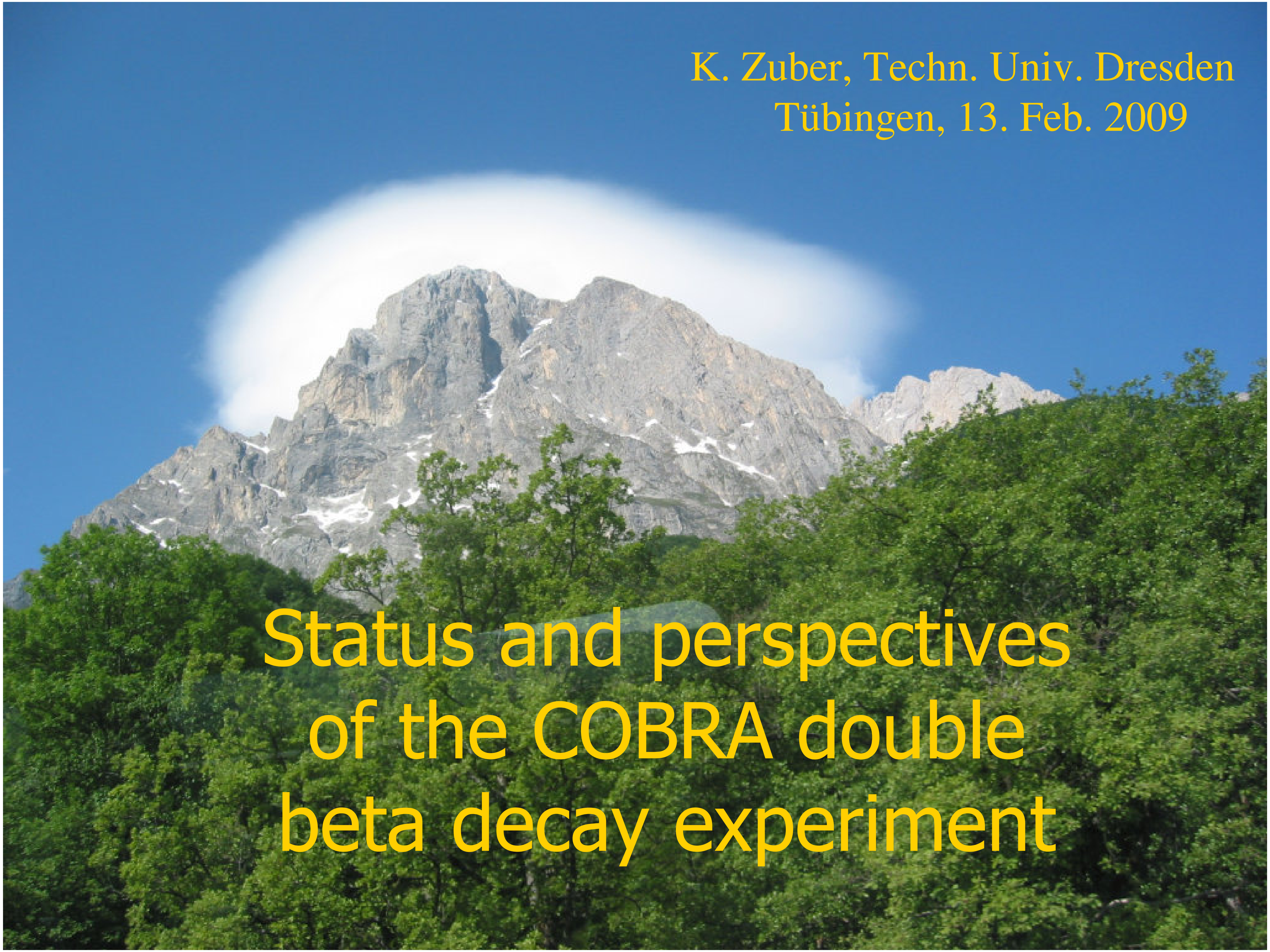
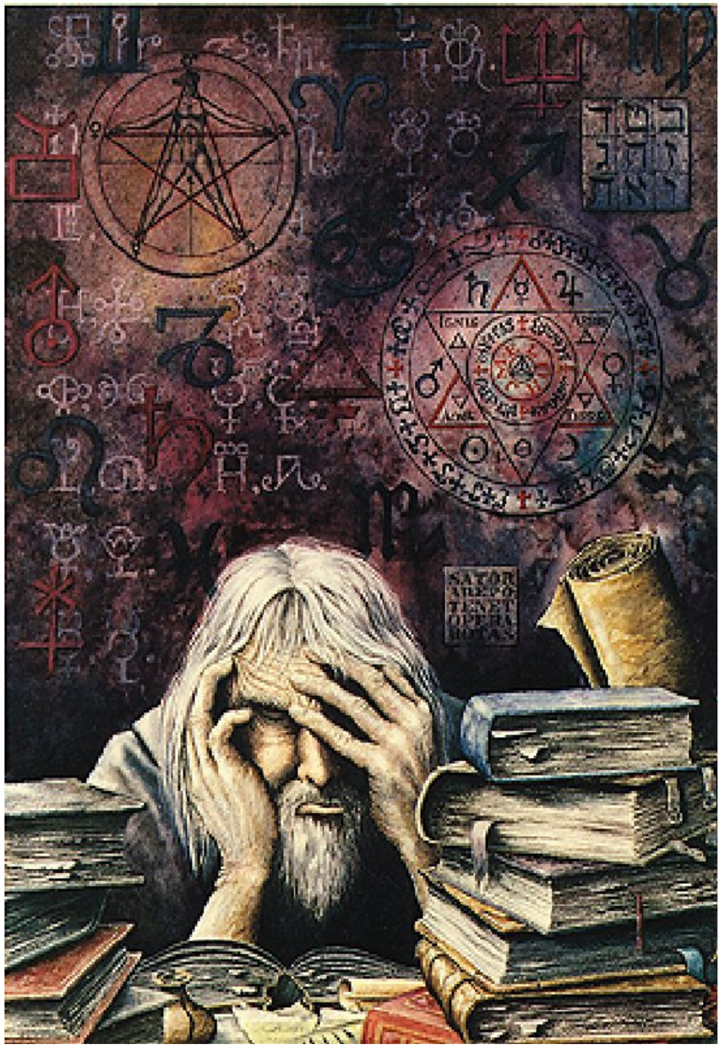


K. Zuber, Techn. Univ. Dresden

Tübingen, 13. Feb. 2009

Status and perspectives of the COBRA double beta decay experiment

Contents



★ General Introduction
★ Experimental considerations
★ COBRA
★ Summary and Outlook

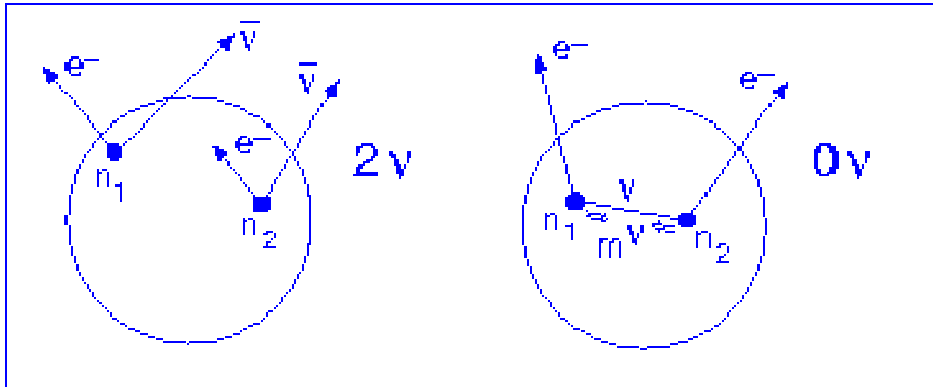
Beta and double beta decay

Beta decay

- $(A,Z) \rightarrow (A,Z+1) + e^- + \bar{\nu}_e$ β-decay
- $n \rightarrow p + e^- + \bar{\nu}_e$

Double beta decay

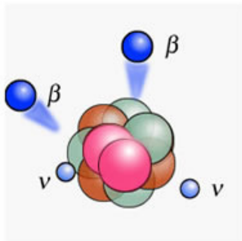
- $(A,Z) \rightarrow (A,Z+2) + 2 e^- + 2\bar{\nu}_e$ $2\nu\beta\beta$
- $(A,Z) \rightarrow (A,Z+2) + 2 e^-$ $0\nu\beta\beta$

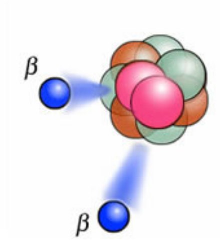


changing Z by two units while leaving A constant

Double beta decay

- $(A,Z) \rightarrow (A,Z+2) + 2e^- + 2\bar{\nu}_e$ — $2\nu\beta\beta$
- $(A,Z) \rightarrow (A,Z+2) + 2e^-$ — $0\nu\beta\beta$





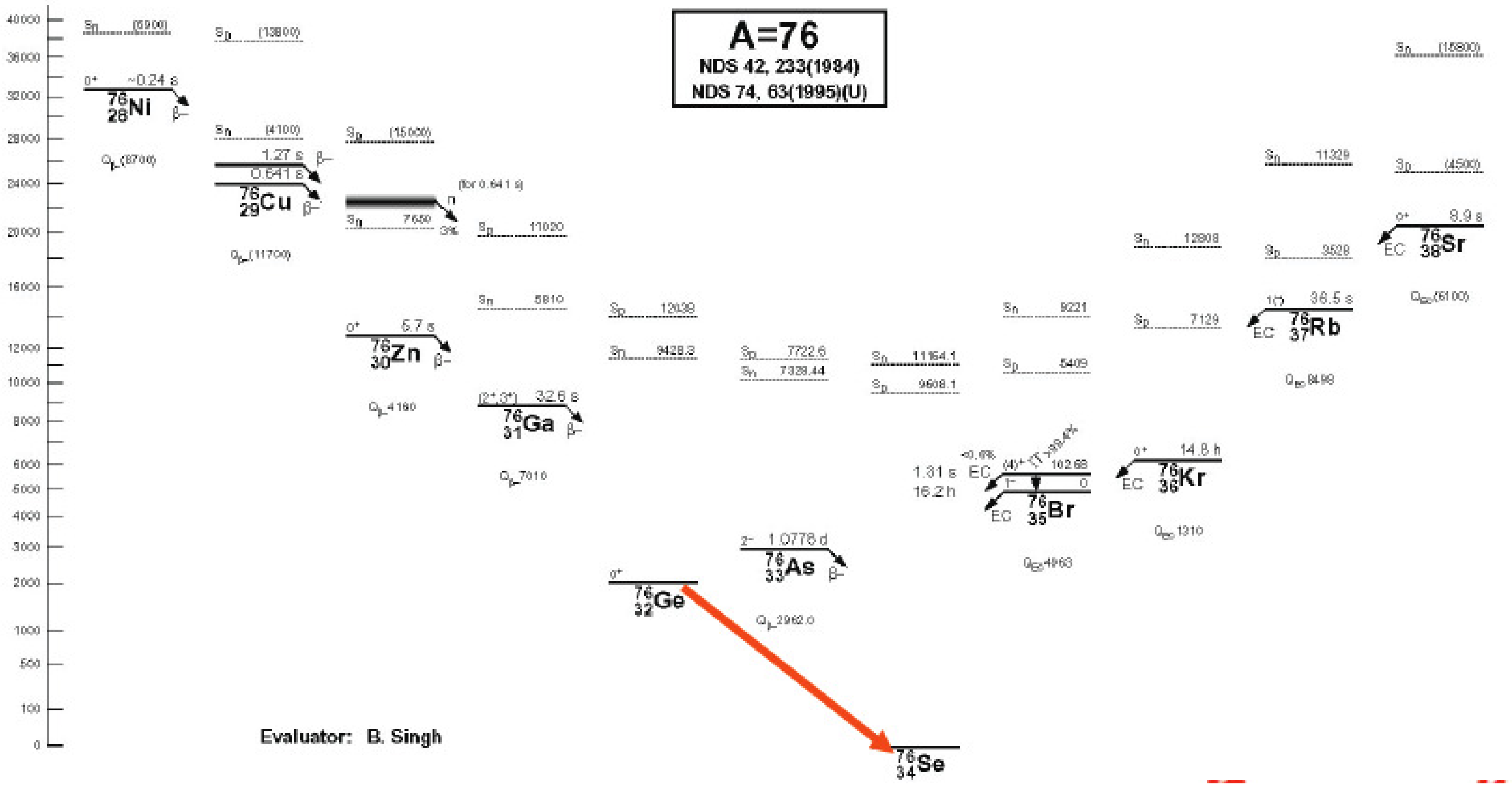
Unique process to measure the mass of the neutrino

Unique process to measure character of neutrino

Requires half-life measurements well beyond 10^{20} yrs!!!!

The smaller neutrino mass the longer is half-life

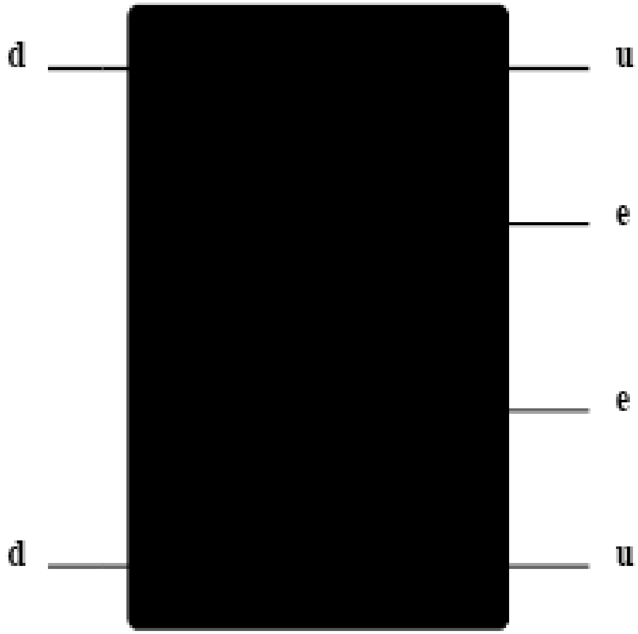
Example - Ge76



There are only 35 candidates

0νββ

Any ΔL=2 process can contribute to 0νββ



R_p violating SUSY
V+A interactions
Leptoquarks
Double charged Higgs bosons
Compositeness
Heavy Majorana neutrino exchange
Light Majorana neutrino exchange
...

$$1 / T_{1/2} = PS * NME^2 * \varepsilon^2$$

The standard lore

Light Majorana neutrino exchange

Measured quantity

Quantity of interest
Effective Majorana neutrino mass

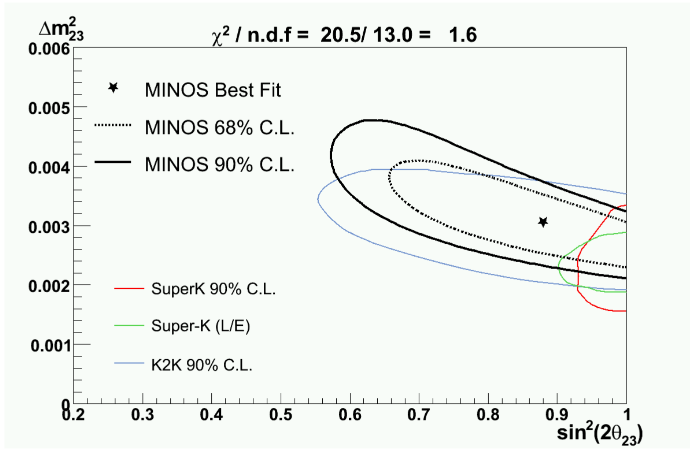
$$1 / T_{1/2} = PS * NME^2 * (\langle m_\nu \rangle / m_e)^2$$

Phase space integral
calculable

Nuclear transition matrix element

Oscillation evidences

depends on $\Delta m^2 = m_2^2 - m_1^2$ No absolute mass measurement

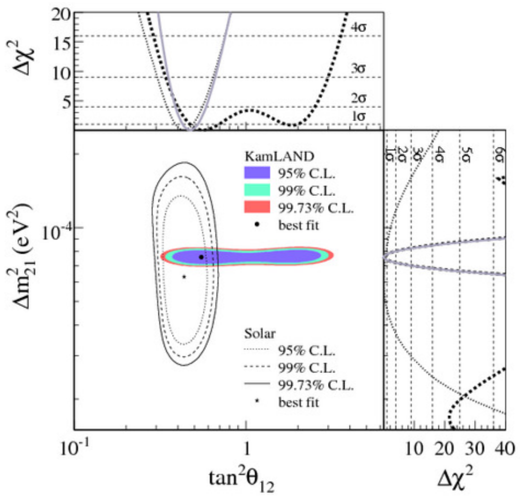


Atmospheric

$\sin^2 2\theta = 1.00$, $\Delta m^2 = 2.5 \times 10^{-3}$ eV^2

Solar + reactors

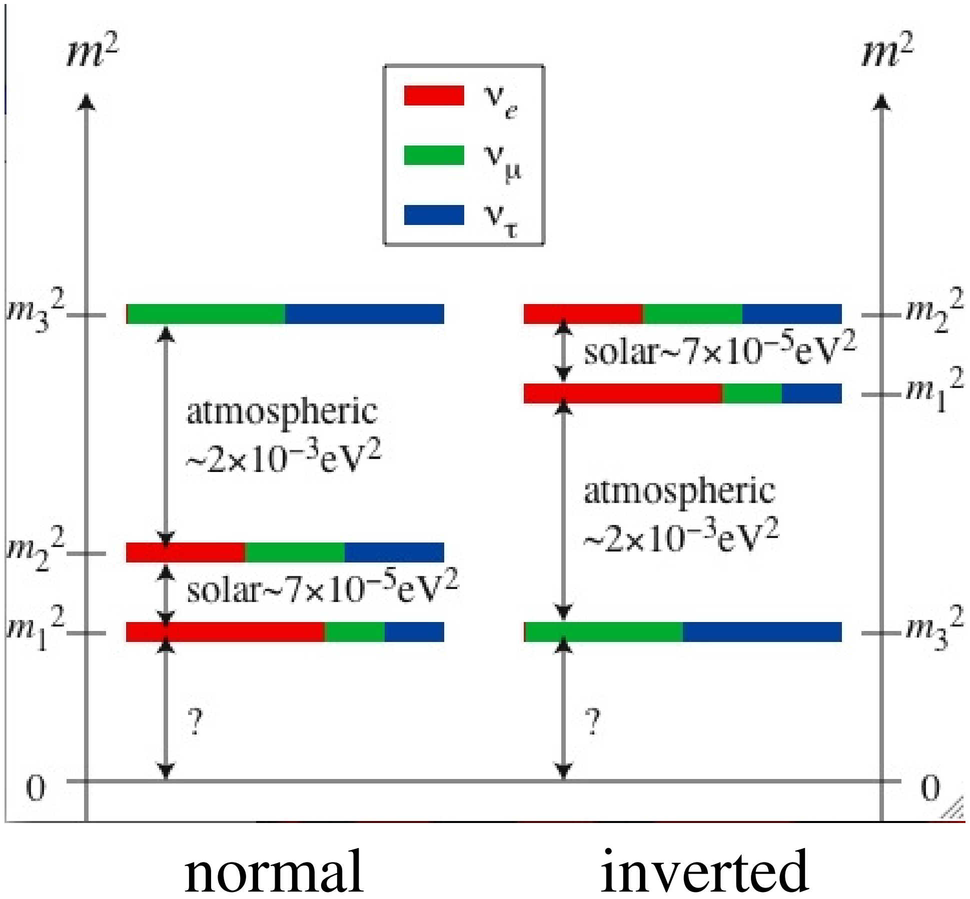
$\sin^2 2\theta = 0.81$, $\Delta m^2 = 8.2 \times 10^{-5}$ eV^2



