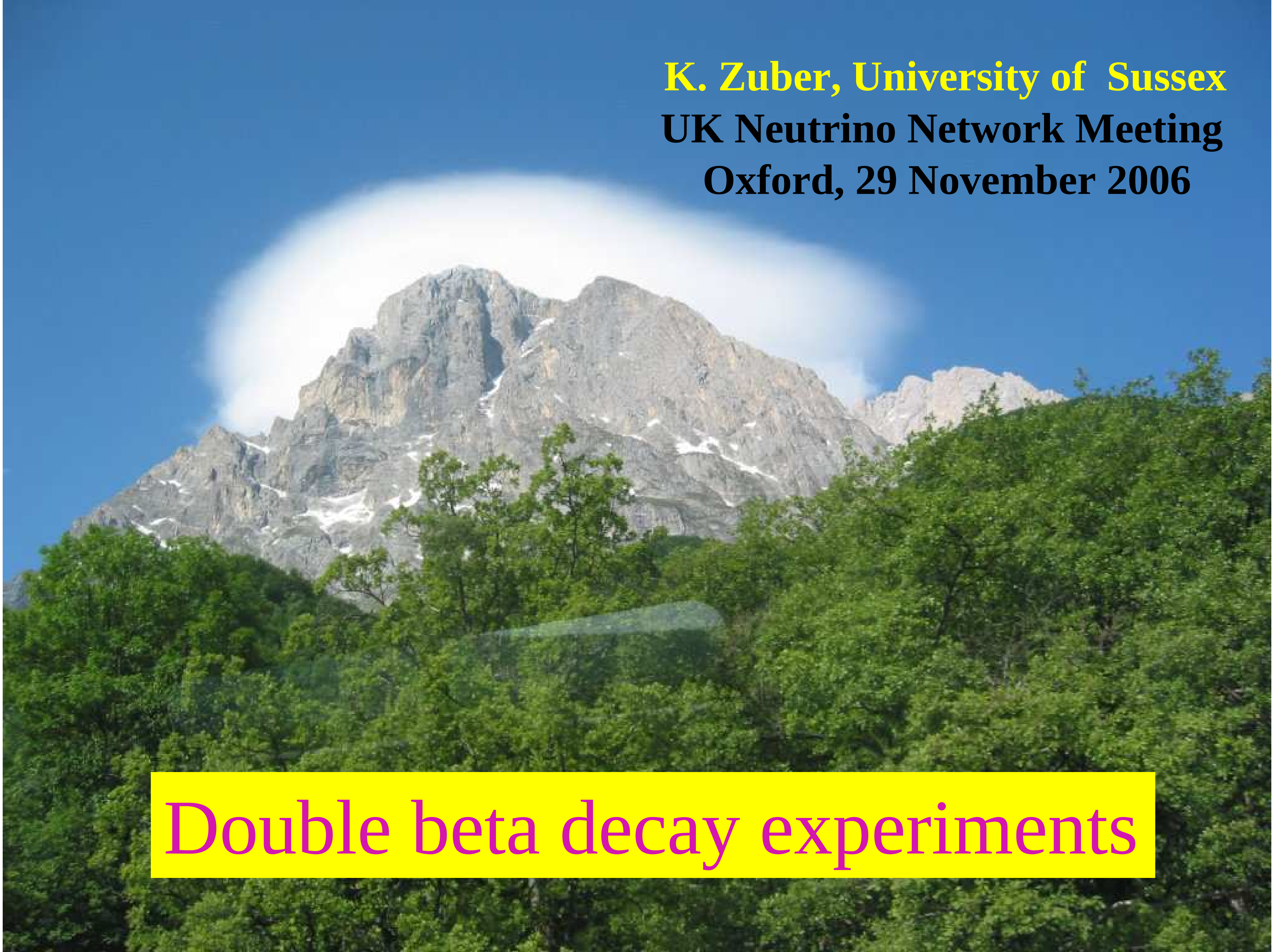
K. Zuber, University of Sussex

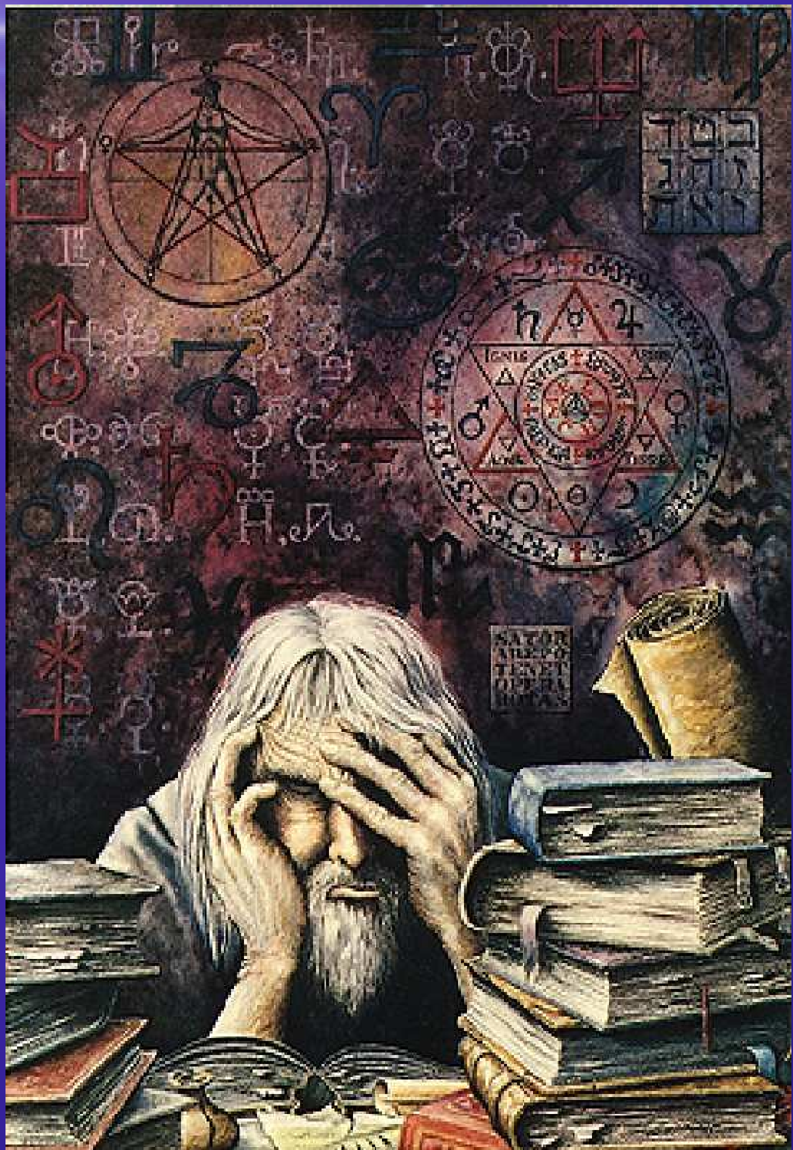
UK Neutrino Network Meeting

Oxford, 29 November 2006



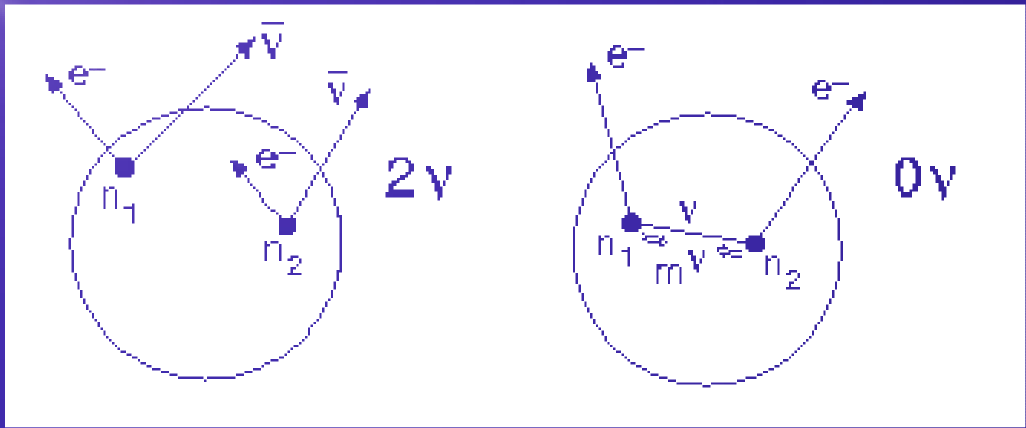
Double beta decay experiments

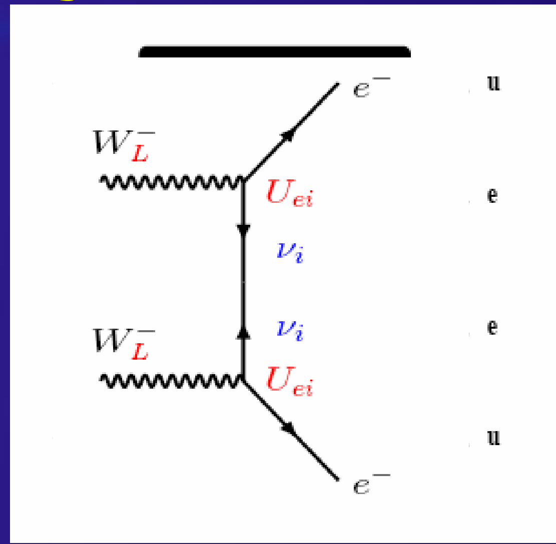
Contents

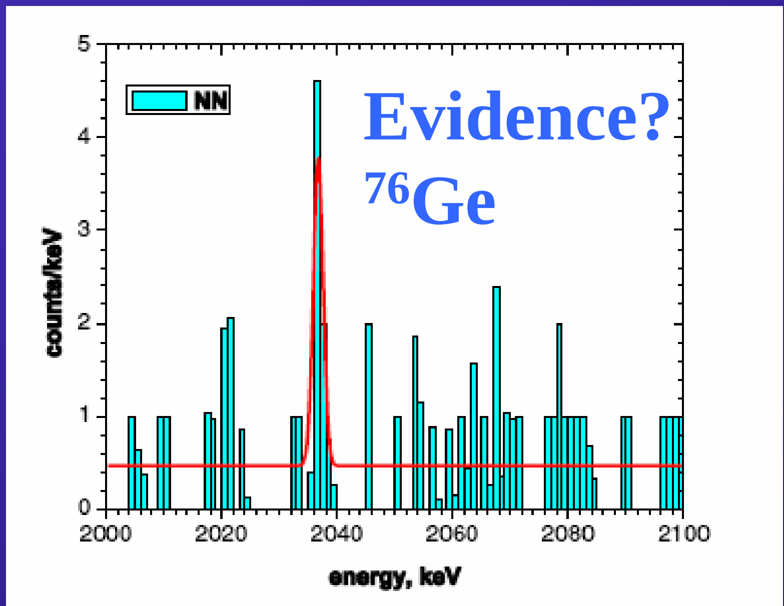


- Short introduction
- Nuclear matrix elements
- Experimental considerations
- Current status of experiments
- Future activities
- Outlook and summary

Double beta decay

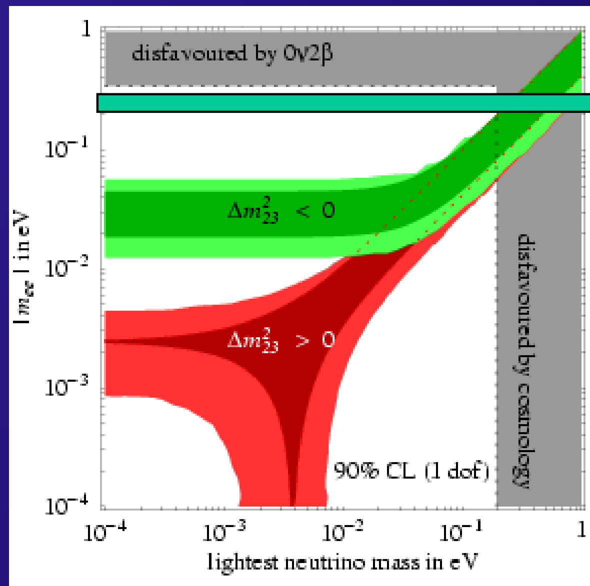






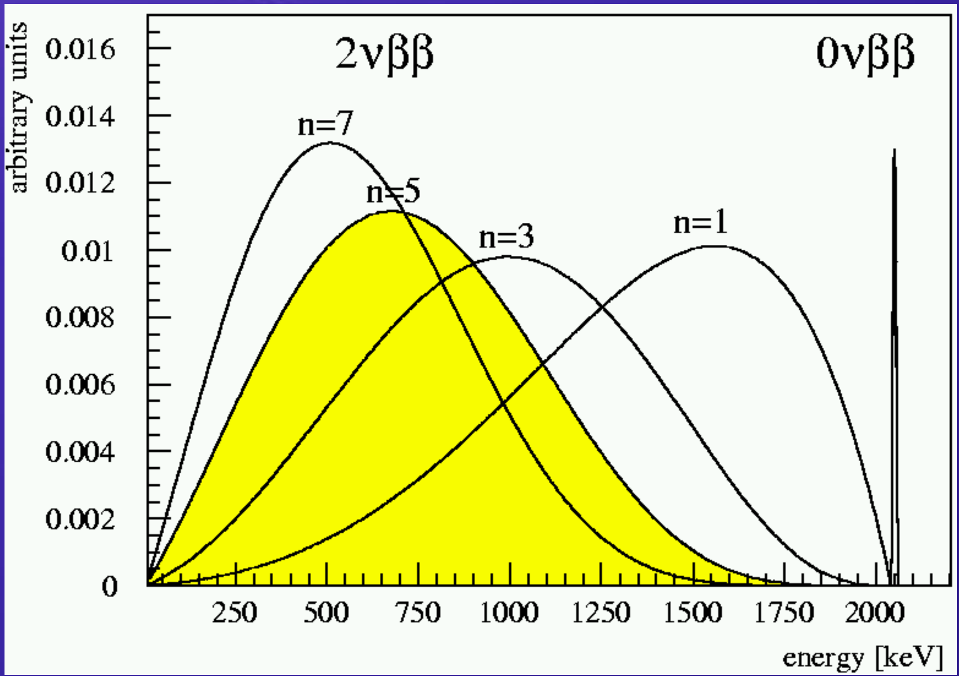
If true...

If not...



