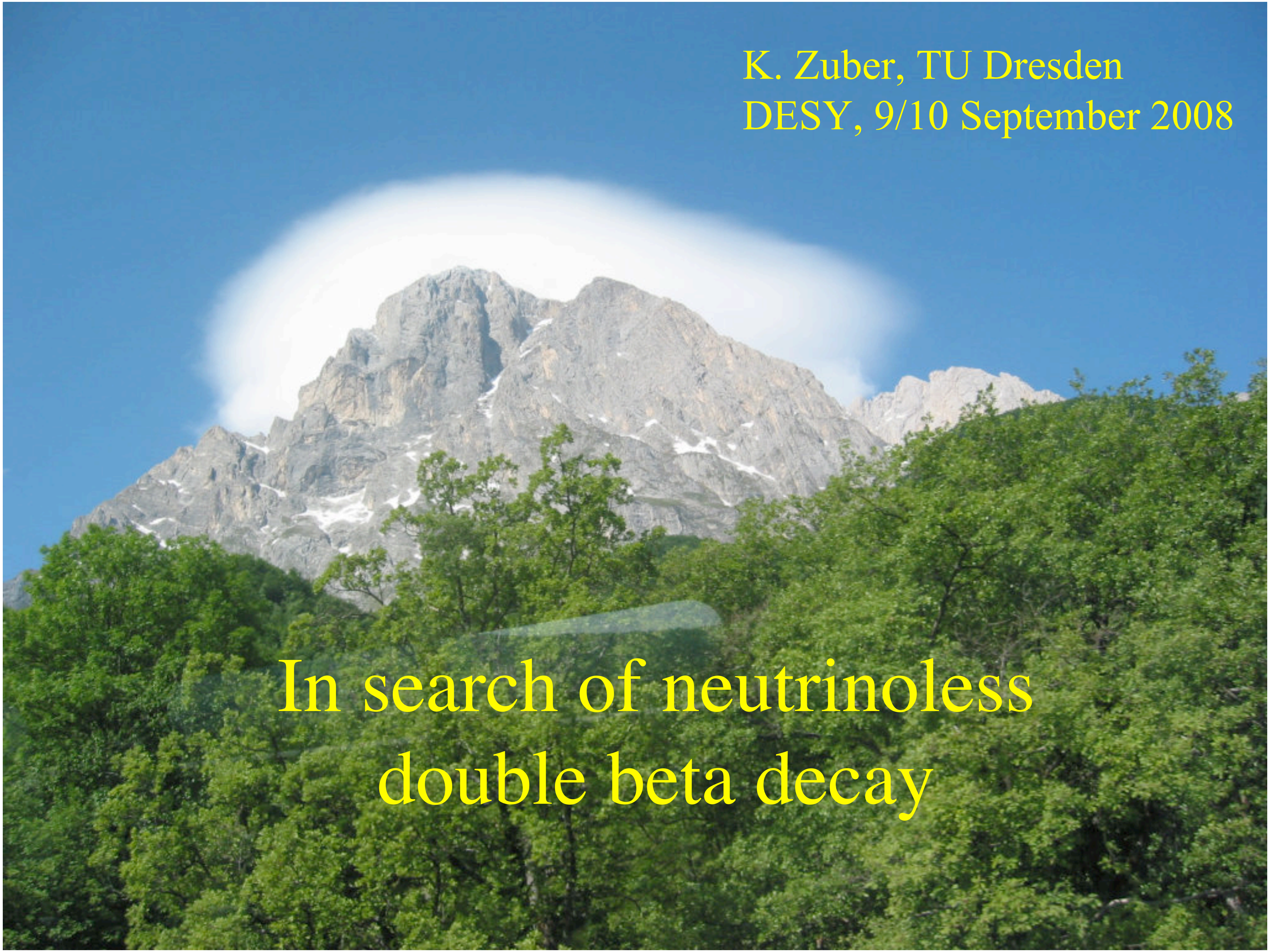
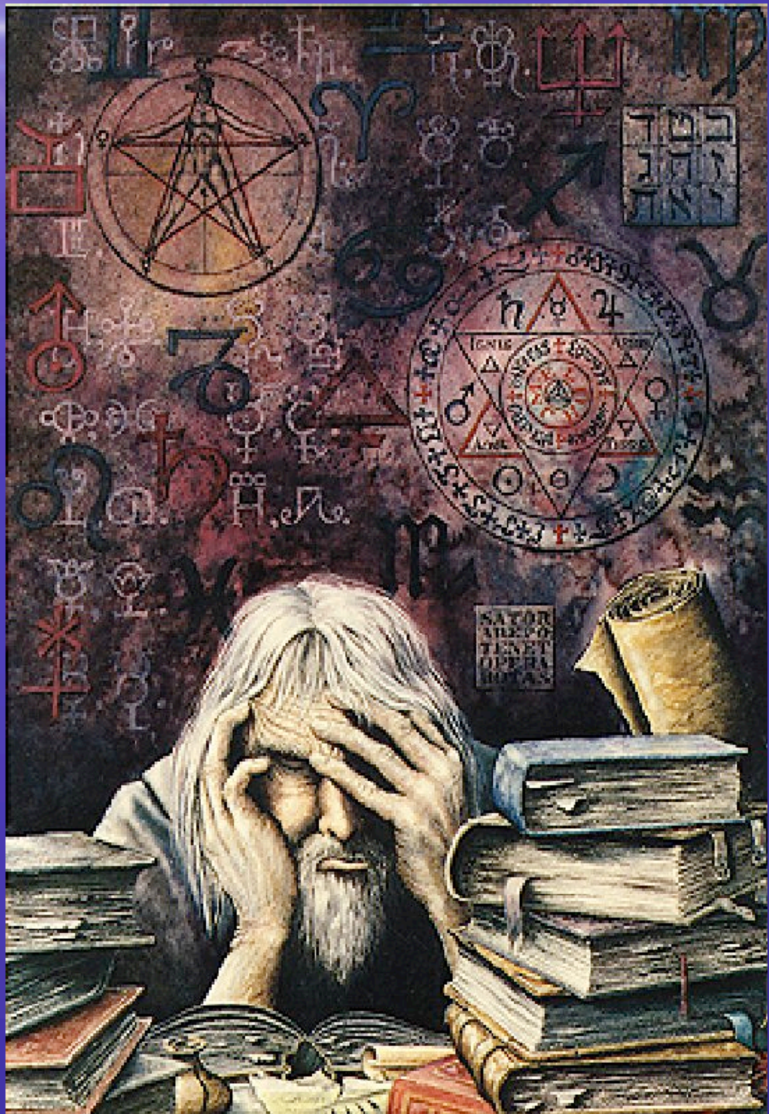


K. Zuber, TU Dresden

DESY, 9/10 September 2008

In search of neutrinoless double beta decay

Contents

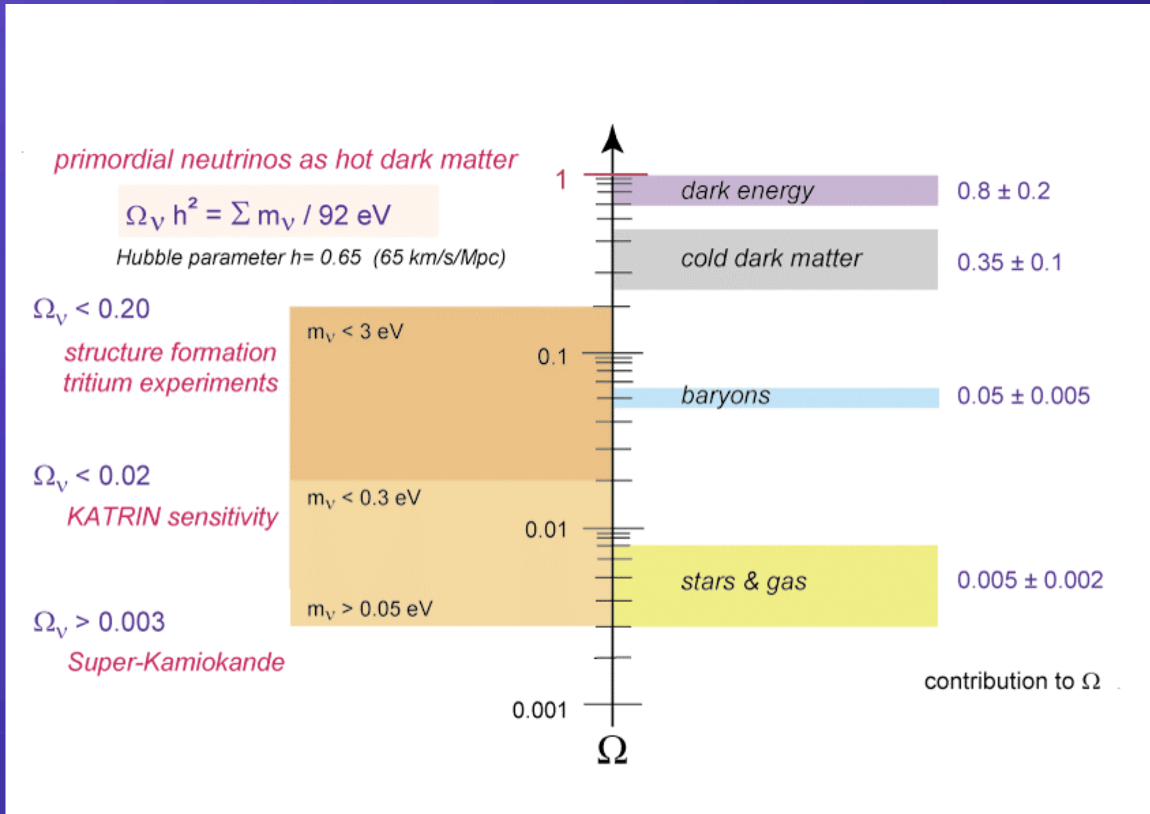


Fundamental neutrino properties

Are neutrinos their own antiparticles?

What is the absolute neutrino mass?

One example:

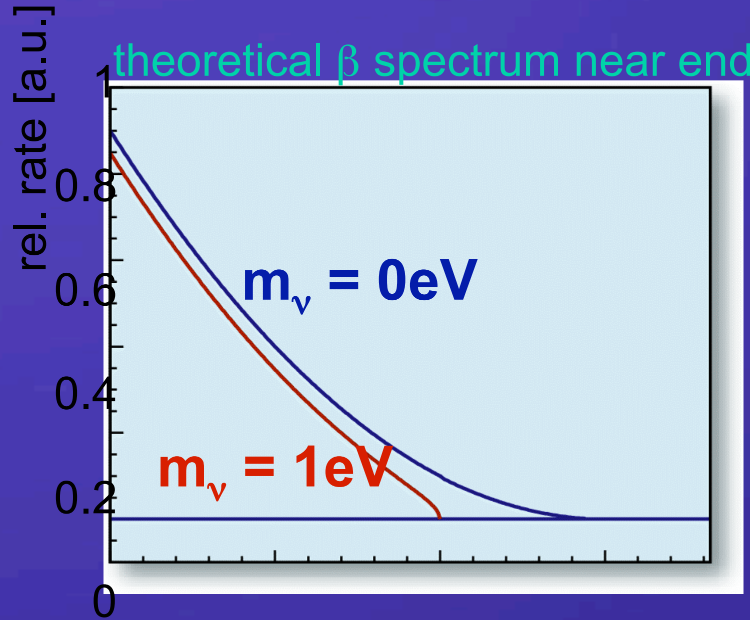


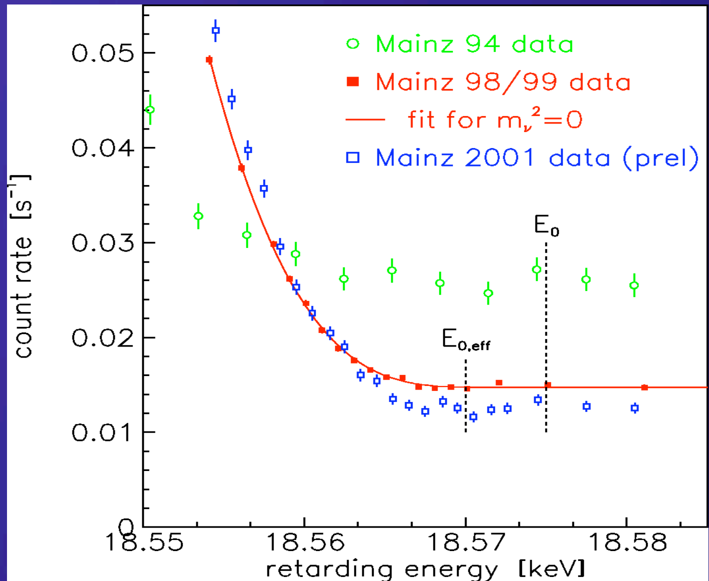
Both questions can be explored with double beta decay

Beta decay

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

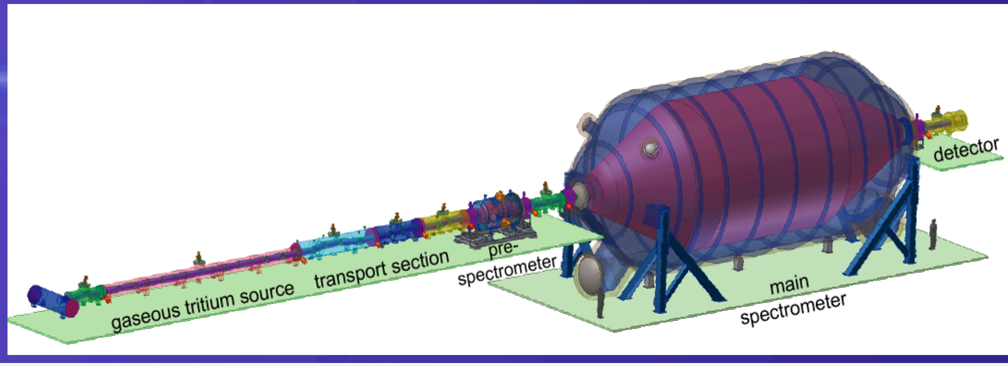
Isotope: ^{3}H Only about 10^{-13} electrons in the last eV

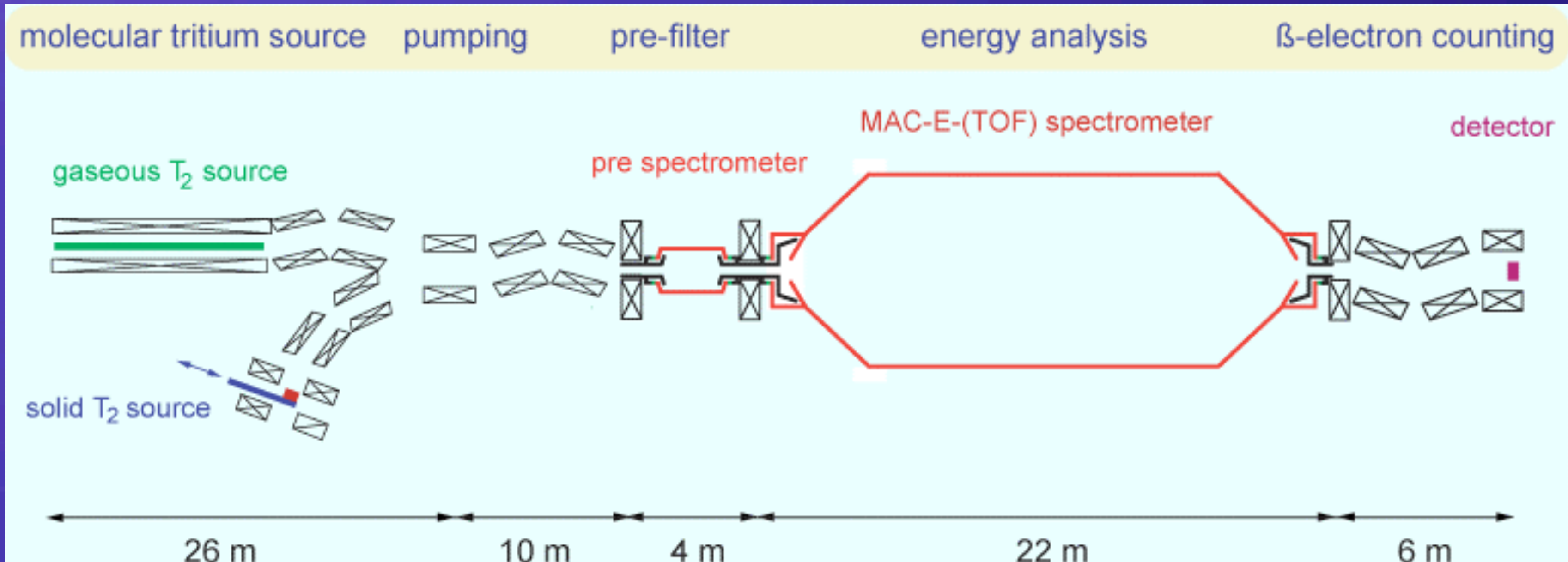




Mainz and Troitsk: $m_{\nu e} < 2.2$ eV (sensitivity limit)

