暗黒物質 by 方向感度検出器

東邦大学
中　竜大

2019.7.5-6 Dark Matter懇談会2019@早稲田大学

Dark Matter in our galaxy

Center of galaxy

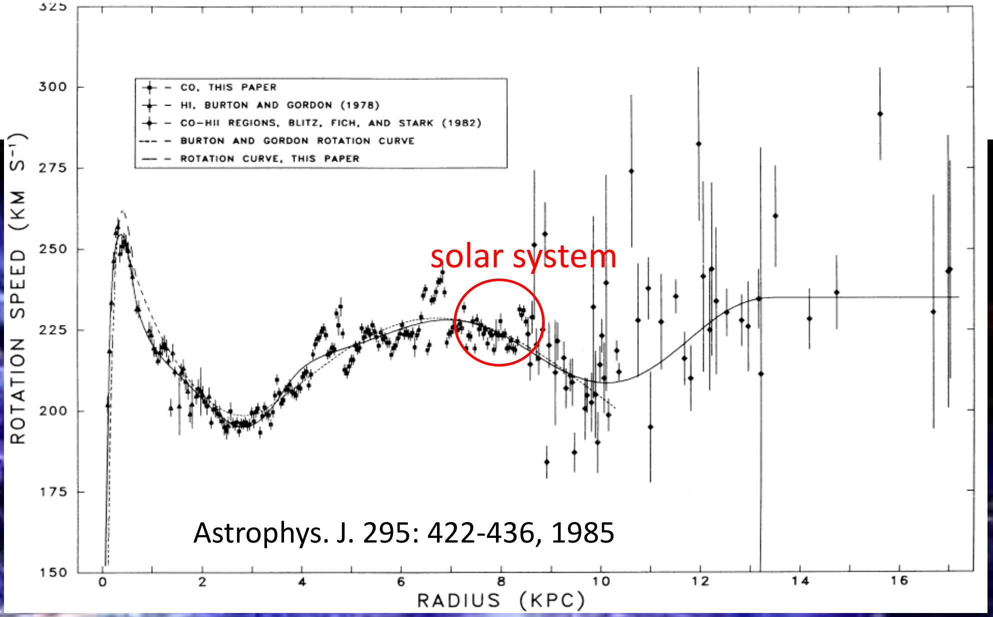
Local dark matter density : 0.4 +- 0.1 GeV/cm^3

- ✓ Independent value on dark matter model
- ✓ Very much mount of DM is condensed in the halo because mean dark matter density in the universe is ~ 1.4 keV/cm^3 (27 % of critical density ratio)

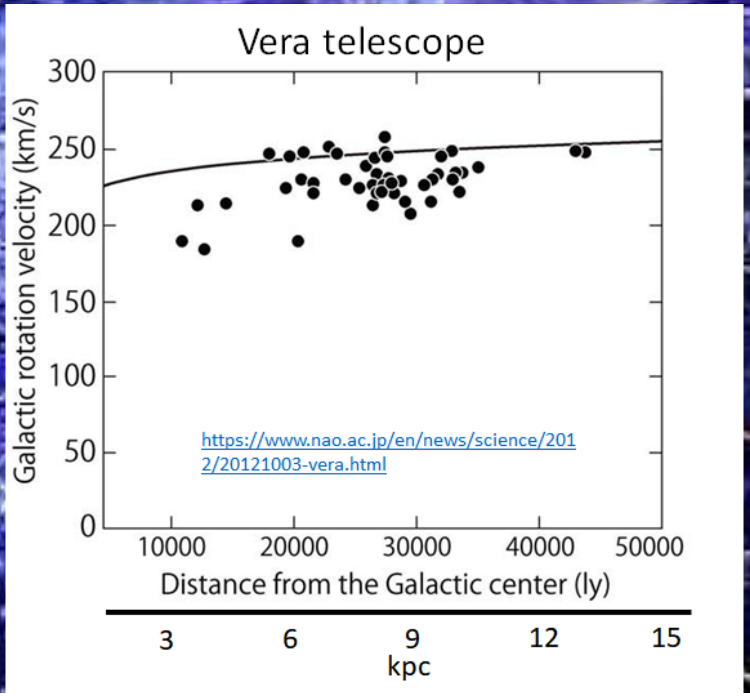
Dark matter flux on the earth

~ 100000 /cm^2/sec @ 100 GeV/c^2 dark matter

Solar system



Astrophys. J. 295: 422-436, 1985



https://www.nao.ac.jp/en/news/science/2012/20121003-vera.html

Idea of “directional” dark mater search

PHYSICAL REVIEW D
PARTICLES AND FIELDS

THIRD SERIES, VOLUME 37, NUMBER 6 — 15 MARCH 1988

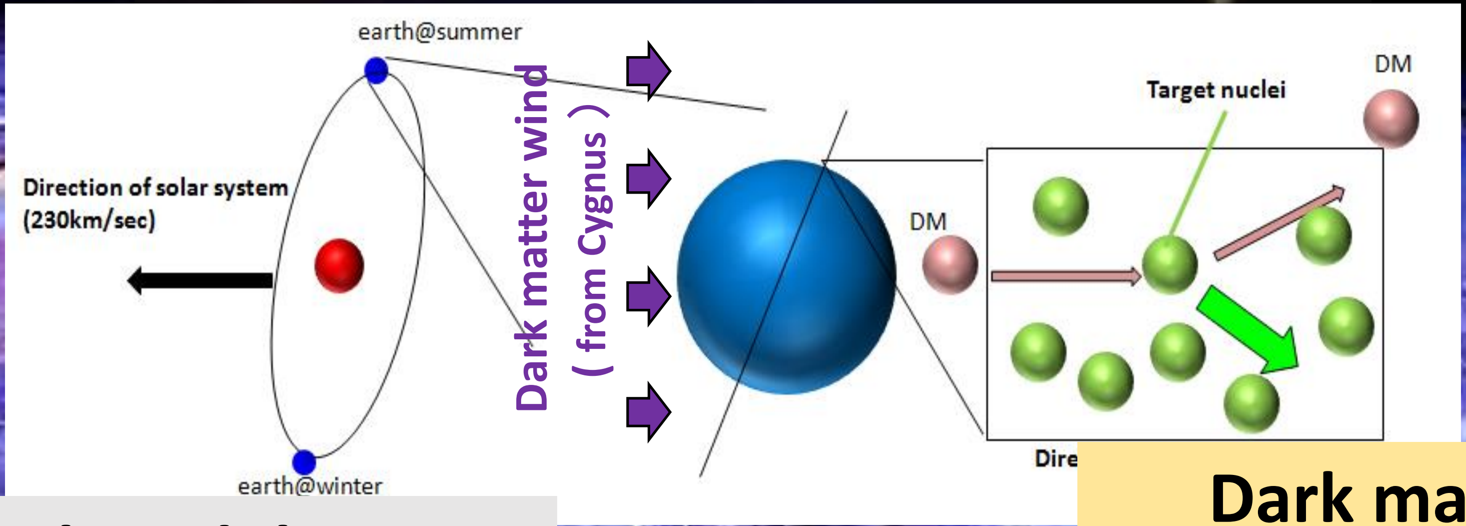
Motion of the Earth and the detection of weakly interacting massive particles

David N. Spergel*
Institute for Advanced Study, Princeton, New Jersey 08540
(Received 21 September 1987)

If the galactic halo is composed of weakly interacting massive particles (WIMP’s), then cryogenic experiments may be capable of detecting the recoil of nuclei struck by the WIMP’s. Earth’s motion relative to the galactic halo produces a seasonal modulation in the expected event rate. The direction of nuclear recoil has a strong angular dependence that also can be used to confirm the detection of WIMP’s. I calculate the angular dependence and the amplitude of the seasonal modulation for an isothermal halo model.

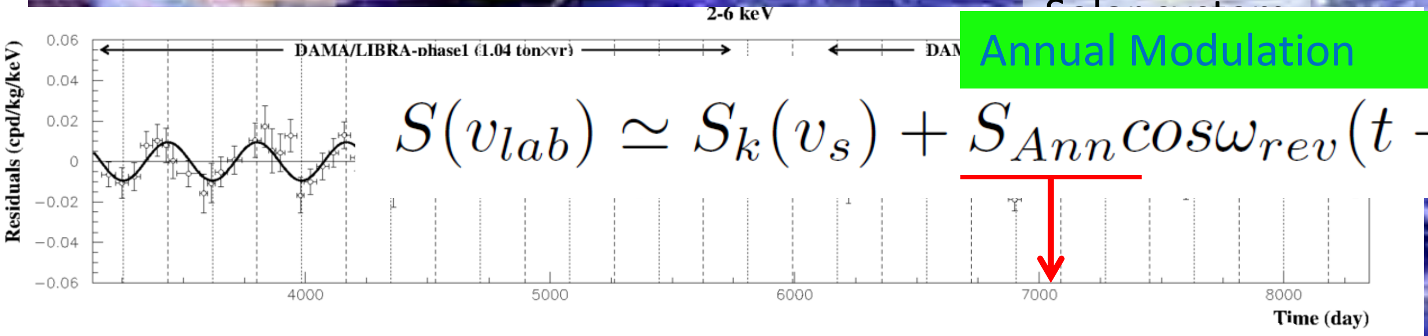
Direct Dark Matter Search

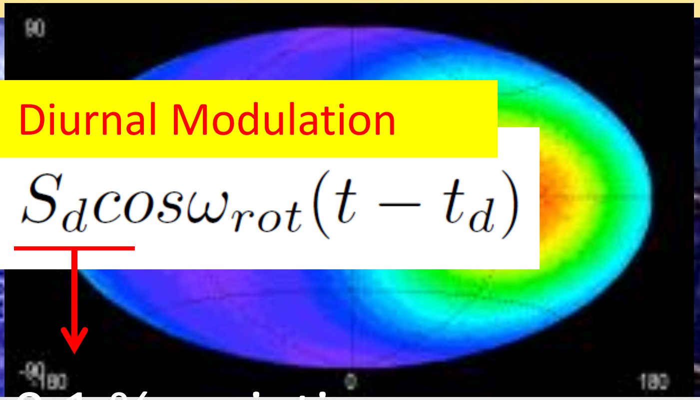
Direct dark matter search



Annual modulation

Dark matter wind





Annual Modulation

Diurnal Modulation

$$S(v_{lab}) \simeq S_k(v_s) + S_{Ann} cos\omega_{rev}(t - t_0) + S_d cos\omega_{rot}(t - t_d)$$

