Rare Event Searches at Deep Underground Laboratory

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Nobel Prize (2015)

- Neutrino oscillation

Photo © Takaaki Kajita

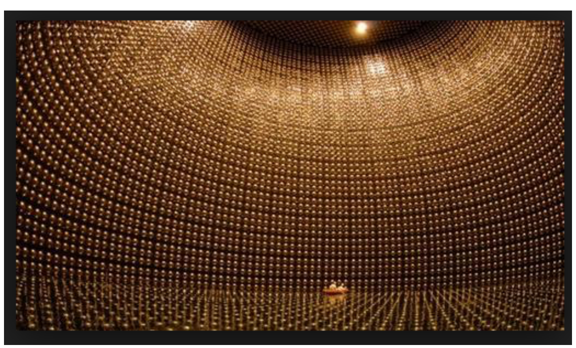
Takaaki Kajita

Prize share: 1/2

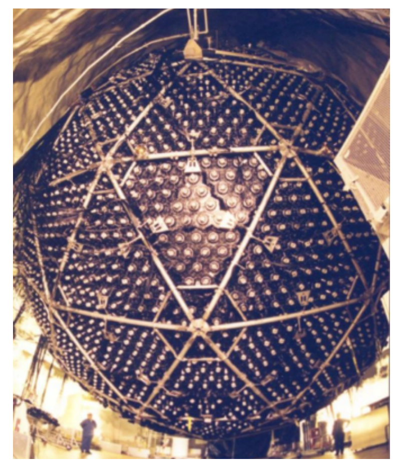
Photo: K. MacFarlane. Queen's University /SNOLAB

Arthur B. McDonald

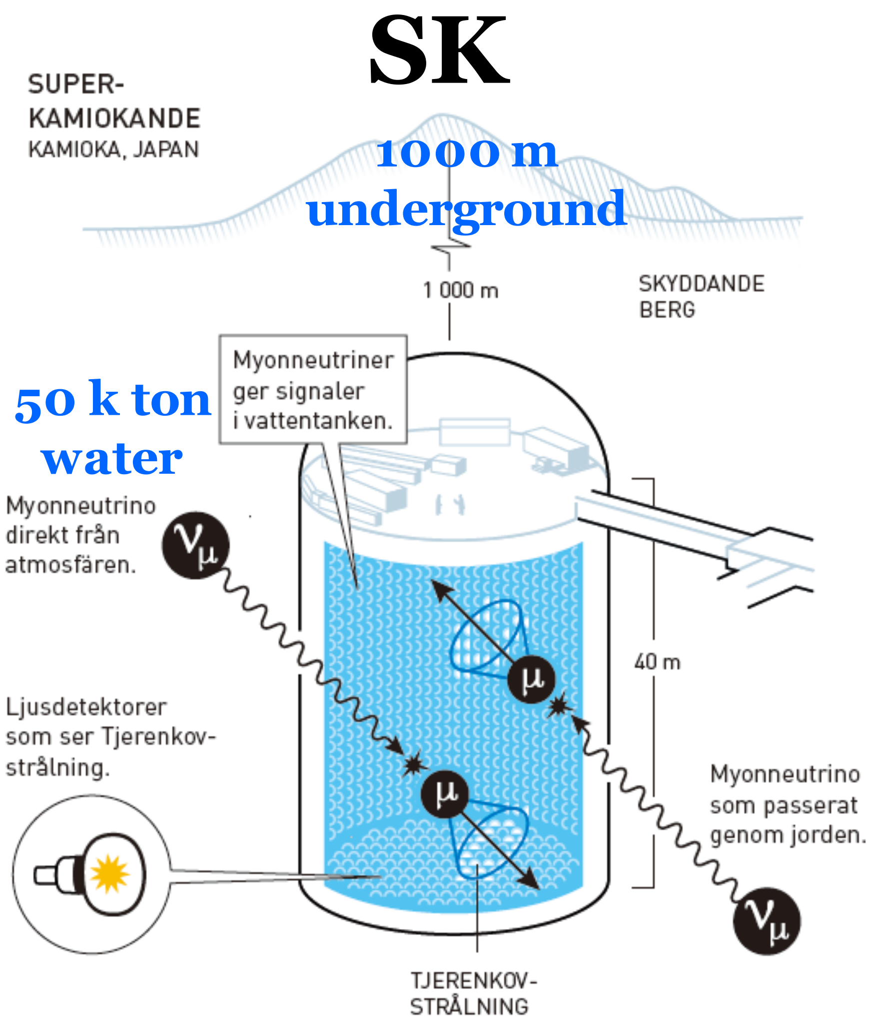
Super Kamiokande (SK)

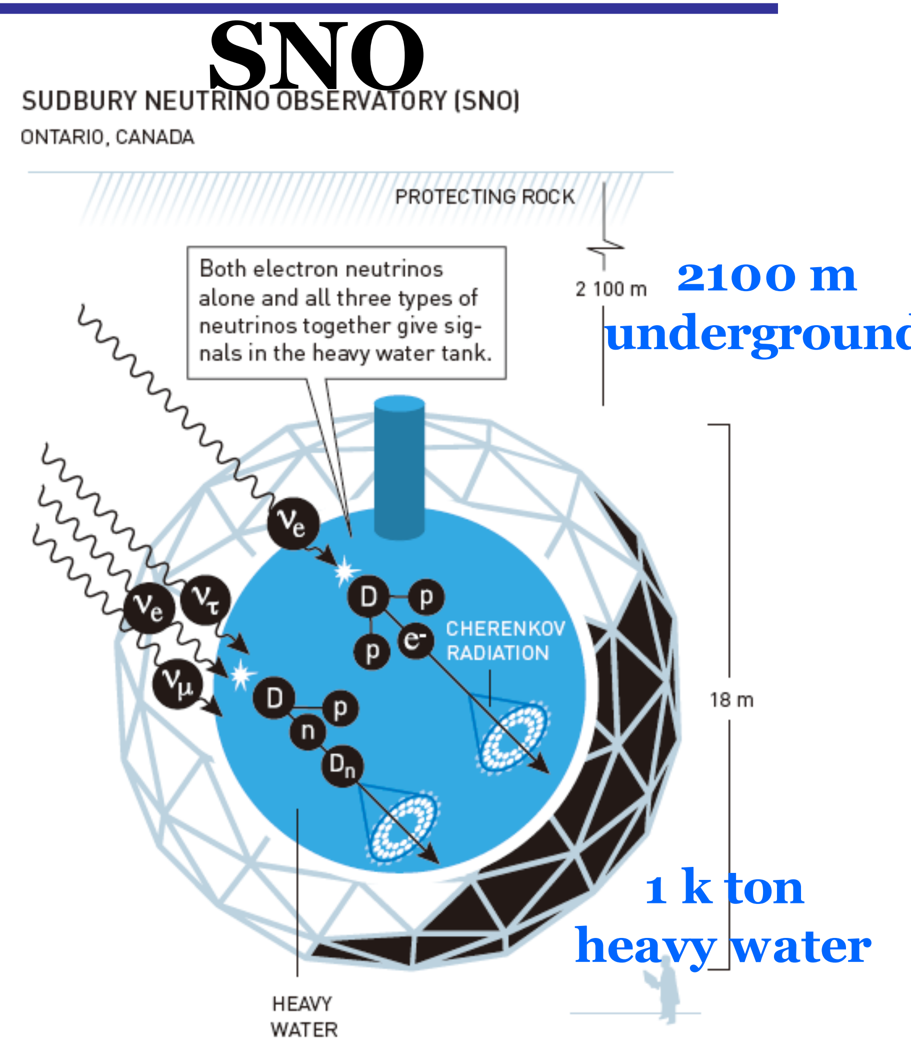


Sudbury Neutrino Observatory (SNO)



Nobel Prize (2015)



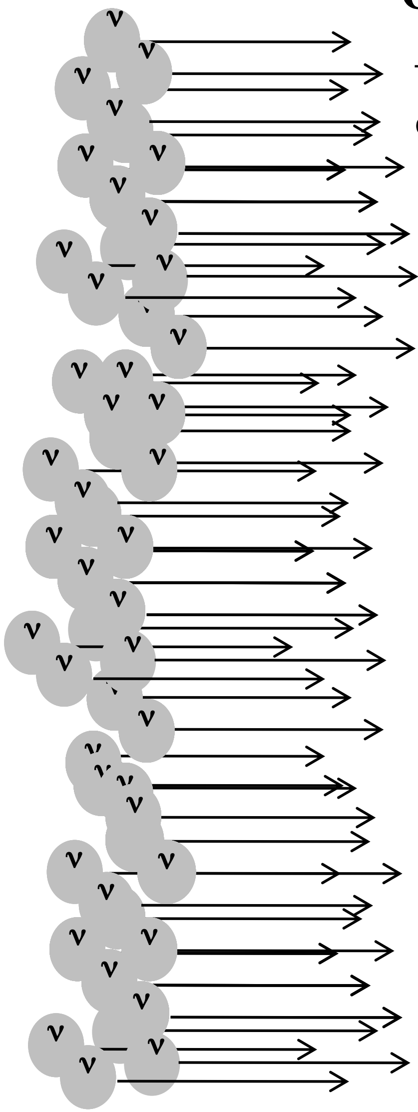


- SK and SNO are Deep Underground Laboratory

Solar neutrino

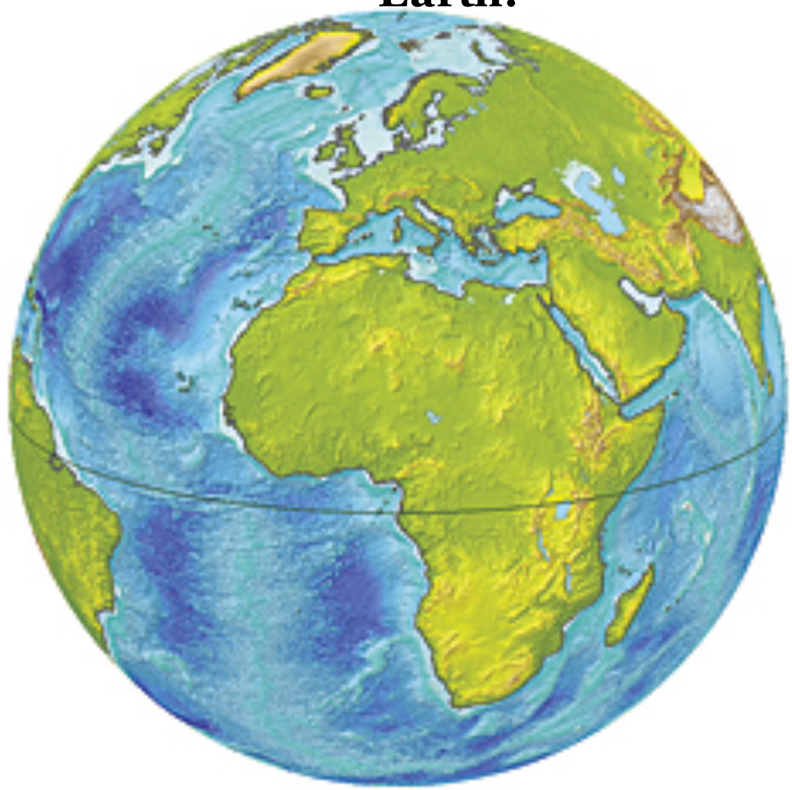
FACT: about 100,000,000,000 neutrinos pass through your thumbnail every second.

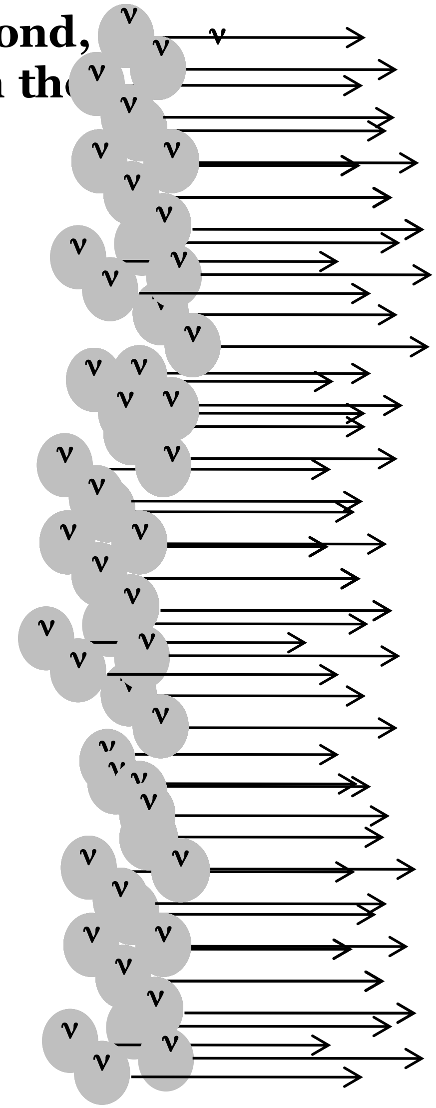
Solar neutrino



Of the 100,000,000,000 neutrinos that went

through your thumb during the last second, only 1 didn't make it all the way through the Earth!





Solar neutrino

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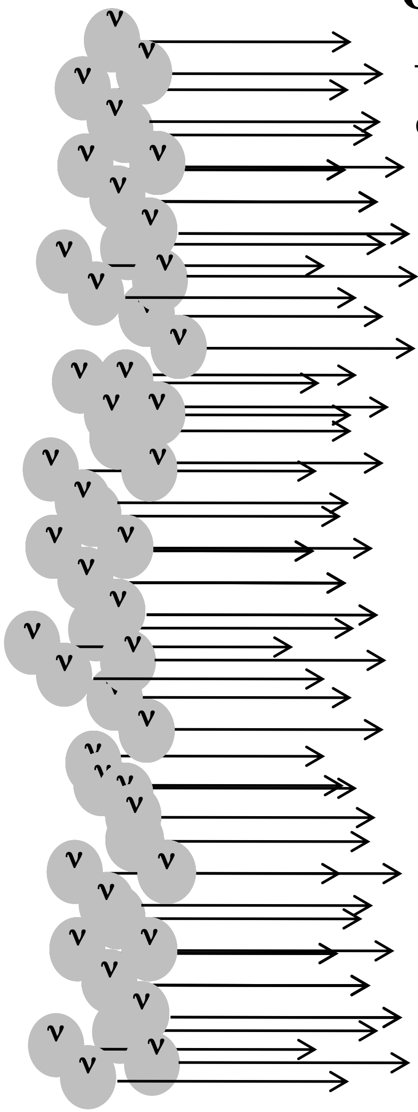
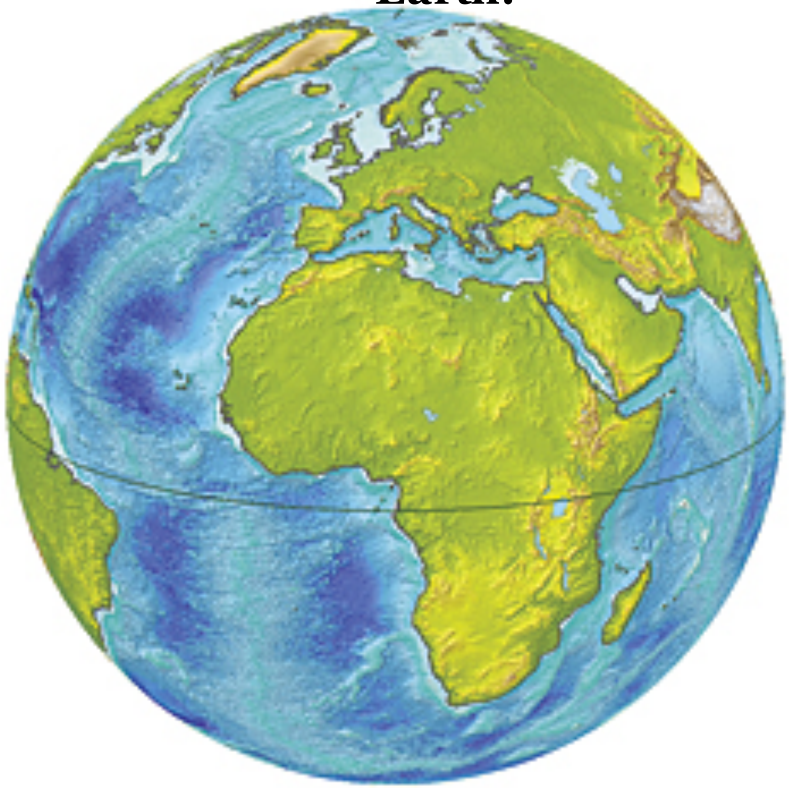
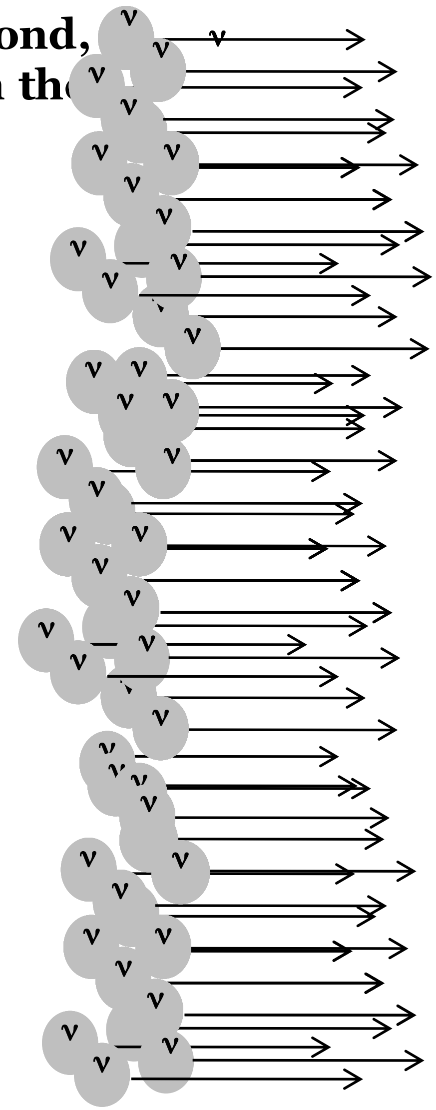






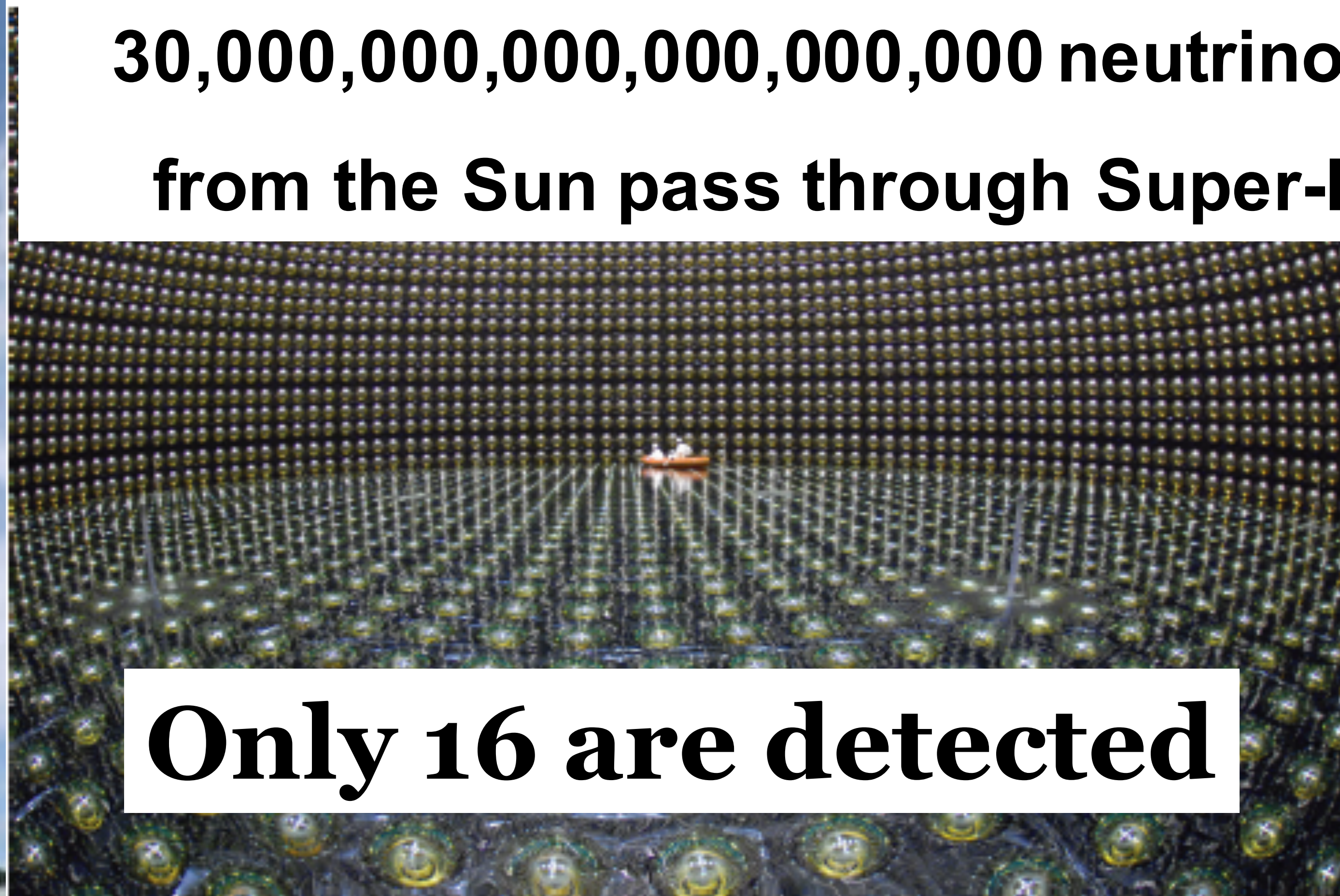
Cross-section of neutrino ~ 10^{-38} cm²

SK neutrino detector

In 1 day:

30,000,000,000,000,000,000 neutrinos

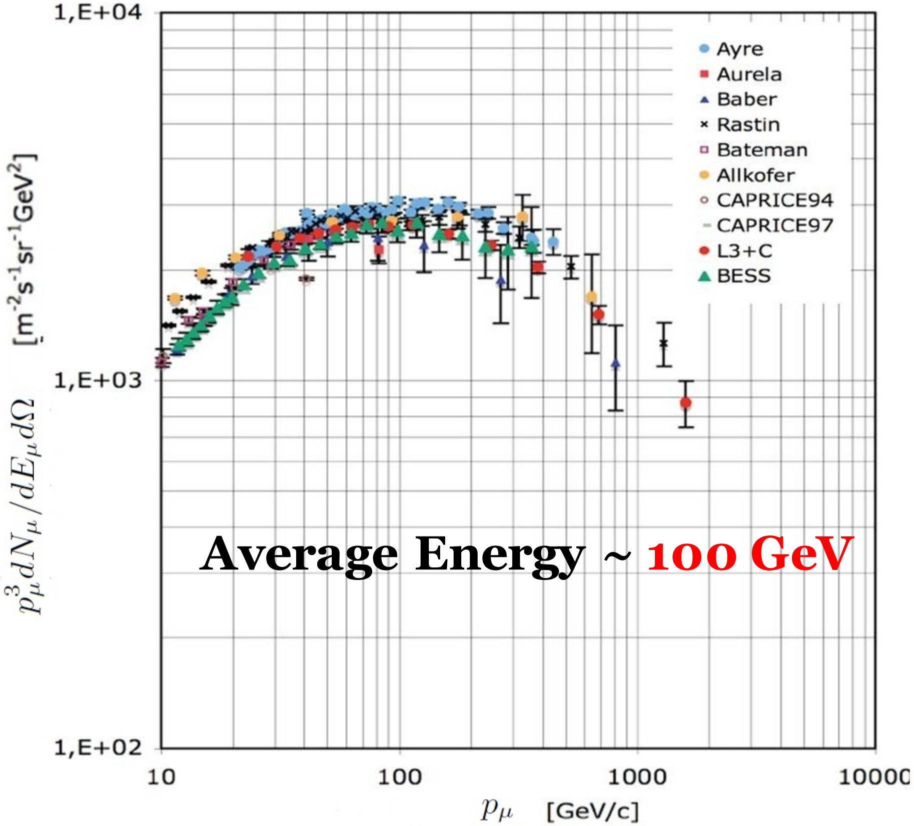
from the Sun pass through Super-K

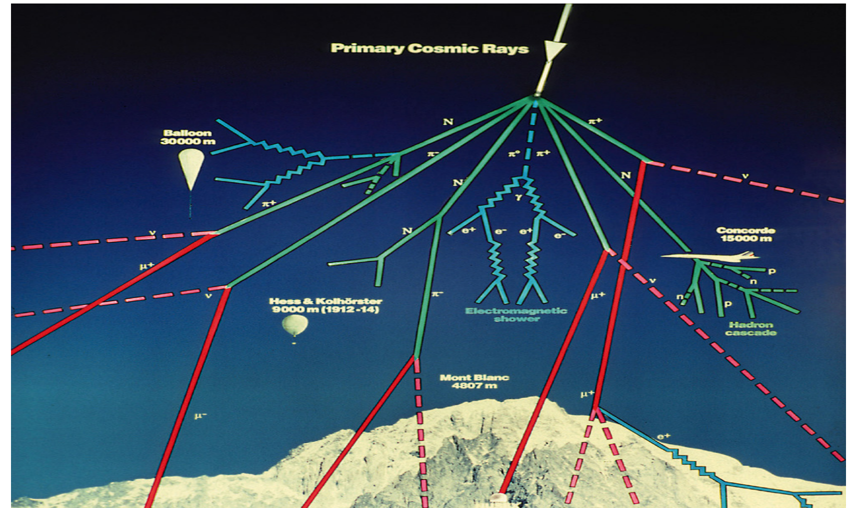


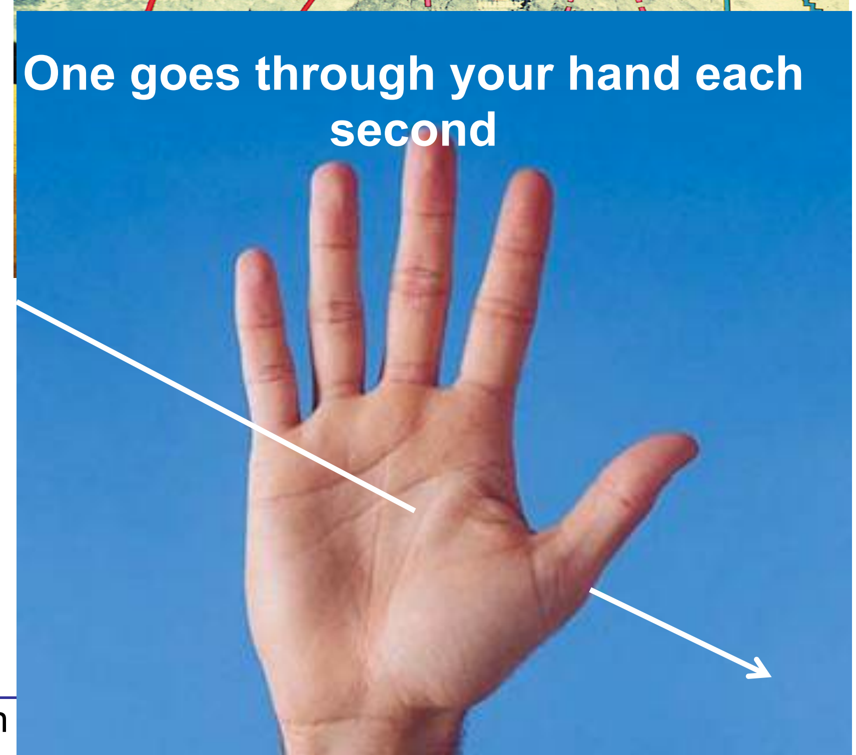
Only 16 are detected

Cosmic Muon background

Muon flux @ Sea level







- ~ 1 muon/hand/s (All give signal!!)
- ~100,000 events/hands/day

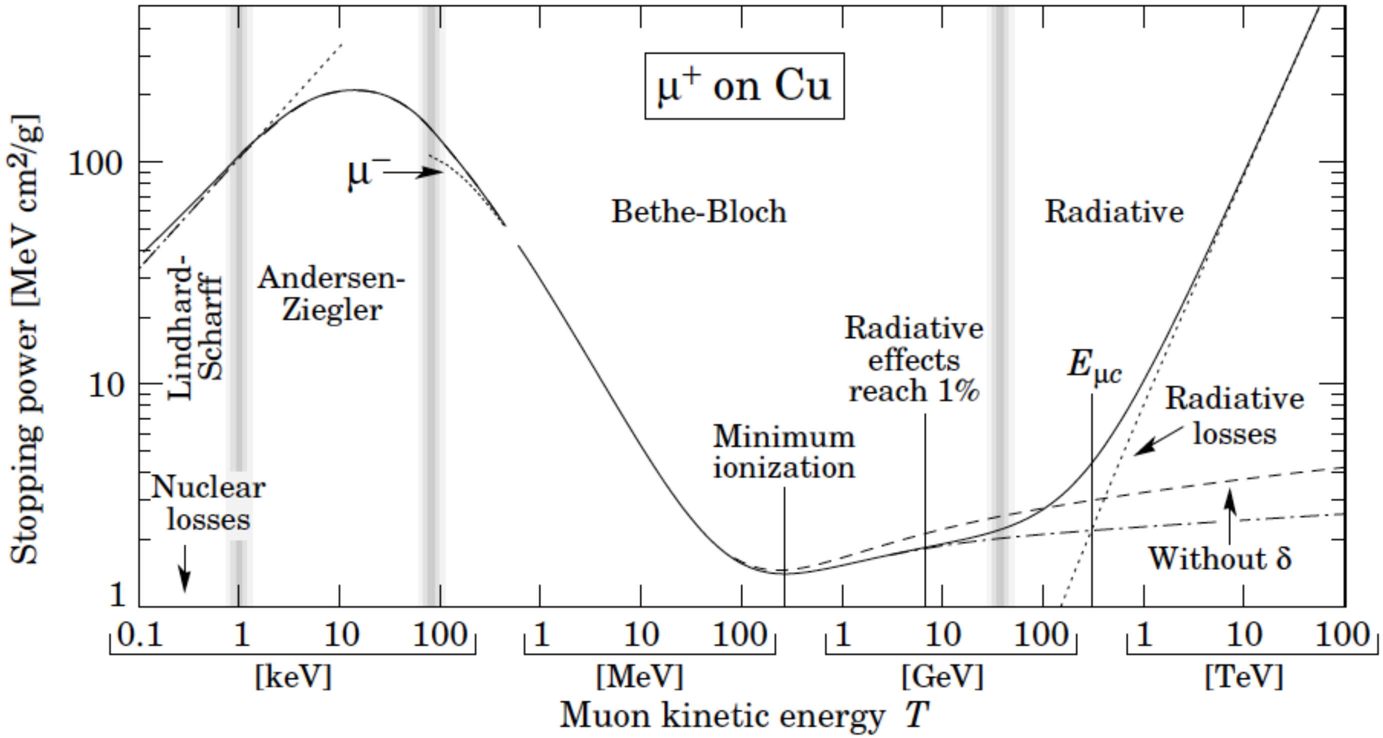
Why deep underground laboratory?

- Find a needle in a haystack

Dealing with 10 signals from 10,000,000 muon backgrounds

Can we stop muon?

- 100 GeV muon lose energy via ionization
  - ❖ ~ 2 MeV cm²/g – For lead, it is about 20 MeV/cm



- To stop 100 GeV muon, we need about 50m thick lead
  - ❖ Oops it too thick and too expensive
    - ❑ roughly 250,000,000,000 Won for 1m²

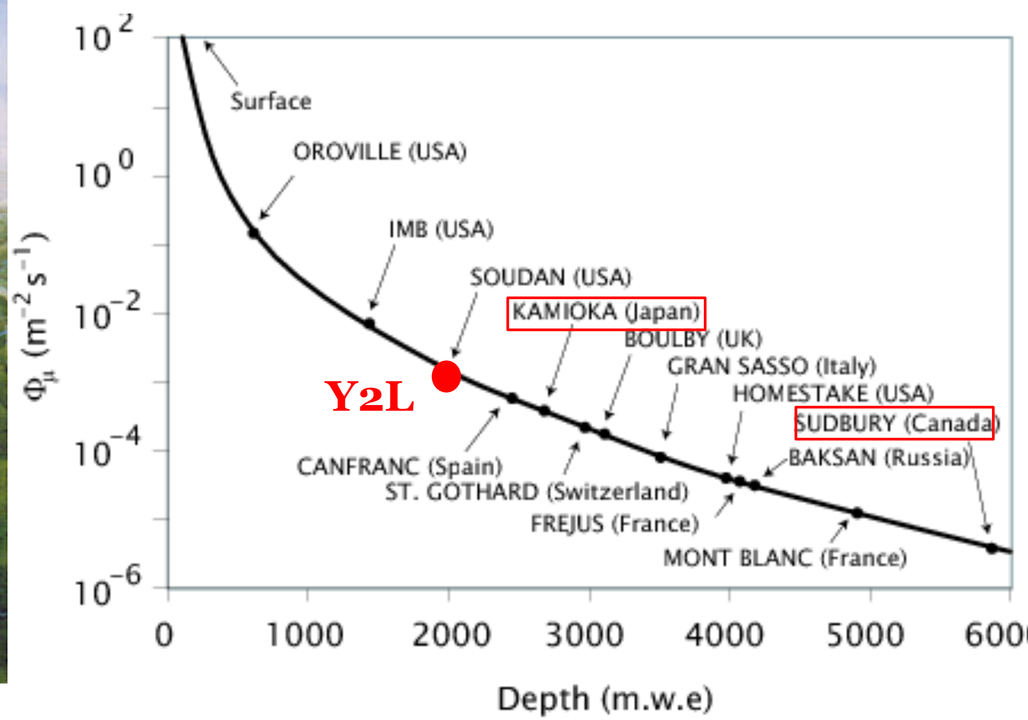
Can we stop muon?

- To stop 100 GeV muon, we need about 50 m lead
- However, **200 m rock is** corresponding to **50 m lead**

Go to underground

Can we stop muon?

- Deep underground laboratory

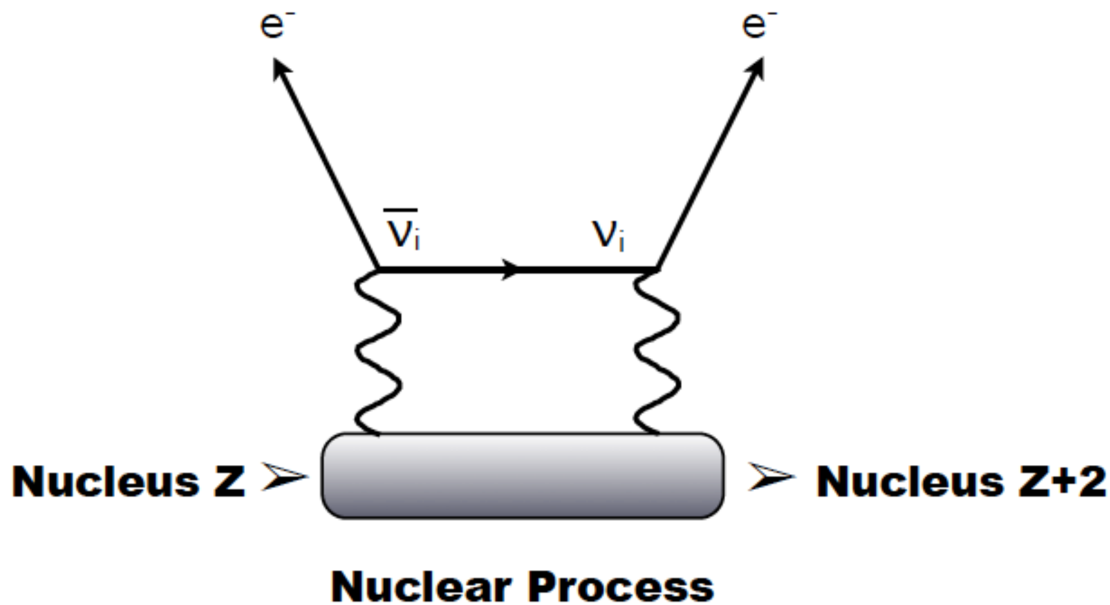


- Muon flux can be significantly reduced

What physics can we perform at underground?

