

宇宙線観測装置の最前線

神戸大学・身内賢太郎

第46回天文天体若手夏の学校

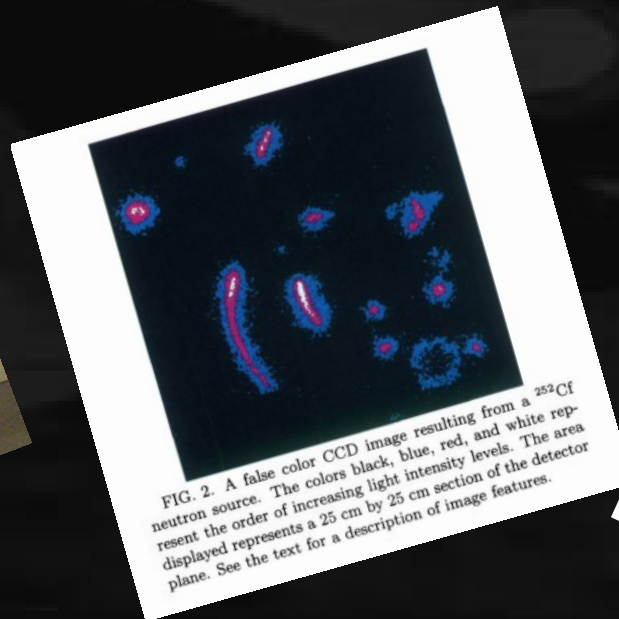
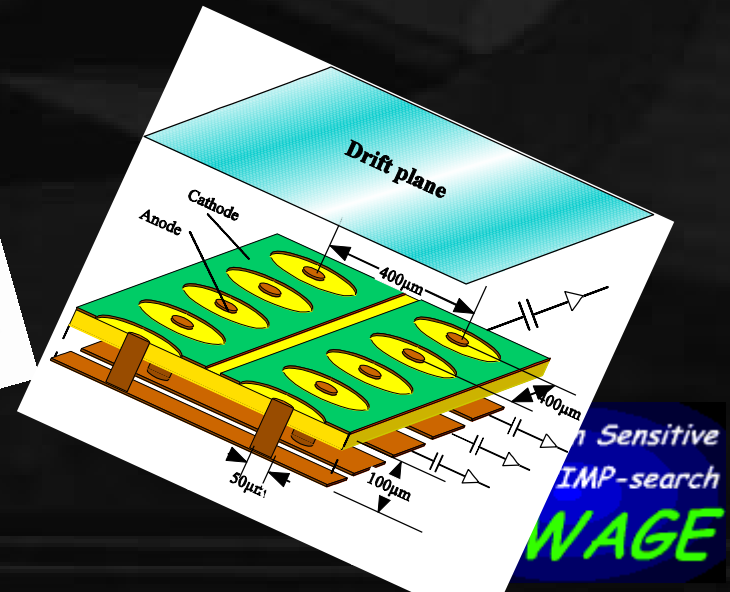


FIG. 2. A false color CCD image resulting from a ^{252}Cf neutron source. The colors black, blue, red, and white represent the order of increasing light intensity levels. The area displayed represents a 25 cm by 25 cm section of the detector plane. See the text for a description of image features.



Sensitive
IMP-search
WAGE

はじめに

■ みなさんの勇気に感謝

観測機器分科会

身内 賢太郎 氏 (神戸大学)

7月27日 17:15 - 18:15 B会場

「宇宙線観測装置の最前線」

宇宙線観測とその観測装置について講演します。

■ 研究者 挑戦する勇氣

■ 成功への第一歩



はじめまして

■ 身内賢太郎

■ 属性 闇

■ 東大みのわ研 ボロメータ

■ 京大宇宙線 ガス

■ 神戸大粒子物理 ガス、液体キセノン

内容：「宇宙線観測機器の最前線」

■ 宇宙線・最前線

■ ダークマター・最前線

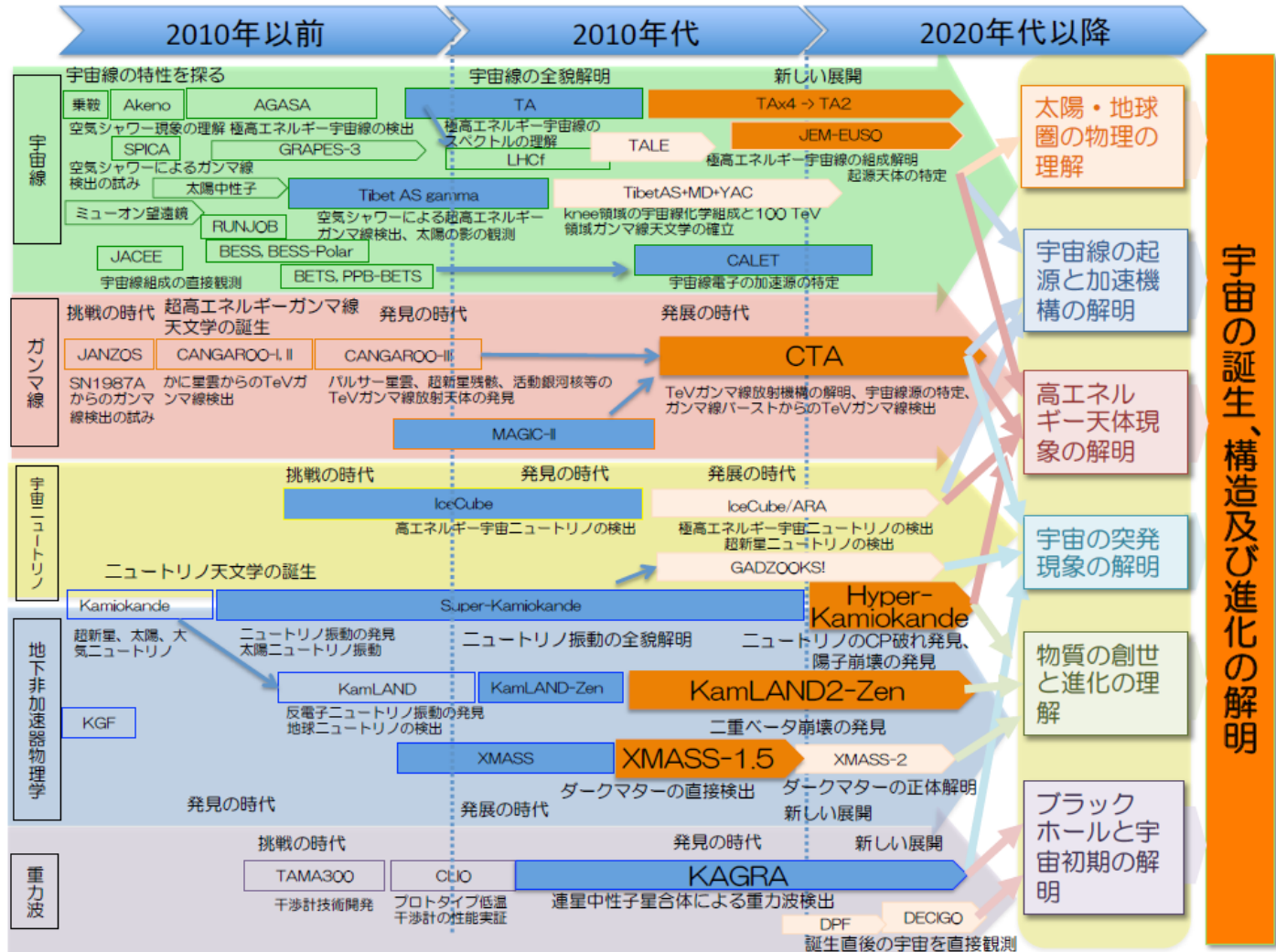
宇宙線

宇宙線

宇宙から飛来する有象無象の（素）粒子

作成：2013-2014年度期CRC将来計画検討小委員会

http://www.icrr.u-tokyo.ac.jp/CRC/townmeeting/doc/CRC_FPSC_report_2013-14-v3.pdf

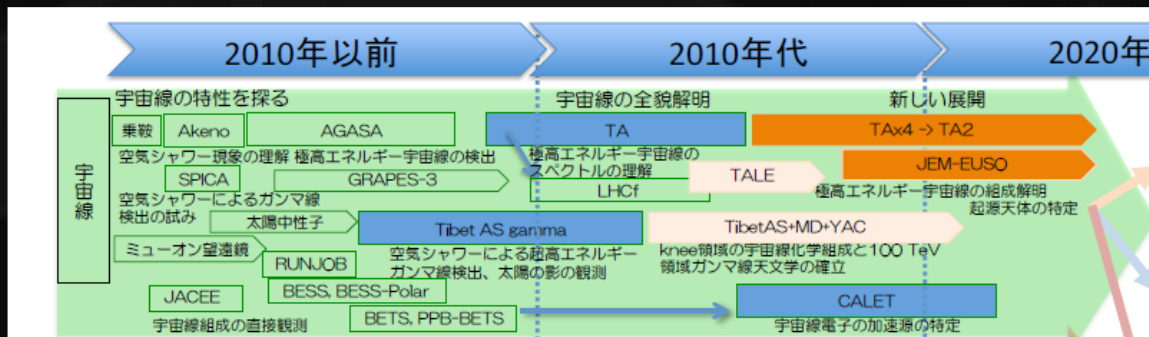


宇宙の誕生、構造及び進化の解明

ation Sensitive
WIMP-search
WAGE

（狭義の / 古き良き）宇宙線

宇宙から飛来する（主に）原子核



テレスコープアレイ実験

Telescope Array (TA)

CALETパンフレット

■ 宇宙線：物理

- 起源・加速機構
- ダークマターなど

「ダークマター？」



「宇宙ステーションで
ダークマター発見します。」

(2015年7月23日 報道ステーション)

宇宙線：最前線

- 比較的成熟した技術を宇宙や砂漠などで大規模に使用

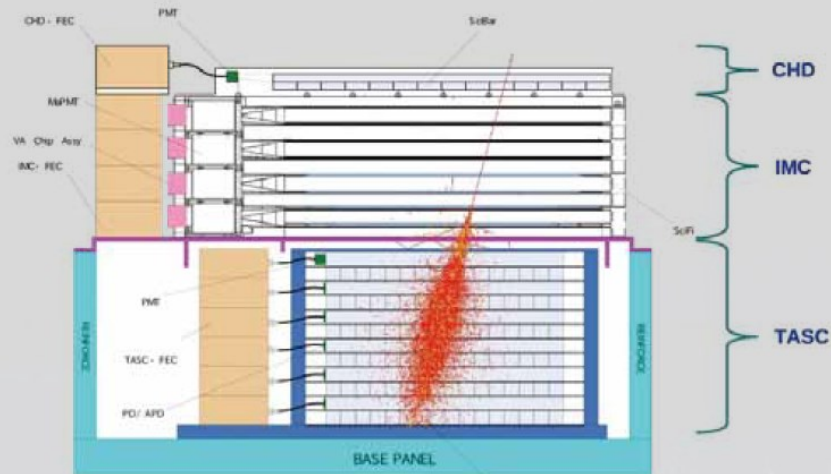
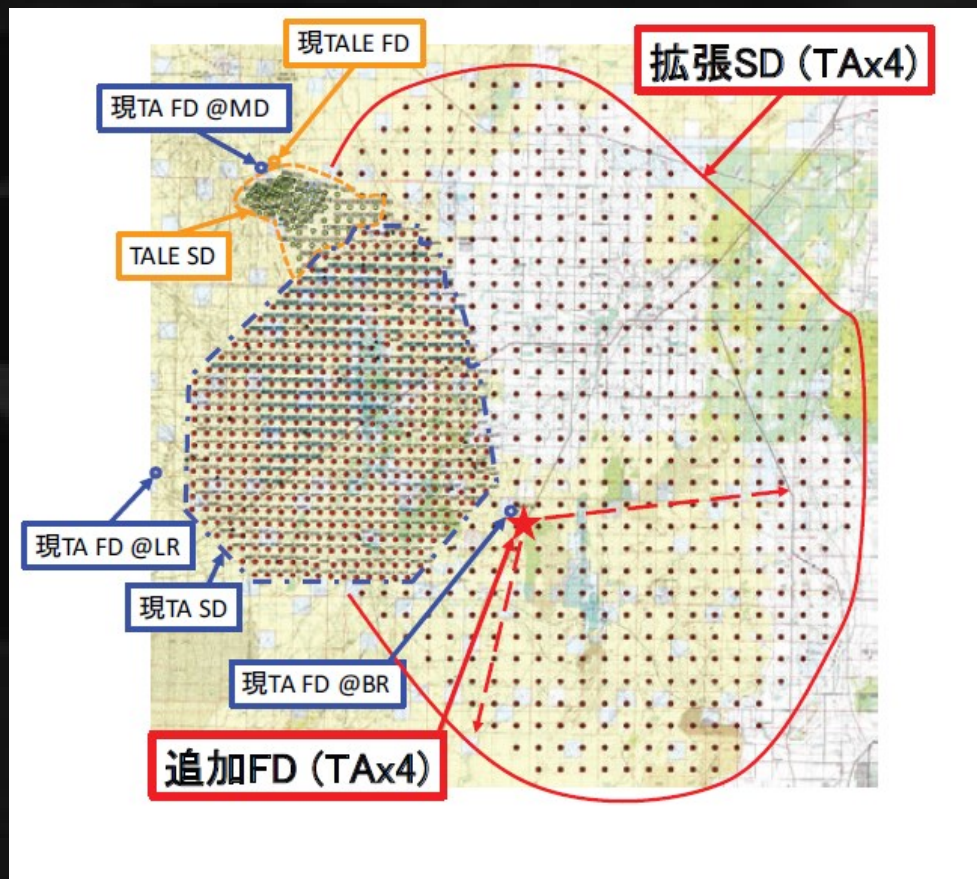
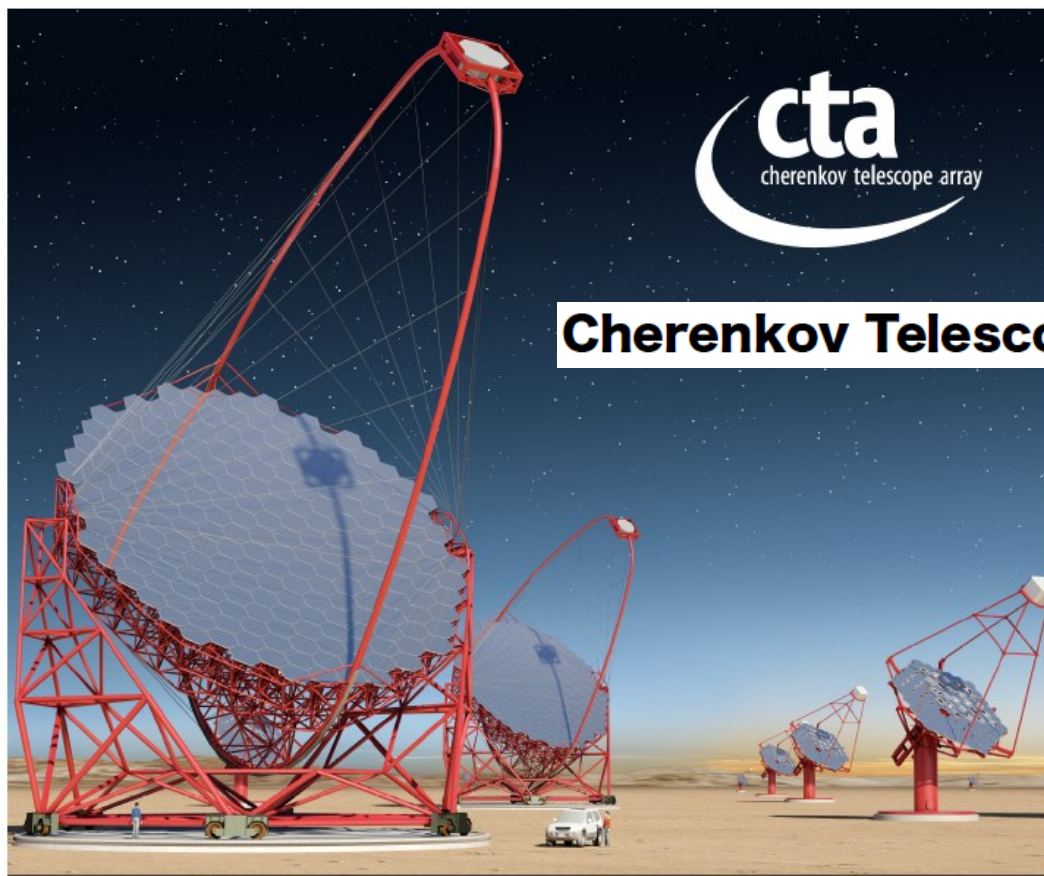
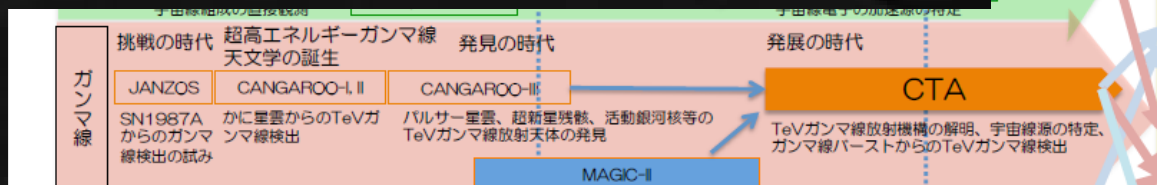


図2: カロリメータの構造とシャワー粒子
Figure 2: Calorimeter structure & shower particles



■ ガンマ線

■ 宇宙から飛来するガンマ線



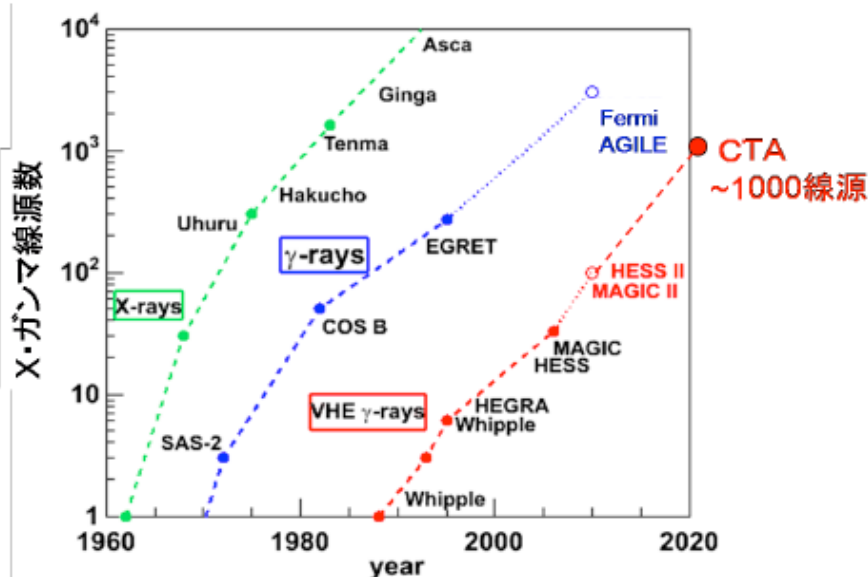
Cherenkov Telescope Array 計画書

2014年7月15日

CTA-Japan Consortium
東京大学宇宙線研究所

■ ガンマ線：物理

■ 多くの天体・多彩な物理



Cherenkov Telescope Array 計画書

2. CTAが狙うサイエンス

2.1. 宇宙線の起源

- 2.1.1. 超新星残骸
- 2.1.2. パルサー
- 2.1.3. White Dwarf Pulsar (白色矮星パルサー)
- 2.1.4. パルサー星雲
- 2.1.5. 連星
- 2.1.6. 天の川銀河の中心領域
- 2.1.7. 拡散ガンマ線
- 2.1.8. 銀河系内サーベイ
- 2.1.9. スターバースト銀河
- 2.1.10. 銀河団

2.2. ブラックホール、宇宙ジェット、宇宙論

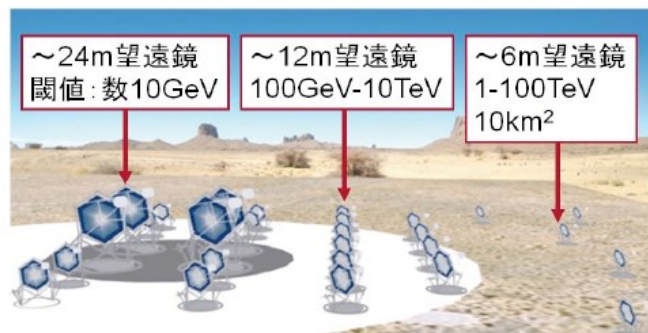
- 2.2.1. ガンマ線バースト
- 2.2.2. 活動銀河核
- 2.2.3. 宇宙背景光と宇宙論
- 2.2.4. 銀河系外サーベイ

2.3. 基礎物理

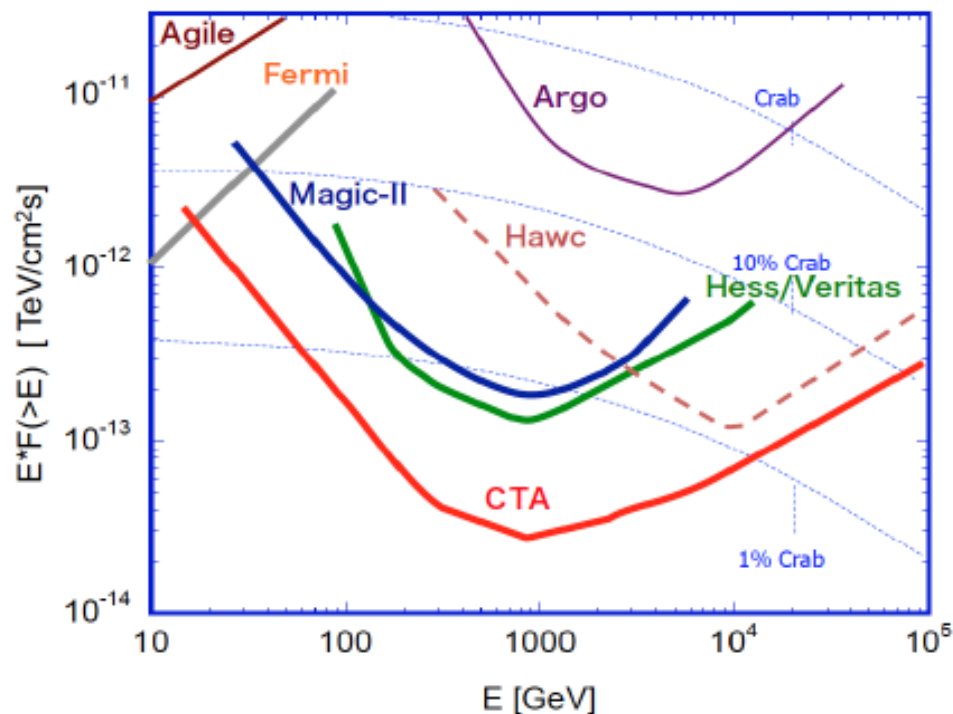
- 2.3.1. ダークマター探査
- 2.3.2. 相対論の検証

■ ガンマ線：最前線

- 確立した チェレンコフ望遠鏡
- 大面積望遠鏡 → 低エネルギー閾値
- 小型を多数配置 → 高感度化



Cherenkov Telescope Array 計画書



Cherenkov Telescope Array 計画書

ニュートリノ

- 宇宙から飛来するニュートリノ
- 宇宙線起源のニュートリノ



Kungliga Svenska Vetenskapsakademien har den 8 oktober 2002 beslutat att med det

NOBELPRIS

som detta är tillerkännes den som inom fysikens område gjort den viktigaste upptäckten eller uppfinnningen med ena hälften gemensamt belöna

Masatoshi Koshiba
och Raymond Davis Jr.
för brytande insatser inom astrofysiken, särskilt för detektion av kosmiska neutriner

