世界と日本の
暗黒物質直接探索の現状

2012年11月20日

神戸大学　粒子物理研究室
身内賢太朗

はじめまして

東大 大学院 みのわ研（1997～2002）

LiFボロメータによる暗黒物質探索実験

Astropart. Phys.19 (2002) 135

京大 宇宙線研究室（2002～2011）

NEWAGE

Phys. Lett. B 686(2010)11

神戸大 粒子物理研究室（2011～）

+= XMASS +=???

15年か。。。

世界と日本の
暗黒物質直接探索の現状

MIUCHI VISION 15

日本の
暗黒物質研究 は、検出器の感度を 飛躍的に向上させ、

世界へ貢献する:分野であり続けます

身内賢太朗 2012年11月20日 @ 寄田研セミナー

WIMP-search
NEWAGE

MIUCHI VISION 15

見えない最先端
見えた人たち
見たい俺たち
アリとゾウ

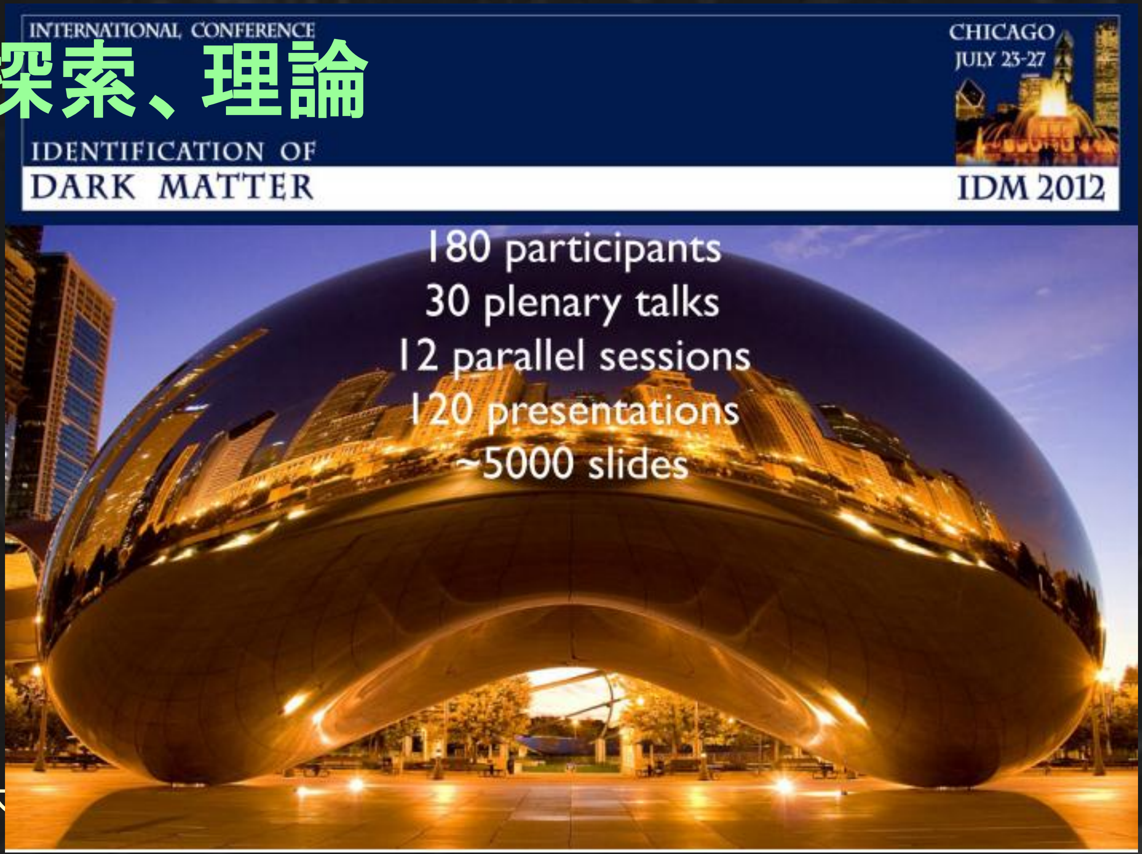
compiled from

http://kicp-workshops.uchicago.edu/IDM2012/

IDM

http://kicp-workshops.uchicago.edu/IDM2012

- 隔年で行われる　DM国際会議
  - 第9回(身内は2000,2002,2004,2006に参加)
  - 初の欧州外での開催
- 直接実験、間接探索、理論



LHC・理論

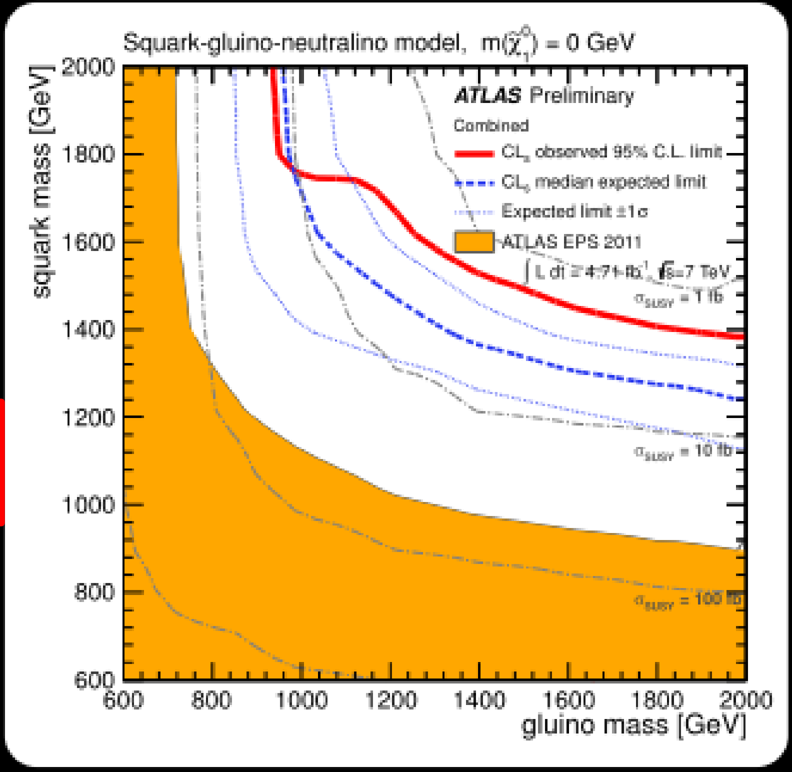
Direction Sensitive WIMP-search NEWAGE

LHCではSUSYの兆候なし

- MSSMはかなりの質量領域がexclude
- 所詮 ”minimal"

Tim M.P. Tait

- Searches for missing energy plus various numbers of jets put bounds on squark and/or gluino (“colored sibling”) production.
  - Gluinos decay to two jets + WIMP
  - Squarks into one jet + WIMP
- For equal masses, searches require them to be larger than about 1.5 TeV
- Limits are still several hundred GeV when one or the other is very heavy.
- These limits hold assuming the WIMP mass is less than 200 GeV.



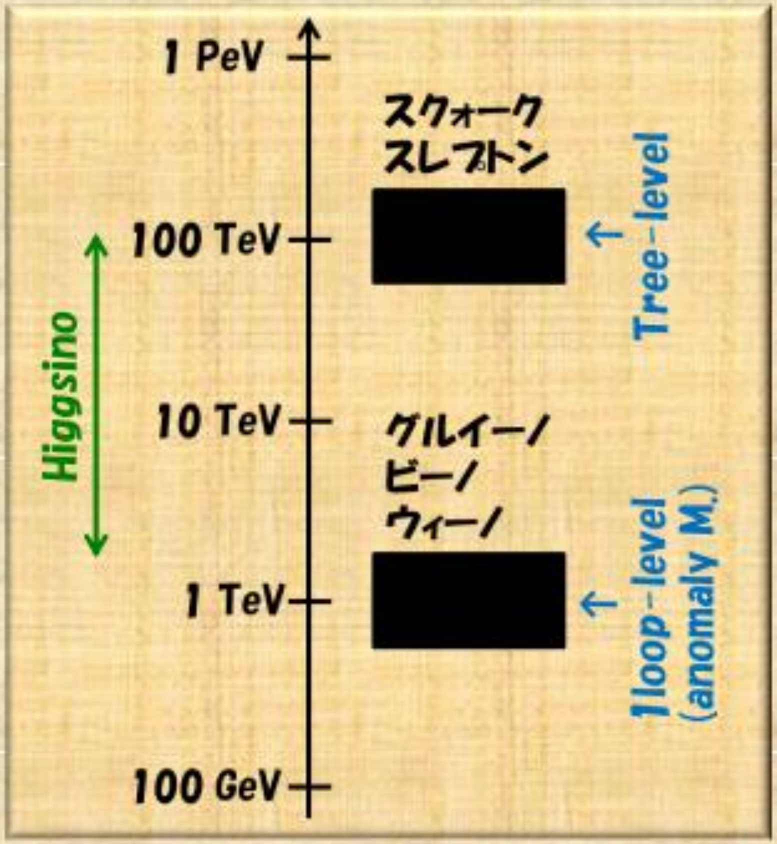
More from Matt about the status of SUSY shortly!

HIGGS 125GeV → WINO DM

現在最も有力な暗黒物質候補

超対称性の自発的な破れが力学的に起こると以下のタイプのスペクトル予言

MSSM Sector ---- SUGRA interactions / Planck suppressed interaction ---- SUSY Sector (No singlets)



ヒッグス発見後に報告された文献達

[M. Ibe, S.M., T. Yanagida, arXiv:1202.2253]
[E. Dudas, A. Linde, Y. Mambrini, A. Mustafayev, K. Olive, arXiv:1209.0499]
[M. Bose, M. Dine, arXiv:1209.2488]
[A. Arvanitakia, N. Craigb, S. Dimopoulos, G. Villadoroc arXiv:1210.0555]
[L. Hall, Y. Nomura, Shirai, arXiv:1210.2395]

ゲージーノの質量がAnomaly mediationの寄与により決まるため暗黒物質候補は

中性ウィーノ($SU(2)_L$-triplet DM)

このシナリオは宇宙論の観点からも優遇
(グラビティー&ポロニー問題がない！)

WINO DM?

arXiv:1210.5985v1

- モデルによっては断面積の下限値が決まることも。

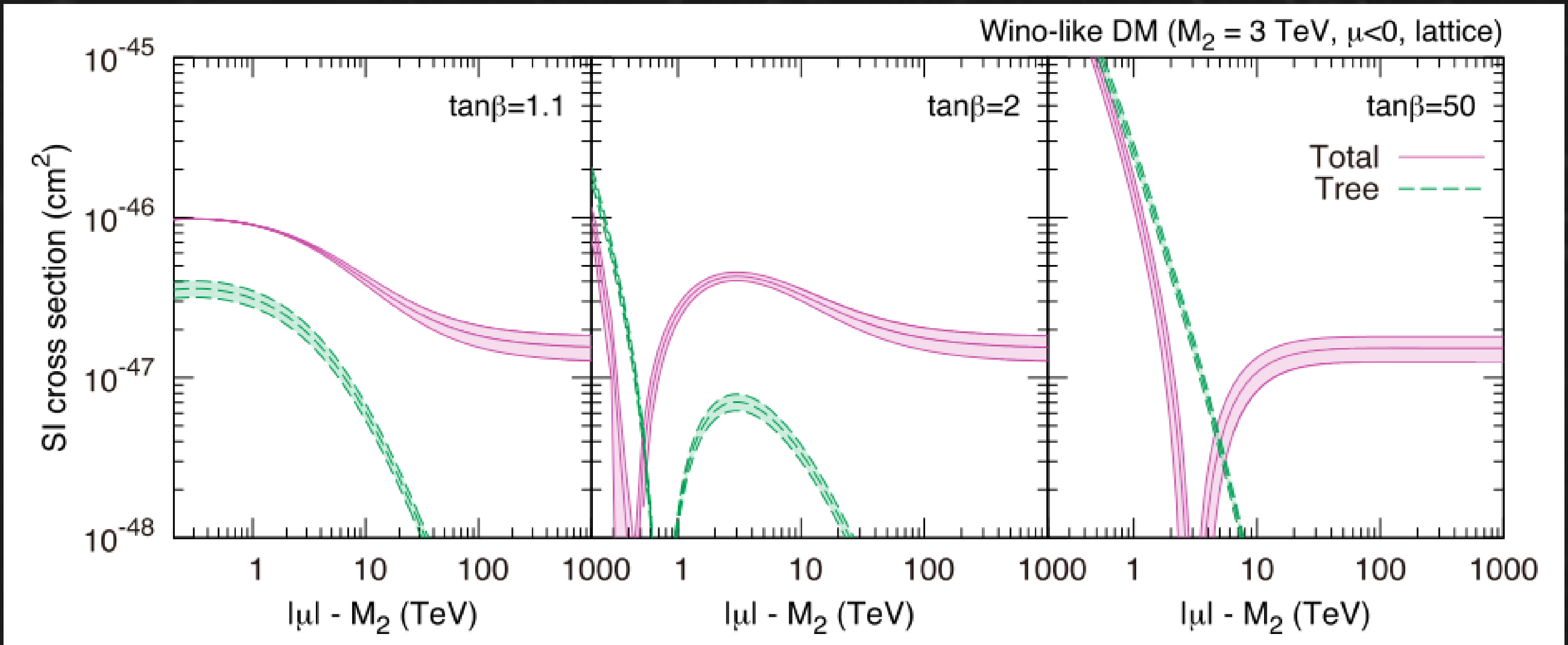


Figure 3: SI cross section of Wino-like neutralino with proton. We take $M_2 = 3$ TeV, $m_h = 125$ GeV and $\mu < 0$ (top) and $\mu > 0$ (bottom). $\tan\beta$ is taken as 1.1 (left), 2 (middle) and 50 (right) in each panel. Purple solid lines show the result from full calculation, while the result only using the Higgs contribution is in green dashed lines (color online). Shaded regions show error from the mass fractions of light quarks evaluated with the lattice QCD simulation.

LHC･理論　まとめ

SUSY兆候なし。
HIGGS質量から、
SUSYあるなら、WINO　!?