- Any particle which has very low cross-section
  - ❖ Rare event searches
- Neutrino
  - ❖ Oscillation (Long baseline neutrino experiment)
  - ❖ Neutrinoless double beta decay
- Weakly Interacting Massive Particle (WIMP)
  - ❖ Stringent candidate of dark matter
  - ❖ Cross section is even lower than neutrino

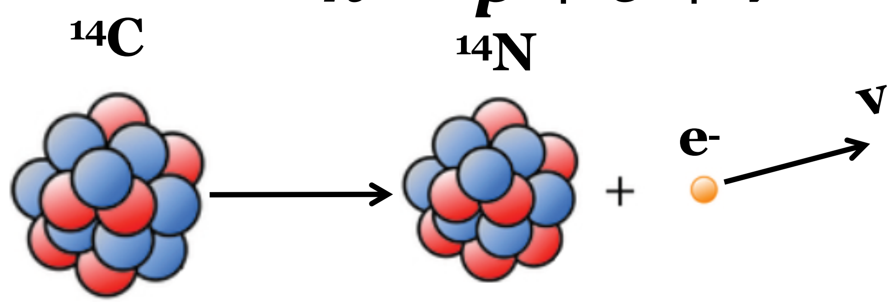
Neutrinoless double beta decay

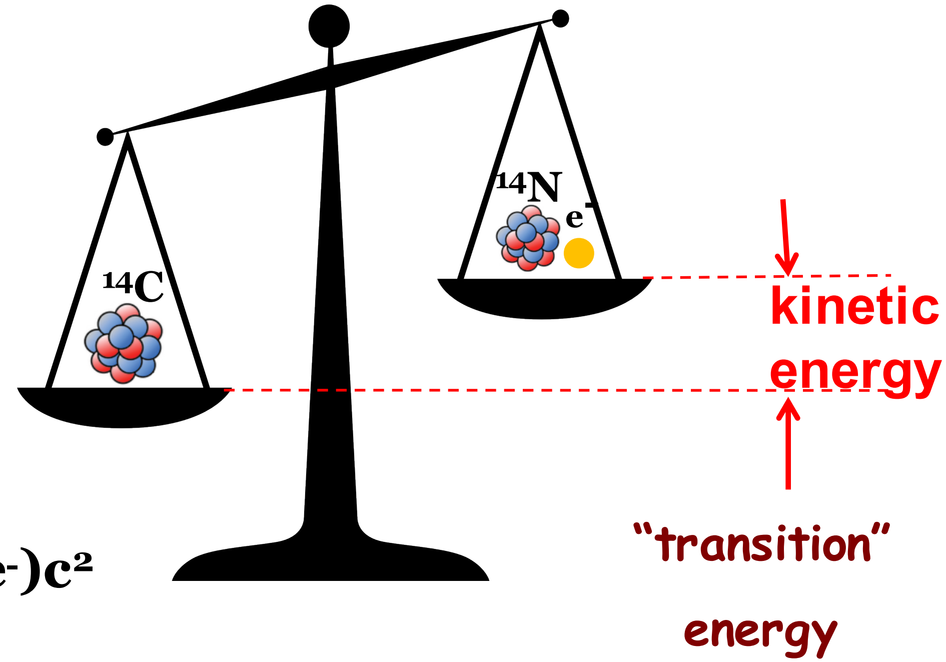


Majorana neutrino ?
Absolute mass of neutrino ?

Beta decay

$$n \rightarrow p + e + \nu$$



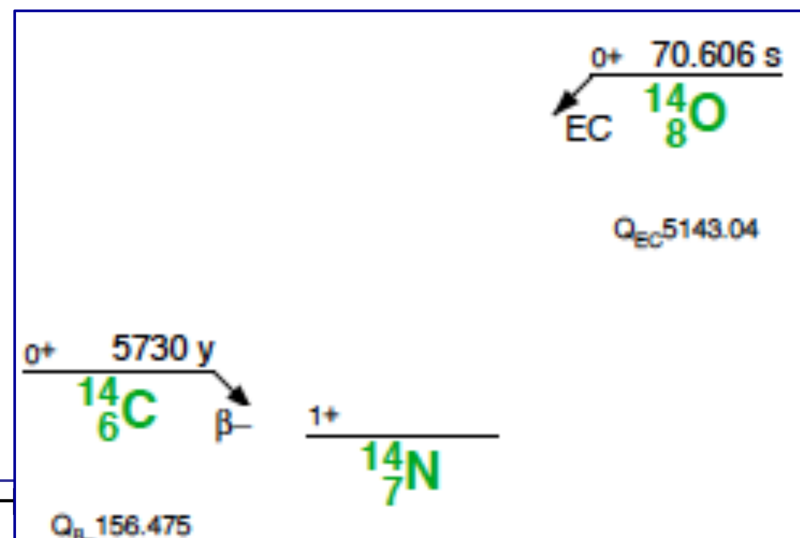


Initial Energy = final energy

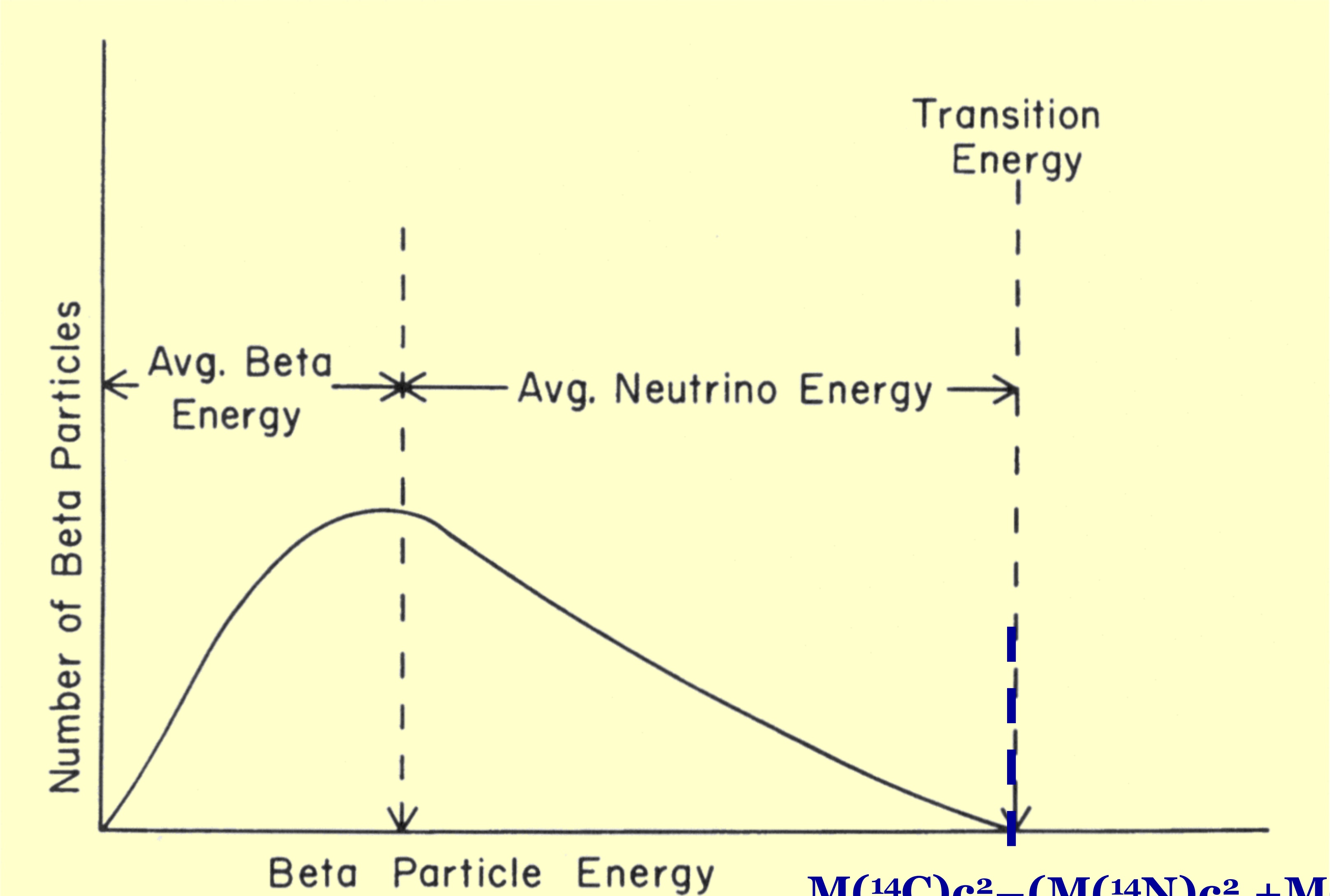
M(^{14}C)c² = M(^{14}N)c² + M(e$^-$)c²

+ kinetic energy

Energy (mass) of ^{14}N is lower than ^{14}C. This bring beta decay of ^{14}C



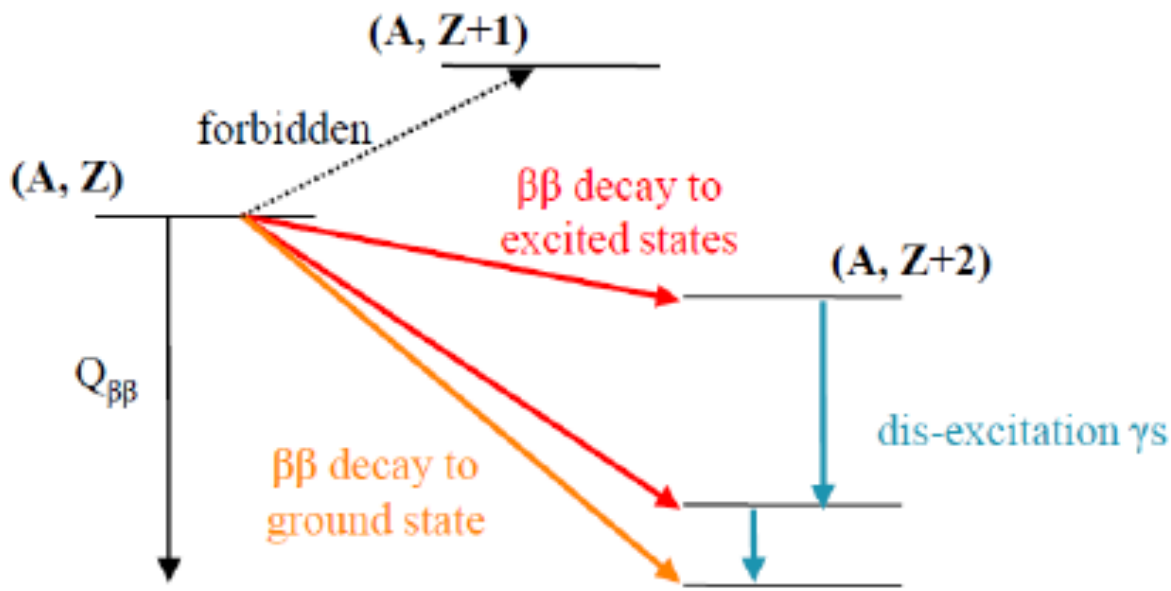
Energy of emitted beta (electron)



$M(^{14}C)c^2 - (M(^{14}N)c^2 + M(e^-)c^2)$

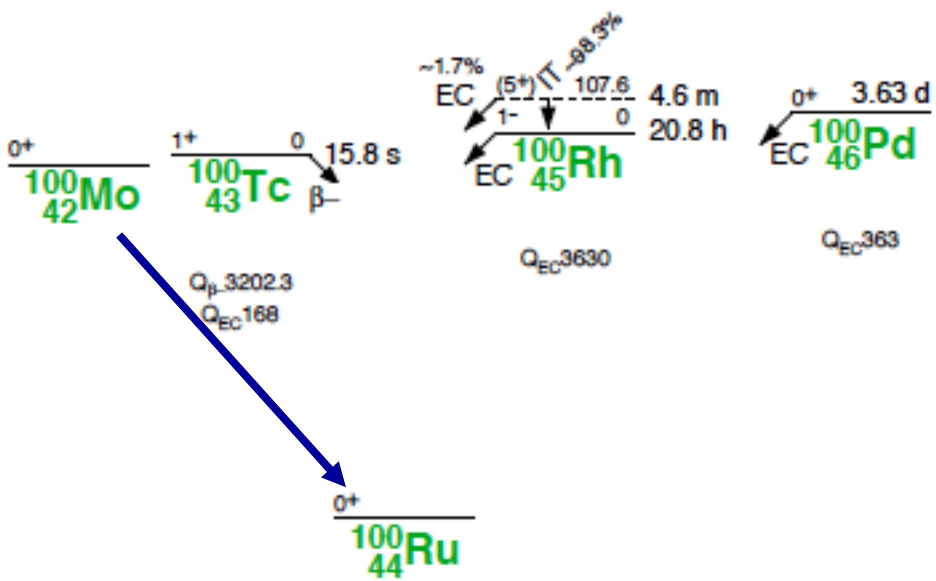
Double beta decay

- If direct beta decay is forbidden, double beta decay is possible

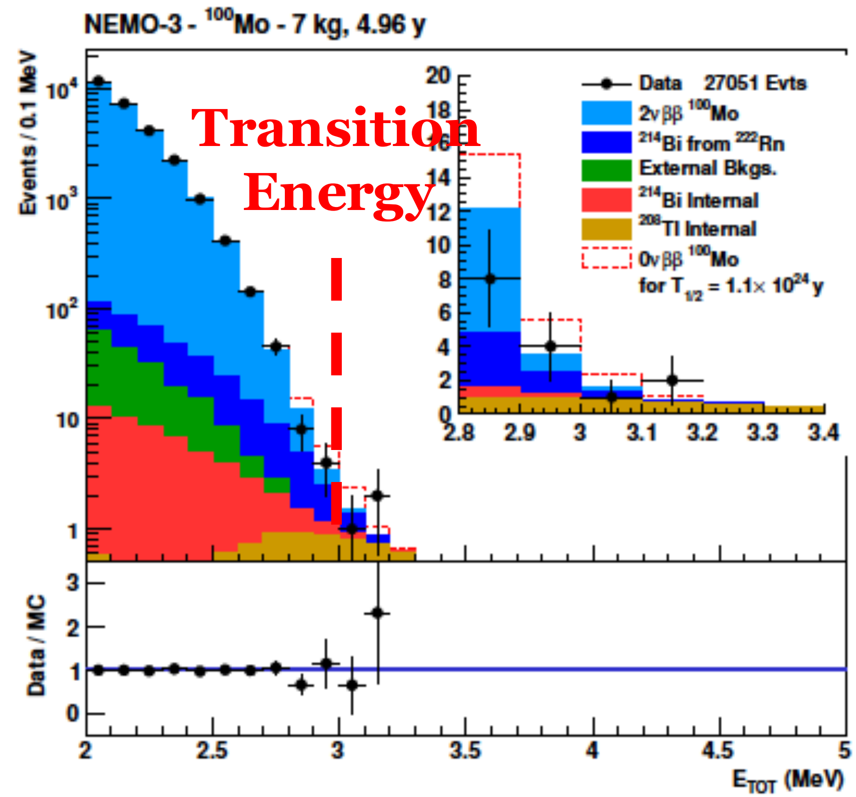


$$2n \rightarrow 2p + 2e + 2\bar{\nu}$$

Double beta decay of ^{100}Mo



PRD 89, 111101 (2014)

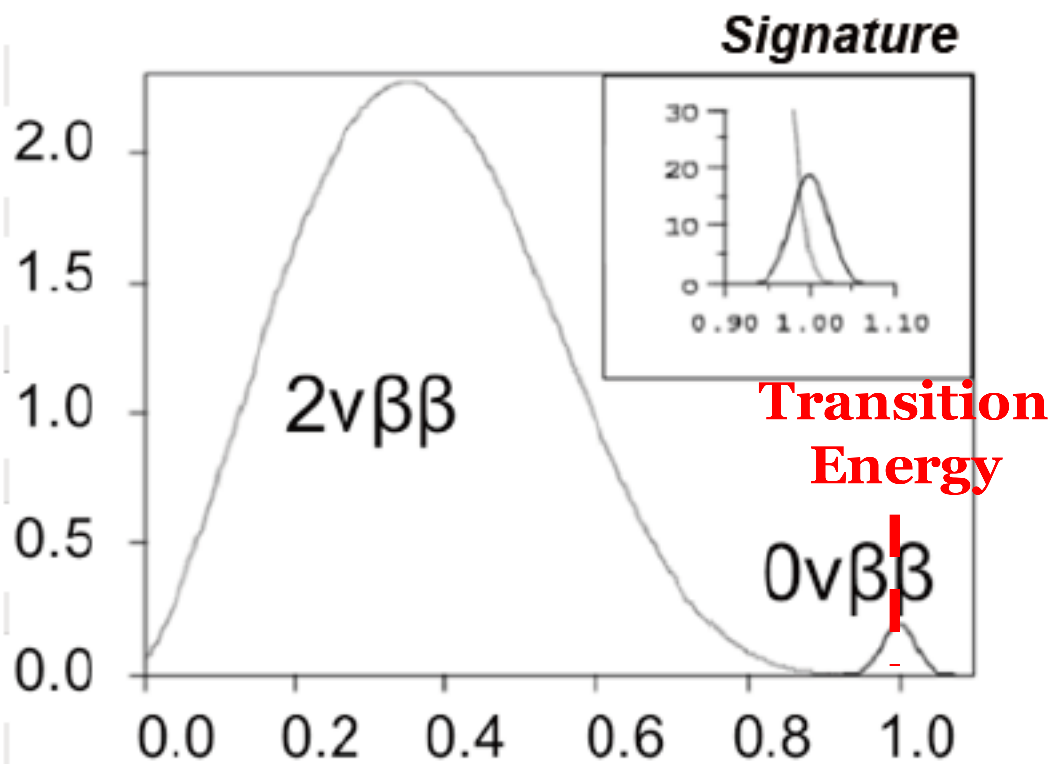


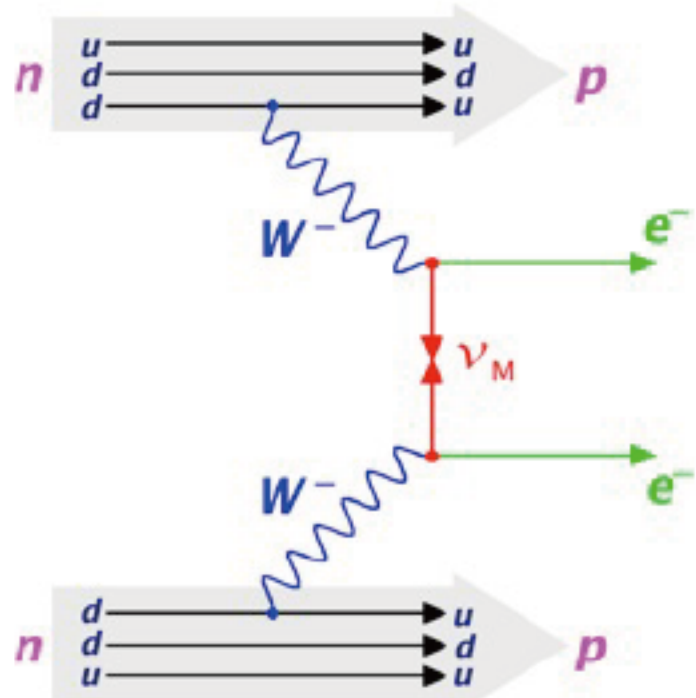
$$T_{1/2} = 6.9 \times 10^{18} \text{ years}$$

Neutrinoless double beta decay-Majorana neutrino?

- If neutrino is majorana particle, neutrino is same as anti-neutrino

$$2n \rightarrow 2p + 2e$$

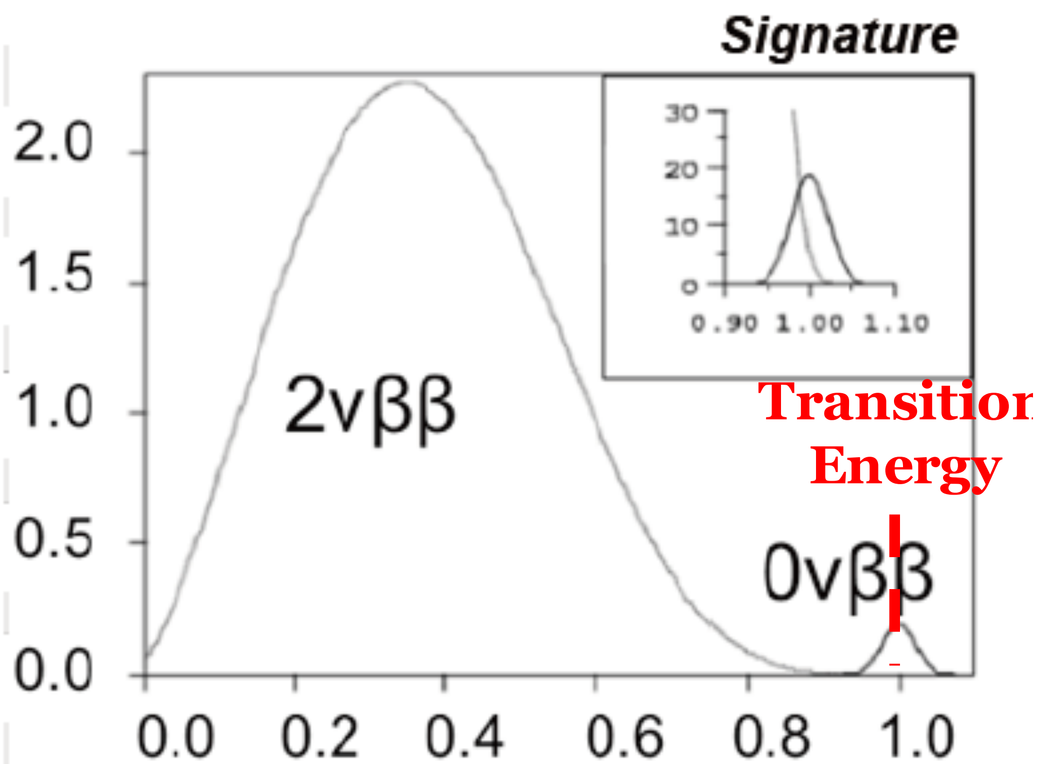


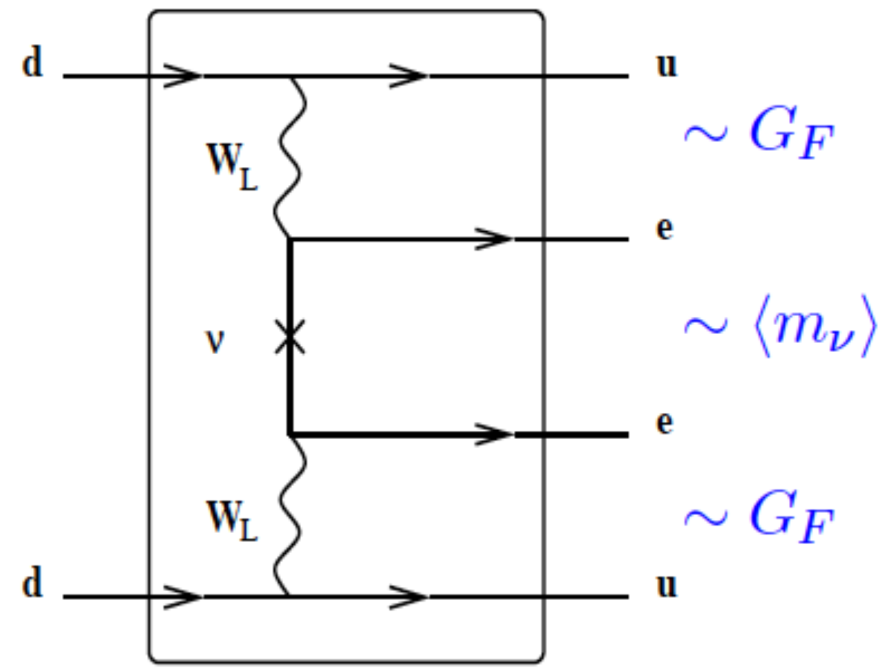


Neutrinoless double beta decay-neutrino mass

- If neutrino is majorana particle, neutrino is same as anti-neutrino

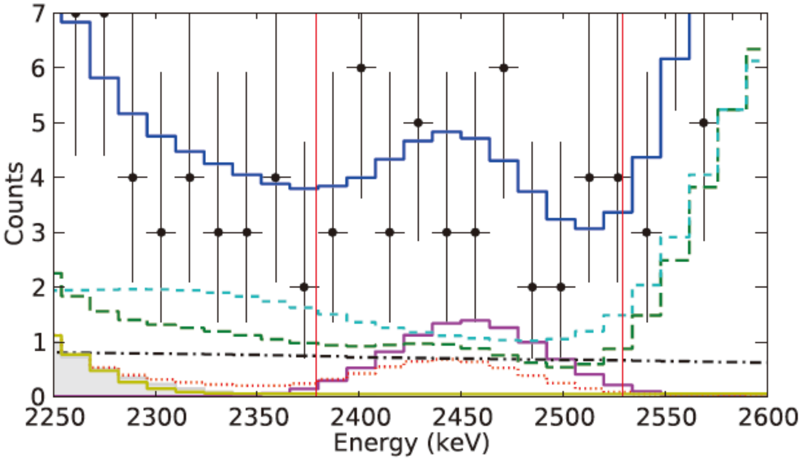
$$2n \rightarrow 2p + 2e$$





So far..

EXO



From profile likelihood:

$T_{1/2}^{0\nu\beta\beta} > 1.1 \cdot 10^{25}$ yr

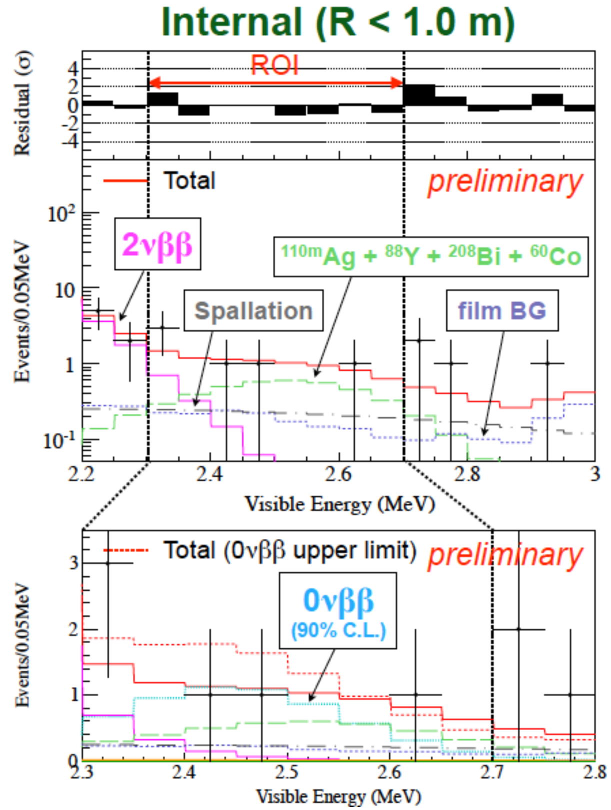
$\langle m_{\beta\beta} \rangle < 190 - 450$ meV

(90% C.L.)

Nature **(2014)**

doi:10.1038/nature13432

KamLAND-Zen

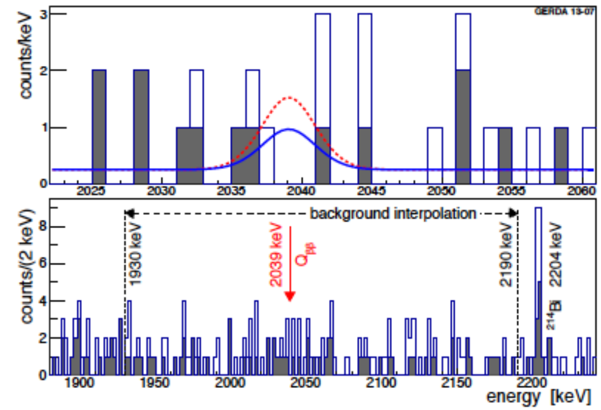


< 17.0 events/day/kton-LS

↓

$T^{0\nu}_{1/2} > 1.3 \times 10^{25}$ yr

GERDA

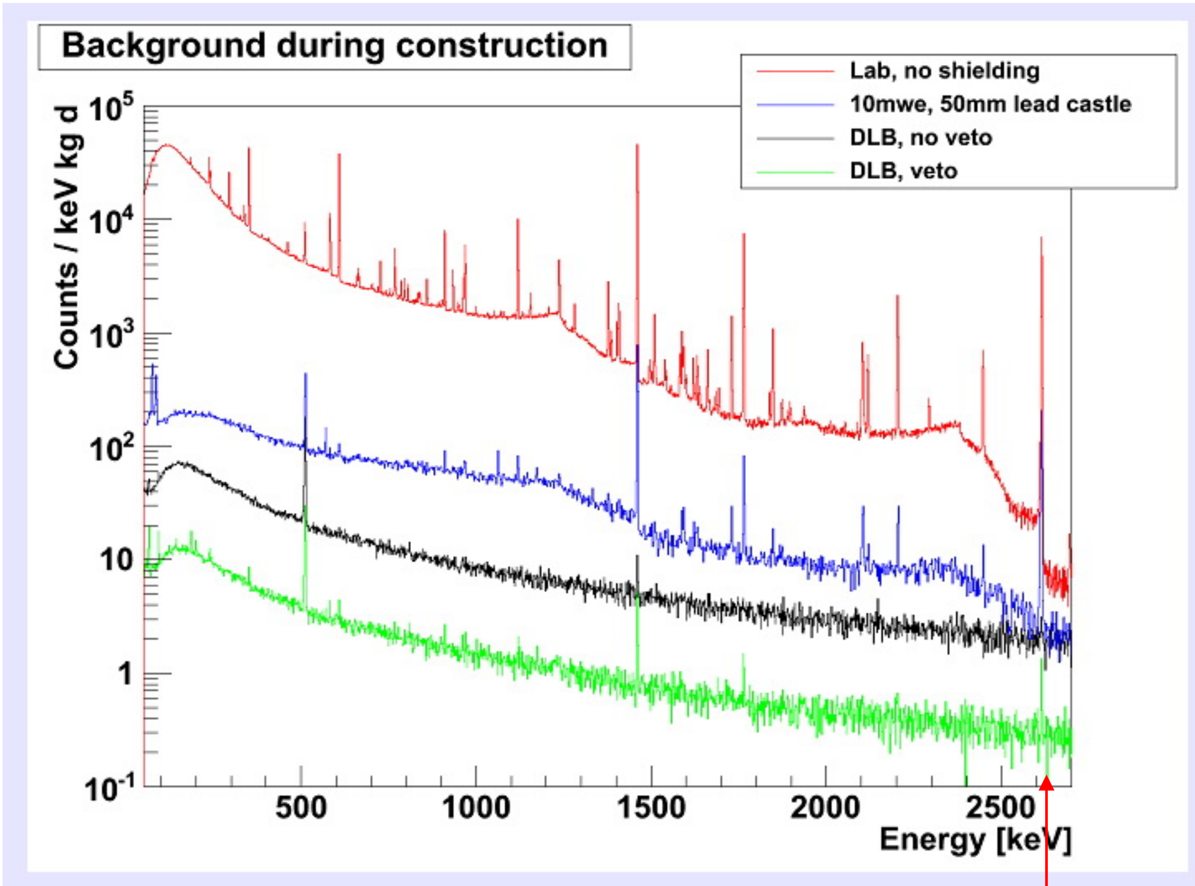


$T^{0\nu}_{1/2} > 2.1 \cdot 10^{25}$ yr

$0\nu\beta\beta$ is not yet observed!!

What's the issue on 0νββ experiment

- Background, Background, Background ..



