July 13, 2016

A Search for Dark Matter

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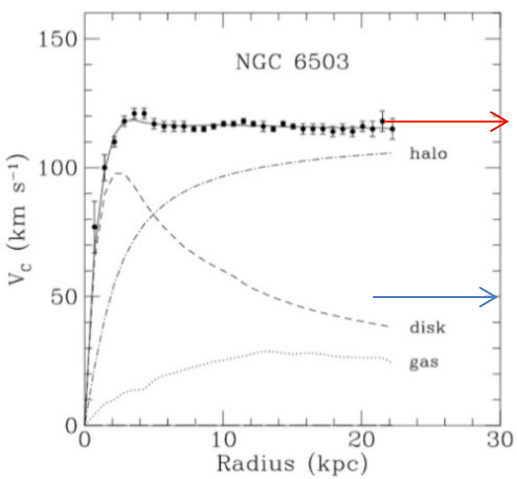
Dark Matter - Evidences

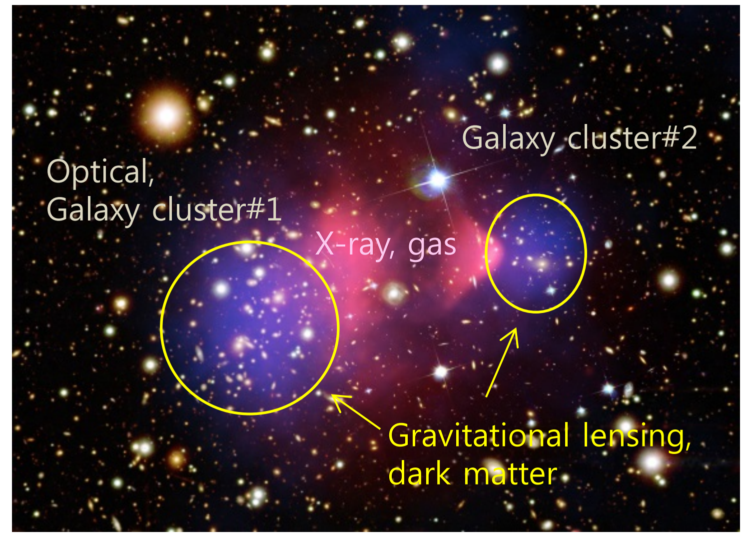
- Galactic scales:
  Rotation curves of galaxies



Observations:
$v_r(r \geq R_0) \approx const$

Expectations: $v_r \propto \frac{1}{\sqrt{r}}$

- Galaxy cluster scales:
  Bullet cluster



- Cosmological: structure formation

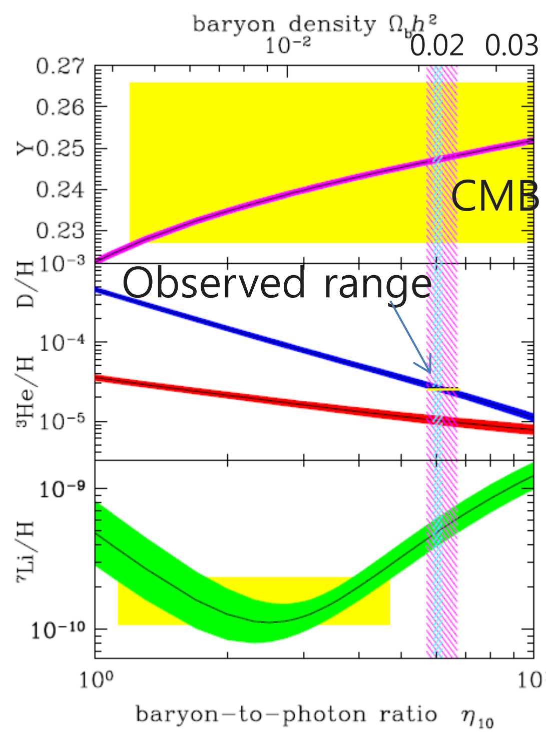
These observations can be explained by dark matter.

Dark Matter

Dark Matter is,

- Stable
- Non relativistic, structure formation (cold dark matter)
- Massive, Gravitational interaction
- Neutral, rarely interacting (dark)
- Non-baryonic

Cosmic Microwave Background (CMB) and Big Bang Nucleosynthesis (BBN) find that the average mass/energy content of the universe is mostly dark.



Supersymmetry

New fundamental symmetry

Q|fermion> = |boson>, Q|boson> = |fermion>

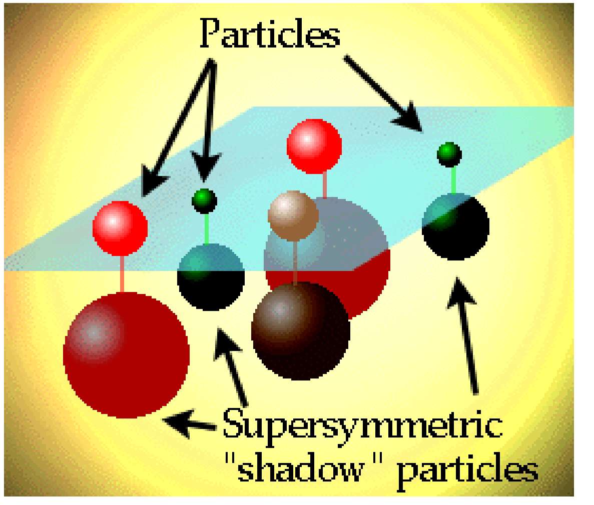
Standard Model (SM) particlces gets Superpartner

(differ in spin by ½ with SM particle)

R parity

$$R = (-1)^{3(B-L)+2S}$$

B: baryon #, L: lepton #, S: spin



Lightest Supersymmetric Particle (LSP) in SUSY is strong candidate for WIMP

→ Neutralino: mixed state of neutral spin ½ superpartners

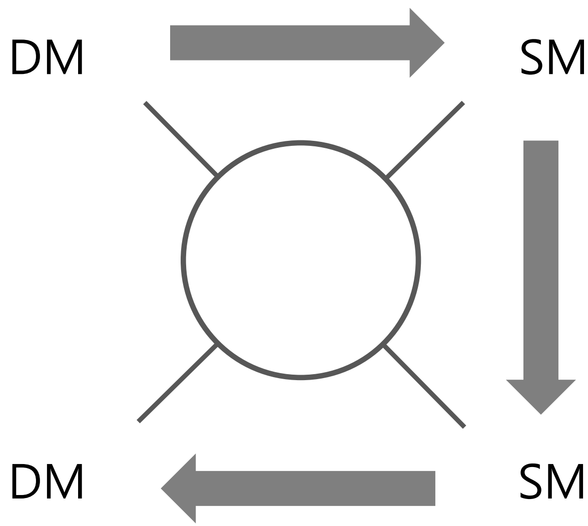
$$\widetilde{\mathrm{B}}, \widetilde{W}, \widetilde{H}_u, \widetilde{H}_d \rightarrow \tilde{\chi}_1, \tilde{\chi}_2, \tilde{\chi}_3, \tilde{\chi}_4$$

- The right relic density of dark matter is naturally obtained.
- WIMP hypothesis can be experimentally testable.

Searches for WIMP

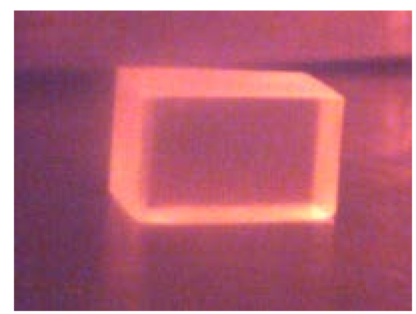
Annihilation
in the Cosmos

Indirect detection



Direct detection

Scattering
in detectors



Production
in colliders

Indirect Detection of WIMP

Indirect Search

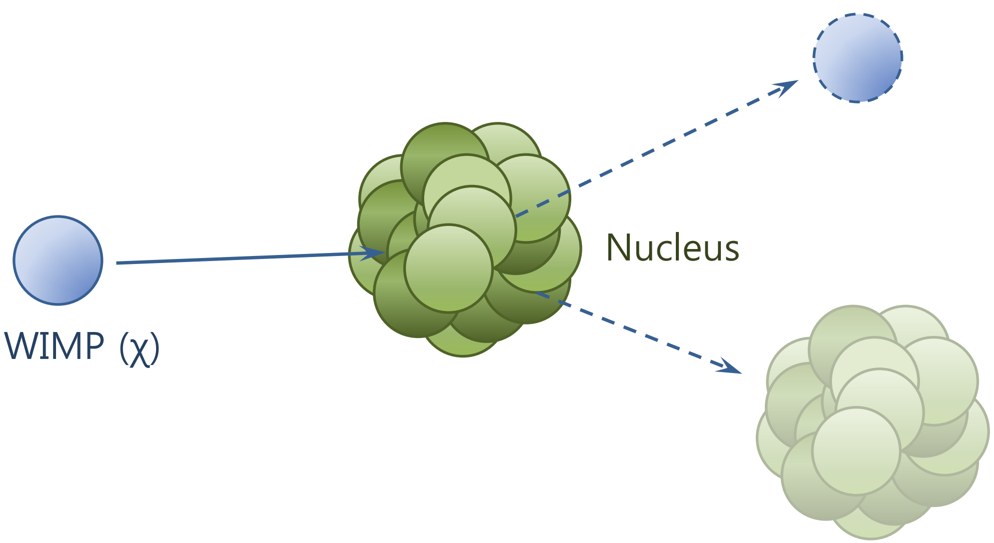
- Detect secondary particle (gamma, neutrino, positron…) produced by annihilation of WIMPs
- Space, ground, underground experiments

- Neutrinos from the center of Sun, Earth
  → Neutrino telescopes : SuperK, AMANDA,…
- Gammas from dark halo
  → EGERET, GLAST
- Positrons/Antiprotons from dark halo
  → HEAT, AMS, …

Direct Detection of WIMP

- Elastic scattering of a WIMP off a nucleus:

- Deposit small amount of recoil energy
- Can occur via spin-dependent/independent channels
- Need to distinguish this event from the number of backgrounds events



Observed recoil energy E_R ~ 30 keV (m_χ = 100 GeV)

Event Rates

- Interaction rate (counts/keV/kg/day)

$$\frac{dR}{dE_R} = \frac{\sigma_0}{m_\chi} \frac{F^2(E_R)}{m_r^2} \frac{\rho_0 T(E_R)}{v_0\sqrt{\pi}}$$

m_χ: WIMP mass , $m_r = \dfrac{m_\chi m_N}{m_\chi + m_N}$

$F^2(E_R)$: *form factor*

ρ_0: local density (0.3 GeV/c^2/cm^3)

$T(E_R)$: inetgral over local WIMP velocity distribution

v_0: local velocity (220 km/s)

- Spin independent interaction:

$$\sigma_0 \cong \frac{4m_r^2}{\pi} f A^2$$

~ Atomic mass (heavy nuclei)

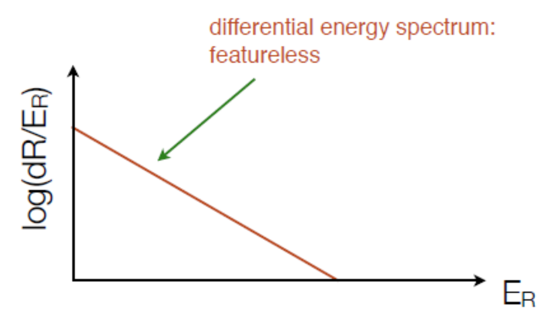
f: coupling constant, A: atomic mass number