Neutrino mass schemes

- almost degenerate neutrinos $m_1 \approx m_2 \approx m_3$

- hierarchical neutrino mass schemes



3 Flavour oscillations (PMNS)

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} \Rightarrow \frac{m_i^2}{2E_\nu} \Rightarrow \begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix}$$

$$U = \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13} e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13} e^{i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha_1} & 0 \\ 0 & 0 & e^{i\alpha_2} \end{pmatrix}$$

solar If $\sin\theta_{13} \neq 0 \rightarrow$ CP-violation atmospheric

Majorana: $U = U_{PMNS}\, diag(1, e^{i\alpha_1}, e^{i\alpha_2})$

Physical quantities

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} \Rightarrow \frac{m_i{}^2}{2E_\nu} \Rightarrow \begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix}$$

Double beta decay: Effective Majorana neutrino mass

$$\langle m_\nu \rangle = \left| \sum U_{ei}^2 m_i \right| = \left| m_1 U_{e1}{}^2 + m_2 U_{e2}{}^2 e^{i\alpha_1} + m_3 U_{e3}{}^2 e^{i\alpha_2} \right|$$

CP-invariance: $\langle m_\nu \rangle = \left| \sum U_{ei}^2 m_i \right| = \left| m_1 |U_{e1}|^2 \pm m_2 |U_{e2}|^2 \pm m_3 |U_{e3}|^2 \right|$

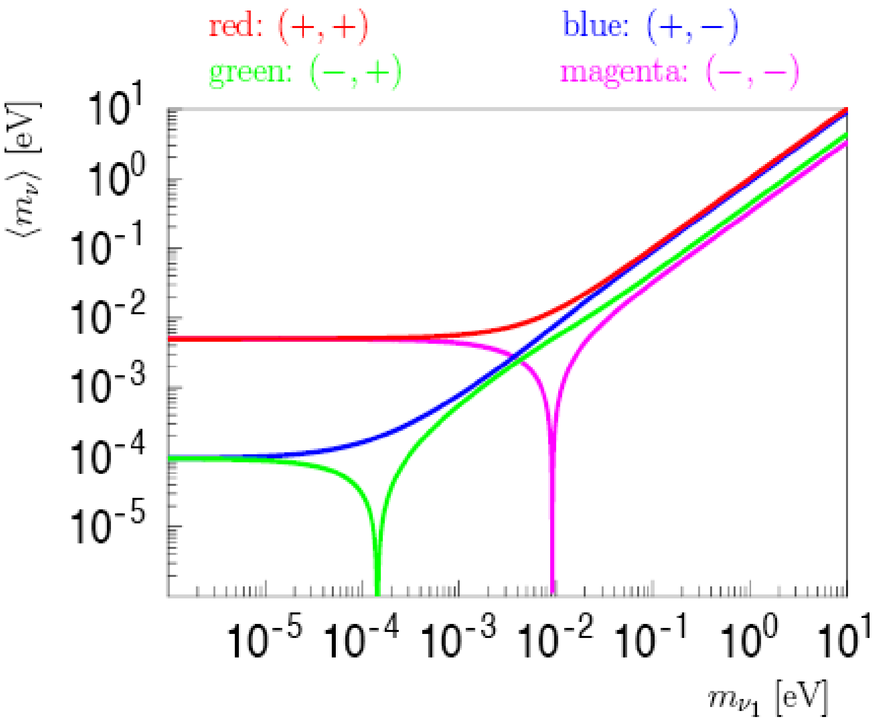
Beta decay

$$m_\nu = \Sigma |U_{ek}|^2 m_k$$

Measurements are complementary

Neutrino mass schemes and 0νββ

Best fit values



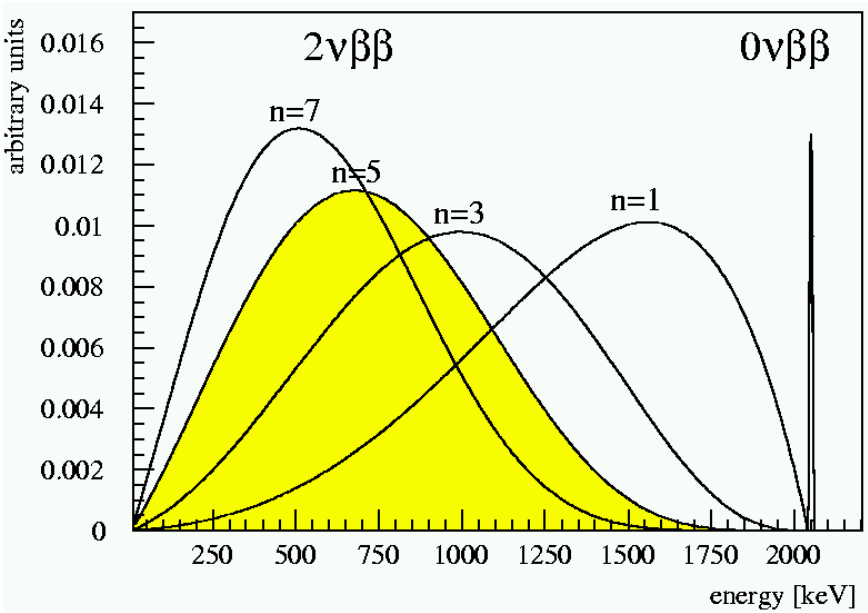
M. Hirsch
Neutrino 2006

$$\Delta m^2_{Atm} = 2.2 \cdot 10^{-3}\ \text{eV}^2, \qquad \Delta m^2_{\odot} = 8.1 \cdot 10^{-5}\ \text{eV}^2,$$

$$\sin^2\theta_{\odot} = 0.3, \qquad \sin^2\theta_R = 0.051$$

Spectral shapes

0νββ: Peak at Q-value of nuclear transition



Sum energy spectrum of both electrons

Measured quantity: Half-life

Dependencies (BG limited)

$T_{1/2} \propto a \bullet \varepsilon\, (M \bullet t / \Delta E \bullet B)^{1/2}$

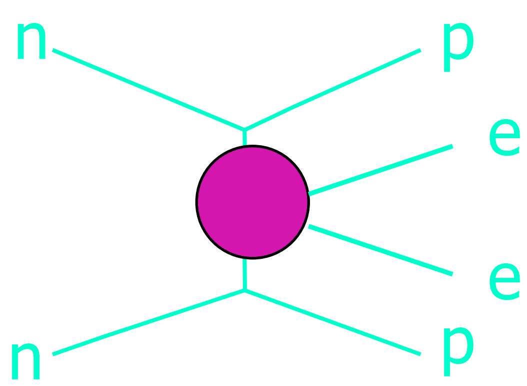
link to neutrino mass

$1 / T_{1/2} = PS * ME^2 * (m_\nu / m_e)^2$

$\beta^+\beta^+$ - modes

In general:

Double charged higgs bosons,
R-parity violating SUSY couplings,
leptoquarks...



- $(A,Z) \rightarrow (A,Z-2) + 2\, e^+ \; (+2\nu_e)$ $\beta^+\beta^+$ $Q-4m_ec^2$
- $e^- + (A,Z) \rightarrow (A,Z-2) + e^+ \; (+2\nu_e)$ β^+/EC $Q-2m_ec^2$
- $2\, e^- + (A,Z) \rightarrow (A,Z-2) \; (+2\nu_e)$ EC/EC Q

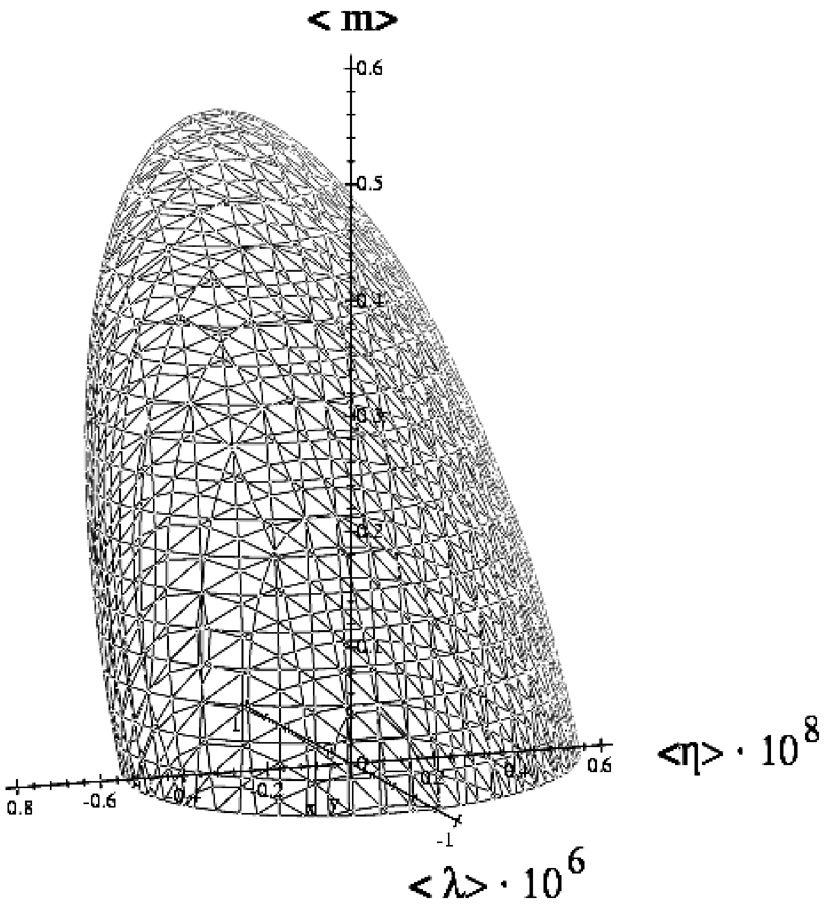
Important to reveal mechanism if $0\nu\beta\beta$ is discovered

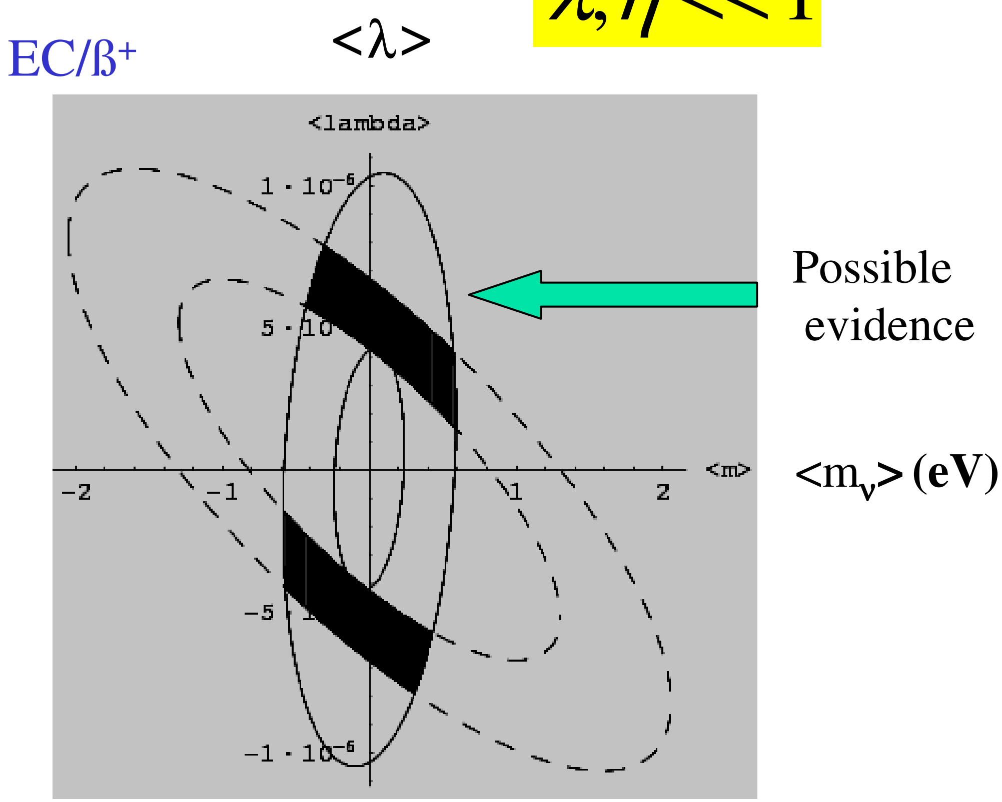
β^+/EC Enhanced sensitivity to right handed weak currents (V+A)

Neutrino mass vs. right handed currents

$$H_{\text{int}} \propto j_L J_L^+ + \kappa j_L J_R^+ + \eta j_R J_L^+ + \lambda j_R J_R^+$$

$$\lambda, \eta << 1$$





M. Hirsch et al., Z. Phys. A 347,151 (1994)

The search for $0\nu\beta\beta$

or

Back of the envelope

$T_{1/2} = \ln 2 \cdot a \cdot N_A \cdot M \cdot t \,/\, N_{\beta\beta}$ ($\tau \gg T$) (Background free)

For half-life measurements of 10^{26-27} yrs

1 event/yr you need 10^{26-27} source atoms

This is about 1000 moles of isotope, implying 100 kg

Now you only can loose: nat. abundance, efficiency, background, ...

Candidates

$0\nu\beta\beta$ decay rate scales with Q^5

$2\nu\beta\beta$ decay rate scales with Q^{11}

Isotope	*Q-Value (keV)*	*Nat. abund. (%)*	*$(PS\ 0\nu)^{-1}$ $(yrs \times eV^2)$*	*$(PS\ 2\nu)^{-1}$ (yrs)*
Ca 48	**4271**	**0.187**	**4.10E24**	**2.52E16**
Ge 76	**2039**	**7.8**	**4.09E25**	**7.66E18**
Se 82	**2995**	**9.2**	**9.27E24**	**2.30E17**
Zr 96	**3350**	**2.8**	**4.46E24**	**5.19E16**
Mo 100	**3034**	**9.6**	**5.70E24**	**1.06E17**
Pd 110	**2013**	**11.8**	**1.86E25**	**2.51E18**
Cd 116	**2809**	**7.5**	**5.28E24**	**1.25E17**
Sn 124	**2288**	**5.64**	**9.48E24**	**5.93E17**
Te 130	**2529**	**34.5**	**5.89E24**	**2.08E17**
Xe 136	**2479**	**8.9**	**5.52E24**	**2.07E17**
Nd 150	**3367**	**5.6**	**1.25E24**	**8.41E15**

Future projects, ideas

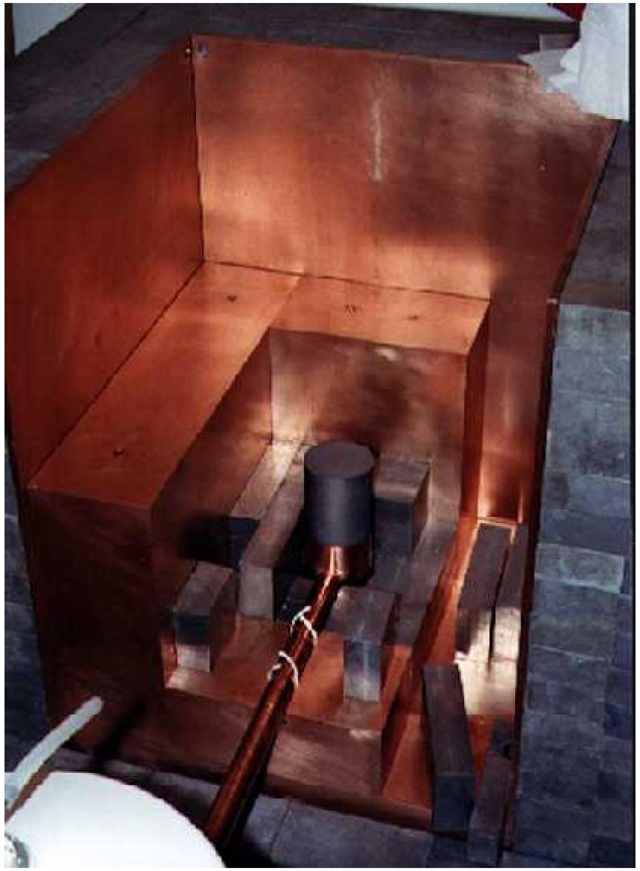
K. Zuber, Acta Polonica B 37, 1905 (2006)

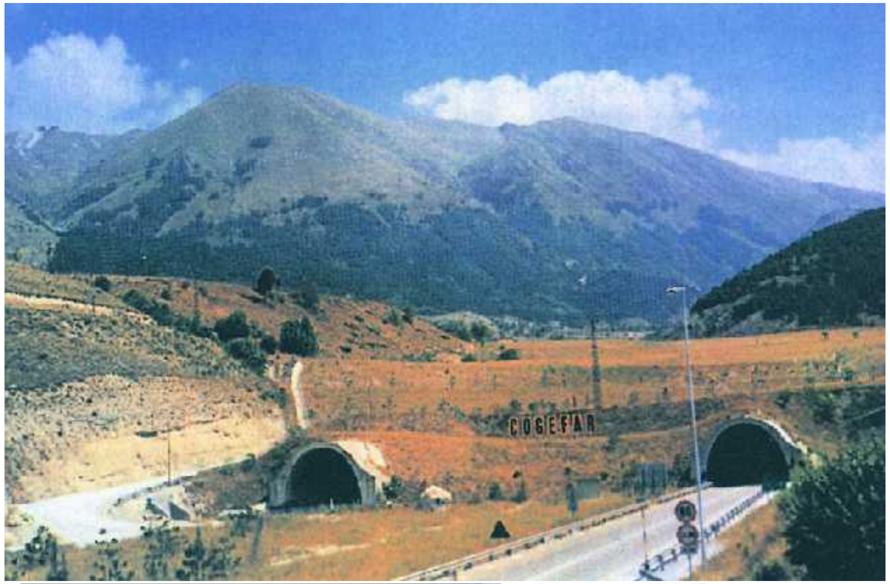
Experiment	Isotope	Experimental approach	
CANDLES	48Ca	Several tons of CaF_2 crystals in Liquid scintillator	
CARVEL	^{48}Ca	100 kg $^{48}CaWO_4$ crystal scintillators	
COBRA	^{116}Cd, ^{130}Te	420 kg CdZnTe semiconductors	
CUORE	^{130}Te	750 kg TeO_2 cryogenic bolometers	running as CUORICINO
DCBA	^{150}Nd	20 kg Nd layers between tracking chambers	
EXO	^{136}Xe	1 ton Xe TPC (gas or liquid)	
GERDA	^{76}Ge	$\sim$ 40 kg Ge diodes in LN_2, expand to larger masses	
GSO	^{160}Gd	2t Gd_2SiO_3:Ce crystal scintillator in liquid scintillator	
MAJORANA	^{76}Ge	$\sim$ 180 kg Ge diodes, expand to larger masses	
MOON	^{100}Mo	several tons of Mo sheets between scint.	
SNO+	^{150}Nd	1000 t of Nd-loaded liquid scint.	
SuperNEMO	^{82}Se	100 kg of Se foils between TPCs	running as NEMO-3
Xe	^{136}Xe	1.56 t of Xe in liquid scint.	
XMASS	^{136}Xe	10 t of liquid Xe	

small scale ones will expand, very likely not a complete list...