^{208}Ti ~ 2.6 MeV

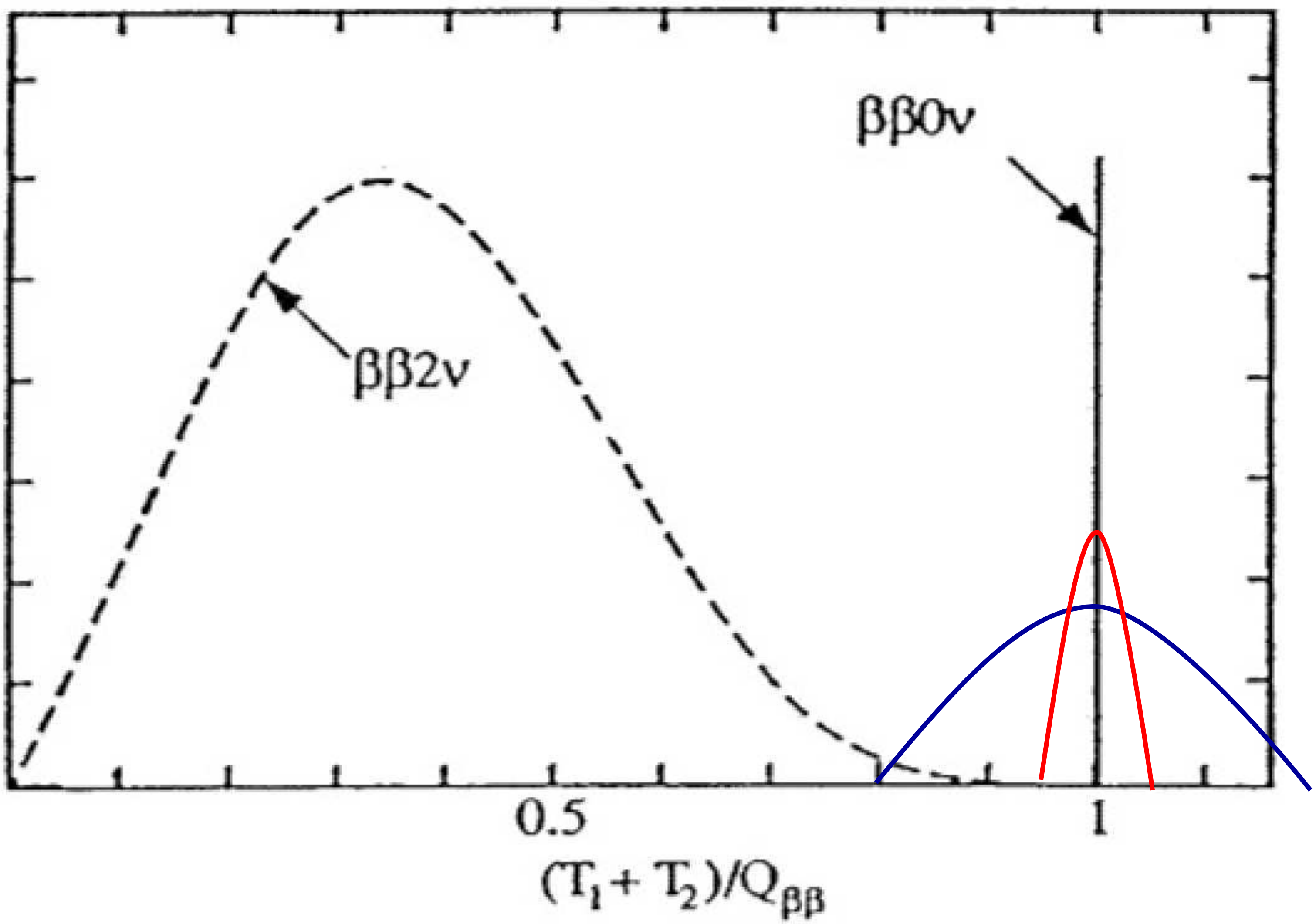
Q value (transition energy) is very important

Q-values of double beta decay element

isotope	$Q_{\beta\beta}$ (keV)	$G^{0\nu}$ ($10^{-15}yr^{-1}$)	nat. abundance (%)	prod. 2013 (tons)	experiment / R&D	FWHM/E at $Q_{\beta\beta}$ (%)
^{48}Ca	4273.7	24.81	0.187	–	CANDLES^{t}	–
^{76}Ge	2039.1	2.36	7.8	155	GERDA^{o}	0.1-0.3
					Majorana Dem.^{p}	0.1
^{82}Se	2995.5	10.16	9.2	$>2.3\times10^{3}$	SuperNEMO ^{p*}	4
					LUCIFER ^{t}	0.3
^{100}Mo	3035.0	15.92	9.6	2.7×10^{5}	MOON^{t*}	–
					AMoRE^{t}	–
^{116}Cd	2809.1	16.70	7.6	2.2×10^{4}	COBRA^{t*}	–
^{130}Te	2530.3	14.22	34.5	>95	CUORE $^{o/p}$	0.2
					SNO+ ^{p}	~10
^{136}Xe	2457.8	14.58	8.9	3-4	EXO^{o}	4
					KamLAND-Zen^{o}	10
					NEXT^{p}	0.6
^{150}Nd	3367.3	63.03	5.6	$\sim1.7\times10^{4}$	DCBA^{t*}	–

Energy resolution

- Excellent energy resolution is mandatory

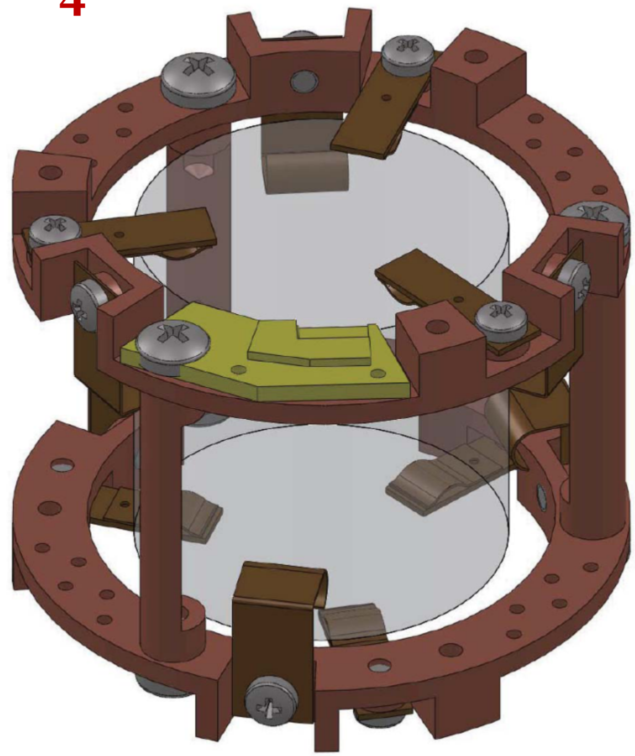


AMoRE experiment

(Advanced Mo-based Rare process Experiment)

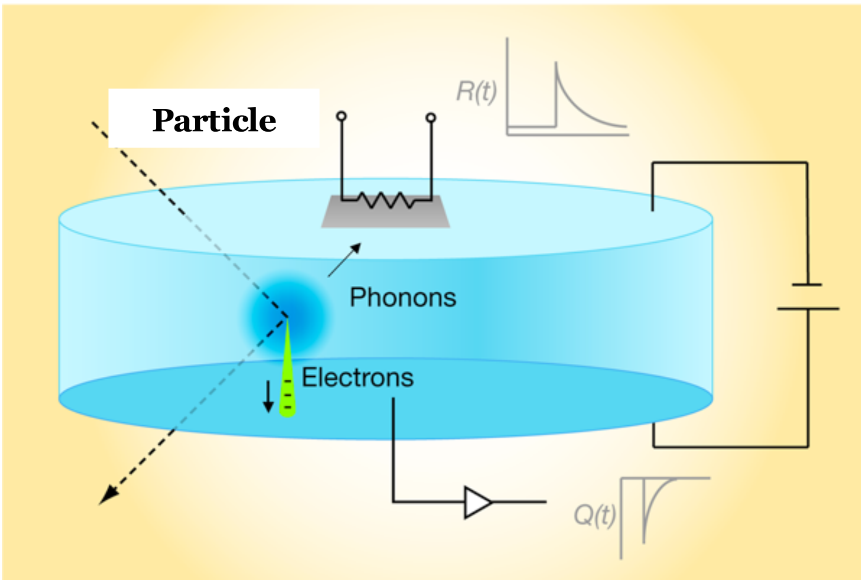
to search for neutrinoless double decay of ^{100}Mo

using cryogenic $CaMoO_4$ detectors



Ø4cmx4cm
$CaMoO_4$ crystal

Cryogenic detector technology



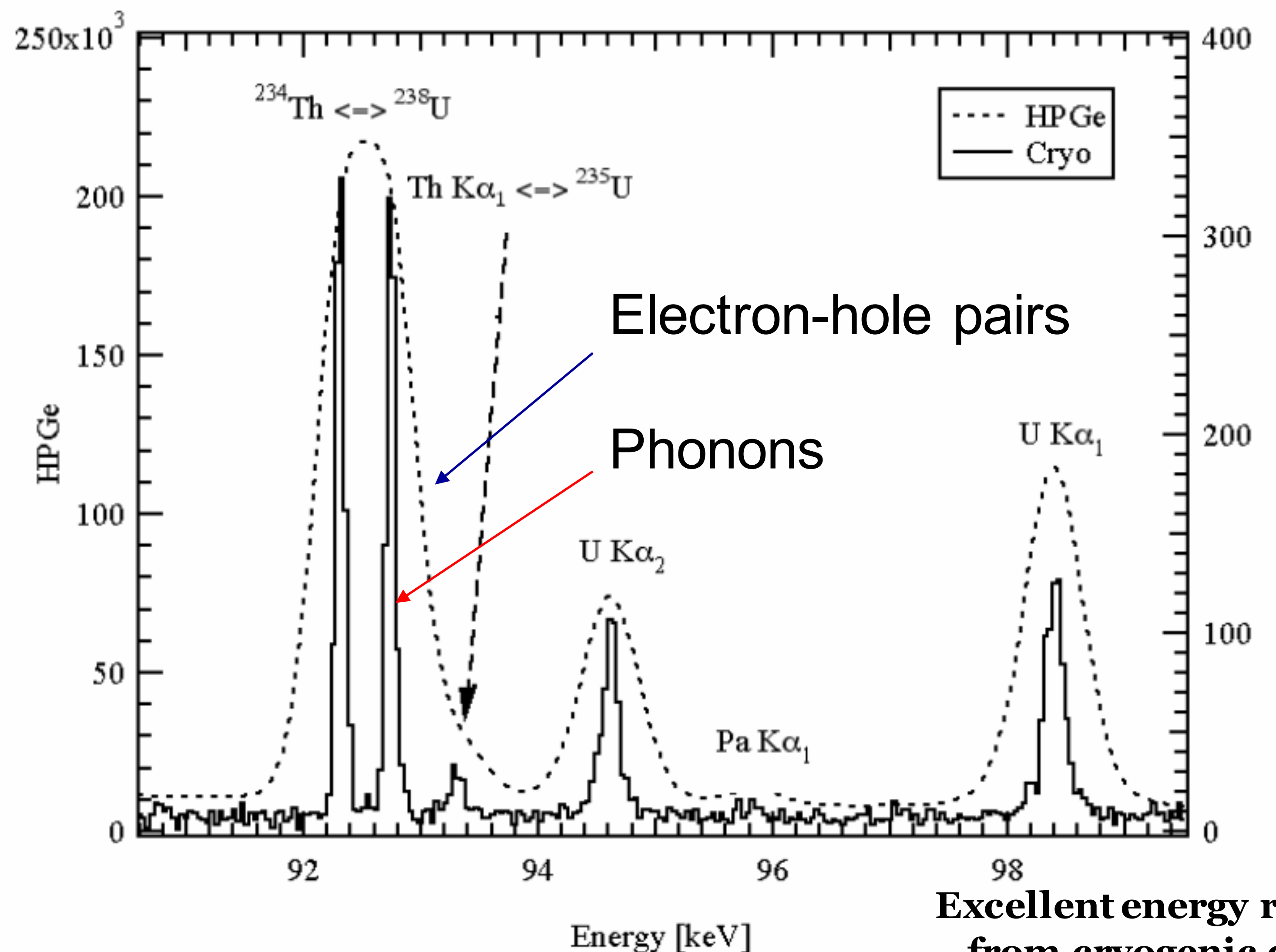
Particle interaction bring electron-hole pairs and phonons

To make 1 e–h pair, we need 3.6 eV but, for 1 phonon it is ~meV

Statistically much more phonon

To avoid thermal noise, this should be almost zero K

Cryogenic detector technology



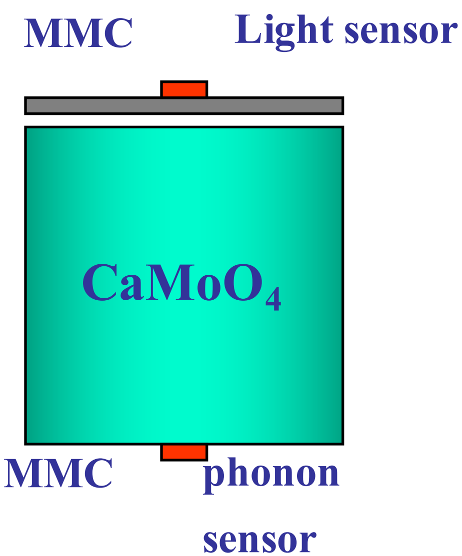
Excellent energy resolution from cryogenic detector

AMoRE detector technology

$^{40}Ca^{100}MoO_4$ + MMC

Low Temp. Detector

Source = Detector



<10-50 mK>

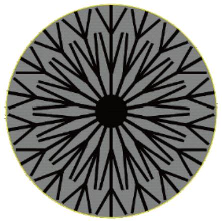
$CaMoO_4$

- Scintillating crystal
- High Debye temperature: $T_D = 438$ K, $C \sim (T/T_D)^3$
- ^{48}Ca, ^{100}Mo $0\nu\beta\beta$ candidates
- AMoRE uses $^{40}Ca^{100}MoO_4$ w. enriched ^{100}Mo and depleted ^{48}Ca

MMC (Metallic Magnetic Calorimeter)

- Magnetic temperature sensor (Au:Er) + SQUID
- Sensitive low temperature detector with highest resolution
- Wide operating temperature
- Relatively fast signals
- Adjustable parameters in design and operation stages

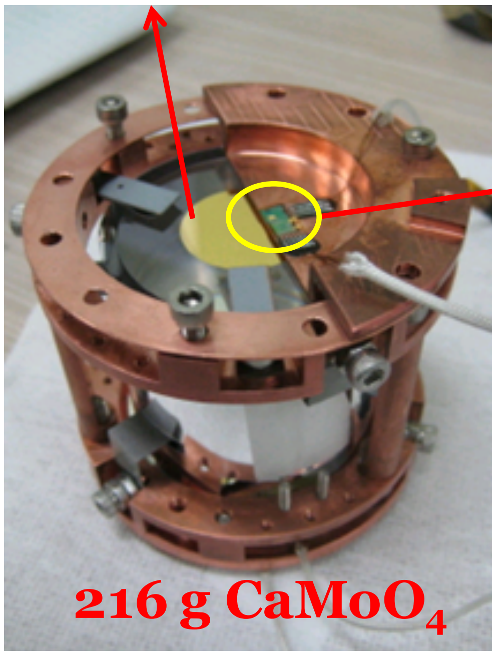
Phonon sensor for AMoRE

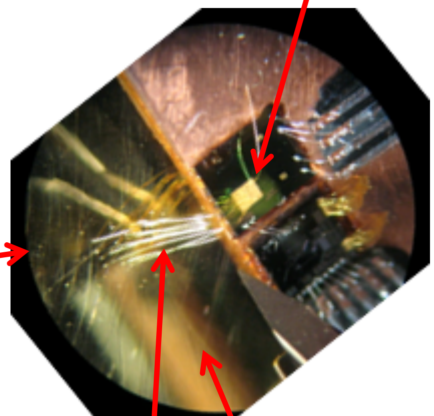


Phonon collector

Patterned gold film

MMC



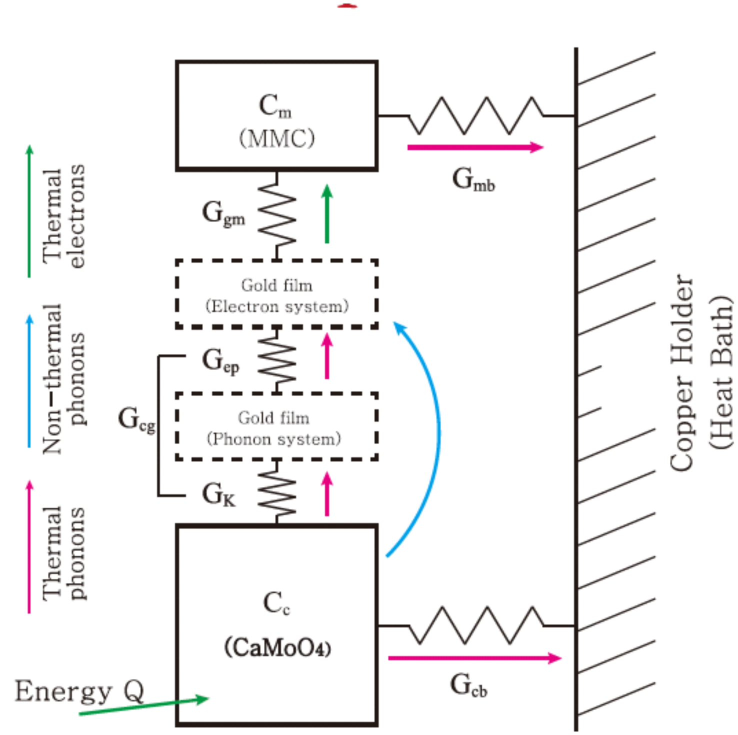


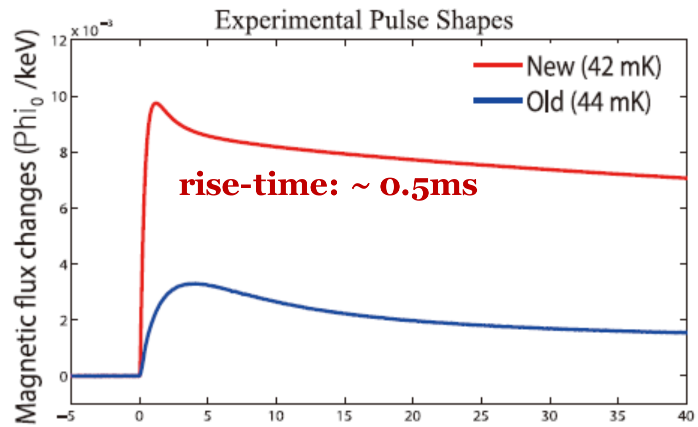
Gold film

Gold wires

(thermal connection)

We measure both thermal and athermal phonons.

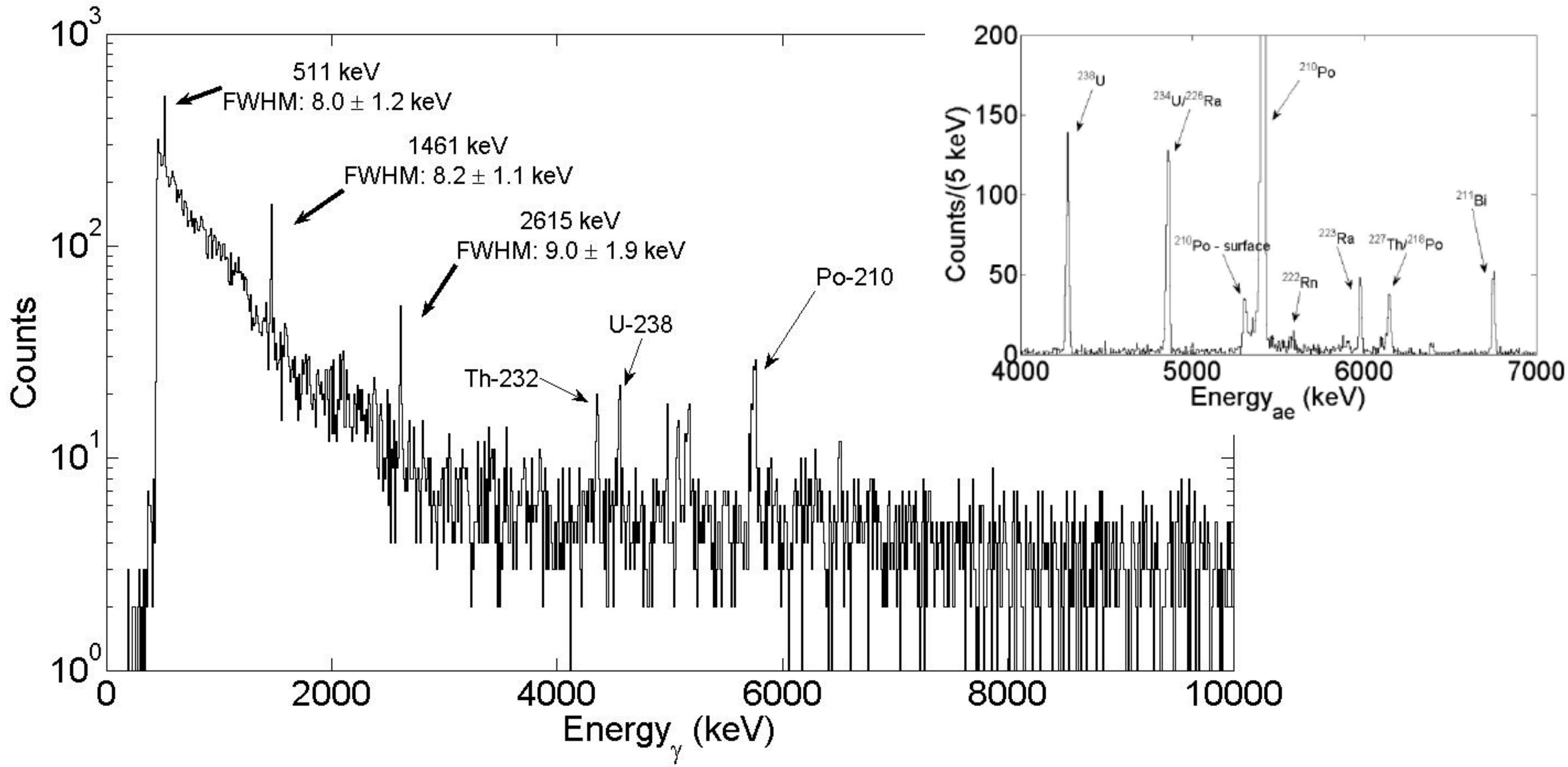




<Heat flow optimization>

Detector R&D in an over-ground laboratory

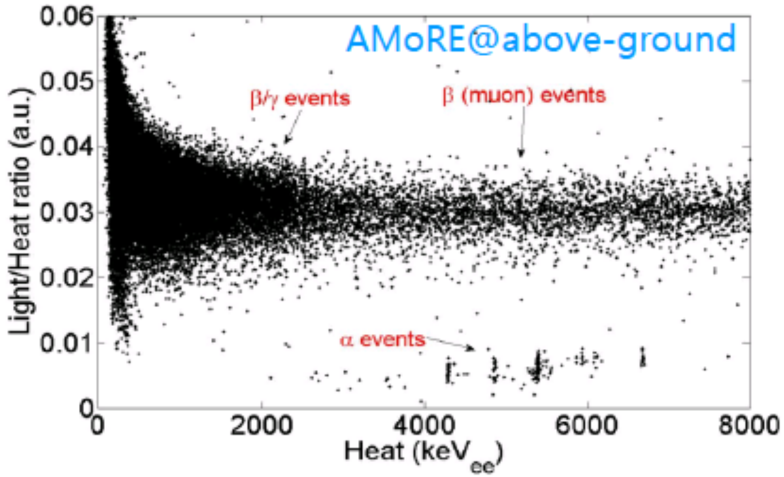
216 g $CaMoO_4$(natural) with a phonon sensor only.



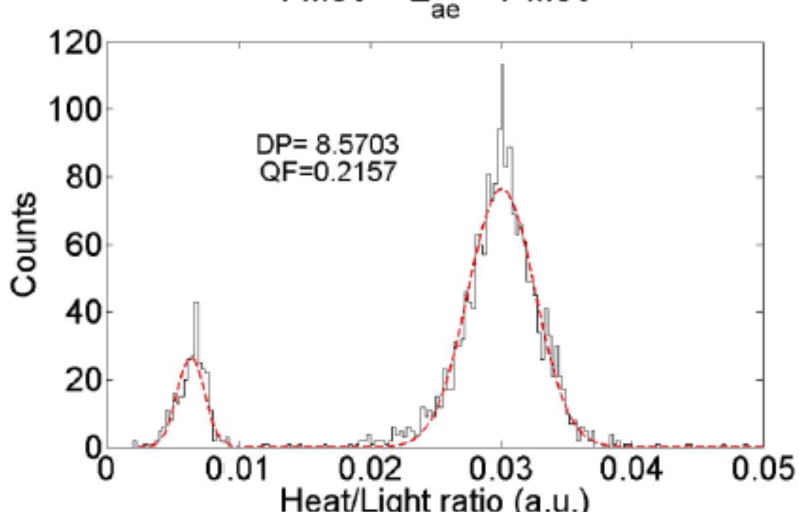
Energy (keV)	511	1461	2615
FWHM (keV)	8.0 ± 1.2	8.2 ± 1.1	9.0 ± 1.9

Particle Discrimination

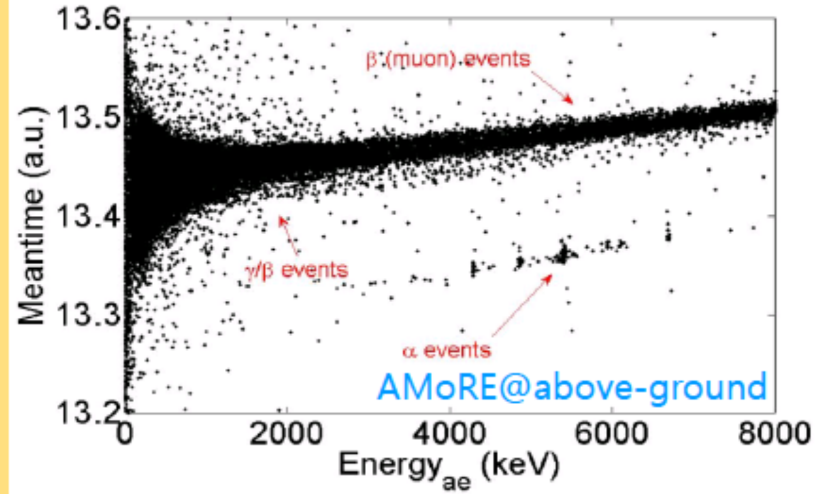
Particle discrimination by light heat ratio



4 MeV < E_{ae} < 7 MeV



Phonon pulse shape discrimination (PSD)



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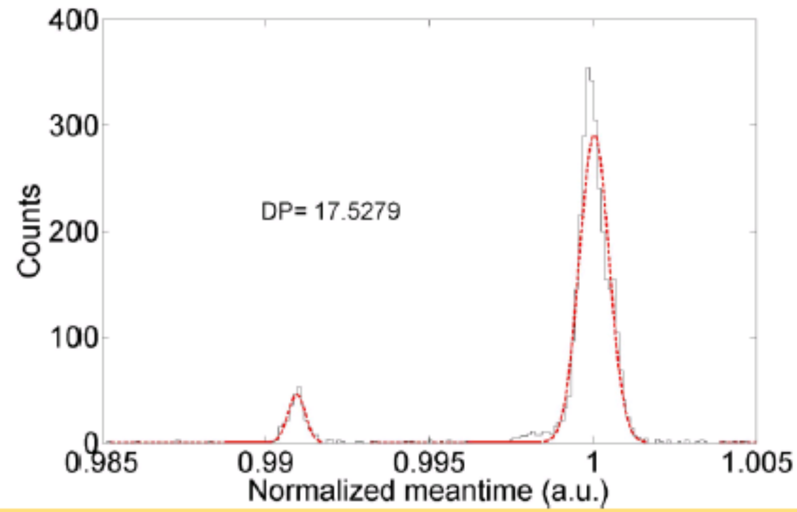
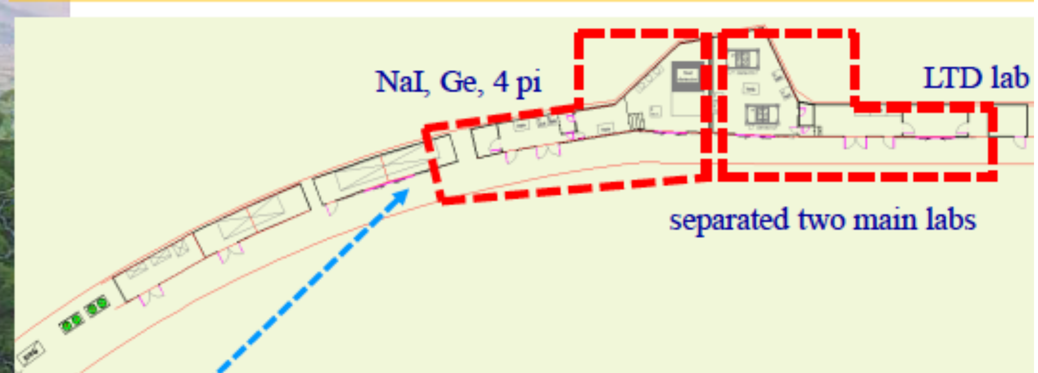
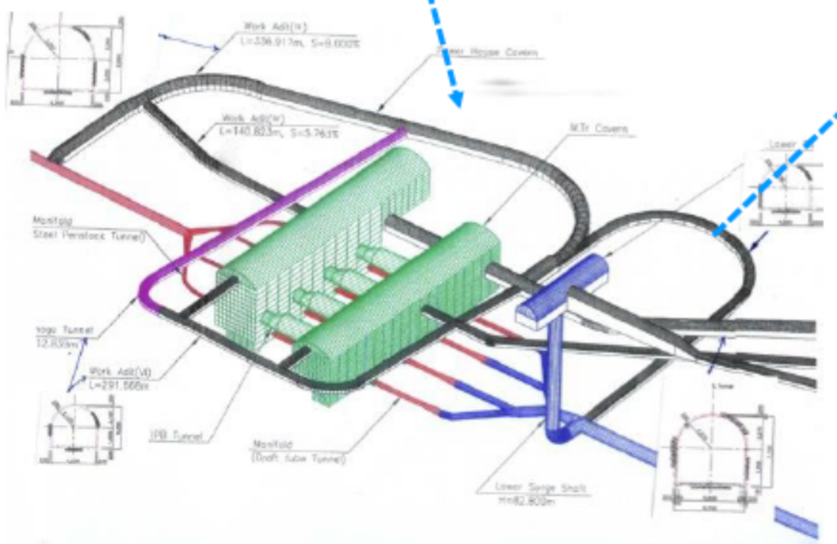



YangYang(Y2L) Underground Laboratory
(Upper Dam)
YangYang Pumped
Storage Power Plant
Center for Underground Physics
IBS (Institute for Basic Science)
1000m
700m
(Power Plant)
(Lower Dam)
Y2L
Seoul
Daejeon
Pyongyang
북한
동해
대한민국 강원도 양양군 양양읍
Incheon
대한민국
Daegu
Kwangju
Busan
Hiroshima
Fukuoka
KIMS (Dark Matter Search)
AMoRE (Double Beta Decay Experiment)
양양양수발전소
Minimum depth : 700 m / Access to the lab by car (~2km)

New underground space at Y2L

AMoRE-pilot and AMoRE-phase1 will be run at Y2L.
AMoRE-phase2 will be run at other place. (New underground lab.)





Yangyang pumped storage Power Plant

Minimum vertical depth : 700 m

Access to the lab by car : around 2 km

Experiments

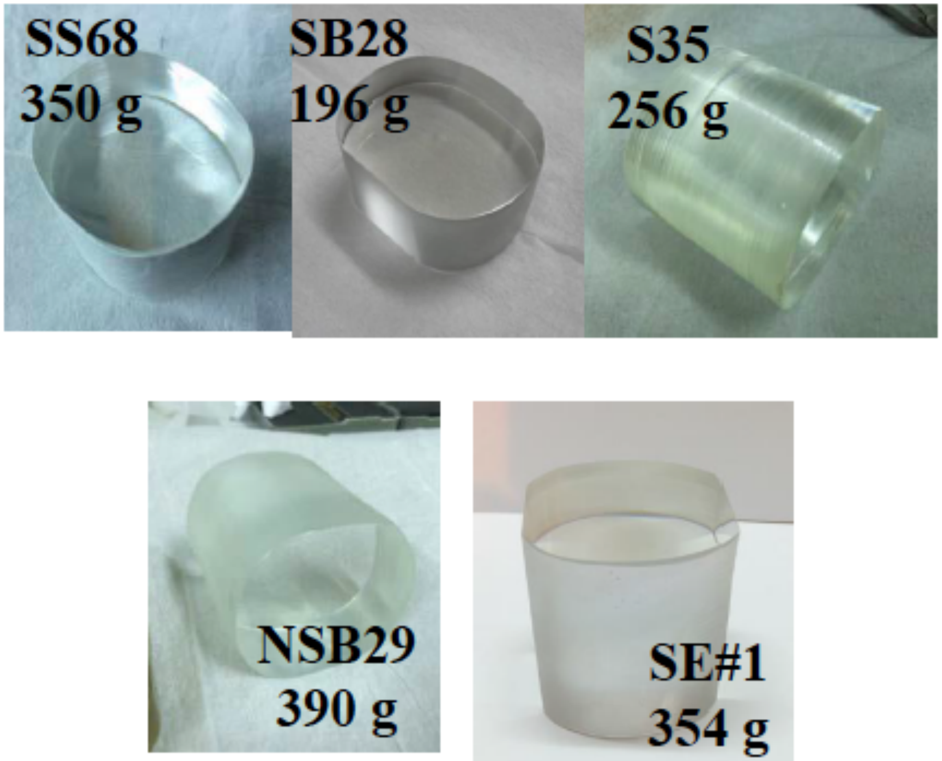
- KIMS : dark matter search experiment
- AMoRE : $0\nu\beta\beta$ decay search experiment

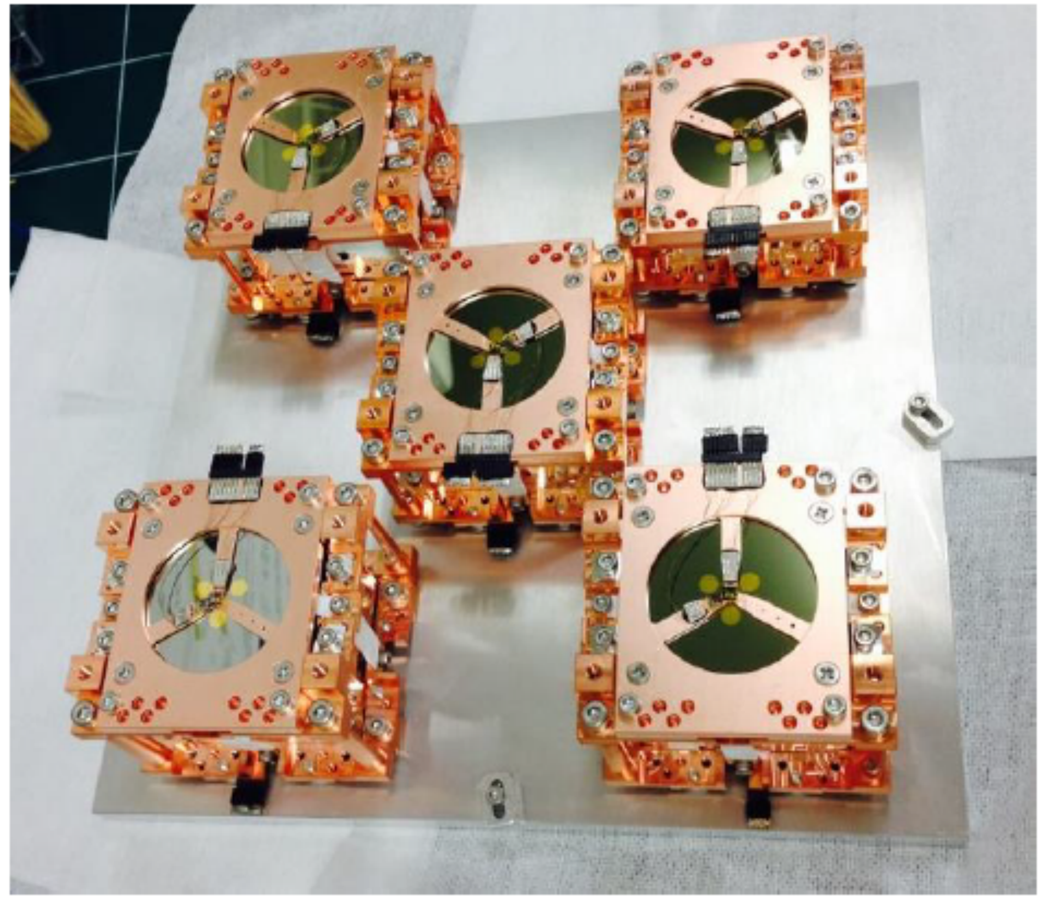
Construction

July 2015

AMoRE pilot : 1.5 kg of $^{40}Ca^{100}MoO_4$

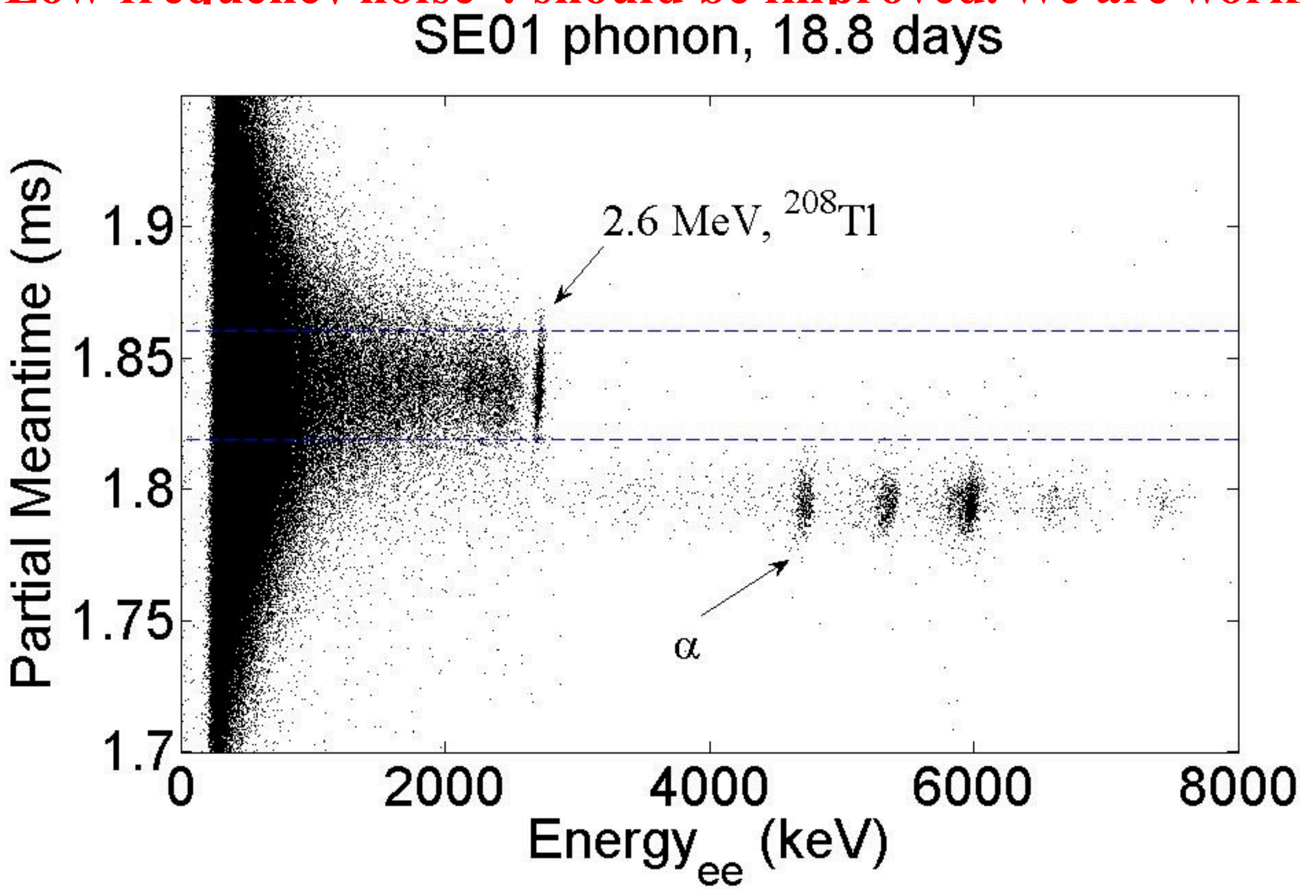
5 Crystals ($^{40}Ca^{100}MoO_4$) with total mass ~1.5 kg