KATRIN-The ultimate beta-decay experiment





Discovery potential $m_{\nu e} = 0.35$ eV at 5σ

Sensitivity $m_{\nu e} < 0.2$ eV (90% CL)

Commisioning in 2008

KATRIN

Aim: Sensitivity to neutrino masses down to 0.2 eV

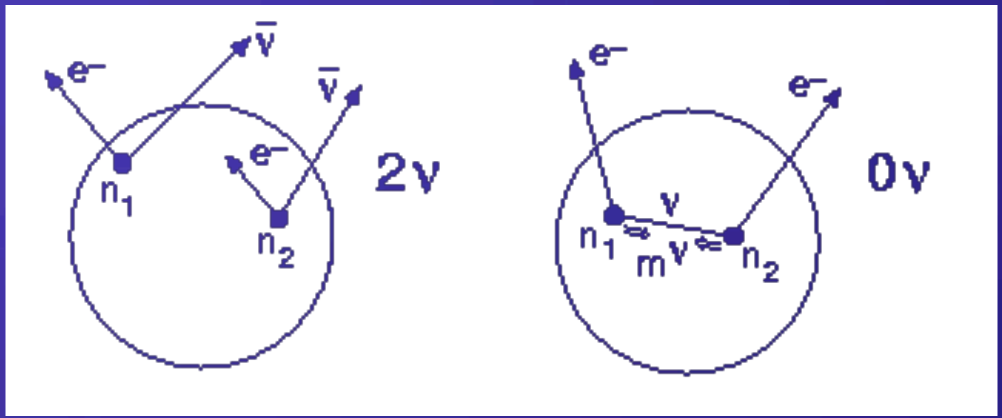
Beta and double beta decay

Beta decay

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

Double beta decay

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

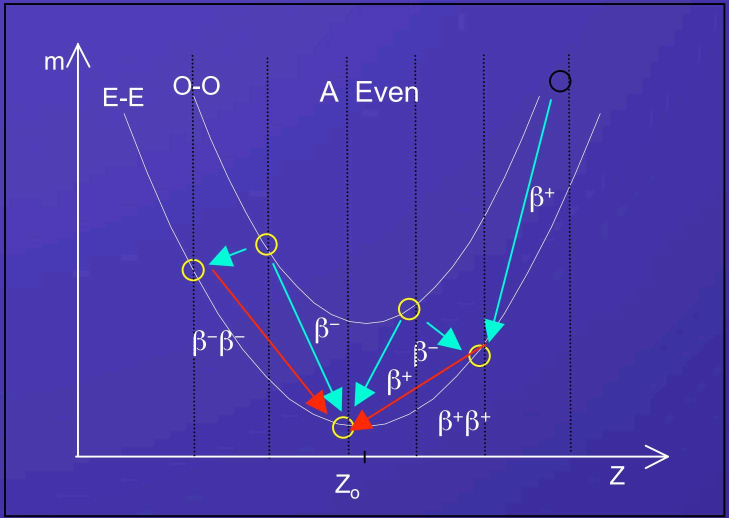


changing Z by two units while leaving A constant

Requirements

Weizsäcker formula for A=const near minimum well approximated by

$$m(Z,A) = const + 2b_S \frac{(A/2 - Z)^2}{A^2} + b_C \frac{Z^2}{A^{1/3}} + m_e Z + \delta$$



Pairing energy δ leads to splitting:

$\delta = 0$ for even-odd, odd-even

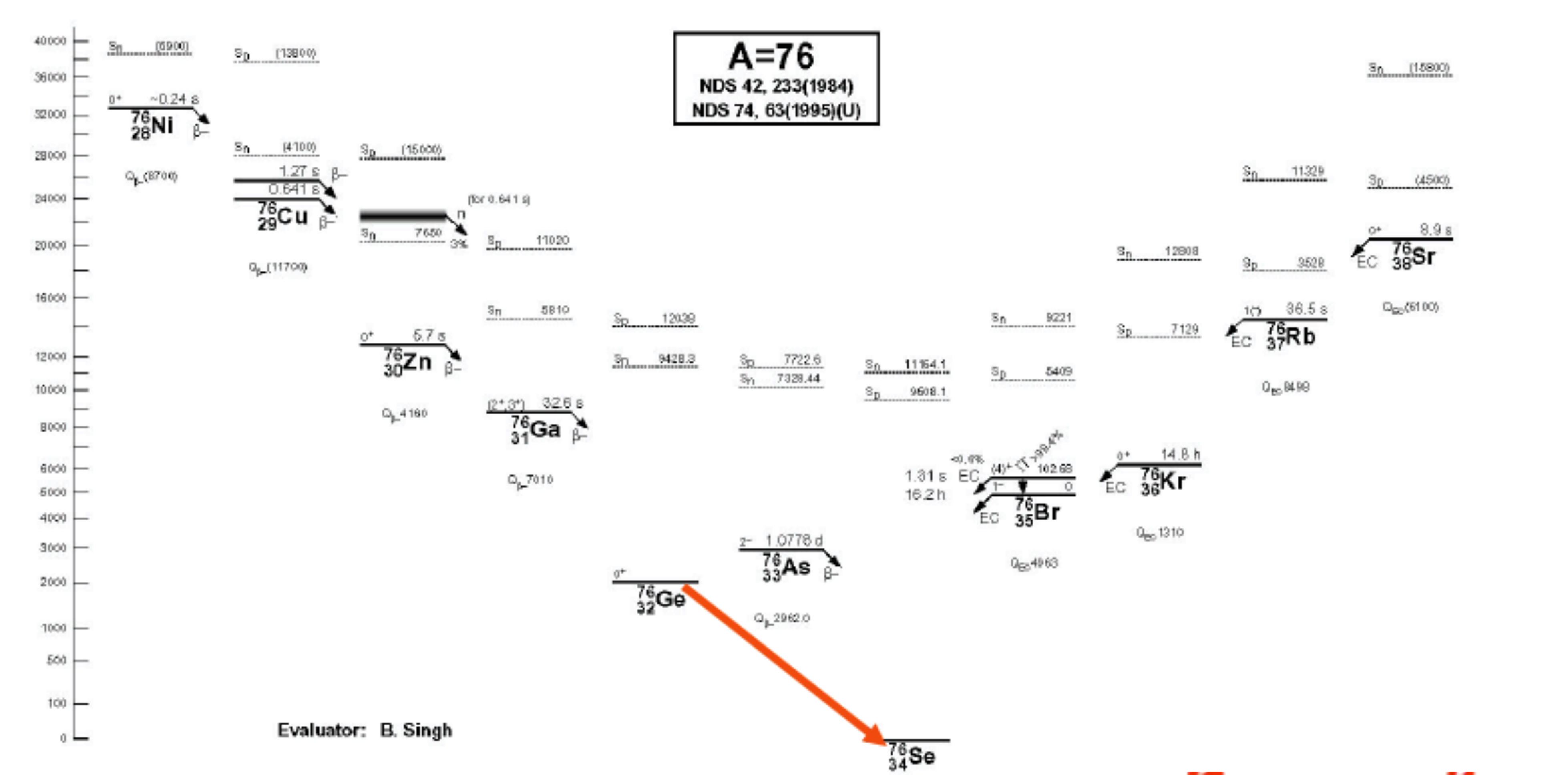
$\delta = -12\ \mathrm{MeV}/A^{1/2}$ for even-even

$\delta = +12\ \mathrm{MeV}/A^{1/2}$ for odd-odd

There are 35 $\beta^-\beta^-$ isotopes in nature

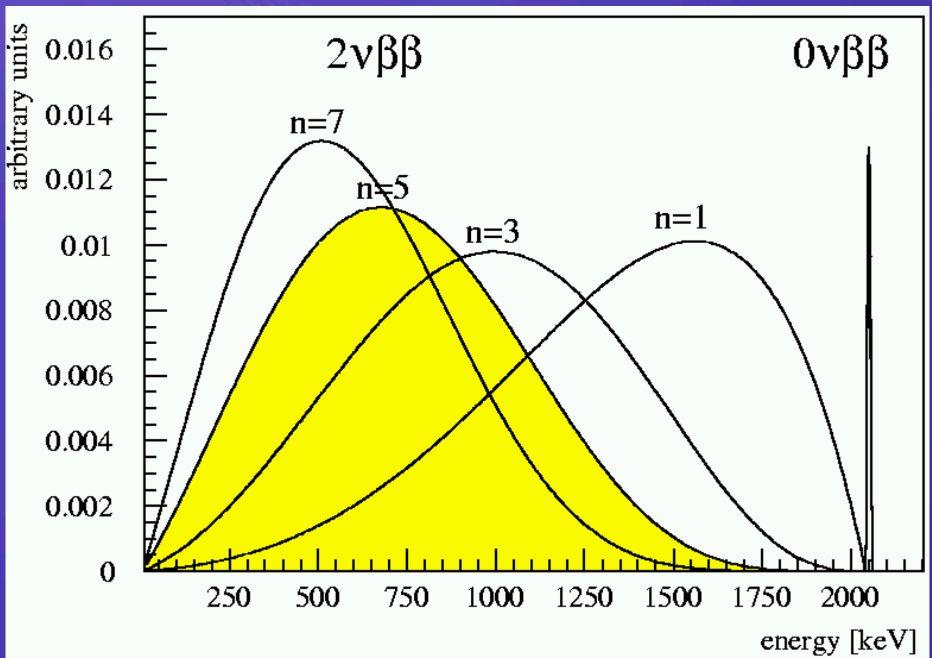
Single beta decay must be forbidden

Example - Ge76



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)

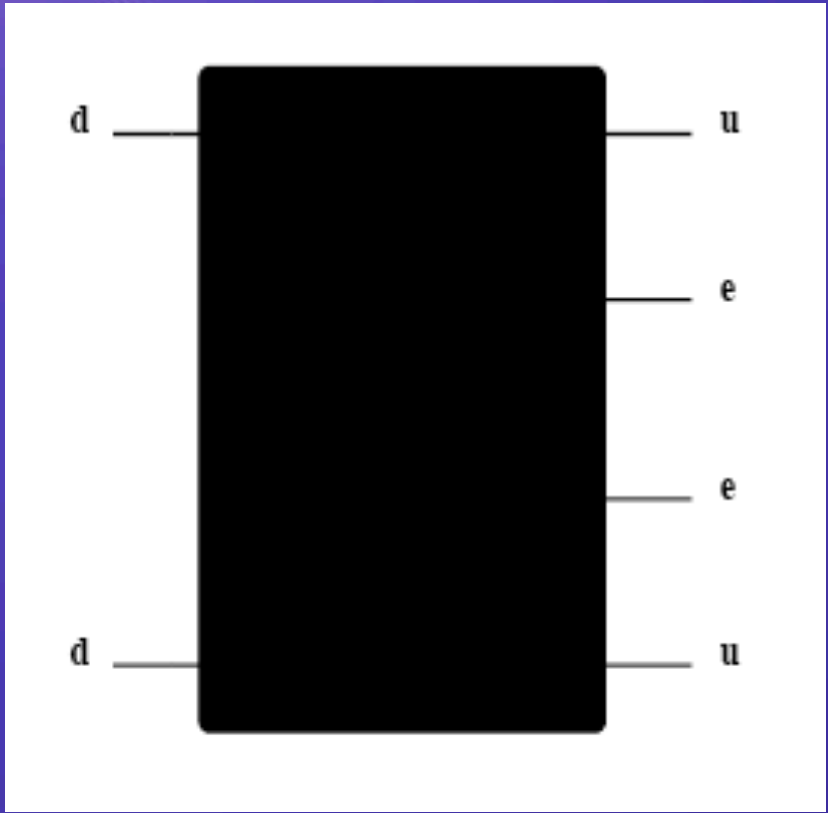
$$T_{1/2} \propto a \bullet \varepsilon \, (M \bullet t / \Delta E \bullet B)^{1/2}$$

link to neutrino mass

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

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

LSND

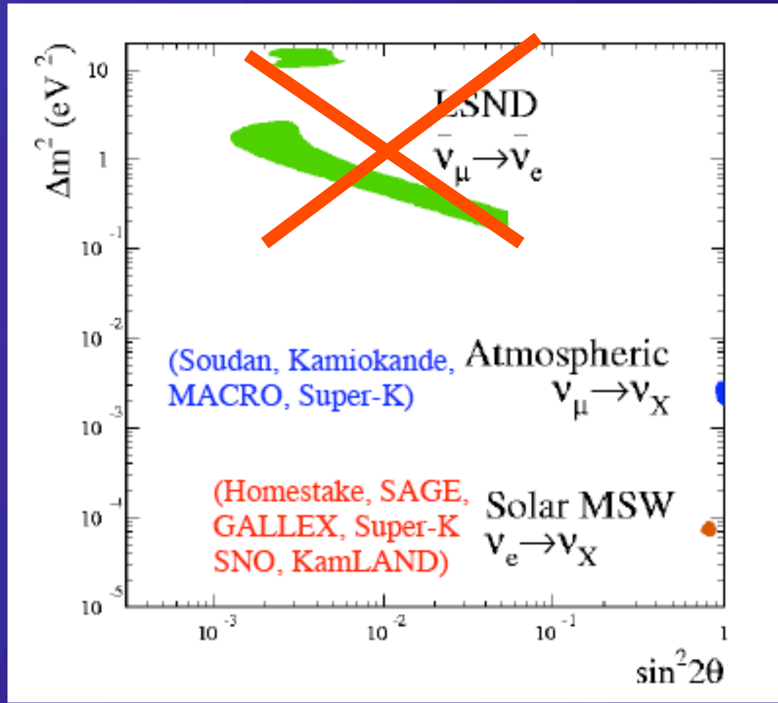
$\sin^2 2\theta = 10^{-1}\text{-}10^{-3}$, $\Delta m^2 = 0.1\text{-}6$ eV^2

Atmospheric

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

Solar + reactors

$\sin^2 2\theta = 0.81$, $\Delta m^2 = 8.0 \times 10^{-5}$ eV^2

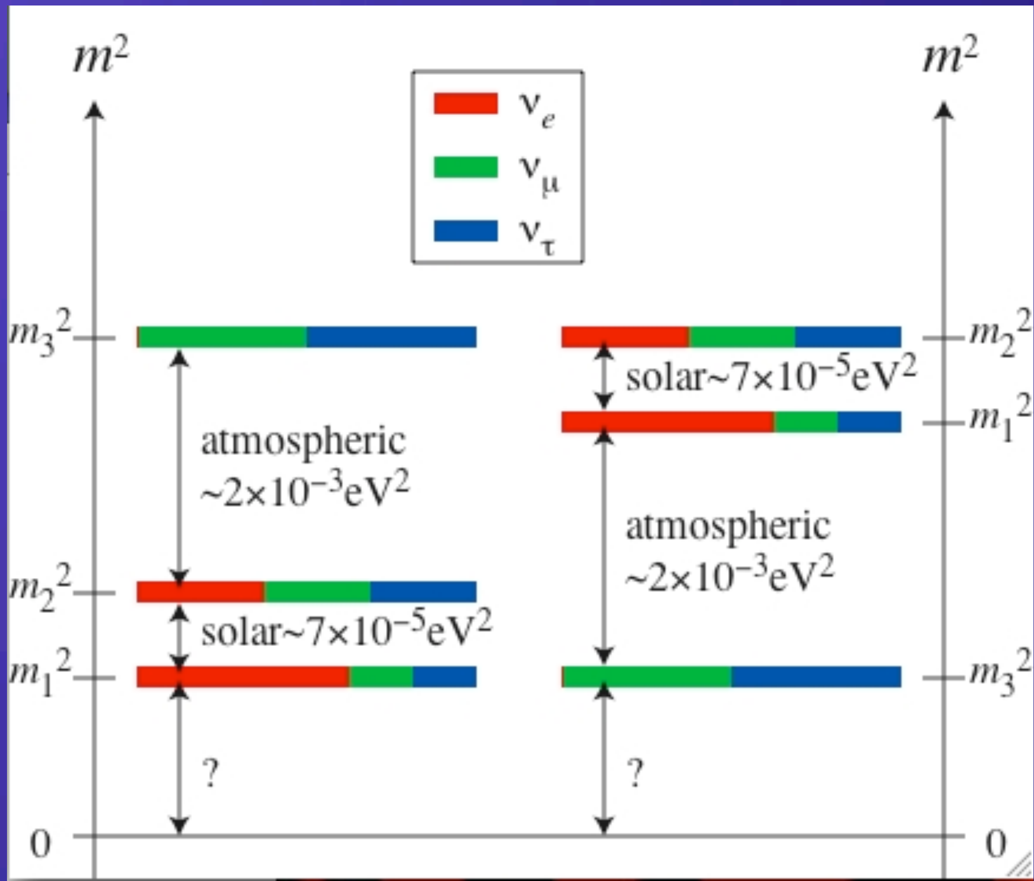


LSND not confirmed by MiniBooNE

Neutrino mass schemes

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

- hierarchical neutrino mass schemes



normal inverted

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

Experimental observable: Half-life

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

Oscillations and 0νββ

General:

