# Searching for dark matter with liquid xenon

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The University of Tokyo

# Contents

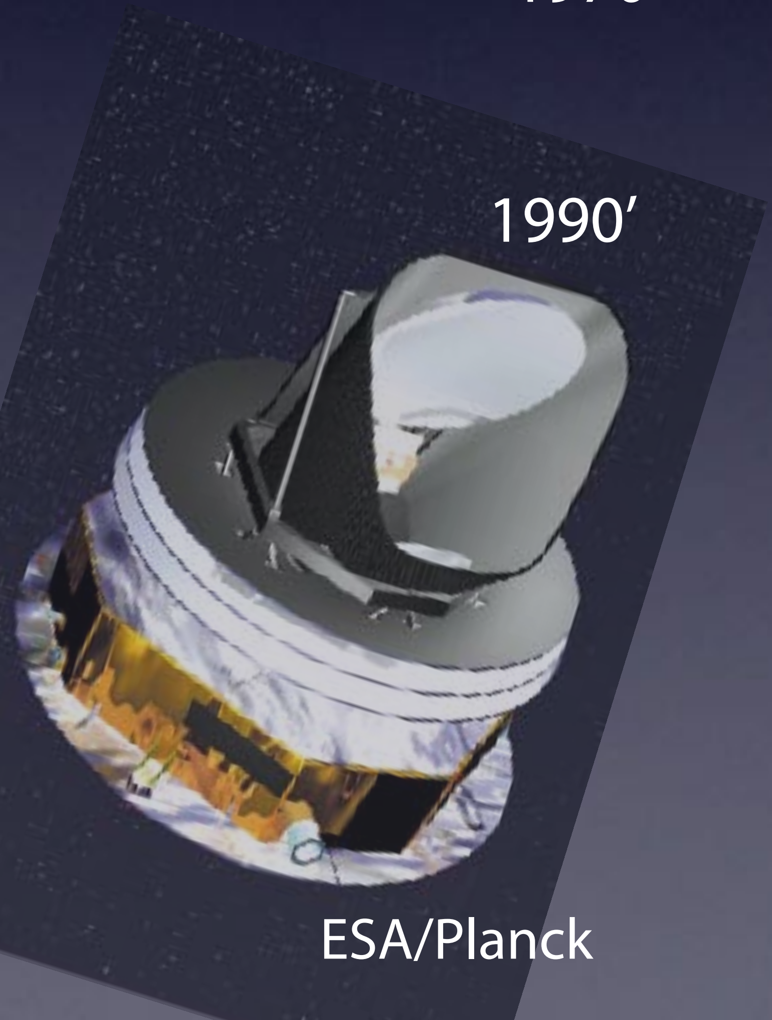
- Introduction to direct dark matter search
- Search by two phase Xe detector (WIMP)
- Search by single phase Xe detector (Non-WIMP)
- Future prospects

# History of Dark Matter Mystery

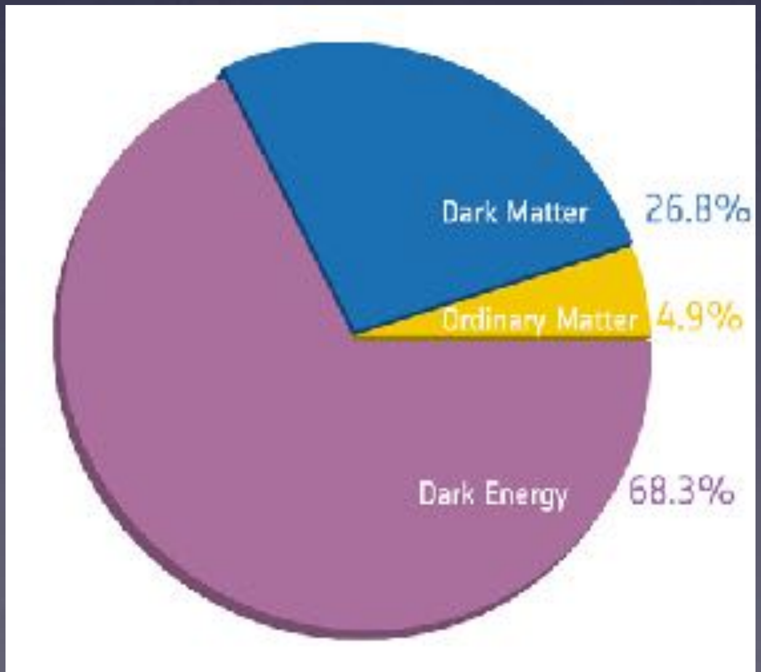


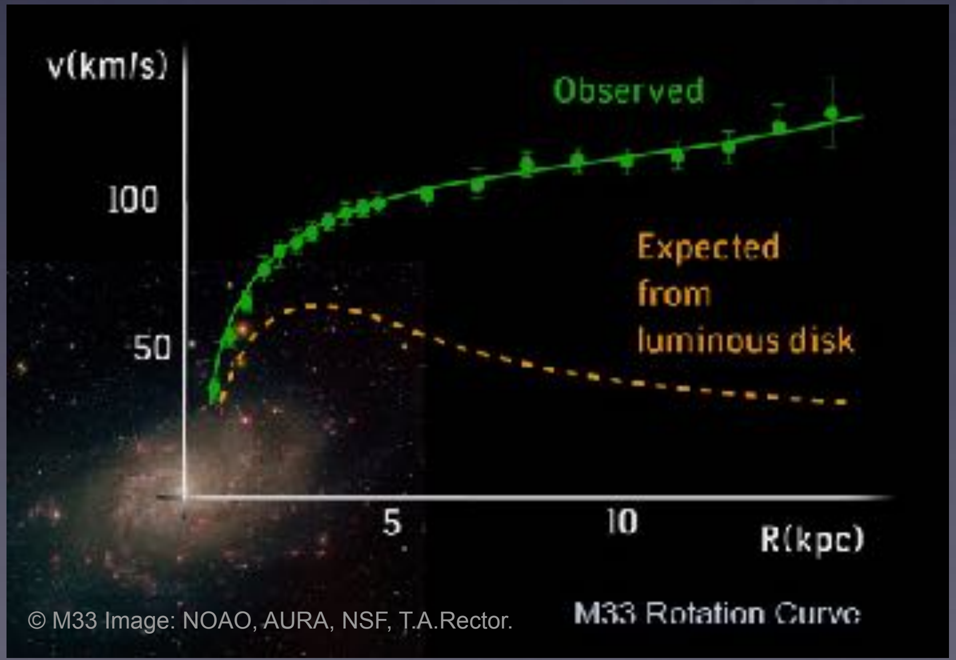

- 1933 F. Zwicky
  Factor 400 of Discrepancy of mass estimation via Doppler Redshift of 8 galaxies in Coma Cluster.
  —＞"Dark Matter"
- 1970' Progress on radio astronomy. Rotation curve for the spiral galaxy via 21cm emission from neutral hydrogen gas by Vera Rubin and others.

1990' CMB observation (COBE, WMAP, Planck)



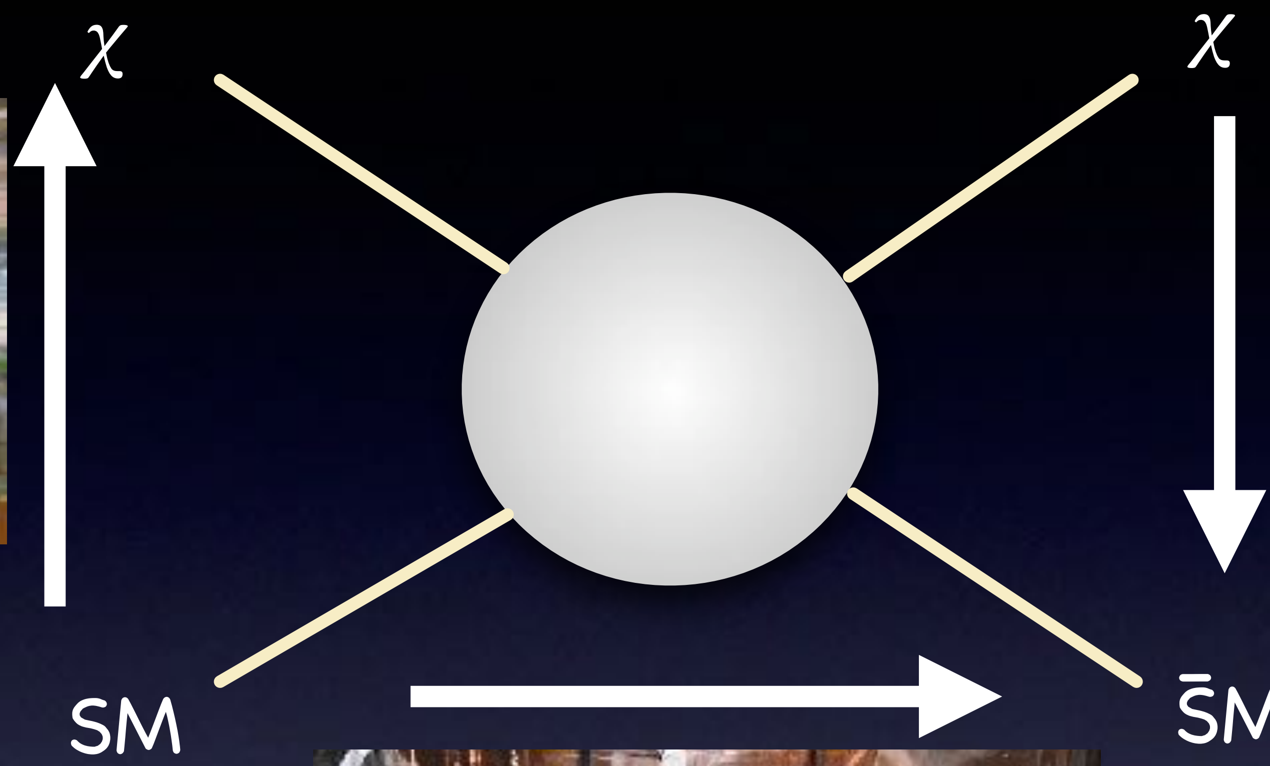
ESA/Planck



# Approaches to look for dark matter

Colliders
LHC, ILC ...




indirect
SK, CTA, AMS02 ...

direct
XMASS, XENON, LZ …


$\rho_{dm} = 0.3\ \mathrm{GeV/cm^3}$

a few dark matter particle around us !

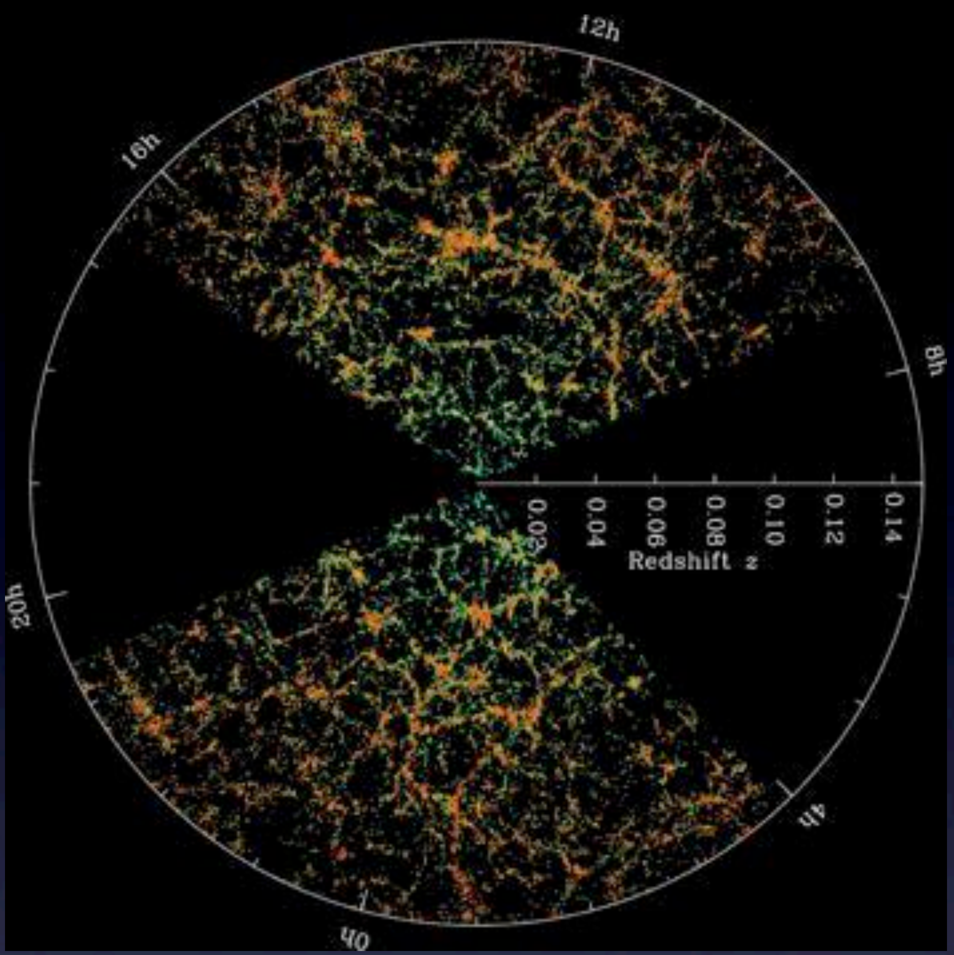
only direct search can tell us about dark matter around us.

# WIMP(dark matter candidate)

Dark Matter is required to be

- Neutral
  ➡ can not see ...
- Non-baryonic
  ➡ weakly interacting
- Cold (non-relativistic)
  ➡ structure formation

astrophysics




M. Blanton and the SDSS

favorite candidate predicted by

SUSY

particle physics

⇒ One of the favored scenario beyond standard model:

The lightest SUSY particle is stable and likely becomes a dark matter candidate

Linear combination of SUSY particles

$$\chi_1^0 = \alpha_1 \tilde{B} + \alpha_2 \tilde{W} + \alpha_3 \tilde{H}_u^0 + \alpha_4 \tilde{H}_d^0$$

# How to detect WIMP ?

## a needle in a haystack

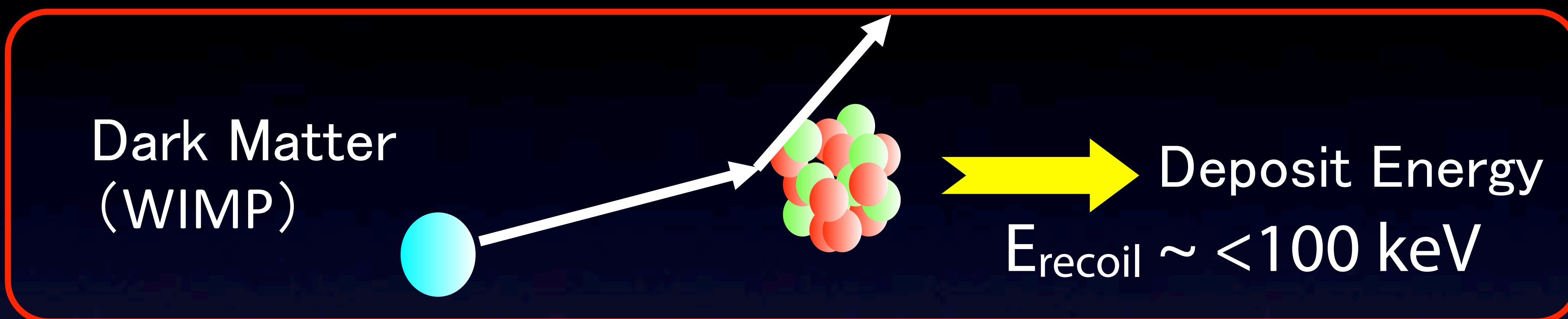

above ground without shield
$10^6$ counts/kg/day

WIMP event
$<10^{-6}$ counts/kg/day

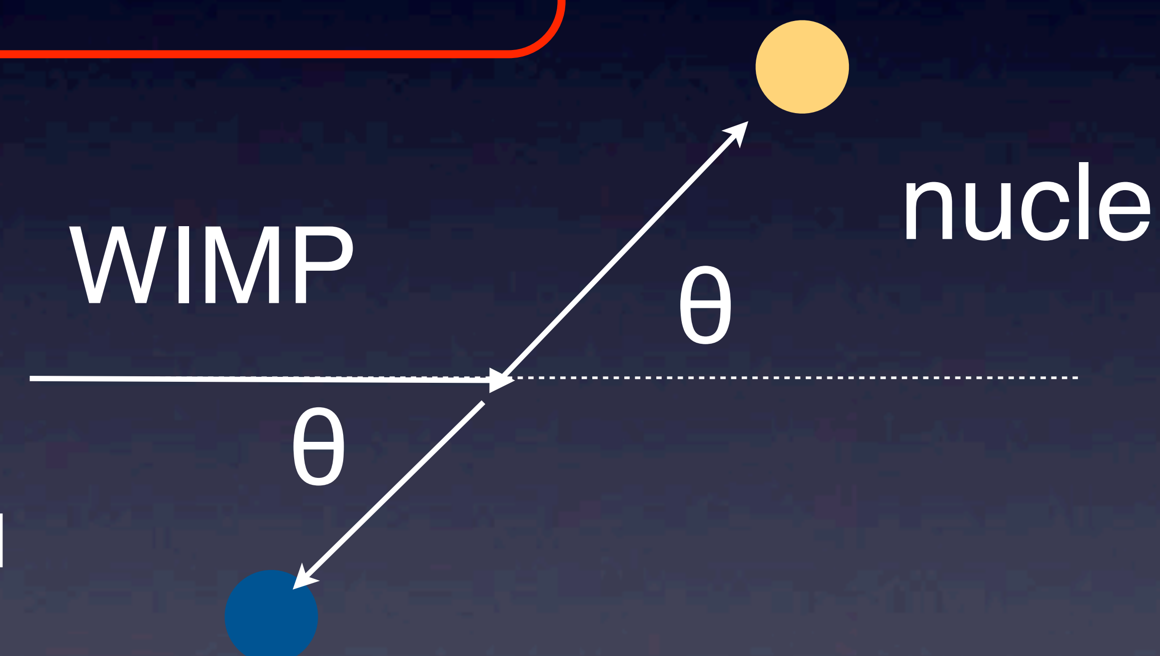
Effort to reduce radioactive background in the under ground laboratory

# Detection principle

## WIMPs elastically scatter target nuclei




$$\chi + N \rightarrow \chi + N$$




For example, assuming

$M_W$ = 100 GeV/c2 , $M_T$ = 100 GeV/c2 , r = 1

WIMP velocity: v~ $0.75 \times 10^{-3}$ = 220 km/sec

$$E_R = \frac{1}{2} M_W \beta^2 c^2$$

$$= 1/2 \times 100 \times \mathrm{GeV}/c^2 \, (0.75 \times 10^{-3})\, c^2$$

$$= \boxed{30 \text{ keV}}$$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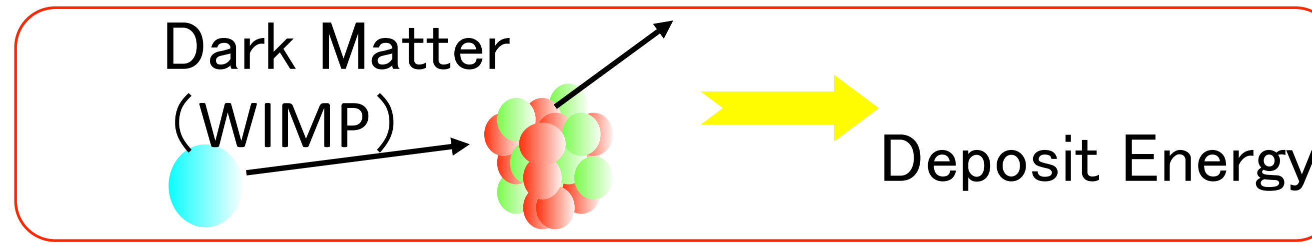
# Differential Rate

Measuring the deposited energy due to elastic scattered nuclei by WIMP.




Expected spectrum:

$$\frac{dR}{dE_R} = \frac{\boxed{R_0}\boxed{F^2(E_R)}}{E_0 r}\frac{k_0}{k}\frac{1}{2\pi v_0}\boxed{\int_{v_{min}}^{v_{max}}\frac{1}{v}f(\mathbf{v},\mathbf{v_E})d^3\mathbf{v}}$$

R0: Event rate @ zero momentum transfer

Spin independent

$$\sigma_0 = \boxed{A^2}\frac{\mu_T^2}{\mu_p^2}\sigma_{\chi-p}$$

F: Form Factor

(depends on atomic nuclei)

motion dynamics

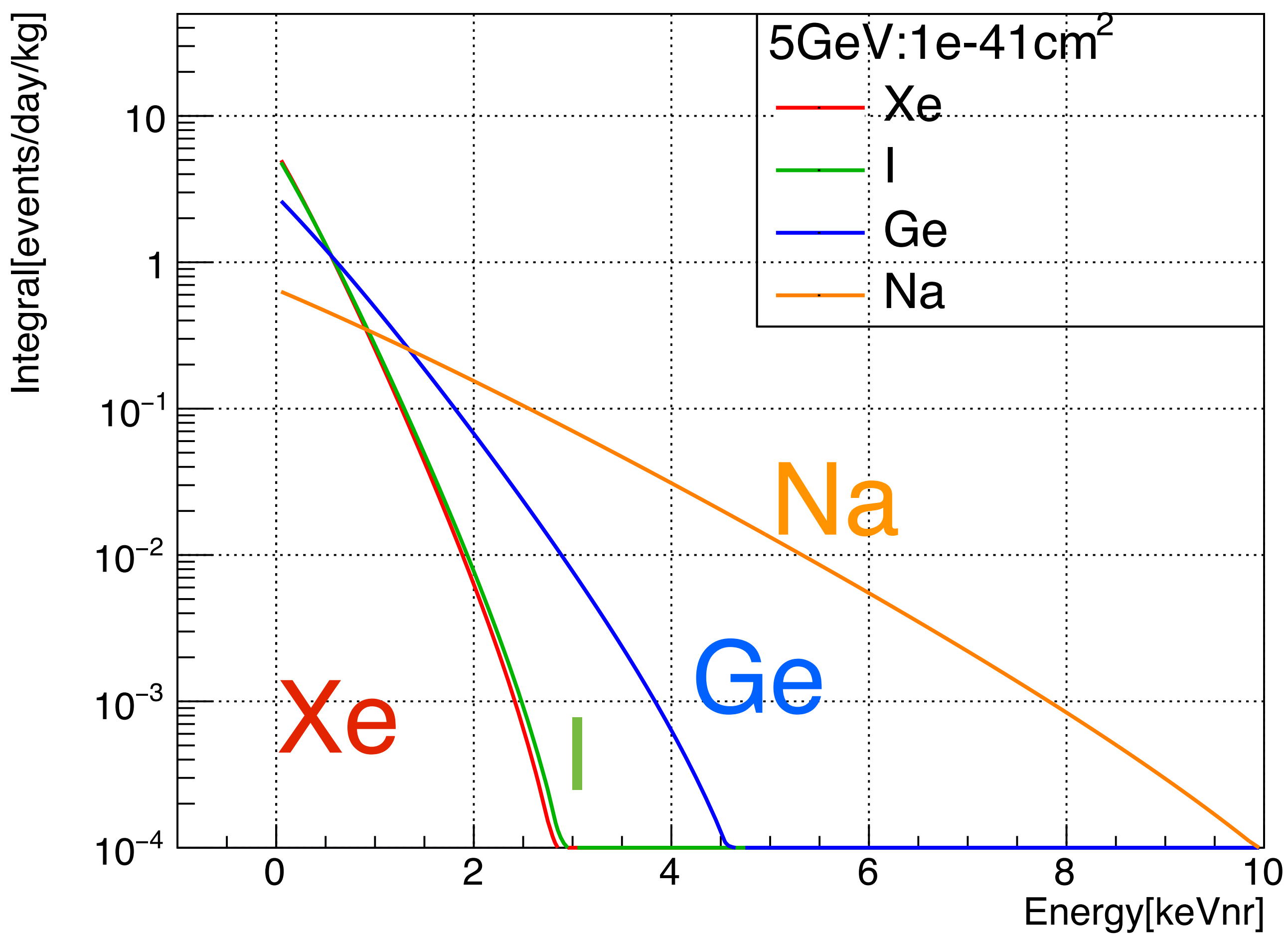
V :velocity onto target,

VE: Earth's motion around the Sun

Maxwellian distribution for DM velocity is assumed.