身内賢太朗　2012年11月20日　@　寄田研セミナー

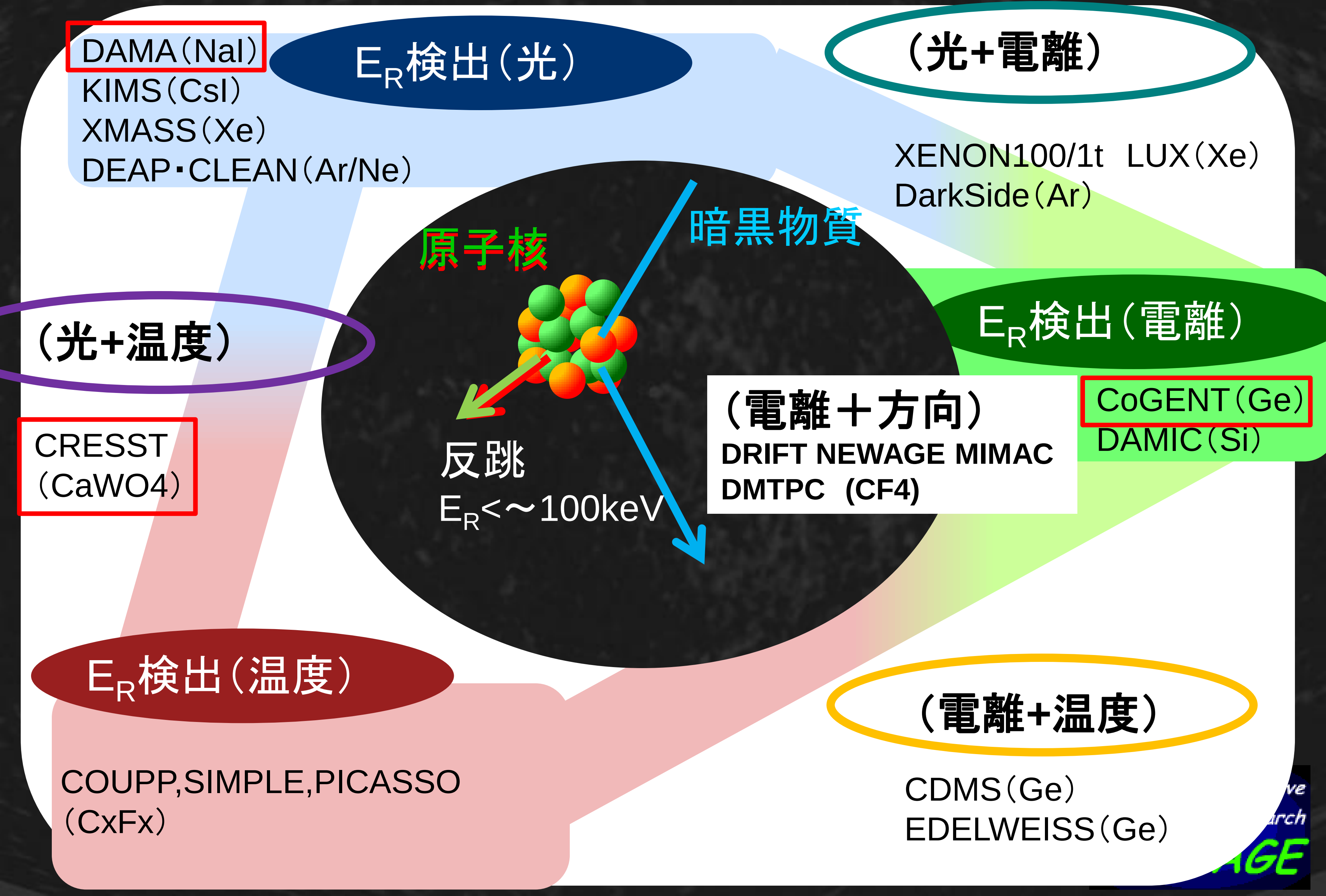
Direction Sensitive WIMP-search NEWAGE

世界と日本の
暗黒物質直接探索の現状

2012年11月20日
神戸大学　粒子物理研究室
身内賢太朗

直接探索：手法でソート

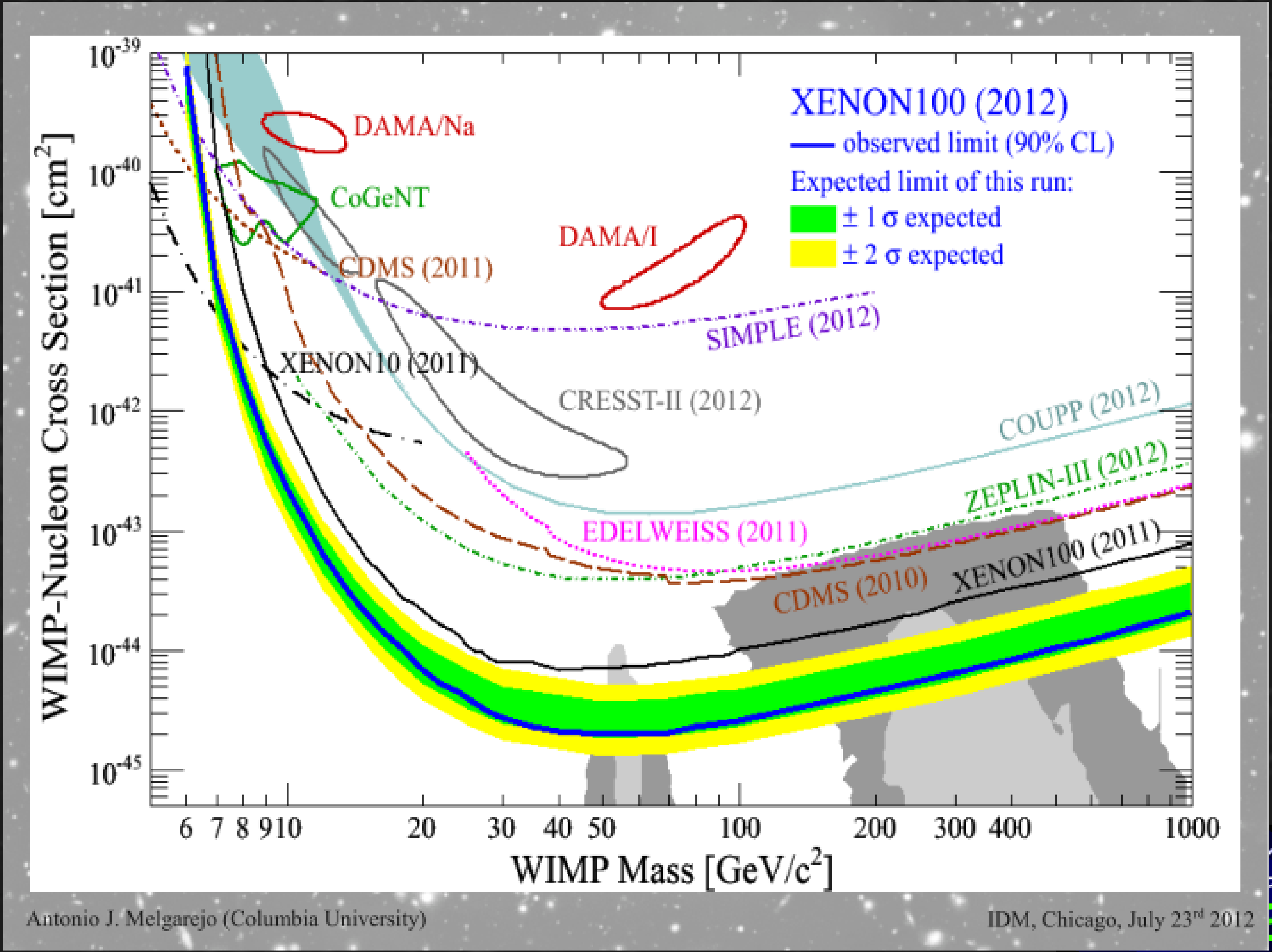
何か見えた　人たち



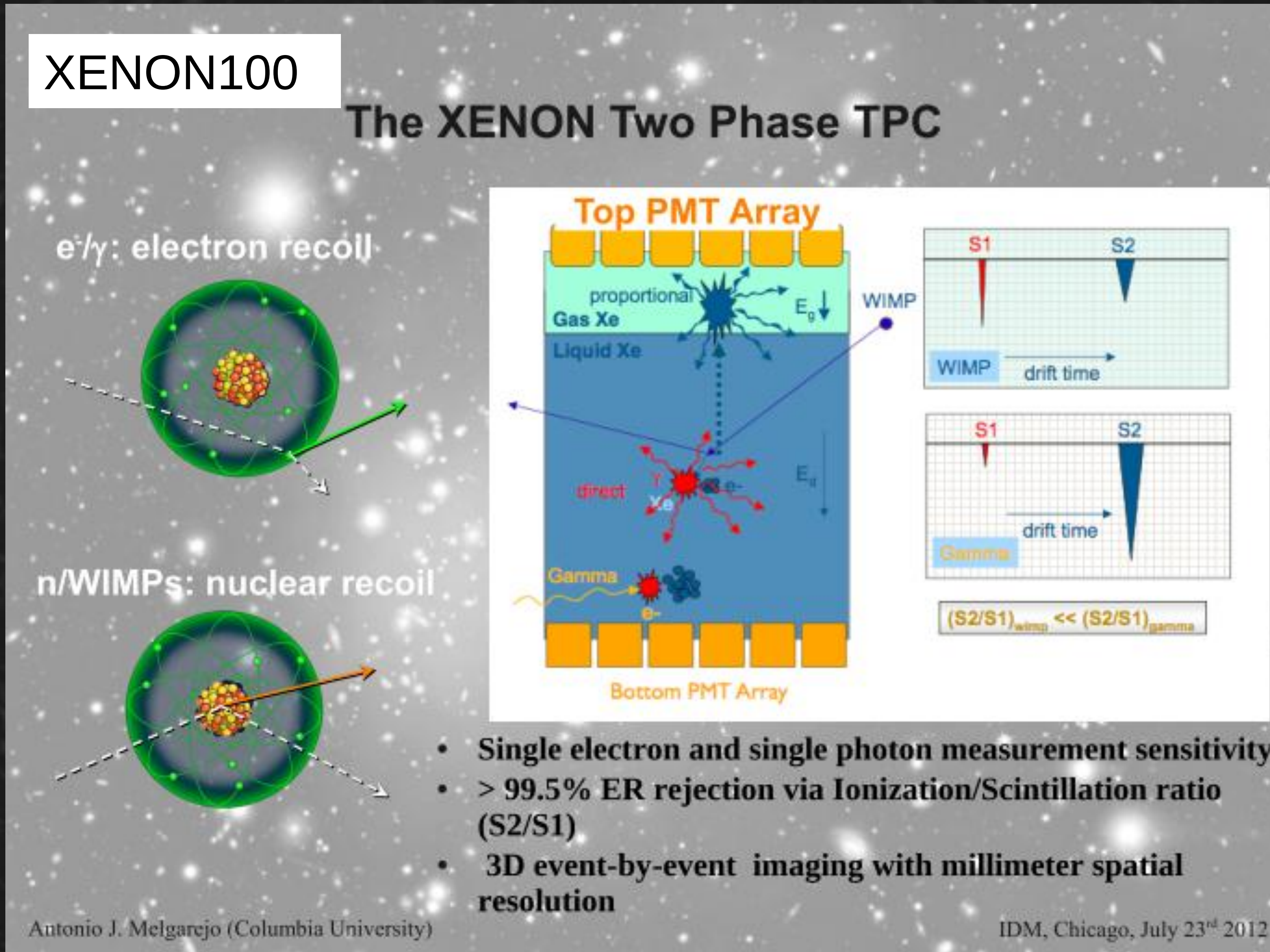
MIUCHI VISION 15

見えない最先端
見えた人たち
見たい俺たち
アリとゾウ

制限の更新（XENON100）



XENON100の特徴:γ線除去



XENON100

The XENON100 Detector

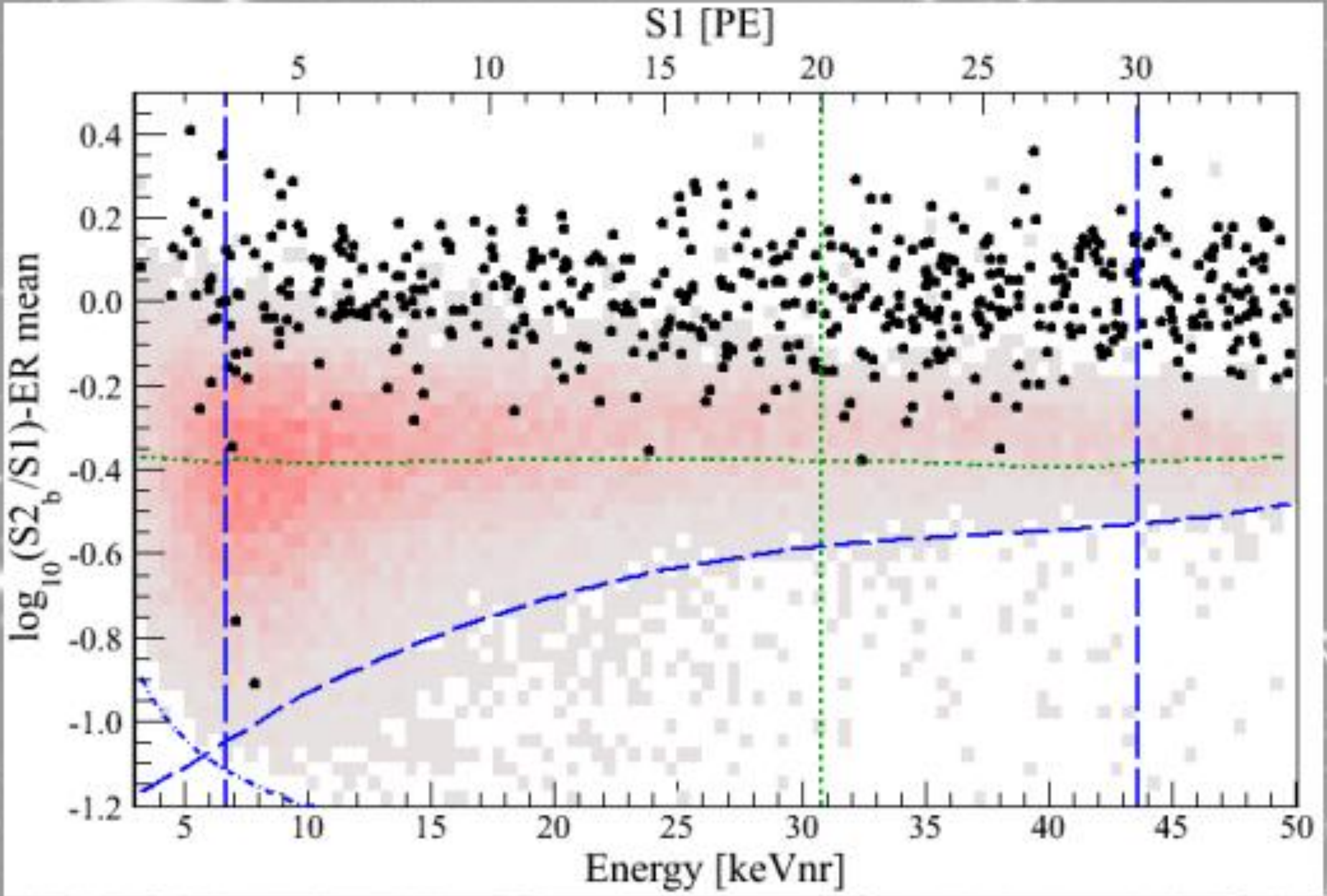
- XENON100 was designed to be ~100 times more sensitive than XENON10
- Target: 30 cm drift x 30 cm diameter TPC
- 162 kg ultra pure LXe (target + veto)
- Cryocooler and FTs outside shield
- Selection of materials for low radioactivity

- 242 1-inch square PMTs: 1 mBq (U/Th) and ~30% QE
- LXe veto around target on all sides
- Multilayer passive shield (Cu,Poly, Pb+Water)

XENON100

2事象あるけれど、BGとconsistent

Unblinding results

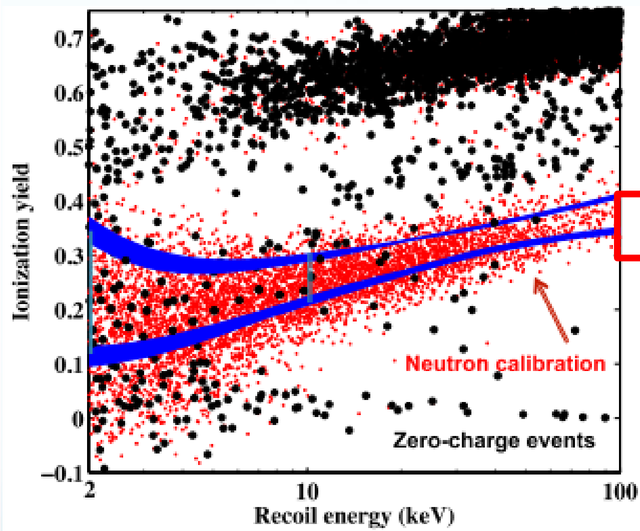


- 2 events observed in the signal region with (1±0.2) expected
- No events below the signal threshold

CDMS,EDELLWEISS（Ge）

CDMS

Yield for best detector (T1Z5)



What do we give up at low threshold ?

Risetime compromised ➔ No phonon timing cut

Ionization signals too small ➔ No fiducial cut

No longer “background-free”

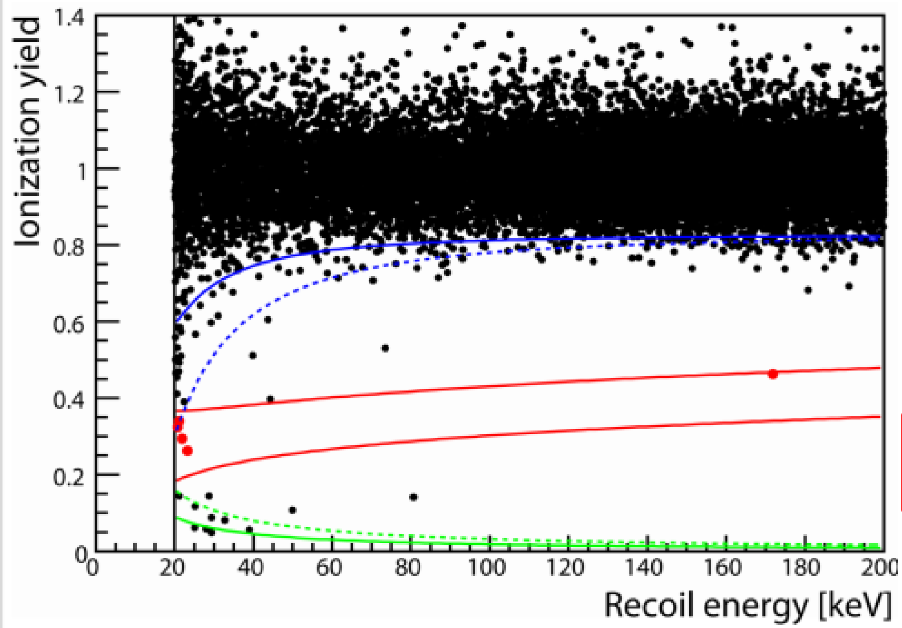
Optimum Interval method sets 90% CL limits in the presence

Priscilla Cushman
University of Minnesota

EDELWEISS

EDW-II final result (2008+2009+2010)

KIT Karlsruhe Institute of Technology



total exposure of 427kg.d →384kg.d in 90% NR band (WIMP RoI) fiducial mass 1.6kg

5 events observed (4 with E<22.5keV; 1 with E=172keV)

3 evts bg expected 20<E<100 keV

→ no indication for a WIMP signal

PLB702,5 (2011) 329

standard halo → σ_{SI} < 4.4 x 10^{-8} pb at 90%C.L. for M_{WIMP} = 85 GeV/c^2

MIUCHI VISION 15

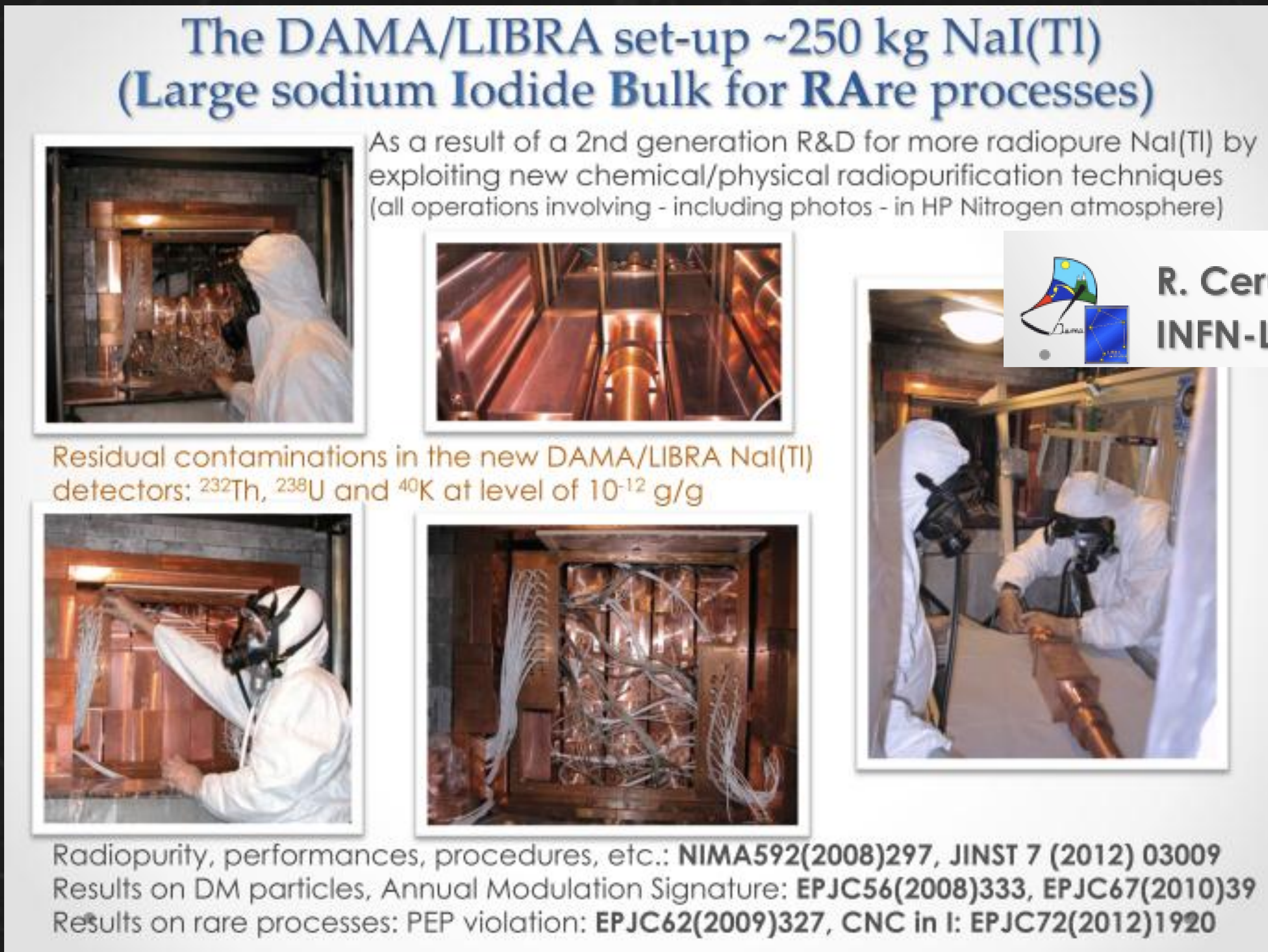
見えない最先端　← XENON100「γ除去」

見えた人たち

見たい俺たち

アリとゾウ

- 「見えた」人たち
  - DAMA（NaI）圧倒的な統計量



R. Cerulli
INFN-LNGS

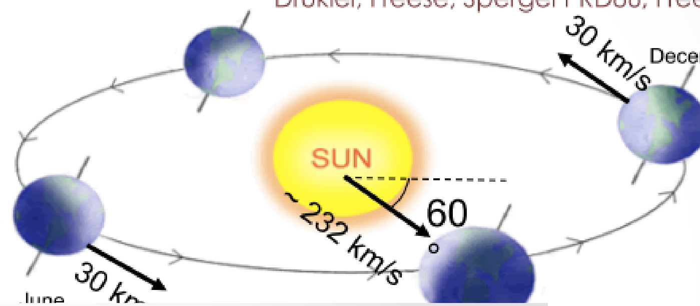
Direction Sensitive WIMP-search NEWAGE

- **DAMA(NaI)は元気に 14サイクル**

…s of the …ulation

1) Modulated rate according cosine
2) In a definite low energy range
3) With a proper period (1 year)
4) With proper phase (about 2 June)