- Spin dependent interaction:

$$\sigma_0 = \frac{32(J+1)}{\pi J} G_F^2 m_r^2 (a_p < S_p > + a_n < S_n >)^2$$

Fermi constant (G_F), coupling constant (a_p), nuclear spin (S_n)

spin-less nuclides, SD = 0



Direct Detection of WIMP

WIMP scattering event rate is low,

$\sigma=2\times10^{-4}$ pb, $m_{WIMP}=10$ GeV, event rate < 1 counts/day/kg

Backgrounds are very large,

Gamma rays, beta decays and Neutrons

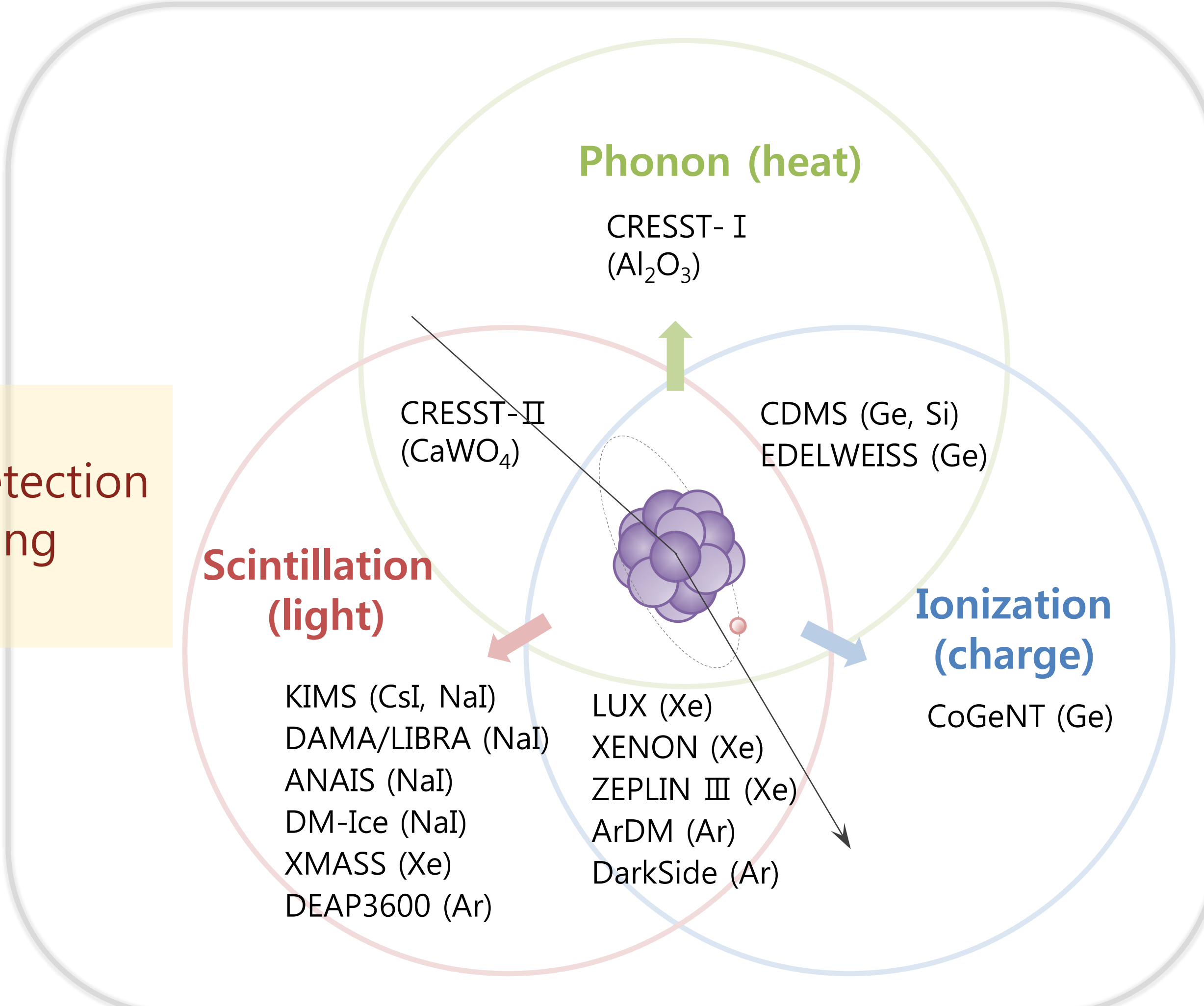
Need low backgrounds

- External, natural radioactive backgrounds
  – underground laboratory, active shield
- Internal radioactive backgrounds – low background crystal

▶ low backgrounds, good signal discrimination,
low energy threshold, large exposure (mass × time)

Detection Strategies

Direct detection
Scattering



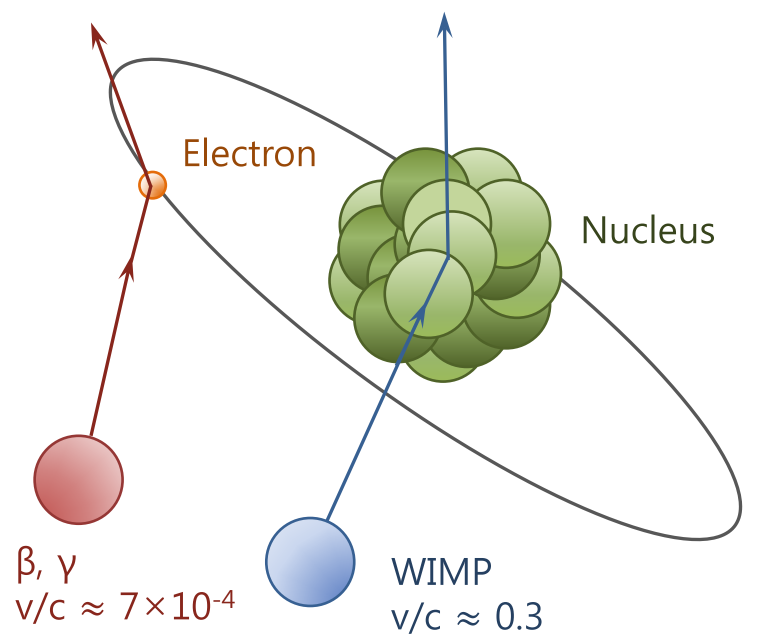
Detection Principles

Signal

- Nuclear recoils (NR);
  WIMP is expected to interact with the nucleus and produce nuclear recoils.

Backgrounds

- Electron recoils (ER);
  Most backgrounds(γ) produce electron recoils.

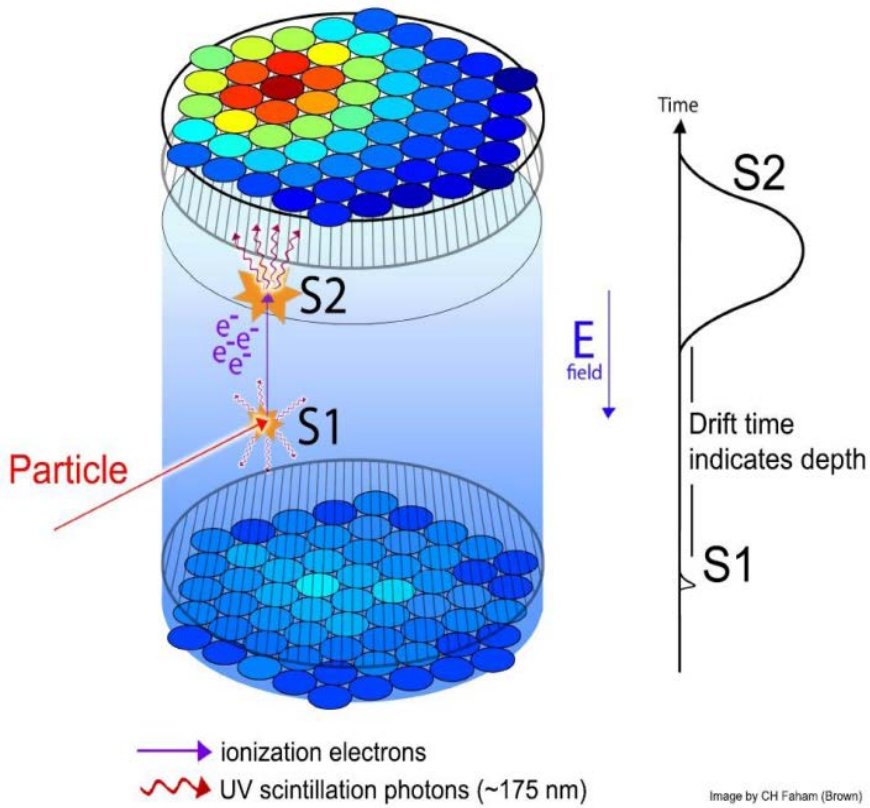


Detection Strategies – Liquid noble gas detector

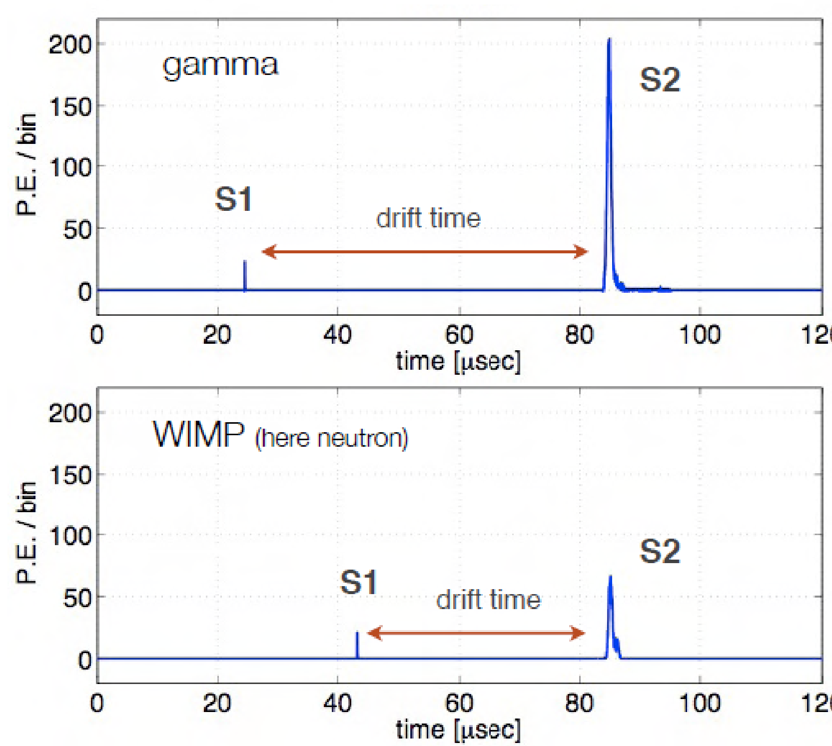
Double phase detector (scintillation – ionization)

Prompt light (S1) after interaction in active volume;

Charge is drifted, extracted into the gas phase and detected as proportional light (S2)



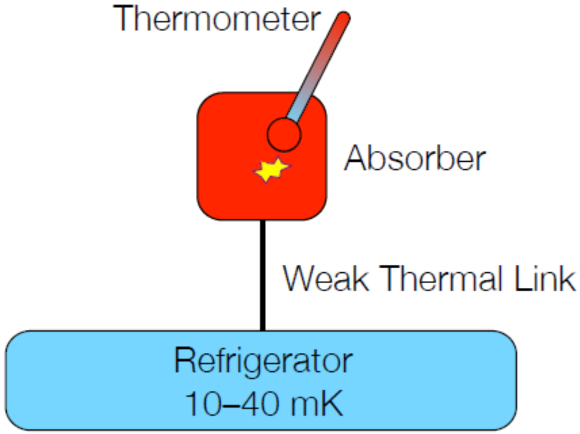
XENON (Xe)



Excitation/Ionization depends on dE/dx!
⇒ discrimination of signal (WIMPs → NR)
and (most of the) background (gammas → ER)!