STOCKHOLM DEN 10 DECEMBER 2002



Kungliga Svenska Vetenskapsakademien har den 6 oktober 2015 beslutat att med det

NOBELPRIS

som detta är tillerkännes den som inom fysikens område gjort den viktigaste upptäckten eller uppfinnningen gemensamt belöna

Takaaki Kajita
och Arthur B. McDonald
för upptäckten av neutrinooscillationer, som visar att neutriner har massa

STOCKHOLM DEN 10 DECEMBER 2015

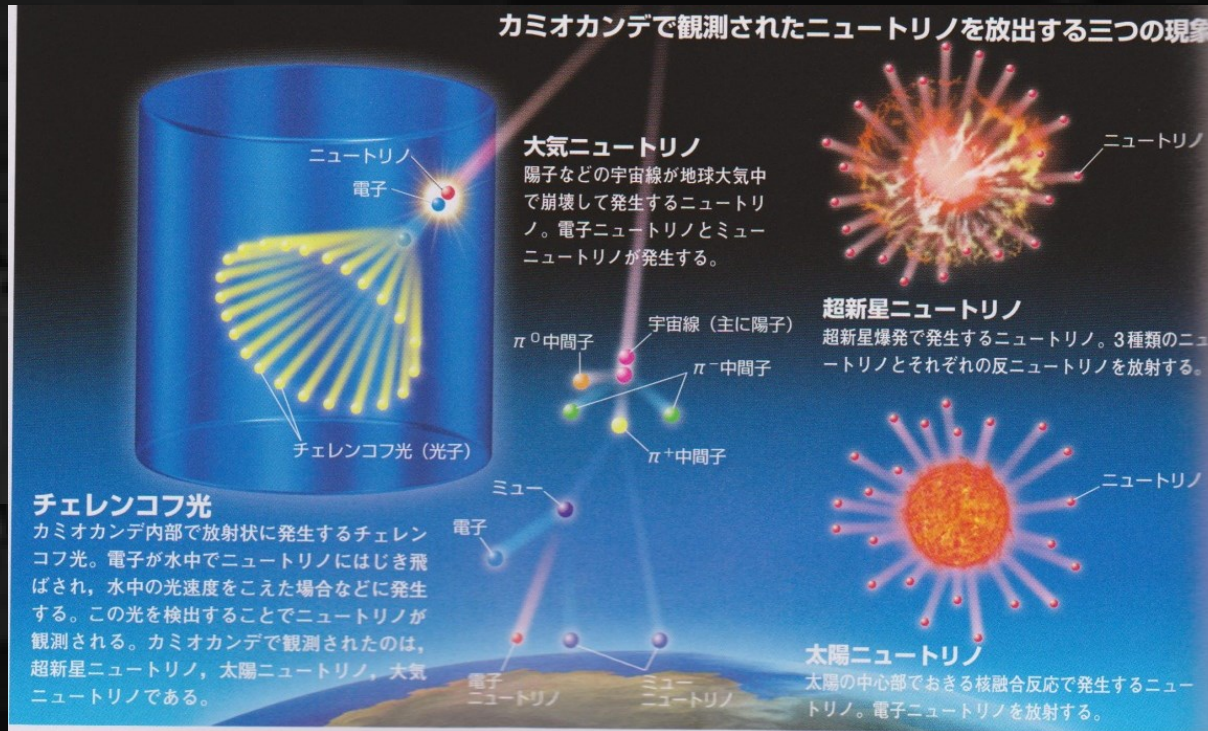
■ ニュートリノ：源

- 太陽ニュートリノ
- 超新星ニュートリノ
- 大気ニュートリノ
- 高エネルギーニュートリノ

エネルギー
低 (MeV)

∩

高 10^{15}eV



+ UNKNOWN

Direction Sensitive
WIMP-search
NEWAGE

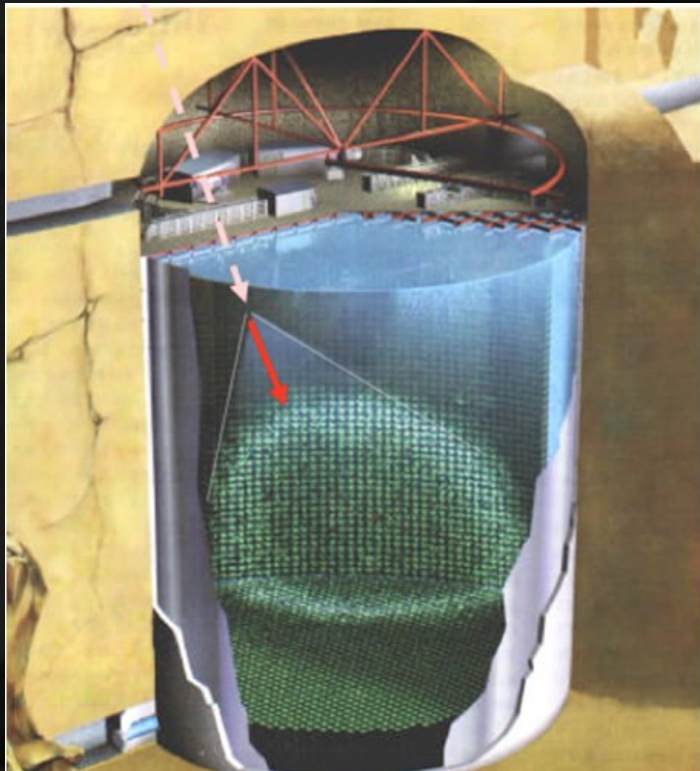
■ ニュートリノ：装置

- チェレンコフ検出器

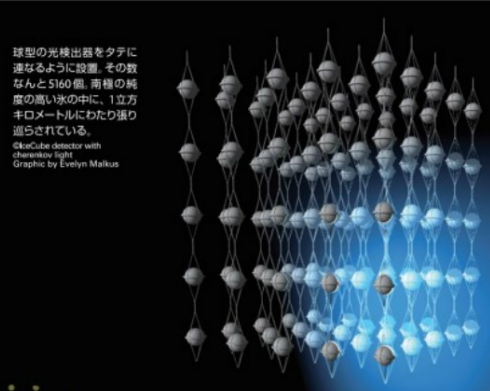
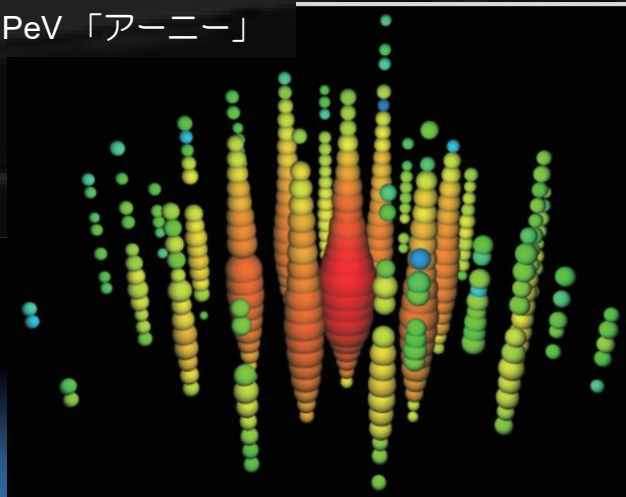
- 水/氷 + 光センサー

- SuperKAMIOKANDE 水5万トン + PMT~10000個

- ICECUBE 1km 角 氷+PMT~5000個



1PeV 「アーニー」



球型の光検出器をタテに
連なるように設置。その数
なんと5160個。南極の純
度の高い氷の中に、1立方
キロメートルにわたり張り
巡らされている。
IceCube detector with
Cherenkov light
Graphic by Evelyn Mathus



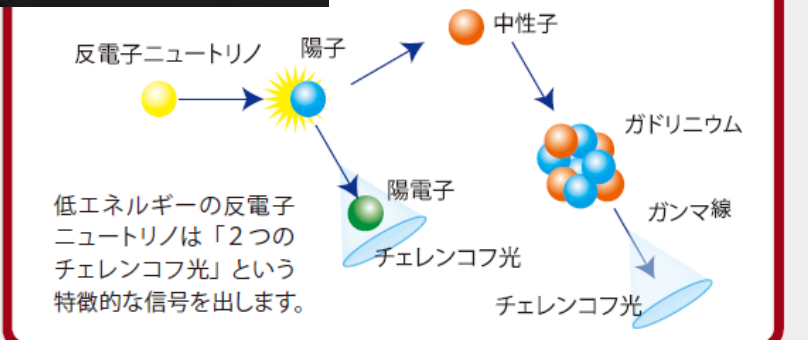
氷の中で宇宙を見つめる

Direction Sensitive
WIMP-search
NEW AGE

■ ニュートリノ装置最先端

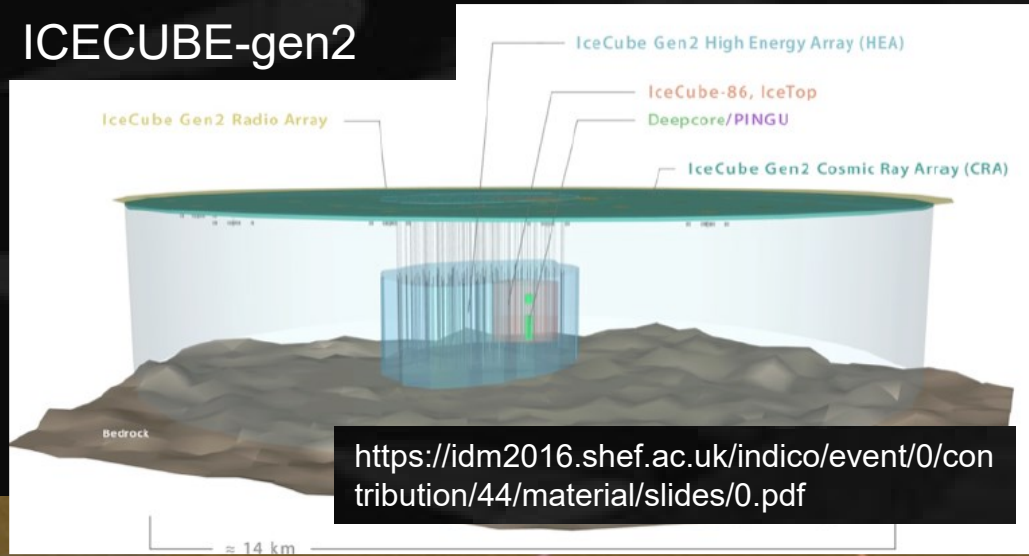
- ハイパーカミオカンデ = SK×10 (有効体積)
- ICECUBE gen2 = ICECUBE×10
- SK-Gd 背景超新星の観測

SK-Gdの原理

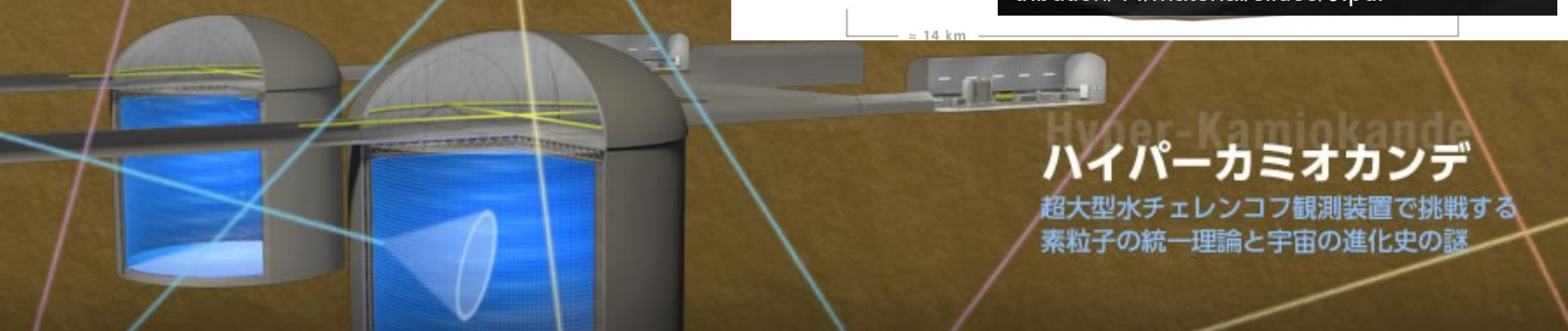


<http://www.icrr.u-tokyo.ac.jp/commemorative/nobel/images/5-future.pdf>

ICECUBE-gen2



<https://idm2016.shef.ac.uk/indico/event/0/contribution/44/material/slides/0.pdf>

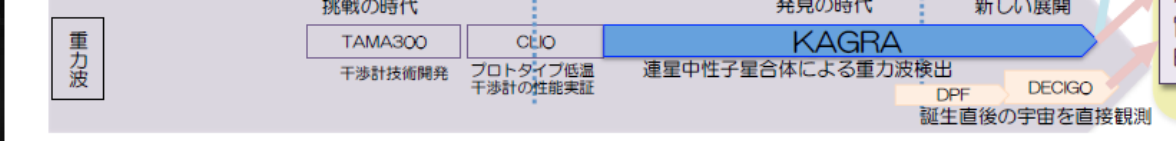


Hyper-Kamiokande
ハイパーカミオカンデ
超大型水チェレンコフ観測装置で挑戦する
素粒子の統一理論と宇宙の進化史の謎

<http://www-sk.icrr.u-tokyo.ac.jp/sk/detector/cherenkov.html>

重力波

- 宇宙から飛来する重力波
- 源：中性子星合体 ブラックホール合体

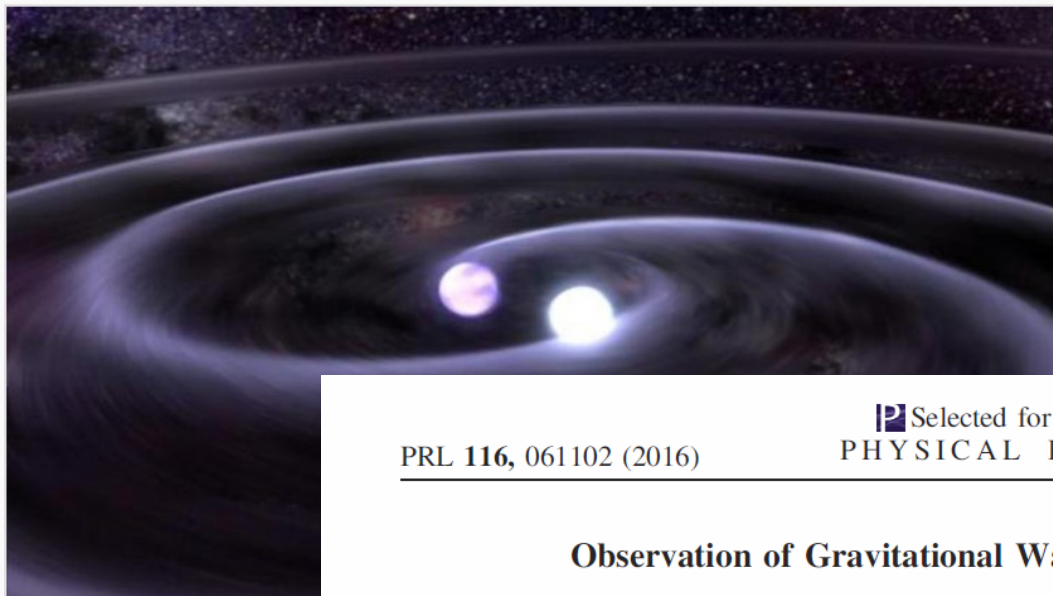


アインシュタインが予言した重力波、米中心のLIGOチームが史上初めて観測に成功

2016年2月12日 by [Emily Calandrelli \(@TheSpaceGal\)](#)

832 List 31 23 157

f シェア ツイート B! はてな g+ 共有 Pocket



広告

Googleが自動運転車用のワイヤレス充電システムを計画中

PRL 116, 061102 (2016)

Selected for a Viewpoint in *Physics*
PHYSICAL REVIEW LETTERS

week ending
12 FEBRUARY 2016



Observation of Gravitational Waves from a Binary Black Hole Merger

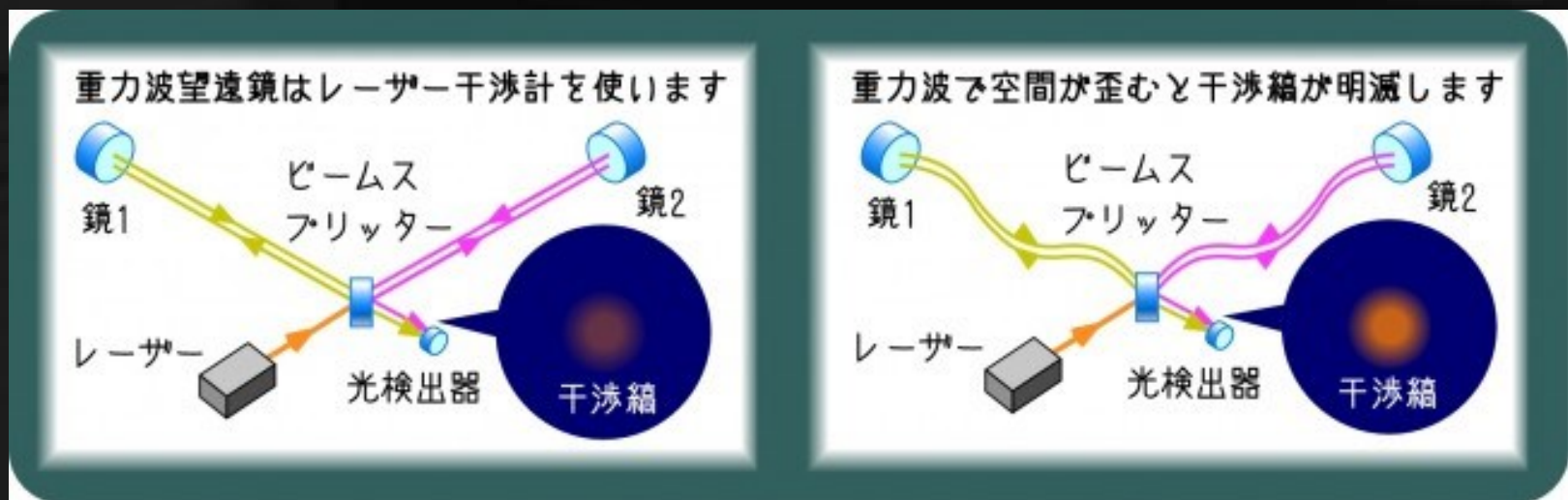
B. P. Abbott *et al.**

(LIGO Scientific Collaboration and Virgo Collaboration)
(Received 21 January 2016; published 11 February 2016)

「われわれは重力波を観測
ライツィー教授

■ 重力波：装置

- 空間の「ゆがみ」を干渉で観測
- 10^{-20} 以下のゆがみを検出



Direction Sensitive
WTAO 2000-01

■ 重力波：最前線

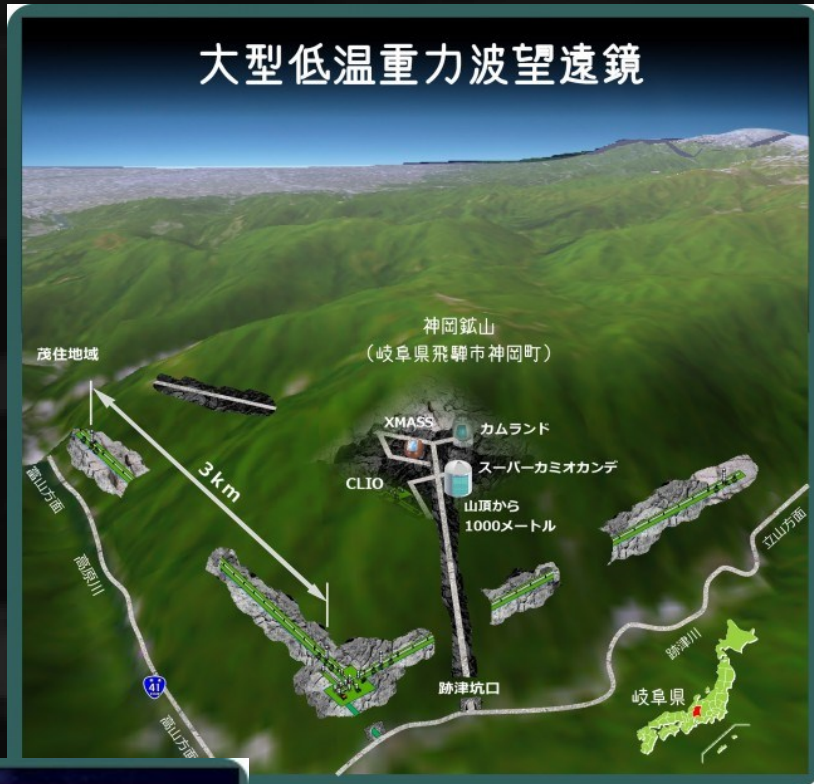
■ LIGO・VIRGO と KAGRA

- 複数台の干渉計が必要
(クロスチェック・方向決定)



■ 重力波最前線：KAGRA

- 神岡 低温 3km
- 防振に有利
遠くまで観測可能
- 多くの事象を検出可能



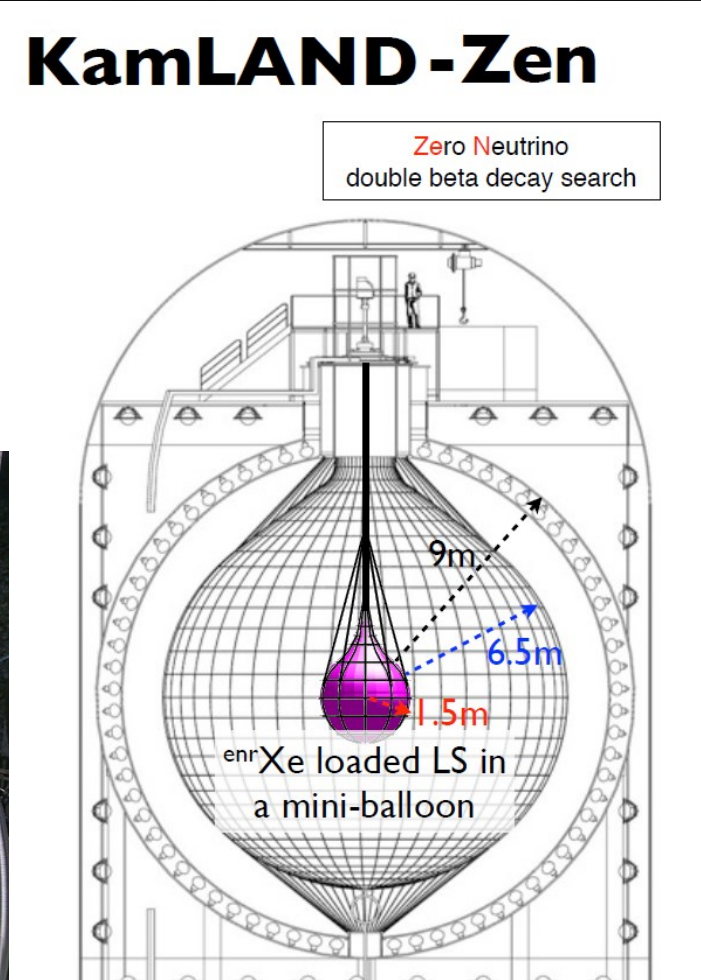
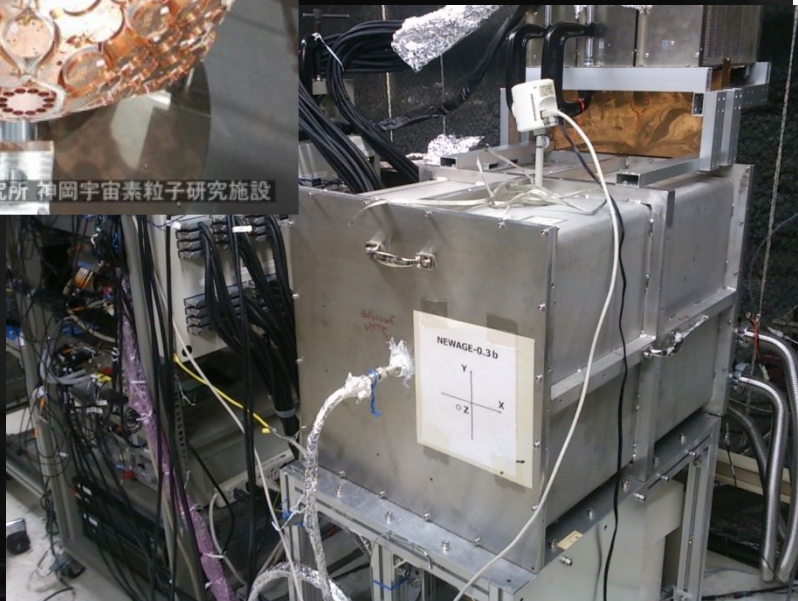
Direction Sensitive
WTAO