Spectral shapes

$0\nu\beta\beta$: Peak at Q-value of nuclear transition



Sum energy spectrum of both electrons

Measured quantity: Half-life

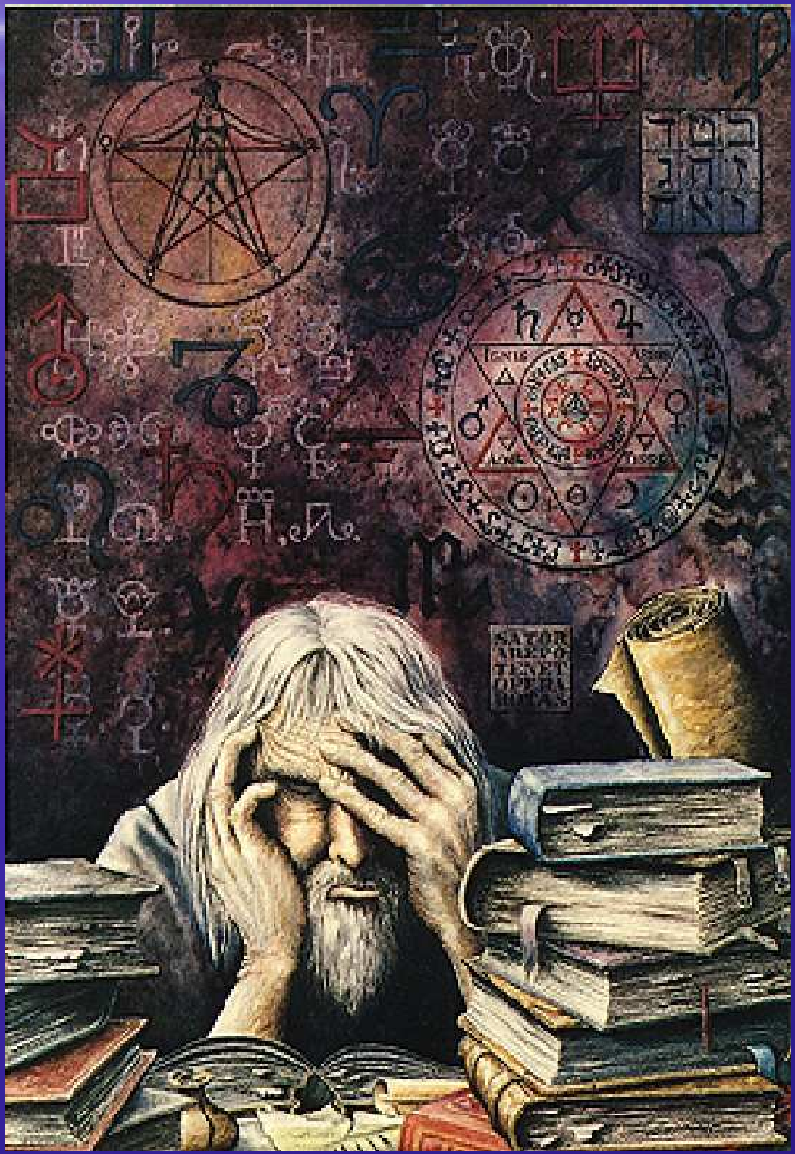
Dependencies (BG limited)

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

link to neutrino mass

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

Contents



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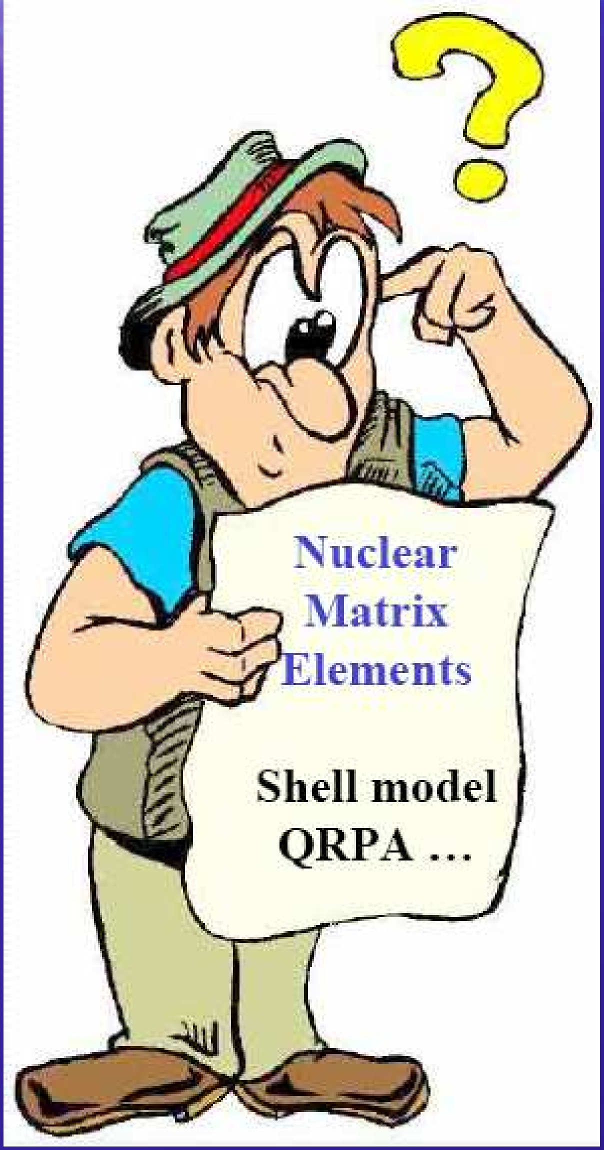
Nuclear matrix elements

The dark side of double beta decay

Nuclear matrix elements



Experimentalists:

- What are the best $0\nu\beta\beta$–decay candidates?

Particle physicists:

- Wat is the absolute ν mass scale?
- Will the evidence of the $0\nu\beta\beta$-decay allow to to conclude about Majorana CP-phases?

It is a complex task

- Medium and heavy open shell nuclei with a complicated nuclear structure
- The construction of complete set of the states of the intermediate nucleus is needed
- Many-body problem $\Rightarrow$ approximations needed
- Nuclear structure input has to be fixed

F. Simkovic

Uncertainties

F. Simkovic

List … E

Quasiparticle … c. (~ 50%)
fixing of pp,nn … idered

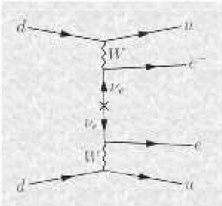
Many-body ap … on (~10%)
QRPA, RQRP … rs

Choice of NN … urr. (~30%)
Schem., realistic … magnetism

the closure ap … ctor
p-h interacti … lap
fixed to GT r

The size of n … coupling
… 25

p-p intera … hape
fixed to β or ββ– … formed yet
or g

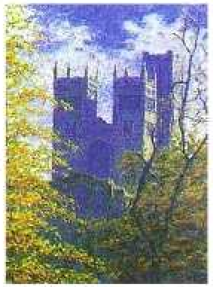


IPPP Workshop on
Matrix Elements for Neutrinoless Double Beta Decay

IPPP, Durham, UK

May 23-24, 2005

Within the Standard Model lepton number is conserved, and so neutrinoless double beta decay (0NU2BD) is forbidden. However, recent neutrino oscillation experiments have shown that neutrinos are massive particles, and imply that the description of neutrinos within the Standard Model is incomplete. To move beyond the Standard Model and formulate a new theoretical framework with which to describe neutrino phenomenology, the mass mechanism must be investigated. 0NU2BD experiments illuminate the nature of the mass term in the neutrino Lagrangian; if 0NU2BD is observed, the neutrino must be a Majorana particle. This represents both theoretical and experimental challenges. In particular, the extraction of precise information on neutrinos is impossible without a detailed understanding of the nuclear matrix elements that enter in the expressions for the decay widths.



The Workshop will focus on the status of and prospects for the nuclear matrix element calculations and measurements that are a key factor in extracting information on the neutrino masses in neutrinoless double decay processes.

The Workshop will take place at the Institute for Particle Physics Phenomenology, University of Durham, Durham, UK. Participants will be accommodated nearby. Because accommodation is strictly limited, attendance is by invitation only. If you wish to attend, please email one of the organisers listed below.

The meeting will start will start at 9.00am on Monday 23rd May and end at lunchtime on Tuesday 24th May 2005. Participants are expected to arrive on Sunday 22nd May. There is no fee and participants' local costs will be paid by the IPPP. There will a conference dinner on the evening of Monday 23rd May, and buffet lunches will be provided on both days.

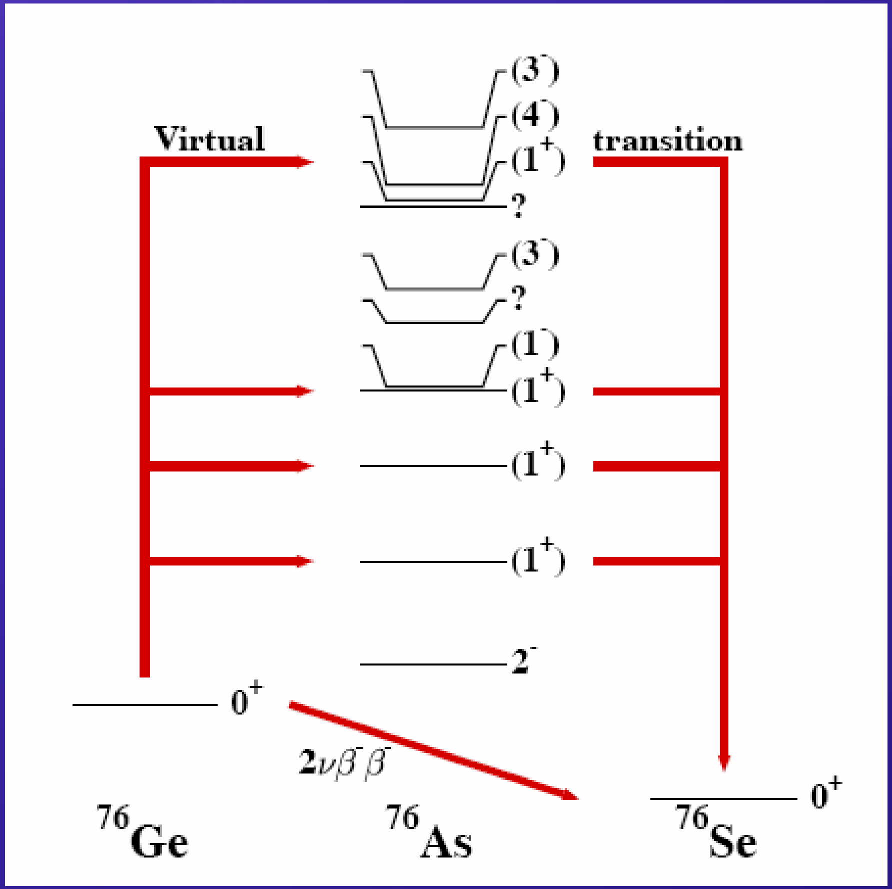
Programme
Participants
Travelling to Durham

Organisers:

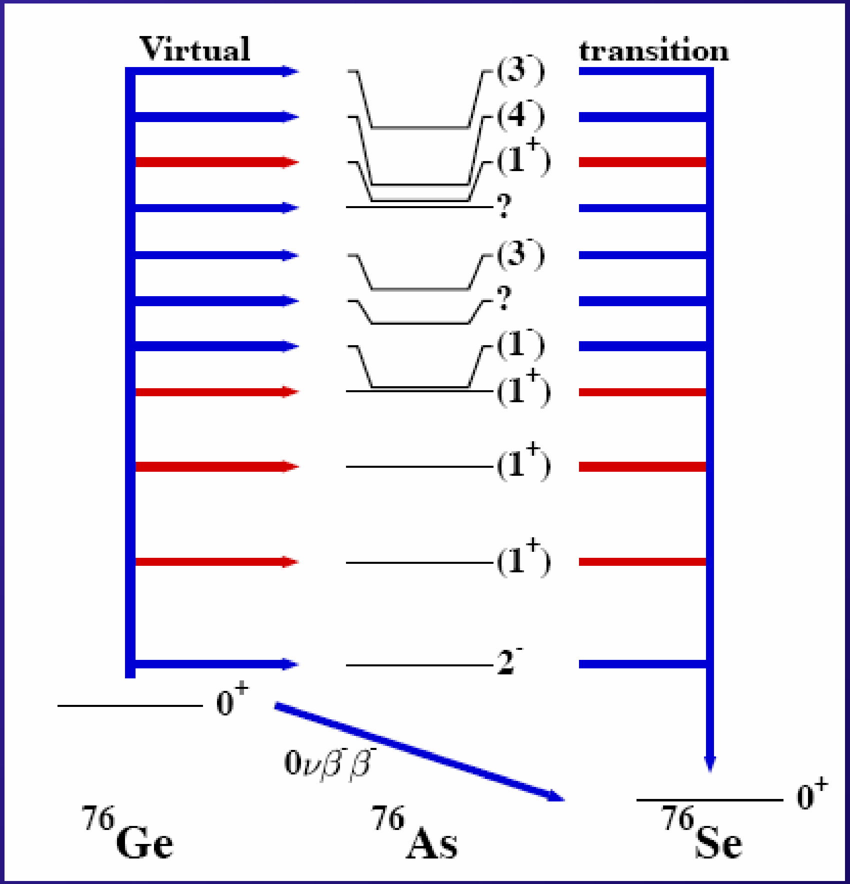
Kai Zuber (Sussex), James Stirling (Durham), Linda Wilkinson (Durham)