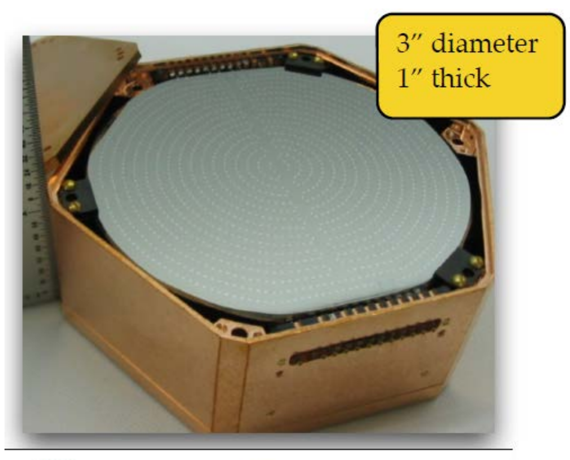
Detection Strategies – Cryogenic solid state detector

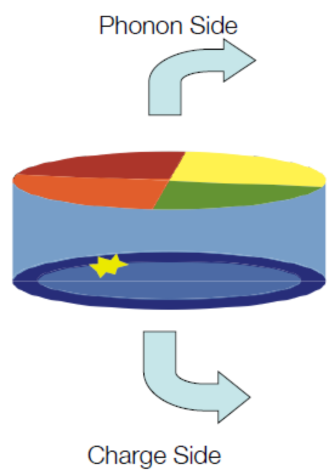
Phonon (heat) detector



Advantage of phonon readout

- Direct measurement of nuclear recoil energy (no QF)
- ~100% of recoil energy → low energy thresholds → better sensitivity
- Good energy resolution → better determination of WIMP recoil spectrum





NR – ER discrimination:
Ionization/phonon or
Scintillation/phonon

CDMS (Ge, Si)

Detection Strategies – Scintillating crystal

Scintillation (light) detector:

Measure photons generated by the energy deposition

Different response to nuclear recoils(NR) and electron recoils(ER)

Velocity: NR < ER

→ Stopping power: NR > ER

→ Ionization quenching: NR > ER

→ slow component: NR < ER

→ Pulse Shape Discrimination (PSD) is possible.

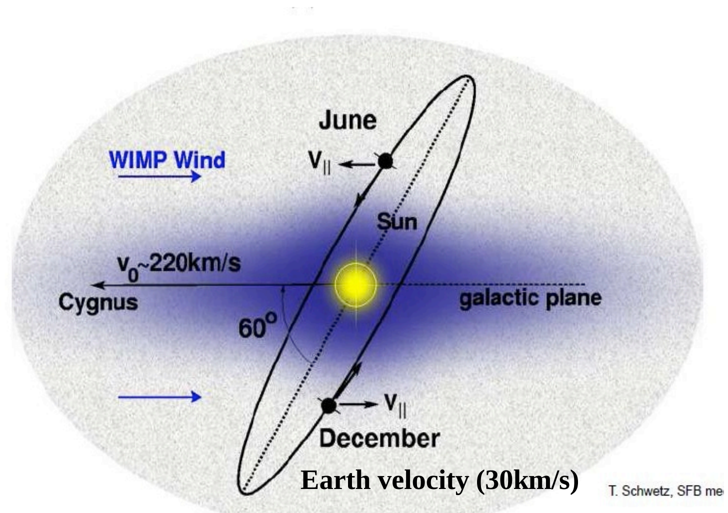
Annual Modulation Signature

The velocity of the Earth varies as the Earth moves around the Sun

→ the velocity modulation ~7%

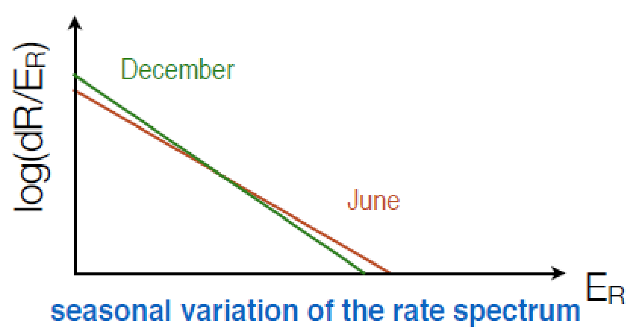
$$v_E(t) = v_0\left(1.05 + 0.07 cos\frac{2\pi(t-t_0)}{1\ yr}\right)$$

t = days
t_0 = 152 d (June 2)
1 yr = 365 days



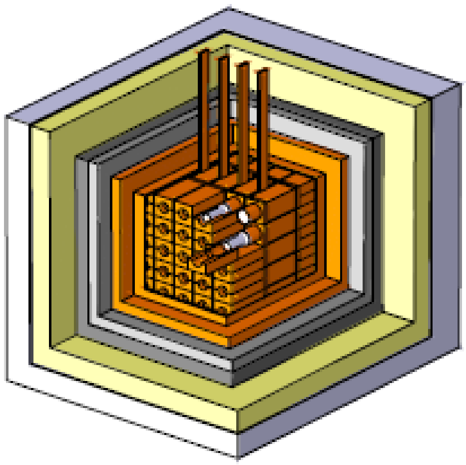
→ ~ 3% modulation in rate

$$\frac{d}{dv_E}\left(\frac{R}{R_0}\right) \sim \frac{1}{2vE}\frac{R}{R_0}$$

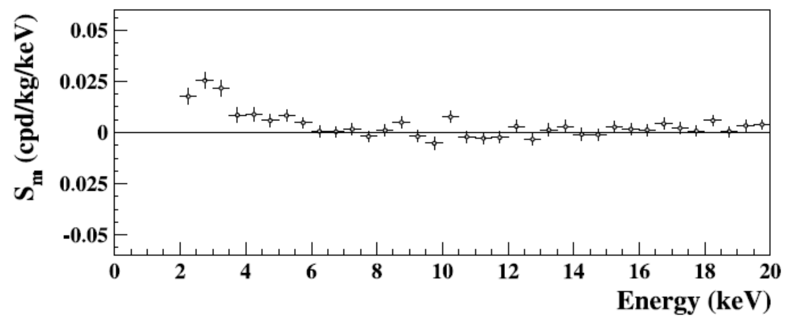


DAMA/LIBRA Experiment

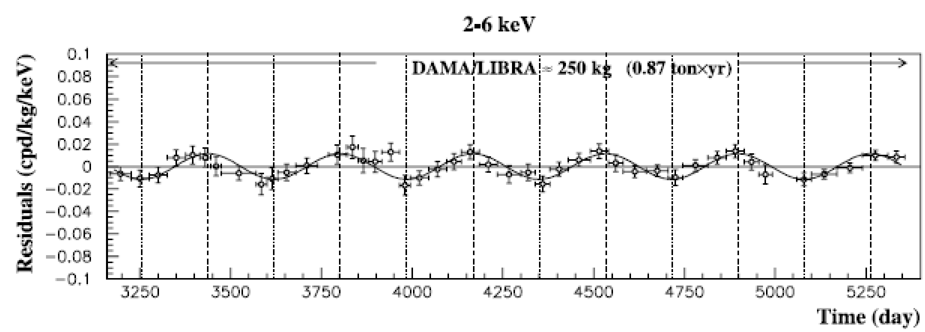
- Operating at LNGS in Italy
- 5 x 5 array, 9.7 kg of NaI(Tl)



- Annual modulation only at the low energies



- Modulating signal w/ 9.3 σ level



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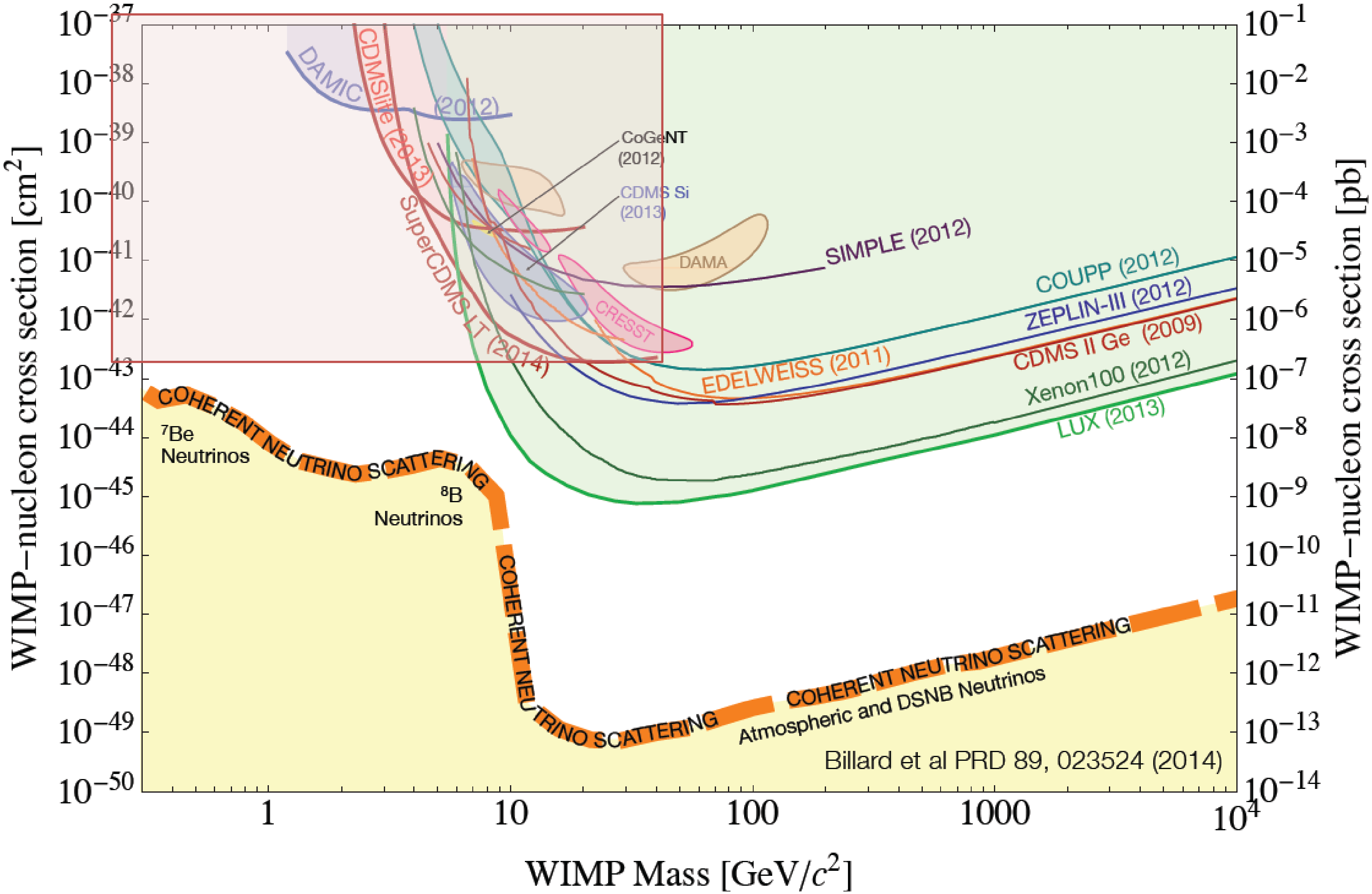
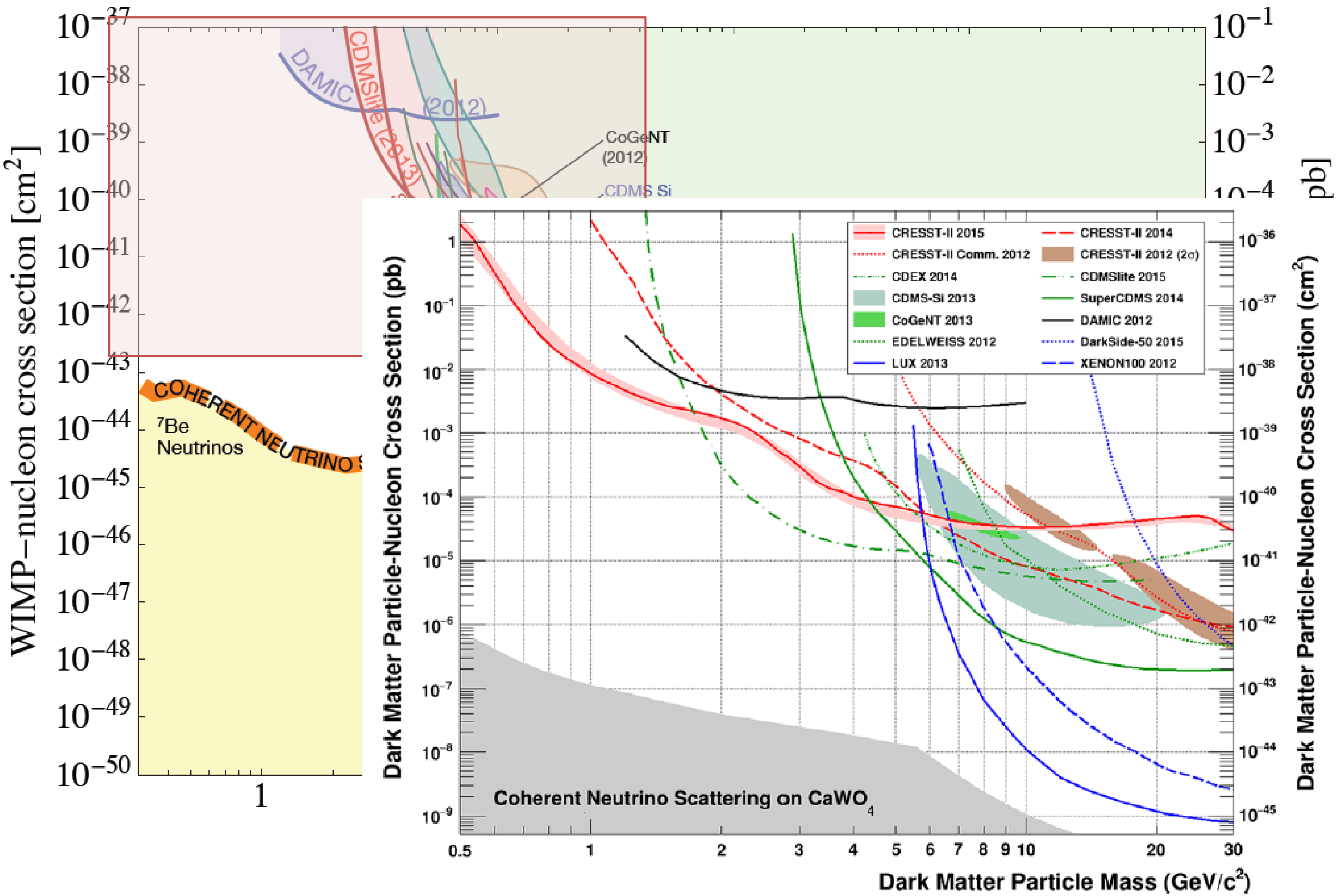
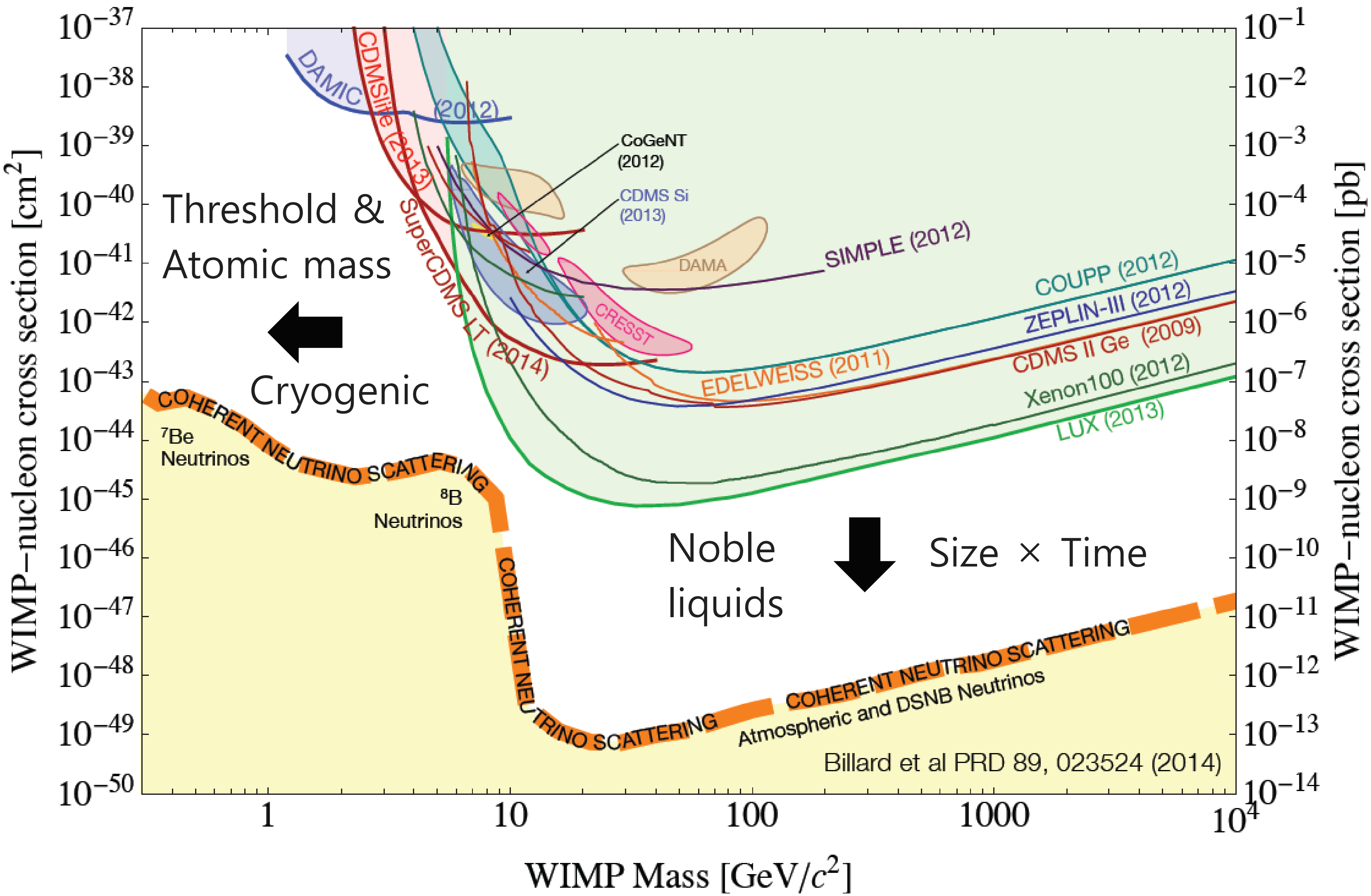
WIMP Search Status



