

暗黒物質直接探索

基研研究会 素粒子物理学の進展2014

神戸大学 身内賢太郎

2014年7月29日



THANKS

Japanese Experimental
Dark matter Investigators



暗黒物質

加速器実験



陽電子・ガンマ線 :
何か兆候?

間接探索

直接探索

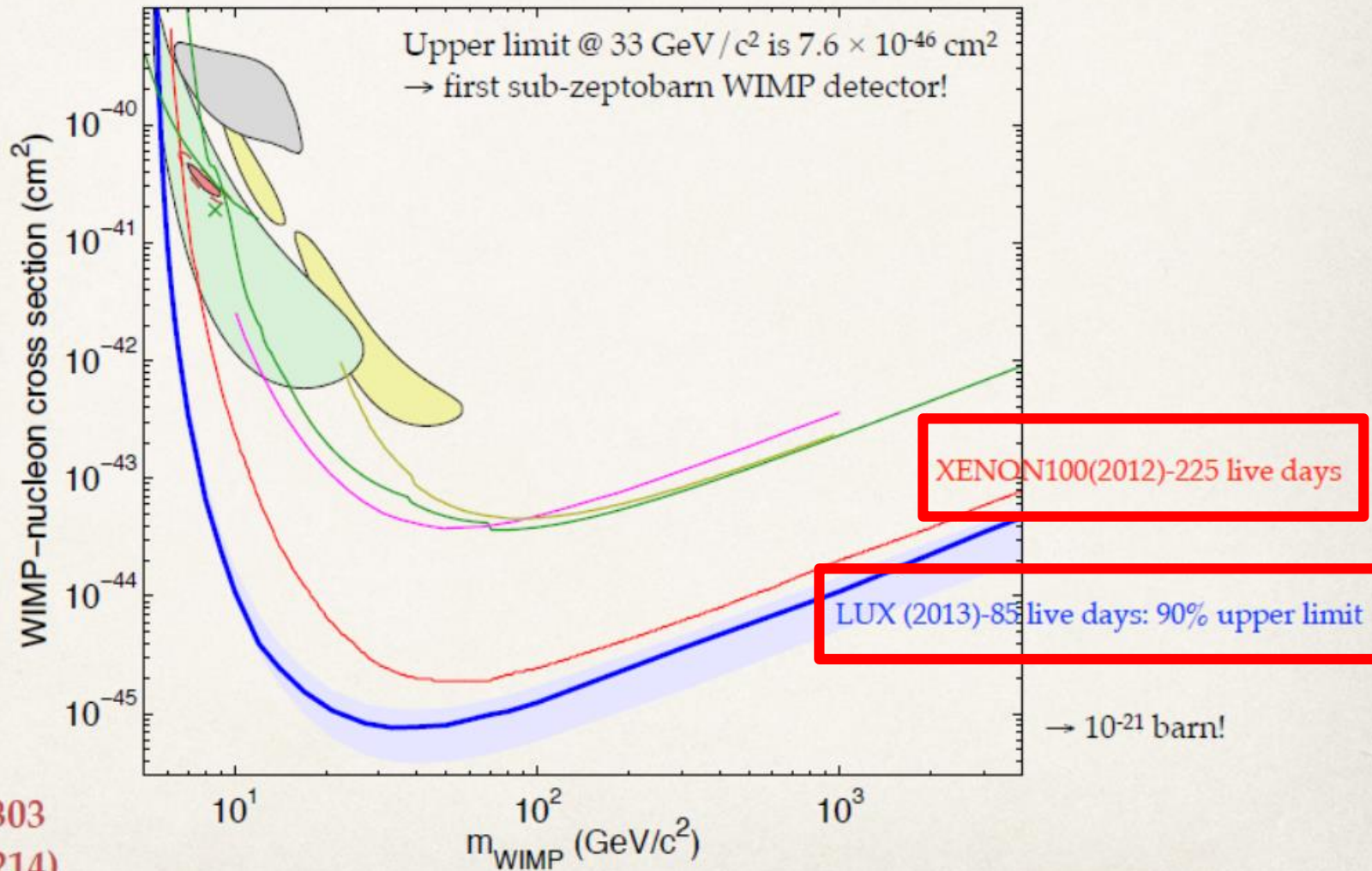
◆ 世界情勢のレビュー (主にIDM20140スライドより)

◆ 伝えたい / 議論したいこと

- 制限曲線には表れない、実験のやばいこと
キーテクノロジー
- 90%リミットと9 σ が同じ土俵でよいのか?

Spin-independent limit

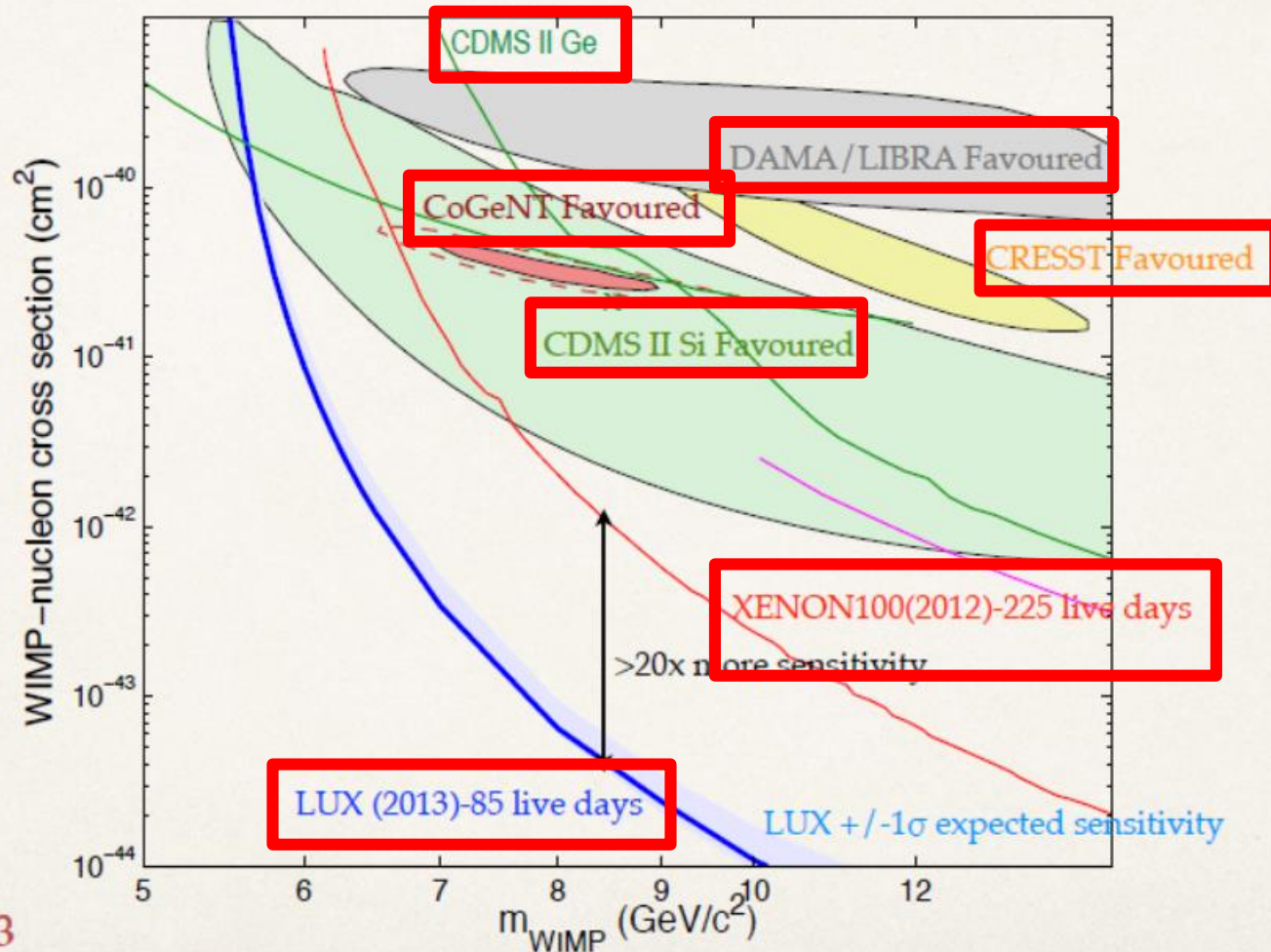
現状把握



PRL.112.091303
(arXiv:1310.8214)

Low-mass WIMP region

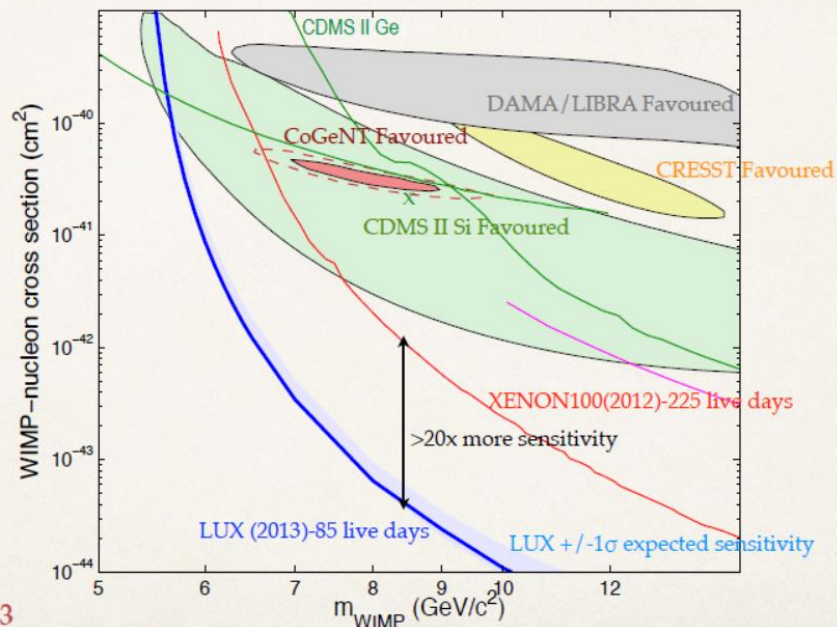
現状把握



PRL.112.091303
(arXiv:1310.8214)

戦いの歴史

- 1997～ DAMA : 「検出」を主張 50GeV程度?
- 2000～ CDMS等に否定される
- 2008年 LIBRAで再現!
- 2009年 CDMS 2事象
- 2010年～ その他の実験も (BGだろうか)
「**事象」を報告 低質量WIMP?
- 2012年～ XENON, LUXによる否定



PRL.112.091303
(arXiv:1310.8214)

暗黒物質の直接検出

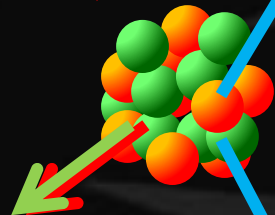
E_R 検出 (光)

DAMA
DM-ICE (NaI)
KIMS (CsI)
XMASS (Xe)

(光+電離)

ZEPOLINE II/III
XENON10/100
LUX (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)

CoGent
HPGe

(光+温度)

CRESST
(CaWO₄)

E_R 検出 (温度)

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

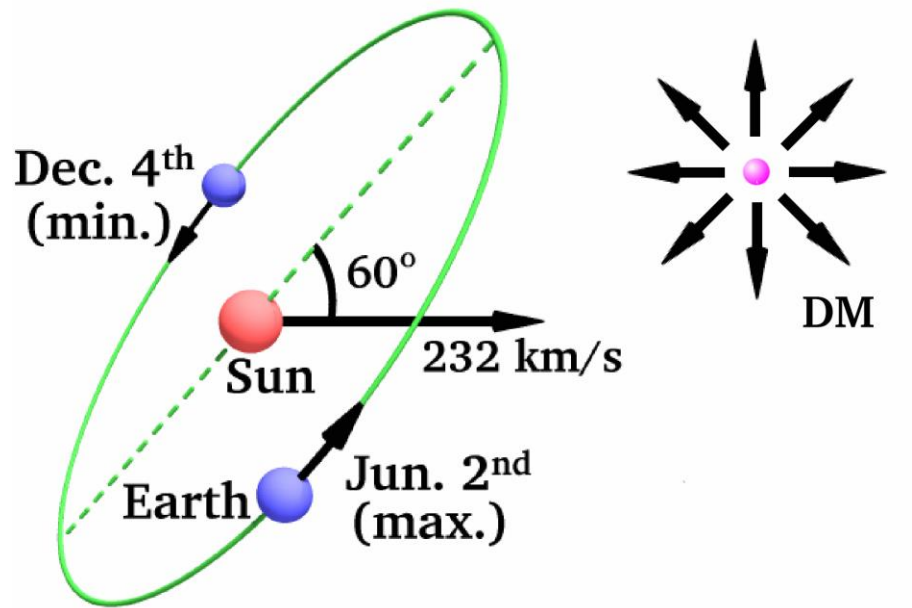
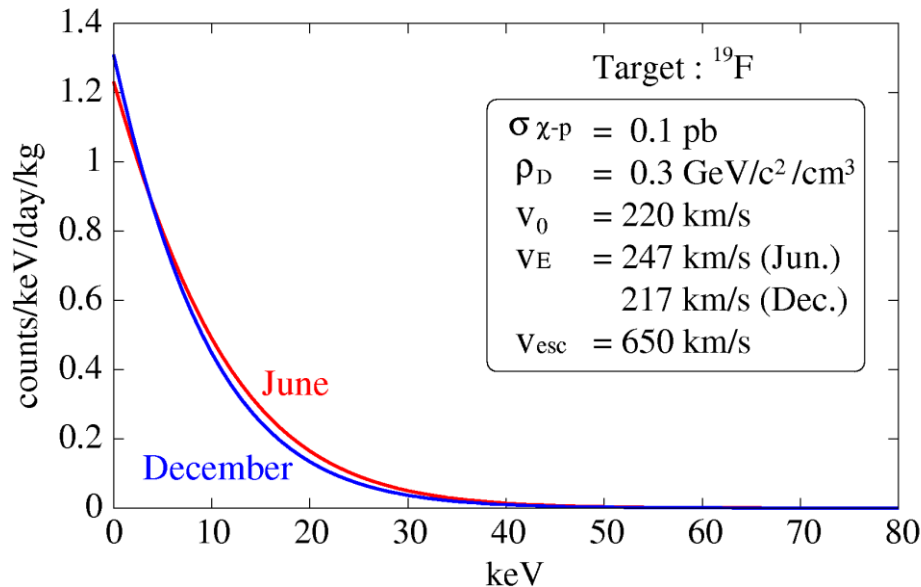
(電離+温度)

