Double Beta Decay: Scintillators

Mark Chen
Queen's University

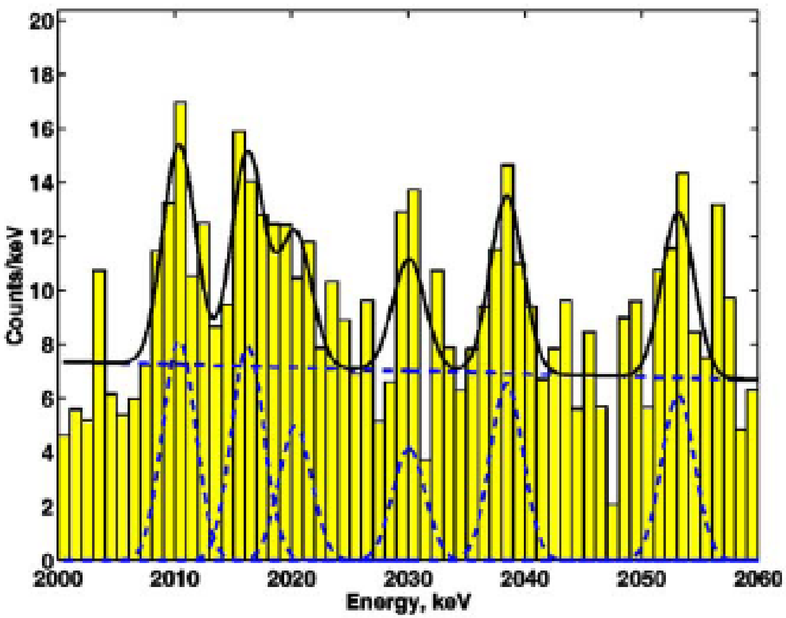
Neutrino 2008
Christchurch, New Zealand

Talk Outline

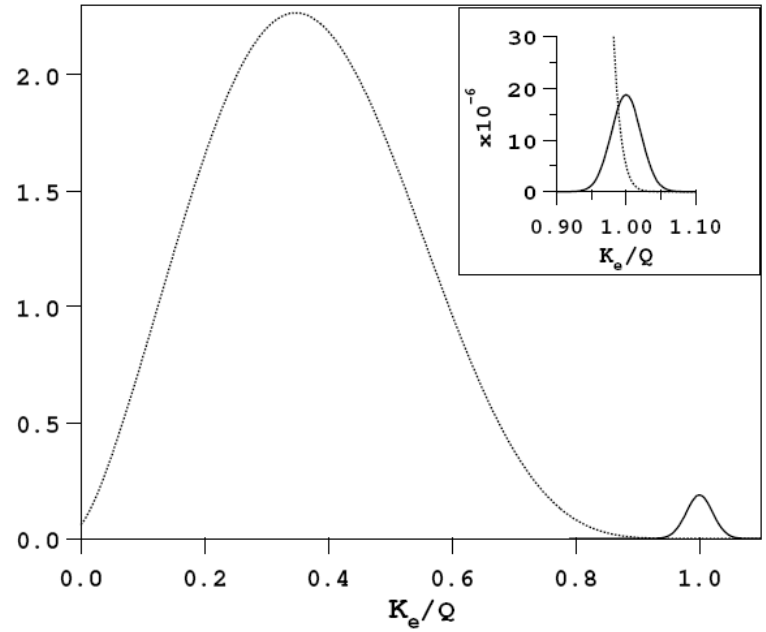
- scintillators for double beta decay:
  - what they can offer
- survey of experimental programs
  - XMASS double beta decay [liquid xenon]
  - ELEGANT / CANDLES [inorganic crystals]
  - Kiev group [inorganic crystals]
  - SNO+ double beta decay [loaded liquid]
- summary

Why Good Energy Resolution is Needed?

- to separate $0\nu\beta\beta$ from $2\nu\beta\beta$
- to separate $0\nu\beta\beta$ signal from other gamma lines



from H.V. Klapdor-Kleingrothaus et al.

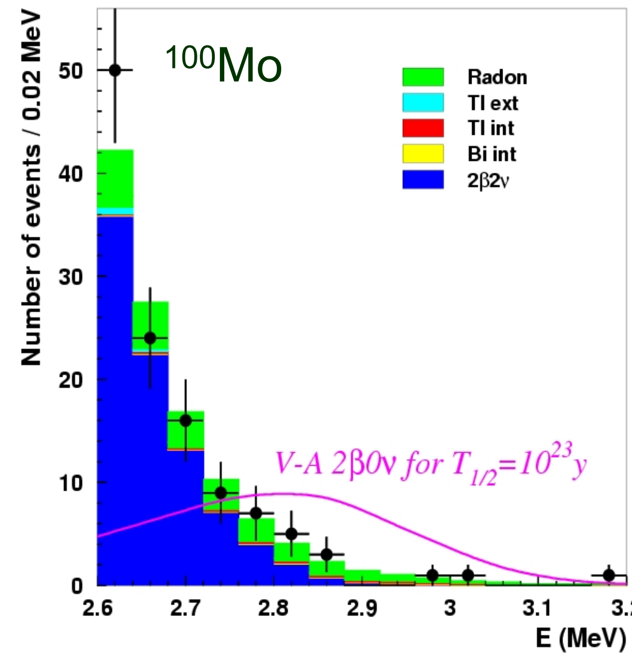


from S. Elliott and P. Vogel

Can You Live With Worse Resolution?

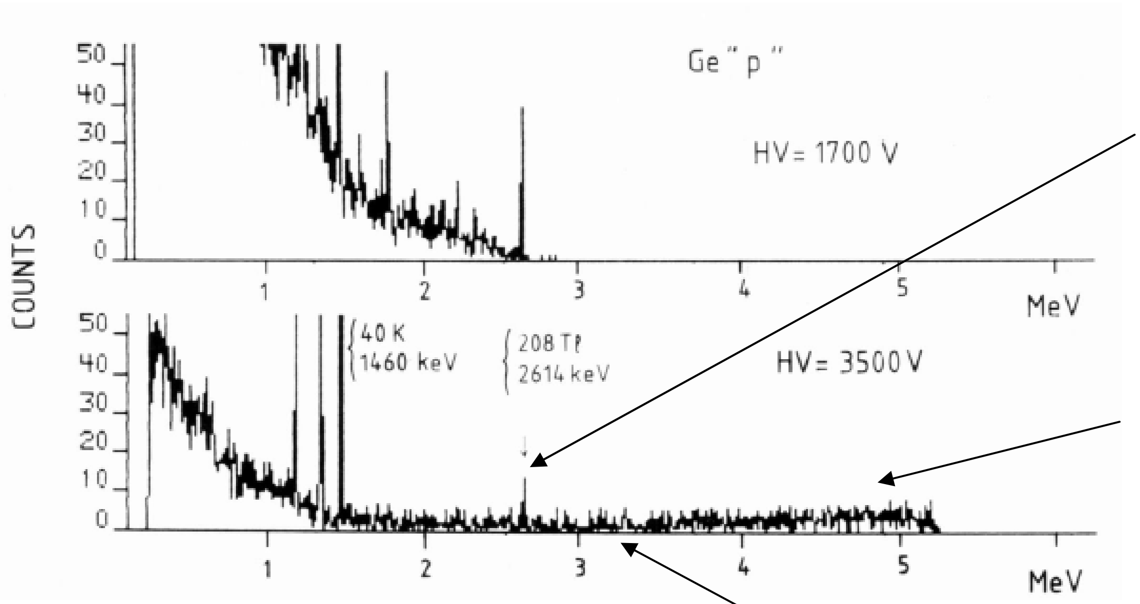
- to separate $0\nu\beta\beta$ from $2\nu\beta\beta$
  - YES! by fitting the endpoint shape…resolution is far less important when fitting spectral shapes than simply counting signal and background events in an energy bin
  - this is already done (e.g. NEMO-3)
- to separate $0\nu\beta\beta$ signal from other gan
  - YES! if there are no backgrounds!
- how to achieve zero (low) γ backgroun
  - use B-field tracking detector: tags $\beta^-\beta^-$ fr

    or
  - choose a high Q-value isotope
  - with an ultra-low background detecto



from F. Piquemal

Above the ^{208}Tl Line at 2.614 MeV



typical Ge spectrum from Ph. Hubert

highest energy line from natural radioactivity

continuum background from internal Th chain contamination

continuum background from internal U chain (radon) contamination ends at 3.2 MeV

if you are searching for a peak, you can live with a low-level continuum background

$\beta\beta$ Isotopes with High Q-values

isotope	Q-value [MeV]	natural abundance
^{48}Ca	4.27	0.19%
^{150}Nd	3.37	5.6%
^{96}Zr	3.35	2.8%
^{100}Mo	3.03	9.6%
^{82}Se	3.00	9.2%
^{116}Cd	2.80	7.5%

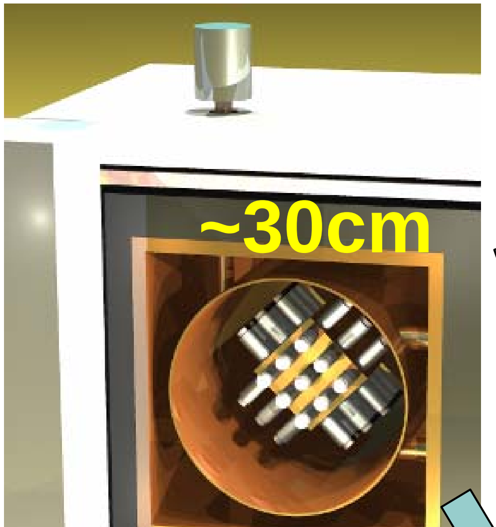
What Do Scintillators Offer?

