Toho University

Discussion of experimental approach to go beyond the neutrino floor in the WIMP search

Tatsuhiro NAKA
Toho University

2019.11.11-13 (talk on 11^{th}) "Dark Matter Searches in the 2020s", U. of Tokyo

Dark Matter in our galaxy

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

Center of galaxy

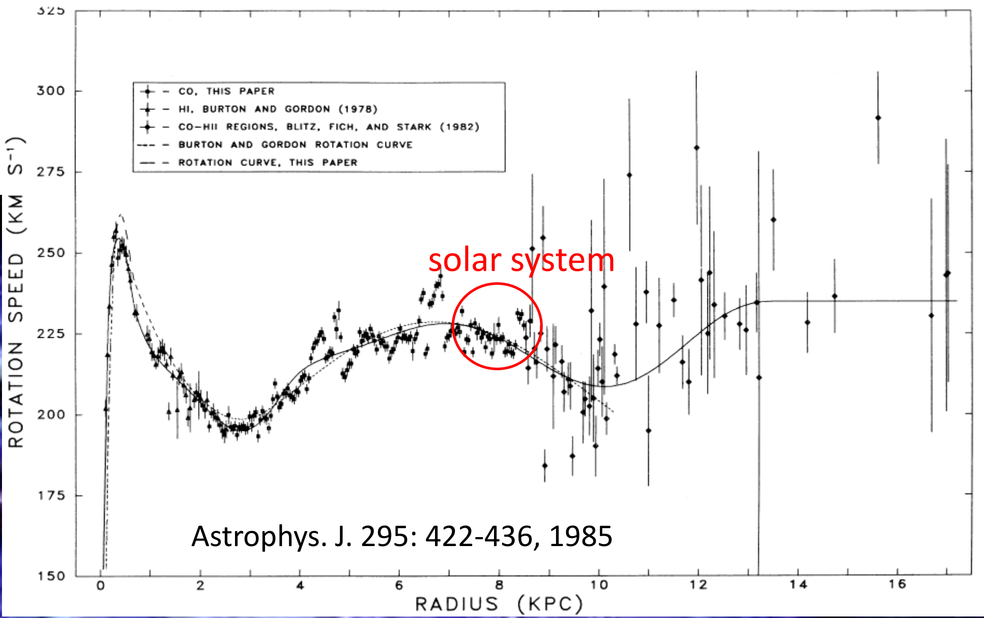
- ✓ Independent value on dark matter model
- ✓ Very much mount of DM is condensed in the halo because mean dark matter density in the universe is ~ 1.4 keV/cm^3 (27 % of critical density ratio)

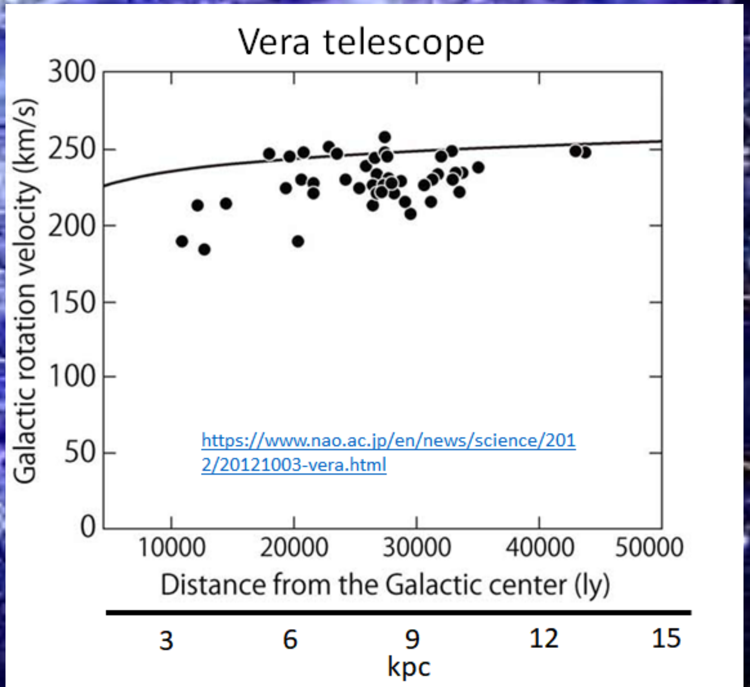
Dark matter flux on the earth

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

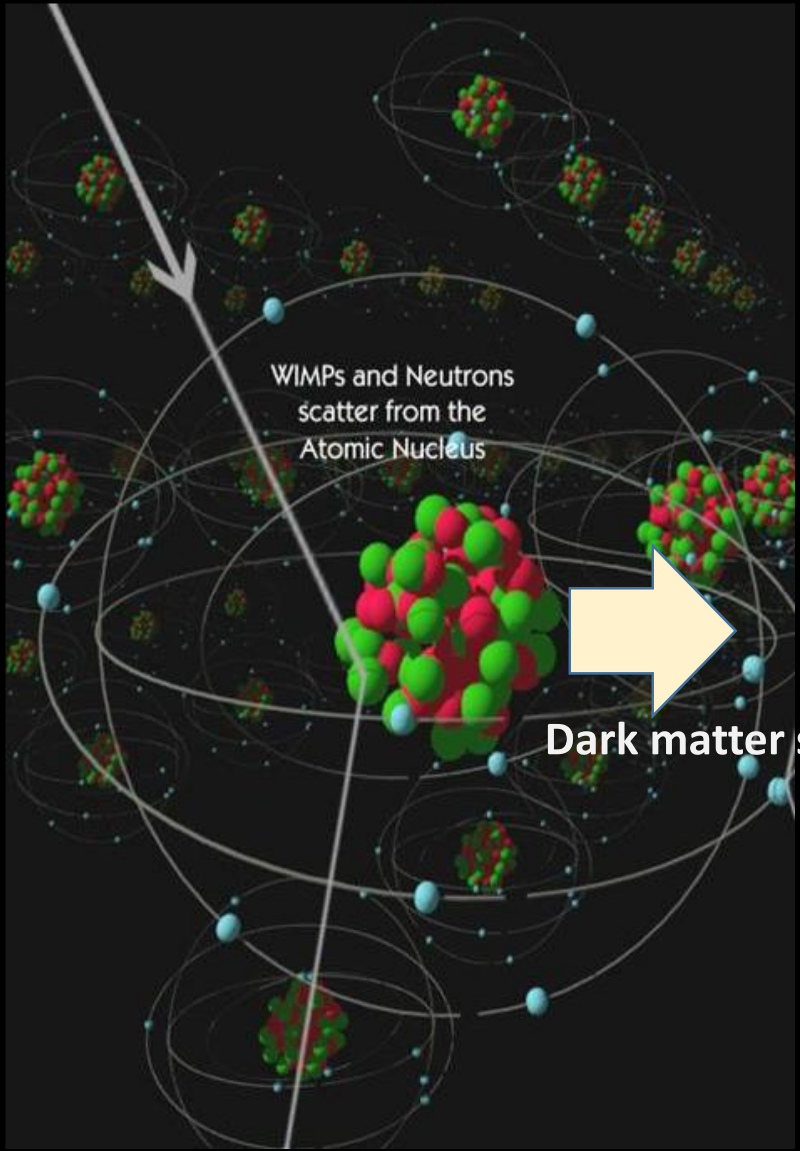
Solar system

Direct dark matter search !





WIMP dark matter interaction with target nuclei



Dark matter signals

Dark Matter velocity : O (100 km/sec)

↓

de Broglie wavelength scale

λ =h/p ~ 10 fm

Nucleus scale!

↓

Coherent scattering with nuclei

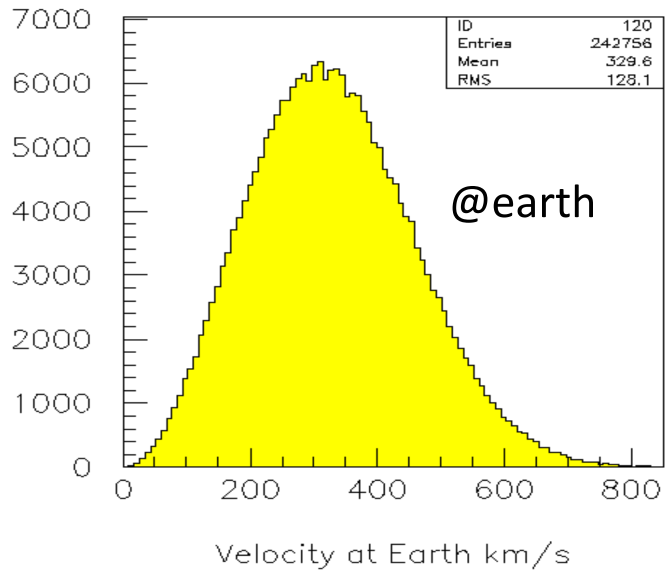
Energy spectrum for coherent scattering

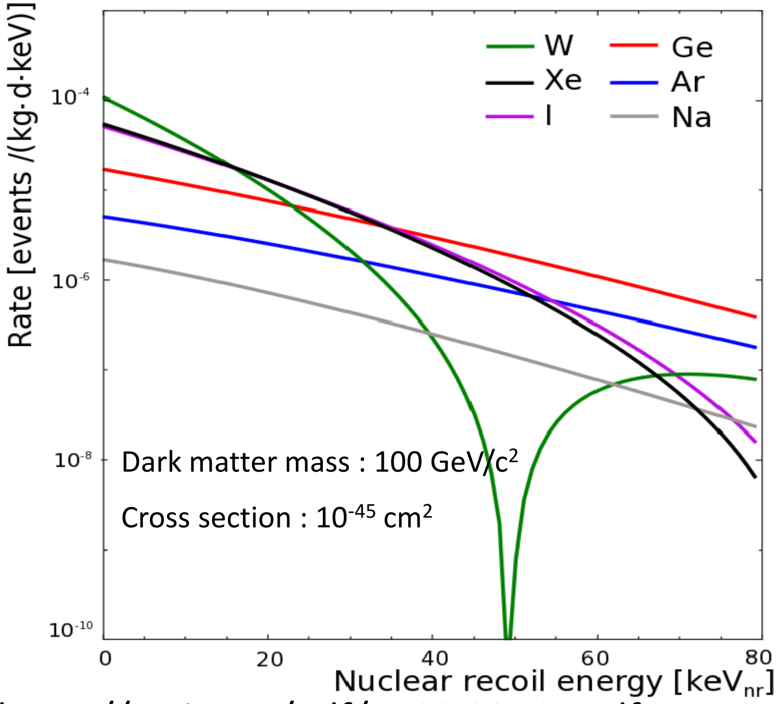
Particle and nuclear physics nature

Astrophysics input

$$\frac{dR}{dE_R} = \frac{A^2 \sigma_{\chi-n} F^2(E_R)}{2M_\chi \mu_{\chi n}} \rho_\chi \int_{v>v_{min}} \frac{f(\boldsymbol{v},t)}{v} d^3v\, \pi r^2$$

~ 0.4 GeV/cm^3





https://arxiv.org/pdf/1509.08767.pdf

- **< O(10-100) keV nuclear recoil energy**
- **Dependence on target nuclei (e.g., form factor, quenching effect and spectrum shape)**
- **Lower energy threshold to get larger number of events**

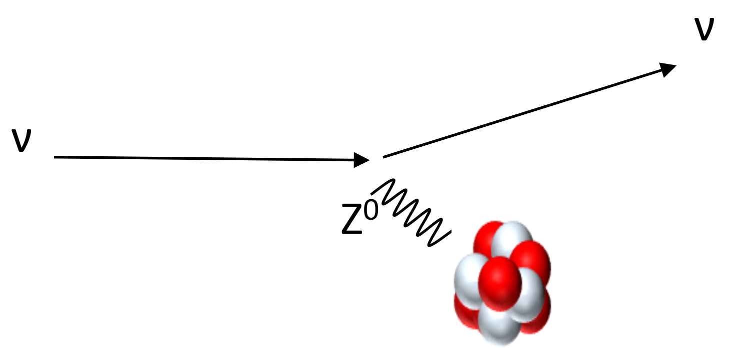
Observation of the signal depending on the motion of earth (e.g., annual modulation, diurnal modulation, direction)