Reminder

2νββ

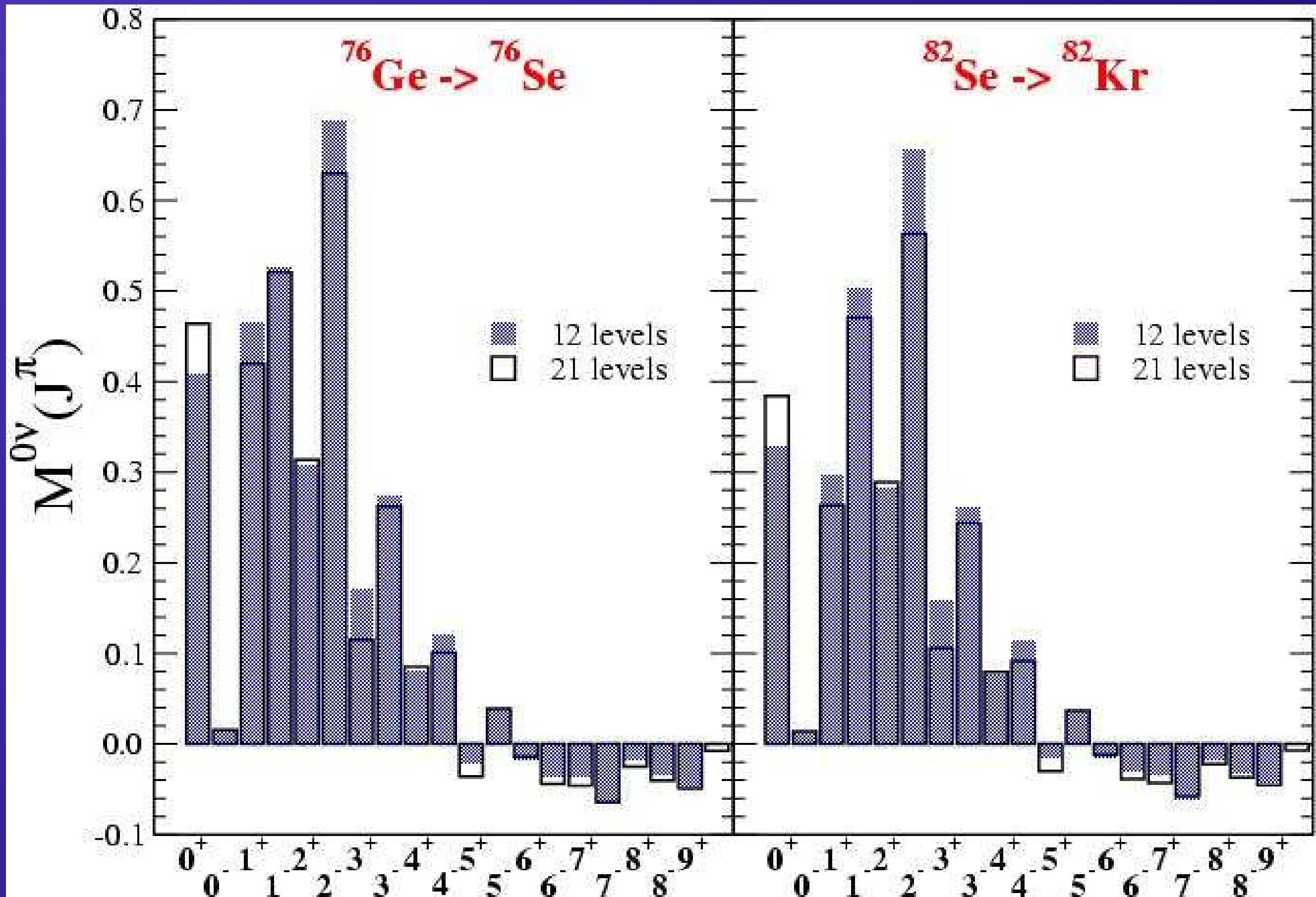


0νββ



Multipoles

$0\nu\beta\beta$: All intermediate states contribute

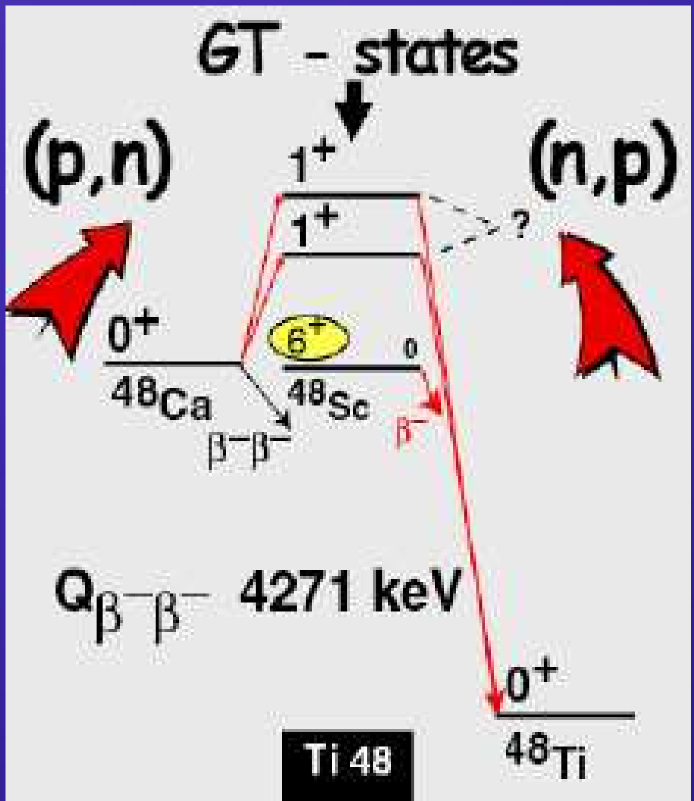


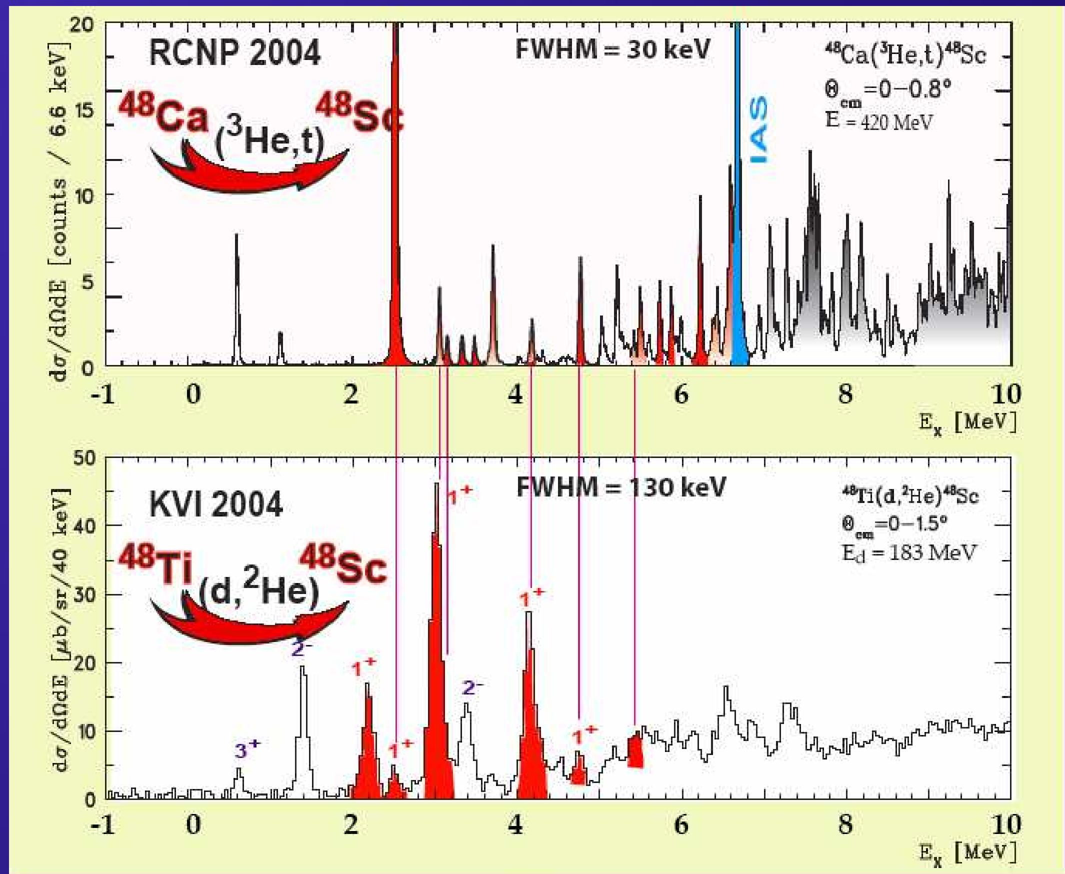
How to explore those???

Charge exchange reactions

2νββ: Only intermediate 1^+ states contribute

Supportive measurements from accelerators

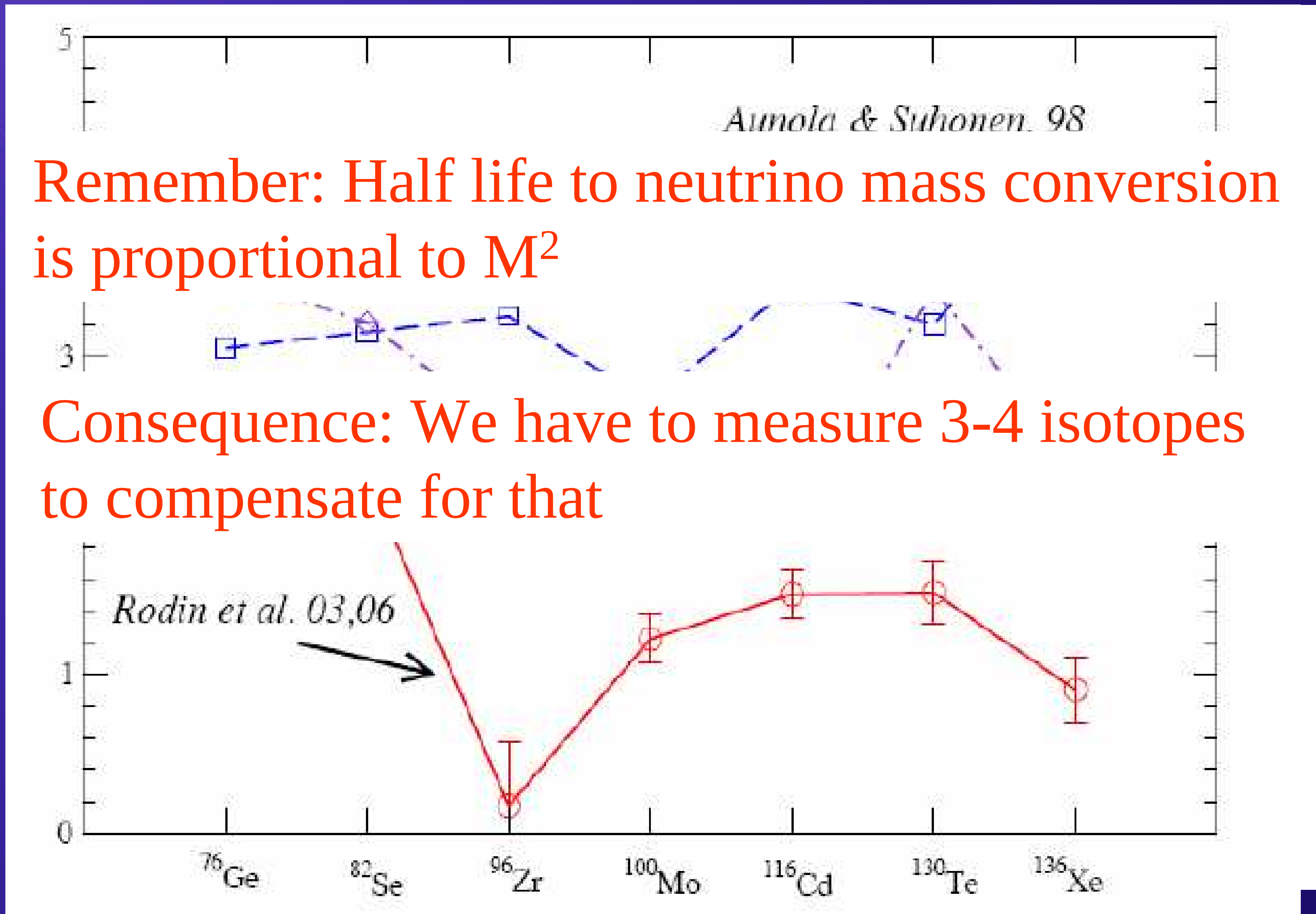




Currently: (d,^{2}He) and (^{3}He,t)

$M^{0\nu}$ calculations

V. Rodin, A. Faessler, F. Simkovic, P. Vogel, nucl-th/0503063

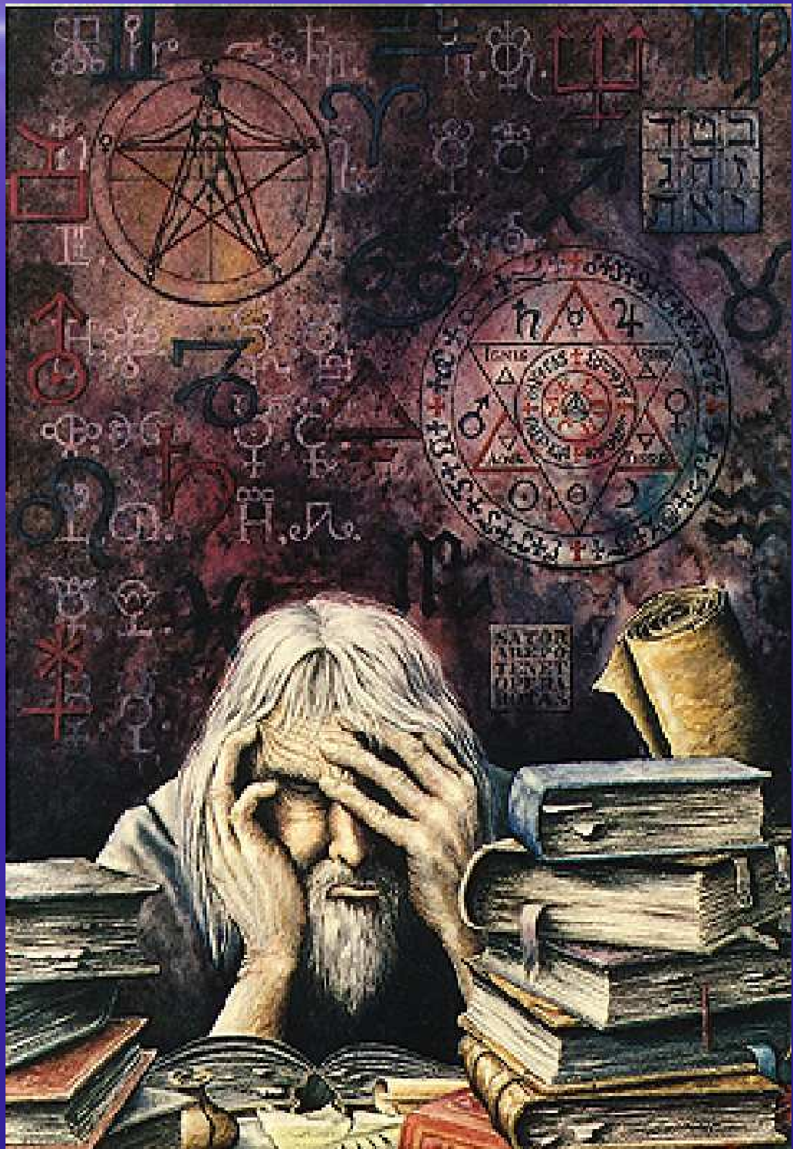


Remember: Half life to neutrino mass conversion is proportional to M^2

Consequence: We have to measure 3-4 isotopes to compensate for that

Looks convincing, but not everybody agrees...

Contents



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Phase space

$0\nu\beta\beta$ 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 x 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	**2802**	**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**

The dominant problem - Background

How to measure half-lives beyond 10^{20} years???

The first thing you need is a mountain, mine,...

- The usual suspects (U, Th nat. decay chains)
- Alphas, Betas, Gammas
- Cosmogenics
- thermal neutrons
- High energy neutrons from muon interactions
- $2\nu\beta\beta$

Experimental techniques

Source = detector

Source ≠ detector

Semiconductors

Heidelberg-Moscow, IGEX,
COBRA, GERDA, MAJORANA

Cryogenic bolometers

CUORICINO, CUORE

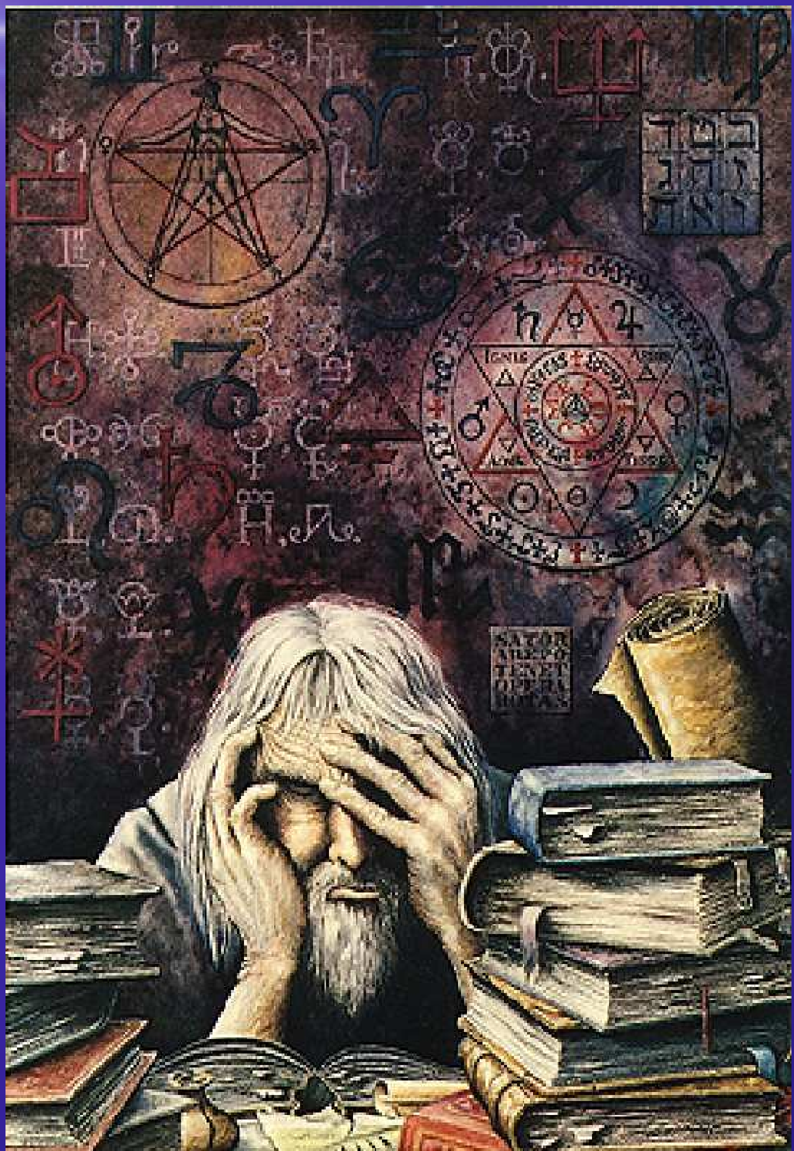
Scintillators

SNO+, CANDLES, MOON,
GSO, XMASS

Time projection chambers (TPC)

