XMASS Experiment
(including a brief review of Direct Dark Matter Search Experiments)

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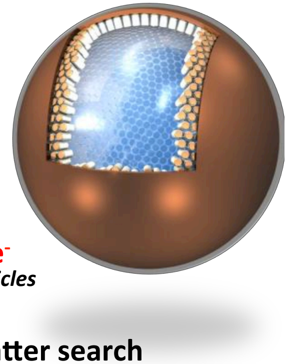
"XMASS Experiment"

Y. Suzuki, hep-ph/0008296



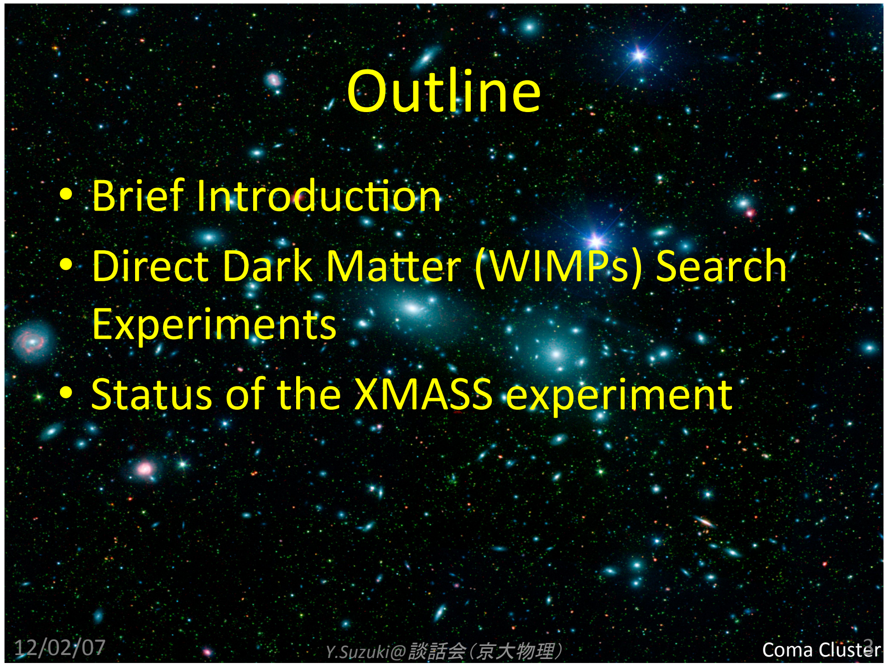
XMASS: Multi-purpose liq. Xenon detector (10 ton fiducial mass(2.5mϕ))

– ***X**enon **MASS**ive detector for Solar neutrino*
  - **pp-solar neutrinos: ν+e → ν+e**
– ***X**enon neutrino **MASS** detector*
  - **Double beta decay ^{136}Xe → $^{136}Ba + 2e^-$**
– ***X**enon detector for Weakly Interacting **MASS**ive Particles*
  - **Dark Matter: χ+Xe → χ+Xe**

➔ Phase-I: 100 kg fid. dedicated for dark matter search

- Construction was completed
- Under commissioning in the Kamioka Underground Observatory
- Conducted by Kamioka Observatory (ICRR, Tokyo), IPMU(Tokyo), Kobe, Tokai, Gifu, STEL(Nagoya), Yokohama National, Miyagi U. of Education and Korean institutions (KRIS, Sejong): 10 institutes & 41 Collaborators

➔ I will discuss 'phase-I XMASS' in my talk.



Why people believe in Dark Matter

Evidence at the different scale of the Universe

- Rotation curve of a galaxy
- Cluster of Galaxies
  – luminosity vs velocity
  – Gravitational lensing
- CMB

and so on.....

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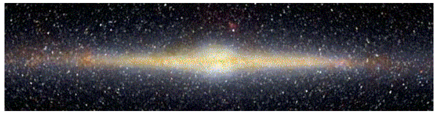

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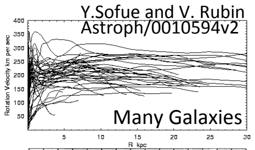
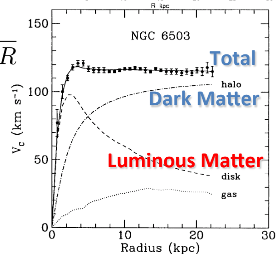
First indicated that invisible matter exist in a galaxy by Vera Rubin in 1972



$$v(R) = \sqrt{GM(R)/R}$$

$$v(R) \approx const.$$

$$M(R) \propto R$$



Rotation vetocity

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- First in 1933: Fritz Zwicky

Luminous matter

<< matter from orbital velocities

← Virial theorem

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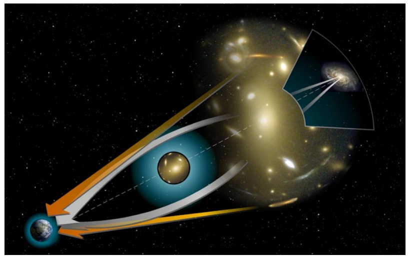

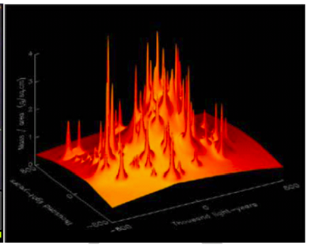

Matter distribution of the foreground (lens) galaxies

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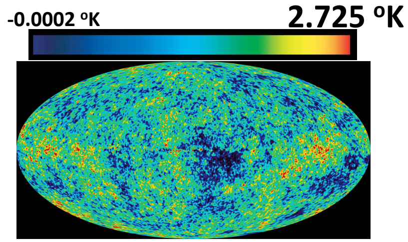
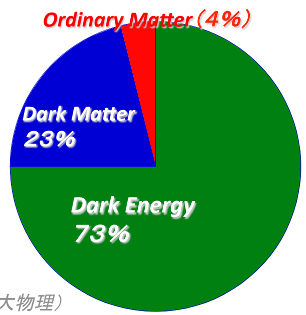




Dark Matter Candidates

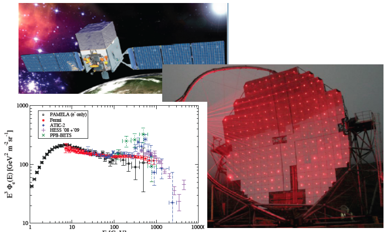
- Gravitationally interacting
- Neutral (not charged)
- Stable or long lived
  - ← Ω_{DM} = 0.23
- Cold (not hot)
  - ←large scale structure
- non-Barionic
  - ← CMB, BBNS

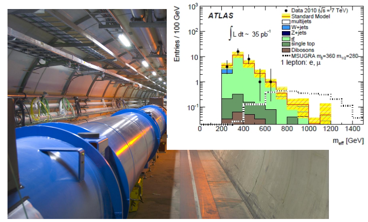
→ ***Physics beyond The Standard Model***

- AXION
- AXINO
- Gravitino
- Sterile Neutrinos
- WIMP
- …..

Detection of DM other than Gravitational Effect

- Indirect Detection
  - Annihilation & decay
    - Charged Particles
      - PAMELA, Fermi, ATIC, HESS..
    - Gammas
    - Neutrinos
- **Direct Detection**
  - ***Scattering in the laboratory detectors***
  - AXION searches…
- Accelerator: Creation and Measurement





WIMPs
(Weakly interacting Massive Particles)

- Gives right relic amount at weak scale

$$\Omega_\chi = \frac{m_\chi n_\chi}{\rho_c h^2} \simeq \left(\frac{3 \times 10^{27} \mathrm{cm^3 sec^{-1}}}{< \sigma_A v >} \right)$$

- Natural candidates from SUSY ??? LHC

<NOW>
- Many experiments to look for WIMPs are conducted
  - For the last couple of years, direct dark matter experiments have been very exciting.
    - Indications of low mass DM (a few ~ 10 GeV)?
    - By DAMA/LIBRA, CoGeNT, CRESST-II
  - Limits and exclusions?
    - By CDMS-II, EDELWEISS, XENON10, XENON100
  - ***Very strong tensions !***

Direct searches for WIMPs

- I will not explain the various efforts to reconcile the conflicting experiments.
- Instead, I will discuss on what experimentalists should do in order to clarify or strengthen the observed results.