Neutrino coherent scattering

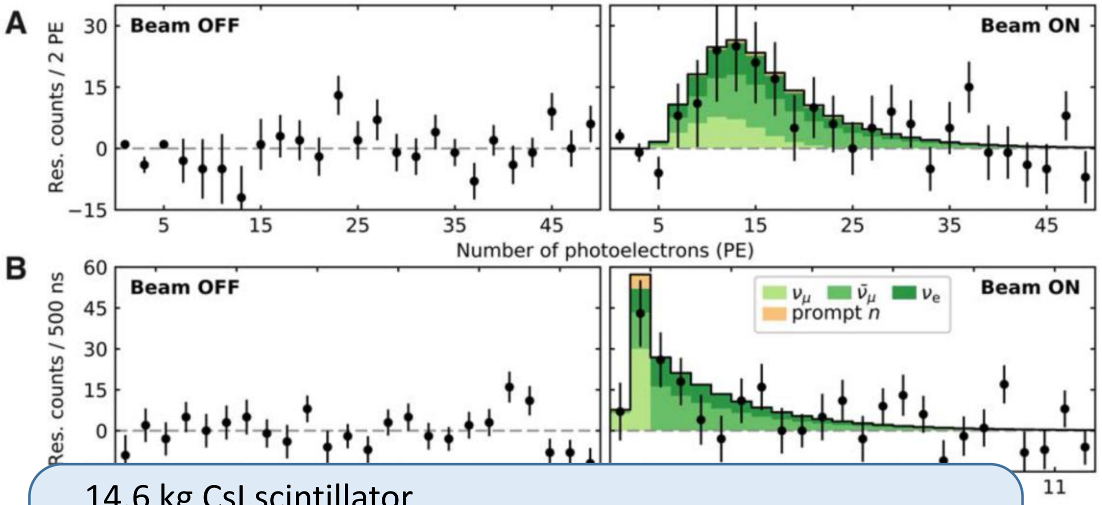
Neutrino coherent scattering is predicted in the standard model.

$$\frac{d\sigma}{dE_r} = \frac{G_F^2}{4\pi^2}(N - (1 - 4sin^2\theta_W)Z)^2 m_N(1 - \frac{m_N E_r}{2E_\nu^2})\pi r^2 F^2(E_r)$$

$\propto N^2$ N: number of neutrons



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

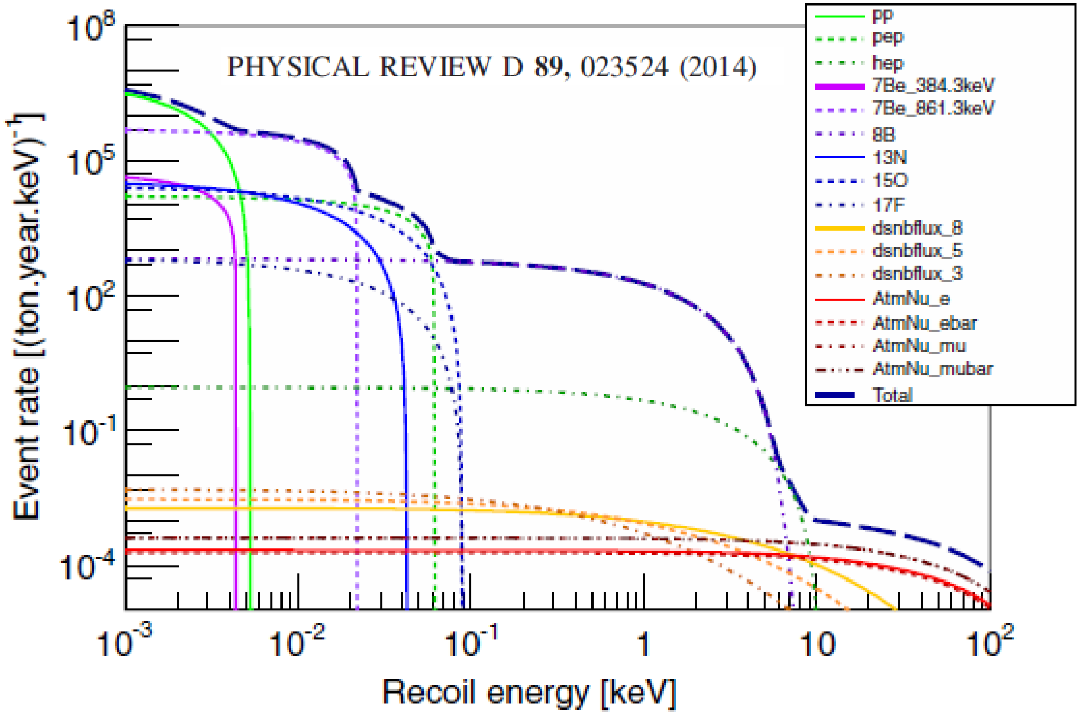


14.6 kg CsI scintillator

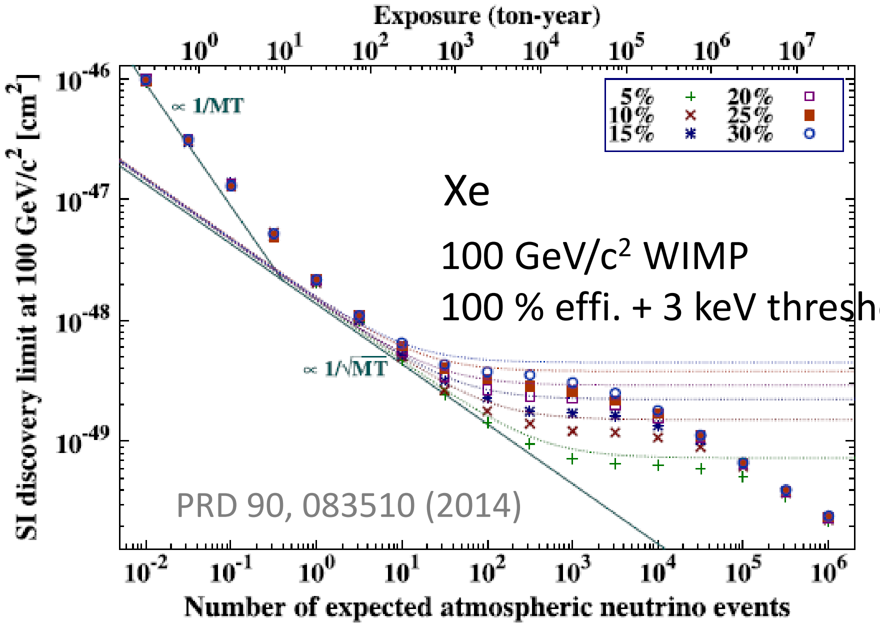
134 +- 22 events observed (173 +- 48 predicted)

Profile Likelifood fit → 6.7σ

Science 15 Sep 2017
Vol. 357, Issue 6356,



How can we distinguish the WIMP signal from CvNES backgrounds ?



☐ Energy spectrum

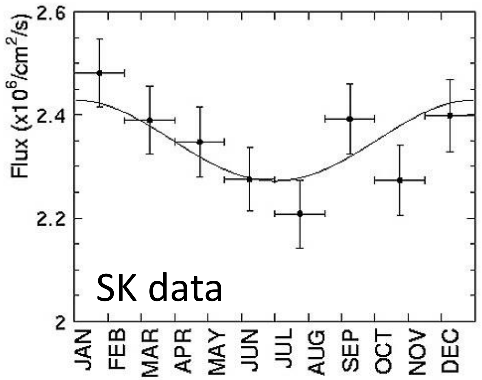
Difference is very few
⇒ very large exposure is needed (> 10^4 neutrino events)

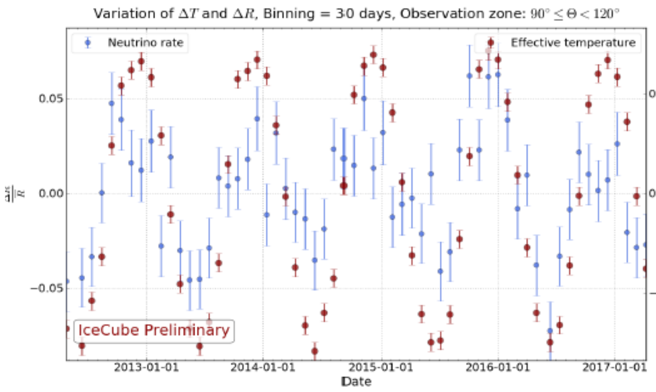
☐ Annual modulation

<u>Standard DM model : Jun. is maximum, and Dec. is minimum</u>

- Atom. Neutrino : June is max, and Dec. is min. on northern hem.
  ⇒ southern hem. Is opposite
- Solar neutrino : Jan. is max. and Jul. is minimum
  ⇒ opposite to DM

Variation is few %, and high statistics + long time exp. are needed





Ev > 100 GeV from air shower
IceCUBE
arXiv:1909.02036v1

☐ Direction Information

Direction information has more than 100 times higher statistical gain.

Advantage of direction information

☐Discovery potential

- Can be claimed with just several 10 events by angular distribution
- Diurnal modulation

☐Background Discrimination

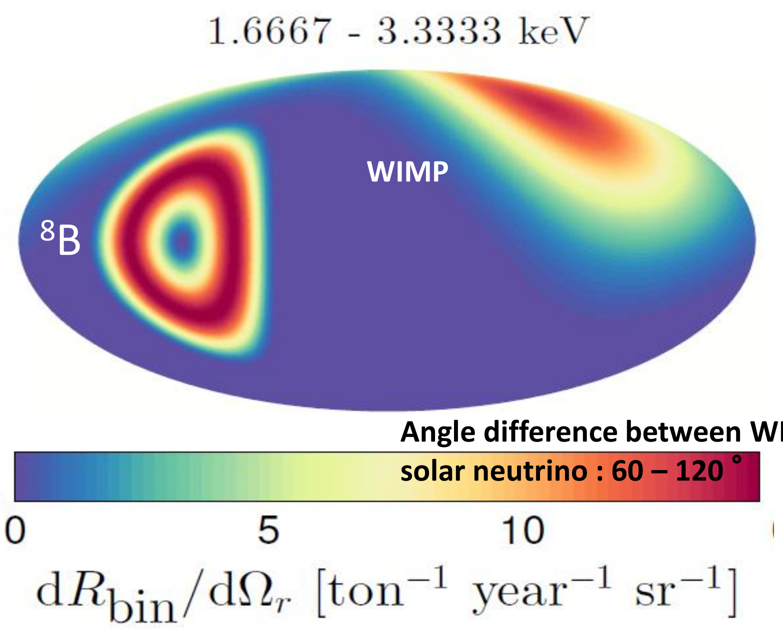
- Clear difference with neutrino direction
- No background with angular bias to solar system motion

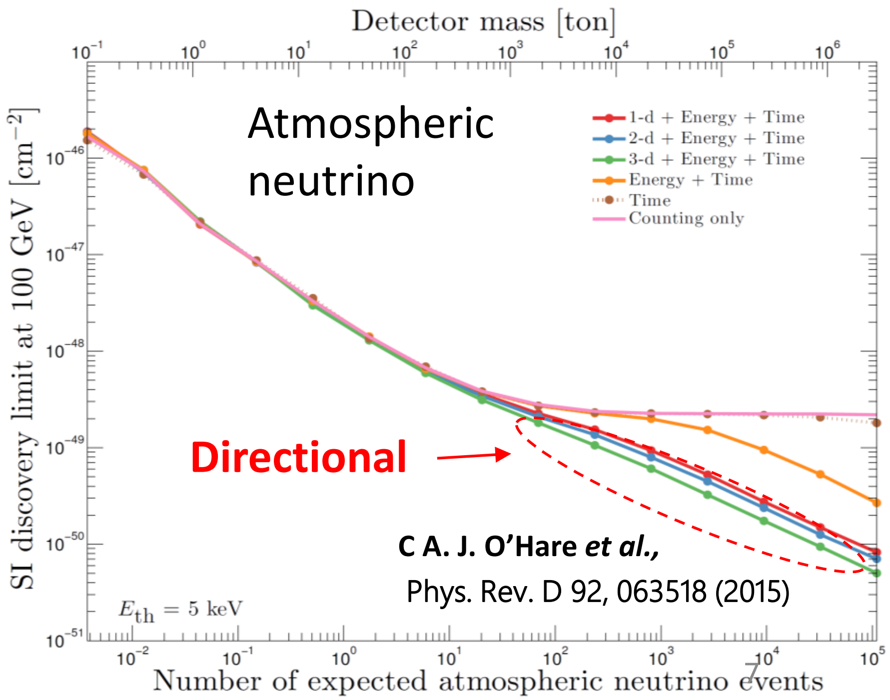
☐Dark matter astronomy

- Obtain the information about dark matter velocity distribution

"Direction" Information is very powerful !!