- "economical" way to build a detector with a **large** amount of isotope
- several isotopes can be made into (or put in) a scintillator
- ultra-low background environment can be achieved (e.g. phototubes stand off from the scintillator, self-shielding of fiducial volume)
- with a liquid scintillator, possibility to purify *in-situ* to further reduce backgrounds

Experimental Programs – I

- XMASS double beta decay
  - liquid xenon scintillation
  - ^{136}Xe, Q-value = 2.48 MeV
  - slides from S. Moriyama

Strategy of the XMASS project



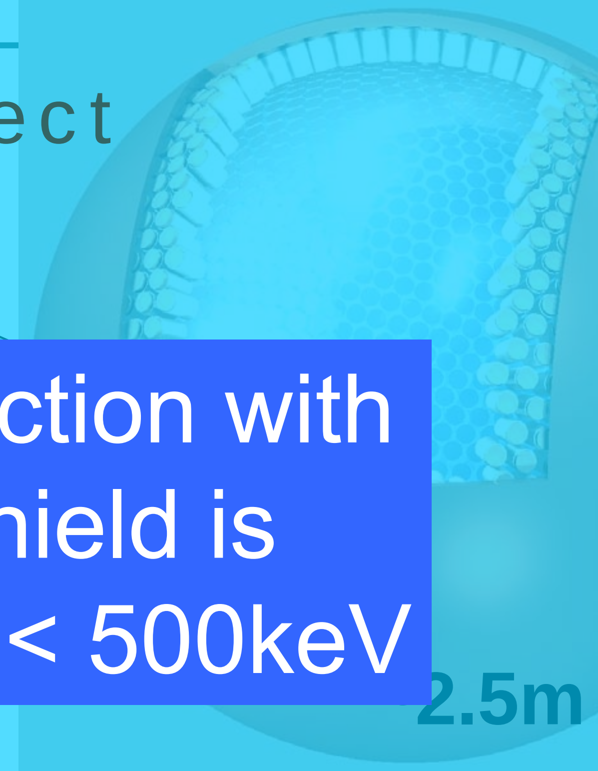
Prototype detector
(FV 3kg)

Confirmation of feasibilities of the ~1ton detector

~1 ton
(FV 100kg)

Dark matter search
Under construction

BG reduction with self shield is effective < 500keV



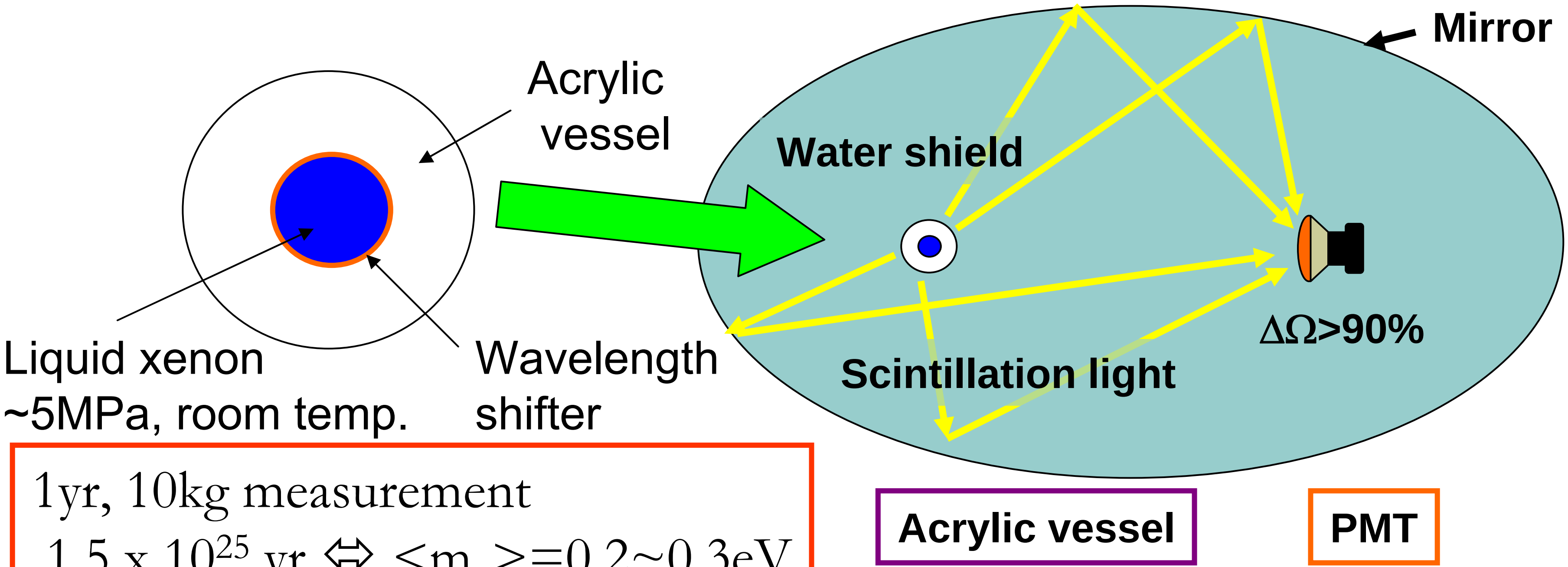
~20 ton detector
(FV 10ton)

Solar neutrinos
Dark matter search

Double beta decay option w/ different design to realize low background at ~MeV.

XMASS: ^{136}Xe double beta decay

- One possible method utilizes a high pressure liquid-xenon detector under room temperature. R&D ongoing.



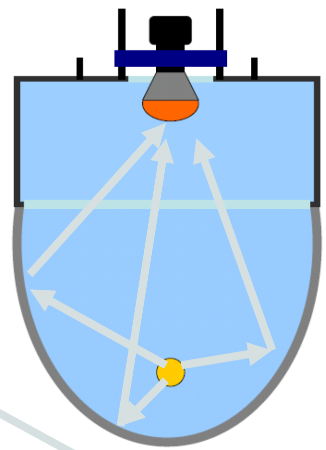
1yr, 10kg measurement
1.5×10^{25} yr ⇔ $<m_\nu>=0.2\sim0.3$eV

RI contamination in the acrylic vessel (~10^{-12}g/gU) limits its sensitivity.

- Photon yield at room temp. ~29 photons/keV (K. Ueshima *et al.*, arXiv0803.2888)
- Energy resolution needs to be evaluated.

