June 21, 2022

- 北海道大学　コロキウム

暗黒物質直接探索の現状

身内賢太朗
(神戸大学)

暗黒物質

暗黒物質直接探索

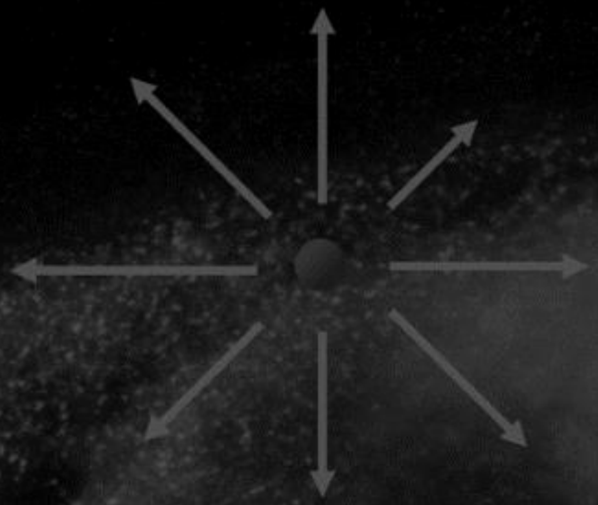
最近の話題

科研費
KAKENHI

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

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

2022年6月12日放映
「ガリレオX」



暗黒物質

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

交流

宇宙のダークマター直接探索の現状

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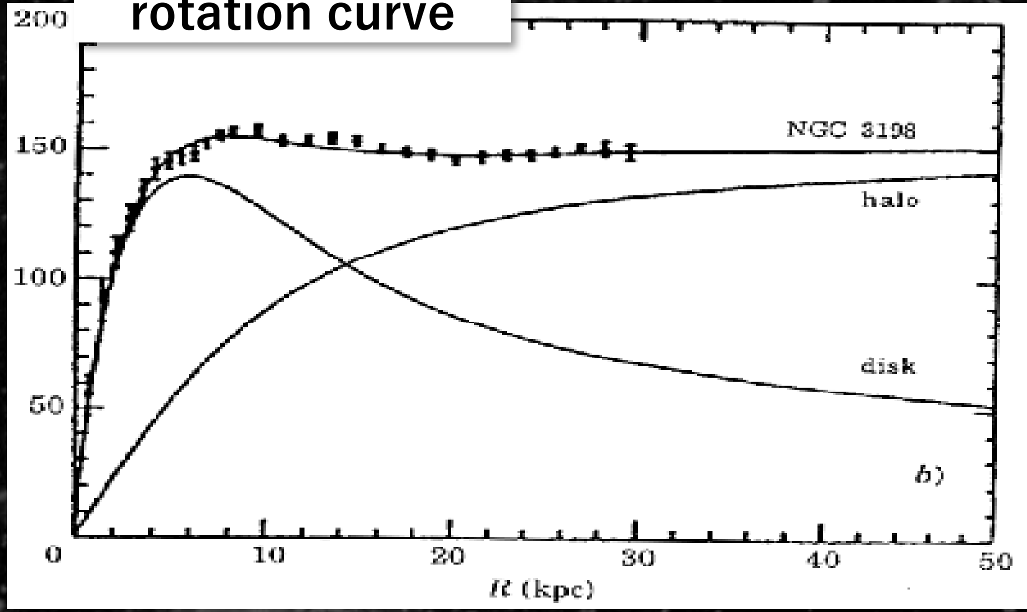
• DM: seen in various scales in the universe

- @ galaxy: rotation curves (1970~)
- @ cluster of galaxies: collision of galaxy clusters (2007~)
- @ universe: CMB and other observations (2002~)

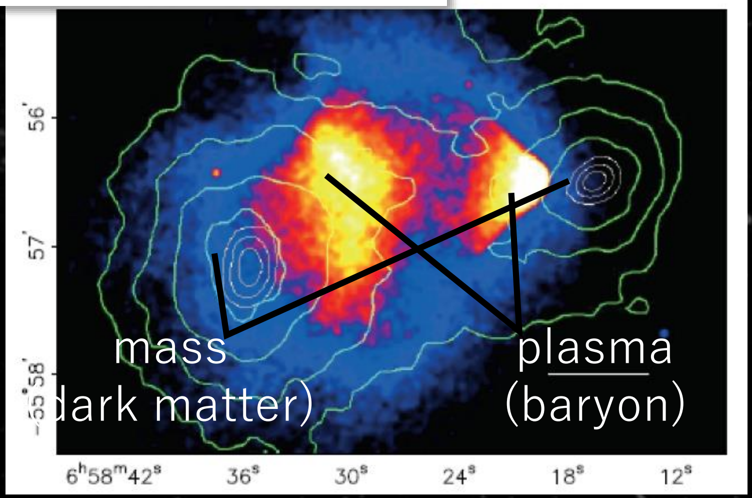
GR !

rotation curve



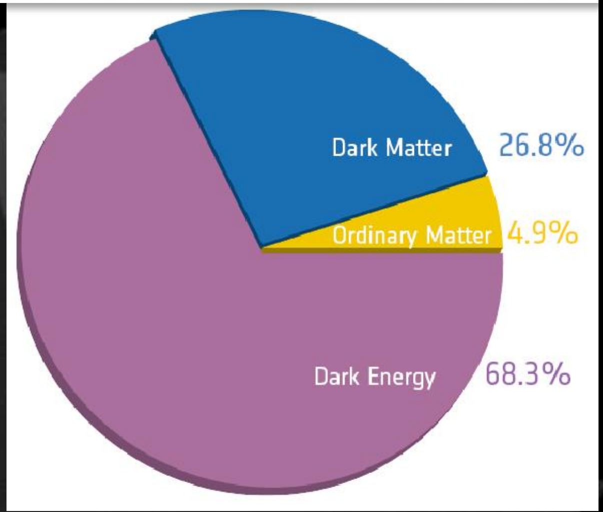
Annu. Rev. Astron. Astrophys. 29(1991)409

cluster collision



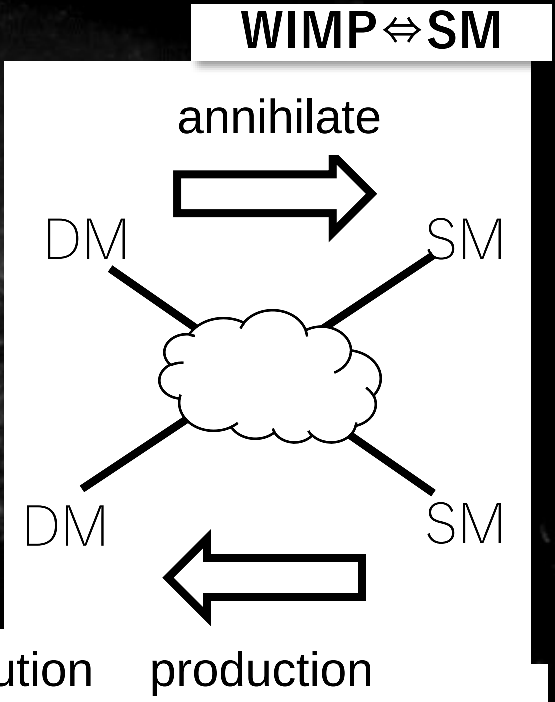
The Astrophysical Journal, 648:L109–L113, 2006 September 10

pie chart of the universe

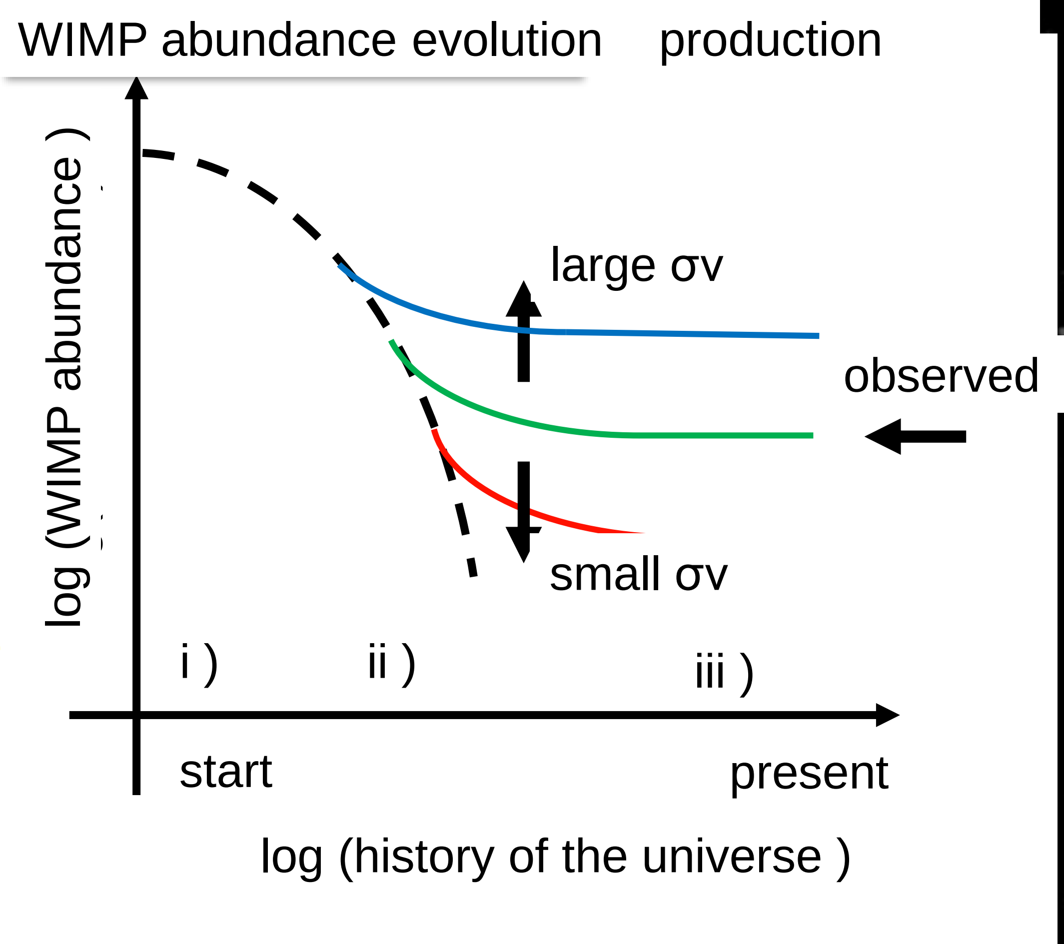


Plank team

- 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)

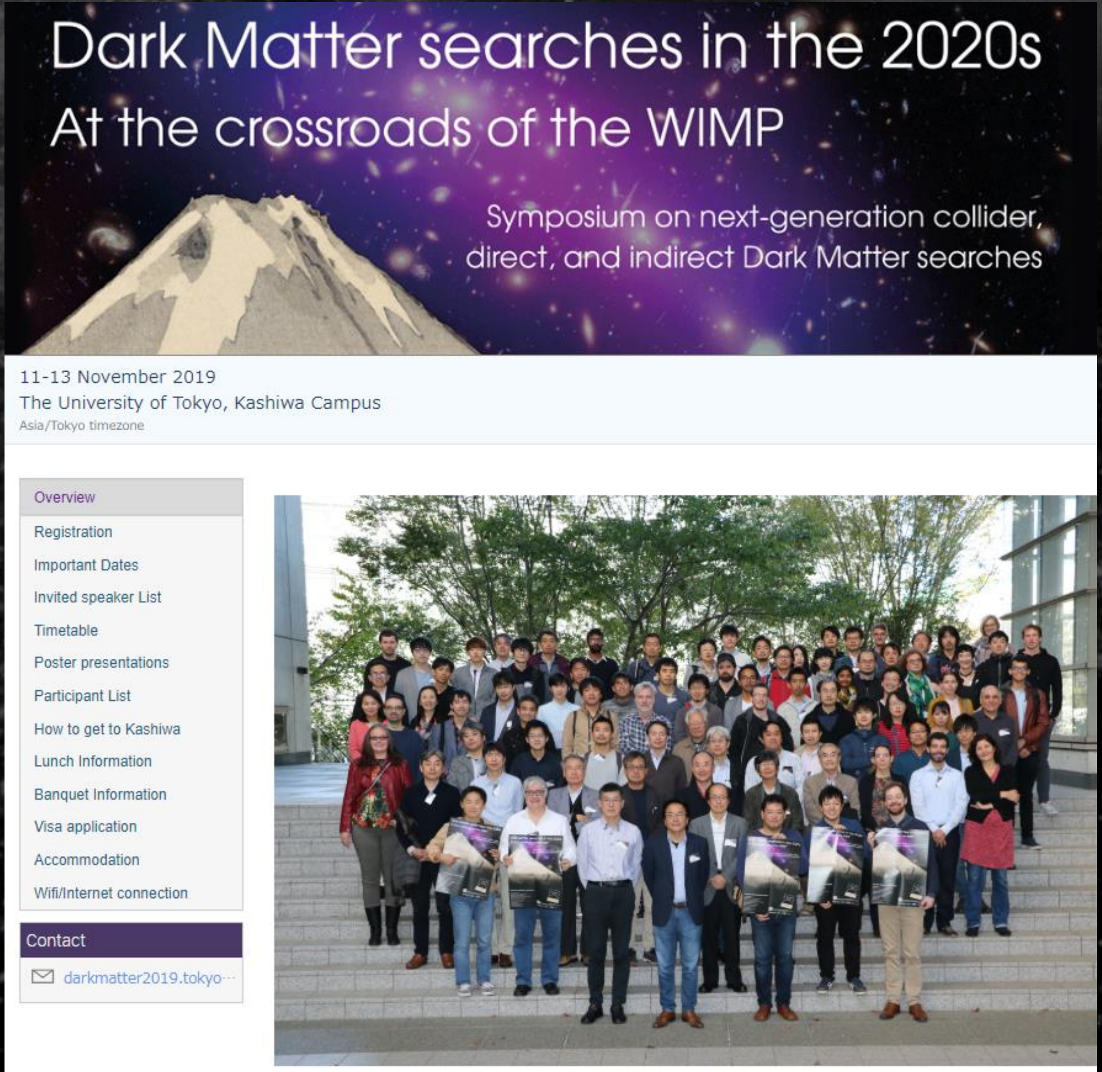


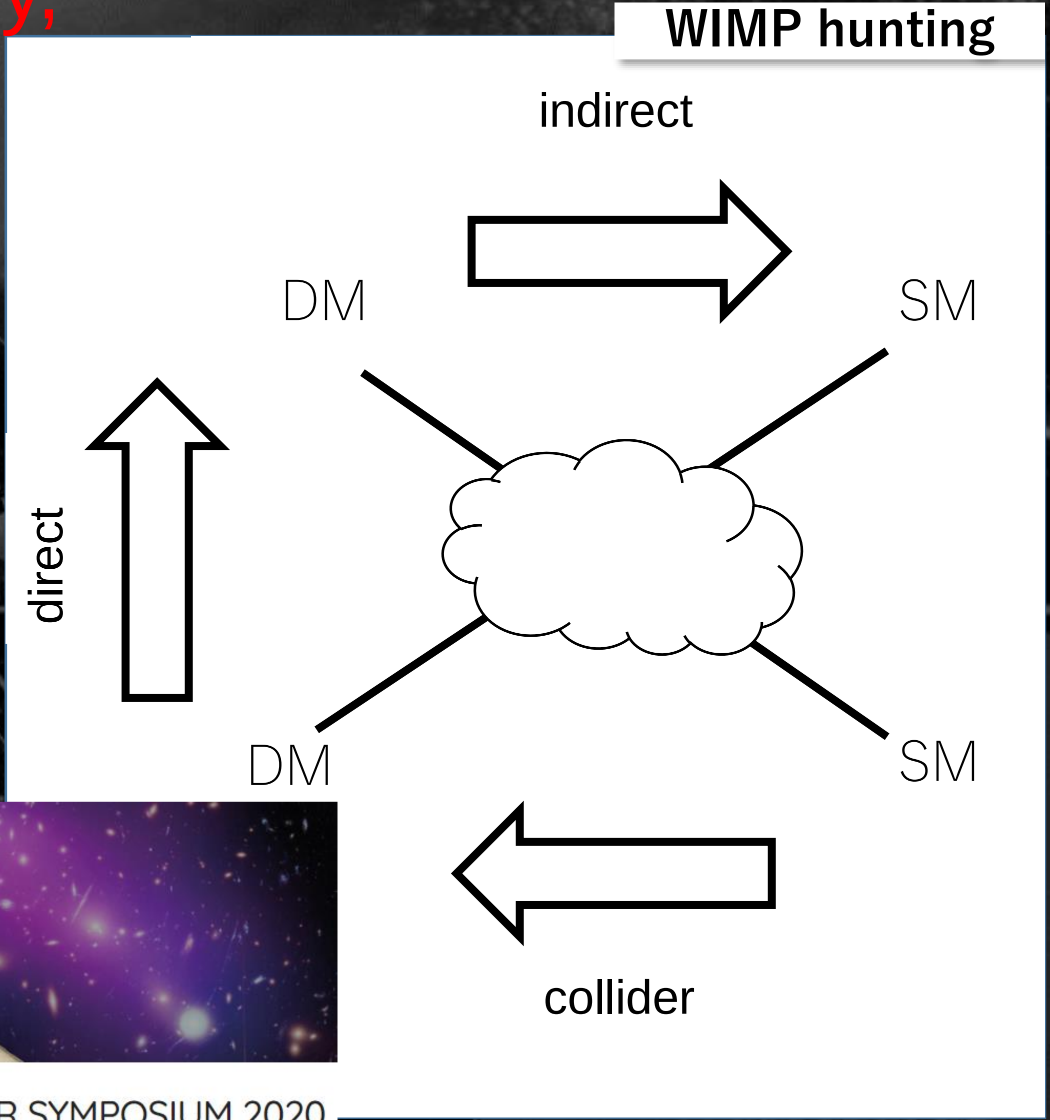
- WIMPs
  - Produced in the early universe
  - Annihilate
    rate ∝ cross section × velocity
  - Freeze out at some point
    abundance is fixed
  - σ～weak scale explains present abundance
    ⇒WIMP miracle !



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

complementary, synergy



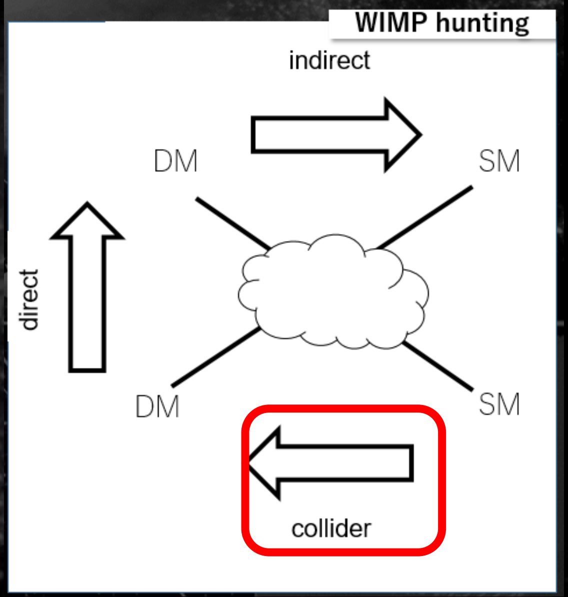


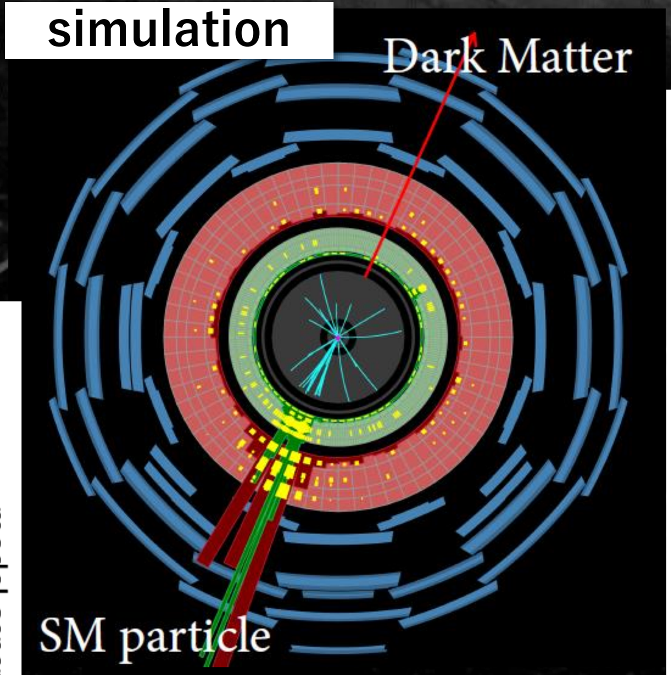
- Collider
  - LHC @ CERN
  - Missing E signal
  - Searches with various ways
  - No hint so far

Dark matter searches at colliders.

Priscilla Pani
on behalf of ATLAS, CMS & LHCb

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



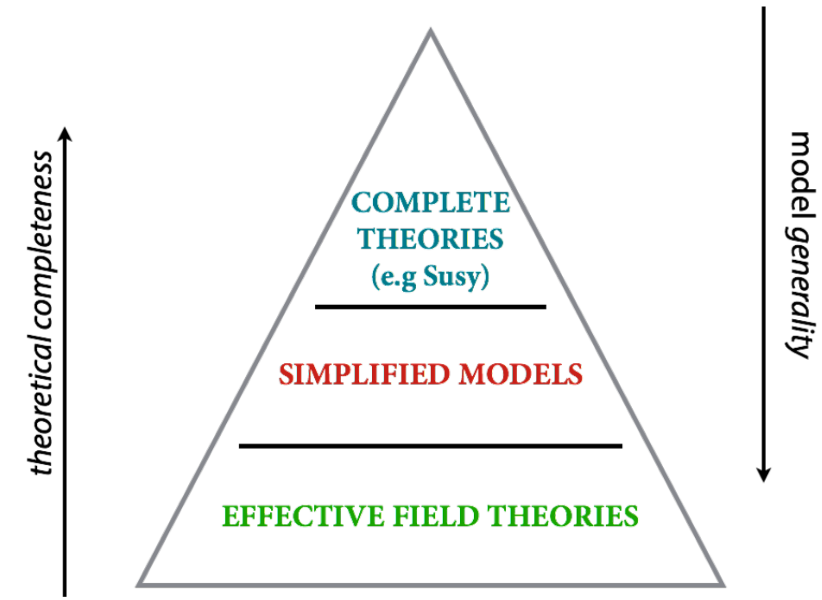


Conclusion - Cheat sheet

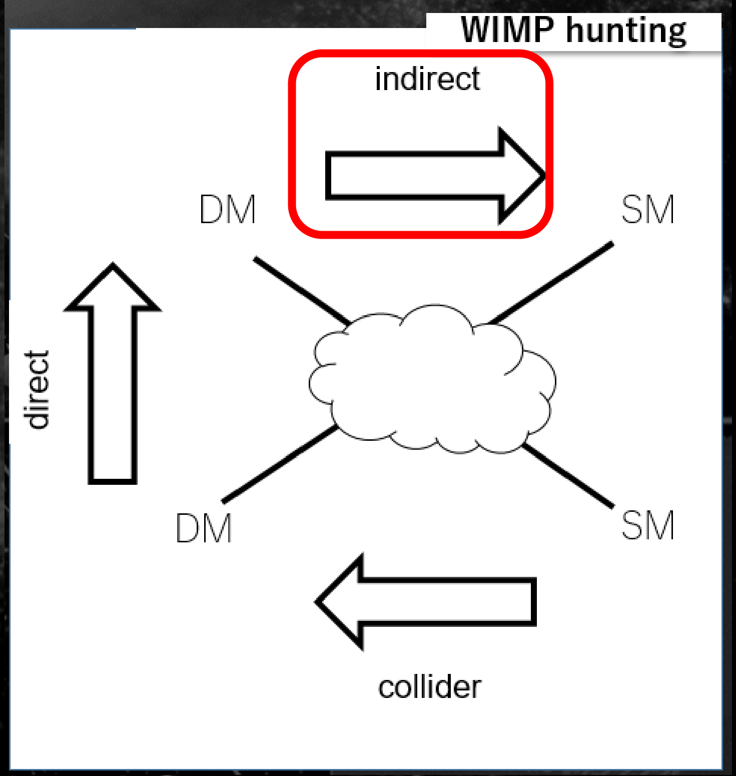
DM-mediator searches

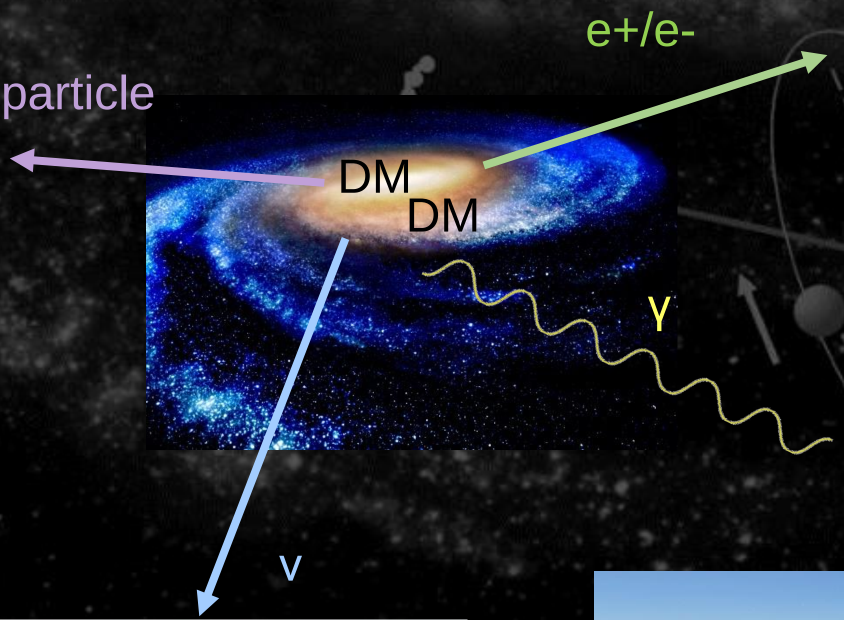
Signature	Dataset	Reference
Di-lepton resonance	139 fb^{-1}	1903.06248
Di-jet, Di-jet + ISR,	139 fb^{-1}	1901.10917, ATLAS-CONF-2019-007, 1808.03124
Di-bjet	80 fb^{-1}	ATLAS-CONF-2018-052
Di-jet + leptons	80 fb^{-1}	ATLAS-CONF-2018-015
Dijet + photons	36 fb^{-1}	1905.10331
Etmiss + Higgs	36 fb^{-1}	1908.01713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

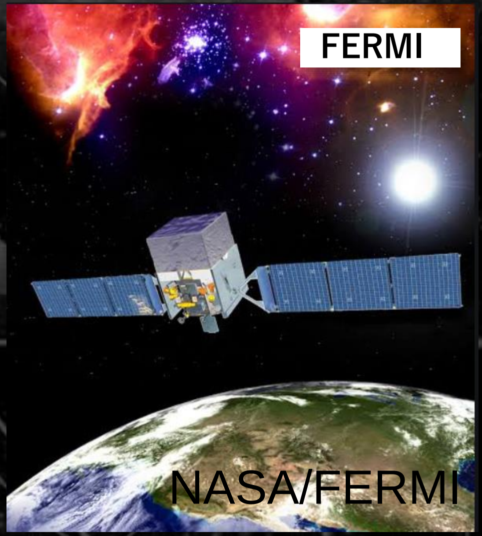
Theoretical framework

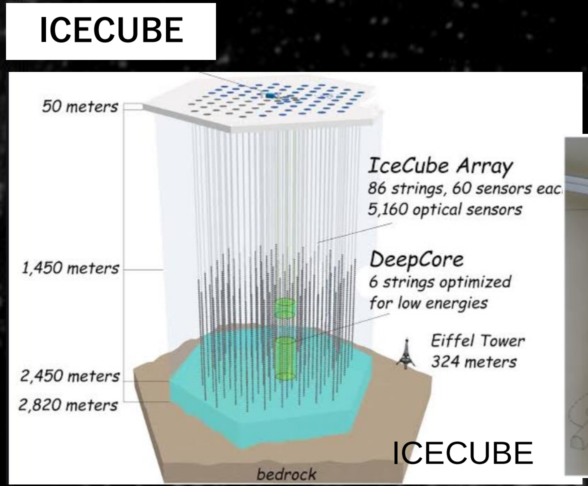


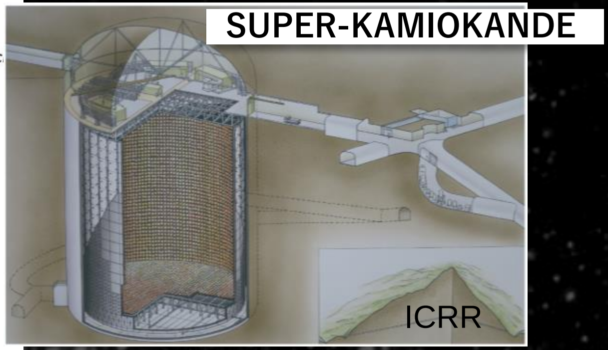
- Indirect Search
  - WIMP's annihilate @ Galactic Center, Dwarf Galaxy, sun…
  - No conclusive result yet