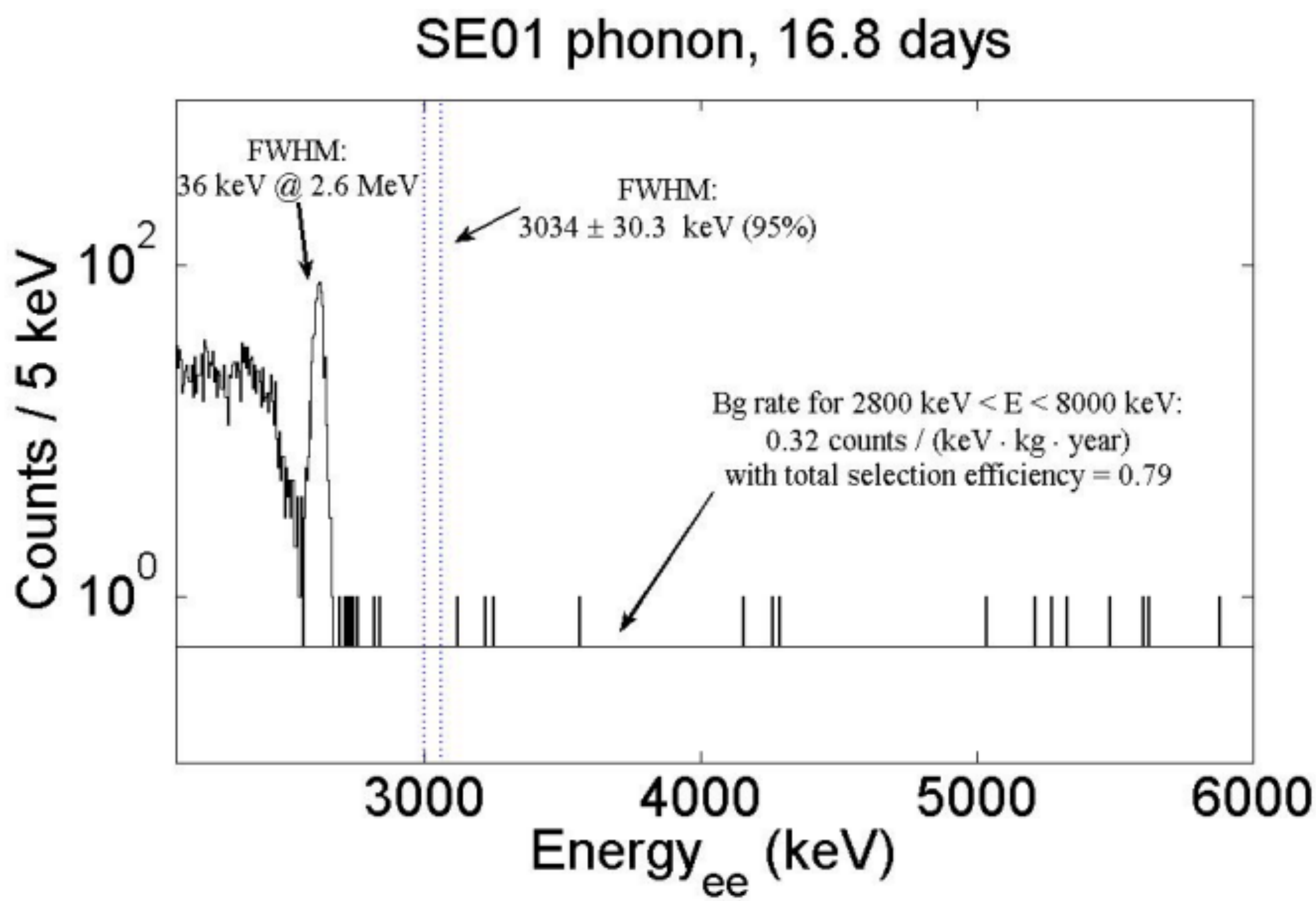


Running at Y2L now

- **All of the shields are mounted.**
- **The dilution fridge reaches 8 mK with 250kg lead attached.**
- **We are improving noise figures now.**
    - **High frequency noise : reasonably low.**
    - **Low frequency noise : should be improved. We are working on this !**



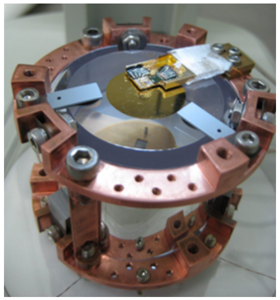
Running at Y2L now



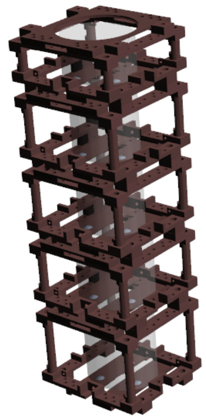
- T(1/2) > 1.07×10^{22} years → ~ 1.02×10^{24} years in a year.
- **This will be the same as the current best limit of ^{100}Mo !**

AMoRE project schedule

<2014>

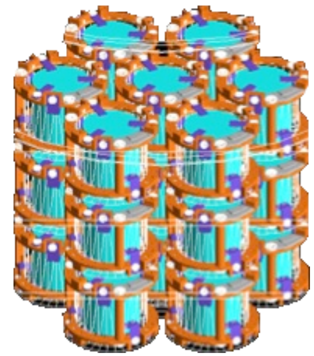


216 g



5 CMOs: ~ 1 kg

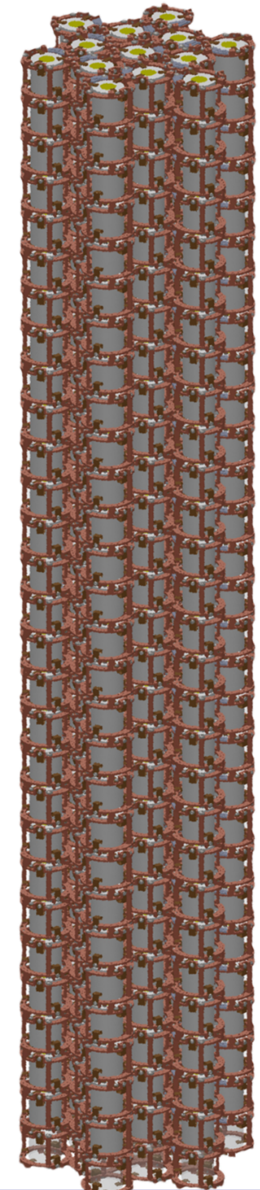
<AMoRE Pilot>



CMO: ~ 5 kg

<AMoRE-I>

<AMoRE-II>



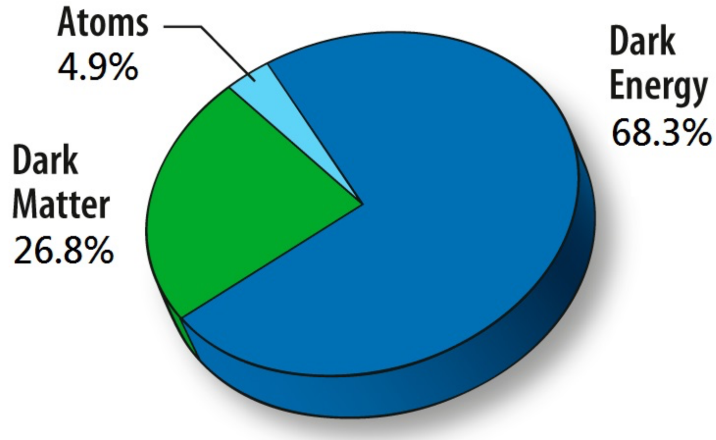
ckky : counts/ (keV kg year)

	AMoRE-Pilot	AMoRE-I	AMoRE-II
Crystal Mass (kg)	1.5	5	200
Backgrounds(ckky)	10^{-2}	10^{-3}	10^{-4}
$T_{1/2}$(year)	1.0×10^{24}	8.2×10^{24}	8.2×10^{26}
$m_{\beta\beta}$ (meV)	380-719	130-250	13-25
Schedule	2015	2016-2017	2019-2023

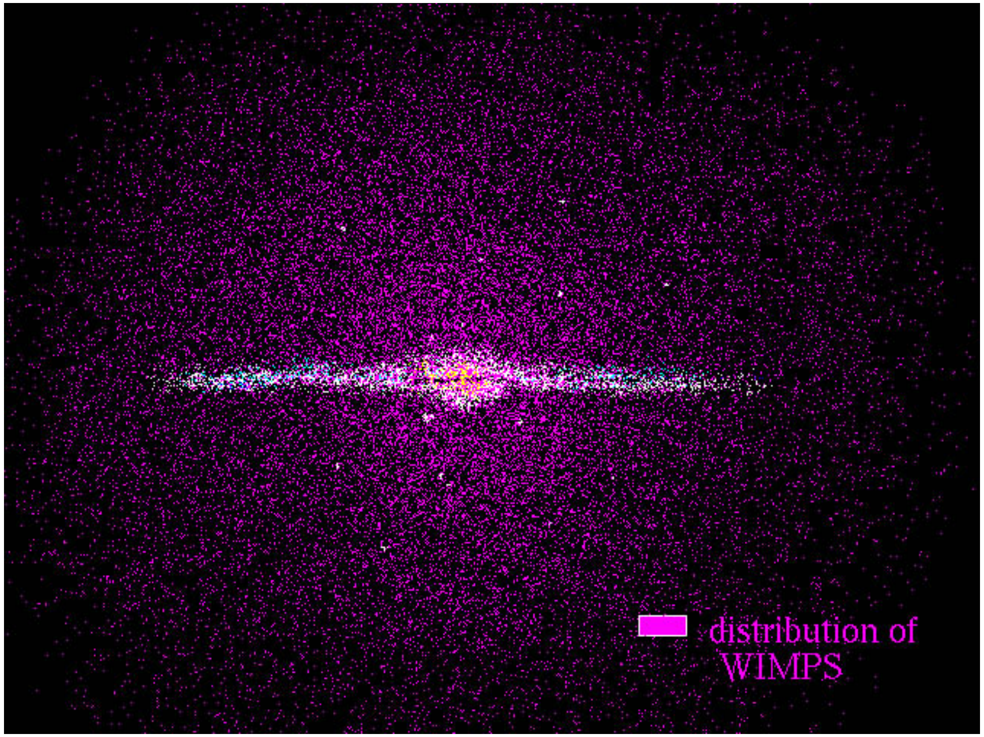
Dark Matter

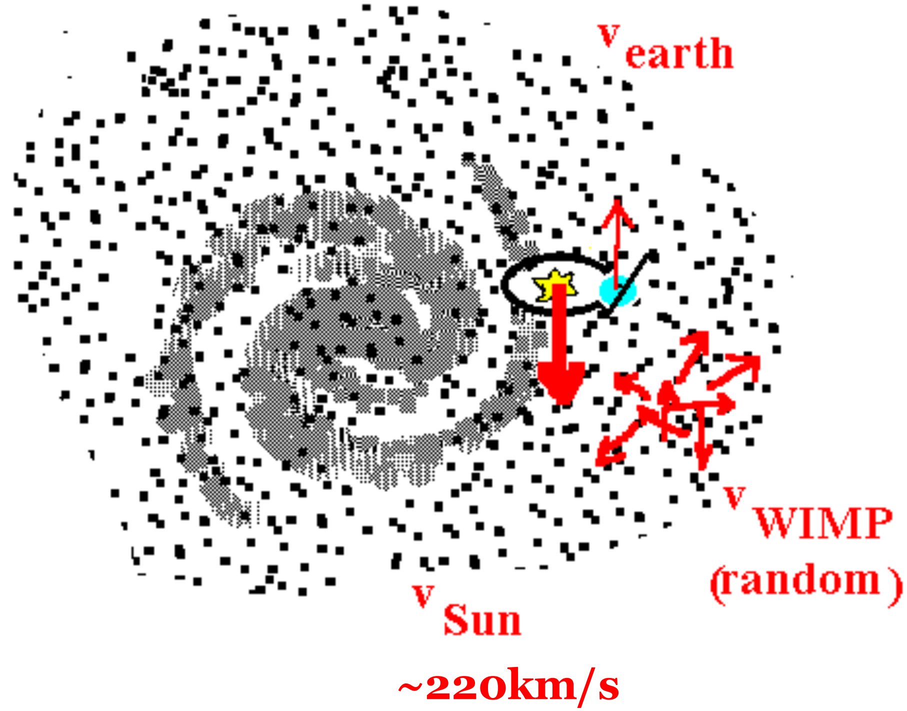
- There are numerous evidences that **dark matter** (DM) exists around us and it is much more than the visible world, **5 times more.**
- It is the most significant subject in modern science. (maybe personally prejudiced !)

  One of the top 10 scientific mysteries for 21 century
- It is clear now that the **DM** is most likely **new particles** yet unknown, and many many theories proposed new particles as DM.
- The most strong candidates are **WIMPs** and AXION. Inside WIMPs category, there are still many different particles proposed. The proposed masses range 10^{-6} eV to 10^{15} eV.



WIMP Wind (If WIMP is dark matter..)

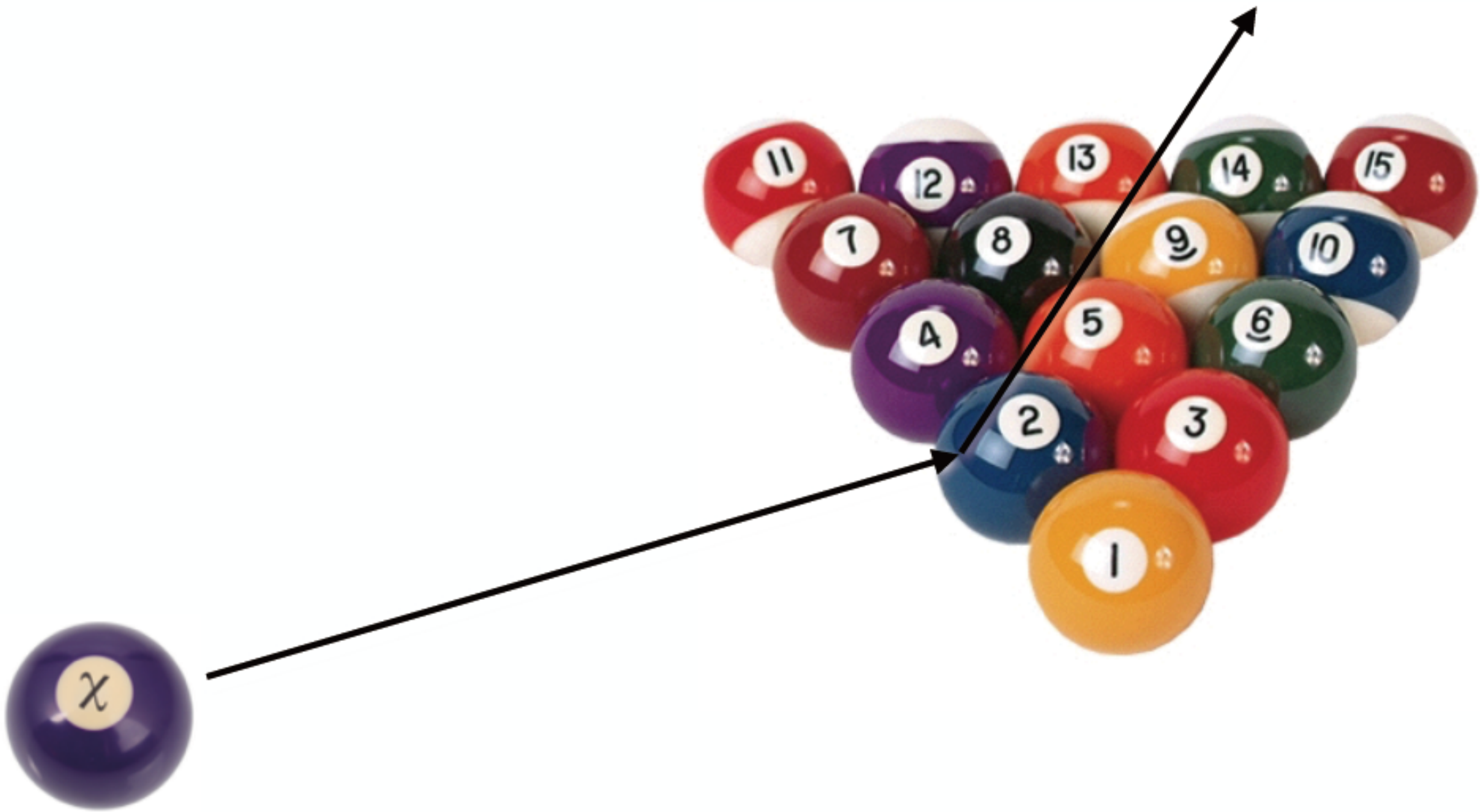




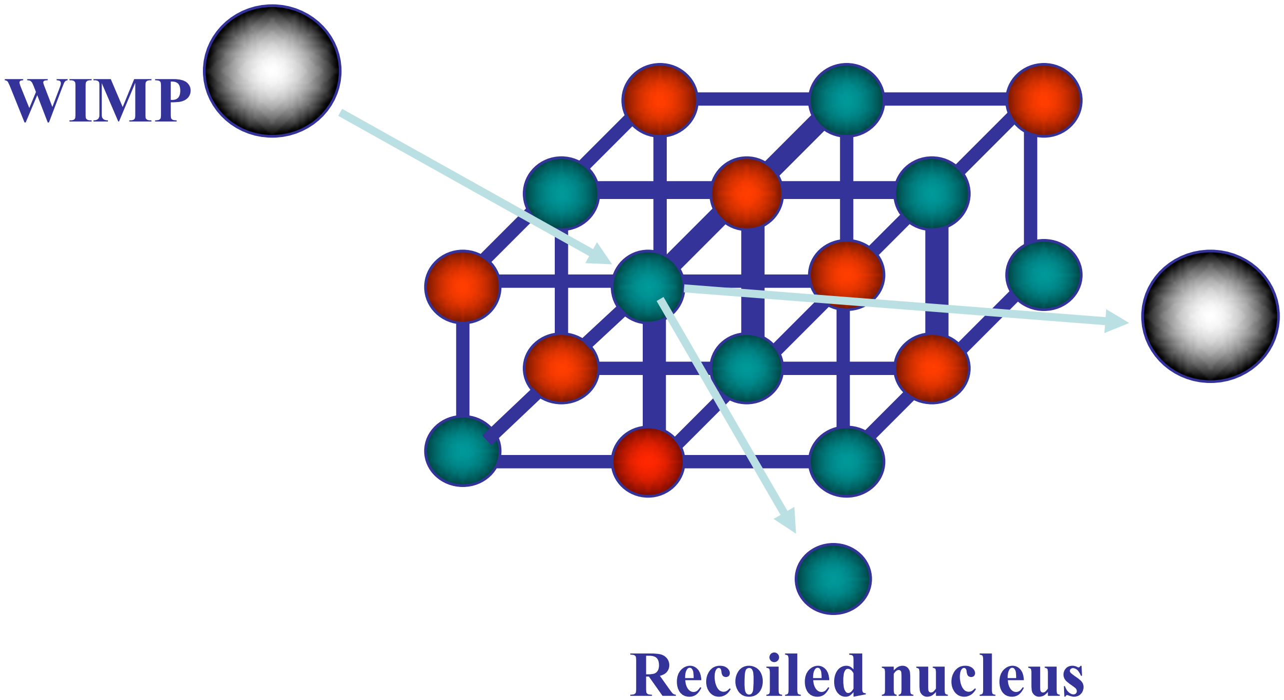
- Assuming Standard Halo Model
- Because of **rotation of the solar system**, we can have WIMP wind with average velocity of ~220km/s

WIMP-nuclei elastic scattering

Elastic Scattering



WIMP-nuclei elastic scattering

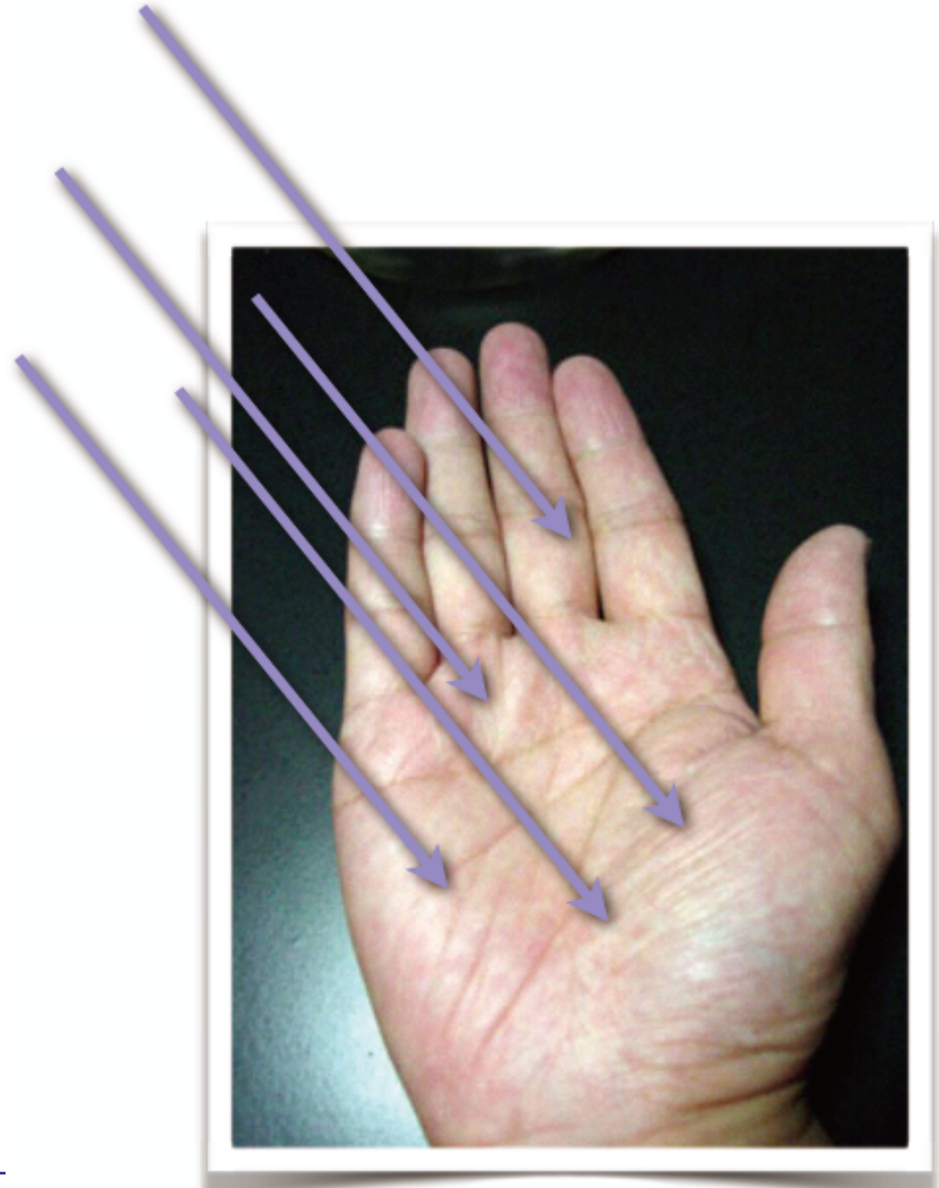


$$R \sim 0.13 \, \frac{\text{events}}{\text{kg year}} \left[\frac{A}{100} \times \frac{\sigma_{WN}}{10^{-38}\,\text{cm}^2} \times \frac{\langle v \rangle}{220\,\text{km}\,\text{s}^{-1}} \times \frac{\rho_0}{0.3\,\text{GeV}\text{cm}^{-3}} \right]$$

By measuring recoil energy of nucleus, we can observe WIMP signals

Dark matter in the earth

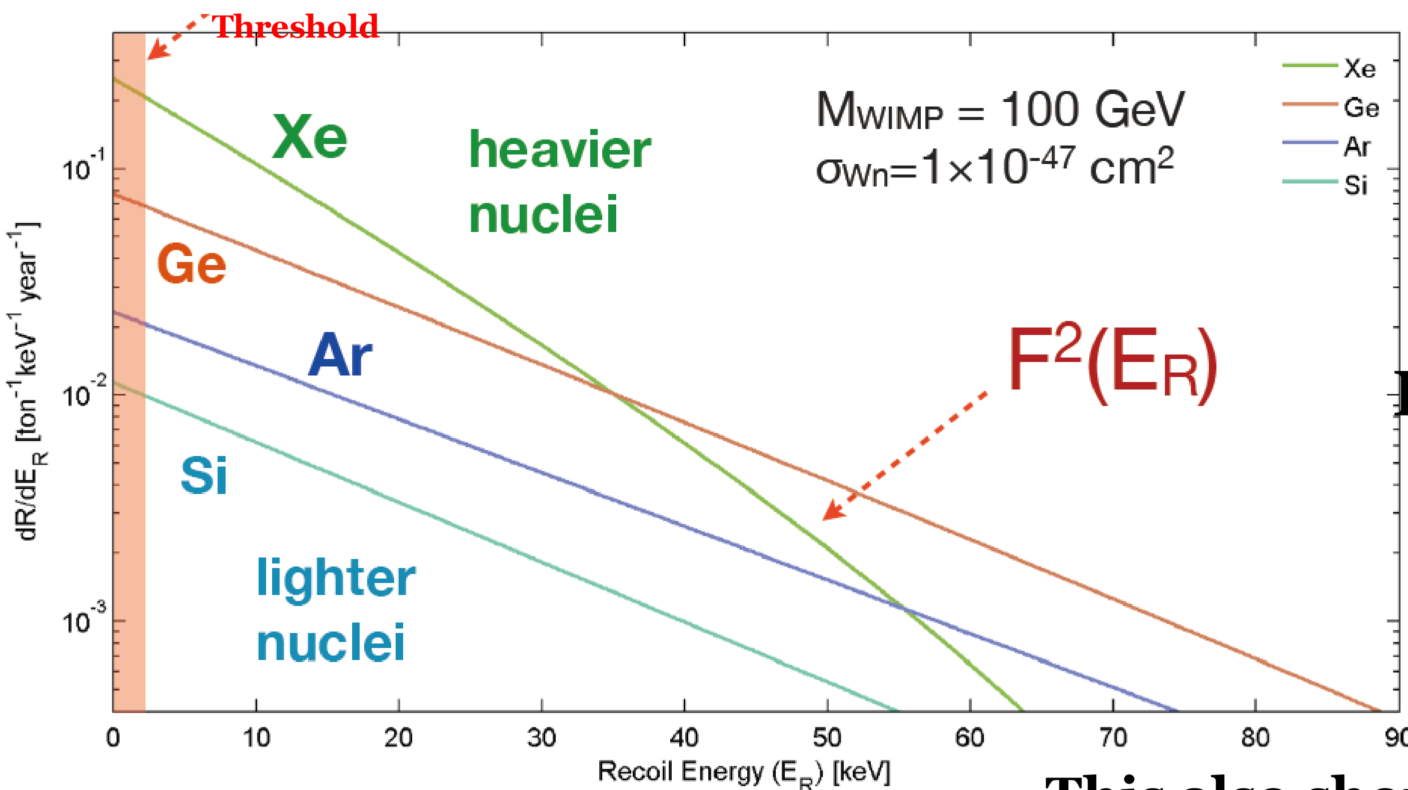
- Dark matter density in the solar system ~ 0.3 GeV/cm^3
  - ❖ Based on rotational curve in our galaxy
- Assuming Maxwell-Boltzmann distribution (standard halo-model)
- Assuming WIMP mass as 60GeV/c^2
- Relative velocity ~ 220 km/s
- Then, ~100,000 WIMPs/cm^2/s
- 20,000,000 /hand/s



Why we can not see WIMP?

$$R \sim 0.13 \frac{\text{events}}{\text{kg year}} \left[\frac{A}{100} \times \frac{\sigma_{WN}}{10^{-38}\,\text{cm}^2} \times \frac{\langle v \rangle}{220\,\text{km}\,\text{s}^{-1}} \times \frac{\rho_0}{0.3\,\text{GeV}\text{cm}^{-3}} \right]$$

- Cross section between WIMP-nucleon is very small ($<10^{-45}$ cm^2)



Order of 1 events/kg/years

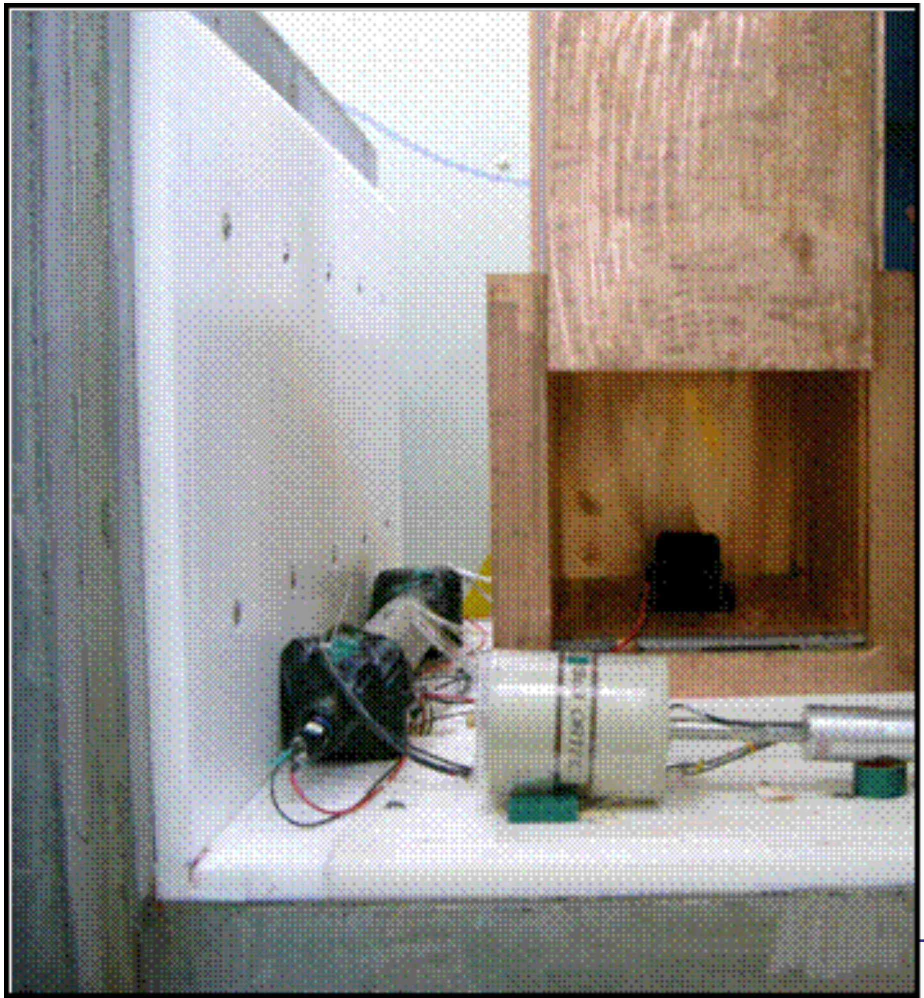
However, there are lots of natural radioactivity

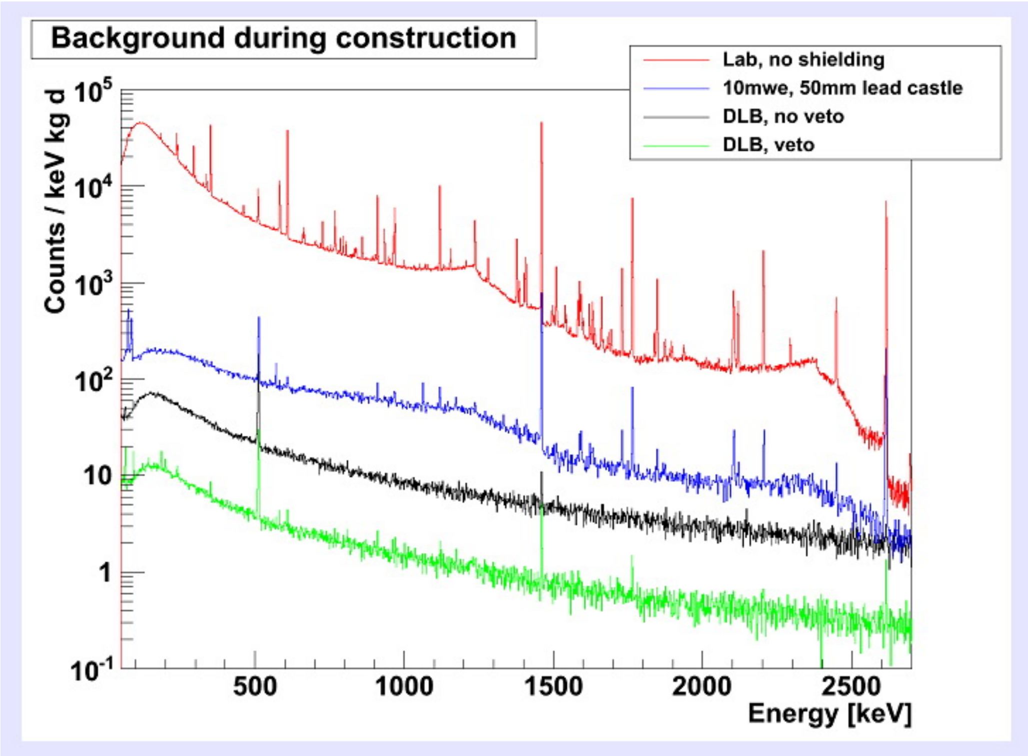
~100 events/kg/s

This also should be underground

Natural radioisotope

- Lots of U, Th, K make many events
  - ❖ Maximum gamma energy is less than 3 MeV
  - ❖ Pb, Cu, PE can effectively shield natural radioisotope





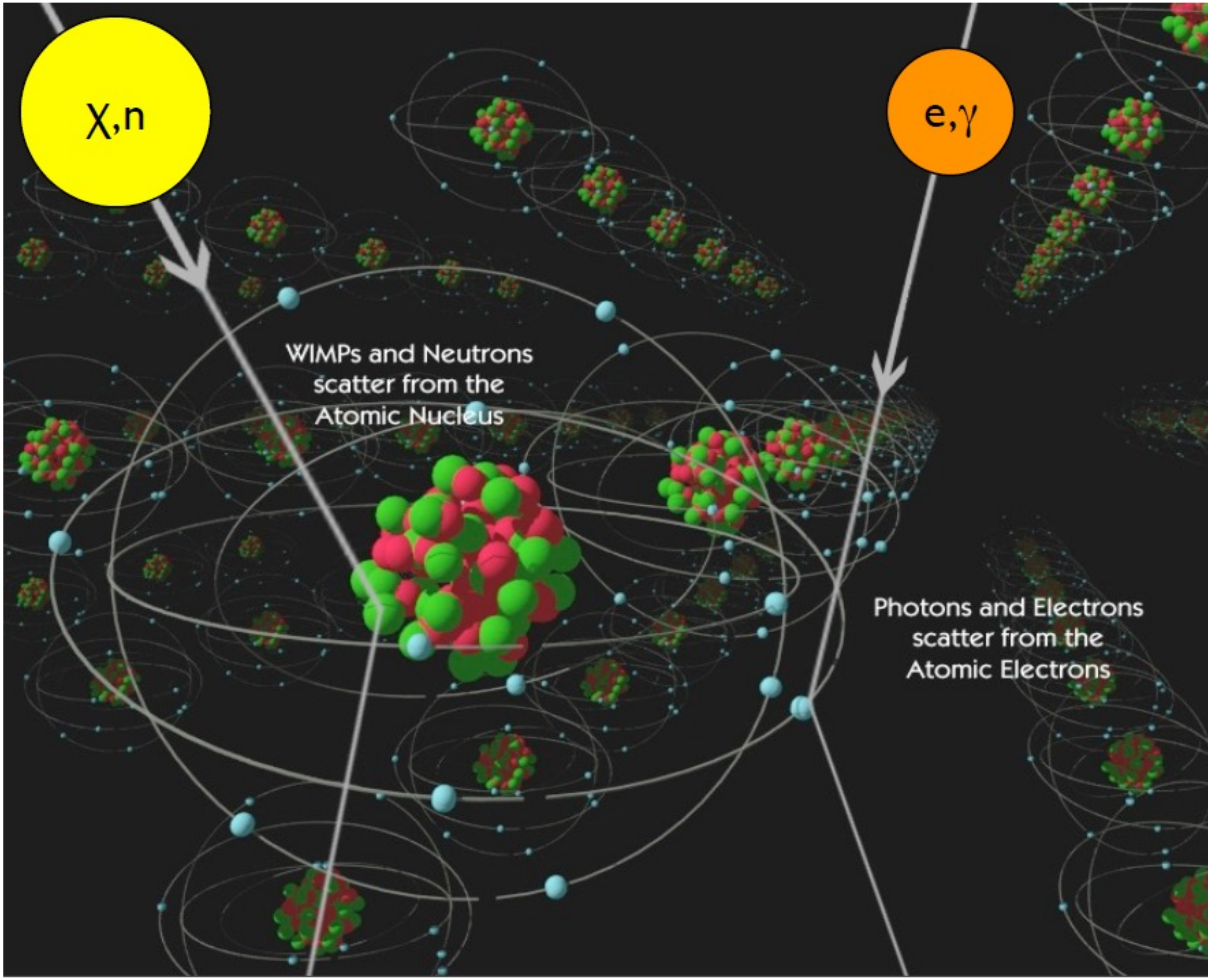
But, still remained ~ 10 events/ keV/kg/day.

