Oct 13, 2020

- KEK-PH

Direct Search of Dark Matter

Kentaro Miuchi
(Kobe University)

ACT 1 Introduction

ACT 2 Direct Search Review

ACT 3 Topics

科研費 KAKENHI

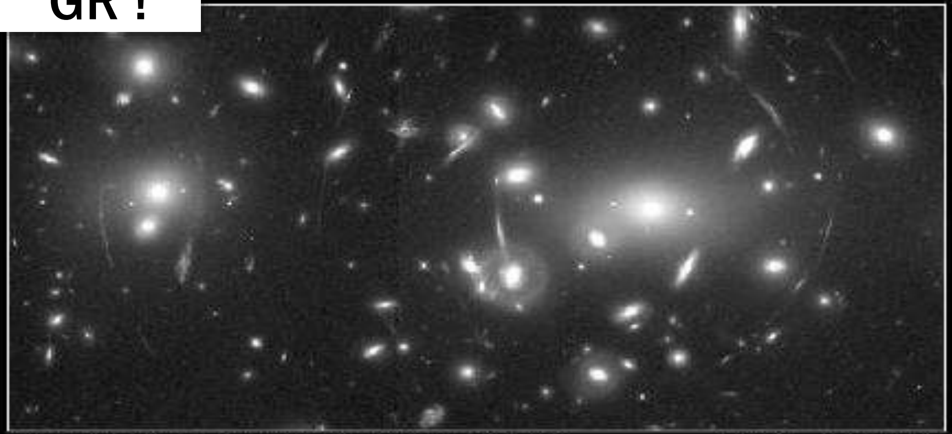
ACT 1：Introduction

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

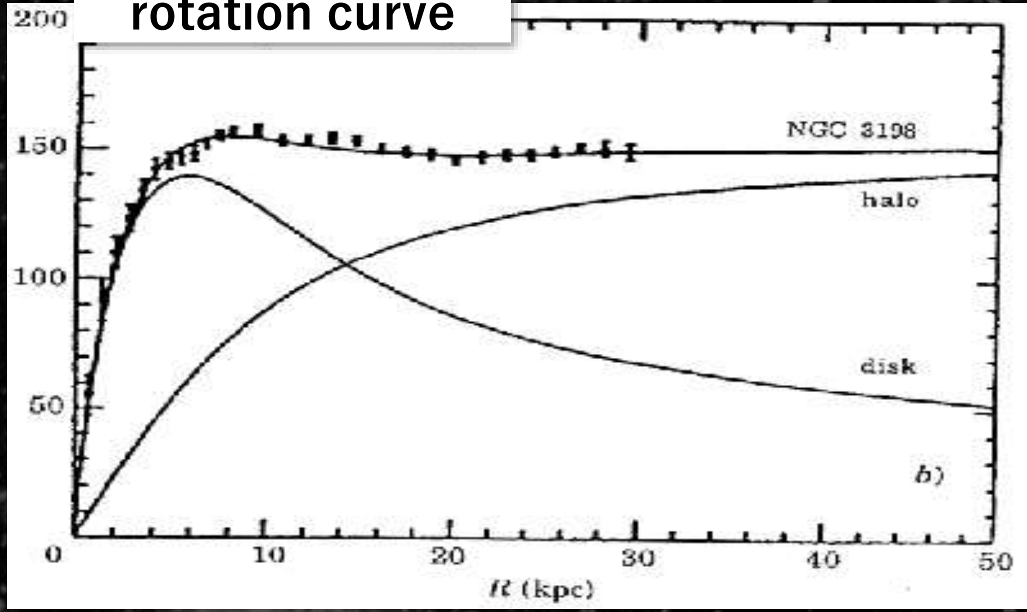
Dark Matter

- 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 !

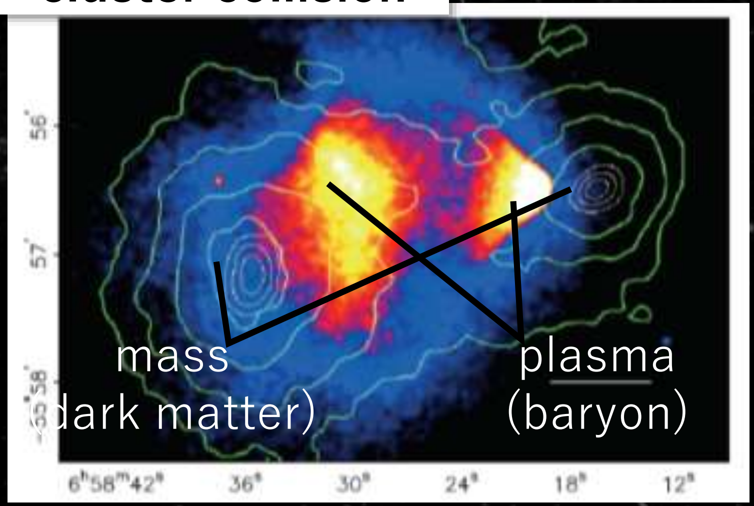


rotation curve



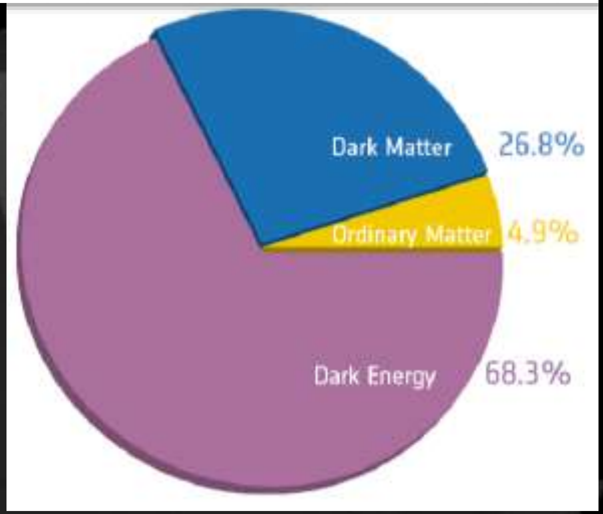
Annu. Rev. Astron. Astrophys. 29(1991)409

cluster collision



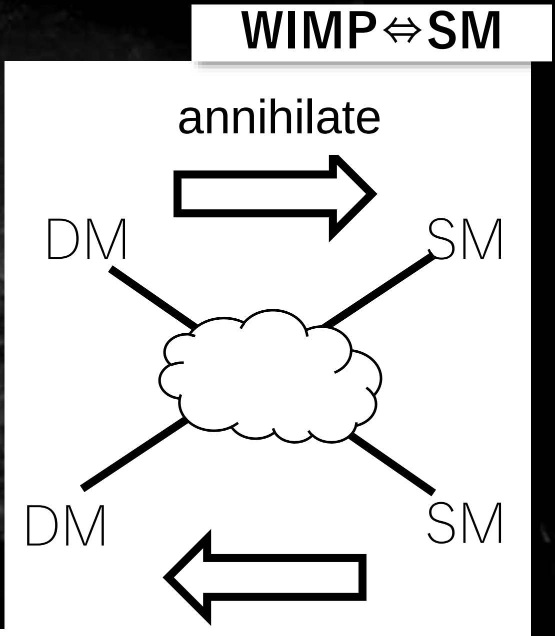
THE ASTROPHYSICAL JOURNAL, 648:L109–L113, 2006 September 10

pie chart of the universe

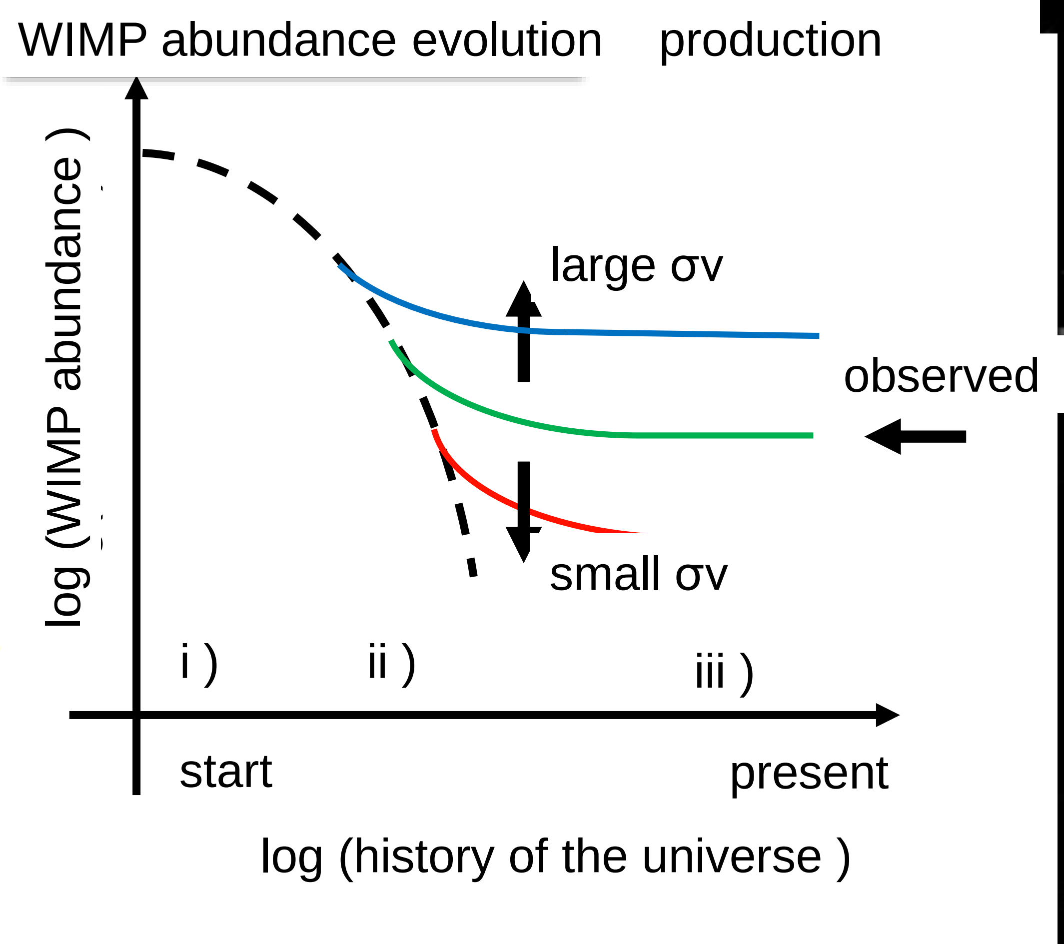


Plank team

- 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)

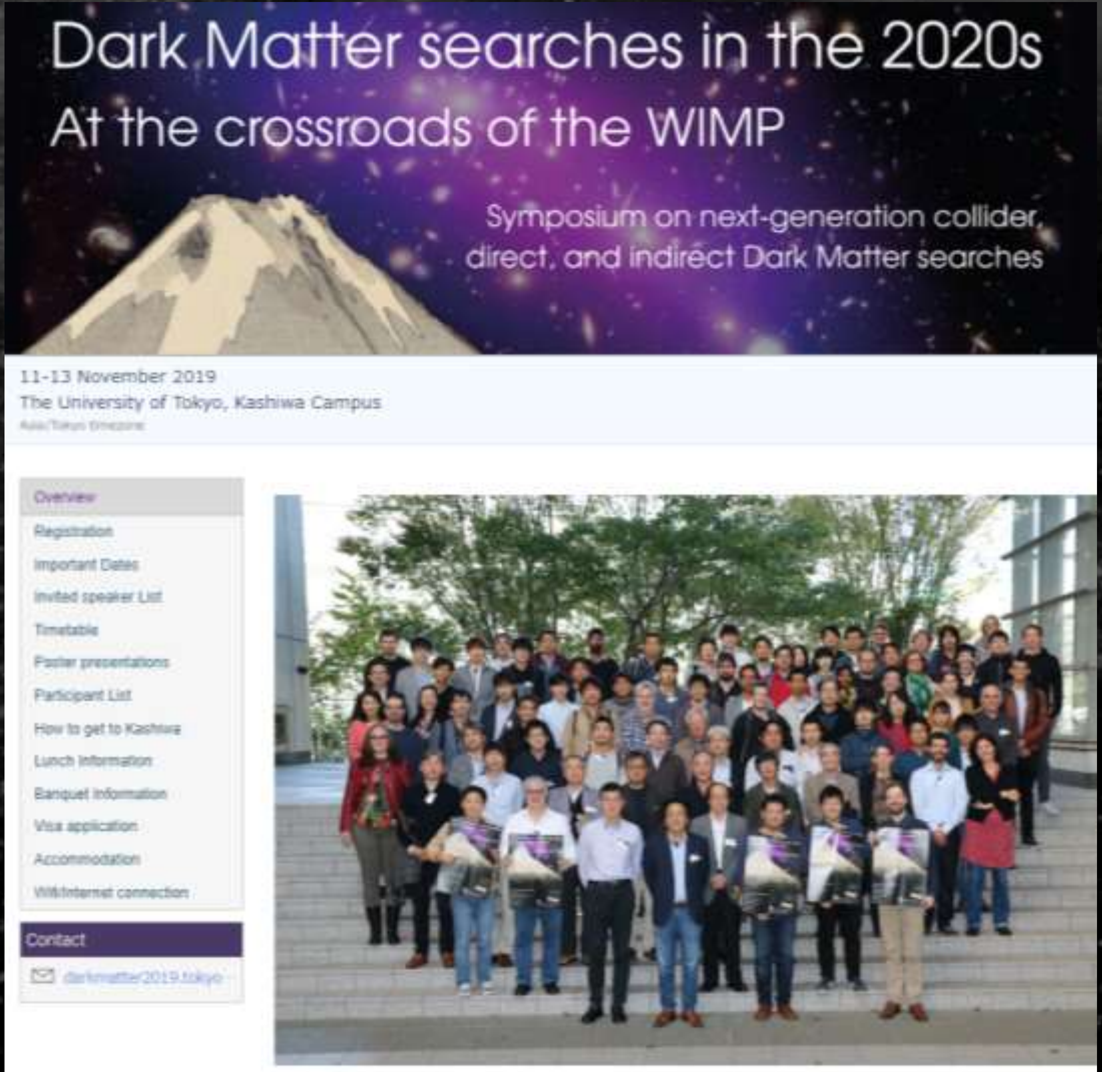


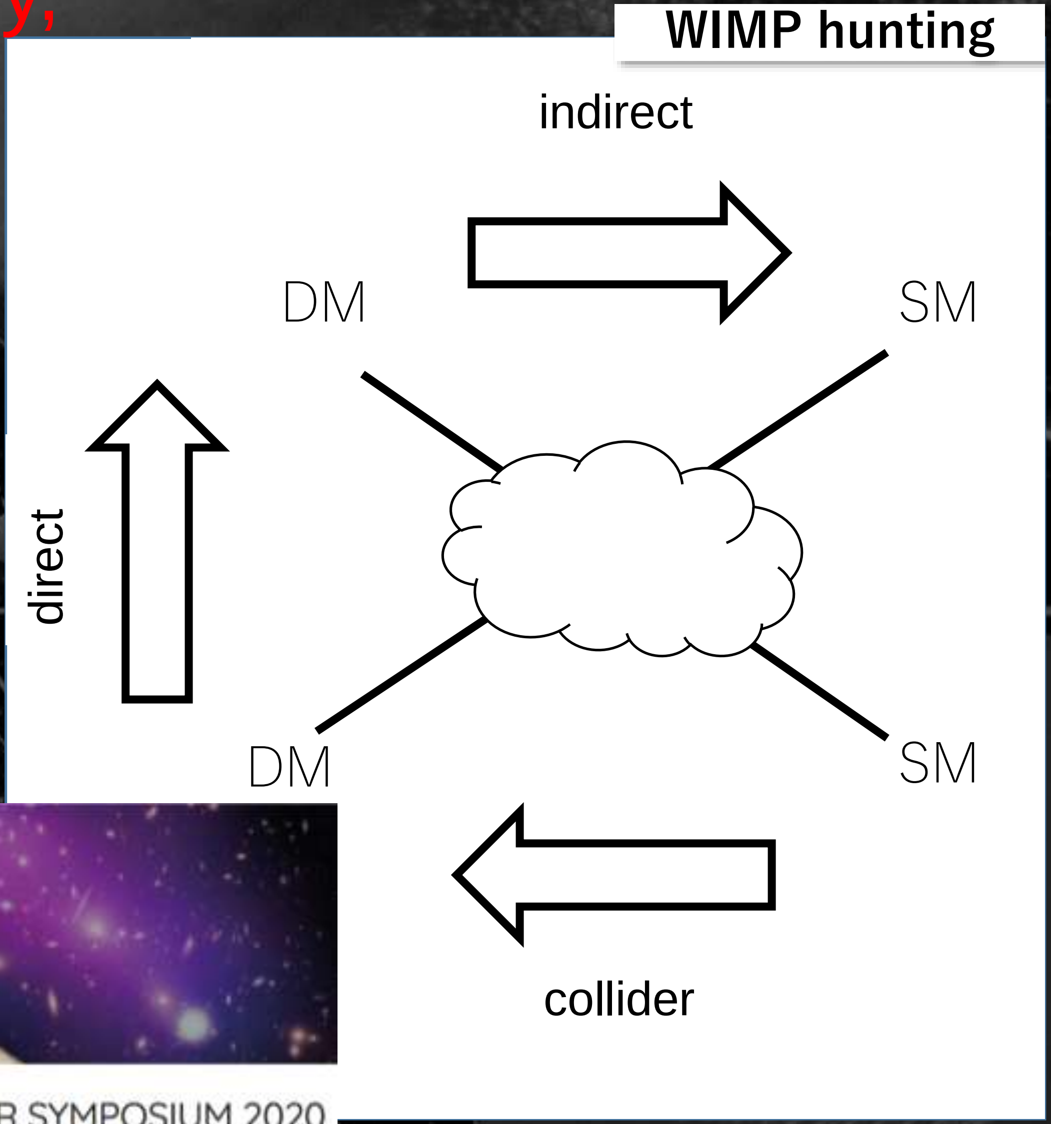
  - WIMPs
    - Produced in the early universe
    - Annihilate
      rate ∝ cross section × velocity
    - Freeze out at some point
      abundance is fixed
    - σ~weak scale explains present abundance
      ⇒WIMP miracle !



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

complementary, synergy



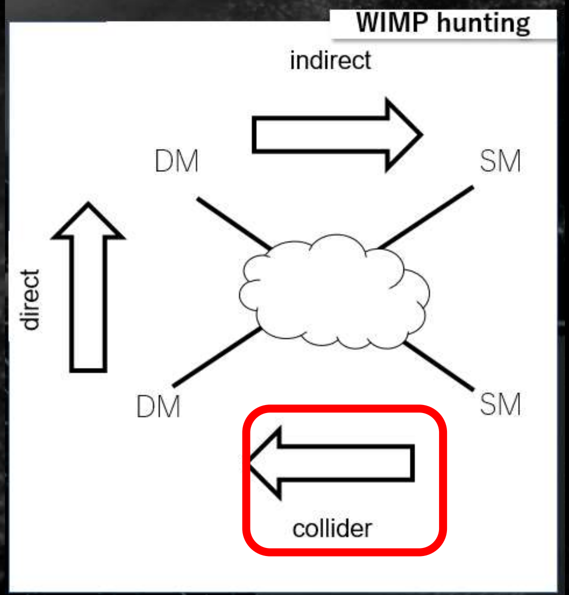


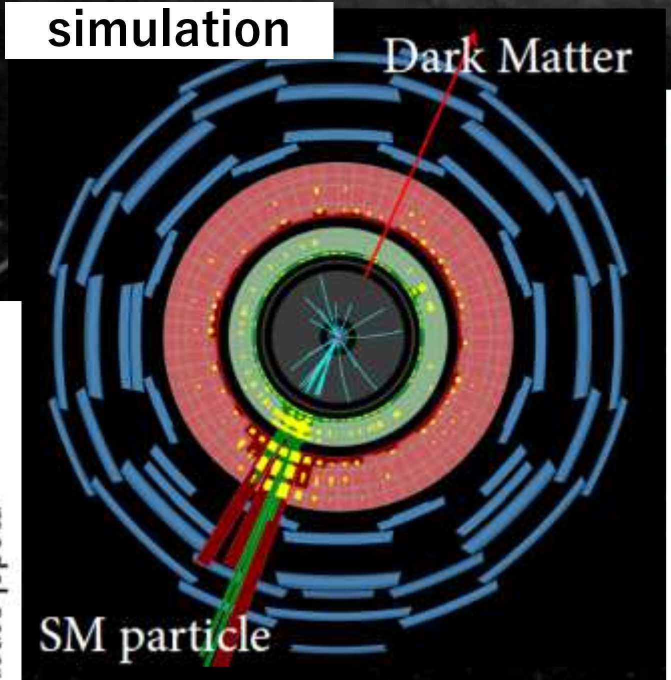
- Collider
  - LHC @ CERN
  - Missing E signal
  - Searches with various ways
  - No hint so far

Dark matter searches at colliders.

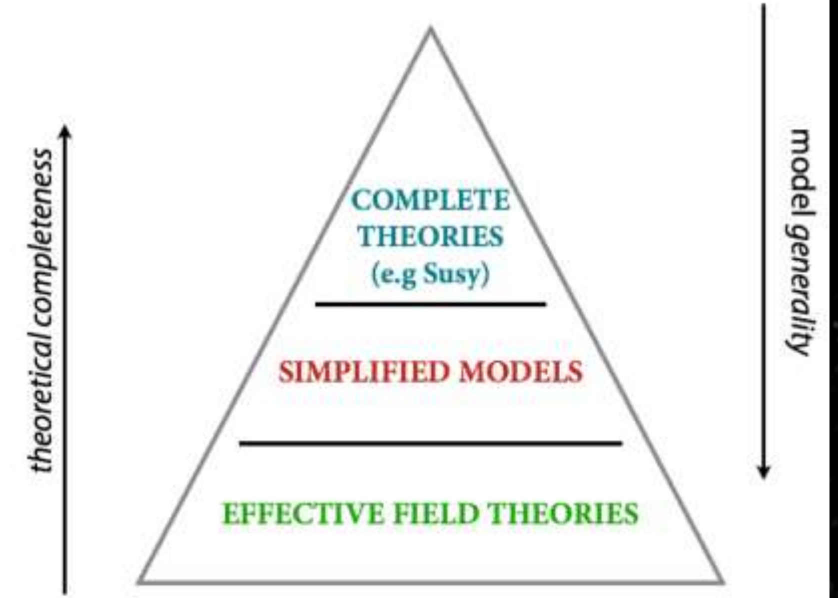
Priscilla Pani
on behalf of ATLAS, CMS & LHCb

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





Theoretical framework



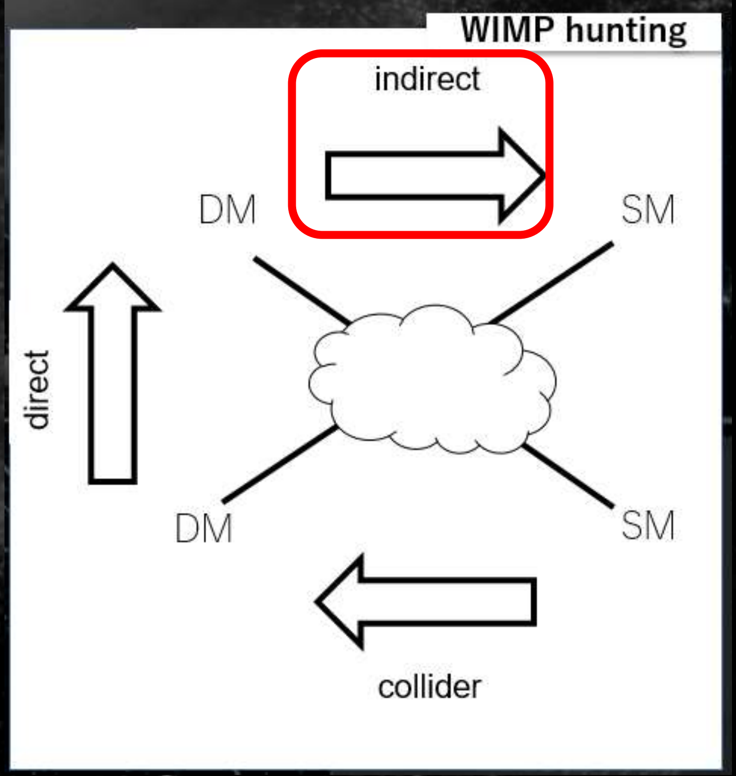
Conclusion - Cheat sheet

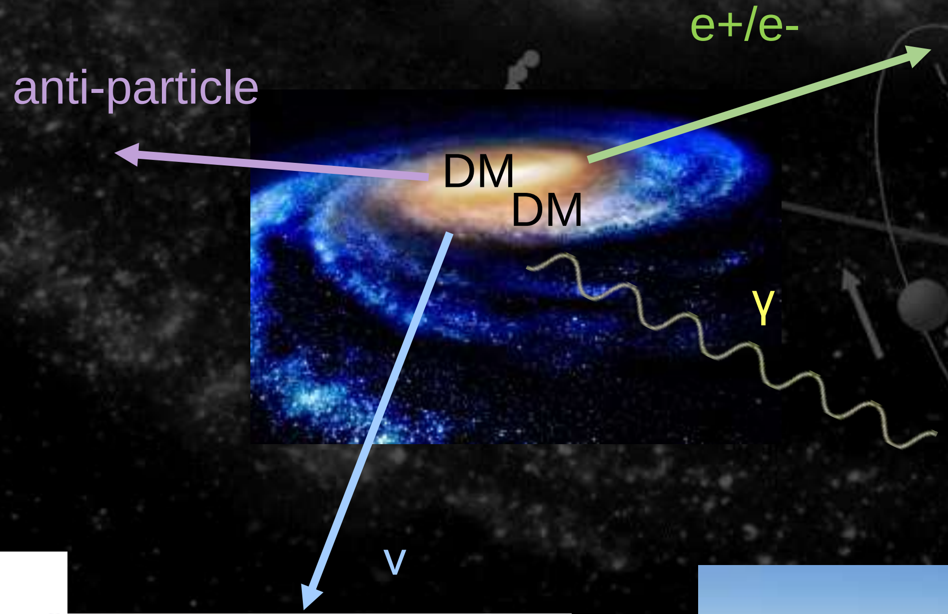
DM-mediator searches

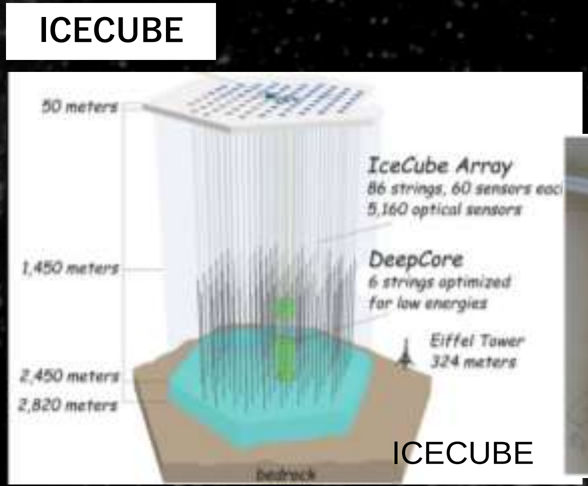
Signature	Dataset	Reference
Di-lepton resonance	139 fb-1	1903.06248
Di-jet, Di-jet + ISR,	139 fb-1	1901.10917, ATLAS-CONF-2019-007, 1808.03124
Di-bjet	80 fb-1	ATLAS-CONF-2018-052
Di-jet + leptons	80 fb-1	ATLAS-CONF-2018-015
Dijet + photons	36 fb-1	1905.10331
Etmiss + Higgs	36 fb-1	1908.01713
Etmiss + 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

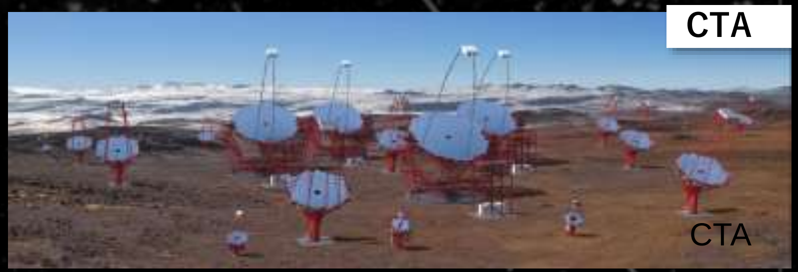
JGRG2019

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



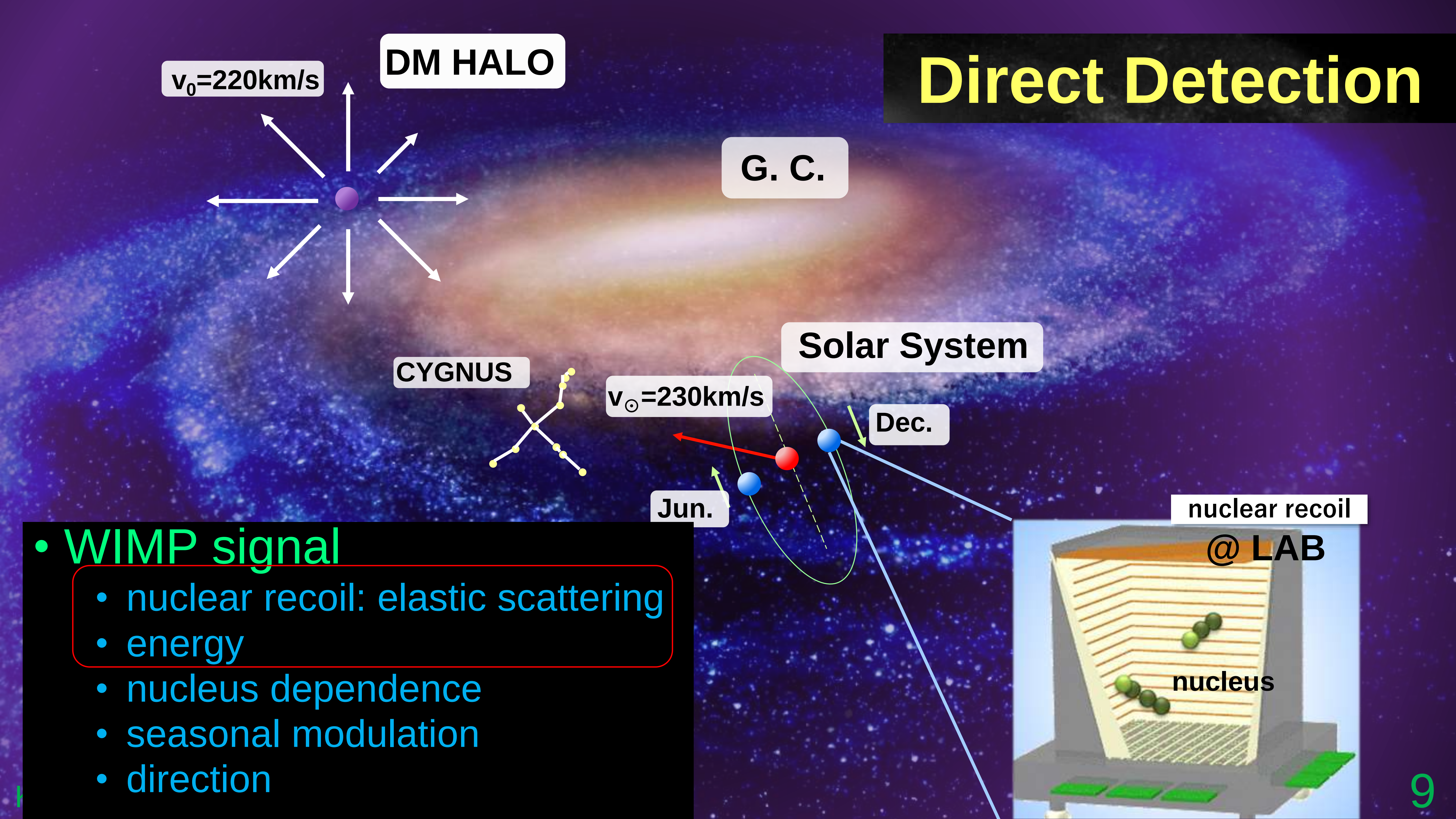






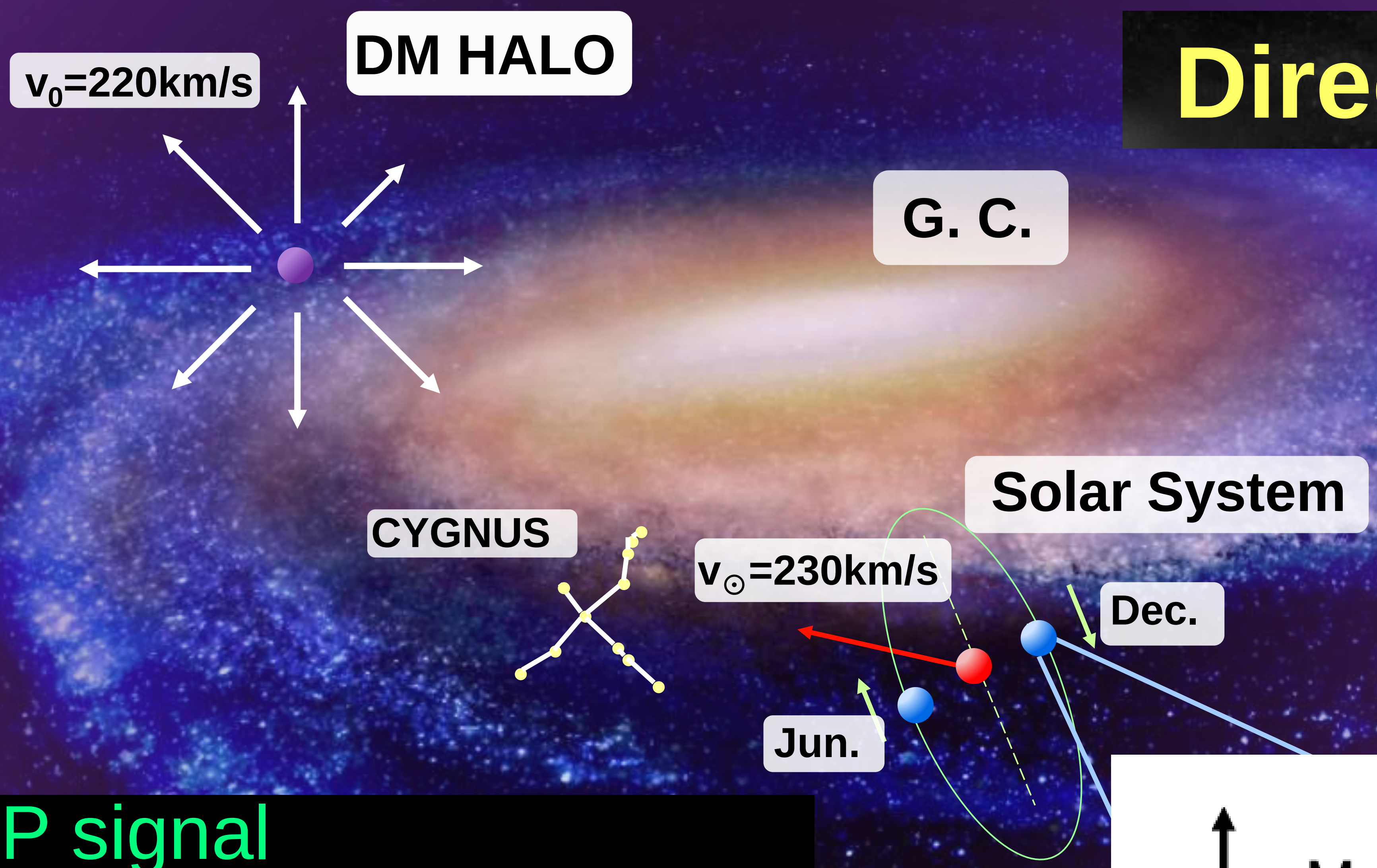
Direct Search

Direct Detection



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

Direct Detection



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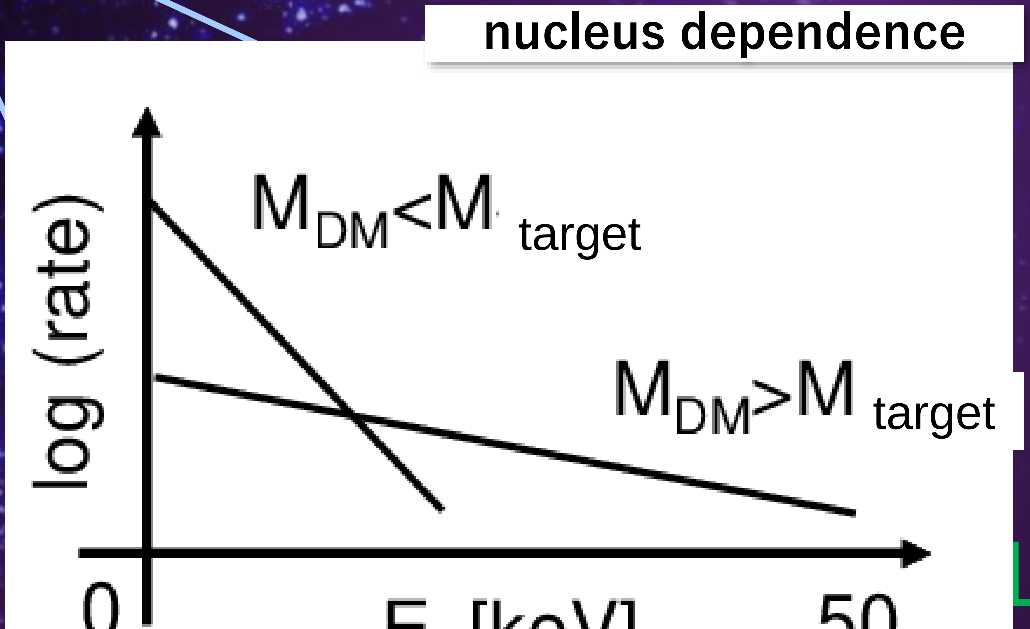
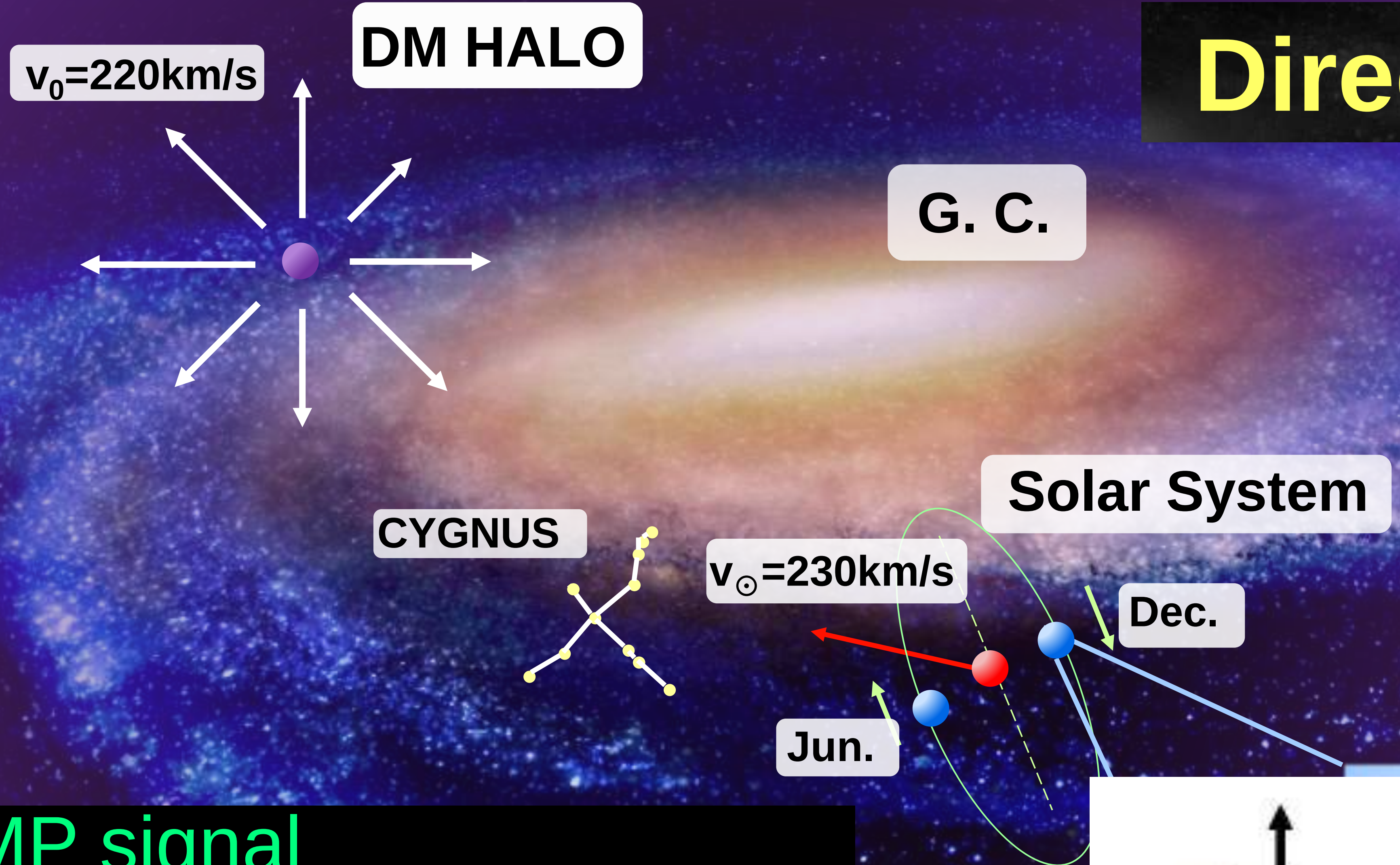
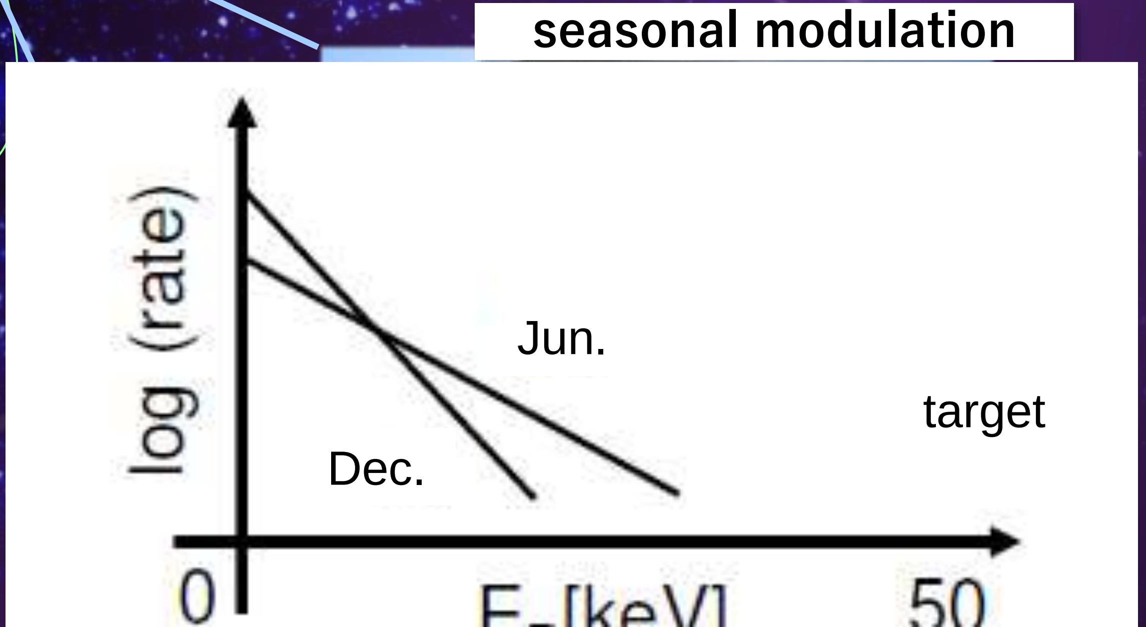


Direct Detection





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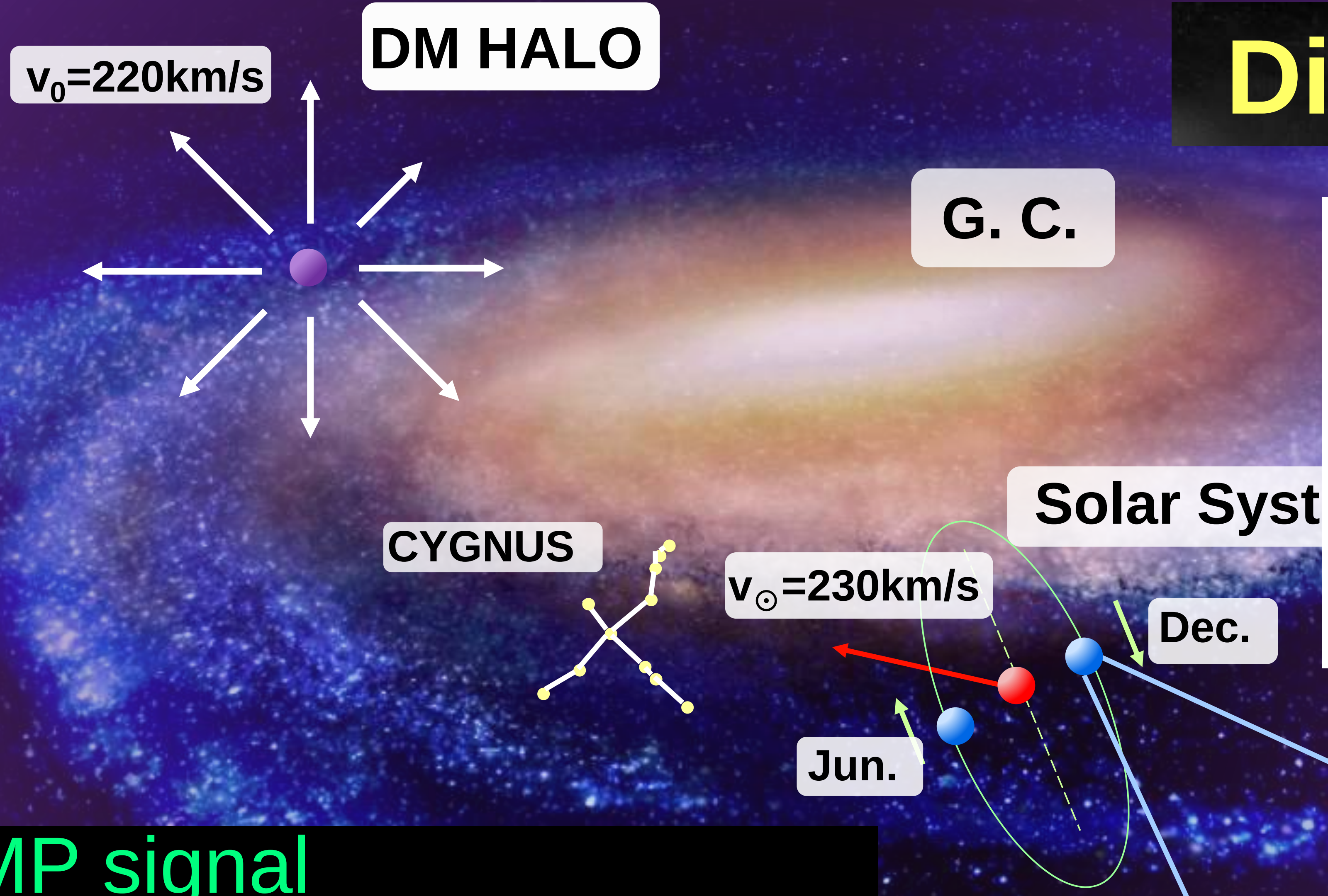
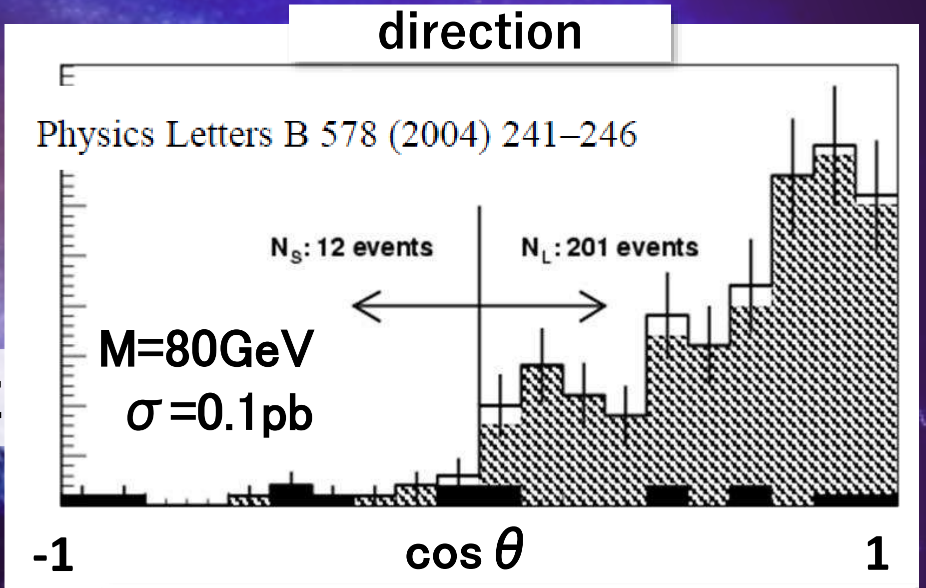
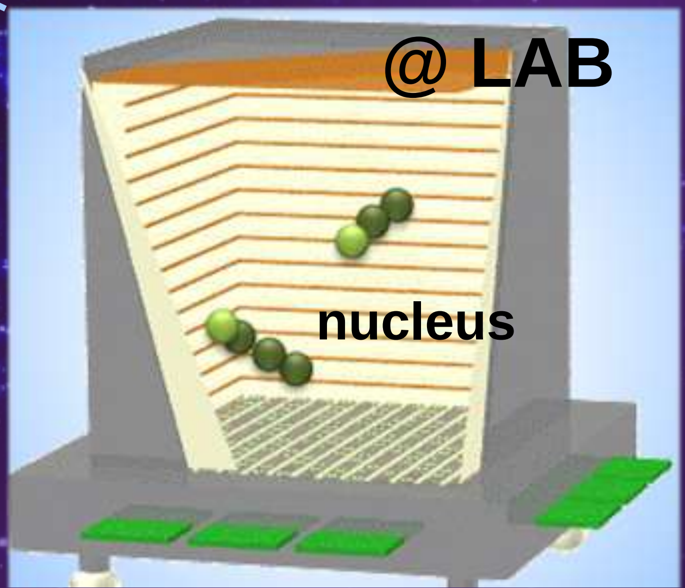




(θ : angle between the nuclear recoil direction and constellation CYGNUS)



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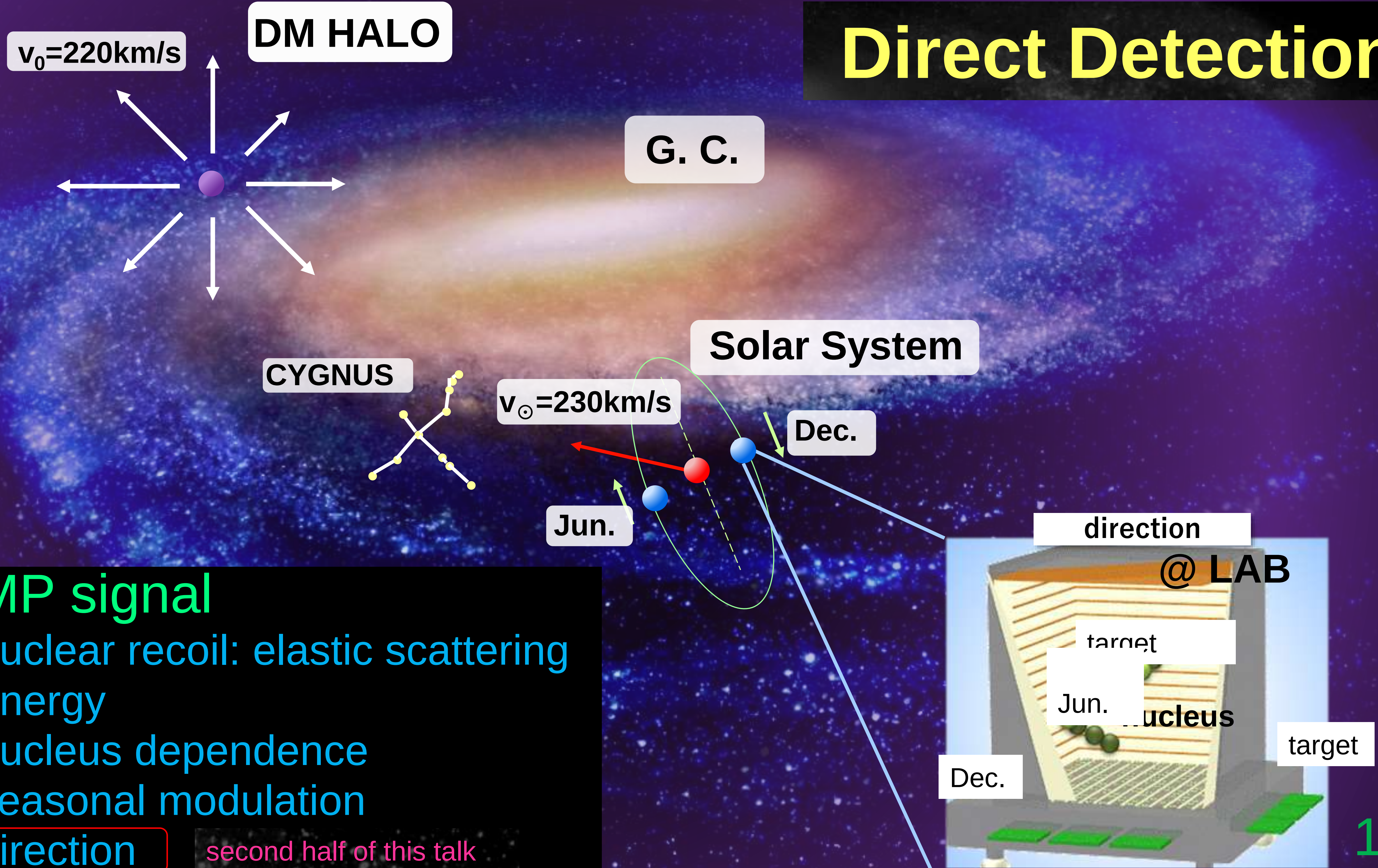
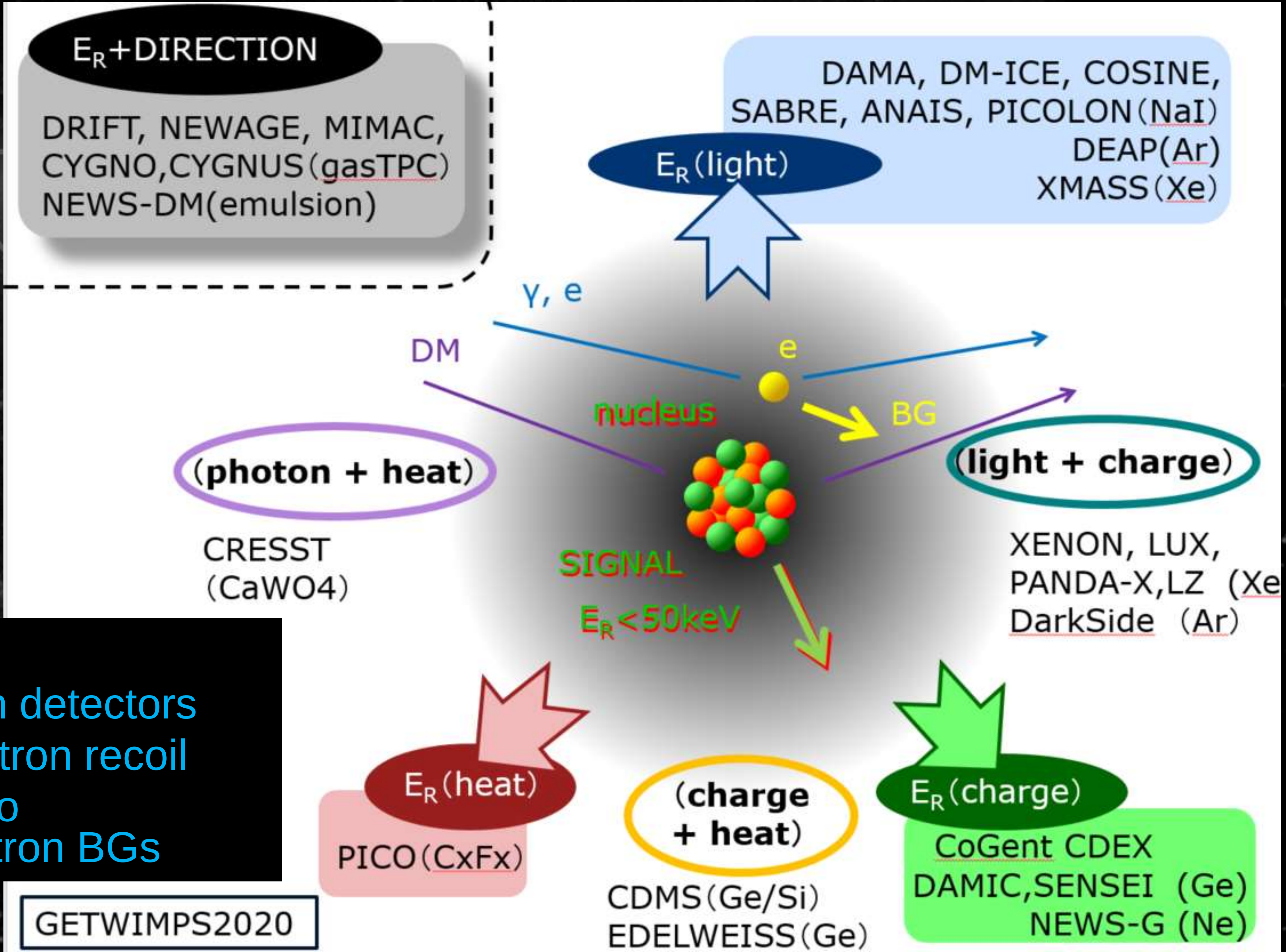


- WIMP signal
  - nuclear recoil: elastic scattering
  - energy
  - nucleus dependence
  - seasonal modulation
  - direction

second half of this talk

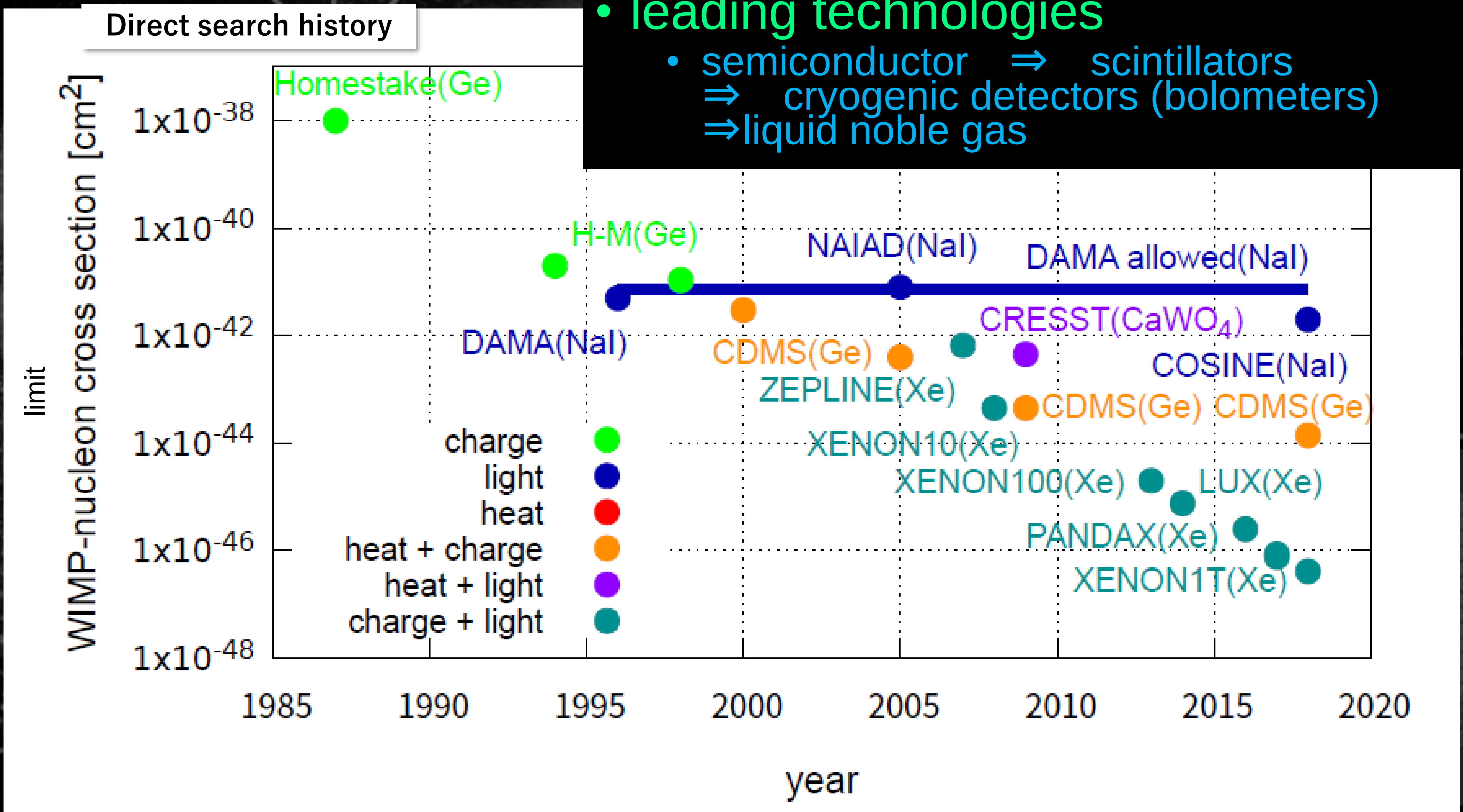
- Technologies
  - Ordinary radiation detectors
  - Background: electron recoil
  - more than two info
    ⇒ reject electron BGs



Kentaro Miuchi

History

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

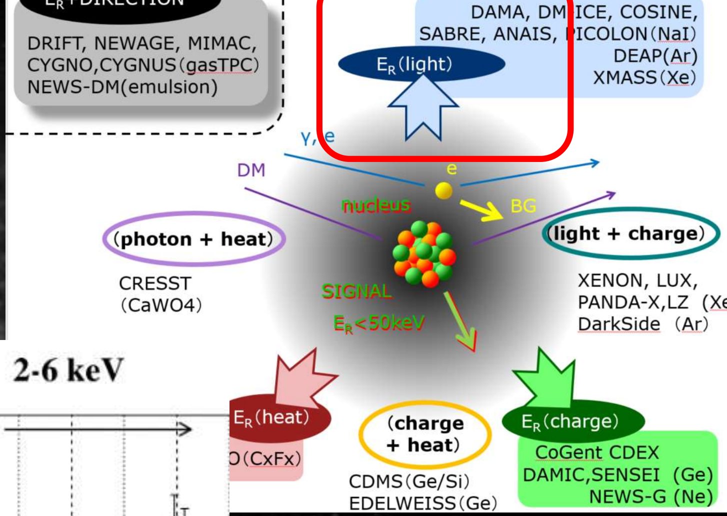


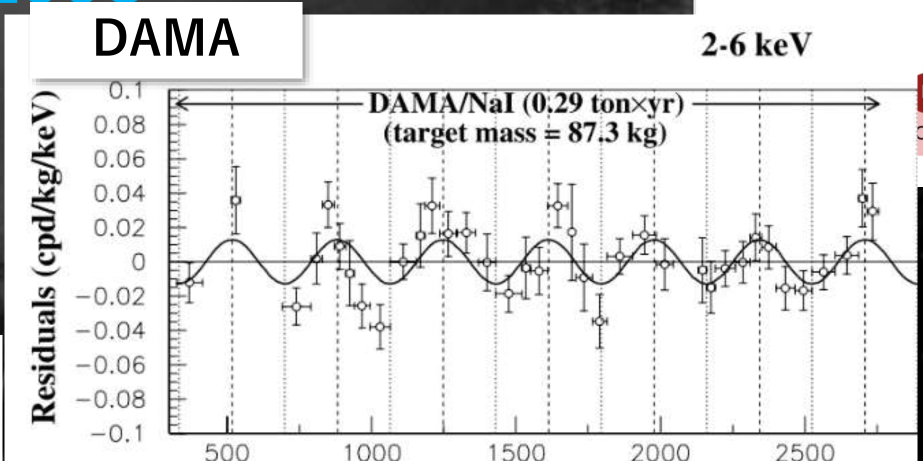
ACT 2 : Direct Search Review


Direct Search Review

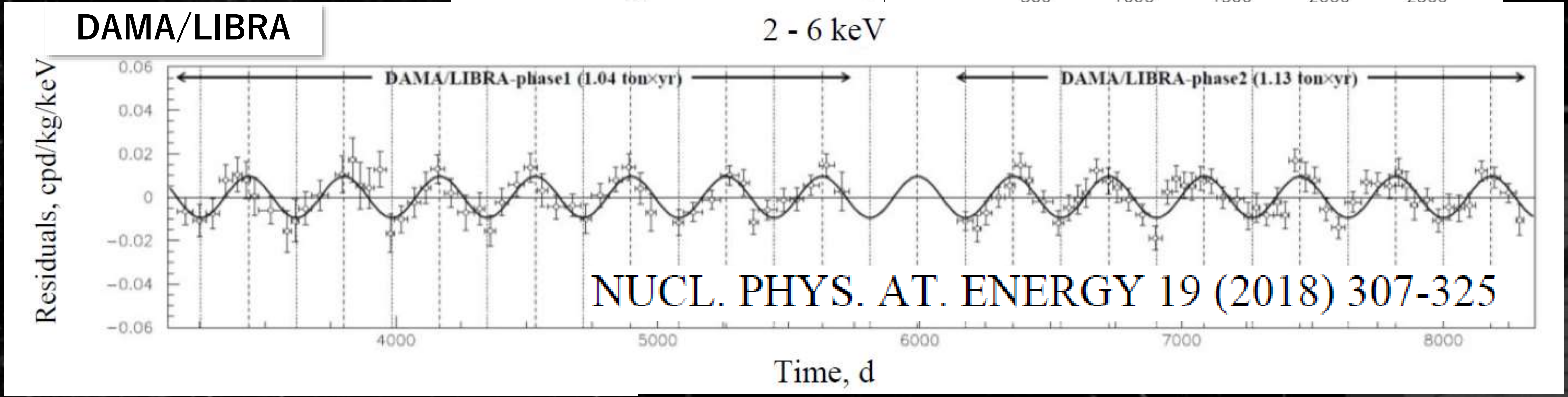

Direct Search Review
1. Mainstream : Large Detectors

- 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



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

No BG explains this modulation

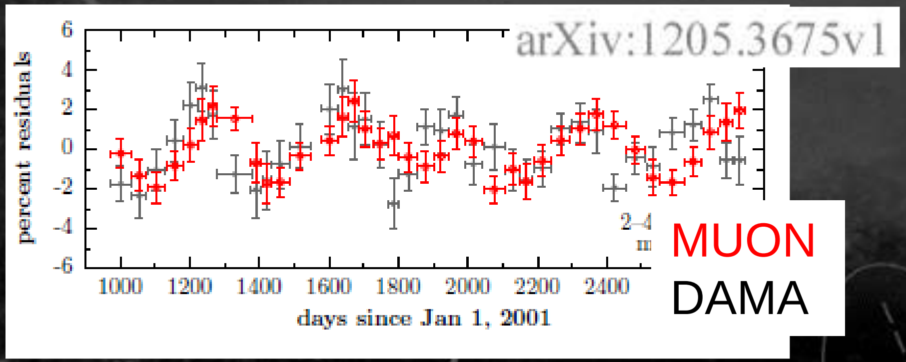
No natural DM model explains, either…

- 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



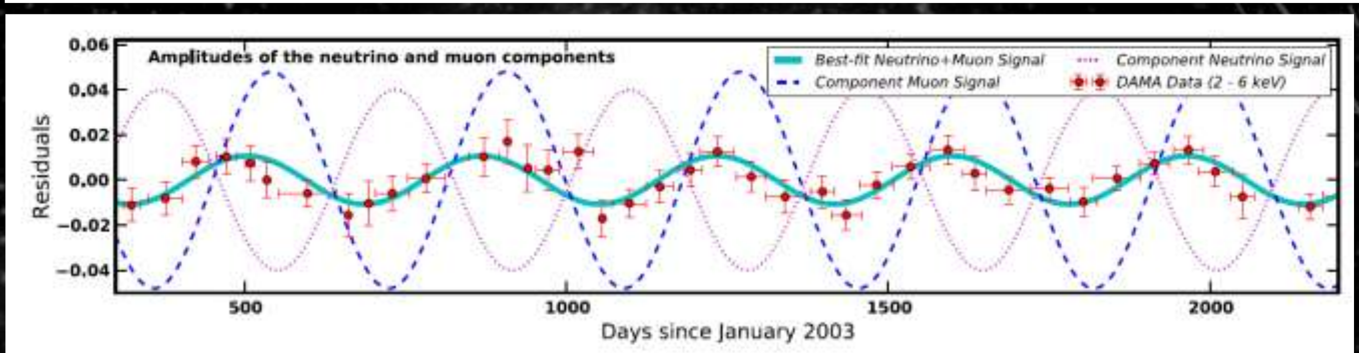
- No, muon comes later

  - 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



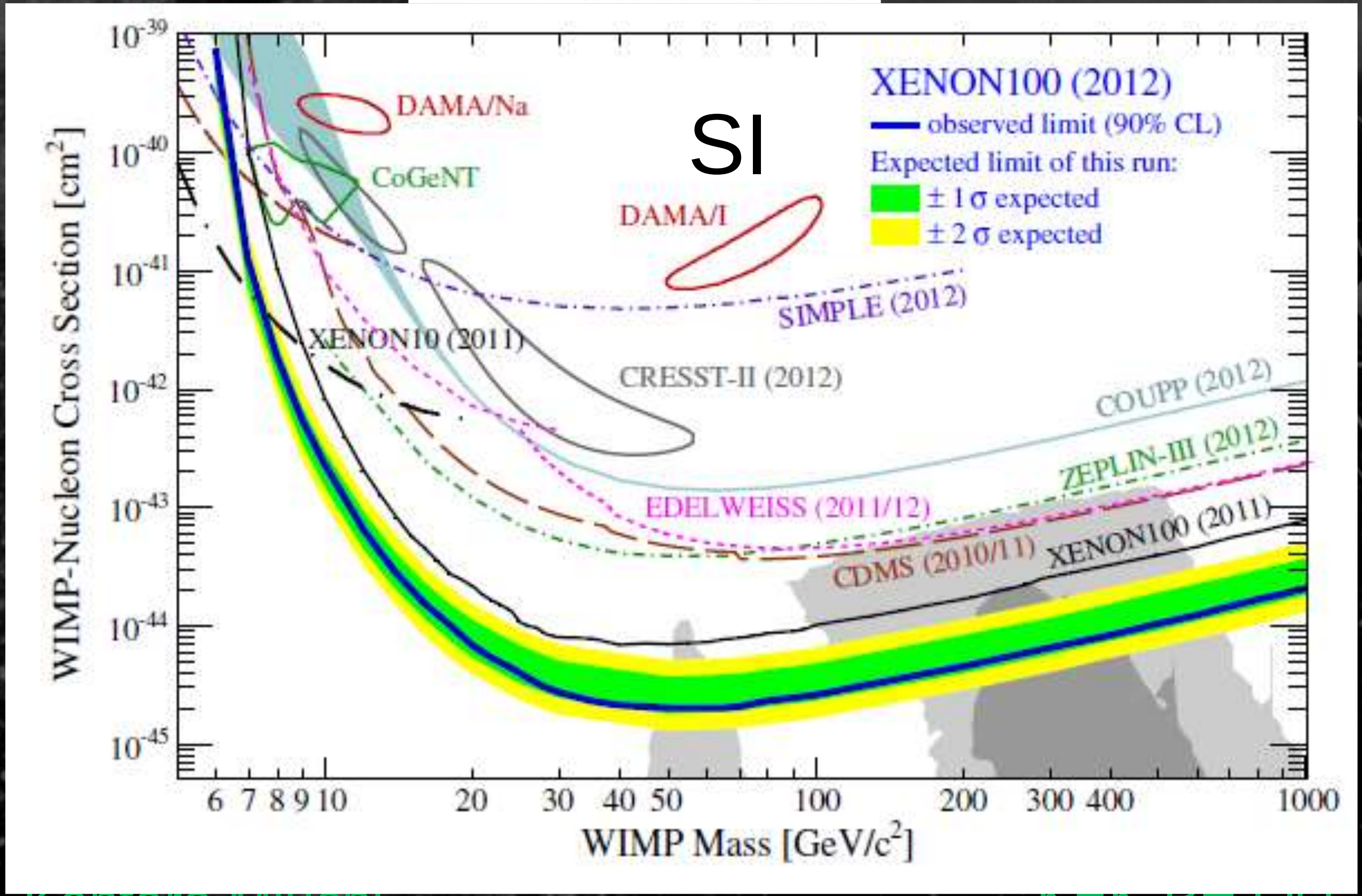
- No, not enough neutrinos

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

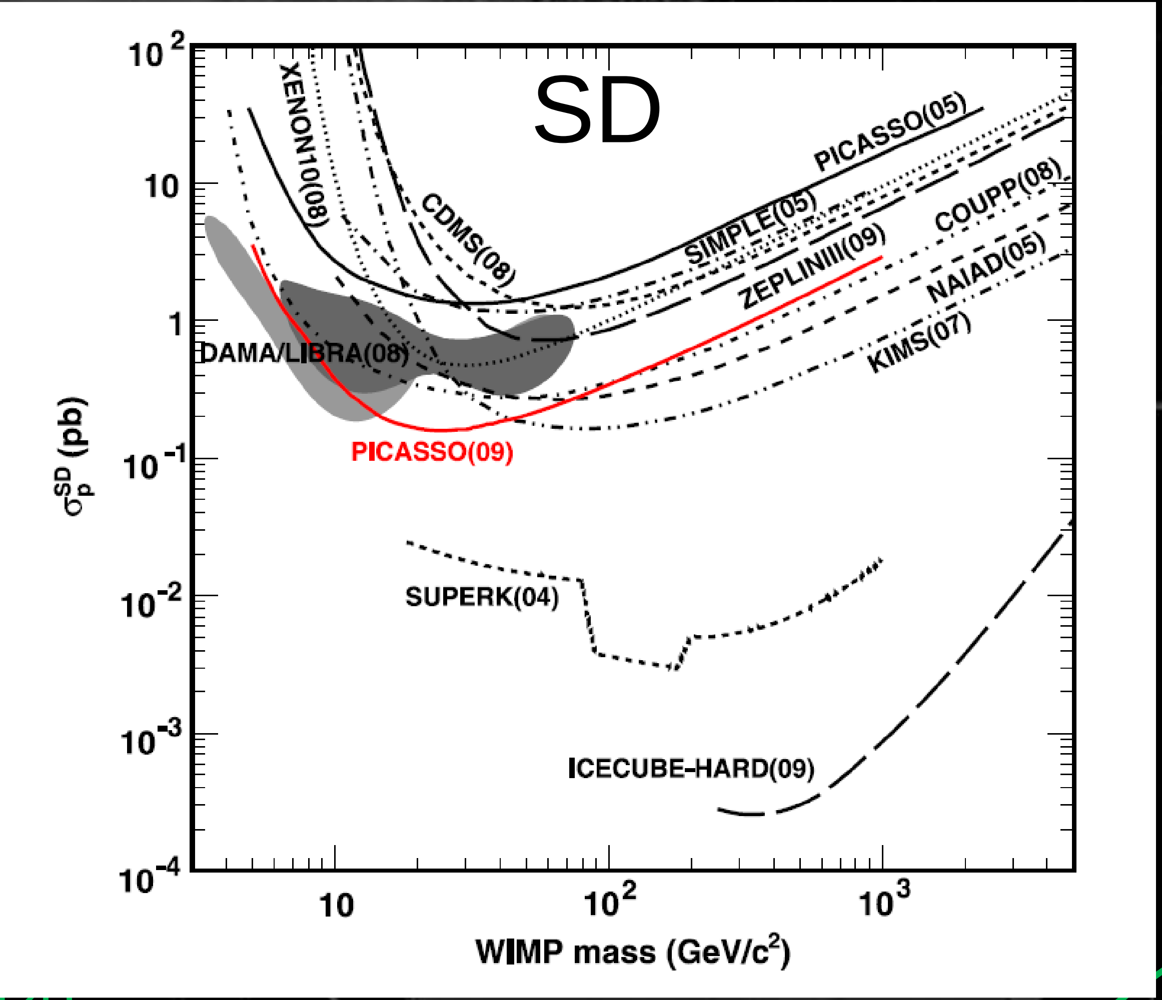
- None worked so far ...
- So the right way is to ...