地下実験

- ダブルベータ
- ダークマター



(c) 東京大学宇宙線研究所 神岡宇宙素粒子研究施設



■ ダブルベータ：物理

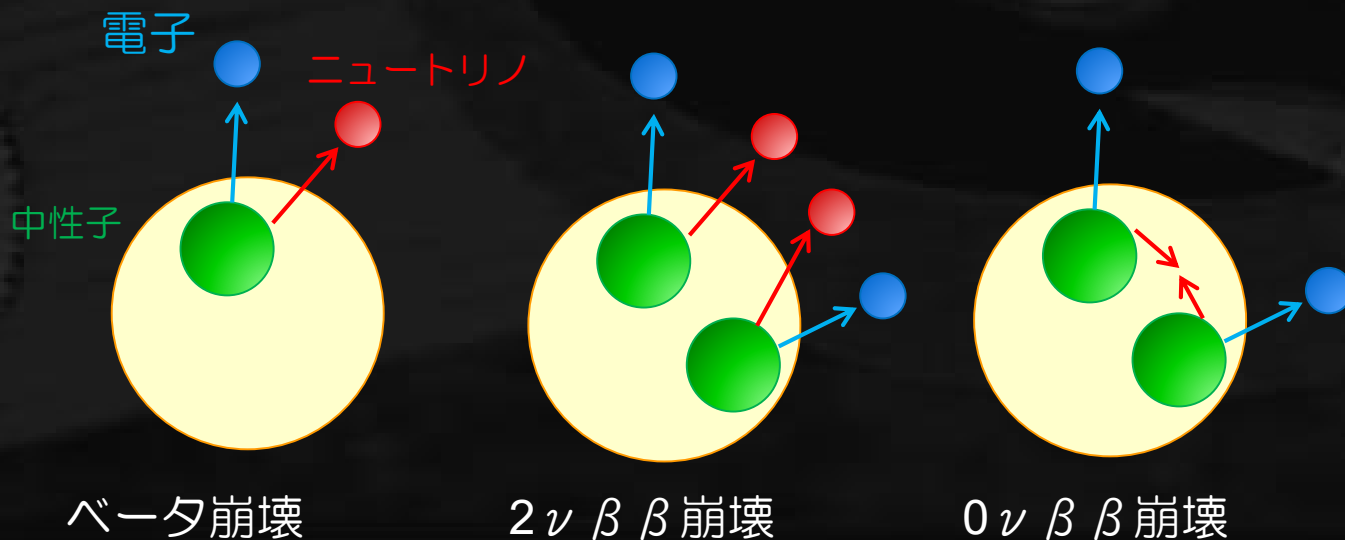
■ β 崩壊 電子とニュートリノを放出。

・ 電子のスペクトルは連続

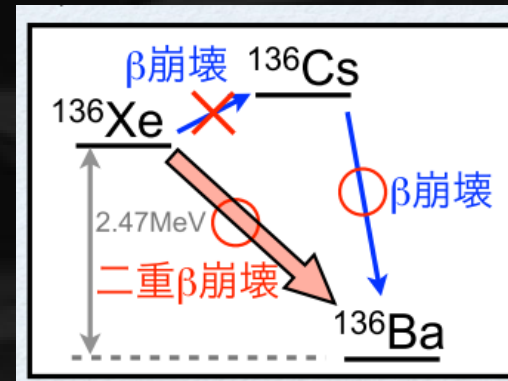
■ 通常の β 崩壊は起こせないが、 $\beta\beta$ 崩壊は可能。
な原子核が存在。観測済み。

・ ニュートリノ2ヶを放出 連続スペクトル

■ もし ν と ν が対消滅可能なら
 $0\nu\beta\beta$ 崩壊が起きる。 探索対象。



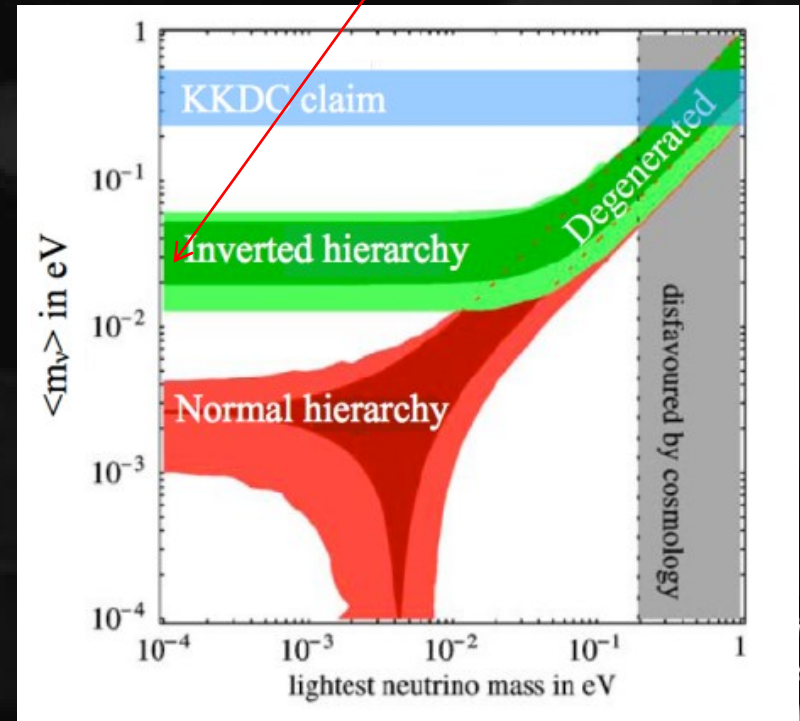
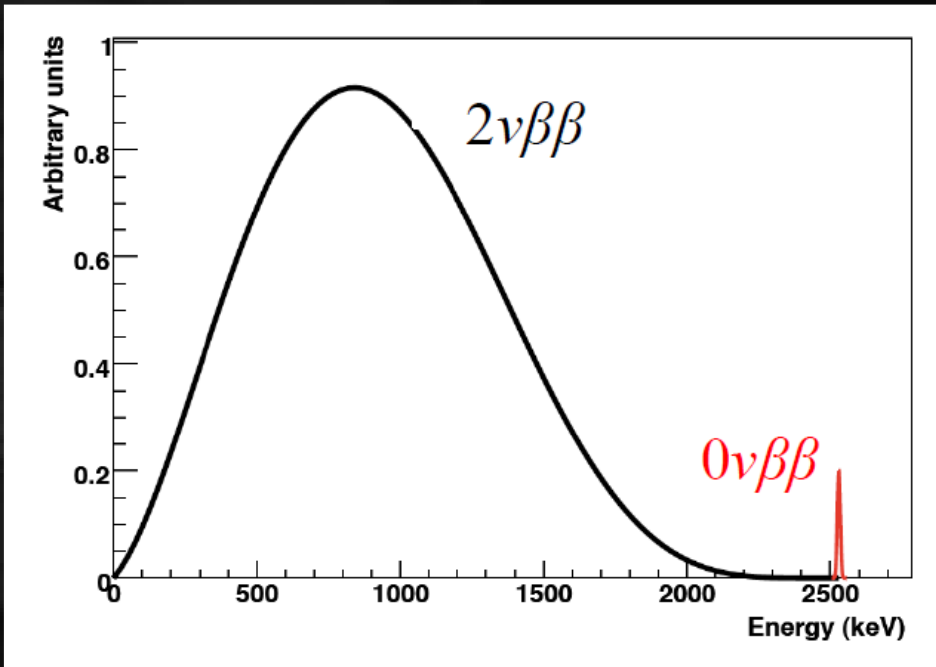
$2\nu\beta\beta$ 崩壊



0νββ崩壊：原理

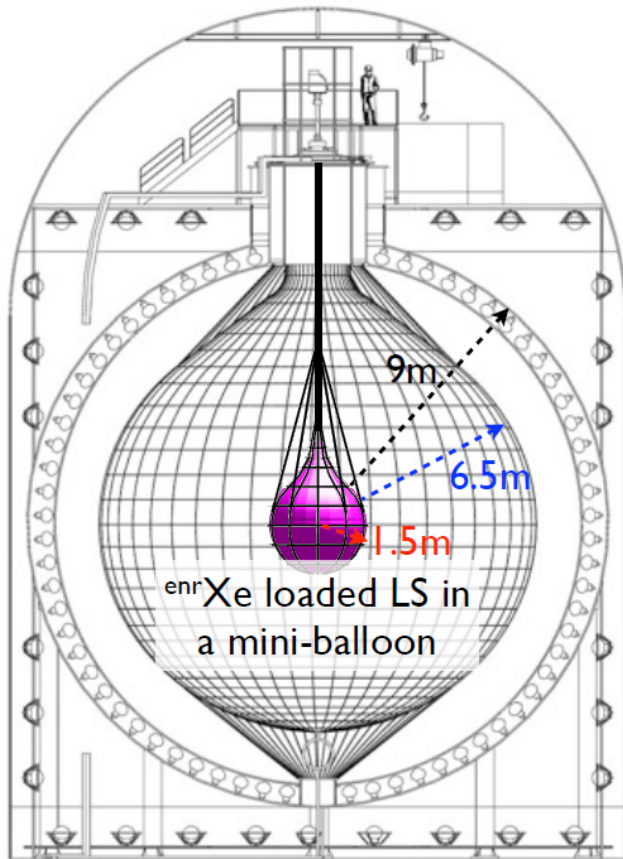
- ニュートリノが対消滅可能：
粒子=反粒子 のマヨラナ粒子
- 寿命と質量に直接的な関係
- エネルギーピークを探す
→低BG、高エネルギー分解能

多くの実験が50meVを
mile stoneとしている。



■ ダブルベータ最前線：KAMLAND-ZEN

Zero Neutrino
double beta decay search

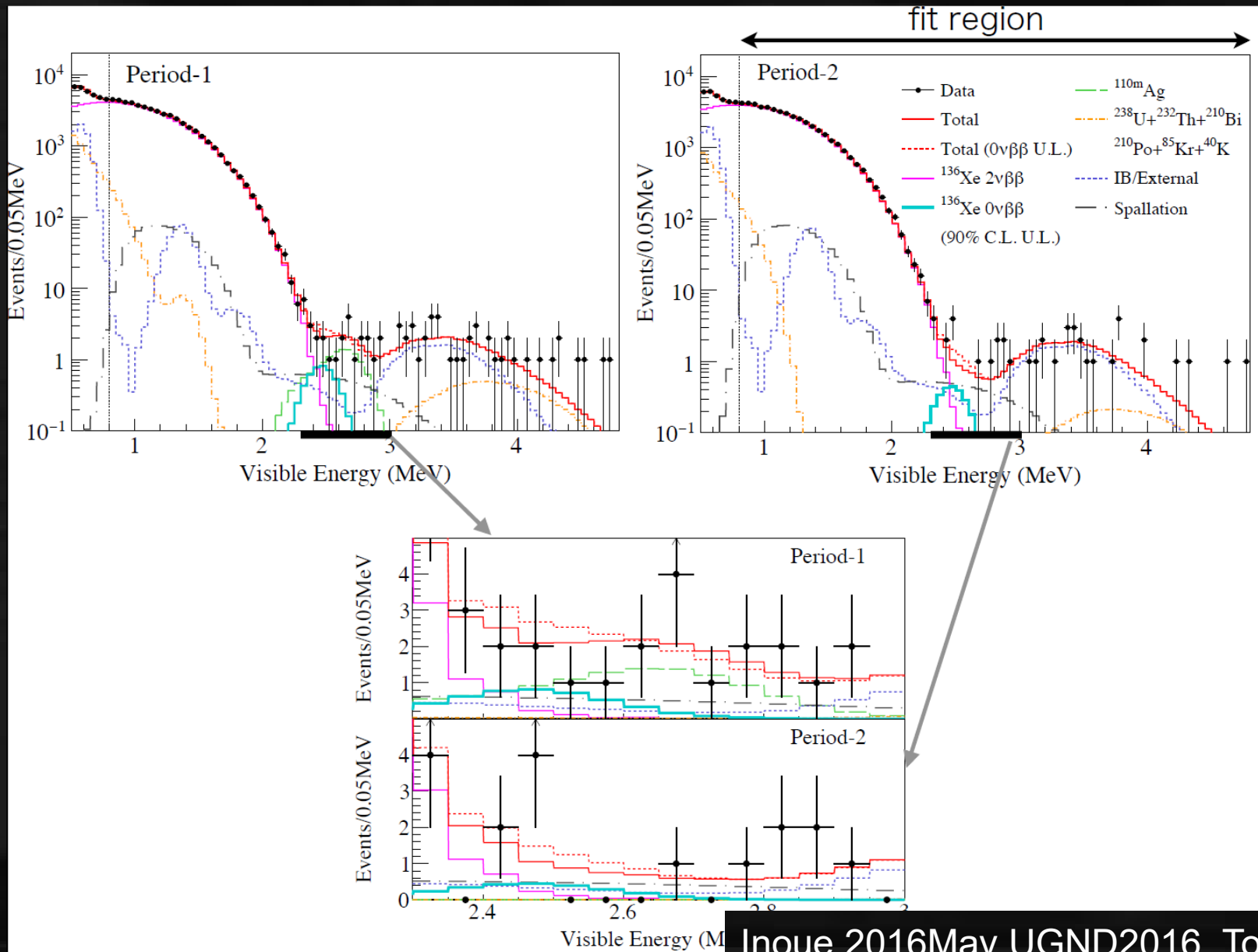


Advantages of using KamLAND

- **running detector**
→ relatively **low cost and quick start**
- **huge and clean** (1200m^3 , U: $3.5 \times 10^{-18}\text{g/g}$, Th: 5.2×10^{-17})
→ negligible external gamma
(Xe and mini-balloon need to be clean)
- **Xe-LS can be purified, mini-balloon replaceable**
if necessary, with relatively low cost
→ **highly scalable** (up to several tons of Xe)
- **No escape or invisible energy from β, γ**
→ BG identification relatively easy
- **anti-neutrino observation continues**
→ geo-neutrino w/o Japanese reactors

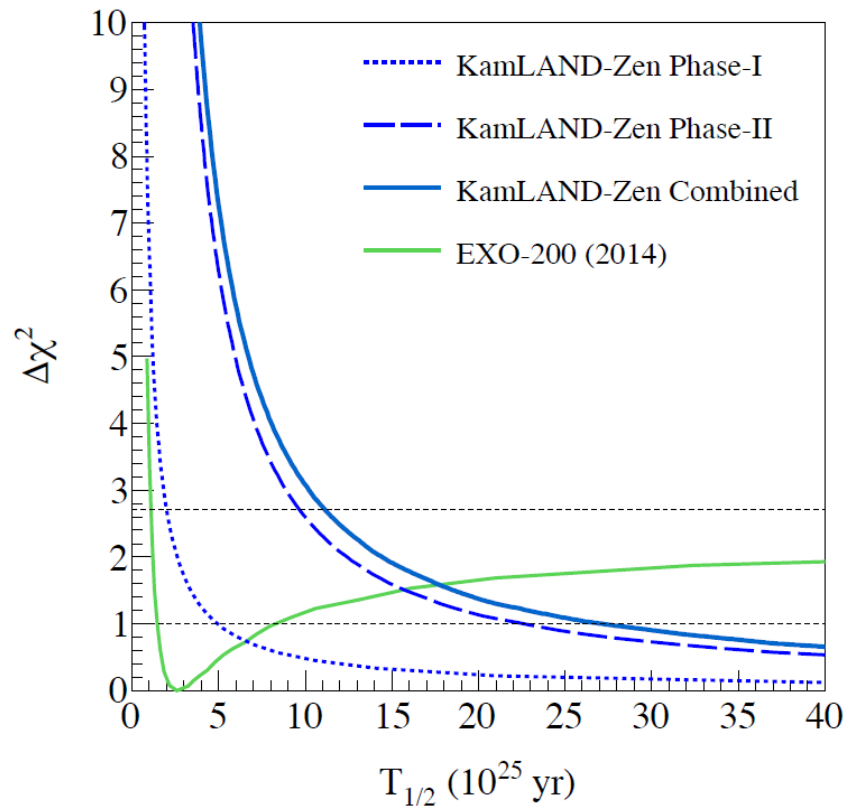
320kg 90% enriched ^{136}Xe installed for phase-1
and 380kg for phase-2

ダブルベータ：最前線



■ ダブルベータ：最前線

Phase-1 & 2 combined limit



$$T_{1/2}^{0\nu} > 1.1 \times 10^{26} \text{ yr}$$

$$\langle m_{\beta\beta} \rangle < (60 - 161) \text{ meV}$$

!!!

ダブルベータ：最前線のその先

Example of improvements

before



after



clean underwear



changing room in a clean room



laundry twice a day



cover sheets

keep staying away
goggle
welding machine
cover sheet .
glove on glove
laundry twice a day .
clean underwear .
changing room in a clean room .
dust visualization
more neutralizer

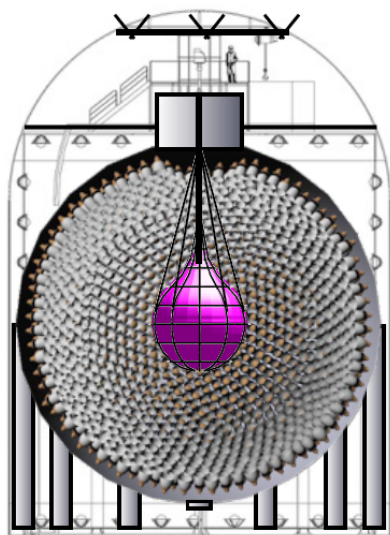
ensitive
-search

■ ダブルベータ：最前線のその先

And more future plans!

Higher energy resolution for reducing 2ν BG

→ KamLAND2-Zen



1000+ kg xenon



Winston cone light collection $\times 1.8$

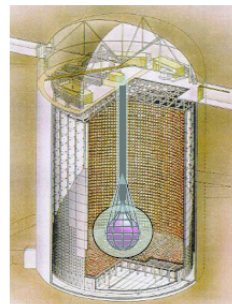
high q.e. PMT
17" $\phi \rightarrow 20"$ $\epsilon = 22 \rightarrow 30+\%$ light collection $\times 1.9$

New LAB LS
(better transparency) light collection $\times 1.4$

expected $\sigma(2.6\text{MeV}) = 4\% \rightarrow \sim 2\%$

target sensitivity 20 meV

And more?



Super-KamLAND-Zen
in connection with Hyper-Kamiokande

target sensitivity 8 meV

25

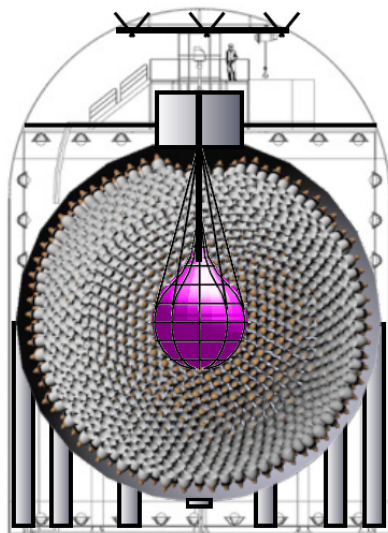
Sensitive
IP-search

■ ダブルベータ：最前線

And more future plans!

Higher energy resolution for reducing 2ν BG

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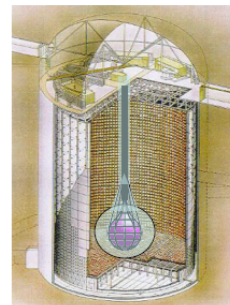
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And more?



