

世界の暗黒物質直接探索実験

京都大学・宇宙線研究室

身内賢太郎

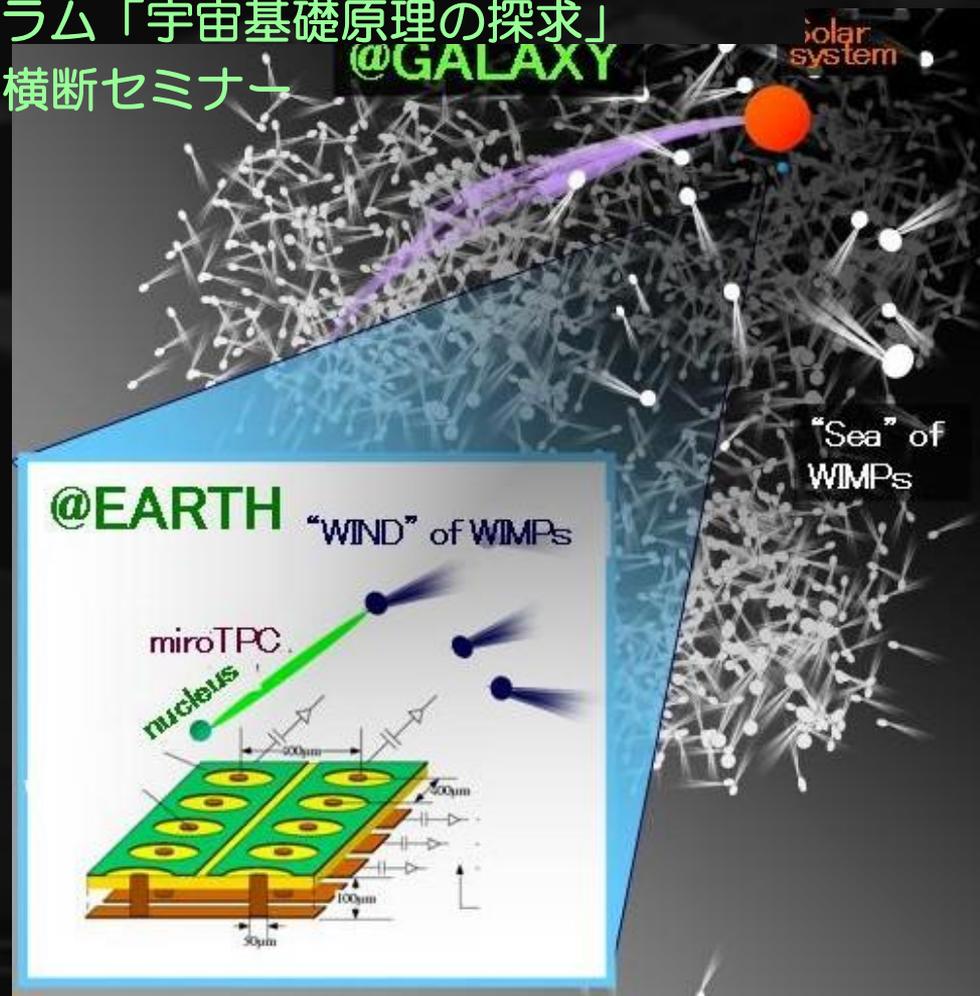
名古屋大学GCOEプログラム「宇宙基礎原理の探求」

若手分野横断セミナー

@GALAXY

New
generation WIMP
search with an advanced
gaseous tracker experiment

内容
暗黒物質
探索実験
NEWAGE



はじめまして

東大 みのわ研 (~2002)

ボロメータを用いた暗黒物質探索実験 (D論)

京大 宇宙線研究室 (2002~)

ガス検出器 μ PICの節操無い各種応用
NEWAGE実験

ライフワーク ICEPPシンポジウム

2009年 11月26日

名古屋大学GCOEセミナー 身内賢太郎



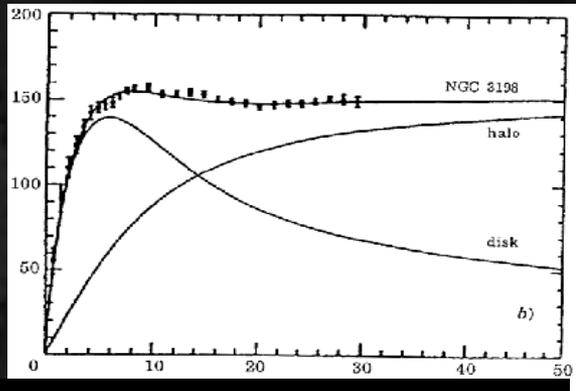
暗黒物質

2009年 11月26日

名古屋大学GCOEセミナー 身内賢太朗



暗黒物質の歴史



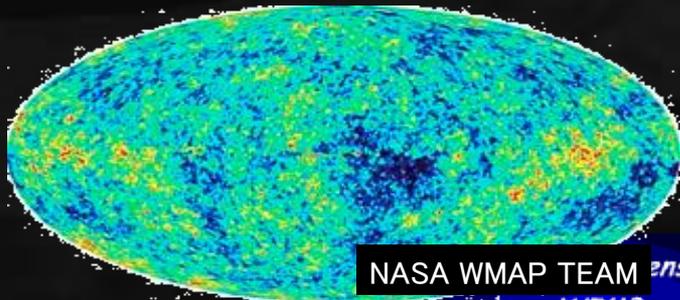
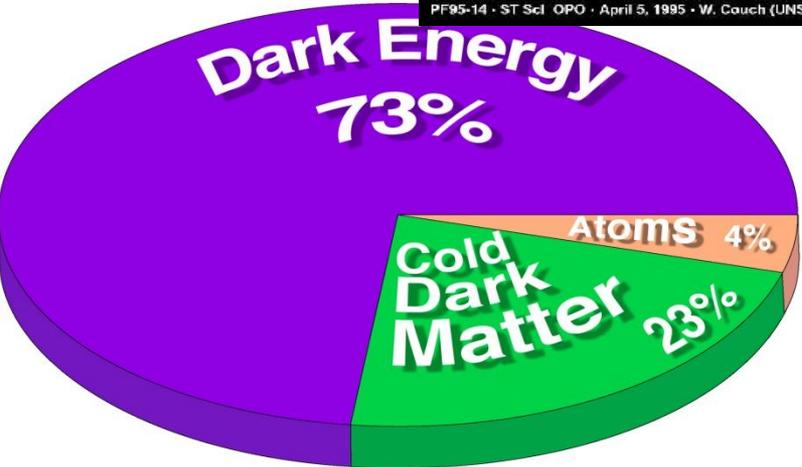
Annu. Rev. Astron. Astrophys. 29(1991)409

- 銀河の回転曲線 (1930s~)



Gravitational Lens in Abell 2218
PF95-14 • ST ScI OPO • April 5, 1995 • W. Couch (UNSW), NASA

- 遠方銀河の重力レンズ効果 (1990s~)



NASA WMAP TEAM

- 宇宙マイクロ波背景放射 (2002~)

最近では

- 宇宙電子線の観測

ATICでエクセスあったり、Fermiで否定されたり。

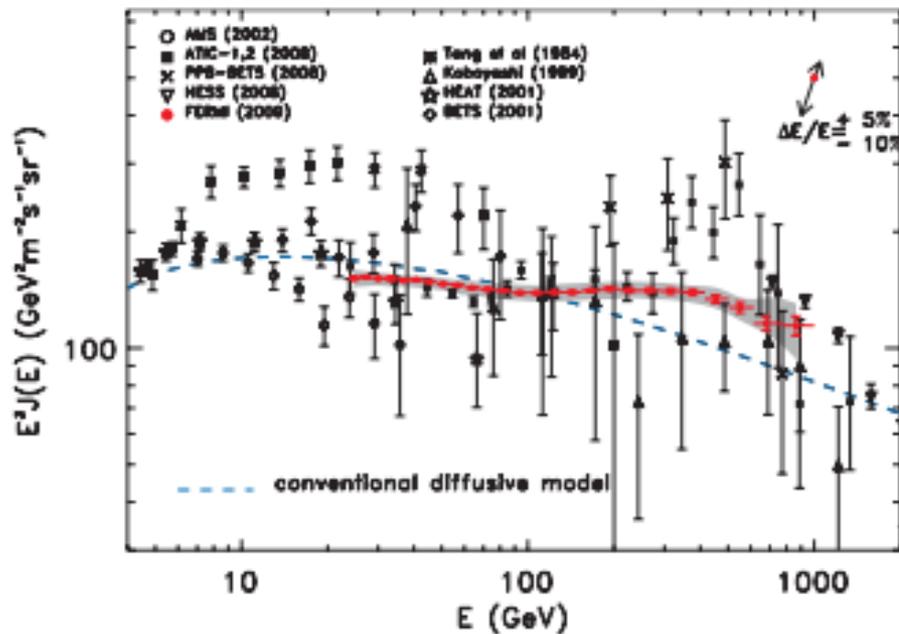


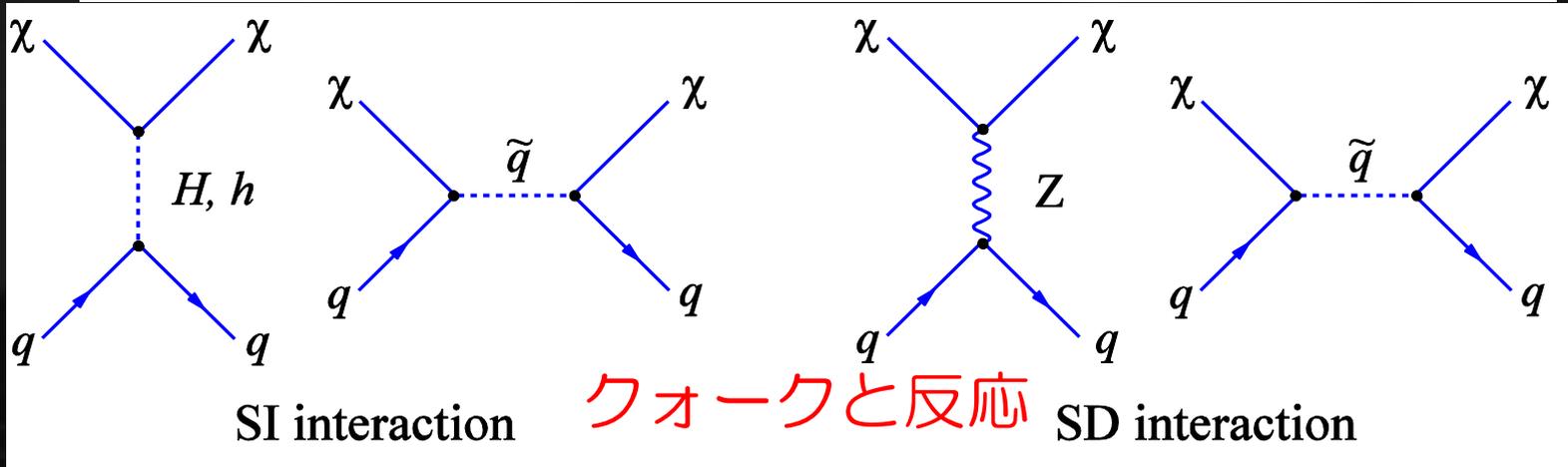
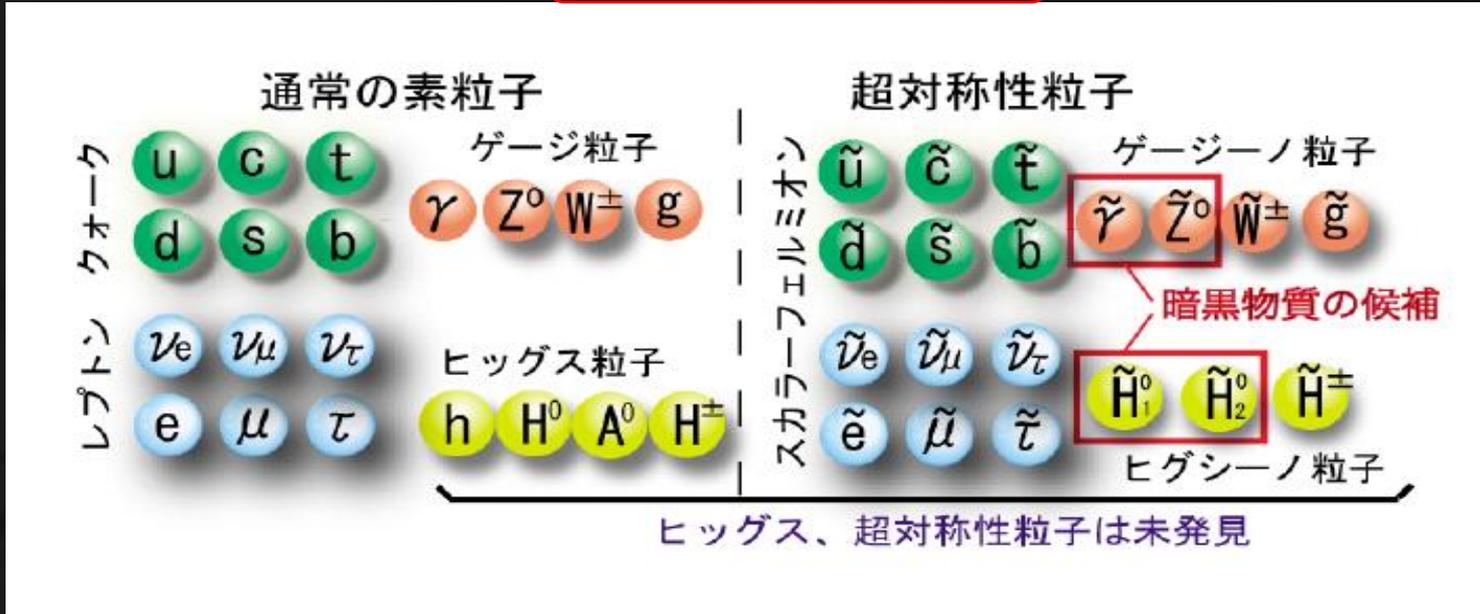
FIG. 3 (color). The Fermi LAT CR electron spectrum (red filled circles). Systematic errors are shown by the gray band. The two-headed arrow in the top-right corner of the figure gives size and direction of the rigid shift of the spectrum implied by a shift of $^{+5\%}_{-10\%}$ of the absolute energy, corresponding to the present estimate of the uncertainty of the LAT energy scale. Other high-energy measurements and a conventional diffusive model [1] are shown.