Photon yield measurement at room temp./ wavelength shifter/elliptic water tank

~29photons/keV
arXiv0803.2888



Elliptic tank

D.N.Mckinsey et.al.
NIMB 132 (1997) 351

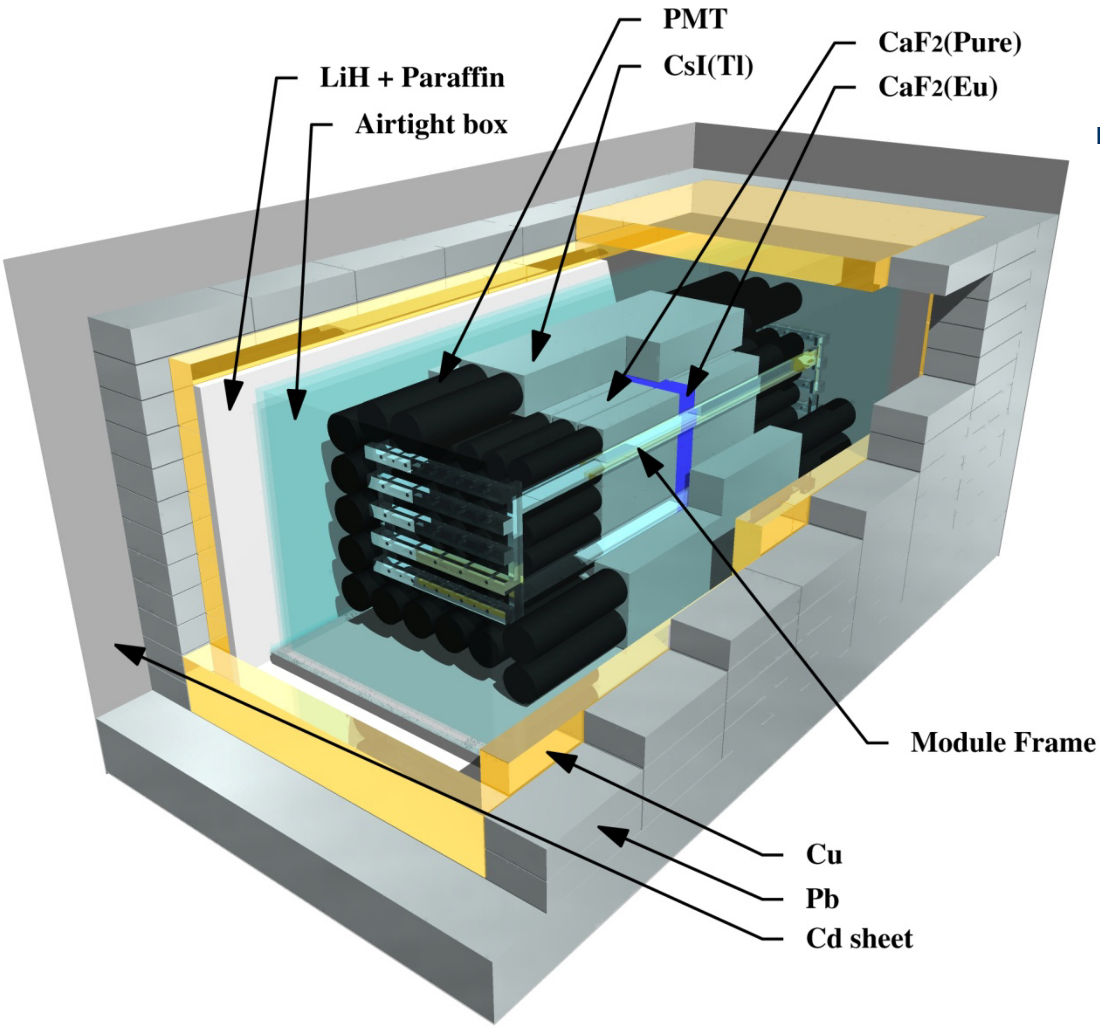
0.5% TPB doped PS, 100μm

- Three components were developed. Under examination.

Experimental Programs – II

- Osaka group: slides from T. Kishimoto and S. Umehara
- past: ELEGANT VI
  - CaF_2(Eu) scintillating crystals
  - 7.7 g of ^{48}Ca, Q-value = 4.27 MeV
  - ran at Oto Cosmo Observatory
- future: CANDLES III
  - pure CaF_2 scintillating crystals
    - U chain: ~36 μBq/kg (30 times better than ELEGANT VI)
    - Th chain: ~29 μBq/kg (3 times better than ELEGANT VI)
  - ~300 kg of crystals (that's ~400-450 g of ^{48}Ca)
  - expected resolution: ~3.5% FWHM at endpoint
  - will run in Kamioka

ELEGANT VI



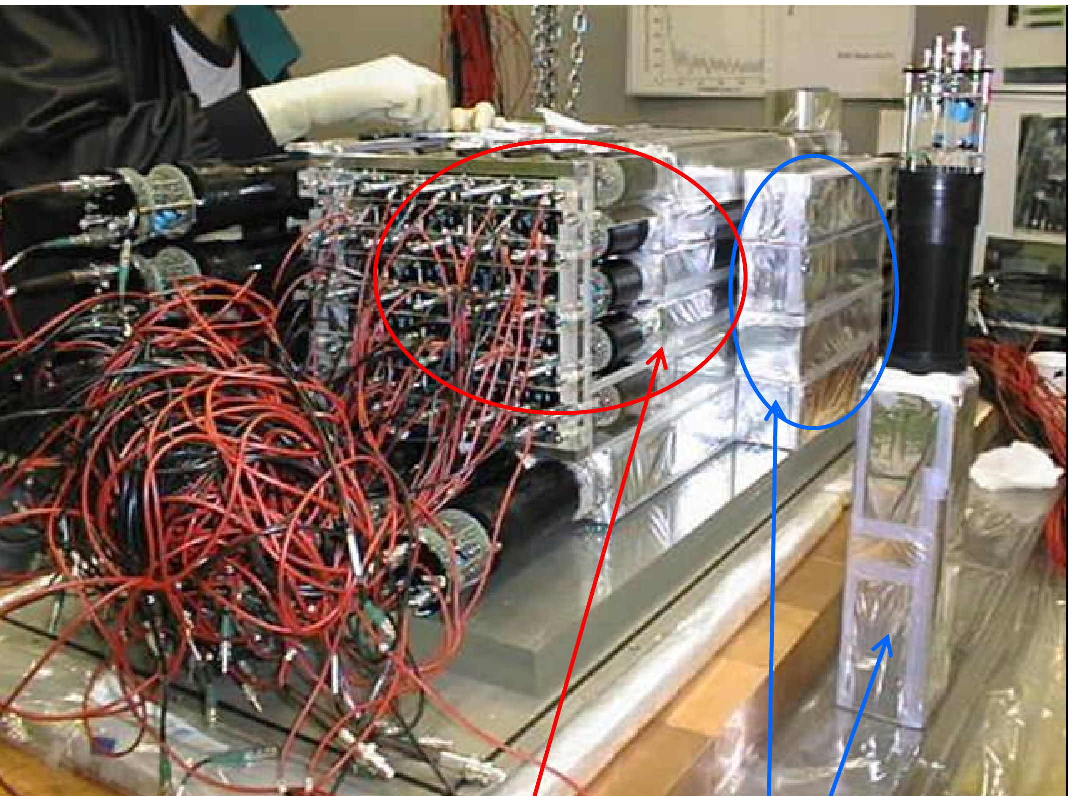
Surrounded by H_3BO_3 loaded-water tank

- 23 CaF_2 modules
  - ~3.5 kg ^{19}F
  - ~7.7 g ^{48}Ca
- Background reduction
  - least material : non hygroscopic
  - 4π active shield
    - CaF_2(Eu)+CaF_2(pure) ⇒ roll-off ratio
    - segmentation
    - CsI(Tl) veto detector
  - passive shield
    - OFHC Cu(t:5 cm), Pb(t:10 cm)
    - air-tight box + N_2 gas purge ⇒ Rn in the air
    - LiH + paraffin(t:15 mm), Cd sheet(t:0.6 mm), and H_3BO_3+H_2O tank ⇒ neutron

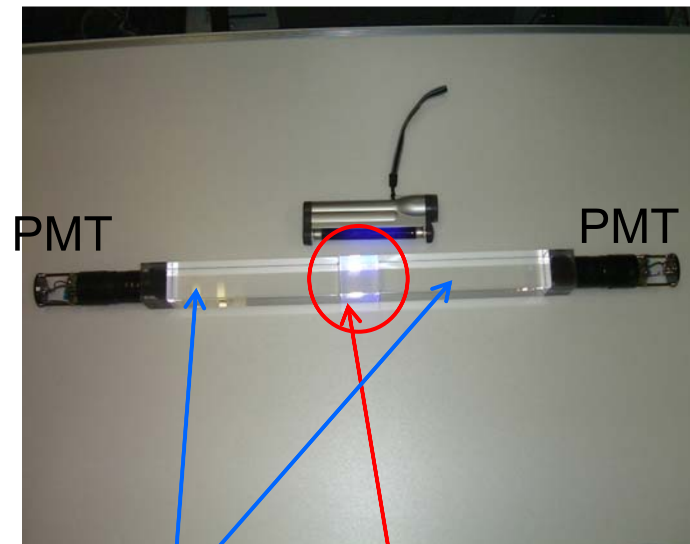
at **Oto Cosmo Observatory**

ELEGANT VI

Scintillators in ELEGANT VI System



CaF$_2$ Module



CaF$_2$ Module CsI(Tl)

