Dark Matter Direct Searches

Shimane Unieversity

Kentaro Miuchi（Kobe University）

August 1st, 2015

THANKS
Japanese Experimental
Dark matter Investigators

ANKOK GROUP

PICO-LON

Emulsion

Direction-Sensitive WIMP-search NEWAGE

XMASS Dark Matter Search

- **Seminar part:**
  Review of Dark Matter Search

- **Discussion part:**
  Potential of direction-sensitive search

Dark Matter

LHC

LHC 8TeV：
SUSY not yet

positrons, antiprotons
not yet

Indirect

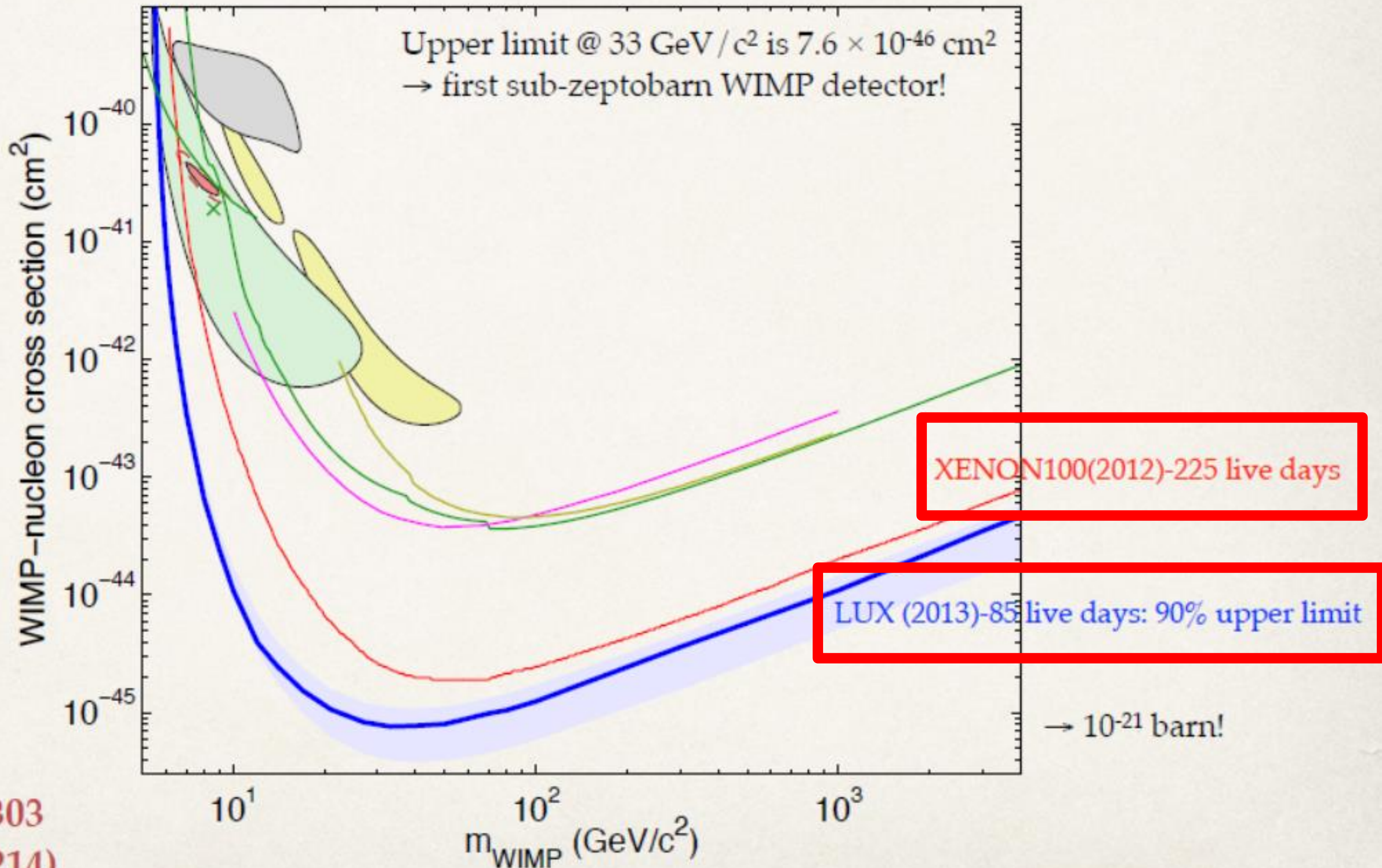
Direct

身内賢太朗

Message of Review part

- look carefully “before” the exclusion limit
- Is it fair to compare 90% limits and 9σ signals?

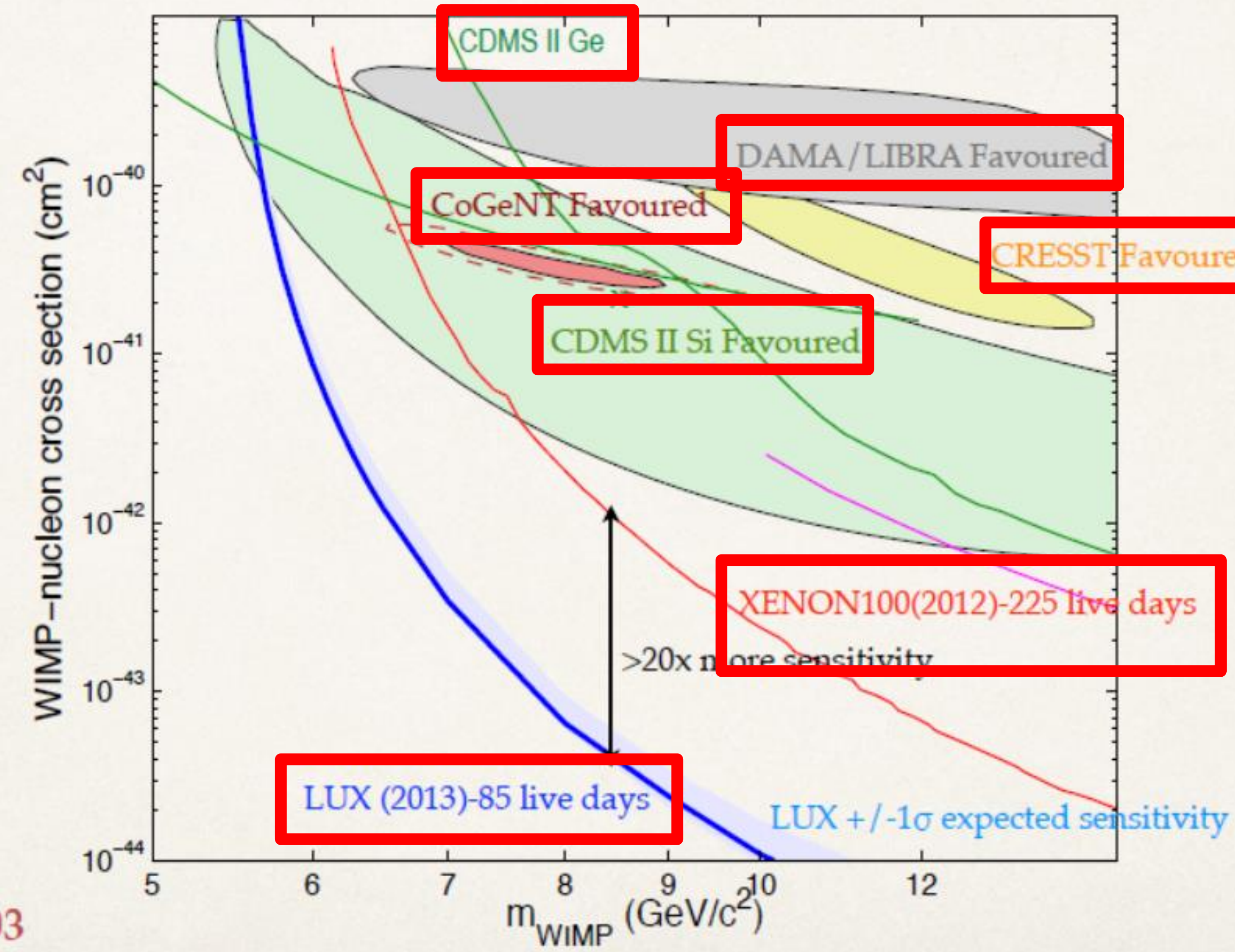
Spin-independent limit



PRL.112.091303
(arXiv:1310.8214)

Low-mass WIMP region

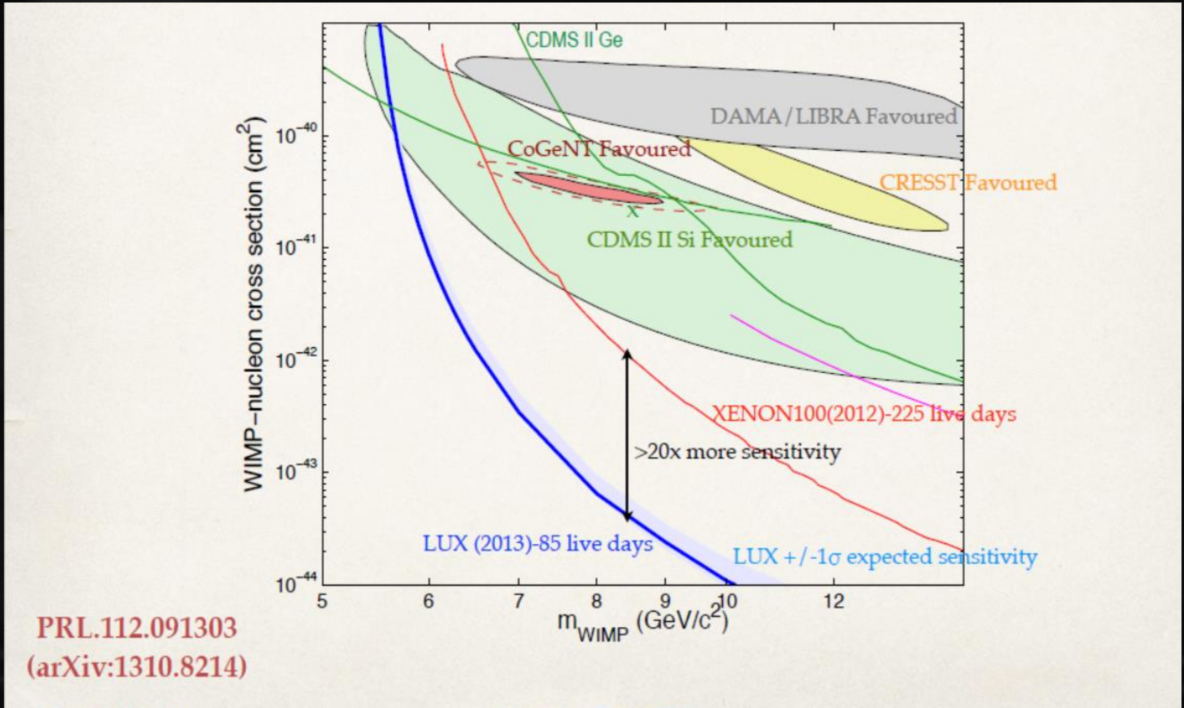
現状把握



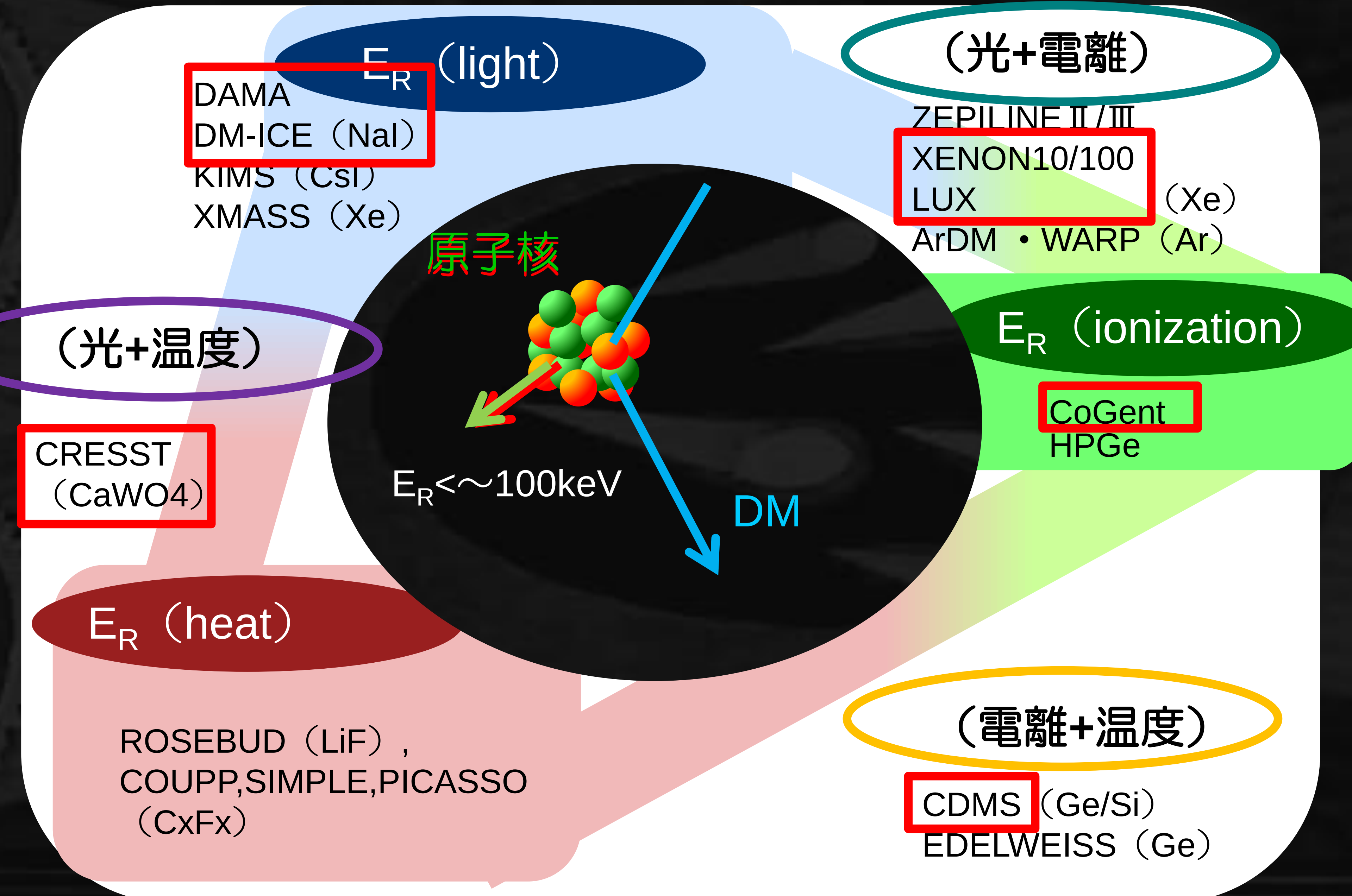
PRL.112.091303
(arXiv:1310.8214)

HISTORY

- 1997～ DAMA：claimed of "DISCOVERY" ~50GeV
- 2000～ Excluded by CDMS,,,
- 2008 LIBRA : reconfirmed
- 2009 CDMS 2 events
- 2010～ others reported ＊＊events（maybe BG）
  light WIMP?
- 2012～ XENON, LUX excluded