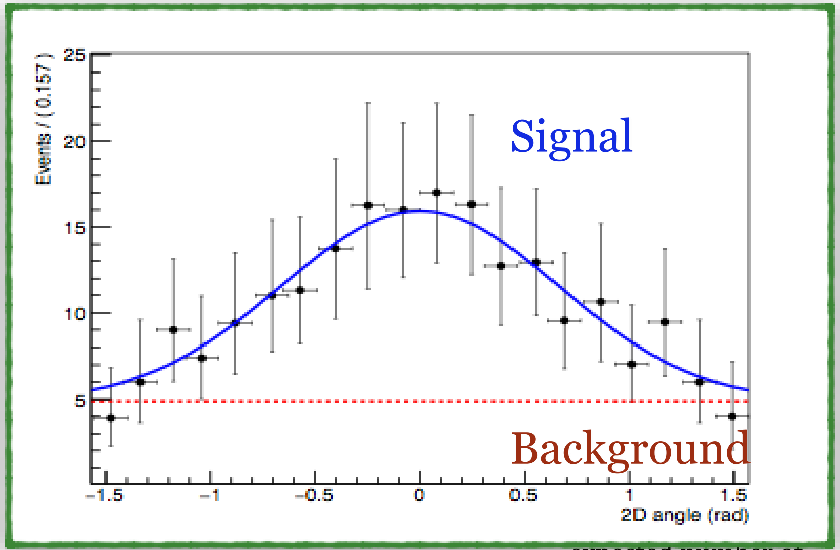
2-3 % variation

0.01 - 0.1 % variation

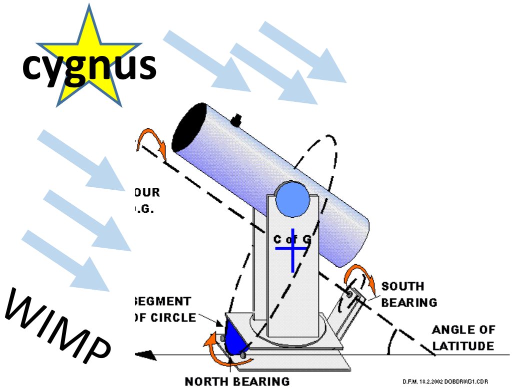
- ➢ DAMA/LIBRA : 2.46 ton･y, 12.9σ
- ➢ (Nucl. Phys. At. Energy 19 (2018) 307-325)
- ➢ Some groups : no significant observation

- ☐ Anisotropic signal for angular distribution
- ☐ Actively observation with lower statistics
- ☐ Currently technical R&D is needed

Potential of Directional Sensitive Search



N. Agfanova *et al.* (NEWSdm collaboration)
Eur. Phys. J. C (2018) 78: 578



expected number of WIMP events

expected number of background events

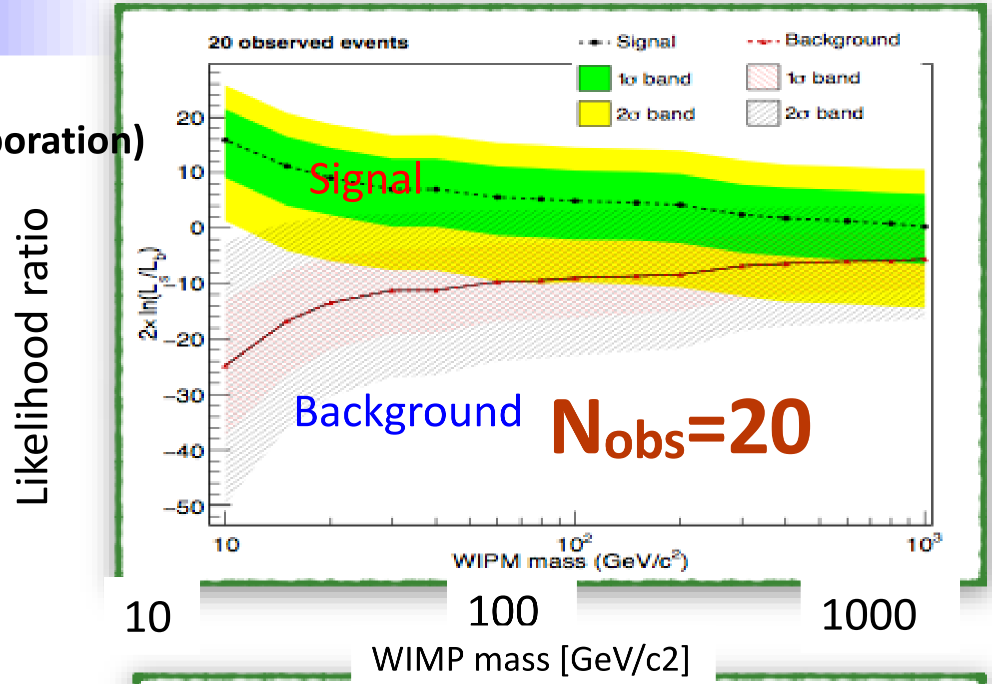
signal pdf

background pdf

$$\mathscr{L}(\sigma_{\chi-n}, R_b) = \frac{e^{-(\mu_\chi+\mu_b)}}{N!} \times \prod_{i=1}^{N} [\mu_\chi f_\chi(\vec{q}_i; t_i) + \mu_b f_b(\vec{q}_i)]$$

total number of observed events

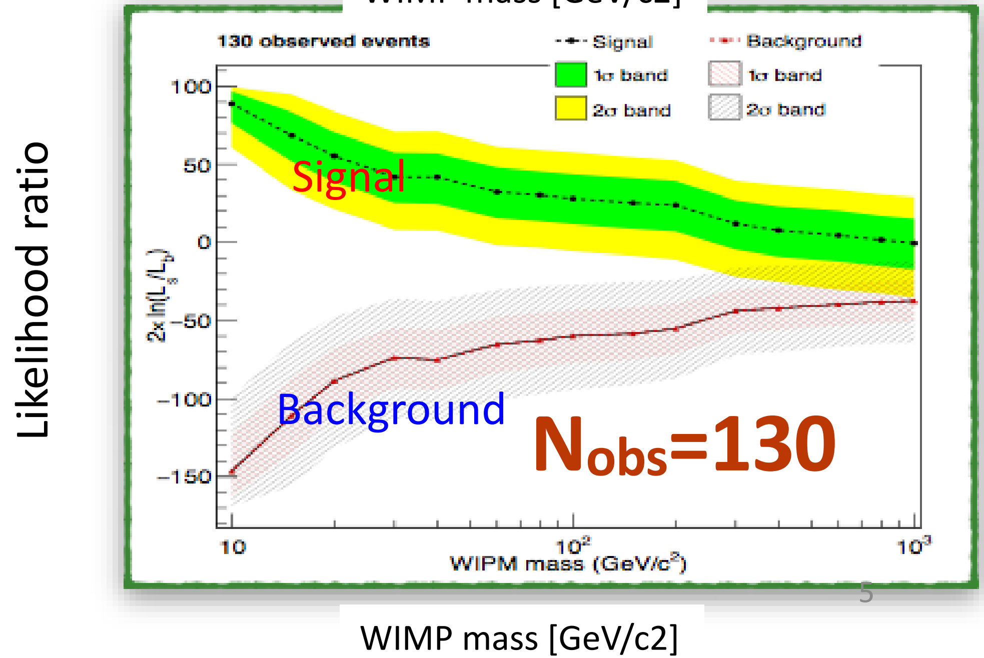
set of observables



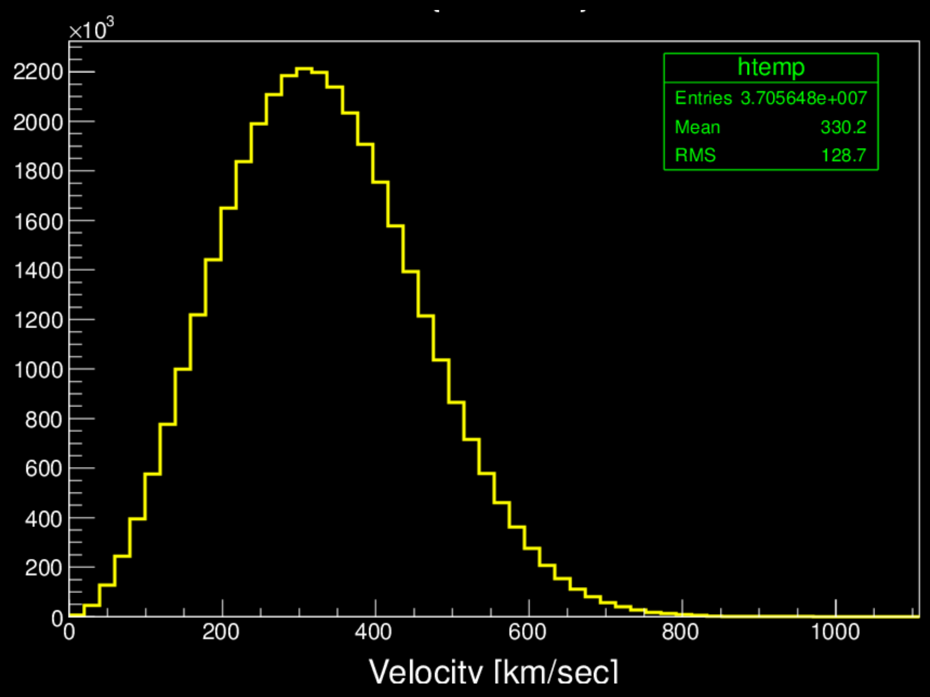
Direction information : Several 10 events

Gain of 100 times

Annual modulation : Several 1000 events



Velocity distribution



$$f(x) = \frac{1}{(\pi v_0{}^2)^{3/2}} \exp(-(v + vE)^2 / v_0{}^2$$

v_0: velocity of the solar system
v_E: Earth's velocity relative to DM

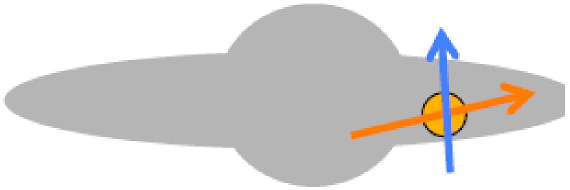
- ☐ Dark mater interaction with gas or something is negligible to standard matter interaction each other.
- ☐ Dark matters are distributing as thermal equilibrium

