Direct Dark matter search in ICRR

1st ICRR young researchers' workshop 2020

2020/11/13

A. Takeda for direct dark matter search group

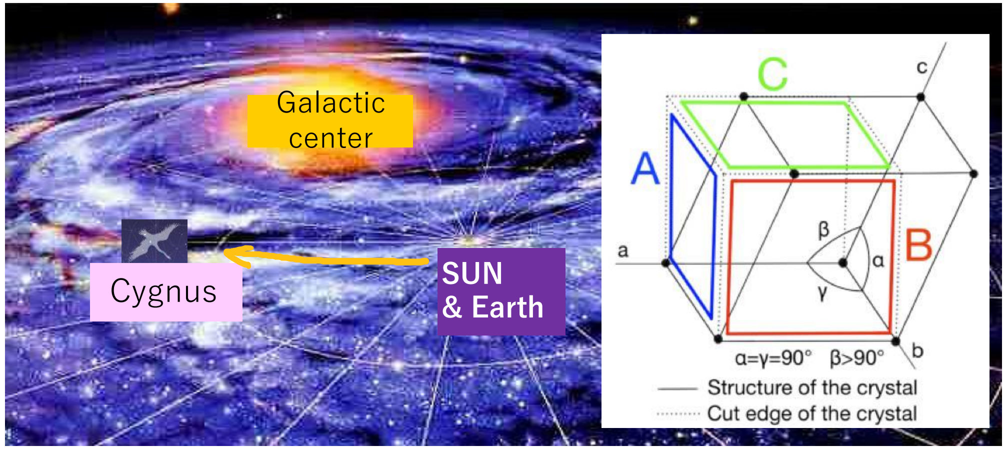
Contents

There are 3 projects related to direct dark matter searches in ICRR

1. **XMASS**
2. **XENONnT**
3. **Development of direction sensitive detector**

K. Abe, N. Kato, S. Moriyama, H. Sekiya, T. Suzuki, and A. Takeda

K. Abe, Y. Haochen, N. Kato, S. Moriyama, and A. Takeda



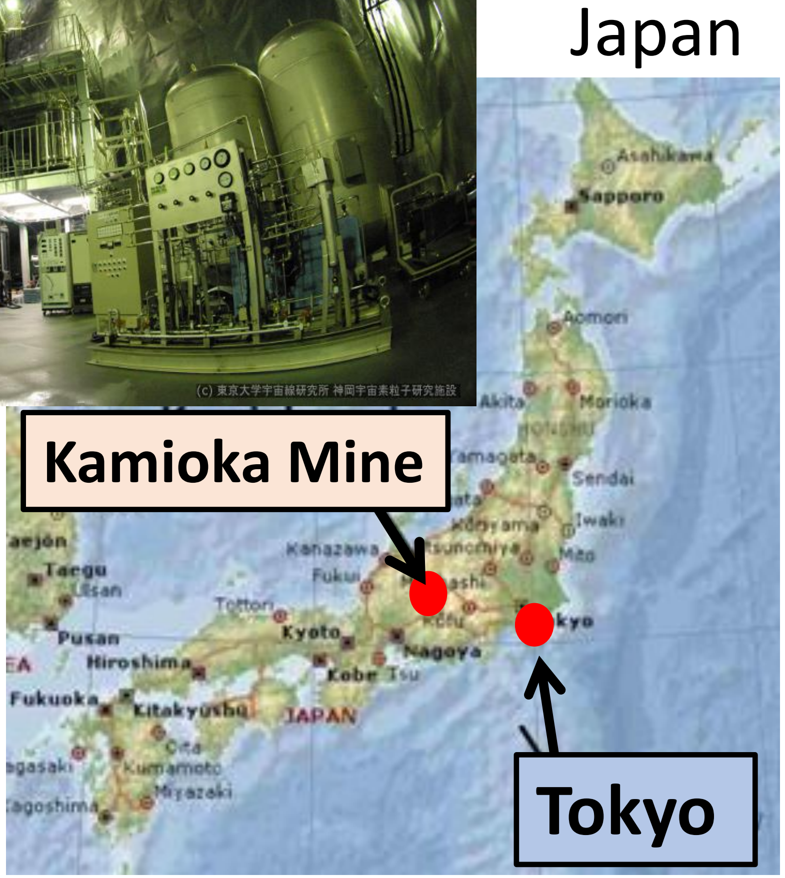
H. Sekiya and M. Shibata

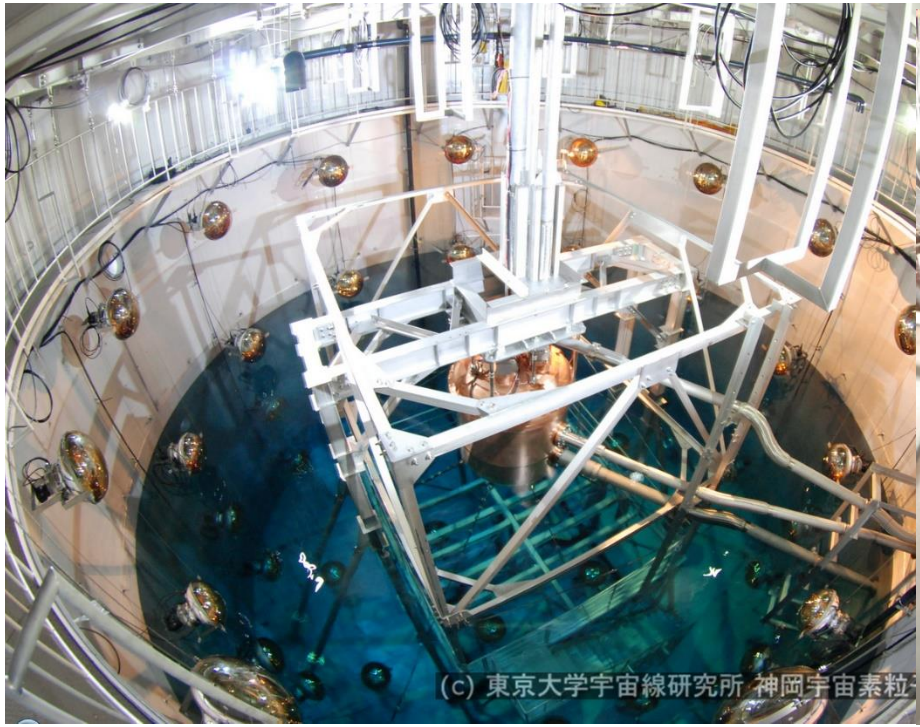
XMASS

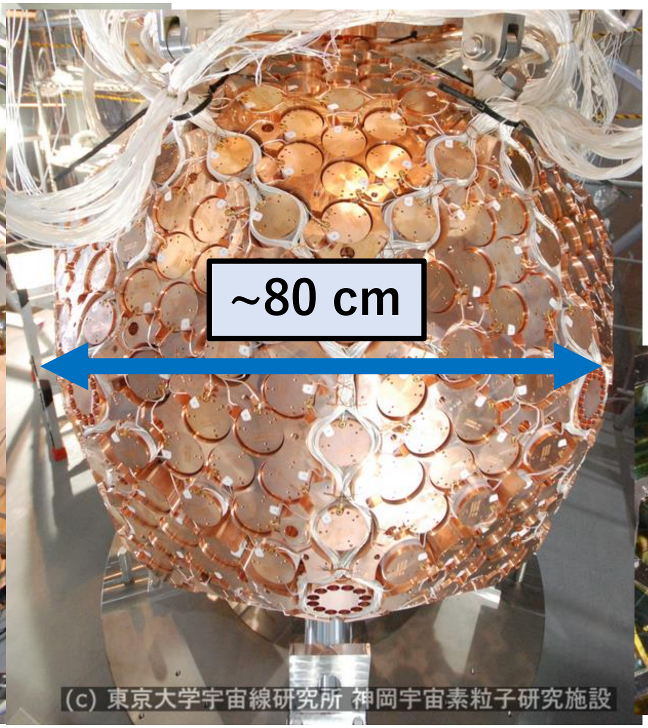
K. Abe, N. Kato, S. Moriyama, H. Sekiya, T. Suzuki, and A. Takeda

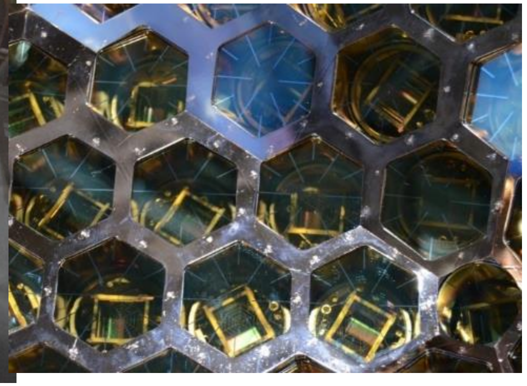
XMASS-I detector

- Single phase (scintillation only) liquid xenon.
- 630 hexagonal & 12 round PMTs : 28-39% Q.E.
- photocathode coverage: ~ 62%
- Amount of sensitive xenon：832 kg (dia. ～80 cm)
- Muon veto: 10x10.5m water tank＋70 20 inch PMTs





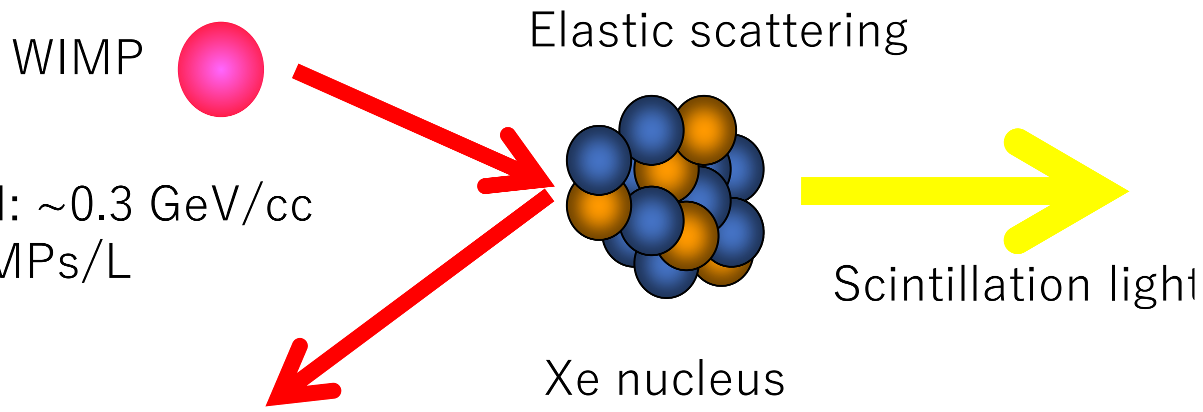




Properties of liquid xenon and WIMP searches

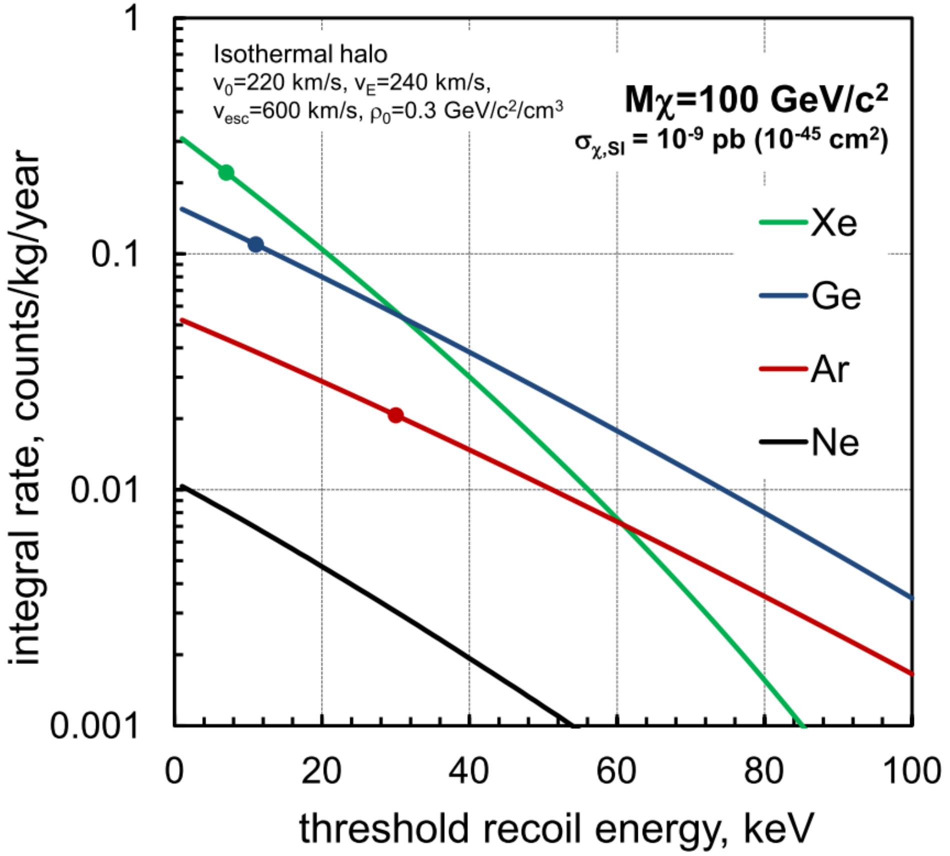
Properties of LXe

- High density: **~3 g/cm³**
- High boiling point: **165 K**
- Good scintillator: **42 photons / keV**
- Wavelength: **175 nm** (directly detected by PMT)
- High ionization yield: **W = 15.6 eV**
- No long-lived RI (except for ββ)



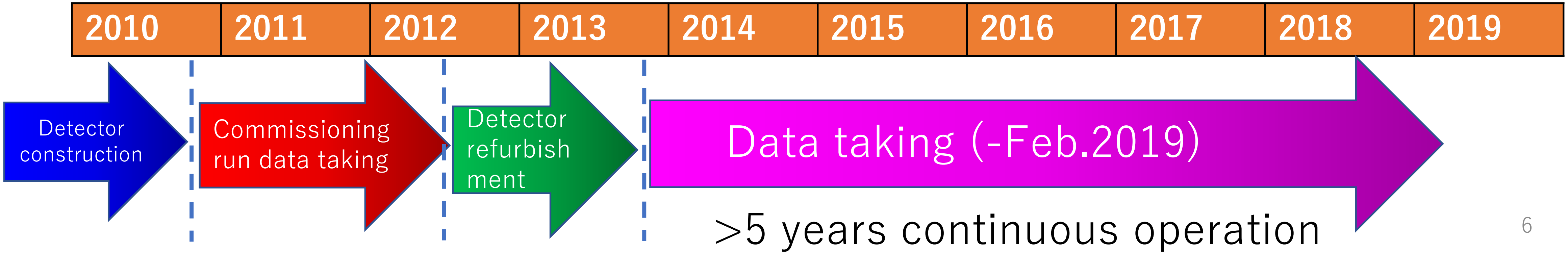
Density of DM: ~0.3 GeV/cc
→ 10–100 WIMPs/L

Expected signal rate (counts/kg/year)
V. Chepel and H. Araujo, arXiv:1207.2292



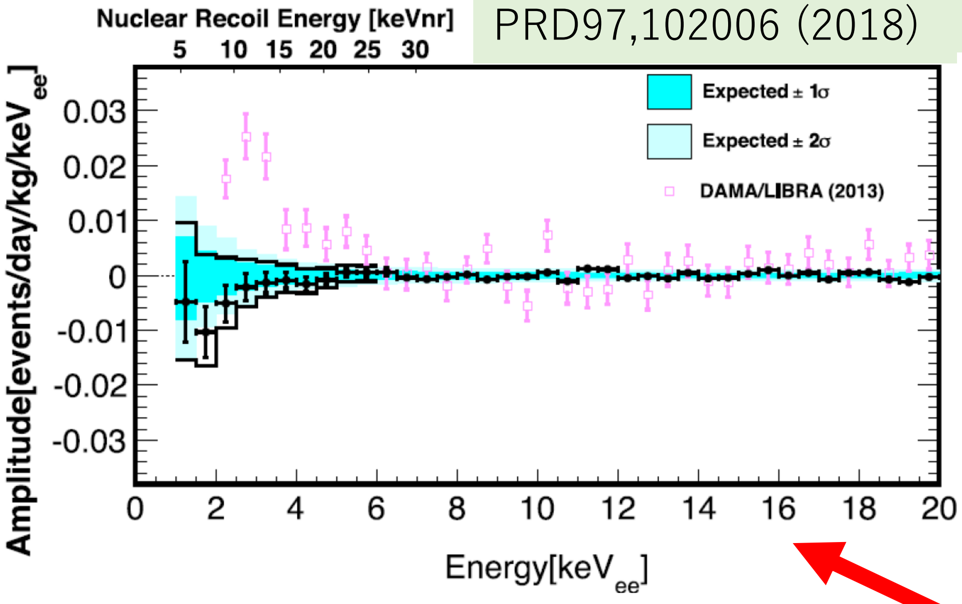
History of XMASS

- Construction of XMASS-I detector was completed on Sep. 2010.
- Commissioning run was conducted till May 2012.
- Detector refurbishment was done for further background reduction.
  → One order of magnitude reduction above 5 keVee for entire volume was achieved.
- Long and stable data taking was conducted from Nov. 2013 to Feb. 2019 (1898.4 days, live time = 1807.3 days)
- Data analysis is continued.

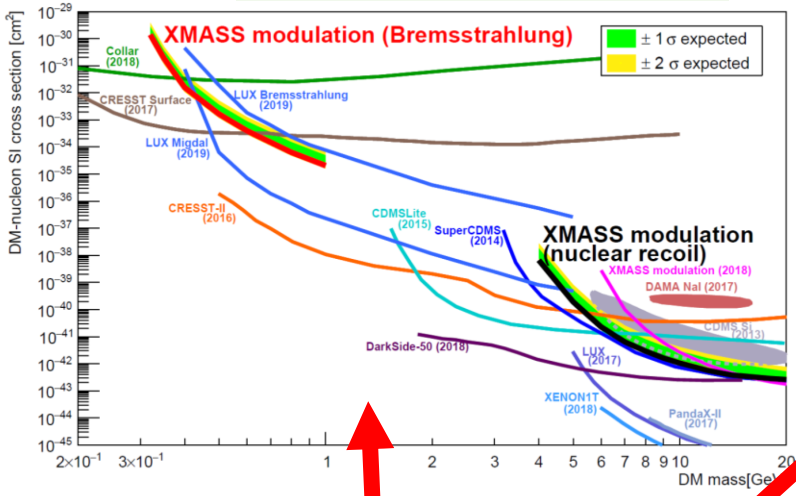


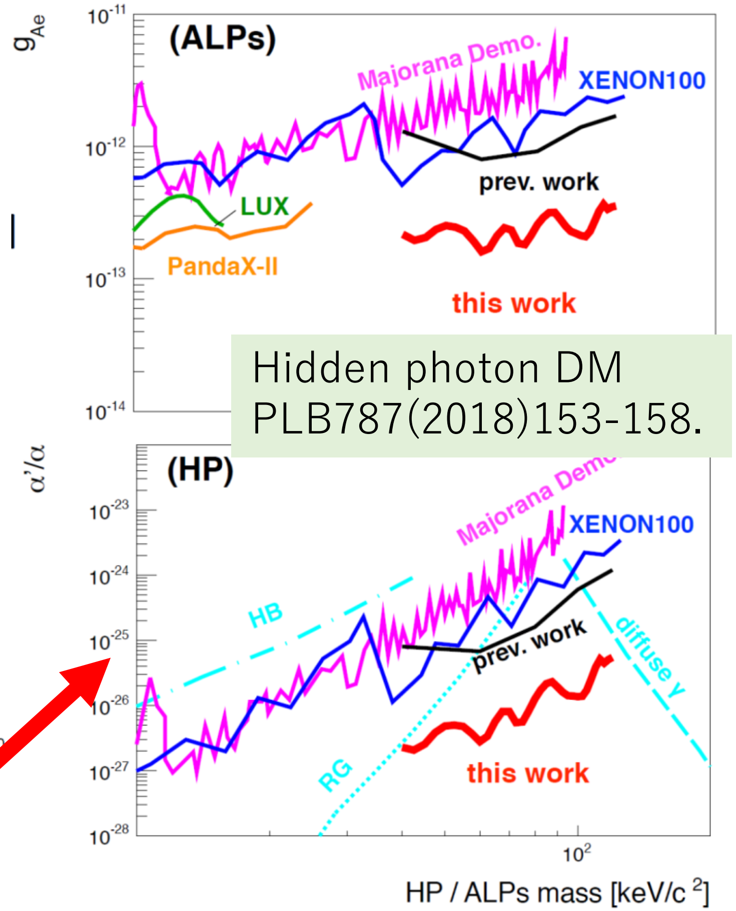
Physics Results from XMASS-I

Annual modulation
PRD97,102006 (2018)



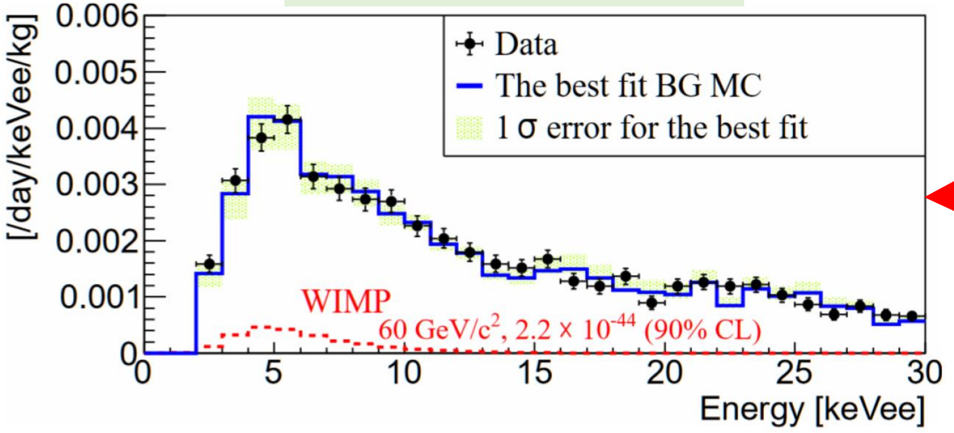
Sub-GeV DM search
PLB795(2019)308-313





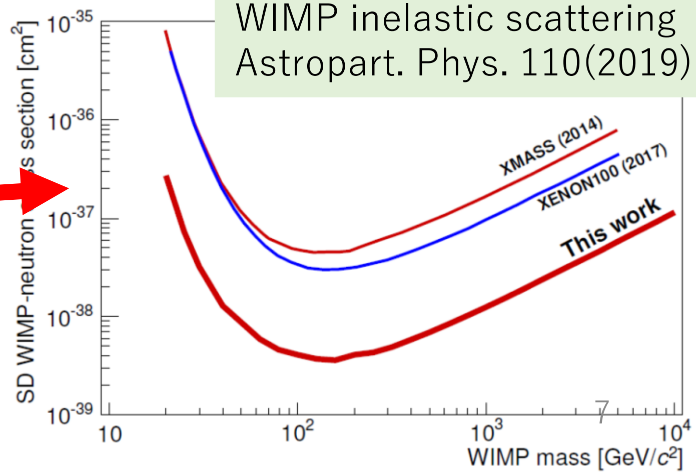
Hidden photon DM
PLB787(2018)153-158.

Direct DM search
PLB789(2019)45-53.