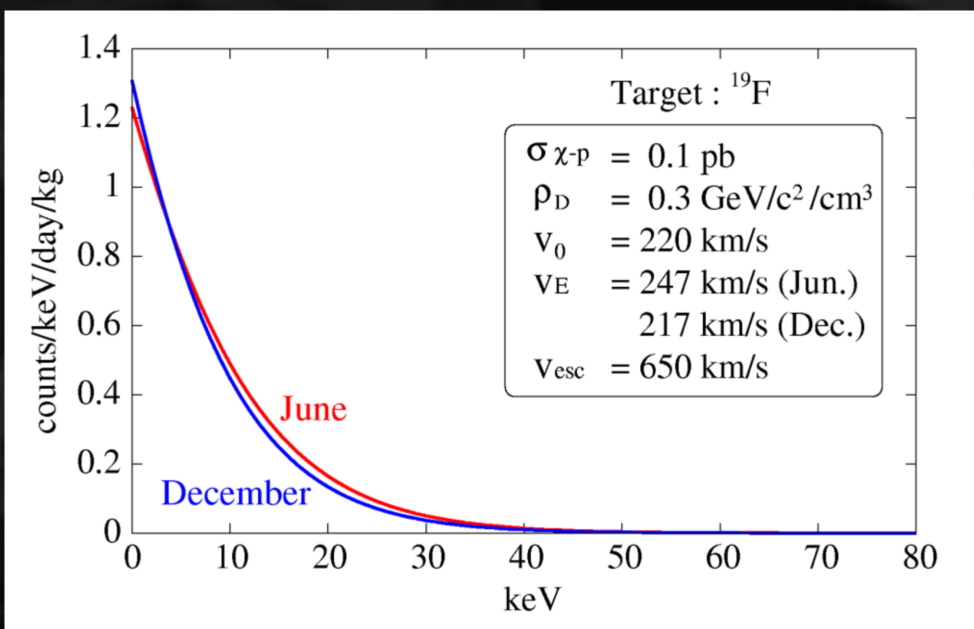


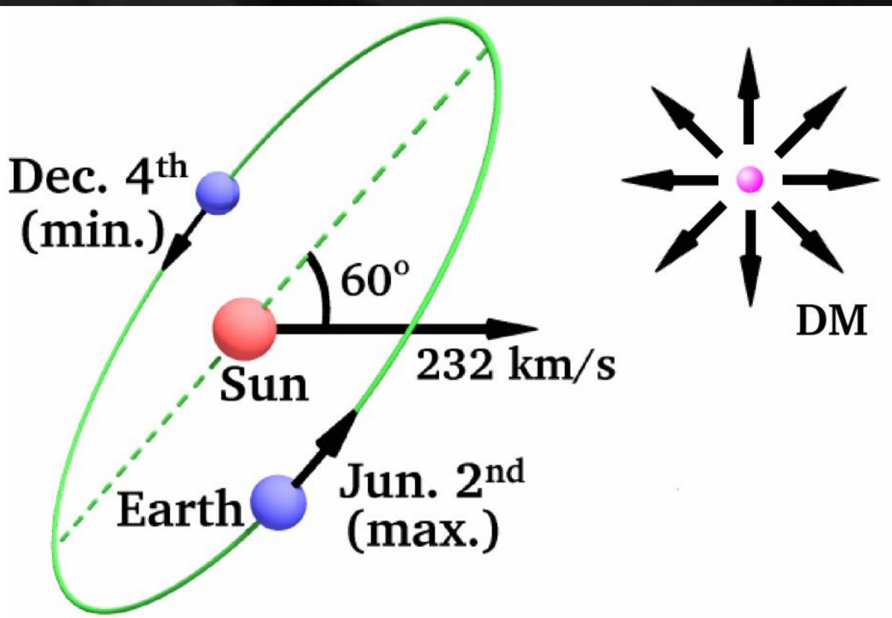
Detection Methods



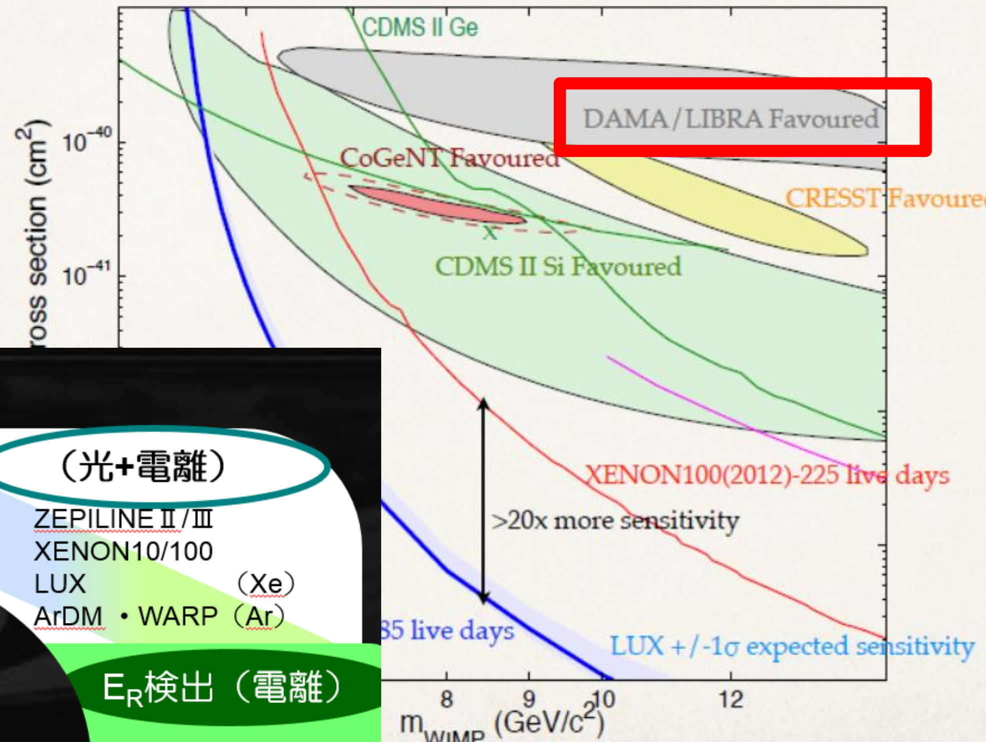
- **Expected signal**
  - signal：nuclear recoil
  - BG：electron recoil

  - signal ①　energy spectrum　／＊＊events
    ←　low threshold detector
  - signal ②　annual modulation
  - signal ③　directional anisotropy

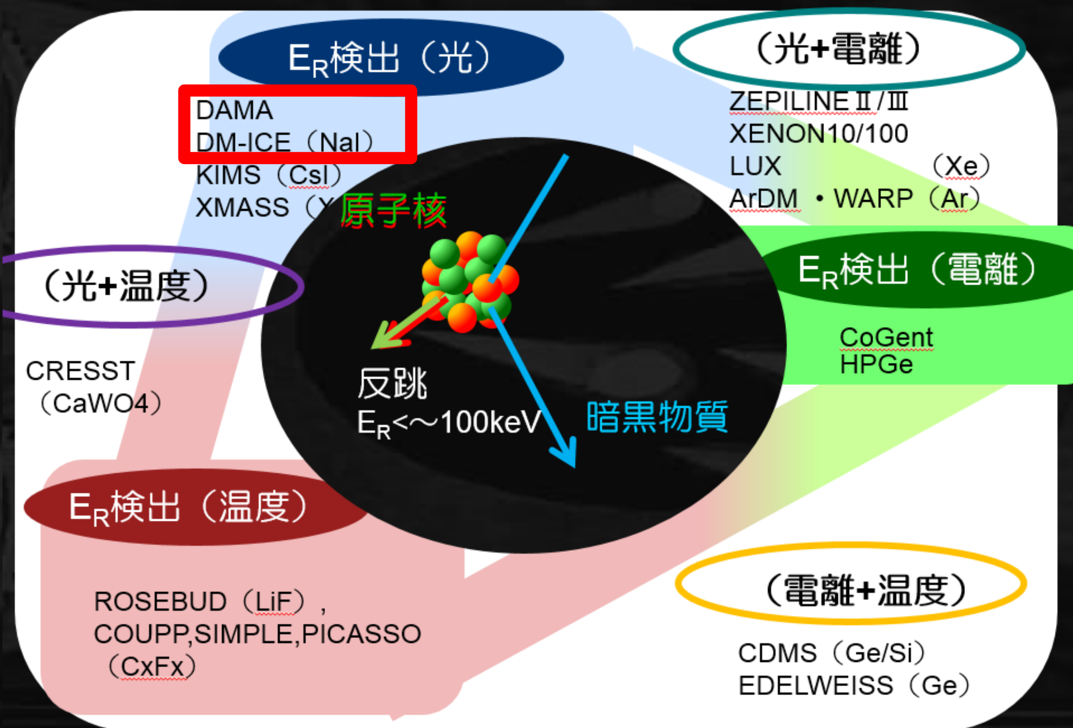




Low-mass WIMP region

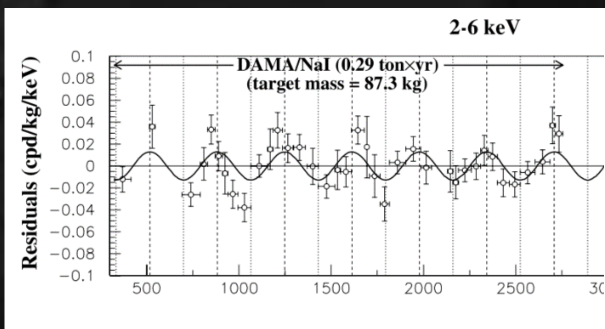


暗黒物質の直接検出

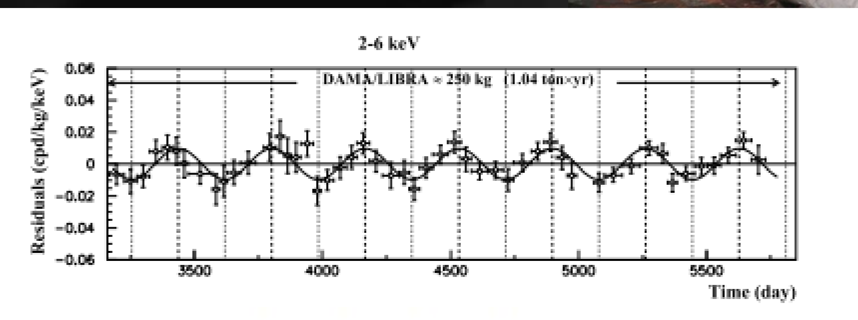


DAMA/LIBRA

- 250kg NaI scintillator
- 1.33ton • year
- 14 cycles modulation（9.3σ）

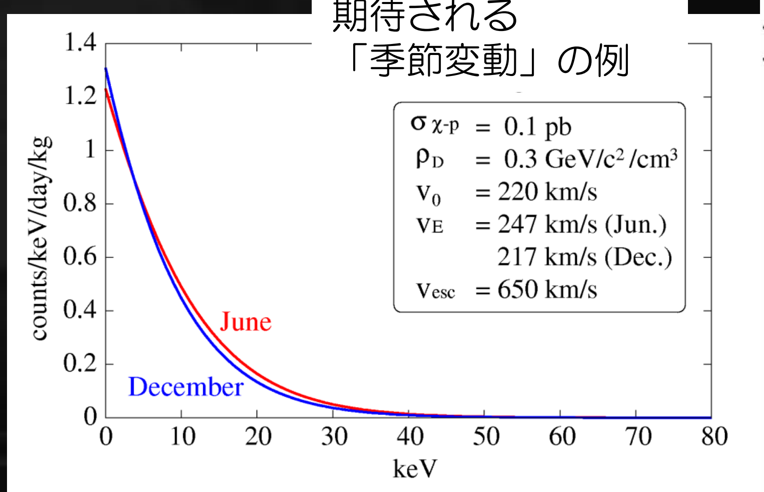


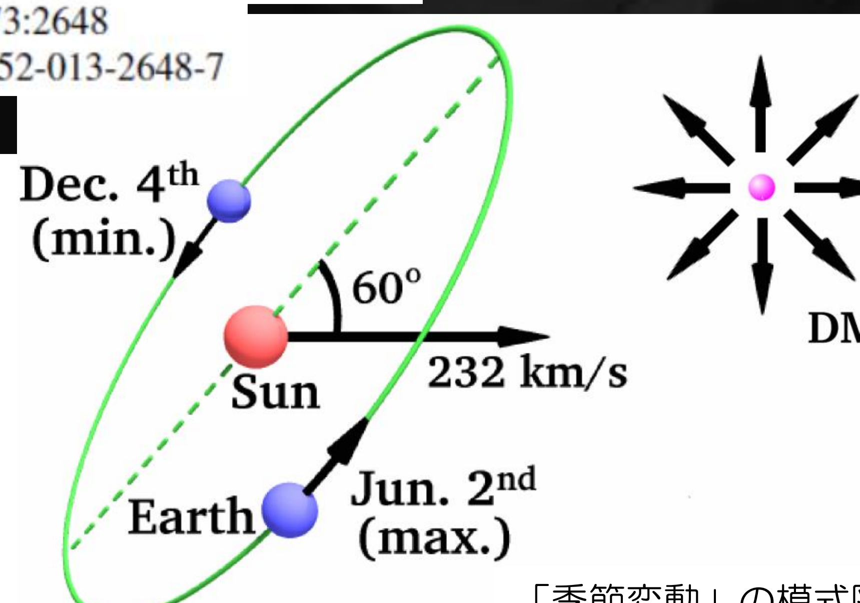
Eur. Phys. J. C (2008) 56: 333–355
DOI 10.1140/epjc/s10052-008-0662-y



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

期待される
「季節変動」の例

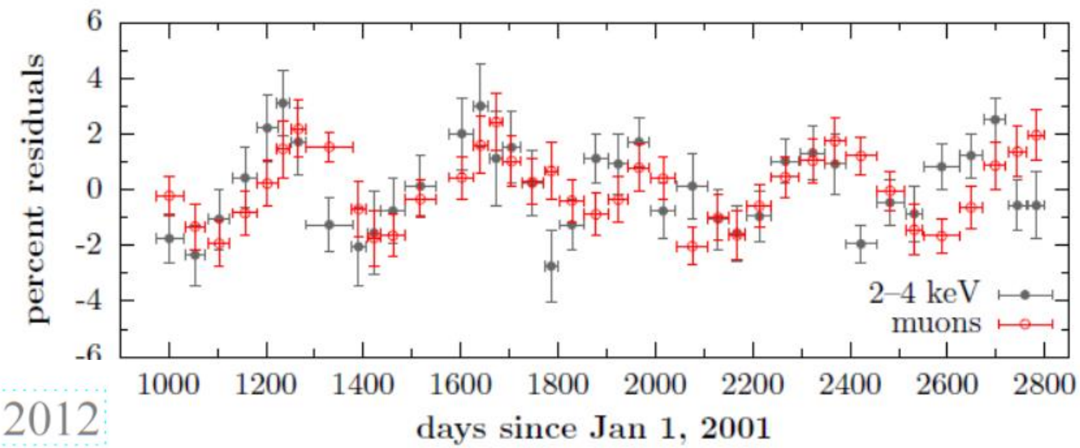




「季節変動」の模式図

Discussion on DAMA

- Can 9.3σ signal be excluded by 90% limits?
- Interpretaions ↓ muon signals… shape is OK. But muon comes after DAMA.
  ⇒ not enough
  - muon flux: maximum in summer (air density)

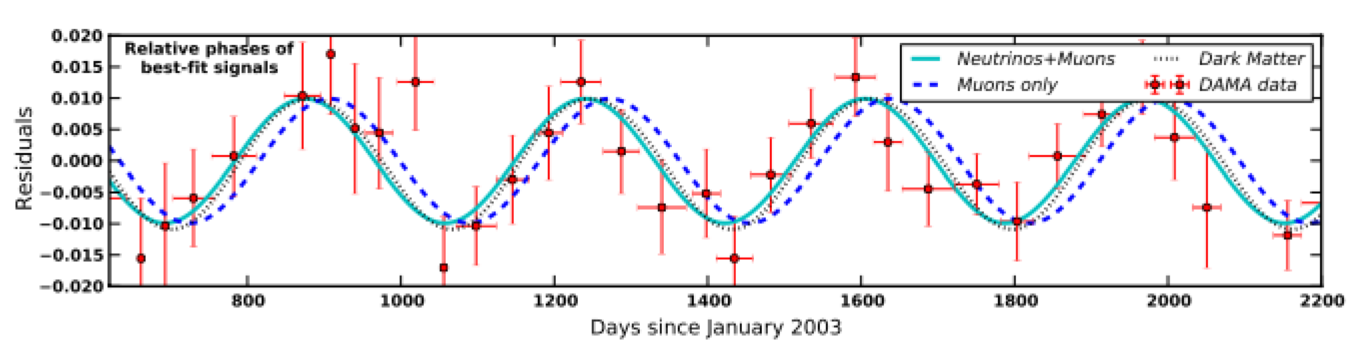


arXiv:1205.3675v1 [hep-ph] 16 May 2012

Figure 1: Percent annual residuals of the LVD measured muon flux when binned in accorda[nce] 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.

- **Artificially add off-phase background**
  - solar neutrino: minimum in winter (distance)

PRL **113**, 081302 (2014)



- **NOT enough to explain DAMA's SIGNAL**
- **DAMA / LIBRA is still alive**

No role for neutrons, muons and solar neutrinos in the DAMA annual modulation results

arXiv:1409.3516v1

Muon-induced neutrons do not explain the DAMA data

J. Klinger, V. A. Kudryavtsev
Department of Physics and Astronomy, University of Sheffield, Sheffield S3 7RH, UK

arXiv:1503.07225v1

What's special in DAMA ?