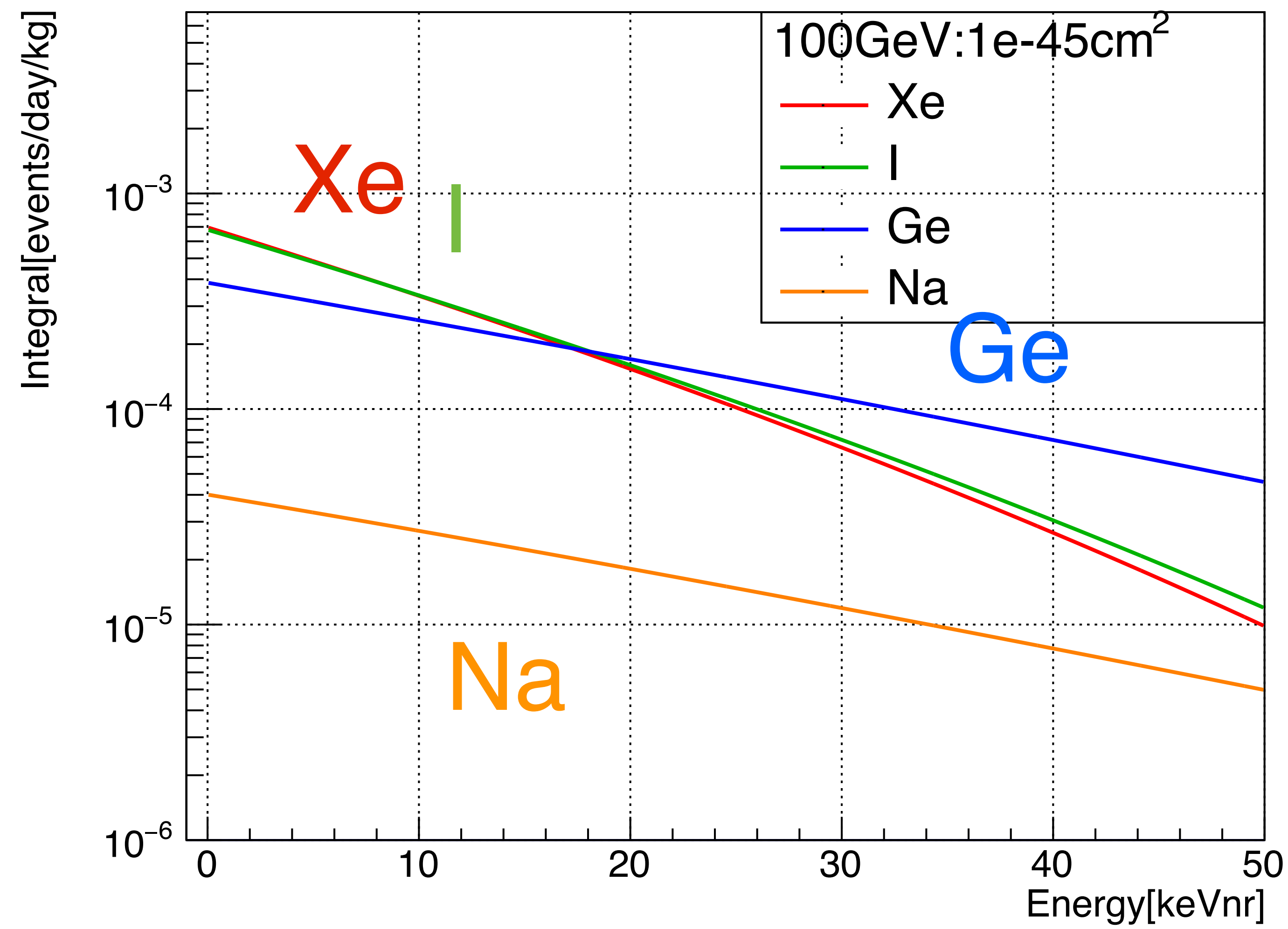
# Differential spectrum

## 5GeV Mass




**Energy threshold is important for low mass WIMPs.**

## 100GeV Mass




**Detector mass is important for high mass WIMPs.**

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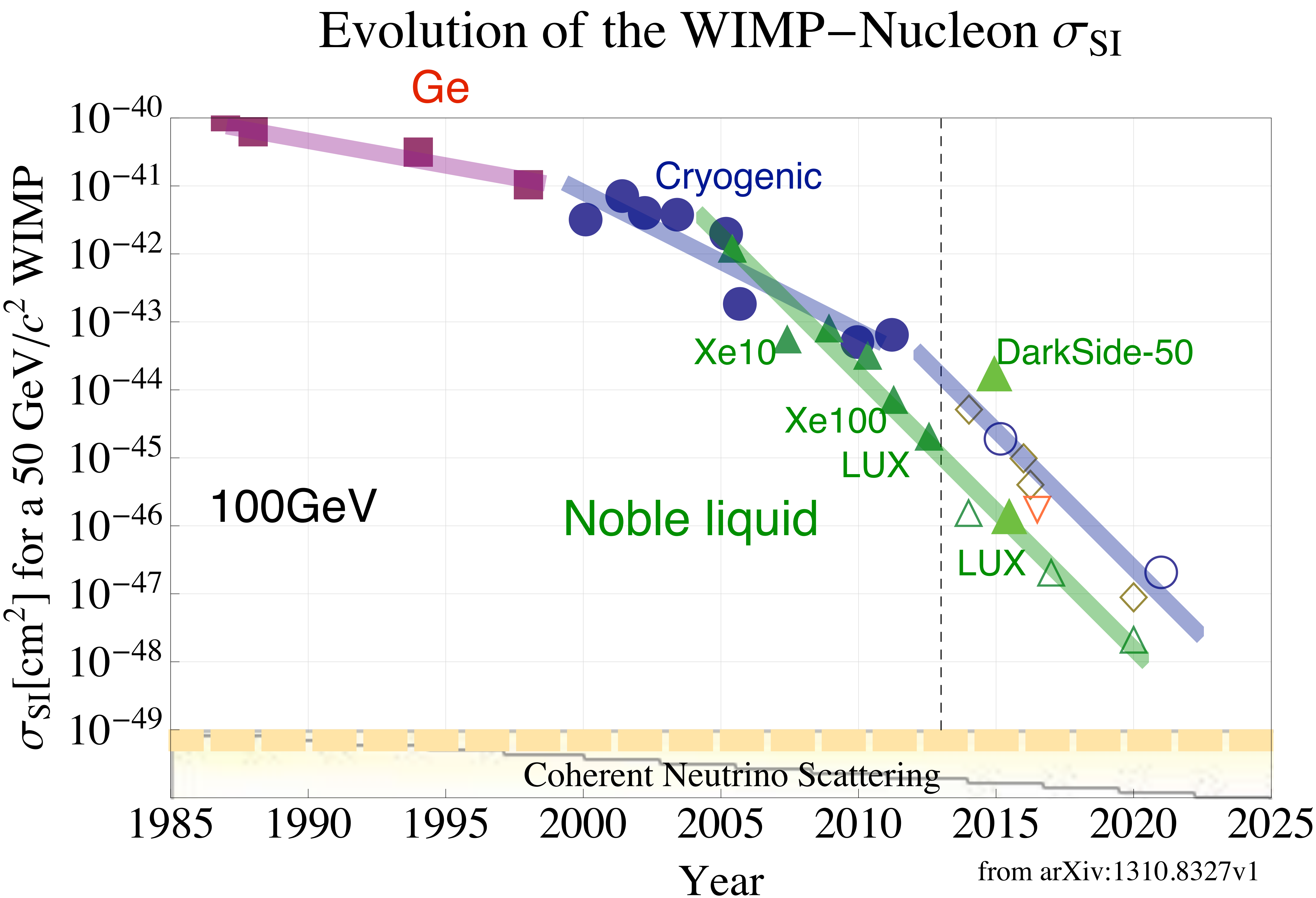
# 30 years

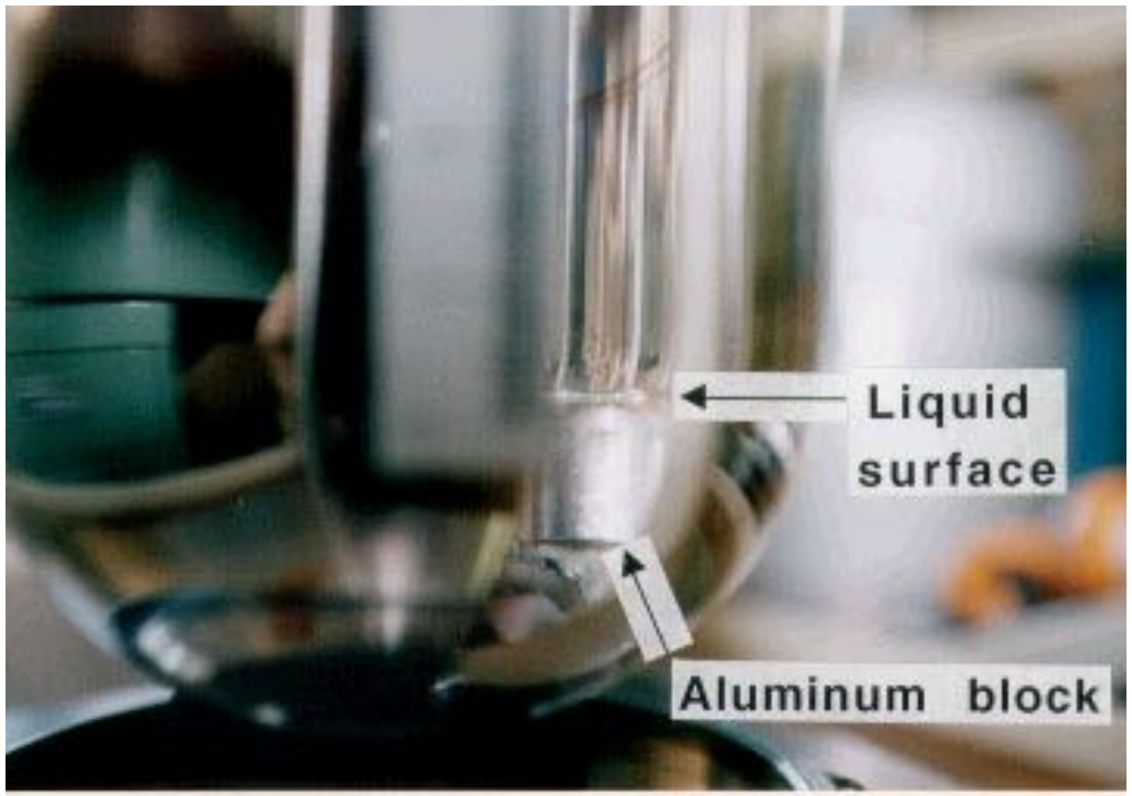


Evolution of the WIMP−Nucleon $\sigma_{SI}$
Ge
Cryogenic
Xe10
Xe100
LUX
DarkSide-50
LUX
Noble liquid
100GeV
Coherent Neutrino Scattering
$\sigma_{SI}[cm^2]$ for a 50 GeV/$c^2$ WIMP
$10^{-40}$
$10^{-41}$
$10^{-42}$
$10^{-43}$
$10^{-44}$
$10^{-45}$
$10^{-46}$
$10^{-47}$
$10^{-48}$
$10^{-49}$
1985
1990
1995
2000
2005
2010
2015
2020
2025
Year
from arXiv:1310.8327v1

# Why Liquid Xenon ?

- High Atomic mass Xe (A~131) good for SI case (cross section $\propto$ $A^2$)
- Odd Isotope (Nat. abun: 48%, 129,131) with large SD enhancement factors
- High atomic number (Z=54) and density (ρ=3g/cc):
  - compact, flexible and large mass detector.
- High photon yield (~ 46000 UV photons/MeV at zero field)
- Easy to purify for both electro-negative and radioactive purity
  - by recirculating Xe with getter for electro-negative
  - Distillation for Kr removal
- No long lifetime radioisotope. (127Xe, 36 days)

# Liquid Xenon



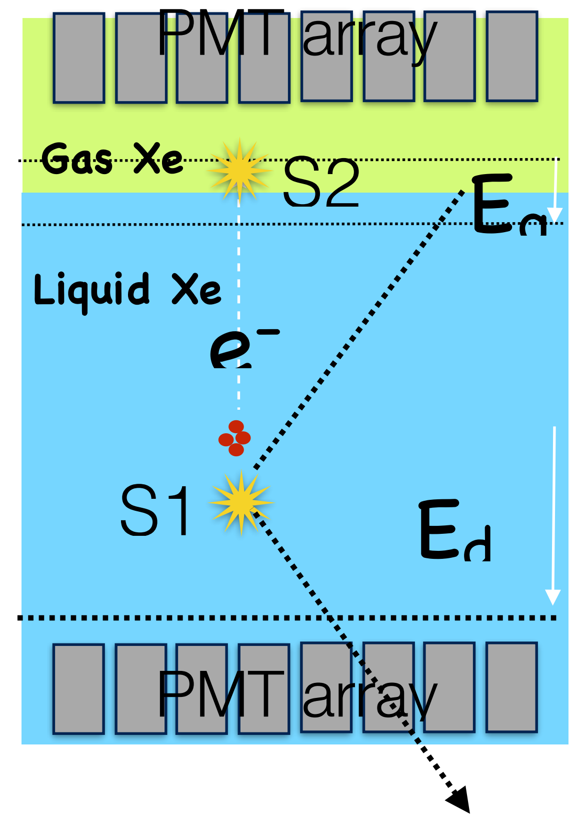

| | |
|---|---|
| boiling point | −108℃ |
| density | 3g/cc |

KEK, Haruyama

**Al(2.7g/cc) is block floating in liquid xenon**

# LXe detector for dark matter

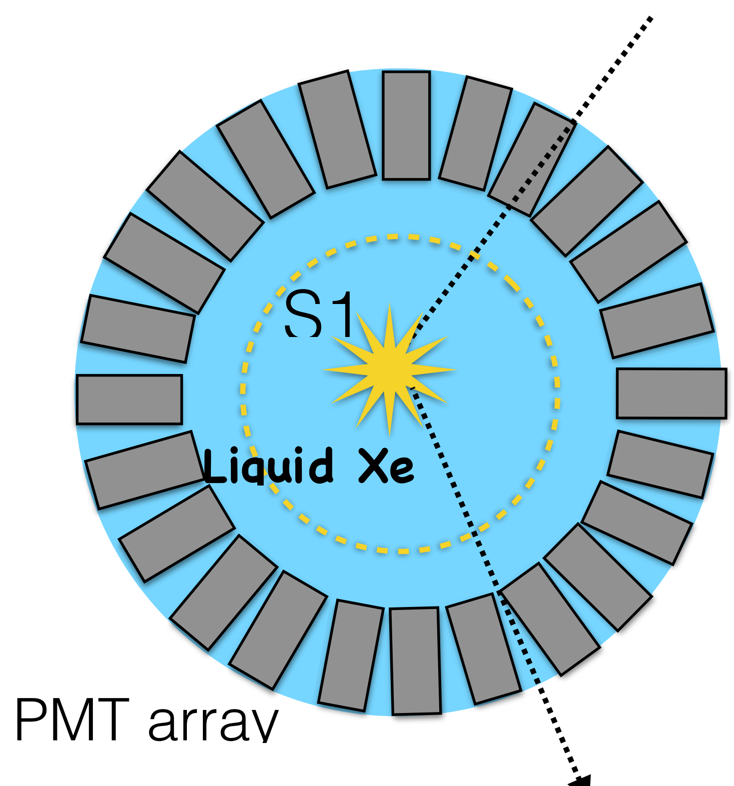
XENON100@LNGS
Two-phase Xe TPC




- S1: direct scintillation light
- S2: secondary light (ionization)

- strong particle ID by S2/S1
- fine spacial resolution (< 1mm)

XMASS-I@Kamioka
Single-phase LXe scintillator

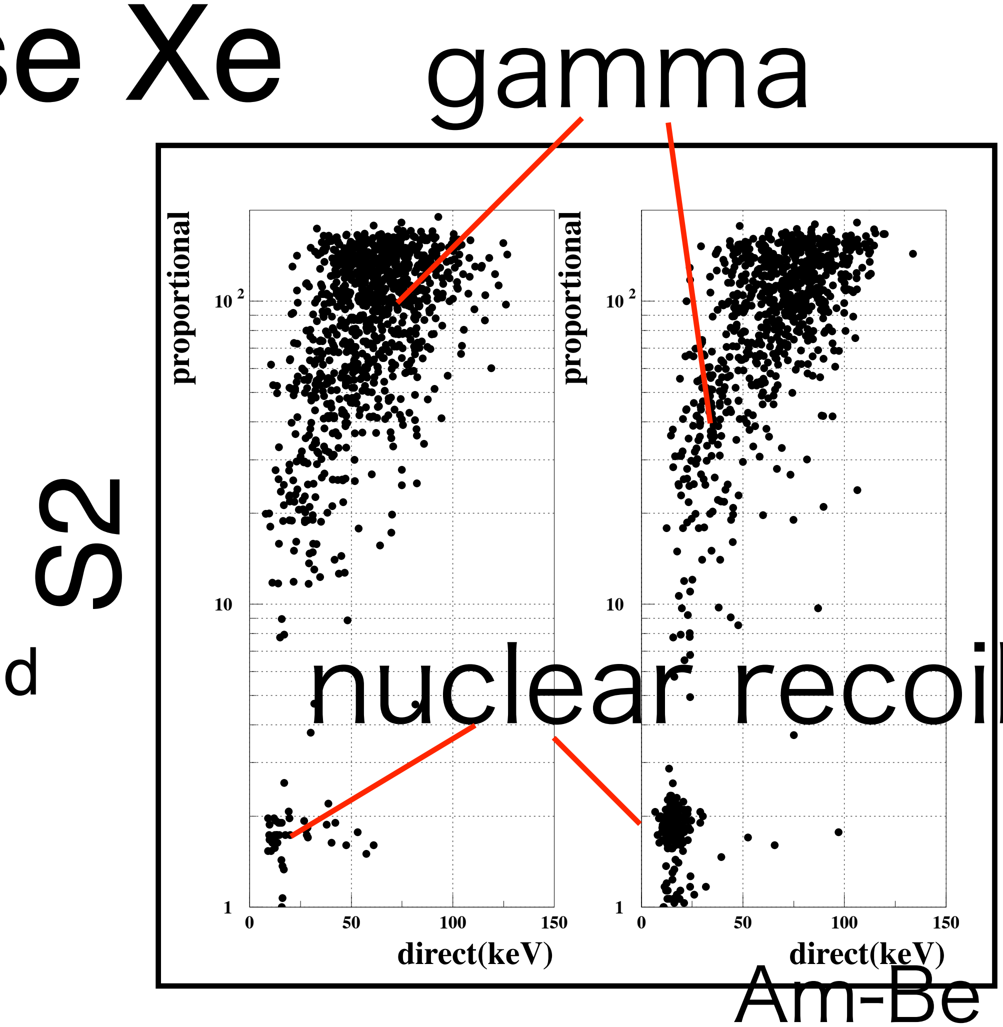



- Easy for scalability
- High light yield (4π PMT)

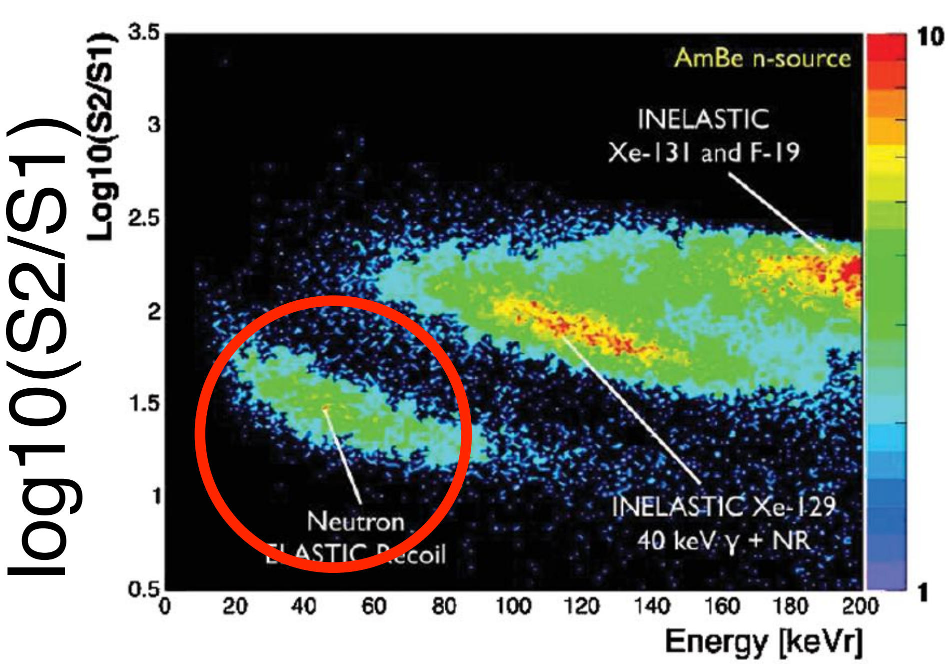
# Brief history of Two phase Xe

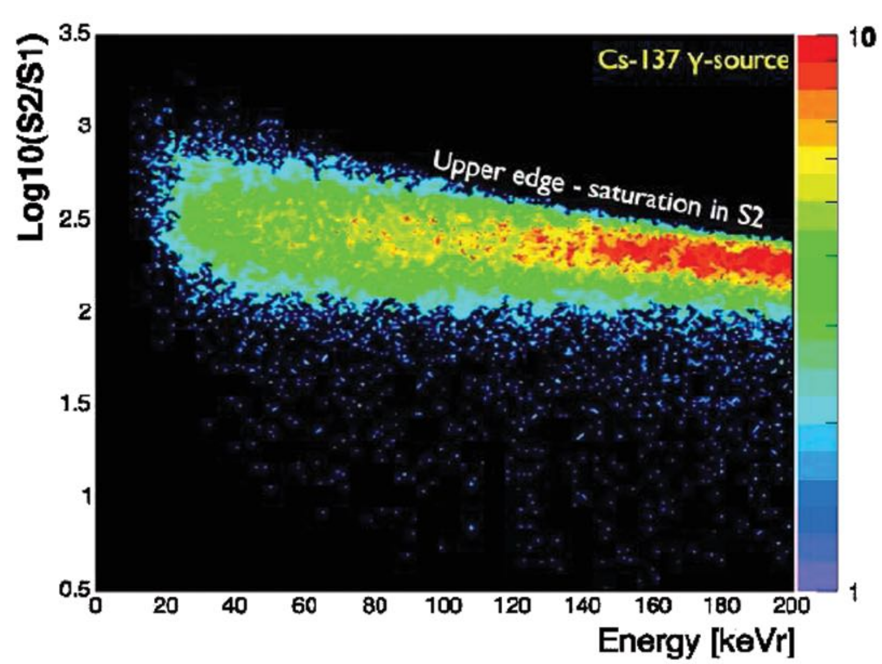
- 1973 Two phase liquid noble gas detector B.A. Dolgoshein et al. (JINR, p167)
- 1990's R&D by ICARUS group at CERN
- ~ 2000 Double phase Xe in Japan. S2 observation from nuclear recoil. First underground run (XMASS).
- 2006 Quantitative study S2 signal.(Part of XENON group) and particle
- 2007 First Physics Result of XENON10

....




M. Yamashita et al. Astropart. Phys. 2003, 79

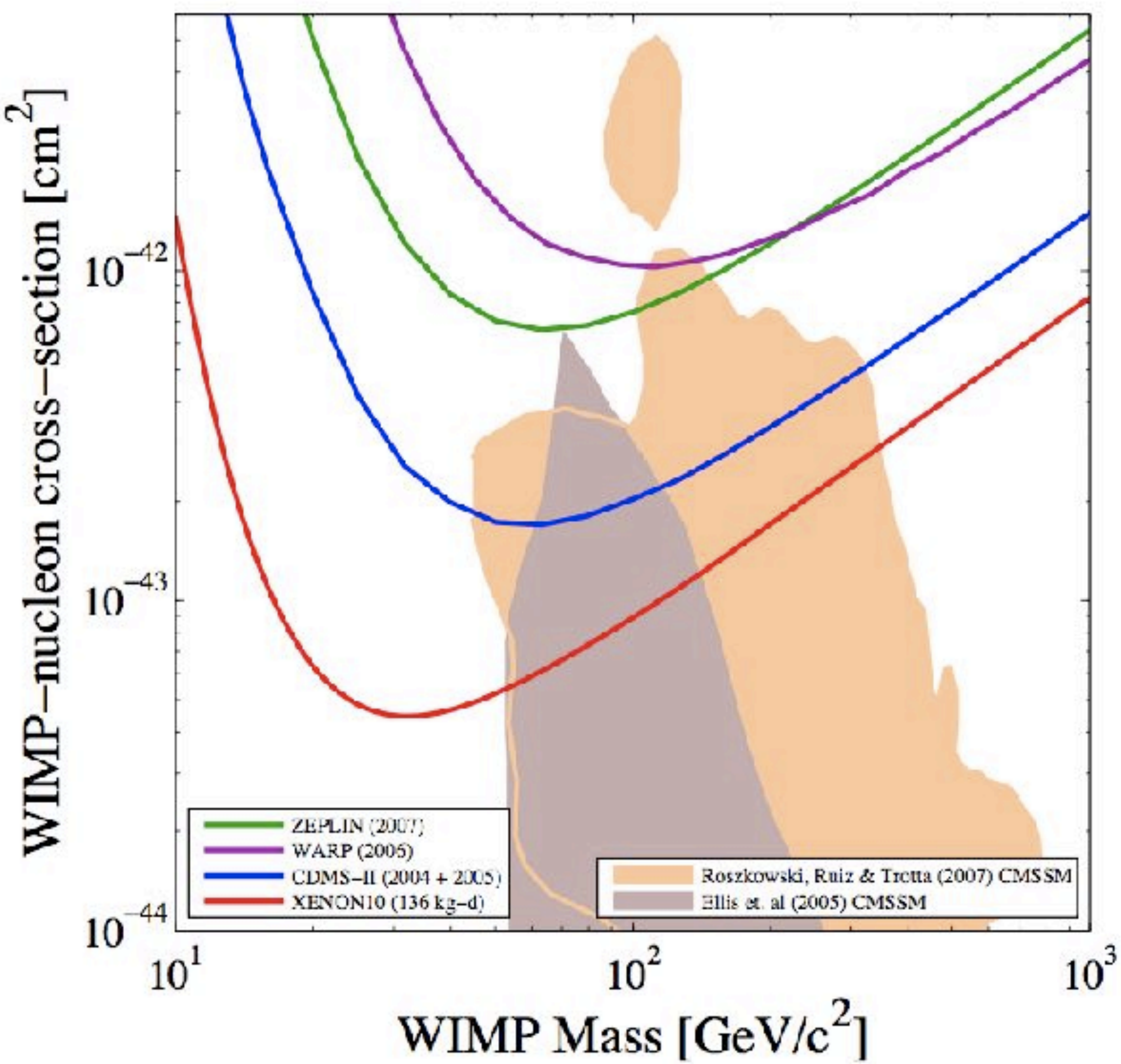


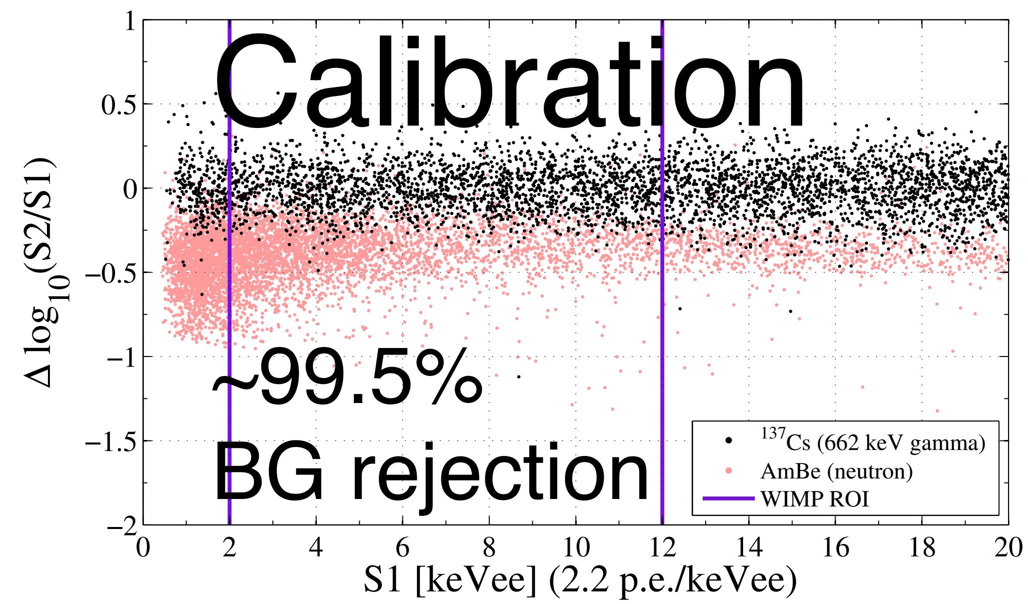



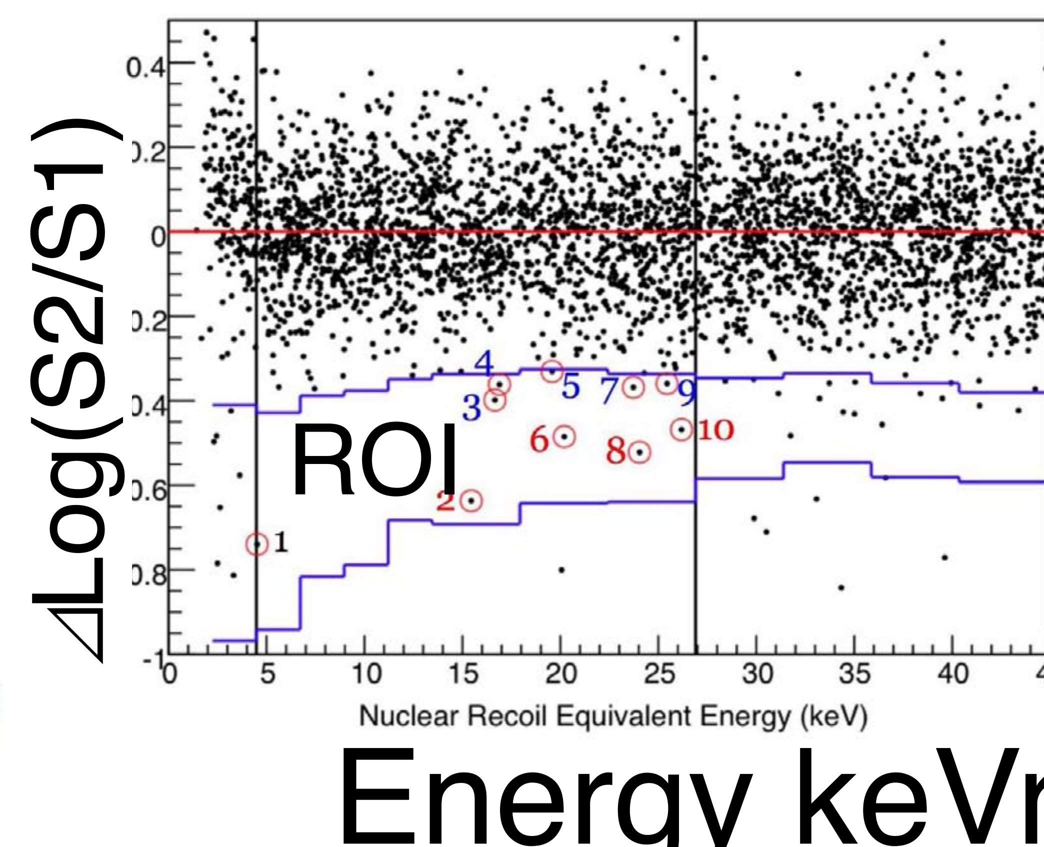

PRL **97,** 081302 (2006)

# XENON10 Spin Independent (2008)

PRL **100,** 021303 (2008)



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# Race is on to detect dark matter

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By Elena Aprile, AP

Enlarge

Dr. Masaki Yamashita, a research scientist working during the final assembly of the XENON10 Detector in the "clean room" of the Astrophysics lab at Columbia University in New York.