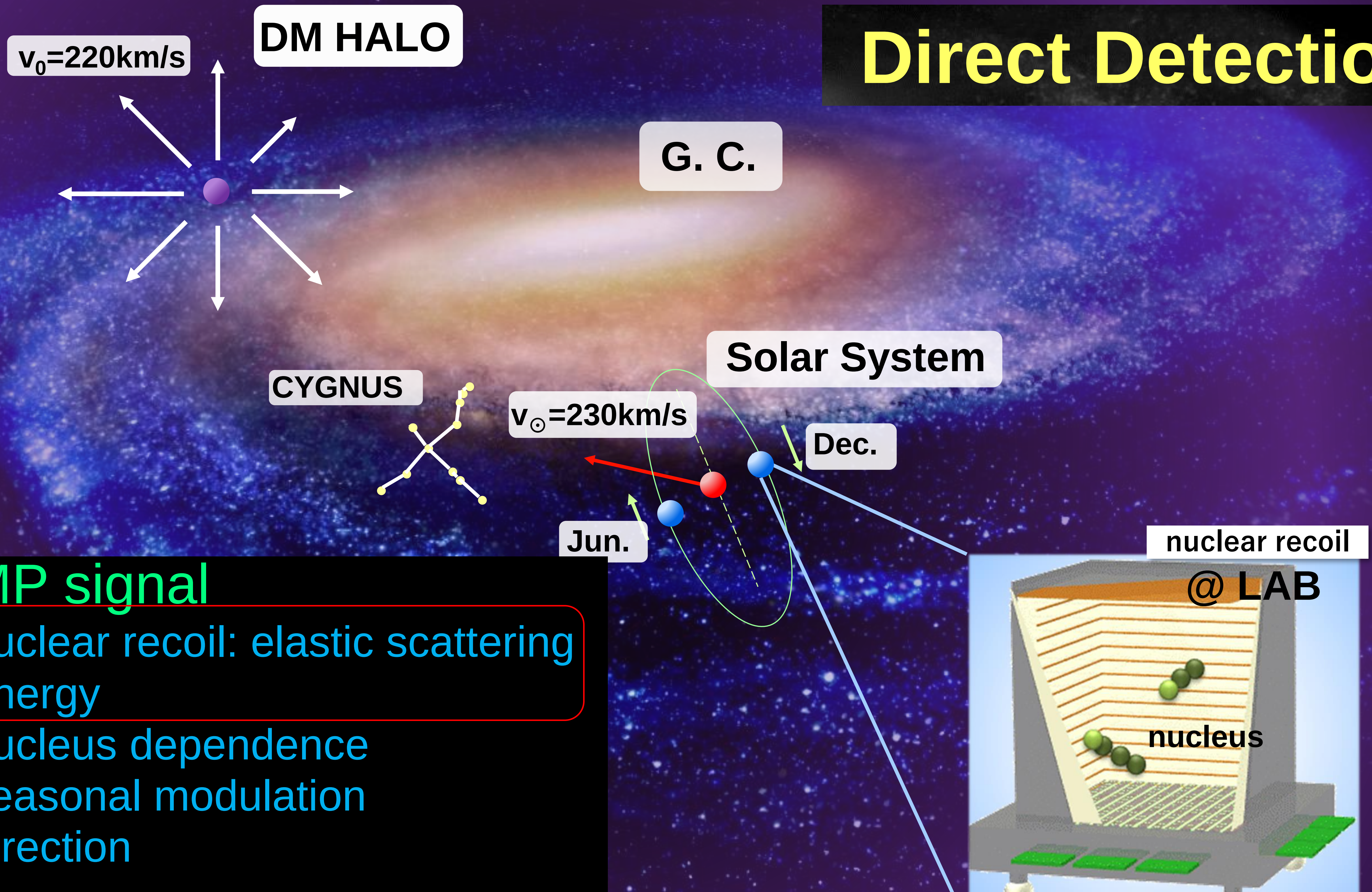






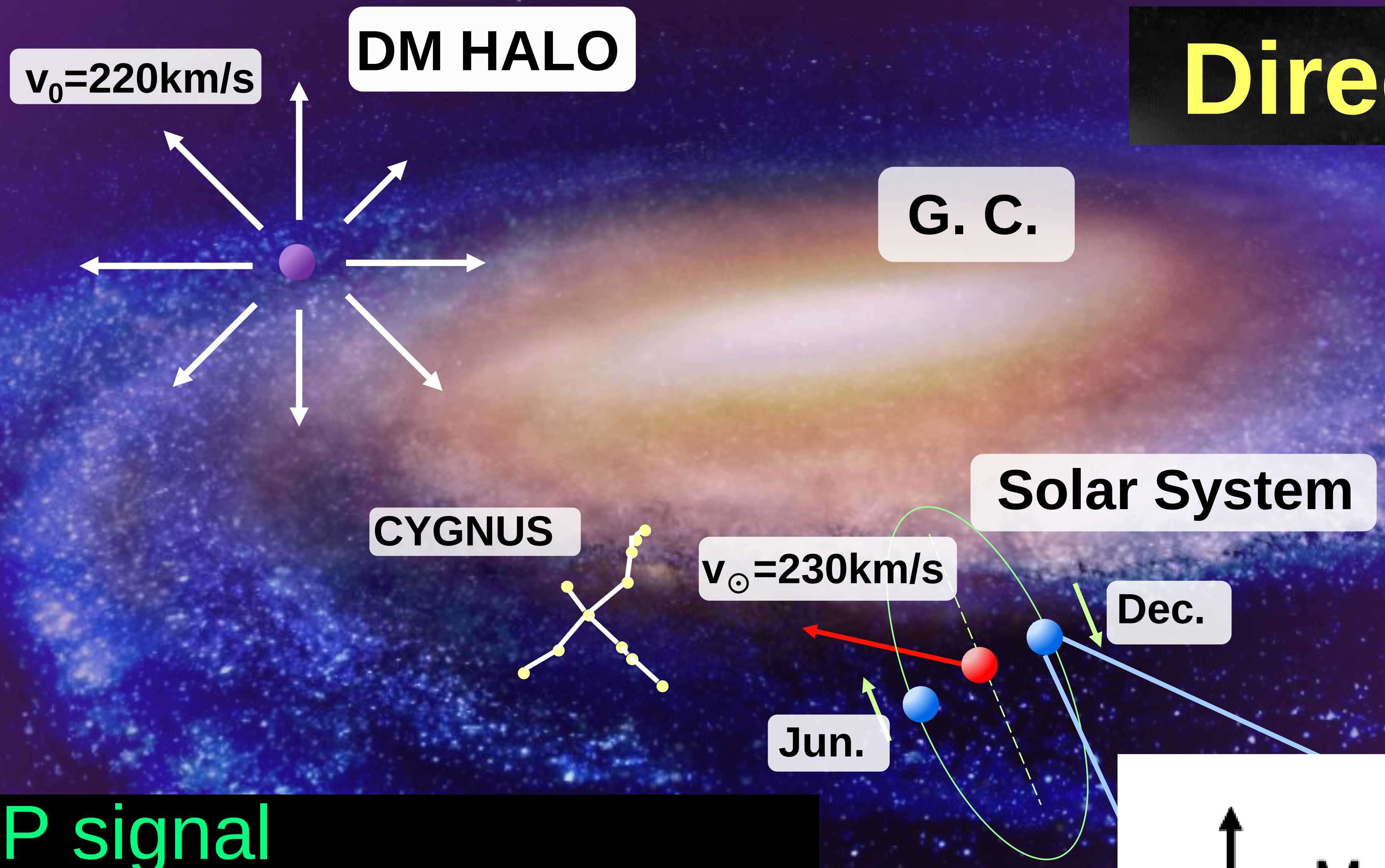
Direct Search

Direct Detection



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

Direct Detection



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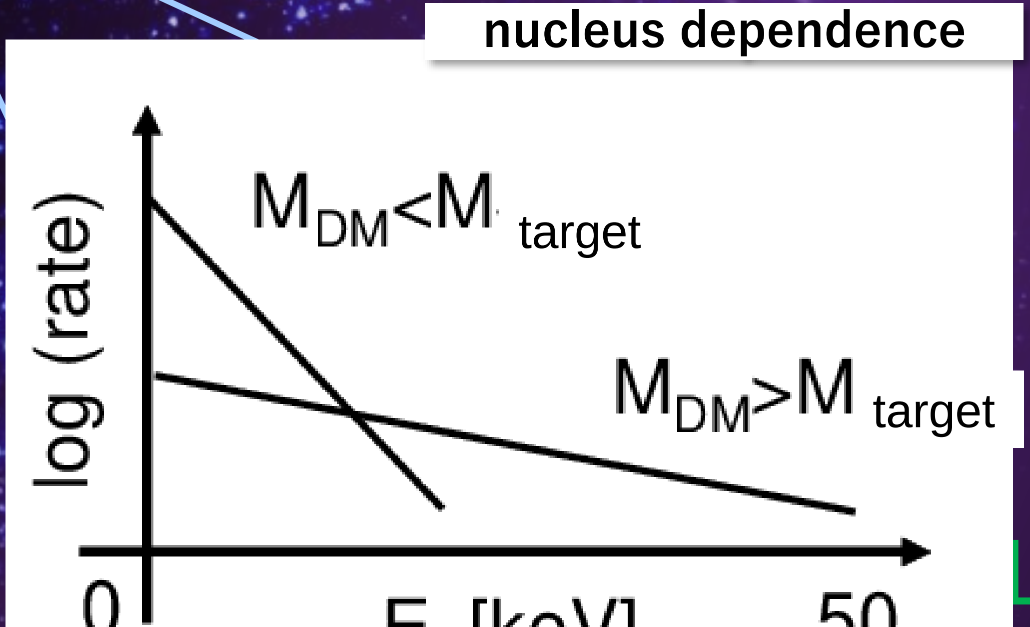
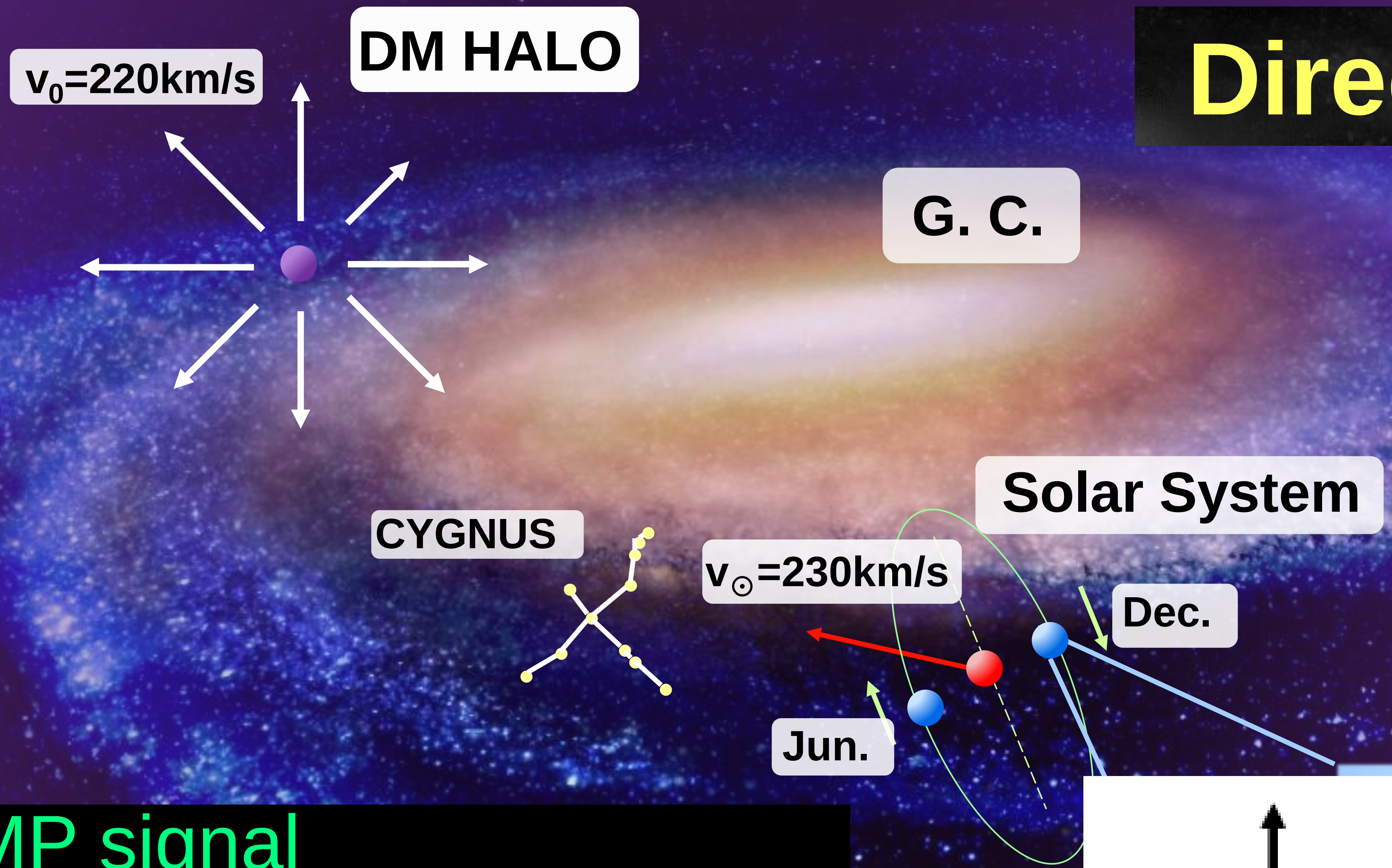
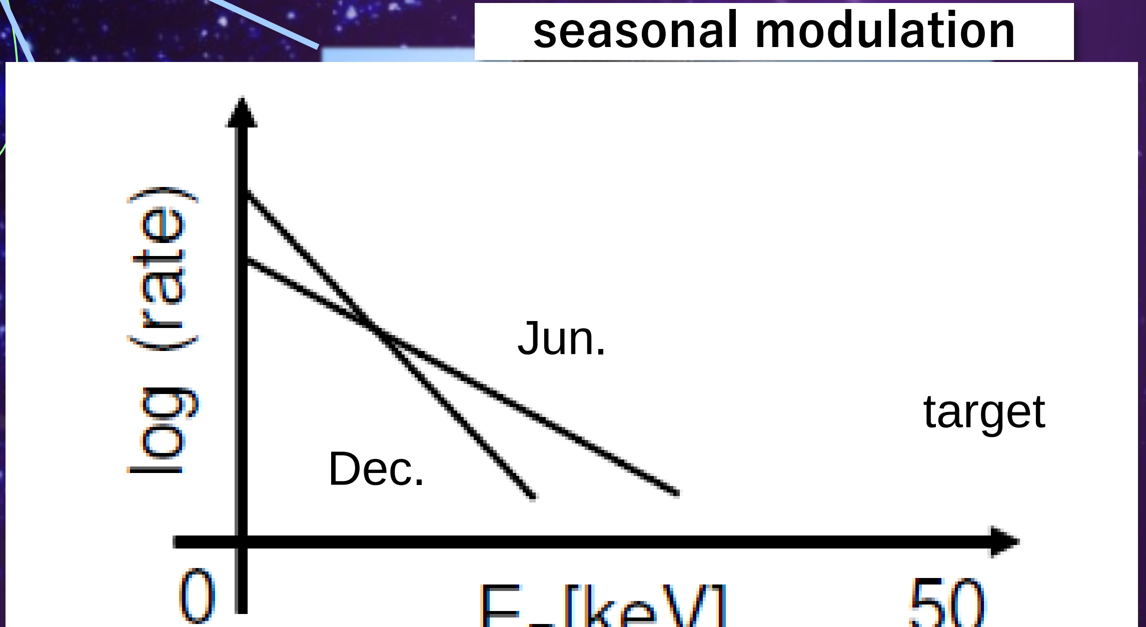


Direct Detection





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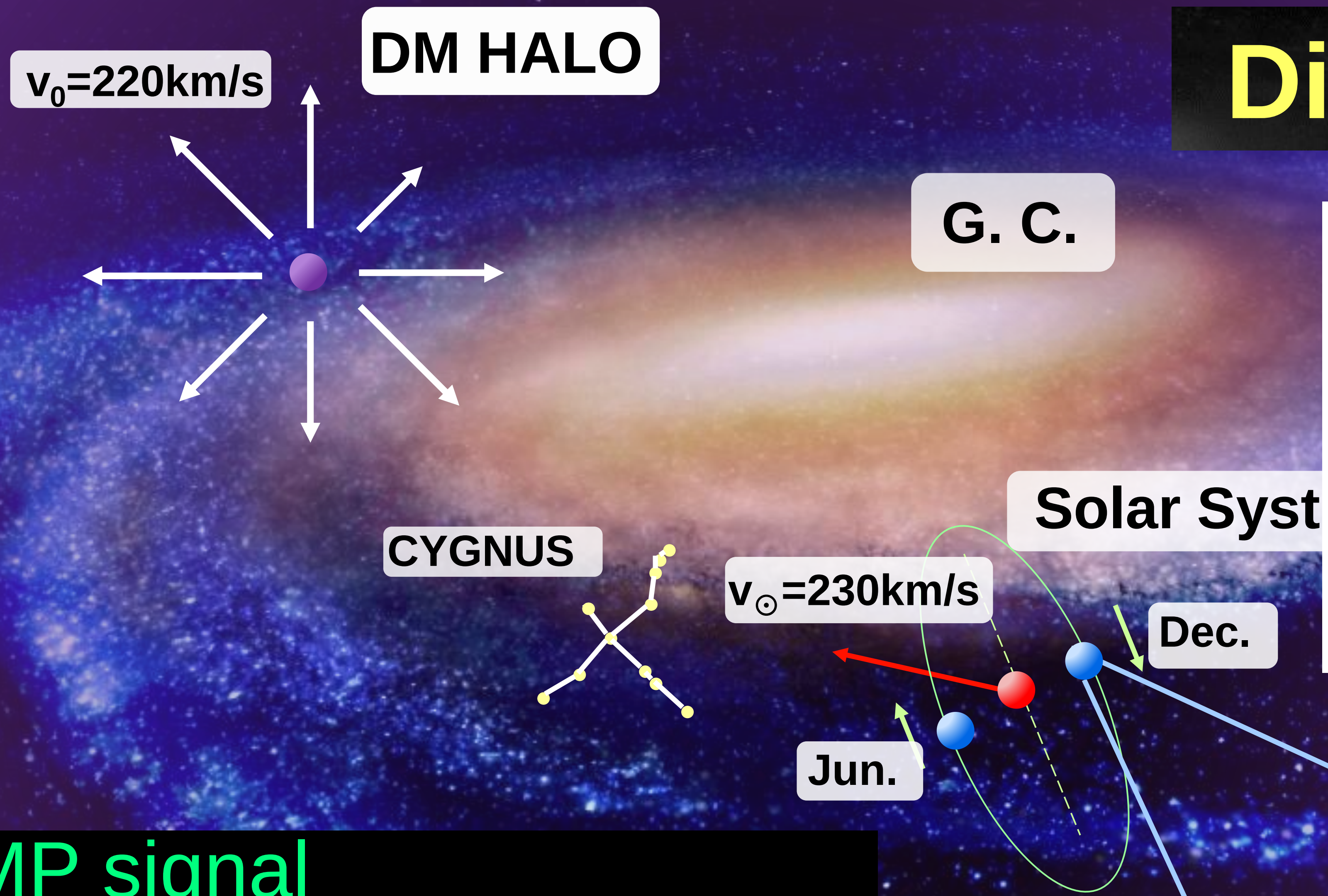
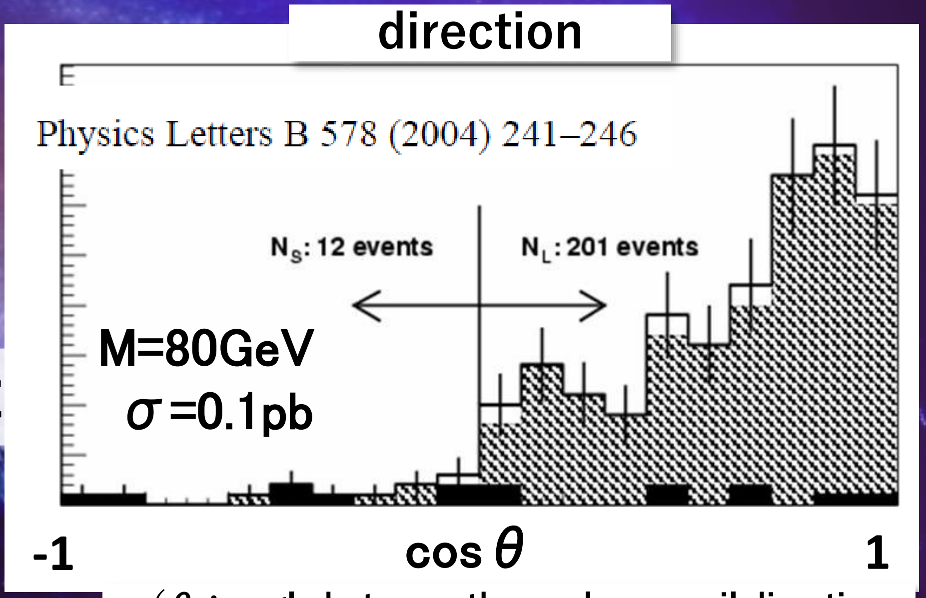
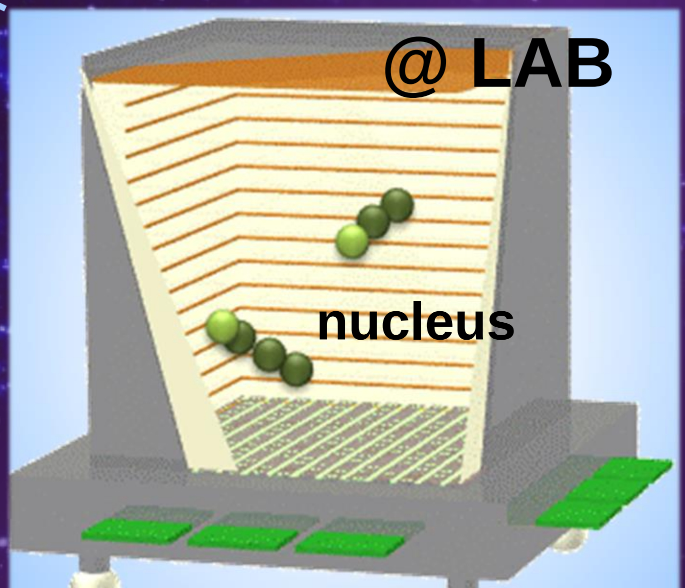




（θ：angle between the nuclear recoil direction and constellation CYGNUS）



- WIMP signal
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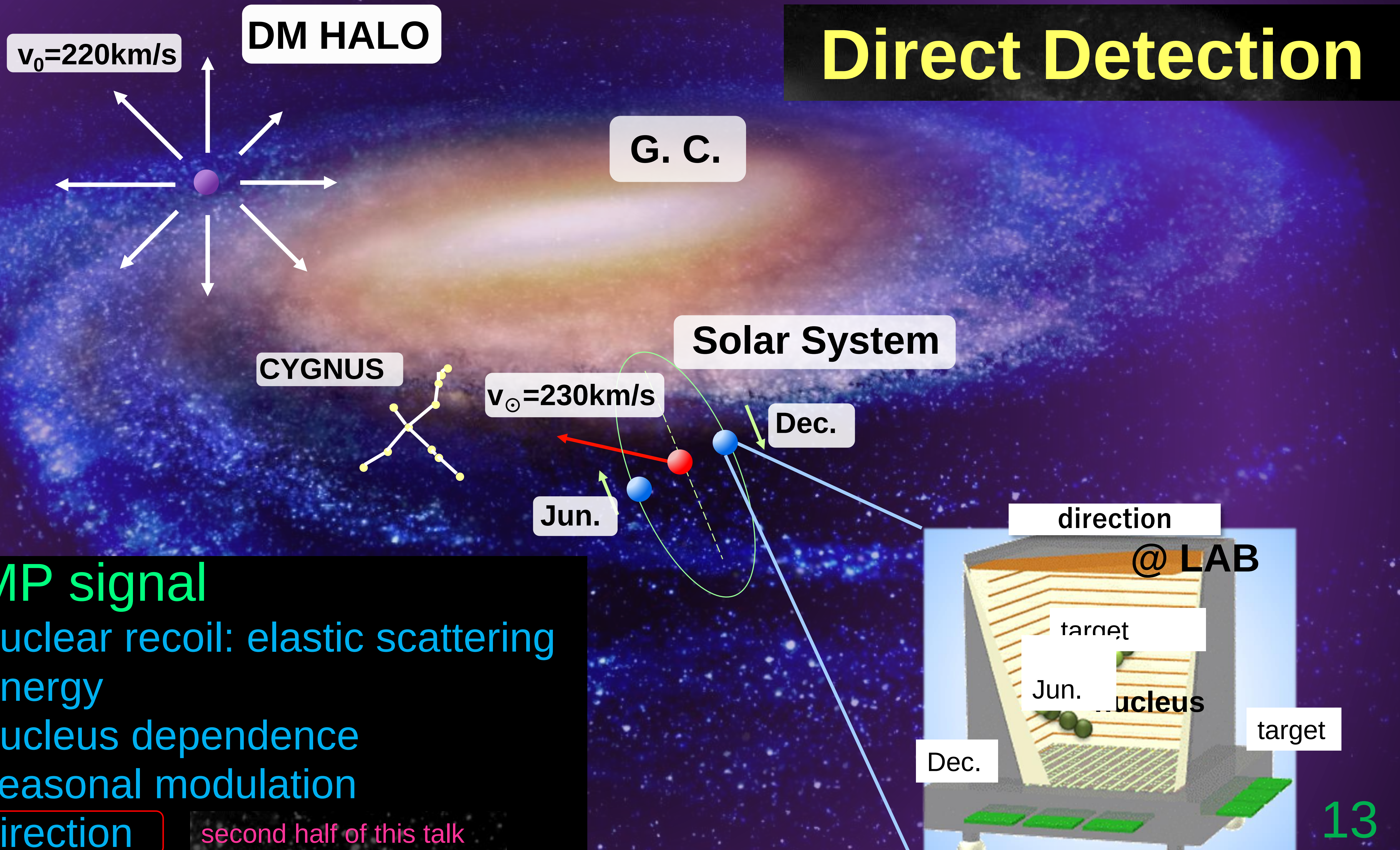
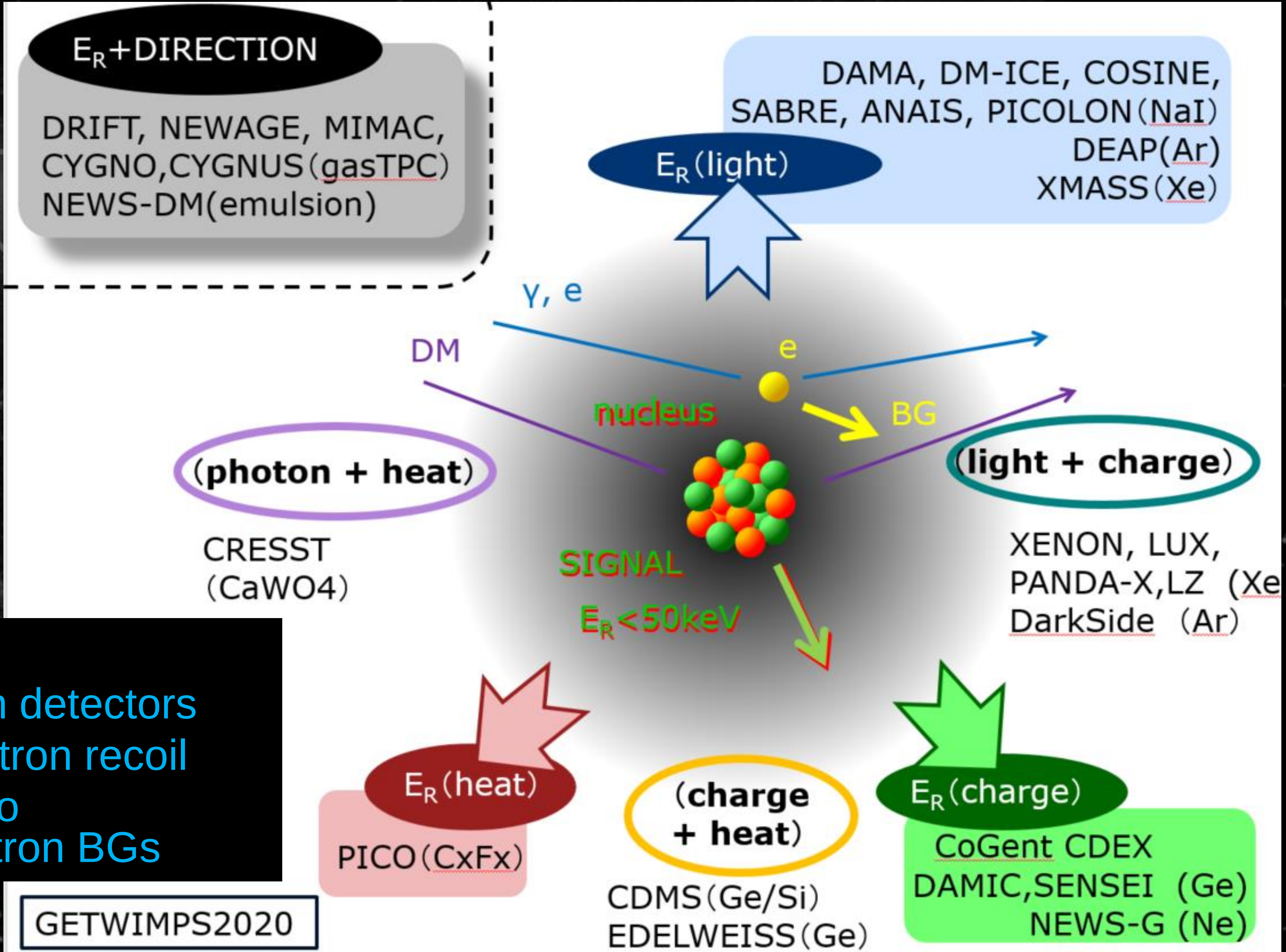
Direct Detection



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

second half of this talk

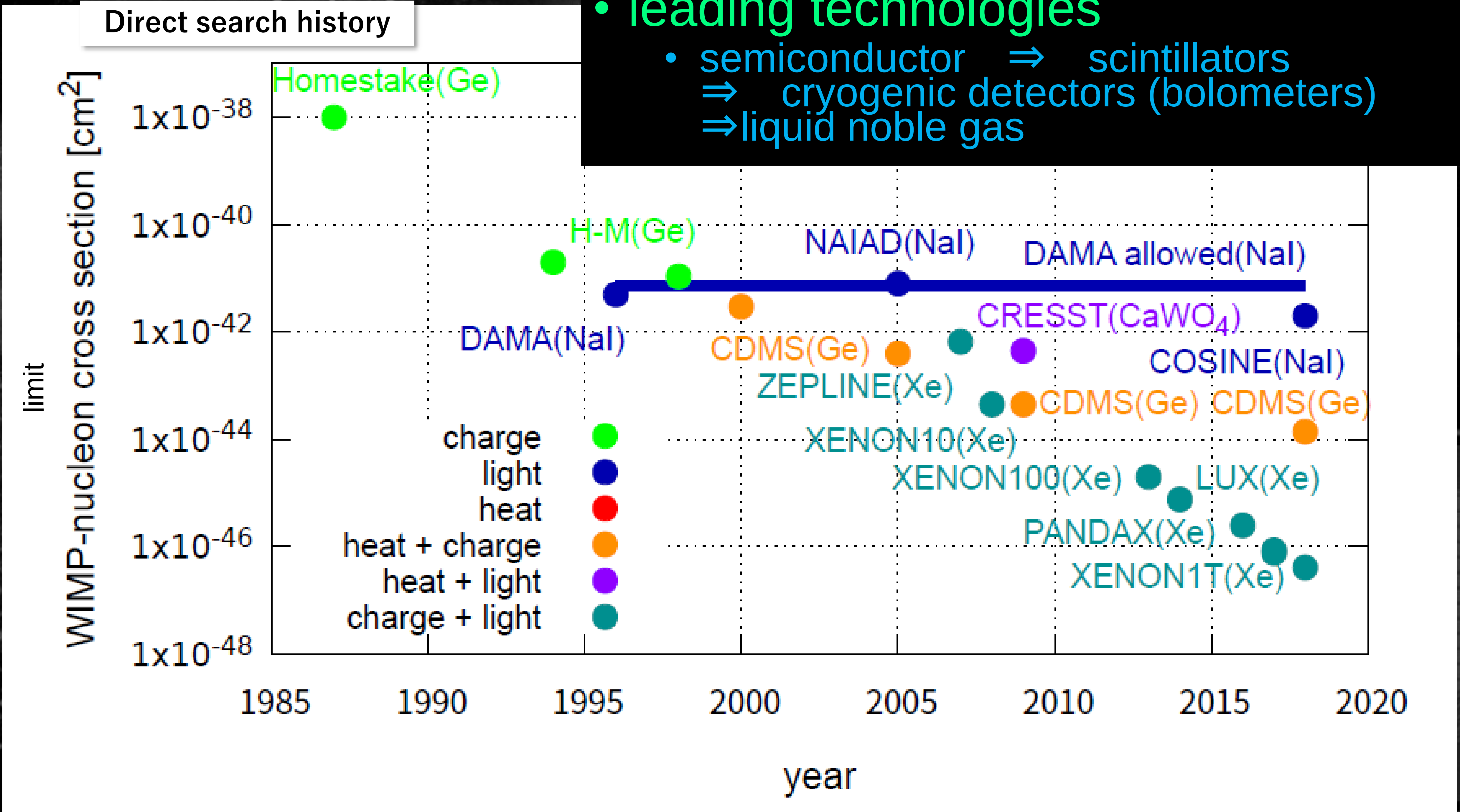


- Technologies
  - Ordinary radiation detectors
  - Background: electron recoil
  - more than two info
    ⇒ reject electron BGs

Kentaro Miuchi

History

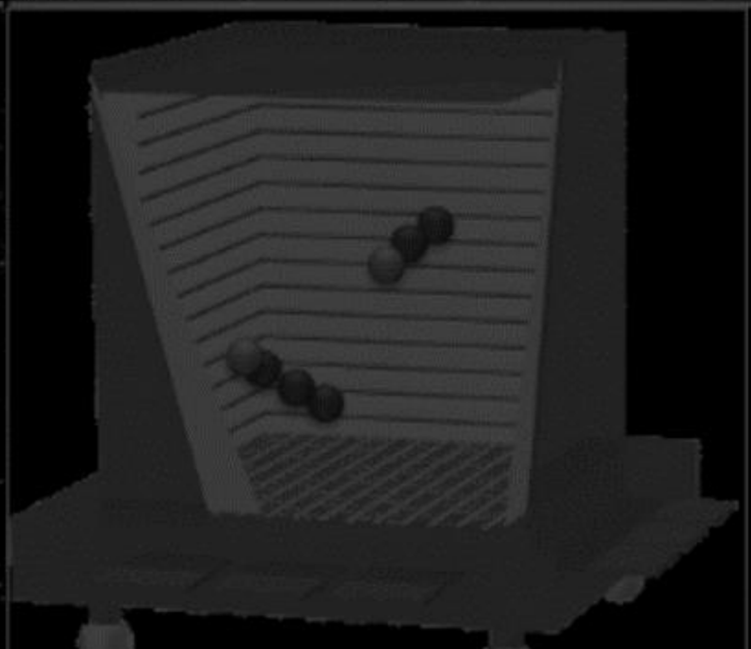
- leading technologies
  - semiconductor ⇒ scintillators ⇒ cryogenic detectors (bolometers) ⇒liquid noble gas



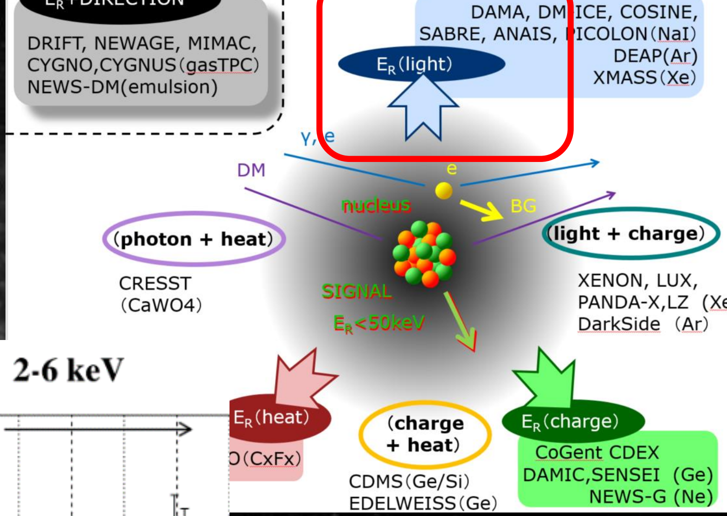
2. 直接探索の現状

Direct Search Review

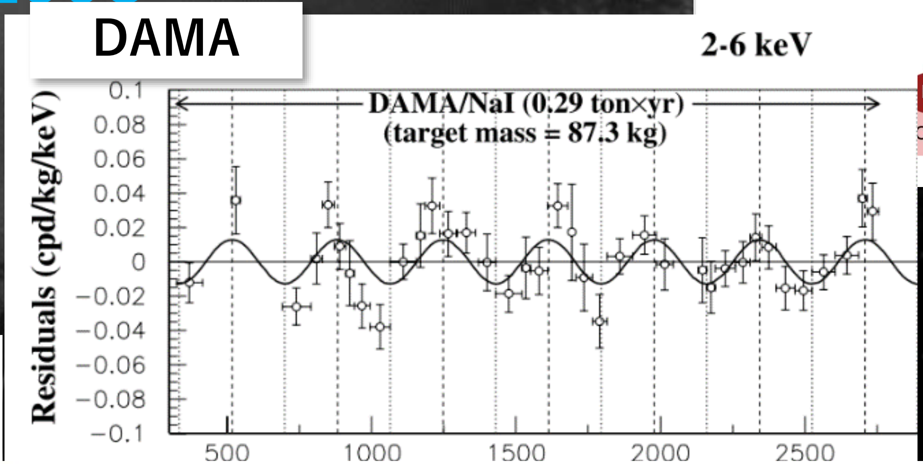
1. Mainstream : Large Detectors

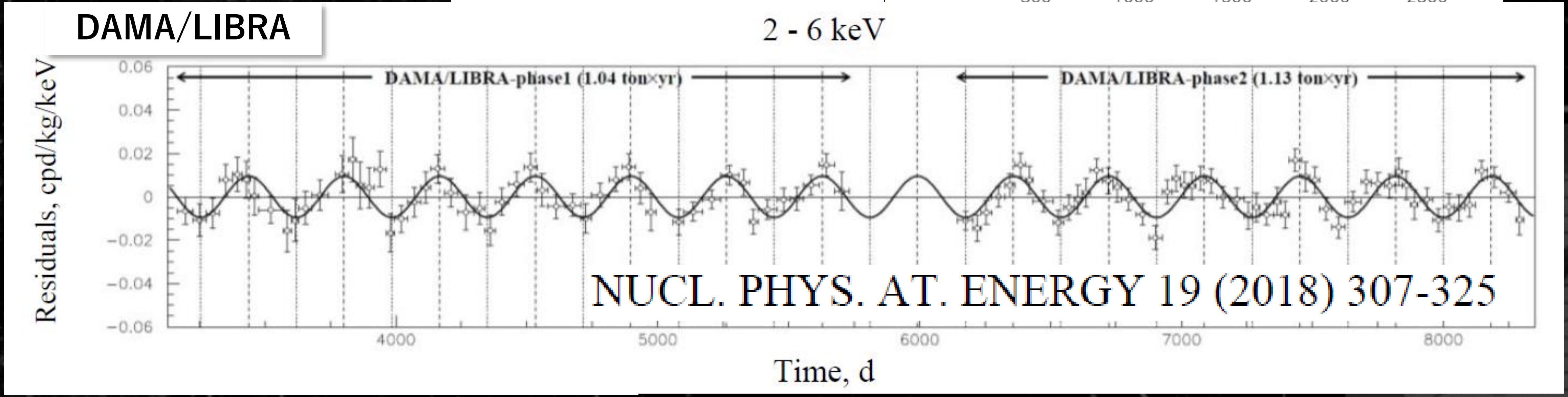


- DAMA　(NaI)
  - 250kg　NaI scintillators
  - Annual modulation were reported：1998～
  - Latest 2.46 ton year　12.9 σ
  - SOMETHING is detected



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





No BG explains this modulation

No natural DM model explains, either…

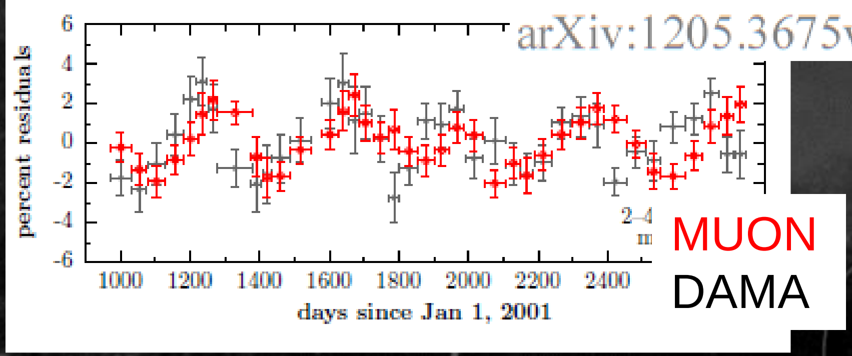
- Explaining DAMA with BG
  - Long discussion on BG modulation

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

  - Muon?