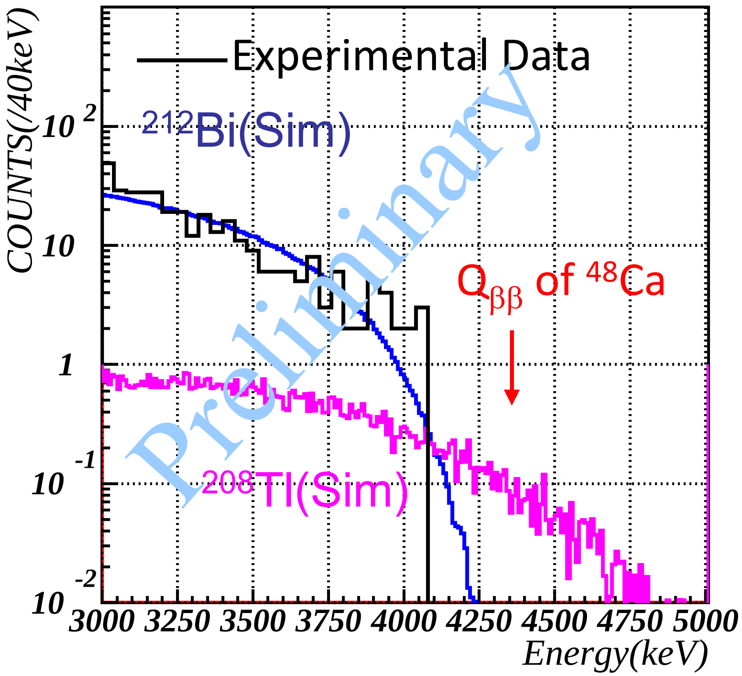
CaF$_2$(pure) . . . UV Light

CaF$_2$(Eu) . . . Visible Light

⇩

Active Shielding Technique in ELEGANT VI system

Double beta decay of ^{48}Ca

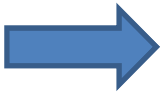


Date	Analysis	Number of Event	Expected BG(^{212}Bi, ^{214}Bi, ^{208}Tl)	Detection Efficiency	Live Time kg・day
Jun 1998 -	without FADC	0	1.30	0.55	1553
Jan 2003 -	with FADC	0	0.27	0.53	1114
Jan 2004 -	with FADC	0	0.43	0.53	2280

$0\nu\beta\beta$ Half-Life of ^{48}Ca :

> 6×10^{22} year (90% C.L.)

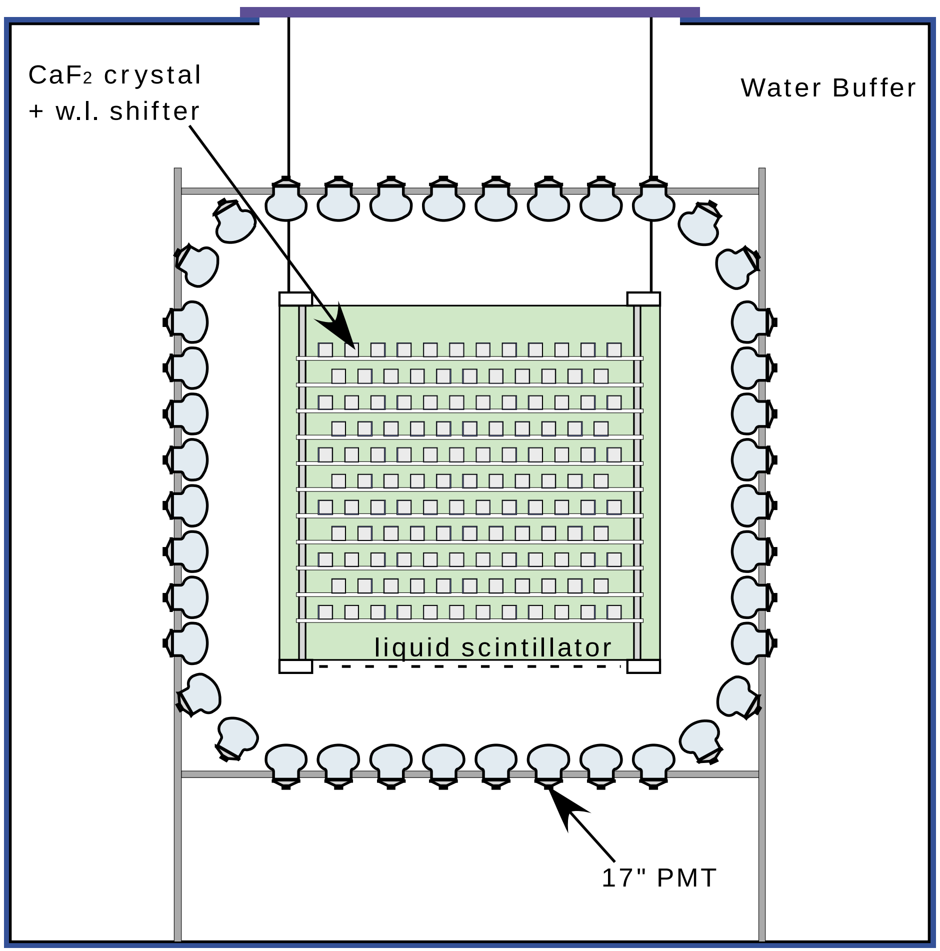
Preliminary



Next step: **CANDLES**

CANDLES

CAlcium fluoride for studies of Neutrino and Dark matters by Low Energy Spectrometer



- undoped CaF_2 (CaF_2(pure))
  - ^{48}Ca (0.187%)
  - 305 kg (III-chika)

    ⇩

    3.4 t (IV) ~0.1 eV

    ⇩

    30 t, 2% enriched (V)

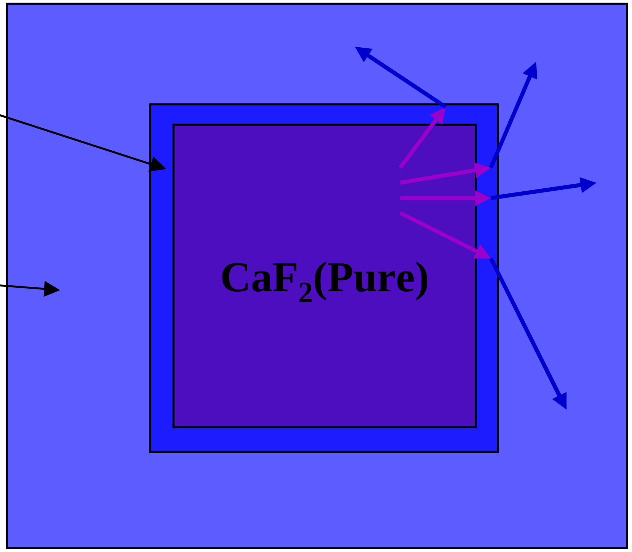
    ~30 meV (best NME)
- Liquid Scintillator (LS)
  - 4π active shield
  - also wavelength shifts light
- Photomultiplier
  - large photo-coverage
- Water buffer
  - Passive shield

CANDLES Collaboration

Two-Layer Wavelength Shifter

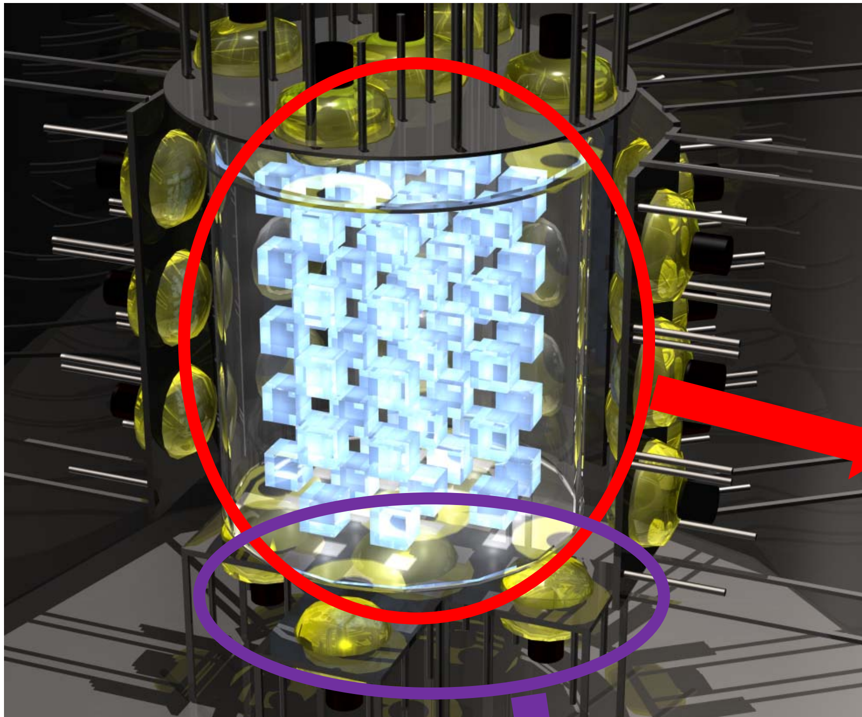
Concept of Method

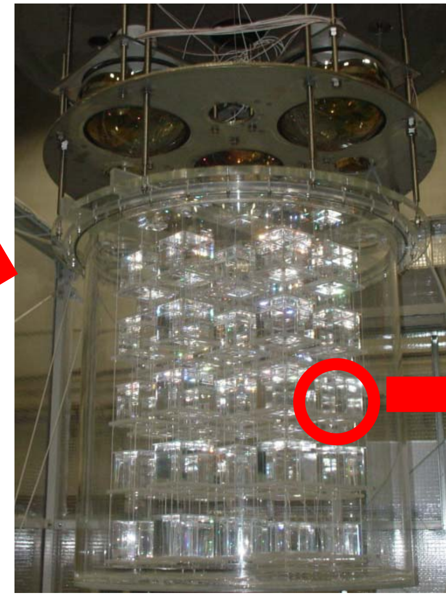
- WLS Phase
  - **M.O.(100%)+PPO(0.3g/L)**
  - **5-10 mm in thickness**
  - large conversion efficiency
- Veto Phase
  - **M.O.(80%)+PC(20%)+PPO(1.0g/L)**
  - large light output



