Jan 25th, 2023

KMI colloquium

Exploring the Nature of the Dark Matter by Direct Searches

focusing on directional methods with gaseous detectors

Kentaro Miuchi

(Kobe University)

科研費 KAKENHI

Dark Matter Overview

see also
日本物理学会誌 第75巻
(2020年) 第2号　68-76頁 交流

交流

宇宙のダークマター直接探索の現状


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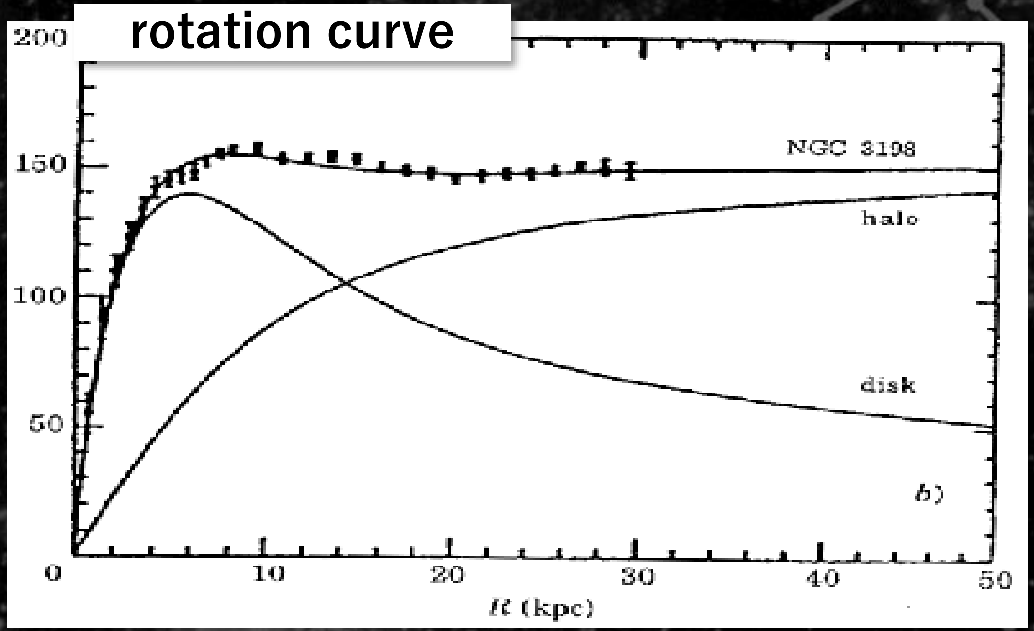
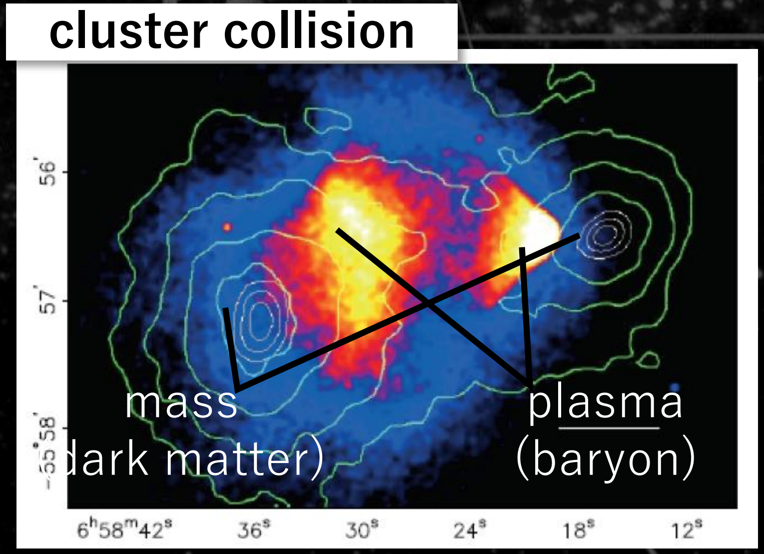
- DM Overview
- Directional
- Related Topics
- Summary

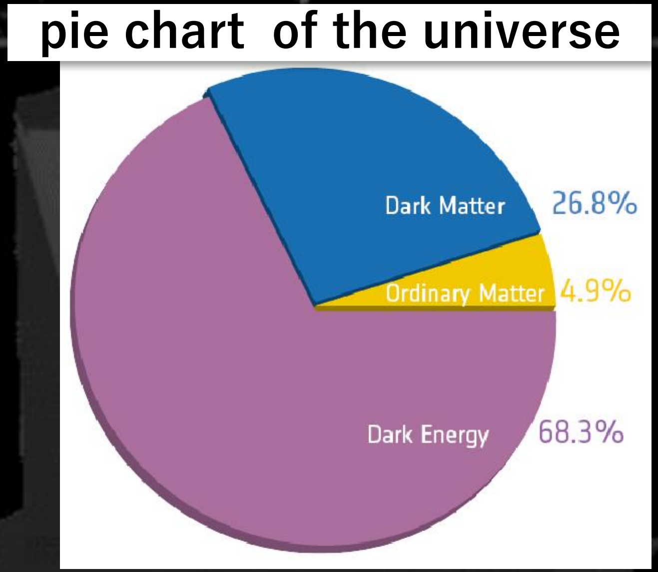
- DM: seen in various scales in the universe
  - @ galaxy: rotation curves（1970~）
  - @ cluster of galaxies: collision of galaxy clusters （2007~）
  - @ universe: CMB and other observations (2002~)



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

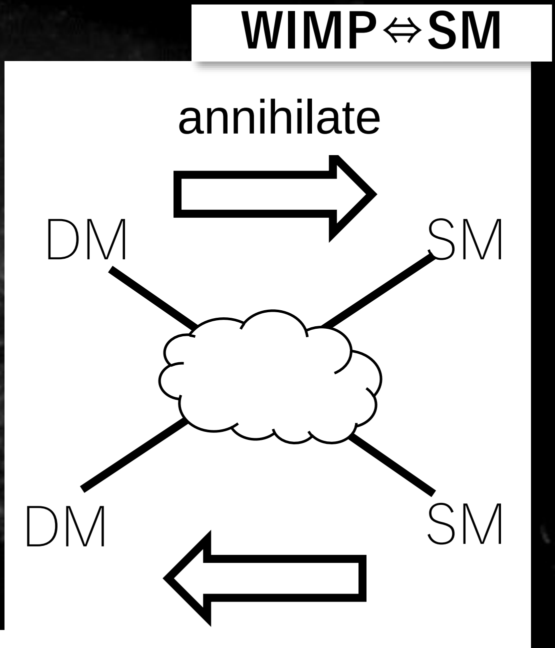


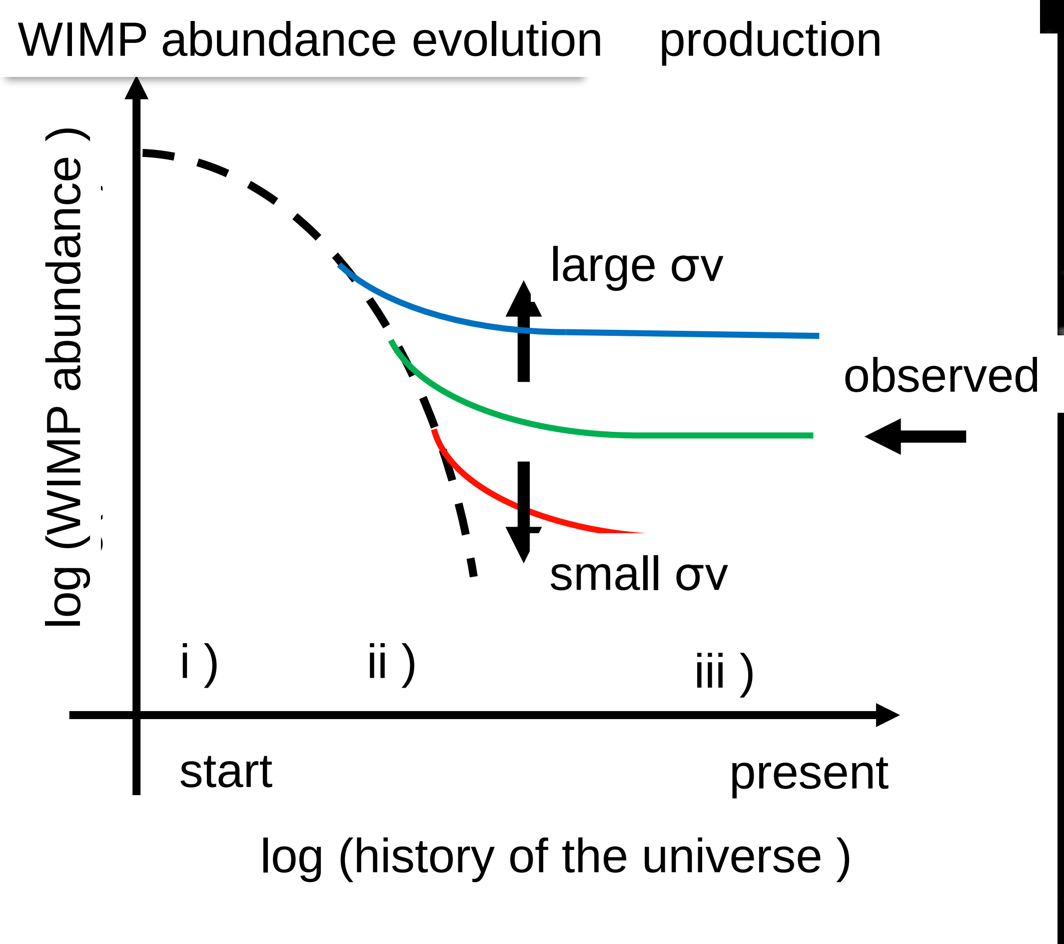
THE ASTROPHYSICAL JOURNAL, 648:L109–L113, 2006 September 10



Plank team

- DM candidates: thousands of them
  - "good" candidates would solve other problems
    - AXION (CP problem in QCD)
    - Primordial black hole (BHs are there!)
    - WIMPs (Weakly Interacting Massive Particles)
  - WIMPs
    - Produced in the early universe
    - Annihilate
      rate ∝ cross section × velocity
    - Freeze out at some point
      abundance is fixed
    - σ ~weak scale explains present abundance
      ⇒WIMP miracle !

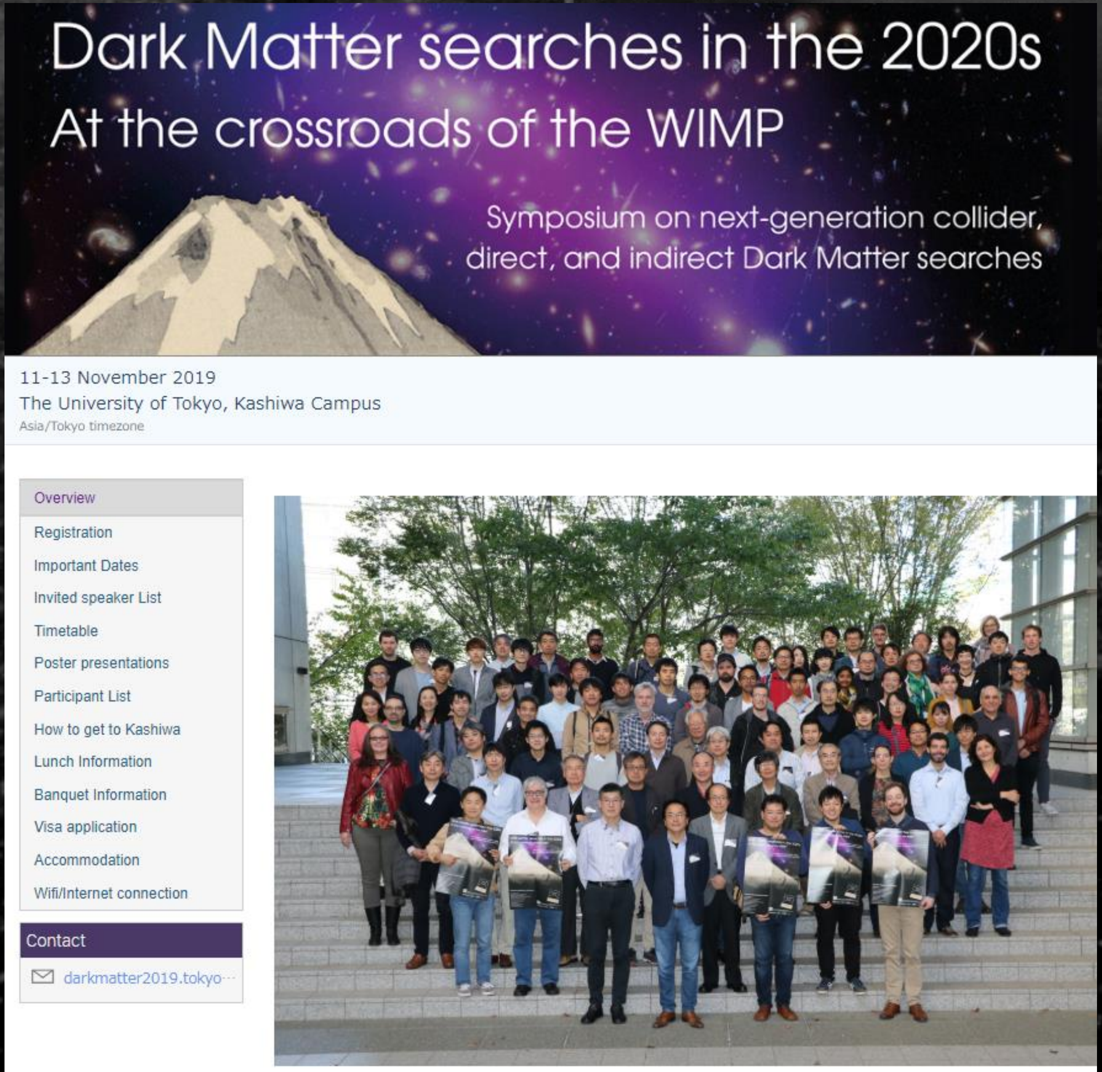


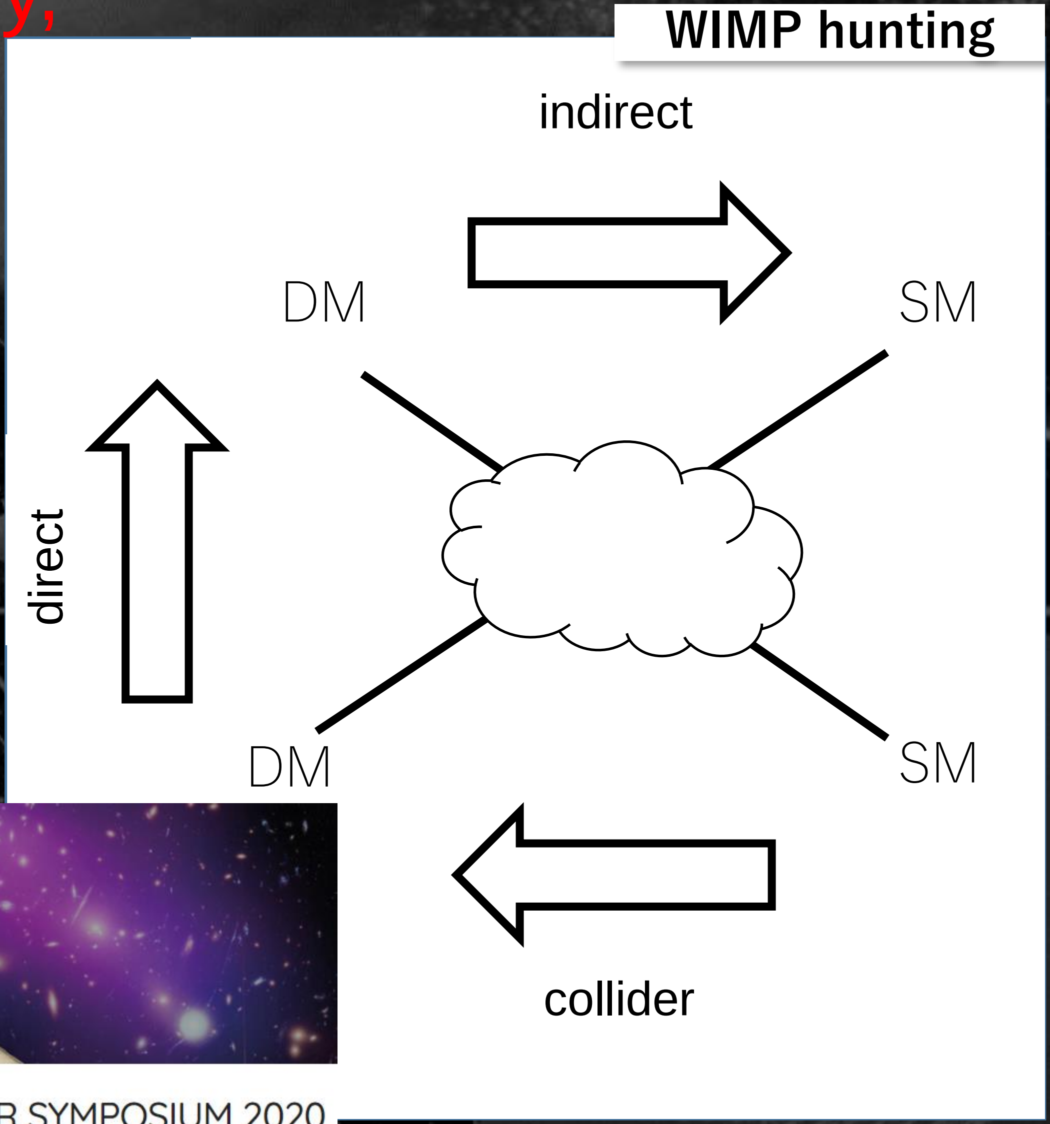


• WIMP hunting

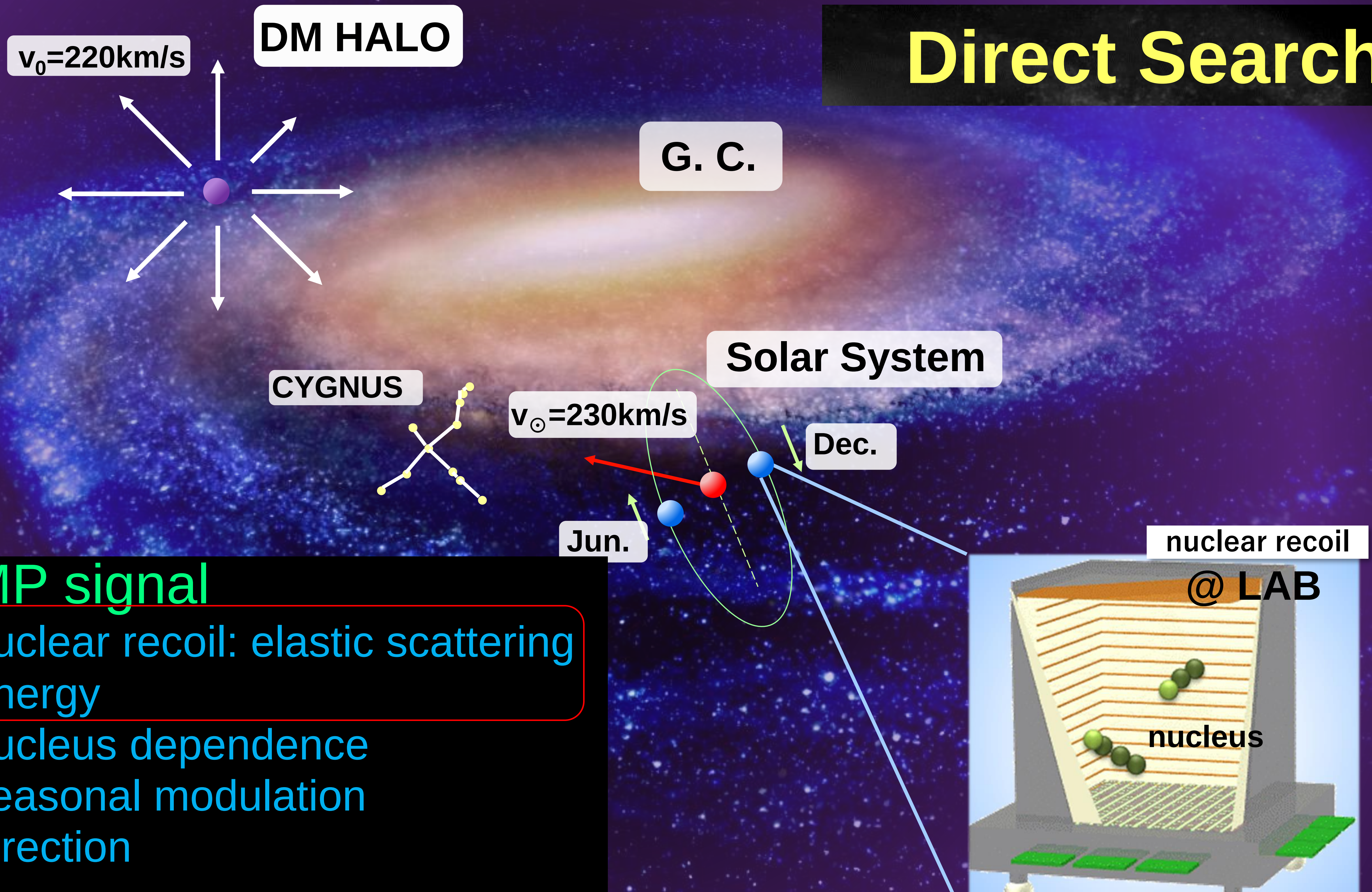
- WIMP-SM (standard model particle, i.e. quarks) particle interaction
  - Direct search
  - Indirect search
  - Collider