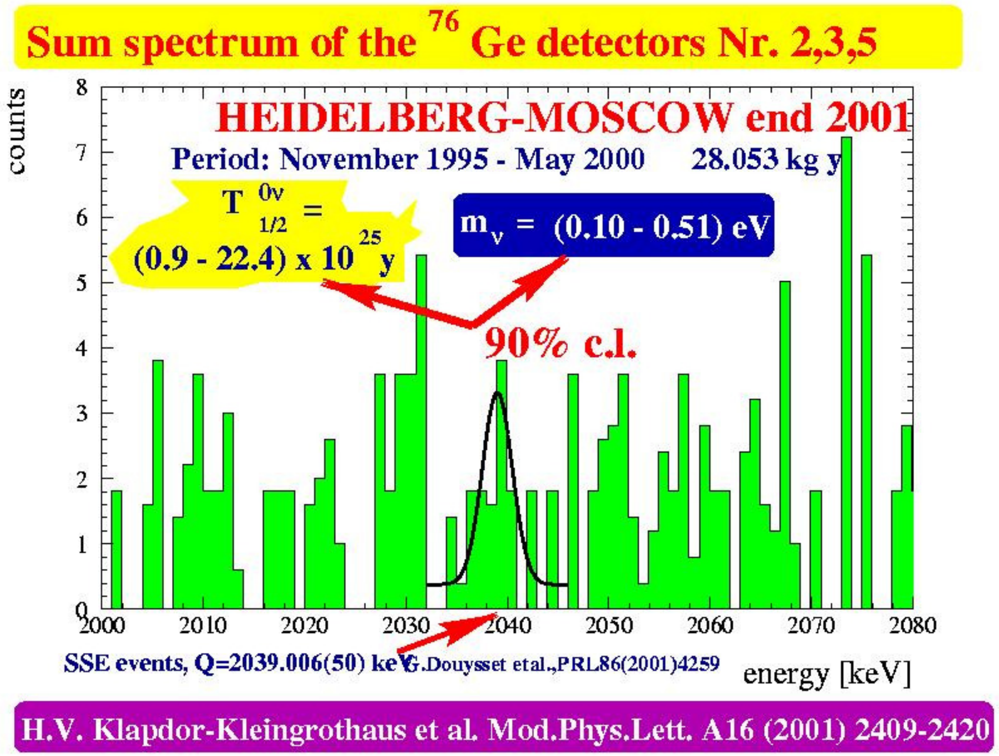
Heidelberg -Moscow

- **The detectors are decaying!!**
- **5 isotopical enriched Ge-detectors**
- **Peak at 2039 keV**





Heidelberg -Moscow



Part of collaboration: $T_{1/2} = 2.23 \pm 0.4 \times 10^{25}$ yr → $m = 0.32 \pm 0.03$ eV

H.V. Klapdor-Kleingrothaus et al., Phys. Lett. B 586, 198 (2004), Mod.Phys.Lett.A21:1547-1566,2006

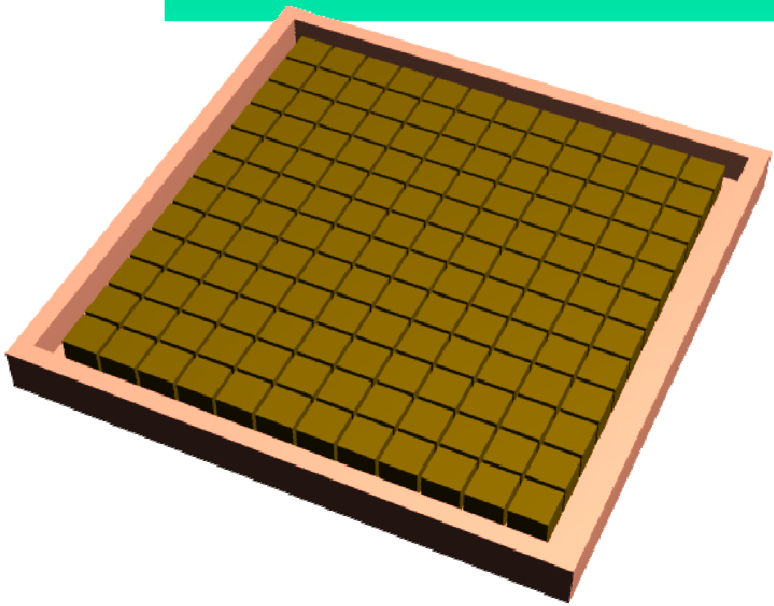
Current aims

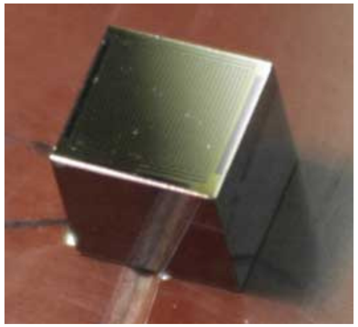
- ★ Check whether observed peak claimed in ^{76}Ge is true (GERDA)
- ★ If yes, observe it with at least one other isotope to confirm that it is double beta decay
- ★ If not, next milestone will be 50 meV suggested by oscillation results
- ★ If still no observation, down to range 1-10 meV

Remember: $$m_\nu \propto \sqrt[4]{\frac{\Delta E B}{M t}}$$

COBRA

Use large amount of CdZnTe Semiconductor Detectors



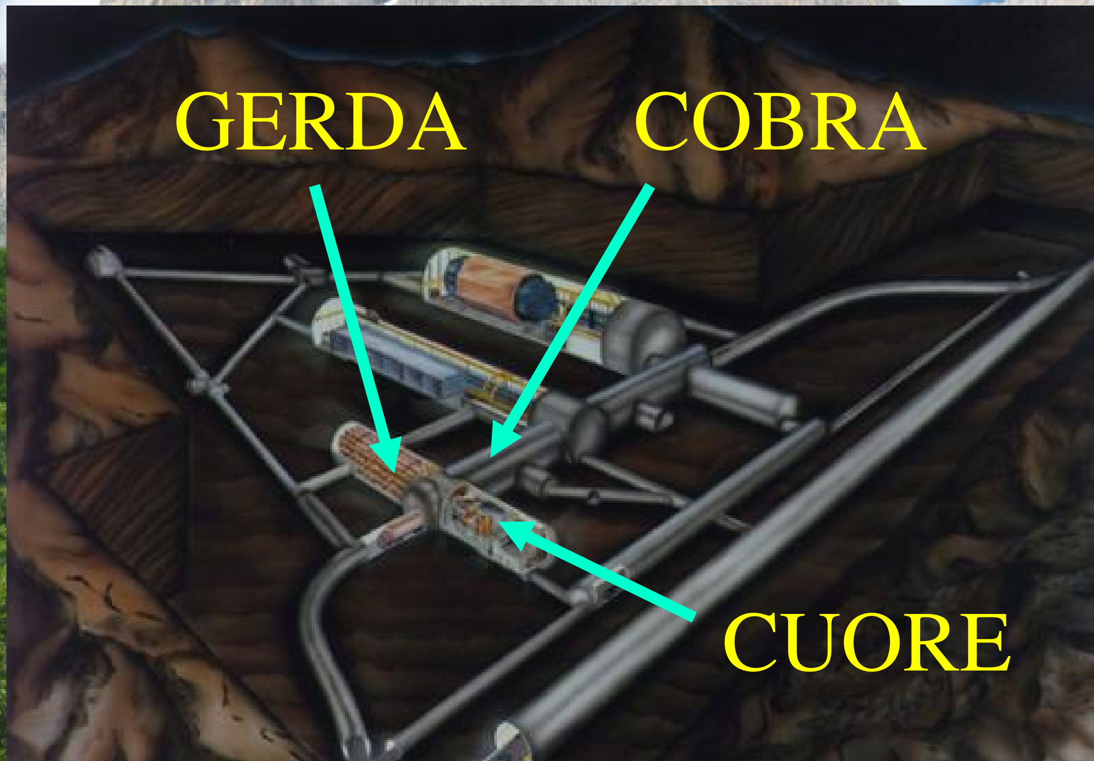


Large array of CdZnTe detectors

K. Zuber, Phys. Lett. B 519,1 (2001)

Gran Sasso (Italy)

It's all about background reduction



COBRA collaboration

TU Dresden
TU Dortmund
Material Research Centre
Freiburg

Washington University
at St. Louis

Czech Technical University
Prague

Laboratori Nazionali del
Gran Sasso

University of Bratislava

University of Jyvaskyla

University of La Plata

JINR Dubna

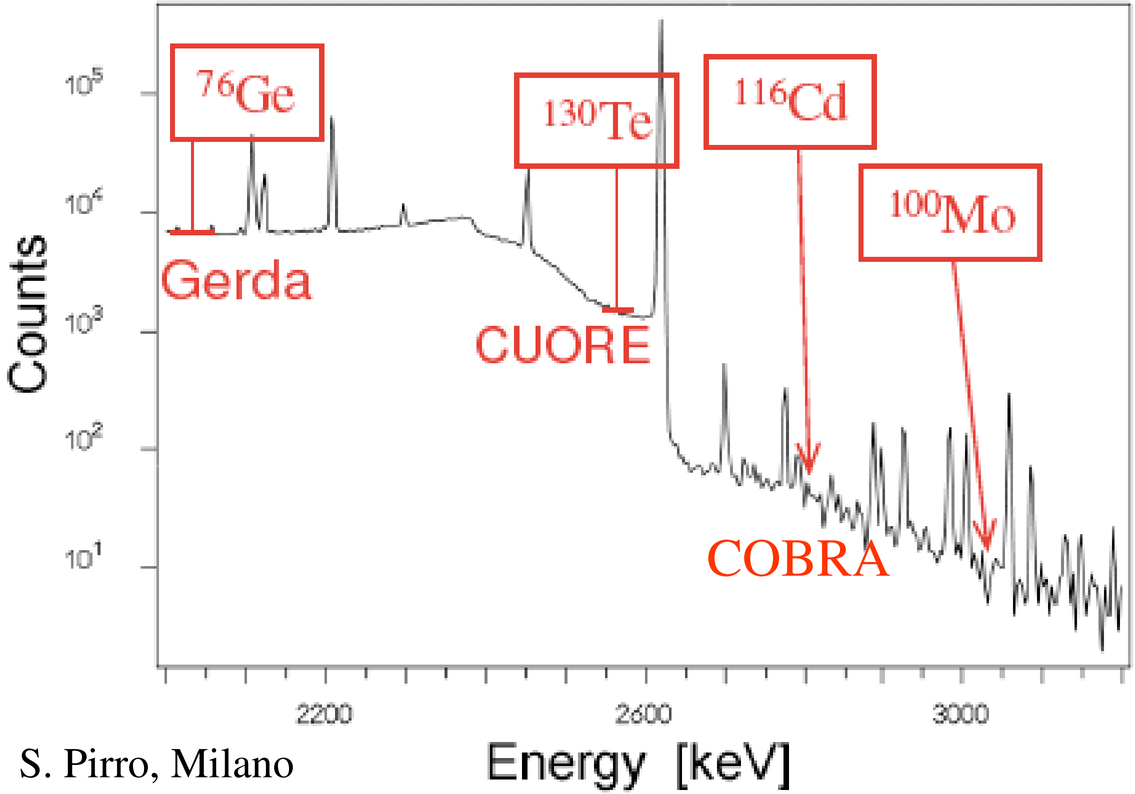
More welcome

Supporting institutes: University of Hamburg (Germany), Jagellonian University (Poland), Los Alamos Nat. Lab. (USA)

Advantages

- Source = detector
- Semiconductor (Good energy resolution, clean)
- Room temperature
- Modular design (Coincidences)
- Two isotopes at once
- Industrial development of CdTe detectors
- ^{116}Cd above 2.614 MeV
- Tracking („Solid state TPC")

Background



S. Pirro, Milano

Beyond 2.614 MeV background a priori much lower

Isotopes

	nat. ab. (%)	Q (keV)	Decay mode
Zn70	0.62	1001	ß-ß-
Cd114	28.7	534	ß-ß-
Cd116	7.5	2809	ß-ß-
Te128	31.7	868	ß-ß-
Te130	33.8	2529	ß-ß-
Zn64	48.6	1096	ß+/EC
Cd106	1.21	2771	ß+ß+
Cd108	0.9	231	EC/EC
Te120	0.1	1722	ß+/EC

Latest shell model calculations

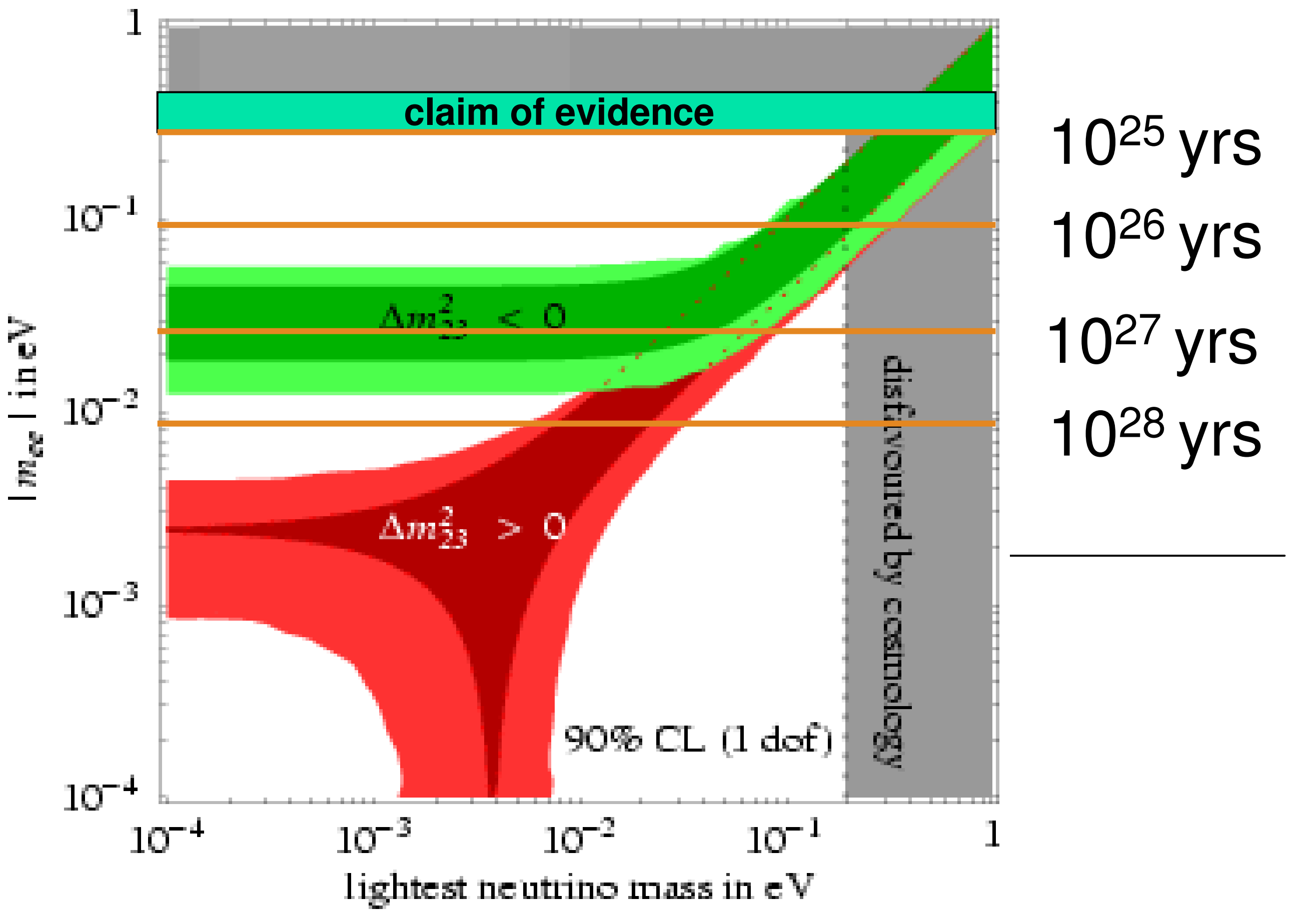
	m_ν for $T_{\frac{1}{2}} = 10^{25}$ y.	$M_{GT}^{(0\nu)}$	$1\text{-}\chi_F$
^{48}Ca	0.85	0.67	1.14
^{76}Ge	0.90	2.35	1.10
^{82}Se	0.42	2.26	1.10
^{110}Pd	0.44	2.67	1.15
^{116}Cd	0.27	2.49	1.18
^{124}Sn	0.45	2.11	1.13
^{128}Te	1.92	2.36	1.13
^{130}Te	0.35	2.13	1.13
^{136}Xe	0.41	1.77	1.13

^{116}Cd comes of best...

E. Caurier et al, arXiv:0709.2137, PRL 100, 052503 (2008)

Needed Sensitivity

$$T_{1/2} \propto a\varepsilon\sqrt{M \times t / \Delta E \times B}$$



Current ideas

Detectors (CdZnTe)

Energy

Pixel

Shielding

Passive

Passive and active

LSci

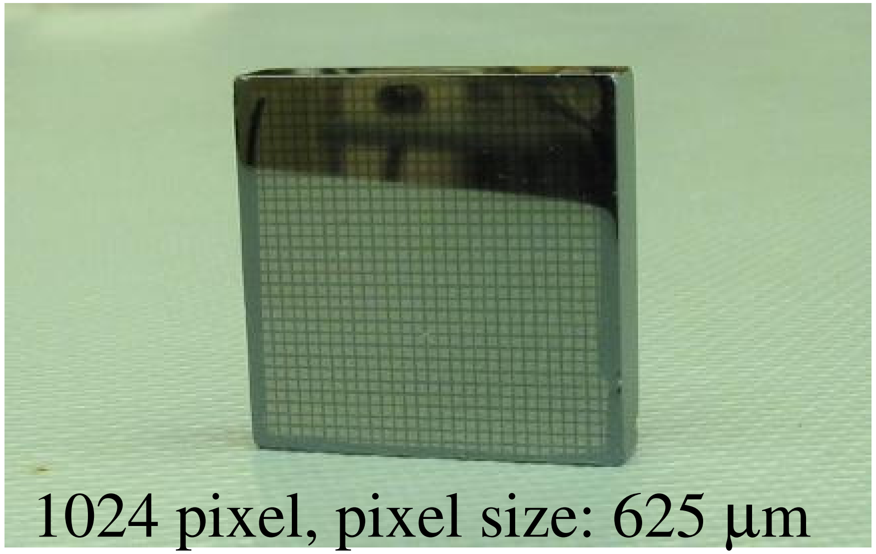
It's all about background

Background from:
natural radioactivity, cosmogenic produced radioisotopes, cosmic rays, neutrons