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

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

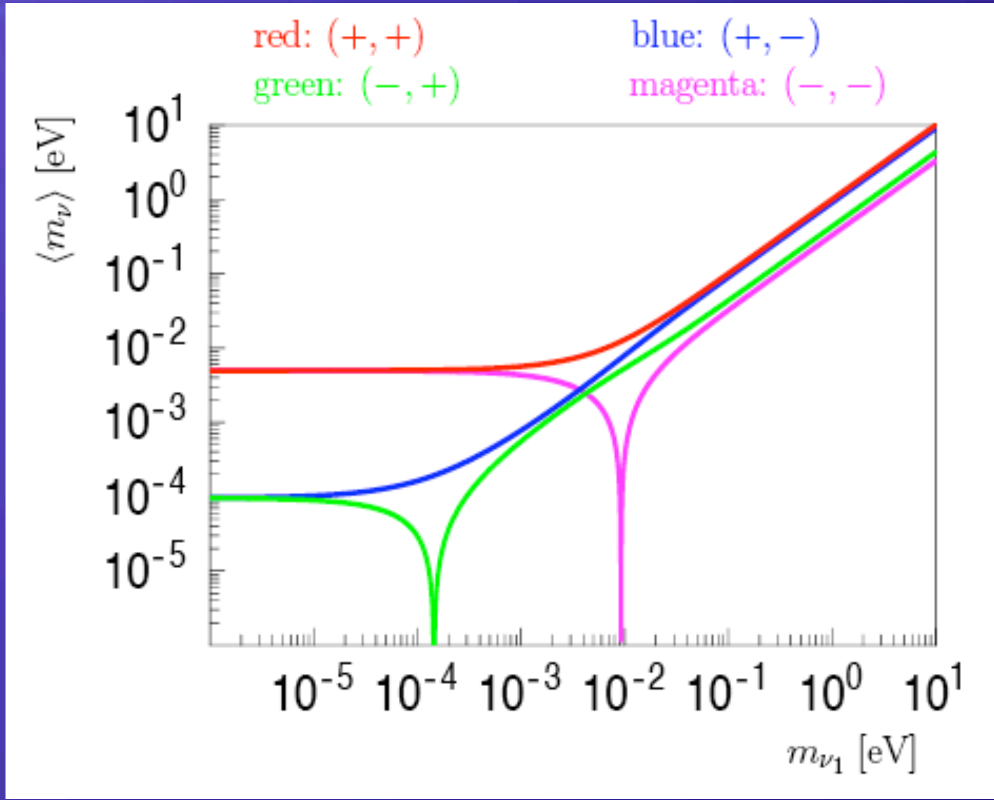
$$\begin{aligned} \langle m_\nu \rangle &= \sum_j U_{ej}^2 m_{\nu_j} \\ &\simeq c_{12}^2 c_{13}^2 m_{\nu_1} + s_{12}^2 c_{13}^2 e^{i\alpha} m_{\nu_2} + s_{13}^2 e^{i\beta} m_{\nu_3} \\ &\sim c_\odot^2 m_{\nu_1} - s_\odot^2 m_{\nu_2} + 0 \end{aligned}$$

Thus:

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

Neutrino mass schemes and 0νββ

Best fit values



M. Hirsch
Neutrino 2006

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

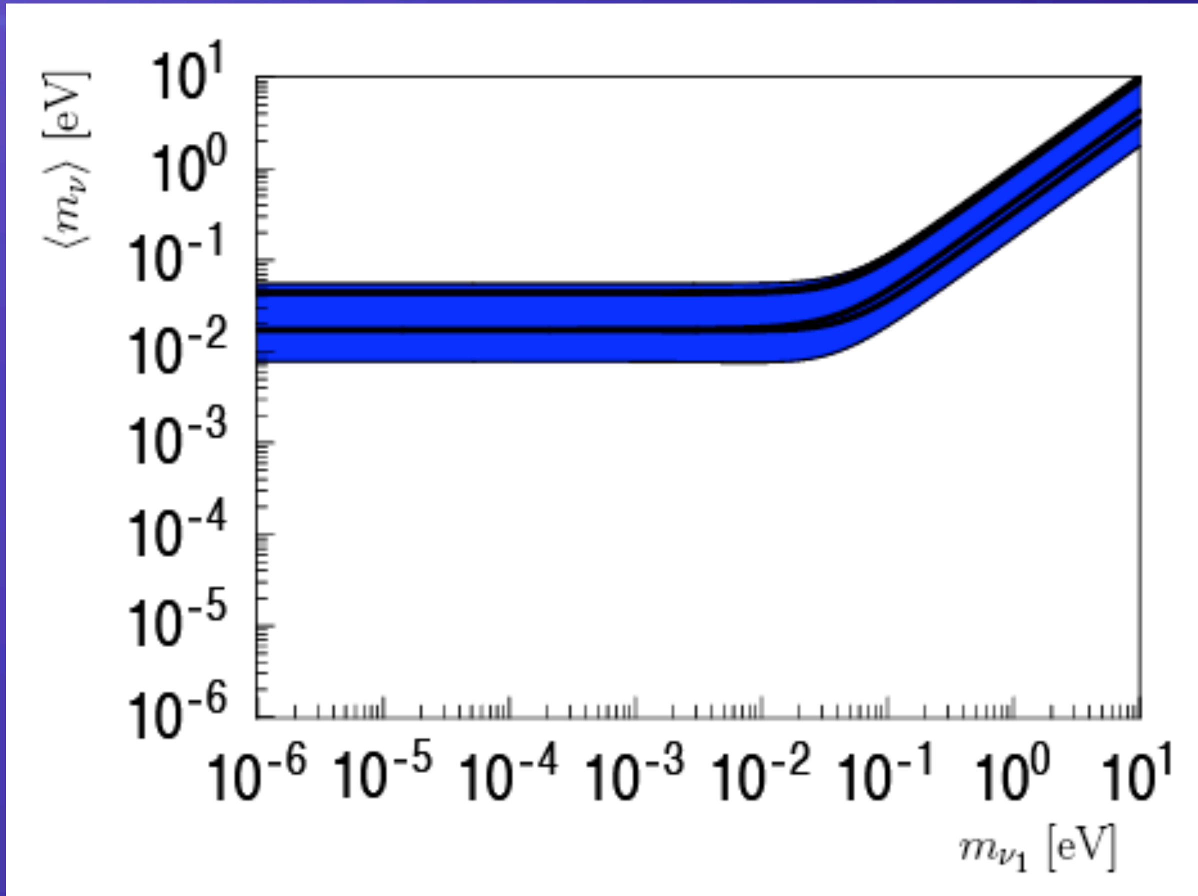
$$\sin^2\theta_{\odot} = 0.3, \qquad \sin^2\theta_R = 0.051$$

0νββ-Inverted mass scheme

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

$\Rightarrow$ Lower limit exists, if $\theta_\odot$ non-maximal $(s_\odot^2 < 1/2)$

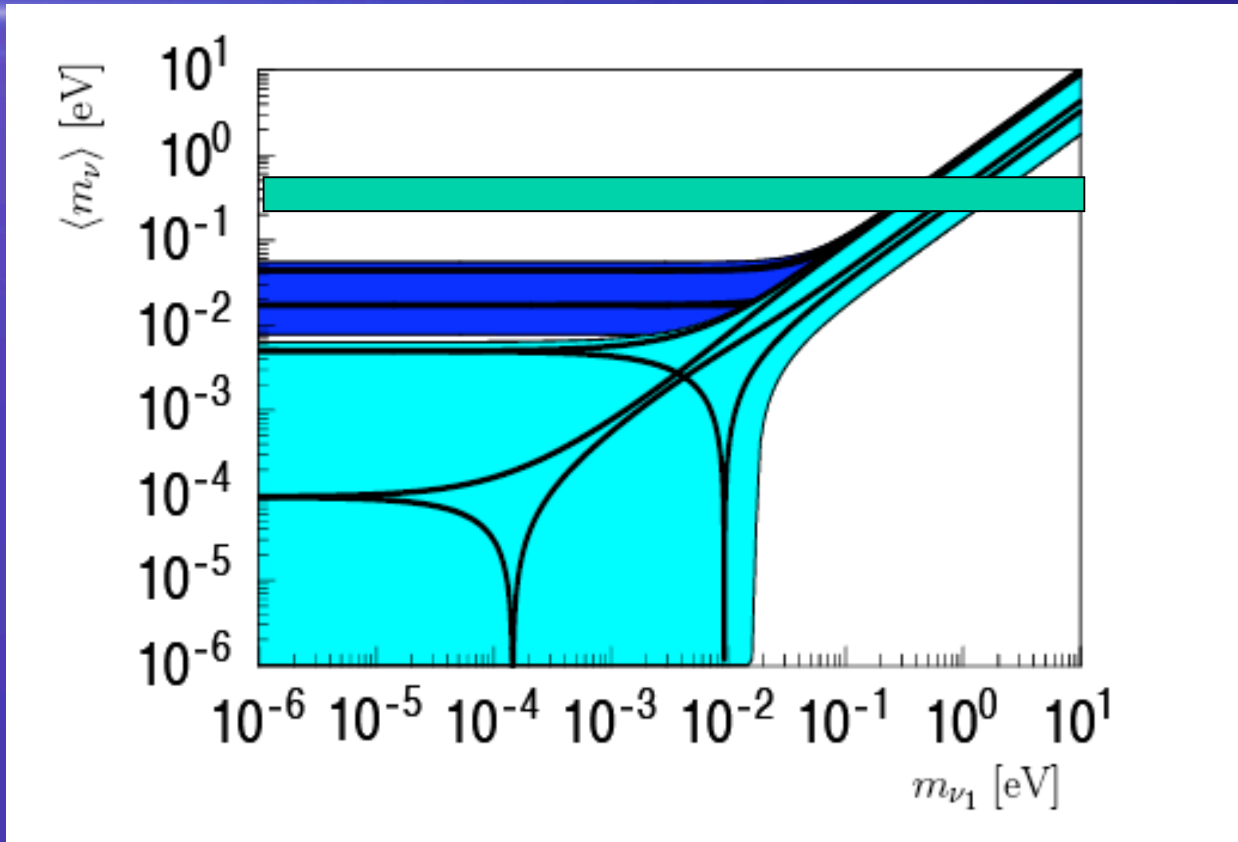
0νββ - Inverted hierarchy



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

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

Normal + inverted scheme



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

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

Phase space

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

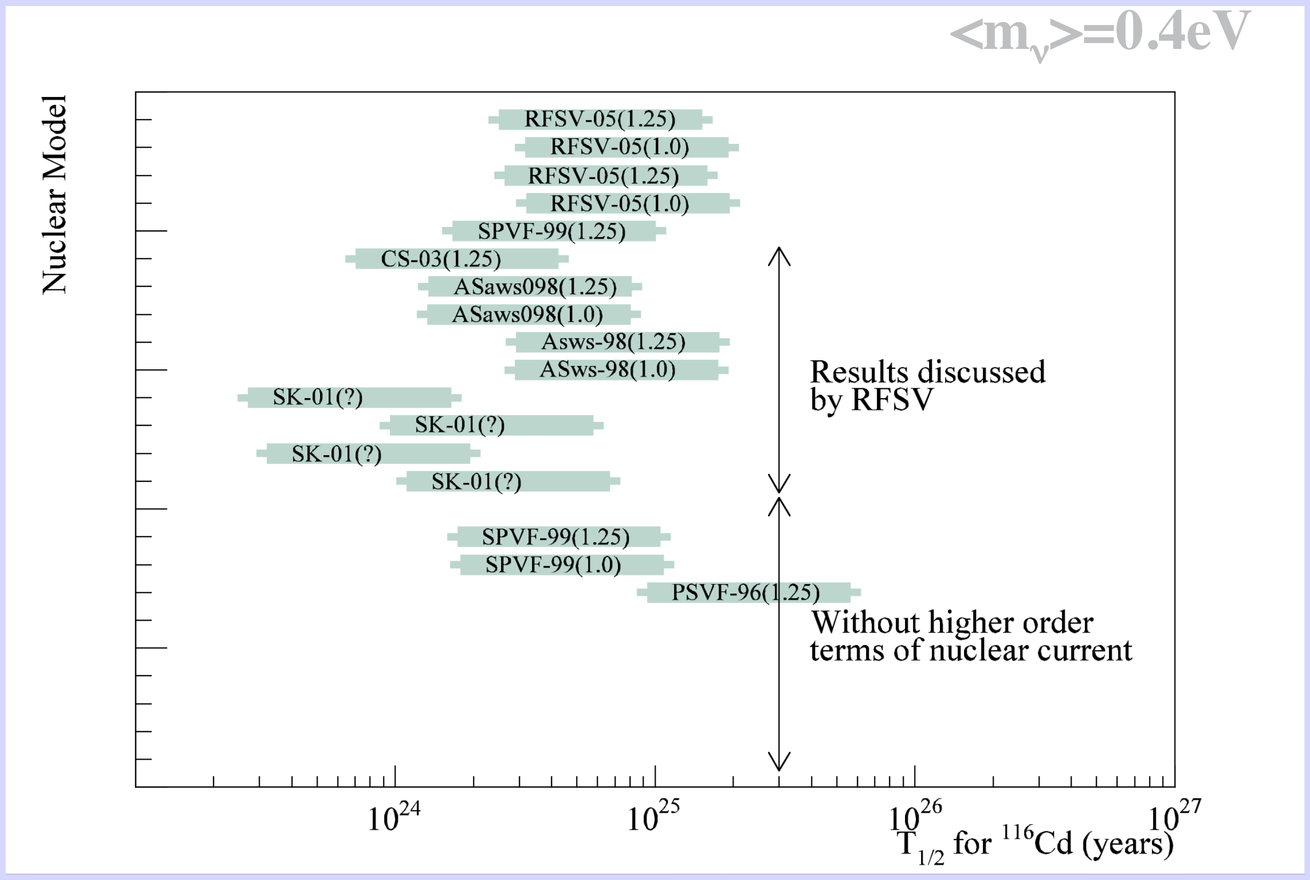
$2\nu\beta\beta$ decay rate scales with Q^{11}

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	**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**

Nuclear matrix elements

The dark side of double beta decay

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



V. Rodin et al., nucl-th/0503063, Nucl. Phys. A 766,107 (2006)

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

or

Back of the envelope

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

For 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, ...