CANDLES III

Candles

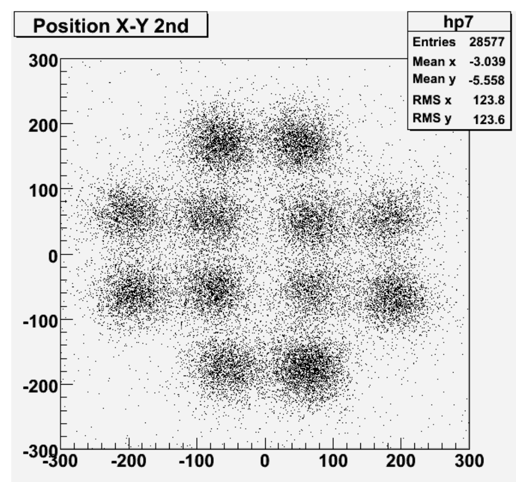




CaF_2: 191 kg
10^3 $cm^3 \times 60$

Tank: $^{\Phi}2.8 \times {}^{h}2.6$ m

40 PMTs



Position reconstruction in X-Y plane

CANDLES III Status

- ICRR completed the excavation of two new chambers in Kamioka (one for XMASS and one for CANDLES)
  - new space ready for occupancy at the end of this year
- ~300 kg of crystal will be installed in detector
  - $<m_\nu> < 0.5$ eV
- data taking starts in 2009
- also in the process of requesting funding to enlarge for the future

Experimental Programs – III

- Kiev group: slides from F. Danevich
  - experiments developed and/or considered in the past with different scintillating crystals with different isotopes
    - e.g. CAMEO, CARVEL, etc.
    - possible deployment of crystals in large, existing detectors (e.g. Borexino, SNO)
  - currently the following scintillating crystals (and experiments) are being developed
    - $^{116}CdWO_4$ with ^{116}Cd, Q-value= 2.80 MeV
      - also ^{106}Cd $\beta^+\beta^+$ decay, Q-value = 2.77 MeV
    - $CaMO_4$ with ^{100}Mo, Q-value = 3.03 MeV
    - $ZnWO_4$ with ^{64}Zn, Q-value = 1.10 MeV

Kyiv Institute for Nuclear Research, Solotvina Underground Laboratory (Ukraine)

Main results

2β decay of ^{116}Cd

$T_{1/2}^{2\nu} = 2.9\times10^{19}$ yr

$T_{1/2}^{0\nu} \geq 1.7\times10^{23}$ yr @ 90% CL

$\langle m_\nu \rangle \leq 1.7$ eV

[PRC 68 (2003) 035501]

Search for ^{160}Gd 2β decay

$T_{1/2}^{0\nu} \geq 1.3\times10^{21}$ yr

[NPA 694 (2001) 375]

First experiment to search for 2β of ^{64}Zn by using $ZnWO_4$

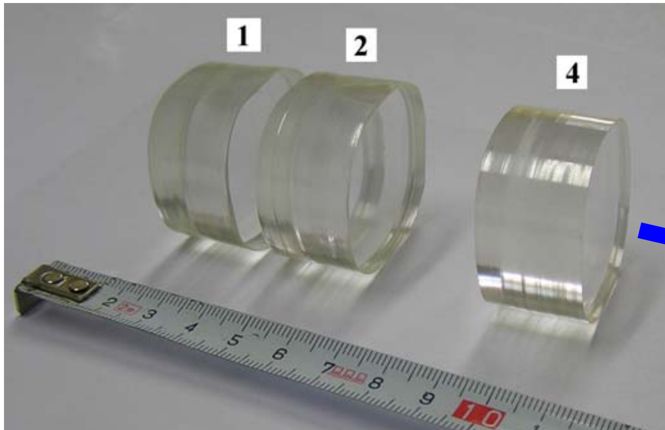
[NIMA 544 (2005) 553]

Present projects

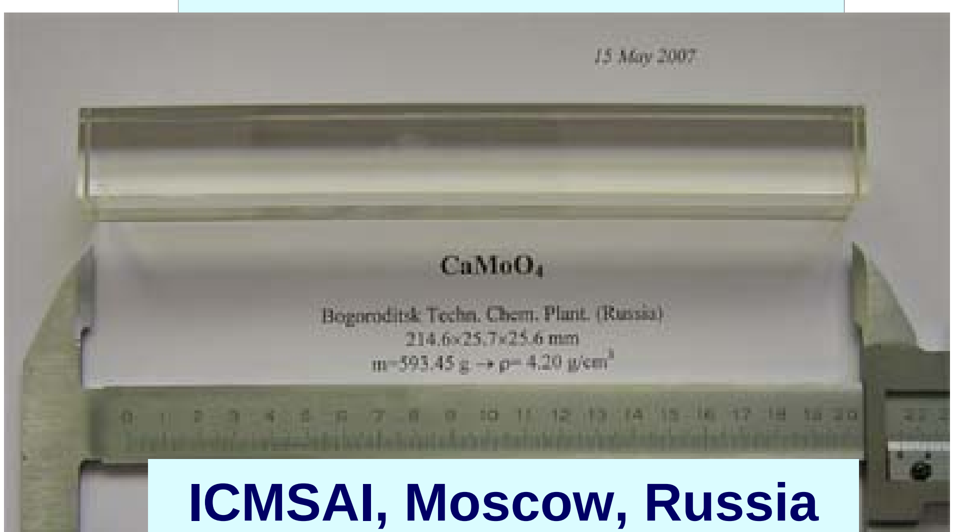
- R&D of advanced ^{116}Cd 2β experiment (producing of ~1.2-1.8 kg $^{116}CdWO_4$ crystal scintillators) in collaboration with ITEP (Moscow, Russia), KIMS (Korea), NIIC (Novosibirsk, Russia)
- Search for 2β of Zinc and Tungsten by $ZnWO_4$ in collaboration with DAMA (experiments are running in the LNGS, Italy)
- $CaMoO_4$ crystal scintillators for 2β decay of ^{100}Mo [large collaboration, see NIMA 584 (2008) 334]
- R&D of ≈0.15 kg $^{106}CdWO_4$ in collaboration with DAMA (Italy), JINR (Dubna, Russia) crystal producers in Ukraine and Russia