Super-KamLAND-Zen
in connection with Hyper-Kamiokande

target sensitivity 8 meV

■ ダブルベータ：最前線

■ CANDLES

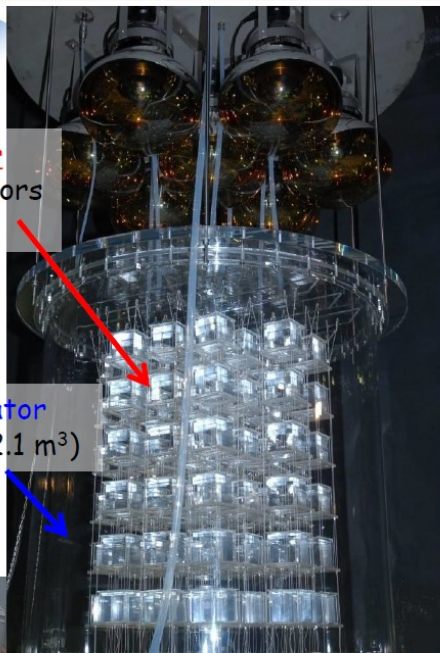


CANDLES III Detector

Main detector
CaF₂ scintillators
(305kg)

Liquid scintillator
acrylic tank (2.1 m³)

PMTs
13 inch (side) : x 48
20 inch (top & bottom) : x 14
Light pipe
Photoelectron yield x ~1.75



◆ CaF₂ Module

- ◆ CaF₂(Pure) ; 96 Crystal → 305 kg
- ◆ WLS Phase ; 280 nm → 420 nm
 - ◆ Thickness ; 5 mm
 - ◆ Composition ; Mineral Oil+bis-MSB (0.1 g/L)

◆ Liquid Scintillator (LS)

4π Active shield

- ◆ 1.37 m φ x 1.4 m height
- ◆ Volume ; 2.1 m³ (1.65 ton)
- ◆ Composition
 - ◆ Solvent ; Mineral Oil(80%)+PC(20%)
 - ◆ Solutes (WLS's) ; PPO (1.0g/L) + bis-MSB (0.1g/L)

◆ Acrylic Tank

- ◆ Container for LS

◆ Water Buffer

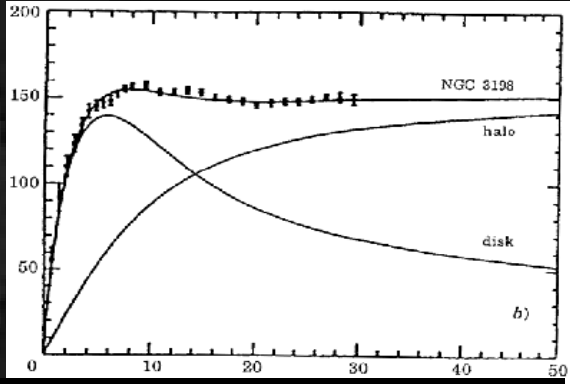
- ◆ Pure Water → Passive Shield
(Pre,Final-filter, Chacoal-filter, UV-lamp, Ion-Exchanger)
- ◆ Distance PMT - LS ; 50 cm

◆ PMTs + Light pipe

- ◆ 13 inch (Side) ; x 48
- ◆ 20 inch (Top and Bottom) ; x 14

ダークマター

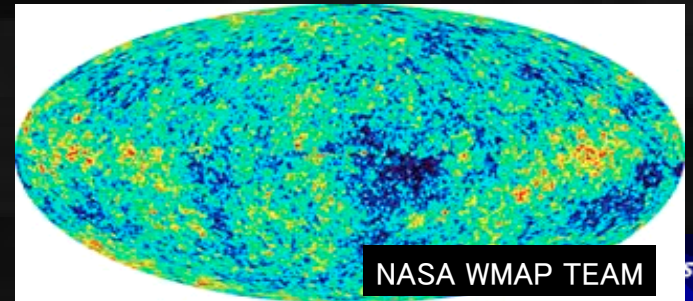
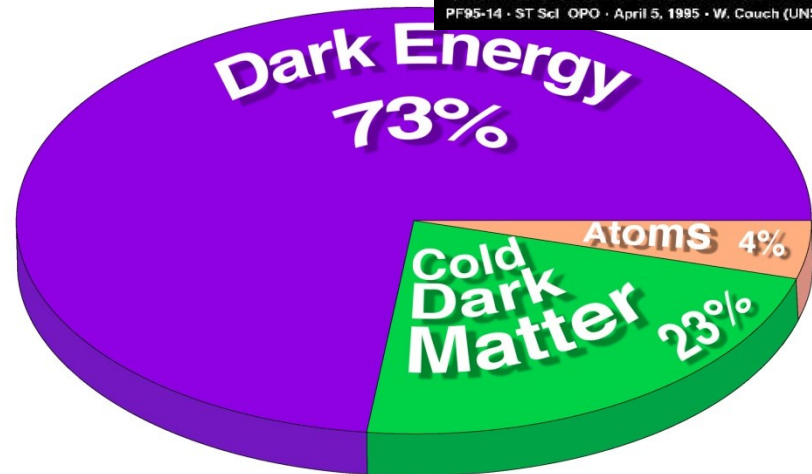
暗黒物質：歴史



Annu. Rev. Astron. Astrophys. 29(1991)409

- 銀河の回転曲線 (1930s~)

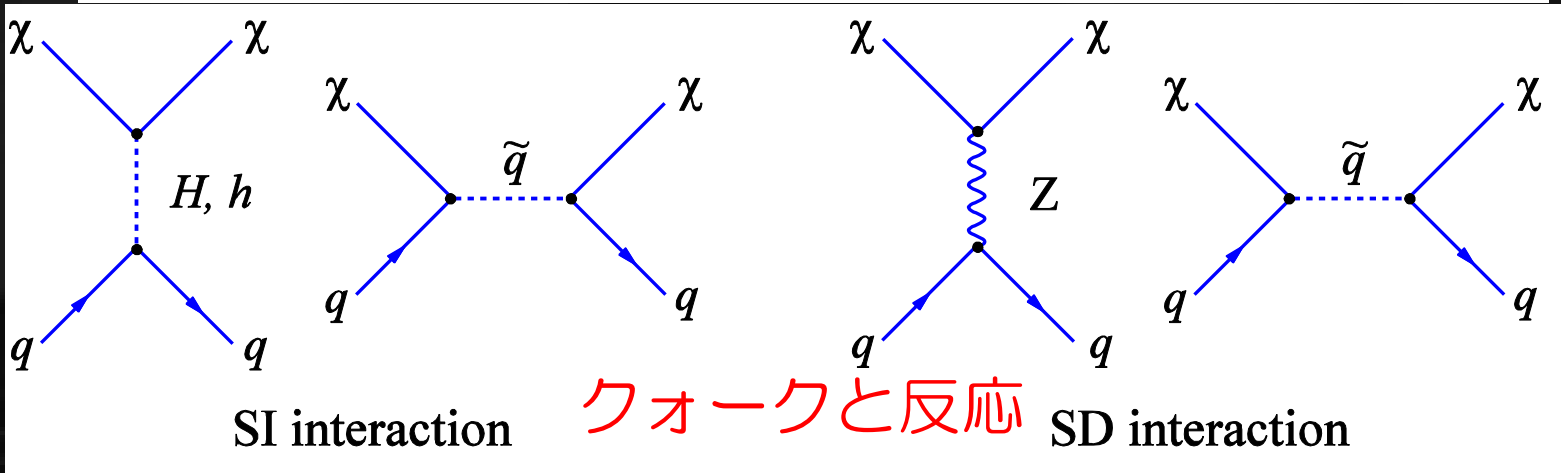
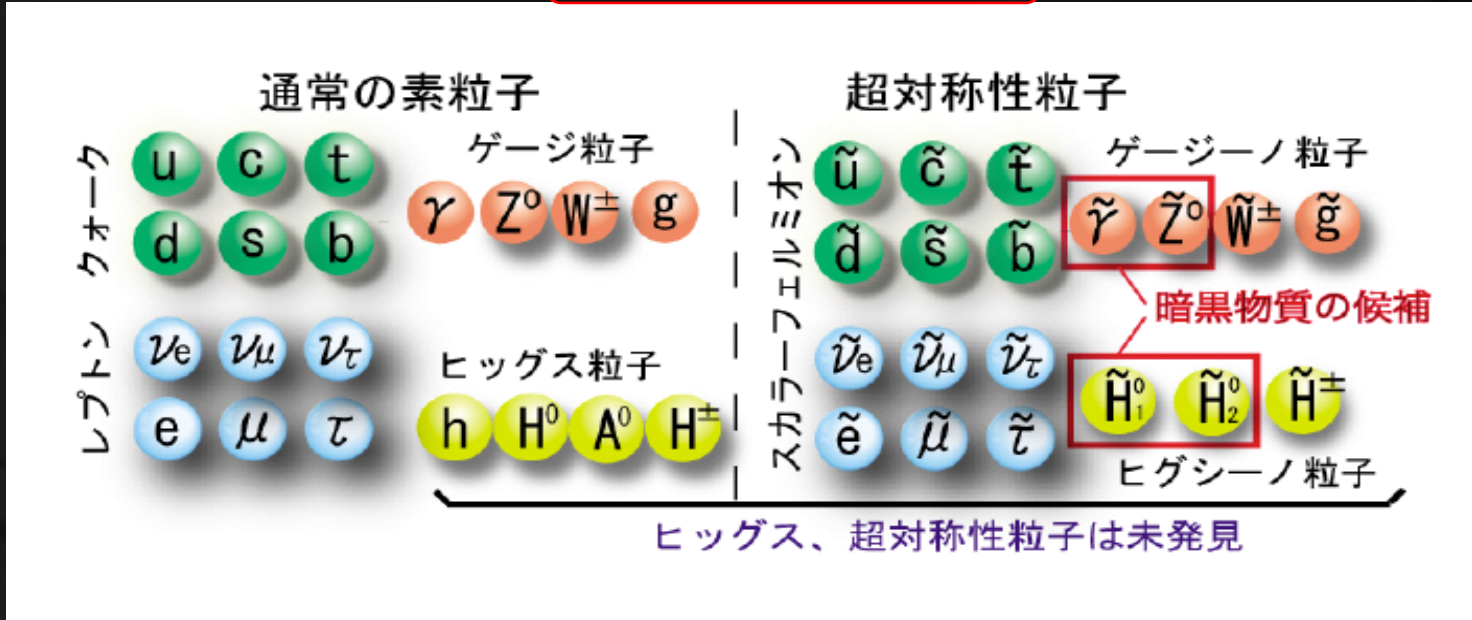
- 遠方銀河の重力レンズ効果 (1990s~)



- 宇宙マイクロ波背景放射 (2002~)

暗黒物質の候補

- バリオン：MACHOs : 元素合成によって上限
- 非バリオン：アクシオン、**ニュートラリーノ**、その他有象無象



暗黒物質の直接検出

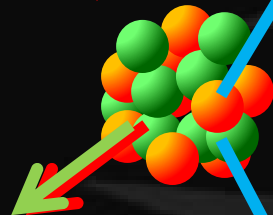
E_R 検出 (光)

DAMA (NaI)
KIMS (CsI)

(光+電離)

ZEPOLINE II/III
XENON10/100 (Xe)
ArDM • WARP (Ar)

原子核



反跳

$E_R < \sim 100 \text{keV}$

暗黒物質



E_R 検出 (電離)

HPGe

(光+温度)

CRESST
(CaWO₄)

E_R 検出 (温度)

ROSEBUD (LiF)
COUPP, SIMPLE, PICASSO
(CxFx)

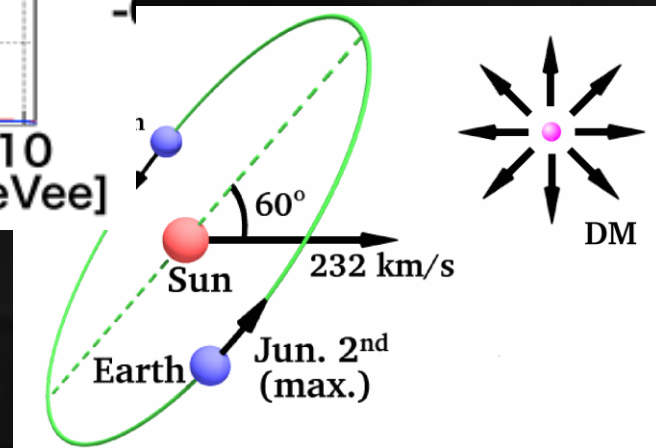
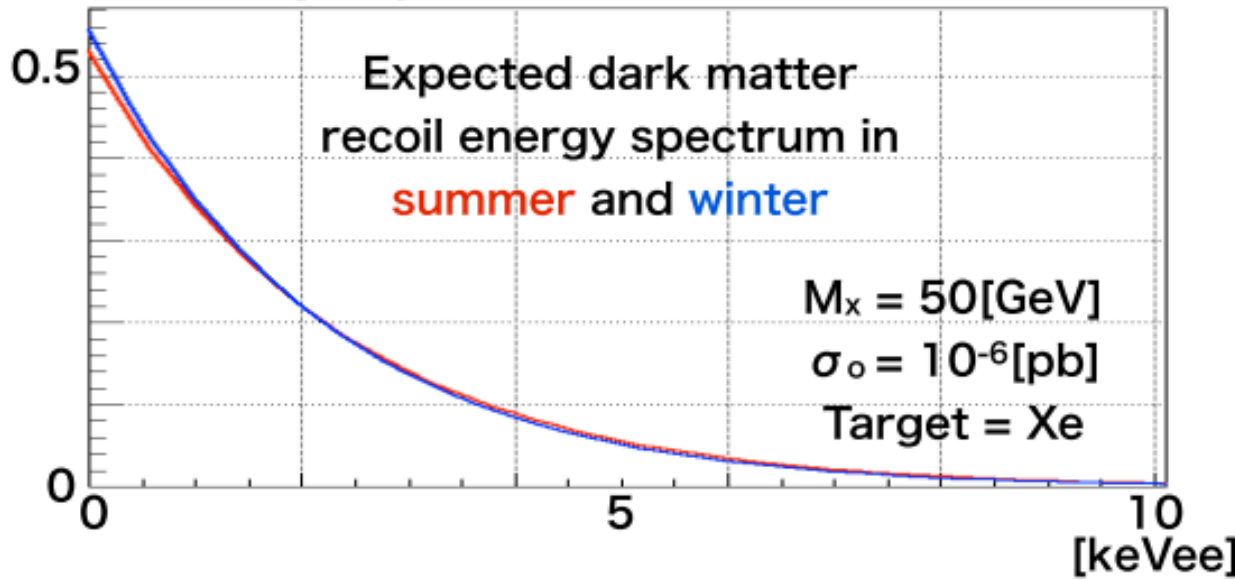
(電離+温度)

CDMS (Ge)
EDELWEISS (Ge)

暗黒物質直接検出の信号

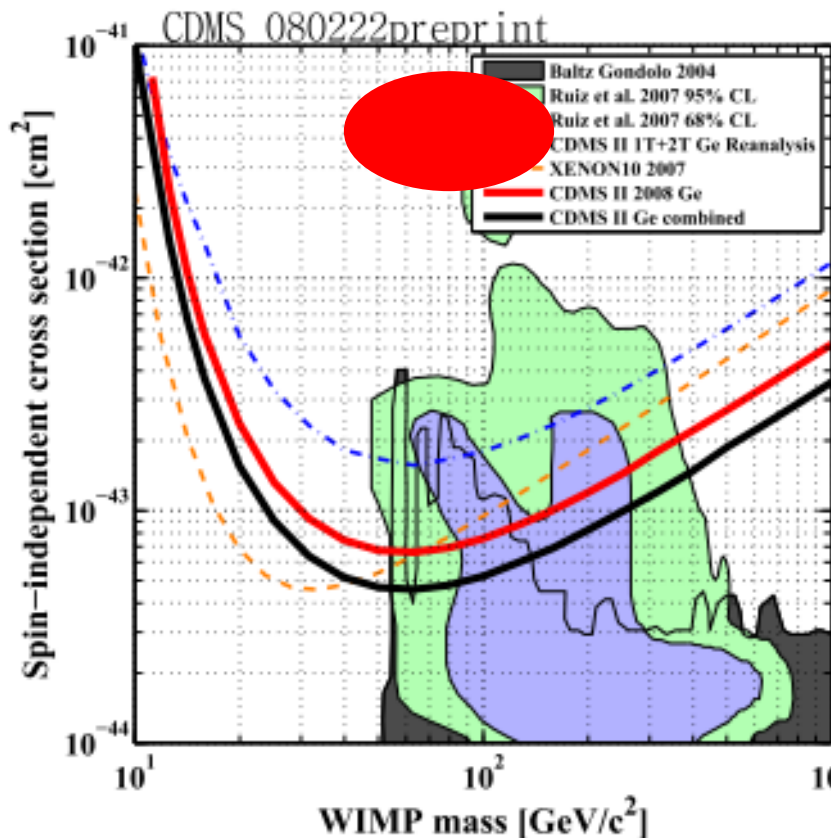
- エネルギースペクトル keV程度
- 特徴のない形状
- 季節変動

[event/keV/kg/day]



■ ダークマター検出器：DAMA/LIBRA

- 唯一の “positive results” を主張
- 1997～DAMAで主張 → CDMS等に否定される
- 2008年4月 LIBRAで再現！



	DAMA (-2002)	LIBRA (2003-2007)
detector	NaI	NaI
Mass	9.7kg×9	9.7kg×25
time	7 yeas	4 years
exposure	0.29 ton year	0.53 ton year

(Large sodium Iodide Bulk for RAre processes)

暗黒物質：DAMA/LIBRA

250kgのNaIシンチレータ

The new DAMA/LIBRA set-up ~250 kg NaI(Tl)
(Large sodium Iodide Bulk for RARE processes)

As a result of a second generation R&D for more radiopure NaI(Tl)
by exploiting new chemical/physical radiopurification techniques
(all operations involving crystals and PMTs - including photos - in HP Nitrogen atmosphere)

installing DAMA/LIBRA detectors

assembling a DAMA/LIBRA detector

detectors during installation; in the
central and right up detectors the new
shaped Cu shield surrounding light
guides (acting also as optical windows)
and PMTs was not yet applied

filling the inner Cu box with
further shield

DAMA/LIBRA started operations on March 2003

BELLI@
TAUP07

closing the Cu box
housing the detectors

view at end of detectors'
installation in the Cu box

Sensitive
P-search
AGE

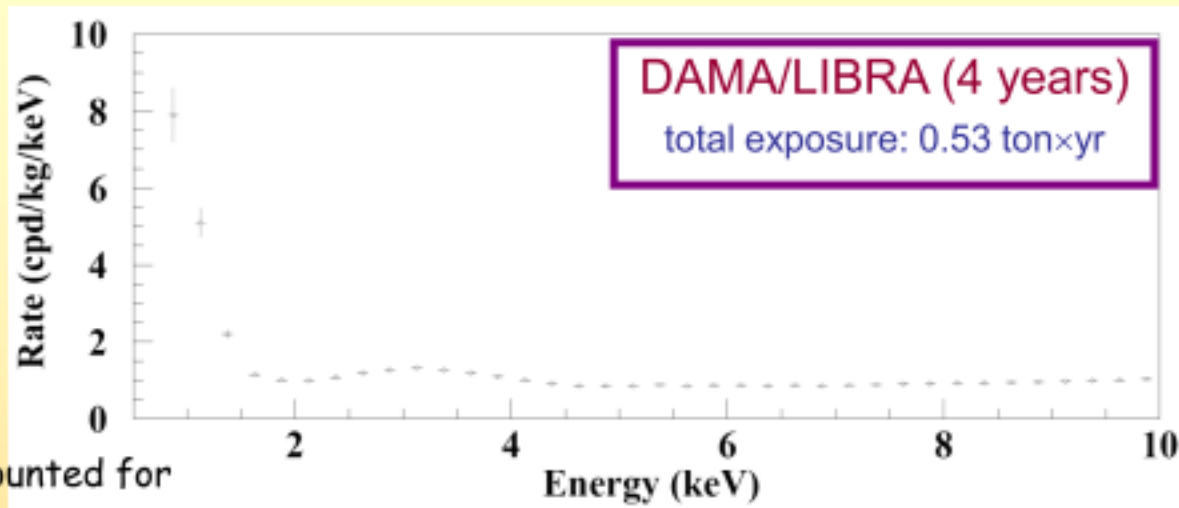
Cumulative low-energy distribution of the *single-hit* scintillation events

スペクトル

Single-hit events = each detector has all the others as anticoincidence

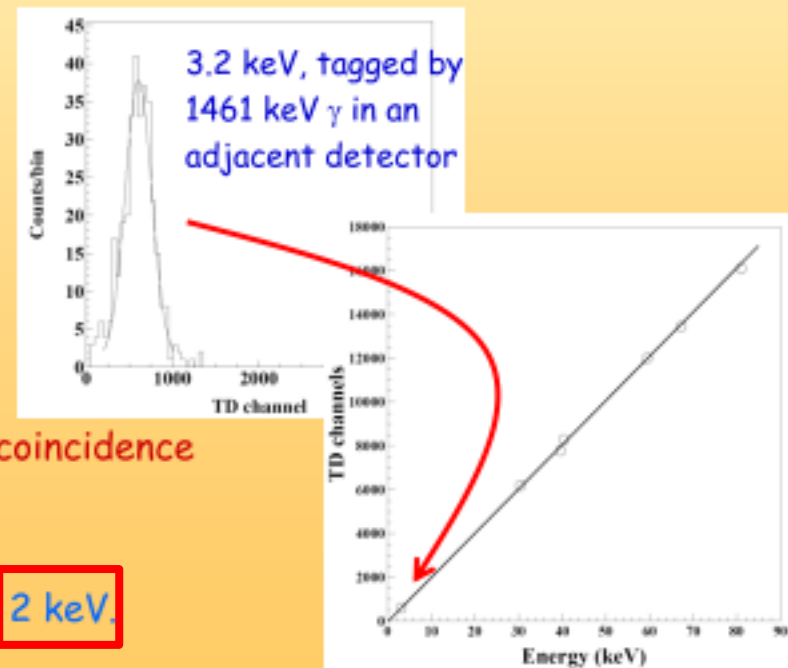
(Obviously differences among detectors are present depending e.g. on each specific level and location of residual contaminants, on the detector's location in the 5x5 matrix, etc.)

Efficiencies already accounted for



About the energy threshold:

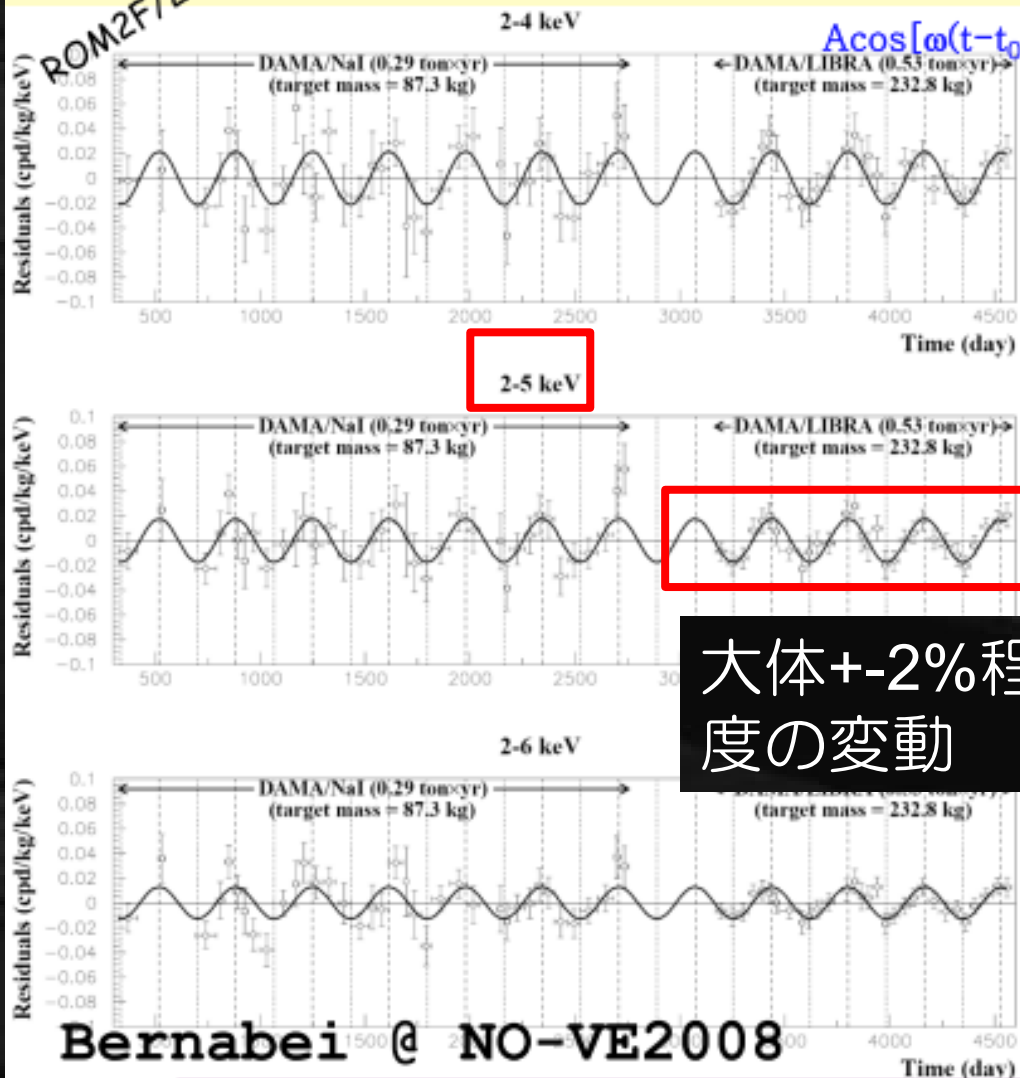
- The DAMA/LIBRA detectors have been calibrated down to the keV region. This assures a clear knowledge of the "physical" energy threshold of the experiment.
- It obviously profits of the relatively high number of available photoelectrons/keV (from 5.5 to 7.5).
- The two PMTs of each detector in DAMA/LIBRA work in coincidence with hardware threshold at single photoelectron level.
- Effective near-threshold-noise full rejection.
- The software energy threshold used by the experiment is **2 keV**.



