Results from KIMS
-Research program and plan

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Seoul National University
for the KIMS collaboration

XLIIInd Rencontres de Moriond
Electroweak session, La Thuile, March 1-8, 2008

KIMS Korea Invisible Mass Search

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Extended collaboration with

V. Kornoukhov et al. *(ITEP, Russia)*
F. Danevich et al., *(INR, Ukraine)*
on development of CaMoO4 crystals
for Double beta decay search

and
H.Wong et al., *(Academia Sinica, Taiwan)*
on development of ULE HPGe detector
for low mass WIMP search

SCIENCE, July 2007

Racing to Capture Darkness

Their gravity holds galaxies together. Their identity has fueled decades of theoretical speculation. Now particle physicists are vying to drag dark-matter particles into the light

YANGYANG, SOUTH KOREA, AND BATAVIA, ILLINOIS—Deep inside Korea's Jeombong Mountain, in a vault suffused with an eldritch red glow, a giant black cube begins to unfold. One thick, lead-lined wall filled with mineral oil, along with the box's base, inches away from the rest of the structure to reveal a smaller cube of shimmering copper. A young man steps up and pulls a chain, hand over hand, and gradually, amid the clatter of steel, the face of the copper cube rises. The rarest of coins or the relics of a saint might be accorded such sanctity, but here, in an anteroom to a tunnel delved for a hydropower station in northeastern Korea, the treasure is precious only to a particle physicist. Inside the copper cube are a dozen blocks of crystalline cesium iodide, doped with thallium and wired with electronics that will register the tiniest scintilla of light produced inside the crystals. Researchers are making a few final tweaks to their crystal array before sealing it up again and beginning an otherworldly quest.

The 15 centimeters of gamma ray–blocking lead and neutron-quenching oil in the black cube, the 10 centimeters of copper that absorb x-rays from the lead, the nitrogen piped into the copper box, the red light, and the 700 meters of rock between the chamber and the outdoors all have a singular purpose: to minimize the number of spurious flashes inside the crystals. Here at the Korea Invisible Mass Search (KIMS) experiment, researchers are hoping to be the first to spot what no one—indisputably—has seen before: particles of dark matter.

After years of preparation, physicist Kim Sun Kee of Seoul National University and his KIMS colleagues began taking data here last month with a 100-kilogram array of crystals. Each day they hope to record one or two instances of weakly interacting massive particles (WIMPs)—prime candidates for dark matter—tickling cesium and iodine nuclei in a way that liberates a flash of light. That's assuming dark particles tangle with ordinary particles as many models predict. "If they don't interact with matter, we have no hope to find them," says Kim.

The KIMS experiment is one of a few dozen experiments racing to detect dark-matter particles. Like Kim's team, groups in several countries are engaged in so-called direct searches, striving to spot the particles jostling ordinary atomic nuclei. Others are turning to the skies in indirect searches that seek signs of dark-matter particles annihilating one another in the hearts of galaxies. Meanwhile, the world's most powerful atom smasher, the Large Hadron Collider (LHC) near Geneva, Switzerland, could make dark matter as soon as it turns on next spring.

"This is the epoch in which the central theoretical predictions are finally being probed," says Blas Cabrera of Stanford University in Palo Alto, California, who for a decade has stalked dark matter as the co-spokesperson of the Cryogenic Dark Matter Search (CDMS) project. "The best guess is within reach." That prospect thrills researchers. At a recent workshop* at Fermi National Accelerator Laboratory (Fermilab) in Batavia, Illinois, more than half the 170 attendees wagered that dark-matter particles will be detected within 5 years.

Discovery is not guaranteed. The favored theoretical models suggest that experimenters should soon have dark matter in their grasp, but others predict the ghostly particles will be so elusive that researchers can never hope to snare them. It's a make-or-break situation, predicts Rocky Kolb, a cosmologist at the University of Chicago in Illinois: "Either in 5 years we will know what dark matter is, or we will never know."

The WIMP miracle

Astronomers first sensed dark matter's shadowy presence more than 70 years ago.

* The Hunt for Dark Matter: A Symposium on Collider, Direct, and Indirect Searches, 10–12 May

Unseen clouds. Astronomers can infer where dark matter lies in space, but nobody knows what it is.

In 1933, Fritz Zwicky of the California Institute of Technology in Pasadena calculated that the Coma Cluster of galaxies contains too little visible matter to hold itself together. Some unseen matter must supply the extra gravity that keeps the galaxies from flying into space, he reasoned. That maverick idea gained credence about 4 decades later when astronomers found that individual galaxies also lack enough luminous matter to hold on to their stars, suggesting that each galaxy is embedded in a vast clump, or "halo," of dark matter.

Evidence continues to mount. In 2003, researchers with NASA's orbiting Wilkinson Microwave Anisotropy Probe (WMAP) measured the big bang's afterglow—the cosmic microwave background—the temperature of which varies ever so slightly across the sky (*Science*, 14 February 2003, p. 991). The pattern of hot and cold spots reveals much about how the universe evolved, and researchers found they could explain the observed pattern if the universe consists of 5% ordinary matter, 22% dark matter, and 73% weird space-stretching "dark energy," all interacting through gravity.

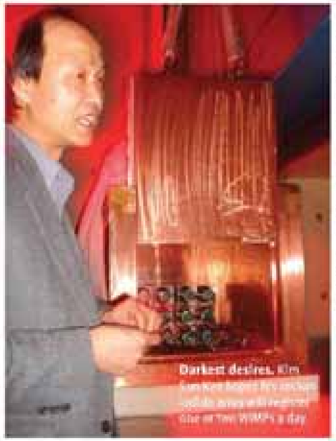
Researchers have never captured a speck of dark matter, however. Like a cosmic Cheshire Cat, the stuff hides in plain sight, presumably floating through our galaxy and the solar system and showing only its gravity as its grin. That coyness vexes physicists, who assume that dark matter must consist of particles. "This is the best evidence we have of new physics," says Jonathan Feng, a theorist at the University of California, Irvine. "It's simply a fact that there is dark matter, and we don't know what it is."

Theorists have dreamed up dozens of possibilities. Dark matter could be particles that would exist if space has minuscule extra dimensions. Or it could be particles called axions that have been hypothesized to patch a conceptual hole in the theory of the strong force that binds the nucleus.

Most promising may be the idea that dark matter consists of particles predicted by supersymmetry, a theoretical scheme that pairs every known particle with a heavier, undiscovered superpartner. The lightest superpartner, expected to be a few hundred times as massive as a proton, could be the long-sought WIMP. And if it interacts with ordinary matter as anticipated, then a simple calculation shows that roughly the right amount of WIMPy dark matter should remain from the big bang. That uncanny coincidence, or "WIMP miracle," suggests that supersymmetry is more than another stab in the dark, Feng says.

Detecting is believing

The proof is in the particles. The most obvious way to find them is to catch them bumping into ordinary matter, and the KIMS experiment joins more than a dozen experiments that are hunting for collisions with ever greater sensitivity—including one that claimed a signal. Spotting dark matter is easier said than done, however. The particles should interact with ordinary matter even more feebly than do neutrinos, which can zip through Earth unimpeded. Researchers must also shield detectors from cosmic rays and other ordinary particles so that they may perceive the soft cries of dark particles amid the din of ordinary collisions.



Darkest desires. Kim Sun Kee hopes his cesium iodide arrays will register one or two WIMPs a day.

In the race to capture darkness, the front-runner for the past few years has been an experiment called CDMS, which runs in the Soudan Mine in northern Minnesota. Its 5-kilogram "cryogenic" detector consists of stacks of germanium and silicon wafers cooled to within a fraction of a degree of absolute zero. If a WIMP crashes into a nucleus, it should knock loose several electrons and produce a tiny pulse of heat. Analyzing both the charge and heat signals, researchers can look for dark-matter particles and weed out neutrons and other red herrings.

Now, another experiment has taken the lead in sensitivity. The XENON10 experiment, which resides in a tunnel in Gran Sasso, Italy, consists of a tank filled with 15 kilograms of liquid xenon. When pinged by a WIMP, a xenon nucleus should rebound through the liquid to produce a flash of light and knock free a handful of electrons. In April, the XENON10 team, led by Elena Aprile of Columbia University, reported that it had searched with five times the sensitivity of CDMS—and found nothing.

To go head to head with such efforts, the KIMS team had to start from scratch. A decade ago, Korea did not have a particle physics facility. "We always had to go abroad for research and training," says Kim, who cut his teeth at Japan's KEK accelerator laboratory in Tsukuba in the 1980s. When South Korea's science ministry launched a Creative Research Initiative in 1997, Kim, with colleagues Kim Hong Joo of Kyungpook National University in Daegu, South Korea, and Kim Yeong Duk of Sejong University in Seoul, pounced. Thrice the trio of Kims submitted their aptly named KIMS proposal, and thrice they failed. Finally, in 2000, they opted for a novel cesium iodide detector—and got funded. They caught a second break when during construction of the Yangyang Pumped Storage Power Plant, a small section off one tunnel caved in, and plant officials were amenable to hosting the experiment. "We were very lucky," says Kim Sun Kee. The collapse "opened up just enough space for the experiment."

Since then, the most arduous task has been to develop a detector largely free of trace radioactive isotopes. The KIMS team has also spent 3 years studying the scintillation signals of gamma rays and stray cosmic rays, which cause chain reactions in the atmosphere that give rise to a background "noise" of hurtling neutrons. "The neutron signal is very similar to what we expect a WIMP signal to look like," Kim explains, so the experimenters must find ways to screen it out. So far they have reduced it by 99.999%, he says.

KIMS won't immediately rival CDMS and XENON10 for overall sensitivity. But KIMS will excel in one important regard: If the WIMP-nucleus interaction depends on how each particle spins, KIMS will have a better chance of seeing the effect. "That makes KIMS complementary with CDMS and XENON10," Kim says.