PRL102(2009)181101

- SUSY@LHC も楽しみ

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



直接探索実験

2009年 11月26日

名古屋大学GCOEセミナー 身内賢太郎



暗黒物質の直接検出

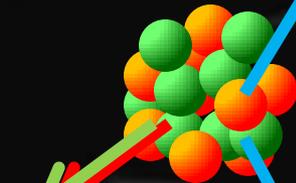
E_R 検出 (光)

DAMA (NaI)
KIMS (CsI)
XMASS (Xe)

(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)

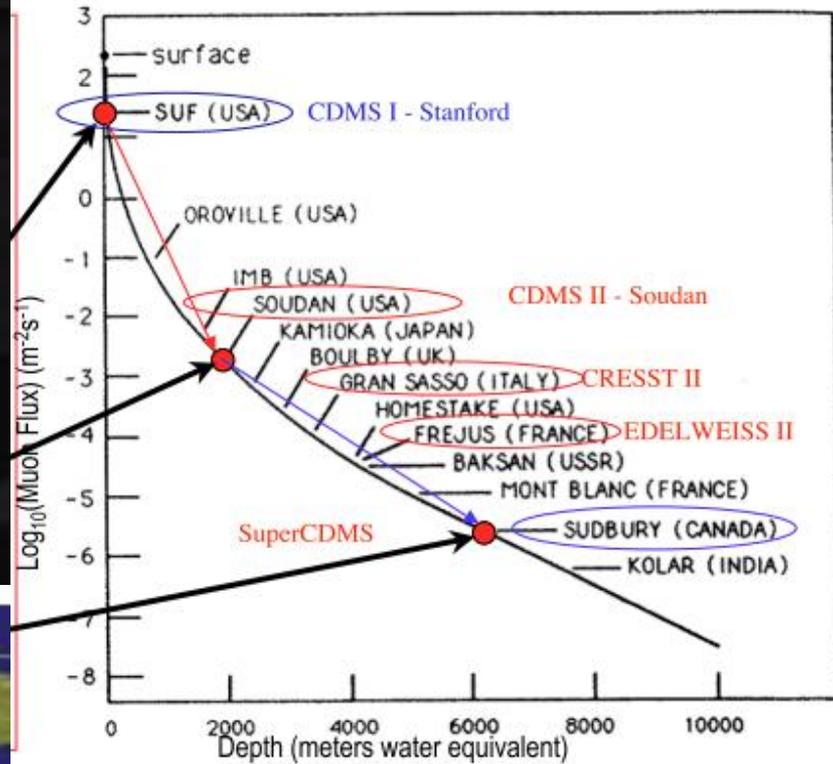
ve
arch
AGE

おもな実験の比較

	CDMS	XENON	DAMA/LIBRA
ターゲット	半導体 (Ge,Si)	液体キセノン	NaI
温度	10mK	~160K	常温
オペレーション	極難	難	易
質量	1kg	10kg	250kg
ガンマ線除去	適用	適用	不使用
最長データ取得	3ヶ月程度	3ヶ月程度	7年+4年

世界の地下実験室

- 宇宙線起源のバックグラウンドを避けるために地下にもぐって実験



ヨーロッパ
英国・フランス
スペイン・イタリア他

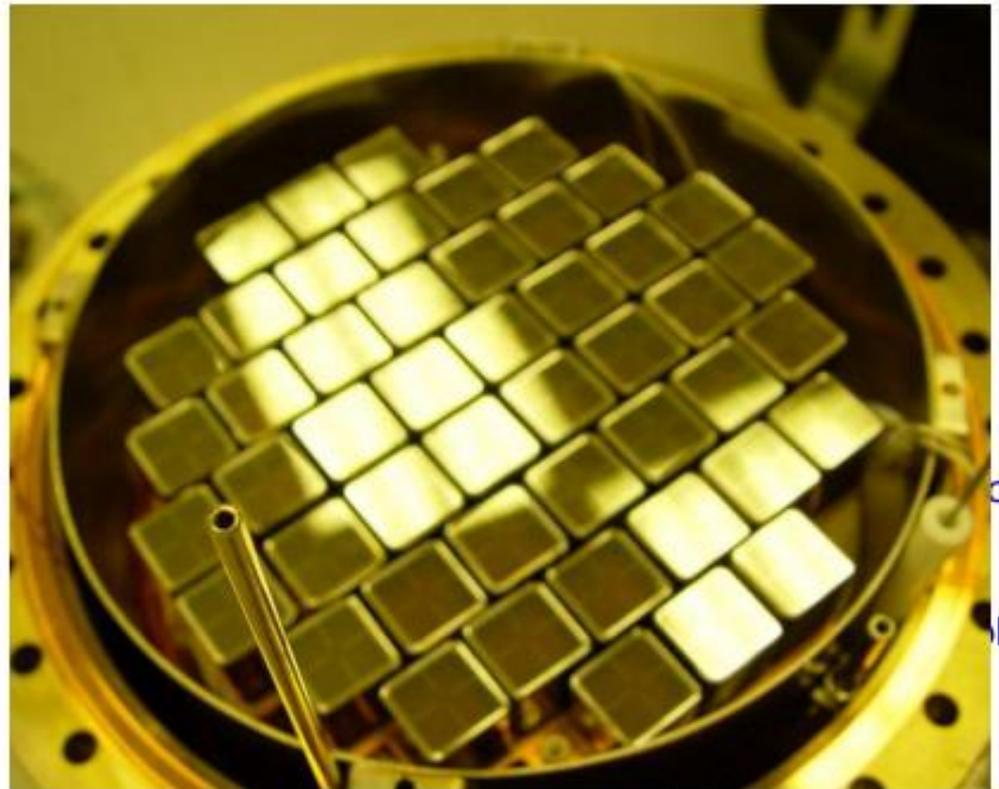
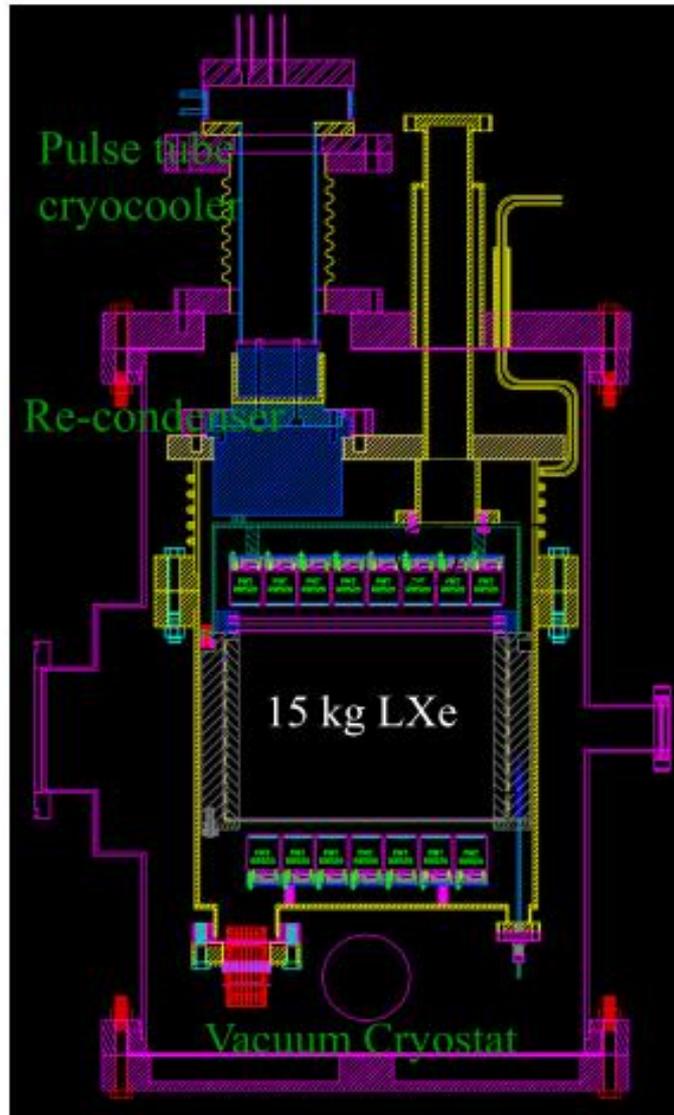
アジア
日本・韓国

北米
米国・カナダ

XENON10 : 液体キセノン

The XENON10 Detector

E. Aprile @TAUP2007

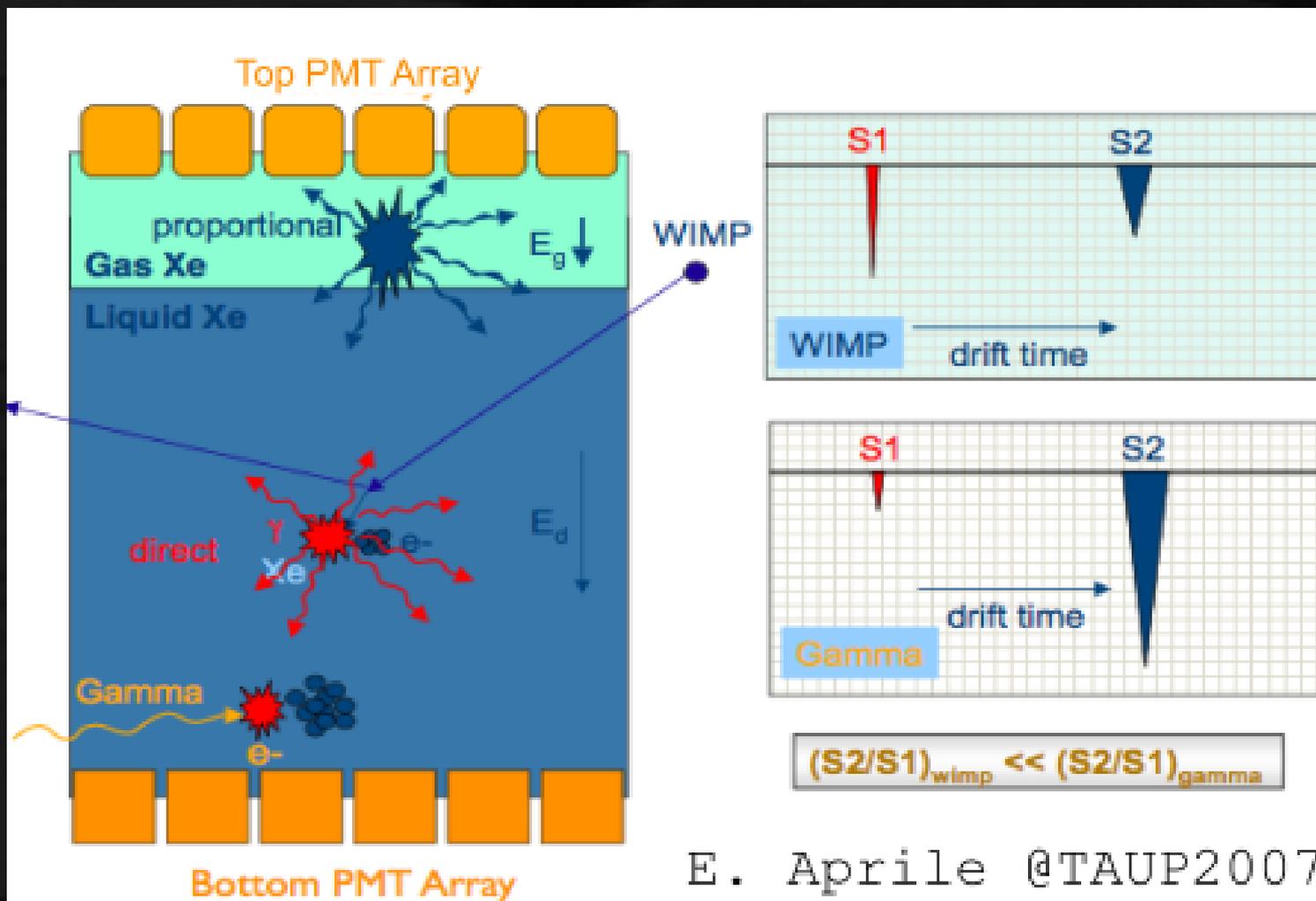


- Hamamatsu R8520 1" × 3.5 cm (metal channel)
- bialkali-PC, Quartz window, operates at -100°C and 5 bar
- Quantum efficiency > 20% @ 178 nm
- Custom HV divider on Cirlex base



XENON10

ガンマ線除去



E. Aprile @TAUP2007

CDMS : ゲルマニウム

CDMS Techniques for Recoil Discrimination

Detectors with readout of both charge and phonon signals

- Charge/phonon AND phonon timing different for nuclear and electron recoils; event by event discrimination!
- Measured background rejection still improving!
99.9998% for γ 's, 99.79% for β 's
- Clean nuclear recoil selection with $\sim 50\%$ efficiency
Can tune between signal efficiency and background rejection



Tower of 6 ZIPs

Tower 1

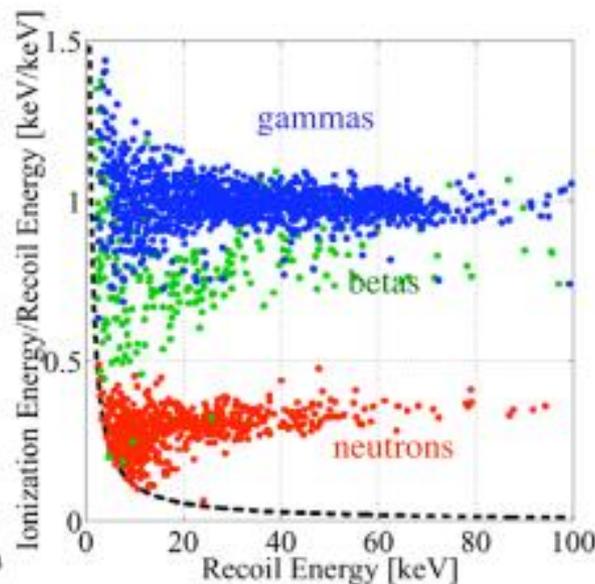
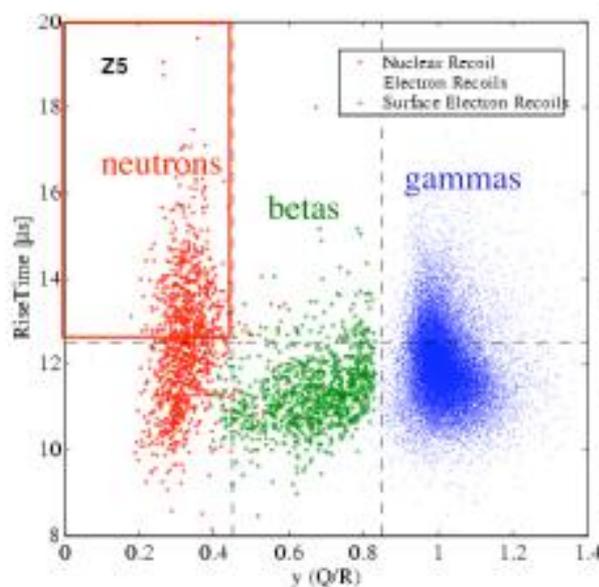
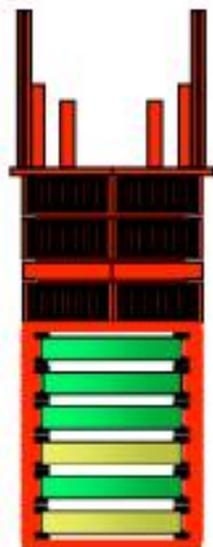
4 Ge