WIMP Search Status

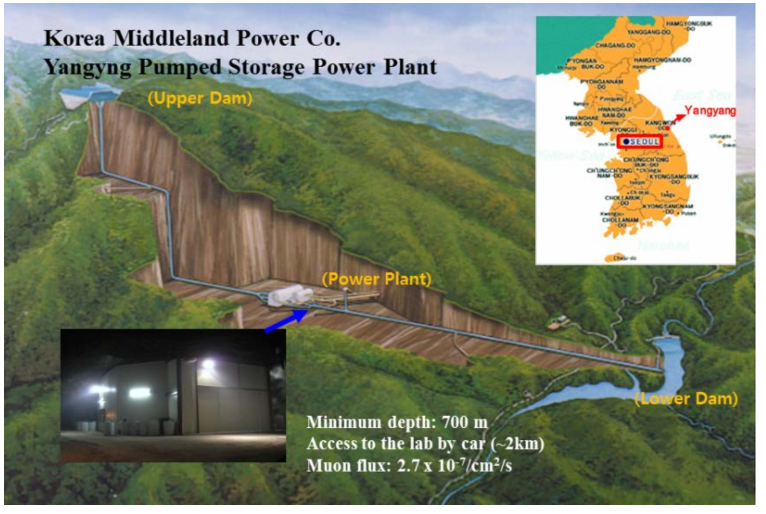


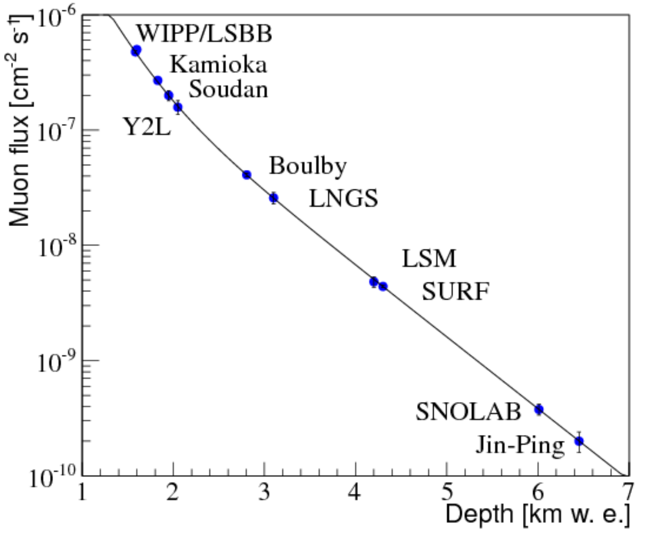
WIMP Search Status



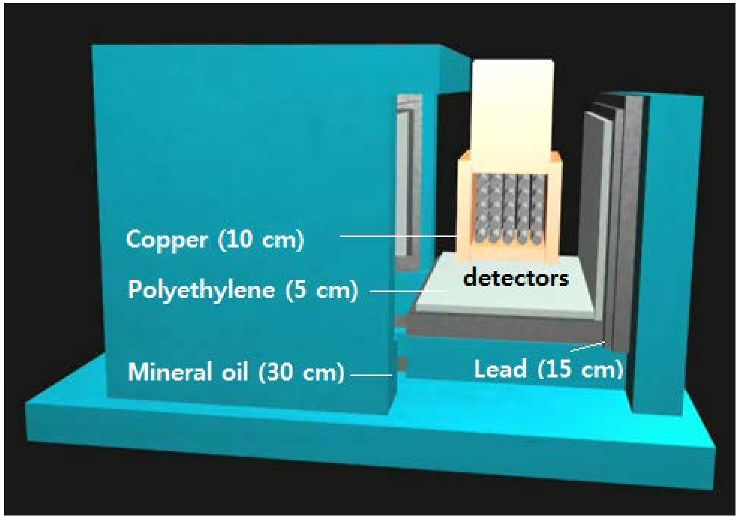
KIMS Experiment

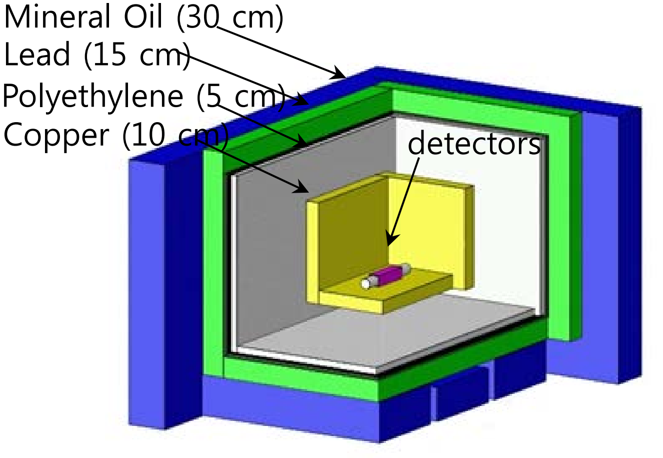
@ Yangyang underground laboratory, Minimum depth: 700 m





Shield structure





KIMS-CsI Experiment

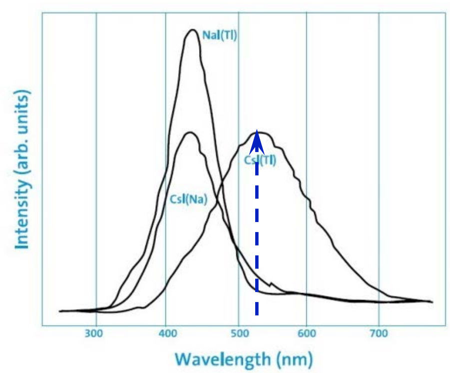
KIMS-CsI setup

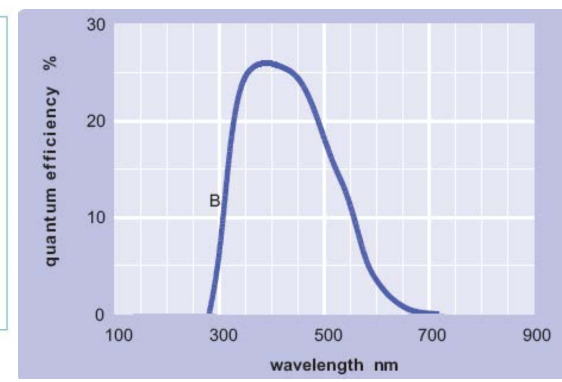
- CsI(Tl)
- 4x3 crystals (104.4 kg)
- Background : 2~3 counts/kg/day/keV (dru)
- Light yield: 5~7 photoelectrons/keV (crystal: ~60 photons/keV)
- Decay constant: 1000 ns
- 1 year data (2009-2010): PSD study
- 3 year data (2009-2012): ANM study