R. Bernabei @NO-VE2008

Model Independent Annual Modulation Result

DAMA/NaI (7 years) + DAMA/LIBRA (4 years) Total exposure: 300555 kg×day = 0.82 ton×yr
 experimental single-hit residuals rate vs time and energy



2-4 keV

$A = (0.0215 \pm 0.0026)$ cpd/kg/keV

$\chi^2/\text{dof} = 51.9/66$ **8.3 σ C.L.**

Absence of modulation? No

$\chi^2/\text{dof} = 117.7/67 \Rightarrow P(A=0) = 1.3 \times 10^{-4}$

2-5 keV

$A = (0.0176 \pm 0.0020)$

cpd/kg/keV

$\chi^2/\text{dof} = 39.6/66$ **8.8 σ C.L.**

Absence of modulation? No

$\chi^2/\text{dof} = 116.1/67 \Rightarrow P(A=0) = 1.9 \times 10^{-4}$

2-6 keV

$A = (0.0129 \pm 0.0016)$ cpd/kg/keV

$\chi^2/\text{dof} = 54.3/66$ **8.2 σ C.L.**

Absence of modulation? No

$\chi^2/\text{dof} = 116.4/67 \Rightarrow P(A=0) = 1.8 \times 10^{-4}$

The data favor the presence of a modulated behavior with proper features at 8.2 σ C.L.

NEWAGE

ダークマター最前線：二層式液体キセノン

Dark-matter results from 332 new live days of LUX data

Detection technique

- LUX is a dual-phase time projection chamber (like most other liquid-noble DM experiments); essentially a cylinder of LXe.
- Primary scintillation light ("S1") is emitted from the interaction vertex, and recorded by an array of PMTs on top and bottom.
- Electrons emitted from the interaction are drifted by an applied field to the surface and into the gas, where they emit proportional scintillation light ("S2"), also recorded by the PMTs.
- This design permits:
 - ▶ 3-D localization of each vertex.
 - ▶ Identification of multiple scatters (via S2 count).
 - ▶ ER/NR discrimination (via S2/S1)
 - ▶ Sensitivity to single ionization electrons.

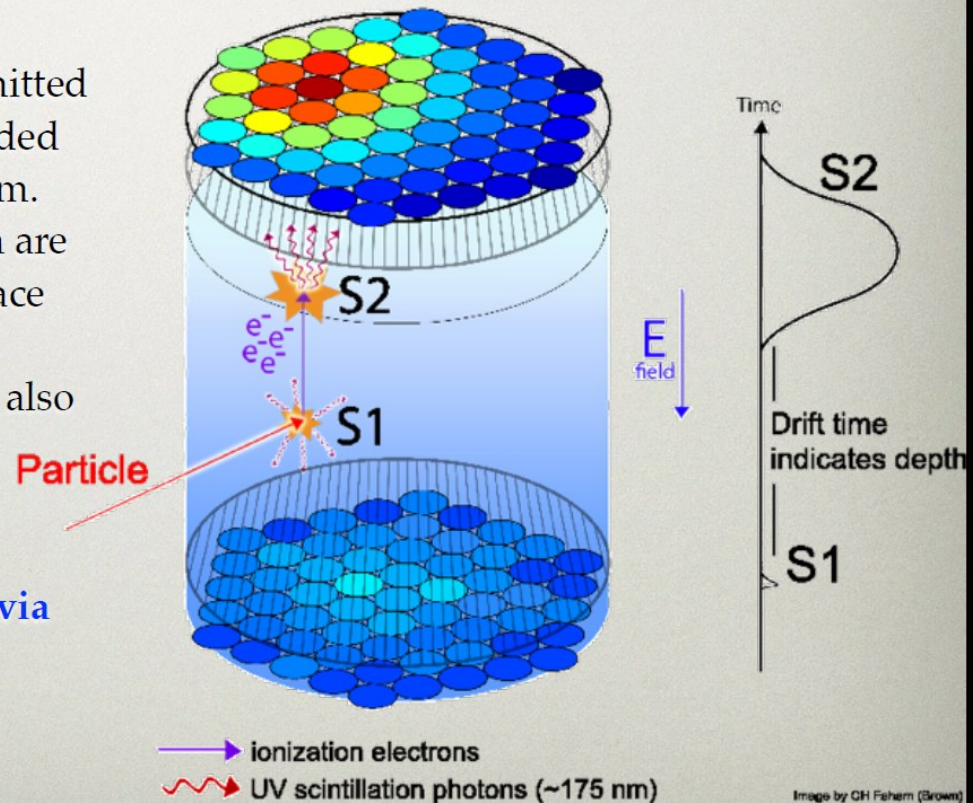
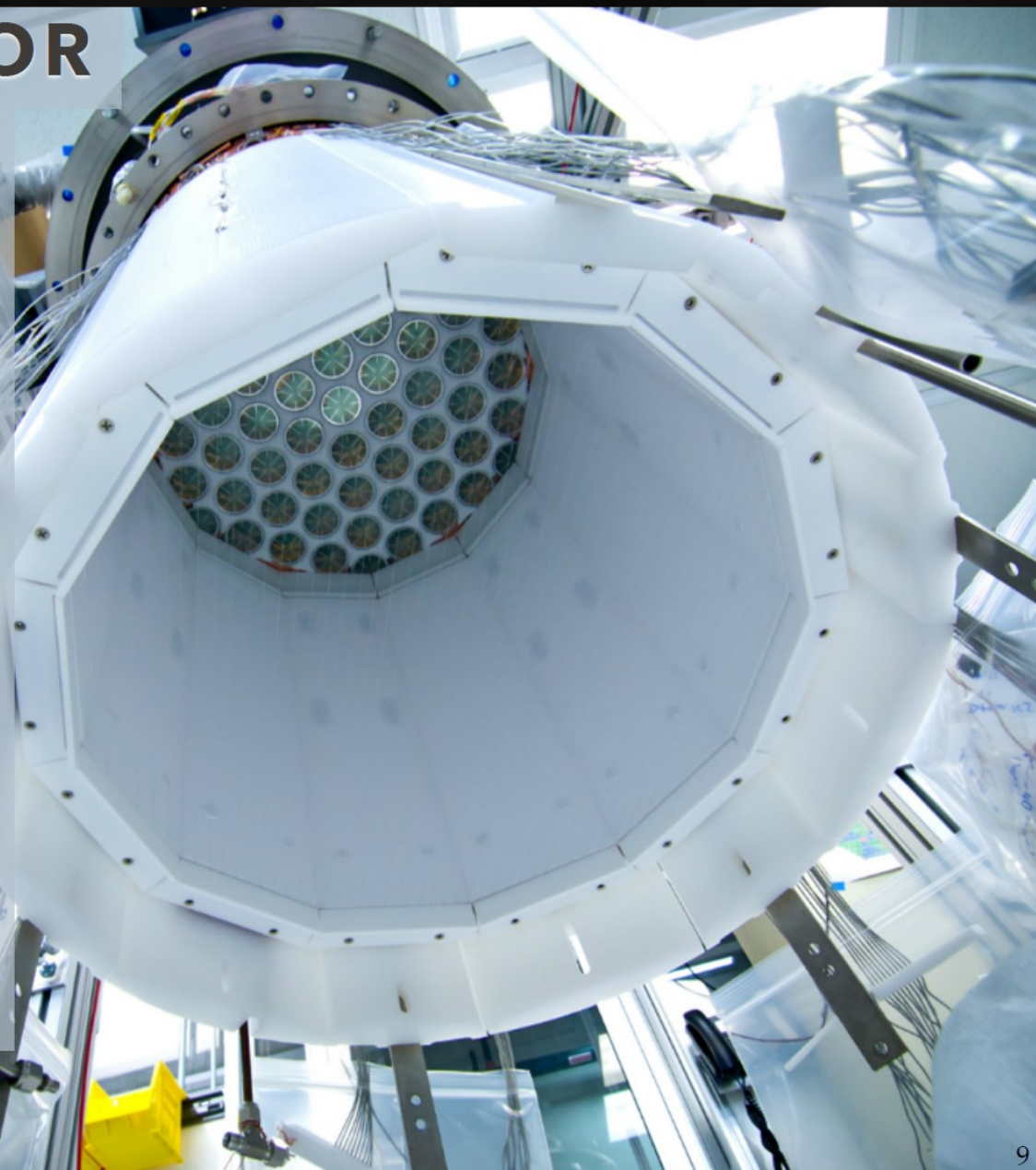


Image by GH Fishem (Brown)

■ ダークマター：検出器 LUX

LUX DETECTOR

- 48cm diameter by 48 cm height dodecagonal “cylinder”.
- 250.9 kg LXe in active region
- 61 PMTs on top, 61 on bottom, specially produced for low radiogenic BGs and VUV sensitivity.
- Xenon was pre-purified via chromatographic separation, reducing residual krypton.
- Liquid is continuously recirculated ($\frac{1}{4}$ tonne per day) to maintain chemical purity.
- Ultra-low BG titanium cryostat.



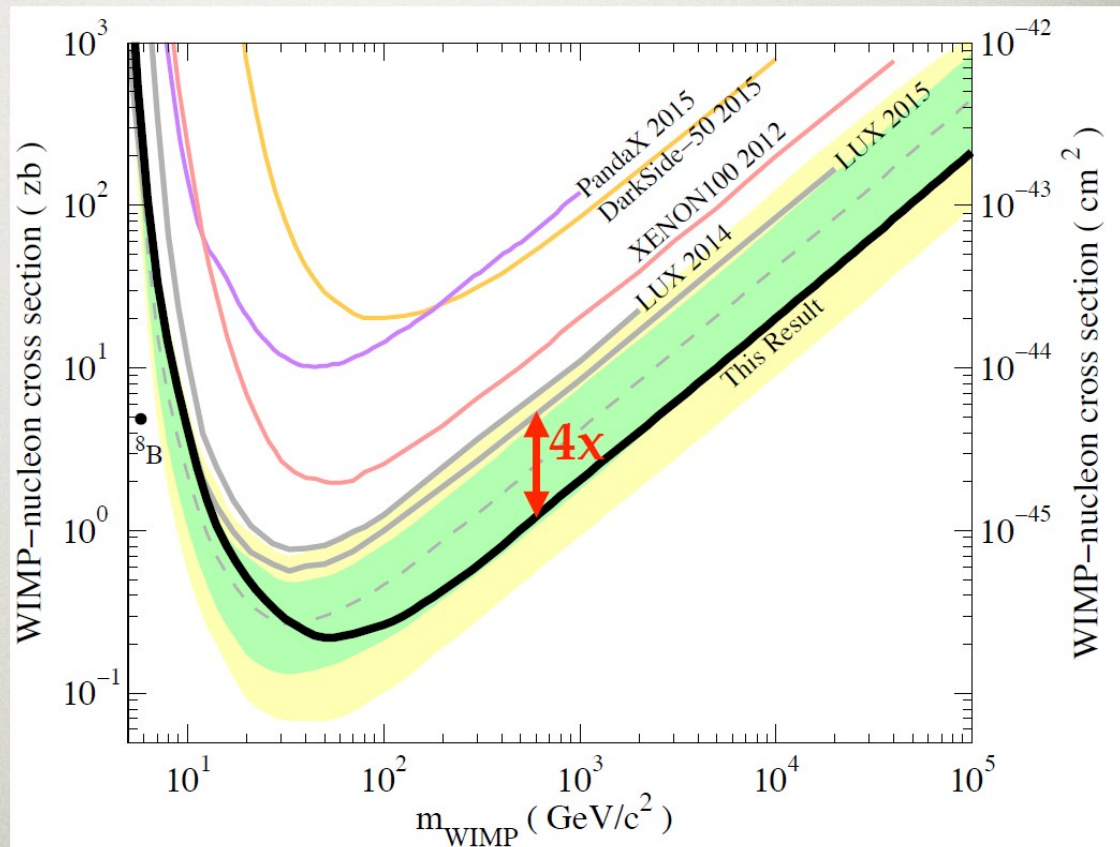
■ ダークマター 超最前線

■ 先週発表。

Dark-matter results from 332 new live days of LUX data

SI WIMP-nucleon exclusion

- Brazil bands show the 1- and 2-sigma range of expected sensitivities, based on random BG-only experiments.
- **Factor of 4 improvement** over the previous LUX result in the high WIMP masses
- Minimum exclusion of $2.2 \times 10^{-46} \text{ cm}^2$ at 50 GeV

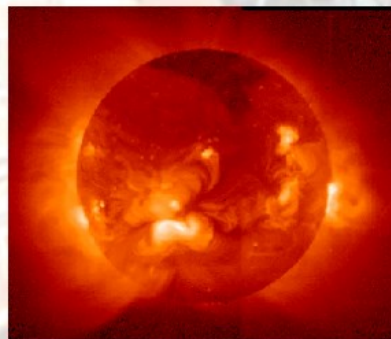


ダークマター：検出器 XMASS

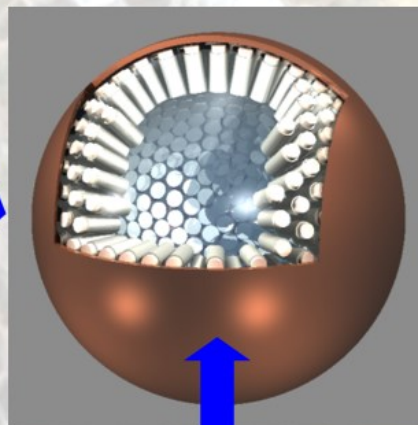
Byeongsu Yang
@PATLAS2016

XMASS project

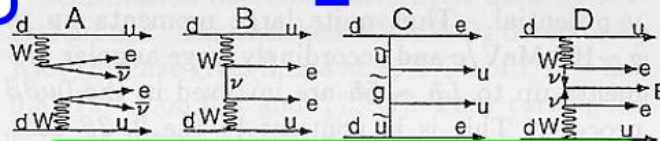
- XMASS experiment is a multi purpose, low-background and low-energy threshold experiment with large volume of liquid Xenon
 - Xenon detector for Weakly Interacting **MASS**ive Particles (**DM search**)
 - Xenon **MASS**ive detector for solar neutrino (**pp/⁷Be**)
 - Xenon neutrino **MASS** detector (**$\beta\beta$ decay**)
- XMASS-I, the first phase of the XMASS project, is dedicated to a direct dark matter search.



Solar neutrino



Dark Matter

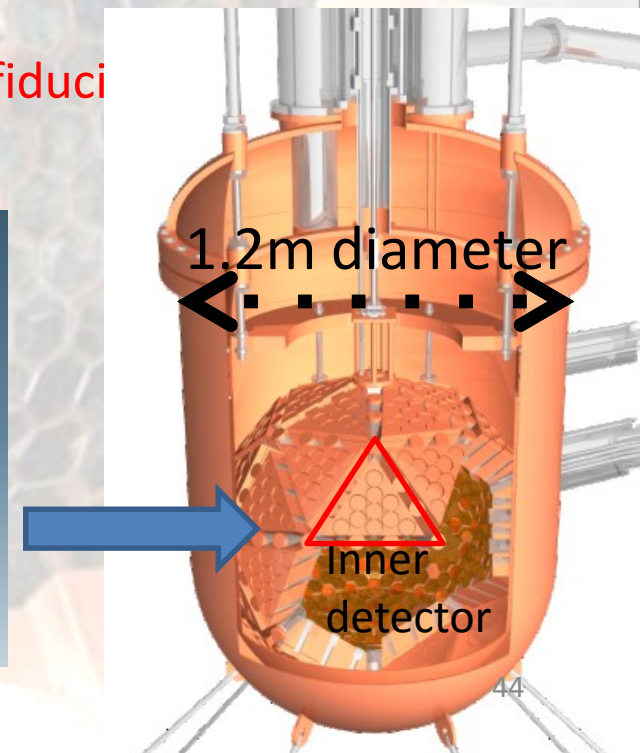
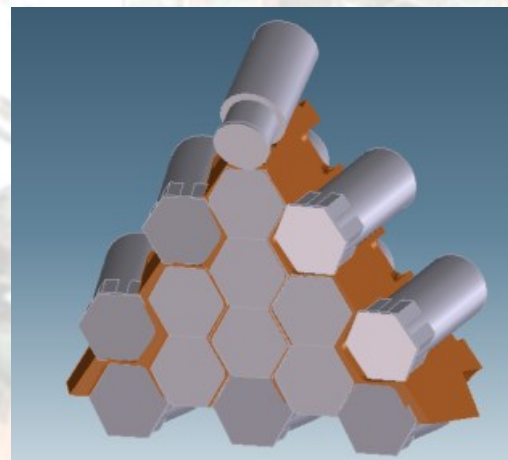


Double beta decay

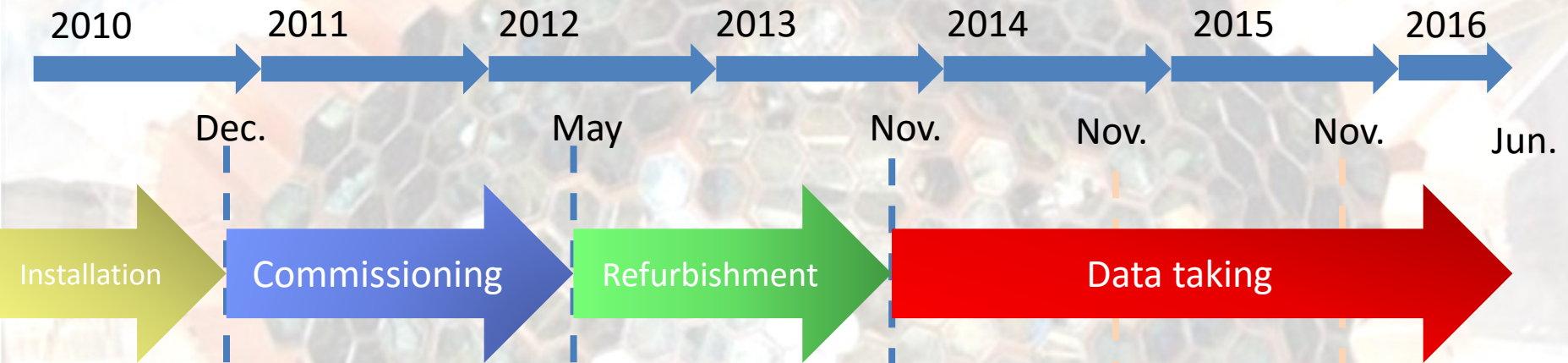
+axion, supernova, etc

XMASS detector

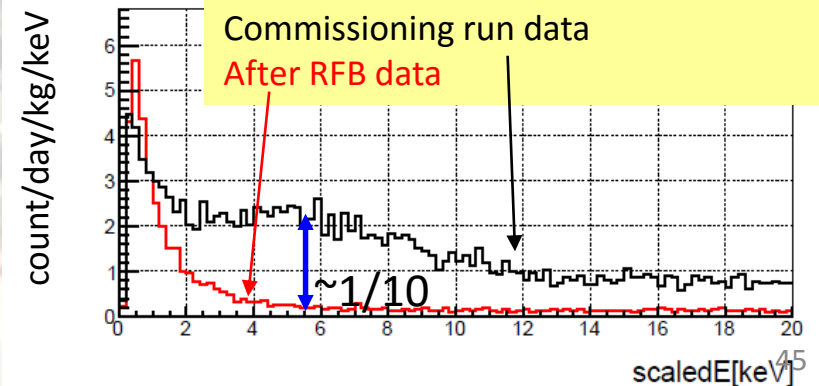
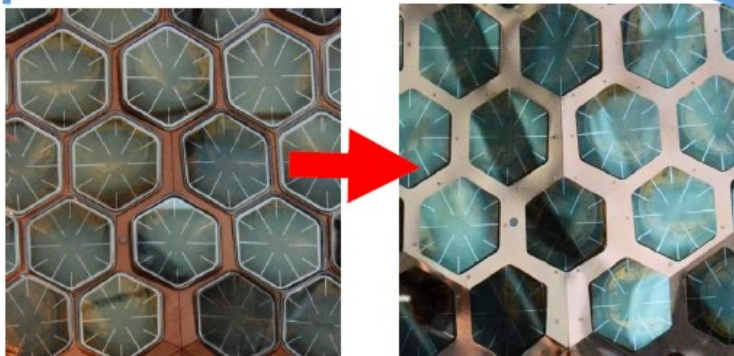
- Single phase (scintillation only) liquid Xenon detector : **sensitive to e/γ events with very low backgrounds as well as nuclear recoil events**
- **Large 100 kg fid. mass & 835 kg inner mass (0.8 m ϕ)**
- 630 hexagonal & 12 round PMTs with 28-39% Q.E.
- High light yields(13.9 pe/keV) & Large photon coverage (> 62% of inner surface)
 - **Low energy threshold : < 5 keV_{ee} (\sim 25 keV_{NR}) for fiduciary volume and 0.3 keV_{ee} for full volume**



History of XMASS-I



PMT Al seal were covered by copper ring and plate to reduce BG as detector refurbishment. After refurbishment, event $\sim 5\text{keV}$ is reduced to $\sim 1/10$. Now, the 3rd year continuity operation (2 years and 7 months) is ongoing. The longest running time among LXe detectors!



XMASS physics results

Byeongsu Yang
@PATLAS2016

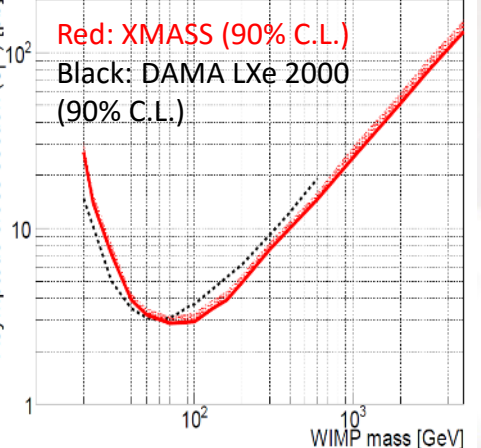
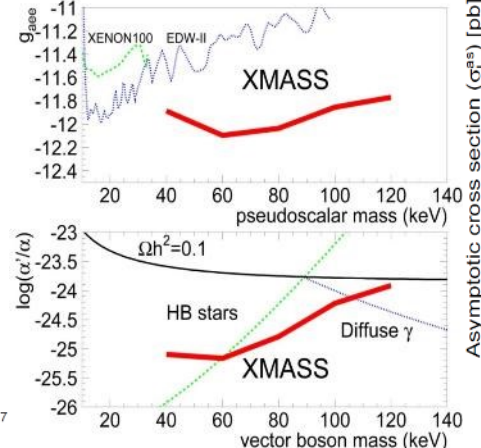
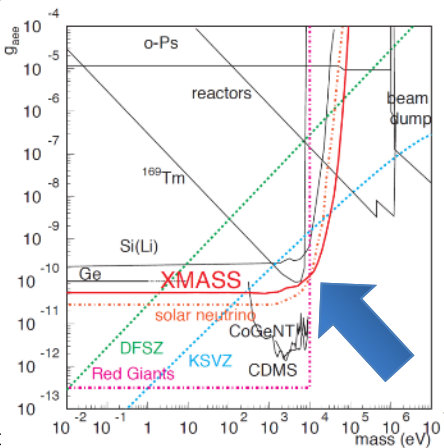
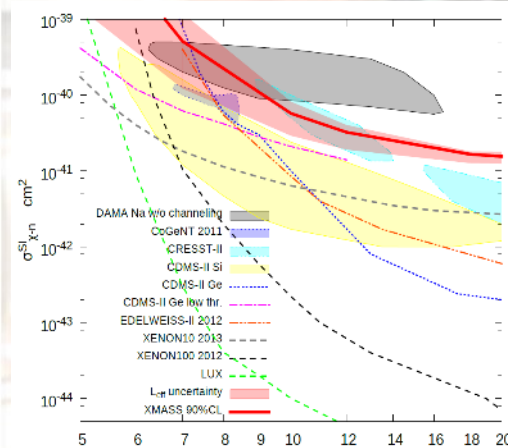
- various kinds of dark matter candidates and physics

Low mass WIMPs search, PLB 719 (2013) 78

Solar axion search, PLB 724 46 (2013)

Bosonic super-WIMPs search, PRL 113, 121301 (2014)

Inelastic WIMP nucleus scattering search, PTEP 063C01 (2014)



Recent results

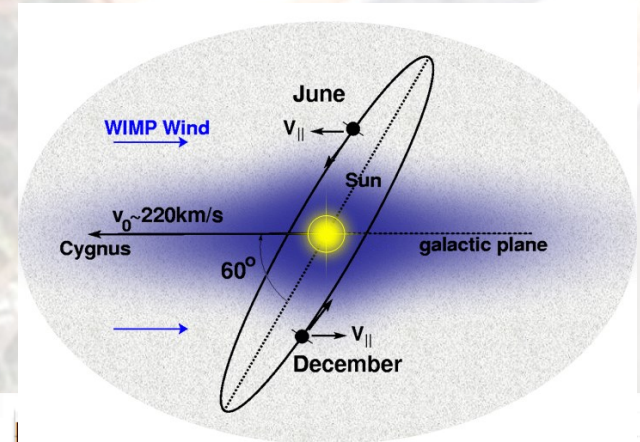
- Direct dark matter search by annual modulation (PLB 759 272 (2016))
- Search for 2ν double electron capture on ¹²⁴Xe (PLB 759 272 (2016))

Search for annual modulation (1)

Physics Letters B 759 (2016) 272–276

KOBE: K. Hosokawa's Doctor thesis

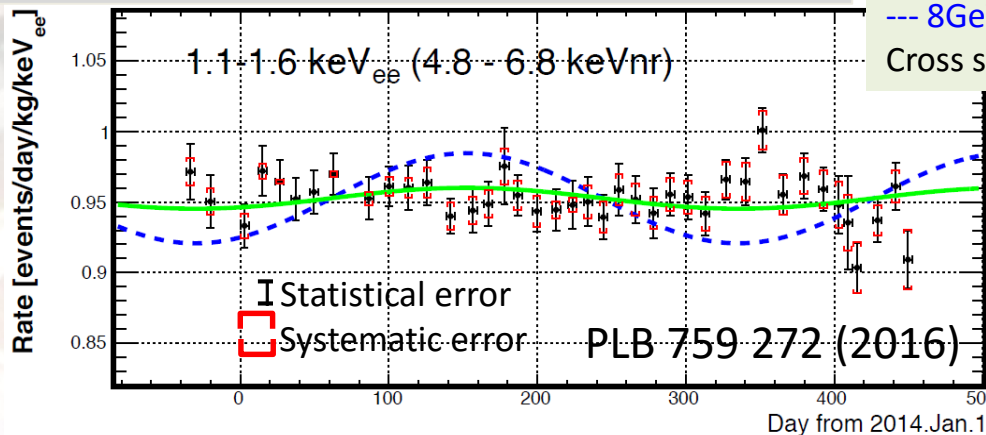
- Dataset: after refurbishment (Nov 2013-Mar 2015)
 - 0.83ton*year data(1 year cycle) with low threshold (1.1keV_{ee}). Comparable to 1.33ton*year of DAMA/LIBRA data (14 cycles)
 - Rejection of noise, Cherenkov and front of PMT event.
 - No particle ID just like DAMA/LIBRA
- The observed count rate as function of time in each energy bin.
- Clear modulation signal is expected if WIMP parameters are in the range where DAMA/LIBRA experiment indicates.