**By Alicia Chang, Associated Press**

LOS ANGELES — In deep underground laboratories around the globe, a high-tech race is on to spot dark matter, the invisible cosmic glue that's believed to keep galaxies from spinning apart.

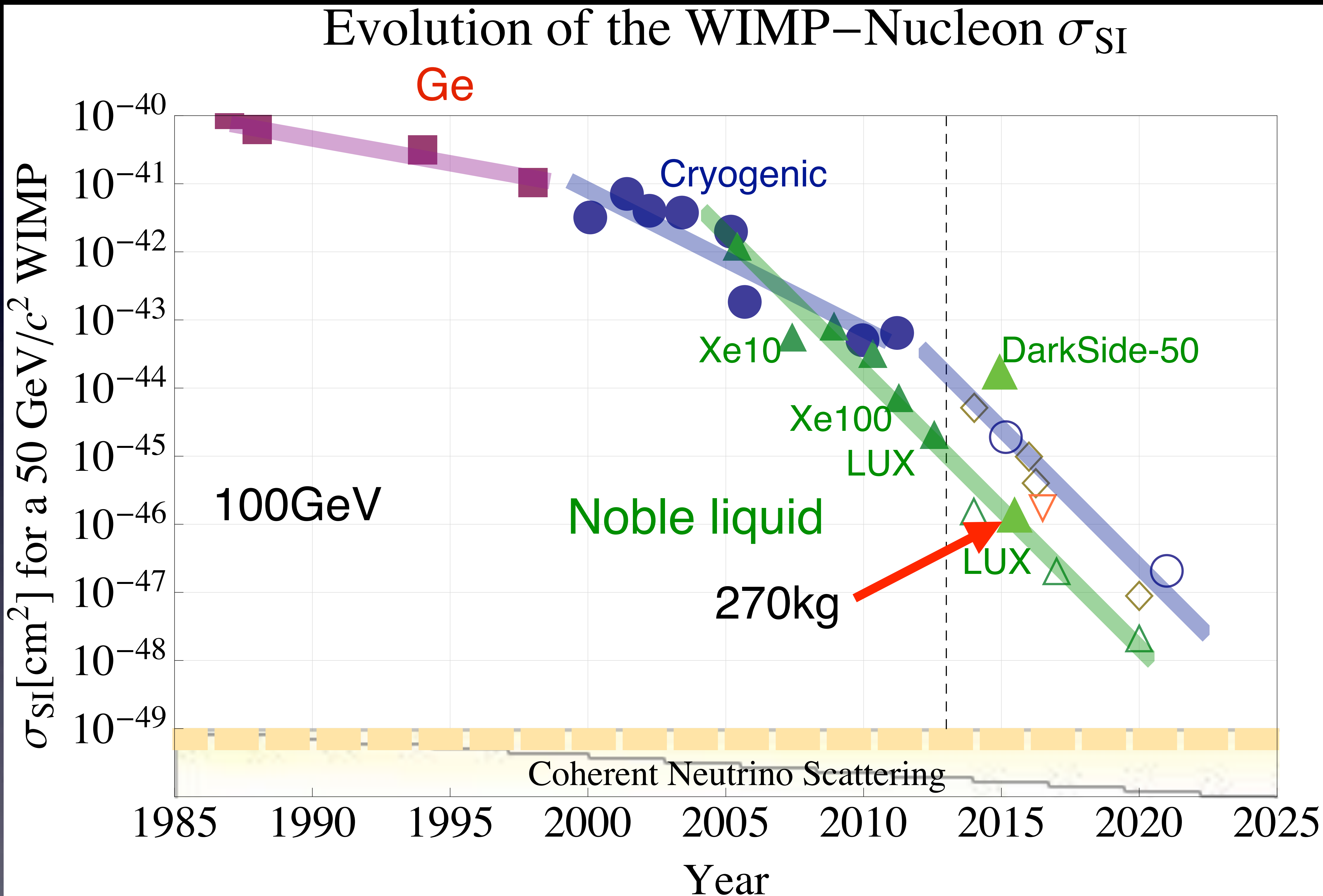
Whoever discovers the nature of dark matter would solve one of modern science's greatest mysteries and be a shoo-in for the Nobel Prize. Yet it's more than just a brainy exercise. Deciphering dark matter — along with a better understanding of another mysterious force called dark energy — could help reveal the ...

previous ... catch a whiff of the stuff. Many ...

detectors or toying with novel technologies to aid in the hunt.

**USA Today: 2007/08/02**
**Researchers use high-tech machines to detect mysterious dark matter**

WIMP–nucleon cross




from arXiv:1310.8327v1

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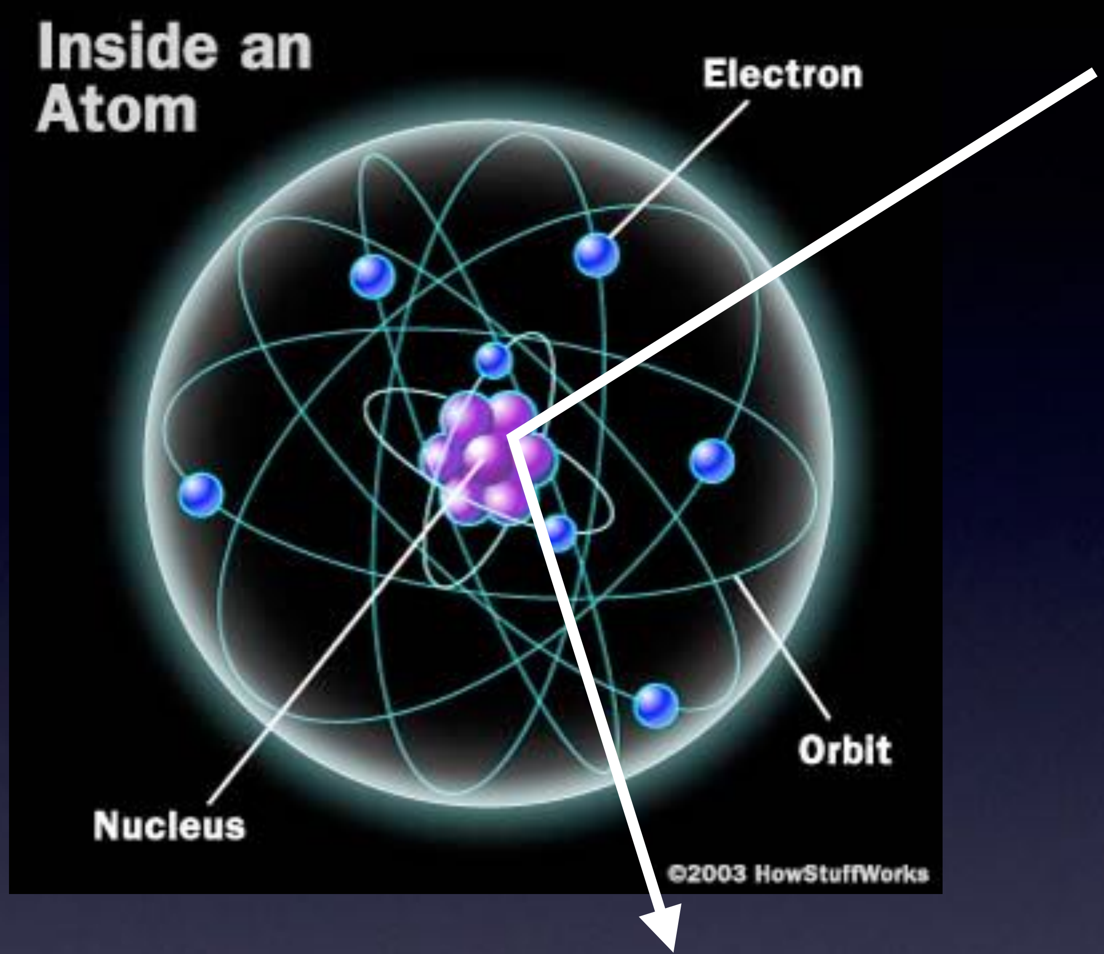
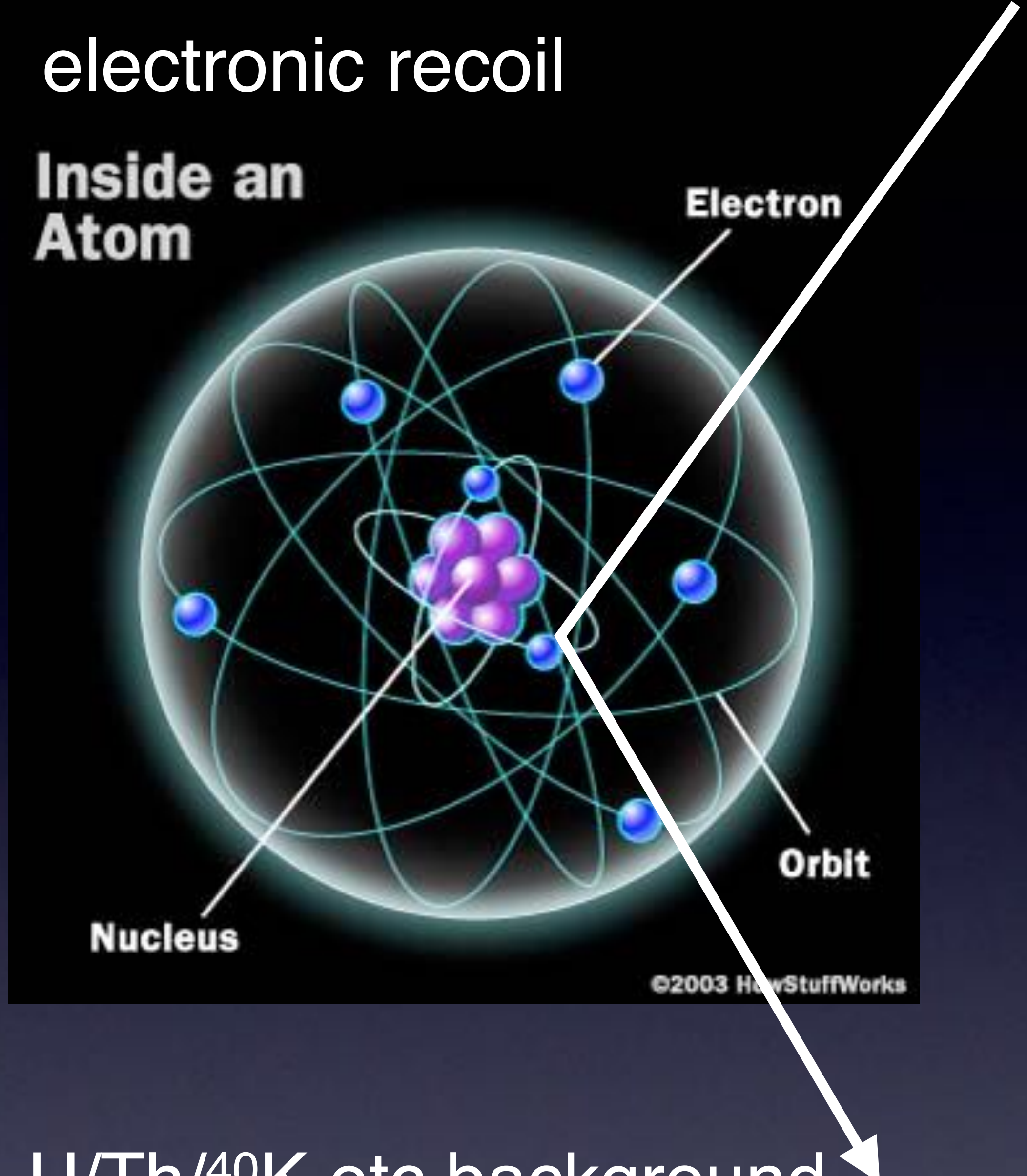
# Interaction with dark matter

nuclear recoil




electronic recoil




fast neutron
WIMP
(SUSY, KK ...)

-U/Th/$^{40}$K etc background

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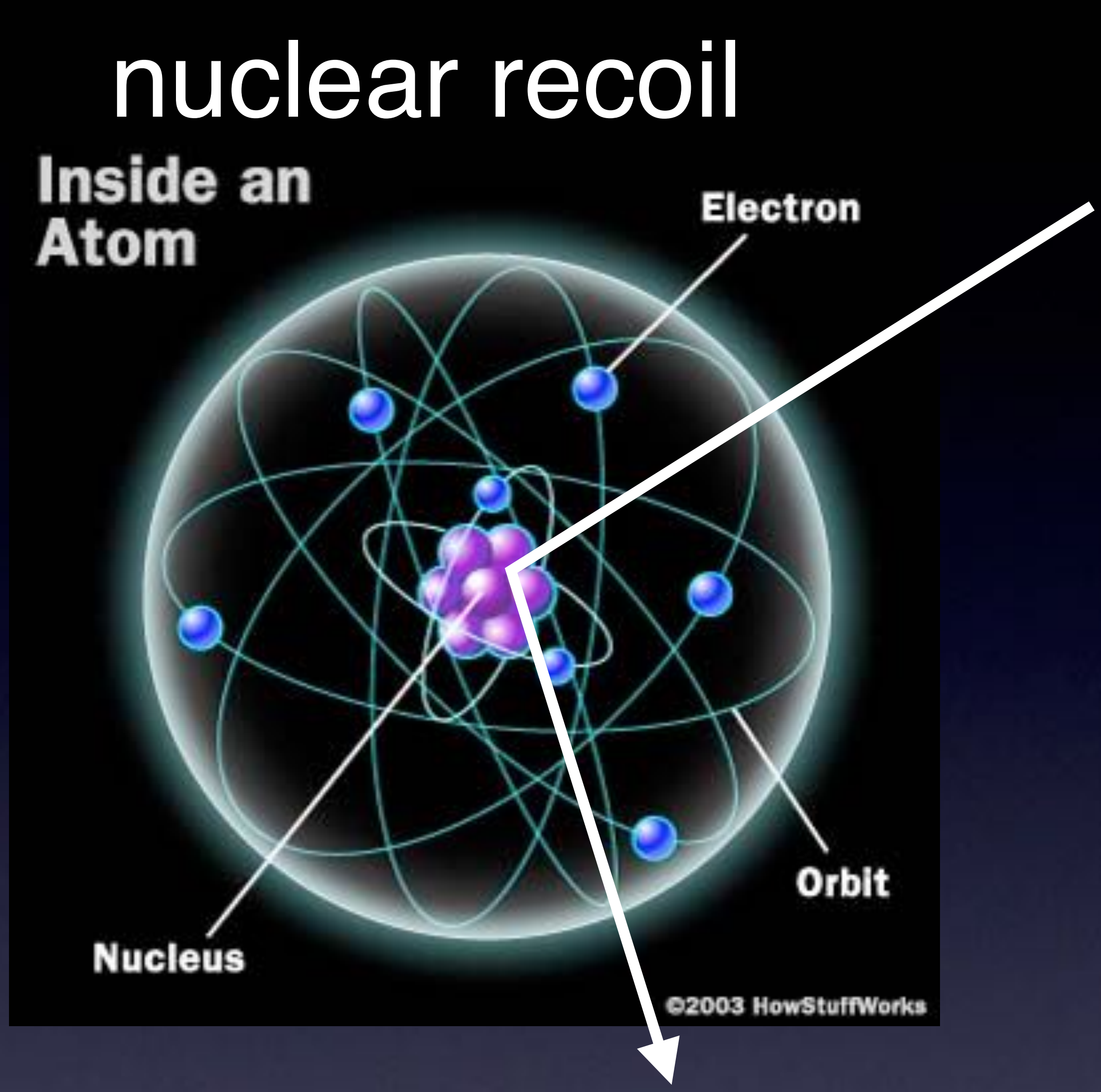
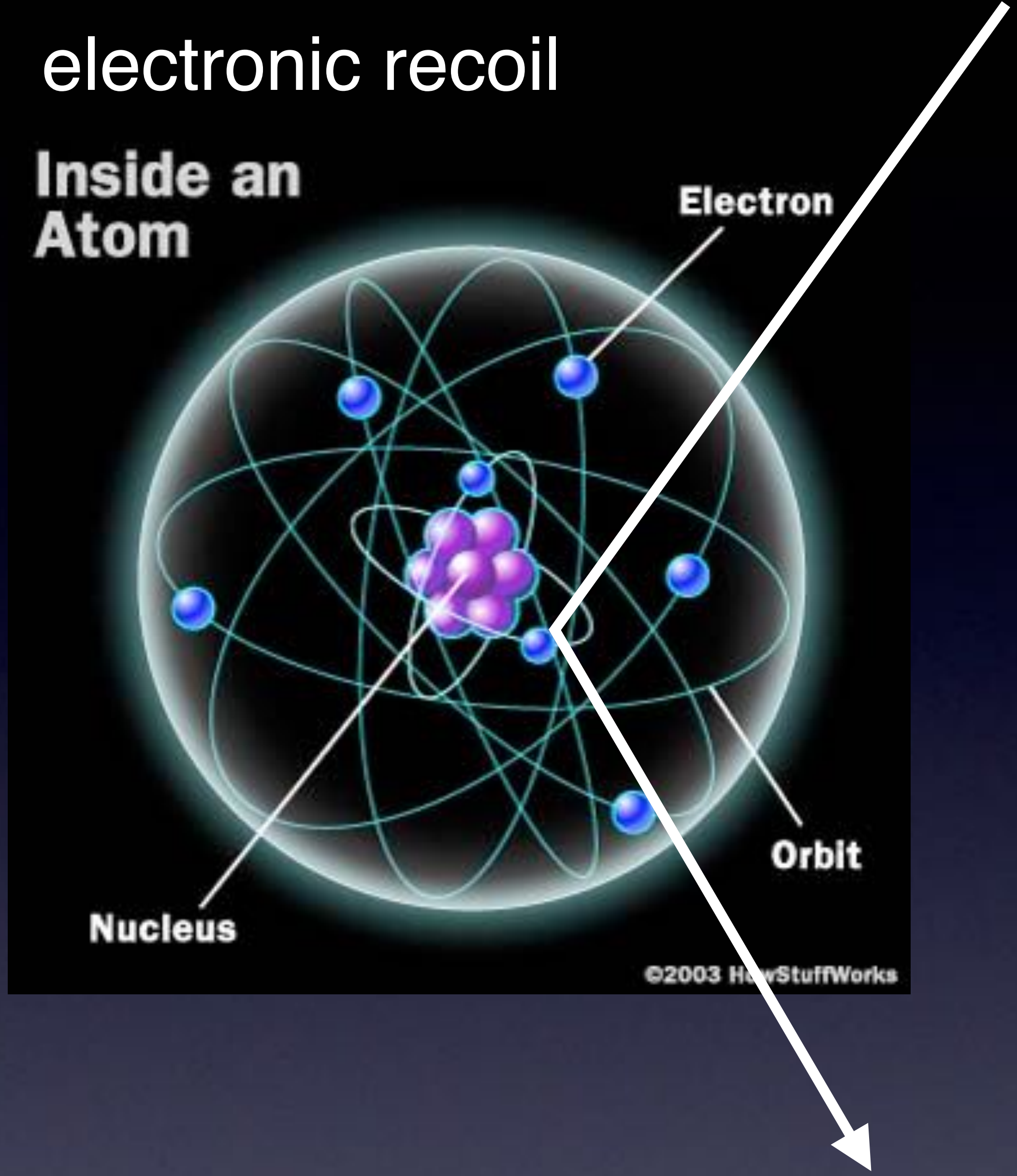
nuclear recoil




fast neutron
WIMP
(SUSY, KK …)

electronic recoil




-U/Th/$^{40}$K etc background
-WIMP-electron
-Super WIMP (bosonic)
-Axion/Axion like particle
-Mirror DM
-Luminous DM …

The signal is in electron recoil ?