CDMS (Ge/Si)
EDELWEISS (Ge)

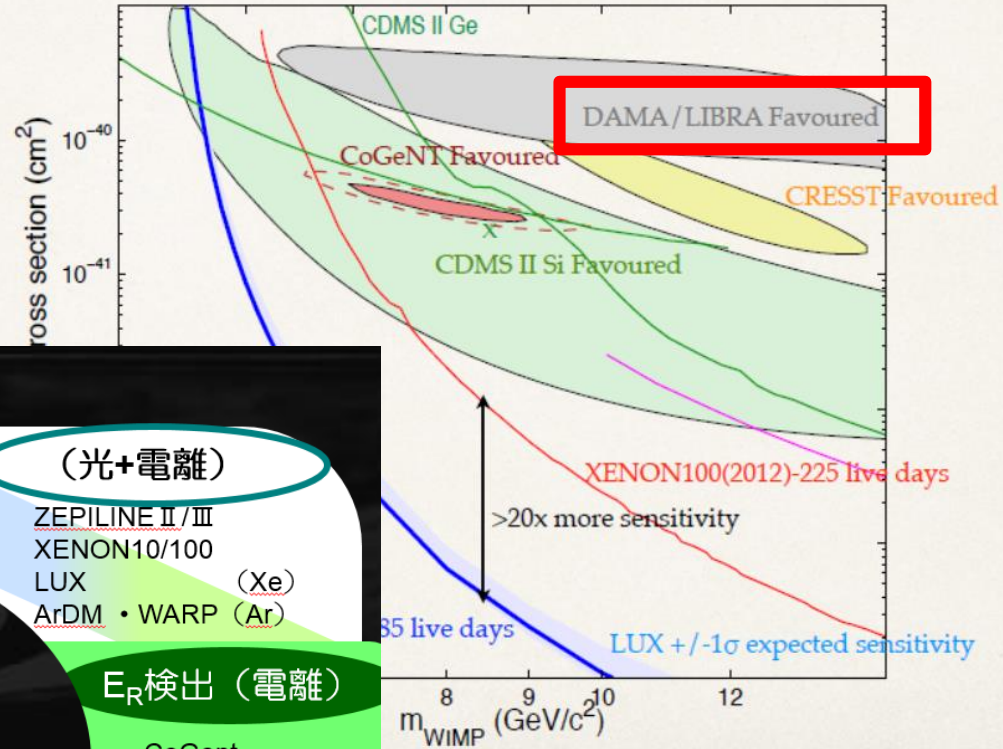
● 期待される信号

- 信号：原子核反跳
- バックグラウンド：電子反跳

- その① スペクトル / 「**事象見つけた」
← とにかく低閾値!
- その② 計数率の季節変動
- その③ 到来方向の検出

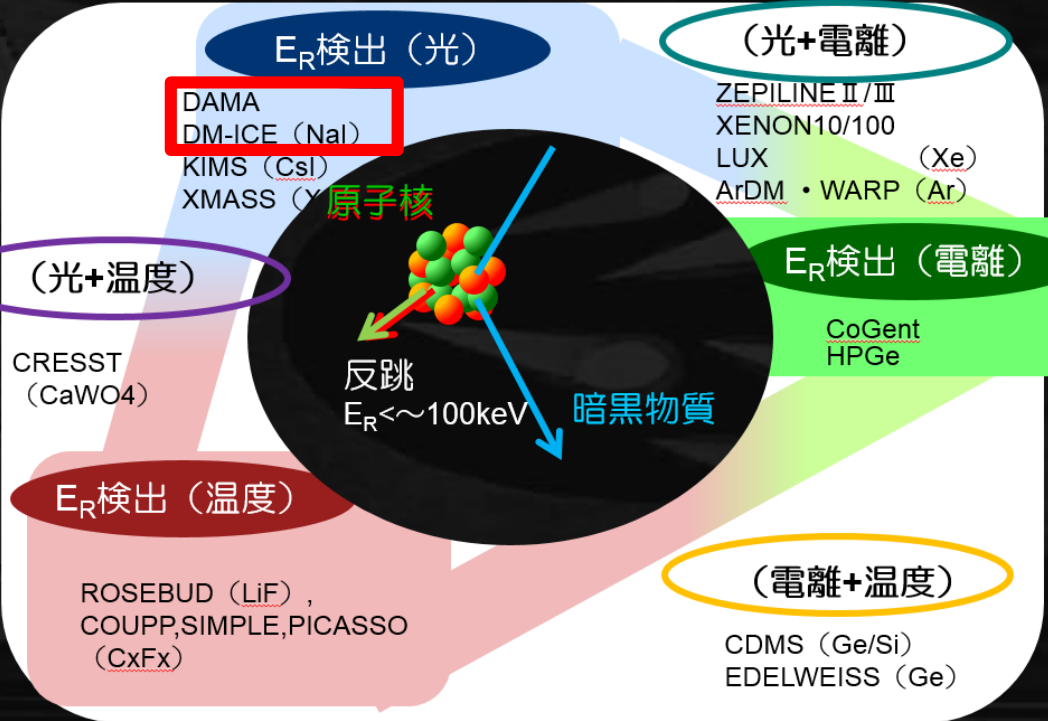


Low-mass WIMP region



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暗黒物質の直接検出



E_R 検出 (光)

- DAMA
- DM-ICE (NaI)
- KIMS (CsI)
- XMASS (Y)

(光+電離)

- ZEPILINE II/III
- XENON10/100
- LUX (Xe)
- ArDM, WARP (Ar)

E_R 検出 (電離)

- CoGent
- HPGe

(電離+温度)

- CDMS (Ge/Si)
- EDELWEISS (Ge)

(光+温度)

- CRESST (CaWO₄)

E_R 検出 (温度)

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

原子核

反跳

$E_R \sim 100\text{keV}$

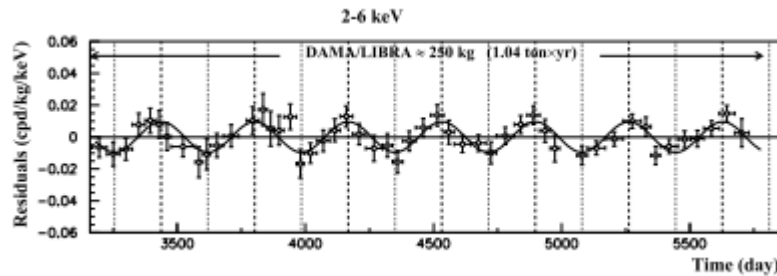
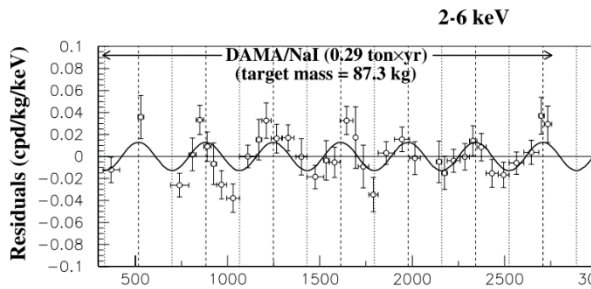
暗黒物質

DAMA/LIBRA

- 250kgのNaIシンチレータ
- 1.33ton・年の観測
- 14サイクルの季節変動 (9.3 σ)

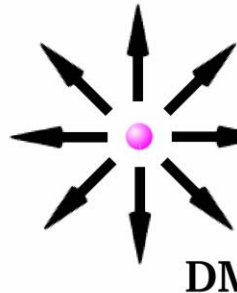
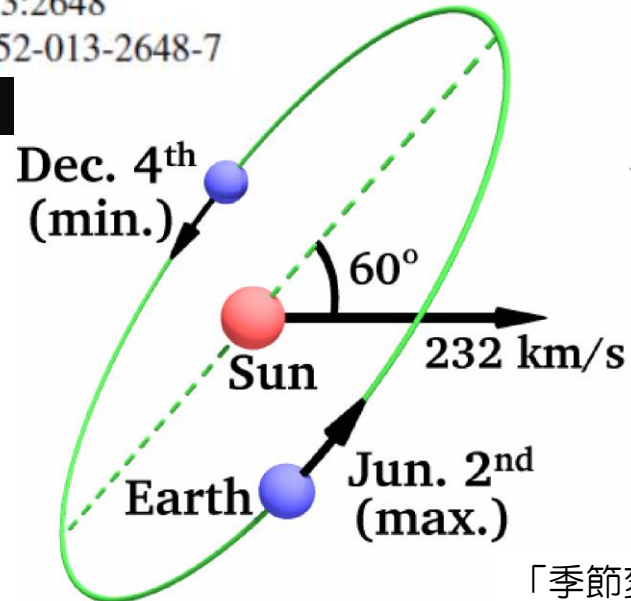
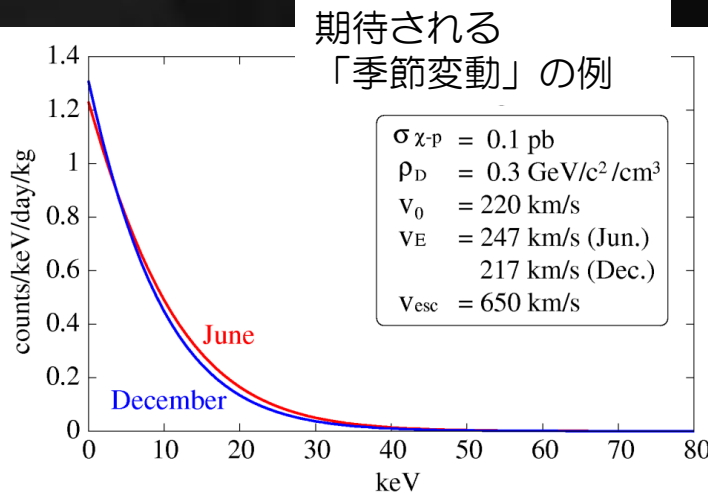


DAMA page



Eur. Phys. J. C (2008) 56: 333–355
DOI 10.1140/epjc/s10052-008-0662-y

Eur. Phys. J. C (2013) 73:2648
DOI 10.1140/epjc/s10052-013-2648-7



「季節変動」の模式図

◆ DAMAのやばいこと

- 9.3 σ が90%リミットで殺されまくっている
- それ以外で一番やばいのは ↓ 。 μ が先行してたらアウトだったな。

arXiv:1205.3675v1 [hep-ph] 16 May 2012

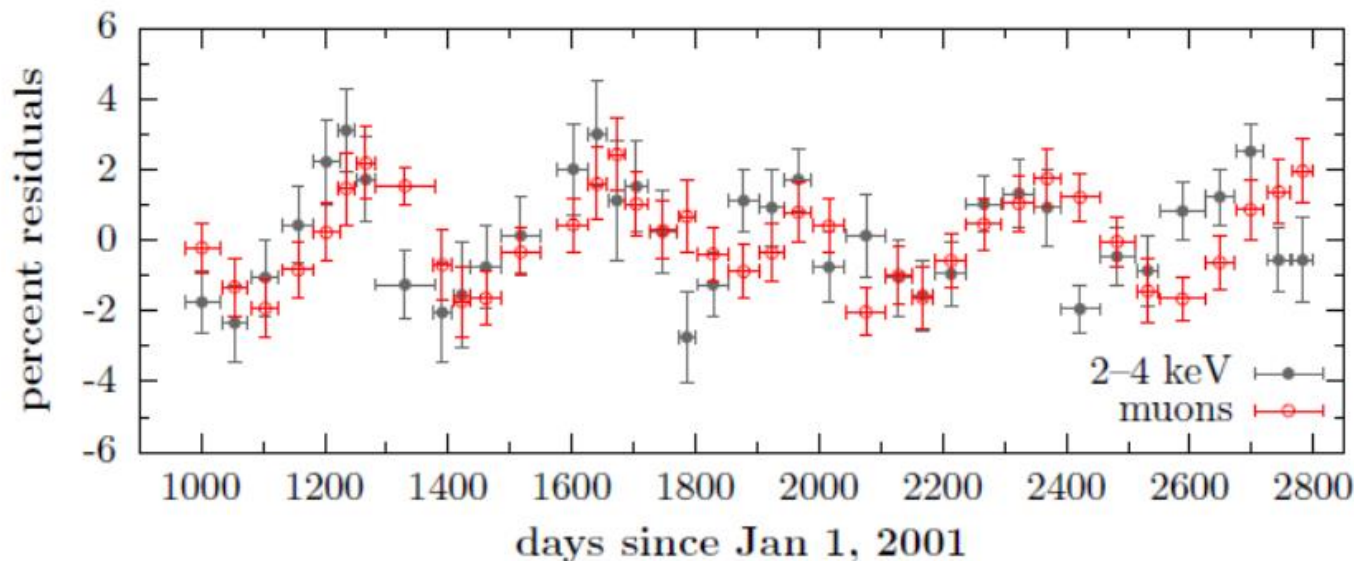


Figure 1: Percent annual residuals of the LVD measured muon flux when binned in accordance with DAMA/LIBRA runs 1–5. The latter residuals are shown for the 2–4 keV bins assuming a baseline $\bar{s} = 1.15$ cpd/kg/keV.