KIMS can also test one of the more spectacular recent claims in physics. In 1997 and

Yangyang Underground Laboratory(Y2L)


Yangyang Underground Laboratory
Korea Middleland Power Co.
Yangyang Pumped Storage Power Plant
(Upper Dam)
Construction of Lab. buildings done in 2003
(Power Plant)
(Lower Dam)
양양양수발전소
Minimum depth : 700 m / Access to the lab by car (~2km)

Research Program of KIMS

Dark Matter Search

- ***CsI(Tl) crystal detector***

  Running → result was published

- ***Ultra-low energy HPGe detector (with Taiwan)***

  R&D setup is running

Neutrinoless Double Beta Decay Search

- ***Metal loaded liquid scintillator***

  Pilot experiment is done – a preliminary result

- ***$CaMoO_4$ crystal (With Russia and Ukraine)***

  R&D effort is on going

Development of Cryogenic Detector

R&D effort is on going

To measure the elastic scattering of WIMP

- expected event rate is very low < 1 counts/kg/keV/day
- recoil energy is very small < 100 keV
- needs low background detectors, environment

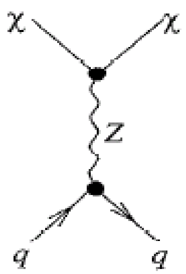
How do we confirm if it is really WIMP if observed?

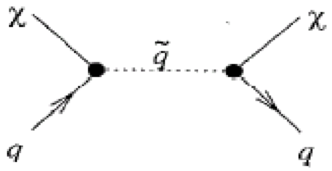
- annual modulation
- direction dependent detection
- target dependence : A^2, $<s_p>$, $<s_n>$

→needs several experiments with different targets and different detection techniques
→will need even larger mass detectors

Elastic scattering of SUSY WIMP with ordinary nucleus

Spin Dependent Interaction



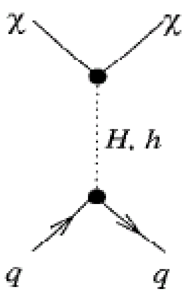


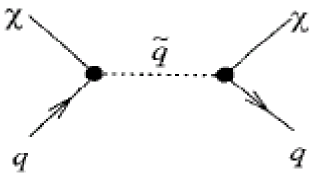
$$L_{axial} = d_q \bar{\chi}\gamma^{\mu}\chi^5 \bar{q}\gamma^{\mu}\chi^5 q$$

$$\sigma_{spin} = \frac{32}{\pi} G_F{}^2 \mu^2 \Lambda^2 J(J+1)$$

$$\Lambda \equiv \frac{1}{J}(a_p < S_p > + a_n < S_n >)$$

Spin Independent Interaction





$$L_{scalar} = a_q \bar{\chi}\chi \bar{q} q$$

$$\sigma_{scalar} = \frac{4}{\pi}\mu^2 \left[Zf_p + (A-Z) f_n \right]^2$$

$$\propto A^2$$

WIMP search with CsI(Tl) Crystals

Easy to get large mass with an affordable cost
High light yield ~60,000/MeV
Pulse shape discrimination : γ background rejection
Easy fabrication and handling (no cryogenics!)

Cs-133, I-127 (SI cross section ~ A^2)
Both Cs-133, I-127 are sensitive to SD interaction
Direct check of DAMA signal

Isotope	J	Abun	<Sp>	<Sn>
^{133}Cs	7/2	100%	-0.370	0.003
^{127}I	5/2	100%	0.309	0.075
^{73}Ge	9/2	7.8%	0.03	0.38
^{129}Xe	1/2	26%	0.028	0.359
^{131}Xe	3/2	21%	-0.009	-0.227

CsI(Tl) crystal

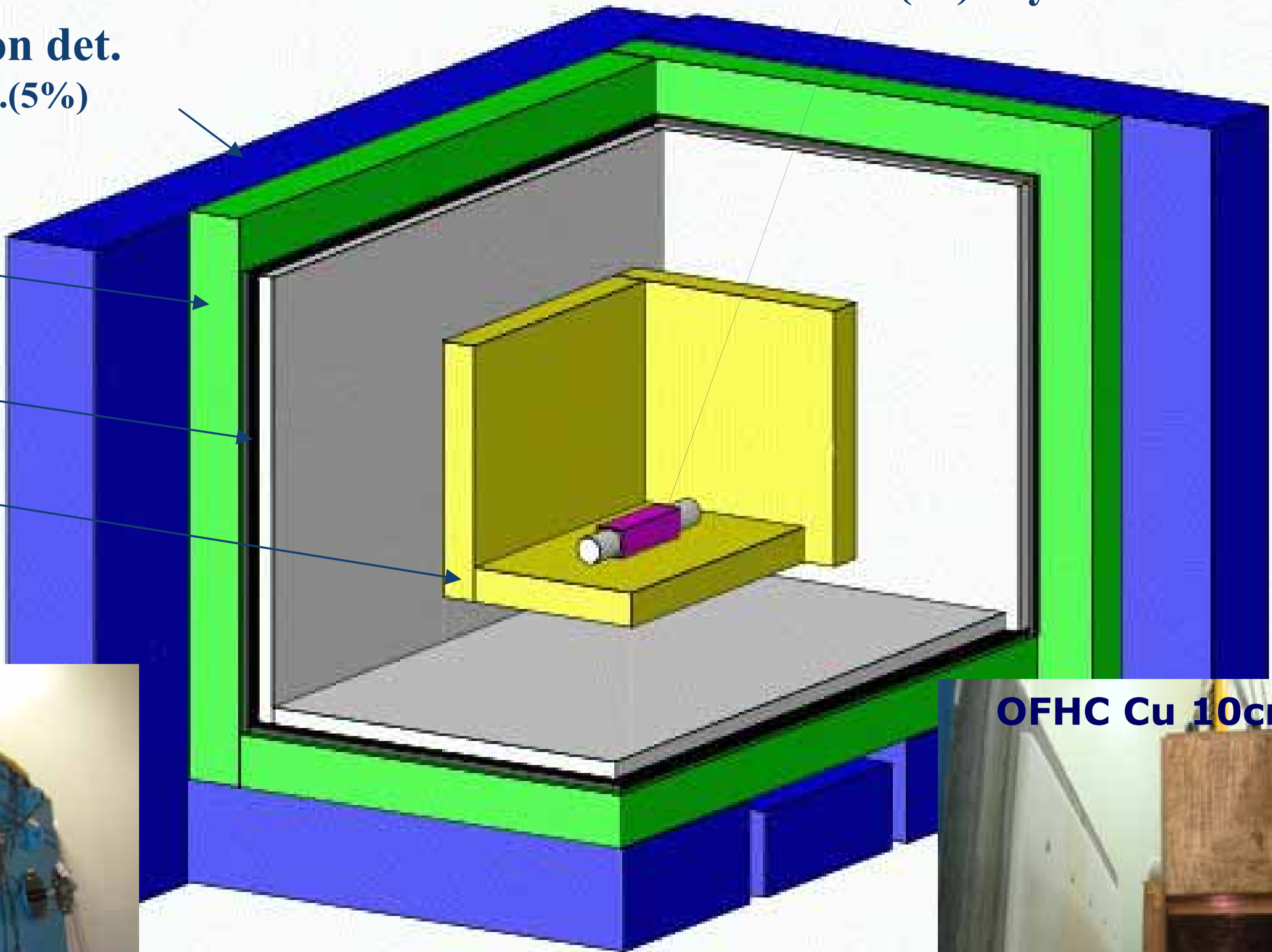
Neutron shield / Muon det.

Minreal oil + liquid scint.(5%)

Lead shield

Polyethylene

Copper shield

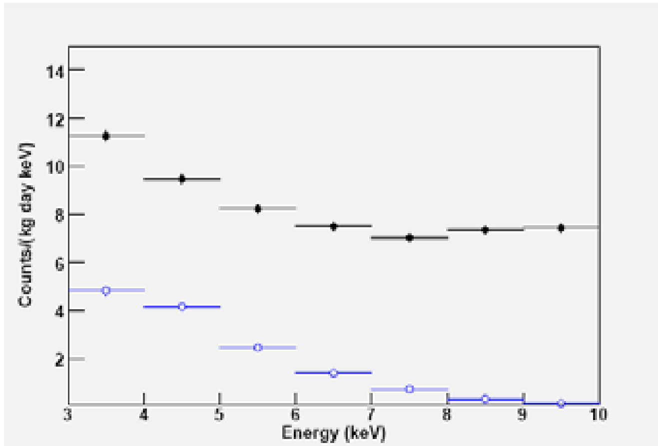


Data set

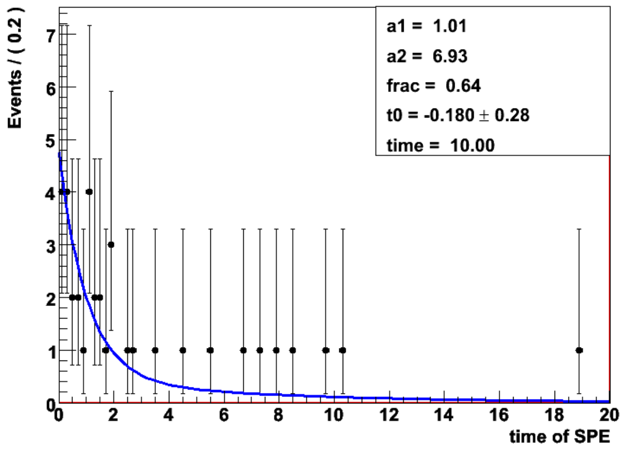
Crystal	p.e./keV	Mass(kg)	Data(kg·days)
S0501A	4.6	8.7	1147
S0501B	4.5	8.7	1030
B0510A	5.9	8.7	616
B0510B	5.9	8.7	616
Total		34.8	3409