Galactic Dark Matter

- Isothermal Halo Model (Standard Halo Model)
  - a single component isothermal sphere with a Maxwellian velocity distribution

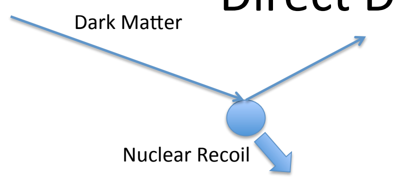
$$f(v)dv = \frac{4\pi v^2}{(v_0^2\pi)^{\frac{3}{2}}} e^{-\frac{v^2}{v_0^2}} dv$$

Typical Values:
- v_0 = 220km/s
- $<v_{DM}^2>$ = 270km/s
- Escape speed, v_{esc} ~ 550km/s
- Density: ρ_x = 0.4 GeV/cm^3

Values and uncertainties of these astrophysical parameters have been revisited and reevaluated, and still under the discussion

$$\phi \sim 10^5/cm^2/s \cdot (\frac{100GeV}{m_\chi})(\frac{\rho_\chi}{0.4GeV/cm^3})$$

Direct Detection

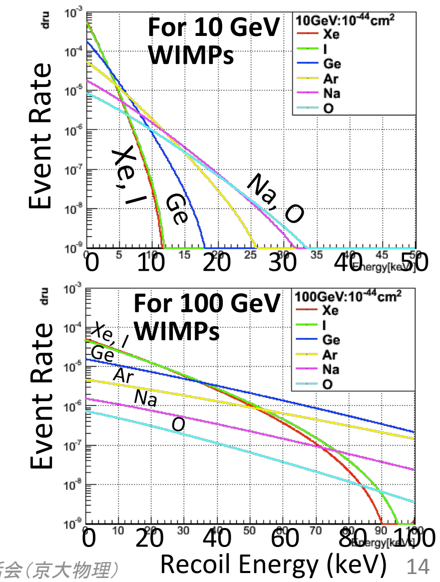


- Direct searches : Observe Nuclear Recoils
  - χ + N → χ + N
- Recoil Energy:

←Kinetic energy of DM

$$E_R = \frac{M_\chi v^2}{2}\frac{4M_\chi M_A}{(M_\chi + M_A)^2}\frac{(1-cos\theta)}{2}$$

  - 1~100 keV
  - For low mass DM, spectrum becomes very soft for heavy target masses like Xe, Ge,,
    - Loose efficiency unless lowering the threshold



Event Rate

$$dR = N_A n_\chi \sigma_{0\chi A} v f(\vec{v}) d^3\vec{v}$$

$$\frac{d\sigma_{\chi A}(q)}{dq^2} = \frac{1}{\pi v^2}|\mathcal{M}|^2 = \frac{\sigma_{0\chi A}F^2(q)}{4\mu_A^2 v^2}$$

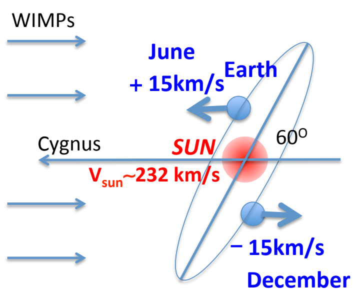
$$\sigma_{0\chi A} = \frac{4\mu_A^2}{\pi}[Zf_p + (A-Z)f_n]^2 + \frac{32G_F^2\mu_A^2}{\pi}\frac{J+1}{J}(a_p < S_p > + a_n < S_n >)^2$$

Spin Independent   Spin dependent

TYPICAL:
- ~0.1 ev/day/100kg-Xenon
  for m_χ = 50 GeV and σ_{SI}=10^{-44} cm^2
  with 10keV$_{NR}$ threshold, 30% detection efficiency

Seasonal Variation

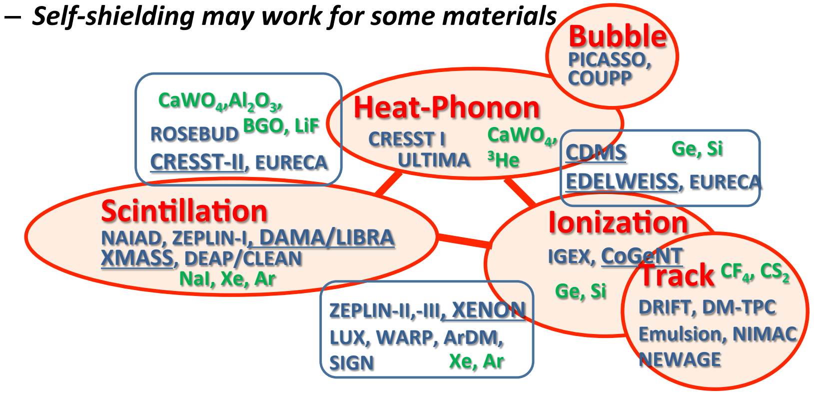
$$\mathbf{v_E} \approx (220+12) + 15 \times \cos\left(2\pi\frac{t-152.5}{365.25}\right) km/s$$



- Seasonal variations of the velocity: ±15km/s
- Max: June-2
- < ~ 10% modulation effects
  - depend upon spectrum shape, trigger efficiency, analysis cuts and so on

Direct Search Experiments

- *Various Detection Technology*
  - *Scintillation, Heat-Phonon and Ionization*
  - *Usually combined technologies to reduce backgrounds*
  - *Self-shielding may work for some materials*

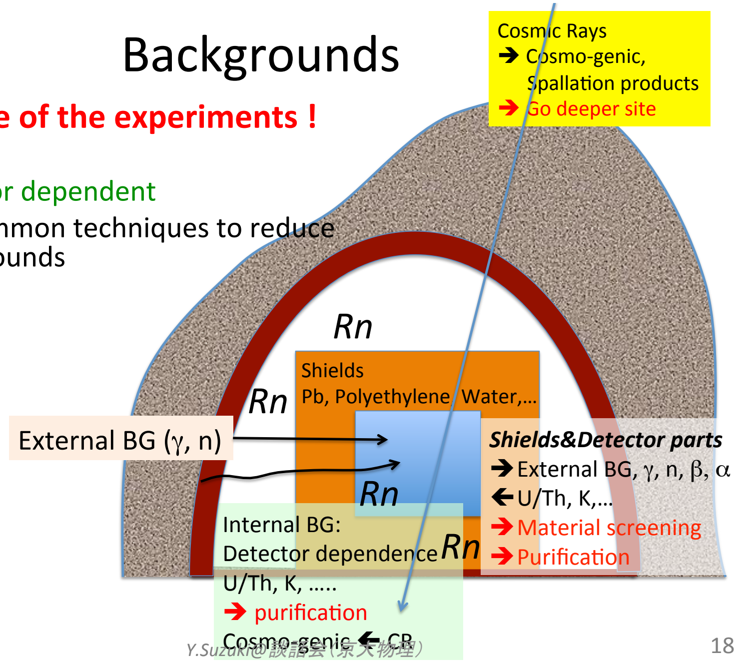


Backgrounds

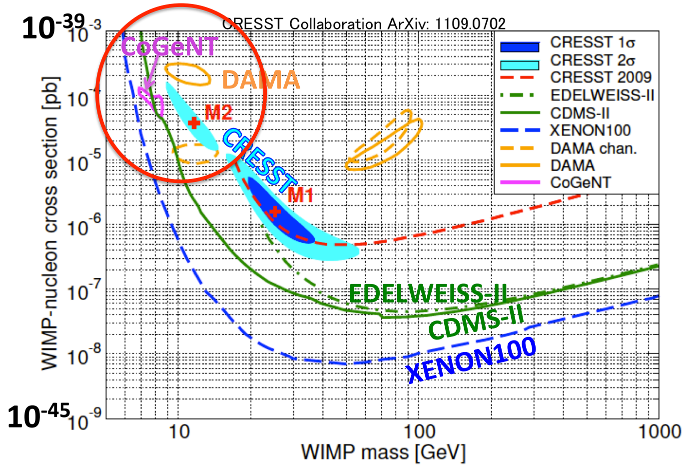
Key Issue of the experiments !