$CaMoO_4$ crystal scintillators

2β decay of ^{100}Mo

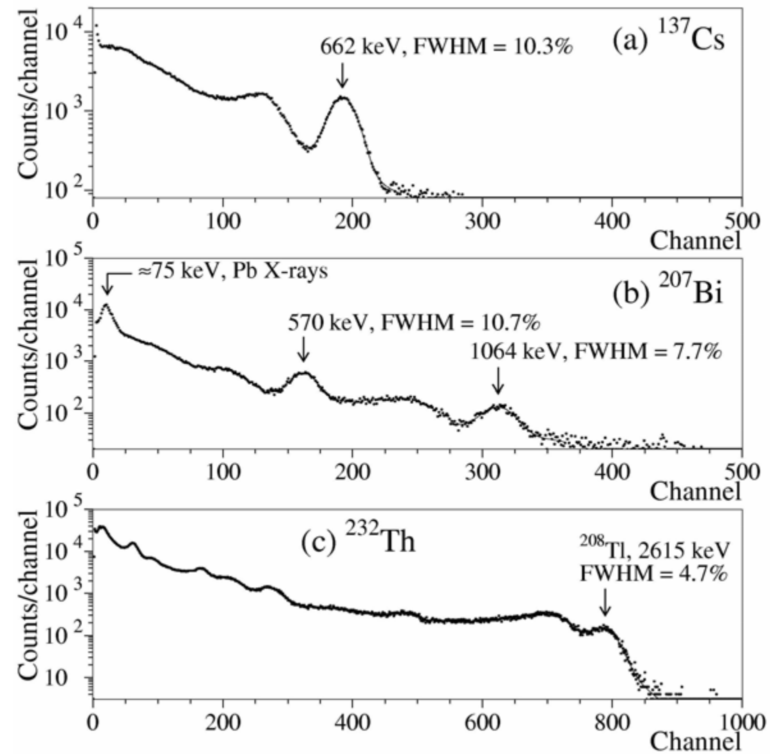


CARAT, Lviv, Ukraine



ICMSAI, Moscow, Russia

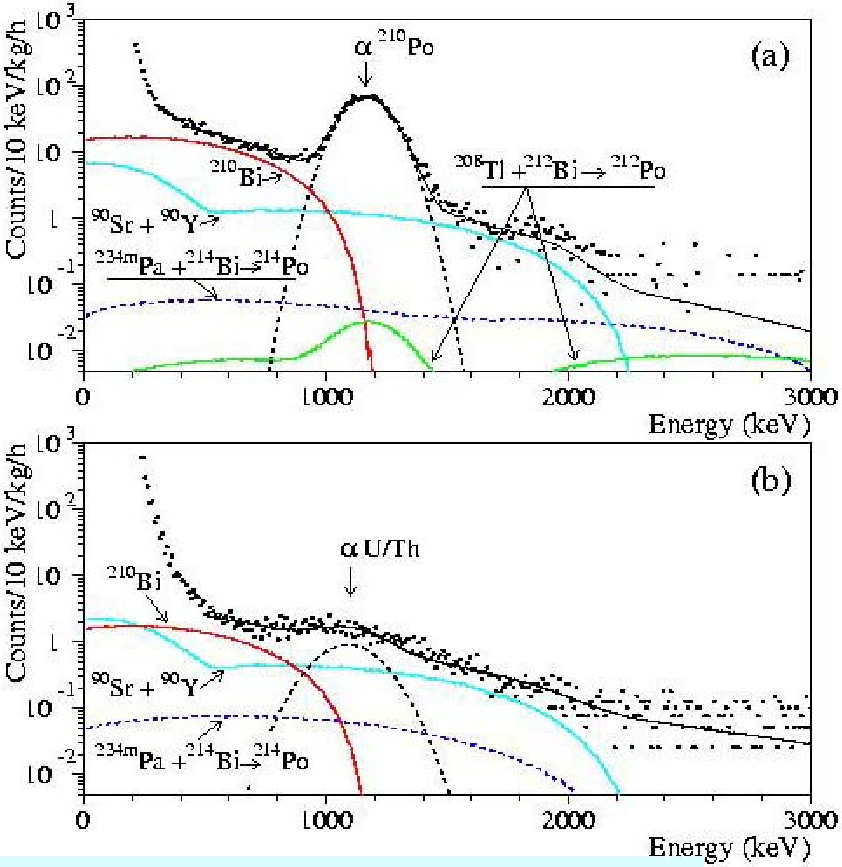
NIMA 584 (2008) 334



Energy resolution FWHM=10.3% for 662 keV γ line of ^{137}Cs was obtained with $CaMoO_4$ crystal scintillators produced by CARAT

$CaMoO_4$ radiopurity

CARAT, Lviv, Ukraine



ICMSAI, Moscow, Russia

Source	Activity (mBq/kg) CARAT	ICMSAI
^{232}Th	< 0.7	< 1.5
^{228}Th	0.2-0.4	0.04
^{238}U	< 0.5	< 1.5
^{226}Ra	2.1-2.5	0.13
^{210}Pb	< 400	< 17
^{210}Po	400-500	< 8
^{40}K	< 1 - <3	< 3
^{90}Sr	<60 - <180	< 23

measured in the Solotvina Underground Lab

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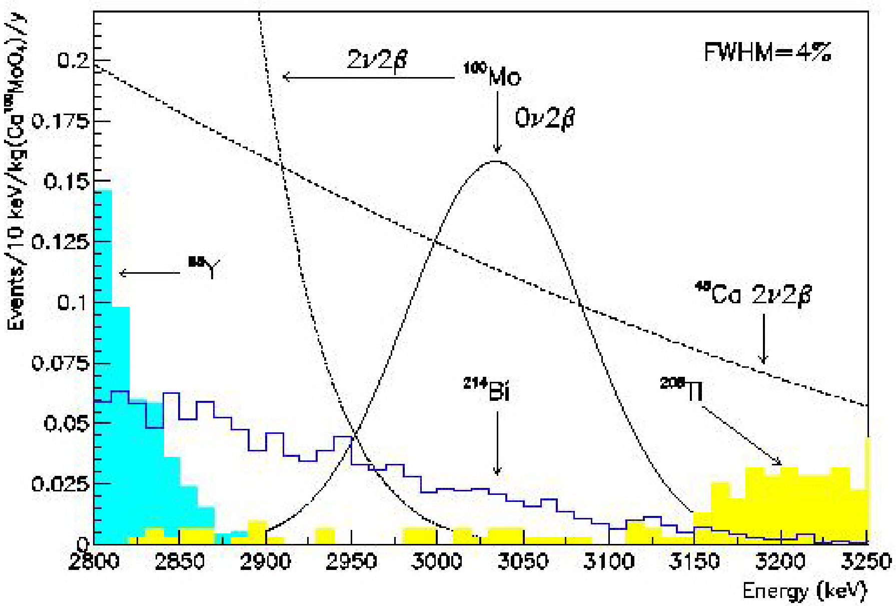
Sensitivity of a pilot experiment with $\approx$1 kg of $Ca^{100}MoO_4$



Main sources of background

- **$2\nu2\beta$ decay of ^{48}Ca** ($T_{1/2}^{2\nu} = 4\times10^{19}$ yr)
- **^{208}Tl** and **^{214}Bi** (both with 0.1 mBq/kg)

A suppression of factor 10 for ^{214}Bi by pulse-shape analysis is supposed.

- **^{88}Y cosmogenic** negligible
- Distributions for ^{100}Mo are shown for:

- $T_{1/2}^{2\nu} = 7\times10^{18}$ yr
- $T_{1/2}^{0\nu} = 10^{24}$ yr.

$T_{1/2}^{0\nu} > 4\times10^{23}$ yr at 90% CL over 1 years with 1 kg $Ca^{100}MoO_4$

$T_{1/2}^{0\nu} > 2\times10^{24}$ yr 10 kg$\times$yr $Ca^{100}MoO_4$

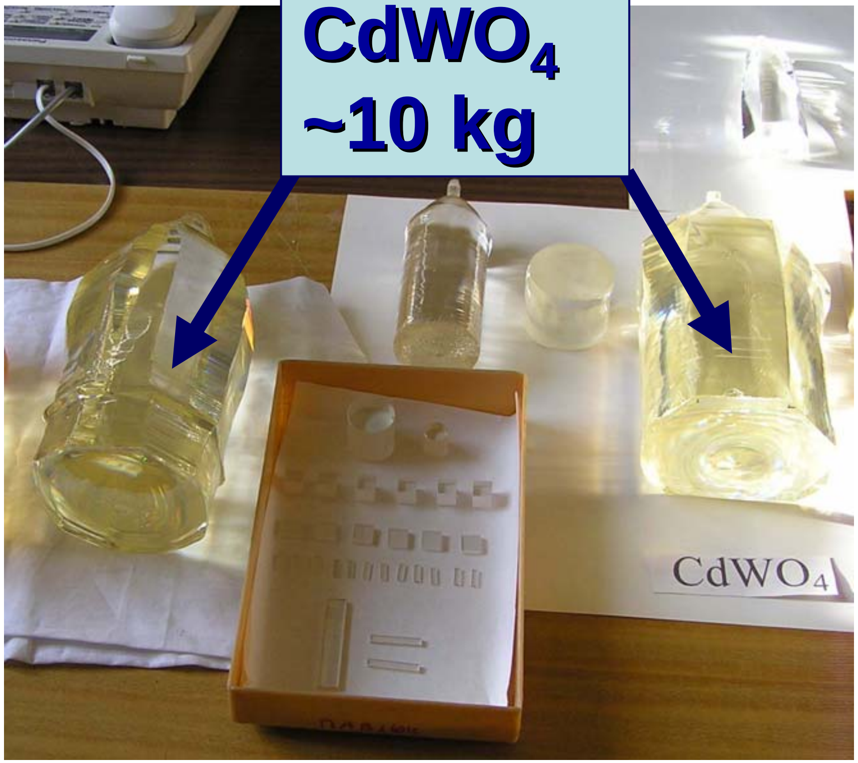
$T_{1/2}^{0\nu} \sim 10^{25}$ yr 200 kg$\times$yr $Ca^{100}MoO_4$

$T_{1/2}^{0\nu} \sim 10^{26}$ yr 1000 kg$\times$yr $Ca^{100}MoO_4$ as low temperature bolometer

NIMA 584 (2008) 334

Unique low-thermal-gradient Czochralski technology in the Nikolaev Institute of Inorganic Chemistry (Novosibirsk, Russia)

$CdWO_4$
~10 kg



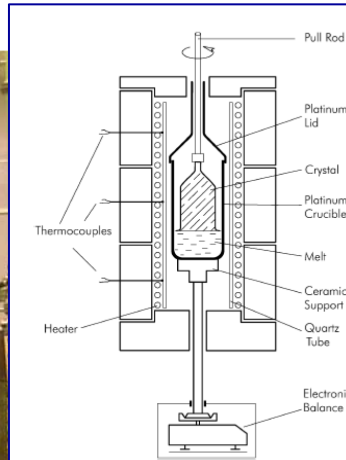


Fig. 1. Schematic diagram of the apparatus for crystal growth of oxide crystals in a low thermal gradient.