2 Si

Tower 2

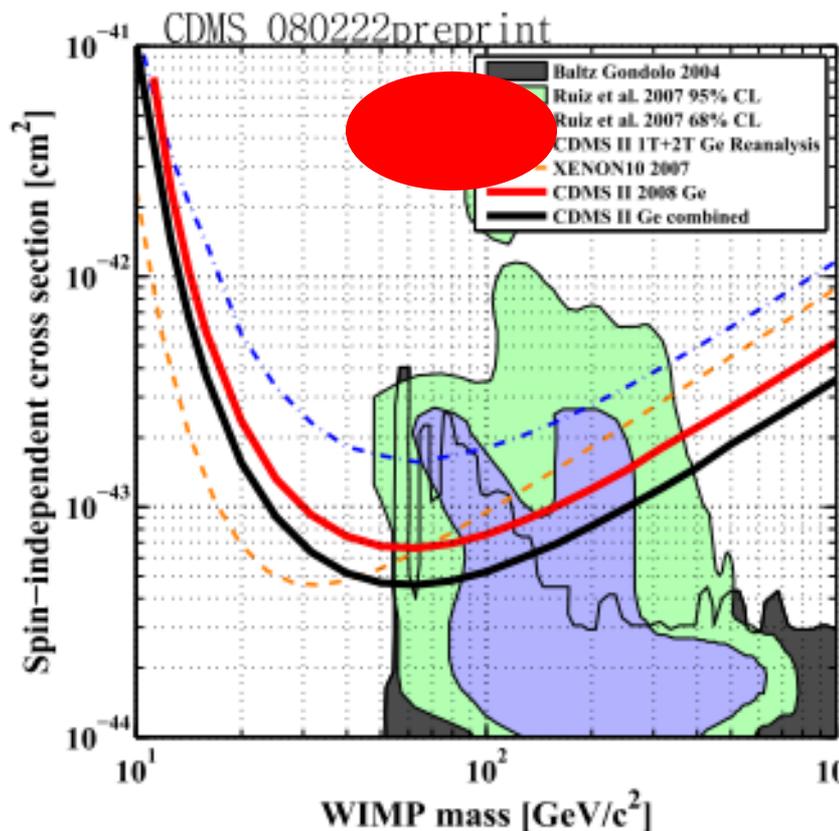
2 Ge

4 Si



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 LIBRAで再現！

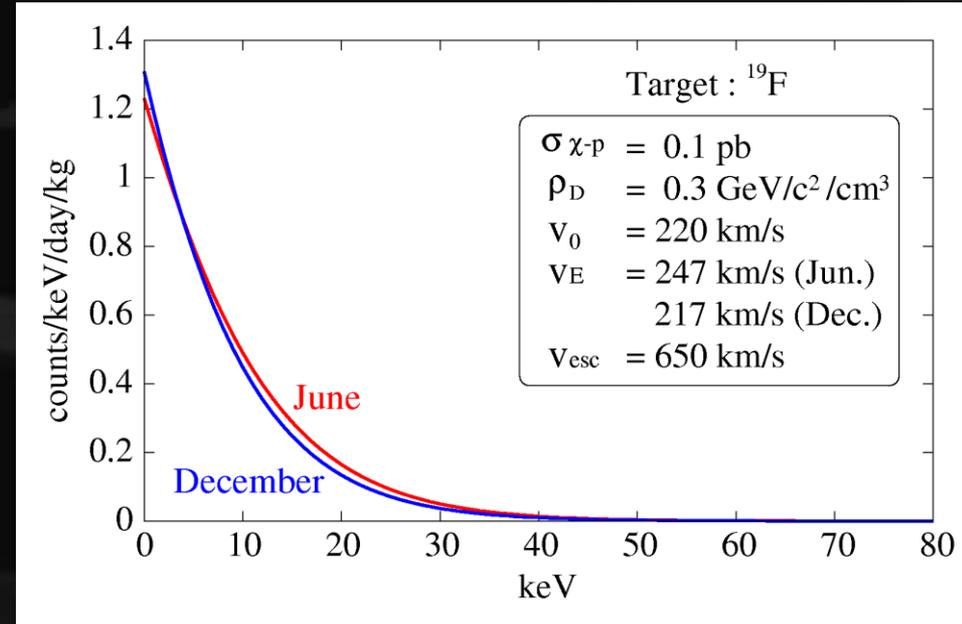
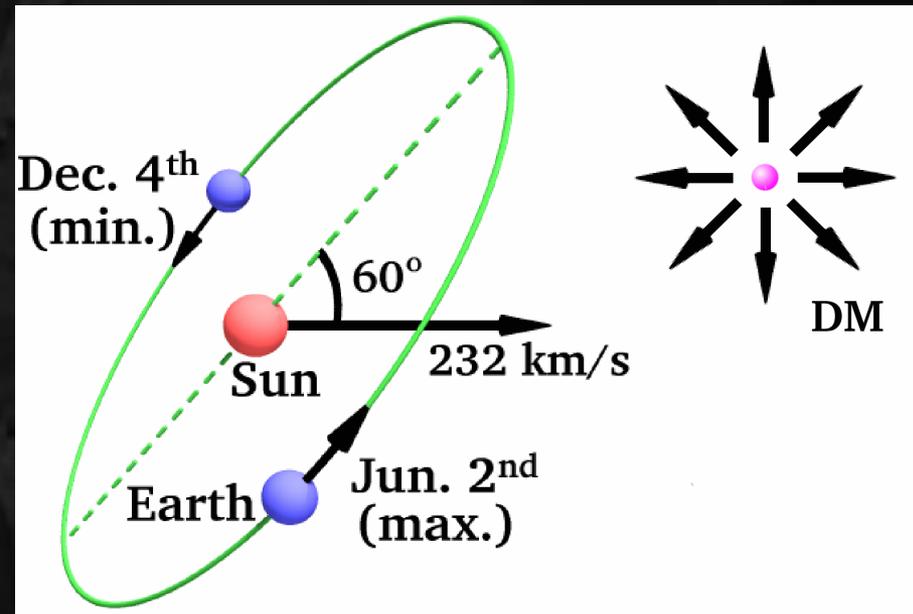


	DAMA (-2002)	LIBRA (2003-2007)
detector	NaI	NaI
Mass	9.7kg×9	9.7kg×25
time	7 yeas	4 years
exposure	0.29 ton year	0.53 ton year

(Large sodium Iodide Bulk for RAre processes)

● ダークマターの季節変動

- 夏と冬の相対速度の差
- スペクトルのレートにして数%の変動



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

filling the inner Cu box with
further shield

BELLI@
TAUP07

closing the Cu box
housing the detectors

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

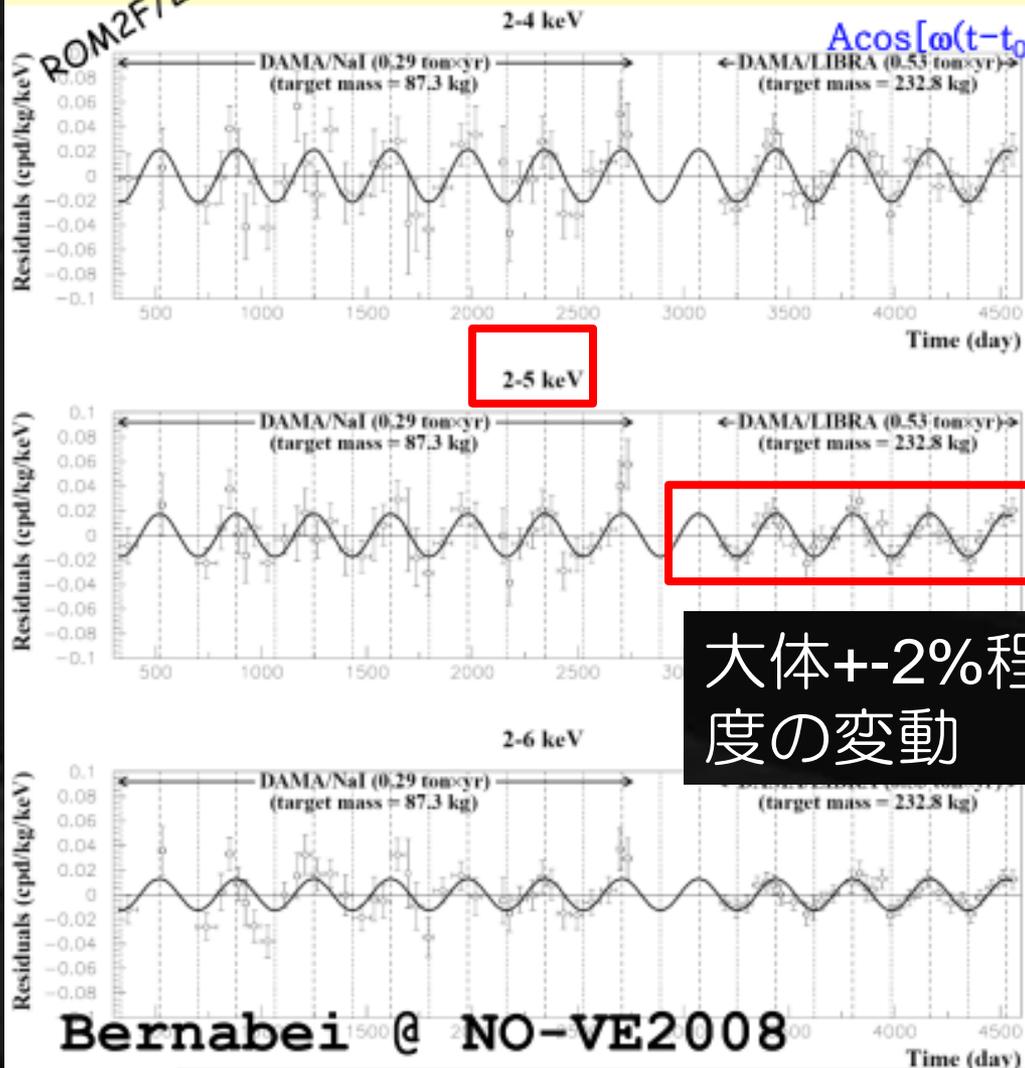
DAMA/LIBRA started operations on March 2003

view at end of detectors'
installation in the Cu box

Sensitive
P-search
AGE

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

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

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

Absence of modulation? No

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

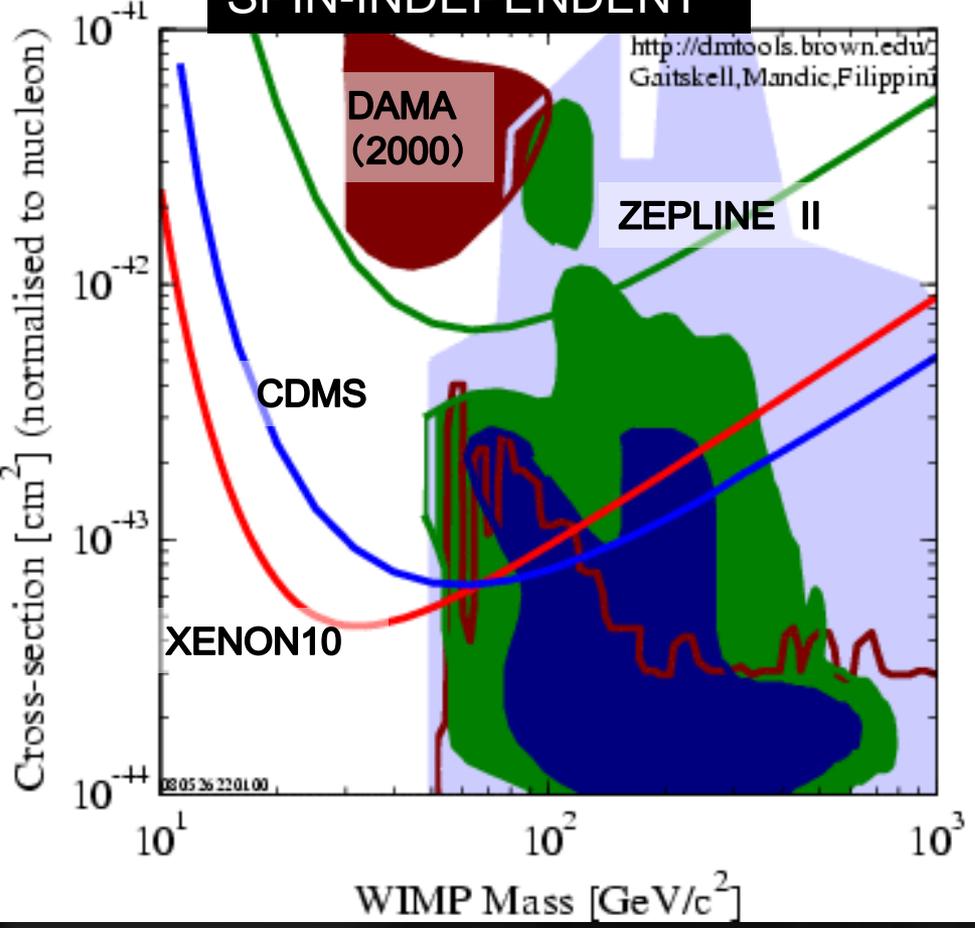
The data favor the presence of a modulated behavior with proper features at 8.2 σ C.L.