DM-ICE

- 南半球でのNaI実験
- 17kg ×2年

arXiv:1401.4804v1 [astro-ph.IM] 20 Jan 2014



First Data from DM-Ice17, Prospects for DM-Ice

Neil Spooner, Reina Maruyama,
on behalf of the DM-Ice Collaboration

TeVPA/IDM - Astroparticle Physics 2014
June 26, 2014
Amsterdam

DM-ICE

- DAMAの結晶がやはり綺麗だ。
- 綺麗な結晶を作って DM-Ice250に
- 日本もいいもの準備しています。

NAIAD/DM-Ice17 crystals: (arXiv:1401.4804v1, PLB 616 (2005) 17–24)

- ~30x DAMA's K-40 contamination
- 5 - 10x DAMA's single-hit event rate (no multi-hit cut applied in NAIAD/DM-Ice17)

Neil Spooner, Reina Maruyama
on behalf of the DM-Ice Collaboration

TeVPA/IDM - Astroparticle Physics 2014
June 26, 2014
Amsterdam

Manufacturer	Form	Measurement	²³⁸ U (ppt)	²³² Th (ppt)	^{nat} K (ppb)
Saint Gobain	Powder	DAMA (HPGe)	< 20	< 20	< 100
Saint Gobain	Crystal	DAMA/LIBRA	0.7 - 10	0.5 - 7.5	< 20
Saint Gobain	Crystal	ANAIS-0	7.6	7.7	410
Bicron/Saint Gobain	Crystal	NAIAD/DM-Ice17	55	33	550
Sigma-Aldrich	Powder (standard grade)	DM-Ice (HPGe)	40	89	440
Sigma-Aldrich	Powder (astro grade)	DM-Ice (HPGe)	63	< 95	< 126
Sigma-Aldrich	Powder (astro grade)	A-S (ICPMS)	-	-	~ 4
Alpha-Spectra	Powder	DM-Ice (HPGe)	< 100	< 200	< 120
Alpha-Spectra	Powder	ANAIS-25 (HPGe)	< 55	< 130	< 90

*DAMA ppt number for other crystals

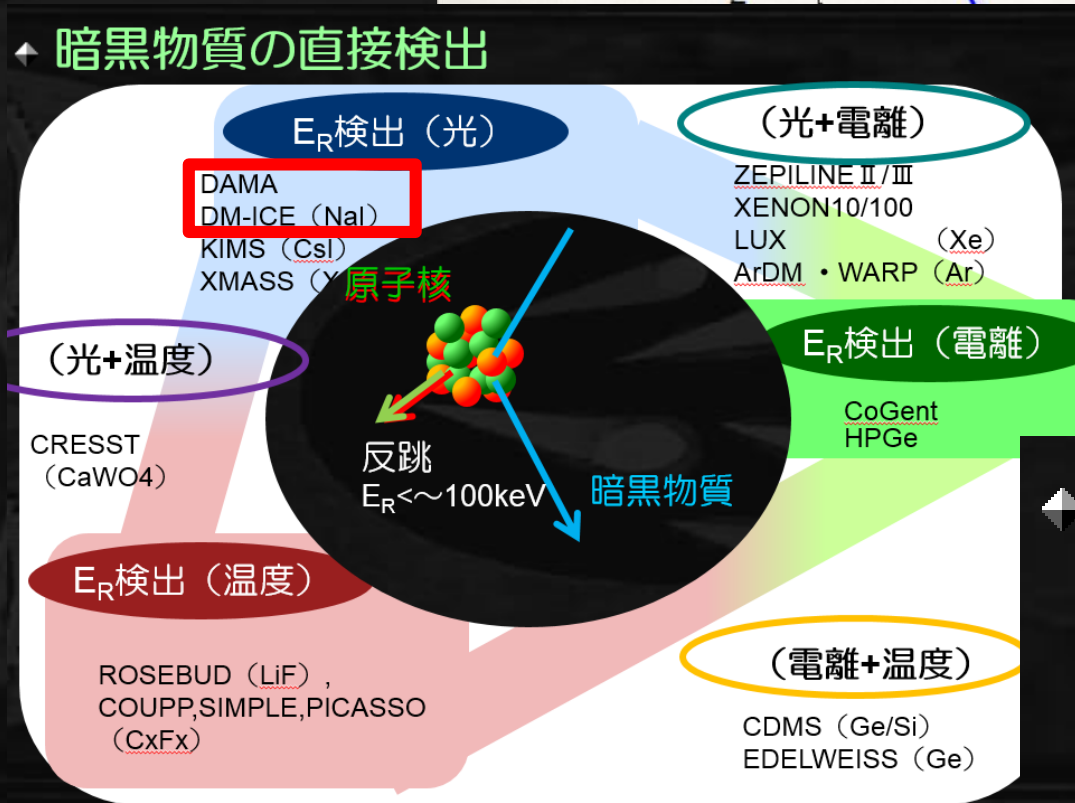
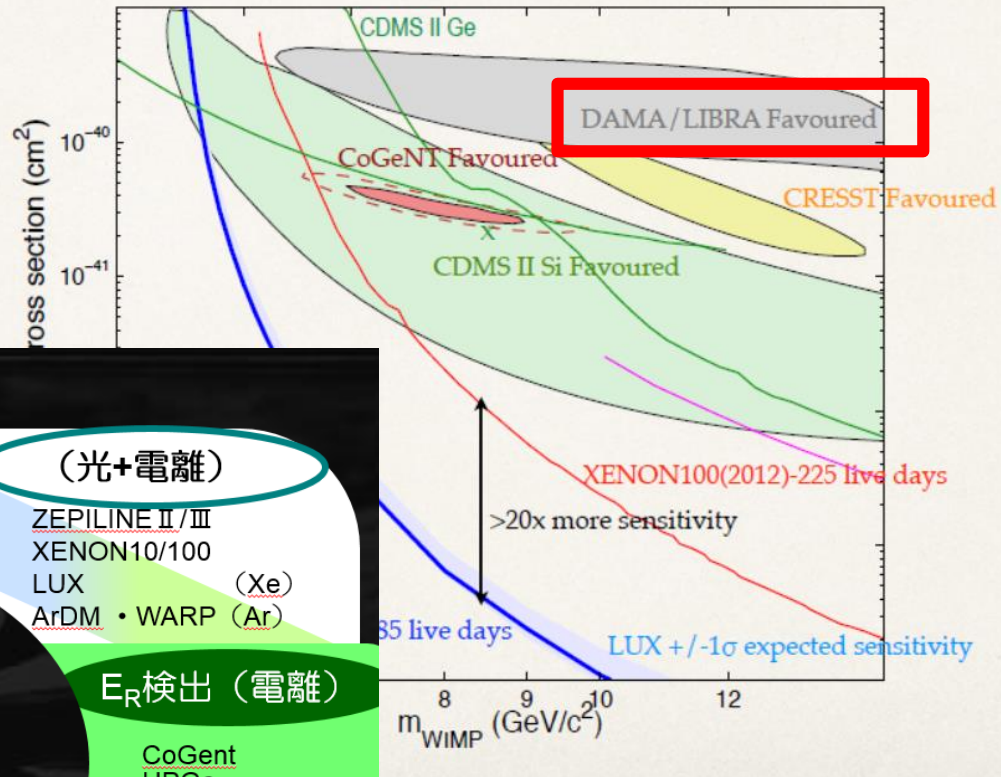
PICO-LON(徳島大学)

~8ppt

<1ppt

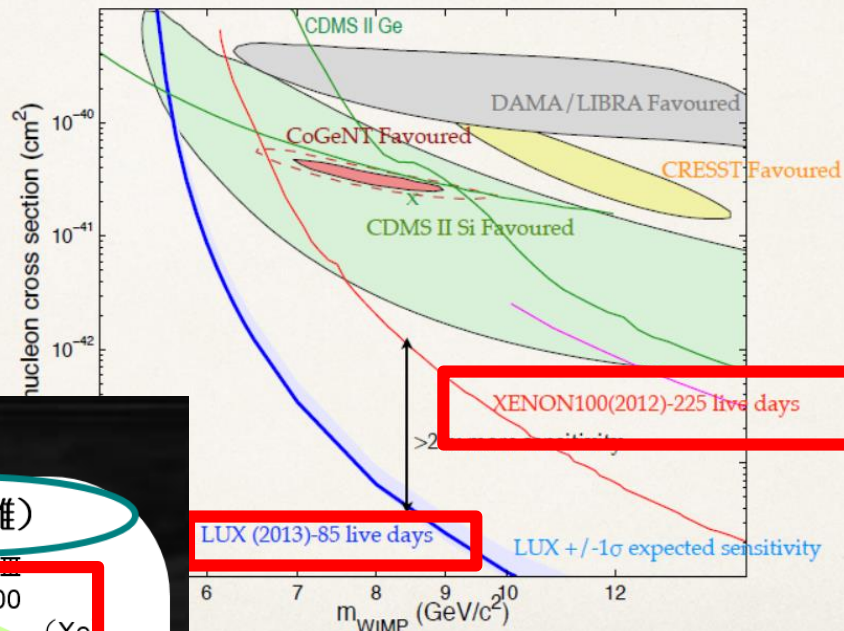
not yet

Low-mass WIMP region



- ## DAMAのやばいこと
- 圧倒的な統計量
 - 綺麗な結晶

Low-mass WIMP region



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暗黒物質の直接検出

E_R 検出 (光)

DAMA
DM-ICE (NaI)
KIMS (CsI)
XMASS (Xe)

(光+電離)

XENON10/100
LUX (Xe)

(光+温度)

CRESST
(CaWO₄)

原子核

反跳

$E_R \sim 100\text{keV}$

暗黒物質

E_R 検出 (電離)

CoGent
HPGe

E_R 検出 (温度)

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

(電離+温度)

CDMS (Ge/Si)
EDELWEISS (Ge)

◆ 2相式液体キセノン

- XENON100 : 161 kg

- LUX : 370 kg

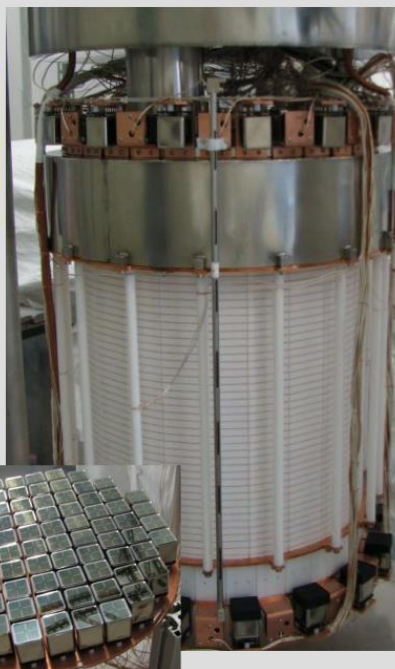
XENON100

Goal (compared to XENON10):

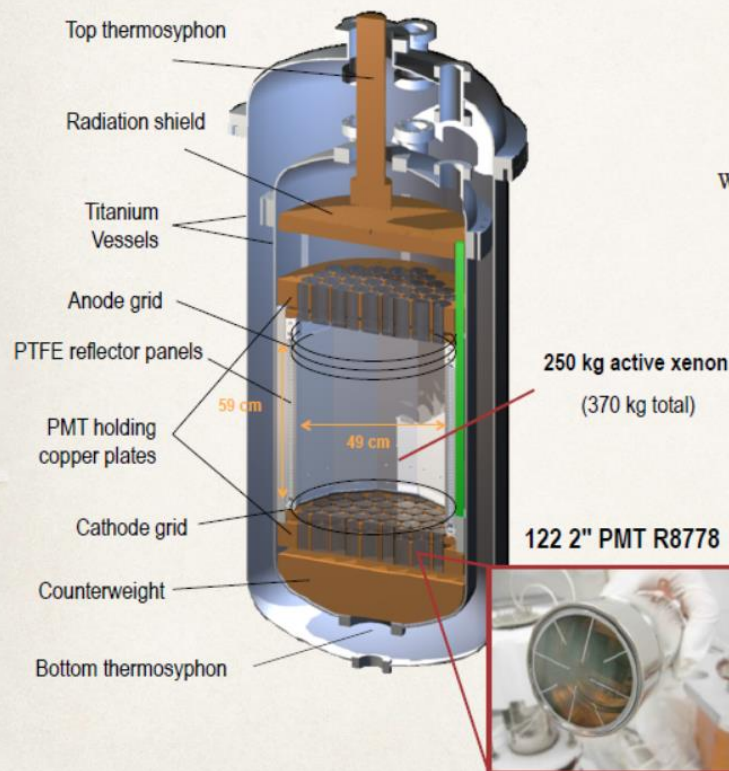
- increase target $\times 10$
- reduce gamma background $\times 100$
→ material selection & screening
→ detector design

Quick Facts:

- 161 kg LXe TPC (mass: $10 \times \text{Xe}10$)
- 62 kg in target volume
- active LXe veto (≥ 4 cm)
- 242 PMTs (Hamamatsu R8520)
- improved Xe10 shield (Pb, Poly, Cu, H₂O, N₂ purge)

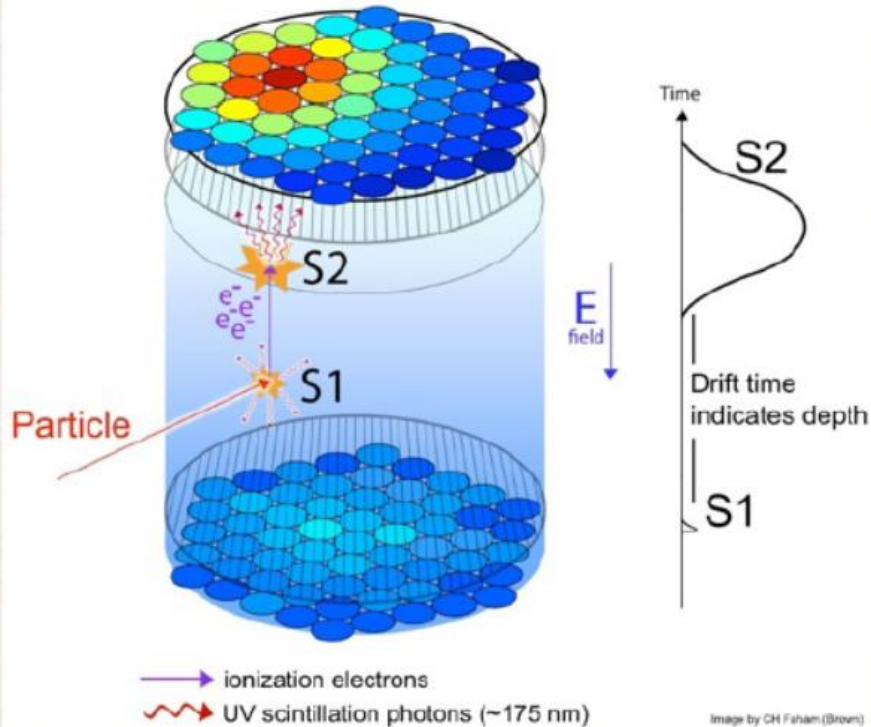


The LUX Detector



液体キセノン

ガンマ線除去



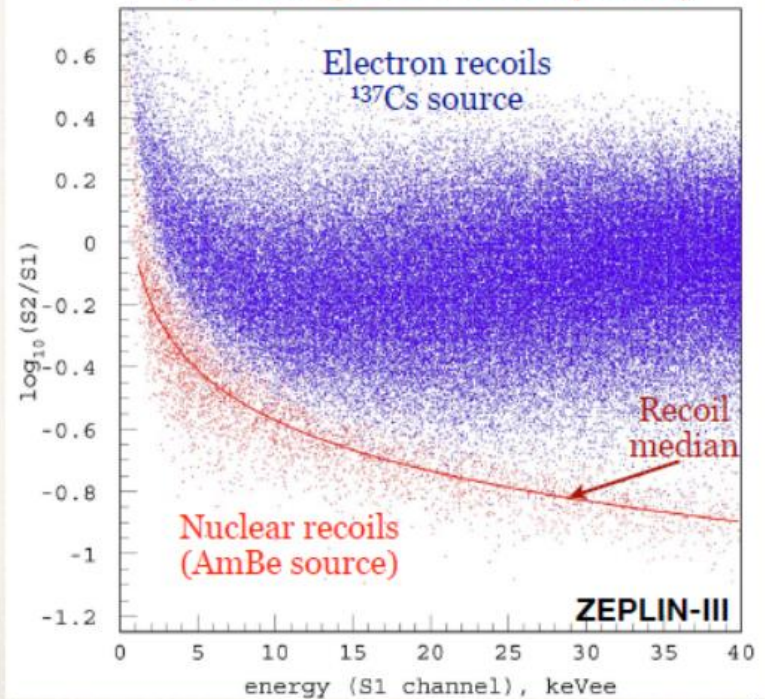
3D Position Reconstruction

- Z from time difference between S1 and S2 (1.5 mm/ μ s @ 181 V/cm)
- XY reconstructed from light pattern (resolution of a few mm in WIMP search region)