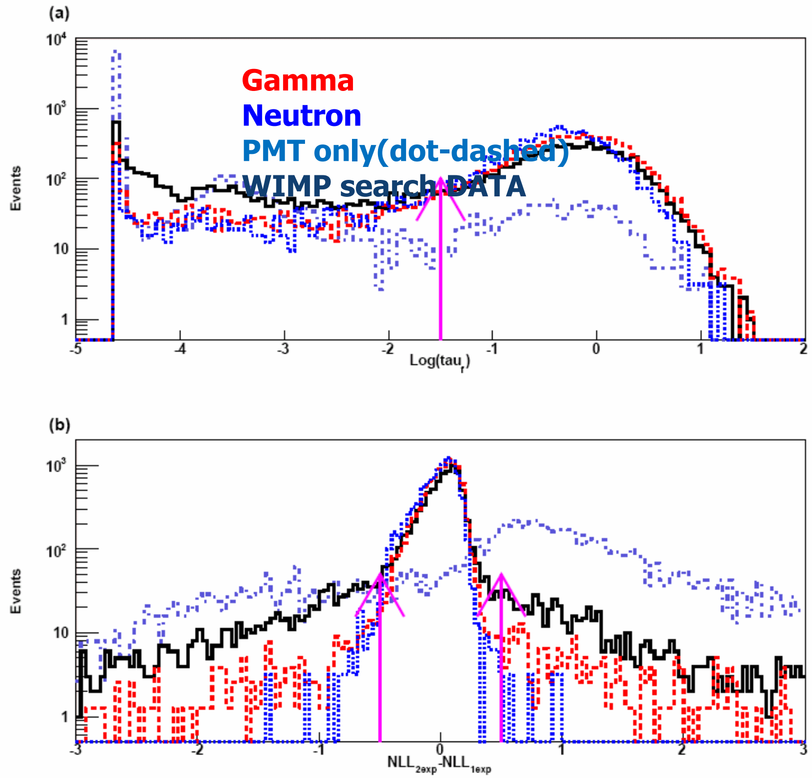
Calibration and control data samples

- Neutron ~ 500 kg days (at 4~6 keV)
- Gamma (using ^{137}Cs) ~ 1100 kg days (0501A), 1650 kg days(0501B)
  910 kg days (0510A), 840 kg days(0510B)
- PMT only ~350 kg days for each crystal with the PMTS used
  for each crystal



Likelihood fit with $F(t) = 1/\tau_f \exp(-(t-t_0)/\tau_f) + r/\tau_s \exp(-(t-t_0)/\tau_s)$

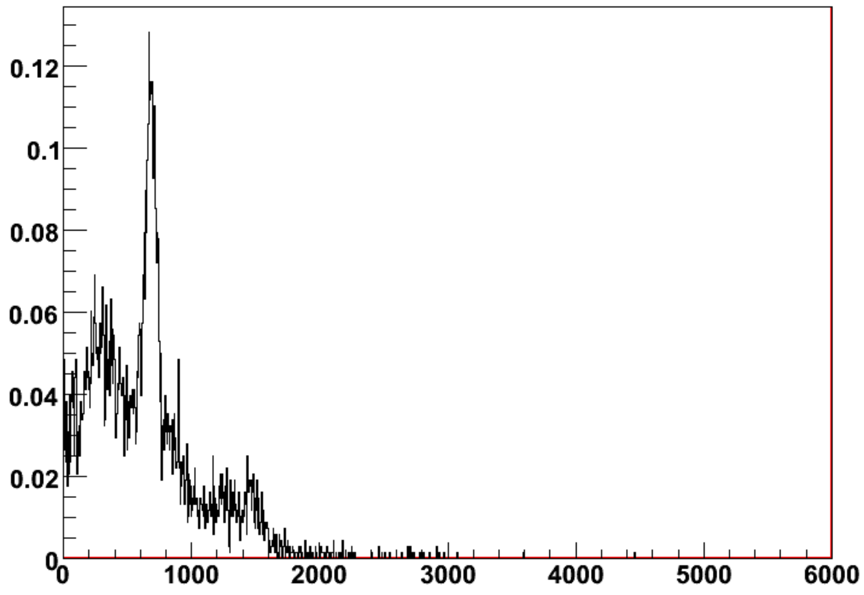




Decay time fit and fit quality cut

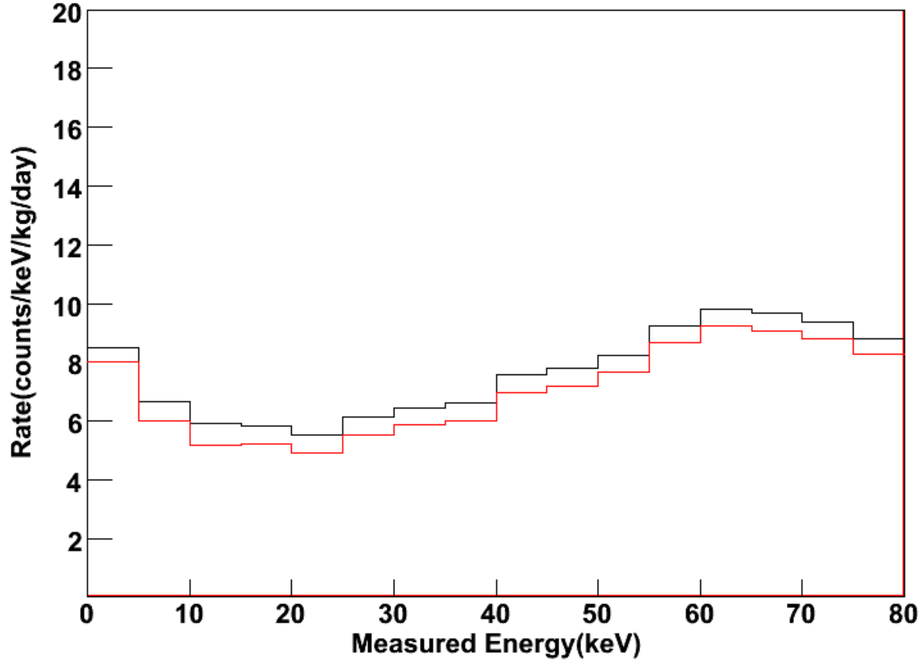
- fitted τ_f
- log likelihood difference between two exponential fit and one exponential fit
- Asymmetry

Coincidence events



Reduction of background
by coincident event veto

Sum of energies in all crystals
for the coincidence events

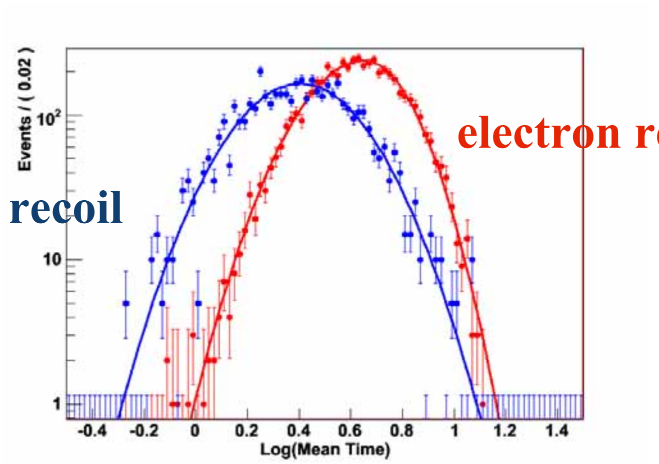


A clean sample of low energy gamma events
→ used for verification of gamma calibration and for efficiency calculation

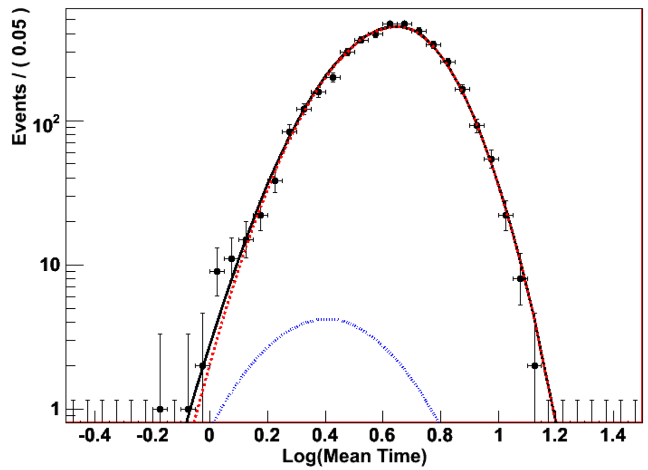
NR event rate

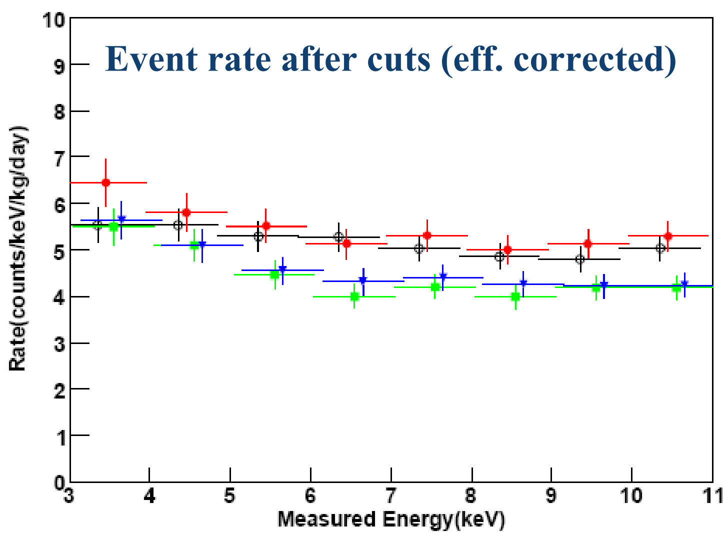
- Modeling of Calibration data with asymmetric gaussian function