NEWAGE

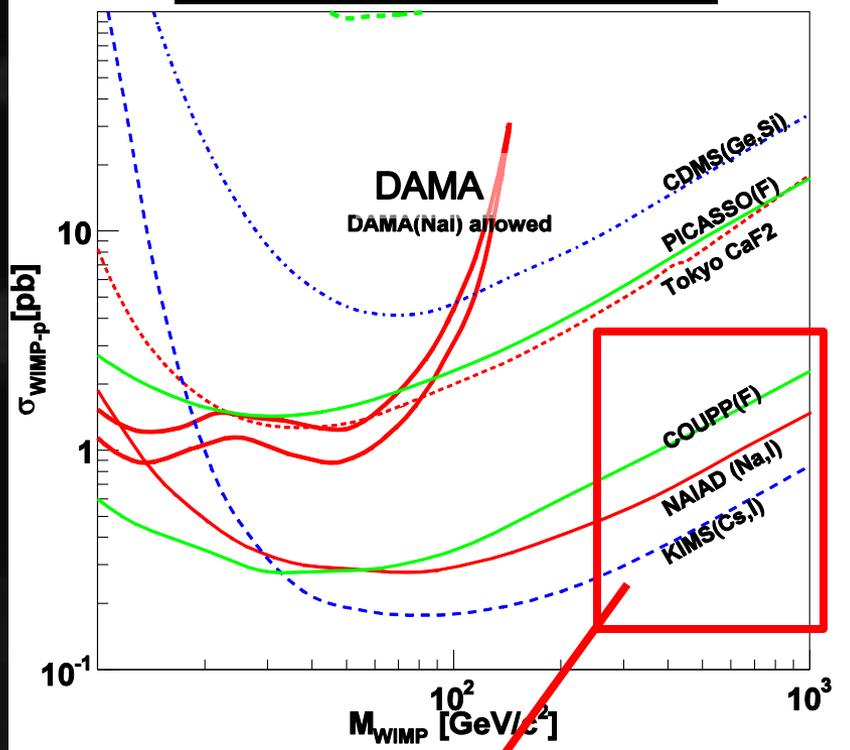
世界の暗黒物質探索：まとめ

大質量・多手法検出器での凌ぎ合い

SPIN-INDEPENDENT



SPIN-DEPENDENT



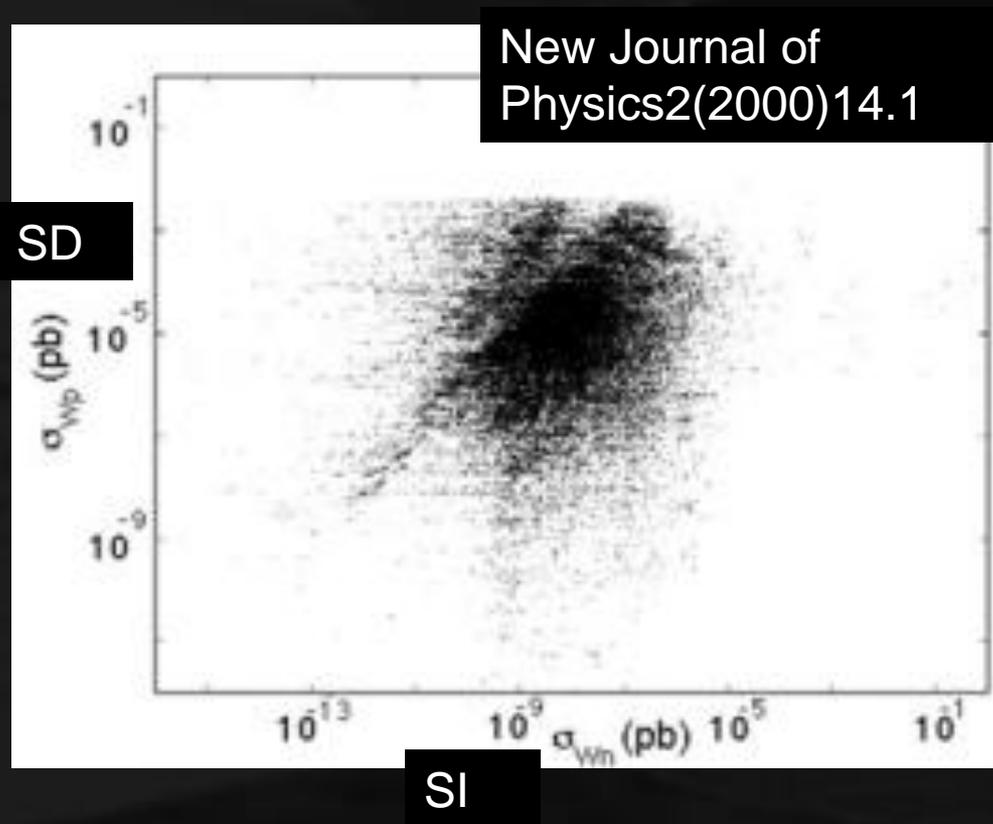
- DATA listed top to bottom on plot
- DAMA 2000 58k kg-days NaI Ann. Mod. 3sigma w/DAMA 1996
- ZEPLIN II (Jan 2007) result
- CDMS 2008 Ge
- XENON10 2007 (Net 136 kg-d)
- Roszkowski/Ruiz de Austri/Trotta 2007, CMSSM Markov Chain Monte Carlos
- Roszkowski/Ruiz de Austri/Trotta 2007, CMSSM Markov Chain Monte Carlos
- Ellis et. al Theory region post-LEP benchmark points
- Baltz and Gondolo 2003
- Baltz and Gondolo, 2004, Markov Chain Monte Carlos

統計処理によるBG subtraction



SI or SD ?

- SUSYのパラメータ依存。
- どちらが探し易いかはわからない。



方向感度を持つ実験

第四の情報：原子核飛跡

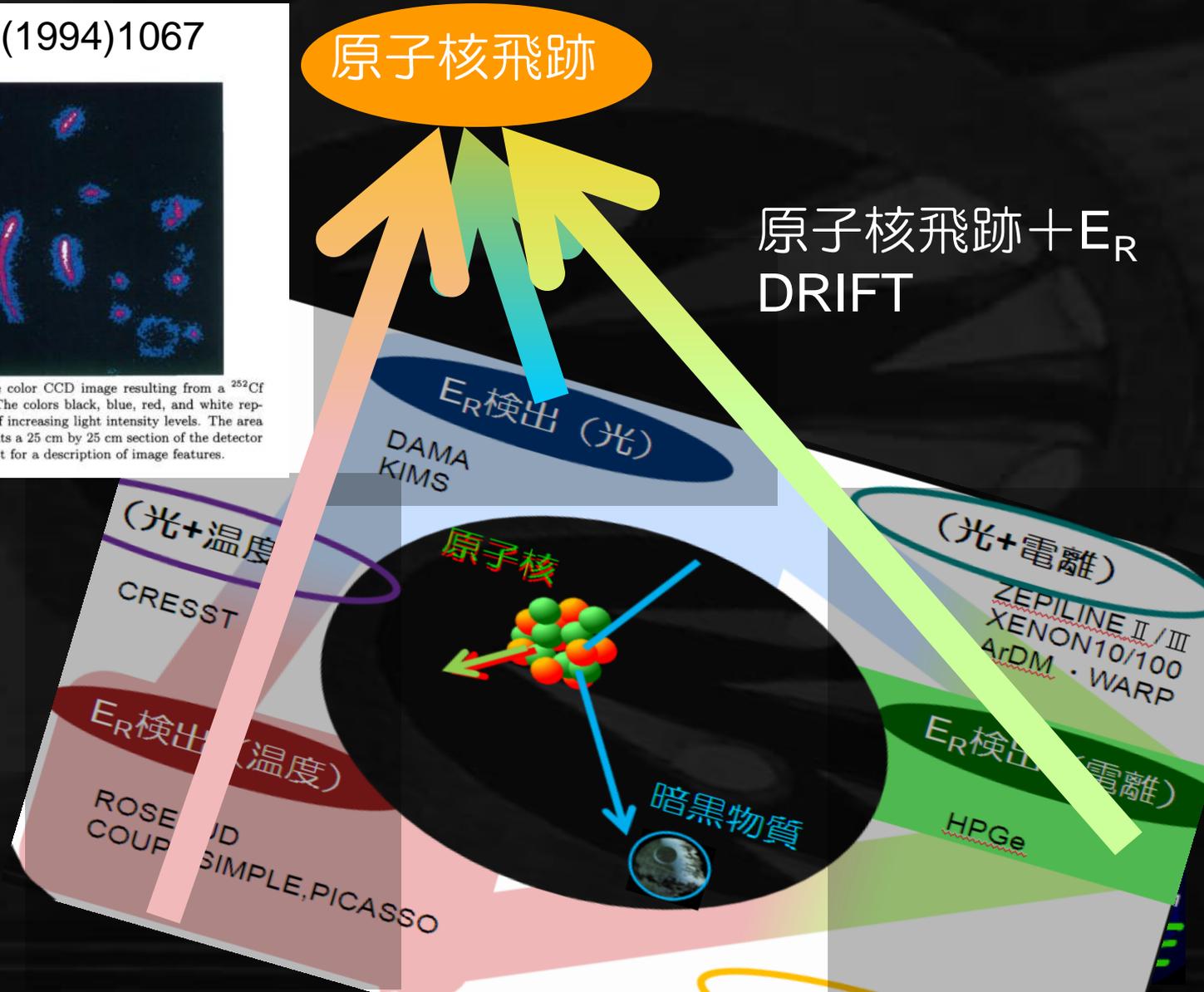
PRL73(1994)1067



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



「方向性」の重要性

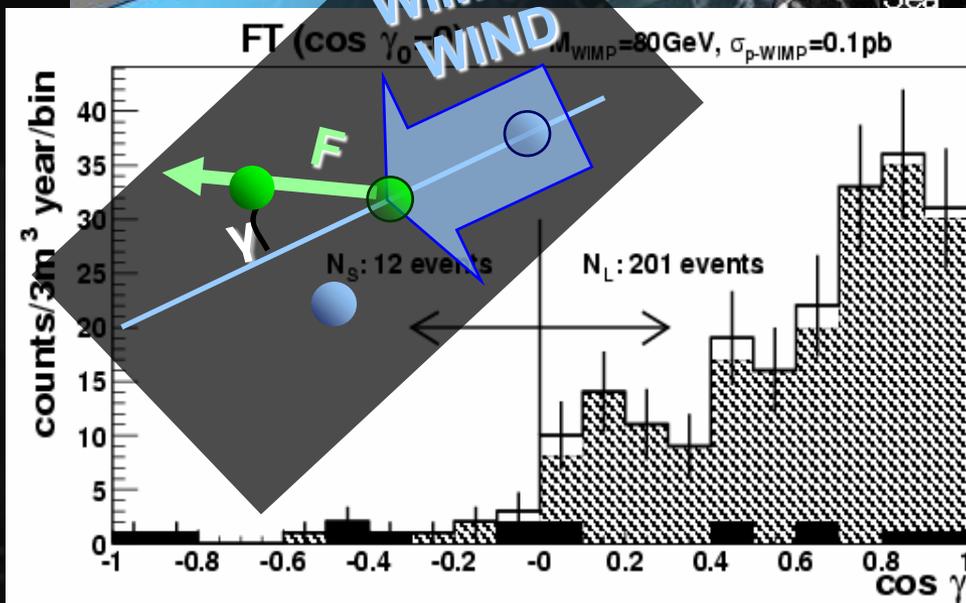
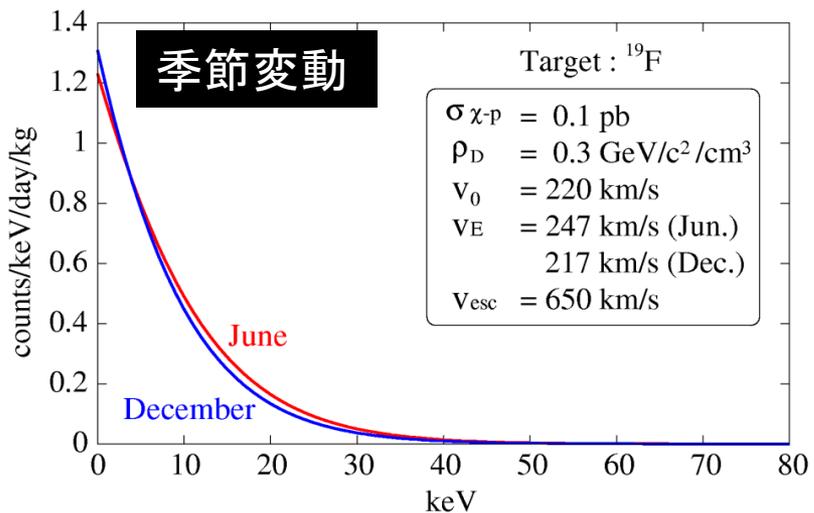


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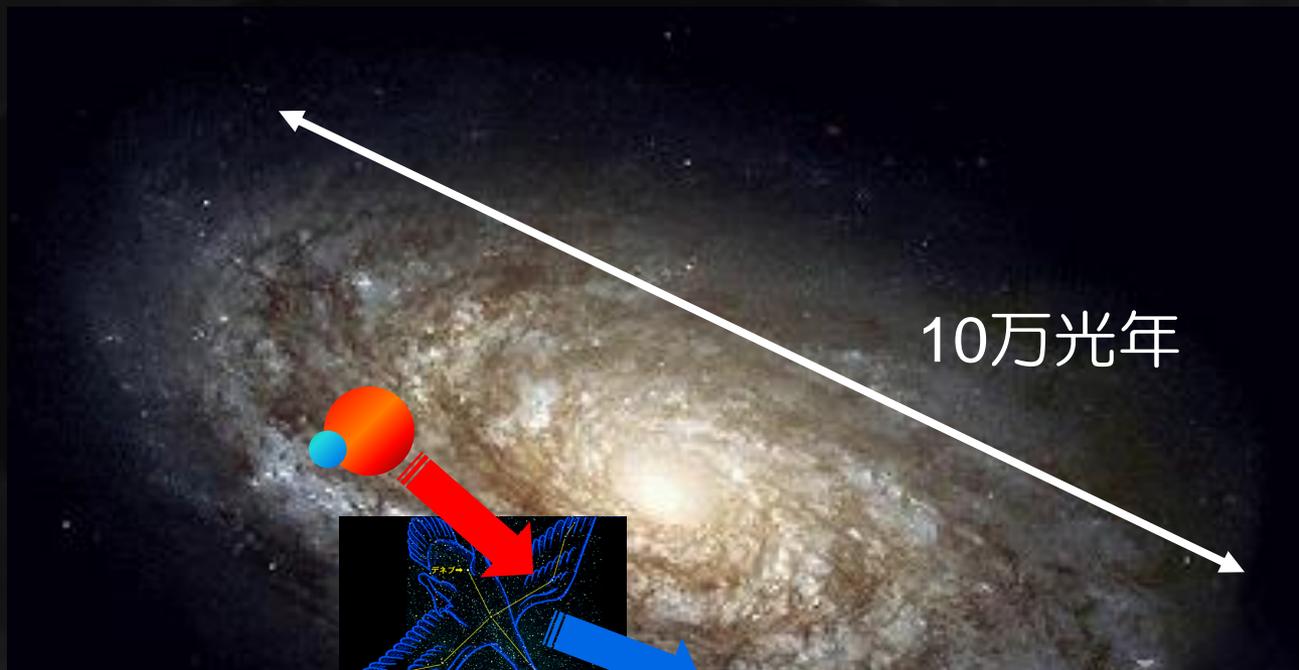
飛跡検出のメリット