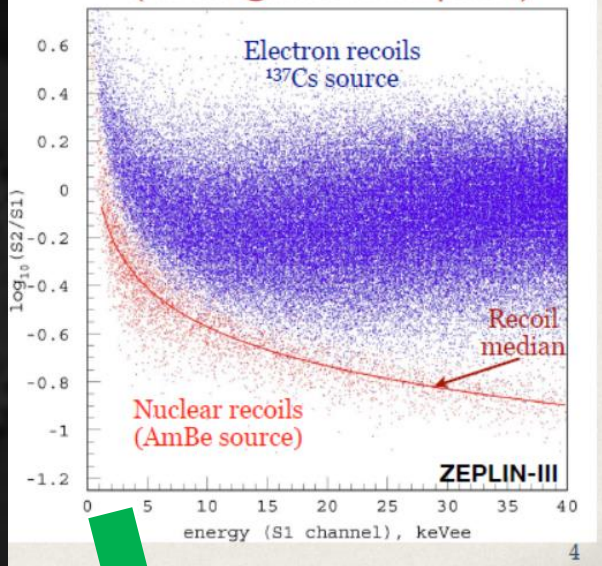
Discrimination technique

- WIMPs and neutrons interact with nuclei short, dense tracks
- γ s and e⁻ interact with atomic electrons longer, less dense tracks

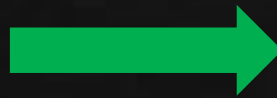
S2/S1 used for discrimination
(>99.5% @ 50% NR acceptance)



S2/S1 used for discrimination
(>99.5% @ 50% NR acceptance)



なるほど、よく分かっている!



制限曲線だけで満足してください。

ちょっとまてよ

オーバーラップあるじゃないか。
閾値付近ではどうなんだ?

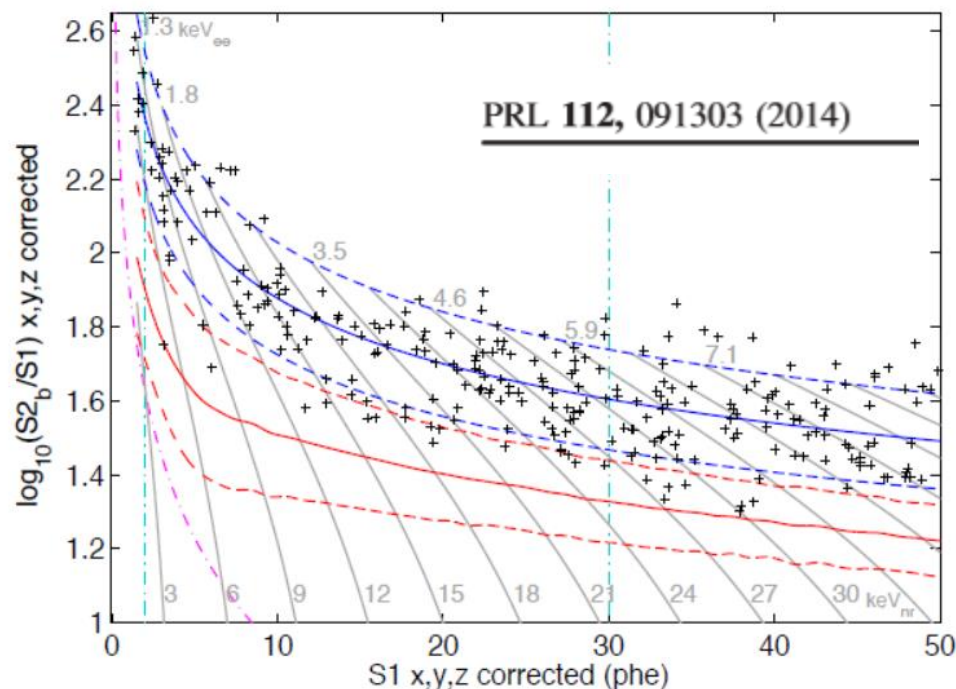


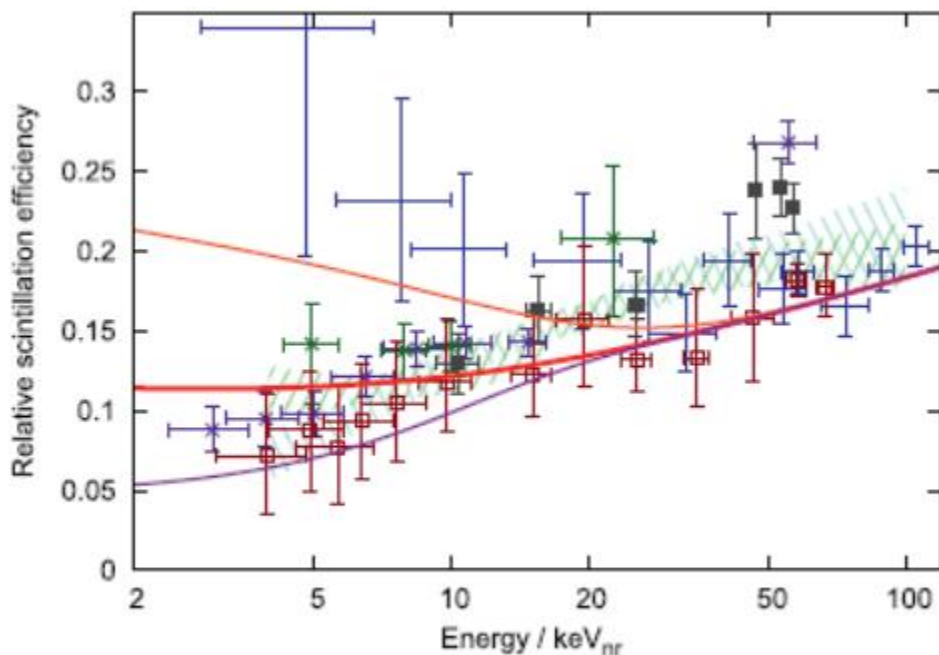
FIG. 4. The LUX WIMP signal region. Events in the 118 kg fiducial volume during the 85.3 live-day exposure are shown. Lines as shown in Fig. 3, with vertical dashed cyan lines showing the 2-30 phe range used for the signal estimation analysis.

ガンマ線BGのしみこみの可能性
⇒制限曲線の上下に効く

液体キセノンのやばいこと

- 発光効率 粒子依存、エネルギー依存

Astroparticle Physics 35 (2011) 119-127



(b) The relative scintillation efficiency

モデルによって低エネルギーで差

発光効率

⇒ エネルギースペクトル（制限曲線）の左右に効く

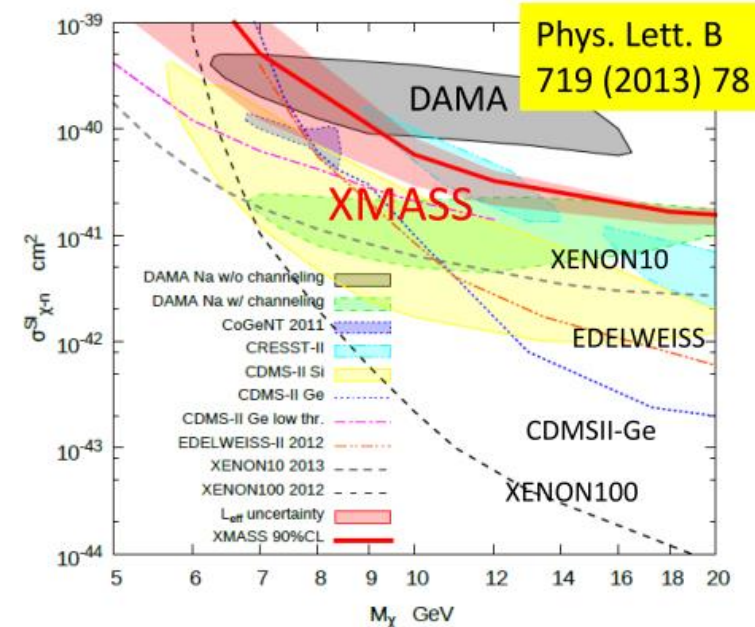
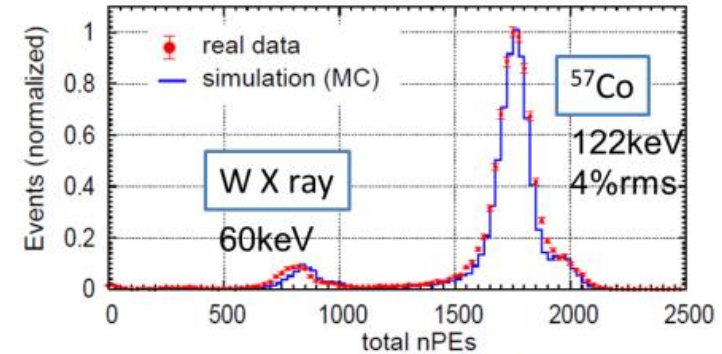
XMASS (東大宇宙線研+)

- キセノン 835kg
- 1層型

森山2013年秋物理学会

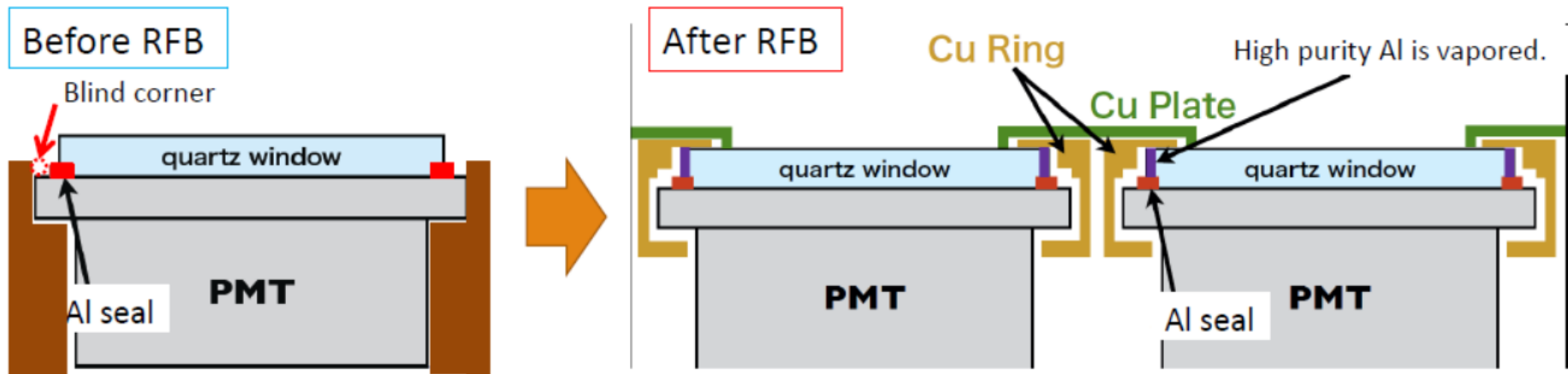
XMASS-I commissioning phase

- 2010年神岡施設に設置。
- 世界最大835kgの液体キセノン、1層型検出器。
- 世界最大14.7p.e./keV
- 低敷居値を実現し、低質量WIMPsや太陽アクシオンの探索も行った。



Detector refurbishment

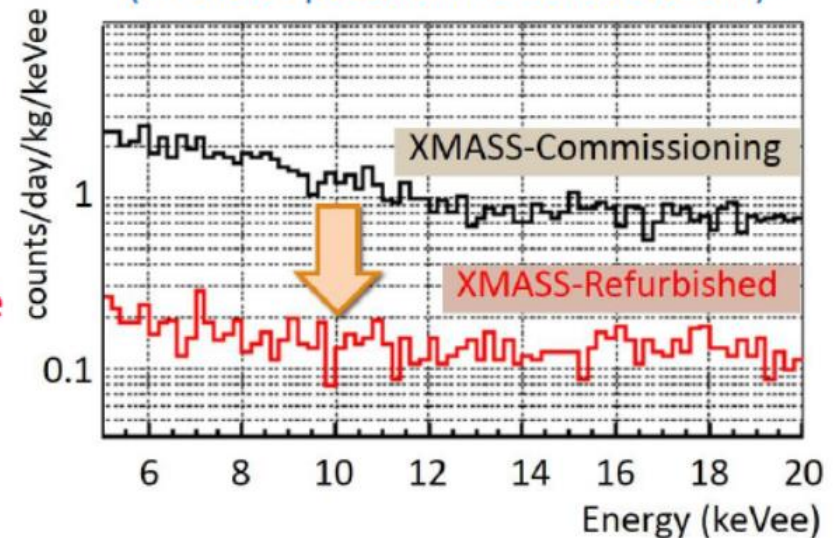
- Found RIs (^{210}Pb , ^{238}U) in the Aluminum seal of PMT.
- BG events at the blind corner of PMT are often misidentified as events in the fiducial volume.
- To reduce this background, new structures to cover this Al seal were installed.