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



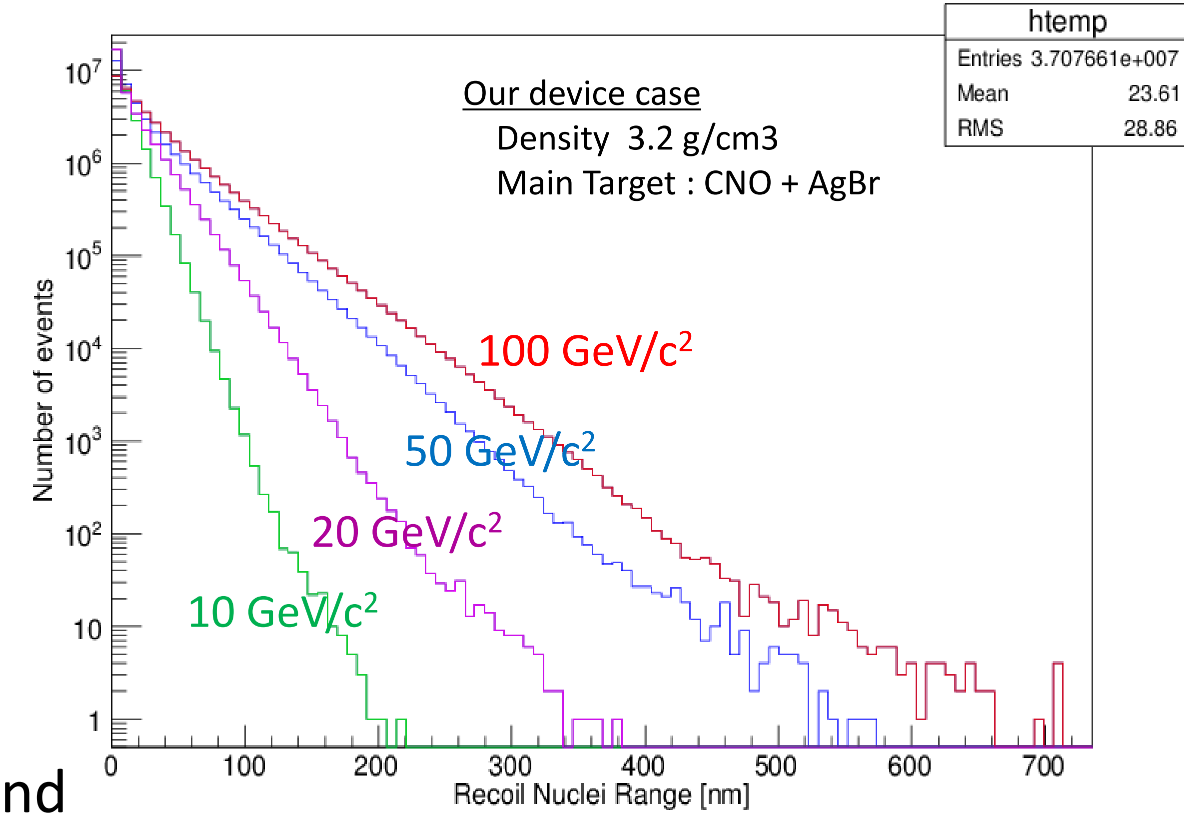


C A. J. O'Hare *et al.*,
Phys. Rev. D 92, 063518 (2015)

Technical Difficulties

Now, there are no feasible detectors possible to do ton scale experiment immediately .

- ➢ New technical challenge ; Obtaining the direction information in nm scale
- ➢ Not ensured the scalability and stability (production, cost, quality) for such new technologies
- ➢ Low-background or understanding the background



Current methodology

- Yellow: Demonstrated
- Light green: Idea or under demonstration

Method	**State**	**Detector**	**Target**
Direct tracking	Gas	Low press. Gaseous TPC	CF4, CS2, SF6 ・・・
	Gas / Solid	Carbon nano-tube + gas	
	Solid	Super-resolution nuclear emulsion	AgBr, C, N, O ・・
	Solid	Diamond + NV center	
Indirect direction information	Gas	High pressure gas + electric field effect	Xe
	Solid	Anisotropic scintillator	ZnWO3

* Any other idea also exist

Current project using the detector already demonstrated direction sensitivity

Direct tracking

Gaseous target

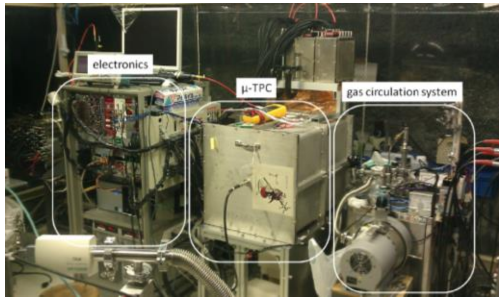
- **DRIFT**
- **NEWAGE**
- **MIMAC**
- **D^3**

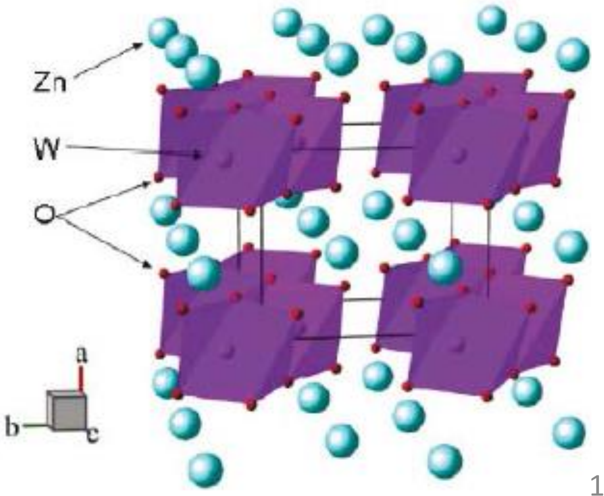
Solid target

- **NEWSdm**

Indirect direction information

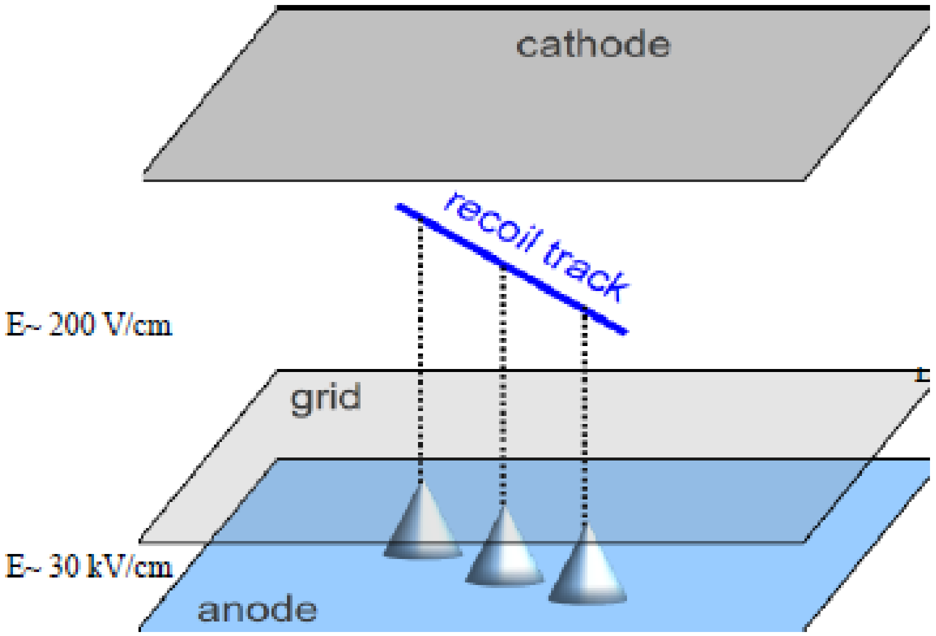
- **ZnWO3**

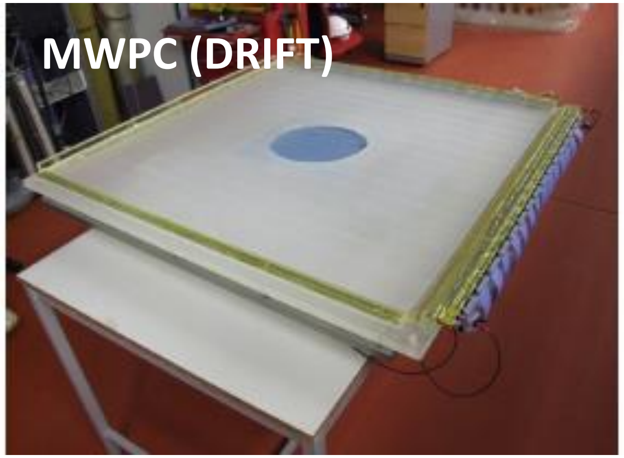


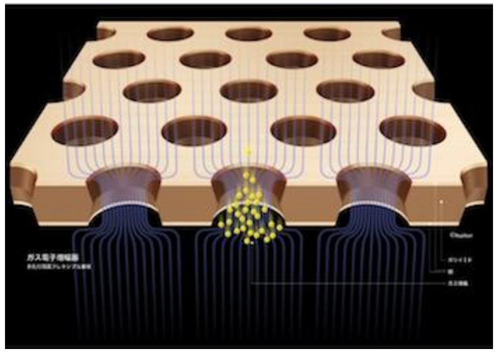


Effort of Gaseous detector

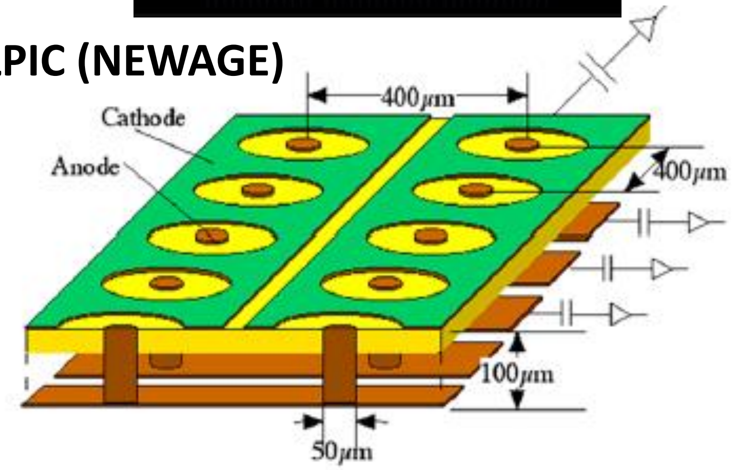
Gaseous TPC







μPIC (NEWAGE)

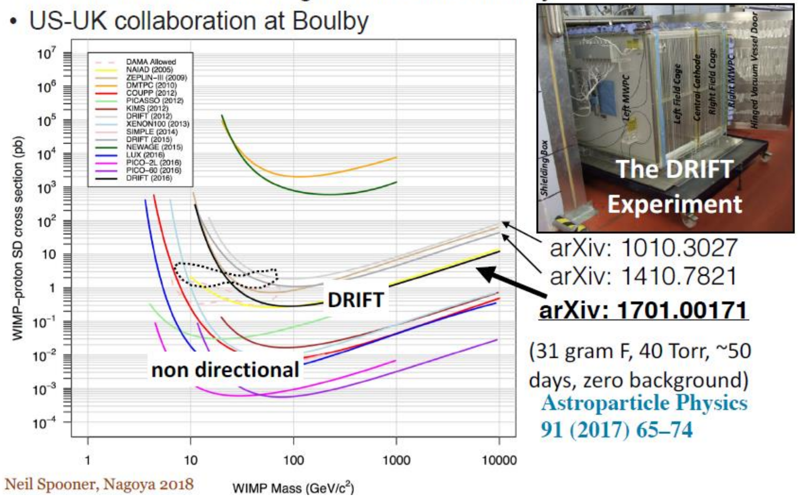


Gas pressure : ~ 0.1 atm ⇒ track length ~ 1 mm
Readout : drifted electron and each readout technologies
Target : C, F, S, He

	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

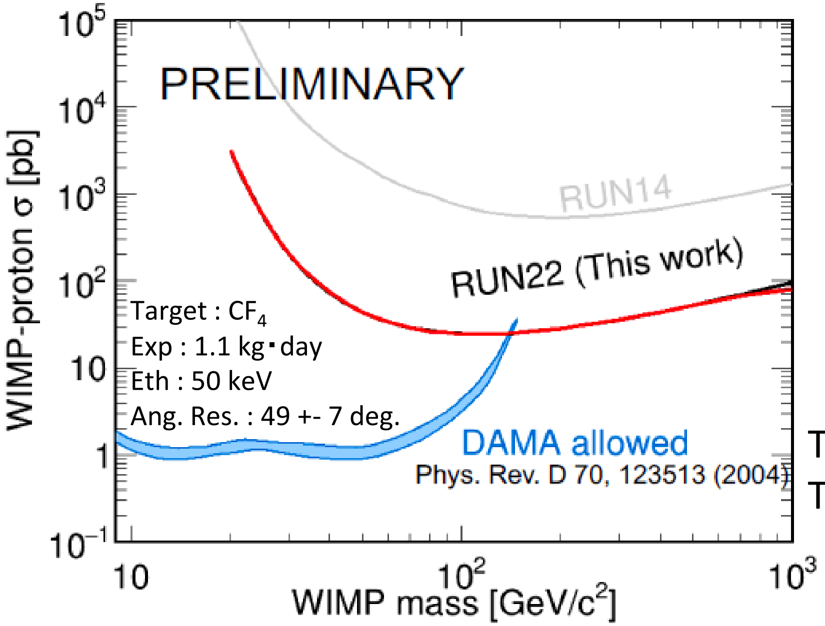
The DRIFT TPC (~1.5D wires)