- **PUREST NaI CRYSTAL for 20 years…**
  - radioactive background matters
- **Other groups are now making pure crystals**

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 appli in NAIAD/DM-Ice17)

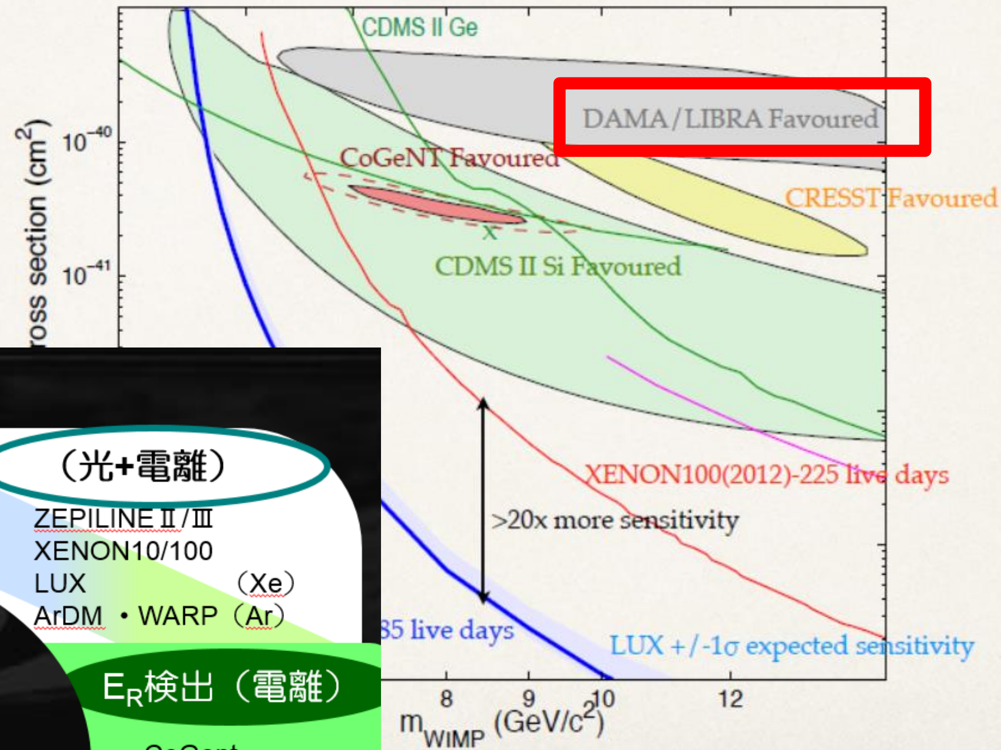
Neil Spooner, Reina Maruyama
on behalf of the DM-Ice Collaboratio

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

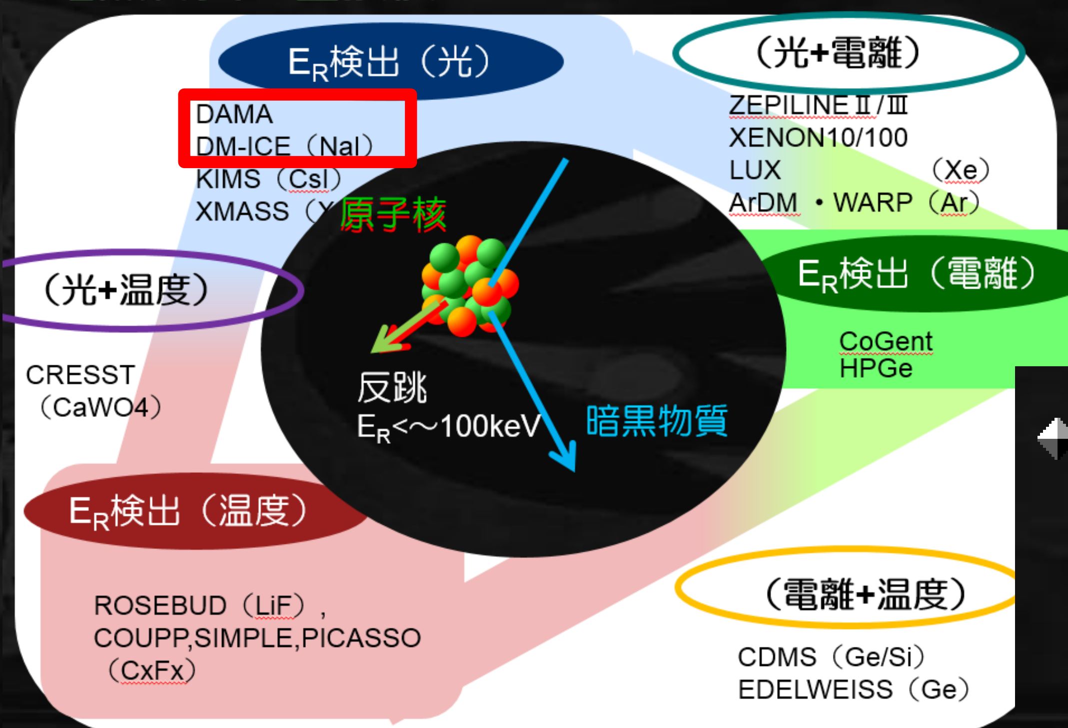
Manufacturer	Form	Measurement	^{238}U (ppt)	^{232}Th (ppt)	^{nat}K (ppb)
Saint Gobain	Powder	DAMA (HPGe)	< 20	< 20	< 100
Saint Gobain	Crystal	DAMA/LIBRA	0.7 - 10	0.5 - 7.5	< 20
Saint Gobain	Crystal	ANAIS-0	7.6	7.7	410
Bicron/Saint Gobain	Crystal	NaIAD/DM-Ice17	55	33	550
Sigma-Aldrich	Powder (standard 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
PICO-LON(徳島大学)			～8ppt	<1ppt	not yet

*DAMA ppt numb
for other crystals

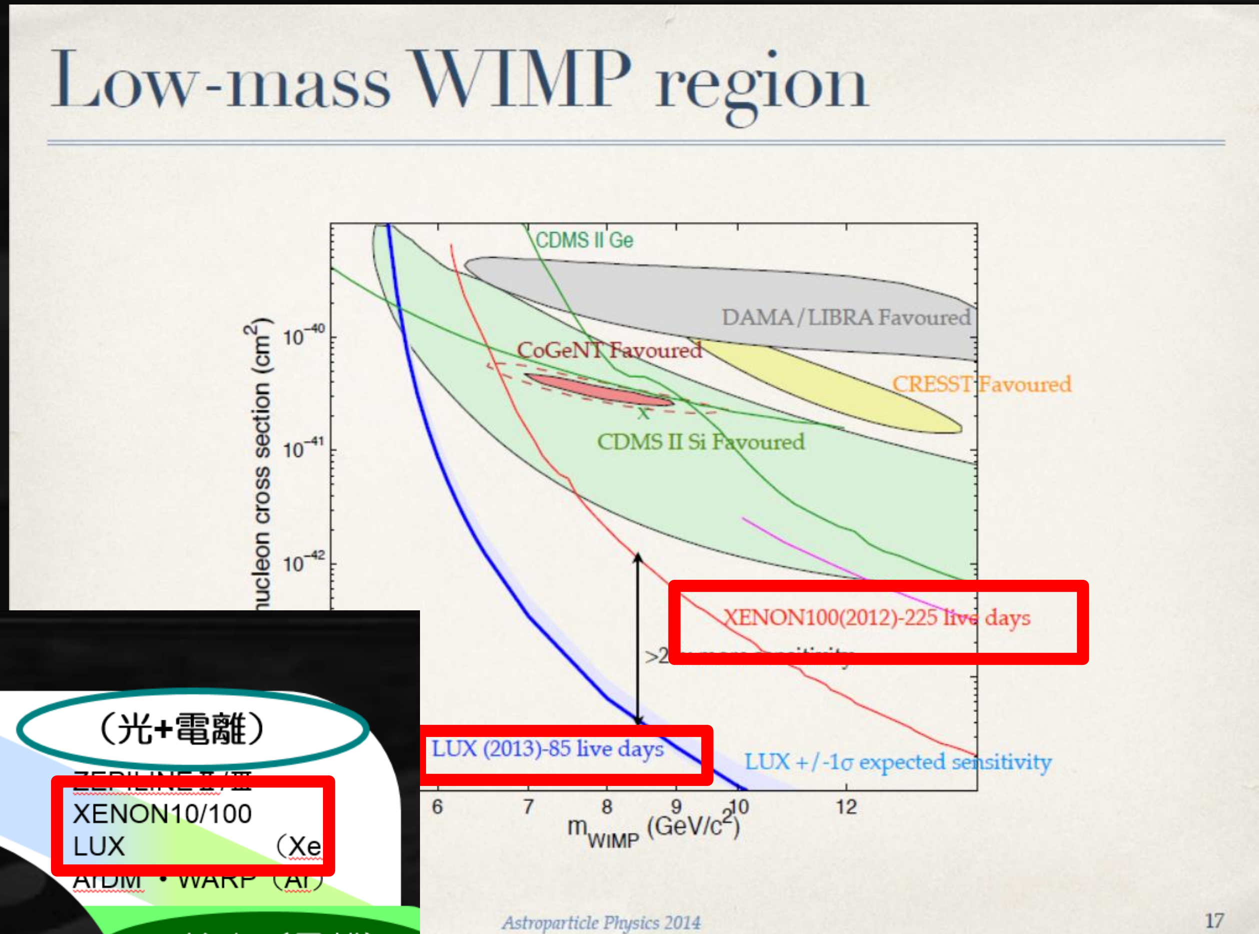
Low-mass WIMP region

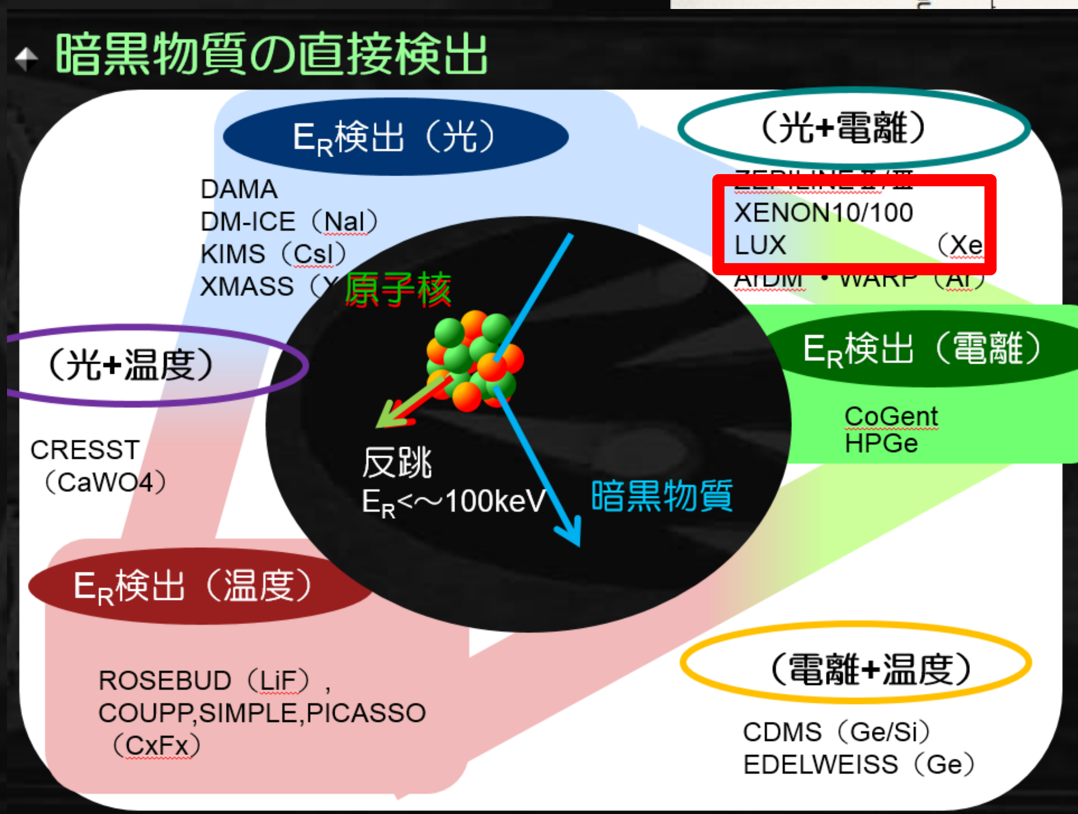


暗黒物質の直接検出



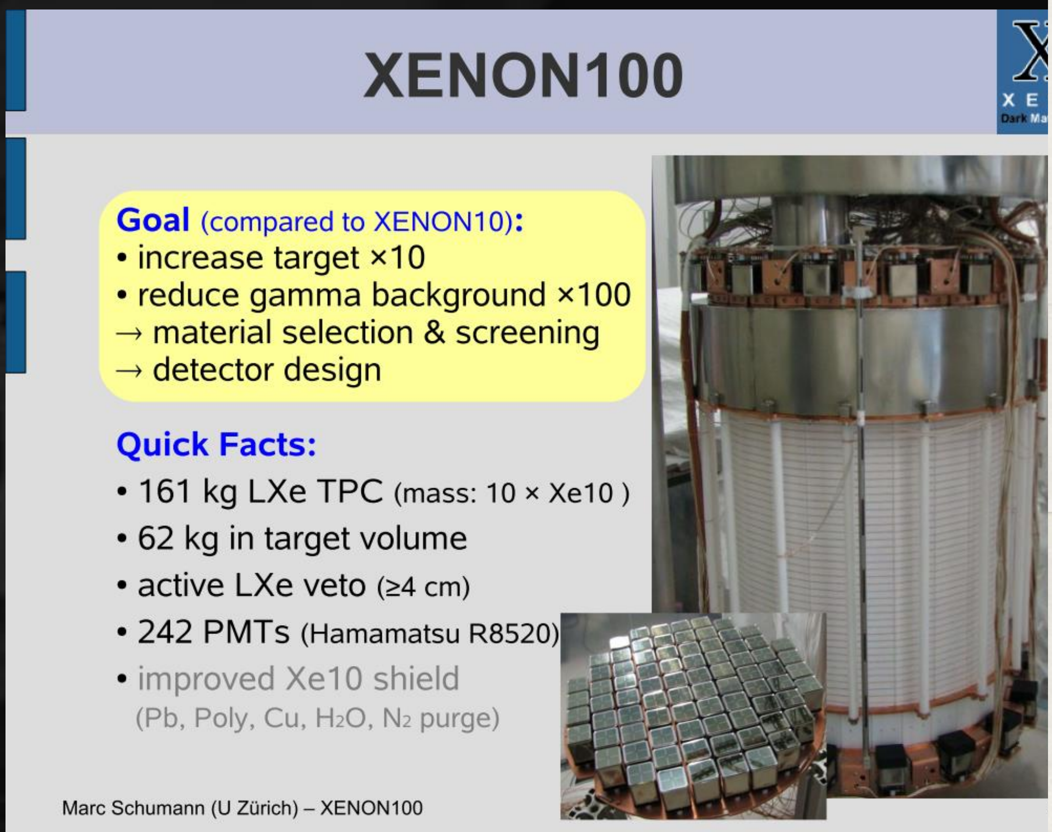
- **DAMA**
  - **largest statistics**
  - **purest crystal**

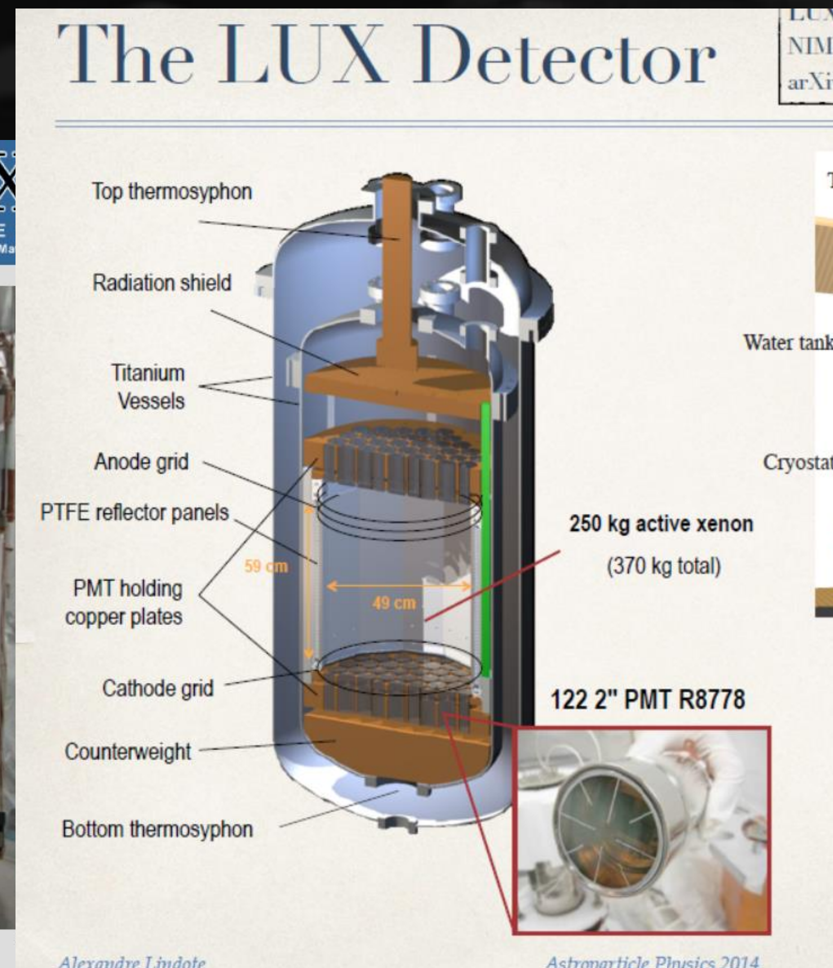

Low-mass WIMP region
CDMS II Ge
DAMA/LIBRA Favoured
CoGeNT Favoured
CRESST Favoured
CDMS II Si Favoured
XENON100(2012)-225 live days
LUX (2013)-85 live days
LUX +/-1σ expected sensitivity
10^{-40}
10^{-41}
10^{-42}
6
7
8
9
10
12
m_{WIMP} (GeV/c^2)
Astroparticle Physics 2014
17


暗黒物質の直接検出
E_R検出（光）
DAMA
DM-ICE（NaI）
KIMS（CsI）
XMASS（X
（光+電離）
XENON10/100
LUX
（Xe
ArDM・WARP（Ar）
原子核
（光+温度）
CRESST
（CaWO4）
E_R検出（電離）
CoGent
HPGe
反跳
E_R<～100keV
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）

