Nov 13, 2023

- Aso Workshop on Particle Physics and Cosmology 2023

暗黒物質直接探索の現状

身内賢太朗
(神戸大学)

暗黒物質

暗黒物質直接探索

最近の話題

科研費
KAKENHI

- はじめまして/お久しぶりです　身内賢太朗です
  - いまのところずっと　暗黒物質直接探索　⇄　見つからない
  - そろそろ　見つけて　性質解明　と行きたい

- D論　　　　　東大物理　みのわ研　　　　LiFボロメータ
- PD～助教　　　京大物理　宇宙線研究室　　ガスTPC
- 准教授　　　　神戸大　粒子物理研究室　　+=液体キセノン検出器　その他

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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暗黒物質

Journal of Advanced Instrumentation in Science　JAIS-ID, 2023
Email address: miuchi@panda.kobe-u.ac.jp
Technical Report

LaTeX Challenges for the directional dark matter direct detection

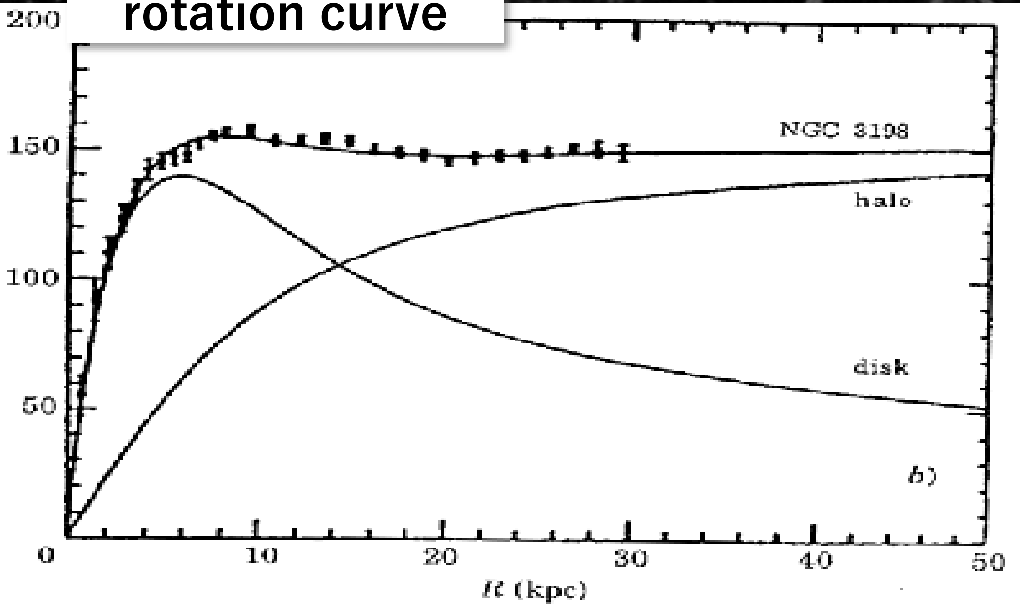
Kentaro Miuchi,[1]
[1] *Department of Physics, Kobe University, Hyogo 657-8501, Japan.*

https://arxiv.org/abs/2309.13923

- 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~)

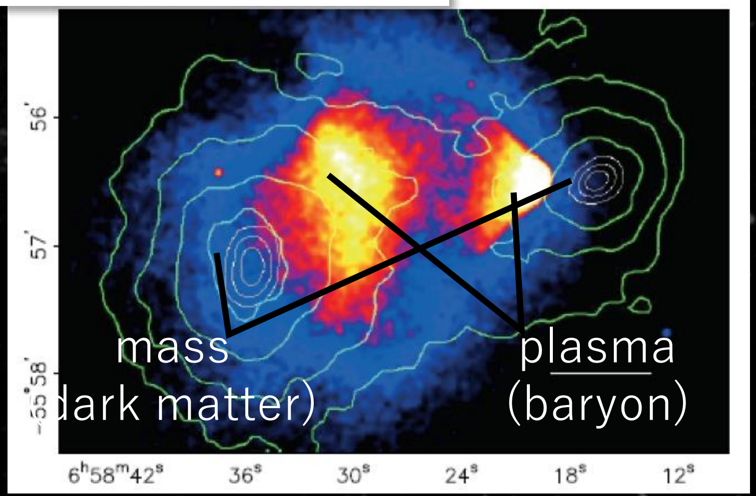
GR !

rotation curve



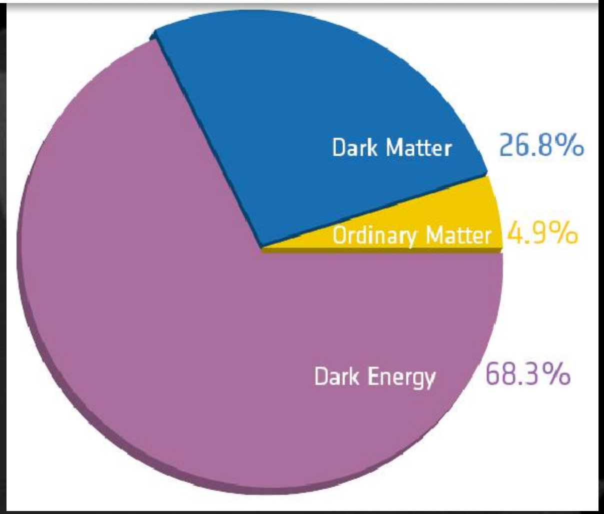
Annu. Rev. Astron. Astrophys. 29(1991)409

cluster collision



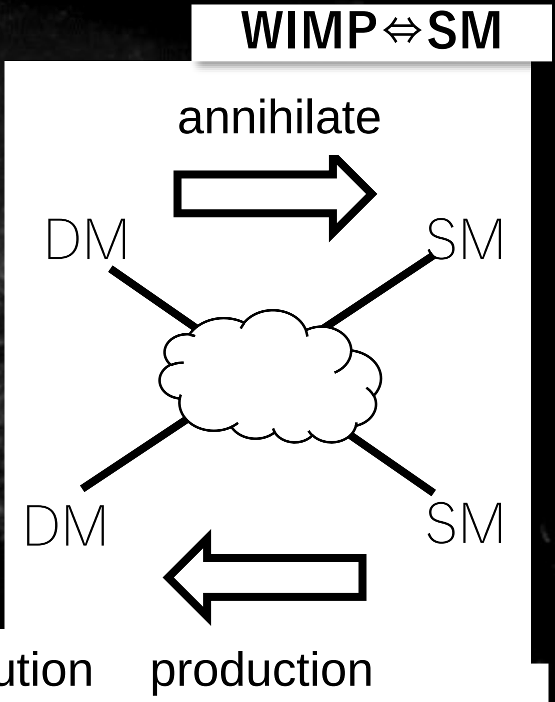
THE ASTROPHYSICAL JOURNAL, 648:L109–L113, 2006 September 10

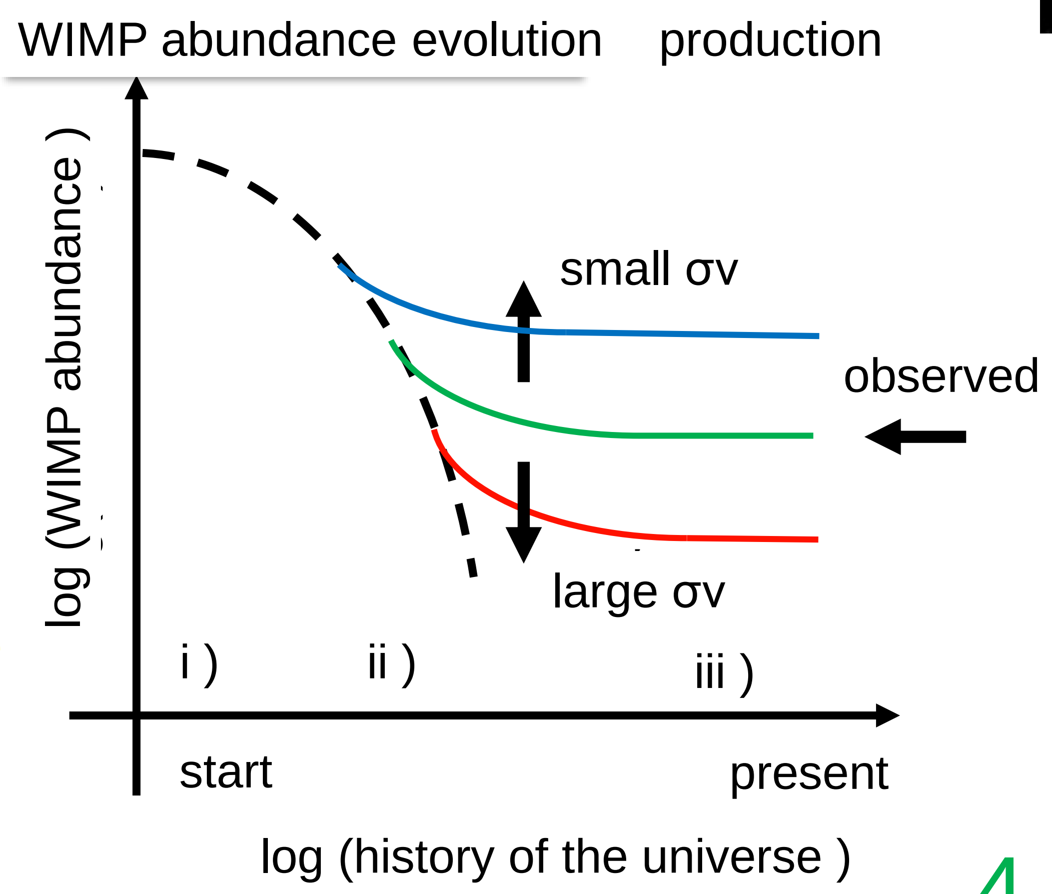
pie chart of the universe



Plank team

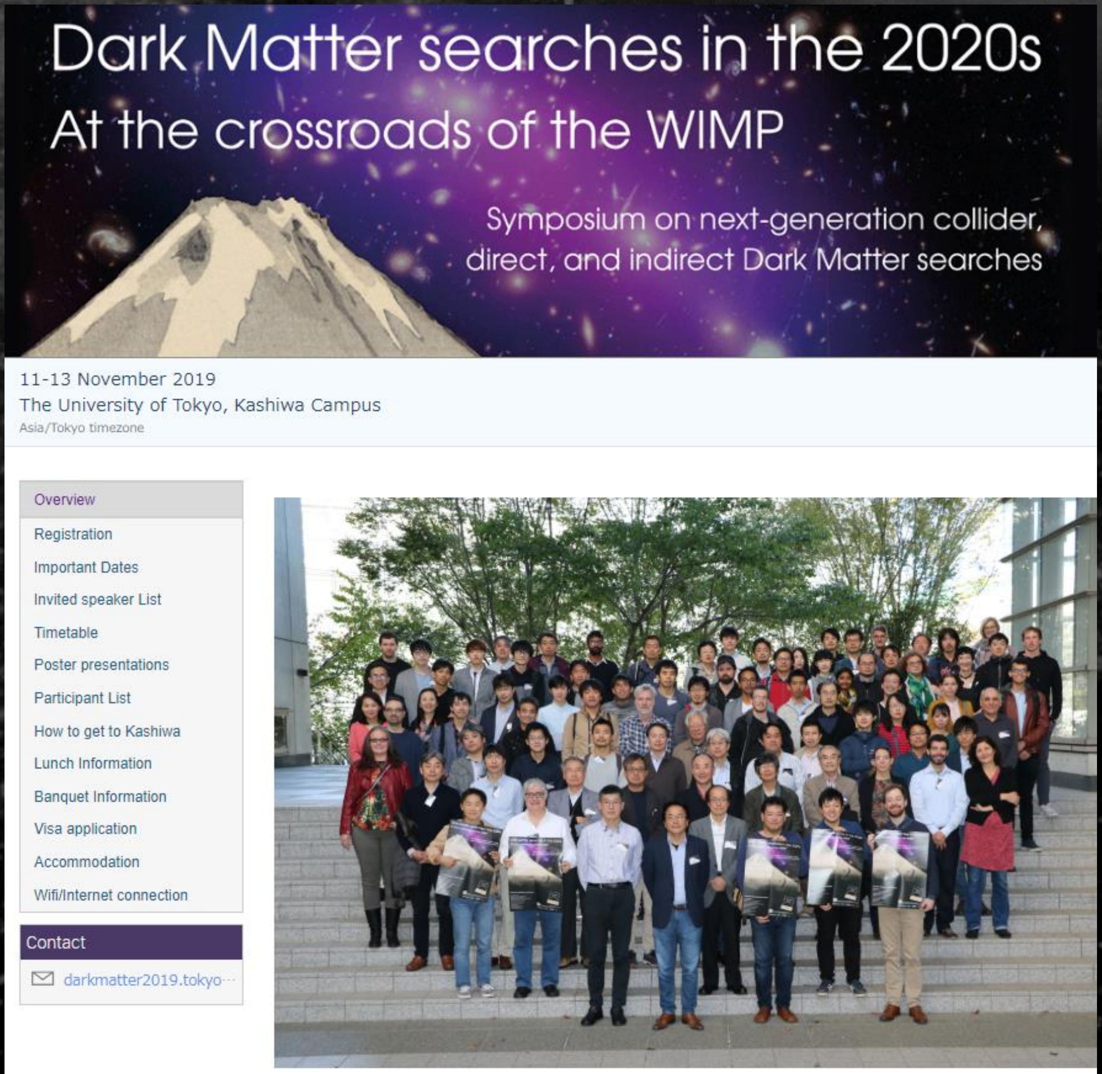
- DM candidates: thousands of them
  - "good" candidates would solve other problems
    - AXION (CP problem in QCD)
    - Primordial black hole (BHs are there!)
    - WIMPs (Weakly Interacting Massive Particles)
  - WIMPs
    - Produced in the early universe
    - Annihilate
      rate ∝ cross section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

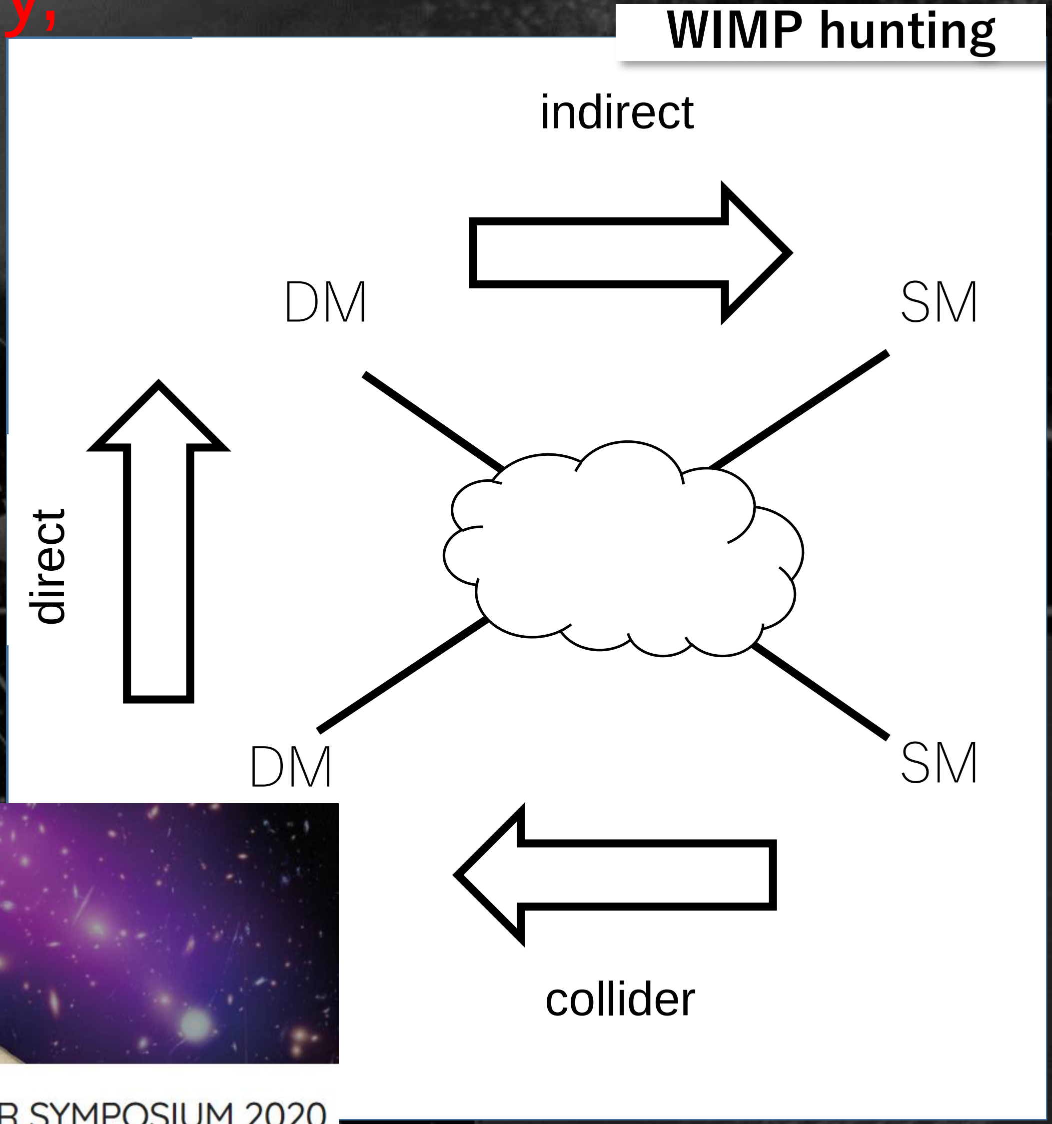




- WIMP hunting
  - WIMP-SM (standard model particle, i.e. quarks) particle interaction
    - Direct search
    - Indirect search
    - Collider

complementary, synergy



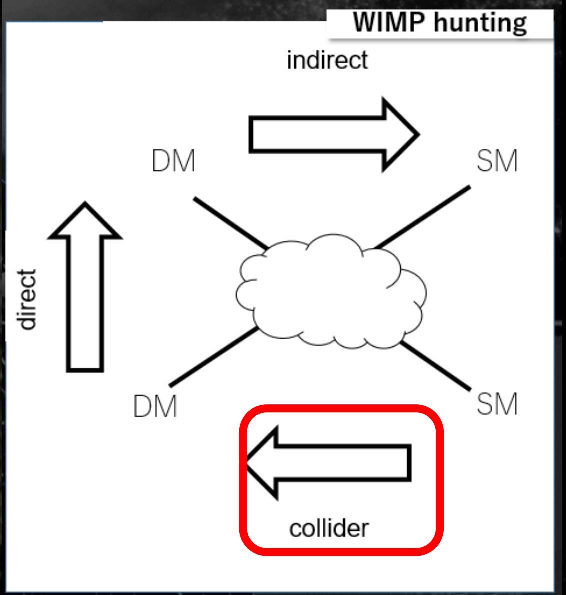


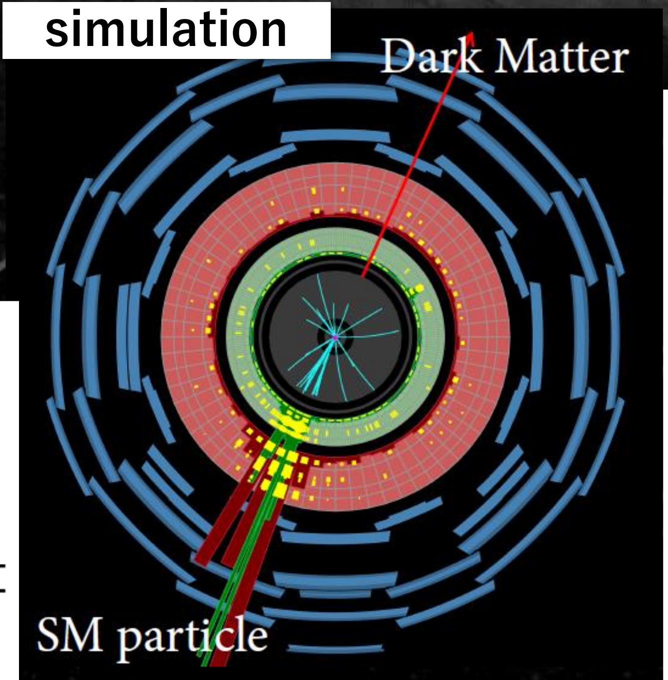
- Collider
  - LHC @ CERN
  - Missing E signal
  - Searches with various ways
  - No hint so far

Dark matter searches at colliders.

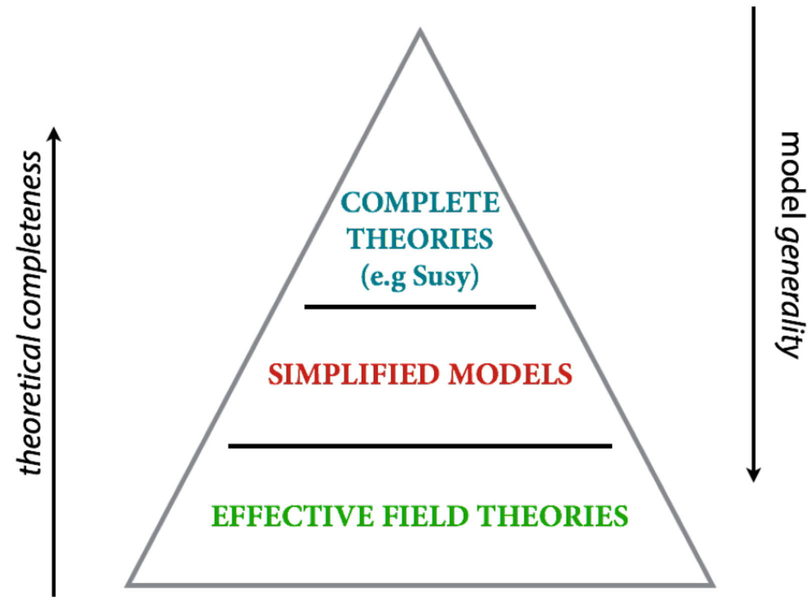
Priscilla Pani
on behalf of ATLAS, CMS & LHCb

Dark Matter searches in the 2020 - Tokyo
11-13 November 2019





Theoretical framework

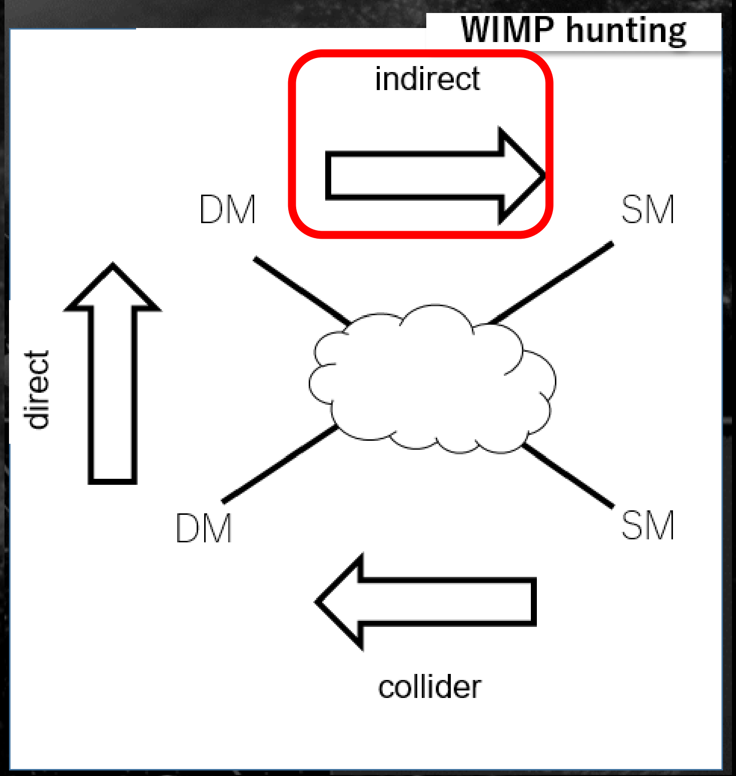


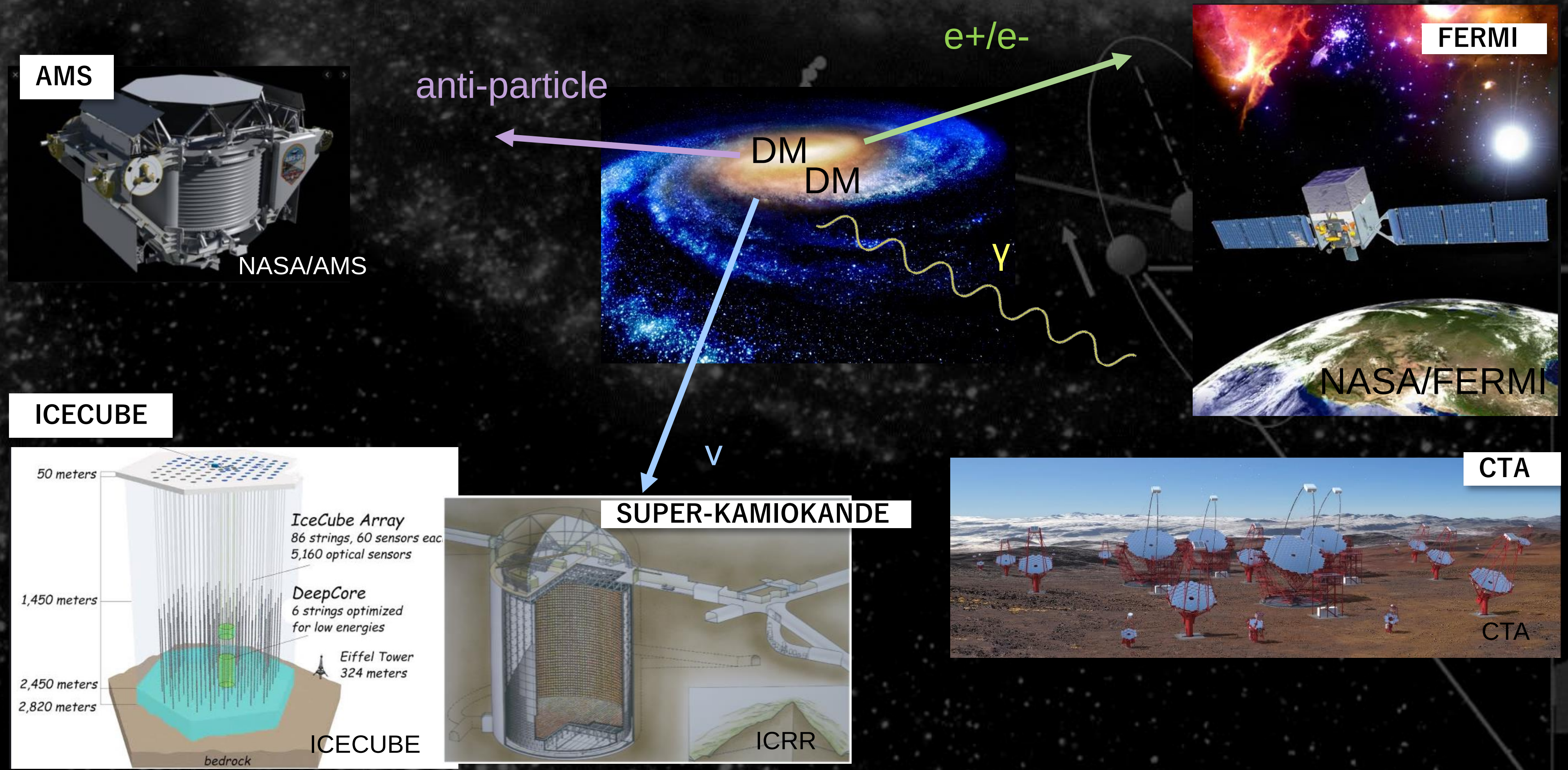
Conclusion - Cheat sheet

DM-mediator searches

Signature	Dataset	Reference
Di-lepton resonance	139 fb^{-1}	1903.06248
Di-jet, Di-jet + ISR,	139 fb^{-1}	1901.10917, ATLAS-CONF-2019-007, 1808.03124
Di-bjet	80 fb^{-1}	ATLAS-CONF-2018-052
Di-jet + leptons	80 fb^{-1}	ATLAS-CONF-2018-015
Dijet + photons	36 fb^{-1}	1905.10331
Etmiss + Higgs	36 fb^{-1}	1908.01713
Etmiss + t/ttbar	36 fb^{-1}	1901.01553
Etmiss + jet	36 fb^{-1}	1712.02345
H invisible	36 fb^{-1}	Phys. Rev. Lett. 122 (2019) 231801
ATLAS DM summary	36 fb^{-1}	JHEP 05 (2019) 142

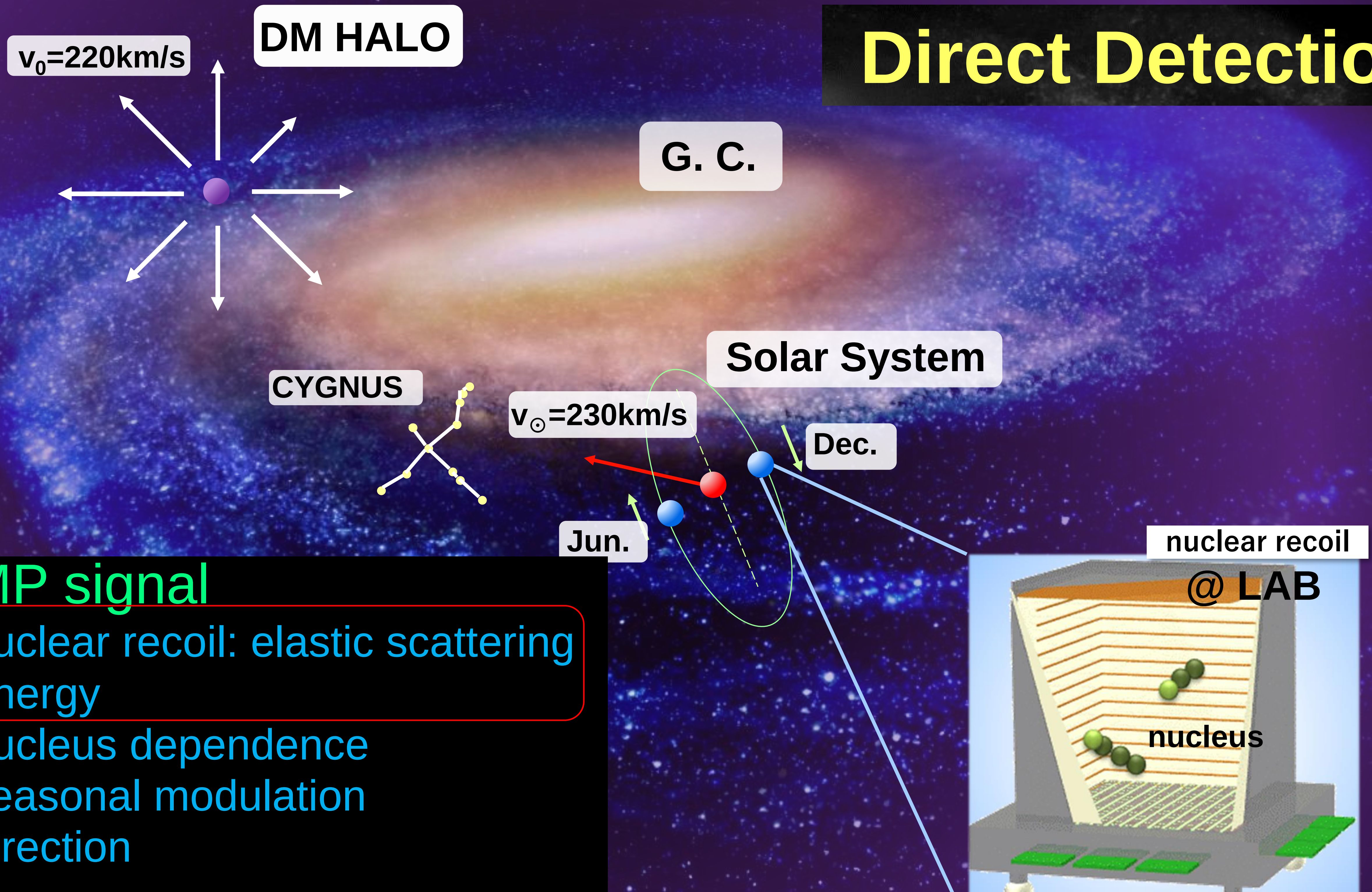
- Indirect Search
  - WIMPs annihilate @ Galactic Center, Dwarf Galaxy, sun…
  - No conclusive result yet