Current status

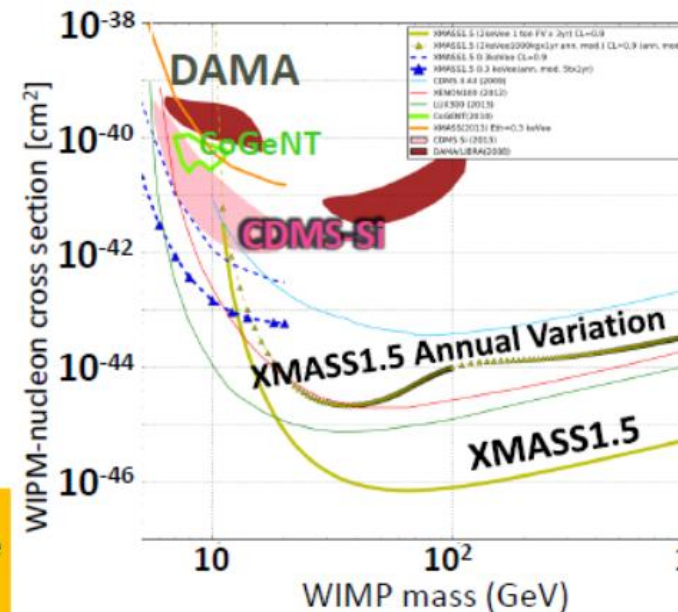
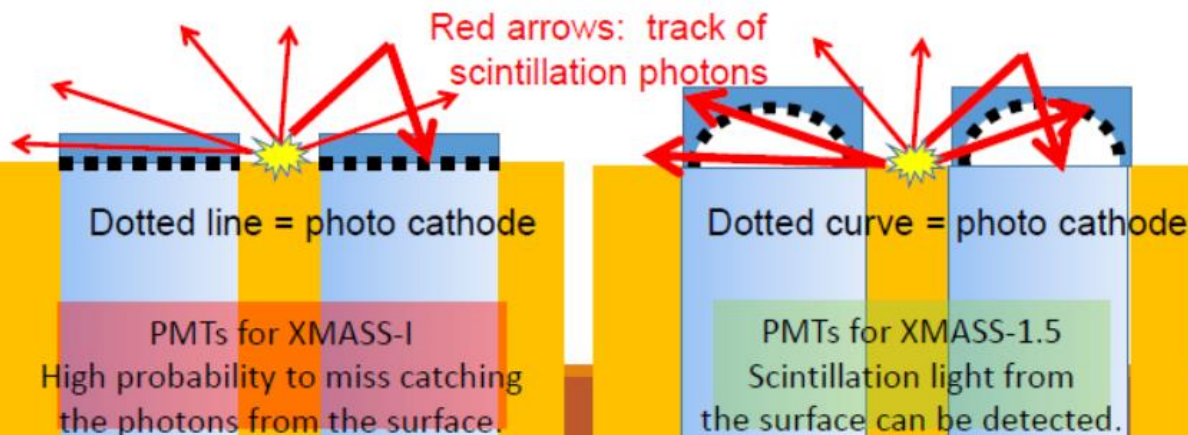
- Understanding of detector response
- Understanding of reconstruction performance
- Understanding of BG
 - They are on-going
- Quick check of BG in entire volume
 - One order of magnitude reduction above 5 keVee for entire volume achieved.
- Results will come in near future

Energy spectra in entire volume
(without position reconstruction)

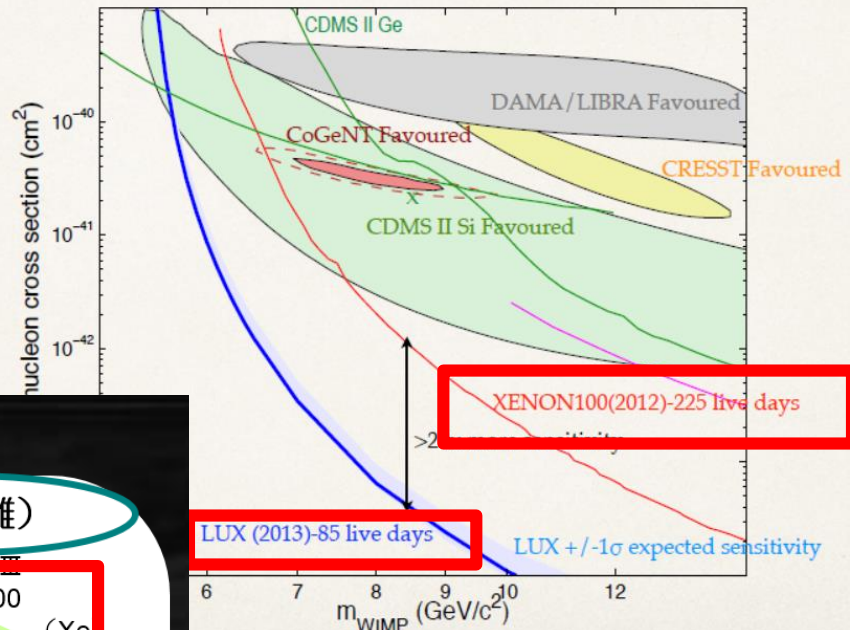


Future: XMASS-1.5

- Total 5 tons of liquid xenon (with fiducial mass of 1 ton)
- Target sensitivity for $\sigma_{SI} < 10^{-46} \text{ cm}^2$ for 100 GeV WIMPs
- Design of the detector is on-going



Low-mass WIMP region



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E_R 検出 (光)

DAMA
DM-ICE (NaI)
KIMS (CsI)
XMASS (Xe)

(光+電離)

XENON10/100
LUX (Xe)

(光+温度)

CRESST
(CaWO₄)

原子核

反跳

$E_R \sim 100\text{keV}$

暗黒物質

E_R 検出 (電離)

CoGent
HPGe

E_R 検出 (温度)

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

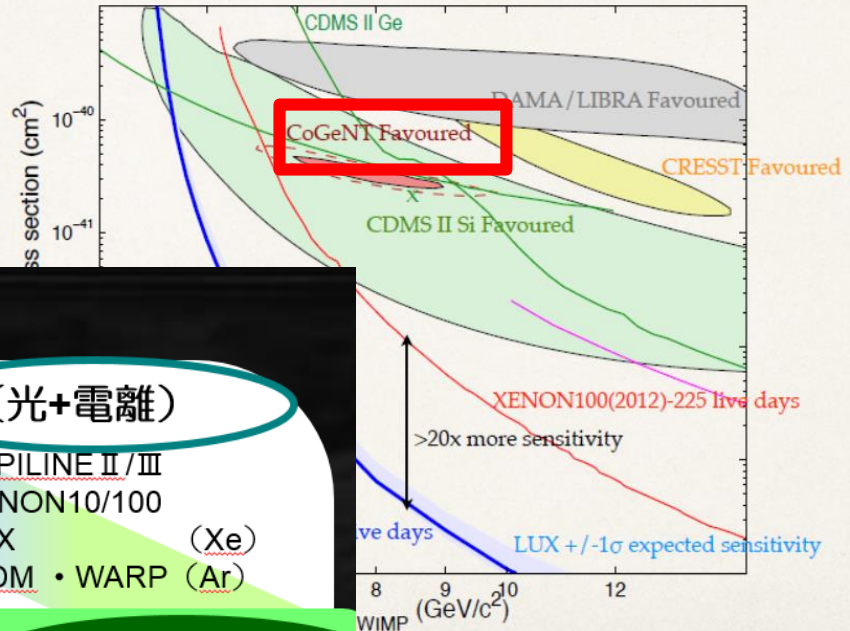
(電離+温度)

CDMS (Ge/Si)
EDELWEISS (Ge)

Liq Xeのやばいこと

- 発光効率・ γ 線除去

Low-mass WIMP region



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暗黒物質の直接検出

E_R 検出 (光)

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DM-ICE (NaI)
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XMASS (Y)

(光+電離)

ZEPILINE II/III
XENON10/100
LUX (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)

CoGent
HPGe

(光+温度)

CRESST
(CaWO₄)

E_R 検出 (温度)

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

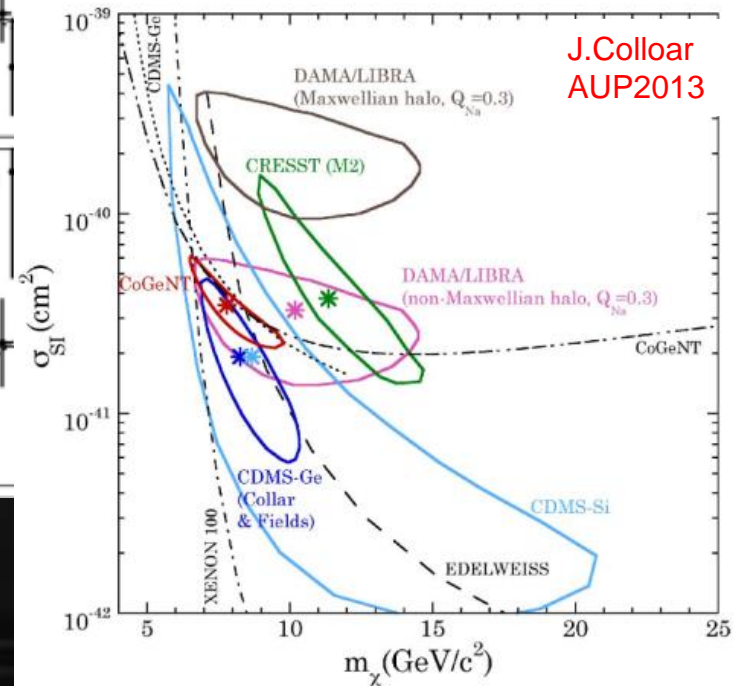
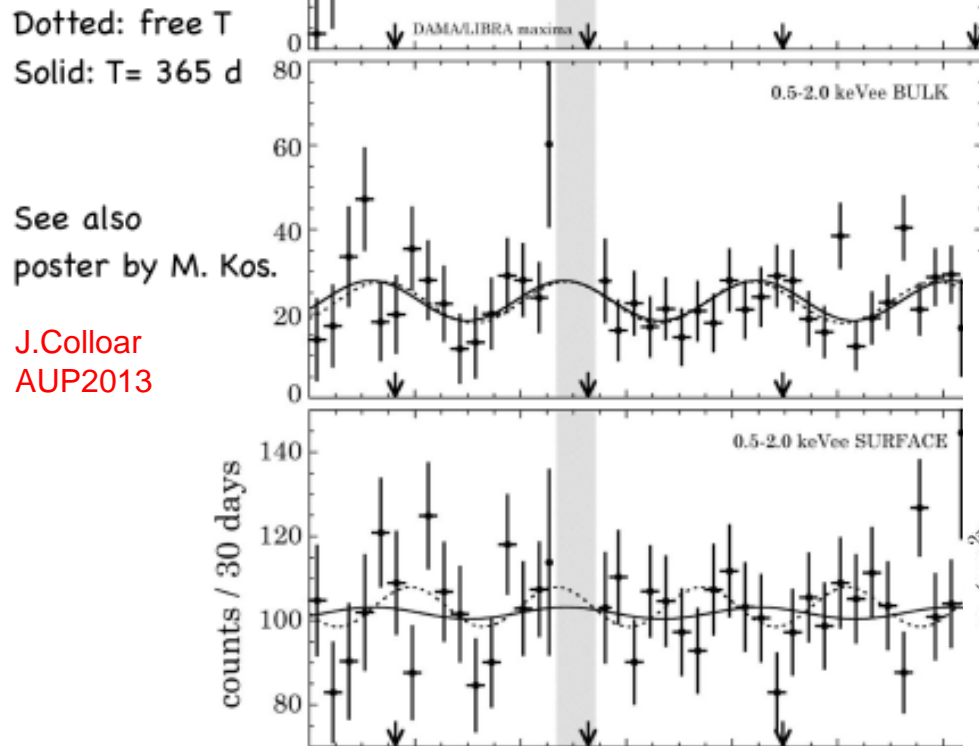
(電離+温度)

CDMS (Ge/Si)
EDELWEISS (Ge)

Ge

CoGent

- 閾値の低い (0.4keV) Ge半導体検出器 (440g)
- 3.4年の季節変動(2.2 σ)
- 10GeV付近を主張



- 表面 β 立ち上がりの時定数で統計的に除去
- CoGentの素敵なこと：データを公開

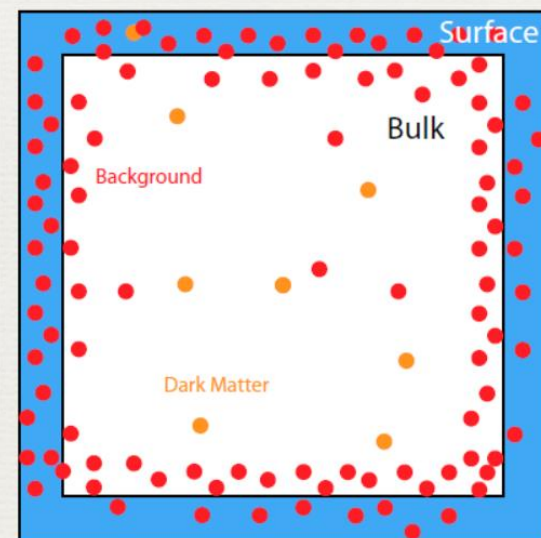
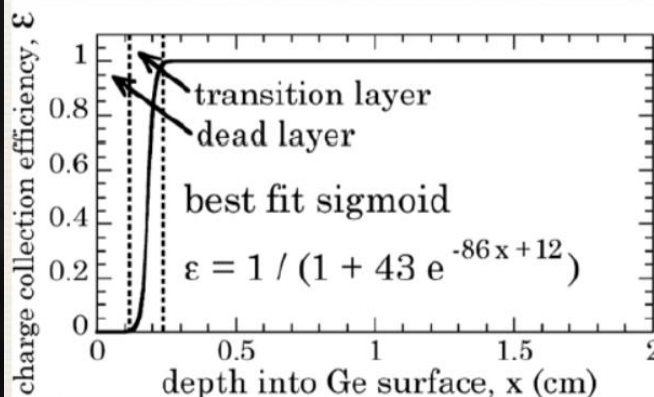
A CoGeNT Analysis

Jonathan Davis
(IPPP, Durham University)

Events

Define the surface by the transition region.