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

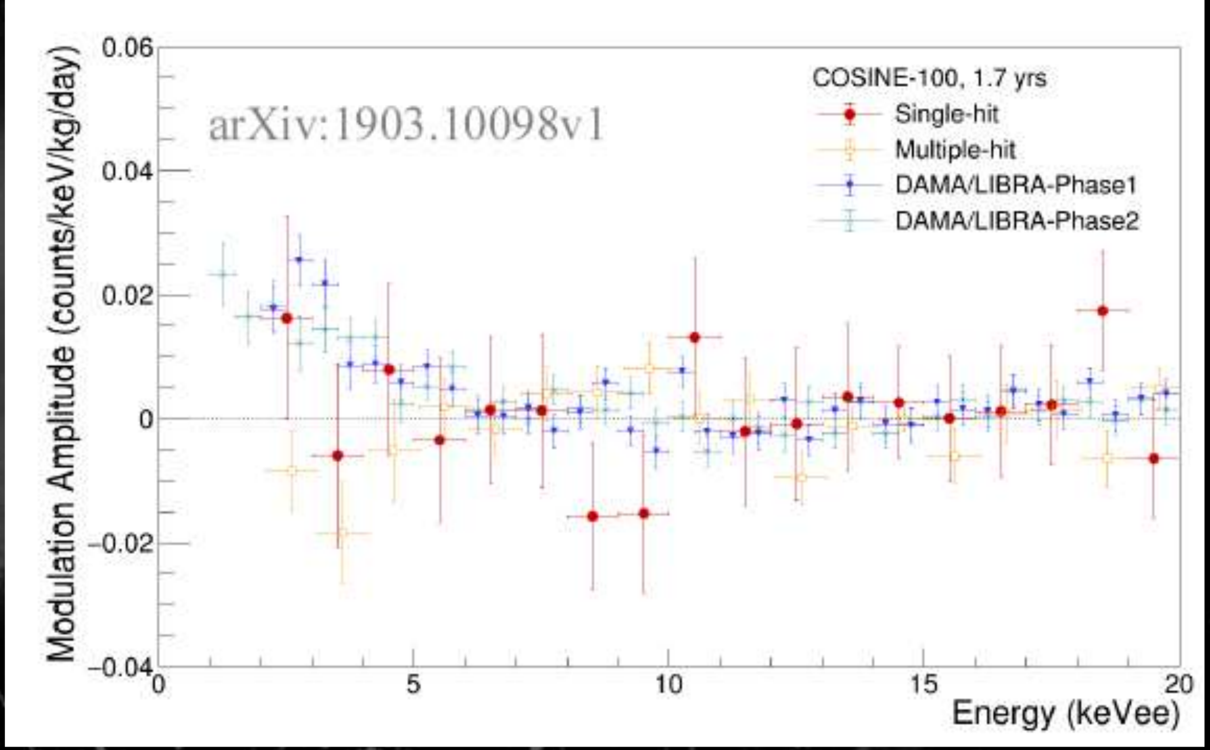
PRL **109**, 181301 (2012)

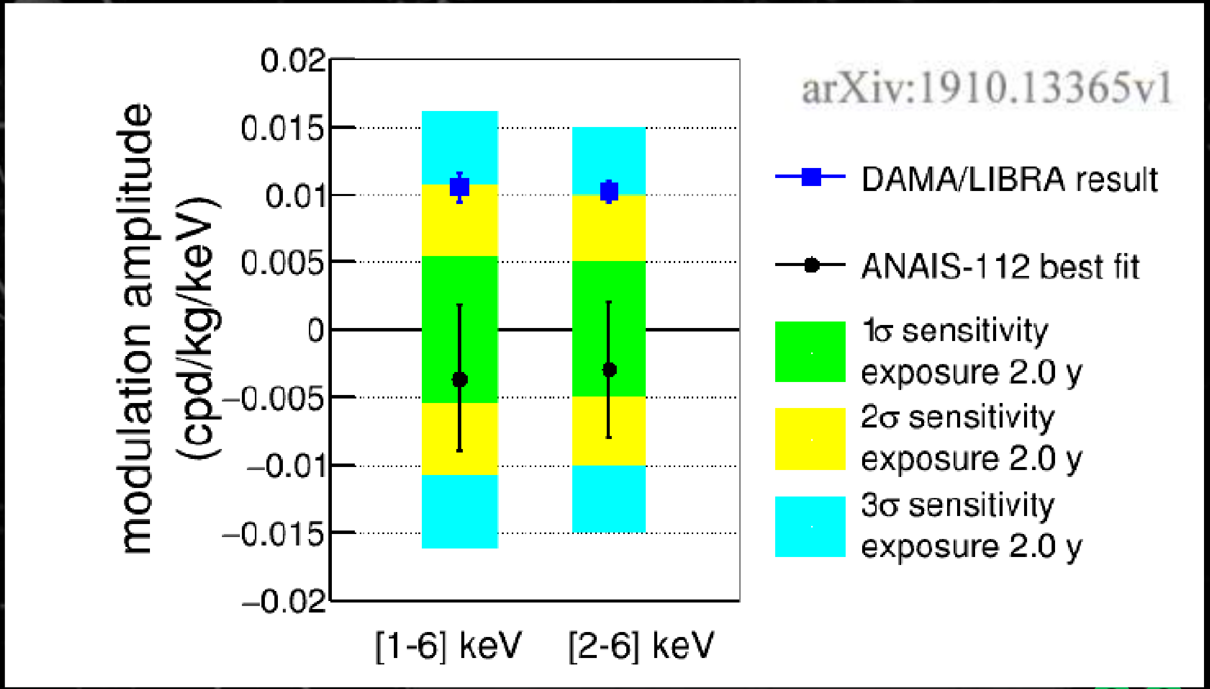


Physics Letters B 682 (2009) 185–192



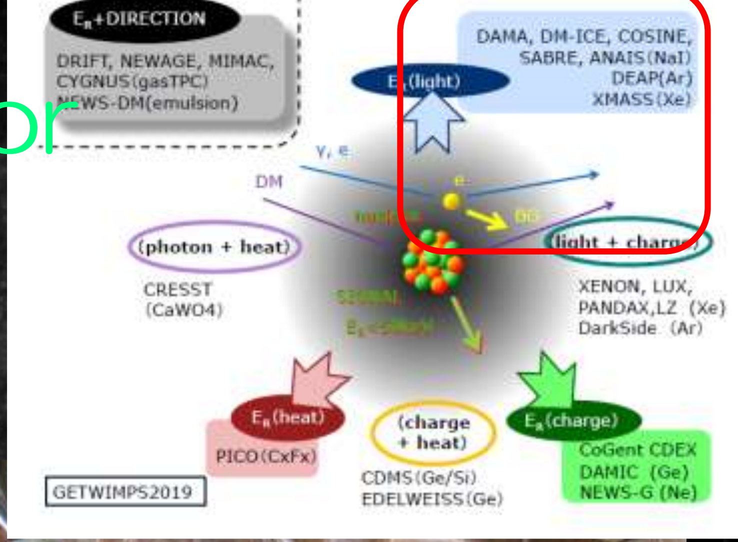
- Other NaI detectors
  - COSINE(106kg), ANAIS (112kg)
    - Annual modulation measurement
    - Consistent with null and DAMA, yet.
  - SABRE
    - North and South
  - PICOLON
    - Pure crystal





Need to be stay tuned.

- Liq Xenon：1 phase (liquid-only) detector
  - XMASS
    - Observation 2013 Nov.～2019 Mar.
    - 642× PMTs
    - 800kg liquid xenon
  - One of the main results ” fiducial paper”
    - “self-shielding” of liquid xenon



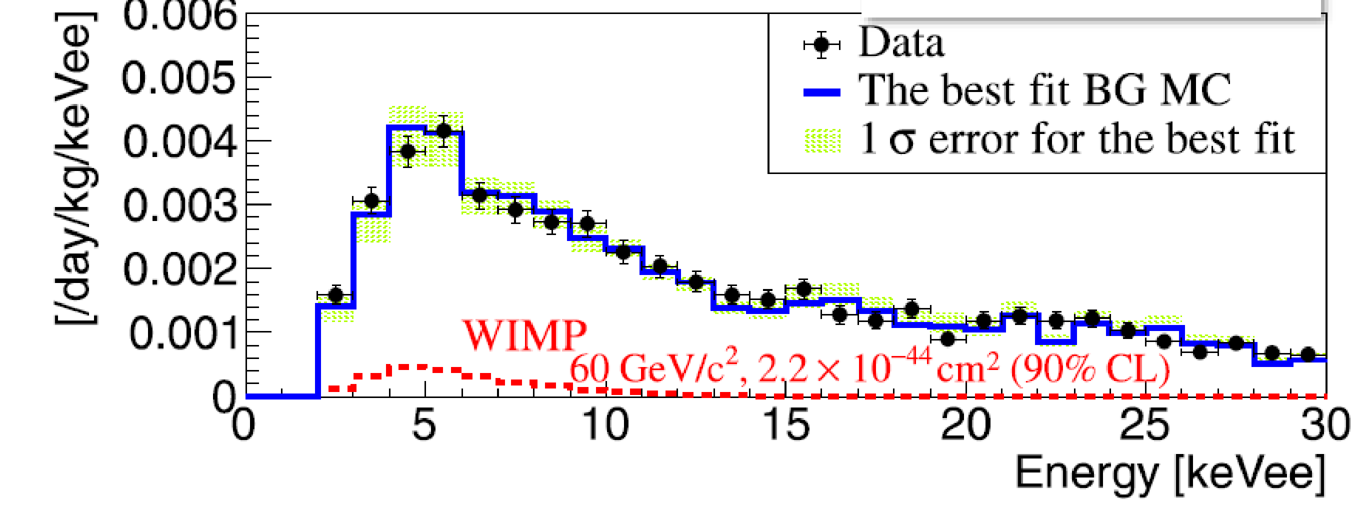
Physics Letters B 789 (2019) 45–53

A direct dark matter search in XMASS-I

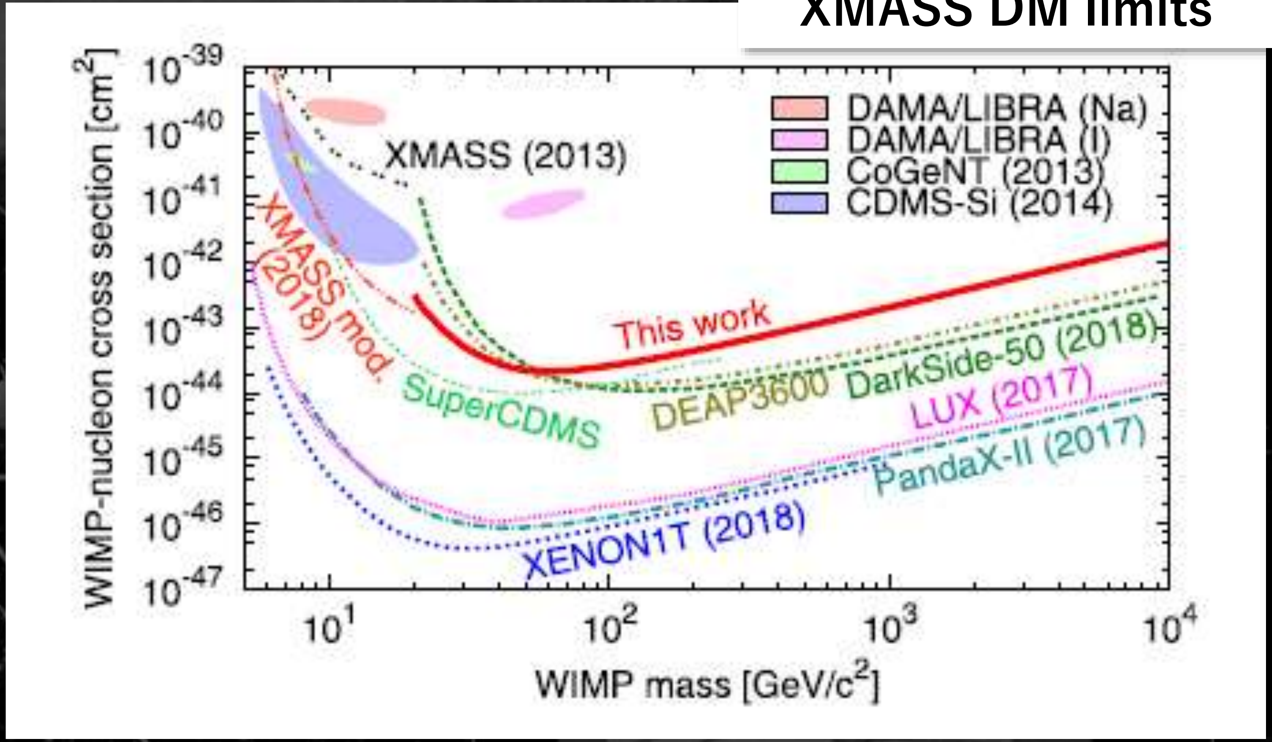
XMASS Collaboration *

- XMASS fiducial paper: limit
  - Fitting the obtained energy spectrum with BG + WIMP
  - Consistent with the BG model

WIMP fit ersults



XMASS DM limits



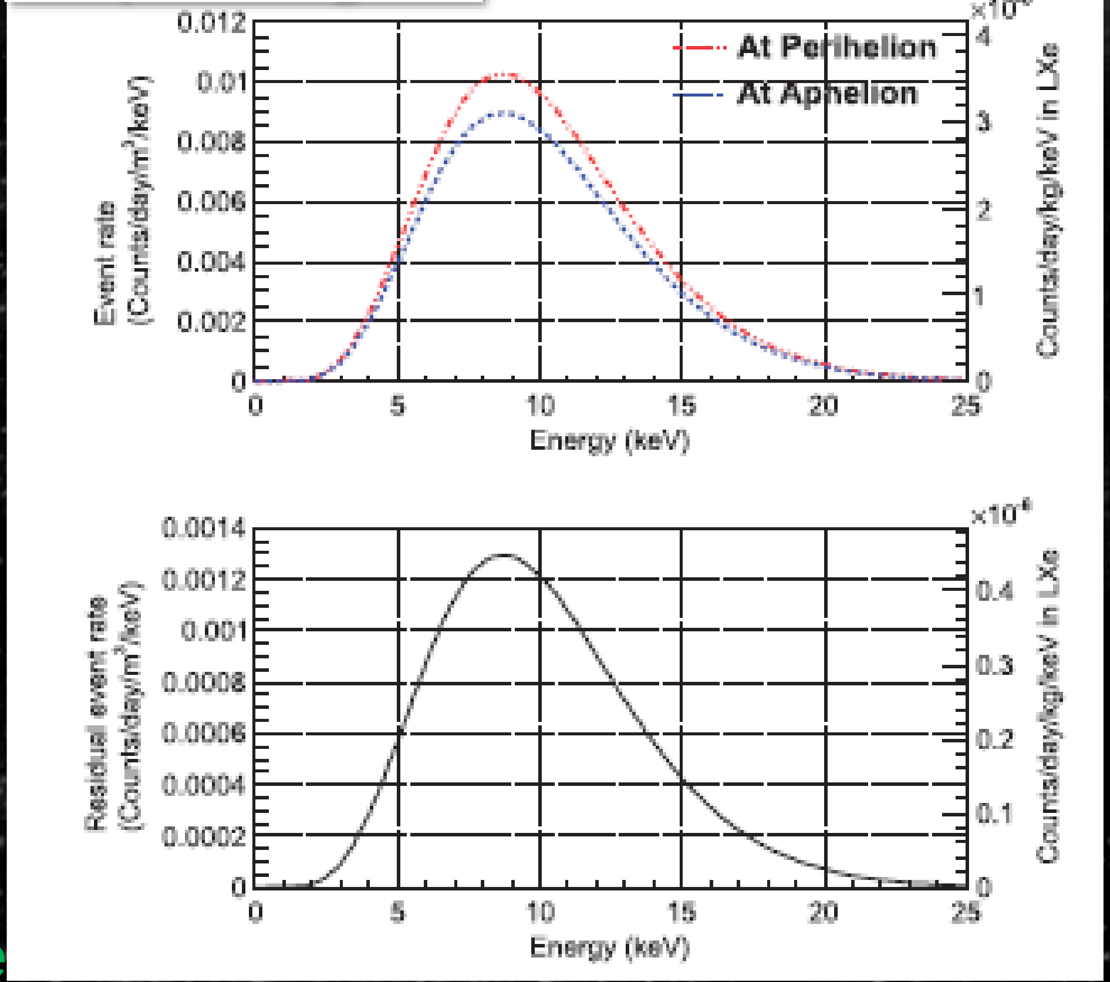
- Best limit as a 1-phase liq. Xe detector
- （Learned lesson） Reduction of the systematic error is important for an effective BG reduction

- XMASS other results
  - Kaluza-Klein solar AXION
  - Extra dimension AXION: mass ~keV
  - Thermally produced in the Sun ⇒ gravitationally trapped ⇒ decays in the detector

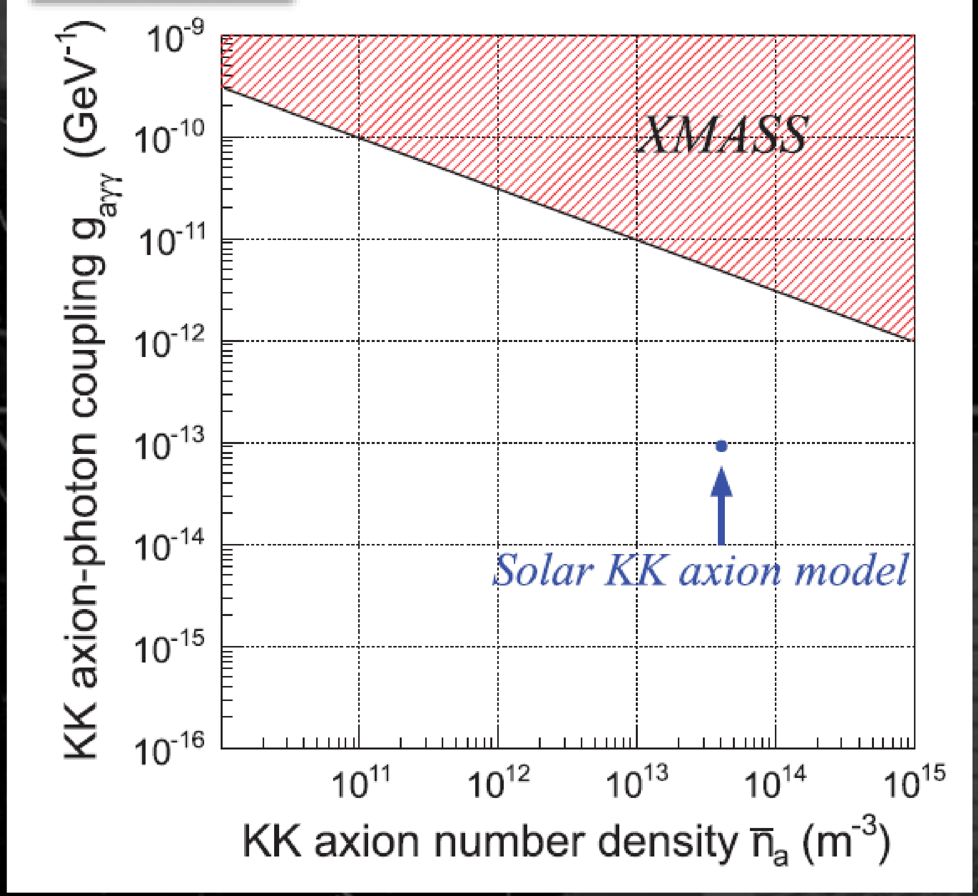
Prog. Theor. Exp. Phys. 2017, 103C01 (10 pages)

N.Oka *et. al.*

expected signal



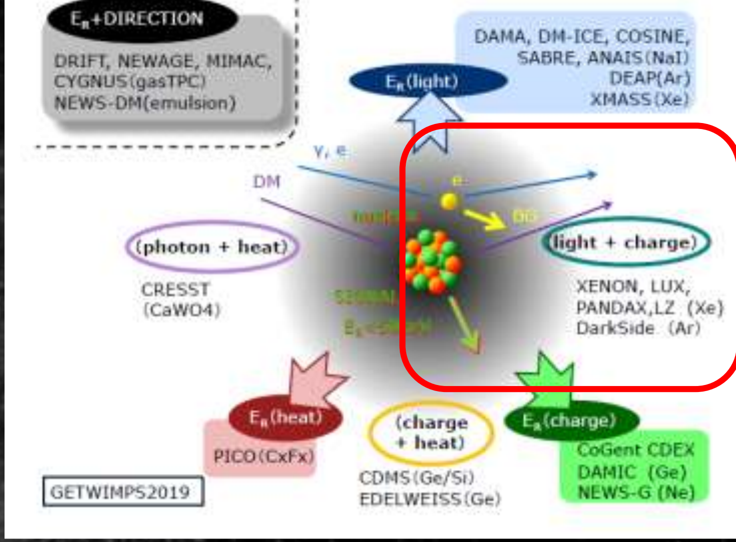
result



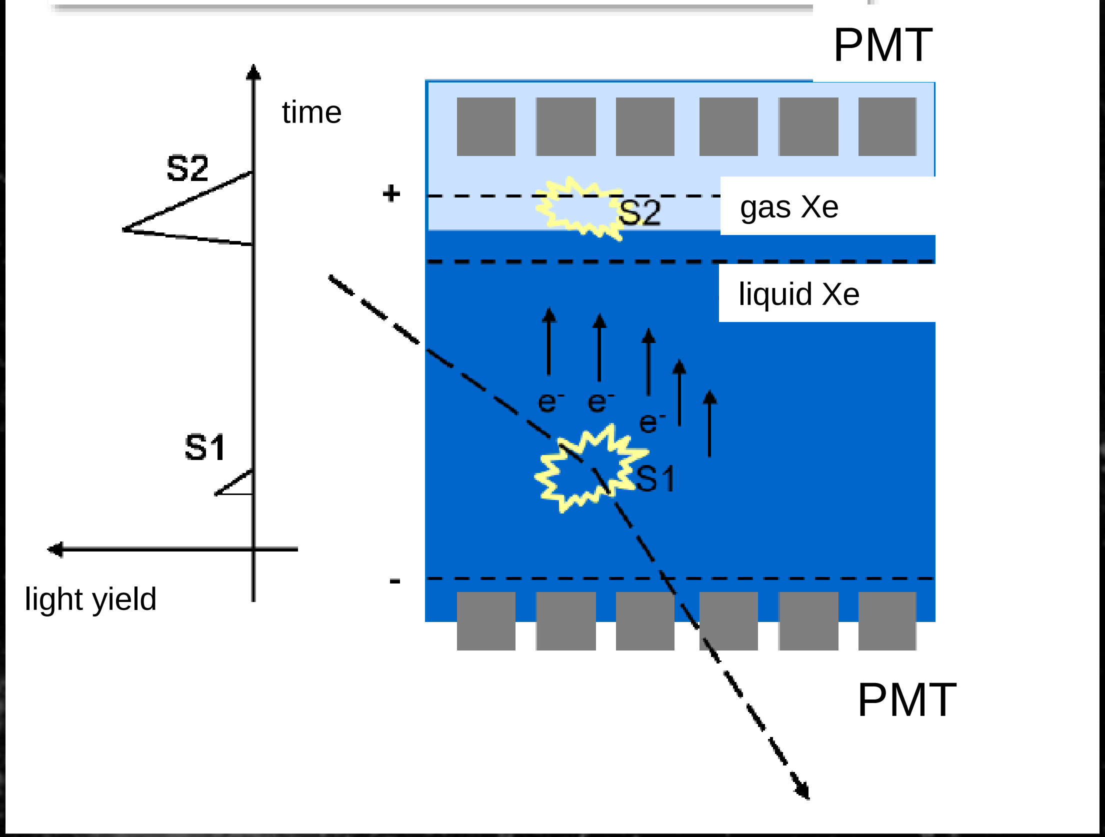
- First experimental limit!

Ke

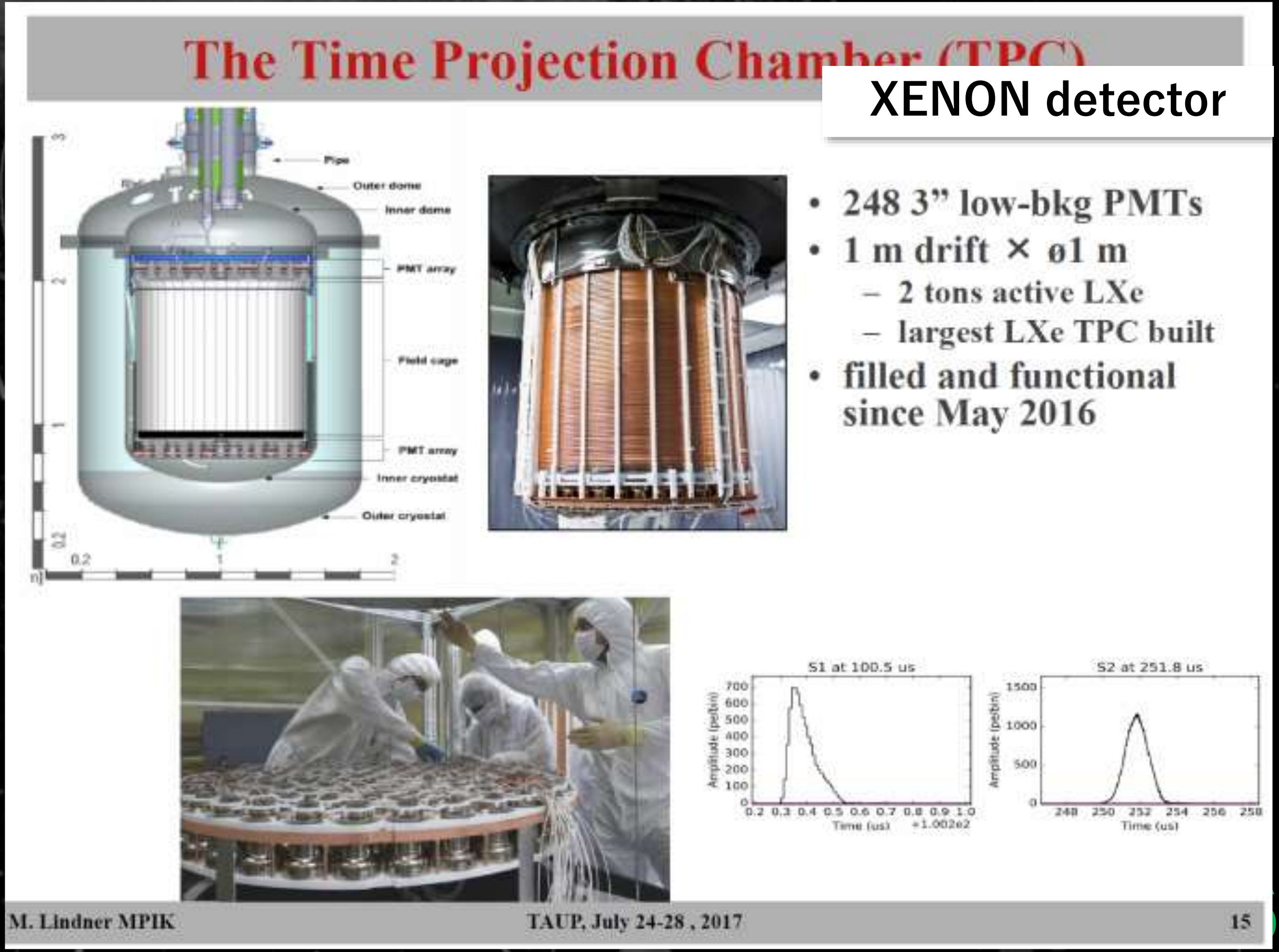
- Liquid Xe/Ar：double-phase（liquid+gas)
  - XENON1T, LUX, PandaX-II（Xe）, DARKSIDE(Ar)
  - Several 100kg ～ 1ton
  - z position can be known
  - Electron background can be discriminated



Double phase detector principle



XENON detector



Kentaro Miuchi

- XENON1T

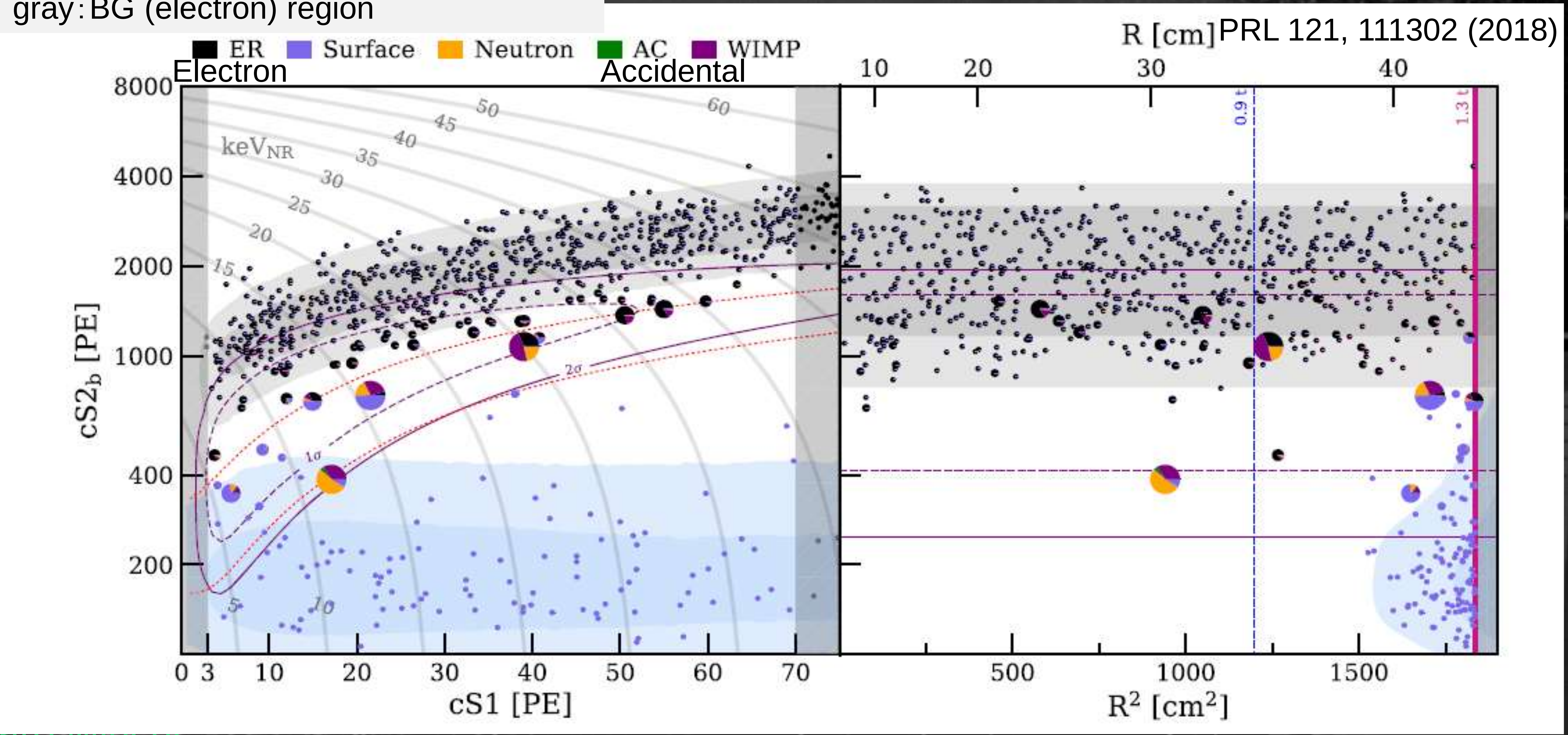
Dark Matter Search Results from a One Ton-Year Exposure of XENON1T

  - Some events in ROI

PRL 121, 111302 (2018)

  - ER ：radon　　neutron：neutrons from α particle

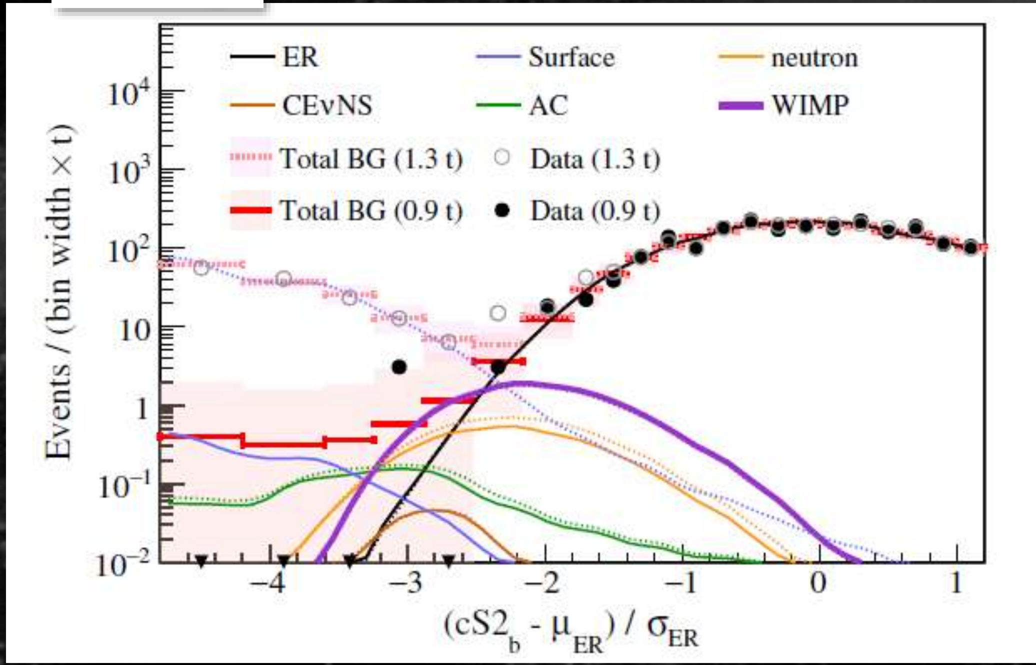
red：nuclear recoil (signal) region
gray：BG (electron) region

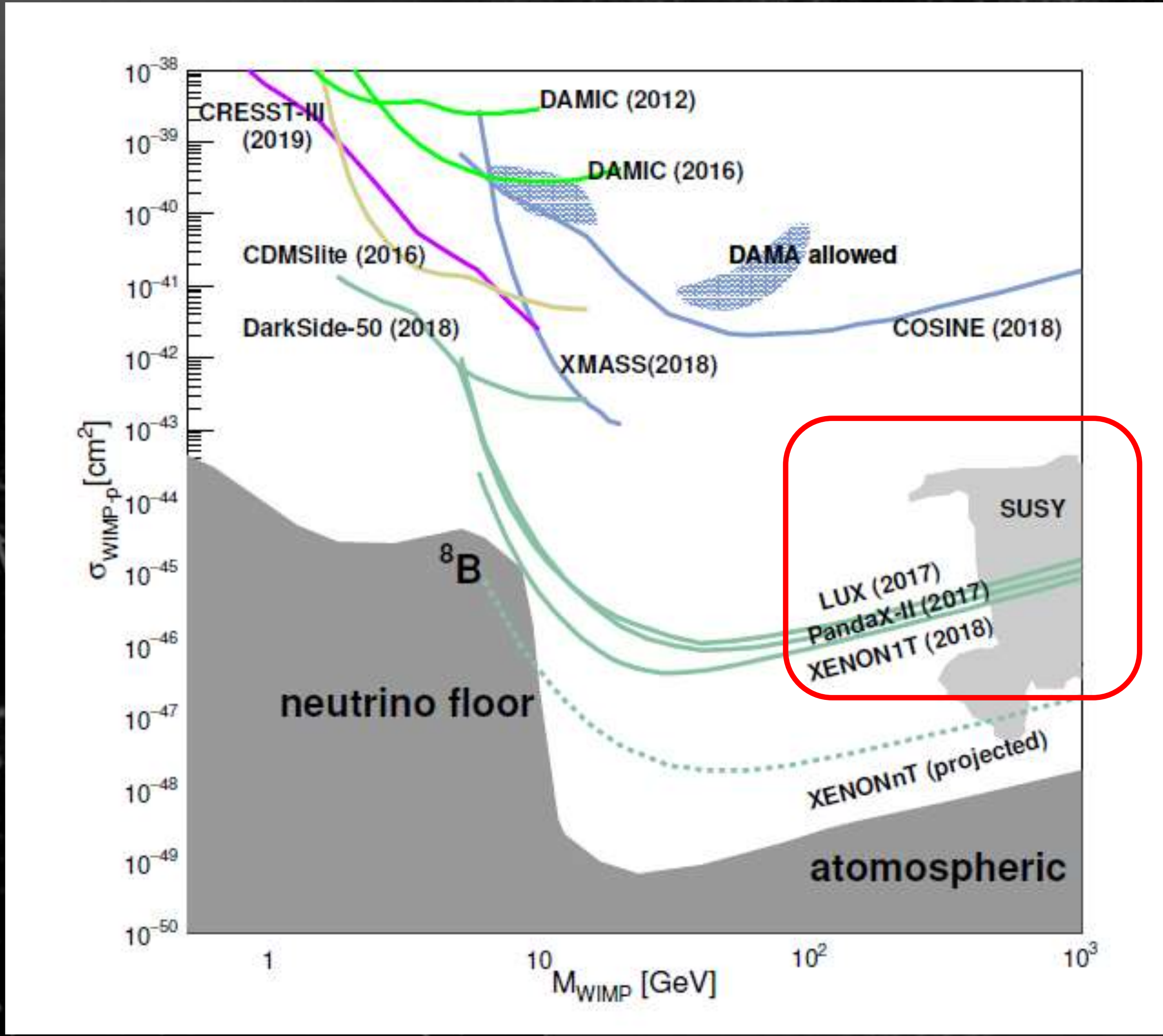


- XENON1T 1ton・year result

fitting

PRL 121, 111302 (2018)

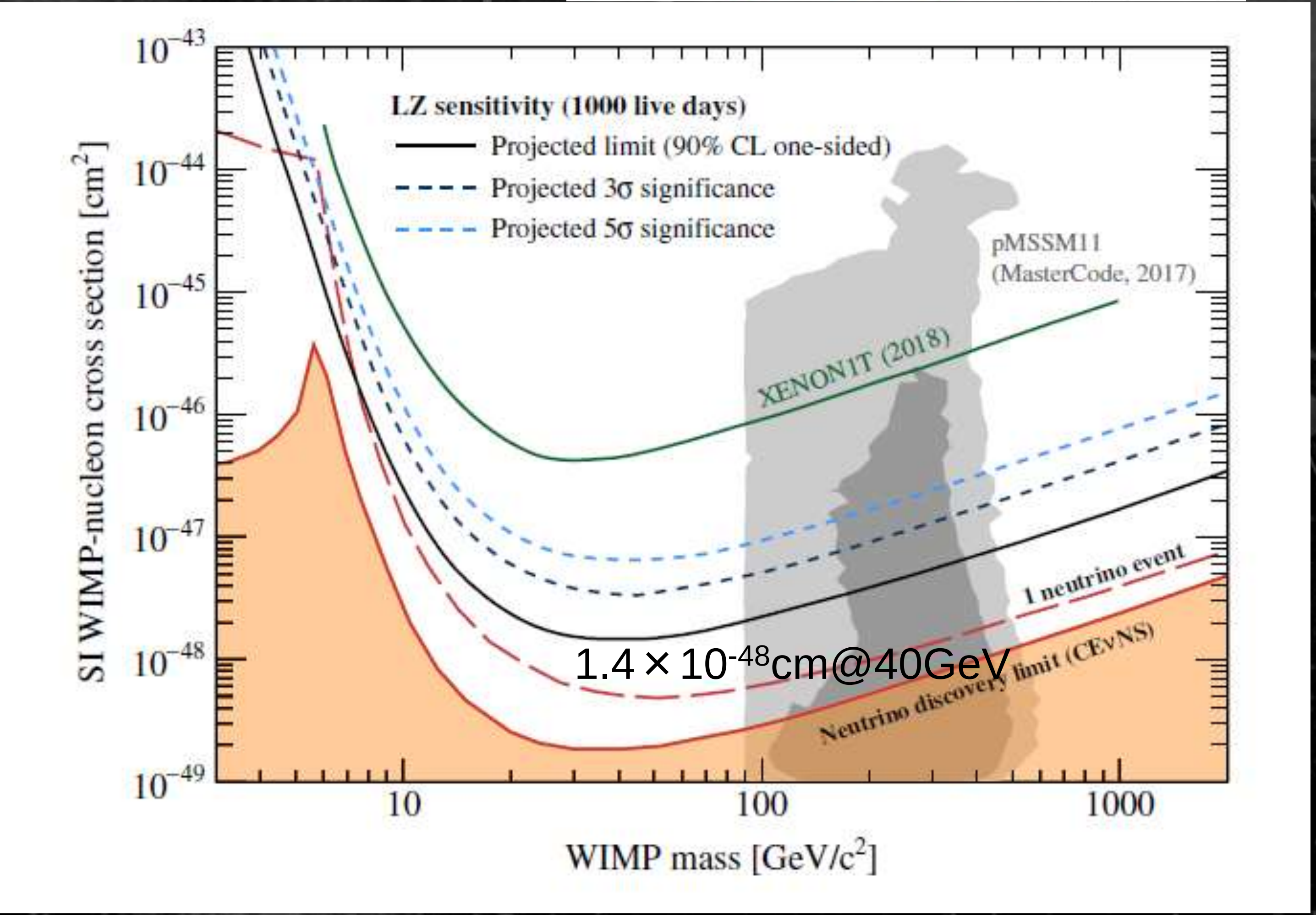




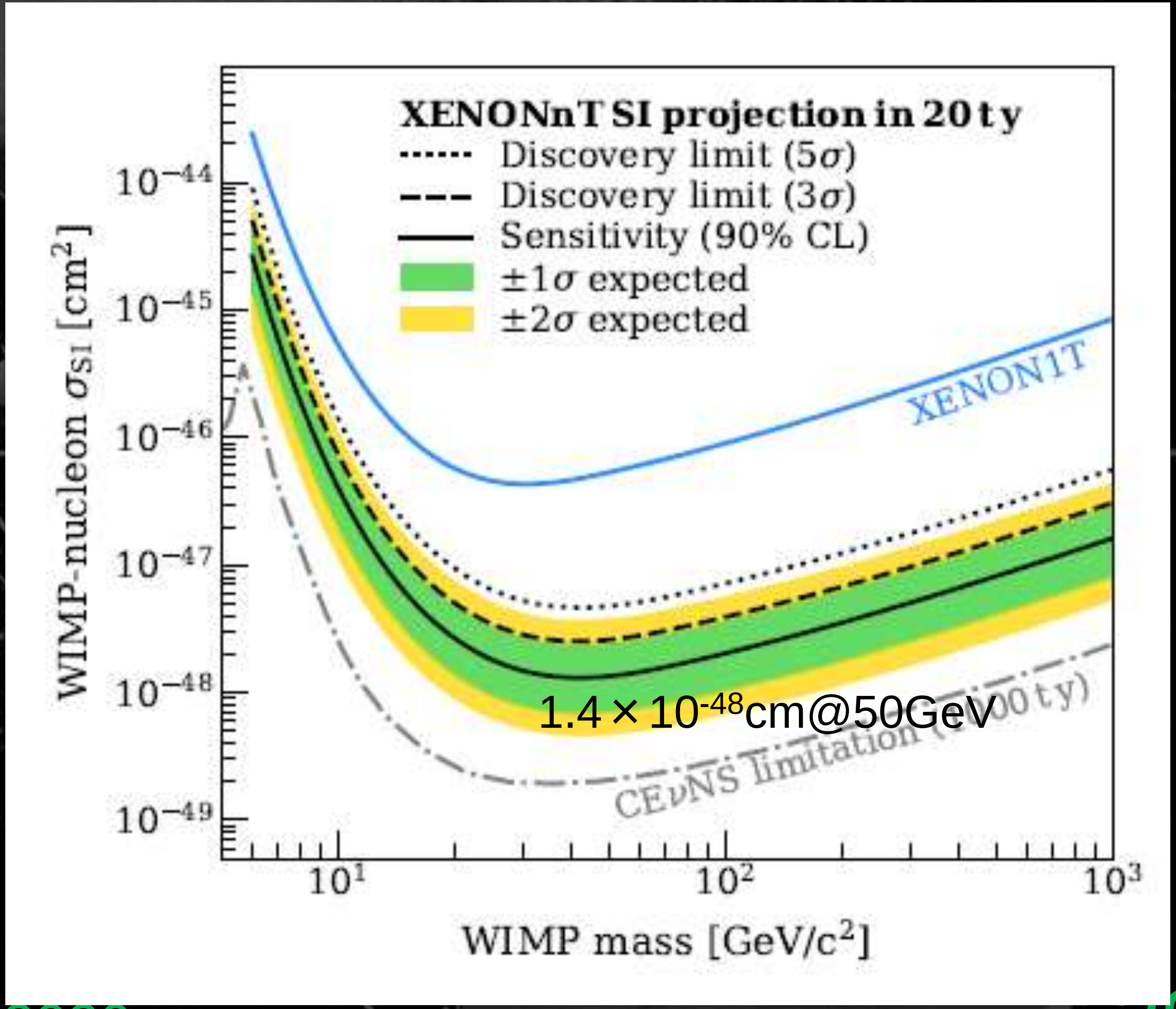
- 4.1×10^{-47}cm^{-2} @30GeV
- Leading the direct detection
- SUSY predictions are investigated

- Next
  - XENONnT
  - LZ
  - PANDA-X

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



arXiv:2007.08796v1



- Next
  - XENONnT
  - LZ

LZ Dark Matterさんがリツイート

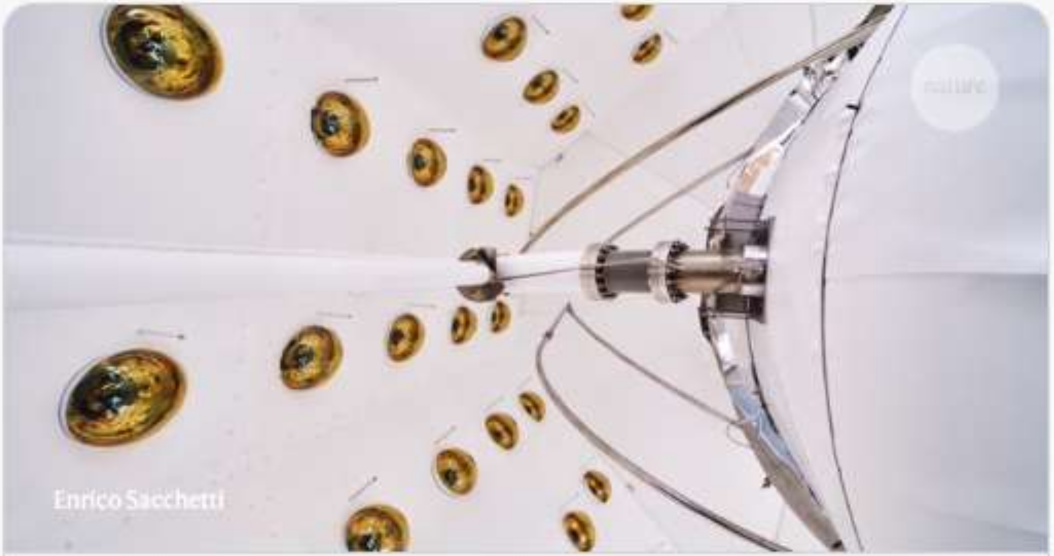
SanfordLab @SanfordLab · 9月17日

ICYMI: @lzdarkmatter collaboration publishes 1,200 assays 😮 and creates library for future rare event searches 📖📚 #darkmatter #WIMPhunt
👉 ow.ly/lpCA50BrON4

6 14

XENONexperiment @XENONexperiment · 10月6日

DARWIN will be the ultimate WIMP detector before the neutrino "fog" gets in the way.



Last chance for WIMPs: physicists launch all-out hunt for dark-matter ca...
Researchers have spent decades searching for the elusive particles — a final generation of detectors should leave them no place to hide.
nature.com

- Final phase of construction

Direct Search Review

2. New Trend : Low Mass DM

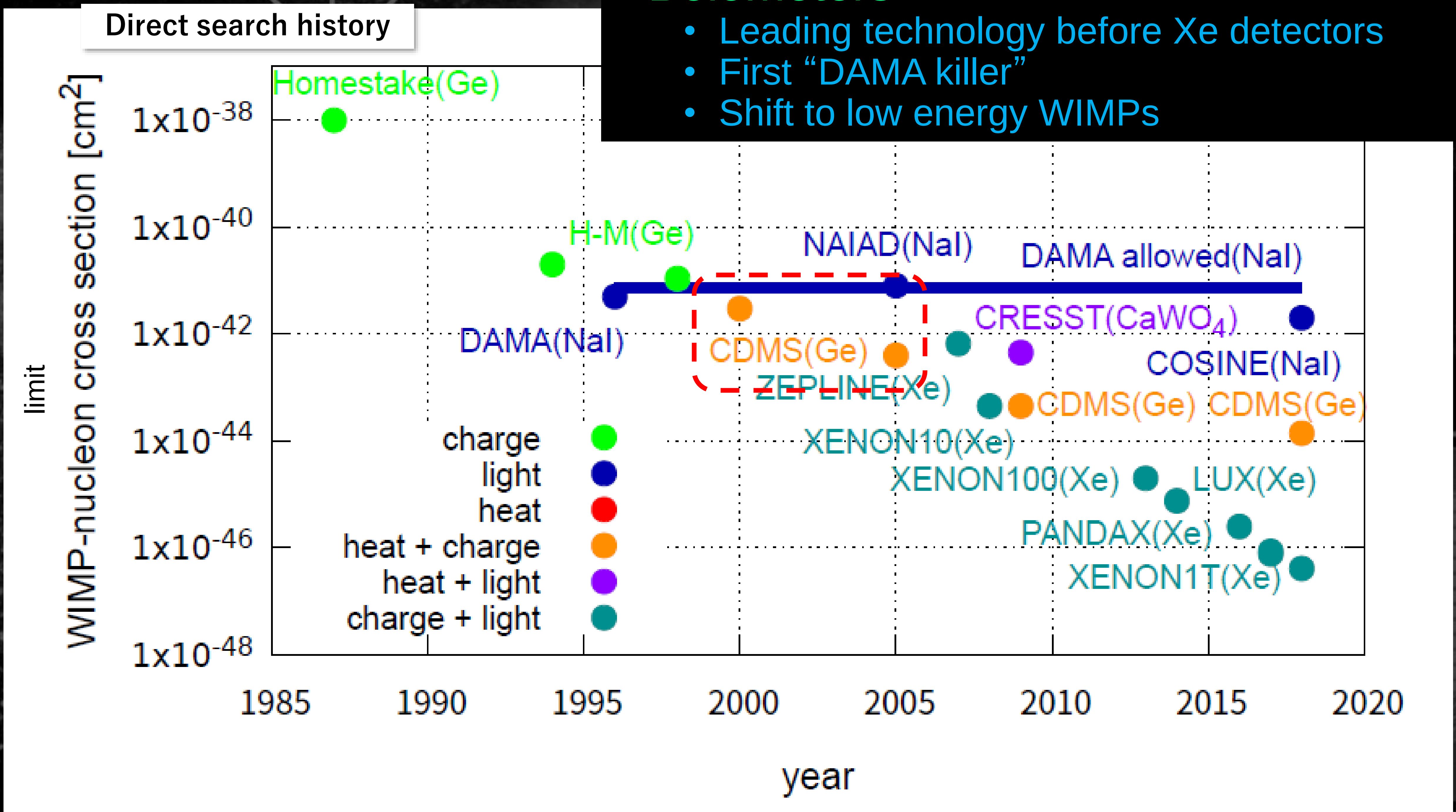
- You may know better than I...

軽い暗黒物質検出のための固体物理入門

中山和則（東京大学）

2020/9/3 @ PPP2020

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



- Bolometers
  - Low energy threshold ⇒ low mass DM

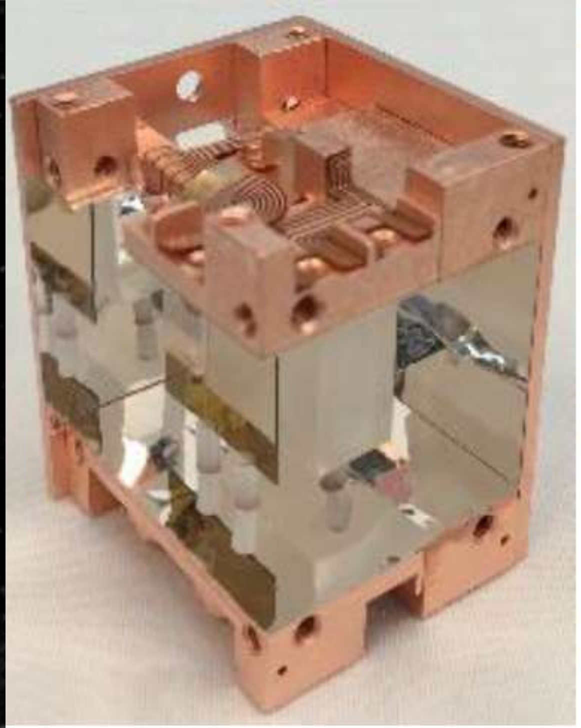
Latest results of CRESST-III's search for sub-GeV/c² dark matter

Holger Kluck
on behalf of the CRESST collaboration

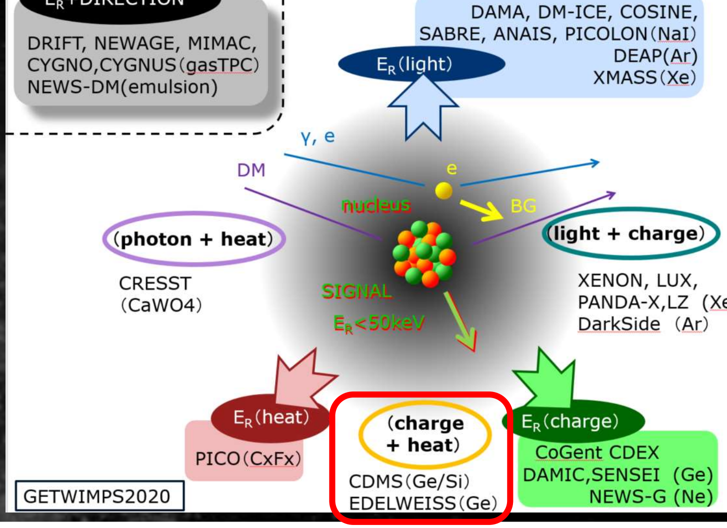
16th International Conference on Topics in Astroparticle and Underground Physics (TAUP2019)

September 10, 2019

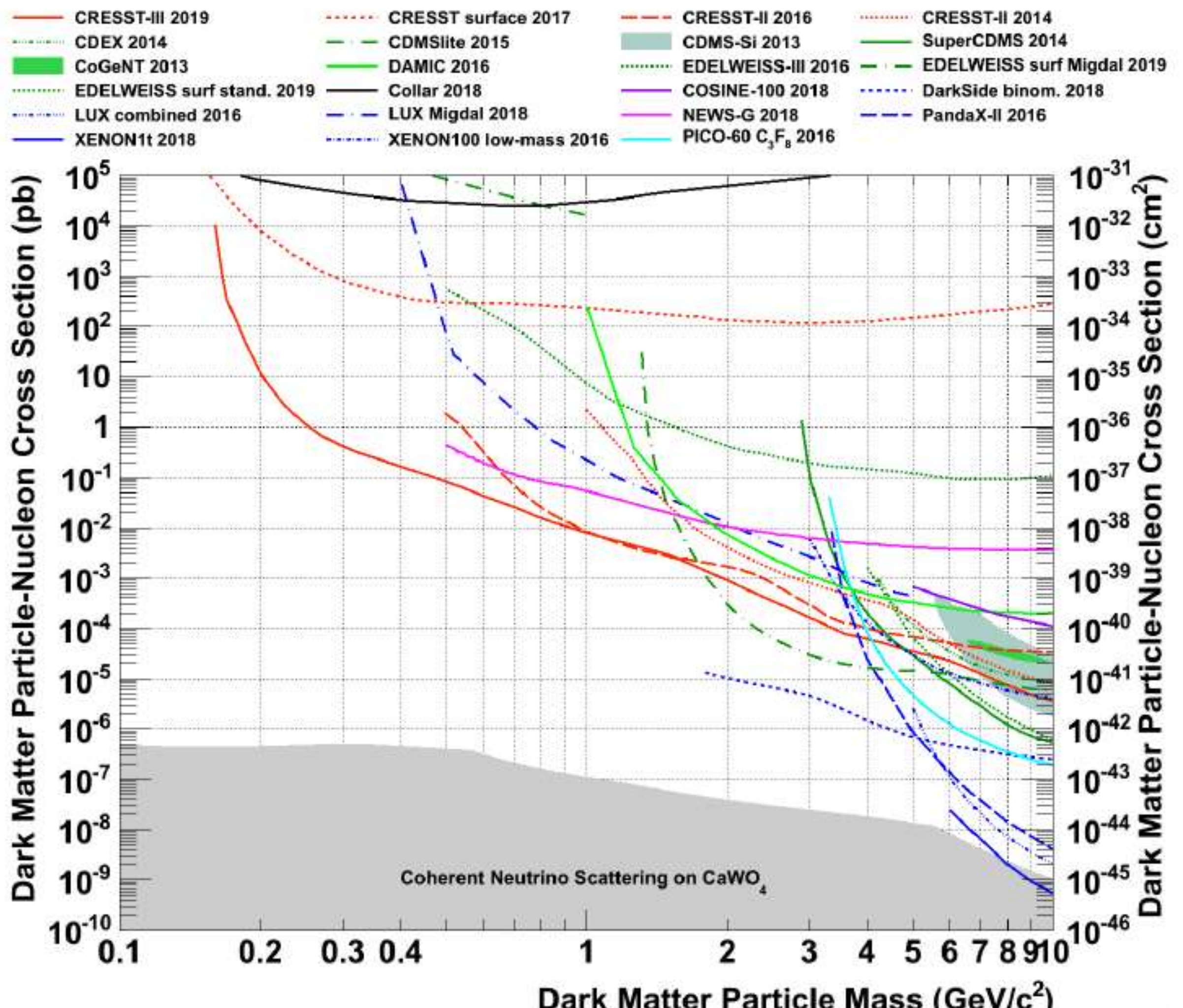
CRESST-III detector



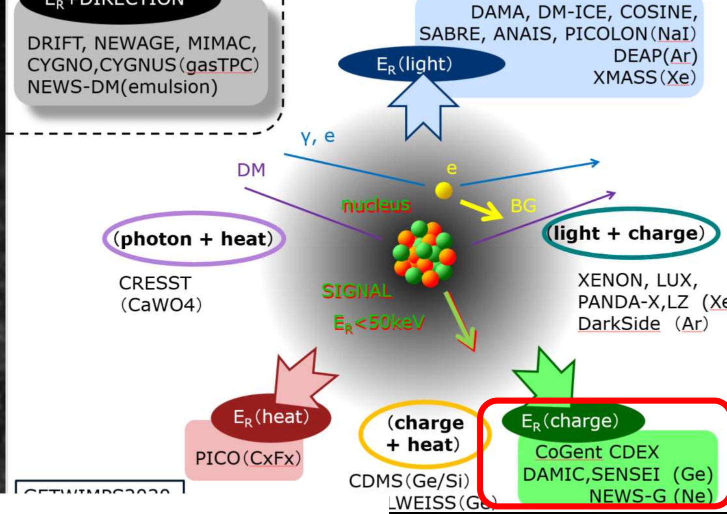
- May 2016: 10 CRESST-III modules installed
- Jul 2016 – Feb 2018: data taking (80% blinded, 20% training set)
- Detector A → lowest nuclear recoil threshold so far: 30.1 eV
- Target crystal mass: 23.6g
- Gross exposure: 5.6 kg d
- [arXiv:1904.00498], accepted by Phys.Rev.D → this talk

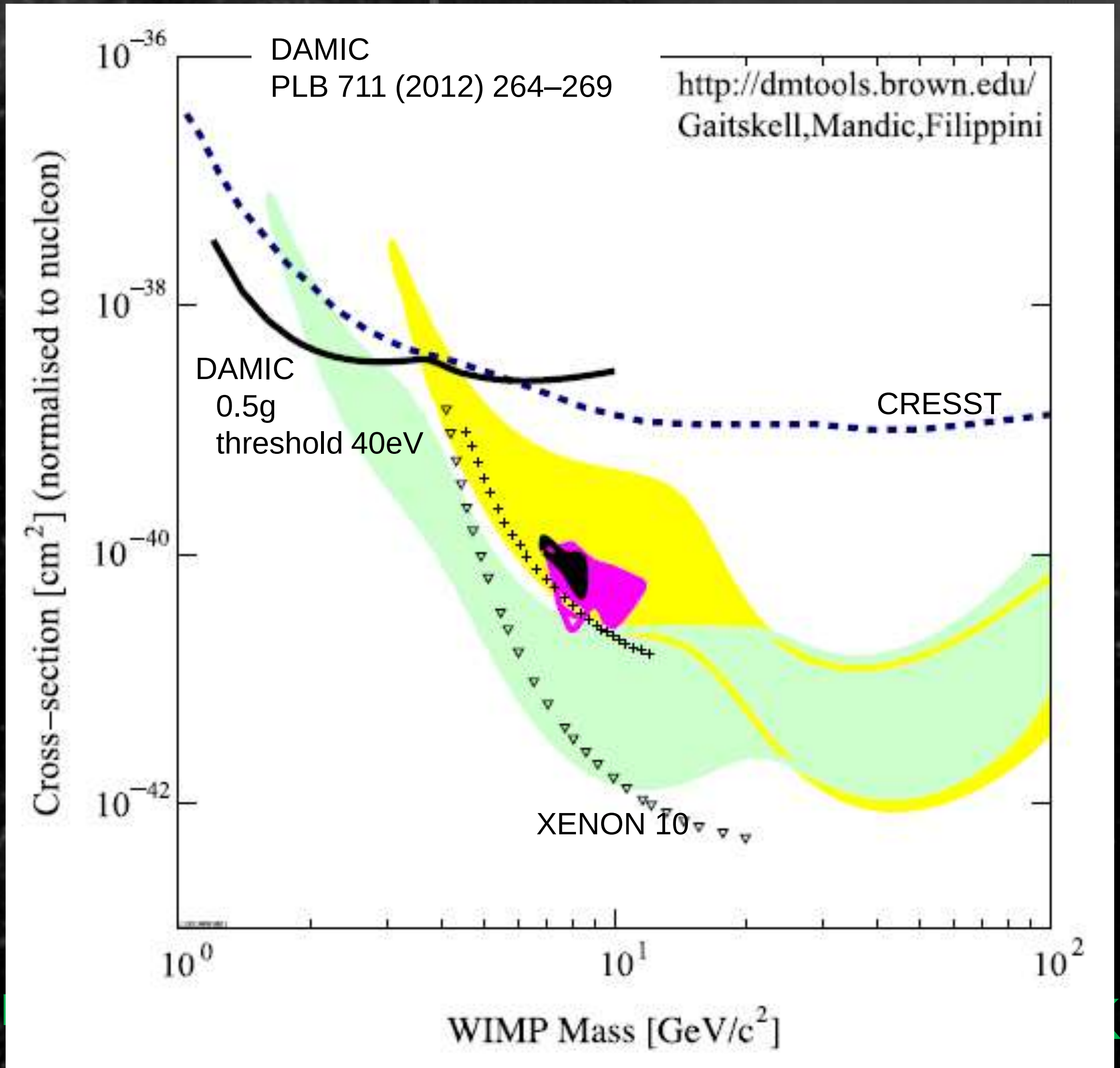


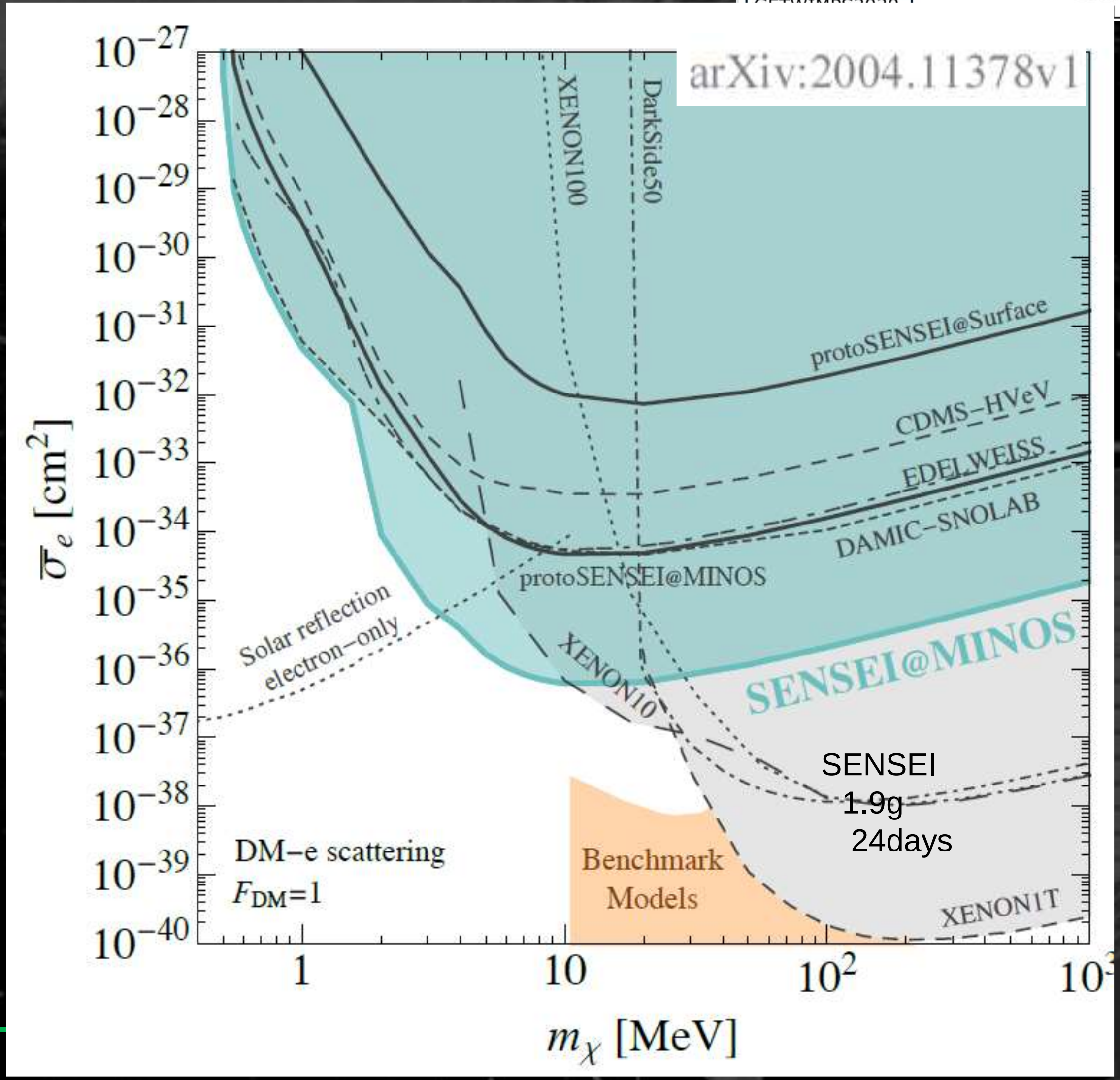
CRESST-III result



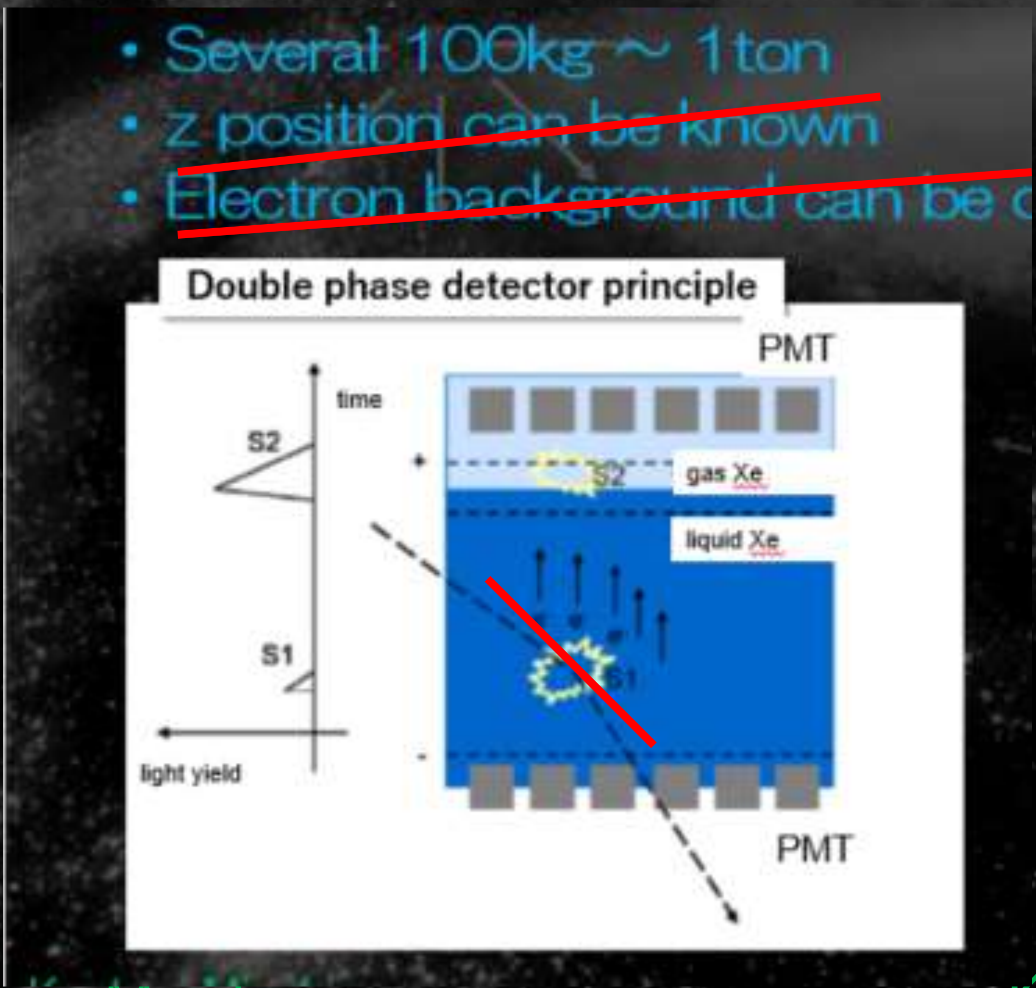
- CCD
  - DAMIC arXiv:2007.15622v1
    - pioneer of low threshold
  - SENSEI arXiv:2004.11378v1
    - skipper CCD
    - sensitive to single electron
    - DM-electron channel

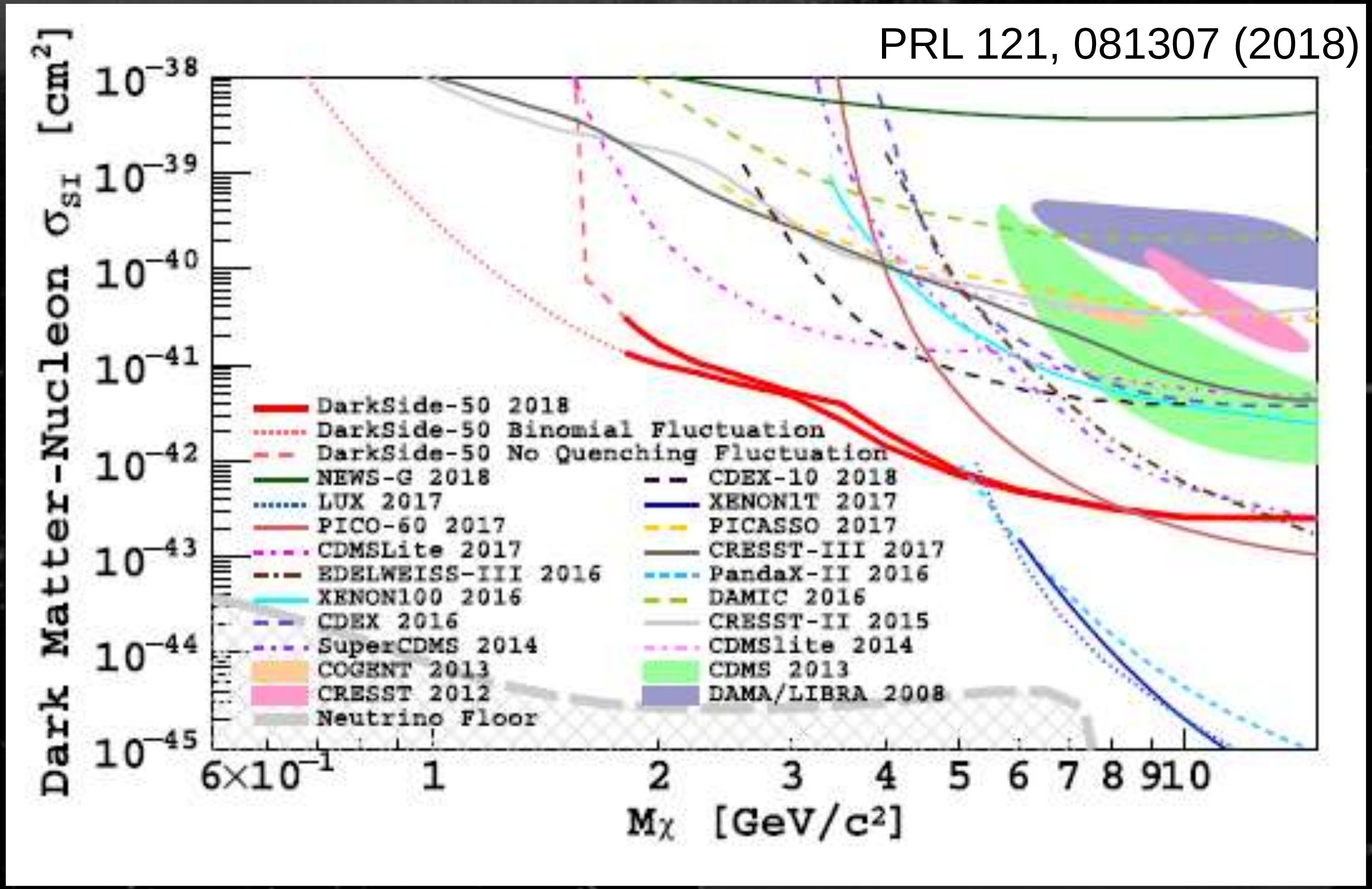




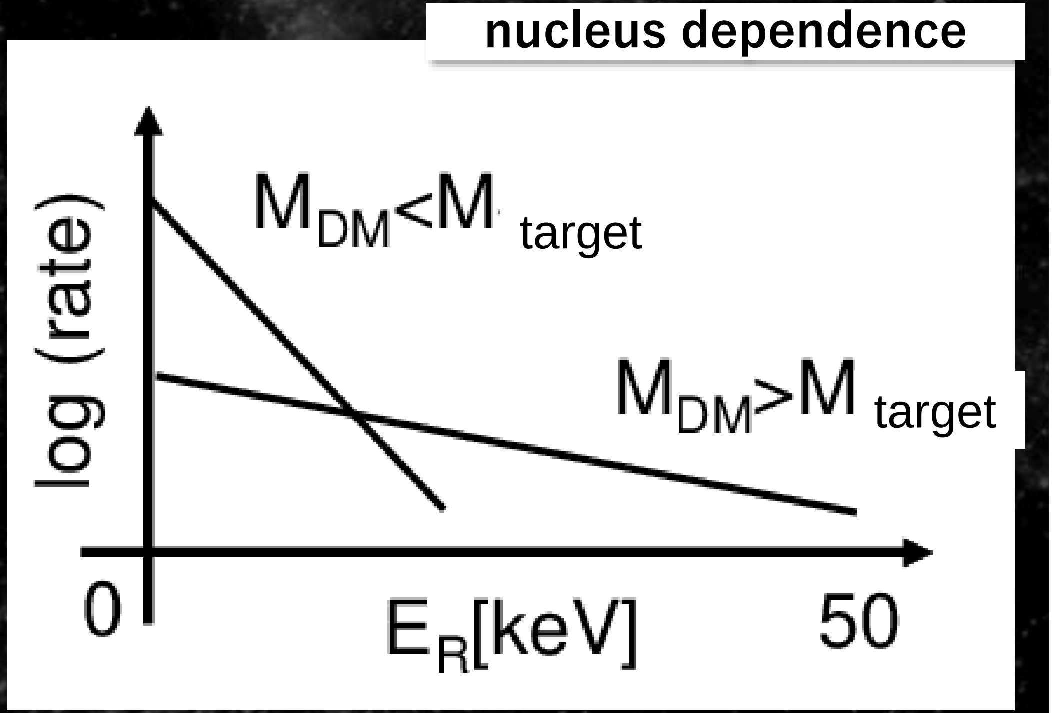


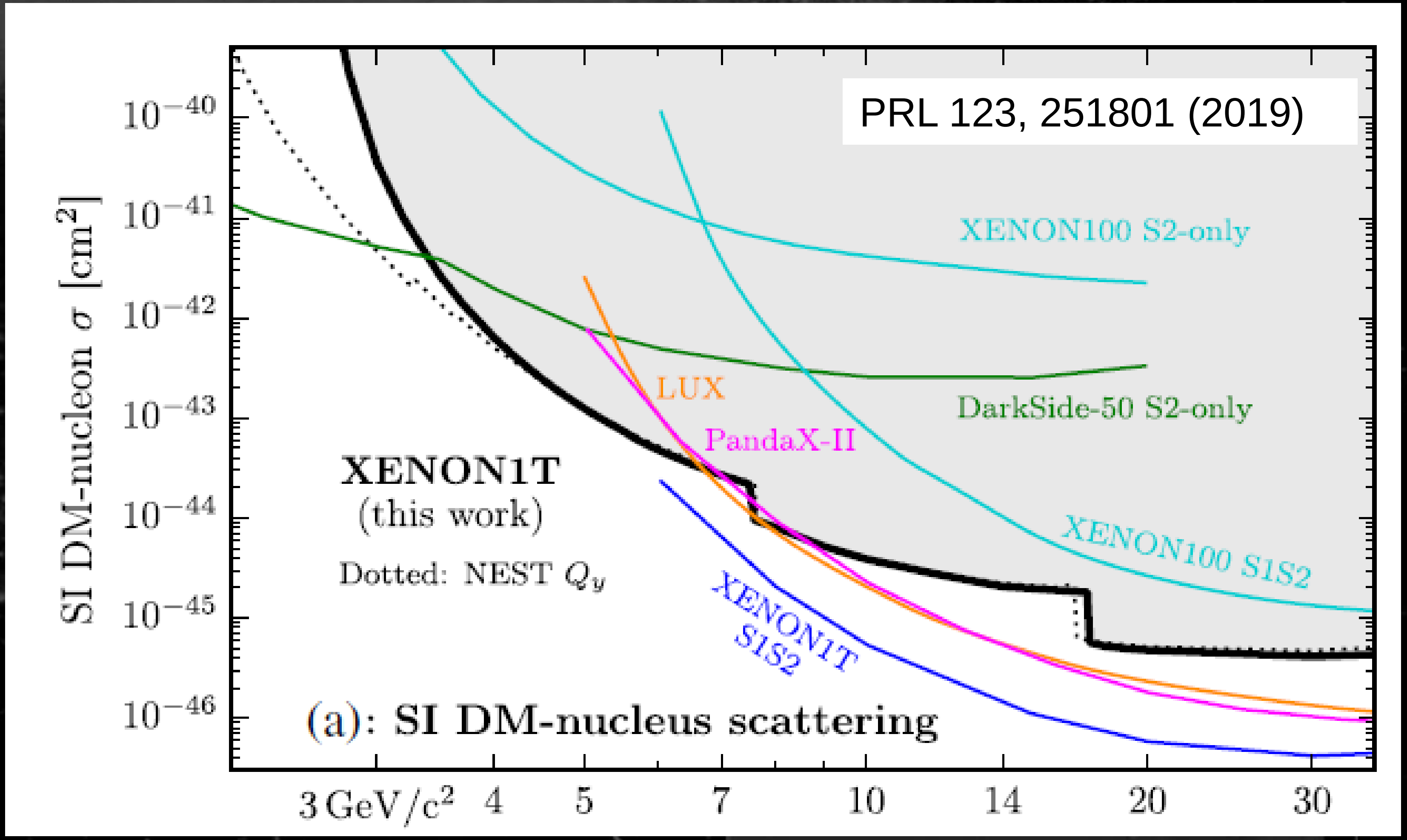
- Liq. noble gas: S2 only analysis
  - can lower threshold ⇒ low mass WIMPs
  - DARKSIDE（Ar） PRL 121, 081307 (2018)





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

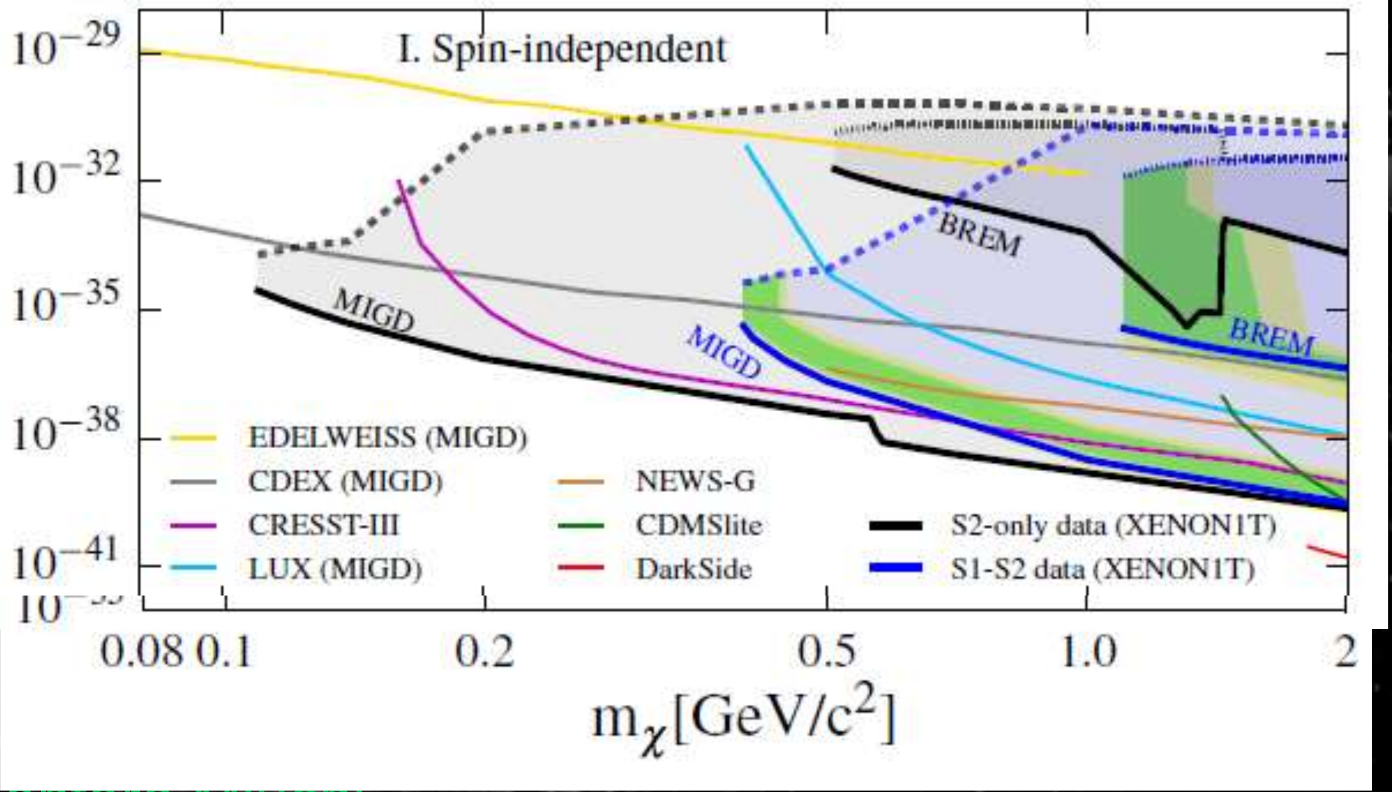


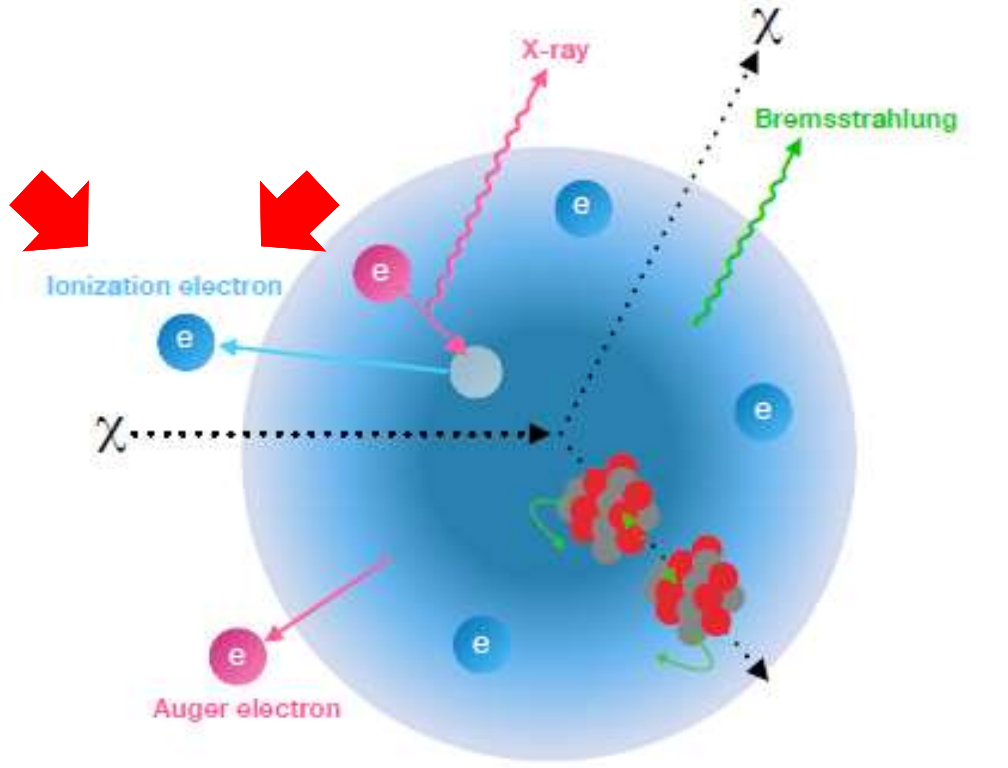


- And still lower: MIGDAL
  - Low mass search with "MIGDAL effect"
  - Ordinary nuclear recoil : ionization along the track
  - Low energy recoil : ionization efficiency is low
    ⇒ cannot be detected
  - Very rare case electrons are emitted

PRL123, 241803 (2019)

PRL123, 241803 (2019)

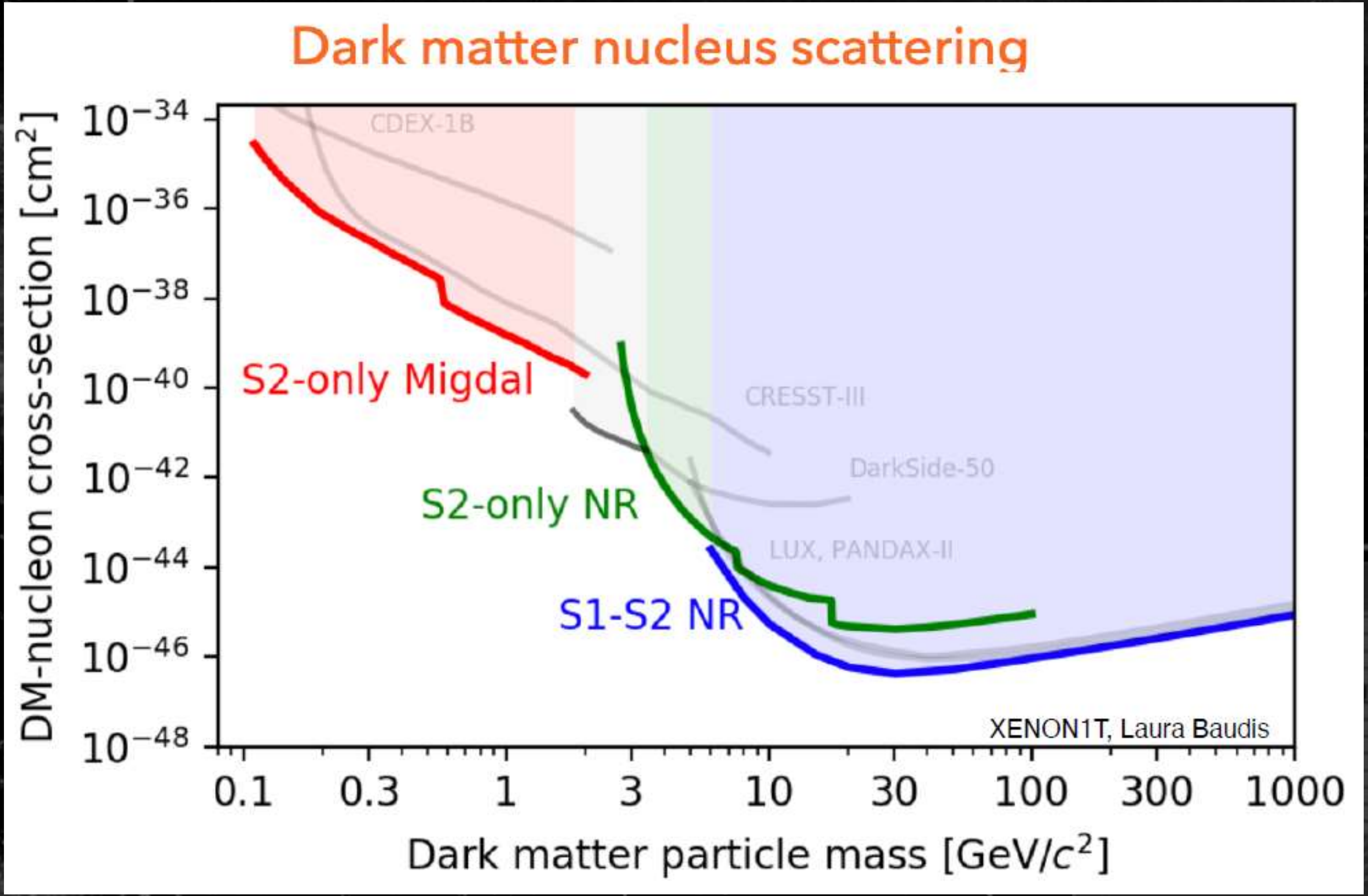




PRL123, 241803 (2019)

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.