Drukier, Freese, Spergel PRD86; Freese et al. PRD8…



- v_{sun} ~ 232 k… (Sun vel in … halo)
- v_{orb} = 30 k… (Earth vel around the Sun)
- $\gamma = \pi/3$, ω … T, T = 1 yea…
- t_0 = 2nd Ju… (when $v_\oplus$ i… maximum)

…$_0$)]

…$\cos[\omega(t-t_0)]$

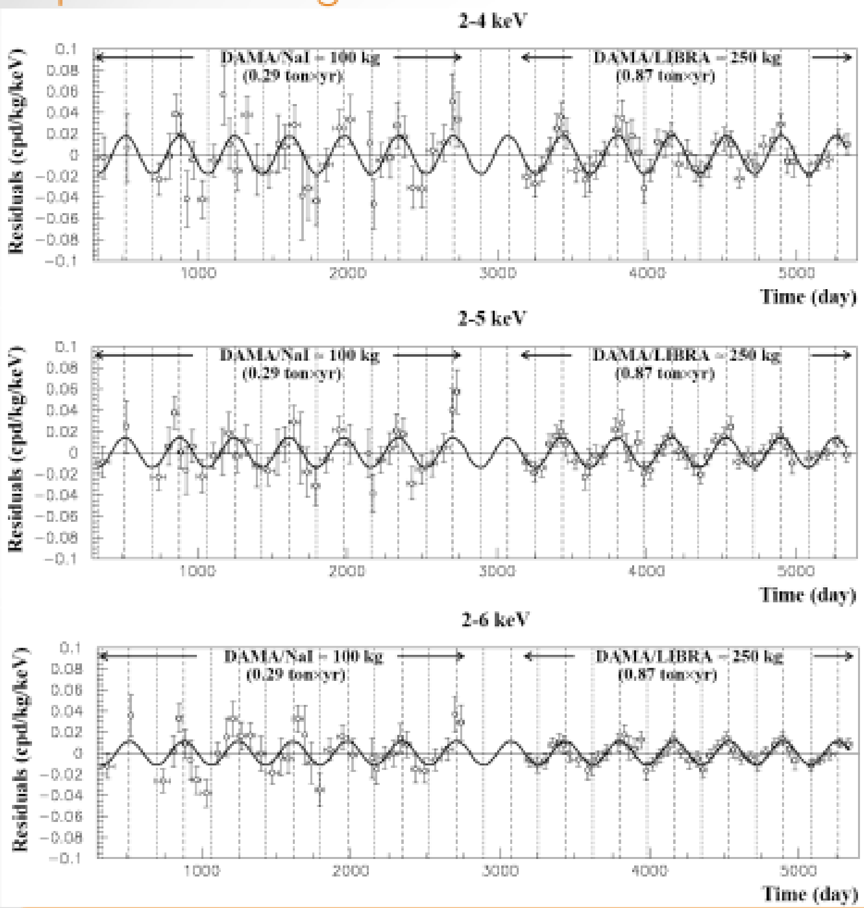
…different origin and peculi… …ed with the seasons

… - obviously - be able t… …sfy contemporaneously

Model Independent Annual Modulation Result

DAMA/NaI (7 years) + **DAMA/LIBRA** (6 years) Total exposure: 425428 kg×day = **1.17 ton×yr**

experimental single-hit residuals rate vs time and energy



2-4 keV

A=(0.0183±0.0022) cpd/kg/keV

χ^2/dof = 75.7/79 8.3 σ C.L.

Absence of modulation? No

χ^2/dof=147/80 ⇒ P(A=0) = 7×10^{-6}

2-5 keV

A=(0.0144±0.0016) cpd/kg/keV

χ^2/dof = 56.6/79 9.0 σ C.L.

Absence of modulation? No

χ^2/dof=135/80 ⇒ P(A=0) = 1.1×10^{-4}

2-6 keV

A=(0.0114±0.0013) cpd/kg/keV

χ^2/dof = 64.7/79 8.8 σ C.L.

Absence of modulation? No

χ^2/dof=140/80 ⇒ P(A=0) = 4.3×10^{-5}

R. Cerulli
INFN-LNGS

Direction Sensitive WIMP-search NEWAGE

- いちゃもんもつくけど、
DAMA(NaI)は元気です

arXiv:1205.3675v1

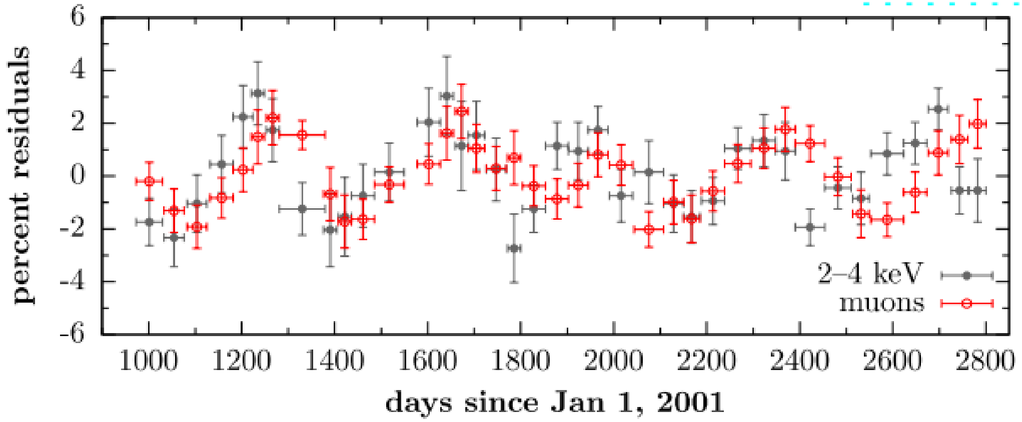


Figure 1: Percent annual residuals of the LVD measured muon flux when binned in accordance with the DAMA/LIBRA runs 1–5. The latter residuals are shown for the 2–4 keV bins assuming a baseline count rate of $\bar{s} = 1.15$ cpd/kg/keV.

形似ているけど、
μが2か月遅れ

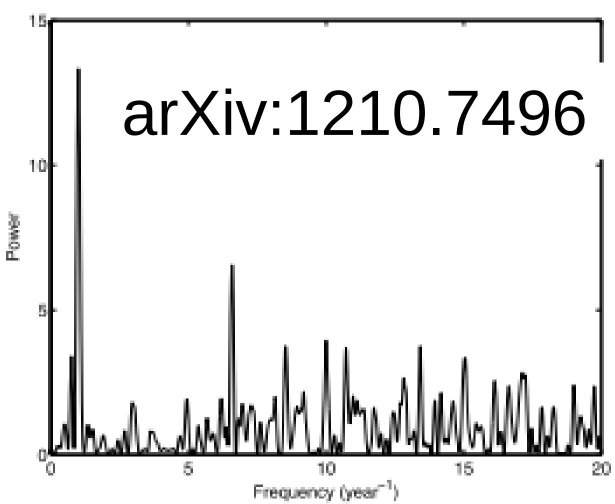
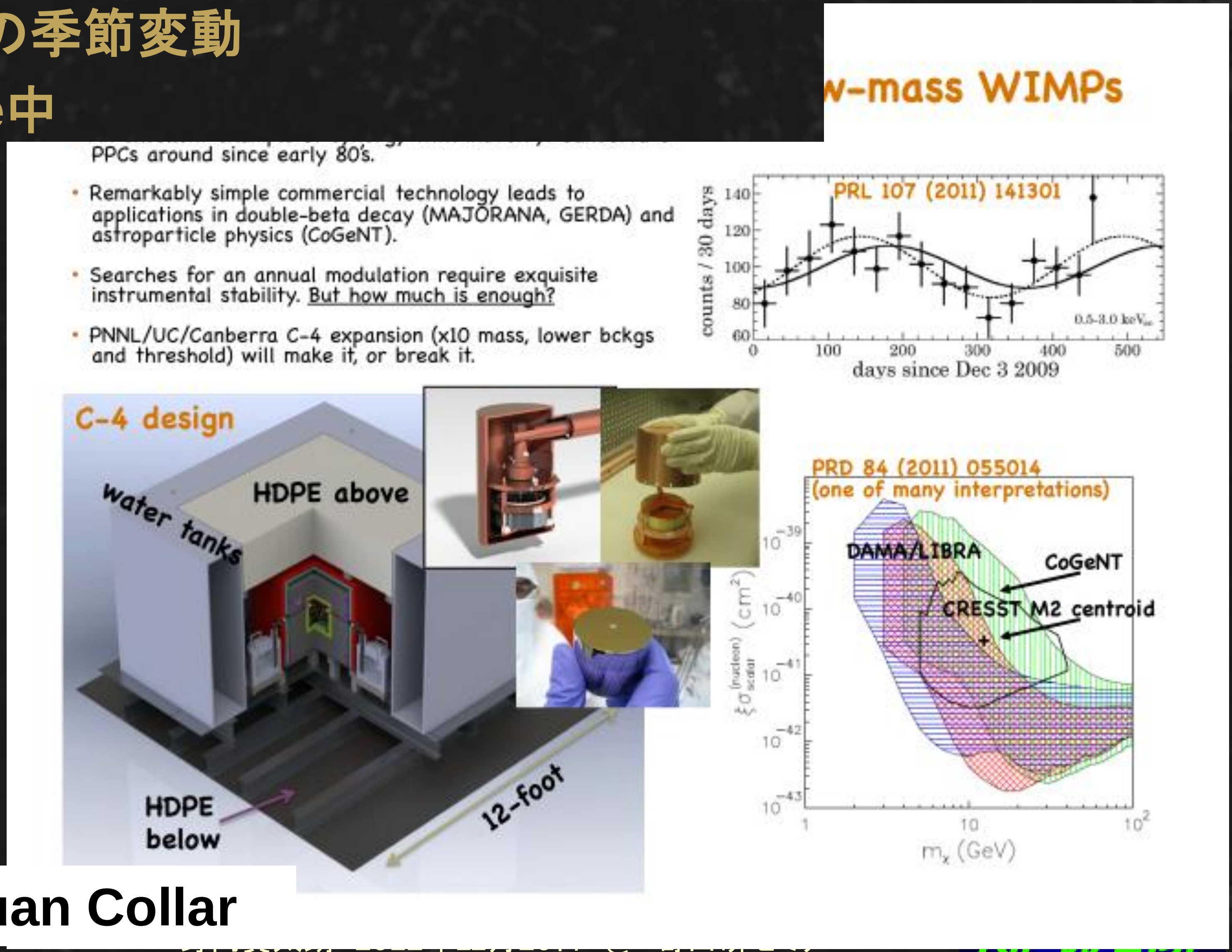


Figure 1. Power spectrum analysis of DAMA/LIBRA data, using the Lomb-Scargle procedure.

11年周期は見えるけど、太陽活動だけでは説明しきれない。

Direction Sensitive WIMP-search NEWAGE

- 「見えた」人たち
  - CoGENT（440g　Ge） 0.4keV threshold
  - 1.5年分の季節変動
  - upgrade中



Juan Collar

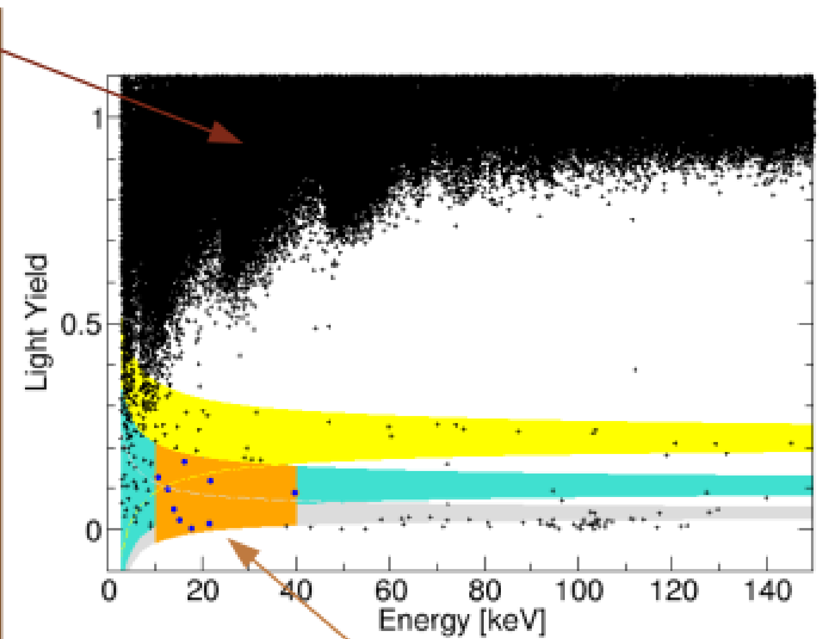
- 「見えた」人たち
  - CRESSTCaWO4　見えすぎちゃって。。。

“Results from 730 kg days of the CRESST-II Dark Matter Search”
Eur. Phys. J. C (2012) 72-1971; arXiv: 1109.0702

grounds

γ / e⁻ background

- dominant background source
- ~10^4 events/kg/yr
- **excellent discrimination**
- **expected gamma leakage** of 1 event per module **defines lower threshold** of acceptance region



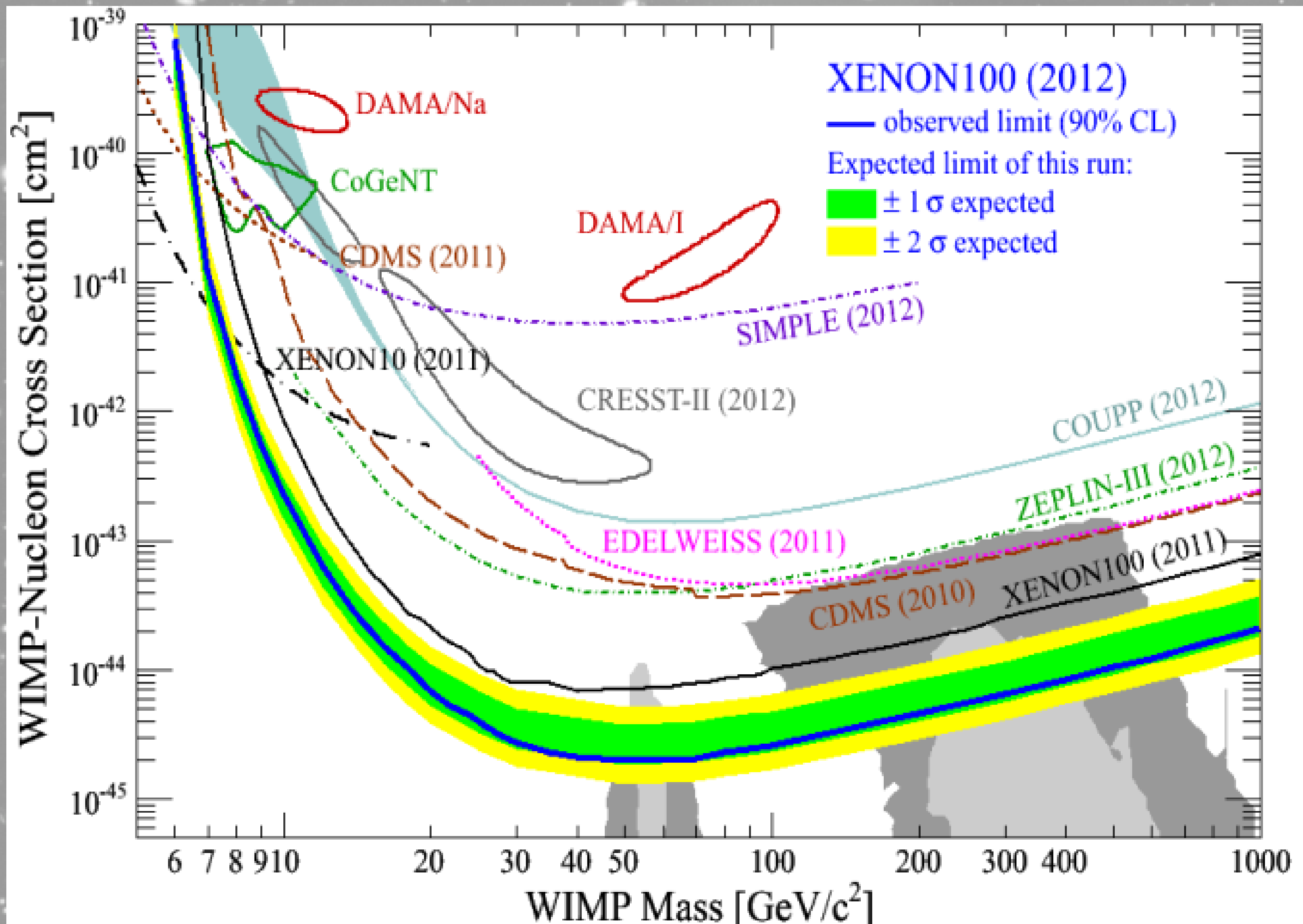
acceptance region:
O,Ca,W bands; ~10-40 keV

	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]	$1.6 \cdot 10^{-6}$	$3.7 \cdot 10^{-5}$
stat. significance	4.7 σ	4.2 σ

Christian Strandhagen (University Tübingen)
on behalf of the CRESST Collaboration