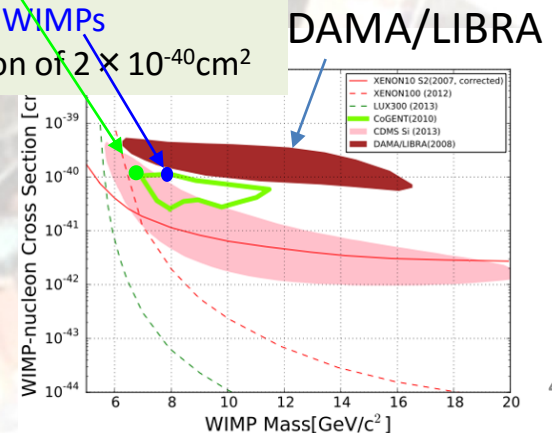
Jun. Dec.

The expected WIMP flux variation due to earth h's orbit.

Time variation of event rate from 1.1 to 1.6 keV_{ee}



Expected rates for
 — 7 GeV/c² WIMPs
 --- 8 GeV/c² WIMPs
 Cross section of $2 \times 10^{-40} \text{cm}^2$



Search for annual modulation (2) Byeongsu Yang @PATLAS2016

- Assuming standard WIMP, data is fitted with the following equation:

$$R^{\text{pred}}(E_i, t_j) = C_i + \sigma \times A(m_\chi, E_i) \cos 2\pi(t_j - t_0)/T$$

t_0 (phase)=152.5days, T (period)=365.25days,

A (modulated amplitude) and C_i
(unmodulated amplitude)

- Two independent modulation analyses were performed using different χ^2 definition.
- Leff uncertainty is taken into account.
- The difference between two methods are within 30%.
- Figure is drawn by Method 1.
- DAMA/LIBRA region is mostly excluded by our measurement.**

Method 1 (pull term)

$$\chi^2 = \sum_i^{E\text{-bins}} \left(\sum_j^{t\text{-bins}} \frac{(R_j^{\text{obs}} - R_j^{\text{pred}} - \alpha K_{i,j})^2}{\sigma(\text{stat})^2} \right) + \alpha^2$$

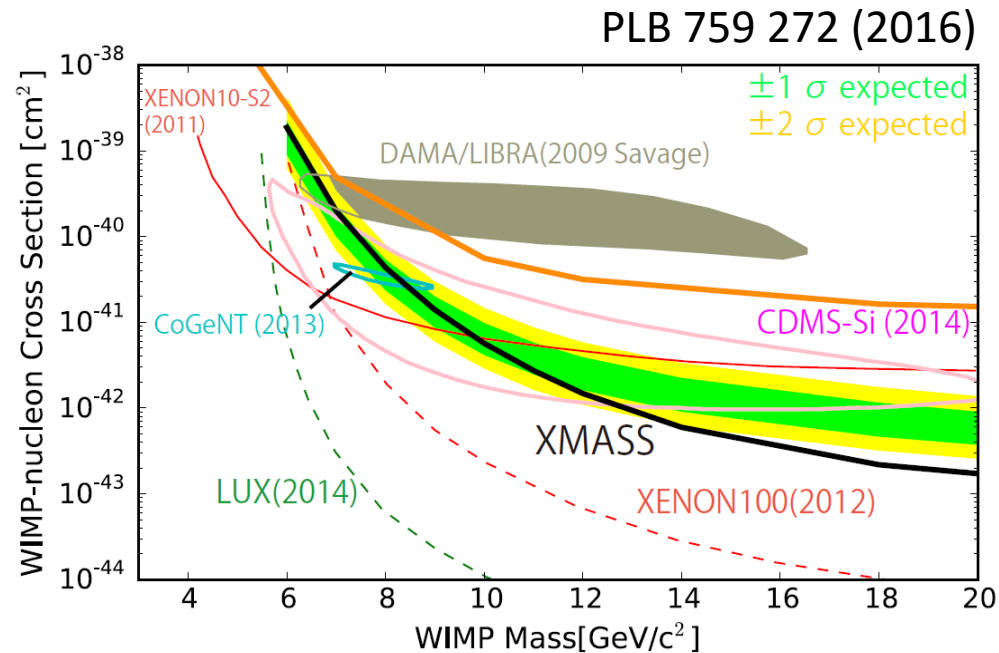
Method 2

(covariance matrix)

$$\chi^2 = \sum_{i,j}^{E\text{-bins}} (R_i^{\text{obs}} - R_i^{\text{pred}})(V_{\text{stat}} + V_{\text{sys}})^{-1}_{ij} (R_j^{\text{obs}} - R_j^{\text{pred}})$$

Model assumption

V_0 : 220.0 km/s
 V_{esc} : 650.0 km/s
 ρ_{dm} : 0.3 GeV/cm³
 Lewin, Smith (1996)



The first extensive search against the DAMA region, including electron recoils.

Search for annual modulation (3)

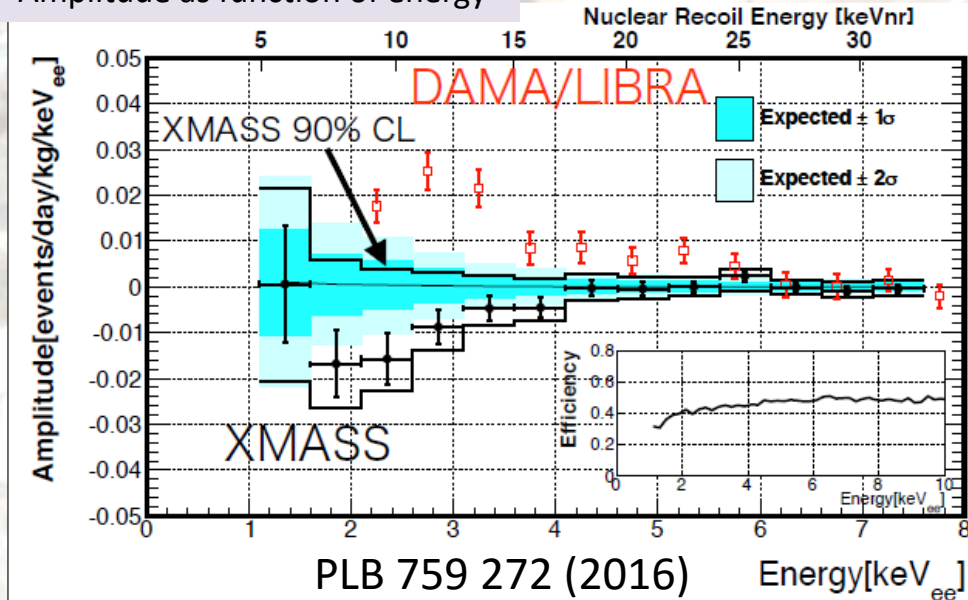
- Annual modulation signal is searched for without any model assumption.
- A_i (modulated amplitude) and C_i (unmodulated amplitude) are fitted by :

$$R_{i,j}^{\text{ex}} = \int_{-\frac{1}{2}\Delta t_j}^{\frac{1}{2}\Delta t_j} (C_i + A_i \cos 2\pi(t_j - t_0)/T) dt_j$$

$t_0=152.5\text{days}$, $T=365.25\text{days}$, fitting range : $1.1\text{-}7.6\text{keV}_{ee}$

- Small negative amplitude is observed in $1.6\text{-}4.1\text{keV}_{ee}$ region. Significance was evaluated with test statistic (10,000 dummy samples) and **no significant modulated signal** has been observed. (p-value= $0.014(2.5\sigma)$ and $0.068(1.8\sigma)$ for 2 methods.)
- Direct comparisons with other experiments: more stringent constraint.

Amplitude as function of energy



Experiments	Amplitude(events/day/kg/keV _{ee})
DAMA/LIBRA	~0.02, 2.0-3.5keV _{ee}
XENON100	3.7×10^{-3} , 90% C.L. upper limit, 2.0-5.8keV _{ee} ^(*)
XMASS	$(1.7\text{-}3.7) \times 10^{-3}$, 90% C.L. positive upper limit, 2-6keV _{ee}

*Estimated based on PRL 115 (2015) 091302 and Science 349 (6250) (2015) 852

ダークマター：最前線

■ 低閾値検出器

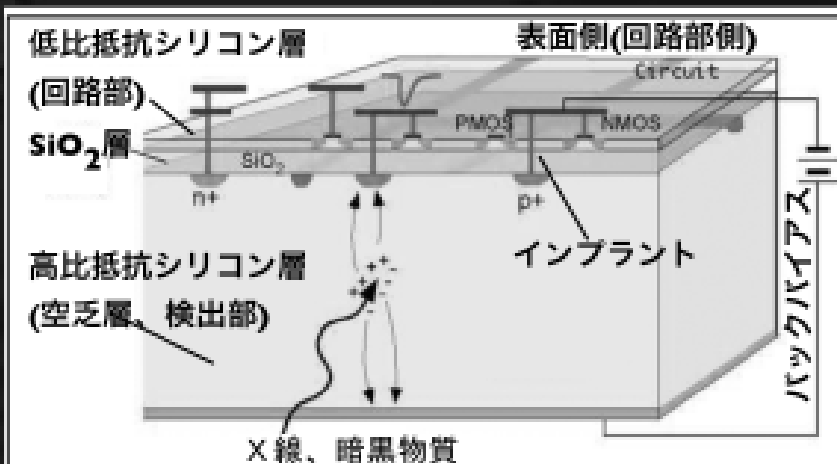
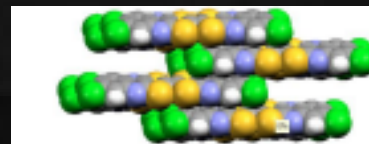
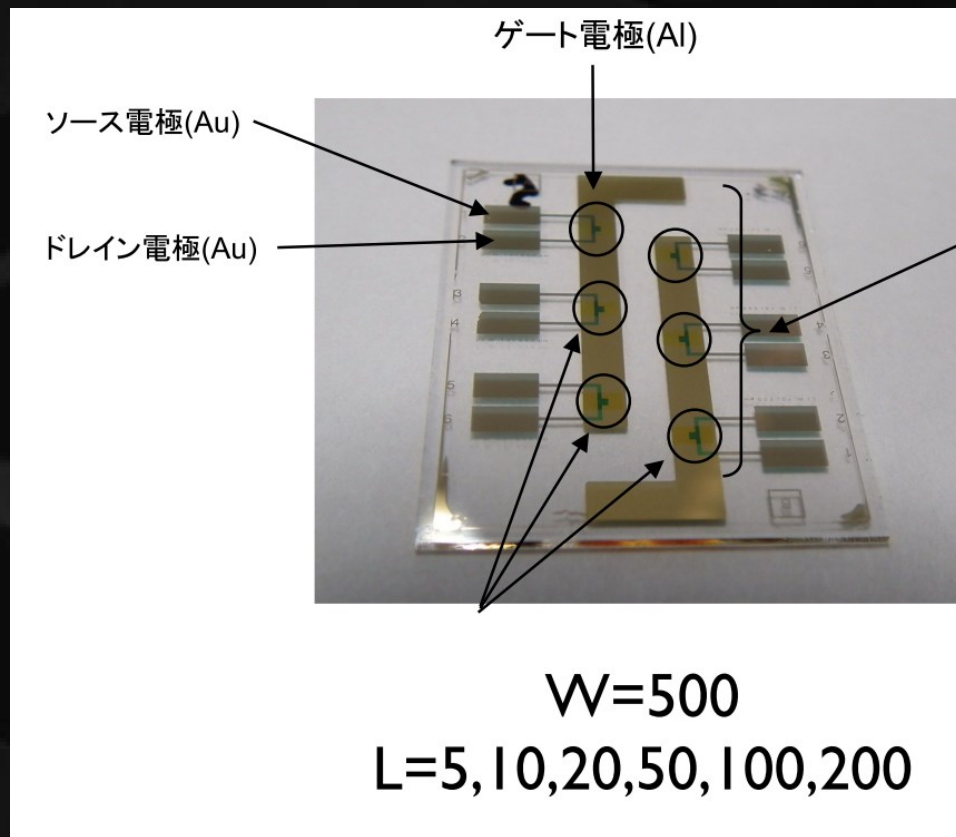


図2: SOIPIXの断面。SiO₂を挟んで低比抵抗部と高比抵抗部にわかれる。SiO₂に設けたインプラントを通じて高比抵抗部で検出した電荷を低比抵抗部に導入、全てのピクセルの低比抵抗部が備えるアンプとトリガ回路で処理して、素子外部へ出力する。

SOI検出器



いずれの有機半導体も、左の様な層構造を持つため、移動度に異方性を持つ。

有機半導体

PRL73(1994)1067



FIG. 2. A false color CCD image resulting from a ^{252}Cf neutron source. The colors black, blue, red, and white represent the order of increasing light intensity levels. The area displayed represents a 25 cm by 25 cm section of the detector plane. See the text for a description of image features.

はるか
はるか昔
身内：博士1年

“What is this?”

“It’s a lightsaber, Jedi’s wepon”

Another piece of information

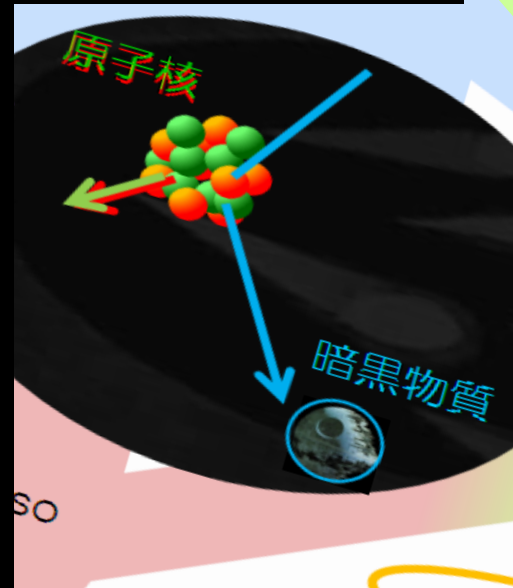
PRL73(1994)1067



FIG. 2. A false color CCD image resulting from a ^{252}Cf neutron source. The colors black, blue, red, and white represent the order of increasing light intensity levels. The area displayed represents a 25 cm by 25 cm section of the detector plane. See the text for a description of image features.

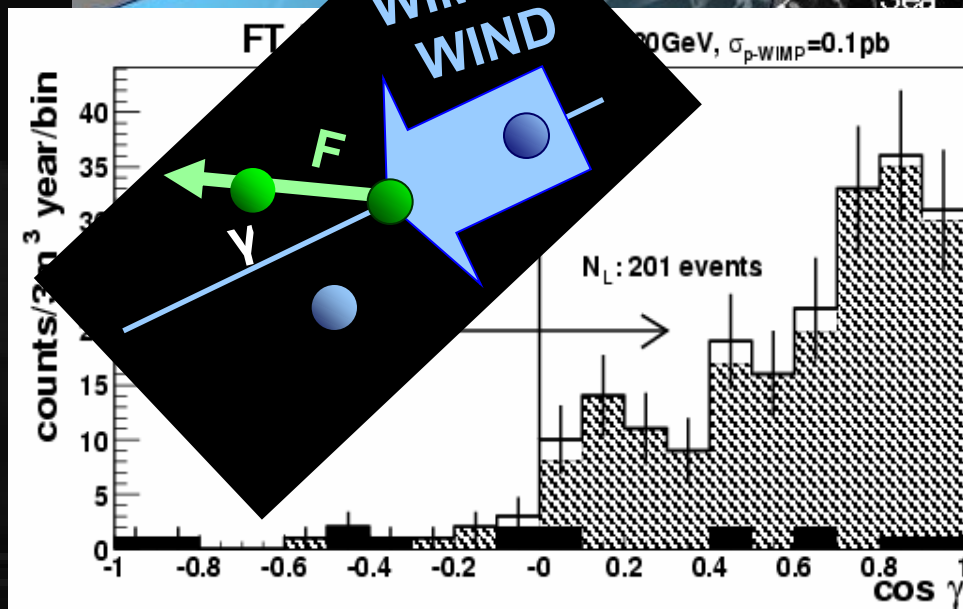
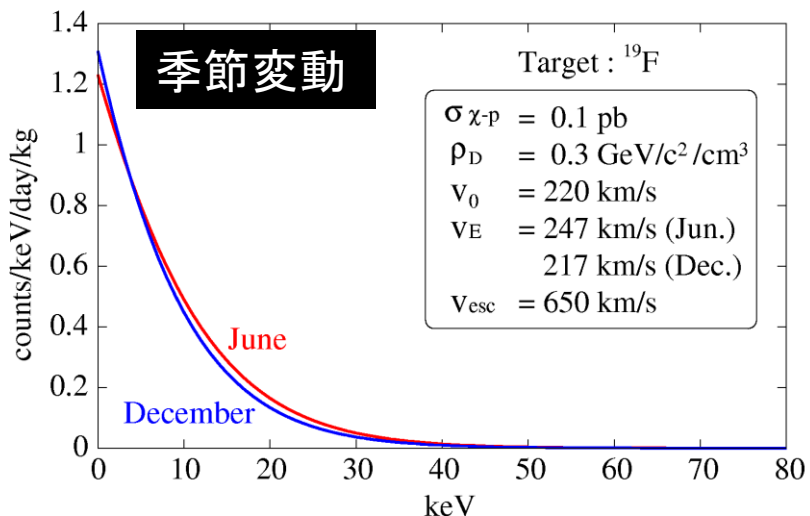
原子核飛跡

原子核飛跡 + E_R
DRIFT



飛跡検出のメリット

- 季節変動(5%以下)と比較して確実な証拠となる
(前後の非対称度は最大で10倍。)
- 検出の後には暗黒物質の性質解明



◆ The Empire: 英国DRIFTグループ

DRIFT IIa design & dimensions

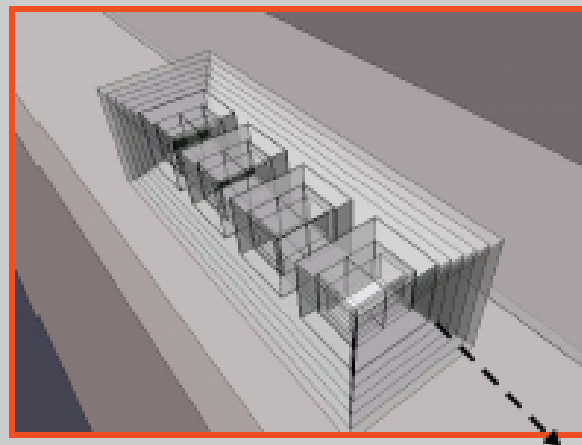
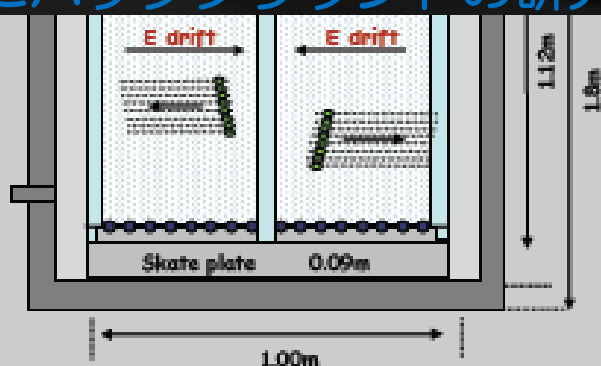
1 m³ 2台目 (3台目も完成。)

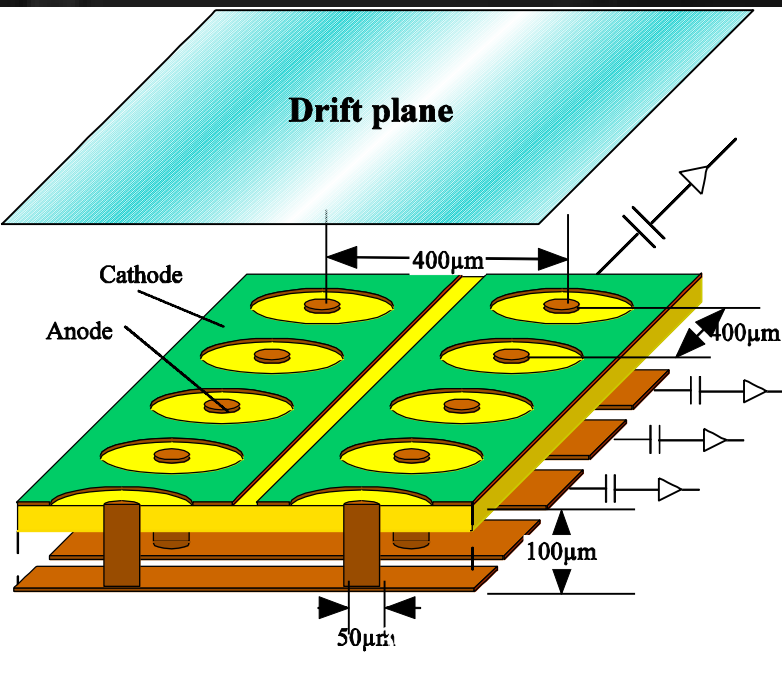


- 1 m³ active volume - back to back MWPCs
 - Gas fill 40 Torr CS₂ => 167 g of target gas
- ▲ 2 mm pitch anode wires left and right
 - Grid wires read out for Δy measurement
 - Veto regions
 - Central cathode
 - diameter wires at 2 mm pitch
 - Drift field 624 V/cm
 - Modular design for modest scale-up