nuclear recoil

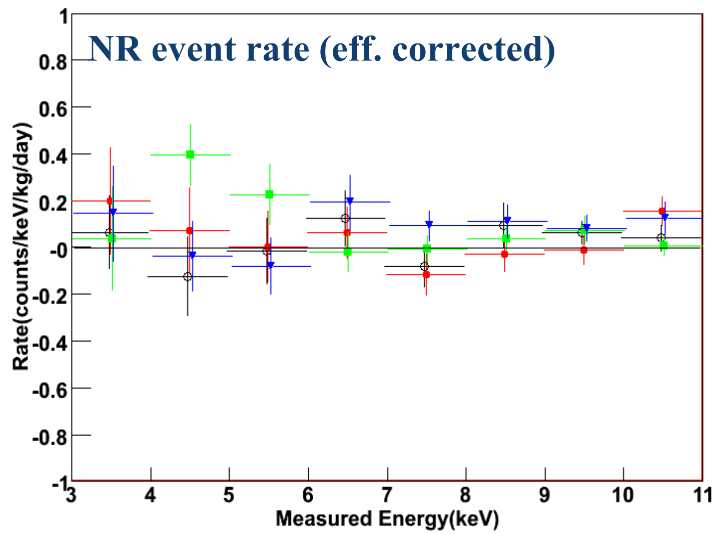


electron recoil



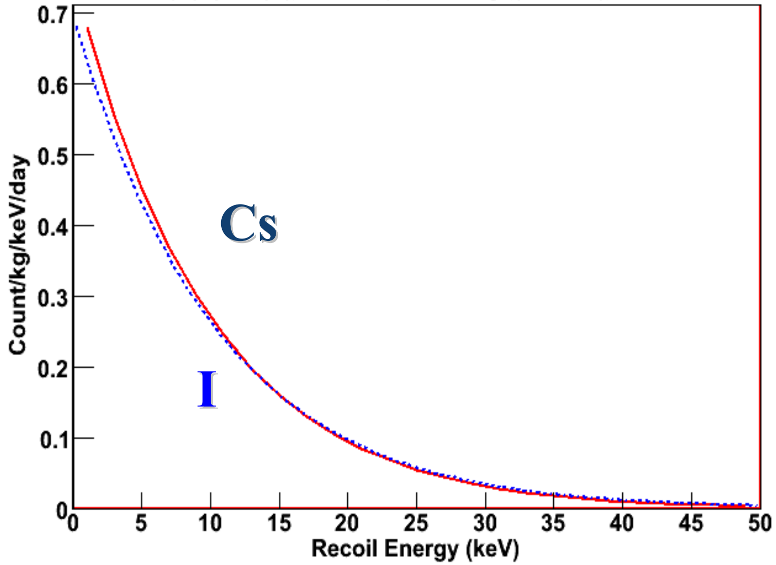


S0501A
S0501B
B0510A
B0510B

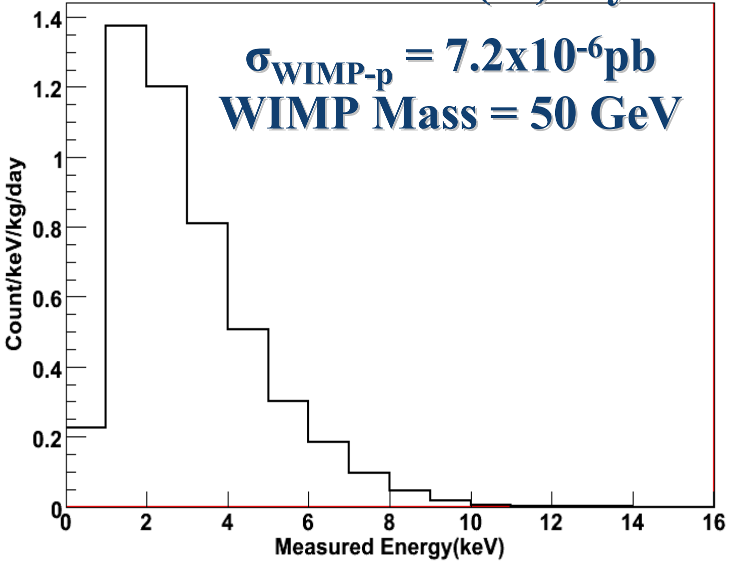


Signal in CsI(Tl) crystal

Recoiled rate in Cs and I



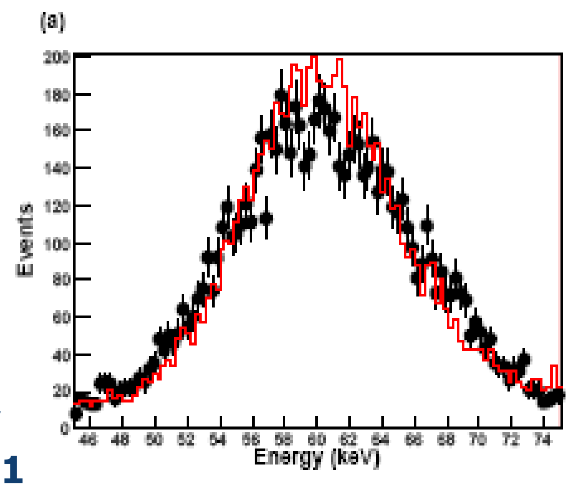
Measured rate in CsI(Tl) crystal



GEANT4 Simulation

Quenching factor
Energy Resolution

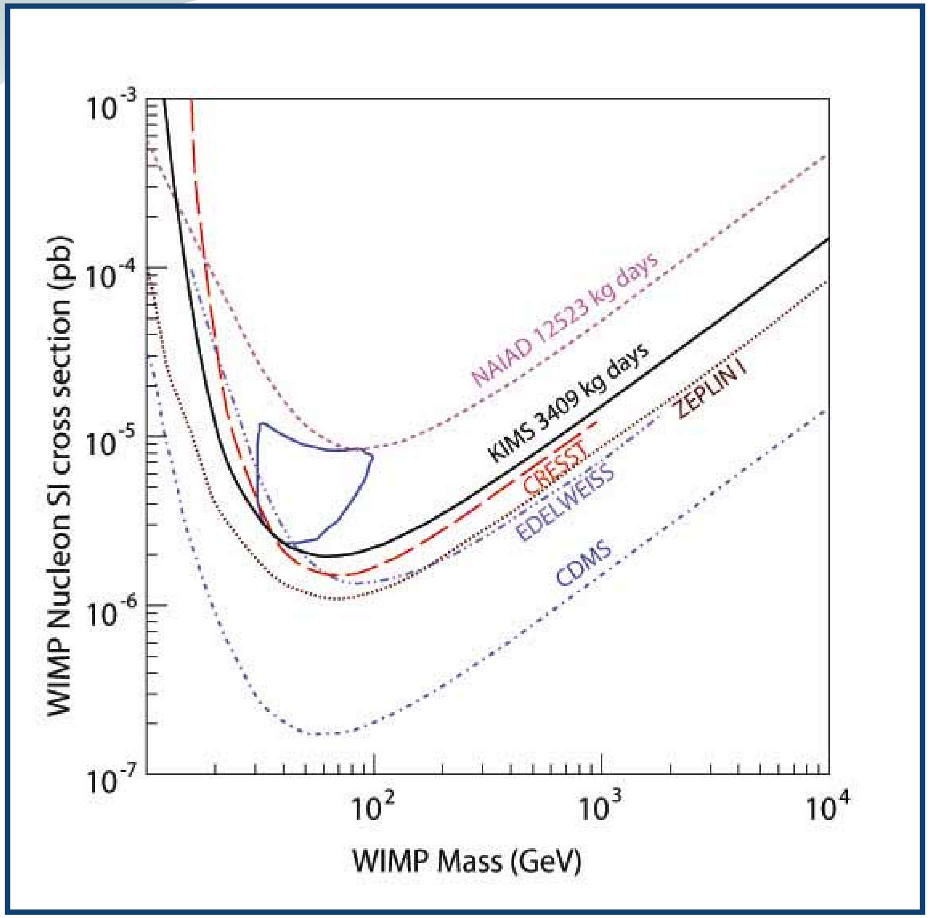
SD form factors for Cs (J.Toivanen)
I (M.T.Ressel *et al*)



59.54 keV from Am241

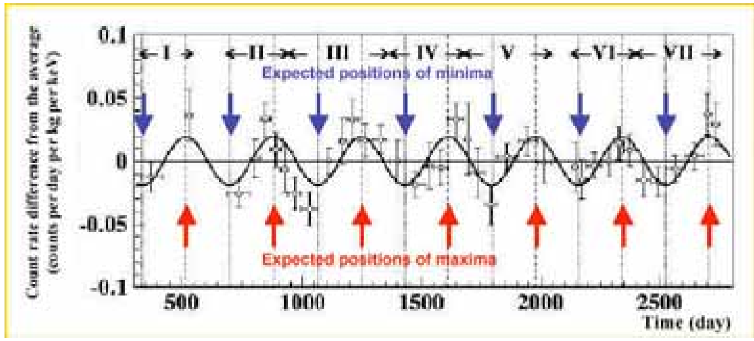
Spin independent limit

PRL 99, 091301 (2007)



ρ_D=0.3 GeV/c²/cm³
v_0=220km/s
v_{esc}=650km/s

Systematic uncertainty
Fitting, Quenching factor
energy resolution…
~ 15% higher than w/o syst.