M1M2の違いは　Wの反応の量

状況再確認



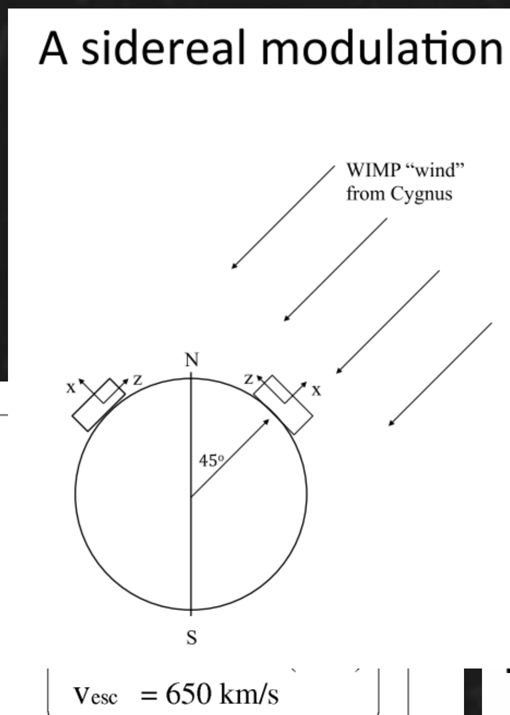
Antonio J. Melgarejo (Columbia University)

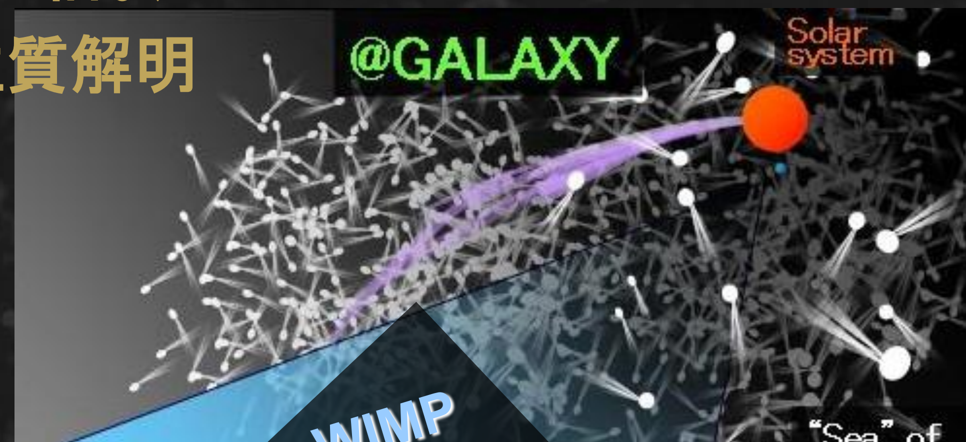
IDM, Chicago, July 23rd 2012

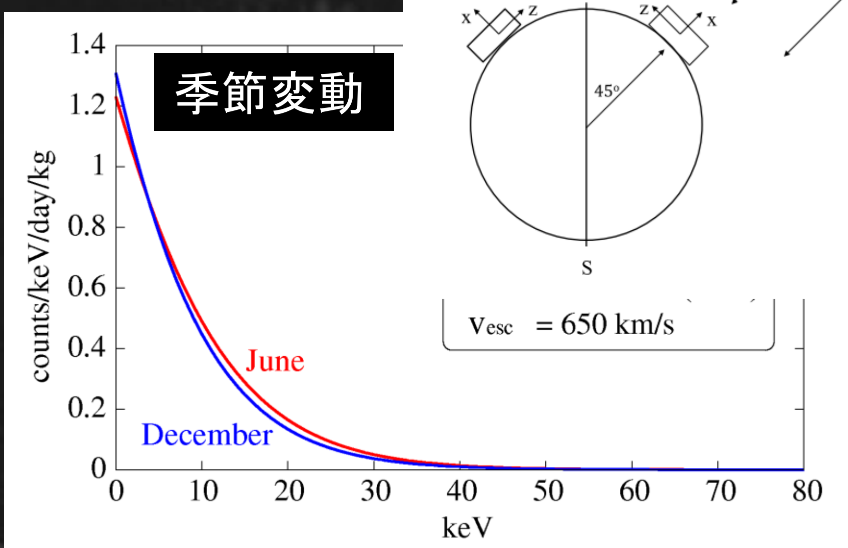
MIUCHI VISION 15

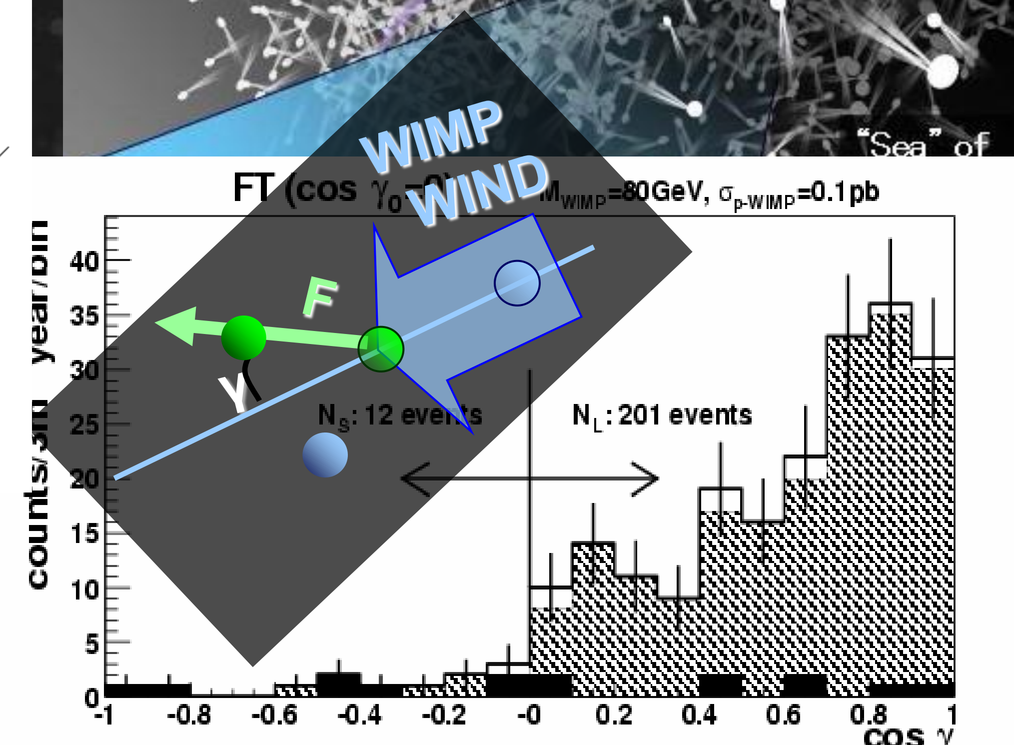
見えない最先端　← XENON100「ガンマ除去」
見えた人たち　← DAMA「統計」
見たい俺たち
アリとゾウ

- 「見たい」おれたち（チームCYGNUS）
  - 到来方向は昼夜で変わる
  - 季節変動(5%以下)と比較して確実な証拠（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









協力と競争の共存

Directional Dark Matter Community -

Directional Conference Series

- Cygnus 2007 – Boulby England
- Cygnus 2009 – Boston USA
- Cygnus 2011 – Aussois France
- Cygnus 2013 – Toyama Japan

January 18, 2010 17:19 WSPC/139-IJMPA 04817

Review

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THE CASE FOR A DIRECTIONAL DARK MATTER DETECTOR AND THE STATUS OF CURRENT EXPERIMENTAL EFFORTS

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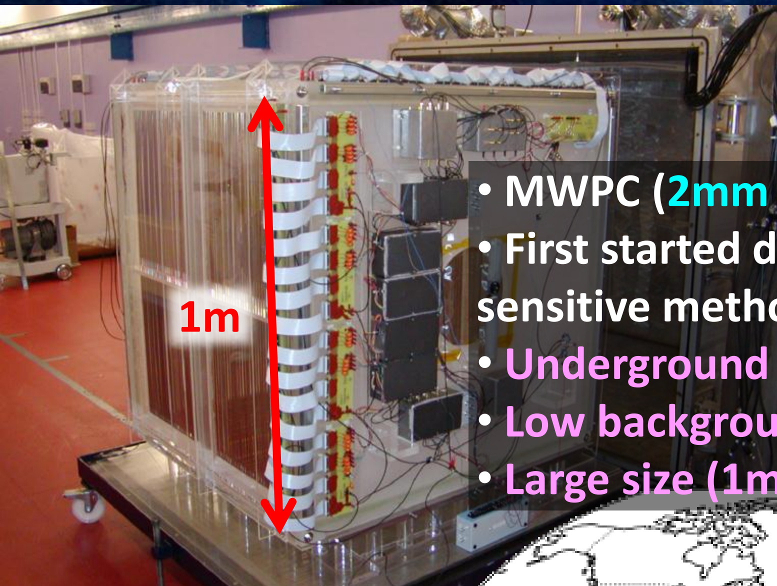
1

「方向性」の重要性

med ena hälften gemensamt belöna
Masatoshi Koshiba
och Raymond Davis Jr
för banbrytande insatser inom astro-fysiken, särskilt för detektion av kosmiska neutriner
STOCKHOLM DEN 10 DECEMBER 2002
Kungliga
Svenska Vetenskapsakademien
har den 8 oktober 2002 beslutat
att med det
NOBELPRIS
som detta år tillerkännes den som inom
fysikens område gjort den viktigaste
upptäckten eller uppfinningen
med ena hälften gemensamt belöna
Raymond Davis Jr
och Masatoshi Koshiba
för banbrytande insatser inom astro-
fysiken, särskilt för detektion av
kosmiska neutriner
STOCKHOLM DEN 10 DECEMBER 2002

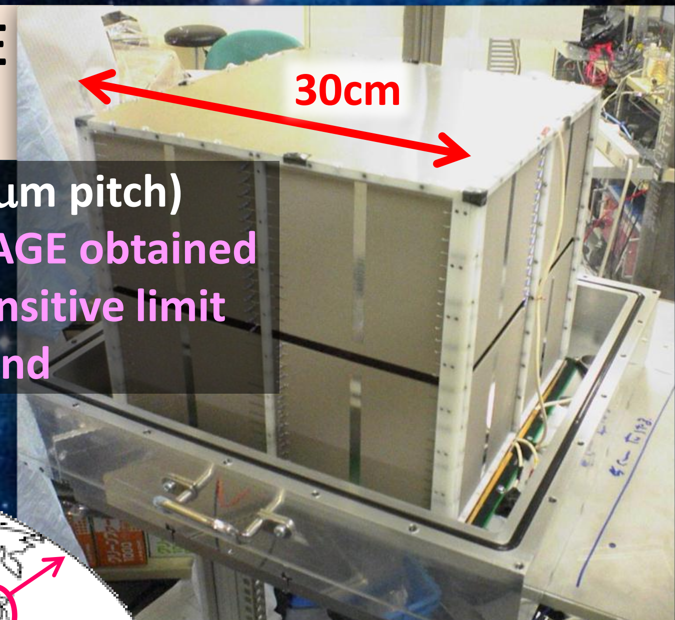
Direction-sensitive DM search

DRIFT [UK]

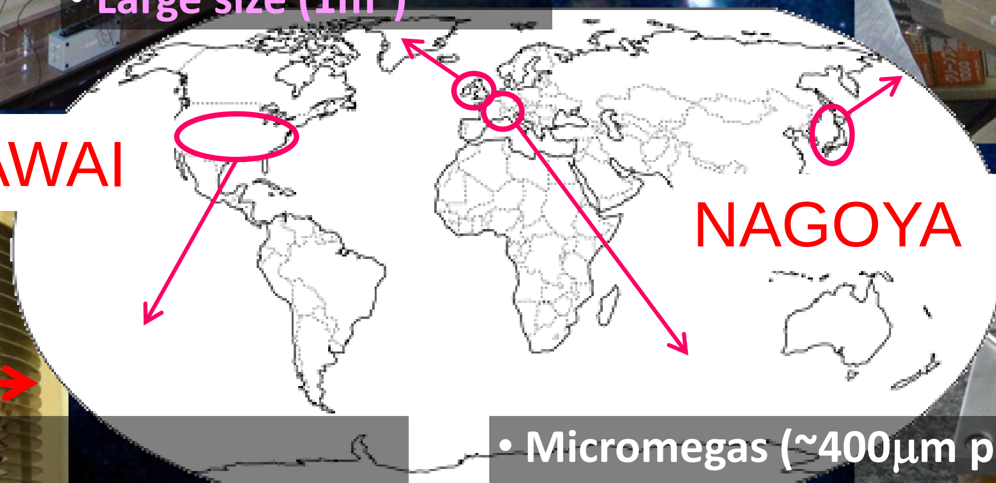


- MWPC (2mm pitch)
- First started direction-sensitive method
- Underground
- Low background
- Large size (1m³)

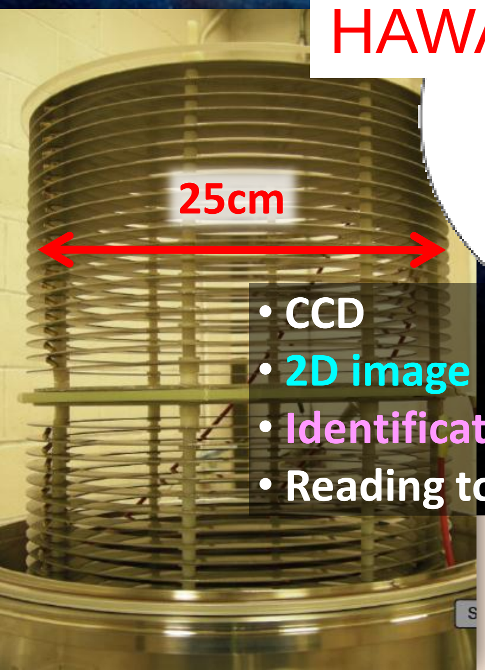
NEWAGE [Japan]



- μ-PIC (400μm pitch)
- Only NEWAGE obtained direction-sensitive limit
- Underground

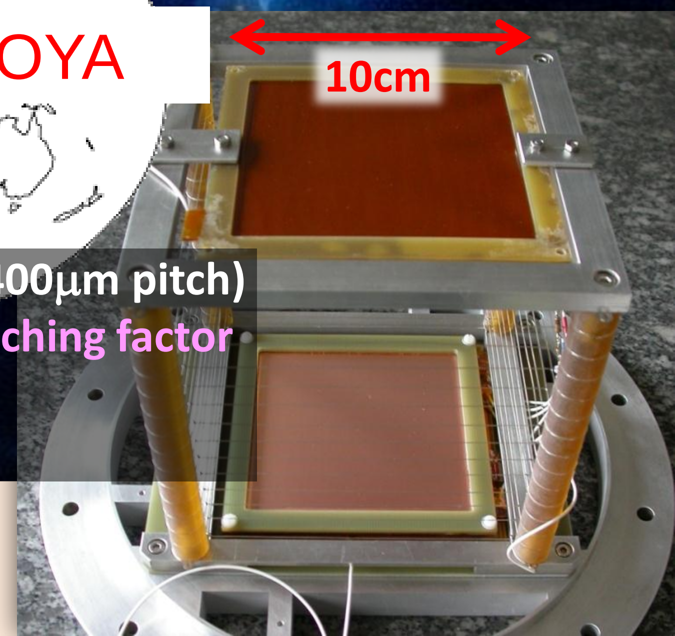


DMTPC [USA]



- CCD
- 2D image
- Identification of head-tail
- Reading to underground

MIMAC [France]



- Micromegas (~400μm pitch)
- Measured quenching factor in detail
- R&D at surface

◆ NIT（名大）

- エマルジョン
- 大質量◎
- 即時性　×
- 角度分解能、エネルギー閾値△

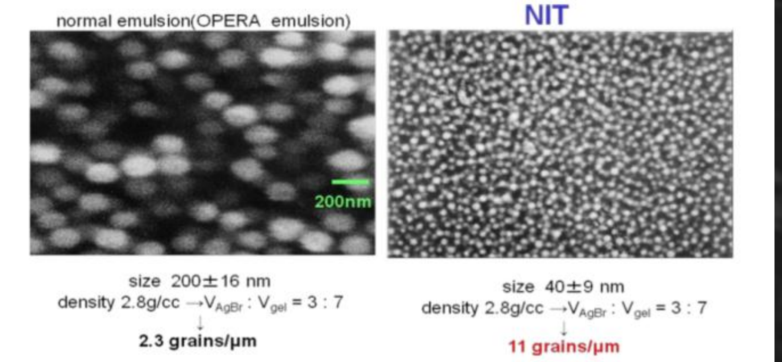


Fig. 33. Electron microscope image of standard emulsion (left) and NIT emulsion (right)