complementary,
synergy



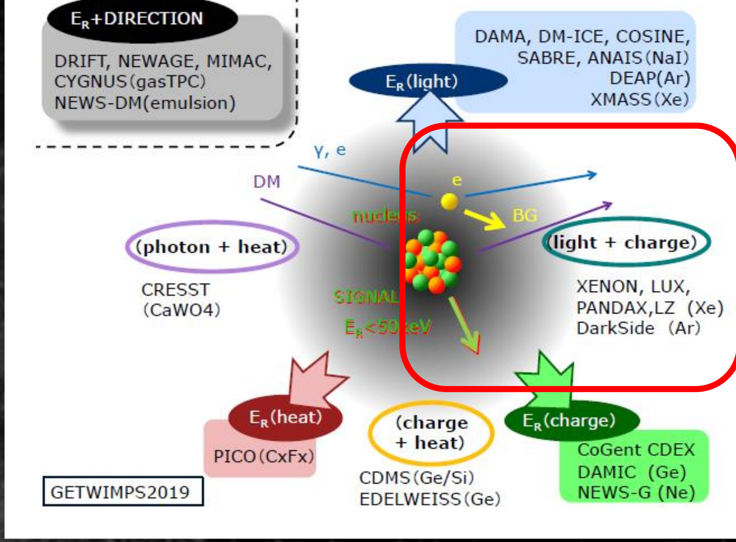


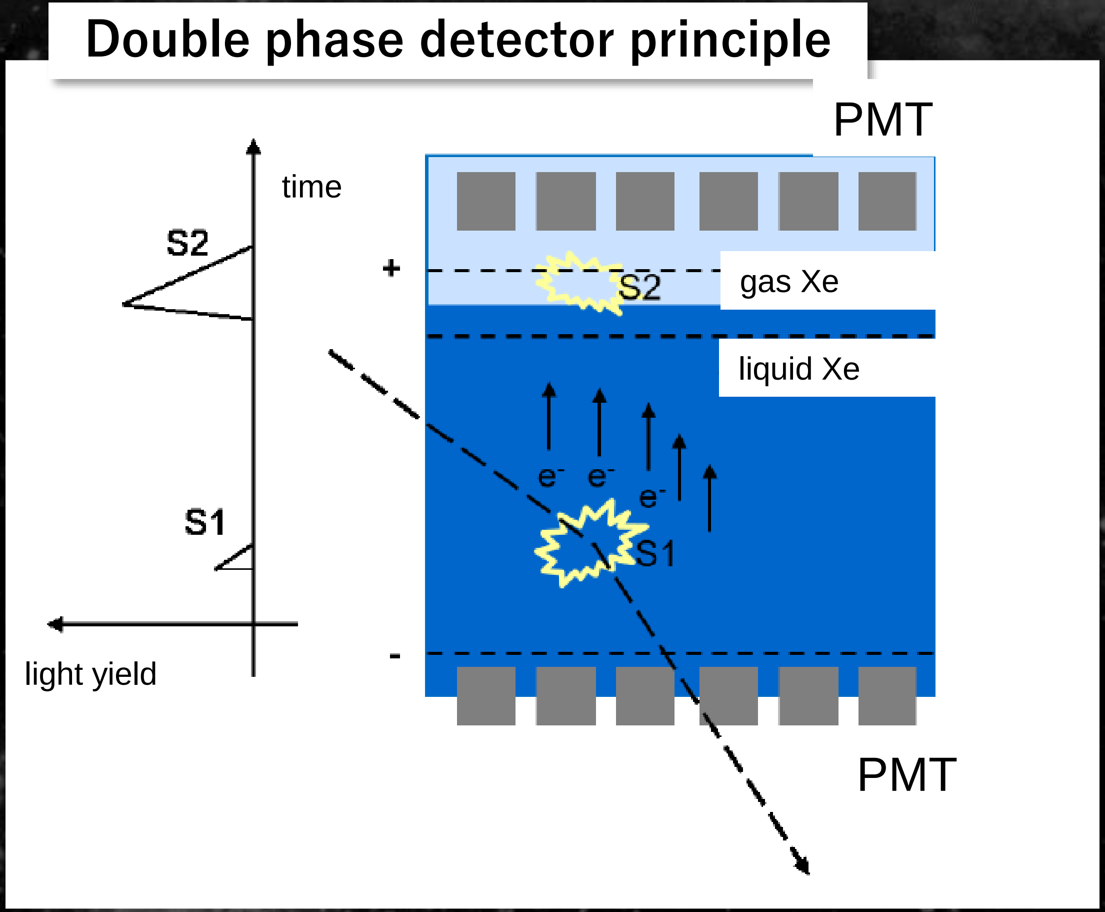
Direct Search

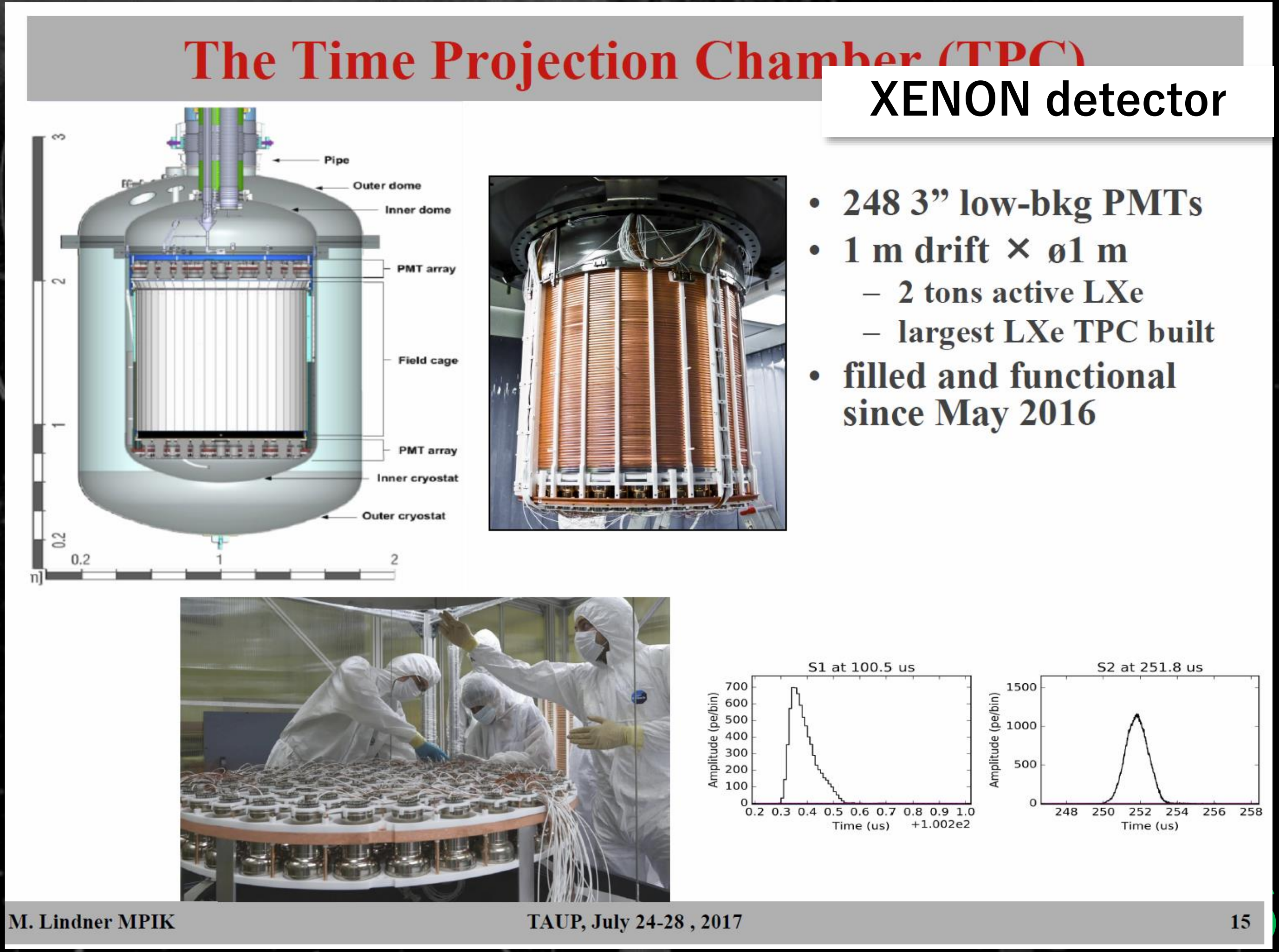


- WIMP signal
  - nuclear recoil: elastic scattering
  - energy
  - nucleus dependence
  - seasonal modulation
  - direction

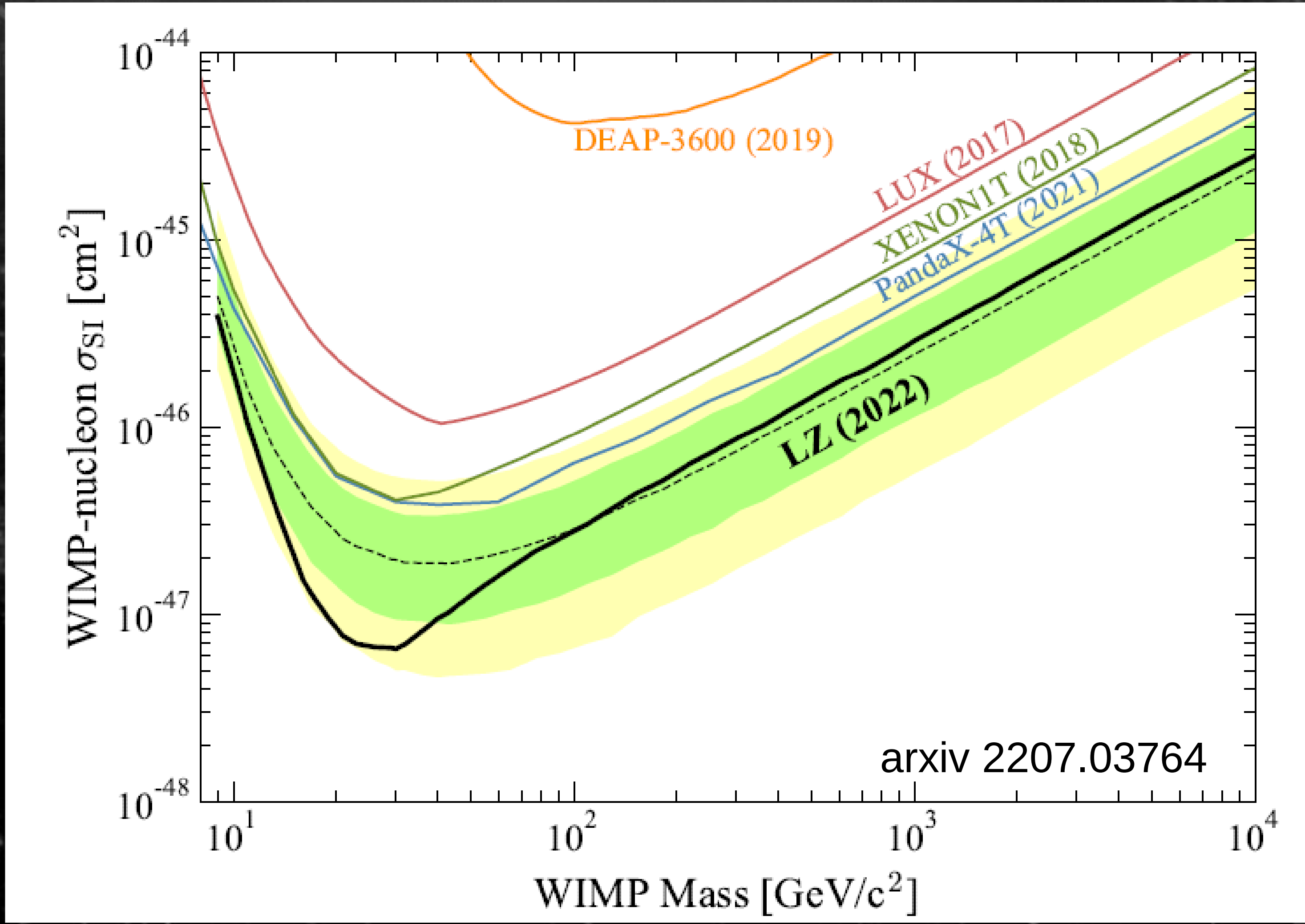
- Liquid Xe/Ar : double-phase (liquid+gas)
  - XENON1T, L/Z, PandaX-II (Xe) , DARKSIDE(Ar)
  - Several 100kg ～ 1ton
  - z position can be known
  - Electron background can be discriminated





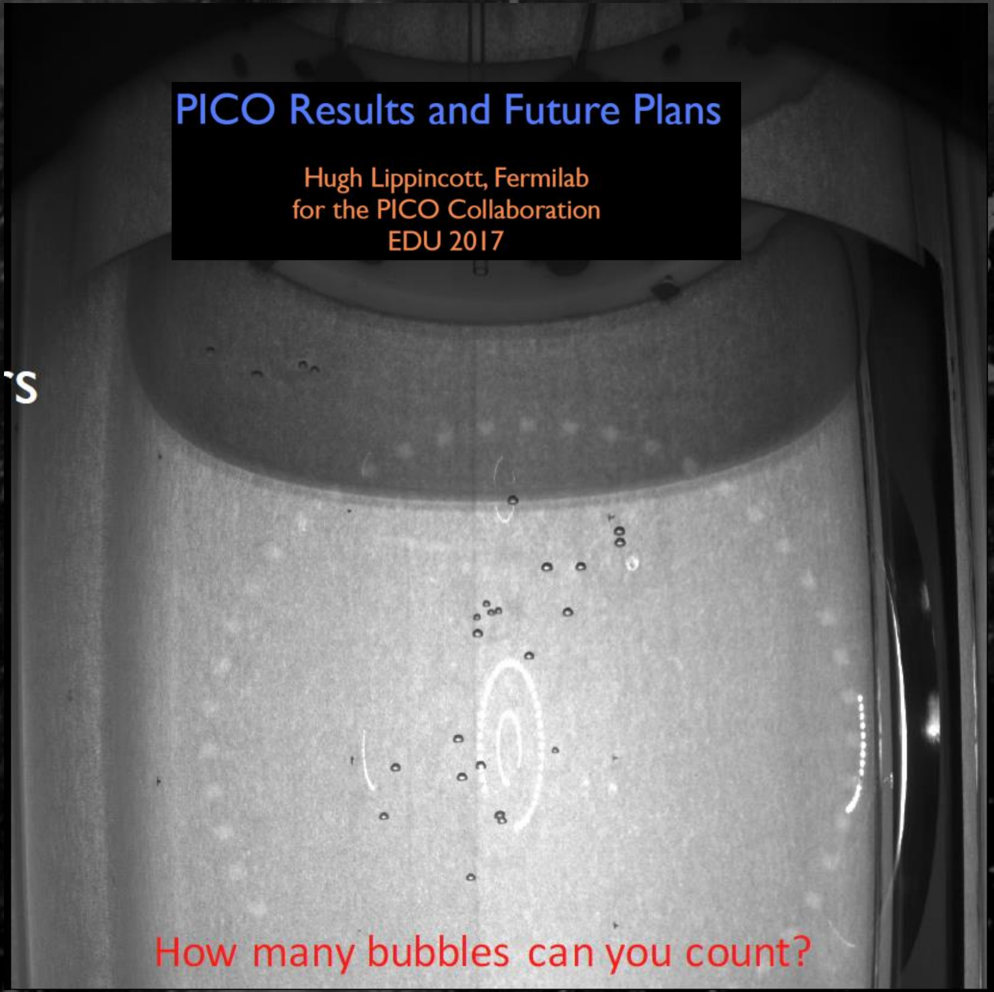


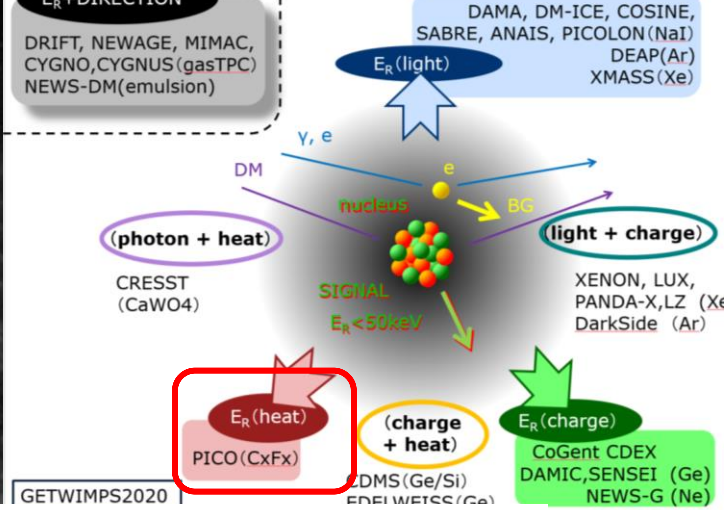
- Leading results（LZ）
  - 5.5ton 60 livedays
  - 6.5×10-48 cm2 @ 30GeV

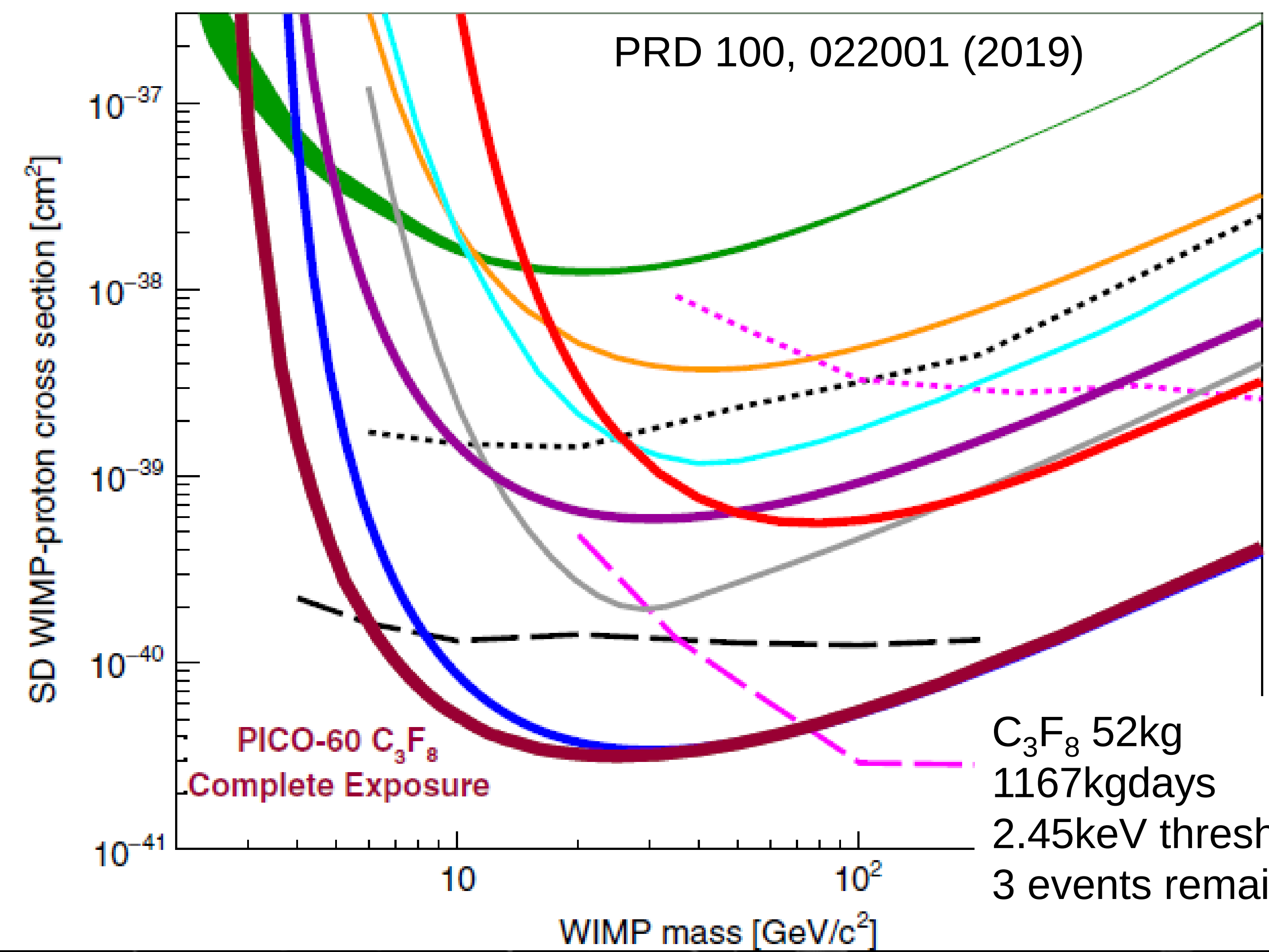


More should come from LZ, XENONnT…

- Bubble chamber (w/ fluorine)
  - PICO
    - Superheated chamber
    - Threshold-type detector
    - Best SD sensitivity







C_3F_8 52kg
1167kgdays
2.45keV threshold
3 events remained

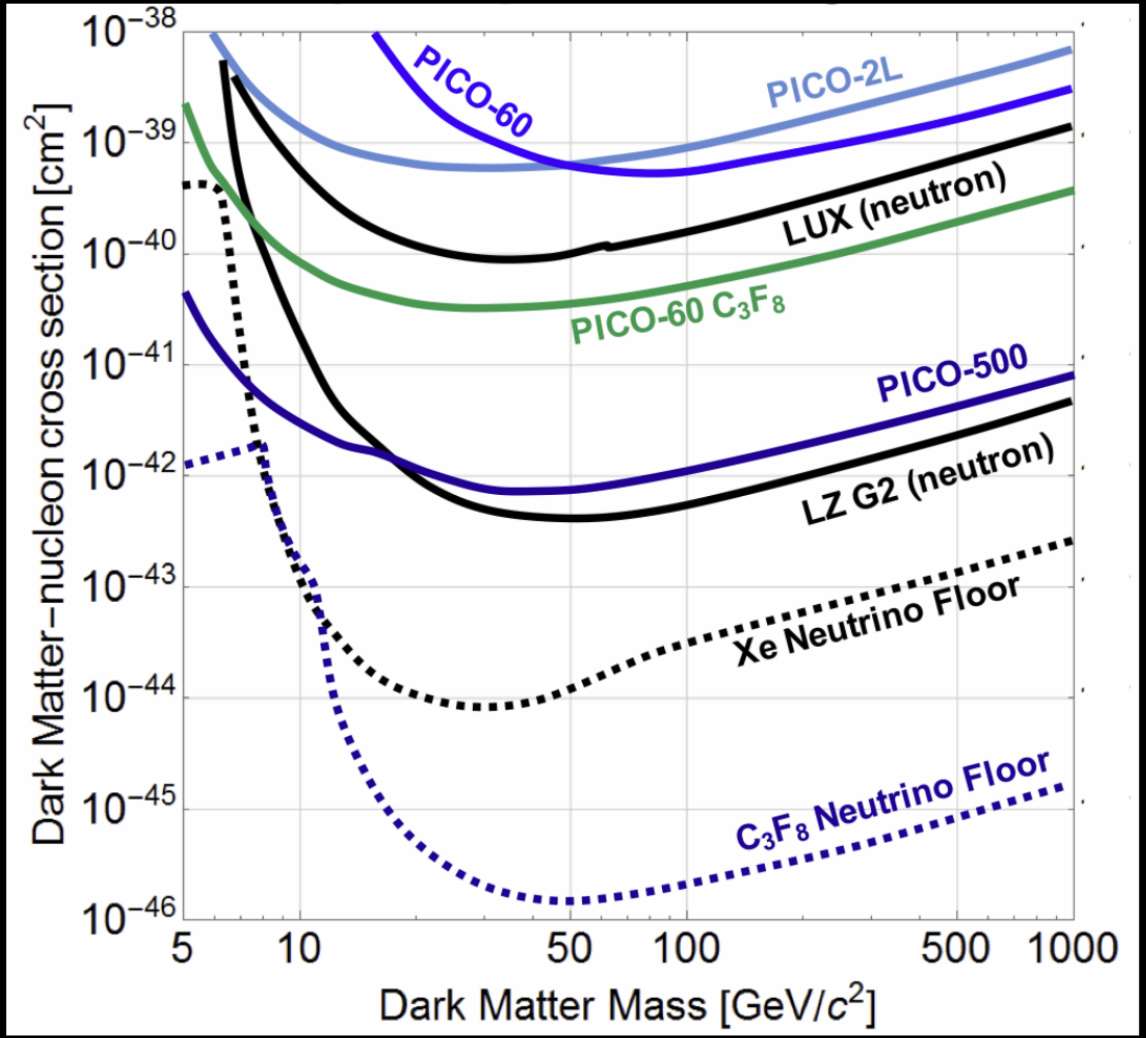
- Fluorine advantage
  - SD search
  - different "Neutrino floor" from xenon

Isotope	J	Abundance(%)	μ_{mag}	$\lambda^2 J(J+1)$	unpaired nucleon
^{1}H	1/2	100	2.793	0.750	proton
^{7}Li	3/2	92.5	3.256	0.244	proton
^{11}B	3/2	80.1	2.689	0.112	proton
^{15}N	1/2	0.4	−0.283	0.087	proton
^{19}F	1/2	100	2.629	0.647	proton
^{23}Na	3/2	100	2.218	0.041	proton
^{127}I	5/2	100	2.813	0.007	proton
^{133}Cs	7/2	100	2.582	0.052	proton
^{3}He	1/2	1.0×10^{-4}	−2.128	0.928	neutron
^{17}O	5/2	0.0	−1.890	0.342	neutron
^{29}Si	1/2	4.7	−0.555	0.063	neutron
^{73}Ge	9/2	7.8	−0.879	0.065	neutron
^{129}Xe	1/2	26.4	−0.778	0.124	neutron
^{131}Xe	3/2	21.2	0.692	0.055	neutron
^{183}W	1/2	14.3	0.118	0.003	neutron