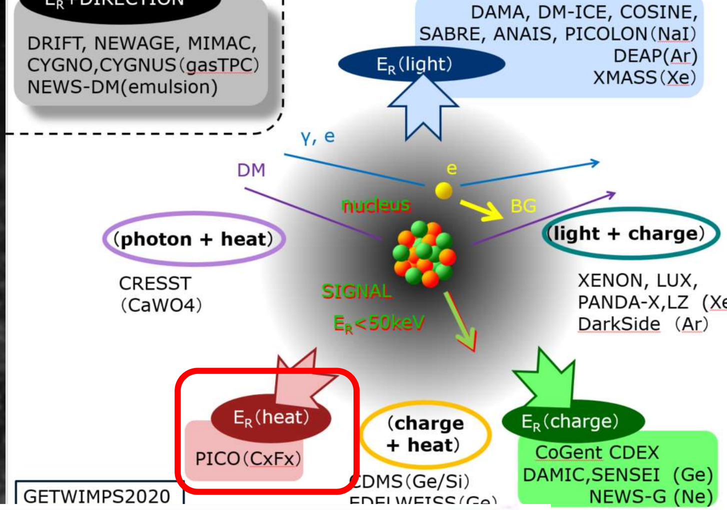
Kentaro Miuchi

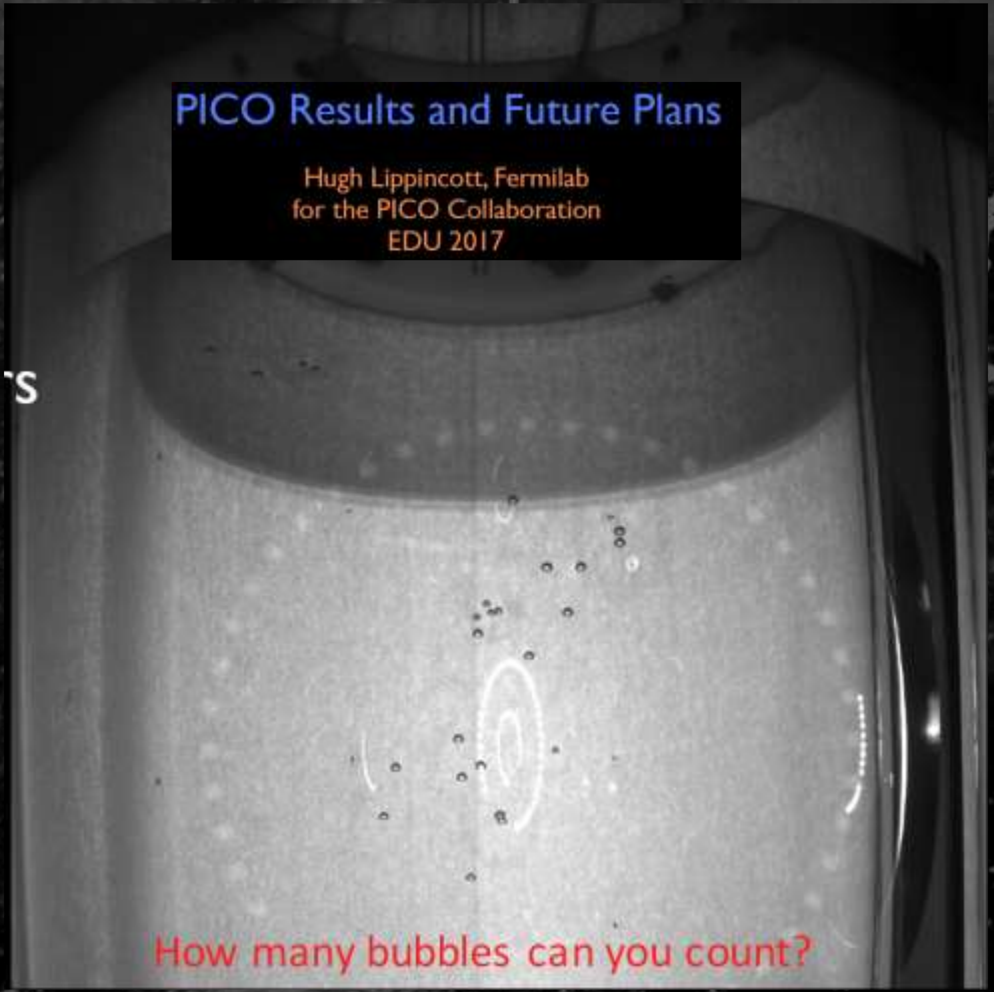

Dark matter nucleus scattering
DM-nucleon cross-section [cm^2]
10^{-34}
10^{-36}
10^{-38}
10^{-40}
10^{-42}
10^{-44}
10^{-46}
10^{-48}
CDEX-1B
S2-only Migdal
CRESST-III
DarkSide-50
S2-only NR
LUX, PANDAX-II
S1-S2 NR
XENON1T, Laura Baudis
0.1
0.3
1
3
10
30
100
300
1000
Dark matter particle mass [GeV/c^2]

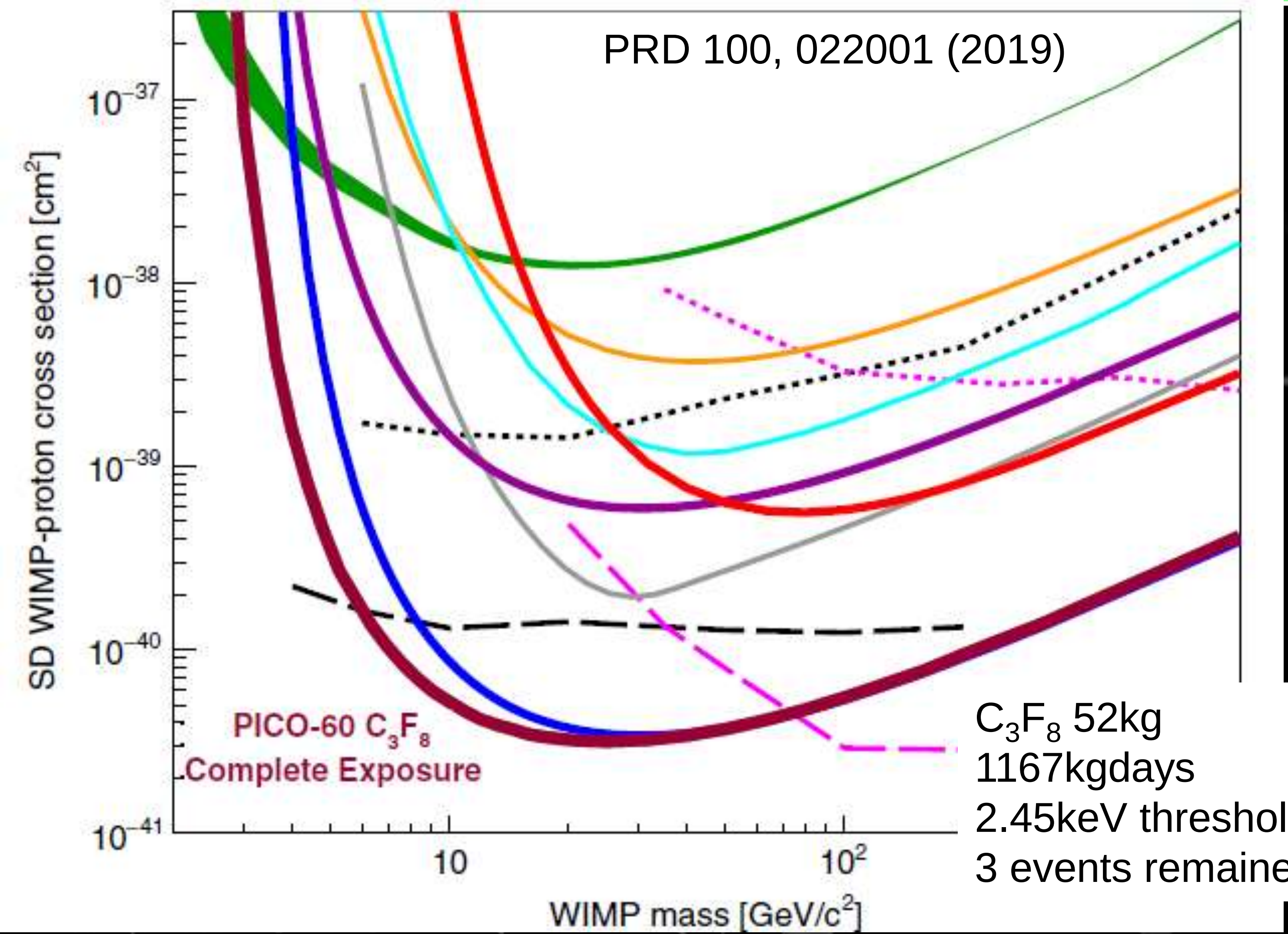
Direct Search Review

3. Others

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







C_3F_8 52kg
1167kgdays
2.45keV threshold
3 events remained

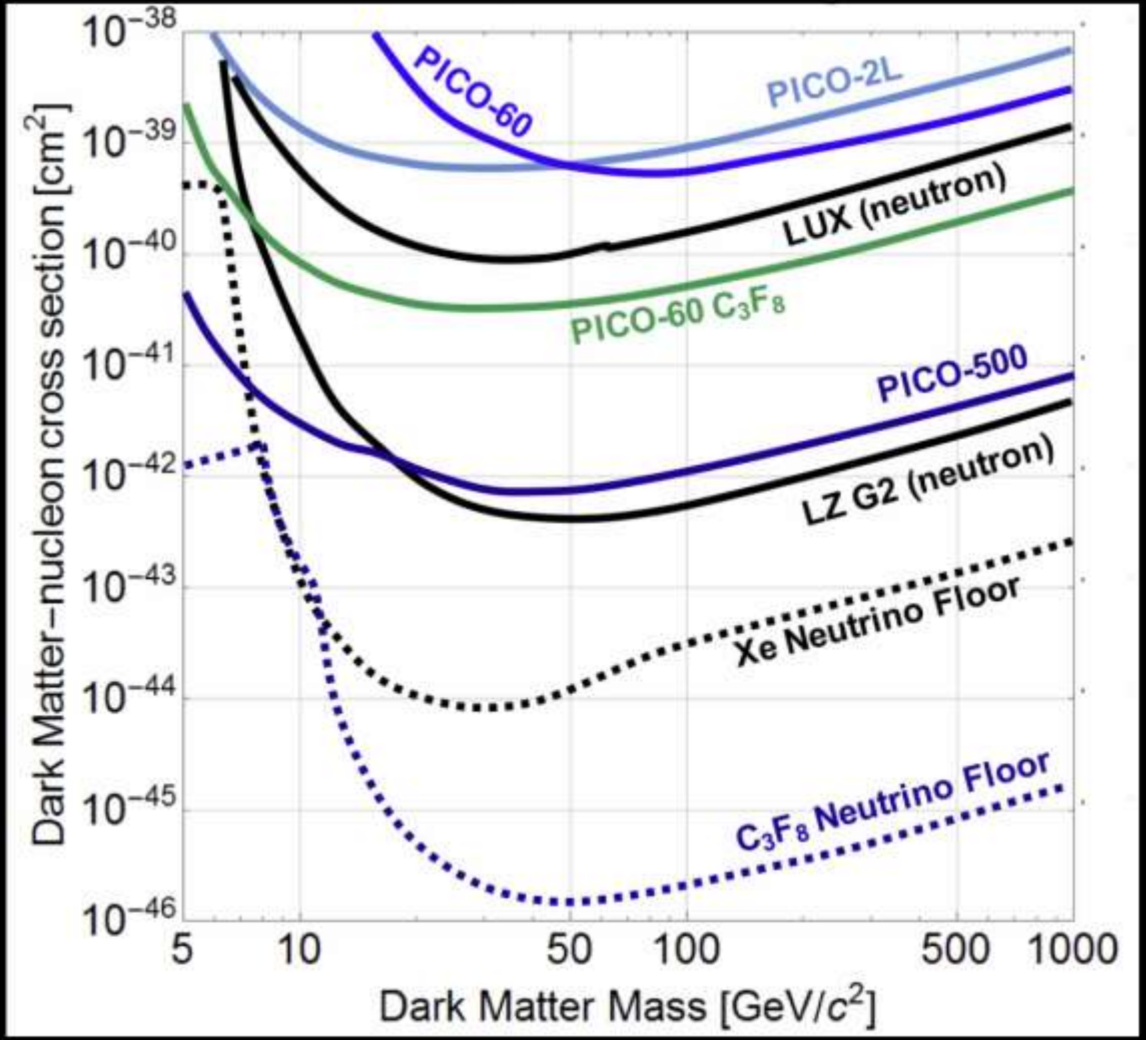
- Fluorine advantage
  - SD search
  - different "Neutrino floor" from xenon

PICO Results and Future Plans

Hugh Lippincott, Fermilab
for the PICO Collaboration
EDU 2017

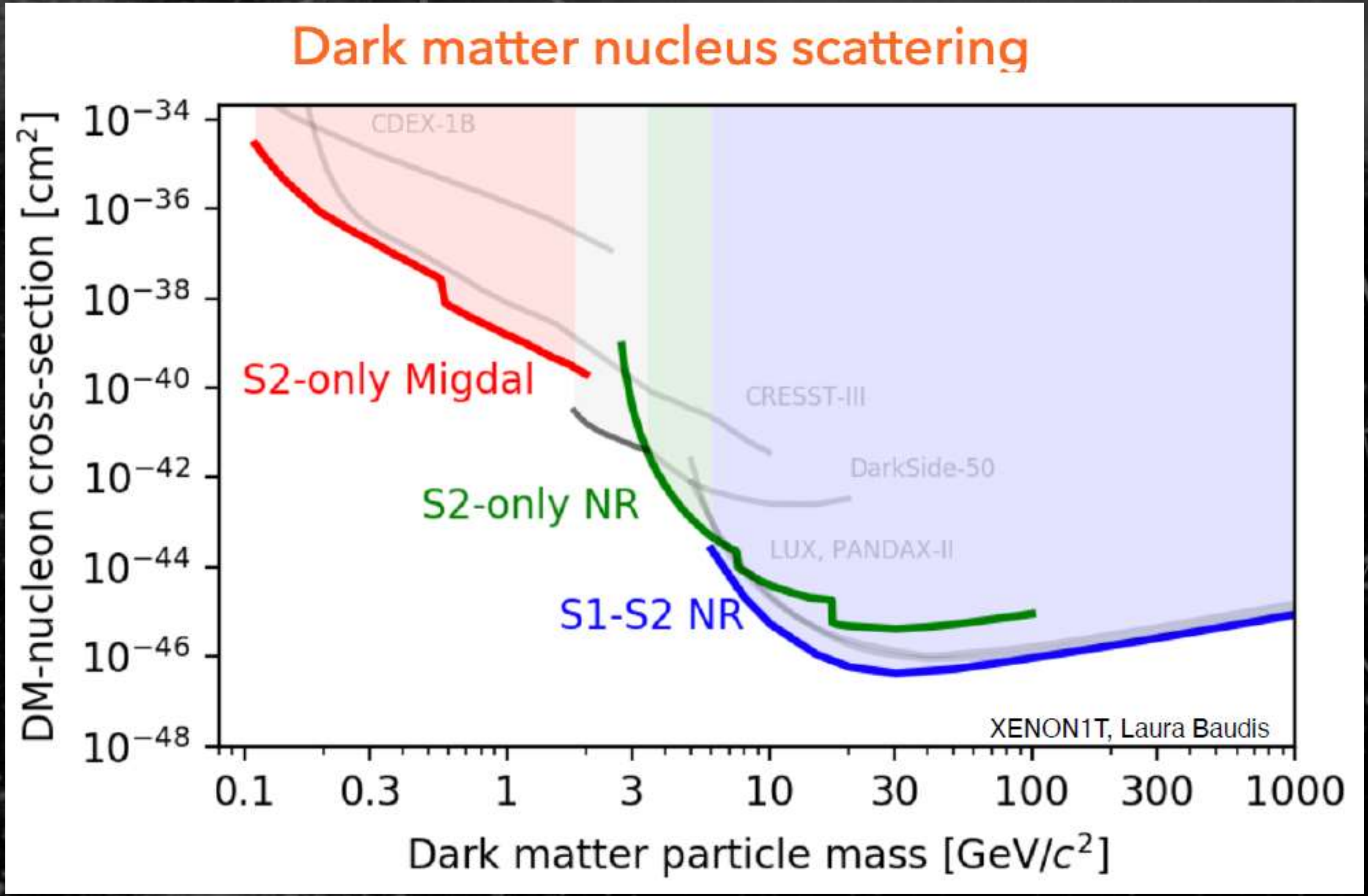
Isotope	J	Abundance(%)	μ_{mag}	$\lambda^2 J(J+1)$	unpaired nucleon
^{1}H	1/2	100	2.793	0.750	proton
^{7}Li	3/2	92.5	3.256	0.244	proton
^{11}B	3/2	80.1	2.689	0.112	proton
^{15}N	1/2	0.4	−0.283	0.087	proton
^{19}F	1/2	100	2.629	0.647	proton
^{23}Na	3/2	100	2.218	0.041	proton
^{127}I	5/2	100	2.813	0.007	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

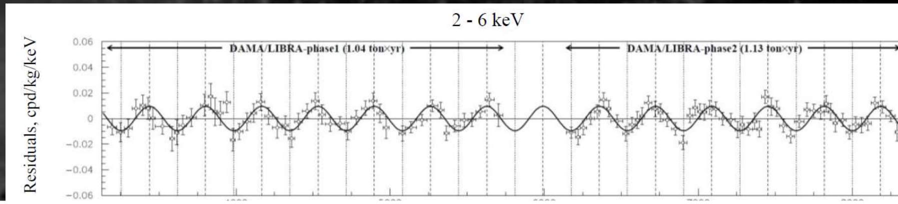
Scaling to PICO-500



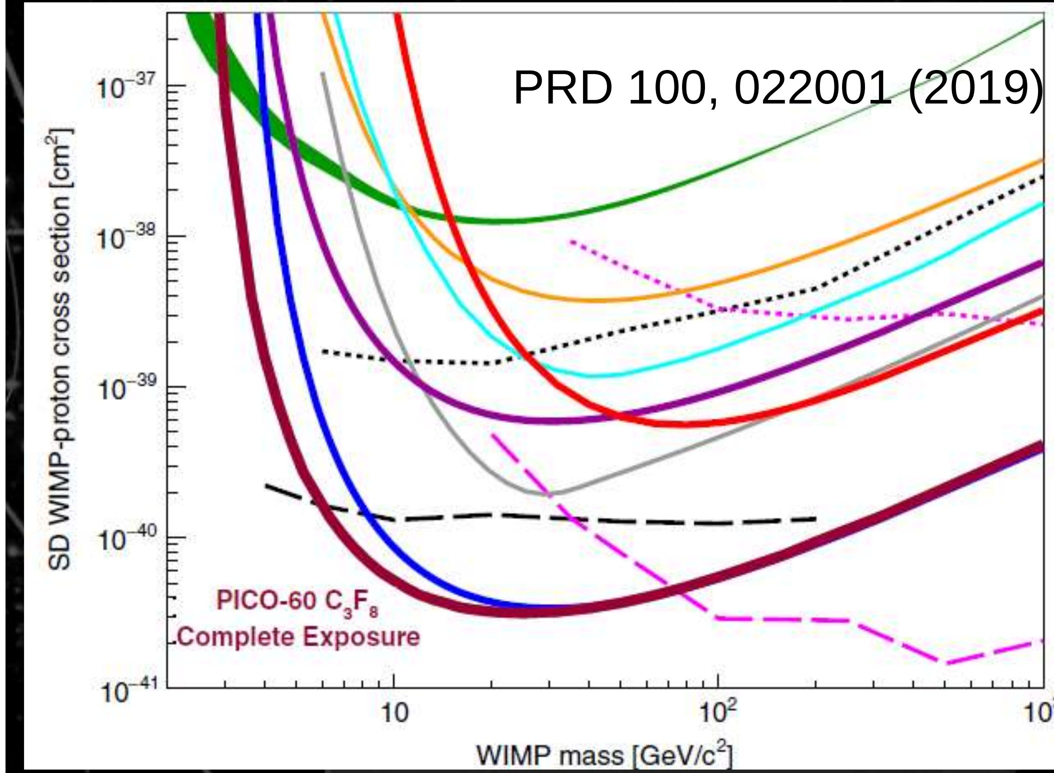
ACT1 SUMMARY

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



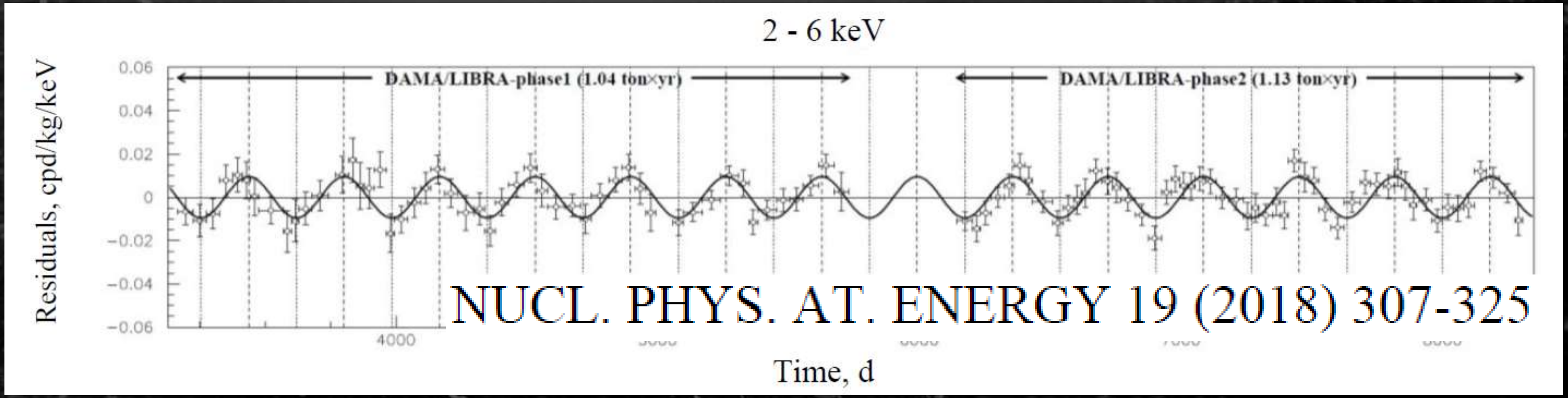


NUCL. PHYS. AT. ENERGY 19 (2018) 307-325

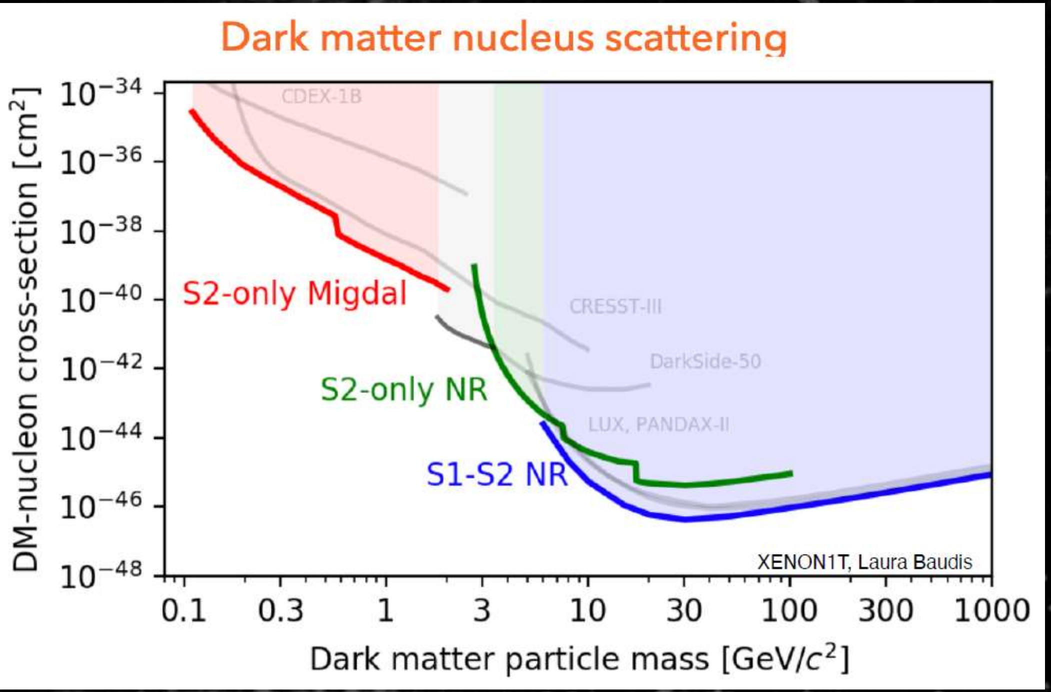


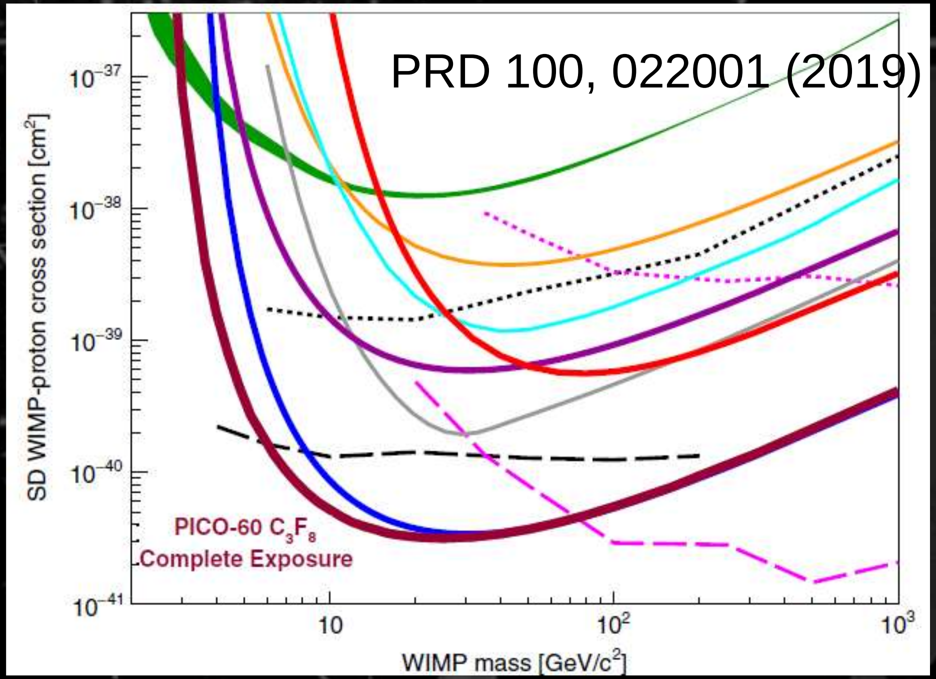
ACT1 SUMMARY

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



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





PRD 100, 022001 (2019)

Intermission

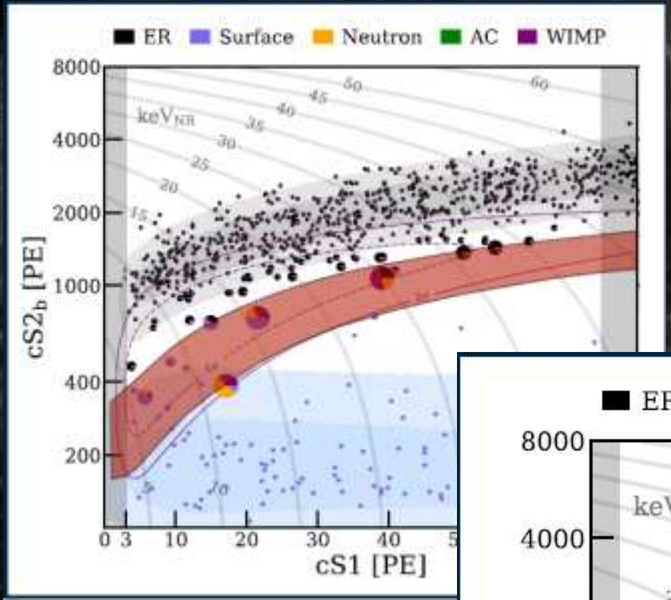
ACT 3 : Topics

Topics

1. Electron Recoil (ER) signal

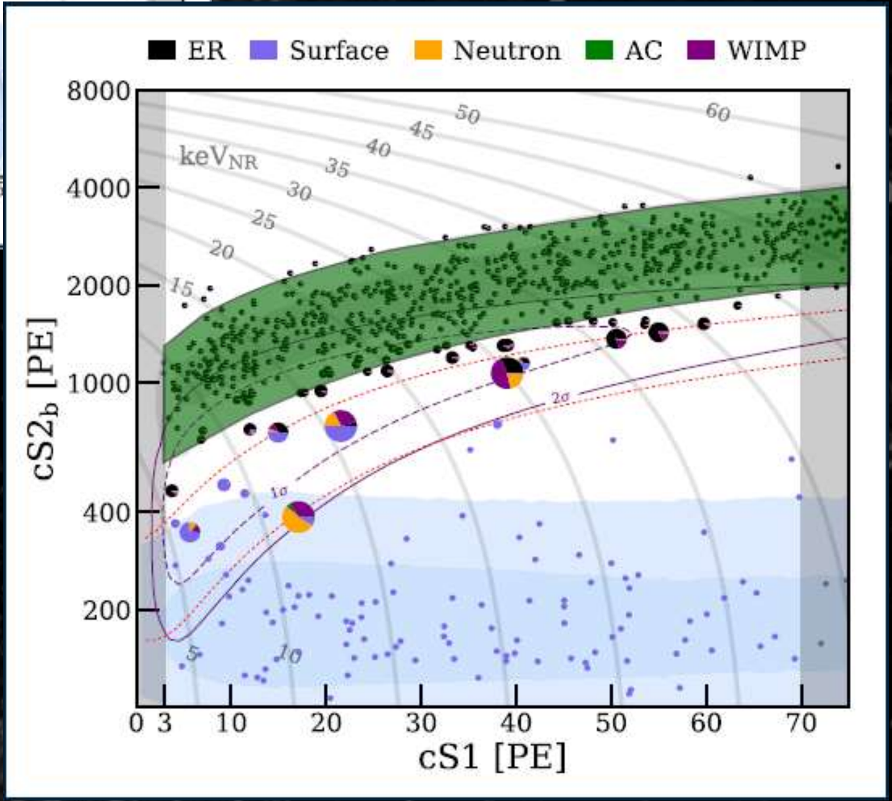
- XENON ER excess
  - 0.65 tonne-years exposure

arXiv 2006.09721 (to appear in PRD)
https://web.bo.infn.it/xenon/sito_web_Bologna/docs/xenon1t_er_excess_20200617.pdf

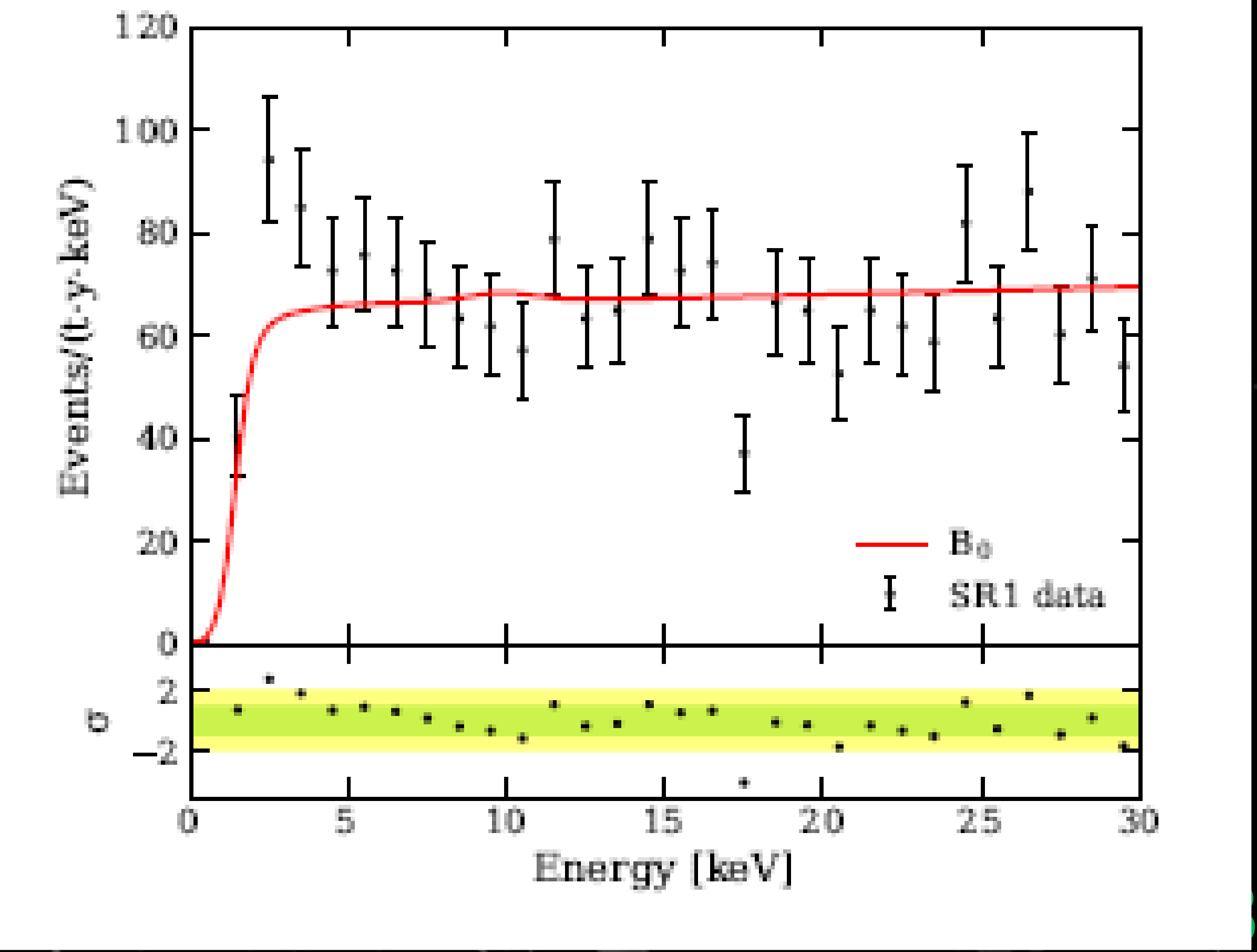


⇐ for NR search
PRL 121, 111302 (2018)

⇩ for ER search

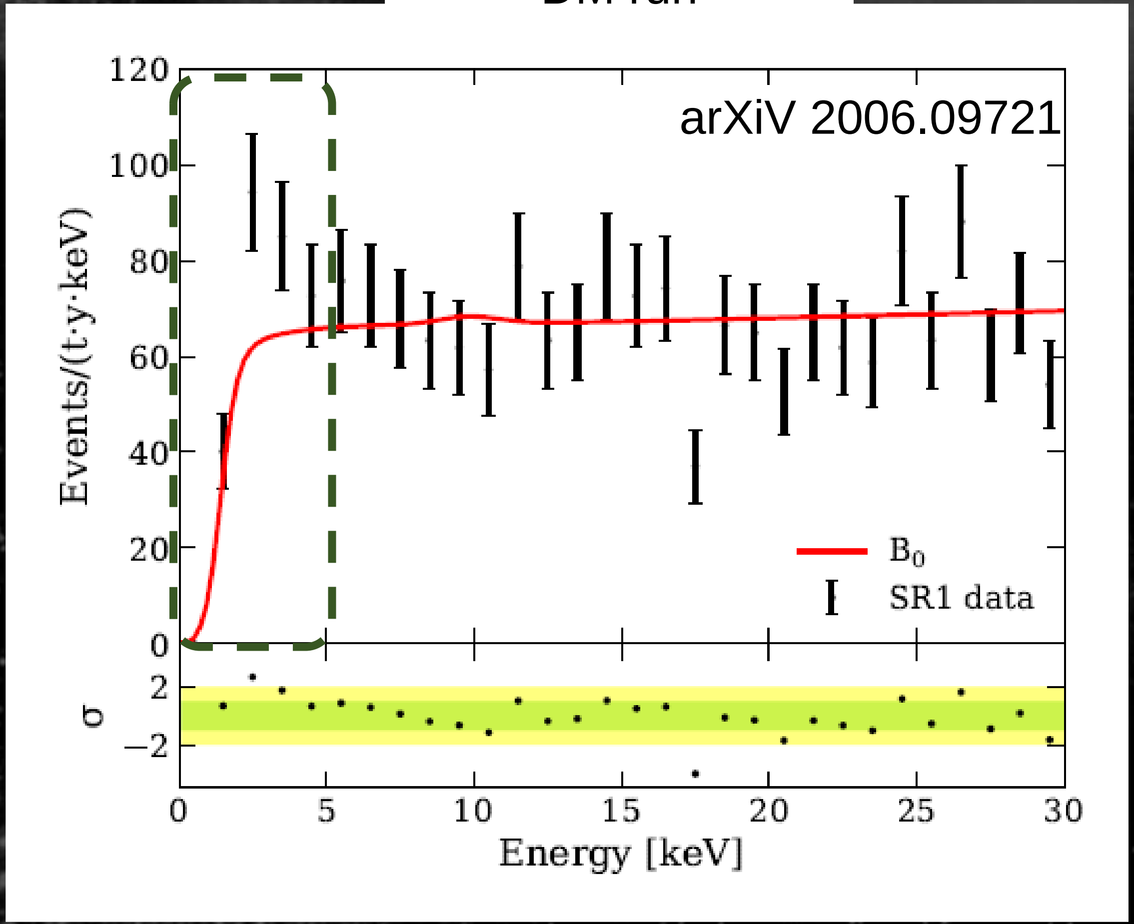


arXiV 2006.09721

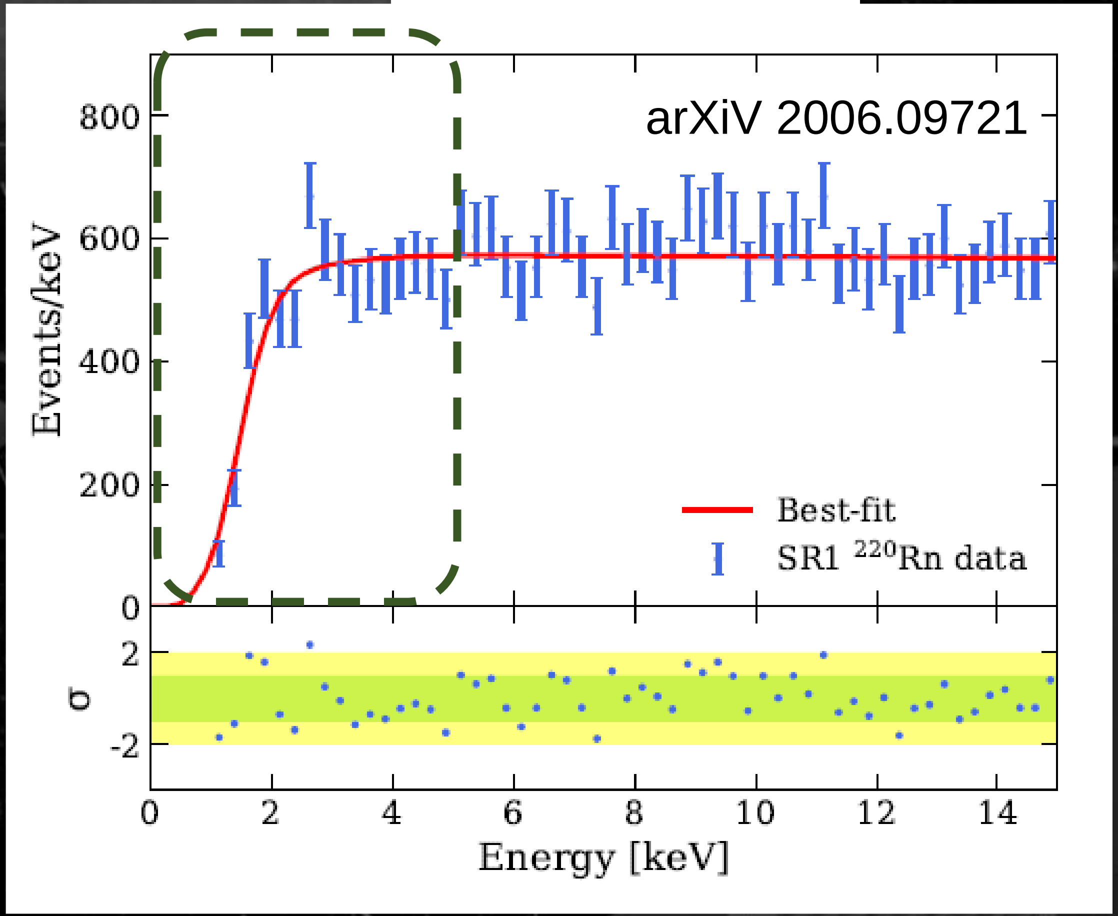


- Detector response
  - Energy scale & Efficiency
    - Both confirmed independently
    - Demonstrated with 220Rn calibration data

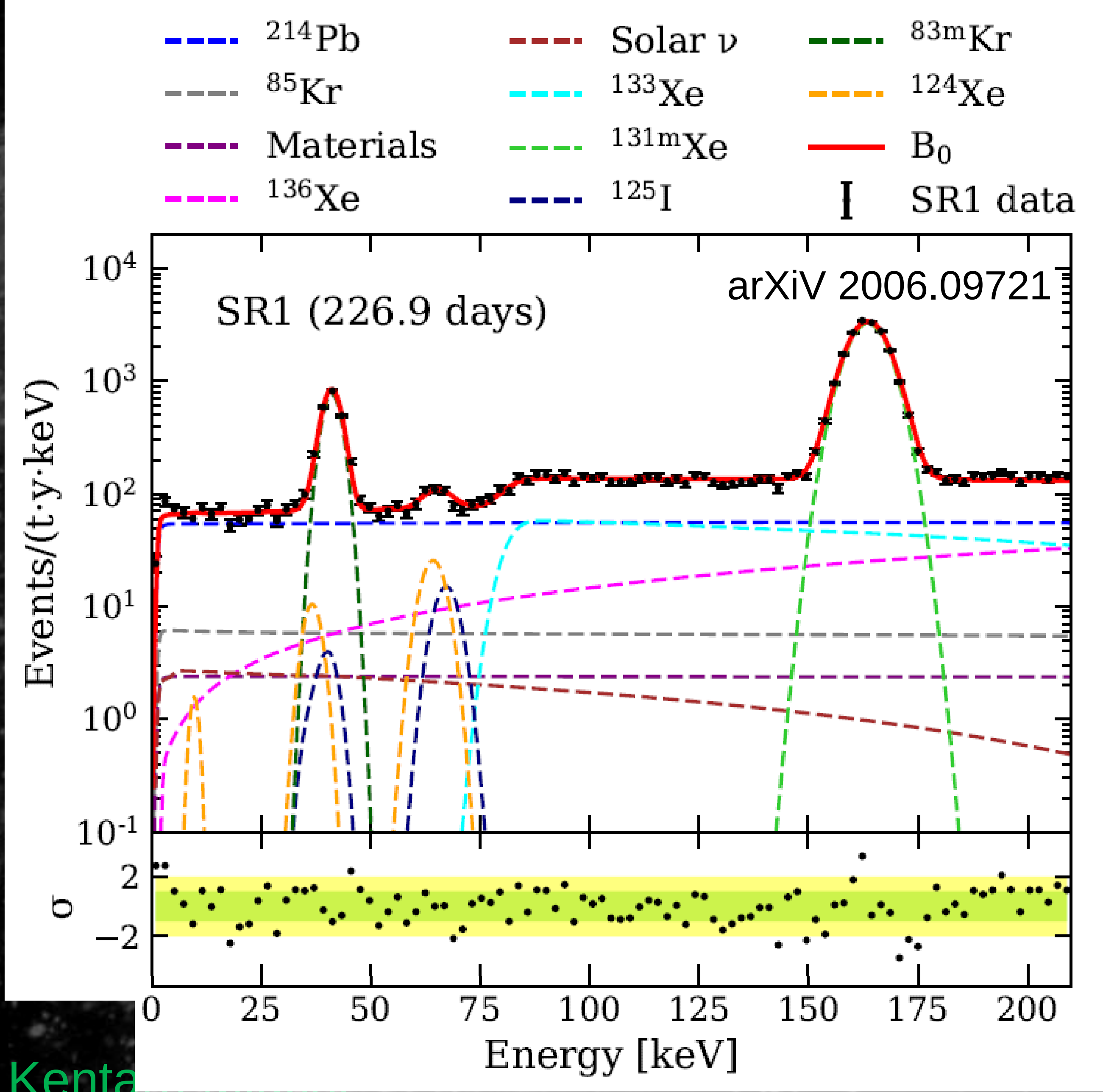
DM run

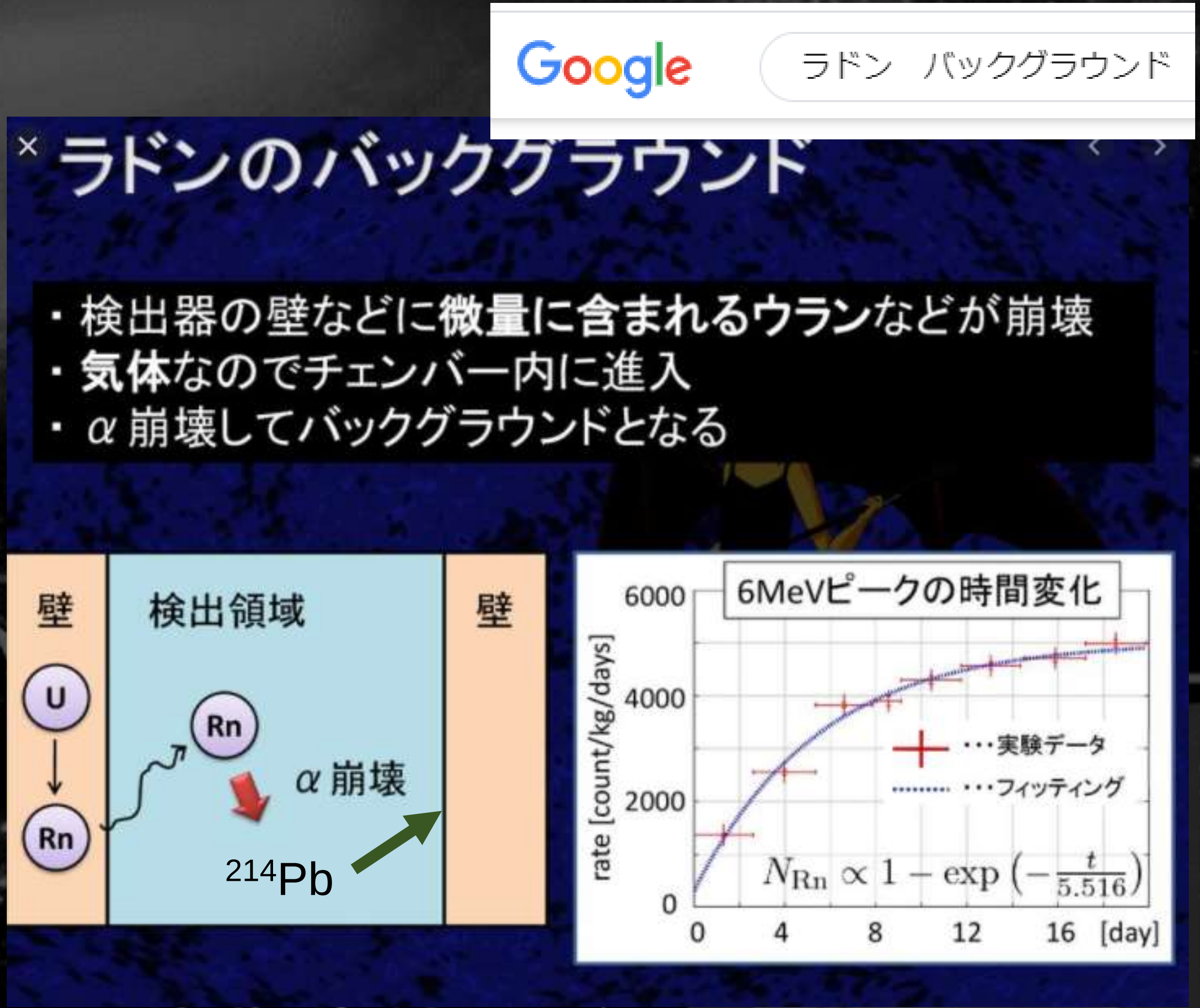


calibration



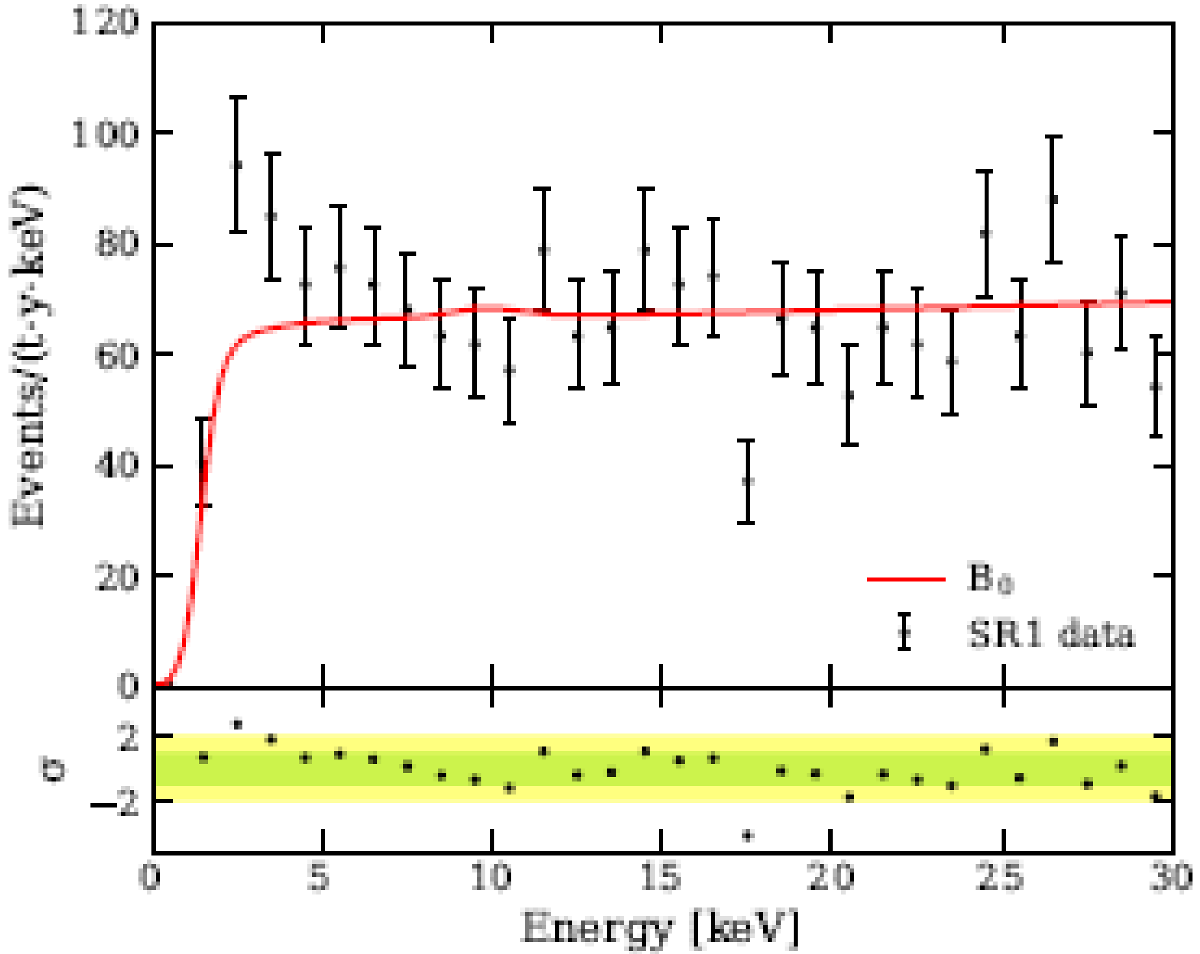
- Background
  - Radioactive isotopes (^{214}Pb: radon daughters)



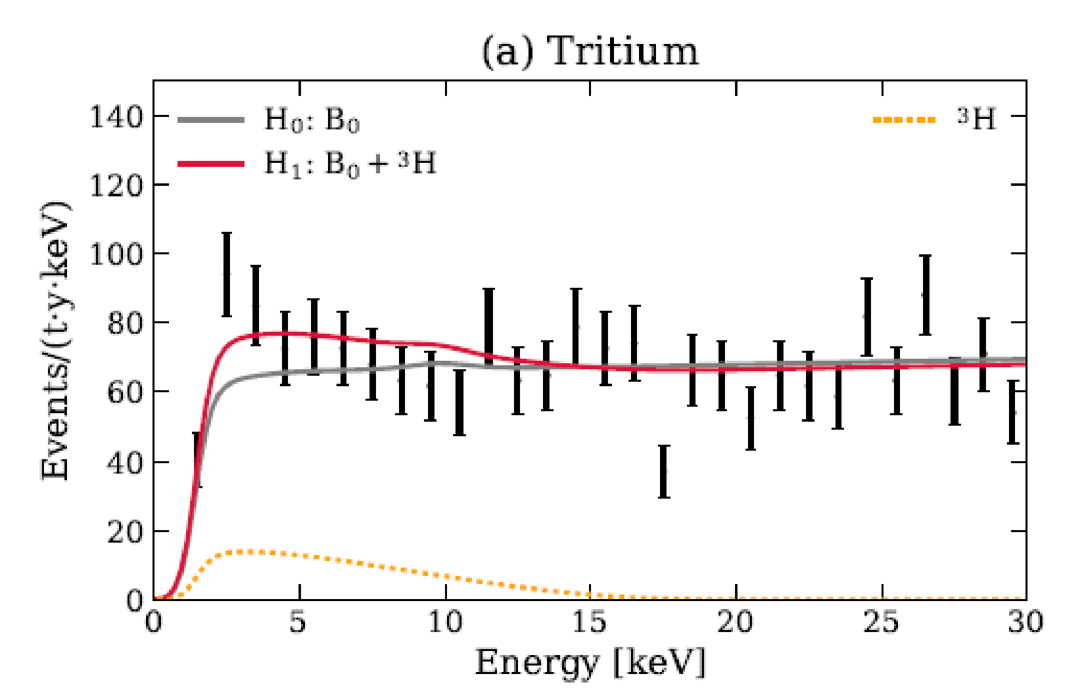


- Results
  - Excess between 1-7 keV
  - 285 events observed
  - 232 events expected (BG only)
  - 3.3 σ Poisson fluctuation

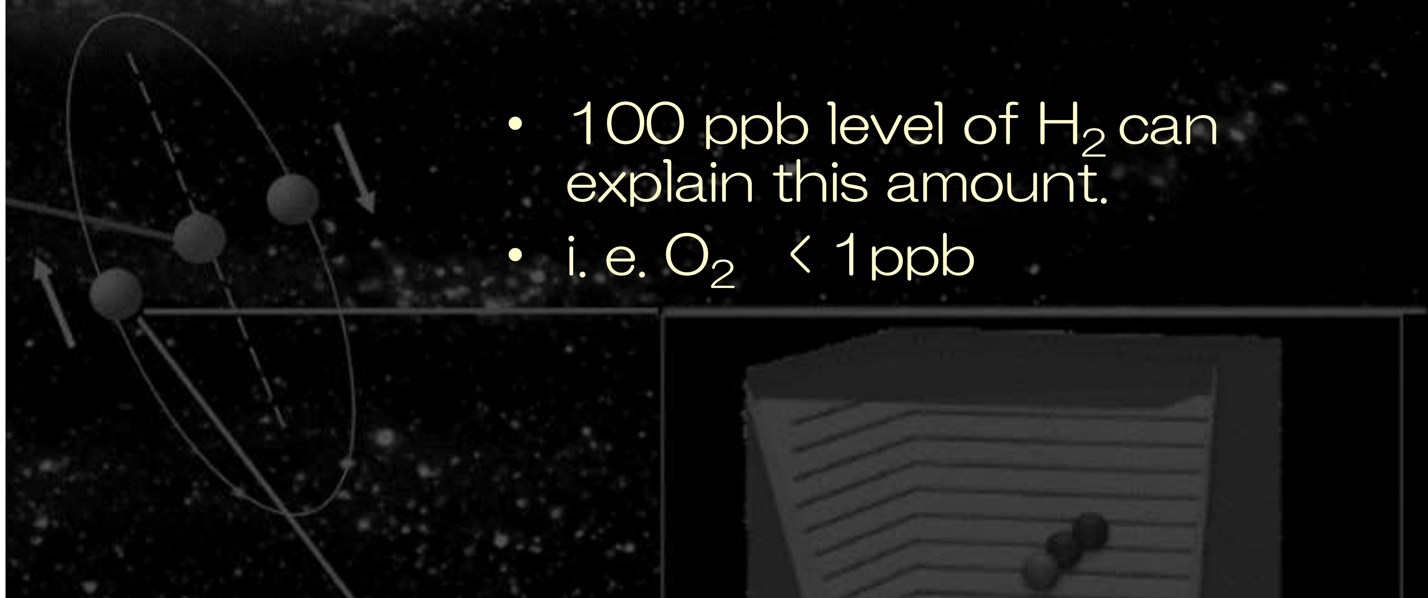
arXiV 2006.09721



- Tritium?
  - 3.2σ
  - $^{3}H/Xe$ = (6.2 ± 2.0) × 10^{-25} mol/mol
  - Two possible source
    - cosmogenics: made from xenon by cosmic-ray unlikely
    - atomosperic: H_2O (HTO) unlikely or H_2 (HT) maybe



- 100 ppb level of H_2 can explain this amount.
- i. e. O_2 < 1ppb



...ilable, we can neither confirm nor exclude it as a background component. Therefore, we report re-

- Compared the significance with other sources.

- And, off you went!

literature | refersto:recid:1801701

Literature

140 results | cite all

Dark Matter and the XENON1T electron recoil excess
Kristjan Kannike (NICPB, Tallinn), Martti Raidal (NICPB, Tallinn), Hardi Veermäe (NICPB, Tallinn), Alessandro Strumia (Pisa U.), Daniele Teresi (Pisa U. and INFN, ...
e-Print: 2006.10735 [hep-ph]
pdf cite

XENON1T anomaly from anomaly-free ALP dark matter and its implications for stellar cooling anomaly
Fuminobu Takahashi (Tohoku U. and Tokyo U., IPMU), Masaki Yamada (Tohoku U. (main)), Wen Yin (Tokyo U.) (Jun 17, 2020)
e-Print: 2006.10035 [hep-ph]
pdf cite

Hidden Photon Dark Matter in the Light of XENON1T and Stellar Cooling
Gonzalo Alonso-Álvarez (Heidelberg U.), Fatih Ertas (RWTH Aachen U.), Joerg Jaeckel (Heidelberg U. and U. Heidelberg, ITP), Felix Kahlhoefer (RWTH Aachen ...
e-Print: 2006.11243 [hep-ph]
pdf cite

Light new physics in XENON1T
Celine Boehm (Sydney U.), David G. Cerdeno (Madrid, IFT), Malcolm Fairbairn (King's Coll. London), Pedro A.N. Machado (Fermilab), Aaron C. Vincent (Queen's ...
e-Print: 2006.11250 [hep-ph]
pdf links cite — 59 citations

Boosted Dark Matter Interpretation of the XENON1T Excess
Bartosz Fornal (Utah U.), Pearl Sandick (Utah U.), Jing Shu (Beijing, Inst. Theor. Phys. and Beijing, GUCAS and CAS, CEPP, Beijing and Peking U., CHEP and HIAS, UCAS, Hangzhou and ICTP-AP, Beijing), Meng Su (Hong Kong U.), Yue Zhao (Utah U.) (Jun 19, 2020)
e-Print: 2006.11264 [hep-ph]
pdf cite — #5 — 58 citations

Solar axions cannot explain the XENON1T excess
Luca Di Luzio (DESY), Marco Fedele (ICC, Barcelona U.), Maurizio Giannotti (Barry U.), Federico Mescia (ICC, Barcelona U.), Enrico Nardi (Frascati) (Jun 22, 2020)
Published in: *Phys.Rev.Lett.* 125 (2020) 13, 131804 • e-Print: 2006.12487 [hep-ph]
pdf DOI cite — #6 — 56 citations

Light vector mediators facing XENON1T data
D. Aristizabal Sierra (Santa Maria U., Valparaiso and Liege U.), V. De Romeri (Valencia U., IFIC), L.J. Flores (Mexico U.), D.K. Papoulias (Ioannina U.) (Jun 22, 2020)
Published in: *Phys.Lett.B* 809 (2020) 135681 • e-Print: 2006.12457 [hep-ph]
pdf DOI cite — #7 — 50 citations

Exploring New Physics with O(keV) Electron Recoils in Direct Detection Experiments
Itay M. Bloch (Tel Aviv U.), Andrea Caputo (Valencia U., IFIC), Rouven Essig (YITP, Stony Brook), Diego Redigolo (CERN and INFN, Florence and Florence U.), Mukul Sholapurkar (YITP, Stony Brook) et al. (Jun 25, 2020)
e-Print: 2006.14521 [hep-ph]
pdf cite — #8 — 48 citations

XENON1T Anomaly and its Implication for Decaying Warm Dark Matter
Gongjun Choi (Tsung-Dao Lee Inst., Shanghai), Motoo Suzuki (Tsung-Dao Lee Inst., Shanghai), Tsutomu T. Yanagida (Tsung-Dao Lee Inst., Shanghai and Tokyo U., IPMU) (Jun 22, 2020)
e-Print: 2006.12348 [hep-ph]
pdf cite

Explaining the XENON1T excess with Luminous Dark Matter
Nicole F. Bell (Melbourne U.), James B. Dent (Sam Houston State U.), Bhaskar Dutta (Texas A-M), Sumit Ghosh (Texas A-M), Jason Kumar (Hawaii U.) et al. (Jun 22, 2020)
e-Print: 2006.12461 [hep-ph]
pdf cite

Atmospheric Dark Matter from Inelastic Cosmic Ray Collision in Xenon1T
Liangliang Su (Nanjing Normal U. and Yantai U.), Wenyu Wang (Beijing U. of Tech.), Lei Wu (Nanjing Normal U.), Jin Min Yang (Beijing, Inst. Theor. Phys. and Beijing, KITPC and Beijing, GUCAS), Bin Zhu (Yantai U. and ... 21, 2020)
e-Print: 2006.11837 [hep-ph]
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Neutrino self-interactions and XENON1T electron recoil excess
Andreas Bally (Heidelberg, Max Planck Inst.), Sudip Jana (Heidelberg, Max Planck Inst.), Andreas Trautner (Hei...
e-Print: 2006.11919 [hep-ph]
pdf cite

Inelastic Dark Matter Electron Scattering and the XENON1T Excess
Keisuke Harigaya (Princeton, Inst. Advanced Study), Yuichiro Nakai (Tsung-Dao Lee Inst., Shanghai and Shangh...
Published in: *Phys.Lett.B* 809 (2020) 135729 • e-Print: 2006.11938 [hep-ph]
pdf DOI cite

Sun Heated MeV-scale Dark Matter and the XENON1T Electron Recoil Excess
Yifan Chen (Beijing, Inst. Theor. Phys.), Ming-Yang Cui, Jing Shu (Beijing, Inst. Theor. Phys. and Beijing, GUCAS ... Phys. and Beijing, GUCAS), Guanwen Yuan (Purple Mountain Observ. and USTC, Hefei) et al. (Jun 22, 2020)
e-Print: 2006.12447 [hep-ph]
pdf cite

Re-examining the Solar Axion Explanation for the XENON1T Excess
Christina Gao (Fermilab), Jia Liu (Chicago U., EFI), ... (Chicago U.), ...
Published in: *Phys.Rev.Lett.* 125 (2020) ... • e-Print: 2006.14598 [hep-ph]
pdf links DOI cite

Shining dark matter in Xenon1T
Gil Paz (Wayne State U.), Alexey A. Petrov (Wayne State U.), Michele Tammaro (Cincinnati U.), Jure Zupan (Cinc...
e-Print: 2006.12462 [hep-ph]
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Constraints on General Light Mediators from PandaX-II Electron Recoil Data
Amir N. Khan (Heidelberg, Max Planck Inst.) (Aug 24, 2020)
e-Print: 2008.10279 [hep-ph]
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Neutron's Dark Secret
Bartosz Fornal (Utah U.), Benjamin Grinstein (UC, San Diego) (Jul 27, 2020)
e-Print: 2007.13931 [hep-ph]
pdf cite

Pico-charged particles explaining 511 keV line and XENON1T signal
Yasaman Farzan, Meshkat Rajaee (Jul 28, 2020)
e-Print: 2007.14421 [hep-ph]
pdf cite

Constraining power of asymptotic safety for scalar fields
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e-Print: 2009.13543 [hep-th]
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Plasma dark matter and electronic recoil events in XENON1T
Lei Zu (Purple Mountain Observ. and USTC, Hefei), R. Foot (Melbourne U. and Sydney U.), Yi-Zhong Fan (Pu...
e-Print: 2007.15191 [hep-ph]
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Boosted Neutrinos and Relativistic Dark Particles as Messengers from Reheating
Joerg Jaeckel (U. Heidelberg, ITP), Wen Yin (KAIST, Taejon and Tokyo U.) (Jul 29, 2020)
e-Print: 2007.15006 [hep-ph]
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Polarized light-by-light scattering at the CLIC induced by axion-like particles
S.C. İnan (Cumhuriyet U.), A.V. Kisselev (Kurchatov Inst., Moscow) (Jul 2, 2020)
e-Print: 2007.01693 [hep-ph]
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Singlet-Doublet Majorana Dark Matter and Neutrino Mass in a minimal Type-I See...
Subhaditya Bhattacharya (Indian Inst. Tech., Guwahati), Manoranjan Dutta (Indian Inst. Tech., Hyderabad), P...
e-Print: 2009.00885 [hep-ph]
pdf cite

Search for gravitational waves from high-mass-ratio compact-binary mergers of st...
Alexander Harvey Nitz (Hannover, Max Planck Inst. Grav. and Leibniz U., Hannover), Yi Fan Wang (Hannover...
e-Print: 2007.03583 [astro-ph.HE]
pdf cite

The Neutrino Magnetic Moment Portal: Cosmology, Astrophysics, and Direct Detec...
Vedran Brdar (Heidelberg, Max Planck Inst.), Admir Greljo (CERN), Joachim Kopp (CERN and Mainz U., Inst. ...
e-Print: 2007.15563 [hep-ph]
pdf cite

Dark Matter interactions in an $S_3 \times Z_5$ flavor symmetry framework
G. Arcadi (Roma III U. and INFN, Rome3), M.B. Krauss (Roma III U.), D. Meloni (Roma III U.) (Jul 21, 2020)
e-Print: 2007.10833 [hep-ph]
pdf cite

see also
広島サーベイ @ ダークマターの懇談会2020

Oct. 2

- XENONnT

ダークマターの懇談会2020 online (darKONline2020)

2020年9月8日

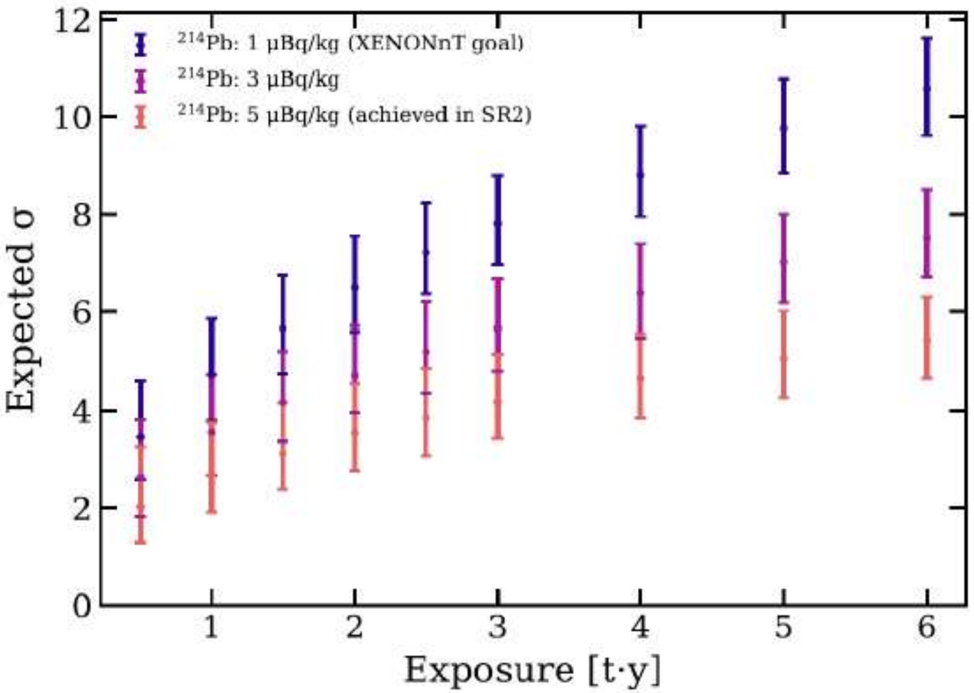
於：オンライン

XENON NT EXPERIMENT

Columbia University
JSPS Postdoctoral research fellow

Masatoshi Kobayashi

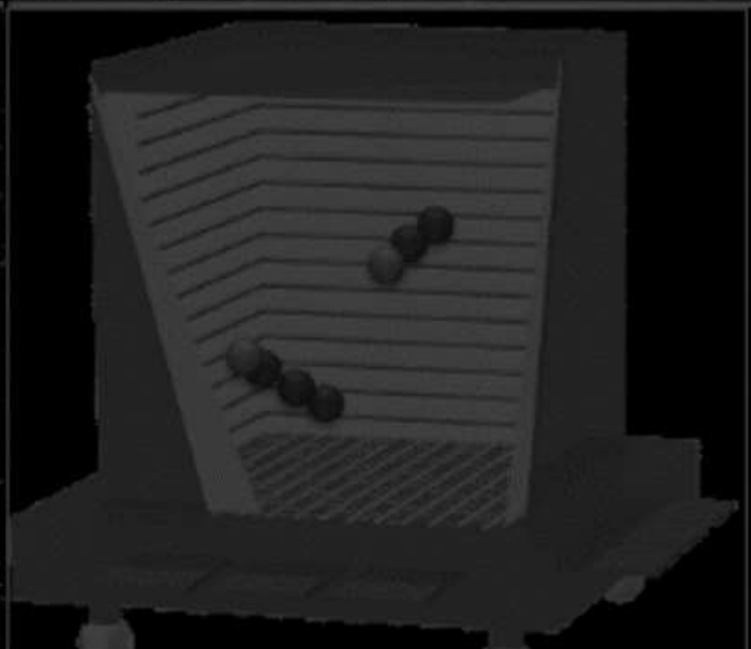
EXPECTED SENSITIVITY: TRITIUM VS ER SIGNAL (AXION) ?