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# XMASS experiment

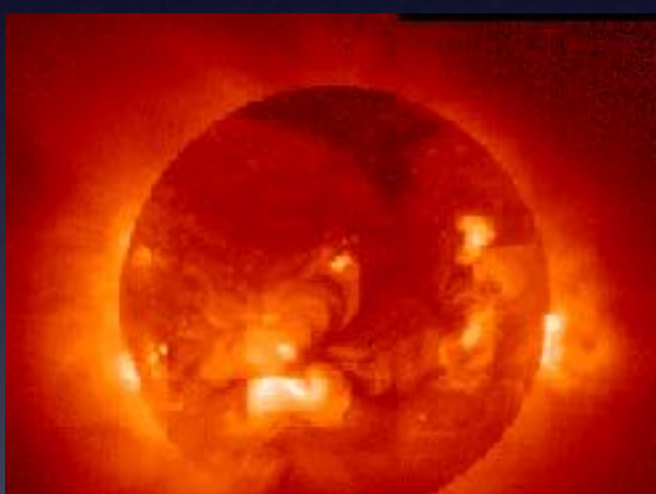
# XMASS

Y. Suzuki for XMASS collab.

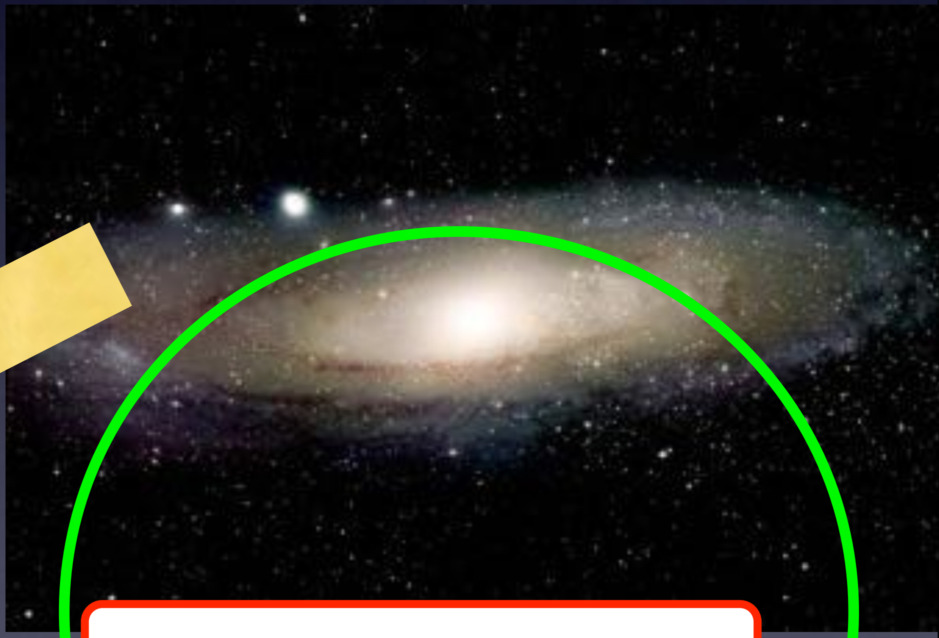
arXiv:hep-ph/0008296 (2000)

## Multi purpose experiment by using LXe

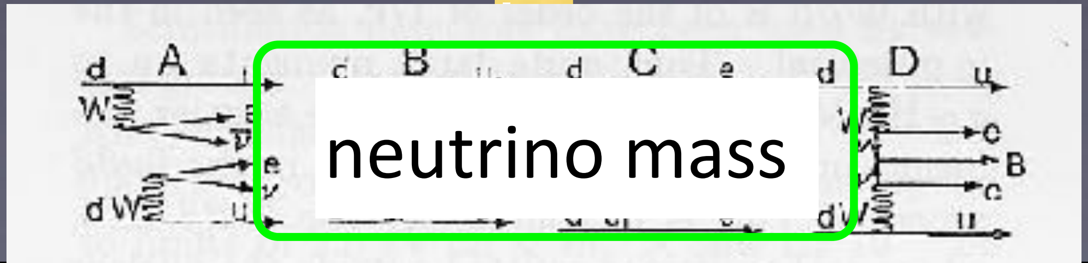
- **Xenon MASSive detector for Solar neutrino**
- **Xenon neutrino MASS detector**
- **Xenon detector for Weakly Interacting MASSive Particles**



Solar neutrino



Dark Matter




neutrino mass

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# The XMASS collaboration:

Kamioka Observatory, ICRR, the University of Tokyo:
K. Abe, K. Hiraide, K. Ichimura, Y. Kishimoto, K. Kobayashi, M. Kobayashi, S. Moriyama, M. Nakahata, N. Kato, H. Ogawa, H. Sekiya, S. Tasaka, A. Takeda, M. Yamashita, B. Yang

Kavli IPMU, the University of Tokyo:
K.Martens, Y. Suzuki, X. Benda

Kobe University:
K. Hosokawa, K. Miuchi, Y. Ohnishi, N. Oka, Y. Takeuchi

Tokai University:
K. Nishijima

Yokohama National University:
S. Nakamura

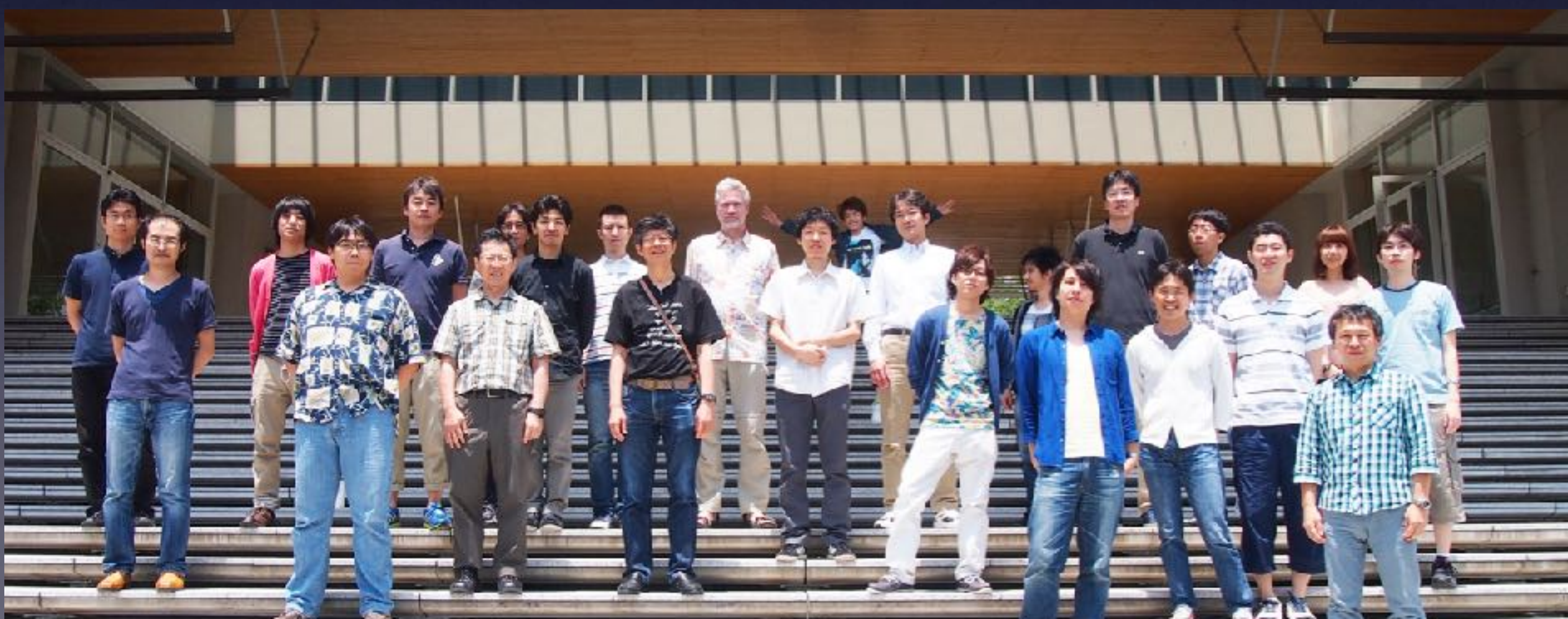
Miyagi University of Education:
Y. Fukuda

STEL, Nagoya University:
Y. Itow, K. Kanzawa, K. Masuda

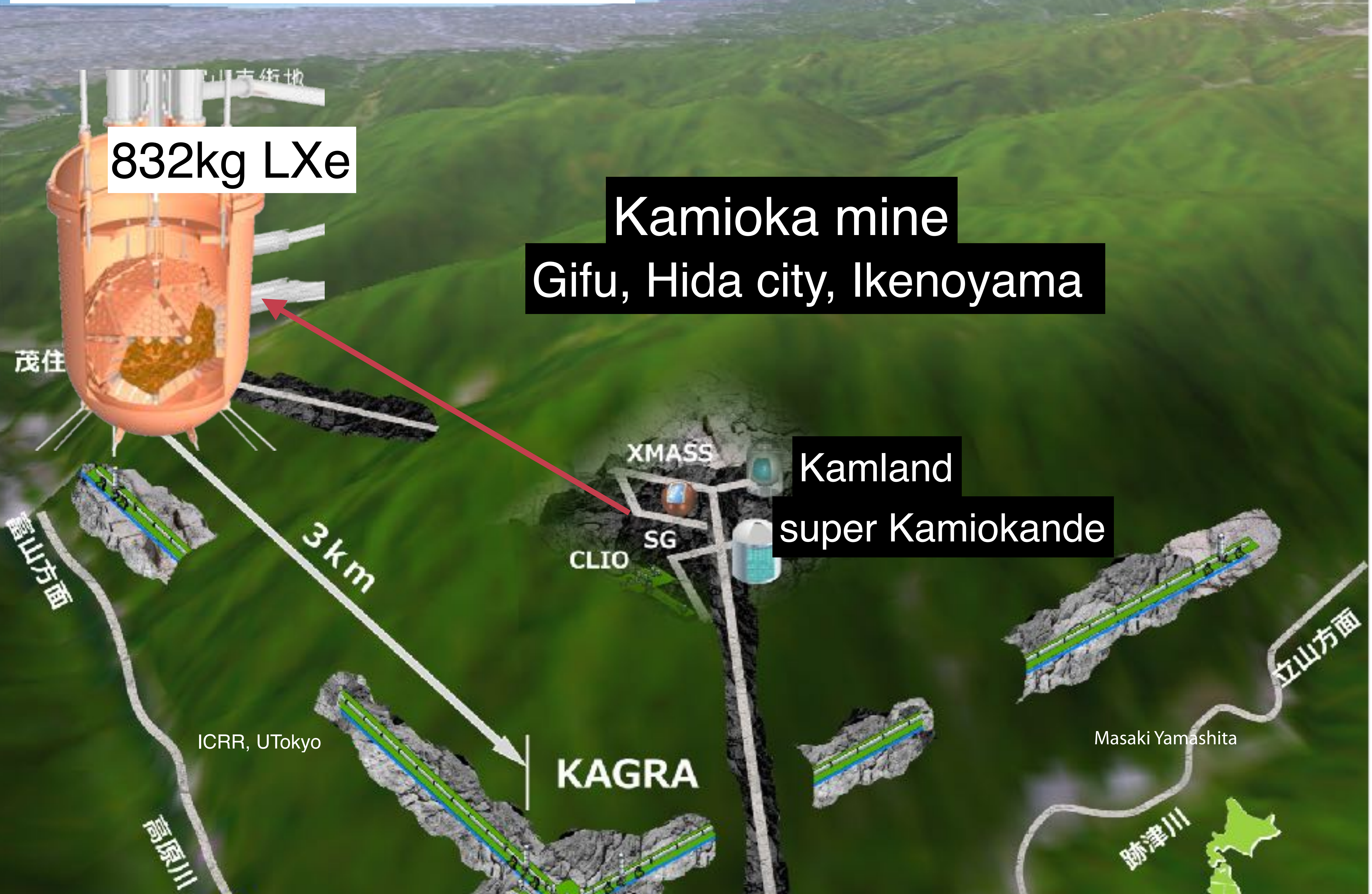
Institute for Basic Science:
N. Y. Kim, Y. D. Kim

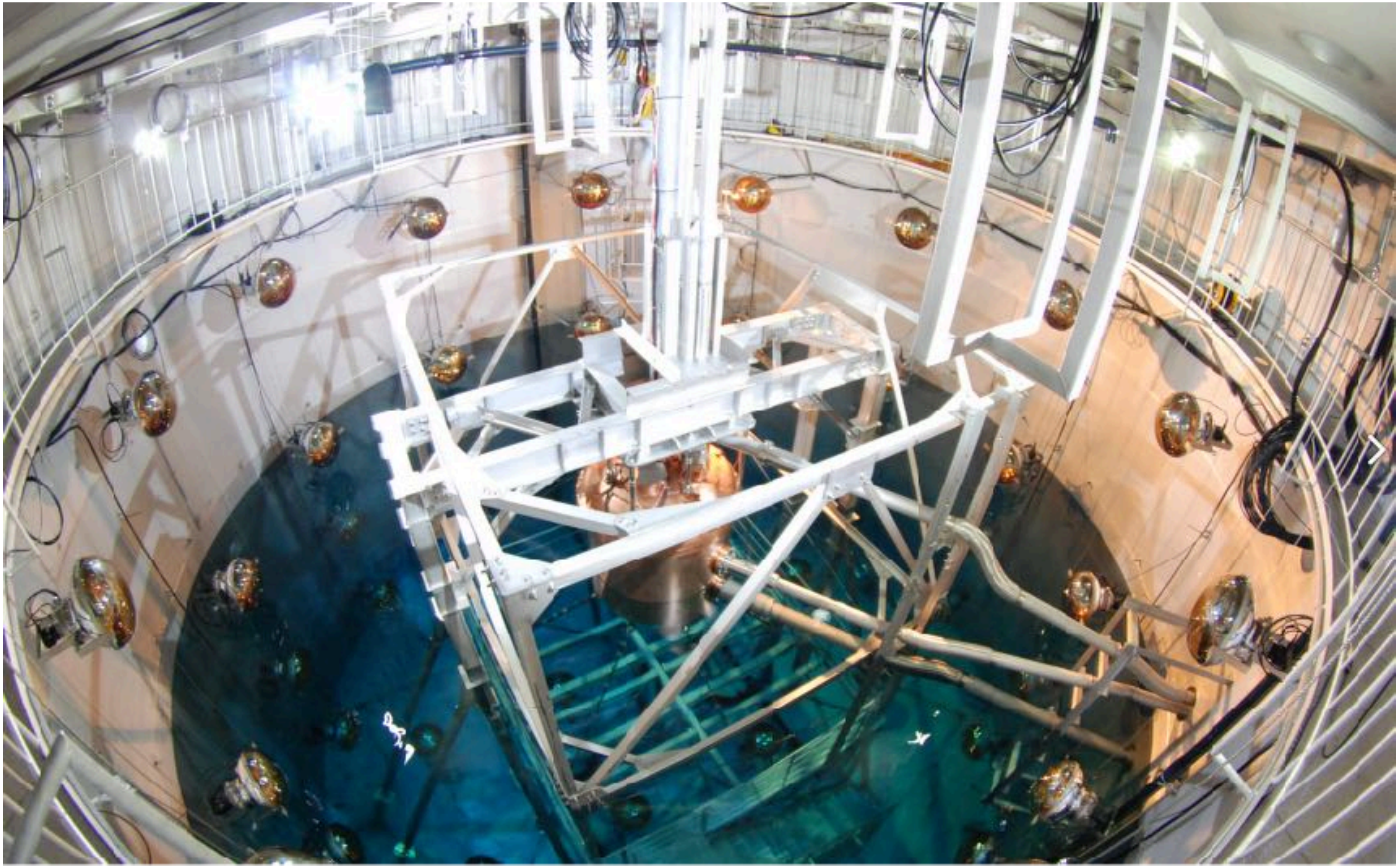
KRISS:
Y. H. Kim, M. K. Lee, K. B. Lee, J. S. Lee

Tokushima University:
K.Fushimi



# XMASS experiment



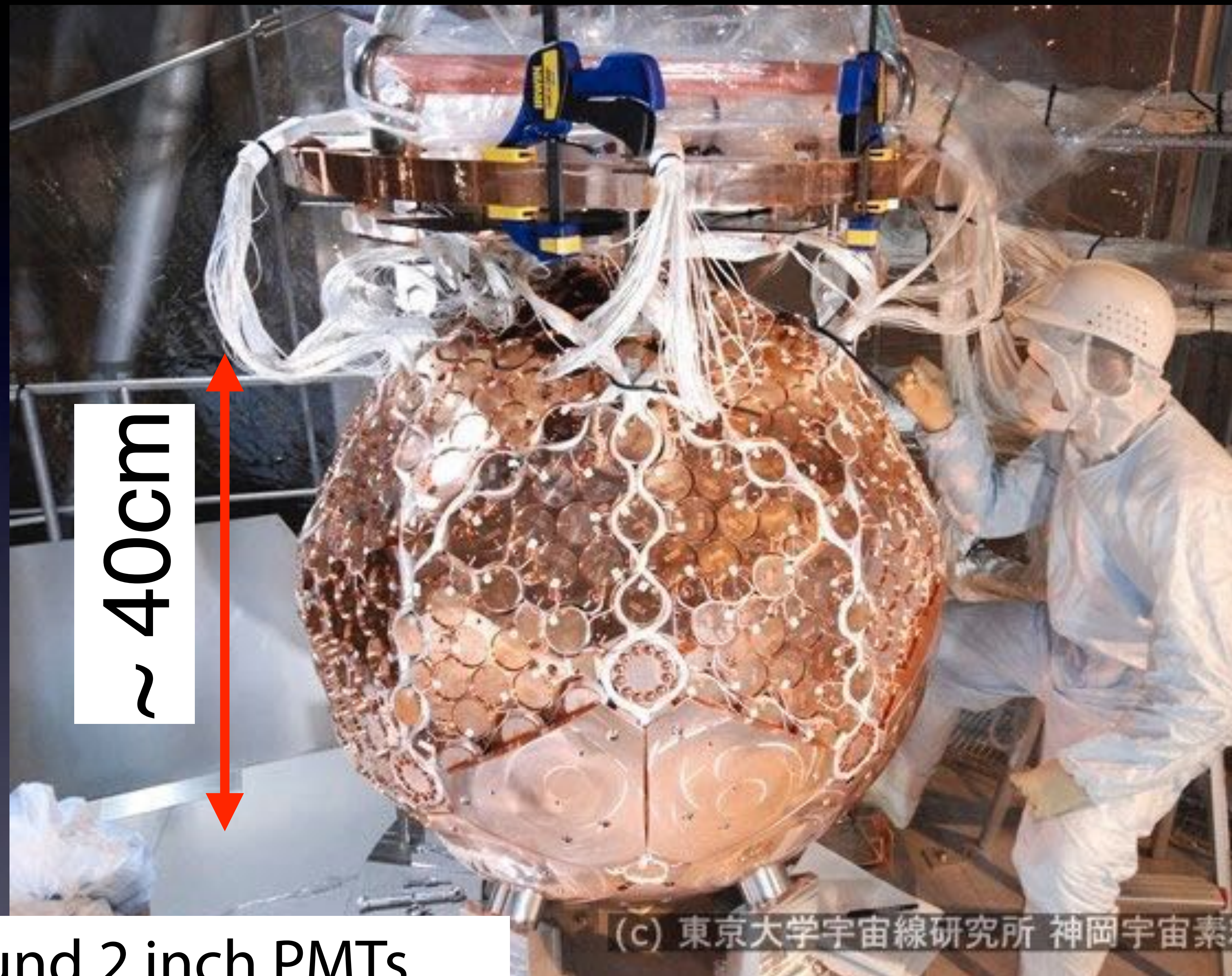


-φ10m x 10m ultra pure water shield with 20 inch x 70 PMTs for muon veto

# XMASS Detector

R10789

| RI in PMT | Activity per 1PMT(mBq/ |
|---|---|
| 238U-chain | 0.70+/-0.28 |
| 232Th-chain | 1.51+/-0.31 |
| 40K | <5.1 |
| 60Co | 2.92+/-0.16 |




- 642 ultra low background 2 inch PMTs
- 62% photo coverage
- Largest detector: 832 kg of LXe for sensitive volume.

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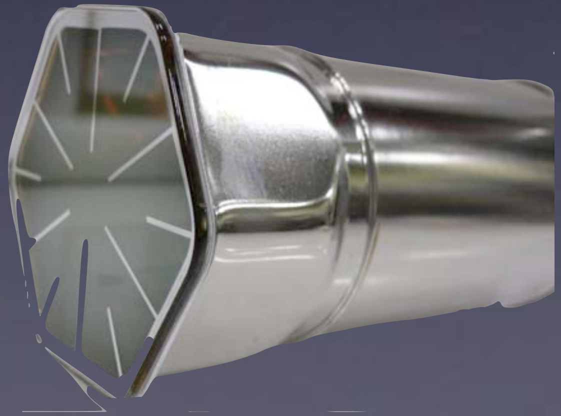
# Challenge for low Radioactivity PMT

e.g. $^{40}K$ case

**4000 Bq/human**

**15 Bq/banana**



**0.01 Bq/PMT**
**6.42 Bq/642 PMTs**

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# History of XMASS PMTs

## XMASS PMT HISTORY

PMT

| YEAR | 2000 | 2002 | 2008 | 2015- |
|---|---|---|---|---|
| Size | 2inch | 2inch | 2inch | 3inch |
| Model | Prototype | R8778 | R10789 | R13111 |
| Material:Body | glass | Kovar | Kovar | goal is 1/10 of R10780 |
| QE | 25% | 25% | 27-39% | |
| U [mBq/PMT] | *50* | *18±2* | 0.70 +/- 0.28 | |
| Th [mBq/PMT] | *13* | *6.9±1.3* | 1.5 +/- 0.31 | |
| $^{40}$K [mBq/PMT] | *610* | *140±20* | < 5.1 | |
| $^{60}$Co [mBq/PMT] | *<1.8* | *5.5±0.9* | 2.9 +/- 0.16 | |

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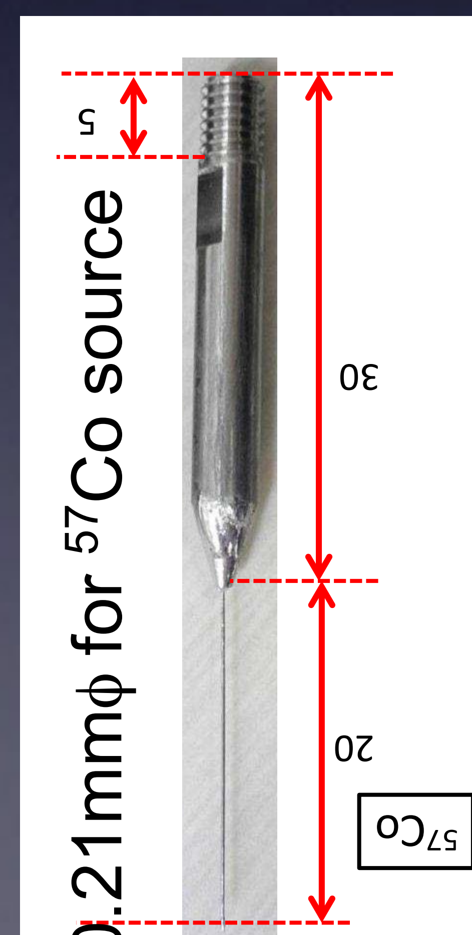
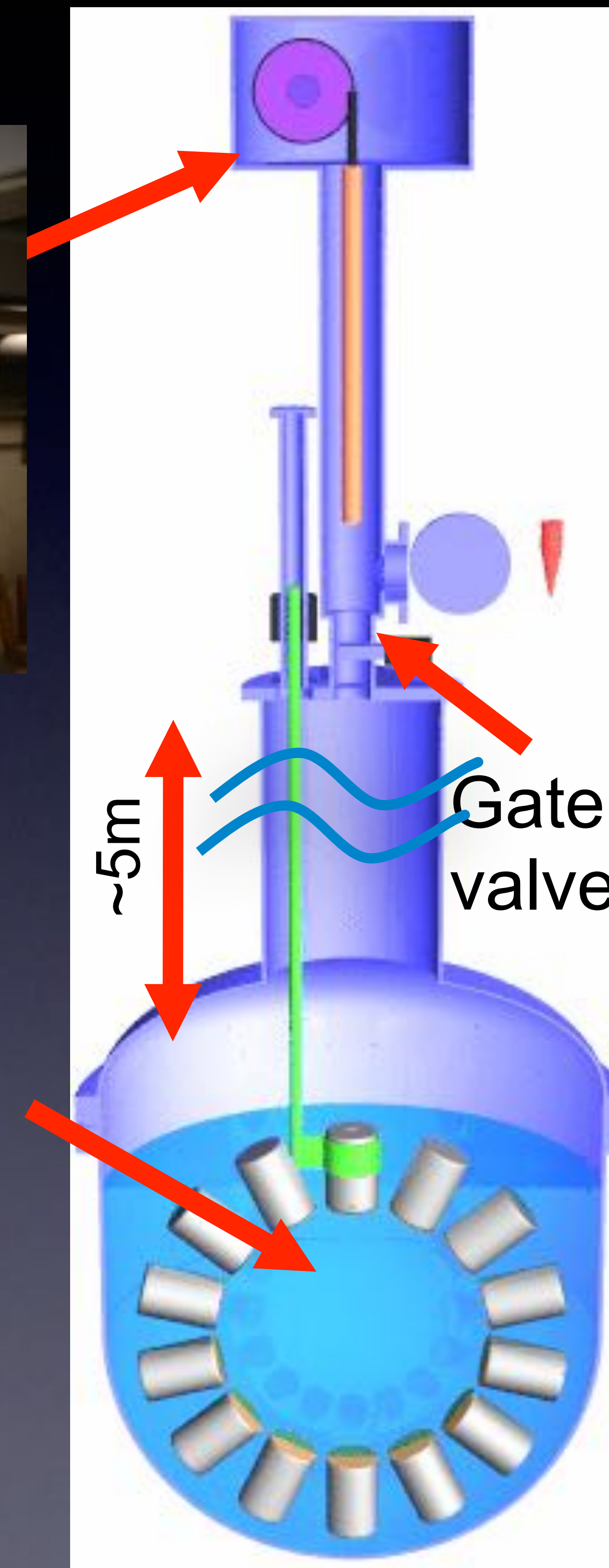
# Detector calibration

-Inner calibration is for energy calibration.


| Isotopes | Energy [keV] | Shape |
|---|---|---|
| $^{55}$Fe | 5.9 | cylinder |
| $^{109}$Cd | 8(*1), 22, 58, 88 | cylinder |
| $^{241}$Am | 17.8, 59.5 | thin cylinder |
| $^{57}$Co | 59.3(*2), 122 | thin cylinder |
| $^{137}$Cs | 662 | cylinder |

sources by Korean collaborator

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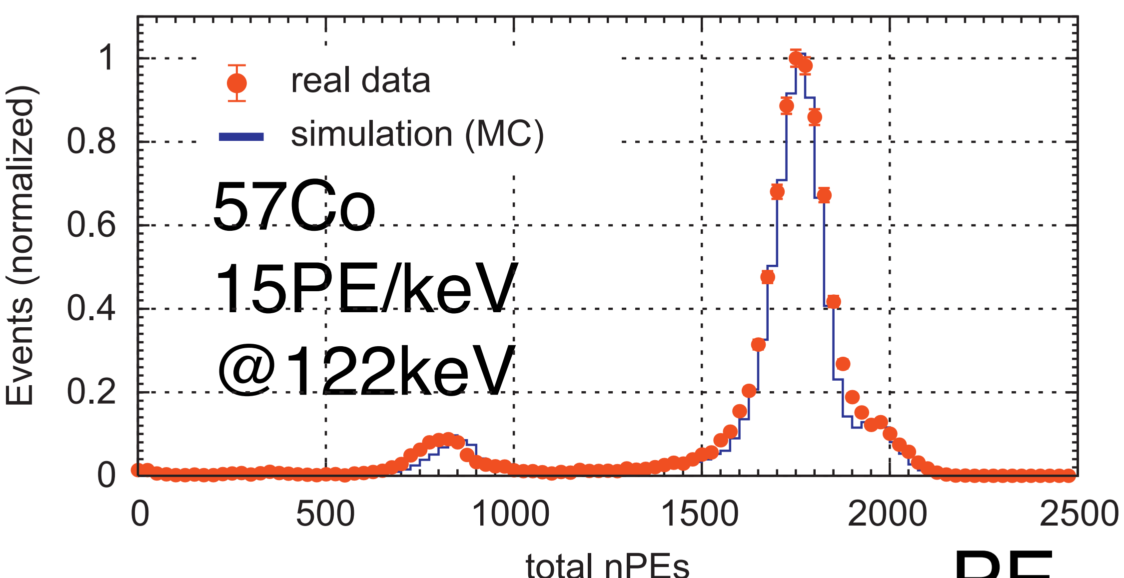
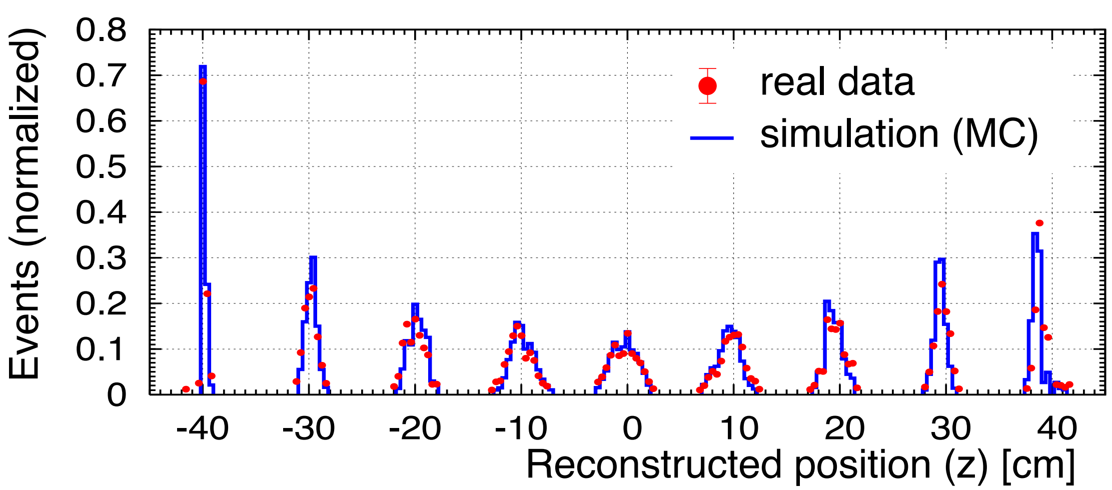
# Energy calibration