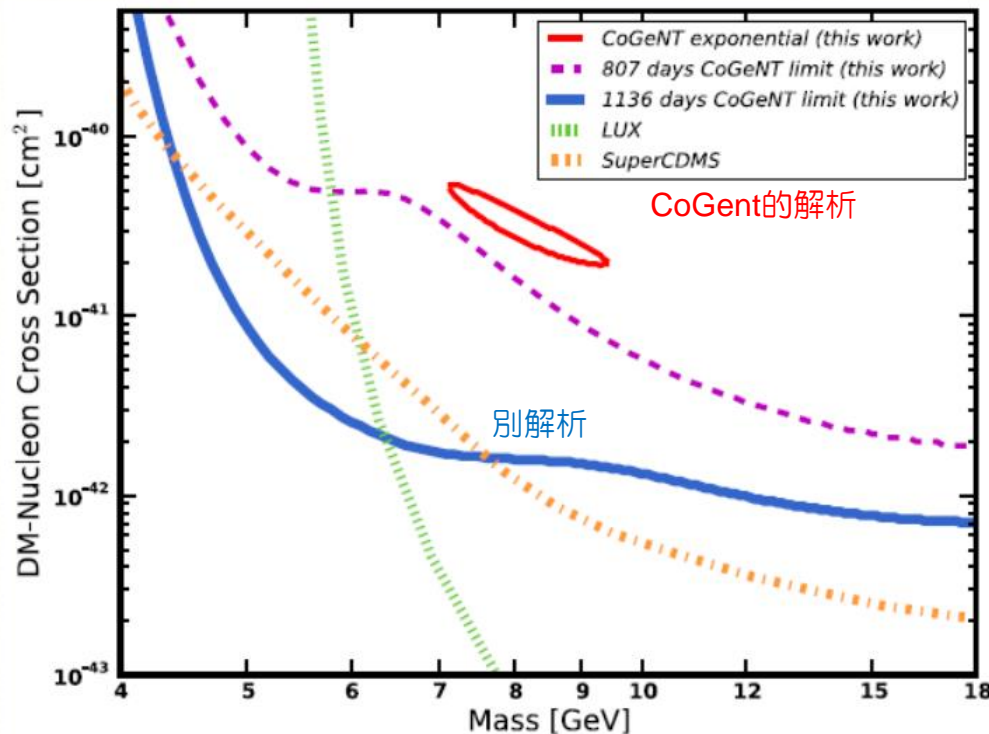
Partial charge collection \rightarrow low-energy rise.
Surface events mimic light Dark Matter.



「表面 β 」の扱いの違いで、、、

Results

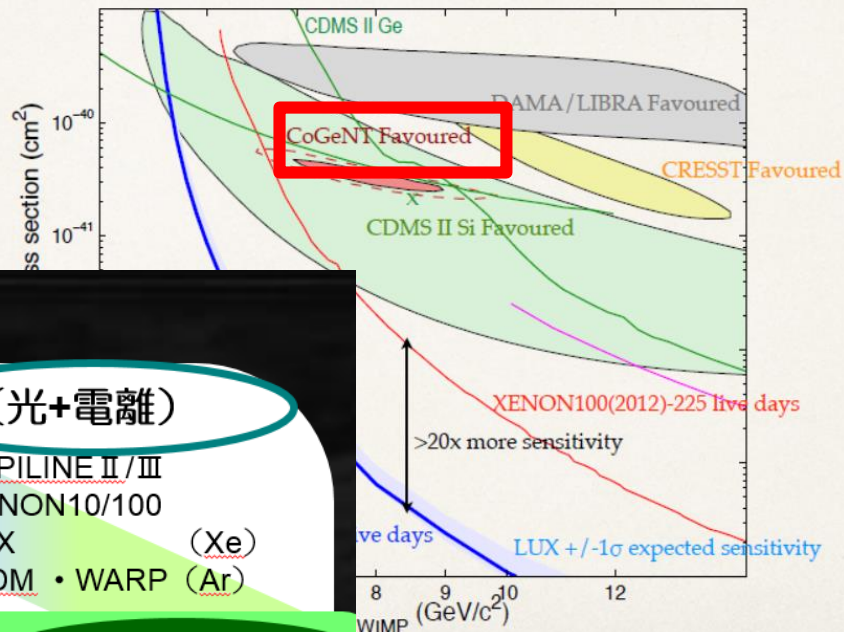
Have summed over many possible functions for the surface events, by varying the positions of the two lowest energy knots.



Less than one sigma evidence for Dark Matter.

Define 90% Bayesian limit by integrating under the Posterior.

Low-mass WIMP region



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XMASS (Y)

(光+電離)

ZEPILINE II/III
XENON10/100
LUX (Xe)
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原子核

E_R 検出 (電離)

CoGeNT
HPGe

(光+温度)

CRESST
(CaWO₄)

反跳

$E_R \sim 100\text{keV}$

暗黒物質

E_R 検出 (温度)

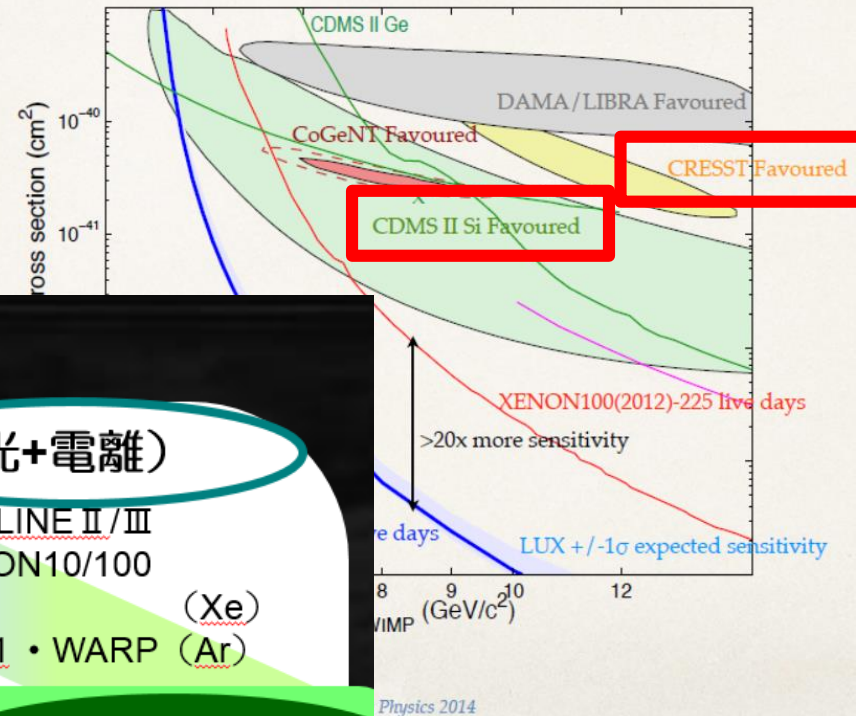
ROSEBUD (LiF),
COUPP, SIMPLE, PICASSO
(CxFx)

(電離+温度)

CDMS (Ge/Si)
EDELWEISS (Ge)

Geのやばいこと

● 表面電子



暗黒物質の直接検出

E_R検出 (光)

- DAMA
- DM-ICE (NaI)
- KIMS (CsI)
- XMASS (Xe)

(光+電離)

- ZEPILINE II/III
- XENON10/100
- LUX (Xe)
- ArDM • WARP (Ar)

原子核

反跳

E_R < ~100keV

暗黒物質

E_R検出 (電離)

- CoGent
- HPGe

(光+温度)

- CRESST (CaWO₄)

E_R検出 (温度)

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

(電離+温度)

- CDMS (Ge/Si)
- EDELWEISS (Ge)

ボロメータ

CDMS II

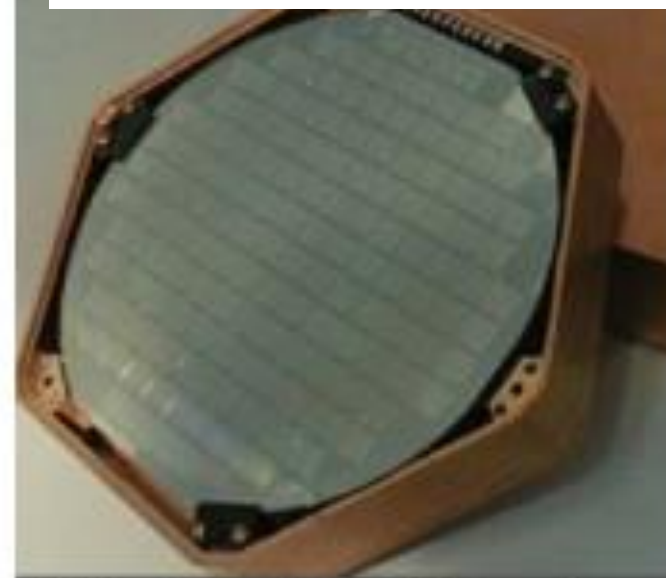
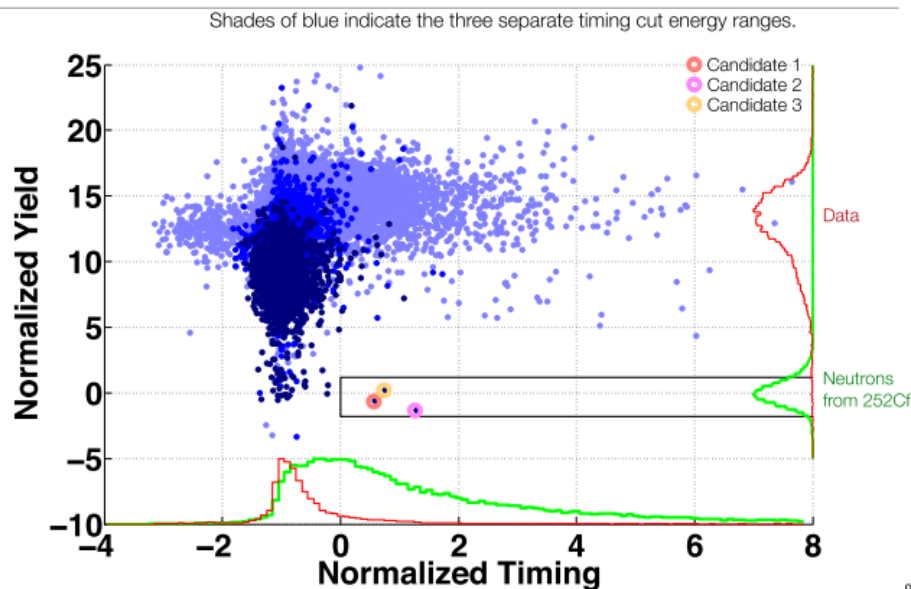
- Ge、Si ボロメータ+半導体検出器
- ガンマ線除去
- 3事象(Si-run, 2013) BG確率5.4%
- 2事象(Ge-run, 2010)

CDMS II (Ge+Si)

- 4.6 kg Ge (19 x 240 g)
- 1.2 kg Si (11 x 106g)
- 35% NR acceptance

Julien Billard (MIT) - TAUP2013

Three events! **Si run** arXiv:1304.4279



240 g Ge or 106 g Si crystals
(1 cm thick, 7.5 cm diameter)

Julien Billard (MIT) - TAUP2013

9

We do not believe this result rises to the level of a discovery, but does call for further investigation.

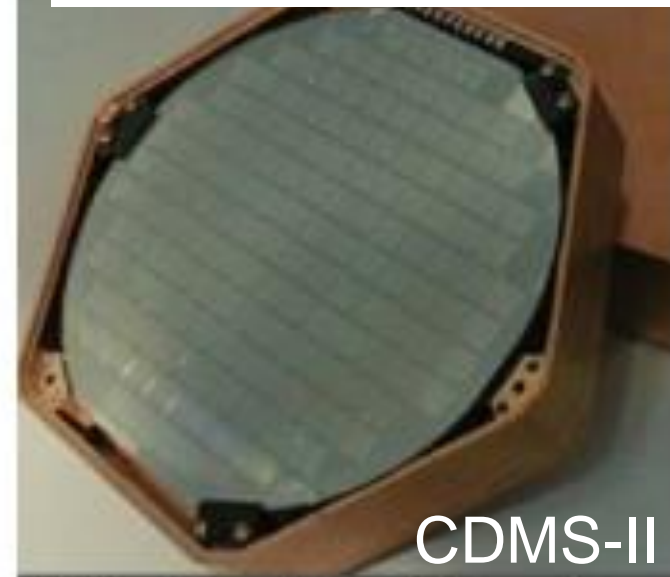
SUPER CDMS

Search for Low-Mass WIMPs with SuperCDMS

- 15×0.6kg Ge
- ボロメータ+半導体検出器
- ガンマ線除去
- 11事象 in 577kg days
BG(7) + 電気ノイズ(1)
+BGモデルの不完全さ(3)
- で「制限」

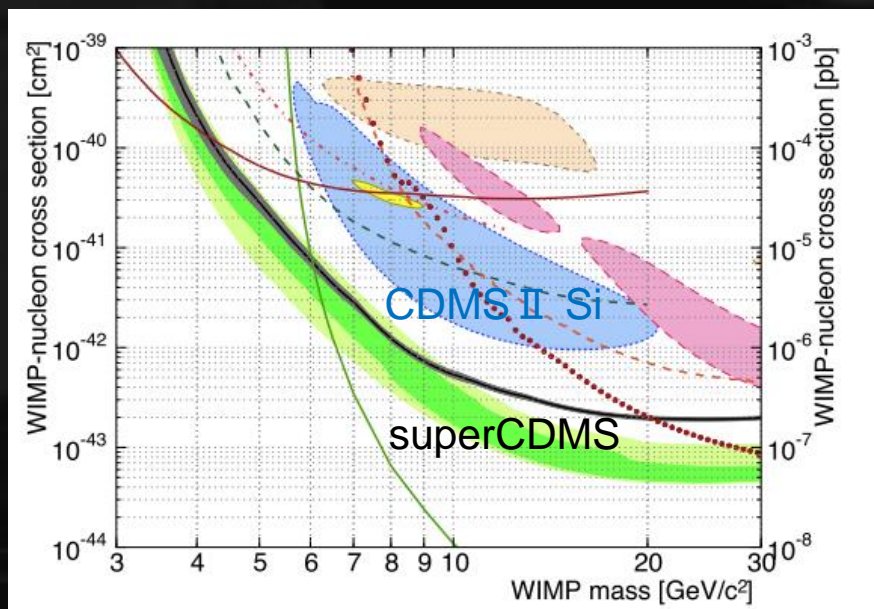
superCDMS
webpage

Julien Billard (MIT) - TAUP2013



CDMS-II

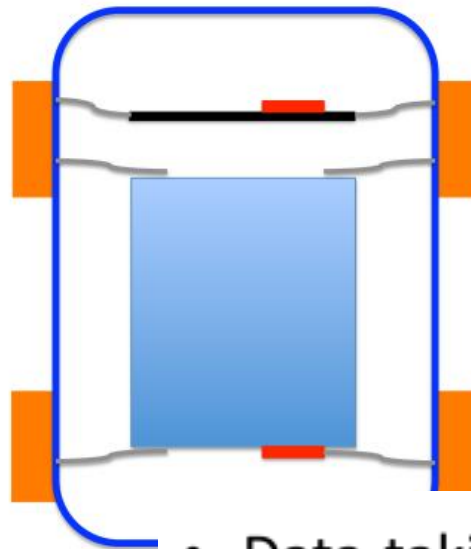
240 g Ge or 106 g Si crystals
(1 cm thick, 7.5 cm diameter)