NEMO-3, SuperNEMO,
DCBA, EXO

Contents



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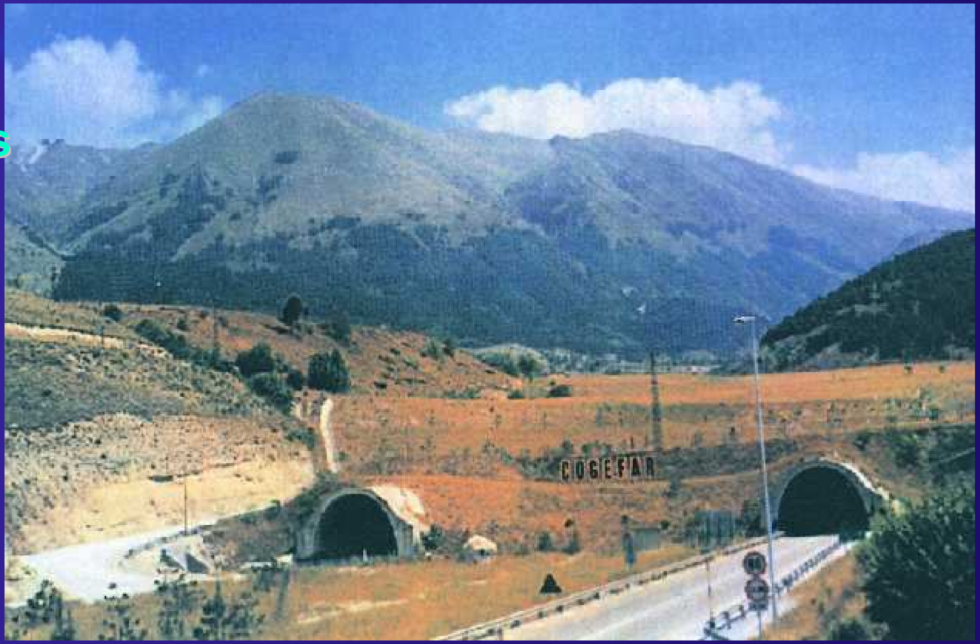
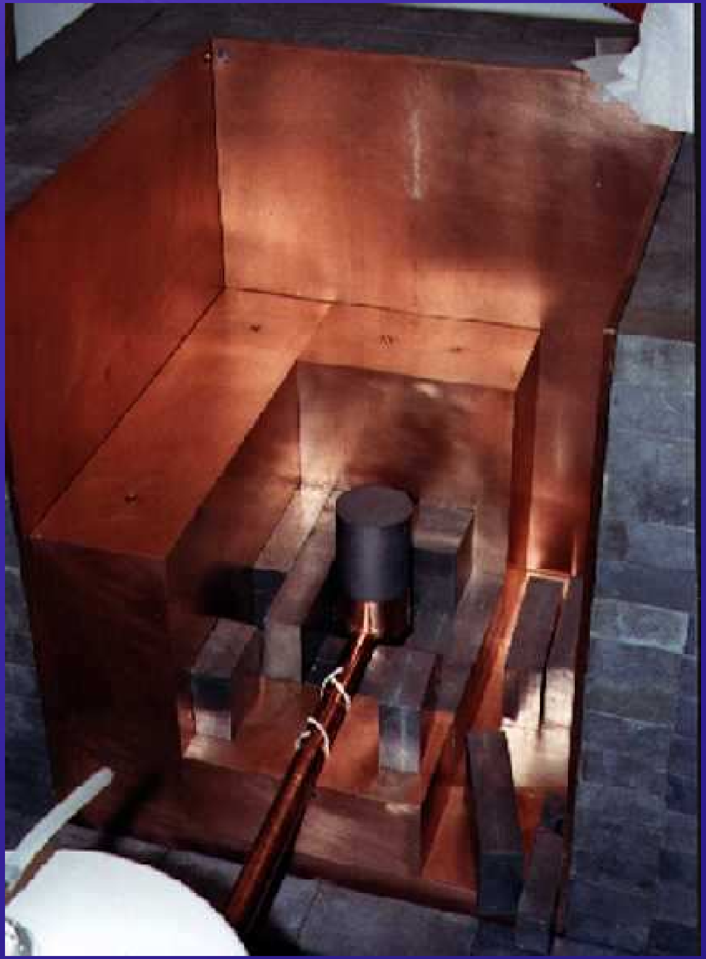
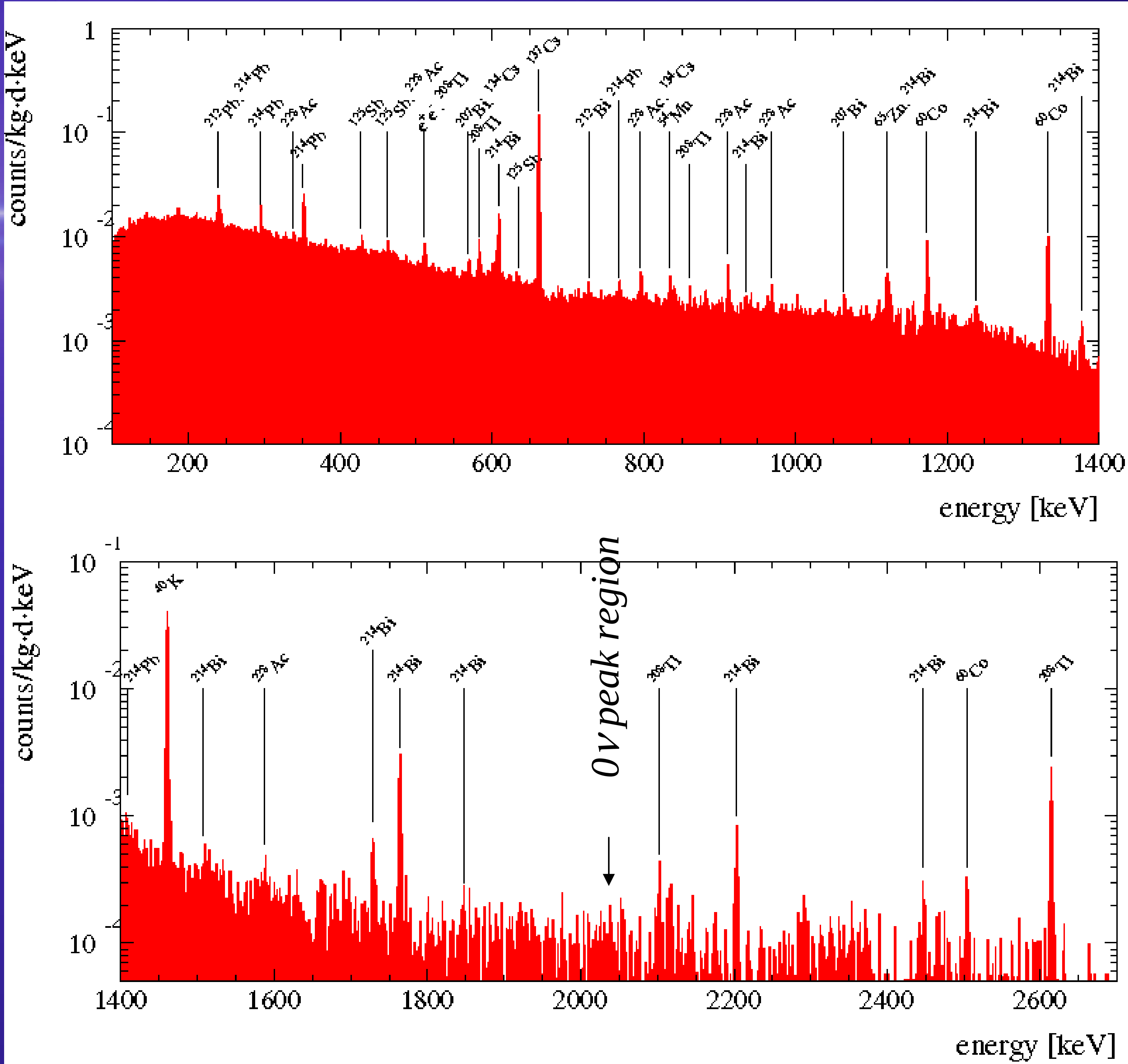
Heidelberg -Moscow

- Five Ge diodes (overall mass 10.9 kg) isotopically enriched (86%) in ^{76}Ge
- Lead box and nitrogen flushing of the detectors
- Digital Pulse Shape Analysis
  Peak at 2039 keV





Spectrum



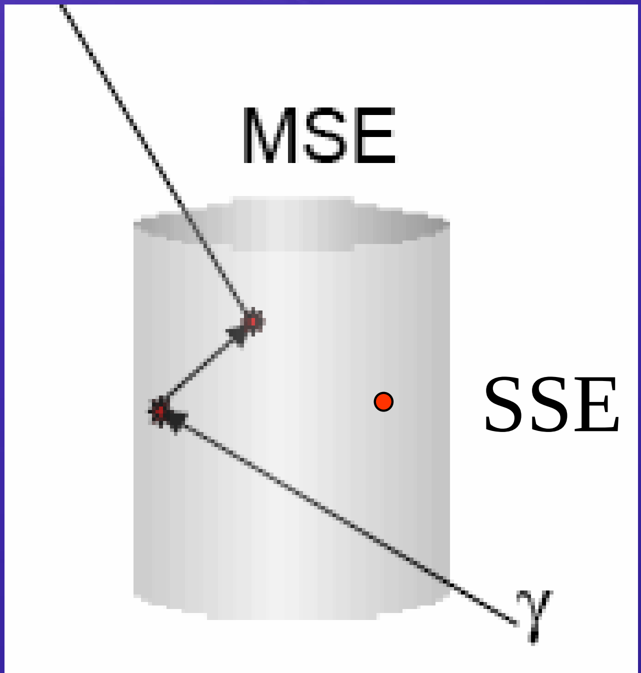
counts/kg·d·keV
energy [keV]
^{212}Pb, ^{214}Pb
^{214}Pb
^{228}Ac
^{125}Sb
^{125}Sb, ^{228}Ac
e^+e^-, ^{208}Tl
^{207}Bi, ^{134}Cs
^{208}Tl
^{214}Bi
^{137}Cs
^{212}Bi
^{54}Mn
^{65}Zn
^{60}Co
^{40}K
0ν peak region

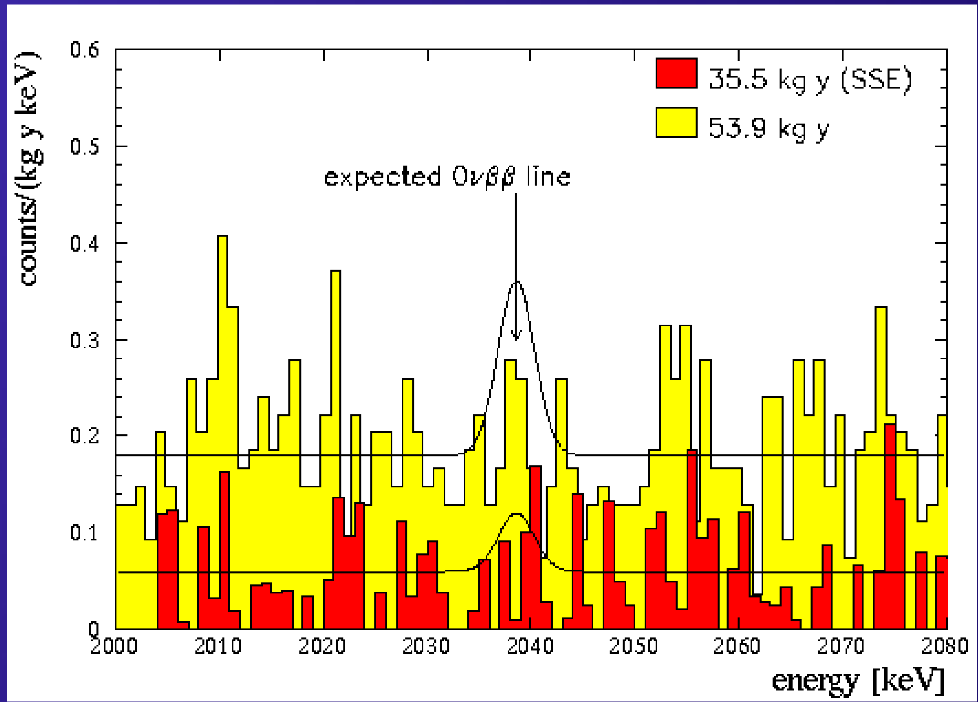
Latest HD-Moscow results

Statistical significance: 54.98 kg x yr

Including pulse shape analysis: 35.5 kg x yr

(installed Nov. 95, only 4 detectors)