- Discrimination power between axion and tritium
  - Note: BGs are based on 1T best fit
- If Rn BG level is enough low, axion/tritium could be distinguished with few month of data
  - Ex. ~4 sigma with 1-3 uBq/kg

Topics

2. MIGDAL

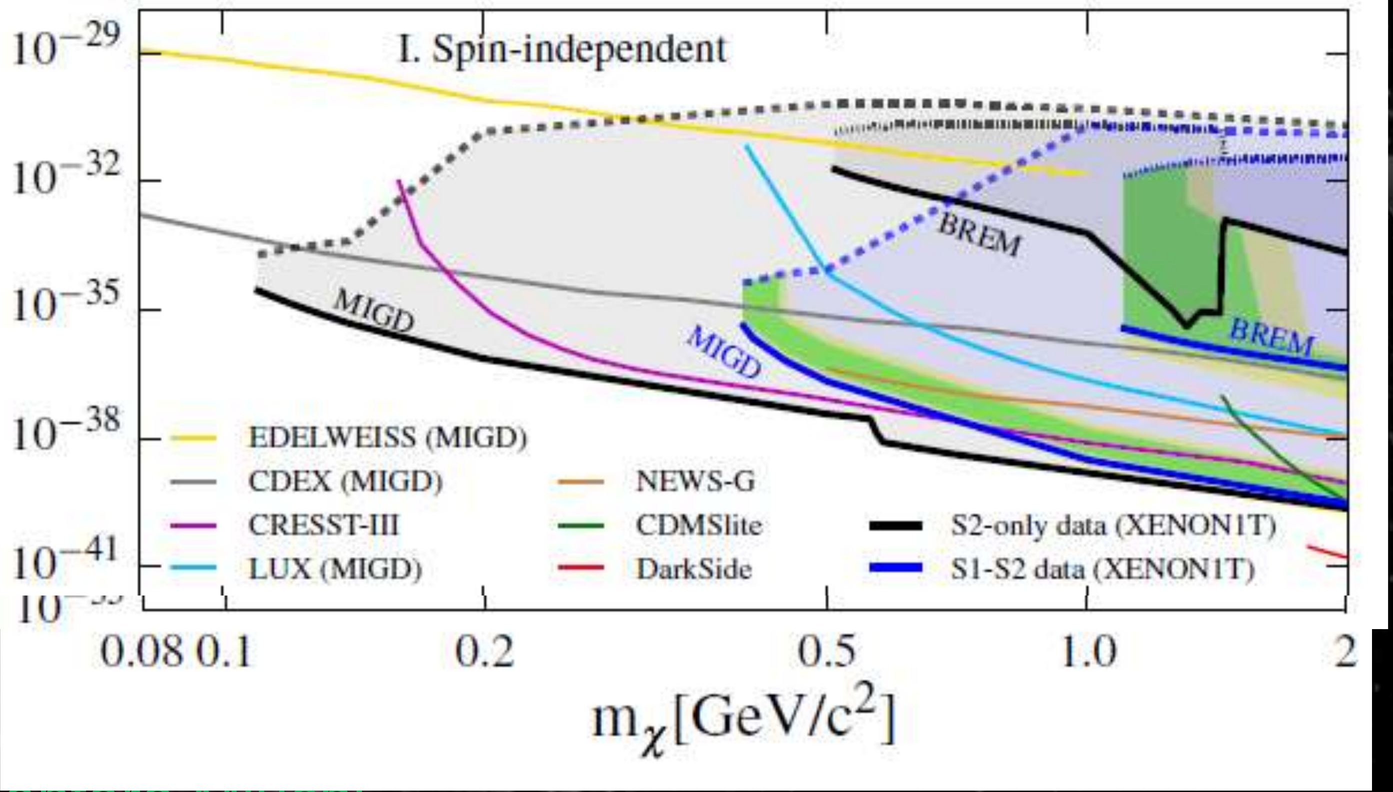


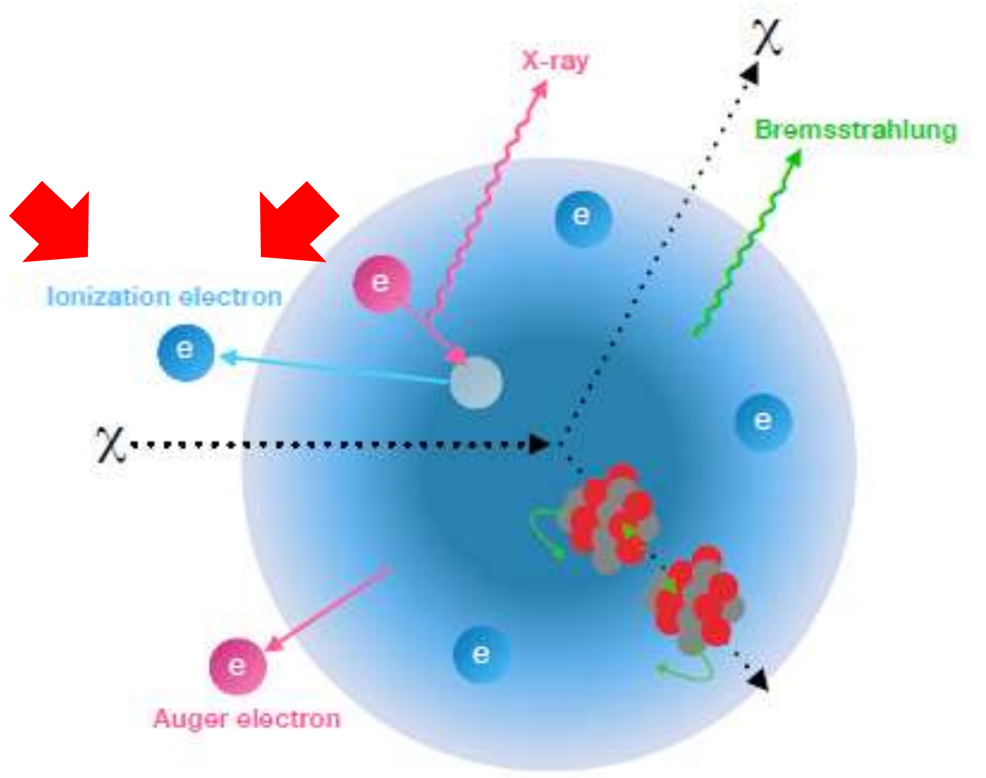
- And still lower: MIGDAL

PRL123, 241803 (2019)

  - 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)

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.

Kentaro Miuchi

- 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]

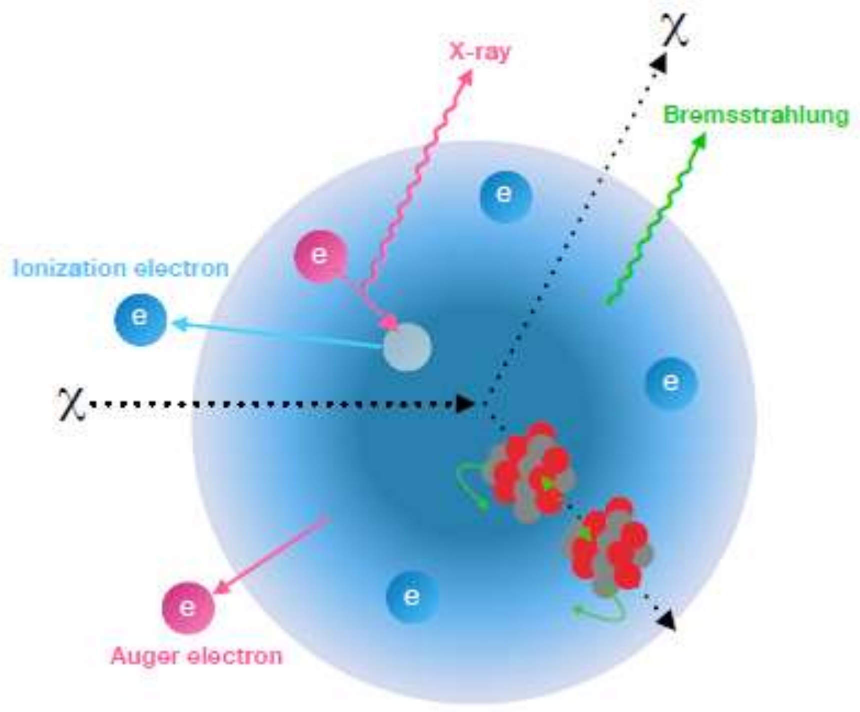
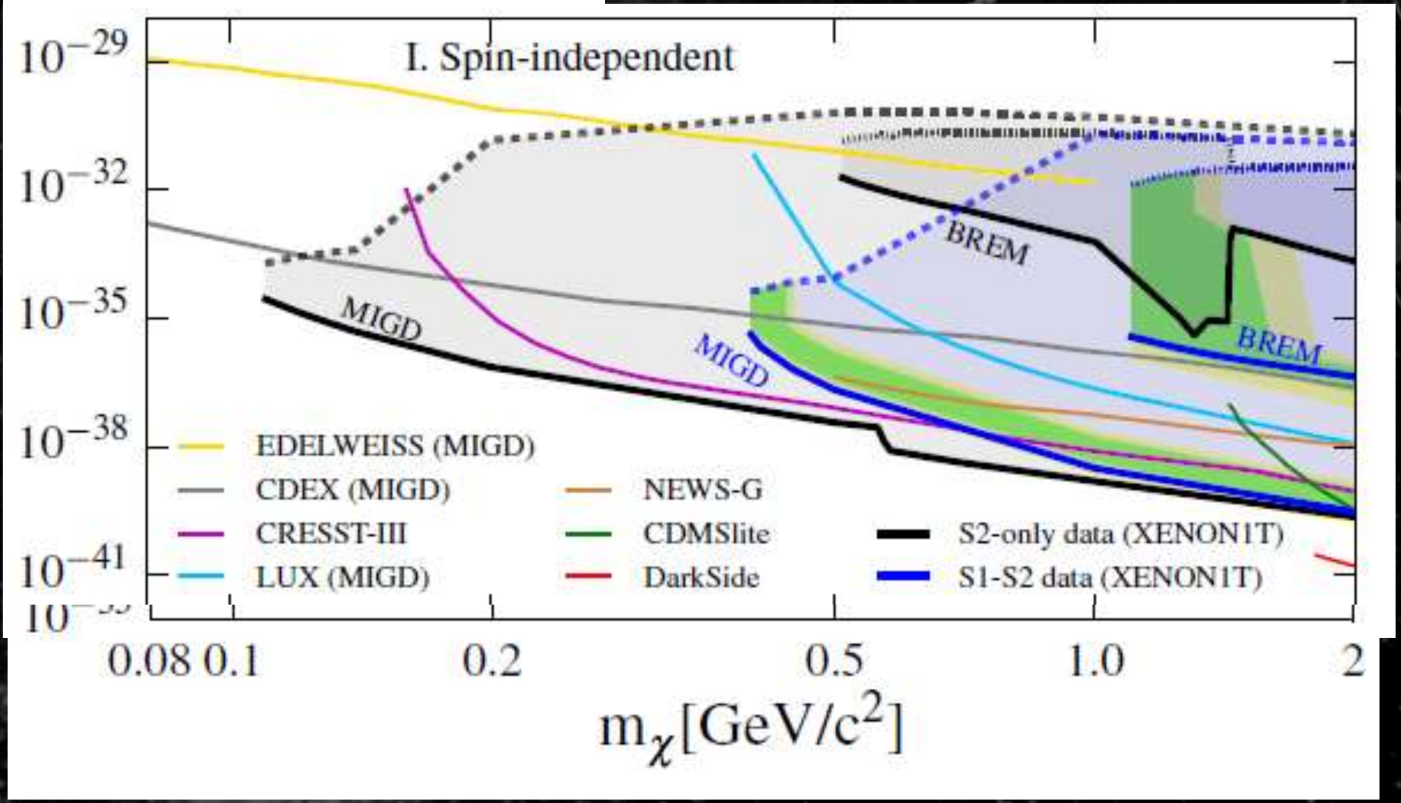


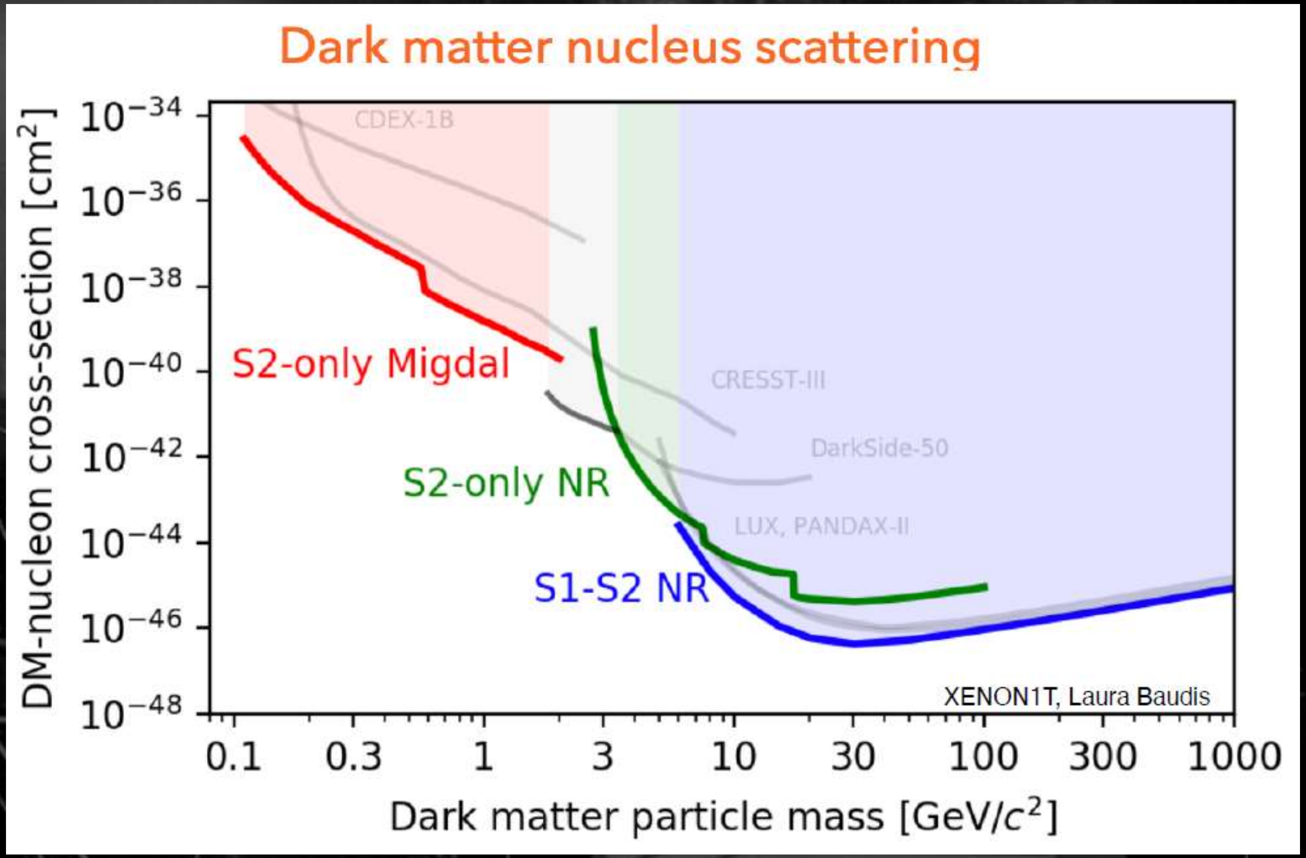
FIG. 1. Illustration of the ER signal production from BREM (green) and Migdal processes (pink) after elastic scattering between DM (χ) and a xenon nucleus.

• 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)

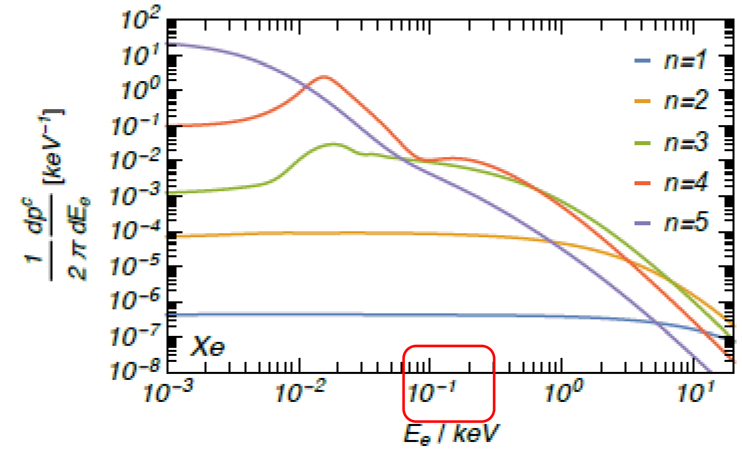




Standard WIMP detector down to 100MeV
CAVEAT: Migdal effect itself is yet to be observed.
loose 3orders of magnitude if we use Bremsstrahlung only.

- 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

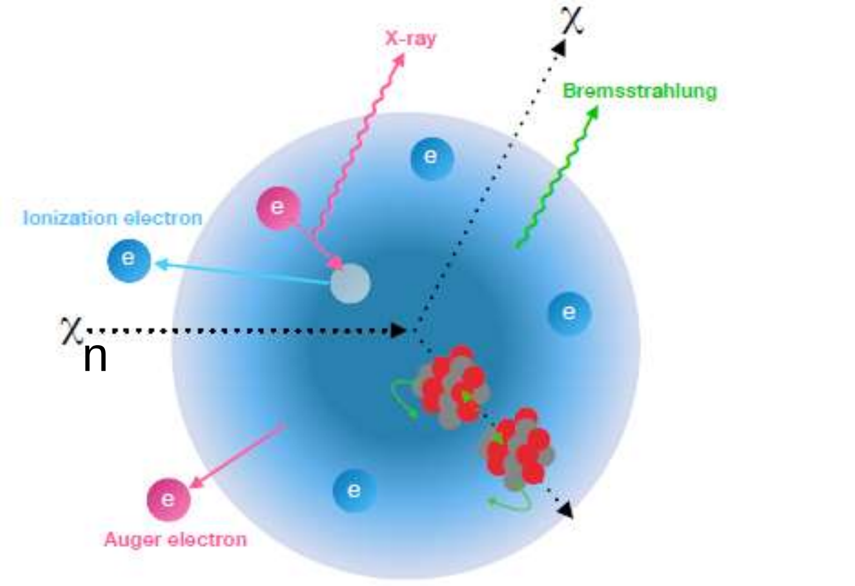


FIG. 1. Illustration of the ER signal production from BREM (green) and Migdal processes (pink) after elastic scattering between DM (χ) and a xenon nucleus.

- Migdal challenge

Observation of the Migdal effect from nuclear scattering using a low pressure Optical-TPC

Pawel Majewski
Rutherford Appleton Laboratory

RD51 mini-week, CERN, 10-15 Jan 2020

CERN-UK

https://indico.cern.ch/event/872501/contributions/3730586/attachments/1985262/3307758/RD51_mini_week_Pawel_Majewski_ver2.pdf

JP

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]

arXiv:2009.05939v1

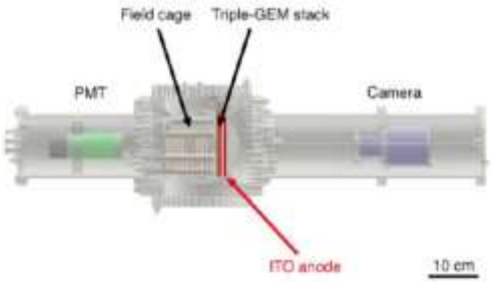
- CERN-UK (in preparation)
  - Straightforward method
  - Nuclear track +electron track with gaseous detector
  - Demonstrations OK for nuclear recoil / electron recoil each.
  - Hard to discriminate from standard nuclear recoil

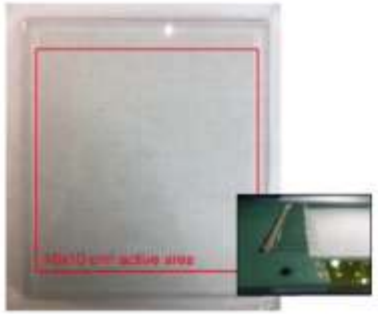
Observation of the Migdal effect from nuclear scattering using a low pressure Optical-TPC

Pawel Majewski
Rutherford Appleton Laboratory

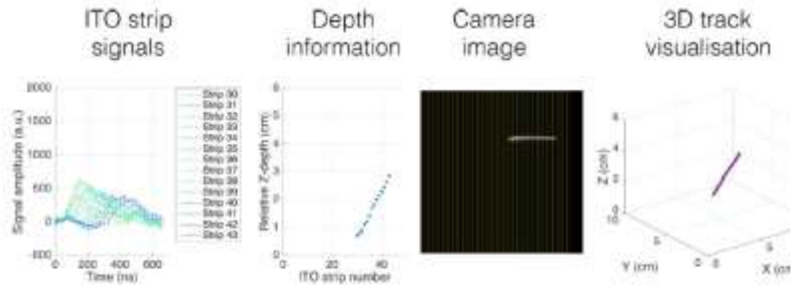
RD51 mini-week, CERN, 10-15 Jan 2020

O-TPC at CERN (from F. Brunbauer)

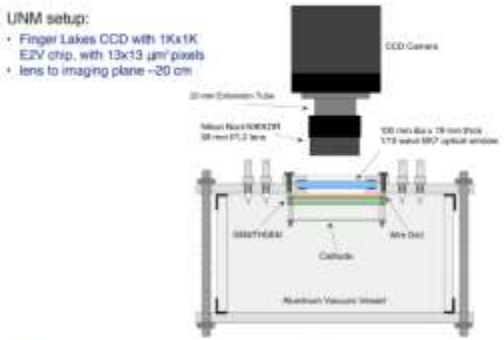




3D track reconstruction
in Ar/CF4 (80/20)
at 100 Torr

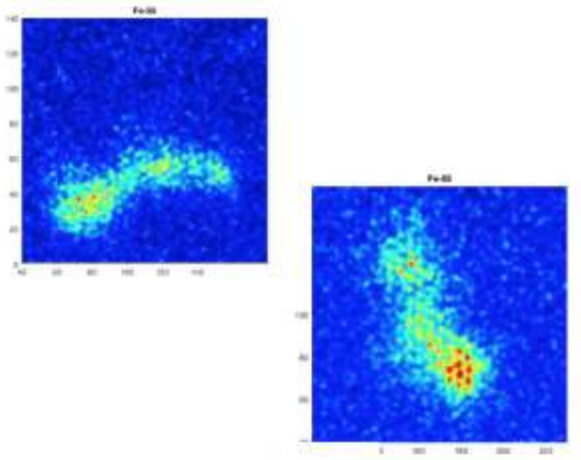


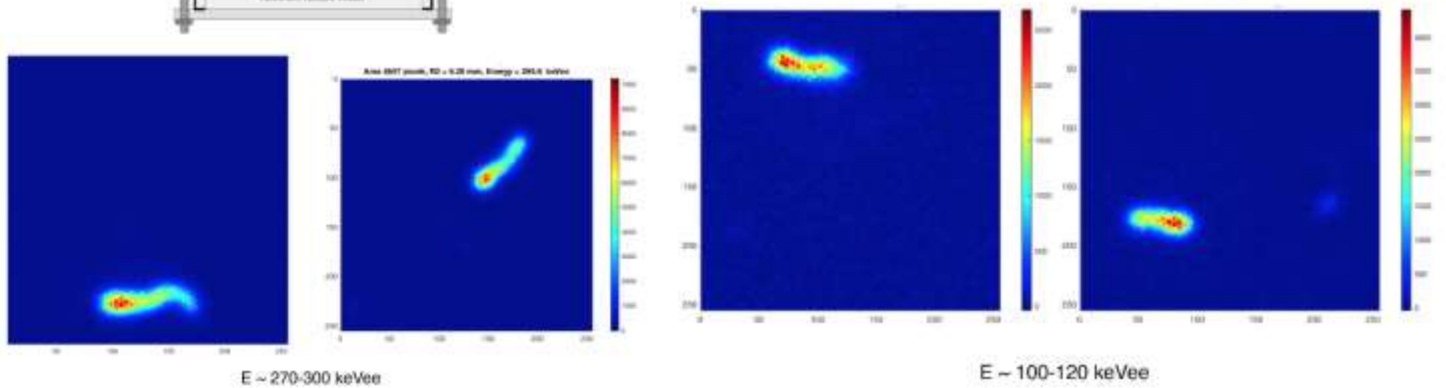
O-TPC at UNM (from D. Loomba)
2D reconstruction



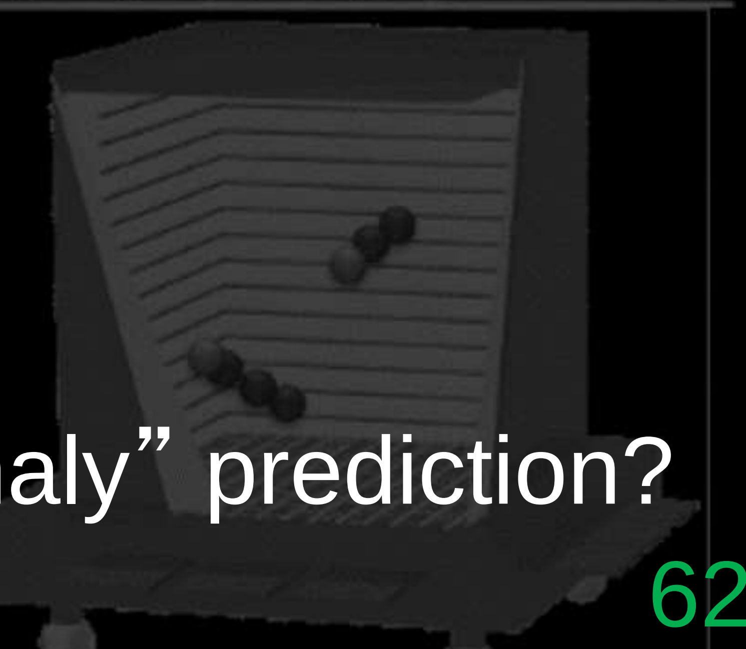
- 25-35 Torr CF4
- 2THGEMs (σ > 0.7 mm)
- Imaging area ~1.9cm x 1.9cm
- 4x4 on-chip binning

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)





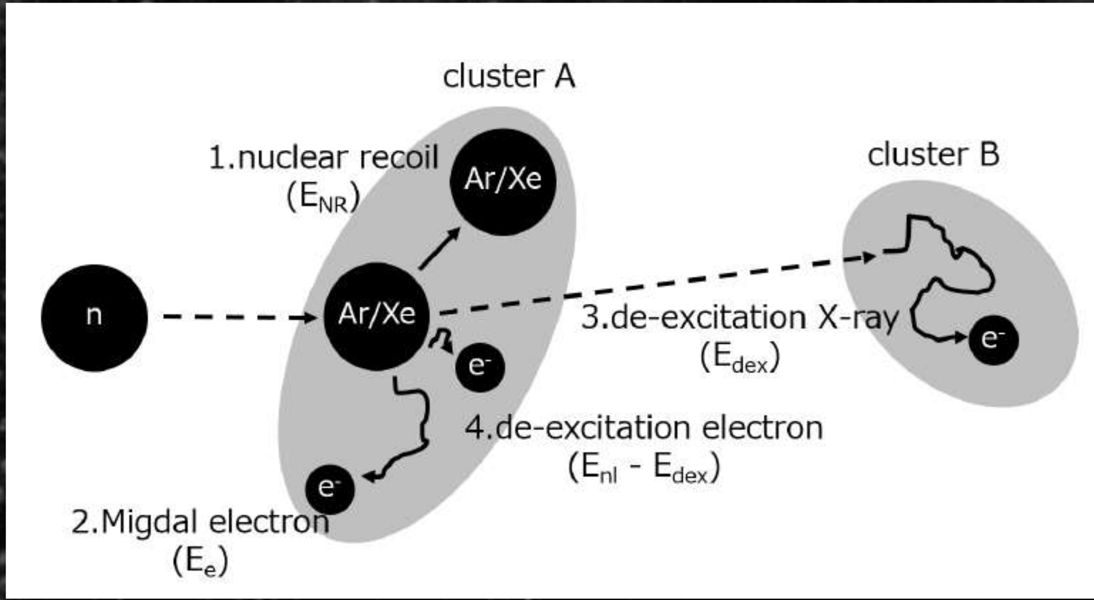
- Our approach (proposal)
  - Detect characteristic signal "two-cluster" events
  - Help to reduce huge background

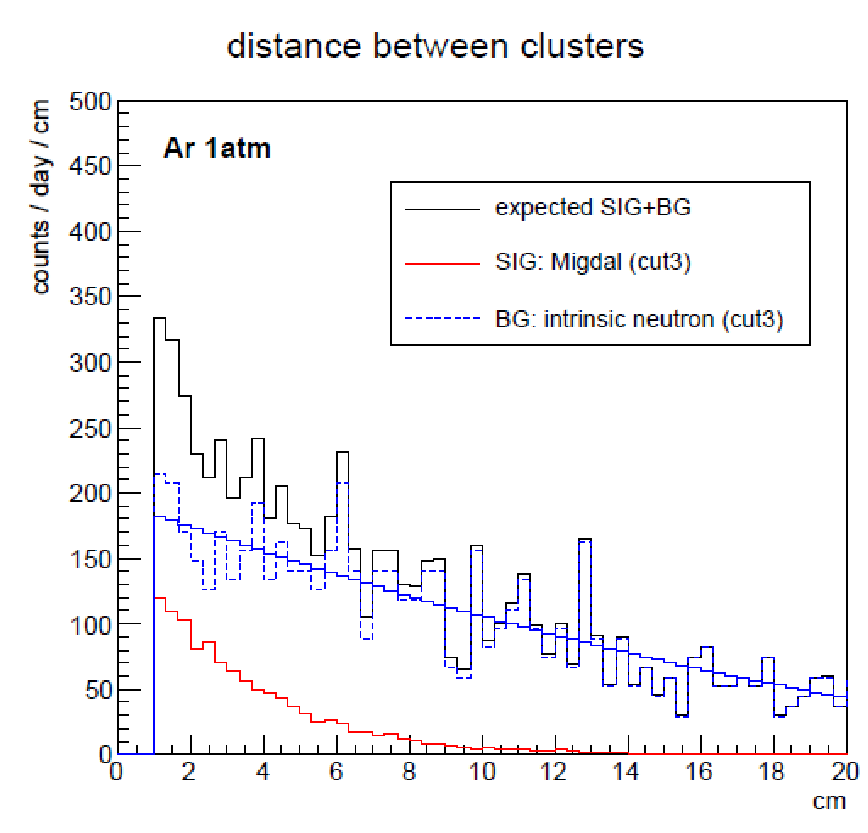


Detection capability of Migdal effect for argon and xenon nuclei with position sensitive gaseous detectors

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

arXiv:2009.05939v1

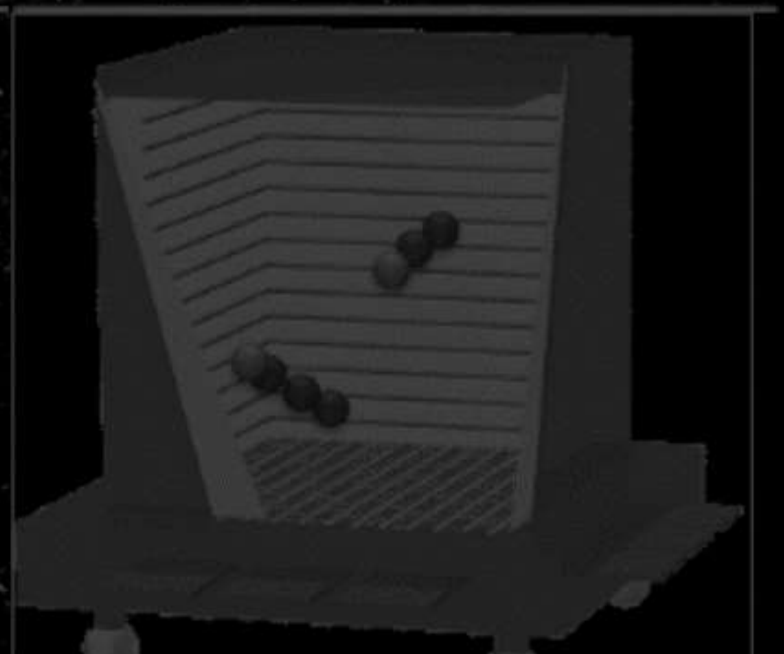




any "MIGDAL anomaly" prediction?

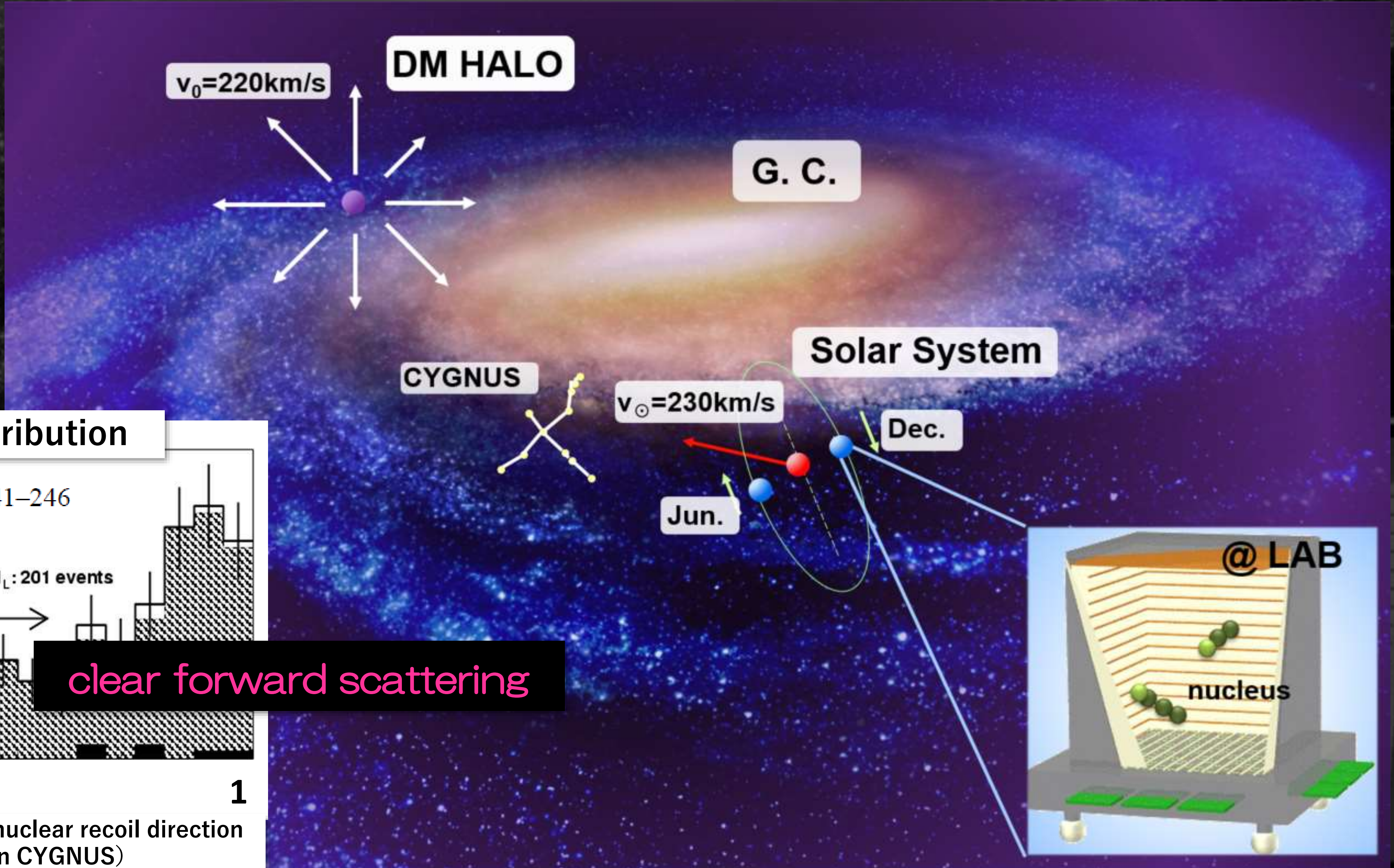
Topics

3. Directionality

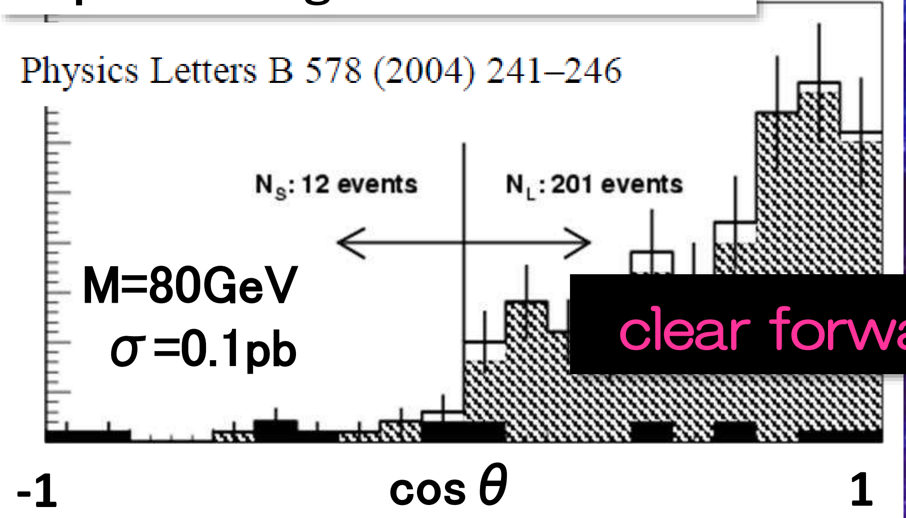


• Directional search：concept “CYGNUS”

- More robust evidence than annual modulation
- Study the DM nature after discovery



expected anguler distribution



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

Ke

World-wide CYGNUS

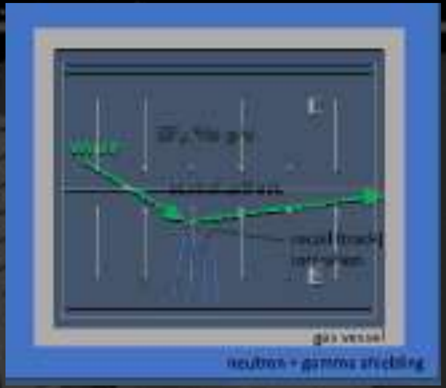
2020 J. Phys.: Conf. Ser. 1468 012044

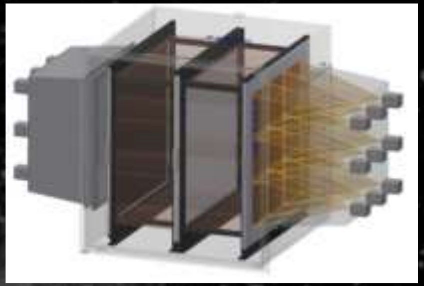
NEWAGE/CYGNUS-KM
Kamioka, Japan
SF6 / CF4
Strip readout

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

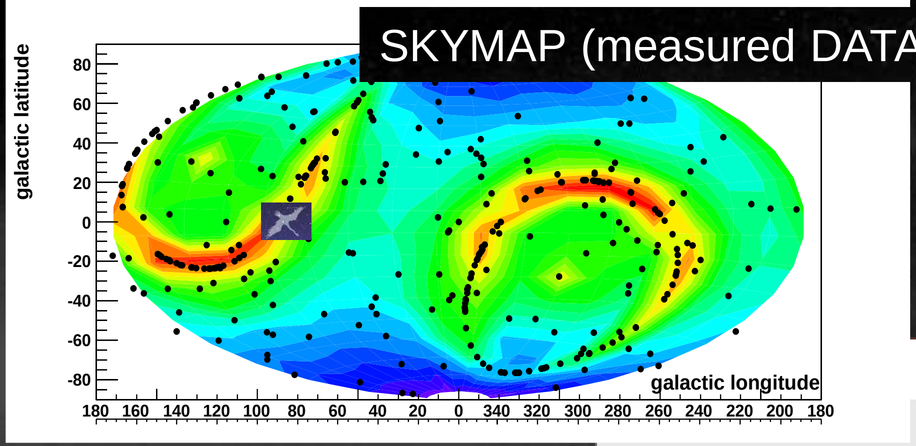
- NEWAGE (Kobe+)
  - 3D tracking
    - μ-PIC
    - SKYMAP
  - CF_4 gas
    - High spatial resolution
    - Spin-Dependent search

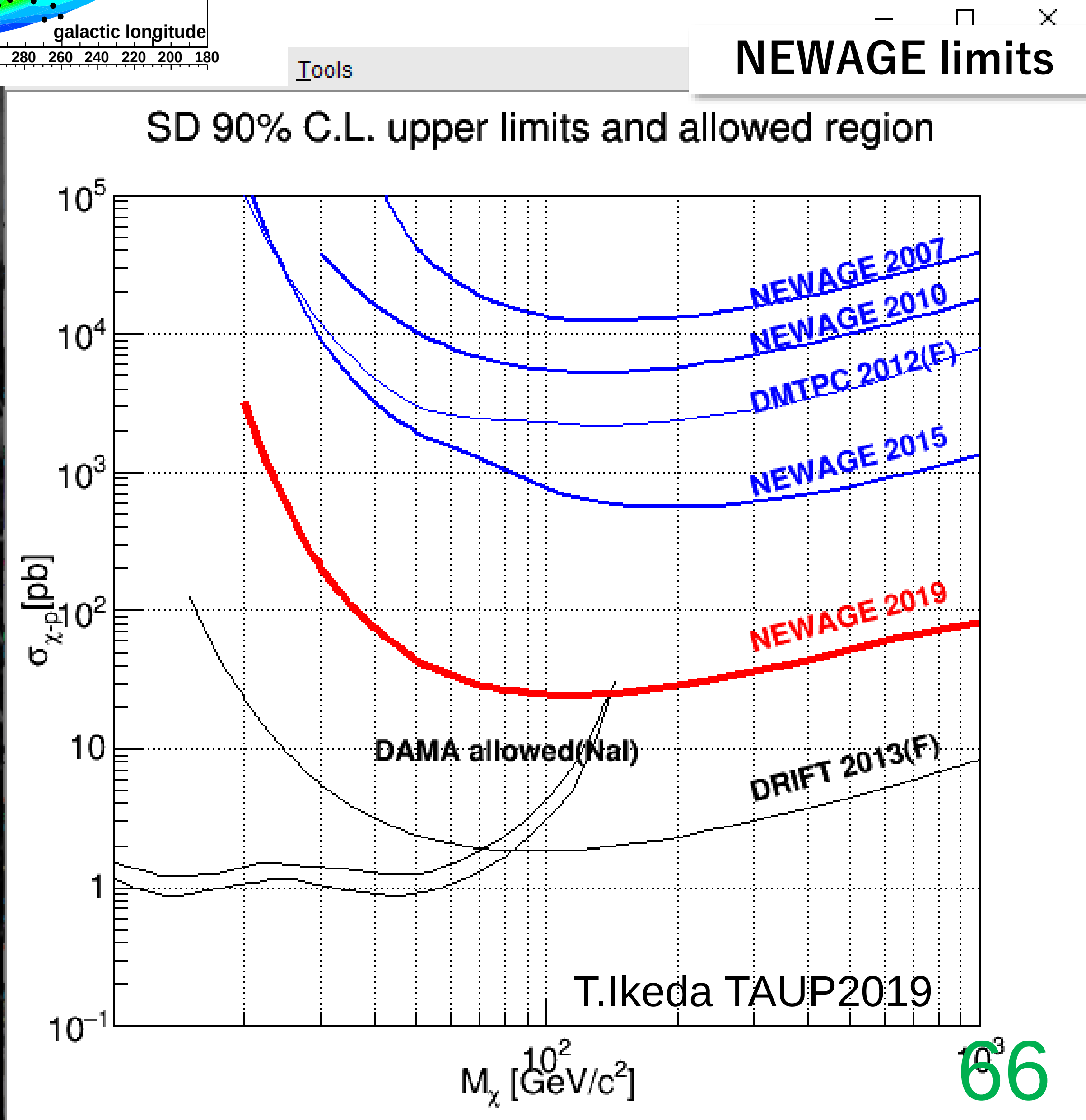
- Proposal

  PLB 578 (2004) 241
- First directional search

  PLB 654 (2007) 58
- Underground measurements

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

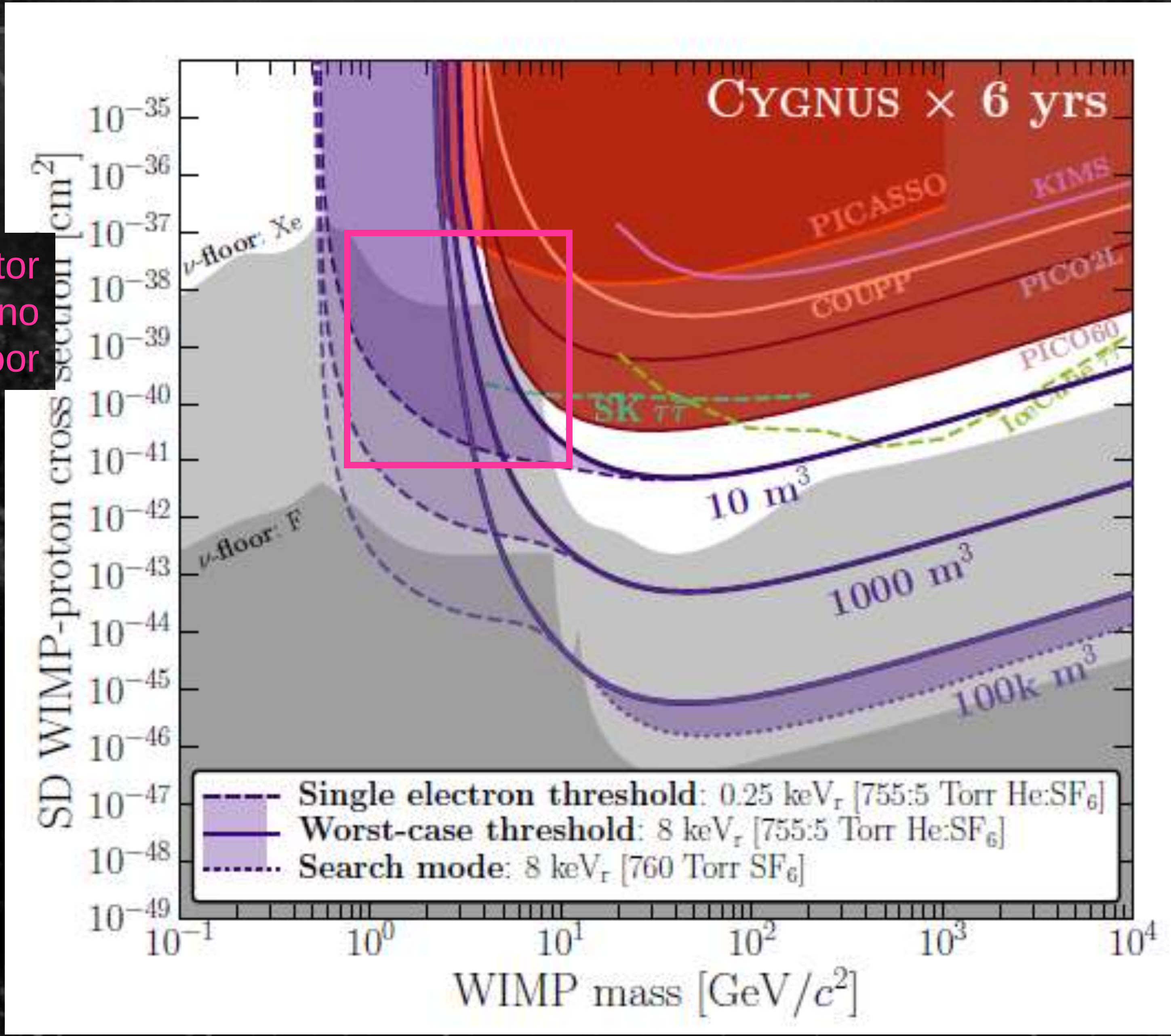




arXiv 2008.12587

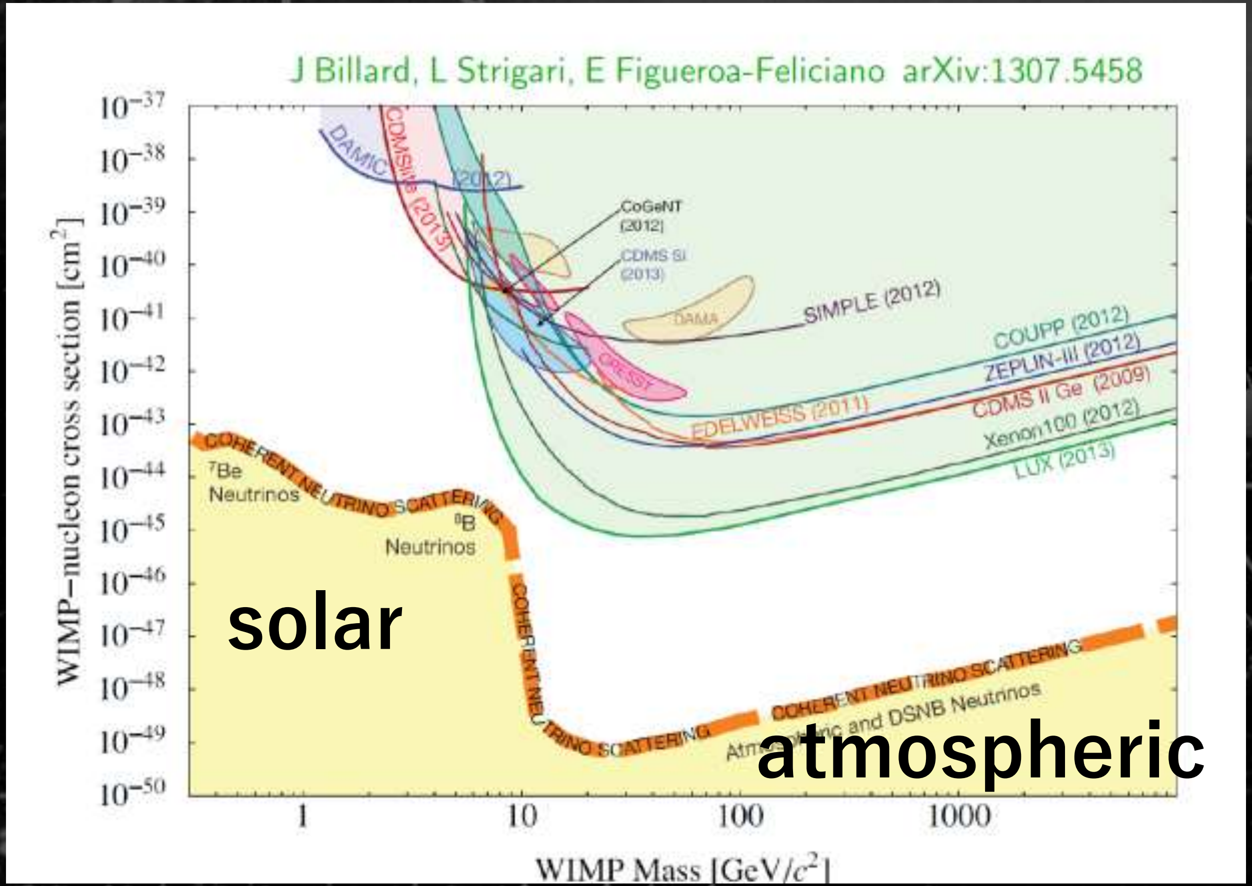
- Realistic simulation (strip readout)

even 10m³ detector can start exploring Xe neutrino floor

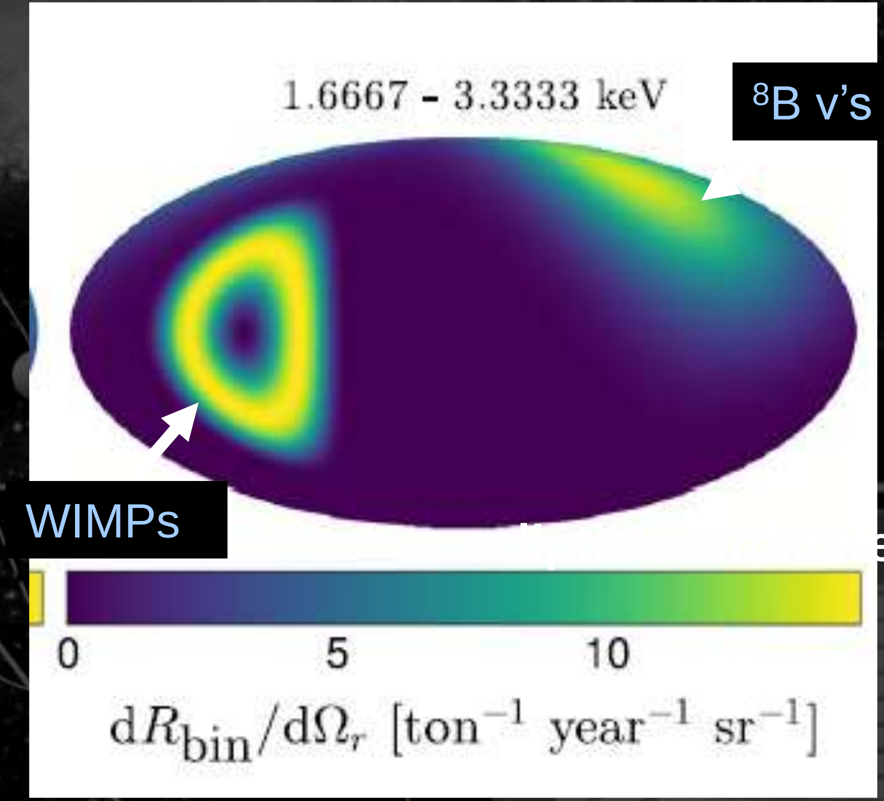


Toward discovery

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



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

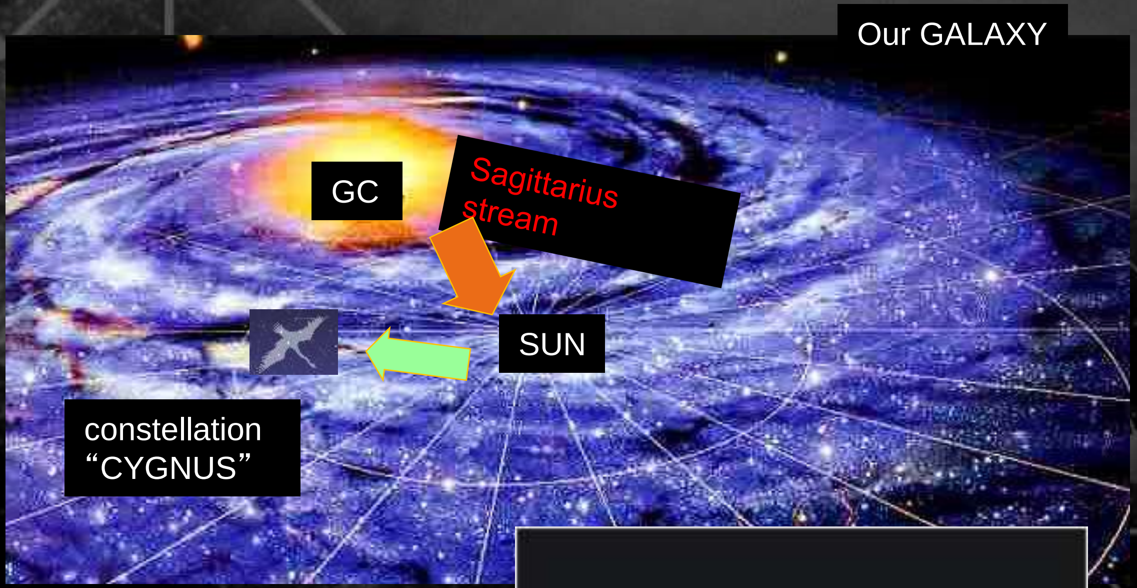


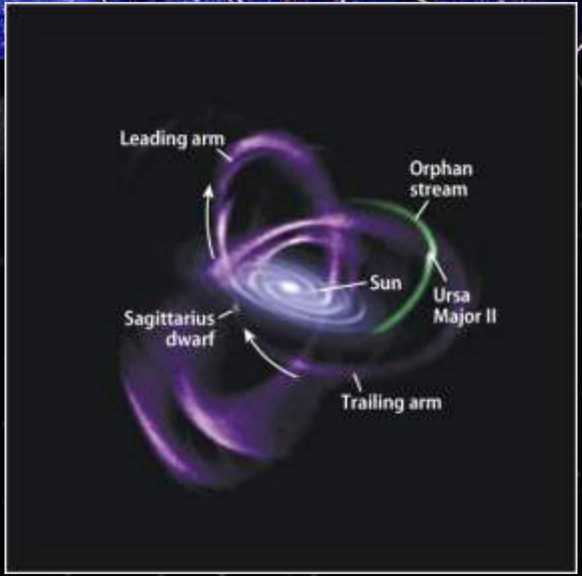
- distinguishable

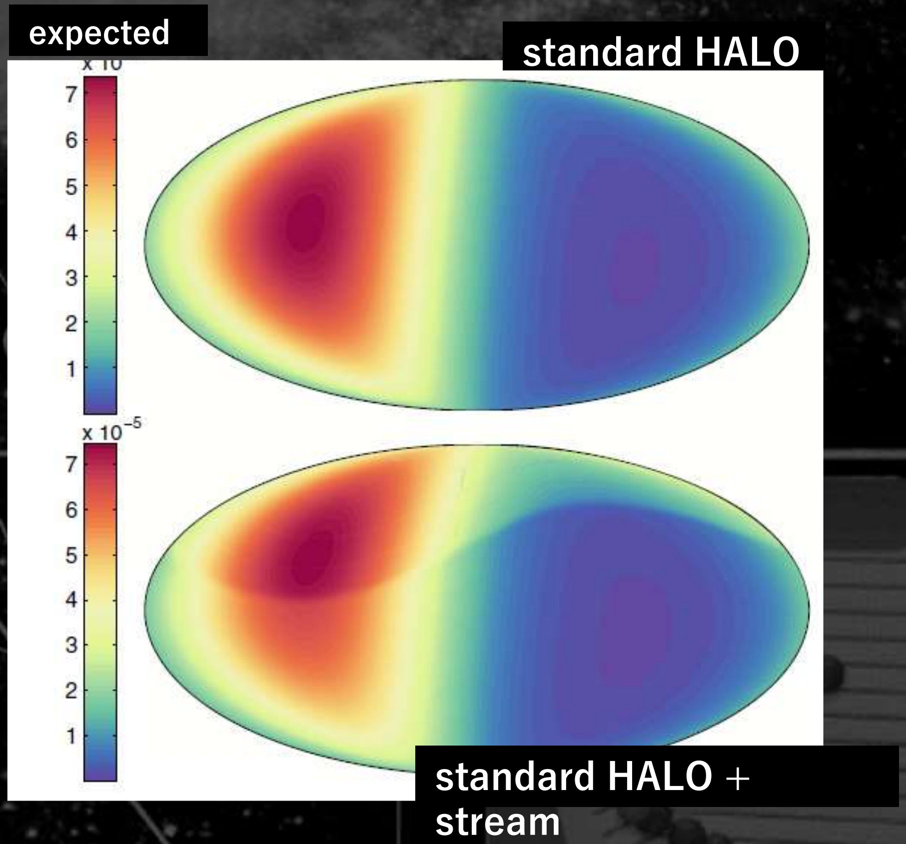
CYGNUS After Discovery: astronomy/cosmology

- Test the HALO model
- （ex） Sagittarius stream

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







galactic coordinate

- **streams, debris…**

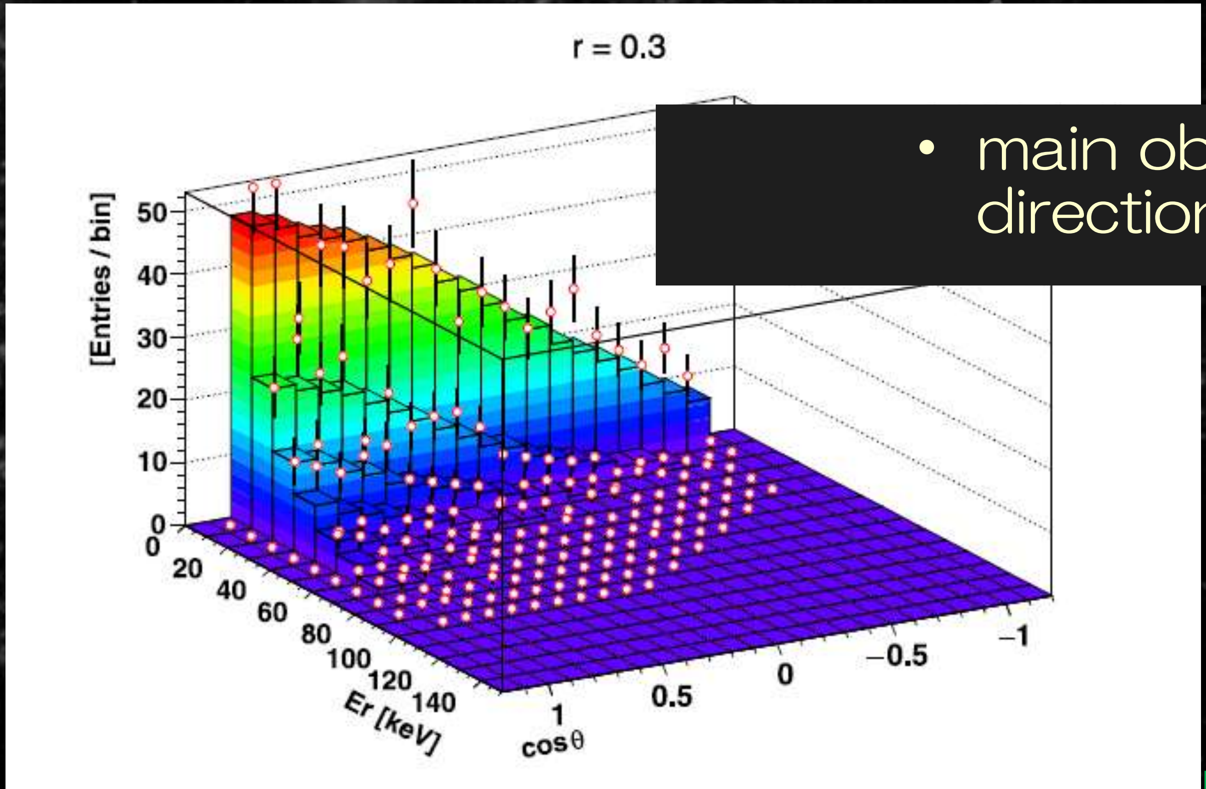
- Halo model test
  - isotropic (1-r) + anisotropic(r) DM HALO model indicated by n-body simulation (r~0.3)

Discrimination of anisotropy in dark matter velocity distribution with directional detectors

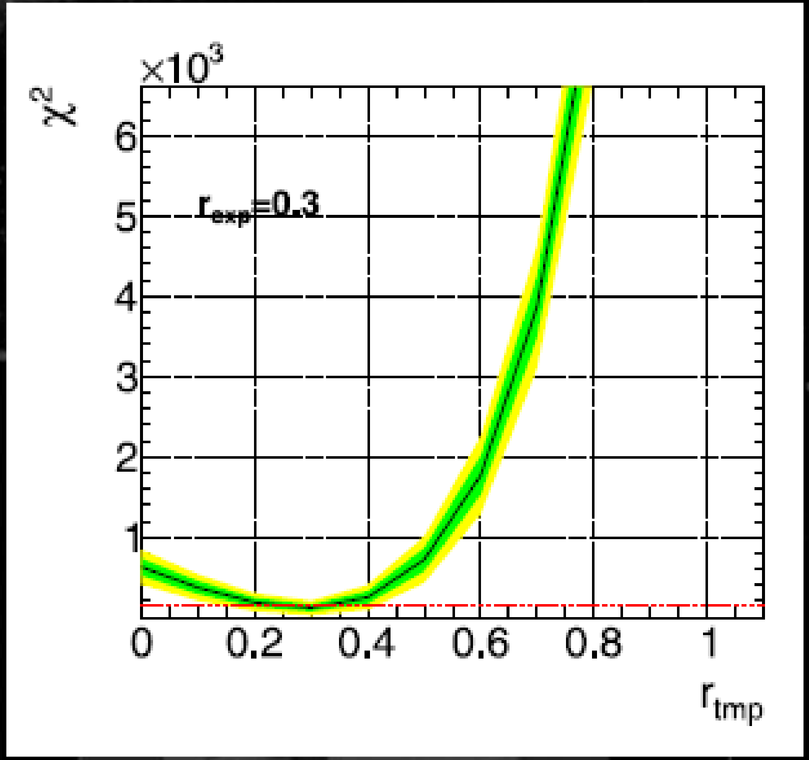
Keiko I. Nagao [a,b,*], Tomonori Ikeda [c], Ryota Yakabe [c], Tatsuhiro Naka [d,e], Kentaro Miuchi [c]

[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

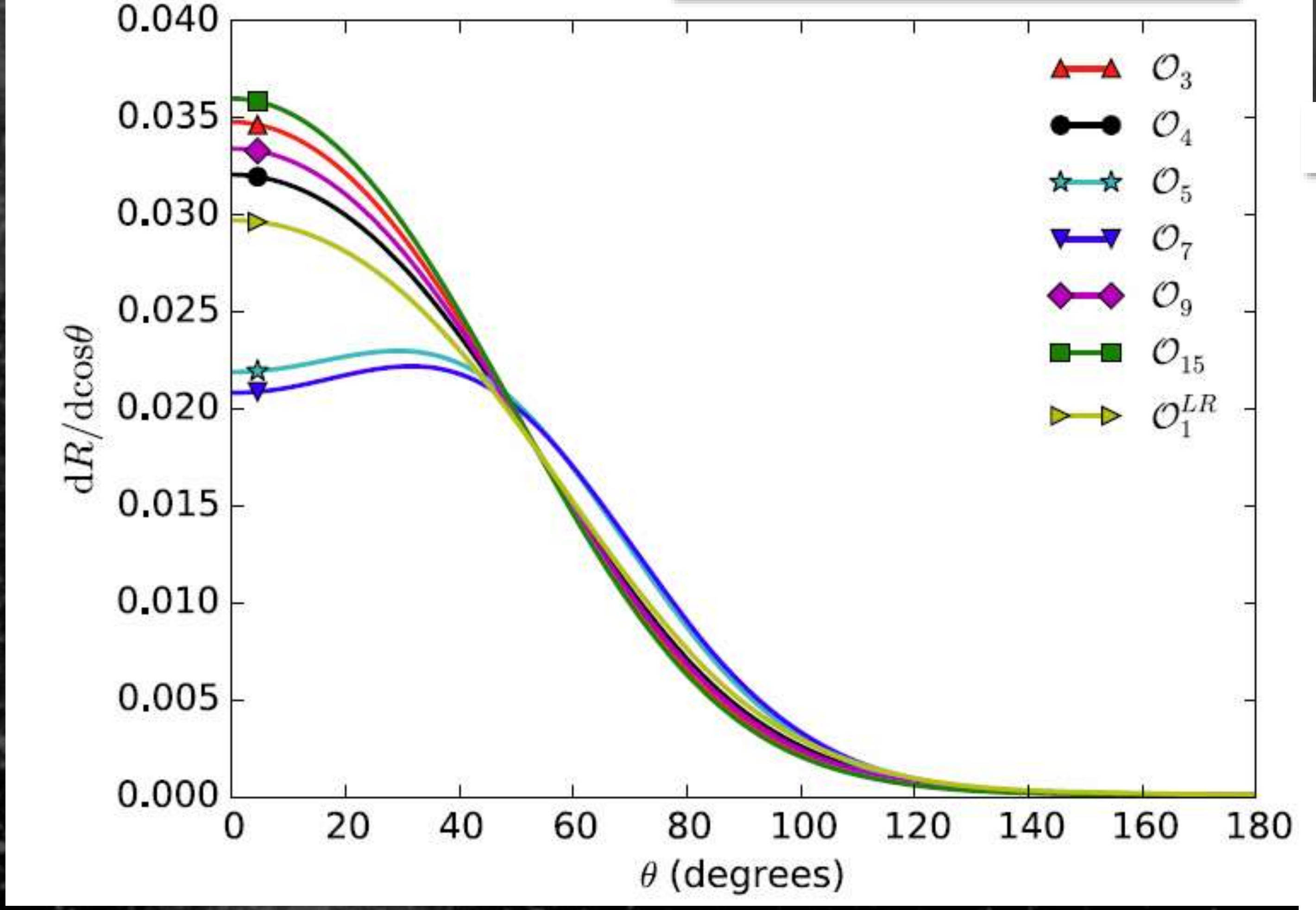


- scan r value

- next:

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

angular distribution



operator

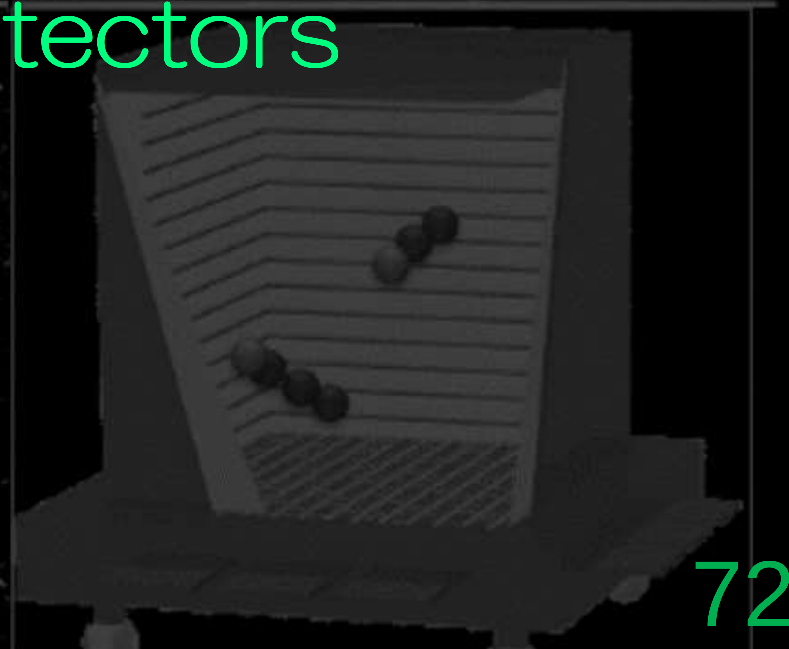
SI SD

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

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

ACT2 SUMMARY

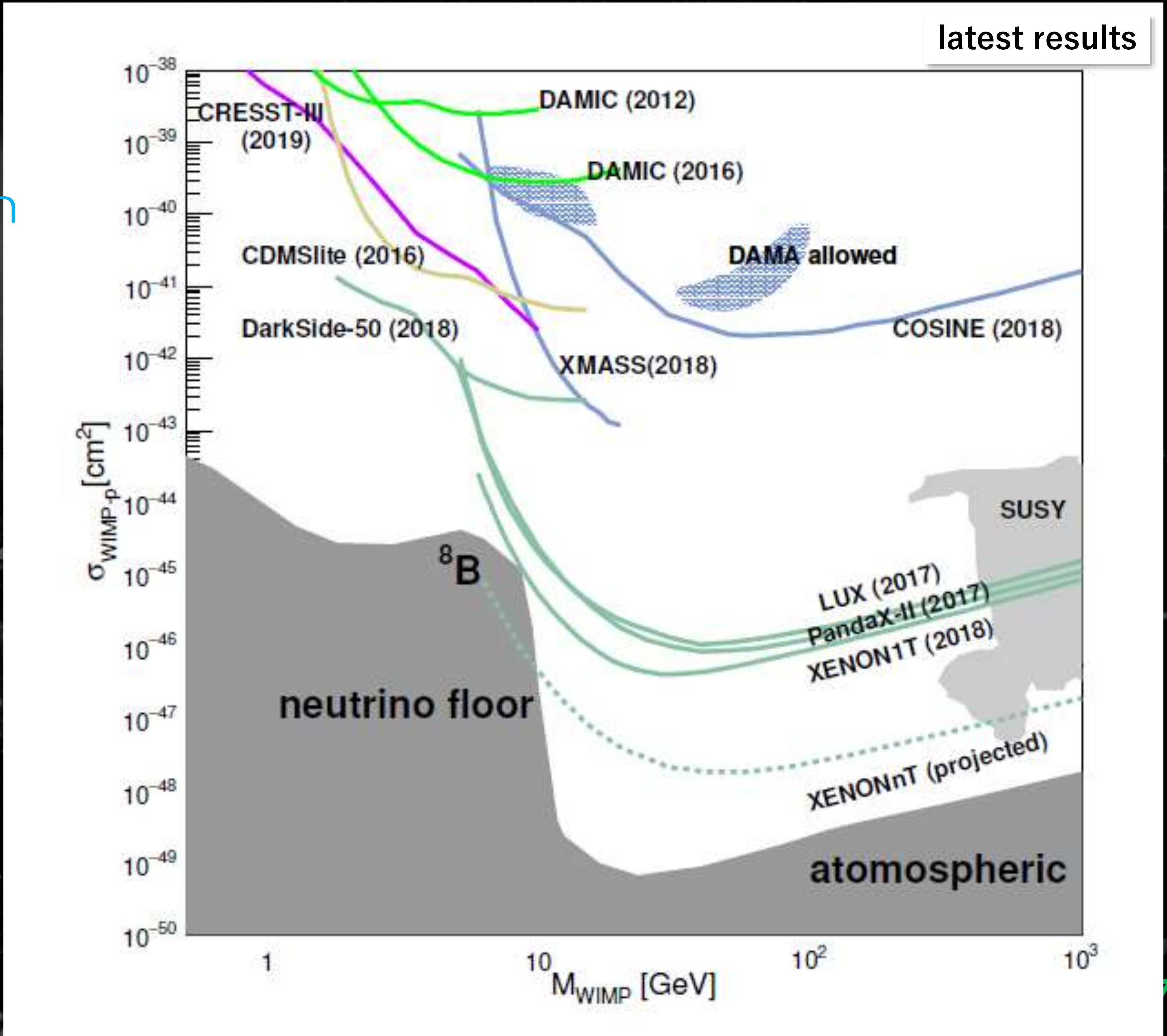
- ER signal
  - XENONnT/LZ are in preparation
- MIGDAL
  - Observation
- Directional Detectors : gas detectors
  - Clear evidence・DM nature study



Thank you!

backups

- Latest results
  - DAMA
    annual modulation
  - bolometers
  - liquid xenon



- Cross section

- Enhancement factor C

$$\sigma_{\chi-\mathrm{N}} = 4G_F^2 \mu_{\chi-\mathrm{N}}^2 C_{\mathrm{N}}$$

$$\mu_{\chi-\mathrm{N}} = \frac{M_\chi M_{\mathrm{N}}}{M_\chi + M_{\mathrm{N}}} : \text{reduced mass}$$

G_F^2 : Fermi coupling constant

- SI interaction

$$C \propto A^2$$

A: atomic number

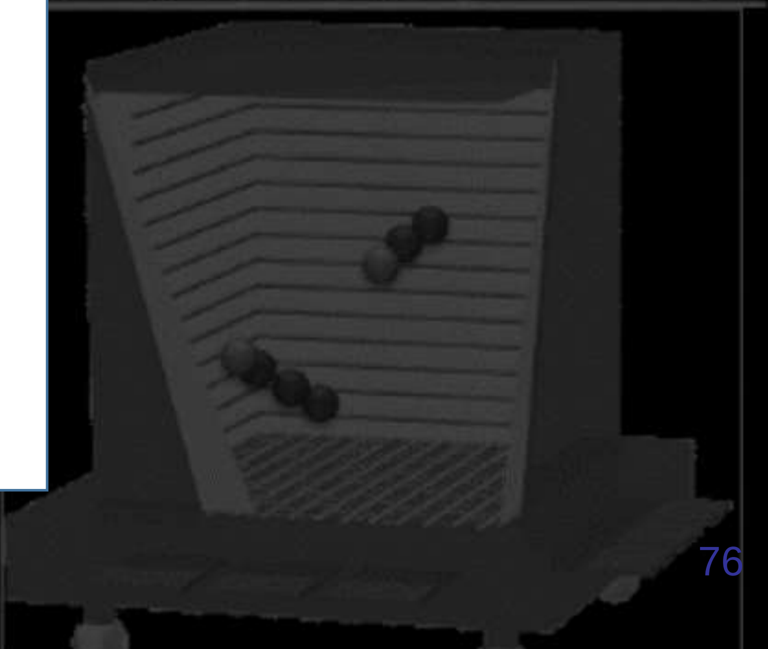
- SD interaction (contribution of either proton or neutron is considered)

$$C \propto \lambda^2 J(J+1)$$

λ: Lande factor

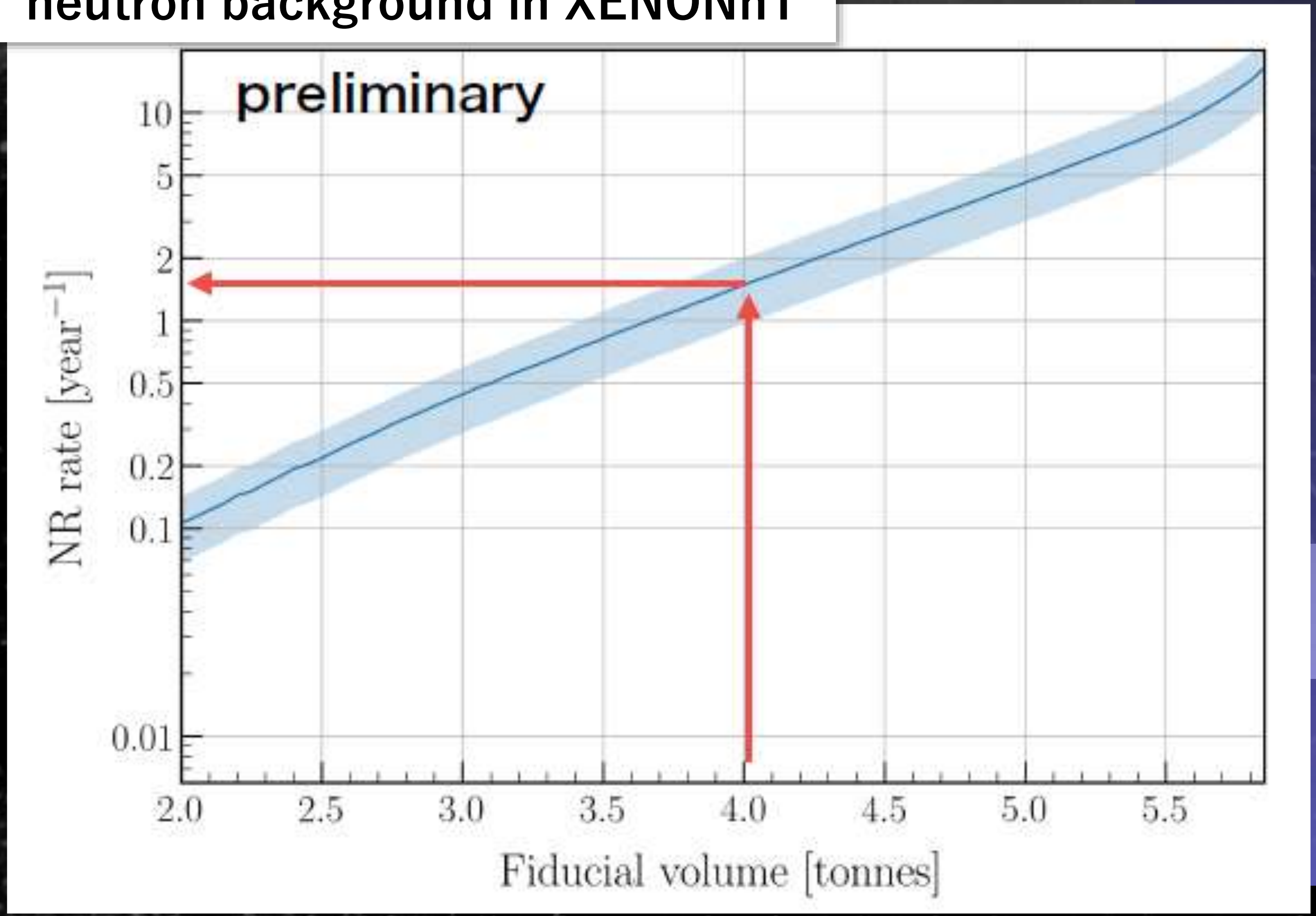
J: total spin of the

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

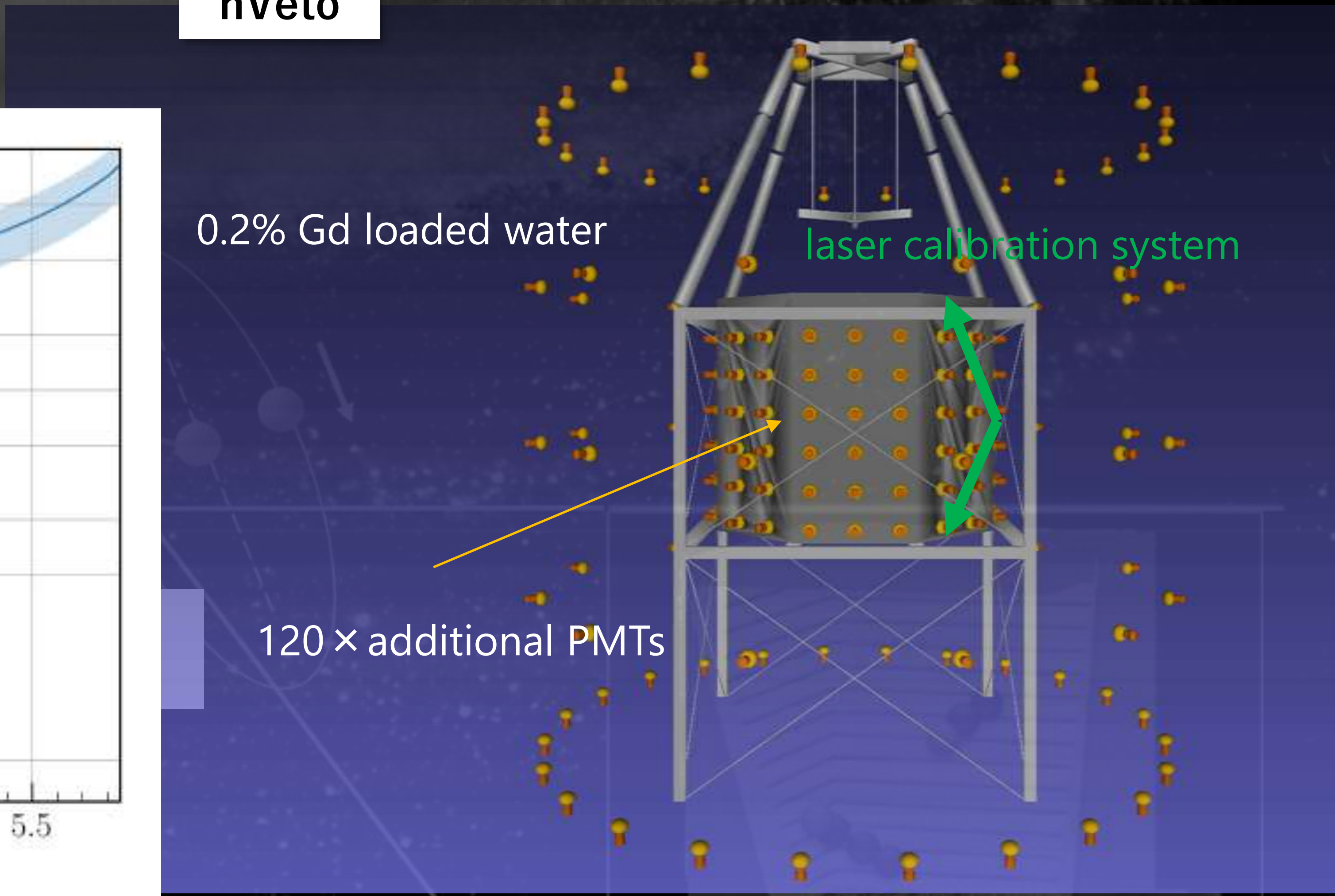


- XENONnT
  - Neutro BG（1.3events/4ton year） ⇒ neutron Veto(nVeto) detector
  - Load Gd in the water