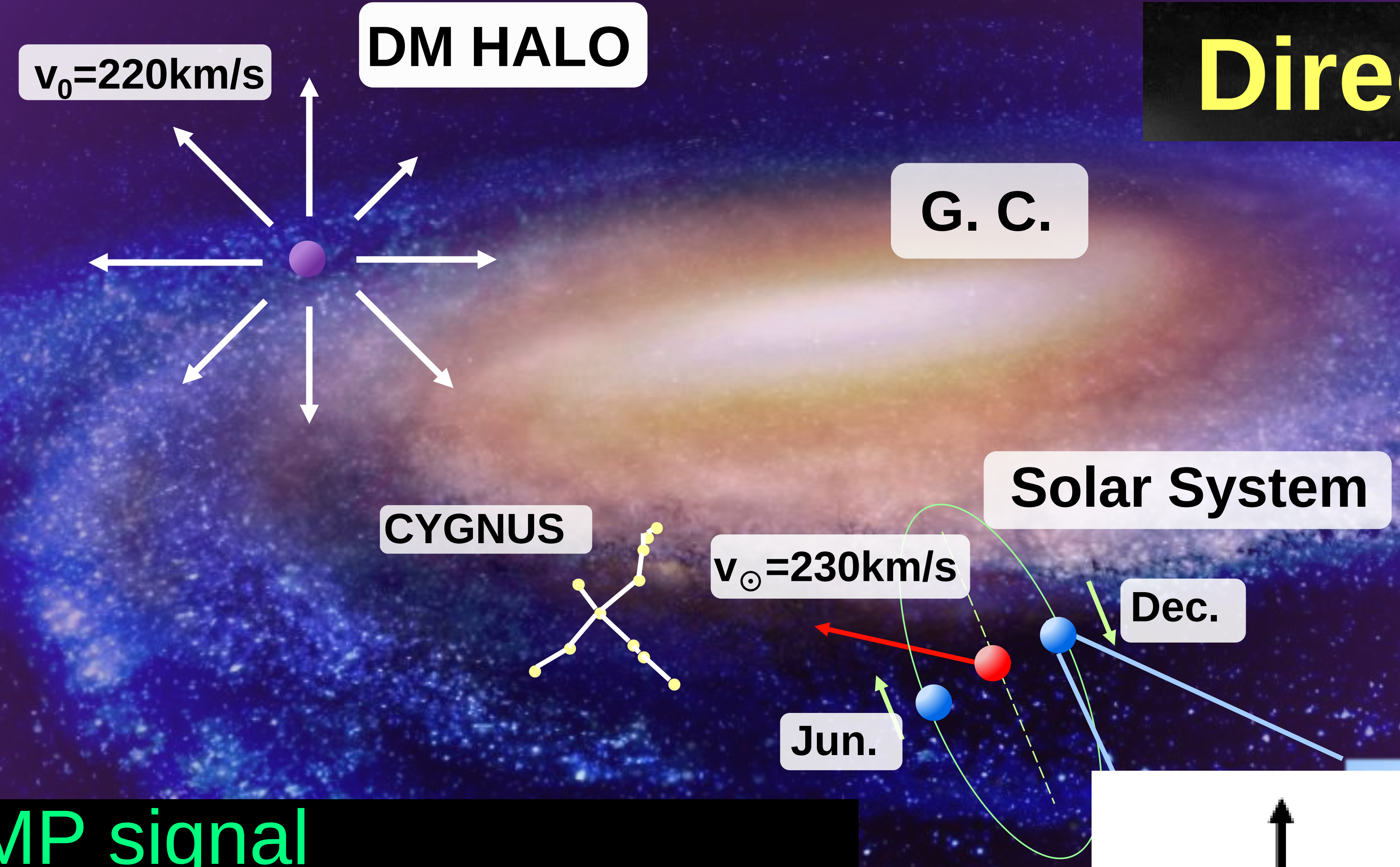
PICO Results and Future Plans

Hugh Lippincott, Fermilab
for the PICO Collaboration
EDU 2017

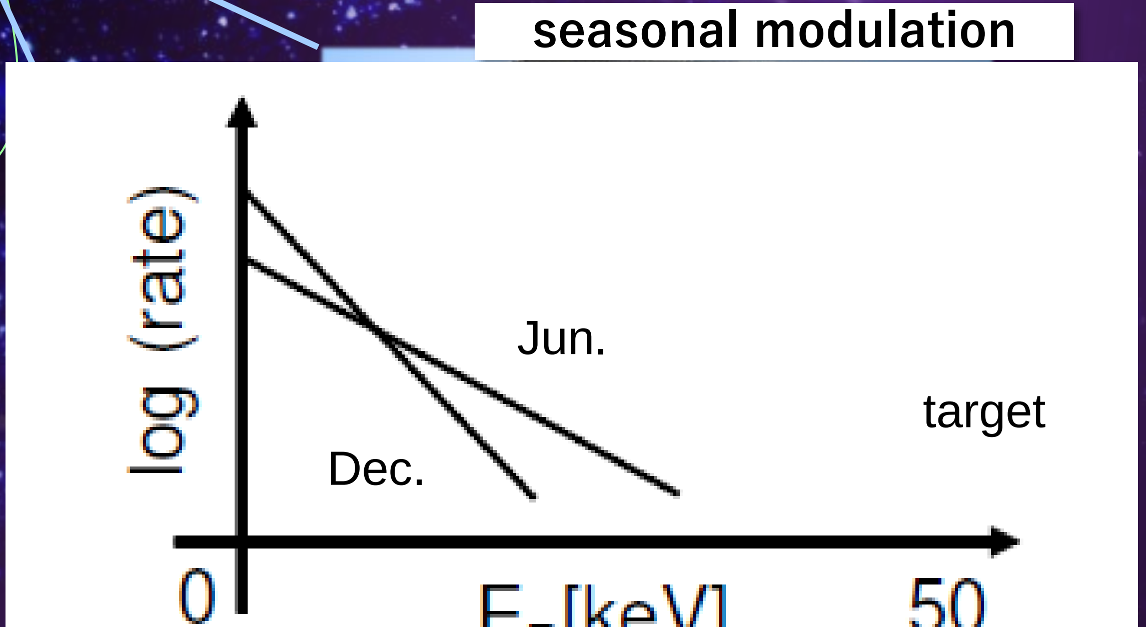
Scaling to PICO-500



Direct Detection

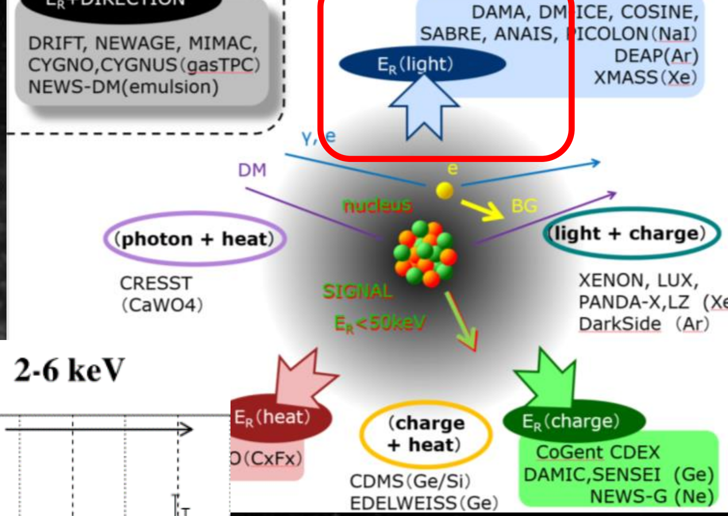


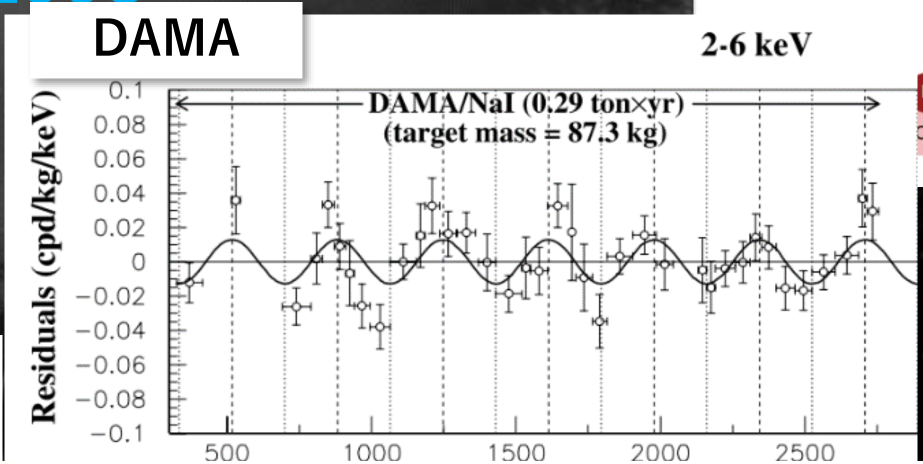
- WIMP signal
  - nuclear recoil: elastic scattering
  - energy
  - nucleus dependence
  - seasonal modulation
  - direction



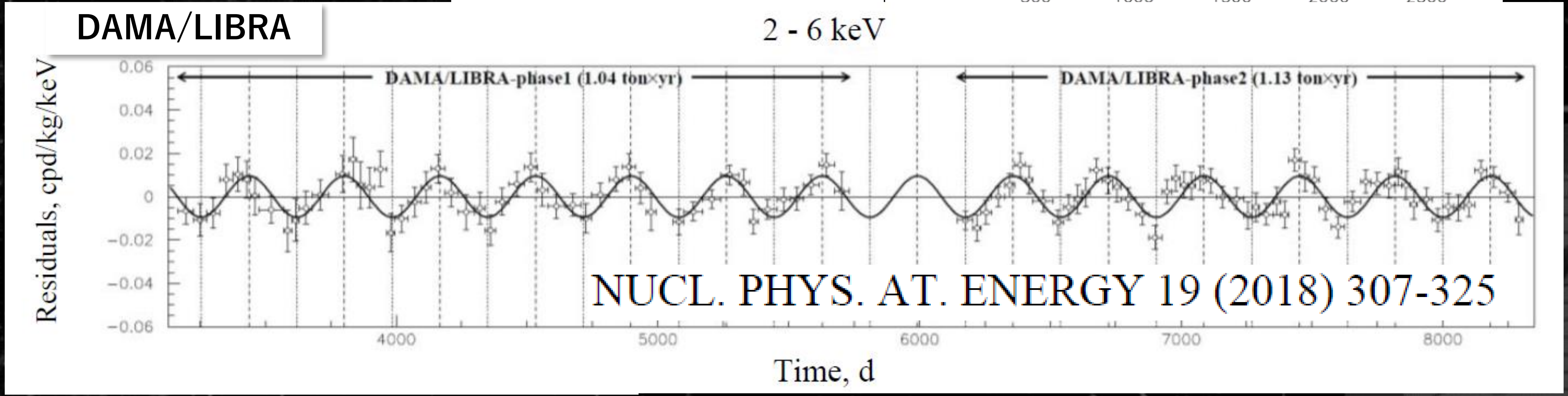
• DAMA (NaI)

- 250kg NaI scintillators
- Annual modulation were reported：1998～
- Latest 2.46 ton year 12.9 σ
- SOMETHING is detected





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

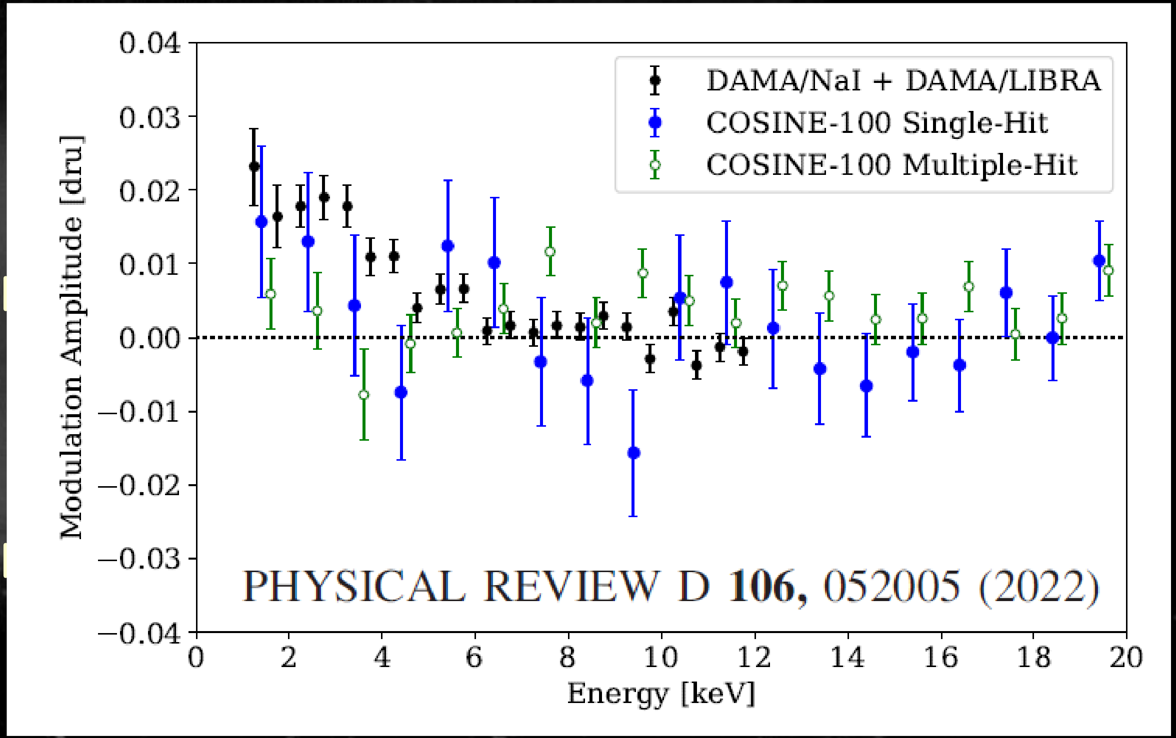


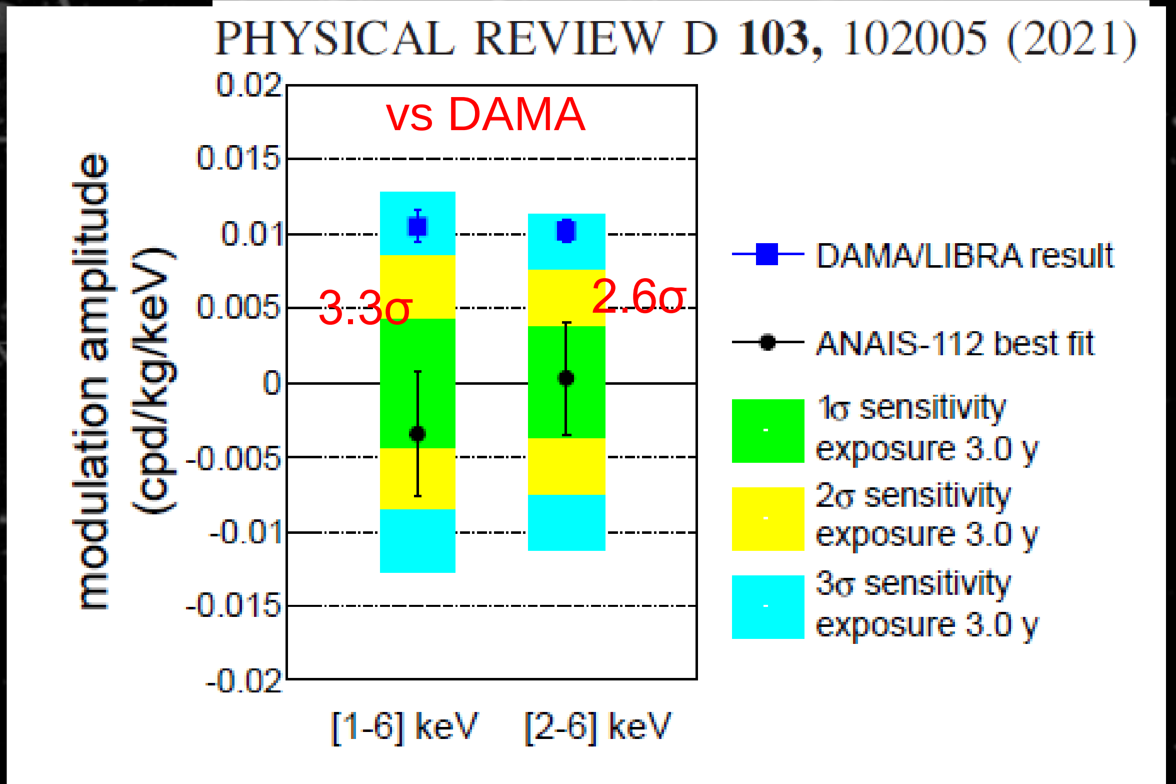
NUCL. PHYS. AT. ENERGY 19 (2018) 307-325

No BG explains this modulation

No natural DM model explains, either…

- Other NaI detectors
  - COSINE(106kg)
    - 3 years' annual modulation measurer
    - Consistent with null and DAMA, yet.
  - ANAIS (112kg)
    - 3 years' annual modulation measurer
    - Incompatible with DAMA @3σ
  - SABRE
    - North and South
  - PICOLON
    - Pure crystal



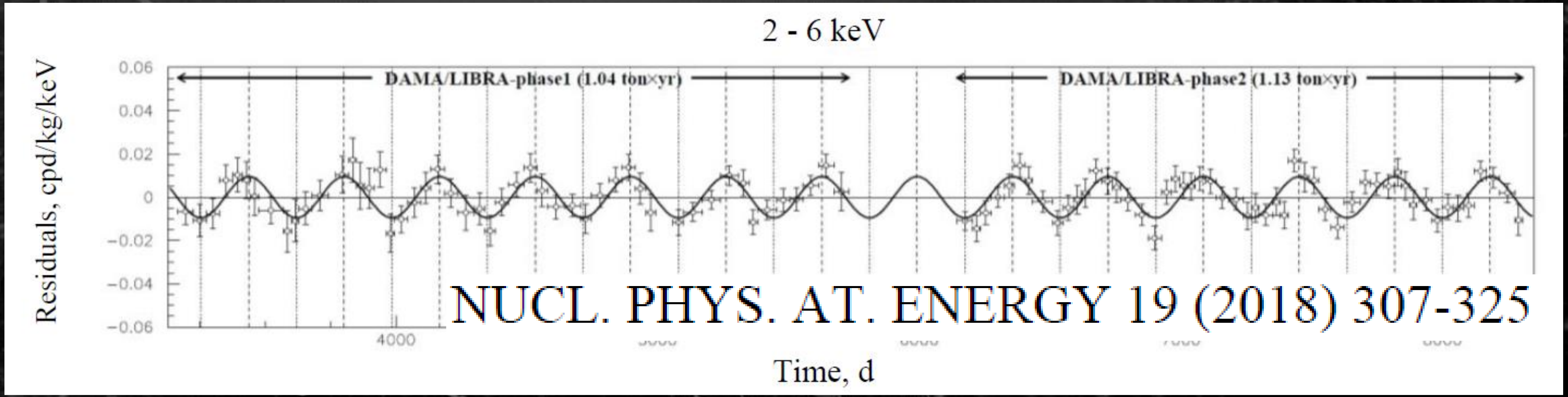


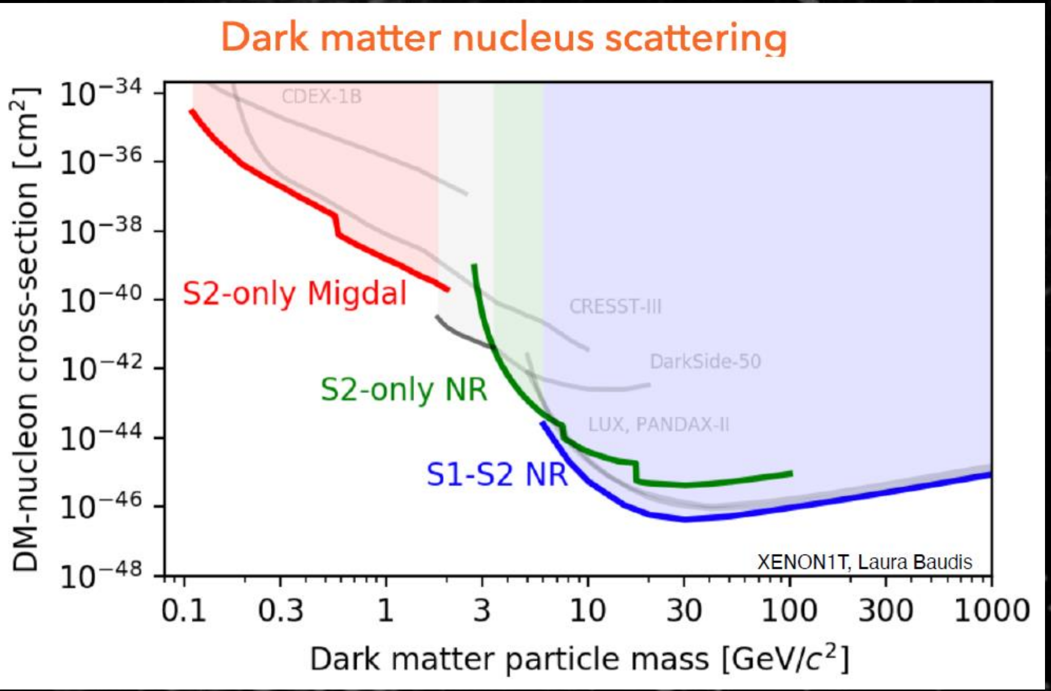
Need to be stay tuned.

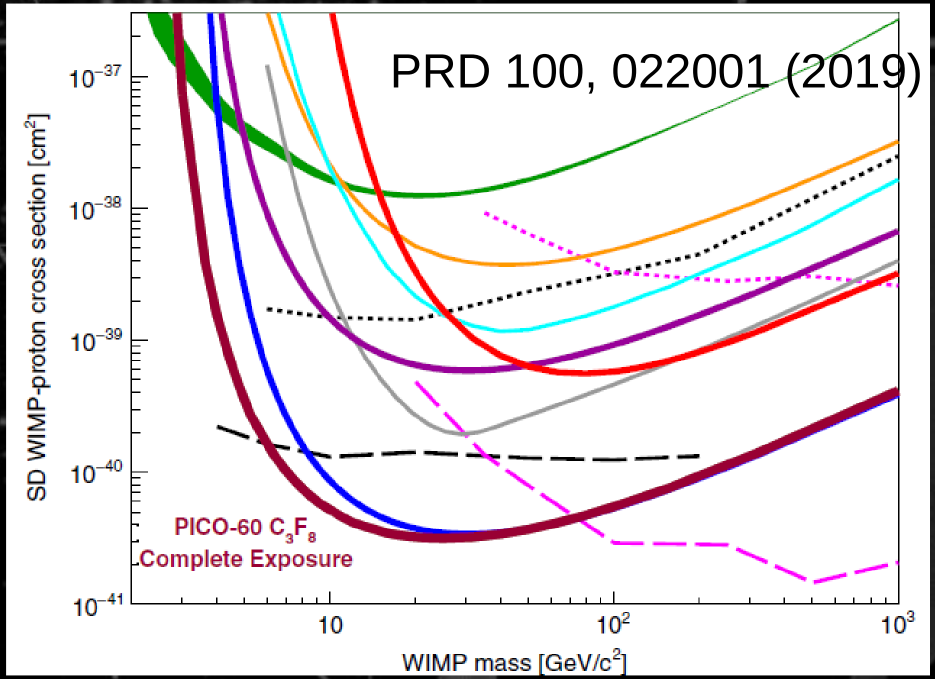
Kentaro Miuchi

Direct Search in a nutshell

- DAMA, Xenon (SI), Fluorine (SD)





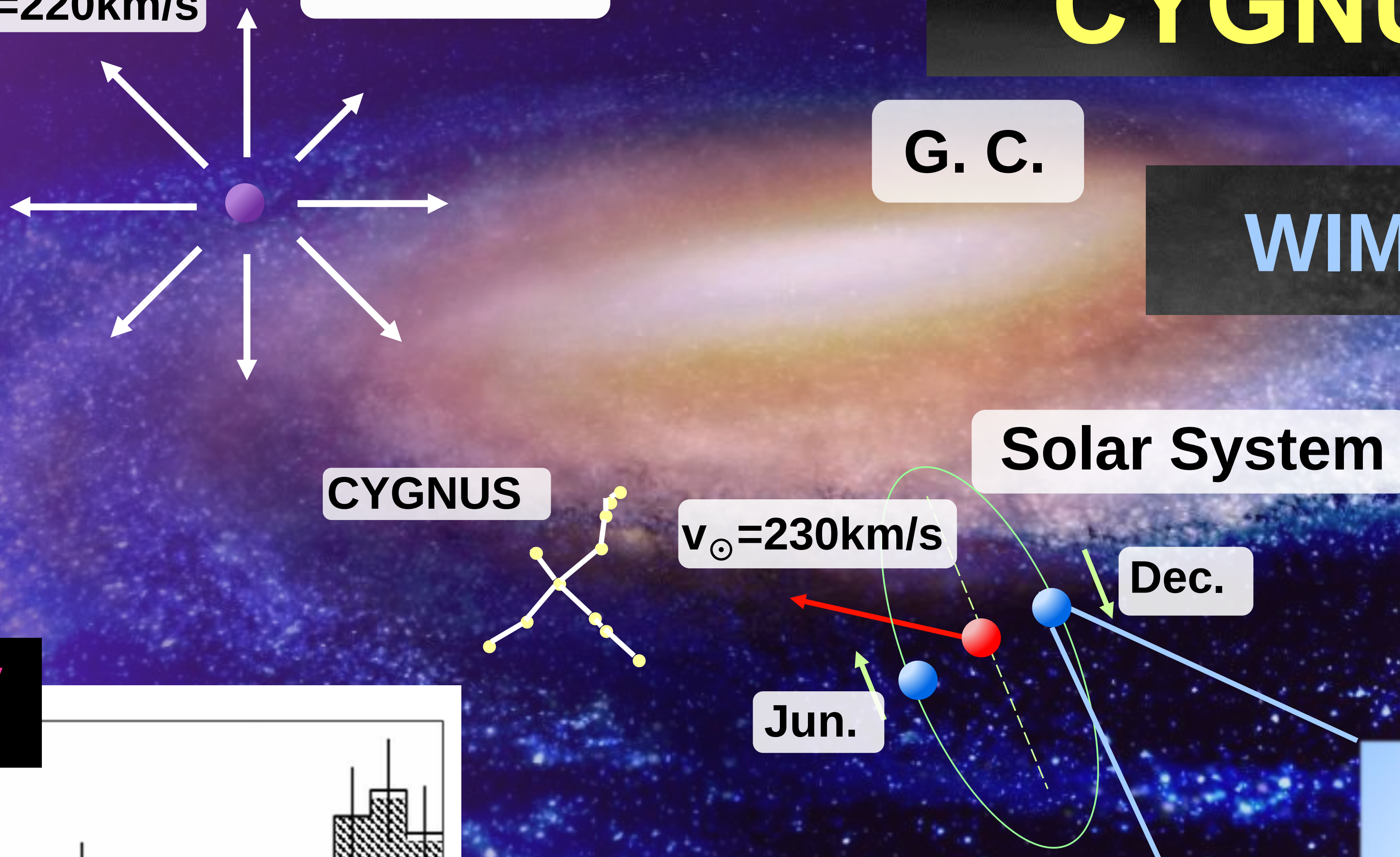


Directional Searches

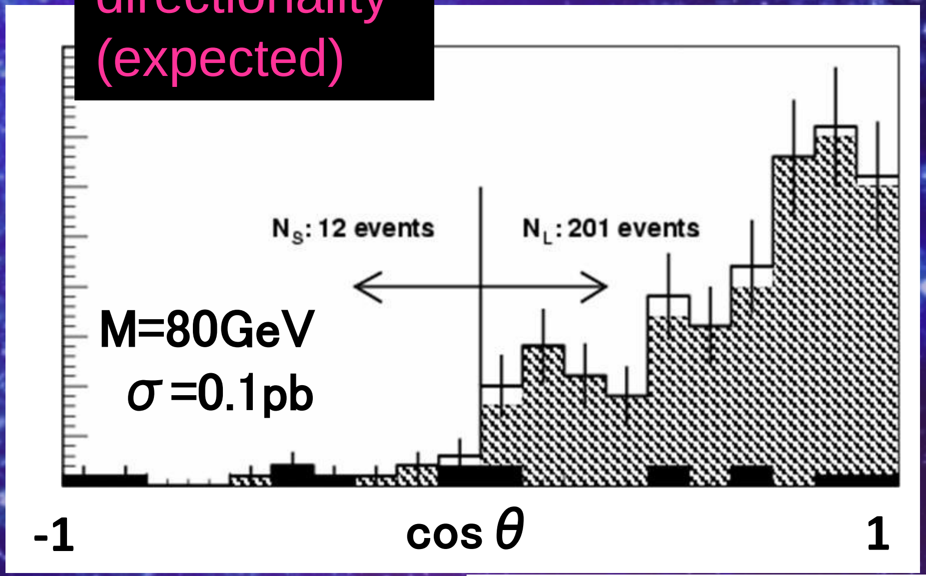
- DM Overview
- Directional
- Related Topics
- Summary