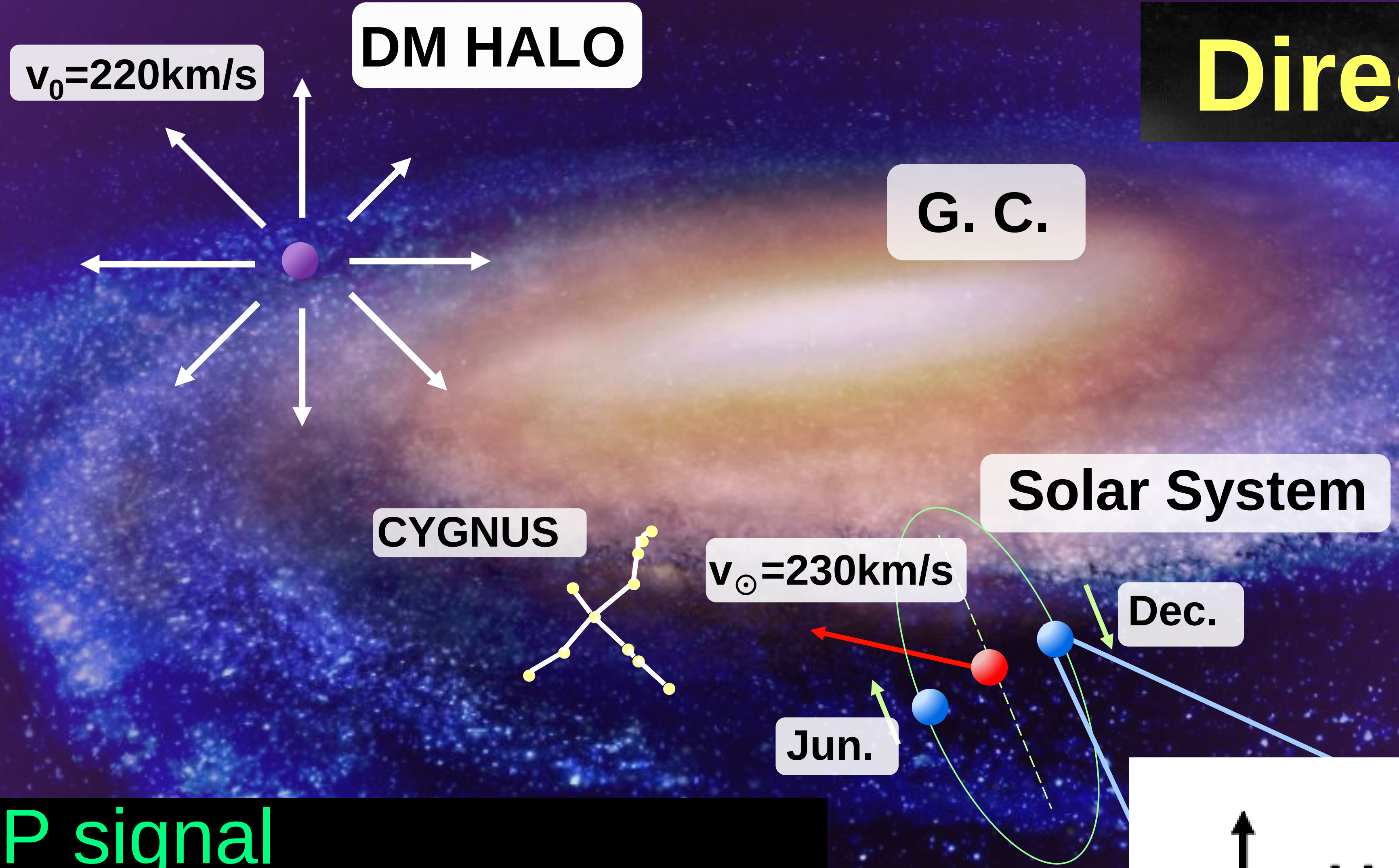

Direct Search

Direct Detection



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

Direct Detection



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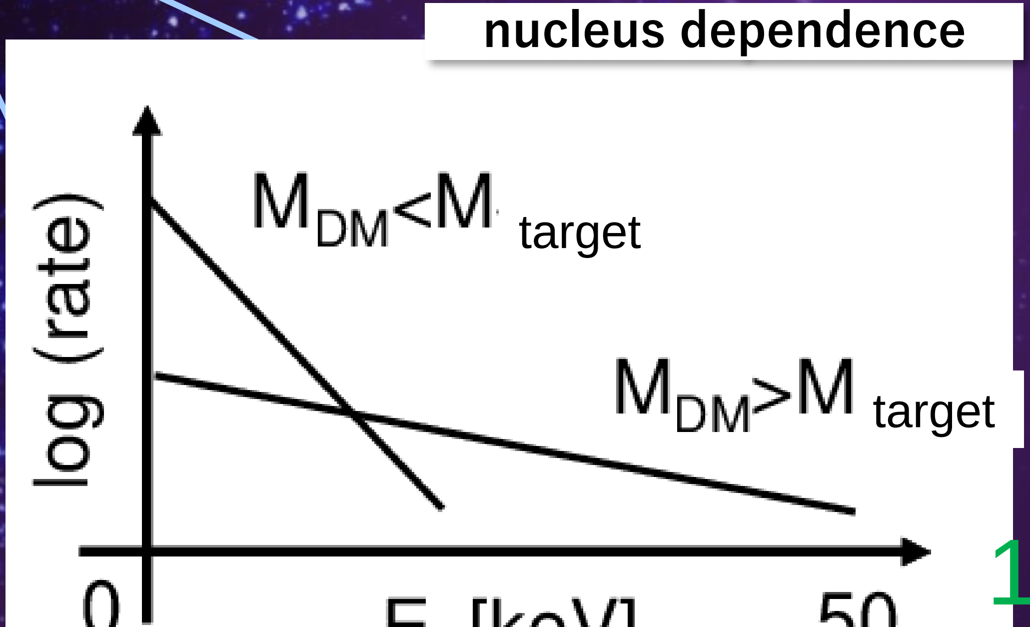
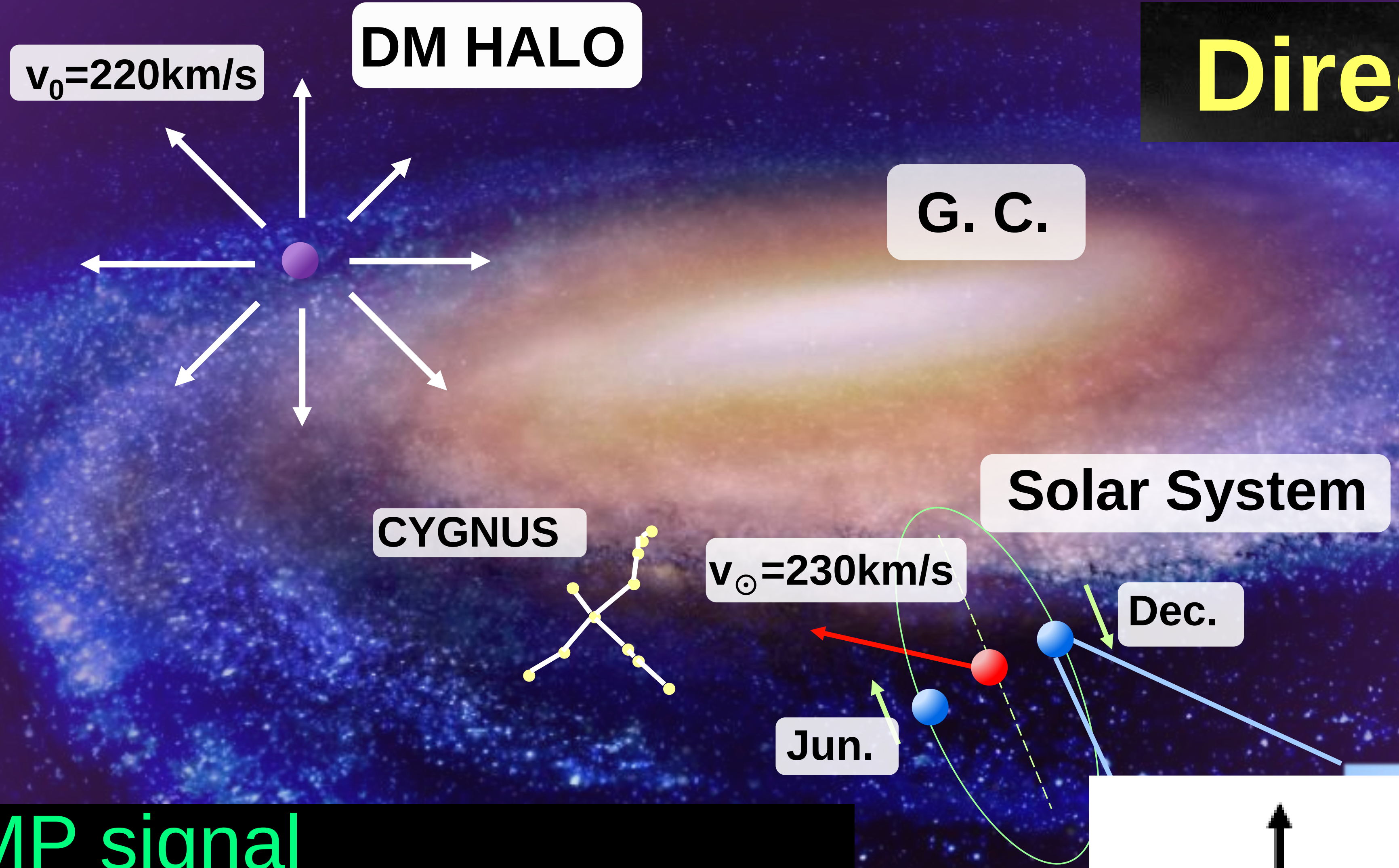


Direct Detection



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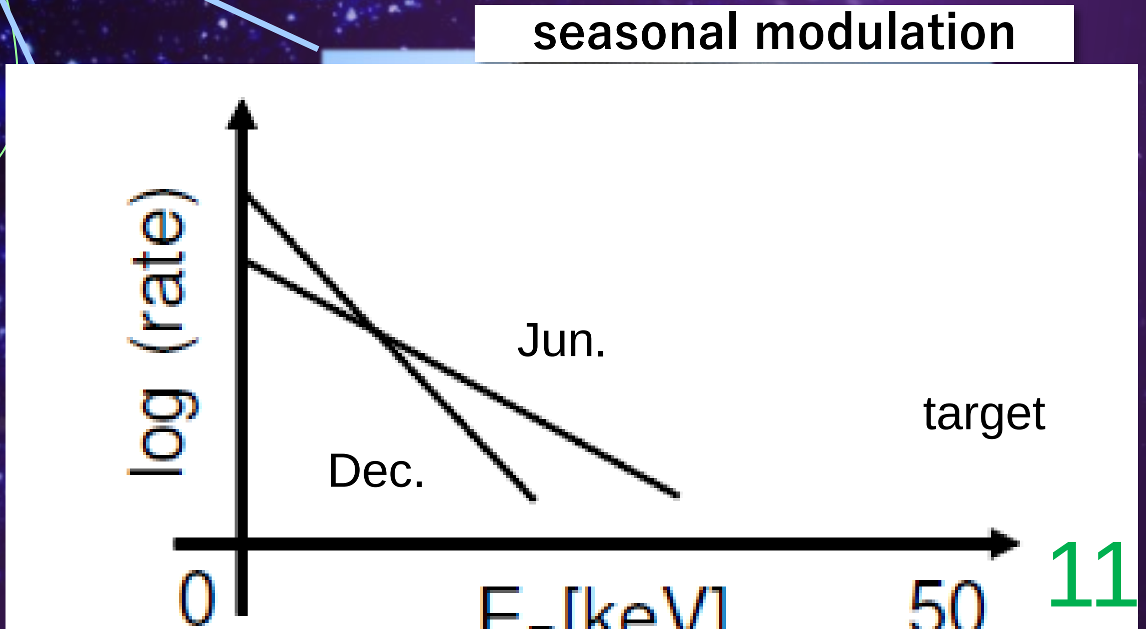
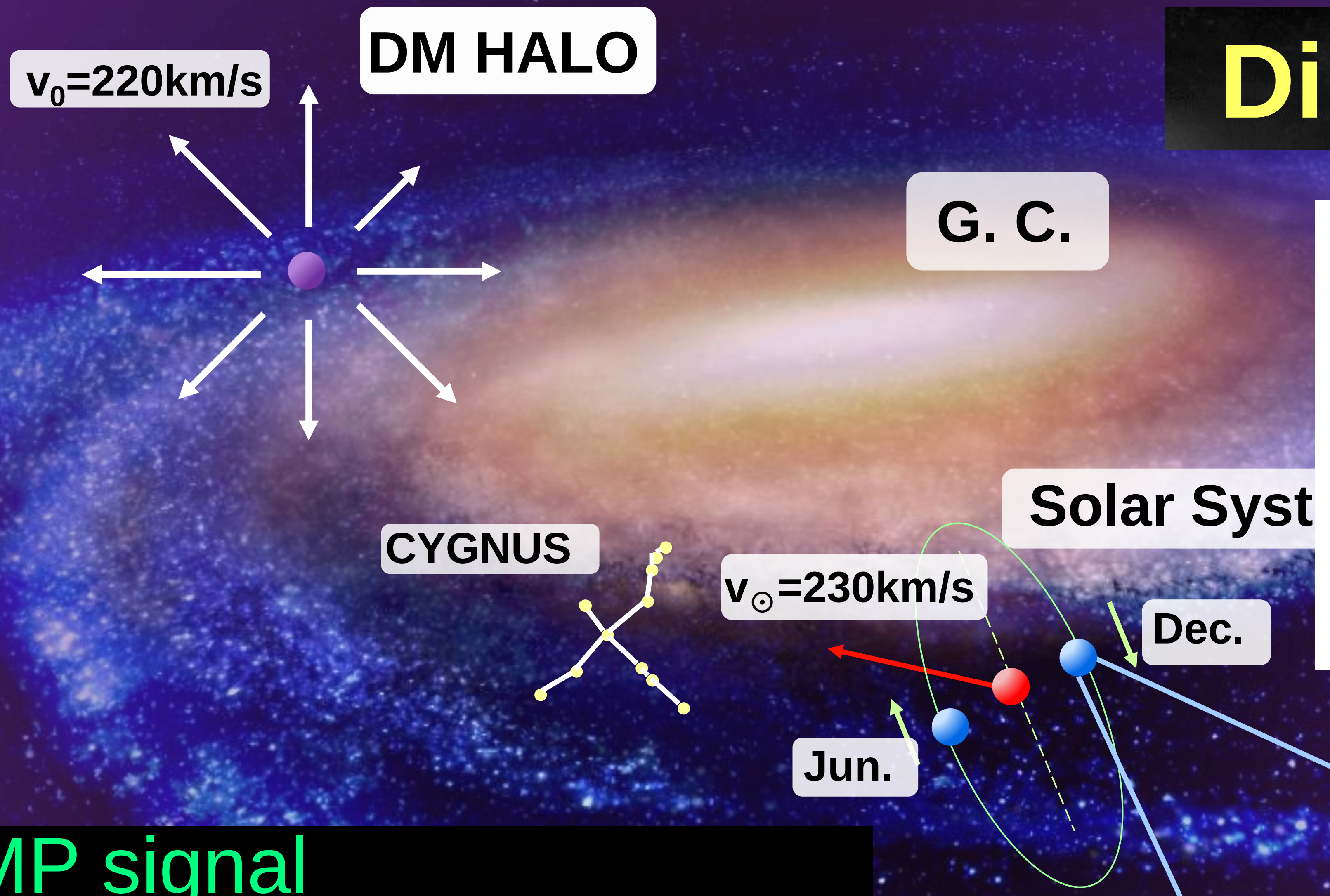
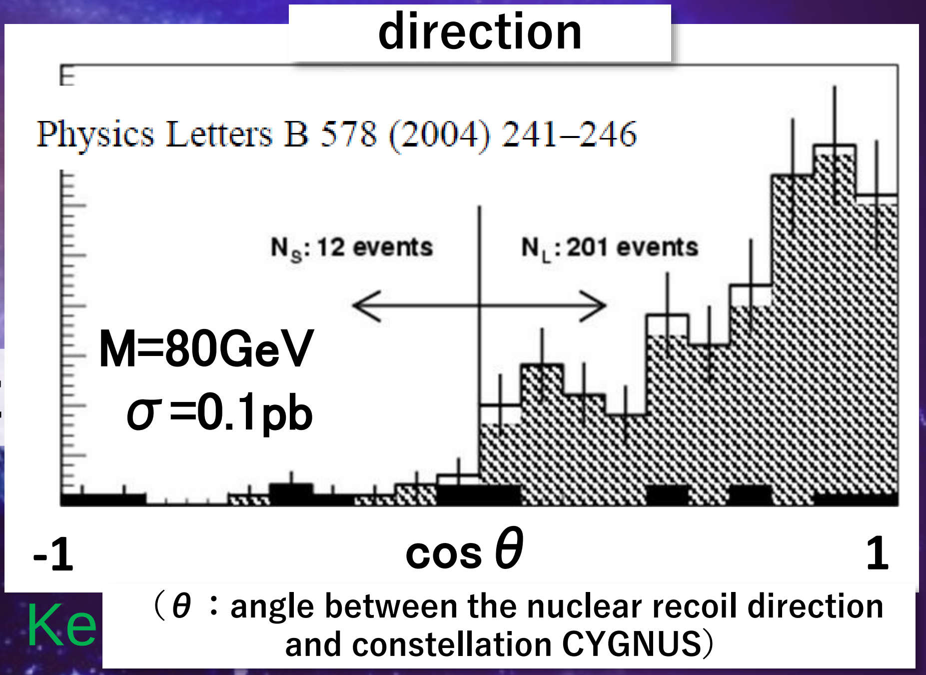
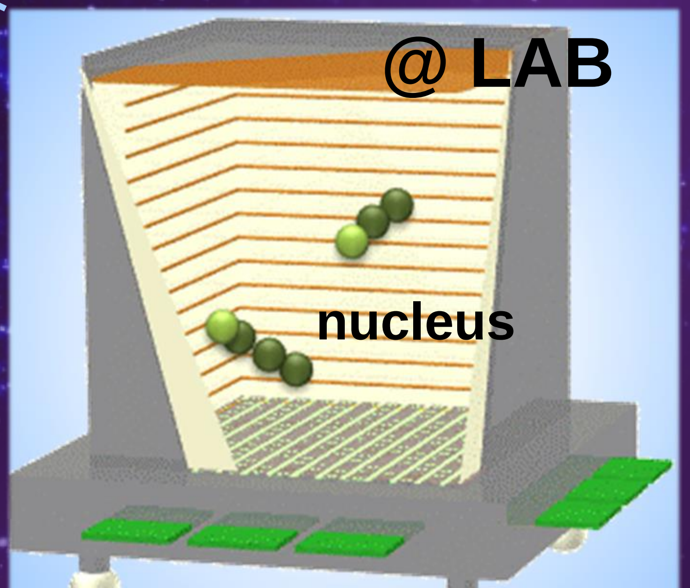


Direct Detection







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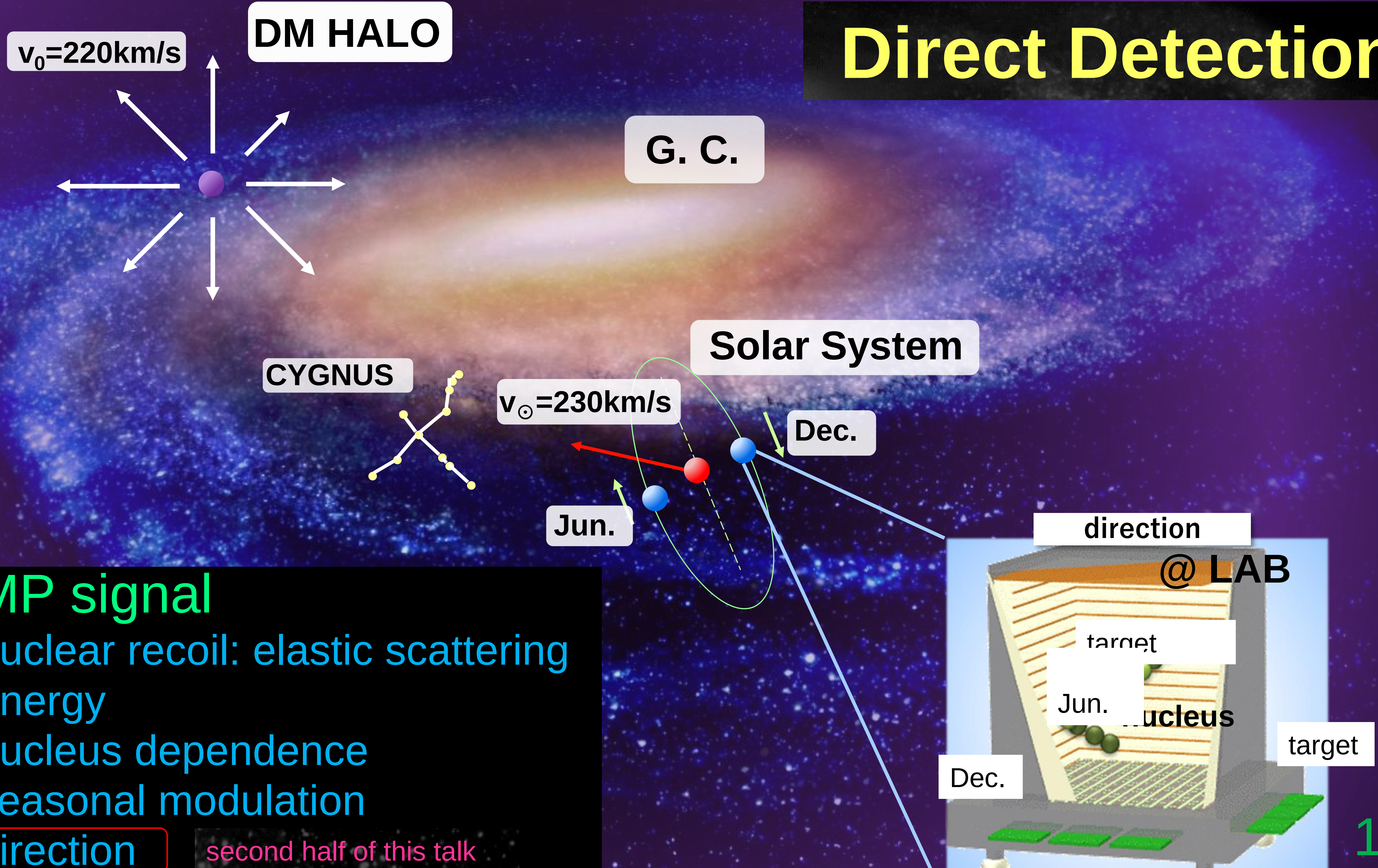
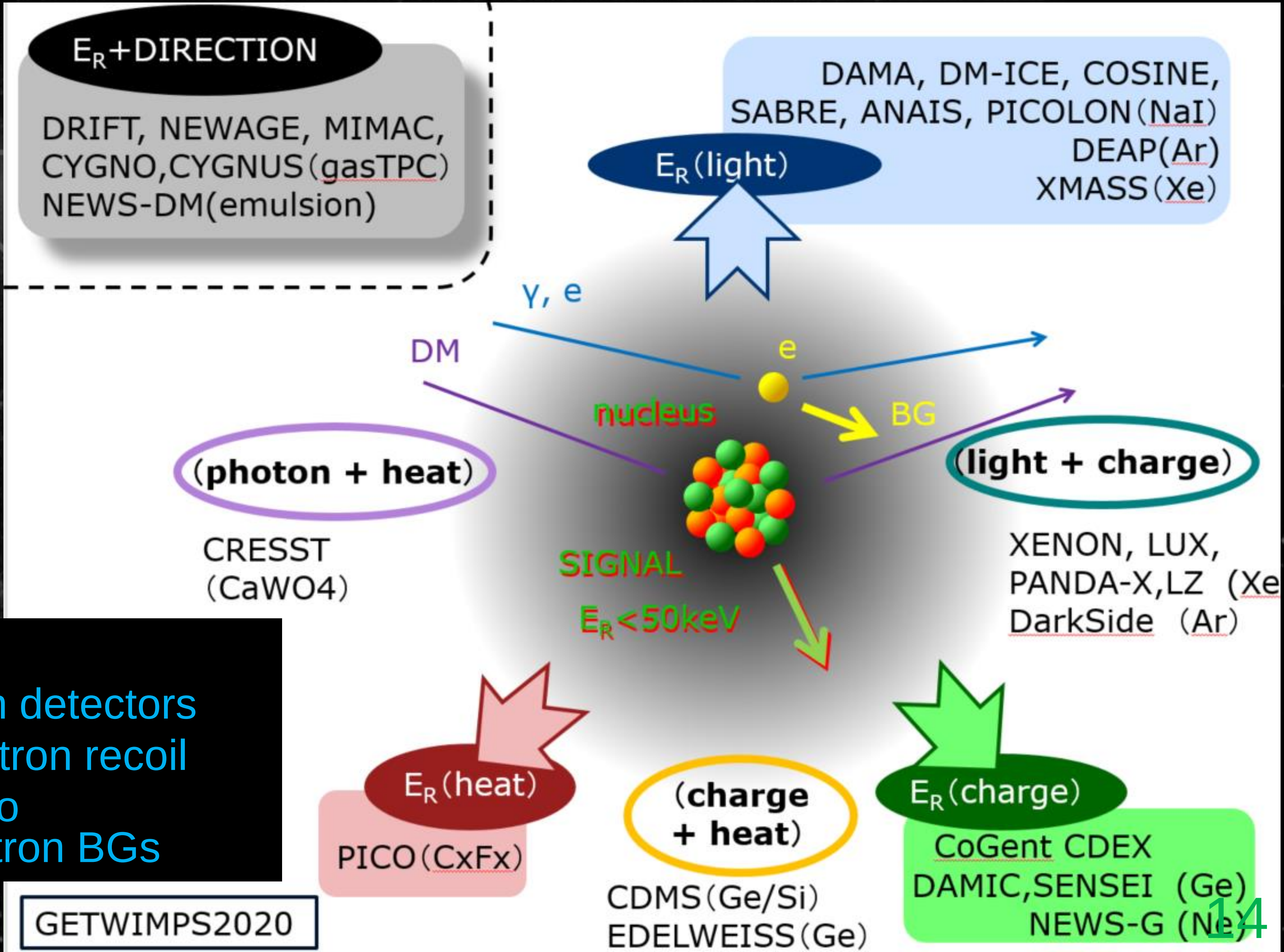
Direct Detection



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

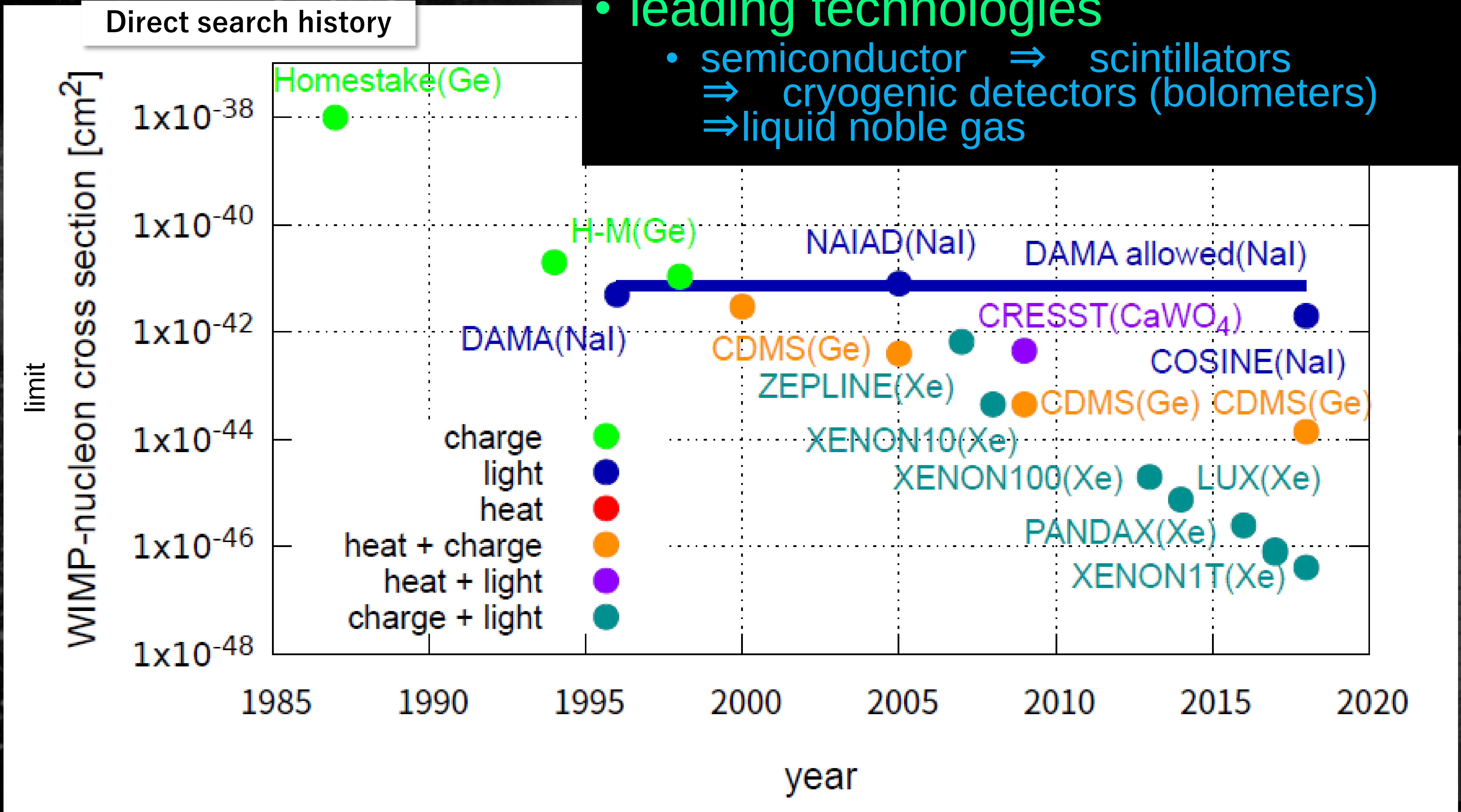
second half of this talk

- Technologies
  - Ordinary radiation detectors
  - Background: electron recoil
  - more than two info
    ⇒ reject electron BGs



History

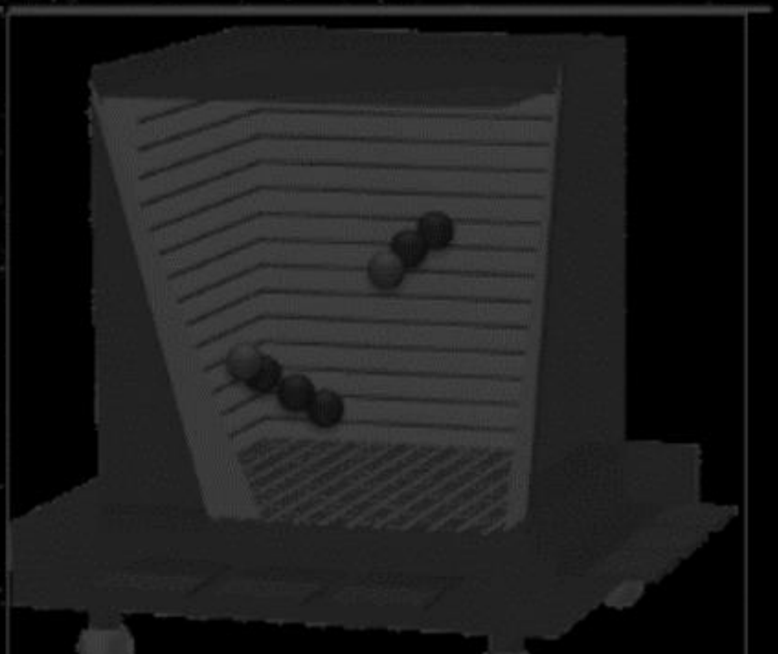
- leading technologies
  - semiconductor ⇒ scintillators ⇒ cryogenic detectors (bolometers) ⇒liquid noble gas



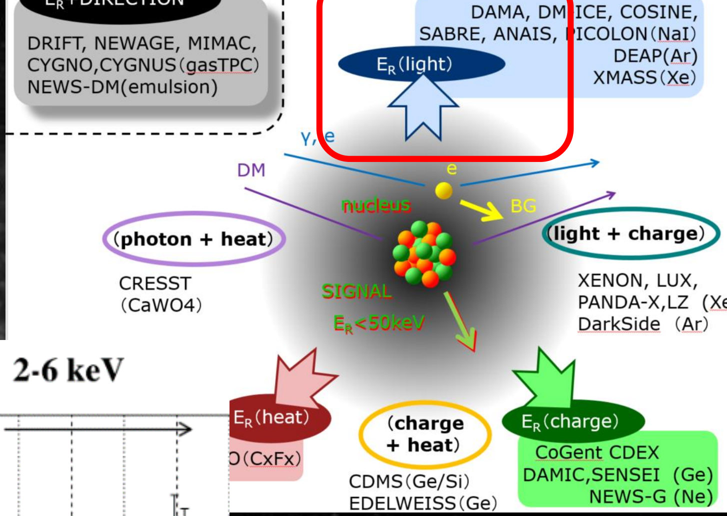
2. 直接探索の現状

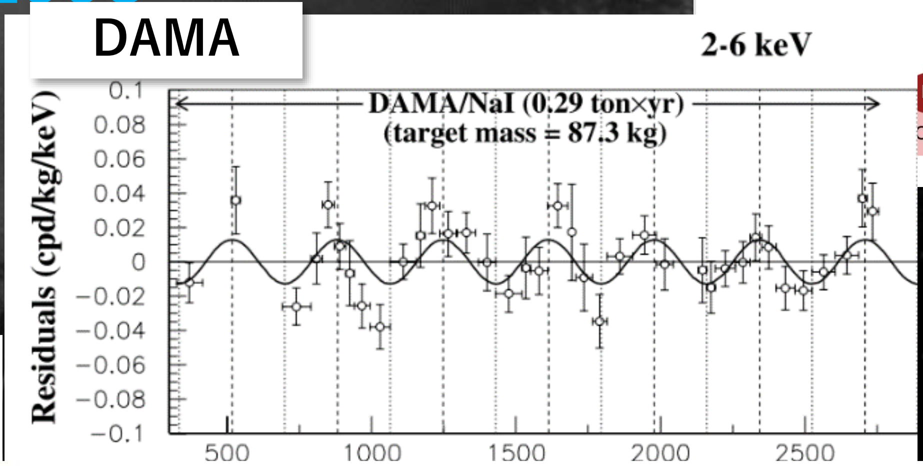
Direct Search Review

1. Mainstream : Large Detectors

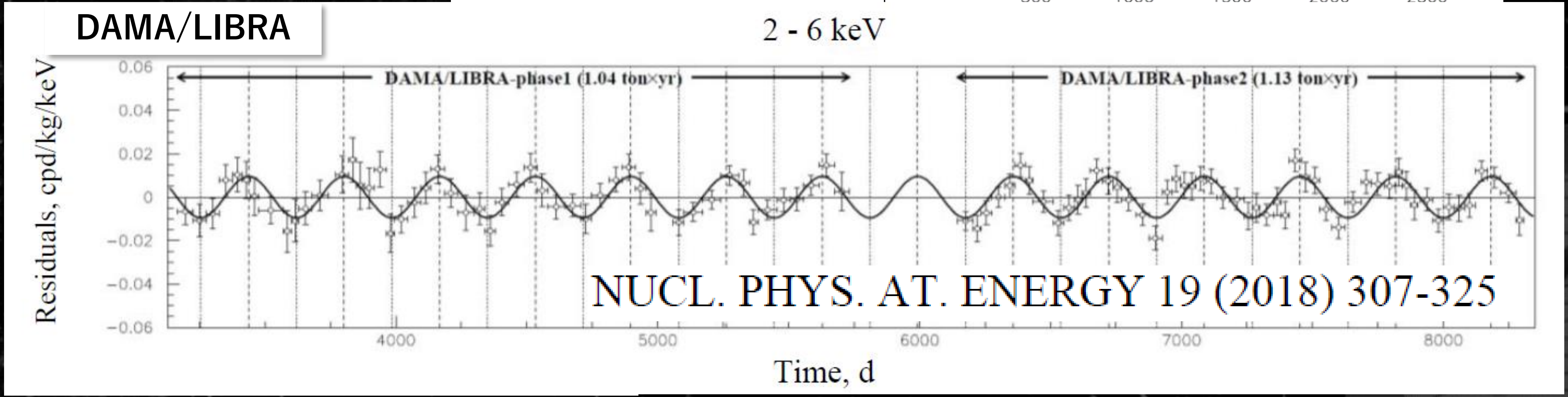


- DAMA　(NaI)
  - 250kg　NaI scintillators
  - Annual modulation were reported：1998～
  - Latest 2.46 ton year　12.9 σ
  - SOMETHING is detected





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



No BG explains this modulation
No natural DM model explains, either…

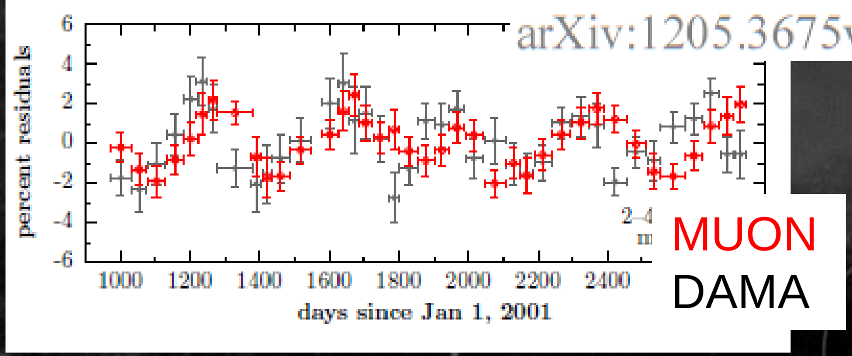
Explaining DAMA with BG

- Long discussion on BG modulation

Eur. Phys. J. C (2012) 72:2064

- Muon?