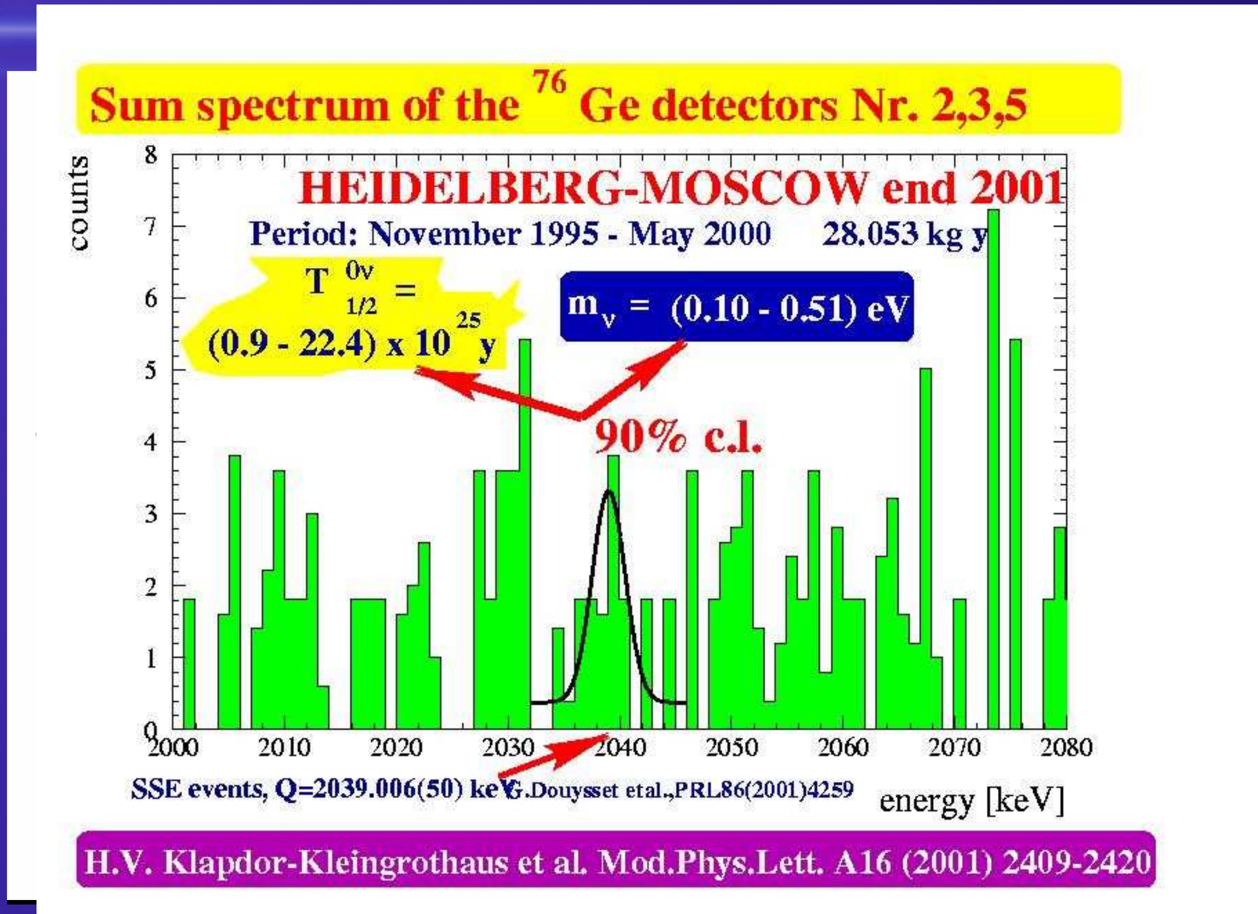


$T_{1/2} > 1.9 \times 10^{25}$ yr (90% CL) → m < 0.35 eV

Heidelberg-Moscow

more statistics

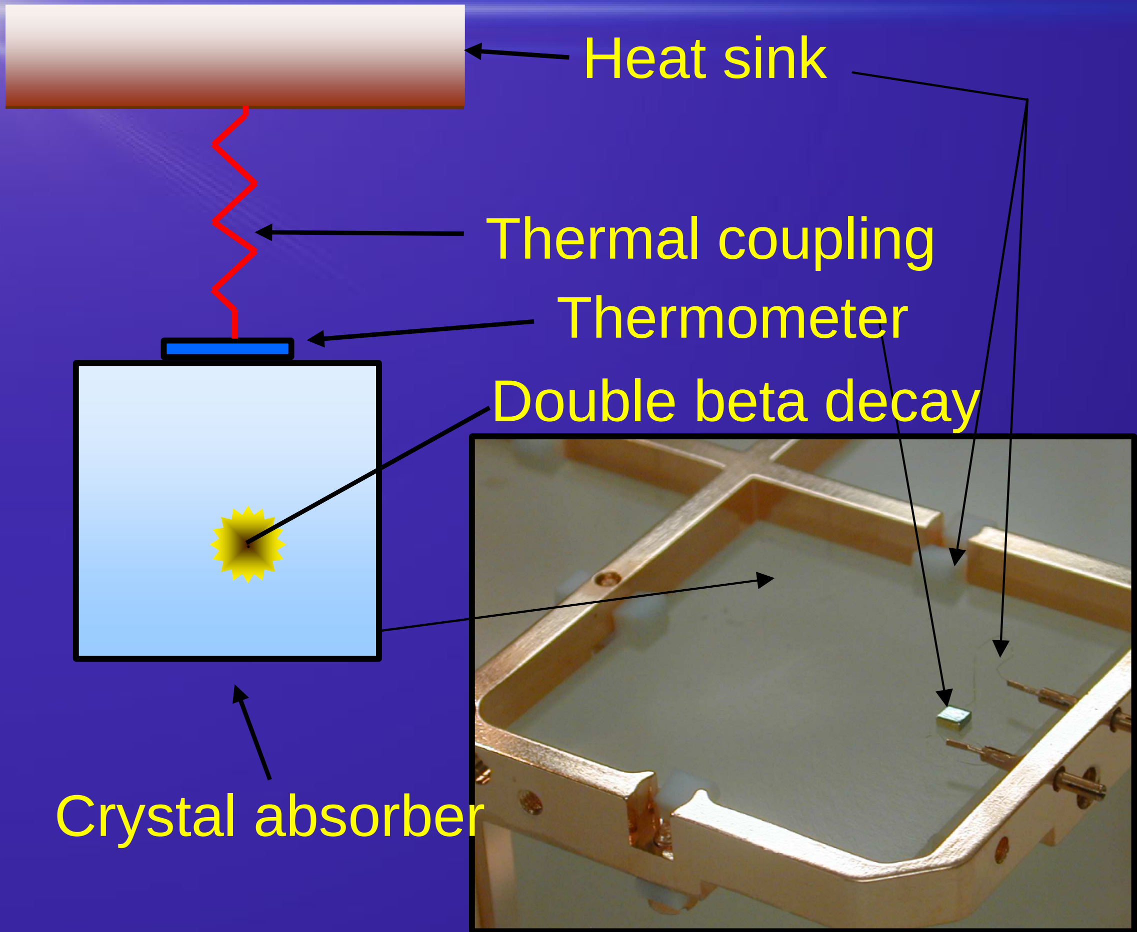
Recalibration

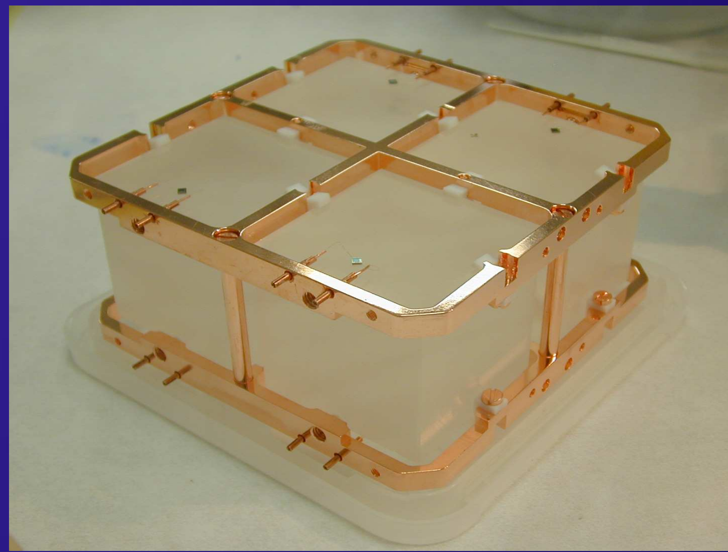


Subgroup of collaboration $T_{1/2} = 0.6 - 8.4 \times 10^{25}$ yr → m = 0.17 - 0.63 eV

H.V. Klapdor-Kleingrothaus et al, Phys. Lett. B 586, 198 (2004)
H.V. Klapdor-Kleingrothaus , I.V. Krivosheina, Mod. Phys. Lett. A 21, 1547 (2006)

CUORICINO-CUORE - Principle





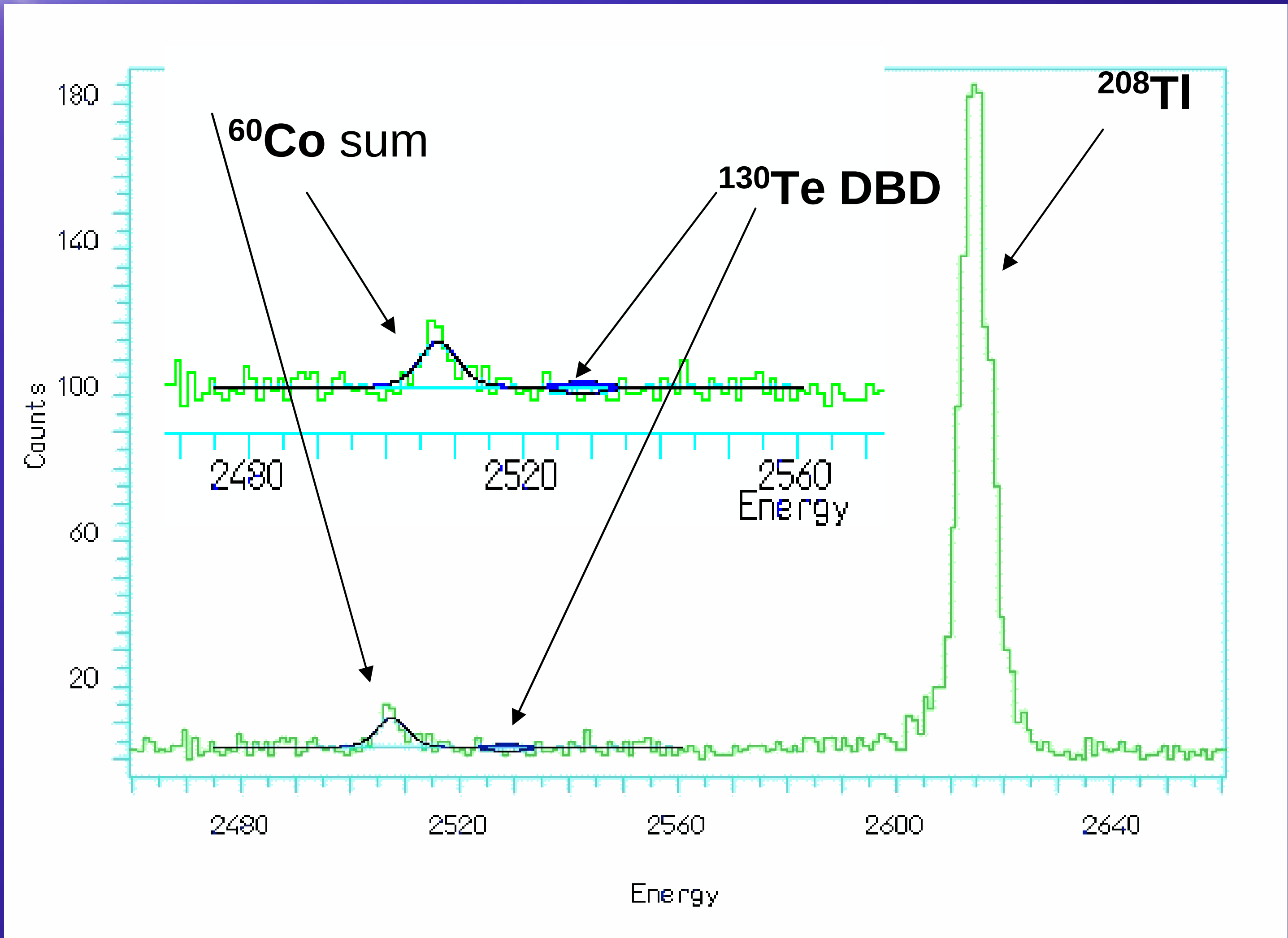
example: 750 g of TeO_2 @ 10 mK

$C \sim T^3$ (Debye) $\Rightarrow C \sim 2\times10^{-9}$ J/K

1 MeV γ-ray $\Rightarrow \Delta T \sim 80\ \mu$K

$\Rightarrow \Delta U \sim 10$ eV

CUORICINO - Results

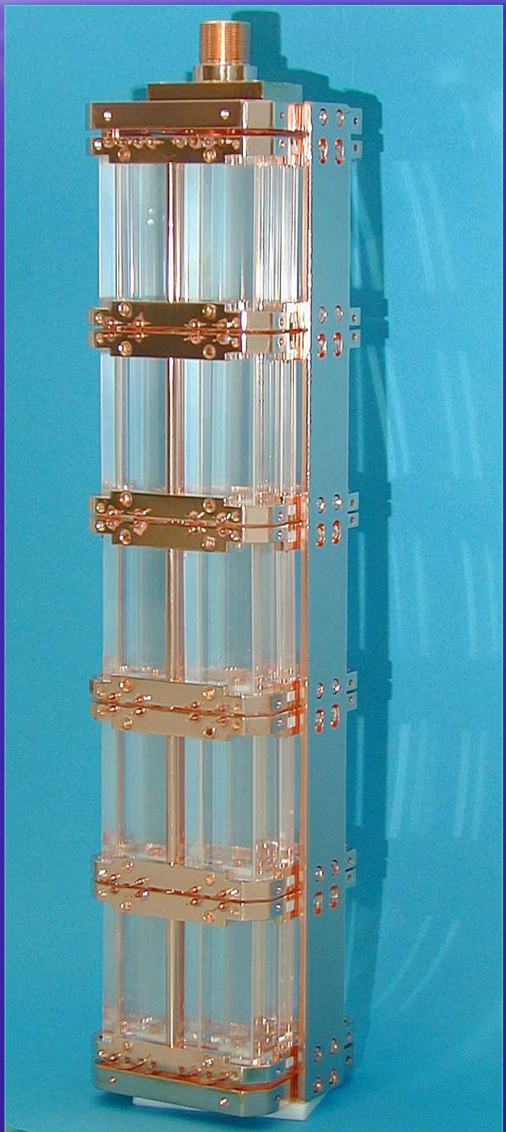


about 40 kg running

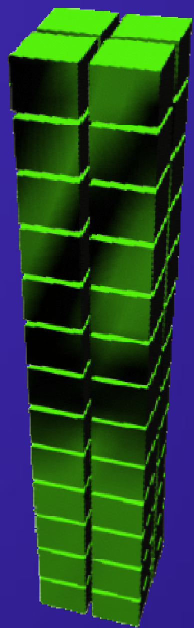
$T_{1/2}$ > 2.4 x 10^{24} yrs (90% CL)

