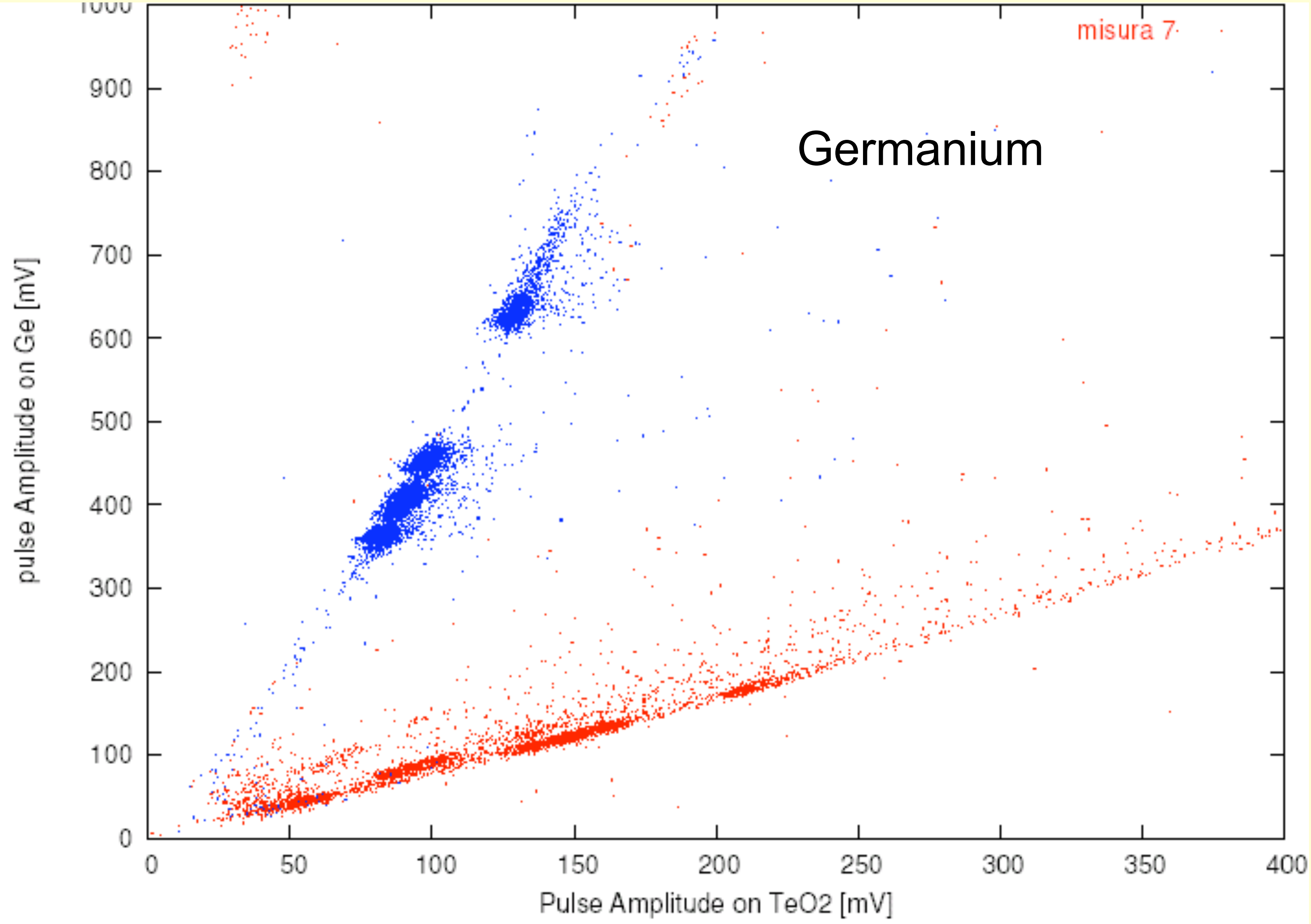
in ββ => slow recoils eleiminated with

=> Surface Sensitive Bolometers

=> scintillation vs.heat

A composite bolometer with a thin crystal of Ge, Si o TeO2