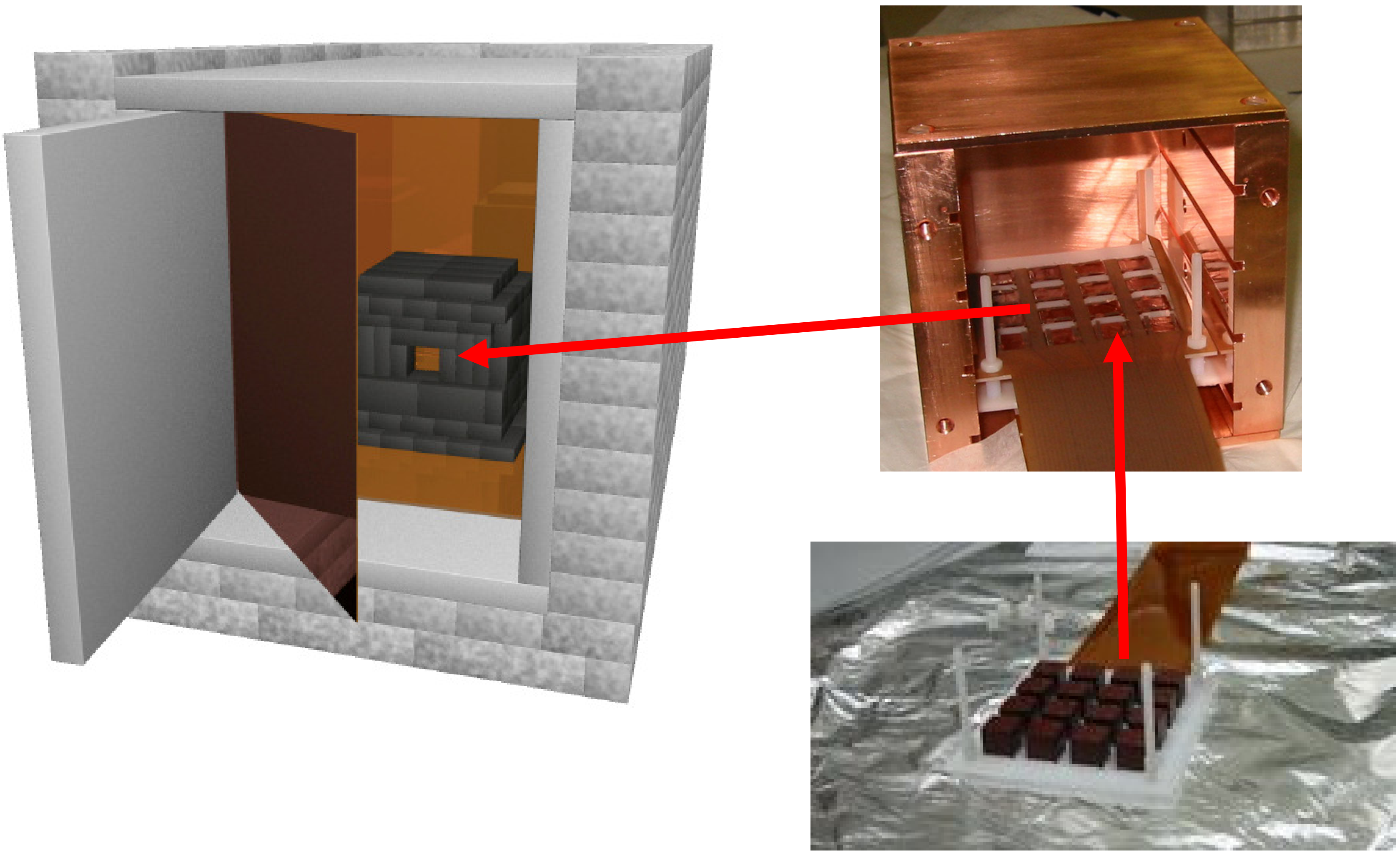
Two options

Energy measurement only

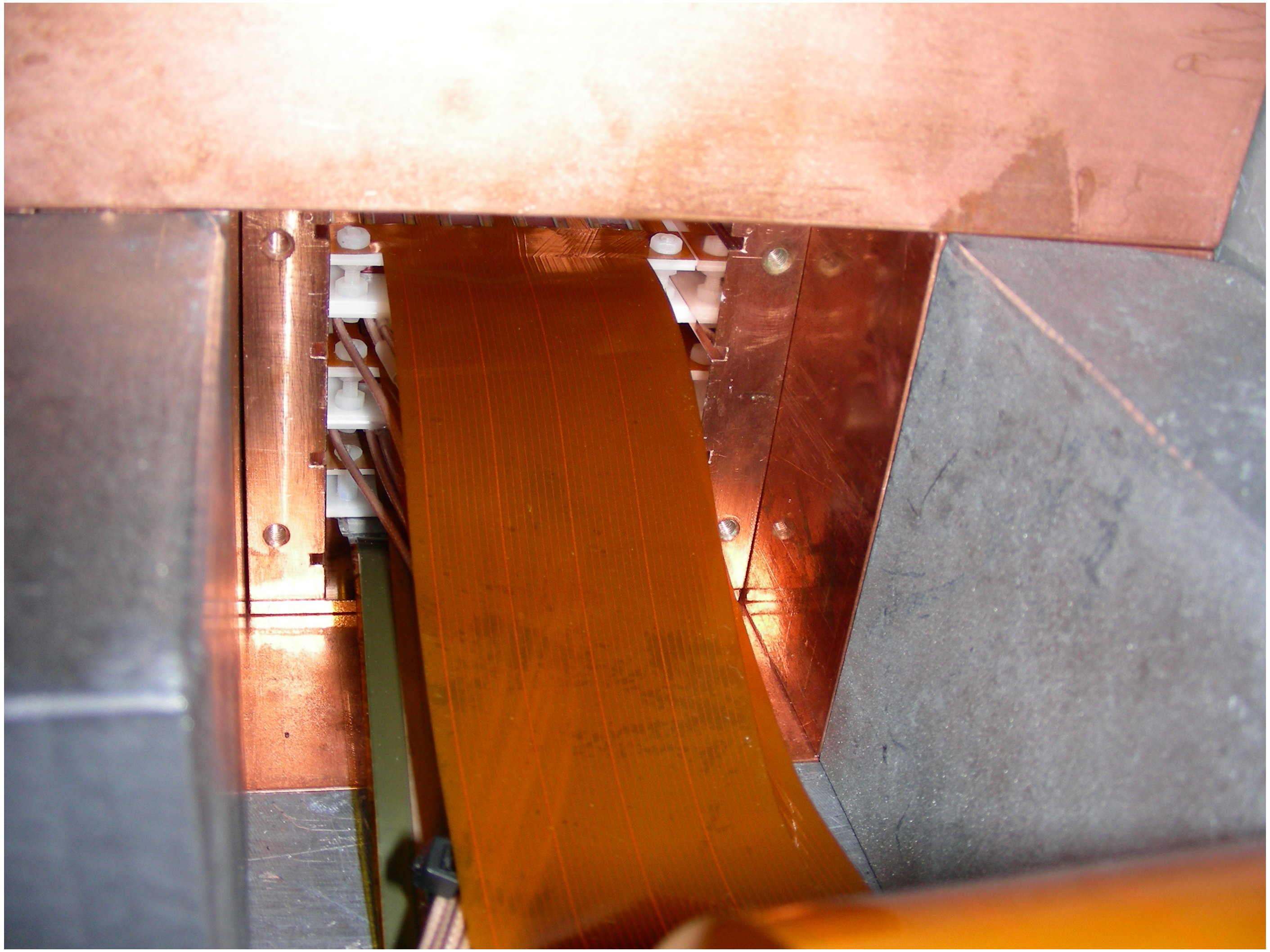
Energy measurement and tracking



COBRA Set-up at LNGS

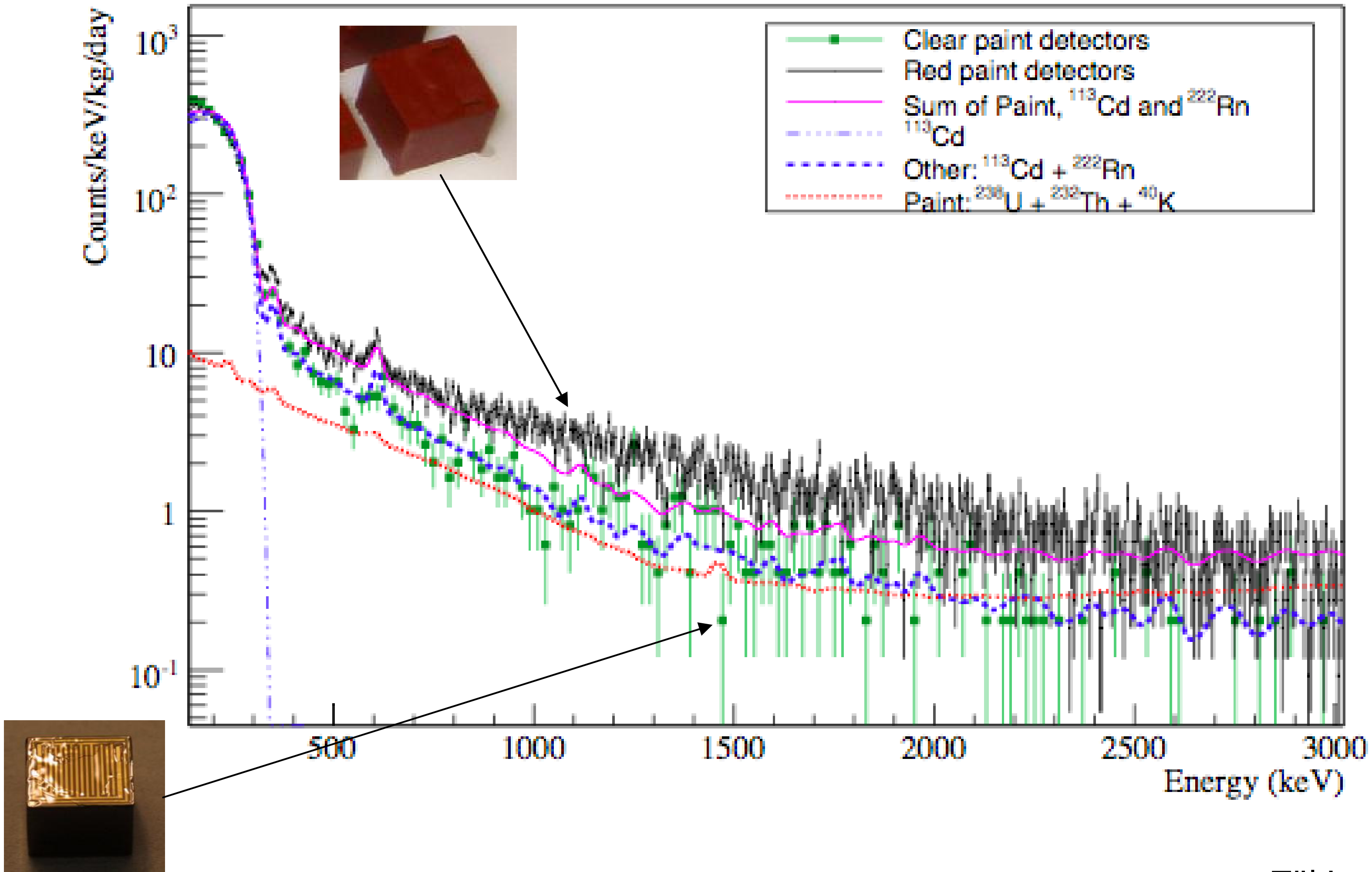


64 array



Background model

Assumption: Major background is paint + radon

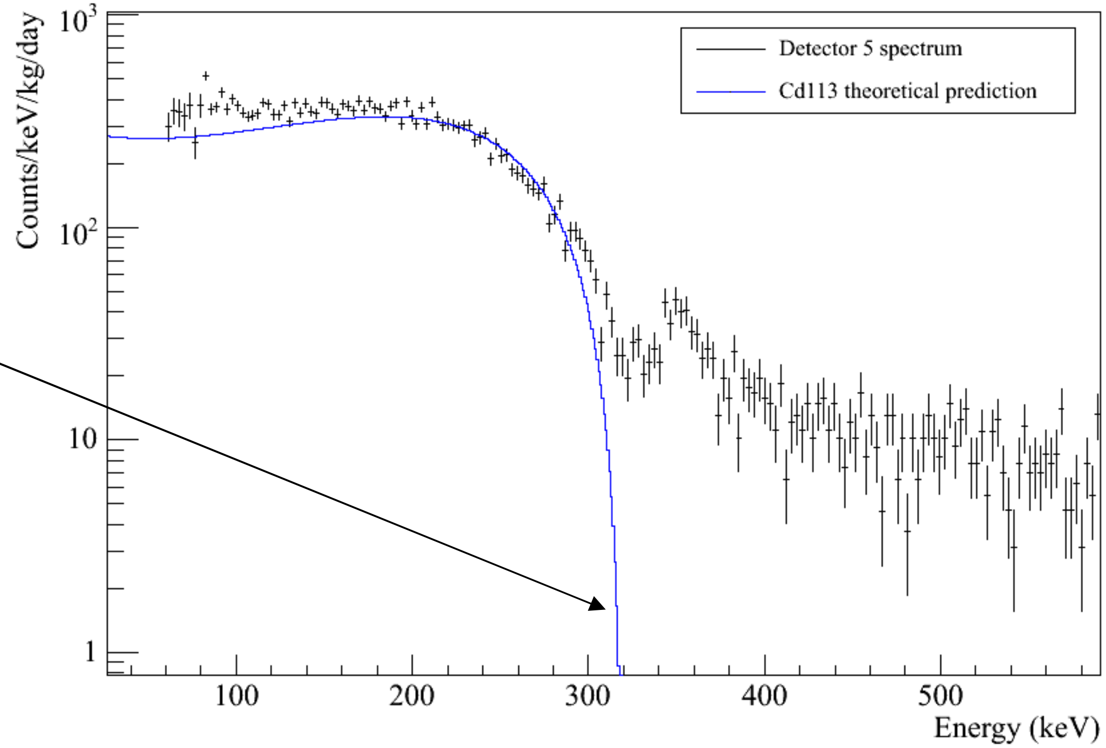


Cd-113

4-fold non-unique beta decay ($1/2^+ \rightarrow 9/2^+$)

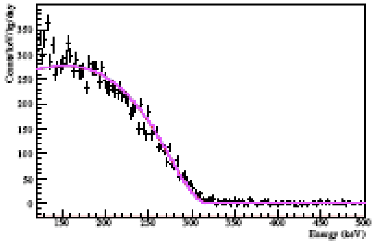
First half-life result published as C. Goessling et al., PRC **72:064328,2005**

First time theoretical model based on nuclear structure calculation (thanks to J. Suhonen)

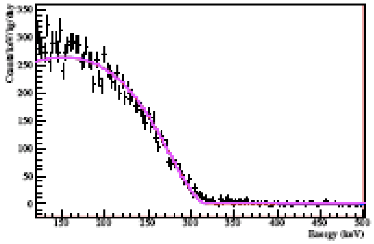


We have more than 10 independent measurements now...

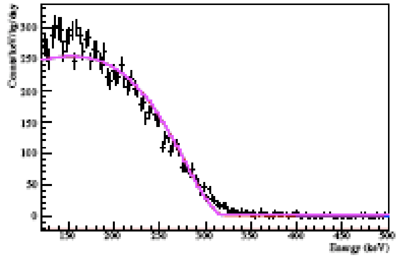
Cd-113



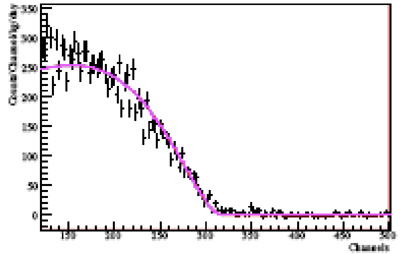
(a) Detector 2



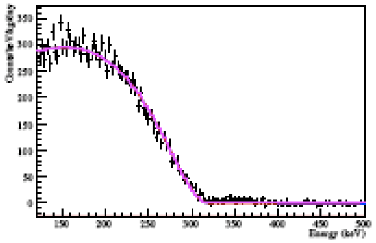
(b) Detector 3



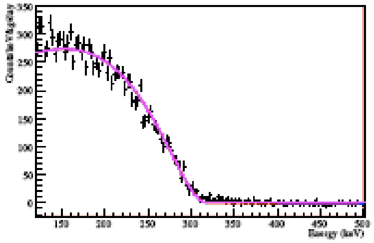
(g) Detector 10



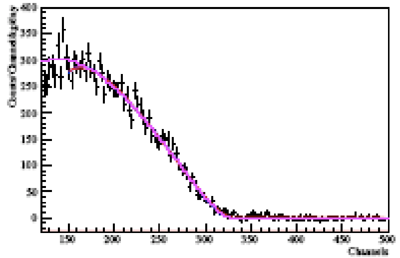
(h) Detector 11



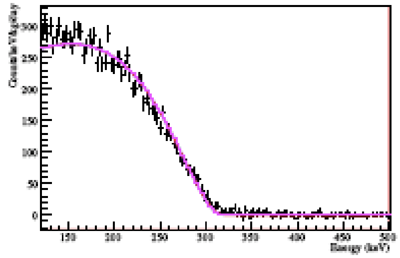
(c) Detector 5



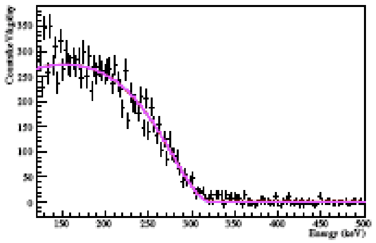
(d) Detector 7



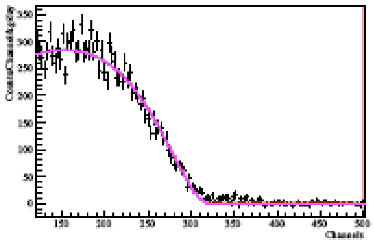
(i) Detector 12



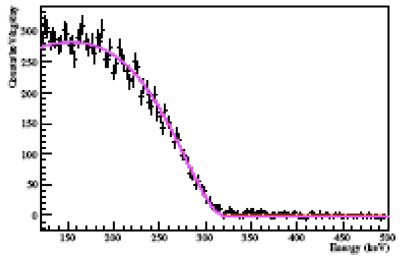
(j) Detector 14



(e) Detector 8



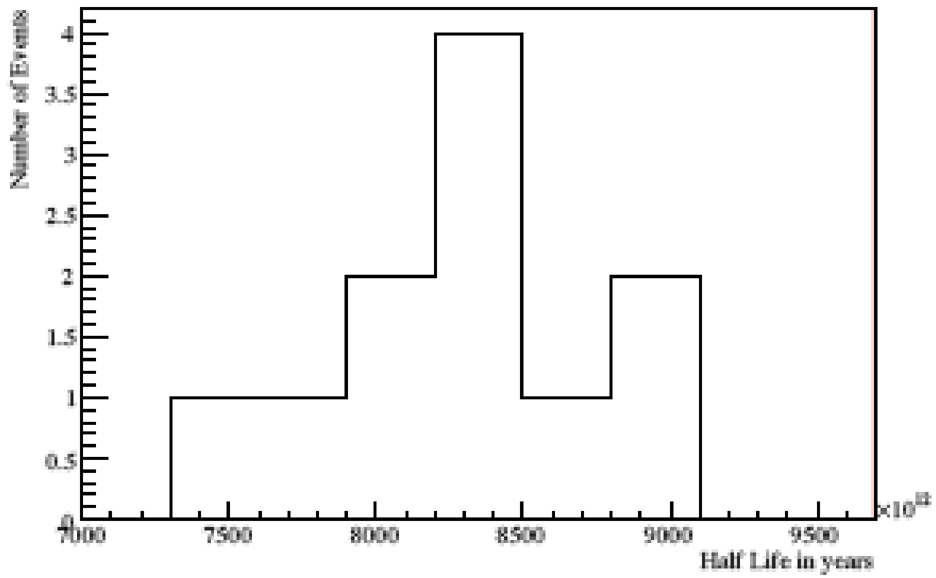
(f) Detector 9



(k) Detector 15

Cd-113

First time histogram of 10^{16} yrs half-life measurements



Half-life: $T_{1/2} = 8.00 \pm 0.11(stat.) \pm 0.24(sys.) \times 10^{15}$ years

Q-value: $322 \pm 0.3(stat.) \pm 0.9(sys.)$ keV

Spectral shape fits better with unique 3-fold forbidden than non-unique transition

J. V. Dawson et al., Nucl. Phys. A 818,264 (2009)

New Results

PRELIMINARY PRELIMINARY

Isotope and Decay	Fit Range (MeV)	$T_{1/2}$ limit (years) This work	Previous [14]
^{116}Cd to gs	2.2–3.2	9.4×10^{19}	3.14×10^{19}
^{130}Te to gs	2.2–3.2	5.0×10^{20}	9.92×10^{19}
^{130}Te to 536 keV	1.7–2.3	3.5×10^{20}	3.73×10^{19}
^{116}Cd to 1294 keV	1.2–1.8	5.0×10^{19}	4.92×10^{18}
^{116}Cd to 1757 keV	0.9–1.3	4.2×10^{19}	9.13×10^{18}
^{128}Te to gs	0.6–1.3	1.7×10^{20}	5.38×10^{19}
^{116}Cd to 2027 keV	0.5–1.2	2.8×10^{19}	1.37×10^{19}
^{116}Cd to 2112 keV	0.5–1.0	4.7×10^{19}	1.08×10^{19}
^{116}Cd to 2225 keV	0.5–1.0	2.1×10^{19}	9.46×10^{18}
^{130}Te to 1794 keV	0.5–1.2	1.9×10^{20}	3.1×10^{18} [15]
^{130}Te to 1122 keV	1.1–1.7	1.2×10^{20}	1.4×10^{19} [15]
^{114}Cd to gs	0.4–1.0	2.0×10^{20}	6.4×10^{18} [15]