The dominant problem - Background

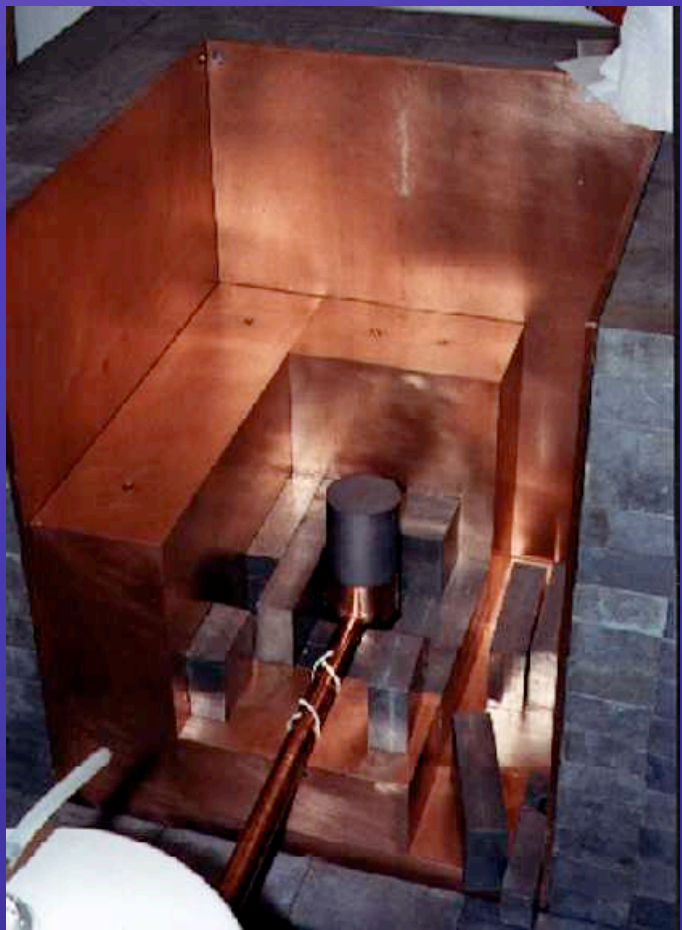
How to measure half-lives beyond 10^{20} years???

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

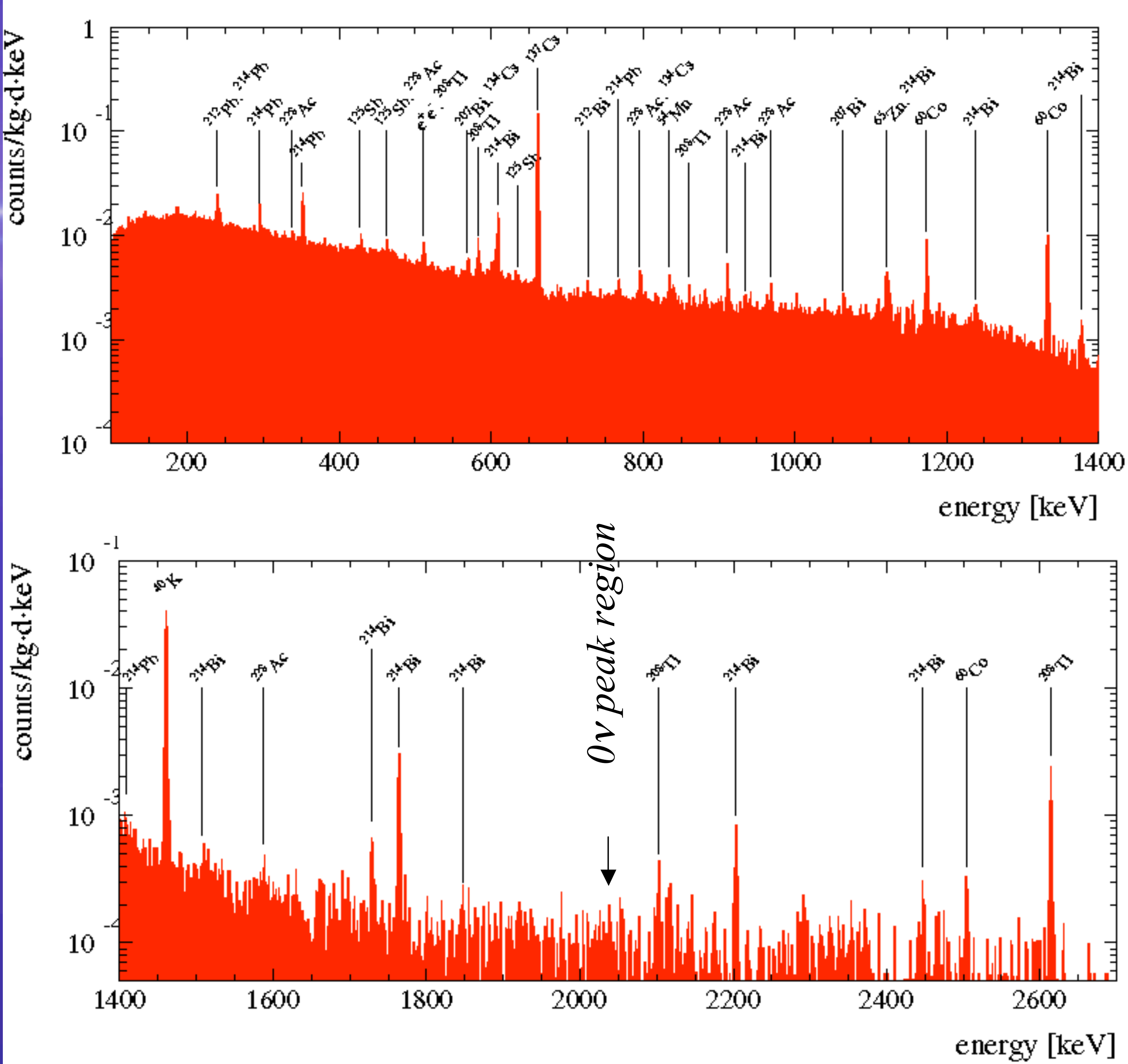
- The usual suspects (U, Th nat. decay chains)
- Alphas, Betas, Gammas
- Cosmogenics
- thermal neutrons
- High energy neutrons from muon interactions
- $2\nu\beta\beta$

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

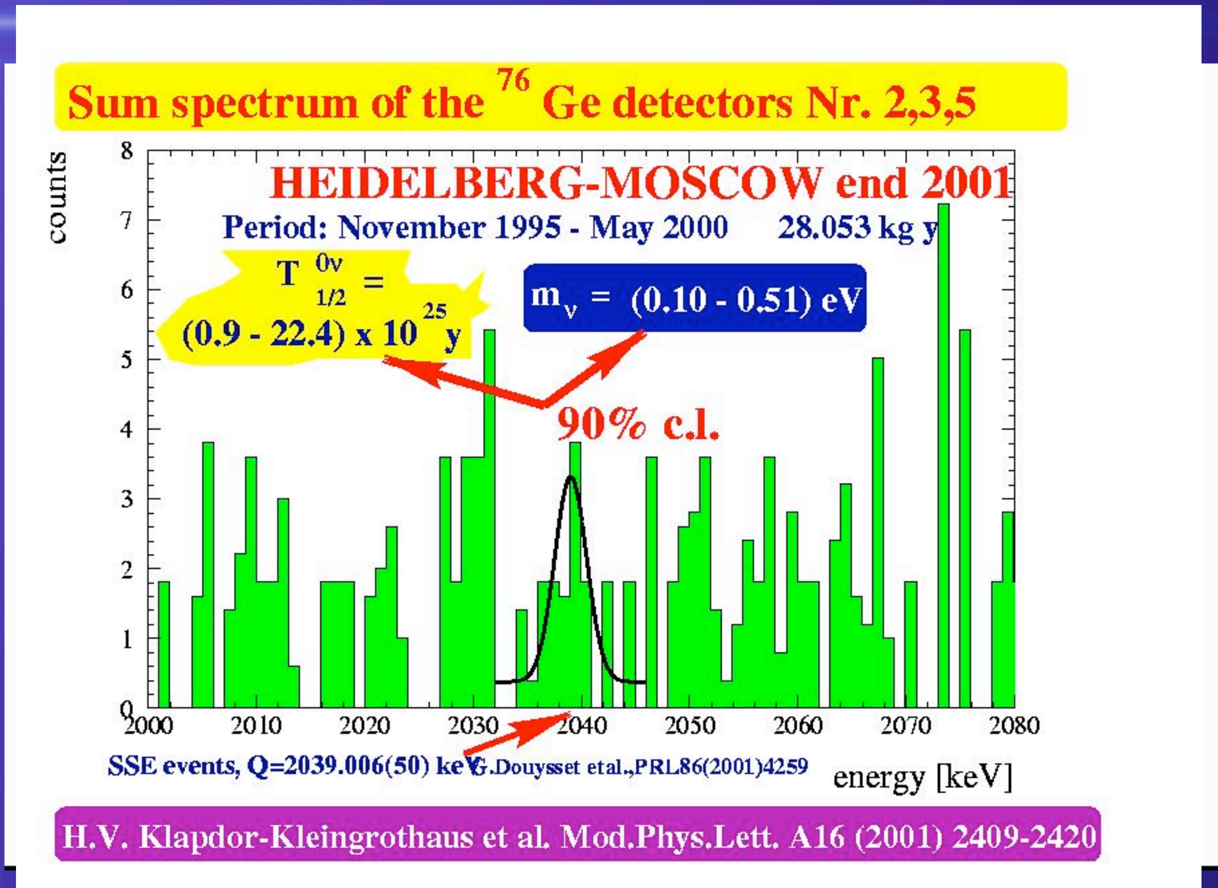


Spectrum



counts/kg·d·keV
energy [keV]
200
400
600
800
1000
1200
1400
^{137}Cs
^{214}Pb
^{214}Bi
^{60}Co
^{40}K
^{208}Tl
^{228}Ac
0ν peak region
1600
1800
2000
2200
2400
2600
counts/kg·d·keV
energy [keV]

Heidelberg -Moscow



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

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

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
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

CUORICINO running

NEMO3 running

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

Current aims of double beta searches

- Check whether observed peak claimed in ^{76}Ge is true
- 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
- Compensation of NME uncertainties might require the measurement of 3-4 different isotopes

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


GERDA
COBRA

Gerda - Motivation

– *Improvement of neutrino mass sensitivity*

– *Check of possible evidence*

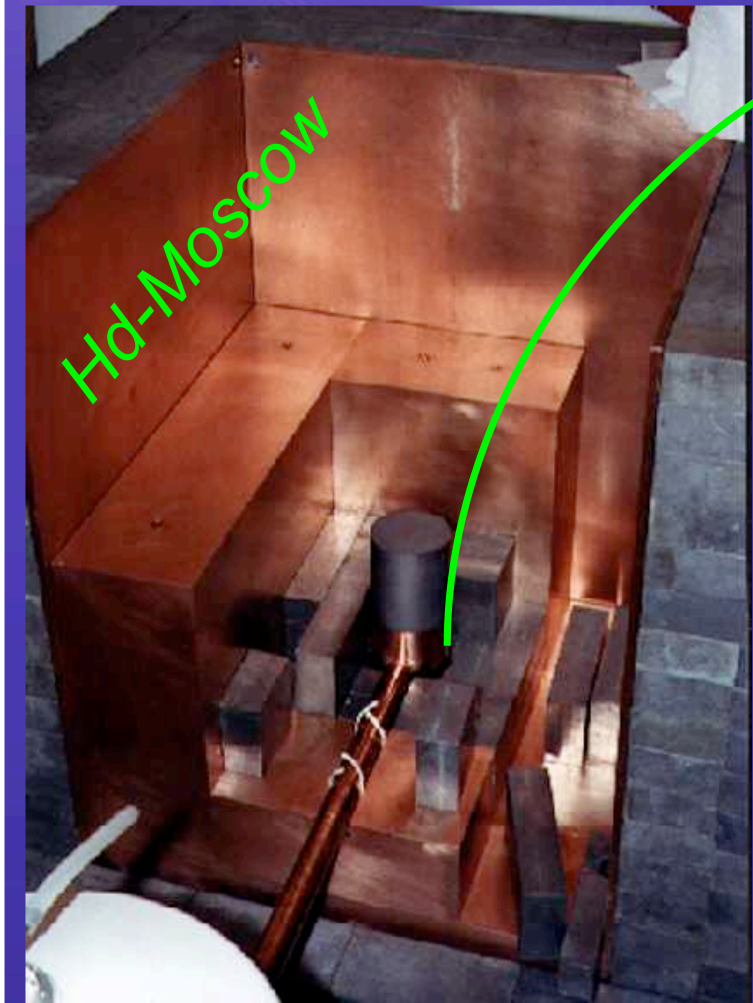
Improve Background by ultra-pure shielding

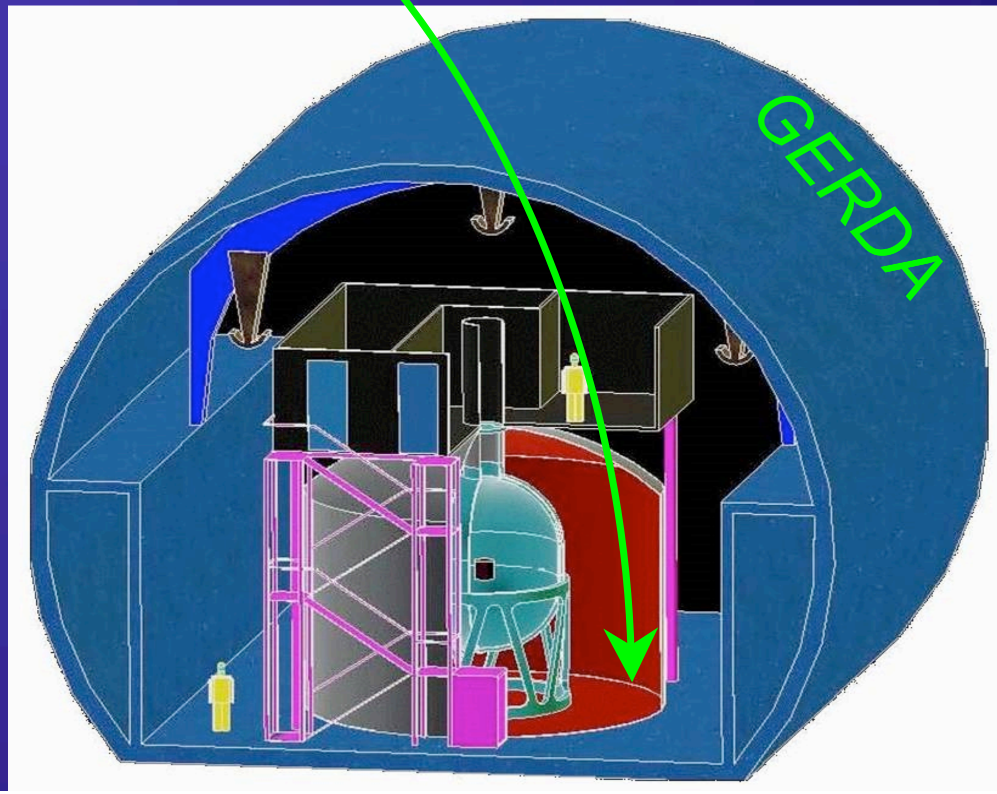
HPGe detectors in *Liquid Argon*

GERDA → 10^{-3} (kg·y·keV)$^{-1}$

[IGEX 0.1–0.3 (kg·y·keV)$^{-1}$]

[Hd-M 0.17 (kg·y·keV)$^{-1}$]