ピッチが少々荒い
3次元飛跡が取りずらい

地下で1年以上稼働
主にバックグラウンドの研究





はるか昔
身内：博士2年

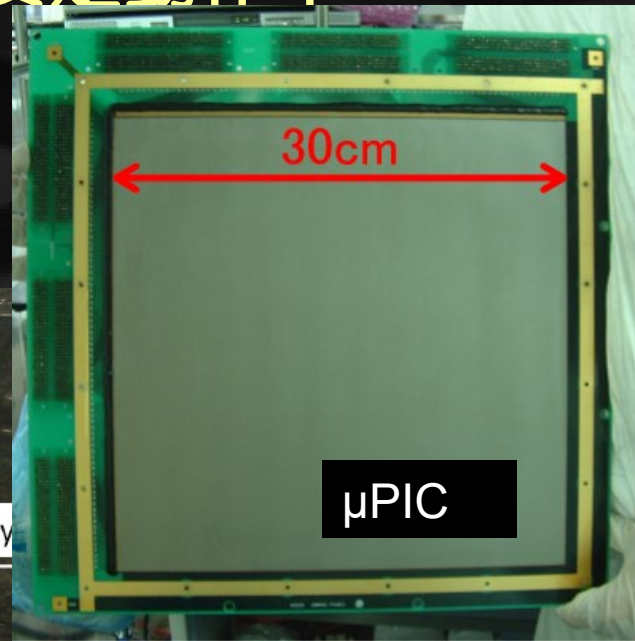
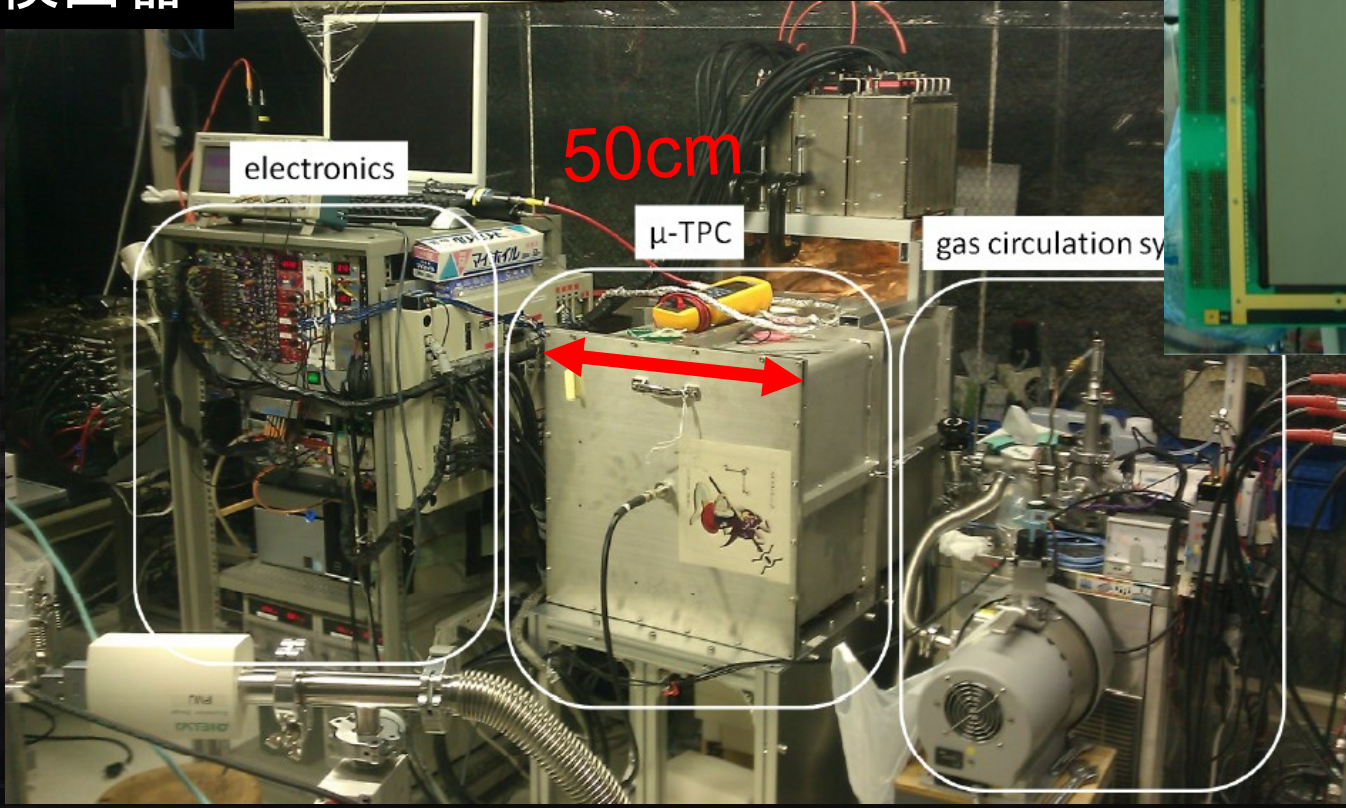
“You have to go to the DAGOVA system and learn the force.”

After the coulomb WAR...

- 最初は10cm角の μ PICも放電まみれ でしたが、
- 現在は30cmキューブが地下で安定動作中

現在の
検出器

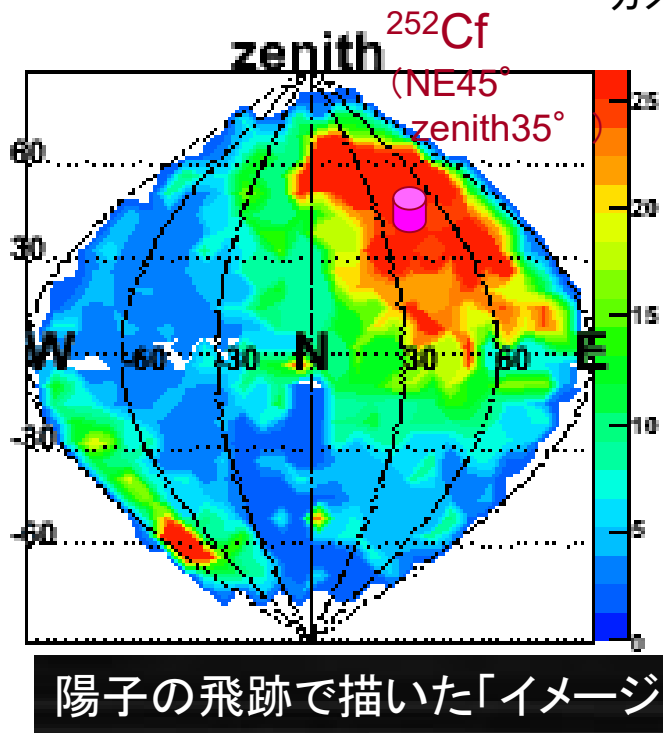
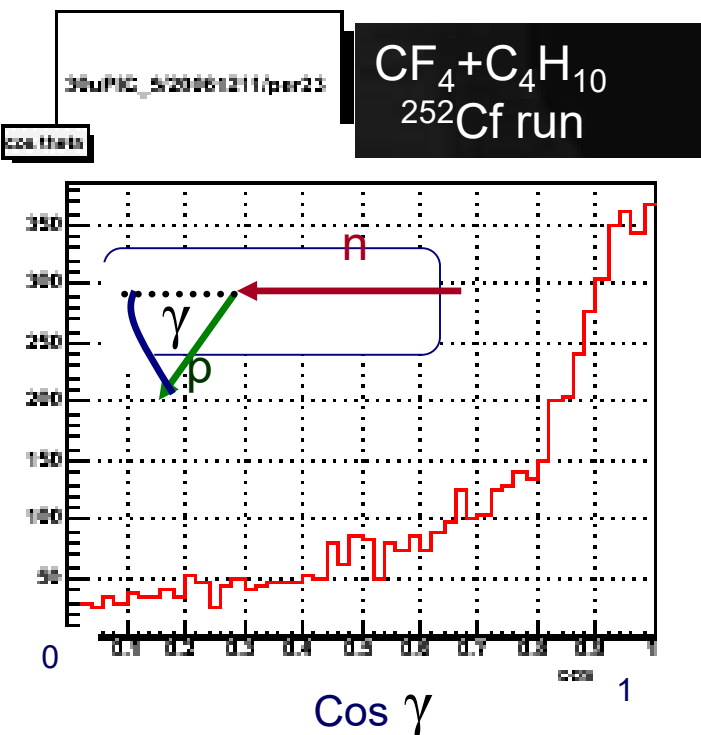
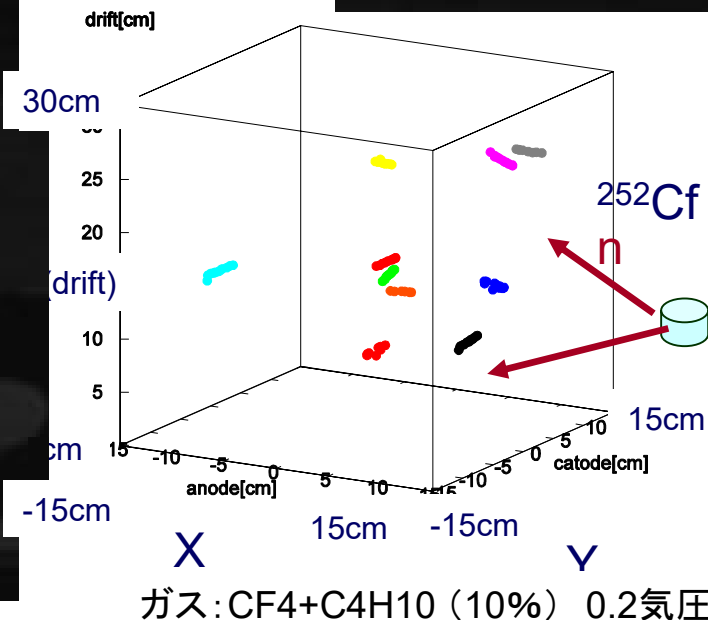
ガス部



飛跡検出、イメージング

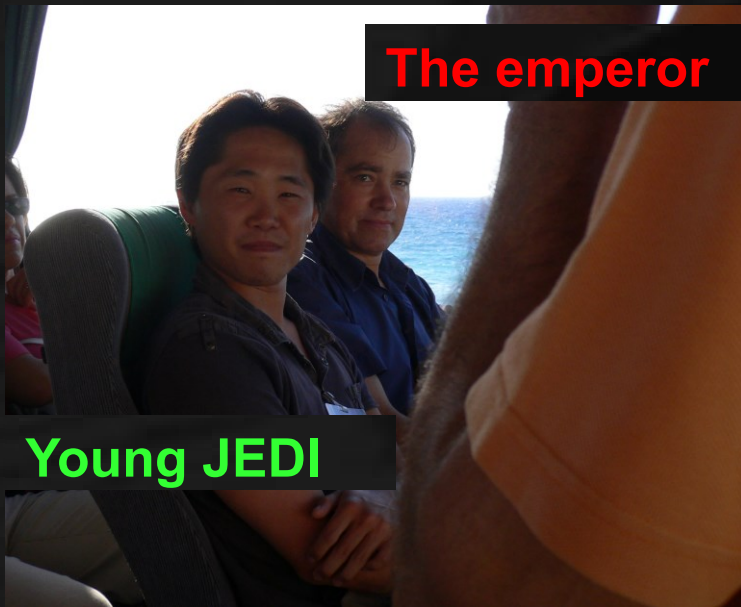
- 中性子に反跳された陽子を検出
- 前方に散乱される様子が見えている
- WIMP → フッ素の反跳で見た現象をエミュレート

陽子飛跡の例



Direction Sensitive
WIMP search
NEWAGE

Jan 27, 2007 3rd MPGD
Workshop



ひとむかし (IDM2006)

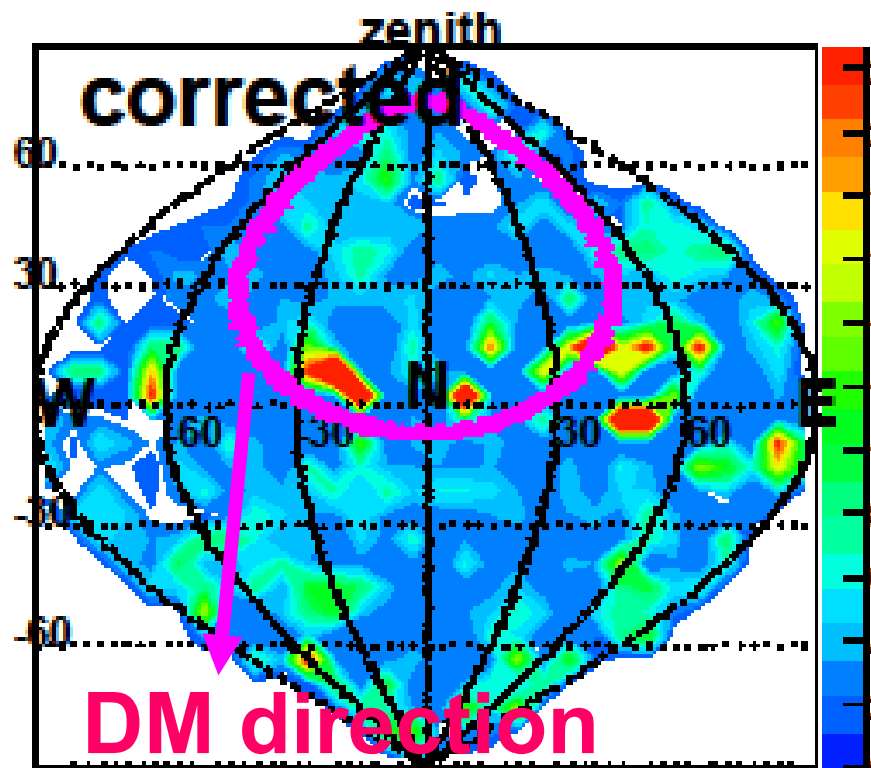
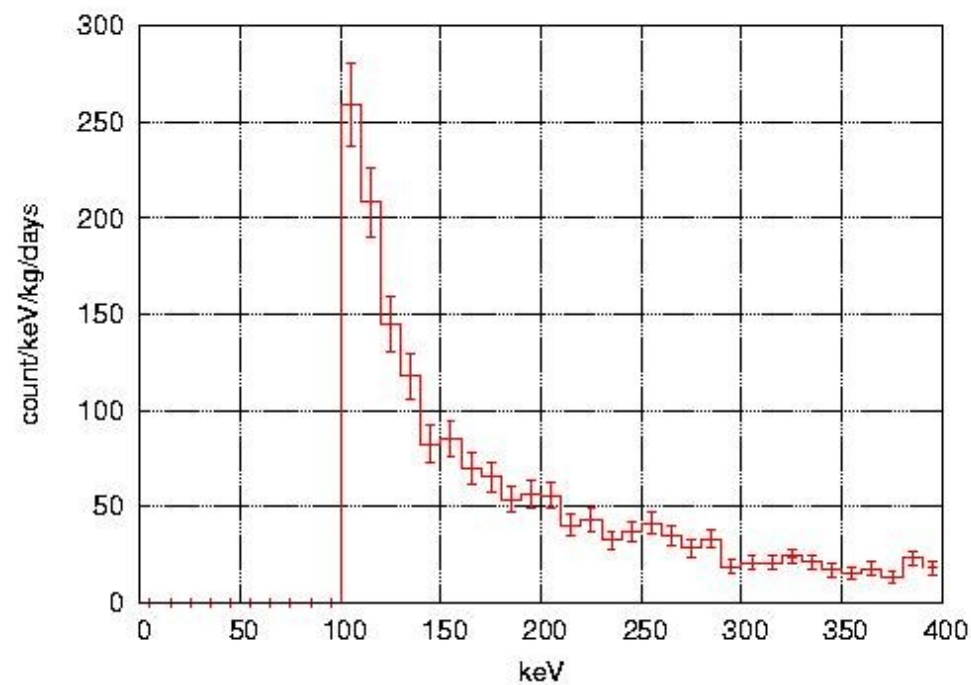
“I see you have constructed a new light
saber. Your skills are complete.”

地上(京大)でのDM探索実験

- 原子核飛跡を用いた手法では初めて
- 2006年11月1日～11月27日
- exposure 0.15 kg days
- シールドなし

PLB654 (2007) 58

North sky view seen by C and F nuclei
(100-400keV)



Last Week (英国・シェフィールド)

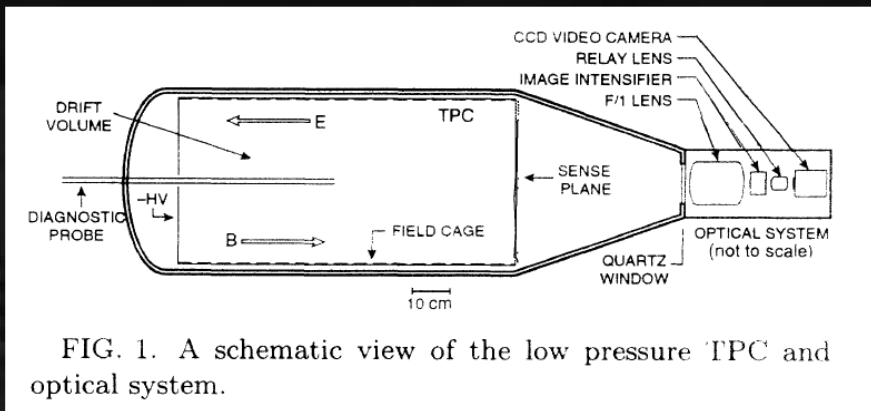


FIG. 1. A schematic view of the low pressure TPC and optical system.

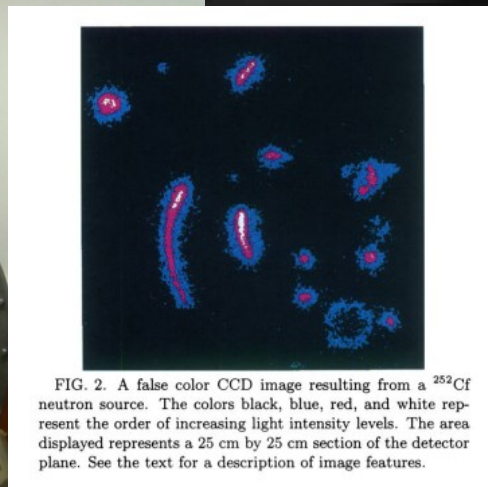
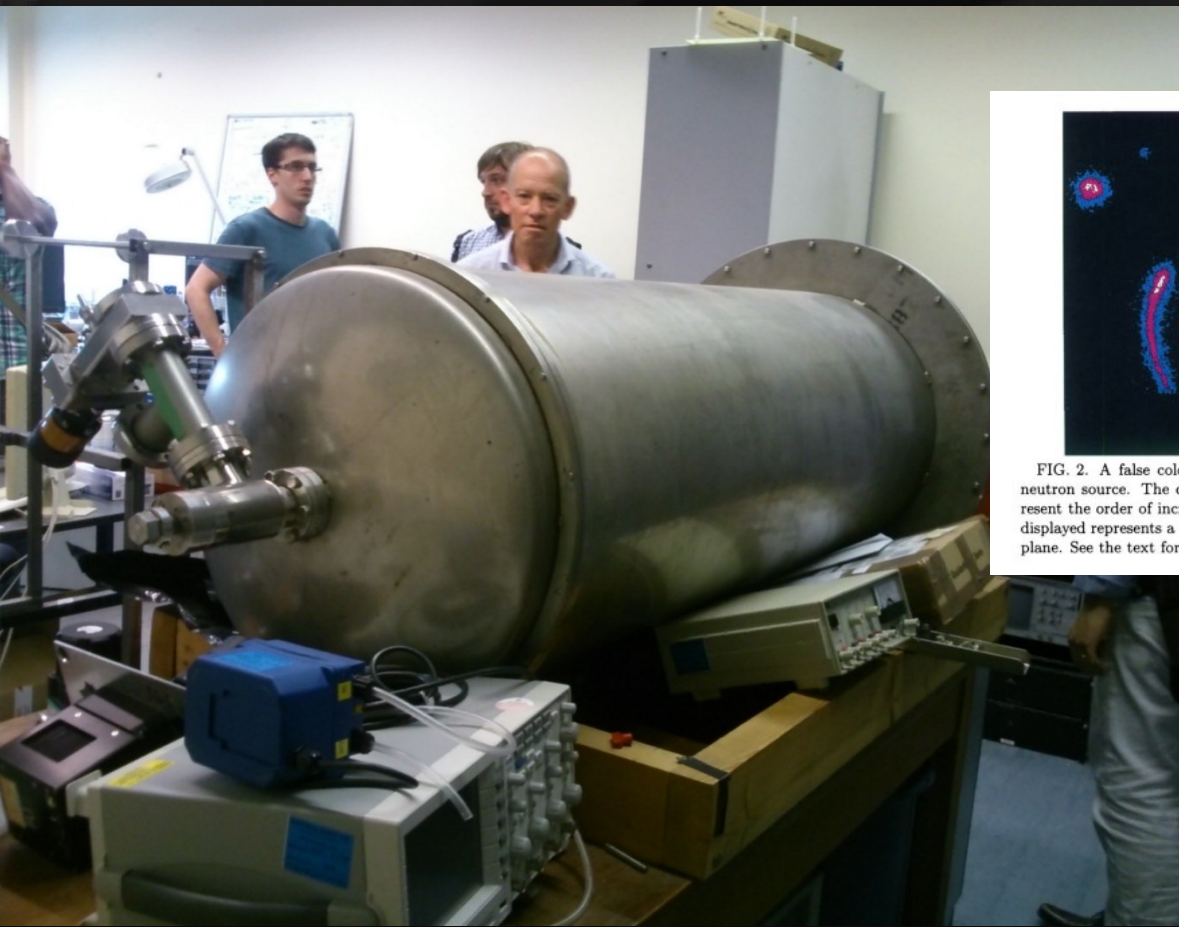
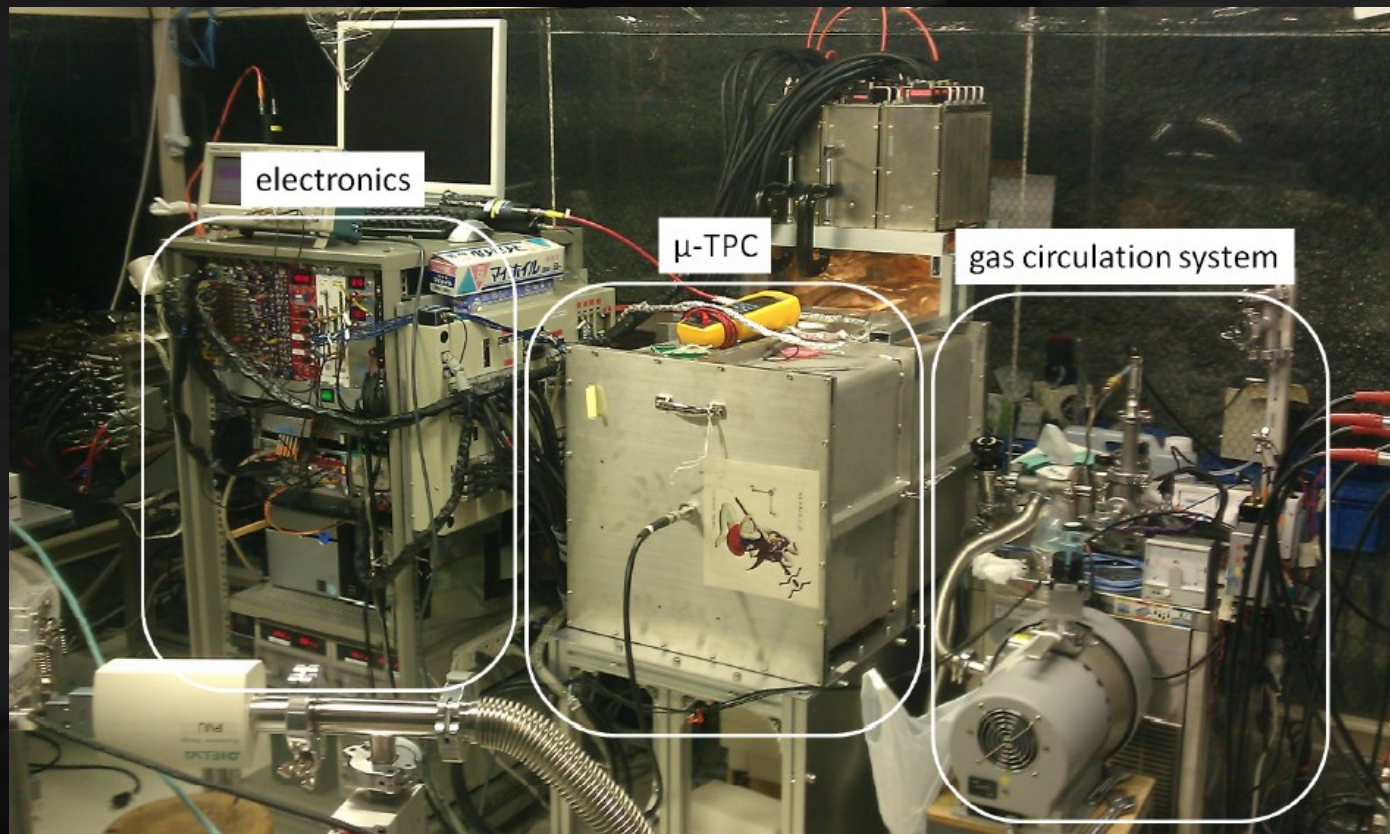


FIG. 2. A false color CCD image resulting from a ^{252}Cf neutron source. The colors black, blue, red, and white represent the order of increasing light intensity levels. The area displayed represents a 25 cm by 25 cm section of the detector plane. See the text for a description of image features.