Many:

- detector dependent
- but common techniques to reduce backgrounds



Current Experimental Situation



Current players of the game

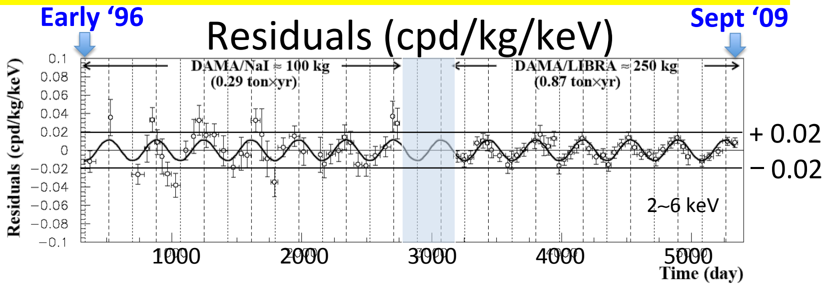
Positive Indication

Experimentð	Target	Threshold	Total Exposure	Recoil Identification	Main body of Signal ?	Modulation
DAMA/LIBRA	NaI	2.0 keV_{ee}	427,000 kg-days	(NR+EM)	—	○
CoGeNT	Ge	0.5 keV_{ee}	140 kg-days	(NR+EM)	○ by fit w/BG	○
CRESST	$CaWO_4$	10.0 keV	>700 kg-days	NR	○ by fit w/BG	—

Negative and set limit

Experimentð	Target	Threshold	Total Exposure	Recoil Identification	Main body of Signal ?	Modulation
CDMS-II	Ge/Si	10.0 keV	612 kg-days	NR		
CDMS-II (LE)	Ge	2.0 keV_{NR}	241 kg-days	(NR+reducedEM)		
EDELWEISS	Ge	20.0 keV	384 kg-days	NR		
XENON100	Xe	8.4 keV_{NR}	1471 kg-days	NR		
XENON10 (LE)	Xe	1.4 keV_{NR}	15 kg-days	(NR+reducedEM)		

DAMA/LIBRA



- DAMA/LIBRA: High purity low BG NaI
  - 250kg NaI(Tl) for DAMA/LIBRA
- Total exposure: 1.17 ton-yr (13 cycles)
  - 427,000 kg-days

Result ➔ Modulation (**8.9σ**)
  - $S_k=S_0+S_m\cos\omega(t-t_0)$
  - Amplitude(S_m): for 2~6 keV
    0.0116±0.0013 cpd /kg /keV (dru)

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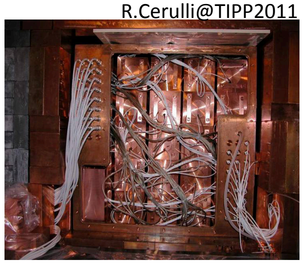
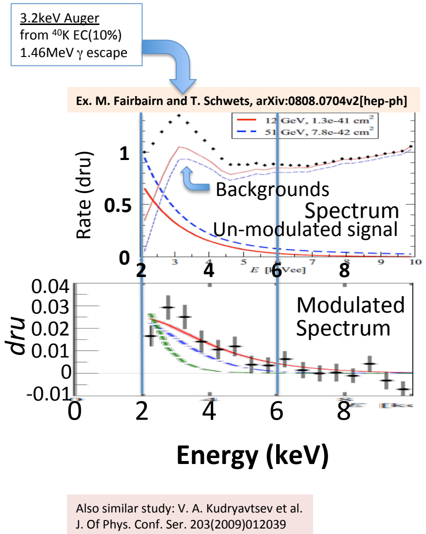


View at the end of DAMA/LIBRA

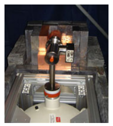
Question: Where is the un-modulated part of signal, S_0 ?

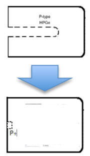


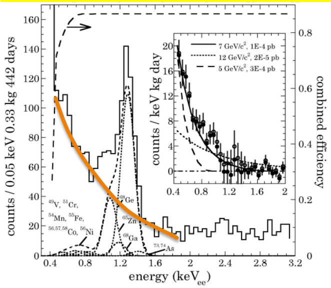
- ***Must be in somewhere underneath of the spectrum !***
- In most of the elastic scattering cases, $S_0(E)$ monotonically goes down as energy increase, then backgrounds must sharply goes down below 3~4 keV.

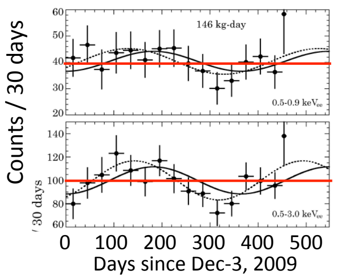
➔**This may not be natural**
➔**Simple Elastic Scattering interpretation may have a internal inconsistency?**
→**Inelastic ?** also **strong tension**
→**Other scenarios ???**

CoGeNT
Coherent Germanium Neutrino Telescope









- P-type Point Contact (PPC) germanium detectors: 440g
  - High resolution (low C)
- Threshold ~ 0.4 keVee (lowest)
- But no Nuclear Recoil separation
- BG: Reject surface events

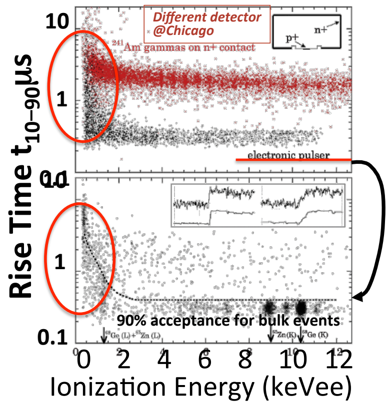
➔**irreducible excess below 3 keV**

- 442 effective days, assuming all the unknown excess is 'signal'

➔ **Modulation (0.5 – 3.0 keVee)**:
  - 2.8 σ
  - Amplitude: 16.6±3.8%
  - Minimum: Oct 16±12 d

➔ Need more data

What should we watch



Backgrounds are crucial for all the DM experiments

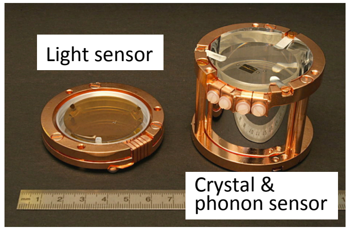
- Surface events (CoGeNT)
  - (n+) 1mm: dead, 1mm transition (~external γ's)

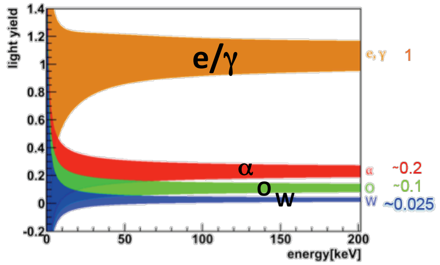
🡐 rise time difference to discriminates
  - bulk (0.3 μs ~ 2 μs @low energy)
  - Surface (2 μs ~ 4μs @low energy)
- They said that any such contamination should be modest
- Calibration was done for different detector

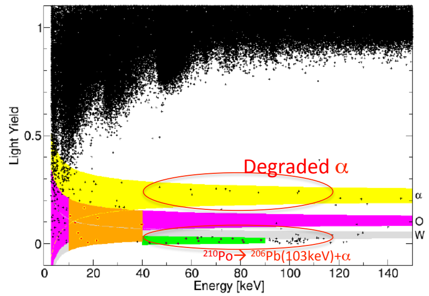
➔ Need clear and quantitative evaluation of the leakage from the surface event