"CYGNUS" concept

WIMP-wind detection

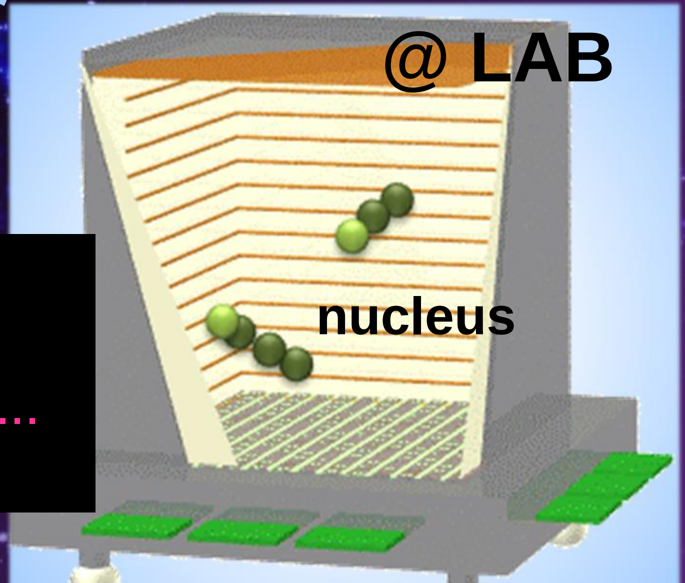


directionality
(expected)

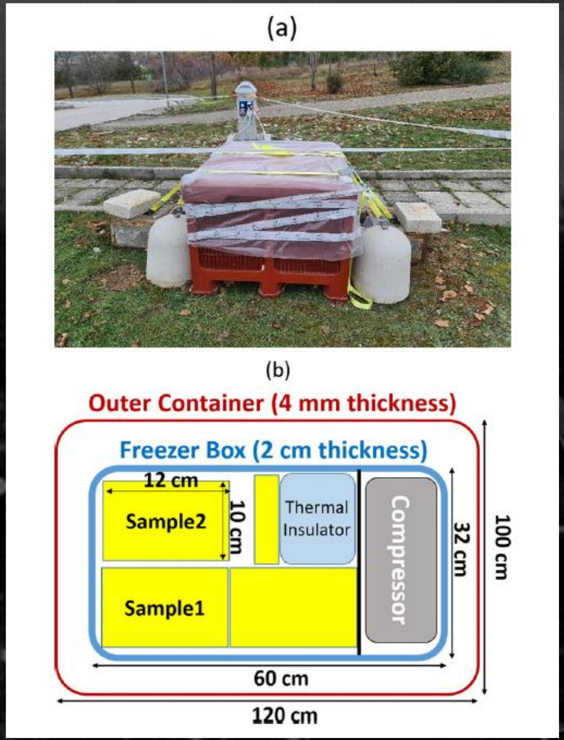


Physics Letters B 578 (2004) 241–246

detector:
- low pressure gas ← this talk
- emulsions ← You know more than I do...
- diamond detectors, scintillators...

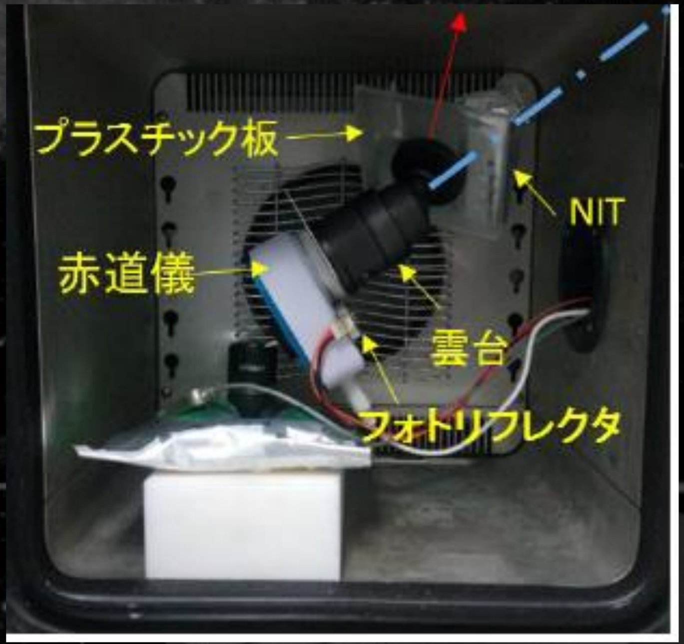


- Emulsions (NEWSdm)
  - Large mass
  - Fine-grain AgBr crystals for fine track detection



PhysRevC.107(2023)014608

DM run



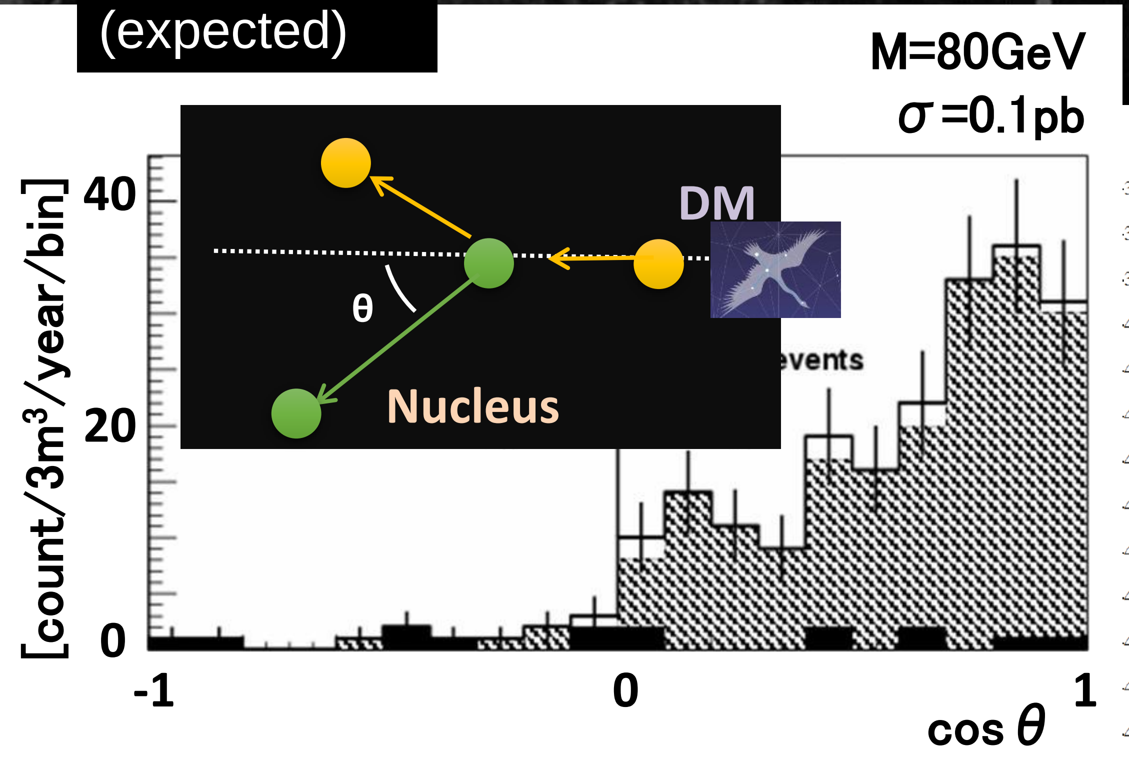
- A number of R&D publications PTEP (2021) 043H01
- Neutron measurement at Gran Sasso surface
- Hope to see DM search paper soon.

PhysRevC.107(2023)014608

Directional Detection

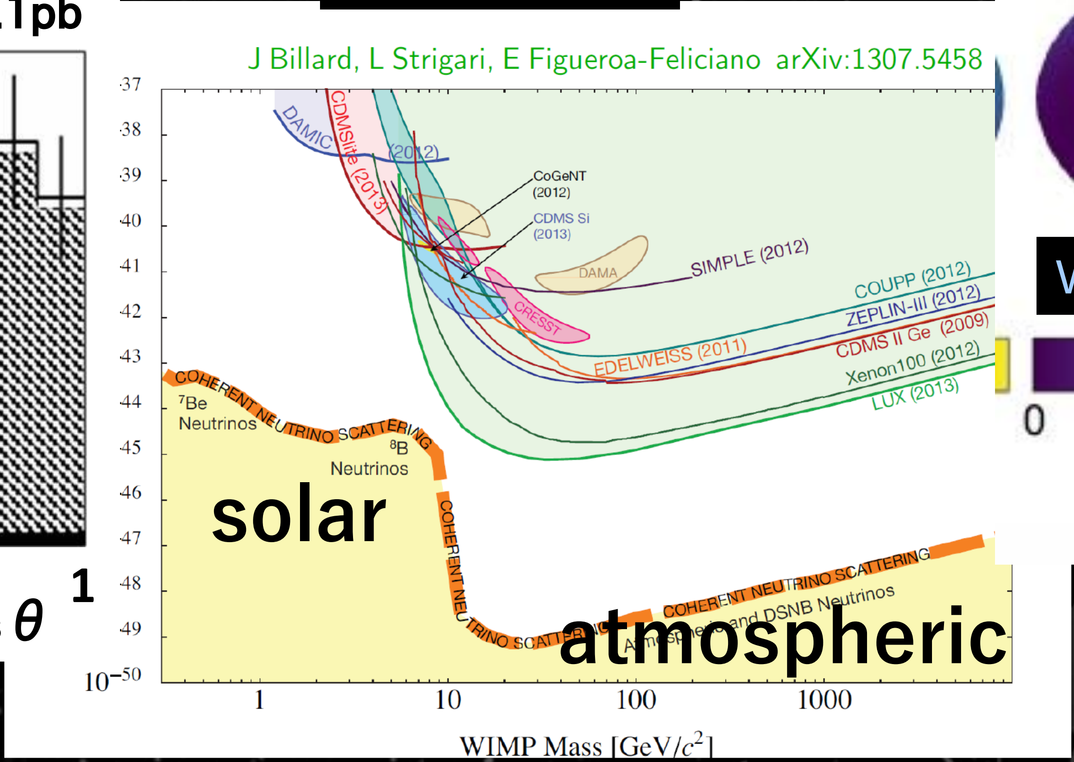
- Clear Discovery
  even with the neutrino BG
  + study the nature of DM after discovery

directionality (expected)

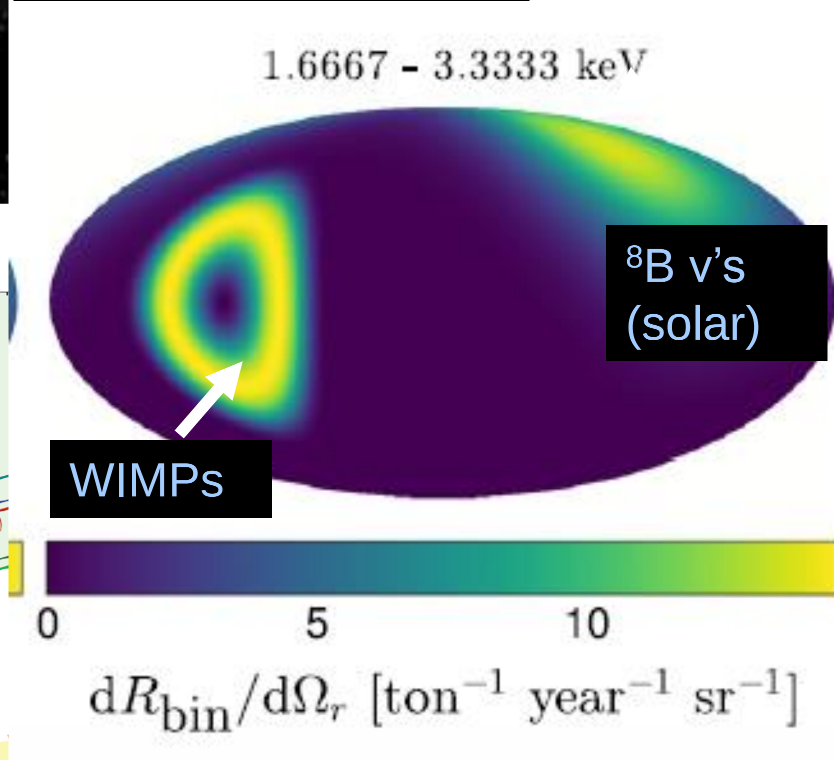


Physics Letters B 578 (2004) 241–246

neutrino floor



w/ neutrino BG (expected)



F. Mayet et al. / Physics Reports 627 (2016) 1–49

NEWAGE

NEWAGE: pre history

- PhD work: DM search with a bolometer (conventional detector)
- Shocked by “proton track“ image in 論文紹介.

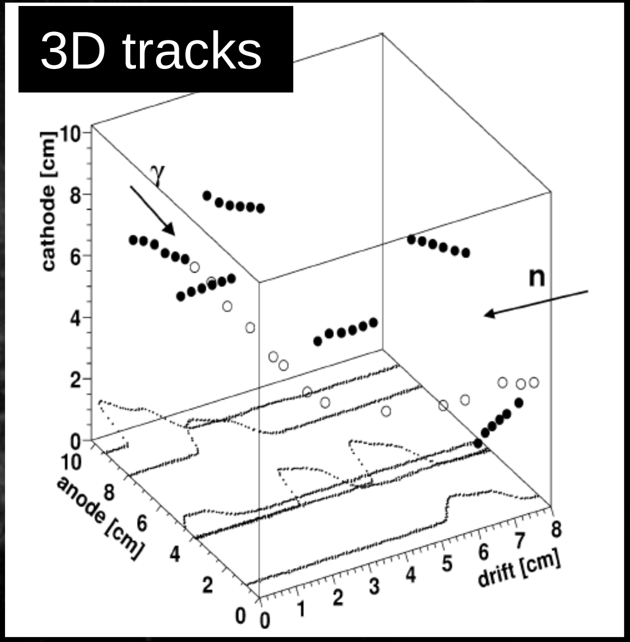
And it all started...

NEWAGE: the history

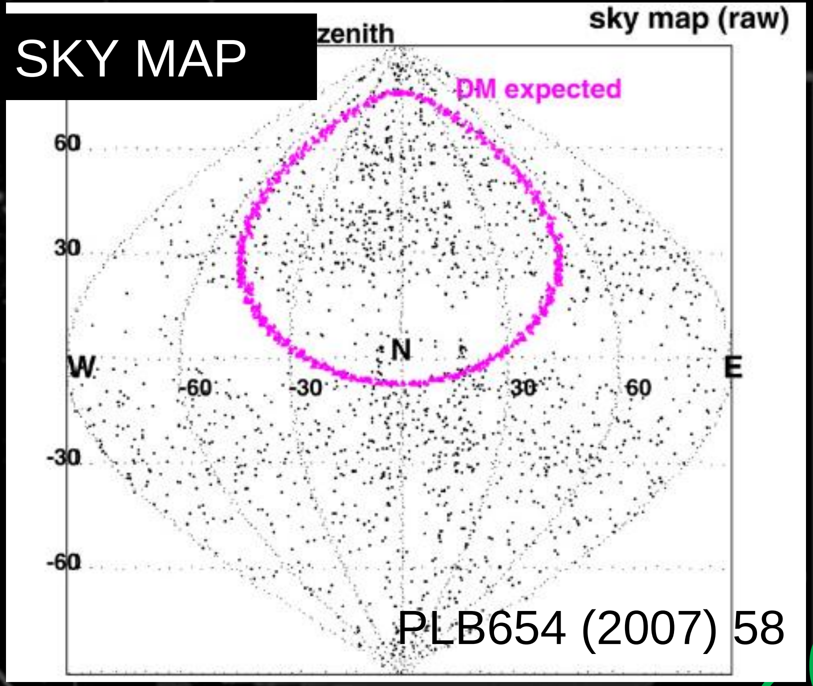
- Proposal PLB 578 (2004) 241
- First direction-sensitive limits → pioneered: use of CF_4 gas, sky map analysis

  PLB654 (2007) 58
- Underground results

  PLB686 (2010) 11 ... , PTEP(2021) 063F01, new arXiv:2301.04779
- Phase for “low BG” & “large volume”



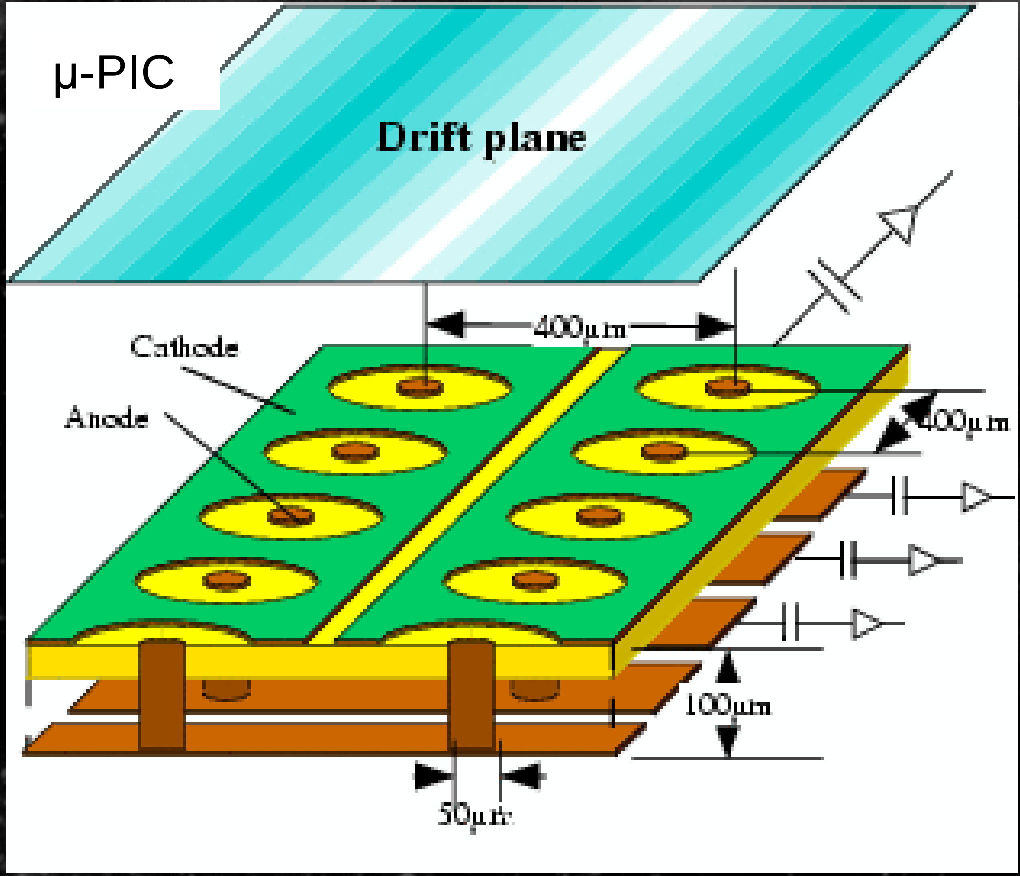
PLB578 (2004)241

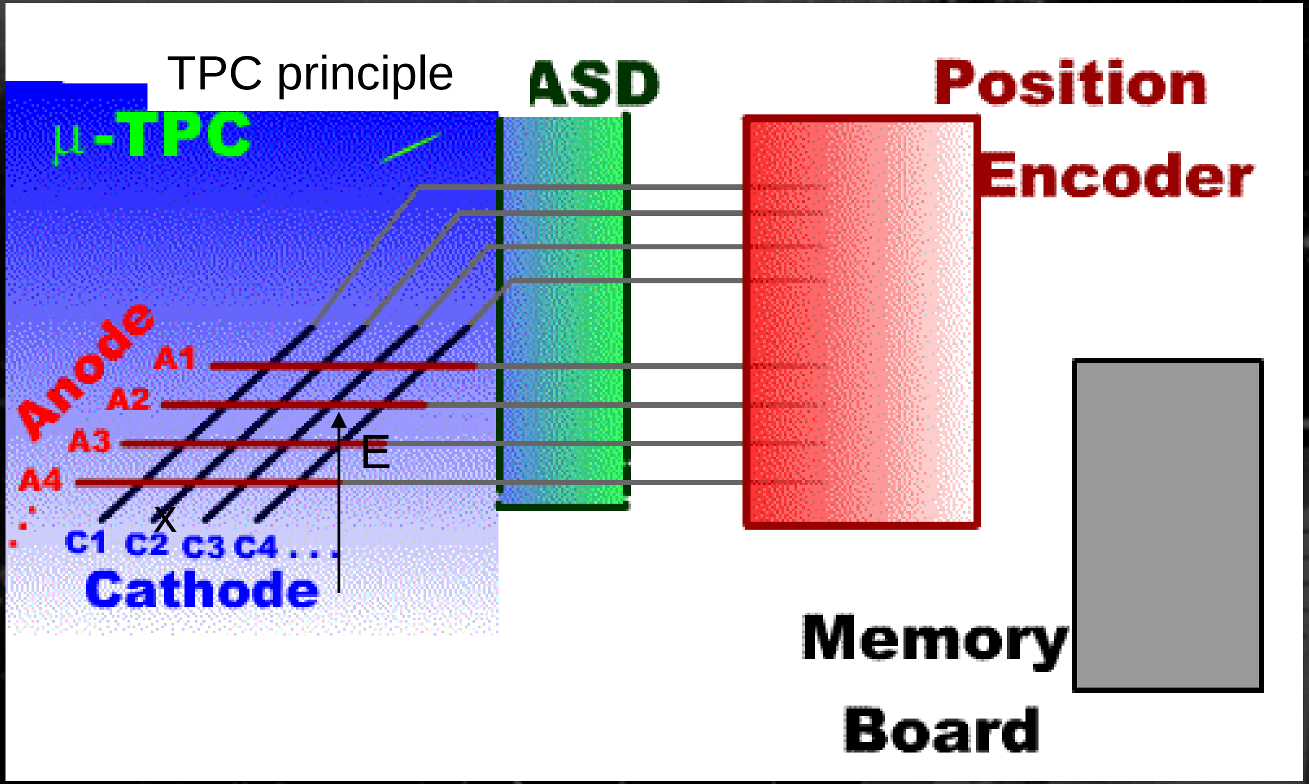


PLB654 (2007) 58

- Technology: Gaseous Time Projection Chamber
  - 2-dimensional image: Micro Patterned Gaseous Detector (MPGD)
  - timing information: 3rd dimension
  - realtime 3-dimensional tracking