Encountered the
Awakening of the
Force

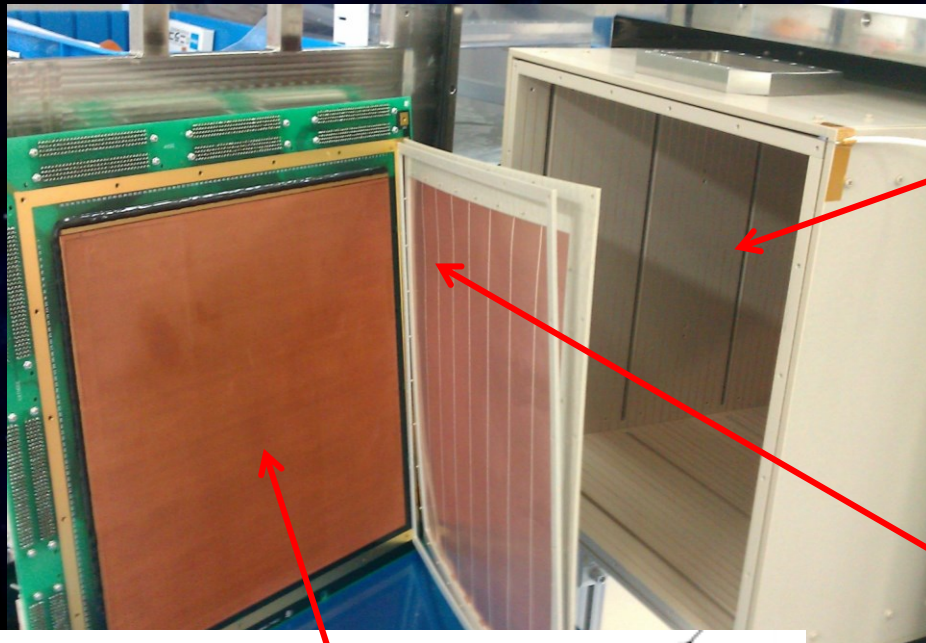
NEWAGE detector

- ❑ NEWAGE-0.3b'
- ❑ Detection Volume: $31 \times 31 \times 41 \text{cm}^3$
- ❑ Gas: CF₄ at 0.1atm (50keVee threshold)
- ❑ Gas circulation system with cooled charcoal

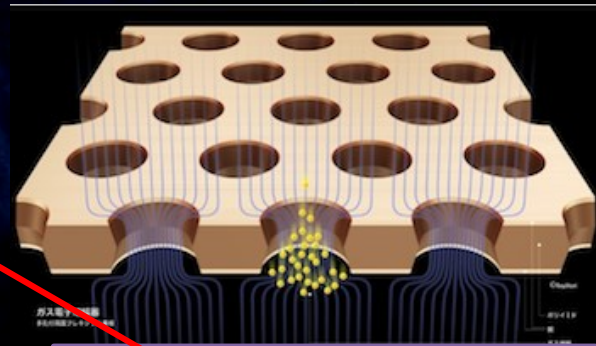


NEWAGE-0.3b' inside view

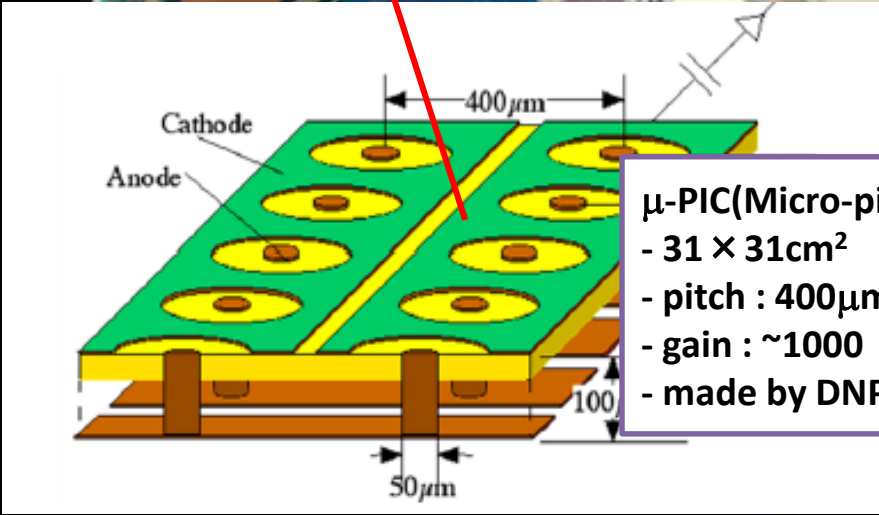
Detection Volume: $30 \times 30 \times 41 \text{ cm}^3$



Field cage
Drift length: 41cm
PEEK + copper wires



GEM
- $31 \times 32 \text{ cm}^2$
- 8-segmented
- hole pitch : $140 \mu\text{m}$
- hole diameter: $70 \mu\text{m}$
- insulator : LCP $100 \mu\text{m}$
- gain : ~ 5
- made by Scienergy, Japan

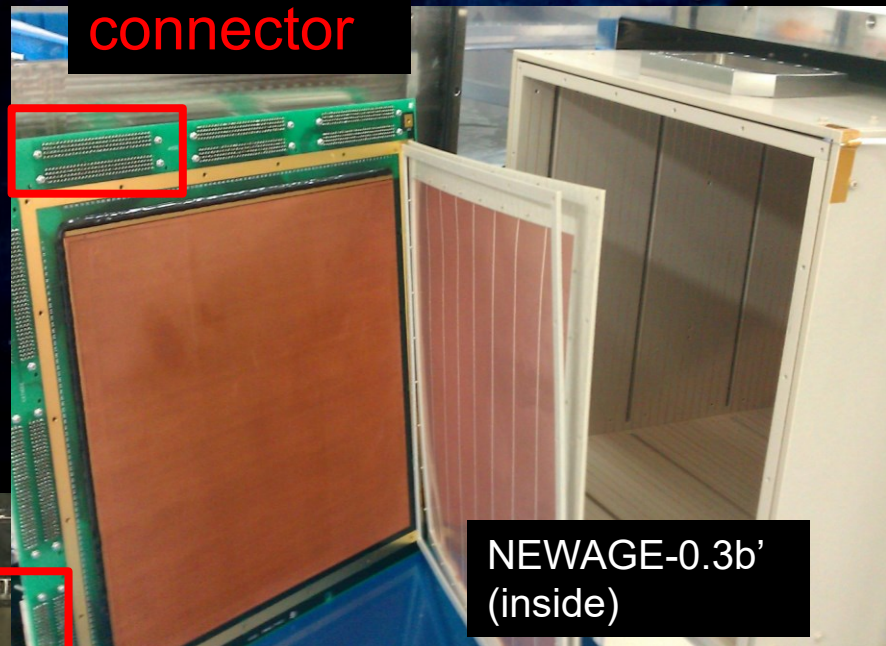


μ -PIC(Micro-pixel chamber)
- $31 \times 31 \text{ cm}^2$
- pitch : $400 \mu\text{m}$
- gain : ~ 1000
- made by DNP, Japan

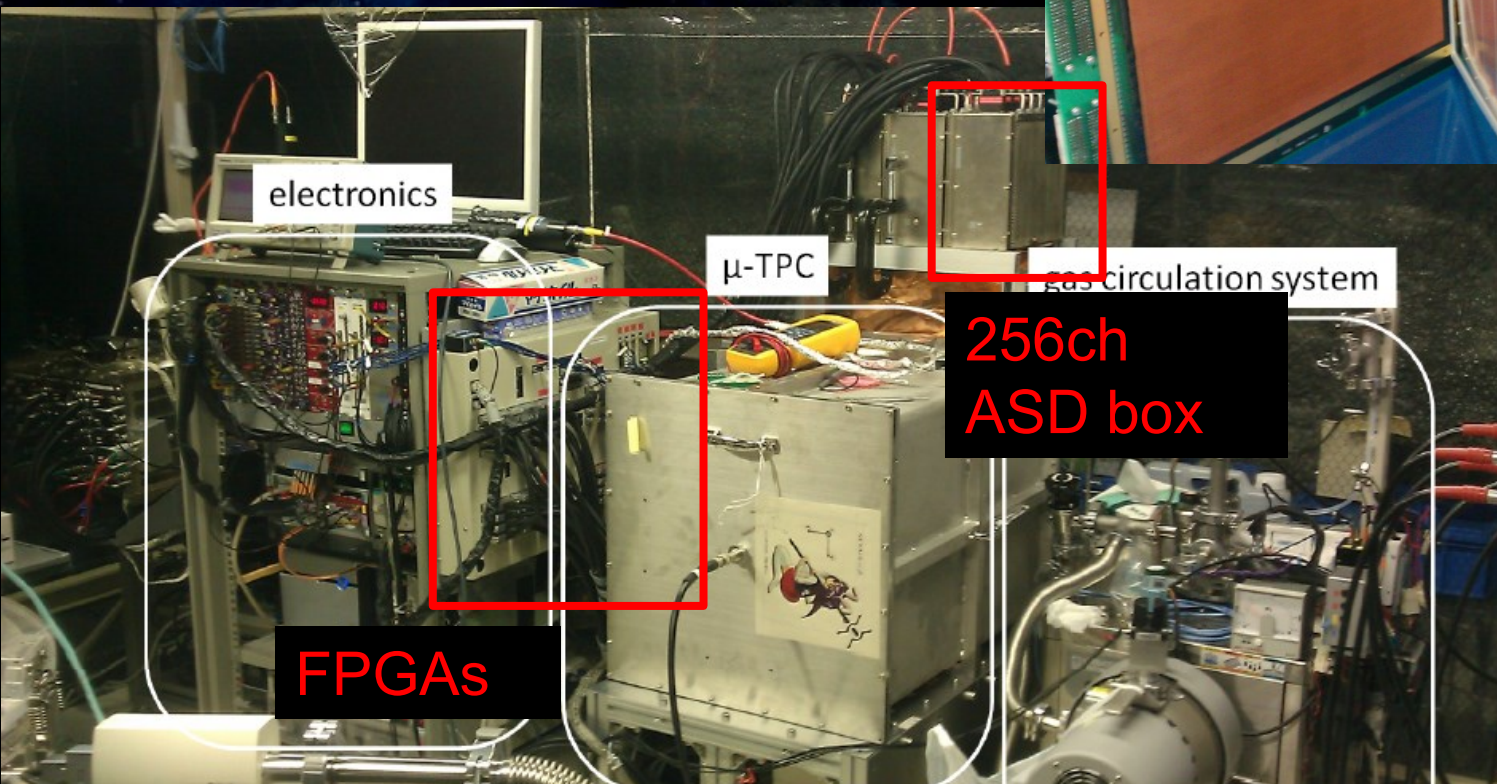
NEWAGE-0.3b' readouts

- μ -PIC is X-Y readout
- General purpose FPGA-based electronics since early 2000's

256ch
connector



NEWAGE-0.3b'
(inside)



electronics

μ -TPC

gas circulation system

256ch
ASD box

FPGAs

NEWAGE-0.3b' data

TOT of every strip by FPGA (clock 100MHz)

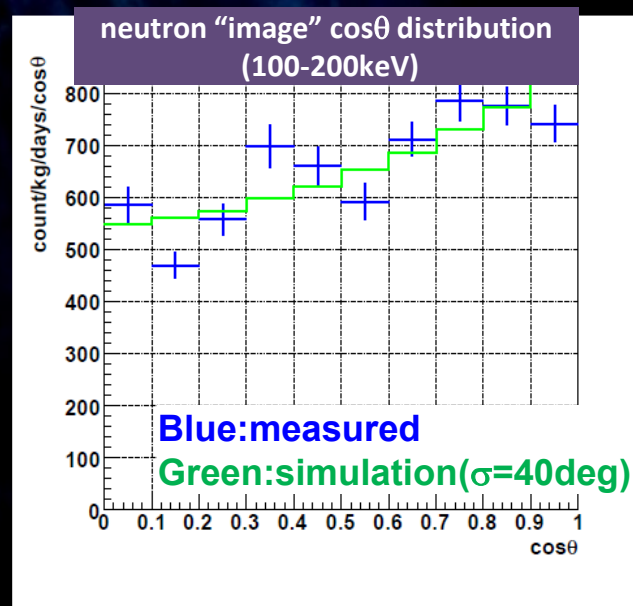
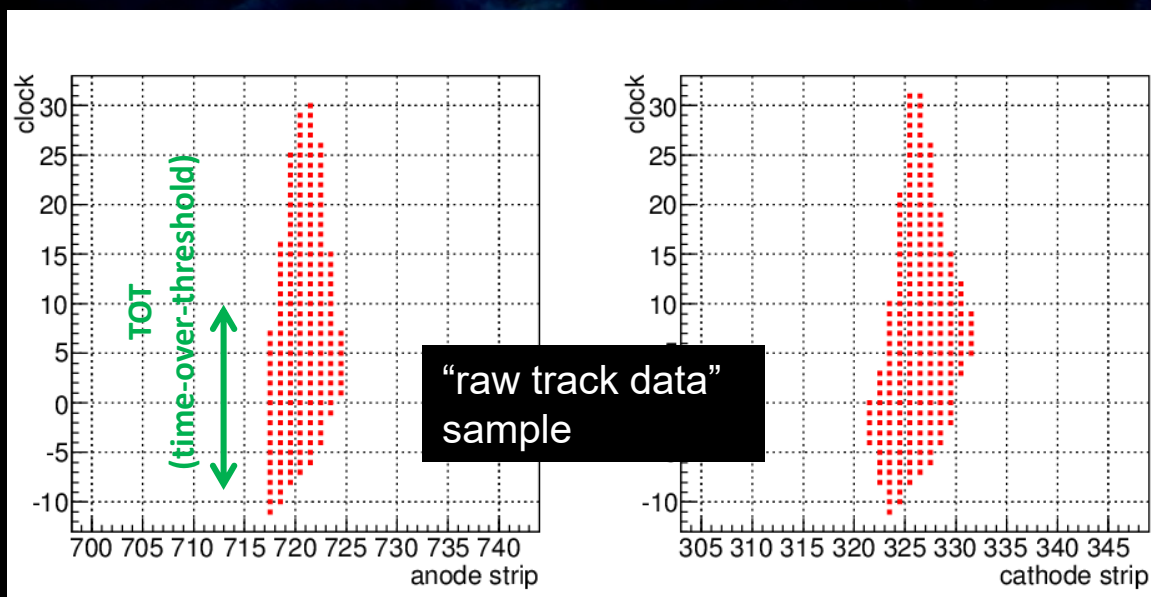
⇒ 3D tracks, headtails in X,Y

+

Summed waveforms by FADC (100MHz)

⇒ energy, headtails in Z

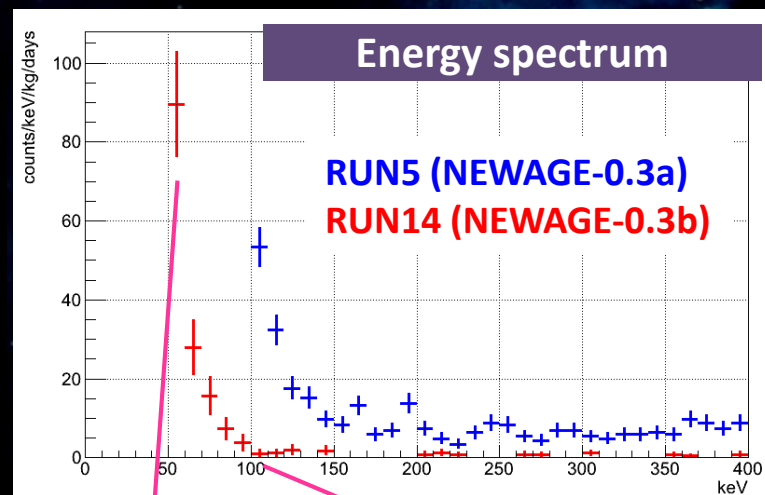
combined ⇒ PID, absolute z



NEWAGE underground run

RUN14

- period : 2013/7/20-8/11, 10/19-11/12
- live time : 31.6 days
- fiducial volume : $28 \times 24 \times 41 \text{cm}^3$
- mass : 10.36g
- exposure : $0.327 \text{ kg} \cdot \text{days}$

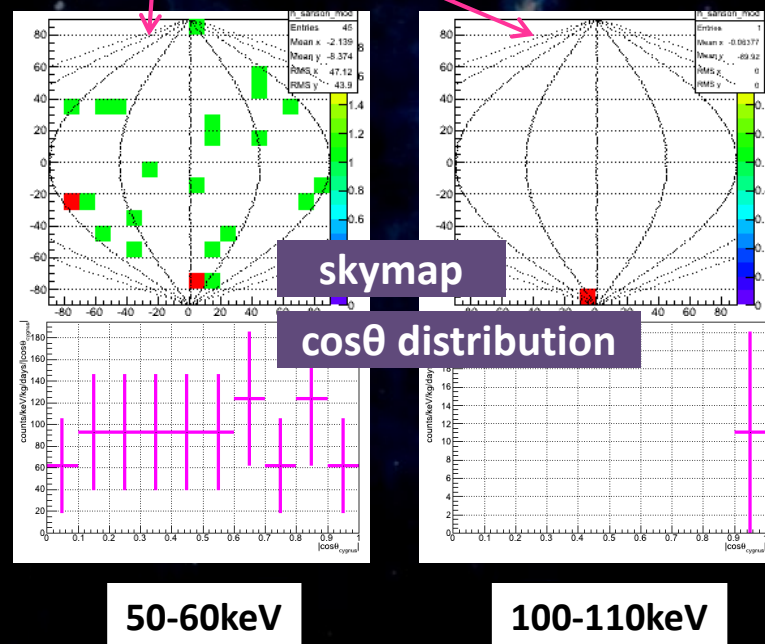


Energy spectrum

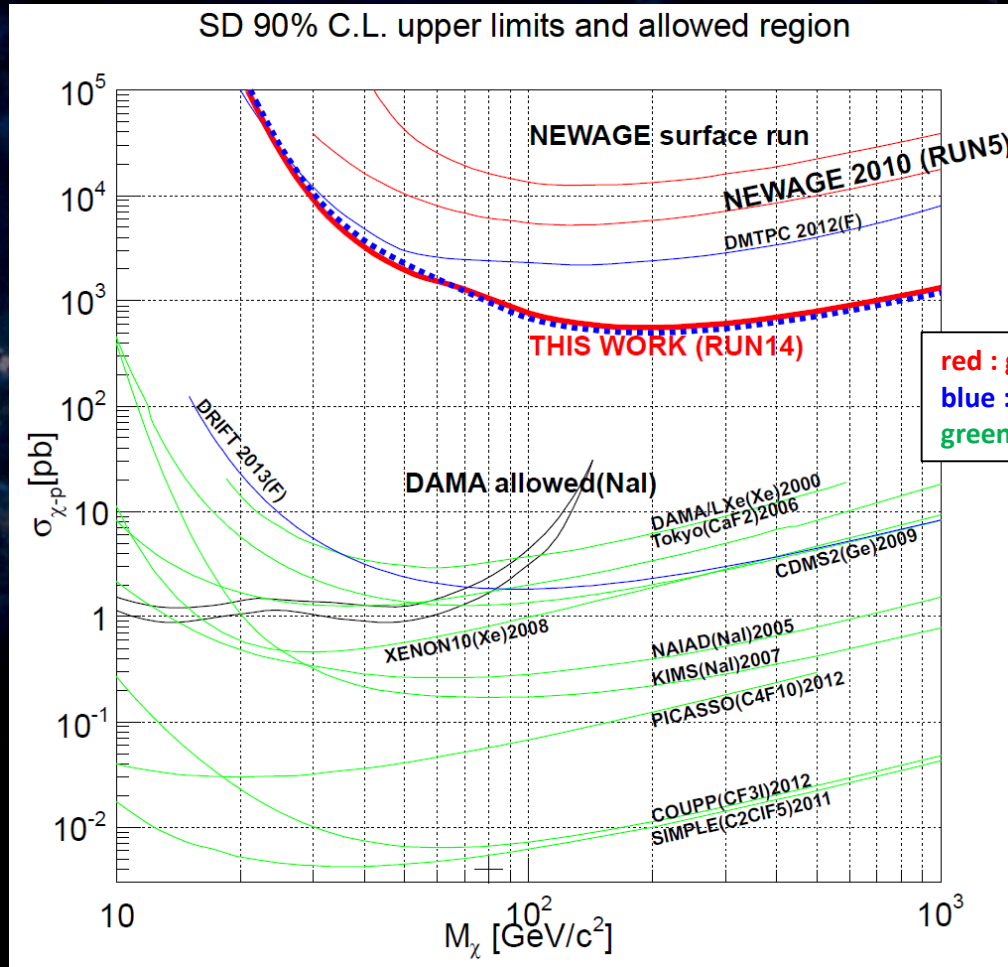
- Threshold : 100 => **50keV**
- BG rate : **1/10**@100keV

Skymap, $\cos\theta$ distribution

- Set limit by significant difference in 2-binned measured $\cos\theta$ and DM-wind simulated $\cos\theta$



Direction-sensitive limit



PTEP (2015) 043F01s

- Obtained limit : **557pb @200GeV**
(Best direction-sensitive limit)
- Improved one order of magnitude from previous RUN5

message to young apprentice

「いろいろなところにきっかけがあるはず。
広く興味をもって挑戦してください。」

May the force be with all of YOU.

ご清聴ありがとうございました。