- High Photoelectron Yield ~15 PE/keV
- Good agreement between data and.
- Evaluated absorption length 4-11 m, scatter 52cm

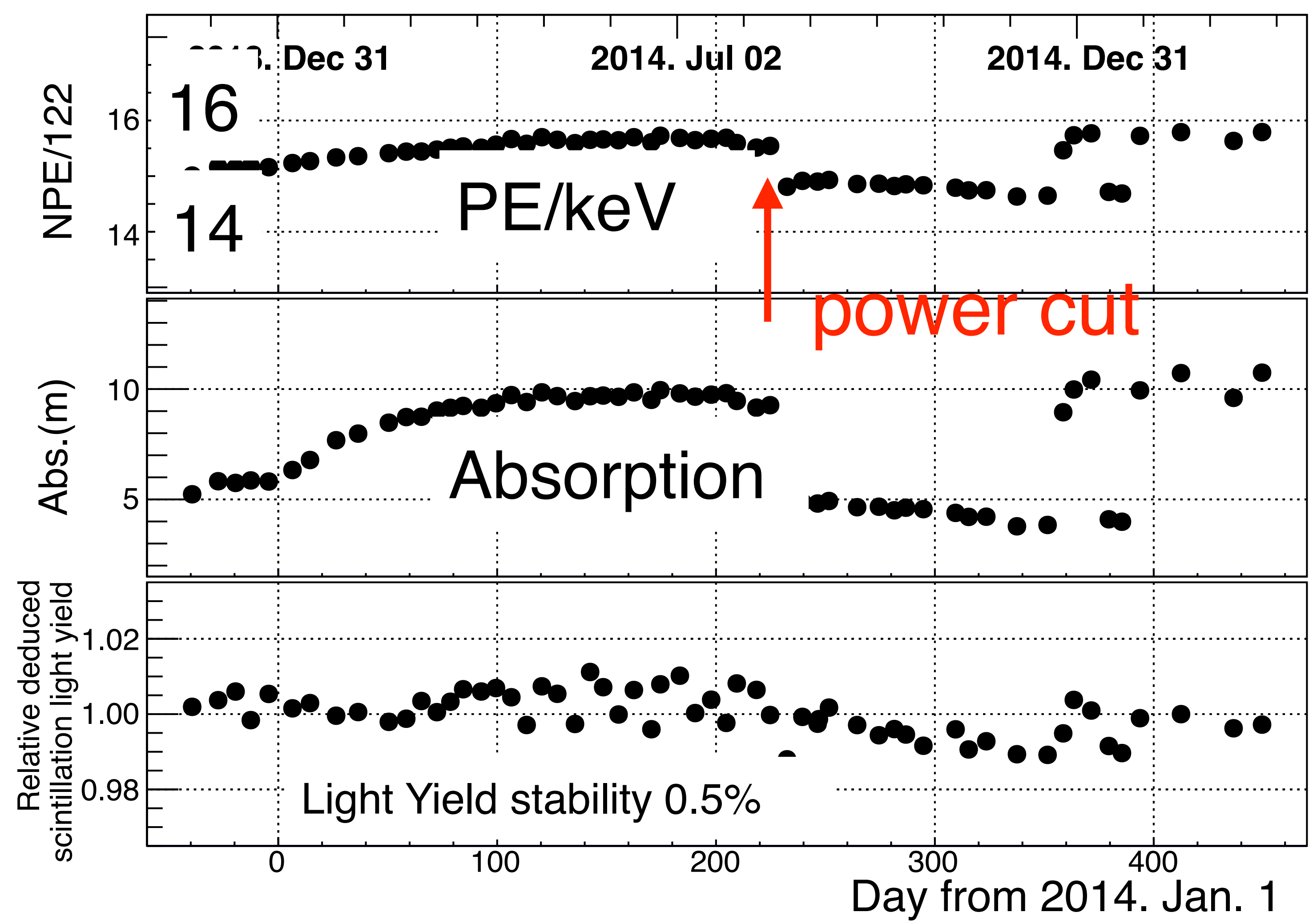
Total PE




PE



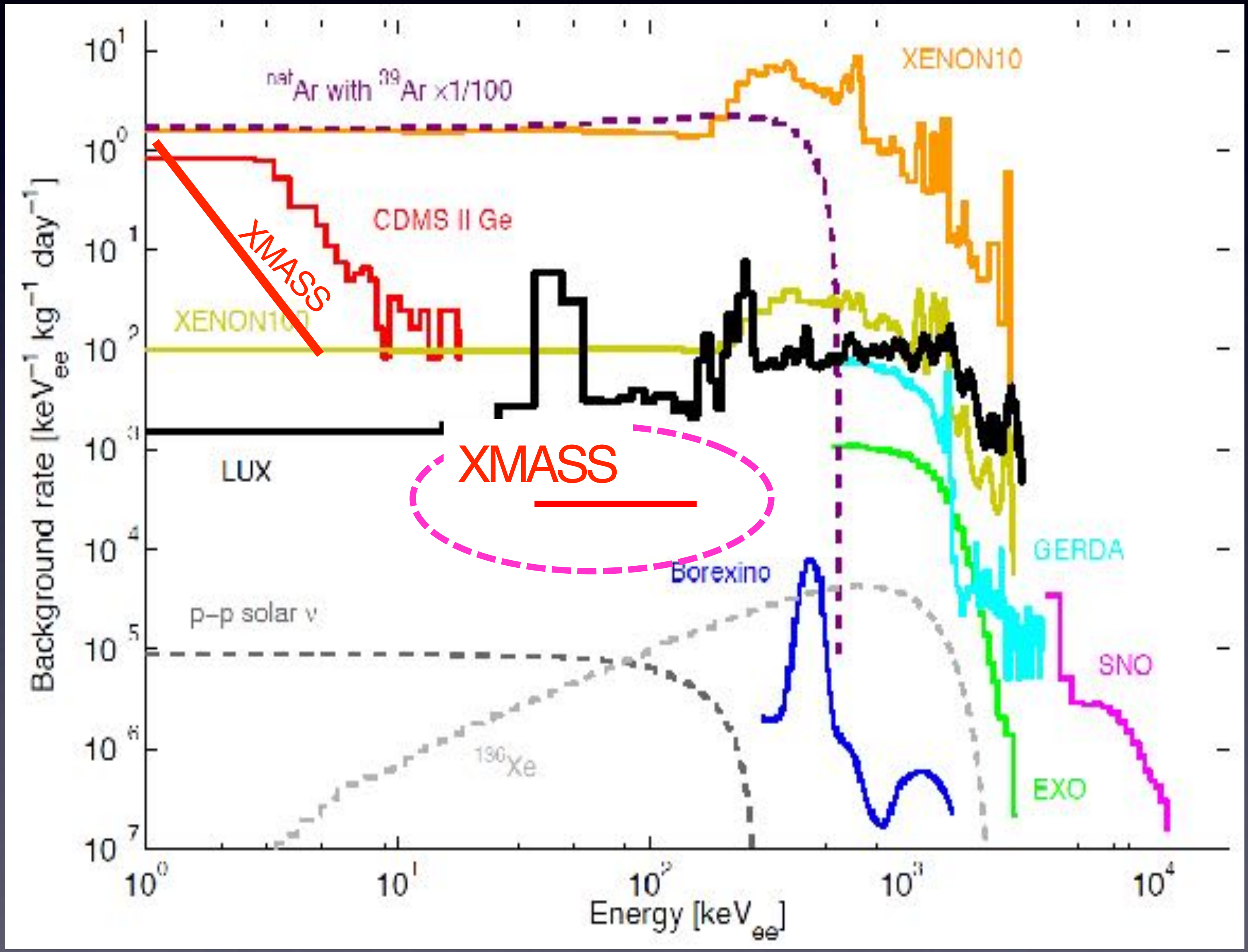

57Co source




~500 days

# Comparison of background rate before particle ID

- Background rate in the fiducial volume before separation of nuclear recoils from e/γ.
- XMASS achieved O($10^{-4}$) event/day/kg/keVee at a few 10's keV.
- Advantage for DM search via electron recoil.




Added to D.C.Malling thesis (2014) Fig.

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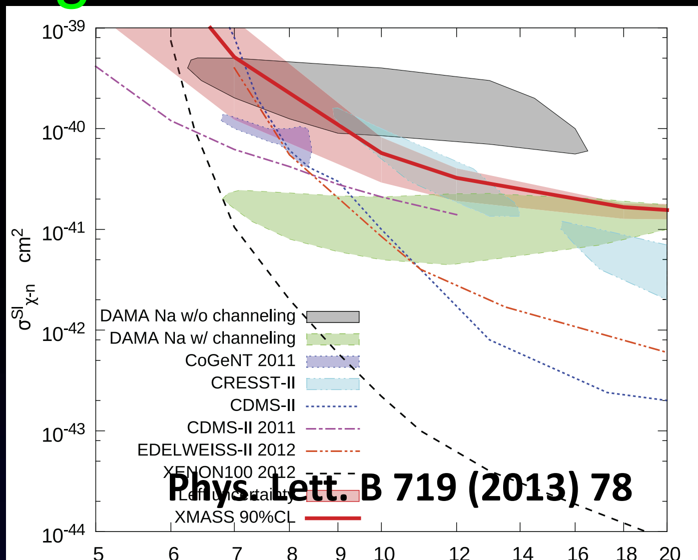
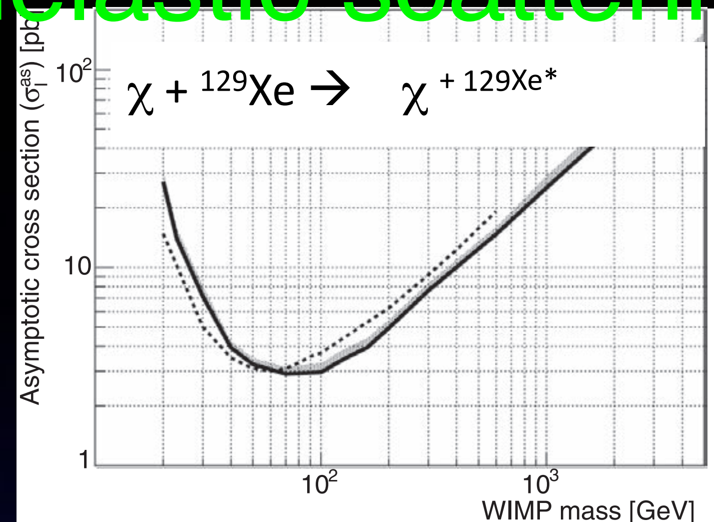
# XMASS experiment@Kamioka

light mass WIMP




Phys. Lett. B 719 (2013) 78

Inelastic scattering




**PTEP 2014, 063C01**

Solar axion

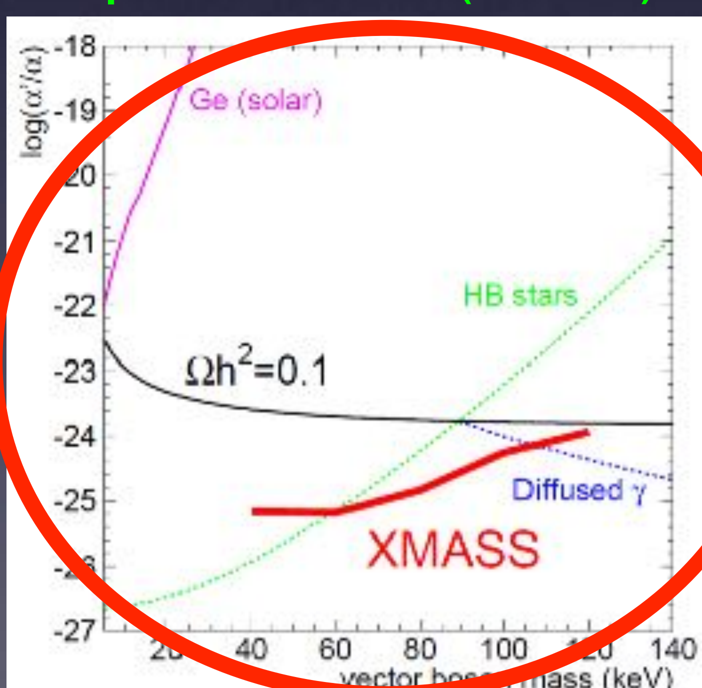
**Phys. Lett. B 724 (2013) 46**

coherent ν-n scattering

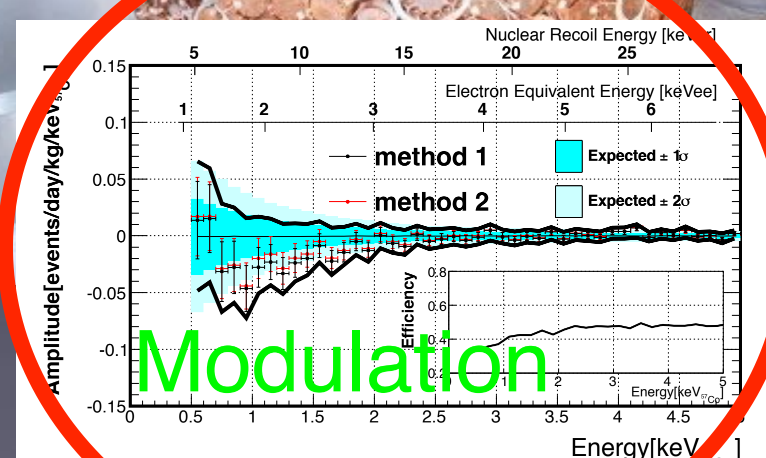
Supernova

**Astroparticle Physics 89 (2017) 51**


super-WIMPs(ALPs)



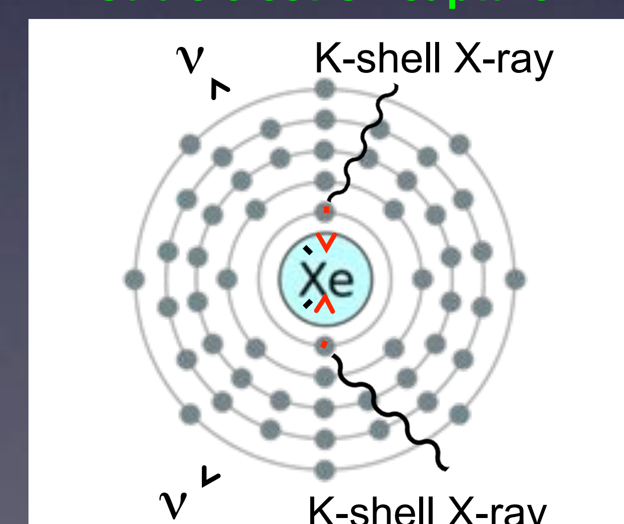

**Phys. Rev. Lett. 113 (2014) 121301**
**editor's suggestion**




Modulation

**Phys. Lett. B (2016), pp. 272**

**Rare decay search**
**Double electron capture**

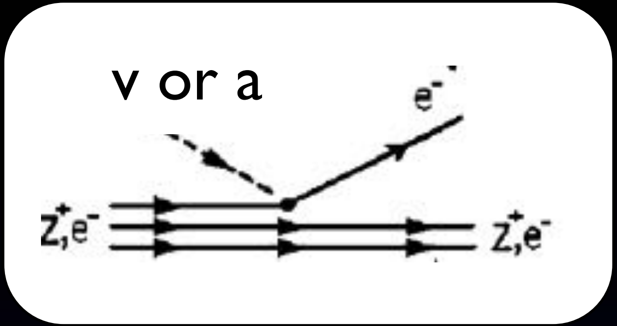



**Phys. Lett. B759 (2016) 64-68**

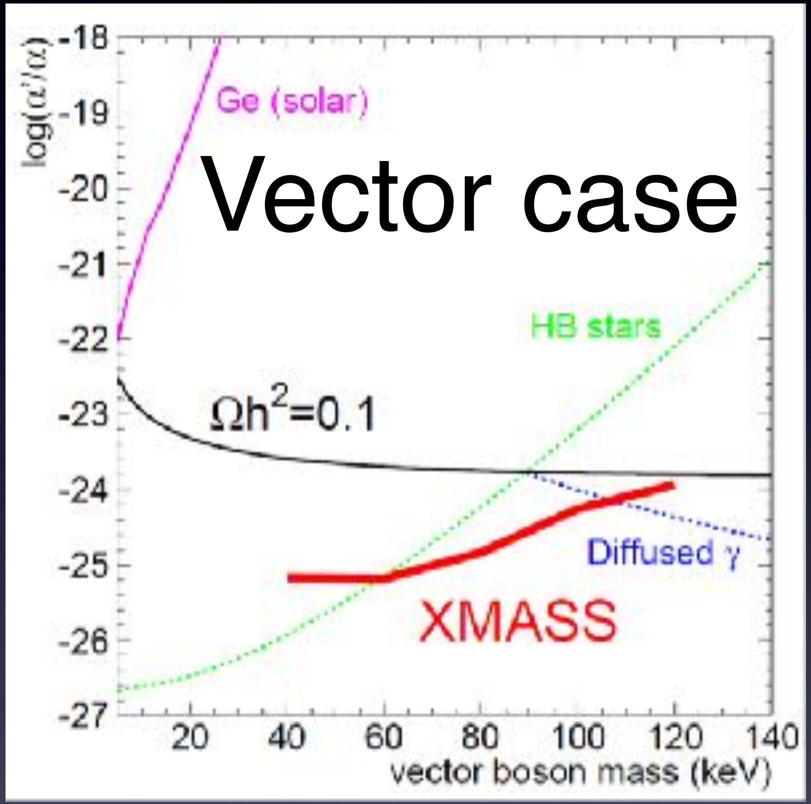
Masaki Yamashita, ICRR, Univ of Tokyo

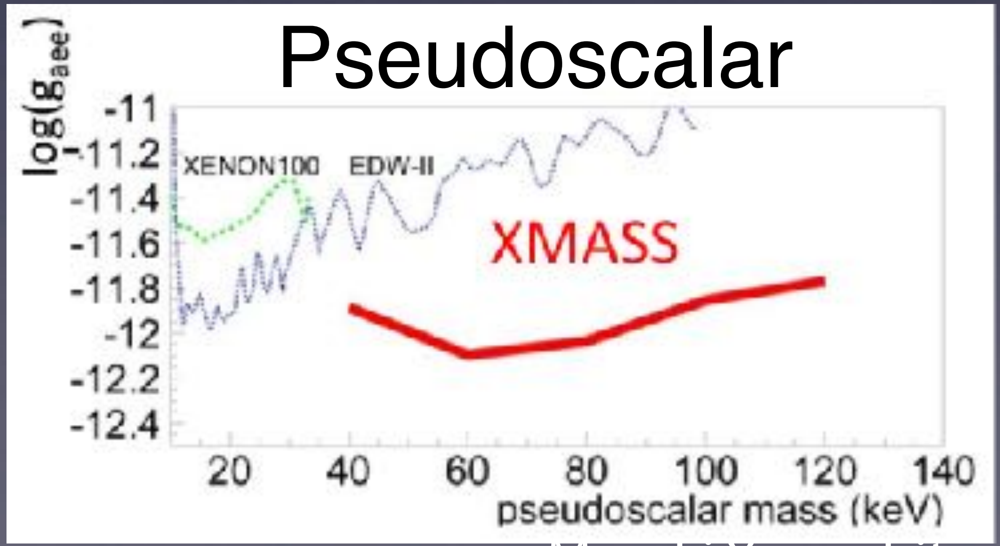
# Search for Bosonic super-WIMPs

***Phys. Rev. Lett. 113 (2014) 121301***




- Motivated by Warm Dark Matter
  - sterile neutrino, gravitino …
- However, it can be pseudoscaler or vector boson and in this case, it can be detected by absorption of the particle, which is similar to the photoelectric effect.
- Search for mono-energetic peak at the mass of the particle( 40-120 keVee)
- Our limit excludes the possibility that such particles constitute all of dark matter.
- The most stringent direct constraint on gaee.

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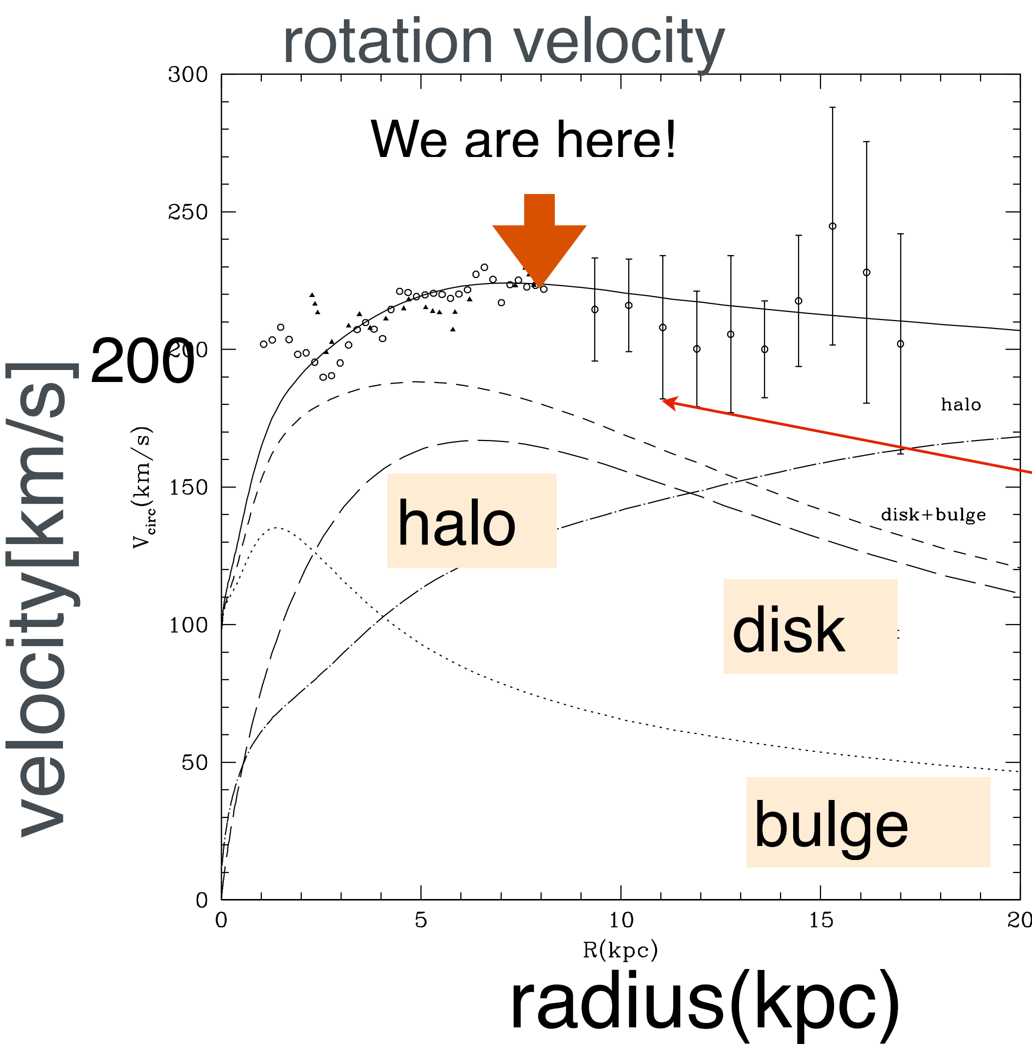
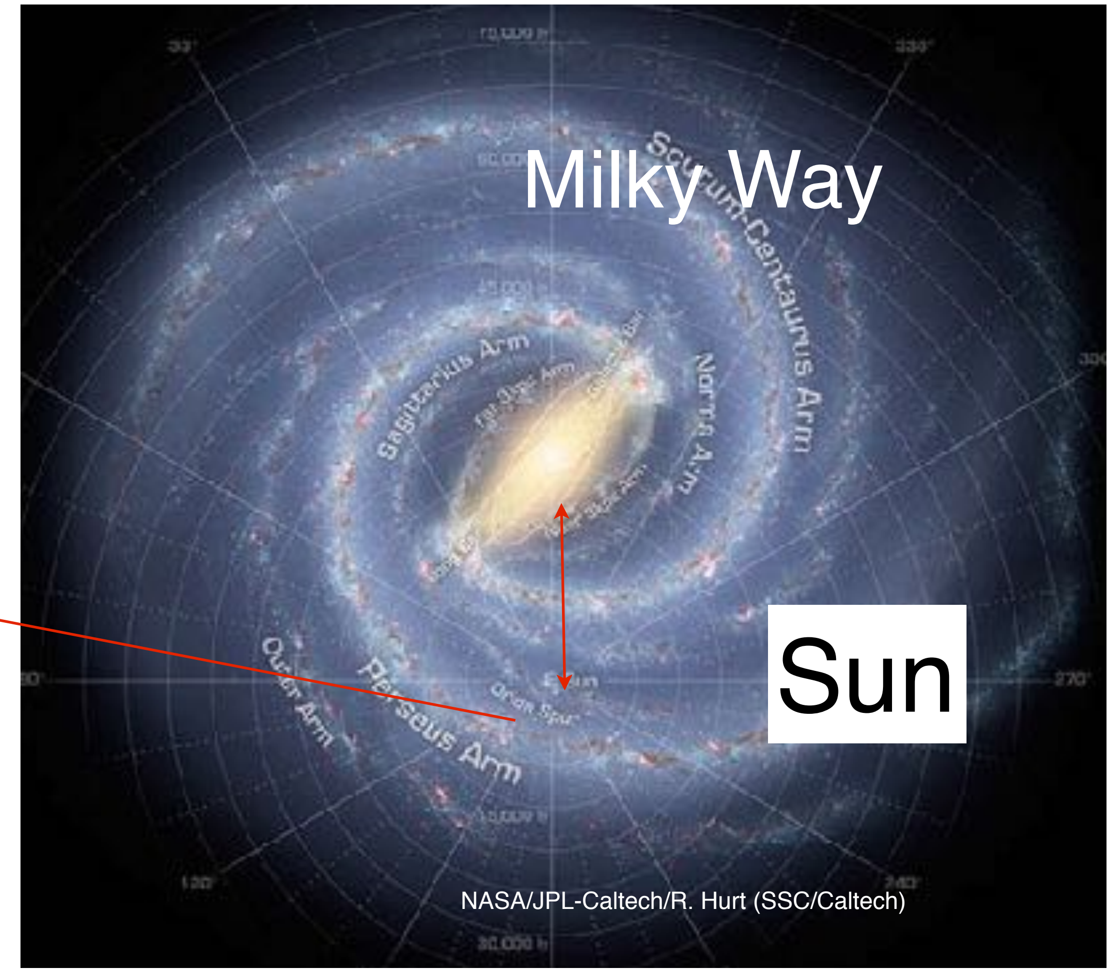
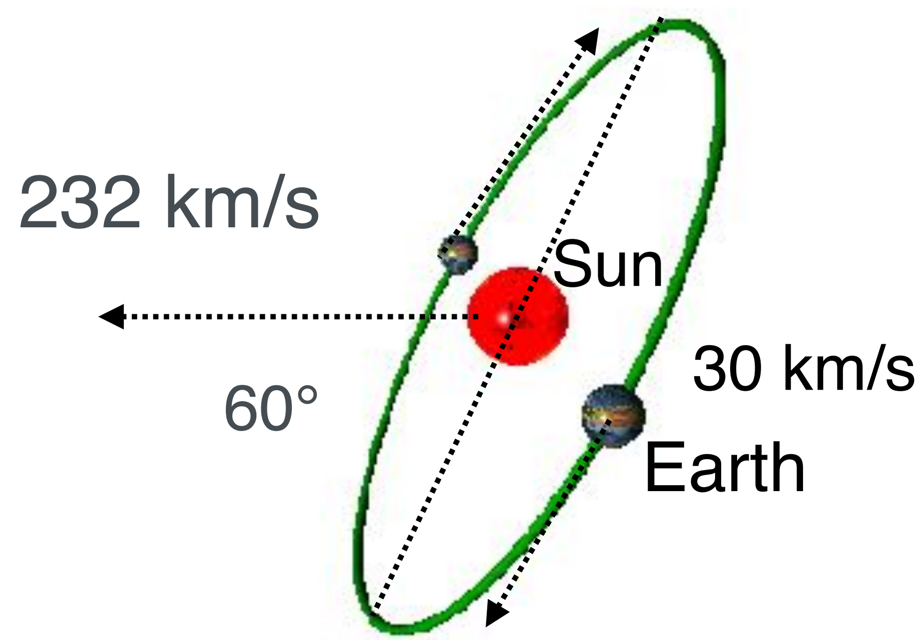
# XMASS annual modulation search