- 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



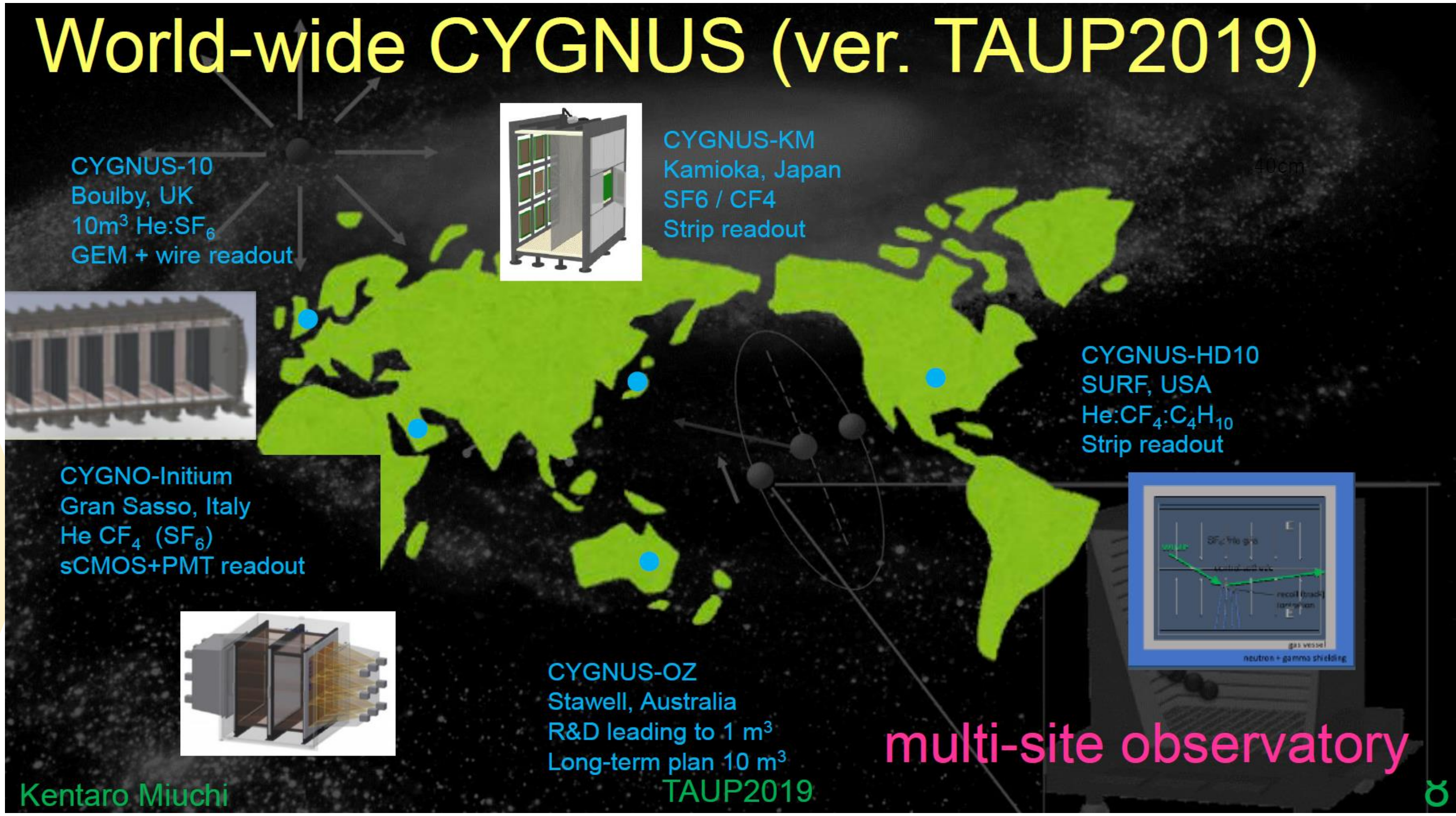
NEWAGE experiment

The 90% C.L. upper limit of SD cross section



T. Ikeda, TAUP2019

Further upgrade

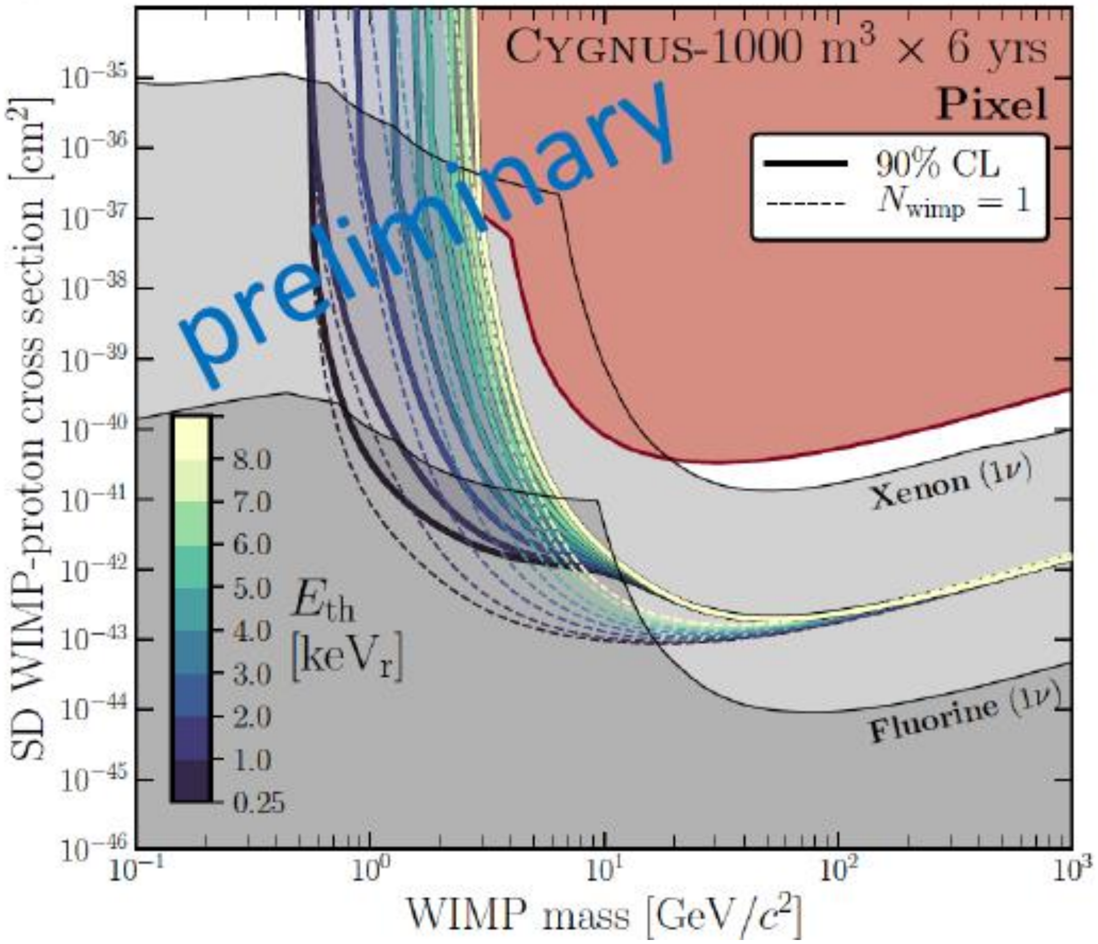


K Miuchi, TAUP2019

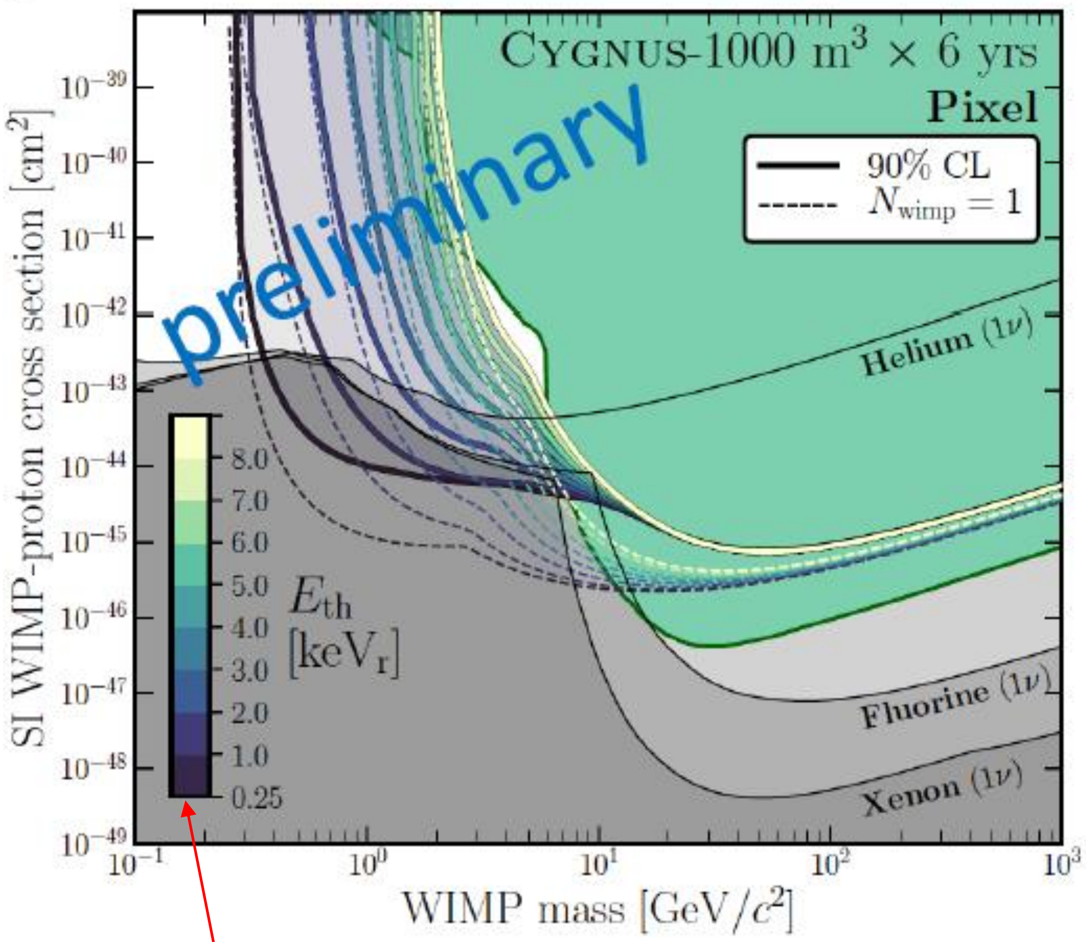
- ➢ **CYGNUS collaboration : sharing the technologies and muti-site observation**
- ➢ **Large volume chamber : under construction 1-10 m³**