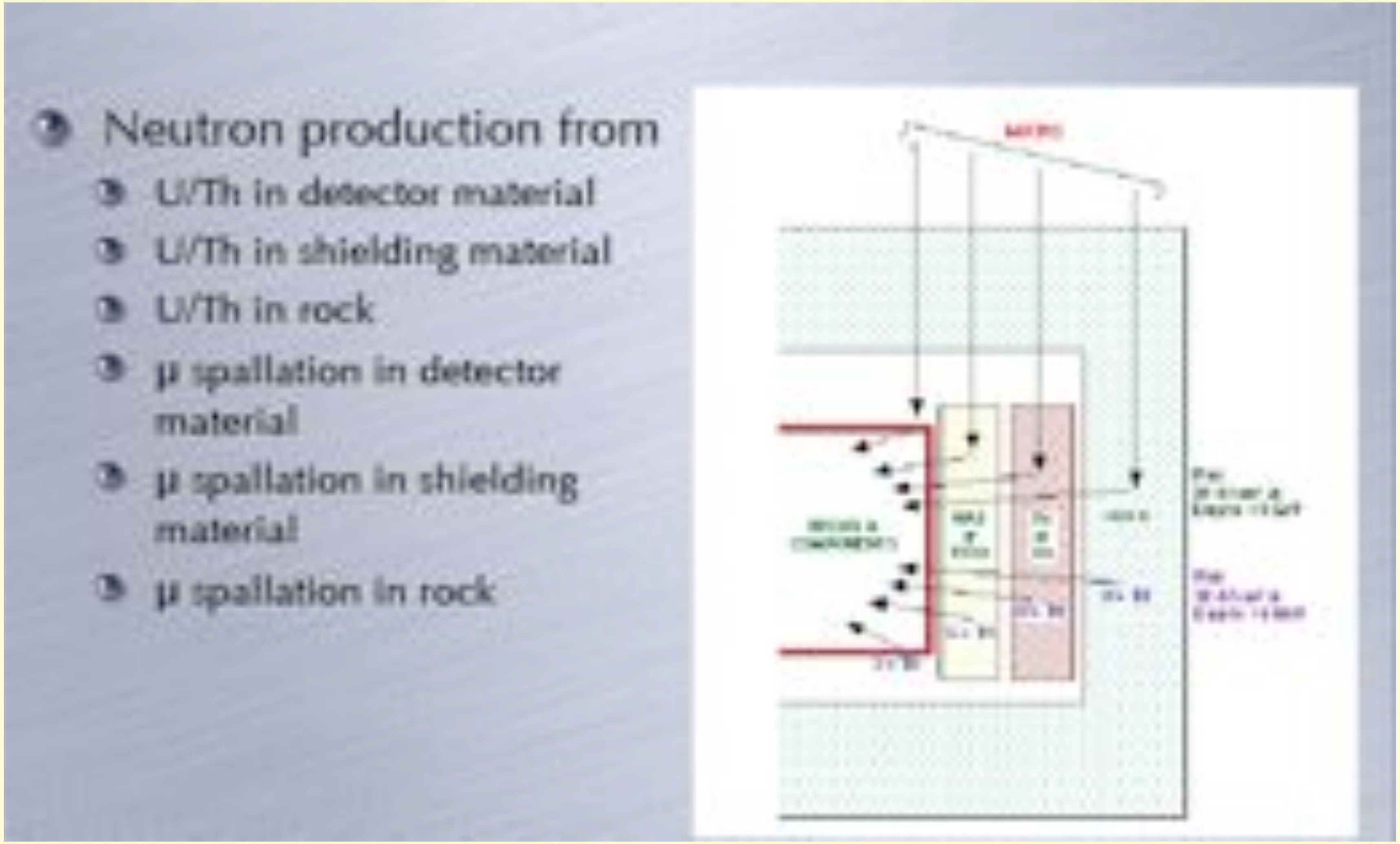


Germanium
misura 7
pulse Amplitude on Ge [mV]
Pulse Amplitude on TeO2 [mV]
0
100
200
300
400
500
600
700
800
900
1000
0
50
100
150
200
250
300
350
400