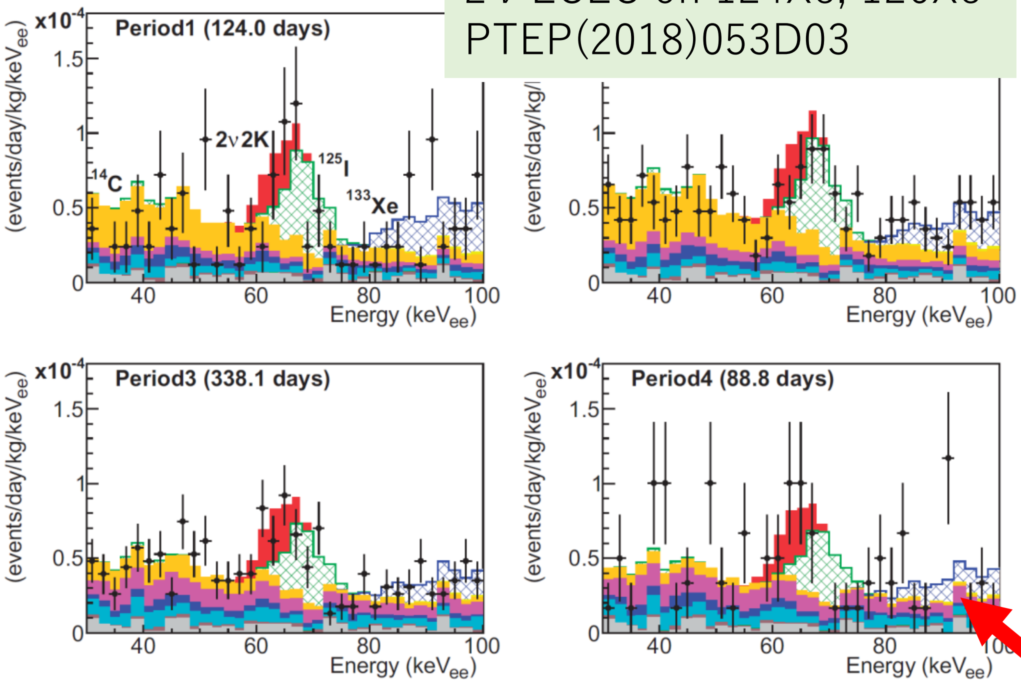
DM searches with several approaches

WIMP inelastic scattering
Astropart. Phys. 110(2019)1-7

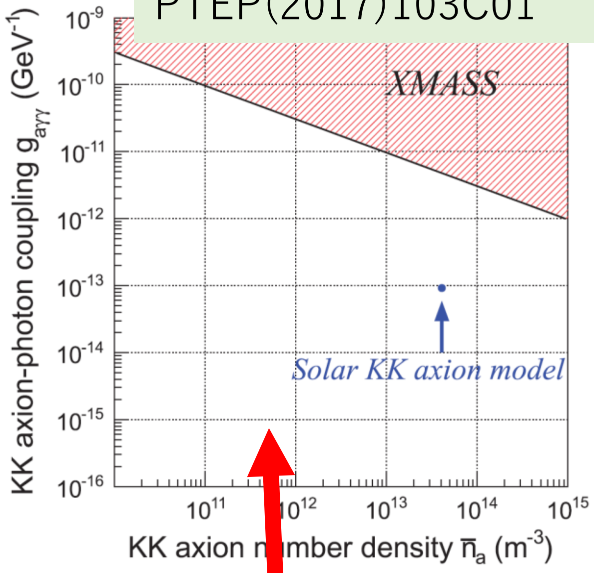


Physics Results from XMASS-I

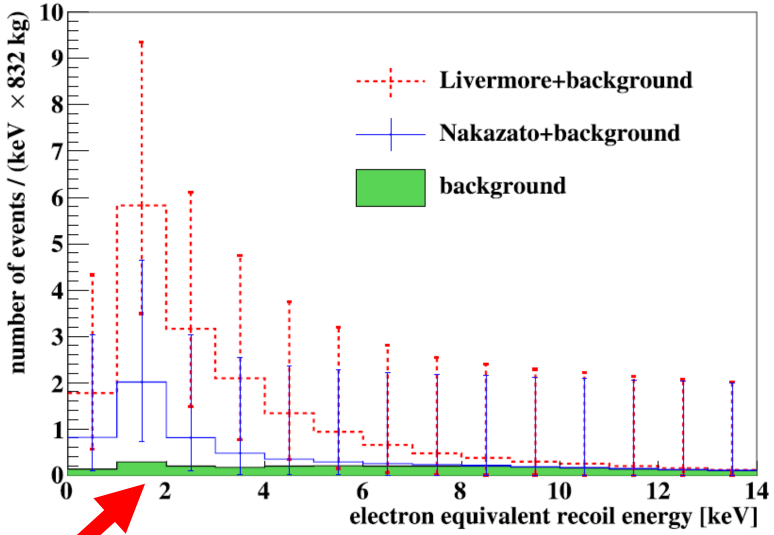
2 ν ECEC on 124Xe, 126Xe
PTEP(2018)053D03



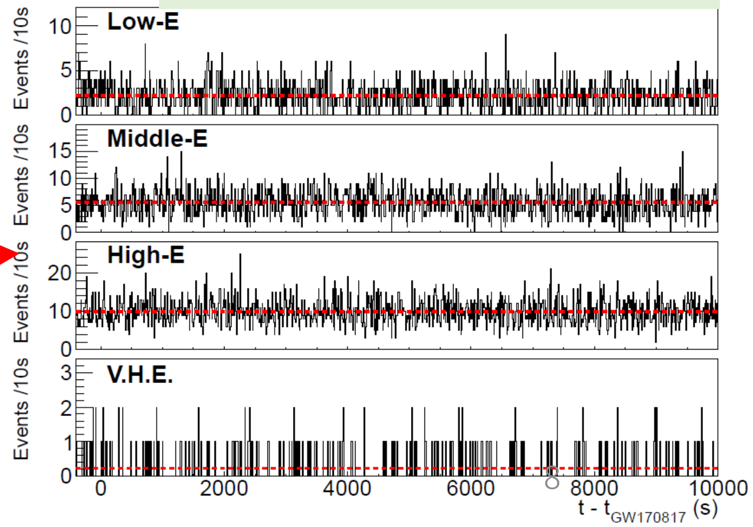
Solar KK axion search
PTEP(2017)103C01



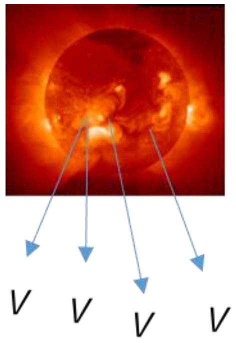
Possibility of SN neutrino detection
Astropart. Phys. 89(2017)51

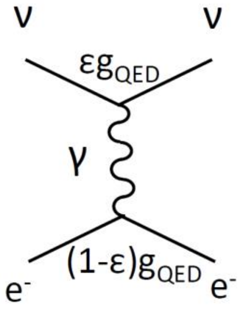


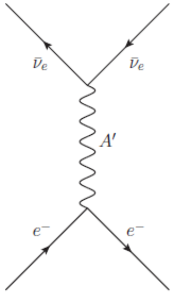
GW related burst search
arXiv:2007.16046
Submitted to Astropart. Phys.

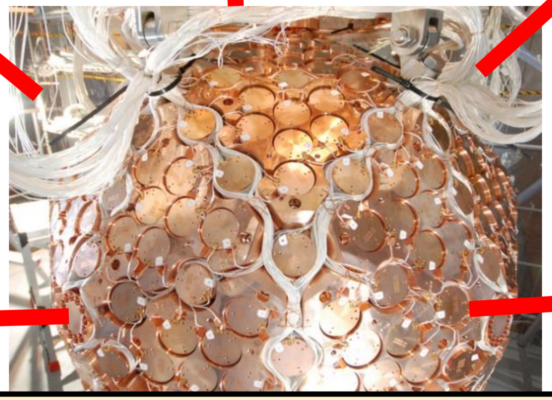


Exotic neutrino interaction search
PLB 809 (2020) 135741 [new!]









Searches for other rare events

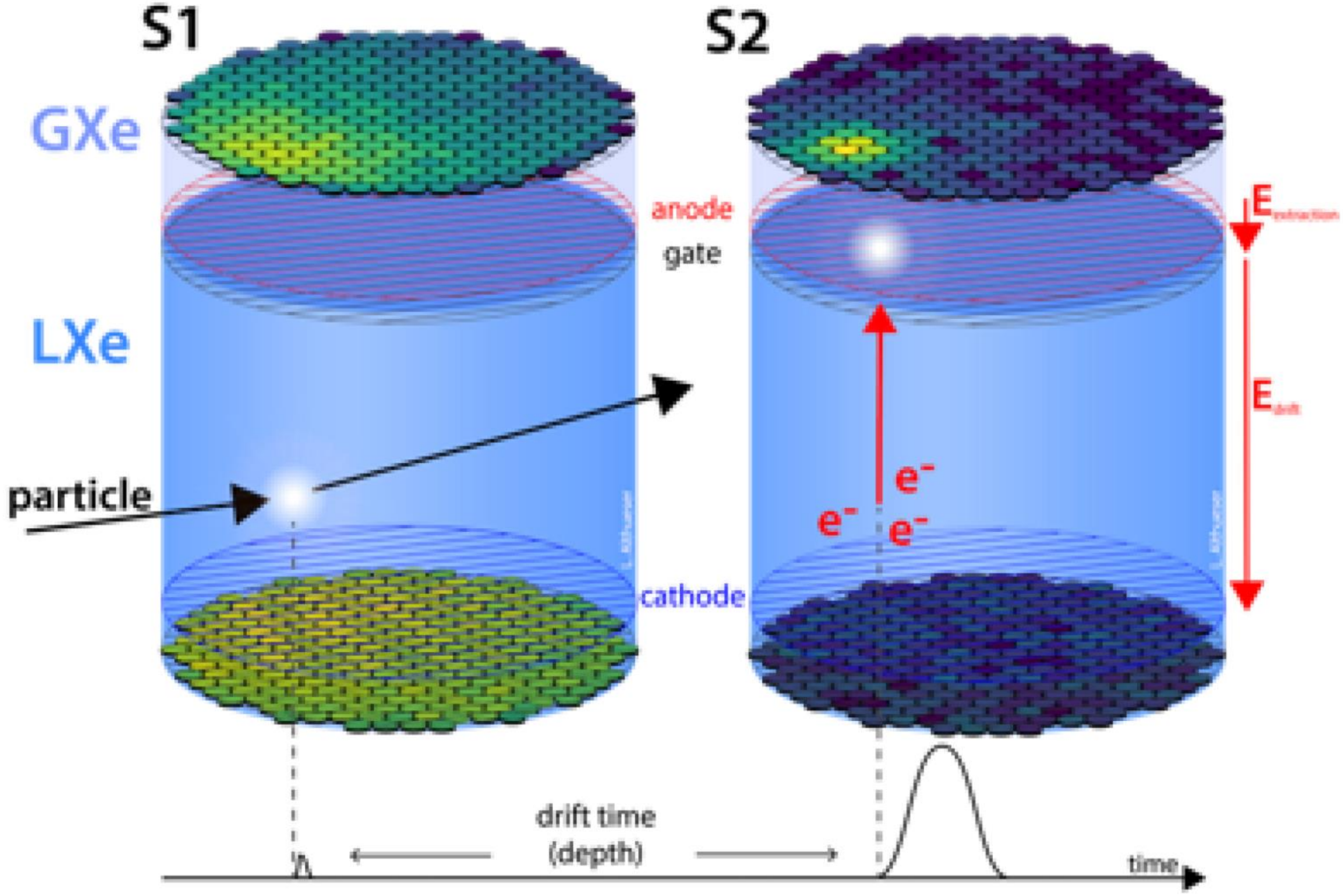
XENONnT

K. Abe, Y. Haochen, N. Kato,
S. Moriyama, and A. Takeda

XENON collaboration

- ~170 scientists, 27 institution, 11 countries.

Liquid Xe TPC



- **S1**: prompt scintillation signal
- **S2**: delayed ionization signal

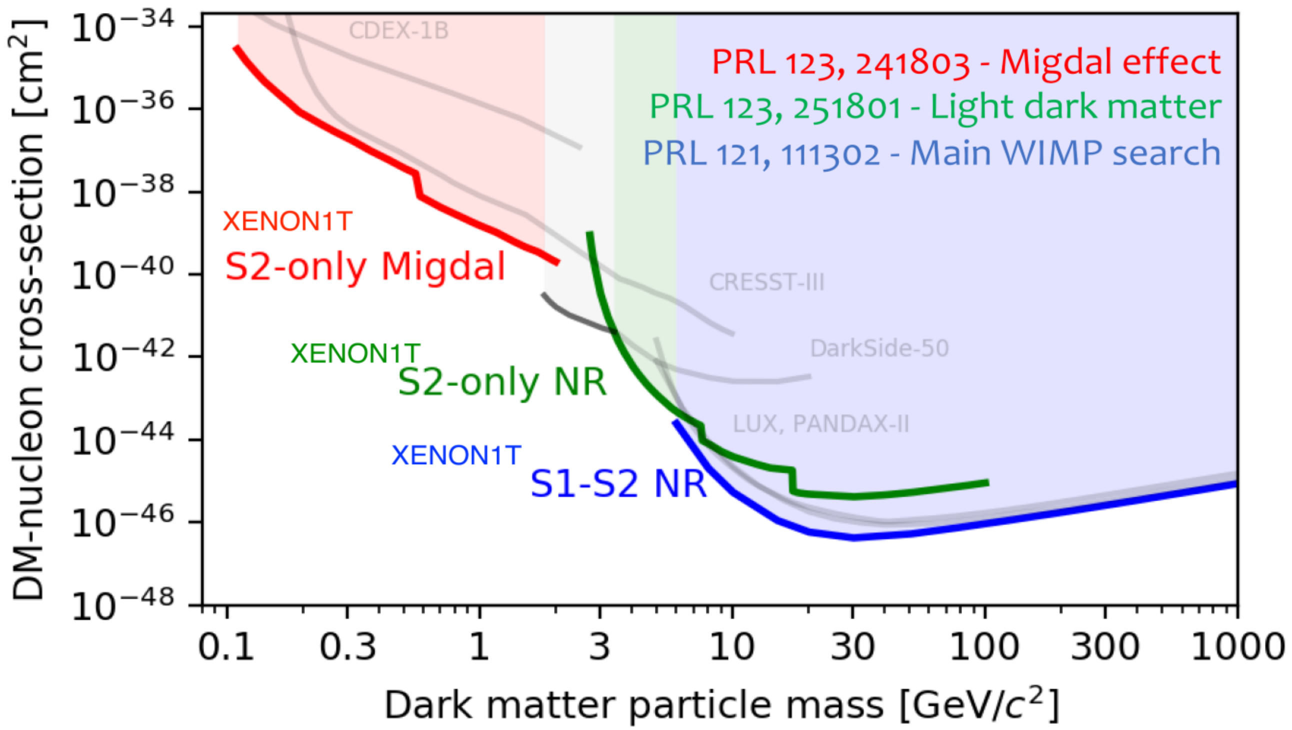
- 3D position reconstruction:
  - XY: S2 hit pattern
  - Z: S2 – S1 delay

- Background discrimination
  - **Nuclear recoil (NR)** from WIMP, neutrons.
  - **Electron recoil (ER)** from β, γ.

$(S2/S1)_{ER} > (S2/S1)_{NR}$

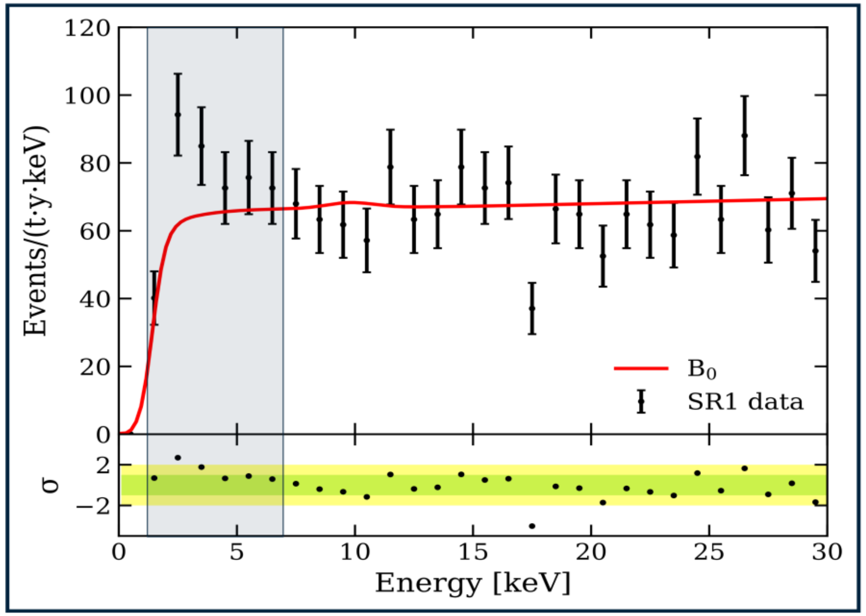
Physics results from XENON1T

Spin independent WIMP-nucleon cross section



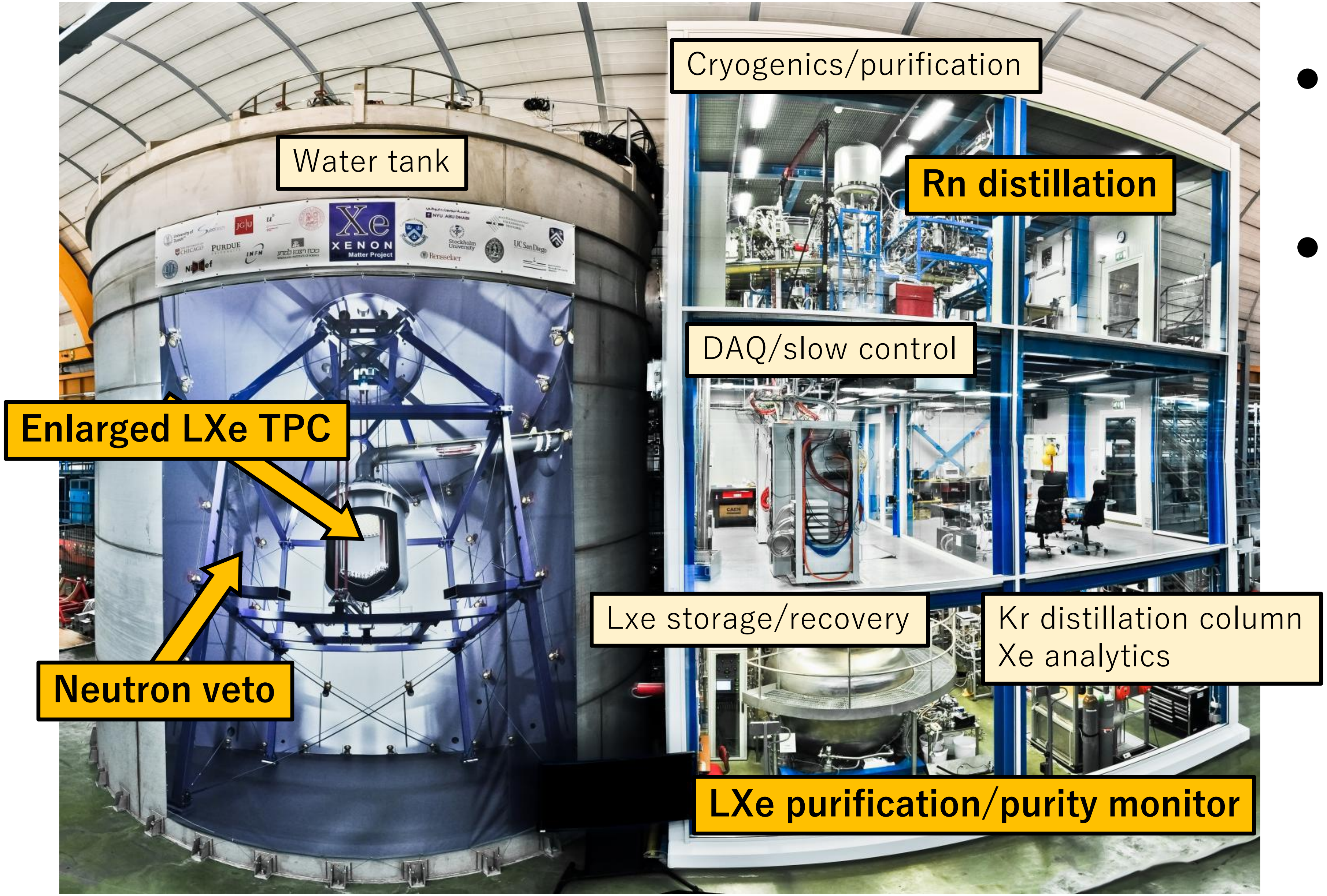
- XENON1T is leading the searches both in low and high WIMP mass region.

Energy spectrum for electron recoil events



- 285 events between 1–7 keV were observed compared from 232±15 expectation.
- This excess can be explained by solar axion (3.4σ), neutrino magnetic moment (3.2σ), or ^{3}H (3.2σ)

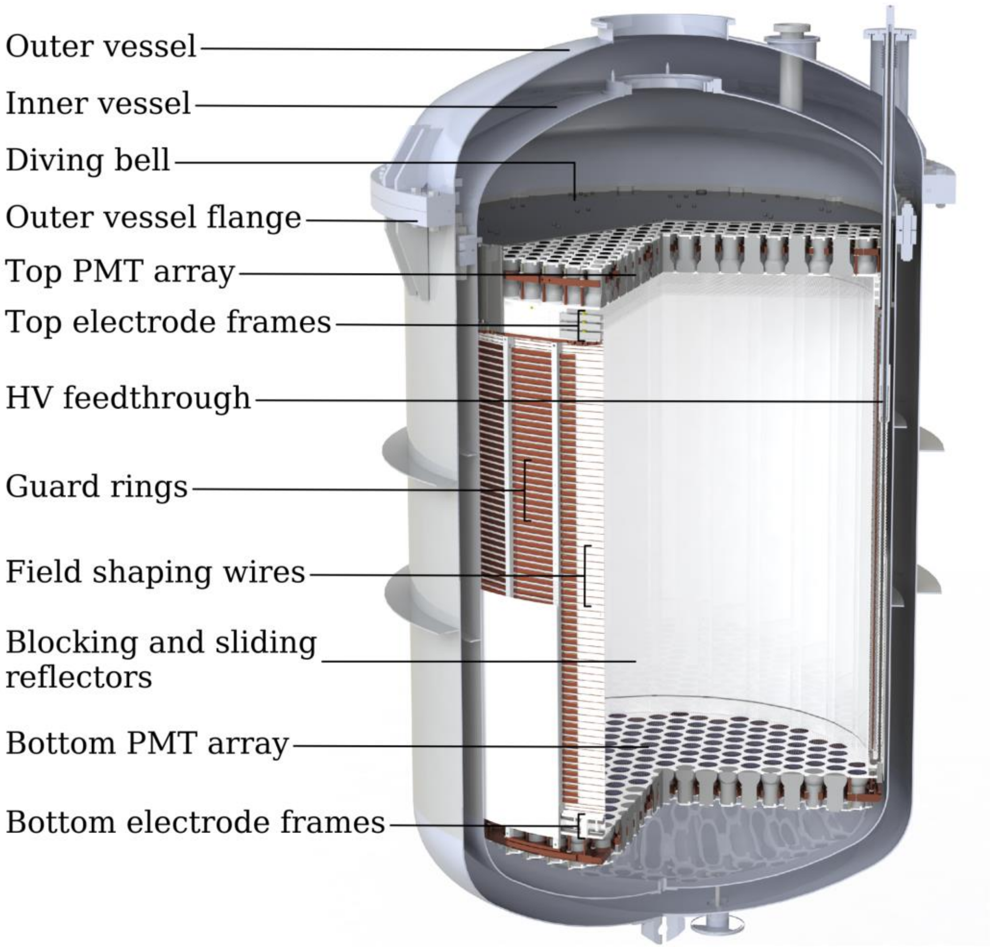
Upgrade from XENON1T to XENONnT

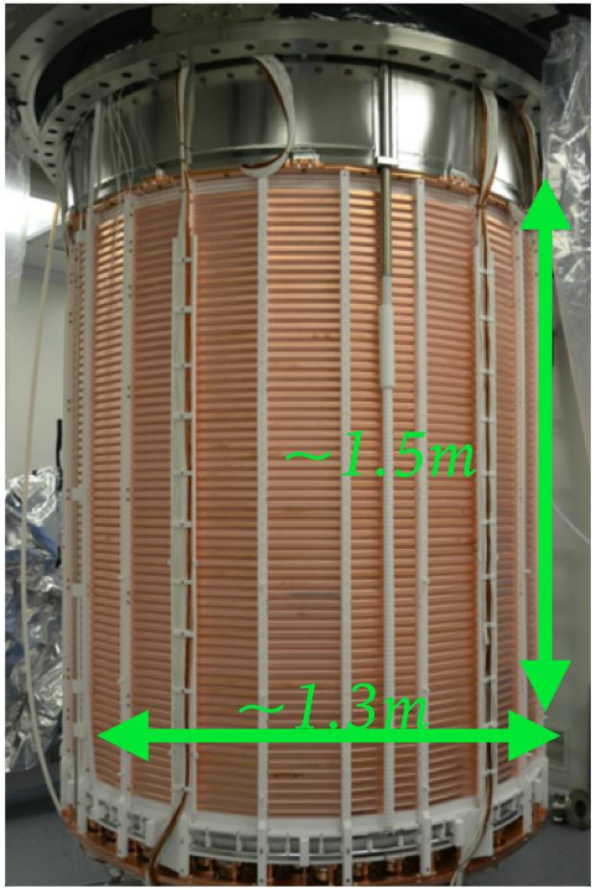


- LXe TPC has been enlarged.
  - Active target mass: 2 ton → **5.9 ton**
- New apparatus:
  - **Rn distillation:** Online reduction of ^{222}Rn emanated from inside the detector.
  - **Neutron veto**: 120 additional PMTs 0.5% $Gd_2(SO_4)_3$
  - **LXe purification**: Faster xenon cleaning 5 L/min LXe (2500 slpm)