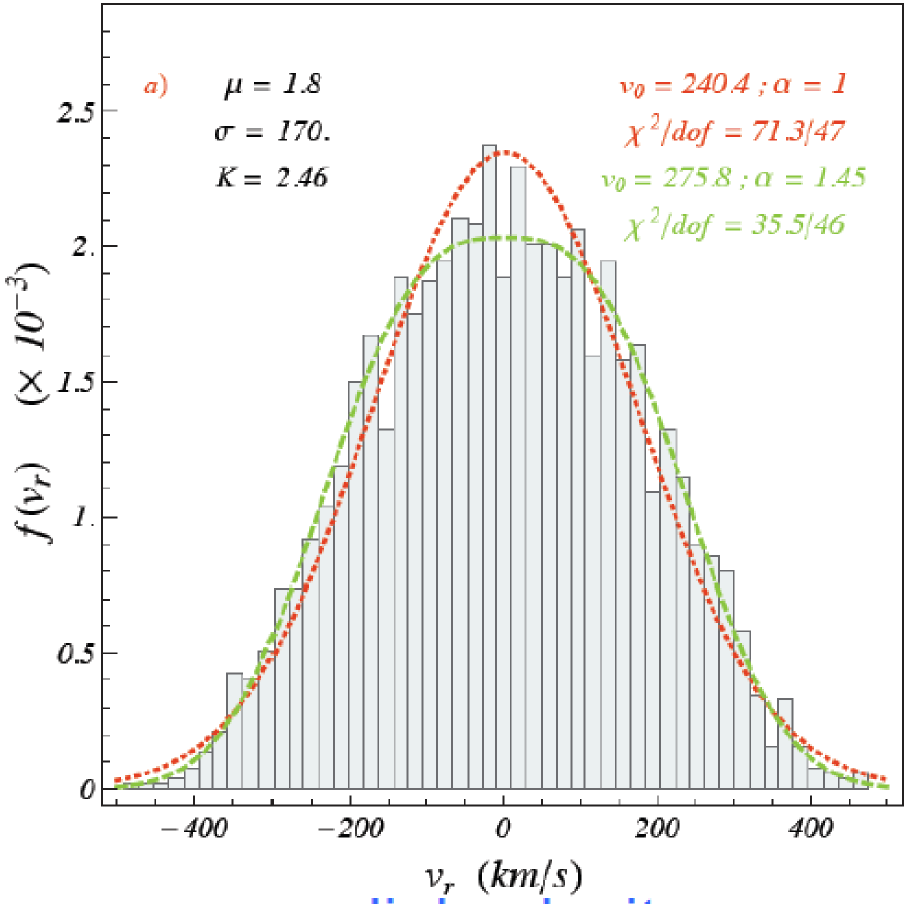
<u>Maxwell distribution</u>

It's big assumption for local scale

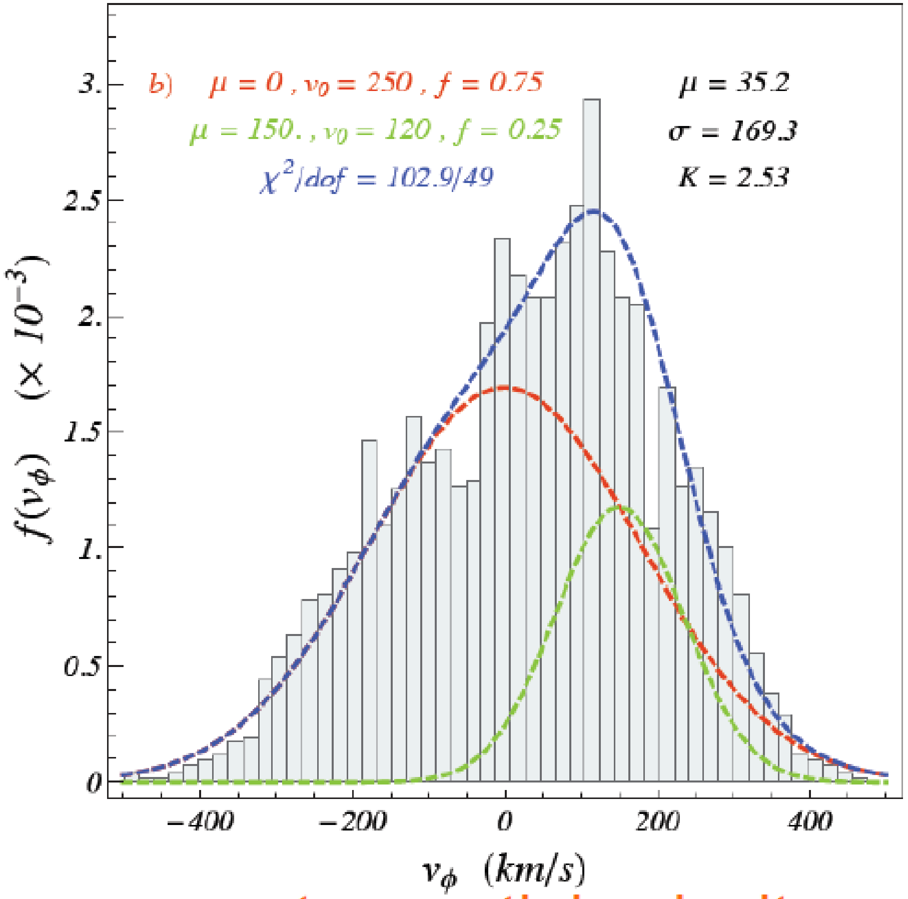
N-body simulation including baryons and gas

- DM co-rotates with baryons in the galaxy.
- Anisotropic distribution





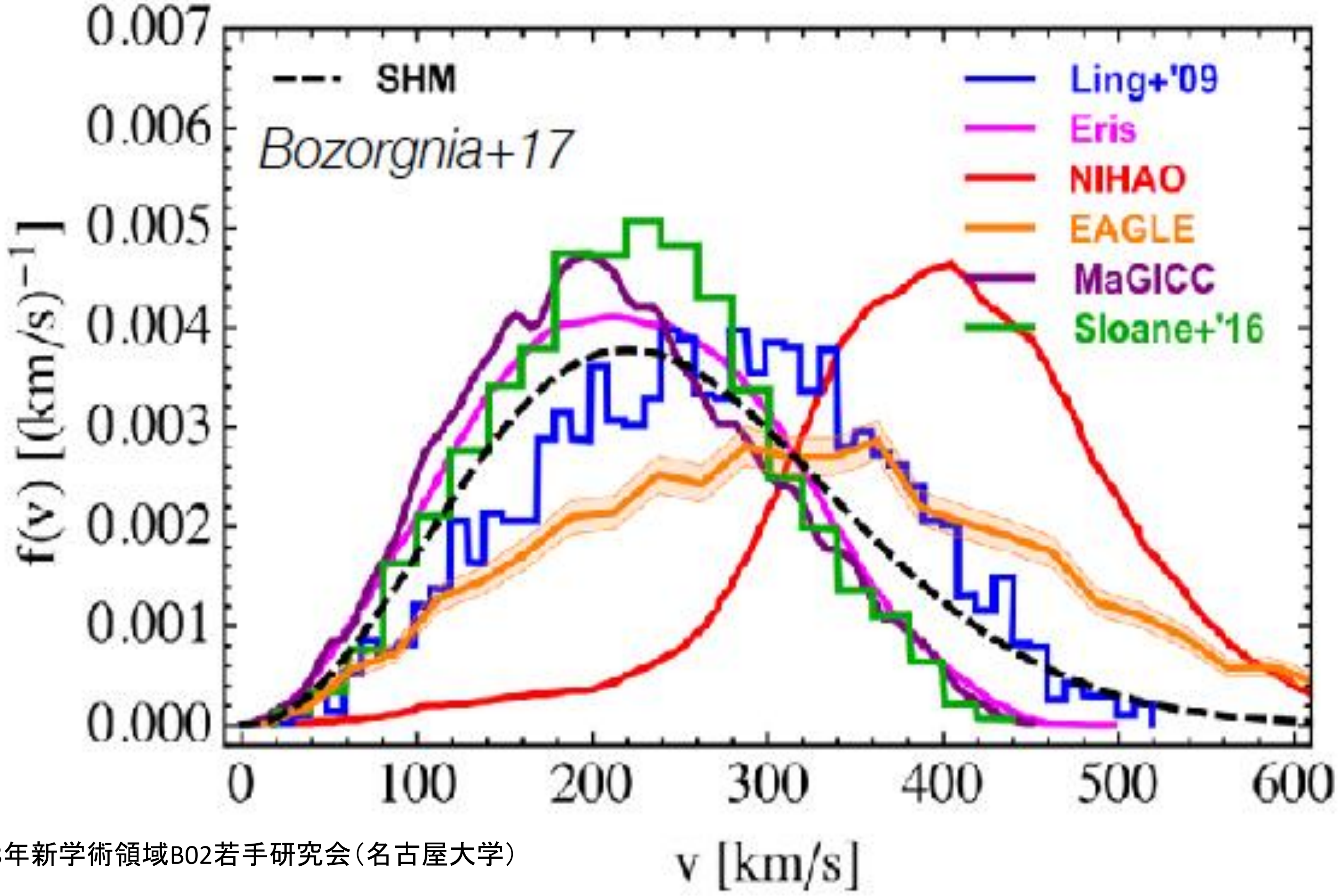
radial velocity



tangential velocity

Ling, Nezri, Athanassoula & Teyssier (2009)

- Variation among research groups (simulation codes).



Slide from S. Masaki @ 2018年新学術領域B02若手研究会（名古屋大学）

- Definition/choice of MW-like galaxies?

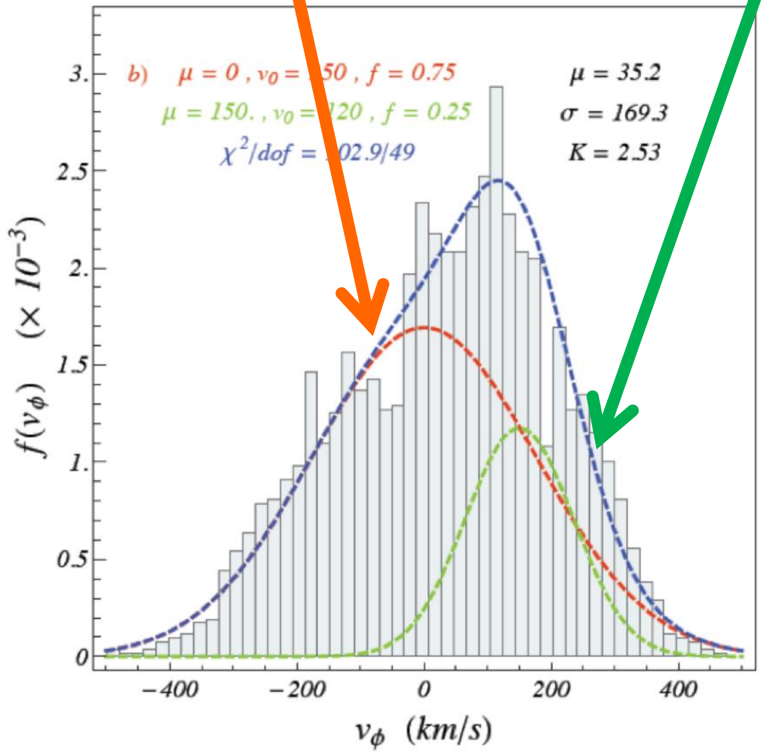
44

Potential of direction sensitive search

$$f(v_\phi) = \frac{1-r}{N(v_{0,\mathrm{iso.}})}\exp\left[-v^2/v_{0,\mathrm{iso.}}^2\right] + \frac{r}{N(v_{0,\mathrm{ani.}})}\exp\left[-(v-\mu)^2/v_{0,\mathrm{ani.}}^2\right]$$