On the Cosmic Ray Muon Hypothesis for DAMA

arXiv:1205.3675v1



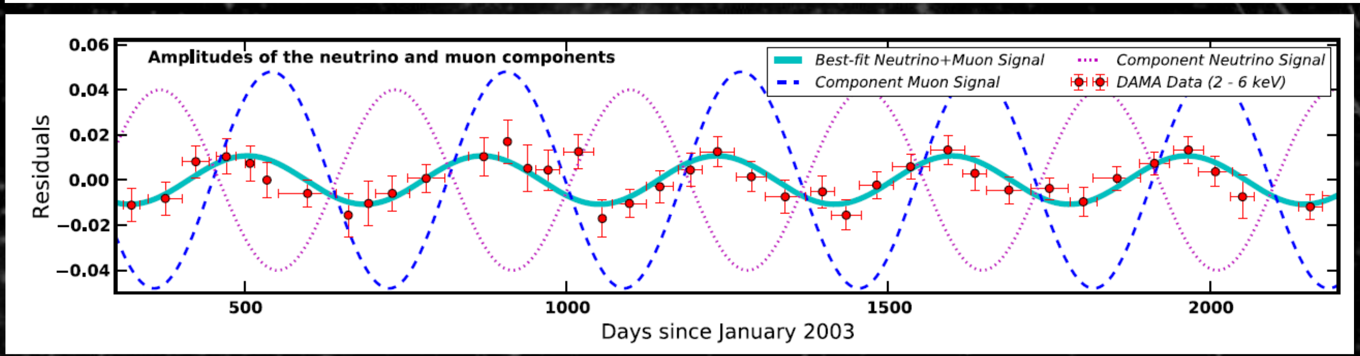
- No, muon comes later

  - Muon & neutrinos

PRL 113, 081302 (2014)

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

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



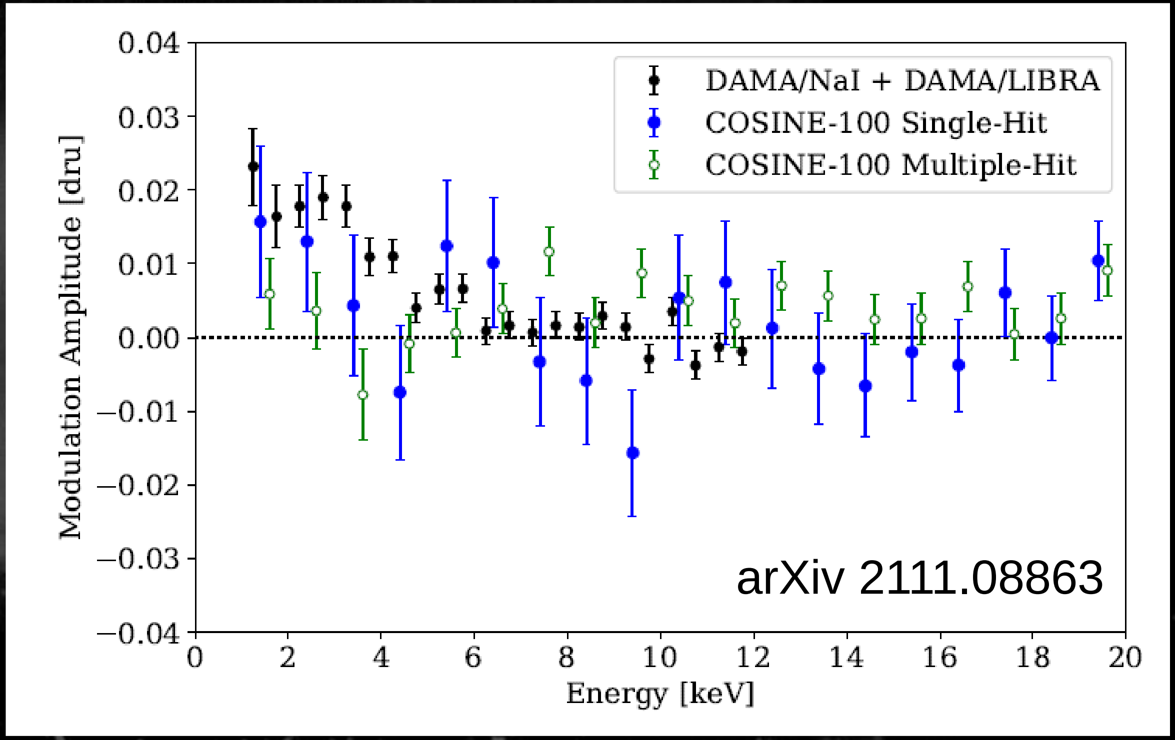
- No, not enough neutrinos

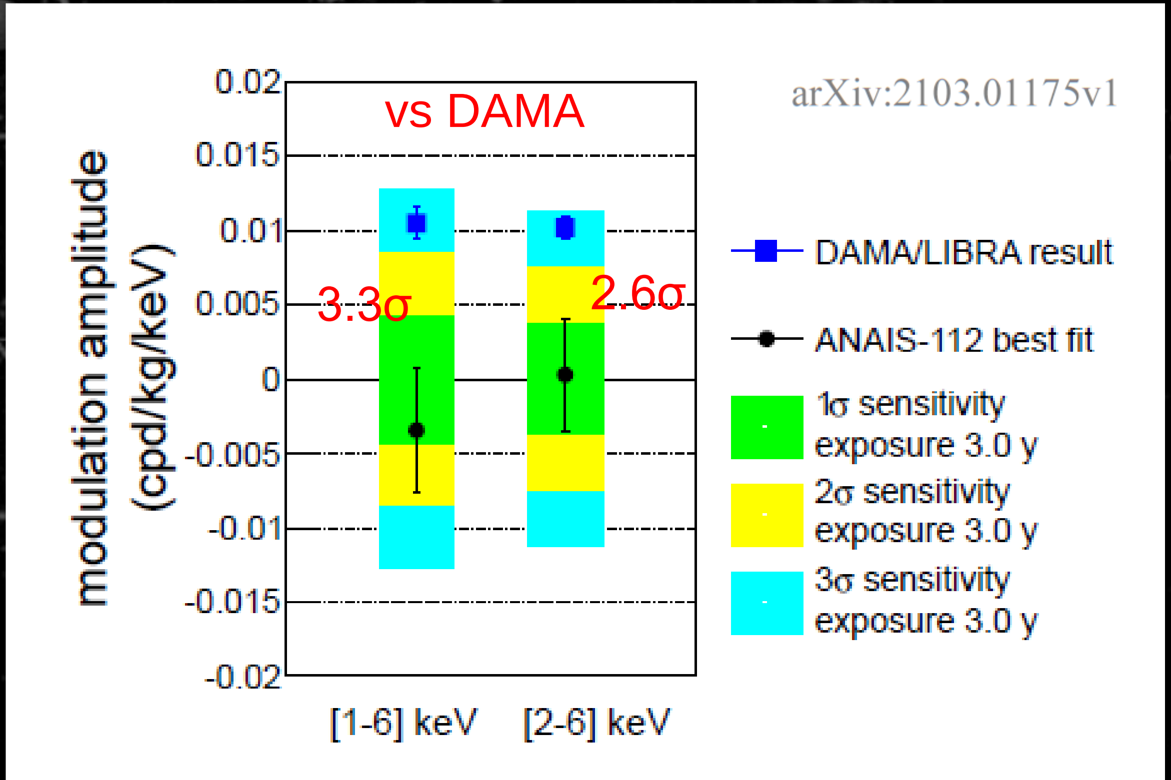
Eur. Phys. J. C (2014) 74:3196

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

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

Need to be stay tuned.

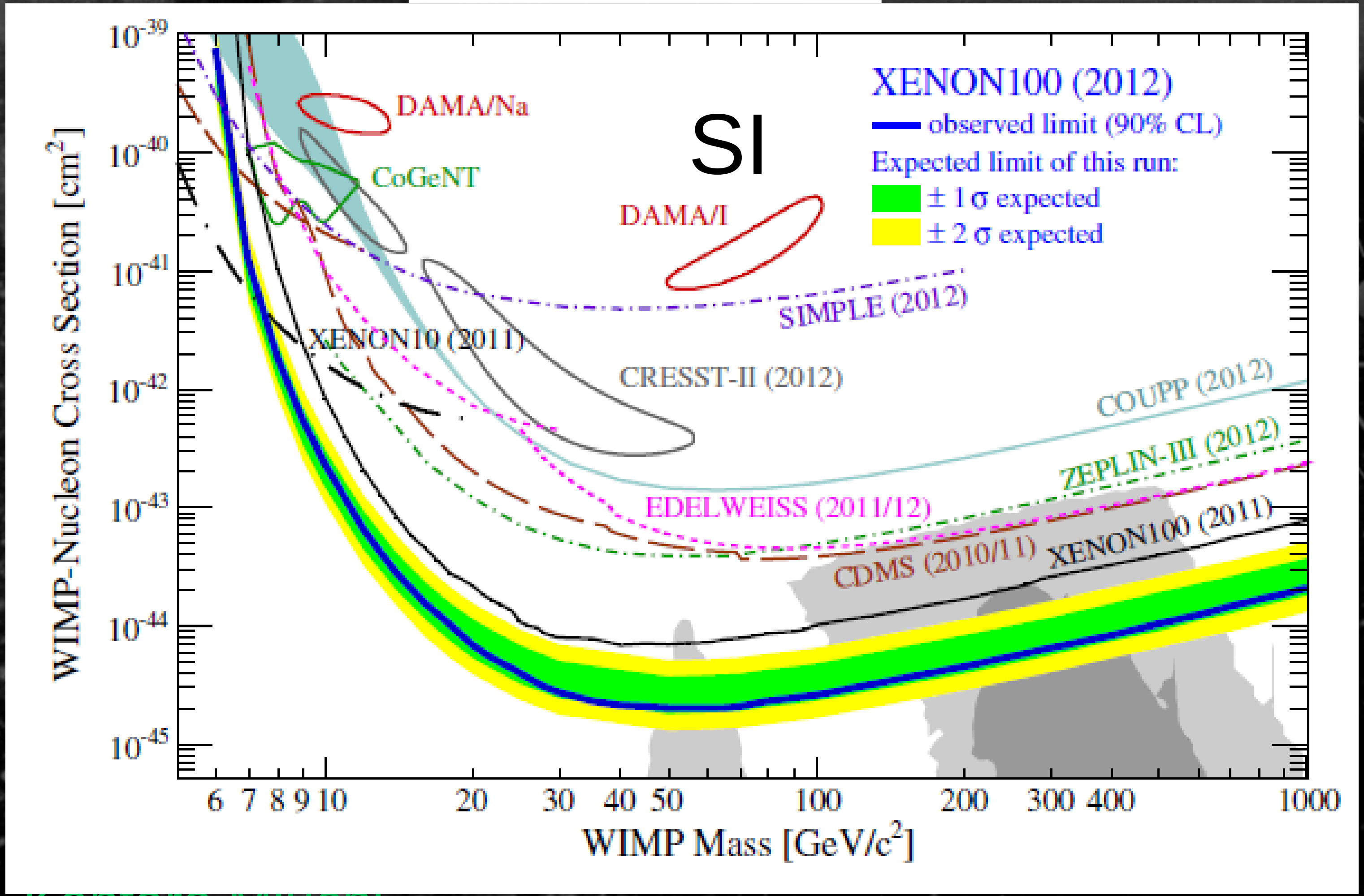




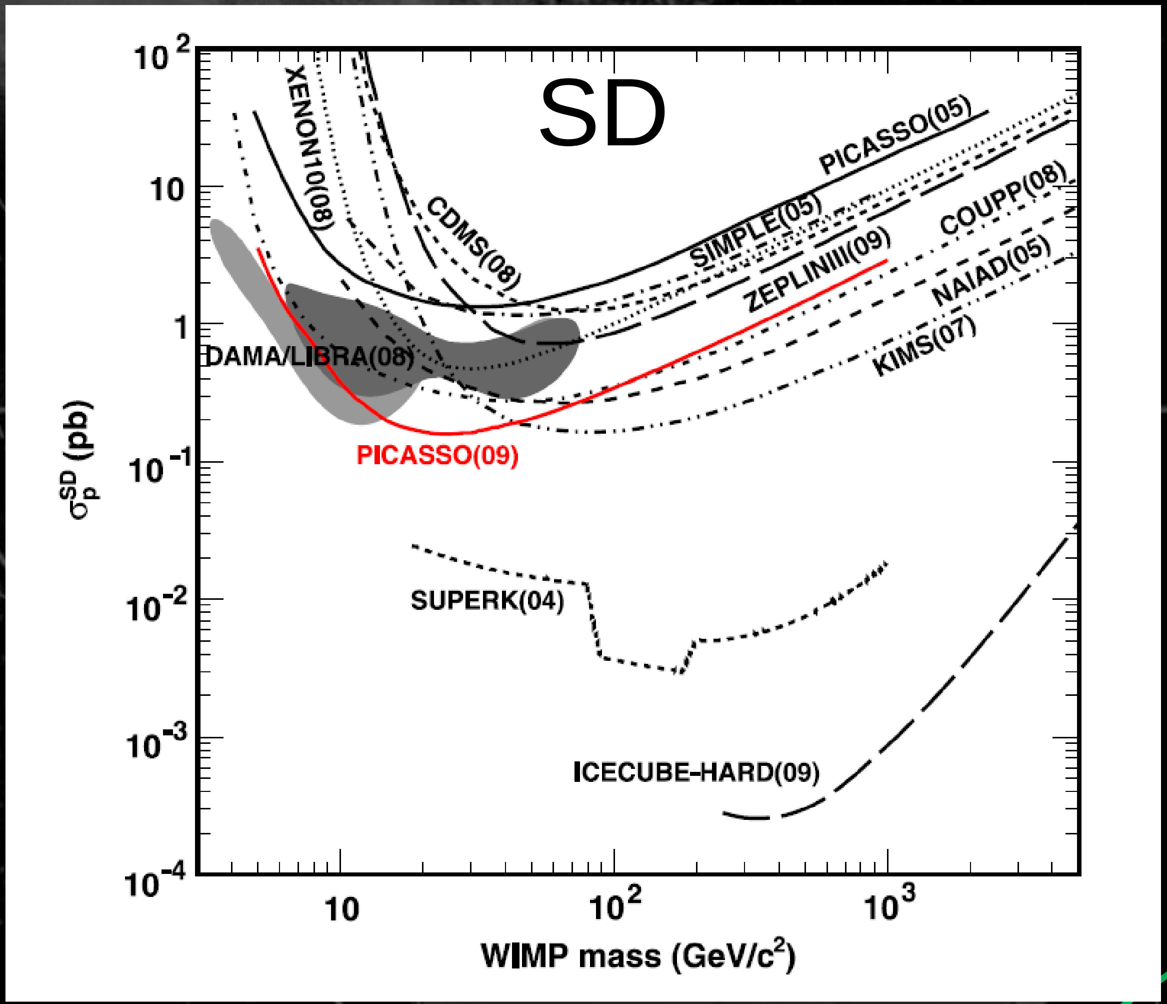
• DAMA：Strong tension with other nuclei

- Recent papers don’t show DAMA’s area.
- It doesn’t mean DAMA signal is gone…

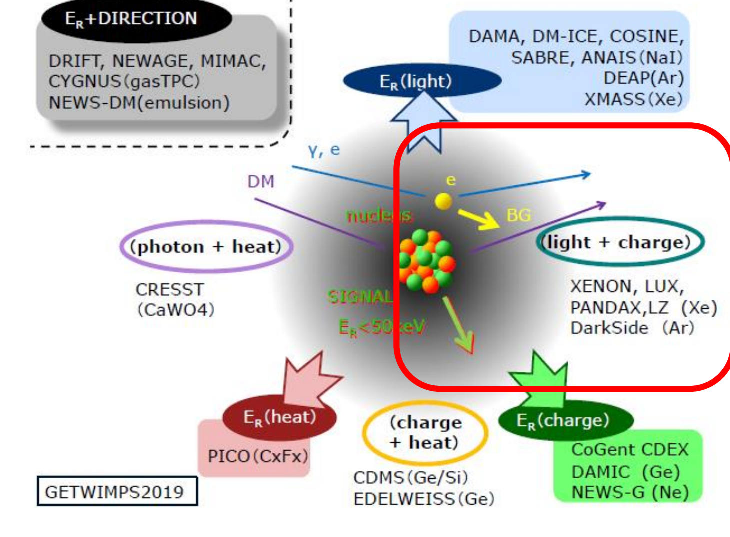
PRL **109,** 181301 (2012)

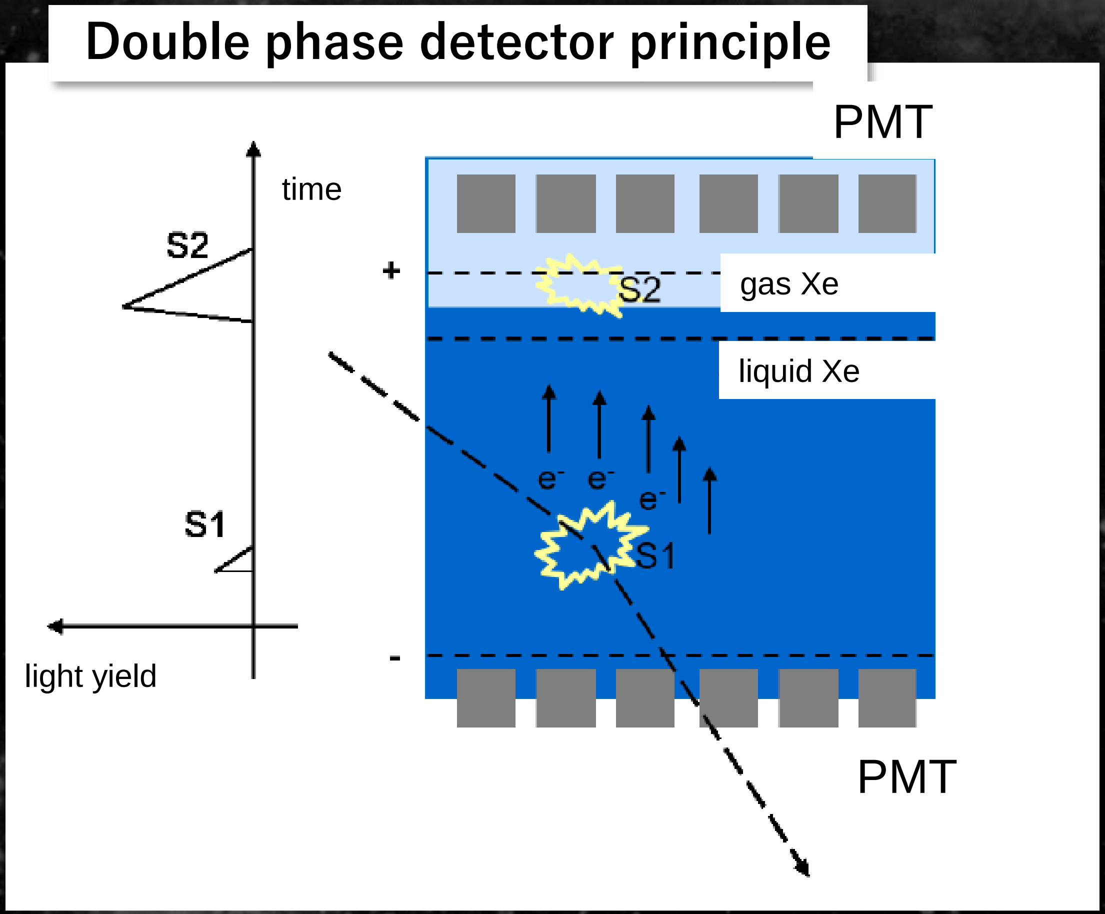


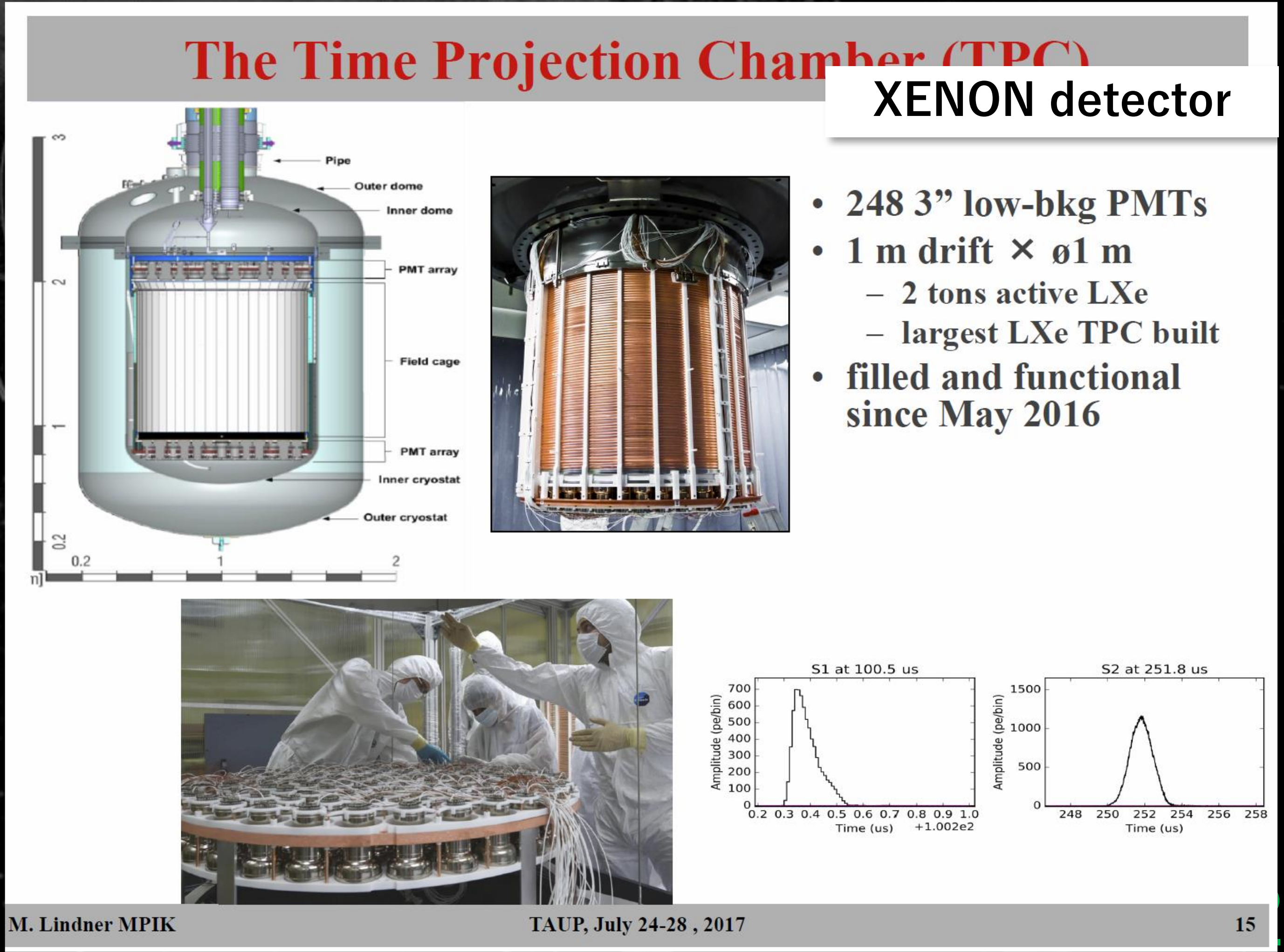
Physics Letters B 682 (2009) 185–192



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



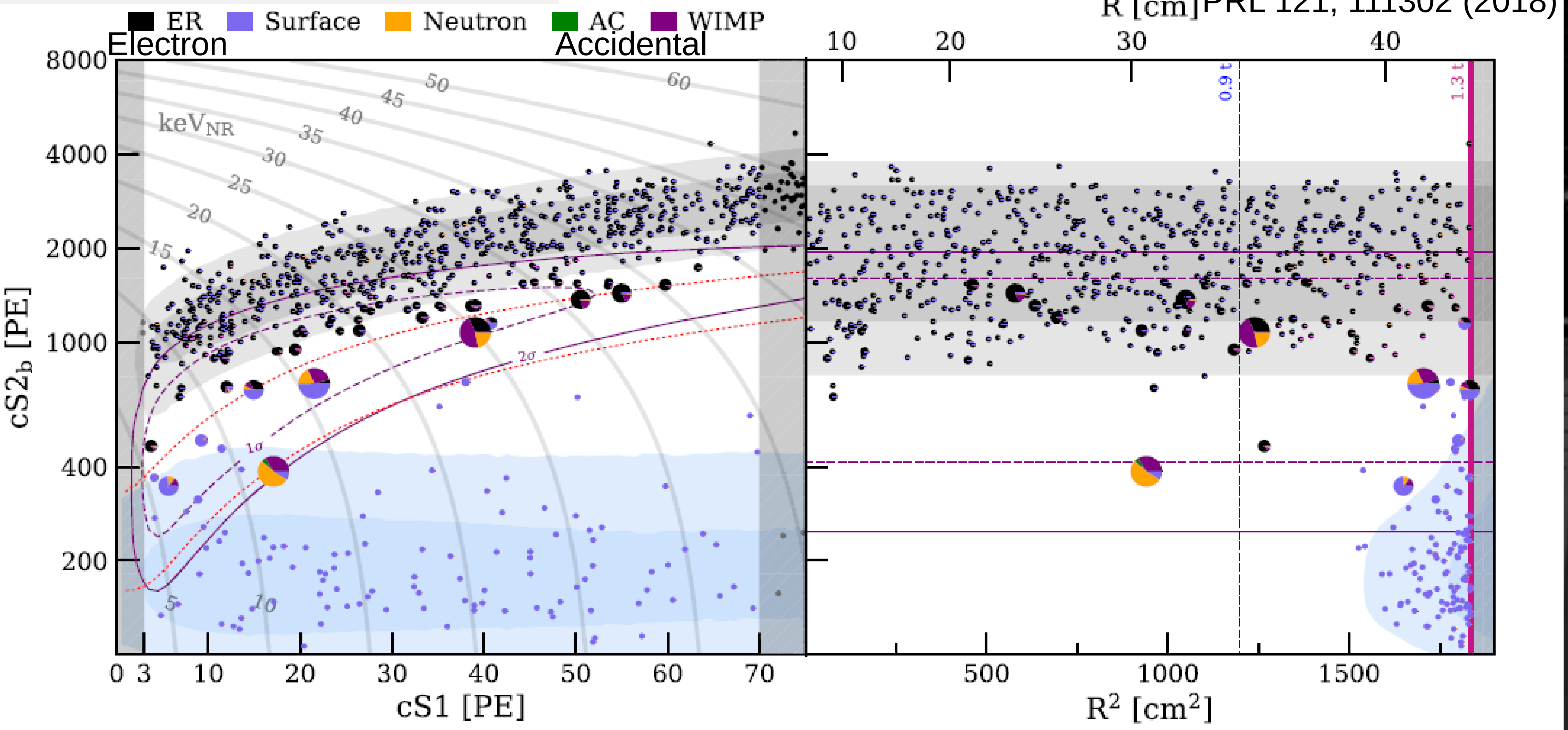




- XENON1T **Dark Matter Search Results from a One Ton-Year Exposure of XENON1T**
  - Some events in ROI
  - ER ：radon　　neutron：neutrons from α particle

PRL 121, 111302 (2018)

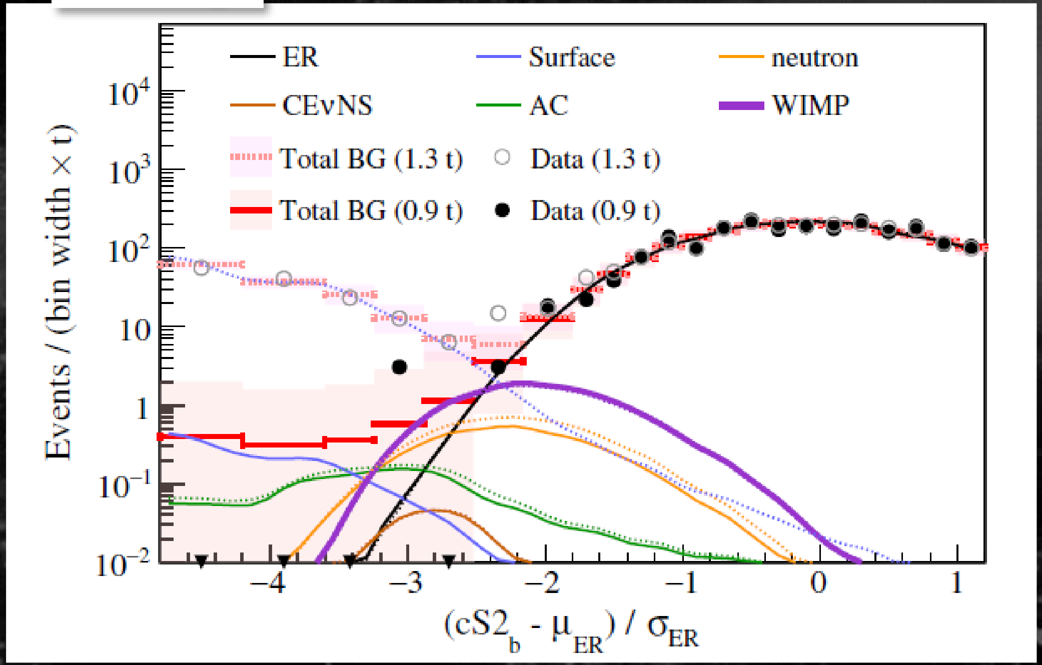
red：nuclear recoil (signal) region
gray：BG (electron) region