m < 0.2-1.1 eV

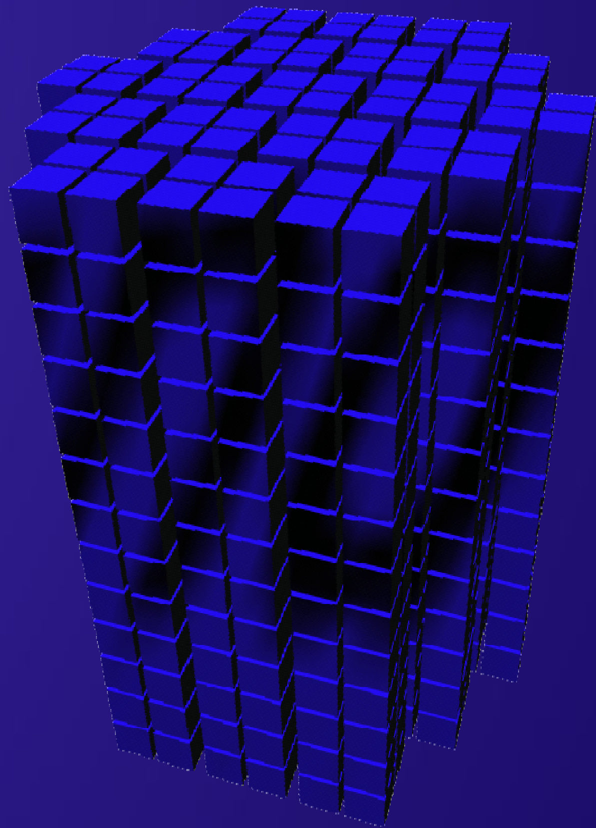
CUORICINO-CUORE



13x4 crystals/tower



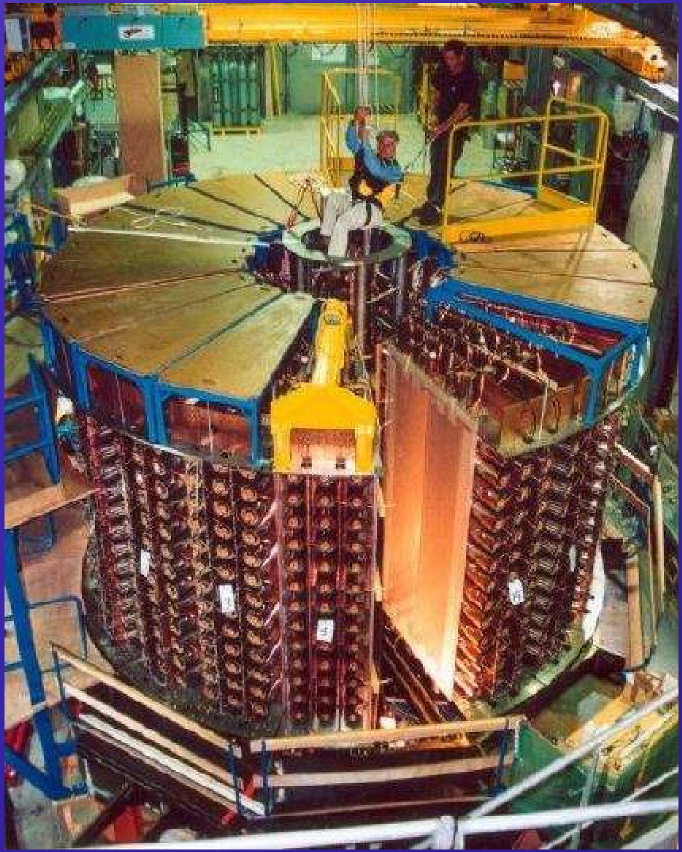
19 towers

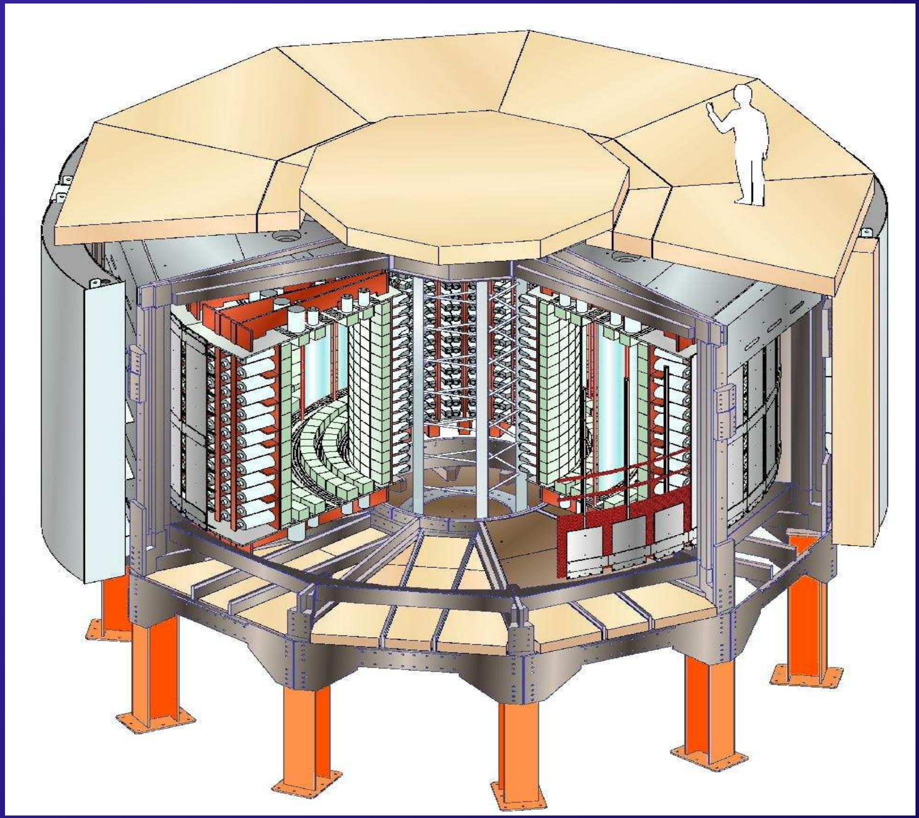


Future: CUORE 760 kg TeO_2 approved

NEMO-3

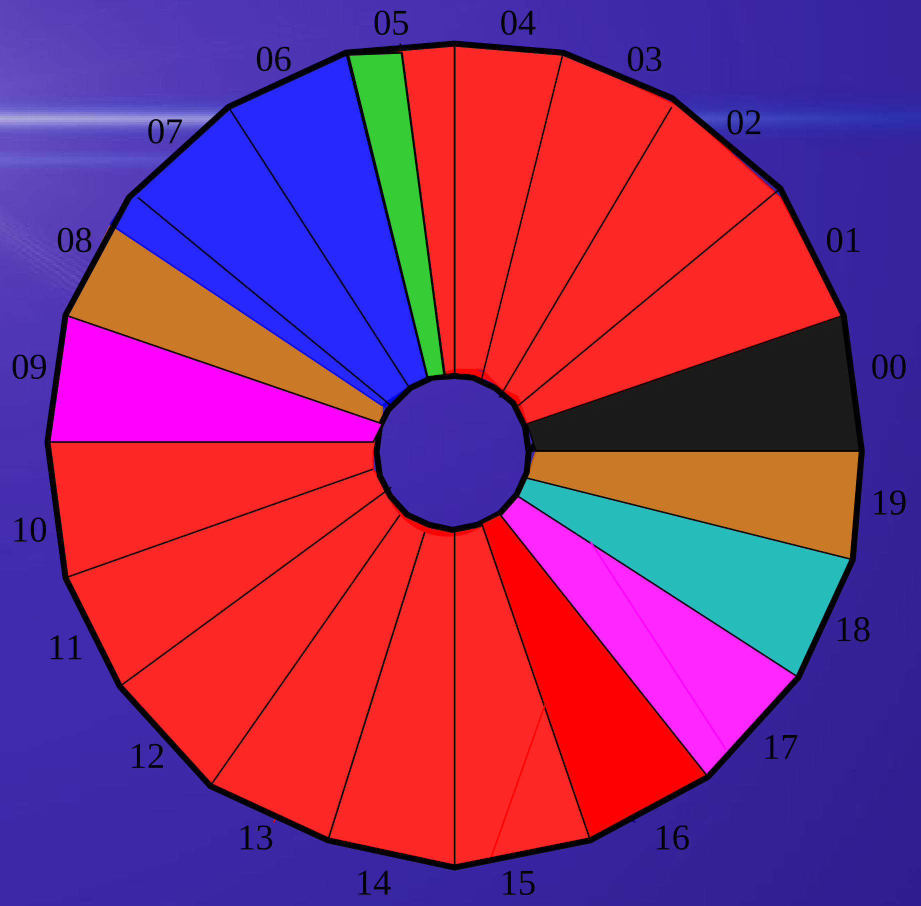
Only approach with source different from detector





UCL, Manchester, IC

ββ decay isotopes in NEMO-3 detector



^{100}Mo 6.914 kg
$Q_{\beta\beta}$ = 3034 keV

^{82}Se 0.932 kg
$Q_{\beta\beta}$ = 2995 keV

ββ0ν search

ββ2ν measurement

^{116}Cd 405 g
$Q_{\beta\beta}$ = 2805 keV

^{96}Zr 9.4 g
$Q_{\beta\beta}$ = 3350 keV

^{150}Nd 37.0 g
$Q_{\beta\beta}$ = 3367 keV

^{48}Ca 7.0 g
$Q_{\beta\beta}$ = 4272 keV

^{130}Te 454 g
$Q_{\beta\beta}$ = 2529 keV

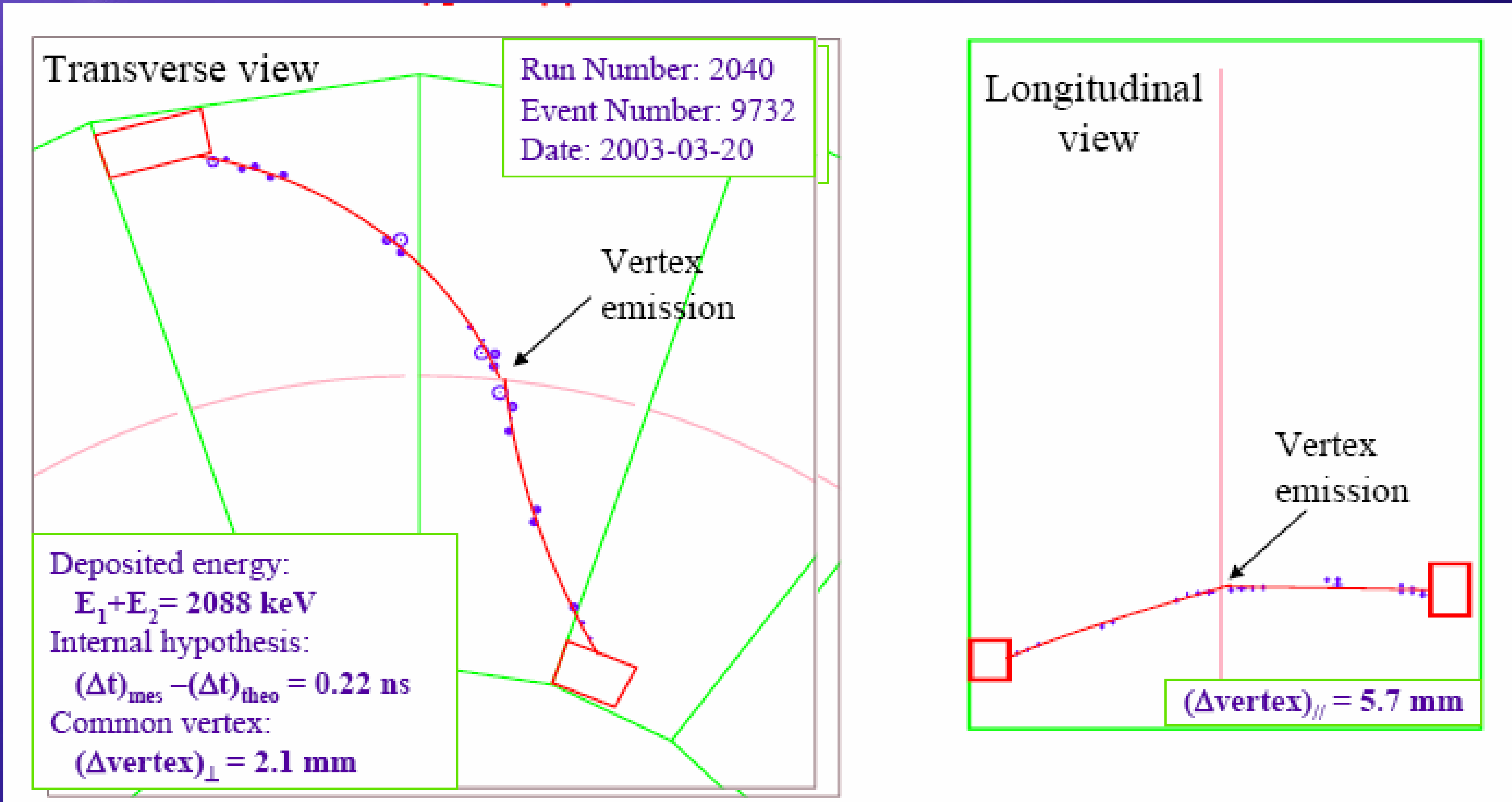
^{nat}Te 491 g

Cu 621 g

External bkg measurement

NEMO-III - Event

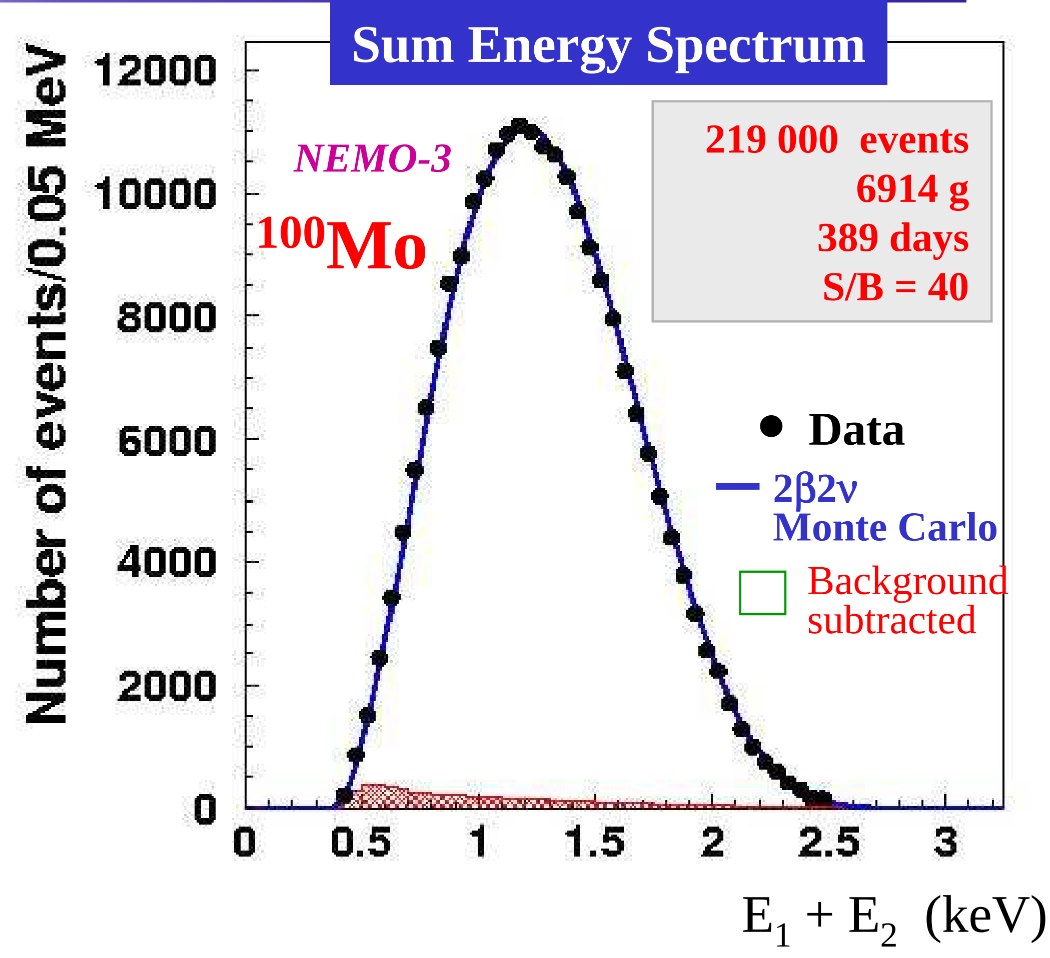
Typical $2\nu\beta\beta$ event of ^{100}Mo

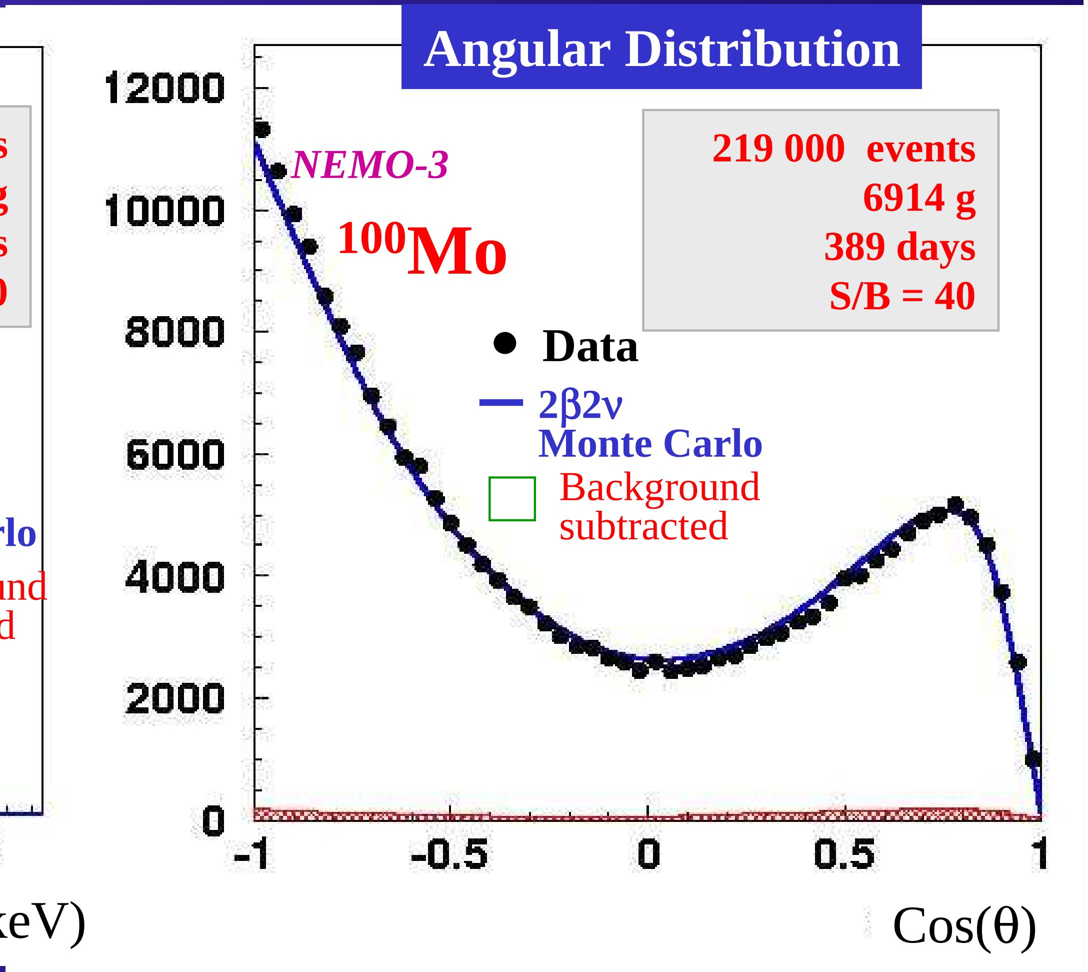


^{100}Mo results

7.37 kg.y

(Data Feb. 2003 – Dec. 2004)





$2\nu\beta\beta$: $T_{1/2} = 7.11 \pm 0.02\ (stat) \pm 0.54\ (syst) \times 10^{18}$ y

$0\nu\beta\beta$: $T_{1/2} > 5.8 \times 10^{23}$ yrs (90% CL)