Japanese contribution

Liquid xenon TPC



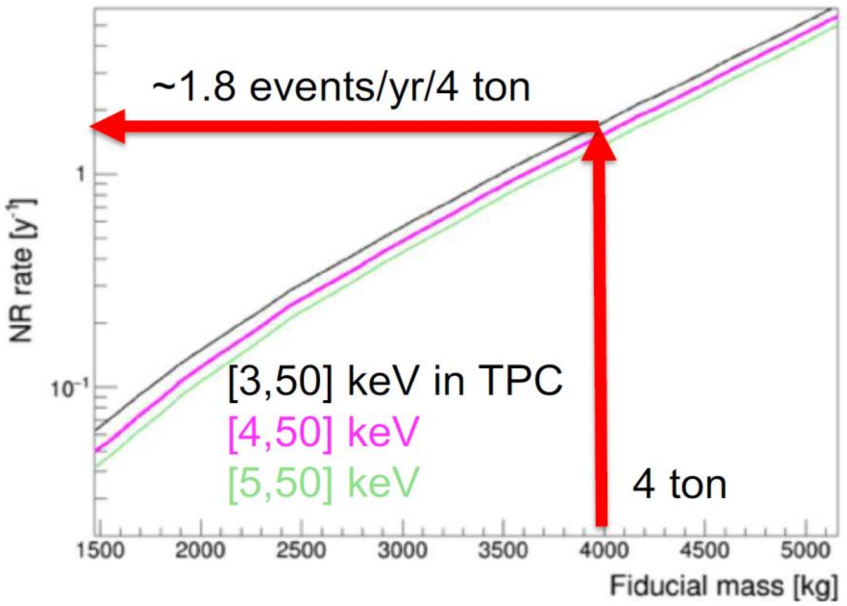


- Diameter = 1.3 m, Height = 1.5 m
- LXe mass:
  - Full: 8.2 ton
  - Active: 5.9 ton
  - Fiducial: 4 ton

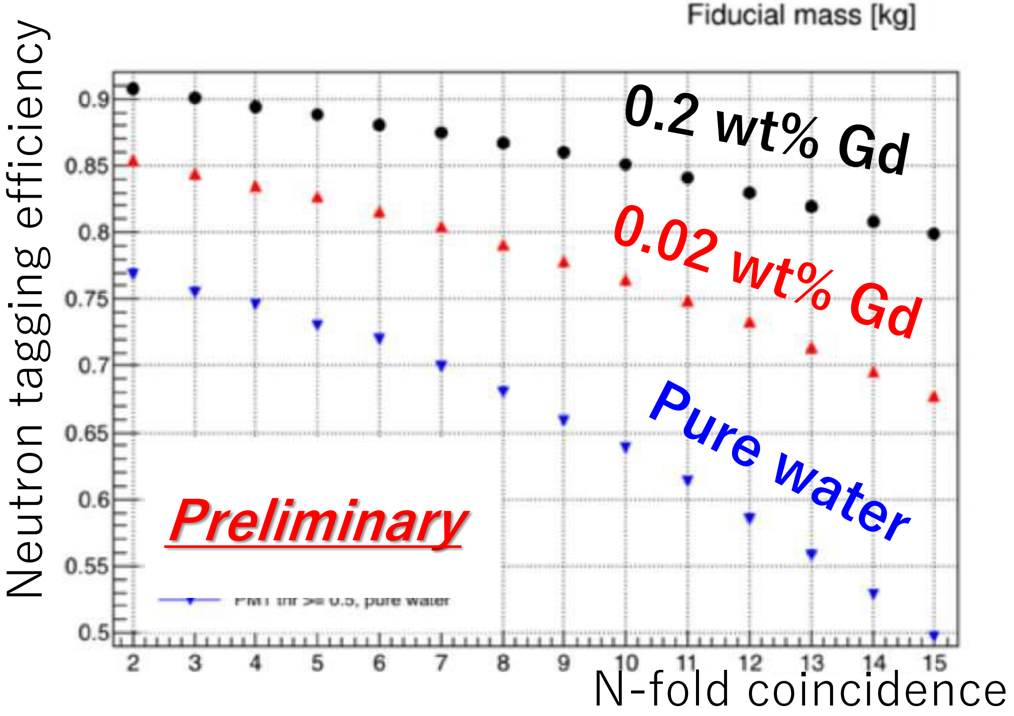
  → 3 times larger than XENON1T
- Top/bottom PMTs: 253/241
- Design drift field: 200 V/cm
- Design extraction field: 8 kV/cm
- Optimized for low material budget (PTFE thickness minimized) and reduction of wall charge-up.

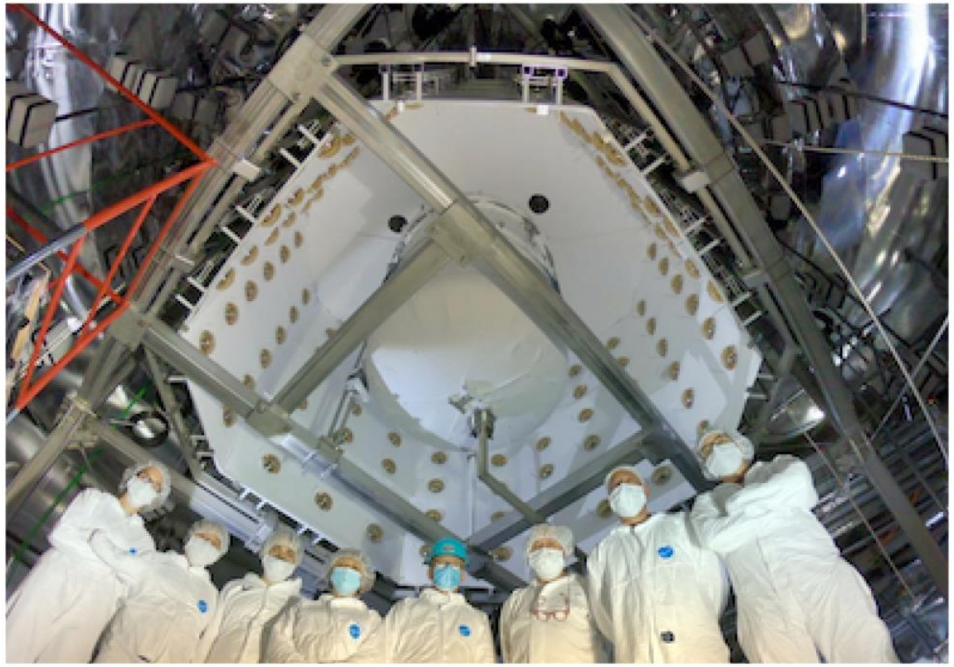
Neutron veto (nVeto)

Irreducible neutron BG w/o neutron veto



- ~1.8 events/year irreducible neutron BG in 4 ton fiducial volume are estimated without neutron veto.
- Tagging efficiency of neutron veto newly installed: **~80–90%** based on simulation.
- 0.5% $Gd_2(SO_4)_3 \cdot 8H_2O$
- Upgrade for Gd-water purification.
  - EGADS/SK-Gd technology
- Purity/reflectivity measurement systems are installed.

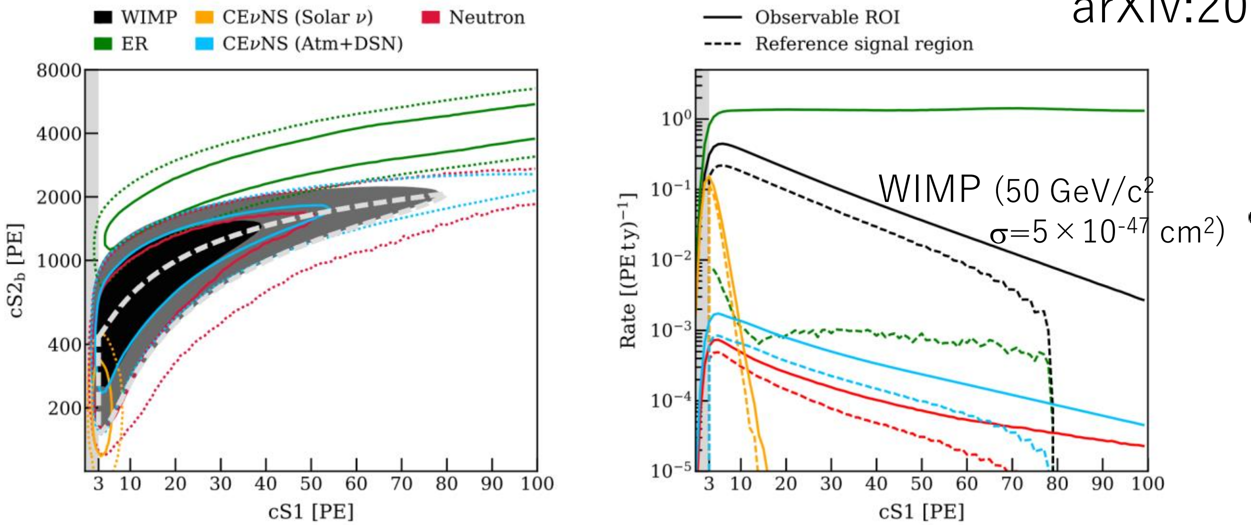


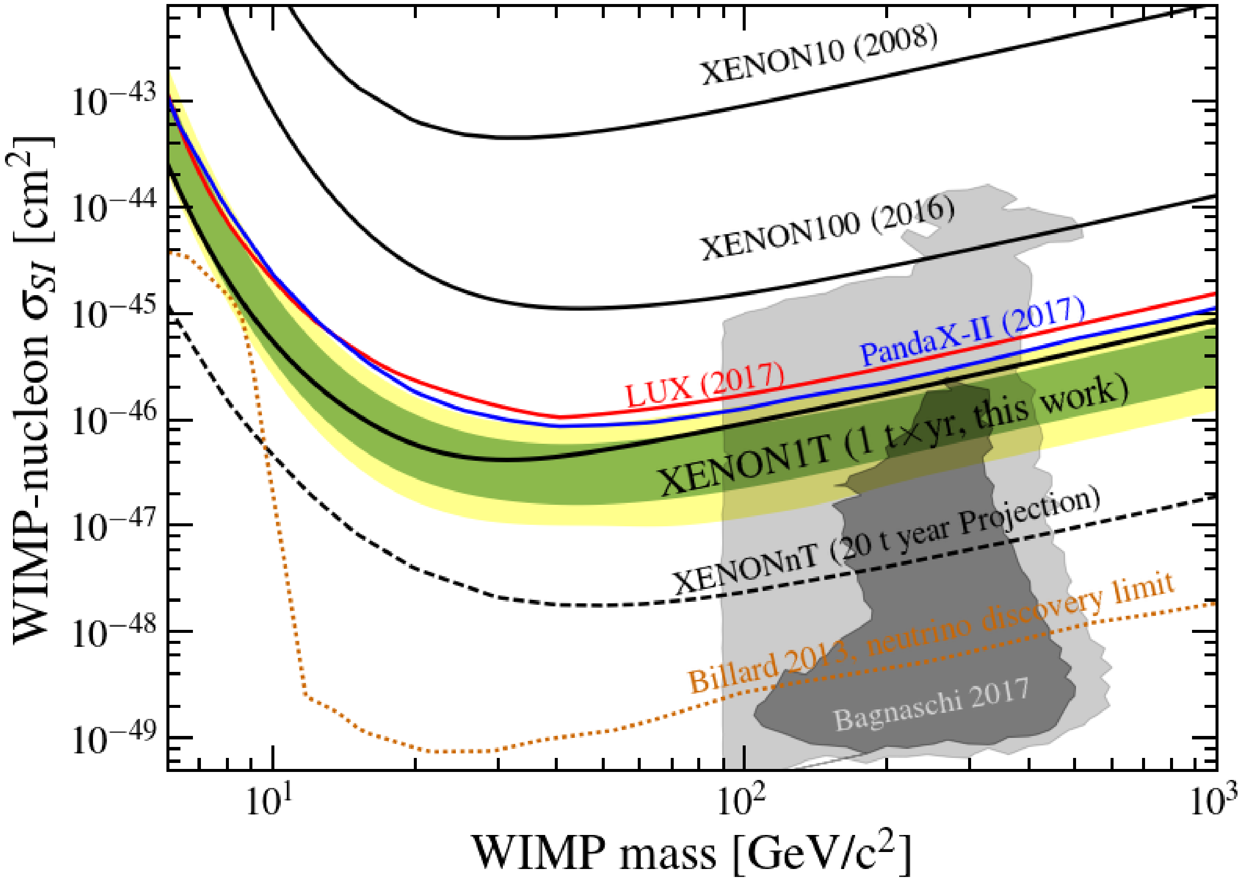


Expected sensitivity

- 1.4×10^{-48} cm^2 for 5 GeV WIMPs for 5 years measurements with 4 ton fiducial mass.

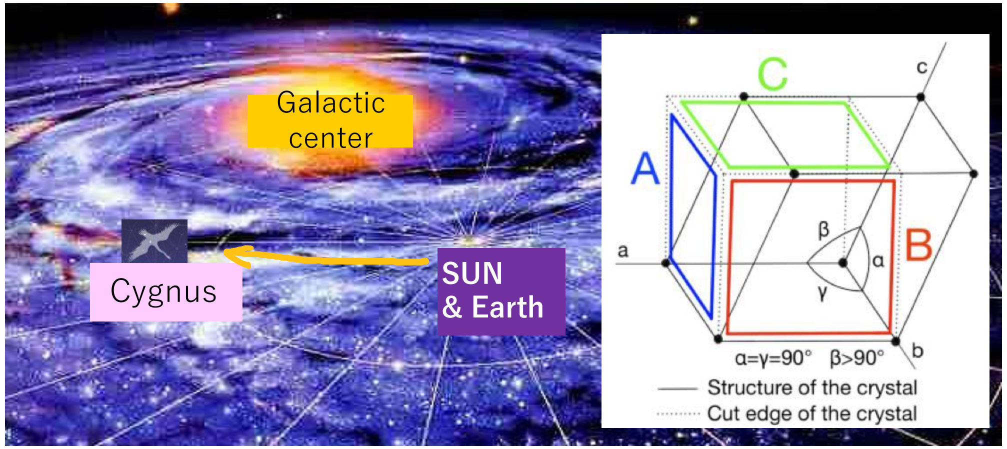
arXiv:2007.08796





Model component	Expectation value (μ) in 20 t y		Rate uncertainty
	Observable ROI	Reference signal region	(ξ)
Background			
ER	2610	1.69	
Neutrons	0.29	0.15	50%
CEνNS (Solar ν)	7.61	5.41	4%
CEνNS (Atm+DSN)	0.82	0.36	20%
WIMP signal			
6 GeV/c^2 ($\sigma_{DM} = 3 \times 10^{-44}$ cm^2)	25	19	
50 GeV/c^2 ($\sigma_{DM} = 5 \times 10^{-47}$ cm^2)	186	88	
1 TeV/c^2 ($\sigma_{DM} = 8 \times 10^{-46}$ cm^2)	286	118	

Direction sensitive DM detector

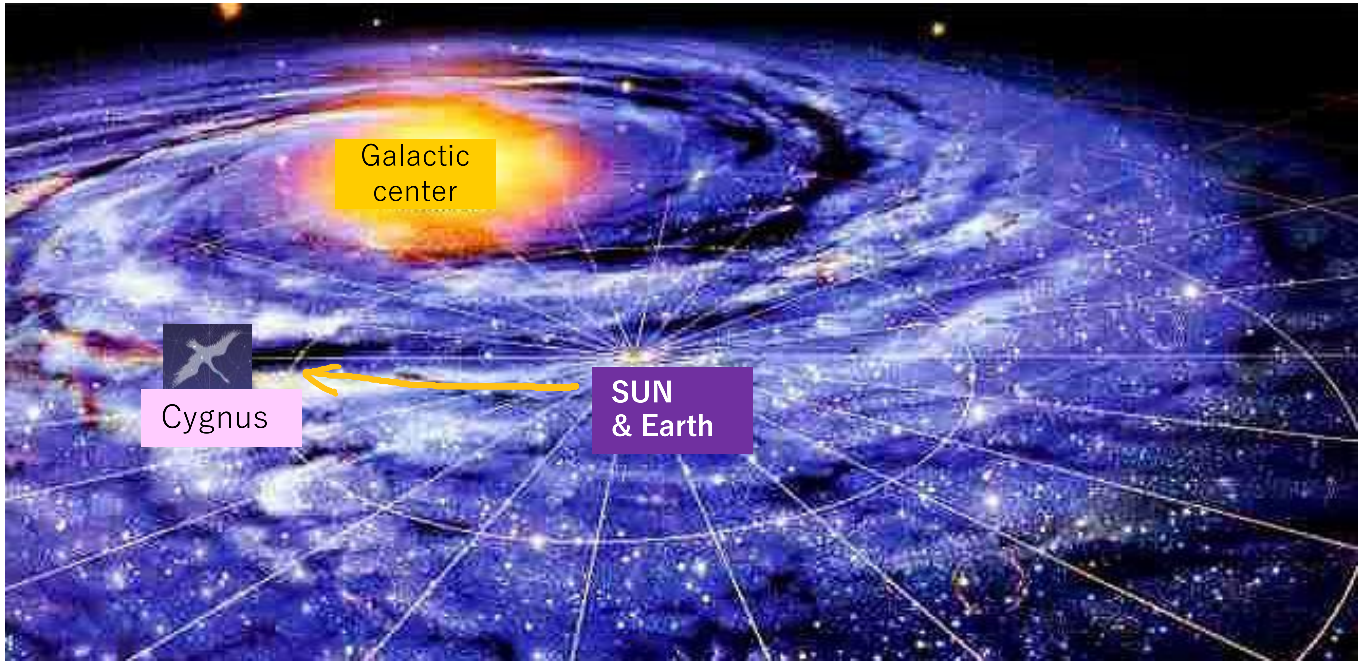


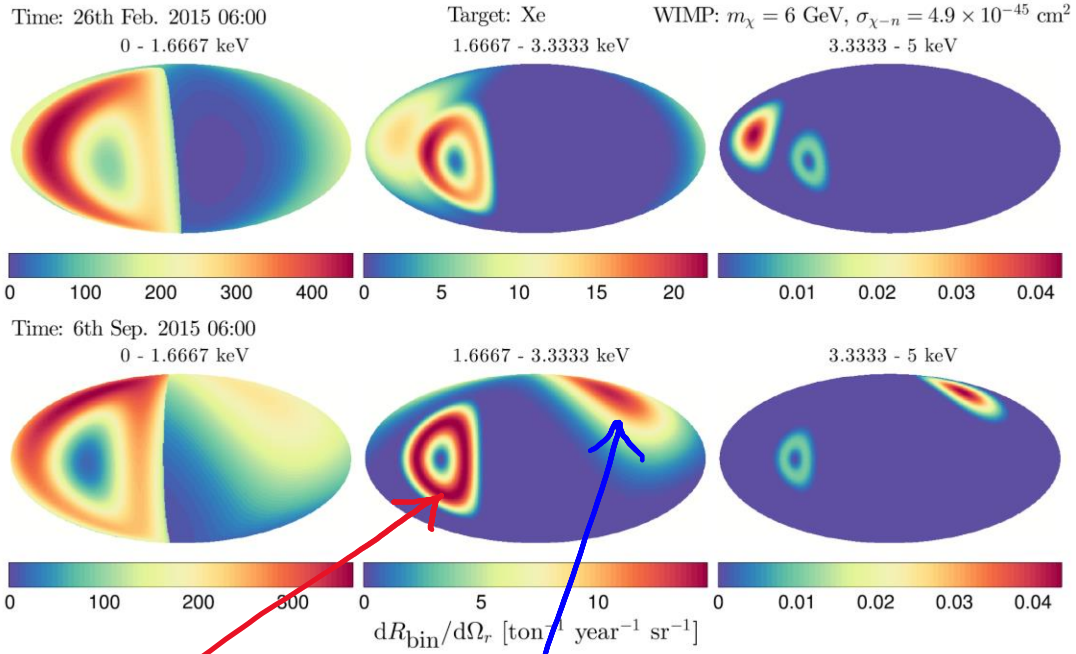
H. Sekiya and M. Shibata

Direction sensitive detectors

- To go beyond Neutrino-floor

PHYSICAL REVIEW D 92, 063518 (2015)





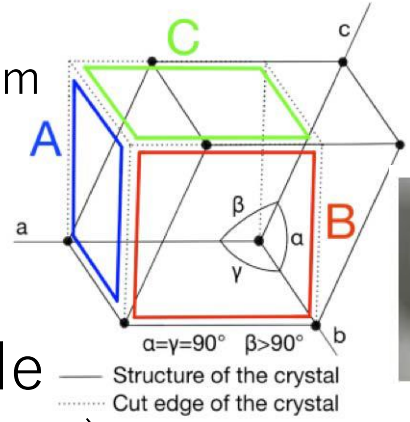
Solar ^{8}B neutrino

WIMP

- Directional detectors have “discovery potential” beyond the neutrino floor
- However, there are no feasible detectors possible to do ton scale experiment yet.
  - Not ensured the scalability and stability (production, cost, quality) for such new technologies

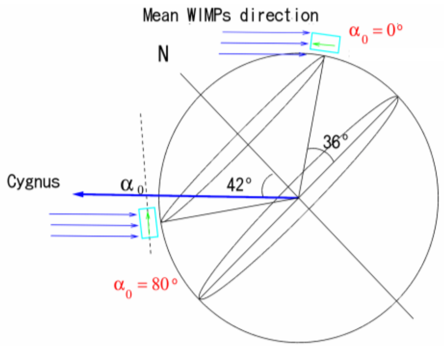
$ZnWO_4$

Monoclinic crystal system

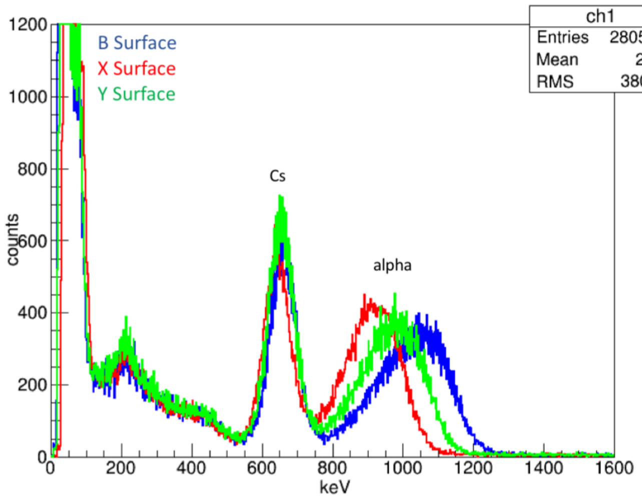


PTEP (2020) 023C01

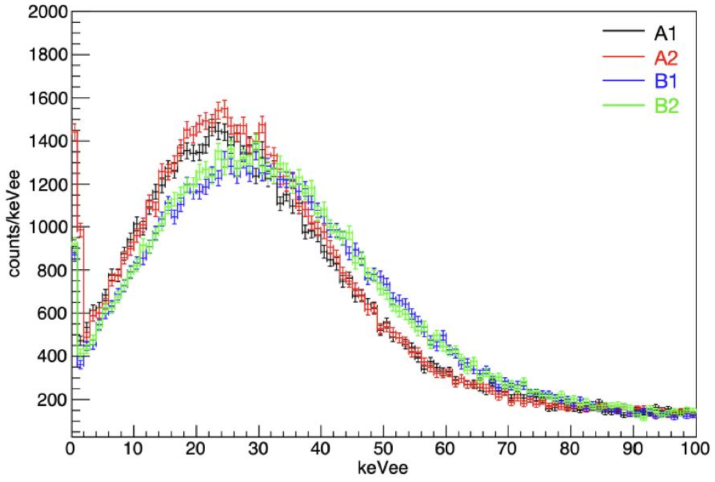
- Anisotropic scintillator
  - Light output depends on the incident angle
    - 14% difference has been observed! (Bottom Figs)
  - Expected “diurnal modulation” of event rate due to earth’s rotation
    - Requires 10 tons of crystal··· Doable! (Right Figs)

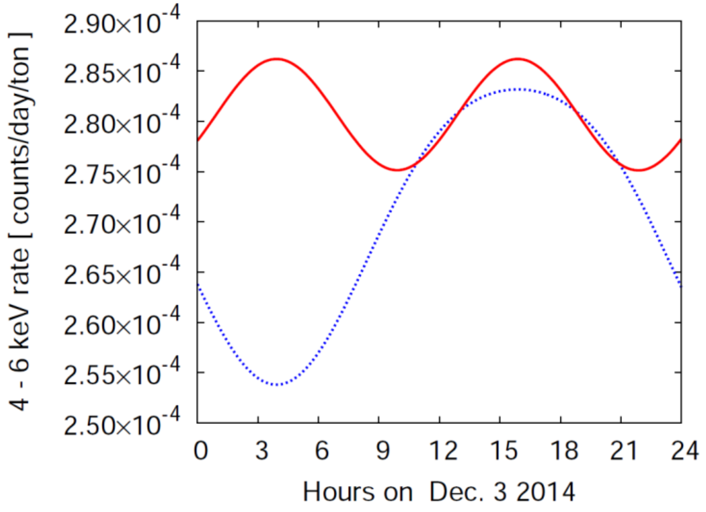


Response to gamma and alpha



Response to 860keV neutron



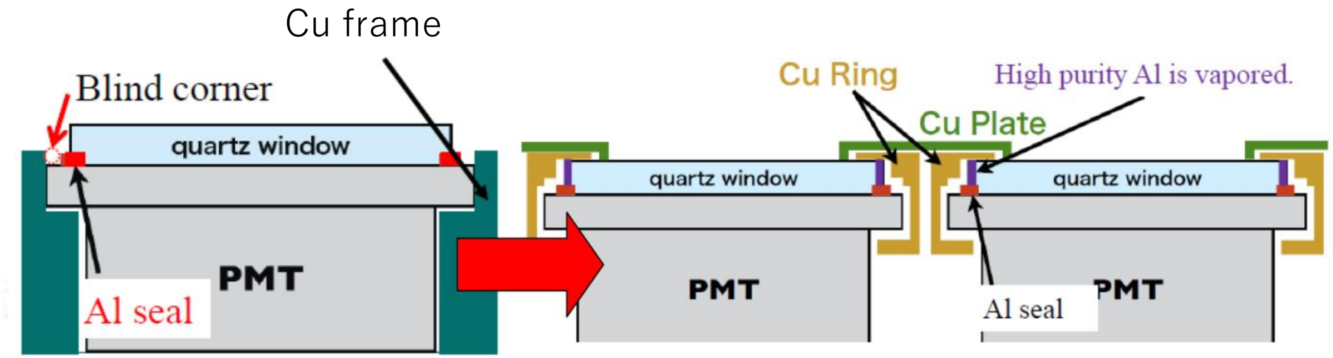


gammas/electrons: multiple scatter in a crystal

Backup

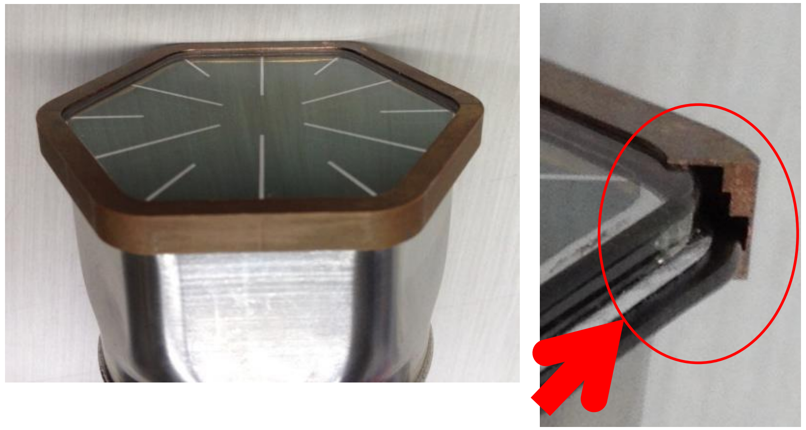
XMASS refurbishment

Purpose of Refurbishment:
- Confirmation of BG reduction by shielding of scintillation light originated from PMT Al
- Also reducing ^{210}Pb (2nd largest component in BG) with electro-polishing and special clean environment.