On the Cosmic Ray Muon Hypothesis for DAMA



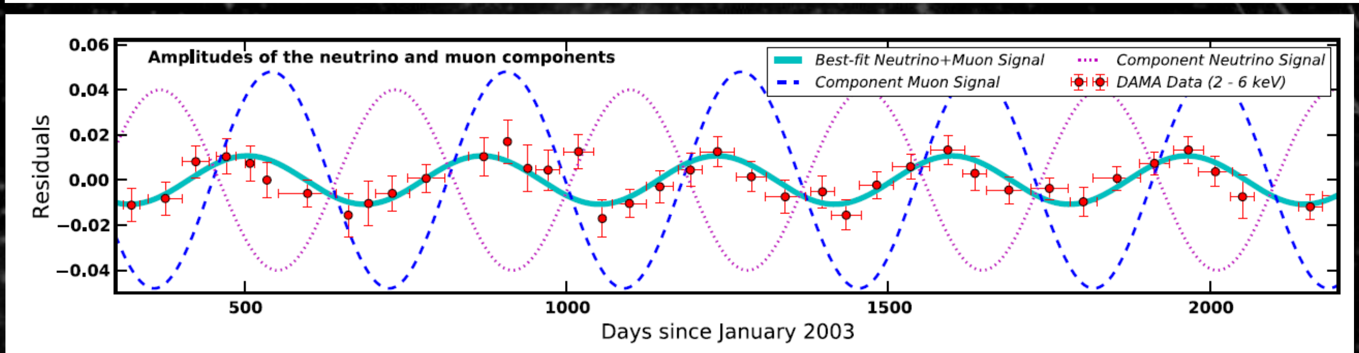
- No, muon comes later

- Muon & neutrinos

PRL 113, 081302 (2014)

  - Solar neutrino has largest flux in winter. (Sun closer.)

Fitting the Annual Modulation in DAMA with Neutrons from Muons and Neutrinos



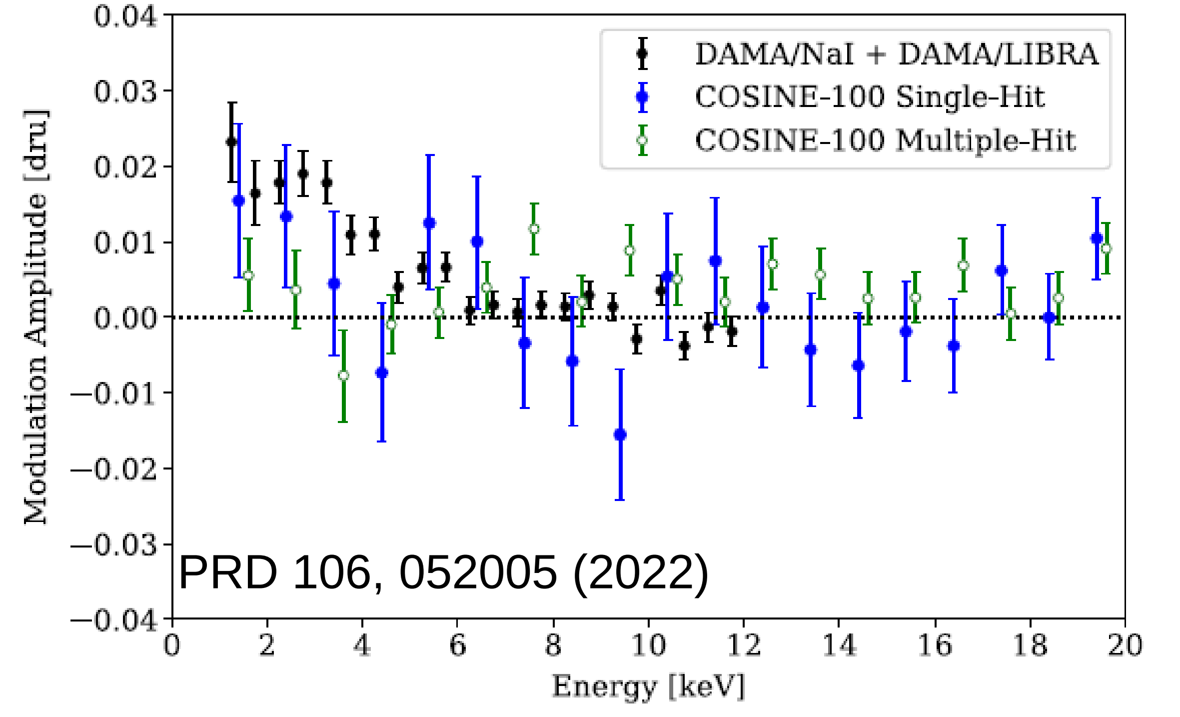
- No, not enough neutrinos

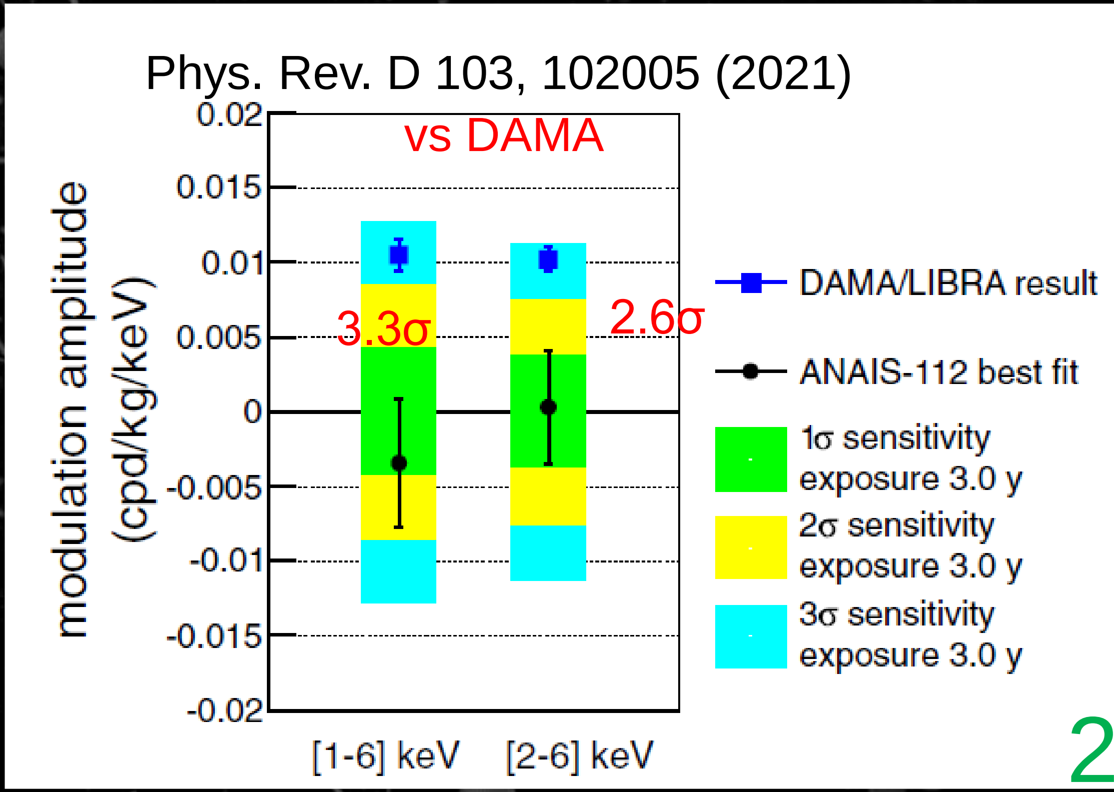
Eur. Phys. J. C (2014) 74:3196

- None worked so far …
- So the right way is to …

- Other NaI detectors
  - COSINE(~100kg):
    - 3 years' measurement completed
    - Consistent with null and DAMA.
    - upgrading (low threshold, mass ×2)
  - ANAIS (112kg)
    - 3 years' measurement
    - incompatible with DAMA
    - 2 more years to test by 5σ
  - SABRE
    - North and South inpreparation
  - PICOLON
    - Pure crystal
  - COSINUS
    - bolometer technique

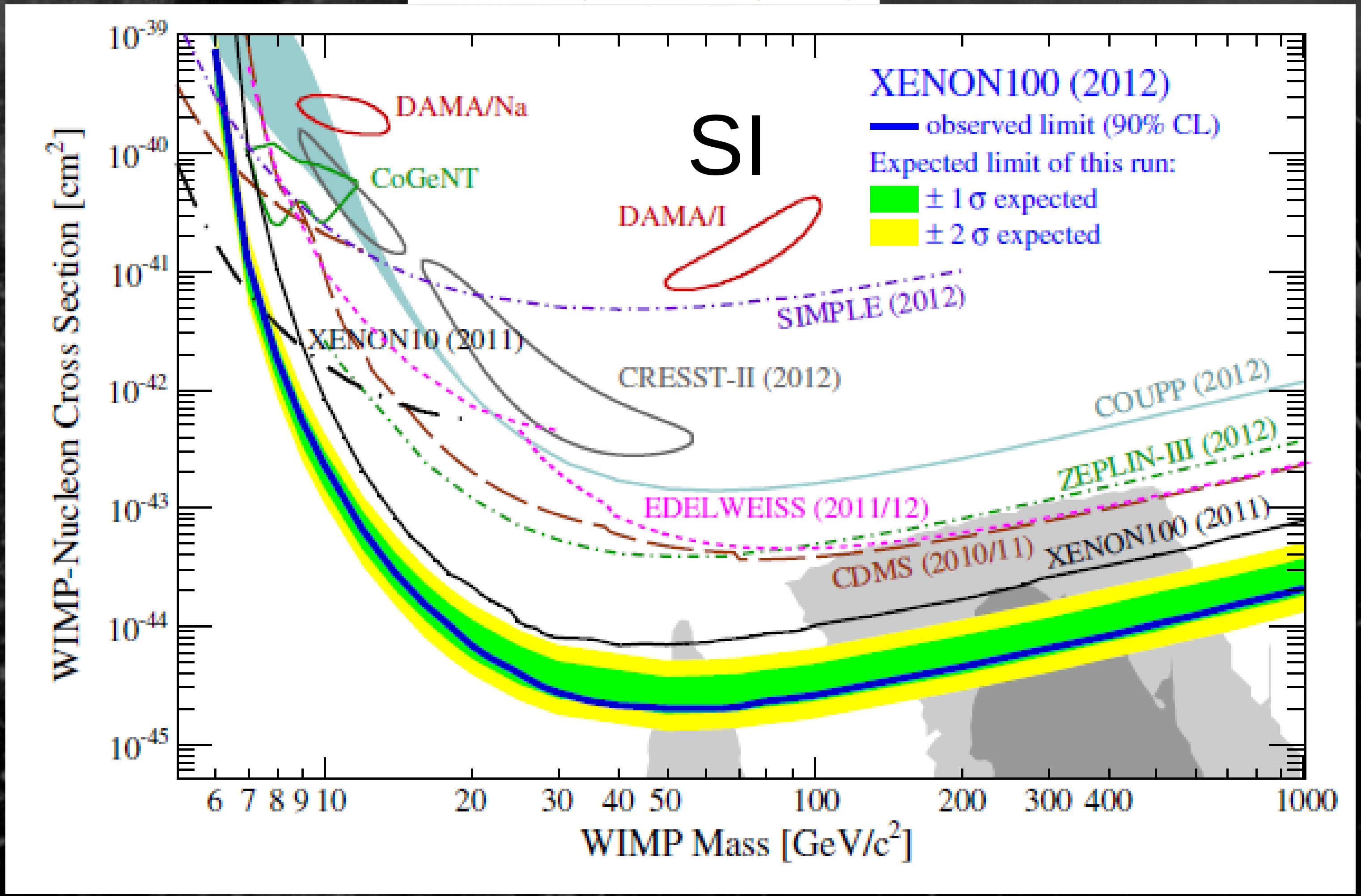
Need to be stay tuned.



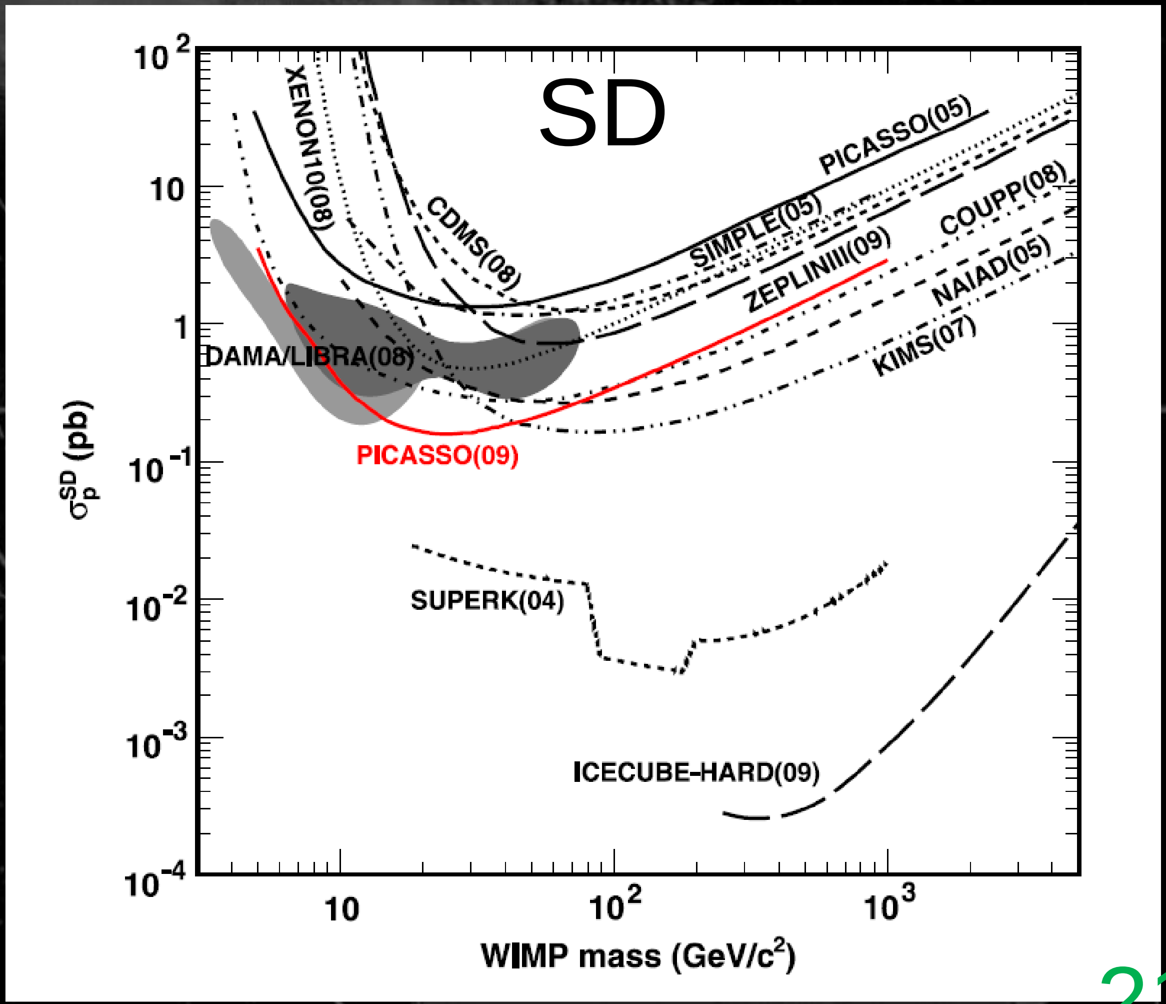


- DAMA：Strong tension with other nuclei
  - Recent papers don't show DAMA's area.
  - It doesn't mean DAMA signal is gone…

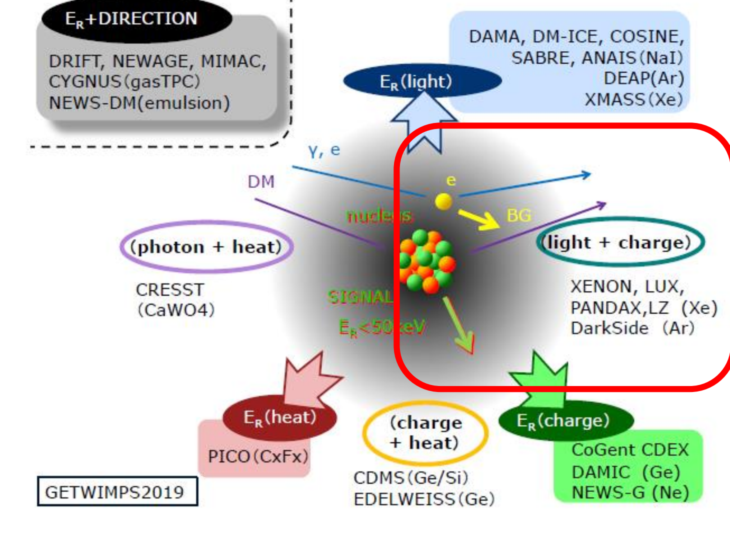
PRL **109**, 181301 (2012)



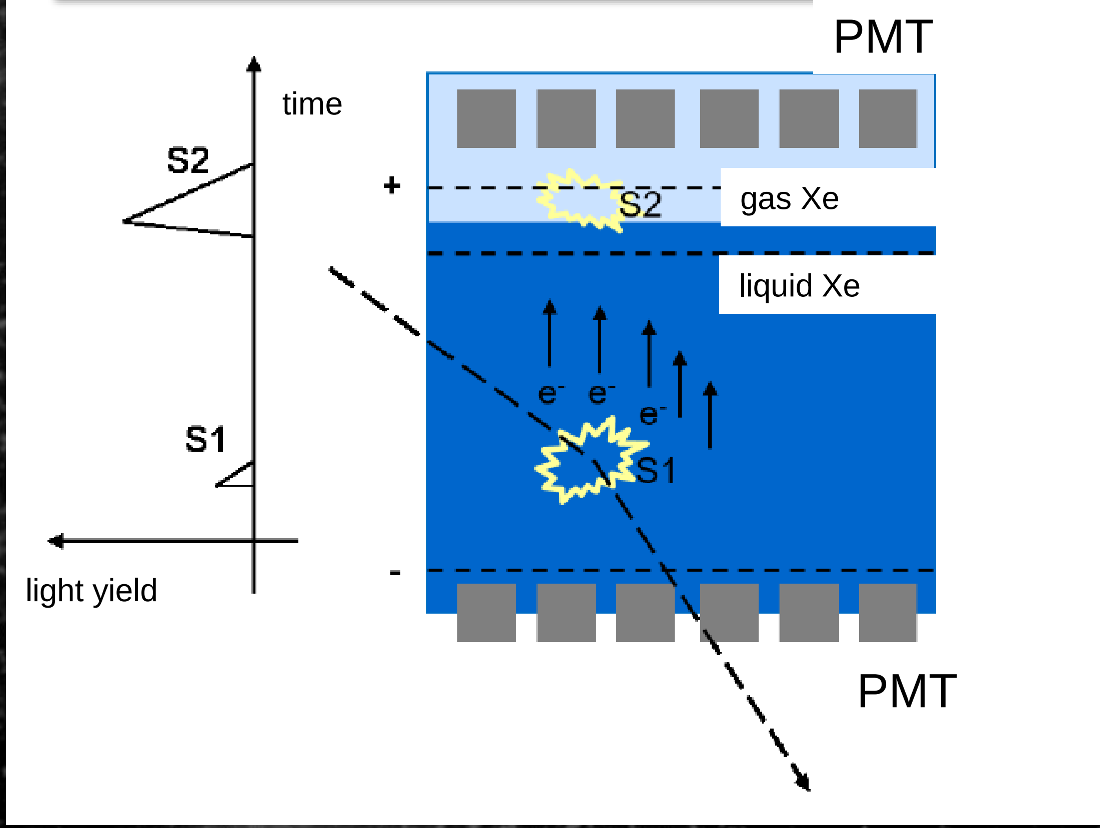
Physics Letters B 682 (2009) 185–192



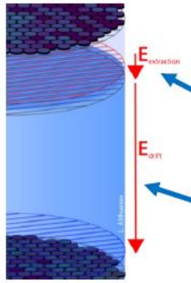
- Liquid Xe/Ar：double-phase（liquid+gas)
  - XENONnT, LZ, PandaX-II（Xe）, DARKSIDE(Ar)
  - Several 100kg ～ 1ton
  - z position can be known
  - Electron background can be discriminated



Double phase detector principle



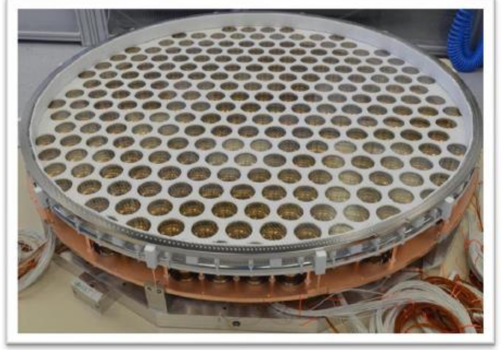
Time projection chamber



Extraction field 2.9 kV/cm (in liquid)
~50% electron extraction efficiency

Drift field 23 V/cm

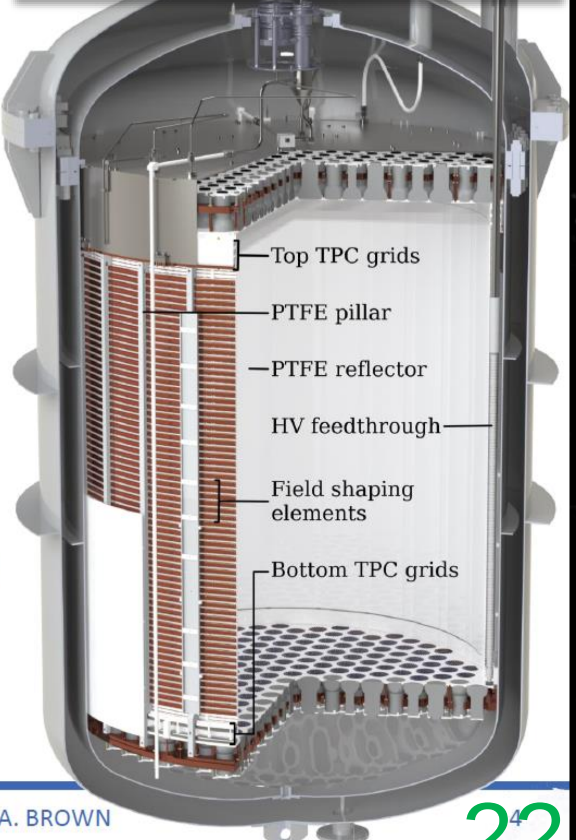
5.9 tonnes Xe in TPC
8.5 t total



Hamamatsu R11410-21
3-inch photomultiplier tubes (PMTs)

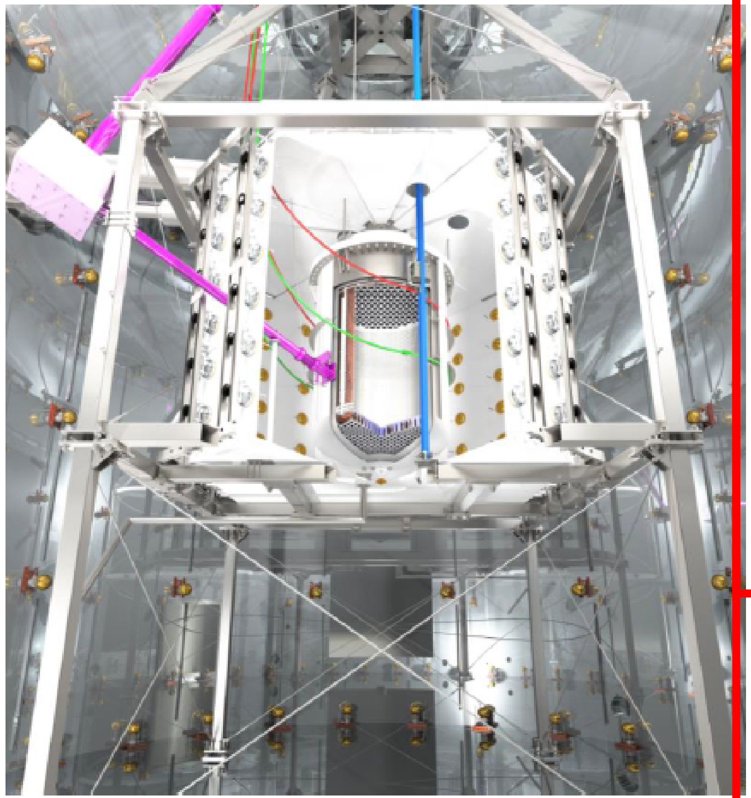
477 out of 494 PMTs operational

XENON nT detector



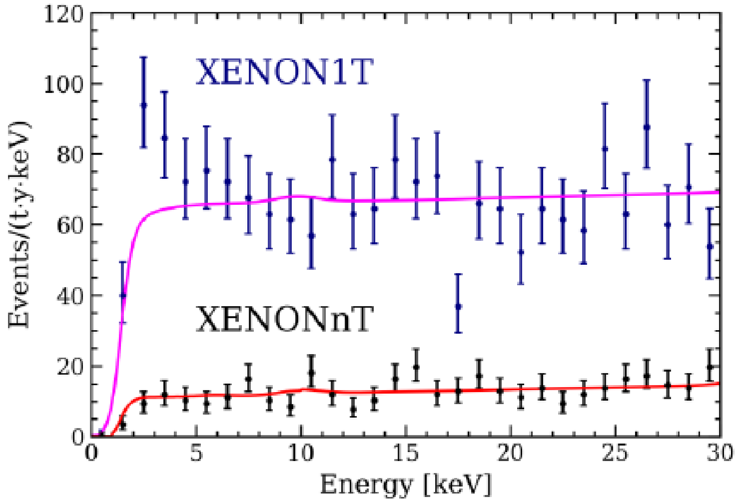
XENON universität freiburg XENONNT STATUS AND RESULTS | ICRC2023 | A. BROWN

From XENON1T to XENONnT: main upgrades



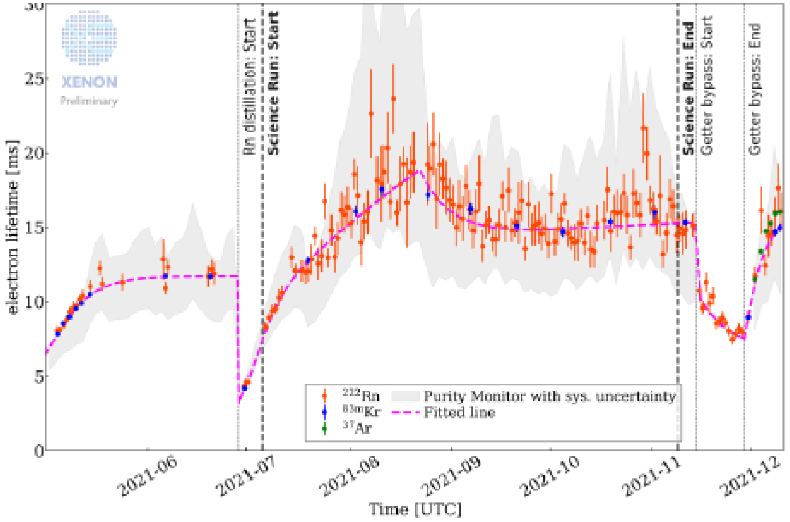
Neutron veto
Built inside existing muon veto
120 PMTs observe
2.2 MeV n-capture gamma
(53 ± 3)% tagging efficiency
(250 μs window) with life time
loss of 1.6%
Gd will improve efficiency to
87% (150 μs window)

Radon distillation column
Continuous radon removal
Activity 1.8 μBq/kg for these results
See poster H. Schulze Eißing (PDM1-3)
EPJC 82, 1104 (2022), 2205.11492



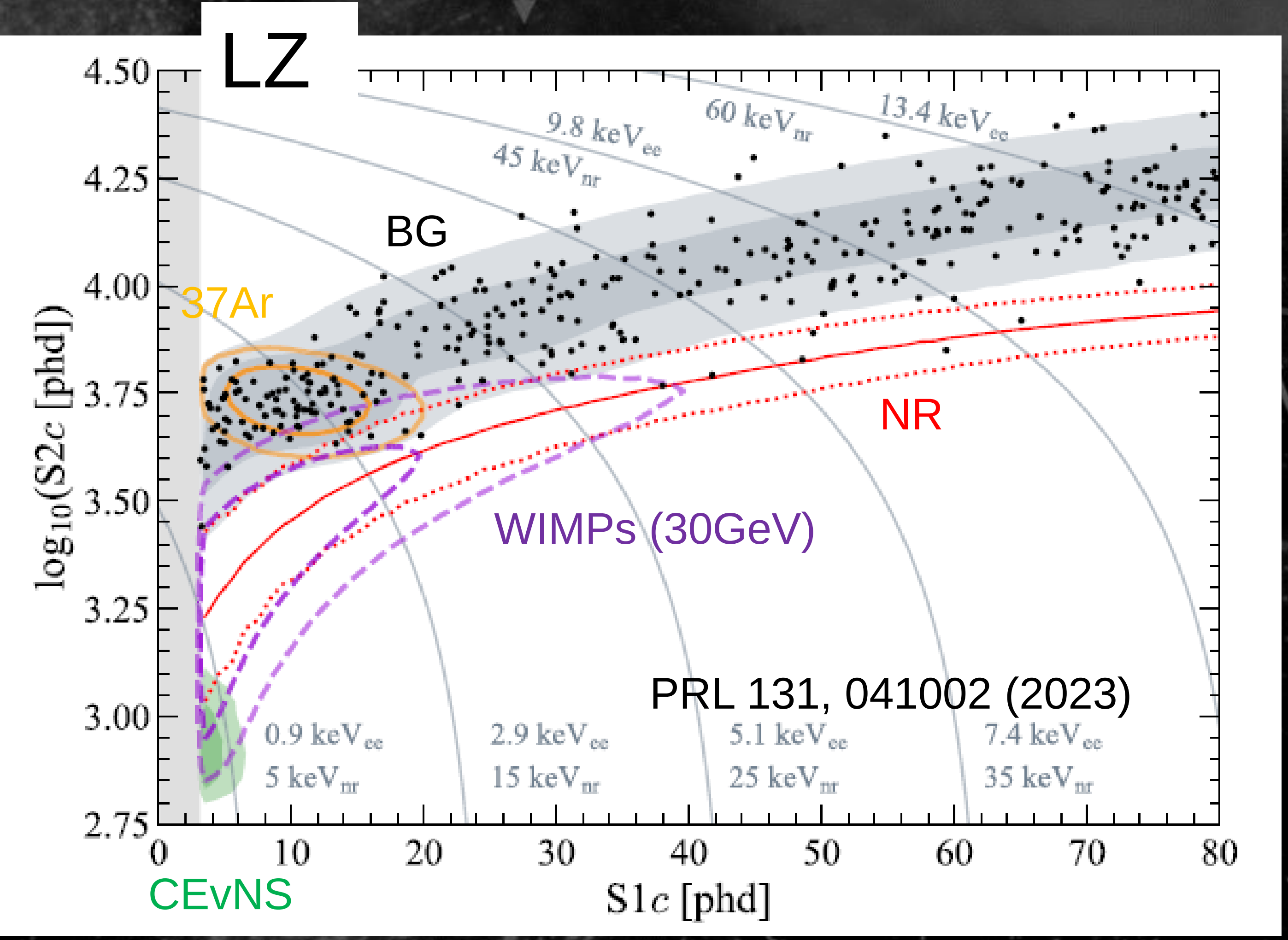
Triggerless DAQ
All signals of photoelectron size
or bigger saved
Improves low-energy sensitivity
2212.11032