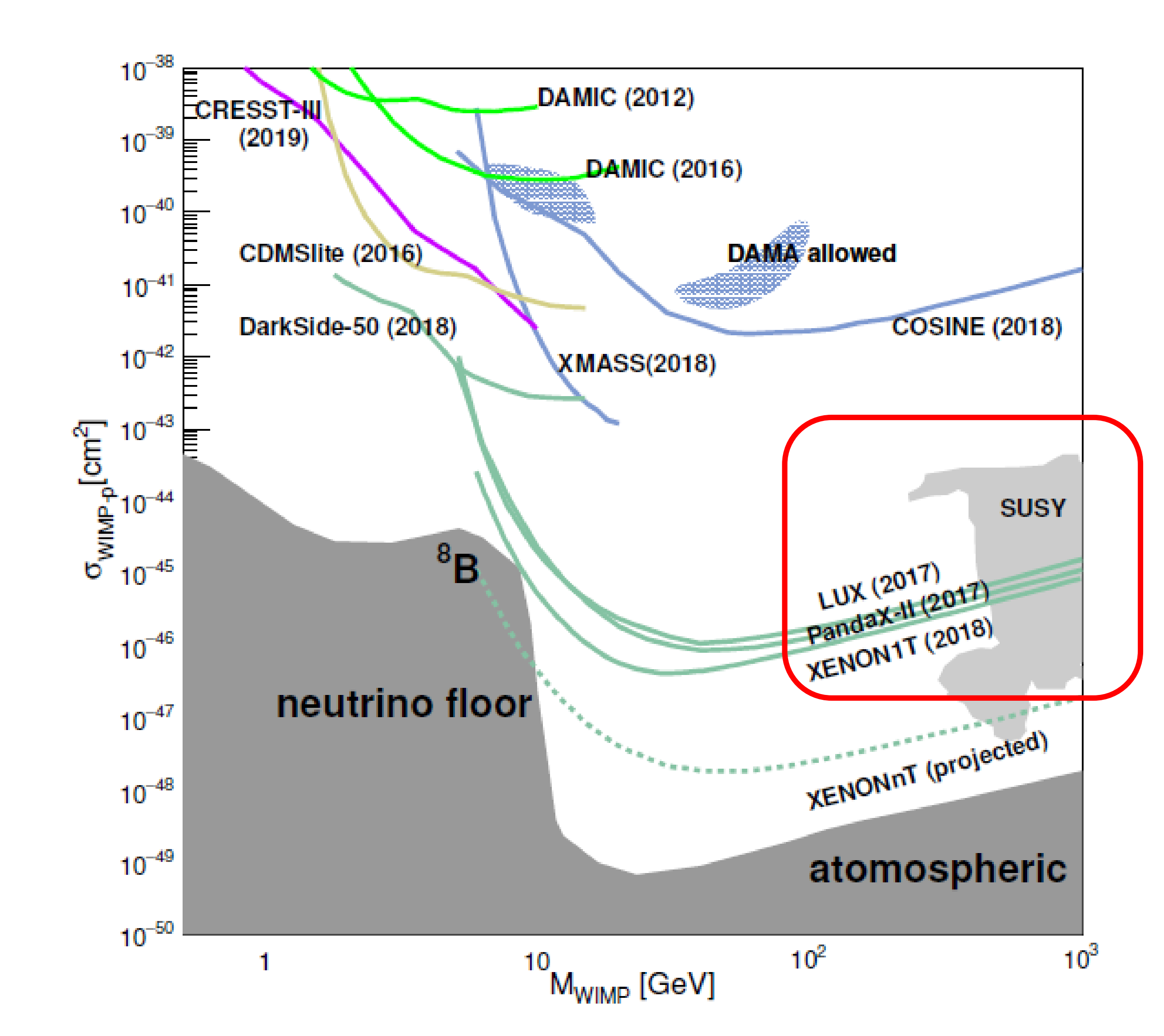


• XENON1T 1ton • year result

fitting

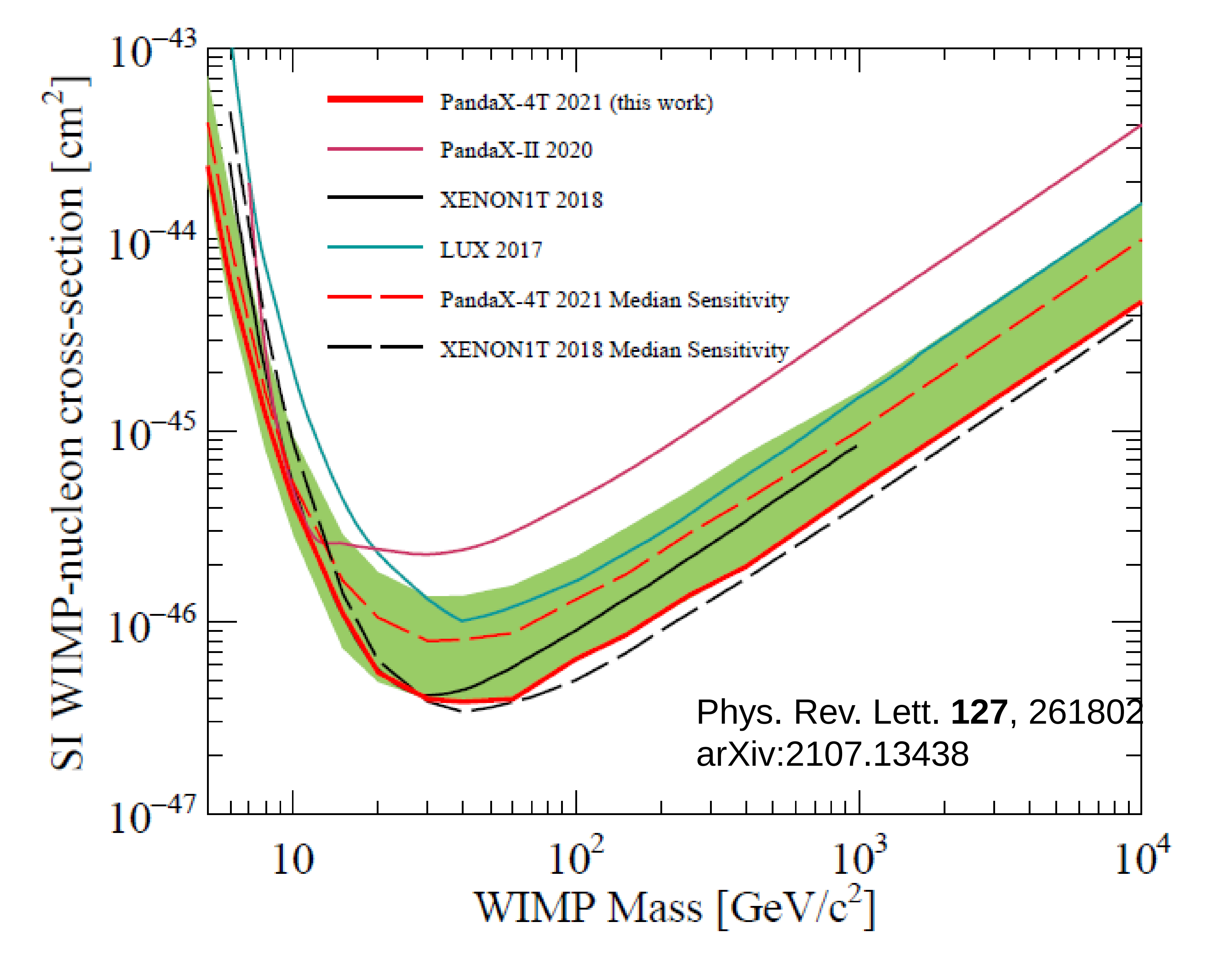
PRL 121, 111302 (2018)





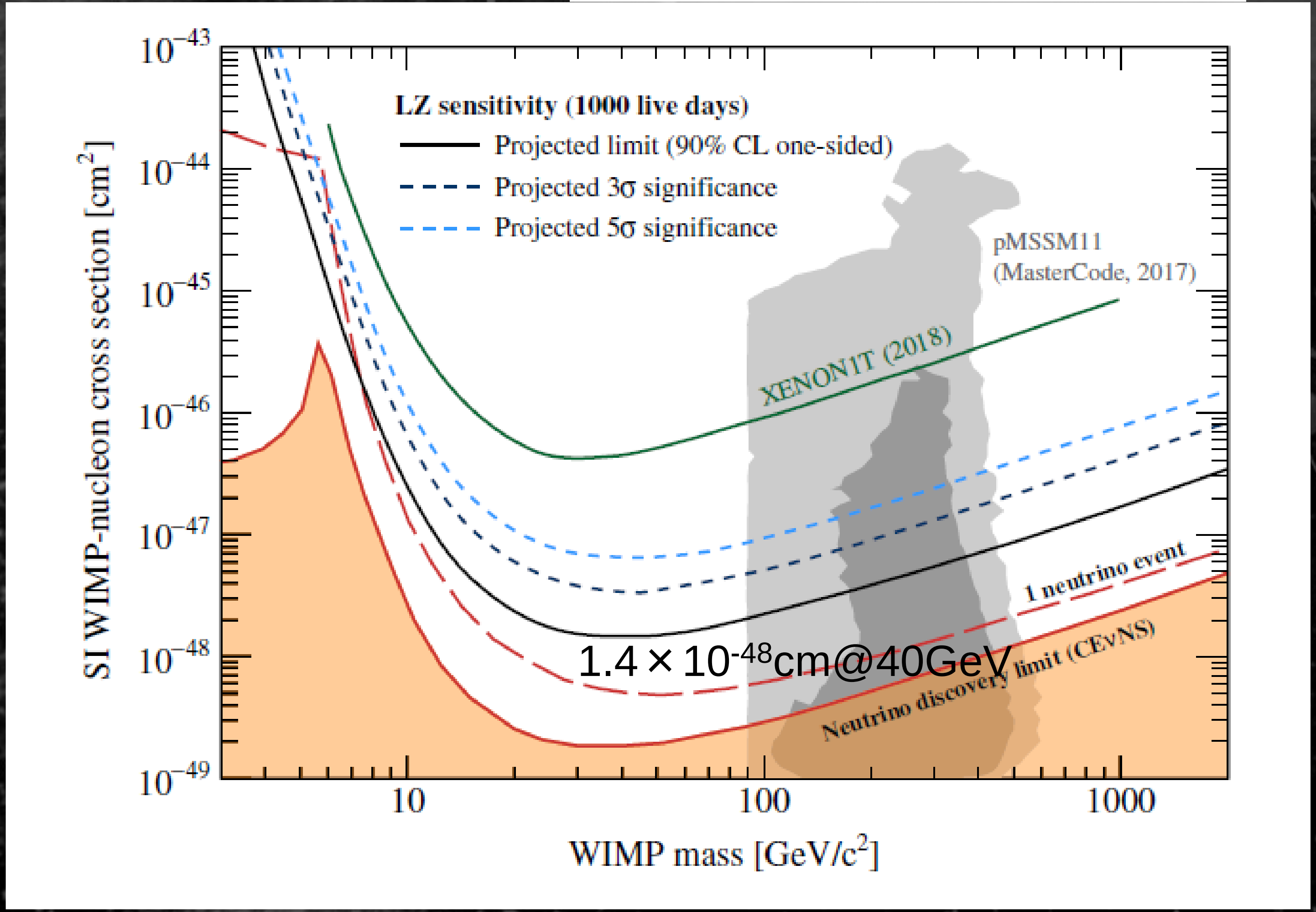
- $4.1\times10^{-47}cm^{-2}$ @30GeV
- Leading the direct detection
- SUSY predictions are investigated

- 最新（PandaX）

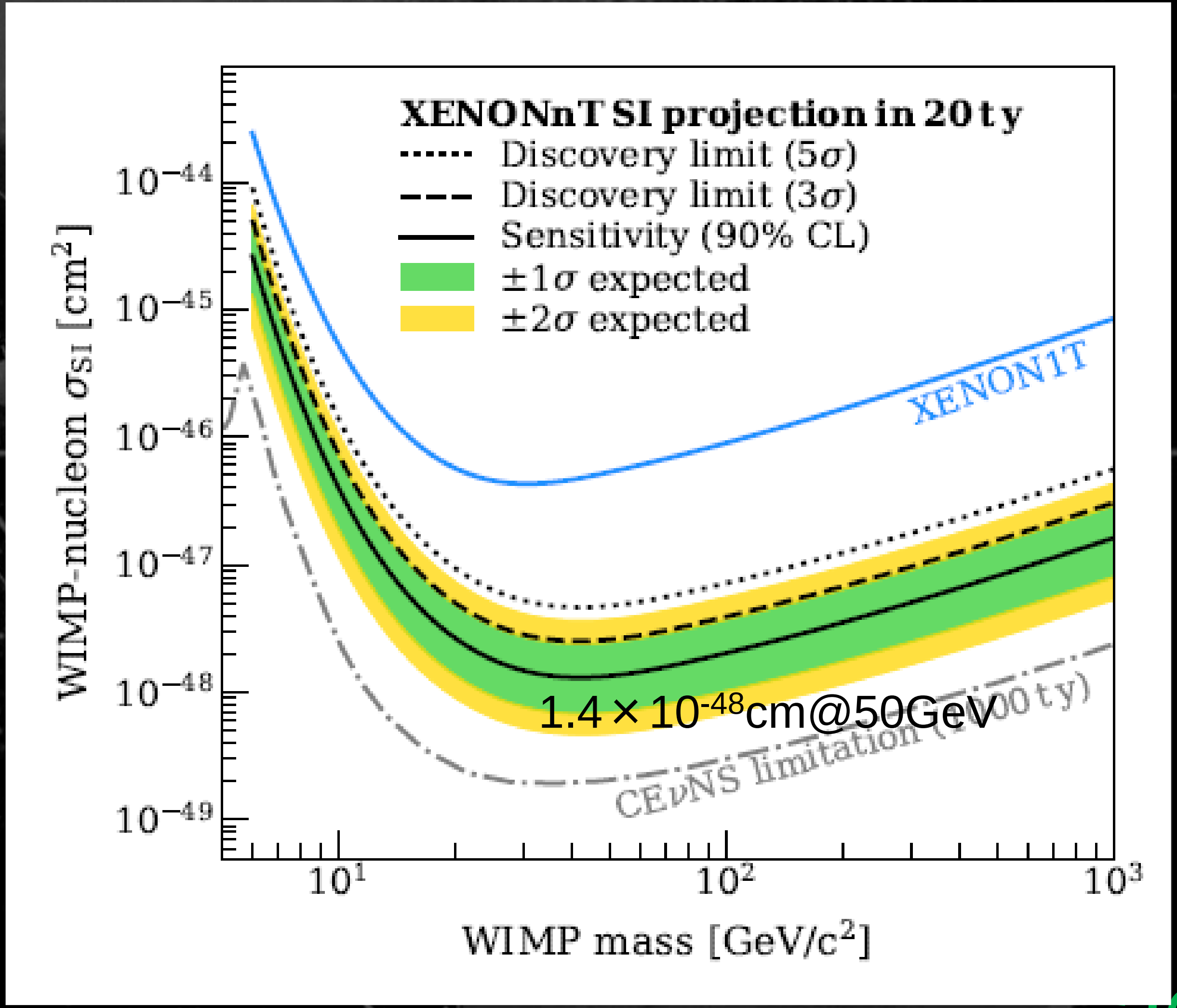

PandaX-4T 2021 (this work)
PandaX-II 2020
XENON1T 2018
LUX 2017
PandaX-4T 2021 Median Sensitivity
XENON1T 2018 Median Sensitivity
SI WIMP-nucleon cross-section [cm^2]
WIMP Mass [GeV/c^2]
10^{-43}
10^{-44}
10^{-45}
10^{-46}
10^{-47}
10
10^2
10^3
10^4
Phys. Rev. Lett. **127**, 261802
arXiv:2107.13438

- Next
  - XENONnT
  - LZ
  - PANDA-X

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



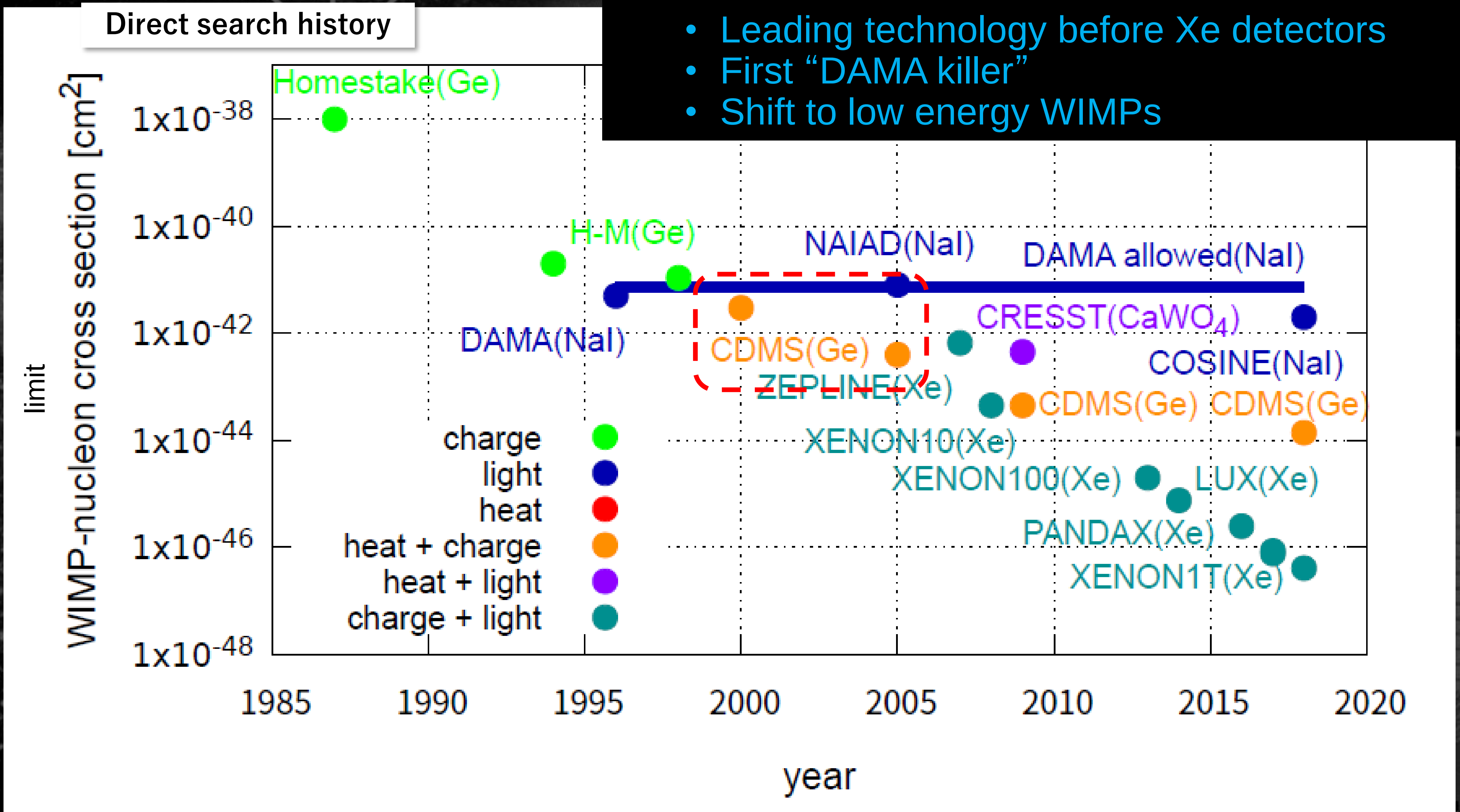
arXiv:2007.08796v1



Direct Search Review

2. New Trend : Low Mass DM

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



- Bolometers
  - Low energy threshold ⇒ low mass DM

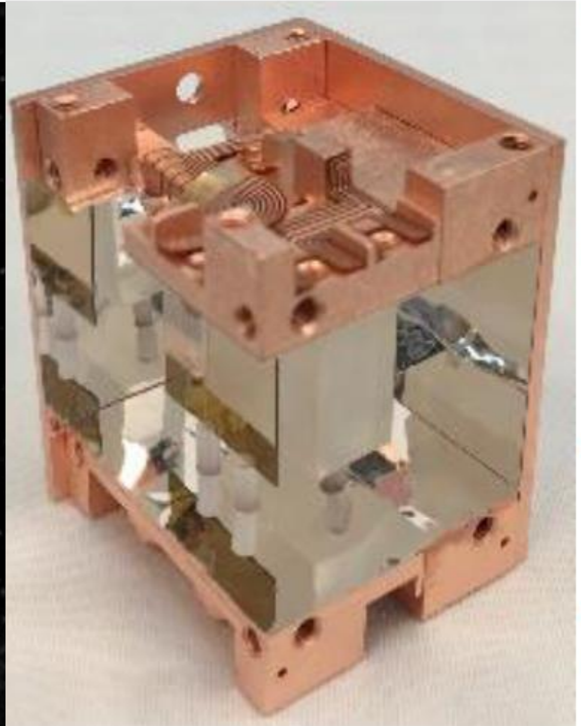
Latest results of CRESST-III's search for sub-GeV/c² dark matter

Holger Kluck
on behalf of the CRESST collaboration

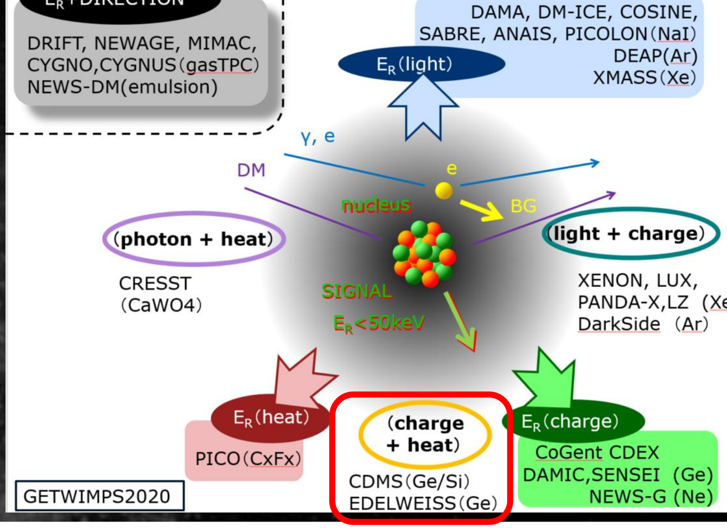
16th International Conference on Topics in Astroparticle and Underground Physics (TAUP2019)

September 10, 2019

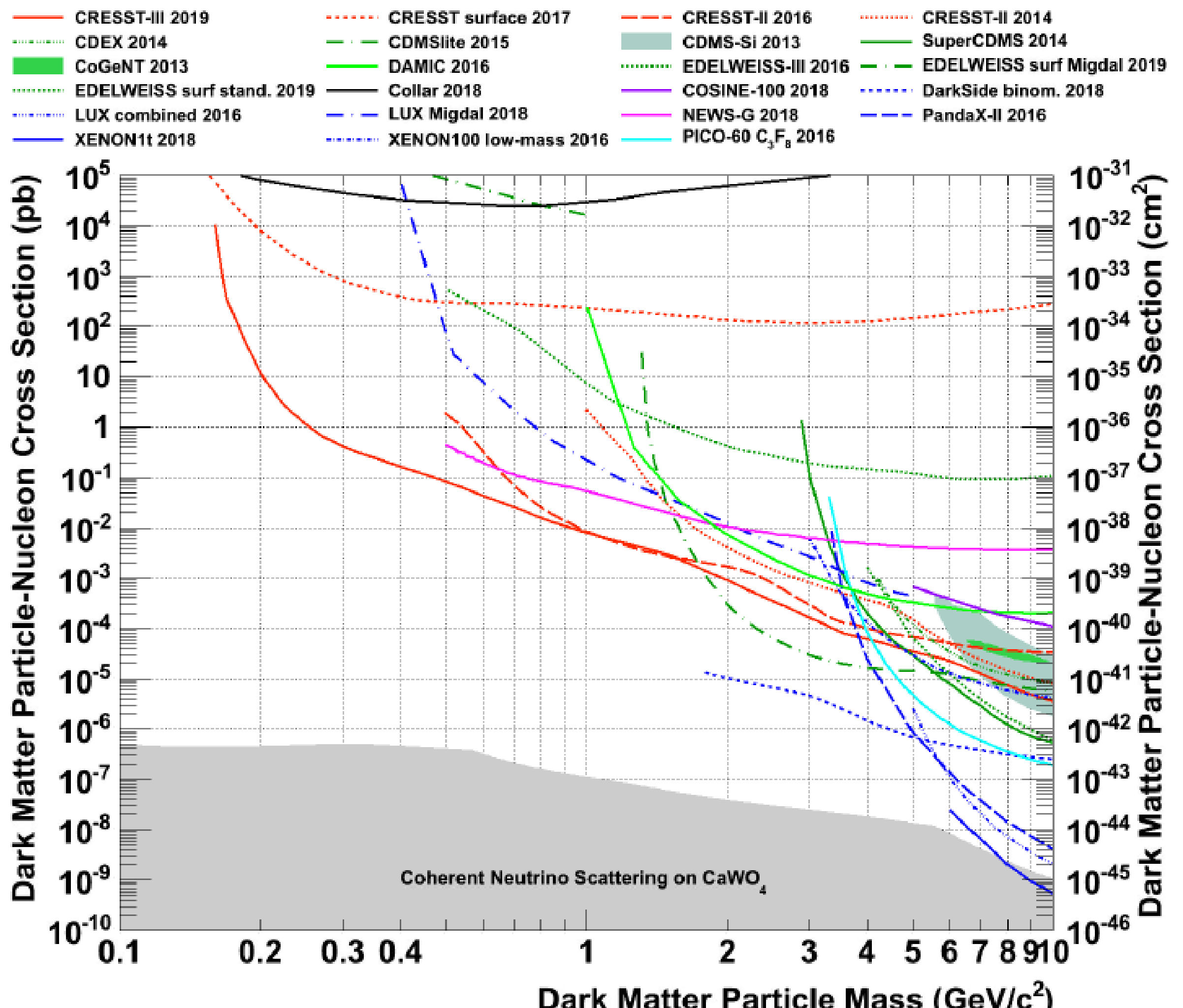
CRESST-III detector



- 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

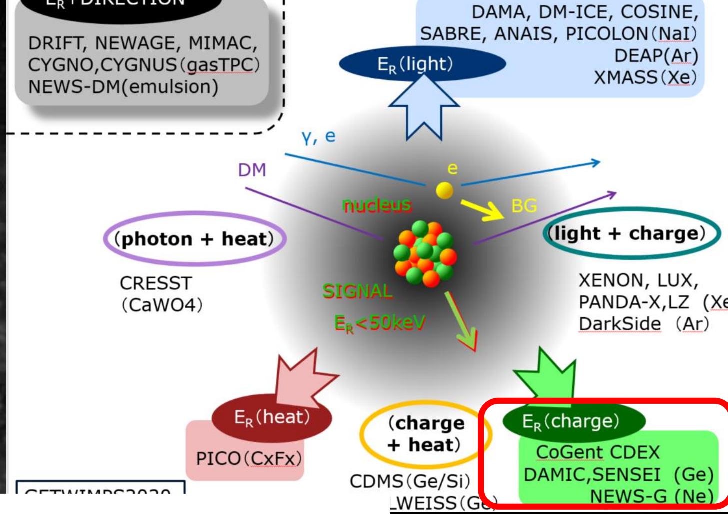


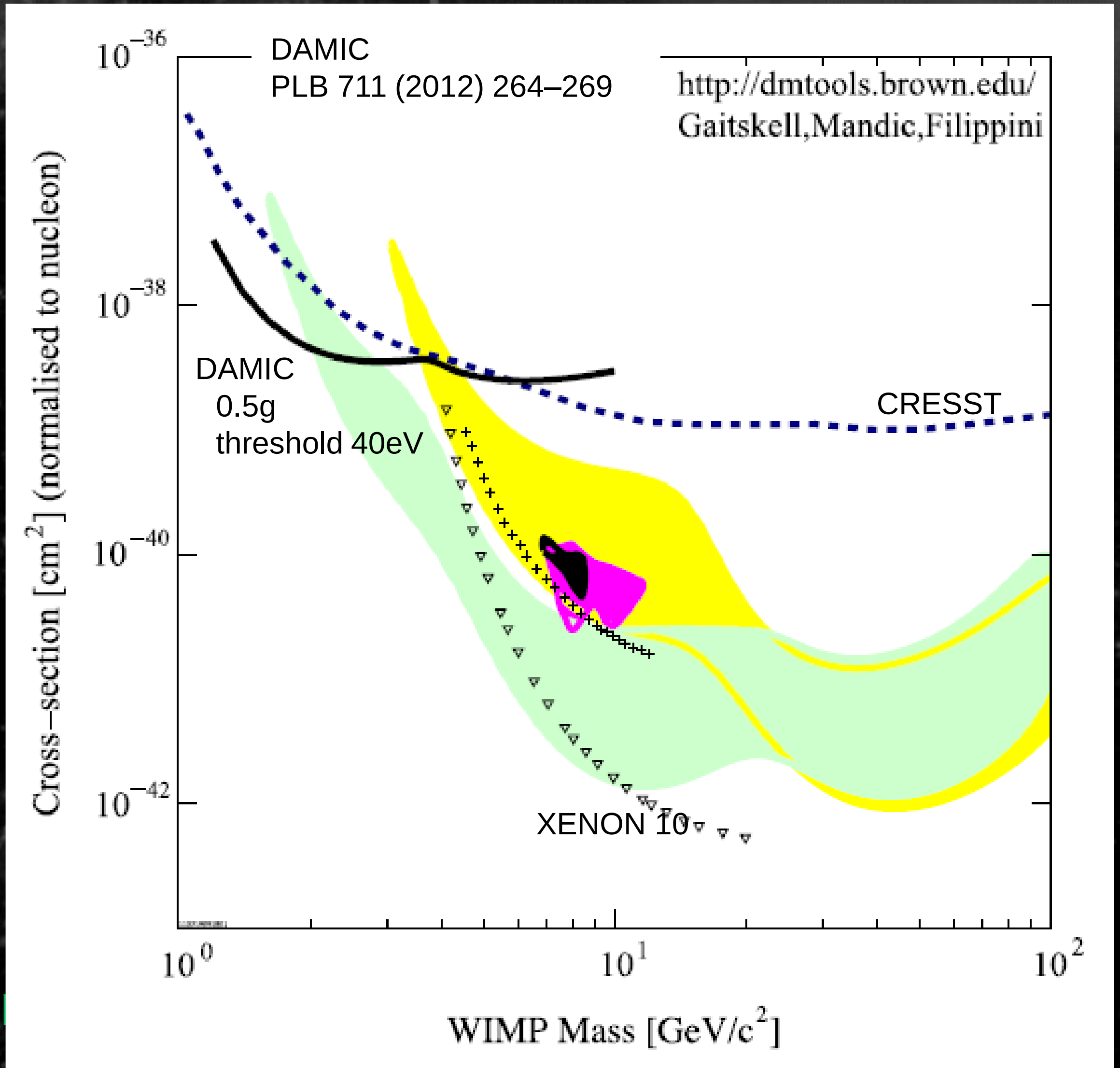
CRESST-III result

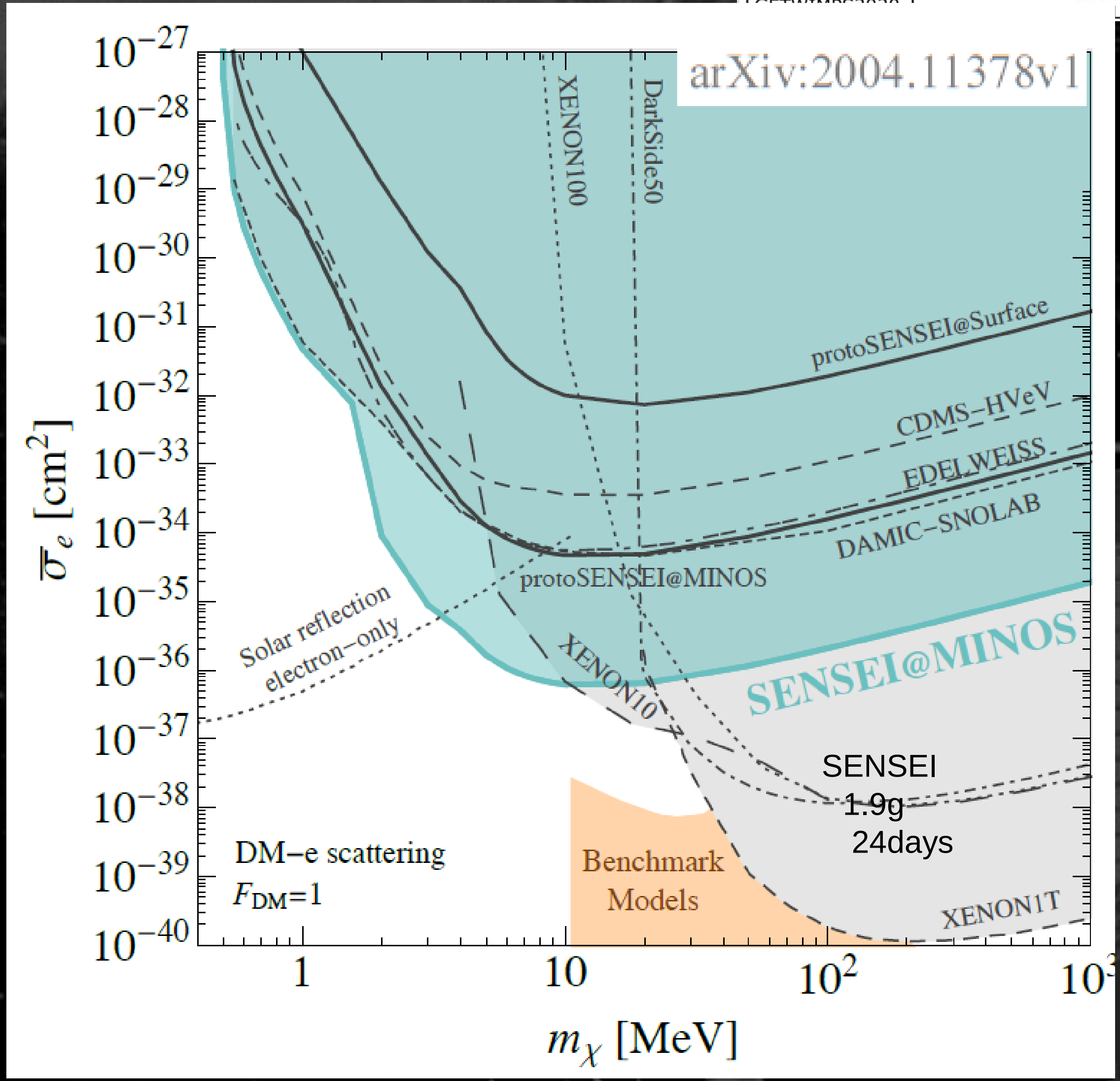


Kenta

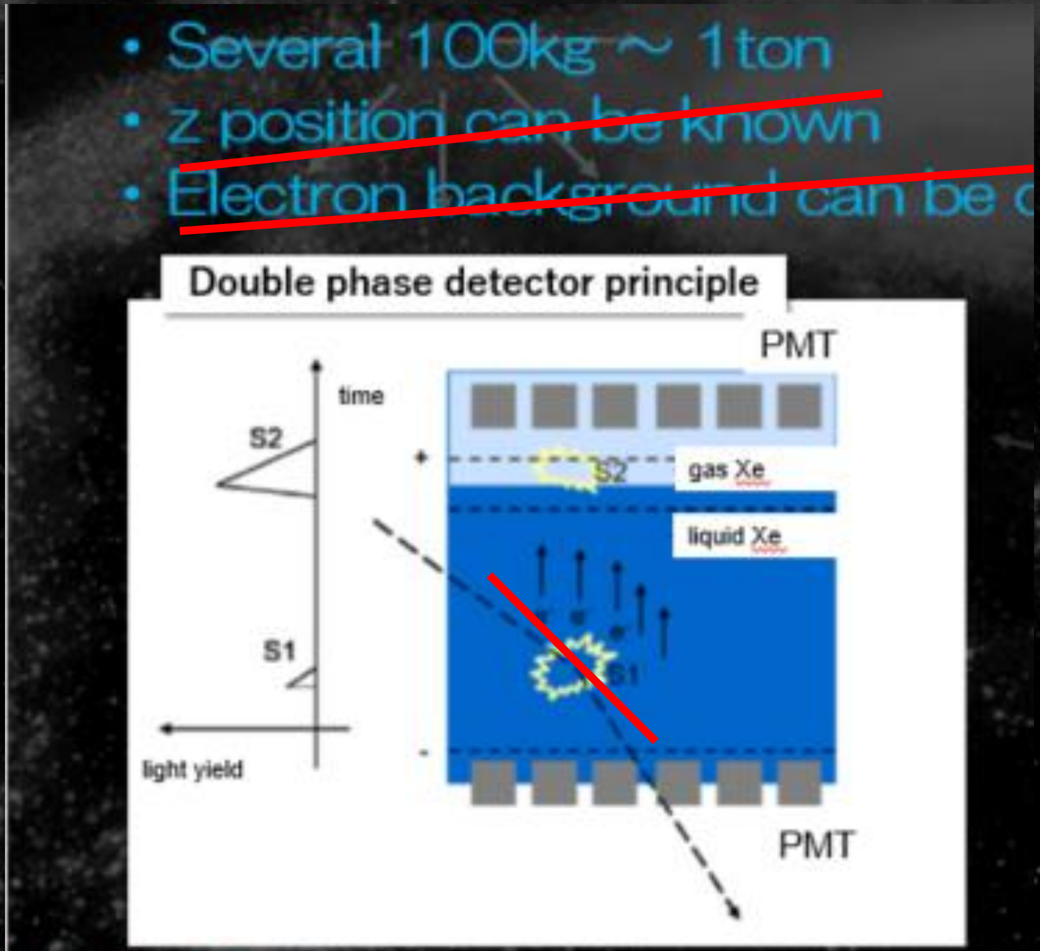
- CCD
  - DAMIC arXiv:2007.15622v1
    - pioneer of low threshold
  - SENSEI arXiv:2004.11378v1
    - skipper CCD
    - sensitive to single electron
    - DM-electron channel