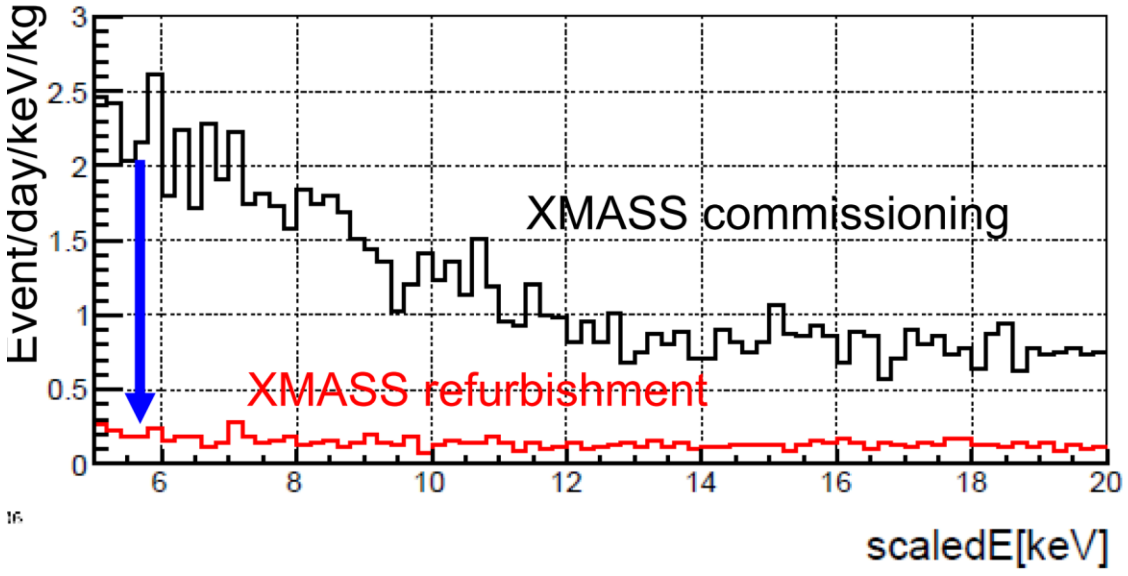


Before refurbishment

After installation of ring



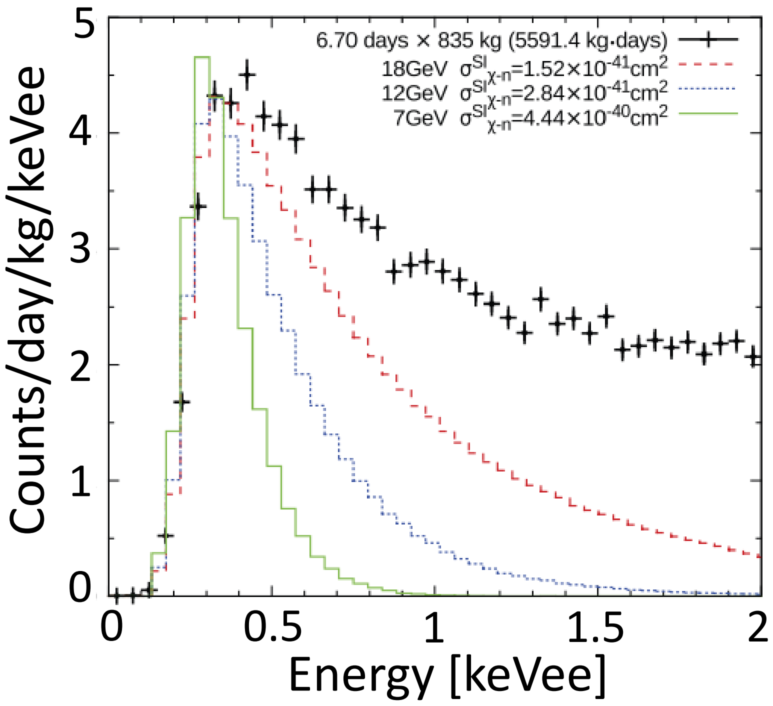
Energy spectrum for whole volume

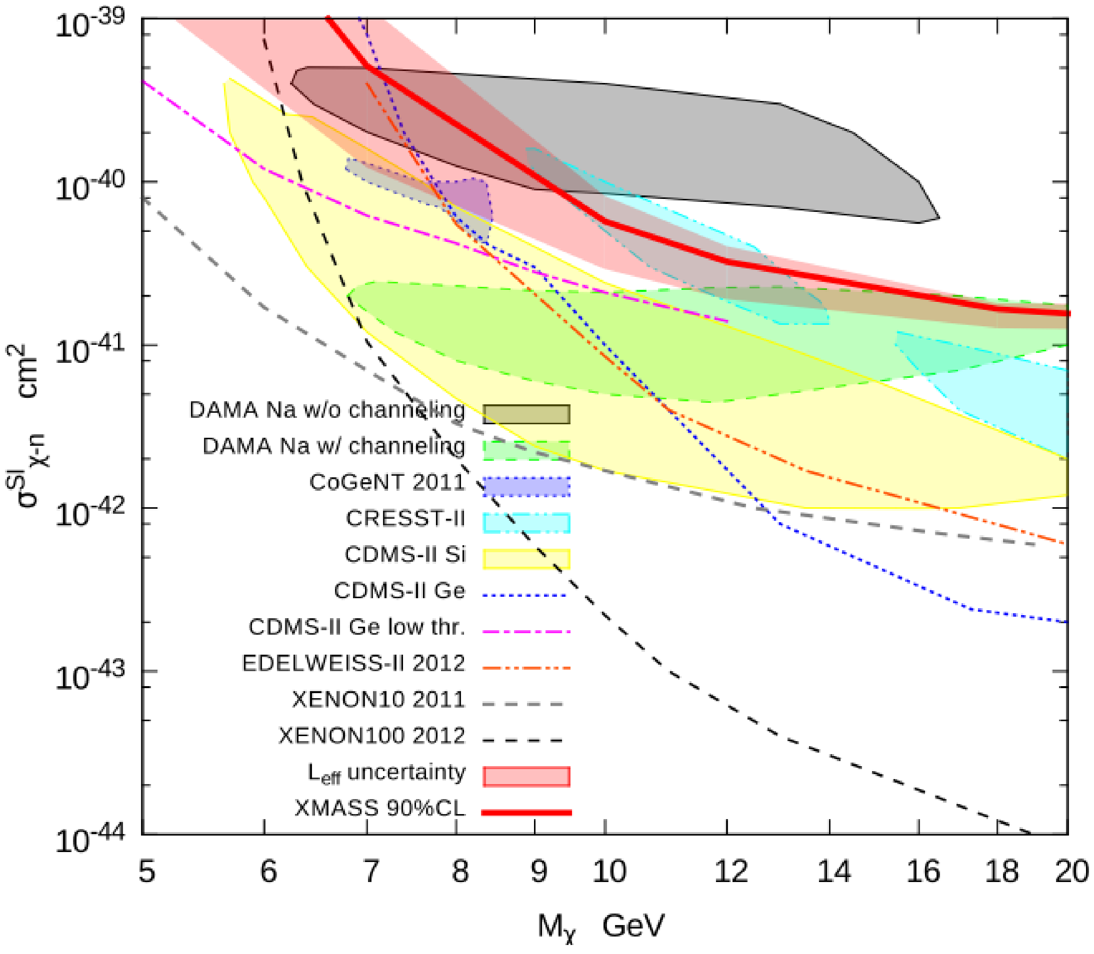


PLB 719 (2013) 78-82

Low mass WIMPs search

- Full volume (835 kg) analysis
- 6.80 days in 2012 Feb.
- 5591.4 kg day exposure
- 0.3 keVee threshold

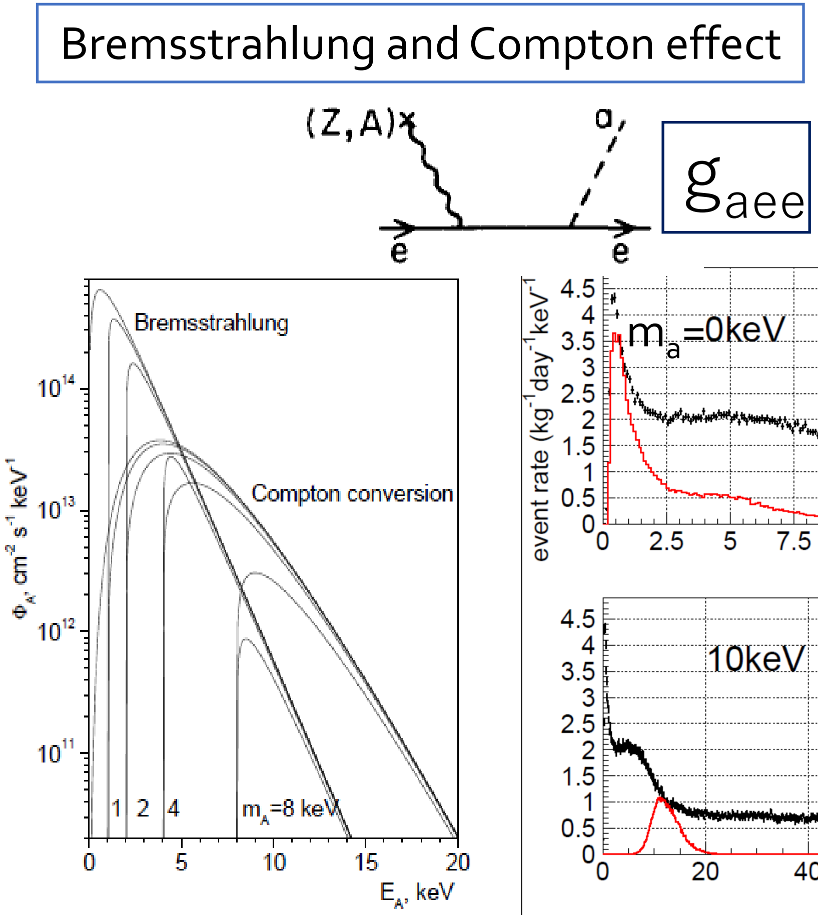


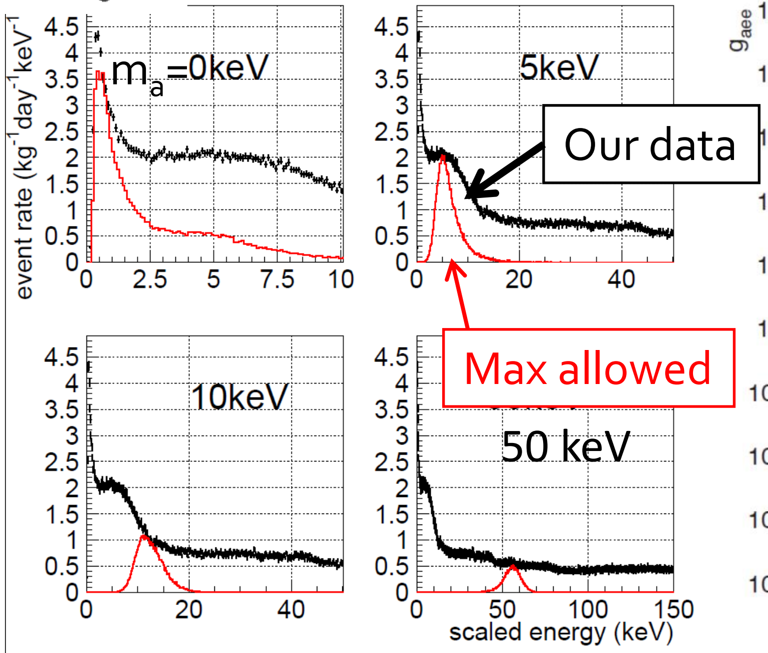


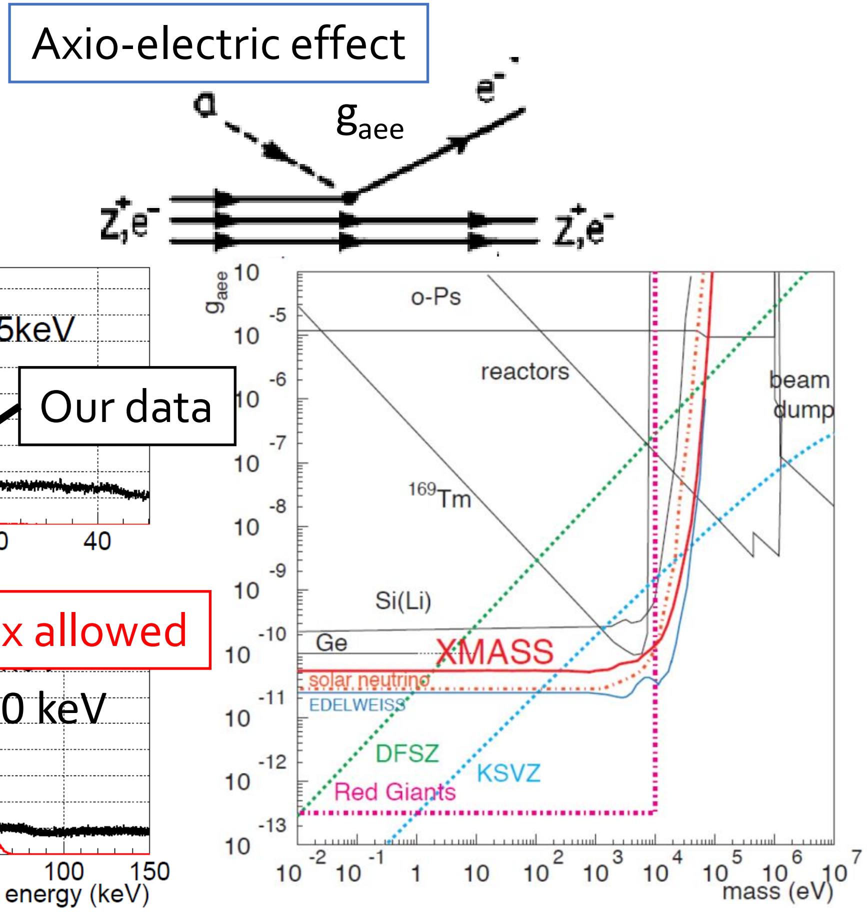
PLB 724 (2013) 46-50

Solar Axion search

- Axion is a hypothetical particle to solve the strong CP problem
- Produced in the Sun by bremsstrahlung and Compton effect, and detected in the detector by axio-electric effect.
- XMASS is suitable to search because of a large mass and low BG







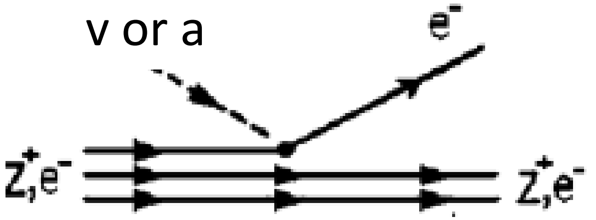
PRL 113 (2014) 121301

Bosonic super-WIMP (1/3)

- Search for lighter and more weakly interacting particles is attracting attention, because
  - So far no evidence of SUSY particles at the LHC.
  - Expectation on the structure on galactic scales of the CDM scenario is richer than observed.

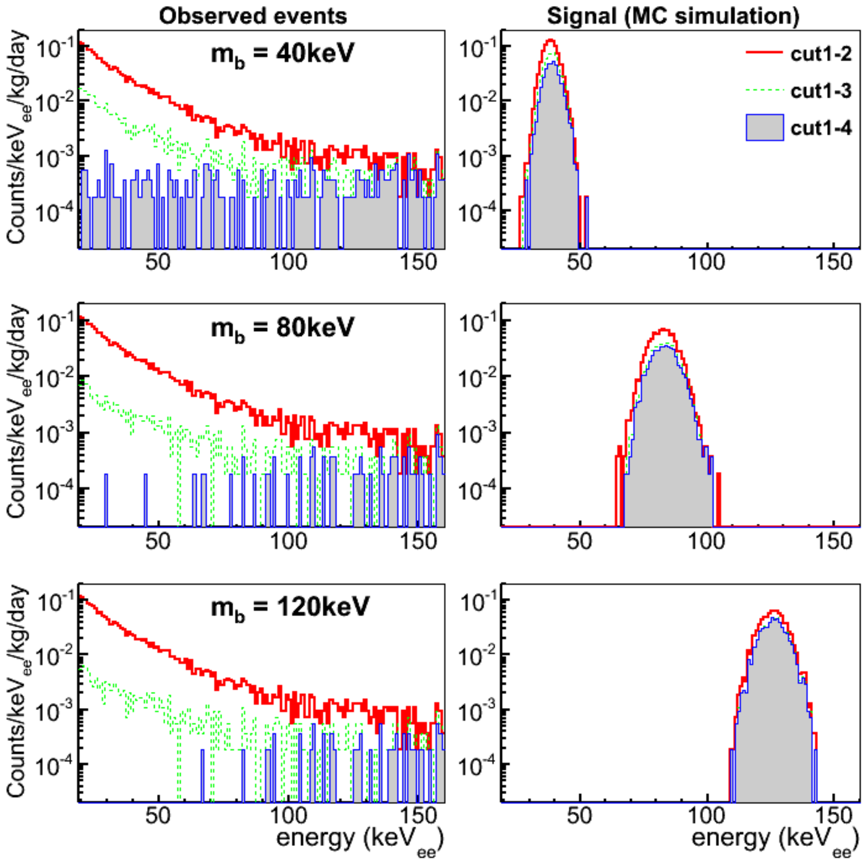
- Bosonic super-WIMPs search (*Pospelov et. al., Phys. Rev. D 78 115012 (2008)*)
  - A lukewarm dark matter candidate, and lighter and more weakly interacting particles than WIMPs.
  - Deposit energy in a target material would essentially equivalent to the super-WIMP rest mass.
  - Search for pseudoscalar and vector boson (called as dark, para, or hidden photon) with photoelectric-like interaction.
  - For vector boson, no experimental constraint so far.

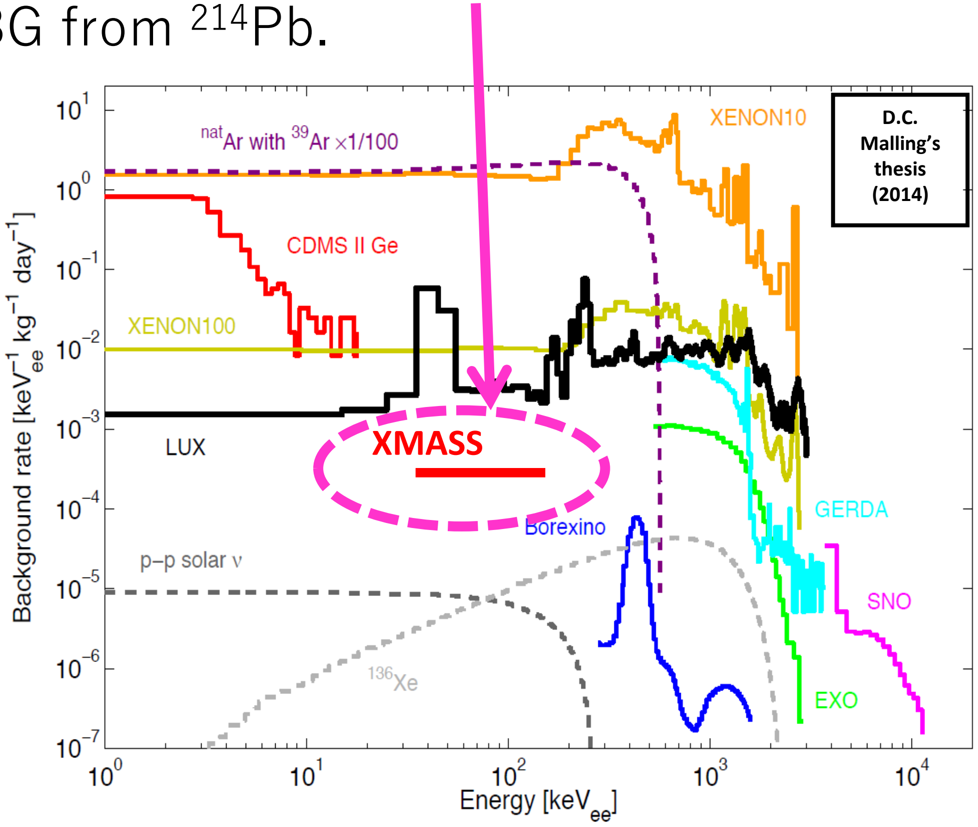
Photoelectric-like interaction



PRL 113 (2014) 121301 Bosonic super-WIMP (2/3)

- 166 days and 41 kg fiducial volume data.
- Search for mono-energetic peak at m_b (the rest mass of a bosonic super-WIMP) using various cuts optimized for each m_b.
  ((1) pre-selection, (2) reconstructed radius (R<15cm) cut, (3) timing cut, (4) pattern cut)
- The remaining event rate of $O(10^{-4})$ /day/keVee/kg is the lowest ever achieved and consistent with expected BG from ^{214}Pb.