- 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



CYGNUS

- 方向に感度を持った暗黒物質実験のworkshop
 - 2007年に初回を立ちあげ、2009年5月に2回目



10万光年

デネブまでは
1500光年程度



@CYGNUS2009 (MIT)

"WHITE PAPER"

(arXiv 200911.0323)

世界の実験

DRIFT (英)

DM-TPC (米)

NEWAGE (京大)

MIMAC (仏)

NIT (名大)

International Journal of Modern Physics A
© World Scientific Publishing Company

The case for a directional dark matter detector and the status of current experimental efforts

S. AHLEN,¹ N. AFSHORDI,^{22,30} J. B. R. BATTAT,¹⁴ J. BILLARD,¹¹ N. BOZORGNIA,³
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11.0323v1 [astro-ph.CO] 1 Nov 2009

Direction Sensitive
WIMP-search
WAGE

DRIFT (英)

- 1990年代～
- 最大 (1m³) ◎
- BG Study ◎
- 2mmピッチ読み出し×
- 3次元飛跡 △
- DMに対する制限：未



Fig. 5. DRIFT IIb detector at Boulby mine. Two back-to-back TPCs each with a 50 cm drift distance, share a common vertical central cathode. Readout is done with two 3-layer MWPCs with 2 mm wire spacing. Operation is with negative ion CS₂ gas at 40 Torr (170 g target mass) [24]

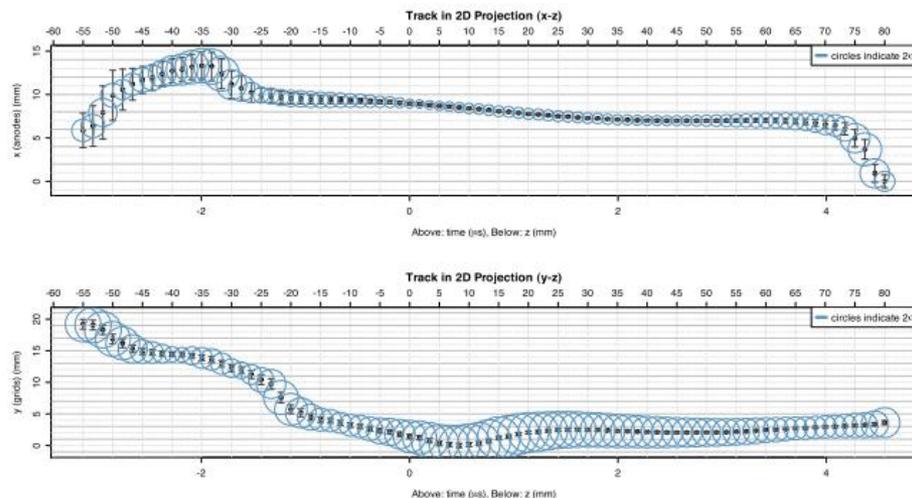


Fig. 8. Example 3D reconstruction (x-z and y-z projections) of a ~ 100 keV S recoil in DRIFT IIb (circle sizes indicate the amount of deposited charge).

DM-TPC (米)

- 2007~
- CCDで2D飛跡 Δ
- 分解能 \odot
- 飛跡の前後判定 \odot
- まだ地上実験

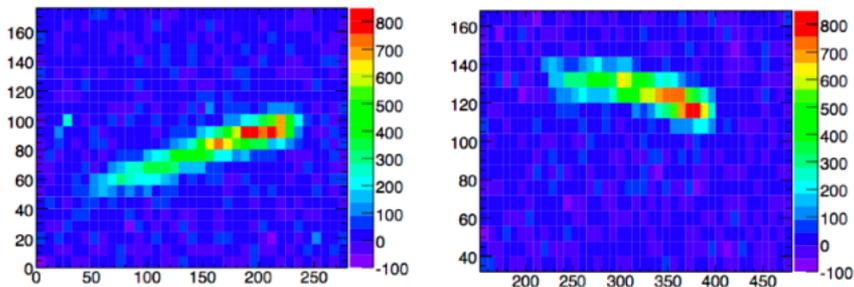
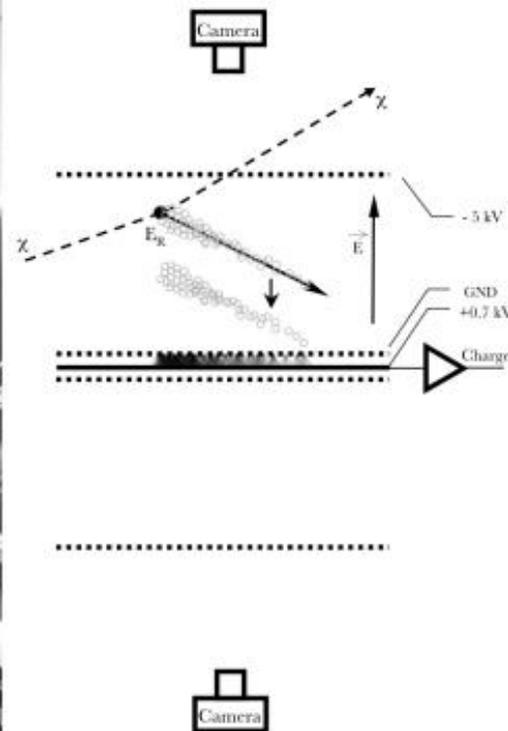


Fig. 17. Sample neutron-induced nuclear recoil candidates. The neutrons were incident from the right. The head-tail is evident from the light distribution along the track. In these images, 100 pixels corresponds to 6 mm. Figures taken from Ref. [58](#).

◆ MIMAC

- マイクロメガス
- まだ小型△
- 微細原子核飛跡検出◎

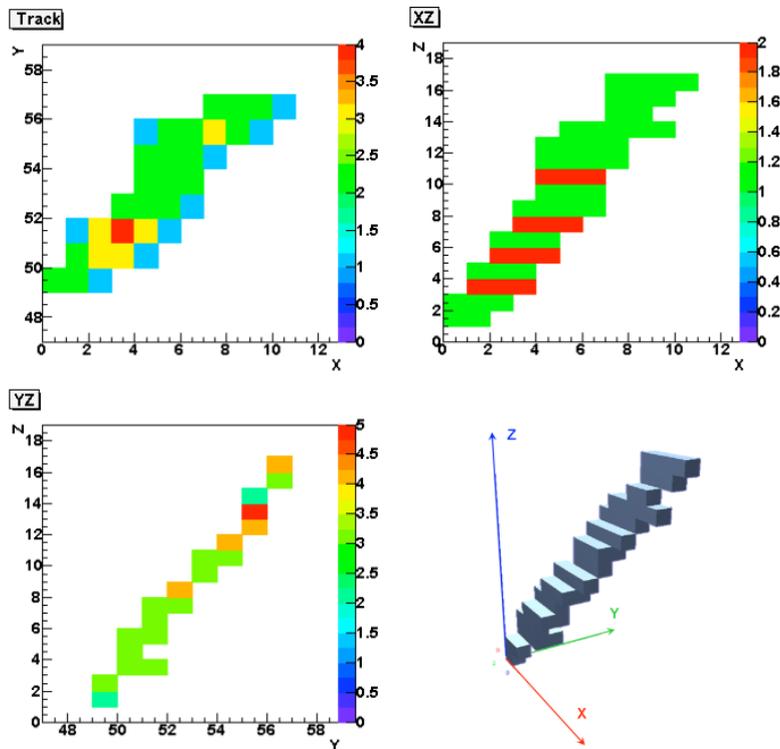
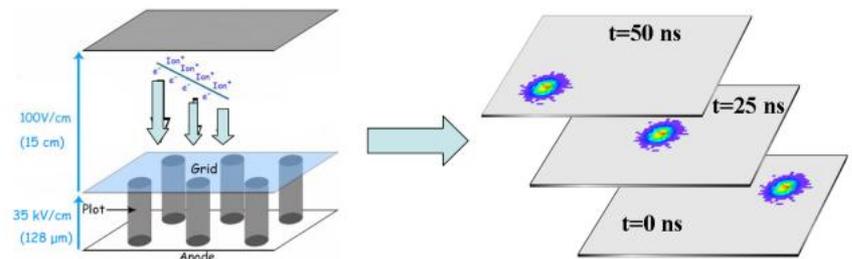


Fig. 32. The x-y, y-z and x-z projections of a 5.9 keV electron track as seen by the MIMAC electronic and acquisition system. The z-coordinate is reconstructed from 25 ns scans of the x-y anode. The lower left panel presents a 3D view of the track. The volume of a pixel is $424 \times 424 \times 400 \mu\text{m}^3$, the size in z being driven by the scanning time (25 ns) and the electron drift velocity (16 $\mu\text{m}/\text{ns}$ in this case).



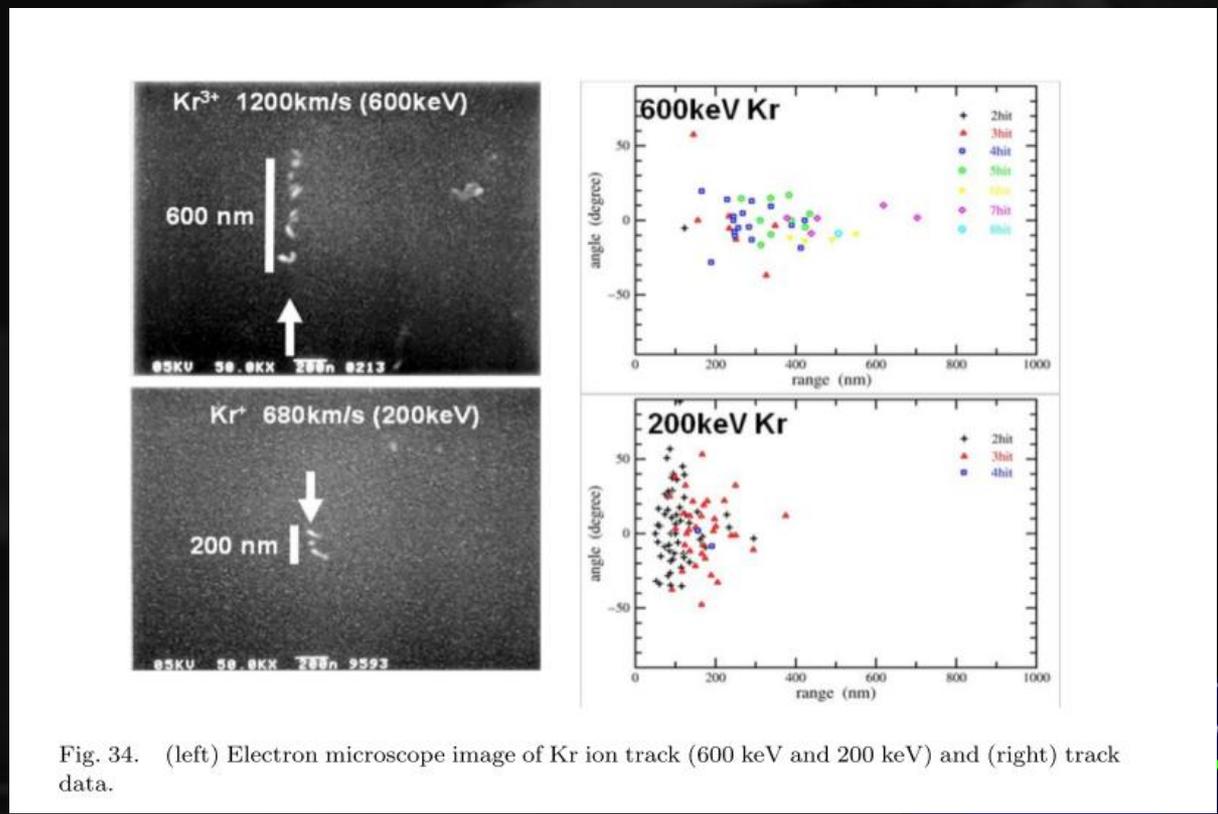
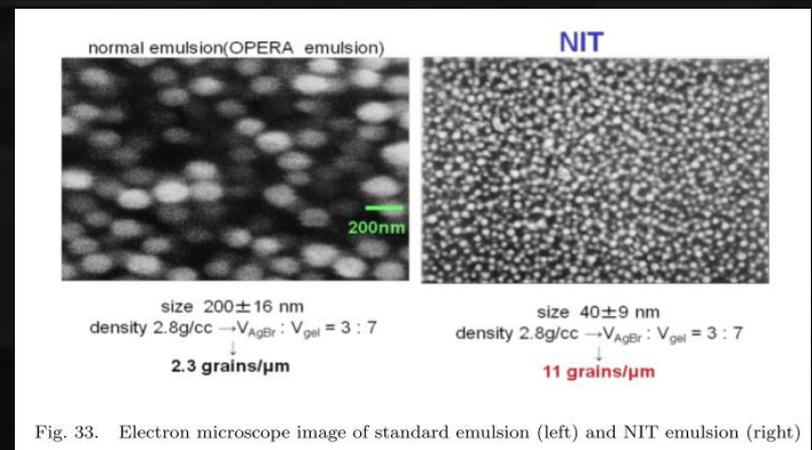
Fig. 27. Ionization Quenching Factor Facility at the LPSC Grenoble.



30. Track reconstruction in MIMAC. The anode is scanned every 25 ns and the 3D track is attracted, knowing the drift velocity, from the series of images of the anode.