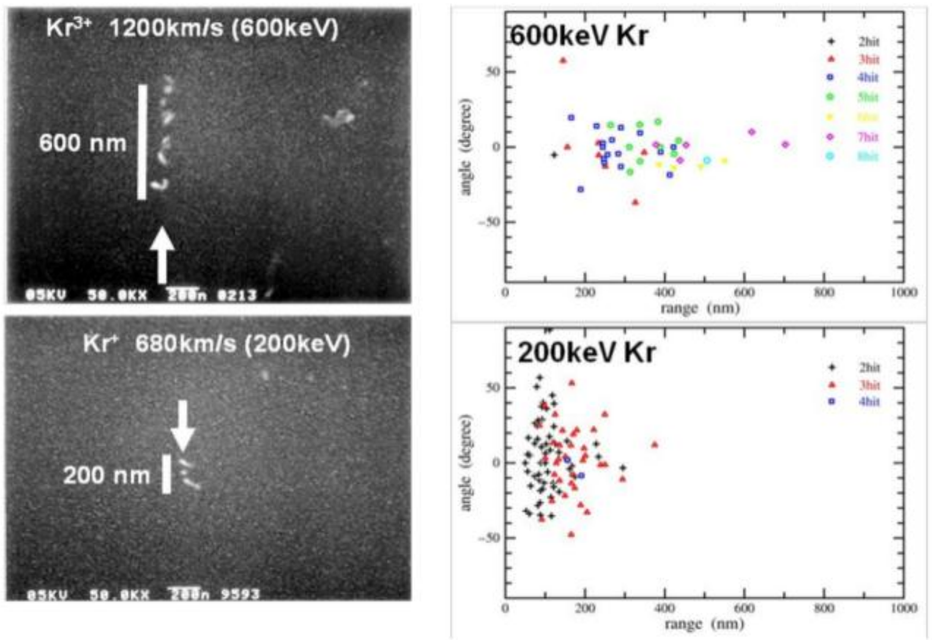
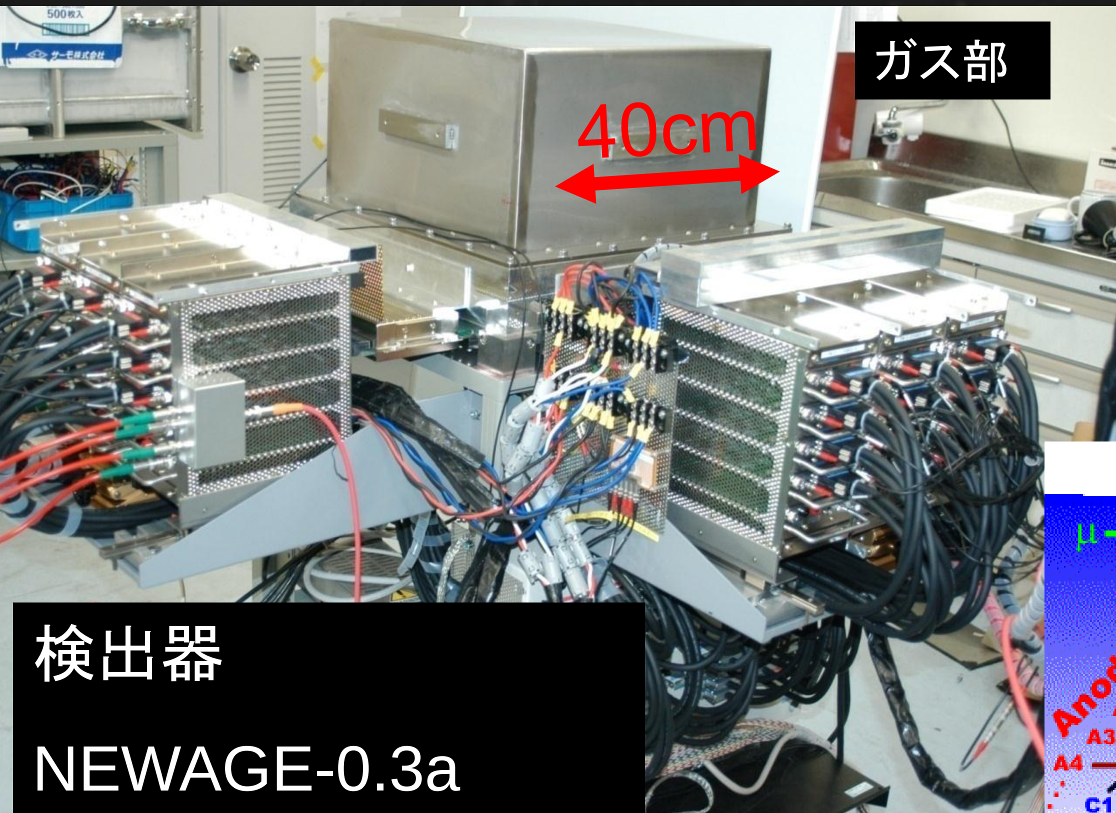
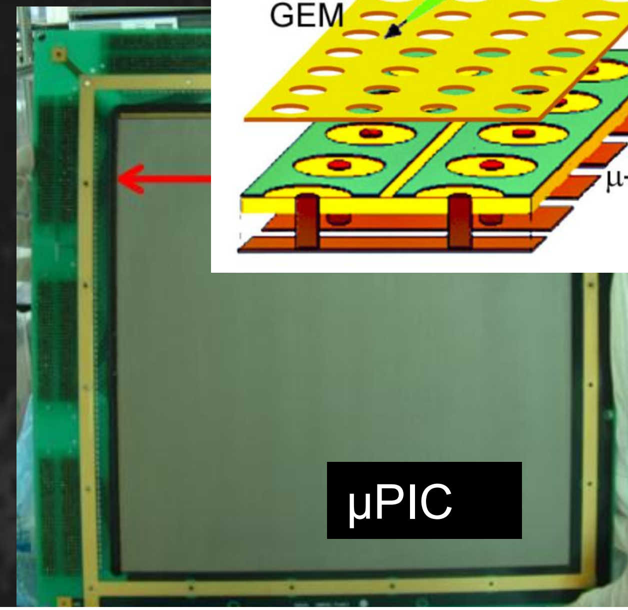


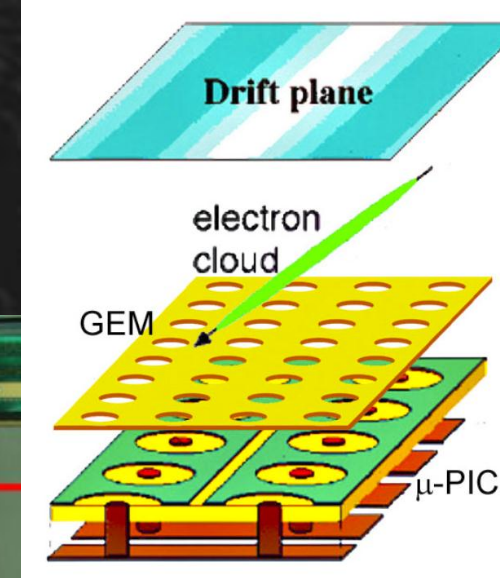
Fig. 34. (left) Electron microscope image of Kr ion track (600 keV and 200 keV) and (right) track data.

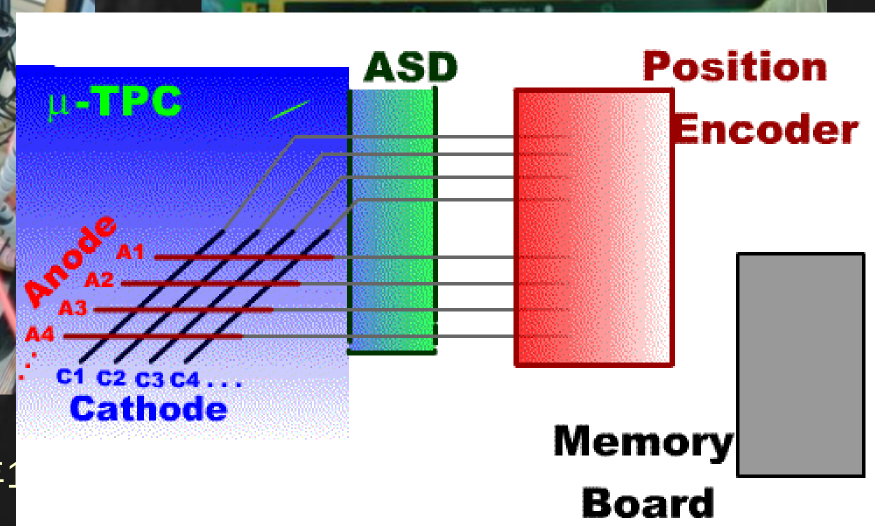
NEWAGE

- 京大で開発した「μPIC」検出器
- 30cm角検出器で地下実験中
- CF4　ガス　SD探索





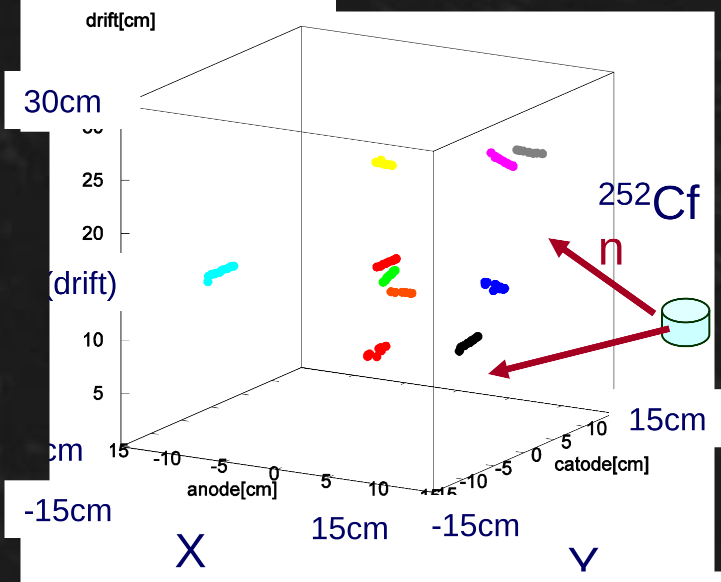




飛跡検出、イメージング

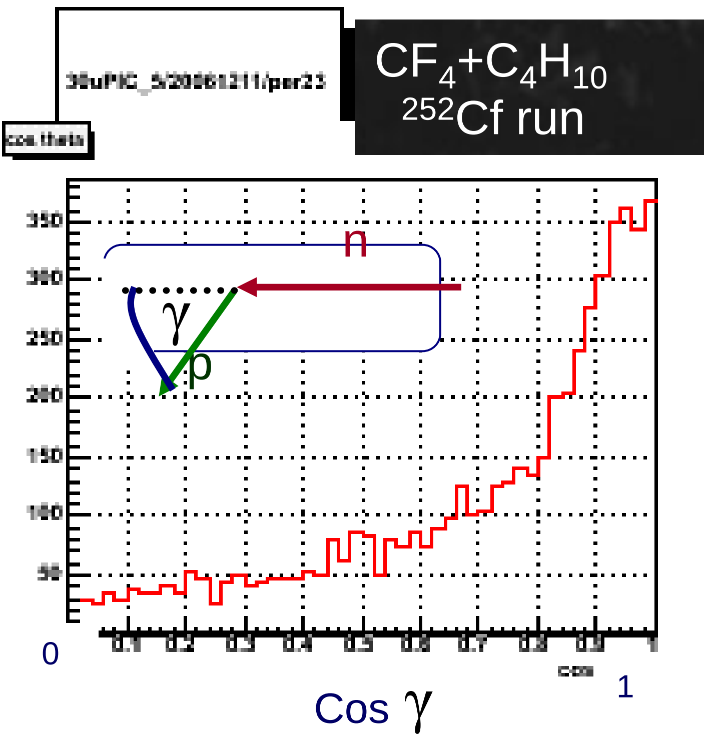
- 中性子に反跳された陽子を検出
- 前方に 散乱される様子が見えている
- WIMP→フッ素の反跳で見たい現象をエミュレート

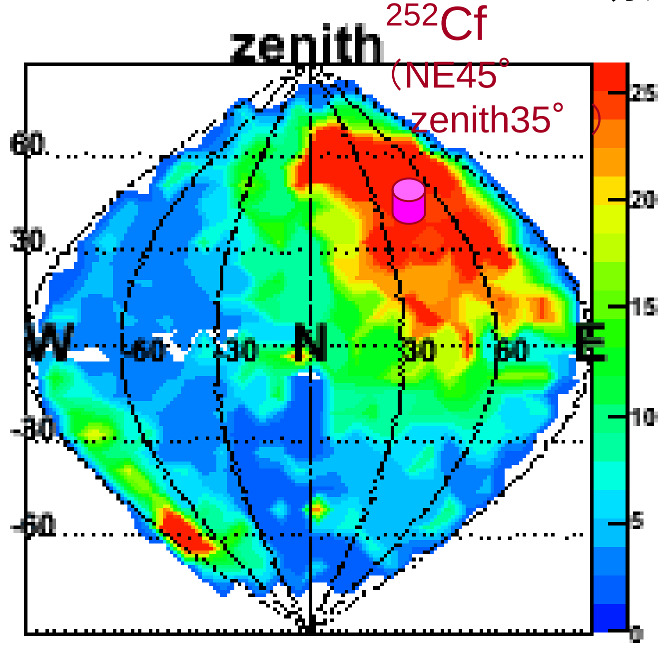
陽子飛跡の例



ガス：CF4+C4H10（10%） 0.2気圧

CF_4+C_4H_{10}
^{252}Cf run





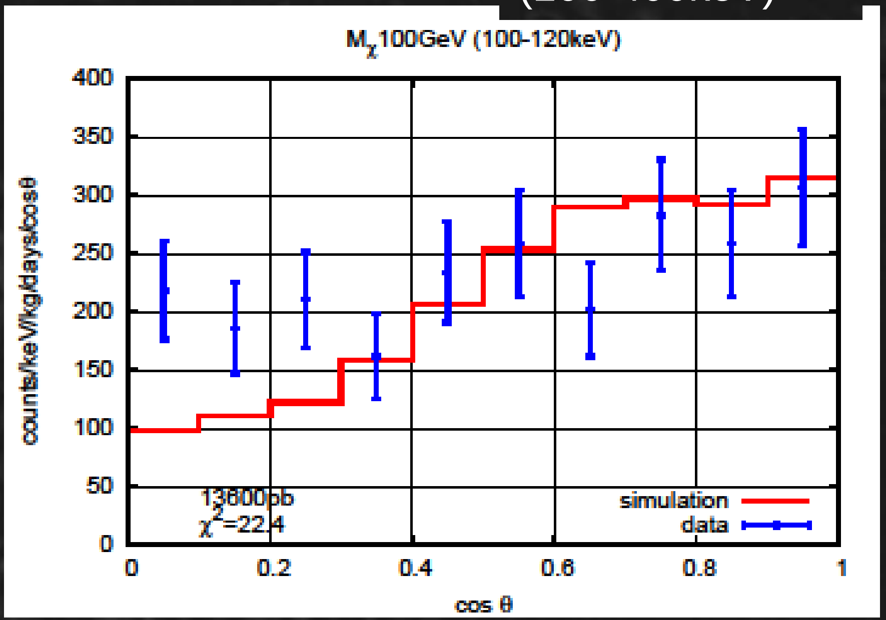
陽子の飛跡で描いた「イメージ」

地上(京大) でのDM探索実験

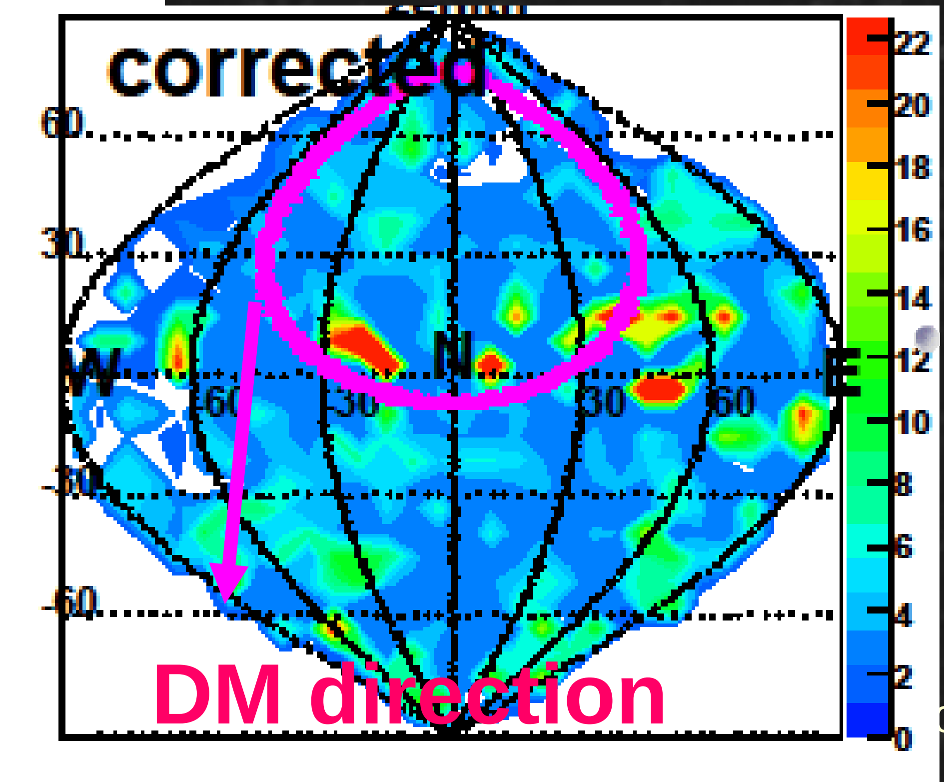
PLB654 (2007) 58-64

- 原子核飛跡を用いた手法では初めて
- 2006 年測定
- exposure 0.15 kg days

Cosθ 分布
(100-400keV)



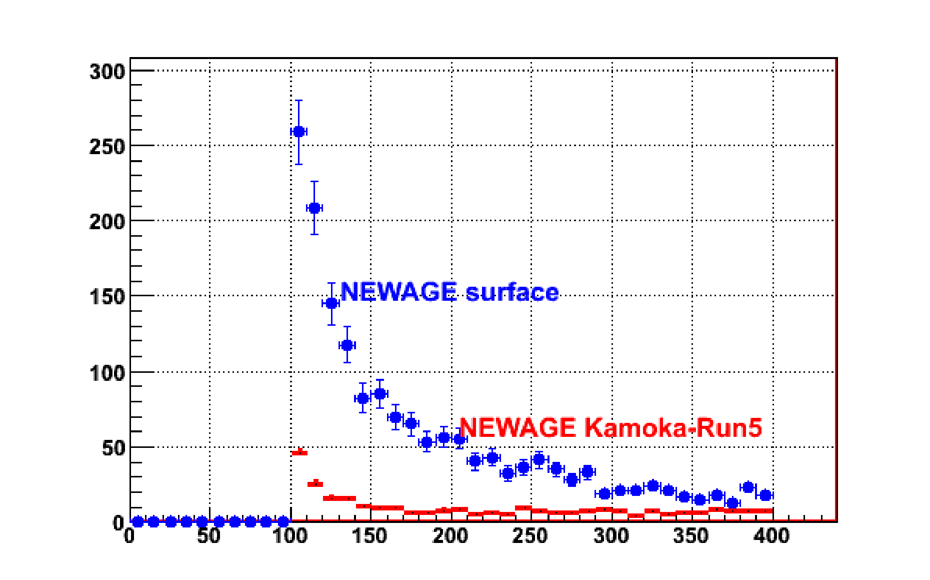
C、Fの原子核で描いた「スカイマップ」
(100-400keV)