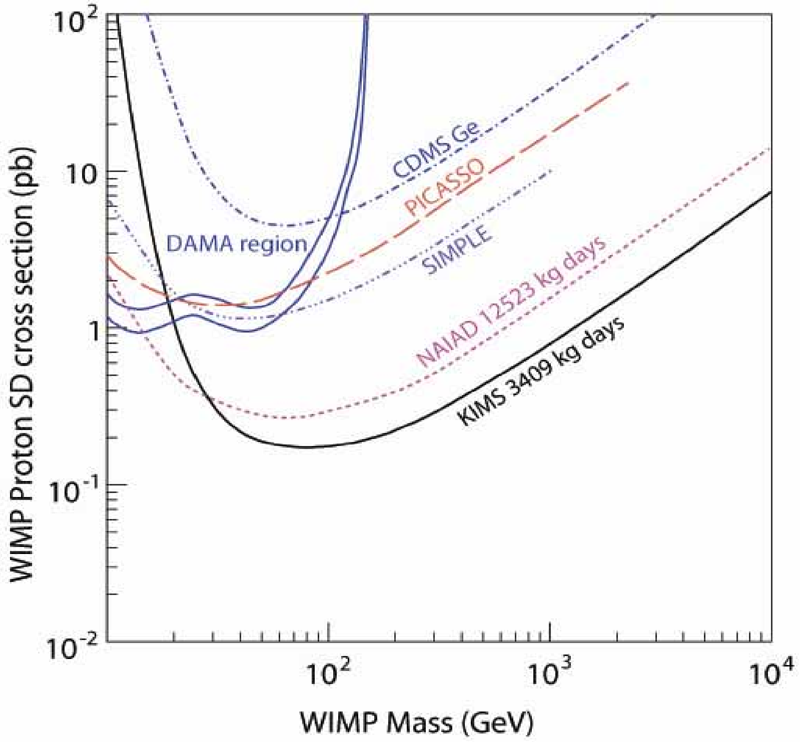
Ruled out the interpretation of DAMA signal as recoil of ^{127}I (dominant target for SI WIMP interaction).

DAMA annual modulation still needs to be checked !

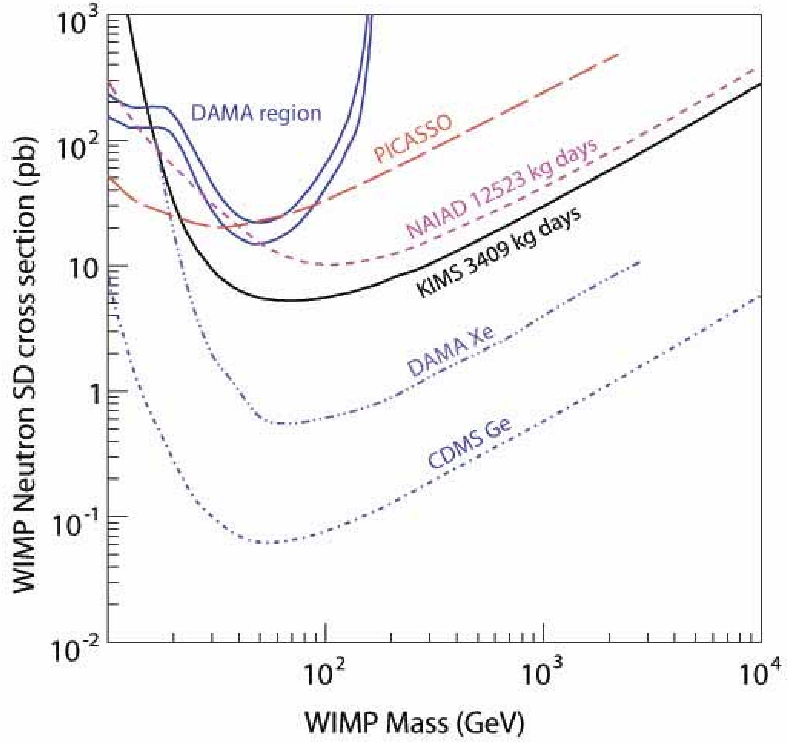
Spin dependent limits

PRL 99, 091301 (2007)

Pure proton case



Pure neutron case



KIMS ruled out DAMA signal region for SI, SD (p), SD(n) for MW>20 GeV by single experiment

Status and Plan

Status

- 12 crystals(104.4kg) in data taking
- Expect a stable data taking for more than a year → annual modulation
- 6 more crystals (52.2 kg) are grown

Plan for the improvement of the sensitivity

- New PMT with higher Q.E. under development
  - lower threshold
  - better PSD
  - lower background from PMT
- Further reduction of internal background

Summary

- **WIMP search results using 3409 kg days data (PRL 99, 091301 (2007))**
  - DAMA signal region is ruled out for both SD and SI interactions at WIMP mass > 20 GeV without ambiguity
  - Most stringent limit on SD interactions for pure proton case

- Successfully reduced internal backgrounds of CsI(Tl) crystals
  - 12 full size crystals($8x8x30cm^3$) ~ 100 kg
  - 6 more full size crystals are grown (to be delivered, to be tested)
  - Current shielding can house 250 kg crystals

- 100 kg crystals installed in the shield and data taking is on going
  → Annual modulation search

- Competitive DBD search using CaMoO4 crystals can be realized rather soon → LOI in preparation

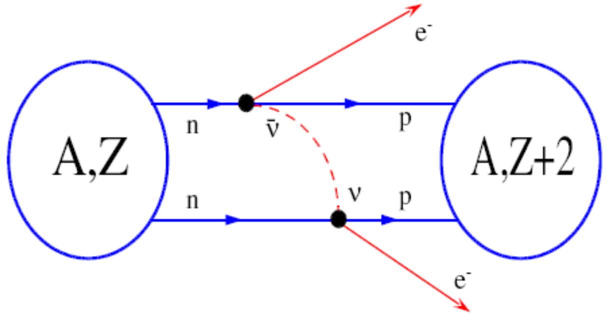
- Possibility of expansion of underground laboratory space is being explored

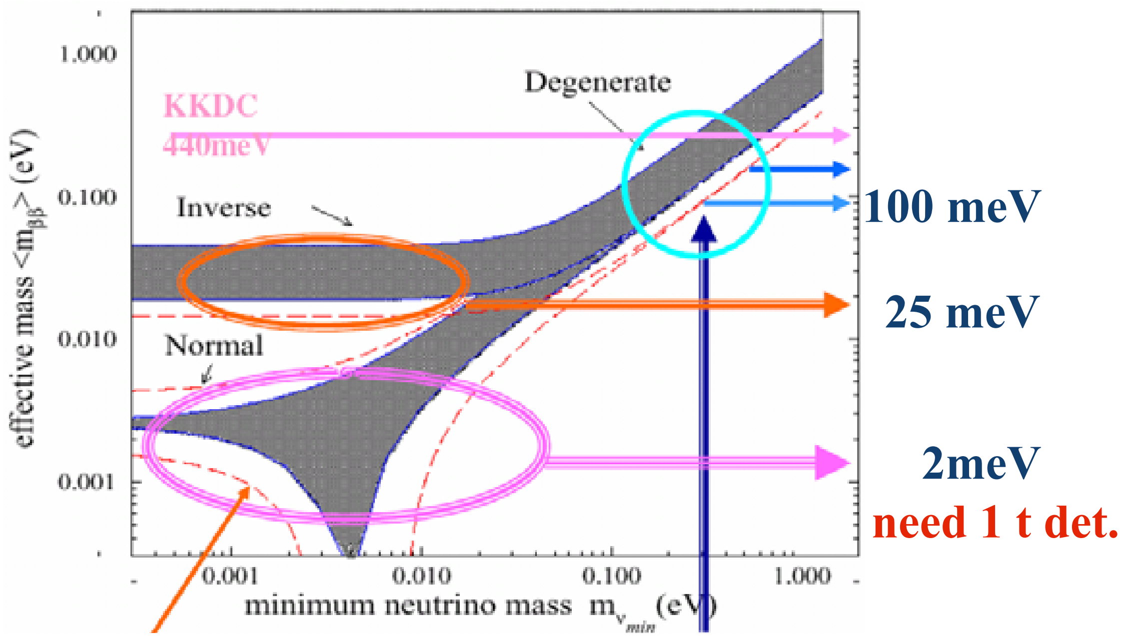
Thank you !

Neutrinoless Double Beta Decay

$$T_{1/2}(0\nu\beta\beta) \sim \langle m_{\beta\beta} \rangle^2 \left| M^{0\nu} \right|^2$$

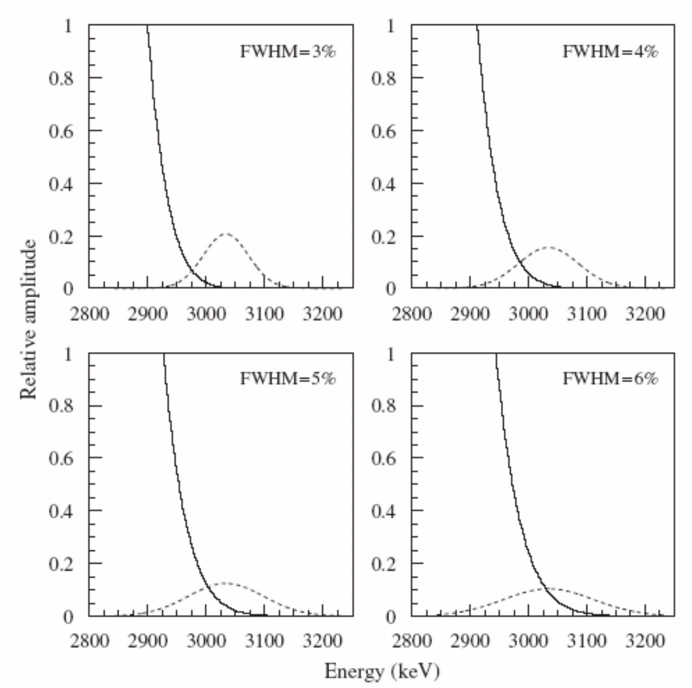
$$m_{\beta\beta} = \sum m_i U_{ei}^2 \sim \frac{1}{2} \left| m_1 + m_2 e^{2i\beta} + 2 s_{13}^2 m_3 e^{2i(\gamma-\delta)} \right|$$