CRESST-II

- $CaWO_4$(Multi-material target)
  - up to 10 kg, 33 crystals, (0.3kg each)
  - phonon (~10 mK)
  - Scintillation
    - ➔ Reduced light output for nuclear recoils
    - ➔Light output decreases with increasing mass number of recoiling nucleus
- Data used (2009 – 2011)
  - 730kg*days
  - 8 detector modules







	M1	M2
e/γ-events	8.00 ± 0.05	8.00 ± 0.05
α-events	$11.5^{+2.6}_{-2.3}$	$11.2^{+2.5}_{-2.3}$
neutron events	$7.5^{+6.3}_{-5.5}$	$9.7^{+6.1}_{-5.1}$
Pb recoils	$15.0^{+5.2}_{-5.1}$	$18.7^{+4.9}_{-4.7}$
signal events	$29.4^{+8.6}_{-7.7}$	$24.2^{+8.1}_{-7.2}$
m_χ [GeV]	25.3	11.6
σ_{WN} [pb]	$1.6 \cdot 10^{-6}$	$3.7 \cdot 10^{-5}$

- O-band events
  - 67 events
- 4 source of BG
  - Leakage from e/γ band
  - Leakage from α related
    - Degraded α events
  - Neutron events (O)
  - Pb recoils:

    ^{210}Po→ ^{206}Pb(103keV) +α(out)
- "room for signal"
  - 36～44 %

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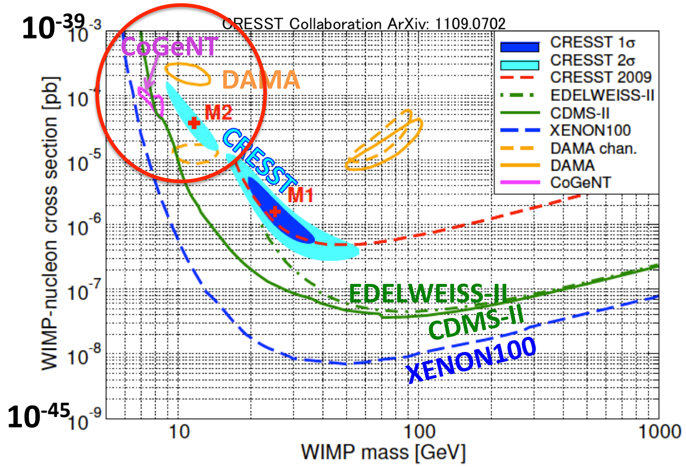

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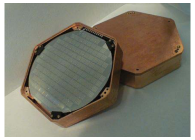
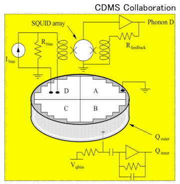
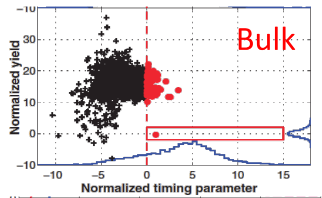
CDMS-II

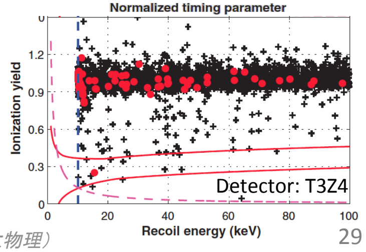
- Ge(&Si) detector (~10mm thick and ϕ=76mm)
- 230g x19 ~ 4 kg
- Ionization and phonon (<50mK)
  - Ionization yield ➔ 1 in 10^4 raj. for γ's
  - Timing cut ➔ surface events ($>10^6$ raj.)
- 10 keV threshold & < 100keV
- Data: 612kg-days
- 2 events found
- Backgrounds: 0.9±0.2
  - 0.8±0.1±0.2 surface events
  - 0.1 neutron events





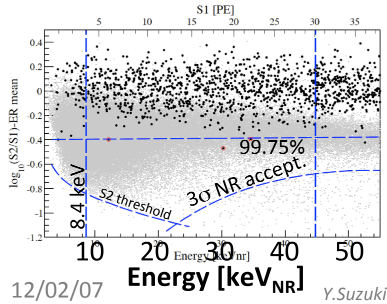
Z-sensitive
Ionization and
Phonon-mediated

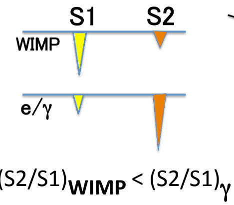


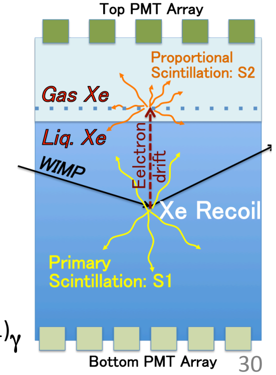


XENON-100 2 phase liquid Xenon detector

- Simultaneous detection of light (S1) and charge (as S2)
  - Ionization e's → S2 (prop. Scinti.)
- S2/S1 →NR and EM discri: ~1/1000
- 100.9 live days (till June in 2010) w/48 kg fiducial mass (62kg)➔ 1471kg-day
- 3 events remain after S2/S1 selection (99.75% EM rejection)
- Expected BG: 1.8±0.6
  - ^{85}KR: 1.14±0.48
  - Others: 0.56(+0.21/-0.27)







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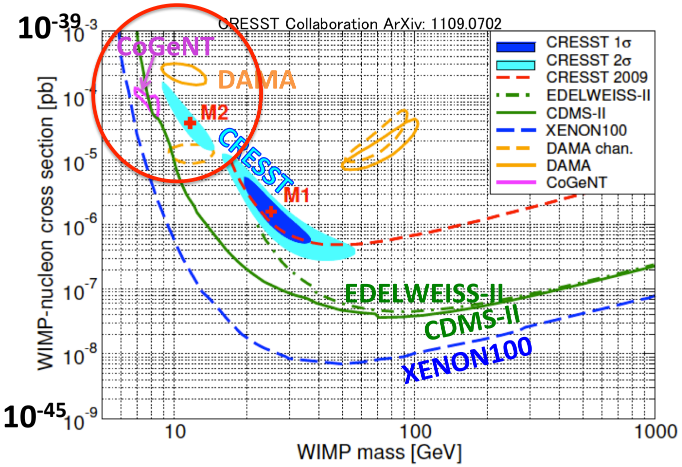


Current and Future direct WIMP Search experiments

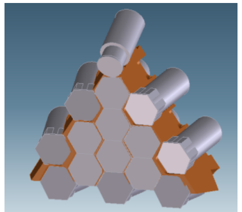
35 programs (not complete list : sorry for those projects I have missed)

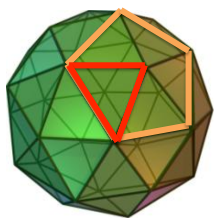
Experiments	site	Target & mass	technology	Achieved (cm^2)	Sensitivity (cm^2)	Status & comments	Year to start
Xenon							
ZEPLIN-III	Boulby	Xe: 8kg	two phase		SI: 10^{-43}	Stop in 5- 2011	results soon
XENON100	LNGS	Xe: 48kg	two phase		SI: 7×10^{-45}		On going
XENON1T	LNGS	Xe: 1t	two phase		SI: 10^{-47}		2015
XMASS	Kamioka	Xe: 100kg	single phase		SI: 10^{-45}	commissioning	On going
XMASS-1.5	Kamioka	Xe: 1ton	single phase		SI: 10^{-46}		2013
XMASS-II	Kamioka	Xe: 10ton	single phase		SI: 10^{-47}		2016
PANDA-X	Jing Ping	Xe: 25kg	two phase		SI: 10^{-45}		> 2013
LUX	SUSEL	Xe: 100kg	two phase		SI: $<10^{-45}$	Surface lab	2012
LZS	SUSEL/ SNO	Xe: 1ton	two phase		SI: 10^{-47}		2015
Ar							
WARP	LNGS	Ar:140kg	two phase		SI: 5×10^{-45}	commissioning	
DarkSide50	LNGS	DAr: 50kg	two phase		SI: 10^{-45}	prototype	
ArDM	Canfranc	Ar: 850kg	two phase			Prototype	2011
DEEP3600	SNOLAB	Ar: 1ton	Single phase		SI: 10^{-45}		2012
MiniCLEAN	SNOLAB	Ar: 150kg	Single phase		SI: 10^{-44}		2011
DARWIN	Europe	Ar or Xe: tons	two phase		SI: $<10^{-47}$		
MAX	DUSEL	Ar and Xe			SI:$<10^{-47}$	R&D	