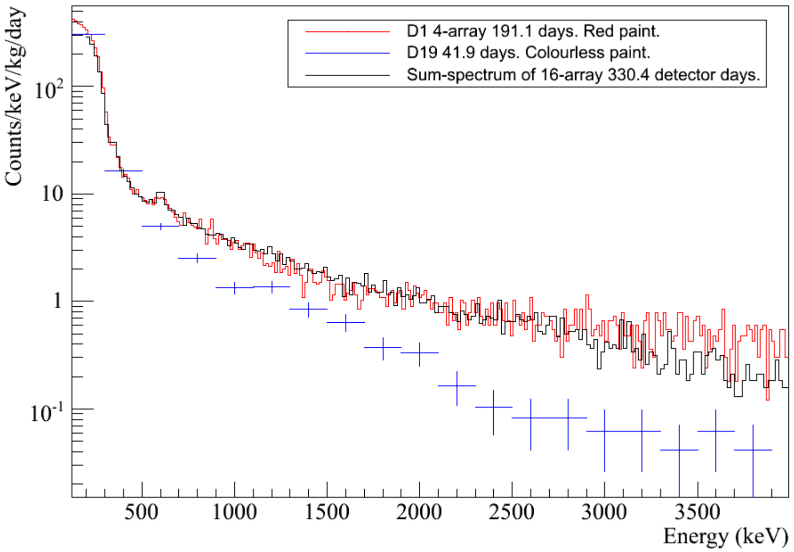
Isotope and Decay	Fit Range (MeV)	$T_{1/2}$ limit (years) This work	Previous [14]
^{64}Zn β^+EC to gs	0.5–1.3	1.1×10^{18}	2.78×10^{17}
^{120}Te β^+EC to gs	1.0–2.0	4.1×10^{17}	1.21×10^{17}
^{120}Te 2EC	0.8–2.0	2.4×10^{16}	2.68×10^{15}
^{120}Te 2EC to 1171 keV	0.6–2.0	1.8×10^{16}	9.72×10^{15}
^{106}Cd $\beta^+\beta^+$ to gs.	0.5–2.0	2.7×10^{18}	4.50×10^{17}
^{106}Cd β^+EC to gs	1.5–3.0	4.7×10^{18}	7.31×10^{18}
^{106}Cd 2 EC to gs	2.0–3.0	1.6×10^{17}	5.7×10^{16}
^{106}Cd $\beta^+\beta^+$ to 512 keV	0.6–1.5	9.4×10^{17}	1.81×10^{17}
^{106}Cd β^+EC to 512 keV	0.8–2.0	4.6×10^{18}	9.86×10^{17}

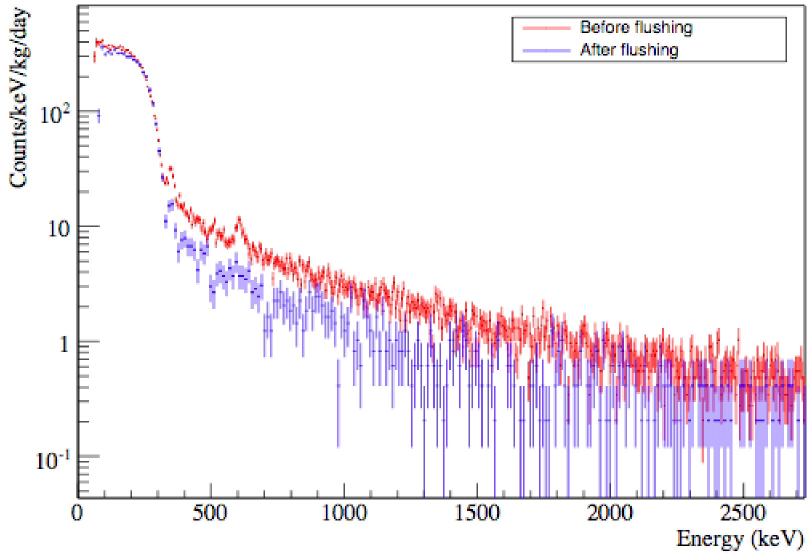
based on 18 kg days of data, analysis ongoing

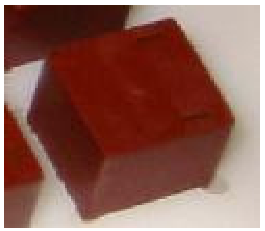
Next things done

Remove passivation paint

Install nitrogen flushing

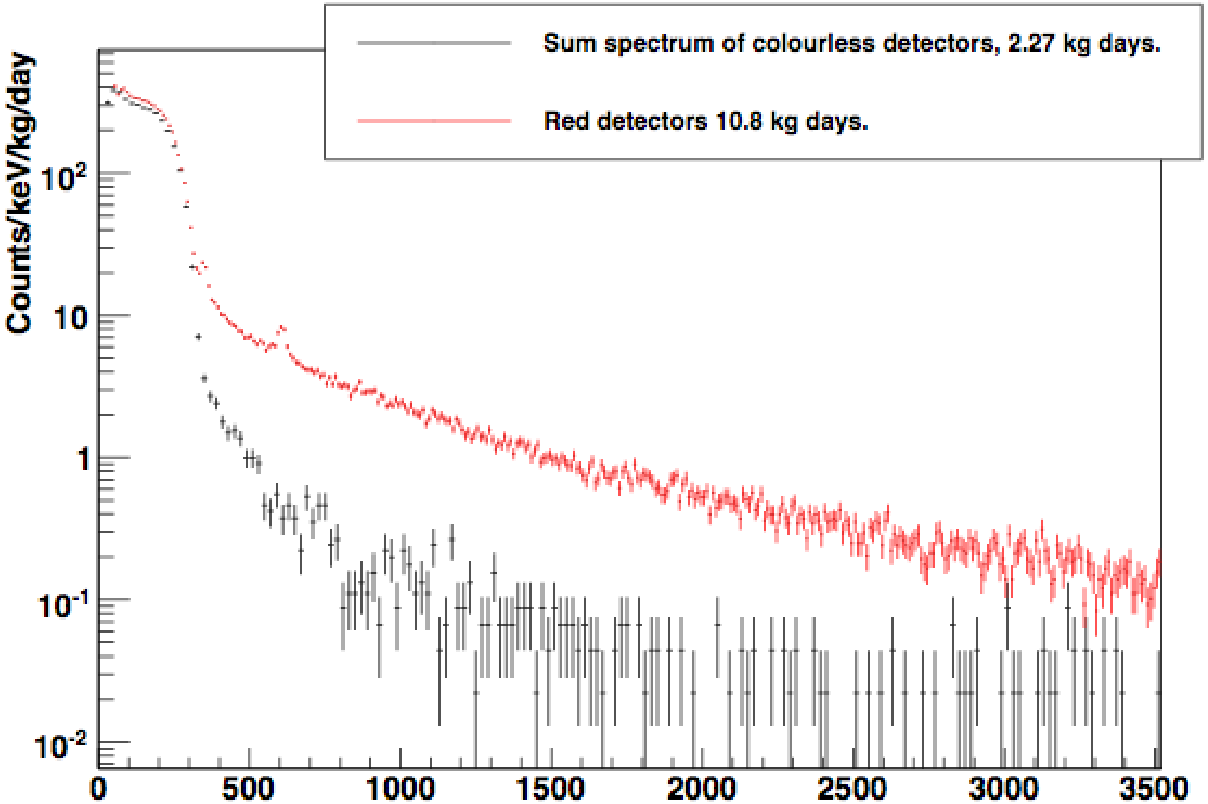






Measured spectrum

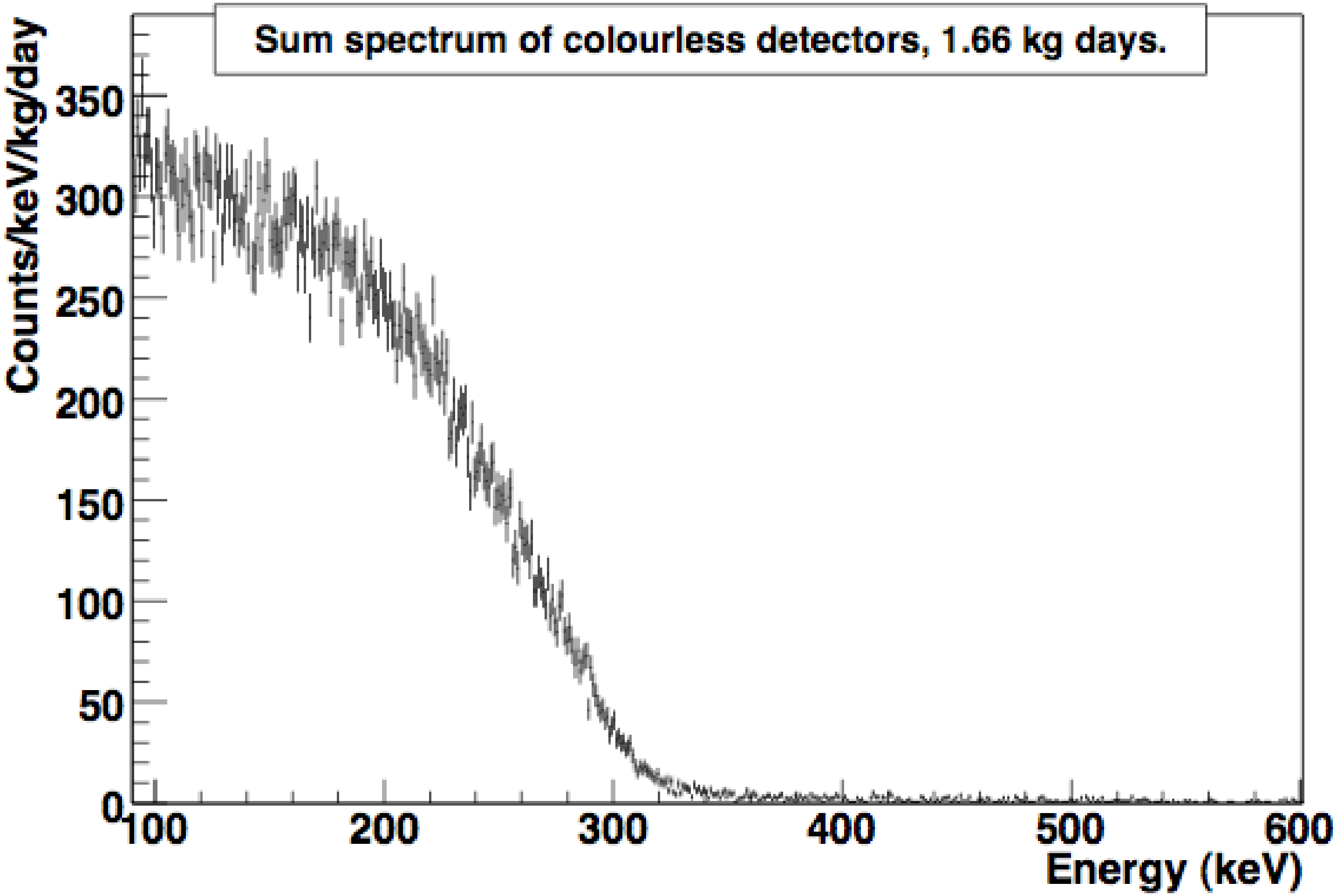
Data taking with red crystals finished, about 18.1 kg*d statistics, currently under analysis



Background at 2.8 MeV around 5 counts/keV/kg/yr !!

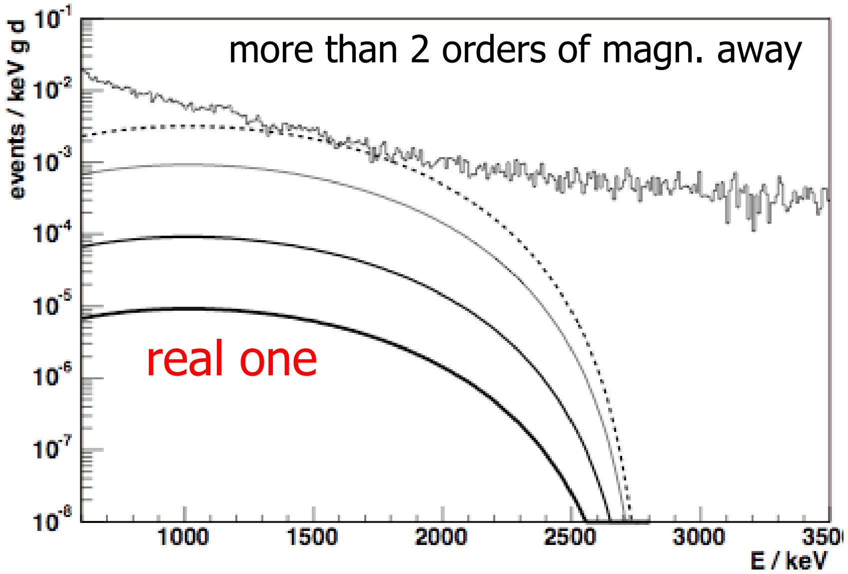
To show the progress...(I)

^{113}Cd spectrum

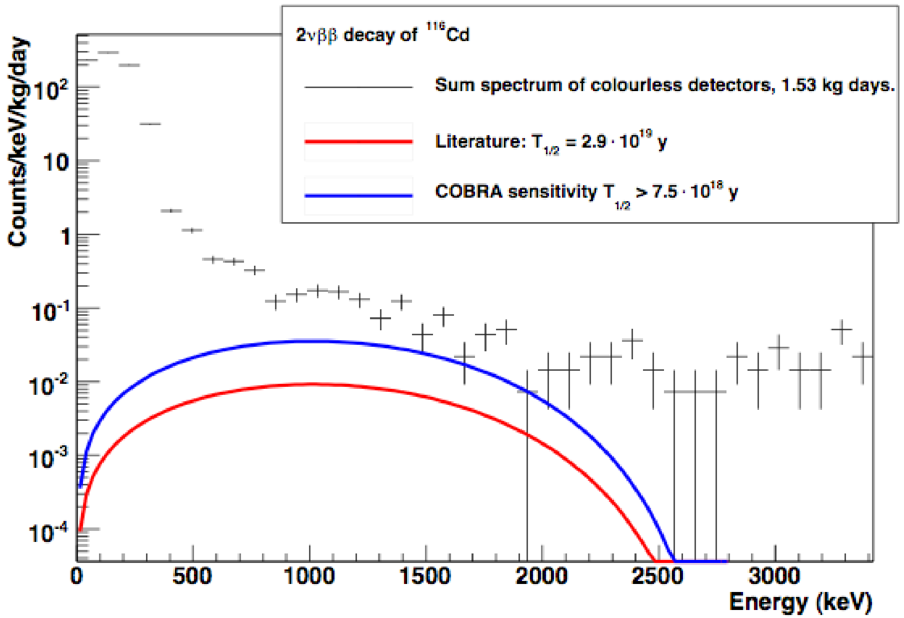


To show the progress... (II)

Approaching 2nu double beta of ^{116}Cd ($T_{1/2}$ =2.9 x10^{19} yrs)

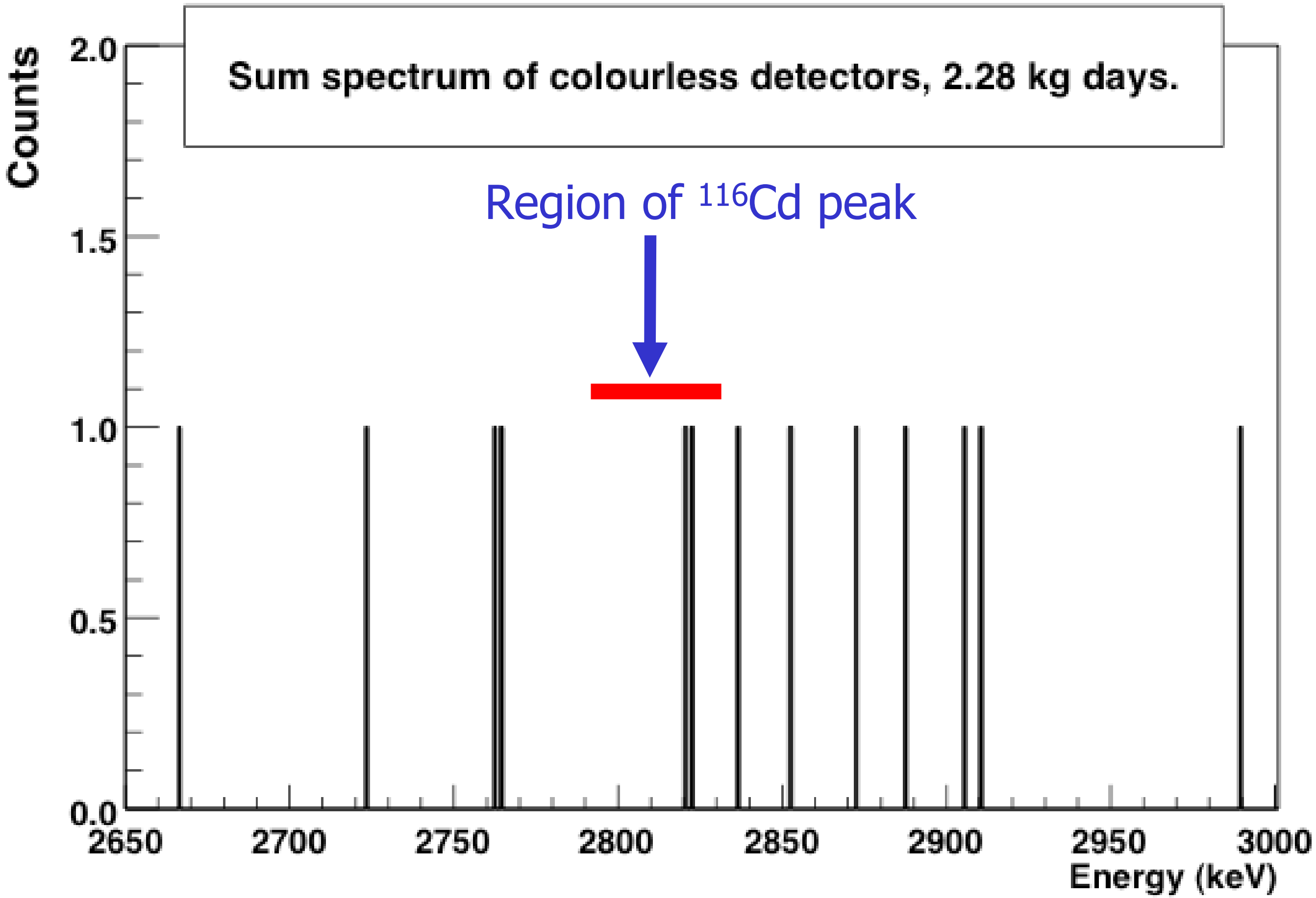


H. Kiel, Ph.D. thesis 2005



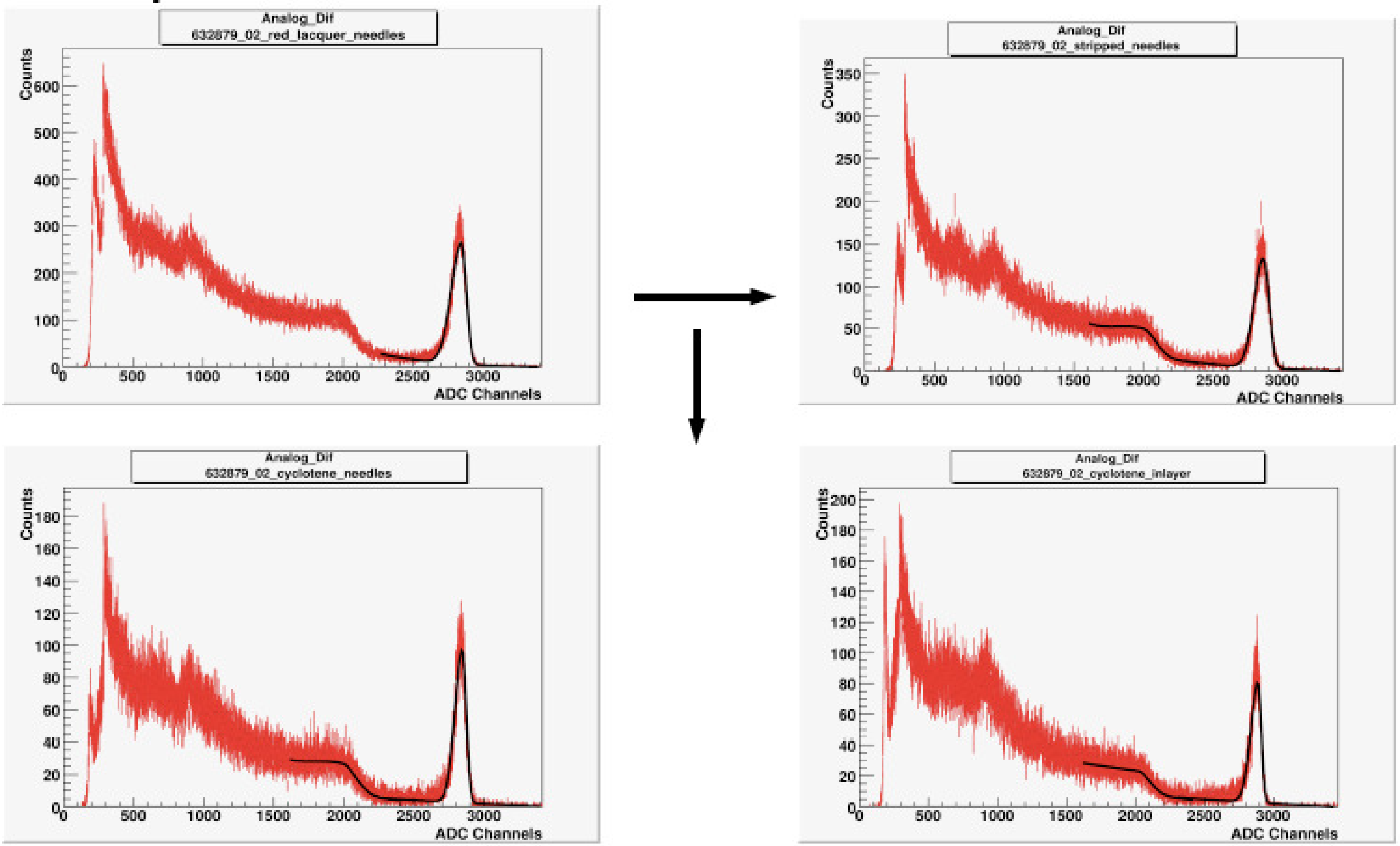
now (2008)

Region of interest



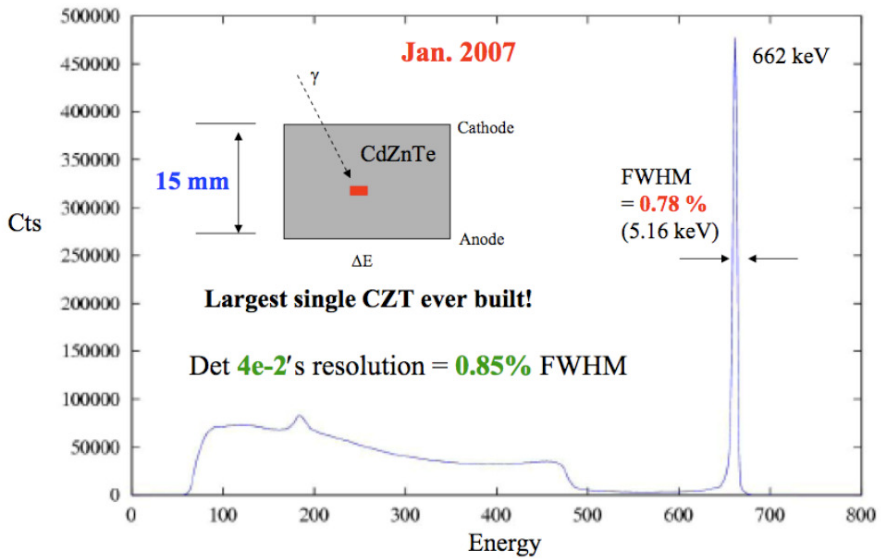
Removing the paint...