KIMS-CsI detector

CsI(Tl) Crystal 8x8x30 cm^3 (8.7 kg)

3″ PMT (9269QA, Electron tube)

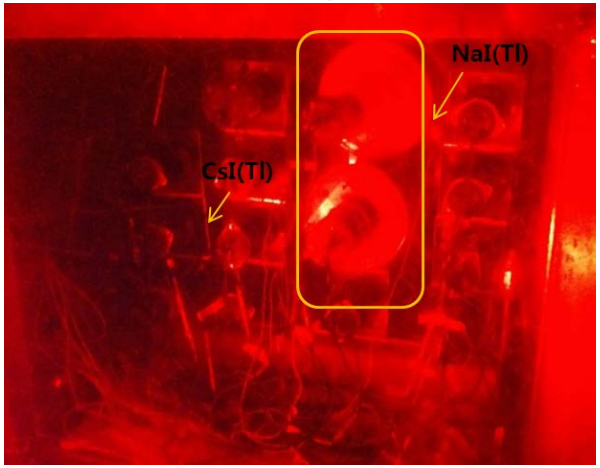




Peak at ~ 520 nm

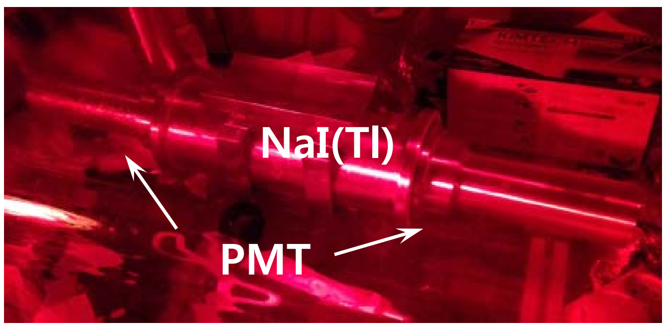
KIMS-NaI Experiment

KIMS-NaI setup

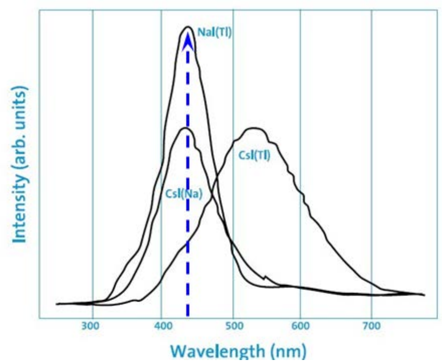


- NaI(Tl)
- different mass and dimensions
- Light yield: ~15 photoelectrons/keV
  (crystal: ~40 photons/keV)
- Decay constant: 250 ns
- 2014~ current

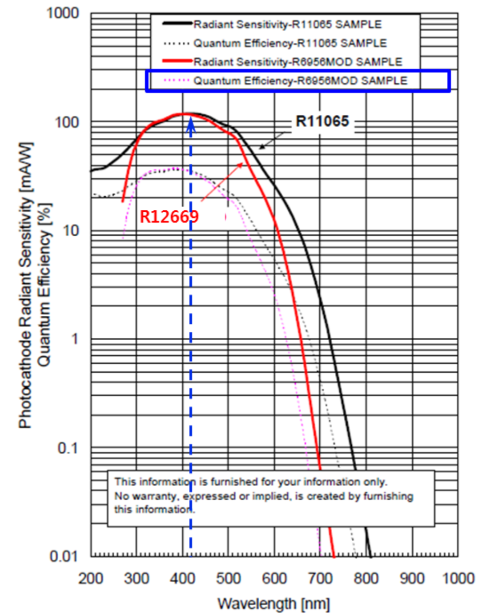
KIMS-NaI detector



NaI(Tl) crystal
3″ PMT (R12669, Hamamatsu)
quantum efficiency: ~35% @ 420 nm



Peak at ~ 420 nm



Pulse Shape Discrimination

Different response to nuclear recoils(NR) and electron recoils(ER)

Velocity: NR < ER

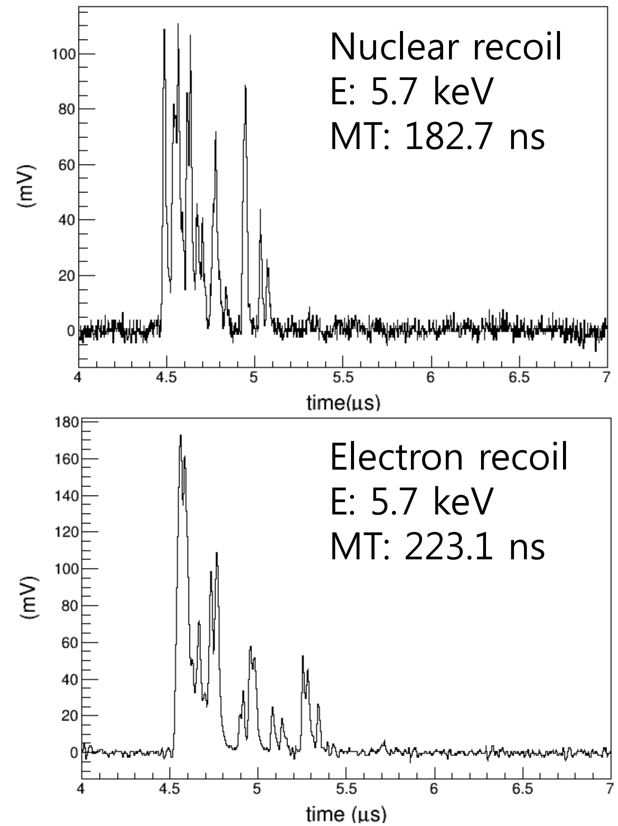
→ Stopping power: NR > ER

→ Ionization quenching: NR > ER

→ slow component: NR < ER

→ Pulse Shape Discrimination (PSD) is possible.

NaI(Tl)



PSD parameter: $\ln(Mean\ Time)$

$$Mean\ Time = \frac{\sum A_i \times t_i}{\sum A_i}$$

A_i: charge of ith signal cluster

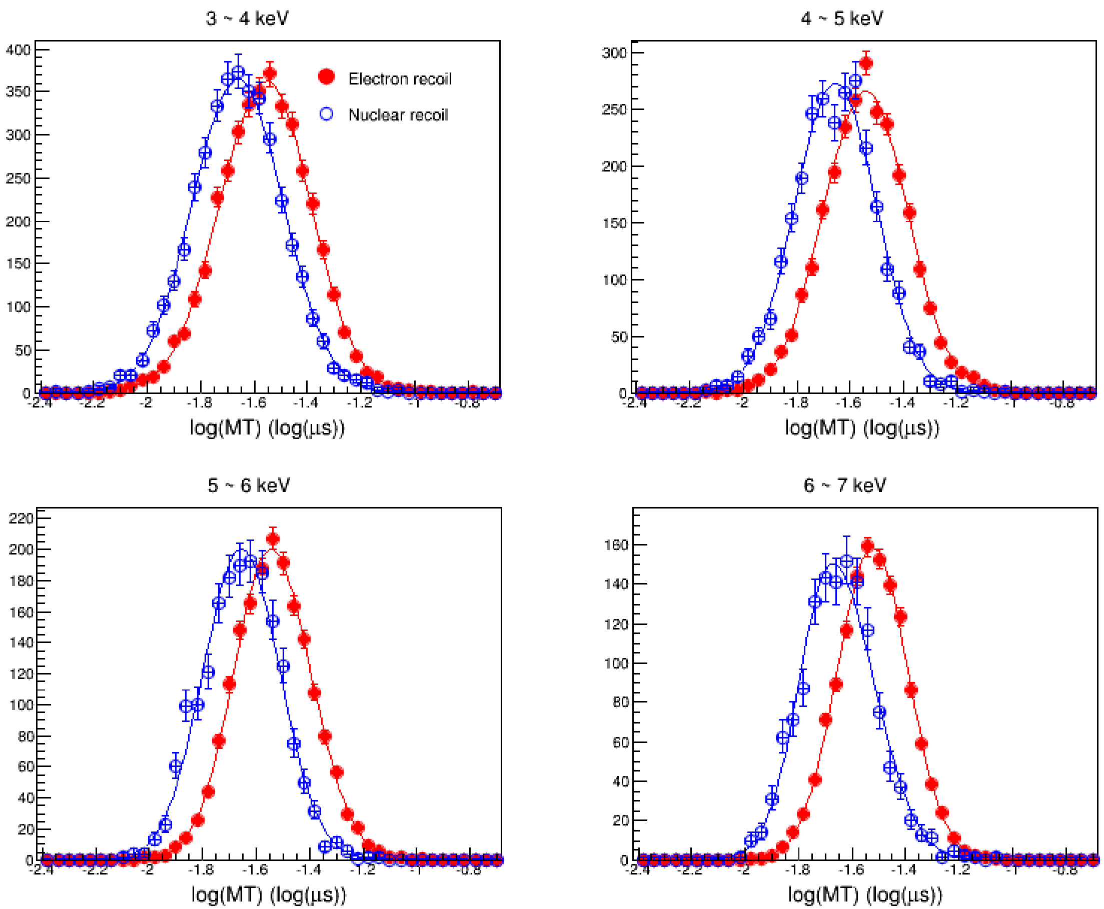
t_i: time of ith signal cluster

PSD Analysis – Neutron calibration (NaI(Tl))

PSD parameter: $\ln(Mean\,Time)$

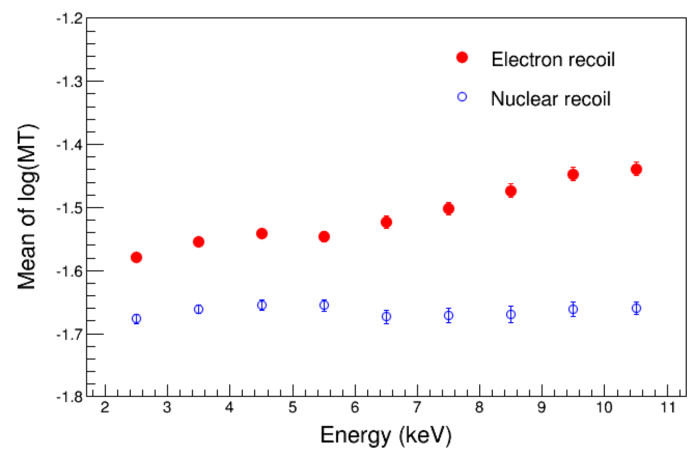
$$Mean\,Time = \frac{\sum A_i \times t_i}{\sum A_i} \; in\ 1.5\ \mu s$$

- Nuclear recoil: A 300mCi Am/Be neutron source
- Electron recoil: ^{137}Cs gamma ray source
- Small test crystal (same ingot with NaI-002)



Fitting parameter:
Mean, RMS

Fitting result – Mean of ln(MT)

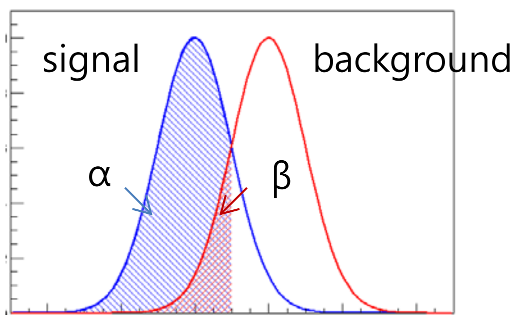


PSD Analysis – The power of discrimination

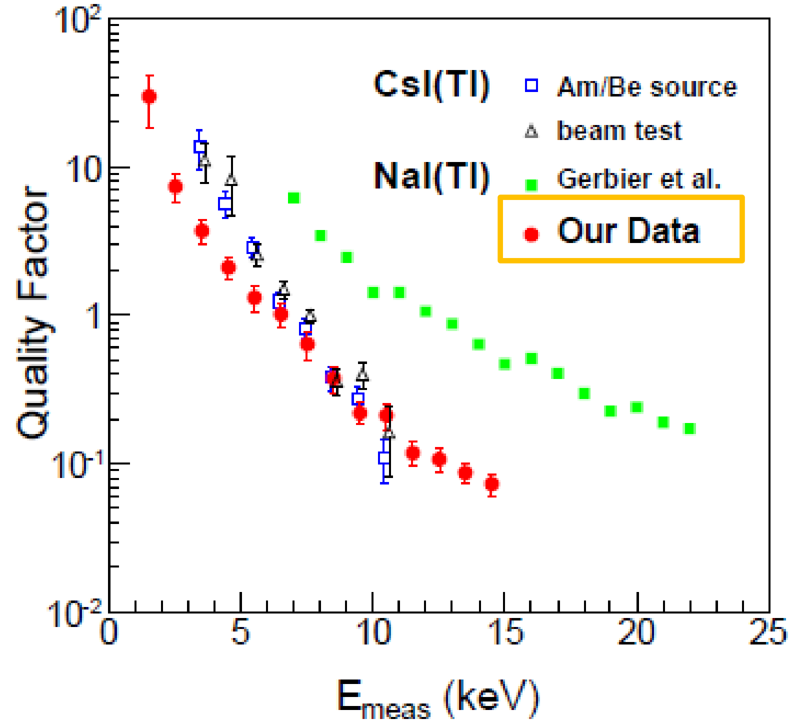
Quality Factor

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

ideal detector
α ~ 1, β ~ 0
K ≪ 1



α: signal acceptance fraction
β: background misidentification fraction



Good pulse shape discrimination capabilities

Nuclear Recoil Rate Extraction (NaI(Tl))