# Annual modulation signal




KLYPIN et al. APJ 2002

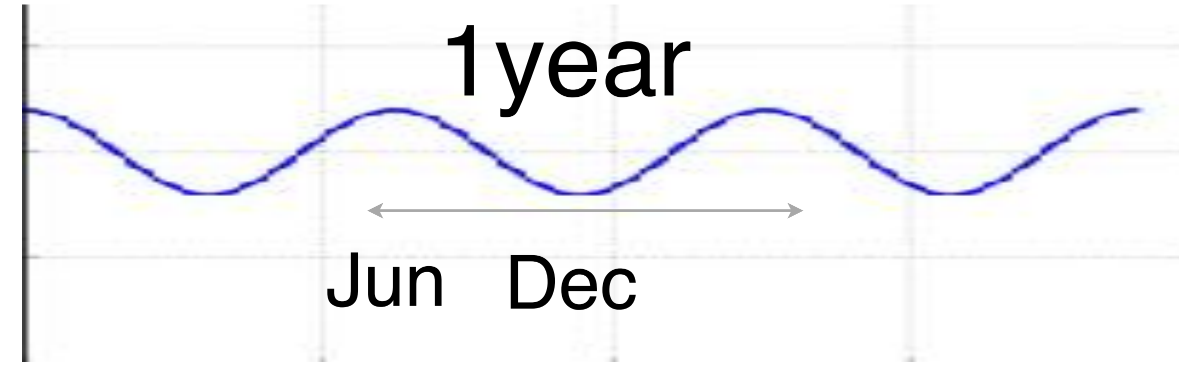


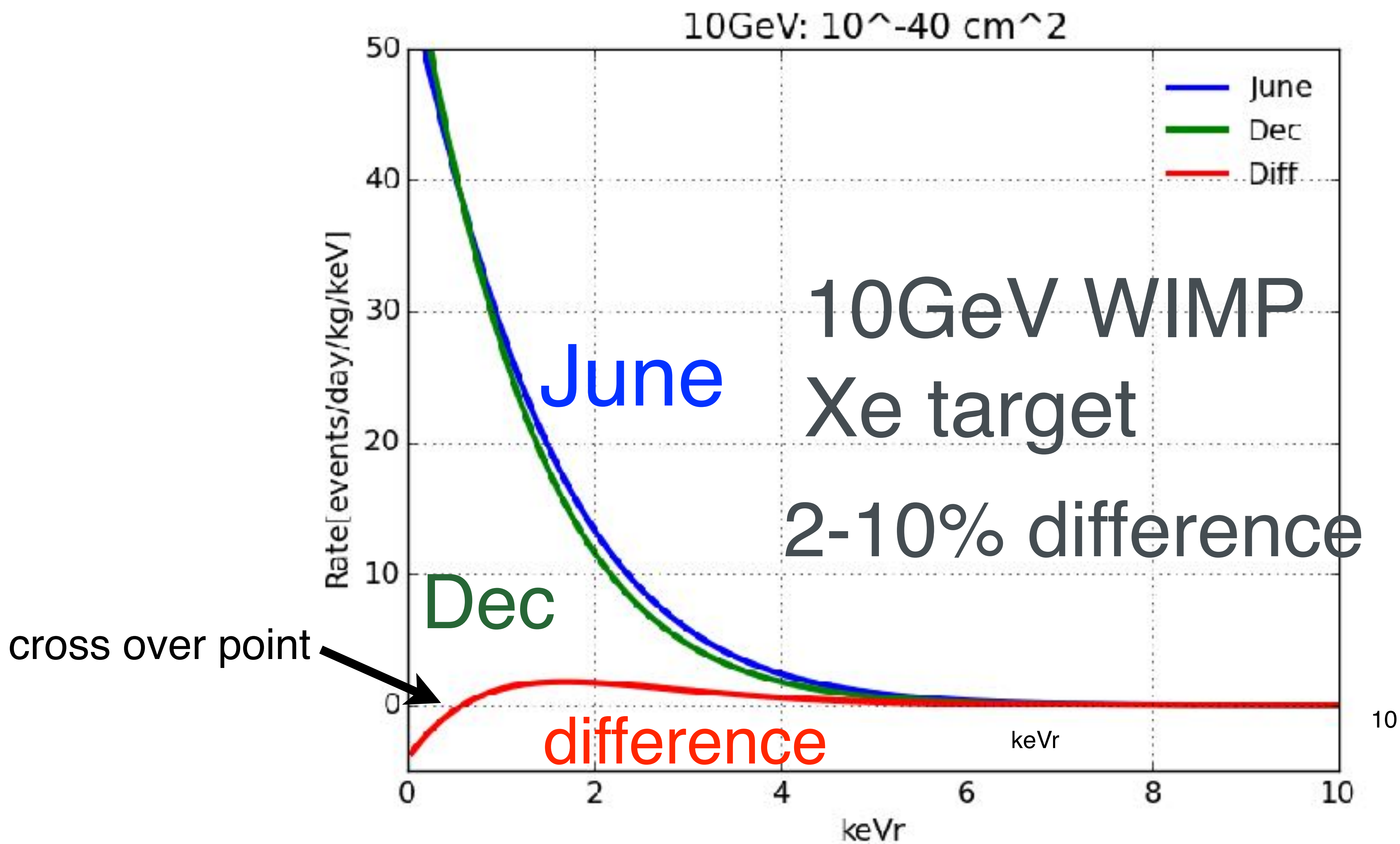




$$\frac{\mathrm{d}R}{\mathrm{d}E}(E,t) \approx S_0(E) + S_m(E)\cos\omega(t - t_c)$$

$$S_m(E) = \frac{1}{2}\left[\frac{\mathrm{d}R}{\mathrm{d}E}(E,\ \mathrm{June}\ 1) - \frac{\mathrm{d}R}{\mathrm{d}E}(E,\ \mathrm{Dec}\ 1)\right]$$

# Energy spectrum

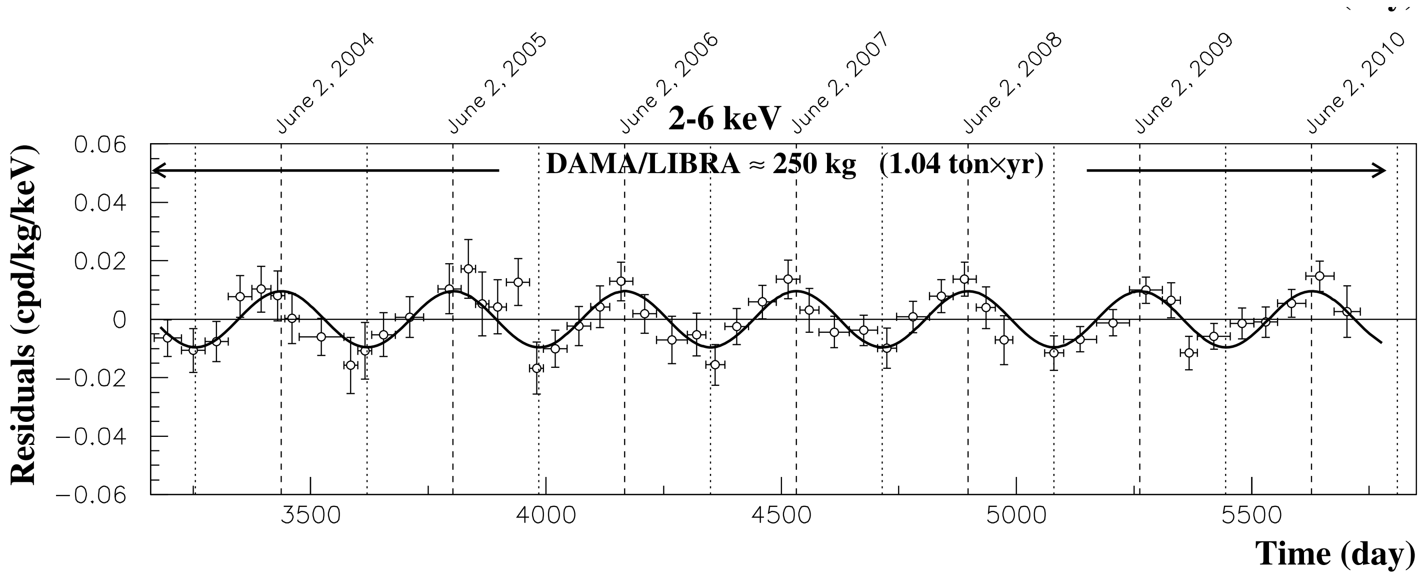


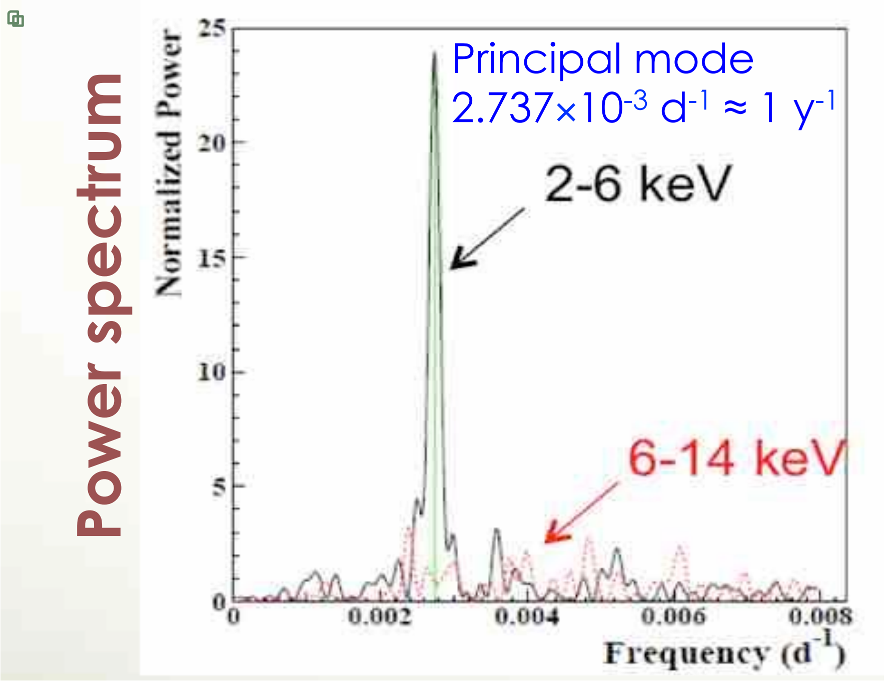



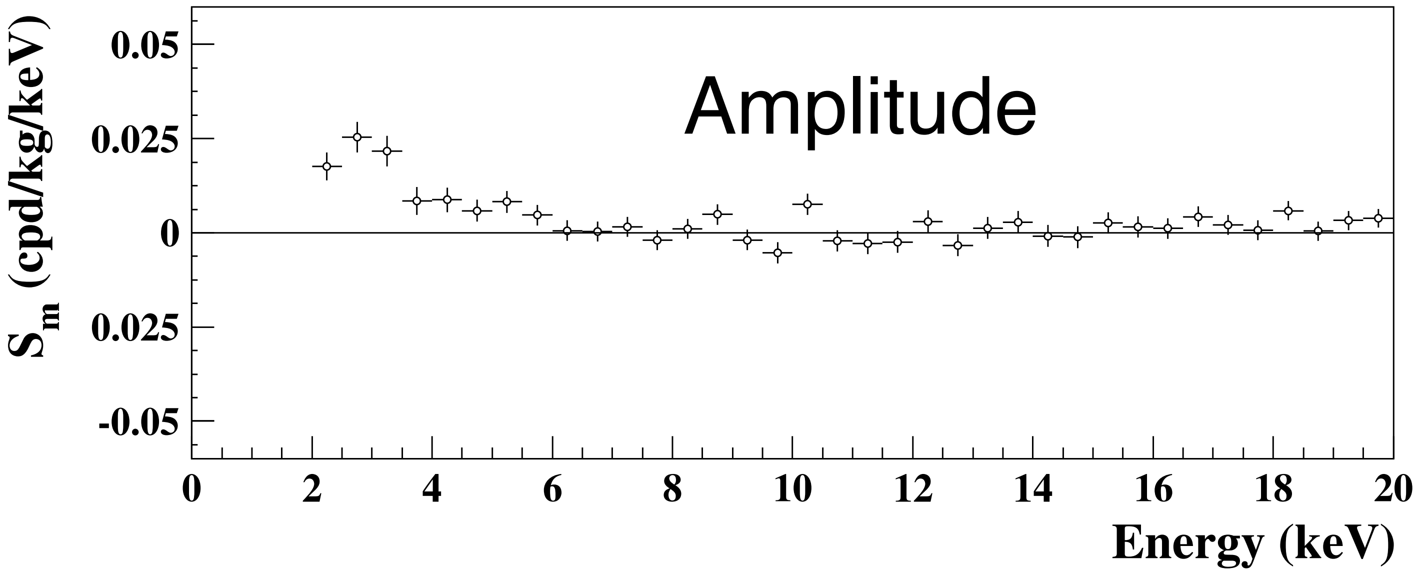
# DAMA/LIBRA

Eur. Phys.J. C(2013) 73, JINST 2012 7 P03009

- DAMA(~100 kg) + LIBRA (~250 kg)
- 14cycle -> 1.33ton x yr
- Annual Modulation 9.2 σ
- Fit with all the parameters free:
  - $A = (0.0112 \pm 0.0012)$ cpd/kg/keV
  - $t_0 = (144 \pm 7)$ days(152 d SHM)
  - $T = (0.998 \pm 0.002)$ y



# Annual Modulation search

-We carried out the analysis without particle ID for WIMP case and model independent case.

-Large mass (832 kg)

- Data set

2013/11/20 - 2015/03/29 (359.2 live days)

# 1 year data of XMASS (0.82 ton x year) vs. 14 years data of DAMA/LIBRA (1.33 ton x year)

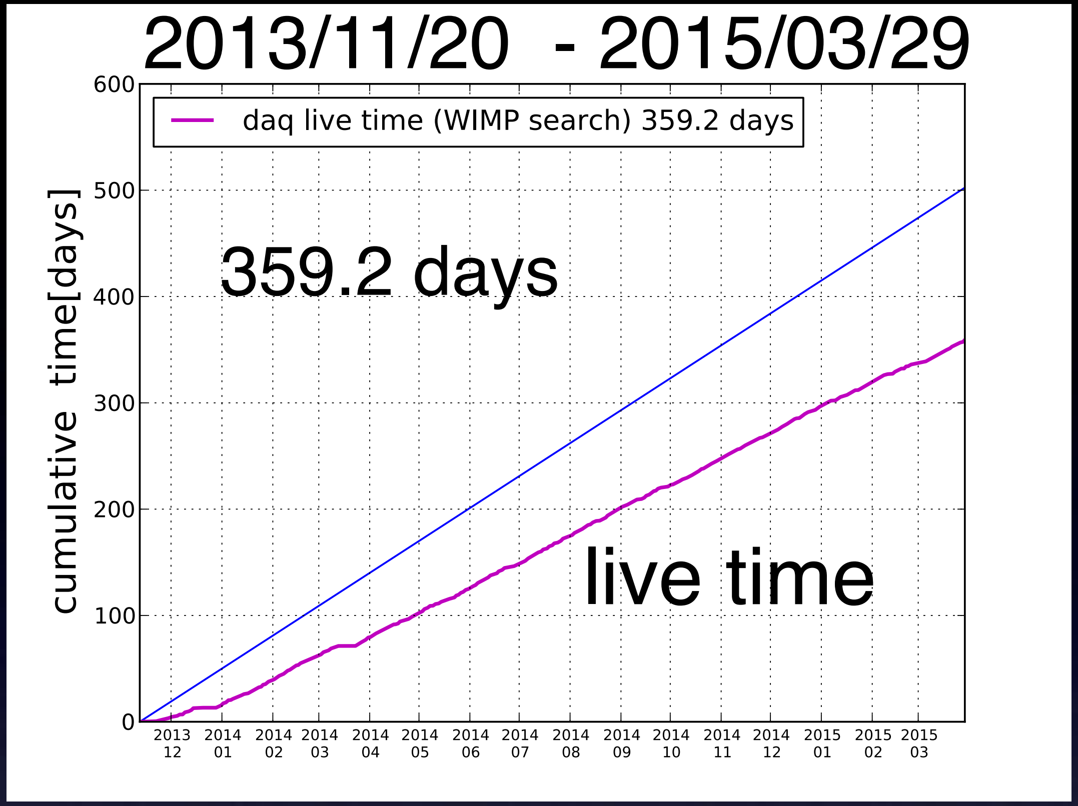
=>Current statistics is already half of DAMA/LIBRA data.

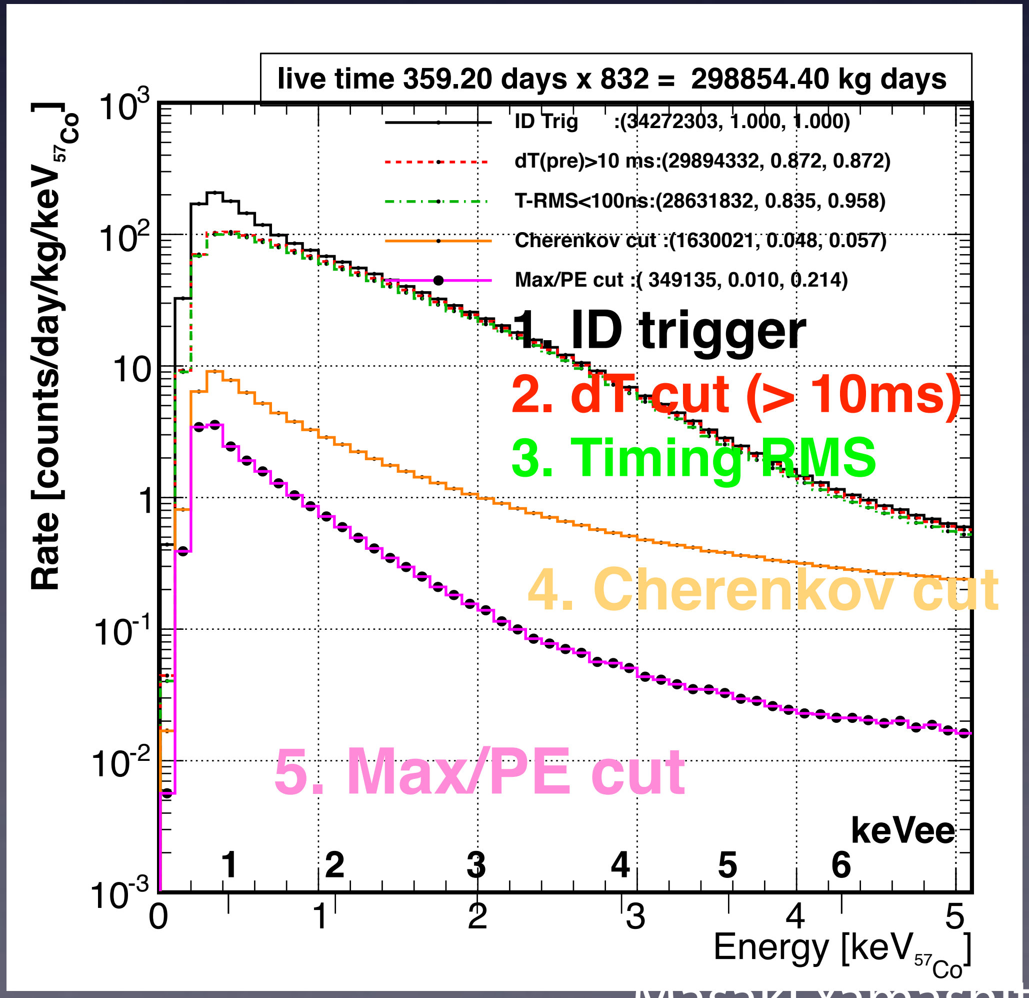
-Low energy threshold: 0.5 keV by 122keV

=> 4.8keVnr (estimated by Aprile et al. PRL(2011) )

1.1 keVee (15% difference from NEST

-Systematic error due to time dependence of light yield (~ 10%) was treated by two method

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# Fitting time variation data

Two independent analysis to treat systematic error.
Main systematic error comes from light yield change during the search period and the error was estimated by MC after tuning by calibration source data. (< +- 5%)

method1: Pull method (pull term α)

$$\chi^2_{\text{method1}} = \sum_i^{E_{bins}} \sum_j^{t_{bins}} \frac{(\mathrm{R}^{\mathrm{data}}_{\mathrm{i,j}} - \mathrm{R}^{\mathrm{ex}}_{\mathrm{i,j}} - \alpha_i \mathrm{K}_{\mathrm{i,j}})^2}{\sigma(\mathrm{stat})^2_{\mathrm{j}}} + \alpha_i^2$$