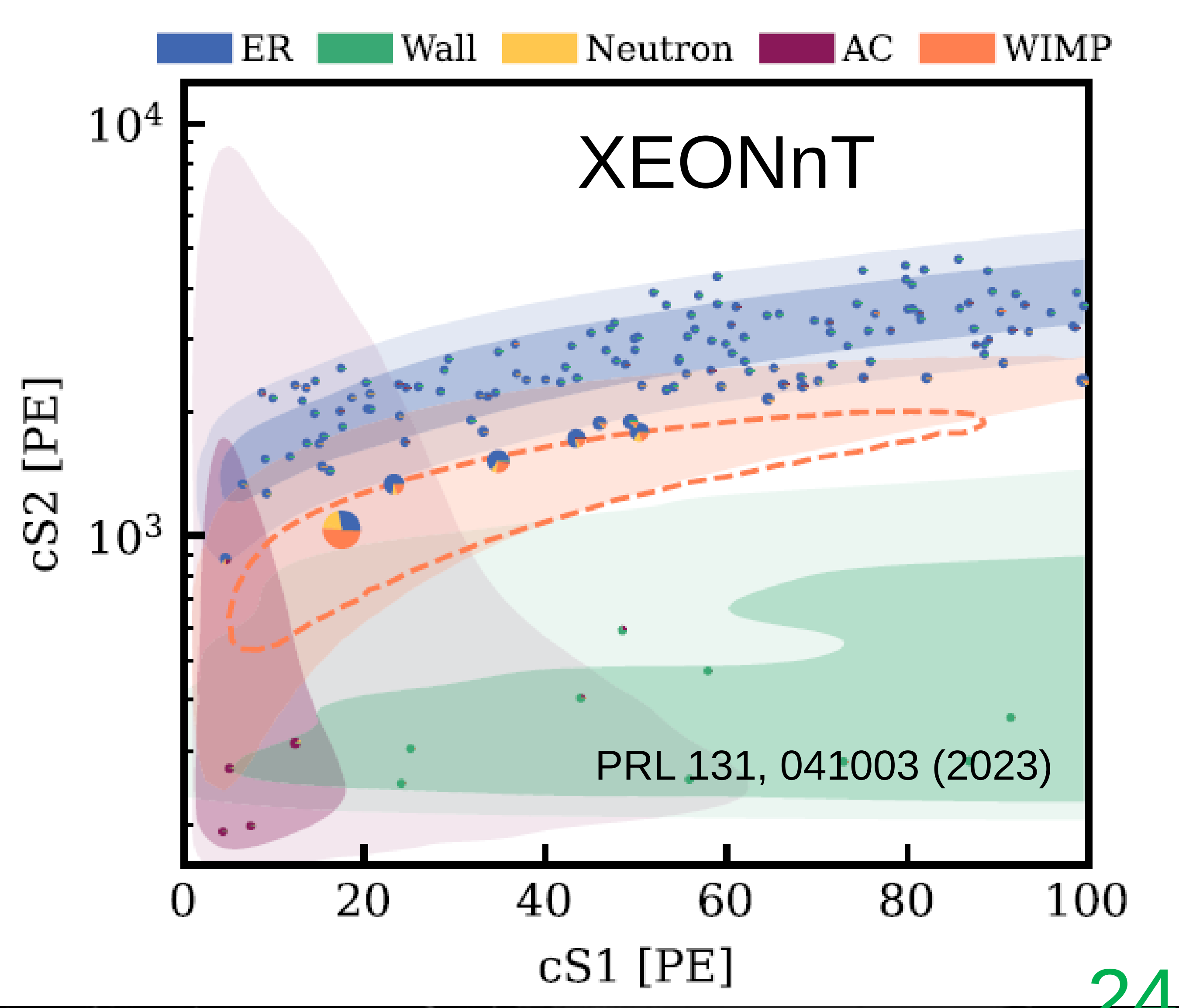
日本グループの貢献



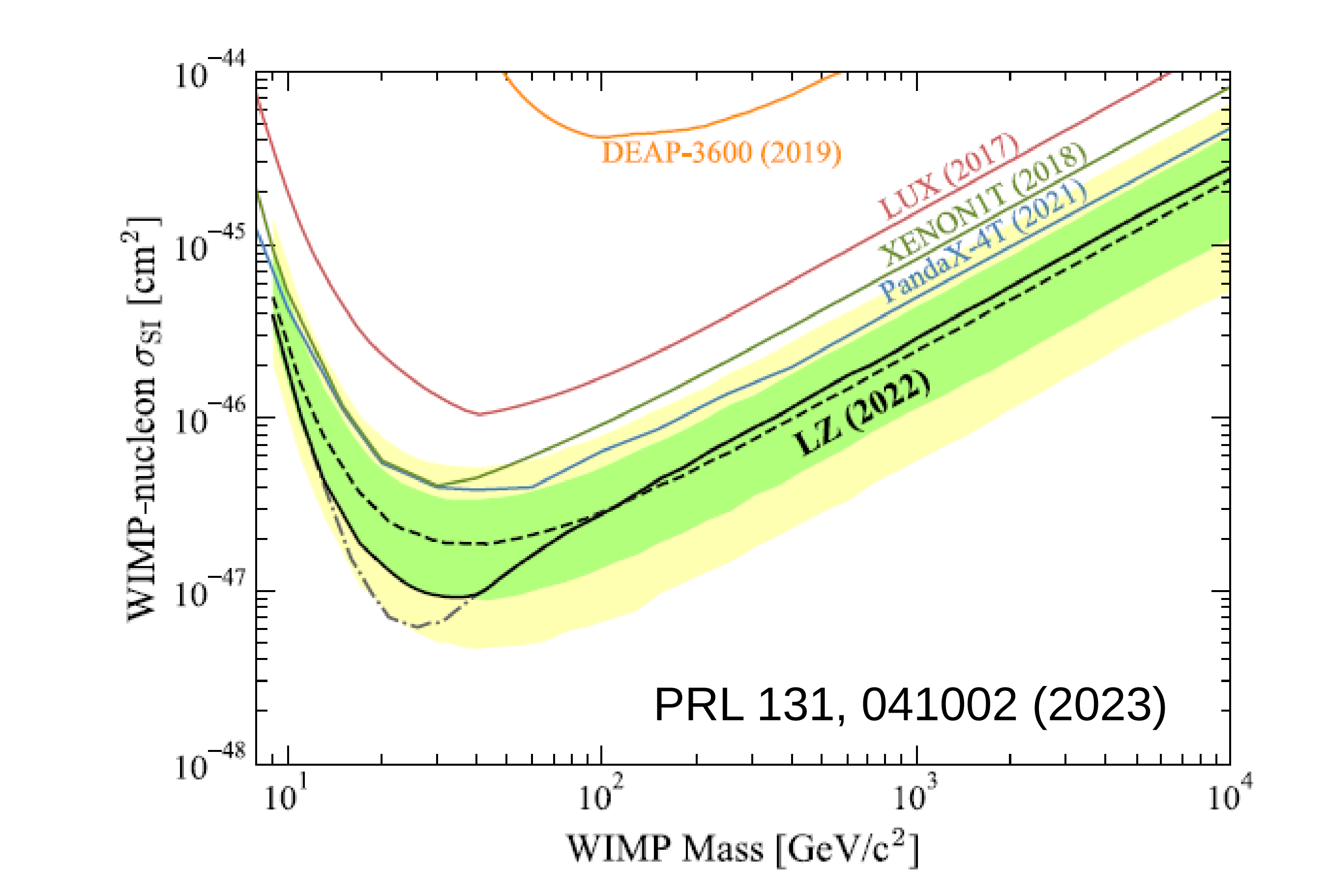
Liquid xenon purification
Clean 2 l liquid Xe per minute
(full 8.5 t in 18 hours)
Lifetime > 15 ms achieved
See poster M. Kobayashi (PDM1-2)
EPJC 82, 860 (2022), 2205.07336

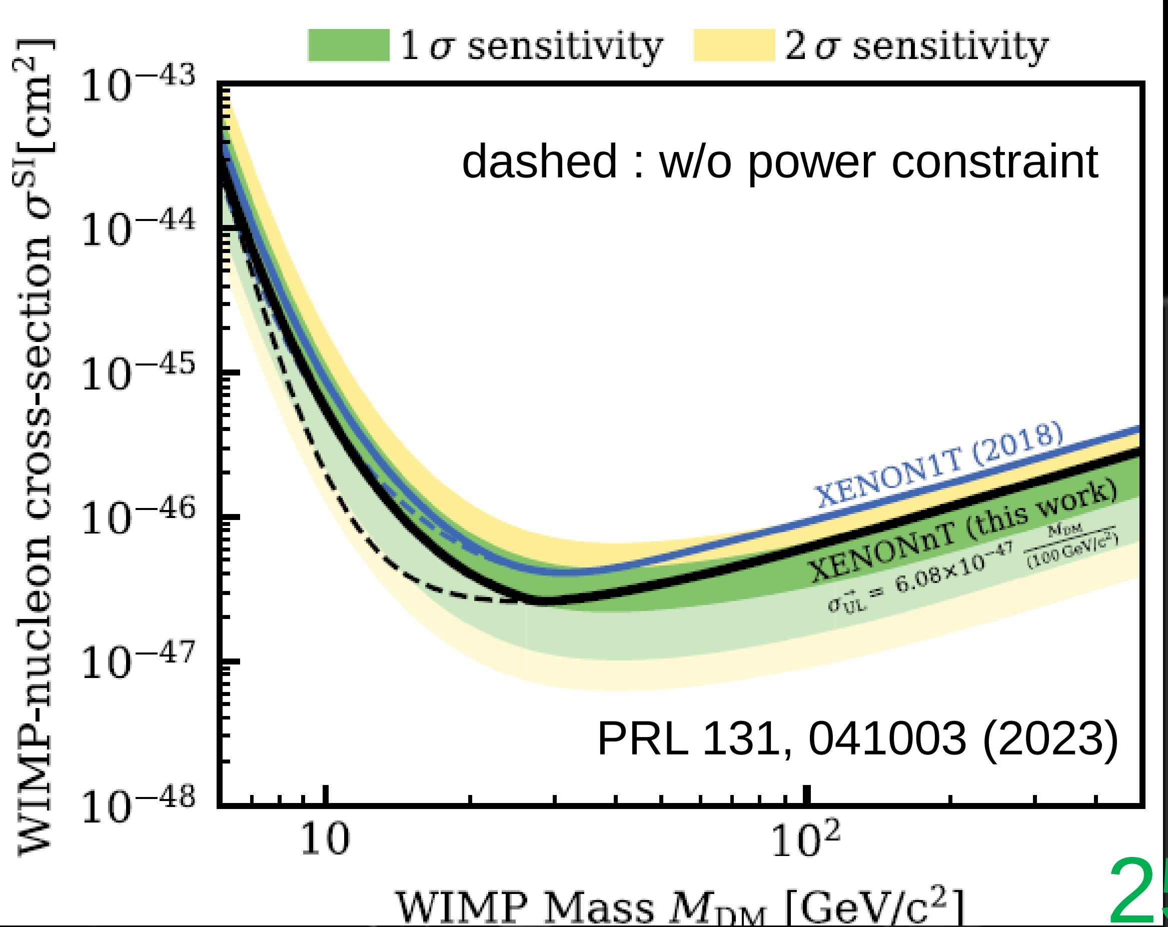
- 結果
  - ER ：radon　　neutron：neutrons from α particle
  - AC：accidental coincidence
  - Some events in ROI consistent with BG 　→ upper limit





- 最新結果
  - LZ : 0.9 ton • year 9.2e-48 cm² for 36 GeV WIMPs
  - XENON : 1.1 ton • year 2.6e-47 cm² for 28 GeV WIMPs (blind analysis + power constraint limit setting)



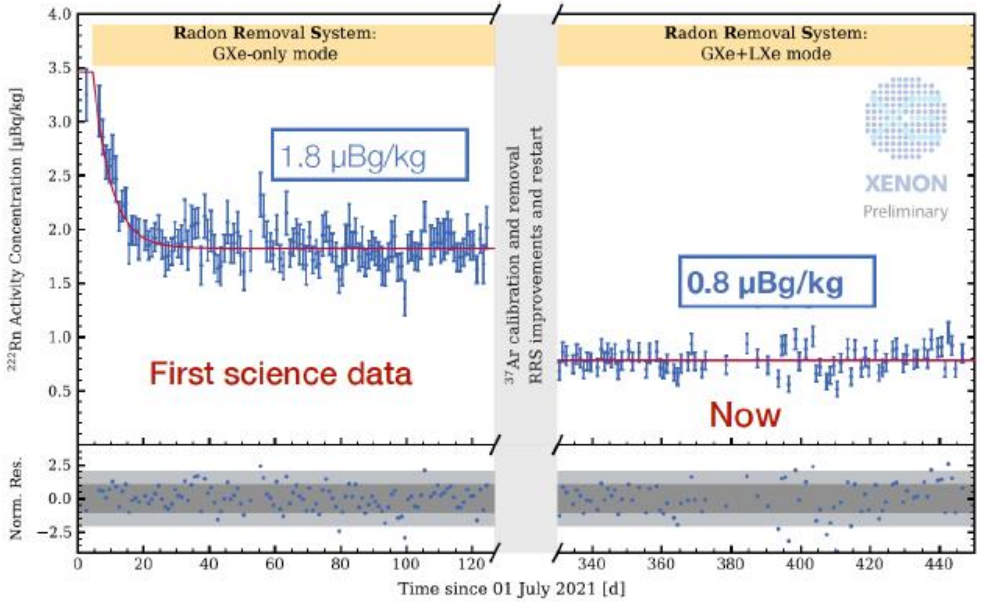


- この先
  - 観測継続 & upgrade

XEONnT

What next?

Even lower radon level
Already achieved < µBq/kg by changing flow path

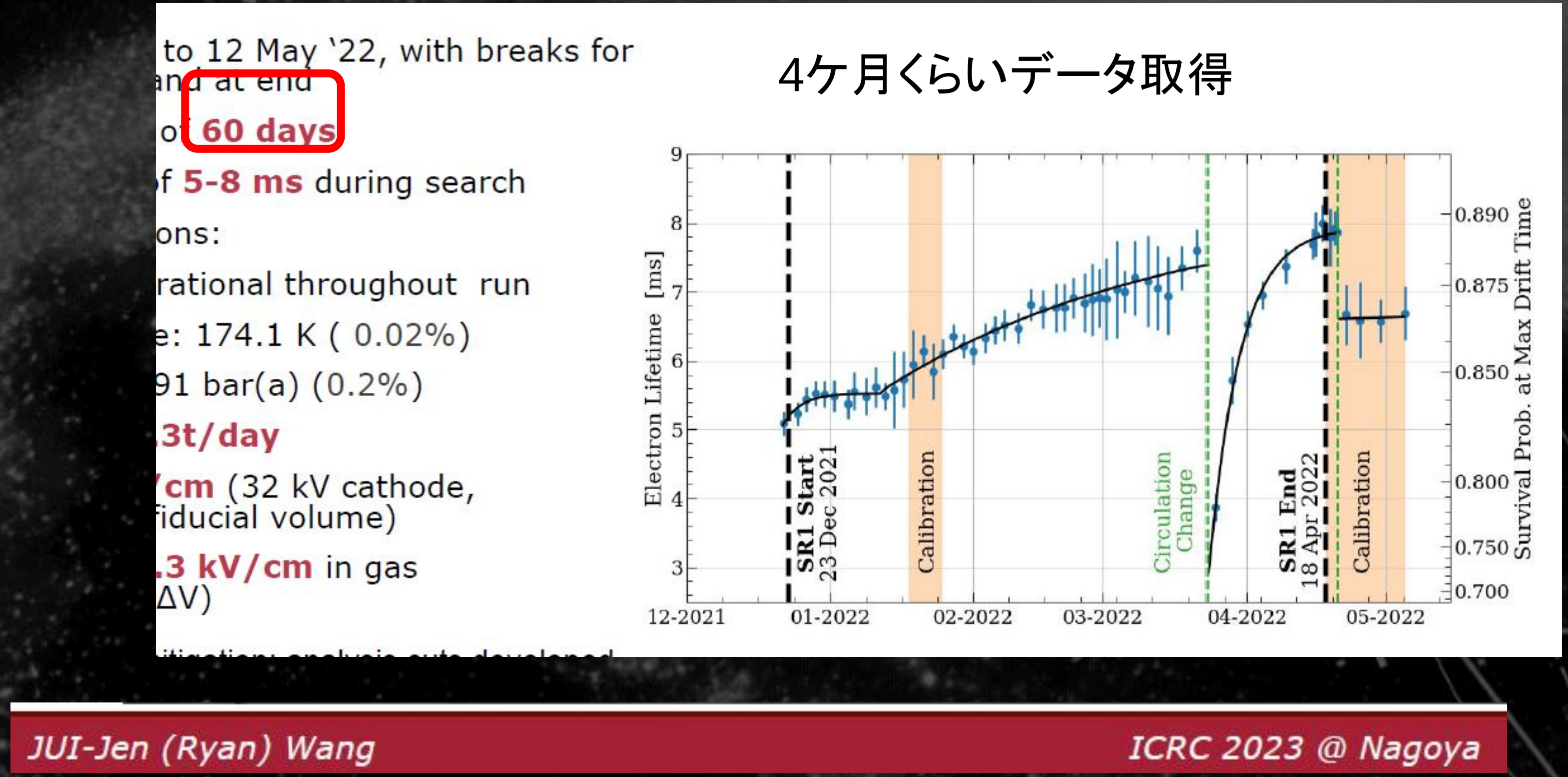


New analyses

And keep taking data!

Neutron suppression
Adding Gd to neutron veto for 87% efficiency

- 論文では強調されない苦労話
  - LZ



半分くらいdead

interactions in the gas phase or in the liquid above the gate electrode, or drifting electrons trapped on impurities and released with $\mathcal{O}(100\ \mathrm{ms})$ time delay [53]. Analysis cuts to remove accidentals target individual sources of isolated S1s and S2s using the expected behavior of the S1 and S2 pulses with respect to quantities such as drift time, top-bottom asymmetry of light, pulse width, timing of PMT hits within the pulse, and hit pattern of the photons in the PMT arrays. The cuts remove > 99.5% of accidentals, measured using single-scatter-like events with unphysical (> 951 μs) drift time and events generated by random matching of isolated S1 and S2 populations.

不純物の影響で
出てくるS2を殺すためのvetoが長い。
今後の液純化が必用

- 論文では強調されない苦労話
  - XENONnT

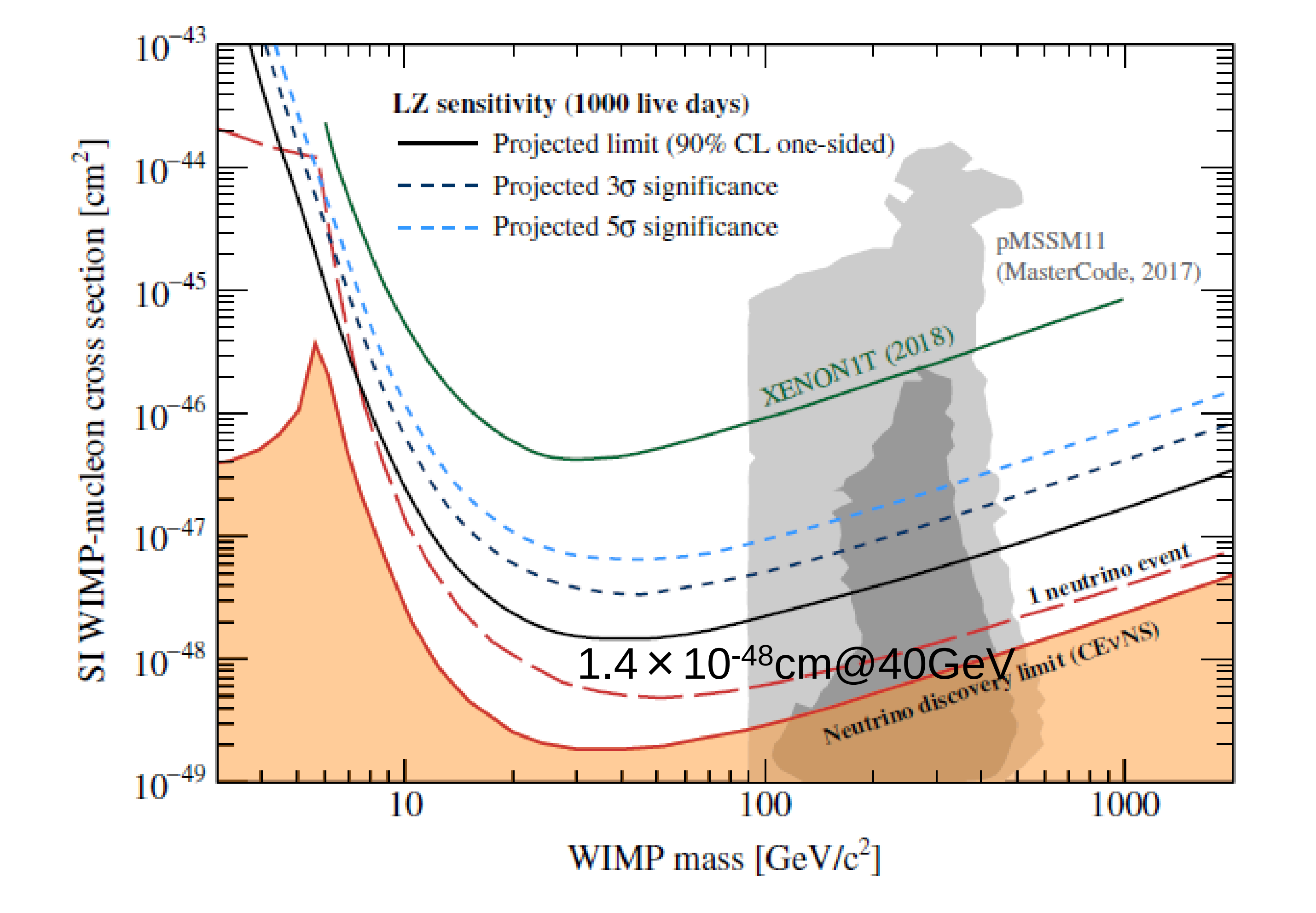
sagging. Two additional parallel-wire screening electrodes are used to shield the PMT arrays from the electric fields. After two months of commissioning at a drift field of 100 V/cm, a short between the bottom screening and cathode electrodes limited the applied drift field to 23 V/cm, corresponding to a maximum drift time of 2.2 ms. The extraction field was set to 2.9 kV/cm in LXe to reduce localized, intermittent bursts of single electron S2 signals. Despite the lower-than-designed drift and extraction fields, the energy and position resolution, as well as the energy threshold, are comparable to those achieved with XENON1T.

電極切れて電場が
デザイン通りには作れない。

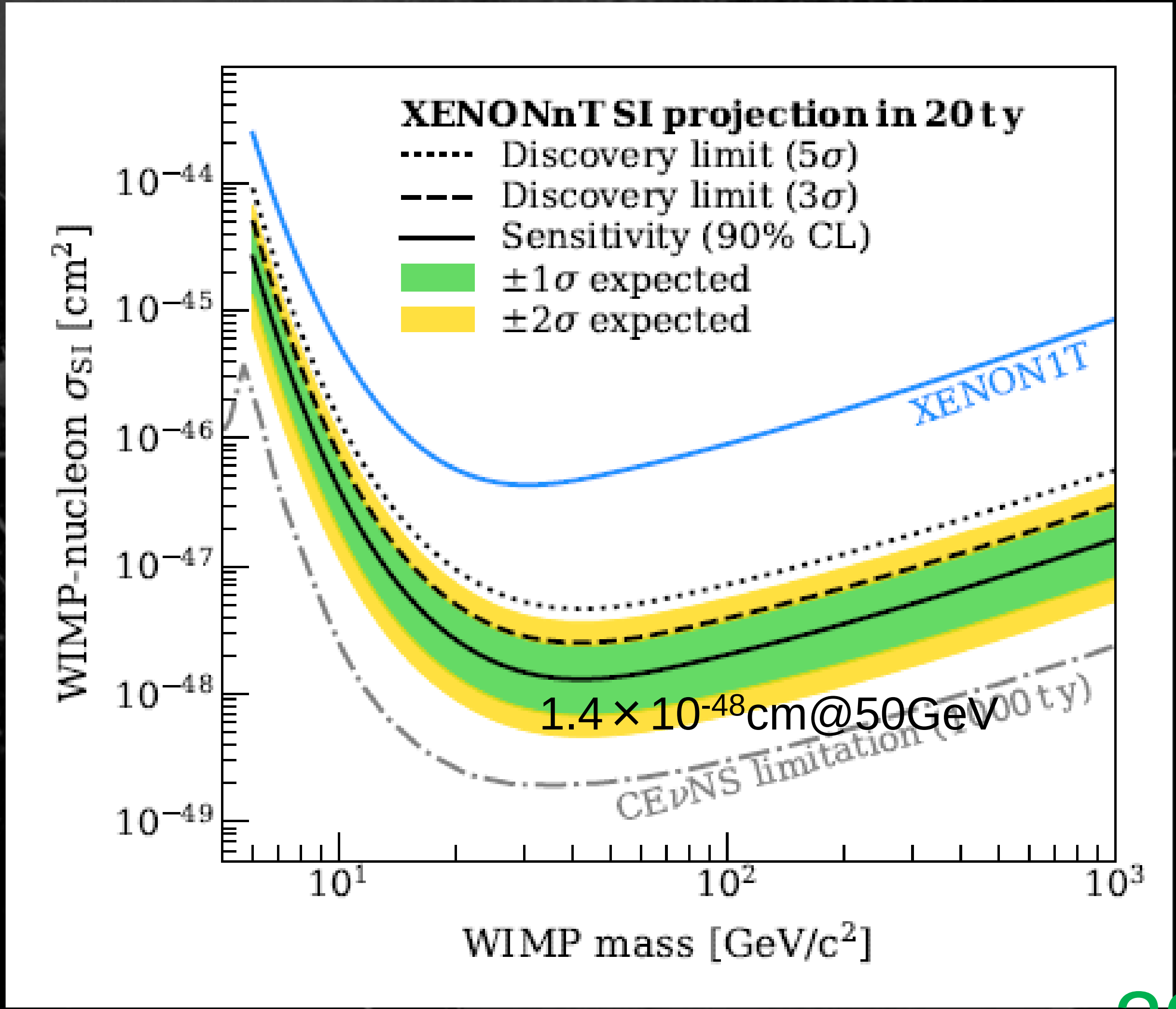
やや影響はあるが、
観測継続

- 今後
  - 5年程度の観測
  - その後 DARWINなどさらに大型化

PHYS. REV. D **101**, 052002 (2020)



arXiv:2007.08796v1

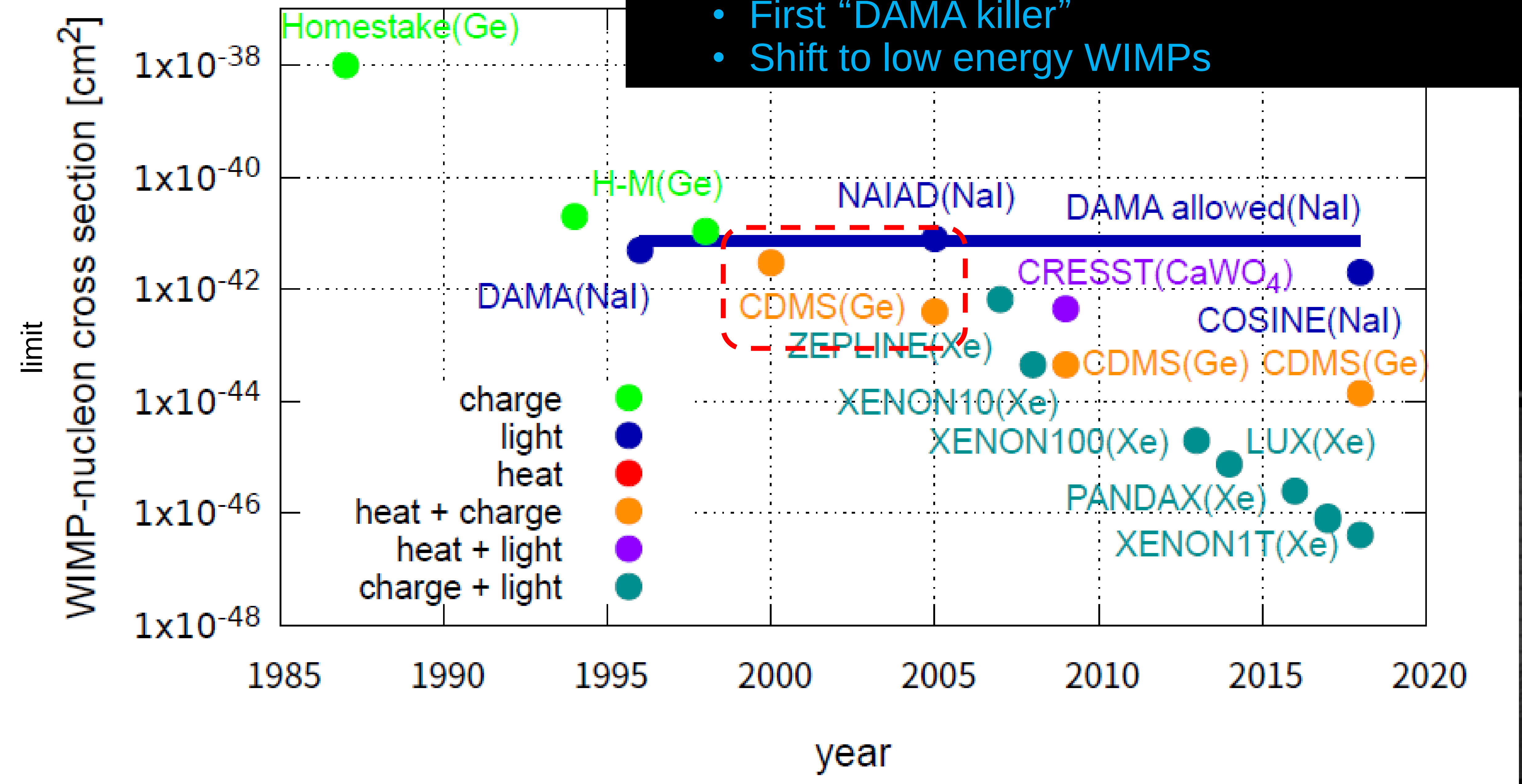


Direct Search Review

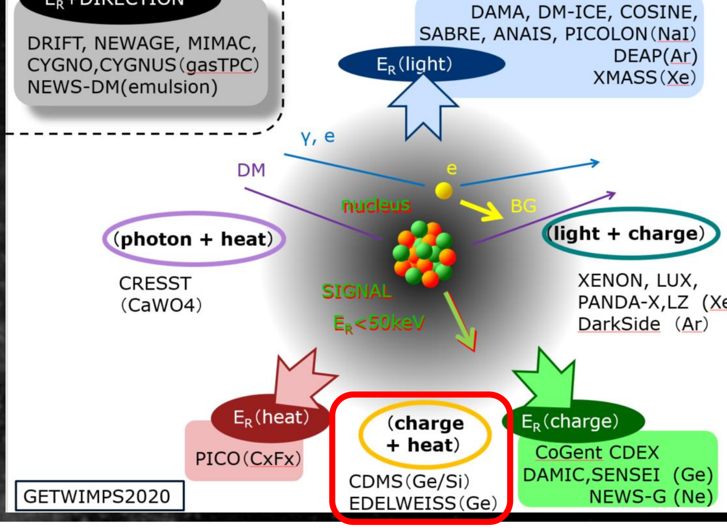
2. New Trend : Low Mass DM

Direct search history

- Bolometers
  - Leading technology before Xe detectors
  - First “DAMA killer”
  - Shift to low energy WIMPs



- Bolometers
  - Low energy threshold ⇒ low mass DM



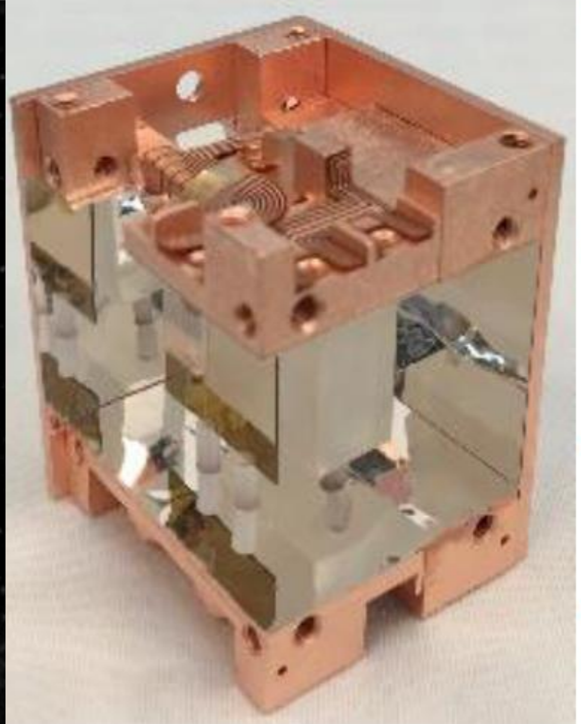
Latest results of CRESST-III's search for sub-GeV/c² dark matter

Holger Kluck
on behalf of the CRESST collaboration

16th International Conference on Topics in Astroparticle and Underground Physics (TAUP2019)