MPGD:
GEM, micromegas, μ-PIC



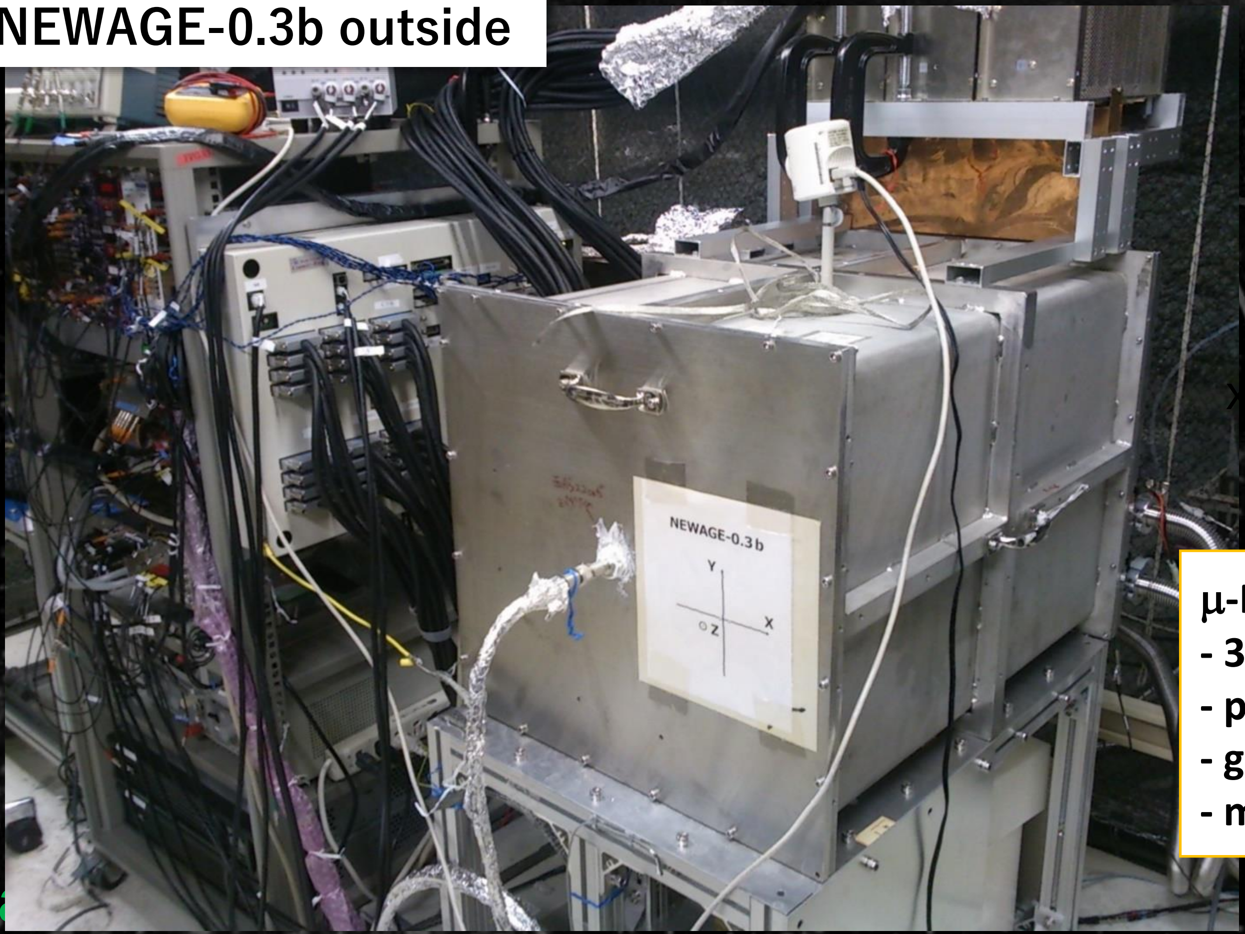


- drawback: small mass O(kg) / m^3

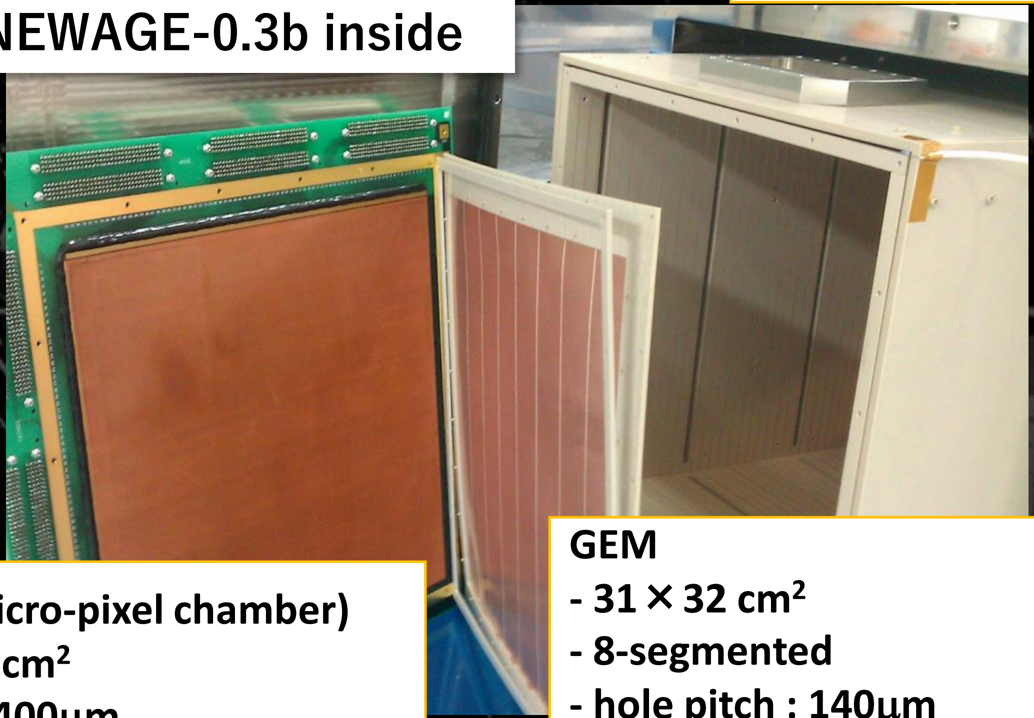
- Detector: NEWAGE-0.3b''
  - Detection Volume: $31 \times 31 \times 41 \mathrm{cm}^3$
  - ～1500ch readout system
  - Gas: CF_4 at 0.1atm (50keVee threshold)
  - Gas circulation system with cooled charcoal

Field cage
Drift length: 41cm
PEEK + copper wires

NEWAGE-0.3b outside



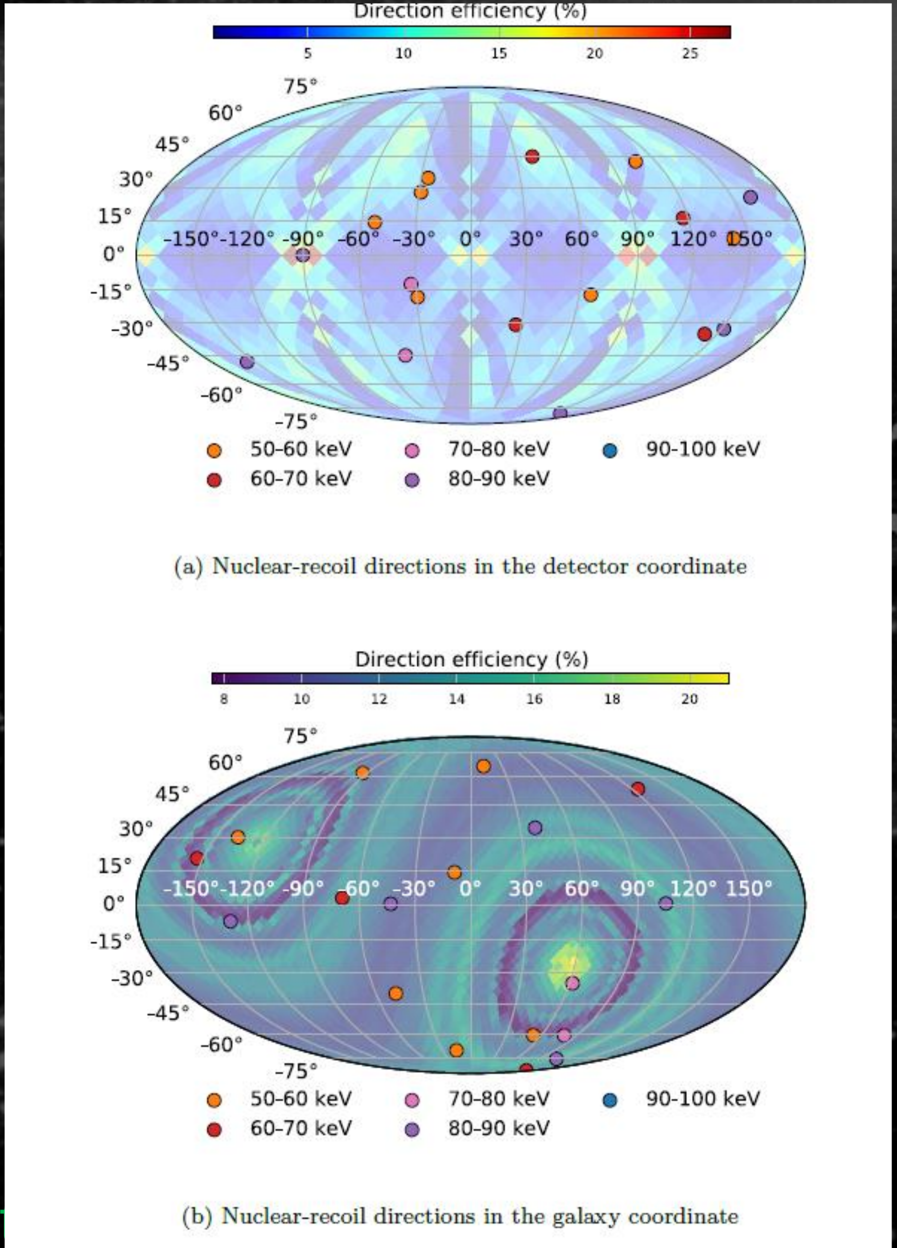
NEWAGE-0.3b inside



μ-PIC(Micro-pixel chamber)
- $31 \times 31 \mathrm{cm}^2$
- pitch : 400μm
- gain : ~1000
- made by DNP, Japan

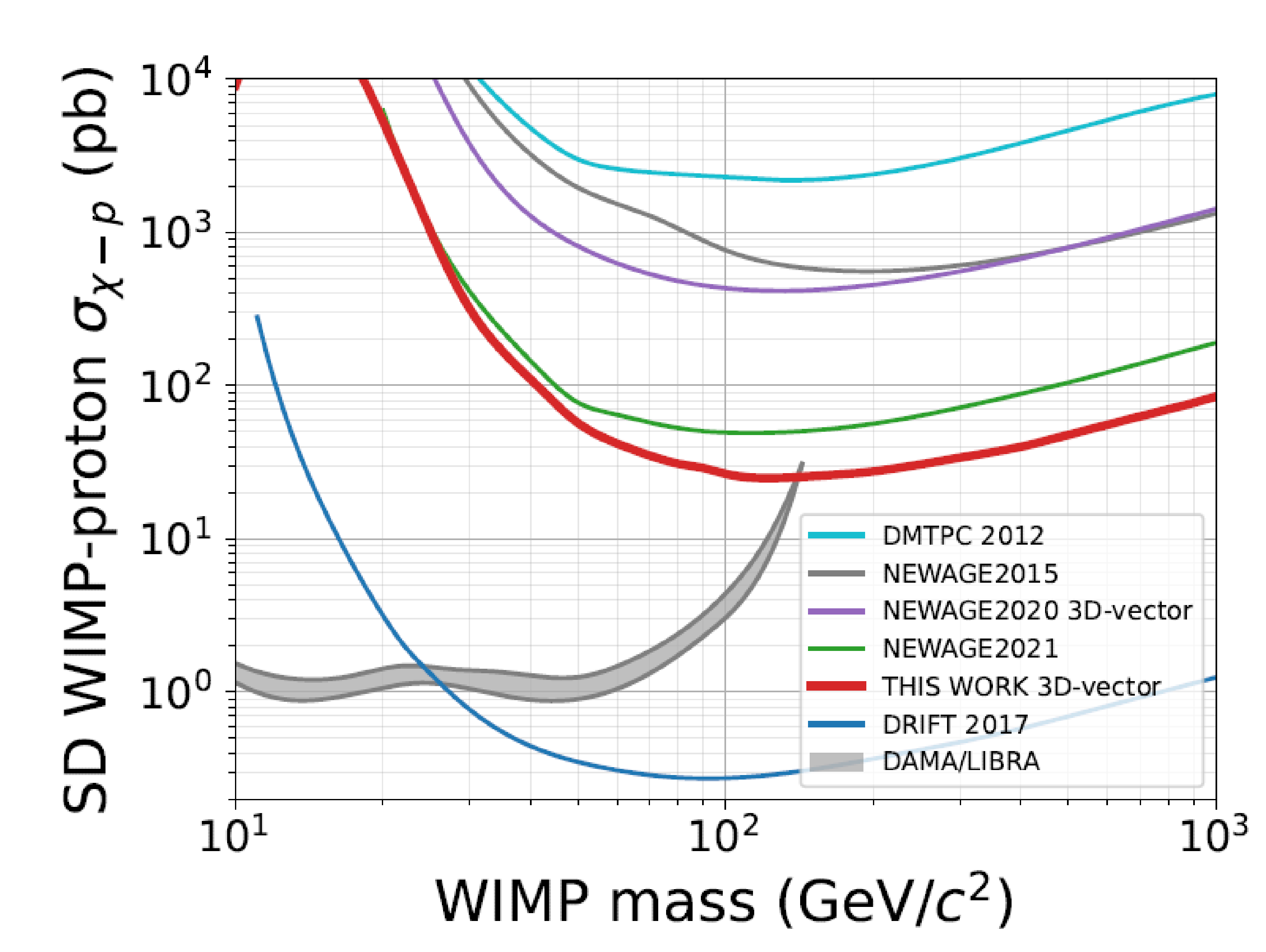
GEM
- $31 \times 32\ \mathrm{cm}^2$
- 8-segmented
- hole pitch : 140μm
- hole diameter: 70μm
- insulator : LCP 100μm
- gain : ~5
- made by Scienergy, Japan

- NEWAGE latest results arXiv:2301.04779
  - 318 days measurement @ Kamioka

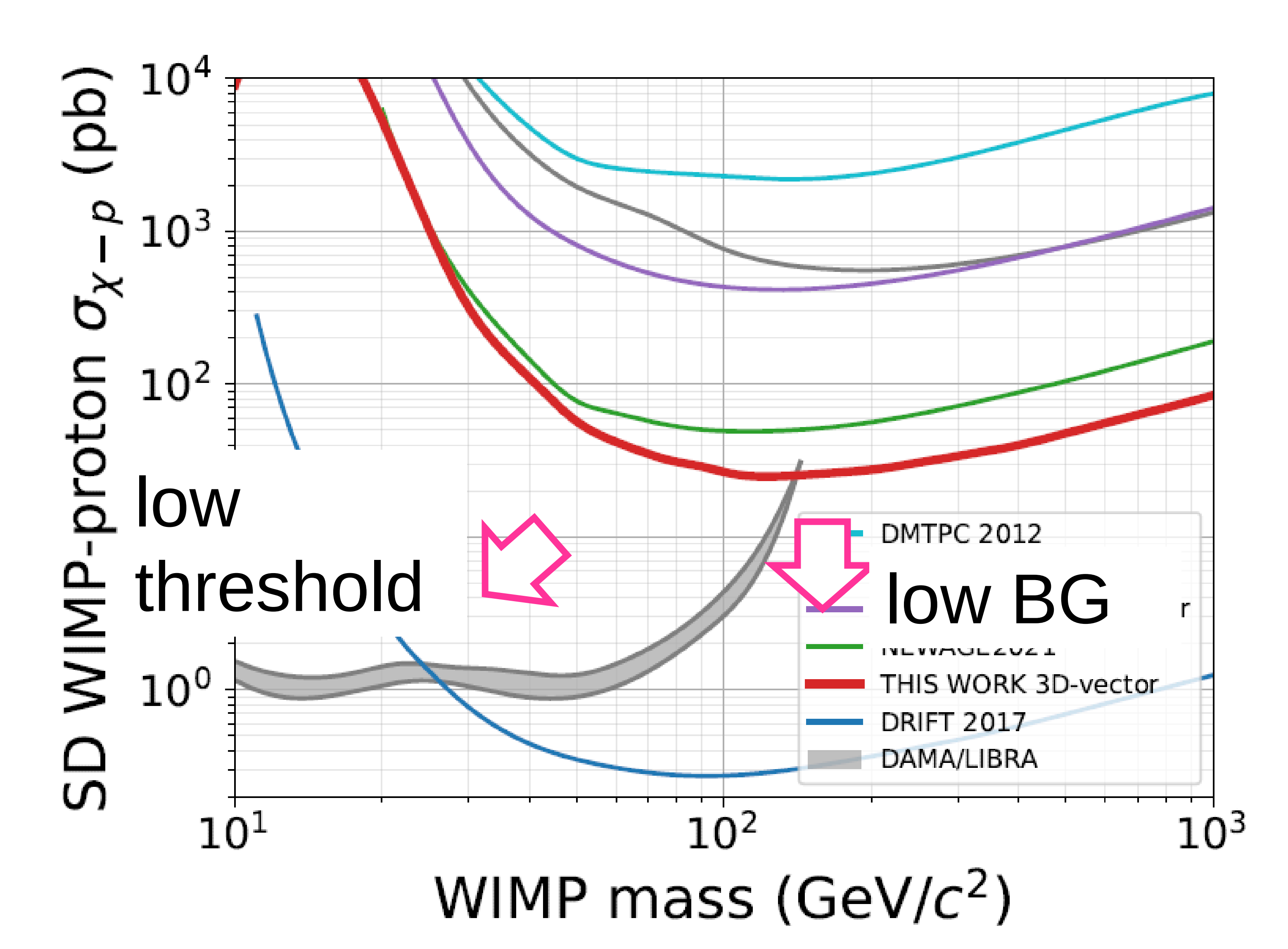


(a) Nuclear-recoil directions in the detector coordinate

(b) Nuclear-recoil directions in the galaxy coordinate



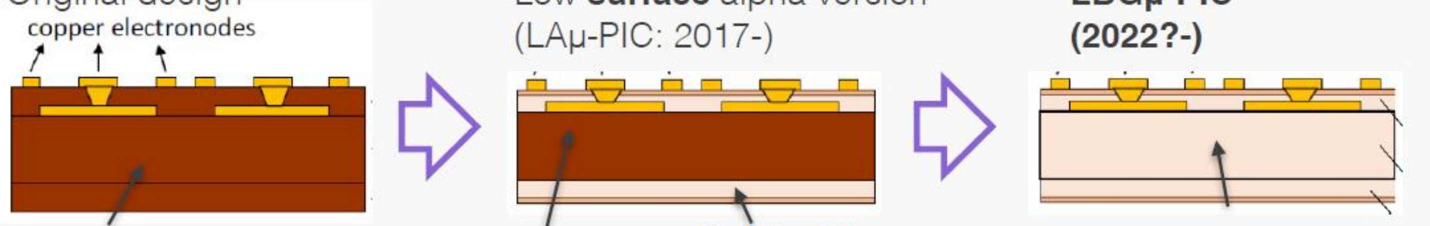
- NEWAGE way to go arXiv:2301.04779
  - low BG and low threshold to explore the DAMA region



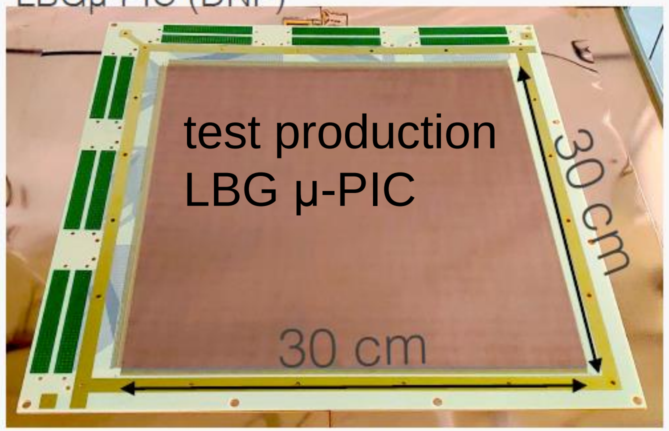
- NEWAGE getting low background ①
  - μPIC of low rate alpha-ray emission (LAμ-PIC) NIM A 977 (2020) 164285
  - μPIC of low background (LBG-PIC)

Low-BG μ-PIC (LBGμ-PIC)

- Proto-type Low-BG μ-PIC is developed and evaluated



LBGμ-PIC (DNP)



Radon emanation measurement:

LAμ-PIC: **2.3 ± 0.5** [mBq / μ-PIC]

LBGμ-PIC: <**0.17** [mBq / μ-PIC]

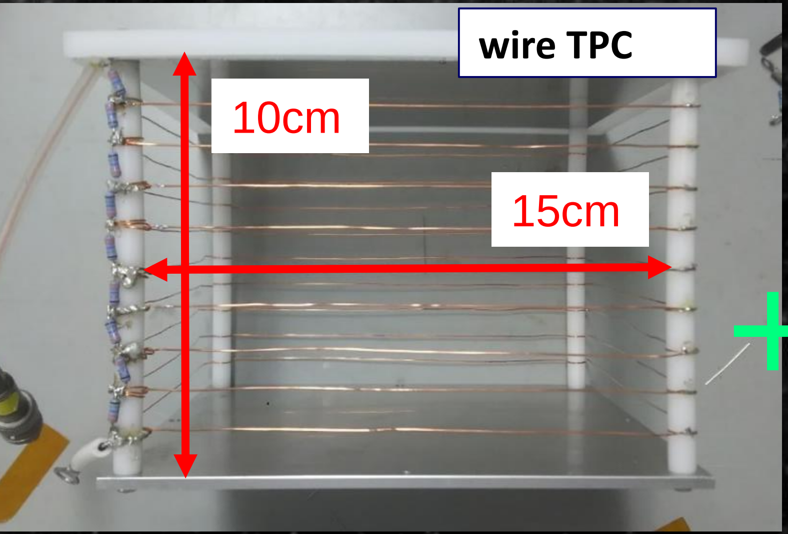
(90% C.L.)

LBGμ-PIC is being manufactured now.