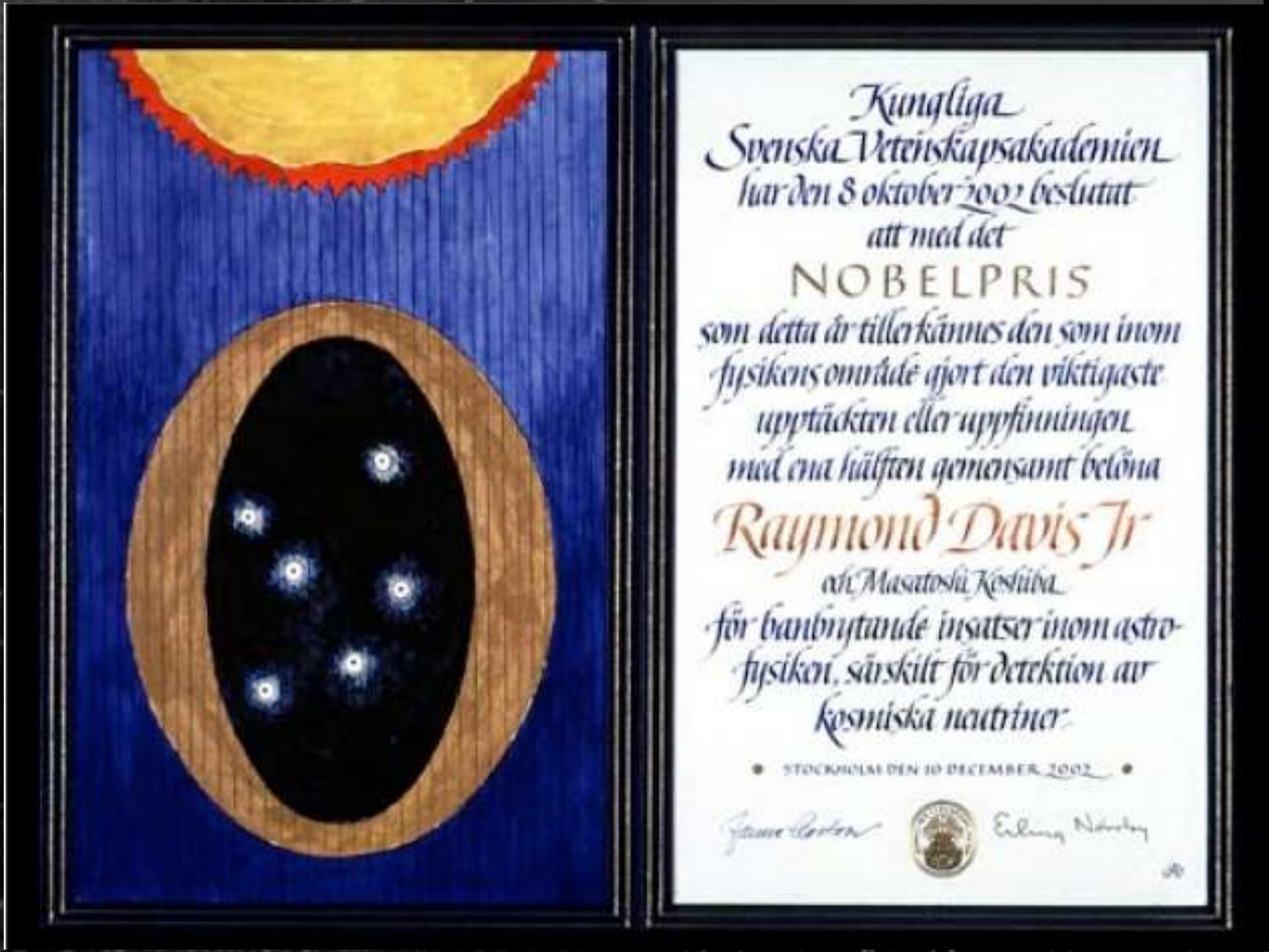
neutron background in XENONnT



nVeto



- 方向感度の重要性
  - 2002年ノーベル物理学賞（ニュートリノ天文学）
    数を数えた実験（Davis）+ 方向に感度を持つ実験（小柴）



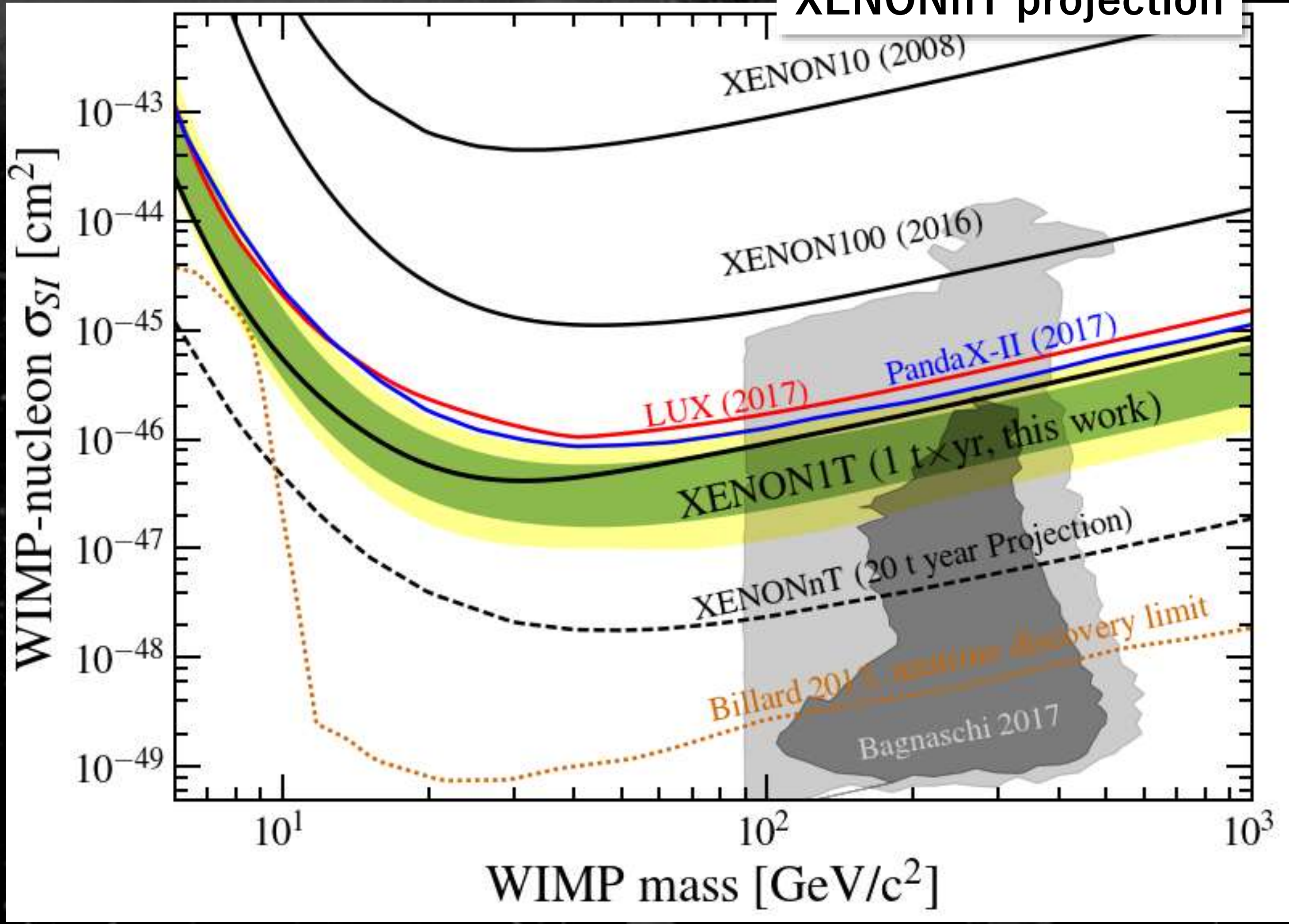
X 何とか

NEWAGE

Future

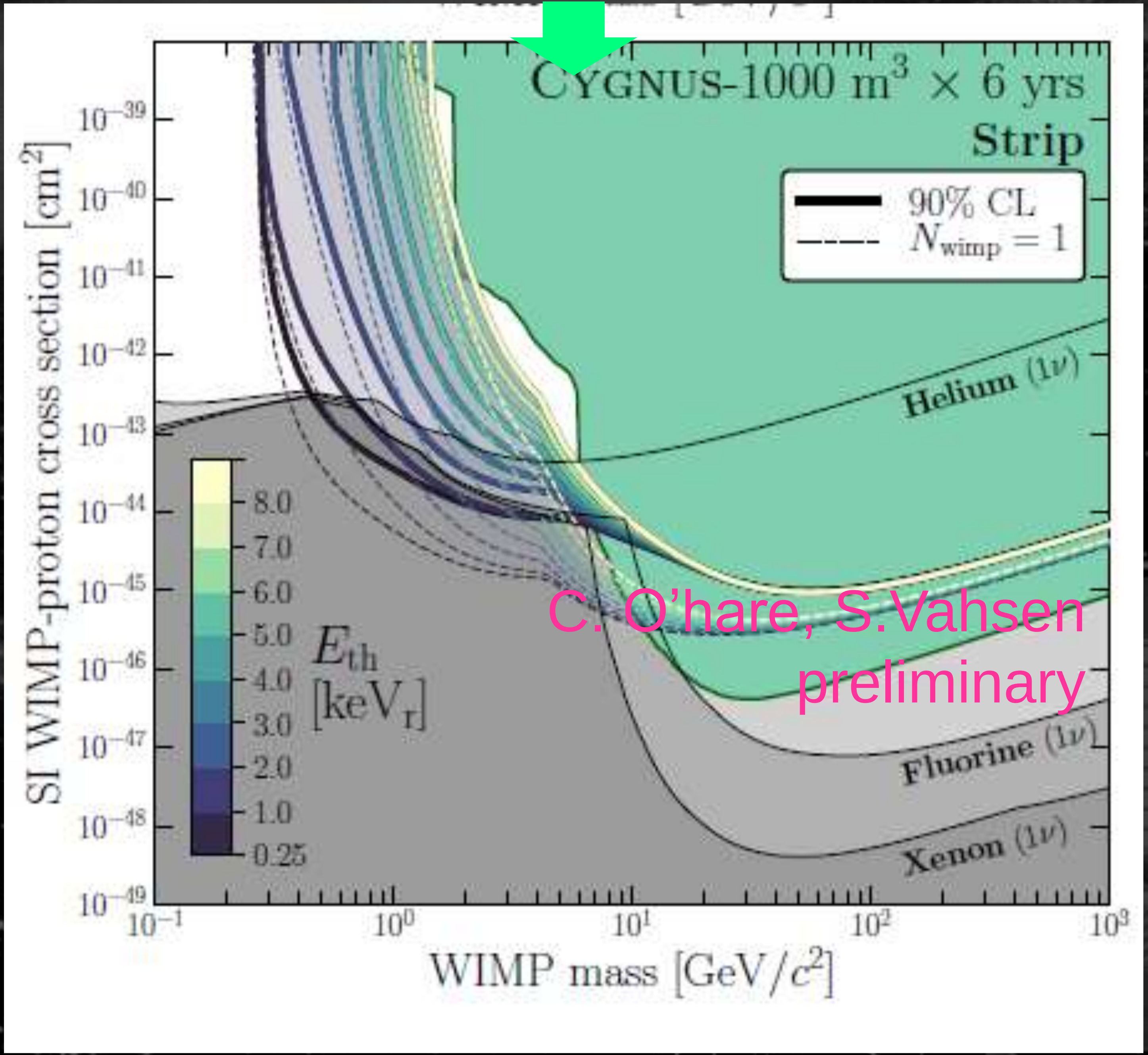
- Upcoming detectors: XENONnT, LZ
  - Fiducial mass: several ton
  - Constructions ongoing: observation 2020～
  - Japanese group （Kobe, Nagoya, Tokyo） joined XENONnT in 2017
  - Goal: a few $\times 10^{-48}$cm^2

XENONnT projection



Kentaro Miuchi

strip readout with
various threshold



- UK / Boulby
  - pioneered this field (DRIFT)
  - 1m^3 detector running underground (Boulby) for years
  - low BG, large volume

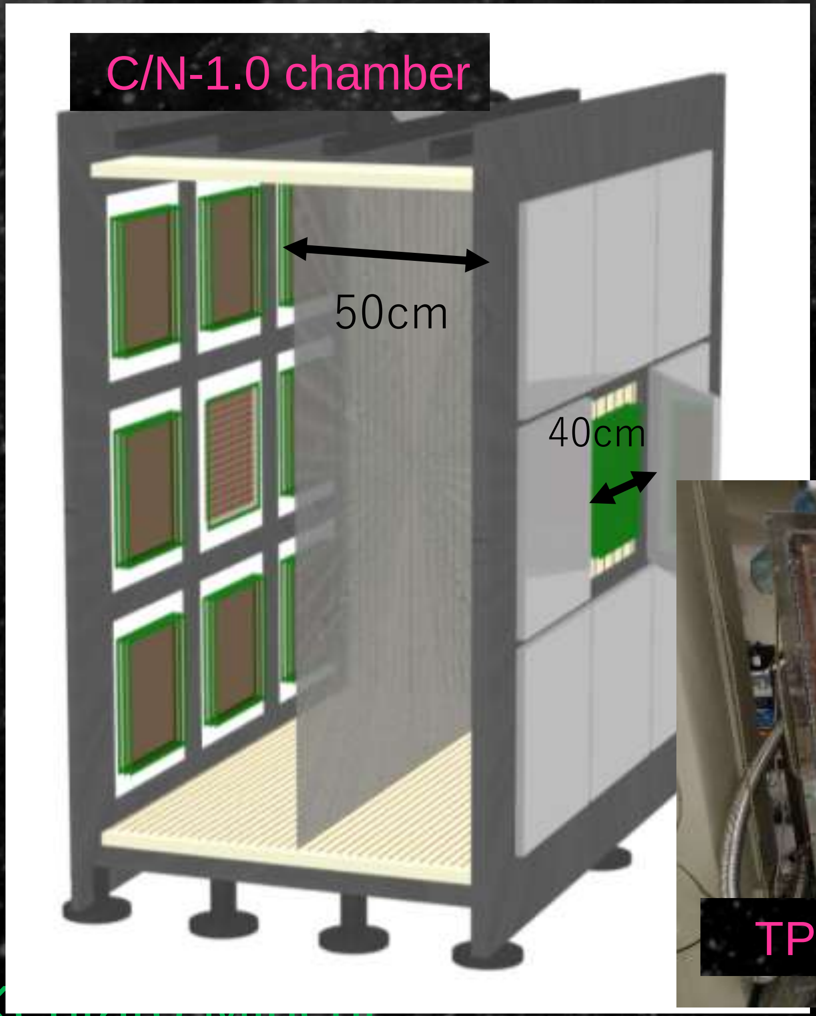
Boulby Underground Lab

- 10m^3 chamber design ongoing
  - low BG vessel design w/ simulation
  - R&D for GEM and wire readout
  - clean space underground at Boulby
  - easy to excavate more

- JAPAN / Kamioka

See T.Ikeda's Talk for NEWAGE

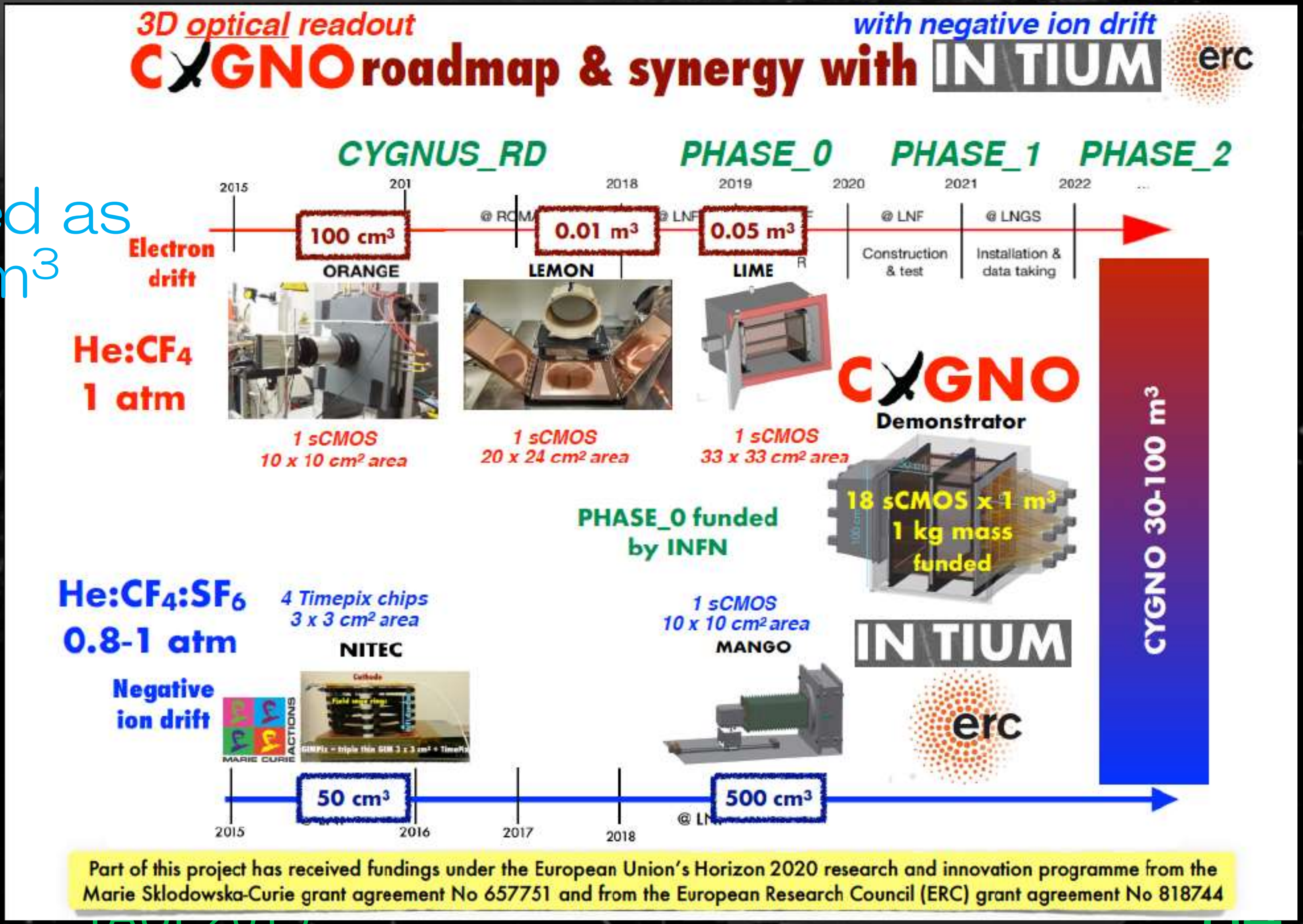
  - pioneered 3d-tracking (direction sensitive) (NEWAGE)
  - C/N-1.0 chamber (18 × 30×30 cm^2 detectors)
    - chamber ready
    - TPC cage (w/ resistive sheet), feedthrough being commissioned



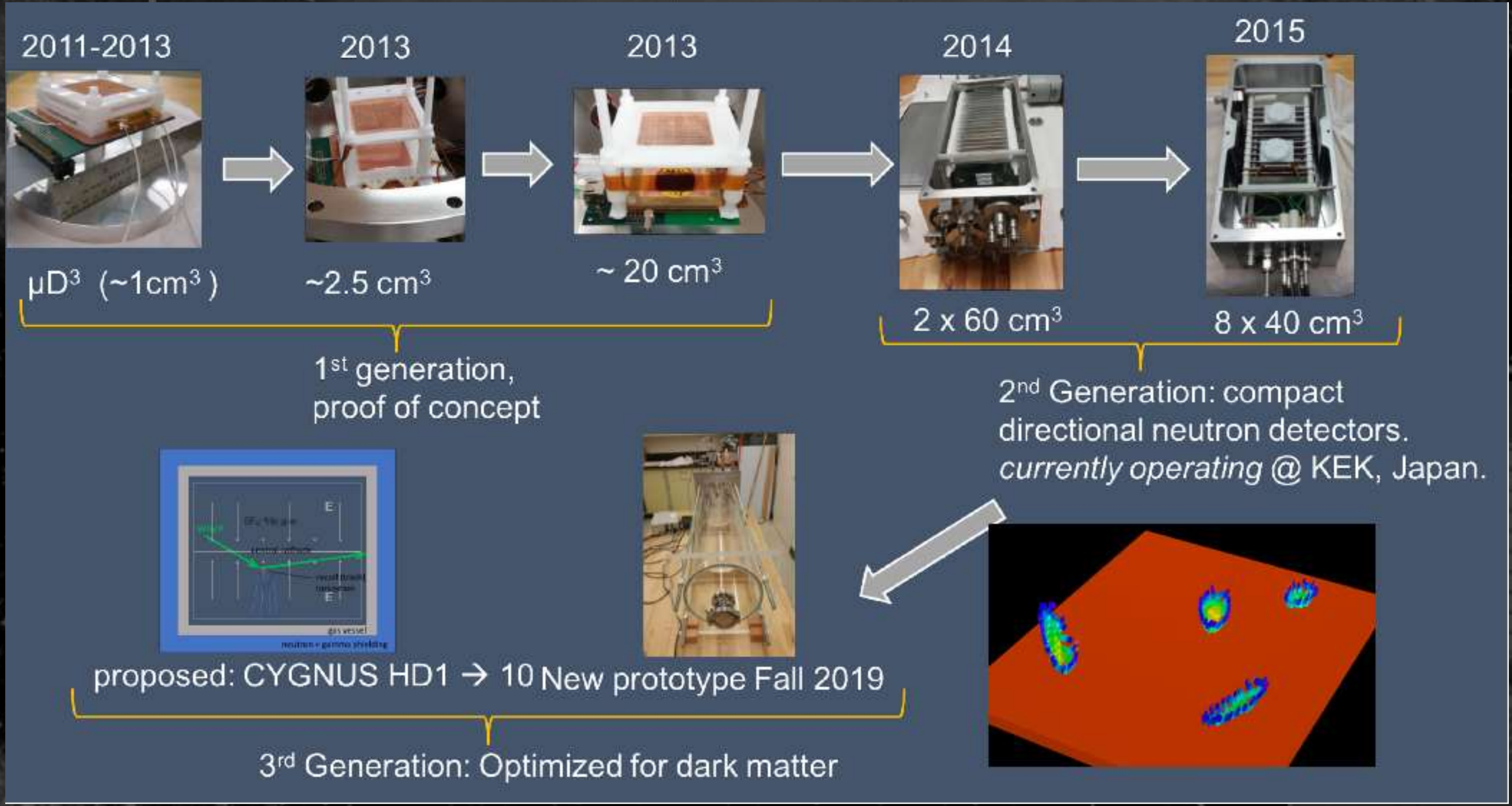
- Negative ion studies
  - 3-D tracking
  - MPGD gas avalanche simulation

- ASICs for negative ion strip readout
  - > 5k channels made
  - chip test started

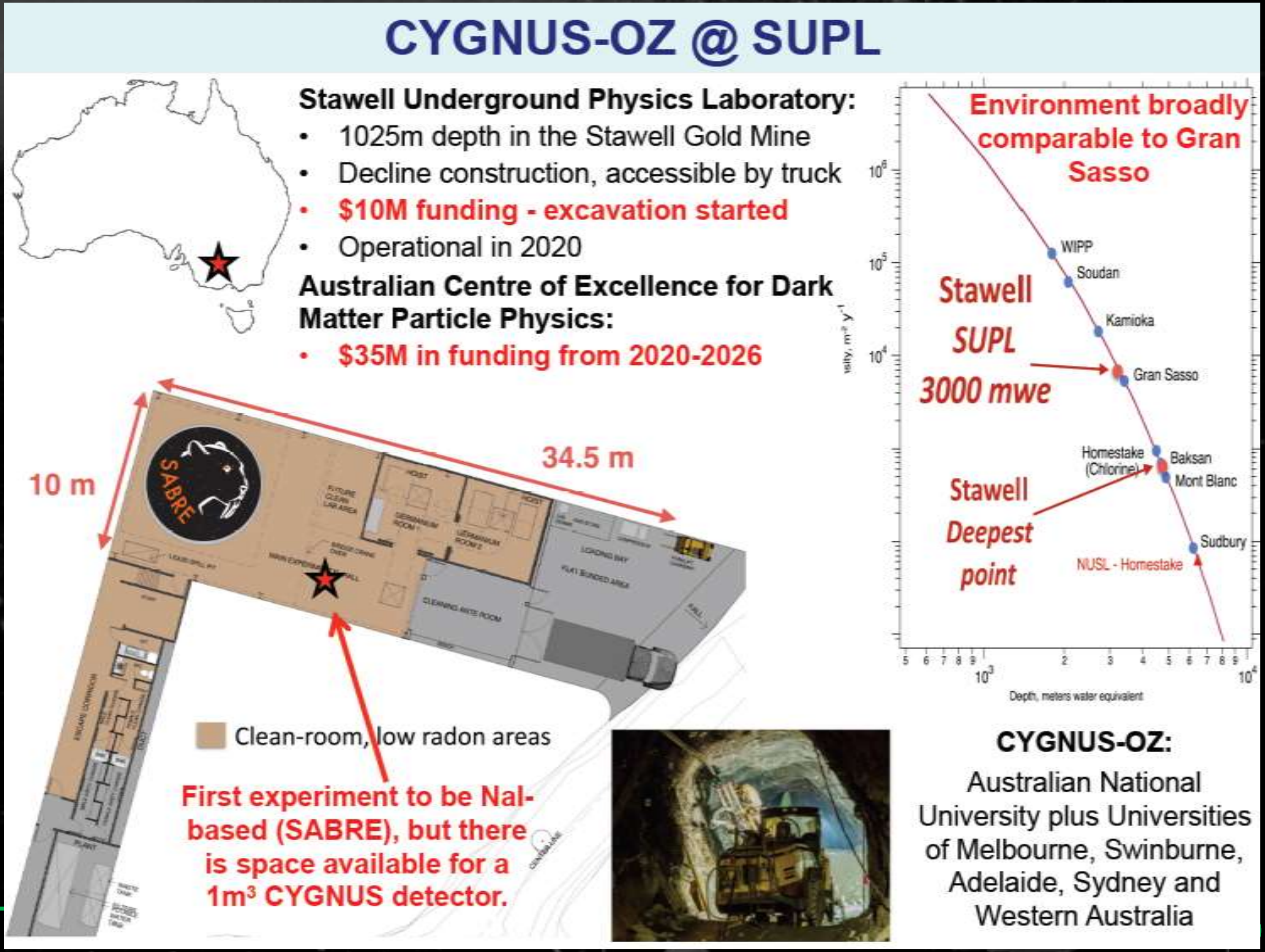
- Italy / GranSasso (intended) See E.Barracchini's Talk
  - Focusing optical readout
  - Two parallel R&D paths
    - electron drift
    - negative ion drift
  - 1 m^3 scale detector funded as demonstrator for 30-50m^3



- US / SURF (intended)
  - Focusing on pixel, strip readout (HD)
  - Extensive prototyping completed
  - CYGNUS HD1 1-m^3, demonstrator for 10 m^3, proposed



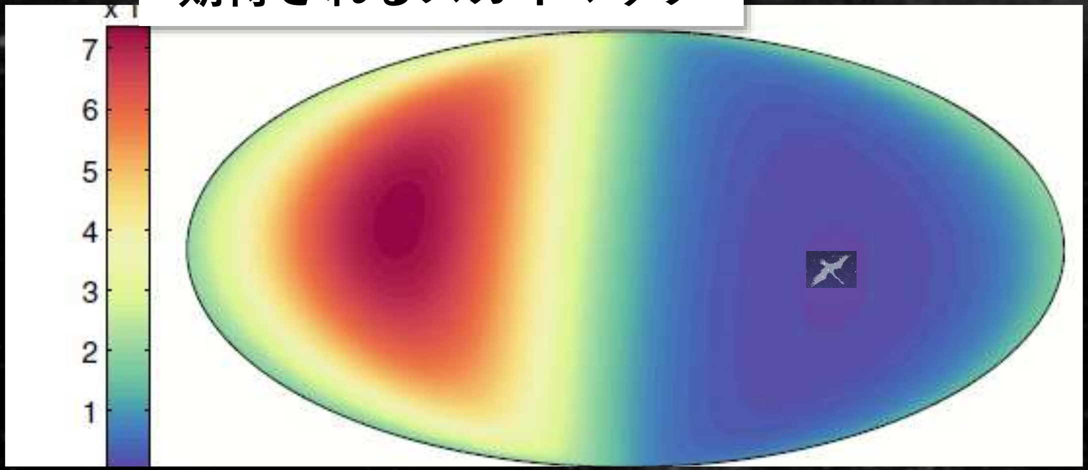
- Australia / Stawell
  - Excavation of new lab started - operation in 2020
  - Space available in 2020 for 1 m³ CYGNUS TPC, 10 m³ in 2025?
  - DM community recently funded - includes R&D for CYGNUS



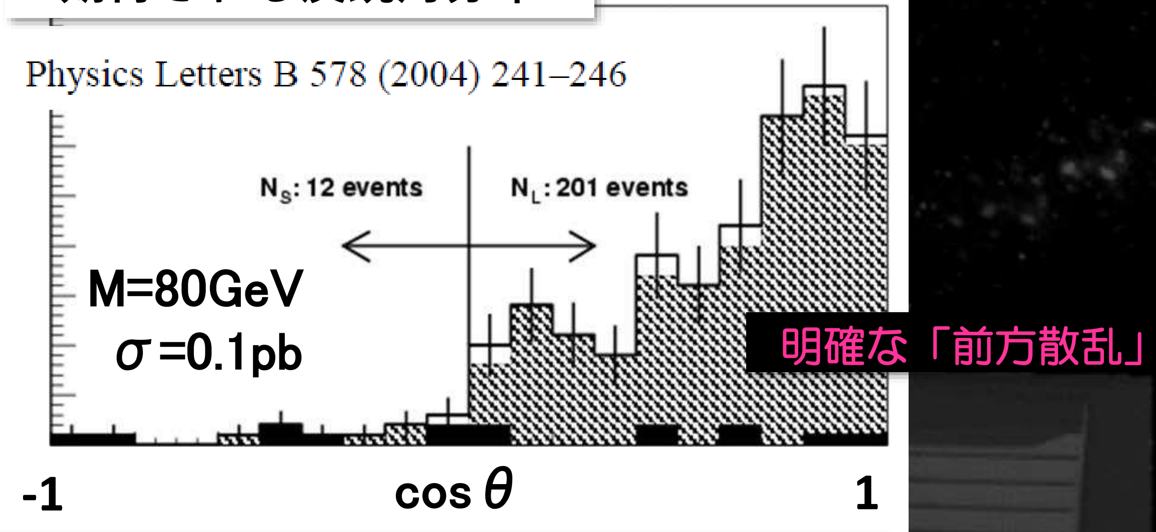
• CYGNUS① 確実な証拠

- 世界を呼び込んで暗黒物質の発見・性質解明
- O(10) 事象で前方散乱の証拠 （c.f. 季節変動 O（1e4）事象）

期待されるスカイマップ



期待される反跳角分布



（θ：はくちょう座の方向と原子核反跳の方向のなす角）

CYGNUS: community

- 7×bi-annual workshops (2007-)

  - CYGNUS 2017 Xichang, Sichuan, China June 13 - 16, 2017
  - CYGNUS 2015 Occidental College, Los Angeles, California, USA June 2 - 4, 2015.
  - CYGNUS 2013 Toyama, Japan June 10 - 12, 2013.
  - CYGNUS 2011 Aussois, France June 7 - 10, 2011.
  - CYGNUS 2009 Massachusetts Institute of Technology, Cambridge, Massachusetts, USA June 11 - 13, 2009.
  - CYGNUS 2007 Boulby Underground Laboratory, Saltburn-by-the-Sea, Cleveland, UK July 22 - 24, 2007.

CYGNUS 2019 @Roma

- 2 × review papers, another is coming

International Journal of Modern Physics A
Vol. 25, No. 1 (2010) 1–51
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www.worldscientific.com

THE CASE FOR A
DIRECTIONAL DARK MATTER DETECTOR AND
THE STATUS OF CURRENT EXPERIMENTAL EFFORTS

Readout technologies for directional WIMP Dark Matter detection

Physics Reports 662 (2016) 1–46

J.B.R. Battat [1,*], I.G. Irastorza [2], A. Aleksandrov
E. Baracchini [6], J. Billard [7,8], G. Bosson [7], O. Bourrion [7], J. Bouvier [7],
A. Buonaura [3,9], K. Burdge [10,11], S. Cebrián [2], P. Colas [12], L. Consiglio [13], T. Dafni [2],


Activities
Overview
Activities
Highlights
Summary

CYGNUS: collaboration

- proto-collaboration (2016-)
  - >50 researchers
  - discussion on-going for actual collaboration

The CYGNUS Galactic Directional Recoil Observatory
Proto-Collaboration Agreement

Now that conventional WIMP dark matter searches are approaching the neutrino floor, there has been a resurgence of interest in the possibility of introducing recoil direction sensitivity into the field. Such directional sensitivity would offer the powerful prospect of reaching below this floor, introducing both the possibility of identifying a clear signature for dark matter particles in the galaxy below this level but also of exploiting observation of coherent neutrino scattering from the Sun and other sources with directional sensitivity. There has also been significant progress recently in development of technology able to record the directional information from nuclear recoils at low energy (sub-100 keV) necessary for these goals. This includes progress on improving the sensitivity of low pressure gas time projection chamber technology but also on novel ideas with higher density targets, such as ultra-fine grain emulsions, scintillation materials, columnar recombination with noble gas targets and concepts using nano-technology. Such world-wide directional expertise, if pooled together and directed

steering committee

E. Baracchini (GSSI)
G. Lane (ANU, Canberra)
K. Miuchi (Kobe)
N. Spooner (Sheffield)
S. Vahsen (Hawaii)

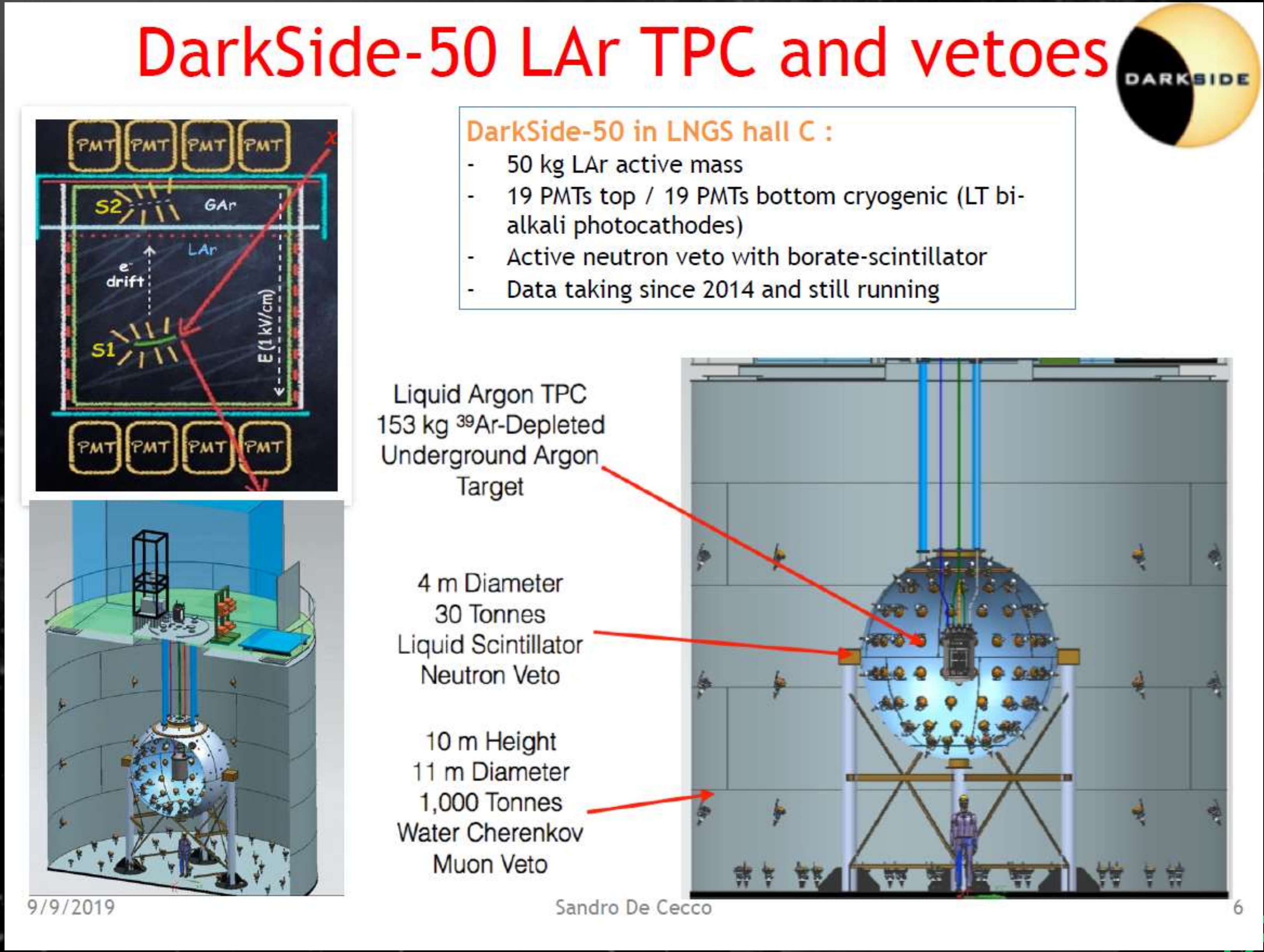
量子エレクトロニクス

- 量子情報とダークマター ①
  - 少ない数の電子を使ってダークマターサーチ
  - DarkSide S2-only 解析

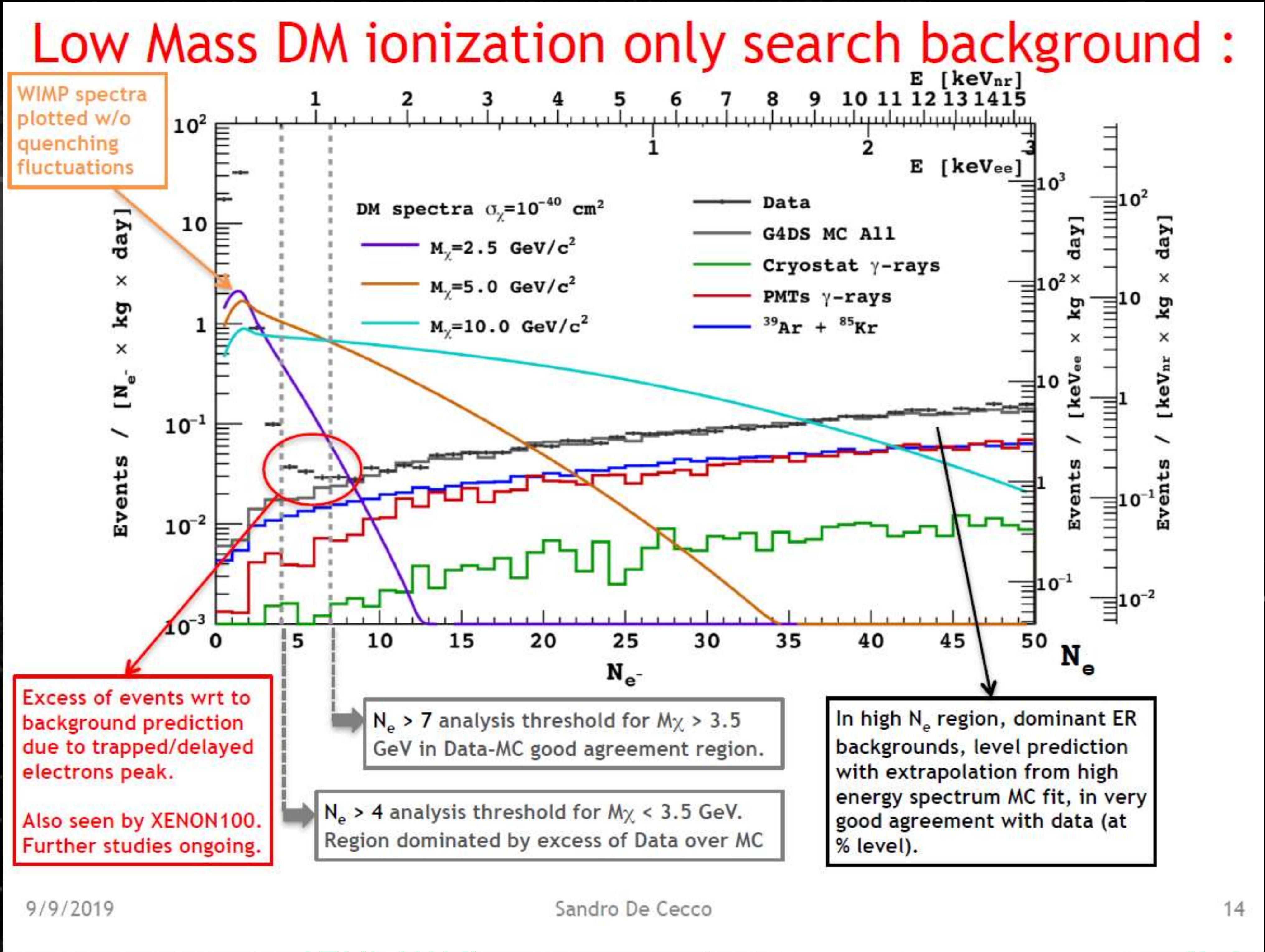
September 9th 2019
TAUP 2019, Toyama Japan

Sandro De Cecco

arXiv:1802.06994v1



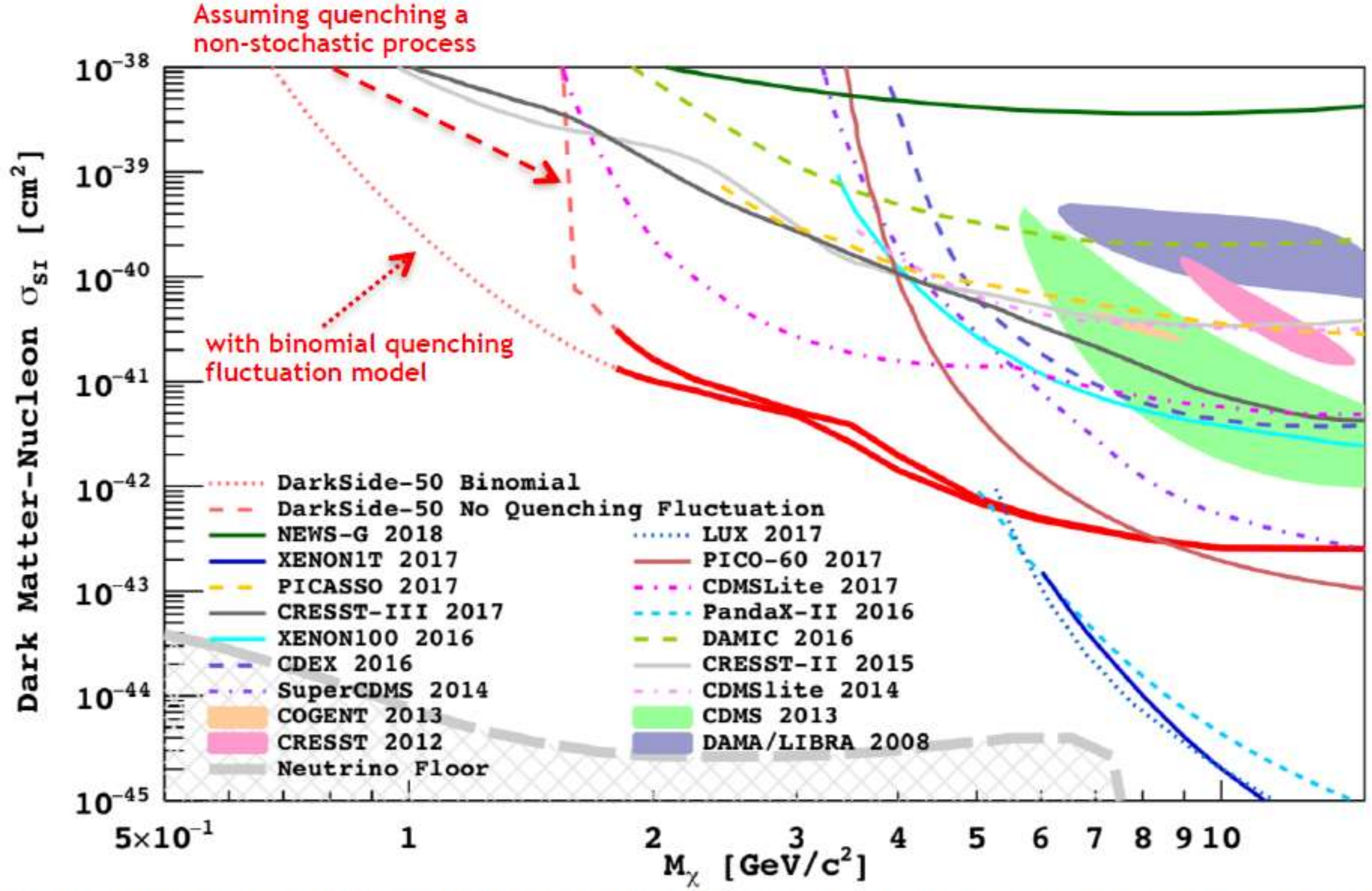
- 電子数>4を利用



Low Mass DM ionization only search background :
WIMP spectra plotted w/o quenching fluctuations
DM spectra σχ=10⁻⁴⁰ cm²
Mχ=2.5 GeV/c²
Mχ=5.0 GeV/c²
Mχ=10.0 GeV/c²
Data
G4DS MC All
Cryostat γ-rays
PMTs γ-rays
³⁹Ar + ⁸⁵Kr
E [keVnr]
E [keVee]
Events / [Ne- × kg × day]
Events / [keVee × kg × day]
Events / [keVnr × kg × day]
Ne-
Ne
Excess of events wrt to background prediction due to trapped/delayed electrons peak.
Also seen by XENON100. Further studies ongoing.
Ne > 7 analysis threshold for Mχ > 3.5 GeV in Data-MC good agreement region.
Ne > 4 analysis threshold for Mχ < 3.5 GeV. Region dominated by excess of Data over MC
In high Ne region, dominant ER backgrounds, level prediction with extrapolation from high energy spectrum MC fit, in very good agreement with data (at % level).
9/9/2019
Sandro De Cecco
14

- 低質量DMでよい制限

Low Mass DM 90% C.L. exclusion limit result :

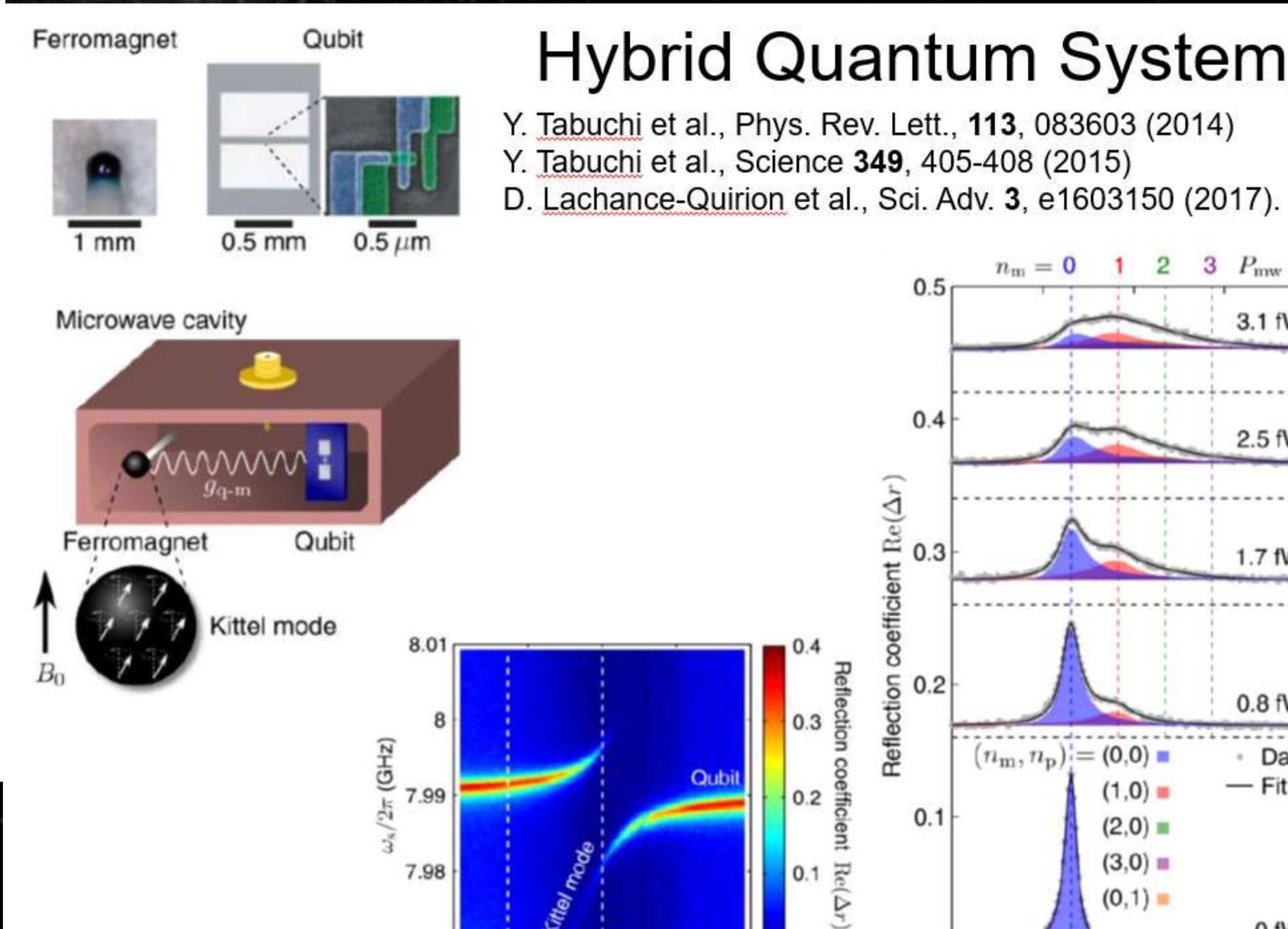


- Profile Likelihood Method for $N_e>4$ and $N_e>7$ thresholds shown respectively for Mχ < 3.5 GeV and Mχ > 3.5 GeV
- Uncertainties for both WIMP signals (NR ionization yield, single electron yields) and BG spectrum (rates, ER ioniz. yield)

Due to lack of knowledge about fluctuation at very low recoil energy, two cases :

- Binomial fluctuation for NR energy quenching, ionization, and recombination processes.
- No Fluctuation for NR energy quenching process. Corresponding to apply hard cut off in quenched energy ~0.6 keV_{nr}

- 量子エレクトロニクス
  - 2018年1月 鹿野氏セミナー@神戸

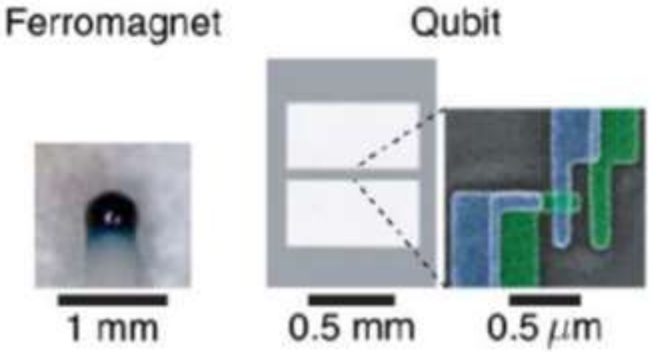


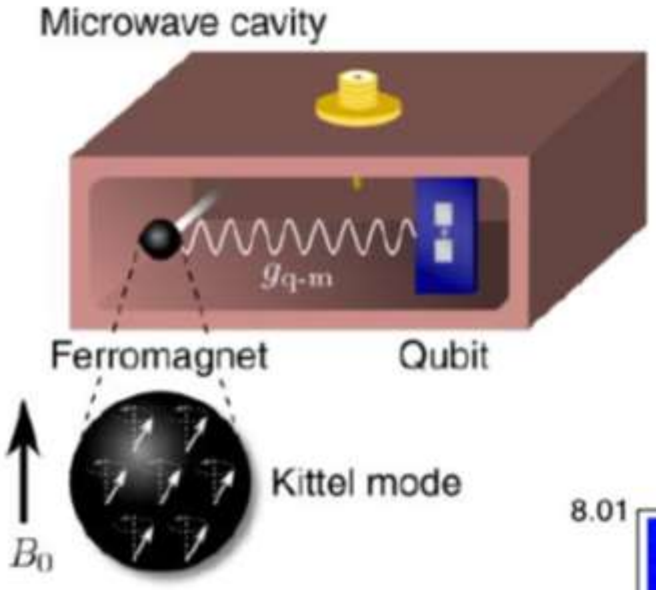
Kentaro Miuchi

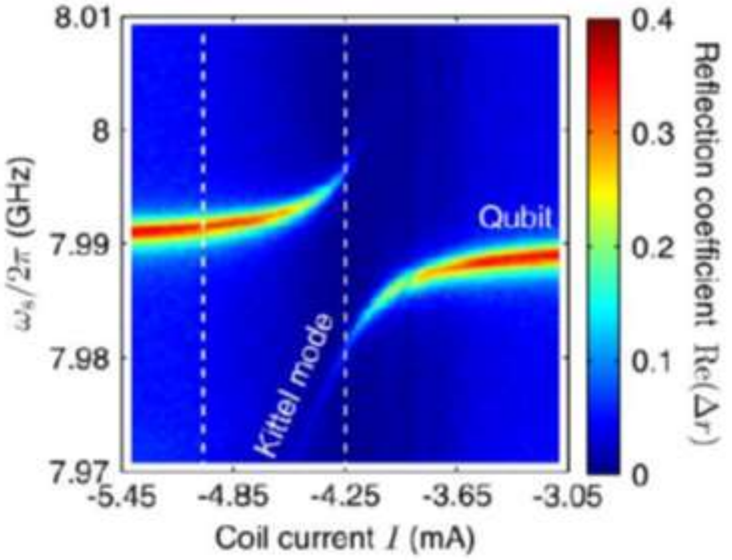
- “QBIT”
  - 磁場を感じる
  - アクシオン探索
    できんじゃね？

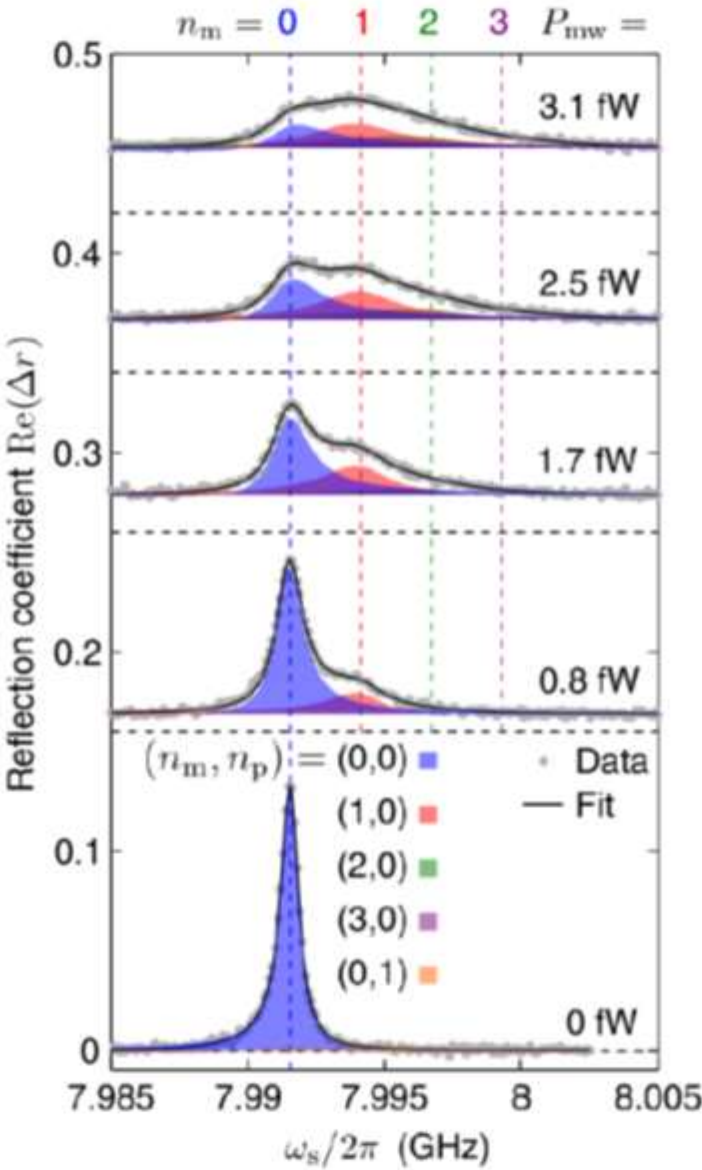
Hybrid Quantum System

Y. Tabuchi et al., Phys. Rev. Lett., **113**, 083603 (2014)
Y. Tabuchi et al., Science **349**, 405-408 (2015)
D. Lachance-Quirion et al., Sci. Adv. **3**, e1603150 (2017).









鹿野セミナー
201801@神戸

Kentaro Miuchi

17aS28-6

マグノン検出器を用いたアクシオン探索実験

池田 智法[A]

身内賢太朗[A]、伊藤飛鳥[A]、早田次郎[A]、鹿野豊[B,C]

神戸大学[A]、慶応大量子[B]、チャップマン大量子科学研[C]

1. モチベーション
2. 観測原理
3. アクシオン探索実験結果
4. まとめ

- DM アクシオン
- 電子と相互作用
  - 電子1個との相互作用は小さい

⇒「マグノン」を用いる

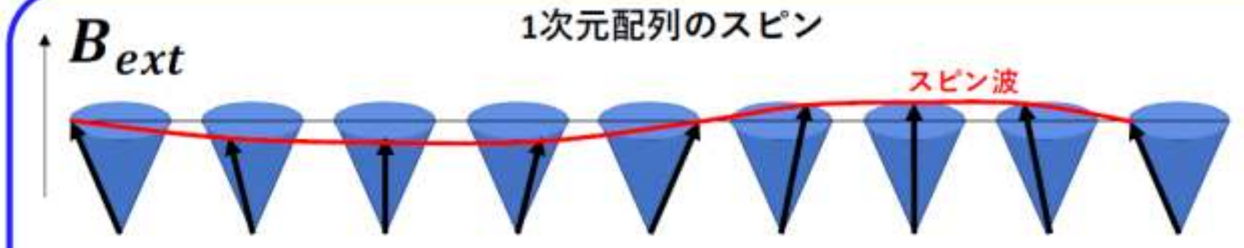
電子のスピン集団

✓ 強磁性体中のスピン同士の相互作用

$$\hat{\mathcal{H}} = -g\mu_B B_z \sum_i \hat{S}_i^z - 2J \sum_{\langle i,j \rangle} \hat{\mathbf{S}}_i \cdot \hat{\mathbf{S}}_j,$$

隣り合うスピンの相互作用
隣のスピンの向きをわずかに傾ける

1次元配列のスピン



➤ スピン集団の励起状態は強磁性体中を伝わる波(マグノン)として記述できる

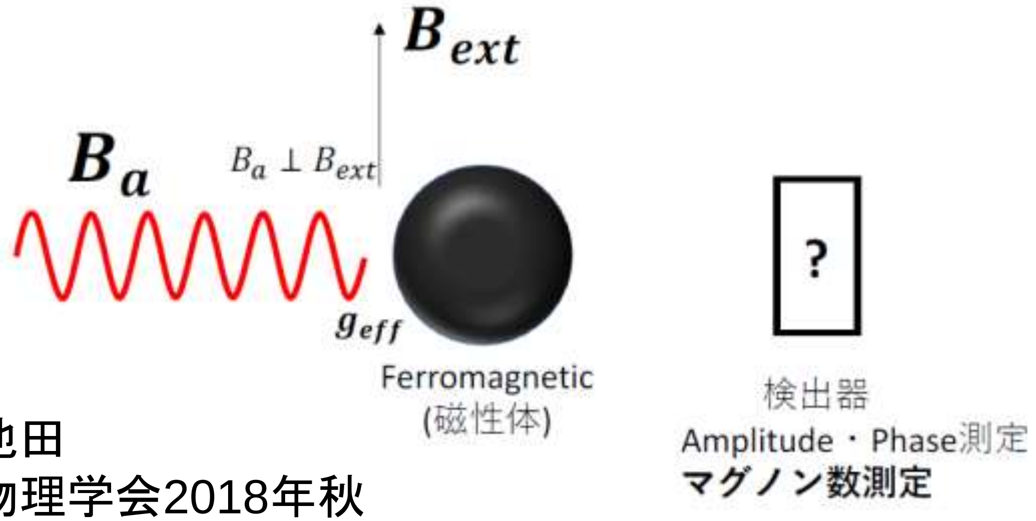
✓ マグノンとアクシオンの相互作用項

$$\mathcal{H}_{int} = \hbar g_{eff}(\hat{a}^\dagger \hat{c} + \hat{a}\hat{c}^\dagger), \quad g_{eff} \equiv \frac{g\mu_B B_a}{2\hbar}\sqrt{2sN},$$

$\sqrt{N}$倍大きい

池田
物理学会2018年秋

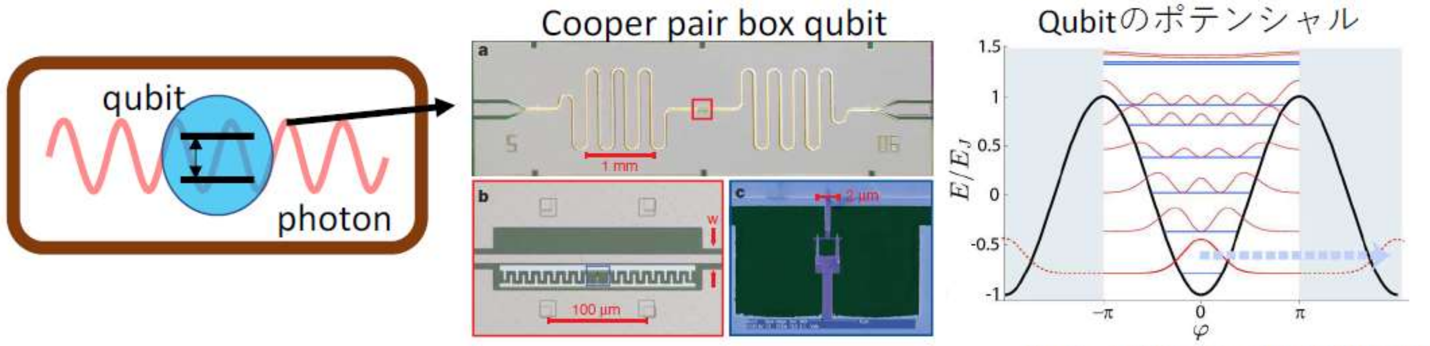
アクシオンの検出方法



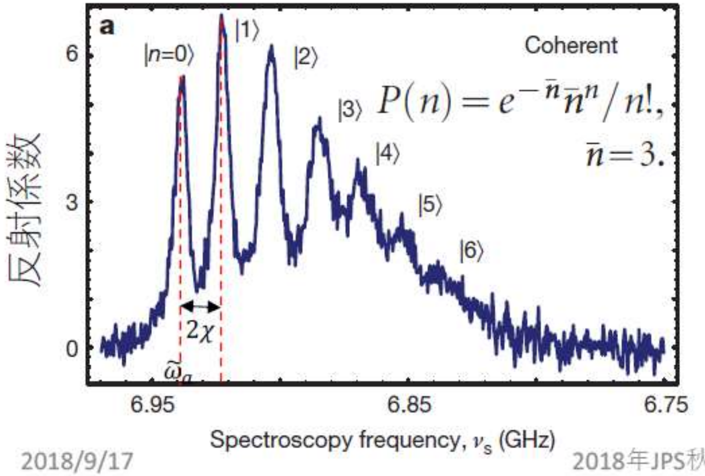
池田
物理学会2018年秋

人工原子(Qubit)を使った光子数測定

✓ リドベルグ原子から人工原子(Qubit)へ **D.I.Schuster, et.al., Nature 445 515(2007)**



J.Koch, et.al, Phys.Rev.A76,042319(2007

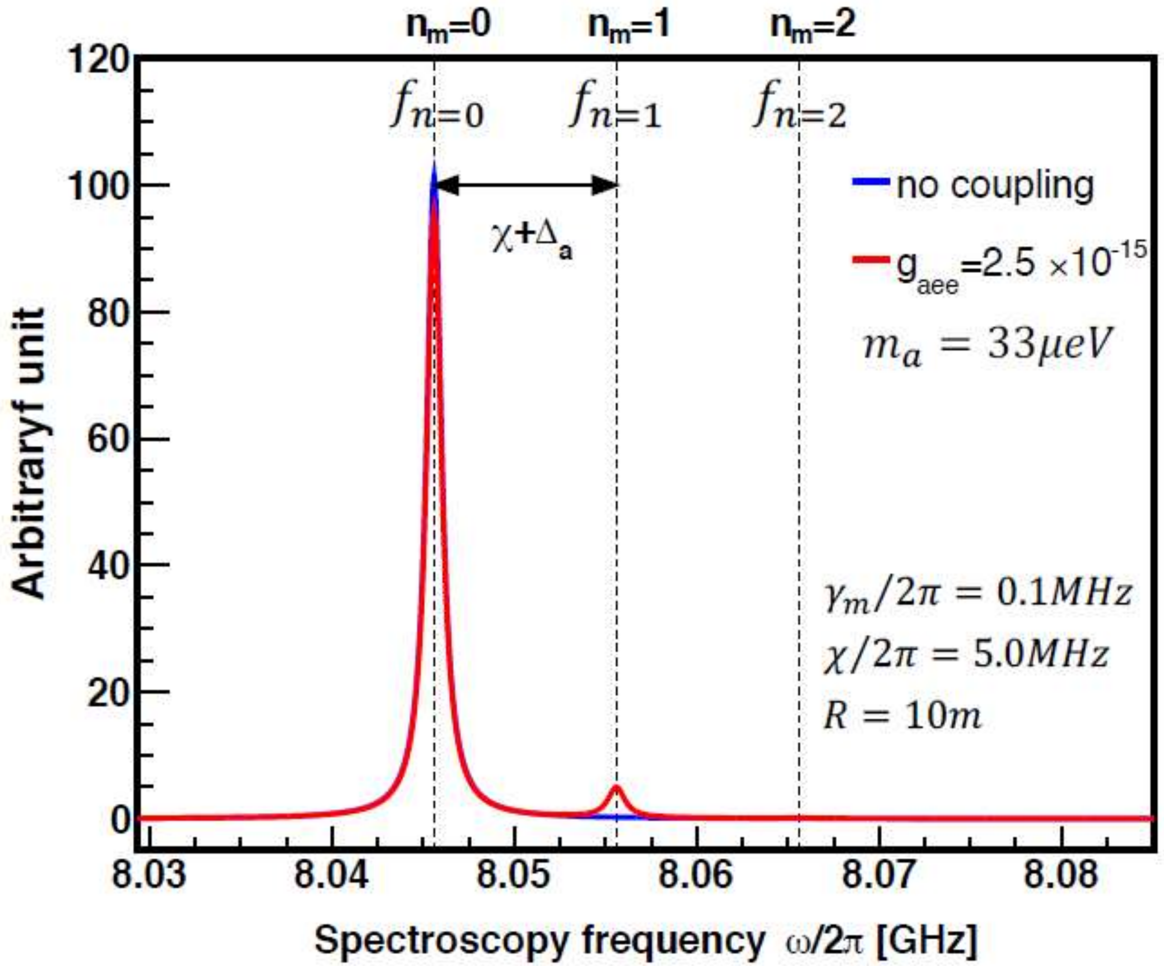


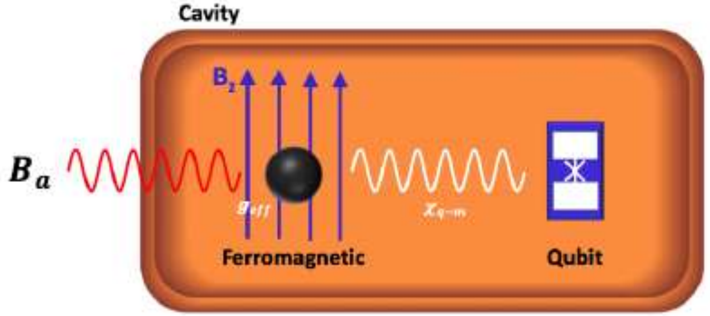
$$H_{\rm eff} = \hbar\omega_r \hat a^\dagger \hat a + \frac{\hbar}{2}\left(\tilde\omega_a + 2\chi \hat a^\dagger \hat a\right)\hat\sigma_z$$

➤ **Qubitの遷移周波数から光子数を決定できている**

池田
物理学会2018年秋

アクシオン-マグノン結合の期待されるスペクトル





✓ アクシオンとマグノンの結合力

$$g_{eff} \equiv \frac{g\mu_B B_a}{2\hbar}\sqrt{2sN},$$

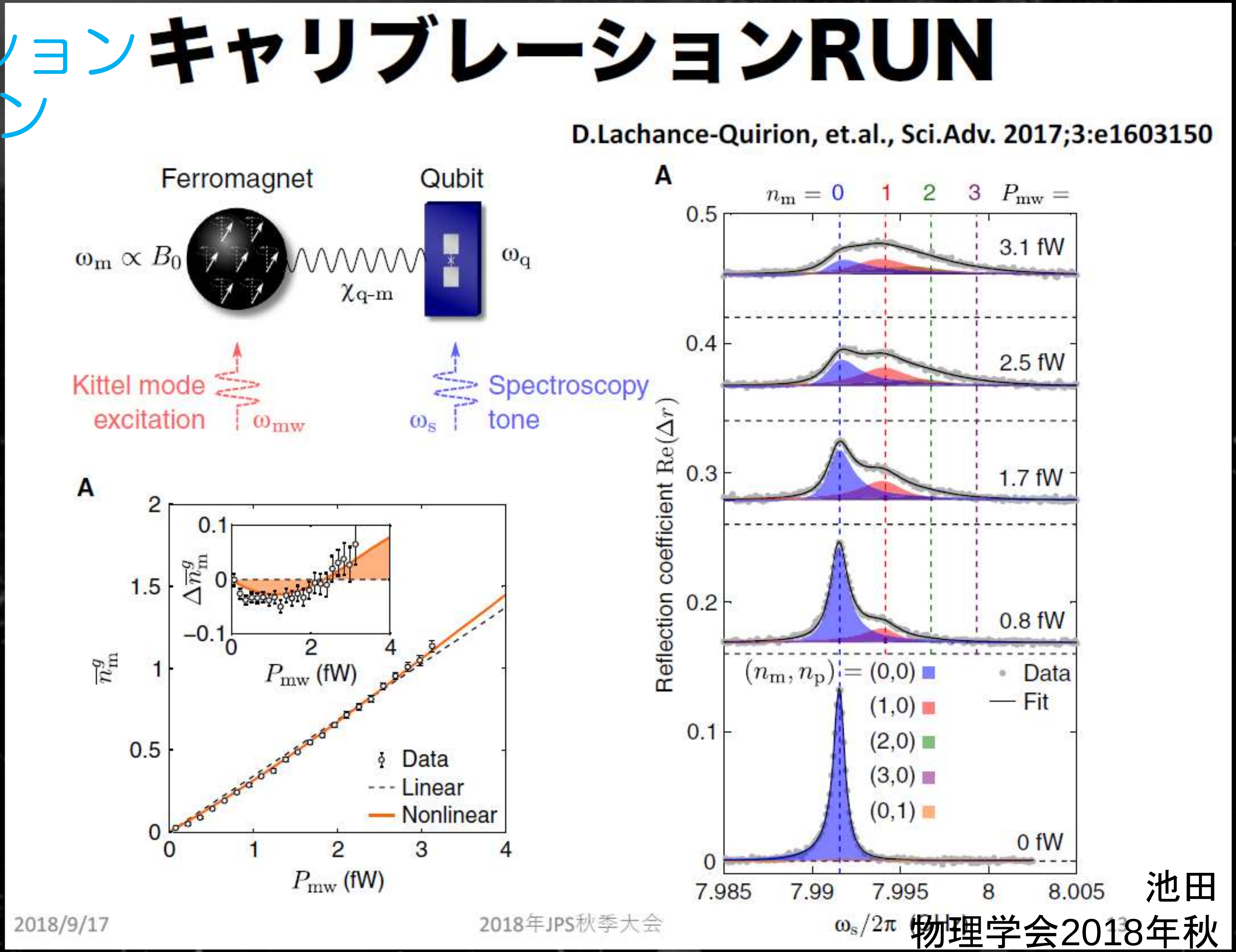
✓ 平均マグノン数

$$\bar{n}^m_\pm = \frac{g^2_{eff}}{\gamma^2_m/4 + (\Delta_a \pm \chi)^2},$$

➤ **アクシオンとマグノンが結合していれば、Qubitの遷移周波数$f_{n=1}$にピークがたつ**

池田
物理学会2018年秋

- 実験
  - アクシオンデータ
    というか量子情報のBGデータ
  - 量子情報のデモンストレーション
    =我々のキャリブレーション



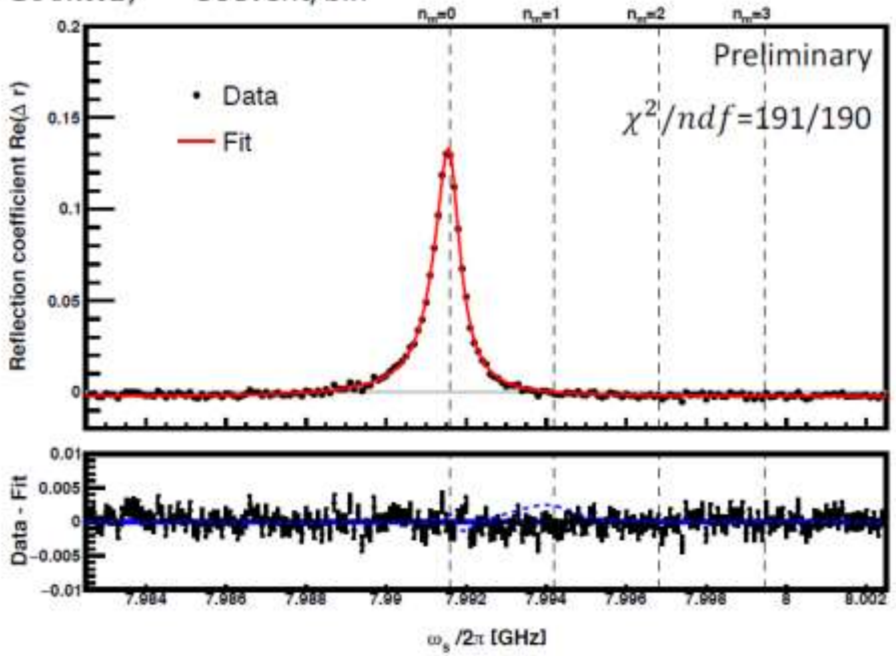
池田
物理学会2018年秋

Kentaro Miuchi

• 結果

DMRUN

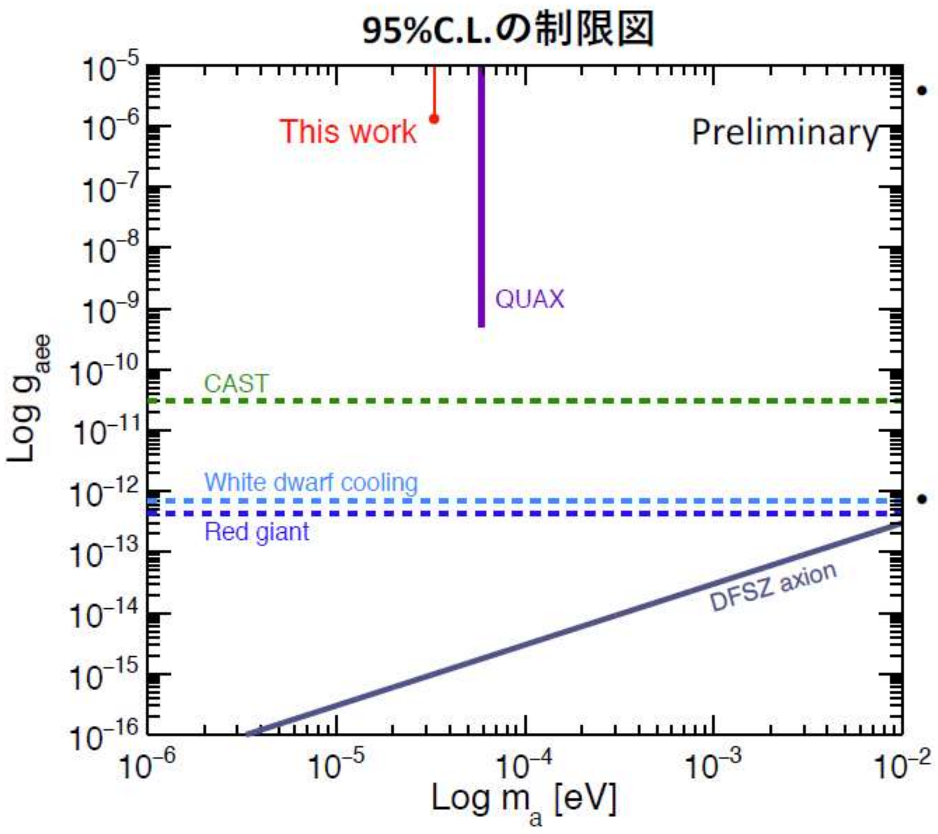
- 2015年8月に取得された4時間分のデータ
  $\Delta f = 100kHz,$ 50event/bin