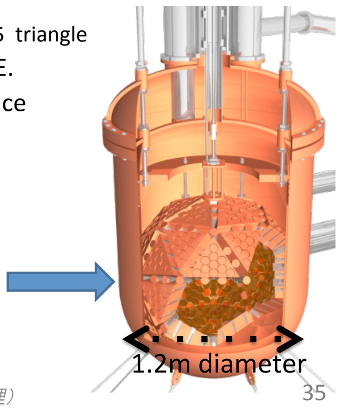
Experiments	site	Target & mass	technology	Sensitivity (cm^2)	Achieve (cm^2)	Status & comments	Year to start
Ge							
Super-CDMS	SOUDAN	Ge: 15kg	char+phonon	SI: $5x10^{-45}$			2011
Super-CDMS	SNOLAB	Ge: 100kg	char+phonon	SI: $3x10^{-46}$			2015
CoGeNT-C4	SOUDAN	Ge: 4kg	charge			installation	2011
CDEX	Jing Ping L	PC-Ge:10 kg	charge	SI: 10^{-43}		1kg test	
Bubble Chamber							
PICASSO	SNOLAB	C_4F_{10}: 2.6kg	BC	SD: $2x10^{-37}$			On going
SIMPLE	Rustrel	C_2ClF_5: 26 kg	BC			Test 0.2kg	Install 2012
COUPP	SNOLAB	60kg	BC			4kg test	2011
Scintillation (+phonon)							
DAMA	LNGS,	NaI: 250kg	Scintillation	SI: 10^{-40}			On going
KIMS	Yang Yang	CsI: 104.4kg	Scintillation	SD:10^{-38}			On going
CINDMS	Jing Ping L	CsI(Na)	Scintillation			R&D	
CRESST-II			Sintill+phonon				On going
ROSEBUD	Canfranc	Al_2O_3 etc.	Scintill+phonon			R&D	
DM-Ice	South pole	NaI:>250kg	Scintillation	Test DAMA		Prototype: 17kg	?
EURECA	LSM	Multi-T: 1ton	many	SI: 10^{-46}		Phase-I: 150kg	2015
Tracking							
Drift-III	Boulby	CS2:4kg,24m^3	TPC	SD: 10^{-40}			?
DM-TPC		CF4	PMT+TPC			Prototype test	
NewAGE	Kamioka	CF4	microTPC			Prototype test	
MiMac	LSM	CF4	microTPC			Prototype	2011 1m^3
Cygnus	World?		Tracking			White paper	

The phase-I XMASS detector

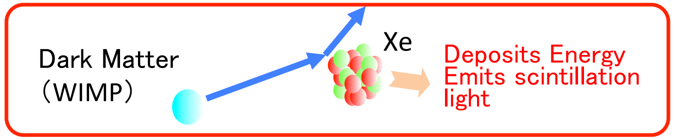
- Detector
  - Single phase (scintillation only) liquid Xenon detector
  - Operated at -100°C and ~0.065MPa
  - 100 kg fid. mass, [835 kg inner mass (0.8 mϕ)]
  - Pentakis-dodecahedron
    ← 12 pentagonal pyramids: Each pyramid ← 5 triangle
  - 630 hex & 12 round PMTs with 28-39% Q.E.
  - photocathode coverage: > 62% inner surface





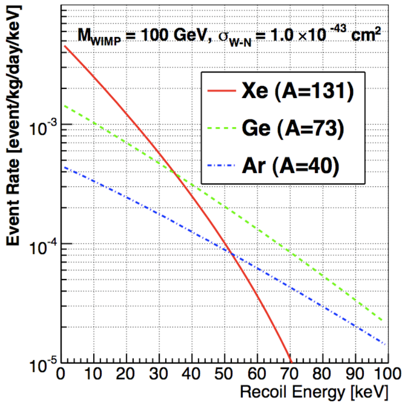


Detection Principle



- WIMPs scattering off nuclei in targets, produce nuclear recoils.
- $\chi + N \rightarrow \chi + N$
  - V_{sun} ~ 232 km/s
  - $E_{recoil} \leq 100$ keV
  - Less than 1 WIMPs/day interactions in 100 kg material

Energy Spectrum (SI)



- $\sigma = A^2(\mu_A{}^2/\mu_n{}^2)\sigma_{\chi n}$
- A^2 ➔ Xe is one of the best target

Xenon Property

- Why liquid Xenon
  - High atomic number (Z=54) and density (ρ=~3g/cm^3)
    - → Effective self-shielding.
    - → Compact for large mass detector.
  - High photon yield (~46000 UV photons/MeV at zero field)
  - Easy to purify for radioactive impurities (Purification in Gas and Liquid phase)
    - → By circulation of Xe with getter
    - → Distillation (for example ^{85}Kr removal)

Characteristics and Aim

- Low energy threshold < 5keV$_{ee}$ (~25keV$_{NR}$) and good energy/vertex resolution
  - ← High light yields (~NaI) and high photo-cathode coverage
- ← Study Spin dependence (option)
  - ← Easier isotope separation (odd $ even)

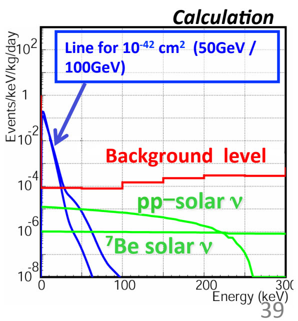
ββ-decay

^{124}Xe	^{126}Xe	^{128}Xe	^{129}Xe	^{130}Xe	^{131}Xe	^{132}Xe	^{134}Xe	^{136}Xe
(0.10%)	(0.09%)	(1.92%)	(26.4%)	(4.07%)	(21.2%)	(26.9%)	(10.4%)	(8.87%)

Mostly Odd | Mostly Even

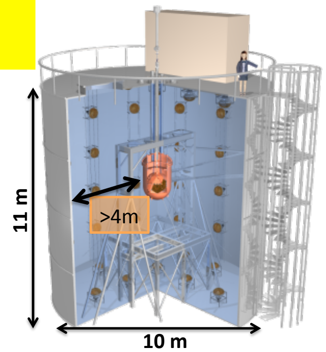
- Aim
  - Background: 10^{-4} dru (ev/kg/keV/day)
  - 10^{-45}cm^2 SI for ~100GeV WIMPs

Challenge to reduce backgrounds

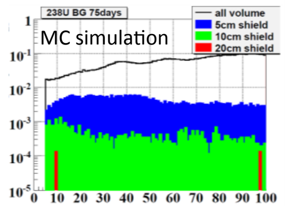


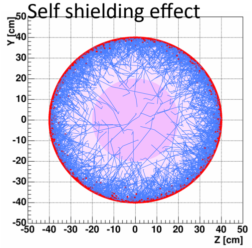
External backgrounds

- γ, n from Rocks
  - Water tank (active: 72 20" PMTs)
    - > 4 m water shields
    - γ: 10^3 reduction by 2m
      - smaller than PMT BG
    - n << 10^{-4}/d/kg (by 2m)
- γ, n from PMT, detector parts
  - Low BG PMT (~1/100 of regular PMT)
  - Material selection by HPGe detector
  - Self-Shields
    - < 10^{-4} /keV/day/kg