- Resistive Sheet TPC

PTEP 2019 (2019)063H01

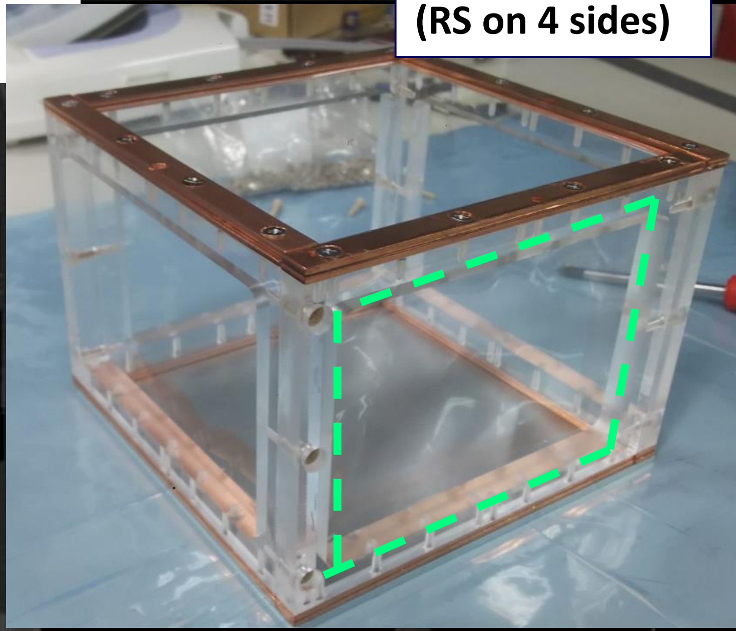
  - need electric field to drift electrons
  - traditional method: wires, ribbons...
  - new approach: resistive sheet
    - easy to assemble
    - radioactive low BG
    - uniform electric field



+

commercially-available
"anti-electric sheet" as cheap starting

carbon sputtered
EVOH sheet (for radon barrier)

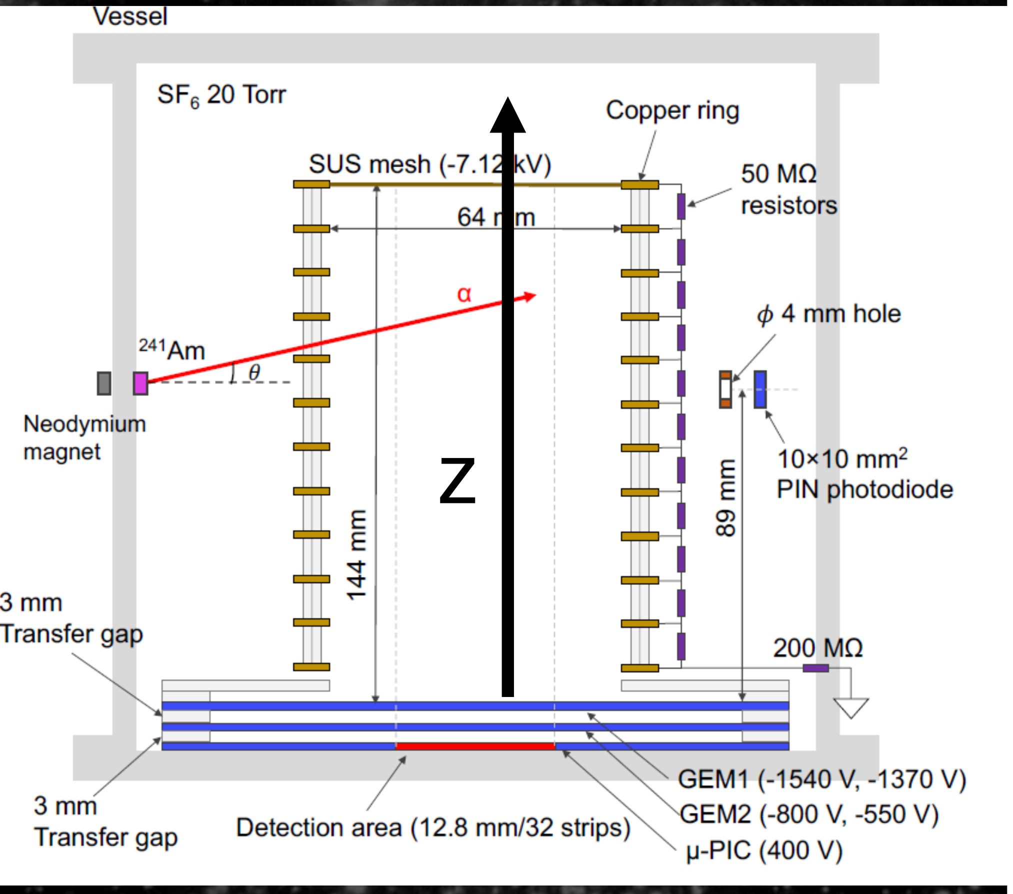


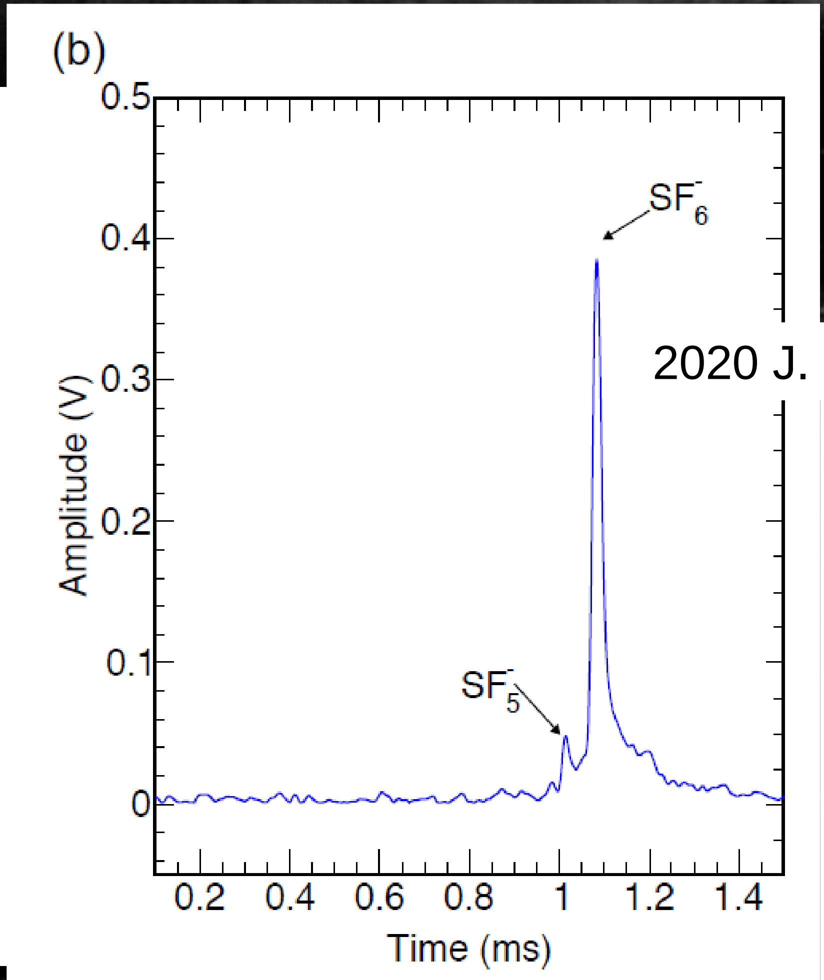
RS-TPC
(RS on 4 sides)

Kentaro Miuchi

- NEWAGE getting low background ② = negative ion TPC
  - Pioneered by DRIFT group
    - originally for small gas diffusion
    - use several ion species with different drift velocities

⇒ z position sensitive ⇒LOW BG !

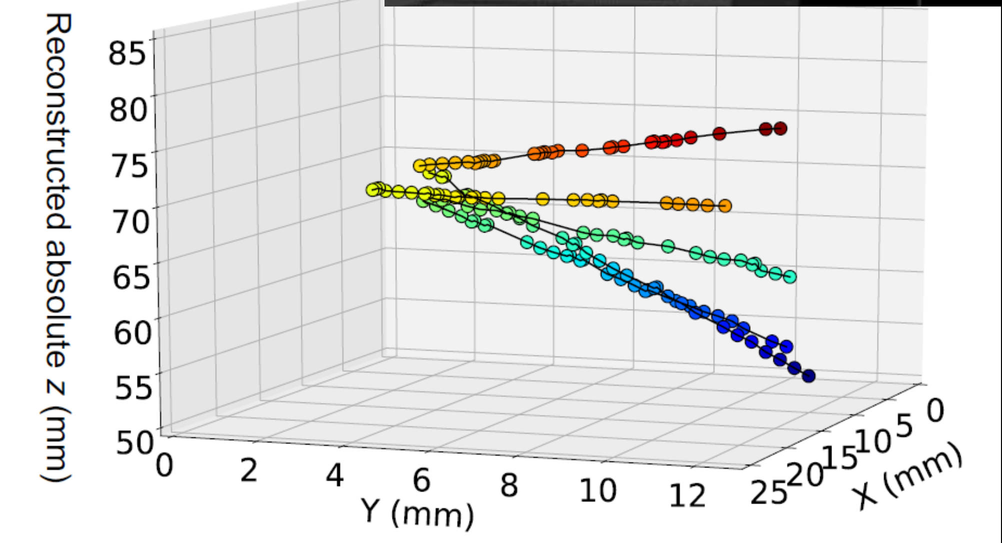




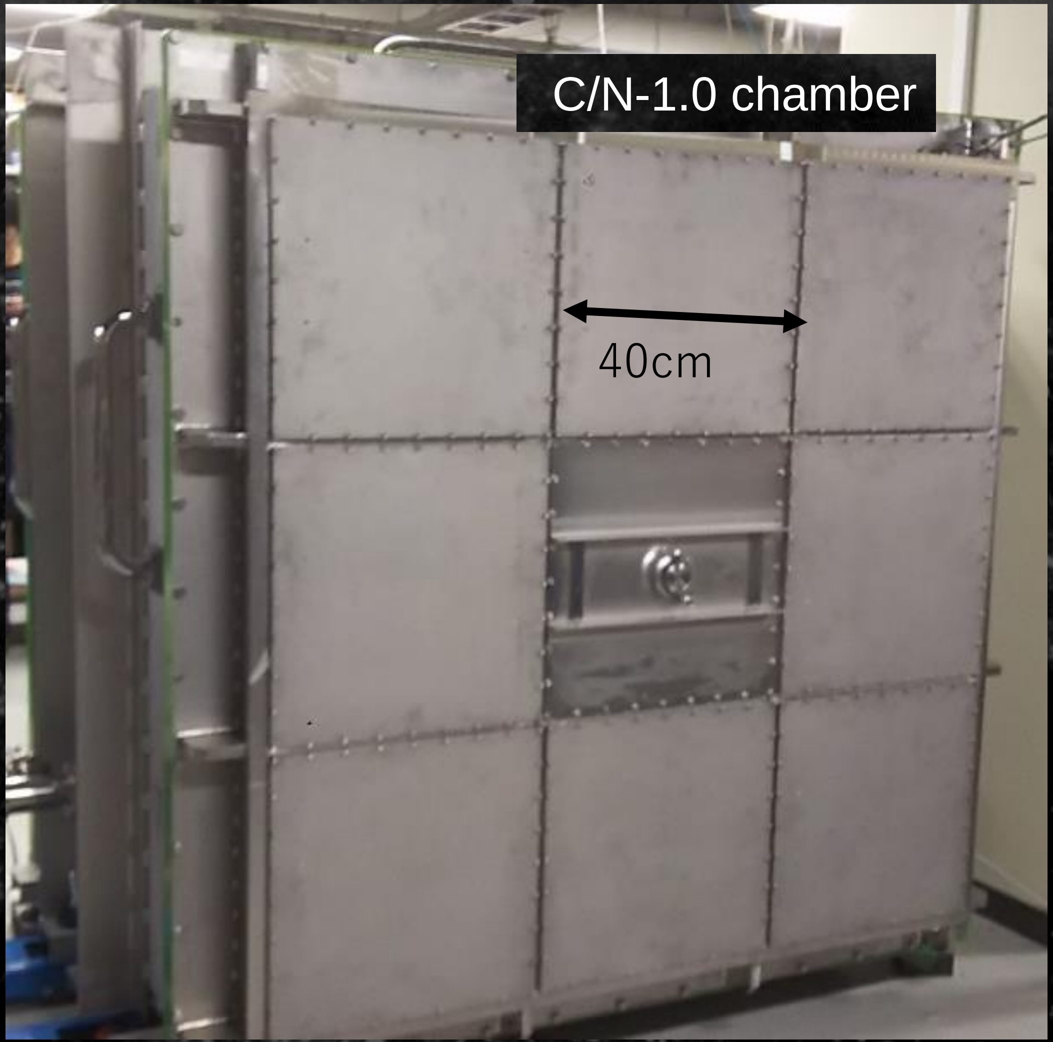
2020 J. Inst. 15 P07015

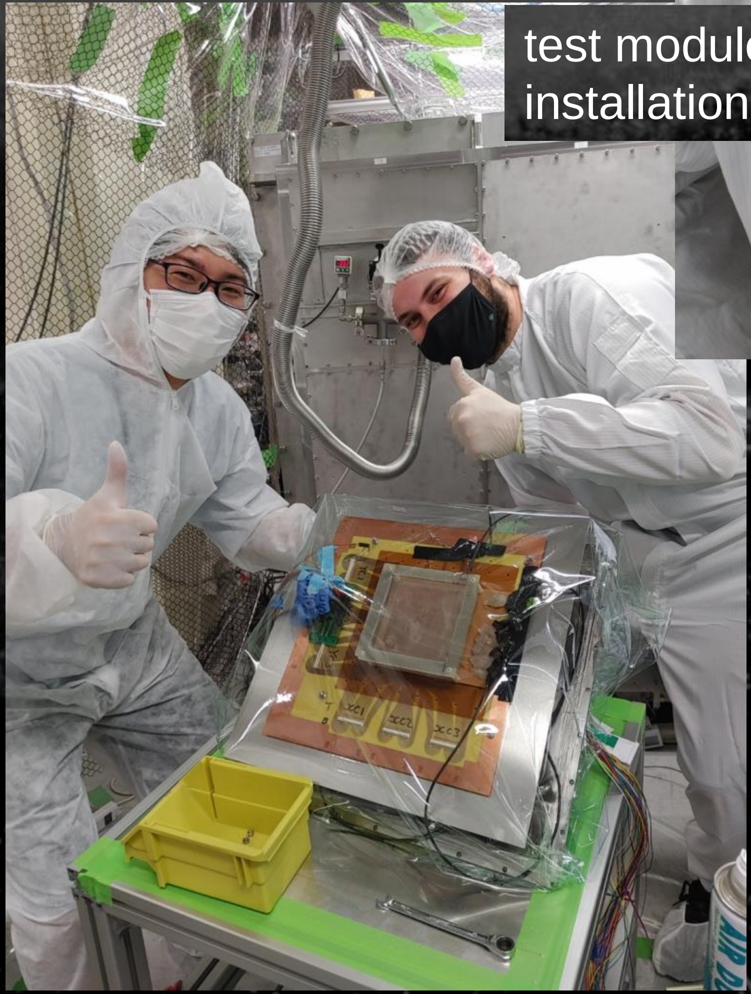
first ever 3D tracking

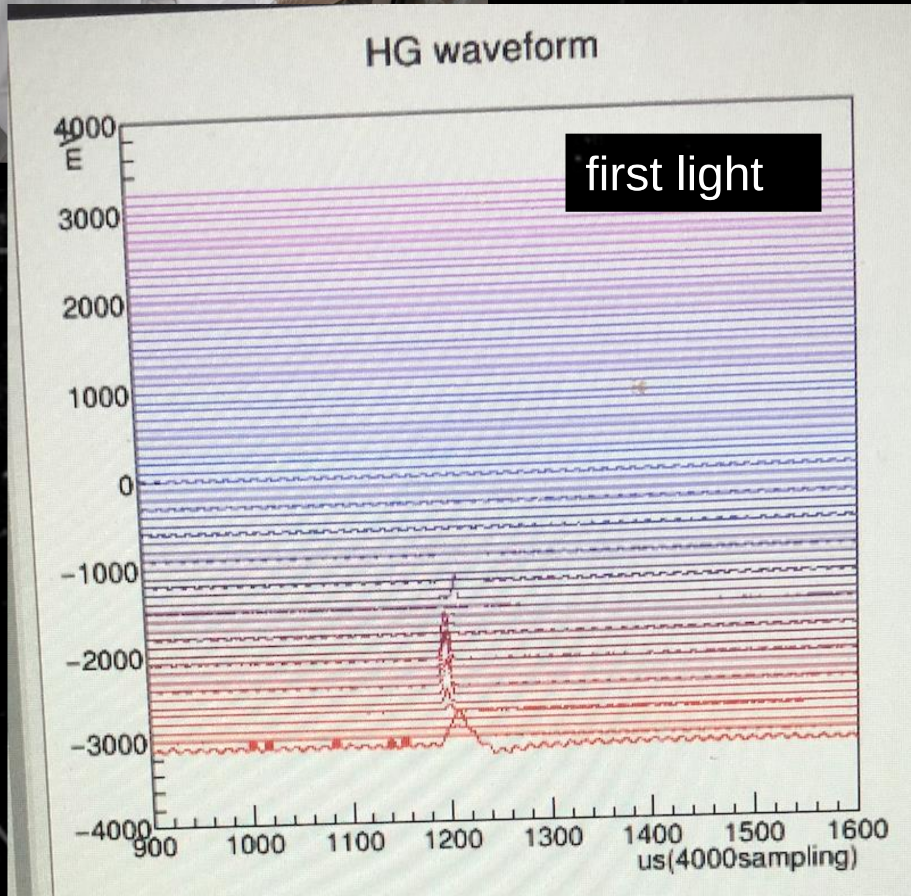
+ fiducialisation



- NEWAGE getting larger
  - C/N(CYGNUS/NEWAGE)-1.0 chamber
  - 18 × 30 × 30 cm^2 detectors
  - being commissioned @ Kobe







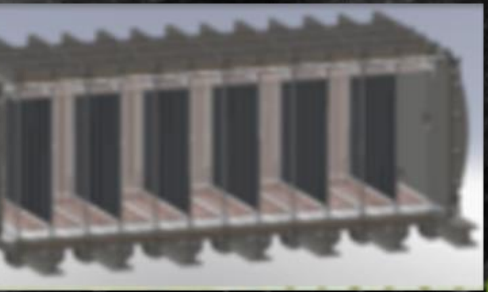
Kentaro Miuchi

• NEWAGE getting international = CYGNUS

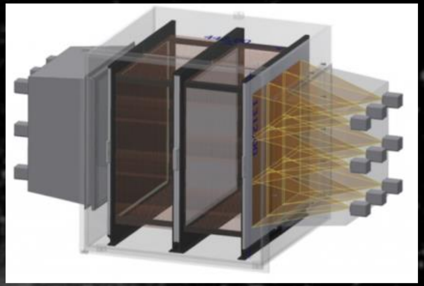
2020 J. Phys.: Conf. Ser. 1468 012044

NEWAGE/CYGNUS-KM
Kamioka, Japan
SF6 / CF4
Strip readout

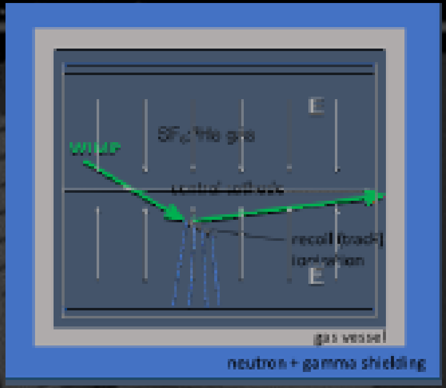
CYGNUS-10
Boulby, UK
10m³ He:SF_6
GEM + wire readout



CYGNO-Initium
Gran Sasso, Italy
He CF_4 (SF_6)
sCMOS+PMT readout



CYGNUS-HD10
SURF, USA
He:CF_4:C_4H_{10}
Strip readout



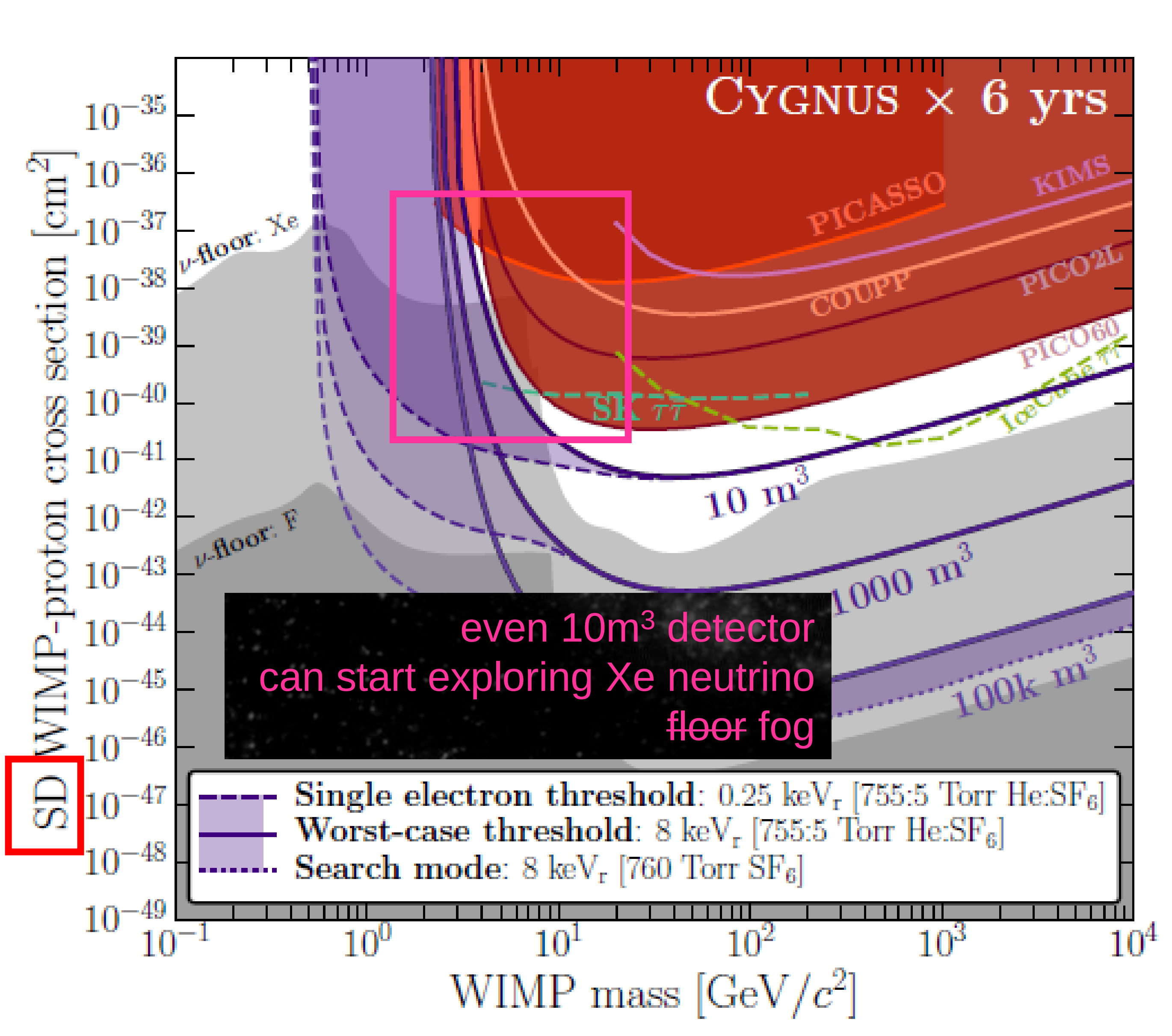
CYGNUS-OZ
Stawell, Australia
R&D leading to 1 m^3
Long-term plan 10 m^3

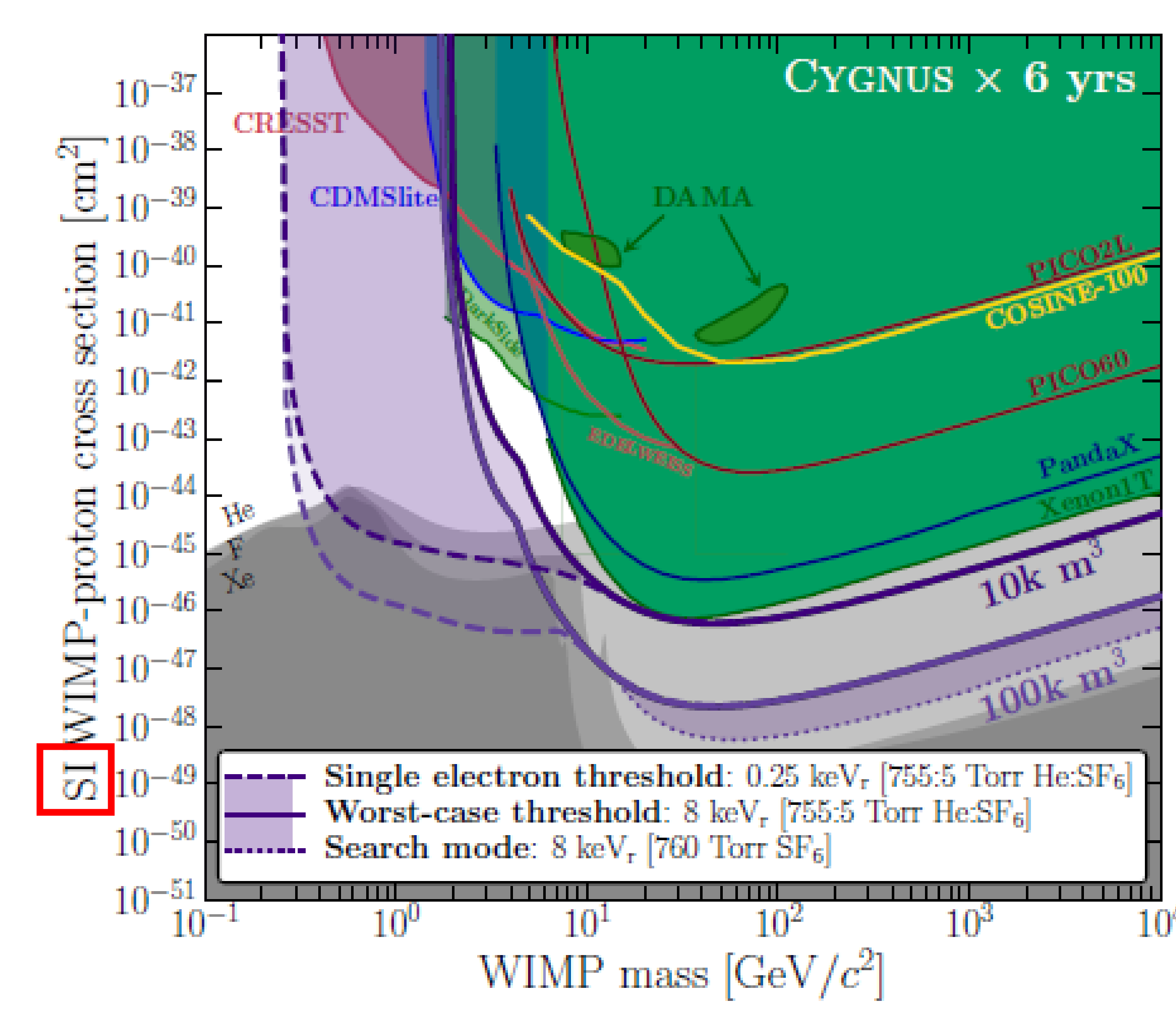
multi-site observatory

CYGNUS: physics reaches

- Realistic simulation (strip readout)