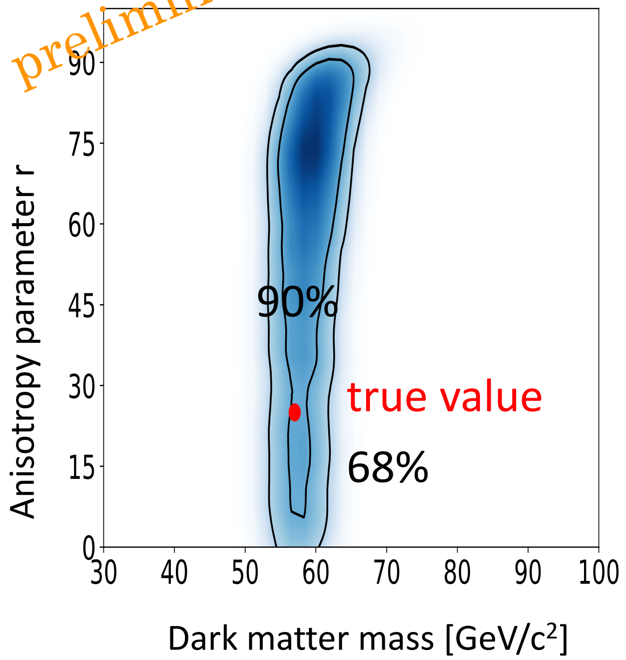
isotropic

anisotropic

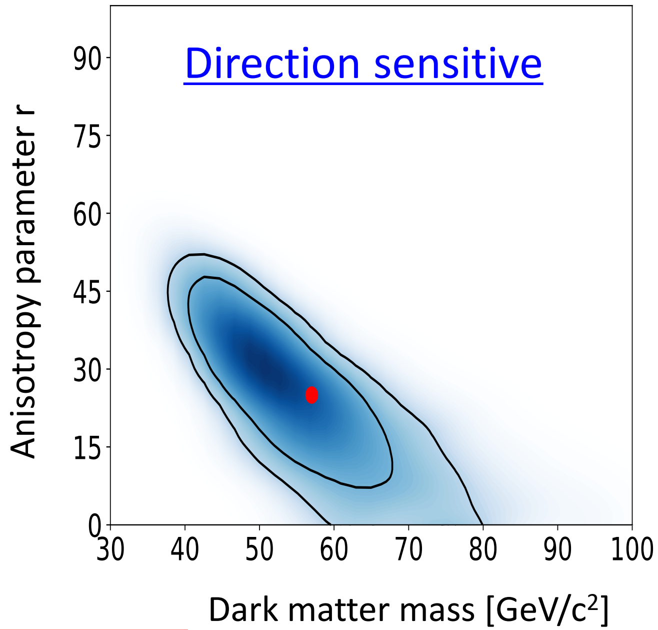


Likelihood Study

ER only



cos only

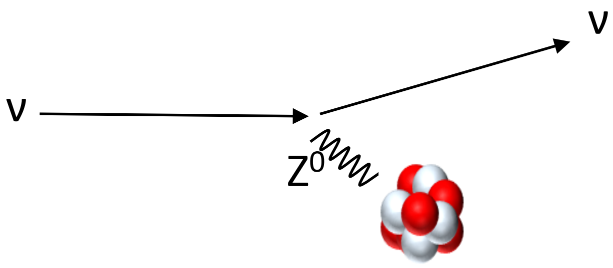


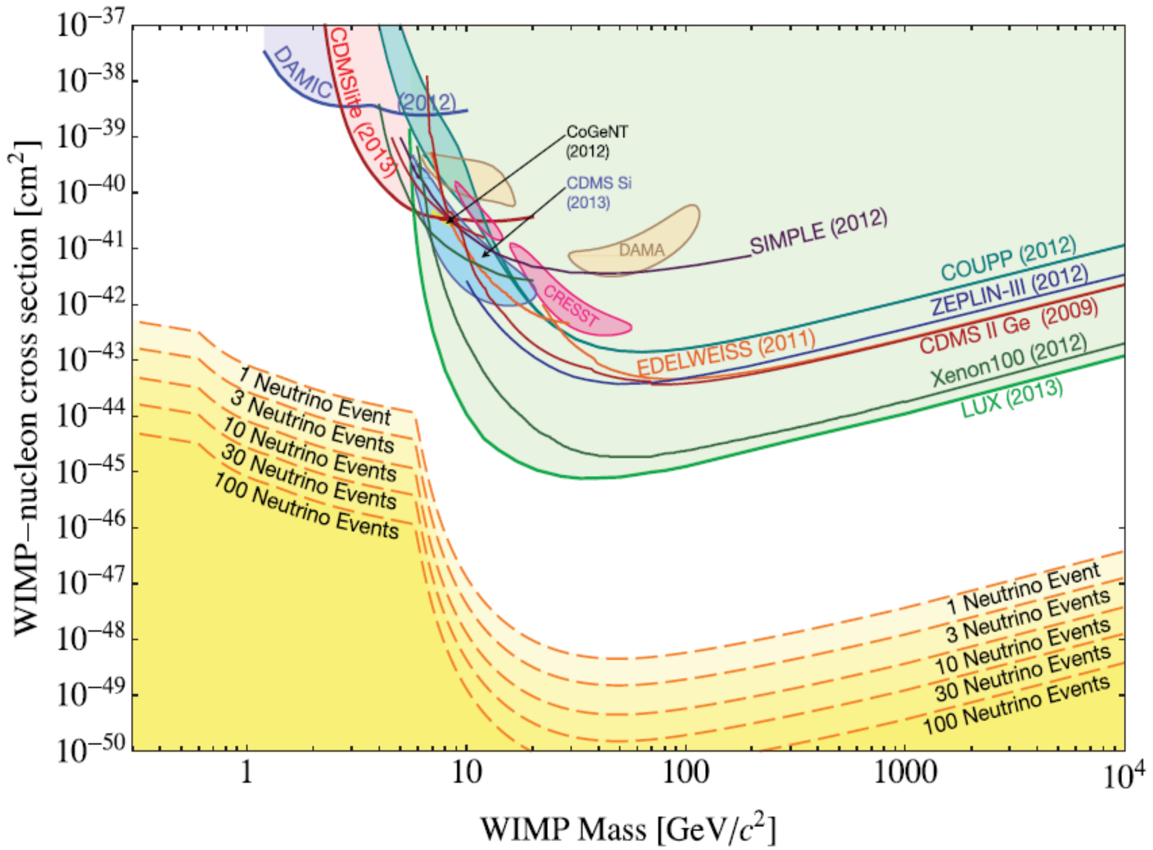
Ethr=50keV (F)
M_{dm}=60GeV
#event: 1000

K. Nagao, H. Ikeda, K. Miuchi and TN

cf. Samuel K. Lee and, Annika H.G. Peter, arXiv:1202.5035

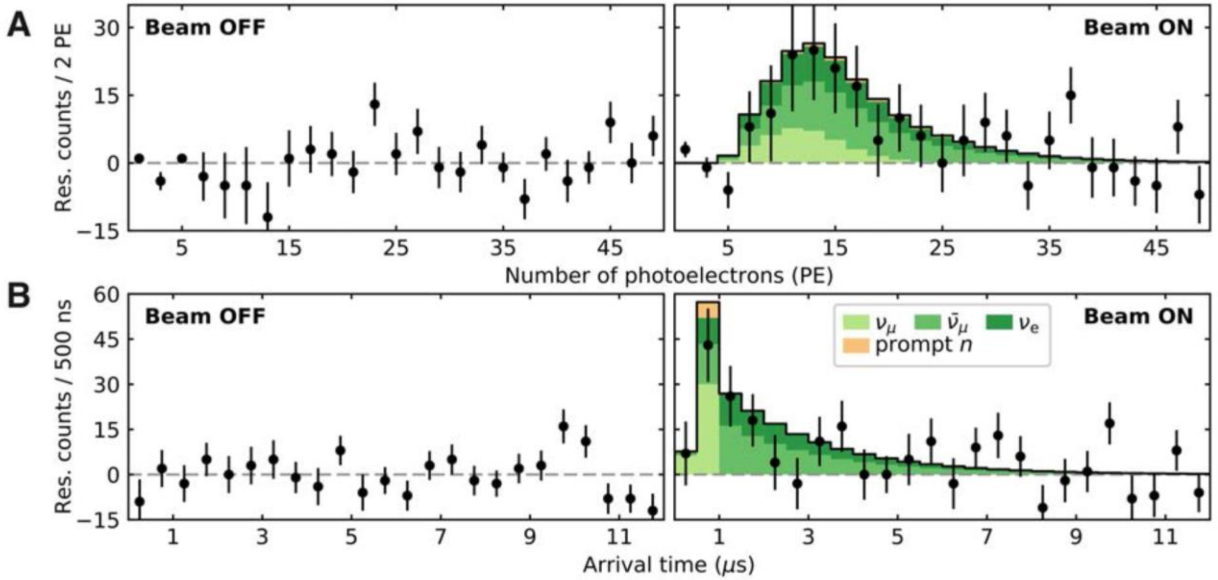
Neutrino coherent scattering





PRD 89, 023524 (2014)

Observation of COHERENT detector by Spallation neutron source (SNS) @Oak Ridge National Laboratory