2 phase Liquid xenon

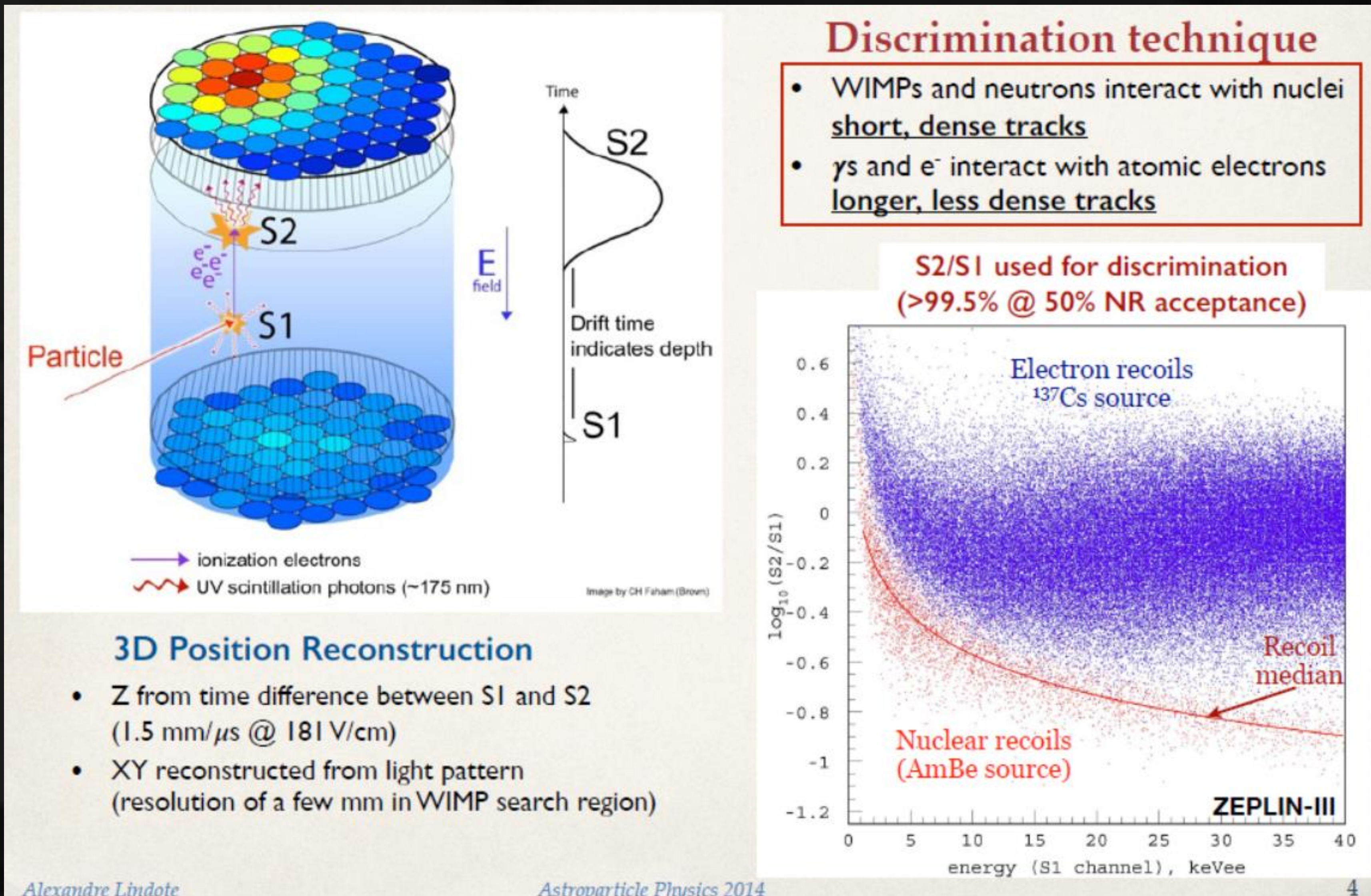
- XENON100：161kg
- LUX：370kg

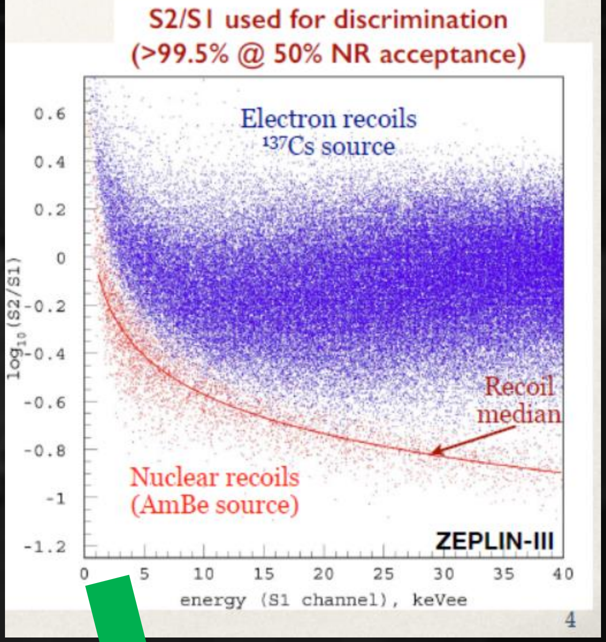




2-phase Liquid Xenon

γ rejection





OK, good rejection

jump to the limit curves

WAIT

OVERUPS?
What about the rejection around threshold?

gamma leakage?

⇒limits could be worse…

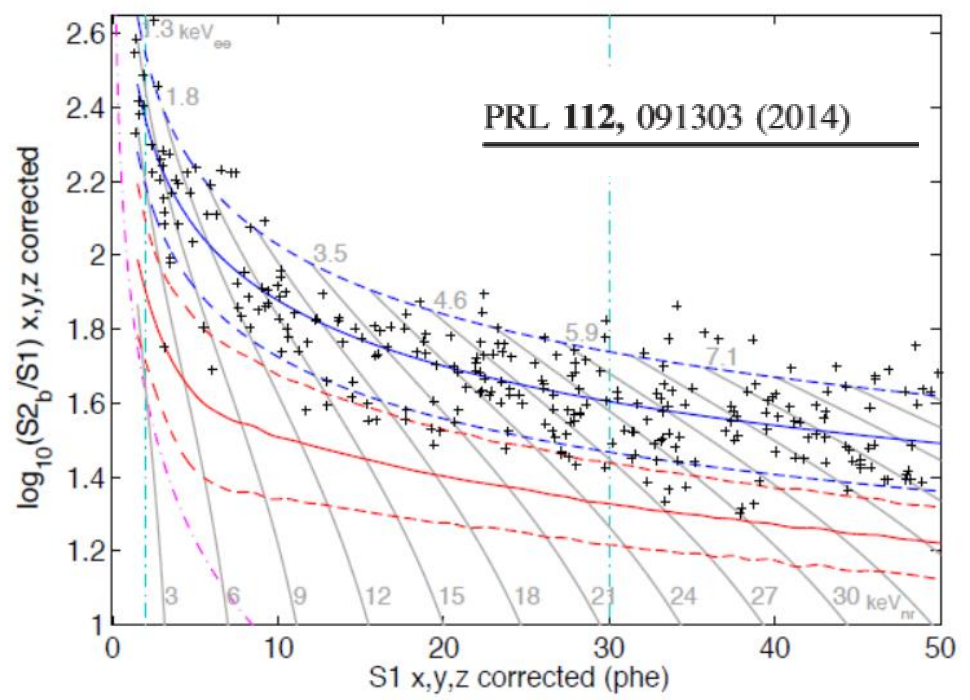


FIG. 4. The LUX WIMP signal region. Events in the 118 kg fiducial volume during the 85.3 live-day exposure are shown. Lines as shown in Fig. 3, with vertical dashed cyan lines showing the 2-30 phe range used for the signal estimation analysis.

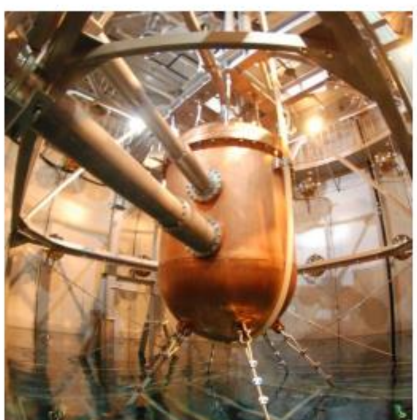
XMASS

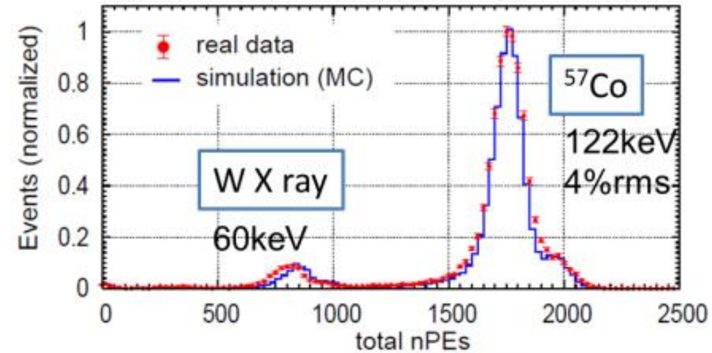
- liquid Xenon 835kg
- 1 phase

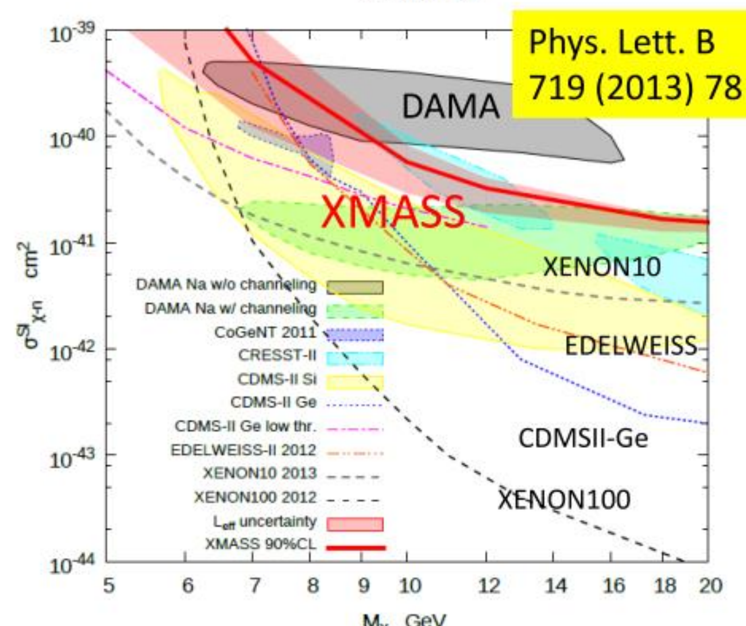
森山2013年秋物理学会

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。







Results from the annual modulation analysis of the XMASS-I dark matter data

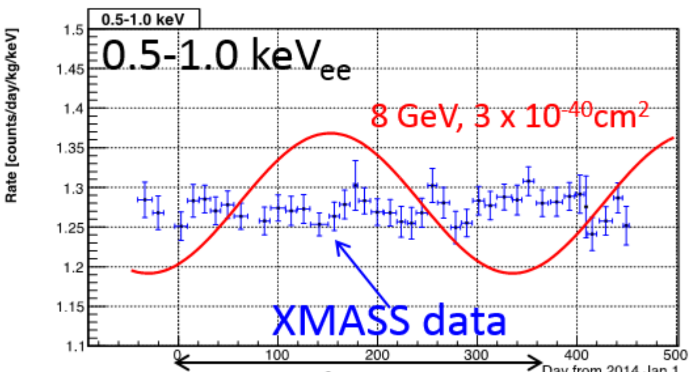
KATSUKI HIRAIDE (ICRR, THE UNIVERSITY OF TOKYO)

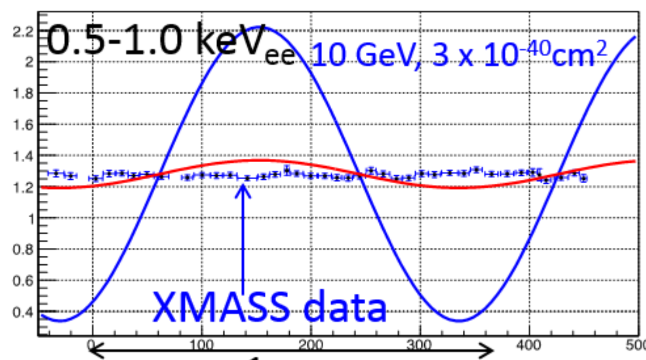
JULY 31ST, 2015

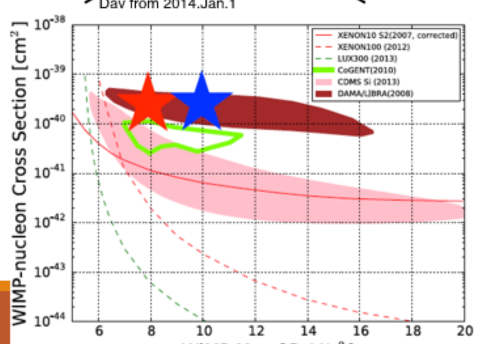
ICRC2015 CONFERENCE

Sensitivity to annual modulation

XMASS 'real' data (359 days); 0.5 -1.0 keVee (4.8 – 8.0 keVr) w/o syst.







- High sensitivity to modulation
  - Largest mass (832 kg)
  - Low threshold (0.5 keVee)
- Sensitive both nuclear recoil and *e*/*γ* signals
  - Same as DAMA
  - If nuclear recoil
    - Direct comparison is possible (lines)
  - If e/γ signal
    - Need models to compar

2013年 12月20日

身内賢太朗

Results from the annual modulation analysis of the XMASS-I dark matter data

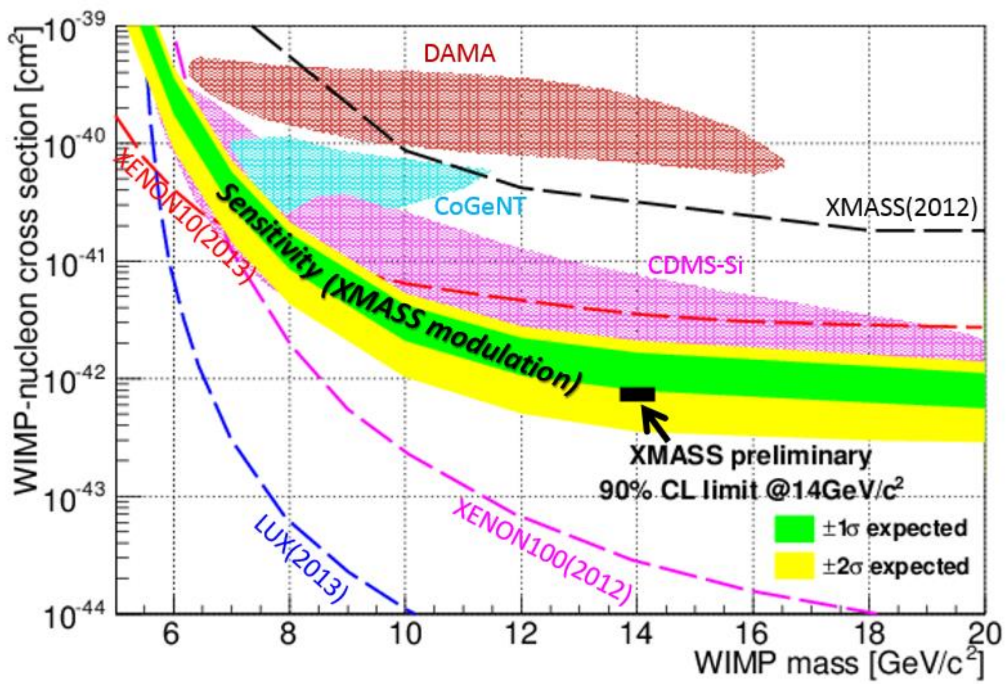
KATSUKI HIRAIDE (ICRR, THE UNIVERSITY OF TOKYO)

JULY 31ST, 2015

ICRC2015 CONFERENCE

Preliminary results on WIMP dark matter

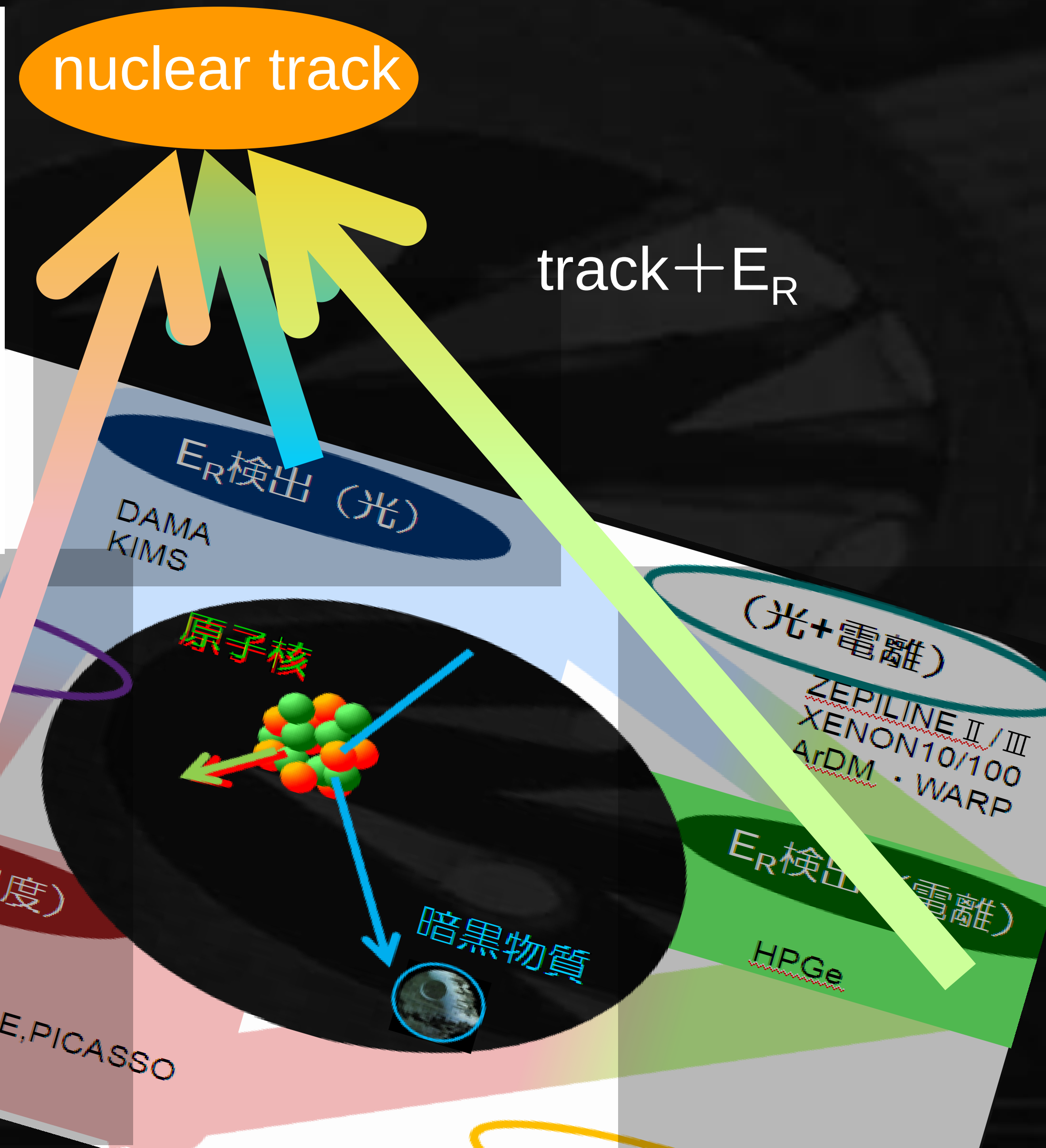
- Astrophysical parameters assumed
  - v_0=220 km/s, v_{esc}= 650 km/s, ρ=0.3 GeV/cm^3
- We show the expected sensitivity from our annual modulation analysis.
  - Covers DAMA's allowed region
- Our preliminary 90% CL upper limits for 14 GeV/c^2 WIMP is also shown.
- We are finalizing systematic error evaluation and final results will come soon.