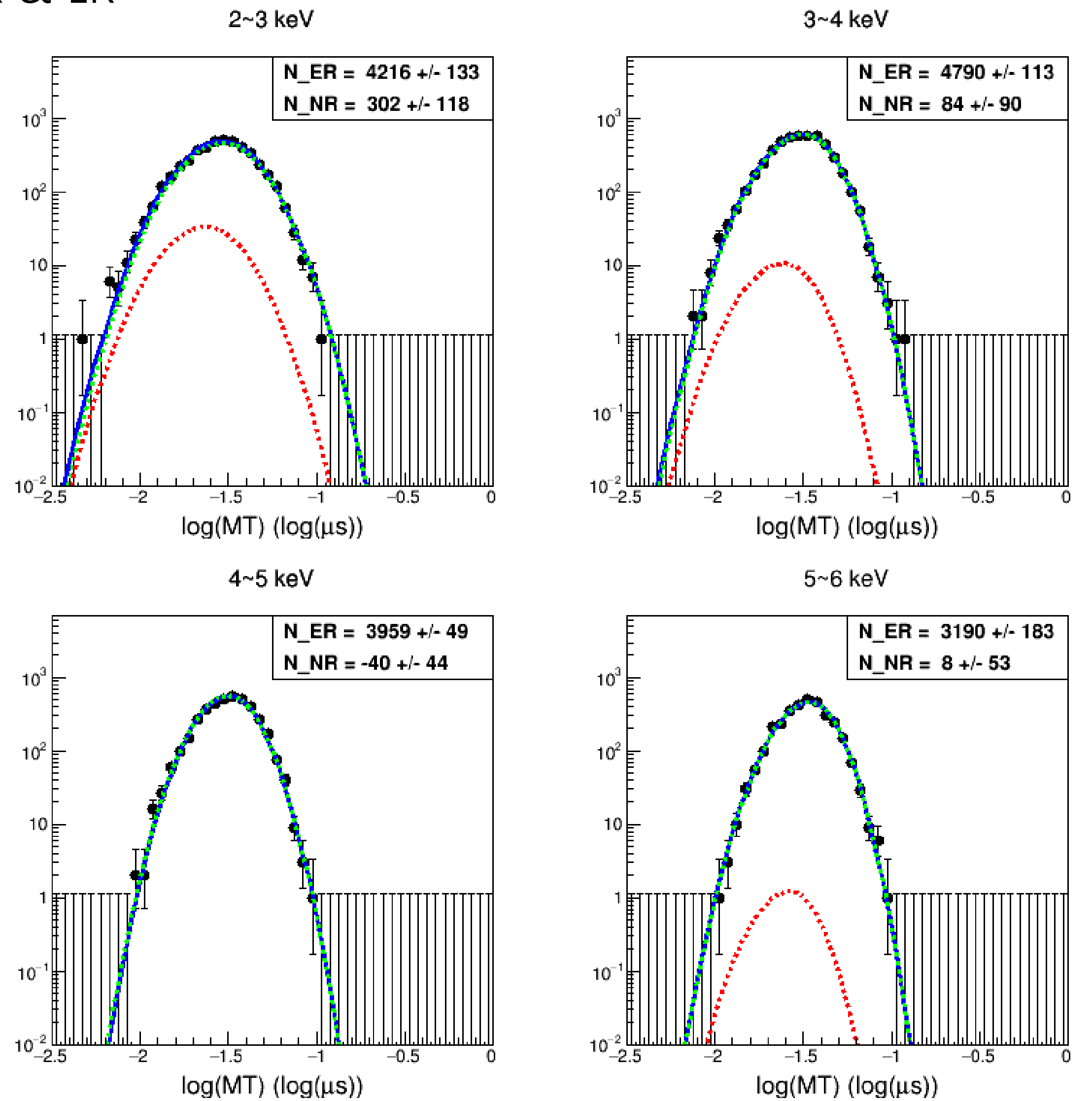
- Data fitted with ln(MT) of NR & ER
  Fitting parameter: N_{ER}, N_{NR}

Black: data

Blue solid: fitting

Green dashed: ER

Red dashed: NR



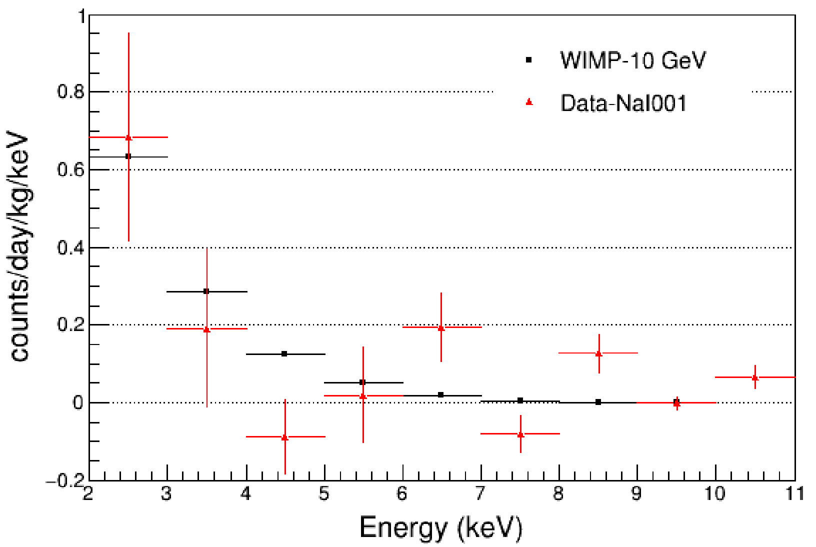
WIMP Mass – Cross Section (NaI(Tl))

WIMP recoil energy spectrum:

E_R → dR/dE(Form factor, interaction considered) · QF · Energy resolution

QF: Na-30%, I-9%,   Energy resolution: $\frac{\sigma}{E} = \frac{p0}{\sqrt{E}} + p1$

$$\chi^2 = \sum_i \frac{(y_i - y_{expected})^2}{\sigma_i^2}$$



WIMP mass: 10 GeV

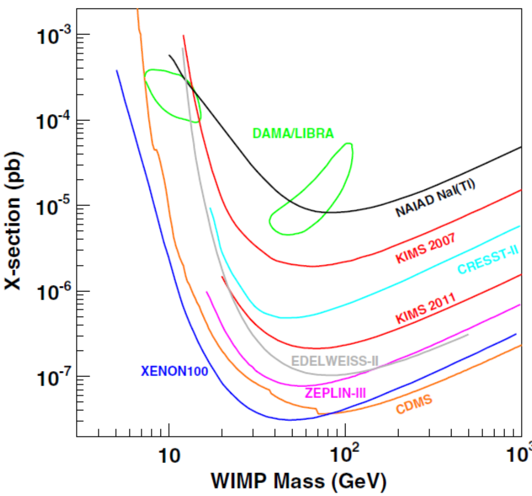
σ: 3.68×10^{-4} pb

WIMP-nucleon cross section limit was estimated by fitting NR rate spectrum to WIMP recoil spectrum.

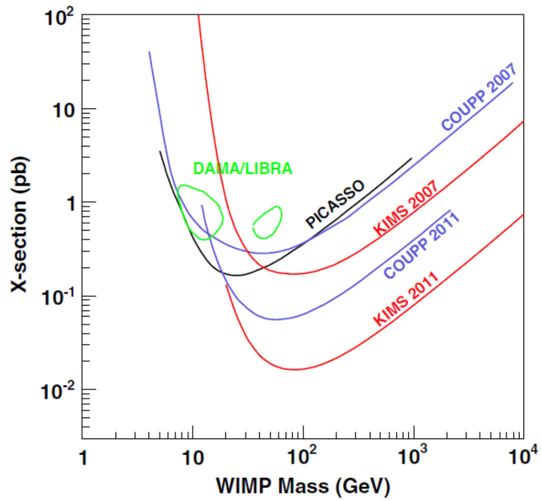
WIMP Mass – Cross Section

KIMS-CsI

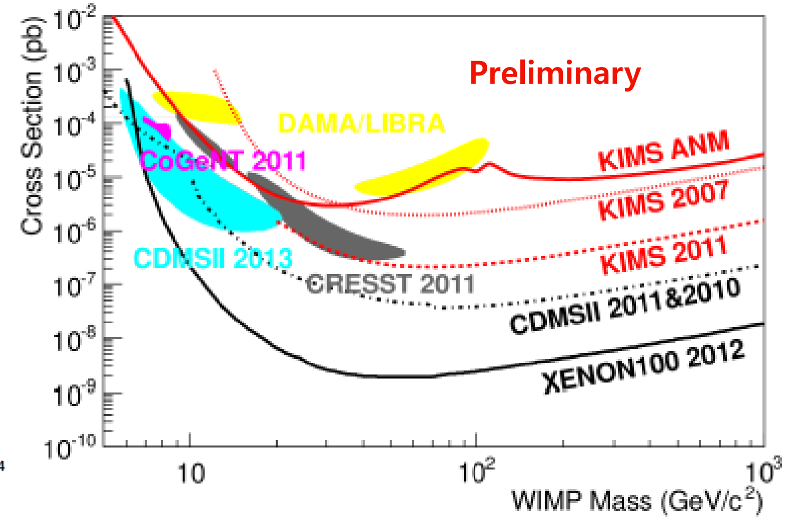
PSD – SI



SD

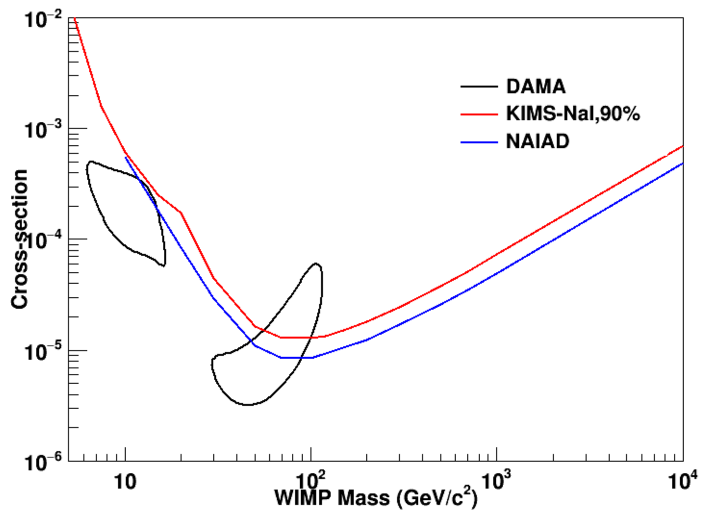


ANM



KIMS-NaI

PSD – SI



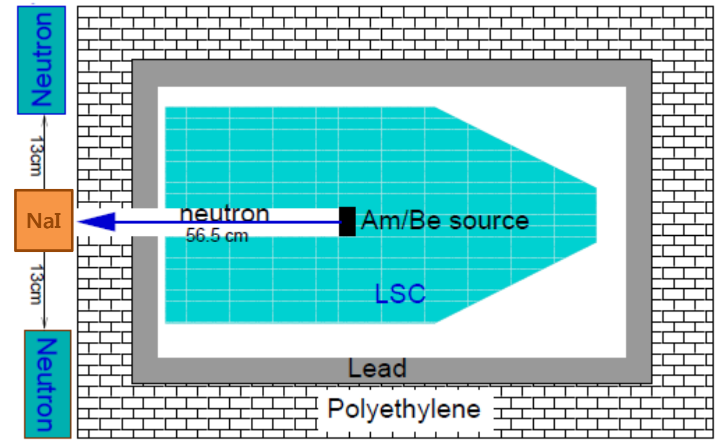
Systematic uncertainty is not included.