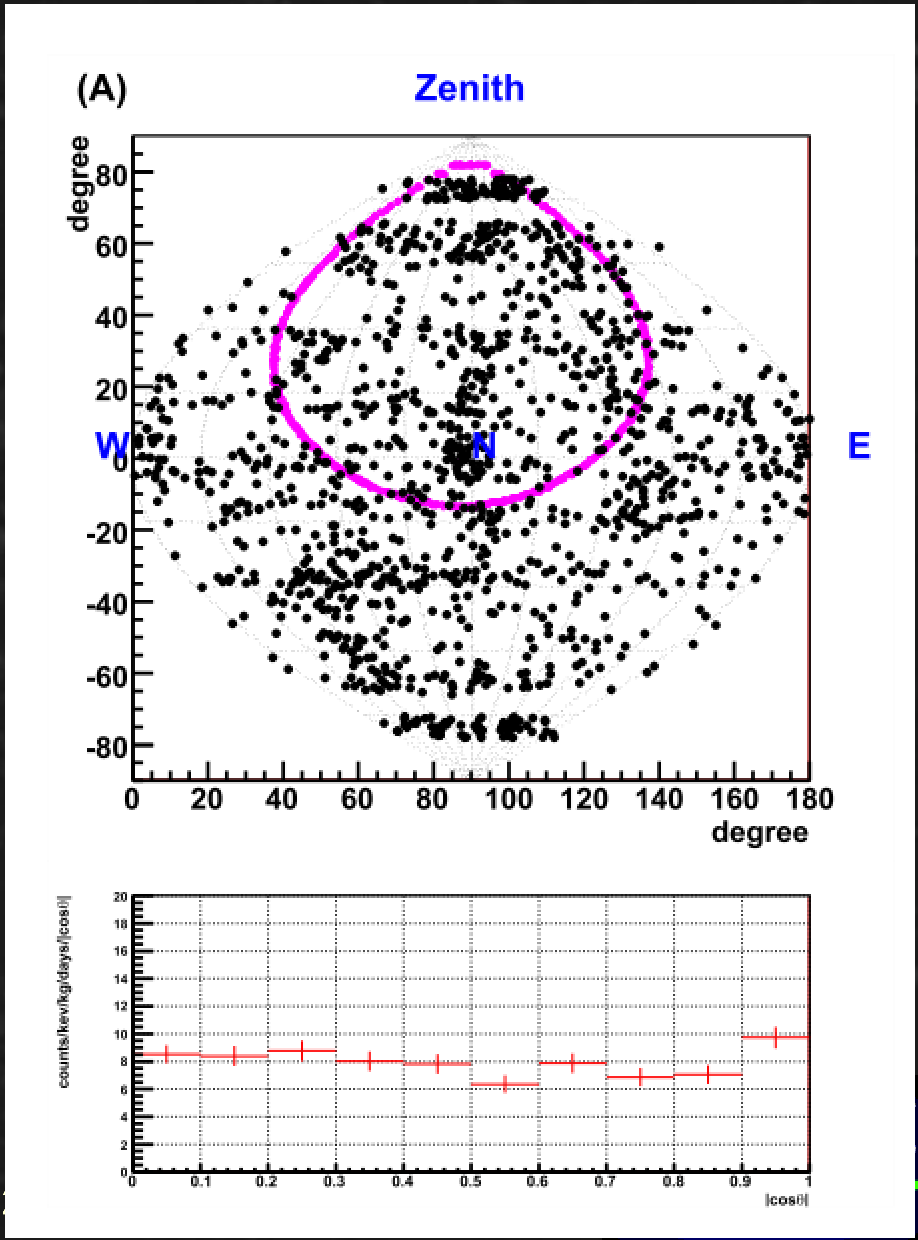


結果

- DMの信号は X^2 テストで排除
- 方向に感度をもった初の制限

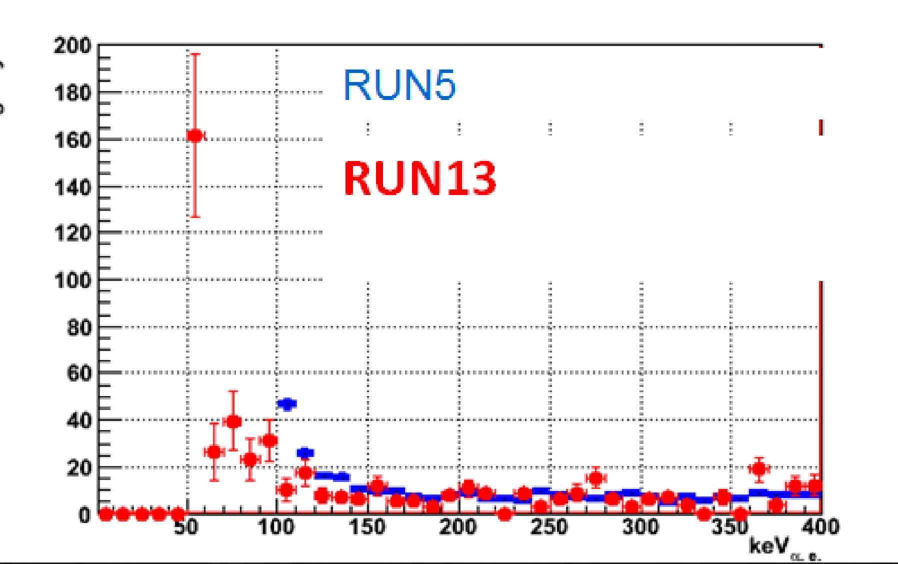
- 地下実験結果(2008年)
  - 観測0.524 kg･days
  - スペクトル
    地上の1/5 程度:新たなBG
  - スカイマップ
    フラットな cosθ 分布

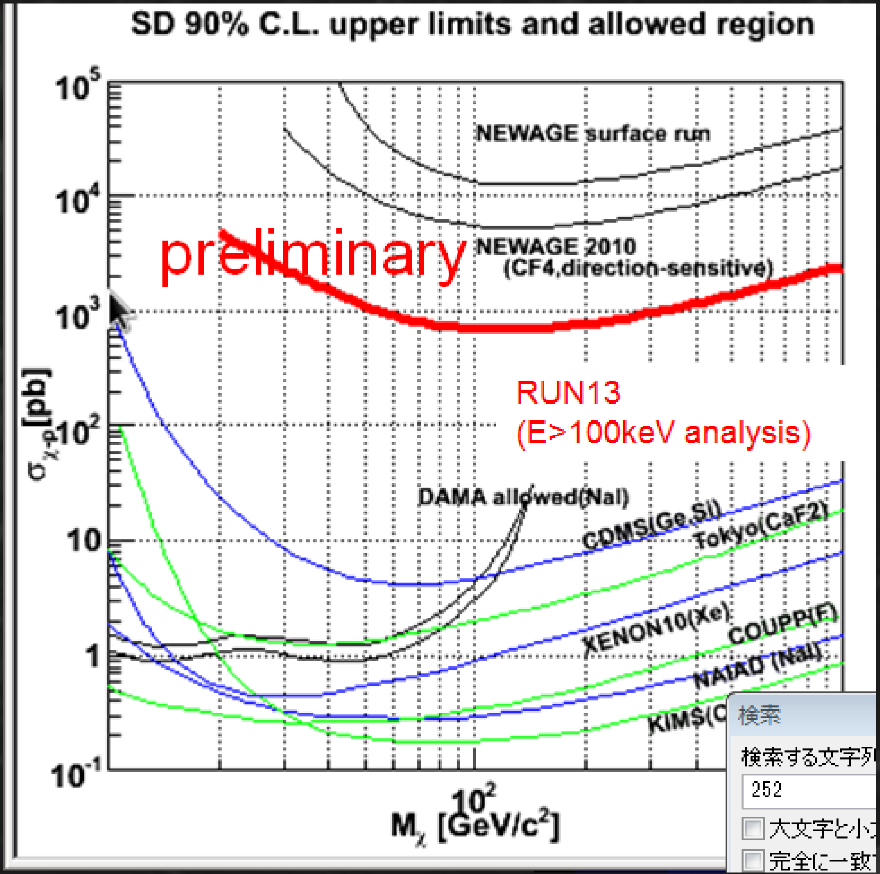




Results(preliminary)

- exposure 0.140kg・days
- spectrum threshold 100keV⇒50keV
- rate: ～1/5 at 100keV
- direction-sensitive analysis: on-going





MIUCHI VISION 15

見えない最先端　←　XENON100「ガンマ除去」
見えた人たち　←　DAMA「統計」
見たい俺たち　←　CYGNUS「方向情報」
アリとゾウ

- **XMASS**
  - 800kgは圧倒的

XMASS

Y. Suzuki

Kamioka Observatory, Institute for Cosmic Ray Research ICRR), University of Tokyo

And

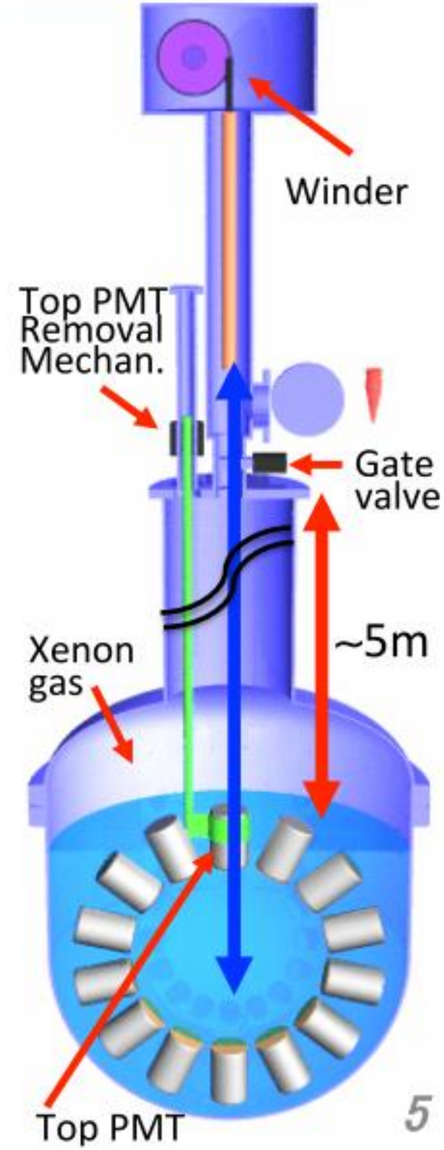
Kamioka Satellite, Kavli Institute for the Physics and Mathematics of the Universe (IPMU), University of Tokyo

XMASS

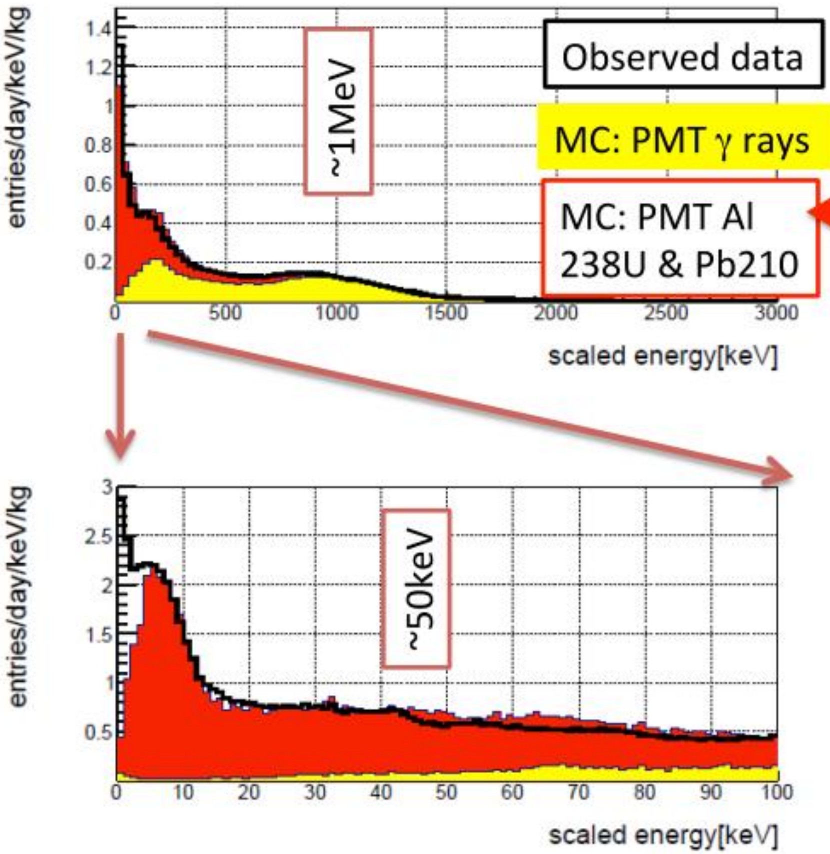
Commissioning run

- Calibration
  - Source Rod (57Co, 241Am, 137Cs, 109Cd, 55Fe)
  - External sources: 60Co, 137Cs, 232Th, Neutron
- Normal Data taking (physics runs)
- Development of Software
- Change of the physical condition of Xenon.
  - High/Low pressure runs, O2 runs to change absorption length, etc.
- Xe Gas run Important to identify the BG
- RI measurement of the detector parts（attach materials at the end of the calibration rod）

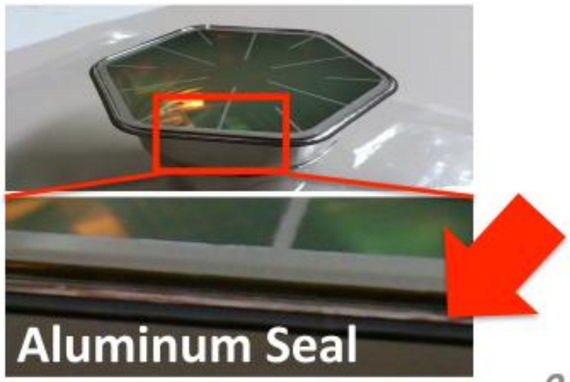
CM runs ended because the calibration rod fell off and stuck



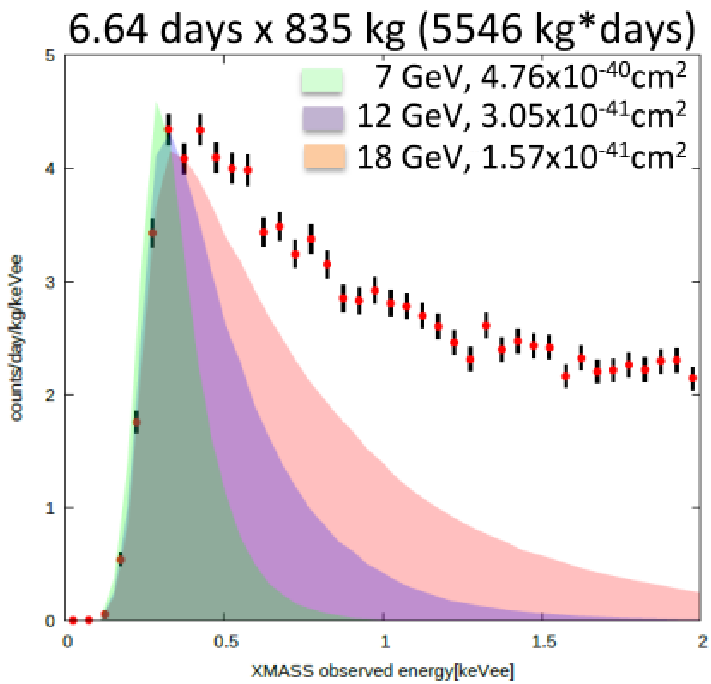
Measured Spectrum (Whole Volume)

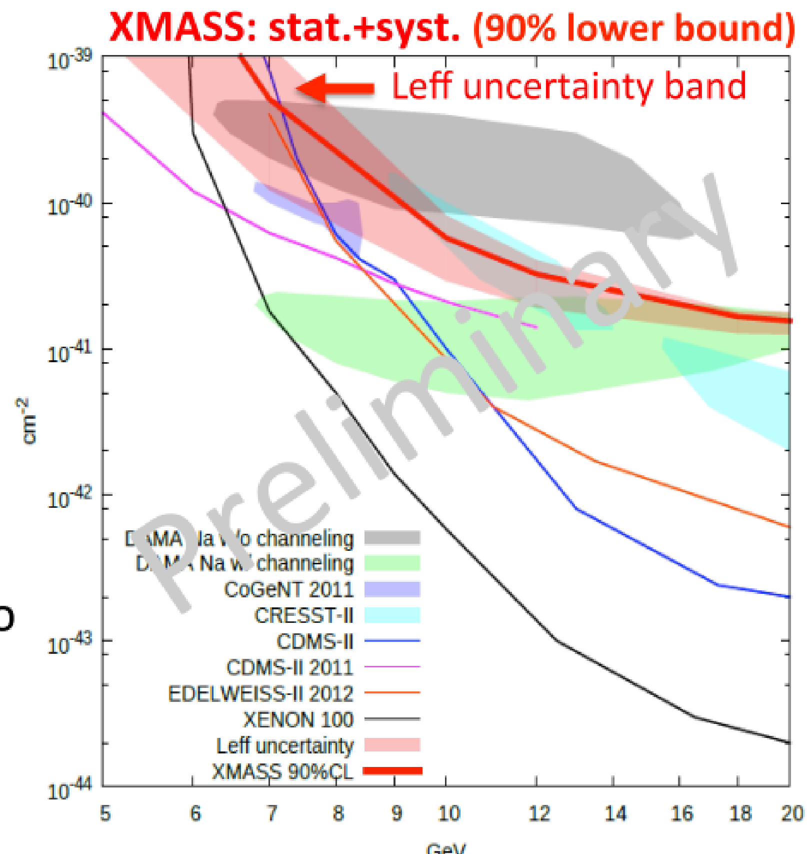


- Suspected detector parts were examined again, and found
  - Aluminum seal used between quarts window and metal body of the PMTs contains ^{238}U (upper chain) and ^{210}Pb
  - ^{210}Pb on Cu surface (as usual)