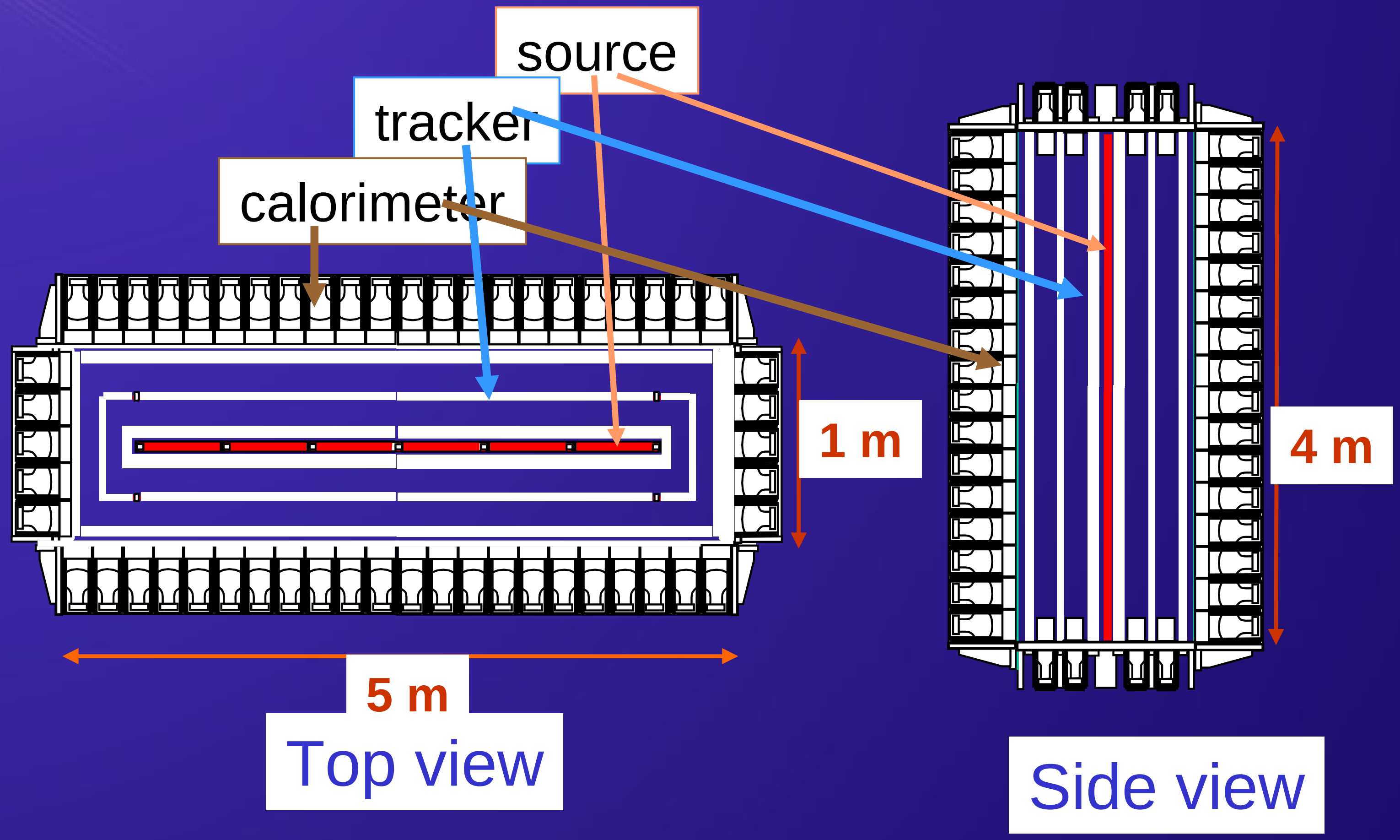
$m_\nu < 0.6 - 2.8$ eV

R. Arnold et al, PRL 95 (2005)

Idea: SuperNEMO (100 kg)

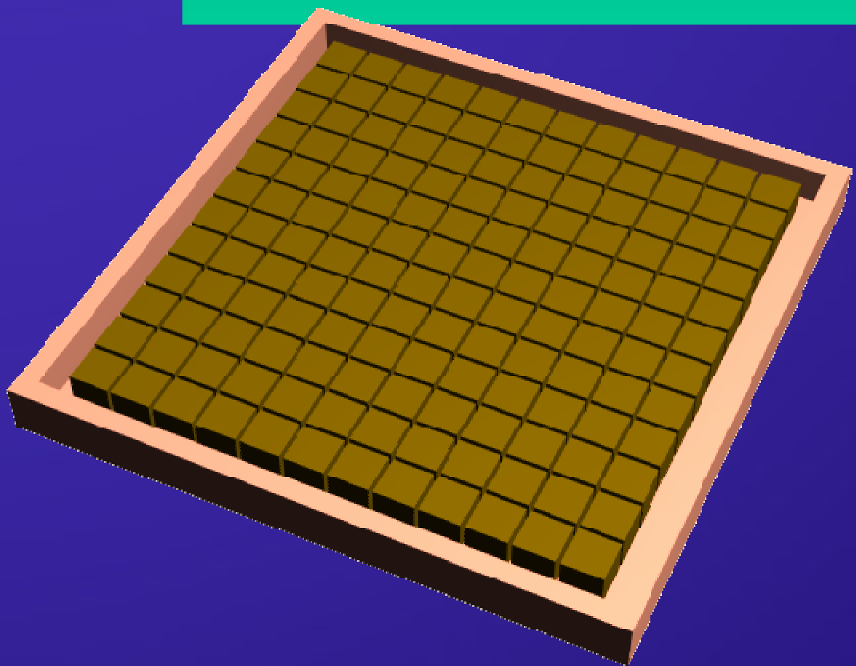
SuperNEMO

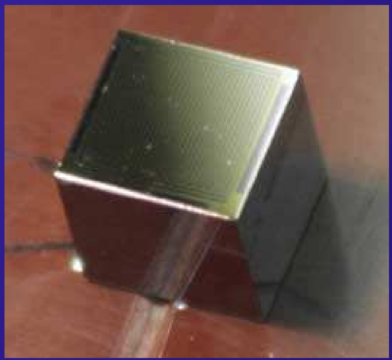
Idea: Use 100 kg enriched ^{82}Se



COBRA

Use large amount of
CdZnTe
Semiconductor Detectors

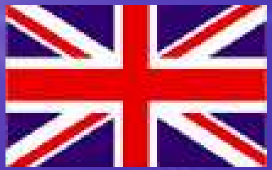




Array of $1cm^3$
CdTe detectors

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

COBRA collaboration

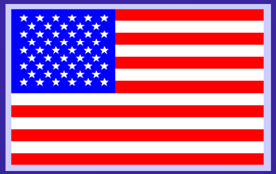


University of Sussex University of York
University of Warwick University of Birmingham
University of Liverpool Rutherford Appleton Laboratory

University of Dortmund
Material Research Centre Freiburg

Laboratori Nazionali del Gran Sasso

University of Bratislava

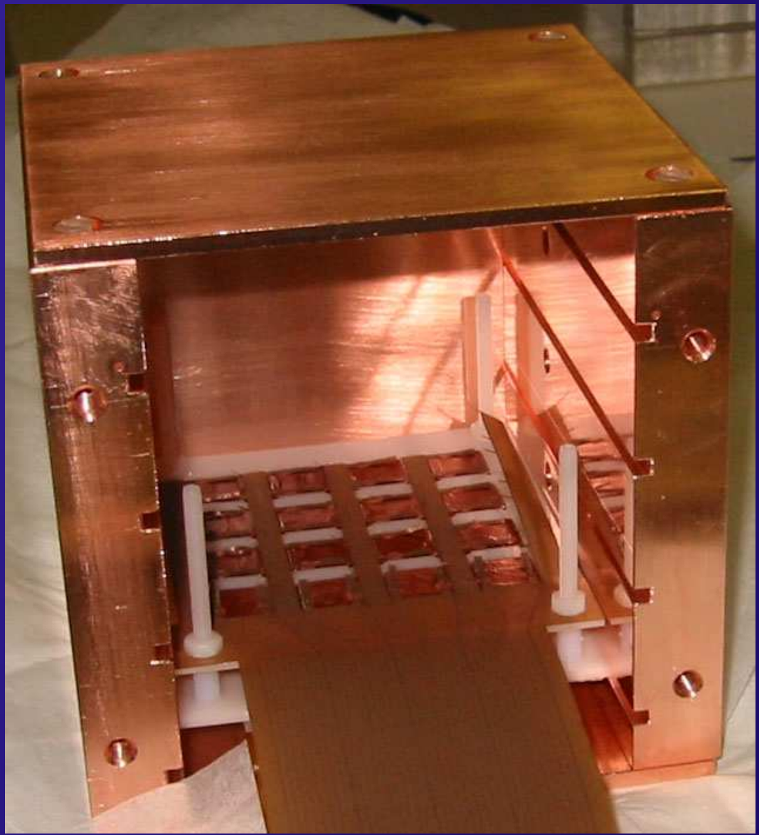


Washington University at St. Louis

University of Surrey (UK), University of Hamburg (Germany), Jagellonian University (Poland), University of Prague (Czech Republik), Louisianna State University (USA)

The first layer

4x4x4 detector array = 0.42 kg CdZnTe semiconductors



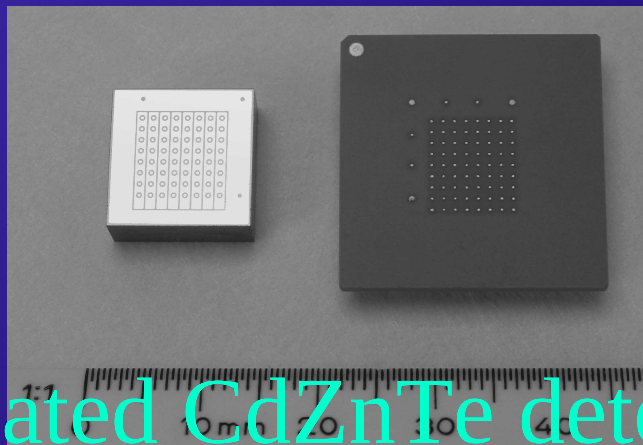
Installed at LNGS in april 2006

The solid state TPC

Energy resolution

Tracking

• Massive background Reduction (Particle-ID)
• Positive signal information

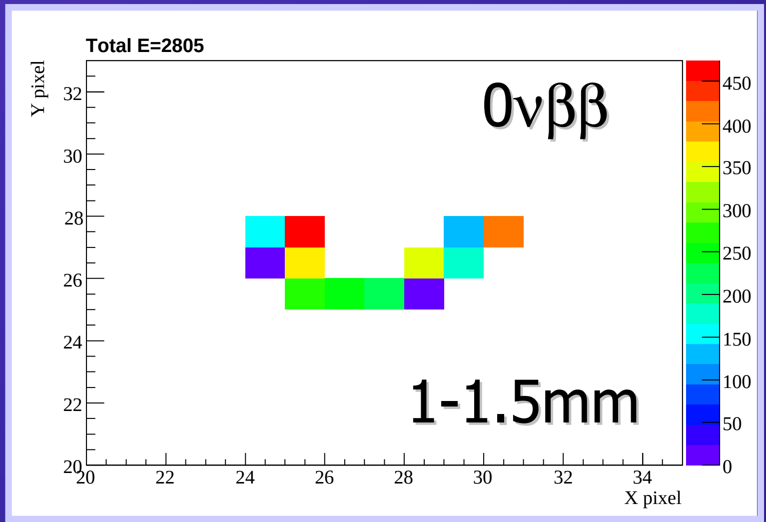


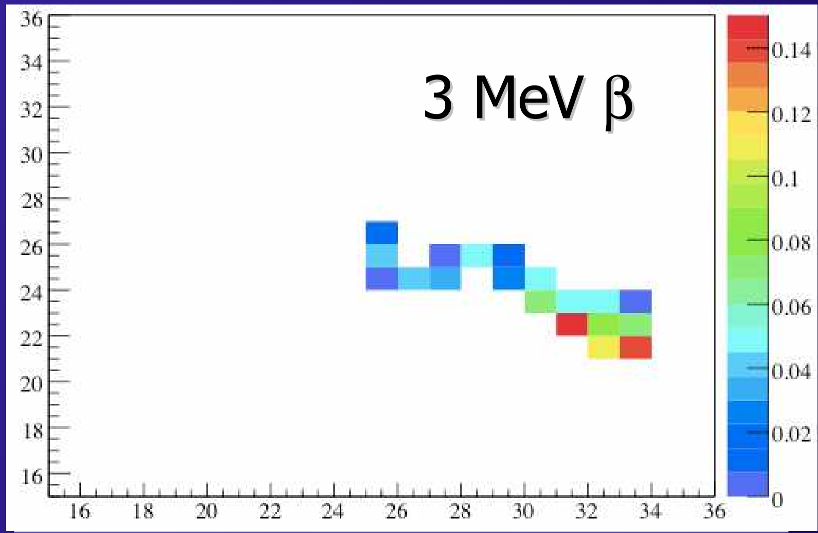
Pixellated CdZnTe detectors

Pixellisation - I

- Particle ID possible, 200μm pixels (example simulations):

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





- eg. Could achieve nearly 100% identification of ^{214}Bi events (^{214}Bi → ^{214}Po → ^{210}Pb)
-