S_{13}

from Ejiri's talk (IDM2006)



$$T_{1/2}(2\nu) = 7 \times 10^{18} \text{ yr}$$

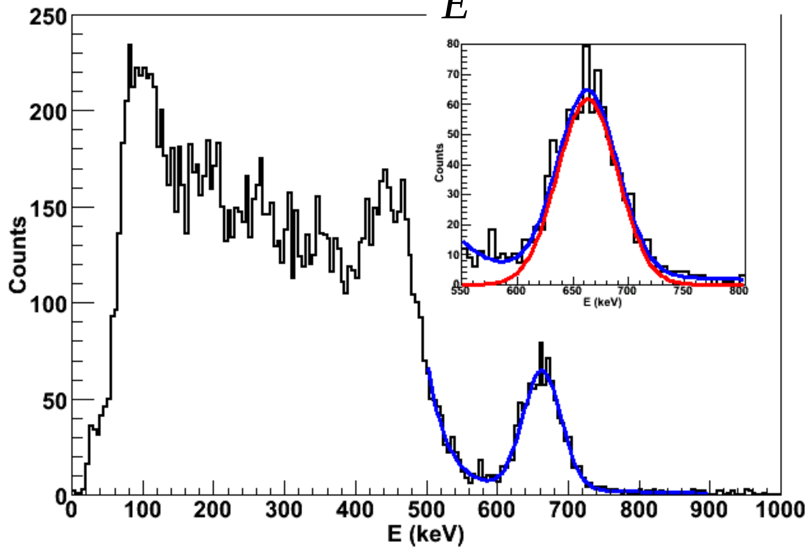
$$T_{1/2}(0\nu) = 1 \times 10^{24} \text{ yr}$$

$CaMoO_4$ ($PbMoO_4$, $SrMoO_4$...)

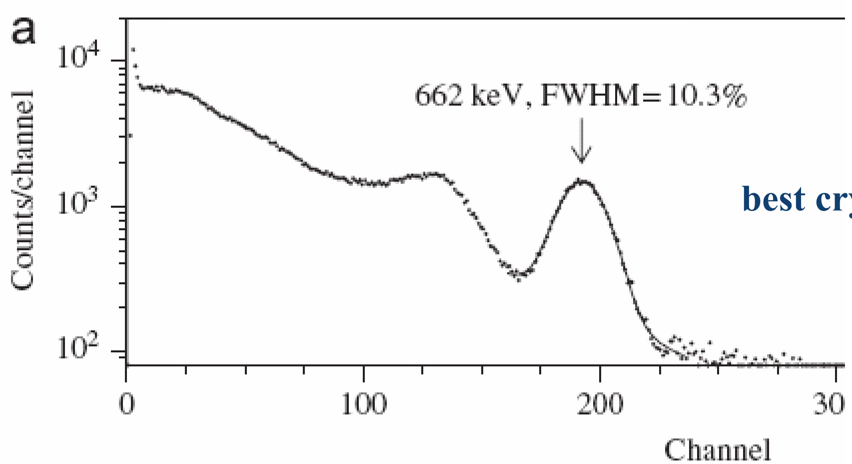
- DBD for Mo-100 (3034 keV), Ca-48(4272 keV)
- Light output; 10-20% of CsI(Tl) at 20°, increase with lower temp.
- Decay time : 16 μ sec
- Wavelength : 450-650ns-> RbCs PMT or APD
- Pulse shape discrimination

•Proc. New View in Particle Physics (VIETNAM '2004) Aug. 2004, p.449
•IEEE Nucl. Sci. 52, 1131 (2005)
•NIMA 584, 334 (2008)

$$\frac{\sigma_E}{E} = 4.1\% \text{ @662 keV}$$



CaMoO4 + LAAPD at -159°C



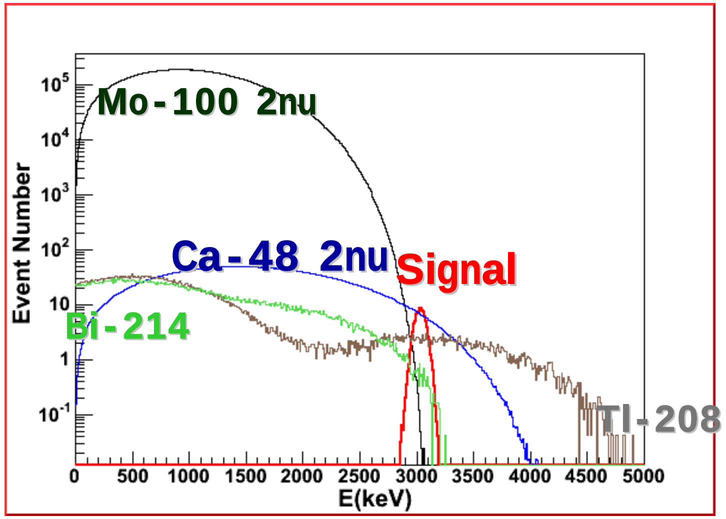
best crystal

PMT, room temp

$$\sigma_{0\nu\beta\beta}(3034keV) \sim 4.5\%\text{FWHM}$$

$CaMoO_4$ Sensitivity on $0\nu\beta\beta$ decay search

Ca, Mo purification
Tl-208, Bi-214 : 0.05 mBq/kg
Active veto : radiopure CsI(Tl) crystals
Time correlation , Pulse shape discrimination



10kg (^{100}Mo) ~20 kg $CaMoO_4$ crystal
5% FWHM resolution
1year ~ $3x10^{24}$ y w/o ^{48}Ca depletion
~ $7x10^{24}$y w ^{48}Ca depletion

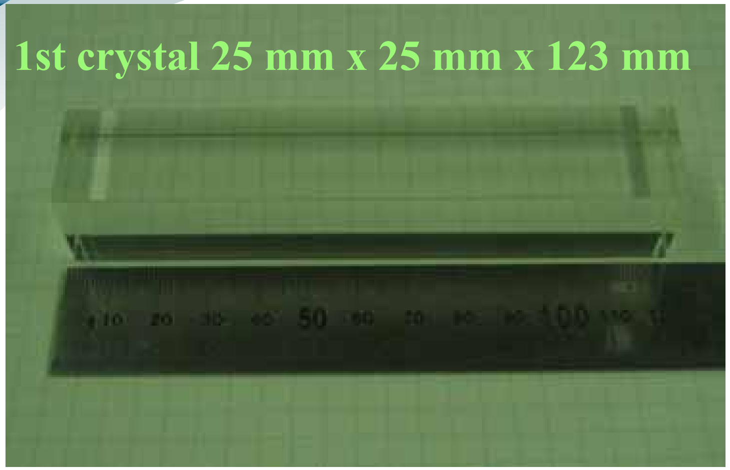
$\langle M_{\beta\beta}\rangle$ ~ 0.2-0.7eV

Current limit on ^{100}Mo :
$4.6x10^{23}$ y by NEMO3 with 6.9kg ^{100}Mo (389 days)

1st phase : 20kg Ca(depl.)$^{100}MoO_4$ with CsI(Tl) crystal active shield

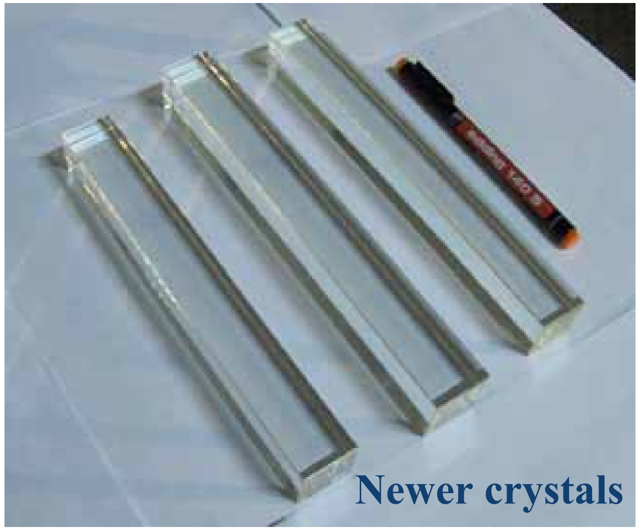
With cryogenic technique : improve the energy resolution