GERDA-collaboration

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G. Meierhofer[m], I. Nemchenok[d], S. Nisi[a], J. Oehm[f], L. Pandola[a], P. Peiffer[f],
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M. Shirchenko[j], H. Simgen[f], A. Smolnikov[d,h], L. Stanco[l], -IN F. Stelzer[k],
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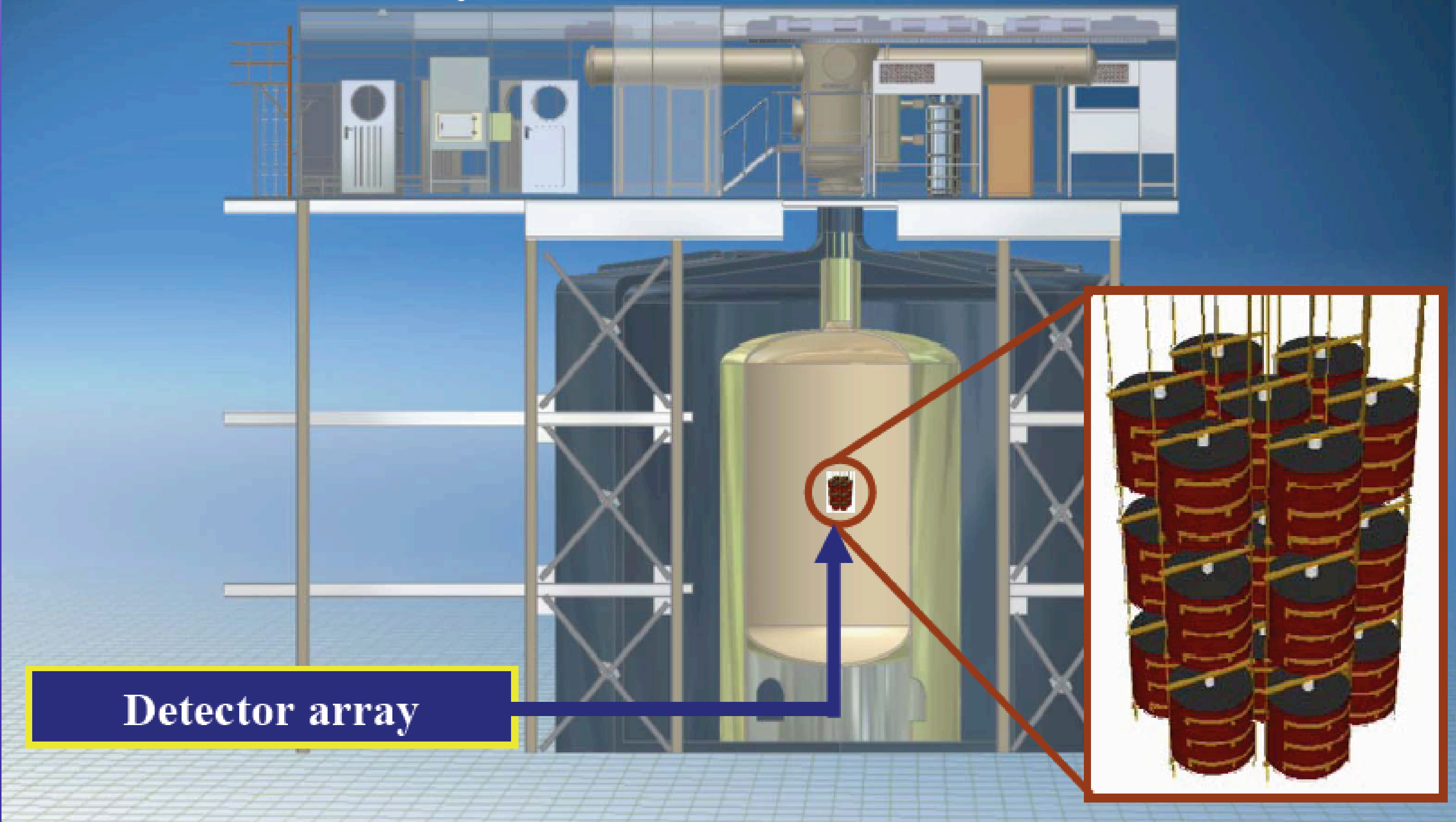
[n] Physik Institut der Universität Zürich, Zürich, Switzerland

~70 physicists
13 institutions
6 countries

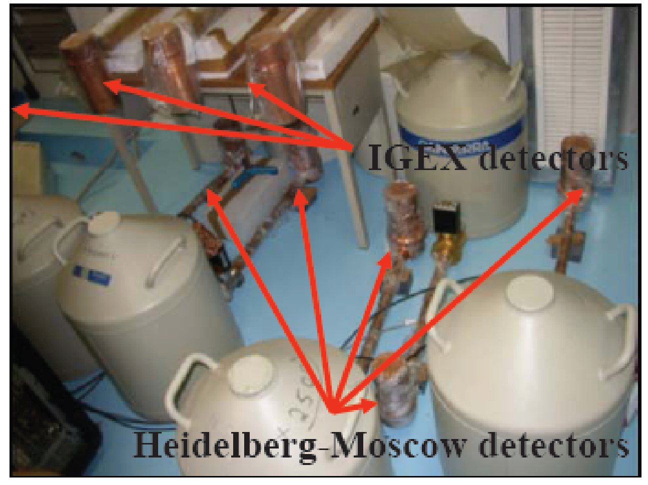
GERDA-Schematics

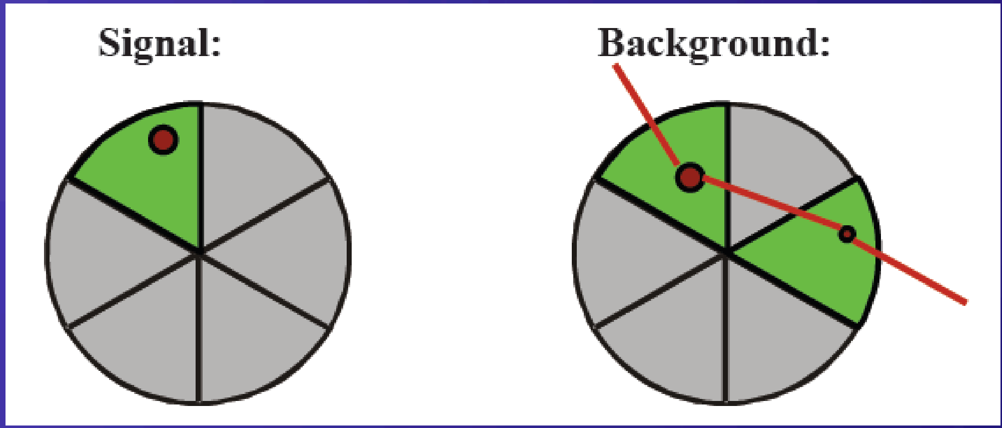
- Place array of naked HPGe-detectors enriched in ^{76}Ge in the center of a stainless cryostat filled with LAr.

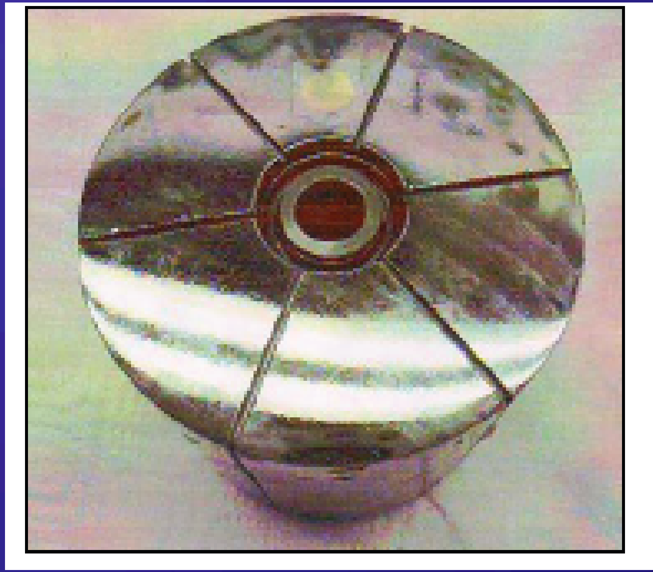


Status GERDA

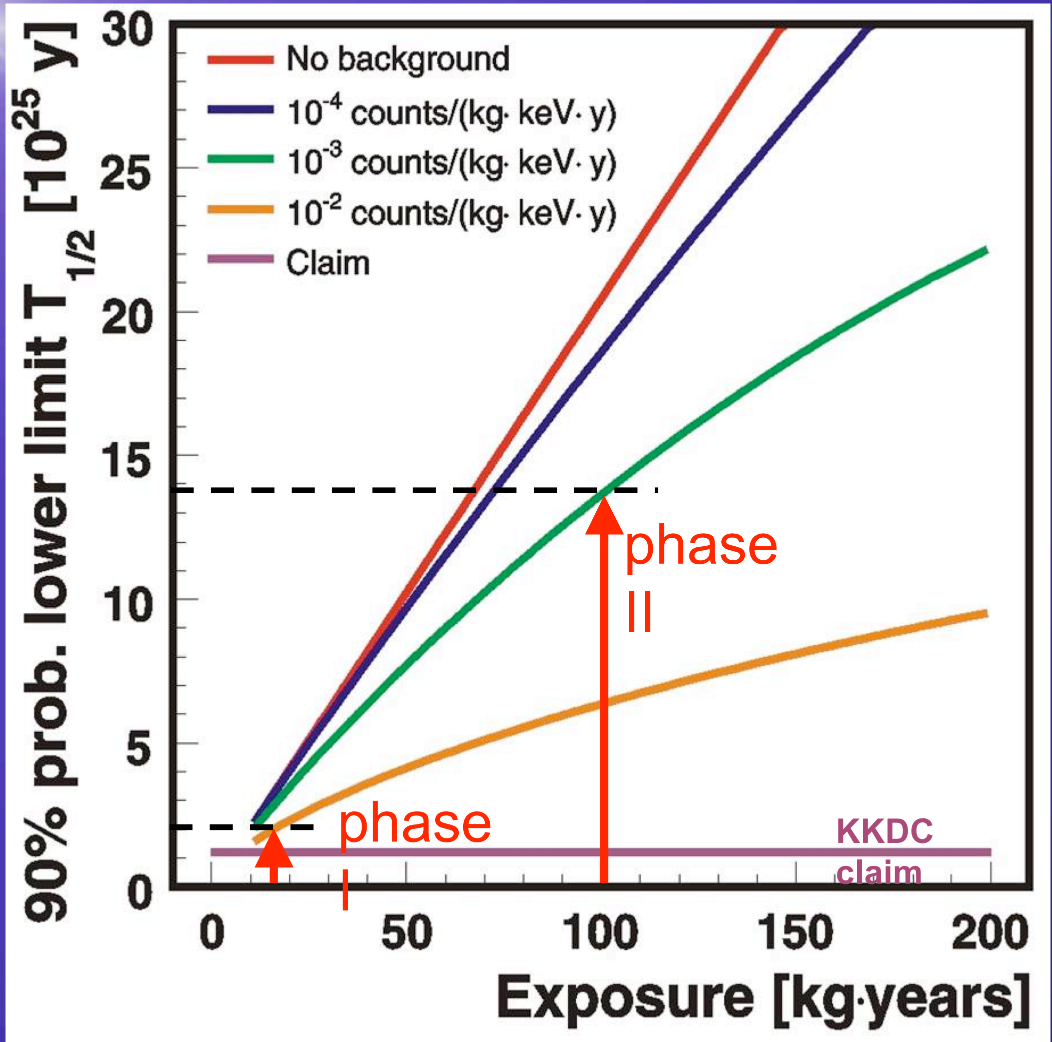
GERDA Detectors







GERDA sensitivity



P I **15 kg y**
at **10^{-2} (keV kg y)$^{-1}$**
$T_{1/2}^{0\nu}$> **$1.2 \cdot 10^{25}$y**
(→HdM: $1.2 \cdot 10^{25}$y)

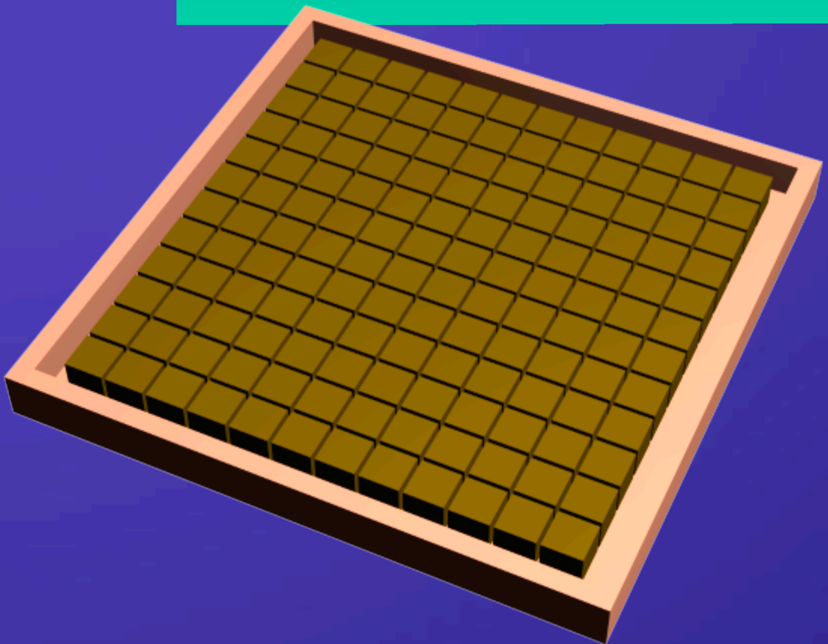
P II **100 kg y**
at **10^{-3} (keV kg y)$^{-1}$**
$T_{1/2}^{0\nu}$> **$1.4 \cdot 10^{26}$y**

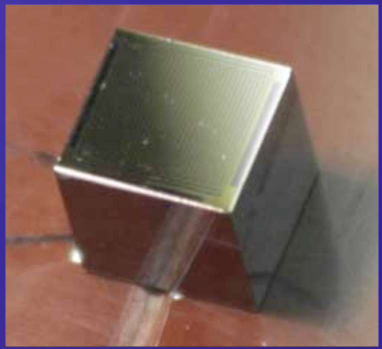
P III 1 ton ^{76}Ge exp. (GERDA/Majorana)
depending on Phase I/II outcome
Background goal **10^{-4} (keV kg y)$^{-1}$**

Phase I commissioning
early 2009

COBRA

Use large amount of
CdZnTe
Semiconductor Detectors





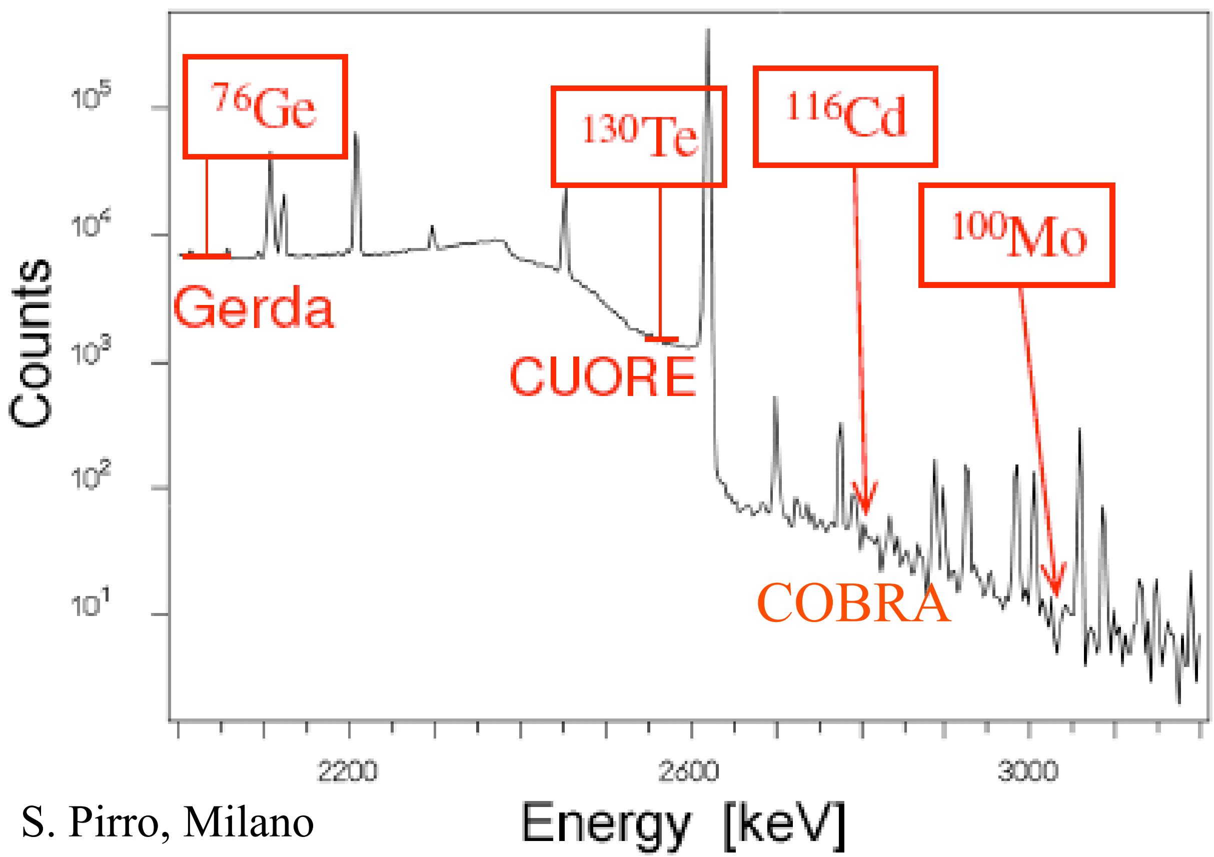
Array of 1cm^3
CdZnTe detectors

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

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



Beyond 2.614 MeV background is a priori much lower

Isotopes

COBRA: CdZnTe semiconductors

		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

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

Latest shell model calculations

(first for those heavier than ^{48}Ca)

	m_ν for $T_{\frac{1}{2}} = 10^{25}$ y.	$M^{(0\nu)}_{GT}$	$1-\chi_F$
^{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...