4th information: track direction

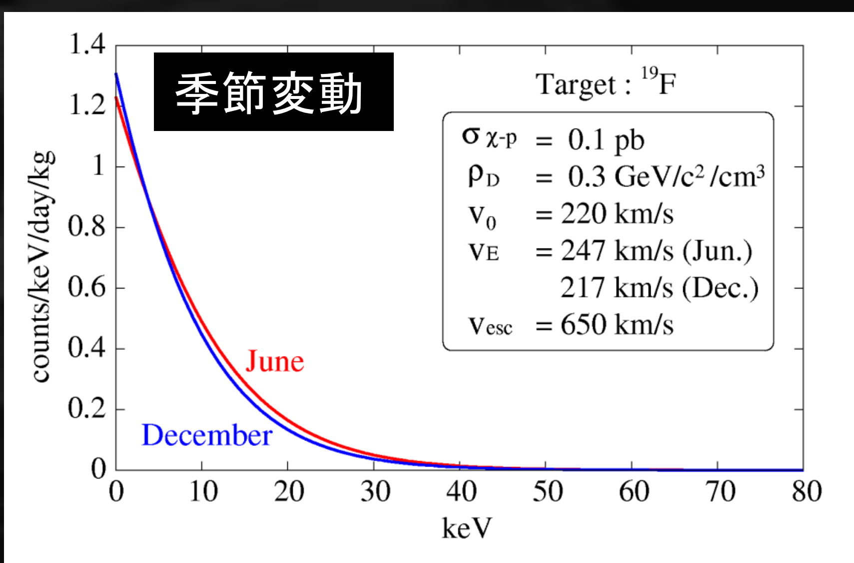
PRL73(1994)1067

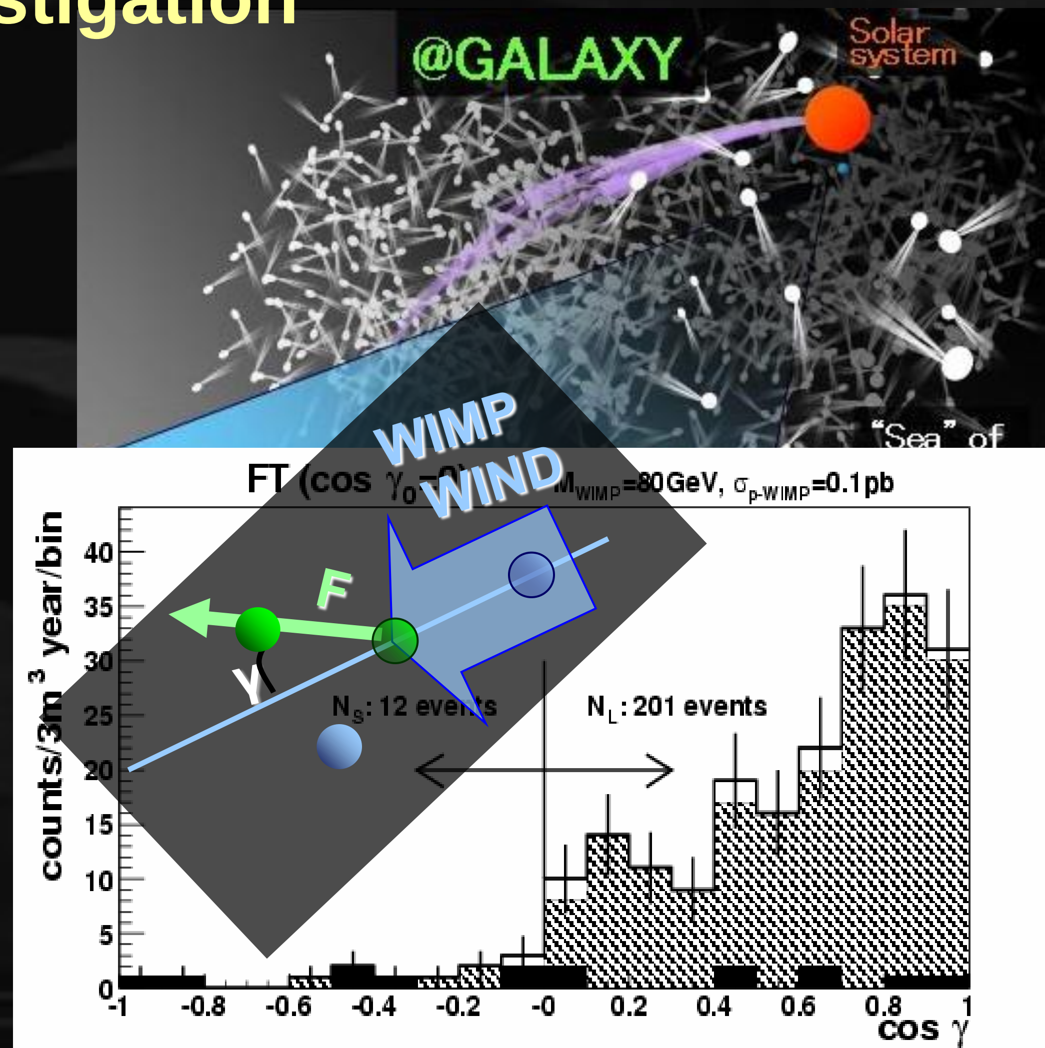
FIG. 2. A false color CCD image resulting from a ^{252}Cf neutron source. The colors black, blue, red, and white represent the order of increasing light intensity levels. The area displayed represents a 25 cm by 25 cm section of the detector plane. See the text for a description of image features.



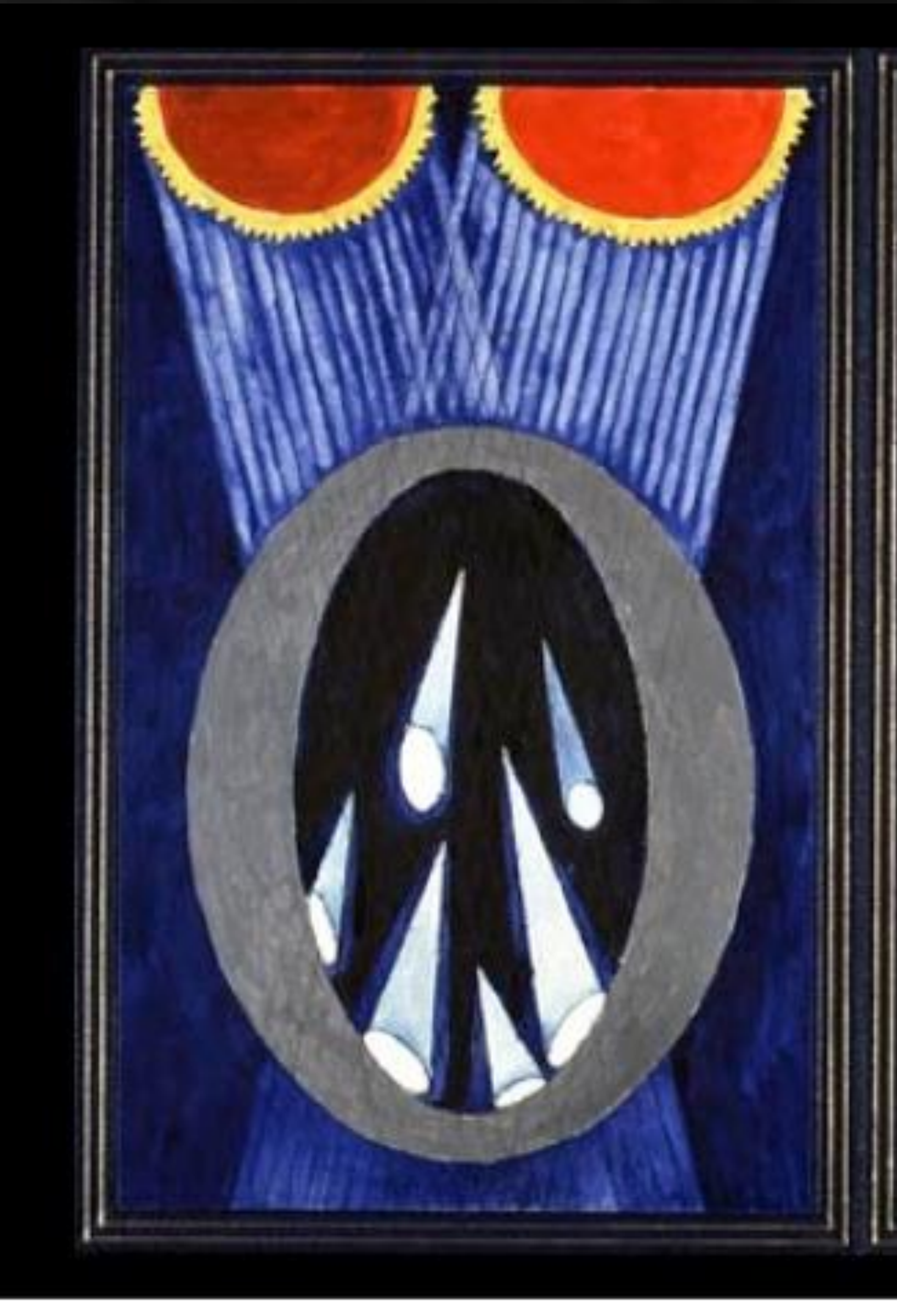
Advantage of track detection

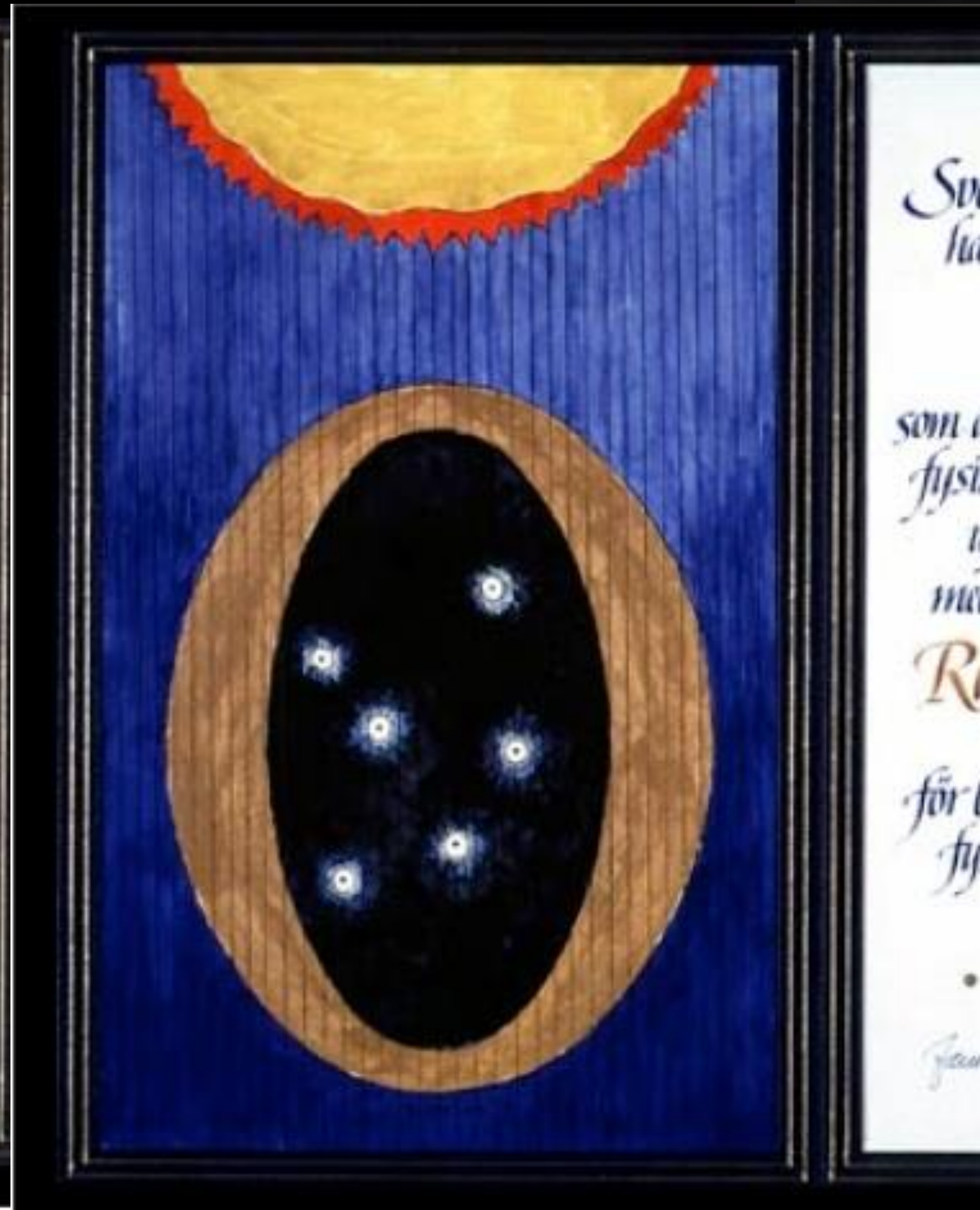
- Larger asymmetry (~10 times) than annual modulation (<5%) -> concrete evidence
- Post discovery investigation



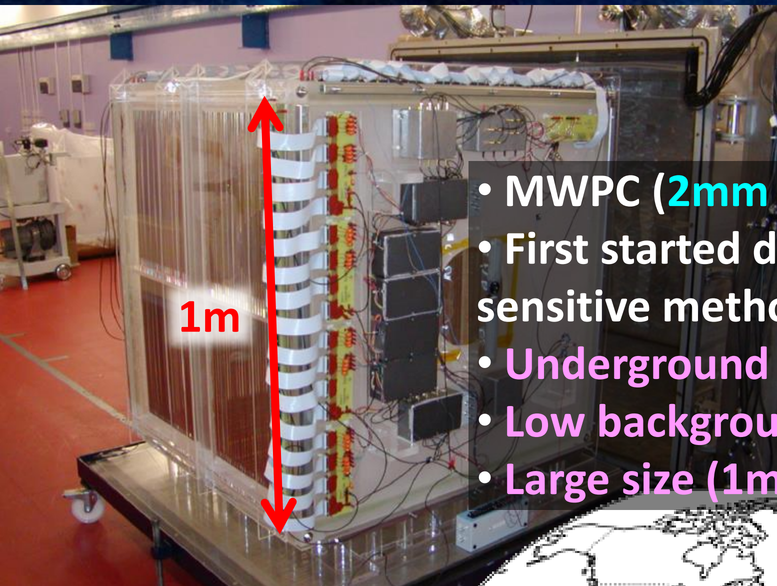


Importance of directionality





directional DM projects in the world

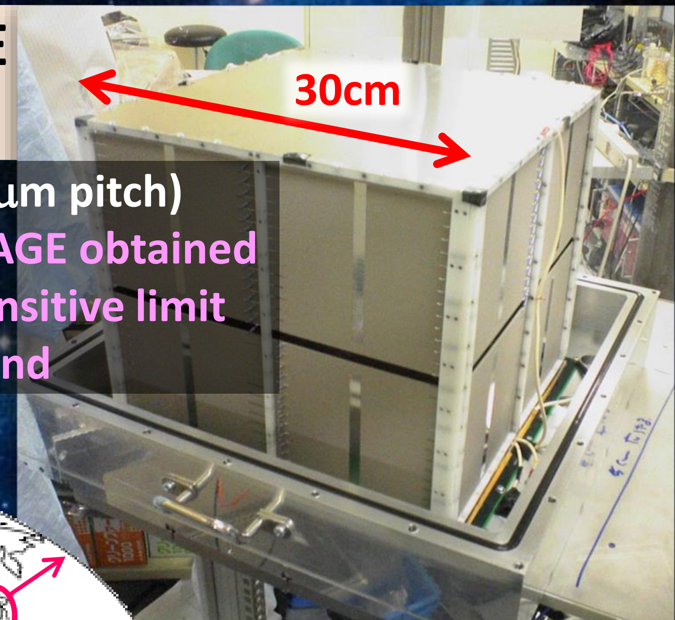


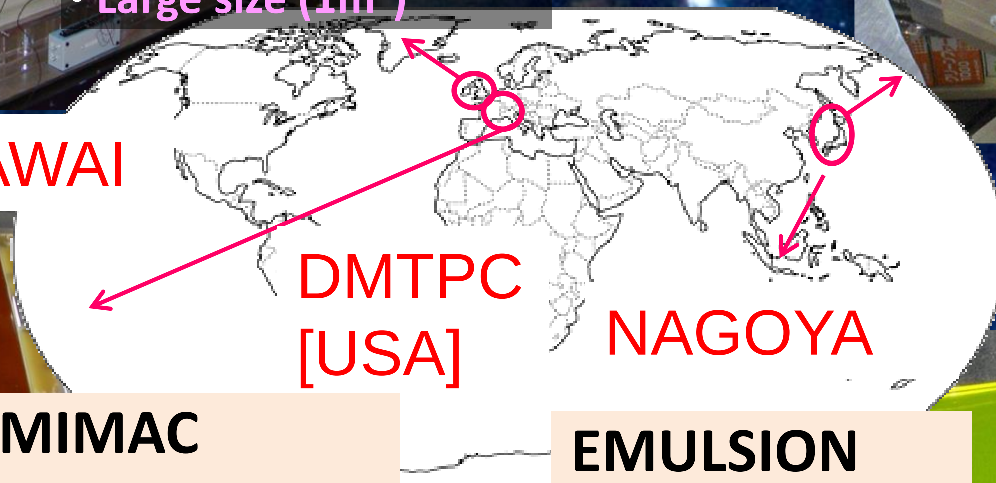
DRIFT
[UK]