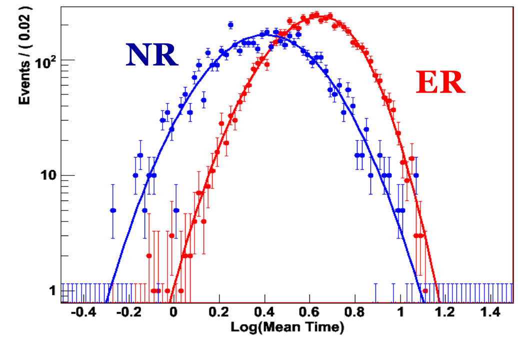
This is mostly detector internal gamma

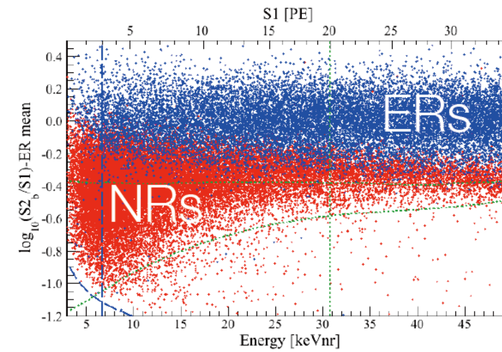
This is still large

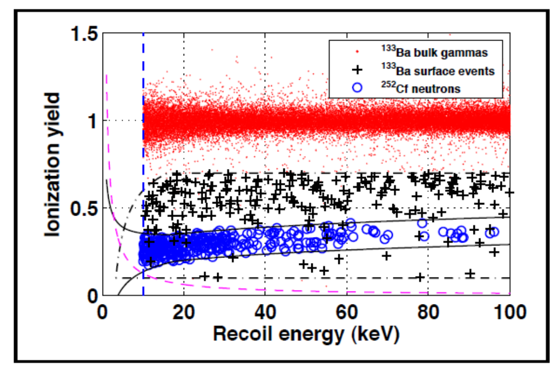
Discrimination between background and WIMP signals

- Different interaction mechanism

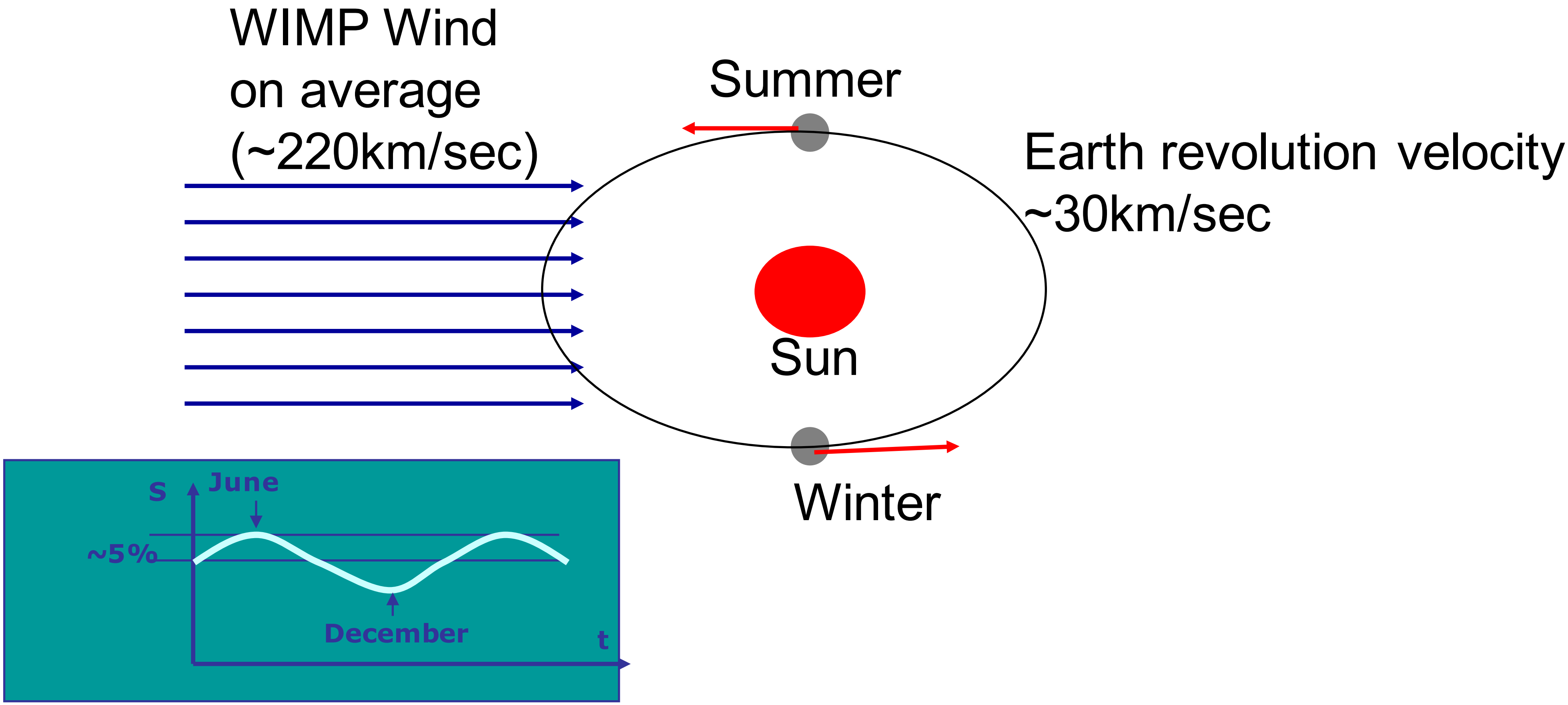








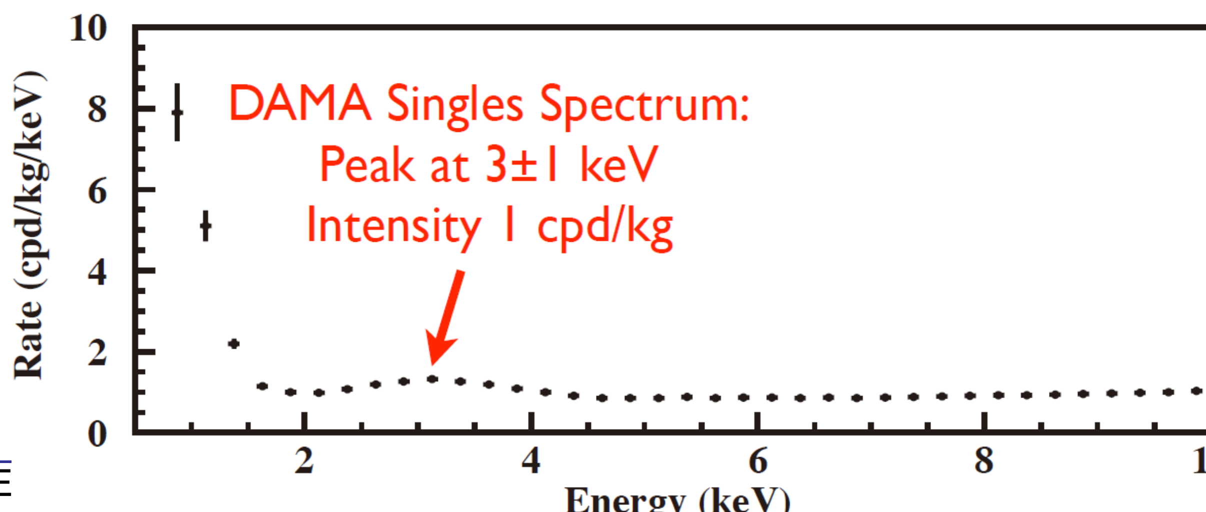
Annual Modulation of WIMP



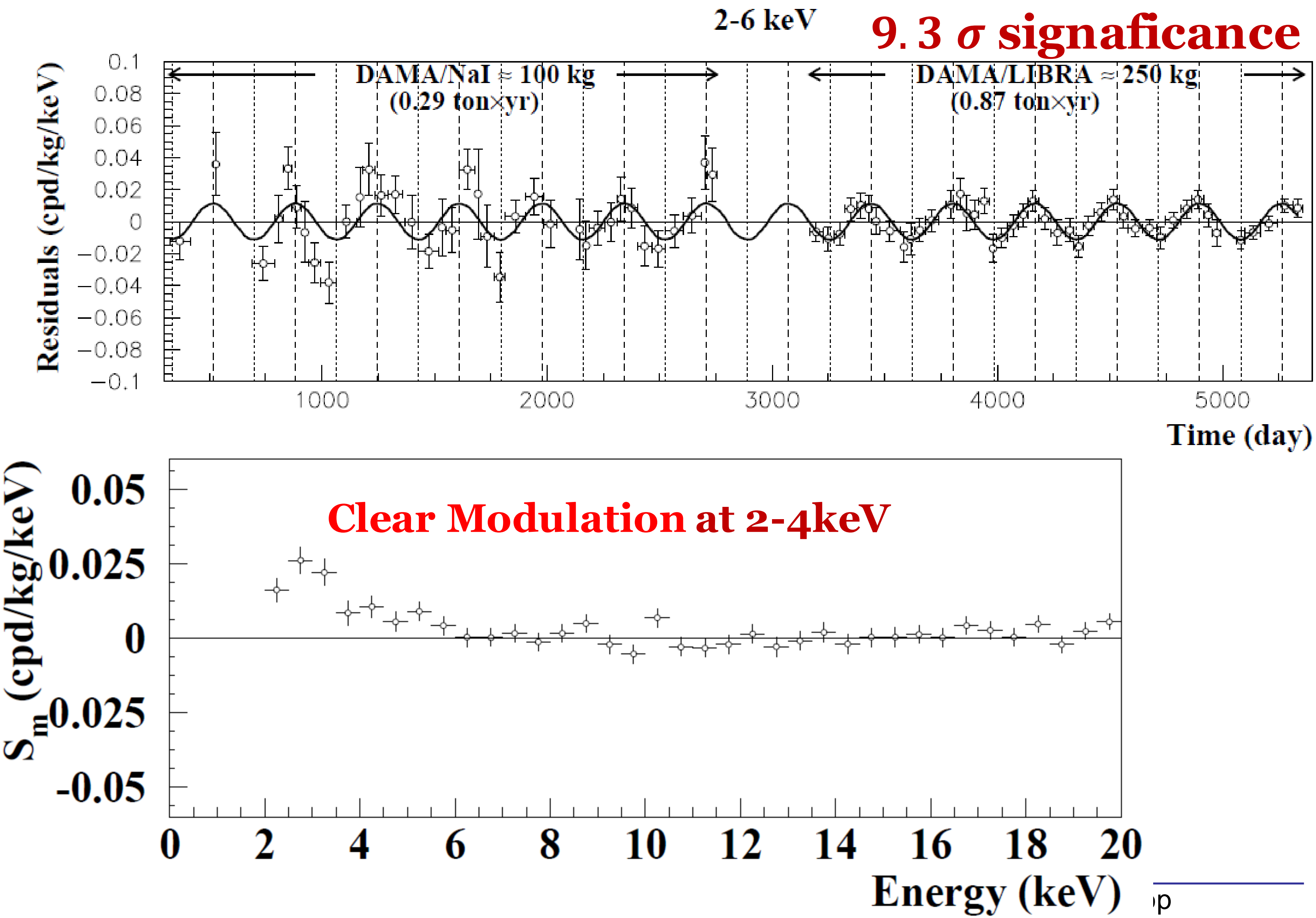
A few % annual modulation of WIMP signature

DAMA/LIBRA

- Annual Modulation Searches with NaI(Tl) crystal detectors
- DAMA/NaI
  - 100 kg target
  - 1997-2003
- DAMA/LIBRA
  - 250 kg target
  - 2003-2012 (phase I), 2013- (phase II)
- No discrimination of nuclear recoil events

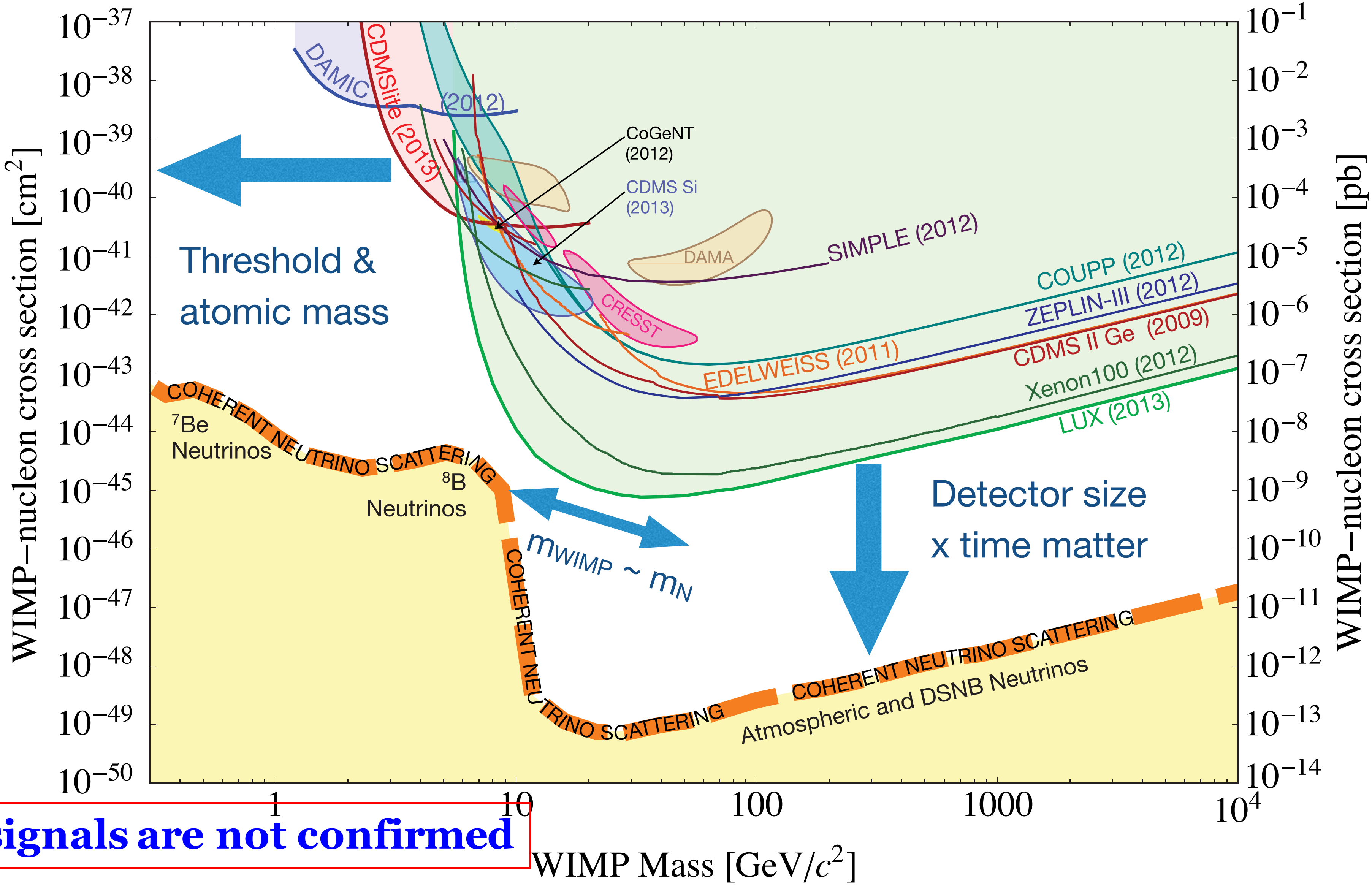


DAMA/LIBRA



2-6 keV
9.3 σ signaficance
DAMA/NaI ≈ 100 kg
(0.29 ton×yr)
DAMA/LIBRA ≈ 250 kg
(0.87 ton×yr)
Residuals (cpd/kg/keV)
Time (day)
Clear Modulation at 2-4keV
S_m (cpd/kg/keV)
Energy (keV)

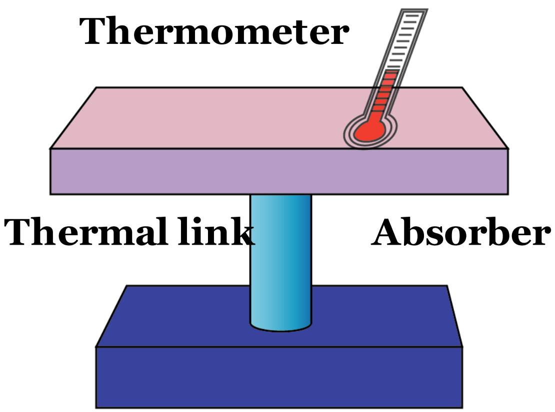
Howevers…

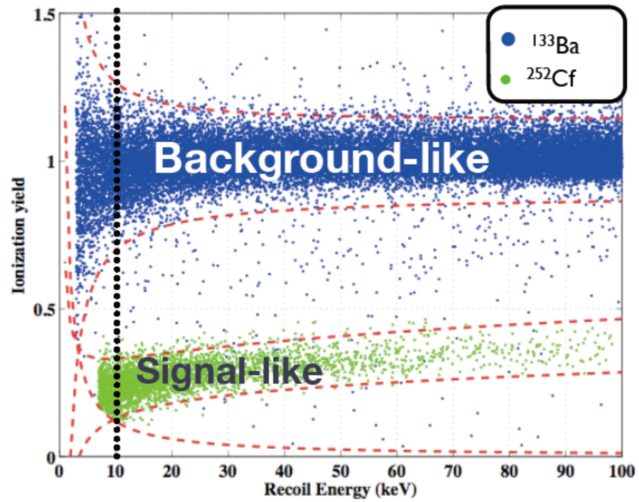


DAMA signals are not confirmed

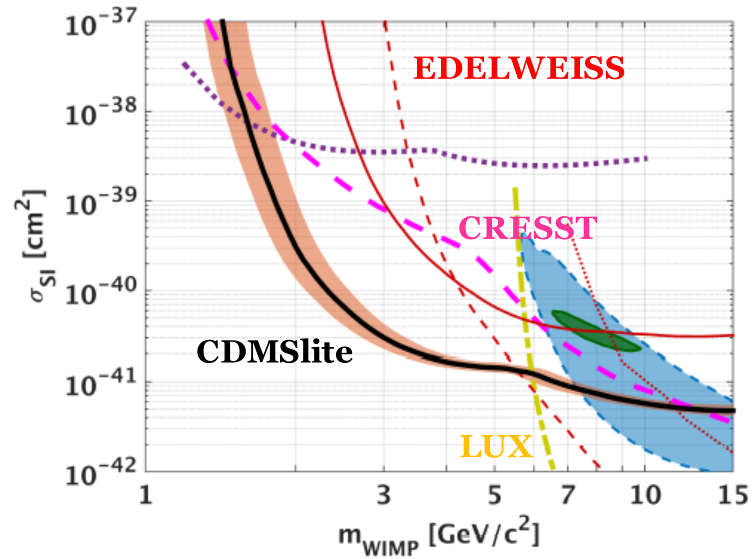
Cryogenic detectors

- Detect a temperature increase (phonons) from particle interaction

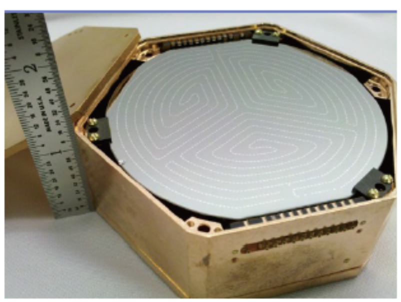




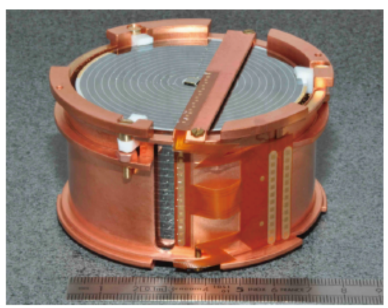
arXiv:1509.02448



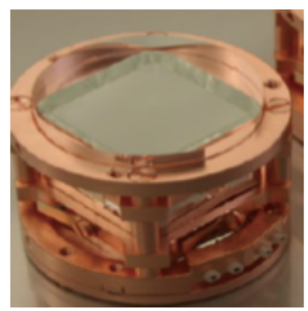
SuperCDMS: Ge, Si



EDELWEISS-III (Ge)



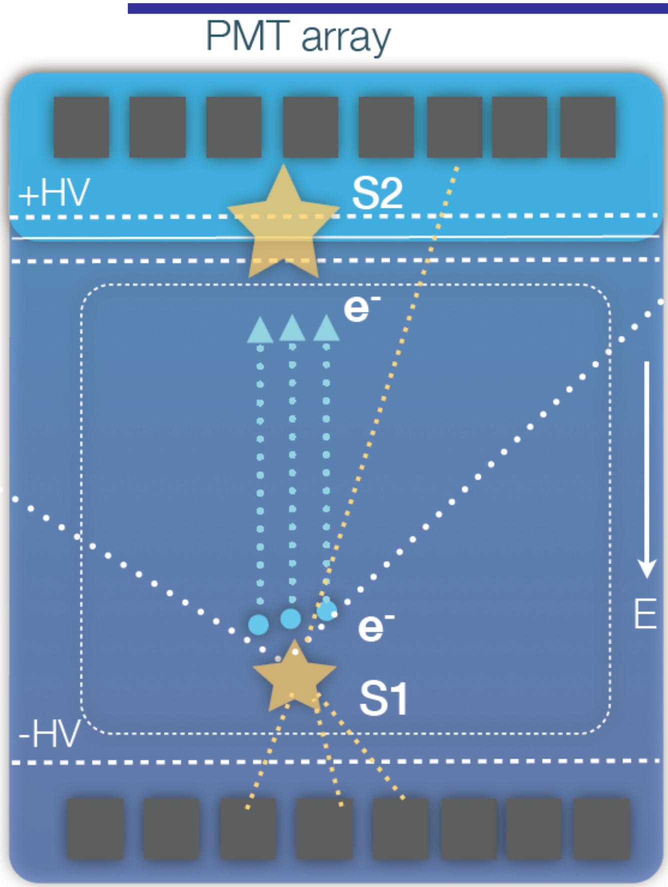
CRESST ($CaWO_4$)

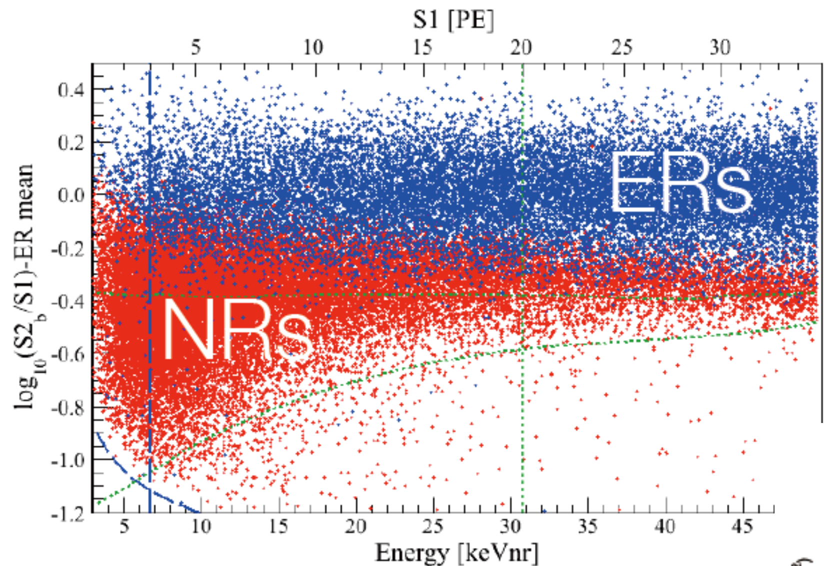


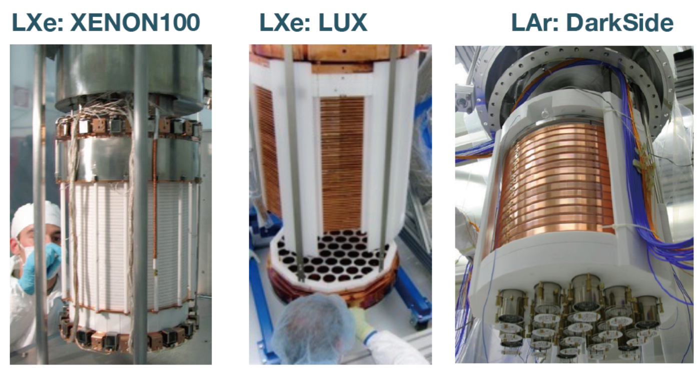
- Order of 10 kg experiment
- Plan to increase ~100 kg detector in next generation

- Can achieve very low energy threshold
  - ❖ Senstive to low-mass WIMP dark matter

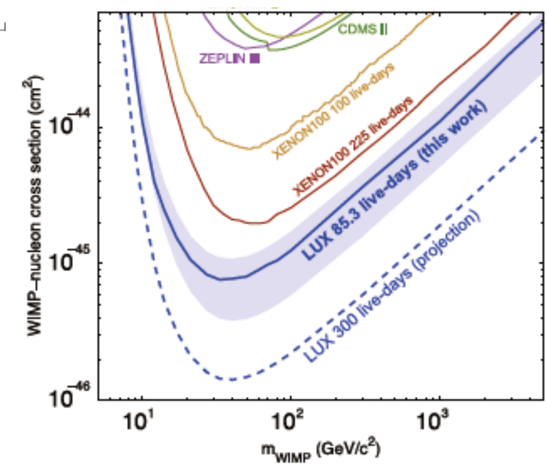
Two phase noble liquid detector







PRL 112, 091303 (2014)



~ **100 kg** detector, plan to ~ 1000 kg detector

- Easy to scale up
  - ❖ The best DM detector for m_W>10 GeV

Dose DAMA really rejected?

- Different detector materials
  - Systematics depending on detectors
  - Quenching factor
  - Spin dependent form factor, spin factor
  - …

- Different signals of WIMP
  - DAMA uses annual modulation
  - Null experiments use extraction of WIMP-nucleus interaction

Dose DAMA really rejected?

- Different detector materials
  - Systematics depending on detectors
  - Quenching factor
  - Spin dependent form factor, spin factor
  - …

- Different signals of WIMP
  - DAMA uses annual modulation
  - Null experiments use extraction of WIMP-nucleus interaction

No!!

Apple-to-apple comparison

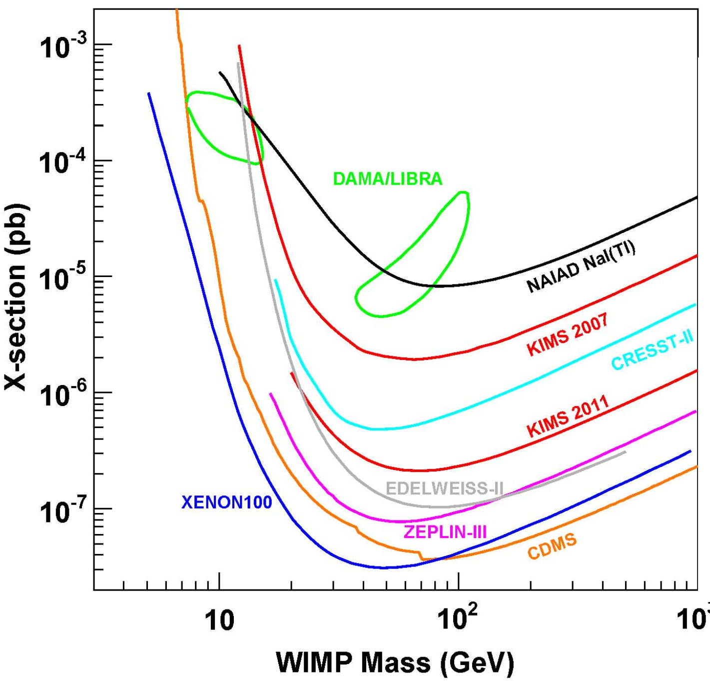
DAMA signals should be verified using same materials and same signal analysis

KIMS NaI experiment

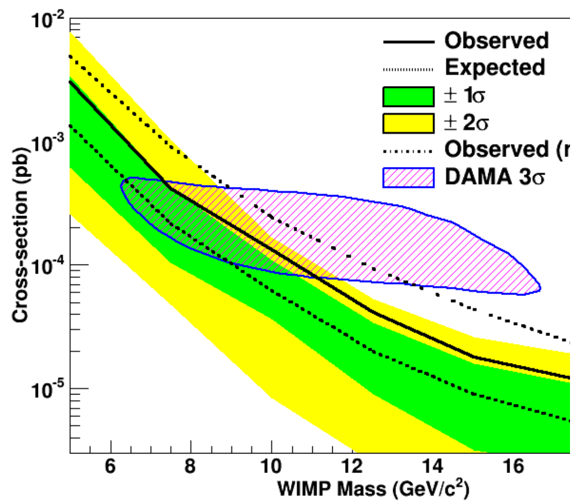
KIMS-CsI experiment

- 12 crystals (104.4 kg)
- 2.5 year data (2009-2012)
- Background : 2~3 count/kg/day/keV (dru)
- Model-independent rejection of DAMA signals interpreted as WIMP-Iodine interaction

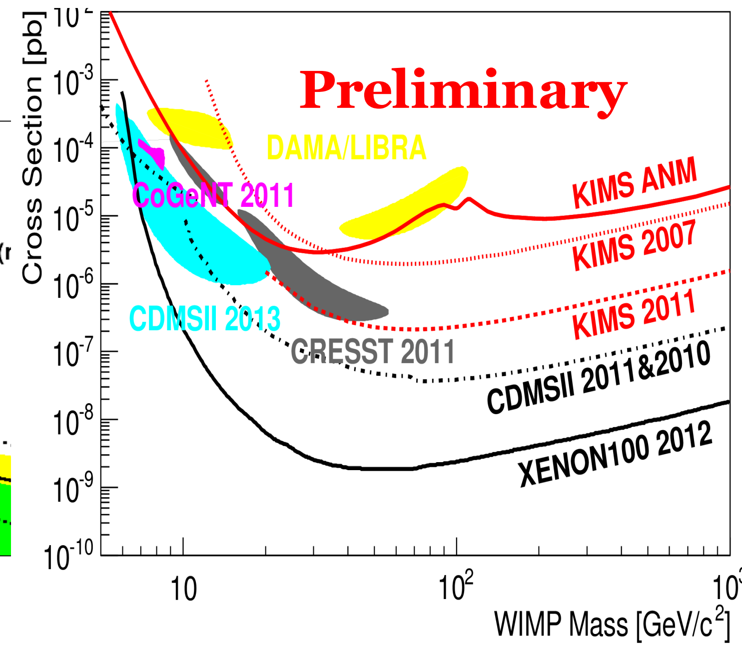
PRL 108 181301 (2012)



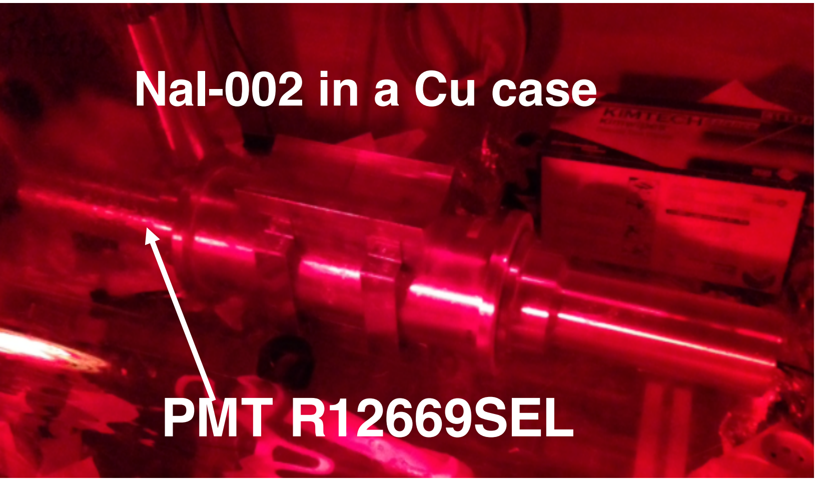
PRD 90 052006 (2014)