Backup Slides

PSD analysis – Neutron Calibration

Nuclear recoil (NR) data:

- Neutron setup (SNU)
  - Am/Be neutron source
  - small test crystal – 2 x 2 x 1.5 ㎤
    same ingot with NaI002
    NaI002: 4.2″(D) x 11″(L)



Electron recoil (ER) data:

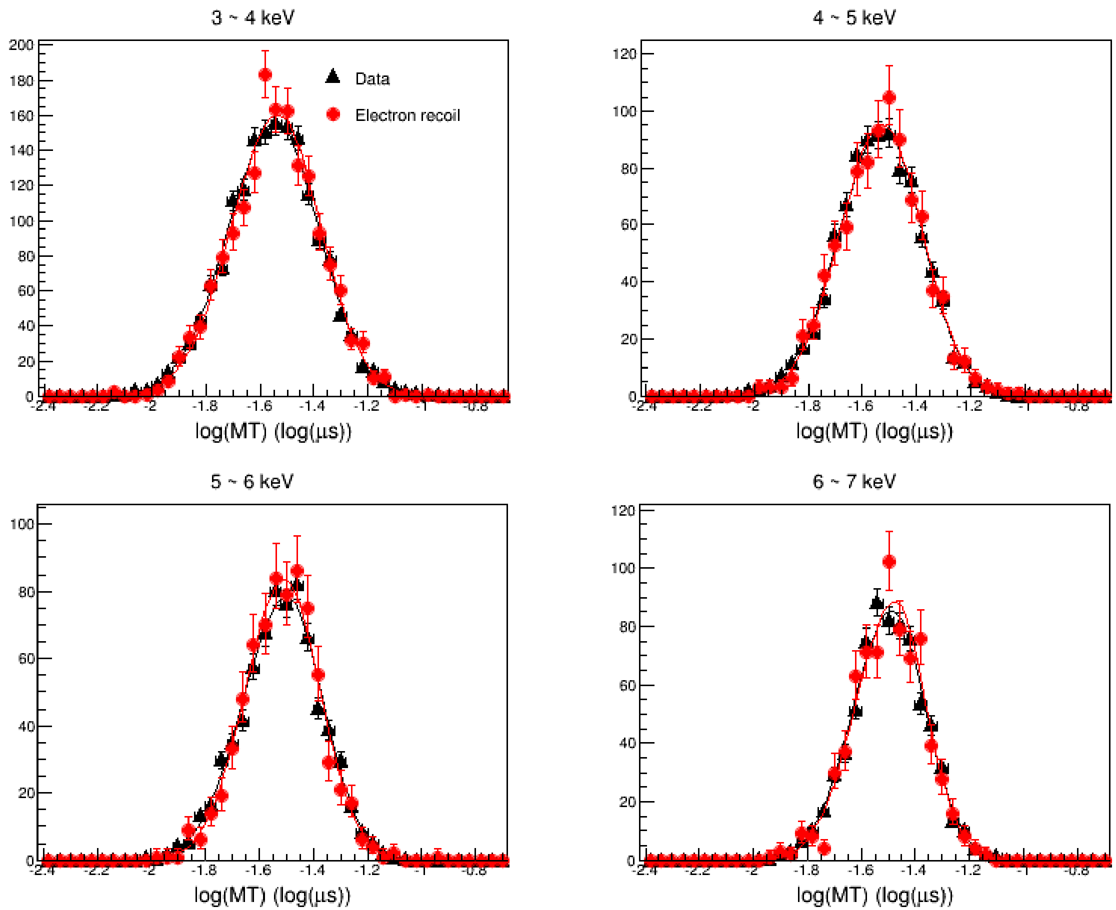
- NaI002, multiple hit event (Y2L)
- Reference data:
  - ^{137}Cs source (small crystal-neutron setup)

PSD analysis – Underground data

PSD parameter: $\ln(Mean\ Time)$

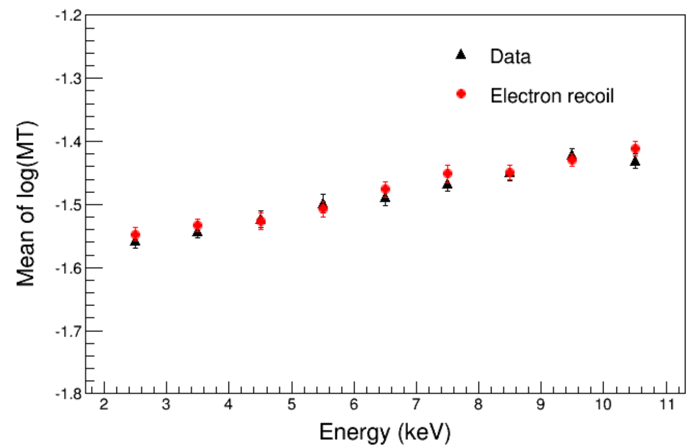
$$Mean\ Time = \frac{\sum A_i \times t_i}{\sum A_i}\ in\ 1.5\ \mu s$$

- NaI001 (8.26 kg), 80.77 days data
- Electron recoil: Multiple hit events



Fitting parameter:
Mean, RMS

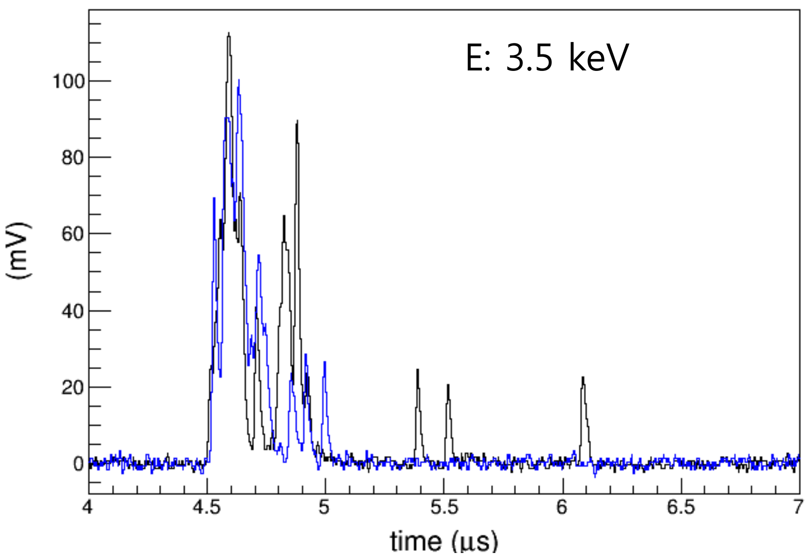
Fitting result – Mean of ln(MT)



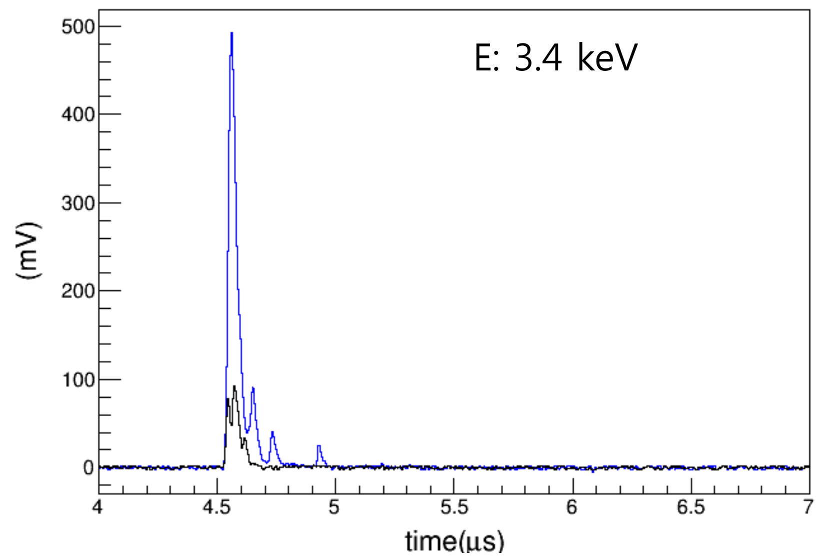
PMT noise rejection

PMT noise event rate ~ a few hundred events/day

Typical NaI(Tl) scintillation signal



noise



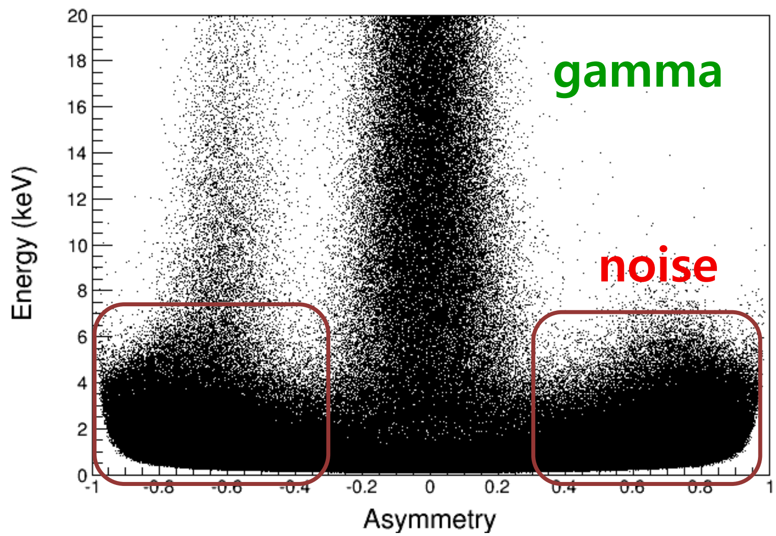
black: PMT0
blue: PMT1

PMT noise rejection

- Charge Asymmetry

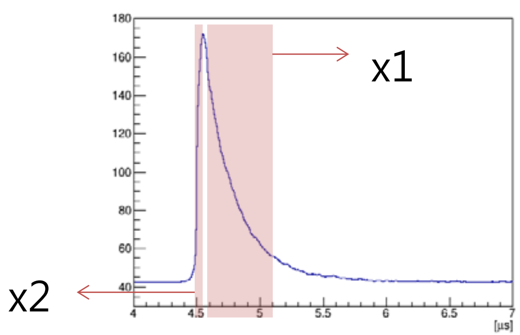
$$Asymmetry = \frac{(Q_{PMT0} - Q_{PMT1})}{(Q_{PMT0} + Q_{PMT1})}$$