Results on low mass dark matter



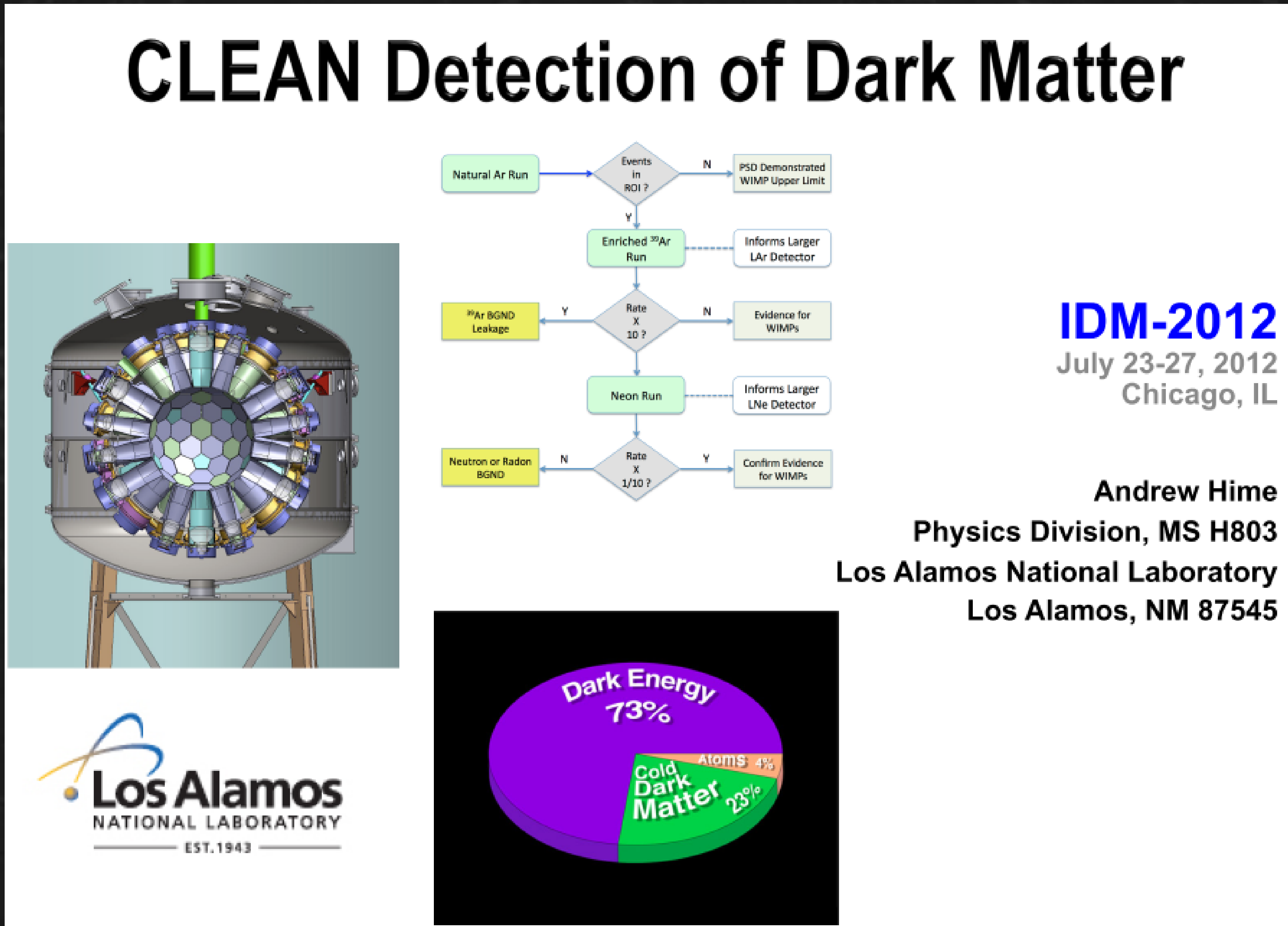


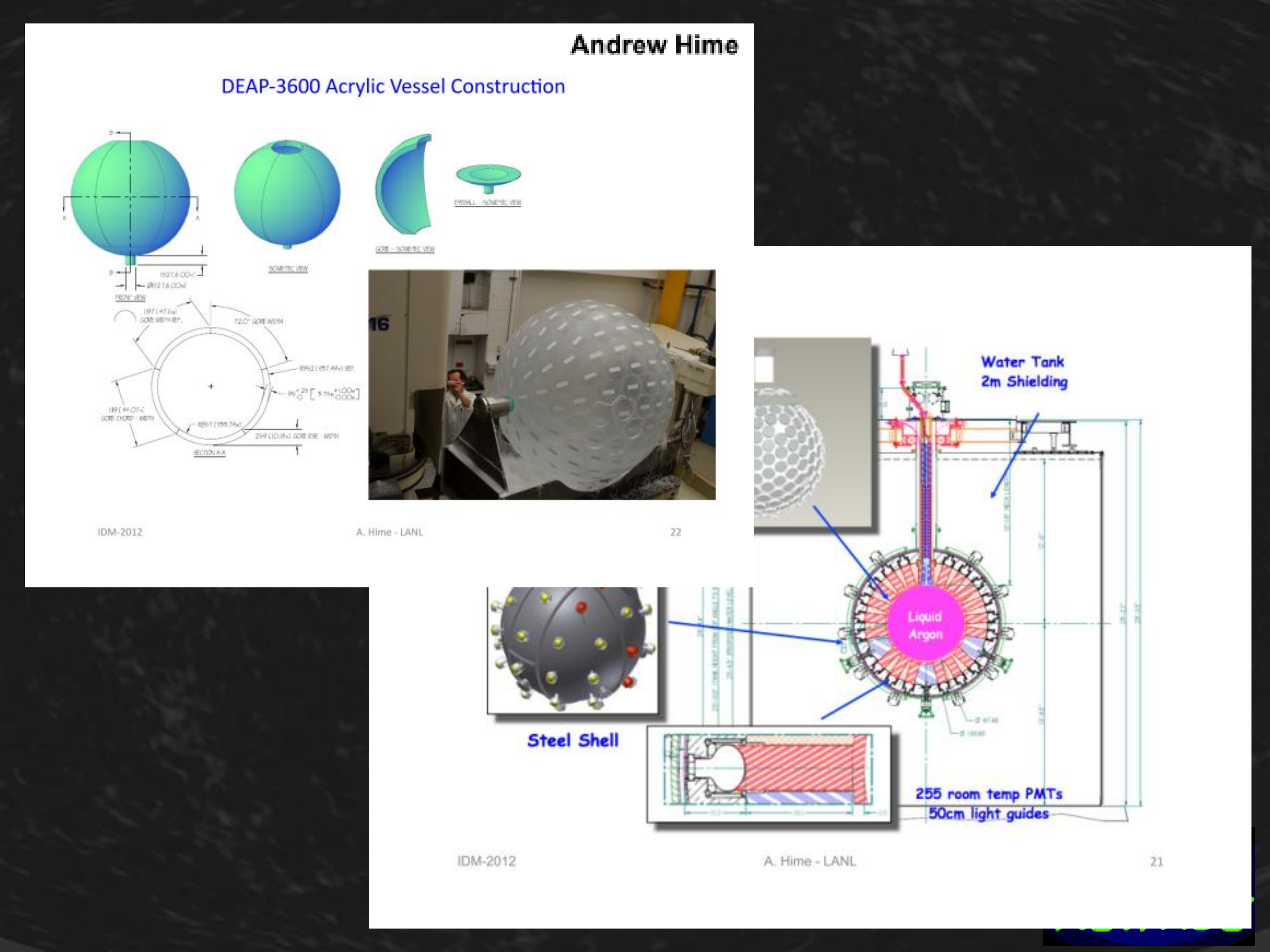
- Compare Dark Matter MC to the data
- Obtain the maximum cross section (upper limits) of the spectrum not to exceed the observed data points.
- Current XMASS is close to the allowed regions of DAMA/CoGeNT/CRESST.

We will reduce the backgrounds in near future

他のゾウのあゆみ

- DEAP/CLEAN　Ar 3.6tonを製作中。




Andrew Hime
DEAP-3600 Acrylic Vessel Construction
IDM-2012
A. Hime - LANL
22
Water Tank
2m Shielding
Liquid
Argon
Steel Shell
255 room temp PMTs
50cm light guides
IDM-2012
A. Hime - LANL
21

- **DARKSIDE**

DarkSide Program

Multi-stage program at Gran Sasso National Laboratory

DarkSide 10
Currently running full prototype detector

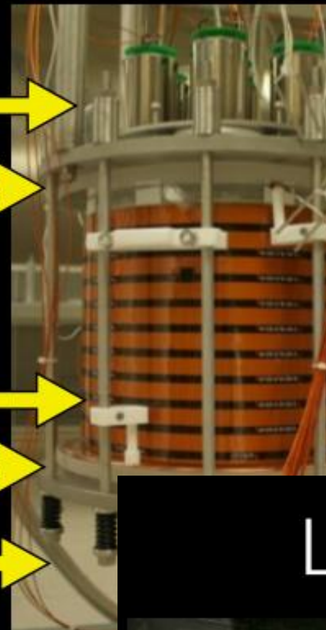
DarkSide 50
First physics detector
Physics goal ~ 10^{-45} cm^2

DarkSide G2
Multi-ton detector
Physics Goal ~ 10^{-47} cm^2

RICHARD SALDANHA

+ multiple smaller test setups and prototypes

DarkSide 10



7x 3” PMTs

TPB + ITO coated quartz window

Acrylic cylinder
with TPB-coated reflector

Flexible PCB field cage

TPB + ITO coated quartz window

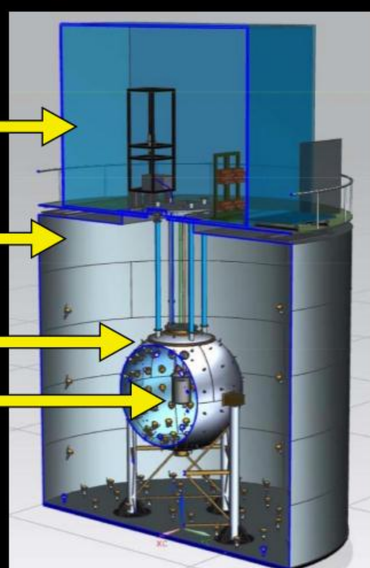
7x 3” PMTs

DS-10 Performance

- Compare performance of different reflectors for light collection
  Detector run with both 3M foils (~ 9 p.e./keV$_{ee}$) and highly crystalline PTFE (~ 7 p.e/keV$_{ee}$)
- Study feasibility of ITO coatings
- Test HHV system (feedthroughs, grid etc.)
  Detector running without problems at nominal field configuration (1 kV/cm drift, 3.8 kV/cm extraction)
- Perform calibration of detector
  Calibrations performed with external γ and neutron sources. ^{83}Kr source to be implemented soon
- Optimize field configuration of TPC
  Different field configurations under consideration

L

DarkSide 50



Radon-free clean room

Instrumented water tank

Liquid scintillator

Inner detector TPC
(Underground argon)

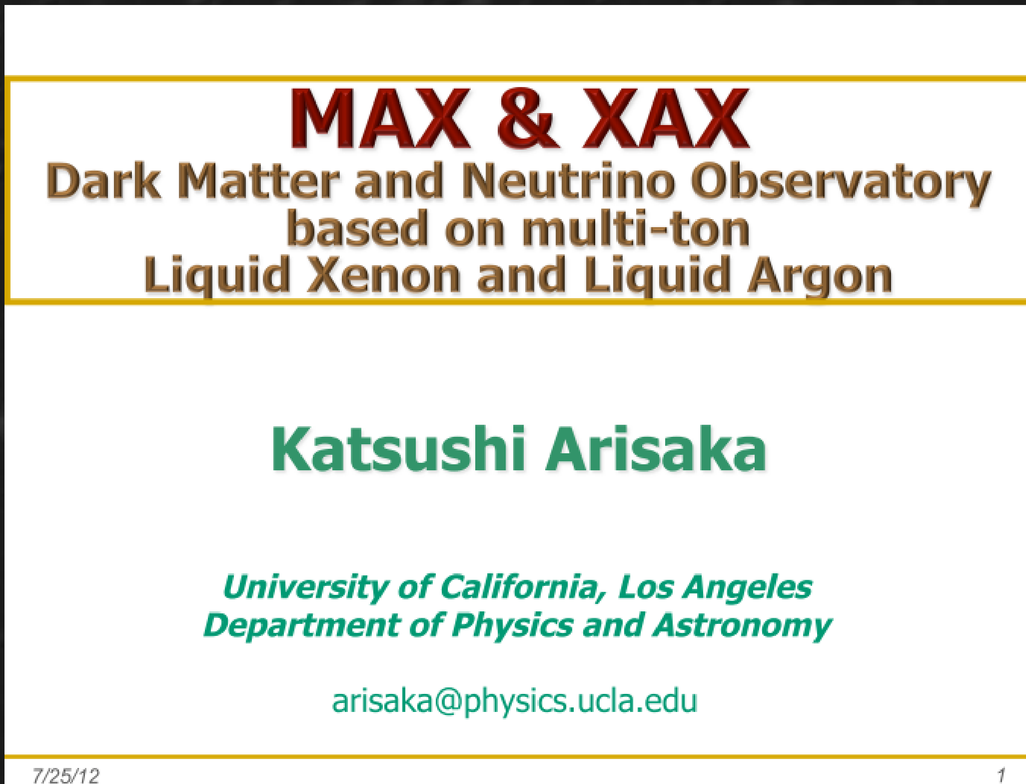
RICHARD SALDANHA

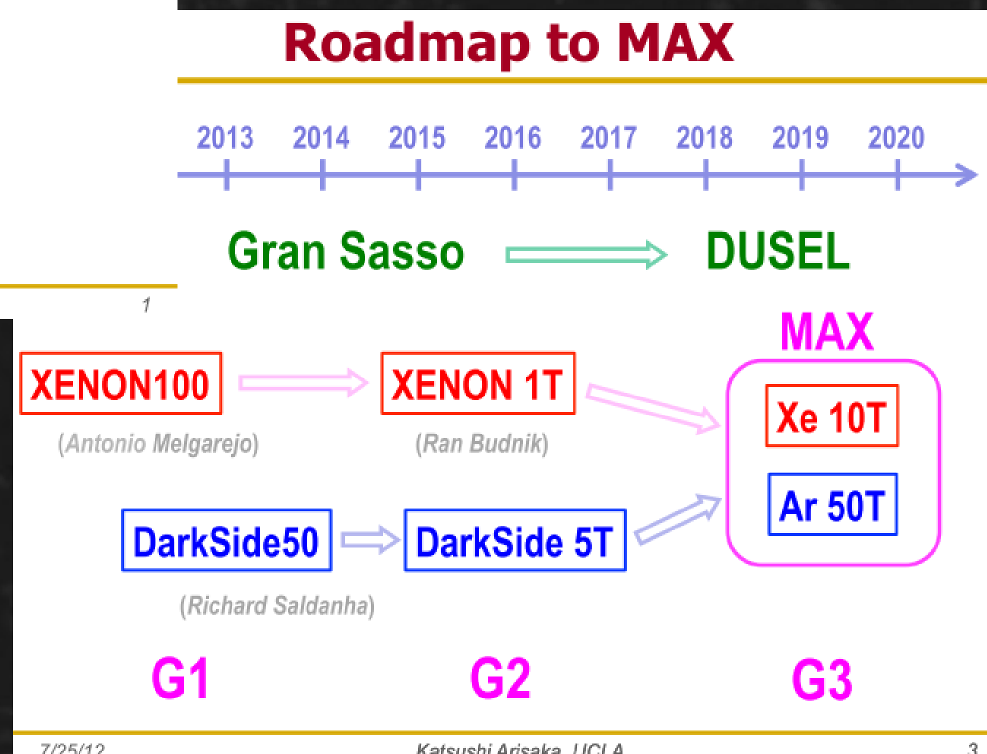
CTF tank has been emptied

Liquid scintillator tank assembly has recently been completed

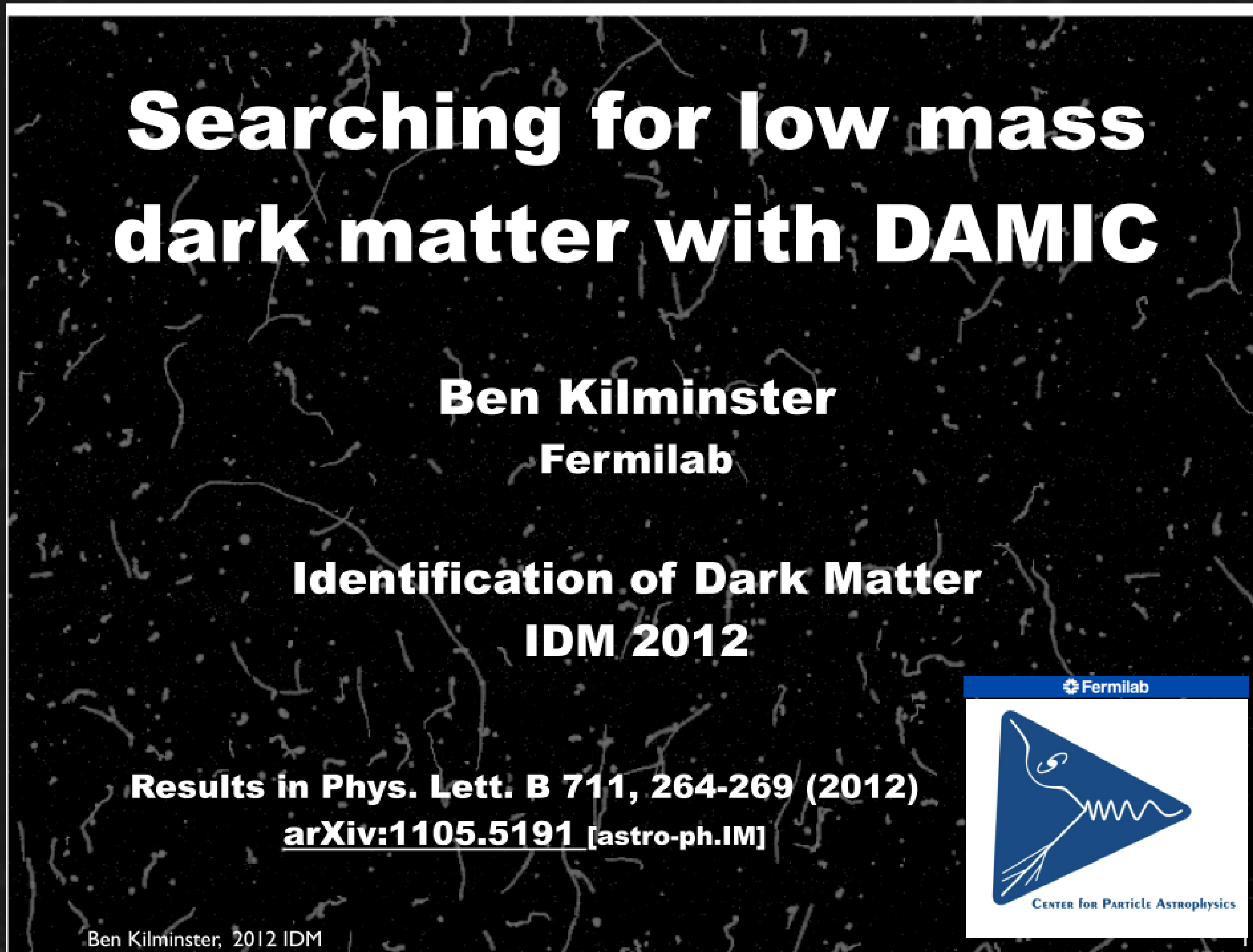
身内賢太

一番景気いい話：MAX&XAX





- そして、アリ
  - CCD　1g

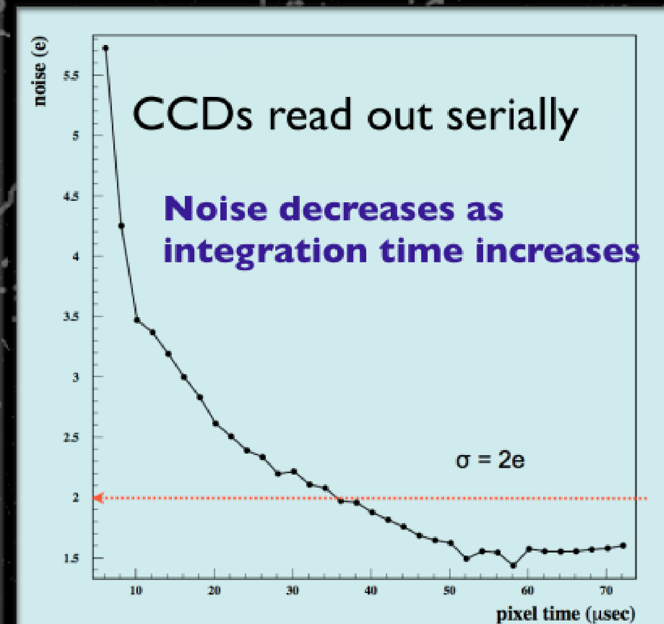


Searching for low mass dark matter with DAMIC
Ben Kilminster
Fermilab
Identification of Dark Matter
IDM 2012
Results in Phys. Lett. B 711, 264-269 (2012)
arXiv:1105.5191 [astro-ph.IM]
Fermilab
Center for Particle Astrophysics
Ben Kilminster, 2012 IDM