CYGNUS collaboration simulated sensitivity

Spin-dependent interaction



Spin-independent interaction



CYGNUS 1000: 10m x 10m x 10m

$He+SF_6$ 755+5

From Sven Vanish slide @CYGNUS2019 workshop

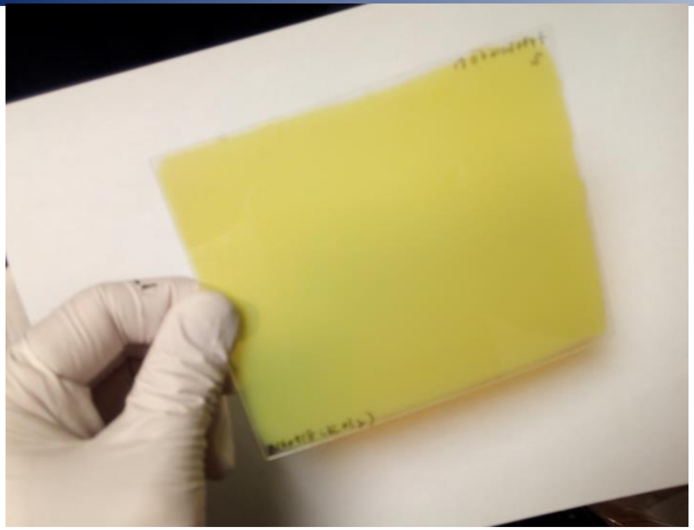
Very low energy recoil is assumed

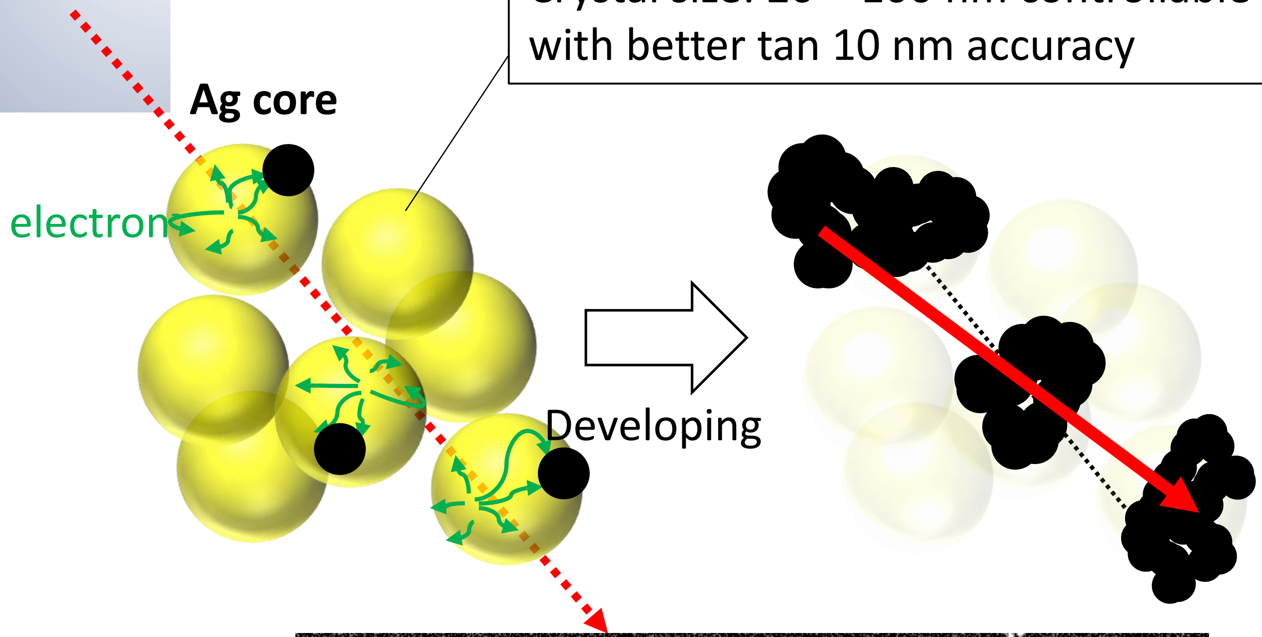
⇒ to be study to obtain direction information to such low energy signal

Effort of Solid detector

Super-fine grained (very high resolution) nuclear emulsion

Super-fine Grained Nuclear Emulsion [Nano Imaging Tracker : NIT]



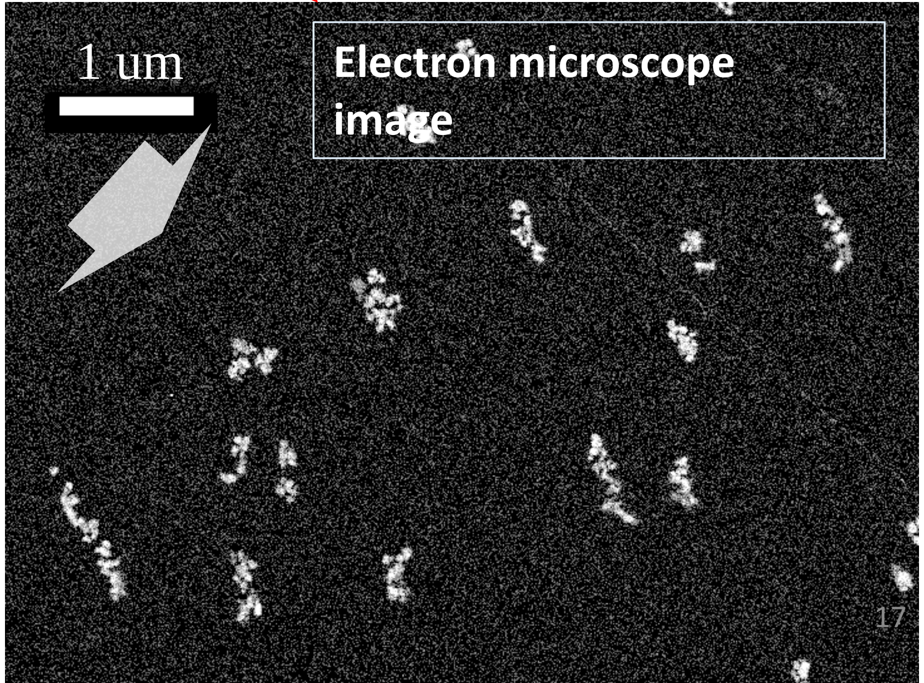


Elemental composition of NIT

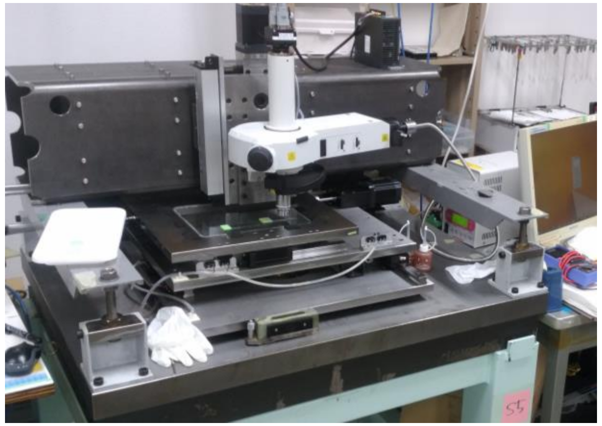
For high-mass DM s

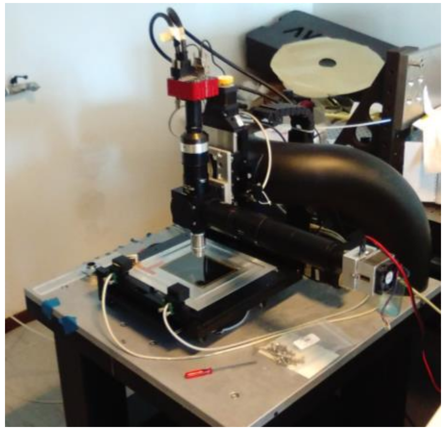
For low-mass DM

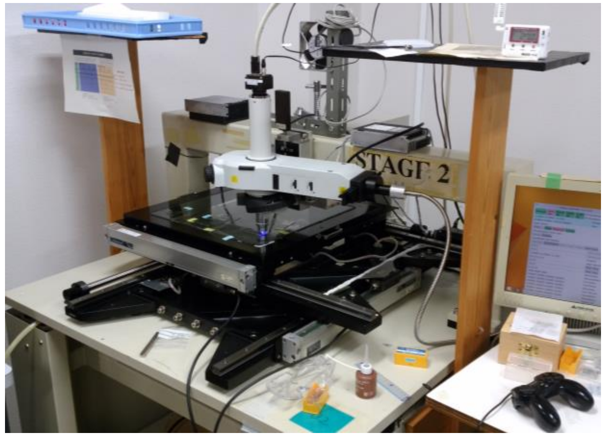
	Mass fraction	Atomic Fraction
Ag	0.44	0.10
Br	0.32	0.10
I	0.019	0.004
C	0.101	0.214
O	0.074	0.118
N	0.027	0.049
H	0.016	0.410
S, Na + others	~ 0.001	~ 0.001

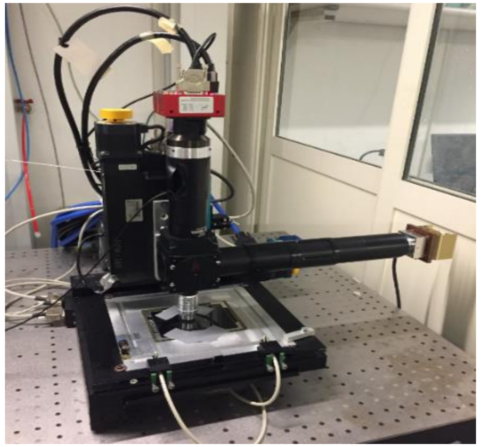


Optical microscope readout system

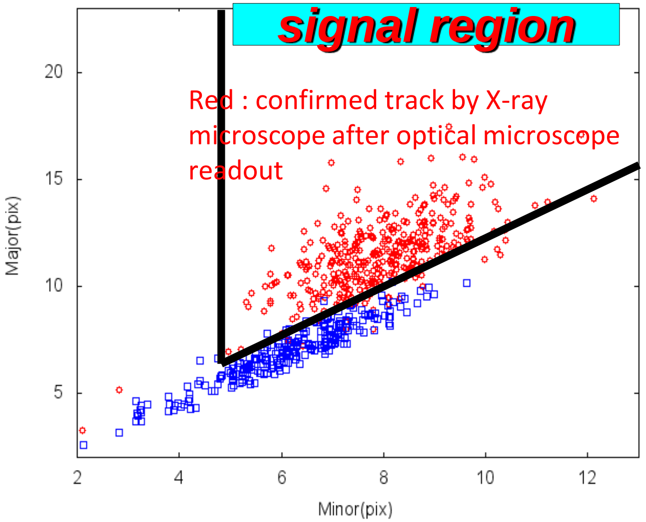


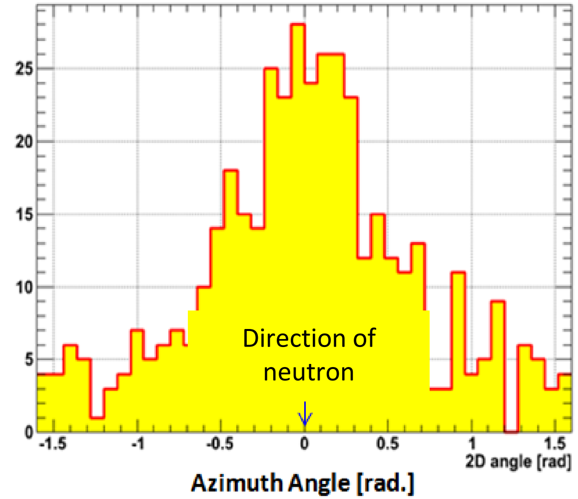






Current scanning speed ~ 30g/y
⇒ Now, continue to develop toward 1 kg scale readout