Annual Modulation

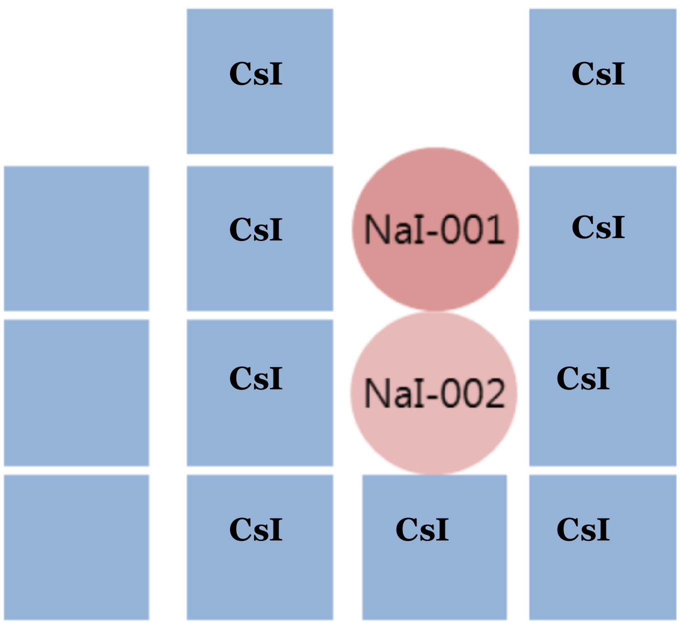


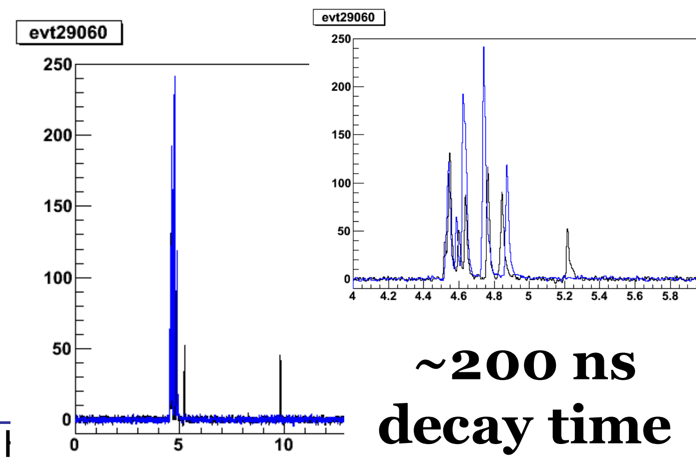
KIMS-NaI experiment



- Will use same NaI crystal and analyze same annual modulation
- Will develop better detector than DAMA

- Background <1 counts/keV/kg/day
- Threshold <2 keV



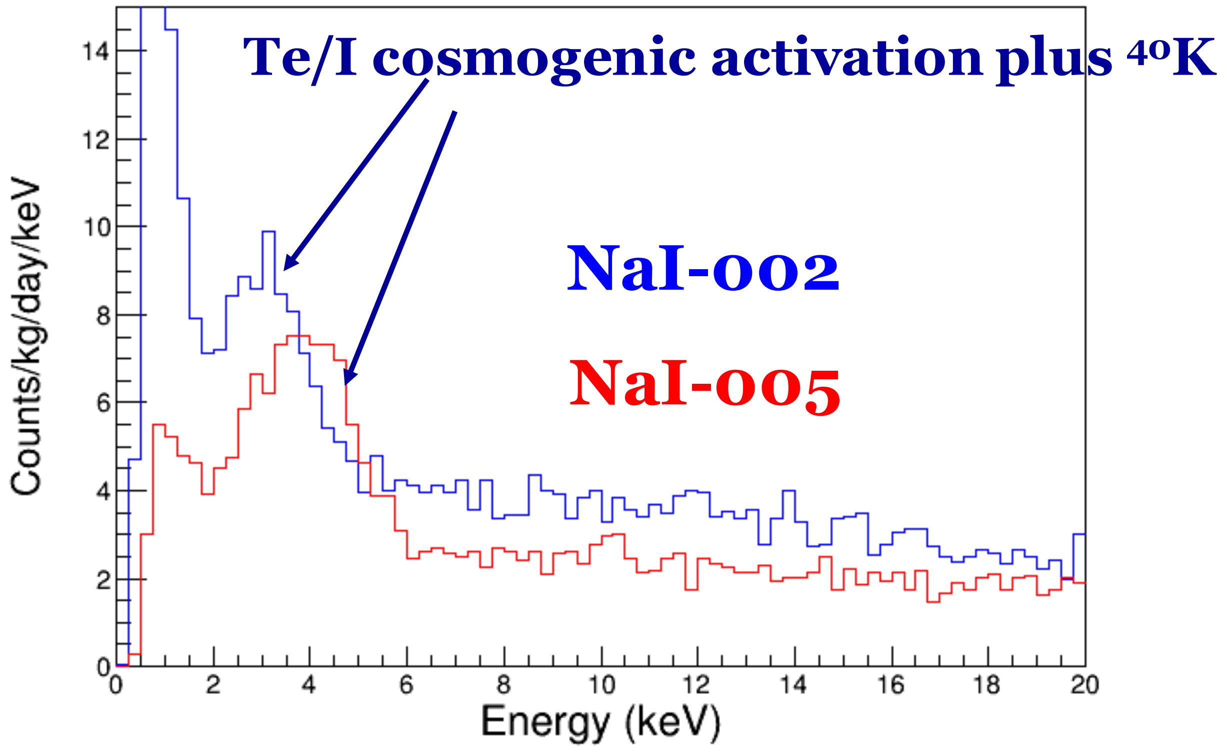


~200 ns decay time

Detector Development

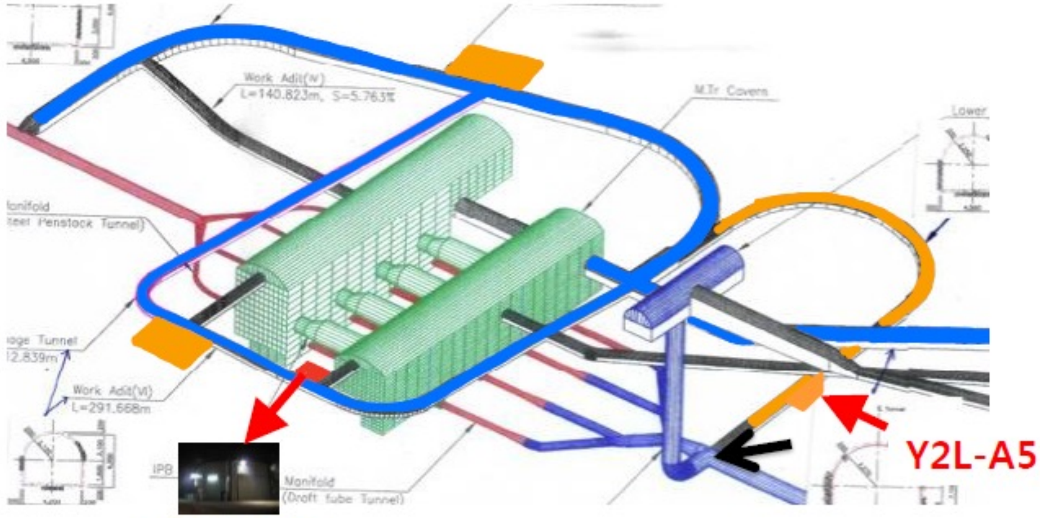
K.W.Kim et al., Astropart. Phys. 62, 249 (2015)

P. Adhikari et al., arXiv:1510.04519

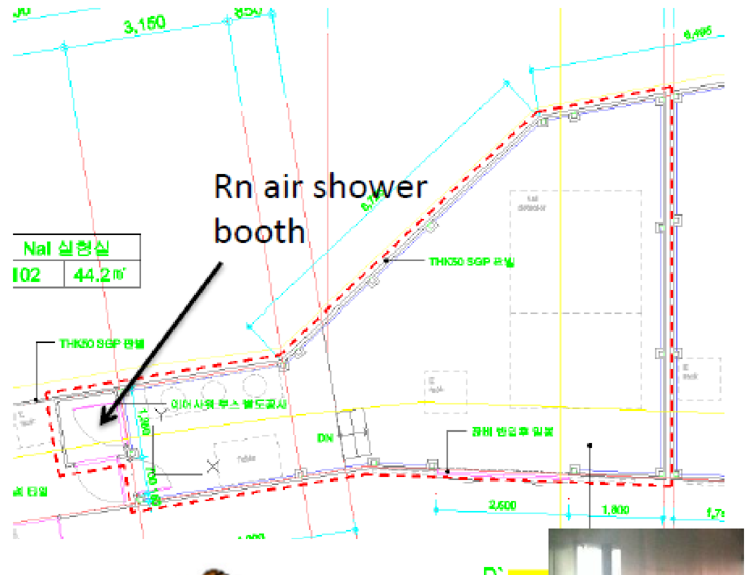


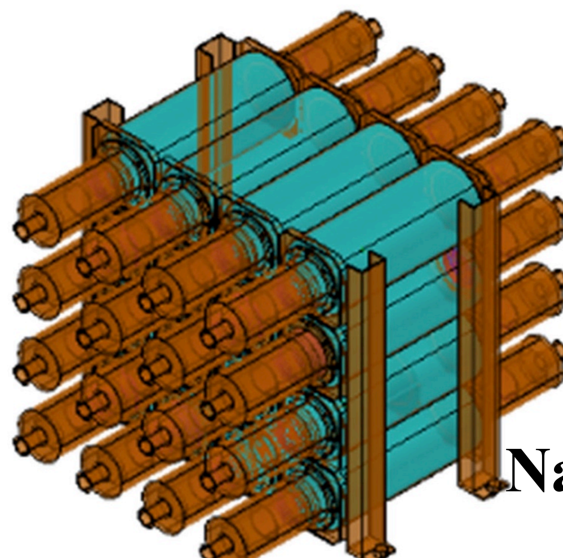
- Understanding internal background well
- We can soon achieve 1 counts/kg/day/keV level
- We will grow 200kg crystals by End of 2016

NaI 200kg experiment



exist Y2L-A6

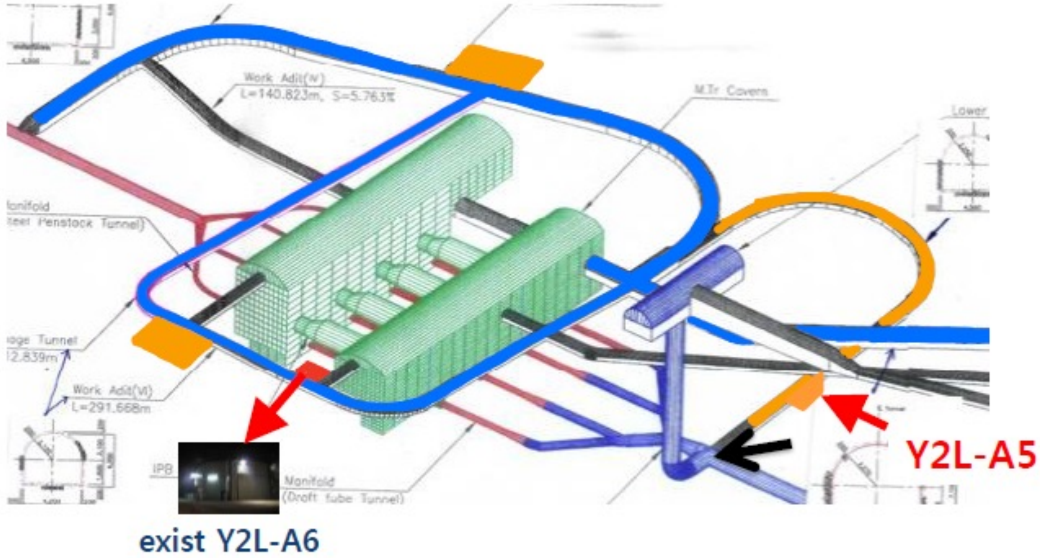


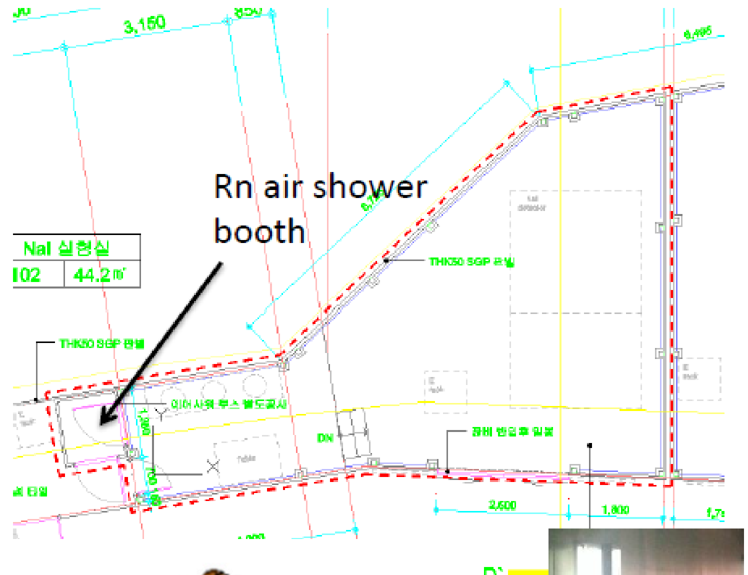


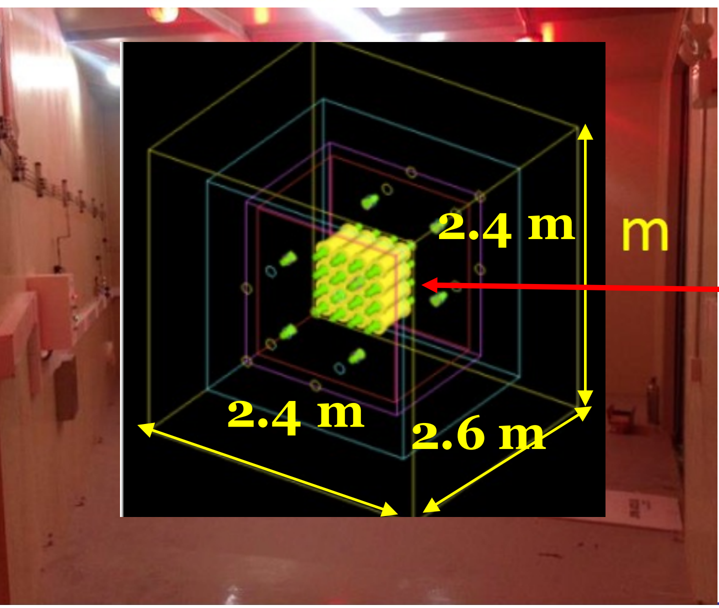
NaI crystal Array

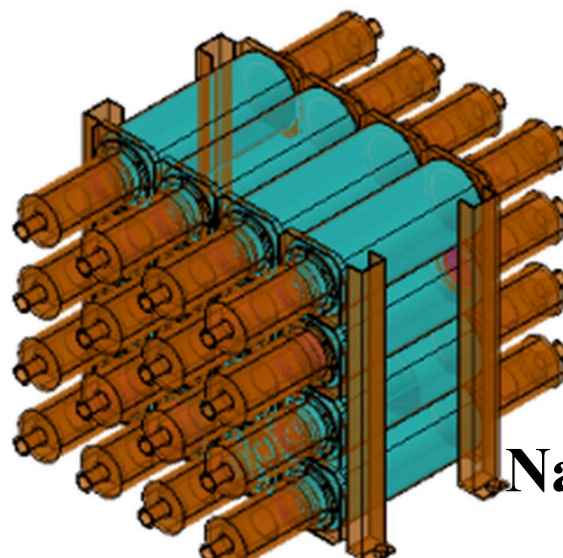
12.5kg X 16 crystals=200kg

NaI 200kg experiment





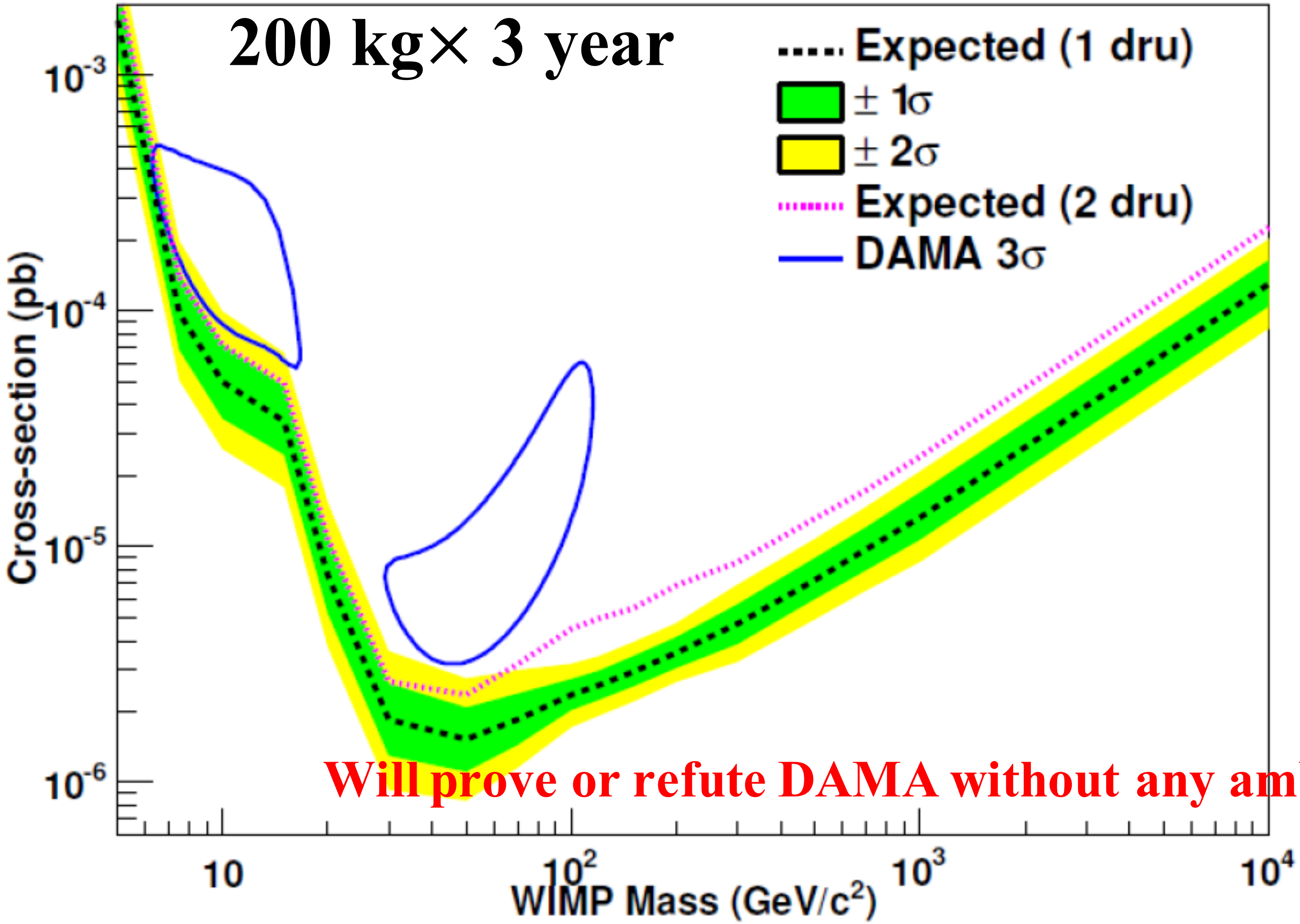




NaI crystal Array

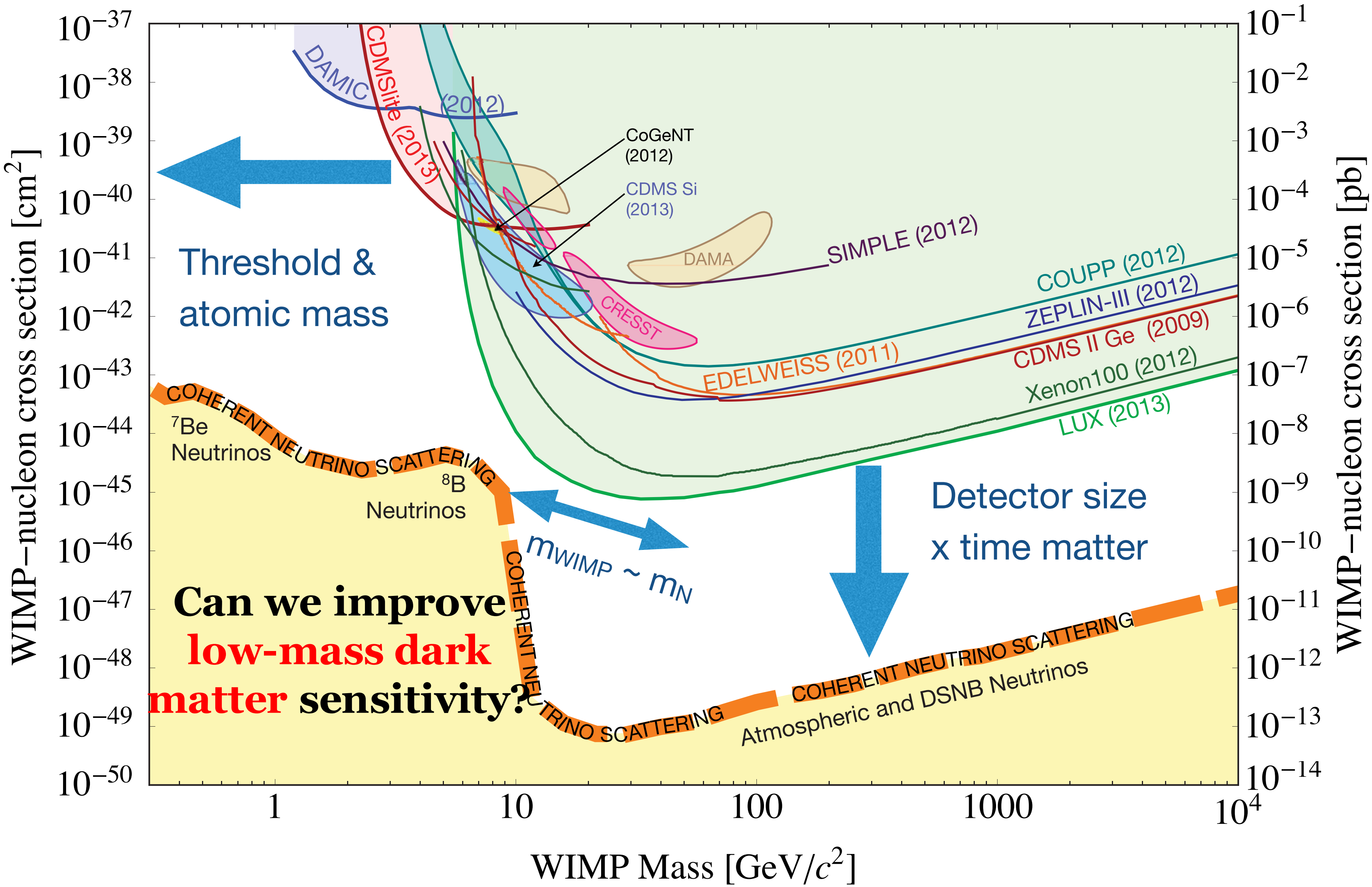
12.5kg X 16 crystals=200kg

Prospect of NaI(Tl) crystal development



Will prove or refute DAMA without any ambiguity

Dark matter search status

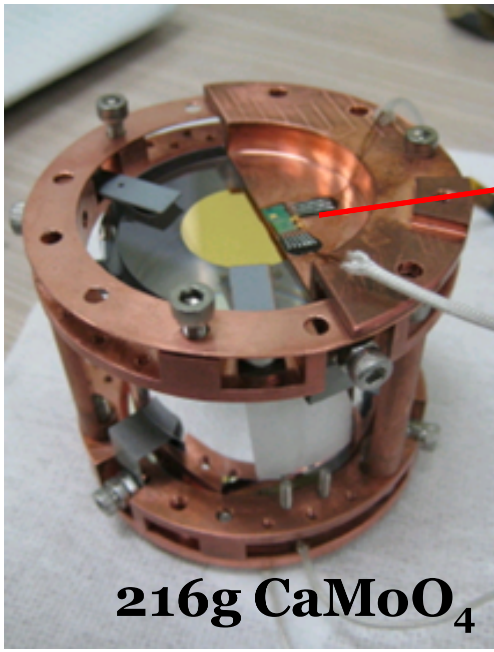


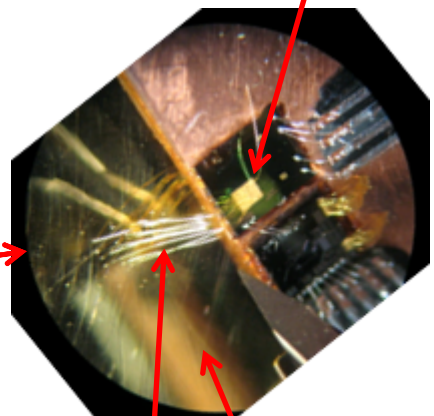
Cryogenic detector for AMoRE experiment

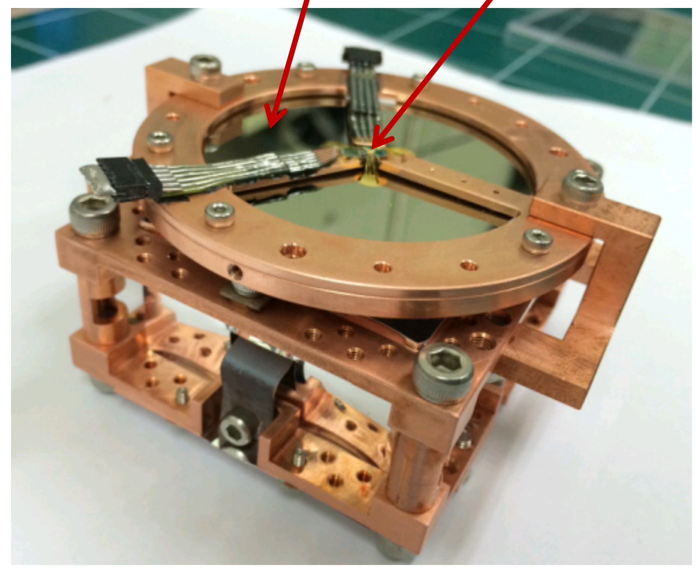
Heat (Phonon) signal

MMC

Light signal
2 inch Ge wafer + MMC







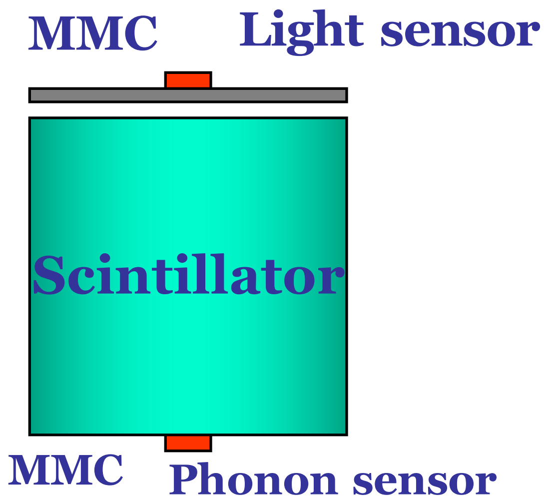
Gold film

Gold wires (thermal connection)

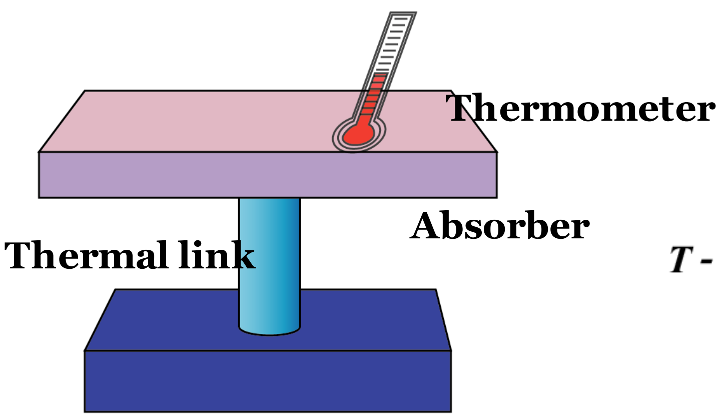
MMC : Metallic Magnetic Calorimeter

- We already developed world best phonon sensor
- Under improvement of light sensor

KIMS-LT experiment

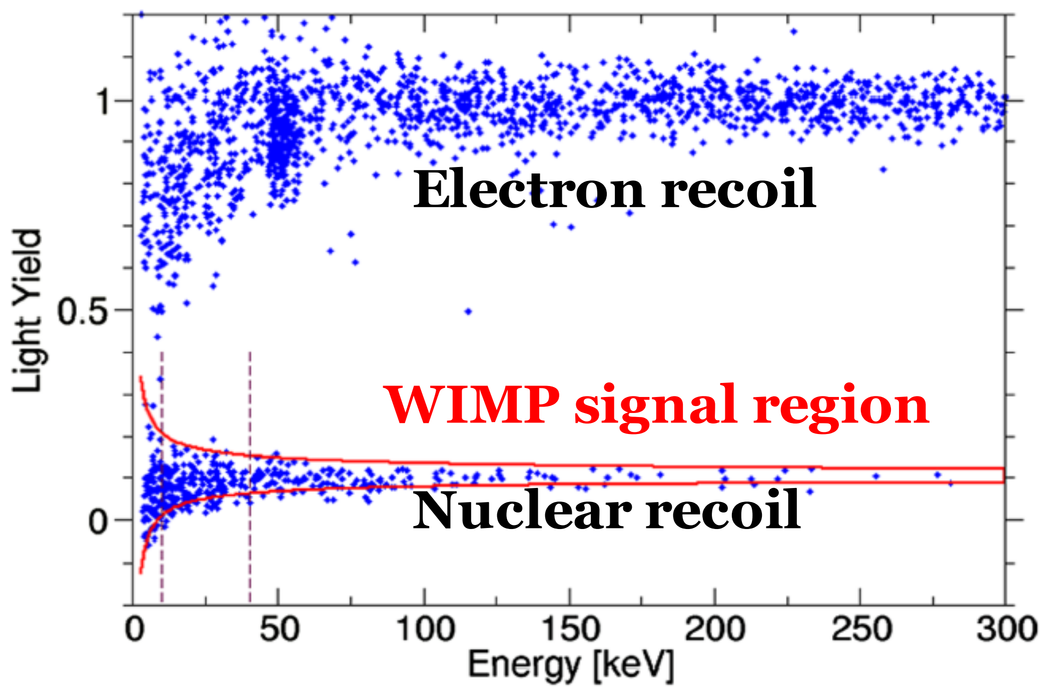


<10-50 mK>



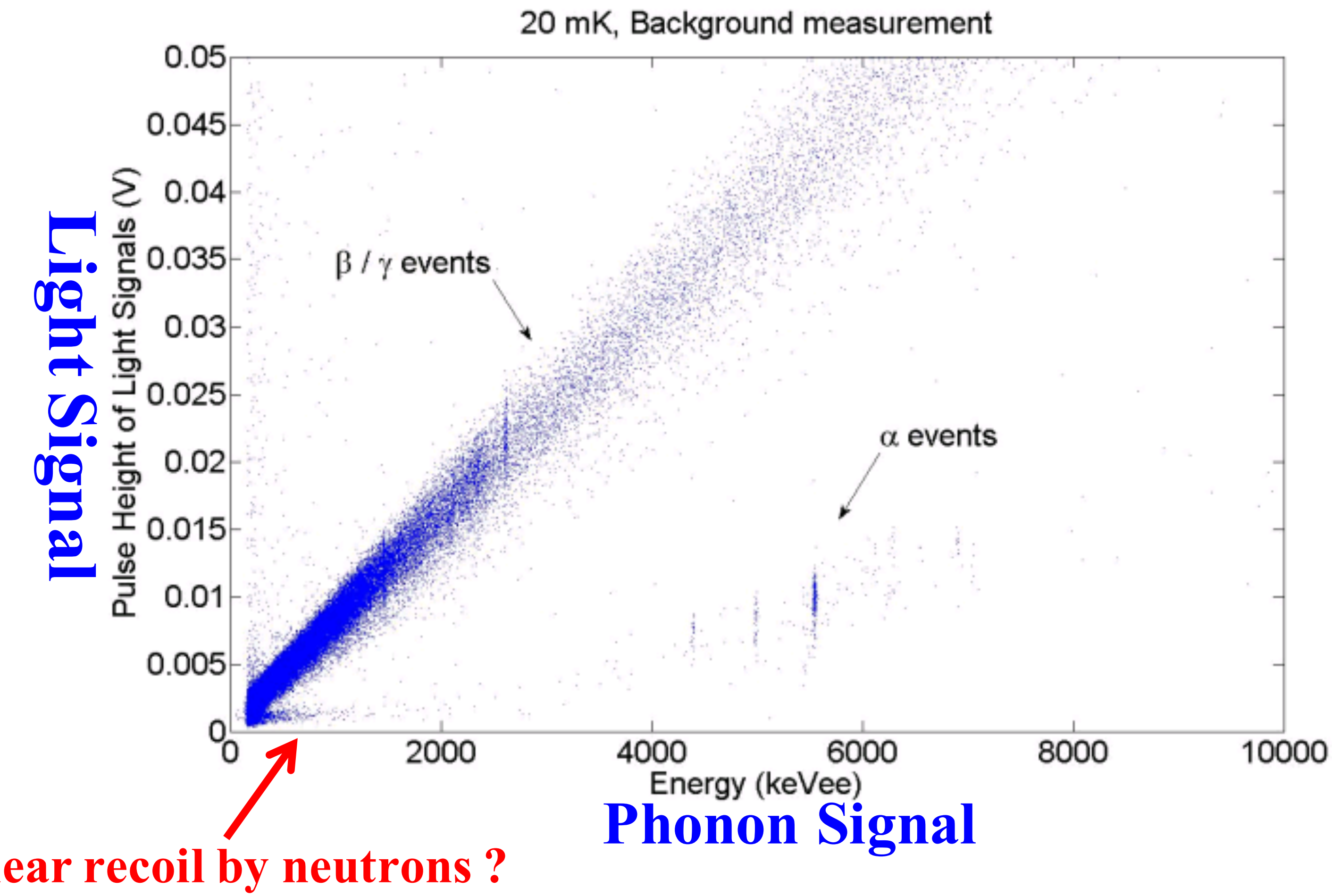
- Scintillator detector @ 10-50 mK
- Ratio of heat-to-light signal make excellent discrimination between WIMP signal and background

CRESST (AmBe neutron source)



Light and Heat signals with our crystal

at KRISS (over-ground) lab



- Need to optimize at low energy

Instrument for crystal development

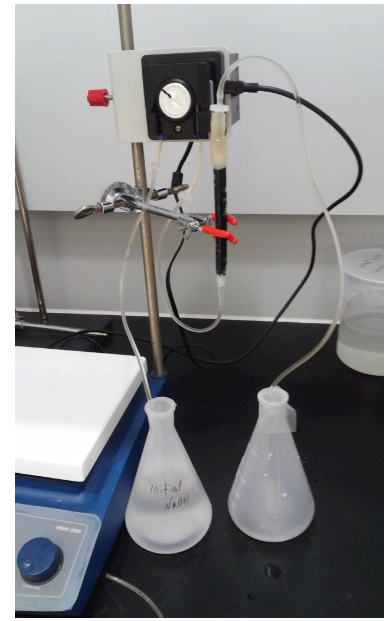
- The center is forming a laboratory for chemical purification and crystal growing.
- Goal : develop the technology for ultra-low background crystals for experiments.
- After construction of new underground lab, underground crystal growing is possible.