◆ CRESST

- CaWO₄ シンチレーティングボロメータ
- ガンマ線除去
- 79事象
- 閾値 0.6keV nr

The CRESST Detector



Raimund Strauss

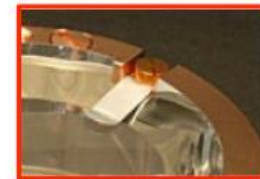
MPI München

TeVPA/IDM, Amsterdam,

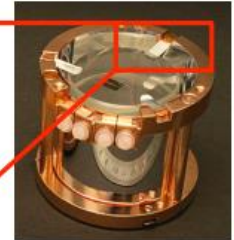
23.6.2014

Support Structure

- radio-pure copper
- flexible bronze clamps



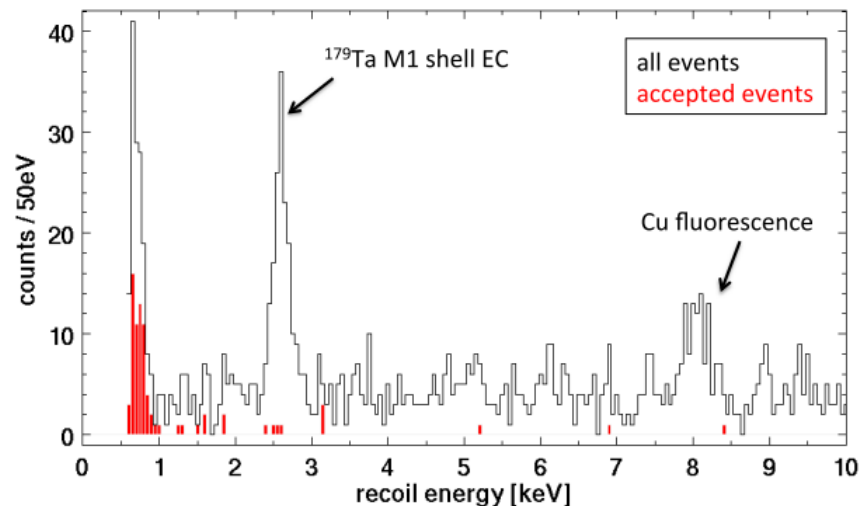
clamps do not scintillate



- Data-taking since July 2013
- 18 modules mounted (~ 5kg)
→ 17 of 18 are fully operational

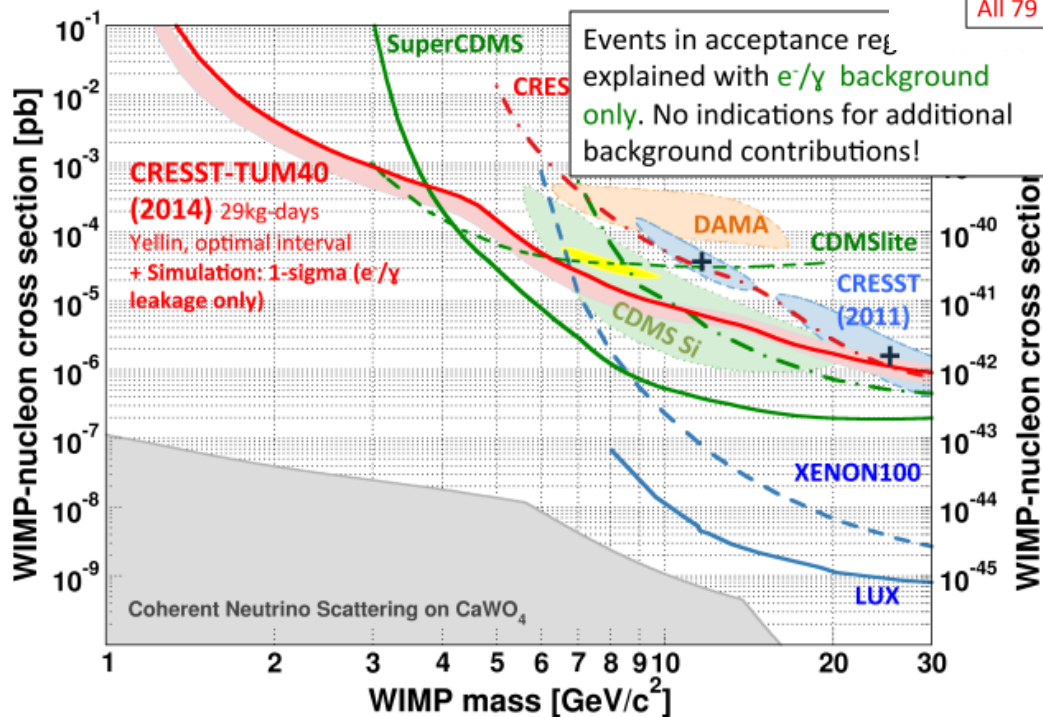
● 79事象 ただし
「BGで解釈可能」

Events in Acceptance Region

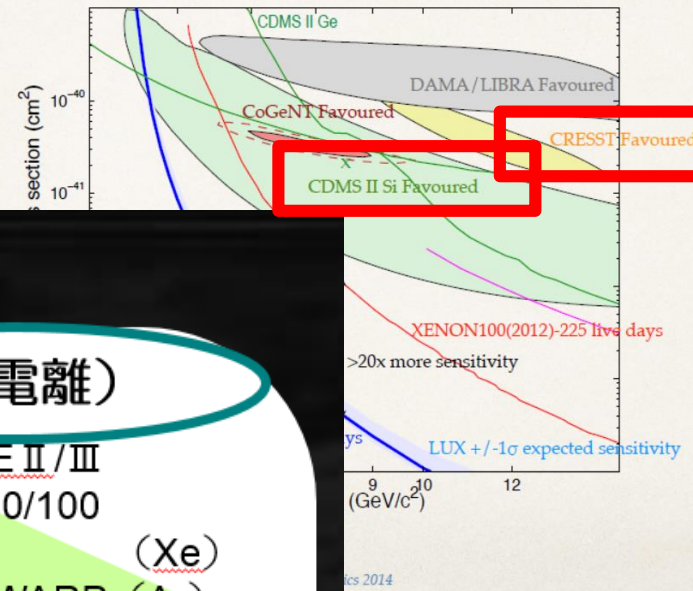


All 79 events accepted are conservatively considered as WIMP scatters!

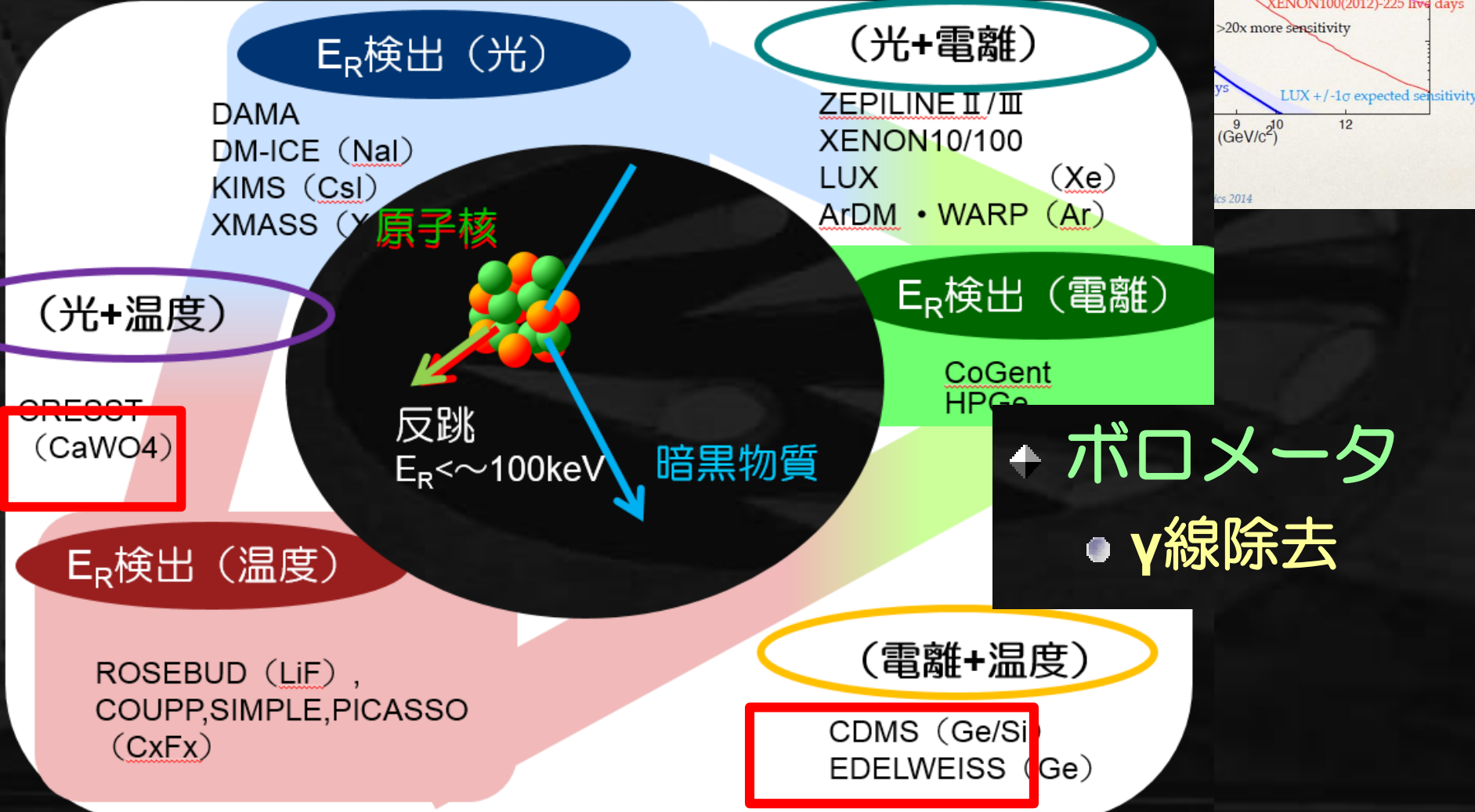
Data vs. Simulation



WIMP-nucleon cross section



暗黒物質の直接検出



ボロメータ
● γ 線除去

第四の情報：原子核飛跡

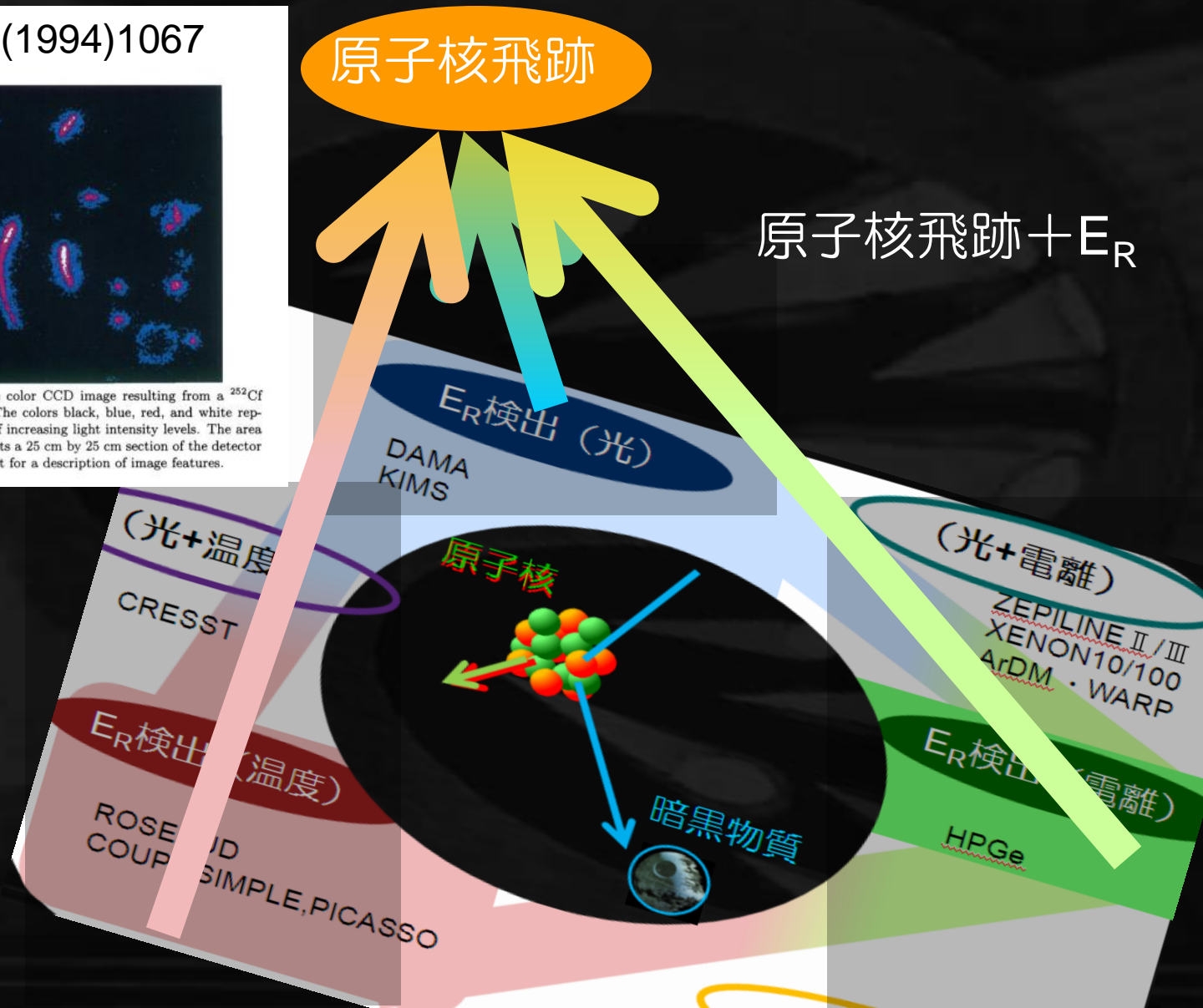
PRL73(1994)1067



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.