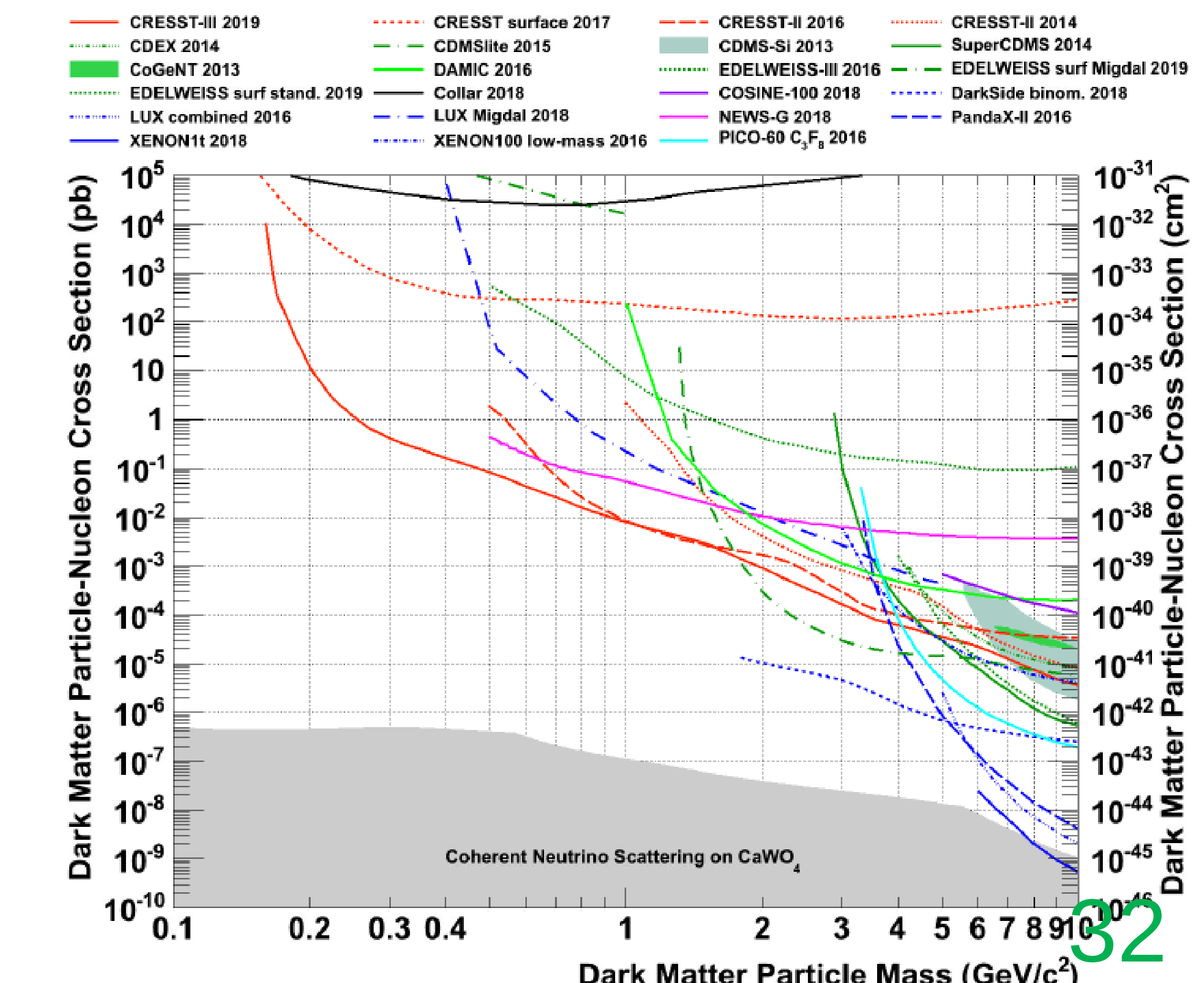
September 10, 2019

CRESST-III detector

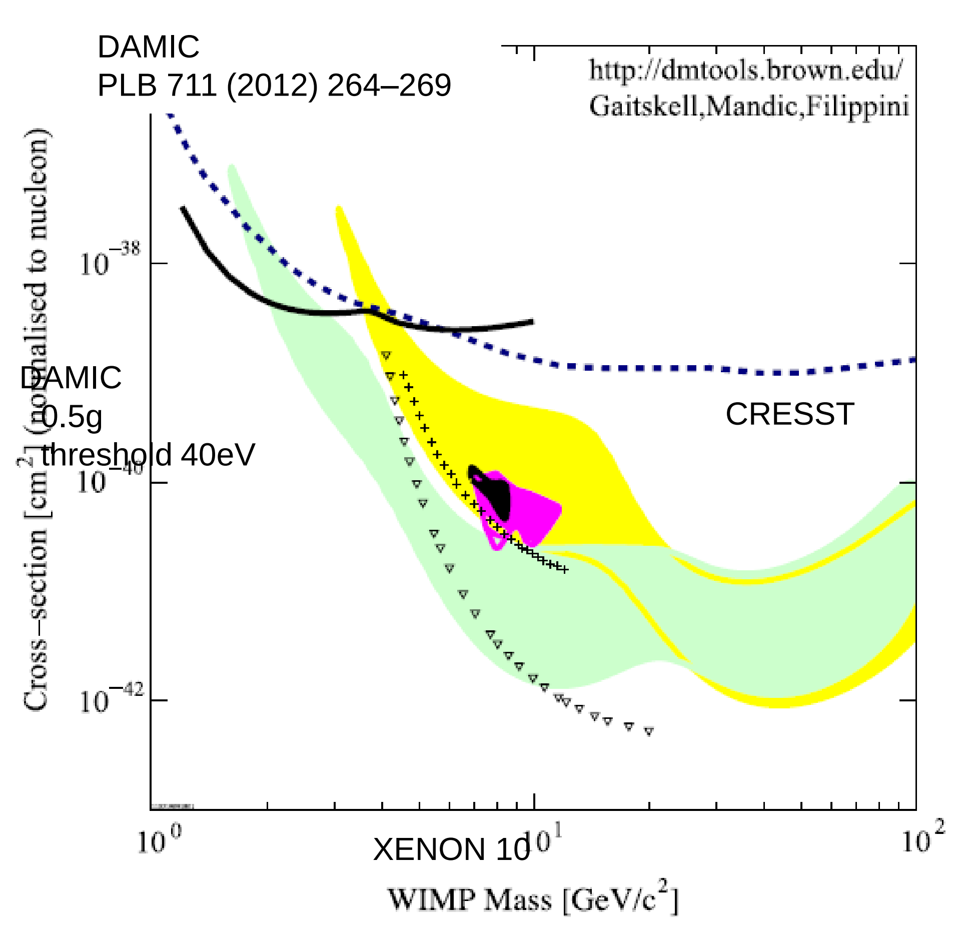


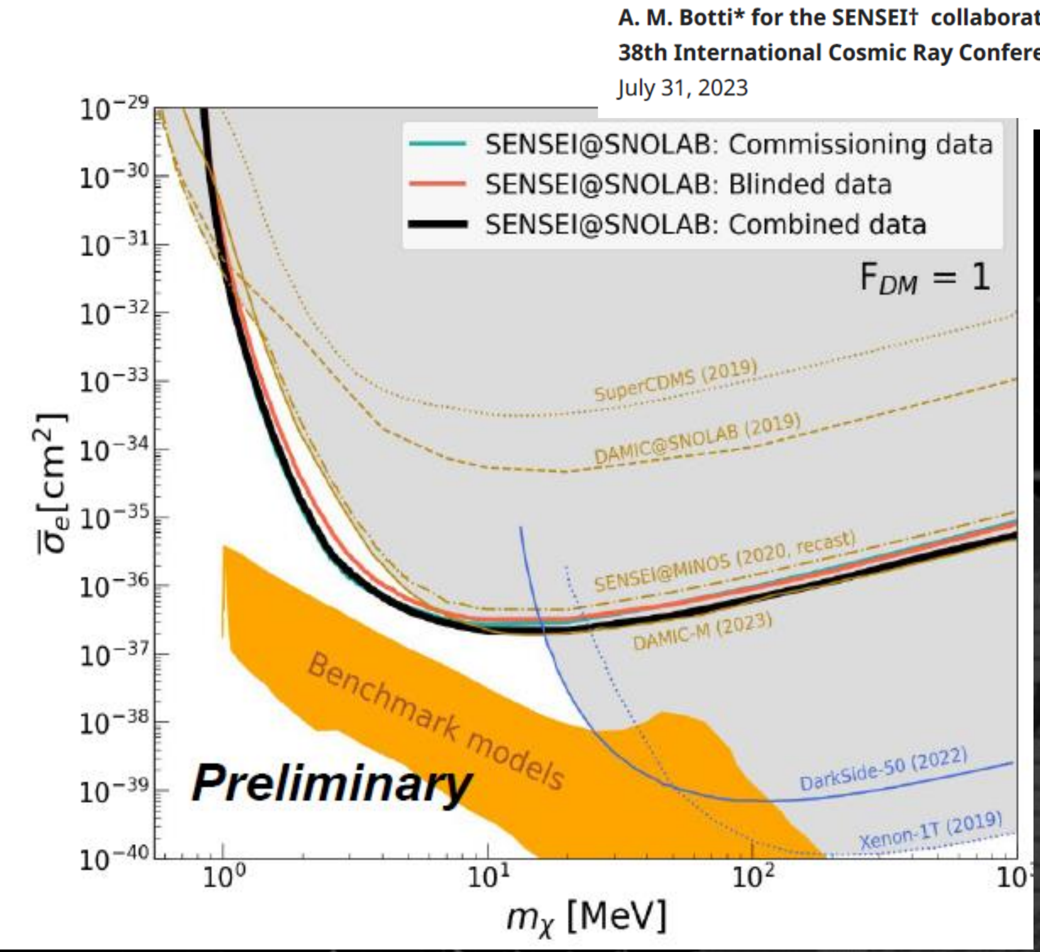
- May 2016: 10 CRESST-III modules installed
- Jul 2016 – Feb 2018: data taking (80% blinded, 20% training set)
- Detector A → lowest nuclear recoil threshold so far: 30.1 eV
- Target crystal mass: 23.6g
- Gross exposure: 5.6 kg d
- [arXiv:1904.00498], accepted by Phys.Rev.D → this talk

CRESST-III result

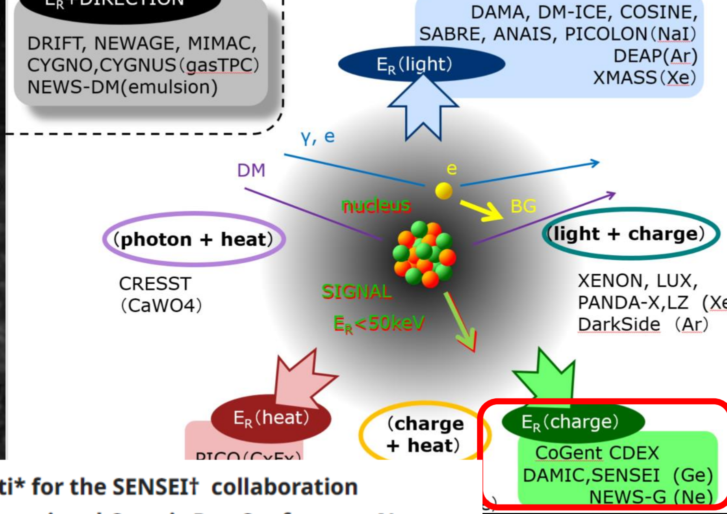


- CCD
  - DAMIC arXiv:2007.15622v1
    - pioneer of low threshold
  - SENSEI *PRL 125, 171802 (2020)*
    - skipper CCD
    - sensitive to single electron
    - DM-electron channel and other



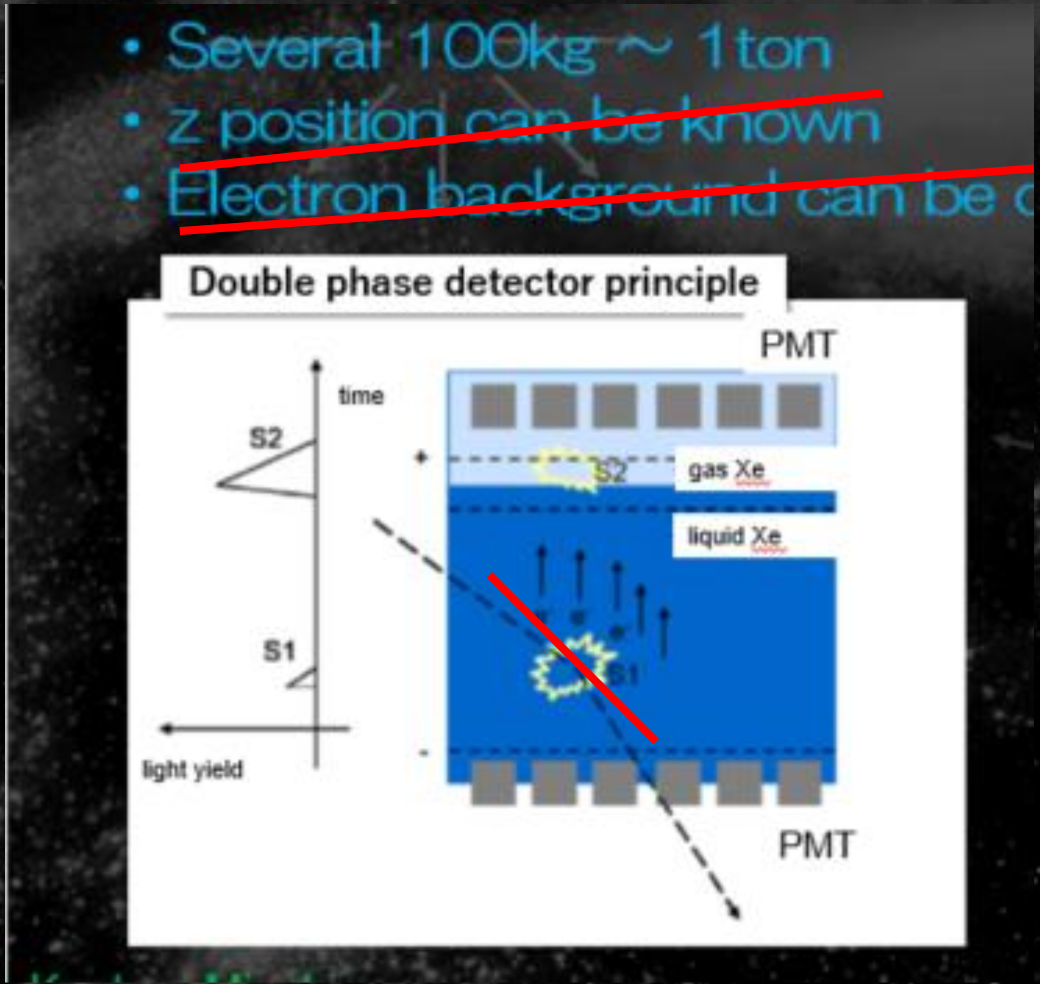


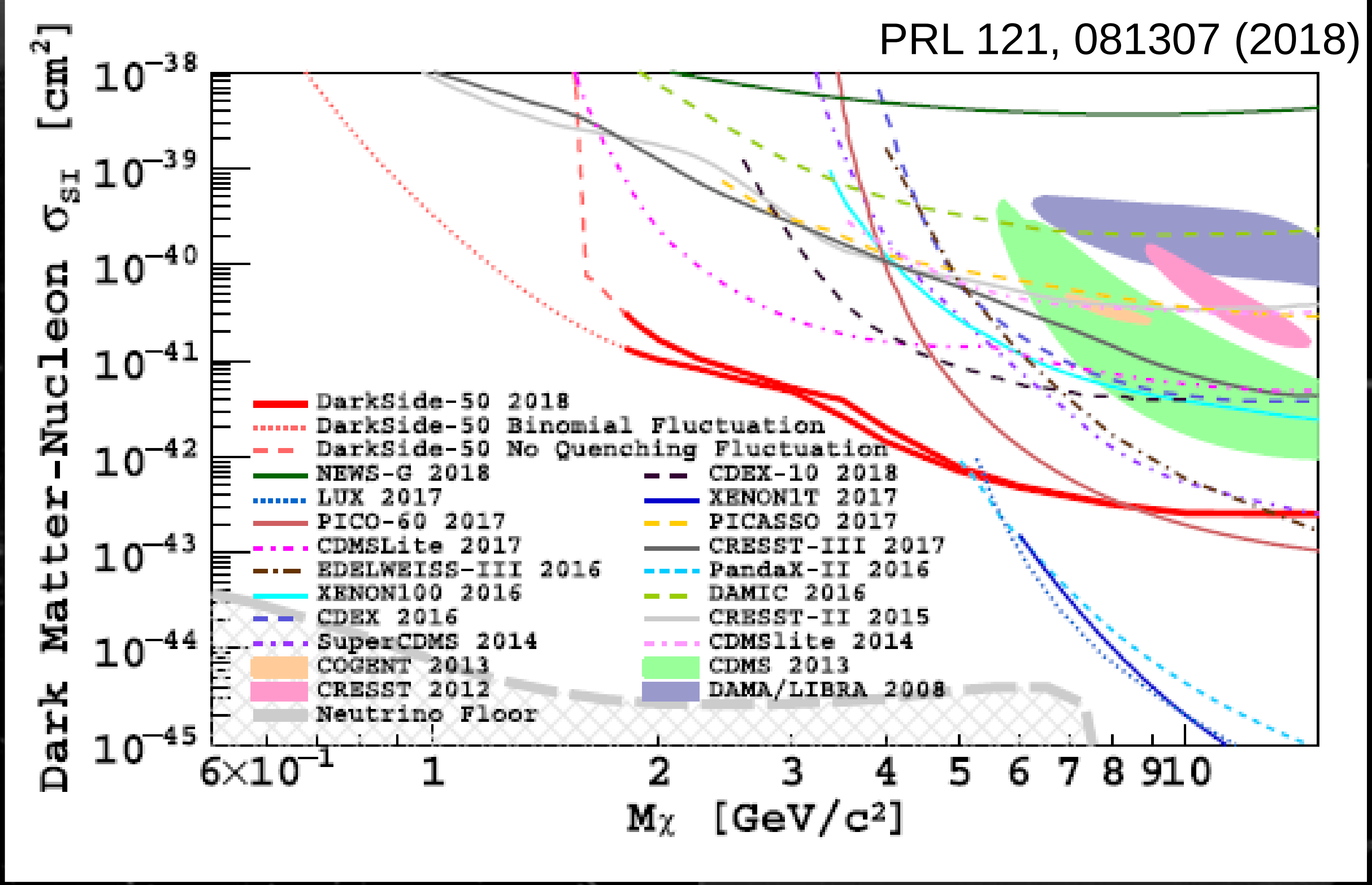
A. M. Botti* for the SENSEI† collaboration
38th International Cosmic Ray Conference, Nagoya
July 31, 2023



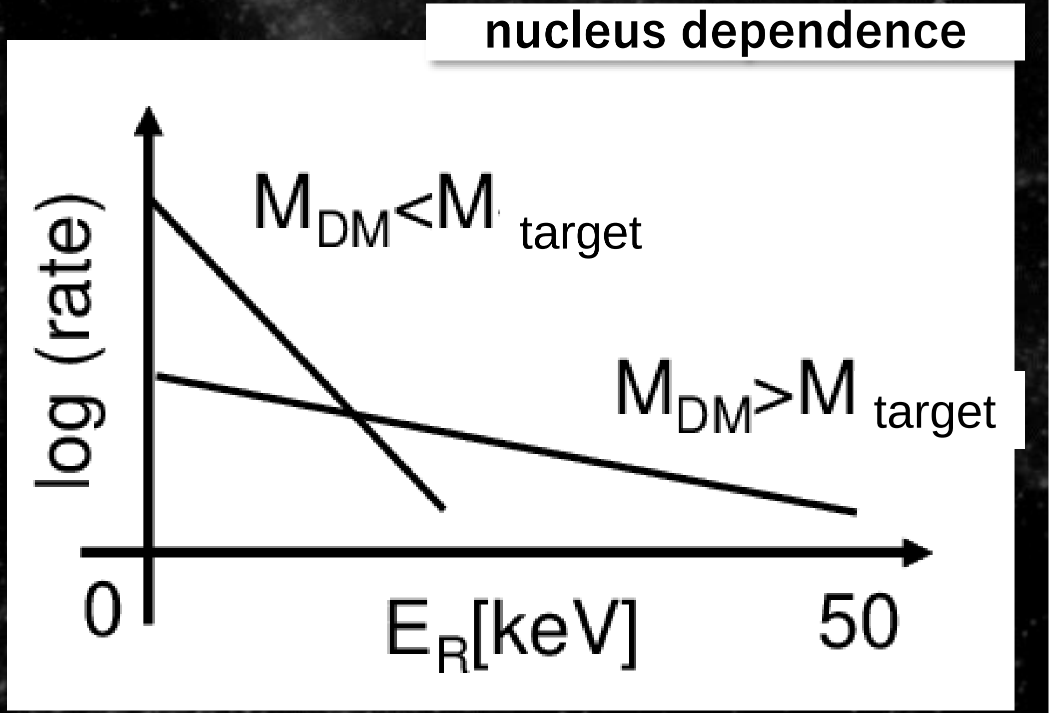
共同の将来計画「OSCURA」

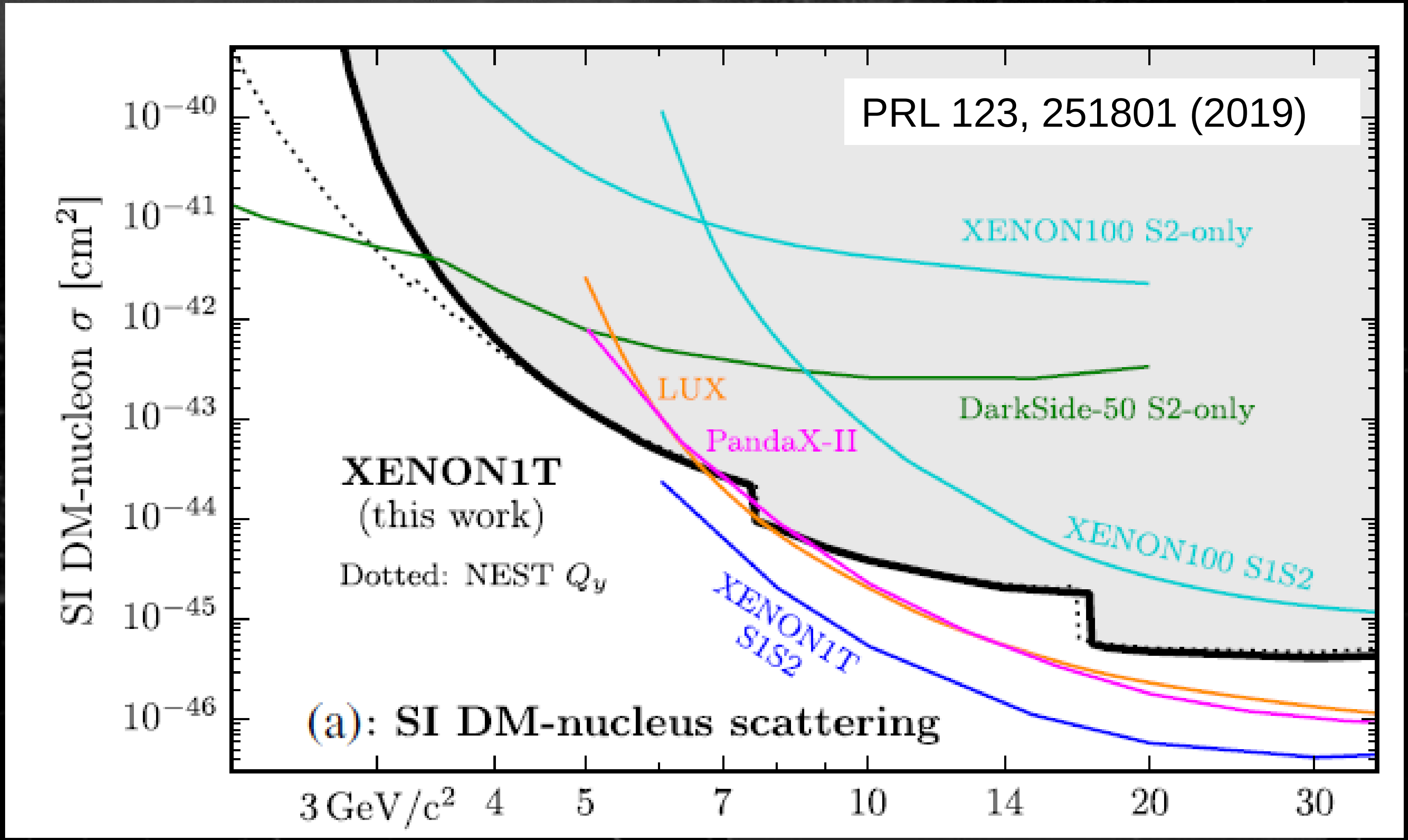
- Liq. noble gas: S2 only analysis
  - can lower threshold ⇒ low mass WIMPs
  - DARKSIDE（Ar） PRL 121, 081307 (2018)





- XENON S2 only PRL 123, 251801 (2019)
  - Improved 4-7 GeV limits
  - note: lighter nucleus (Ar) is better for low mass WIMPs

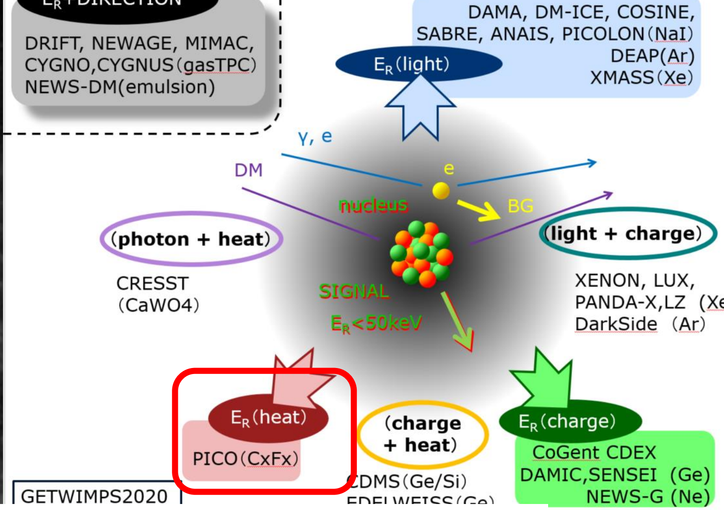


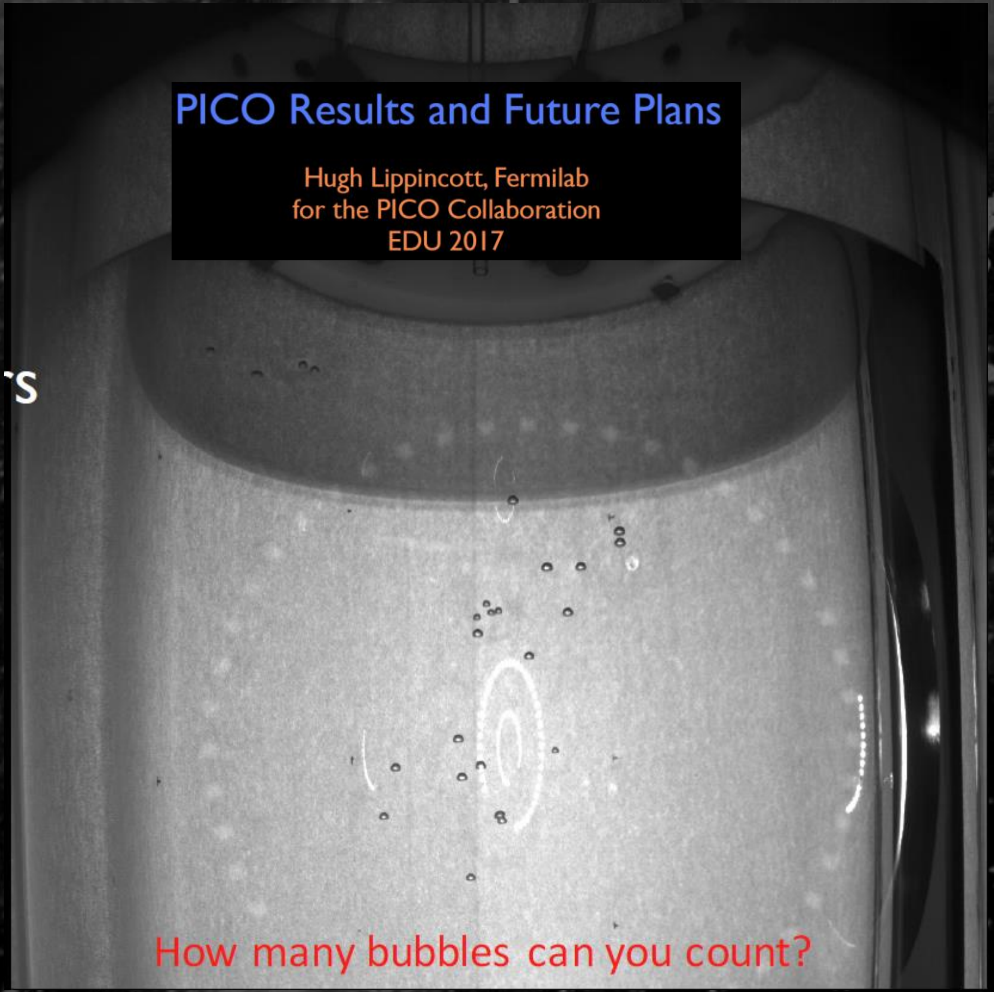


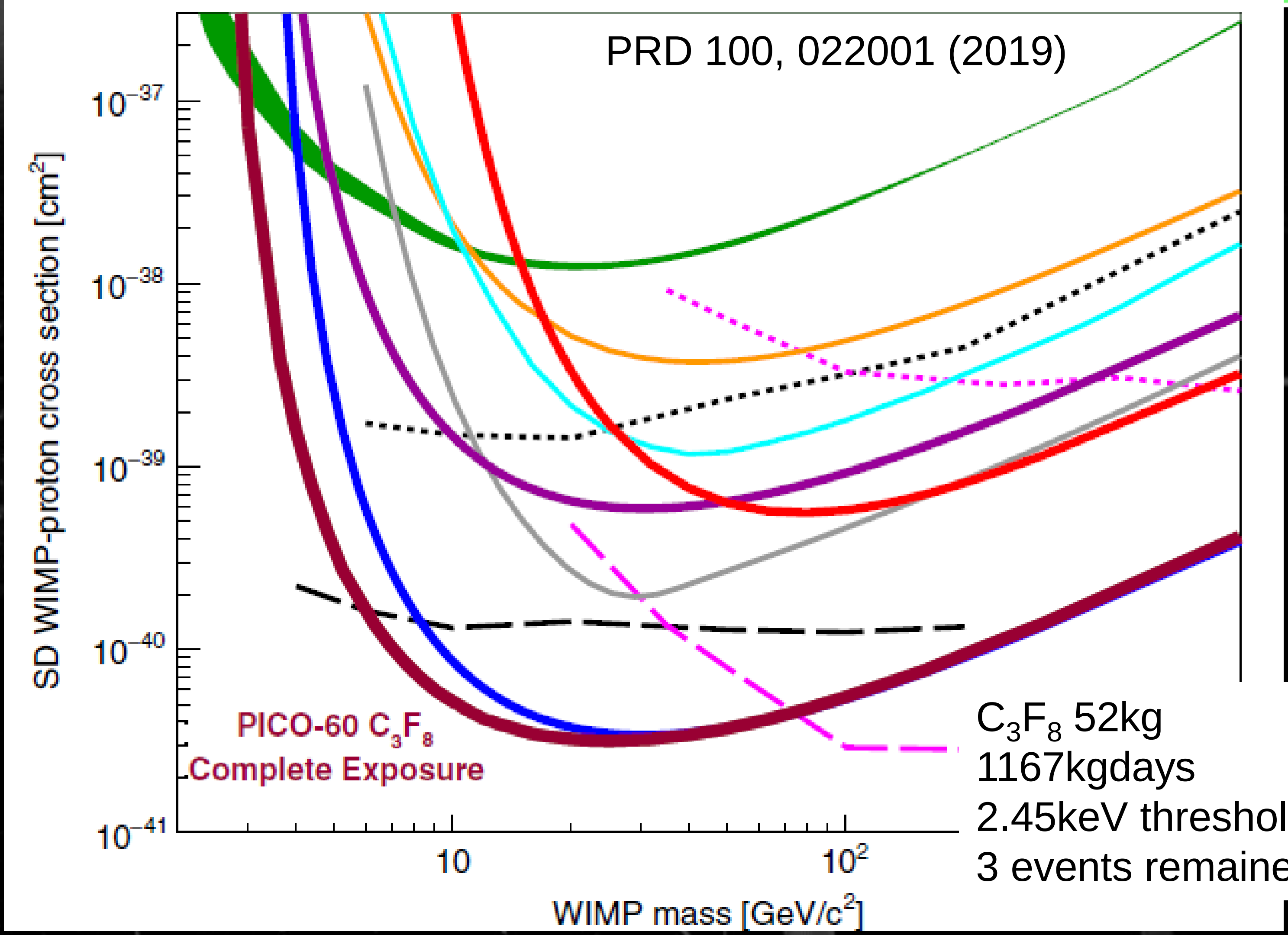
Direct Search Review

3. Others

- Bubble chamber
  - PICO
    - Superheated chamber
    - Threshold-type detector
    - Best SD sensitivity







C_3F_8 52kg
1167kgdays
2.45keV threshold
3 events remained

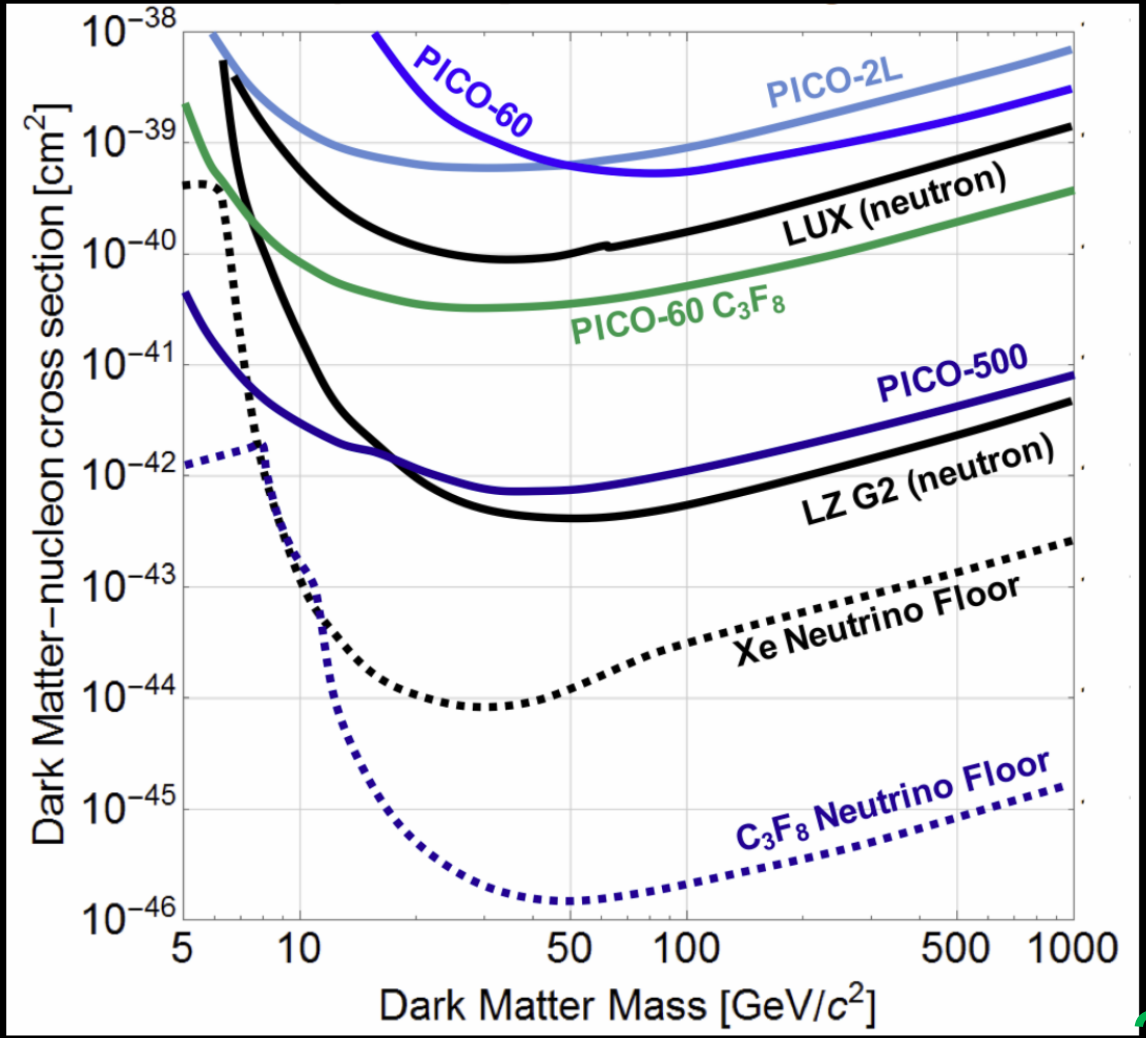
- Fluorine advantage
  - SD search
  - different "Neutrino floor" from xenon