↑BG level of each experiment (before separation for nuclear recoil in 2–phase DM search detector)

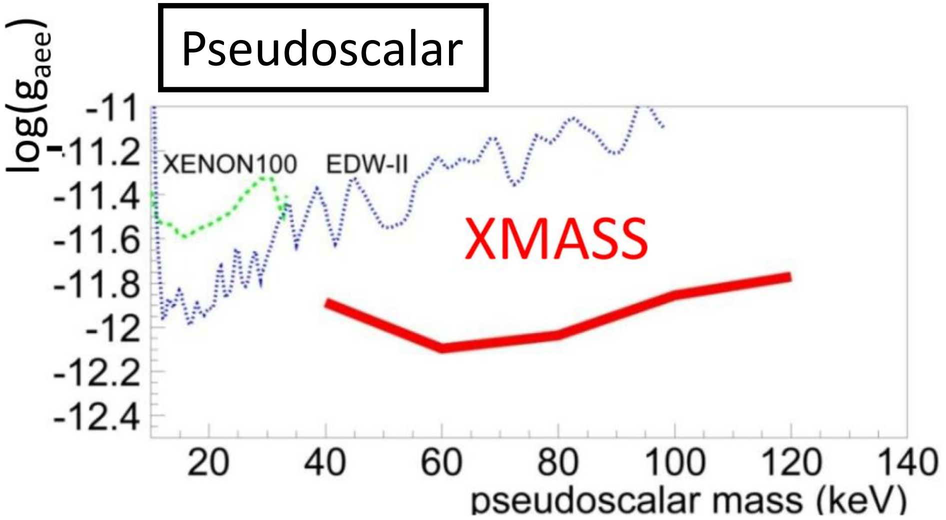
PRL 113 (2014) 121301

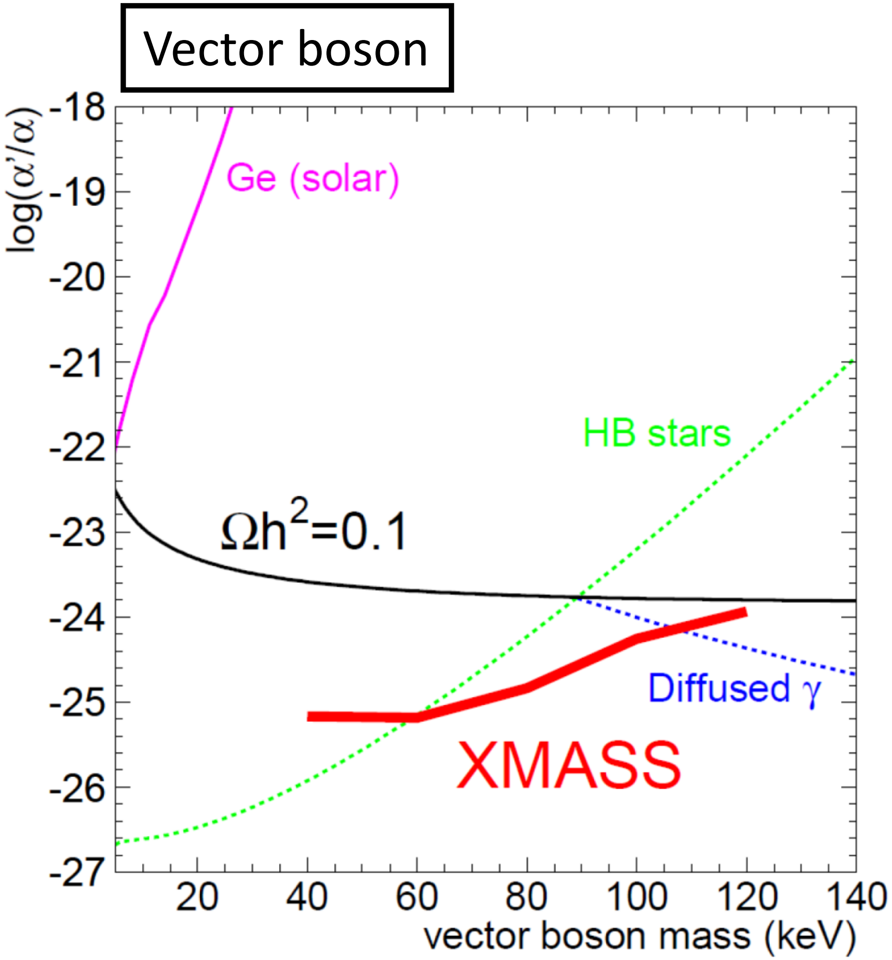
Bosonic super-WIMP (3/3)

- Constraint on coupling constant.
- For vector bosonic super-WIMPs, the first direct search in the 40–120 keV range.

The limit excludes the possibility that such particles constitute all of dark matter.

The most stringent direct constrair on g_{aee} thanks to the low BG in thi energy region.

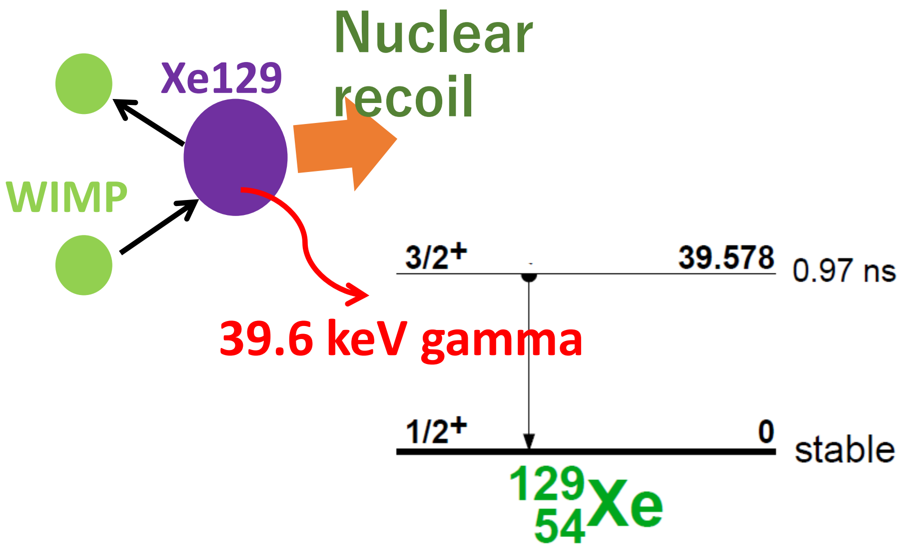




PTEP 063C01 (2014)

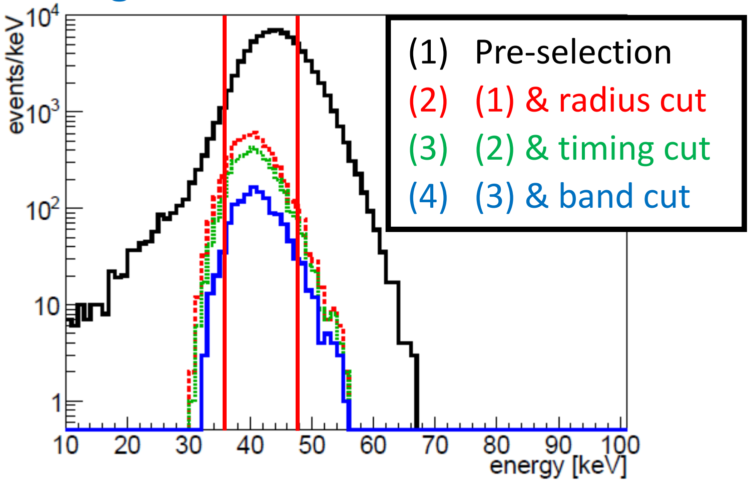
Inelastic scattering DM search (1/2)

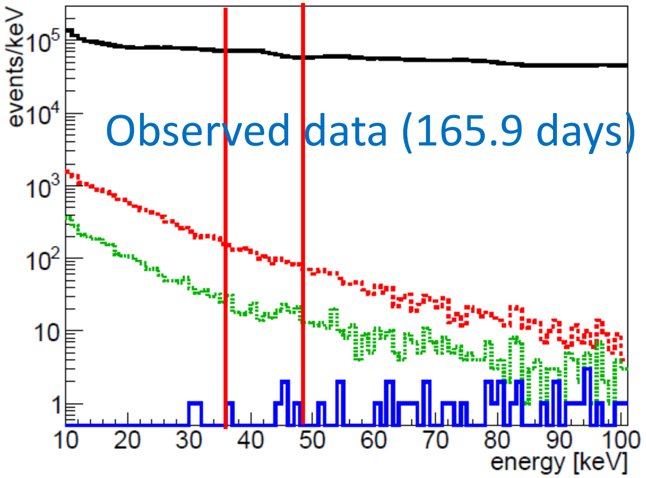
- WIMPs would cause inelastic scattering on ^{129}Xe.
  Nuclear recoil as well as 39.6 keV γ ray emission are expected.
- Peak search at 39.6 keV with various cuts are used.
  Reconstructed radius cut (R<15cm), timing cut, and pattern cut.



- $\chi + {}^{129}Xe \rightarrow \chi + {}^{129}Xe^*$
  ${}^{129}Xe^* \rightarrow {}^{129}Xe + \gamma$ (39.6keV)
- Natural abundance of ^{129}Xe: 26.4%

Signal MC for 50GeV WIMP

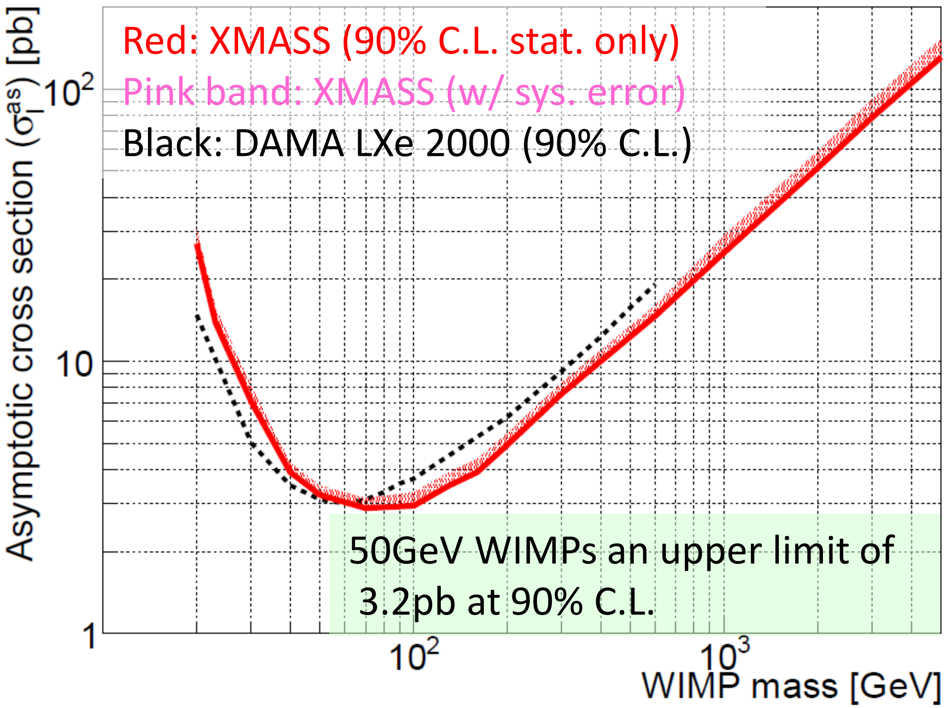


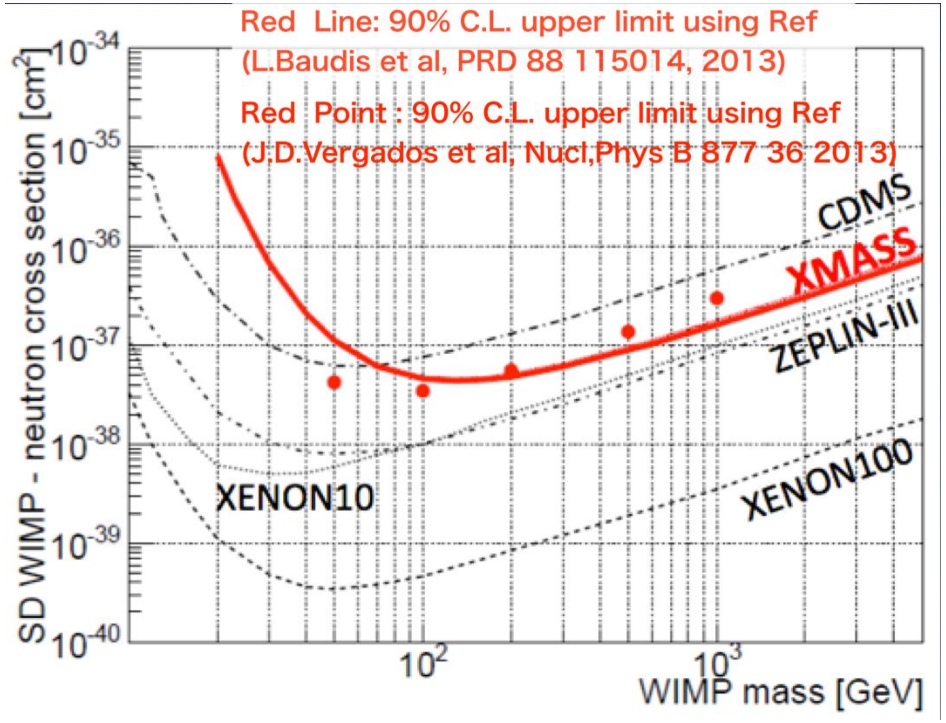


PTEP 063C01 (2014)

Inelastic scattering DM search (2/2)

- 41 kg fiducial volume (^{129}Xe: 11 kg) w/o BG subtraction
- Better limit than DAMA for > 50 GeV WIMPs
- Another way for study on SD interaction.





PLB 759 (2016) 64-66

2ν double electron capture on ^{124}Xe (1/2)

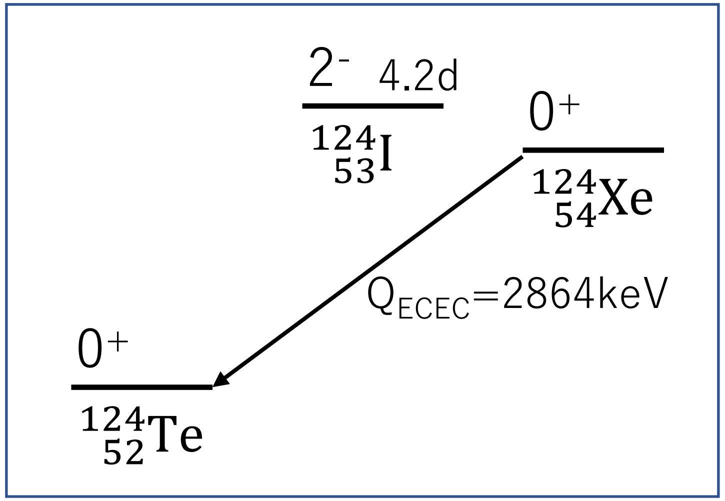
- Natural xenon contains ^{124}Xe (N.A.=0.095%) which can undergo 2νECEC.

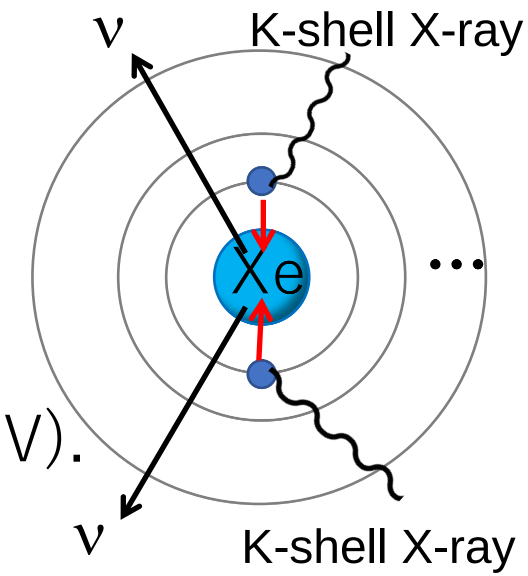
  $^{124}Xe\ (g.s., 0^+) + 2e^- \rightarrow {}^{124}Te\ (g.s., 0^+) + 2\nu_e + 2864\text{keV}$

- In the case of 2 K-shell electrons are captured,
  - Only X-rays and Auger electrons are observable
  - Total energy deposit is 2 x E_B = 63.6 keV

- Expected half-life is 10^{20}-10^{24} years.

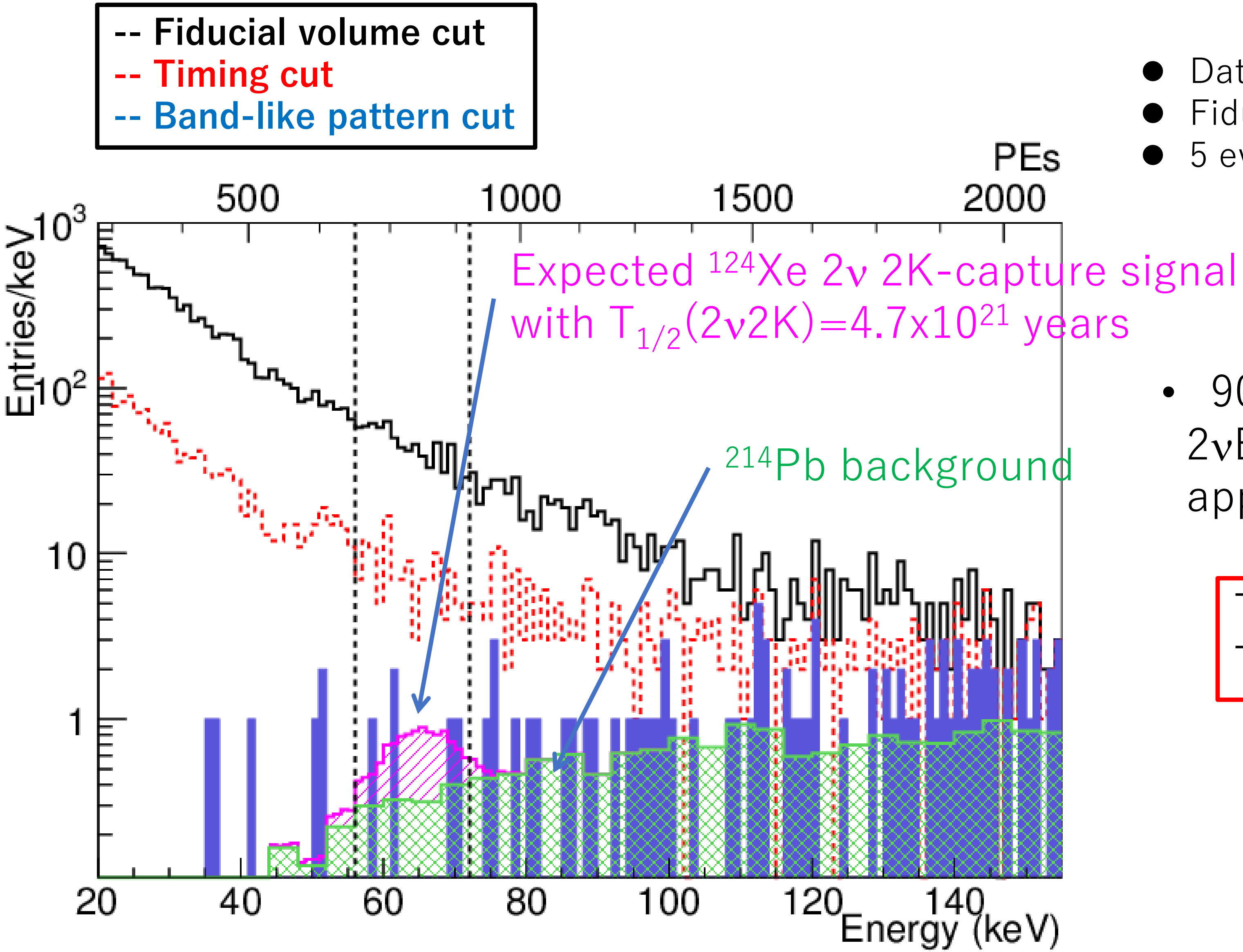
- ^{126}Xe (N.A.=0.089%) can also undergo 2νECEC, but it is much slower due to smaller Q-value (896keV).





PLB 759 (2016) 64-68

2ν double electron capture on ^{124}Xe (2/2)



- Data set: Dec. 2010–May 2012 (132.0 live days)
- Fiducial mass of 41 kg (39 g of ^{124}Xe)
- 5 events remained in the signal region.

- 90% C.L. lower limit on ^{124}Xe 2νECEC half-life using the Bayesian approach was set.

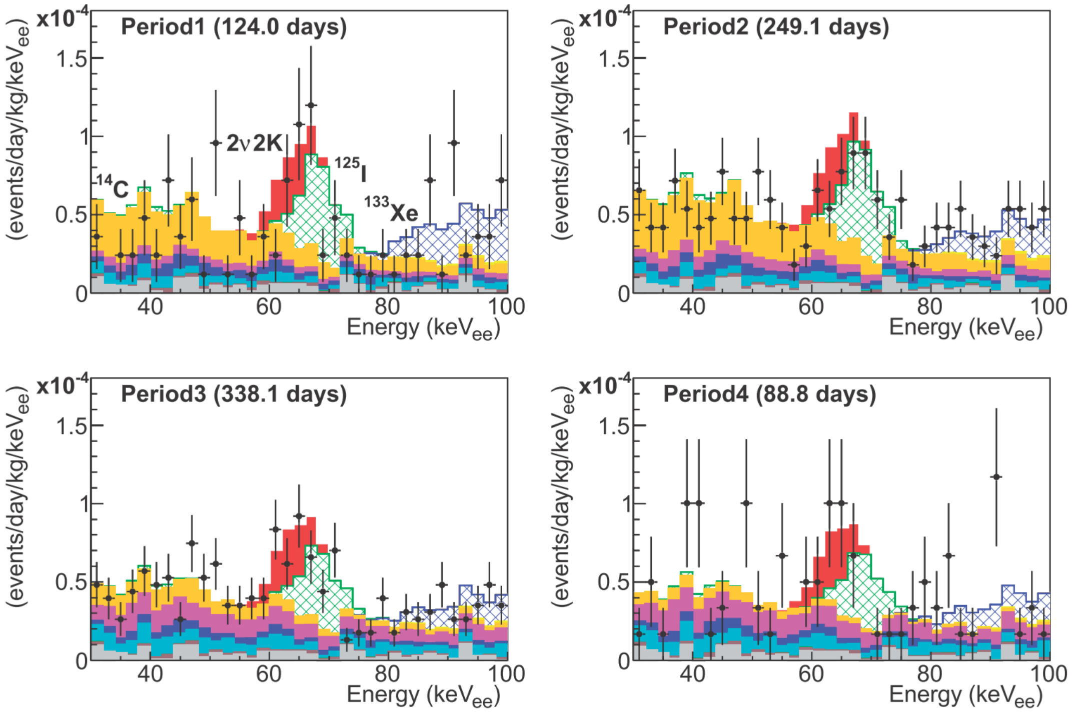
$T_{1/2}^{2\nu 2K}(^{124}Xe) > 4.7\times10^{21}$ yrs
$T_{1/2}^{2\nu 2K}(^{126}Xe) > 4.3\times10^{21}$ yrs
(90%CL)

PTEP (2018) 053D03

Improved 2ν double electron capture on ^{124}Xe and ^{126}Xe

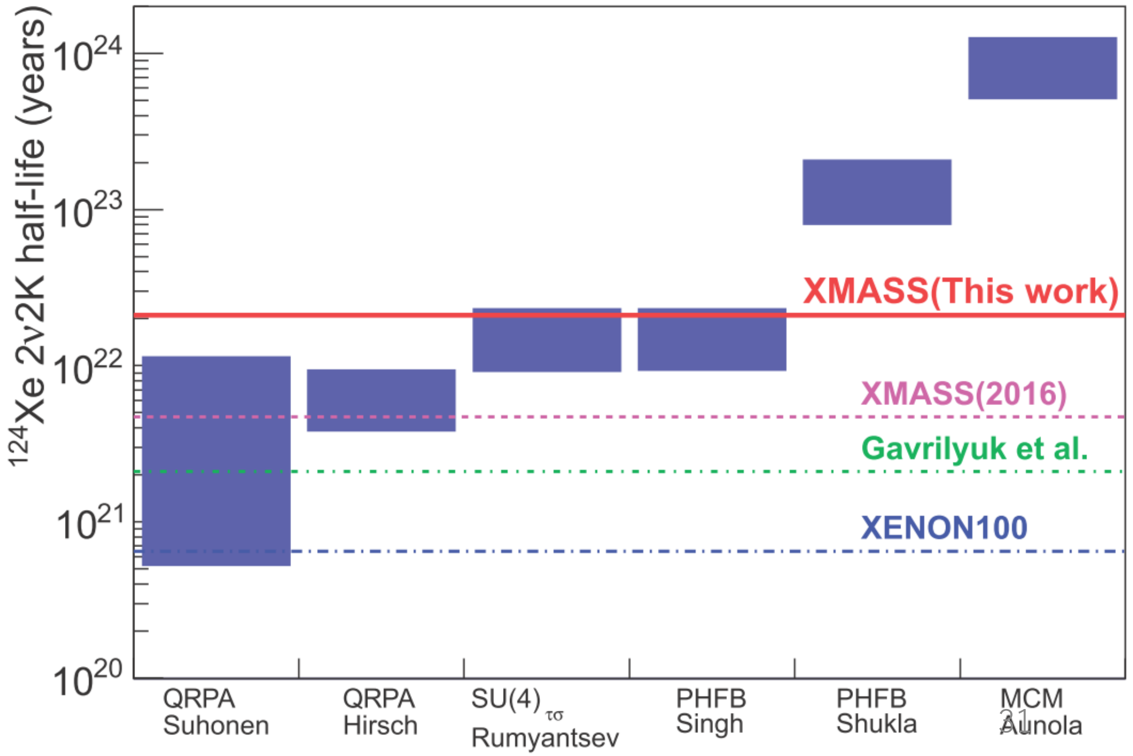
- Data set: Nov. 2013–Jul. 2016 (800.0 live days)
- Fiducial mass of 327 kg (311 g of ^{124}Xe, 291 g of ^{126}Xe)