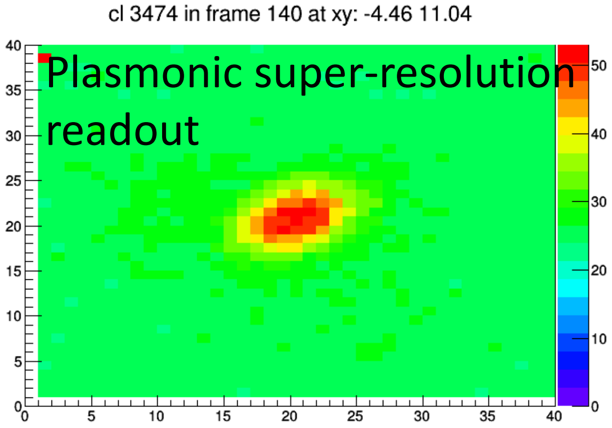


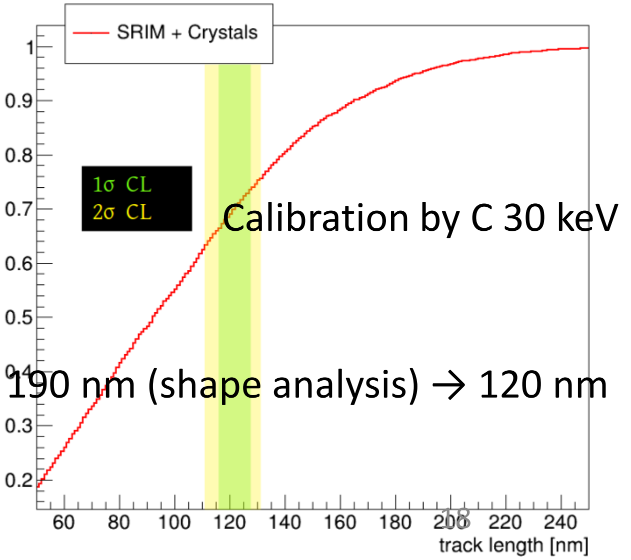


Already demonstrated automatic readout to nuclear recoil and low-velocity ions

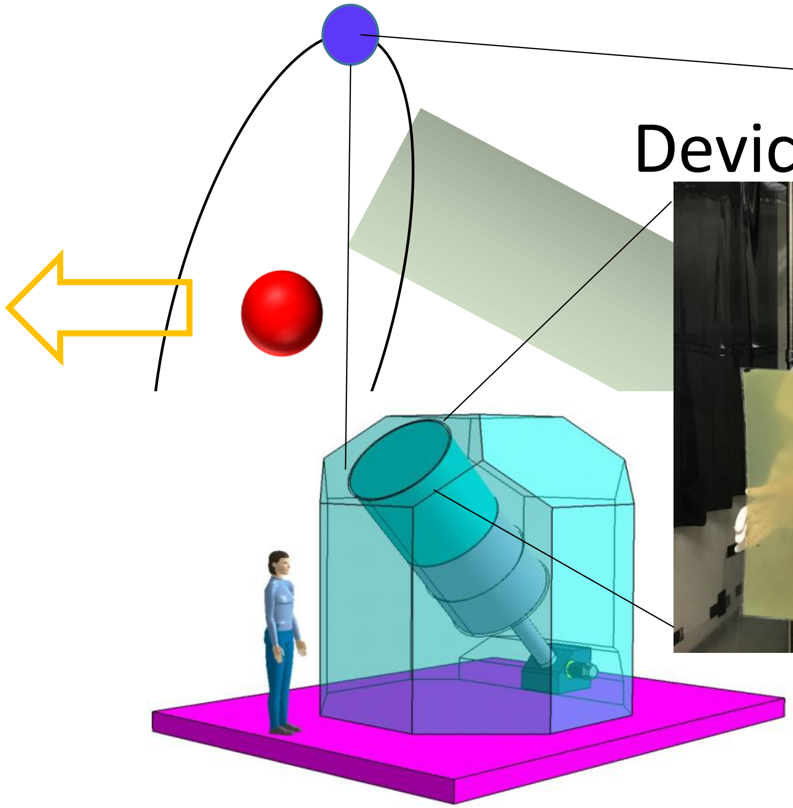
Current threshold ~ 60 keV@C recoil (⊿Φ ~ 35 deg.)

Super-resolution tracking with localized surface plasmon (LSPR)

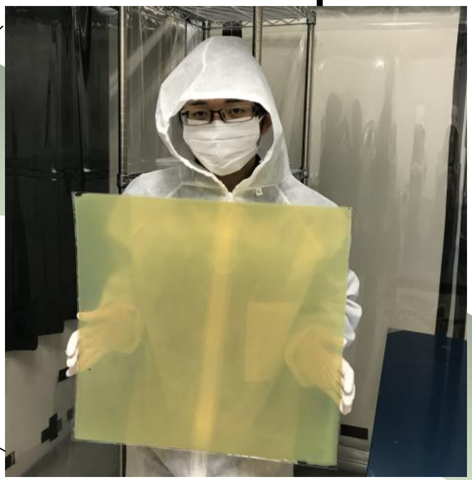




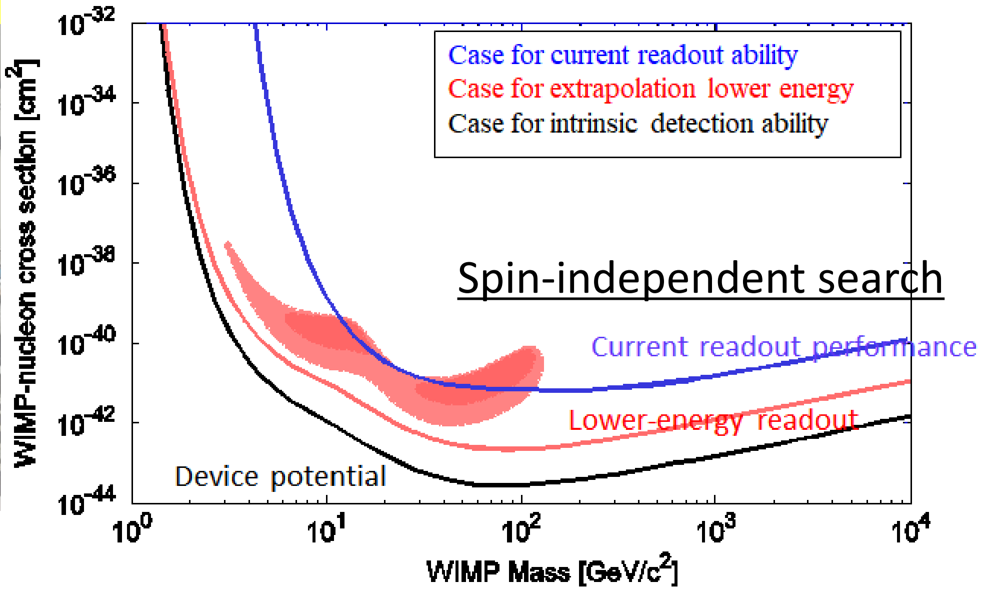
Concept of NEWSdm experiment



Device self-producti



10 kg·year simulated sensitivity [90 % C.L.] + zero BG



exposure on the telescope

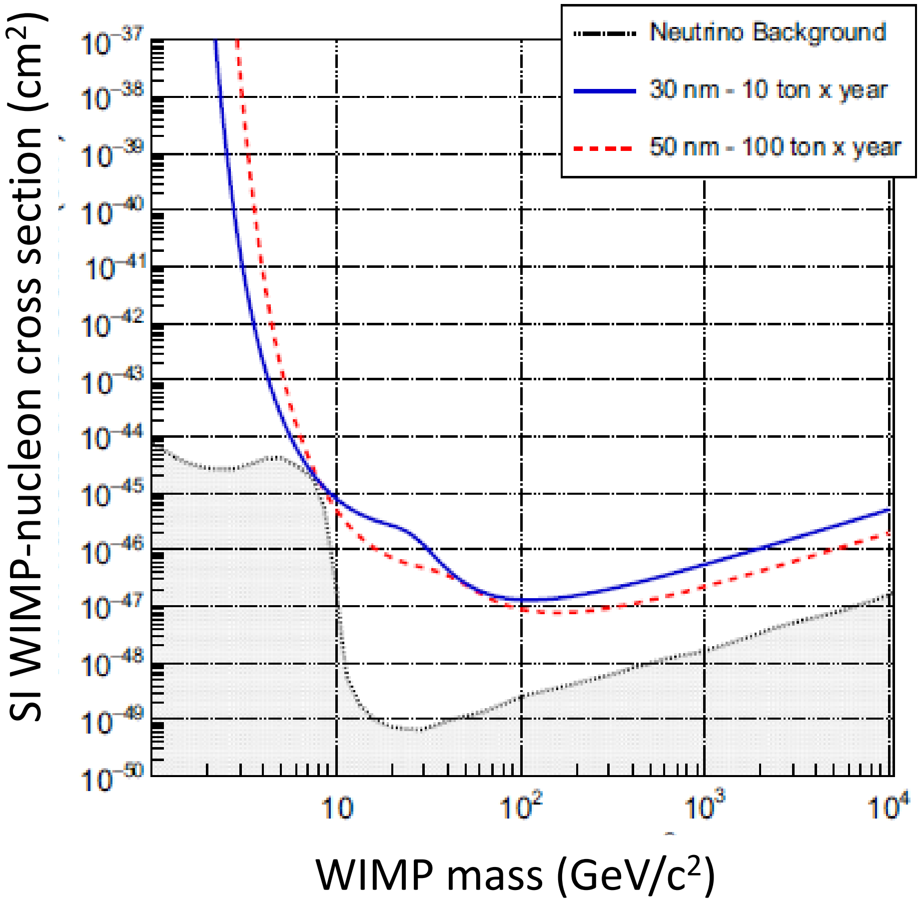
Underground laboratory

Chemical development treatment

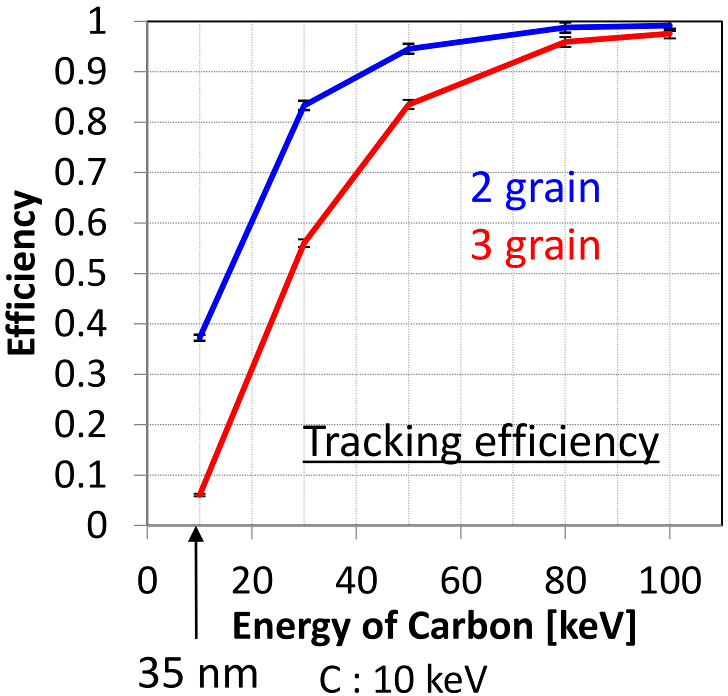
Readout + analysis

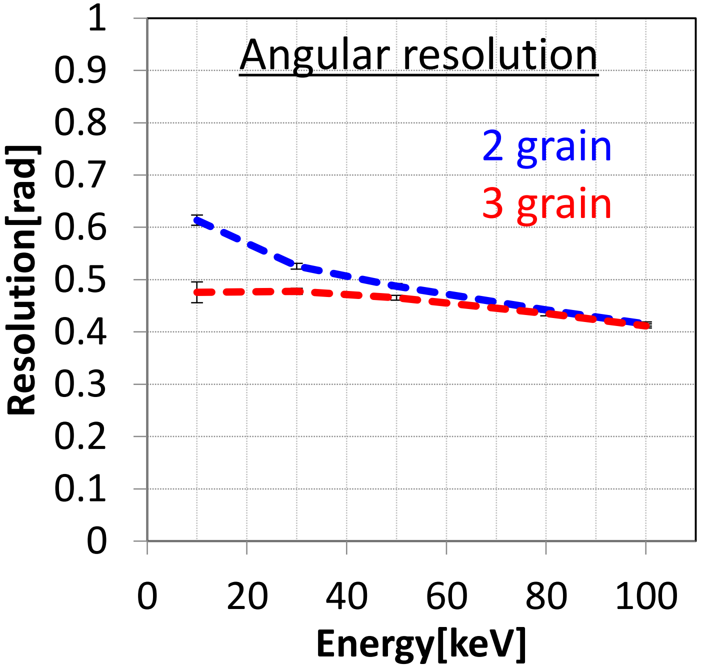
Using microscope techniques

Toward neutrino floor



Simulation for NIT device intrinsic potential





C : 10 keV
Br : 45 keV
Ag : 55 keV

☑ 10 ton production : special machine optimized this device is required (more simple system : current machine is over speck)

☑ High scanning speed machine is needed (current highest machine in the nuclear emulsion field is 1 ton/y)

☑ under discussing whether light emission information from NIT

Anisotropic scintillator

$ZnWO_4$

- Proposed by ADAMO Group in 2011
- Reported 40-50 % anisotropy response for MeV alpha particle

Eur. Phys. J. C (2013) 73:2276
DOI 10.1140/epjc/s10052-013-2276-2

THE EUROPEAN PHYSICAL JOURNAL C

Regular Article - Experimental Physics

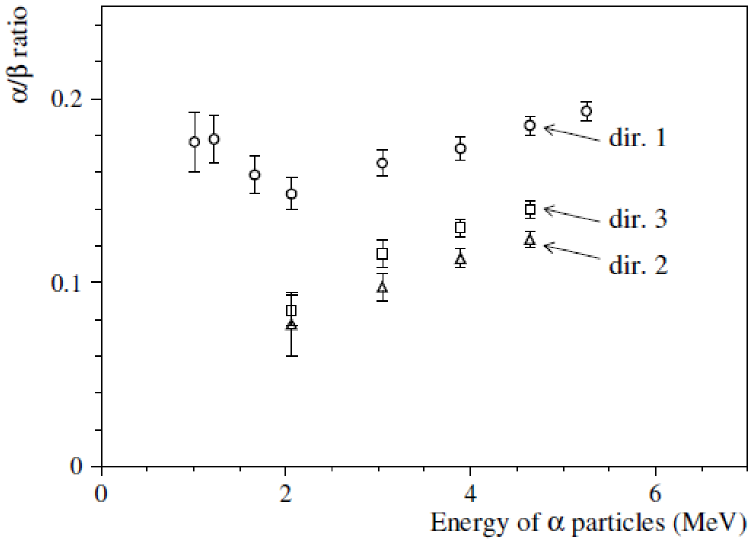
On the potentiality of the $ZnWO_4$ anisotropic detectors to measure the directionality of Dark Matter