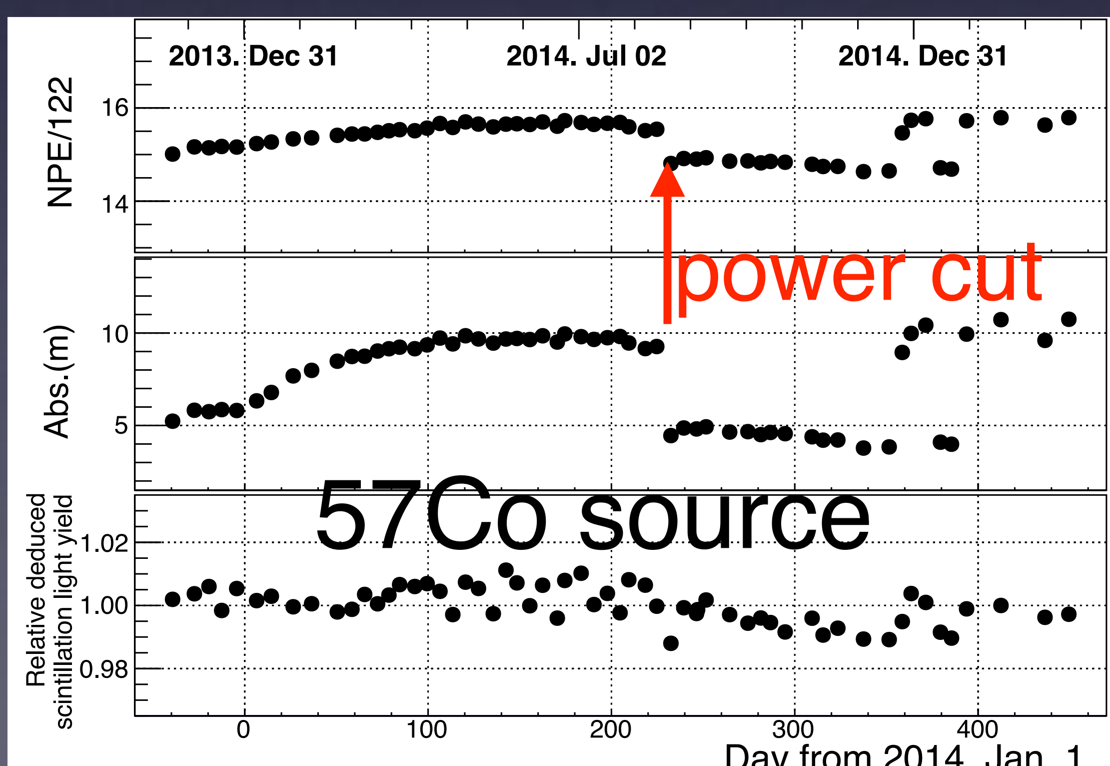
$R^{data}$: observed data
$R^{ex}$: expected rate
Nbins:Ebins x tbins

method2: Covariance Matrix

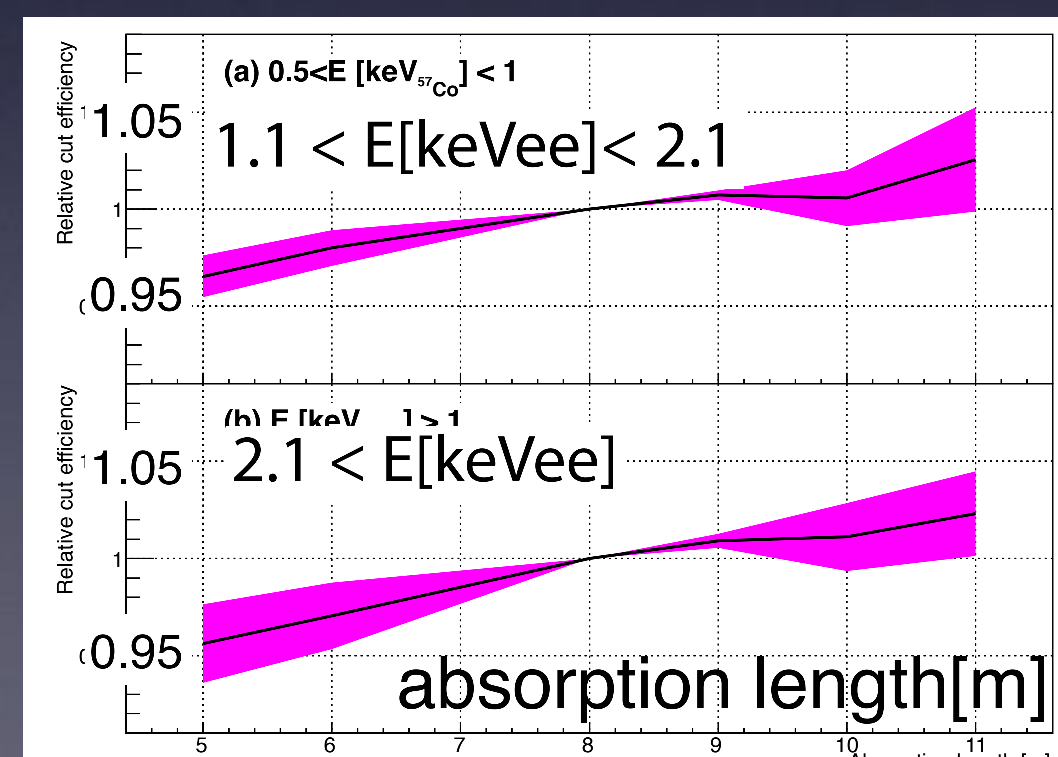
$$\chi^2_{\text{method2}} = \sum_{i,j}^{N_{\text{bins}}} (R_i^{\text{data}} - R_i^{\text{ex}})(V_{\text{stat}} + V_{\text{sys}})^{-1}_{ij}(R_j^{\text{data}} - R_j^{\text{ex}})$$

systematic term

size




relative efficiency uncertainty

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# WIMP case

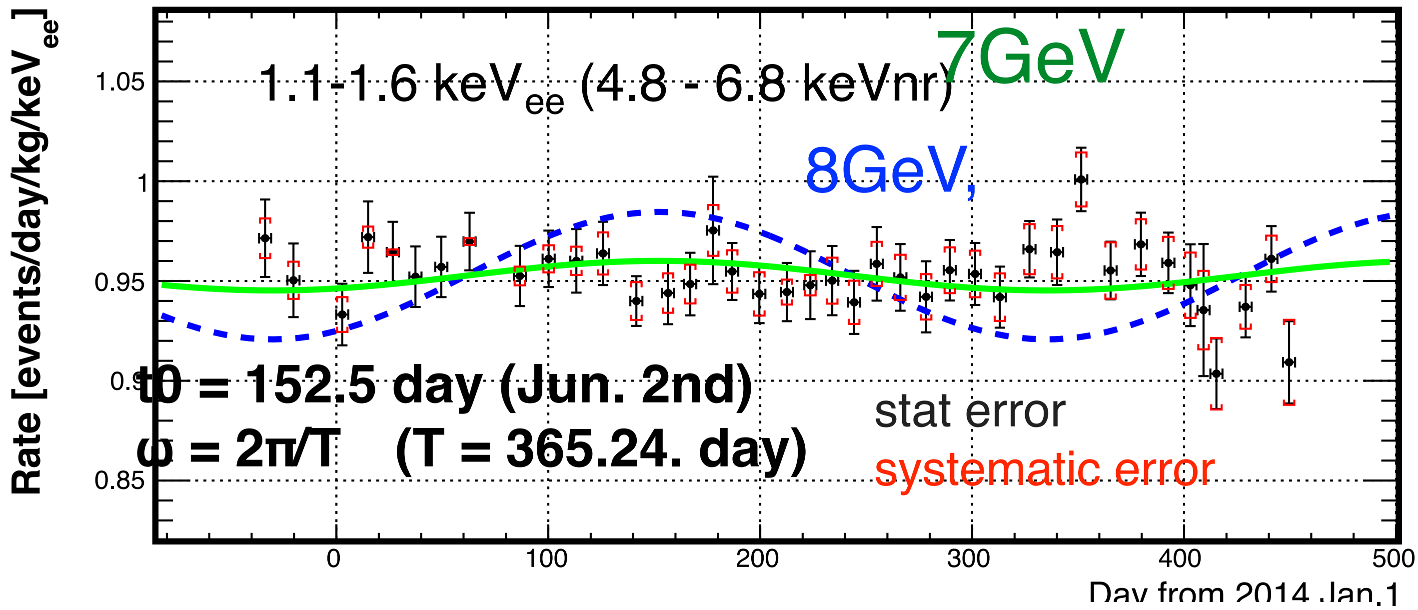
Abe et al. (XMASS collaboration ) Phys Lett. B (2016)272

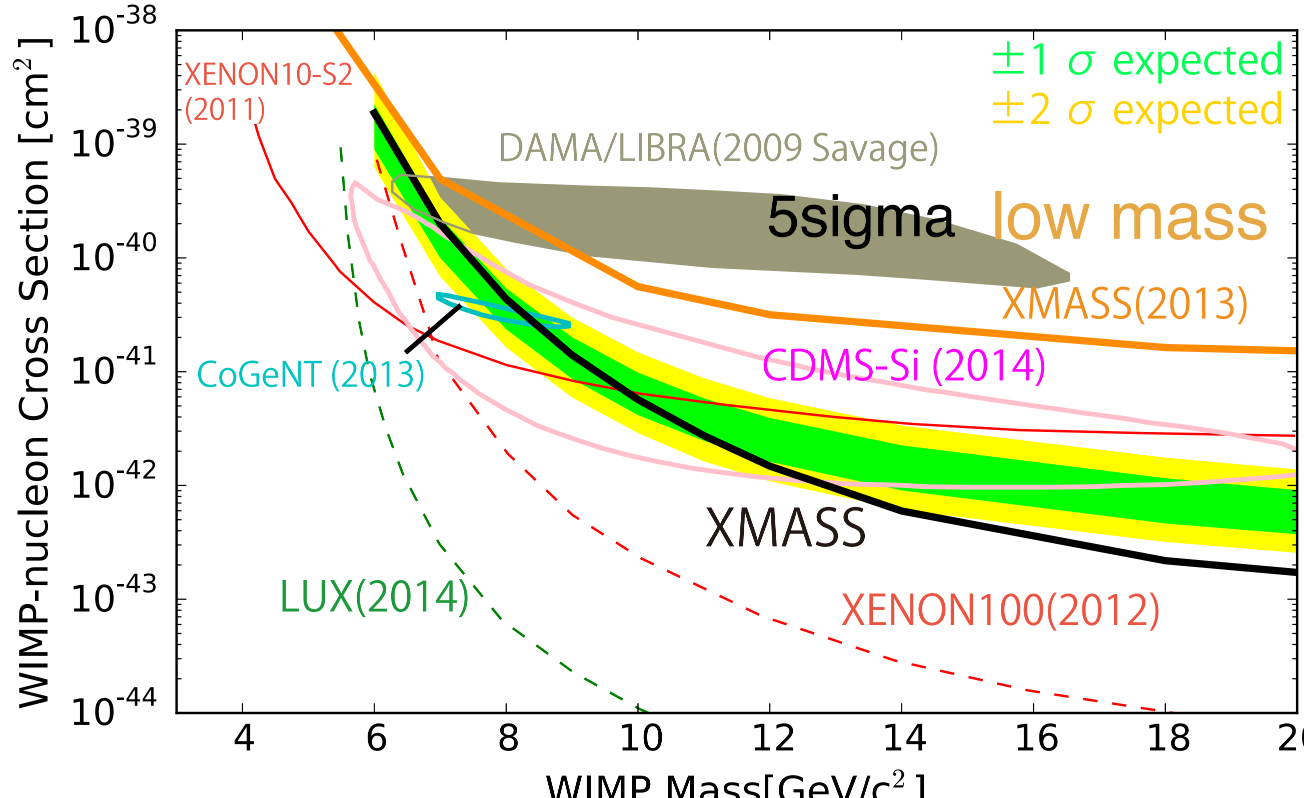
- 2013 Nov - 2015 March (359.2 live days)
- assuming WIMP spectrum
- 2D fitting (time and energy bin )

$$R^{\mathrm{ex}}_{i,j} = \int_{t_j-\frac{1}{2}\Delta t_j}^{t_j+\frac{1}{2}\Delta t_j} \left(C_i + \sigma_{\chi n} \cdot A_i(m_\chi)\cos 2\pi \frac{(t-t_0)}{T}\right) dt,$$

Ai: amplitude
Ci: constant
$\sigma_\chi$: WIMP-nucleus cross section
$m_\chi$:WIMP mass
t0:152.5 day
T : 1 year

- DAMA/LIBRA region is mostly excluded by annual modulation search.
  $<4.3 \times 10^{-41}$cm$^2$ (90% CL) @ 8GeV



# Model Independent Case

Abe et al. (XMASS collaboration ) Phys Lett. B (2016)272

$$R^{\mathrm{ex}}_{i,j} = \int_{t_j-\frac{1}{2}\Delta t_j}^{t_j+\frac{1}{2}\Delta t_j} \left( C_i + A_i \cos 2\pi \frac{(t-t_0)}{T} \right) dt$$

free in energy bin

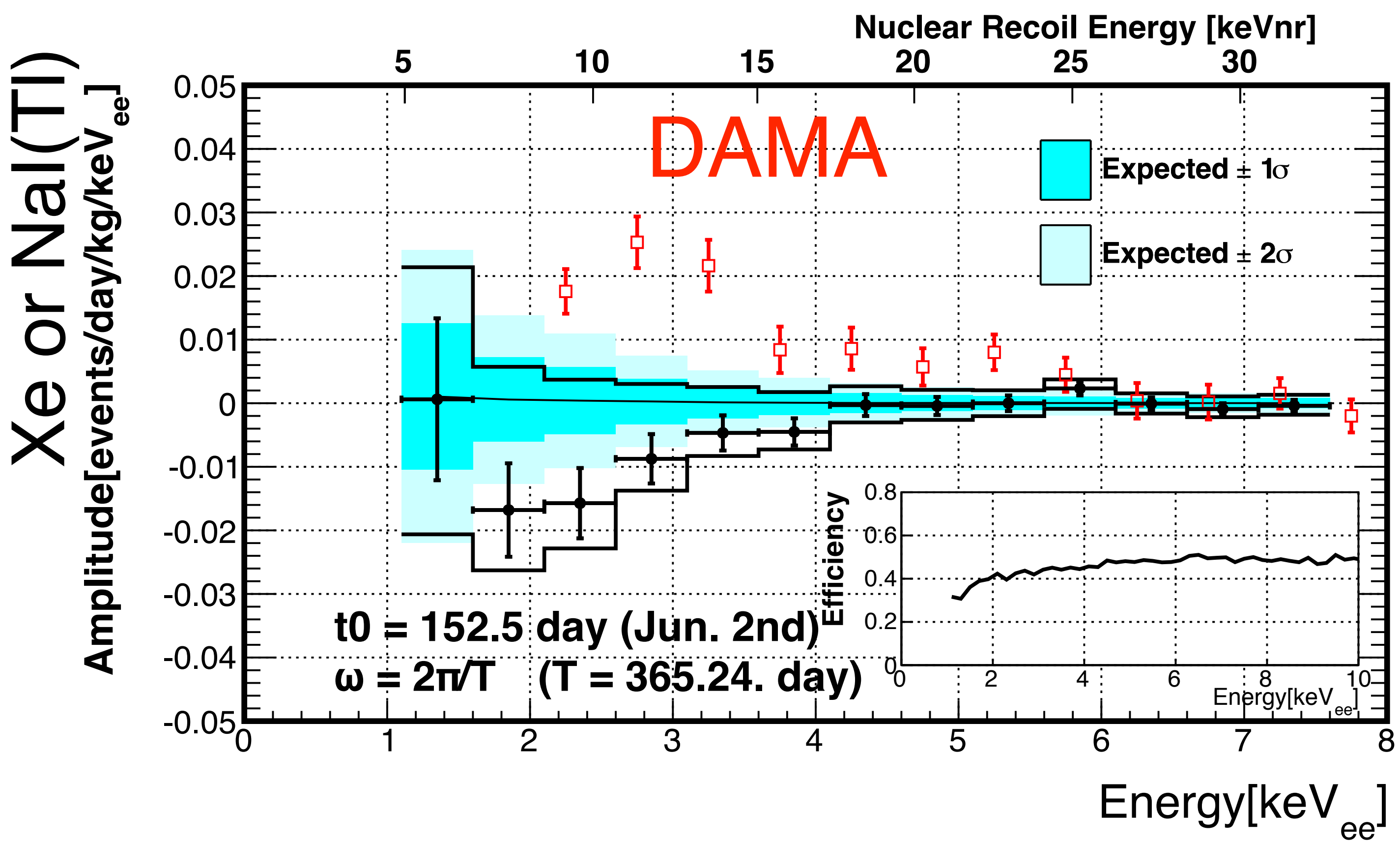
$$\chi^2 = \sum_i^{E_{bins}} \sum_j^{t_{bins}} \left( \frac{(R^{\mathrm{data}}_{i,j} - R^{\mathrm{ex}}_{i,j} - \alpha K_{i,j})^2}{\sigma(\mathrm{stat})^2_{i,j} + \sigma(\mathrm{sys})^2_{i,j}} \right) + \alpha^2,$$

Model independent analysis :

- No sign  for SUSY particle at LHC so far.
- No sign in direct detection for more than decade.
- important to look for variety candidate.
- Annual modulation signal is searched for without any model assumption.
- Amplitude (Ai) and Constant (Ci) are free parameter.
- Slightly negative amplitude was observed.

Significance  was evaluated with test statistic (10,000 sample) and no significant modulated signal has been observed. (1.8σ)

< (1.7-3.7)x10$^{-3}$x10$^{-3}$ counts/day/kg/keVee in 2-6keVee (0.5keVee bin width). (90 CL, Bayesian)



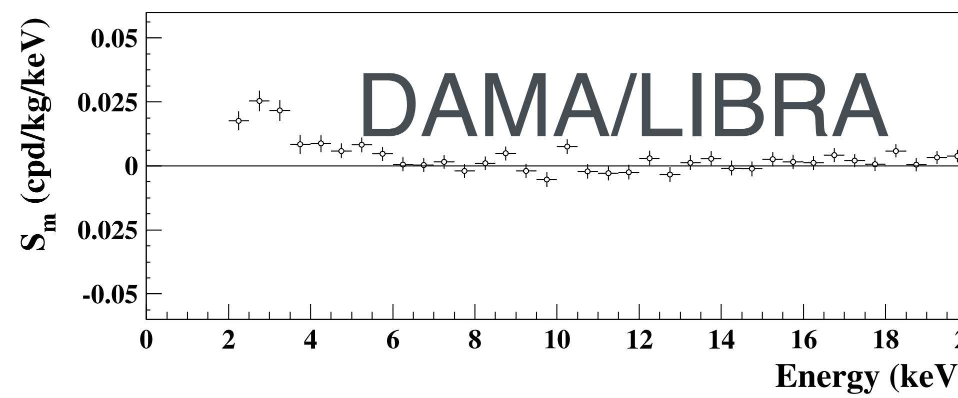
# DM - electron recoil models

- Signal is not a nuclear recoil.
  - e.g.
    - no loop-induced nuclear recoil - axial vector interaction
    - photon emission from excited DM (Luminous dark matter)
- modulation signal
  - axion like particle can not be candidate because σ ~1/v , dm flux ~ v.
- DAMA/LIBRA vs LXe
  - Energy deposit ~ 3 keV energy deposit. (from DAMA/LIBRA)
- Event rate is similar for Xe(z=54) and Iodine (z=53)
- modulation analysis is not depend on the halo model.

- WIMP-electron scattering
  - R. Bernabei et al. PRD, 77 02308 (2008),
  - J. Kopp et al. PRD 80, 083502 (2009)
  - B.M. Roberts et al., PRL 116, 023201 (2016)
- Luminous dark matter
  - B. Feldstein et al., PRD 82, 075019 (2010)
- Mirror Dark Matter
  - R. Foot, Int. J. Mod. Pays. A 29, 126, (2014)
- Plasma Dark Matter
  - J. D. Clarke at el. axXiv1512.06471v
- …

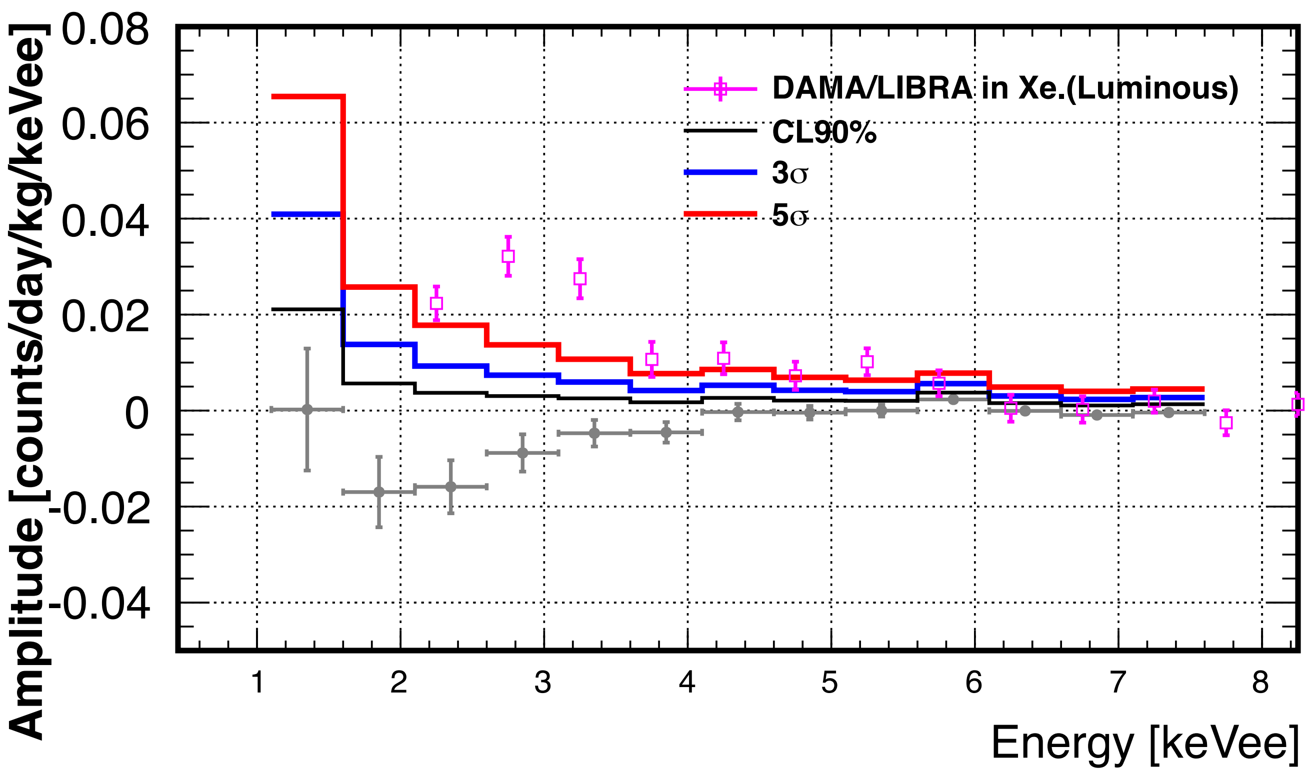
# Luminous dark matter

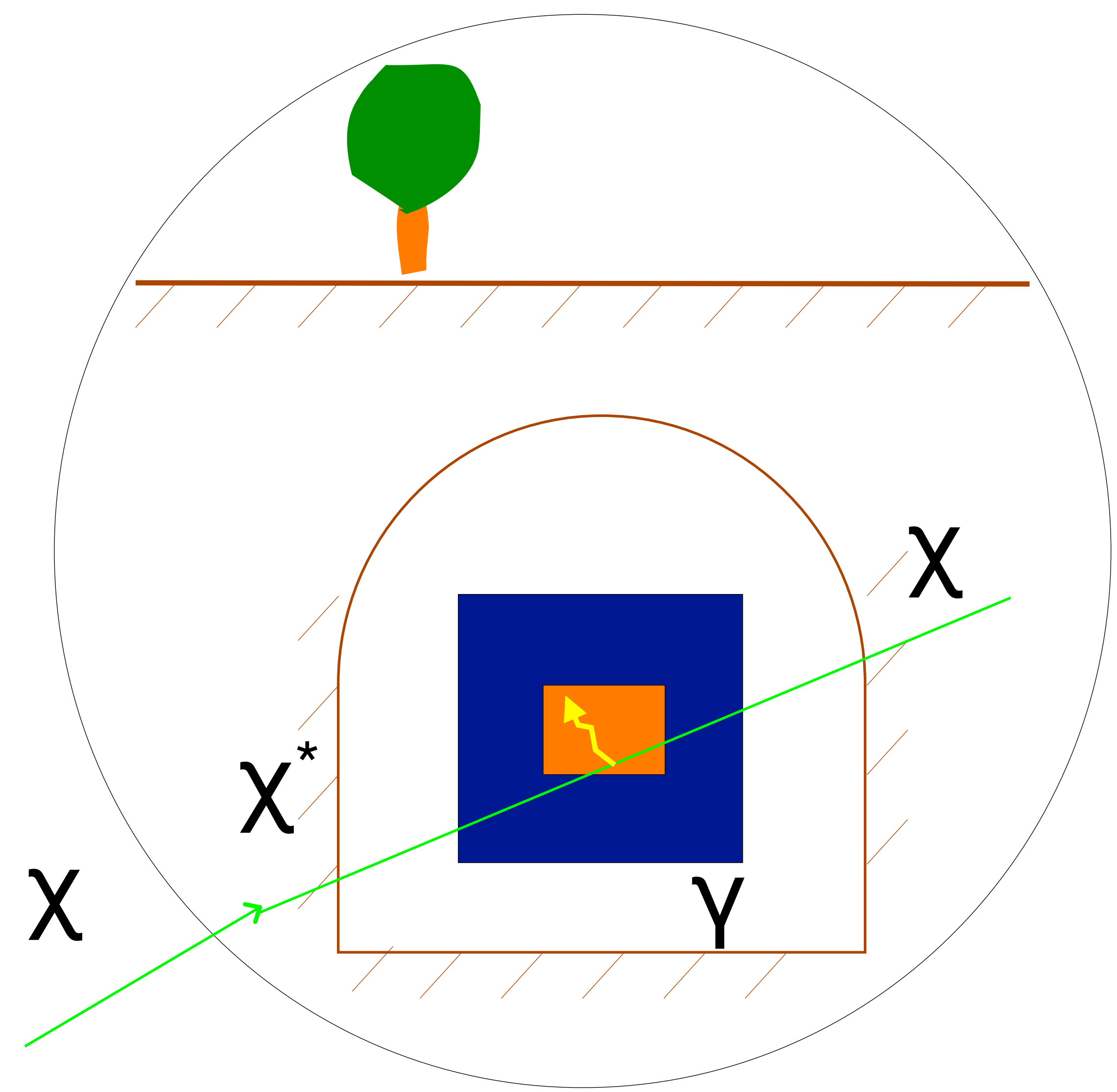
B. Feldstein et al., PRD 82, 075019 (2010)




- DM is excited by hitting the Earth rock.
- Emit photon in the detector
  - $\chi^{excited}$ -> $\chi^{ground}$ + $\gamma$ (~ 3keV)
- Unlike axion-like particle, the signal has annual modulation
- rate depends not mass but volume of the detector.
- We consider only density for comparison.

$$\mathrm{Rate(Xe/NaI)} = \frac{\rho(\mathrm{NaI})}{\rho(\mathrm{Xe})} = \frac{3.67}{2.88} = 1.27$$