➢ 統計的に有意な差は見られなかった

2018/9/17 2018年JPS秋季大会

制限図



- アクシオン質量33μeVについて、95%信頼度の上限を与えた

$$B_a < 4.1 \times 10^{-14} \ [\mathrm{T}].$$

$$g_{aee} < 1.3 \times 10^{-6}$$

- 感度を制限している要因
  - ✓ 強磁性体のQ値(約1000)

$$\bar{n}^m_{\pm} = \frac{g^2_{eff}}{\gamma^2_m/4 + (\Delta_a \pm \chi)^2},$$

現状CavityのQ値より3桁悪い

2018/9/17 2018年JPS秋季大会

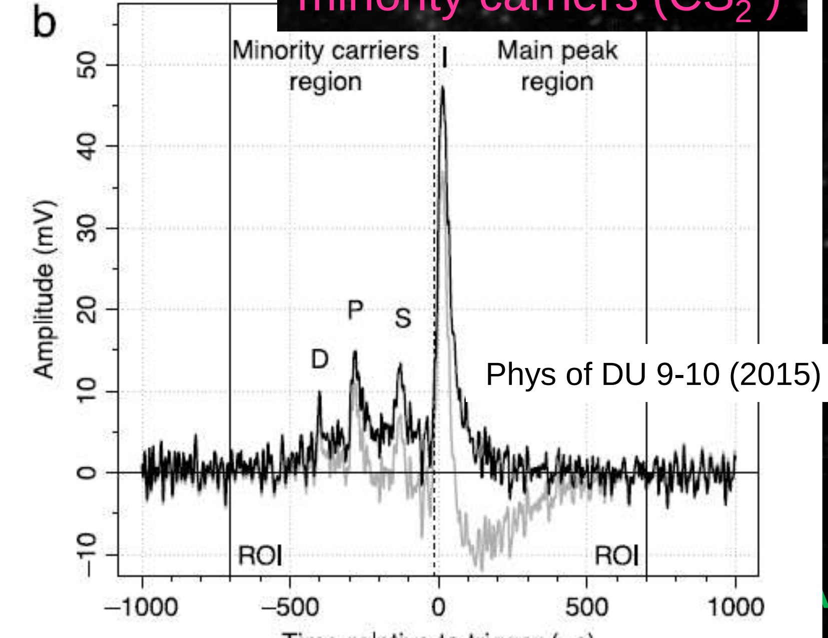
池田
物理学会2018年秋

- この先：Q値（カップリング）を上げながら大きくしたい
- ちなみに：マグノン-GHｚ重力波のカップルもある（らしい） 1903.04843

Highlight 2: Negative ion TPC Study

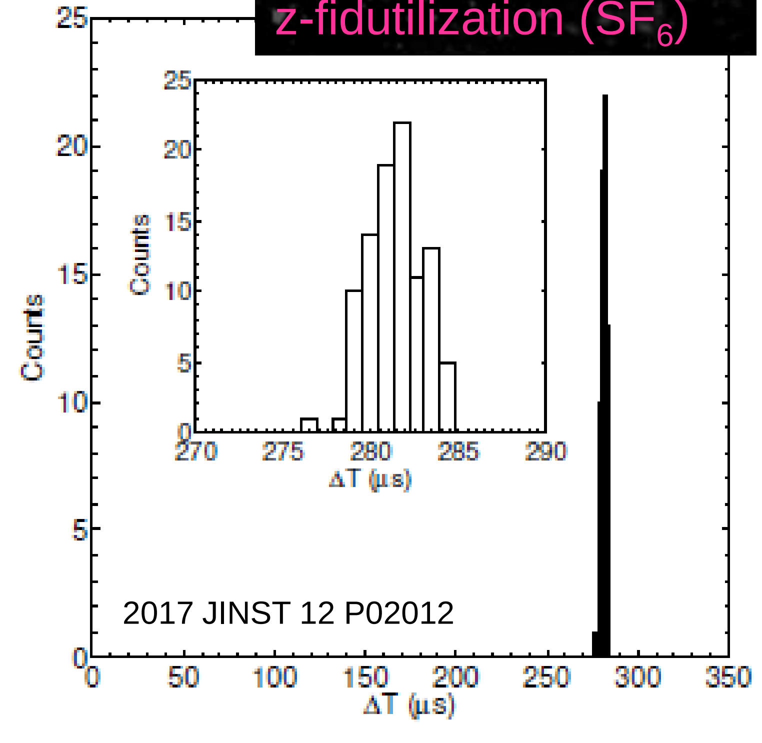
- Pioneered by DRIFT group — small diffusion
- Minority carrier discovery (CS_2+O_2, Occidental group)
  - use several ion species with different drift velocities
  - ⇒ z fiducialization possible ⇒LOW BG !
- SF_6 discovery (2015, UNM group)
  - z-fiducialization 7.3mm FWHM

minority carriers (CS_2)



Phys of DU 9-10 (2015) 1

z-fidutilization (SF_6)



2017 JINST 12 P02012

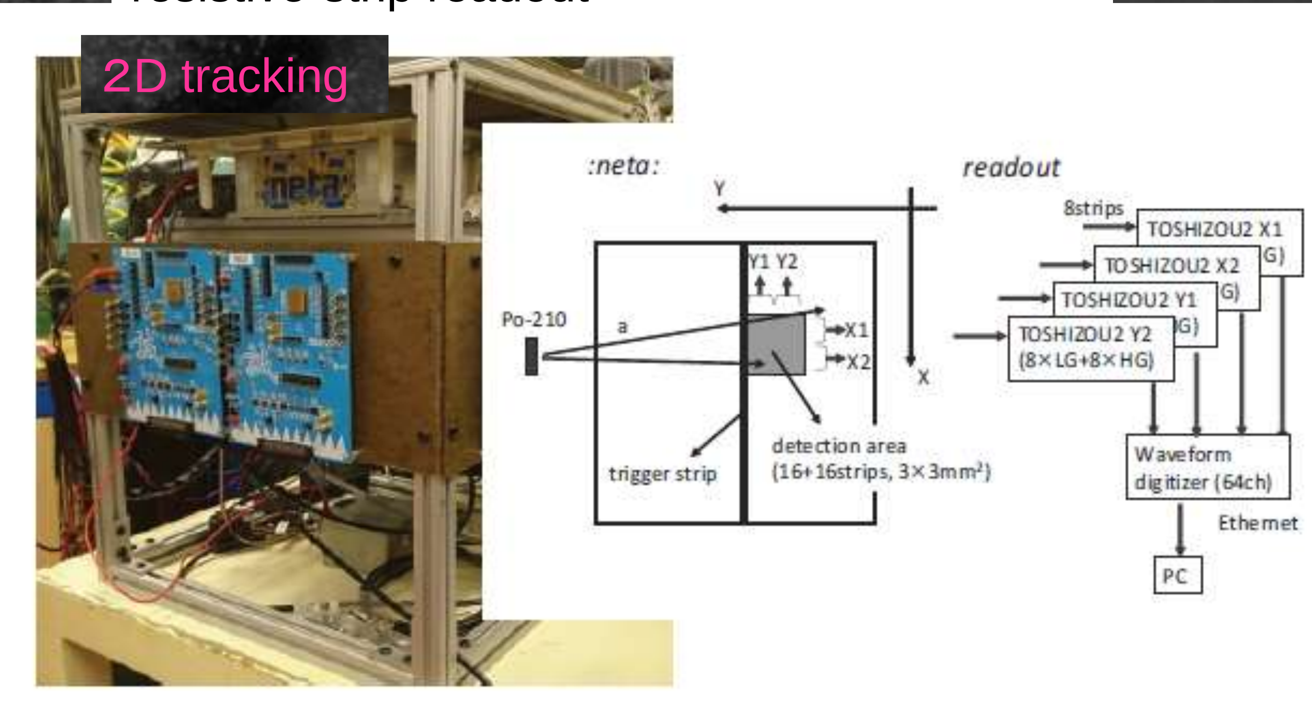
(a) ΔT laser calibration pulses

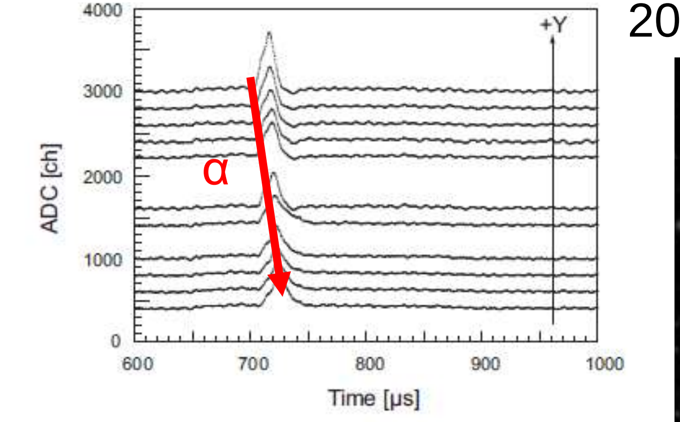
• to be CYGNUS: Trackings

• strip readout + ASICs

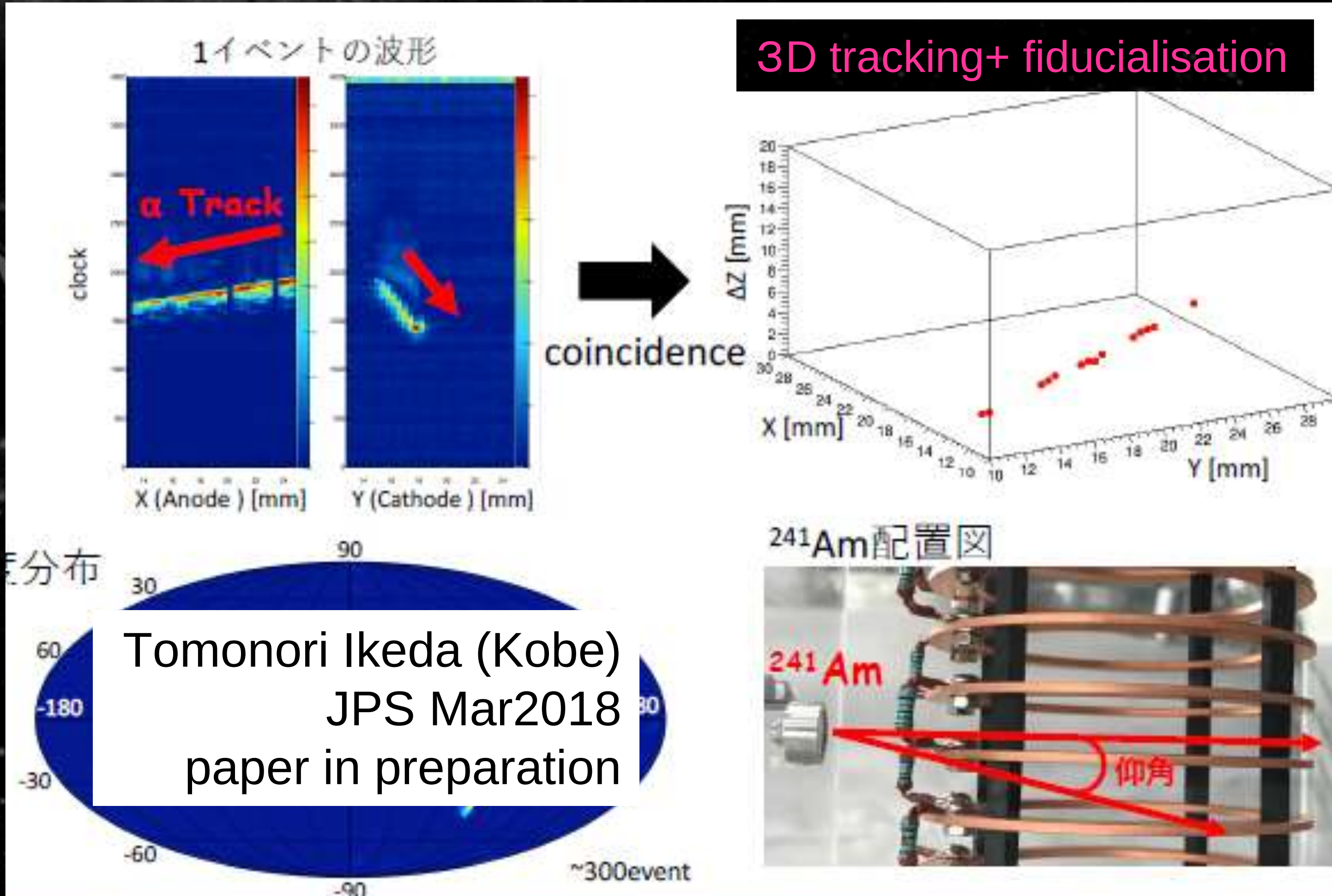
for optical redout: See E.Barracchini's Talk

LTARS2016 + Wellesley's micromegas resistive-strip readout



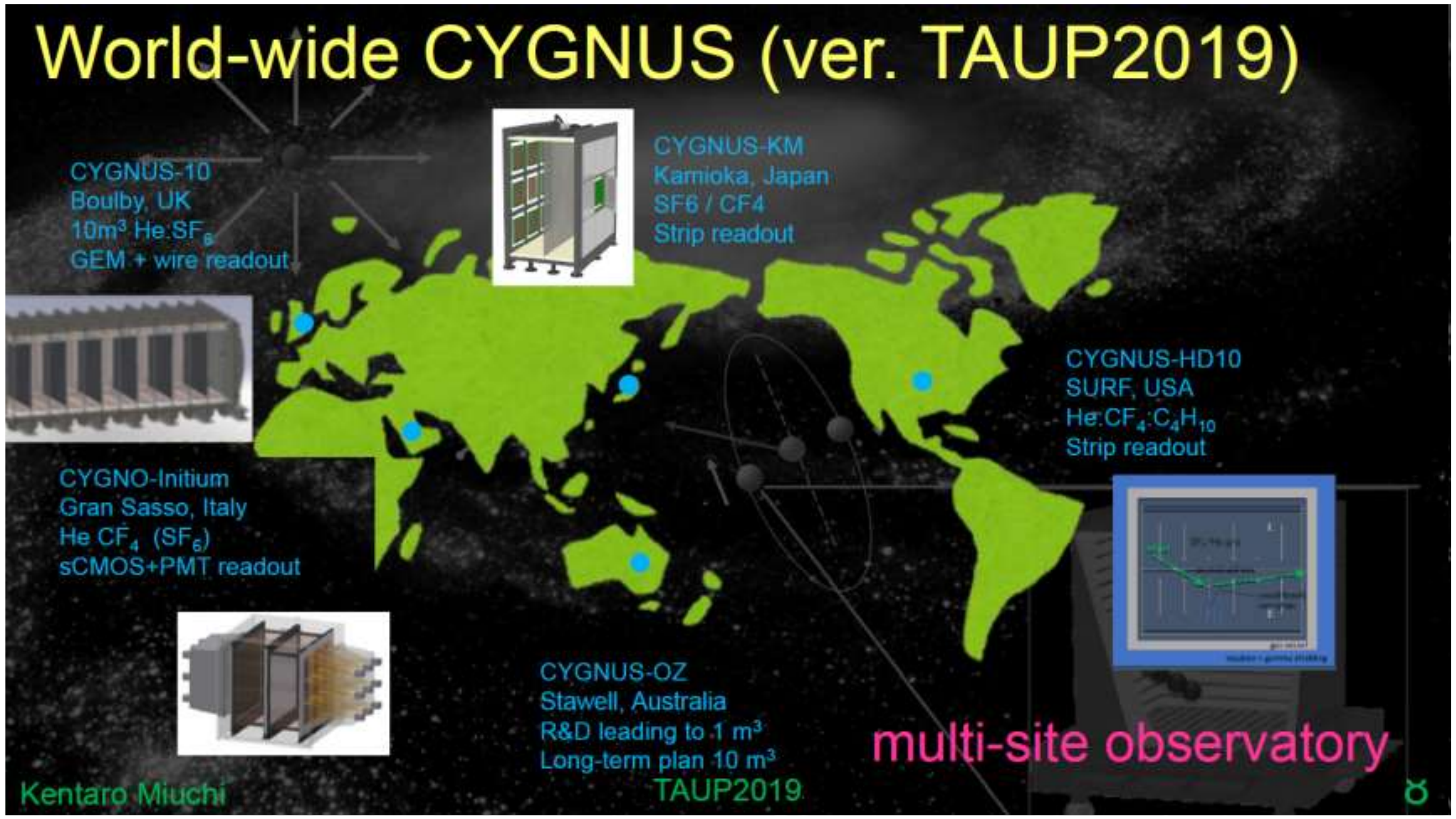


2019 J. Inst. 14 T01008



Tomonori Ikeda (Kobe)
JPS Mar2018
paper in preparation

- NEWAGE/CYGNUS
  - 方向感度の国際共同フレームワーク：CYGNUS
  - 5人のsteering committeeの1員として議論をリード



NEWAGE 検出器　NEWAGE-0.3b

- 検出容積: 31×31×41cm3
- ターゲットガス: CF_4 at 0.1気圧 (エネルギー閾値 50keVee)
- 冷却活性炭を用いたガス循環システム

Field cage
Drift length: 41cm
PEEK + copper wires

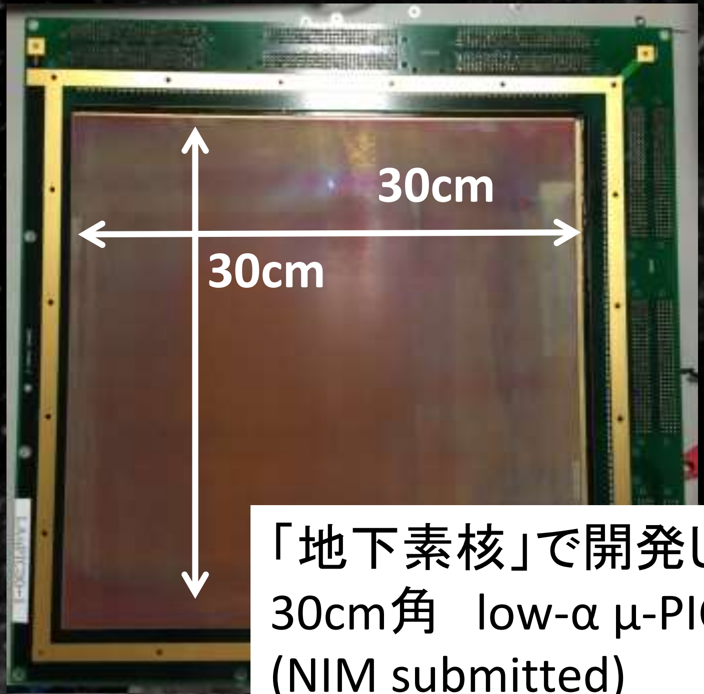
μ-PIC(Micro-pixel chamber)
- 31×31cm²
- pitch : 400μm
- gain : ~1000
- made by DNP, Japan

GEM
- 31×32 cm²
- 8-segmented
- hole pitch : 140μm
- hole diameter: 70μm
- insulator : LCP 100μm
- gain : ~5
- made by Scienergy, Japan

- NEWAGE技術（1/3）：「低放射能」
  - 低バックグラウンド（低放射能）化：材料中のウラン、トリウム（U、Th）を低減
  - 新学術「地下素核」（H26-H30）、「地下宇宙」（R1-R5）

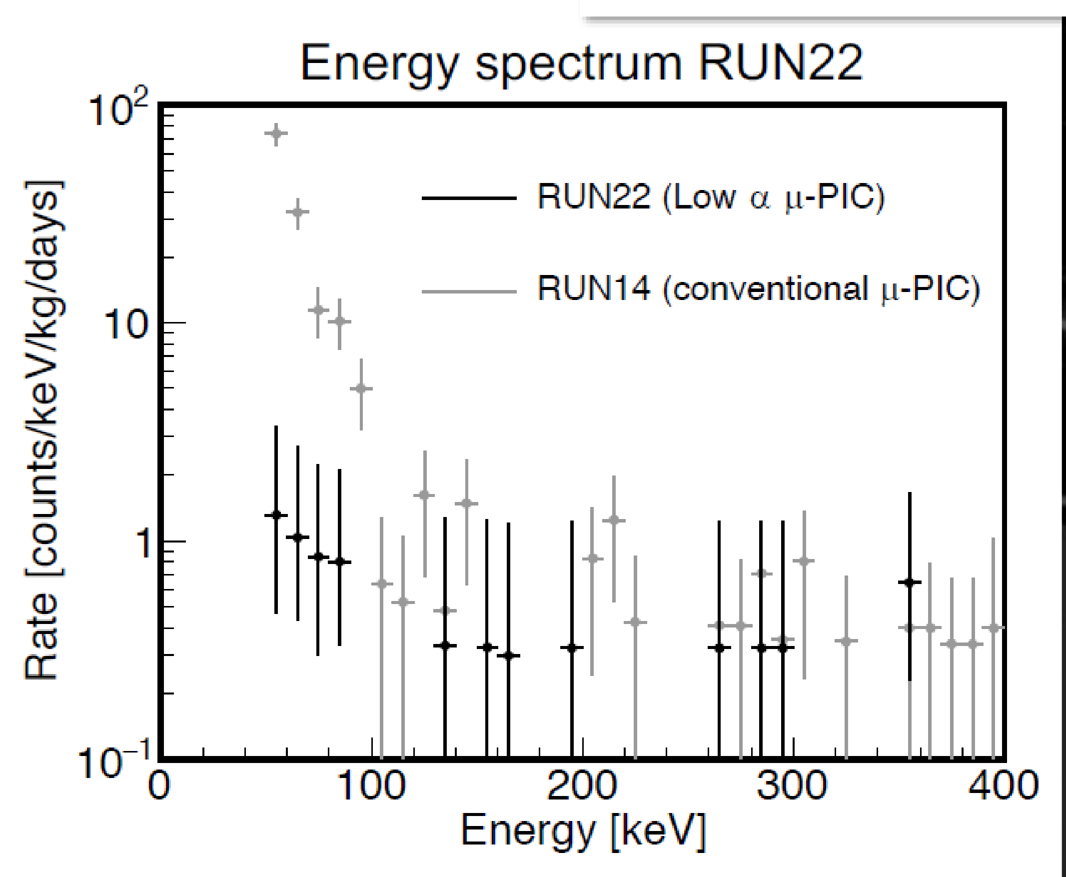
材料探索

	^{238}U[ppm]	^{232}Th[ppm]
Standard material (PI+glass cloth)	0.39±0.01	1.81±0.04
New material (PI+epoxy)	$< 2.98\times10^{-3}$	$< 6.77\times10^{-3}$



「地下素核」で開発した
30cm角　low-α μ-PIC
(NIM submitted)

エネルギースペクトル

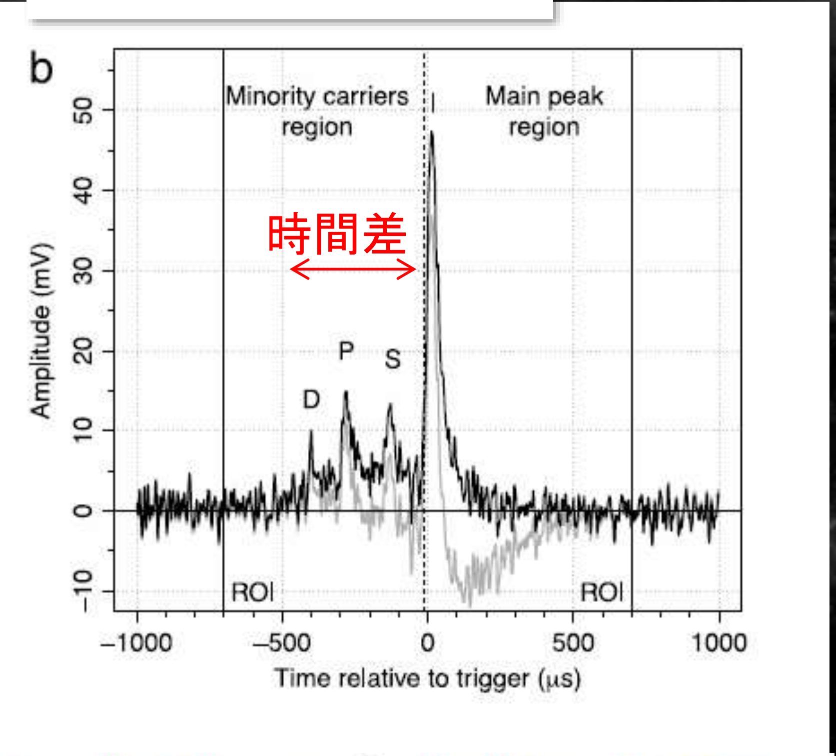


BGの低減(1/50以下)に成功
さらなる低BG化　進行中

• NEWAGE技術（2/3）　：「陰イオンガスTPC」
  • セルフトリガーのTPCでは不可能だったドリフト方向の絶対値決定
  • 海外グループによって初報告
  • 三次元飛跡検出（w/ASIC開発）と組み合わせた独自の発展

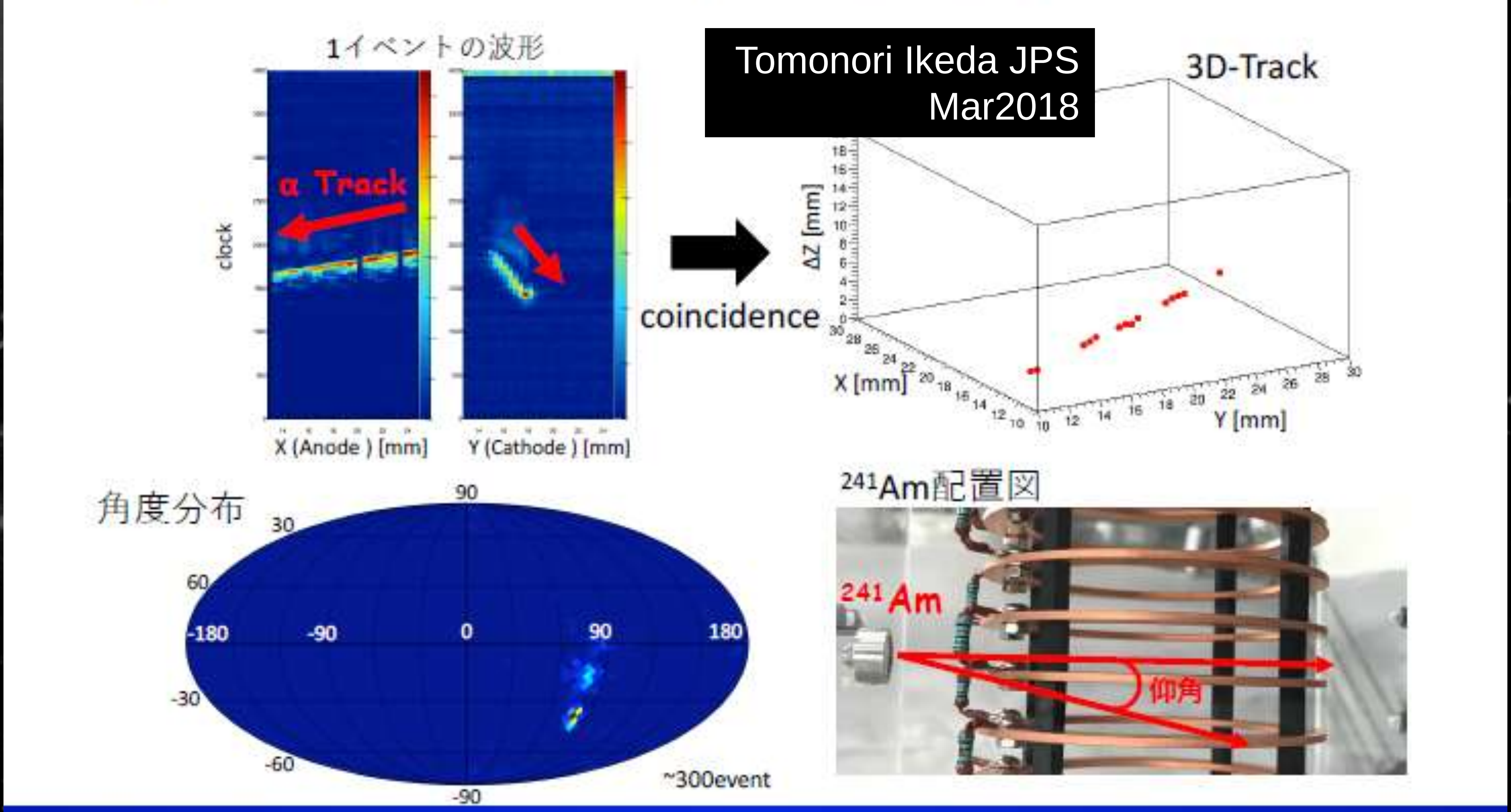
2019 J. Inst. 14 T01008

絶対値決定の例



J.B.R. Battat et al. / Physics of the Dark Universe 9–10 (2015) 1–7

ドリフト速度の違う複数種のイオン
⇒　時間差から絶対値

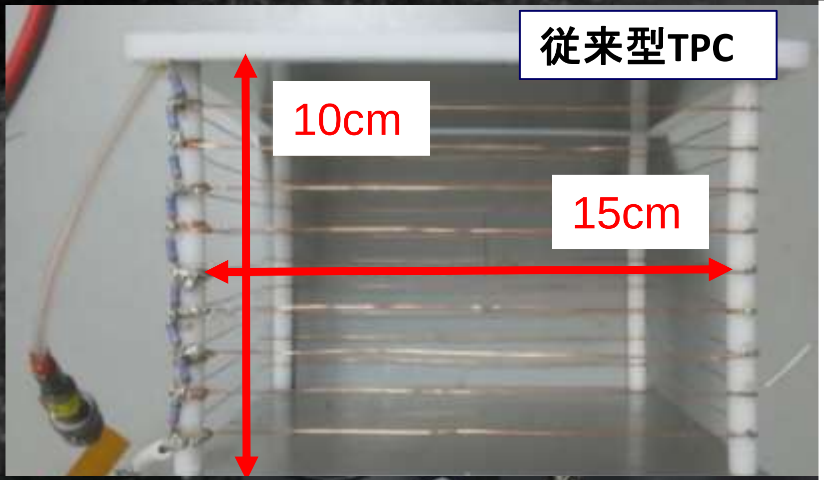


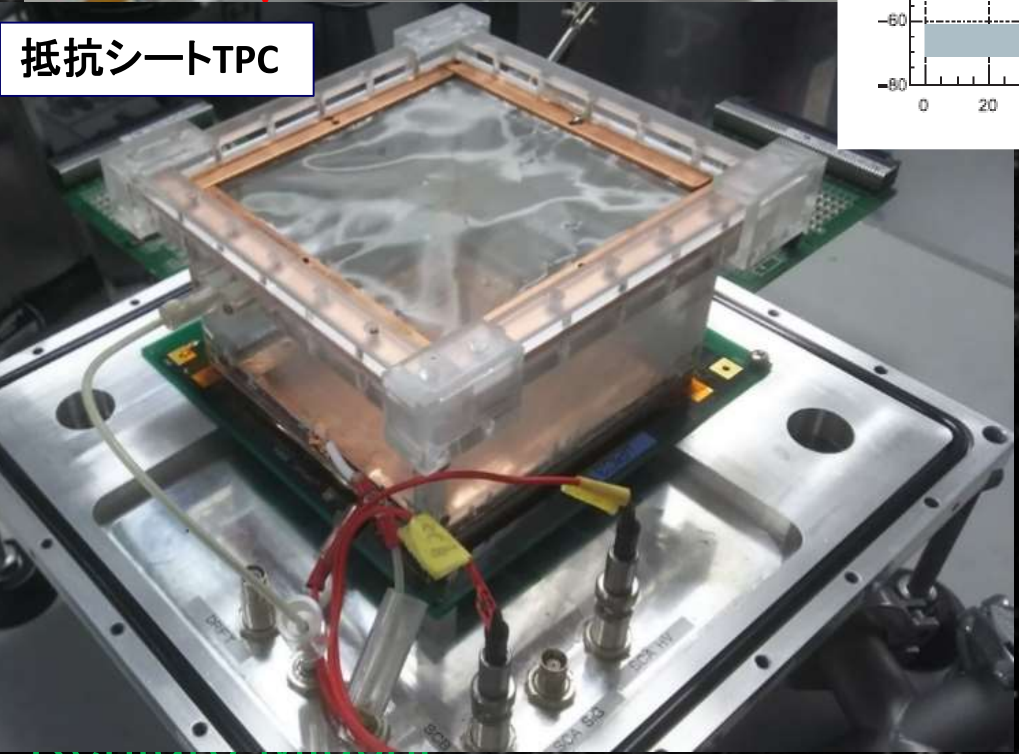
三次元飛跡＋絶対値決定のはじめての例

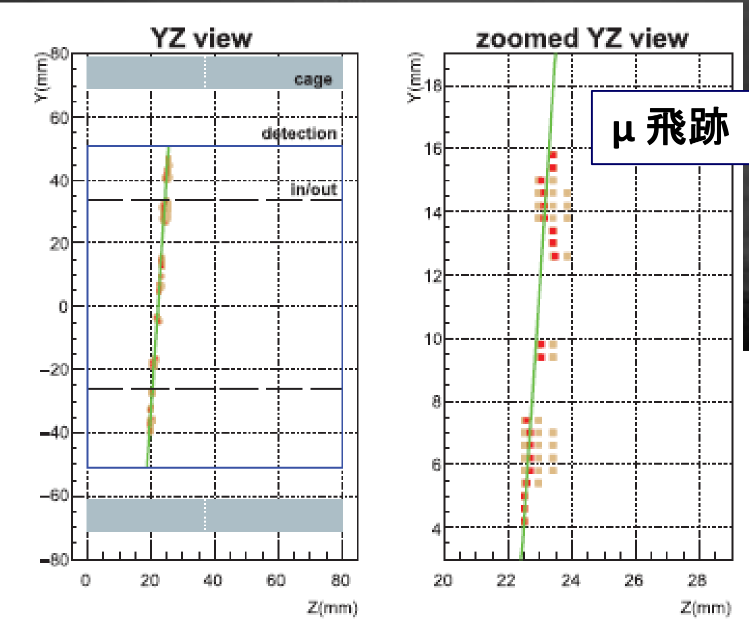
Kentaro Miuchi

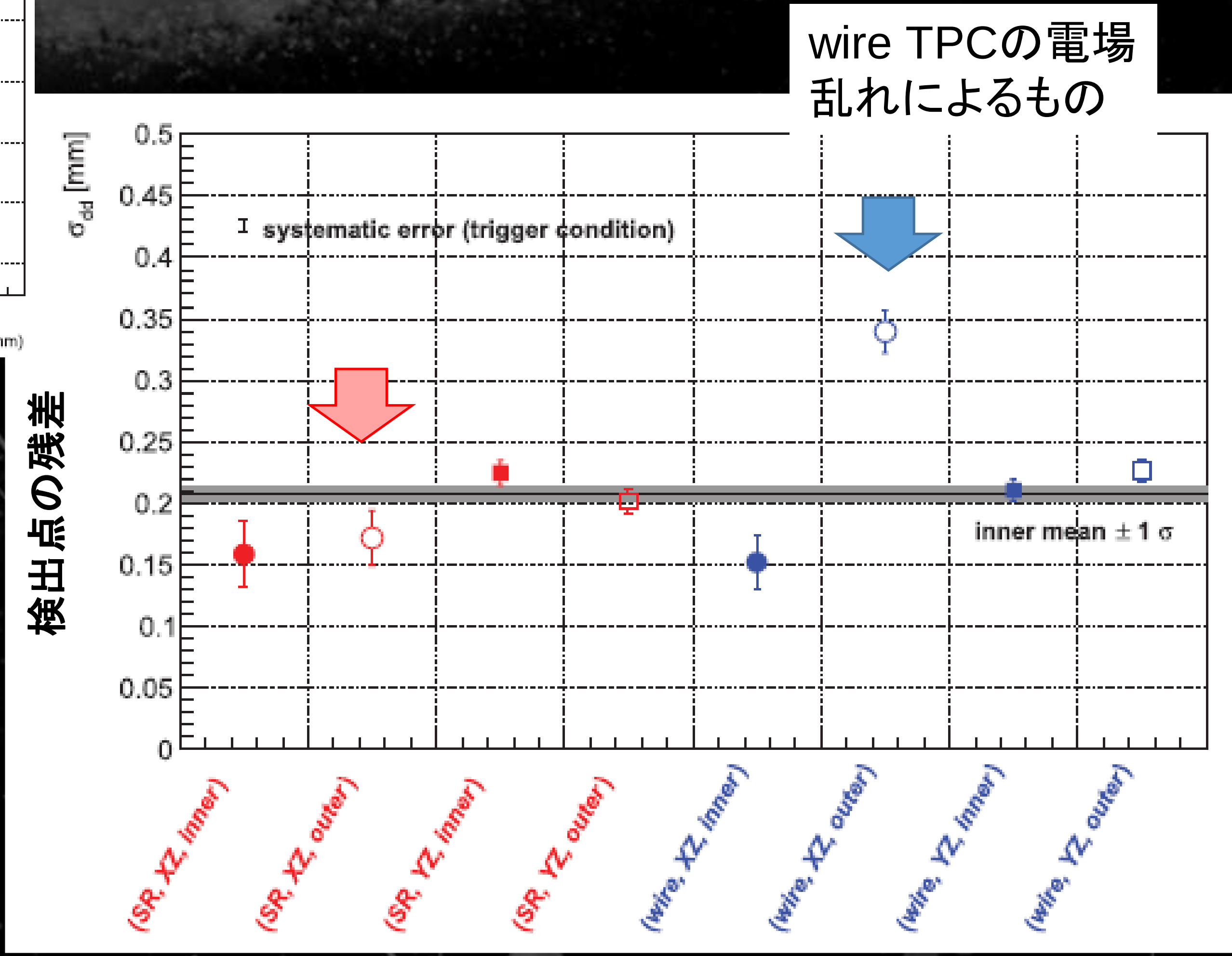
• NEWAGE技術（3/3）　：「抵抗シートTPC」 PTEP 2019 (2019)063H01

- 連続抵抗（市販のシート）を使ったTPC電場形成
- ワイヤータイプよりシンプルな構造　一様な電場

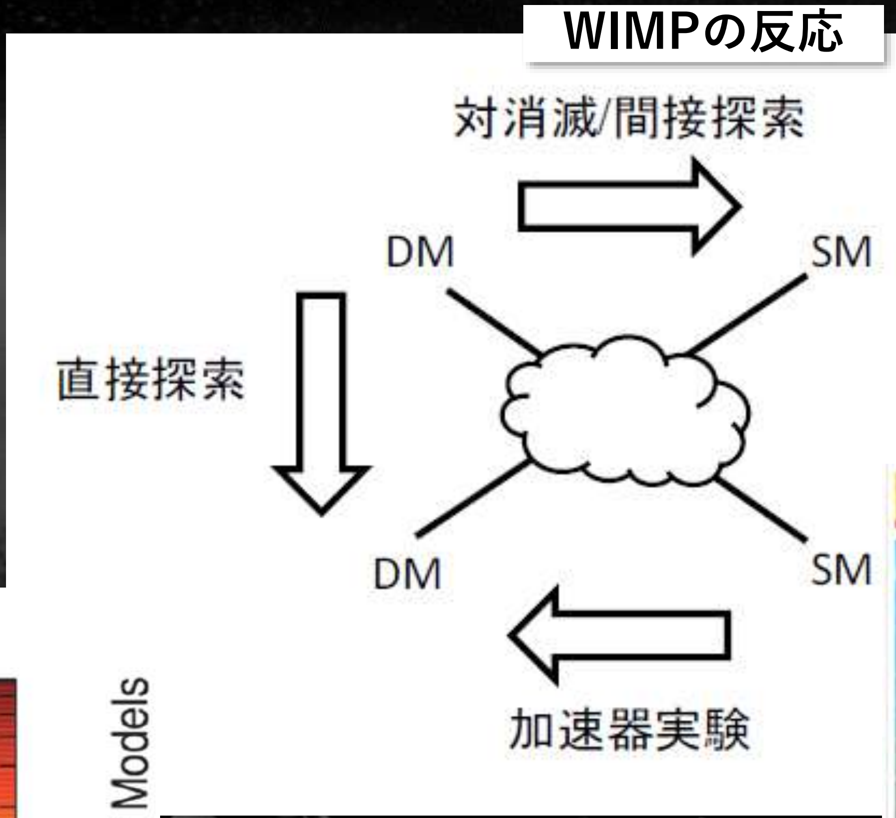




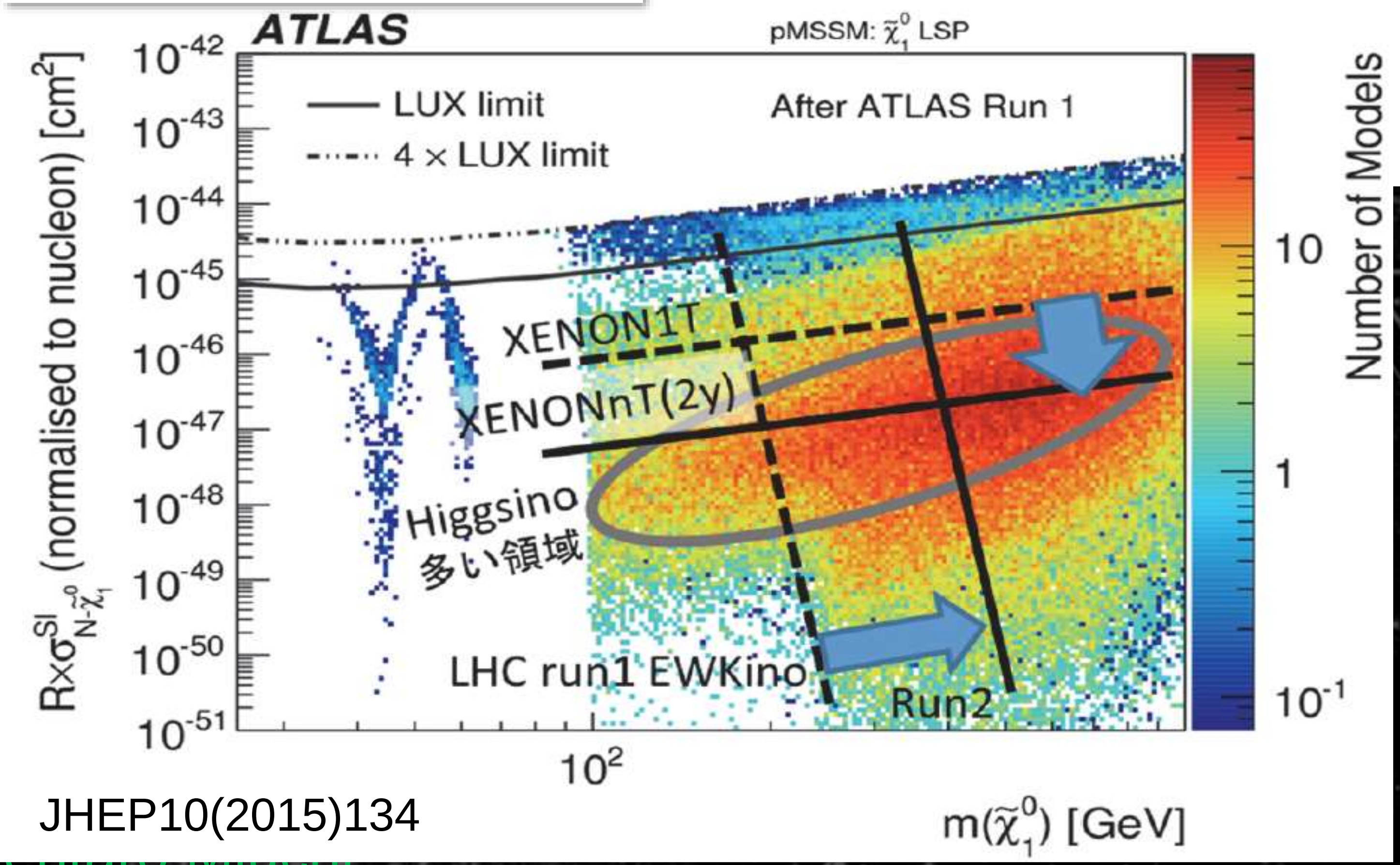




- WIMP探索
  - 加速器実験：LHCなど
  - 対消滅：FERMI、CTAなど
  - 直接探索　⇒　本講演

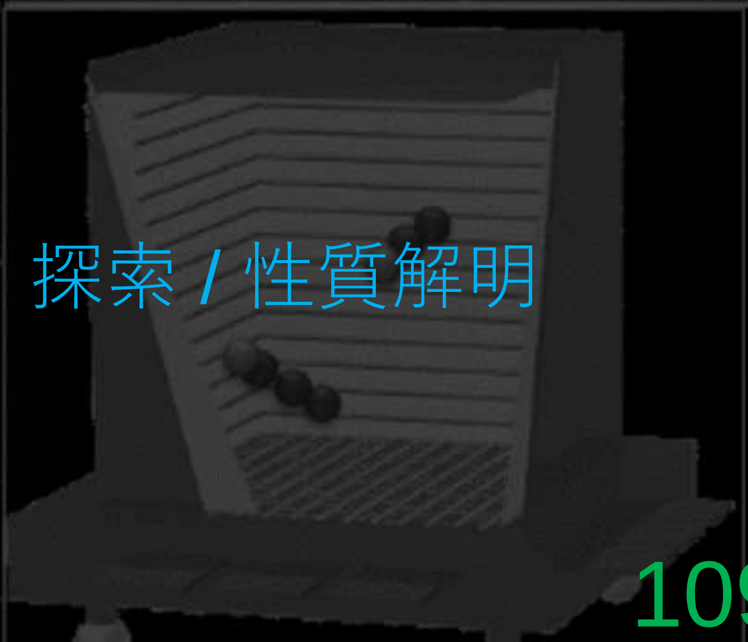


直接探索と加速器実験



JHEP10(2015)134

- 相補的　探索 / 性質解明



- マグノンでGHz重力波
  - 理論屋さんが式をこねくり回すと重量波もカップルするらしい

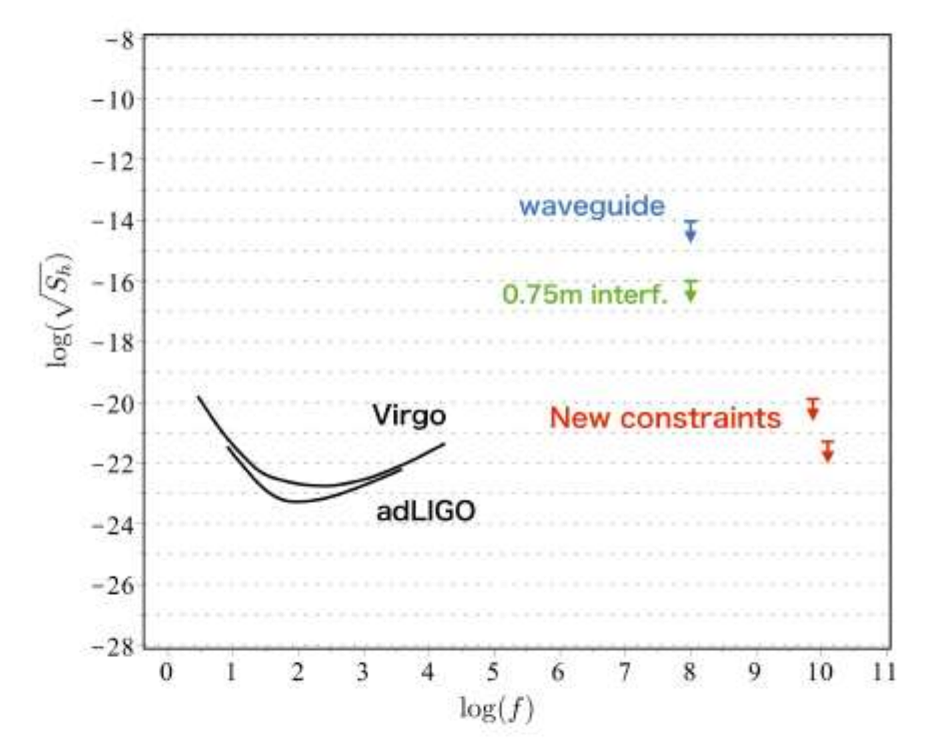
1903.04843

Probing GHz Gravitational Waves with Graviton-magnon Resonance

Asuka Ito,* Tomonori Ikeda,† Kentaro Miuchi,‡ and Jiro Soda§
Department of Physics, Kobe University, Kobe 657-8501, Japan
(Dated: May 17, 2019)

$$g_{eff} = \frac{1}{4\sqrt{2}}\mu_B B_z \sin\theta\sqrt{N}\left[\frac{1+\cos^2\theta}{2}I - \frac{\sin^2\theta}{2}Q + \cos\theta V\right]^{1/2}$$

$$\begin{cases} I = (h^{(+)})^2 + (h^{(\times)})^2 \,, \\ Q = (h^{(+)})^2 - (h^{(\times)})^2 \,, \\ U = 2\cos\alpha\, h^{(+)}h^{(\times)} \,, \\ V = 2\sin\alpha\, h^{(+)}h^{(\times)} \,. \end{cases}$$

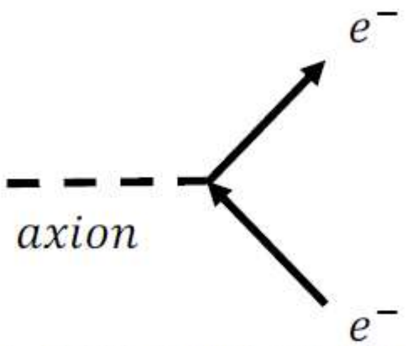


h: 重力波よるひずみ

アクシオンと電子の相互作用

✓ フェルミオンとのカップリング項

$$\mathcal{L} = g_{aff}\partial_\mu a(x)\bar{\psi}(x)\gamma^\mu\gamma_5\psi(x)$$



✓ 非相対論的なところでのアクシオンと電子の相互作用項

$$-\frac{g_{aee}\hbar}{2m}\hat{\sigma}\cdot\nabla a = -2\left(\frac{e\hbar}{2m}\right)\left(\frac{1}{2}\hat{\sigma}\right)\cdot\left(\frac{g_{aee}}{e}\nabla a\right)$$

μ_B:ボーア磁子　B_a:アクシオン磁場

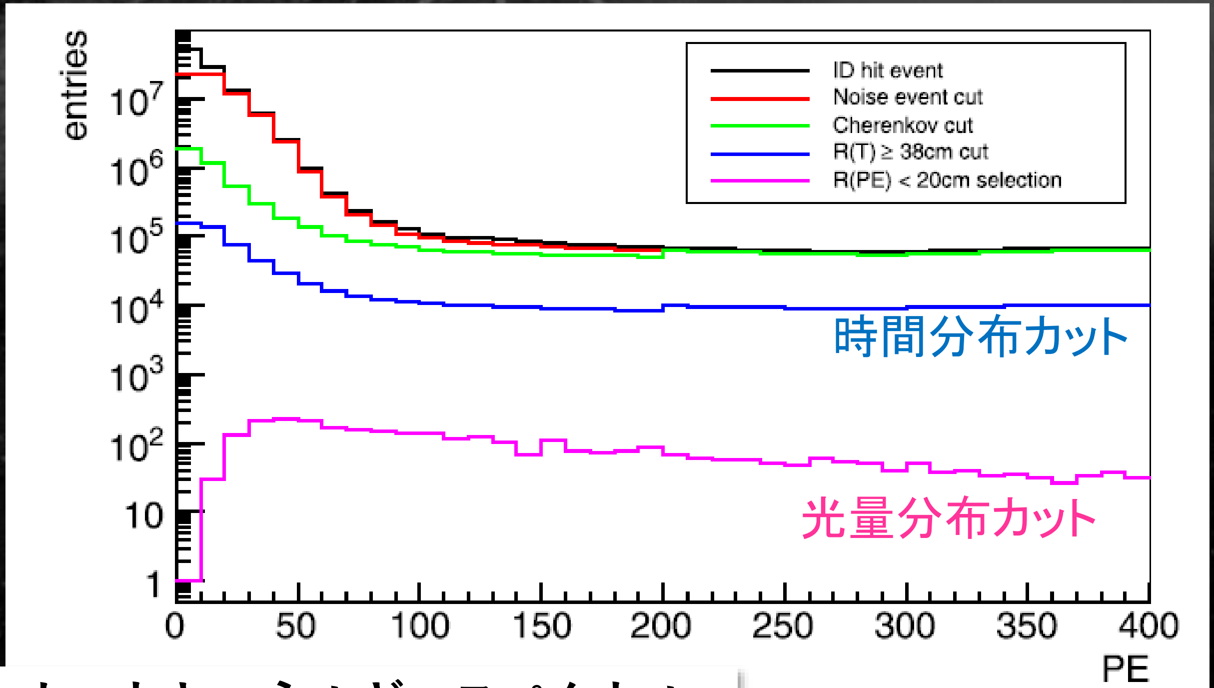
S:電子スピン

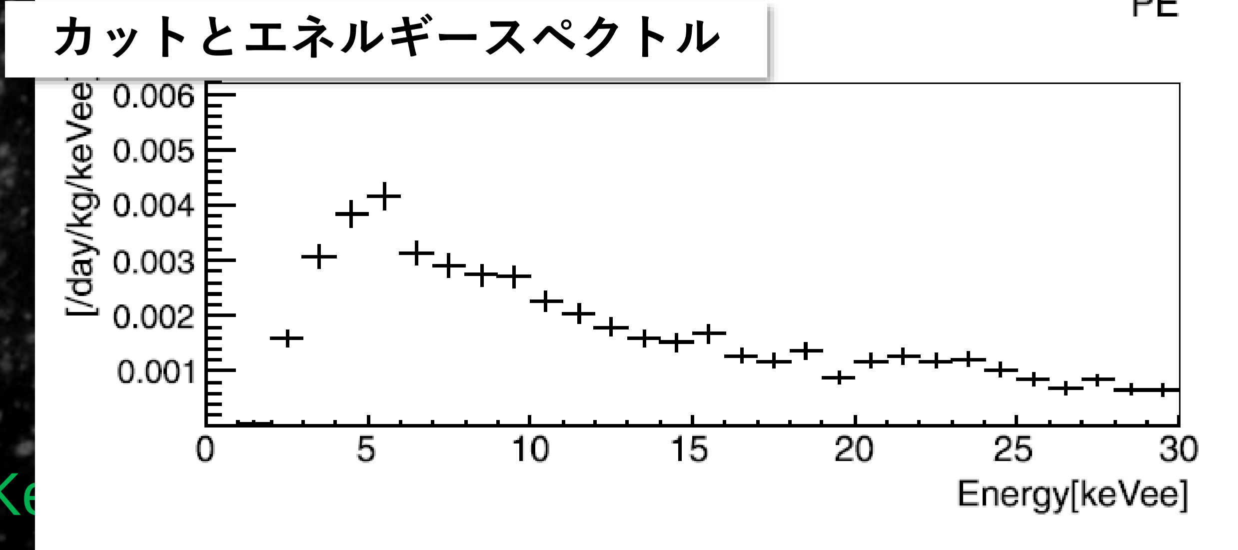
✓ アクシオン磁場の強さ

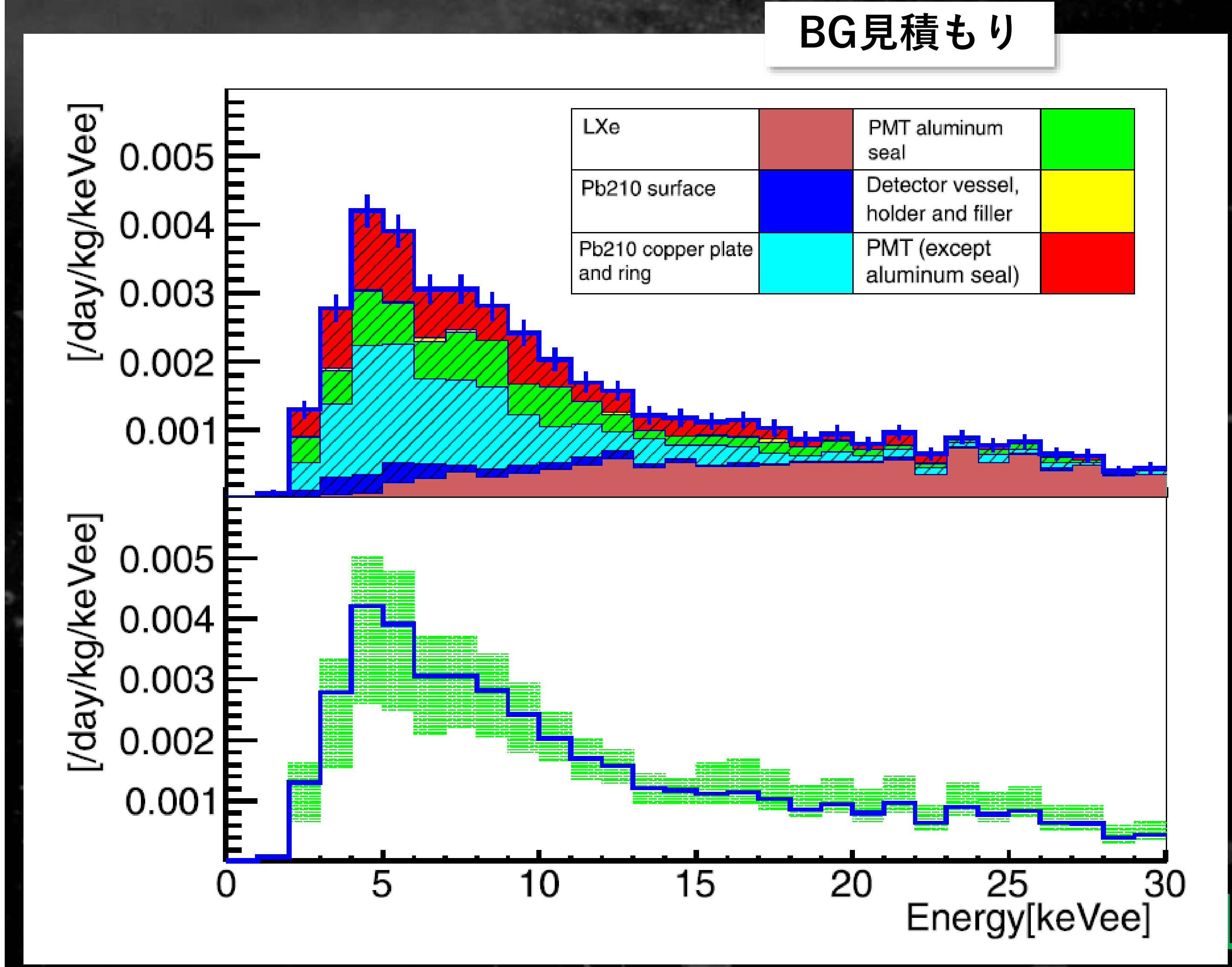
$$B_a = 3.3\times10^{-8}\times g_{aee}\times\left(\frac{\rho}{0.45GeV/cm^3}\right)^{1/2}\left(\frac{v_a}{220km/s}\right)[\mathrm{T}]$$

✓ 1電子あたりの相互作用は非常に小さい

- XMASS fiducial paper: BG（バックグラウンド） study
  - fiducialカット後で$O(10^{-3})$ counts/keV/kg/days を達成
  - 各種手法（高エネルギーのスペクトル、Ge検出器での部材選定）でBGを評価
  - 系統誤差を詳しく評価







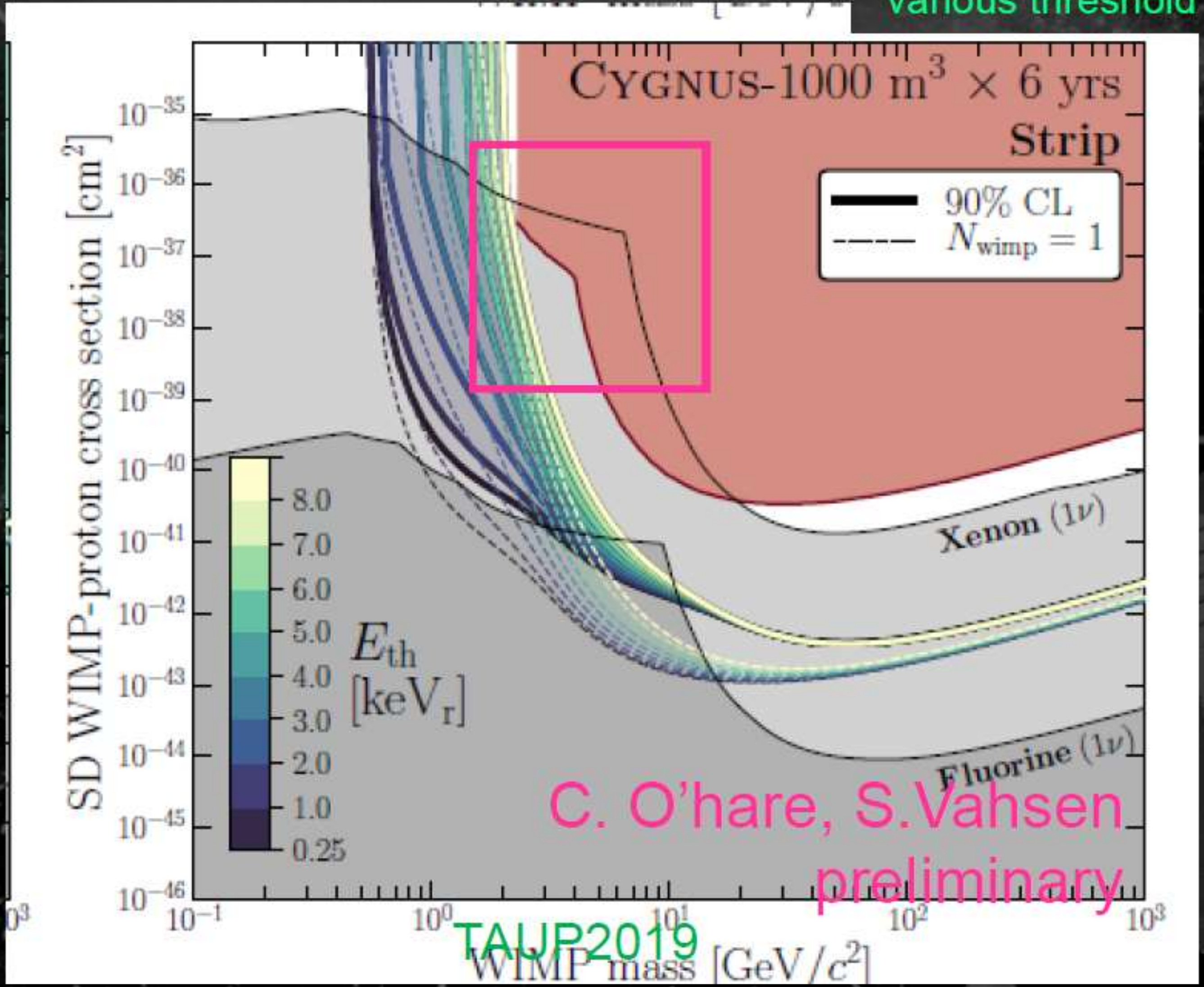
- Migdal効果
  - XENON：低質量DMまで感度
- この現象自体未確認
- 特徴的なトポロジー（原子核反跳+特性X線）　⇒　ガスで実証を!

- CYGNUSとして目指したいこと
  - 世界を呼び込んで暗黒物質の発見・性質解明

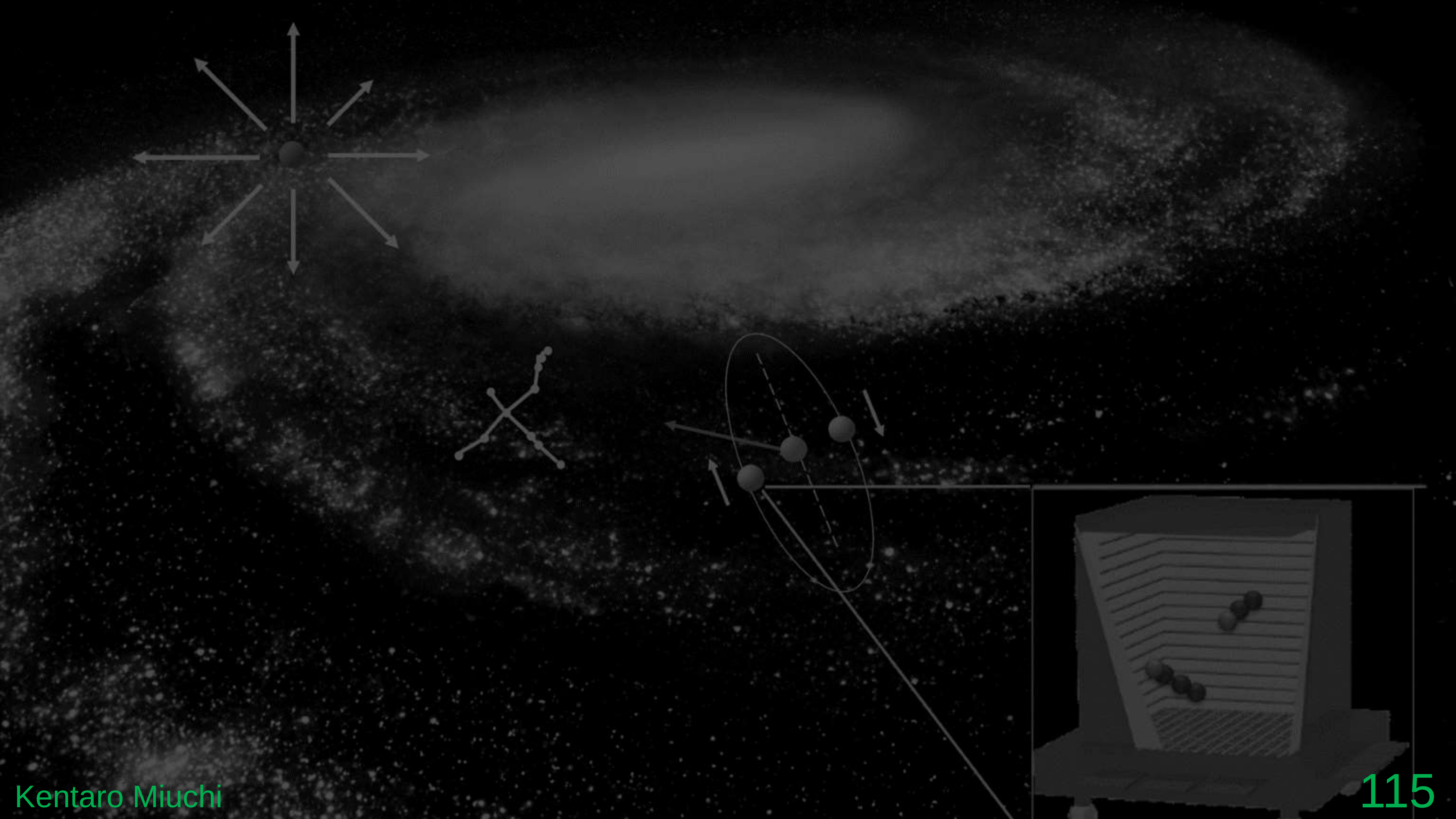
- Realistic simulation (strip readout)

1000m^3
strip readout with
various threshold

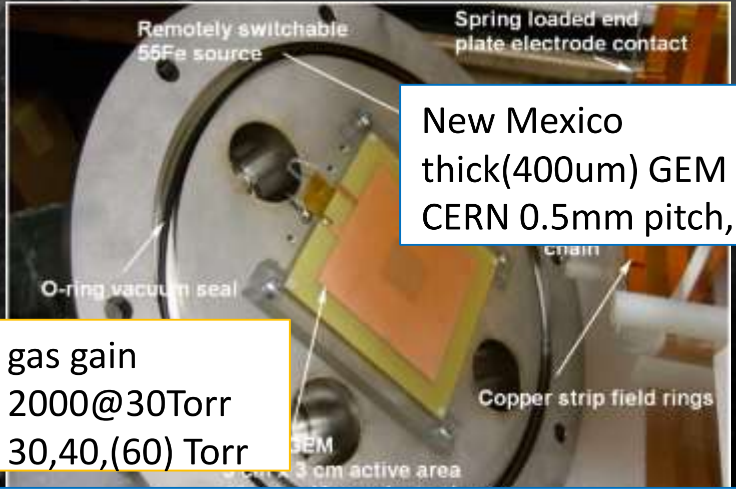
even 10m^3 detector
(3 order magnitude higher than
the shown curves) can start
exploring Xe neutrino floor



TAUP2019

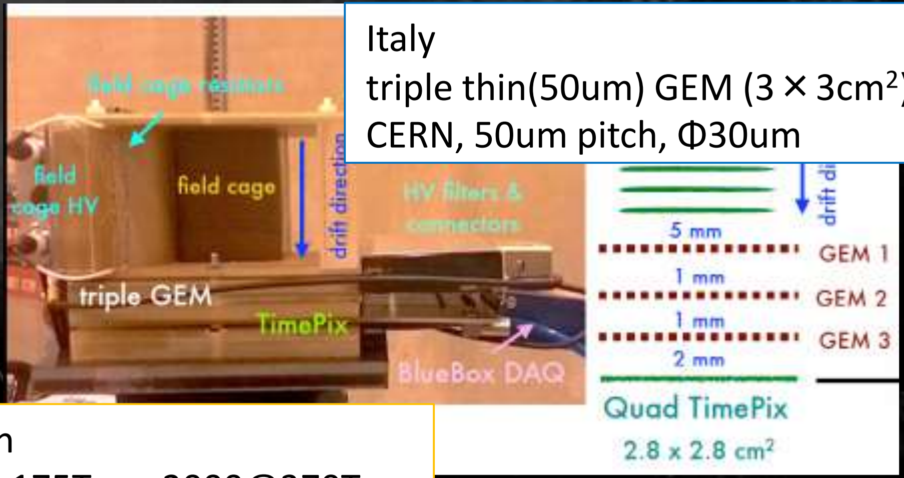


- World-wide SF_6 activities (convener: Miuchi)
  - Wide varieties of MPGD(micro patterned gaseous detectors)
  - very active, new comers are welcome!