F. Cappella[1], R. Bernabei[2,3,a], P. Belli[3], V. Caracciolo[4], R. Cerulli[4], F.A. Danevich[5], A. d'Angelo[1,6], A. Di Marco[2,3], A. Incicchitti[6], D.V. Poda[5], V.I. Tretyak[5]

Table 2 Quenching factors for O, Zn and W ions with energy 5 keV for different directions in $ZnWO_4$ crystal. Systematic uncertainties are estimated on the level of 20 % using data of [90]

Ion	Quenching factor		
	dir. 1	dir. 2	dir. 3
O	0.235	0.159	0.176
Zn	0.084	0.054	0.060
W	0.058	0.037	0.041

perpendicular to (010): dir1
(001): dir2
(100): dir3



ADAMO group
Reported α/β ratio of 55% anisotropic response

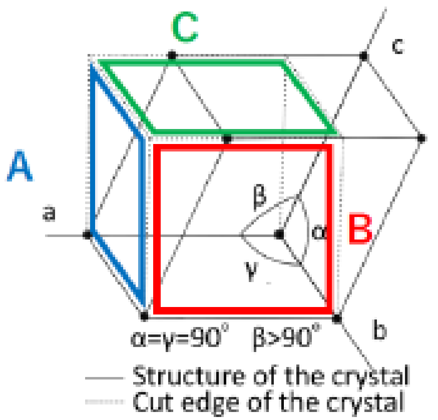
Eur. Phys. J. C (2013) 73:2276

Current active groups
1. Italian Group (ADAMO)
2. Japanese Group (Prof. Sekiya *et al.*)

Demonstration for anisotropic response

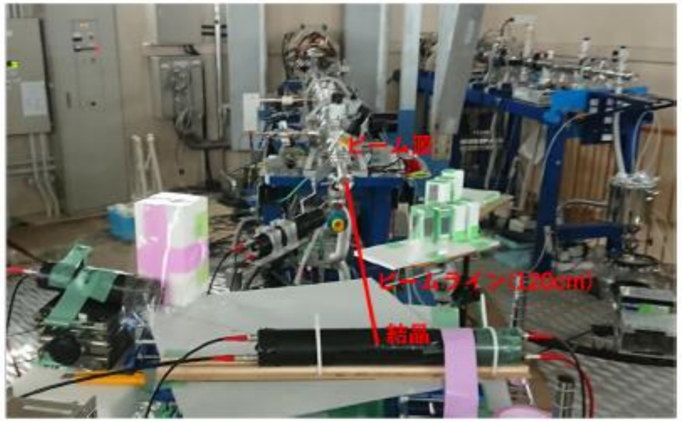
- 結晶構造

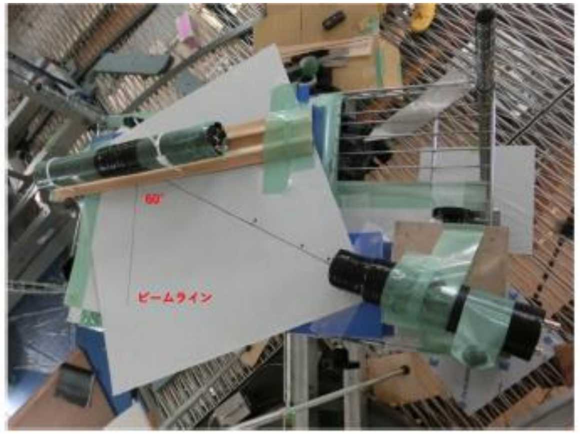
単斜晶系



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

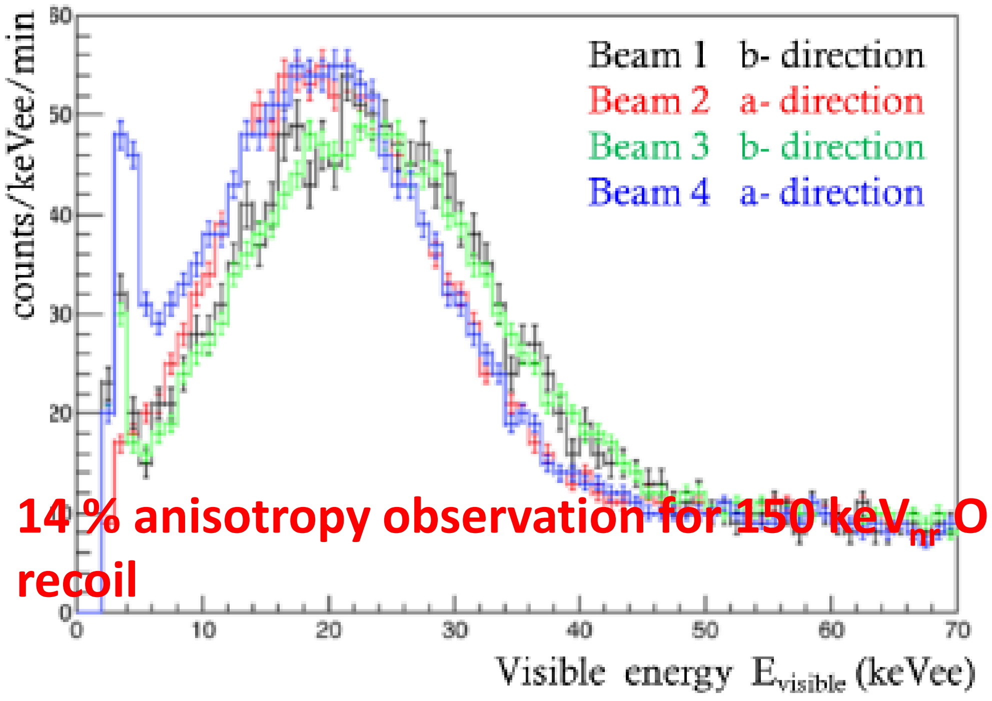
単位格子の長さと角度





Direct detection of nuclear recoil due to neutron by TOF

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

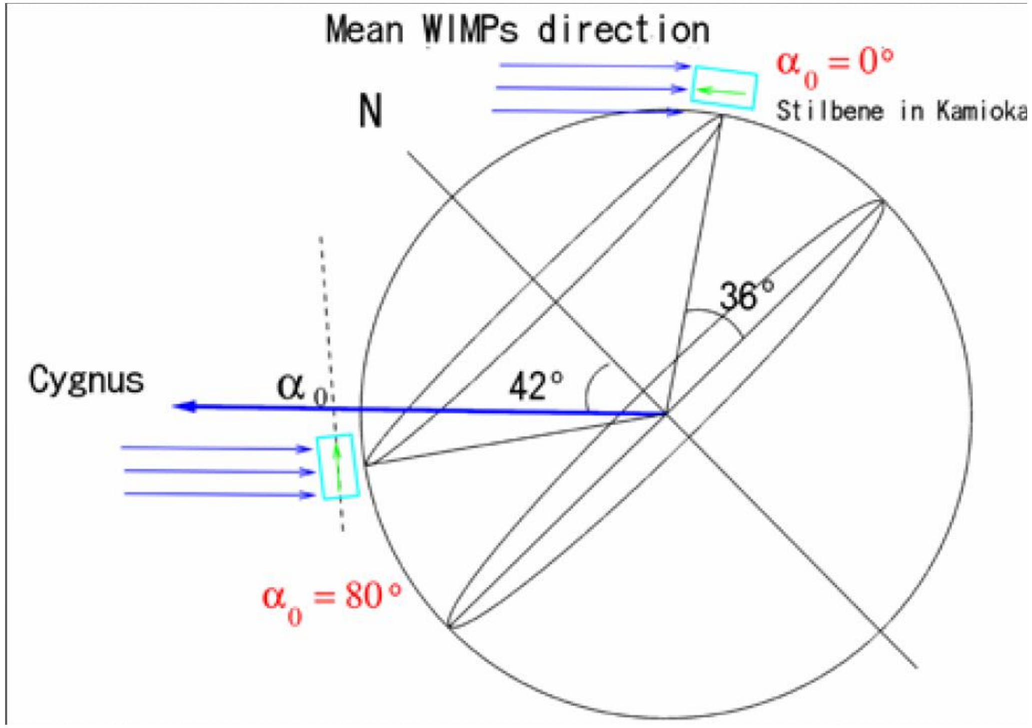


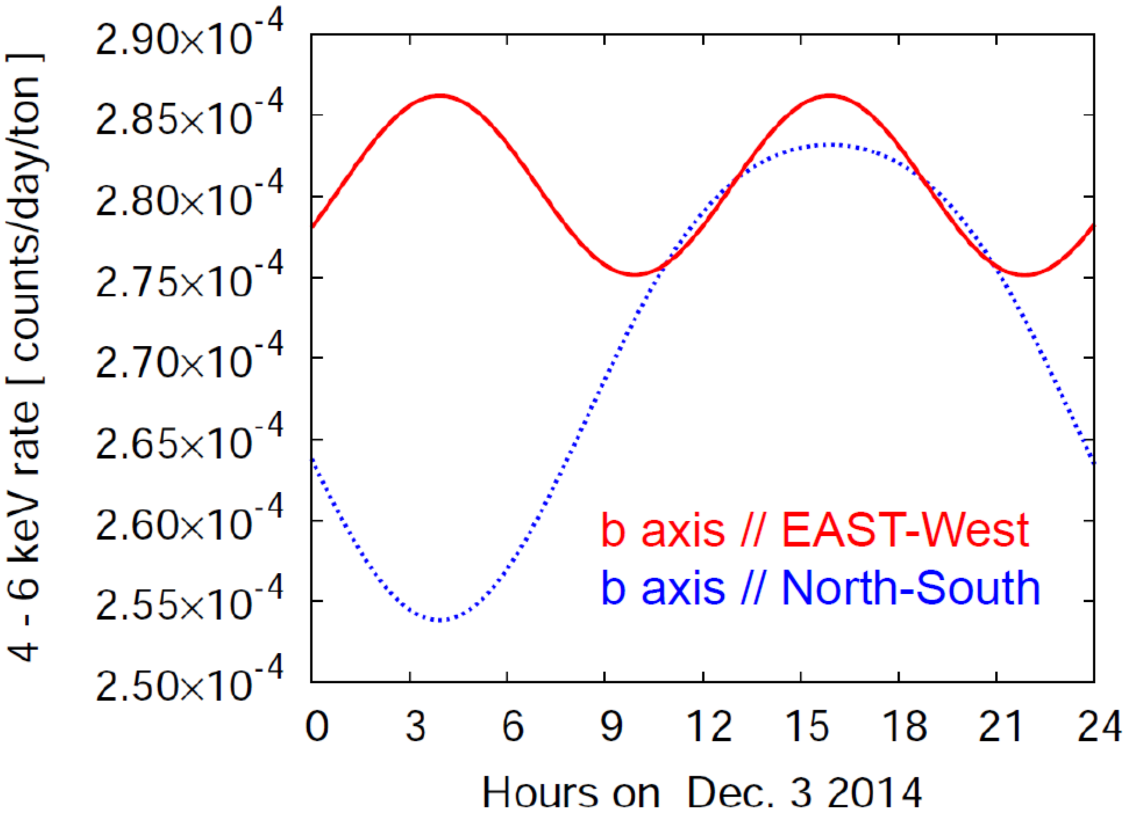
14 % anisotropy observation for 150 keV_{nr} O recoil

Beam	//axis	Peak $E_{visible}$ keVee	Quenching factor @151keV
1	b	22.67±0.40	0.150±0.003
2	a	19.50±0.22	0.129±0.002
3	b	22.73±0.21	0.150±0.002
4	a	19.65±0.18	0.129±0.002

H. Sekiya CYGNUS2019

Anisotropic scintillator [$ZnWO_4$]