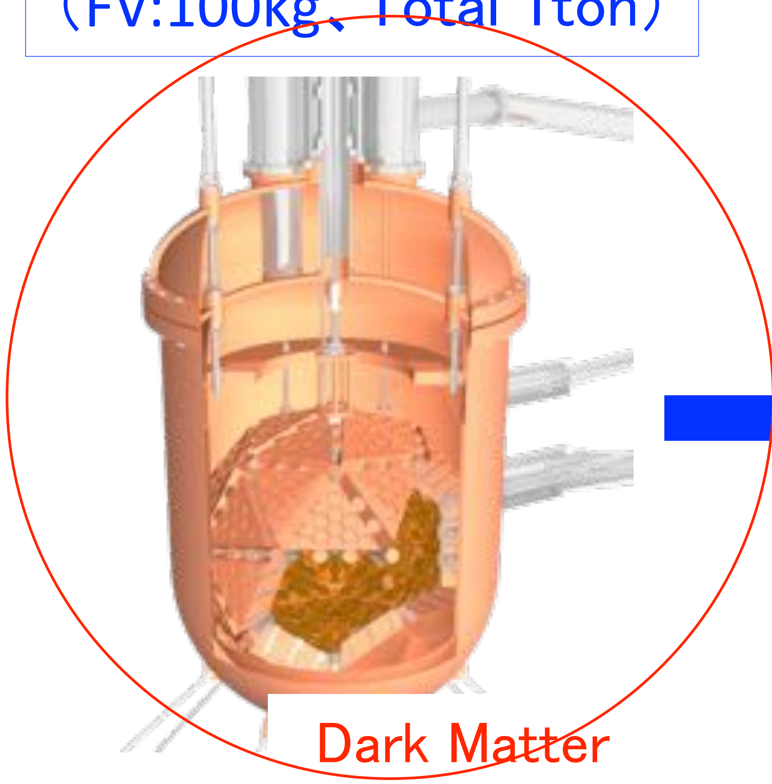


# Future prospects

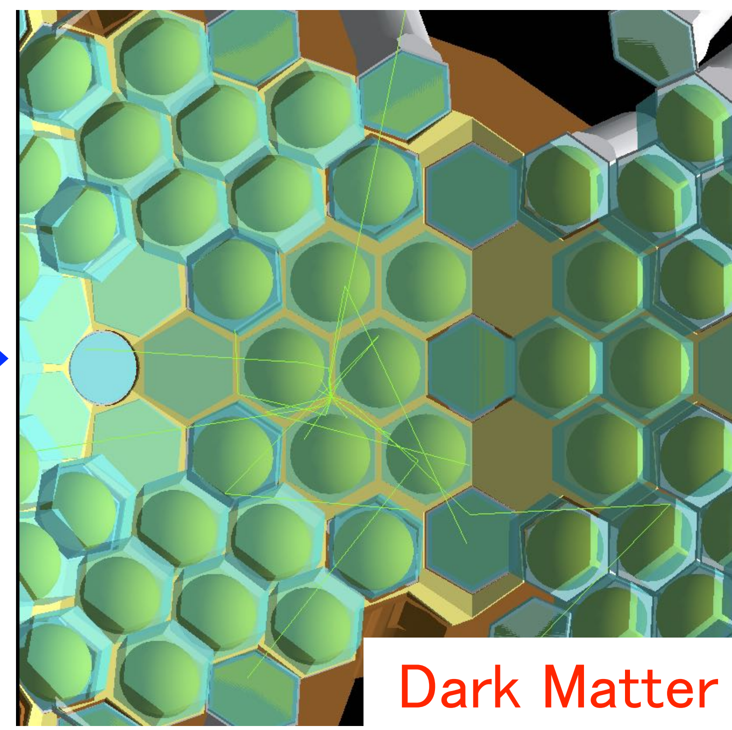
# XMASS Experiment

XMASS I
(FV:100kg、Total 1ton)



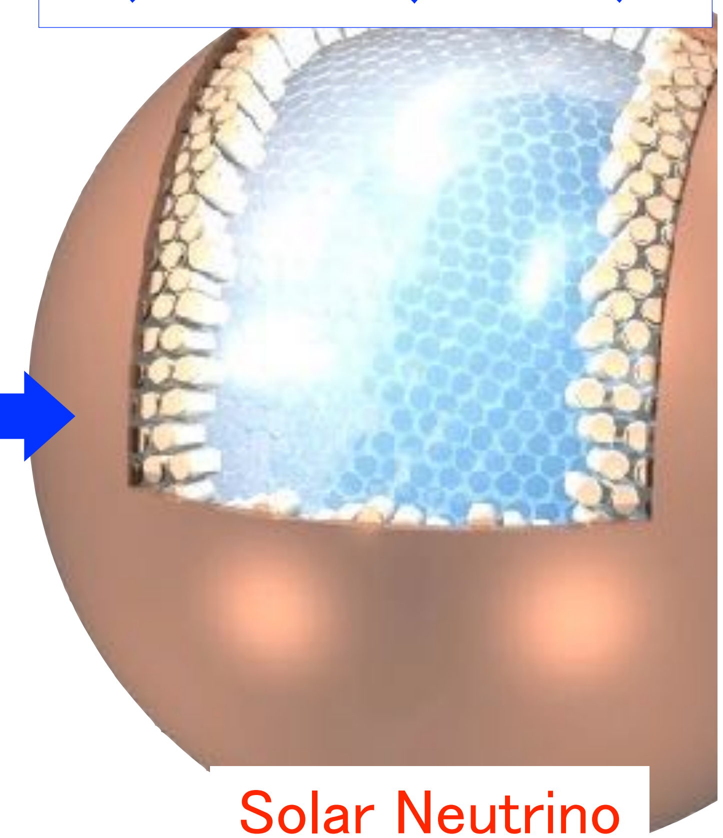

2007: Project was funded.
2013〜: Data taking

XMASS 1.5
(FV:3ton、Total 6ton)



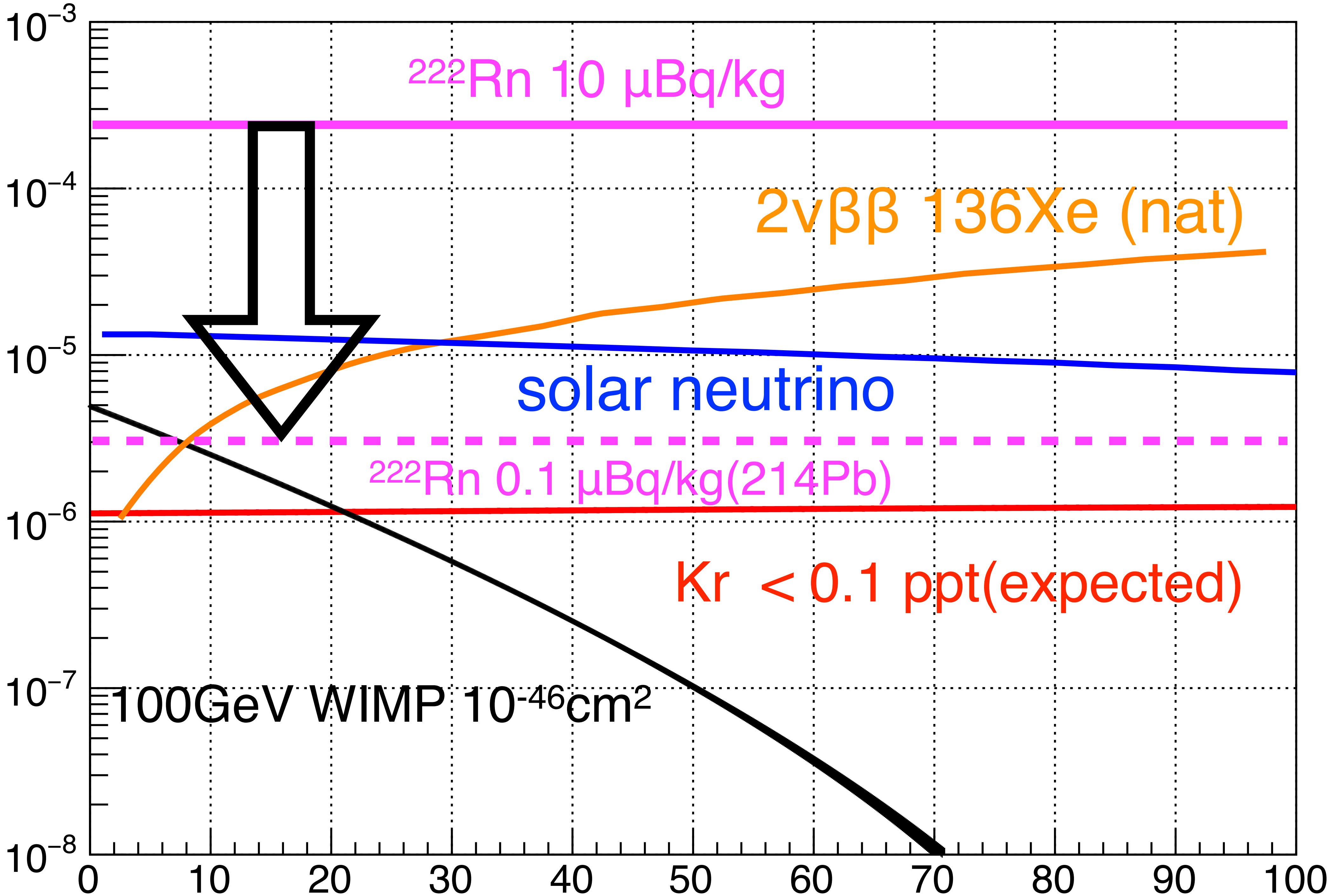

3inch dome shape PMT

XMASS II
(FV:10ton、24Ton)



Solar Neutrino
Dark Matter
DBB

# Background




Rn background is the key for any DM and neutrino physics search. (WIMP, Super-WIMP, Axion, 2nuECEC etc)

Two phase reduces ~1/200 for electron recoil events.

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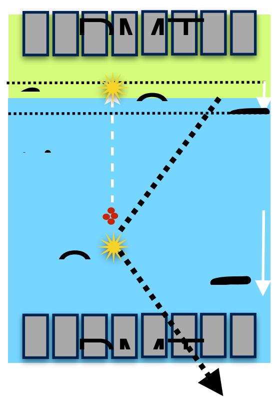
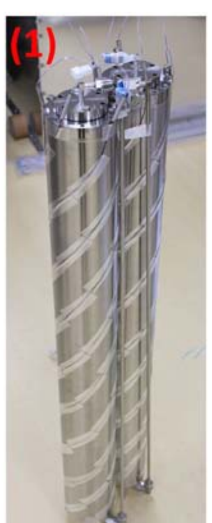
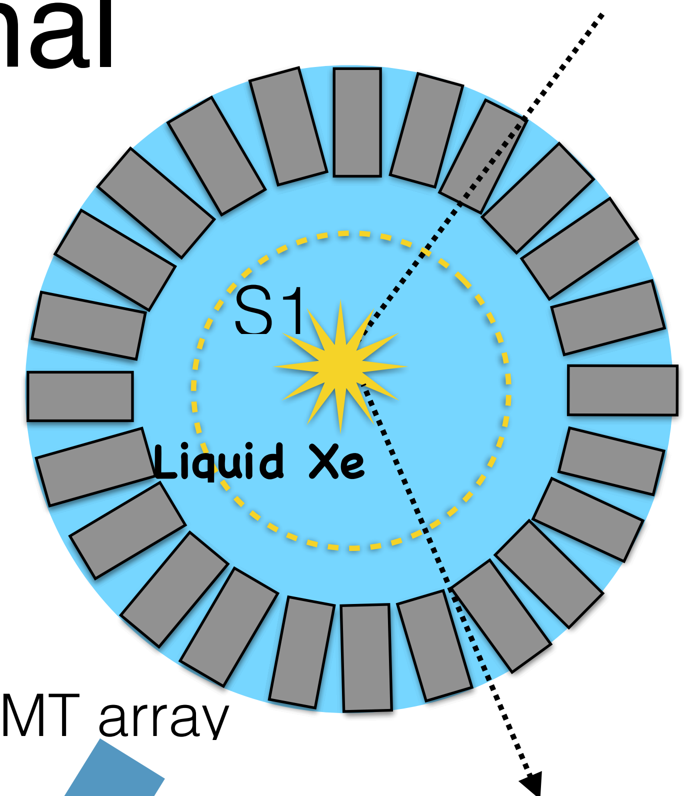
# LXe detector for dark matter final



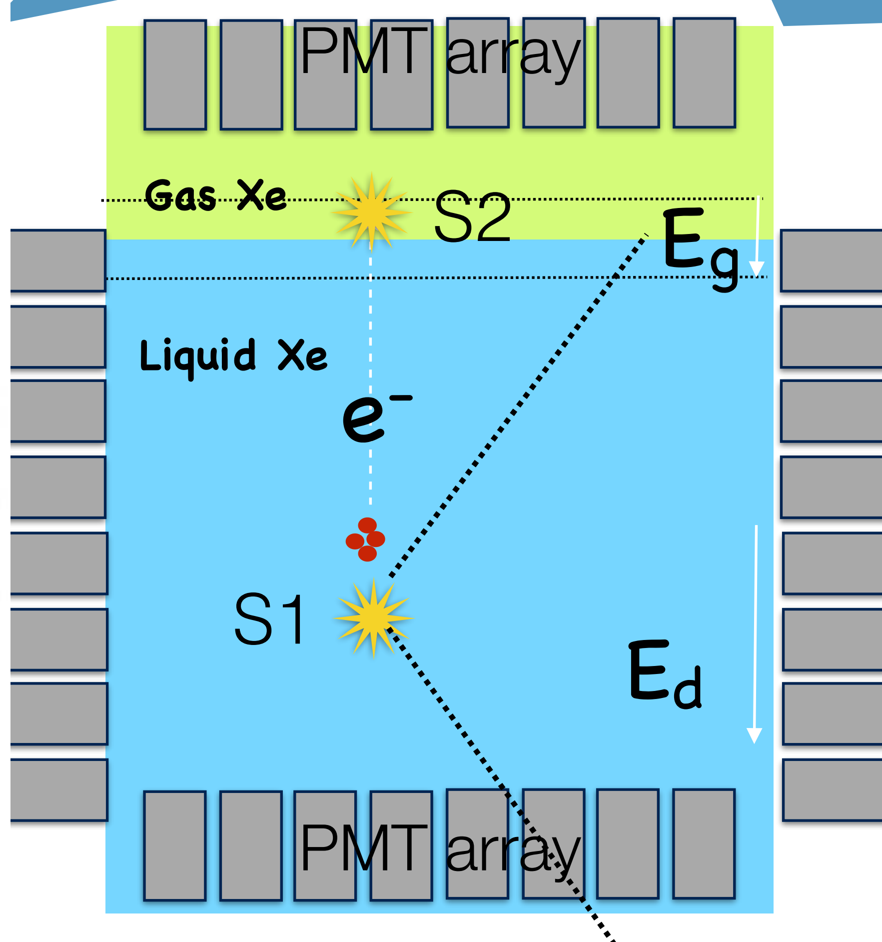
lowest BG
PMT



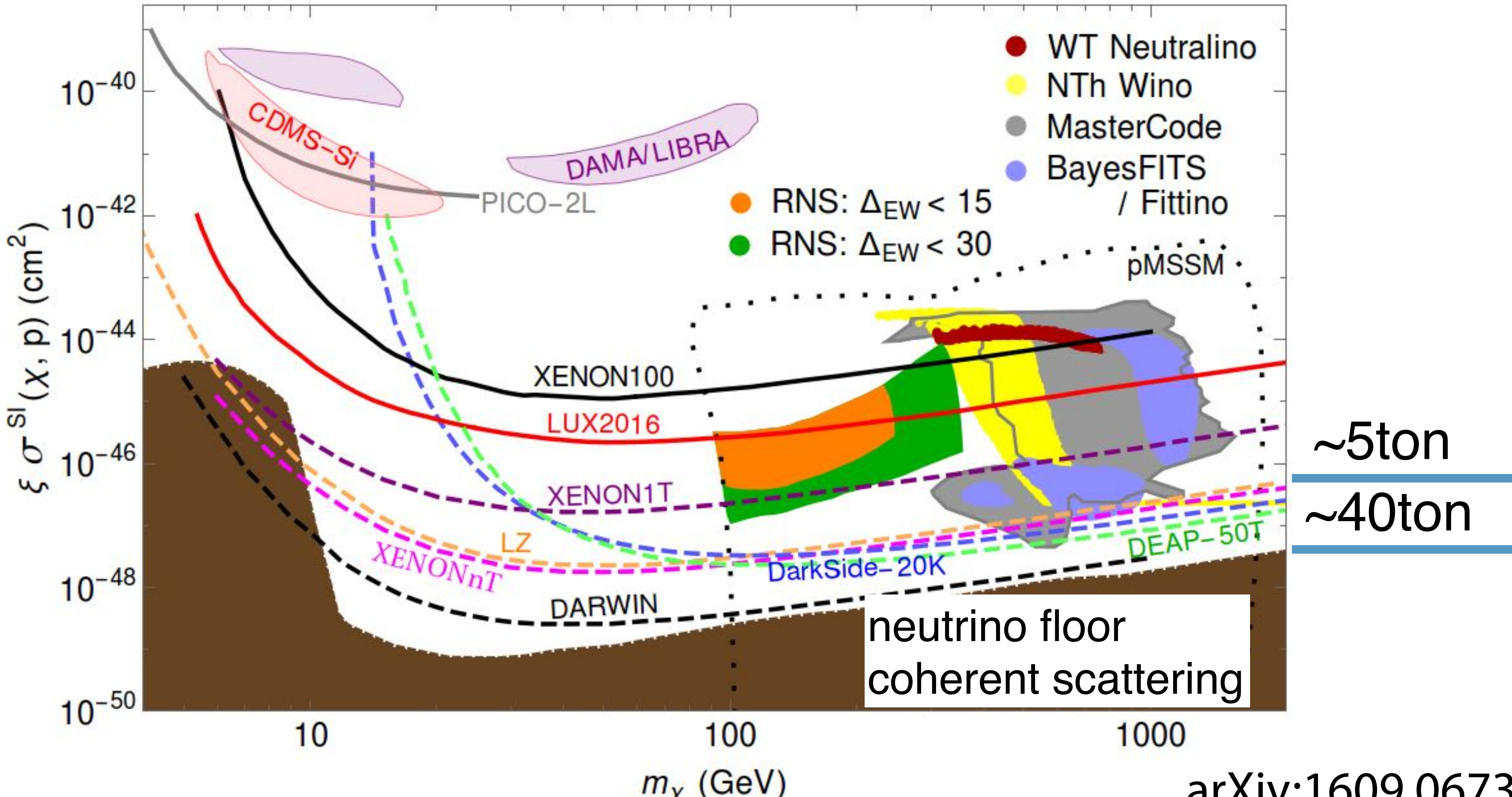

Rn removal
chamber
(charcoal)


PMT array




surrounded by Photo sensor
> 10 ton volume




arXiv:1609.06735

WIMP mass [GeV/c$^2$]

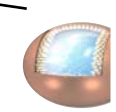
Figure 1: Plot of rescaled spin-independent WIMP detection rate $\xi\sigma^{SI}(\chi, p)$ versus $m_\chi$ from several published results versus current and future reach (dashed) of direct WIMP detection experiments. $\xi = 1$ (*i.e.* it is assumed WIMPs comprise the totality of DM) for the experimental projections and for all models *except* RNS and pMSSM.

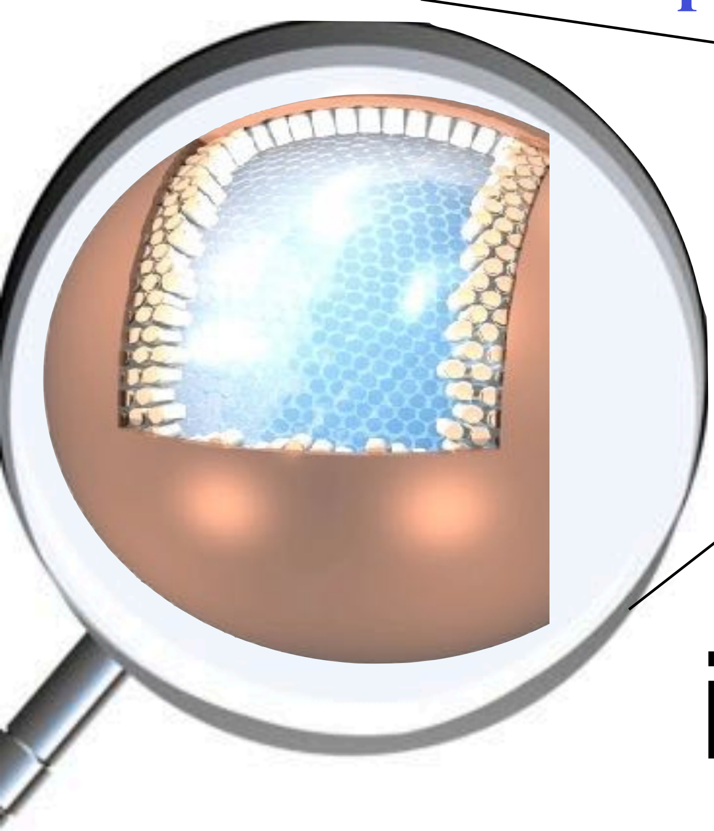
# low background liquid xenon detector

- WIMP $1 \times 10^{-47} cm^2$
- > x 10 lower background for DM search via electron recoil
- pp solar (~ SK)
- With this detector, carrying out those physics search (models are welcome) in XMASS.

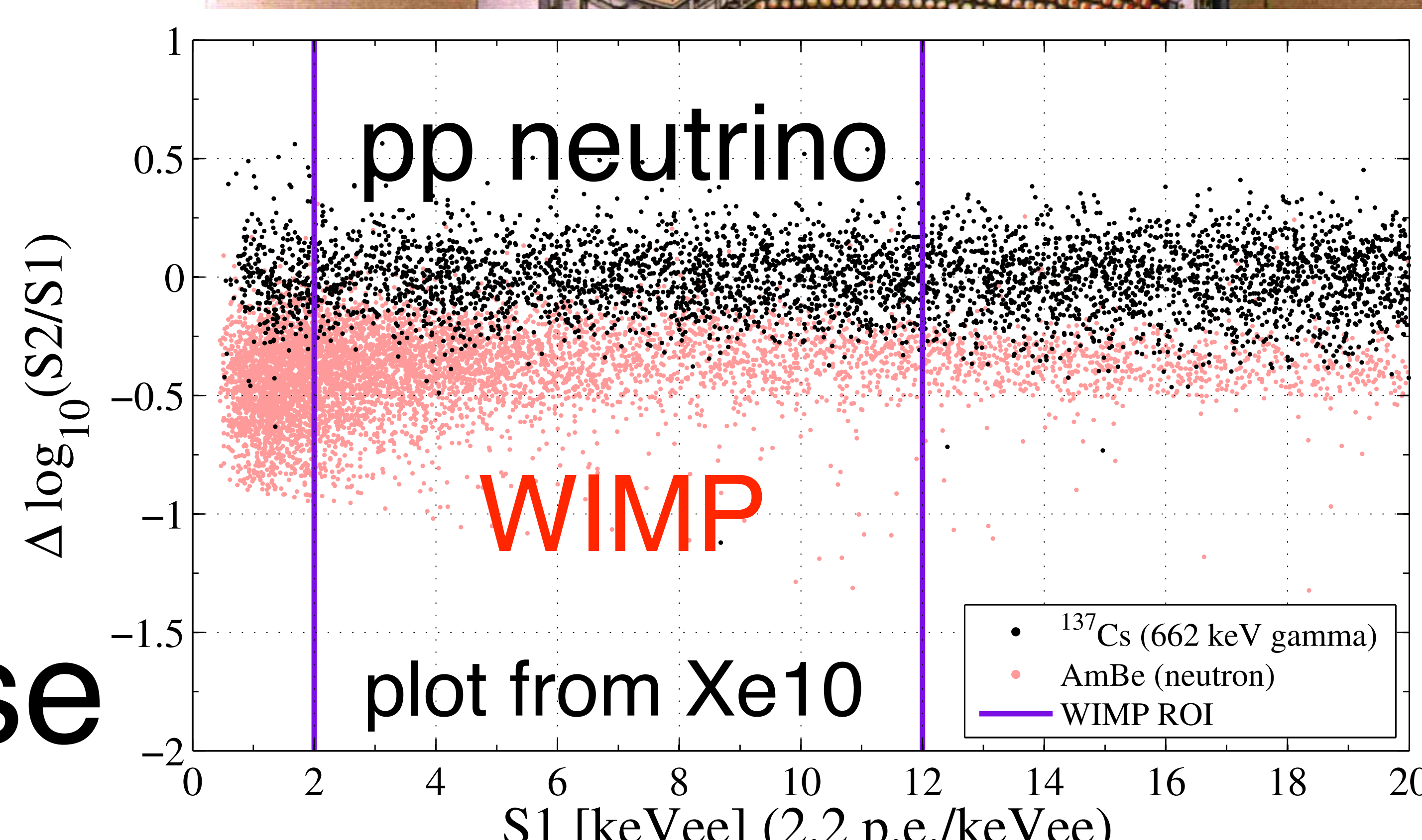
Rn


~**10pp /5 $^{7}$Be** events/day/10ton





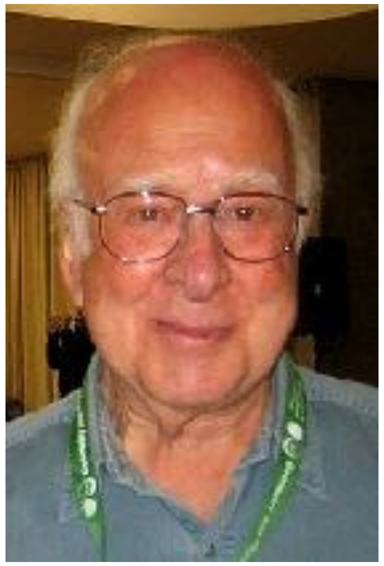
ideal case



# Summary

- Both two phase liquid xenon detector and single phase detector play main role for direct dark matter search.
- XMASS-I carried out variety of candidate dark matter
    - low-mass WIMP, modulation search, Super-WIMP + solar Axion and 2nuECEC.
- Future liquid xenon experiment will be able to detect pp solar neutrino, double beta decay.
- Keys for future DM search are the light sensor and Rn background and XMASS group has strong points for these challenges.
- With this detector, not only WIMP but also variety of DM search and neutrino physics study will be conducted in XMASS.

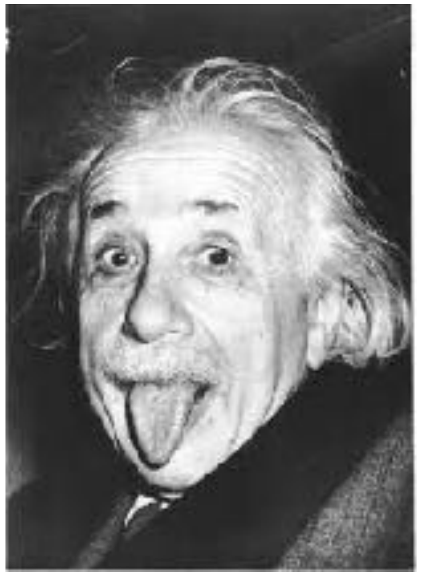
Higgs



Copyright: MFO

50 yrs

GW



100 yrs

Dark Matter

80 yrs

40 yrs

# Thank you