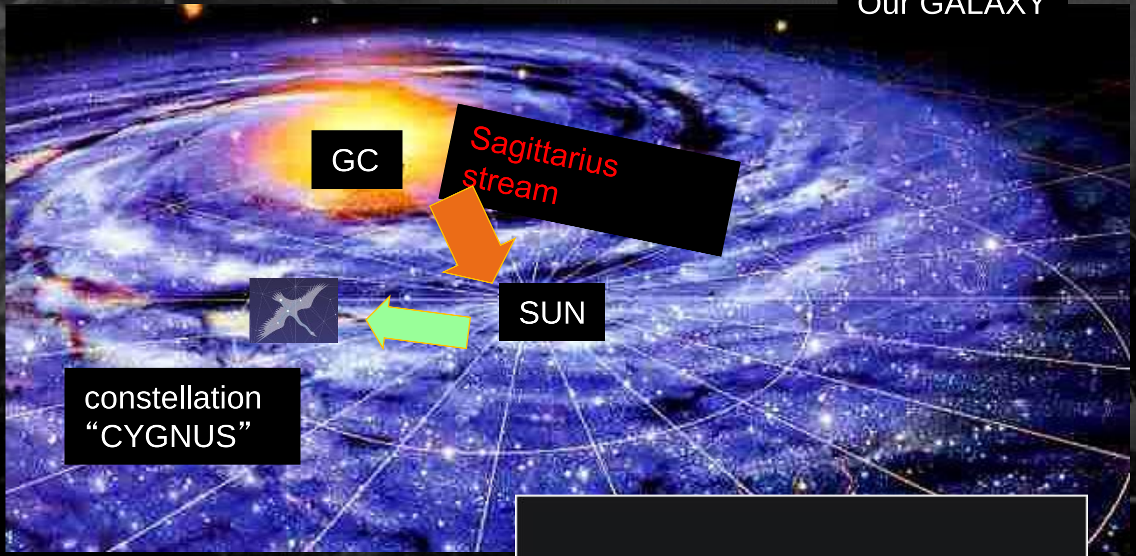
arXiv 2008.12587

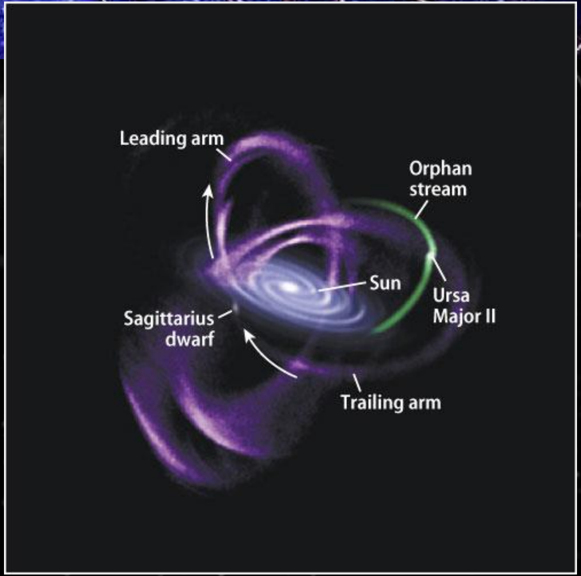




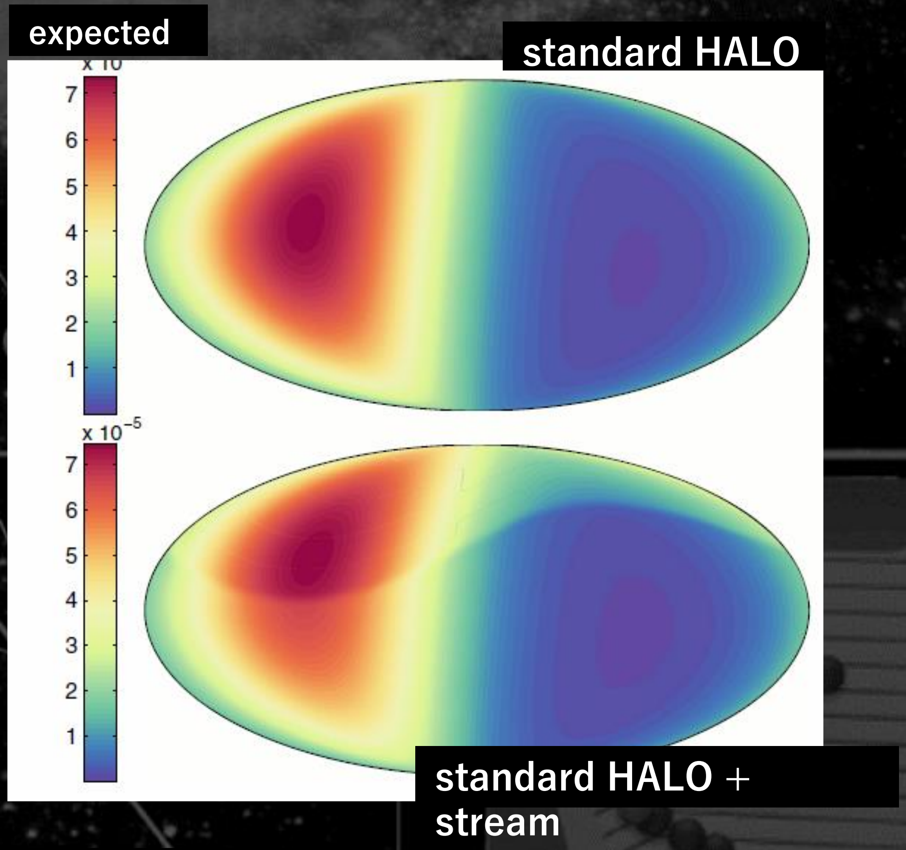
Exploring the Nature of the Dark Matter ①

- astronomy/cosmology
  - Test the HALO model
  - （ex） Sagittarius stream



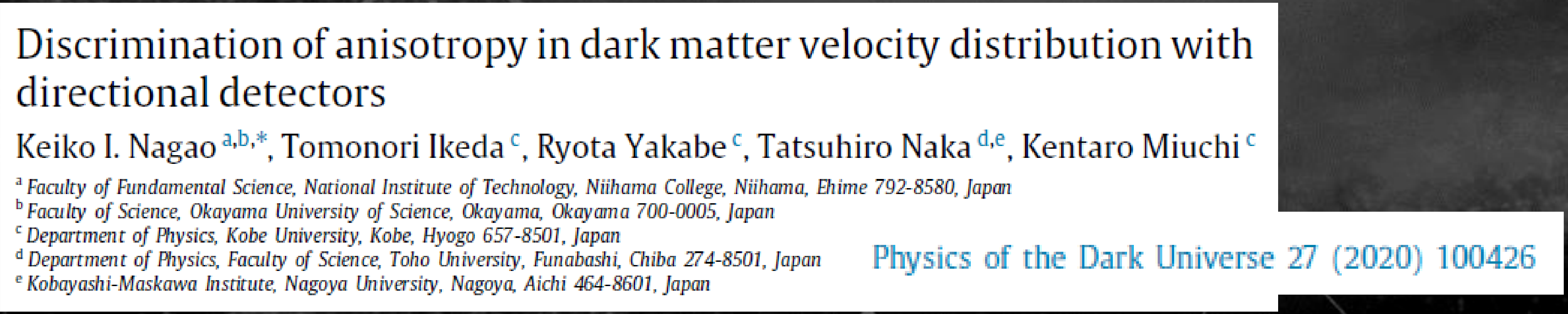


PHYSICAL REVIEW D **90,** 123511 (2014)



- streams, debris…

- Halo model test
  - isotropic (1-r) + anisotropic(r) DM HALO model indicated by n-body simulation (r∼0.3)

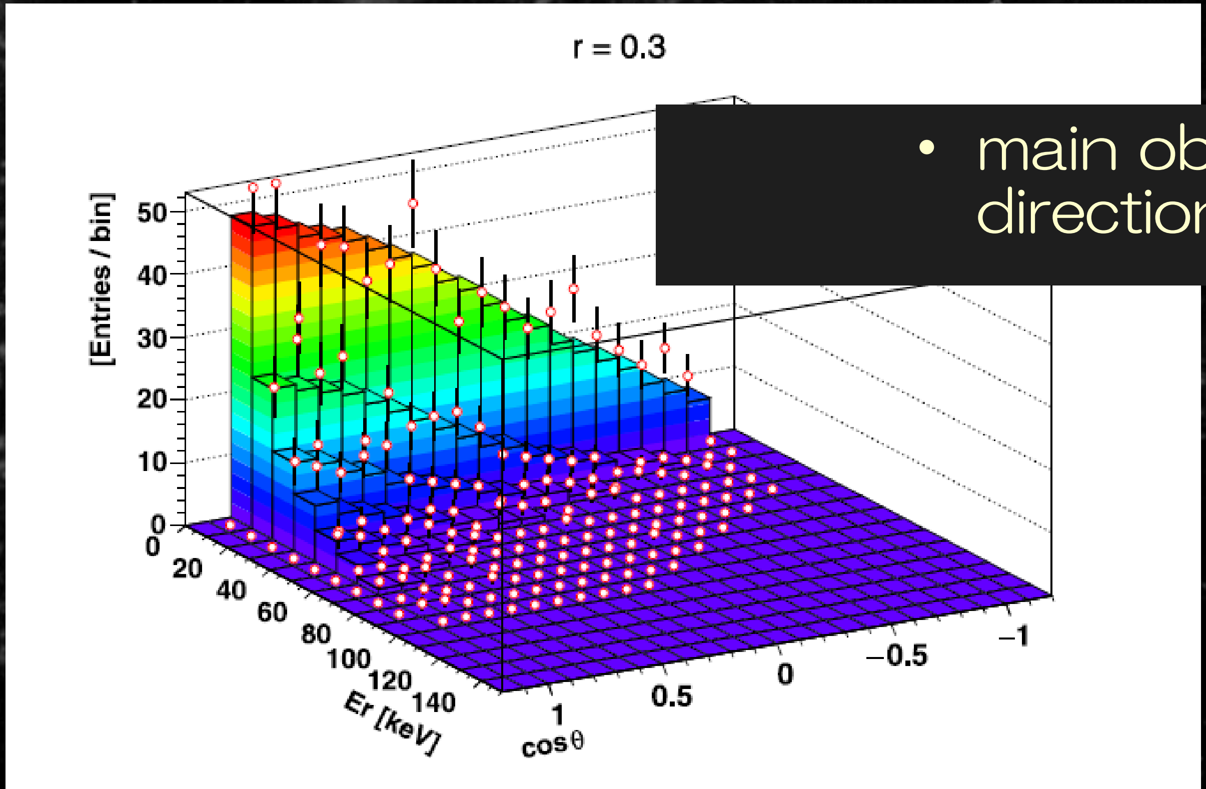


Discrimination of anisotropy in dark matter velocity distribution with directional detectors

Keiko I. Nagao [a,b,*], Tomonori Ikeda [c], Ryota Yakabe [c], Tatsuhiro Naka [d,e], Kentaro Miuchi [c]

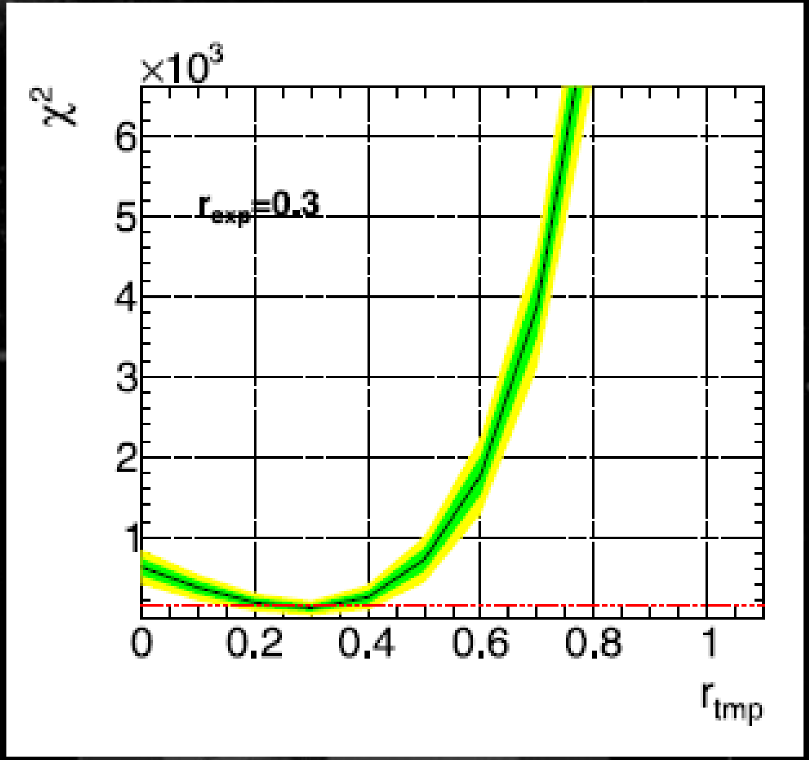
[a] Faculty of Fundamental Science, National Institute of Technology, Niihama College, Niihama, Ehime 792-8580, Japan
[b] Faculty of Science, Okayama University of Science, Okayama, Okayama 700-0005, Japan
[c] Department of Physics, Kobe University, Kobe, Hyogo 657-8501, Japan
[d] Department of Physics, Faculty of Science, Toho University, Funabashi, Chiba 274-8501, Japan
[e] Kobayashi-Maskawa Institute, Nagoya University, Nagoya, Aichi 464-8601, Japan

Physics of the Dark Universe 27 (2020) 100426



- main observables: energy + direction（θ）　⇒2D fitting

- scan r value

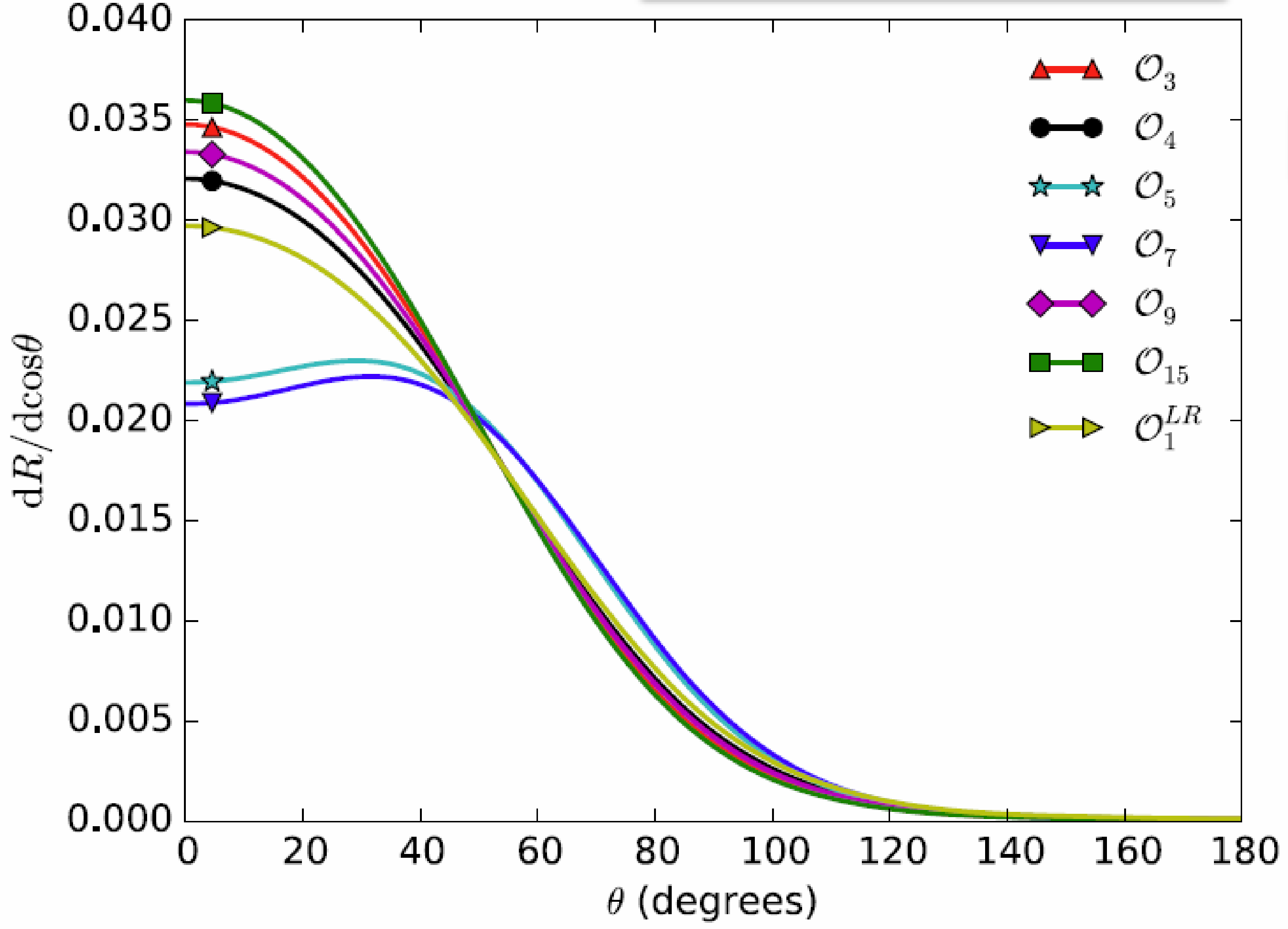


- next:

Exploring the Nature of the Dark Matter ②

- CYGNUS After Discovery : particle physics
  - Some interaction provide characteristic angular distributions

angular distribution



PHYSICAL REVIEW D **92**, 023513 (2015)

operator

SI SD

$$\text{Proportional to} \begin{cases} 1 & : \mathcal{O}_1, \mathcal{O}_4, \\ v_\perp^2 & : \mathcal{O}_7, \mathcal{O}_8, \\ q^2 & : \mathcal{O}_9, \mathcal{O}_{10}, \mathcal{O}_{11}, \mathcal{O}_{12}, \\ v_\perp^2 q^2 & : \mathcal{O}_5, \mathcal{O}_{13}, \mathcal{O}_{14}, \\ q^4 & : \mathcal{O}_3, \mathcal{O}_6, \\ q^4(q^2 + v_\perp^2) & : \mathcal{O}_{15}, \\ q^{-4} & : \mathcal{O}_1^{\mathrm{LR}}. \end{cases}$$

Related Topics

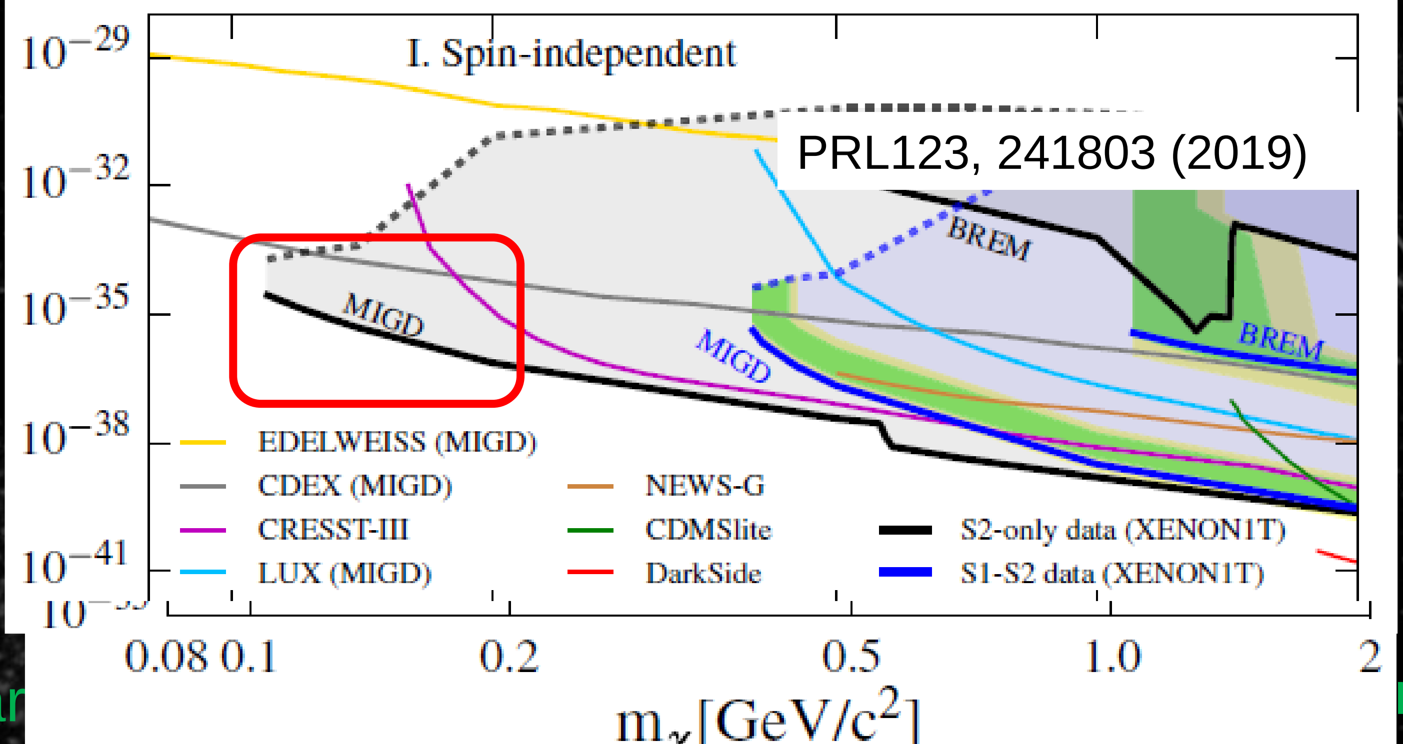
Related Topic ①: MIRACLUE PTEP (2021) 013C01

= Migdal effect observation by gaseous TPC

lead by Kiseki Nakamura (Tohoku University)

- MIGDAL effect
  - Low mass search with "MIGDAL effect"
  - Ordinary nuclear recoil : ionization along the track
  - Low energy recoil : ionization efficiency is low ⇒ difficult to detect
  - Very rare case electrons are emitted

PRL123, 241803 (2019)



PRL123, 241803 (2019)

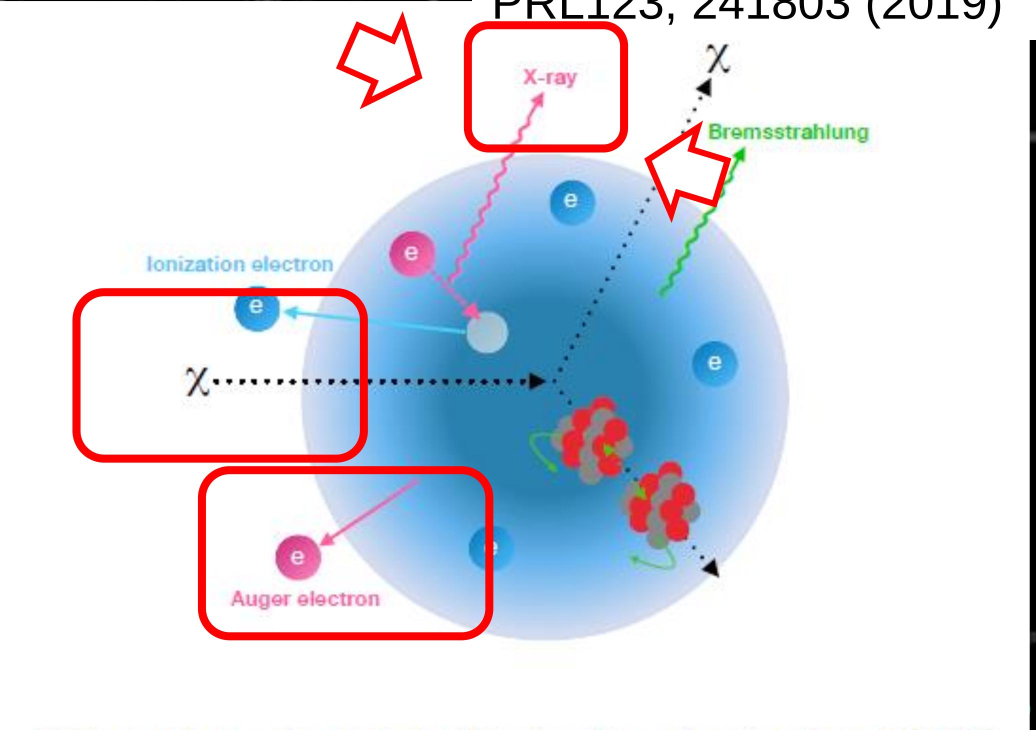


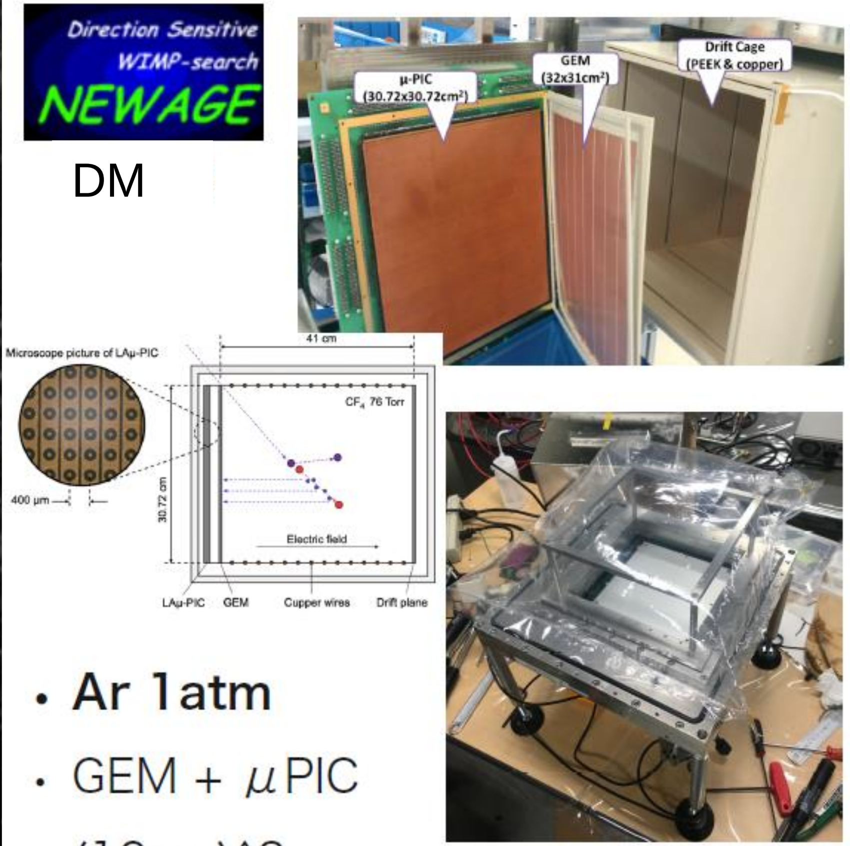
FIG. 1. Illustration of the ER signal production from BREM