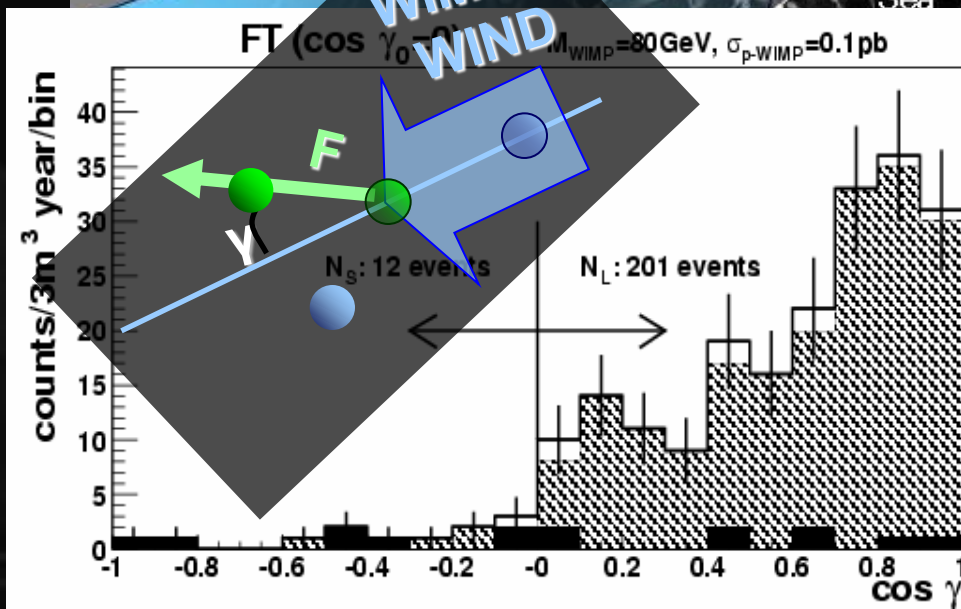
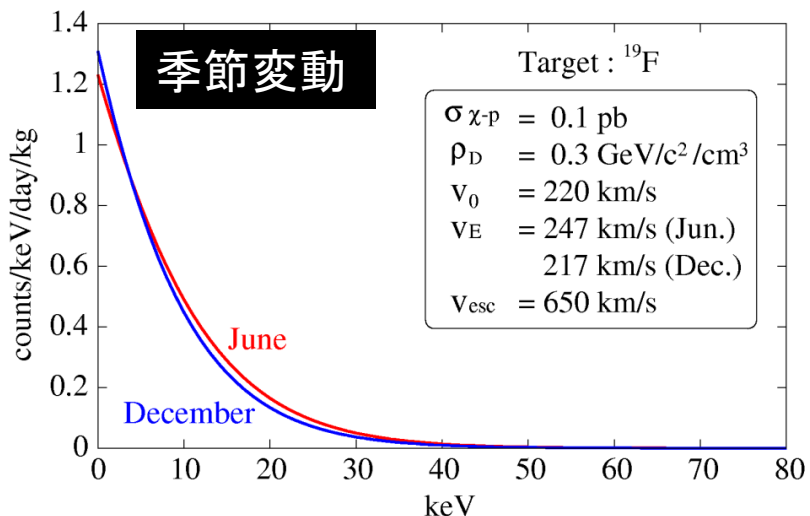
原子核飛跡

原子核飛跡 + E_R



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



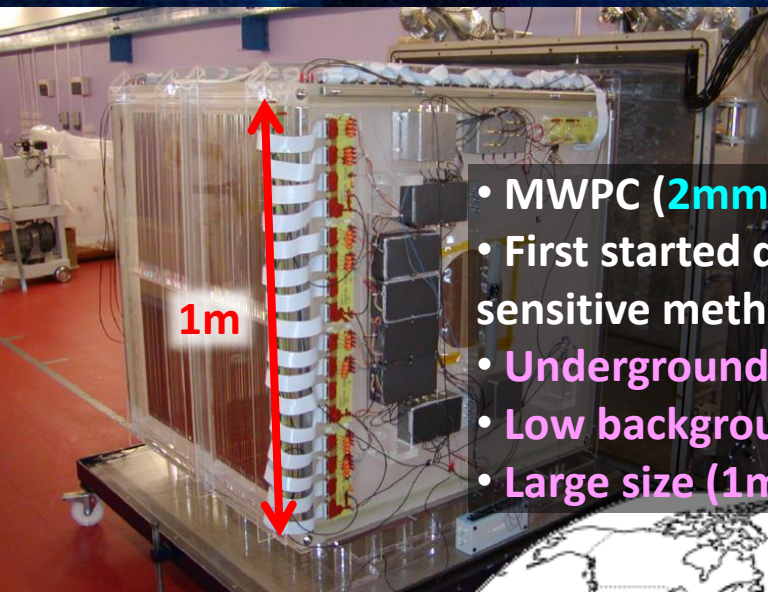
「方向性」の重要性



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世界の方向感度DM実験

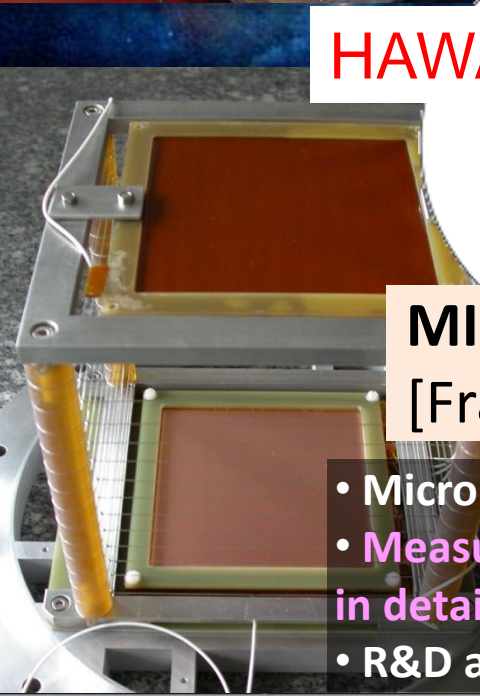
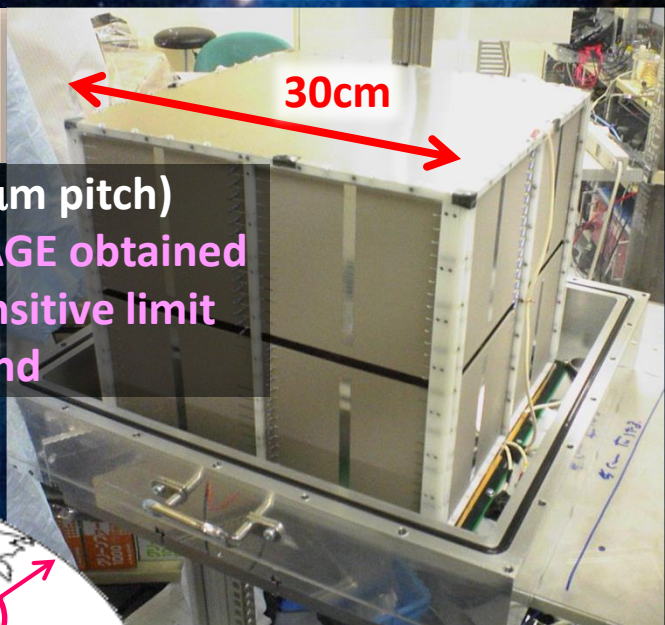


DRIFT
[UK]

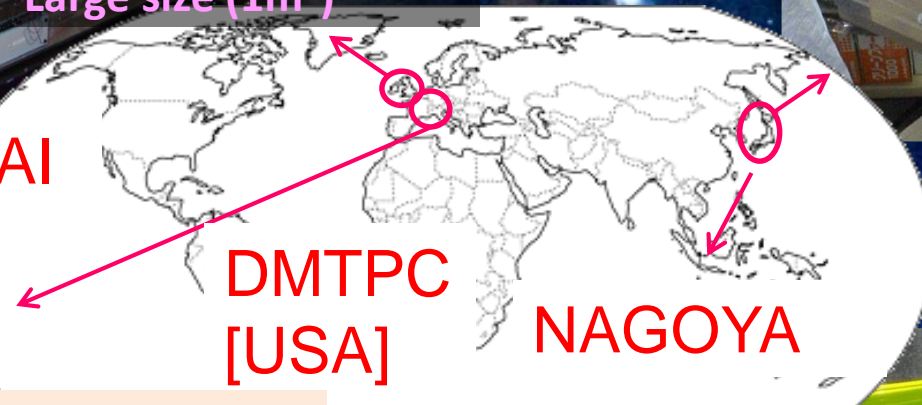
- MWPC (2mm pitch)
- First started direction-sensitive method
- Underground
- Low background
- Large size (1m³)

NEWAGE
[Kobe +]

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



HAWAII



DMTPC
[USA]

NAGOYA

MIMAC
[France]

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

EMULSION
[Nagoya +]

- emulsion (400 μ m pitch)
- good position resolution
- large mass
- No time resolution



◀ 飛跡検出のやばいこと

- ようやく原理実証→低バックグラウンド実験へ
- 角度分解能!
- for details, たとえば



地下素核研究 研究会
"宇宙の歴史をひもとく地下素粒子原子核研究"

トップ 会場 登録

"宇宙の歴史をひもとく地下素粒子原子核研究" 研究会

研究会開催, 2014年8月23日、24日
大阪大学豊中キャンパスΣホール(基礎工学部国際棟)

Google

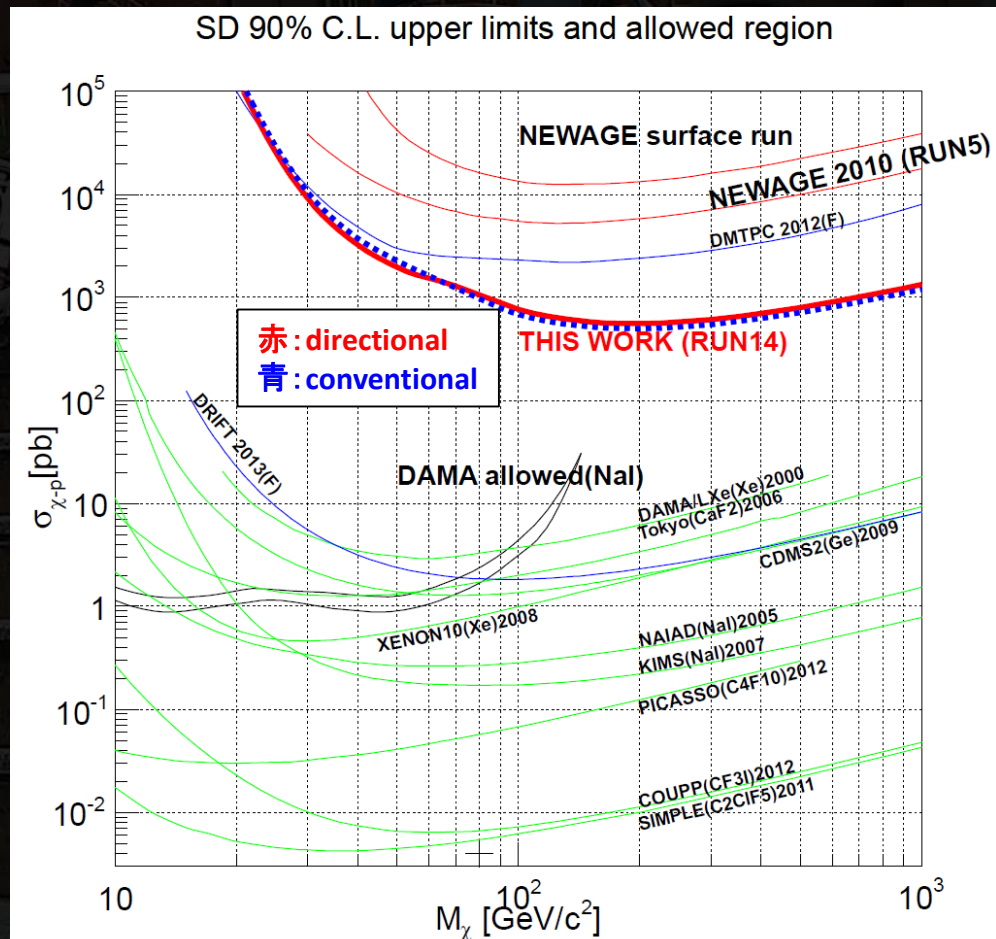
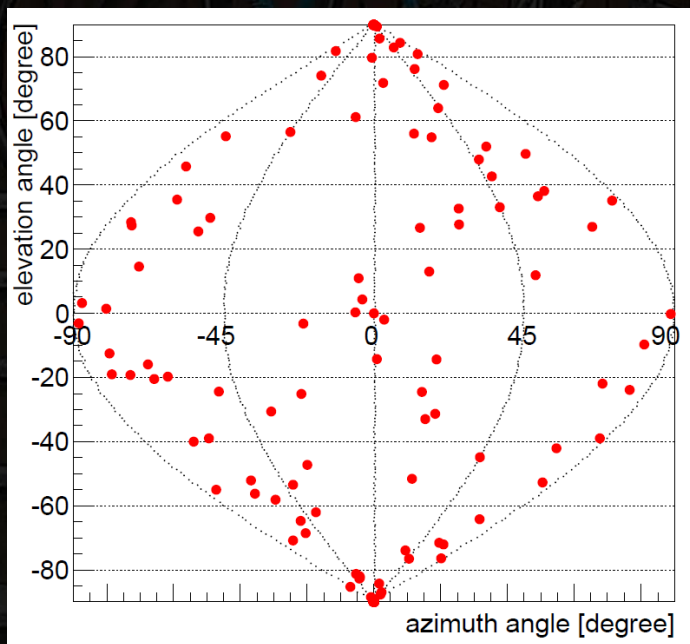
lowbg.org

Direction-sensitiveな制限

中村D論
2014

- Directionalな世界最良のlimit: **557pb @200GeV**
- 前回の測定(RUN5)を一桁更新

50-400keV
C,F SKYMAP



◆ まとめ

- それぞれの技術で特色を活かしている。
 - ・ 季節変動 : 統計量・優位度 9σ と90%リミット
 - ・ 粒子識別 : 事象ごとor統計的?
 - ・ 方向感度 : 角度分解能
- キーテクノロジーであり「やばいところ」でもある