◆ 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△



NEWAGE

最新結果 西村D論(2009) PLB投稿中
検出器 Astroparticle Physics 31 (2009)185
地上実験 Physics Letters B 654 (2007) 58
実験提唱 Physics Letters B 578 (2004) 241

2009年 11月26日

名古屋大学GCOEセミナー 身内賢太朗



NEWAGE

- 実用的なサイズのMPGD ◎
- 初の制限◎
- ガス循環システム ○
- 原子核の前後判定 △
- バックグラウンドレベル△

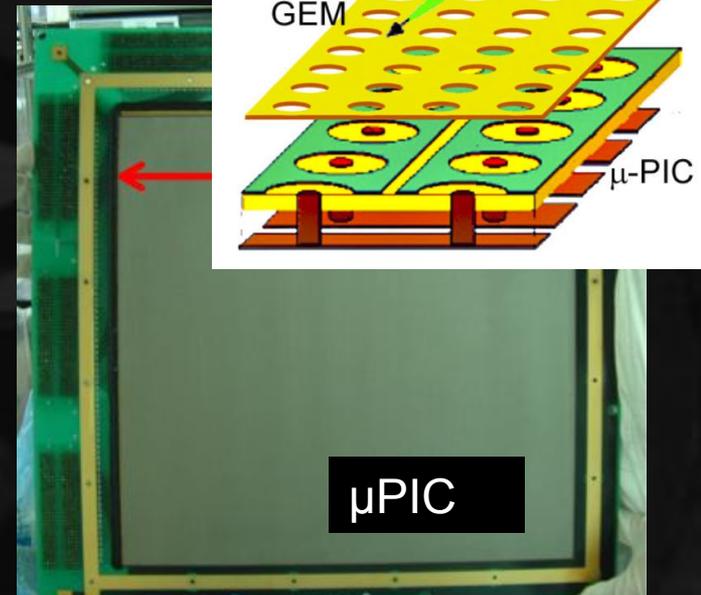
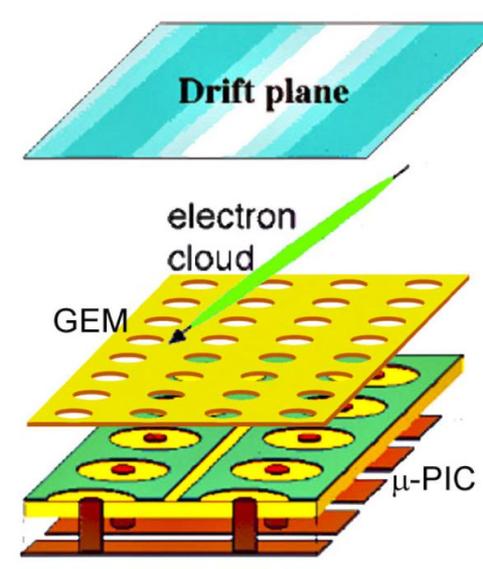
2009年 11月26日

名古屋大学GCOEセミナー 身内賢太郎

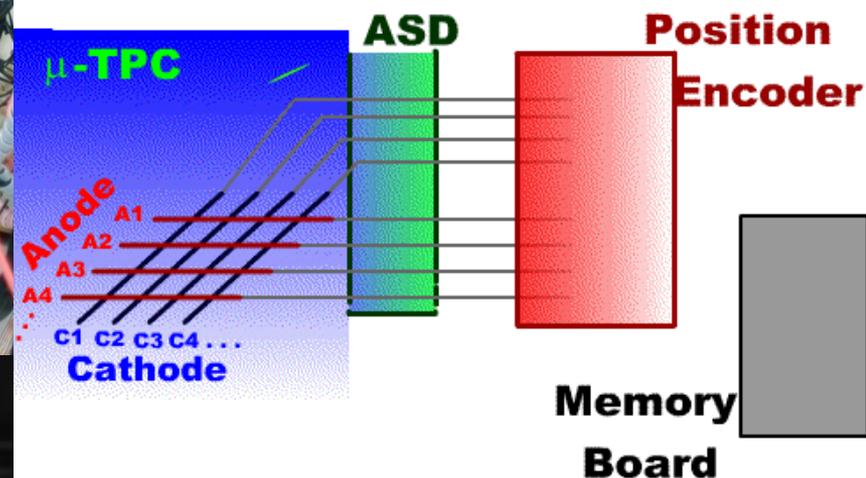


そしてNEWAGE

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



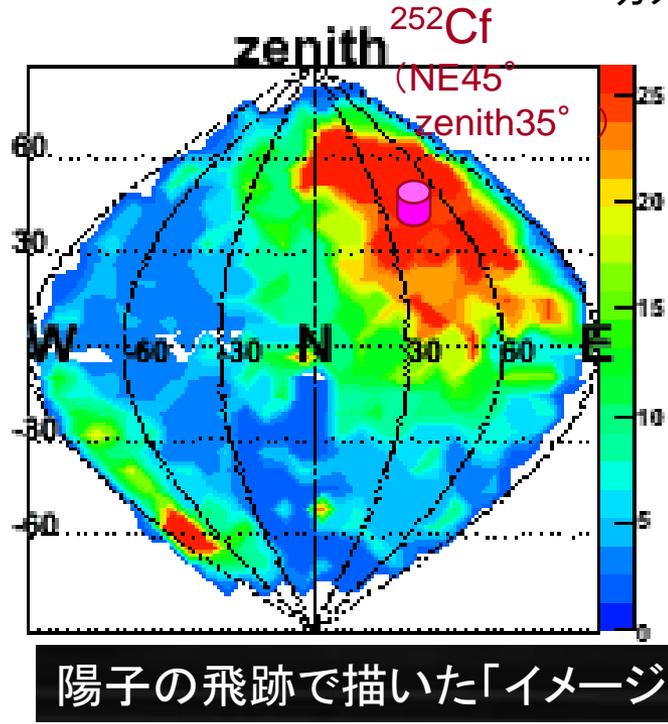
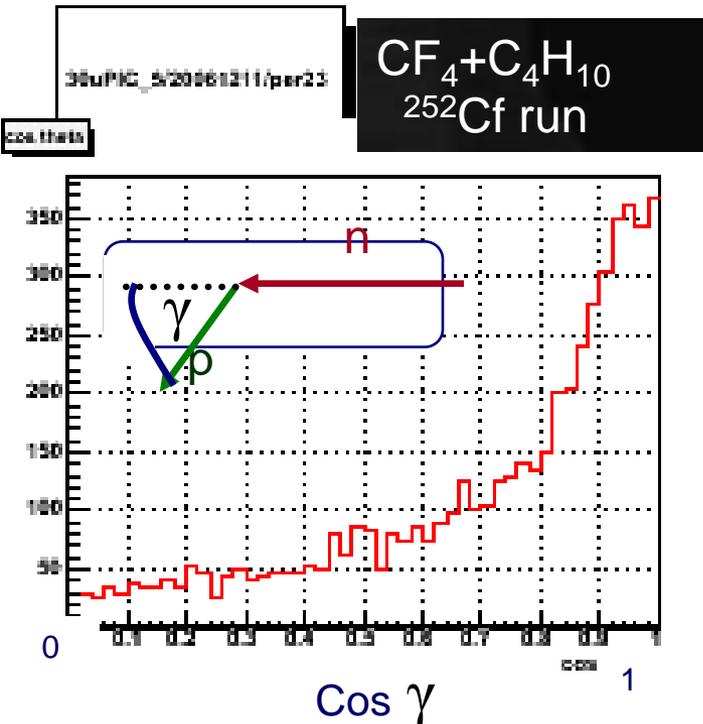
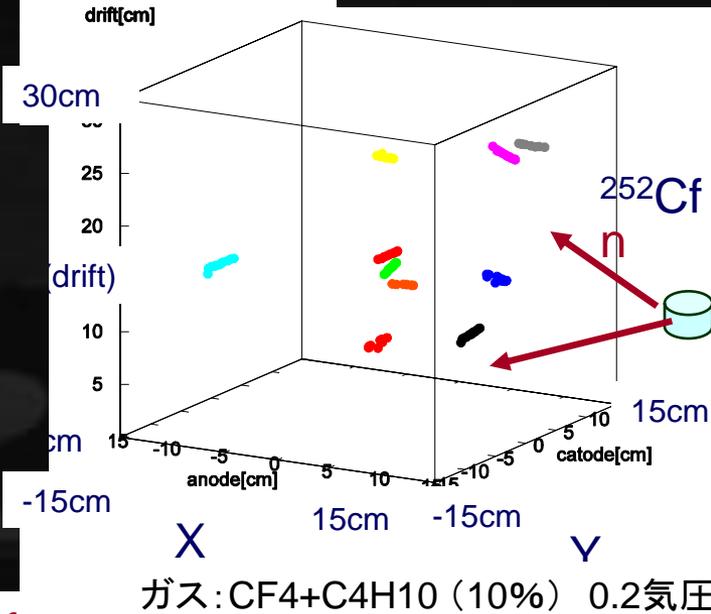
検出器
NEWAGE-0.3a



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

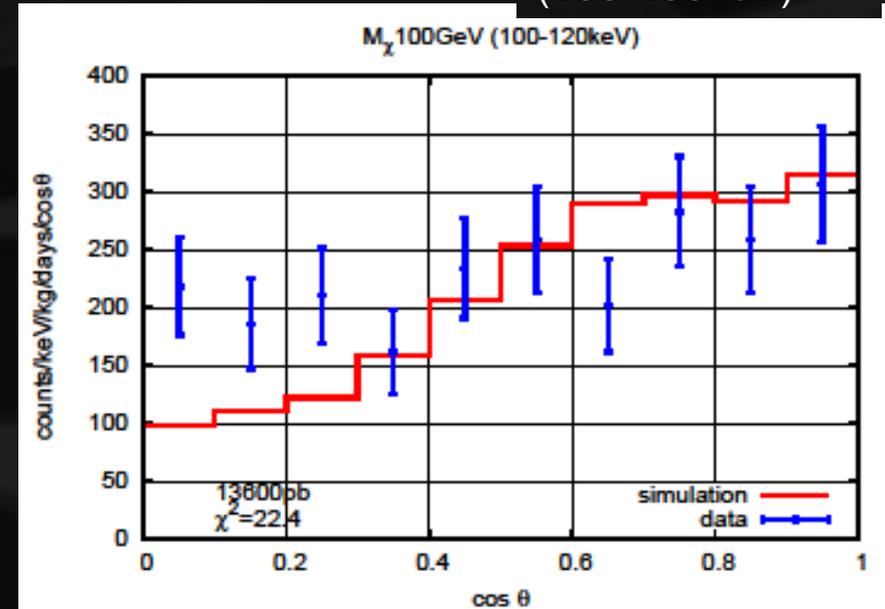
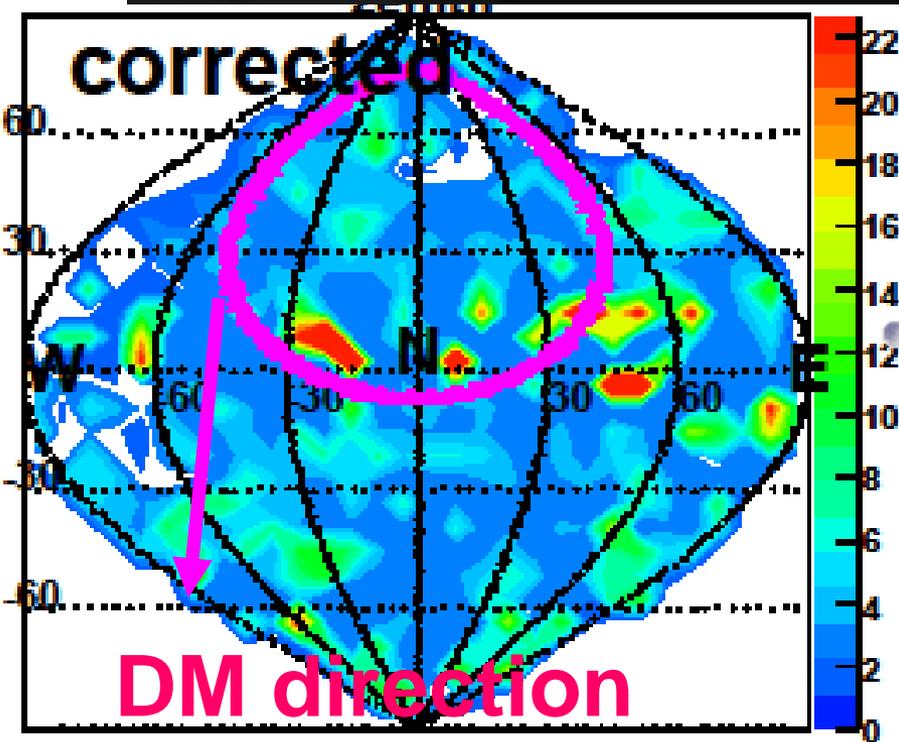


地上(京大)でのDM探索実験

- 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 χ^2 テストで排除
- 方向に感度をもった初の制限

最新結果 (2008年)

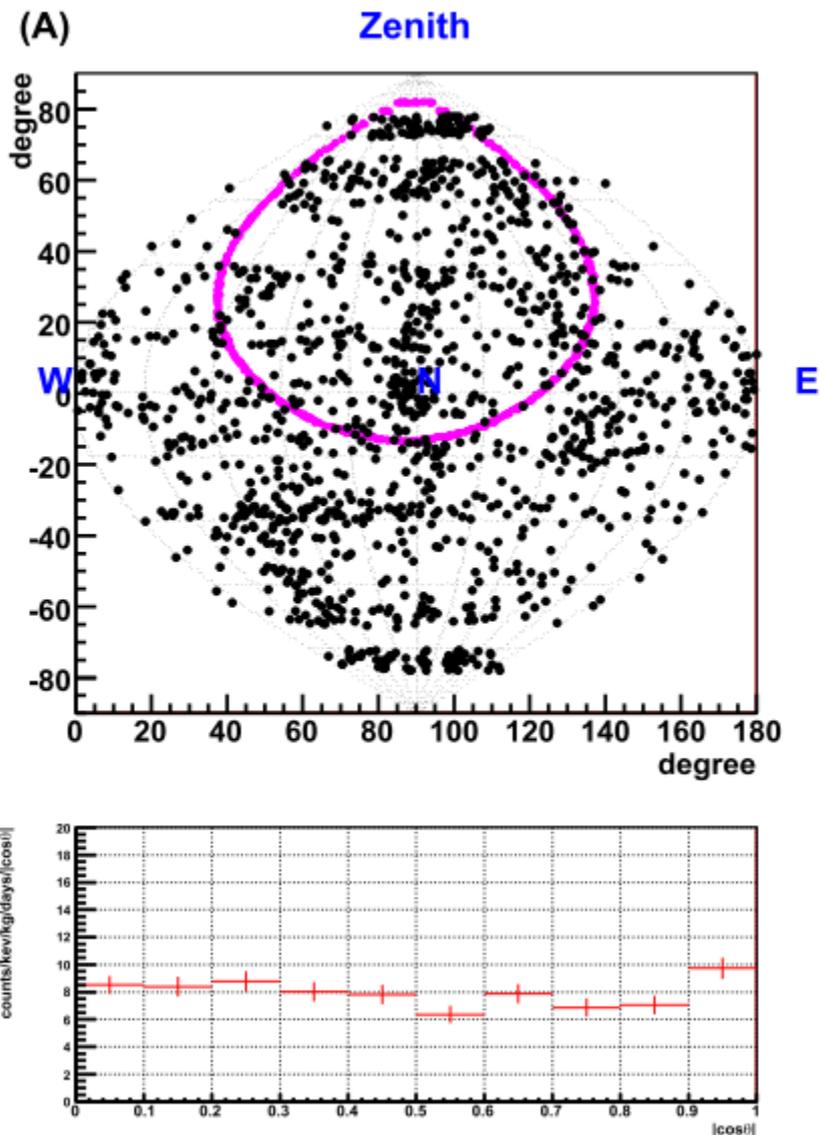
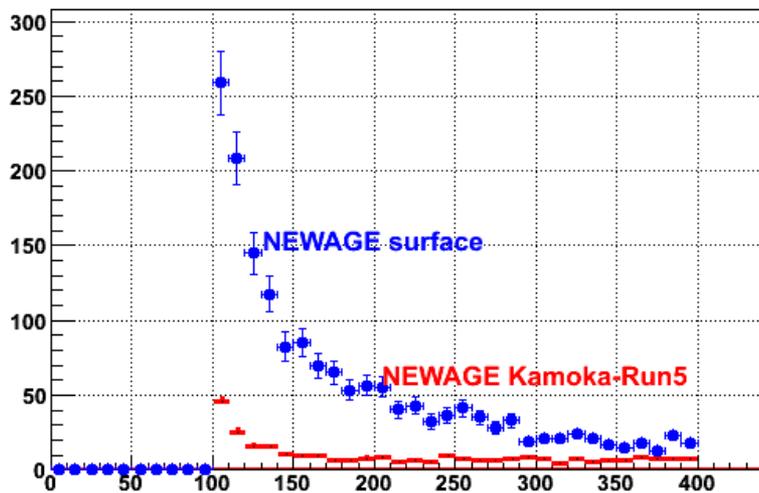
- 観測0.524 kg · days