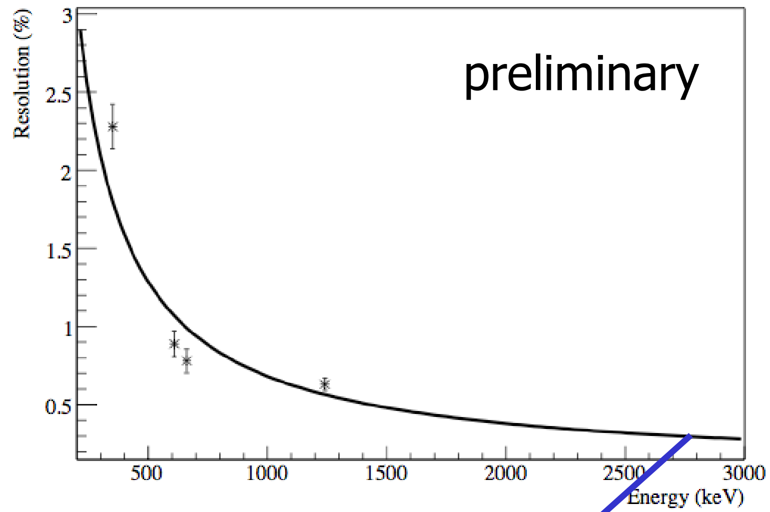
- ^{137}Cs-spectrum:

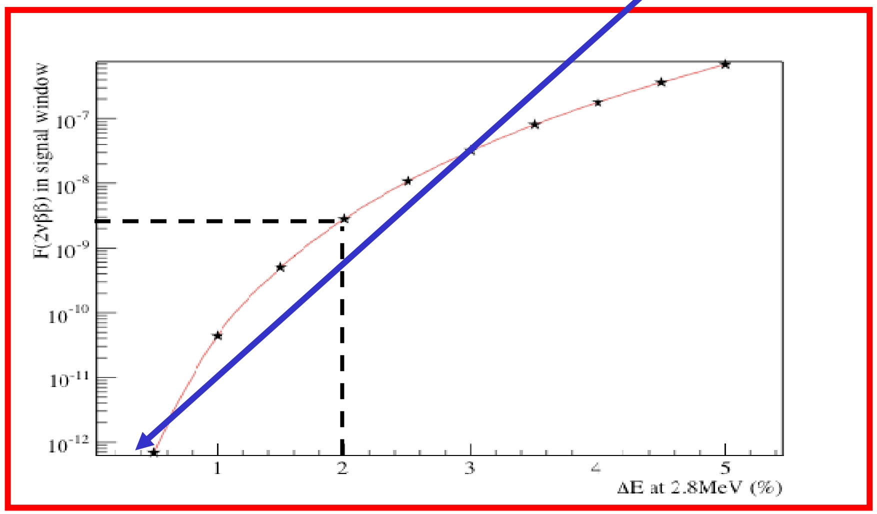


If stable will be done for all remaining detectors

Latest development on CZT



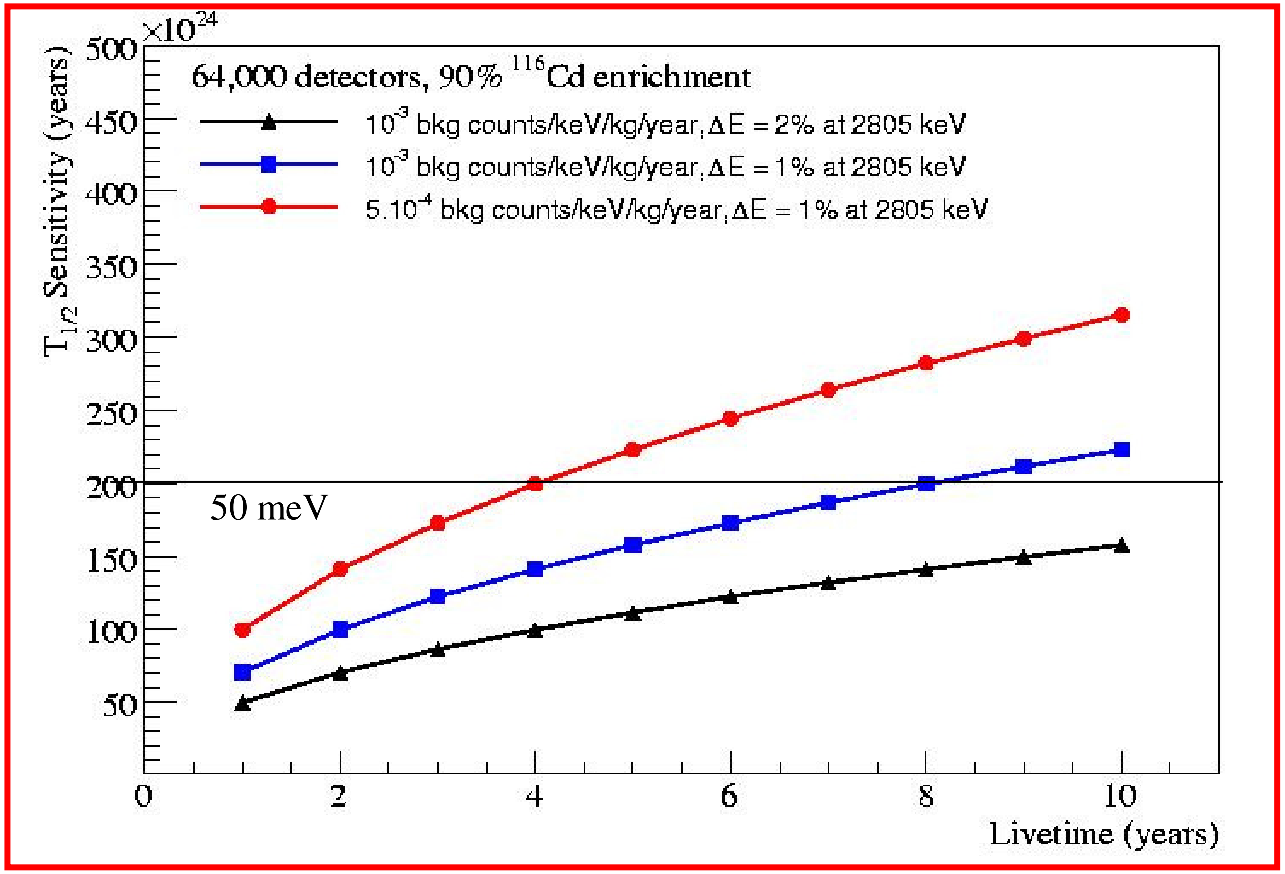




36 gram detector,
6 times larger than
current COBRA detectors

Needed Sensitivity

$$T_{1/2} \propto \sqrt{M \times t / \Delta E \times B}$$



KING COBRA - Below 50 meV

Current idea: 40x40x40 CdZnTe detectors = 420 kg, enriched in 116Cd

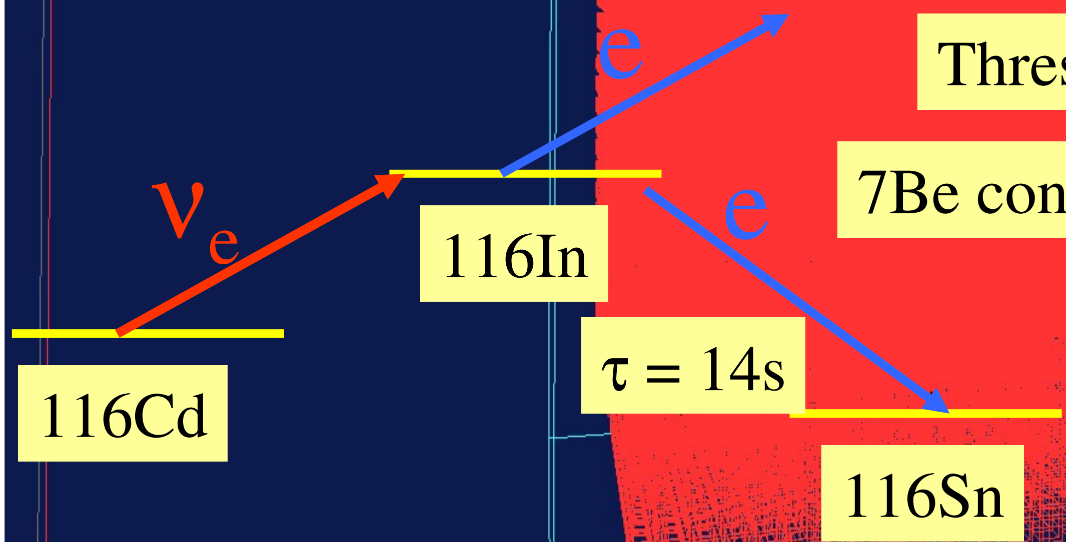
Down to 10 meV you might be

...

A real time low-energy solar neutrino and Supernova experiment?

Threshold energy: 464 keV

7Be contribution g.s. alone: 227 SNU

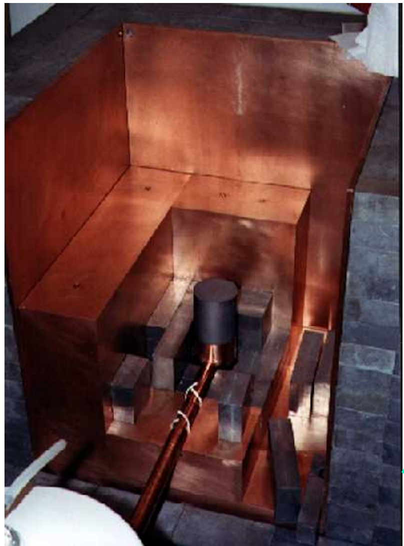


K. Zuber, Phys. Lett. B 571,148 (2003)
K Balasi, T.Kosmas, P. Divari, subm.

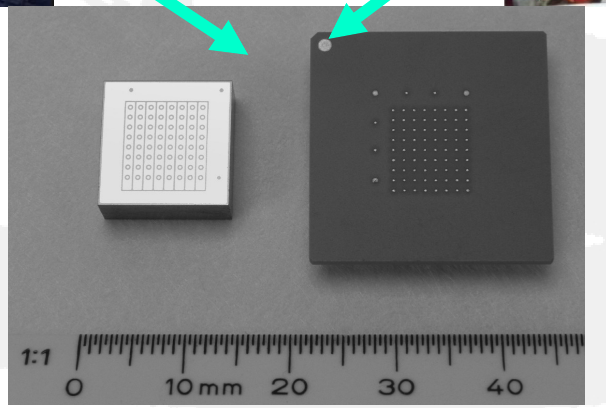
The solid state TPC

Semiconductor Tracker

Energy resolution



Tracking



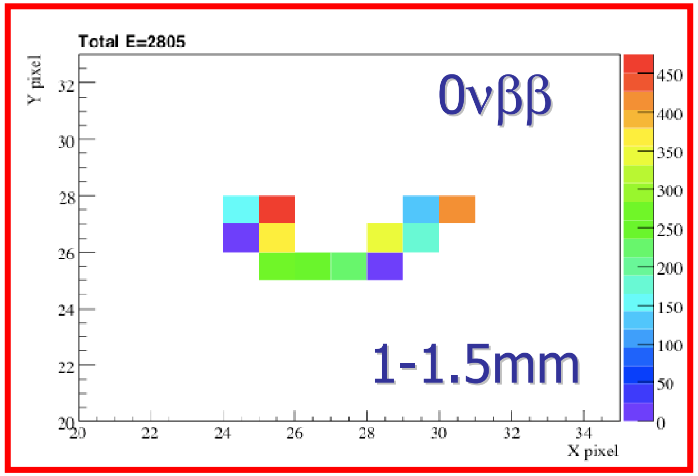
- Massive background reduction
- Positive signal identification

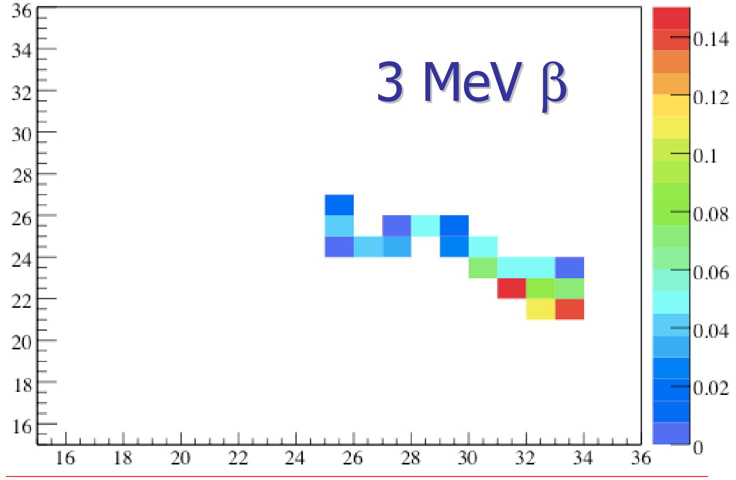
Pixelated CdZnTe detectors

Pixelisation

★ Idea: Massive background reduction by particle identification

α= 1 pixel, β and ββ= several connected pixel, γ= some disconnected p.

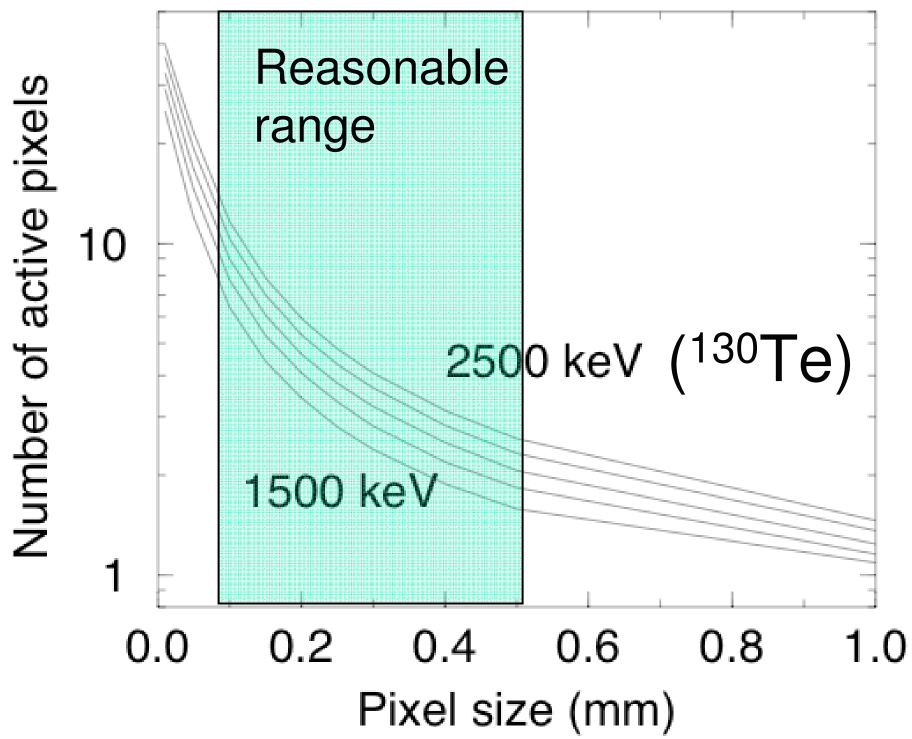




Beta with endpoint 3.3MeV

7.7MeV α life-time = 164.3μs

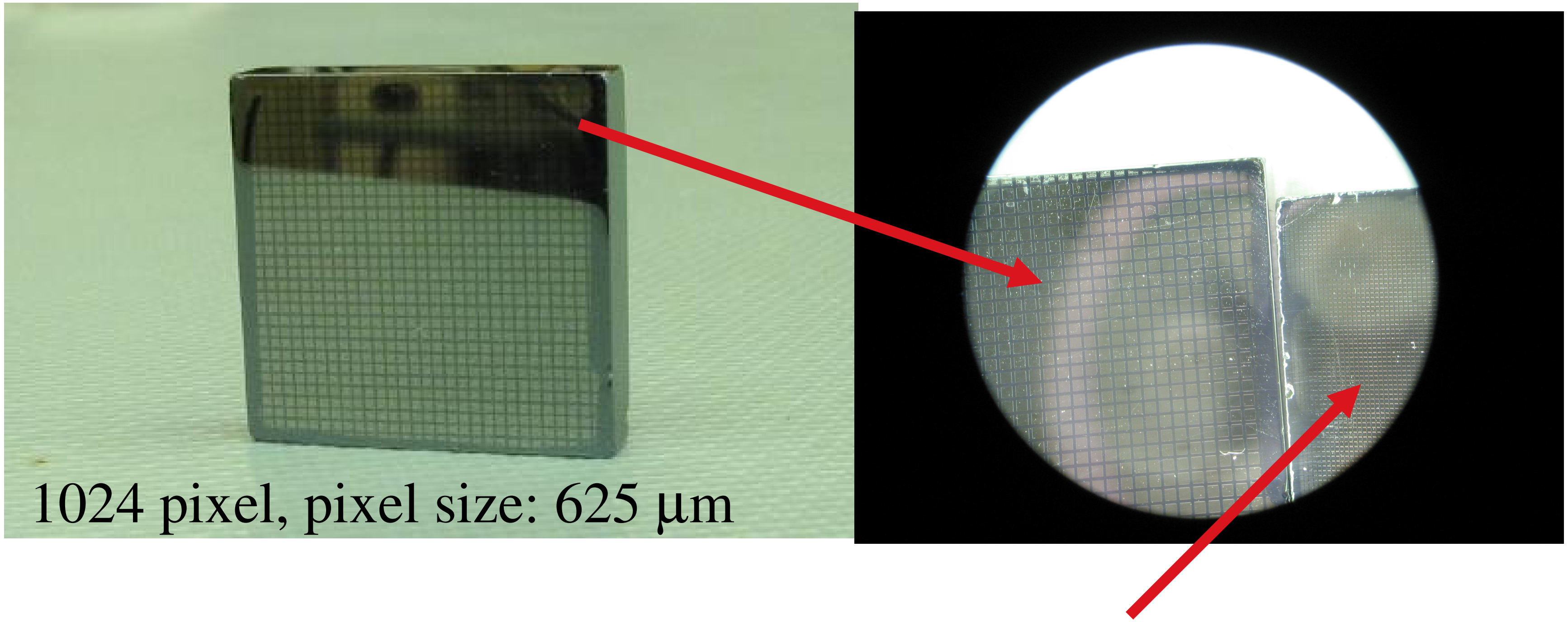
Pixel size



For 200 μm ^{130}Te and ^{116}Cd would hit about 7-10 pixel

Pixel detectors

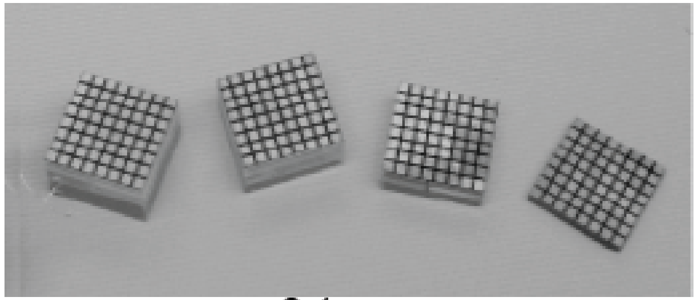
Two options: Timepix , CZT ASICs

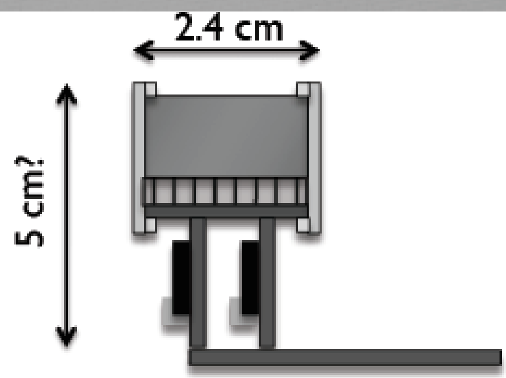


Pixel detector with 200 µm pixels (10000 pixel) produced!