Period	Start date–end date	Live time (days)	Gas circulation	Comment
1	20 Nov 2013–13 May 2014	124.0	None	Activated
2	13 May 2014–13 Mar 2015	249.1	None	
3	13 Mar 2015–29 Mar 2016	338.1	~1.5 L/min	
4	14 Apr 2016–20 Jul 2016	88.8	~1.5 L/min	Activated



- 90% C.L. upper limits:

$T_{1/2}^{2\nu2K}(^{124}Xe) > 2.1\times10^{22}$ yrs
$T_{1/2}^{2\nu2K}(^{126}Xe) > 1.9\times10^{22}$ yrs

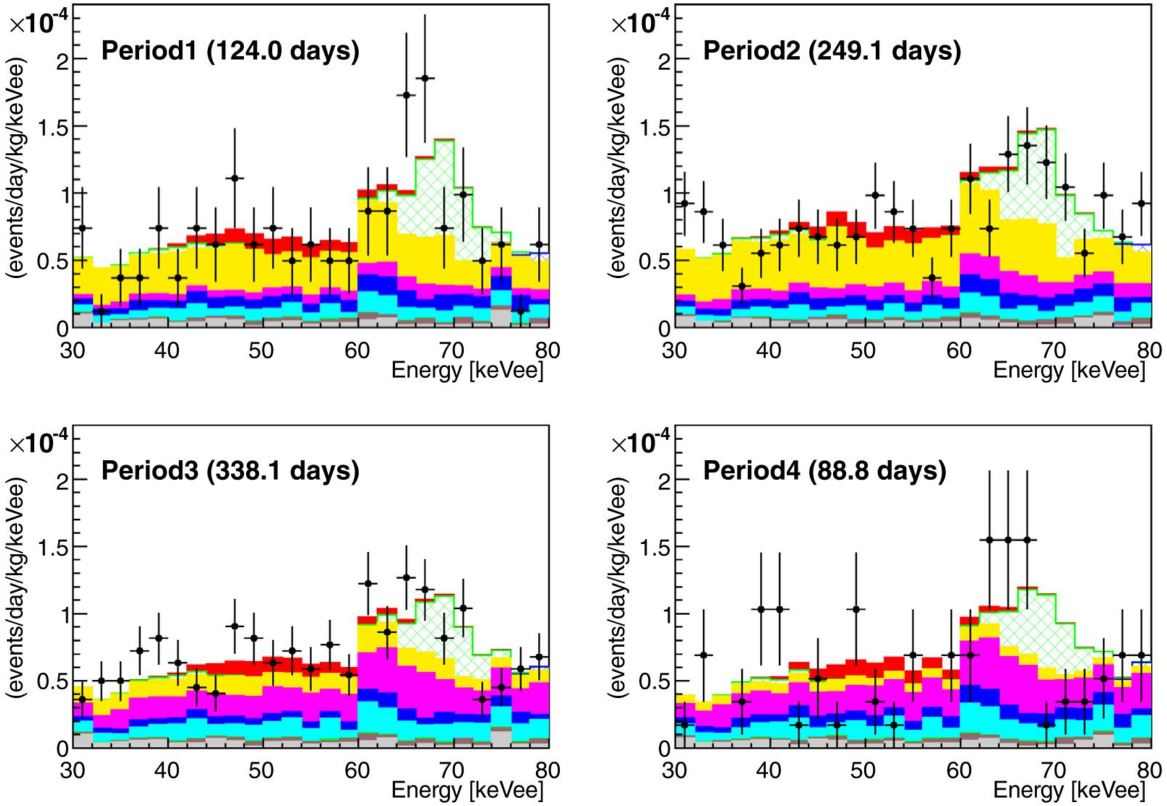


Astropart. Phys. 110 (2019) 1–7

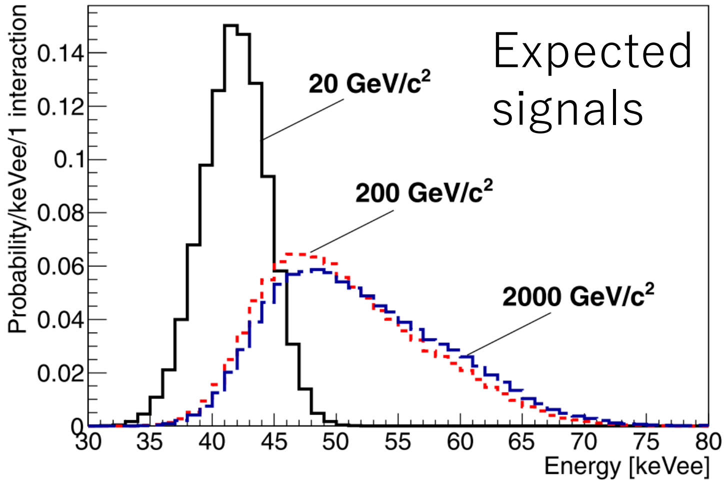
Search for WIMP-^{129}Xe inelastic scattering

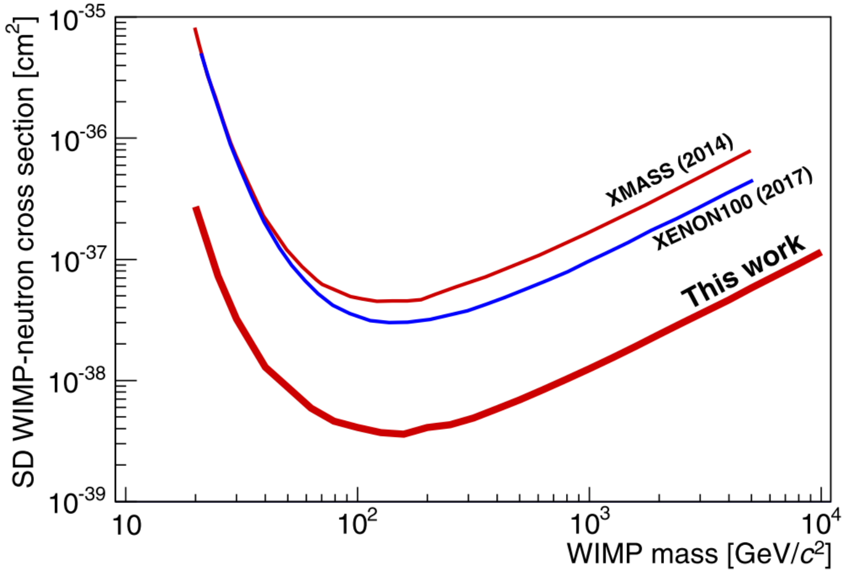
- 327 kg × 800.0 days data.
- Detailed evaluation of background events.
- Event classification (β-like and γ-like) based on scintillation timing

β-depleted spectra with 200 GeV WIMP



BG:
^{125}I (green)
^{14}C (orange)
^{39}Ar (magenta)
^{85}Kr (blue)
^{214}Pb(cyan)
^{136}Xe(brawn)
ext. γ (gray)

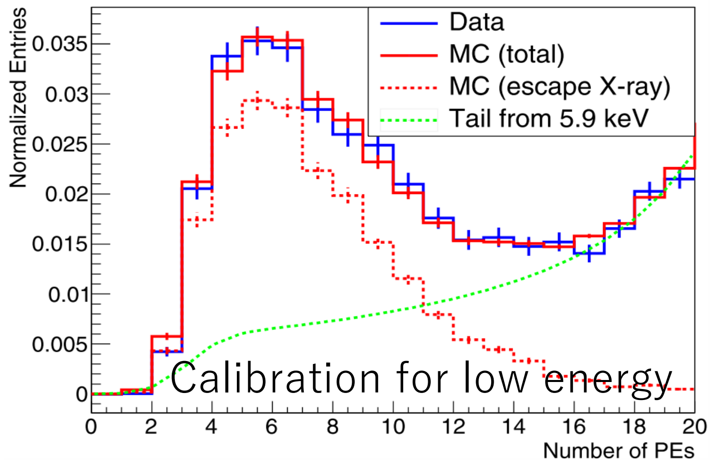




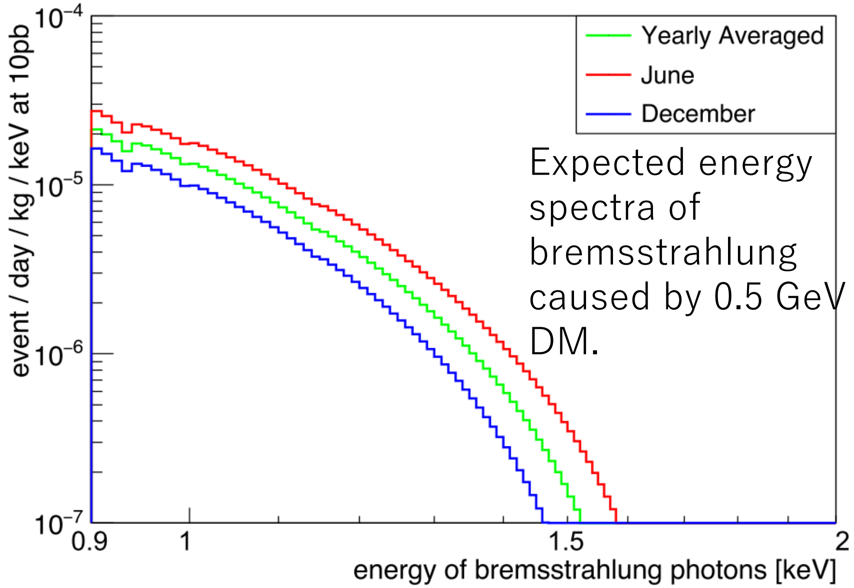
PLB 795 (2019) 308-313

Sub-GeV DM searches

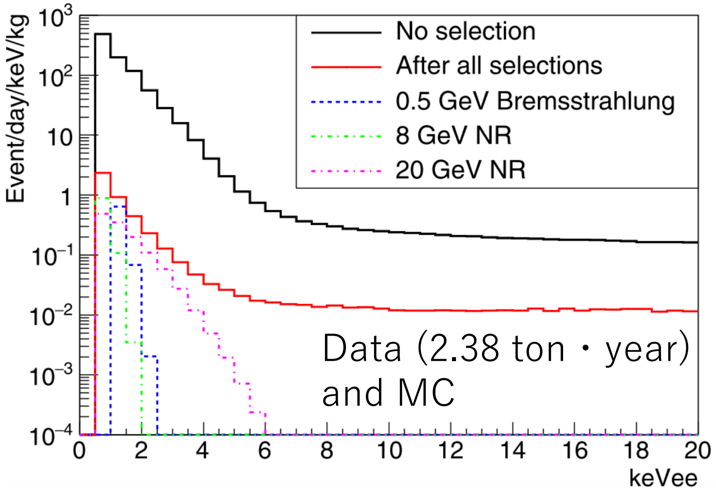
- Inelastic nuclear scattering accompanied by bremsstrahlung emission was used to search sub-GeV WIMPs (0.32–1 GeV).
- Upper limit of 1.6×10^{-33} cm^2 @0.5 GeV was set.
- This is the first experimental result of a search for DM mediated by the bremsstrahlung effect.



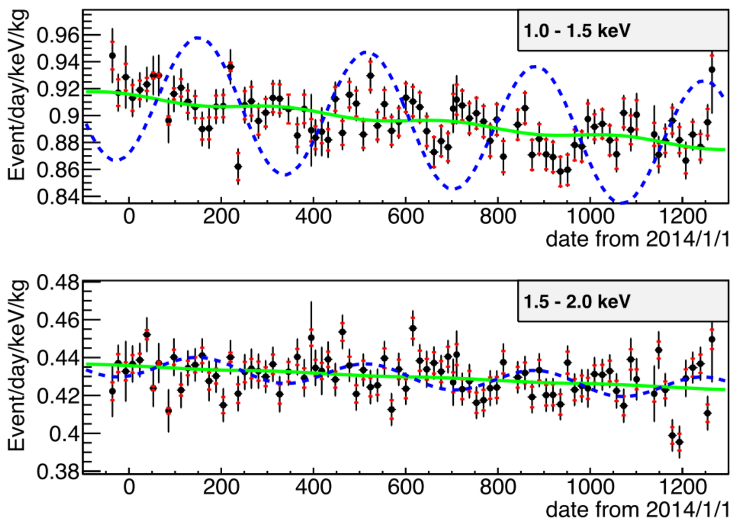
Calibration for low energy

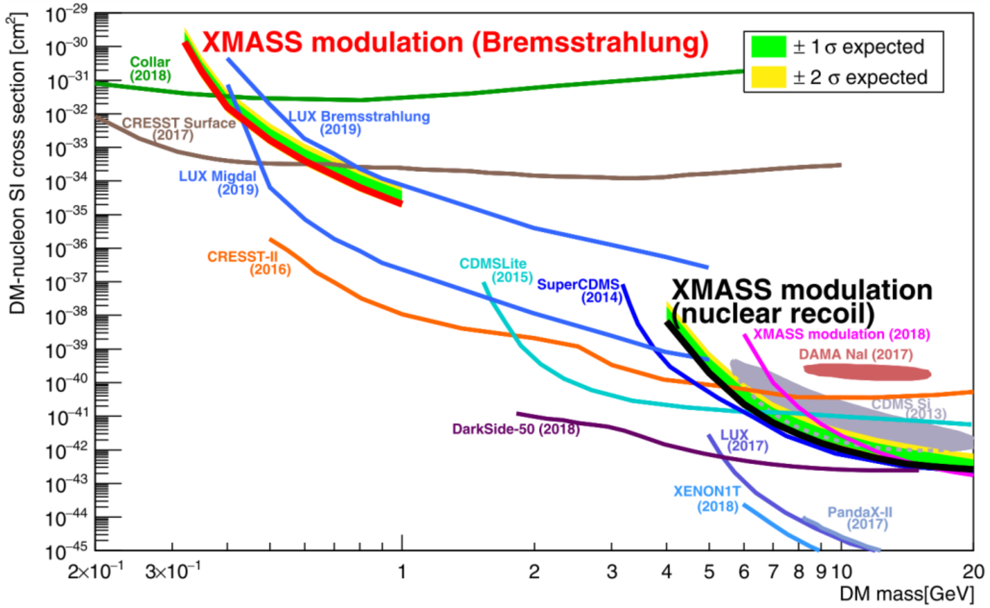


Expected energy spectra of bremsstrahlung caused by 0.5 GeV DM.



Data (2.38 ton・year) and MC

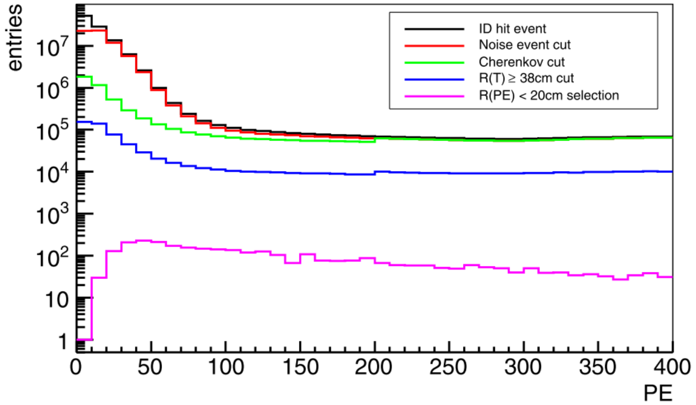


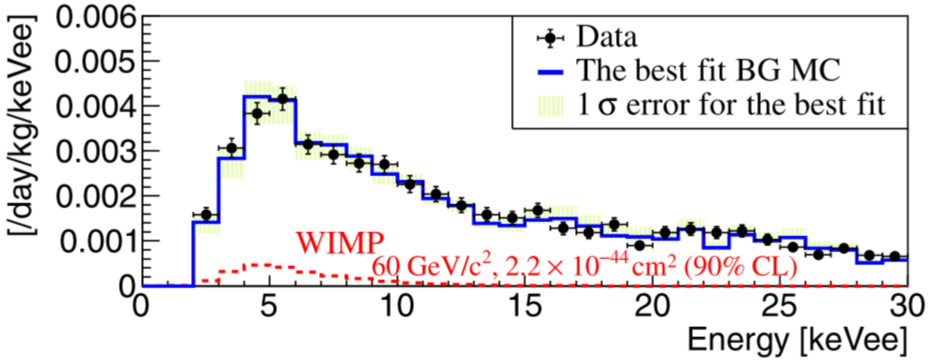


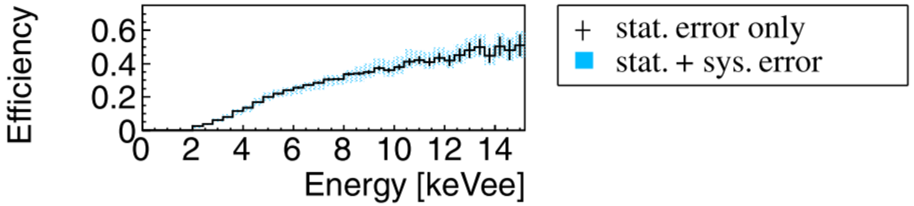
PLB 789 (2019) 45-53

WIMP search in FV data

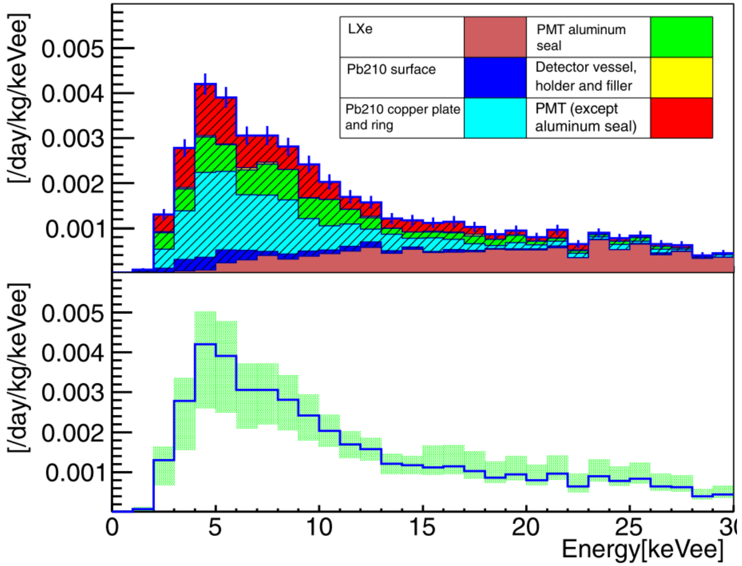
- WIMP search in FV (97 kg LXe).
- 705.9 live days.
- $(4.2 \pm 0.2) \times 10^{-3}$ /day/kg/keV$_{ee}$ @5 keV$_{ee}$
- Detailed BG evaluation.
- Best limits among single phase liquid xenon detectors.

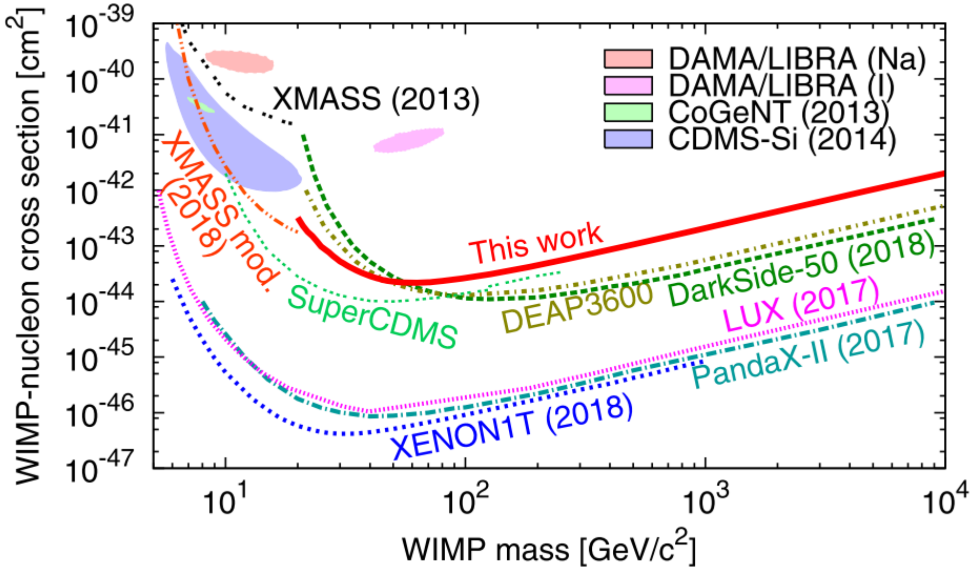






Contents	Systematic error	
	2–15 keV$_{ee}$	15–30 keV$_{ee}$
(1) Plate gap	+6.2/−22.8%	+1.9/−6.9%
(2) Ring roughness	+6.6/−7.0%	+2.0/−2.1%
(3) Copper reflectivity	+5.2/−0.0%	+2.5/−0.0%
(4) Plate floating	+0.0/−4.6%	+0.0/−1.4%
(5) PMT aluminum seal	+0.7/−0.7%	–
(6) Reconstruction	+3.0/−6.2%	–
(7) Timing 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%

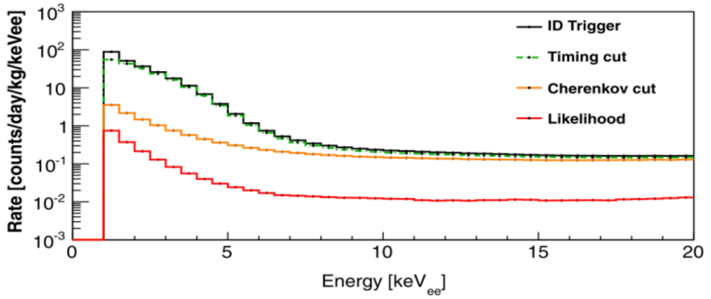


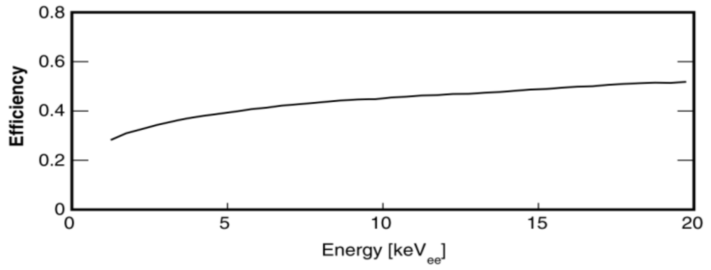


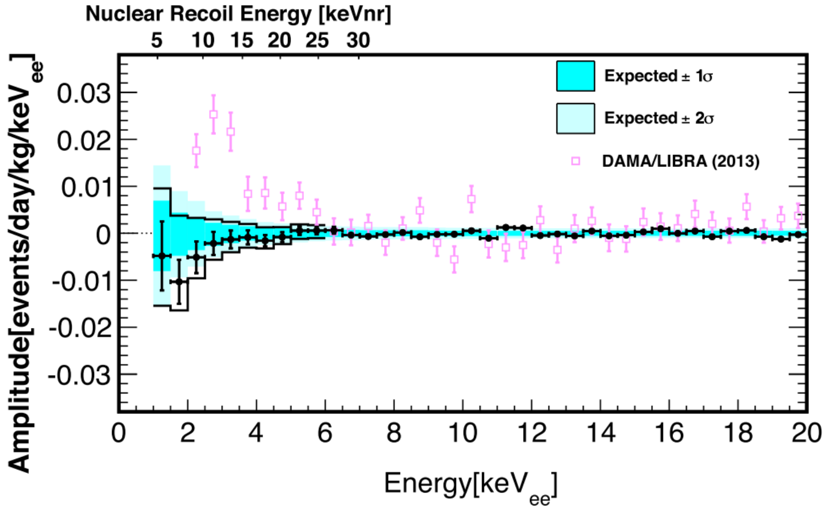
PRL D97 (2018) 102006

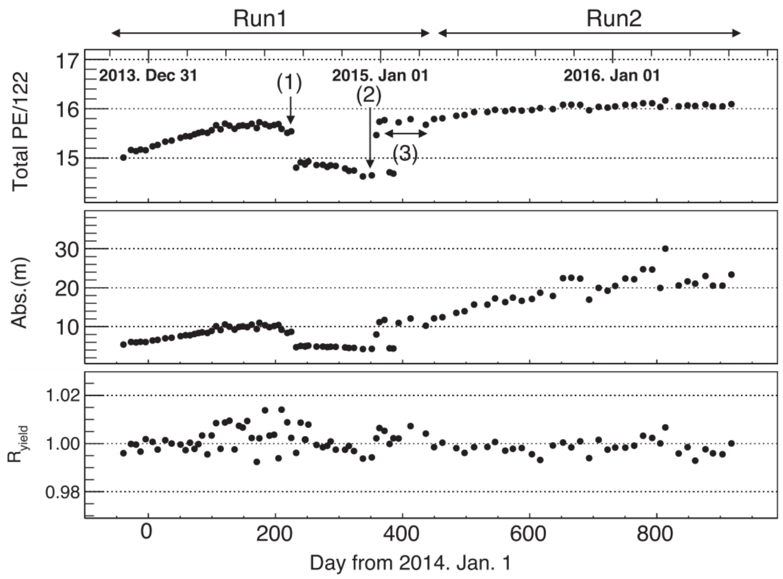
Annual modulation with 2.7 years data

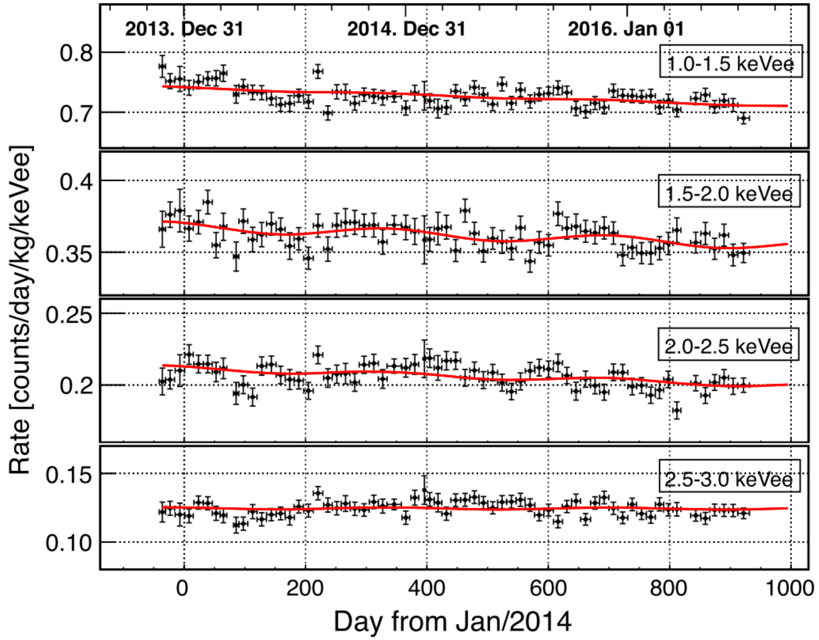
- 832 kg × 800 live days.
- 1.9×10^{-41} cm^2 at 8 GeV WIMPs (factor 2 improved from 2016)