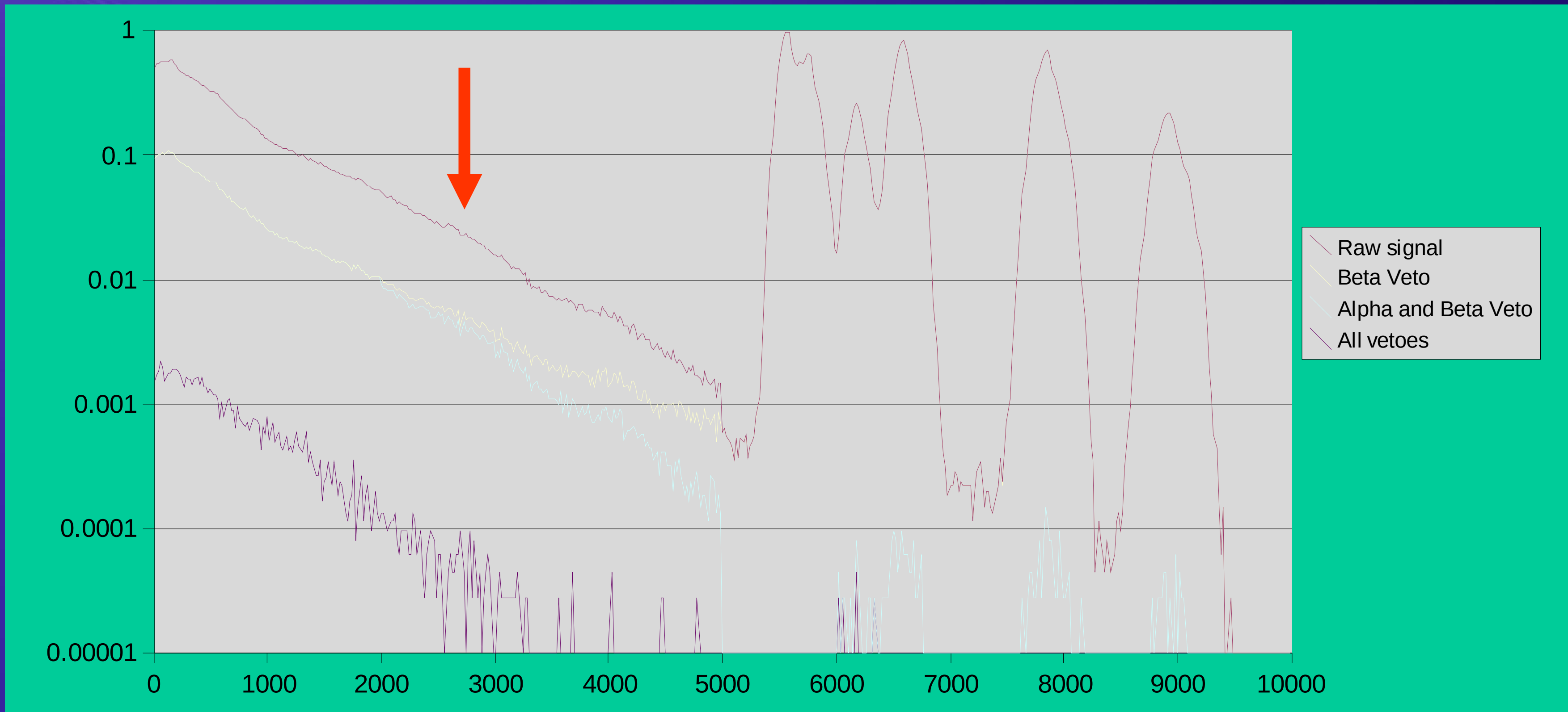
Beta with endpoint 3.3MeV

7.7MeV α life-time = 164.3μs

Rejection power of pixels

T. Bloxham, M. Freer, in preparation

First look on rejection power

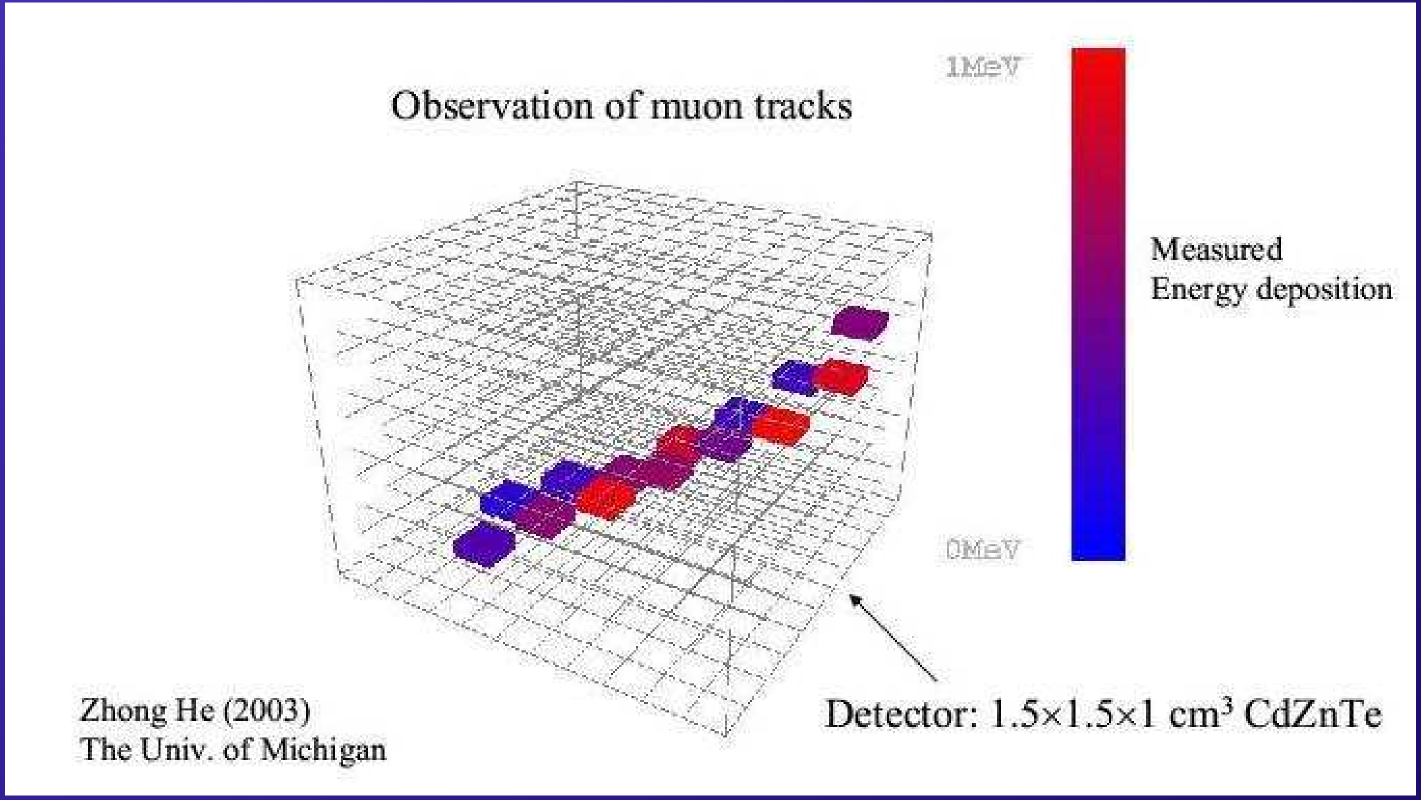


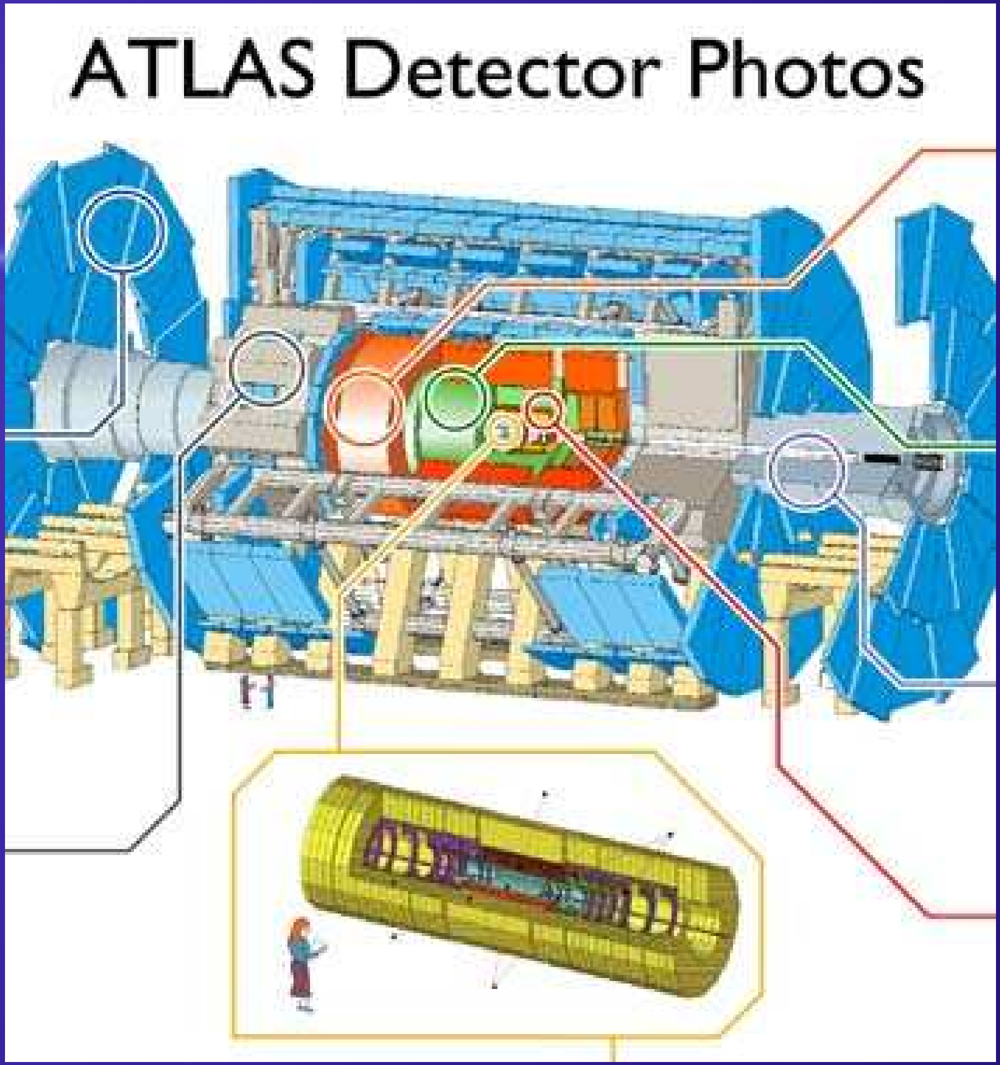
Suggests a background reduction of 1000!

Pixellated detectors

Solid state TPC

3D - Pixelisation:





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

George W. Bush

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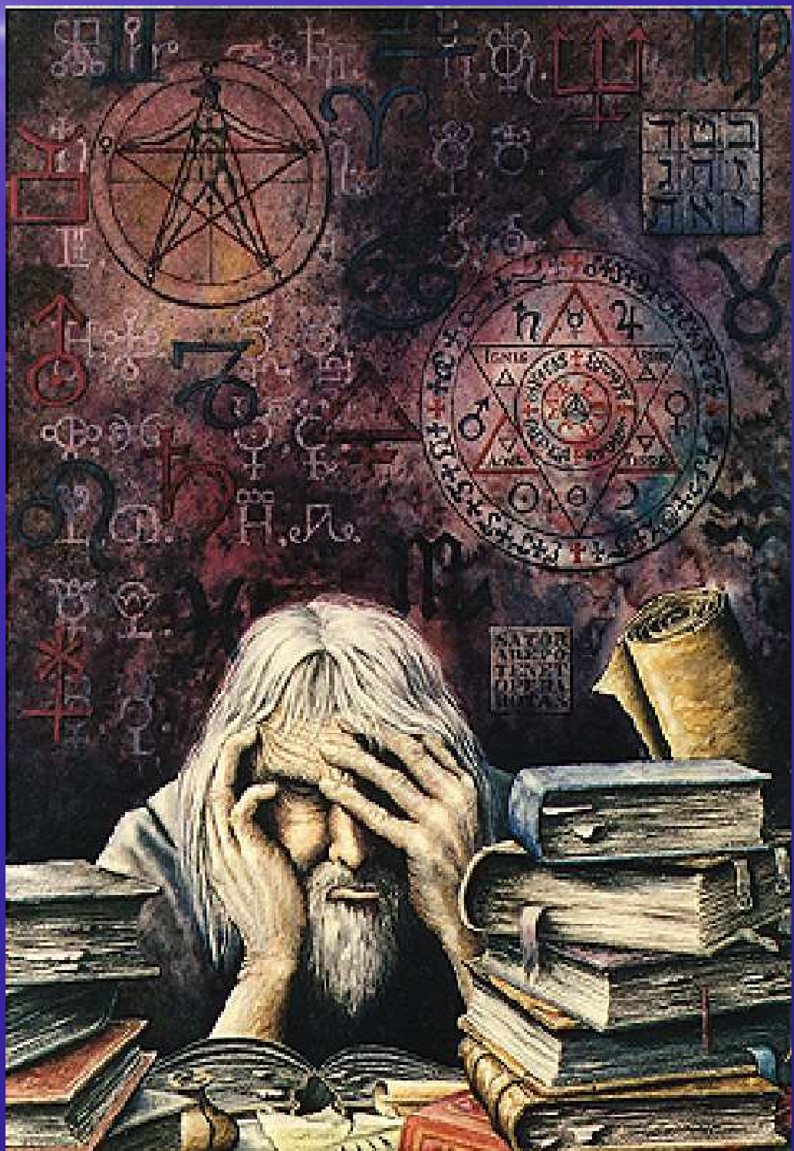


- Short introduction
- Nuclear matrix elements
- Experimental considerations
- Current status of experiments
- Future activities
- Outlook and summary

Back of the envelope

$T_{1/2} = \ln 2 \bullet a \bullet N_A \bullet M \bullet t / N_{\beta\beta}$ (τ>>T) (Background free)

50 meV implies half-life measurements of $10^{26\text{-}27}$ yrs

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

This is about 1000 moles of isotope, implying 100 kg

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

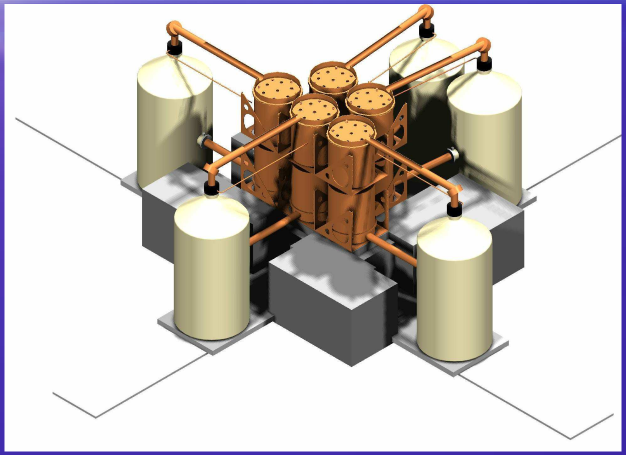
Future projects, ideas

Status 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
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
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...

Future - Ge approaches



MAJORANA

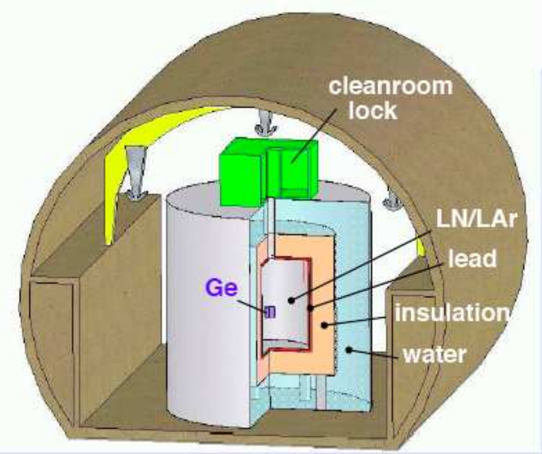
500 kg of enriched Ge detectors

Segmentation and pulse shape discrimination

GERDA

Naked enriched Ge-crystals in LAr with lead shield

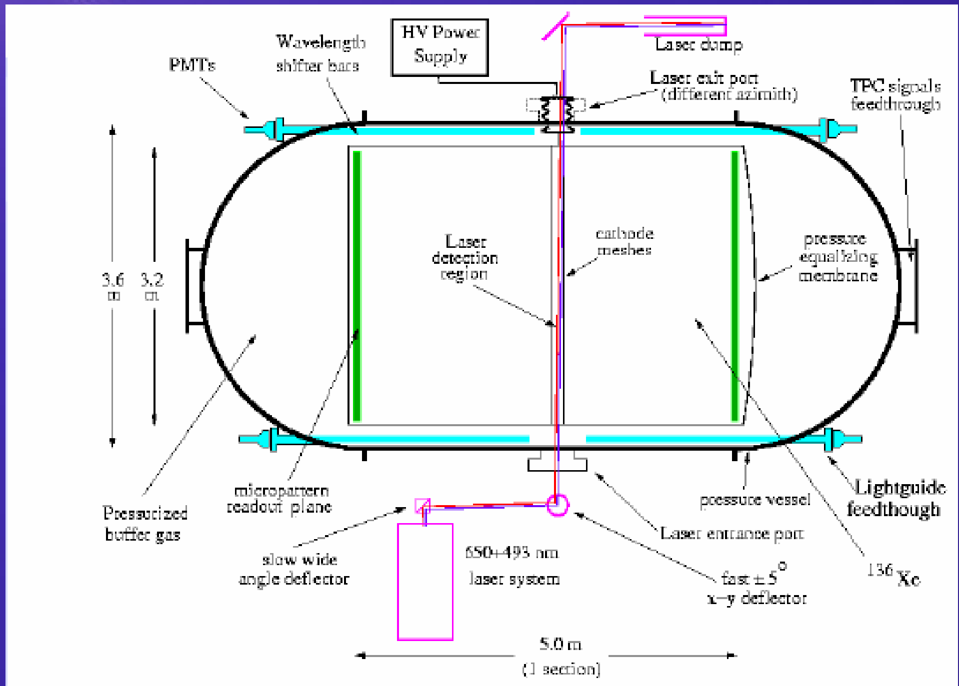
20 kg enriched Ge-detectors at hand (former HD-MO and IGEX), 35 kg enriched bought



MERGE

EXO

Tracking and scintillation

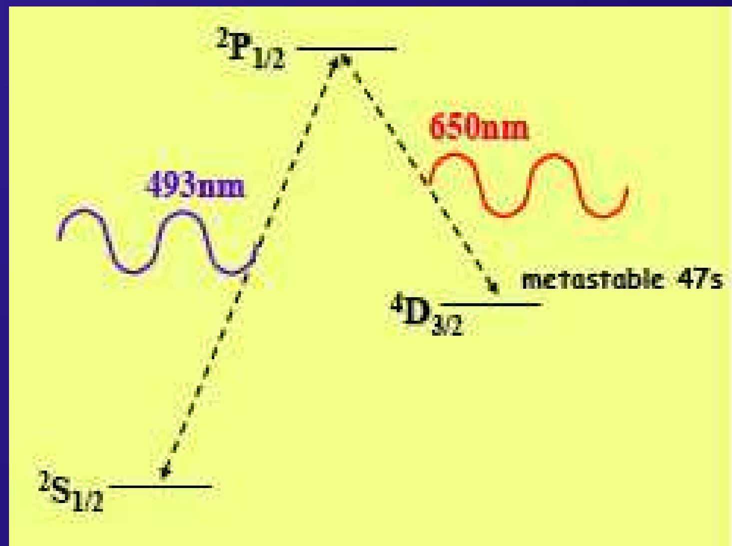


200 kg enriched Xe prototype under construction at WIPP

New feature:

$^{136}Xe \rightarrow {}^{136}Ba^{++}\ e^-\ e^-$ final state can be identified using optical spectroscopy

(M.Moe PRC44 (1991) 931)



Summary

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

Taking current evidences from oscillation data it is likely to be the only way to fix the absolute neutrino mass

To go below 50 meV requires hundreds of kilograms of enriched material

However, there is a hotly discussed evidence by the Heidelberg group, which would imply almost degenerate neutrinos

To account for matrix element uncertainties and to disentangle the physics mechanism we need at least 3(4) isotopes measured

A lot to do

Hope....