	BG/PMT with base parts
U chain	0.70 ± 0.28 mBq
Th chain	1.5 ± 0.31 mBq
40K	< 5.1 mBq
60Co	2.9 ± 0.16 mBq



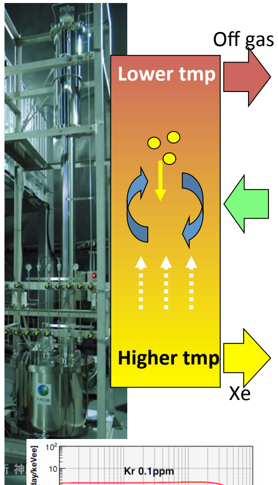


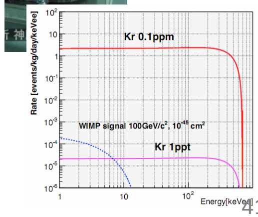
Internal backgrounds

- Kr (Q_β = 687 keV)
  - Distillation: Kr has lower boiling point
  - 5 orders of magnitude reduction (test)
    - 0.1ppm → 1ppt with 4.7kg/hr

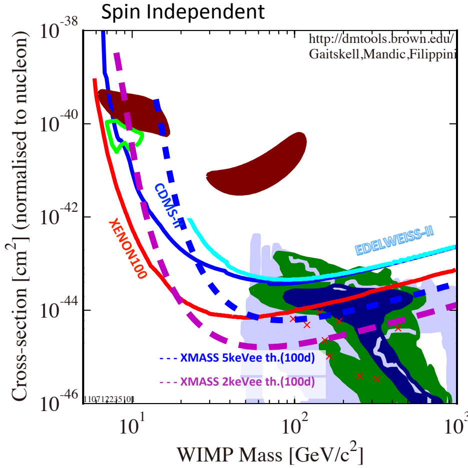
K. Abe et al. for XMASS collab., Astropart. Phys. 31 (2009) 290

  - Distillation: 10 days before filling into the detector (~ 1 ton)
- Rn
  - target value
    - ^{222}Rn: target 1.0mBq for 835 kg inner volume
    - ^{220}Rn: target 0.43mBq for 835 kg inner volume
  - Filtering by circulation
    - liquid → gas (30litter-GXe/min) → liquid
      - Charcoal
    - liquid (a few litter-LXe/min)
      - Under study



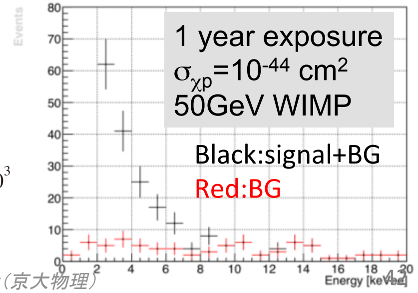


Expected sensitivity

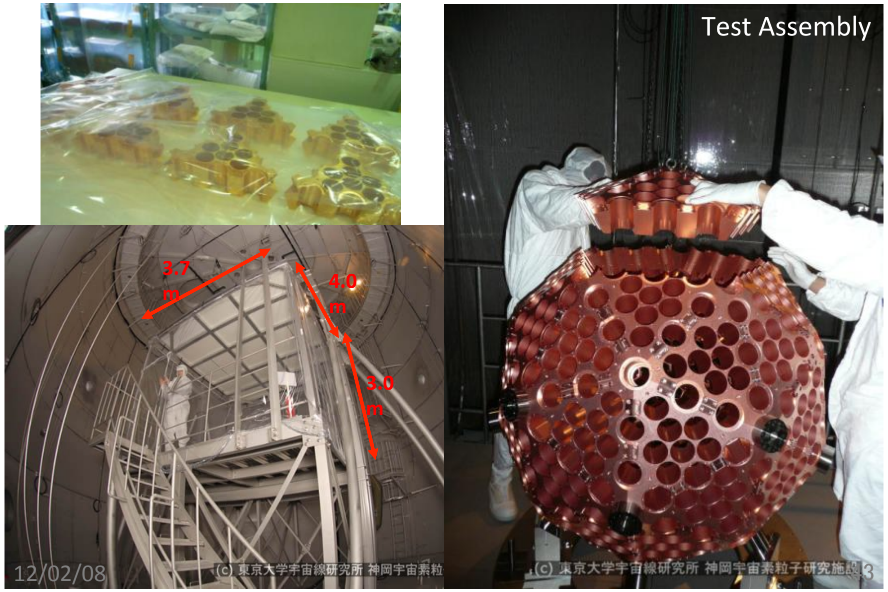


$\sigma_{\chi p}$>2x10^{-45} cm^2
for 50-100GeV WIMP, 90%C.L.
1yr exposure, 100kg FV,
BG: 1x10^{-4} /keV/d/kg
Scintillation efficiency: 0.2