New Mexico
thick(400um) GEM (3×3cm^2)
CERN 0.5mm pitch, Φ0.3mm

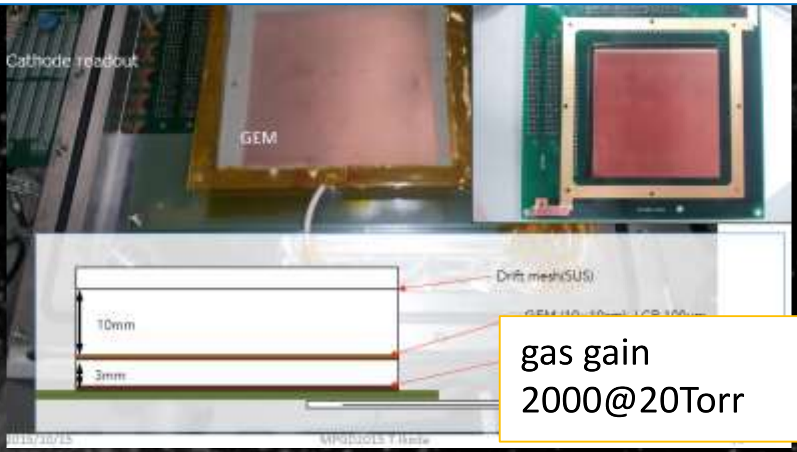
gas gain
2000@30Torr
30,40,(60) Torr



Italy
triple thin(50um) GEM (3×3cm^2)
CERN, 50um pitch, Φ30um

gas gain
5000@ 175Torr, 2000@370Torr

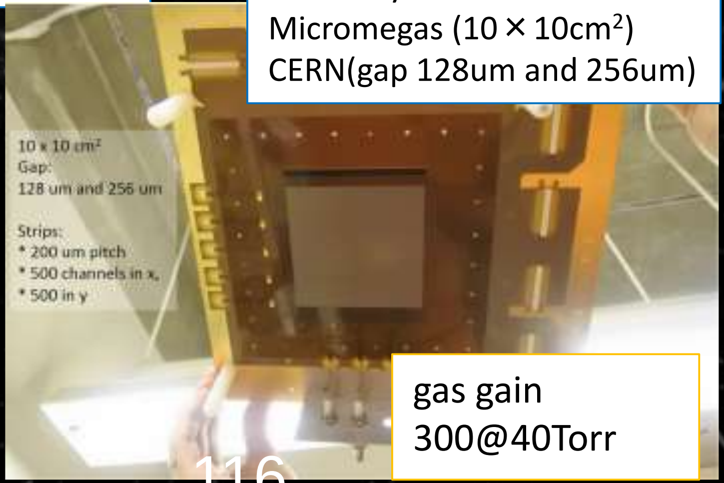
Kobe
thin(100um) GEM (10×10cm^2) Scienergy, 140um pitch, Φ70um
+ μ-PIC(10×10cm^2) DNP, 400um pitch strip readout
triple thin (100um) GEM Scienergy, 140um pitch, Φ70um



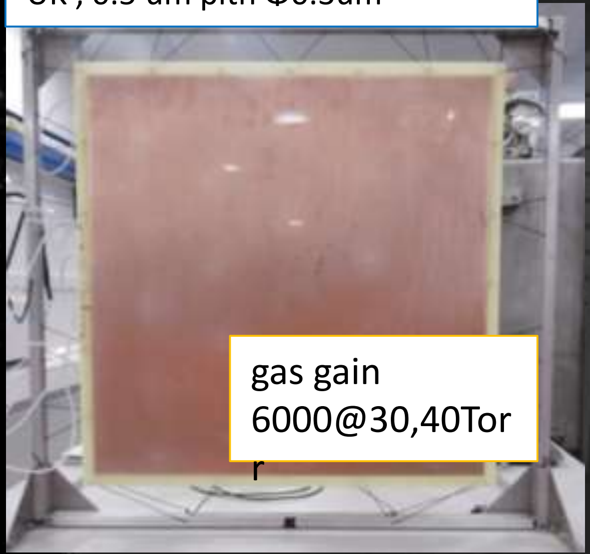
gas gain
2000@20Torr

Sheffield
thick(400um) GEM(50×50cm^2)
UK , 0.5 um pith Φ0.3um

Wellesley
Micromegas (10×10cm^2)
CERN(gap 128um and 256um)



gas gain
300@40Torr

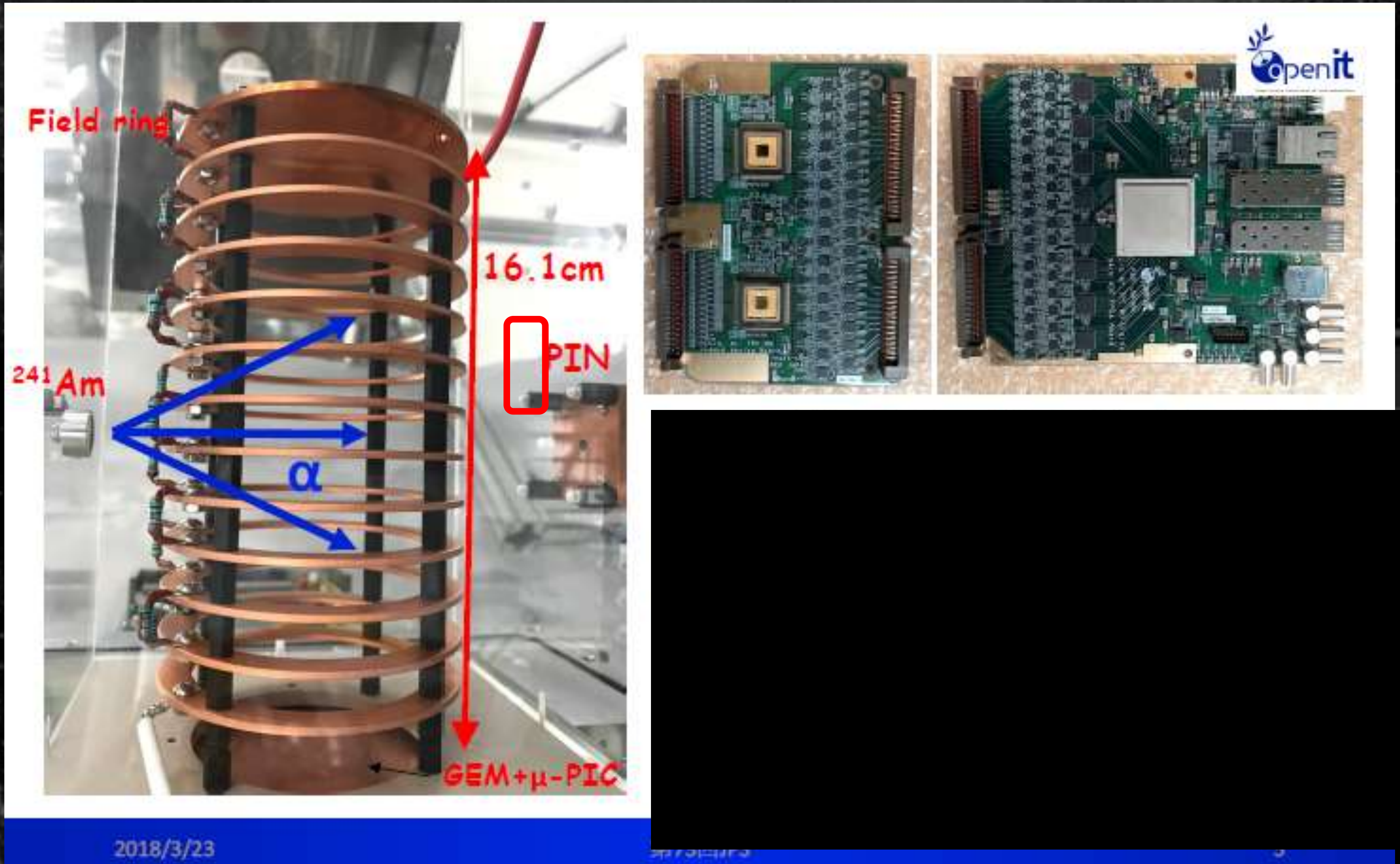


gas gain
6000@30,40Tor
r

• KOBE's activity μ-PIC in SF6

- tracking test (α-rays)
- ASIC development
- simulation (Garfield++)

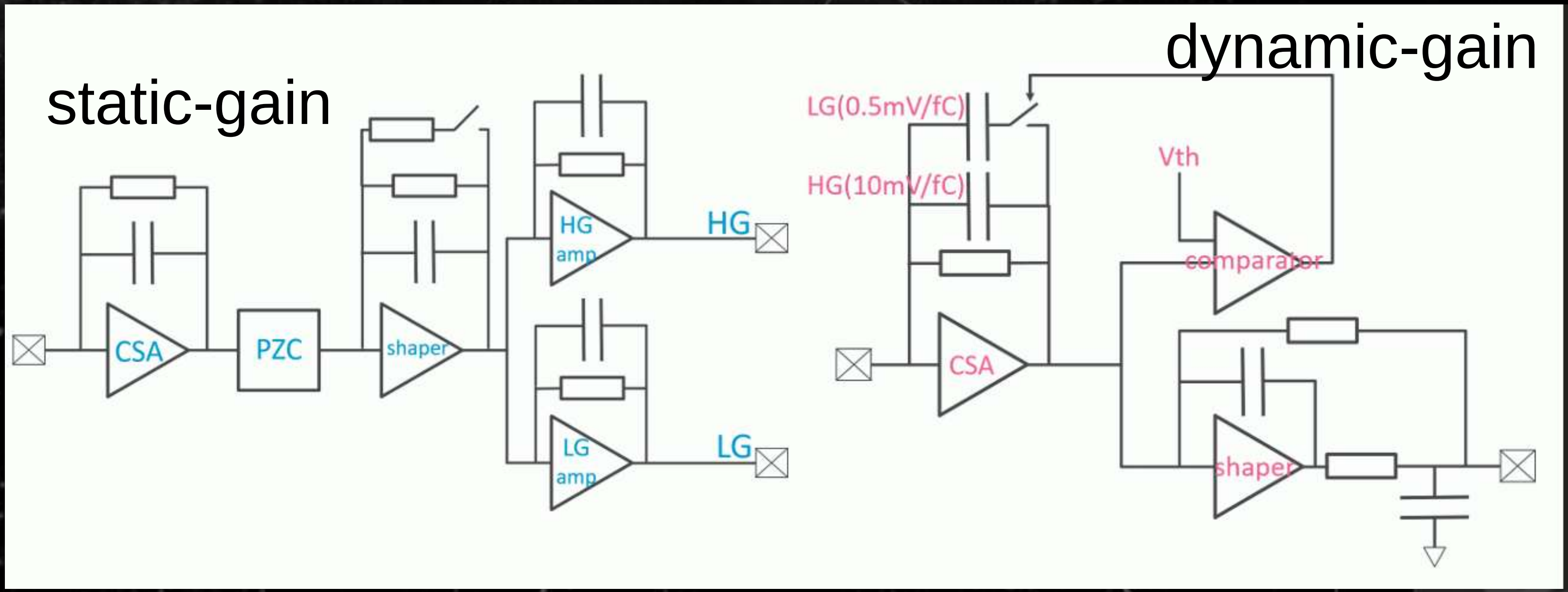
[redacted]



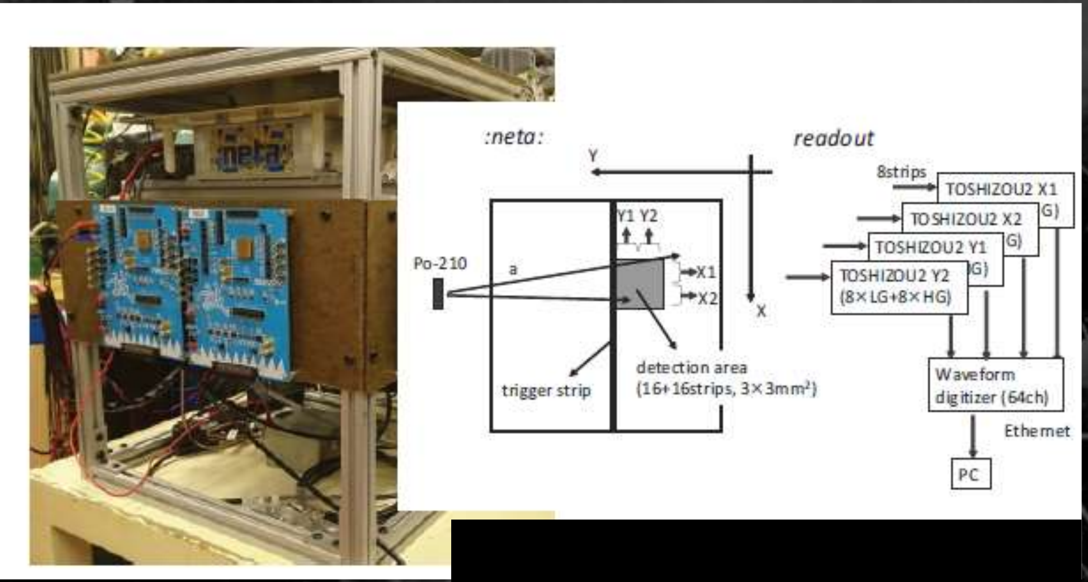
[redacted]

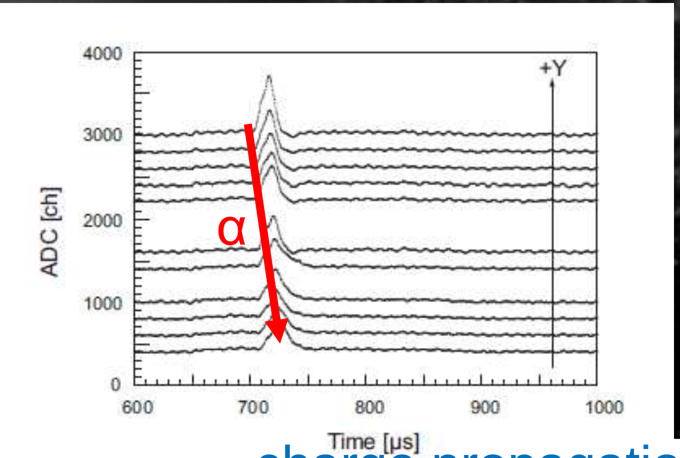
- ASIC development for strip readout
  - Wide dynamic range(1.6pC)
  - Large Cdet (300pF)

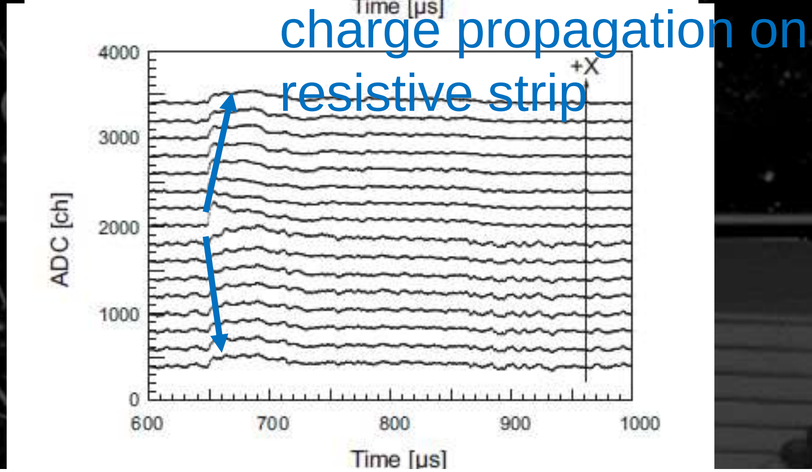
two types of architectures were implemented in LTARS 2016



- ASIC (cont’ d)
  - Test at Wellesley (Oct 2018) coupled with micromegas
  - 16ch+16ch active area

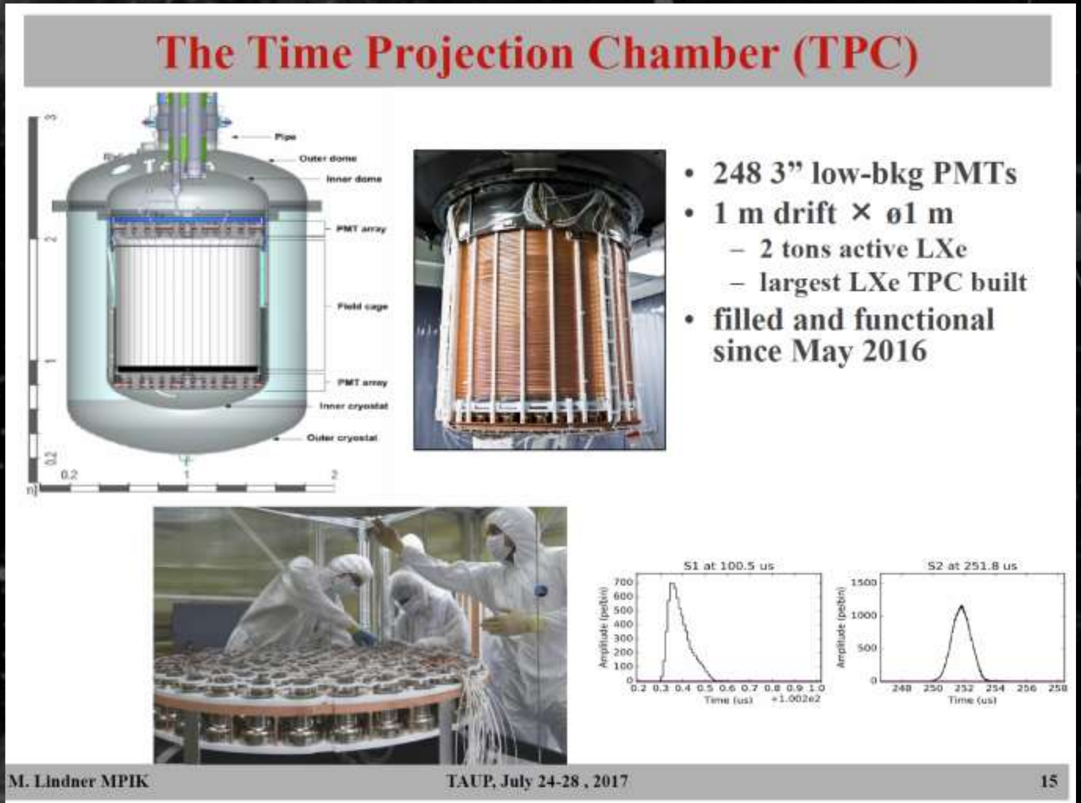


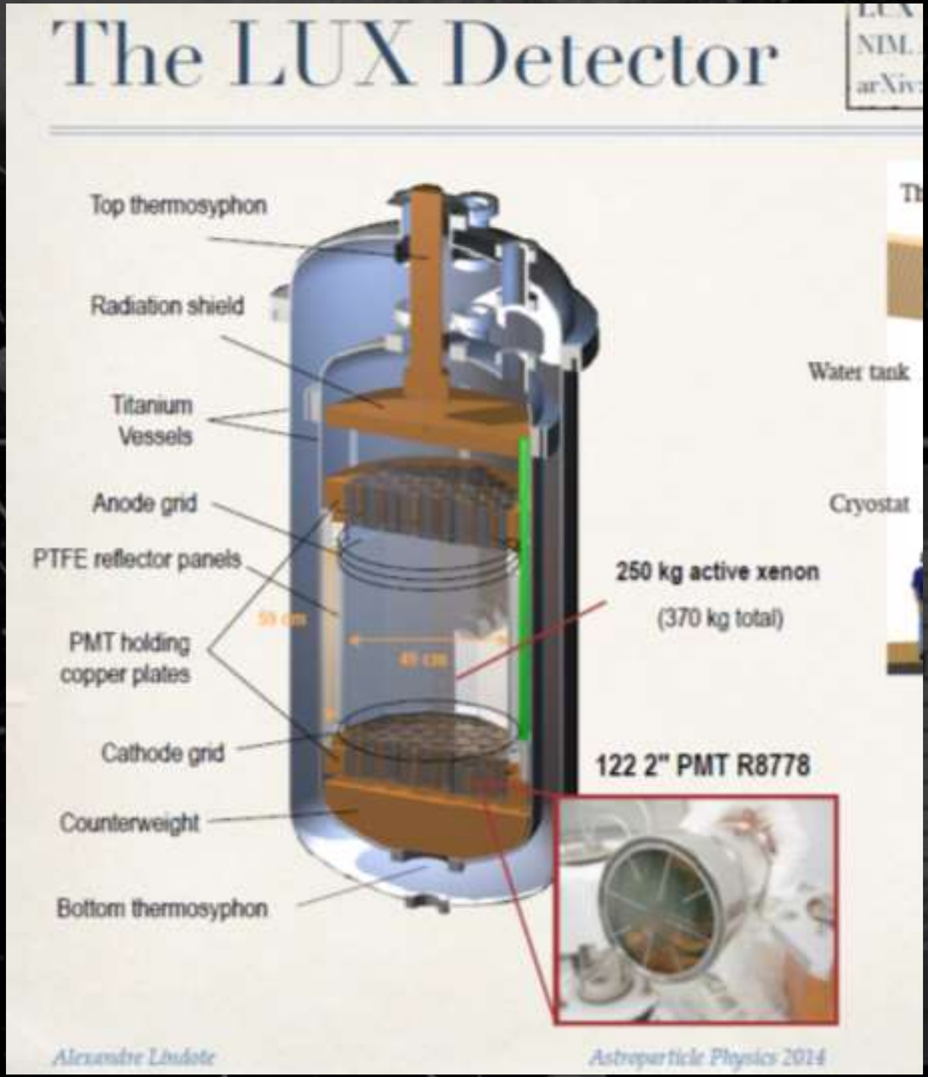




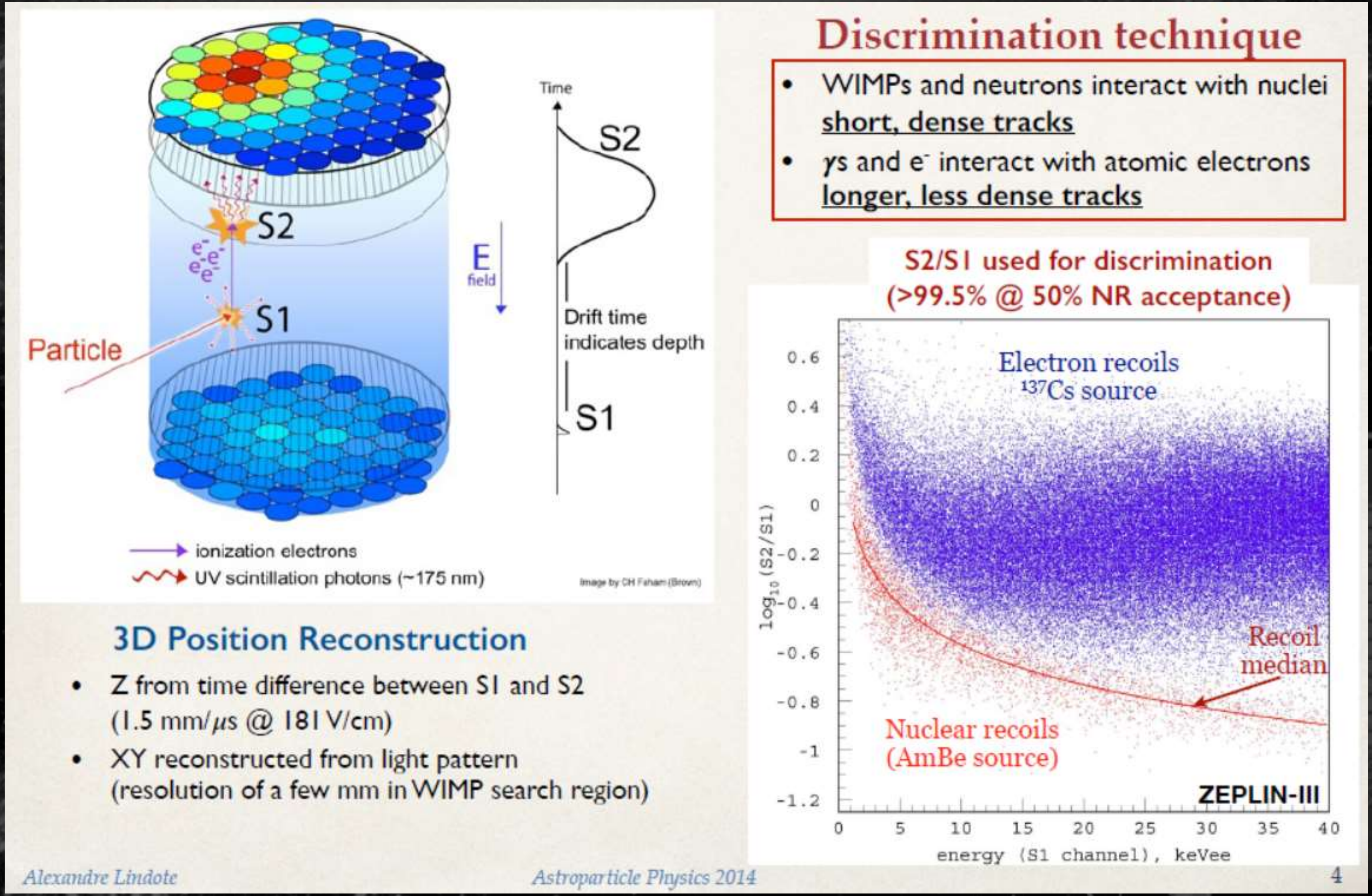
2相式液体キセノン

- XENON 1T：2T active
- LUX：370kg
- pandaX-II 500kg
- ガンマ線除去

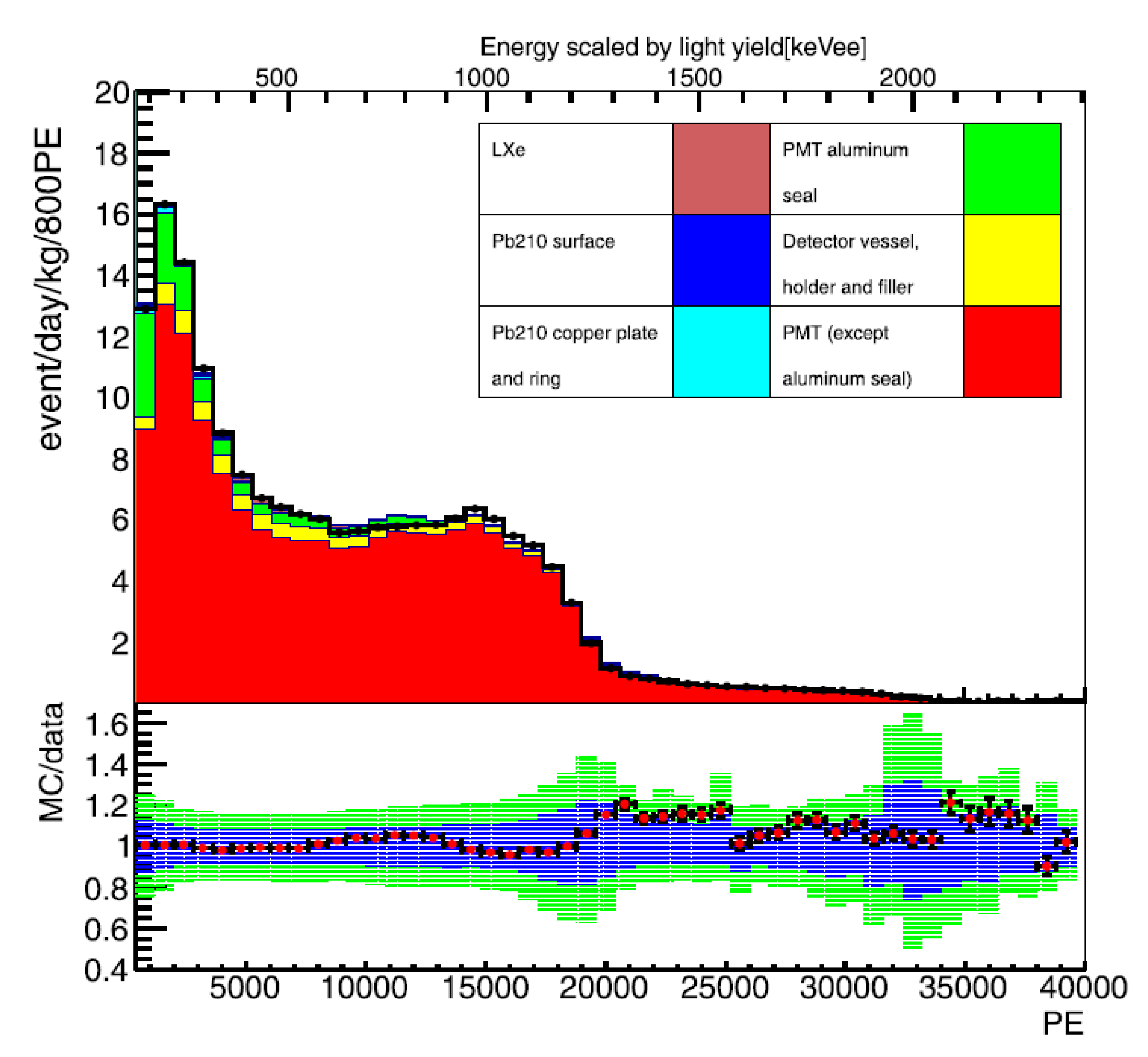




- 2-phase Liquid Xenon
  - γ rejection



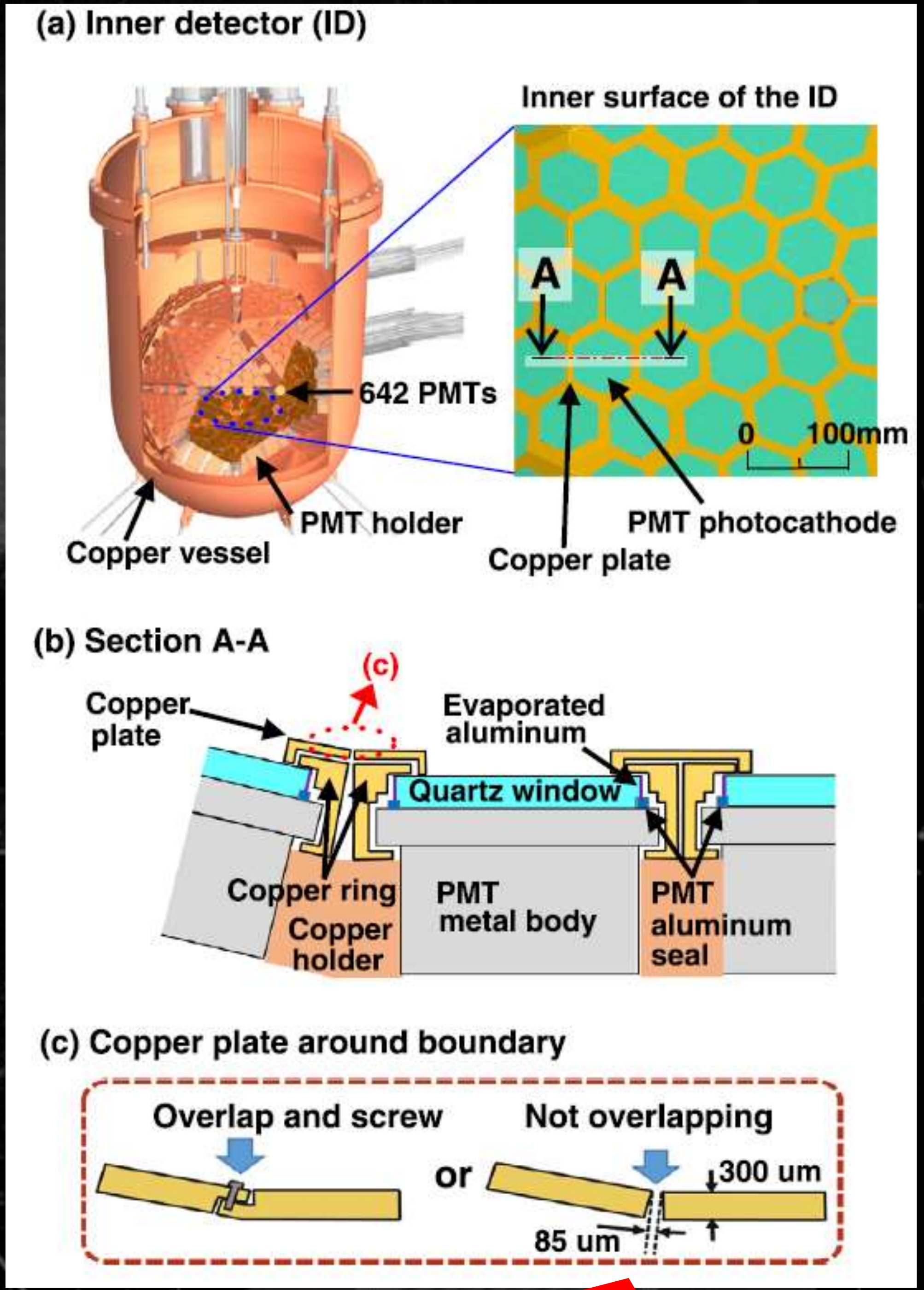
Location of RI	RI	Activity [mBq/detector] initial value of the fit	Activity [mBq/detector] the best fit value
LXe	^{222}Rn	–	8.53 ± 0.16
	^{85}Kr	–	0.25 ± 0.04
	^{39}Ar	–	0.65 ± 0.04
	^{14}C	–	0.19 ± 0.01
Copper plate and ring	^{210}Pb	–	$(6.0 \pm 1.0)\times10^2$
Copper surface	^{210}Pb	–	0.7 ± 0.1
PMT quartz surface	^{210}Pb	–	6.4 ± 0.1
PMT (except aluminum seal and quartz surface)	^{238}U	$(1.5\pm0.2)\times10^3$	$(2.0\pm0.2)\times10^3$
	^{232}Th	$(1.2\pm0.2)\times10^3$	$(1.1\pm0.3)\times10^3$
	^{60}Co	$(1.9\pm0.1)\times10^3$	$(1.6\pm0.2)\times10^3$
	^{40}K	$(5.8\pm1.4)\times10^3$	$(9.6\pm1.7)\times10^3$
	^{210}Pb	$(1.3\pm0.6)\times10^5$	$(2.2\pm0.7)\times10^5$
PMT aluminum seal	^{238}U	$(1.5\pm0.4)\times10^3$	$(9.0\pm4.1)\times10^2$
	^{235}U	$(6.8\pm1.8)\times10^1$	$(4.1\pm1.8)\times10^1$
	^{232}Th	$(9.6\pm1.8)\times10^1$	$(5.5\pm2.2)\times10^1$
	^{210}Pb	$(2.9\pm1.2)\times10^3$	$(3.4\pm1.2)\times10^3$
Detector vessel, holder and filler	^{238}U	$(1.8\pm0.7)\times10^3$	$(9.0\pm7.6)\times10^2$
	^{232}Th	$(6.4\pm0.7)\times10^3$	$(6.4\pm3.2)\times10^3$
	^{60}Co	$(2.3\pm0.1)\times10^2$	$(3.0\pm1.9)\times10^2$
	^{210}Pb	–	$(3.8\pm0.5)\times10^4$



- 系統誤差
  - plate gap 40~130μm (図では代表値85μm)

Table 2
List of the systematic error on the total event rate in the BG MC simulations. Negligible values are indicated as a blank entry. The contents are categorized according to the uncertainty of the detector geometry (a) for (1)–(5), the systematic errors for the detector response (b) for (6)–(8) and the systematic errors related to the LXe properties (c) for (9).

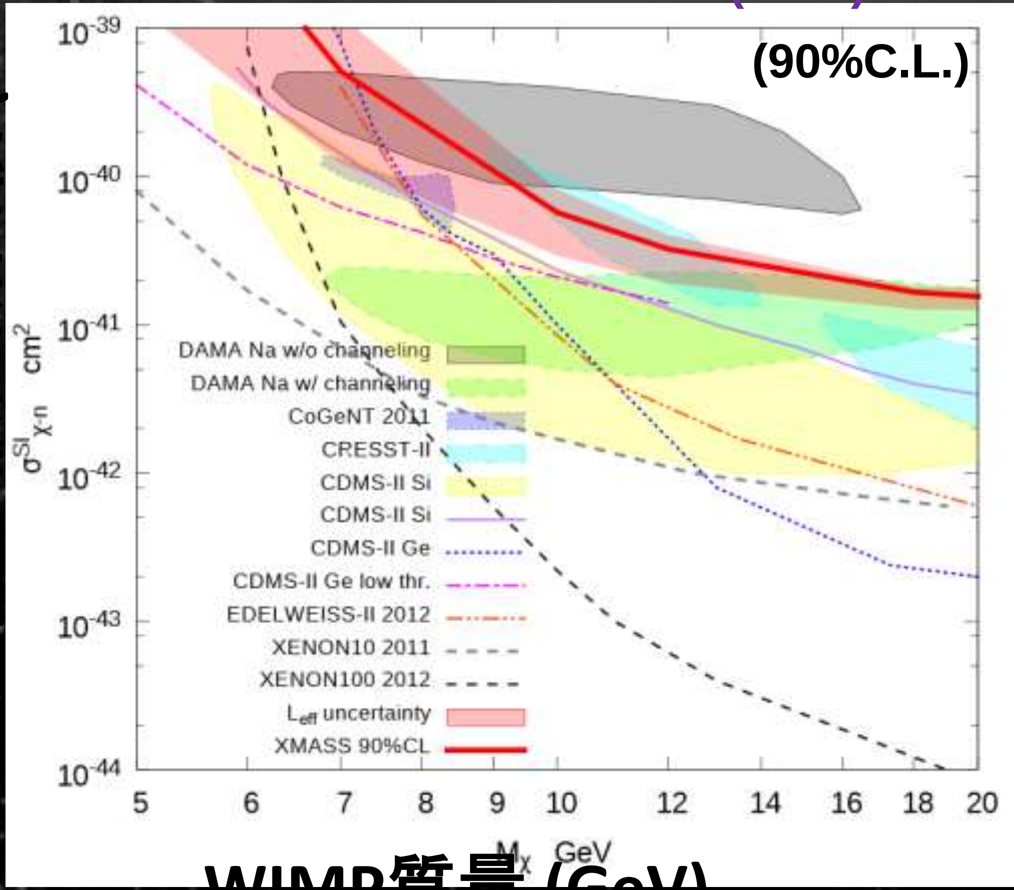
Contents	Systematic error	
	2–15 keV_{ee}	15–30 keV_{ee}
(1) Plate gap	+6.2/−22.8%	+1.9/−6.9%
(2) Ring roughness	+6.6/−7.0%	+2.0/−2.1%
(3) Copper reflectivity	+5.2/−0.0%	+2.5/−0.0%
(4) Plate floating	+0.0/−4.6%	+0.0/−1.4%
(5) PMT aluminum seal	+0.7/−0.7%	–
(6) Reconstruction	+3.0/−6.2%	–
(7) Timing response	+4.6/−8.5%	+0.4/−5.3%
(8) Dead PMT	+10.3/−0.0%	+45.2/−0.0%
(9) LXe optical property	+0.7/−6.7%	+1.5/−1.1%



観測結果

・低質量暗黒物質探索：
先行研究の領域を排除

PLB 719 (2013) 78



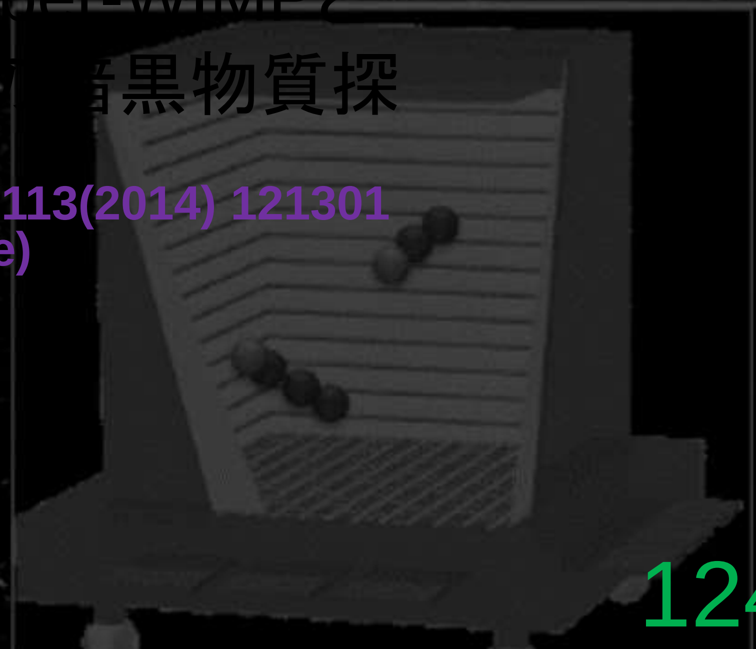
散乱断面積 (cm²)

WIMP質量 (GeV)

・非弾性散乱をする
暗黒物質探索

PTEP(2014)063C01

ボゾン的なsuper-WIMPと
暗黒物質探
索



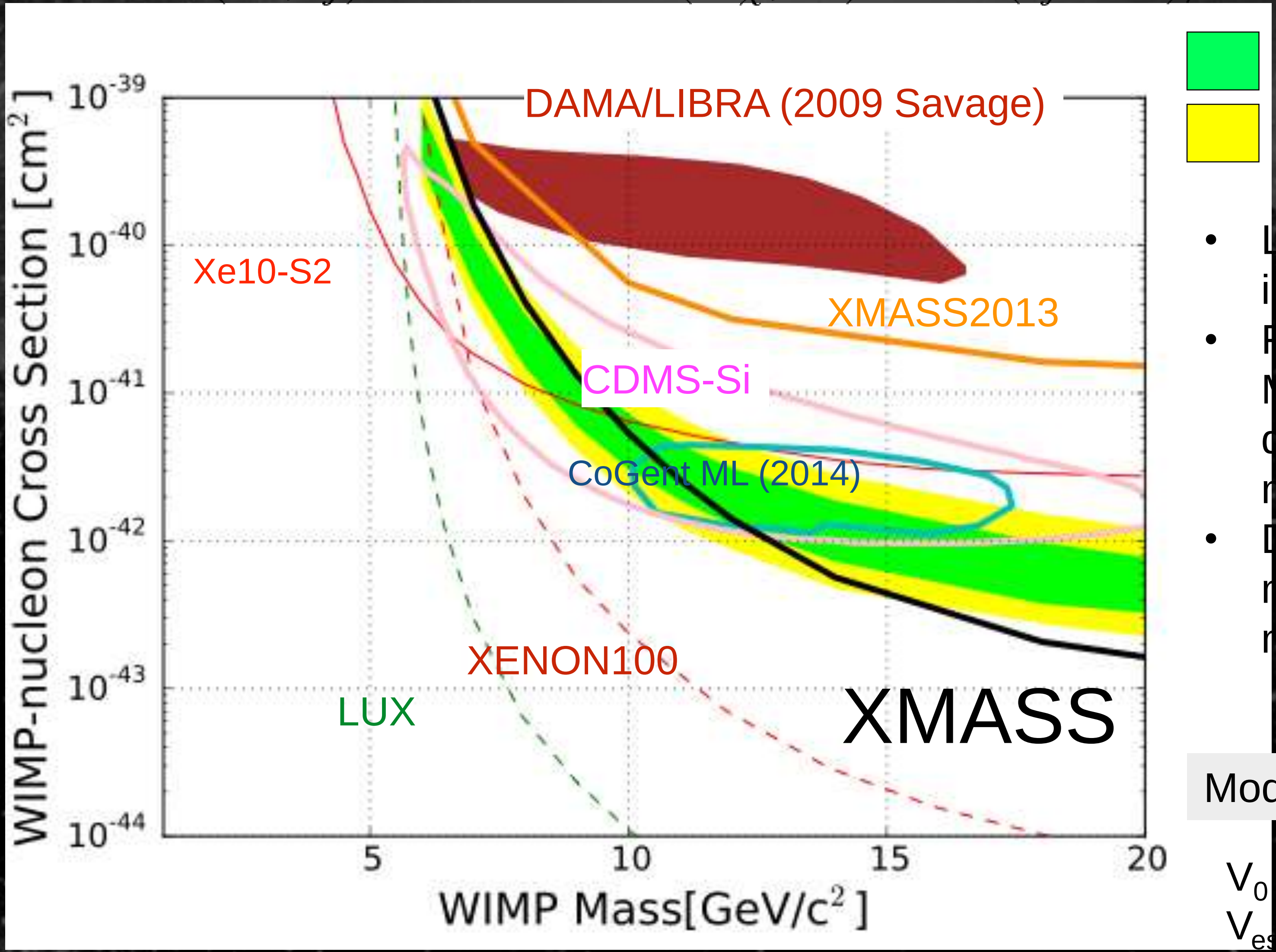
Phys. Rev. Lett. 113(2014) 121301
(editor's choise)

by annual modulation

Standard WIMP search

Assuming standard WIMP, data is fitted with the following equation:

$$R^{pred}(E_i, t_j) = C_i + \sigma \times A(m_\chi, E_i) \cos 2\pi (t_j - t_0)/T$$



±1 σ expected

±2 σ expected

- ... region is ... cluded by our ... ment.

Model assumption

V_0 ... 0 km/s

V_{es} ... .0 km/s

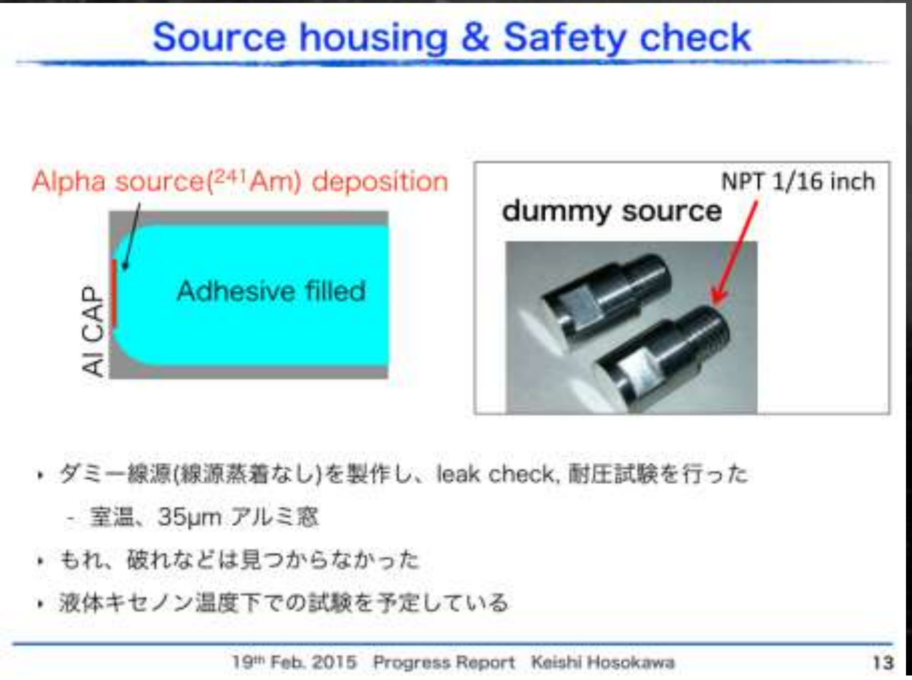
... 0.3 GeV/cm^3

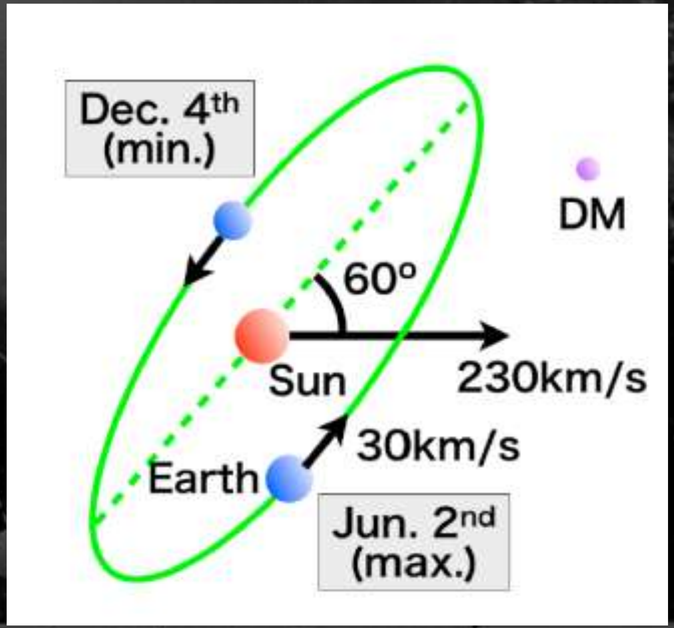
... Smith (1996)

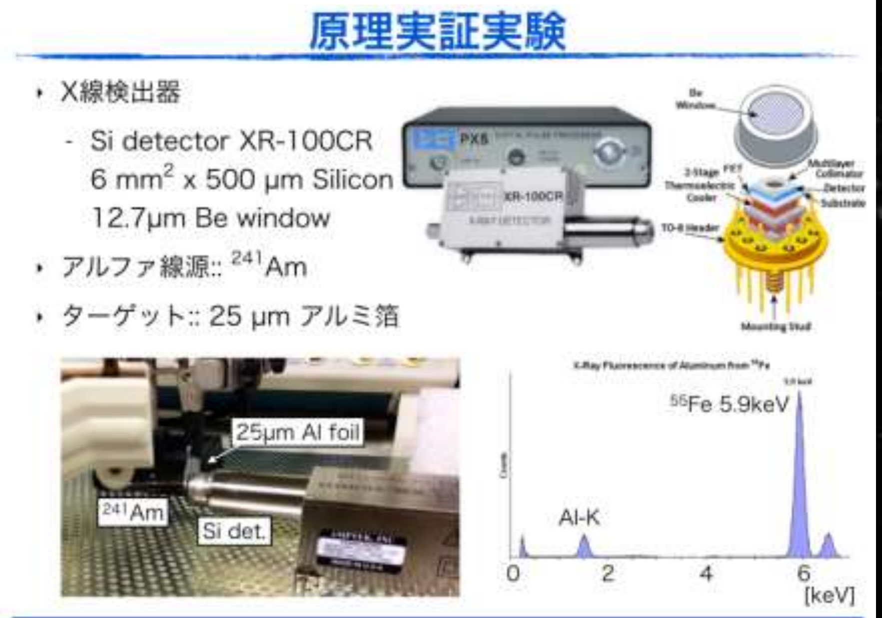
XMASS

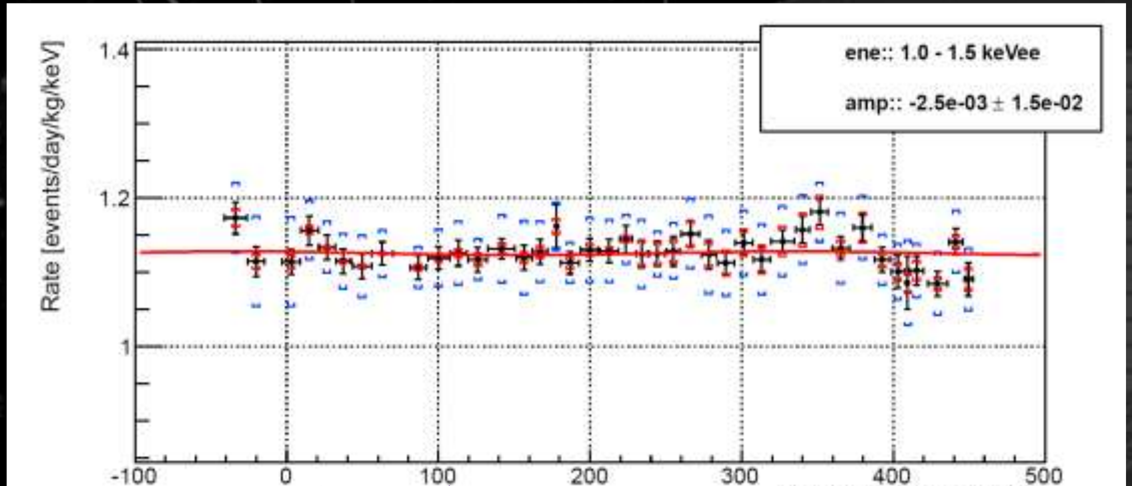
2016年8月 細川D論
Physics Letters B 759(2016), pp. 272-276

■細川ソース・物理解析（XMASSの花形:季節変動







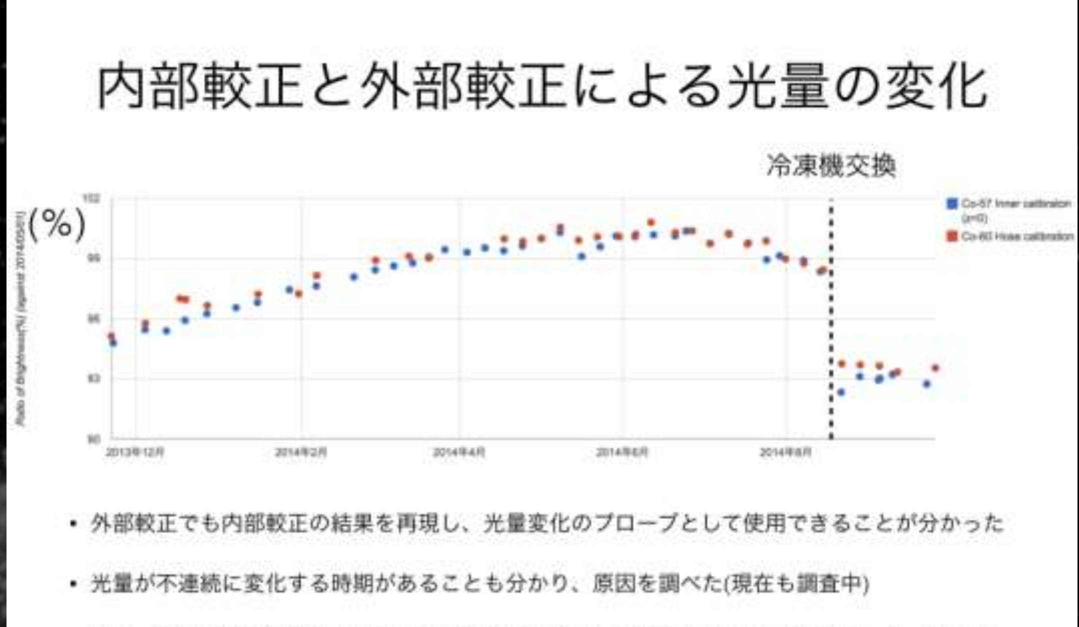


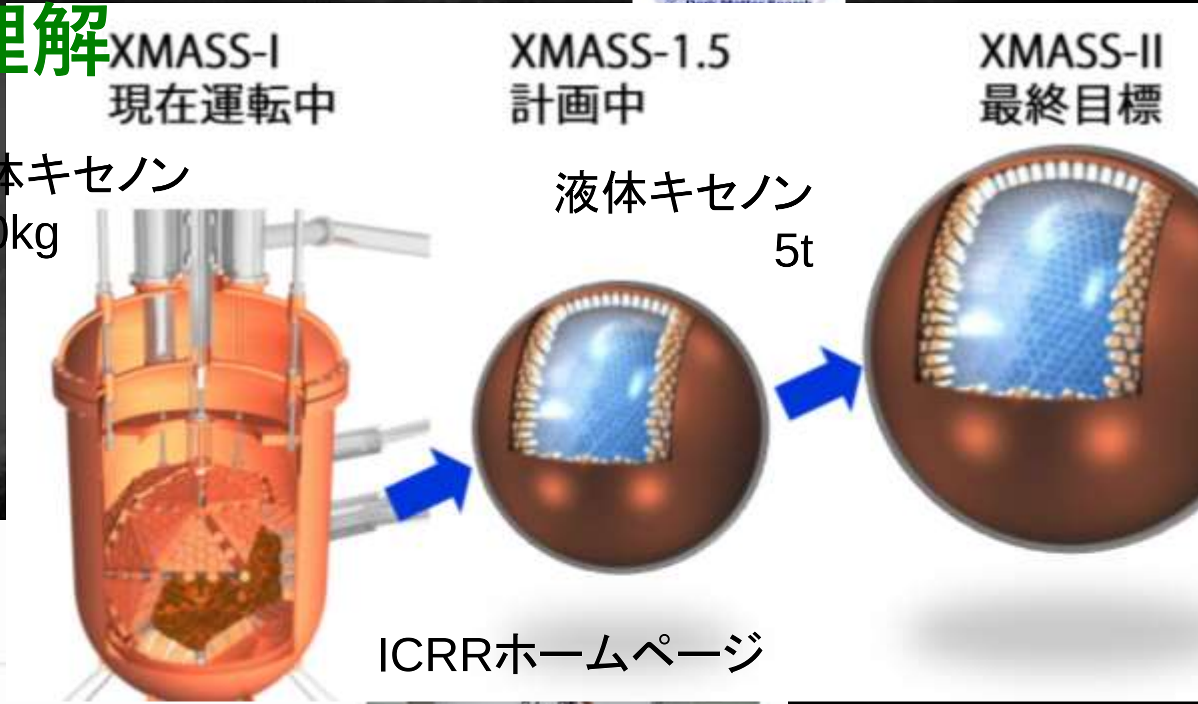
その他:ラドン計の開発
PTEP(2015) 033H01

神戸大 in XMASS

- ■岡ホース・新型PMT開発・物理解析

2015年2月岡D経過発表

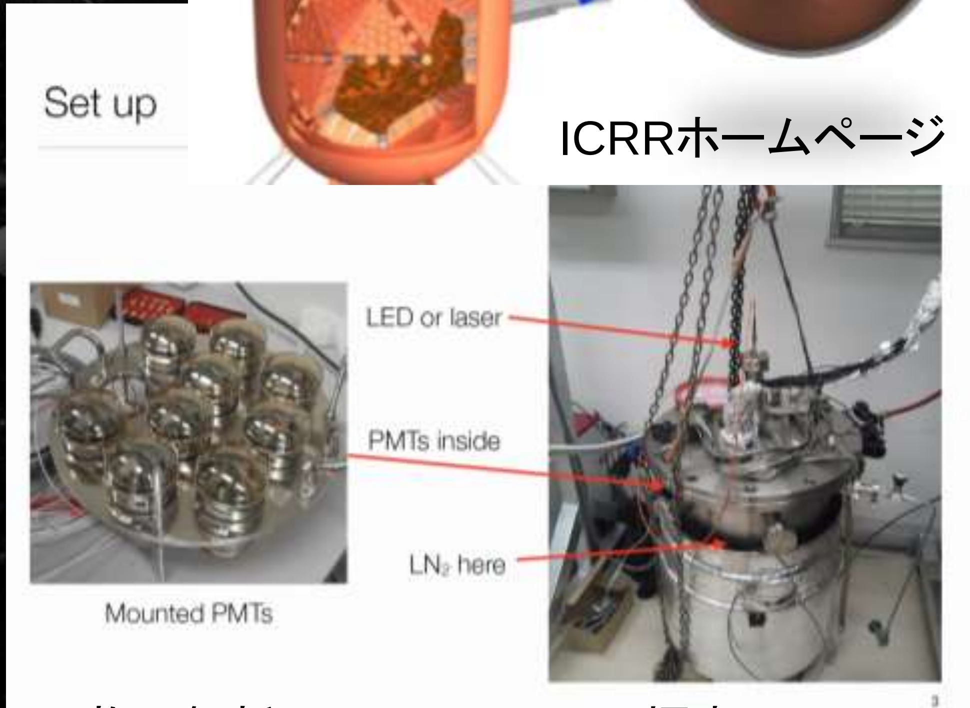




液体キセノン
800kg

液体キセノン
5t

ICRRホームページ

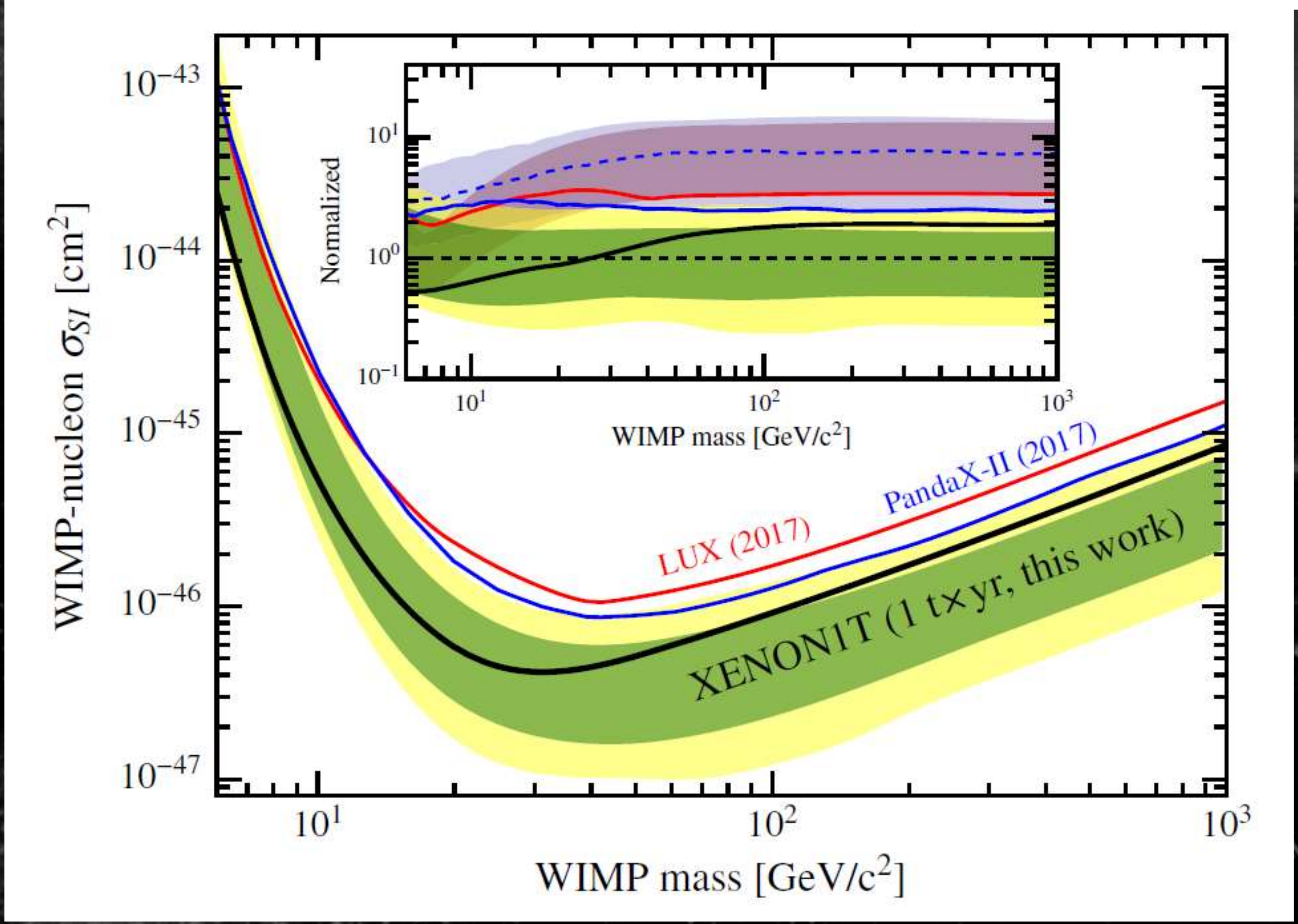


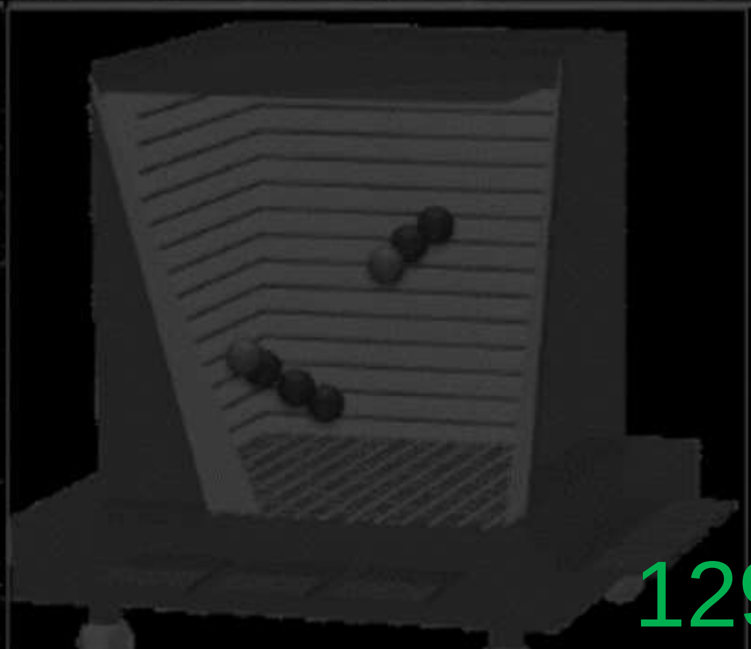
物理解析:KK solar AXION探索

[illegible]が太陽中で作られてい

- 現状

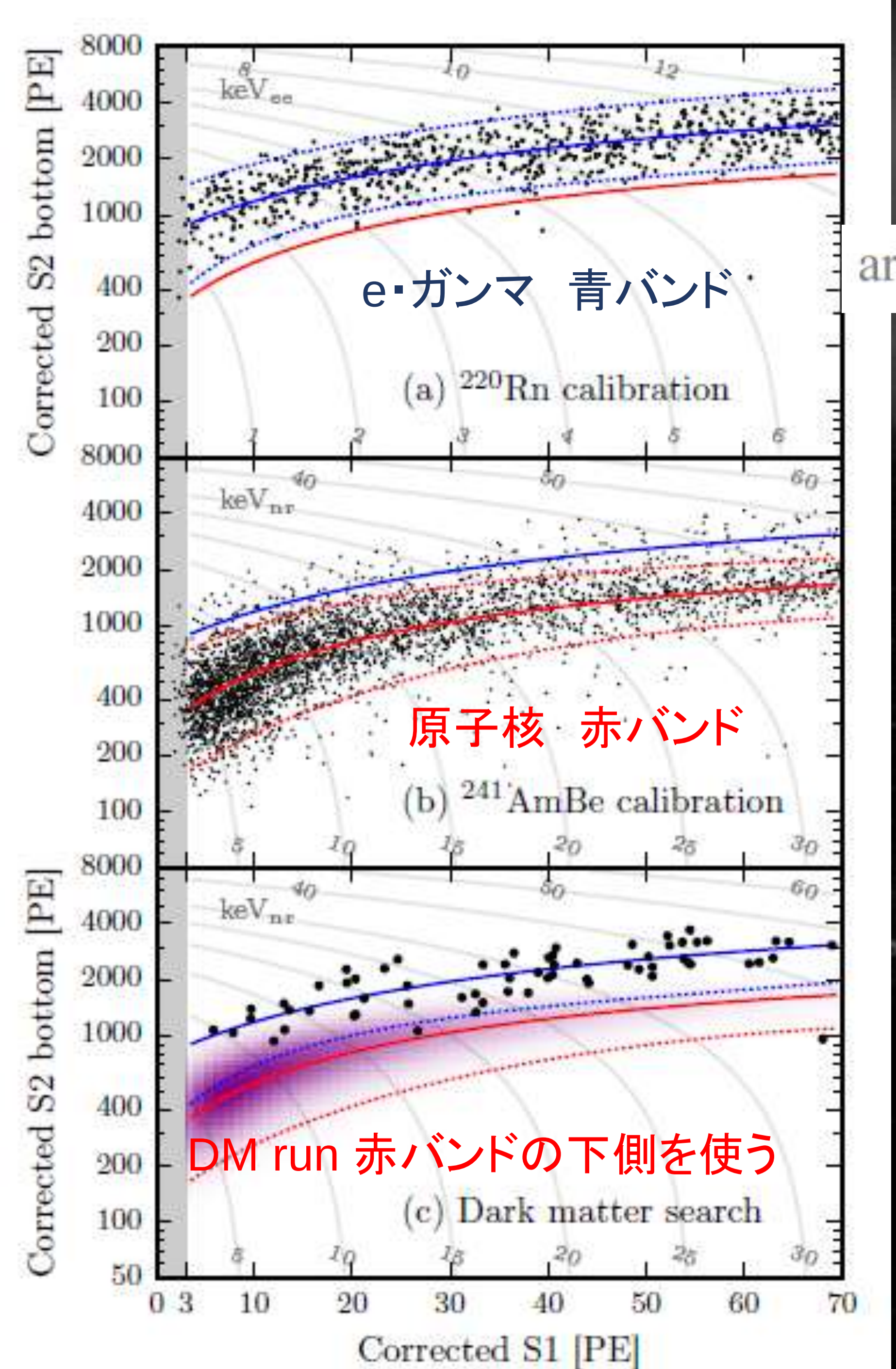
PHYSICAL REVIEW LETTERS **121**, 111302 (2018)





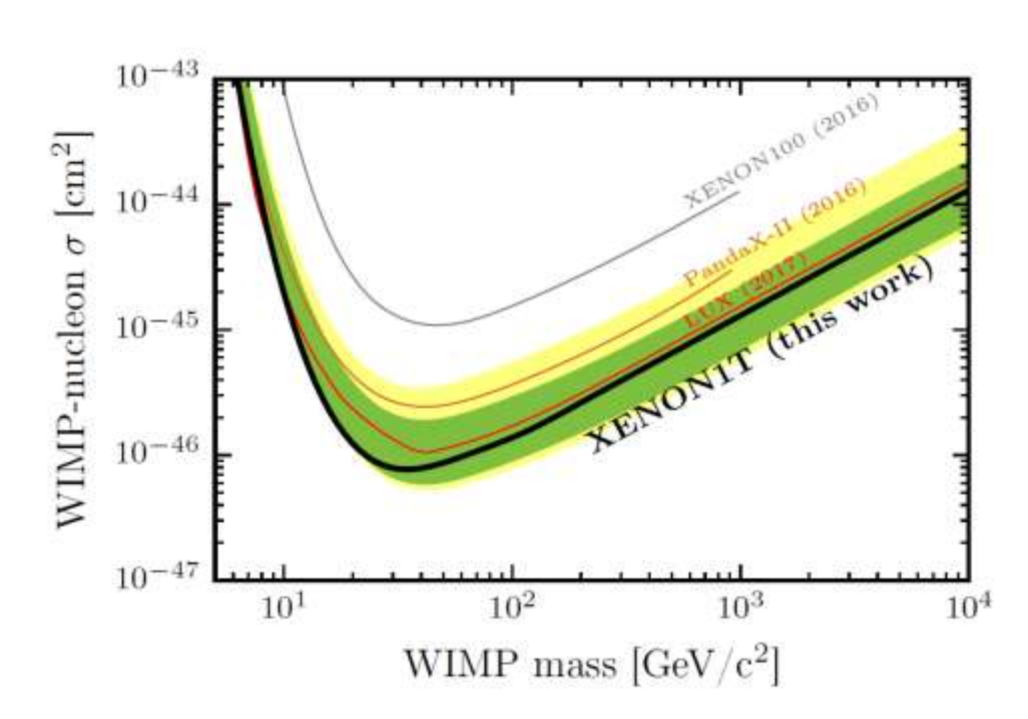
Xenon 1T 2017結果

34.2 live-days
1042kg fiducial mass



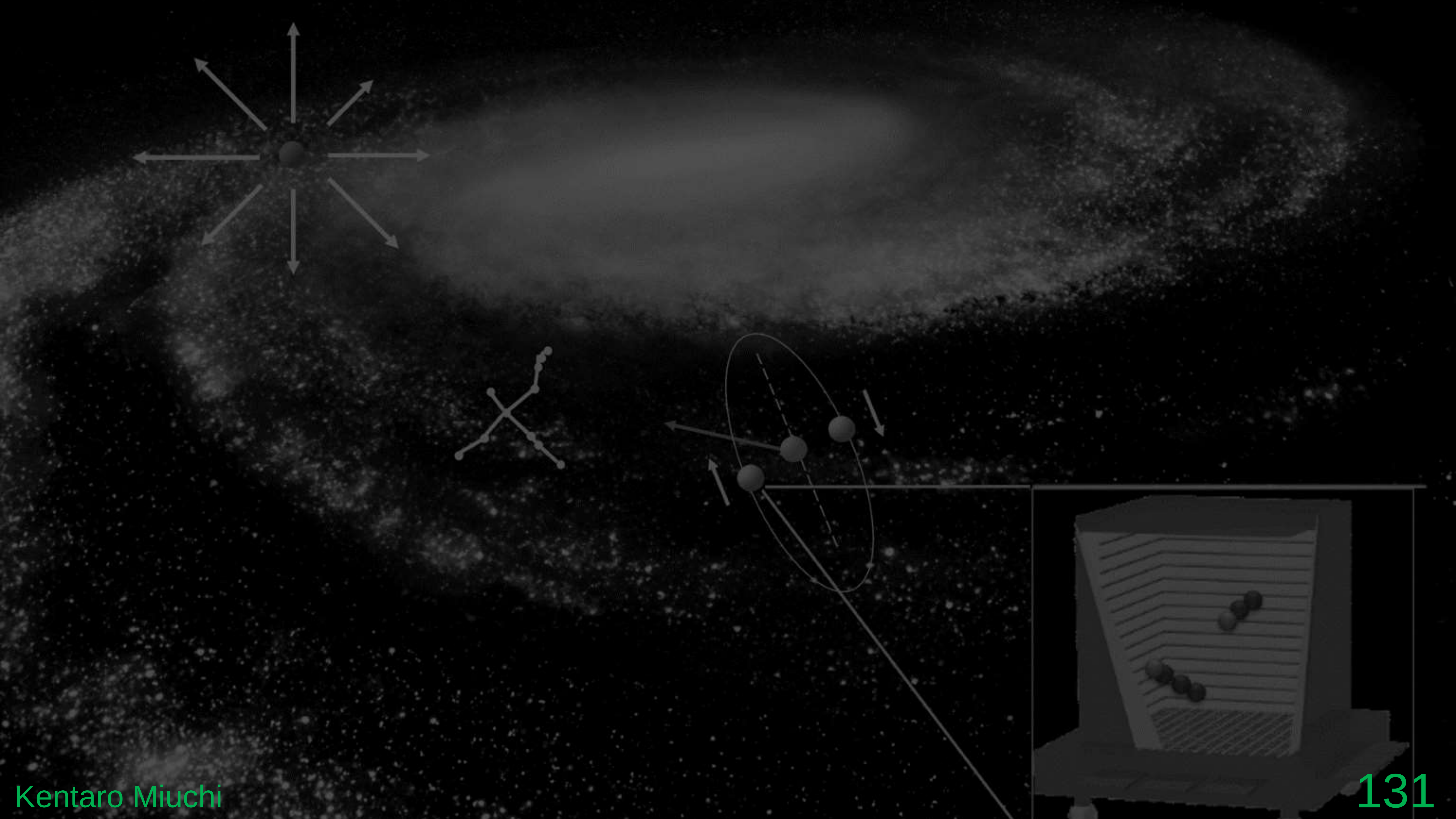
arXiv:1705.06655v2

$7.7\times10^{-47}cm^2$



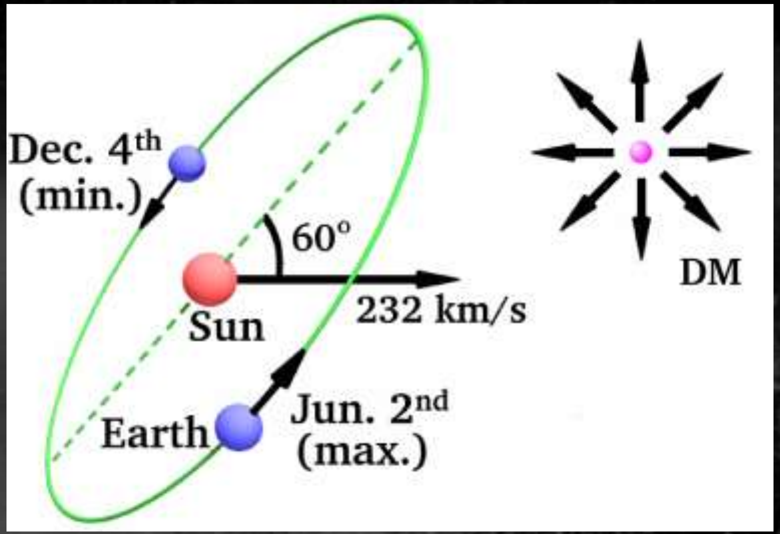
赤線より下はBGフリー

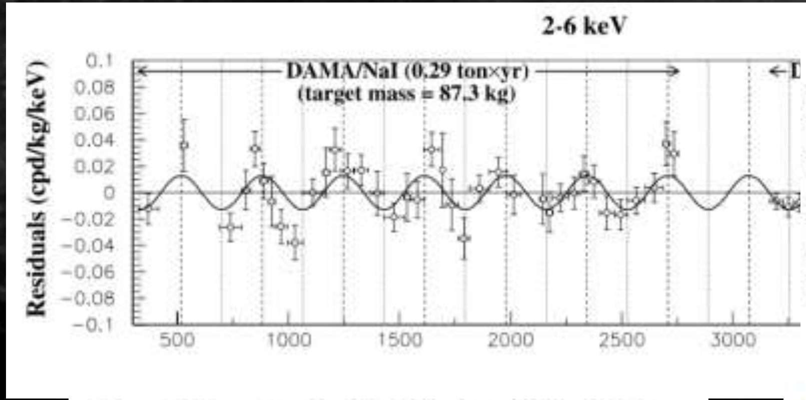
今後：上からの染み出しもありうる（^{214}Pb,^{85}Kr）



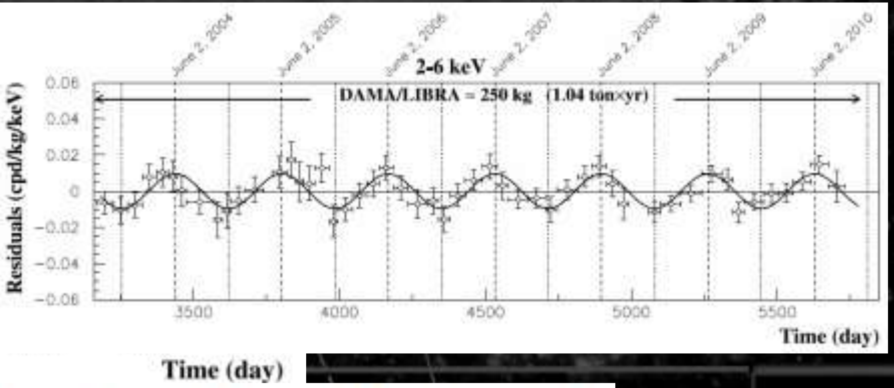
忘れちゃいけないNaI

- DAMAにまつわるエトセトラ
- 250kgのNaIシンチレータ
- 1.33ton・年の観測
- 14サイクルの季節変動　　　（9.3σ）





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



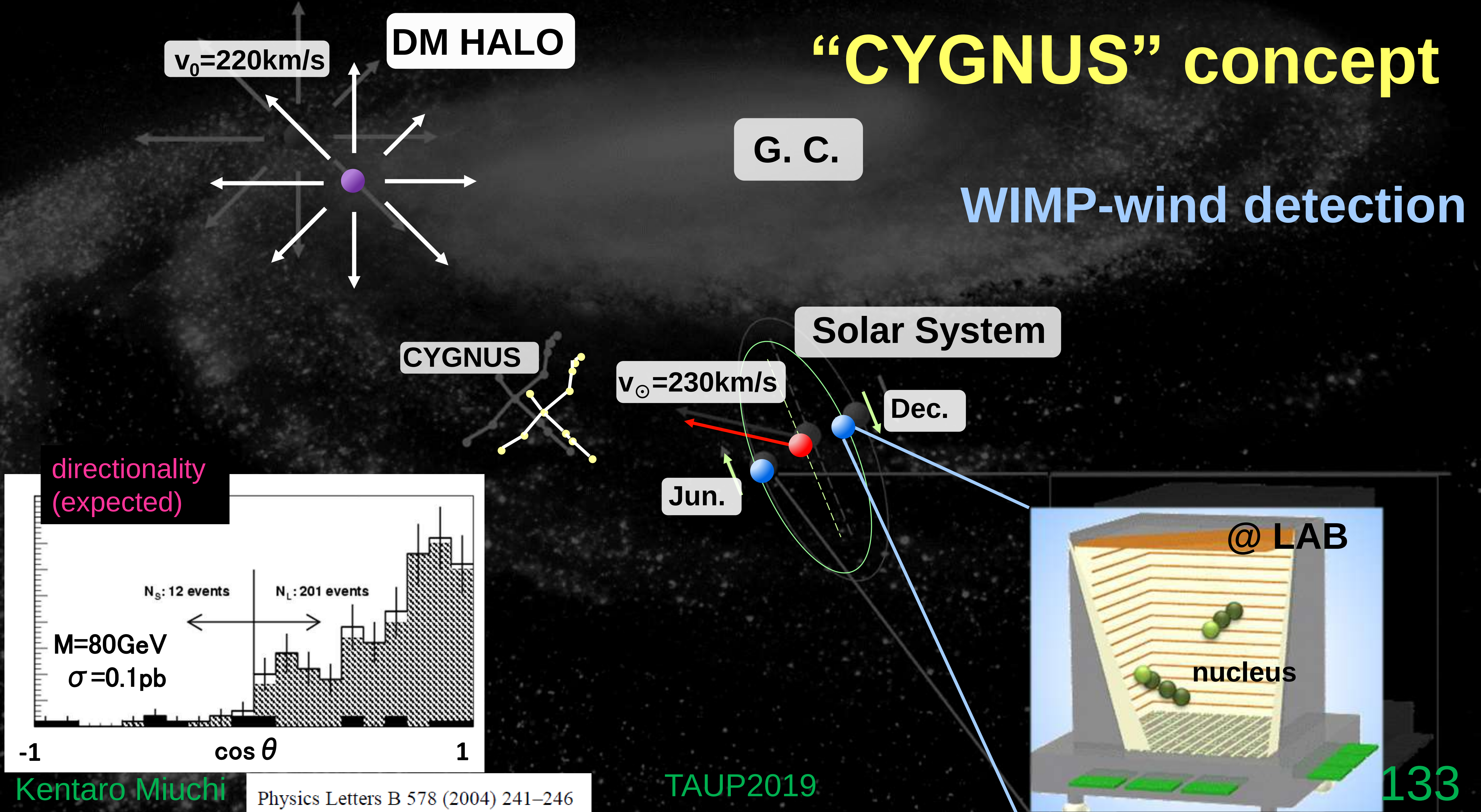
Eur. Phys. J. C (2013) 73:2648

- 中性子、太陽ニュートリノなどでの説明が試みされた
  ⇒　結局十分なモデルは構築されず。
- キセノンなどの実験では排除　↔　NaI実験では未試験

PRL 113, 081302 (2014)
PRL 114, 151301 (2015)
Eur. Phys. J. C (2014) 74:3196

- DAMAはまだ生きている。　今年か来年あと7年分でるはずだが。。。

"CYGNUS" concept



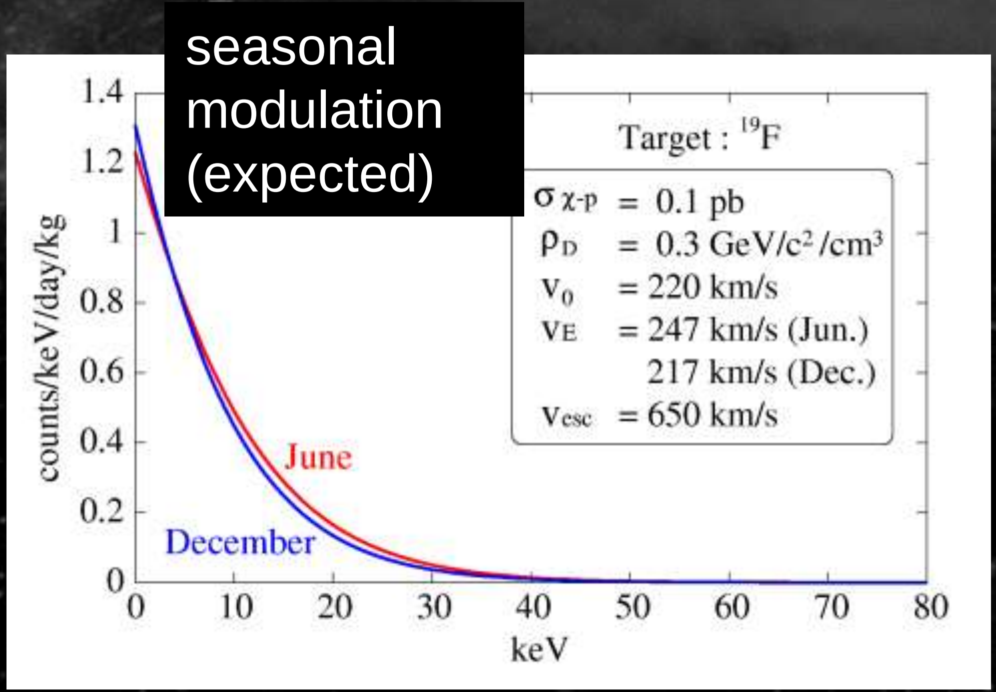
Physics Letters B 578 (2004) 241–246

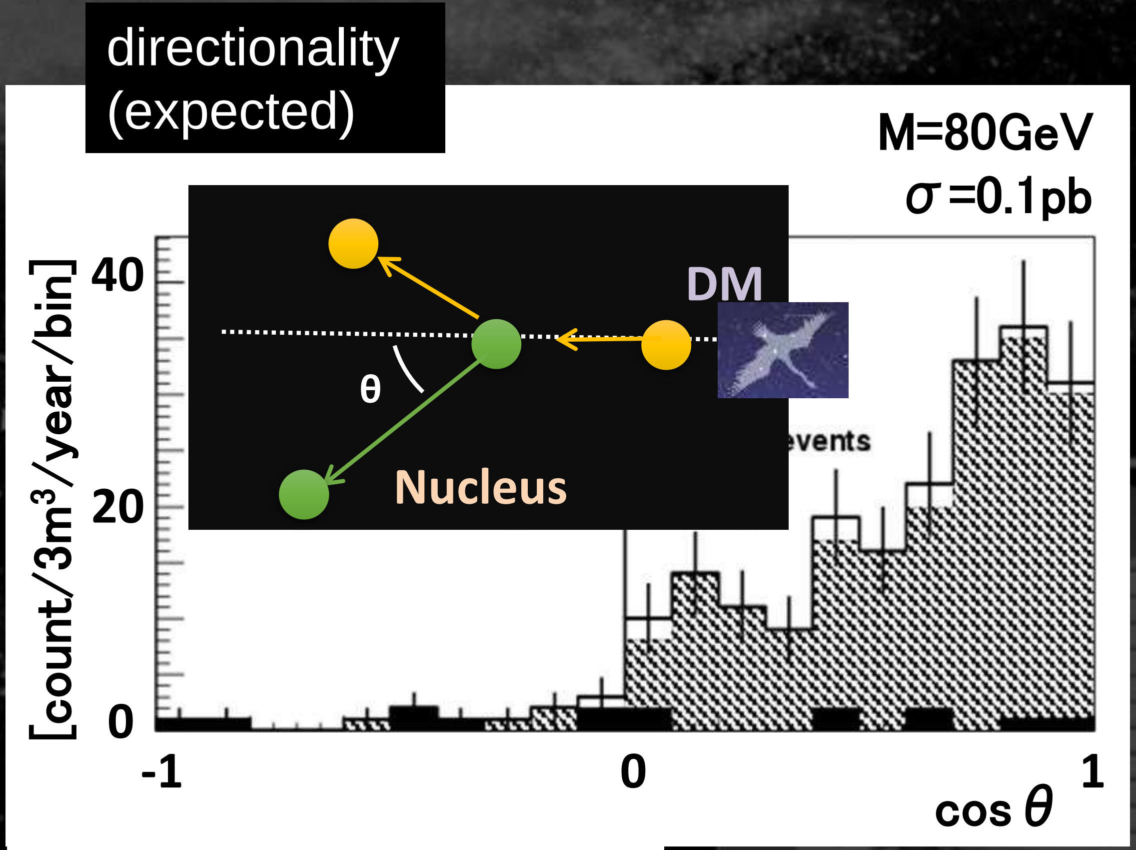
直接探索のこれから

- 暗黒物質
- これまで
- これから
- まとめ

CYGNUS: Directional Detection

- Clear Discovery
  + study the nature of DM after discovery

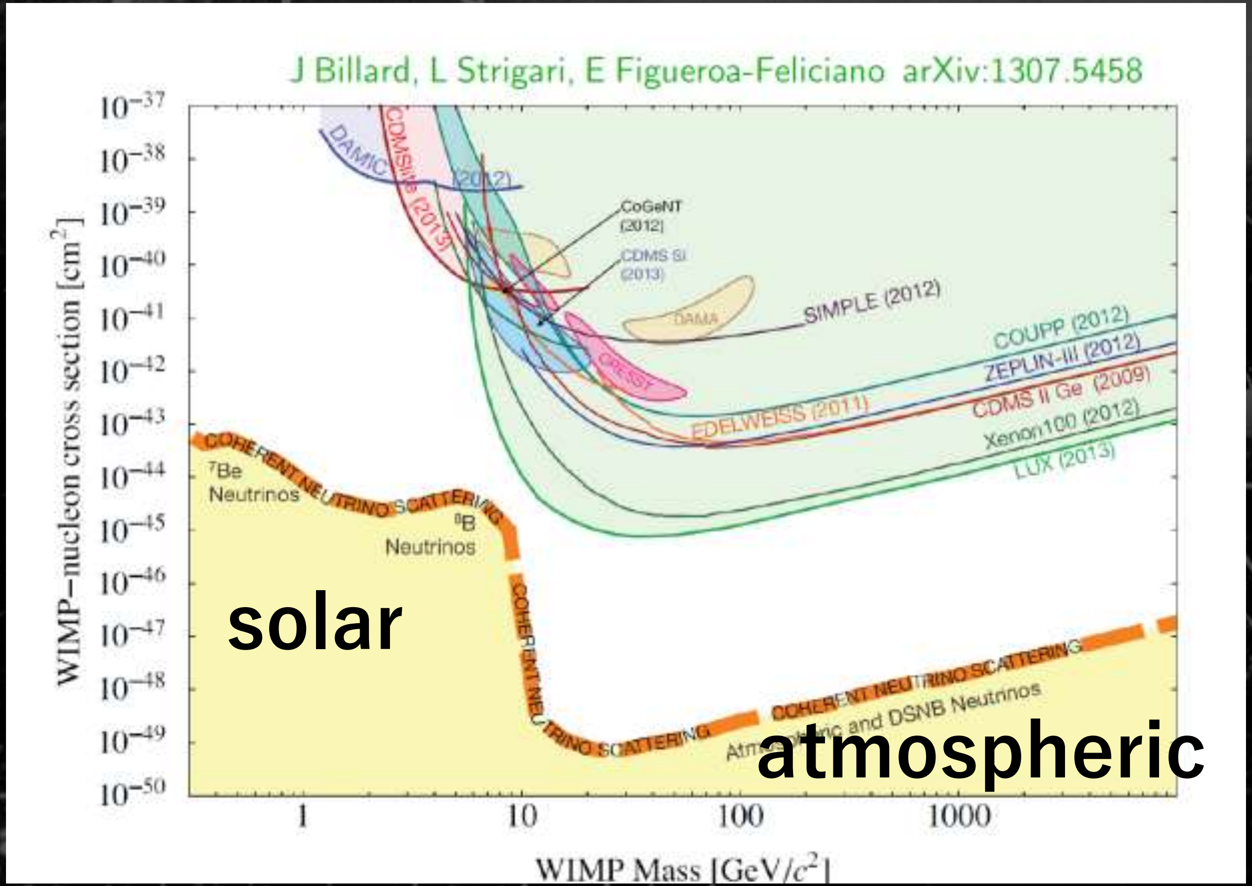




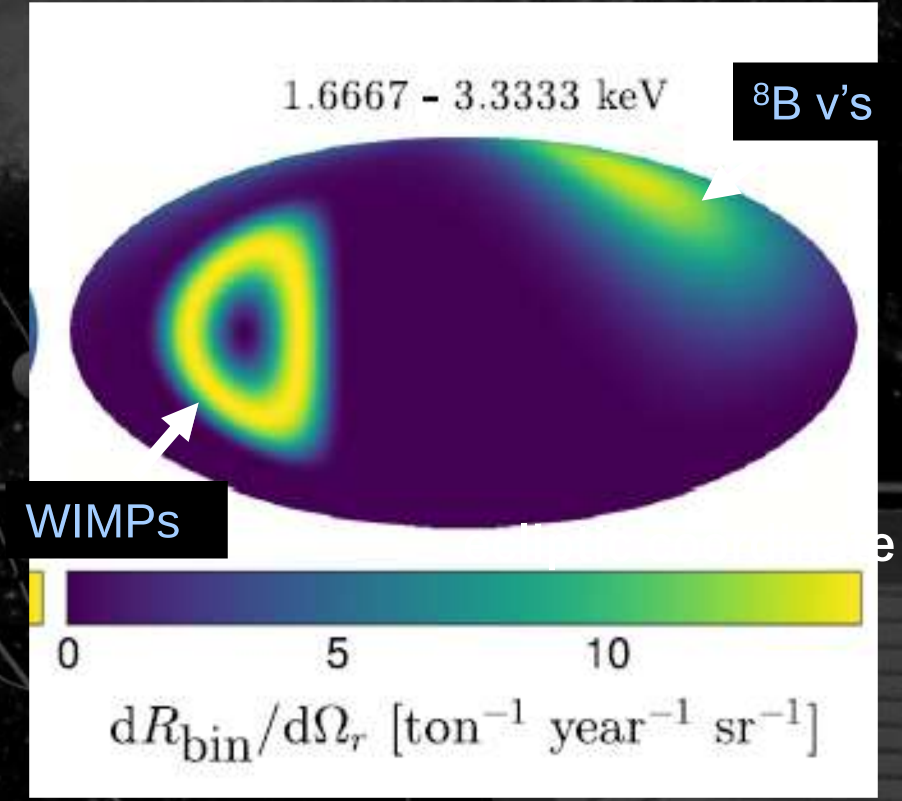
Physics Letters B 578 (2004) 241–246

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: community

- 7×bi-annual workshops (2007-)

- CYGNUS 2017 Xichang, Sichuan, China June 13 - 16, 2017
- CYGNUS 2015 Occidental College, Los Angeles, California, USA June 2 - 4, 2015.
- CYGNUS 2013 Toyama, Japan June 10 - 12, 2013.
- CYGNUS 2011 Aussois, France June 7 - 10, 2011.
- CYGNUS 2009 Massachusetts Institute of Technology, Cambridge, Massachusetts, USA June 11 - 13, 2009.
- CYGNUS 2007 Boulby Underground Laboratory, Saltburn-by-the-Sea, Cleveland, UK July 22 - 24, 2007.