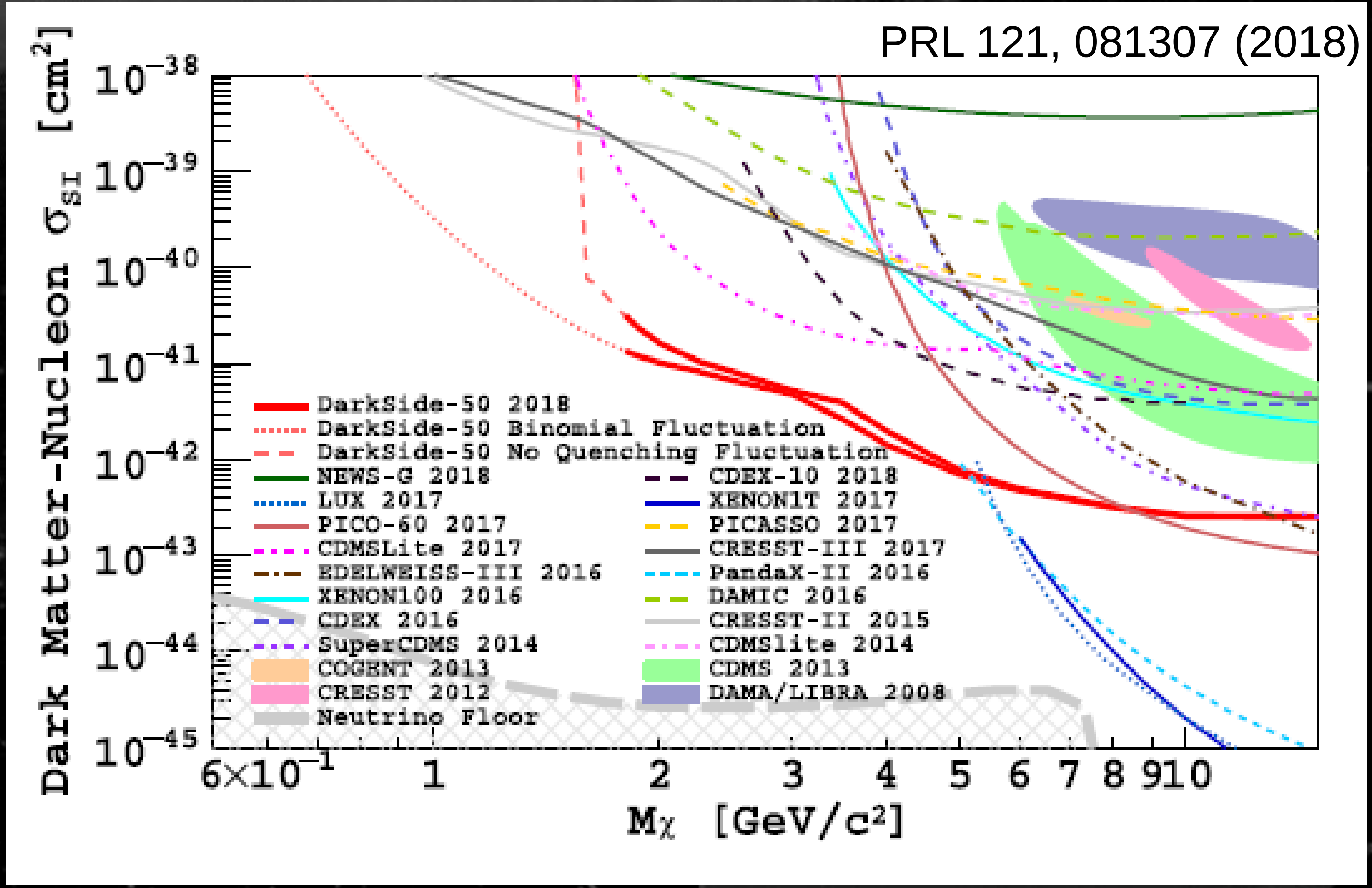




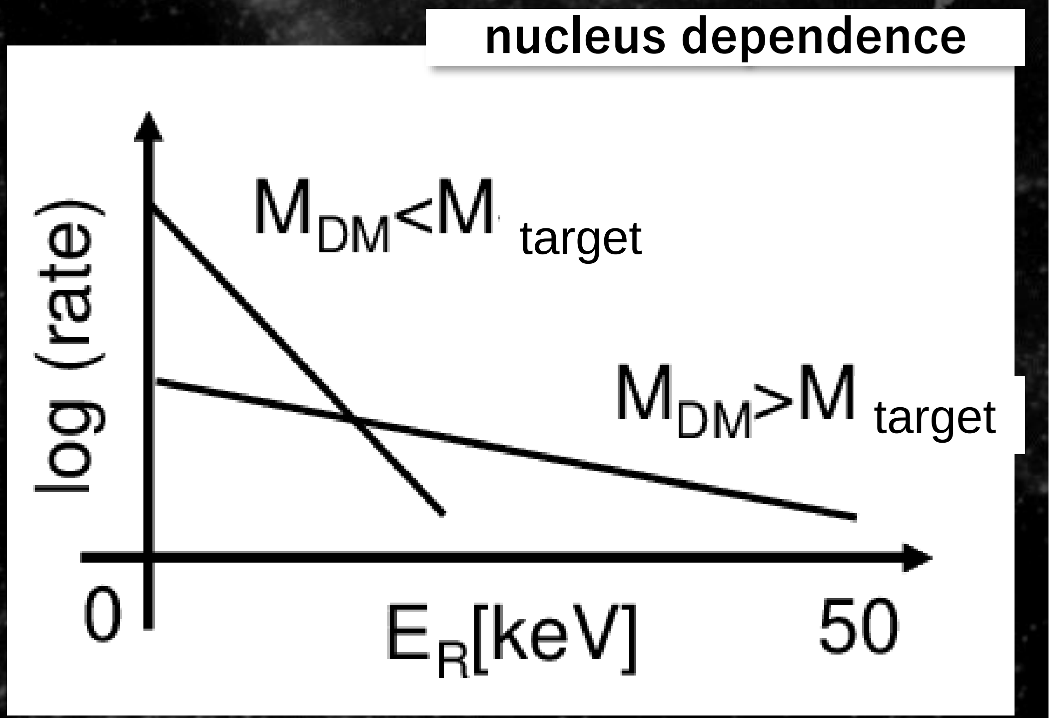


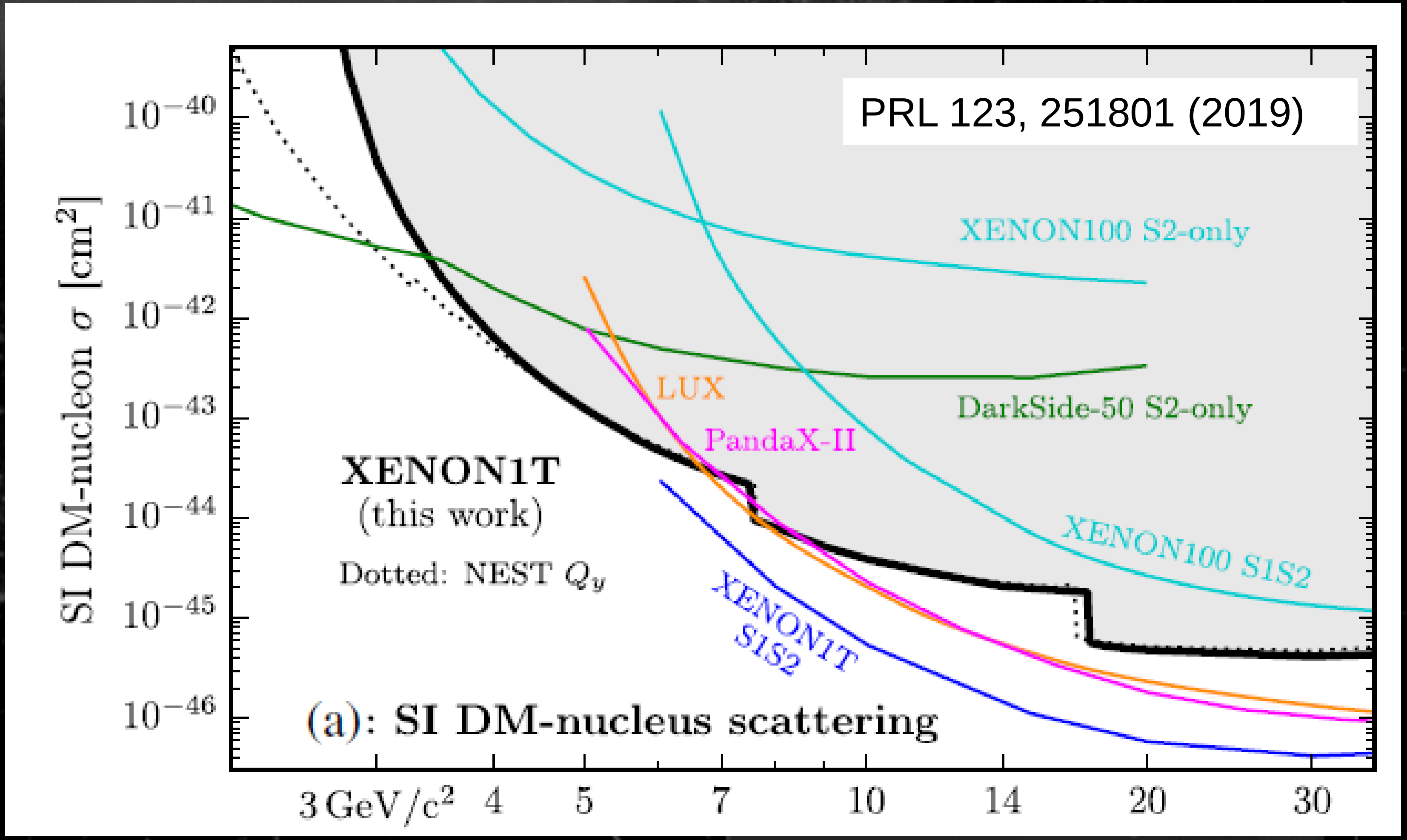
- Liq. noble gas: S2 only analysis
  - can lower threshold ⇒ low mass WIMPs
  - DARKSIDE（Ar） PRL 121, 081307 (2018)





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

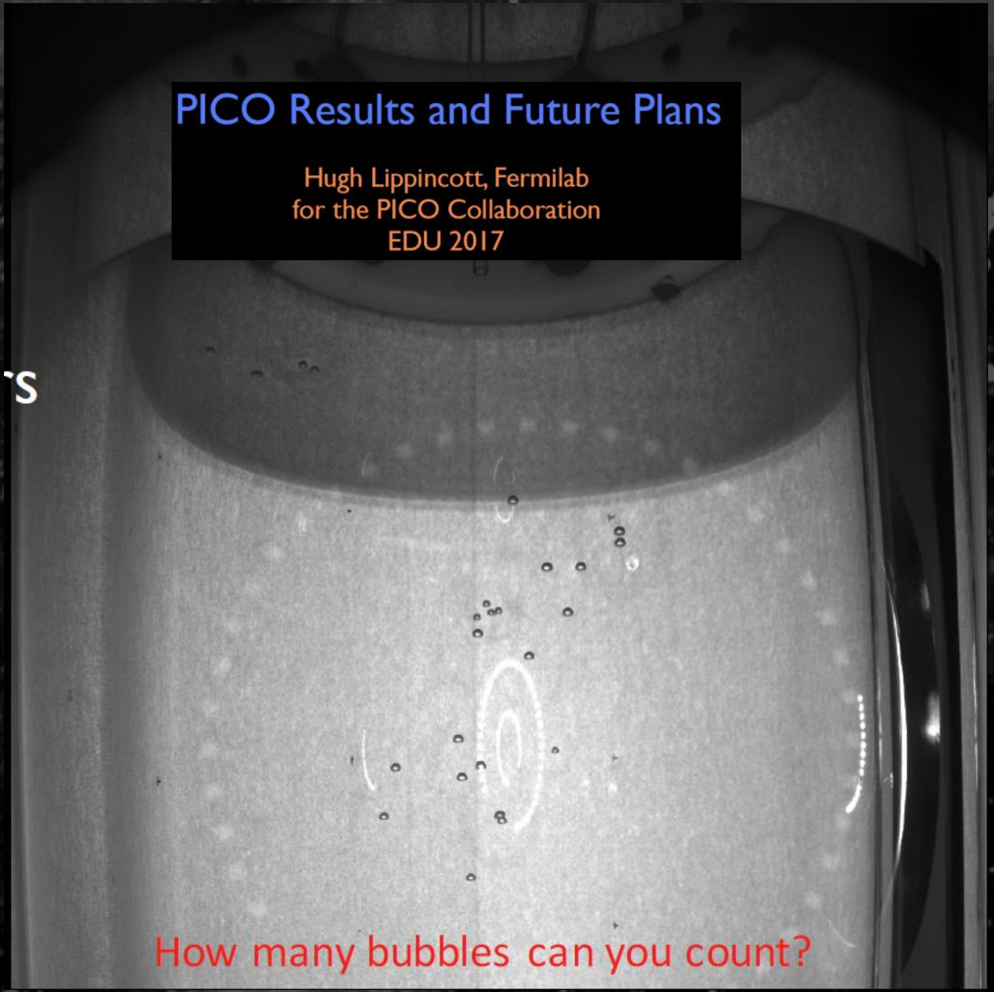


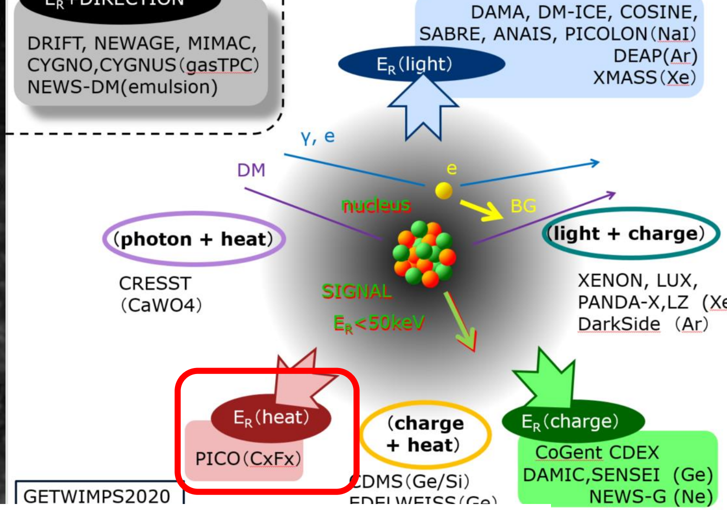


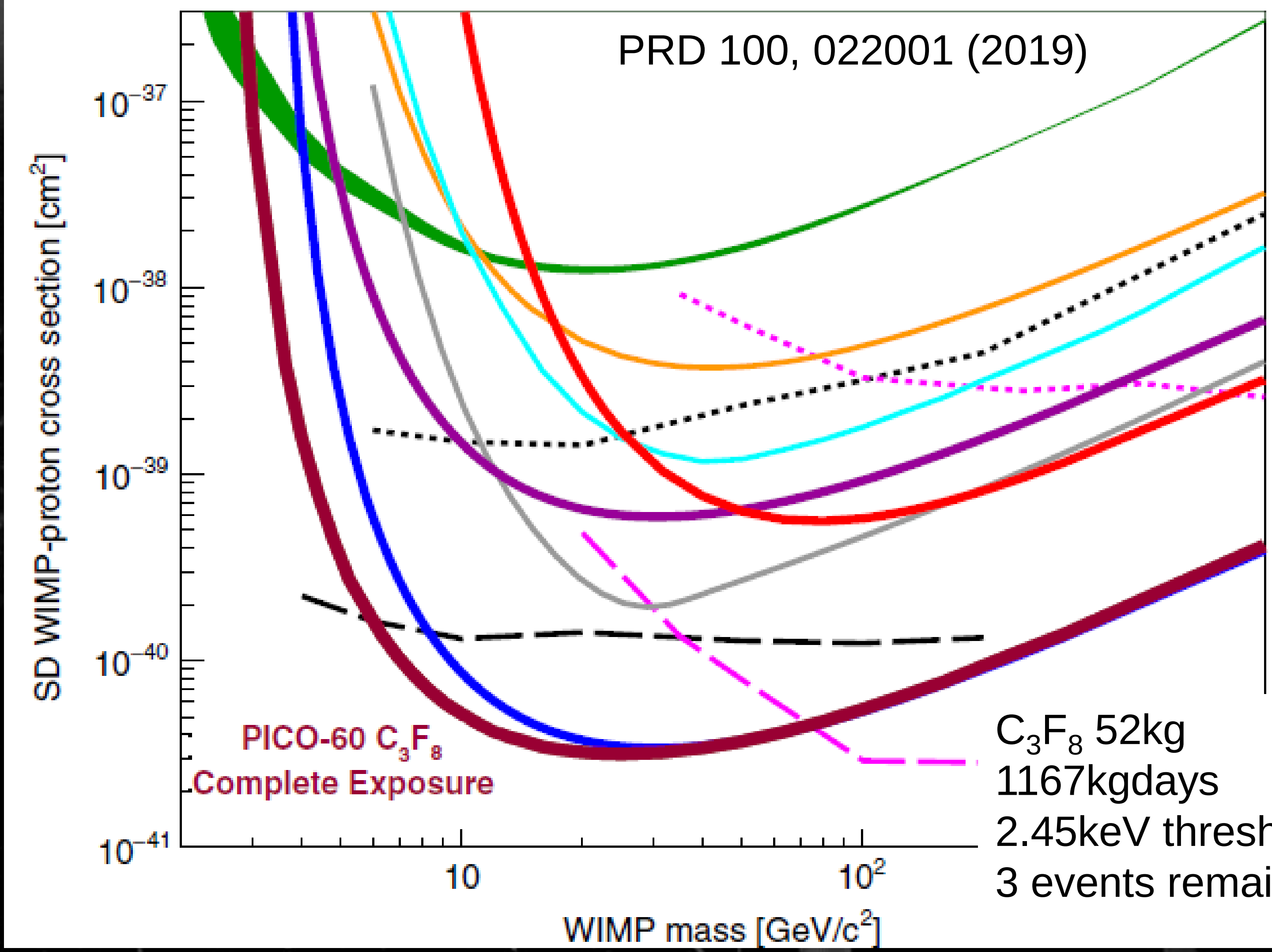
Direct Search Review

3. Others

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







C_3F_8 52kg
1167kgdays
2.45keV threshold
3 events remained

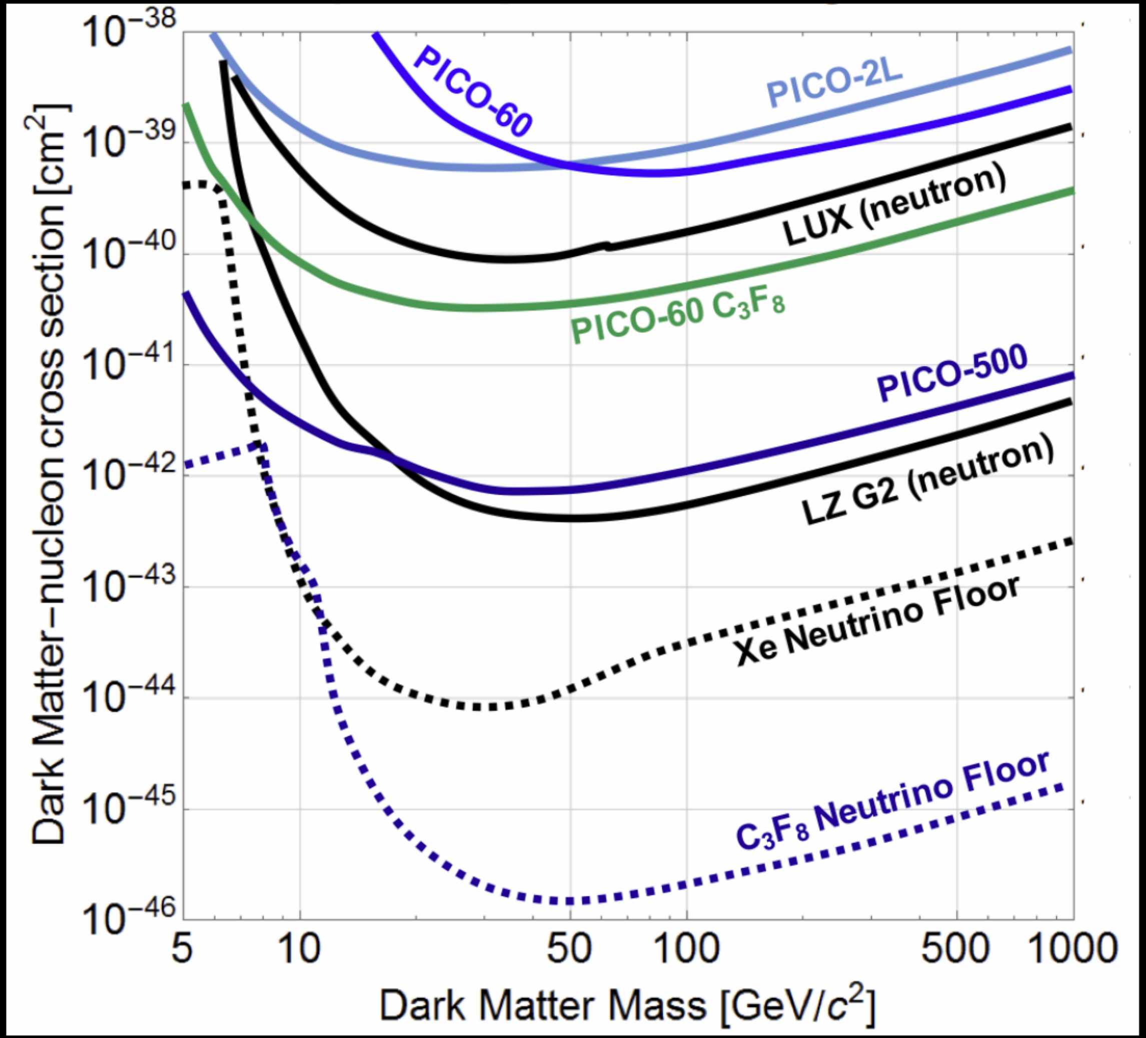
- Fluorine advantage
  - SD search
  - different "Neutrino floor" from xenon

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

PICO Results and Future Plans

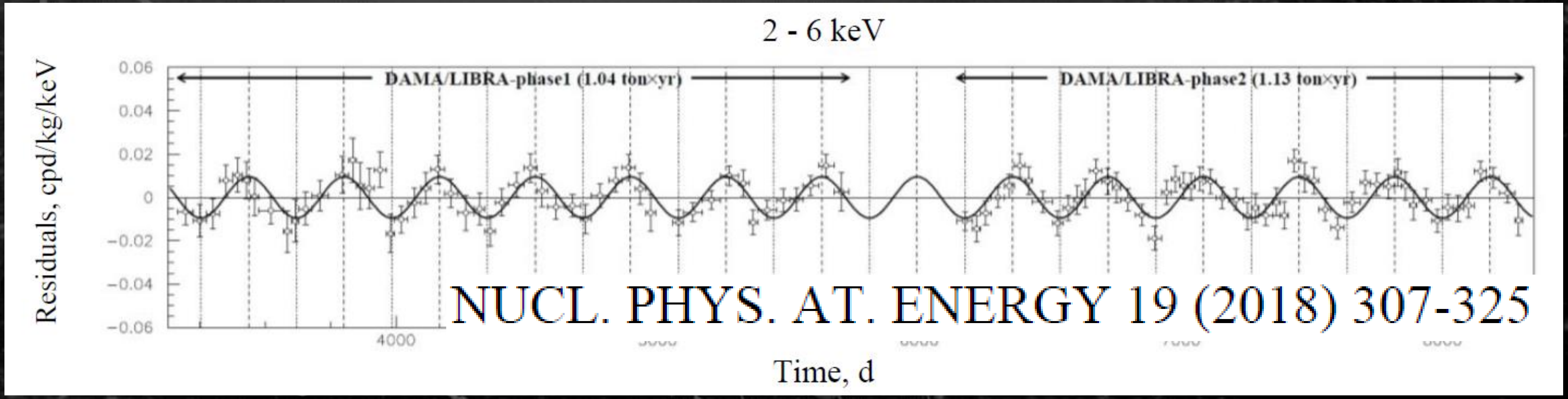
Hugh Lippincott, Fermilab
for the PICO Collaboration
EDU 2017

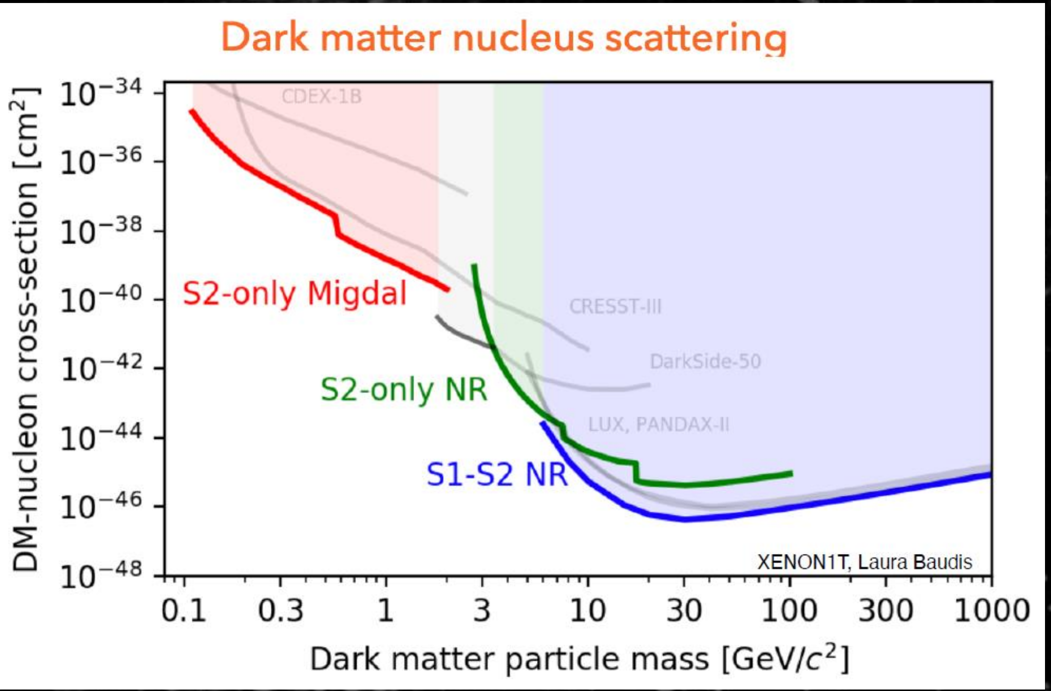
Scaling to PICO-500

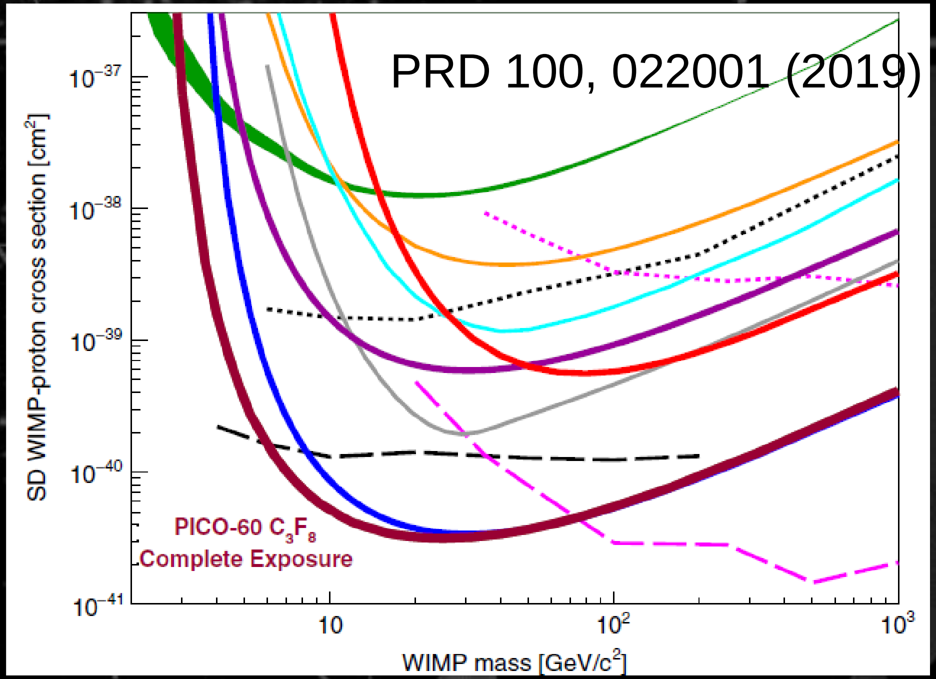


直接探索の現状

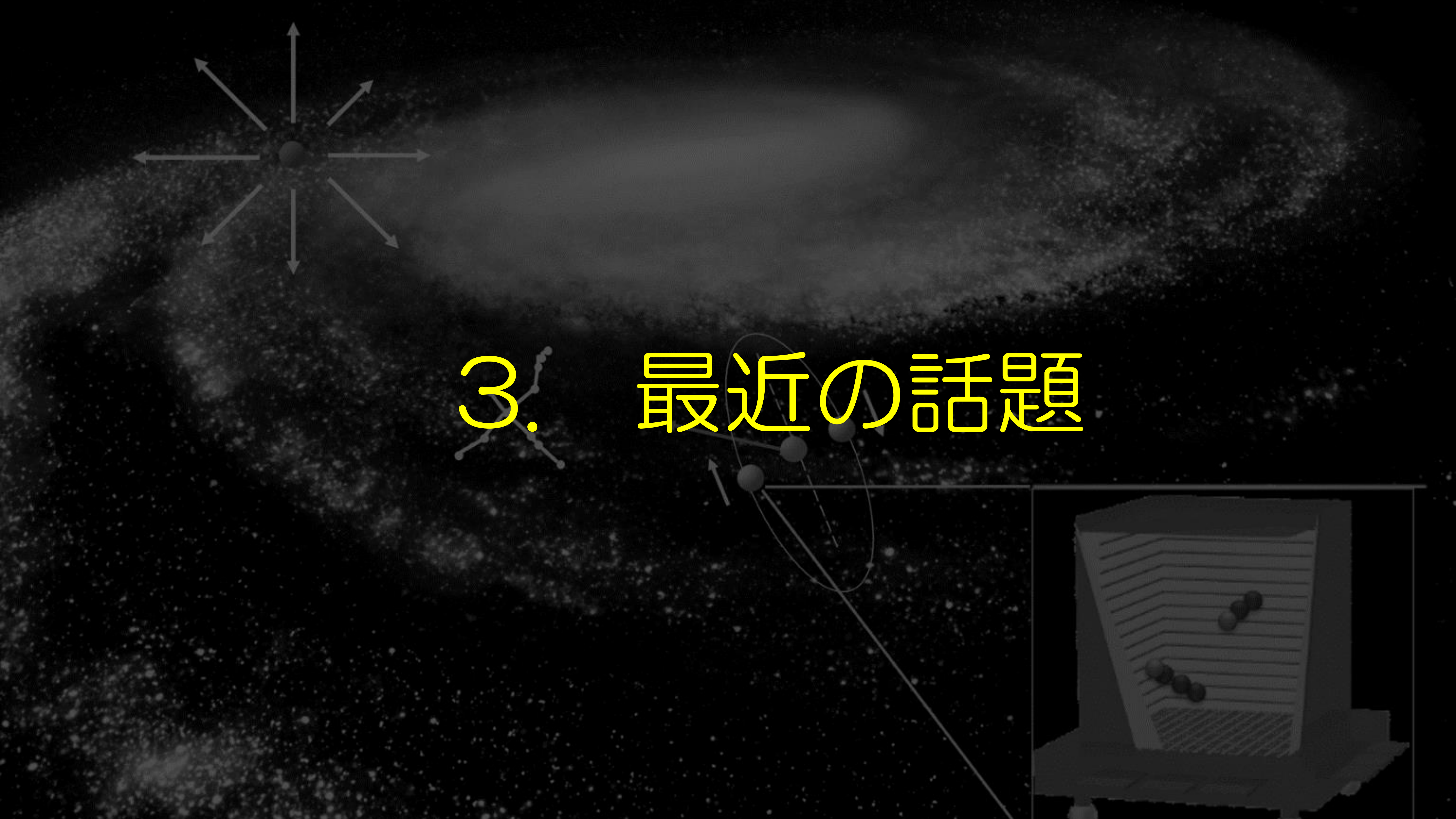
- DAMA, Xenon(SI), Fluorine (SD)