Crystal Growth



Carried out by ISTC program with ITEP, Russia

installed @ Y2L, taking data now

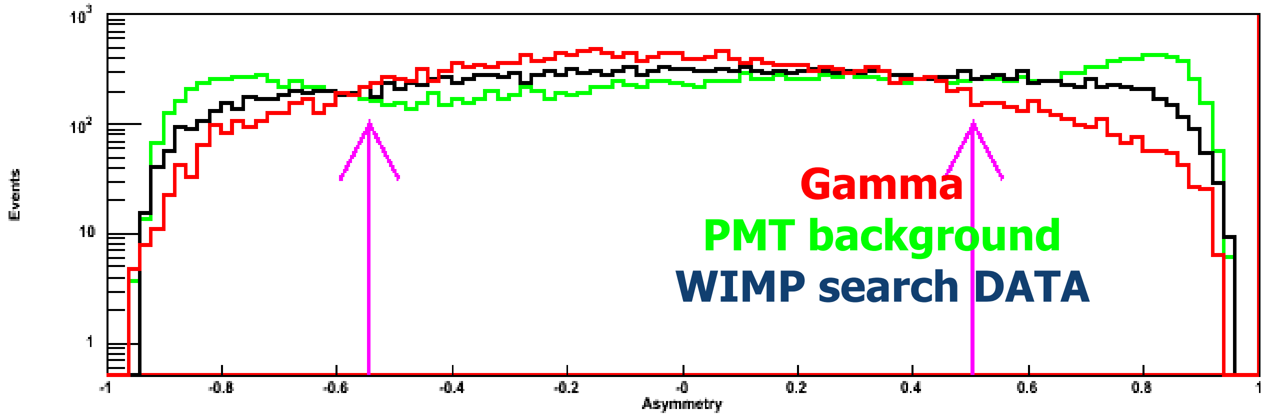


So far with Natural Mo to develop growth technique for the large size crystals

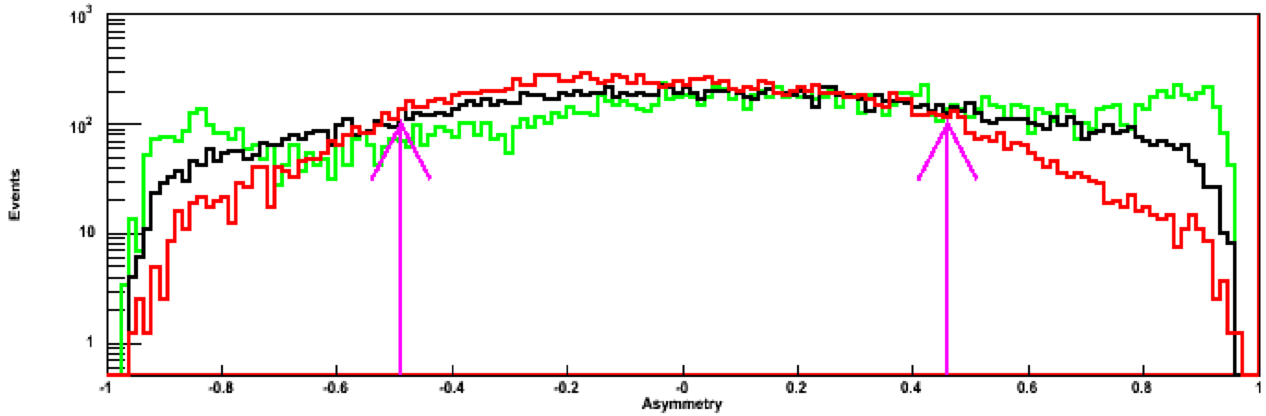
Next step : to grow $Ca^{100}MoO_4$

Asymmetry events rejection

3-5keV



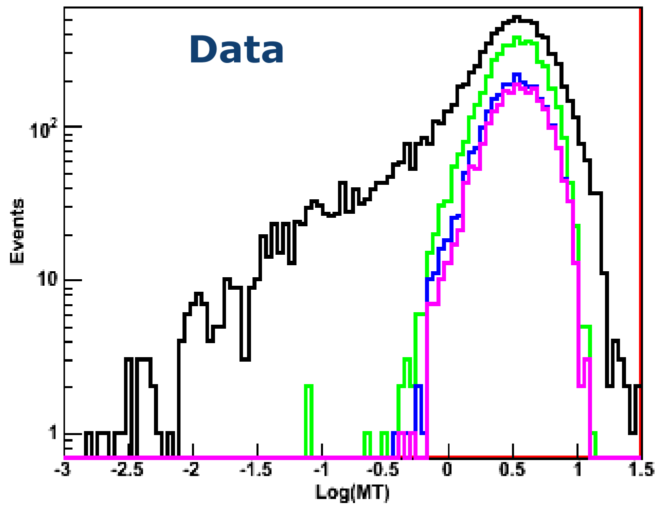
5-7keV

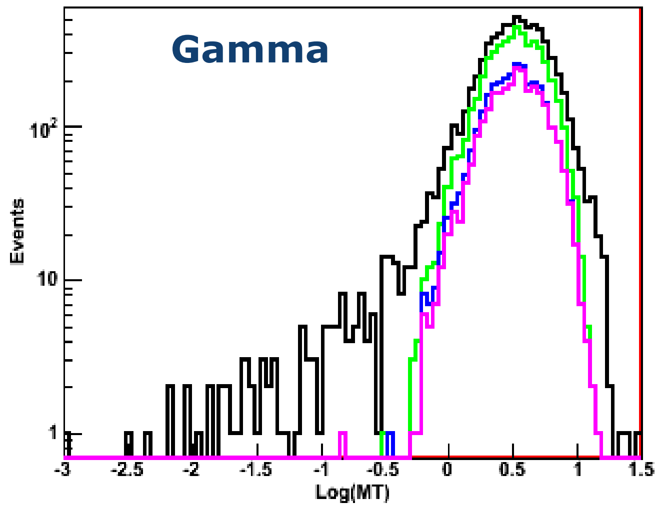


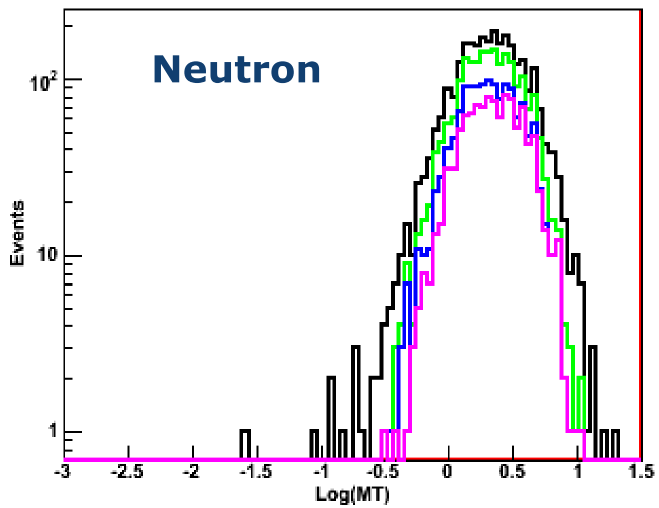
Asymmetry=(PMT1 charge-PMT2 charge)/(Total charge)