R&D to produce ~1.2-1.8 kg of enriched $^{116}CdWO_4$ crystals is in progress in collaboration with ITEP (Moscow, Russia) and KIMS (Korea)

R&D of ≈0.15 kg $^{106}CdWO_4$ to search for 2β processes in ^{106}Cd

- **Technology to purify Cd at the level of 0.1 ppm was developed**
- **^{nat}Cd and ^{106}Cd were purified**
- **Technology to produce raw material for crystal growing was developed and $CdWO_4$ and $^{106}CdWO_4$ powders were produced (NeoChem company, Moscow, Russia)**
- **$^{nat}CdWO_4$ scintillator ~0.12 kg with 8% energy resolution for 662 keV ^{137}Cs was produced (ISMA, Kharkov, Ukraine)**
- ***The next step: $^{106}CdWO_4$ (NIIC, Novosibirsk, Russia)***

Minimization and careful control of ^{106}Cd losses at all the steps

collaboration with DAMA (Italy), JINR (Dubna, Russia) and crystal producers in Ukraine and Russia. Experiment in the LNGS (Italy).

Experimental Programs – IV

- SNO+ with Nd-loaded liquid scintillator
  - …also called SNO++
- 0.1% Nd in 1000 tons of scintillator
  - with natural Nd corresponds to 56 kg of ^{150}Nd isotope
- sensitivity below 100 meV with natural Nd
- meters of ultra-low background self-shielding against gammas and neutrons
  - leads to well-defined background model
- liquid detector allows for additional *in-situ* purification
- possibility to enrich neodymium at French AVLIS facility

Why ^{150}Nd?

- 3.37 MeV endpoint (2nd highest of all $\beta\beta$ isotopes)
  - above most backgrounds from natural radioactivity
- largest phase space factor of all $\beta\beta$ isotopes
  - factor of 33 greater compared with ^{76}Ge
  - for the same effective Majorana neutrino mass, the $0\nu\beta\beta$ rate in ^{150}Nd is the fastest
- cost of $NdCl_3$ is $86,000 for 1 ton (not expensive)
- upcoming experiments use Ge, Xe, Te; we can deploy a large and comparable amount of Nd

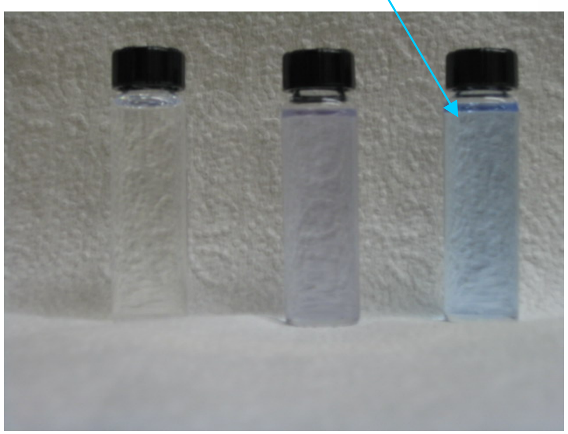
How Does ^{150}Nd Compare?

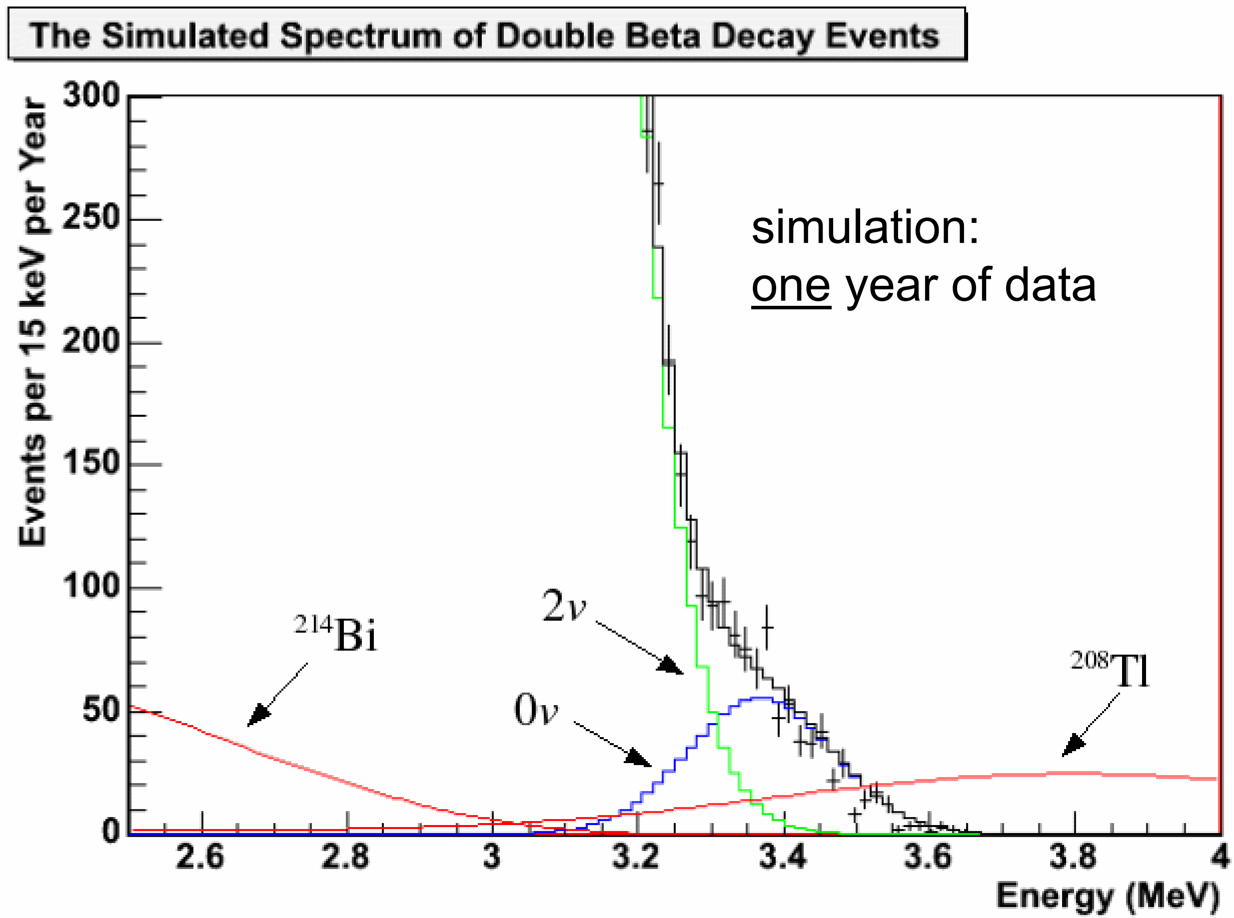
- 56 kg of ^{150}Nd is equivalent to:
- considering only the phase space factor
  - ~220 kg of ^{136}Xe
  - ~230 kg of ^{130}Te
  - ~950 kg of ^{76}Ge
- including QRPA matrix element calculations
  - ~1500 kg of ^{136}Xe
  - ~400 kg of ^{130}Te
  - ~570 kg of ^{76}Ge