3.　最近の話題

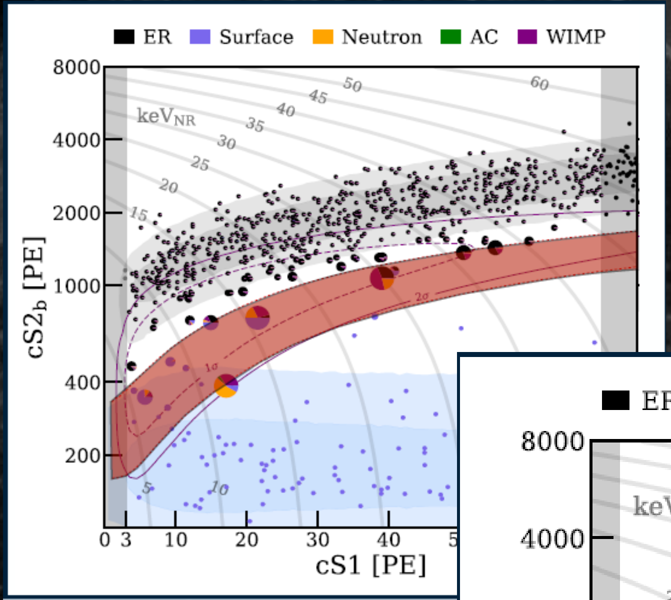


Topics

1. Electron Recoil (ER) signal

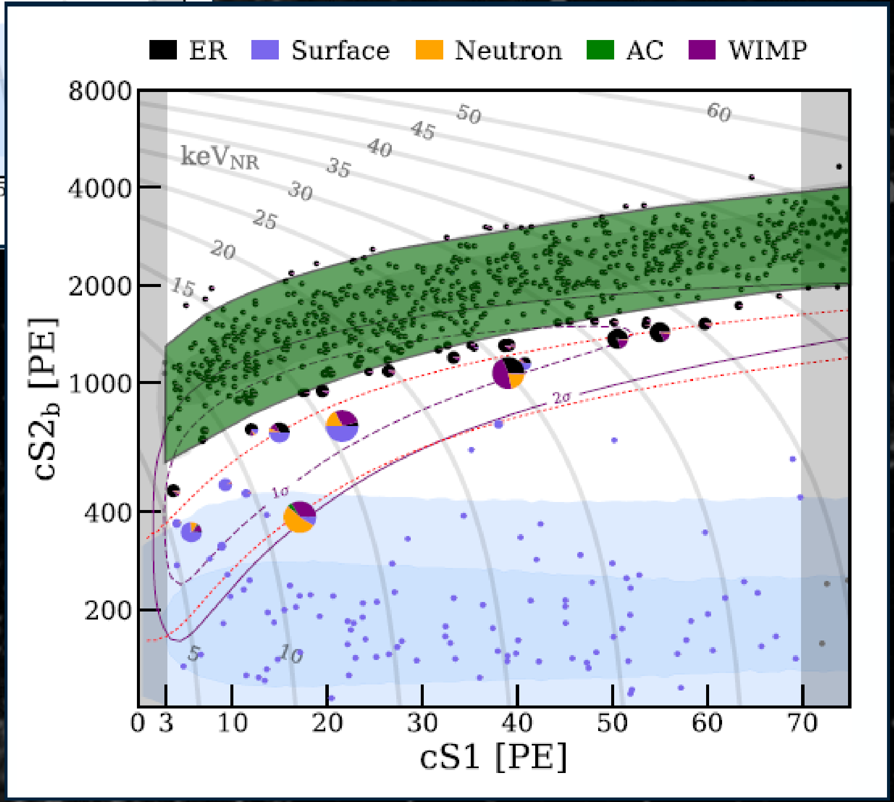
- XENON ER excess
  - 0.65 tonne-years exposure

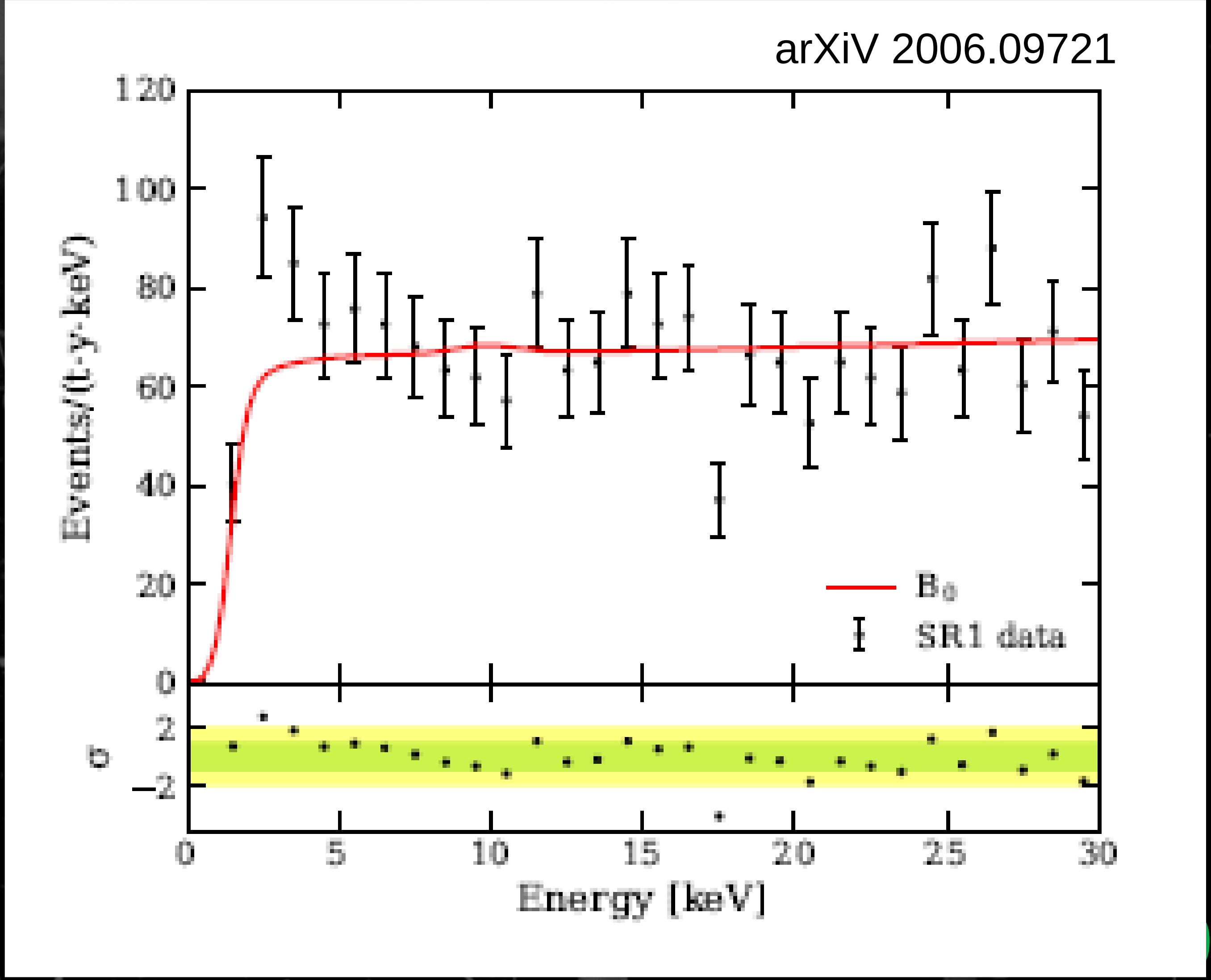
arXiv 2006.09721 (to appear in PRD)
https://web.bo.infn.it/xenon/sito_web_Bologna/docs/xenon1t_er_excess_20200617.pdf



⇐ for NR search
PRL 121, 111302 (2018)

⇩ for ER search

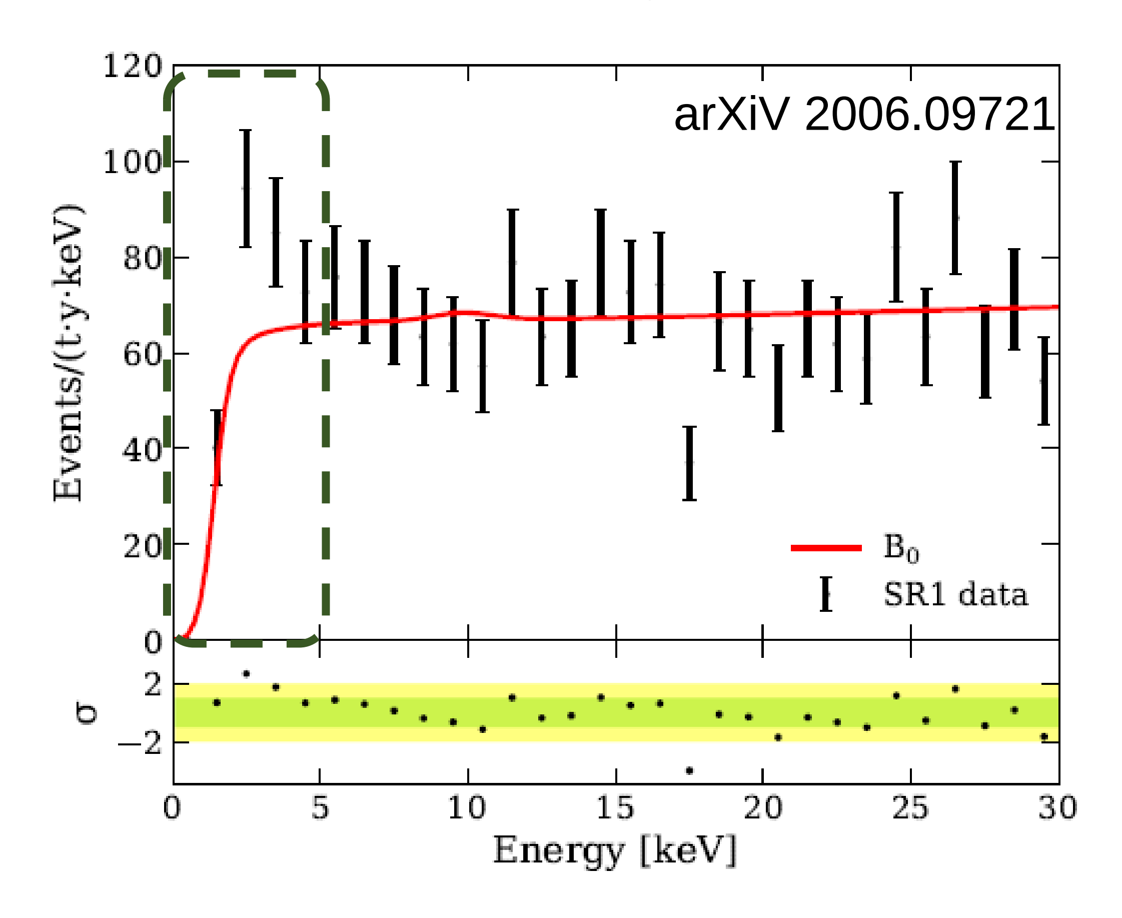




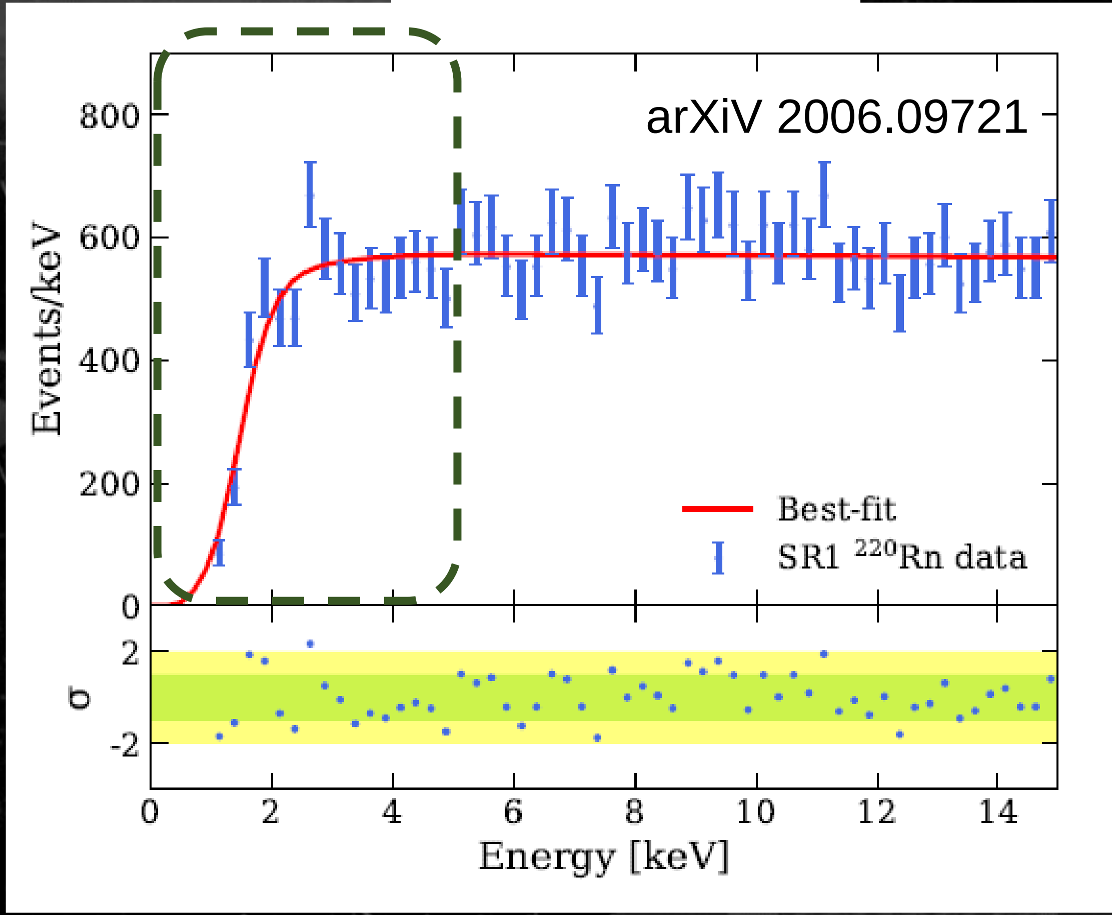
Kentaro Miuchi

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

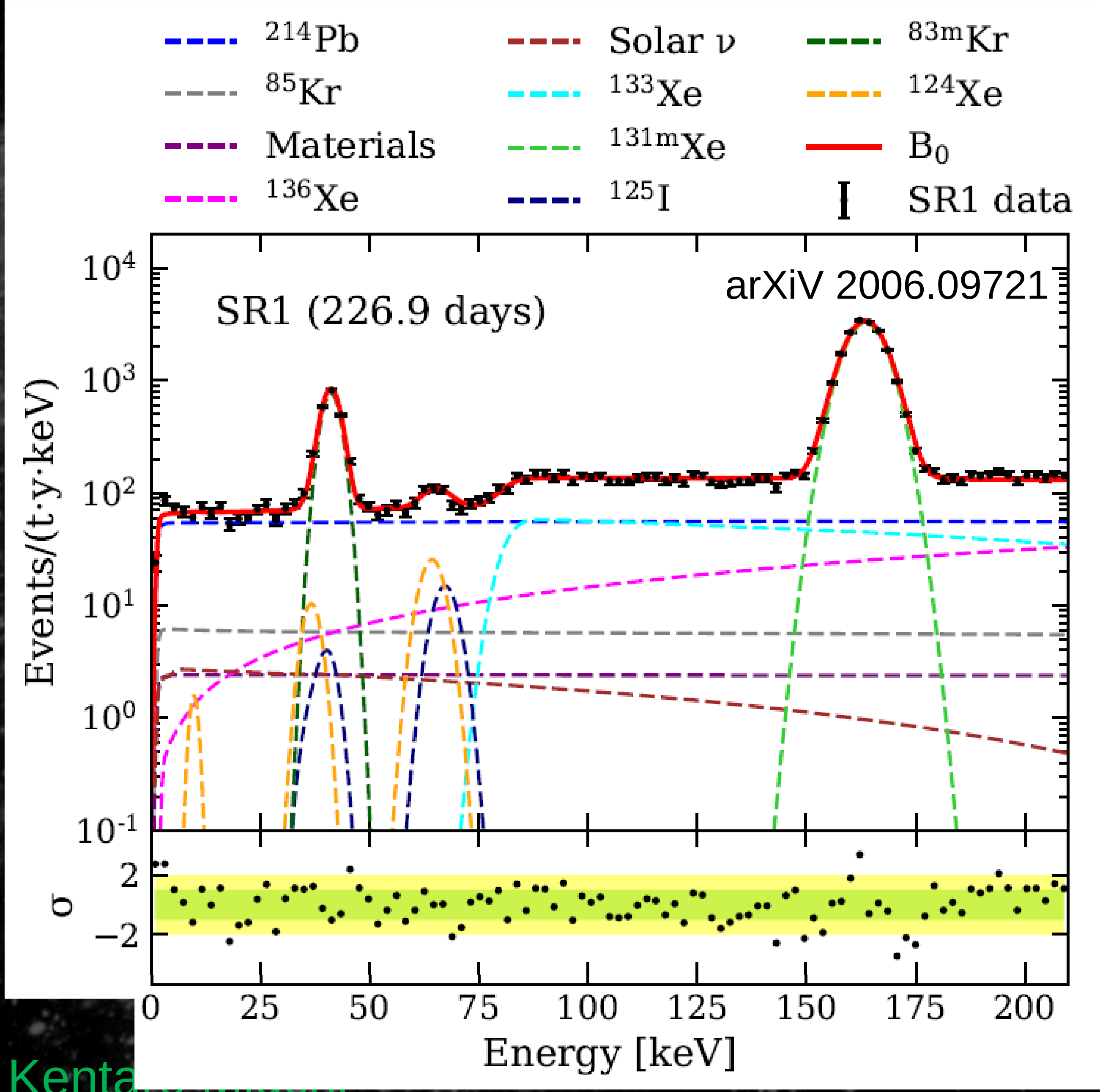
DM run

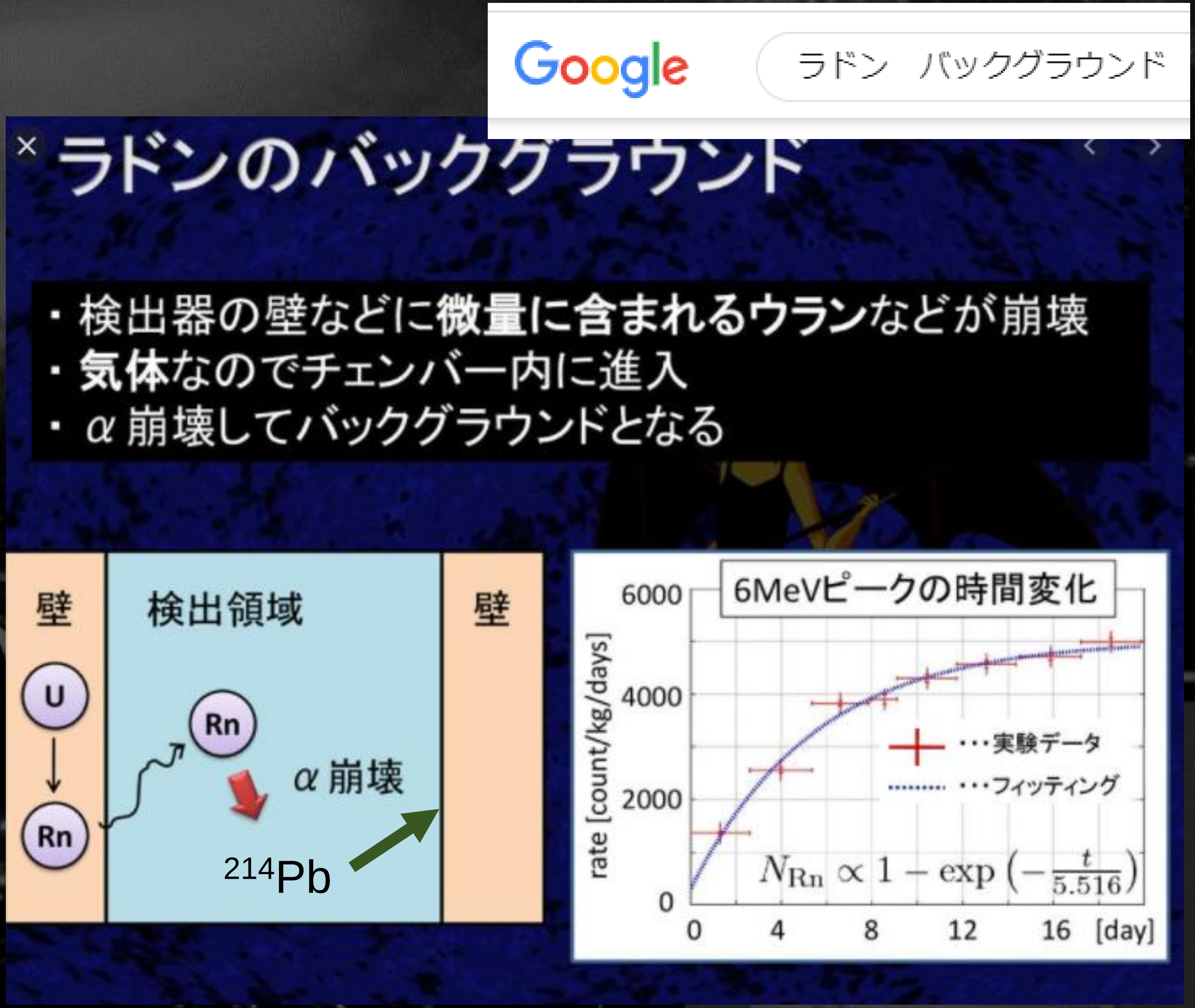


calibration

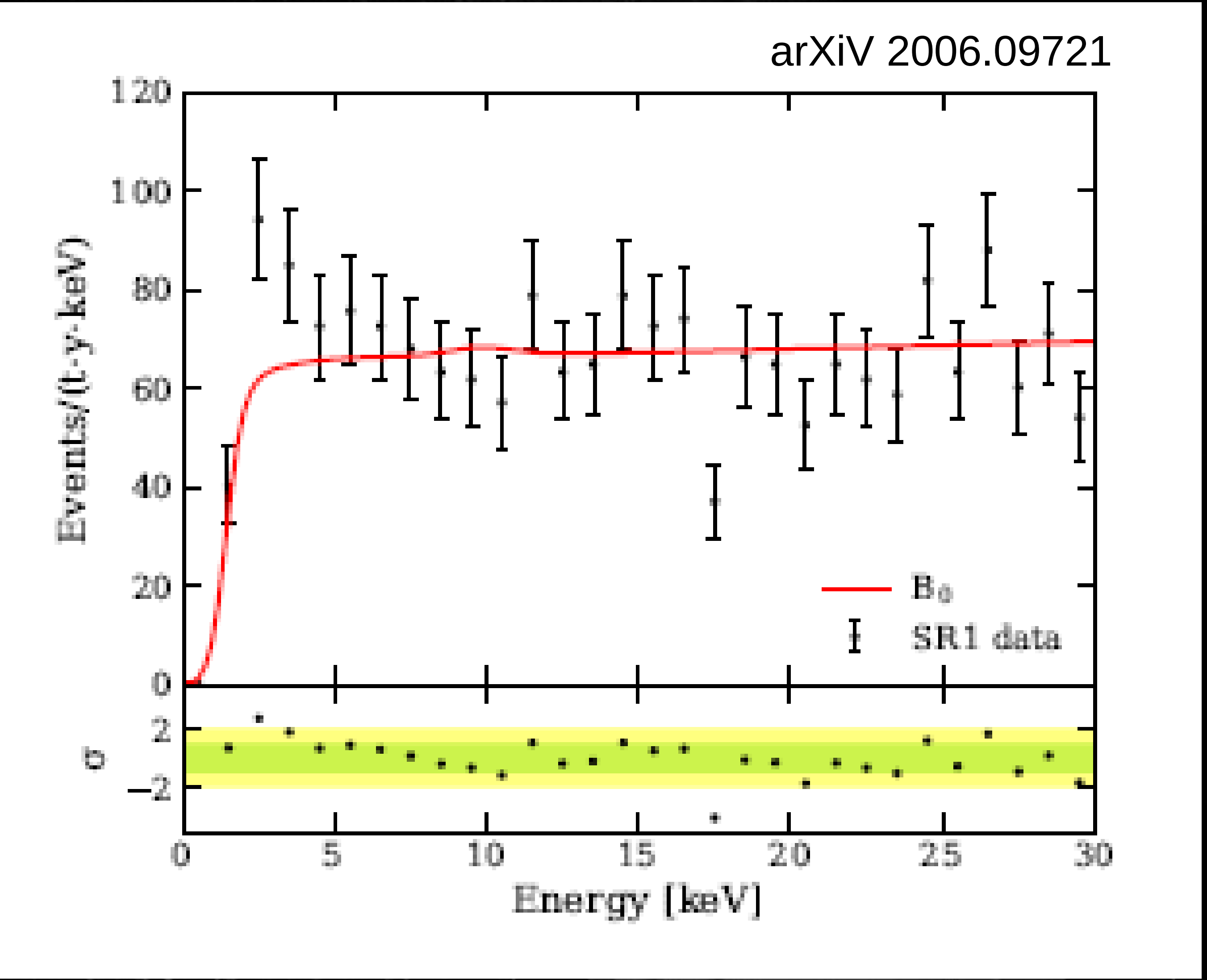


- Background
  - Radioactive isotopes (^{214}Pb: radon daughters)

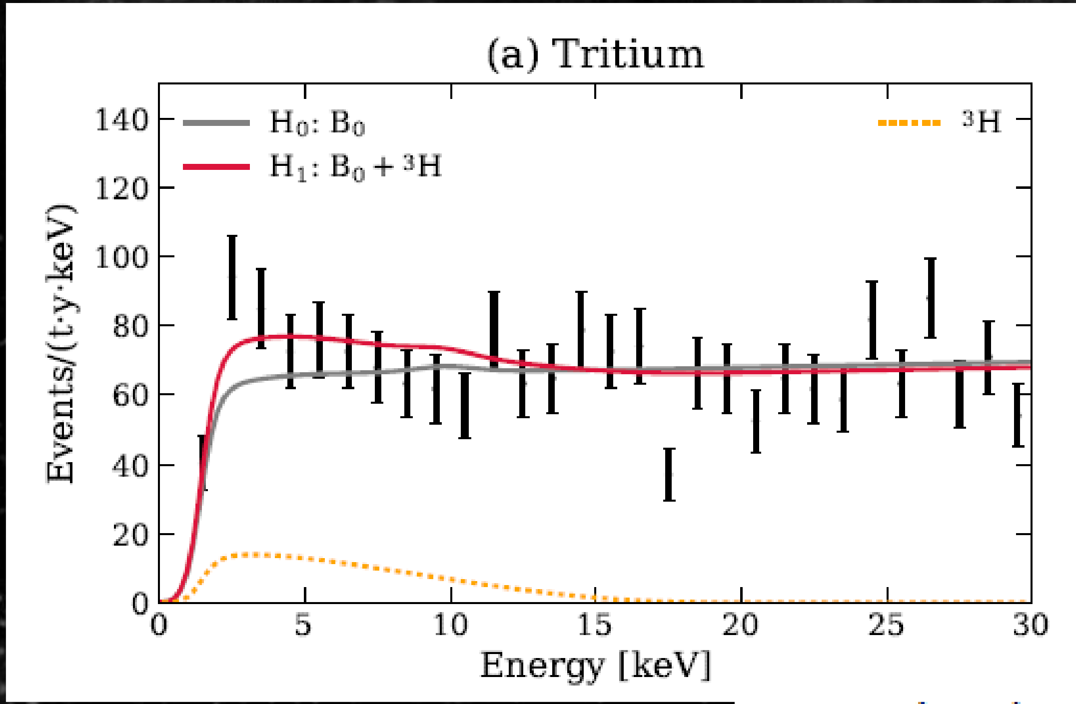




- Results
  - Excess between 1-7 keV
  - 285 events observed
  - 232 events expected (BG only)
  - 3.3 σ Poisson fluctuation



- Tritium?
  - 3.2σ
  - $^3H/Xe$ = (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



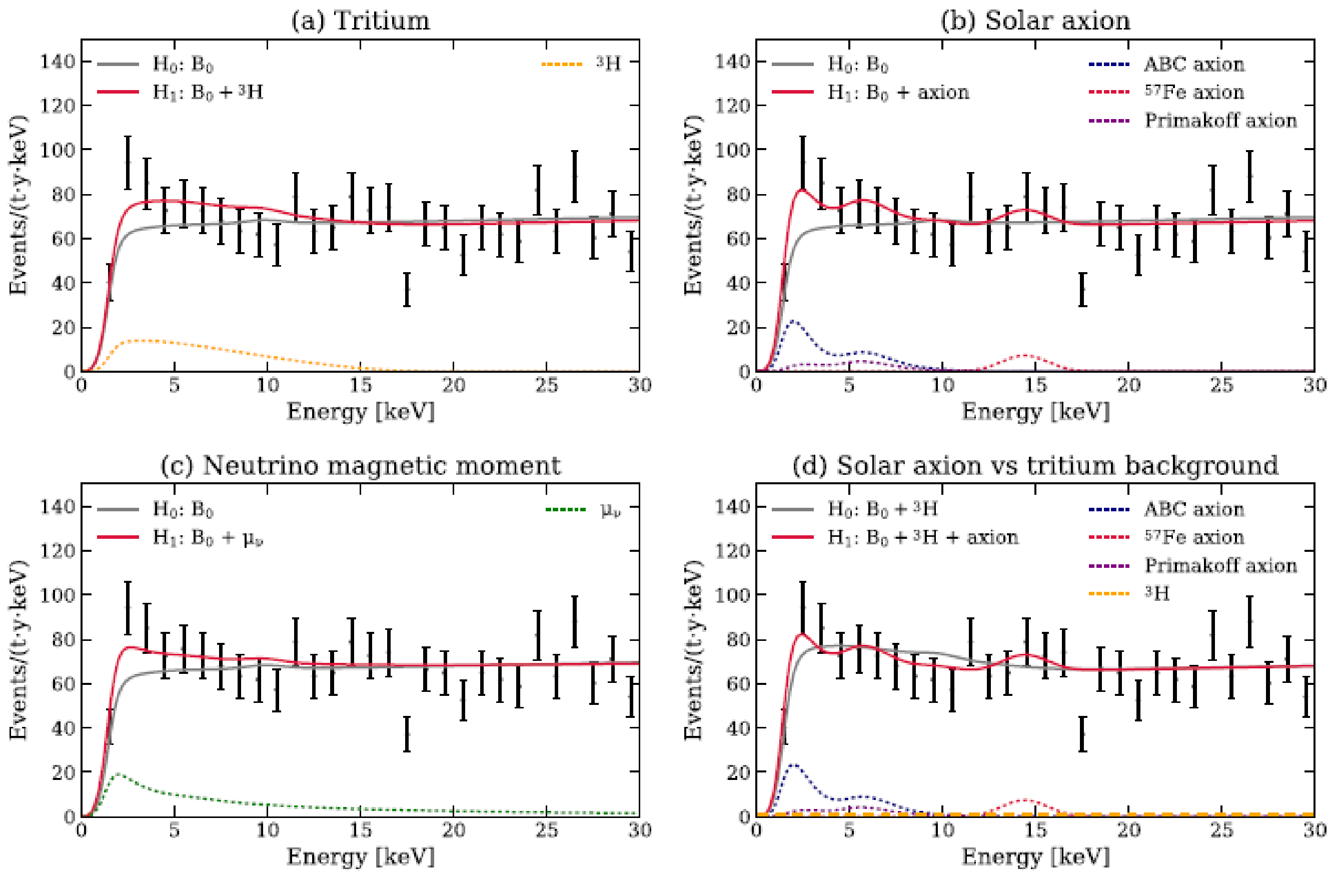
- 100 ppb level of H_2 can explain this amount.
- i. e. O_2 < 1ppb

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

- Compared the significance with other sources.