Option1: ASICs for CZT

64 pixel detectors

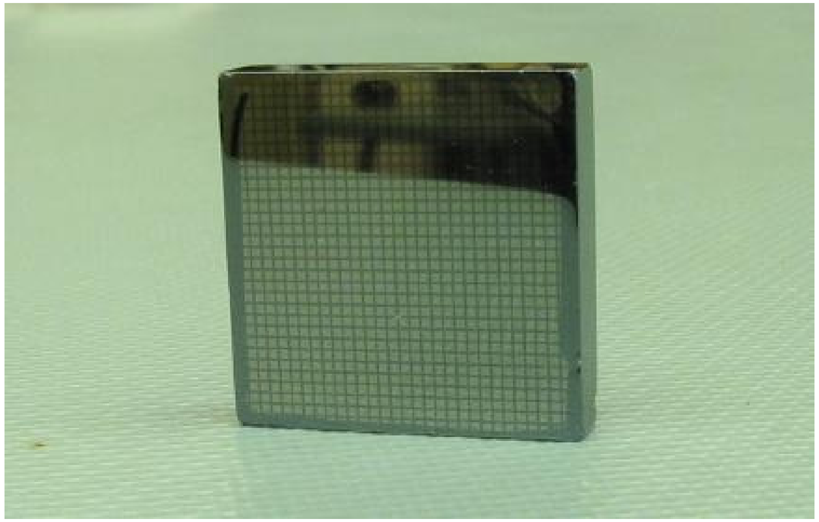




- Use DELRIN, pogo-pins, and teflon boards.
- ASICs and ADCs below detector.
- FPGA and all other electrons outside shielded area.

Installation at LNGS spring 2009

Detectors: 2x2x0.5 cm^3



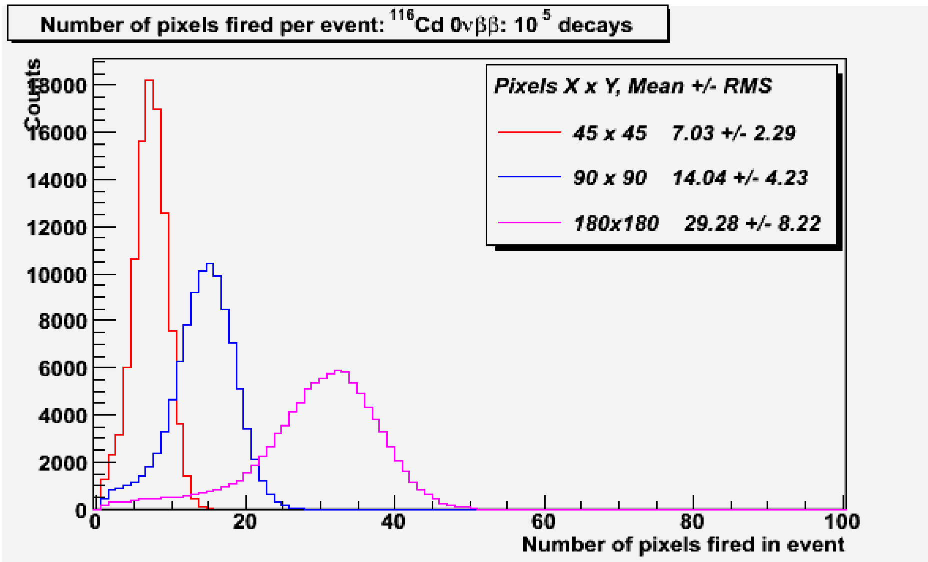
One 32x32 pixels sent for bonding to 1024 channel ASIC

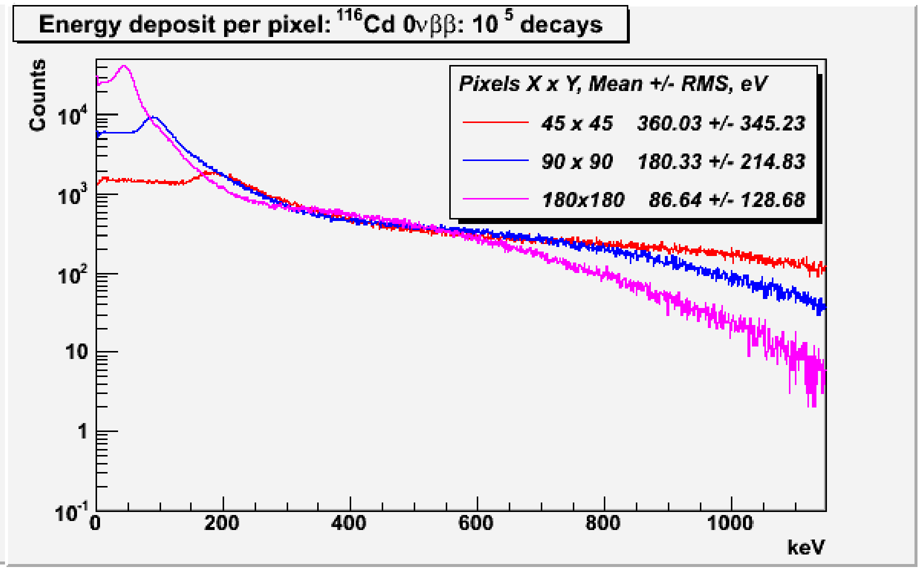
Second one 55x55 pixels sent fo bonding to 2048 channel ASIC

Option2: Timepix

55, 110, 220 μm option, 65000 channels (256x256)

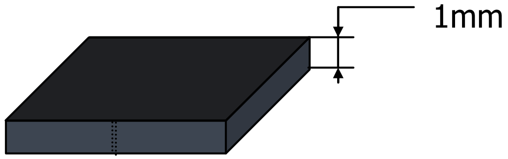
Simulation: 116Cd neutrinoless decay

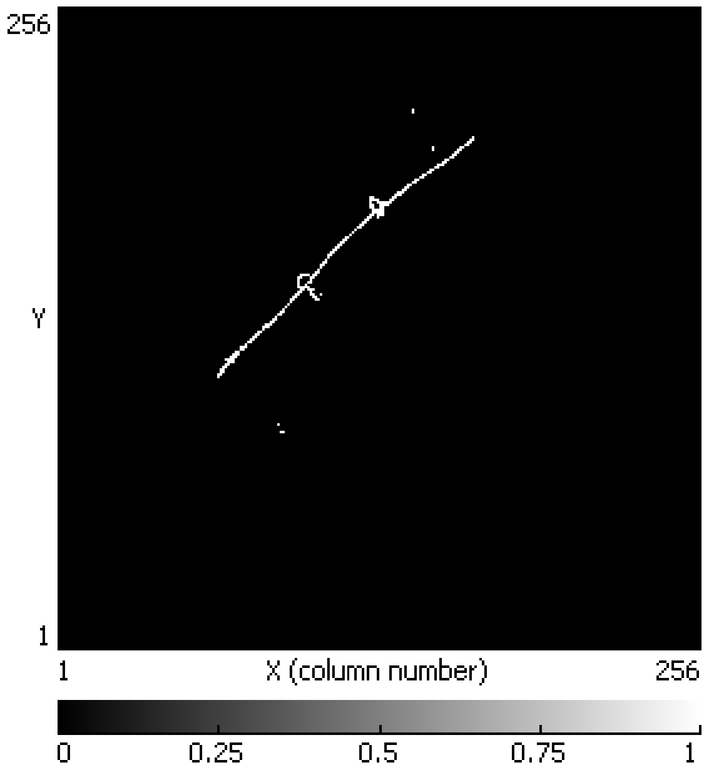




Option 2: Timepix

- ★ TimePix CdTe Detektor
- ★ 1mm Dicke, 256x256 Pixel, 55μm pitch, 1.4x1.4 cm^2

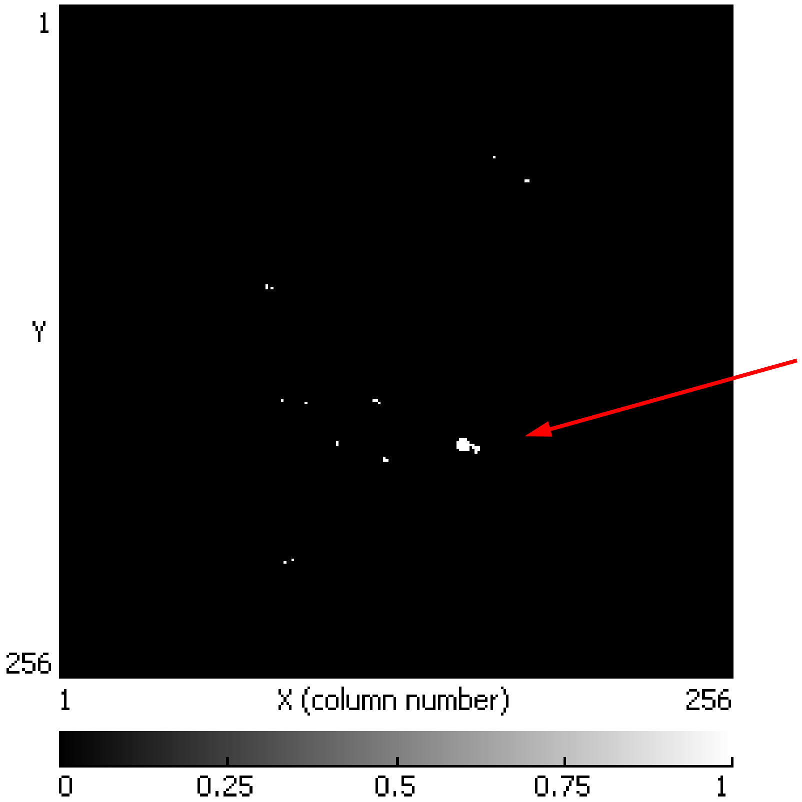


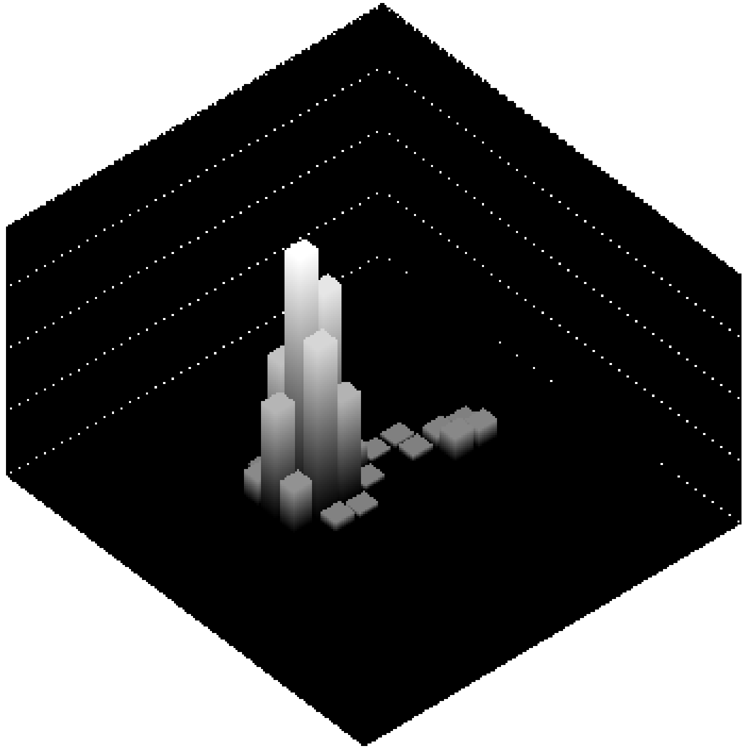


Myon candidate

snapshot...

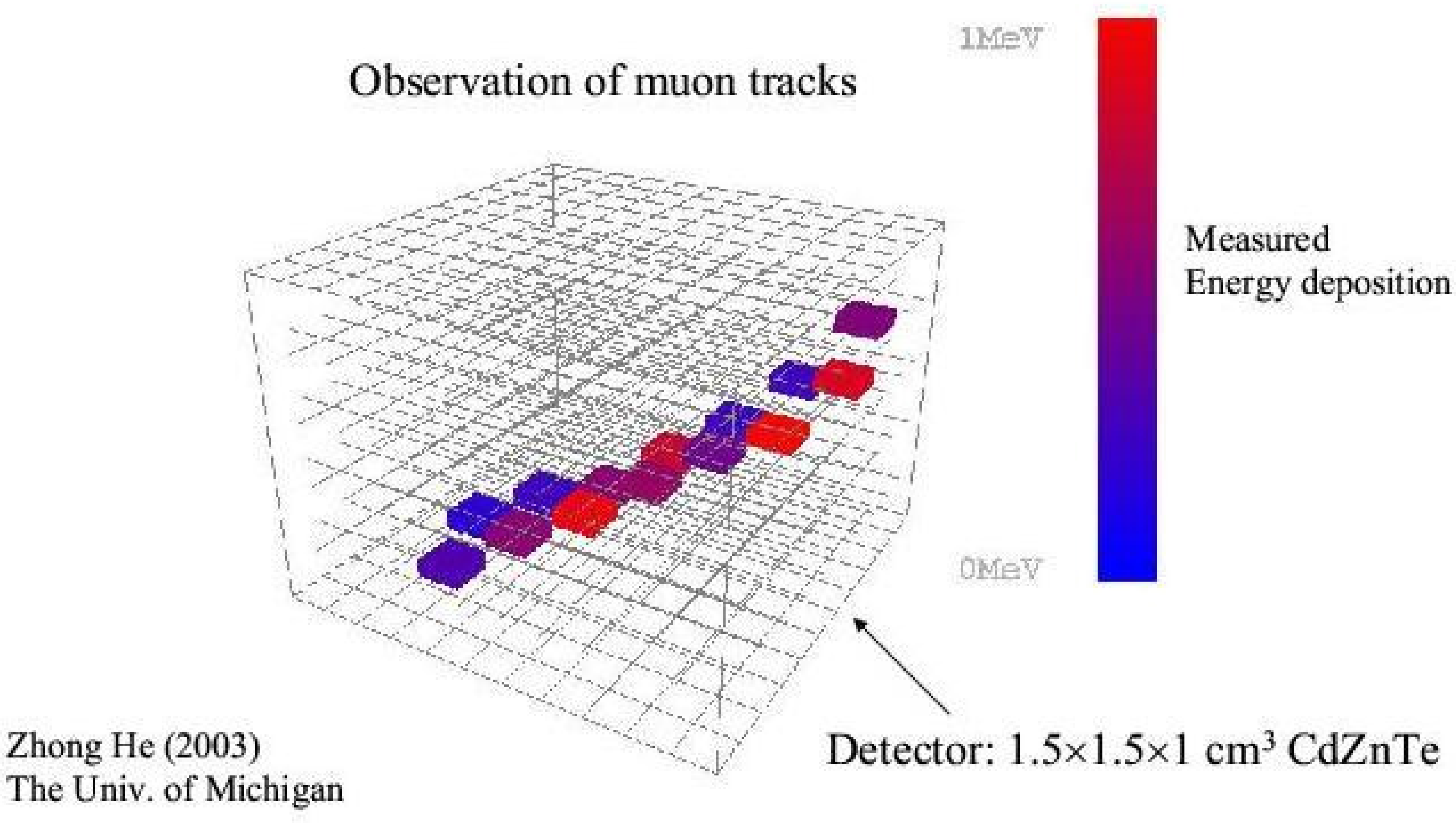
^{214}Bi alpha-beta coincidence candidate



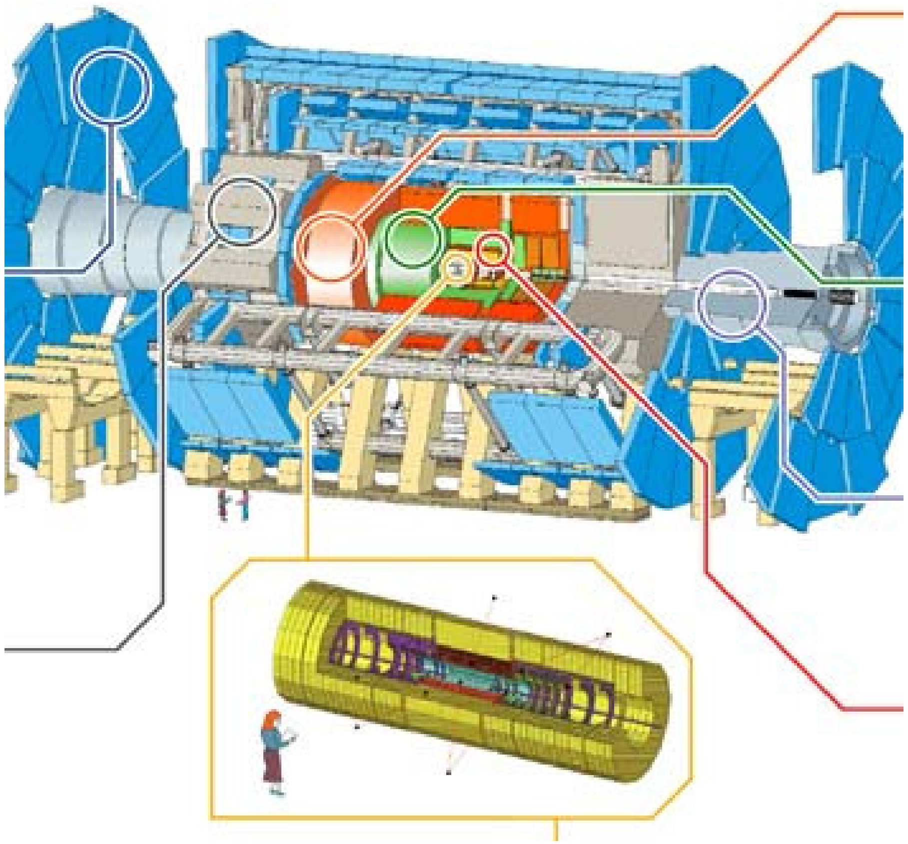


Unfortunately I can't show you a double beta event ...