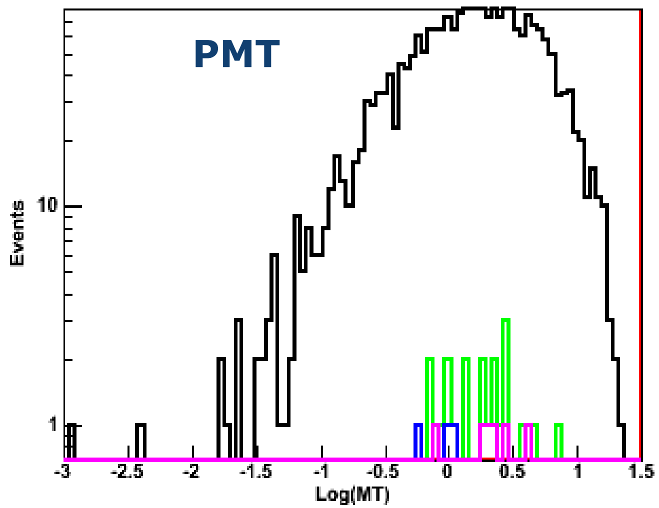
85% region with gamma calibration

Effect of cuts on MT distribution

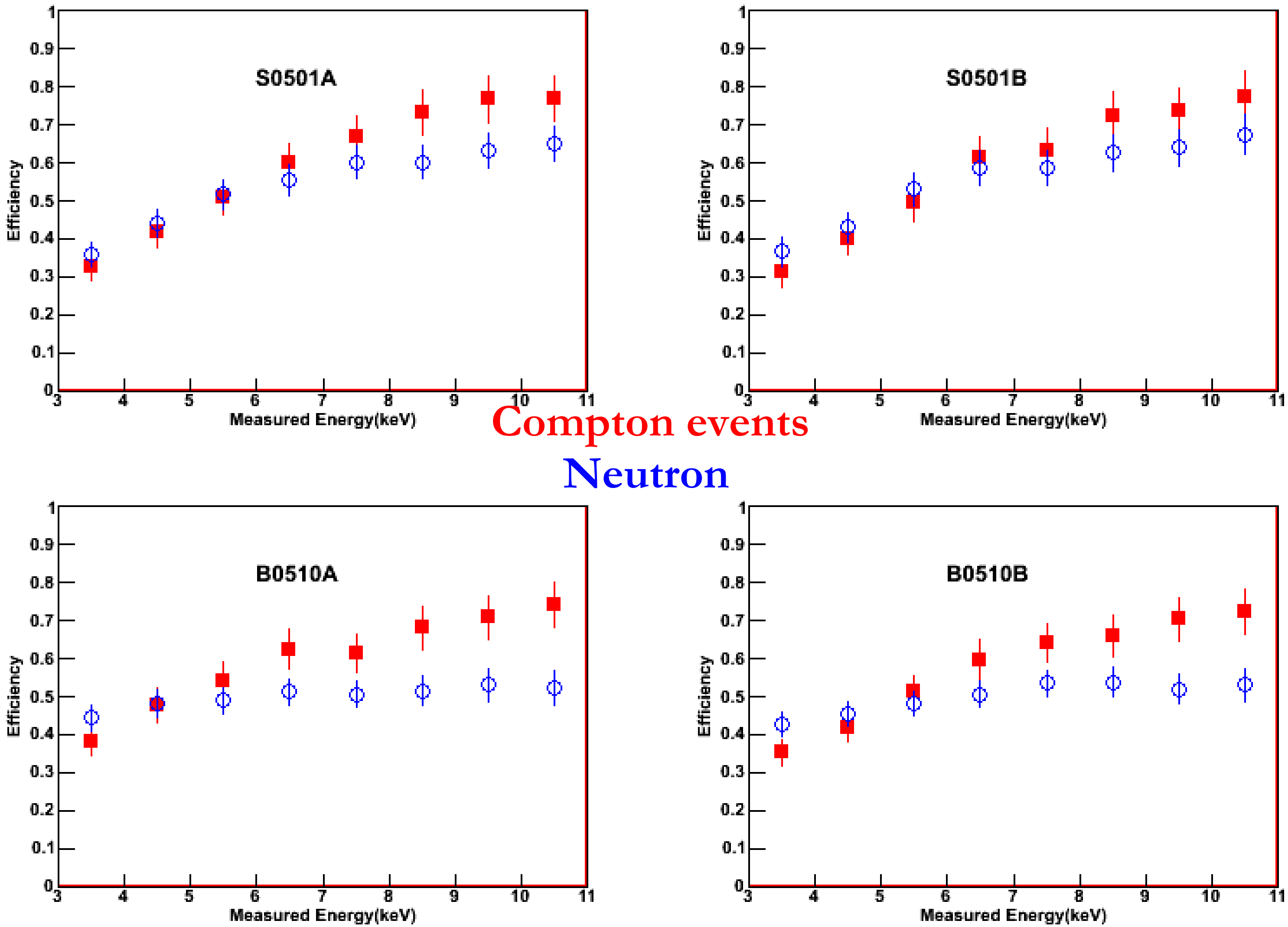






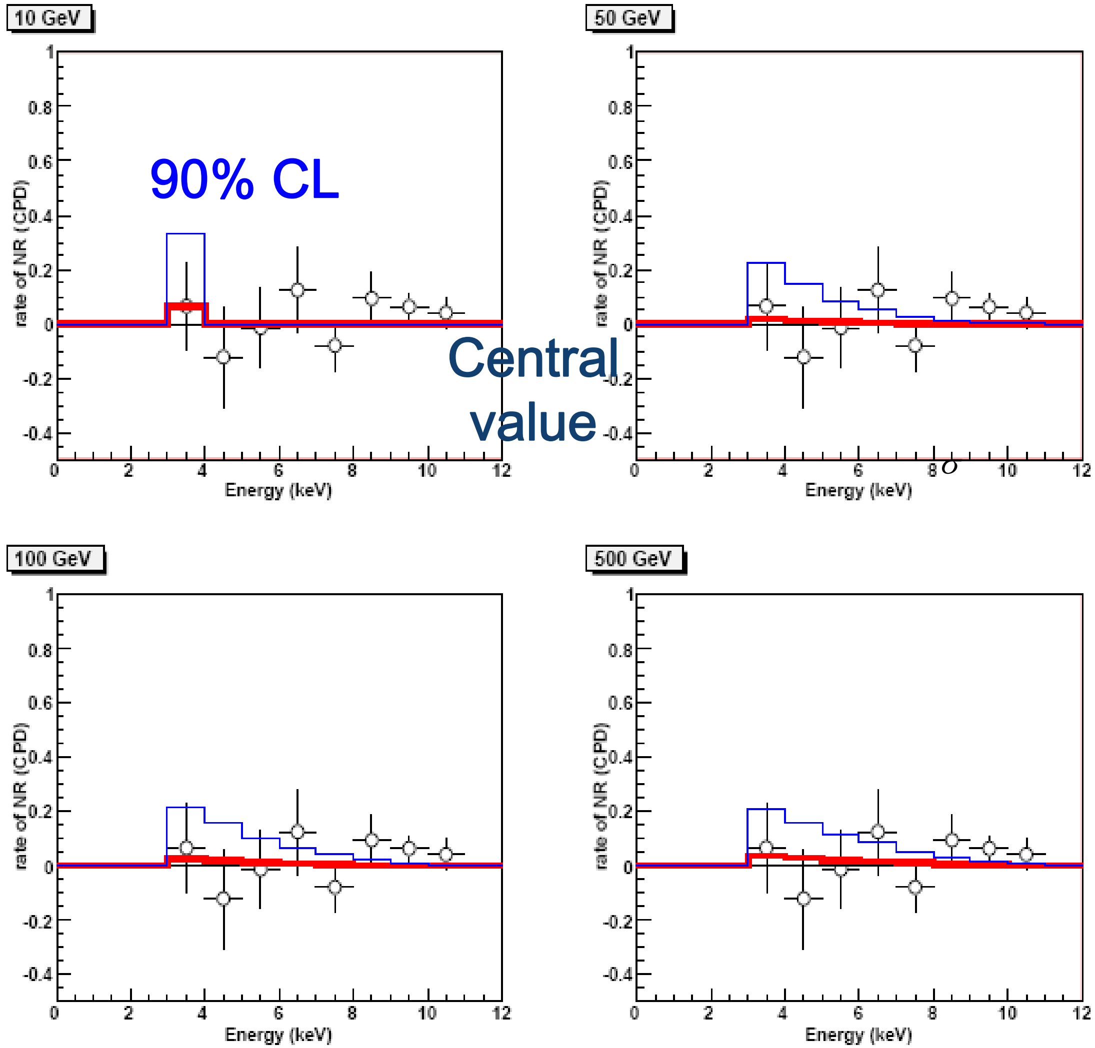


Efficiency



S0501A
S0501B
B0510A
B0510B
Efficiency
Measured Energy(keV)
Compton events
Neutron

Limit on WIMP-nucleus cross section



$$\sigma_{WA}$$

$$\sigma^{\rm SI}_{W-n} = \sigma_{W-A}\frac{\mu_n^2}{\mu_A^2}\frac{1}{A^2},$$

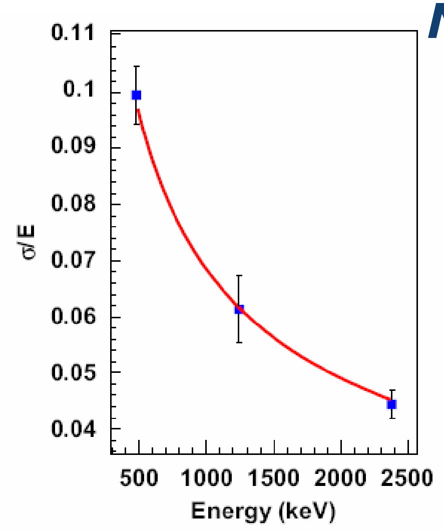
$$\sigma^{\rm SD}_{W-n,p} = \sigma_{W-A}\frac{\mu_{n,p}^2}{\mu_A^2}\frac{3}{4}\frac{J}{(J+1)}\frac{1}{\langle S_{n,p}\rangle^2}$$

Loading Sn (TMSn)

base scintillator:
PC+PPO(4g/l)+POPOP(30mg/l)

very stable over a year

NIMA 570, 454(2007)



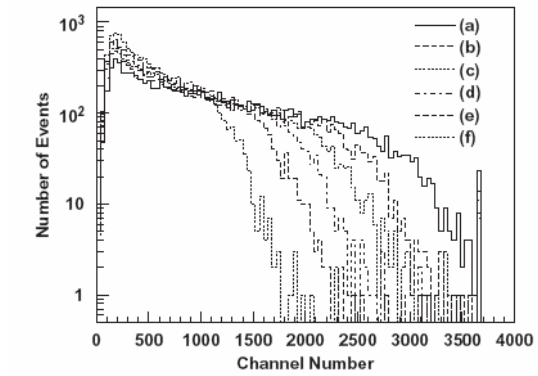
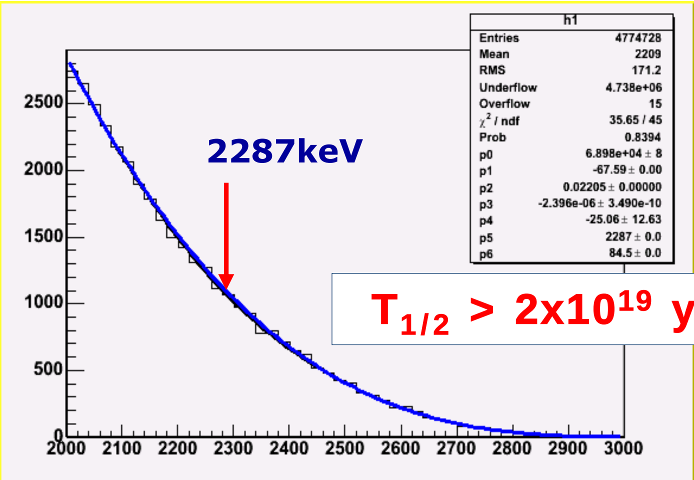


Fig. 1. The variation of light yield with TMSN concentration in a PC+PPO+POPOP. (a) PC+PPO+POPOP, (b) TMSN10%, (c) TMSN20%, (d) TMSN30%, (e) TMSN40% and (f) TMSN50%.

1.1 liter 30% Tin-loaded Liquid scintillator
$^{124}Sn \rightarrow {}^{124}Te$ + 2β-decay

TMSN loading



9 Months data

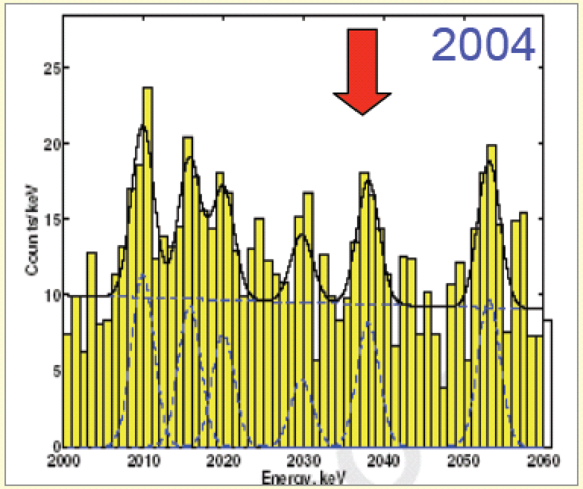
$T_{1/2}$ > 2×10^{19} yr at 90% C.L

paper in preparation

previous limit : $T_{1/2}$ < 2.4×10^{17} yr at 90% C.L

Status of DBD searches

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



71.7 kg•y 4 σ