Summary

Tritium favored over background-only at **3.2σ**



Solar axion favored over background-only at **3.5σ**

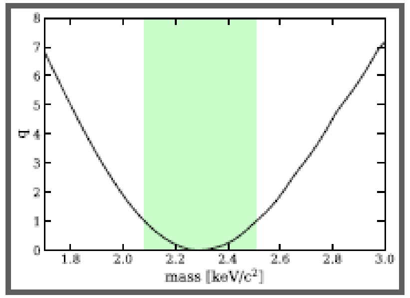
g_ae: 3.1e-12
g_ag: 8.1e-11
g_an: 7.6e-7

Neutrino magnetic moment (see backup slides) favored over background-only at **3.2σ**

μ_v: 2.3e-11

Axion + ^{3}H favored **over ^{3}H** hypothesis **at 2.1σ**

Monoenergetic peak at 2.3 +/- 0.2 keV favored over background-only at **3.0σ (global)**



- XENONnT

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

2020年9月8日

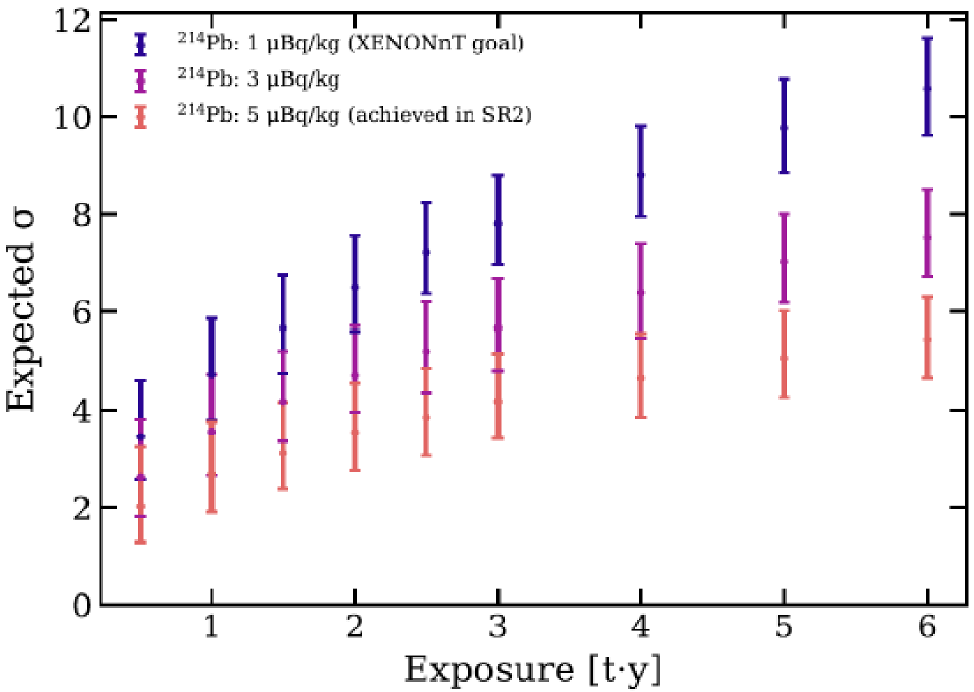
於：オンライン

XENON NT EXPERIMENT

Columbia University
JSPS Postdoctoral research fellow

Masatoshi Kobayashi

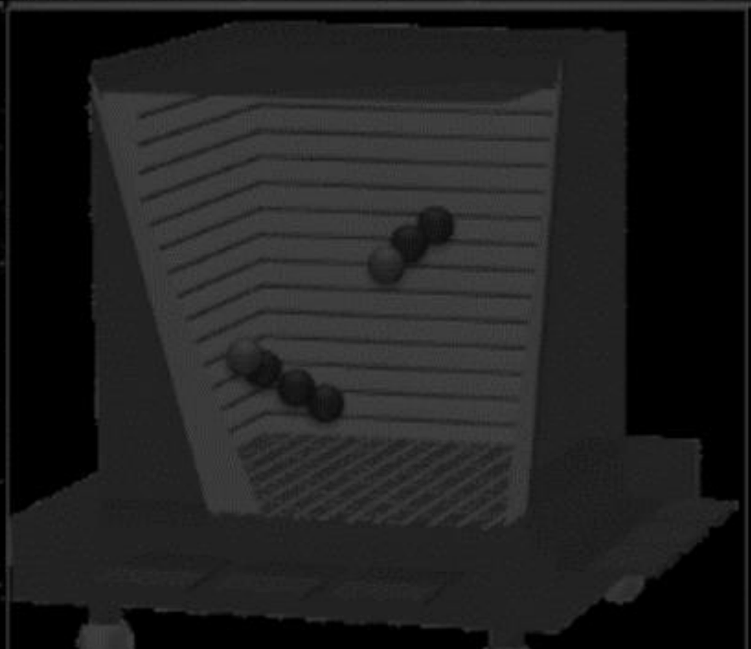
EXPECTED SENSITIVITY: TRITIUM VS ER SIGNAL (AXION) ?



- 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

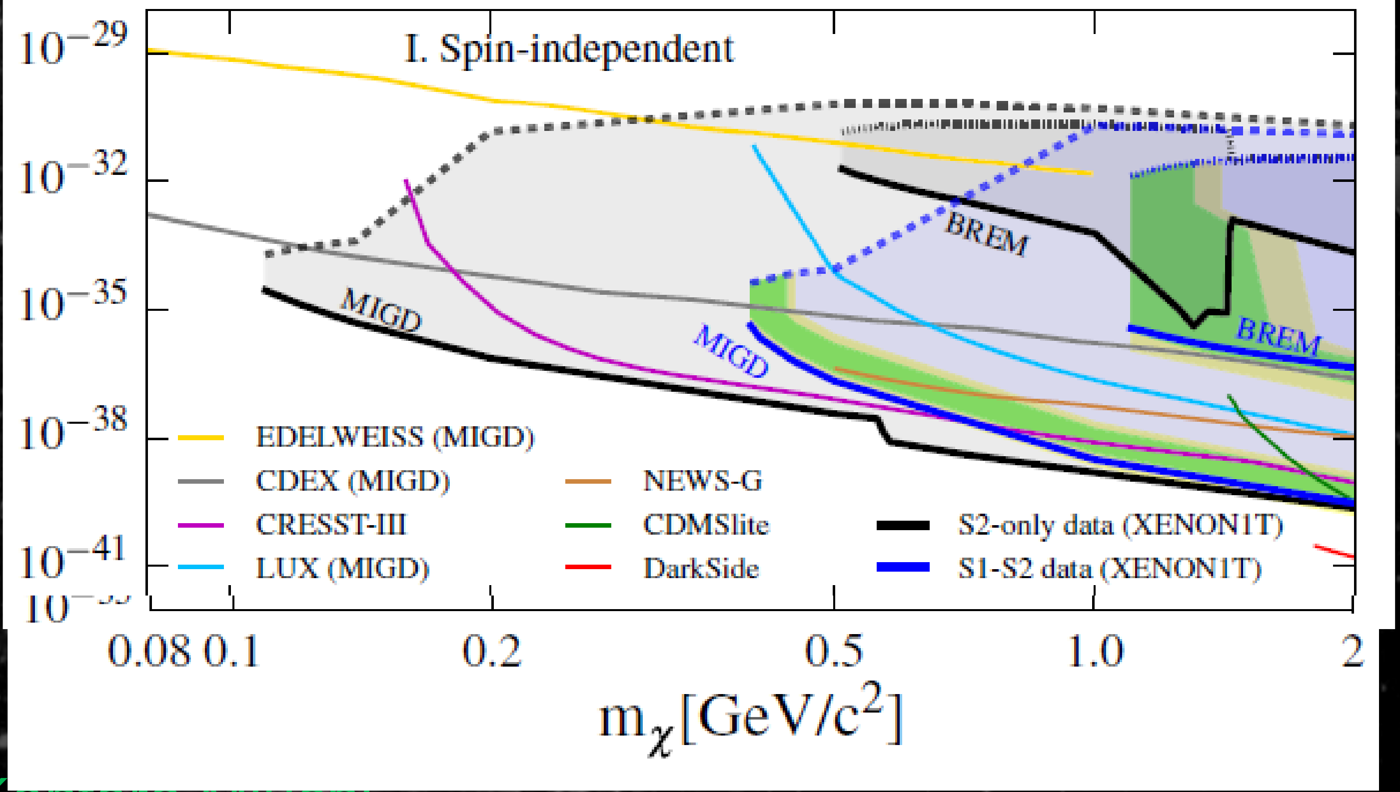
2. MIGDAL

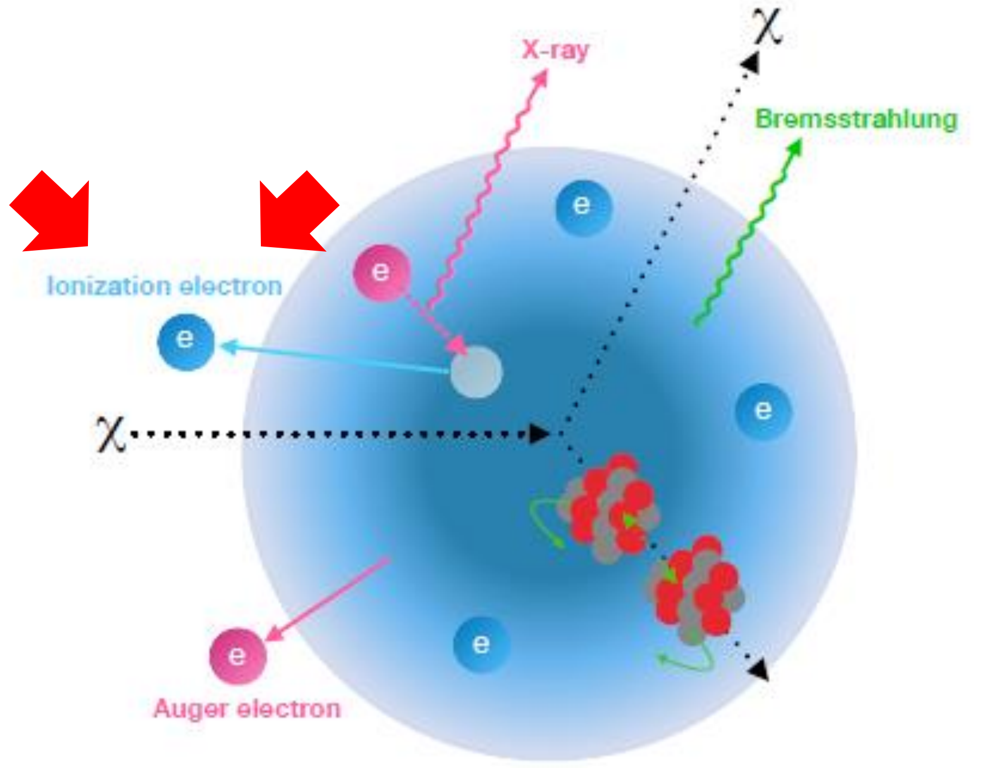


- And still lower: MIGDAL
  - Low mass search with "MIGDAL effect"
  - Ordinary nuclear recoil : ionization along the track
  - Low energy recoil : ionization efficiency is low
    ⇒ cannot be detected
  - Very rare case electrons are emitted

PRL123, 241803 (2019)

PRL123, 241803 (2019)





PRL123, 241803 (2019)

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

- MIGDAL effect ?
  - A. B. Migdal J. Phys. USSR 4(1941)449
    - calculated (predicted)
    - nuclear recoil ⇒ excitation / ionization
    - caused by a sudden change of the nuclear velocity
    - small probability
  - Ibe et. al. 2018 JHEP03(2018)194
    - reformulated
      - energy momentum conservation
      - probability conservation
    - can be used for DM search

Migdal effect in dark matter direct detection experiments

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

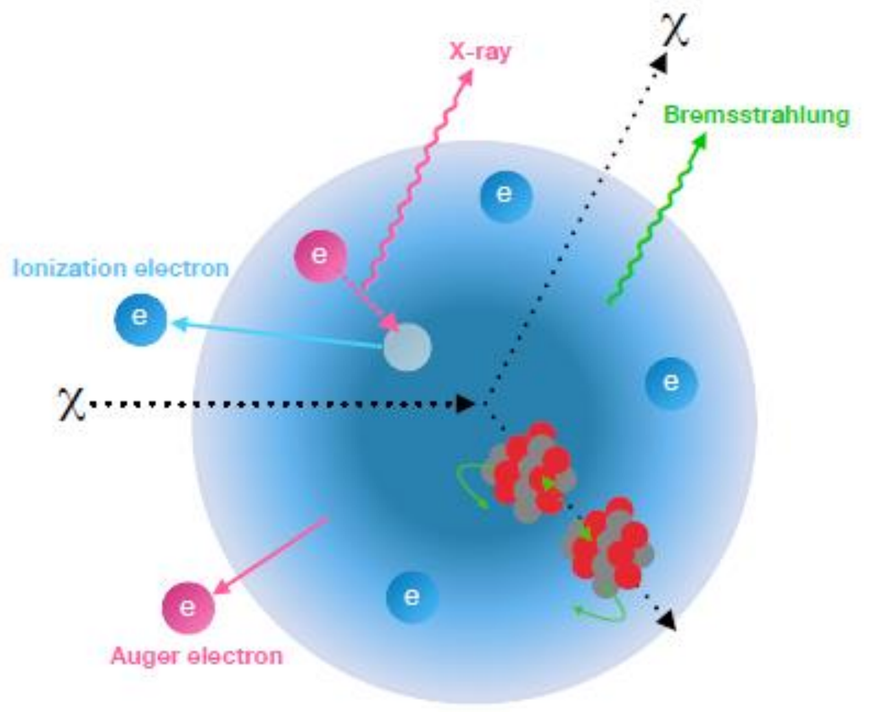
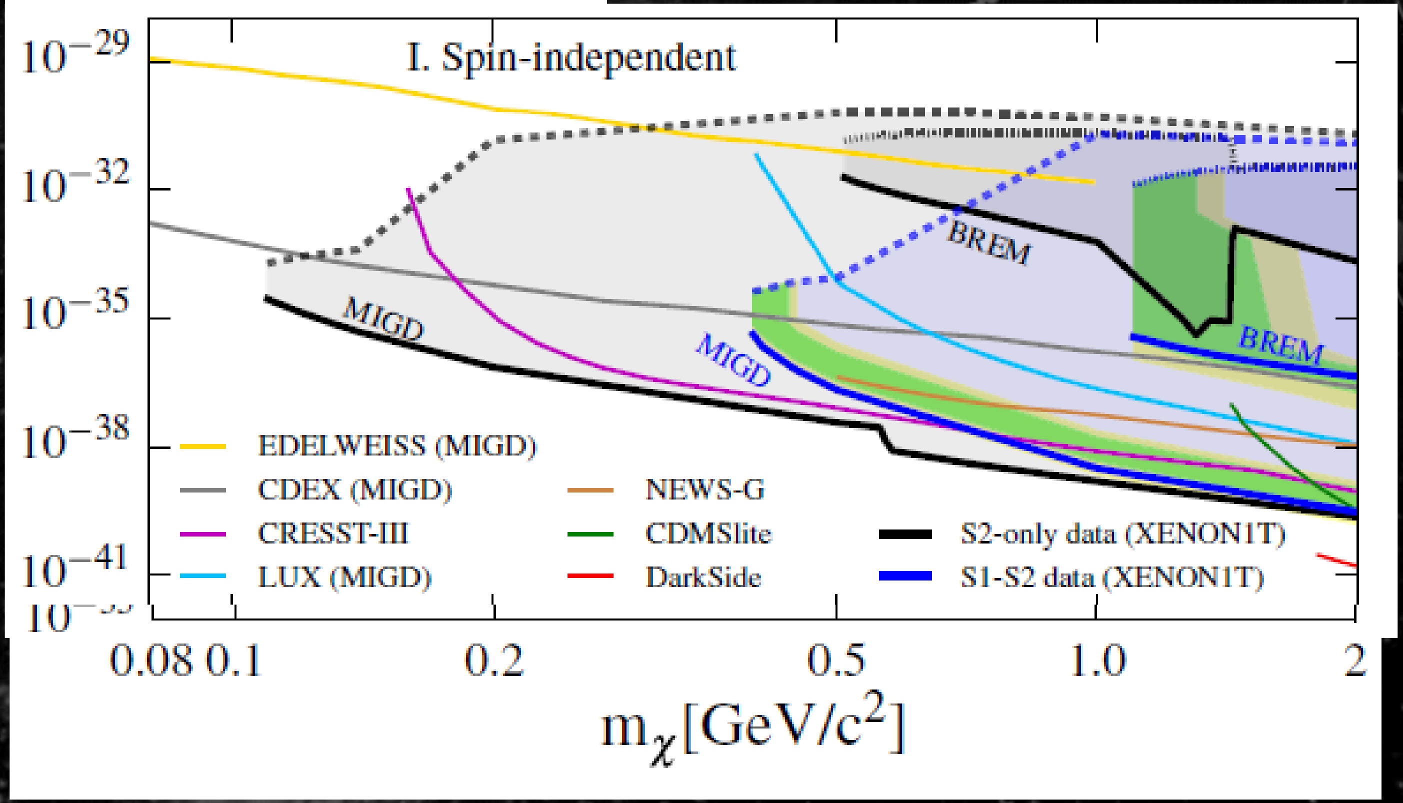


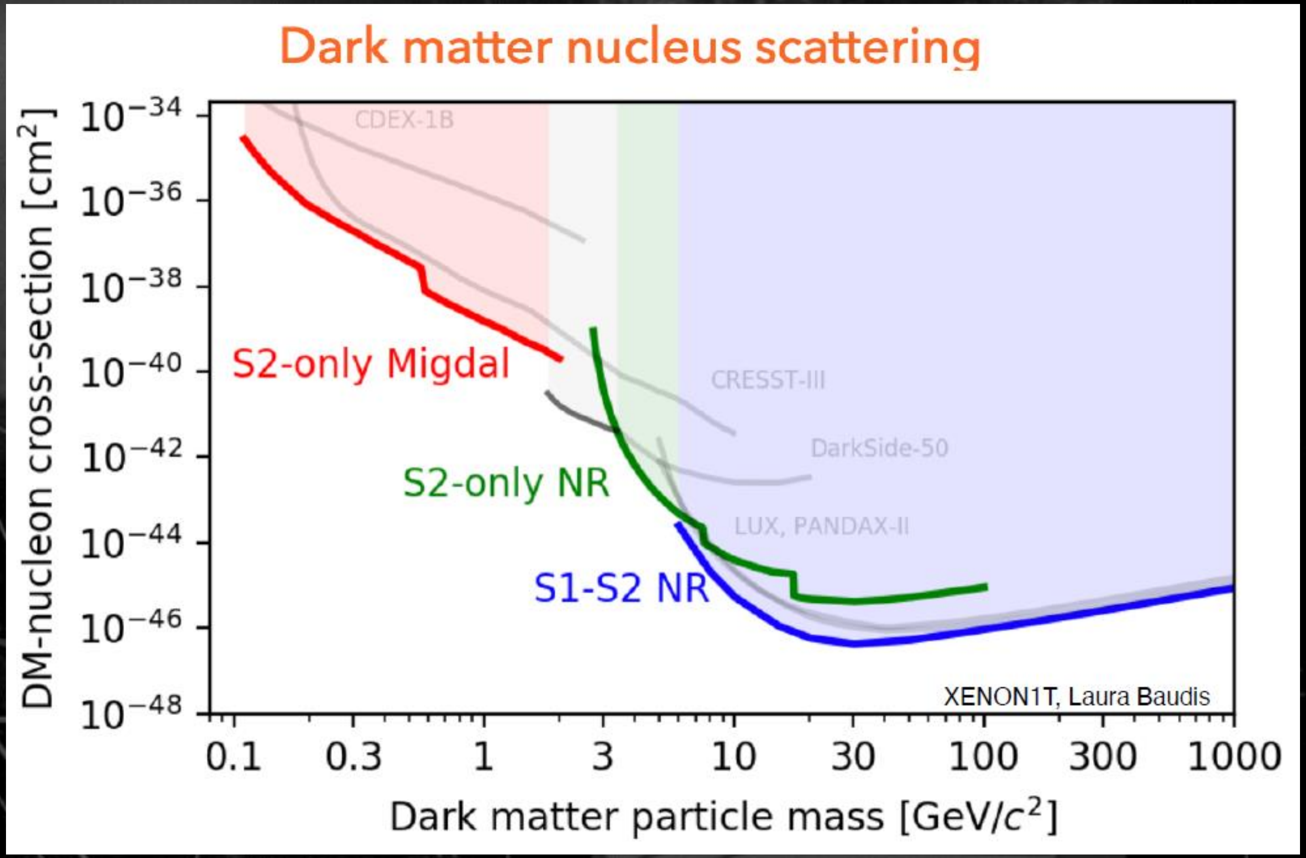
FIG. 1. Illustration of the ER signal production from BREM (green) and Migdal processes (pink) after elastic scattering between DM (χ) and a xenon nucleus.

• Low mass WIMP search by MIGDAL effect

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

PRL123, 241803 (2019)

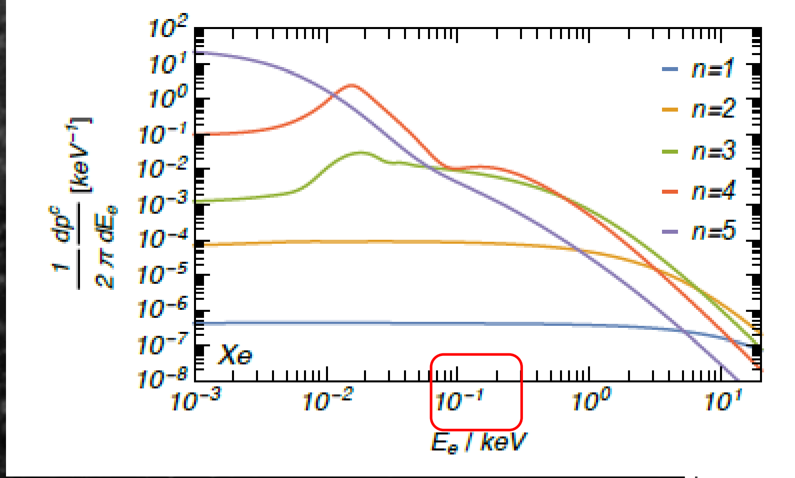




Standard WIMP detector down to 100MeV
CAVEAT: Migdal effect itself is yet to be observed.
loose 3orders of magnitude if we use Bremsstrahlung only.

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

JHEP03 (2018) 194



JHEP03 (2018) 194

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

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

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

JHEP03 (2018) 194

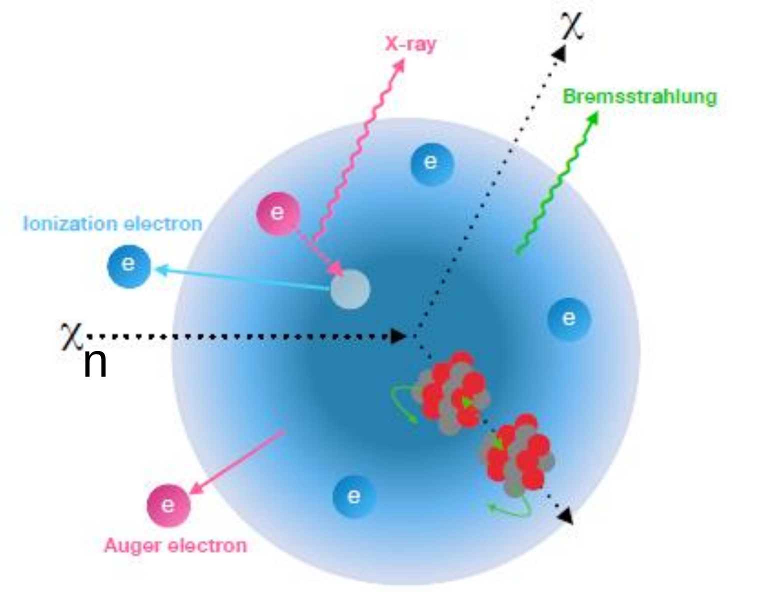


FIG. 1. Illustration of the ER signal production from BREM (green) and Migdal processes (pink) after elastic scattering between DM (χ) and a xenon nucleus.

• Migdal 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]

Prog. Theor. Exp. Phys. 2021, 013C01 (14 pages)
DOI: 10.1093/ptep/ptaa162

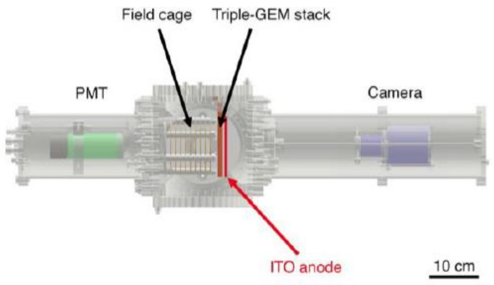
- CERN-UK (in preparation)
  - Straightforward method
  - Nuclear track +electron track with gaseous detector
  - Demonstrations OK for nuclear recoil / electron recoil each.
  - Hard to discriminate from standard nuclear recoil

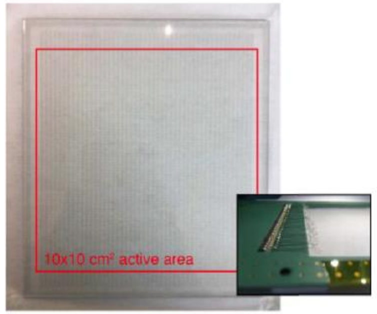
Observation of the Migdal effect from nuclear scattering using a low pressure Optical-TPC

Pawel Majewski
Rutherford Appleton Laboratory

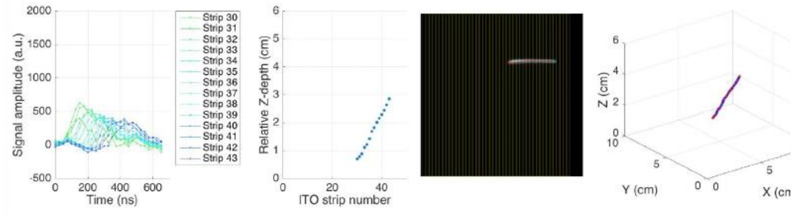
RD51 mini-week, CERN, 10-15 Jan 2020

O-TPC at CERN (from F. Brunbauer)



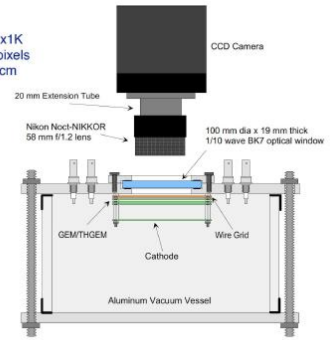


3D track reconstruction in Ar/CF4 (80/20) at 100 Torr



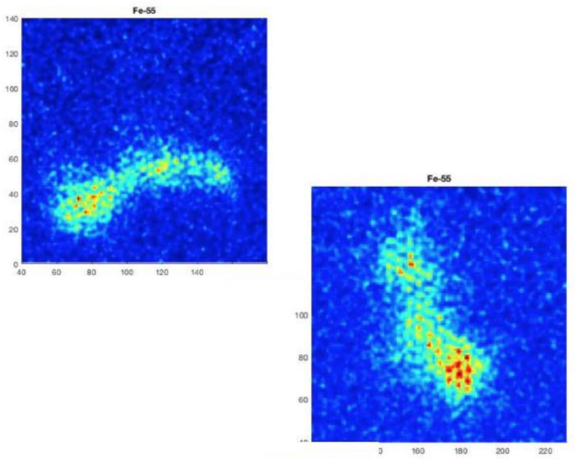
O-TPC at UNM (from D. Loomba) 2D reconstruction

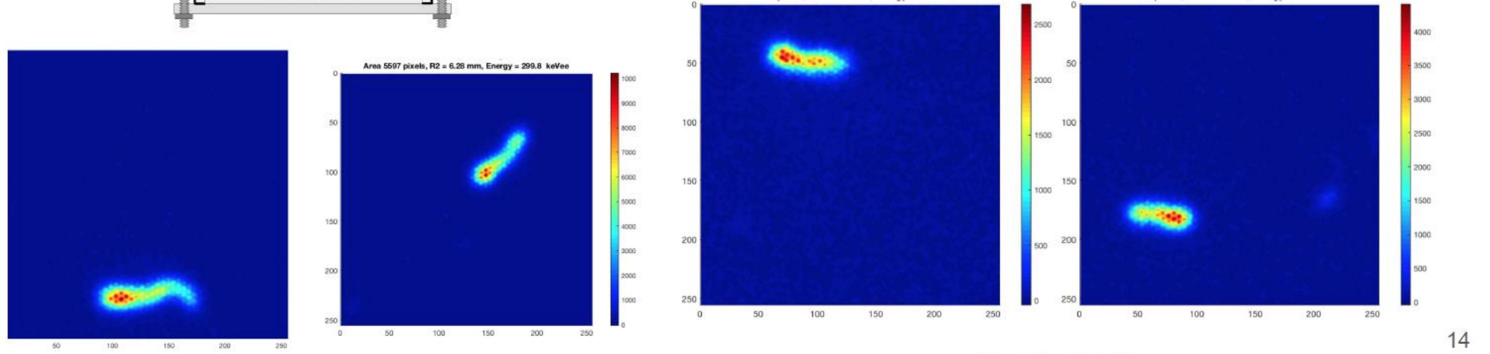
UNM setup:
- Finger Lakes CCD with 1Kx1K E2V chip, with 13x13 μm² pixels
- lens to imaging plane ~20 cm



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

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





E ~ 270-300 keVee

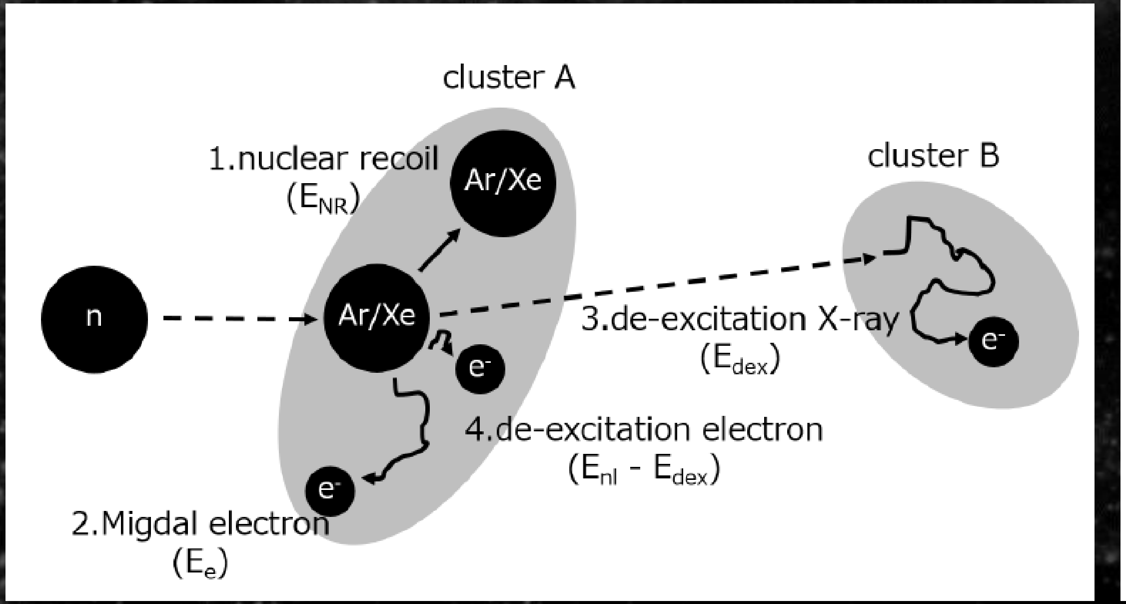
E ~ 100-120 keVee

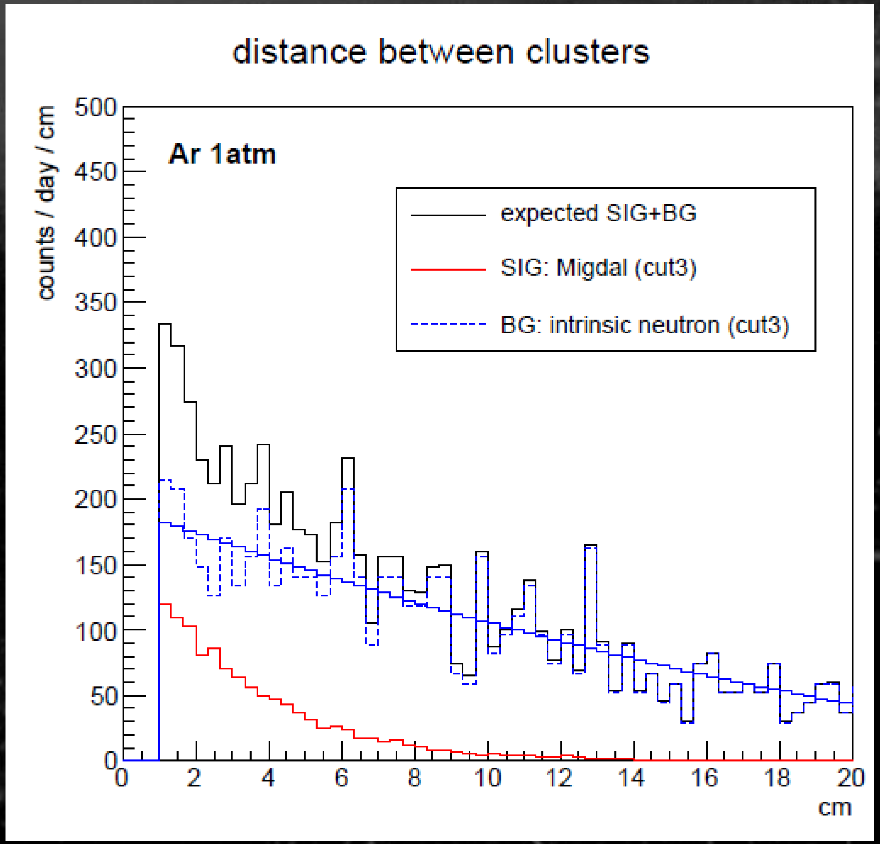
- Our approach (proposal)
  - Detect characteristic signal "two-cluster" events
  - Help to reduce huge background

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]

PTEP(2020)ptaa162





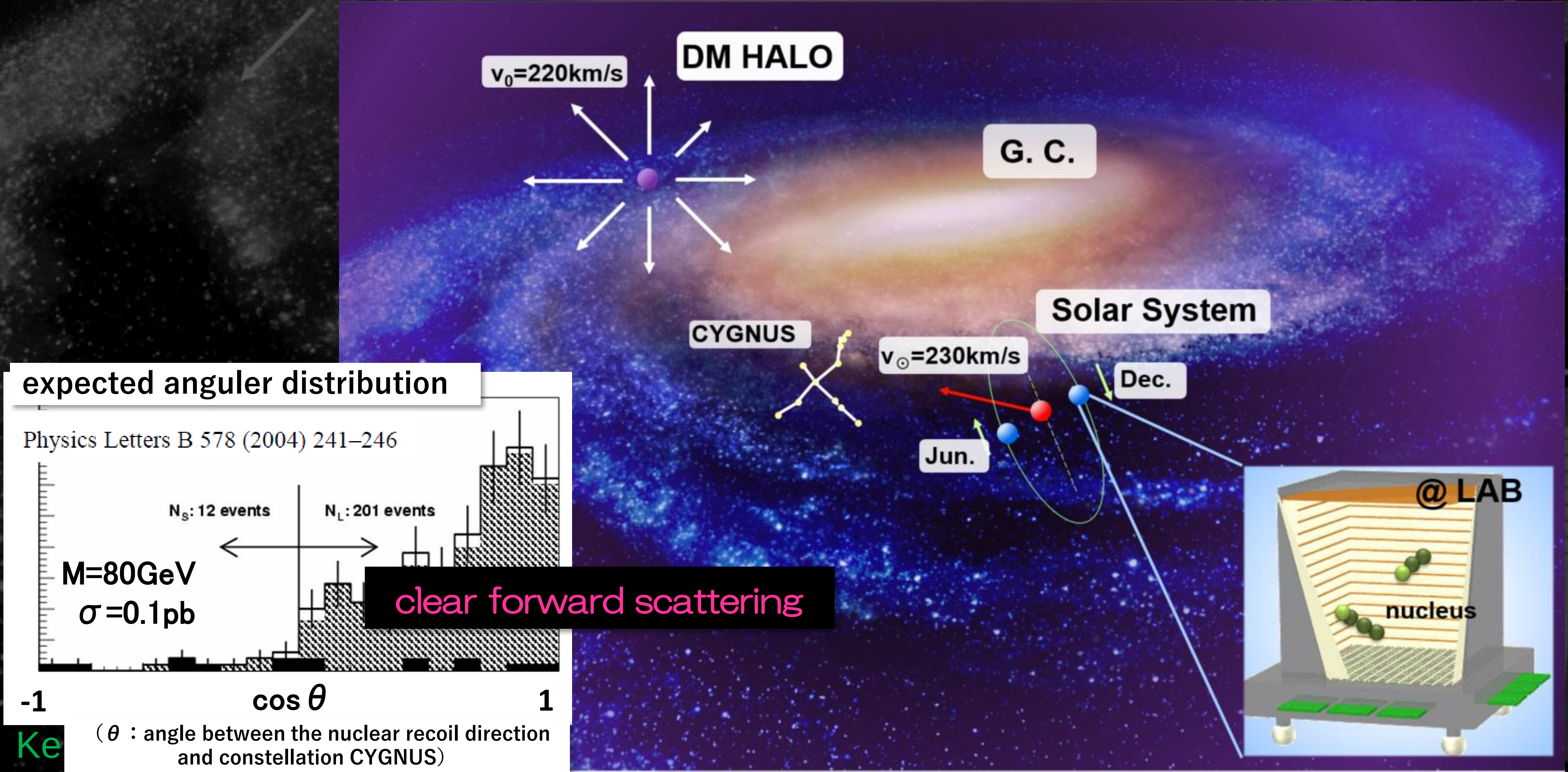
any "MIGDAL anomaly" prediction?