- MIRACLUE concepts
  - Ar (1atm) and Xenon (8 atm) gas : direct interests in DM search
  - start with existing technologies : less R&D
  - characteristic X-ray channel for 2-cluster detection (as the first step) : less BG
  - low energy (565keV) neutrons : less BG

MIRACLUE detectors

Direction Sensitive WIMP-search NEWAGE

DM

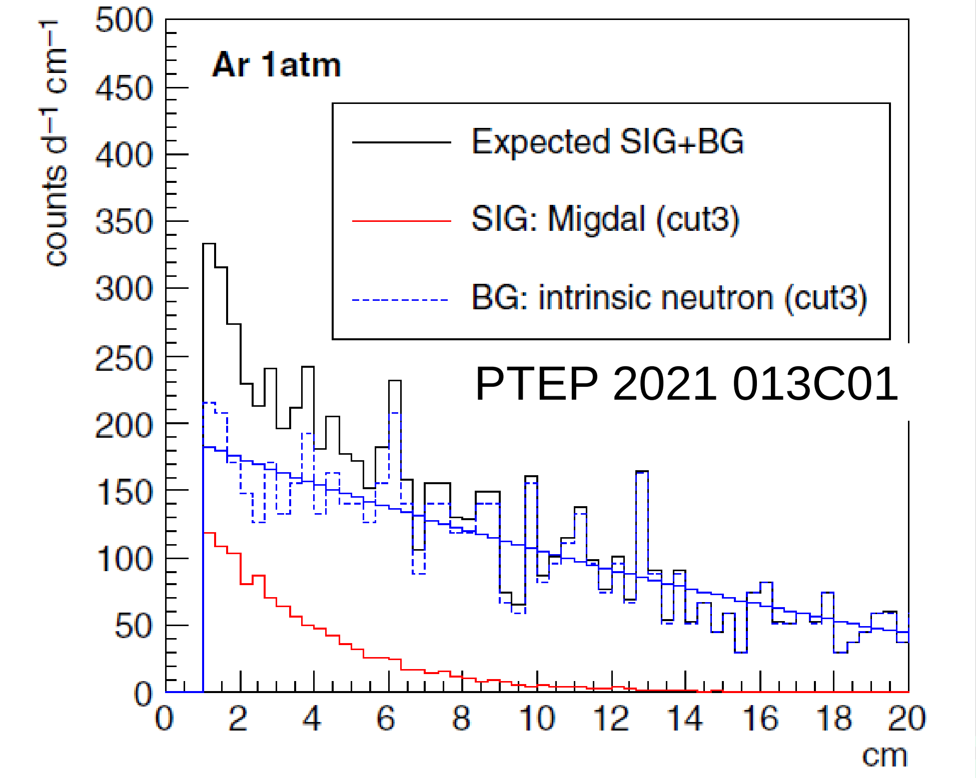


- Ar 1atm
- GEM + μPIC
- (10cm)^3

AXEL

Xe gas 8atm
ELCC＋MPPC
16cmΦ×10cm

expected signature
（2-cluster distance）



PTEP 2021 013C01

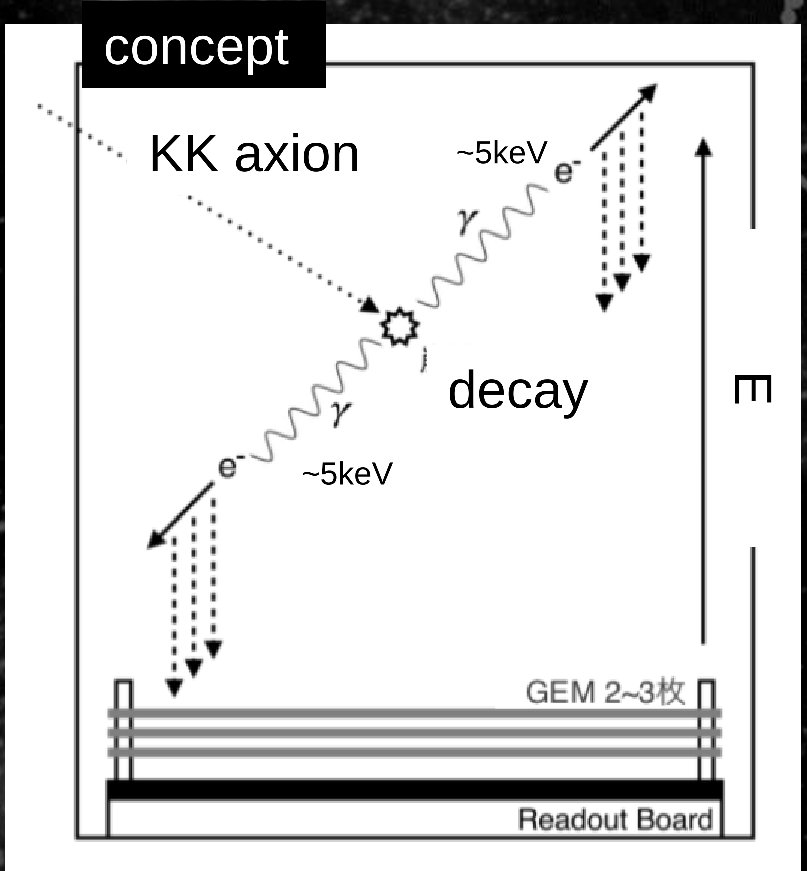
Related Topic ②: KC

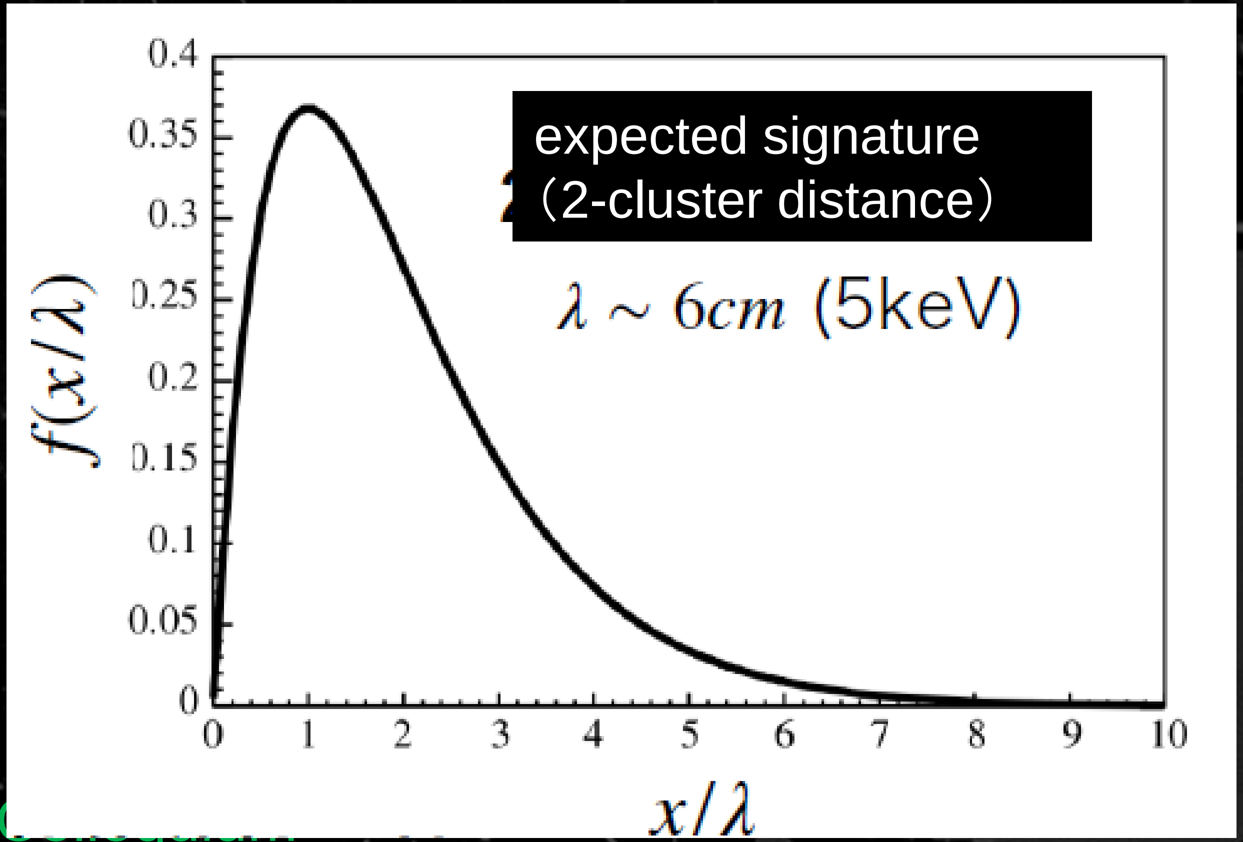
= solar KK axion search by gaseous TPC

search by XMASS:
PTEP（2017）103C01

lead by Keishi Hosokawa （ICRR）

- Kaluza-Klein axion produced in the sun
  → decays to 2 photons in the detector
  → can be detected as “2-cluster” in gaseous TPC





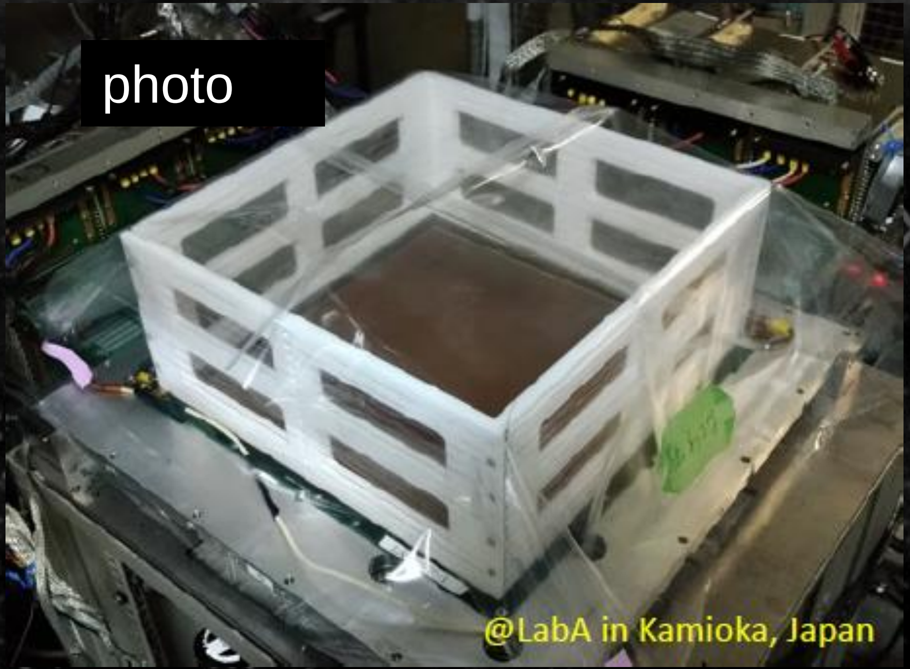
Related Topic ③: AICHAM
= alpha-ray imaging by gaseous TPC

- For material screening
- sensitivity: O（10^{-3}） $\alpha/cm^2/hour$

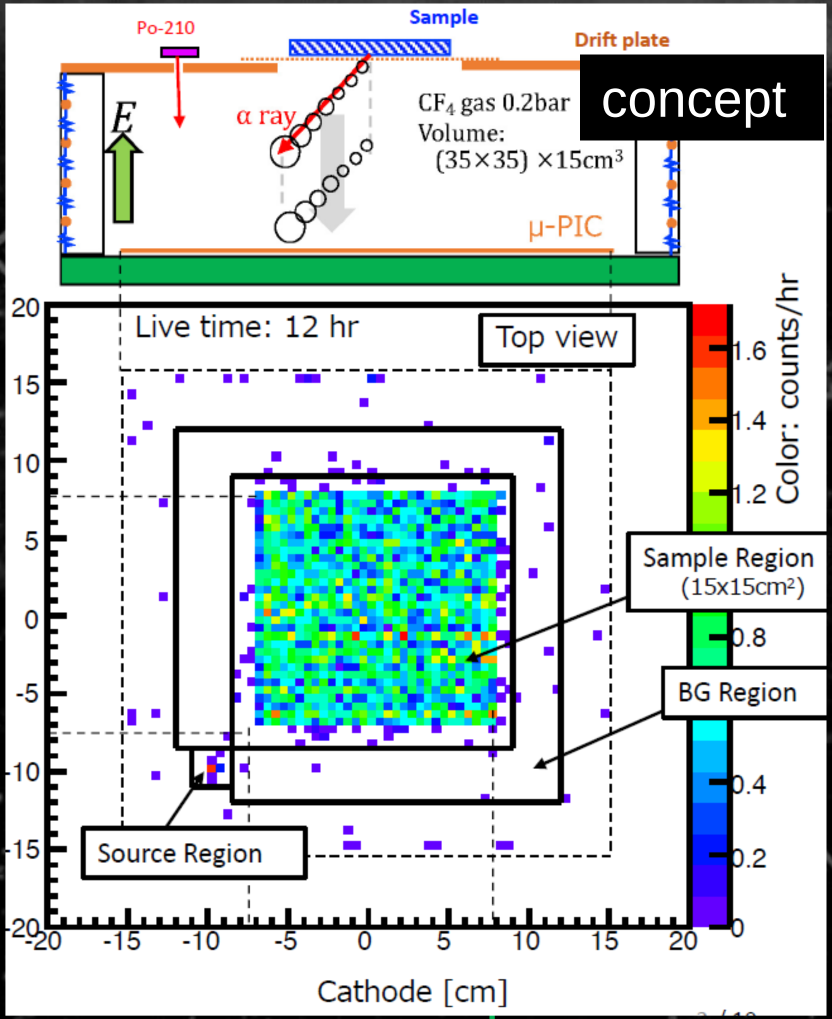
NIM A 953, (2020), 163050
J. Phys.: Conf. Ser. 2156 (2021) 012176.

lead by Hiroshi Ito
（Tokyo University of Science）

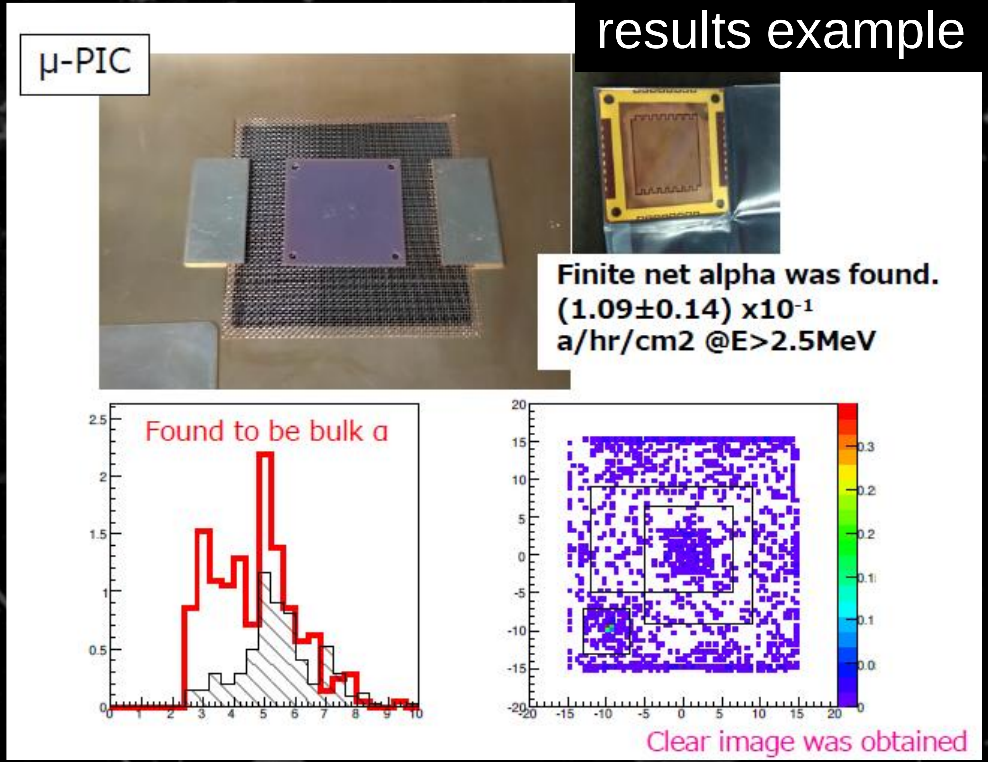
photo



concept



results example



Related Topic ④: QPIX

= Pixel readout ASIC for gaseous TPC

- Fine pitch : lower energy threshold
- pixel: better angular resolution without "ghost"

lead by Satoshi Higashino (Kobe University)

concept

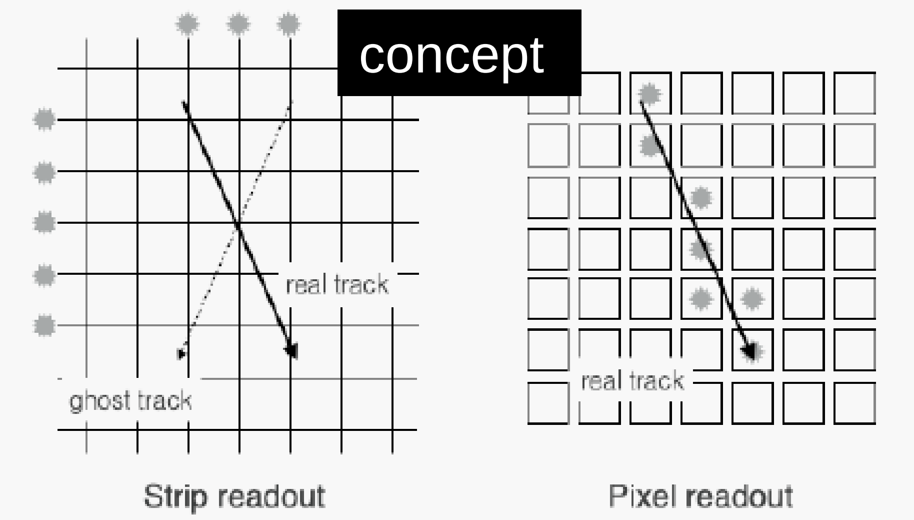
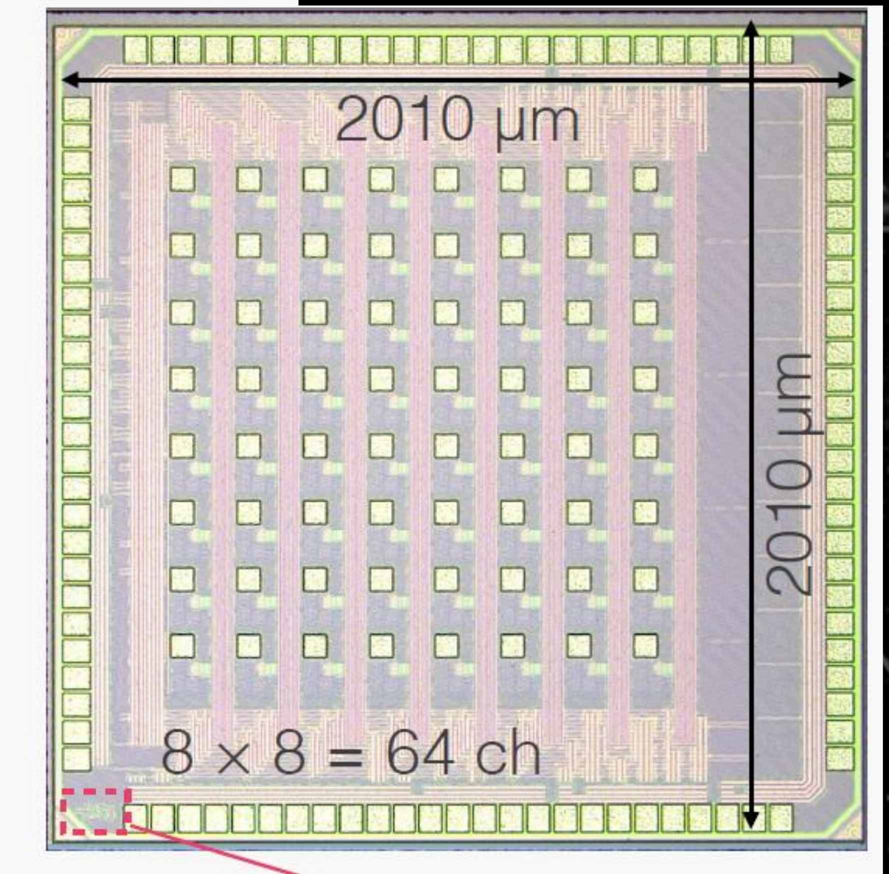
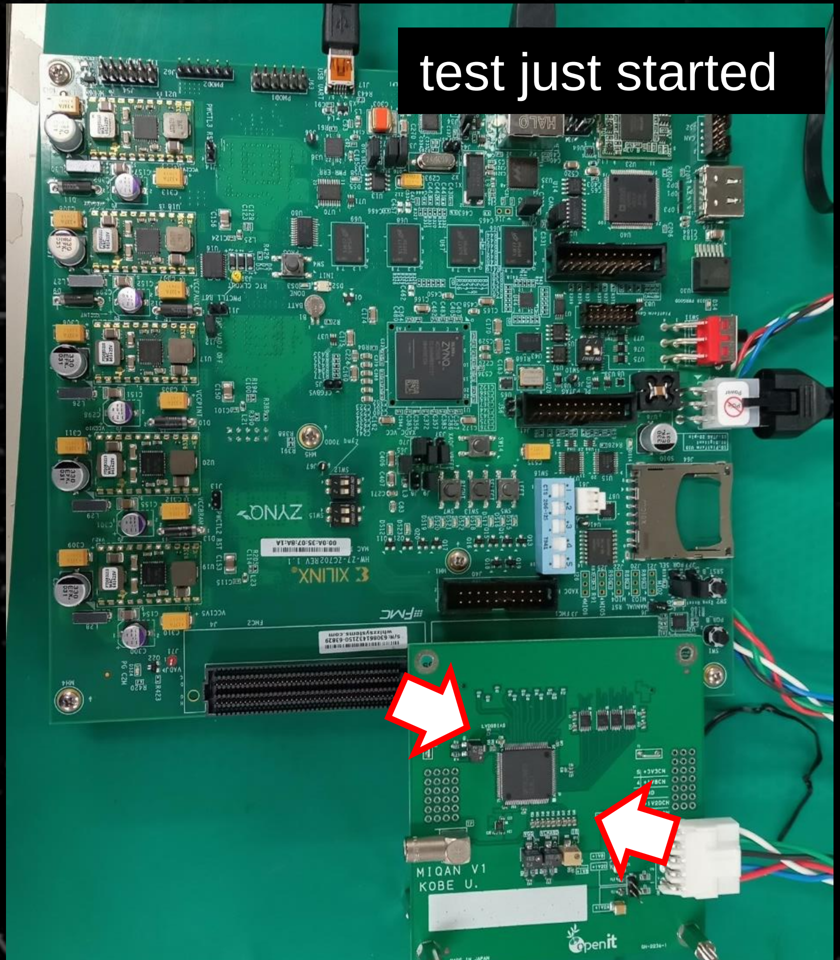


photo (QPIX neo v1)



test just started



SUMMARY

The nature of the dark matter can be explored

by directional method

with gaseous TPCs

which also have a variety of other applications.

KEK プラットフォームC

Kentaro Miuchi

科研費 KAKENHI

地下から解き明かす宇宙の歴史と物質の進化

Unraveling the History of the Universe and Matter Evolution with Underground Physics

DMNet

Physics cases for directional TPCs as a function of exposure

THIS TALK

N = volume in m³ assuming 1 atm operation

Many interesting physics opportunities already at relatively small scale