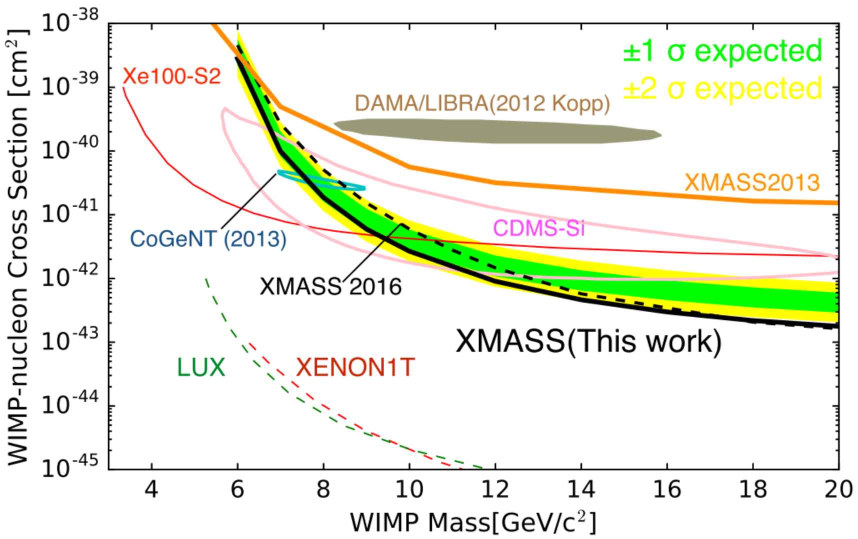










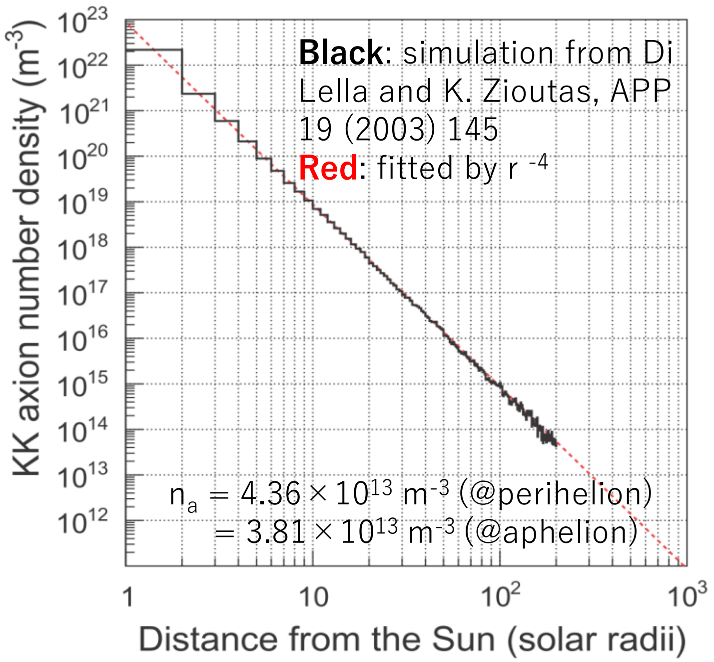


PTEP (2017) 103C01

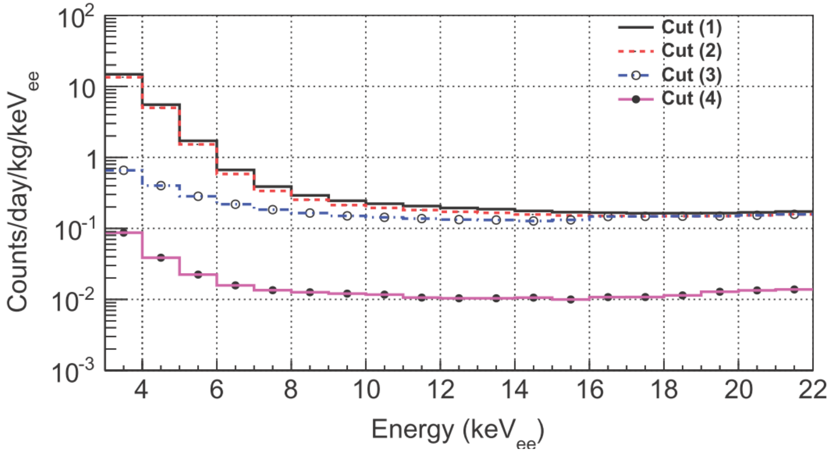
Solar KK axion search

- In theories with large extra dimensions beyond the standard 4D spacetime, axions could propagate in such extra dimensions and acquired Kaluza-Klein (KK) excitations.
- KK axions are produced in the Sun, and could solve the unexplained heating of solar corona.
- Search for modulated 2 photon events (~9 keV) from the decay of trapped KK axion by using 832 × 359 kg・days data.

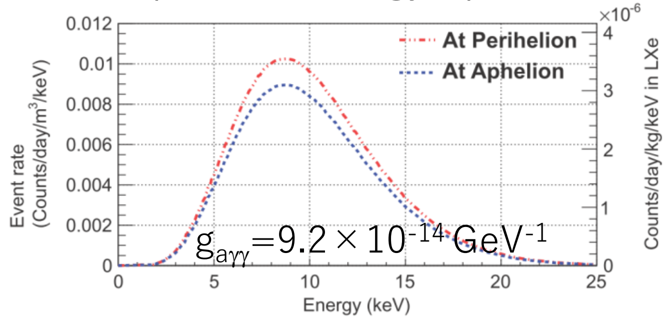
Number density of trapped KK axions as a function of the distance from the Sun



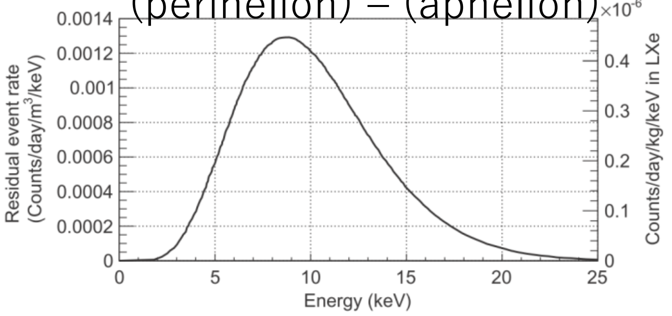
Perihelion: 211.44 $R_\odot$
Aphelion: 218.63 $R_\odot$

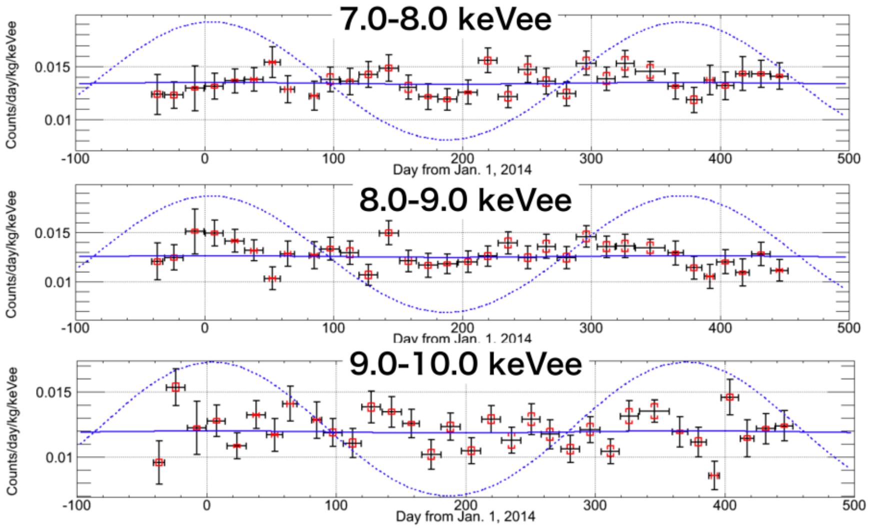


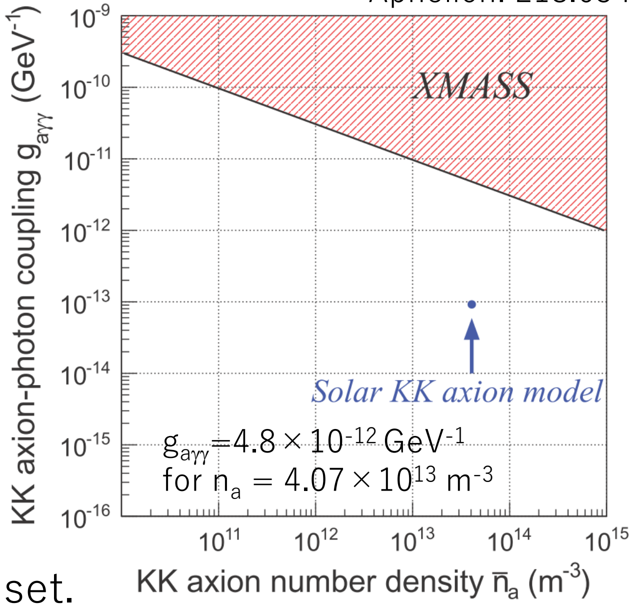
Expected energy spectra



(perihelion) – (aphelion)







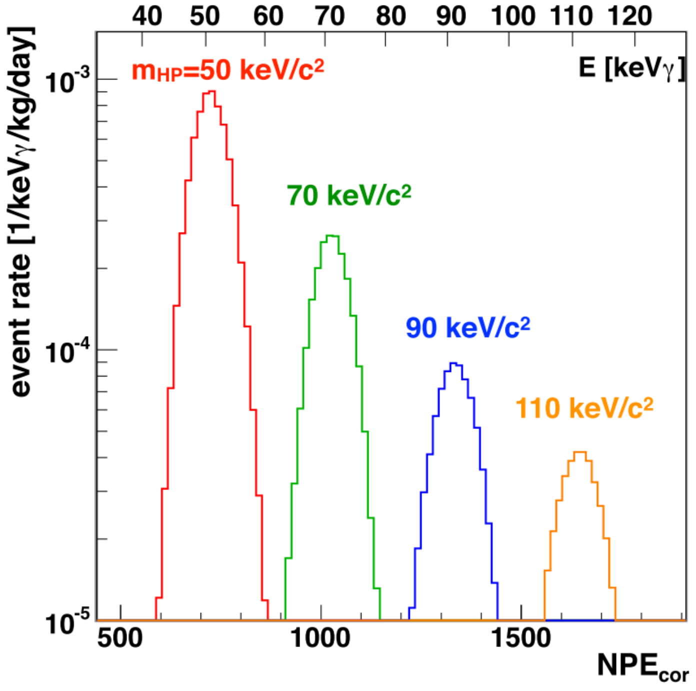
No significant modulation was observed. → limit was set.

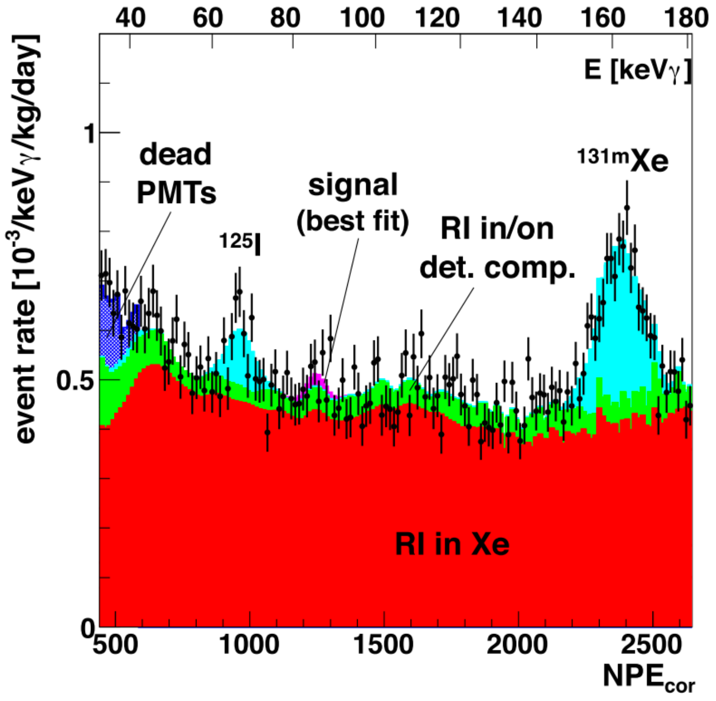
PLB 787 (2018) 153–158

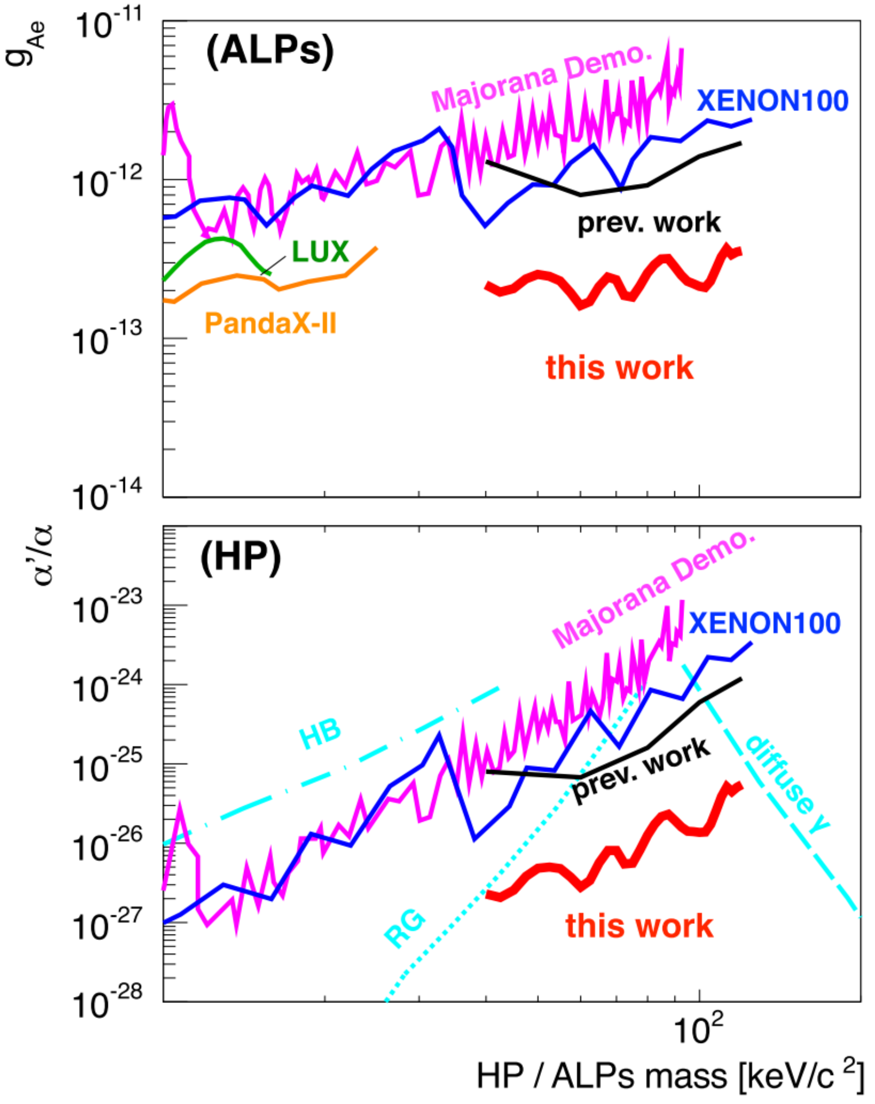
Hidden photon and axion-like particles

- Hidden photons (vector) and axion-like particles (pseud-scalar) are candidates for cold DM if they were produced non-thermally in the early universe.
- 327 kg $\times$800 live days data.
- $\alpha'/\alpha < 6\times10^{-26}$ and $\gamma_{Ae} < 4\times10^{-13}$ (40–120 keV/c^2)

Expected hidden photons signal
$\alpha'/\alpha = 4\times10^{-26}$



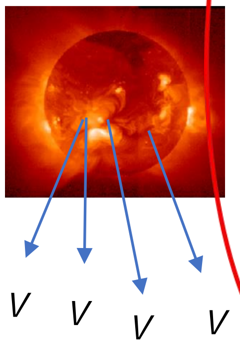


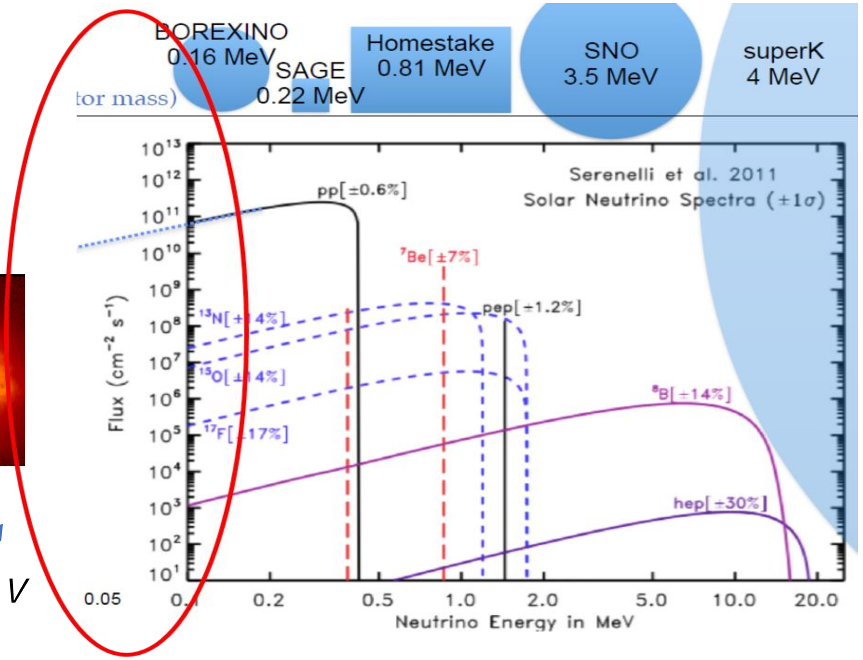


PLB 809 (2020) 135741

Exotic neutrino interaction searches by using solar neutrino

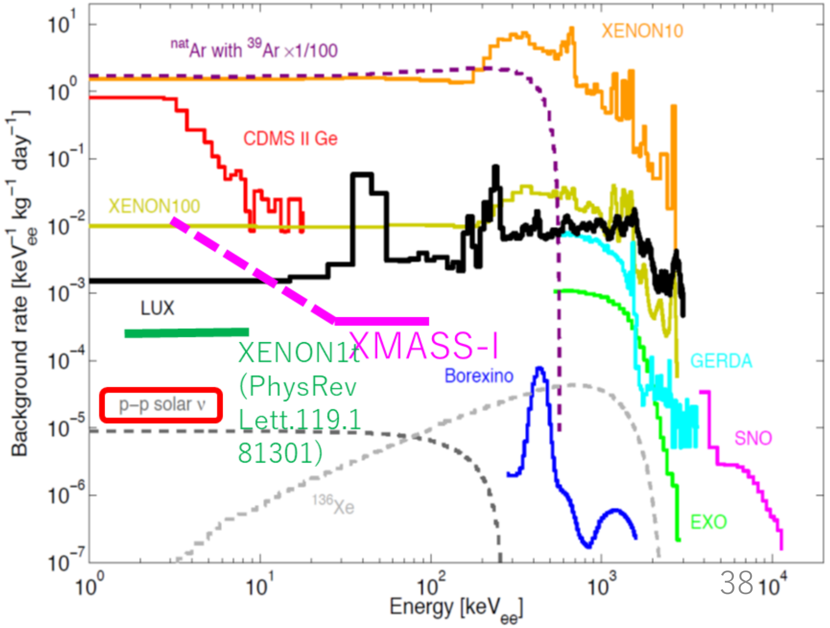
- For observation of solar neutrino in low energy with DM search detector like XMASS-I → more than 2 order of magnitude BG reduction is needed.
- If neutrino has exotic interaction predicted from expansion of standard model, increasing of events in low energy region is expected. ➡ DM search detector with low energy threshold is suitable to search for such kinds of interaction.
- XMASS-I searched for:
  - Neutrino millicharge
  - Neutrino magnetic moment
  - Dark photon ($U(1)_{B-L}$)

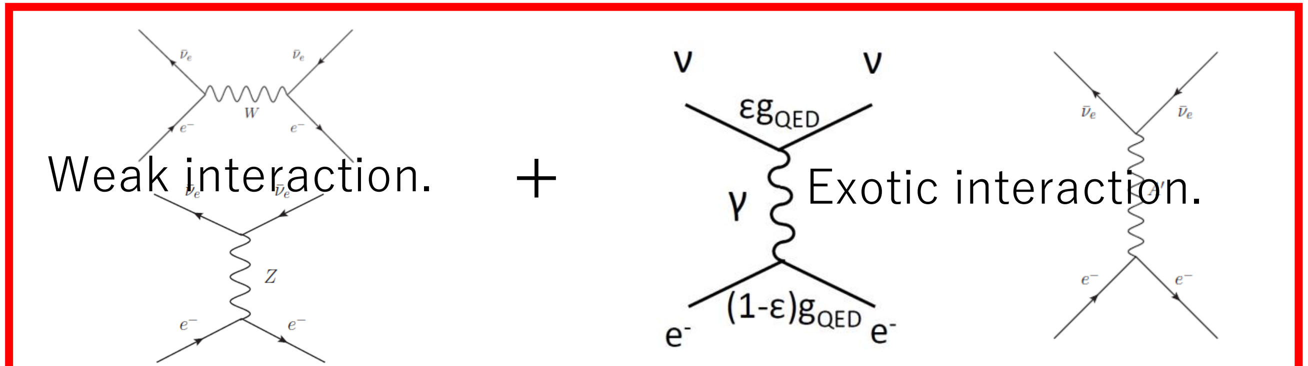




Peter Sorensen Neutrino2016

Original figure ; D.C.Mailing Ph.D (2014) Fig 1.5





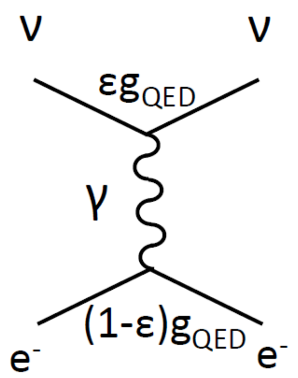
PLB 809 (2020) 135741

Neutrino millicharge

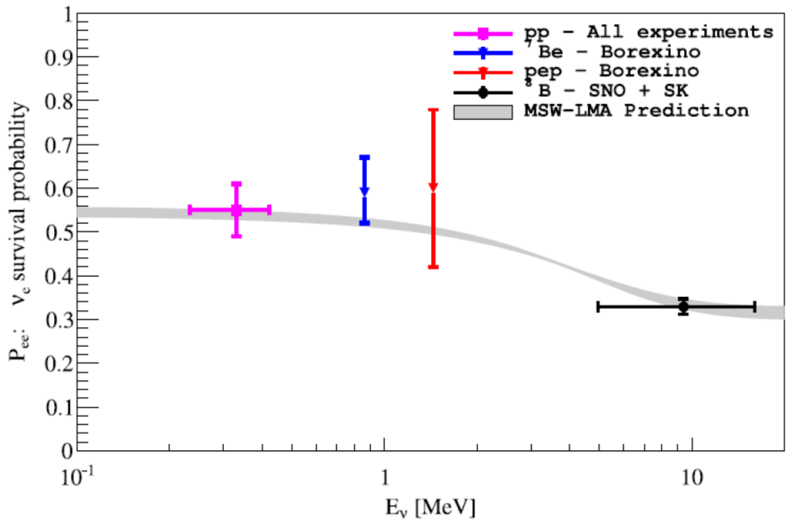
- In standard model, neutrinos are assumed to have 0 charge.
- But, they may have non-zero charge in expansion of standard model.
- Previous researches：
  - GEMMA's data, (A.Studenikin, Europhys.Lett. 107 (2014)39901) $\delta_e < 1.5 \times 10^{-12} e$
  - PVLAS, (F.Della Valle et al., Eur. Phys. J. C 76(2016)24) $\delta_{e,\mu,\tau} < 3 \times 10^{-8}$ e @ m_ν<10meV
- XMASS:
  - Search for electro magnetic interaction in solar neutrino

$$\left(\frac{d\sigma}{dT_e}\right)_{EM} \cong \frac{2\pi\alpha}{m_e T_e^2}\delta^2$$

  - Search for each flavor neutrino resulted from neutrino oscillation.