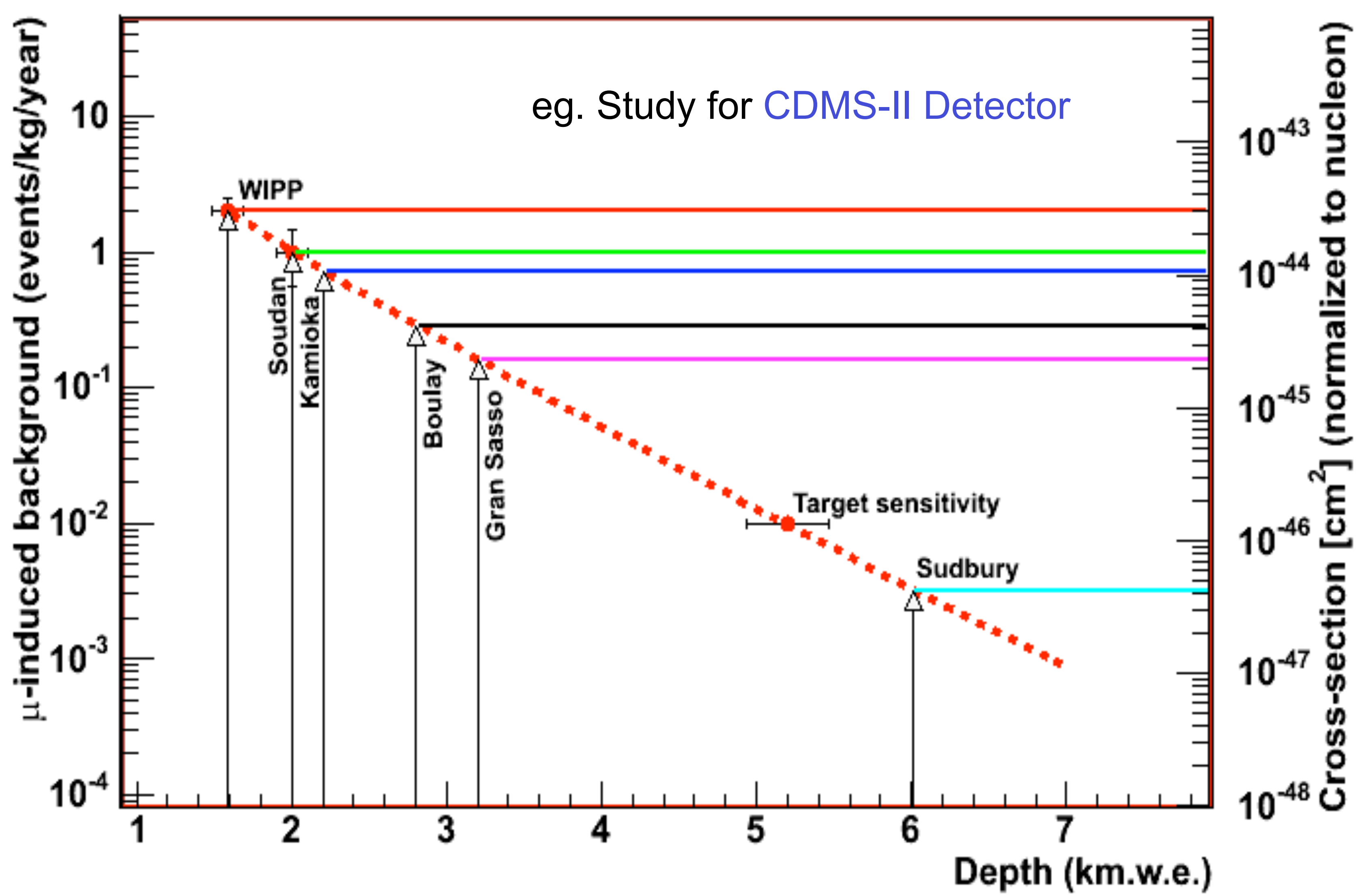
How deep should we go, for DM and DBD?