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

NEWAGE
[Kobe＋]

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





MIMAC
[France]

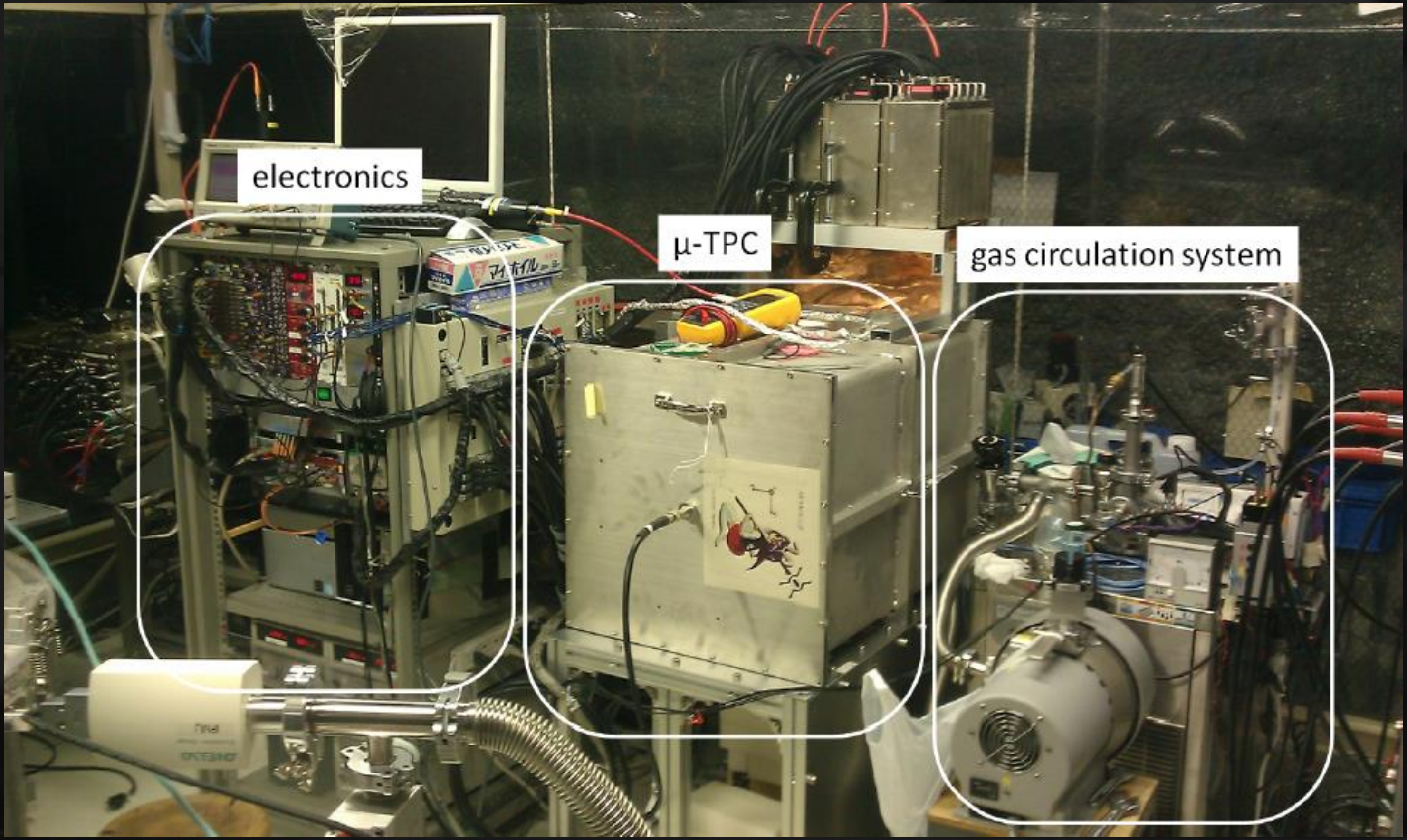
- Micromegas (~400μm pitch)
- Measured quenching factor in detail
- R&D at surface

EMULSION
[Nagoya +]

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

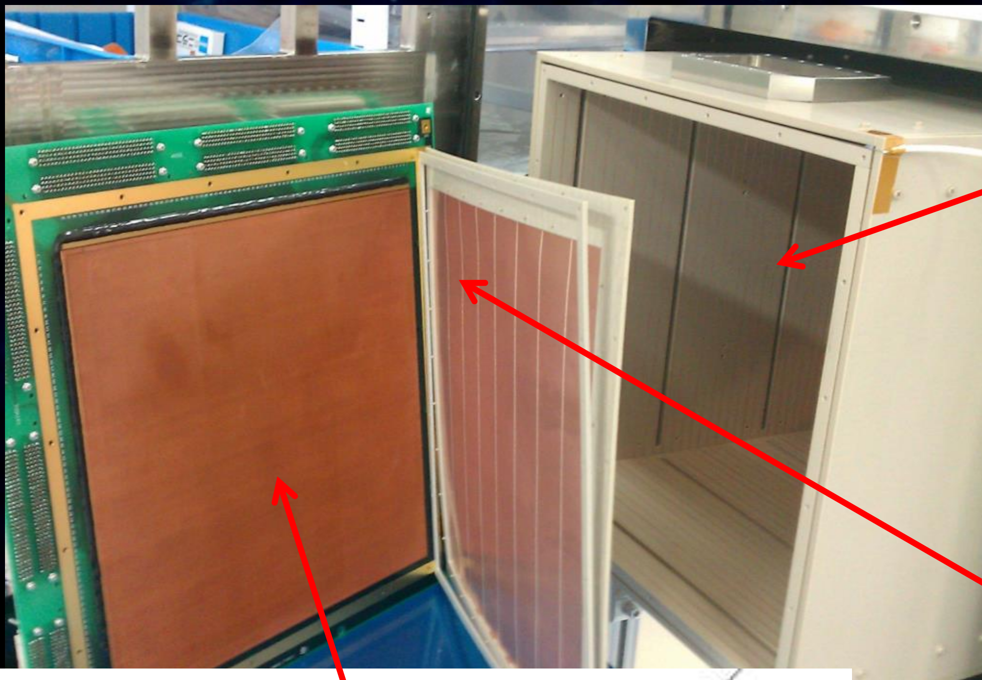
NEWAGE detector

- **NEWAGE-0.3b'**
- **Detection Volume: 31×31×41cm^3**
- **Gas: CF4 at 0.1atm (50keVee threshold)**
- **Gas circulation system with cooled charcoal**

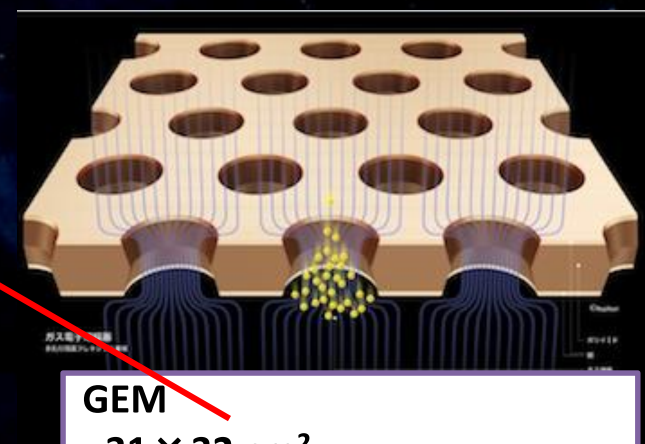


NEWAGE-0.3b' inside view

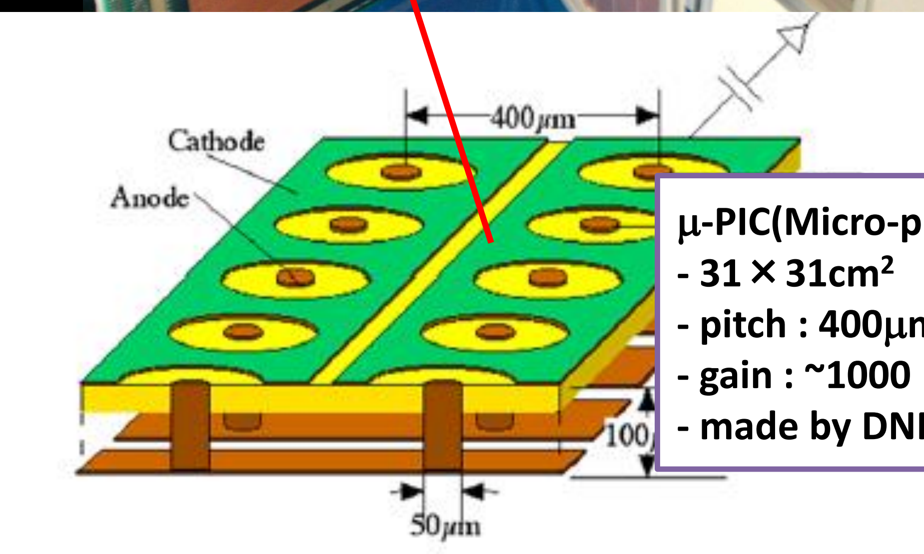
- Detection Volume: 30×30×41cm^3



Field cage
Drift length: 41cm
PEEK + copper wires



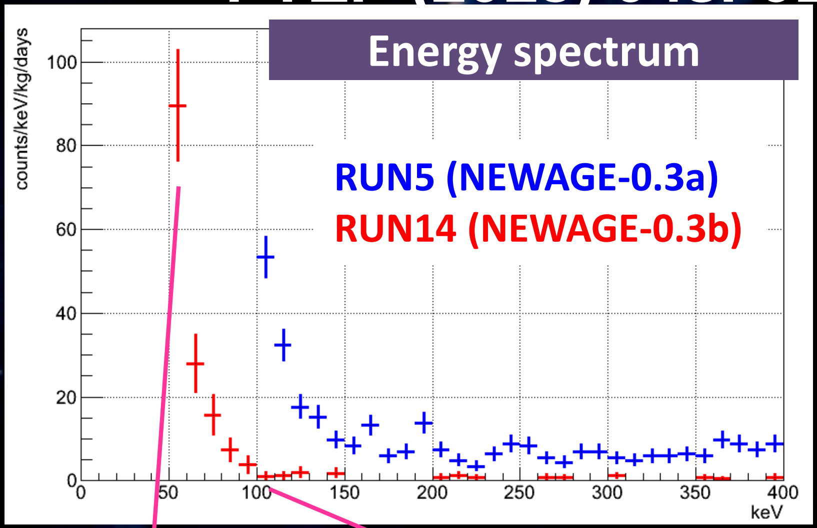
GEM
- 31×32 cm^2
- 8-segmented
- hole pitch : 140μm
- hole diameter: 70μm
- insulator : LCP 100μm
- gain : ~5
- made by Scienergy, Japan



μ-PIC(Micro-pixel chamber)
- 31×31cm^2
- pitch : 400μm
- gain : ~1000
- made by DNP, Japan

NEWAGE latest results

PTEP (2015) 043F01s

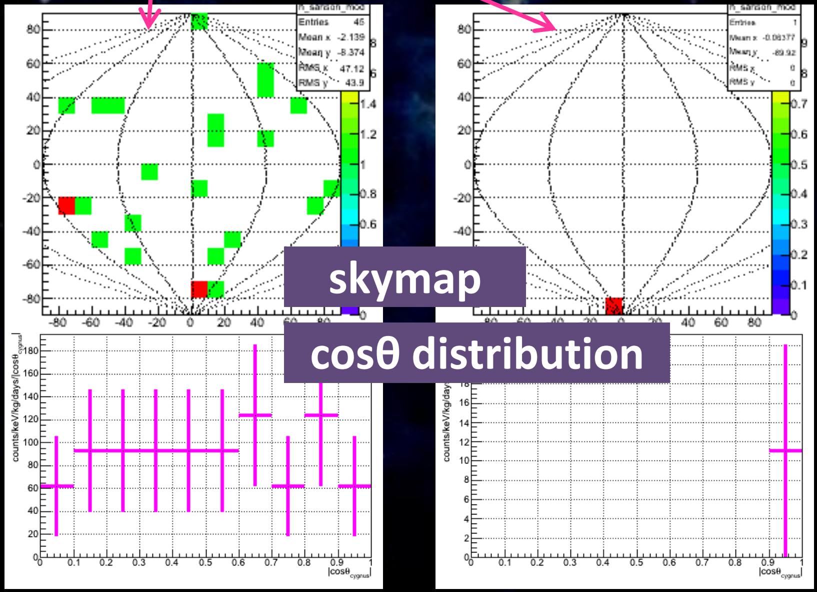


RUN14

- period : 2013/7/20-8/11, 10/19-11/12
- live time : 31.6 days
- fiducial volume : $28x24x41cm^3$
- mass : 10.36g
- exposure : 0.327 kg・days

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

- *Skymap, cosθ distribution*
  - Set limit by significant difference in 2-binned measured cosθ and DM-wind simulated cosθ



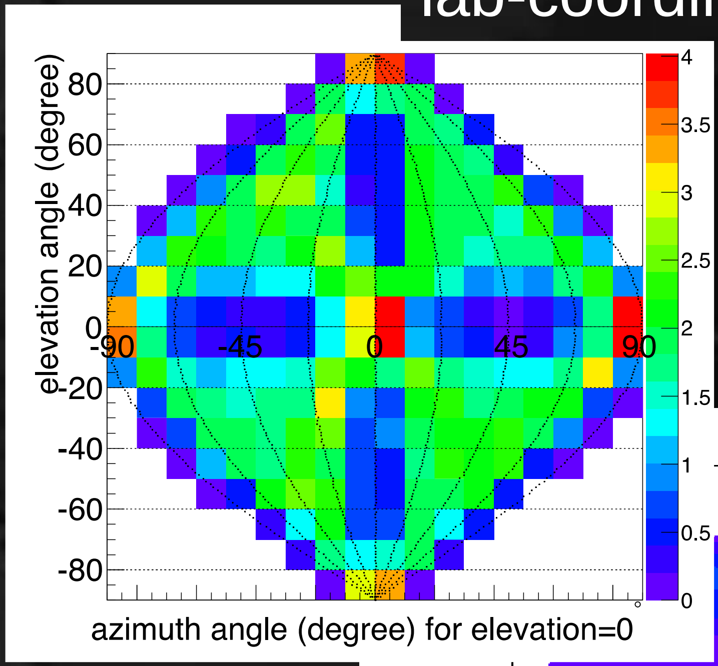
50-60keV

100-110keV

Detection efficiency in Galactic-coordinate

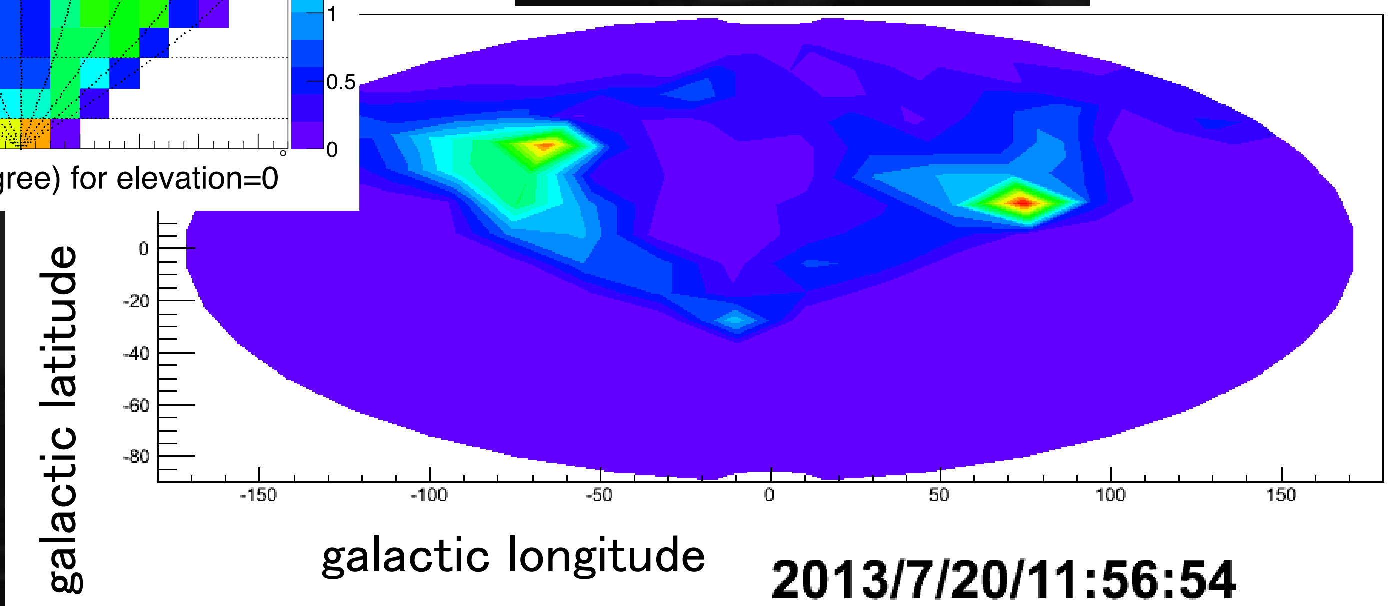
- Time variation of the efficiency map in the galactic coordinate