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

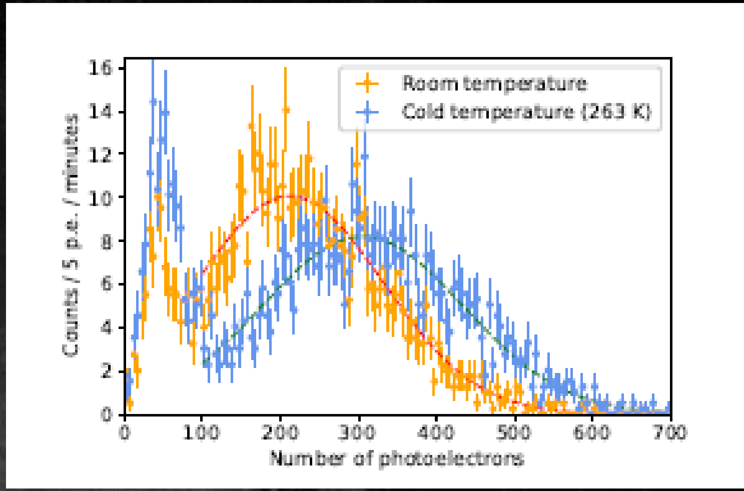
PICO Results and Future Plans

Hugh Lippincott, Fermilab
for the PICO Collaboration
EDU 2017

Scaling to PICO-500



- フッ素使ってエネルギーもとりたい。
  ：　液化CF_4シンチレータの開発
  - 2021年論文　冷却CF_4ガスの発光（増光）

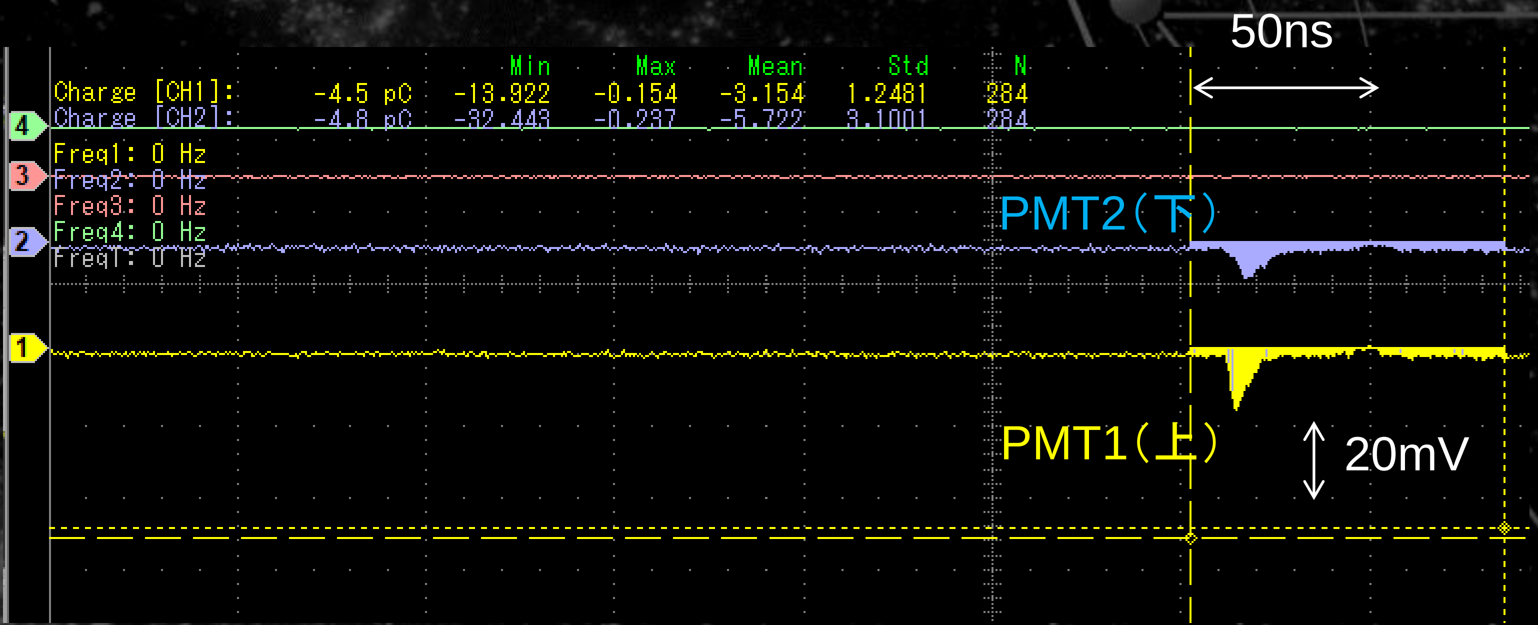


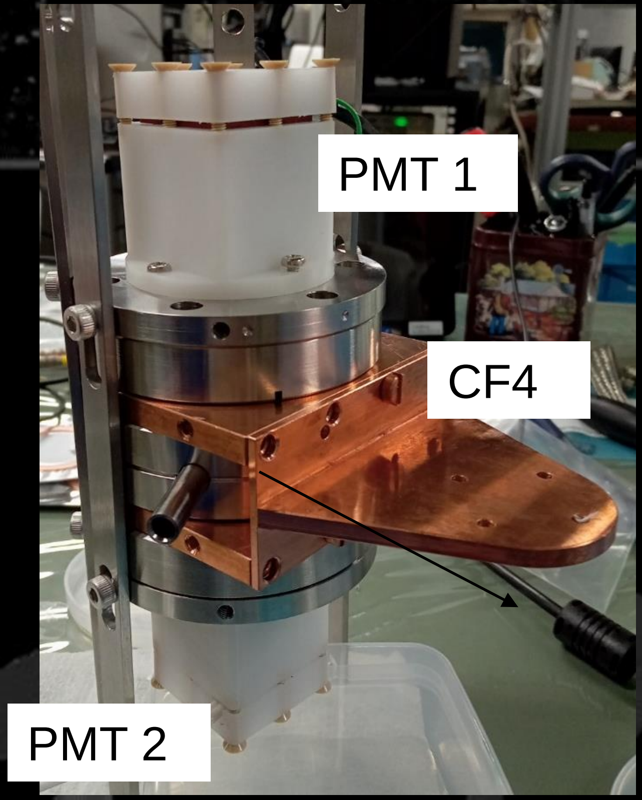
Scintillation light increase of carbontetrafluoride gas at low temperature

2021 JINST 16 P12033

K. Mizukoshi,* T. Maeda, Y. Nakano,[1] S. Higashino and K. Miuchi

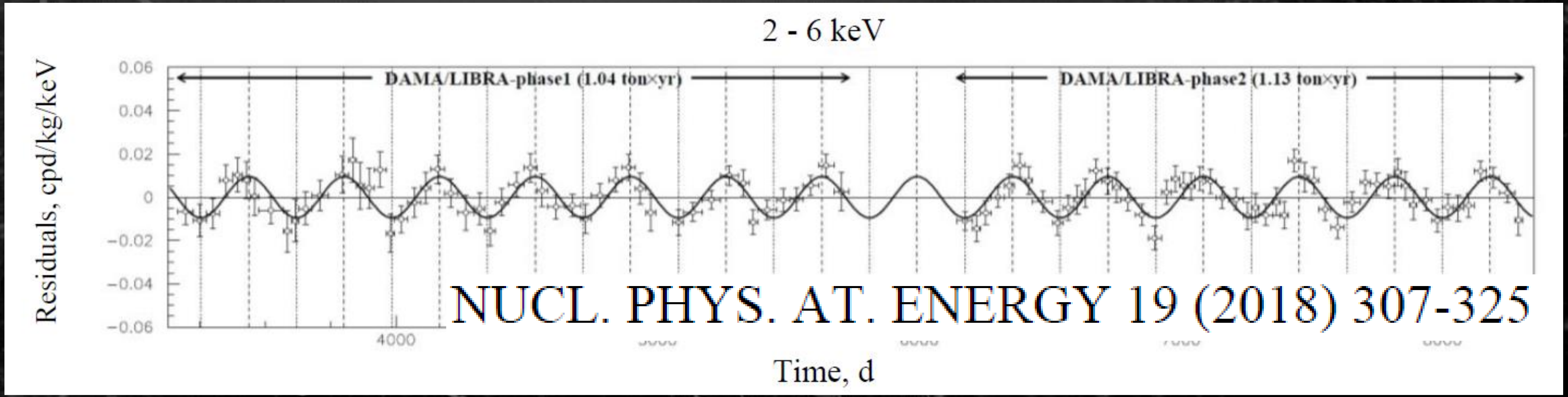
  - 2023年実験　液化CF_4の発光確認

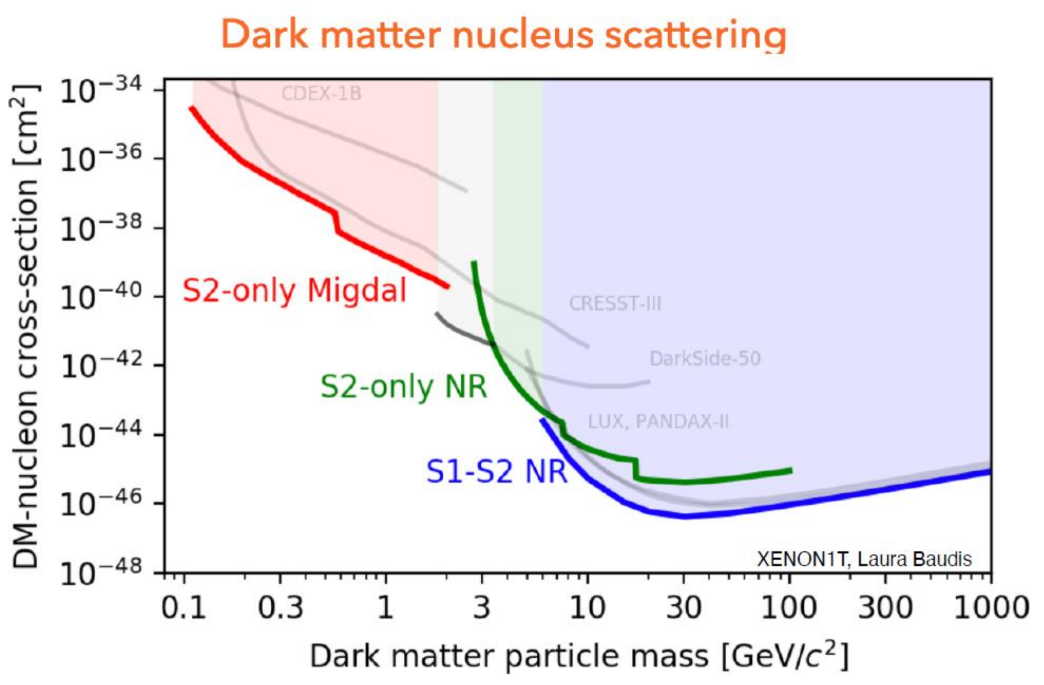


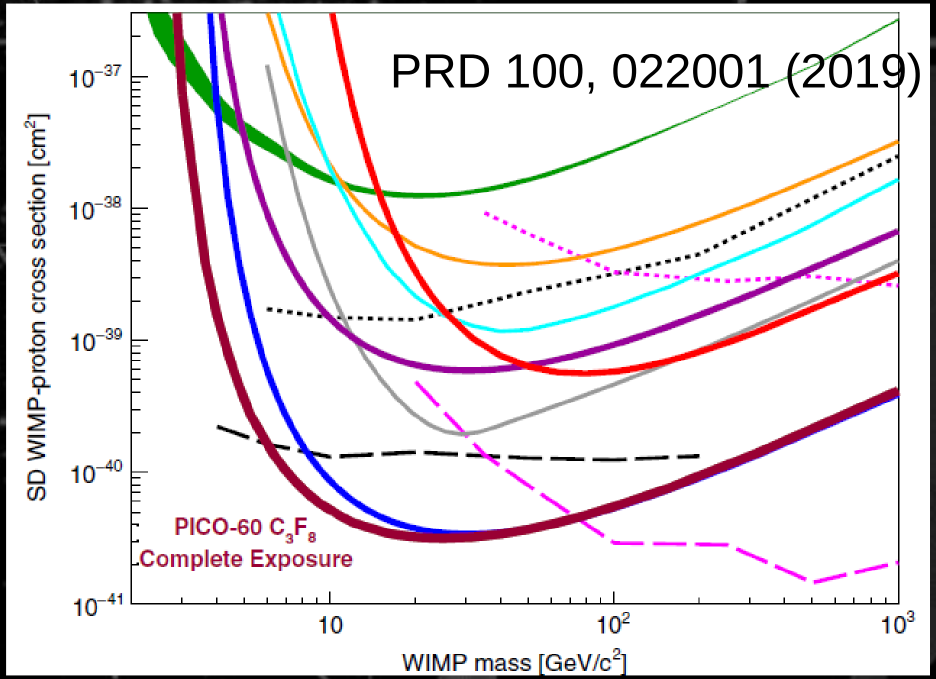


直接探索の現状

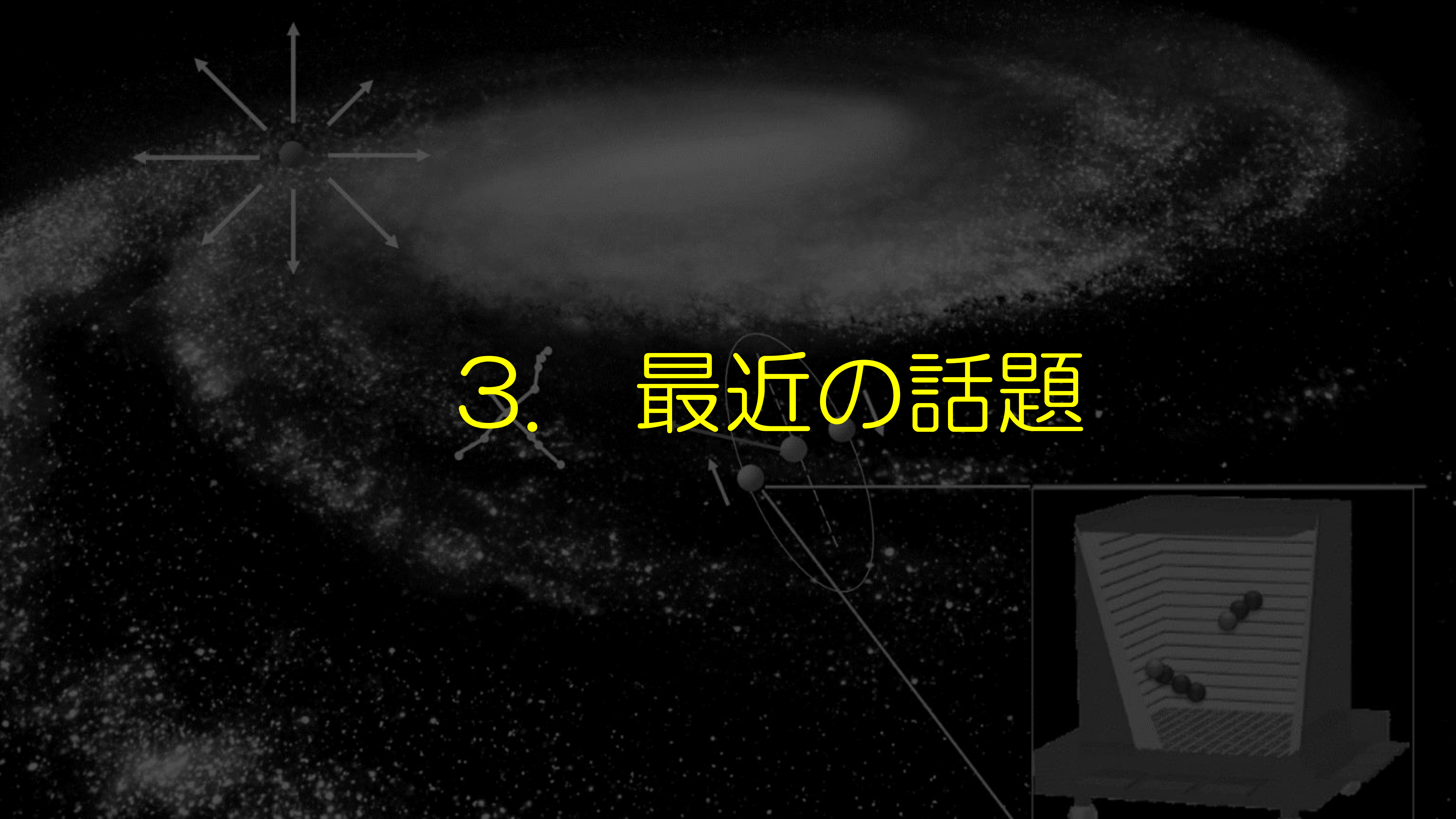
- DAMA, Xenon(SI), Fluorine (SD)





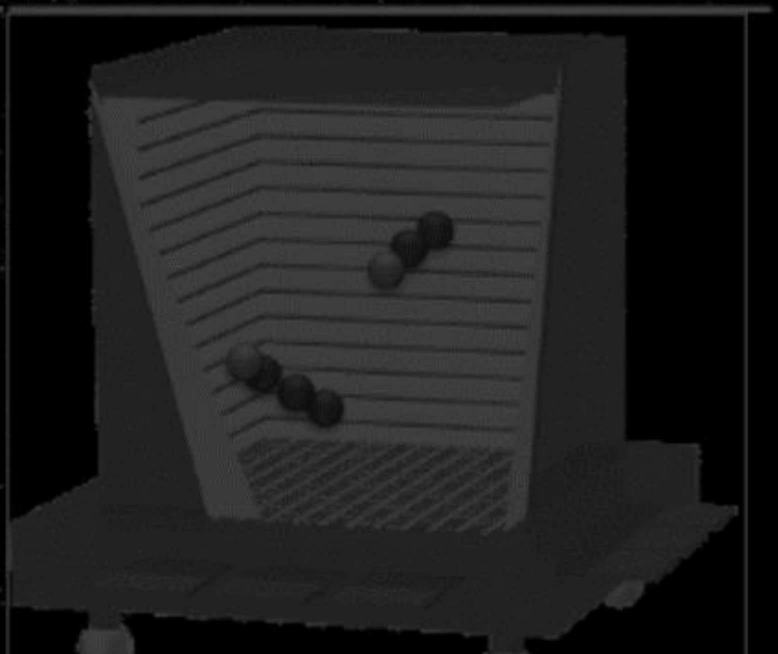


3.　最近の話題



Topics

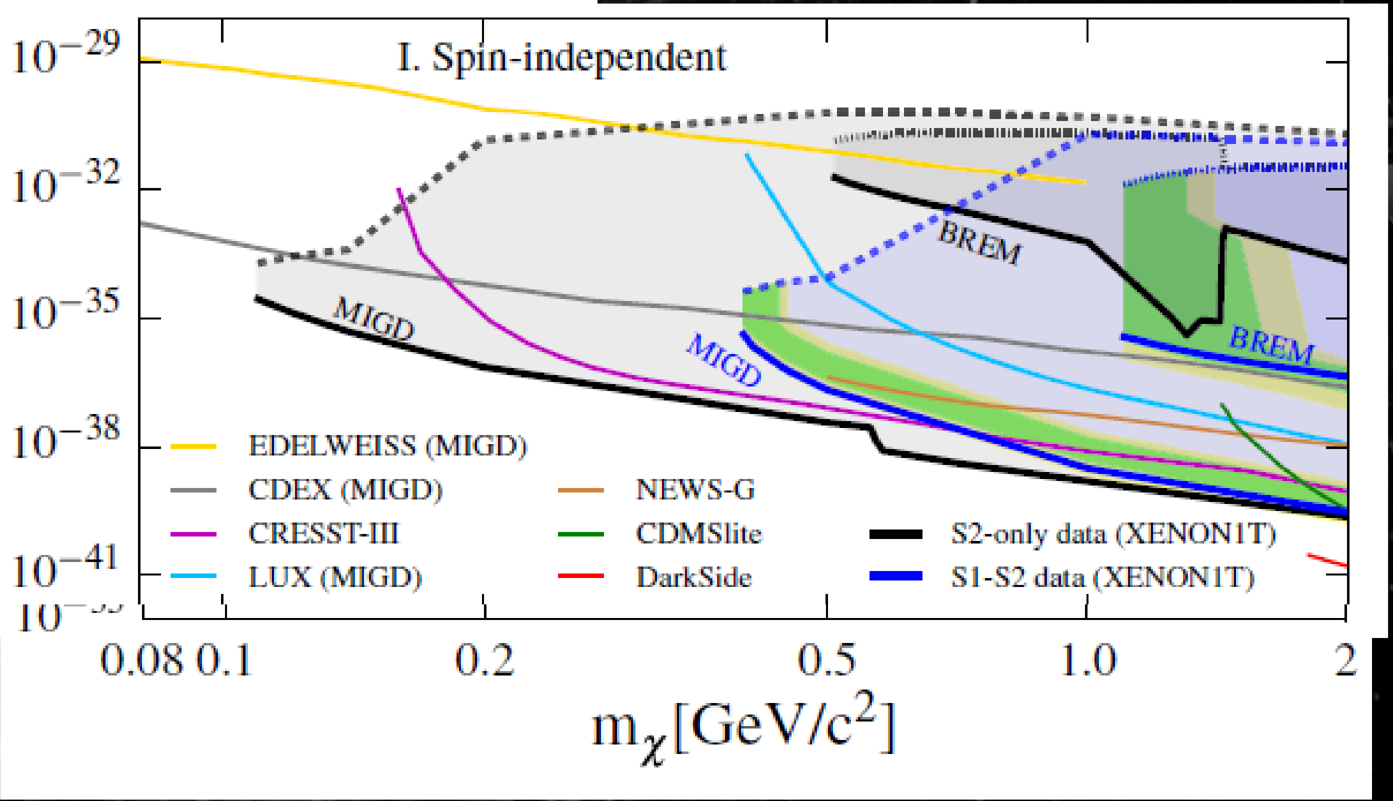
1. MIGDAL

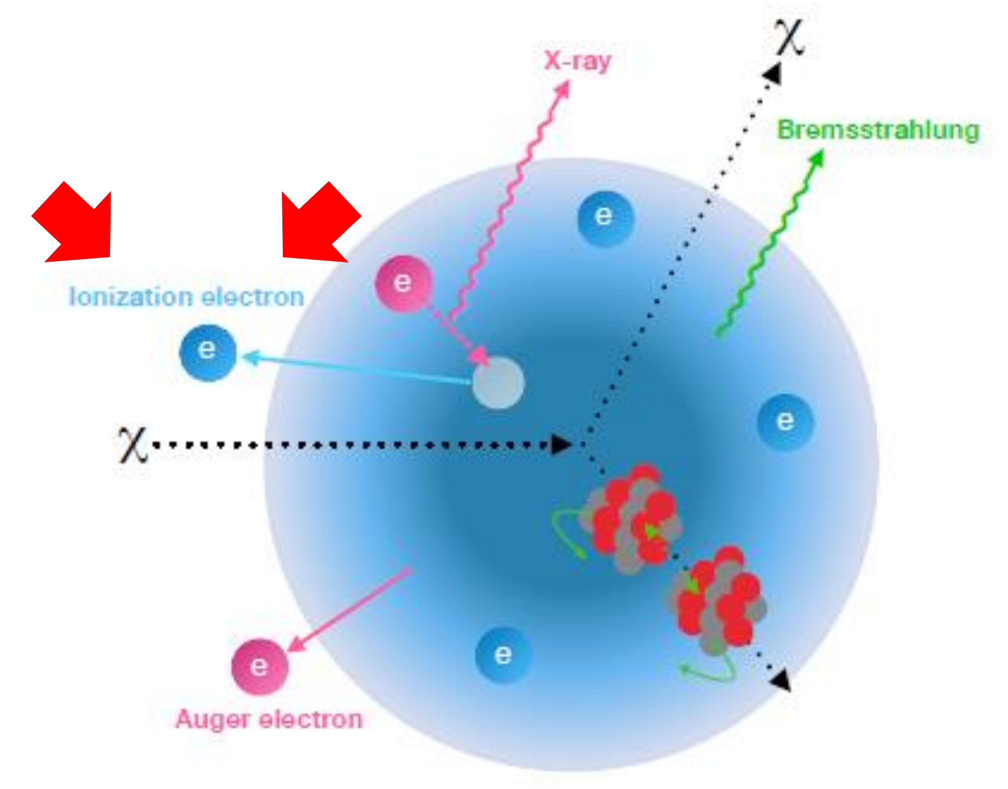


- And still lower: MIGDAL
  - Low mass search with "MIGDAL effect"
  - Ordinary nuclear recoil : ionization along the track
  - Low energy recoil : ionization efficiency is low
    ⇒ cannot be detected
  - Very rare case electrons are emitted

PRL123, 241803 (2019)

PRL123, 241803 (2019)





PRL123, 241803 (2019)

FIG. 1. Illustration of the ER signal production from BREM (green) and Migdal processes (pink) after elastic scattering between DM (χ) and a xenon nucleus.

- MIGDAL effect ?
  - A. B. Migdal J. Phys. USSR 4(1941)449
    - calculated (predicted)
    - nuclear recoil ⇒ excitation / ionization
    - caused by a sudden change of the nuclear velocity
    - small probability

  - Ibe et. al. 2018 JHEP03(2018)194
    - reformulated
      - energy momentum conservation
      - probability conservation
    - can be used for DM search

Migdal effect in dark matter direct detection experiments

Masahiro Ibe,[a,b] Wakutaka Nakano,[a] Yutaro Shoji[a] and Kazumine Suzuki[a]

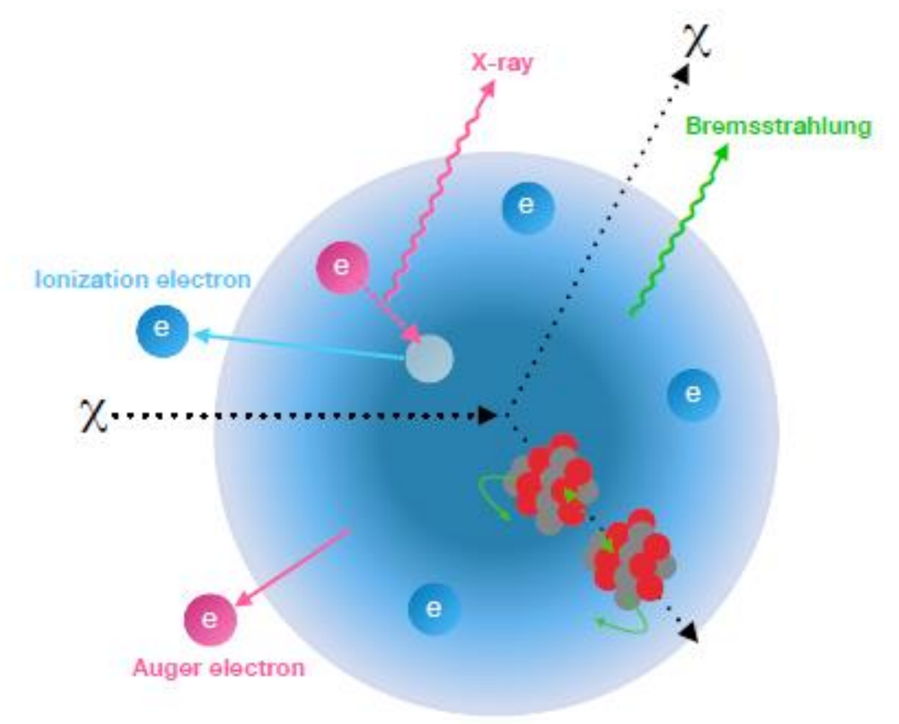
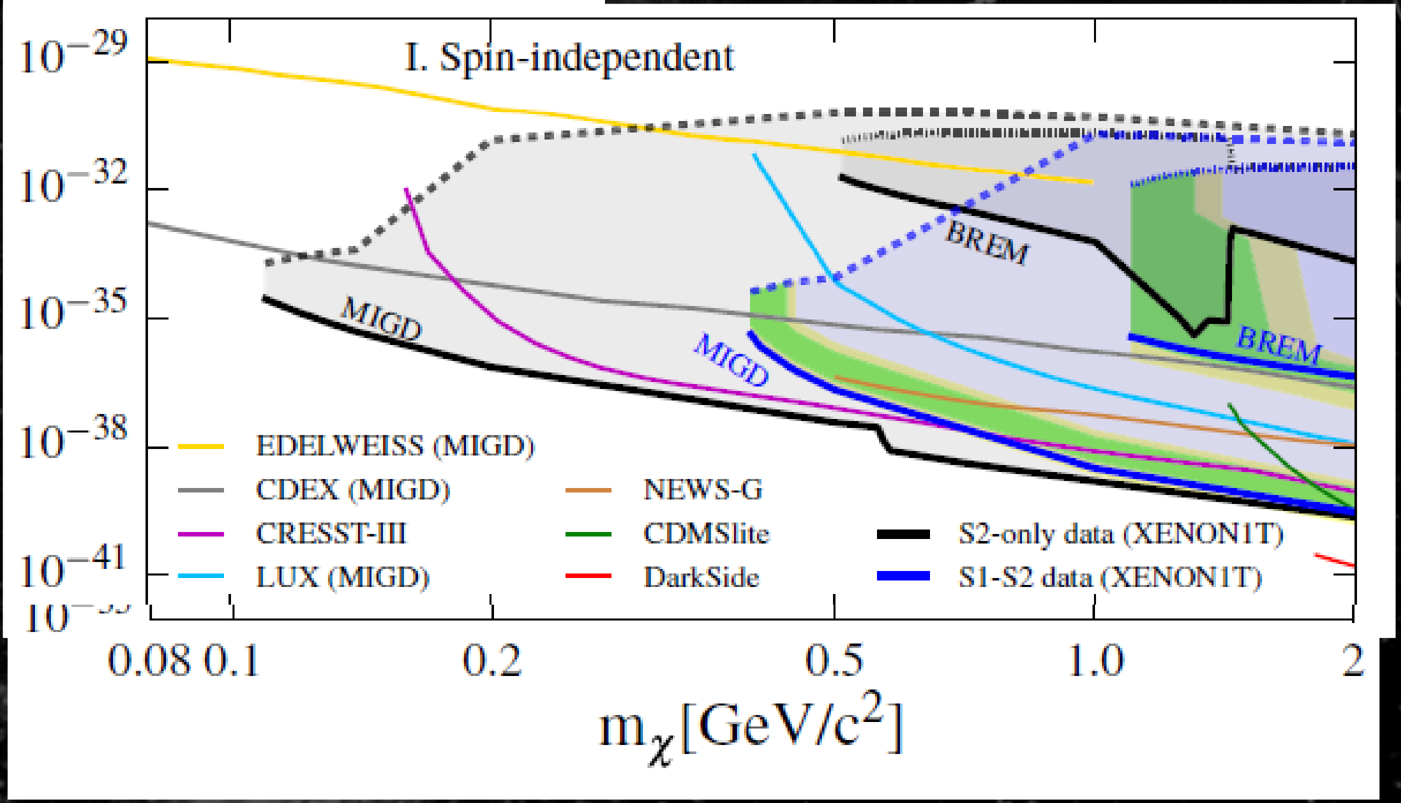


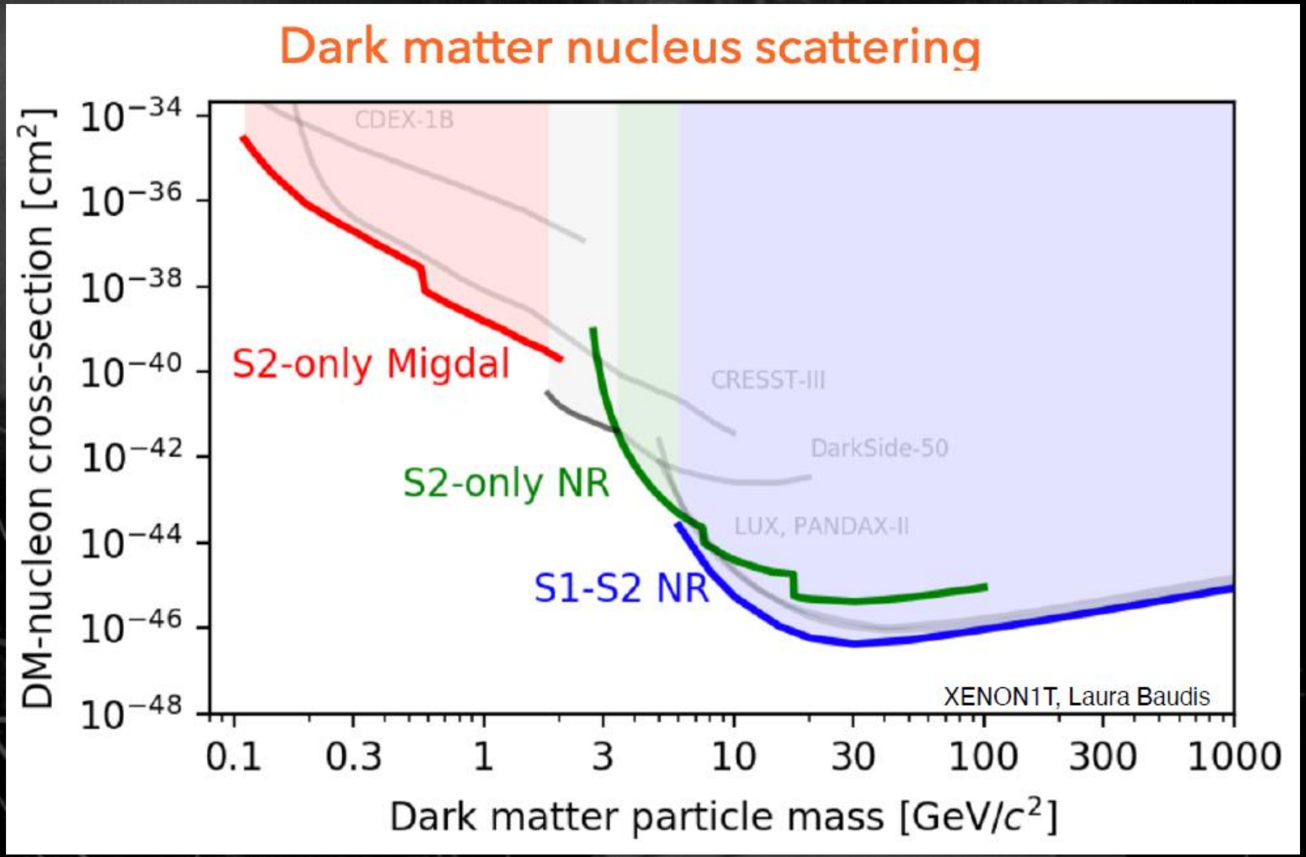
FIG. 1. Illustration of the ER signal production from BREM (green) and Migdal processes (pink) after elastic scattering between DM (χ) and a xenon nucleus.

• Low mass WIMP search by MIGDAL effect

LUX: PRL 122(2019)131301
EDELWEISS: PRD 99(2019)082003
CDEX: PRL 123 (2019) 161301
XENON: PRL 123 (2019) 241803
SENSEI: arXiv:2004.11378v1

PRL123, 241803 (2019)

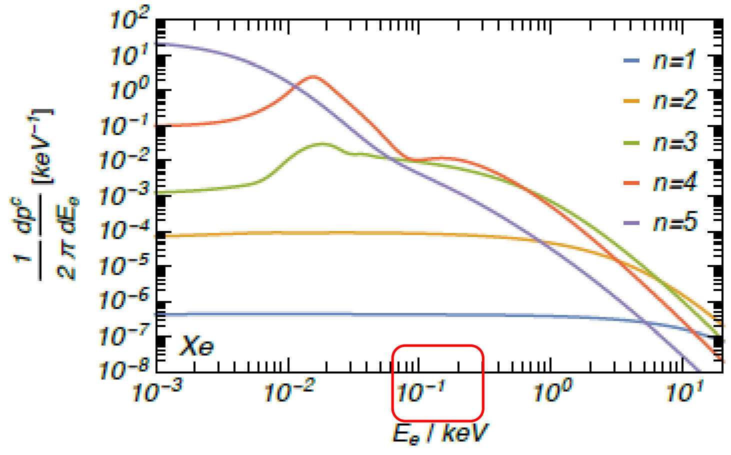




Standard WIMP detector down to 100MeV
CAVEAT: Migdal effect itself is yet to be observed.
loose 3orders of magnitude if we use Bremsstrahlung only.