<u>14.6 kg CsI scintillator</u>

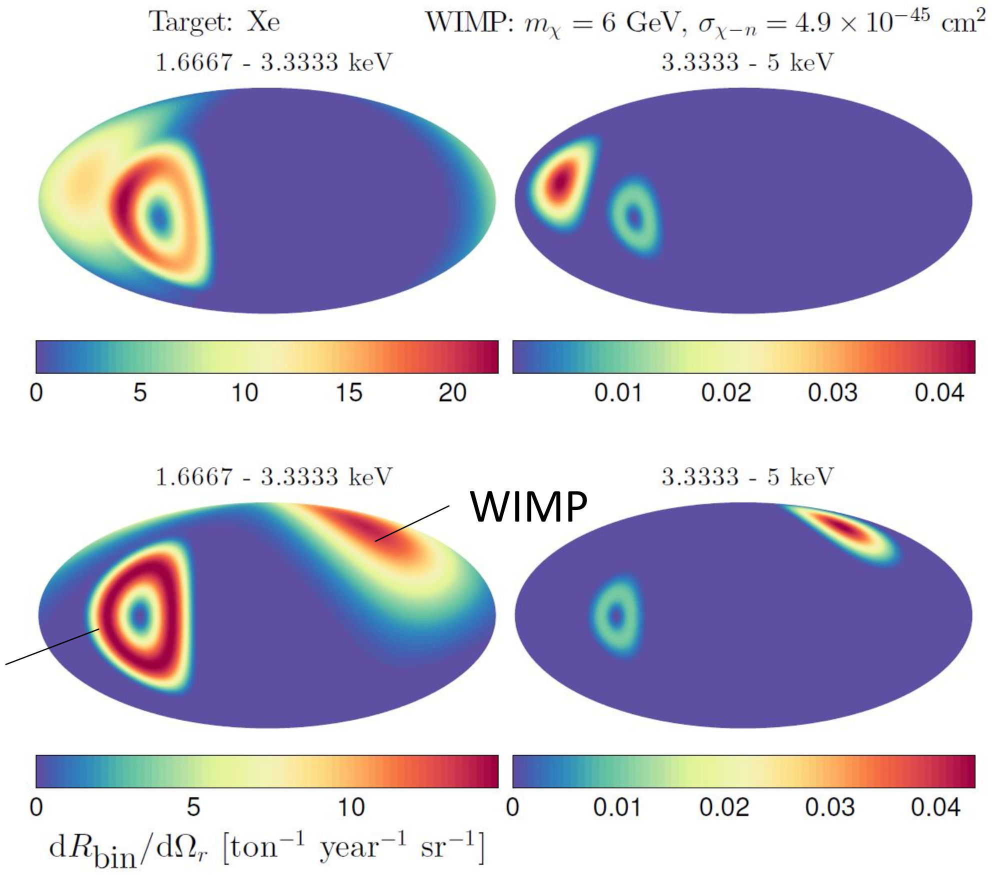
134 +- 22 events observed

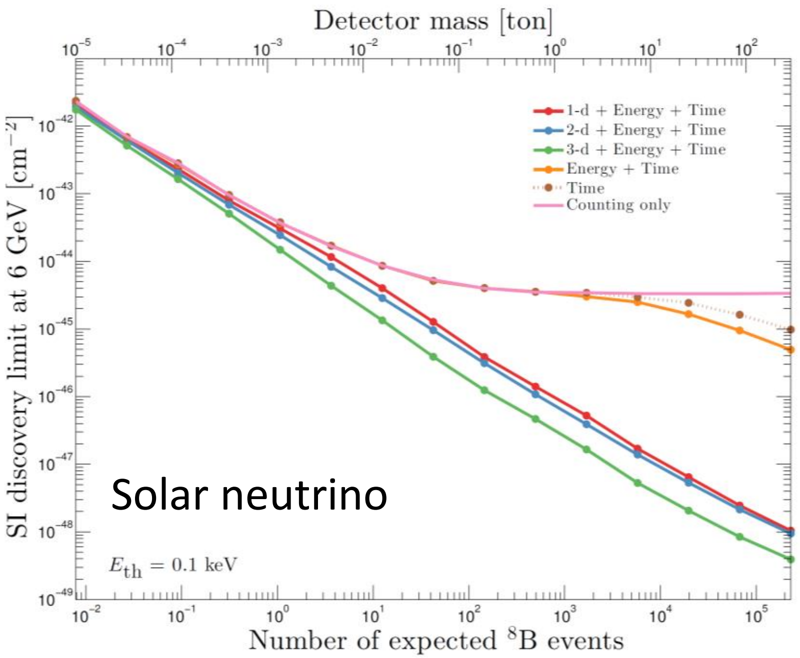
(173 +- 48 predicted)

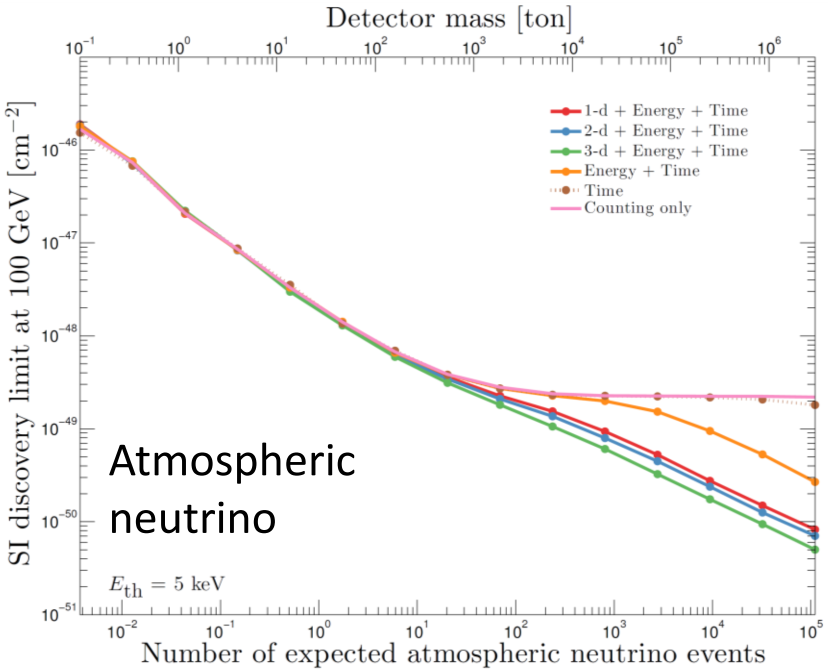
Profile Likelifood fit → 6.7σ

Science 15 Sep 2017:
Vol. 357, Issue 6356, pp. 1123-1126

Over the neutrino floor







Target : Xe
Er : 0 – 5 keV
WIMP mass : 6 GeV/c^2
Cross section : 4.9 x 10^{-45} cm^2
Case of ^{8}B neutrino

Angle difference between WIMP and solar neutrino : 60 – 120 °

Ciaran A. J. O'Hare *et al.*,
Phys. Rev. D 92, 063518 (2015)

Technologies for direction sensitive detectors

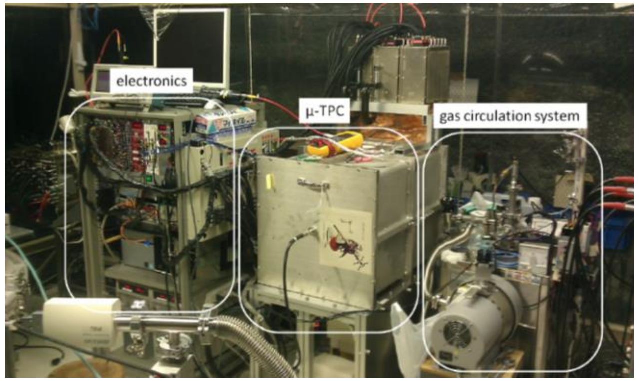
	Gaseous detector	Solid detector
Track length	0.1 – 1 mm	0.1 – 1 μm
Difficulties	Poor target mass Diffusion of drift electrons	Readout technologies Understanding of BG
Angular resolution	Several 10 °	Several 10 °

Current experimental effort

Gaseous TPC

- **DRIFT**
- **NEWAGE**
- **DM-TPC**
- **MIMAC**
- **D^3**

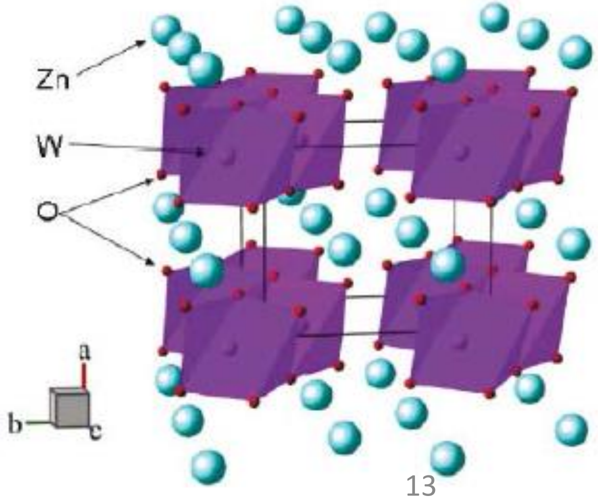
and some R&D project



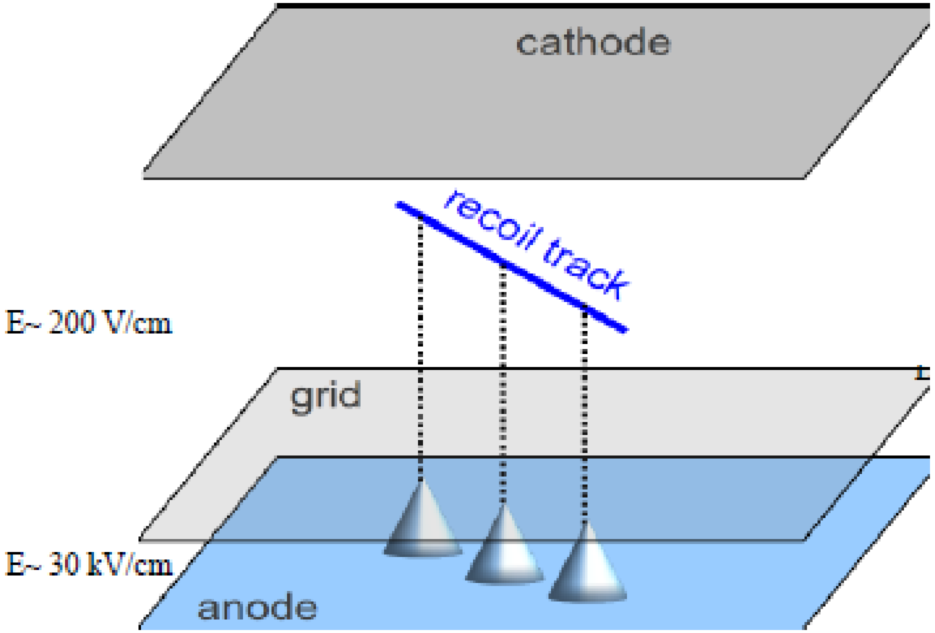
Solid detector

- **NEWSdm (fine-grained nuclear emulsions)**

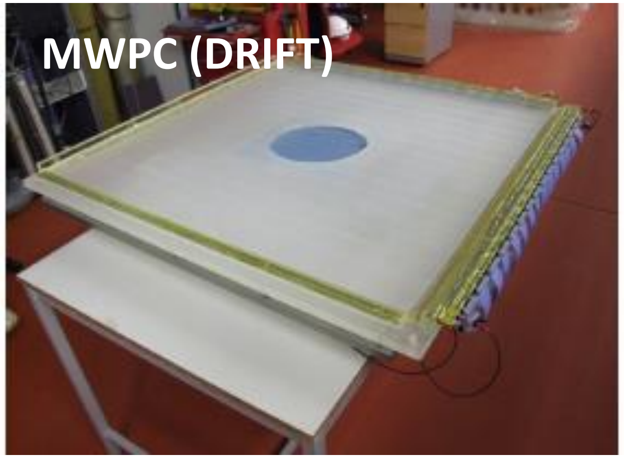
- **ZnWO4 scintillator**

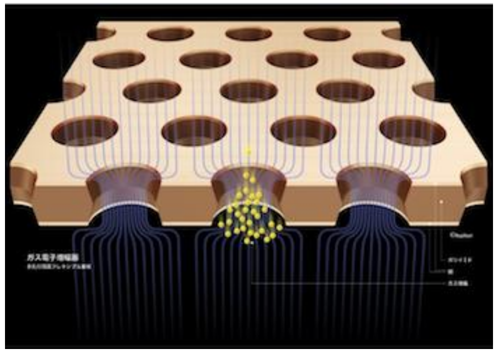


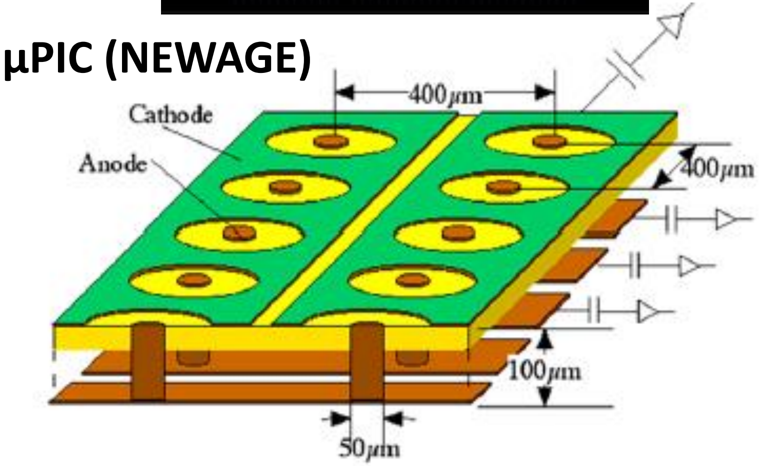
Gaseous TPC



Gas pressure : ~ 0.1 atm
Readout : drifted electron and each readout technologies
Target : C, F, S, He