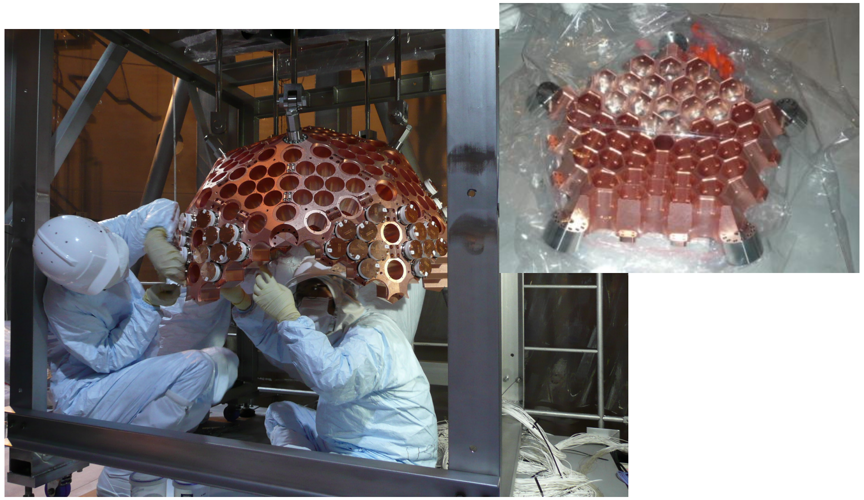
Expected energy spectrum



PMT holder

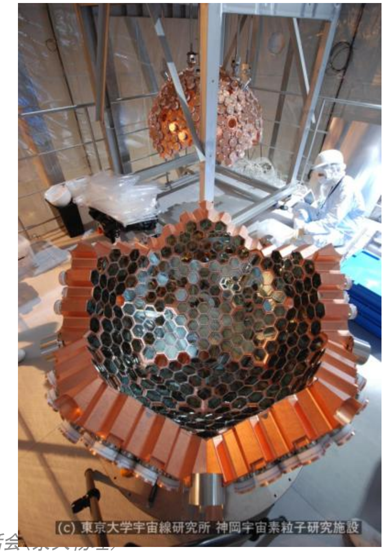


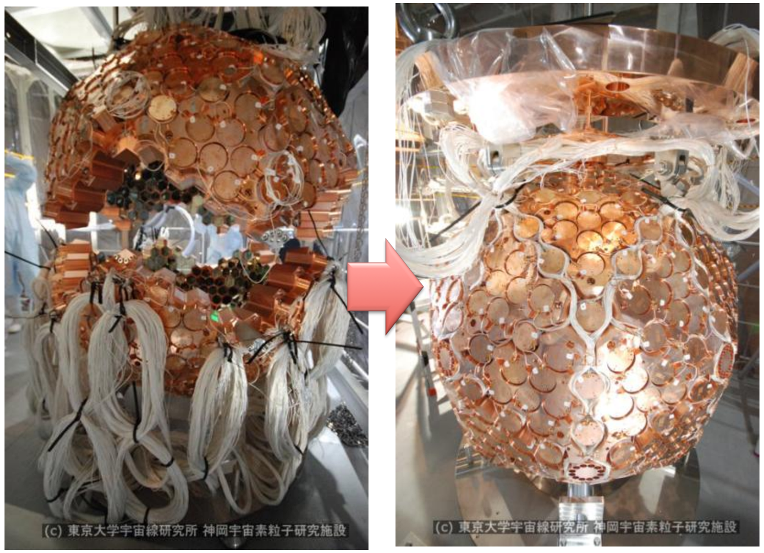
PMT Holders



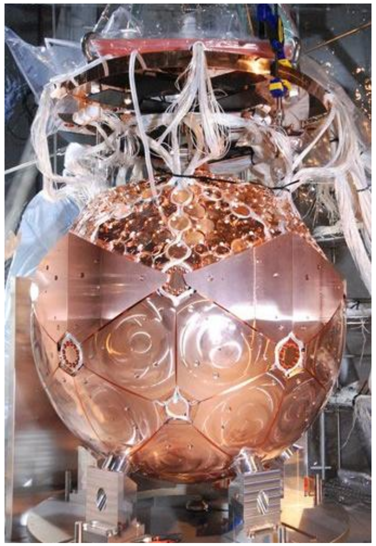
Assemble PMTs

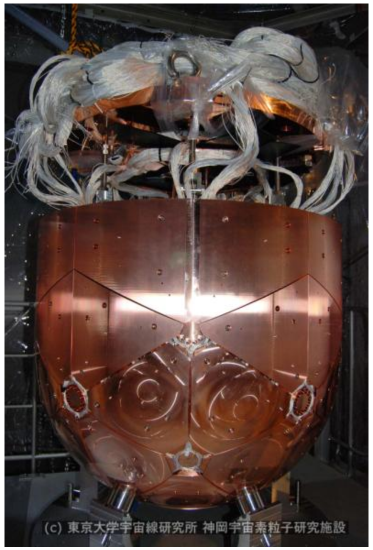
- 642 PMTs are attached during 13 days.
- 200g/PMT
- ~200kg for all PMTs





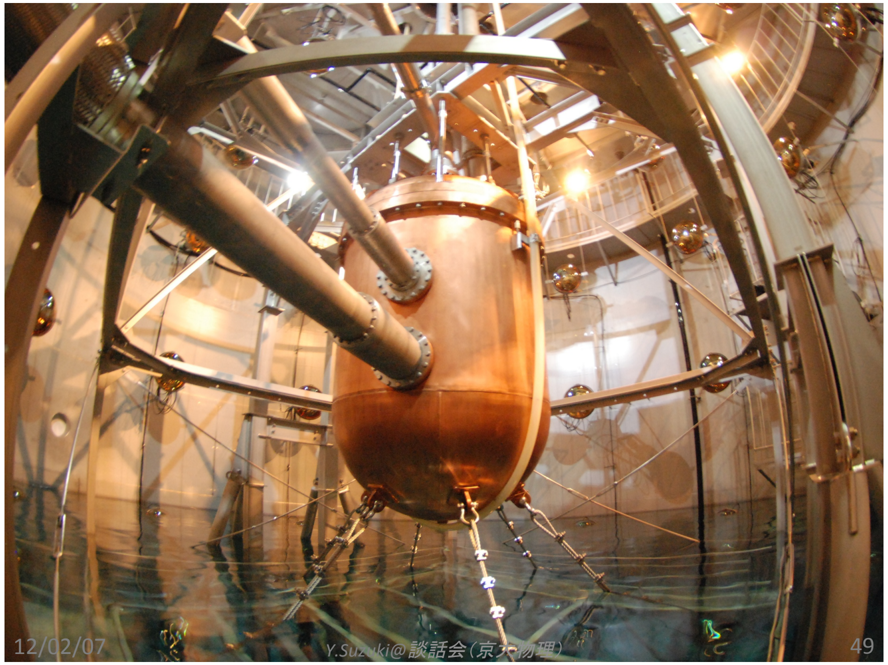
Filler (total 2.8ton) attachment.

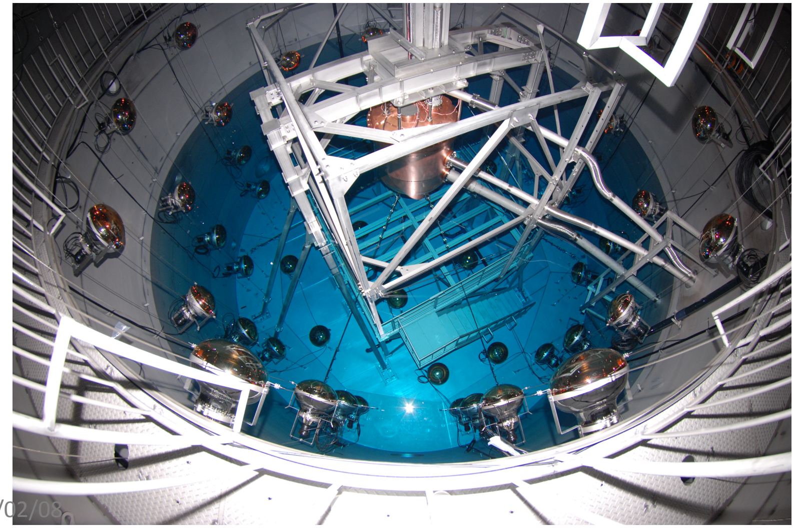




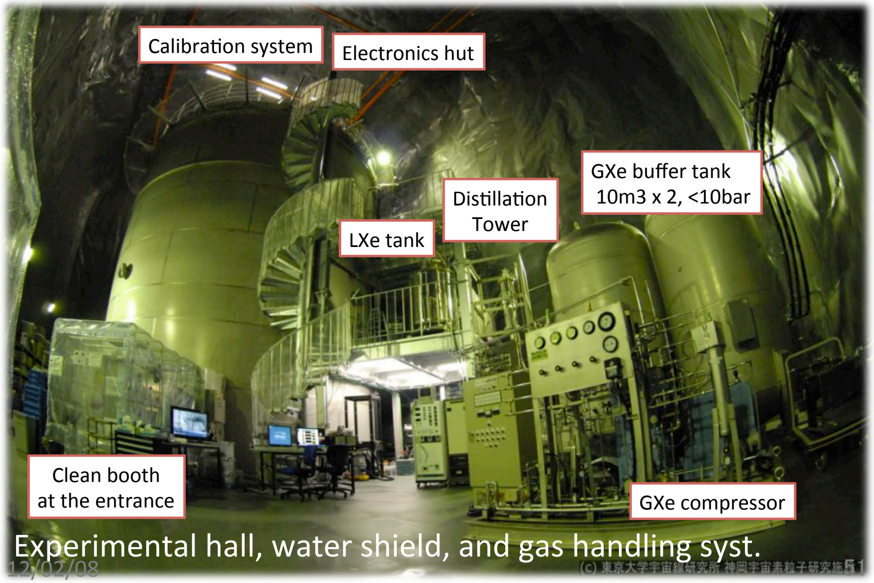
Manufacturing detector vessel

- A challenge: Manufacturing a large flange with soft OFHC copper. Inside: Electro-polished
- Due to insufficient strength of its neck part, it needed to be reinforced by adding ribs.
- It took four months.





Each components and construction status

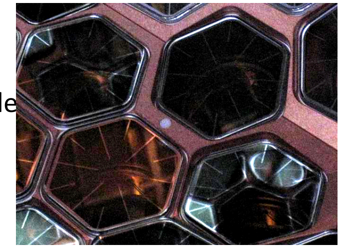


Calibration

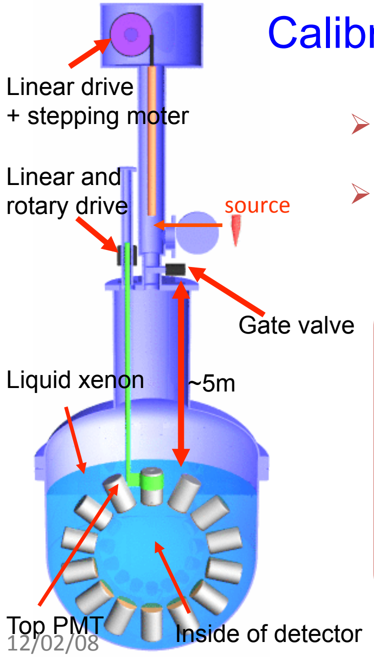
Calibration system

- Gamma source
  - To check
    - Position reconstruction
    - Energy resolution
  - From inside and outside of the detector.