- 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 $\cos\theta$ 分布

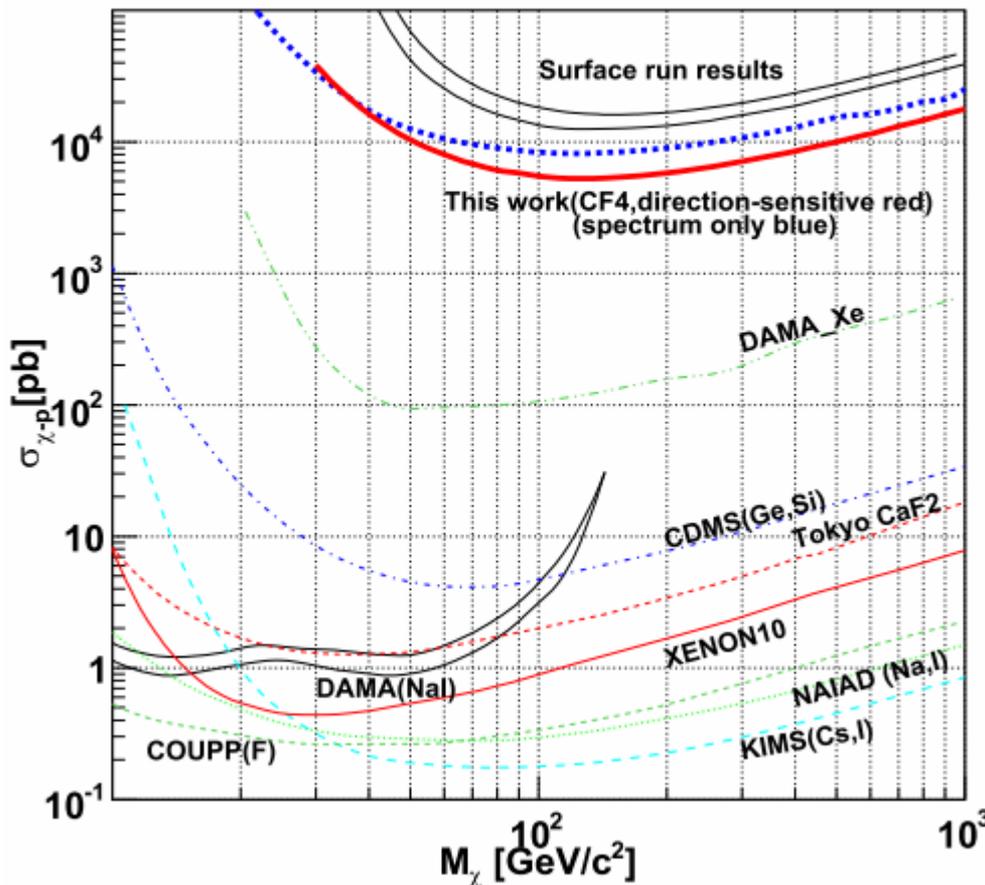


● 地下実験 first results

● 5400pb for 150GeV

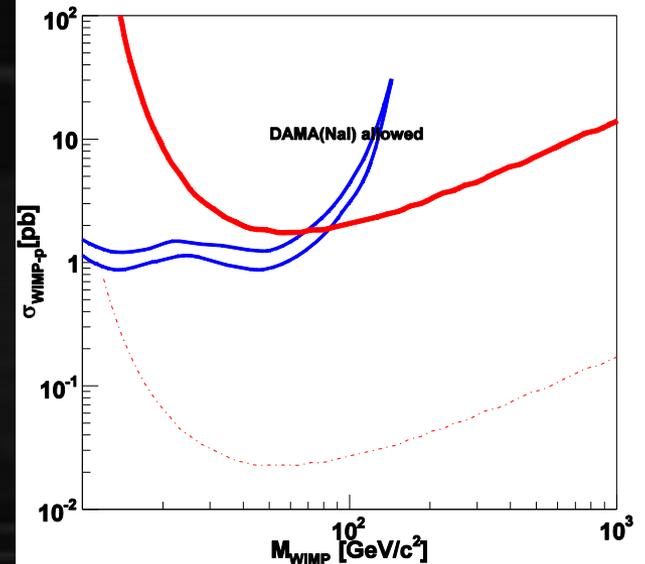
● まだまだに見えるが、、、

SD 90% C.L. upper limits and allowed region



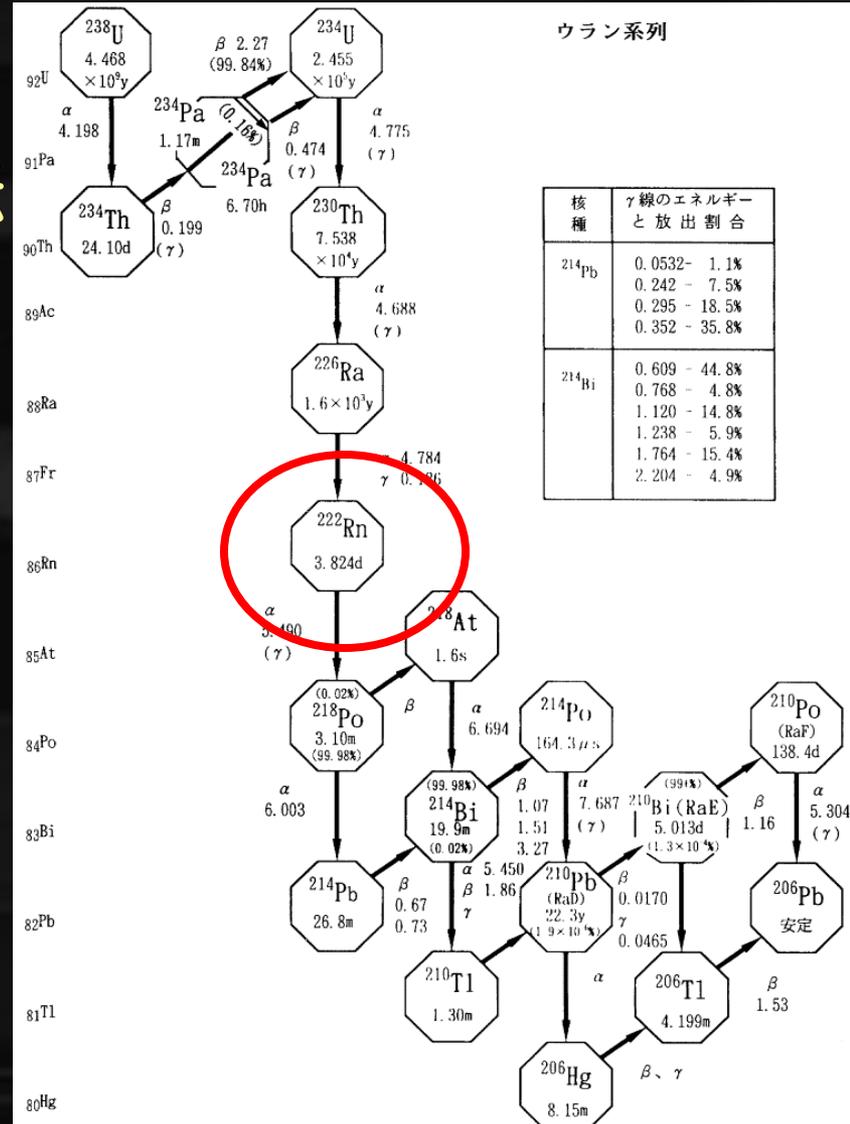
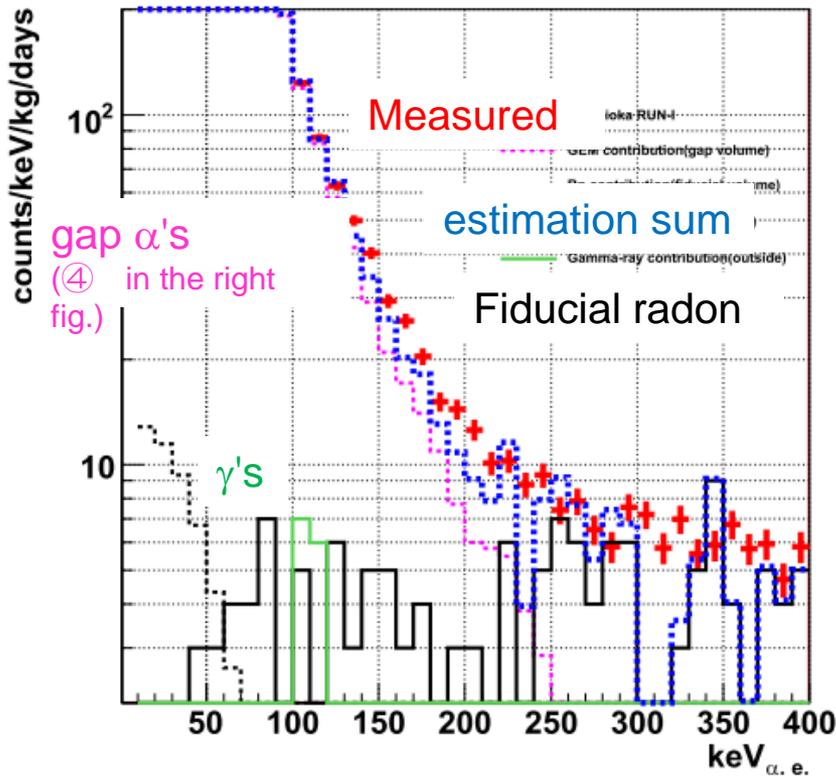
BGを1/10に低減
0.1m³年 の観測
すれば、

SD 90% C.L. upper limits



BGの低減

- 検出器内部の物質に含まれる U、Thなどの崩壊によるα線 が主成分
- 主にラドンとして侵入
- 材料の選択とラドンの除去



材料選択

自作のラドン計 (NEWAGE RD-1)

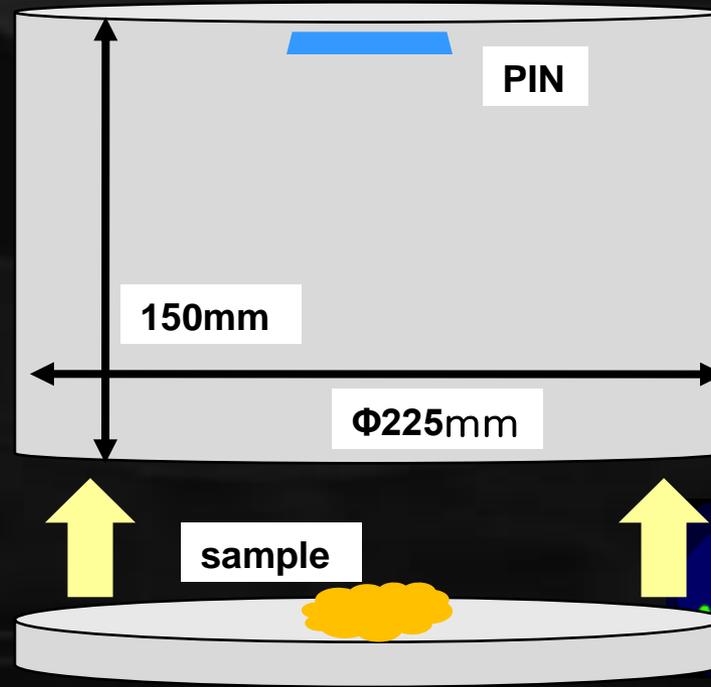


仕様

SUS 304 3mm厚 内面 電界研磨
窓無しPINフォトダイオード
(10×10mm² S3590-02)

動作環境

-375V Po+ 静電捕集 / 9V 逆バイアス
DAQ LPC-320901 (PCI-bus 40MHz FADC)



NEWAGE RD-1 results (preliminary)

TEST SOURCE

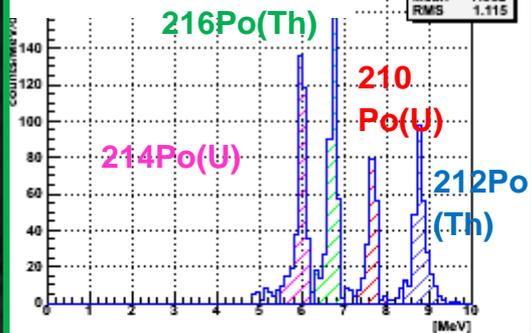
(calibration to be done somehow...)