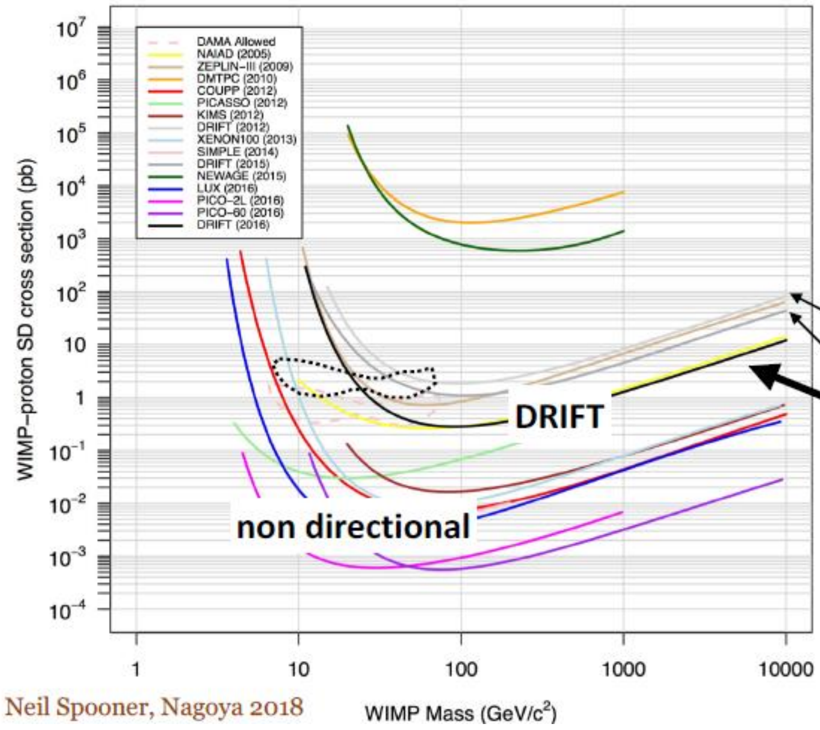


	Readout	Target
DRIFT	MWPC	CS_2, CF_4
NEWAGE	μPIC	CF_4 , SF_6
MIMAC	Micromegas	CF_4, C_6H_{10}
D^3	ATRAS Pixel chips	$He+CO_2$, SF_6

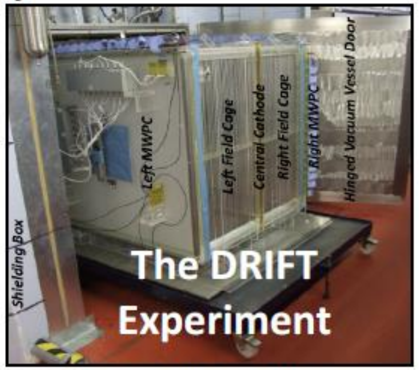
Spin-dependent directional search limit with Gaseous detector

The DRIFT TPC (~1.5D wires)

- 1m³ negative ion (CS_2:CF_4:O_2), 3D fiducialised, zero background
- First result in “DAMA Region” with directionality
- US-UK collaboration at Boulby



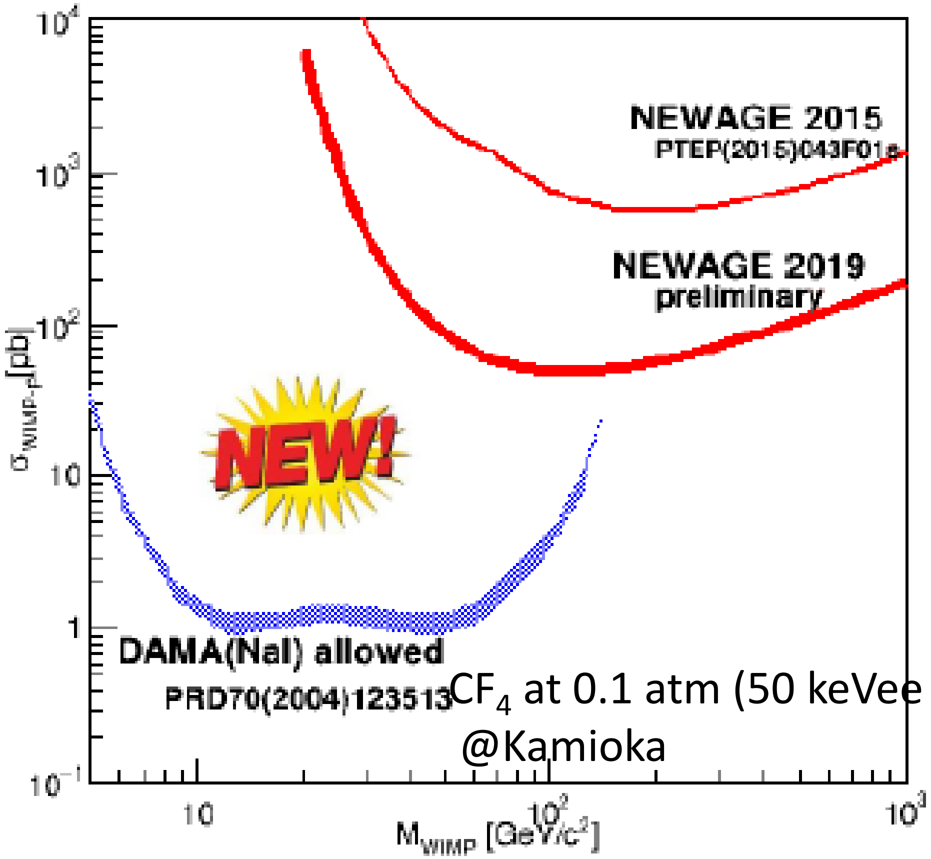
Neil Spooner, Nagoya 2018



arXiv: 1010.3027
arXiv: 1410.7821
arXiv: 1701.00171

(31 gram F, 40 Torr, ~50 days, zero background)
Astroparticle Physics 91 (2017) 65–74

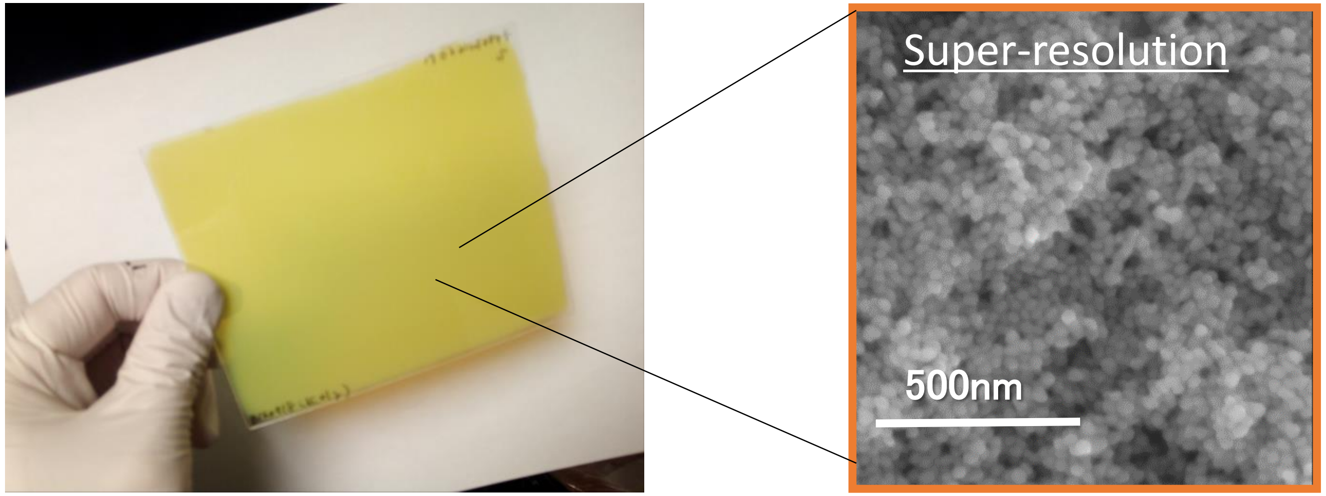
SD 90% C.L. directional upper limits

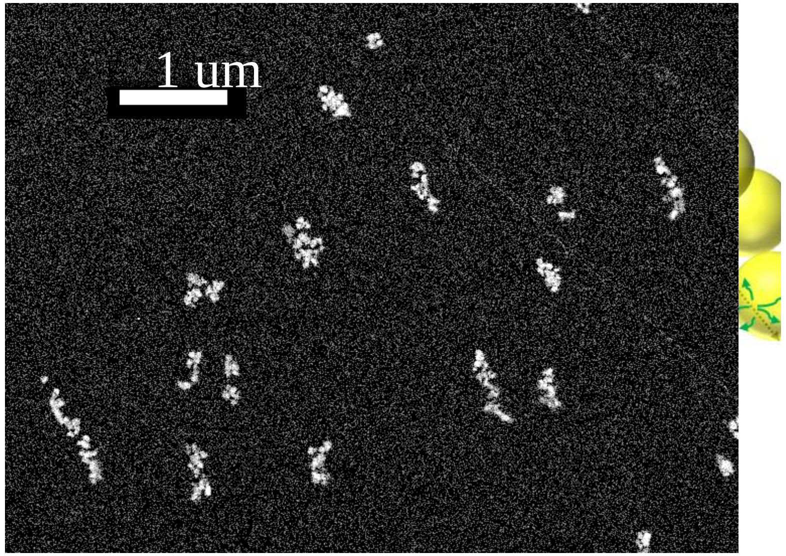


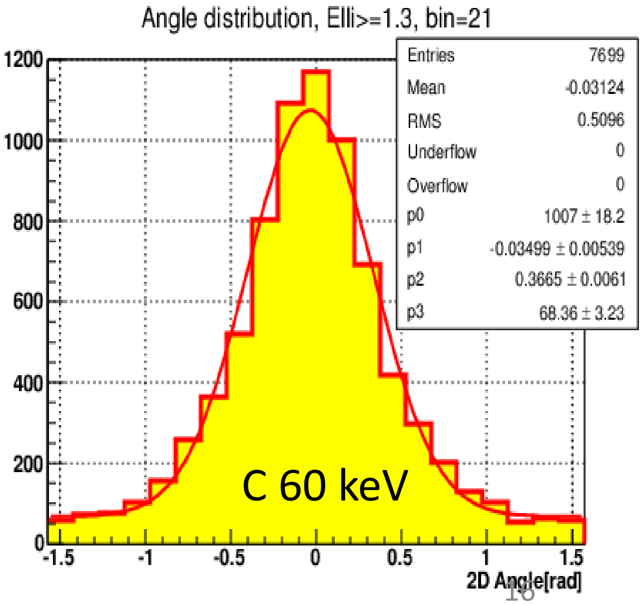
CF_4 at 0.1 atm (50 keVee threshold)
@Kamioka