Czochralski Furnace

Bridgman Furnace

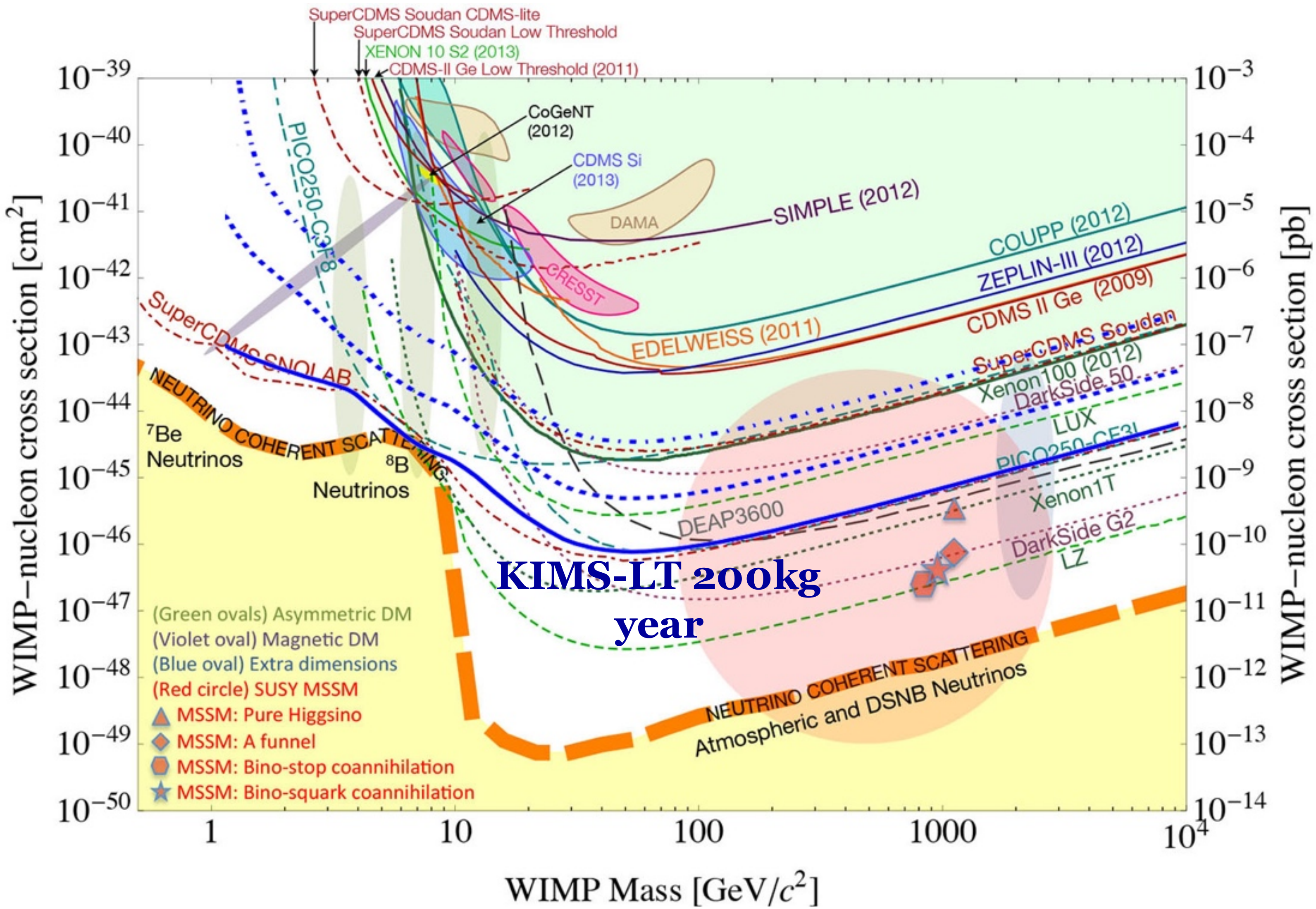
1^{st} crystal (Sapphire) grown ~ 30kg !

Kyropoulos Furnace



$CaMoO_4$ grown

Sensitivity of KIMS-LT

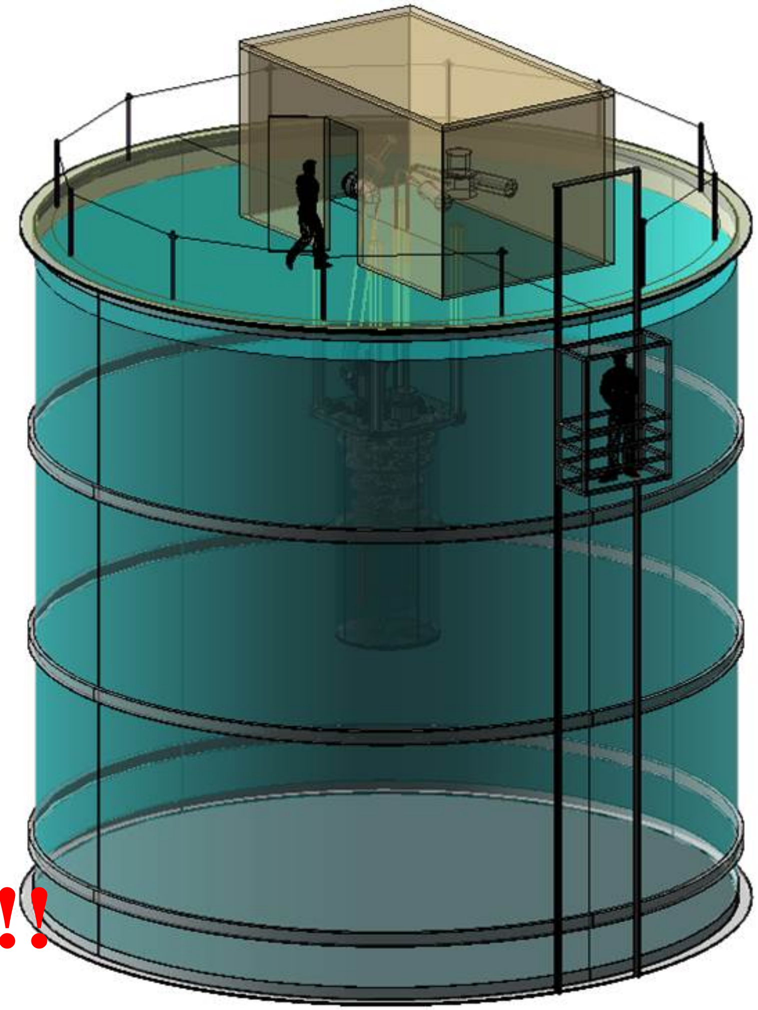


Goal to have **the most sensitive** **detector for the low-mass dark matter**

F

KIMS-LT

- We should achieve below 10^{-2} counts/kg/keV/day event rate
  - To reduce muon : We need deeper underground laboratory
  - External background : 10m water tank need larger space



New underground laboratory is proposed to be deeper and to be wider !!

Summary

- Rare event searches are scientifically very important
  - Neutrino properties
  - Neutrinoless double beta decay
  - WIMP dark matter searches

감사합니다

ありがとうございます

Thank you

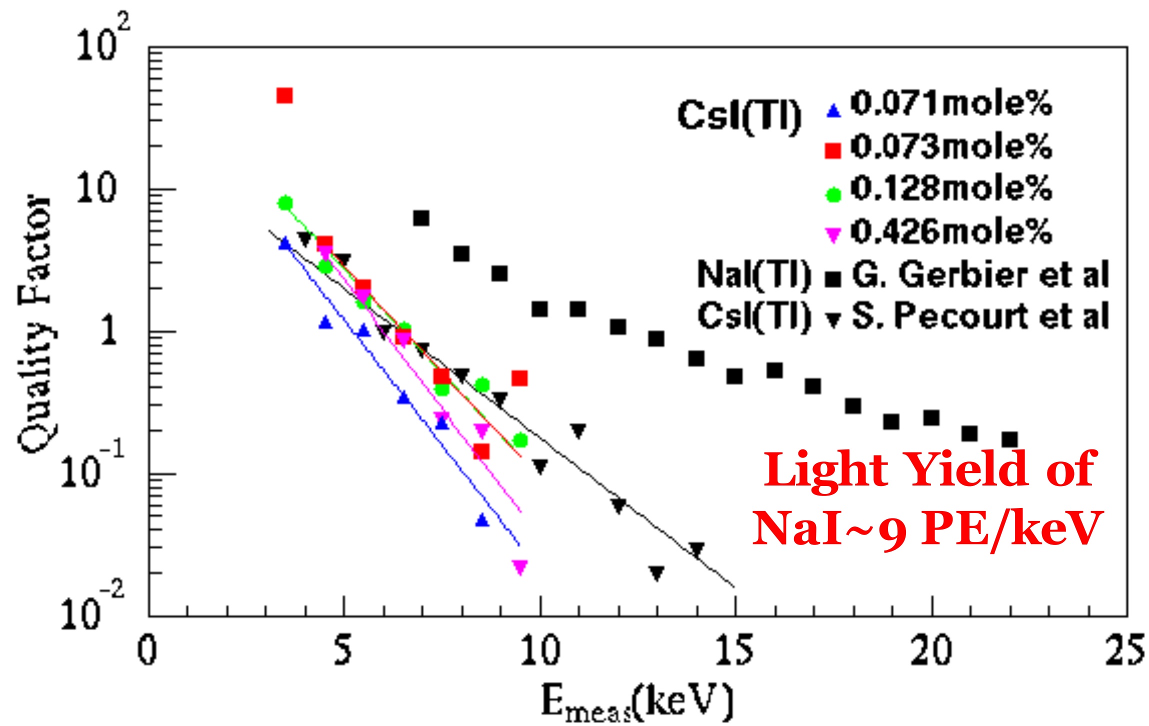
Pulse shape discrimination (PSD) of NaI

Quality Factor

$$K = \frac{\beta(1-\beta)}{(\alpha-\beta)^2}$$

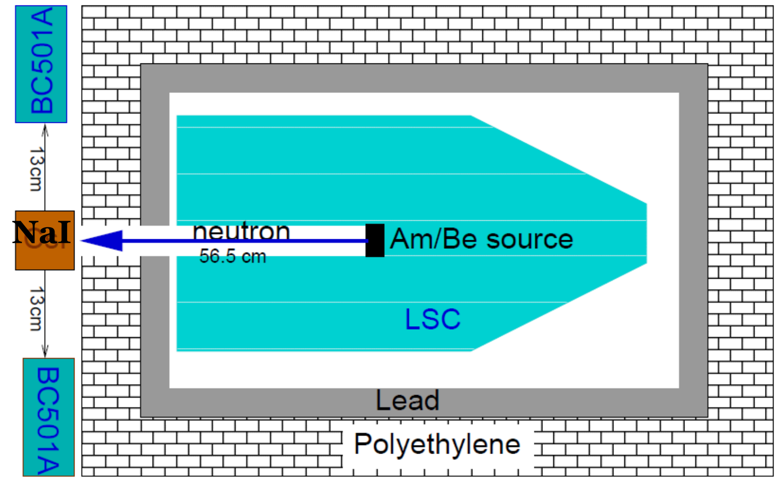
Ideal detector
$\alpha \sim 1$, $\beta \sim 0$
K << 1

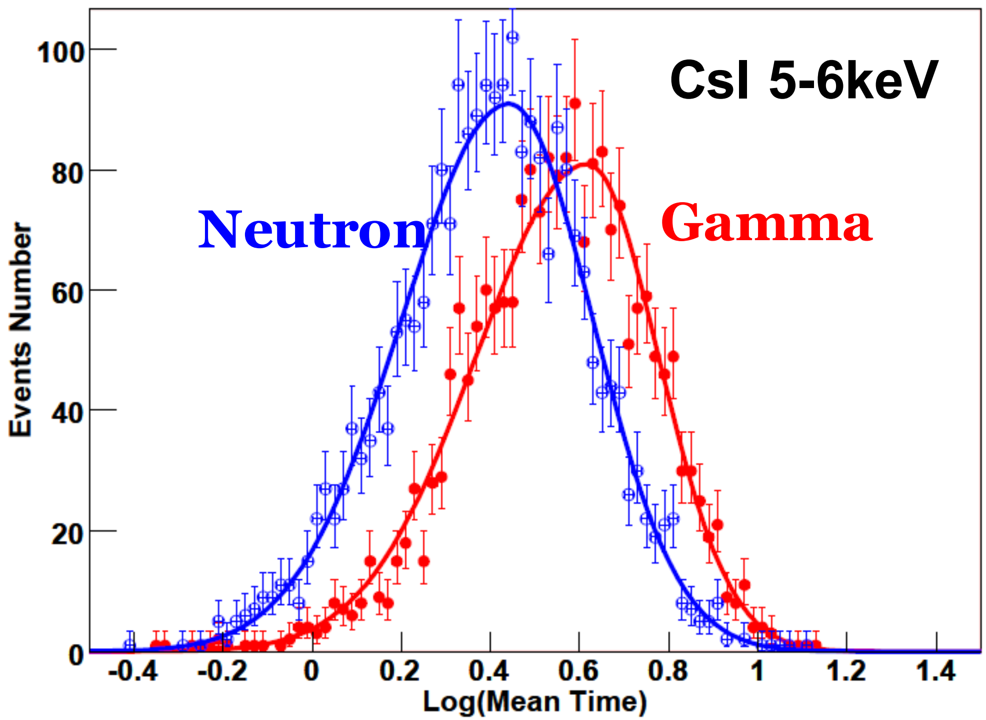
- PSD power of NaI is much poorer than CsI
- However, light yields are important parameter for PSD
  - ❖ Currently ~15 PE/keV

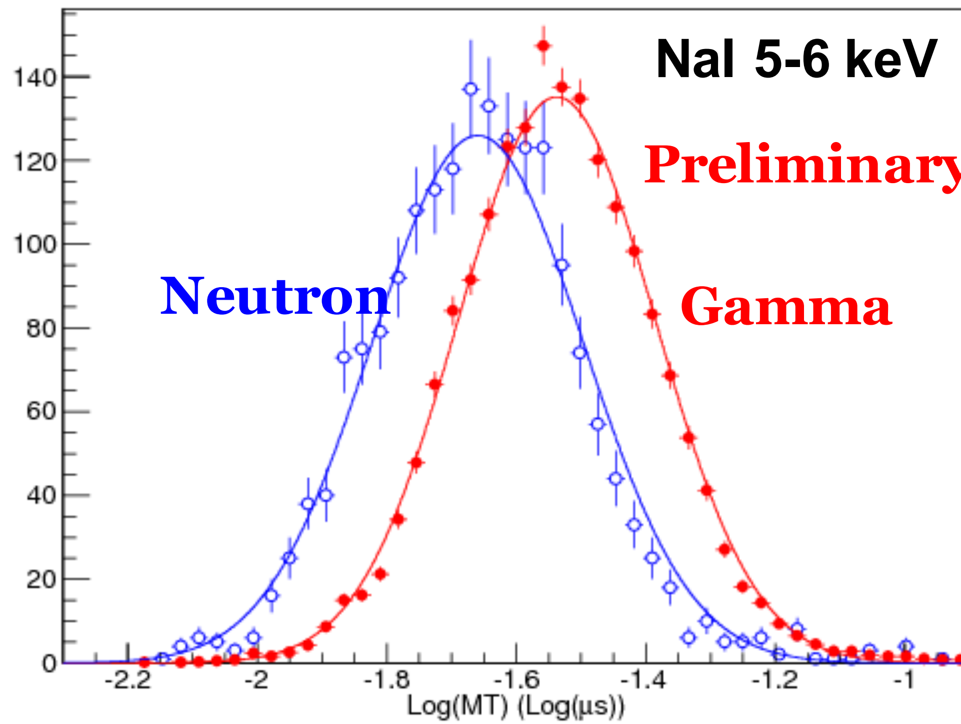


PSD of NaI

- A 300 mCi Am/Be source
- Small test crystal (2×2×1.5cm^3) made in same ingot of NaI-001
- ~16 PE/keV light yield

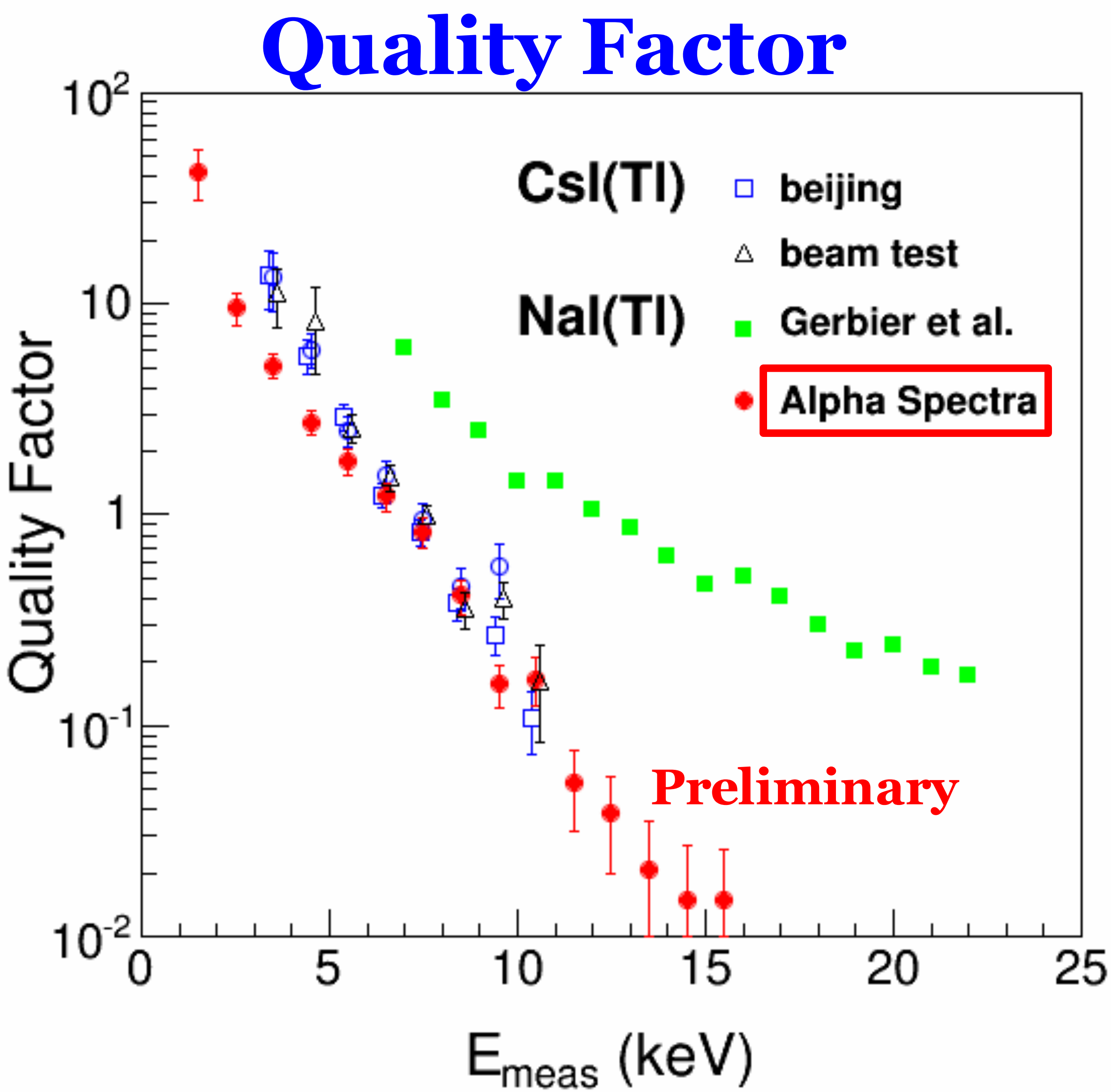


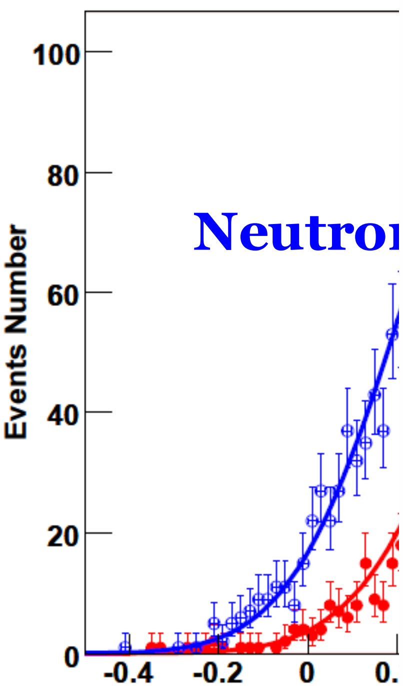


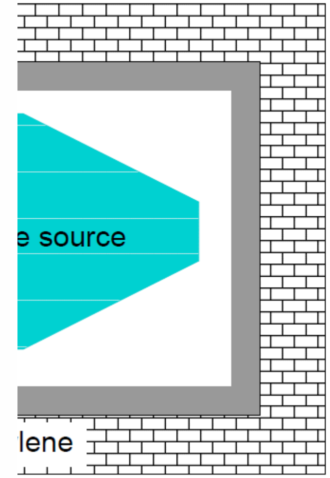


PSD of NaI

- A 300
- Small made w
- ~16 PI



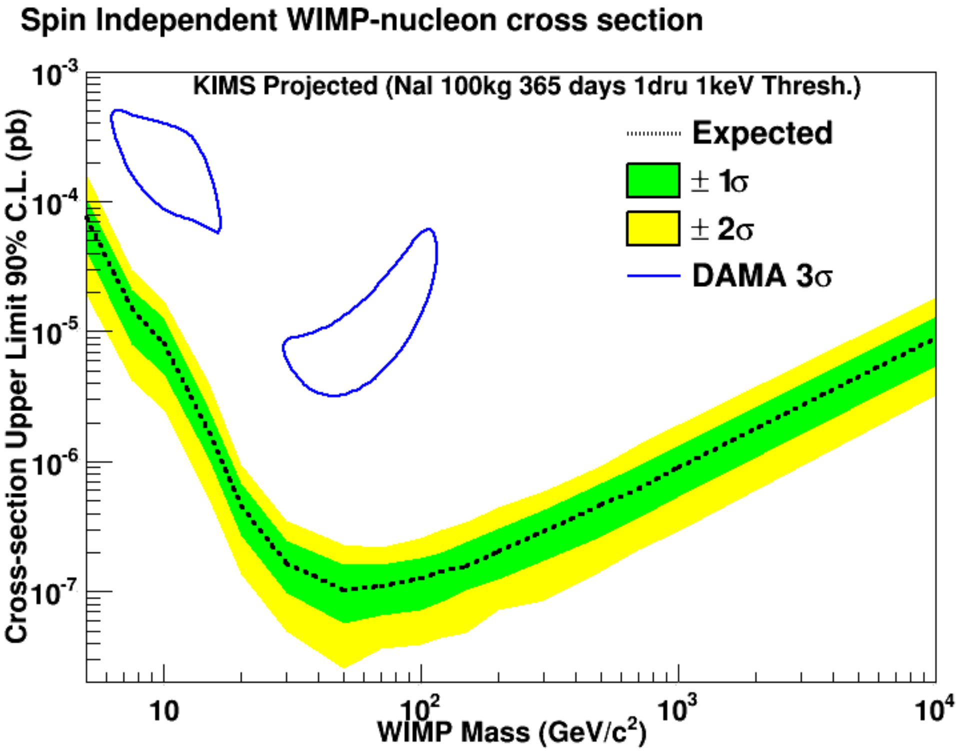




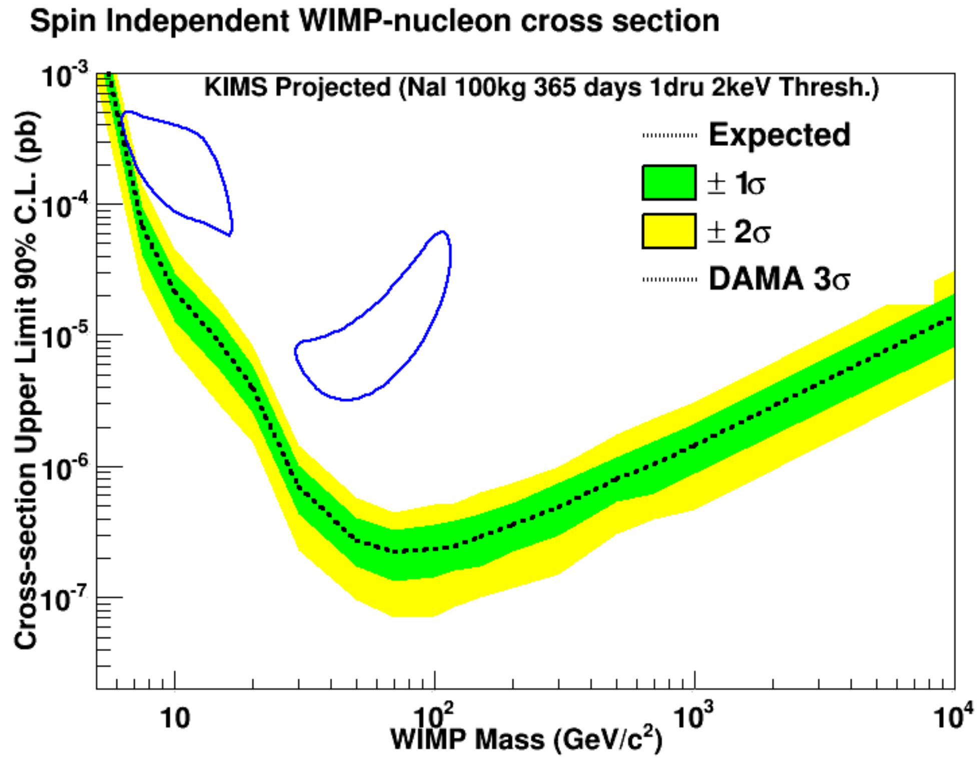
KIMS-NaI Sensitivity only using PSD

- Assuming **100kg NaI (1 dru)**crystal and **1 year** data taking
  - **100% efficiency**
  - **No constraints** on background rate
  - **Assuming no signals**

1 keV Threshold



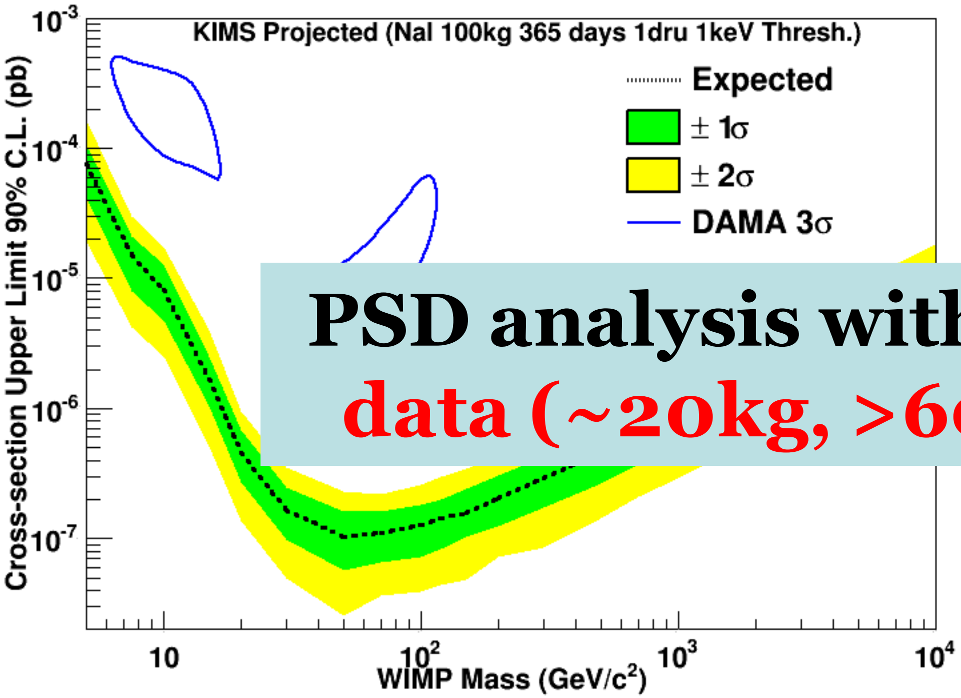
2 keV Threshold



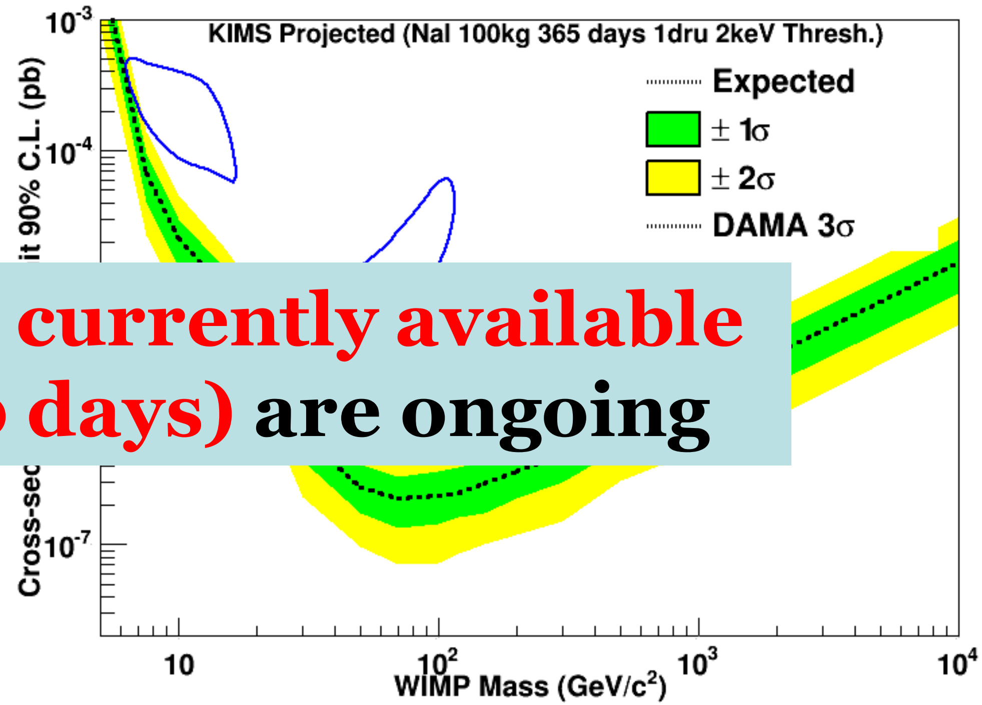
KIMS-NaI Sensitivity only using PSD

- Assuming **100kg NaI (1 dru)** crystal and **1 year** data taking
  - ❖ **100% efficiency**
  - ❖ **No constraints** on background rate
  - ❖ **Assuming no signals**

1 keV Threshold



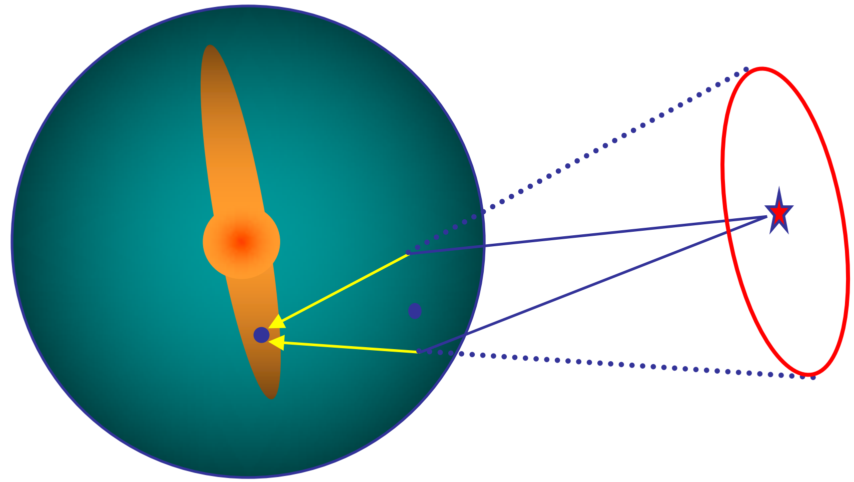
2 keV Threshold

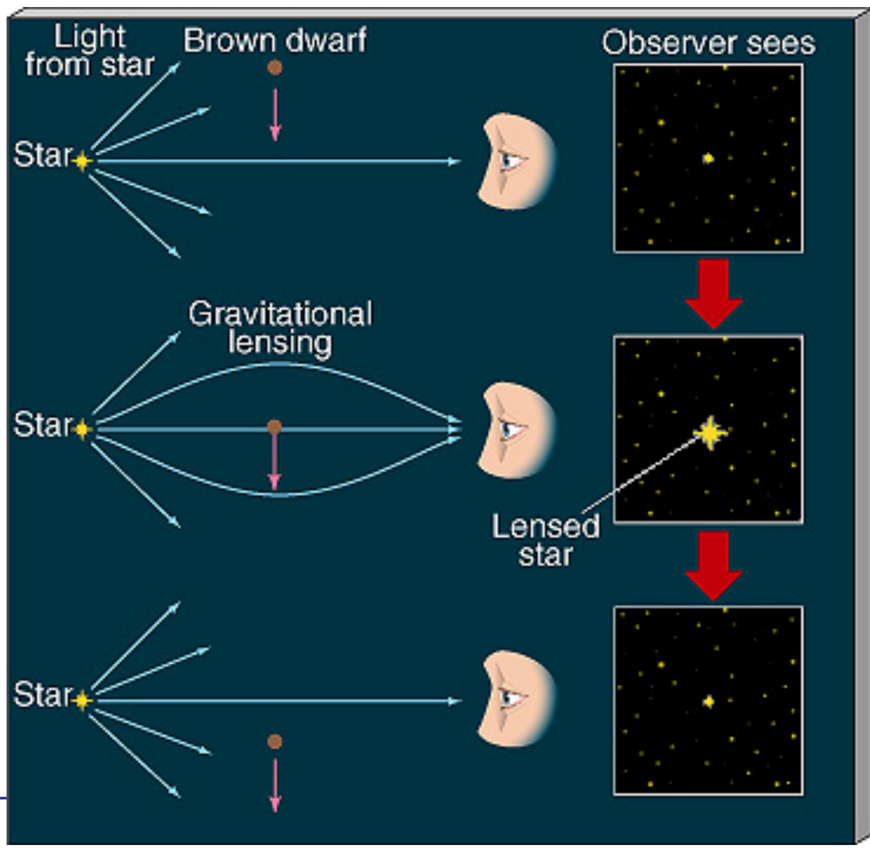


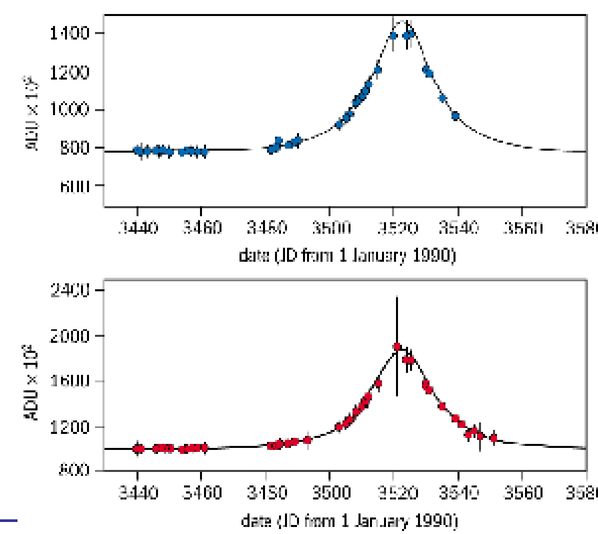
PSD analysis with currently available data (~20kg, >60 days) are ongoing

암흑물질은 우리가 알고 있는 물질(Baryon)?