Neutrons =>Simulate DM

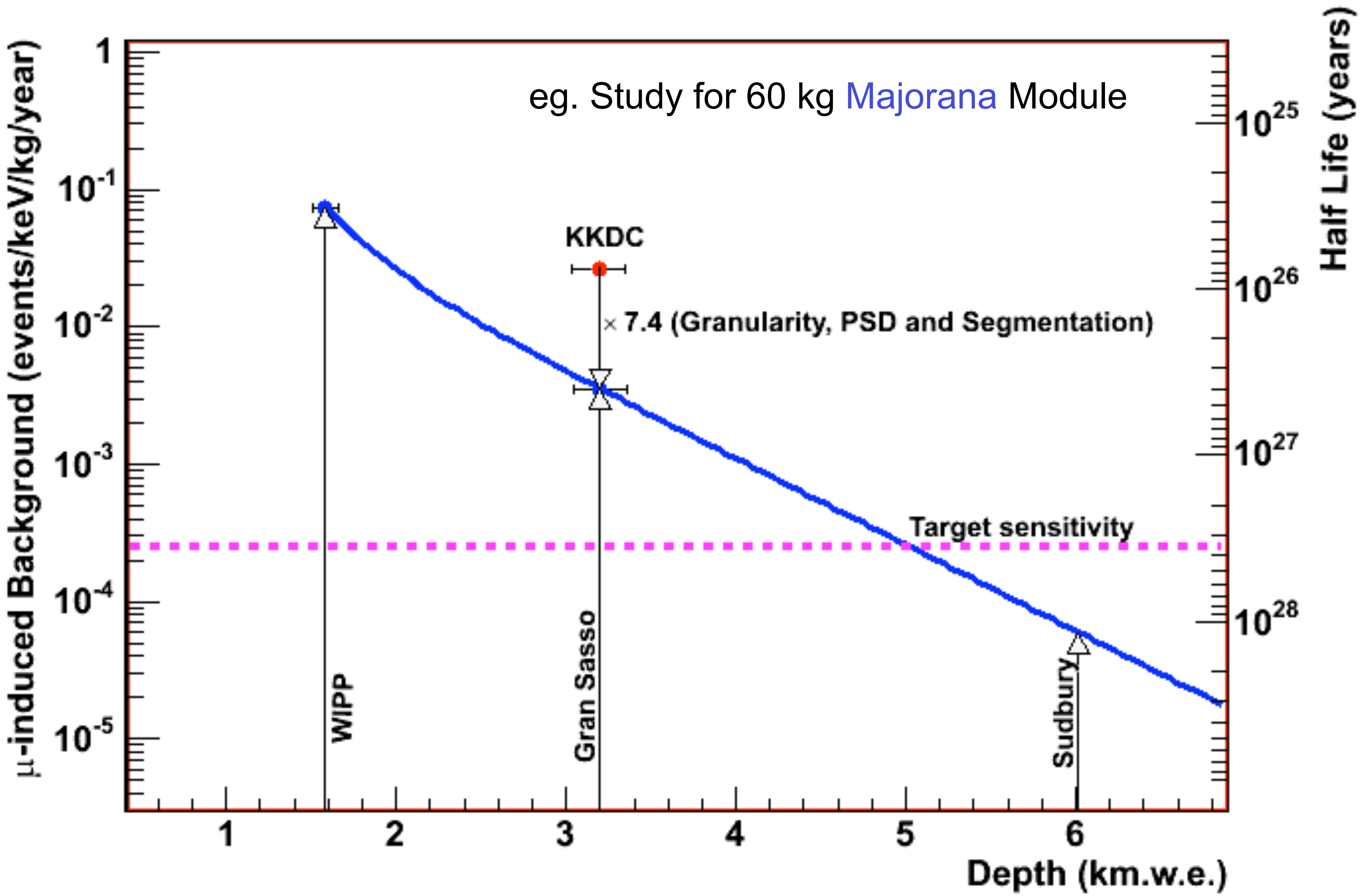
=> Background in the regtion of neutrinoless DBD



Depth Sensitivity Relation for Dark Matter



Depth Sensitivity Relation for DBD



Neutron background in CUORE (ββ region):

- neutrons produced in the rock by radioactivity

total	$8\ 10^{-3}$ c/keV/kg/y	*Can be reduced by neutron shield*
anticoincidence	$2\ 10^{-4}$ c/keV/kg/y	

- neutrons produced in the rock by muon

total	$6\ 10^{-5}$ c/keV/kg/y	*Negligible*
anticoincidence	$1\ 10^{-6}$ c/keV/kg/y	

- neutrons produced in the lead shield by muon

total	$2\ 10^{-3}$ c/keV/kg/y	*Can be reduced by muon veto*
anticoincidence	$1\ 10^{-4}$ c/keV/kg/y	

No limit to CUORE sensitivitydue to *neutron flux* @ LNGS

What about the background from the rocks: two tests were planned with weak neutron source

CONCLUSIONS

The interest of experiments on DM and neutrinoless $\beta\beta$ decay is obvious.
Establishing the existence of DM particles , would support Supersymmetry and have far reaching consequences not only in astrophysics , but also in subnuclear physics.
Oscillations exists and Δm^2 is finite . We need to determine the Majorana nature of the neutrino and the absolute value of $<m_\nu>$
Evidence has been presented in an experiment on the existence of WIMPs and in another on the existence of neutrinoless DBD.
They are not yet confirmed by other experiments (somebody disagree on the term yet)
Fundamental physics has received in the last years great advantages from the "wedding" between nuclear and subnuclear physics and astrophysics.
Searches on DM and DBD are, and much more will be in the future a beautiful example of synergy, but this synergy will be likely extended soon to other interesting subjects like solar ands supernova neutrino physics.
But this is not the end: in the fashinating field of astroparticle physics more results are expecting us and are probably beyond our imagination.