COBRA collaboration

TU Dortmund
TU Dresden
Material Research Centre Freiburg

Technical University Prague

Laboratori Nazionali del Gran Sasso

Washington University at St. Louis
Idaho National Laboratory

University of Bratislava

University of Jyvaskyla

University of La Plata

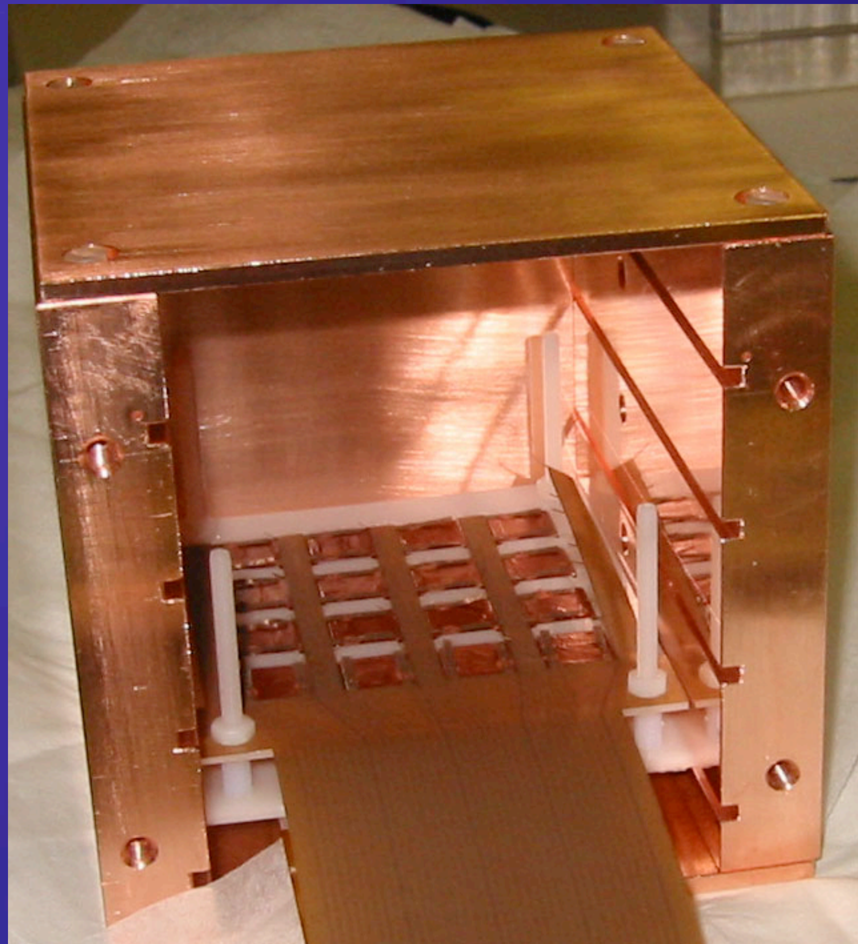
More welcome

Jagellonian University (Poland), Los Alamos Nat. Lab. (USA)

Current R&D

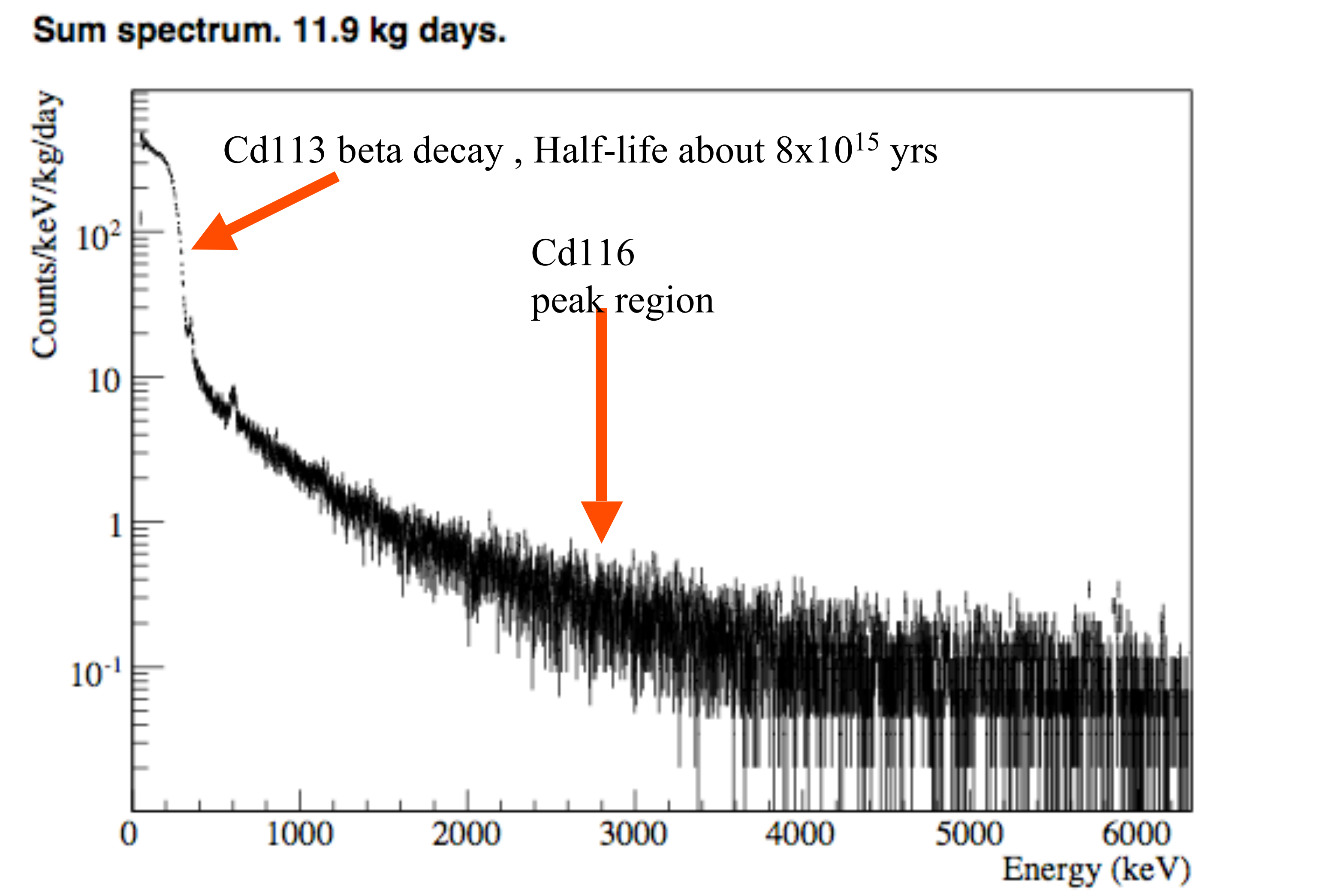
- Two detector concepts
  - energy measurement only (coplanar grid technology)
  - energy measurement and tracking (pixelated detectors)
- Three shielding concepts
  - passive (currently used)
  - passive-active (LSc inside passsive shielding)
  - mostly active (naked crystals in large LSc tank)

The 64 array - first layer



Installed at LNGS in april 2006, world wide largest array of this type of detector

Spectrum



Dominated by radon in air and red passivation on detector surface

New Results

About 8 kg days

PRELIMINARY PRELIMINARY

Isotope and Decay		T_{half} limit (years, 90% C.L.)	
		Current Data	Previous
$\beta^-\beta^-$ Decays			
^{116}Cd	to g.s	6.05×10^{19}	3.14×10^{19}
^{130}Te	to g.s	3.44×10^{20}	9.92×10^{19}
^{130}Te	to 536 keV	2.49×10^{20}	3.73×10^{19}
^{116}Cd	to 1294 keV	2.80×10^{19}	4.92×10^{18}
^{116}Cd	to 1757 keV	3.03×10^{19}	9.13×10^{18}
^{116}Cd	to 2027 keV	3.14×10^{19}	1.37×10^{19}
^{116}Cd	to 2112 keV	4.16×10^{19}	1.08×10^{19}
^{116}Cd	to 2225 keV	2.67×10^{19}	9.46×10^{18}
^{130}Te	to 1794 keV	1.45×10^{20}	
^{130}Te	to 1122 keV	9.48×10^{19}	
^{114}Cd	to g.s.	4.71×10^{20}	

Previous = T. Bloxham et al., PRC 76,025501 (2007)

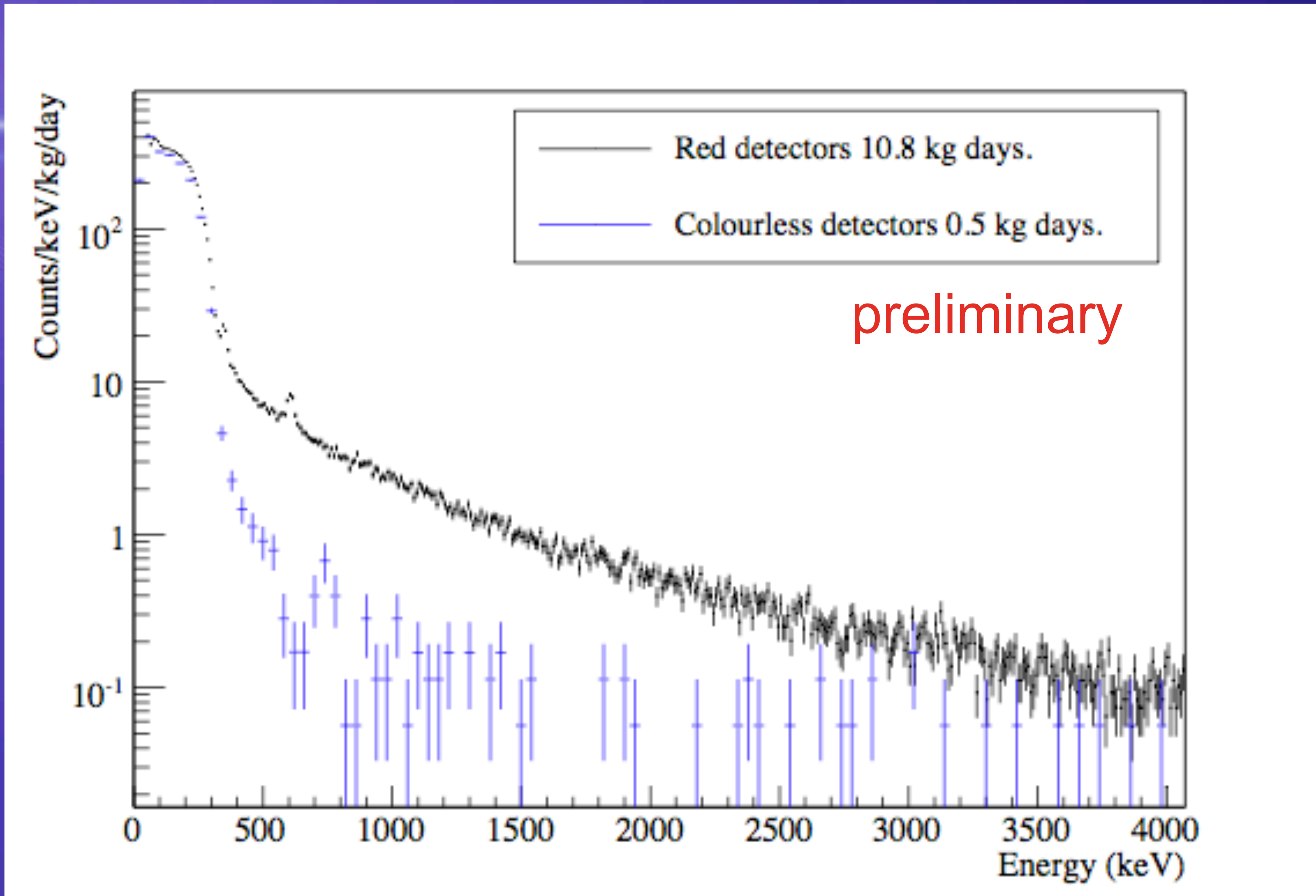
New Results

PRELIMINARY PRELIMINARY

Isotope and Decay		T_{half} limit (years, 90% C.L.)	
		Current Data	Previous
$\beta^+\beta^+$ Decays			
^{64}Zn	$0\nu\beta^+$EC to g.s.	1.18×10^{18}	2.78×10^{17}
^{64}Zn	0ν2EC to g.s.	$\mathbf{7.43}\times10^{18}$	1.19×10^{17}
^{120}Te	0ν2EC to g.s.	$\mathbf{1.13}\times10^{17}$	2.68×10^{15}
^{120}Te	0ν2EC to 1171keV	$\mathbf{3.43}\times10^{16}$	9.72×10^{15}
^{106}Cd	$0\nu\beta^+\beta^+$ to g.s.	5.12×10^{18}	4.50×10^{17}
^{106}Cd	0ν2EC to g.s.	$\mathbf{5.48}\times10^{18}$	5.70×10^{16}
^{106}Cd	$0\nu\beta^+\beta^+$ to 512keV	7.17×10^{17}	1.81×10^{17}

Some new world-best limits

Alternative painted detectors (four 1 cm^3 CdZnTe)