Assuming 7% anisotropy @5keVnr in ZnWO4

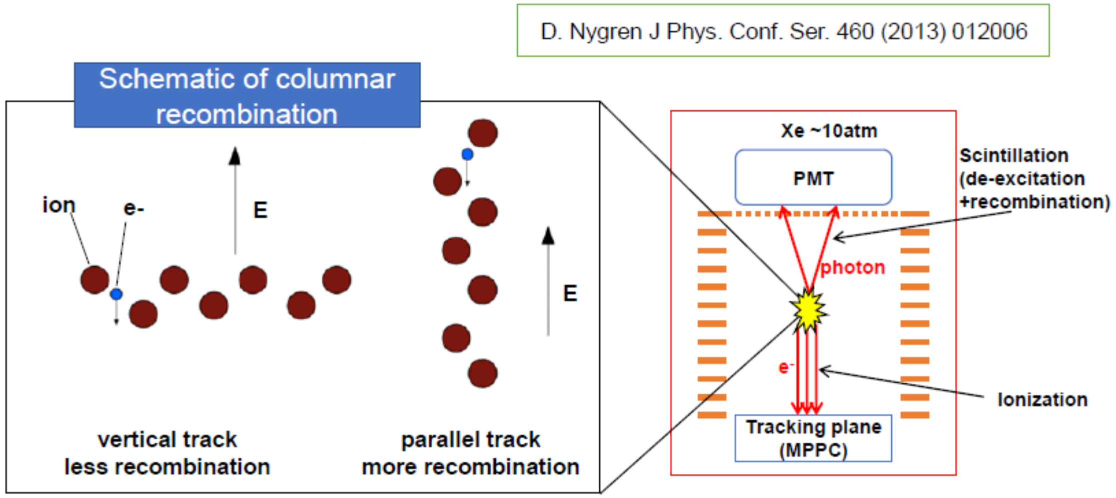
10^4 ton・day for 10^{-48} cm2 (neutrino floor)

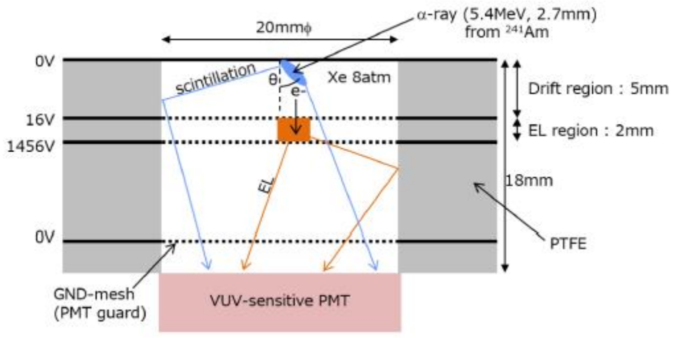
H. Sekiya, JPS meeting 2017

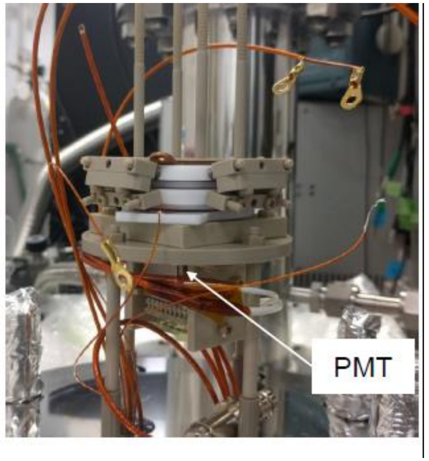
Any other Idea and under R&D for demonstration of direction sensitivity

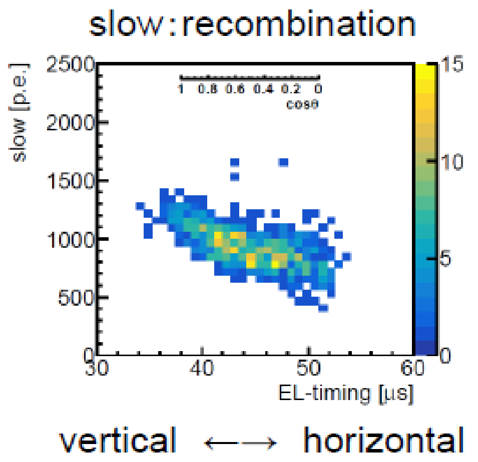
High pressure gaseous (Xe) detector + Columner recombination

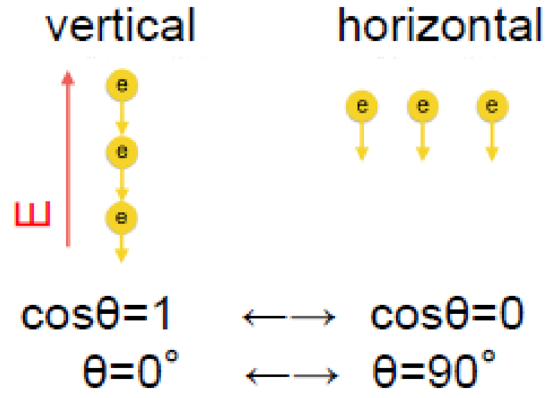
K. Nakamura CYGNUS2019











Columner recombination

- **Recombination efficiency of ionized electrons should have dependence on relative direction between track and electric field**
- **Time profile of scintillation emission (especially slow component) should be affected**

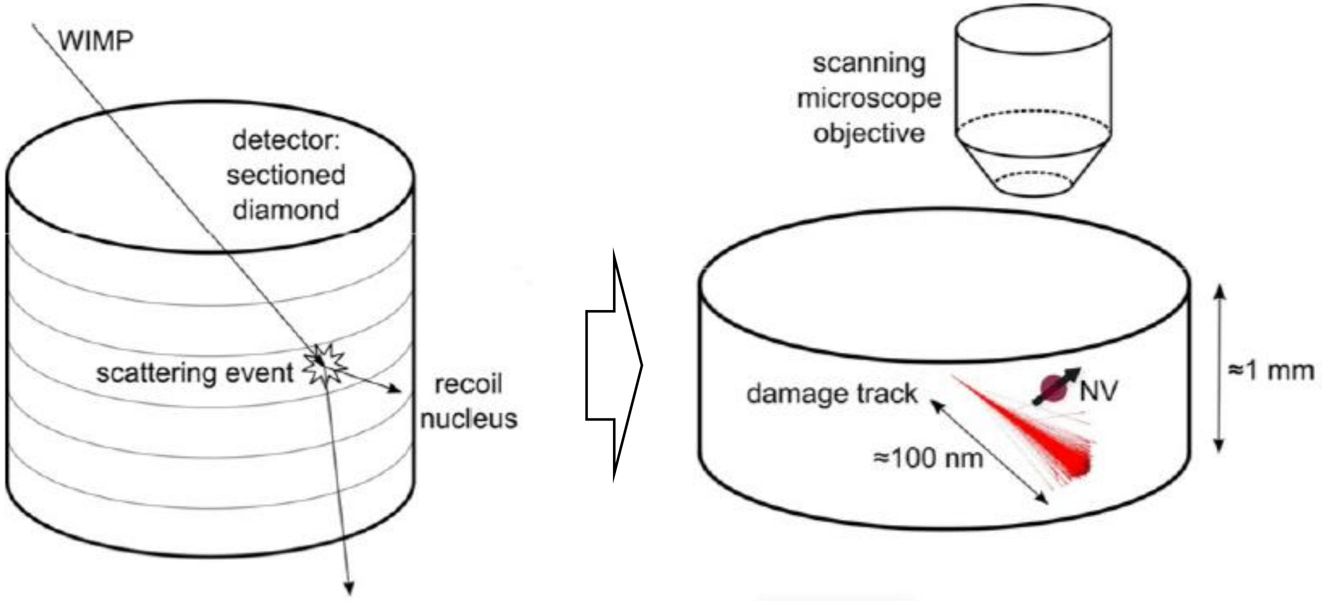
⇒ Directional search is possible if this effect would be confirmed in low-energy nuclear recoil

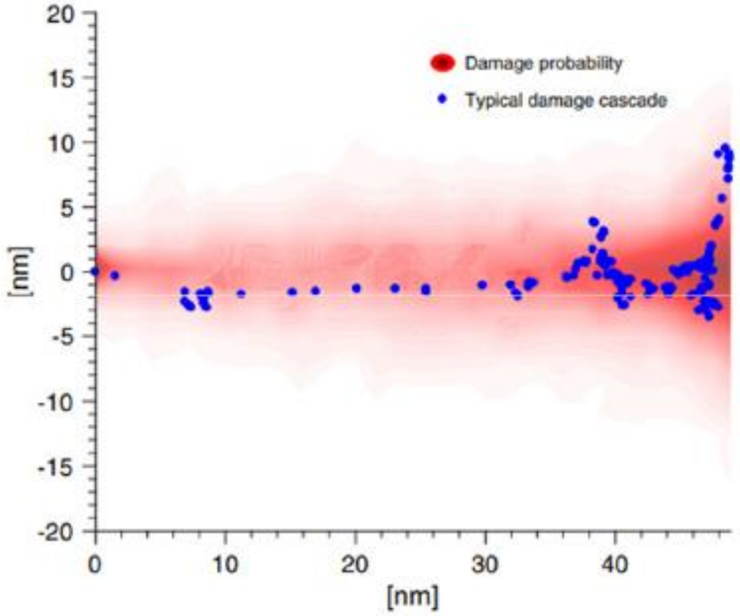
8 atom Xe gus

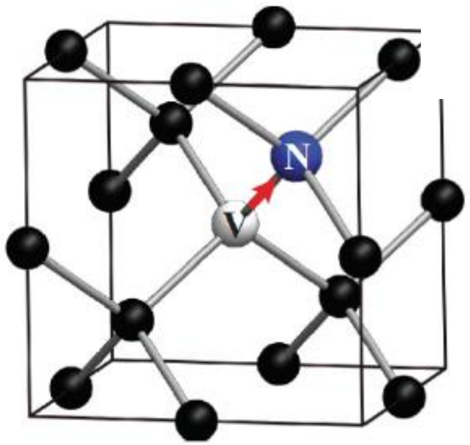
Observed angular dependence due to Colamnur recombination

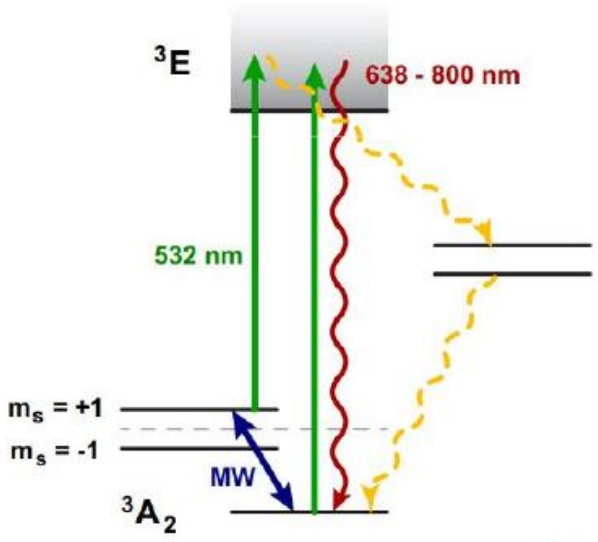
20 % difference @alpha particle (~ MeV)

Diamond detector using N-V center effect









- ➢ To be demonstrated the feasibility to low-velocity atom (recoiled nuclei) ⇒ number of vacancy and density of nitrogen center are not clear yet for detecting of nuclear recoil
- ➢ Scalability (e.g., readout speed etc.) is not clear
- ➢ But, it's interesting idea.

- Surjeet Rajendran et al., Phys. Rev. D 96, 035009 (2017)
- *Mason Marshall, CYGNUS2019*

Discussion

- For current directional dark matter search, first motivation was search in DAMA anomaly region rather than neutrino floor. (this motivation is yet remained)

- Feasibility for going beyond neutrino floor (> 10 GeV/c2 mass and < 10^{-45} cm^2 for SI WIMP-nucleon cross section) is under discussion.

- In parallel, discussion for new technologies and new methodology is very important in this field

⇒ Then, perhaps new collaboration may be needed with material science and phenomenology because obtaining the direction information for such low energy atomic recoil is new experience for particle physics.

Direction information can provide the most powerful evidence.

Conclusion

- Standard WIMP scenario is attractive for thermal relic such as CMB, and energy scale.
- several 10-100 GeV/c^2 dark matter will face the wall due to neutrino
- Directional information is the most promising information to overcome that.
- Now, some experimental groups are studying that about feasibility and further scale up + low-background

	Tracking or direction sensitivity	Scalability	Background
Gaseous detector	◎	△	○
Nuclear emulsion	◎	○	△
Anisotropic scintillator	○	◎	△
Diamond	△	△	△
High pressure gas	△	△	△

◎ : Good and already demonstrated
○ : Good or Conditionally good
△ : Now on study or unknown