Topics

3. Directionality

• Directional search：concept “CYGNUS”

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

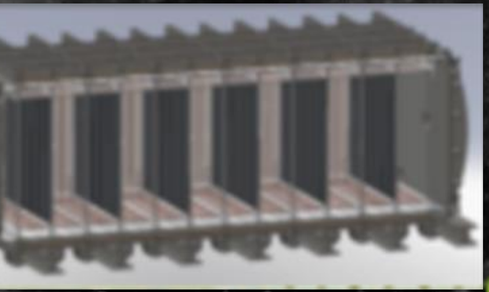


World-wide CYGNUS

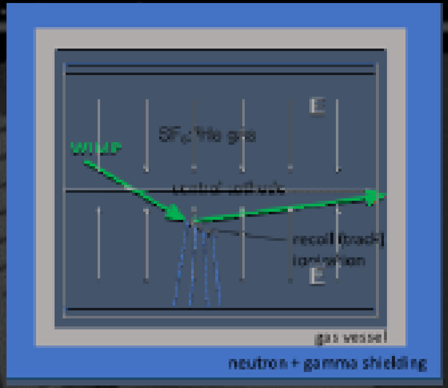
2020 J. Phys.: Conf. Ser. 1468 012044

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

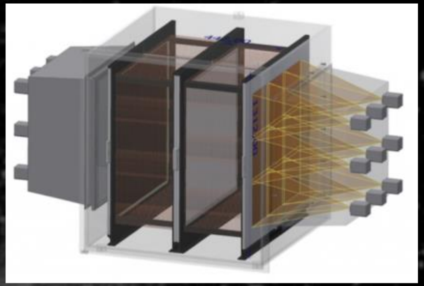
CYGNUS-10
Boulby, UK
$10 m^3$ $He:SF_6$
GEM + wire readout



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

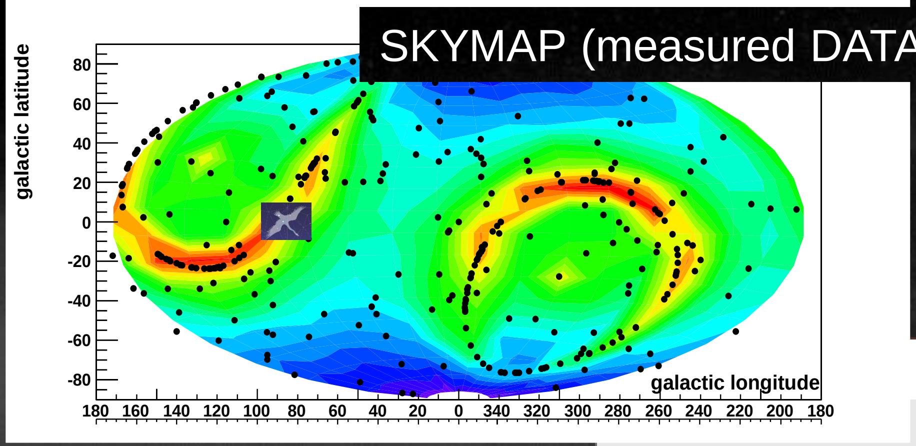
  - Proposal

    PLB 578 (2004) 241
  - First directional search

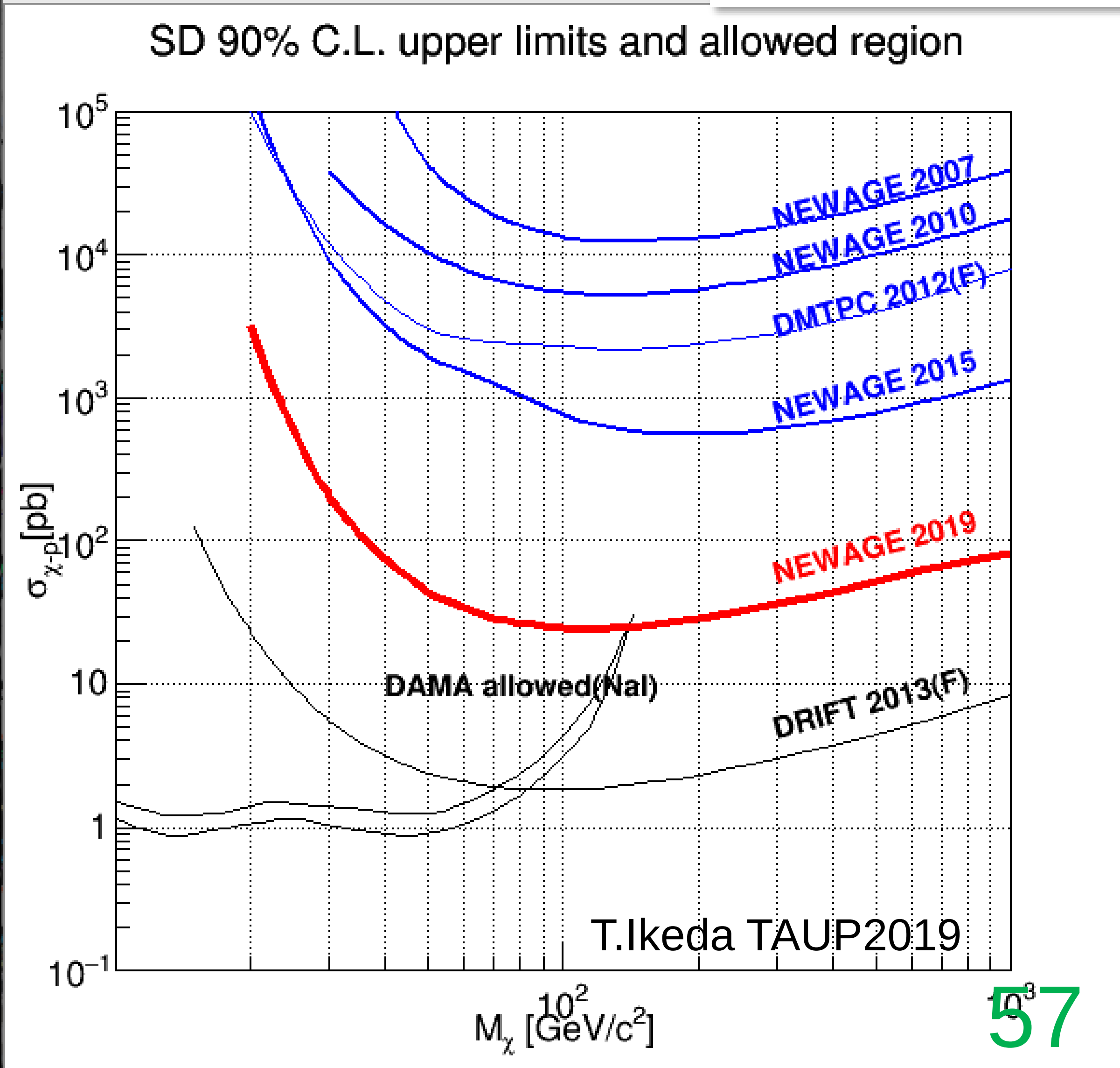
    PLB 654 (2007) 58
  - Underground measurements

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

SKYMAP (measured DATA)



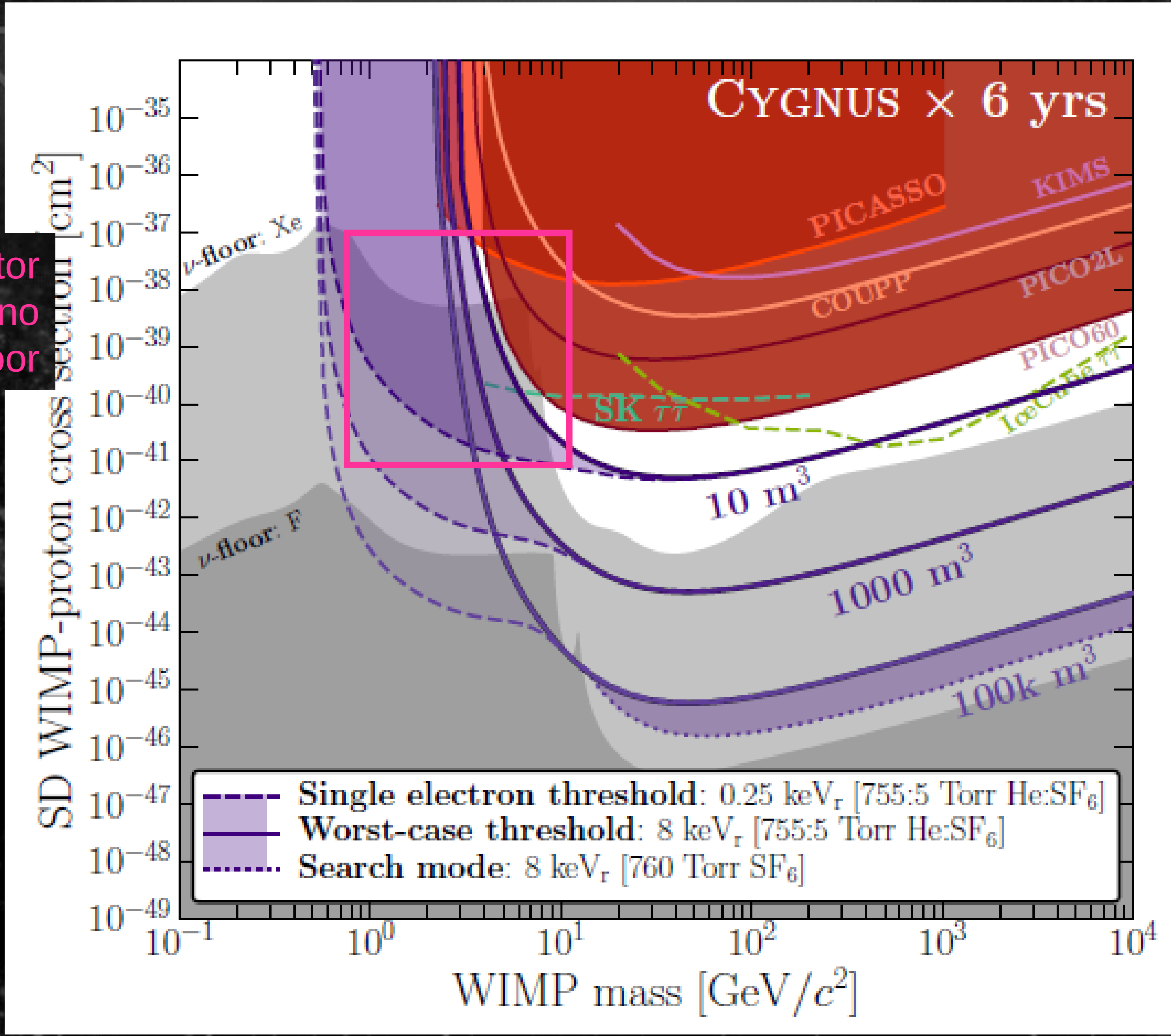
NEWAGE limits



arXiv 2008.12587

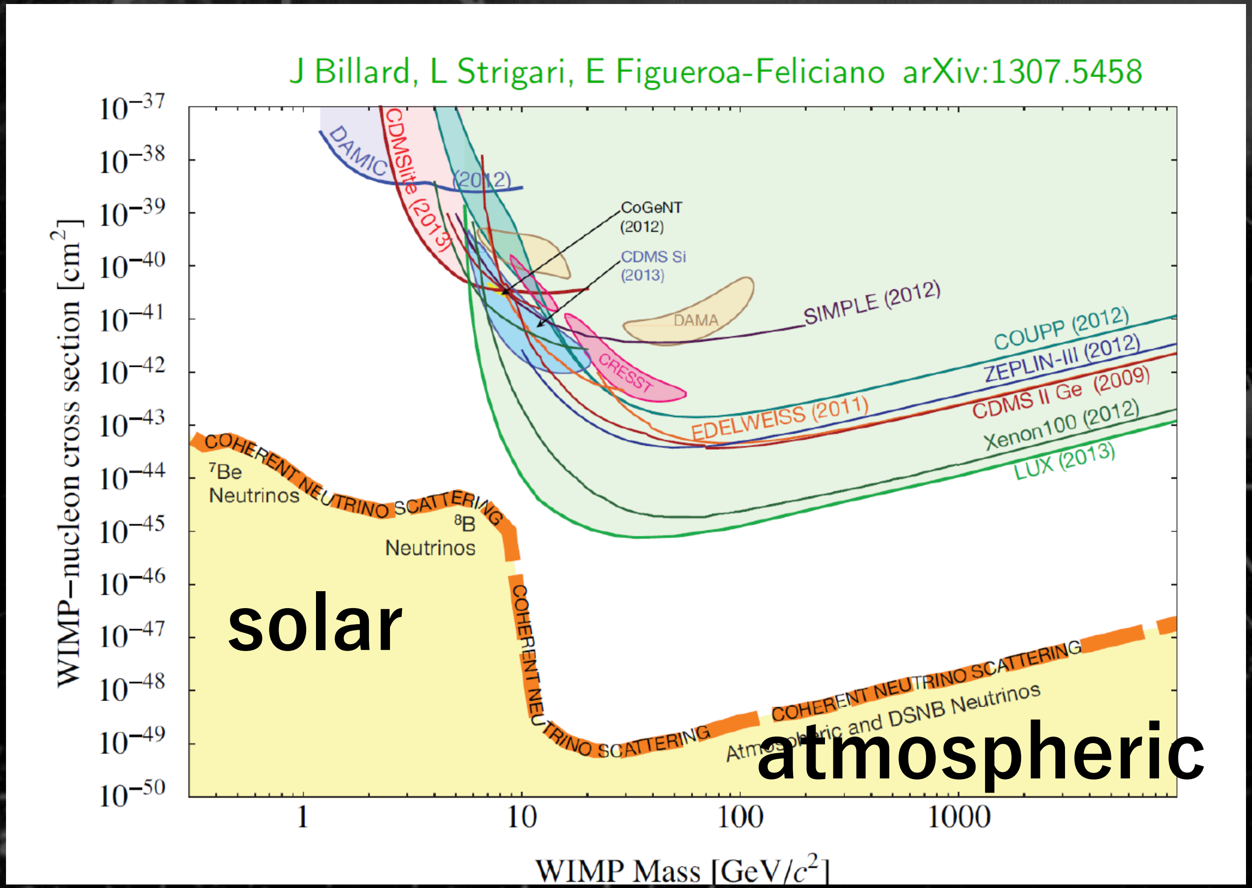
- Realistic simulation (strip readout)

even 10m³ detector can start exploring Xe neutrino floor

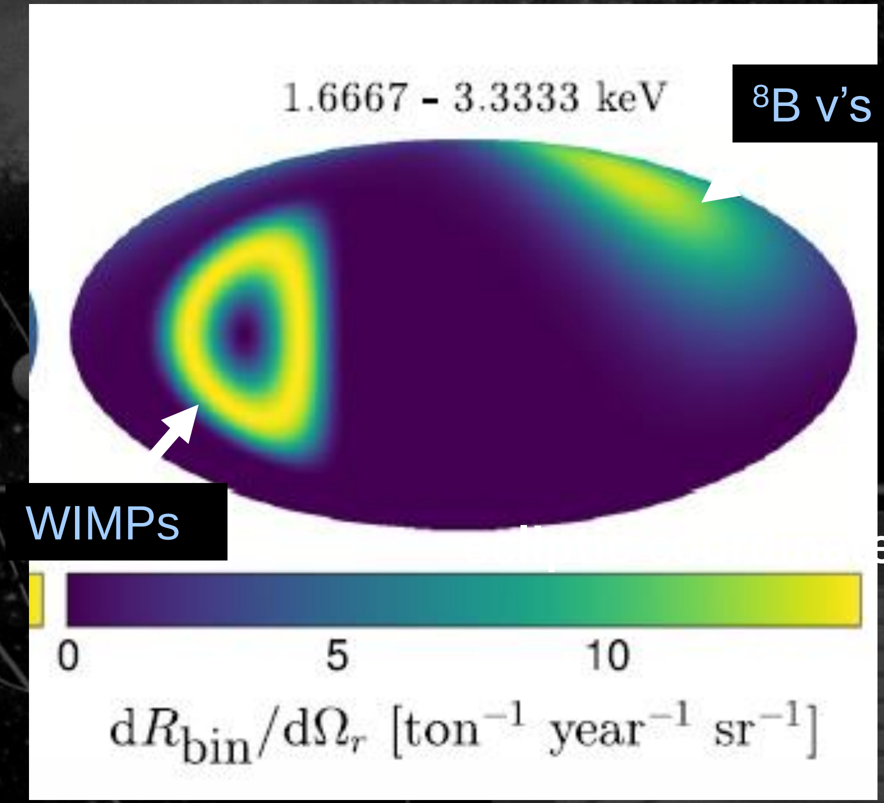


Toward discovery

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

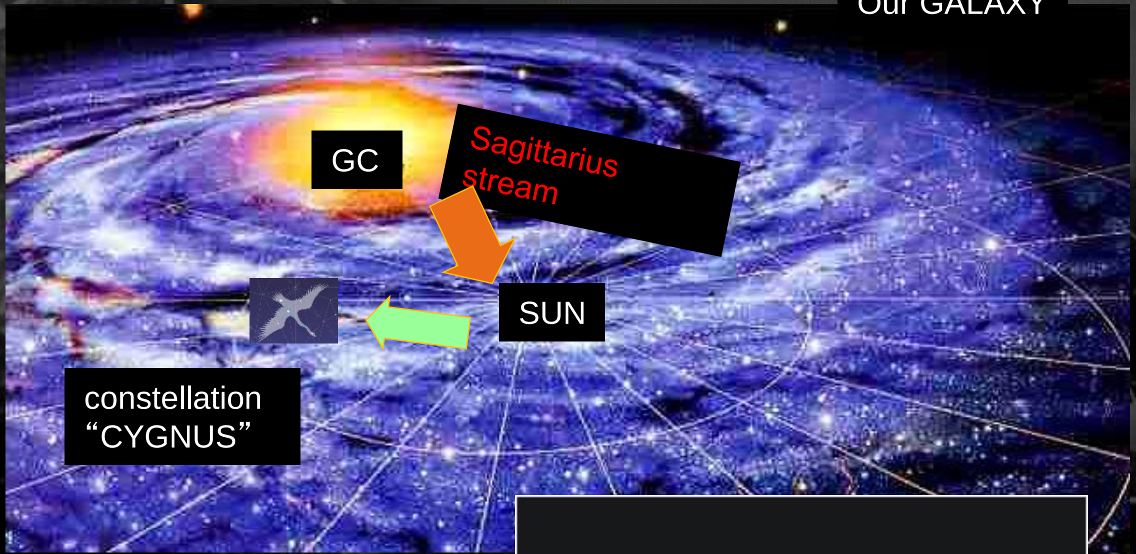


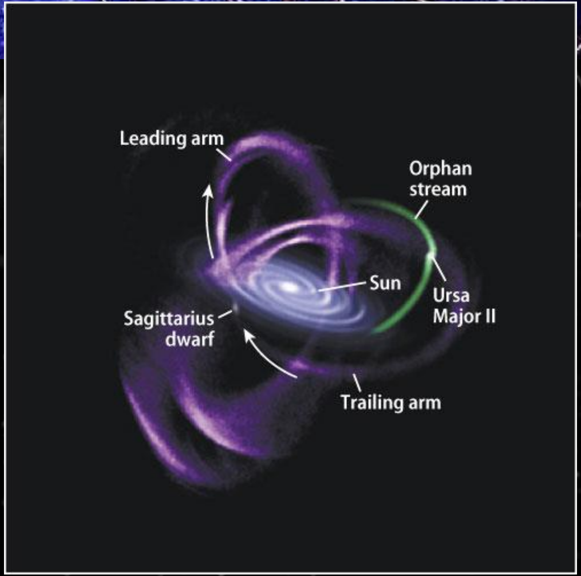
F. Mayet et al. / Physics Reports 627 (2016) 1–49



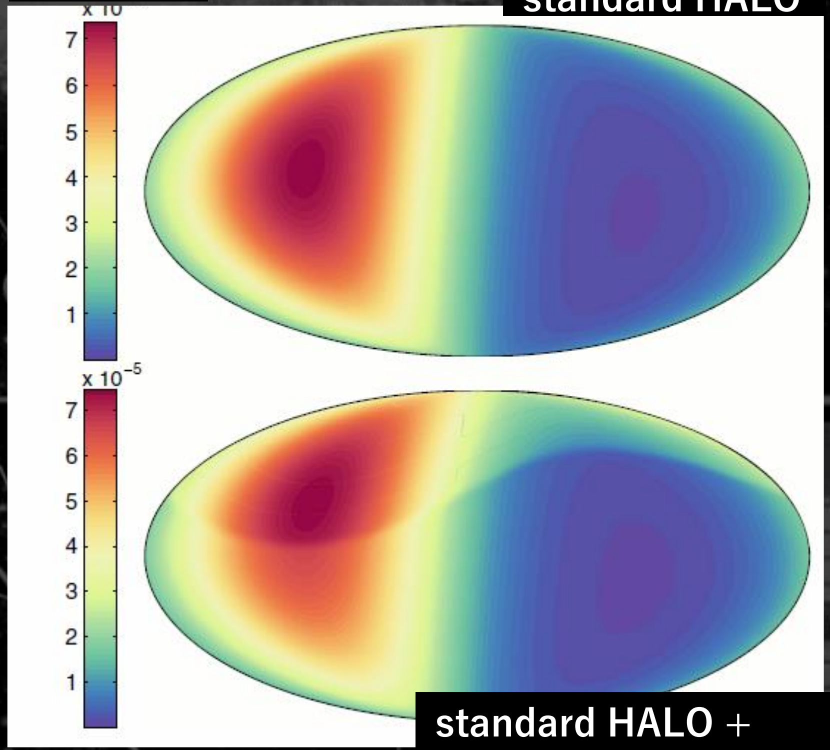
- distinguishable

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





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



galactic coordinate

- **streams, debris…**

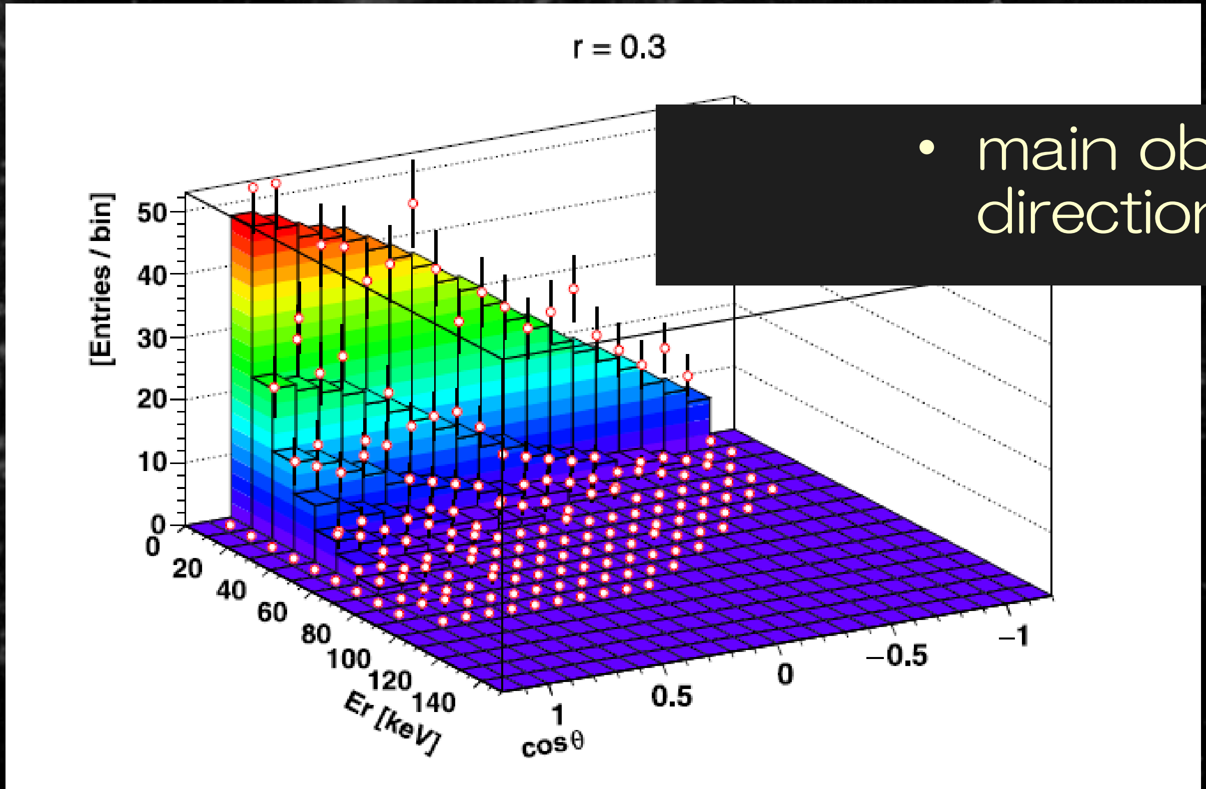
- Halo model test
  - isotropic (1-r) + anisotropic(r) DM HALO model indicated by n-body simulation (r~0.3)

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]

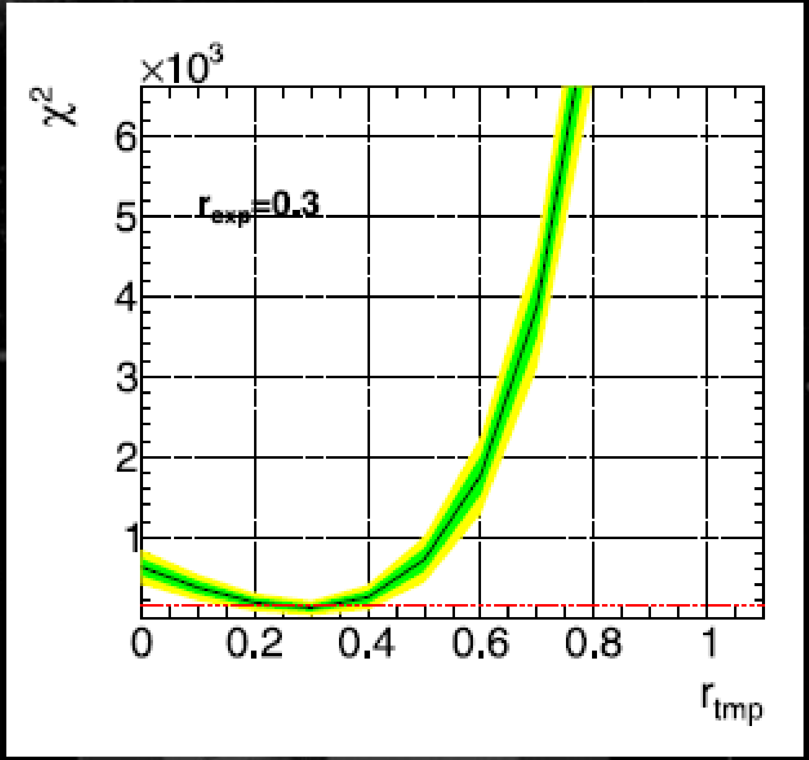
[a] Faculty of Fundamental Science, National Institute of Technology, Niihama College, Niihama, Ehime 792-8580, Japan
[b] Faculty of Science, Okayama University of Science, Okayama, Okayama 700-0005, Japan
[c] Department of Physics, Kobe University, Kobe, Hyogo 657-8501, Japan
[d] Department of Physics, 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

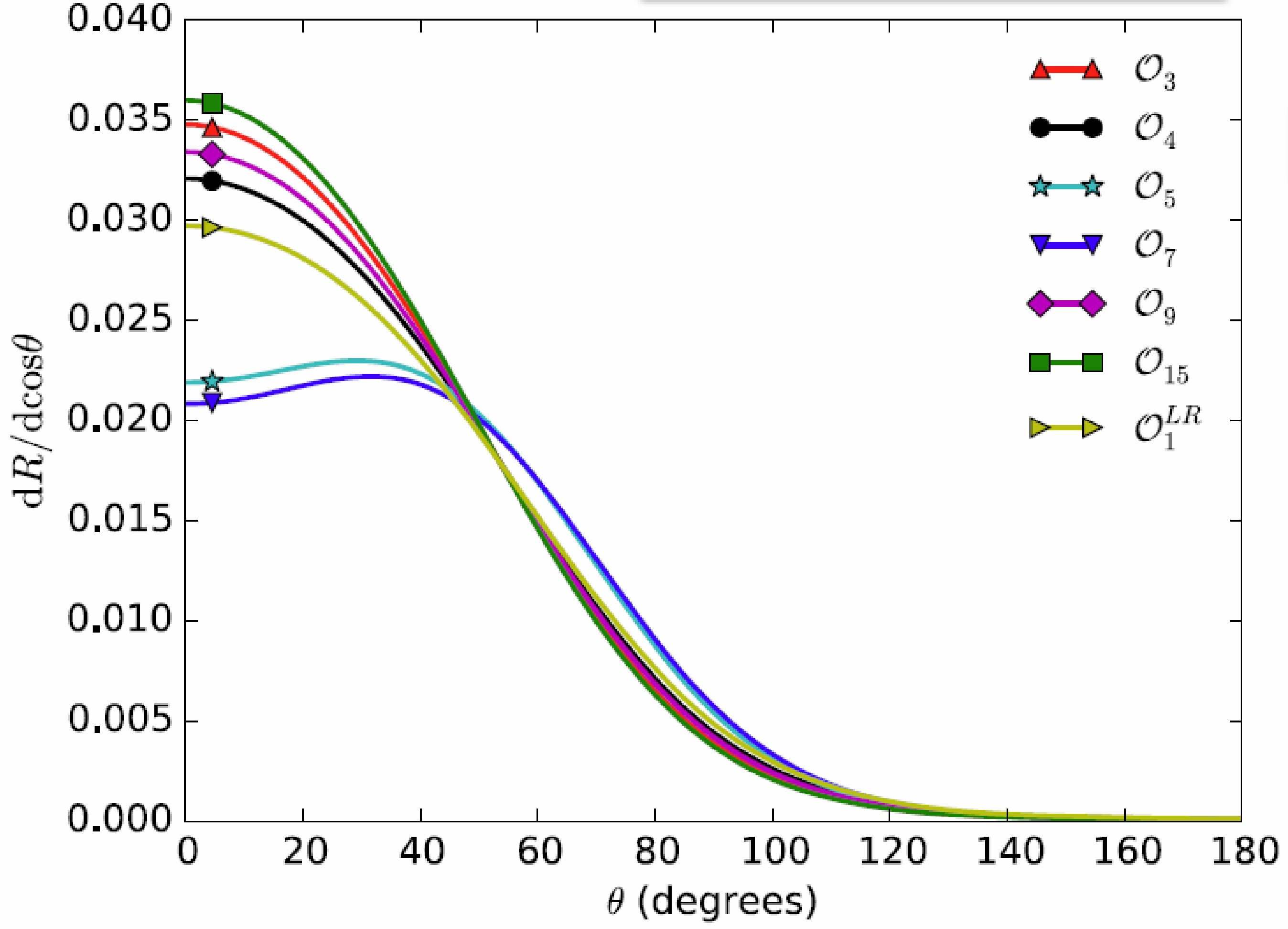
- scan r value



- 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)

最近の話題　まとめ

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

Thank you!