Pixellated detectors



ATLAS Detector Photos



Nobody said it was going to be easy, and nobody was right

George W. Bush

Summary

Double beta decay is the gold plated channel to probe the fundamental character of neutrinos

Near term experimental goals are driven by the Klapdor claim of a peak in Ge-76

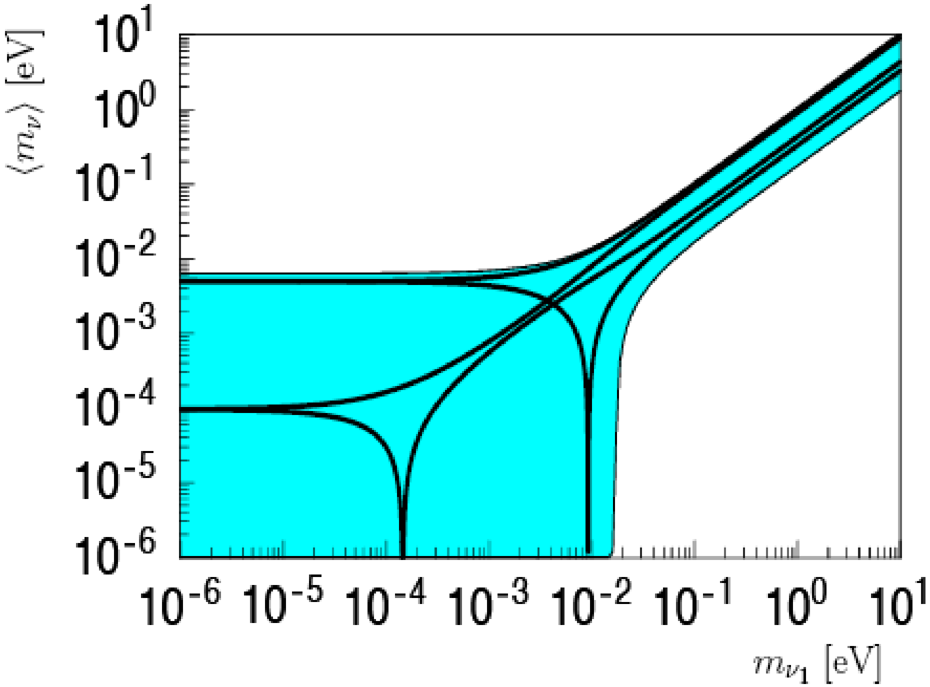
COBRA is a rather new approach making use of CZT room temperature semiconductors

First background sources have been identified and removed, working towards larger array (64), lower background

The solid state TPC (semiconductor tracker) can be the major step beyond existing double beta experiments.

Neutrino mass schemes and 0νββ

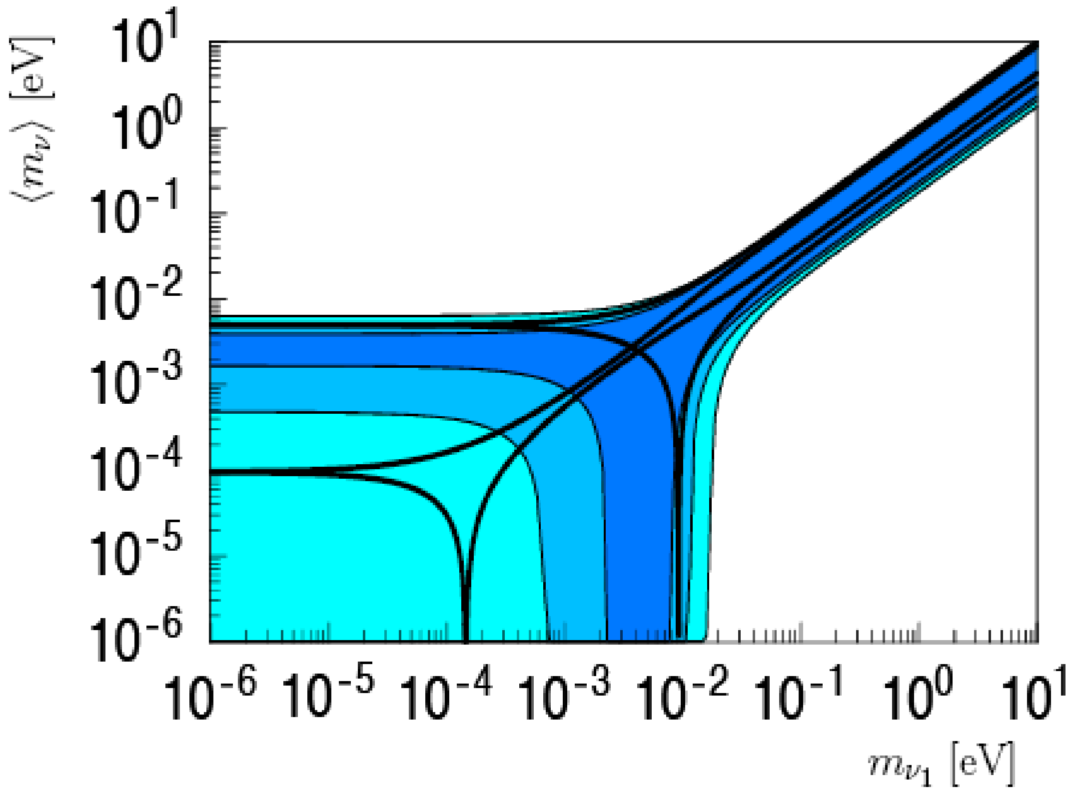
Adding errors



$$\Delta m^2_{Atm} = [1.4, 3.3] \cdot 10^{-3}\ \mathrm{eV}^2, \qquad \Delta m^2_{\odot} = [7.2, 9.1] \cdot 10^{-5}\ \mathrm{eV}^2,$$

$$\sin^2\theta_{\odot} = [0.23, 0.38], \qquad \sin^2\theta_R = [0, 0.051]$$

Effect of Θ_{13} in normal hierarchy



$\sin^2\theta_R =$
$[0, 5.1 \cdot 10^{-2}]$
$[0, 2.5 \cdot 10^{-2}]$
$[0, 5.1 \cdot 10^{-3}]$

$\Delta m^2_{Atm} = [1.4, 3.3] \cdot 10^{-3}$ eV^2, $\Delta m^2_{\odot} = [7.2, 9.1] \cdot 10^{-5}$ eV^2,
$\sin^2\theta_{\odot} = [0.23, 0.38]$

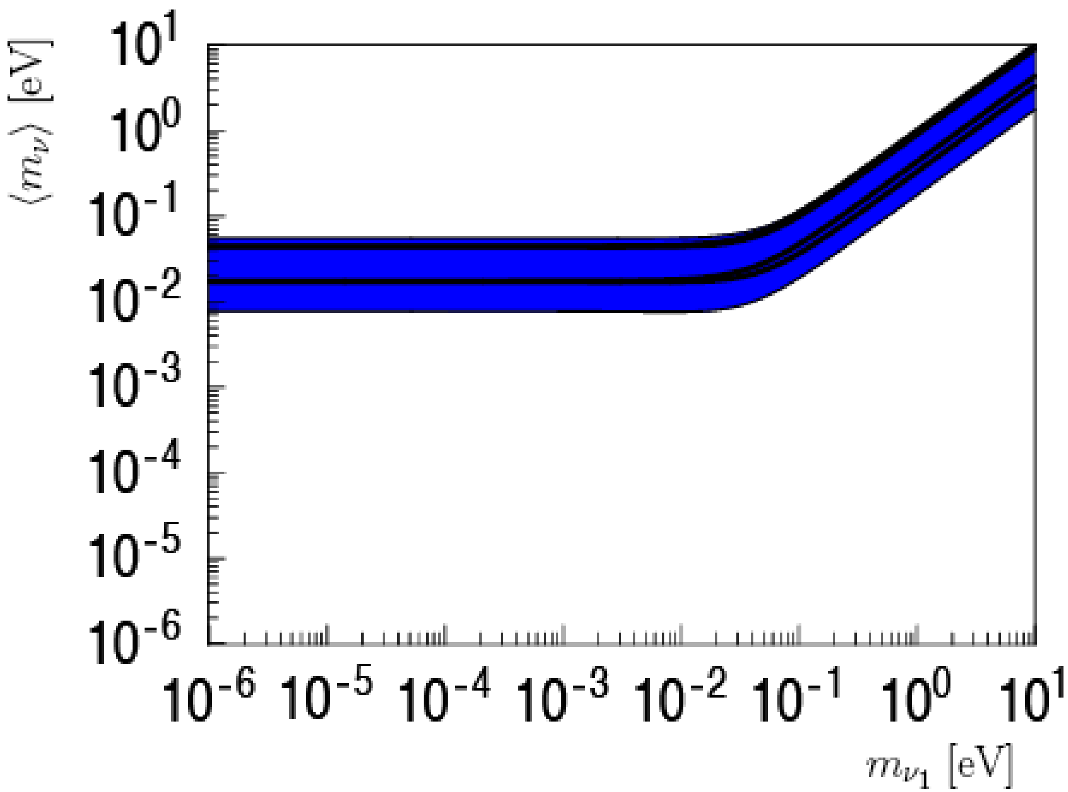
0νββ-Inverted mass scheme

$$\begin{aligned}
\langle m_\nu \rangle &= \sum_j U_{ej}^2 m_{\nu_j} \\
&\simeq c_{12}^2 c_{13}^2 m_{\nu_1} + s_{12}^2 c_{13}^2 e^{i\alpha} m_{\nu_2} + 0 \\
&\sim (c_\odot^2 - s_\odot^2)\sqrt{\Delta m^2_{Atm}} \\
&\simeq (0.7 - 0.3) \cdot \sqrt{2.2 \cdot 10^{-3}}\ \mathrm{eV} \\
&\simeq 0.4 \cdot \sqrt{2.2 \cdot 10^{-3}}\ \mathrm{eV} \ \simeq 19\ \mathrm{meV}
\end{aligned}$$

$\Rightarrow$ Lower limit exists, if $\theta_\odot$ non-maximal

$(s_\odot^2 < 1/2)$

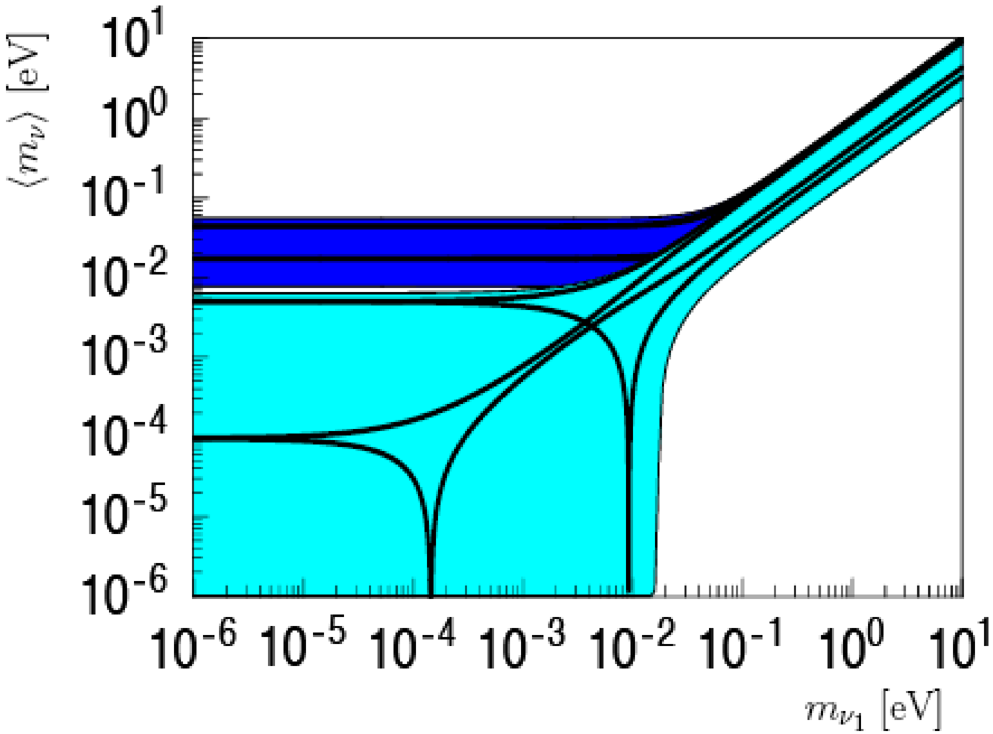
0νββ - Inverted hierarchy



$$\Delta m^2_{Atm} = [1.4, 3.3] \cdot 10^{-3}\ \mathrm{eV}^2, \qquad \Delta m^2_{\odot} = [7.2, 9.1] \cdot 10^{-5}\ \mathrm{eV}^2,$$

$$\sin^2\theta_{\odot} = [0.23, 0.38], \qquad \sin^2\theta_R = [0, 0.051]$$

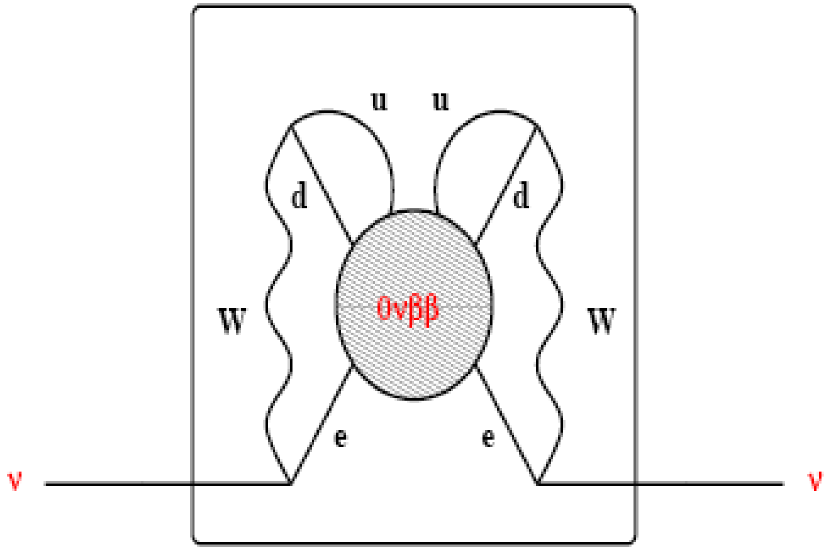
Normal + inverted scheme



$$\Delta m^2_{Atm} = [1.4, 3.3] \cdot 10^{-3}\ \mathrm{eV}^2, \qquad \Delta m^2_\odot = [7.2, 9.1] \cdot 10^{-5}\ \mathrm{eV}^2,$$

$$\sin^2\theta_\odot = [0.23, 0.38], \qquad \sin^2\theta_R = [0, 0.051]$$

Schechter-Valle theorem



Schechter & Valle, 1982

Independent of
mechanism of $0\nu\beta\beta$ decay
Majorana neutrino mass
will appear
in higher order!

Thus:

Observe $0\nu\beta\beta$ decay

$\equiv$

Neutrinos are Majorana particles

Oscillations and 0νββ

General:

$$\langle m_\nu \rangle = c_\odot^2 c_R^2 m_{\nu_1} + s_\odot^2 c_R^2 e^{i\alpha}\sqrt{m_{\nu_1}^2 + \Delta m_\odot^2} + s_R^2 e^{i\beta}\sqrt{m_{\nu_1}^2 + \Delta m_\odot^2 + \Delta m_{\rm Atm}^2}$$

Rough estimate:

Normal hierarchy: $\langle m_\nu \rangle \simeq s_{12}^2 \sqrt{\Delta m_\odot^2} \simeq 3 \times 10^{-3}$ eV

Inverse hierarchy: $\langle m_\nu \rangle \simeq \sqrt{\Delta m_{Atm}^2} \simeq 5 \times 10^{-2}$ eV

0νββ - Normal hierarchy

$$\langle m_\nu \rangle = \sum_j U_{ej}^2 m_{\nu_j}$$
$$\simeq c_{12}^2 c_{13}^2 m_{\nu_1} + s_{12}^2 c_{13}^2 e^{i\alpha} m_{\nu_2} + s_{13}^2 e^{i\beta} m_{\nu_3}$$
$$\sim c_\odot^2 m_{\nu_1} - s_\odot^2 m_{\nu_2} + 0$$

Thus:

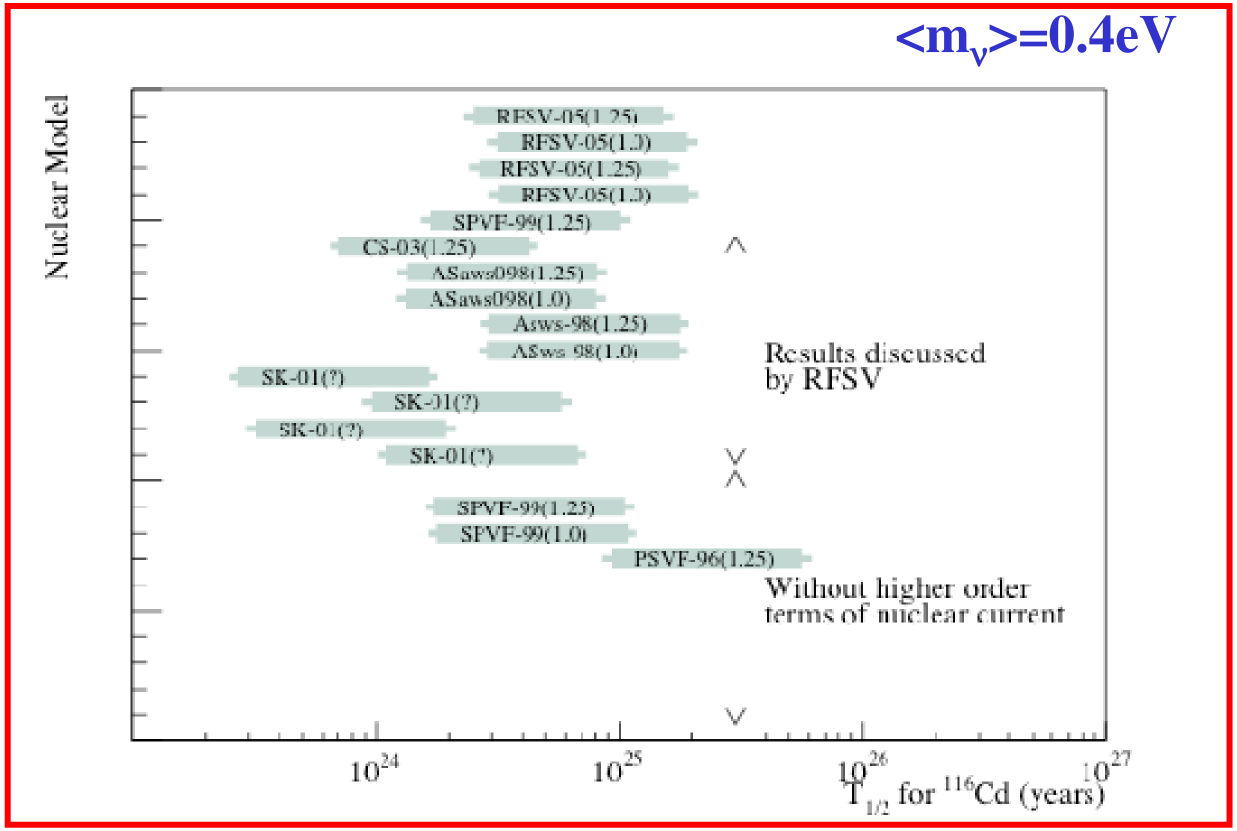
$$\langle m_\nu \rangle \equiv 0 \quad \Leftrightarrow \quad m_{\nu_1} = \tan^2 \theta_\odot m_{\nu_2}$$

Nuclear matrix elements

The dark side of double beta decay

Uncertainties in nuclear matrix elements, example ^{116}Cd

→ Check with a different isotope



V. Rodin et al., nucl-th/0503063, Nucl. Phys. A 2006