- LED
  - PMT Gain (1pe)
  - 8 LEDs are attached to the PMT holde



- Laser + diffuser
  - PMT Timing



Calibration system for inside detector

- ➢ To introduce calibration source to inside detector
- ➢ Operate from the water tank top, 5m above detector

- Move top PMT and make window through which source can enter
- Introduce source to inside of the detector.
- Open/close of the window can be checked by optical fiber scope.
- Source can be changed even during observation.

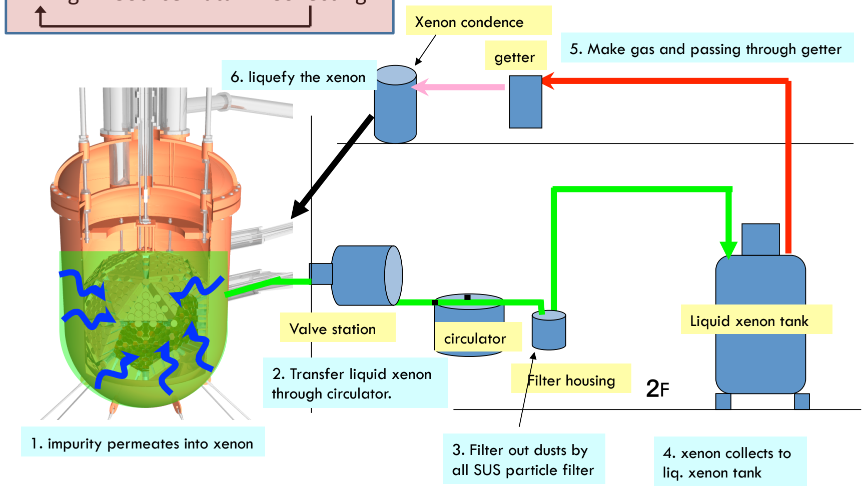
Calibration source rod

- ϕ12mm, length 1560mm,1.54kg
- Lift up and down by ϕ0.3mm SUS301 wire
- Calibration source is attached at the end of rod.

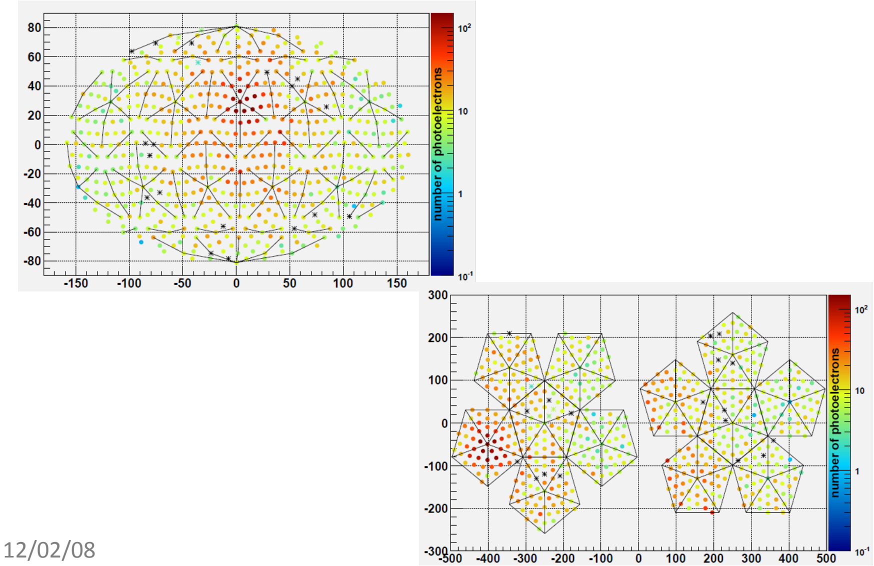
Commissioning

Detector cleaning

Filling → Source Data → Collecting

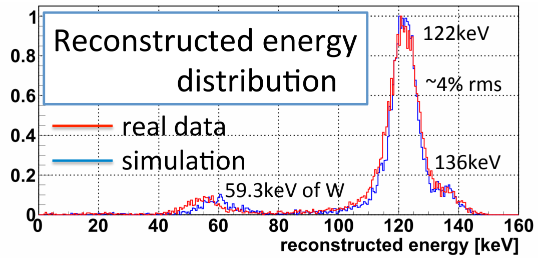


Event Display

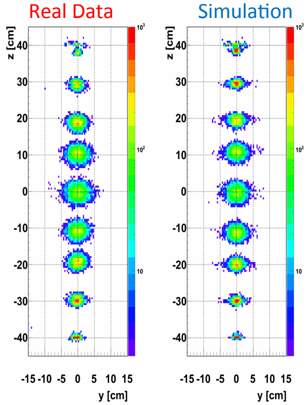


Detector performance

Reconstruction



Reconstructed position

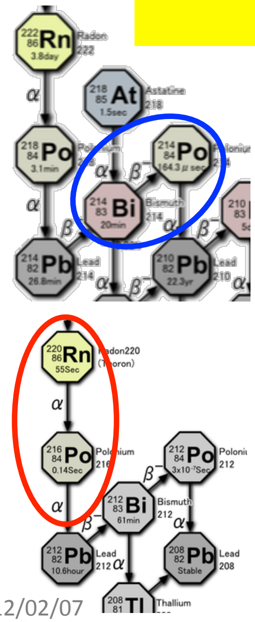


- Reconstruction:
  - pe-distribution, hit pattern (and timing)
  - →energy, position (and particle id)
  - →High p.e. yield: 15.1±1.2 pe/keV

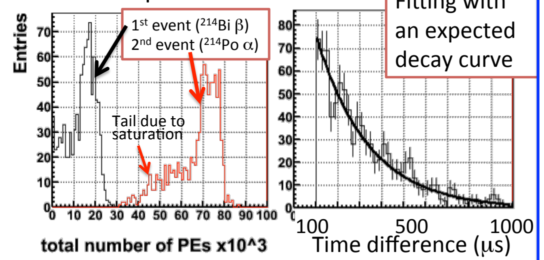
- Energy resolution for ^{57}Co (122keV, γ-rays)
  - 4% rms

Position Resolution for ^{57}Co (122keV γ rays)
1.4cm rms (0cm: center)
1cm rms (@r=±20cm)

Internal BG (Rn)



- ^{222}Rn: Identify ^{214}Bi → ^{214}Po → ^{210}Pb decays
  - ^{214}Po decays with 164 μs half life
  - β and α coincidence
  - 8.2±0.5mBq in the inner volume



Fitting with an expected decay curve

- ^{220}Rn: Identify ^{220}Rn → ^{216}Po → ^{212}Pb decays
  - ^{216}Po decays with 0.14sec half life
  - two α's with short coincidence
  - Upper limit <0.28mBq (90%C.L.)

?

Summary

- XMASS phase I (100kg fiducial) is a single phase liquid Xenon detector which has a sensitivity to 2×10^{-45} cm^2 (SI cross section)
- Commissioning runs are on going to understand the detector performance and backgrounds
  - Energy resolution and vertex resolution were as expected: ~1cm position resolution and ~4% energy resolution for 122 keV γ.
  - Radon backgrounds are close to be expected.
- Direct dark matter search experiments are in a very exciting and interesting stage: Some indications for low mass DM, but there are conflicting results.
- We 'hope' that we will show some results in next month.

END