Kamioka rock



energy spectrum

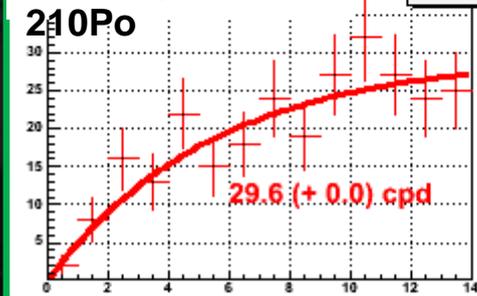
h3
Entries 1838
Mean 7.062
RMS 1.115



time dependence

210Po

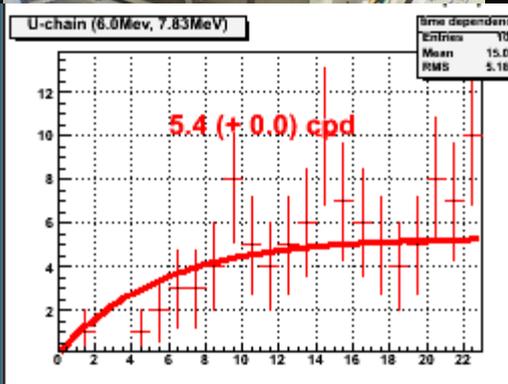
time dependence
Entries 295
Mean 8.382
RMS 3.541



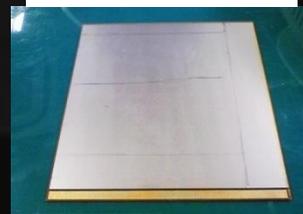
GUILTY



Fluoro-plastic for TPC board

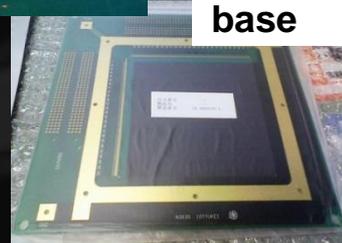


NOT GUILTY



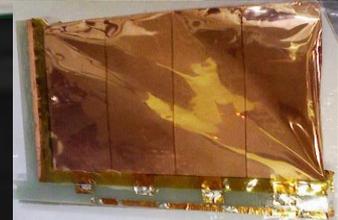
μ-PIC

μ-PIC base



抵抗

GEMs



テフロン板



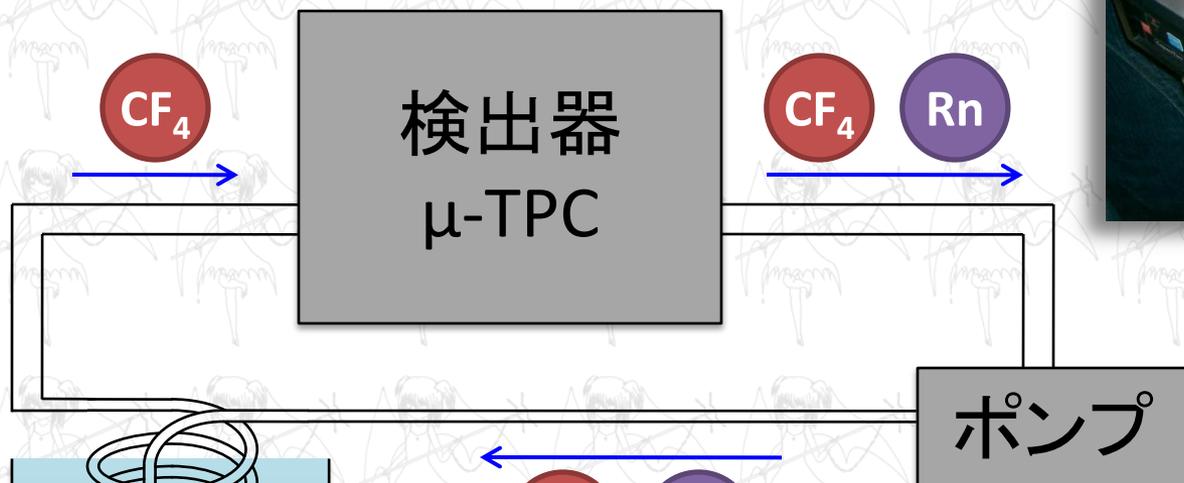
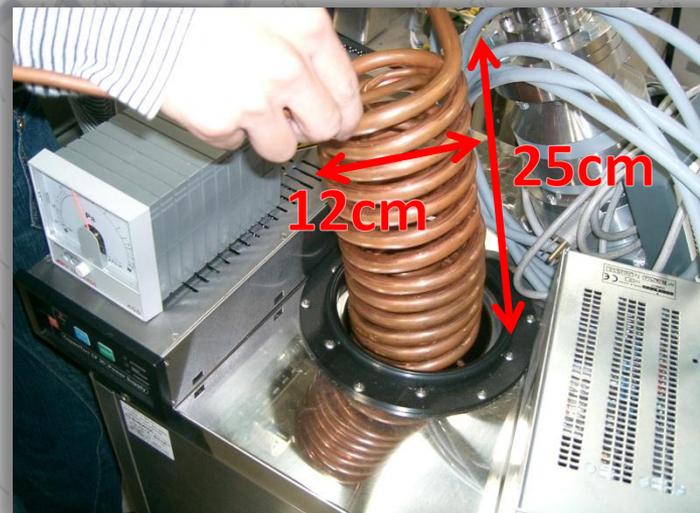
Direction Sensitive
WIMP-search

NEWAGE

中村発表
(JPS2009秋)

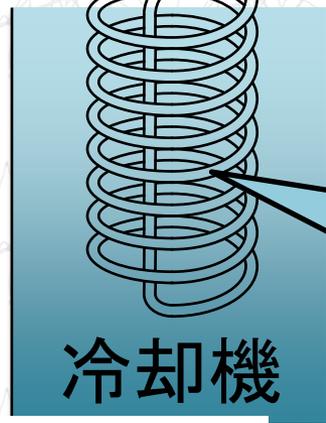
冷却活性炭システム

冷却(183K)・・・ラドンを液化
活性炭・・・ラドンを吸着

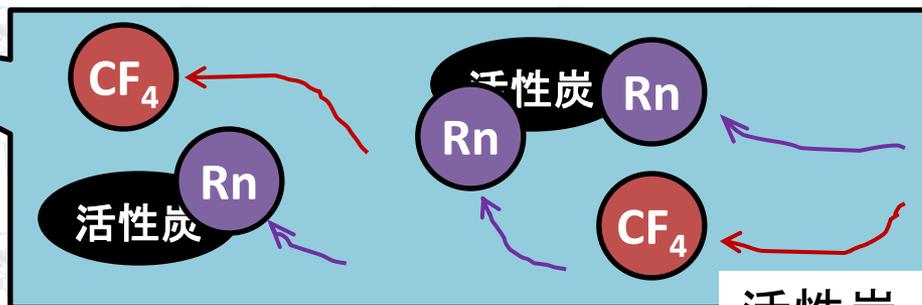


Rnの沸点: 211K
CF₄の沸点: 145K

ポンプ流量: 300ml/min



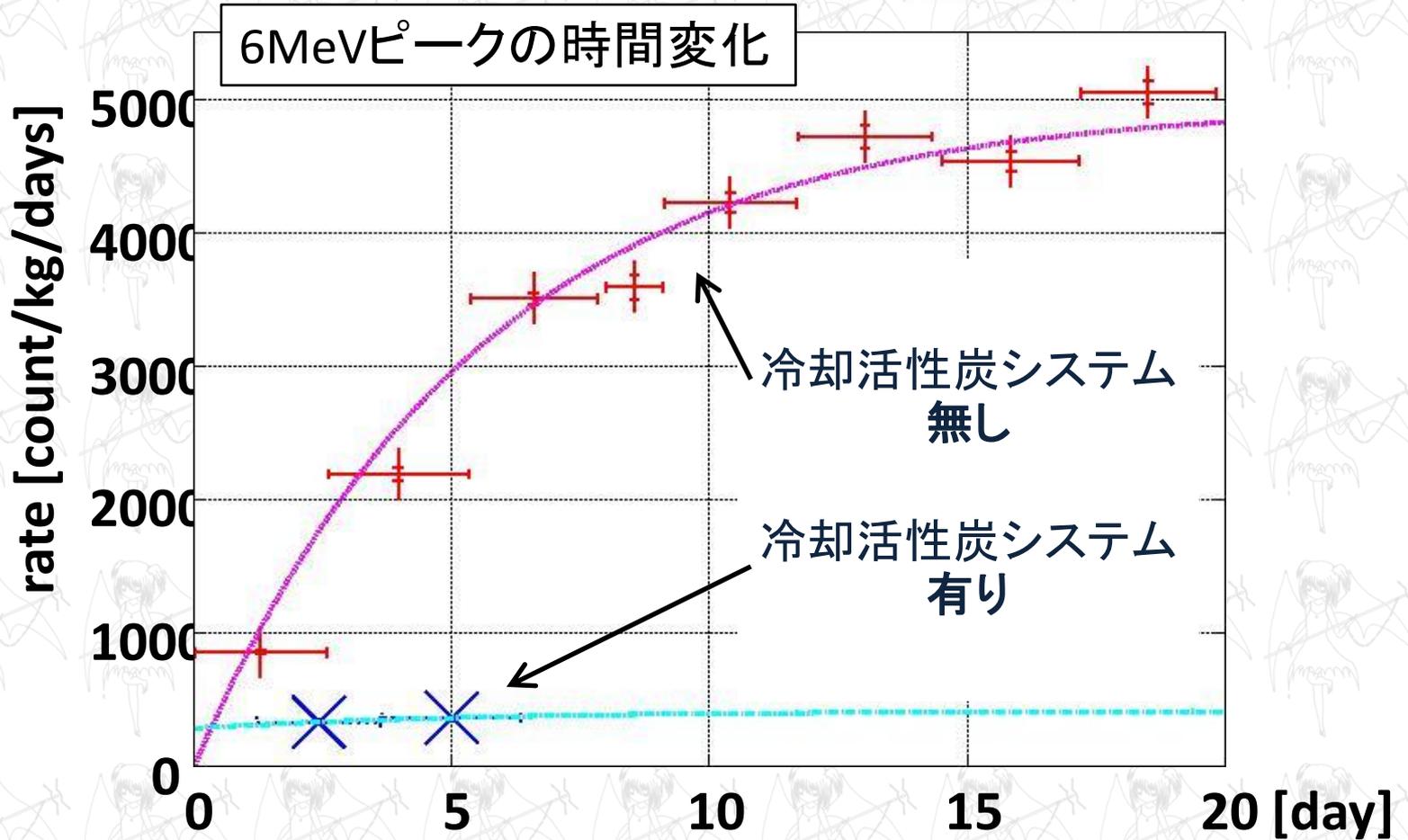
冷却温度: 183K



活性炭: 159g

中村発表
(JPS2009秋)

ラドン 減少の結果



5000

count/kg/days



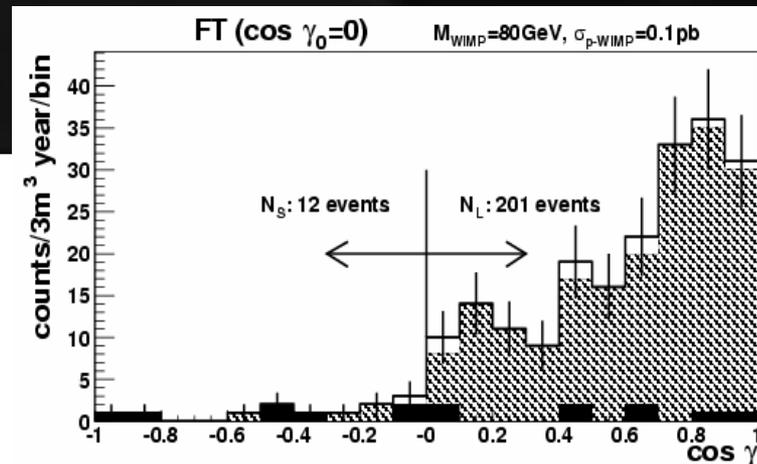
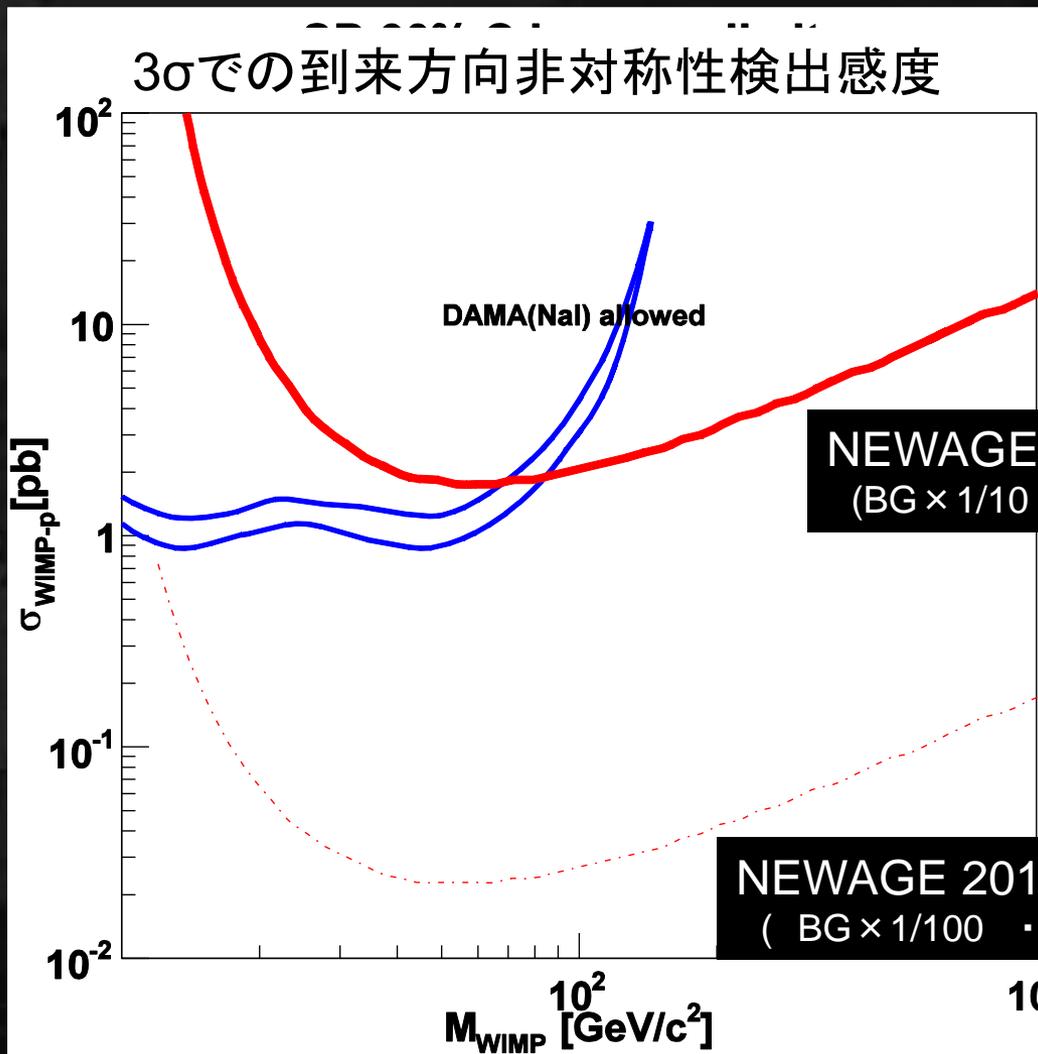
400以下

count/kg/days

ラドン: 8%以下に削減

NEWAGEのこのさき

- DAMA領域の探索へ



まとめ

暗黒物質の直接検出を目指して
世界中で研究がおこなわれています。

NEWAGEもそのうちのひとつです

ご清聴ありがとうございました。