thanks L. Simard and F. Piquemal

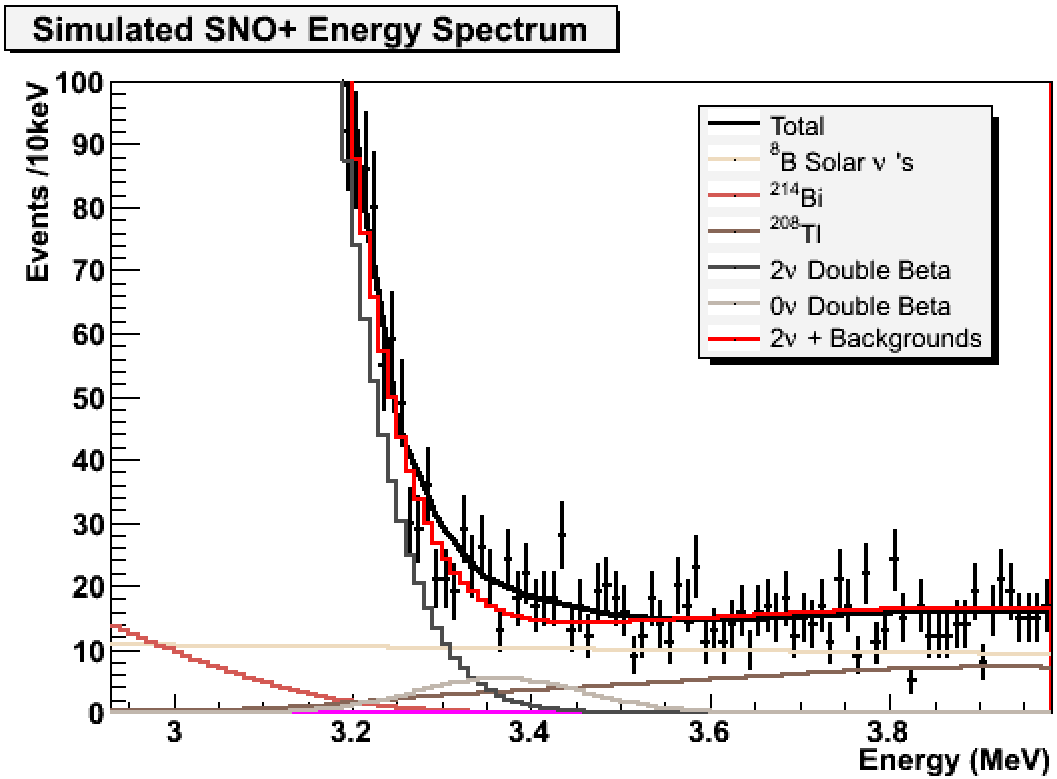
$0\nu\beta\beta$ Signal for <m_ν> = 0.150 eV

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



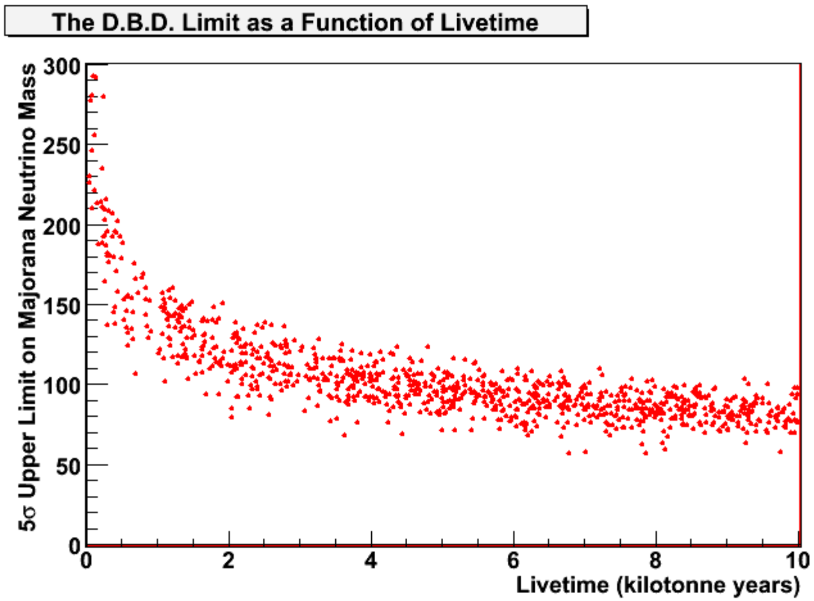


56 kg of ^{150}Nd and $<m_\nu>$ = 100 meV

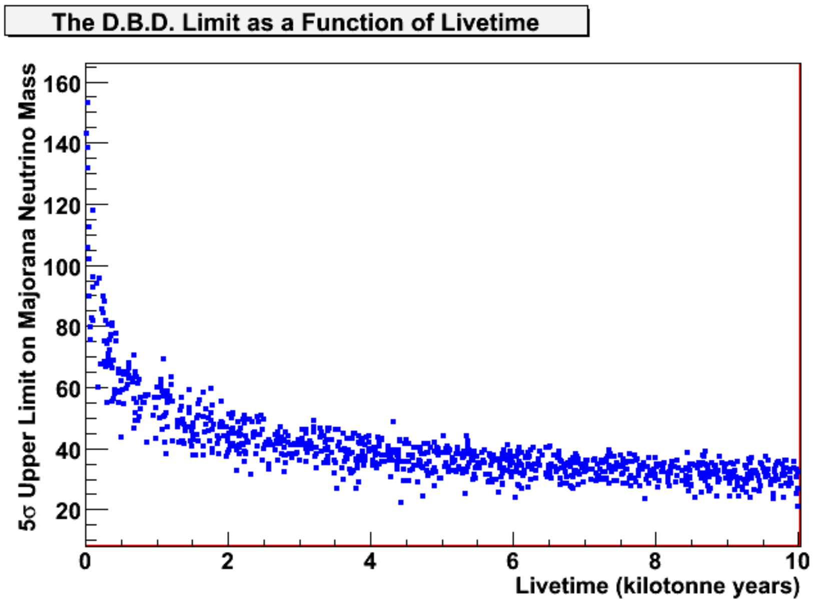


- 6.4% FWHM at Q-value
- 3 years livetime
- U, Th at Borexino levels
- 5σ sensitivity
- note: the dominant background is ^{8}B solar neutrinos!
- ^{214}Bi (from radon) is almost negligible
- ^{212}Po-^{208}Tl tag (3 min) might be used to veto ^{208}Tl backgrounds; ^{212}Bi-^{212}Po (300 ns) events constrain the amount of ^{208}Tl

Neutrino Mass Sensitivity



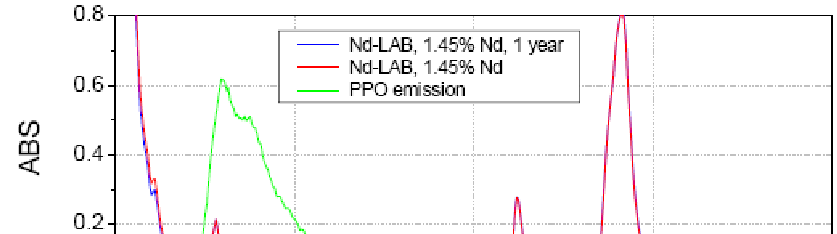
With natural Nd SNO+ is sensitive to effective neutrino masses as low as 100 meV.

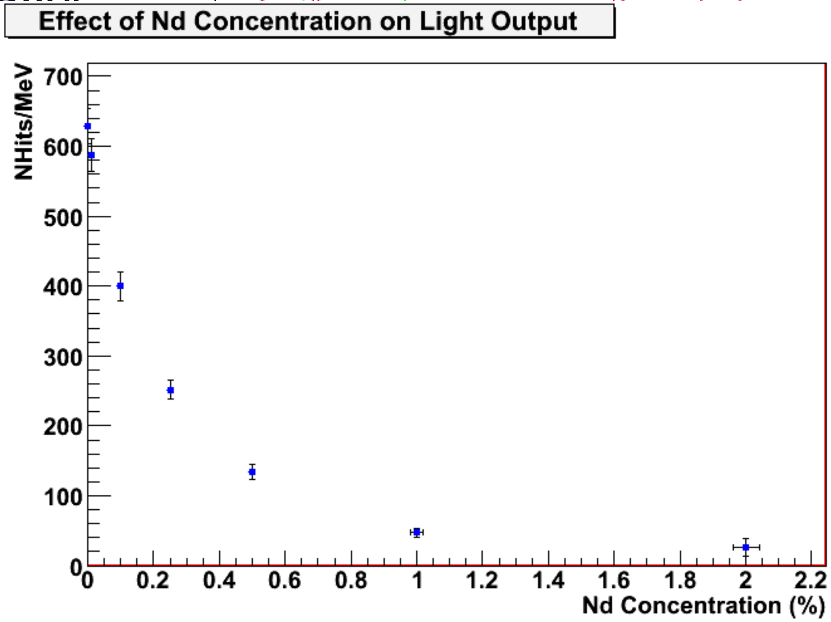


With 10X enriched Nd our sensitivity extends to 40 meV.

^{150}Nd Scintillator Properties

- stable Nd-loaded liquid scintillator optic
- scintillation optical properties studied
- target background levels achievable w
  - $NdCl_3$ … bcxyl
    scintill… e -
  - purifica… n c
    $BaSO_4$…
  - using … r
    demon… r
  - remem… h
    are the… t p
    organi… m





Status of SNO+

- funded by NSERC for final design/engineering and initial construction 2008-2010
- submission of full capital proposal to CFI in Q4 2008 with decision in Q2 2009
- construction of hold-down net begins in 2009
- construction of scintillator process and purification begins in 2010
- end of 2010 → ready for scintillator filling
- *new collaborators welcome!*

Summary

- future double beta decay experiments with scintillators utilize many different double beta decay candidate isotopes
  - it's very useful to search for neutrinoless double beta decay in many isotopes
- particularly interesting (IMHO) are experiments that will have a large mass of the high Q-value isotopes like ^{48}Ca and ^{150}Nd