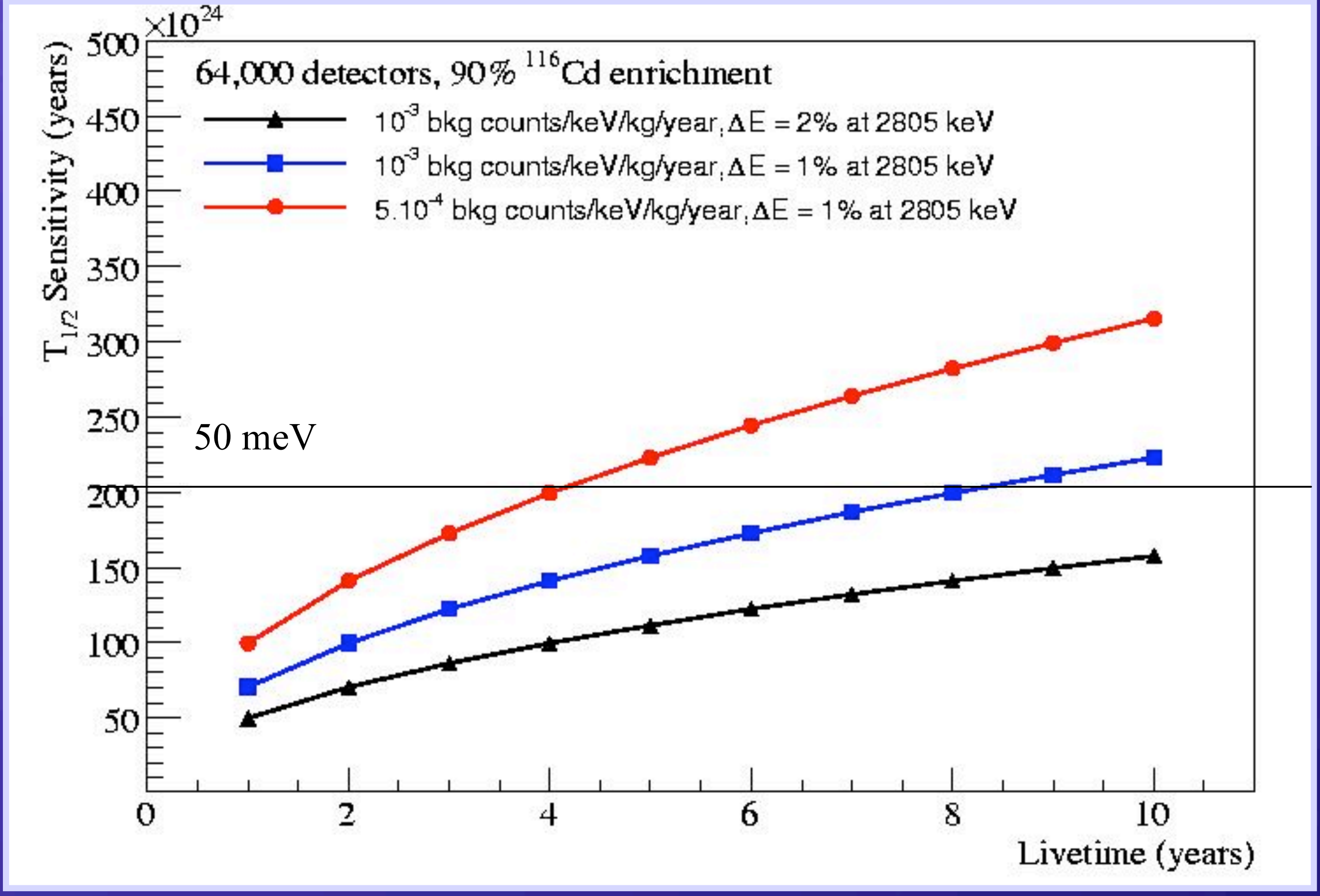


blue = colourless painted detectors + nitrogen flushing

black = 16 layer with red passivation + air

Sensitivity

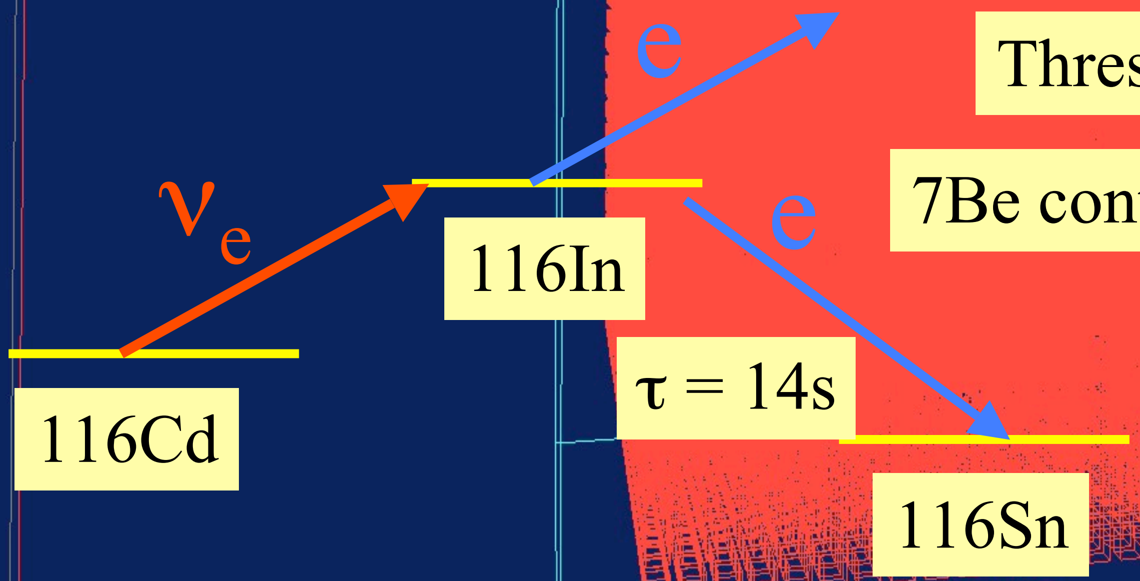
$$T_{1/2} \propto \sqrt{M \times t / \Delta E \times B}$$



KING COBRA - Below 40 meV

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

A real time low-energy solar neutrino experiment?



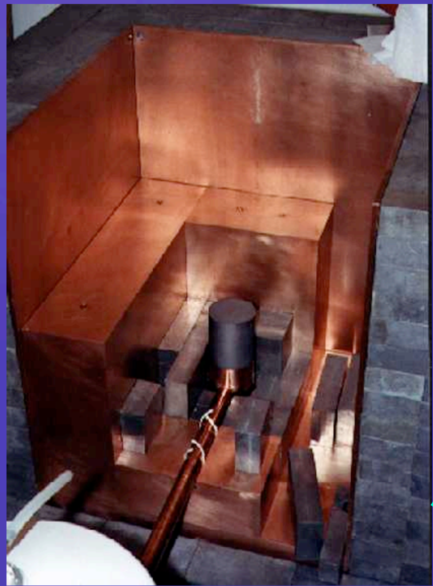
Threshold energy: 464 keV

7Be contribution g.s. alone: 227 SNU

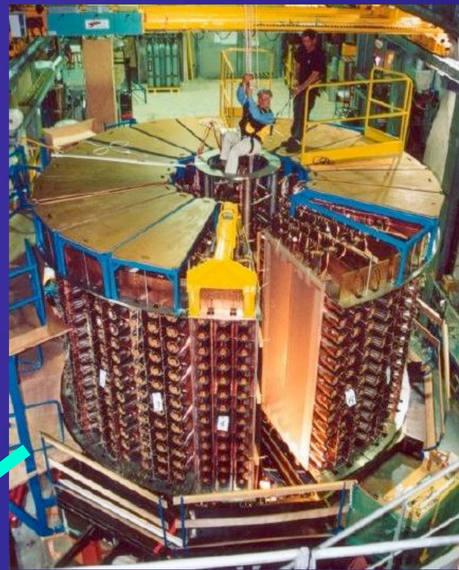
K. Zuber, Phys. Lett. B 571,148 (2003)

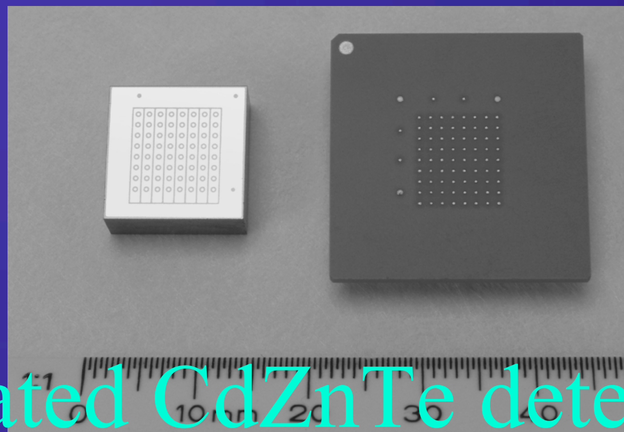
The solid state TPC

Energy resolution



Tracking





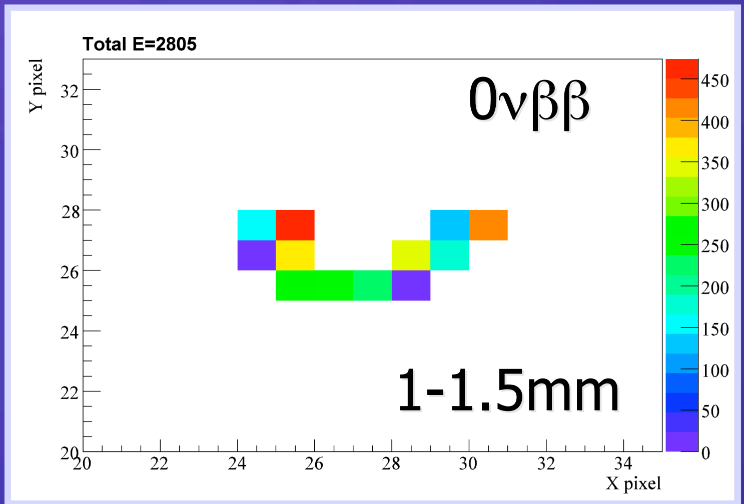
- Massive background reduction
- Positive signal information

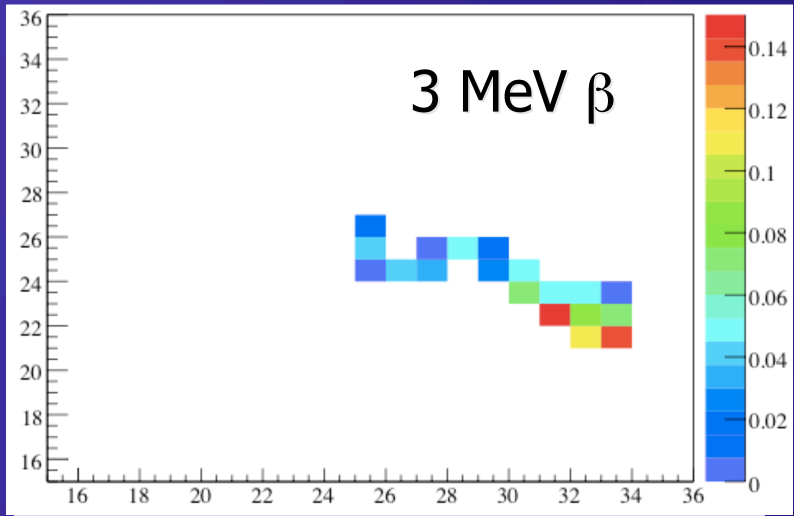
Pixelated CdZnTe detectors

Pixelisation - I

- Massive BG reduction by particle ID , 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 ($^{214}Bi \rightarrow {}^{214}Po \rightarrow {}^{210}Pb$)

.

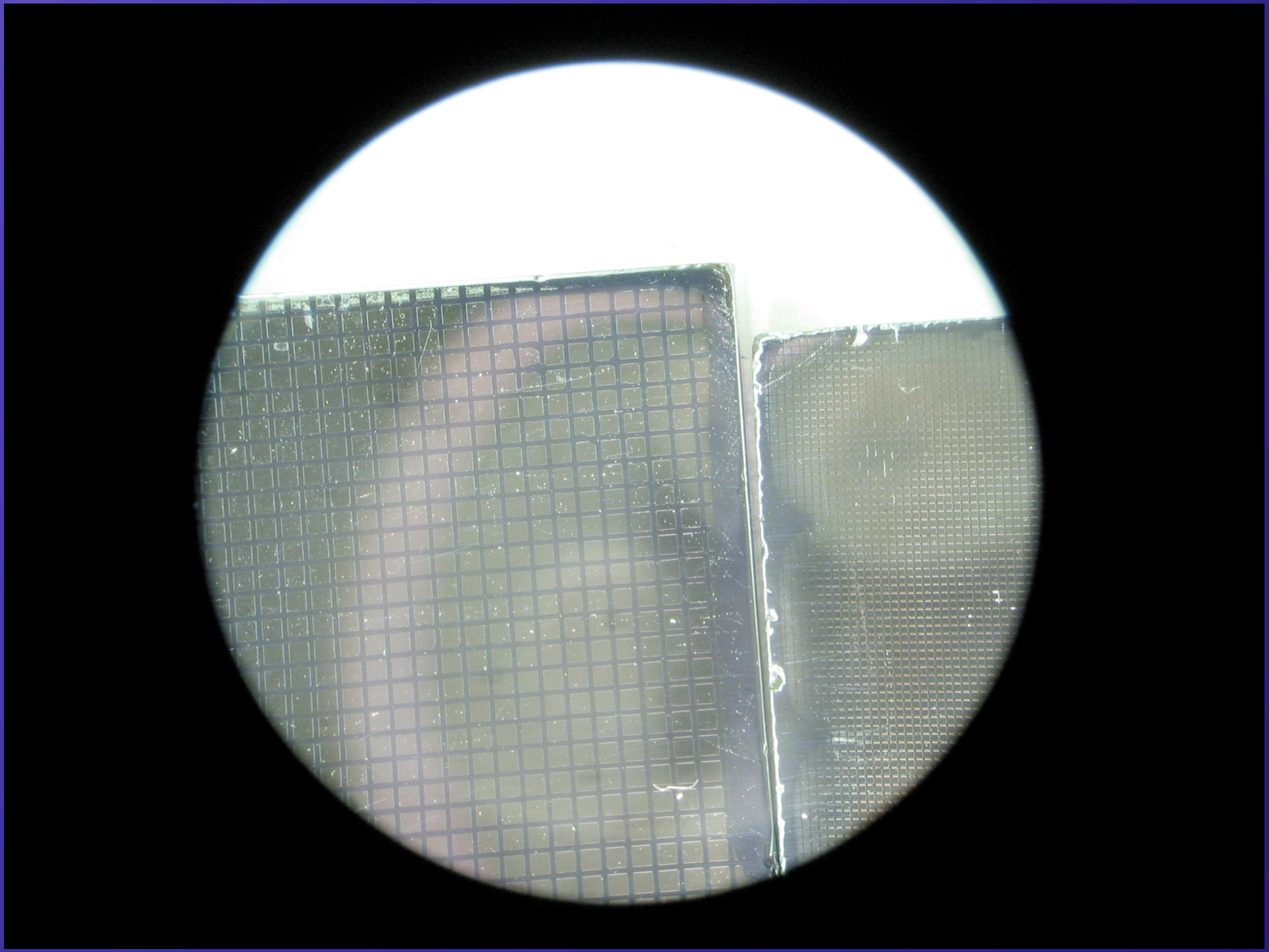
Beta with endpoint 3.3MeV

7.7MeV α life-time = 164.3μs

Pixel detectors

Operating 16 pixel (conv. electronics) and 256 pixel (ASIC)

Next step: 64 pixel detectors 2x2x0.5 cm^3 (pixel size: 2.5 mm)