Q_{PMT} : charge sum

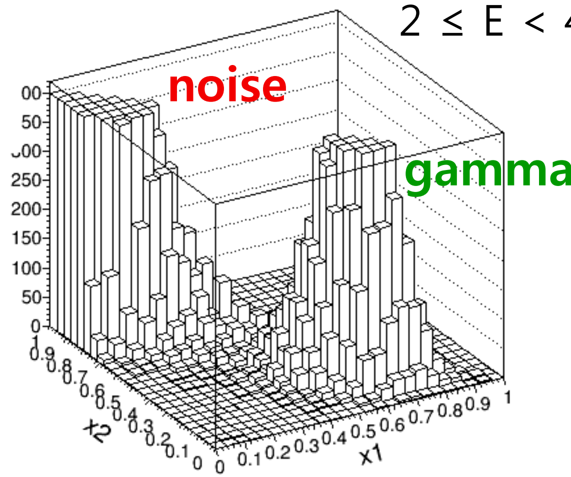


- Charge ratio

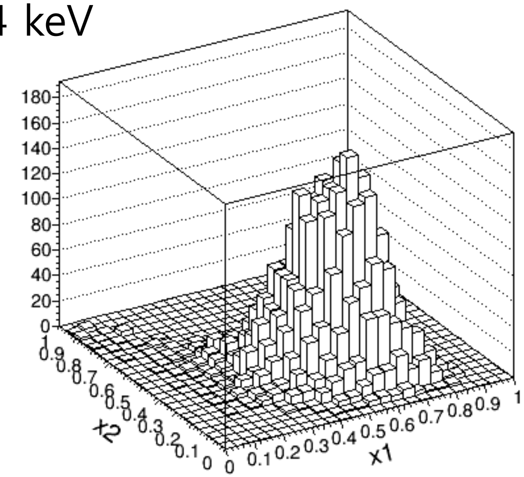
x1: slow component
x2: fast component



2 ≤ E < 4 keV



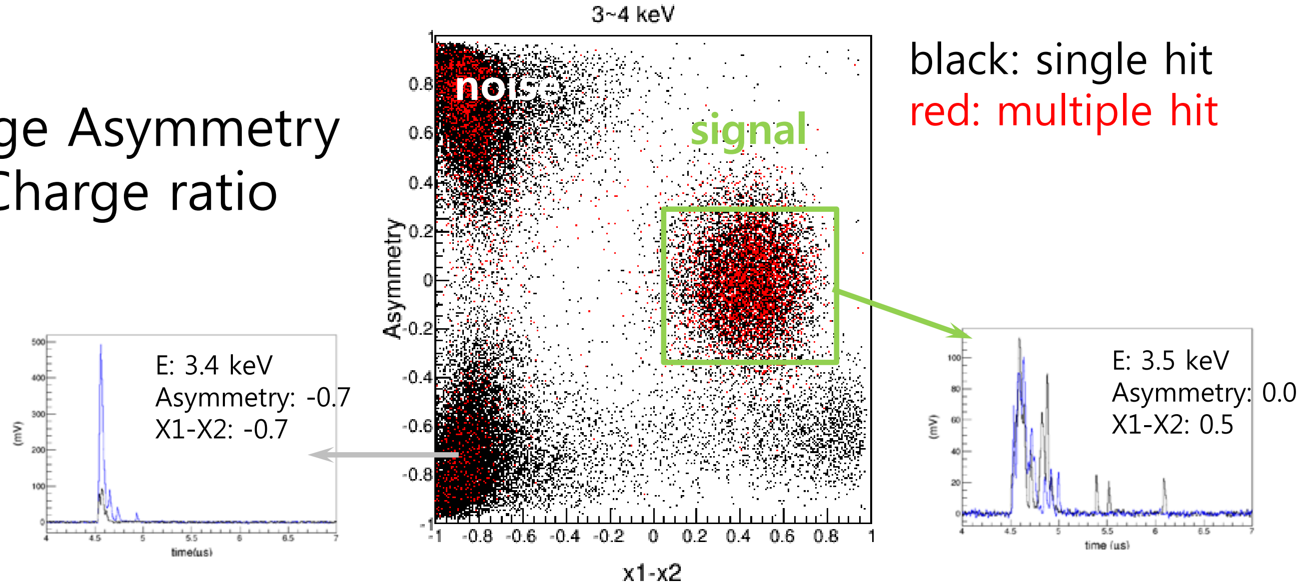
Backgrounds



Gamma source

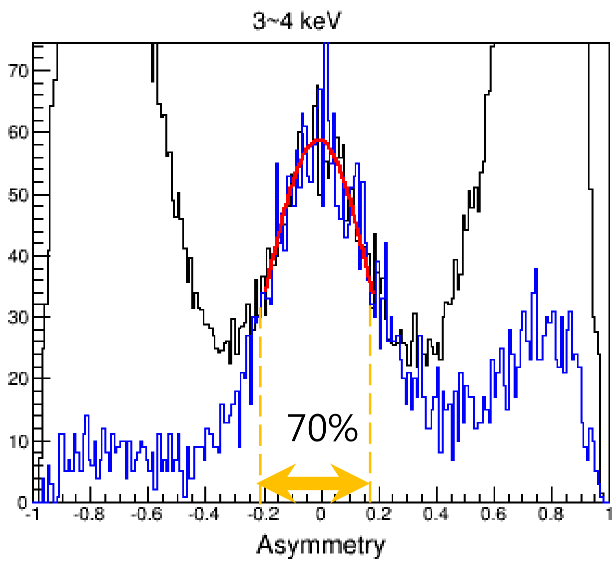
PMT noise rejection

- Charge Asymmetry vs Charge ratio

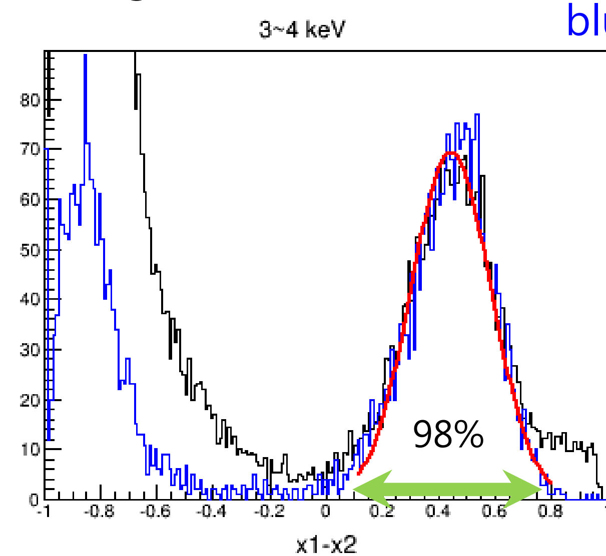


black: single hit
red: multiple hit

Charge Asymmetry



Charge ratio

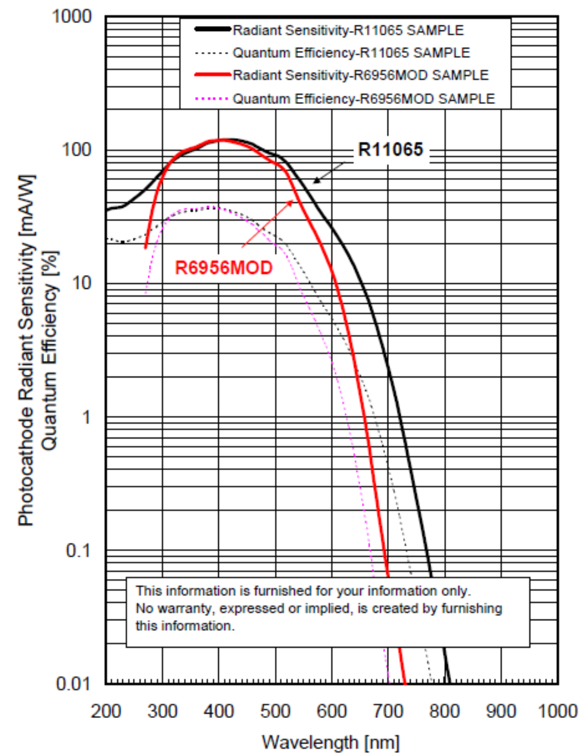


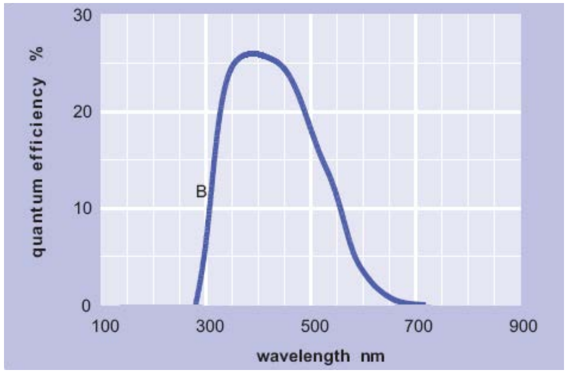
black: single hit
blue: multiple hit

KIMS NaI detector – Photo Multiplier Tube (PMT)

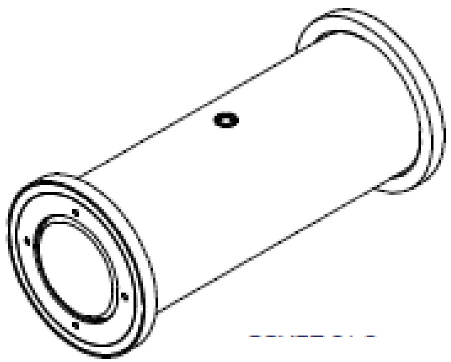
Property	R12669	9269QA
Manufacturer	Hamamatsu	Electron tubes
Window material	Brosocilicate	Quartz
Body material	Brosocilicate	Quartz+Borosilic ate
Photocathode material	SBA	RbCs
Effective Dia. (mm)	70	76
Dark Current (nA, 30min)	6	4
U (mBq/PMT)	25±5	83
Th(mBq/PMT)	12±5	48
K (mBq/PMT)	58±5	1866
Gain (HV)	1 x 10^6	$1.8x10^6$
Remarks	Same PMT used in DAMA, ANAIS	Used in KIMS-CsI

Quantum Efficiency





KIMS NaI detector – NaI(Tl) crystal



Property	NaI(Tl)
Density (g/cm^3)	3.67
Decay constant (ns)	~ 250
Peak emission (nm)	415
Light yield (photon/MeV)	~ 40000

NaI002 (Dec. 2013)

- Alpha Spectra in US
- 4.2″(D) X 11″(L), 9.2 kg
- Encapsulated in OFH Cu case
- Aluminized Mylar window

good

- High light yield
- Easily growing in large size crystals
- Enable spin-dependent interaction

bad

- High hygroscopic
- Low quenching factor
- No particle discrimination(?)

Radio nuclei	NaI002	ANAIS	DAMA
^{238}U (^{214}Bi)	<0.001 mBq/kg	0.01 mBq/kg	1-10 ppt
^{228}Th (^{216}Po)	0.002±0.001 mBq/kg	0.003 mBq/kg	1-10 ppt
^{40}K	49.3 ppb	41 ppb	< 20 ppb
^{210}Pb	1.76±0.01 mBq/kg	3.28±0.02 mBq/kg	

VI. Expected WIMP recoil energy spectrum

E_r → dR/dE * Form factor (SI) * quenching factor

dR/dE:

$$\frac{dR(v_E, v_{esc})}{dE_R} = \frac{k_0}{k_1}\left[\frac{dR(v_E,\infty)}{dE_R} - \frac{R_0}{E_0 r} e^{-v_{esc}^2/v_0^2}\right].$$

$$\frac{dR(v_E,\infty)}{dE_R} = c_1 \frac{R_0}{E_0 r} e^{-c_2 E_R/E_0 r}, \quad k = k_1 = k_0\left[\mathrm{erf}\left(\frac{v_{esc}}{v_0}\right) - \frac{2}{\pi^{1/2}}\frac{v_{esc}}{v_0} e^{-v_{esc}^2/v_0^2}\right]; \quad \frac{c_1}{c_2} = \frac{R(v_E,\infty)}{R_0}.$$

$$R_0 = \frac{503}{M_D M_T}\left(\frac{\sigma_0}{1\,\mathrm{pb}}\right)\left(\frac{\rho_D}{0.4\,\mathrm{GeV}c^{-2}\,\mathrm{cm}^{-3}}\right)\left(\frac{v_0}{230\,\mathrm{km\,s^{-1}}}\right)\mathrm{tru} \qquad E_0 = \tfrac{1}{2} M_D v_0^2 = (v_0^2/v^2)E$$

v_0 = 220 km/s, v_{esc} = 544 km/s, ρ_D = 0.3 GeV/c^2/cm^3
M_D: WIMP mass, M_T: target material mass

Form Factor: (SI)

$$F(qr_n) = 3\frac{j_1(qr_n)}{qr_n} \times e^{-(qs)^2/2},$$

$$r_{rms}^2 = \frac{3}{5} r_n^2 + 3s^2, \quad r_n = a_n A^{1/3} + b_n \qquad q(\mathrm{MeV}c^{-1}) = [2 \times 0.932(\mathrm{GeV}c^{-2}) A E_R(\mathrm{keV})]^{1/2}$$

Quenching Factor: Na-0.3, I-0.09

E_r → energy resolution

$$\frac{\sigma}{E} = \frac{p0}{\sqrt{E}} + p1$$

From ^{40}K, ^{125}I, ^{241}Am: (3.07, 30.77, 59.54) keV
p0 = 0.3122, p1 = 0.006