新学術領域「宇宙の歴史をひも解く地下素核研究」2019領域研究会

NEWSdm project with super-fine nuclear emusions



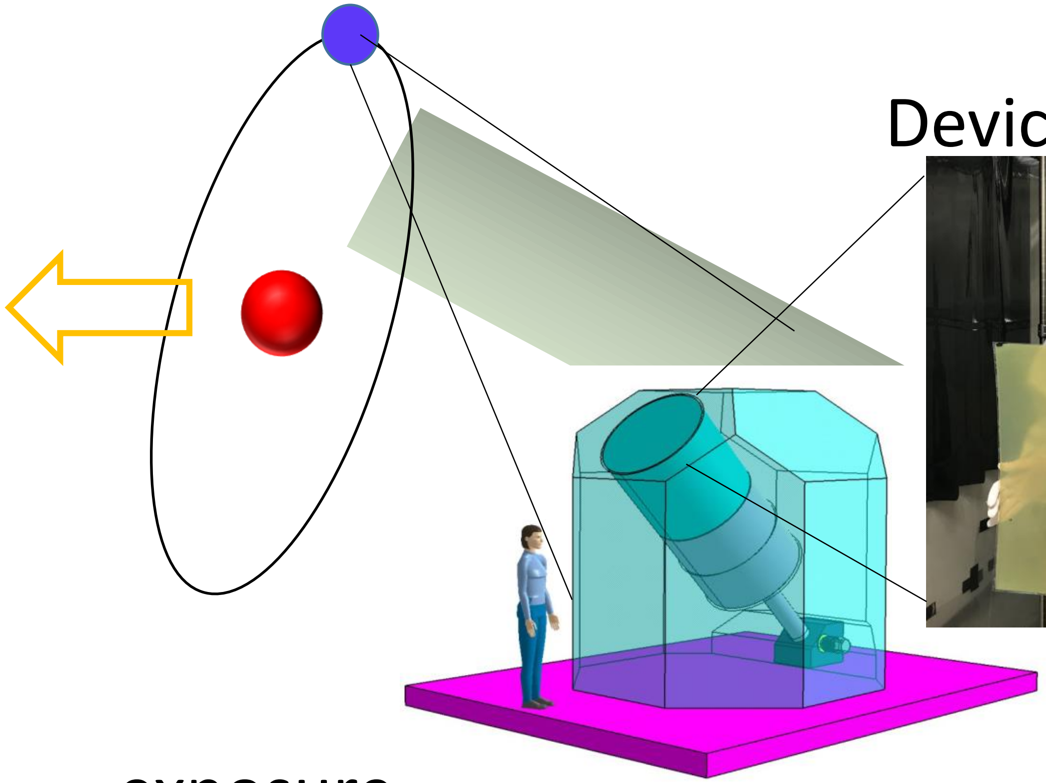


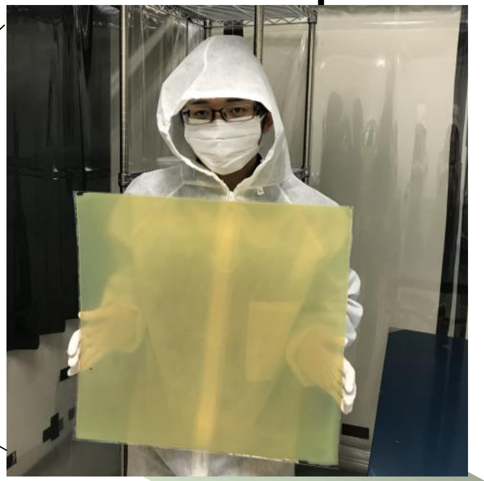


Detector : Super-resolution nuclear emulsions
Site : Grann Sasso Laboratory
Target : CNO (light DM) + ArBr (Heavy DM)
Readout : optical based microscope system

Concept of NEWSdm experiment

Device self-producti





exposure on the telescope

Surface laboratory

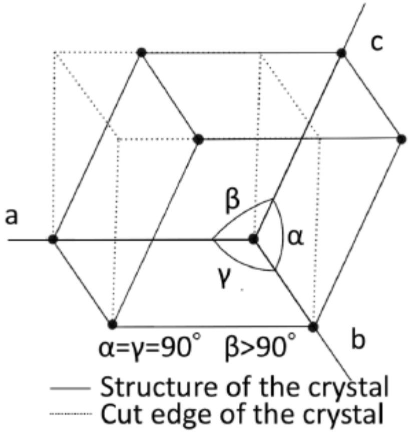
Chemical development treatment

Underground laboratory

Readout + analysis
Using microscope techniques

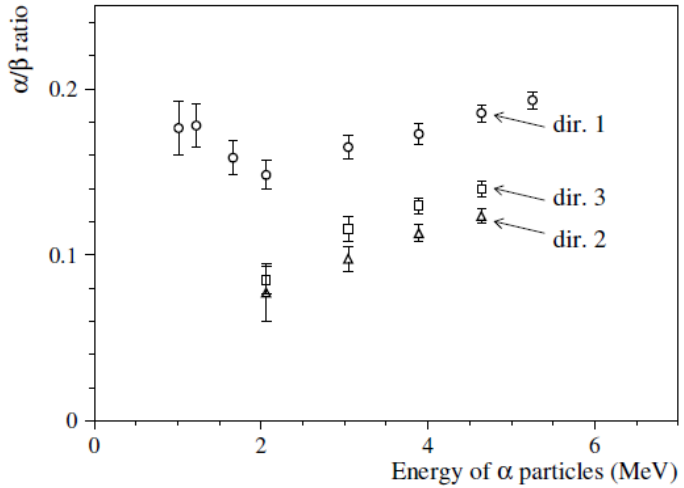
Anisotropic scintillator [$ZnWO_4$]

- 結晶構造
  単斜晶系



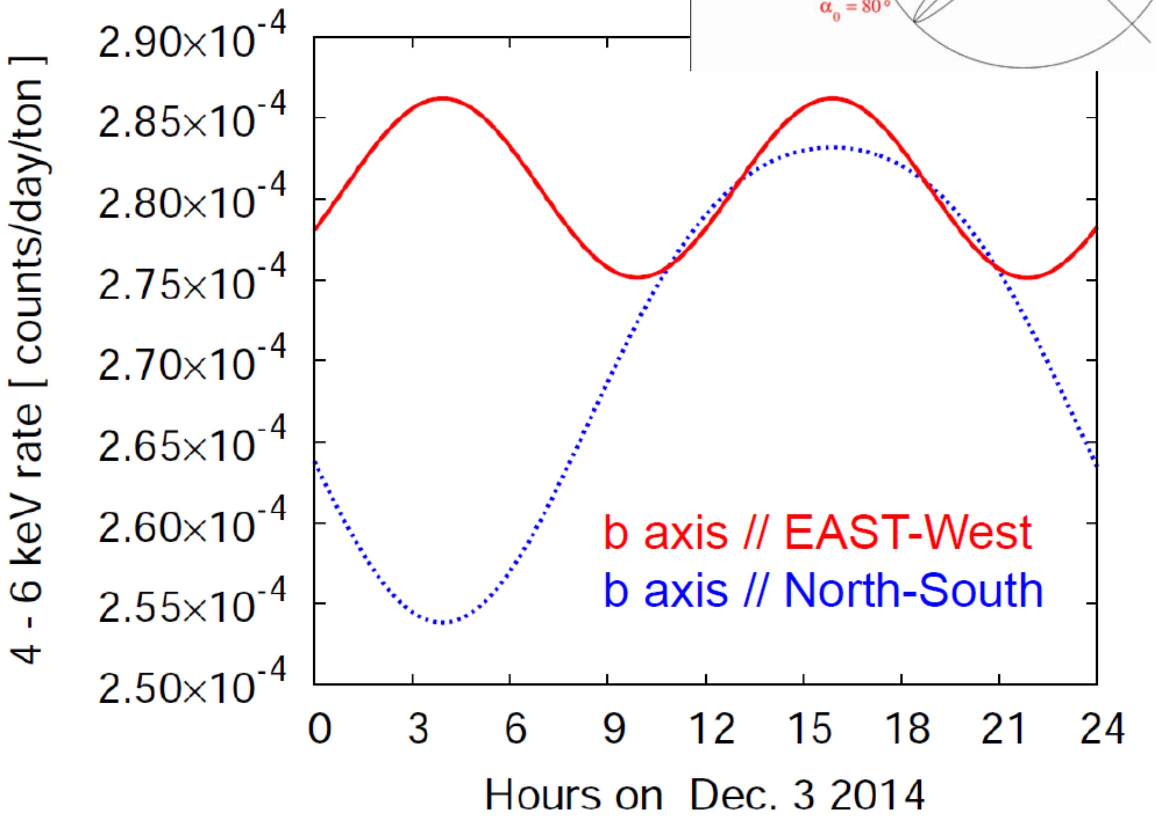
α[deg.]	β[deg.]	γ[deg.]
90.0000	90.6210	90.0000
a[Å]	b[Å]	c[Å]
4.96060	5.71820	4.92690