lab-coordinate

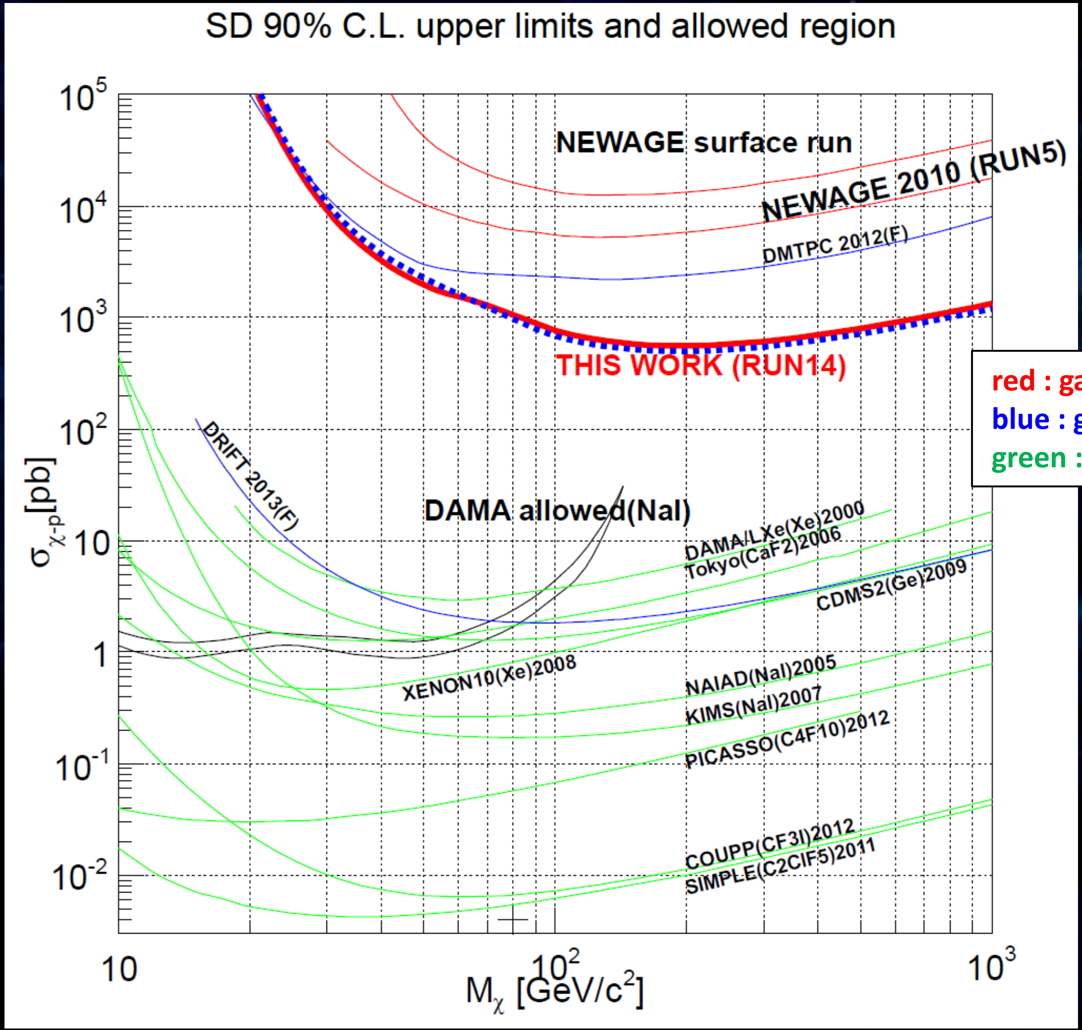


- auto-scanning is demonstrated
- "vertical" and "horizontal" detectors would be needed

galactic coordinate



Direction-sensitive limit



red : gas, with directional analysis
blue : gas, without directional analysis
green : solid, liquid detector

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

- **Seminar part:**
  Review of Dark Matter Search

- **Discussion part:**
  Potential of direction-sensitive search

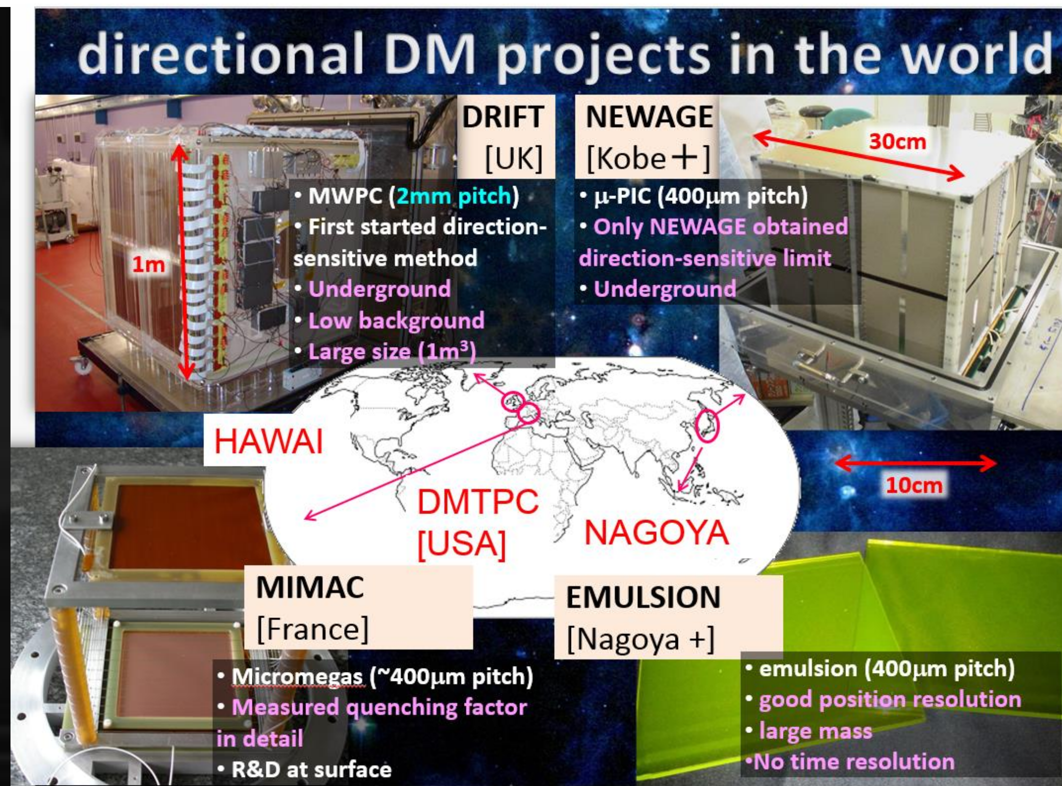
Cygnus 2015

Cygnus 2015

fifth workshop on directional detection of dark matter

Home

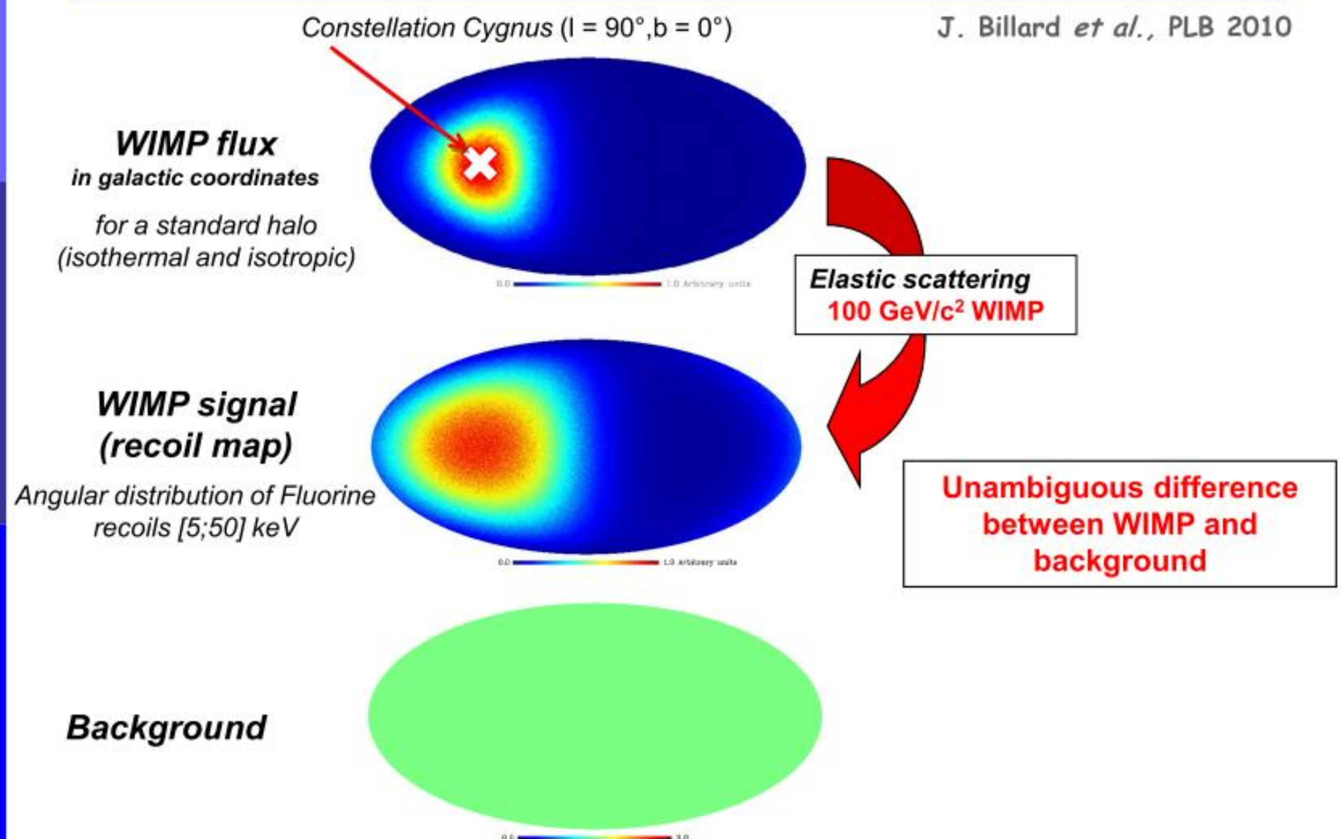
The fifth CYGNUS workshop on directional dark matter detection is the fifth in a series of directional dark matter detection workshops. The workshop will be held from June 2-4, 2015 on the campus of beautiful Occidental College in Los Angeles, California.



A review on the discovery reach of directional detection

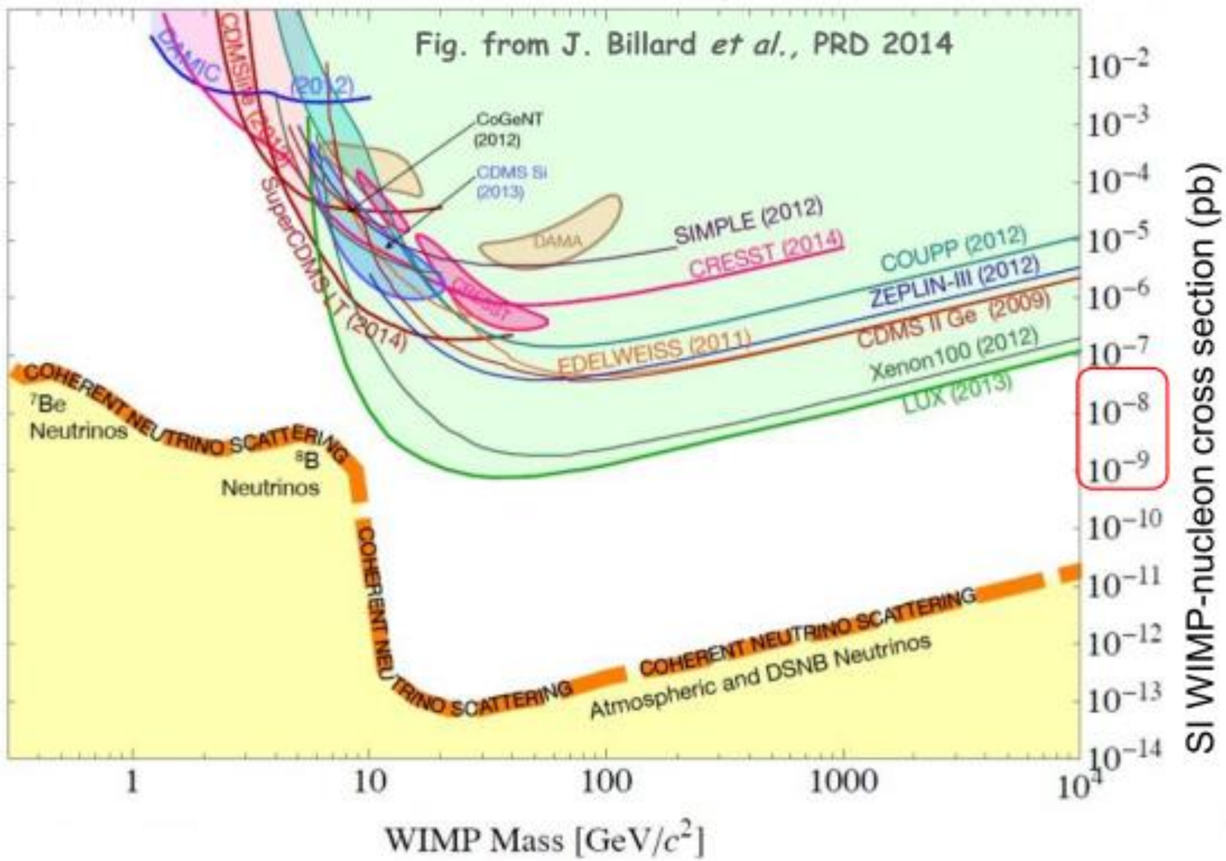
F. Mayet
LPSC
Université Joseph Fourier
Grenoble, France

Directional features: dipole



Directional detection and neutrino floor

J. Billard *et al.*, PRD 2014



→The neutrino floor sets **a lower limit** for SI direct detection

Directional Identification

J. Billard *et al.*, PRD 2011

Directional detection may be used to identify Dark Matter

i.e. measure WIMP and halo properties

ɔn (10^{-3} pb)

Identification: probing halo substructures

N-body simulations suggest the presence of velocity substructures in the halo

- → tidal streams *(spatially localized)*
- → debris flows (spatially homogenized)
- → co-rotating dark disk

1) Tidal stream

→Detection is possible

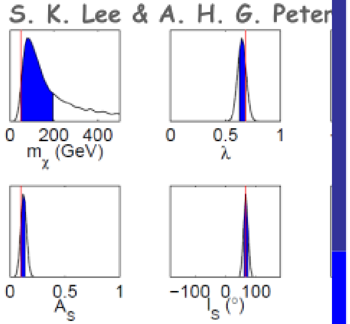
C. A. J. O'Hare & A. M. Green, PRD 2014

(CF4, 10 kg-year, 10^{-3} pb, 50 GeV)

→ Identification also

(CF4, 30 kg-year, 5 keV thr. 10^{-3} pb, 50 GeV)

S. K. Lee & A. H. G. Peter



F. Ma

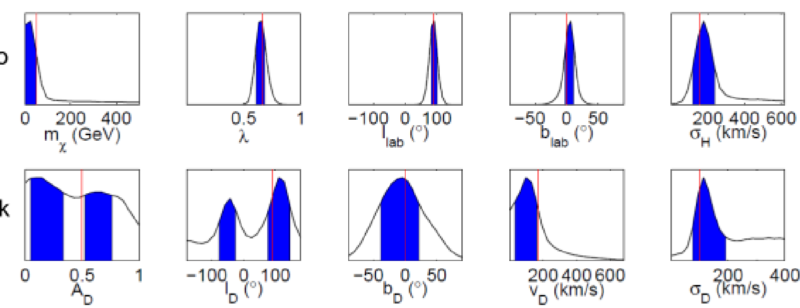
Identification: probing halo substructures