- Why MIGDAL observation is difficult?
  - Neutron beam for nuclear recoil
  - Standard elastic scattering (Nuclear Recoil): huge background
  - Signal: NR + electron track ~0.1 keV
    - ≪ energy resolution
    - ≪ spatial resolution

JHEP03 (2018) 194



JHEP03 (2018) 194

Xe ($q_e = m_e \times 10^{-3}$)

(n,ℓ)	$\mathcal{P}_{\to 4f}$	$\mathcal{P}_{\to 5d}$	$\mathcal{P}_{\to 6s}$	$\mathcal{P}_{\to 6p}$	$E_{n\ell}$ [eV]	$\frac{1}{2\pi}\int dE_e \frac{dp^c}{dE_e}$
1s	–	–	–	7.3×10^{-10}	3.5×10^{4}	4.6×10^{-6}
2s	–	–	–	1.8×10^{-8}	5.4×10^{3}	2.9×10^{-5}
2p	–	3.0×10^{-8}	6.5×10^{-9}	–	4.9×10^{3}	1.3×10^{-4}
3s	–	–	–	2.7×10^{-7}	1.1×10^{3}	8.7×10^{-5}
3p	–	3.4×10^{-7}	4.0×10^{-7}	–	9.3×10^{2}	5.2×10^{-4}
3d	2.3×10^{-9}	–	–	4.3×10^{-7}	6.6×10^{2}	3.5×10^{-3}
4s	–	–	–	3.1×10^{-6}	2.0×10^{2}	3.4×10^{-4}
4p	–	4.1×10^{-8}	3.0×10^{-5}	–	1.4×10^{2}	1.4×10^{-3}
4d	7.0×10^{-7}	–	–	1.5×10^{-4}	6.1×10	3.4×10^{-2}
5s	–	–	–	1.2×10^{-4}	2.1×10	4.1×10^{-4}
5p	–	3.6×10^{-2}	2.1×10^{-2}	–	9.8	1.0×10^{-1}

(n,ℓ)	4f	5d	6s	6p
$E_{n\ell}$[eV]	0.85	1.6	3.3	2.2

JHEP03 (2018) 194

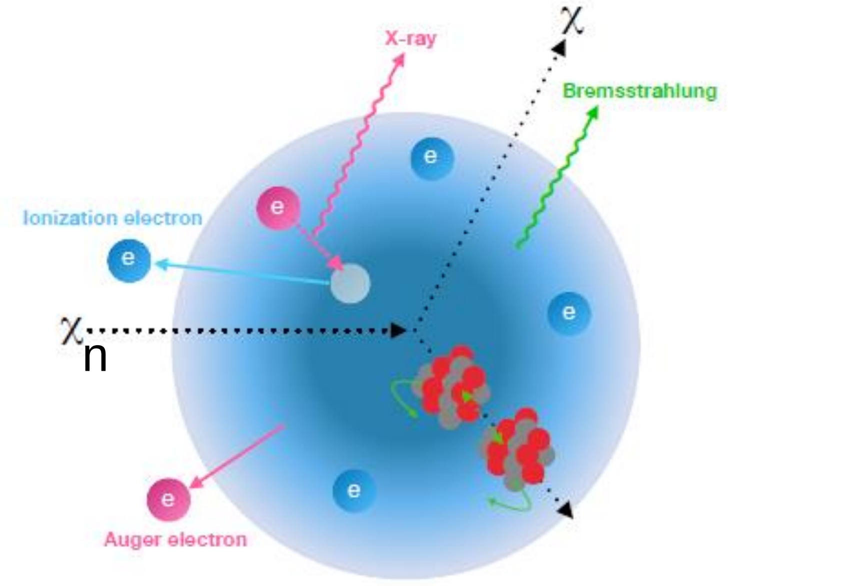


FIG. 1. Illustration of the ER signal production from BREM (green) and Migdal processes (pink) after elastic scattering between DM (χ) and a xenon nucleus.

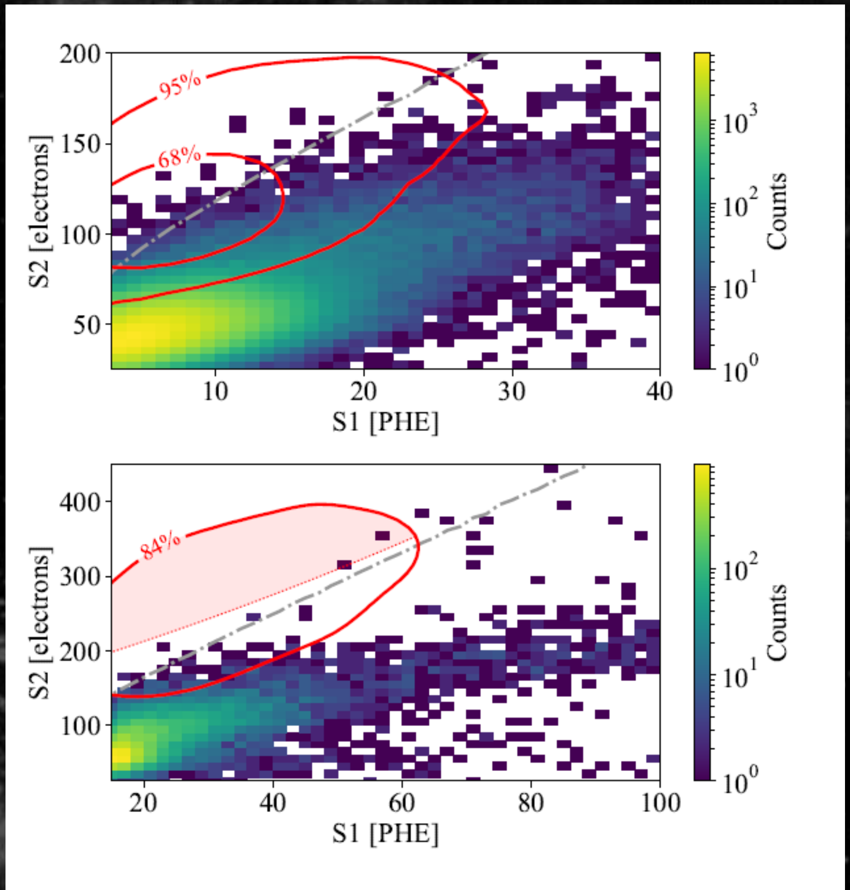
• MIGDAL探し

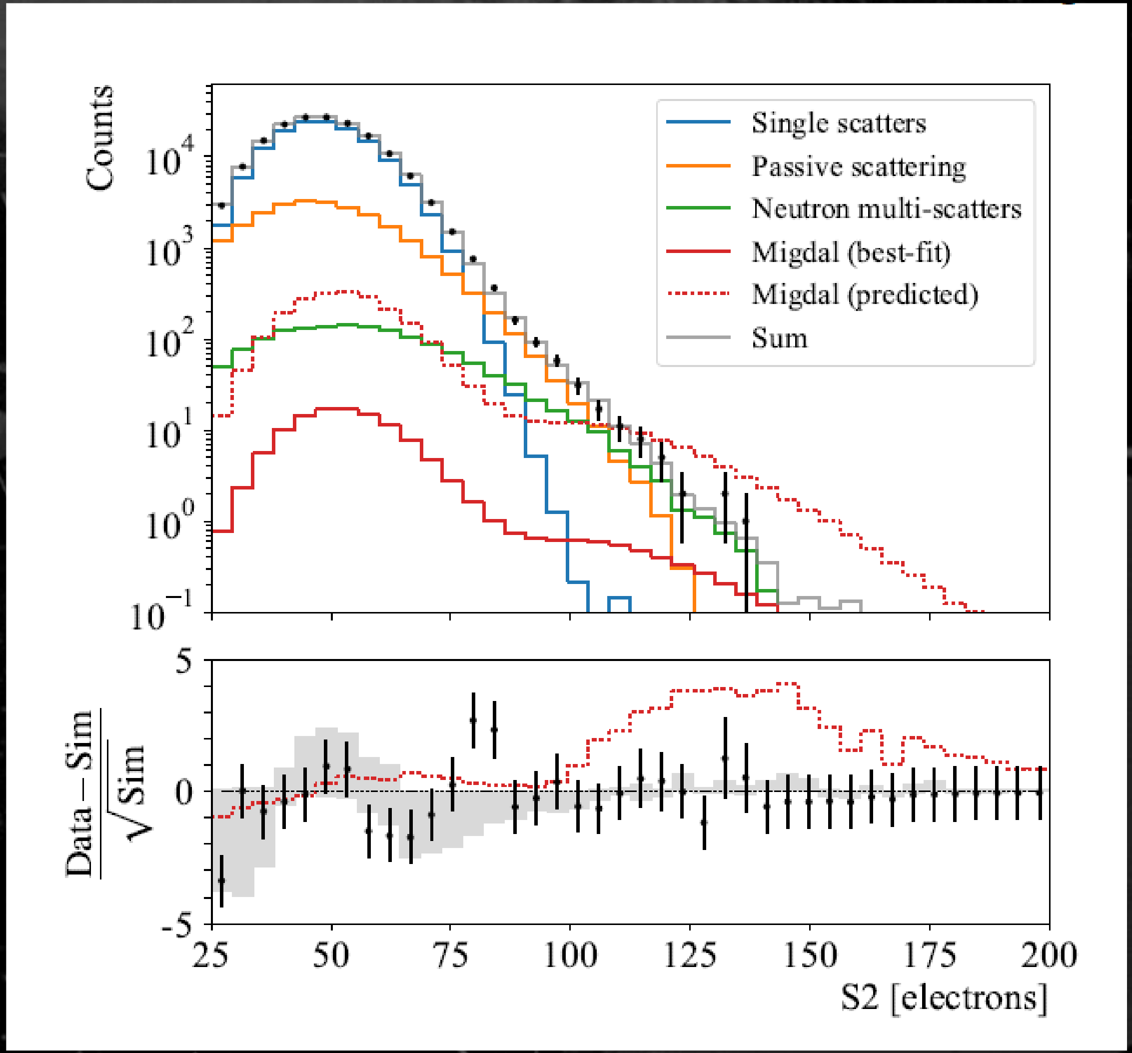
- 2相式キセノン検出器
- 14MeV中性子　→　7keV nuclear recoil　S2超過事象を探す
- 観測されず　原因を調査中

arXiv:2307.12952v1

Search for the Migdal effect in liquid xenon with keV-level nuclear recoils

J. Xu,[1,*] D. Adams,[2] B. Lenardo,[3,†] T. Pershing,[1] R.L. Mannino,[1] E. Bernard,[1] J. Kingston,[4,1] E. Mizrachi,[5,1] J. Lin,[6] R. Essig,[2] V. Mozin,[1] P. Kerr,[1] A. Bernstein,[1] and M. Tripathi[4]





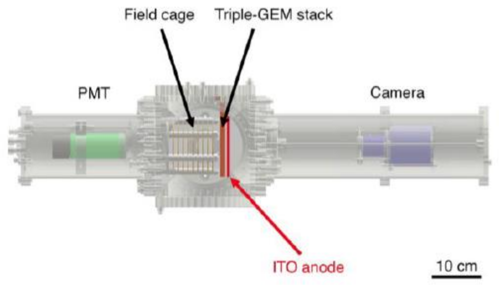
- Migdal探し：MIGDAL実験
  - Straightforward method
  - Nuclear track +electron track with gaseous detector
  - Demonstrations OK for
    nuclear recoil / electron recoil each.
  - Hard to discriminate from standard nuclear recoil

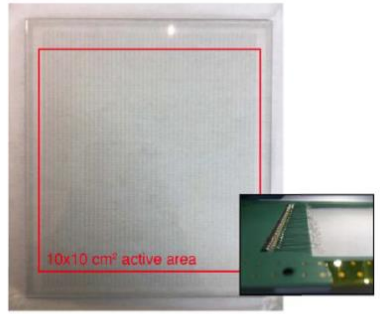
Astroparticle Physics 151 (2023) 102853

The MIGDAL experiment: Measuring a rare atomic process to aid the search for dark matter

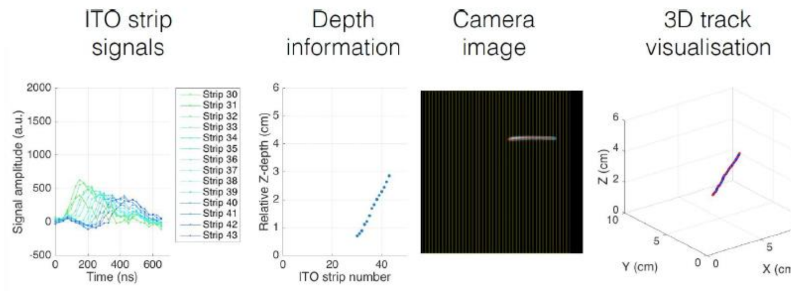
H.M. Araújo [a,*], S.N. Balashov [b], J.E. Borg [a], F.M. Brunbauer [c], C. Cazzaniga [d], C.D. Frost [d], F. Garcia [e], A.C. Kaboth [f], M. Kastriotou [d], I. Katsioulas [g], A. Khazov [b], H. Kraus [h], V.A. Kudryavtsev [i], S. Lilley [d], A. Lindote [j], D. Loomba [k], M.I. Lopes [j], E. Lopez Asamar [j,l], P. Luna Dapica [d], P.A. Majewski [b,*], T. Marley [a,b], C. McCabe [m], A.F. Mills [k], M. Nakhostin [a,b], T. Neep [g], F. Neves [j], K. Nikolopoulos [g], E. Oliveri [c], L. Ropelewski [c], E. Tilly [k], V.N. Solovov [j], T.J. Sumner [a], J. Tarrant [n], R. Turnley [d], M.G.D. van der Grinten [b], R. Veenhof [c]

O-TPC at CERN (from F. Brunbauer)

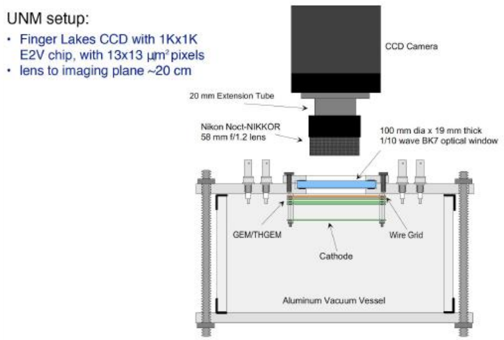




3D track reconstruction in Ar/CF4 (80/20) at 100 Torr

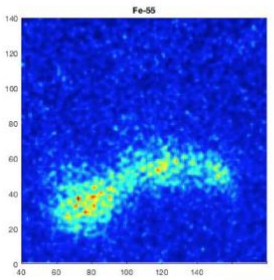


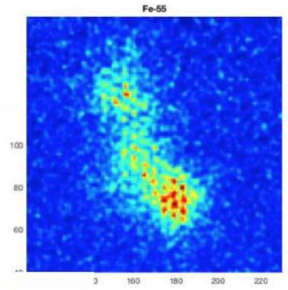
O-TPC at UNM (from D. Loomba) 2D reconstruction

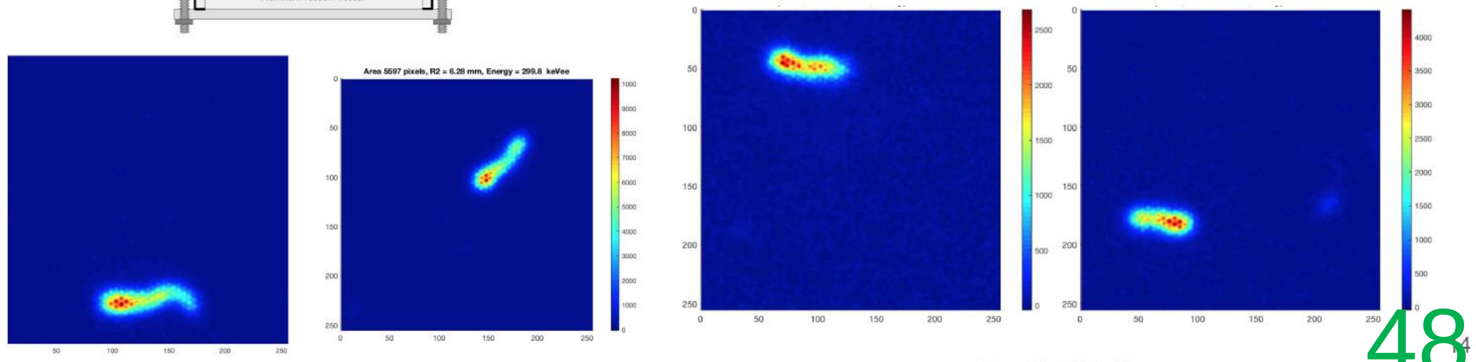


- 25-35 Torr CF4
- 2THGEMs (σ > 0.7 mm)
- Imaging area ~1.9cm x 1.9cm
- 4x4 on-chip binning

Data acquired using following sources:
- Fe-55 (5.9 keV x-rays)
- Co-60 (γ's)
- DD neutron generator (~2.2 MeV n's + γ's)







E ~ 270-300 keVee

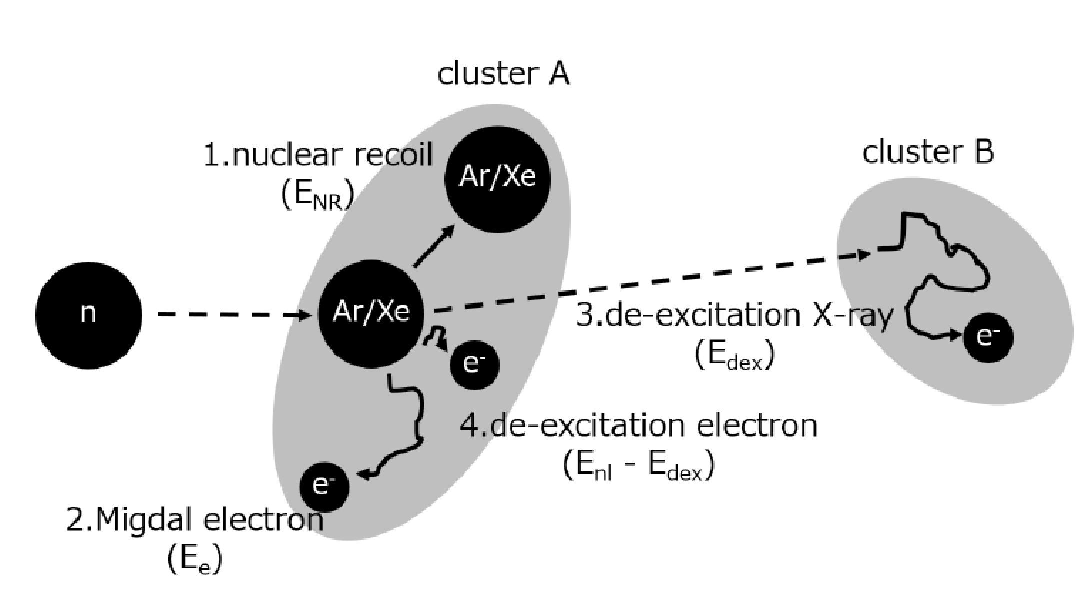
E ~ 100-120 keVee

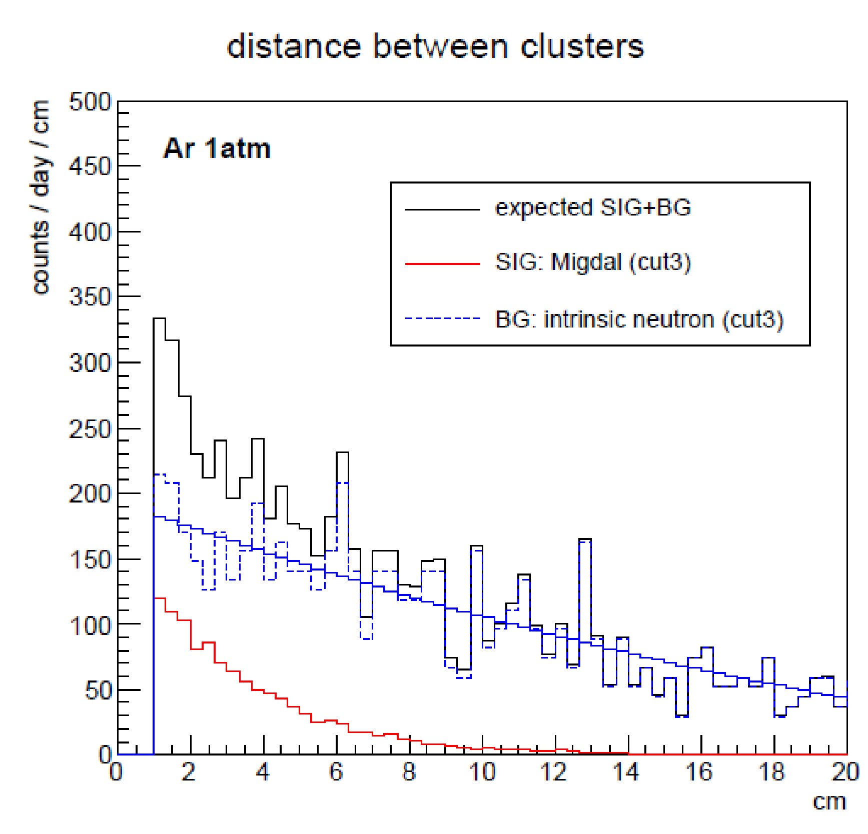
- Migdal探し MIRACLUE実験
  - Detect characteristic signal “two-cluster” events
  - Help to reduce huge background

Detection capability of Migdal effect for argon and xenon nuclei with position sensitive gaseous detectors

Kiseki D. Nakamura[1], Kentaro Miuchi[1], Shingo Kazama[2], Yutaro Shoji[3], Masahiro Ibe[4,5], and Wakutaka Nakano[6]

PTEP(2020)ptaa162





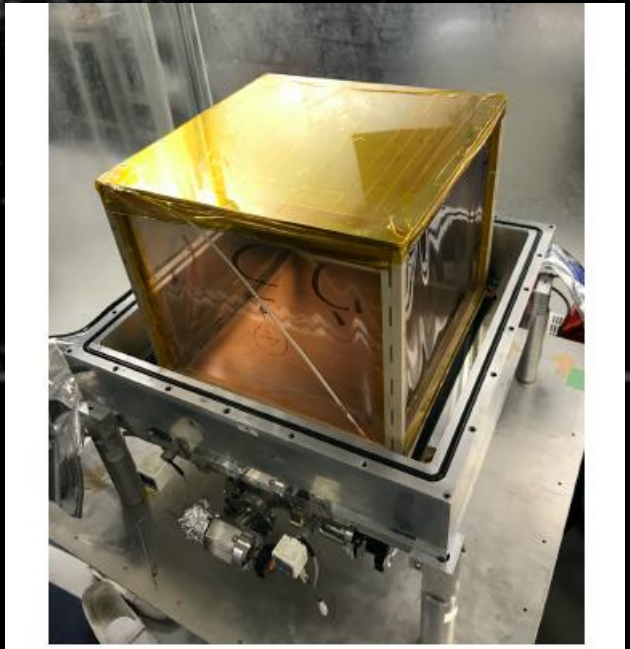


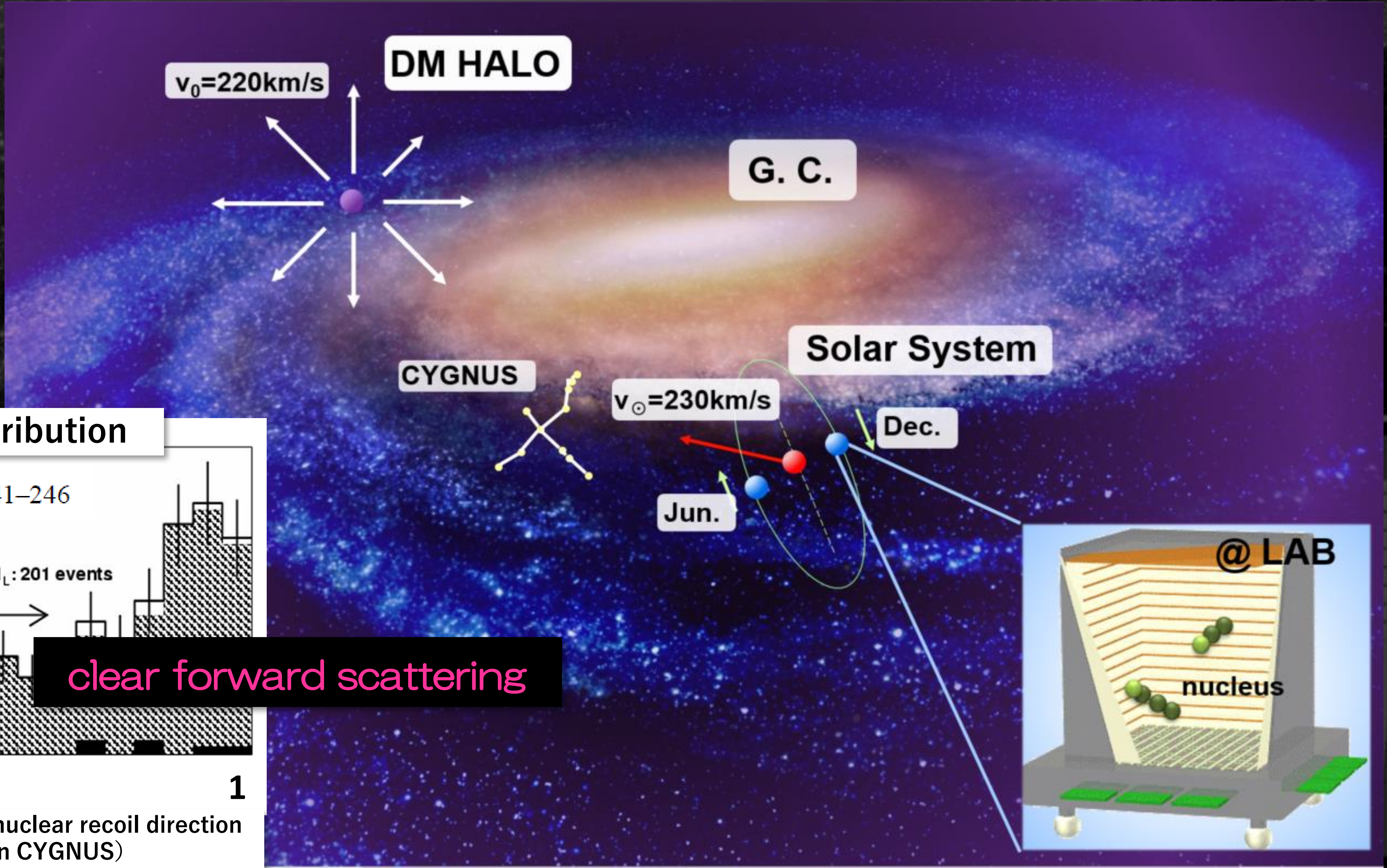
図 3.16: TPC 容器に設置したフィールドケージの様子。

金崎奎修士論文(2023年神戸大学)

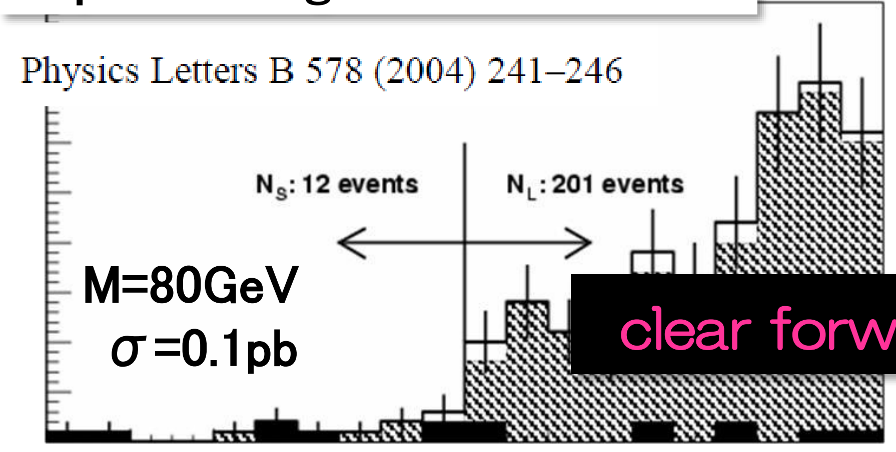
- 検出器準備中


Topics
2. Directionality

- Directional search : concept "CYGNUS"
  - More robust evidence than annual modulation
  - Study the DM nature after discovery



expected anguler distribution



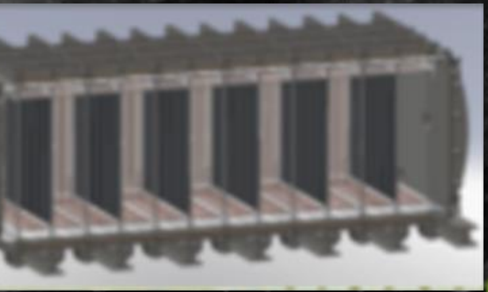
clear forward scattering

(θ : angle between the nuclear recoil direction and constellation CYGNUS)

World-wide CYGNUS

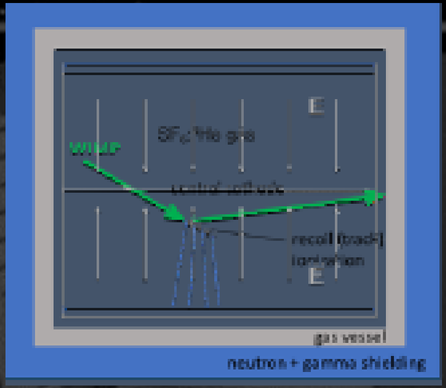
2020 J. Phys.: Conf. Ser. 1468 012044

CYGNUS-10
Boulby, UK
$10m^3$ $He:SF_6$
GEM + wire readout

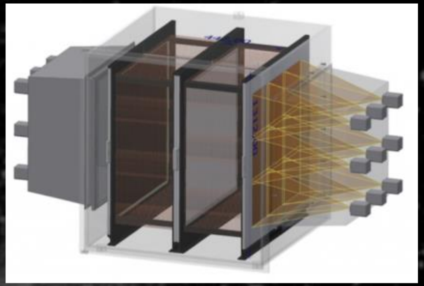


NEWAGE/CYGNUS-KM
Kamioka, Japan
SF6 / CF4
Strip readout

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



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



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

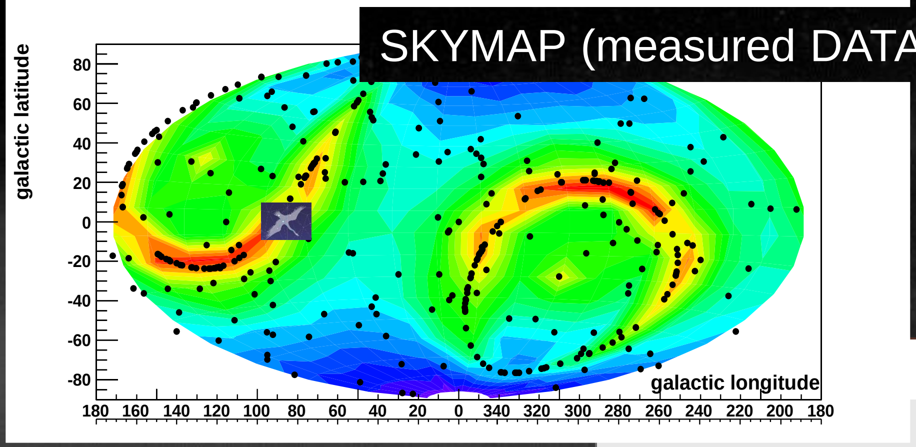
multi-site observatory

- NEWAGE (Kobe+)
  - 3D tracking
    - μ-PIC
    - SKYMAP
  - CF_4 gas
    - High spatial resolution
    - Spin-Dependent search
  - Proposal

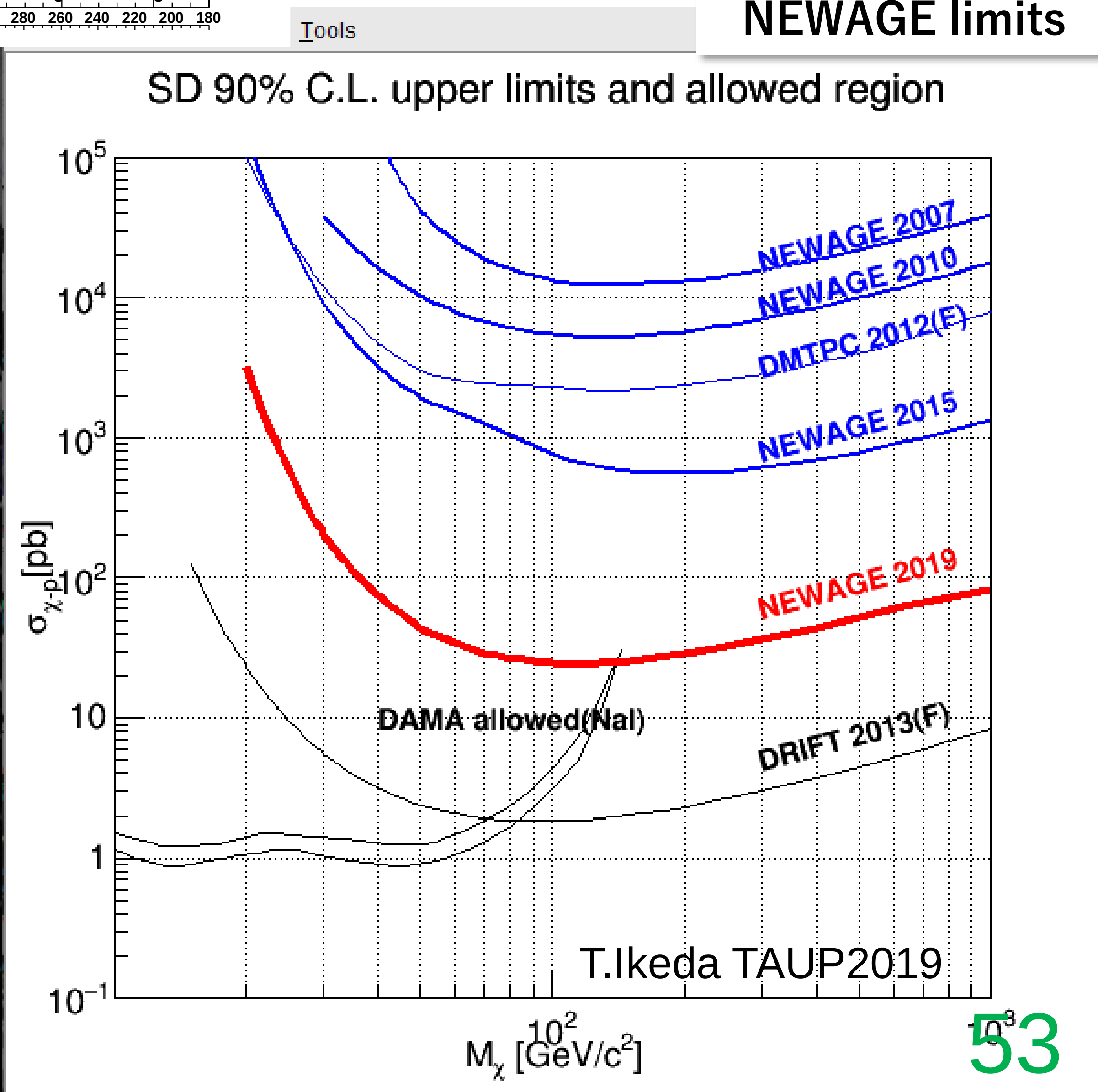
    PLB 578 (2004) 241
  - First directional search