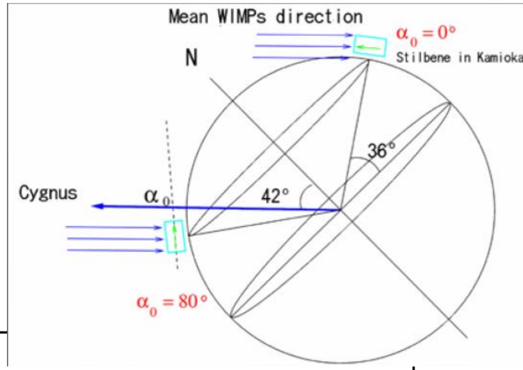
表 2.2 単位格子の長さおよび角度



<u>ADAMO group</u>
α/β比55% の異方性が
あることを報告

Eur. Phys. J. C (2013) 73:2276



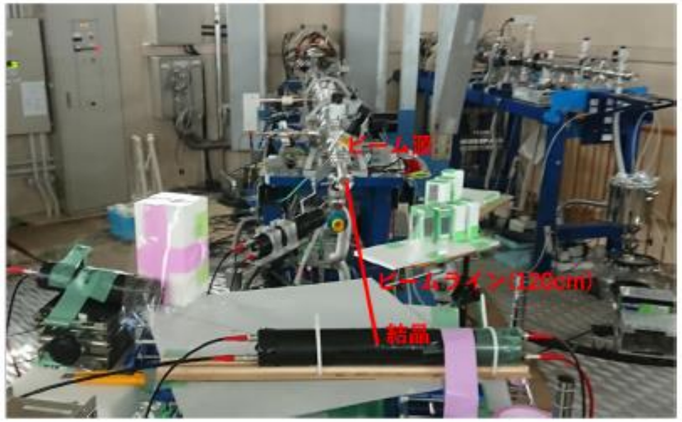


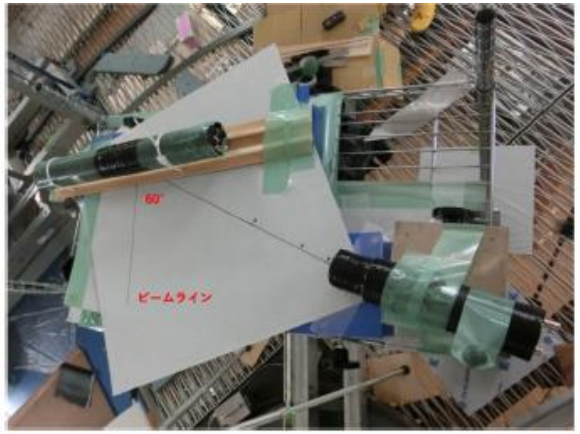
Assuming 7% anisotropy @5keVnr in ZnWO4
10^4 ton・day for 10^{-48} cm2 (neutrino floor)

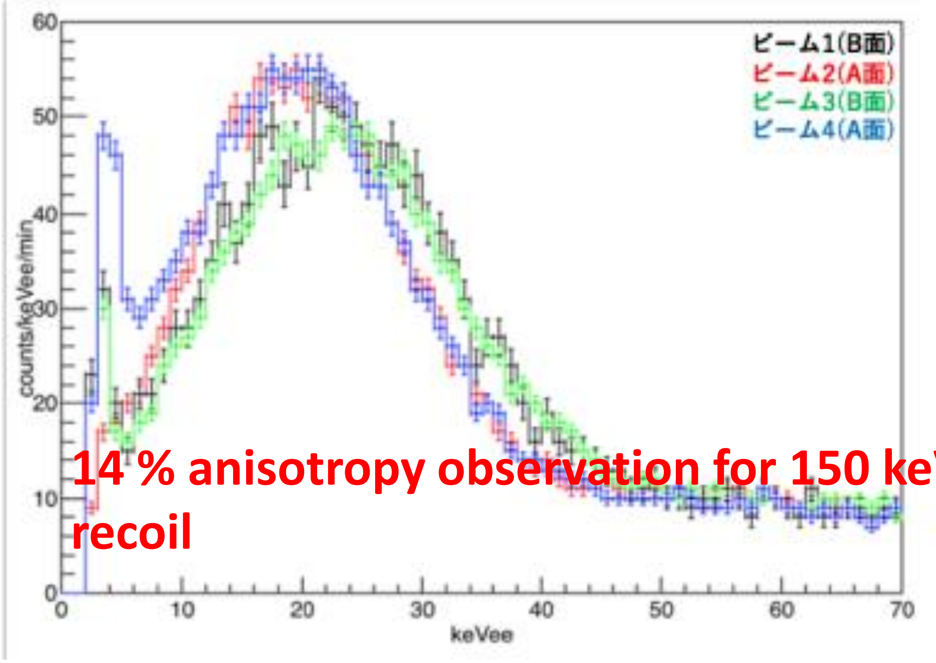
From 関谷洋之, JPS meeting 2017

Demonstration for anisotropic response

~ 880keV monochromatic neutron test @ AIST (T(p,n) reaction)

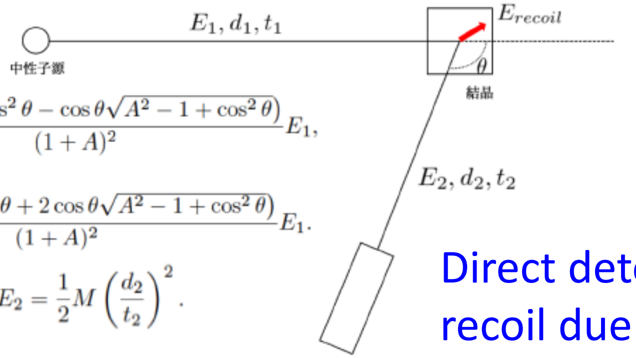






14 % anisotropy observation for 150 keV$_{nr}$ O recoil

- 中性子散乱の概要図



$$E_{recoil} = \frac{2\left(A+1-\cos^2\theta - \cos\theta\sqrt{A^2-1+\cos^2\theta}\right)}{(1+A)^2}E_1,$$

$$E_2 = \frac{\left(A^2-1+2\cos^2\theta + 2\cos\theta\sqrt{A^2-1+\cos^2\theta}\right)}{(1+A)^2}E_1.$$

$$E_1 = \frac{1}{2}M\left(\frac{d_1}{t_1}\right)^2, \quad E_2 = \frac{1}{2}M\left(\frac{d_2}{t_2}\right)^2.$$

Direct detection of nuclear recoil due to neutron by TOF

中性子源～結晶、結晶～散乱後の検出器のTOFと$E_{visible}$を測定することでクエンチングファクターを算出できる

ビーム	照射面	クエンチングファクター	Q_3 に対する相対値の比率
ビーム 1	B 面	0.150 ± 0.003	0.000
ビーム 2	A 面	0.129 ± 0.002	0.140
ビーム 3	B 面	0.150 ± 0.002	0.000
ビーム 4	A 面	0.129 ± 0.002	0.140

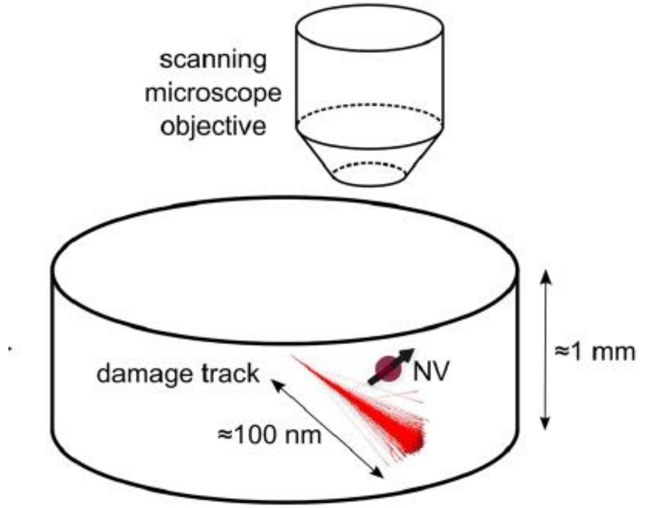
ピーダーセン珠杏氏のスライドより引用

New Idea

➢ Diamond

Microscope imaging of luminescence due to N-V center in diamond

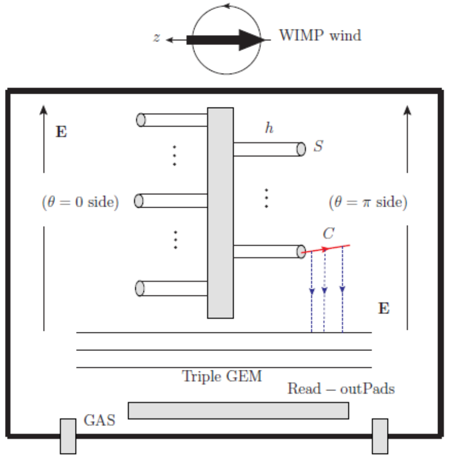
Phys. Rev. D. 96 035009 (2017)



➢ Carbon nano tube

Carbon nanotube target + gaseous TPC

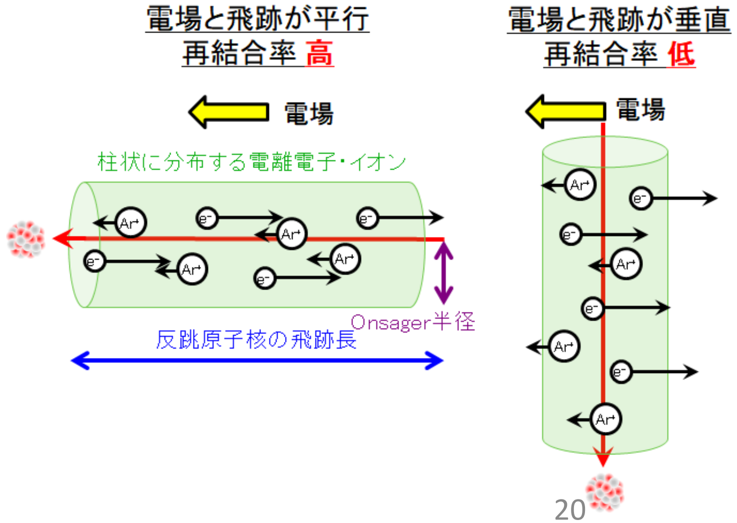
arXiv:1412.8213 [physics.ins-det]



➢ Columnar recombination with high pressure gas

Dependence of Recombination efficiency on direction between nuclear recoil and drift field

J. Phys. Conf. Ser. 460, 012006 (2013).



Conclusion

- Anisotropic flux of dark matter on the earth is expected, and it's sound information for direct dark matter detection if we can obtain that.

- Direction information give strong and high reliable evidence for dark matter discovery and the properties.
  - essentially difference systematic from annual modulation
  - statistical gain for discovery
  - velocity distribution
  - beyond the neutrino floor

- Currently various experiment and technologies are studied and promoting

  <u>current actively effort</u>
  - gaseous TPC
  - fine-grained nuclear emulsion
  - ZnWO4 anisotropic scintillator

  <u>new idea and feasibility study</u>
  - Diamond, carbon nano-tube, high pressure Xe with colamner recombination