CYGNUS 2019 @Roma

- 2 × review papers, another is coming

International Journal of Modern Physics A
Vol. 25, No. 1 (2010) 1–51
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THE CASE FOR A
DIRECTIONAL DARK MATTER DETECTOR AND
THE STATUS OF CURRENT EXPERIMENTAL EFFORTS

Readout technologies for directional WIMP Dark Matter detection

Physics Reports 662 (2016) 1–46

J.B.R. Battat [1,*], I.G. Irastorza [2], A. Aleksandrov
E. Baracchini [6], J. Billard [7,8], G. Bosson [7], O. Bourrion [7], J. Bouvier [7],
A. Buonaura [3,9], K. Burdge [10,11], S. Cebrián [2], P. Colas [12], L. Consiglio [13], T. Dafni [2],

CYGNUS: collaboration

- proto-collaboration (2016-)
  - >50 researchers
  - discussion on-going for actual collaboration

The CYGNUS Galactic Directional Recoil Observatory
Proto-Collaboration Agreement

Now that conventional WIMP dark matter searches are approaching the neutrino floor, there has been a resurgence of interest in the possibility of introducing recoil direction sensitivity into the field. Such directional sensitivity would offer the powerful prospect of reaching below this floor, introducing both the possibility of identifying a clear signature for dark matter particles in the galaxy below this level but also of exploiting observation of coherent neutrino scattering from the Sun and other sources with directional sensitivity. There has also been significant progress recently in development of technology able to record the directional information from nuclear recoils at low energy (sub-100 keV) necessary for these goals. This includes progress on improving the sensitivity of low pressure gas time projection chamber technology but also on novel ideas with higher density targets, such as ultra-fine grain emulsions, scintillation materials, columnar recombination with noble gas targets and concepts using nano-technology. Such world-wide directional expertise, if pooled together and directed

steering committee

E. Baracchini (GSSI)
G. Lane (ANU, Canberra)
K. Miuchi (Kobe)
N. Spooner (Sheffield)
S. Vahsen (Hawaii)

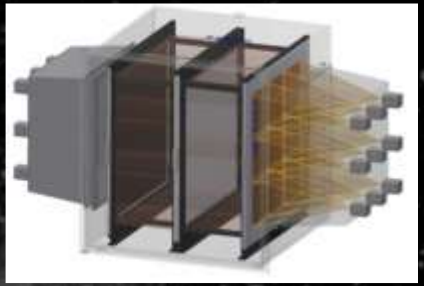

Activities
Overview
Activities
Highlights
Summary

World-wide CYGNUS (ver. TAUP2019)

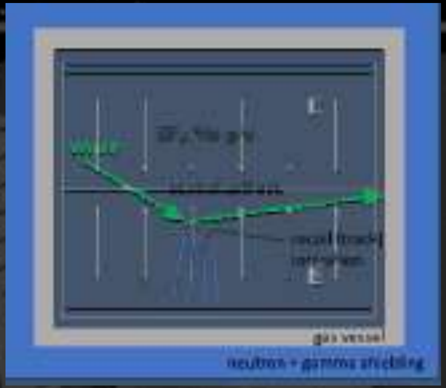
CYGNUS-KM
Kamioka, Japan
SF6 / CF4
Strip readout

CYGNUS-10
Boulby, UK
$10m^3$ $He:SF_6$
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

- UK / Boulby
  - pioneered this field (DRIFT)
  - 1m^3 detector running underground (Boulby) for years
  - low BG, large volume

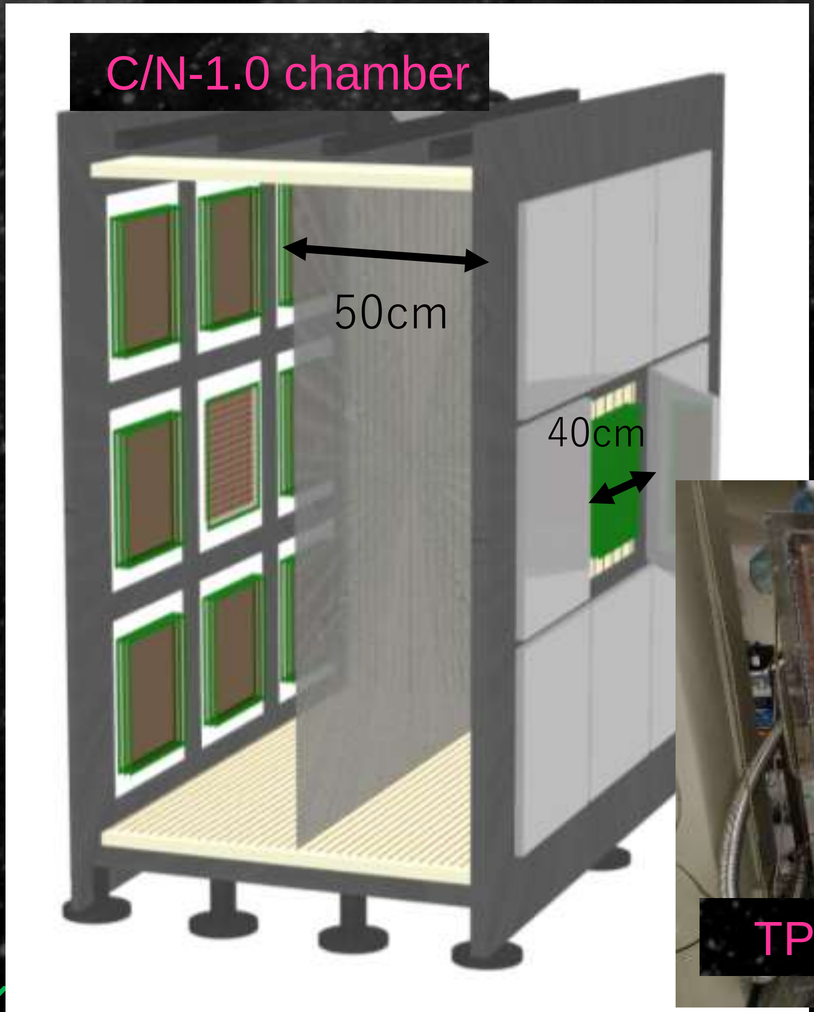
Boulby Underground Lab

- 10m^3 chamber design ongoing
  - low BG vessel design w/ simulation
  - R&D for GEM and wire readout
  - clean space underground at Boulby
  - easy to excavate more

- JAPAN / Kamioka

See T.Ikeda's Talk for NEWAGE

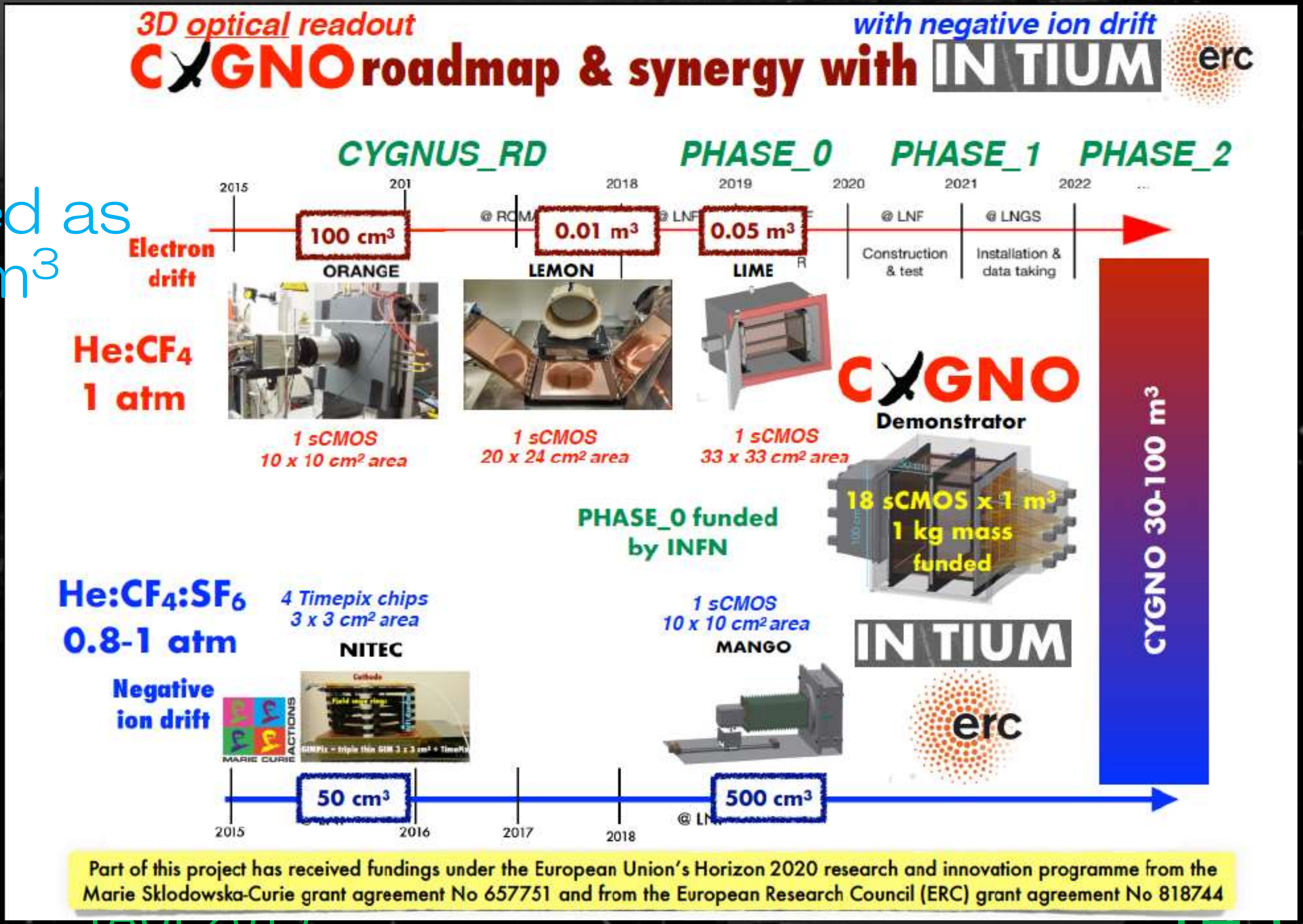
  - pioneered 3d-tracking (direction sensitive) (NEWAGE)
  - C/N-1.0 chamber (18 × 30×30 cm^2 detectors)
    - chamber ready
    - TPC cage (w/ resistive sheet), feedthrough being commissioned



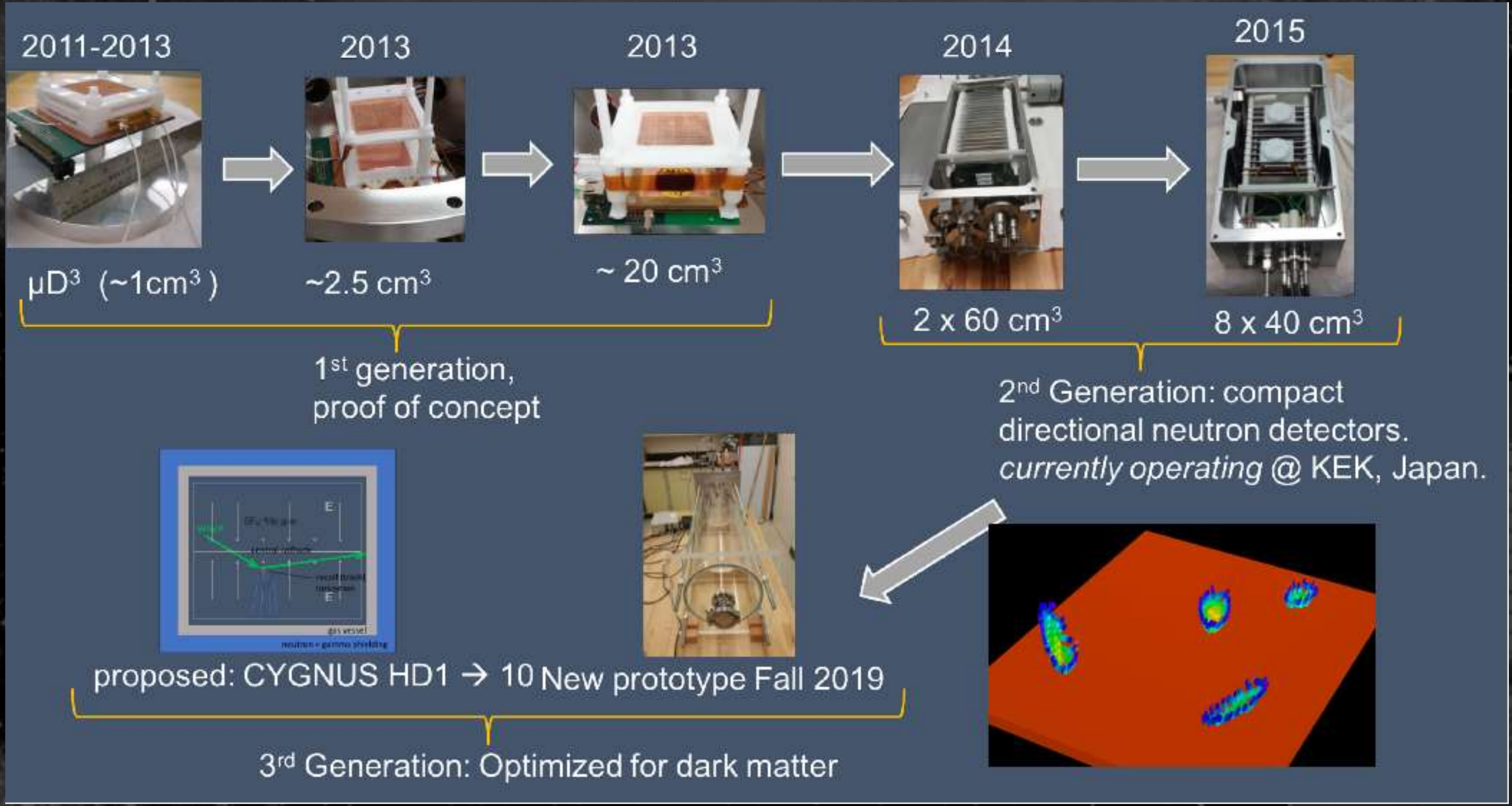
- Negative ion studies
  - 3-D tracking
  - MPGD gas avalanche simulation

- ASICs for negative ion strip readout
  - > 5k channels made
  - chip test started

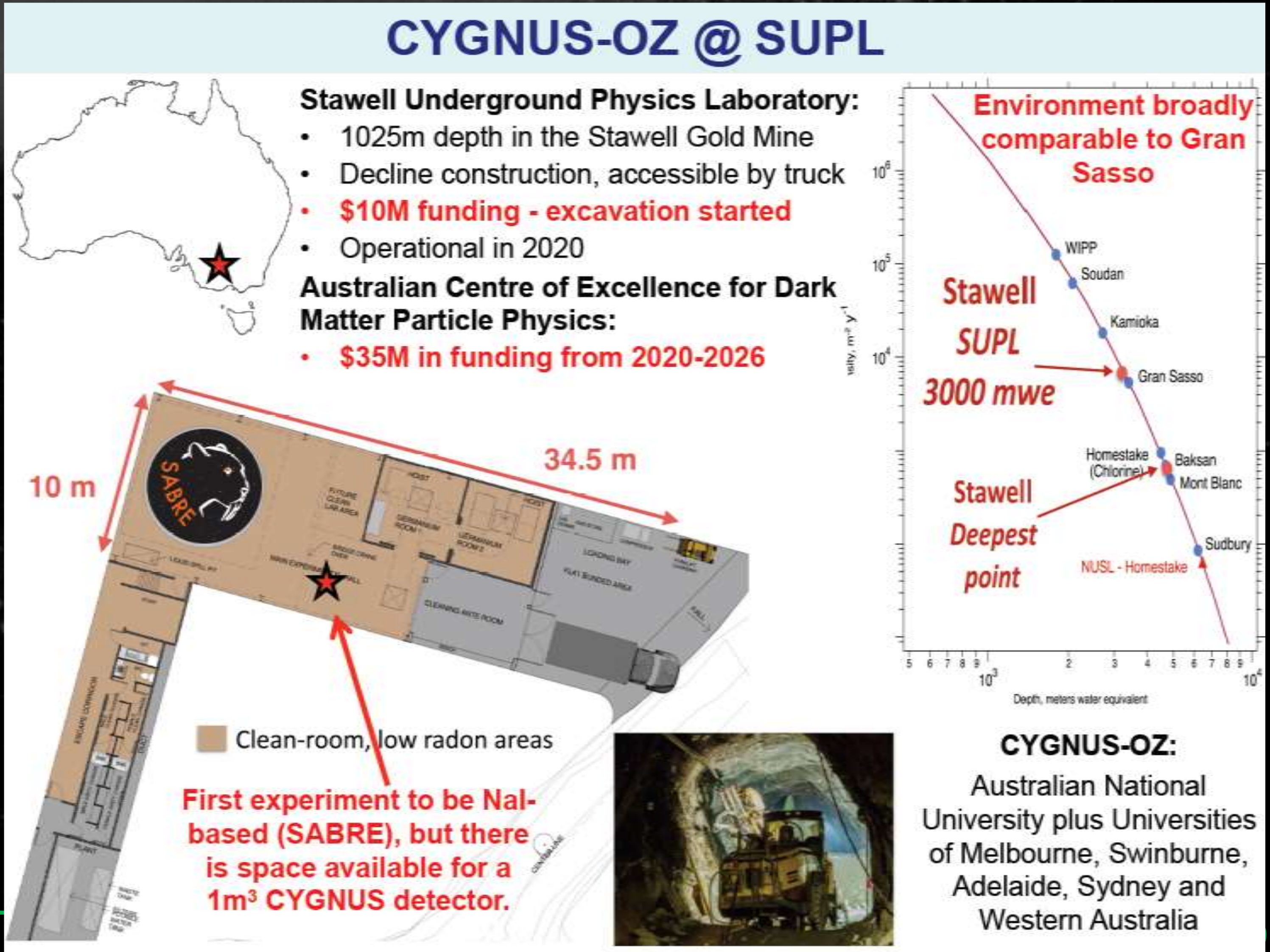
- Italy / GranSasso (intended) See E.Barracchini's Talk
  - Focusing optical readout
  - Two parallel R&D paths
    - electron drift
    - negative ion drift
  - 1 m^3 scale detector funded as demonstrator for 30-50m^3



- US / SURF (intended)
  - Focusing on pixel, strip readout (HD)
  - Extensive prototyping completed
  - CYGNUS HD1 1-m^3, demonstrator for 10 m^3, proposed

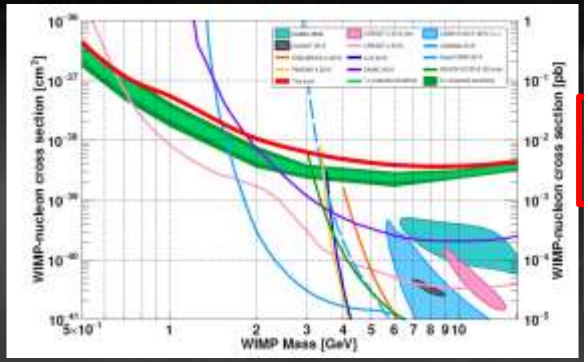


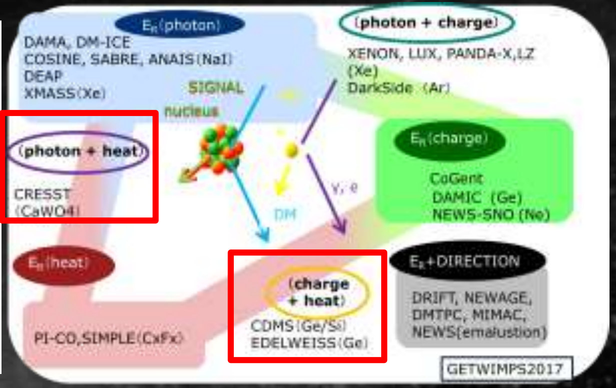
- Australia / Stawell
  - Excavation of new lab started – operation in 2020
  - Space available in 2020 for 1 m^3 CYGNUS TPC, 10 m^3 in 2025?
  - DM community recently funded – includes R&D for CYGNUS



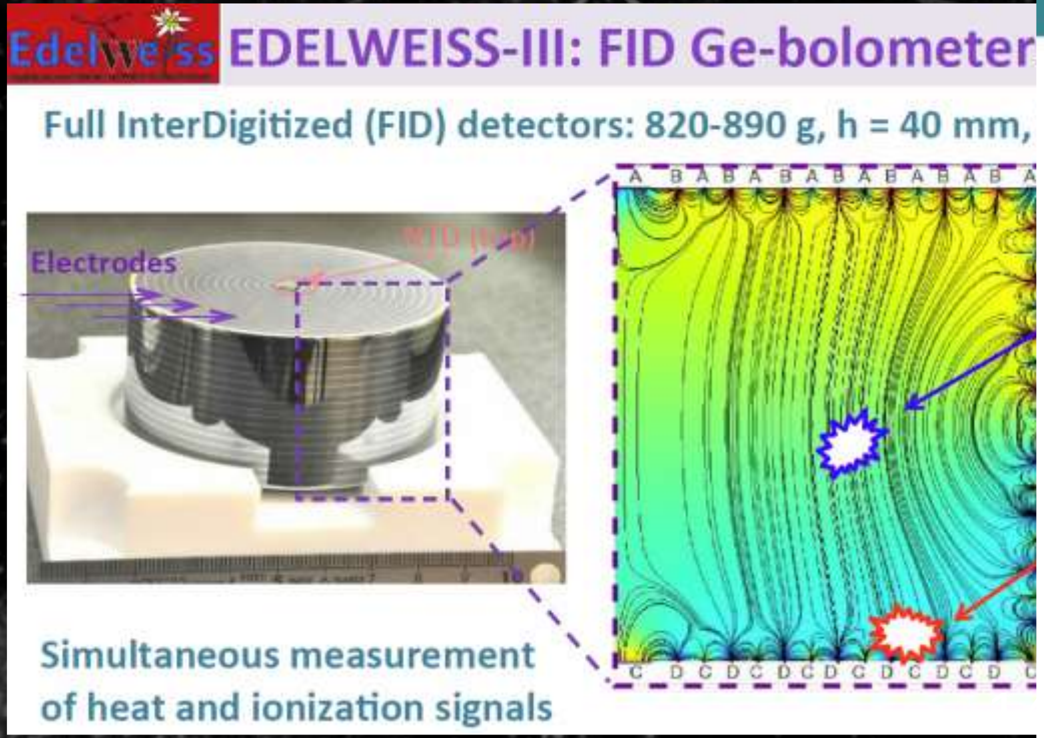
低mass低温

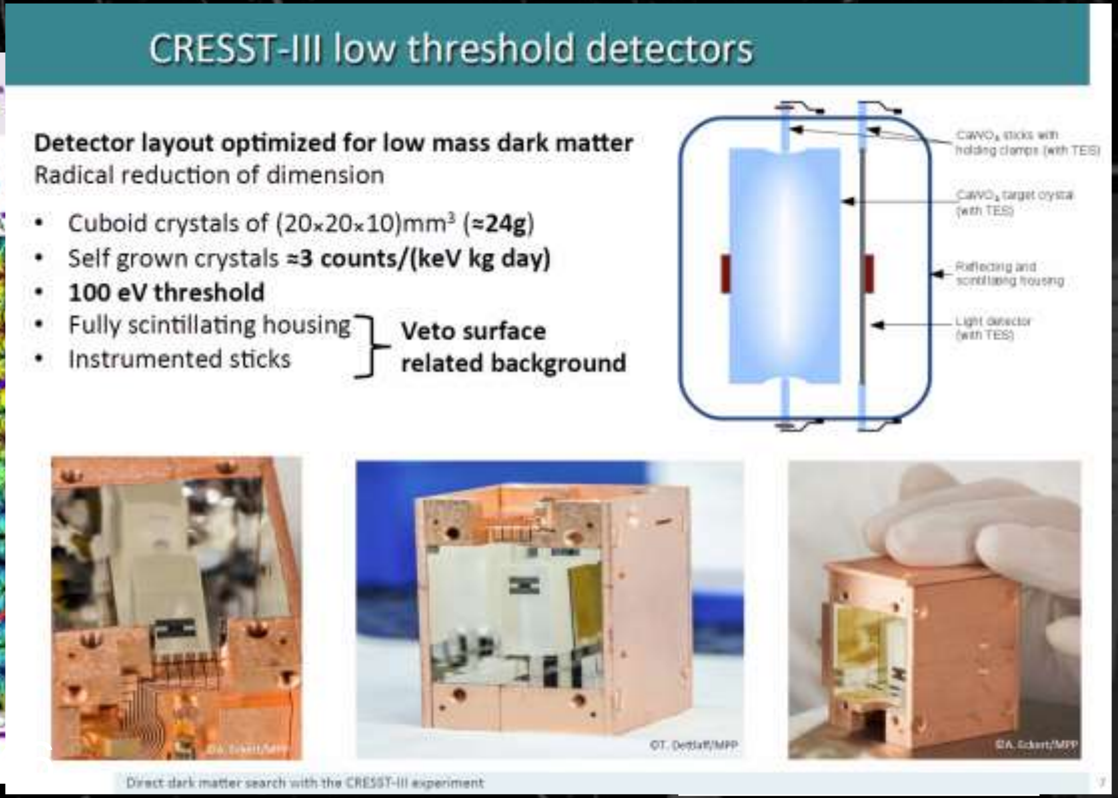
- 閾値を下げて低質量WIMPに特化





- SuperCDMSlite (Ge)　閾値 56eVee　600g
- EDELWEISS (Ge)　閾値 900eVnr 800g
- CRESST-III (CaWO4)　閾値 100eVnr　24g



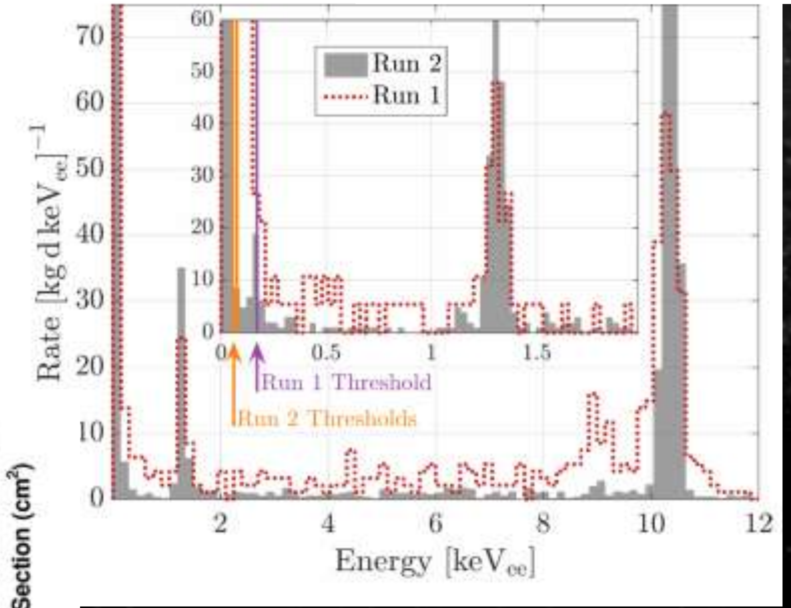


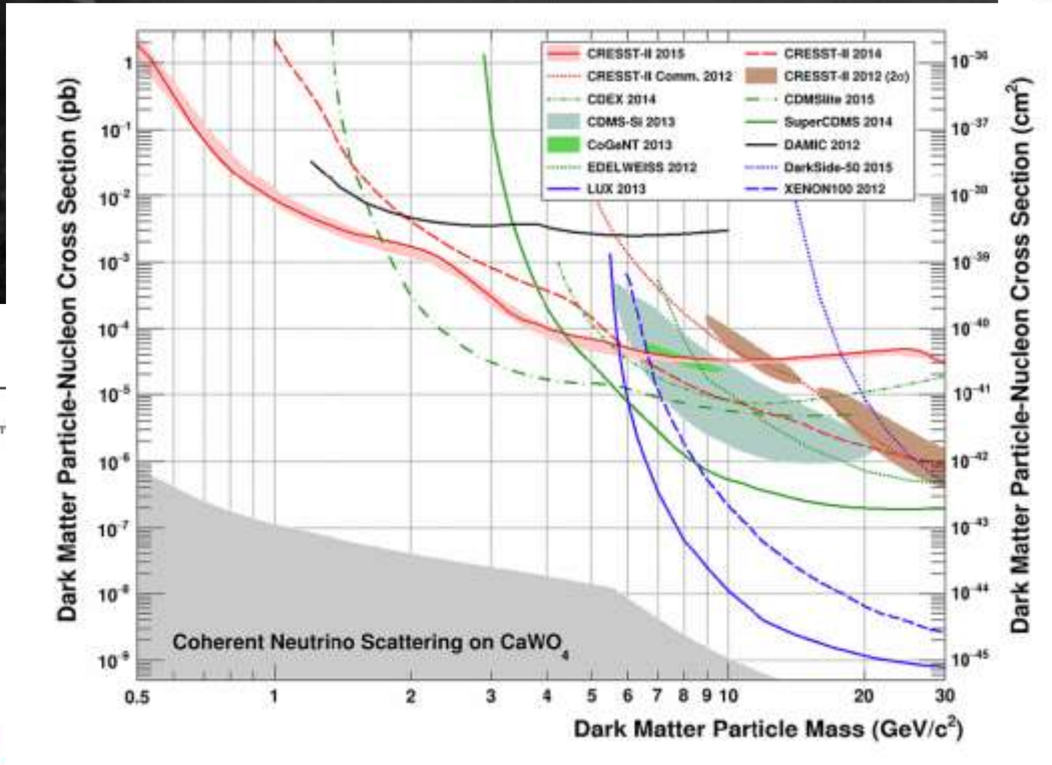
BG free?

- 3実験とも、0事象ではない。
- が低質量では十分良い探索能力。
- conservativeに制限をつけているが、、、

CDMS

arXiv:1707.01632v2





Eur. Phys. J. C (2016) 76:25

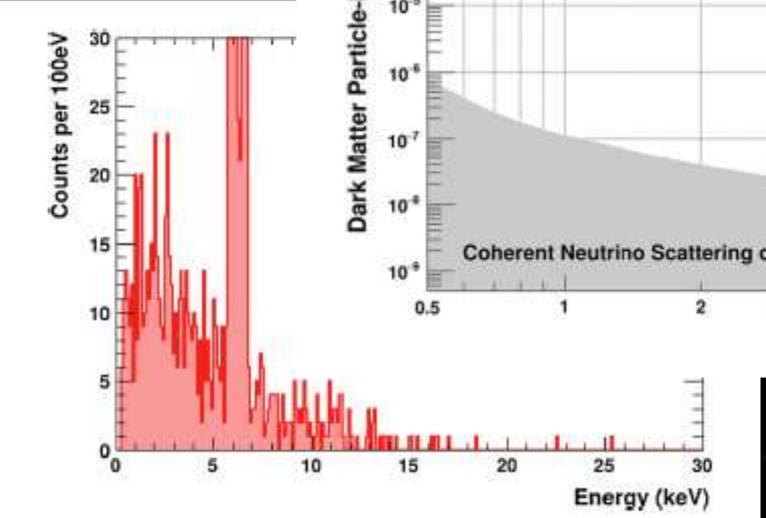
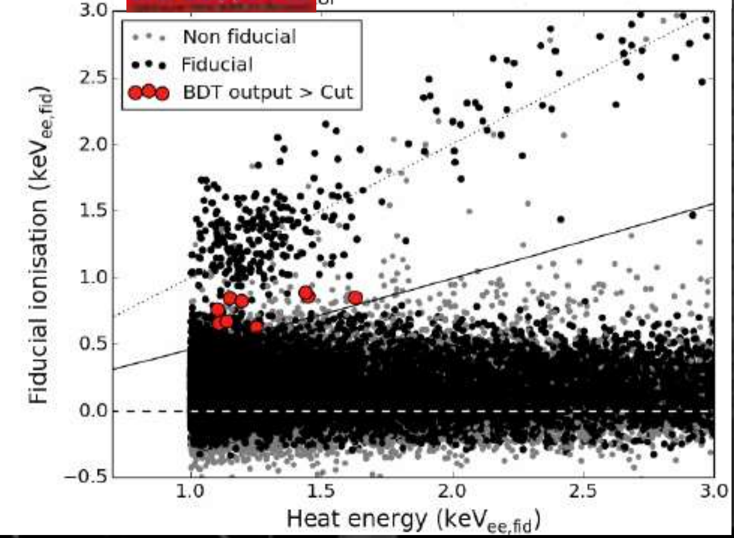


Fig. 6 Energy spectrum of all events in the acceptance region (307 eV–40 keV, see Fig. 5) truncated at a bin content of 30 for reasons of clarity. For the final result all events are conservatively considered as potential signal events to extract an exclusion limit using Yellin's optimum interval method

CRESST

Edelweiss

JCAP05(2016)019



Highlights

- Overview
- Activities
- Highlights
- Summary

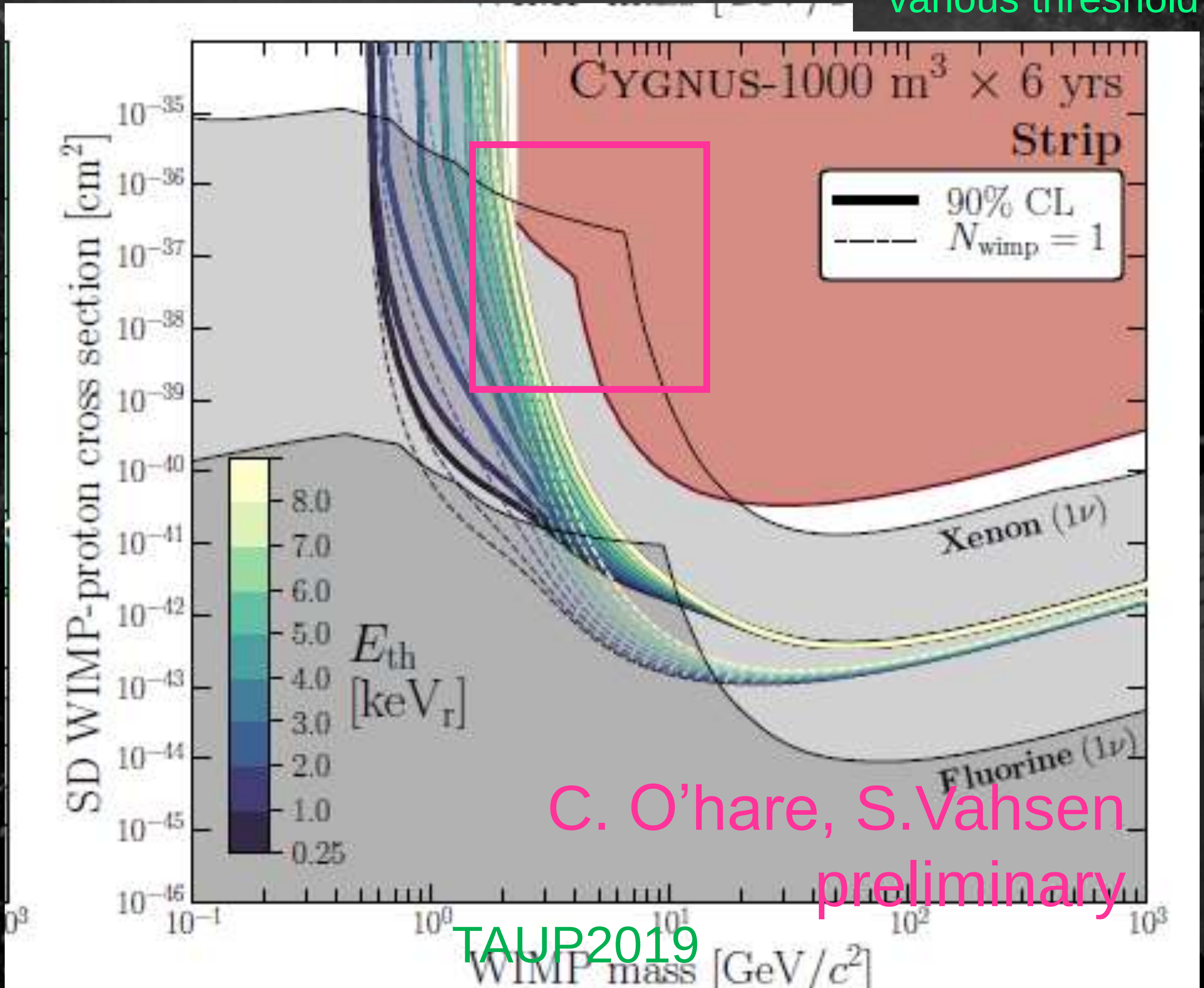
Highlight 1: Feasibility Study

Paper in internal review

- Realistic simulation (strip readout)

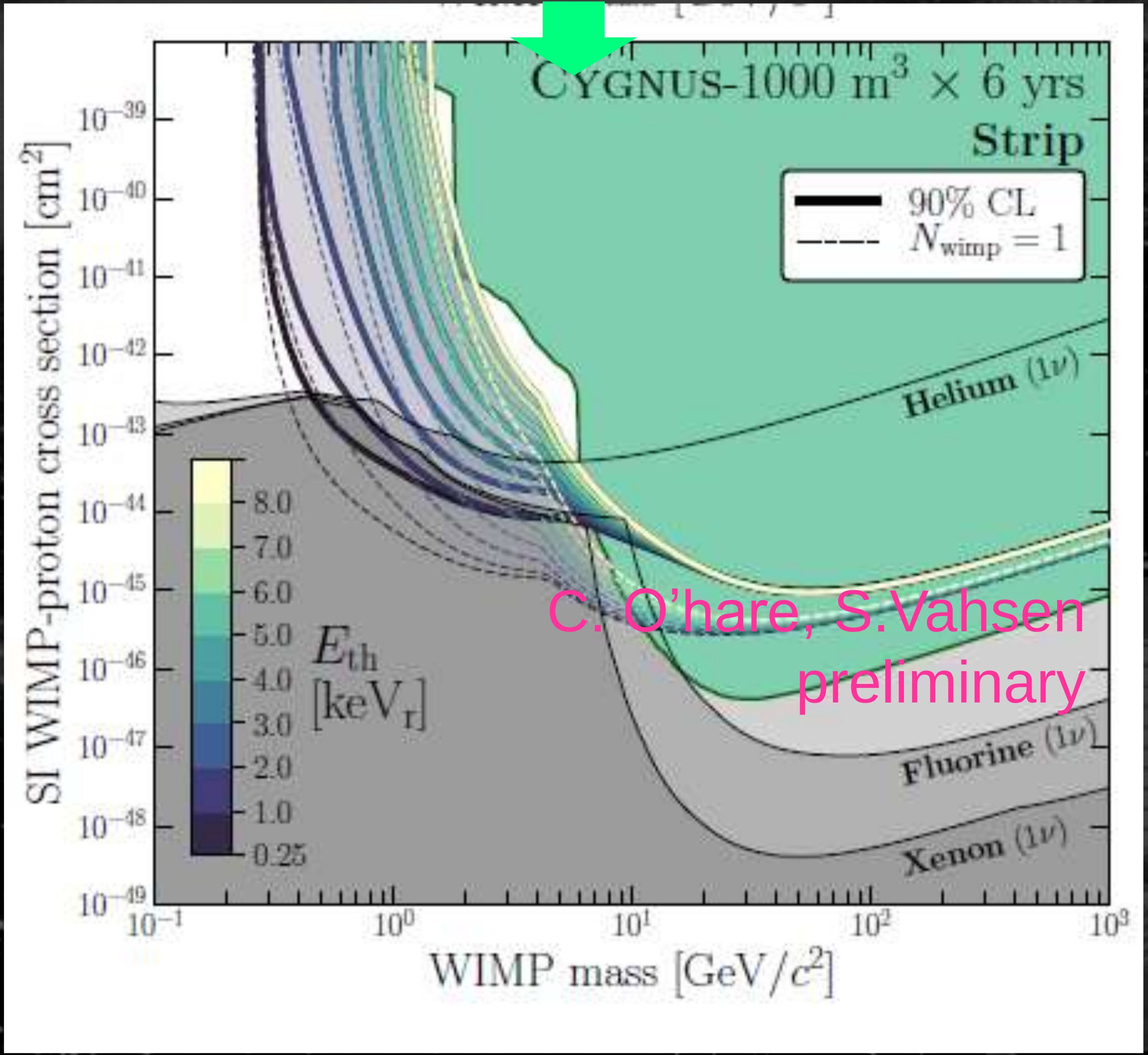
1000m^3
strip readout with
various threshold

even 10m^3 detector
(3 order magnitude higher than
the shown curves) can start
exploring Xe neutrino floor



C. O'hare, S.Vahsen
preliminary

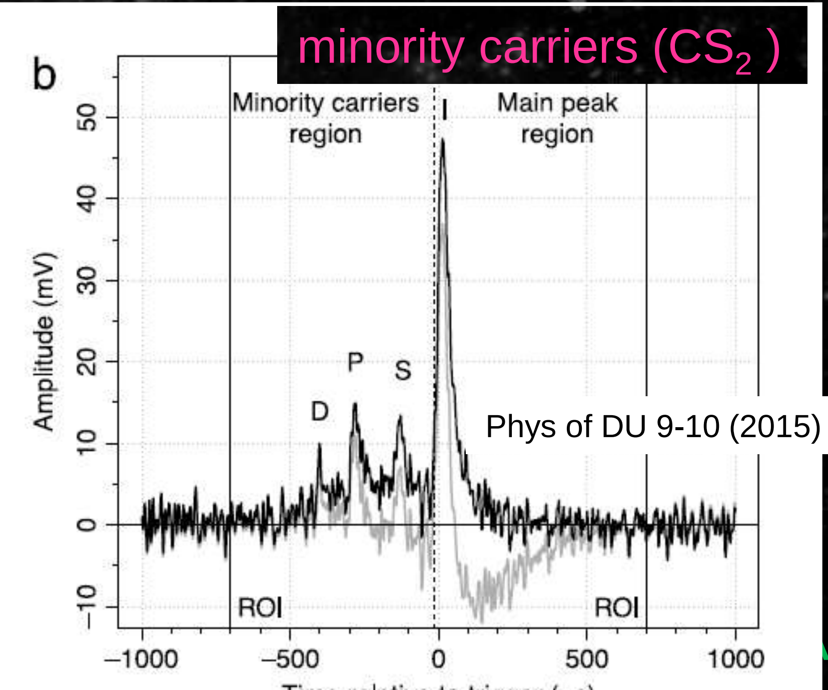
strip readout with
various threshold



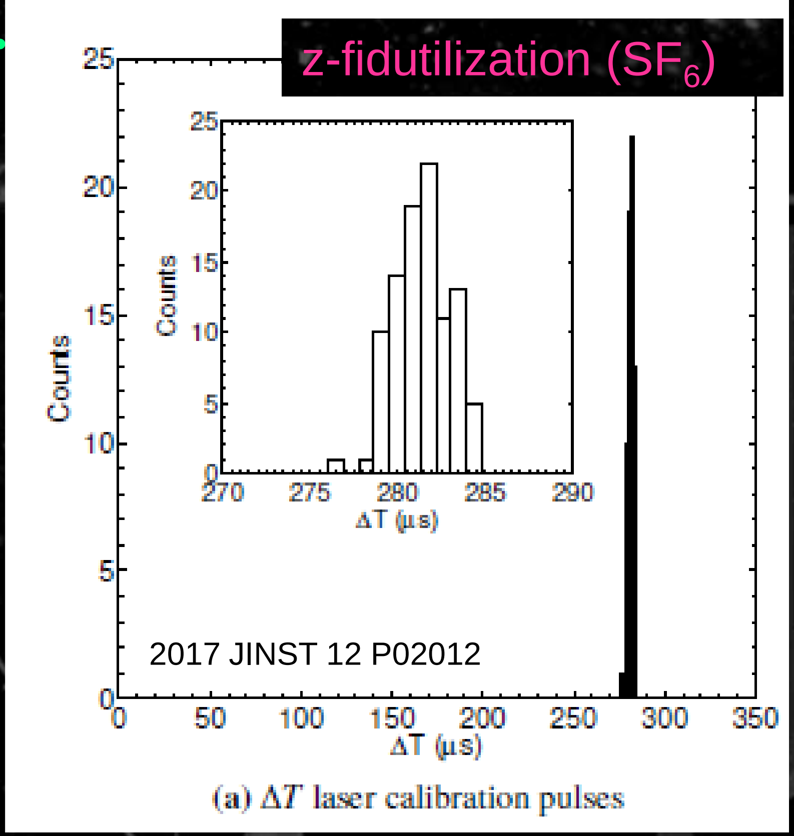
Kentaro Miuchi

Highlight 2: Negative ion TPC Study

- Pioneered by DRIFT group small diffusion
- Minority carrier discovery (CS_2+O_2, Occidental group)
  - use several ion species with different drift velocities
  - ⇒ z fiducialization possible ⇒LOW BG !
- SF_6 discovery (2015, UNM group)
  - z-fiducialization 7.3mm FWHM



Phys of DU 9-10 (2015) 1



2017 JINST 12 P02012

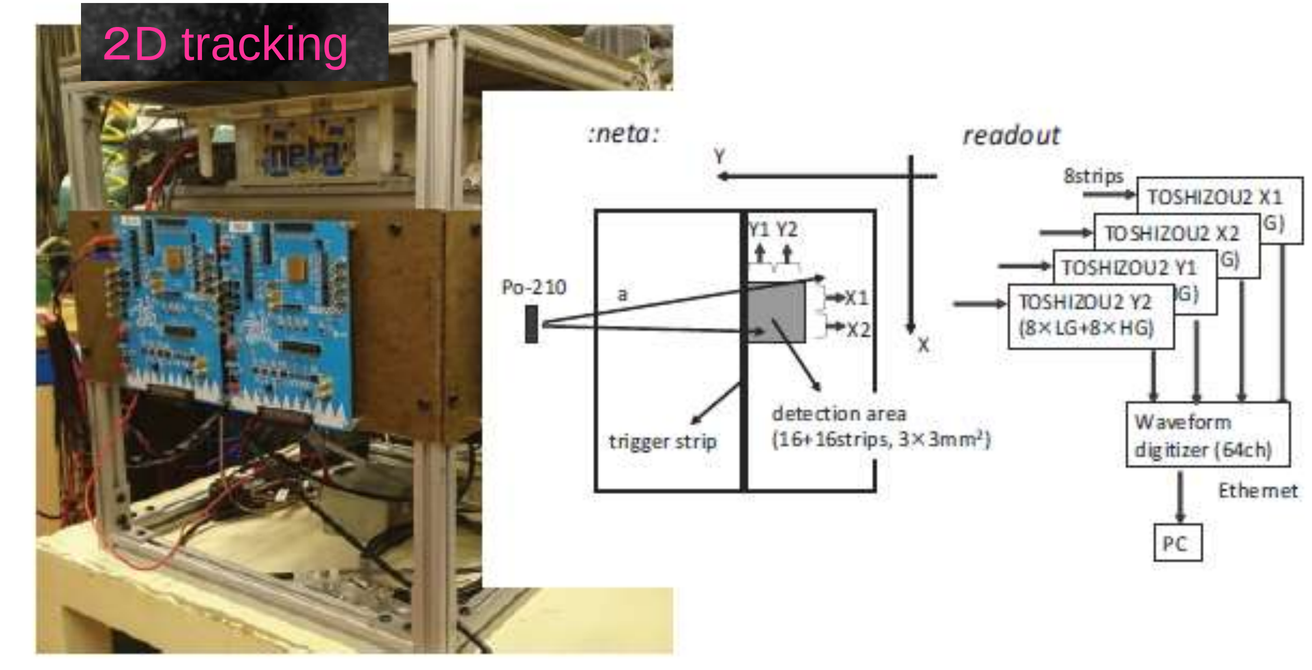
• to be CYGNUS: Trackings

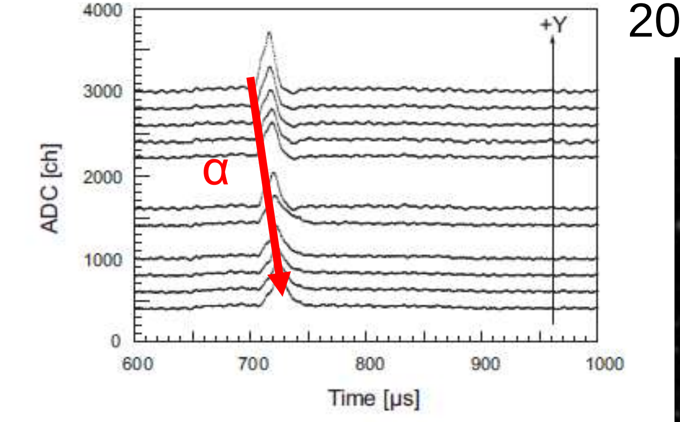
• strip readout + ASICs

for optical redout: See E.Barracchini's Talk

LTARS2016 + Wellesley's micromegas resistive-strip readout

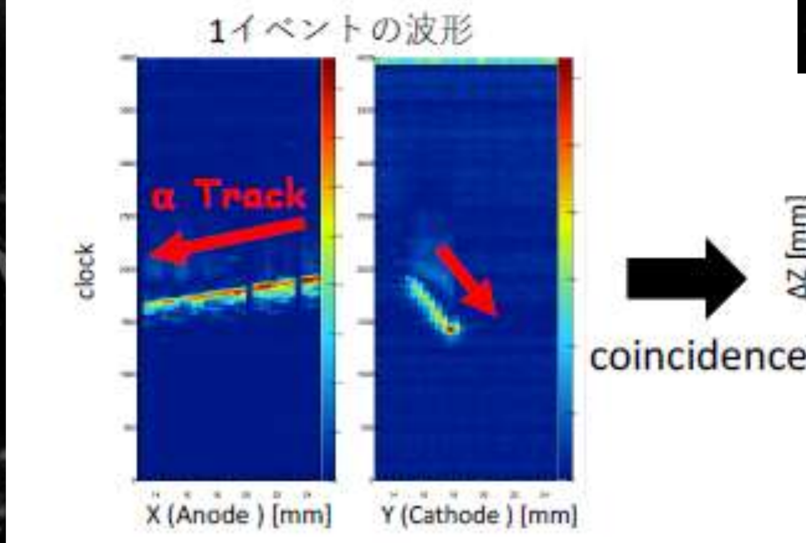
2D tracking

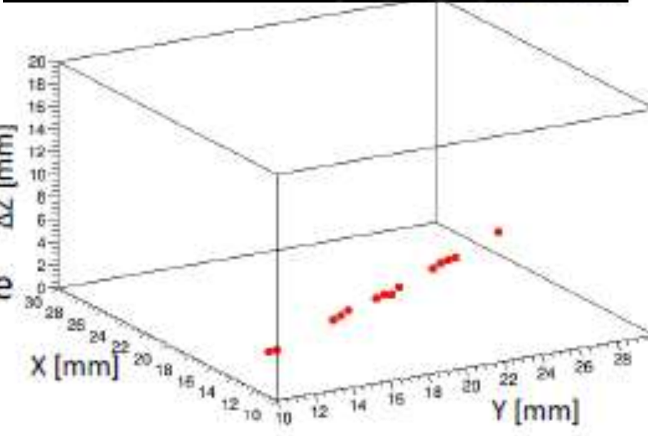


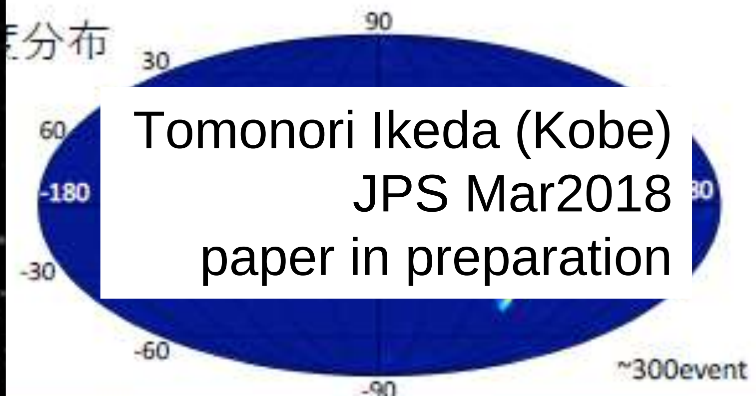


2019 J. Inst. 14 T01008

3D tracking+ fiducialisation







Tomonori Ikeda (Kobe)
JPS Mar2018
paper in preparation

Summary

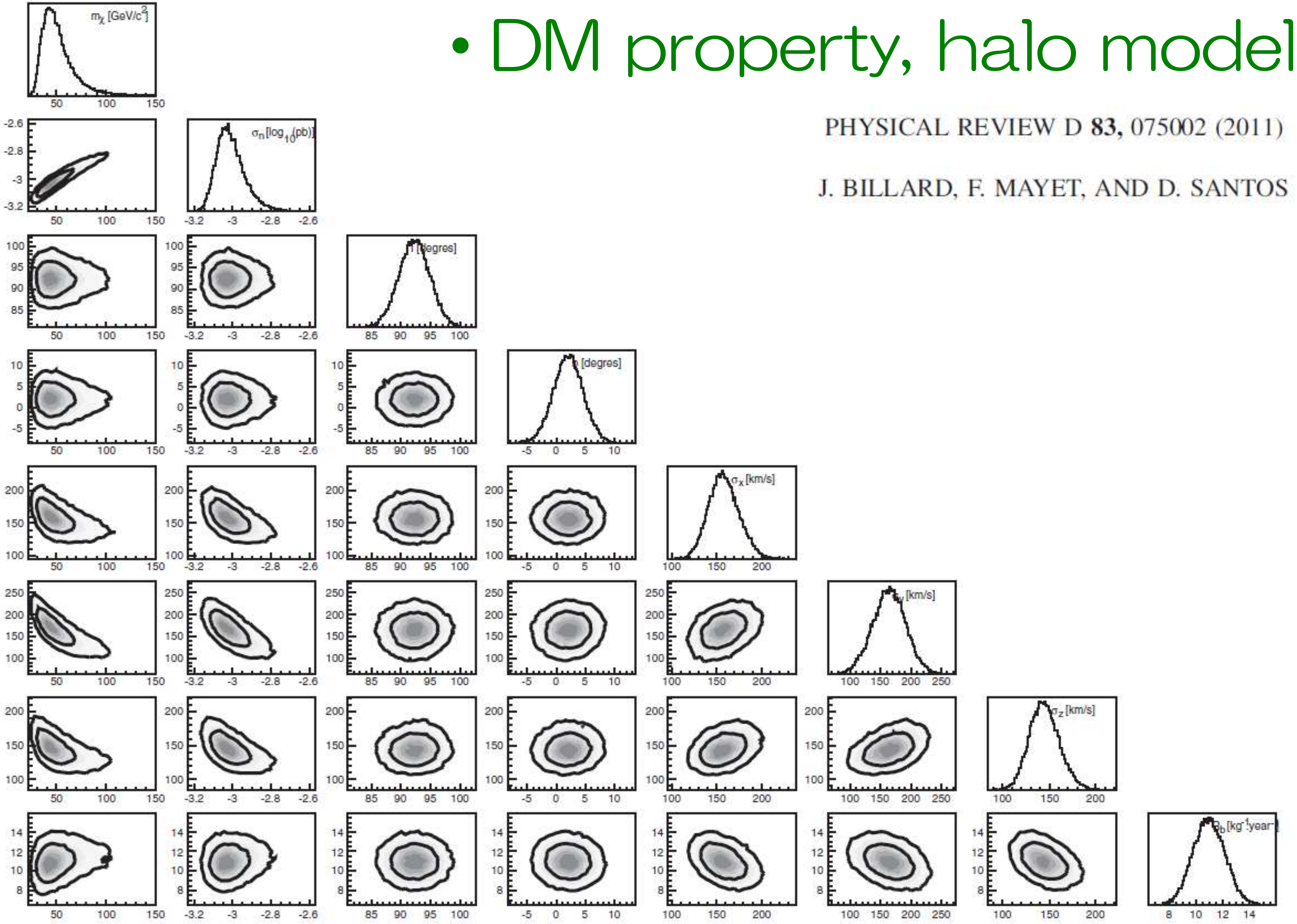
- CYGNUS: direction sensitive DM direct search
- community, collaboration
- multi-site observatory （$1 m^3$ ⇒ larger scale detectors)
- New comers （physics, detectors…）are welcome!

Physics after discovery

- DM property, halo model

PHYSICAL REVIEW D **83,** 075002 (2011)

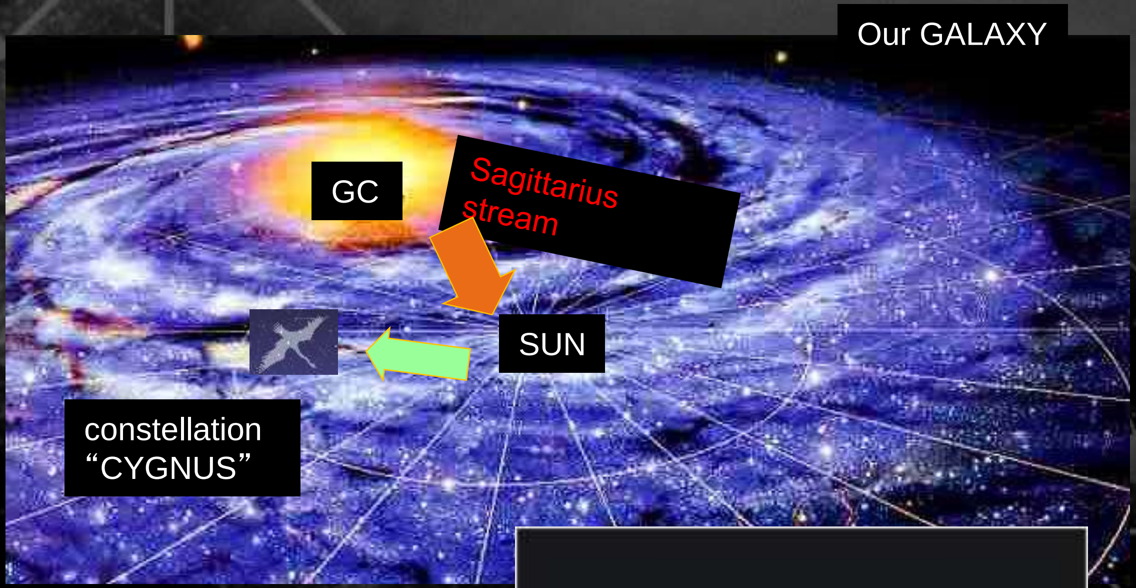
J. BILLARD, F. MAYET, AND D. SANTOS

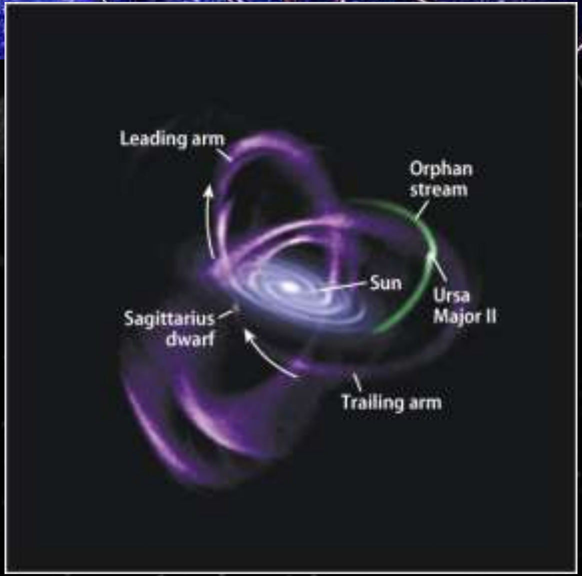


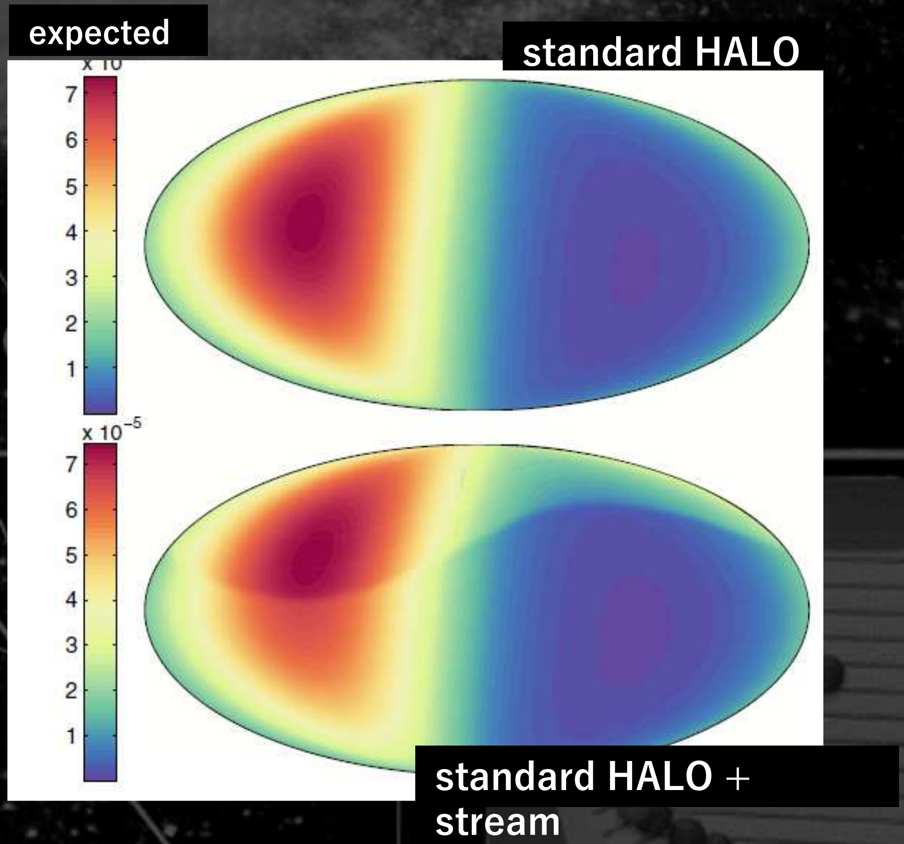
Physics after discovery

- Astrophysics
  - Sagittarius stream

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



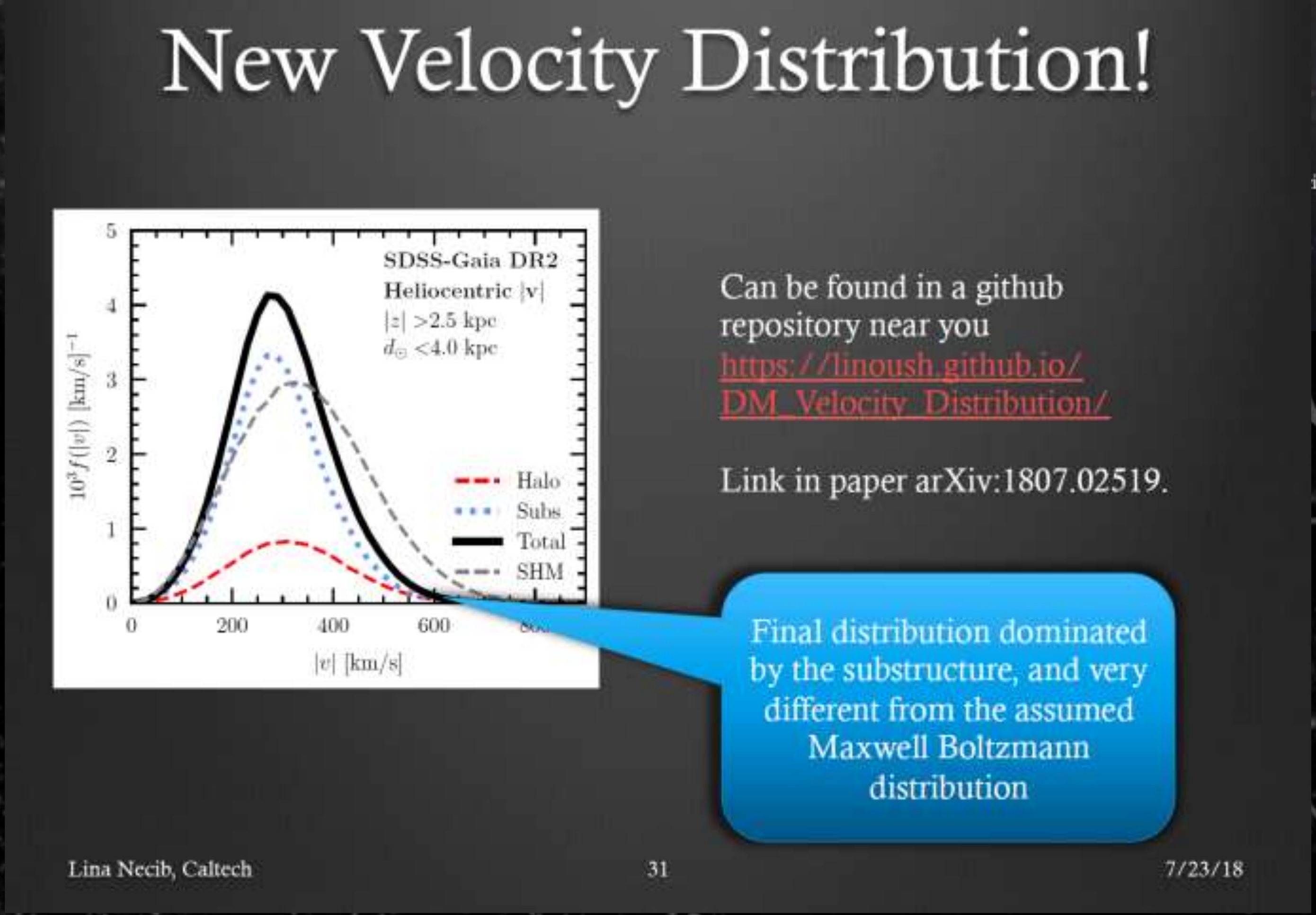


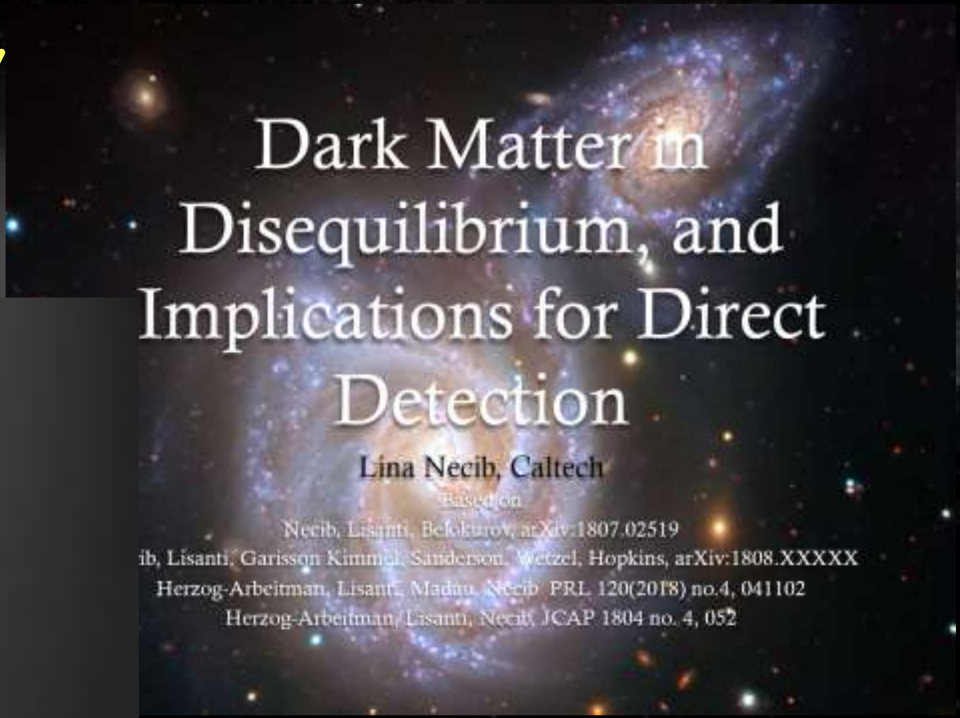


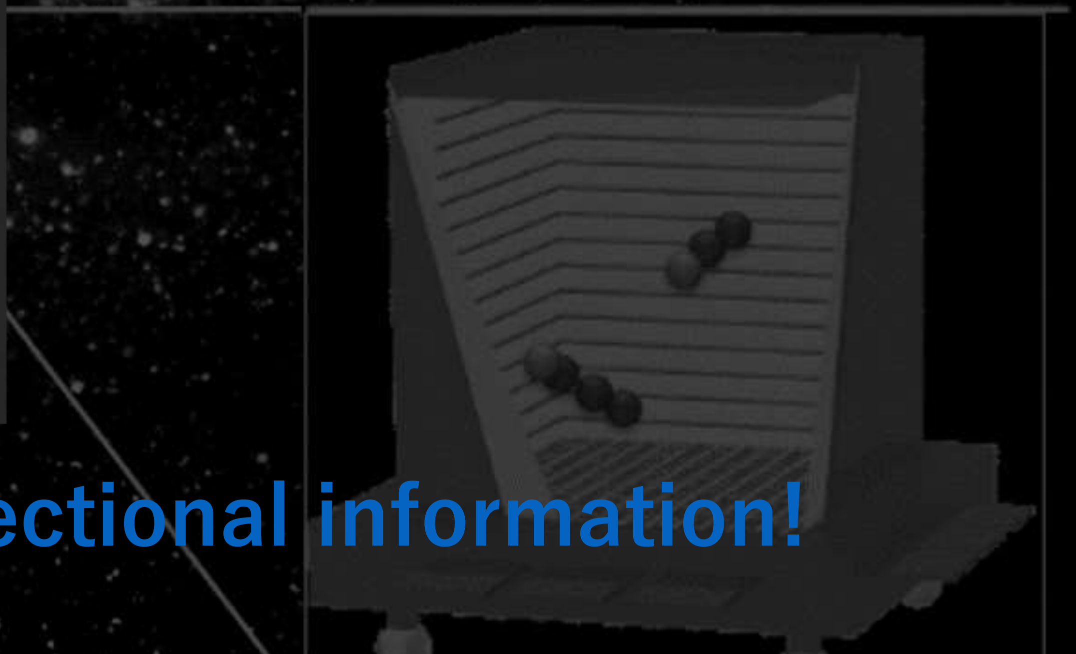
- streams, debris…

Physics after discovery

- Astrophysics
  - Dibris





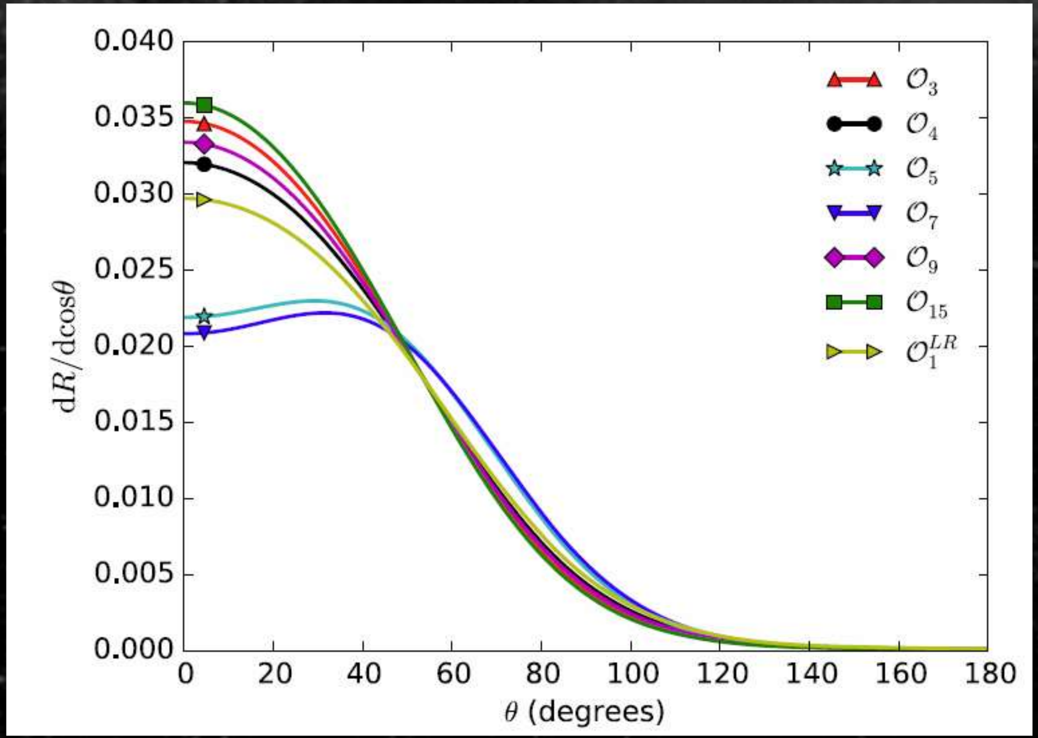


- can be studied by directional information!

Physics after discovery

- Particle physics①
  - Test the interaction by scattering angle

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



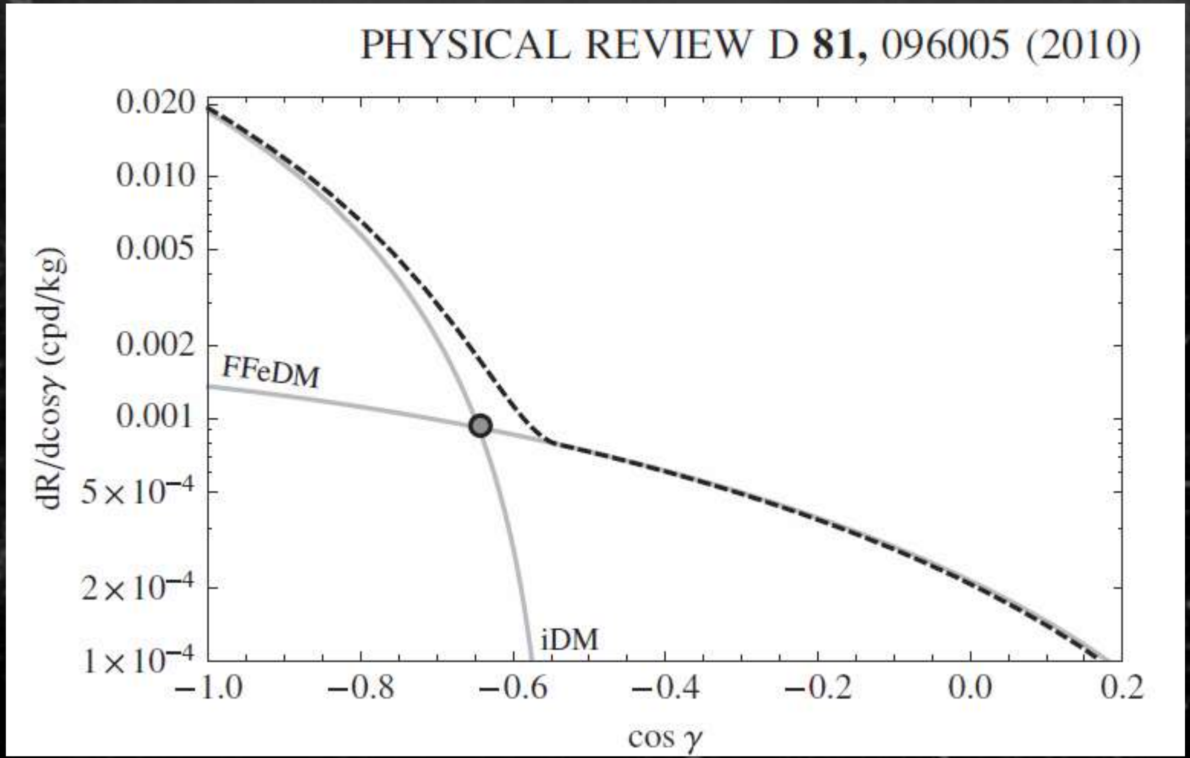
SI **SD**

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

- **some operators are distinguishable**

Physics after discovery

- Particle physics②
  - inelastic scattering



- **iDM (inelastic scatterings dark matter) and normal darkmatter (FFeDM** (form factor elastic dark matter)) **show different angular DISTRIBUTION**