    PLB 654 (2007) 58
  - Underground measurements

    PLB 686 (2010) 11, PTEP (2015) 043F01S, TAUP2019
    PTEP (2020) ptaa147



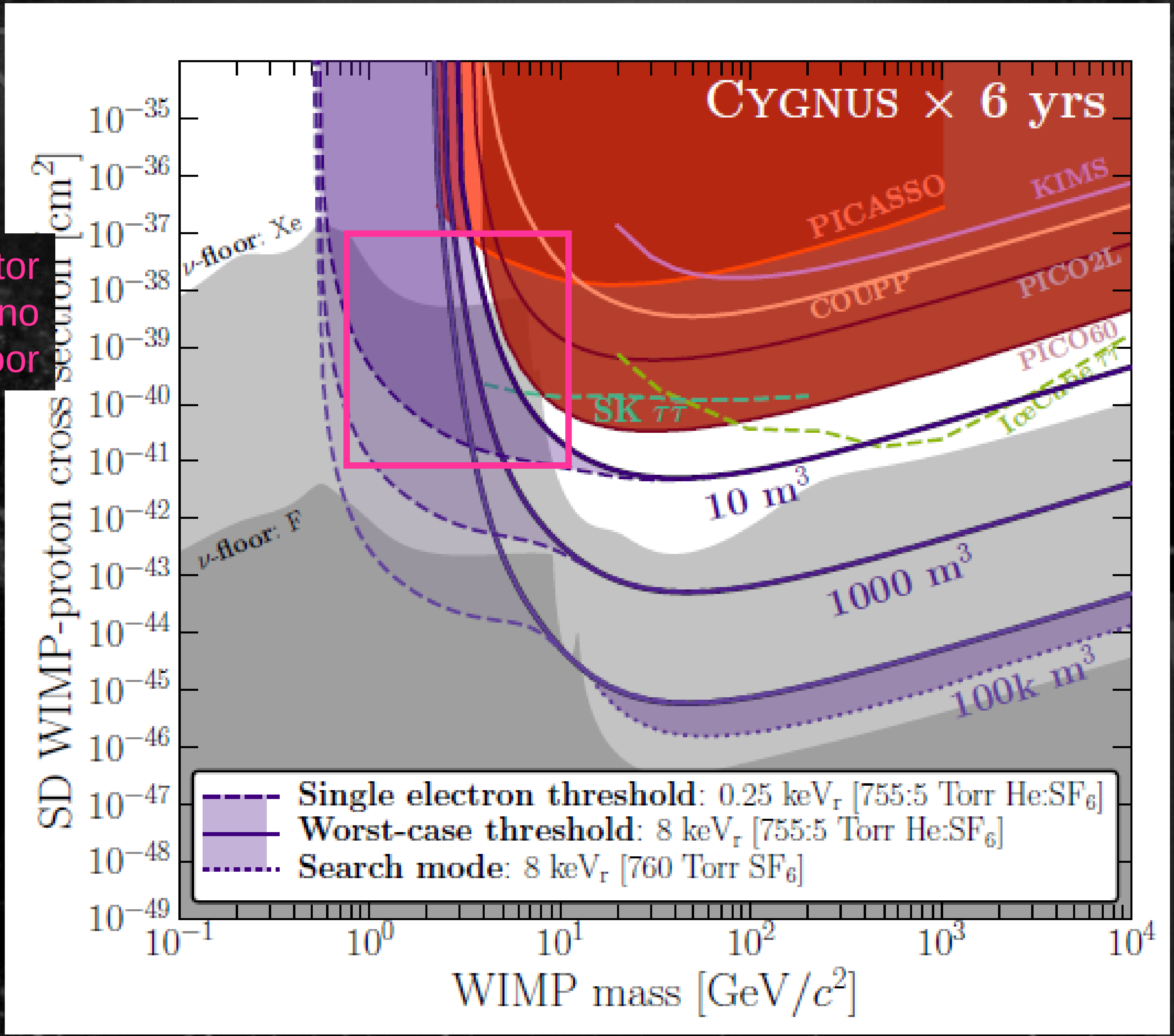
NEWAGE limits



arXiv 2008.12587

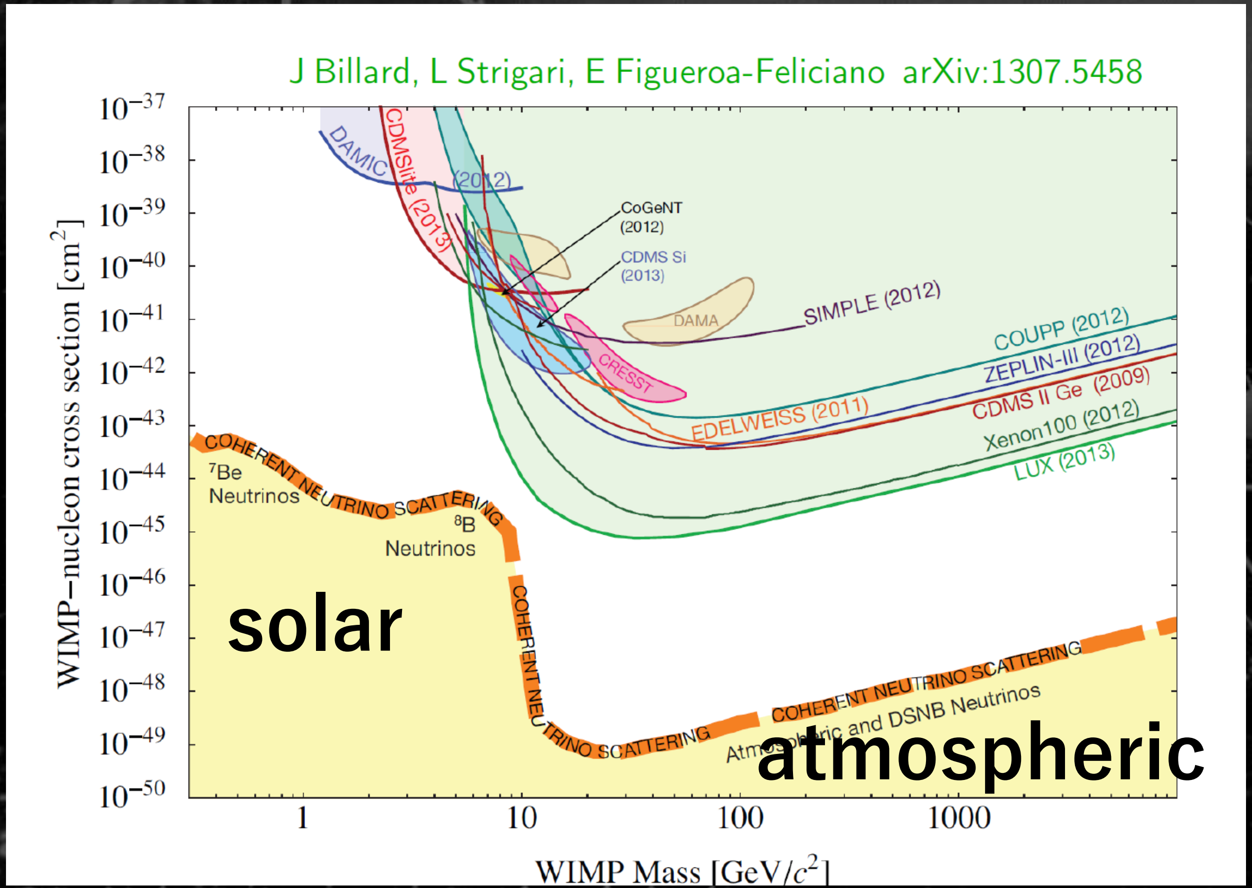
- Realistic simulation (strip readout)

even $10m^3$ detector can start exploring Xe neutrino floor

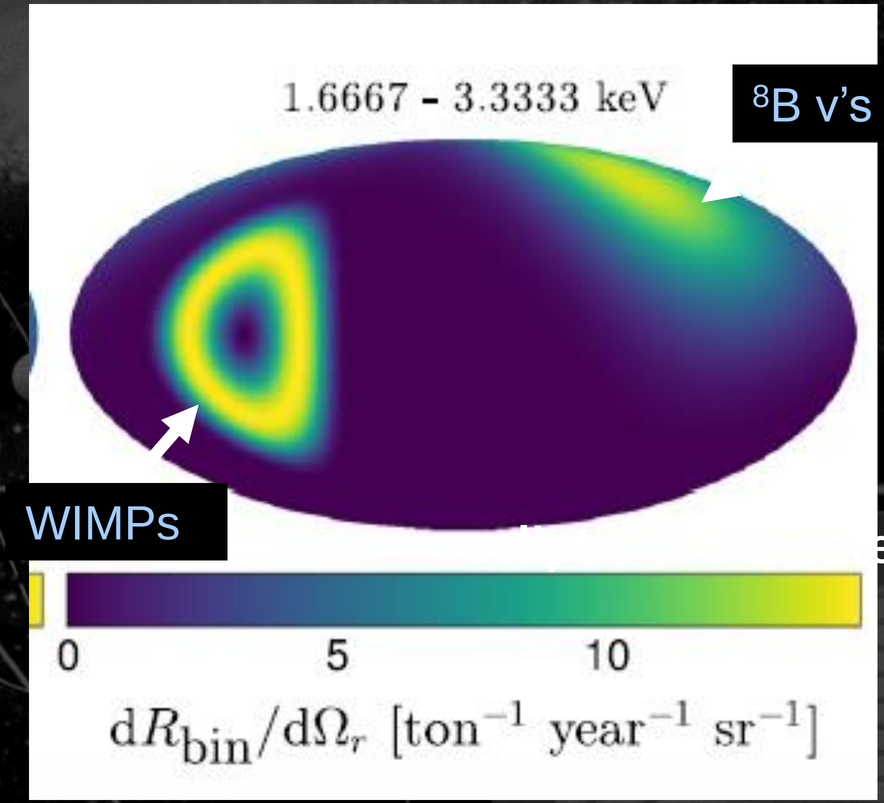


Toward discovery

- Potential to search beyond the "neutrino floor" where large detectors are reaching.

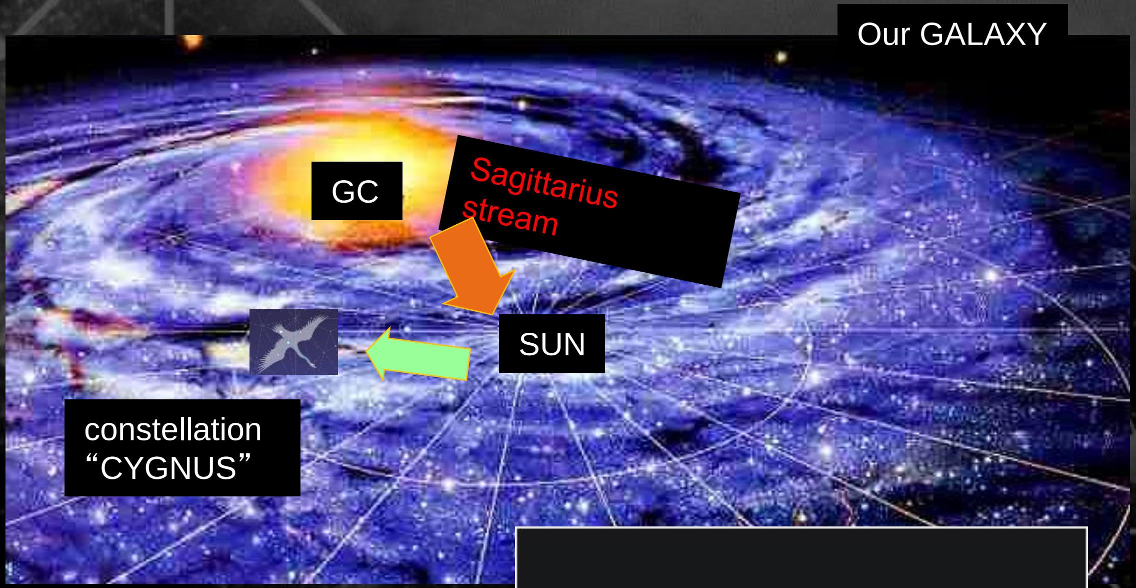


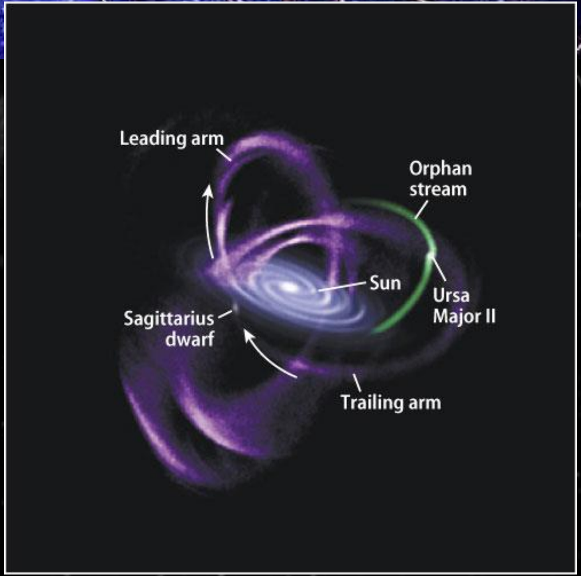
F. Mayet et al. / Physics Reports 627 (2016) 1–49



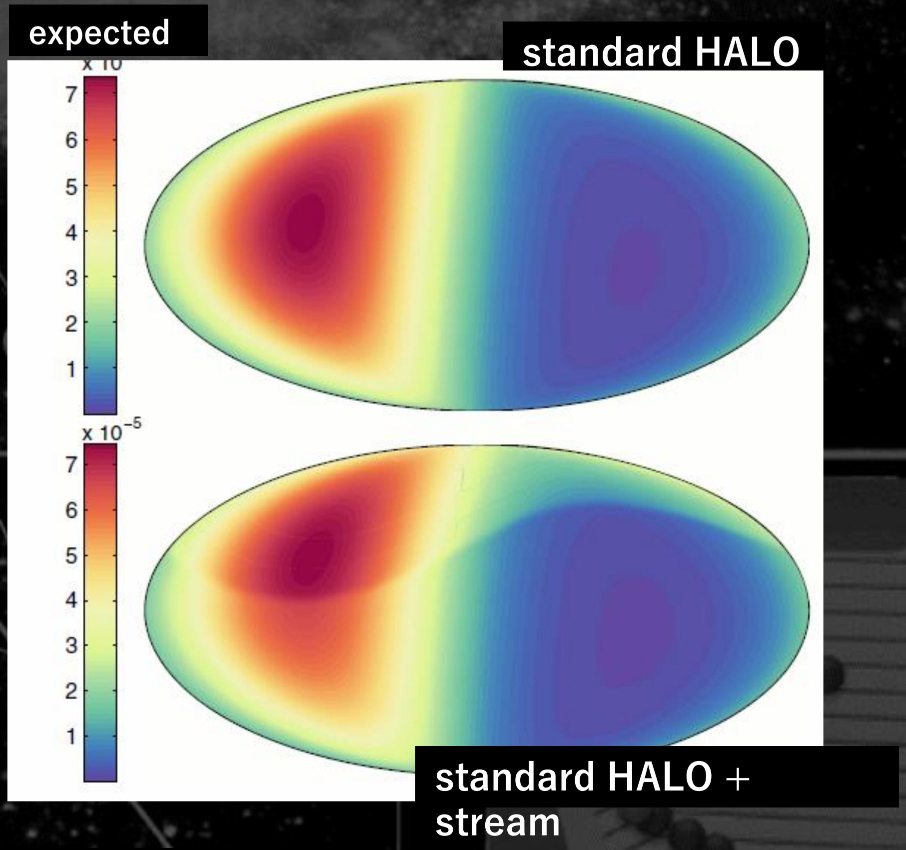
- distinguishable

- CYGNUS After Discovery: astronomy/cosmology
  - Test the HALO model
  - (ex) Sagittarius stream





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



galactic coordinate

- **streams, debris…**

- Halo model test　(w/長尾さん)
  - isotropic (1-r) + co-rotating(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]

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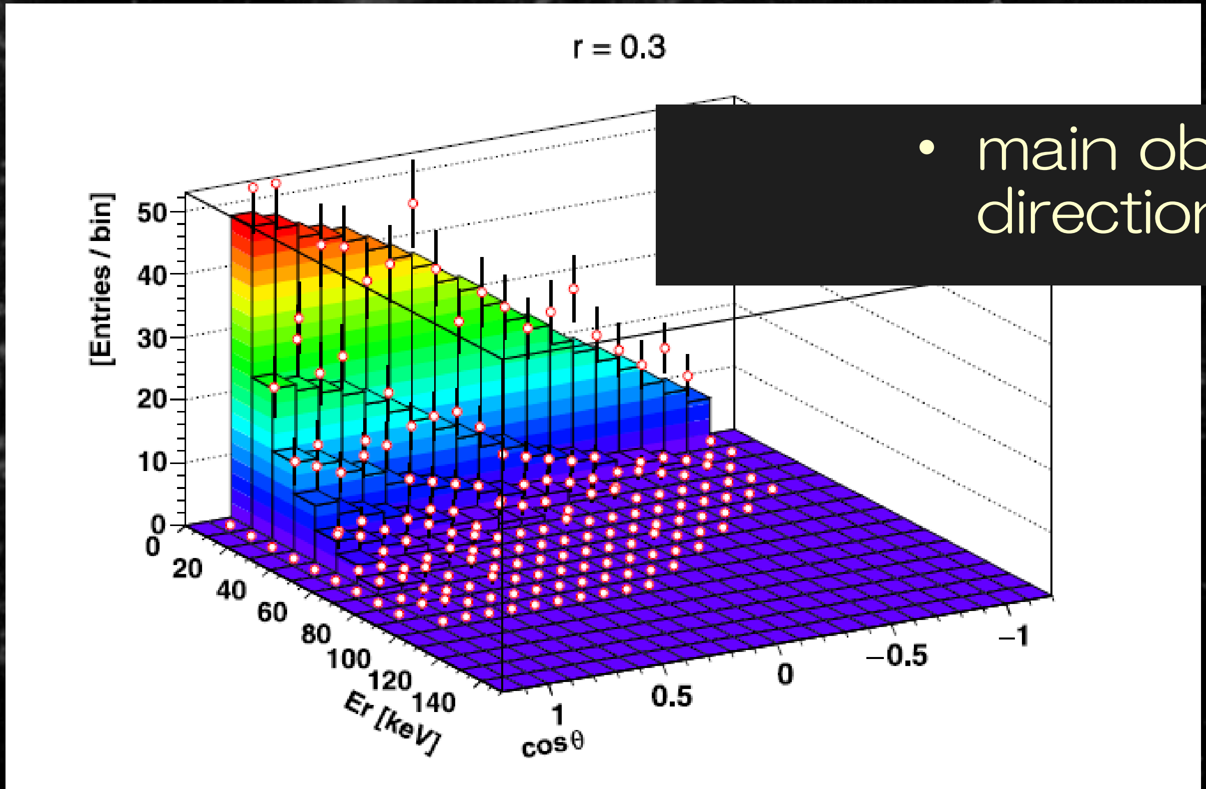
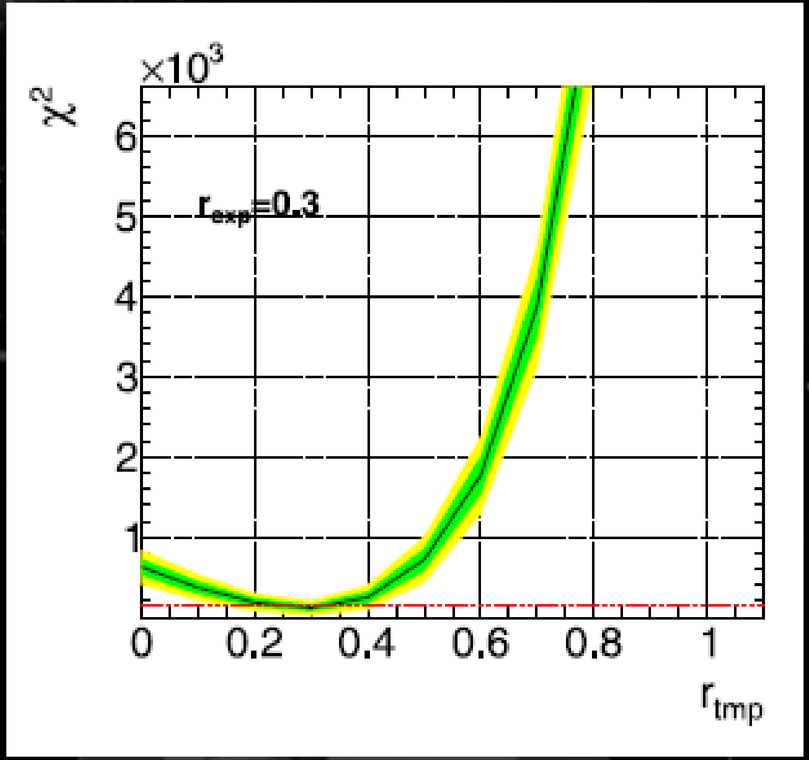
[b] Faculty of Science, Okayama University of Science, Okayama, Okayama 700-0005, Japan
[c] Department of Physics, Kobe University, Kobe, Hyogo 657-8501, Japan
[d] Department of Physics, Faculty of Science, Toho University, Funabashi, Chiba 274-8501, Japan
[e] Kobayashi-Maskawa Institute, Nagoya University, Nagoya, Aichi 464-8601, Japan

Physics of the Dark Universe 27 (2020) 100426



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



- know r value by directionality

- （いい意味で）気になるはなし
  - co-rotating halo成分：Sagitarius streamの形にも影響
  - directionalな観測との合わせ

Detecting the Figure Rotation of Dark Matter Halos with Tidal Streams

Monica Valluri[1], Adrian M. Price-Whelan[2], and Sarah J. Snyder[1]
[1] Department of Astronomy, University of Michigan, 1085 S. University Ave., Ann Arbor, MI 48109, USA; mvalluri@umich.edu
[2] Center for Computational Astrophysics, Flatiron Institute, 162 Fifth Ave., New York, NY 10010, USA
Received 2020 September 16; revised 2021 February 8; accepted 2021 February 9; published 2021 April 6

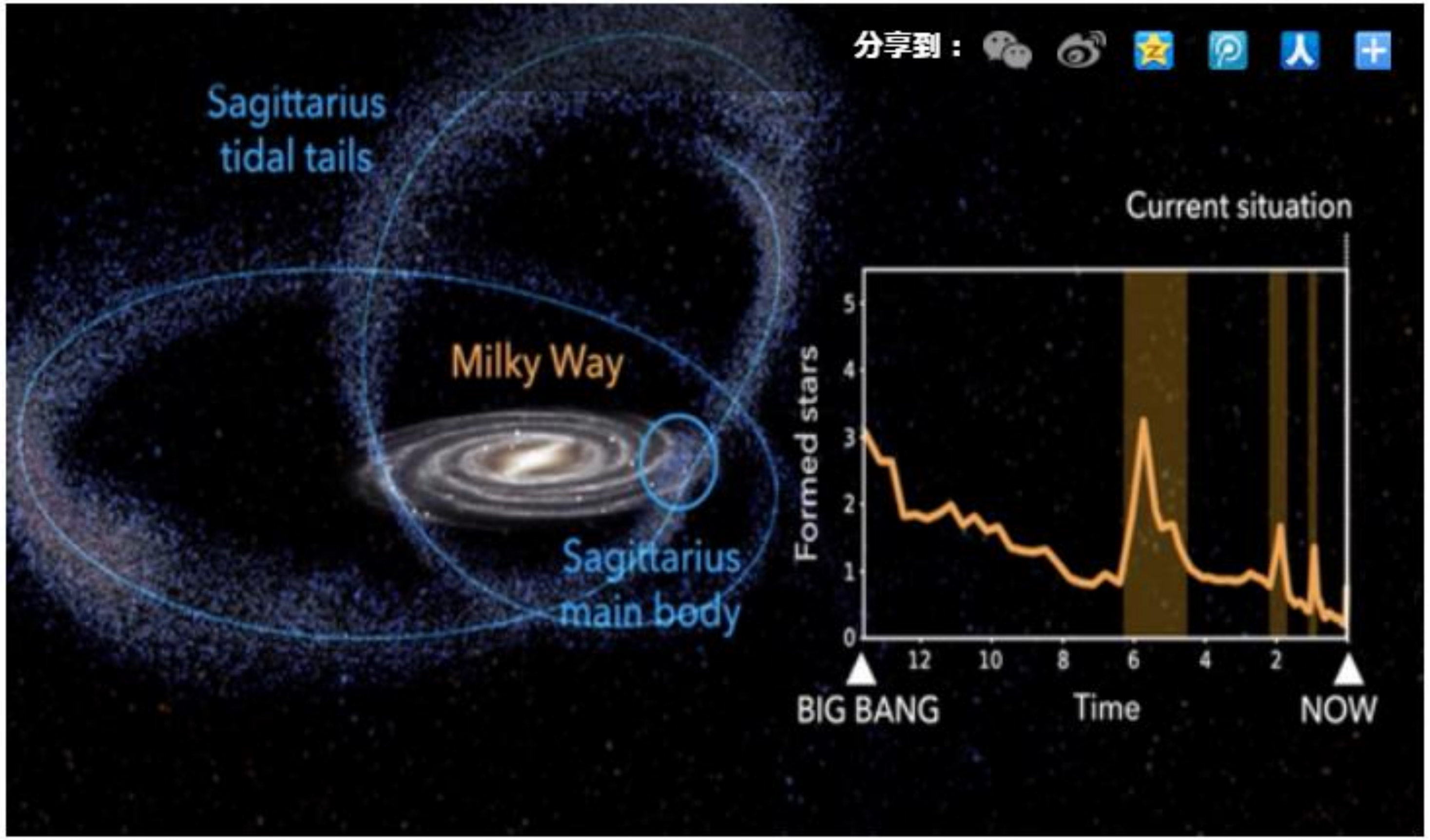
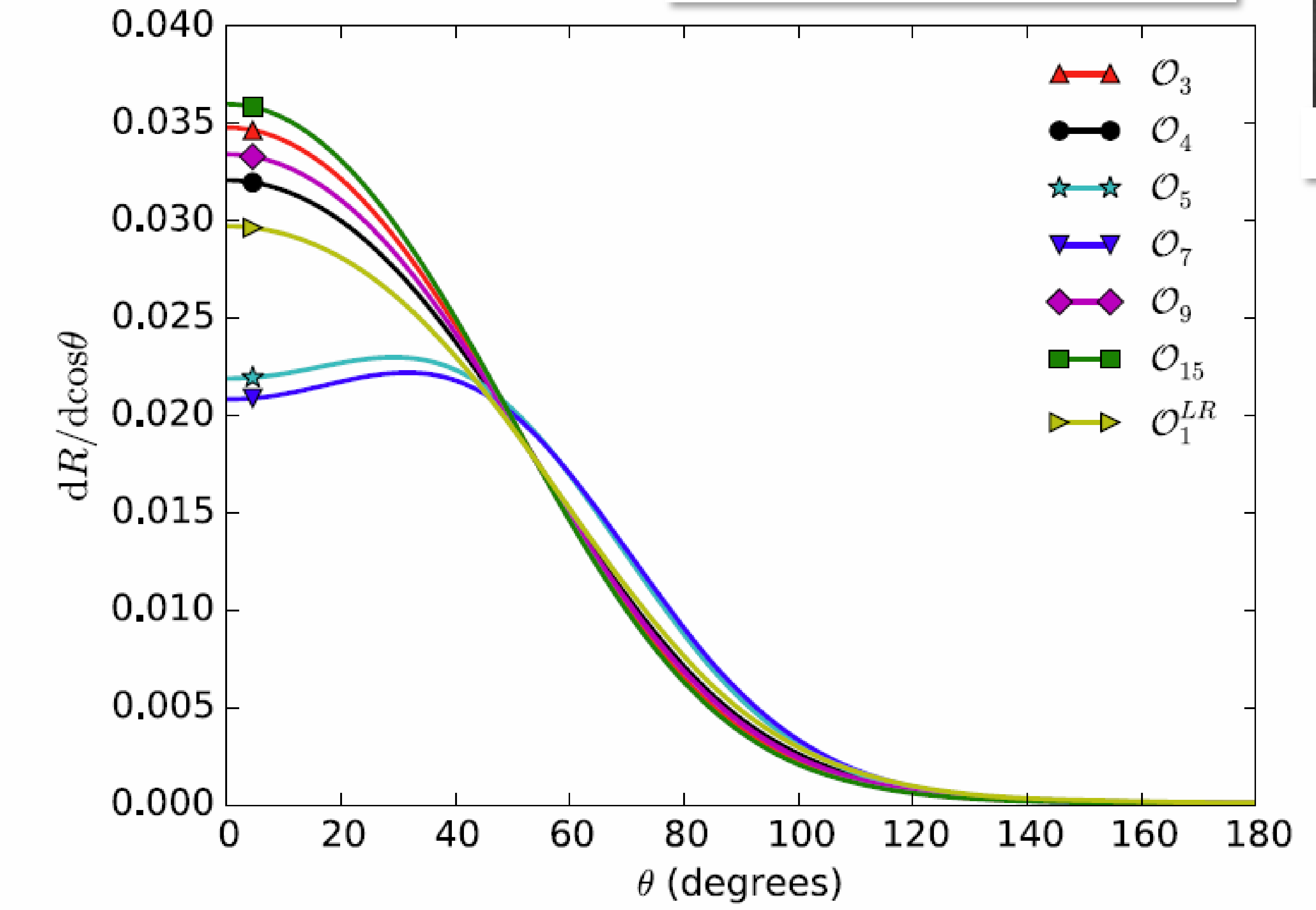


Fig. 2: Sagittarius dwarf galaxy accreted by the Milky Way. (Credit: Gabriel Pérez Díaz, SMM (IAC))

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

angular distribution



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

operator

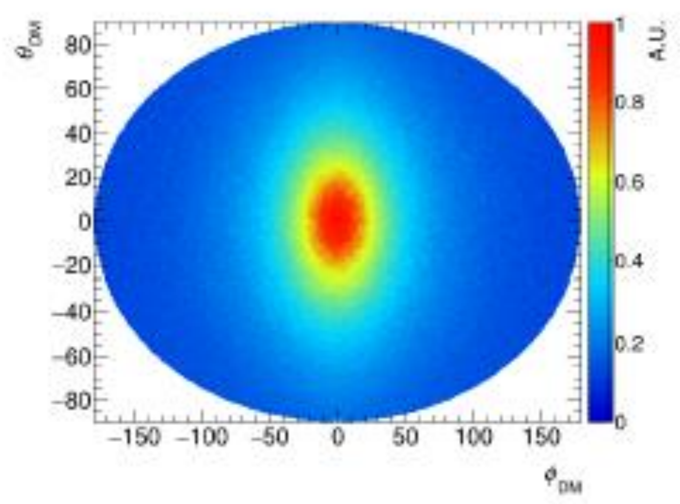
SI **SD**

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

- CR boosted DM　(w/長尾さん)
  - keV〜MeV程度のWIMP
  - 銀河中心で高エネルギー宇宙線（陽子）に蹴られる
  - 方向感度を持つWIMP検出器（ガスや原子核乾板）で見ると銀河中心が明るいはず
  - 観測量は必用だが、原理的には見える。

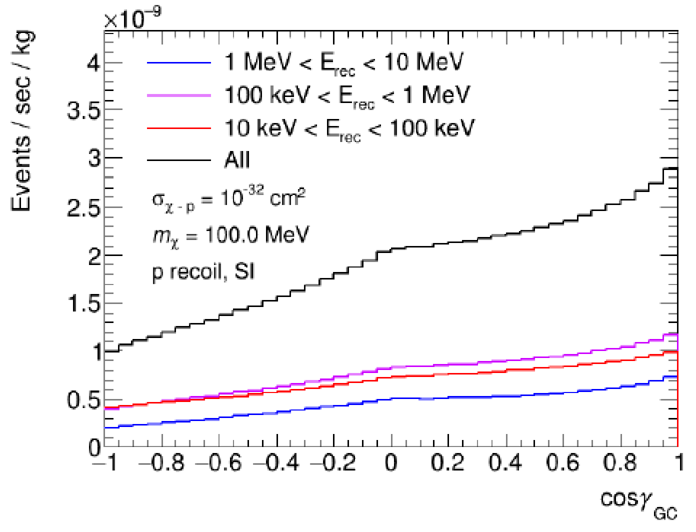
Directional direct detection of light dark matter up-scattered by cosmic rays from direction of the Galactic center

JCAP07(2023)061



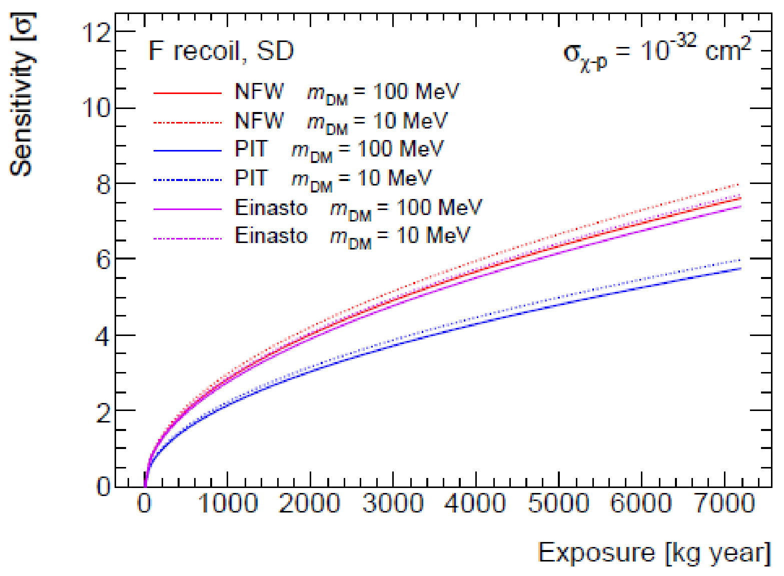
PIT

到来方向



PIT, $m_\chi = 100$ MeV

反跳角分布

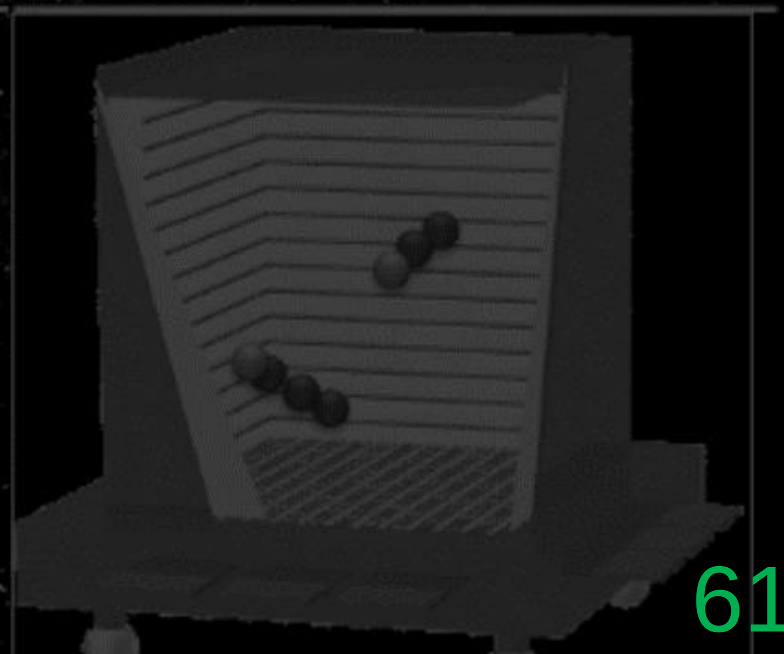


F

銀河中心エクセスの有意度

最近の話題　まとめ

- MIGDAL
  - Observation
- Directional Detectors：gas detectors
  - Clear evidence
  - DM nature study



Thank you!