2) Dark Disk (DD)

→Identification is challenging

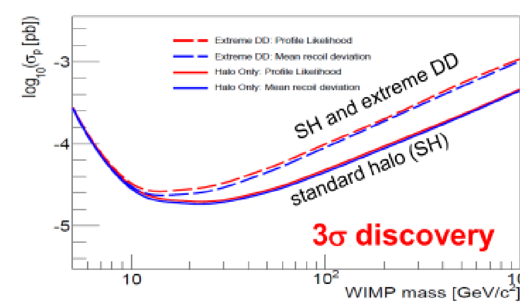
S. K. Lee & A. H. G. Peter JCAP 2012

(CF4, 30 kg-year, 5 keV thr. 10^{-3} pb, 50 GeV, slowly co-rotating DD (170 km/s)



→but DD is no a threat to directional detection

J. Billard *et al.*, PLB 2013



Discretising the velocity distribution for directional dark matter experiments
or
'Pi in the sky'

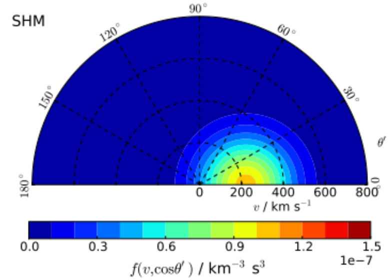
Bradley J. Kavanagh (IPhT - CEA/Saclay)

CYGNUS 2015 - 4th June 2015

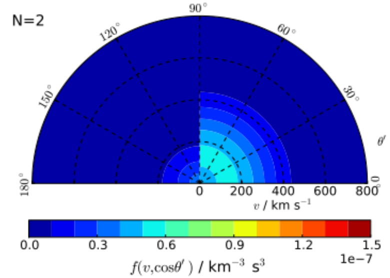
Based on arXiv:1502.04224

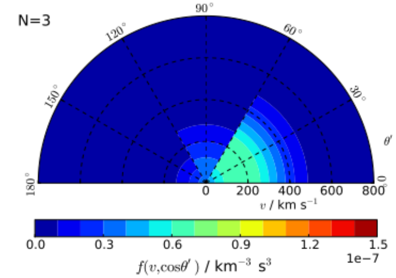
Examples: SHM

$f(\mathbf{v})$



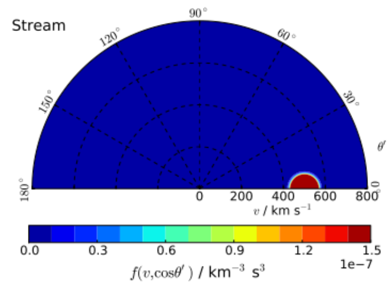
$$v_{\mathrm{lag}} = 220\ \mathrm{km\,s^{-1}}$$
$$\sigma_v = 156\ \mathrm{km\,s^{-1}}$$



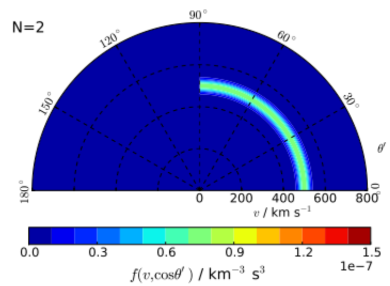


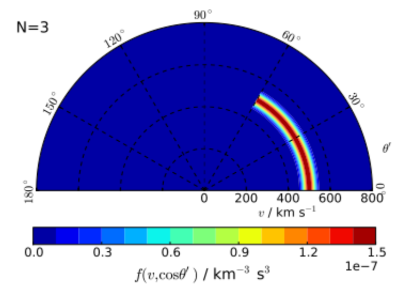
Examples: Stream

$f(\mathbf{v})$



$$v_{\mathrm{lag}} = 500\ \mathrm{km\,s^{-1}}$$
$$\sigma_v = 20\ \mathrm{km\,s^{-1}}$$





2013年 12月20日

Full Disclosure

New directional signatures from non-relativistic effective field theory
or
'Who ordered all these operators?'

Bradley J. Kavanagh (IPhT - CEA/Saclay)

CYGNUS 2015 - 3rd June 2015

Based on arXiv:1505.07406

Dark matter directional detection in non-relativistic effective theories

[arXiv:1505.06441]

1 [hep-ph] 24 May 2015

Riccardo Catena[a]

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Abstract. We extend the formalism of dark matter directional detection to arbitrary one-body dark matter-nucleon interactions. The new theoretical framework generalizes the one currently used, which is based on 2 types of dark matter-nucleon interaction only. It includes 14 dark matter-nucleon interaction operators, 8 isotope-dependent nuclear response functions, and the Radon transform of the first 2 moments of the dark matter velocity distribution. We

[arXiv:1505.07406]

SACLAY-t15/093

New directional signatures from the non-relativistic effective field theory of dark matter

27 May 2015

Bradley J. Kavanagh*

Institut de physique théorique, Université Paris Saclay, CNRS, CEA, F-91191 Gif-sur-Yvette, France

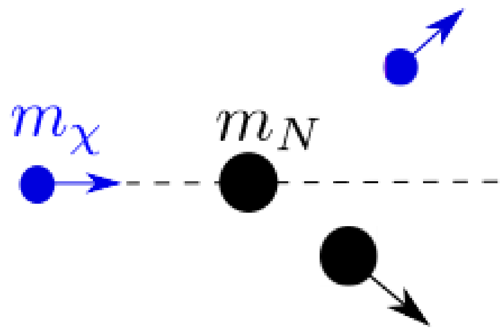
The framework of non-relativistic effective field theory (NREFT) aims to generalise the standard analysis of direct detection experiments in terms of spin-dependent (SD) and spin-independent (SI) interactions. We show that a number of NREFT operators lead to distinctive new directional signatures, such as prominent ring-like features in the directional recoil rate, even for relatively low mass WIMPs. We discuss these signatures and how they could affect the interpretation of future results from directional detectors. We demonstrate that considering a range of possible operators introduces a factor of 2 uncertainty in the number of events required to confirm the median recoil direction of the signal. Furthermore, using directional detection, it is possible to distinguish the more general NREFT interactions from the standard SI/SD interactions at the 2σ level with $\mathcal{O}(100-500)$ events. In particular, we demonstrate that for certain NREFT operators, directional sensitivity provides the only method of distinguishing them from these standard operators, highlighting the importance of directional detectors in probing the particle physics of dark matter.

I. INTRODUCTION

for DM-nucleus interactions. The non-relativistic effective field theory (NREFT; introduced by Fan et al. [22] and extended in Refs. [23–25]) considers all possible non-

The Directional Spectrum

Recoil distribution for WIMP-nucleus recoils in direction $\hat{q}$ with fixed WIMP speed $\vec{v}$:



$$\mu_{\chi N} = \frac{m_\chi m_N}{m_\chi + m_N}$$

$$v_{\min} = \sqrt{\frac{m_N E_R}{2\mu_{\chi N}^2}}$$

$$\frac{\mathrm{d}R}{\mathrm{d}E_R \mathrm{d}\Omega_q} = \frac{\rho_0 v}{m_\chi} \frac{\langle |\mathcal{M}|^2 \rangle}{32\pi m_N^2 m_\chi^2 v^2} \frac{v\,\delta\left(\vec{v}\cdot\hat{q} - v_{\min}\right)}{2\pi}$$

WIMP flux — Cross section — Kinematics

For standard SI and SD interactions: $\langle |M|^2 \rangle \sim v^0 q^0$

Non-relativistic effective field theory (NREFT)

The interaction is (ultra-)non-relativistic, so we can write down all possible non-relativistic (NR) WIMP-*nucleon* operators which can mediate the *elastic* scattering.
[Fan et al - 1008.1591, Fitzpatrick et al. - 1203.3542]

The building blocks of these operators are:

$$\vec{S}_n \qquad \vec{S}_\chi \qquad \frac{\vec{q}}{2m_n} \qquad \vec{v}_\perp$$

The WIMP velocity operator is not Hermitian, so it can appear only through the Hermitian *transverse velocity*:

$$\vec{v}_\perp = \vec{v} + \frac{\vec{q}}{2\mu_{\chi n}} \qquad \Rightarrow \vec{v}_\perp \cdot \vec{q} = 0$$

NREFT Operators

Write down all operators which are Hermitian, Galilean invariant and time-translation invariant:

SI

$$\mathcal{O}_1 = 1$$

$$\mathcal{O}_3 = i\vec{S}_n \cdot (\frac{\vec{q}}{m_n} \times \vec{v}^\perp)$$

$$\mathcal{O}_4 = \vec{S}_\chi \cdot \vec{S}_n$$

SD

$$\mathcal{O}_5 = i\vec{S}_\chi \cdot (\frac{\vec{q}}{m_n} \times \vec{v}^\perp)$$

$$\mathcal{O}_6 = (\vec{S}_\chi \cdot \vec{q})(\vec{S}_n \cdot \vec{q})$$

$$\mathcal{O}_7 = \vec{S}_n \cdot \vec{v}^\perp$$

$$\mathcal{O}_8 = \vec{S}_\chi \cdot \vec{v}^\perp$$

$$\mathcal{O}_9 = i\vec{S}_\chi \cdot (\vec{S}_n \times \vec{q})$$

$$\mathcal{O}_{10} = i\vec{S}_n \cdot \vec{q}$$

$$\mathcal{O}_{11} = i\vec{S}_\chi \cdot \vec{q}$$

$$\mathcal{O}_{11} = i\vec{S}_\chi \cdot \vec{q}$$

$$\mathcal{O}_{12} = \vec{S}_\chi \cdot (\vec{S}_n \times \vec{v}^\perp)$$

$$\mathcal{O}_{13} = i(\vec{S}_\chi \cdot \vec{v}^\perp)(\vec{S}_n \cdot \frac{\vec{q}}{m_n})$$

$$\mathcal{O}_{14} = i(\vec{S}_\chi \cdot \frac{\vec{q}}{m_n})(\vec{S}_n \cdot \vec{v}^\perp)$$

$$\mathcal{O}_{15} = -(\vec{S}_\chi \cdot \frac{\vec{q}}{m_n})((\vec{S}_n \times \vec{v}^\perp) \cdot \frac{\vec{q}}{m_n}) .$$

NB: two sets of operators, one for protons and one for neutrons…

[1308.6288]

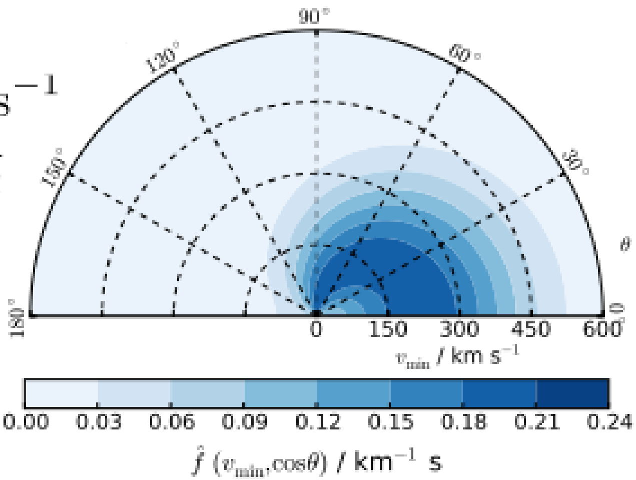
Transverse Radon Transform (examples)

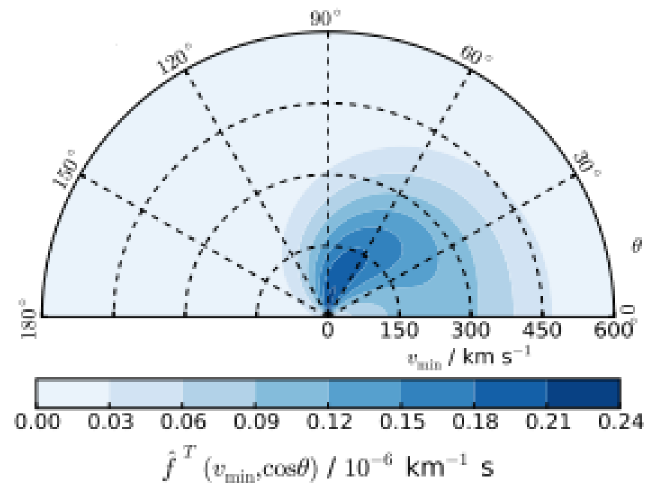
$\hat{f}(v_{\min}, \hat{q})$ | $\hat{f}^T(v_{\min}, \hat{q})$

SHM:

$v_{\text{lag}} = 220\,\text{km}\,\text{s}^{-1}$

$\sigma_v = v_{\text{lag}}/\sqrt{2}$

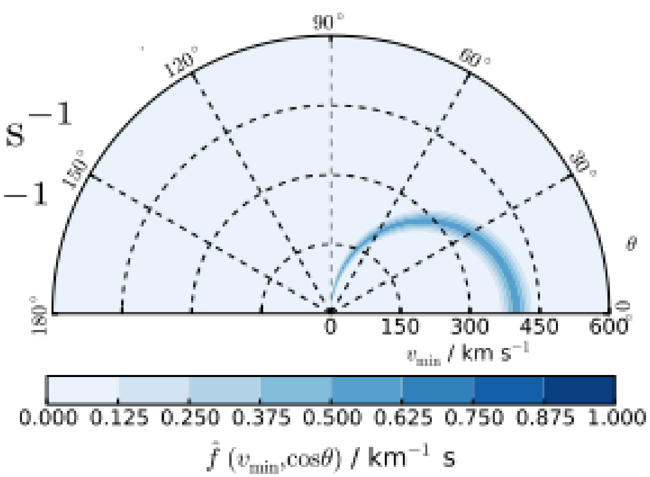


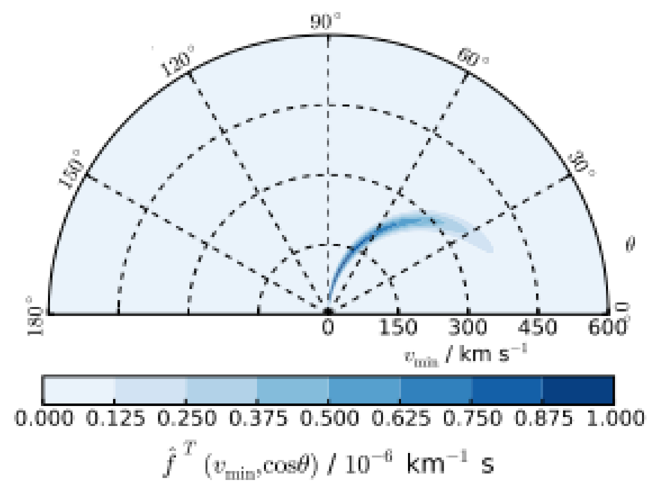


Stream:

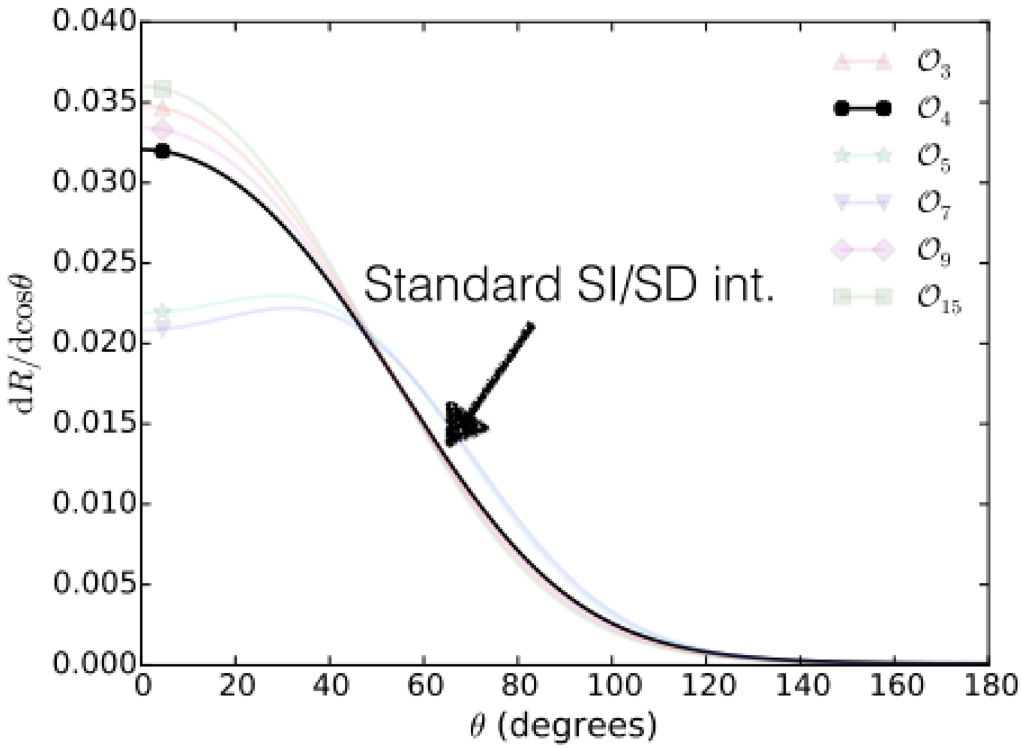
$v_{\text{lag}} = 400\,\text{km}\,\text{s}^{-1}$

$\sigma_v = 20\,\text{km}\,\text{s}^{-1}$





Directional Spectra



What would be the impact if we set limits from our experimental data?

- **Seminar part:**
  Review of Dark Matter Search

- **Discussion part:**
  Potential of direction-sensitive search

Thank You