低閾値　それだけ
（低質量のDMに特化）

Energy threshold for DM search

- CCDs cooled to -150 C to reduce noise
- 50 μs / pixel
  - RMS of 2 e-
    - 7.2 eV equivalent ionizing in Silicon
  - Threshold of 40 eVee
    - Lowest of current DM experiments
- We are pushing energy threshold even further
  - RMS of 0.2 e- may be possible



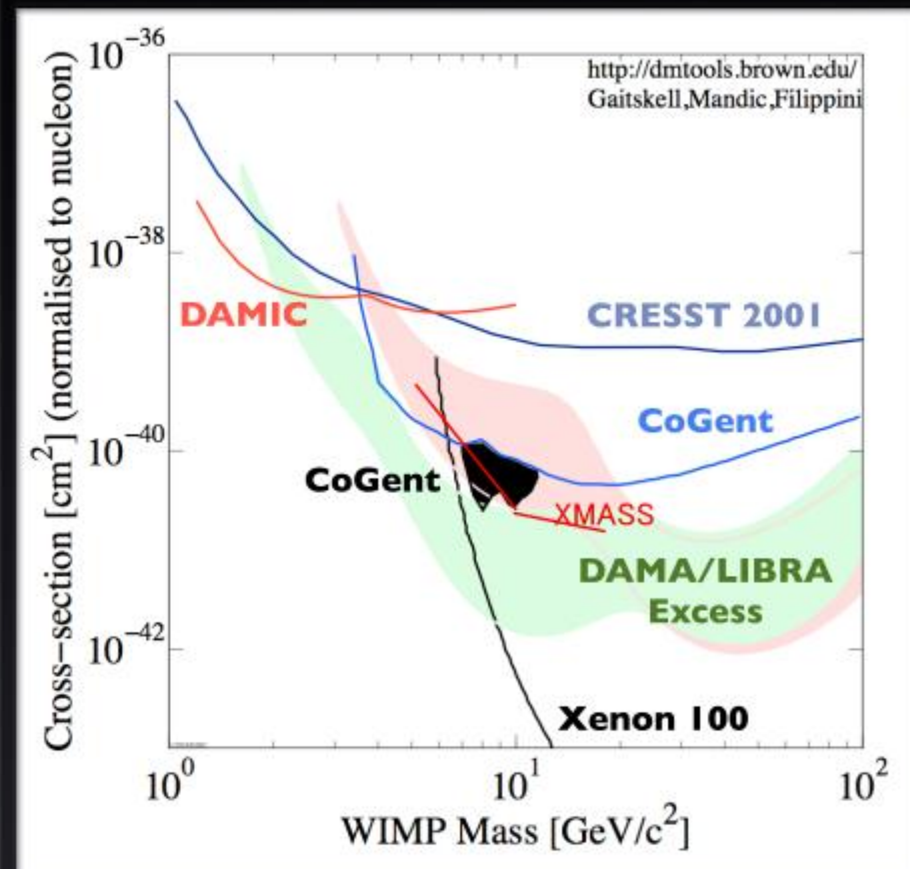
Experiment	Threshold
DAMIC	0.04 keV_{ee}
COGENT	0.5 keV_{ee}
CDMS II	3 keV_{ee}
Xenon 100	8.4 keV_{nr}

Ben Kilminster, 2012 IDM

Results from First Run

- **Wimp density → 0.3 GeV/cm**
- **V_{earth} = 244 km/s**
- **V_{escape} = 650 km/s**

Assumes Lindhard quenching factor for conservative limits



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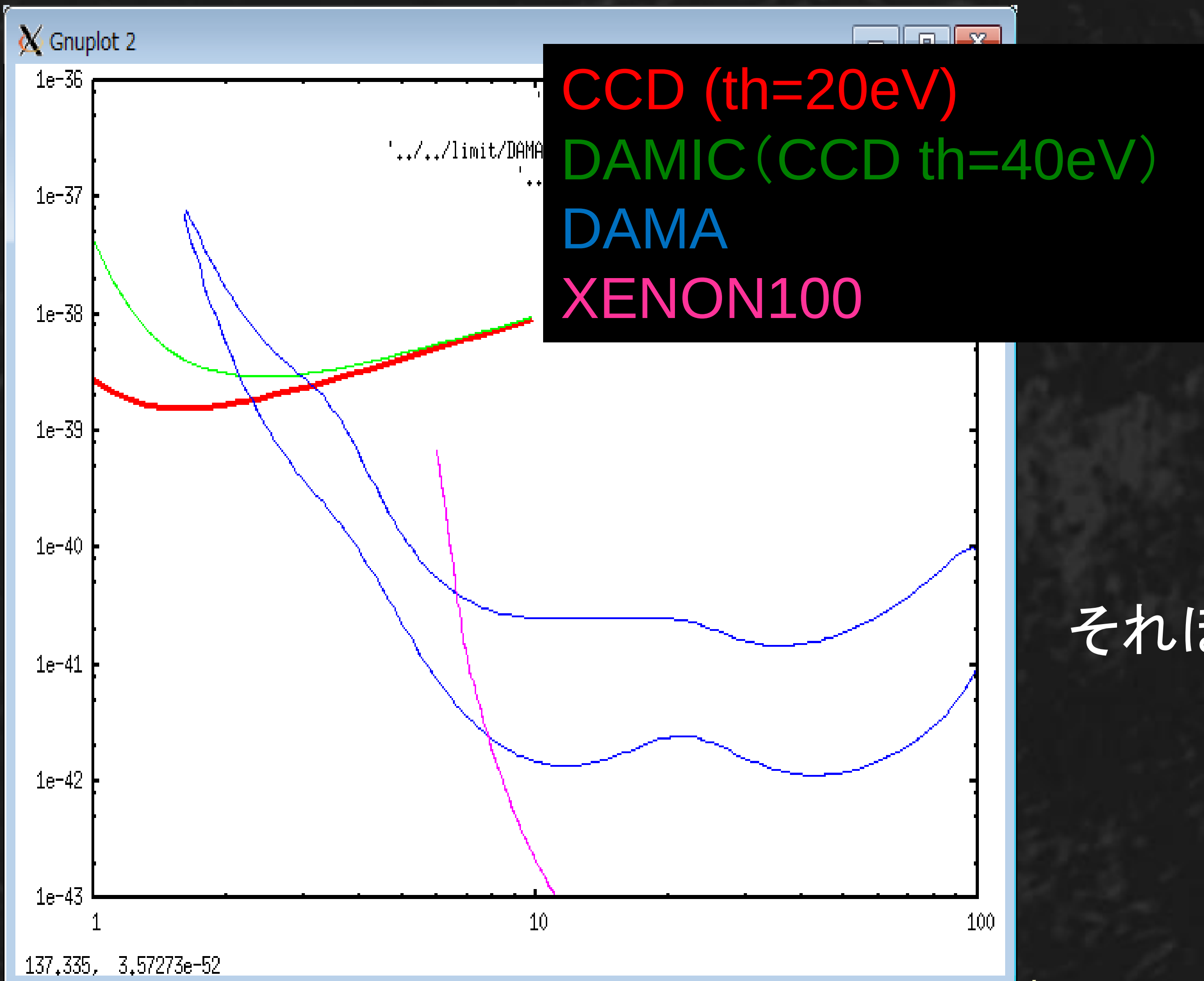
アリとゾウ ← DAMIC「超低閾値」

http://kicp-workshops.uchicago.edu/IDM2012/

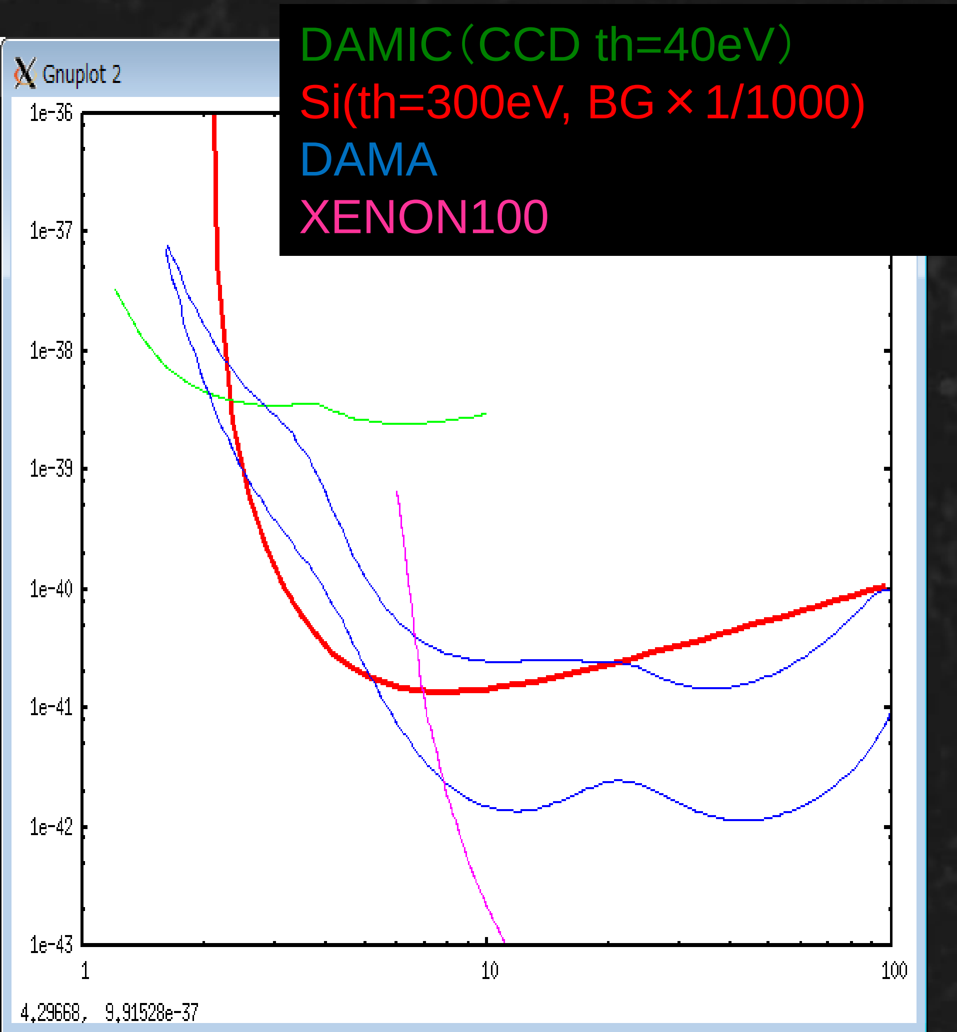
二匹目のアリ?

- ①閾値をさらに頑張る



それほど意味がない。

②CCDの弱点：VETOをかけられない。をつく
→SOIPIX （ピクセル読み出し） with 鶴氏（京大）



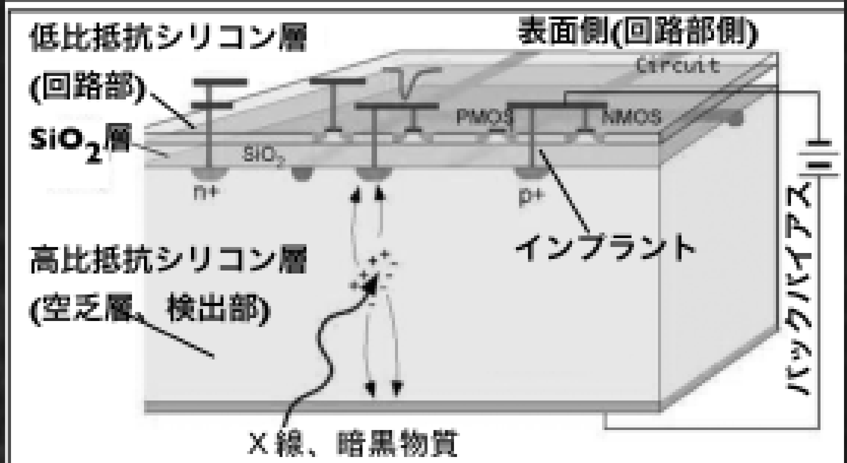
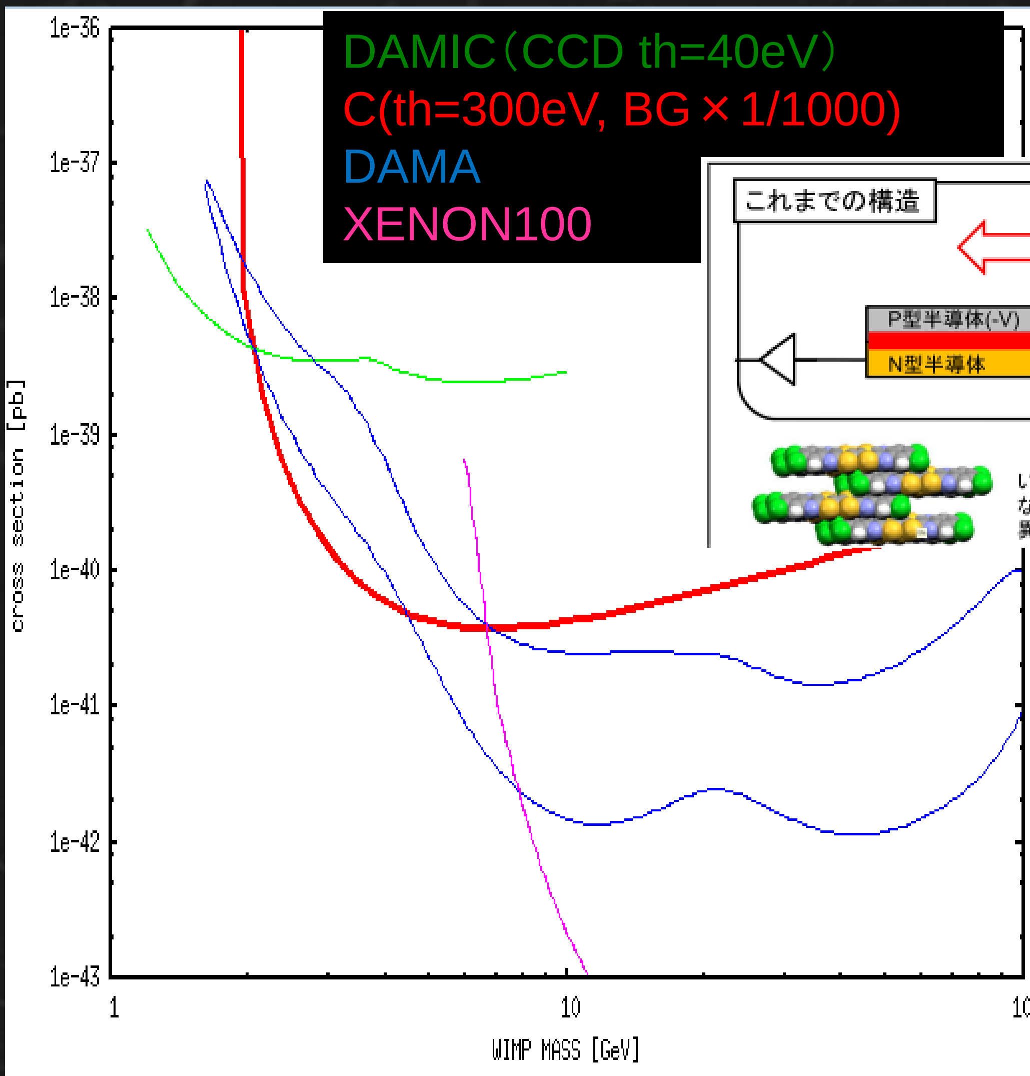
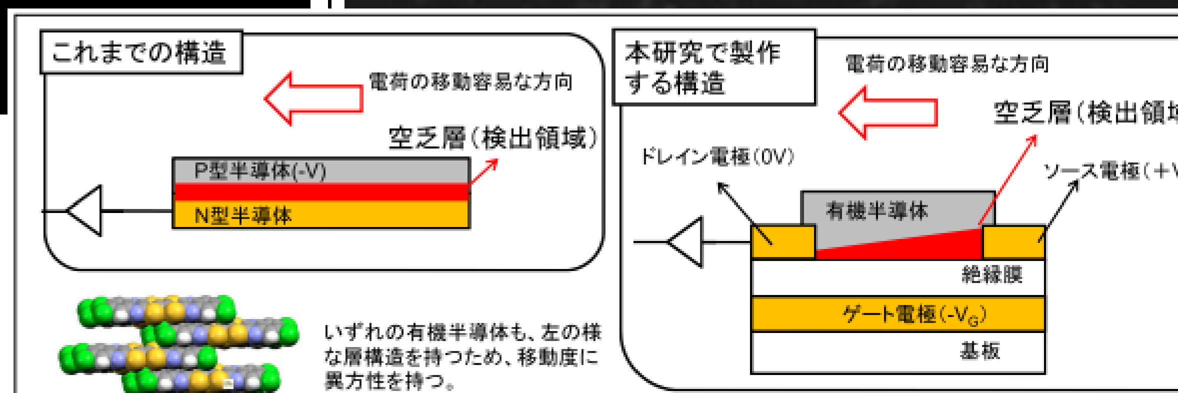


図2：SOIPIXの断面。SiO2を挟んで低比抵抗部と高比抵抗部にわかれる。SiO2に設けたインプラントを通じて高比抵抗部で検出した電荷を低比抵抗部に導入、全てのピクセルの低比抵抗部が備えるアンプとトリガ回路で処理して、素子外部へ出力する。

BGを落とせれば
閾値が300eVでも戦える。

③low mass WIMPには原子量の小さい物質 →有機半導体　with 田中氏(KEK)





BGを落とせれば
閾値が500eVでも戦える。

Direction Sensitive WIMP-search NEWAGE

など も　おもしろいかと。

日本の
暗黒物質研究は、検出器の感度を飛躍的に向上させ、

世界へ貢献する分野であり続けるために、

MIUCHI VISION 15

見えない最先端 ← XENONの「ガンマ除去」
見えた人たち ← DAMAの「統計」
見たい俺たち ← CYGNUSの「方向情報」
アリとゾウ ← DAMICの「超低閾値」

これぞ という武器を持って
切り込もう

Direction Sensitive
WIMP-search
NEWAGE