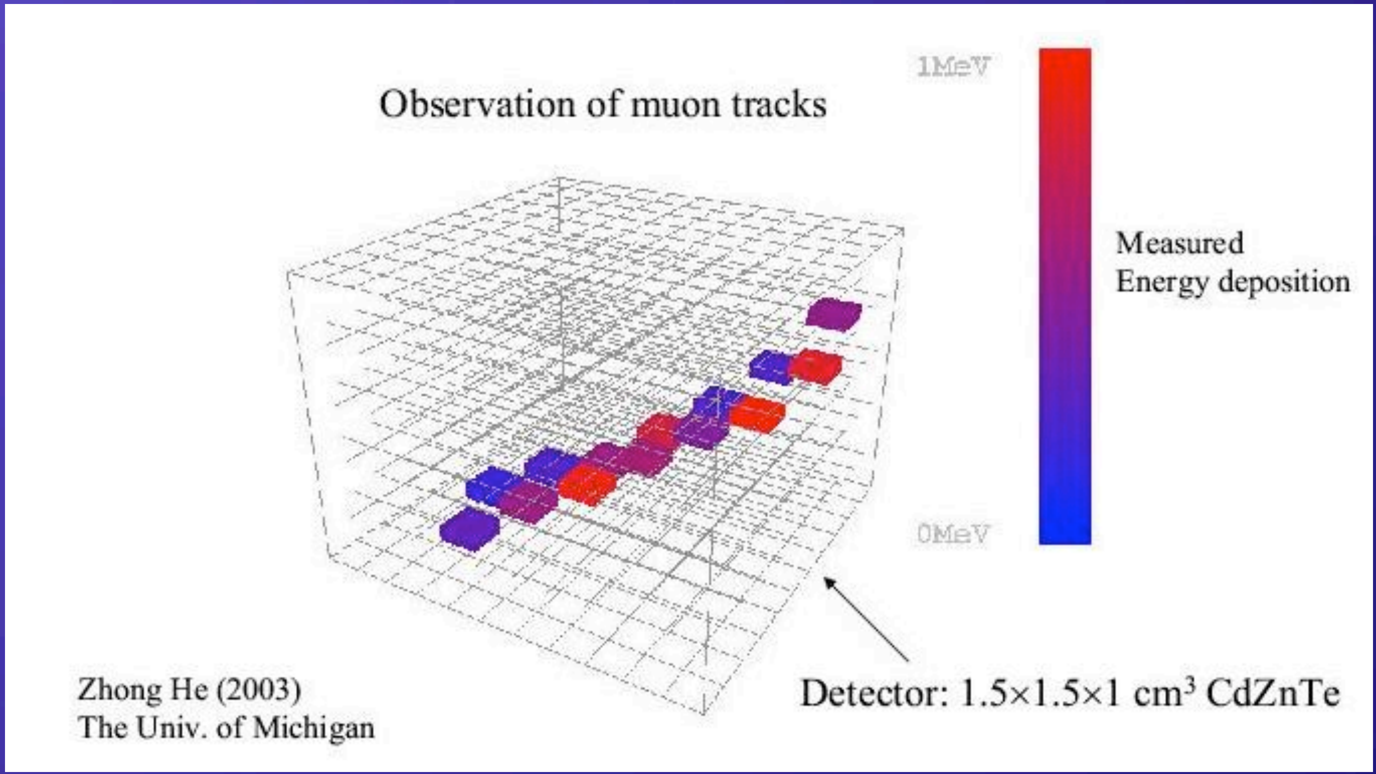


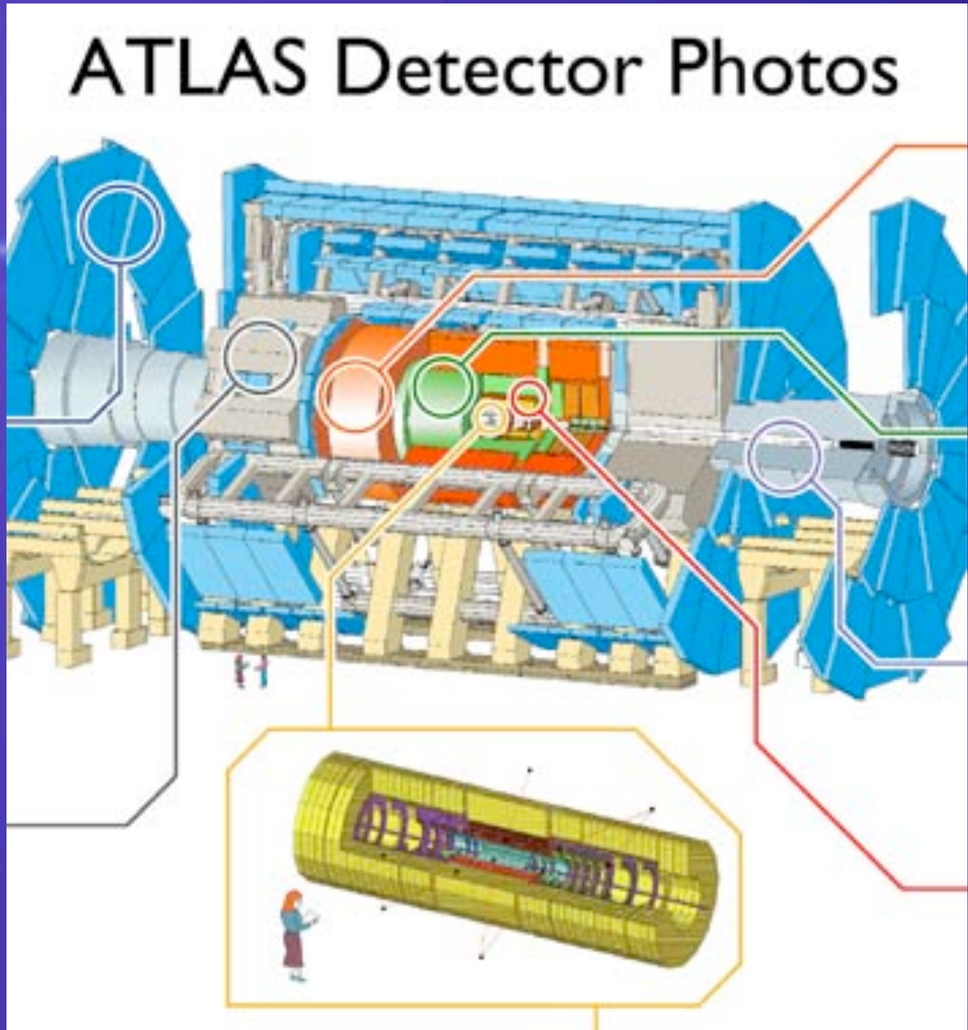
Pixel detector with 200 μm pixels produced!

Pixellated detectors

Solid state TPC

2D - Pixelisation on both electrodes

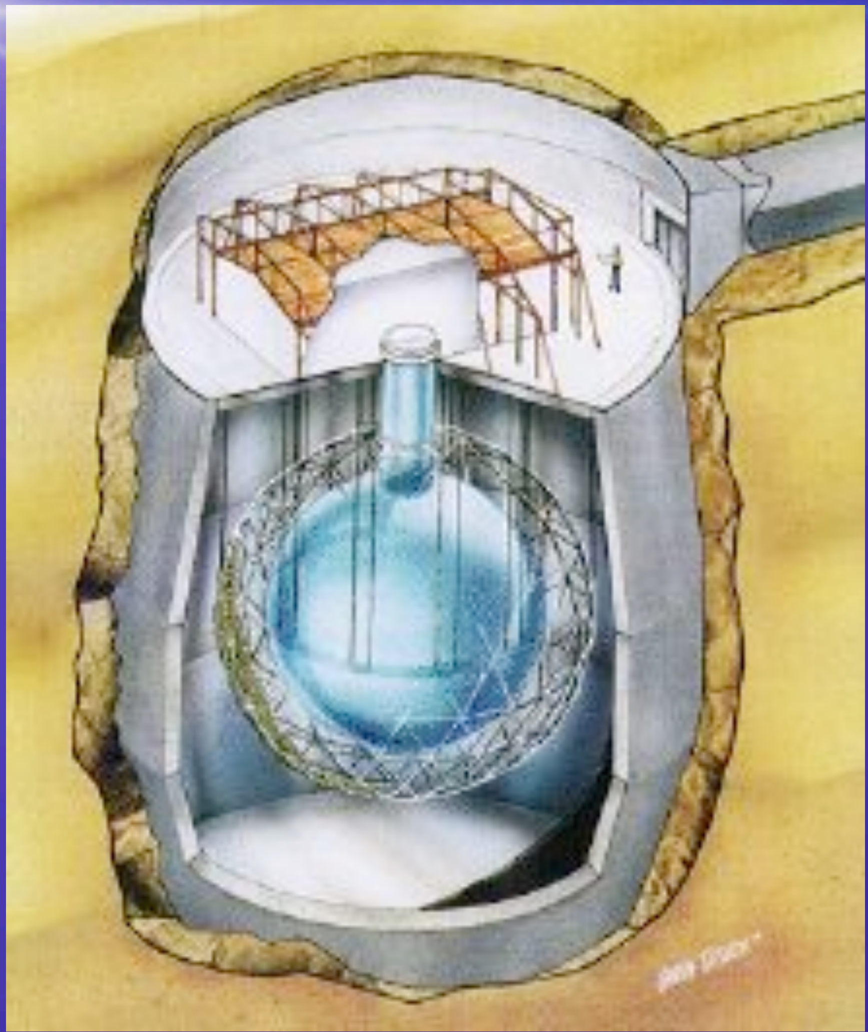




Nobody said it was going to be easy, and nobody was right

George W. Bush

SNO – The smoking gun



1000 t heavy water (D_20)

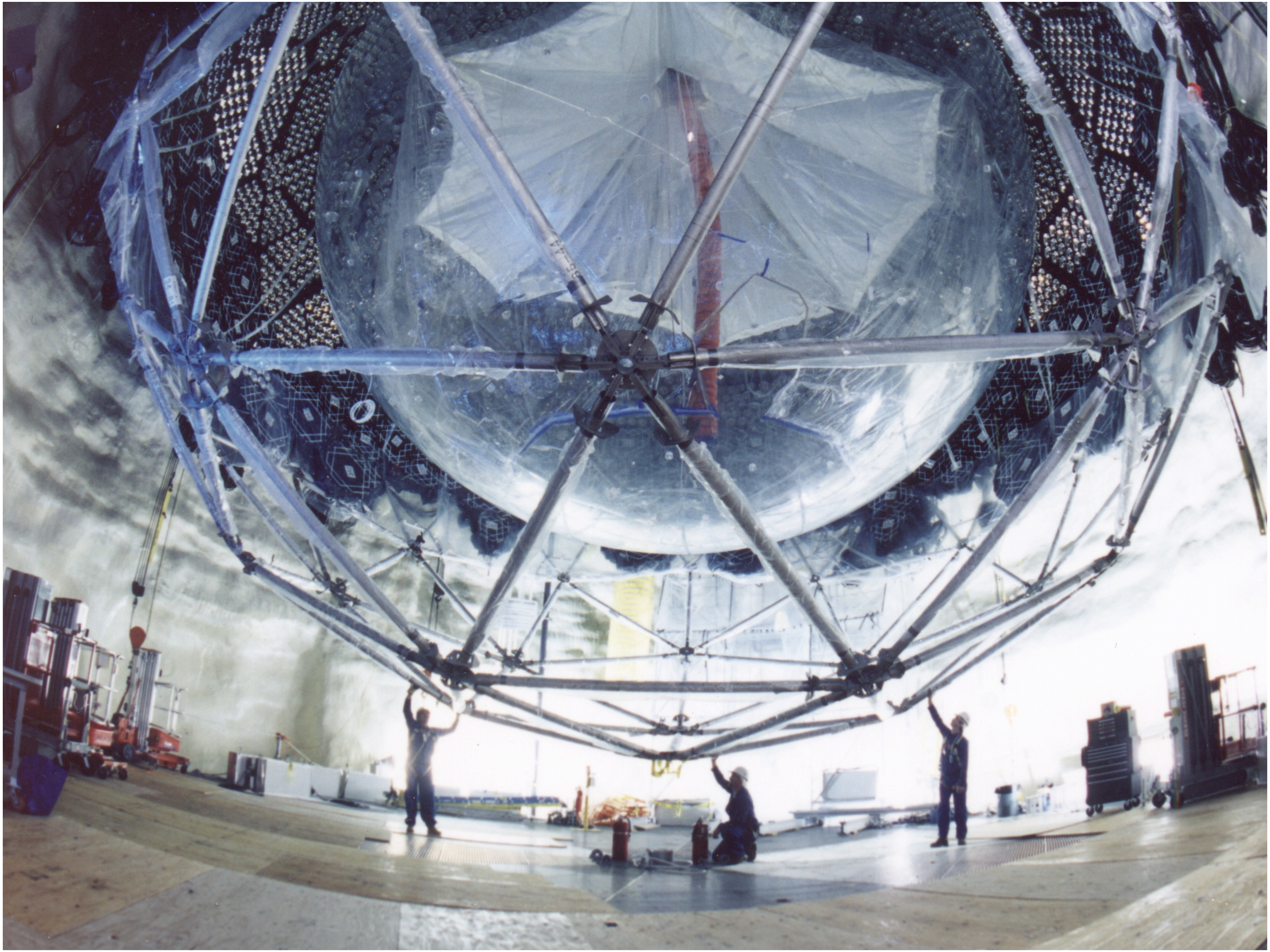
CC $\nu_e + d \Rightarrow p + p + e^-$

NC $\nu_x + d \Rightarrow p + n + \nu_x$

ES $\nu_x + e^- \Rightarrow \nu_x + e^-$

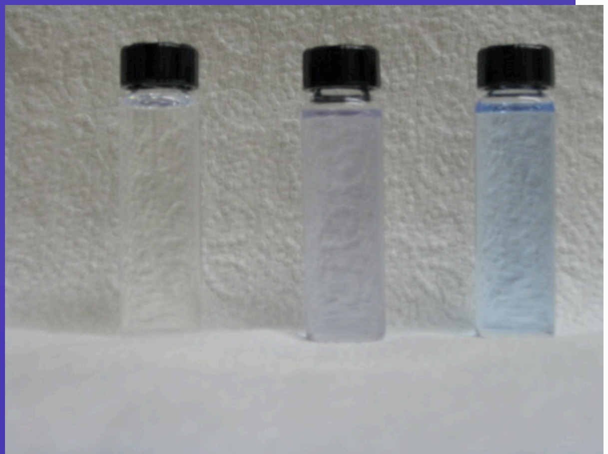
$$\frac{CC}{ES} = \frac{\nu_e}{\nu_e + 0.14(\nu_\mu + \nu_\tau)}$$

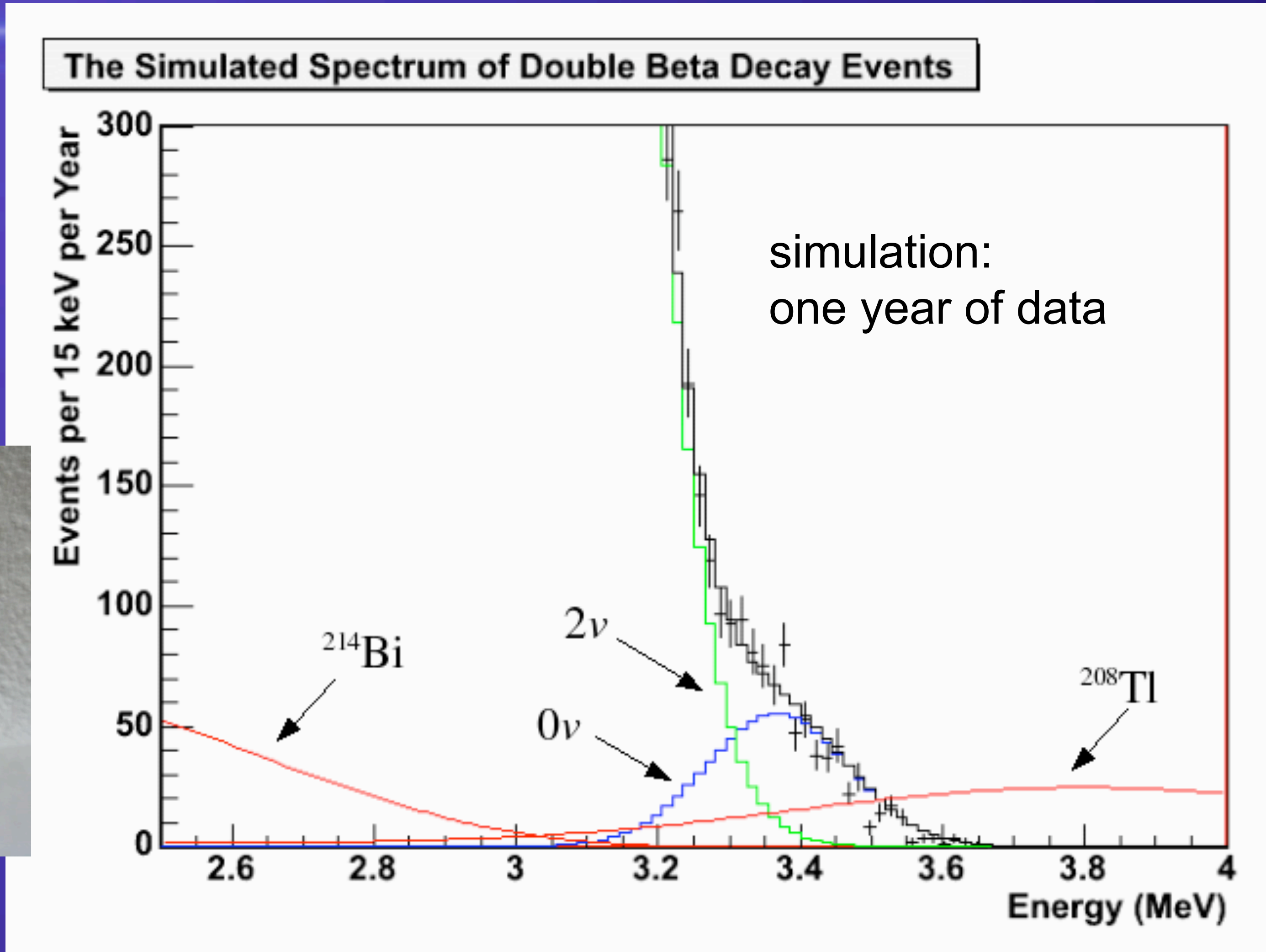
$$\frac{CC}{NC} = \frac{\nu_e}{\nu_e + \nu_\mu + \nu_\tau}$$



Test <m$_\nu$> = 0.150 eV

0ν: 1000 events per year with 1% natural Nd-loaded liquid scintillator in SNO+





maximum likelihood statistical test of the shape to extract 0ν and 2ν components…~240 units of $\Delta\chi^2$ significance after only 1 year!

Summary

- Neutrinoless double beta decay crucial for neutrino physics
- Gold plated channel for Majorana character and neutrino mass
- Sensitivity of 50 meV neutrino mass requires hundreds of kg of isotopes (enrichment)
- A lot of experimental proposals/ideas
- GERDA/MAJORANA, COBRA are the semiconductor approaches (energy resolution)
- SNO+ could be done on a short timescale on large scale
- Revived interest in neutrinoless double EC
- Progress is fast....