標準模型における微電荷をもつニュートリノと電子の反応



Phys. Of the Dark Univ. 4 (2014) 44-49

Fig. 5. Survival probability for solar ν_e using the low-Z SSM. The LMA-MSW

PLB 809 (2020) 135741

Neutrino magnetic moment

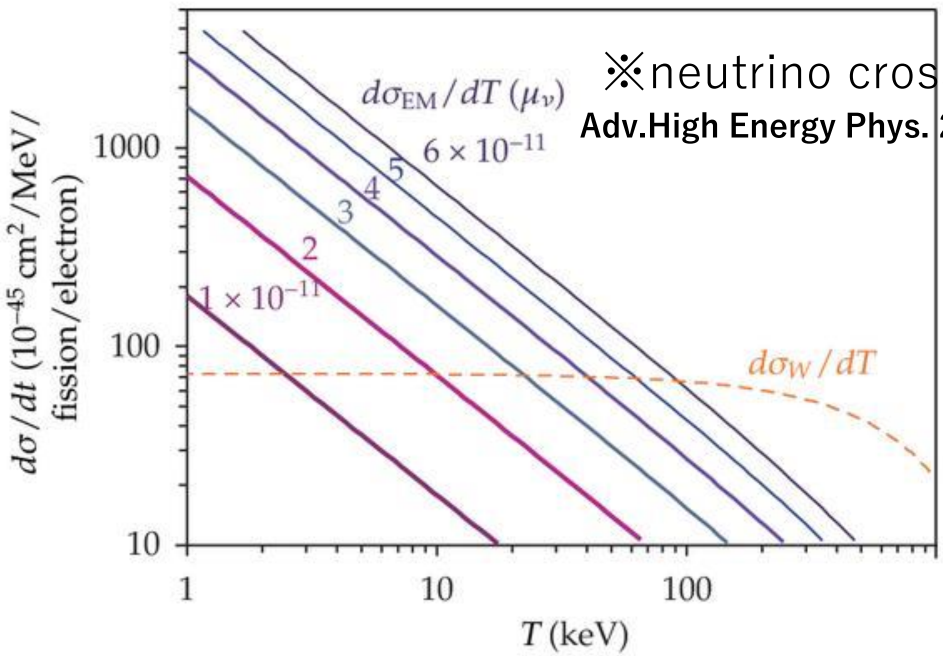
- Neutrino magnetic moment with expansion of standard model:

$$\mu_\nu = \frac{3 m_e G_F}{4\pi^2\sqrt{2}} m_\nu \mu_B \approx 3.2\times10^{-19}\left(\frac{m_\nu}{1eV}\right)\mu_B$$

- From further expansion of standard model, $10^{-(10\sim12)}\,\mu_B$ of magnetic moment is expected (PRL58.1807(1987))
  - Majorana particle
  - ※ limited $<10^{-14}\,\mu_B$ for Dirac particle
- If neutrino has magnetic moment, “electro magnetic interaction” is added.

$$\frac{d\sigma_{\nu_\ell e^-}}{dT_e} = \left(\frac{d\sigma_{\nu_\ell e^-}}{dT_e}\right)_{SM} + \left(\frac{d\sigma_{\nu_\ell e^-}}{dT_e}\right)_{mag}$$

$$\left(\frac{d\sigma_{\nu_\ell e^-}}{dT_e}\right)_{mag} = \frac{\pi\alpha^2}{m_e^2}\left(\frac{1}{T_e} - \frac{1}{E_\nu}\right)\left(\frac{\mu_{\nu_\ell}}{\mu_B}\right)^2$$



※neutrino cross section
Adv.High Energy Phys. 2012 (2012) 350150

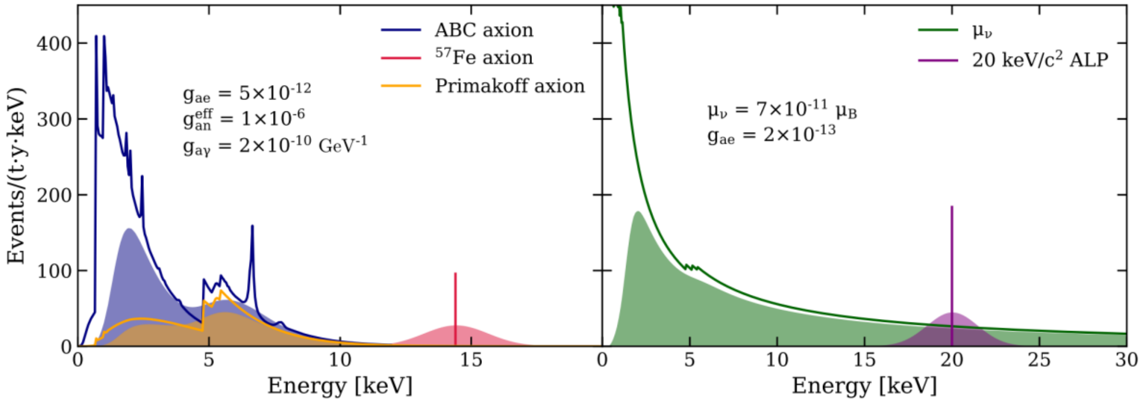
Previous researches:
Borexino $\mu_{\nu s}$(E_ν <1MeV) < $2.8\times10^{-11}\,\mu_B$ (90% C.L.) [solar neutrino]
10.1103/PhysRevD.96.091103

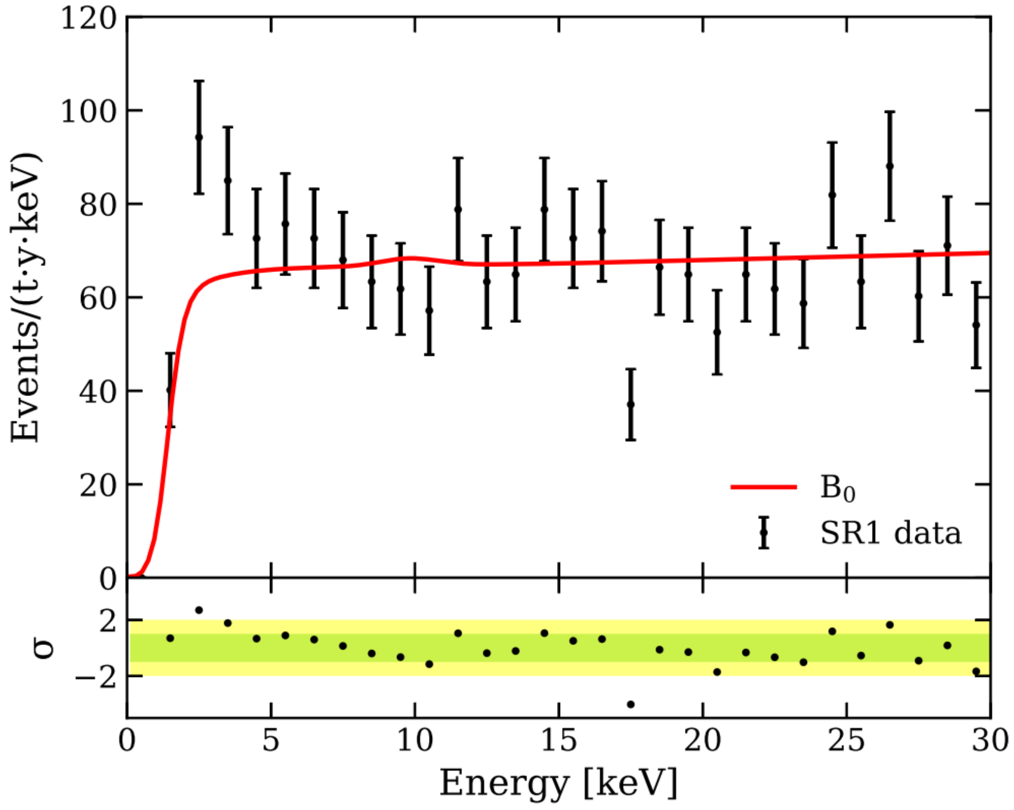
GEMMA $\mu_\nu < 2.9\times10^{-11}\,\mu_B$ (90% C.L.) [reactor neutrino]
Adv.High Energy Phys. 2012 (2012) 350150

arXiv:2006.09721v3

Excess Electronic Recoil Events in XENON1T

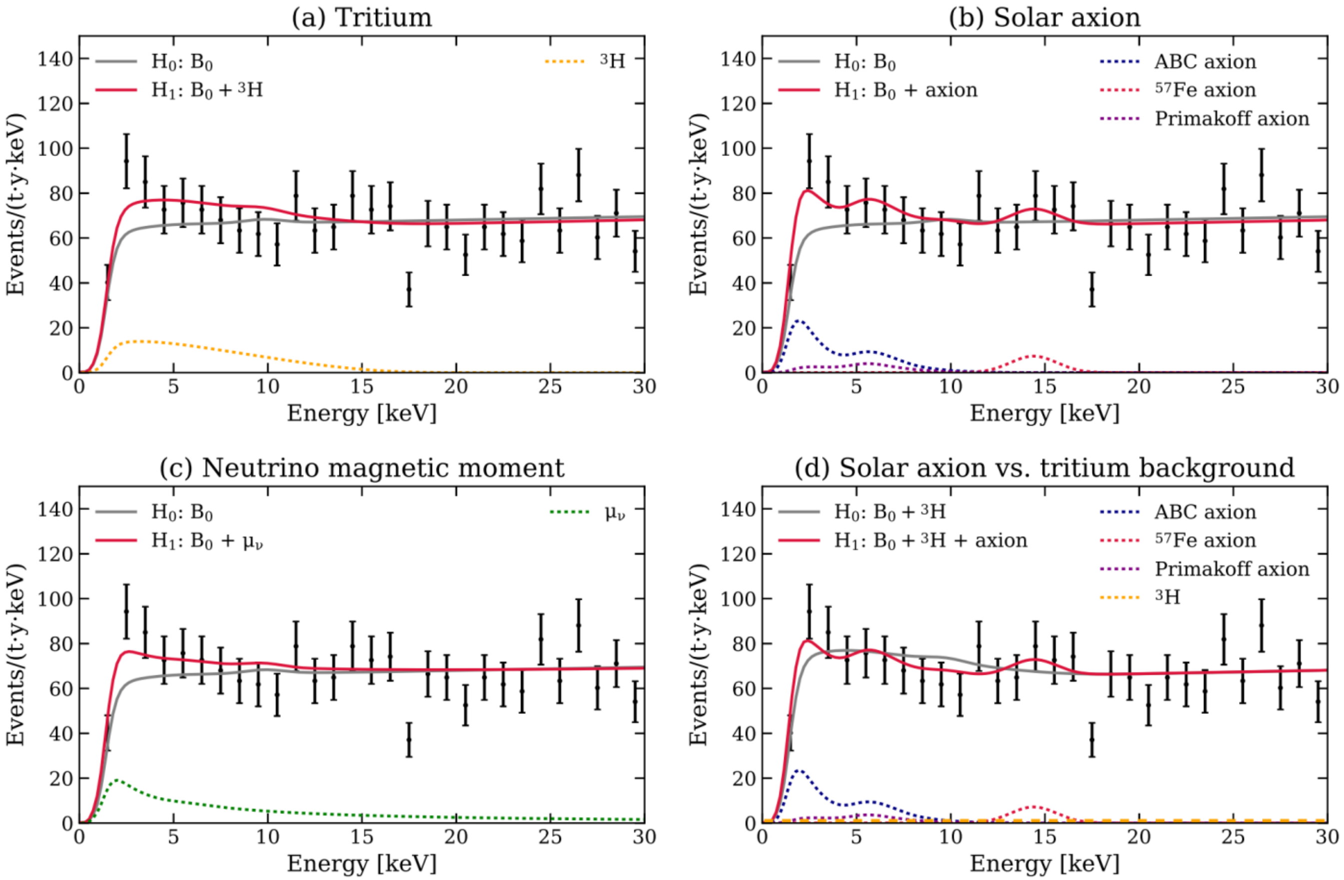
- 0.65 ton・year data.
- Excess around 2–3 keV region was observed.
- Solar axion model: 3.4σ significance.
  - Atomic recombination and deexcitation, Bremsstrahlung, and Compton (ABC).
  - 14.4 keV M1 nuclear transition of ^{57}Fe.
  - Primakoff conversion of photons to axion.
- Neutrino magnetic moment: 3.2σ significance.
- β decays of ^{3}H: 3.2σ significance.

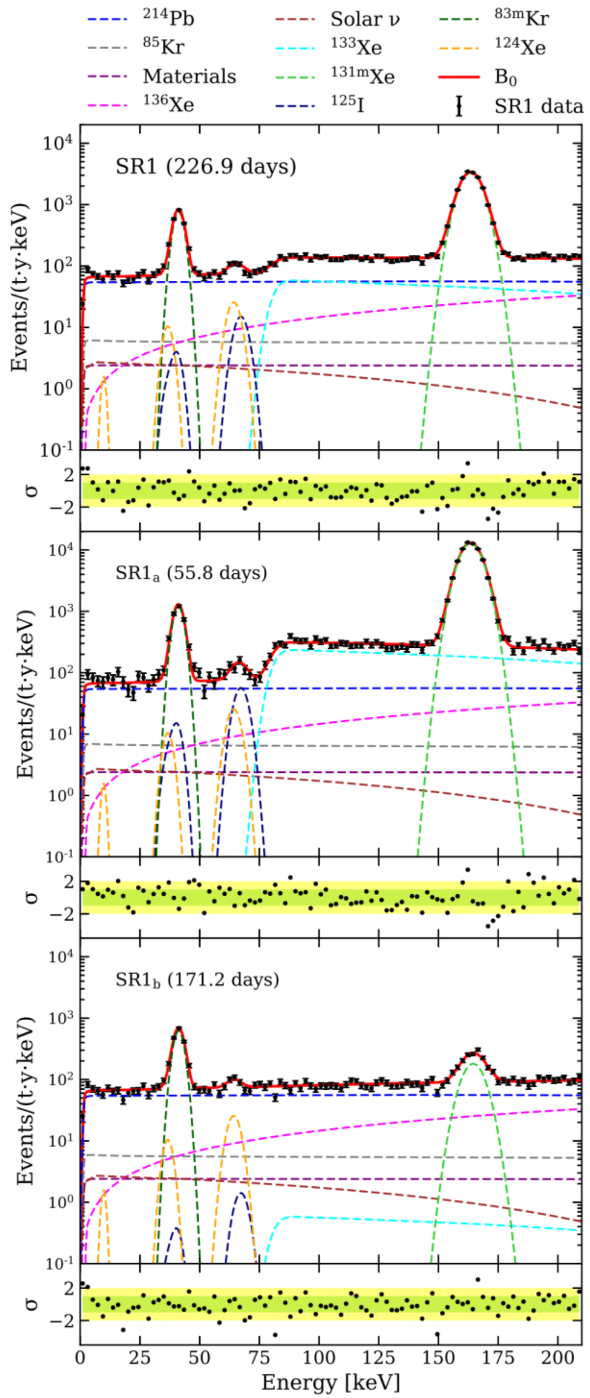




arXiv:2006.09721v3

Excess Electronic Recoil Events in XENON1T

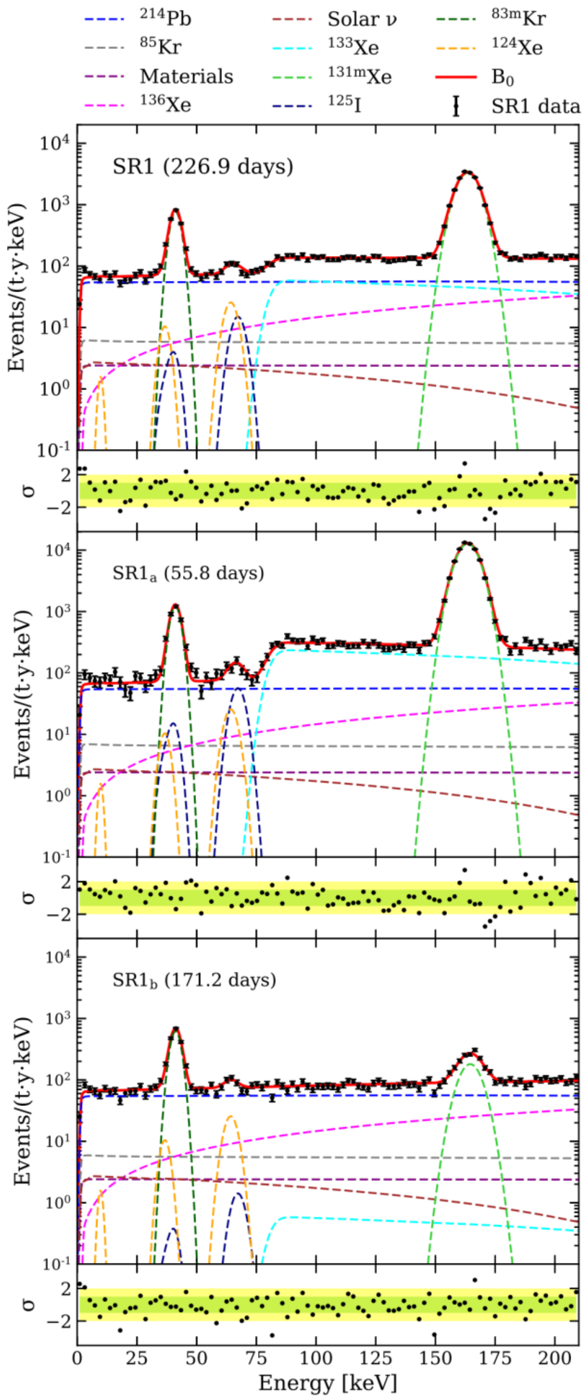




arXiv:2006.09721v3

Excess Electronic Recoil Events in XENON1T

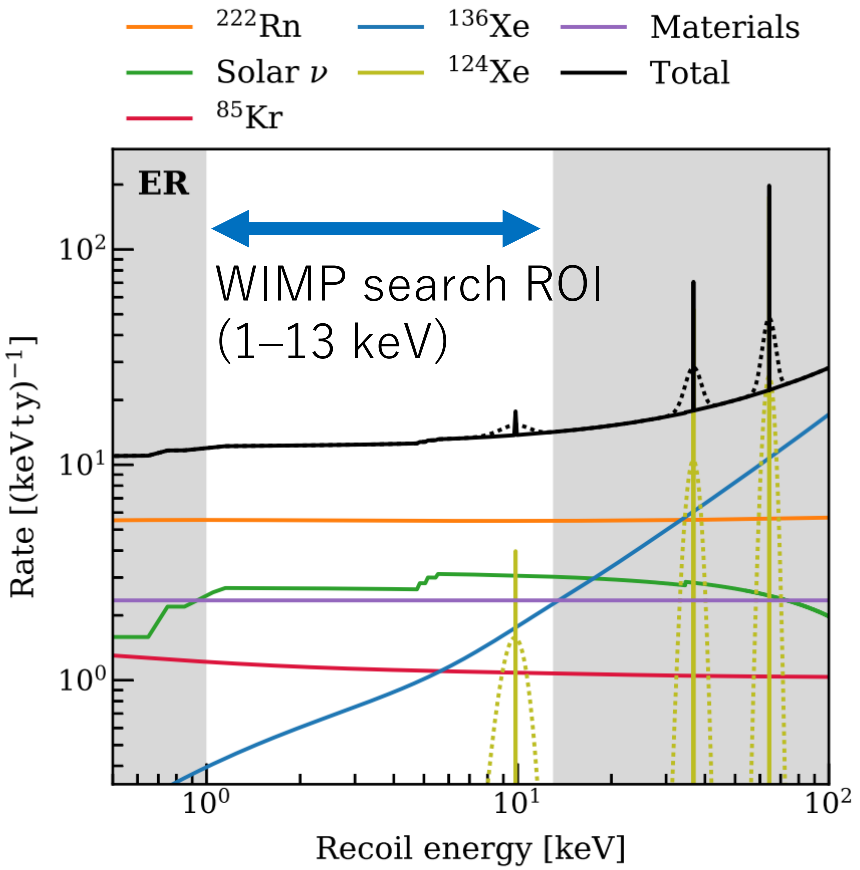
- $^{3}H/Xe$ concentration: $(6.2 \pm 2.0) \times 10^{-25}$ mol/mol
- Assuming abundance of ^{3}H in H_2 is same as atmospheric H_2, $(5–10) \times 10^{-18}$. (H_2O+H_2) concentration > 30 ppb in LXe would be required.
  - High light yield in S1 indicates O(1)-ppb H_2O.
  - But, no direct or indirect measurements for H_2 concentration.

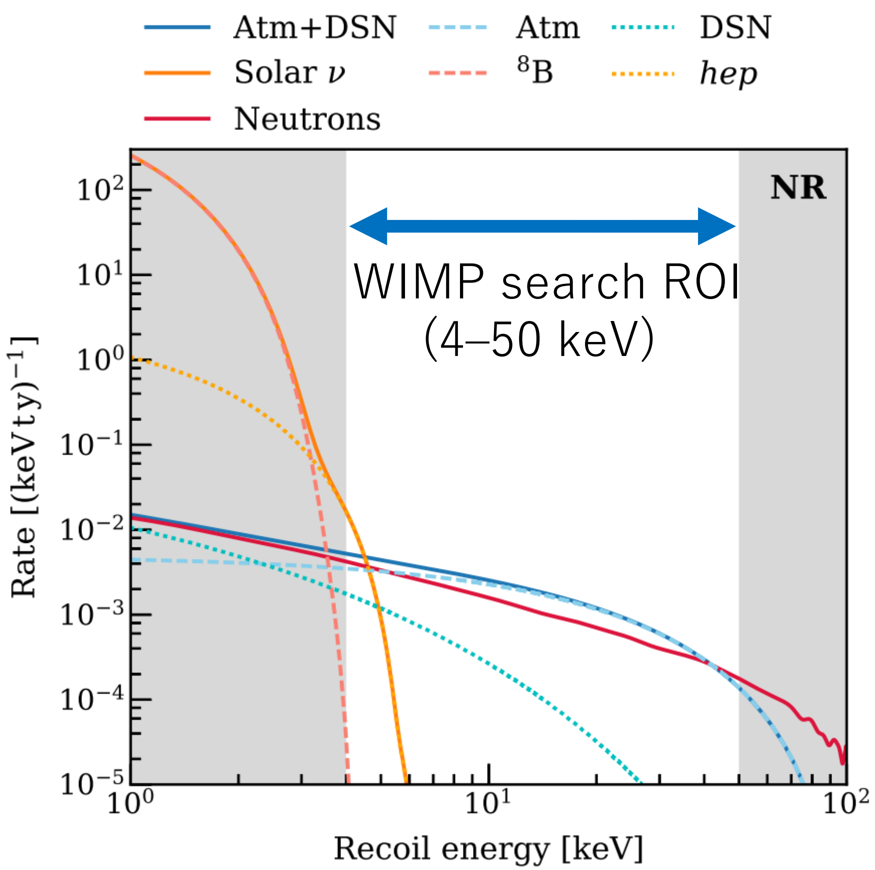


arXiv:2007.08796v3

Background in XENONnT

- Estimated energy spectra of the ER and NR background in 4 ton fiducial volume of XENONnT.





^{222}**Rn** is largest (1 μBq/kg) although it is reduced one order magnitude from XENON1T (10 μBq/kg).

Radiogenic neutrons accounts for neutron tagging efficiency with nVeto.