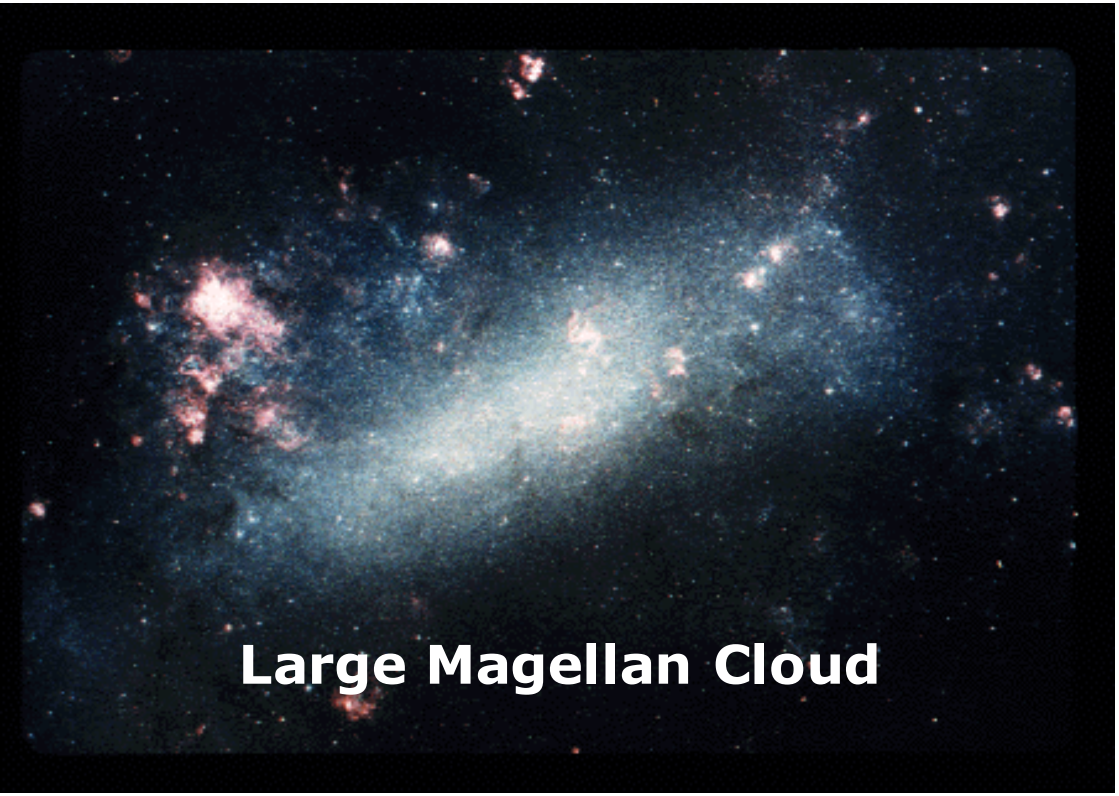
- MACHO (Massive Compact Halo Objects)
  - ❖ 난장이별 (dwarf stars) 중성자별 (neutron stars) 블랙홀 (black hole)
  - ❖ 중력 렌즈 효과로 탐색 가능



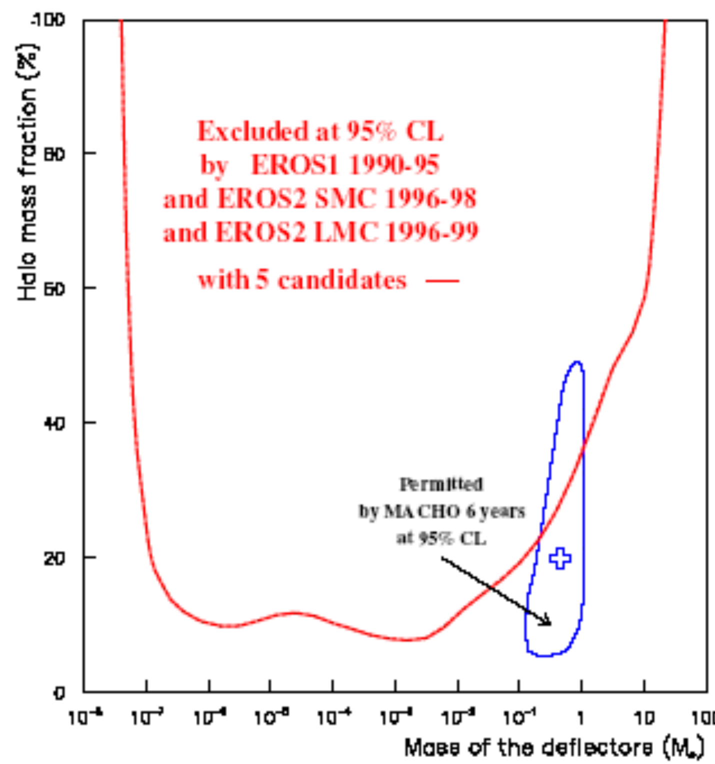




MACHO & EROS 실험



- 마젤란 성운의 별 약 천만 개를 관측한 결과 **MACHO**를 확인하였으나 암흑물질을 설명하기에 **충분하지 않다**

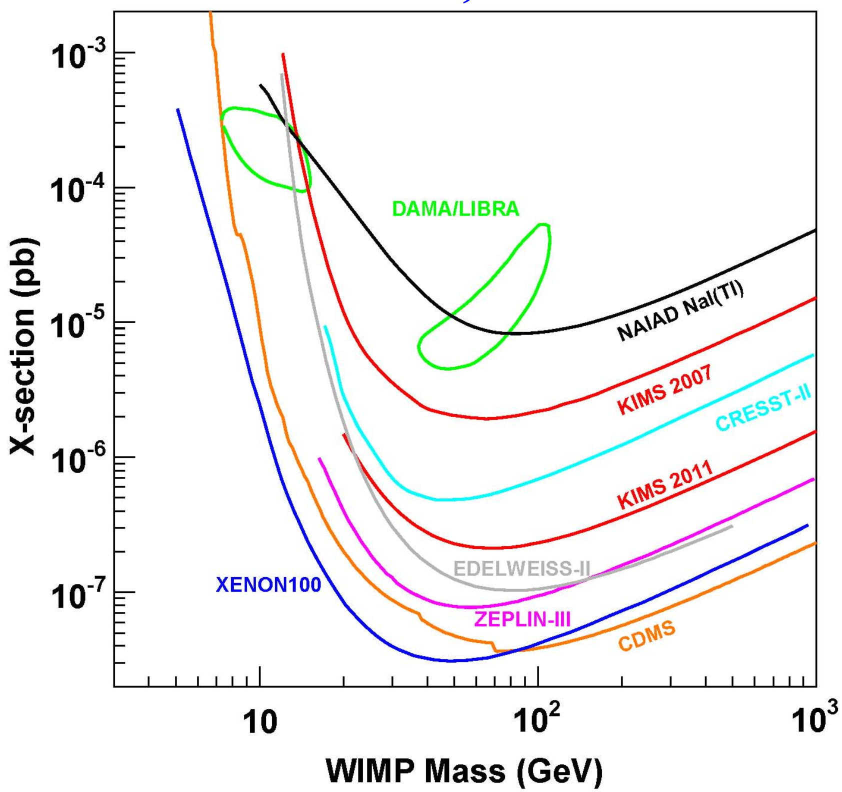


우리가 모르는 새로운 물질

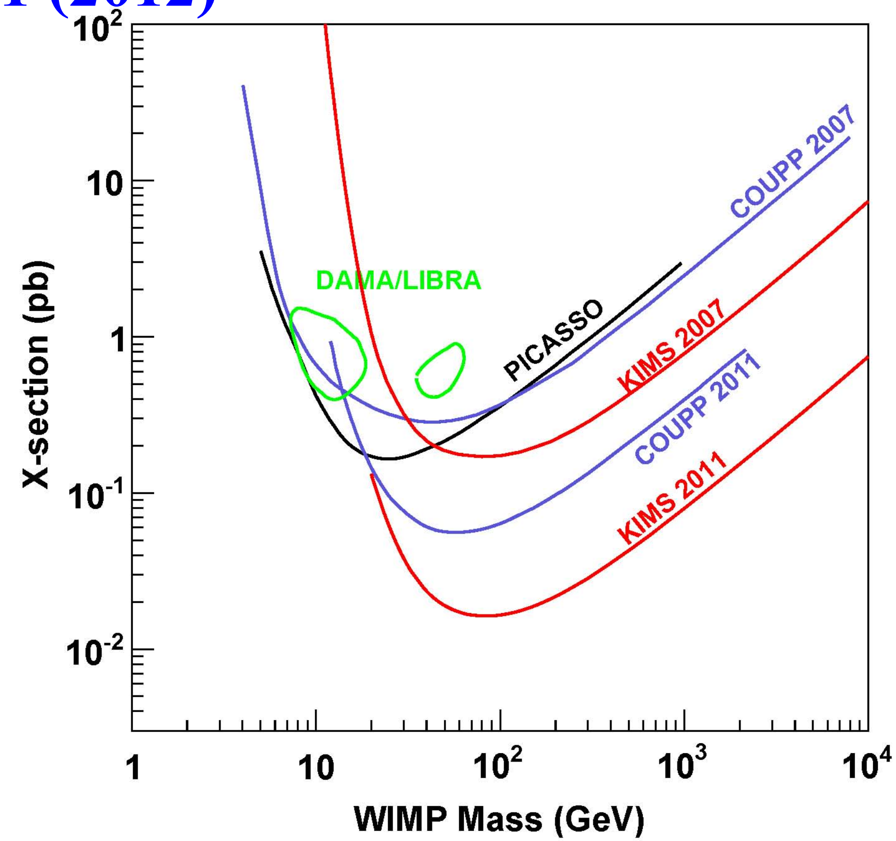
새로운 입자 ?

KIMS CsI – PSD analysis

S.C. Kim et al., PRL 108 181301 (2012)



SI cross section limit



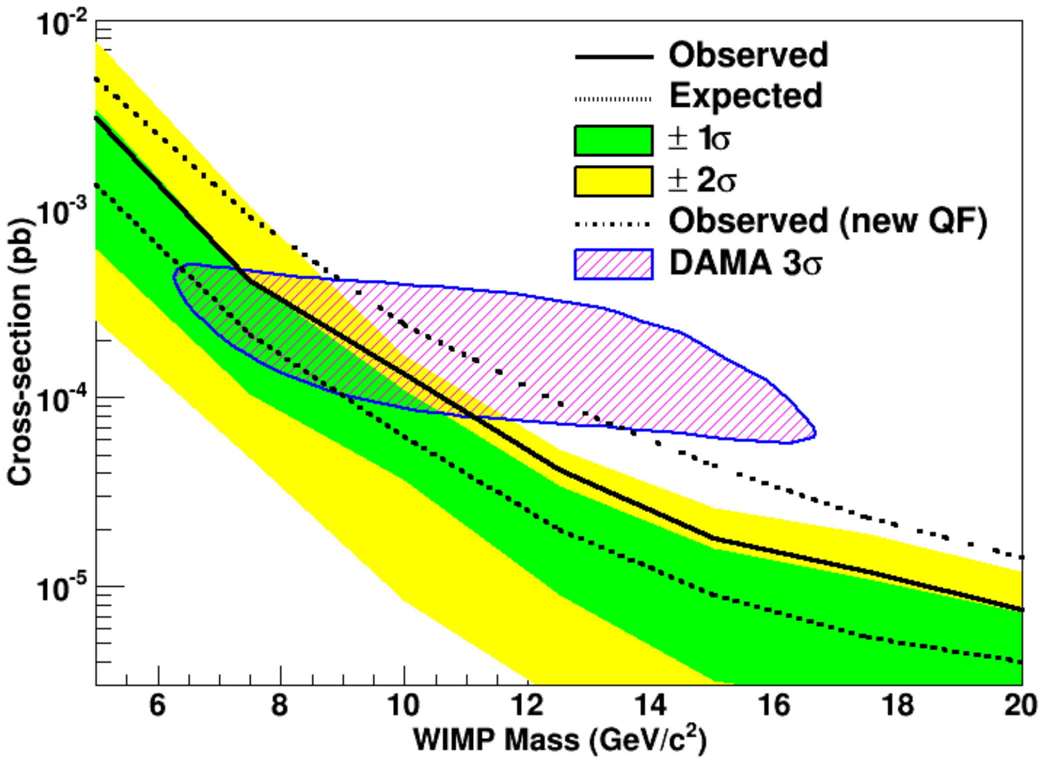
SD cross section limit

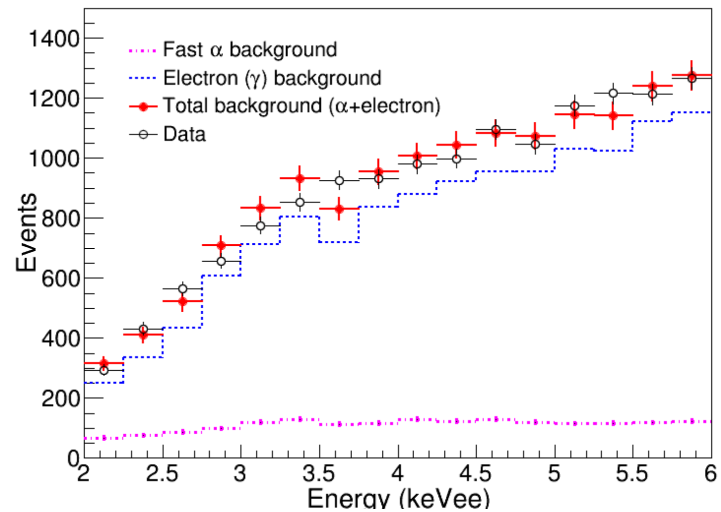
Significant limits are given at an order of magnitude below DAMA Iodine signal.

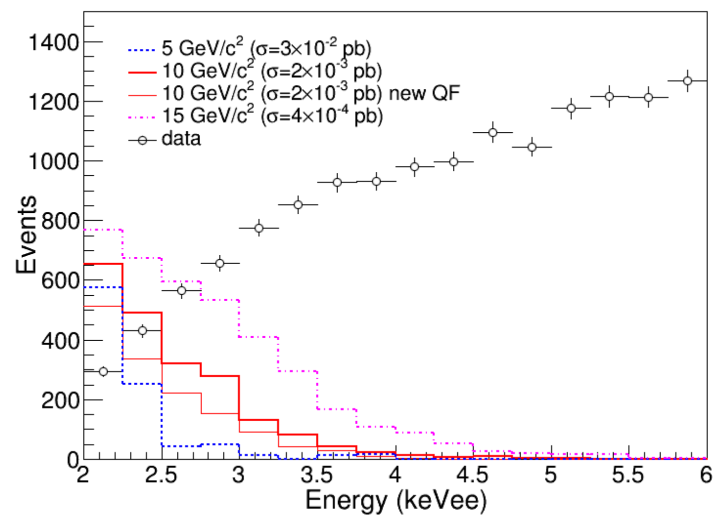
Used only 1 year data so, need to analyze full data set

KIMS CsI – Low Mass WIMP

H.S. Lee et al., PRD 90, 052006 (2014)

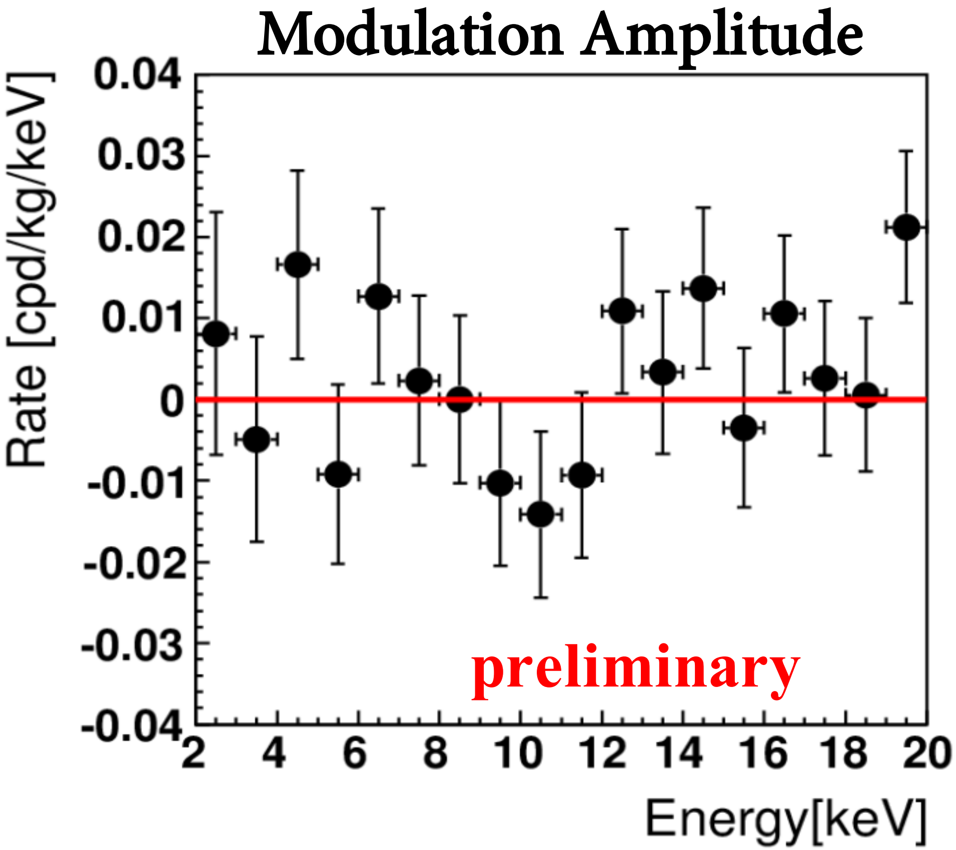


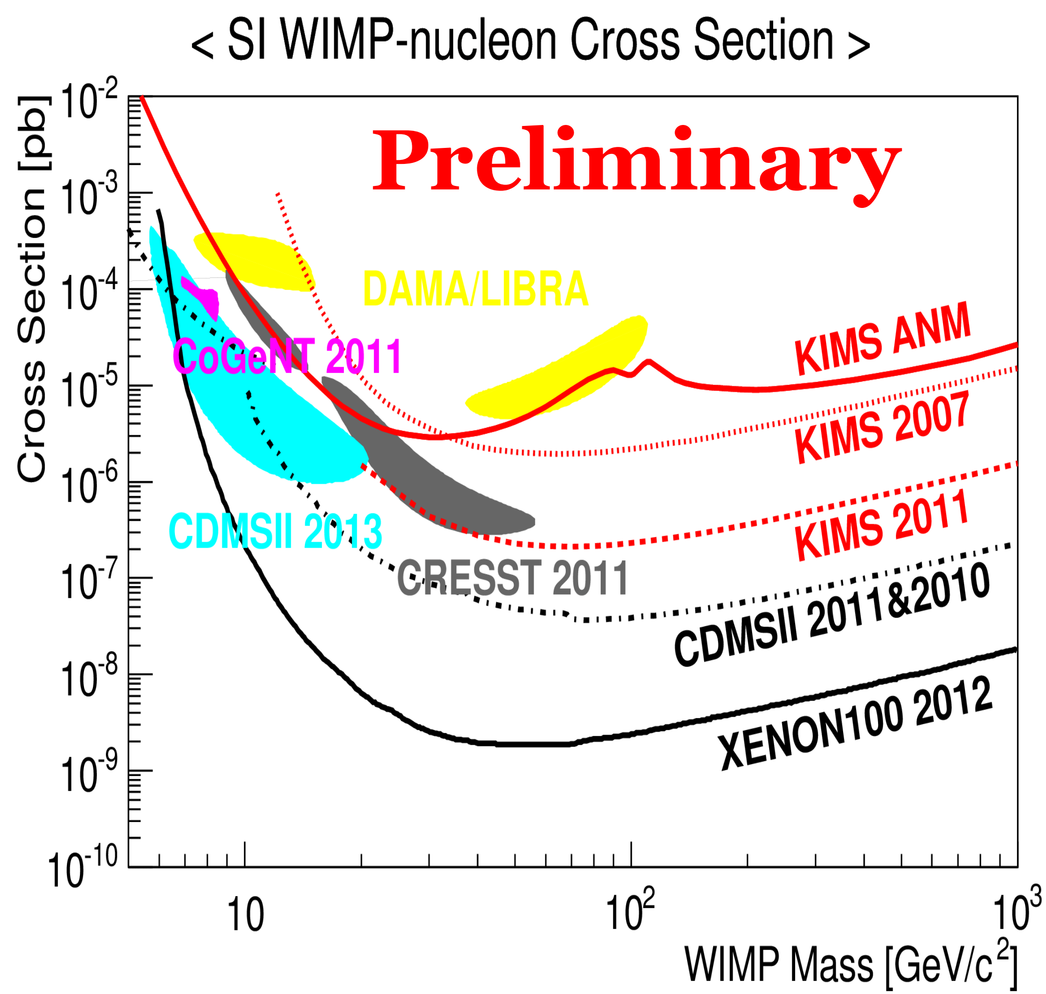




- No PSD but, fit energy spectra
  - ❖ Down the energy threshold as 2keV
- No clear signal, so set limits
- Use 1 year data

KIMS CsI – Annual Modulation





- **Null annual modulation is observed. (0.0008±0.0068 cpd/kg/keV)**

Intrinsic Background of NaI crystals

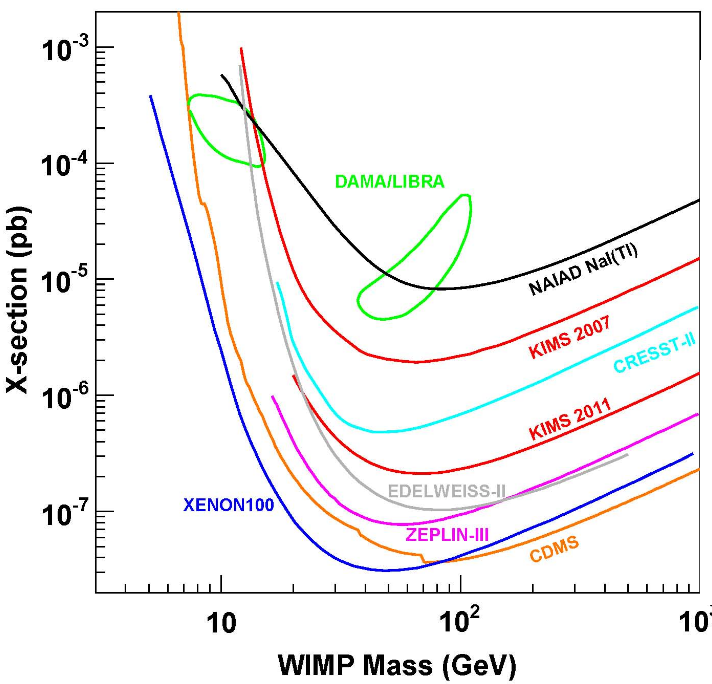
	NaI-001	NaI-002	NaI-003	NaI-004	NaI-005	NaI-006
Powder	AS	AS	SA-AG	SA-CG	AS	SA-CG
K (ppb)	41.4±3.0	49.3±2.4	**25.3**±3.6	>117	40.1±4.2	>127
K (powder)	?	?	**25.1**	~200	43	~200
^{238}U	<0.02	<1.04	<0.14	-	<0.04	<0.05
^{232}Th	<3.17	<0.48	0.46±0.07	-	0.19±0.002	8.9±0.04
α rate(mBq/kg)	**3.29**±0.01	**1.77**±0.01	2.43±0.01	-	**0.48**±0.004	1.53±0.01
LY(pe/keV)	12.1±0.9	15.1±1.1	12.6±0.1	3.8±0.4	11.3±0.2	4.8±0.4

- Important backgrounds are ^{40}K and ^{210}Pb
  - 25 ppb K ~ 0.4 dru @ 2-4 keV
  - 0.5 mBq/kg ^{210}Pb ~ 0.7 dru @ 2keV
- Powder is the main source of K contamination
  - ~ 10 ppb K powder are available from both SA and AS
- AS reduced ^{210}Pb by a factor 4

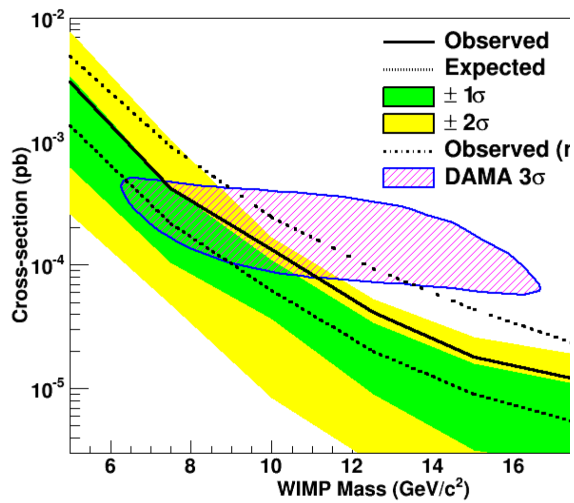
KIMS-CsI experiment

- 12 crystals (104.4 kg)
- 2.5 year data (2009-2012)
- Background : 2~3 count/kg/day/keV (dru)
- Model-independent rejection of DAMA signals interpreted as WIMP-Iodine interaction

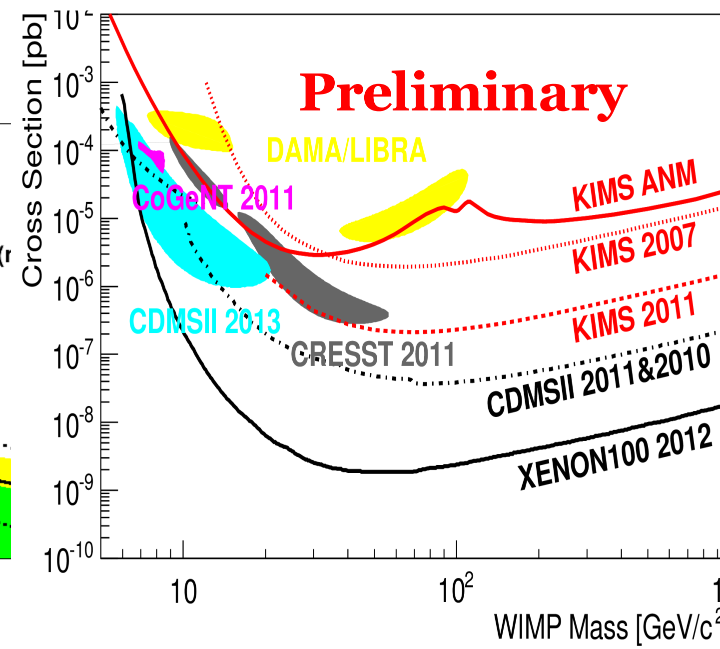
PRL 108, 181301 (2012)



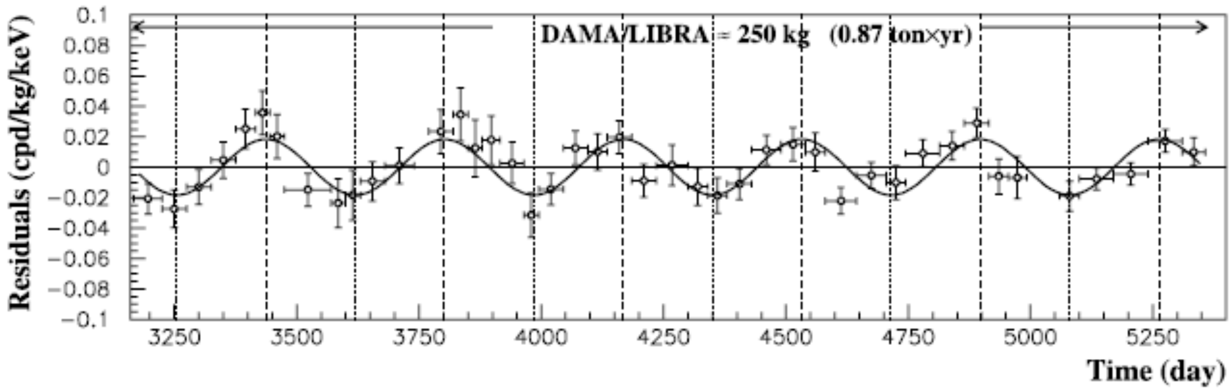
PRD 90, 052006 (2014)



Annual Modulation



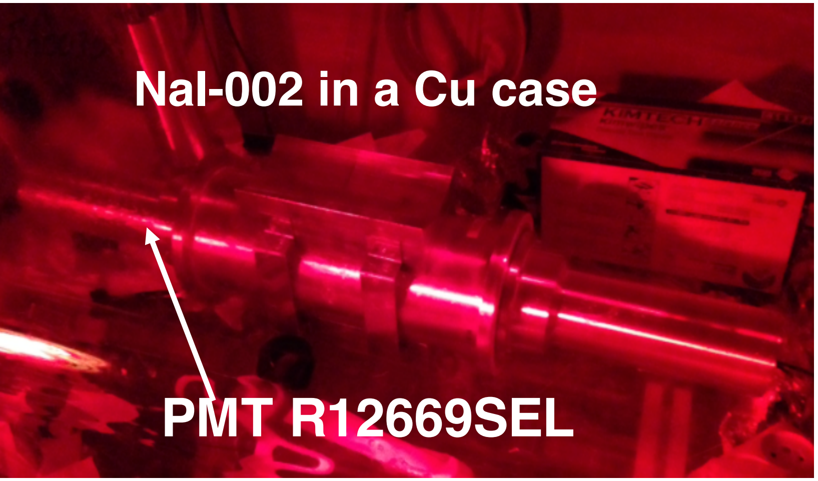
KIMS-NaI experiment

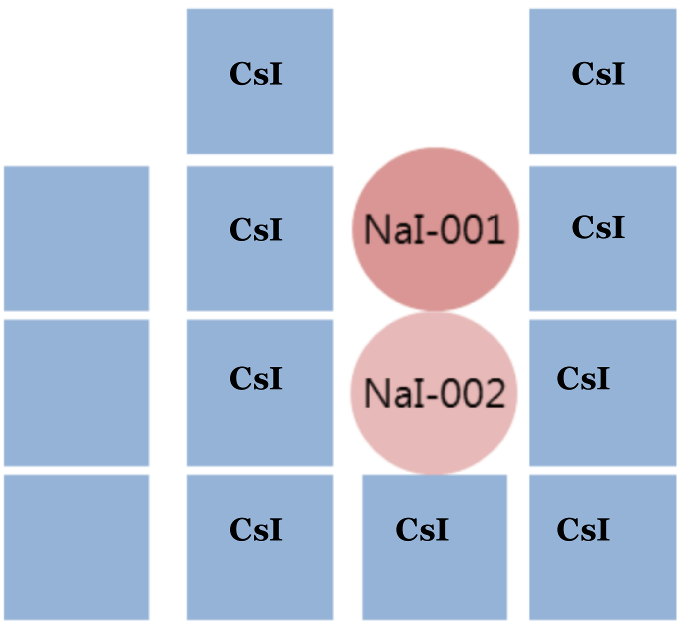


- To confirm DAMA annual modulation signature
  - **CsI** is not enough for **WIMP-Na** interaction
  - Same NaI crystal for the same annual modulation signature
- Need to develop ultra-pure NaI(Tl) crystals
  - Goal is less than DAMA background (~1 dru = 1 counts/keV/kg/day)
  - 200 kg×3 years data will prove DAMA signature without any ambiguity
- COSINE (**CO**n**S**oritum of **I**nternation **N**aI **E**xperiment)
  - KIMS & DM-Ice will run in Yangyang together
  - ANAIS will run in Canfranc

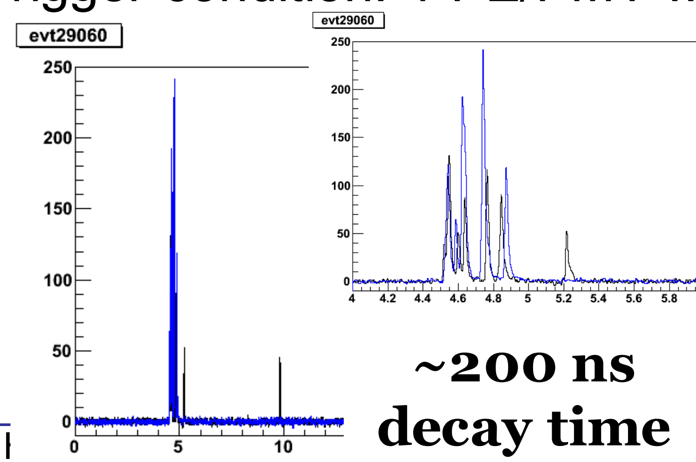
Compare and combine the data

KIMS-NaI detector module





- Hamamastu R12669 PMTs are attached
  - ❖ Supposed same PMTs with recently upgraded DAMA PMTs
  - ❖ ~35% quantum efficiency at 420nm
- Light Yield: ~15 photoelectrons/keV
  - ❖ More than 50% larger than DAMA crystals
- Data taking
  - ❖ 400MHz Flash ADC (Notice Korea)
    - ❑Flexible trigger logic with FPGA
    - ❑Trigger condition: 1 PE/PMT within 100ns



~200 ns decay time

KIMS-NaI crystals

- Development of low background NaI(Tl) crystals

	NaI-001	NaI-002	NaI-003	NaI-004	NaI-005	NaI-006
Mass	8.26 kg	9.15 kg	3.35kg	3.35kg	9.16 kg	11.44 kg
Powder	AS	AS	SA-AG	SA-CG	AS	SA-CG
Crystal	AS	AS	AS	AS	AS	BH
Arrive	2013.9	2014.1	2014.8	2014.8	2014.11	2014.12

K.W.Kim et al., Astropart. Phys. 62, 249 (2015)

P. Adhikari, arXiv:1510.04519

NaI-007 (replacement of NaI-005) was arrived at Y2L

Glossary

AS = Alpha Spectra Inc (US company)

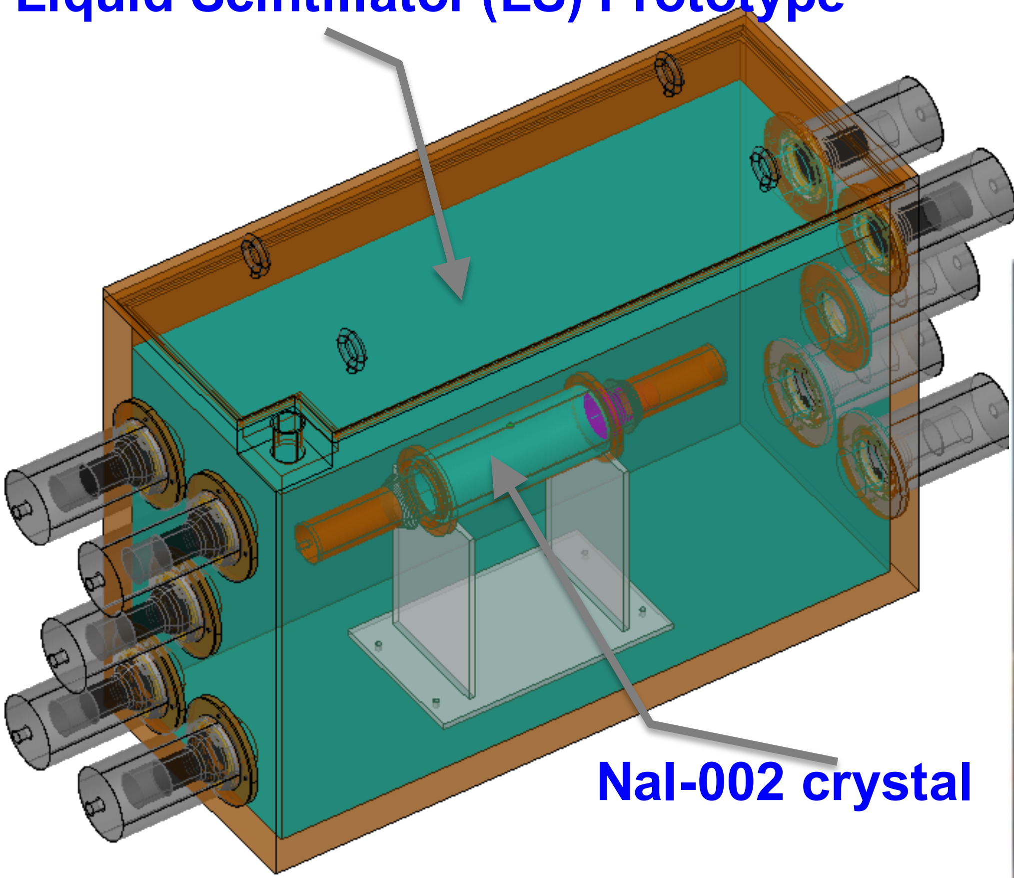
SA-AG = Sigma Adrich, Astro-grade (less K40)

SA-CG = Sigma Adrich, Crystal-grade

BH = Beijing Hamamatsu (China)

External background reduction

- We prepared liquid scintillator active veto system prototype
  - Veto efficiencies for sources from PMT radioisotopes (U, Th, K) were greater than 80% at low energy (0-10 keV)



Internal ^{40}K ~ 40% veto efficiency