Status of XENONnT and the final results of XMASS

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March 5, 2024

地下から解き明かす宇宙の歴史と物質の進化
Unraveling the History of the Universe and Matter Evolution with Underground Physics

DMNet

ICRR
Institute for Cosmic Ray Research
University of Tokyo

KAVLI IPMU INSTITUTE FOR THE PHYSICS AND MATHEMATICS OF THE UNIVERSE

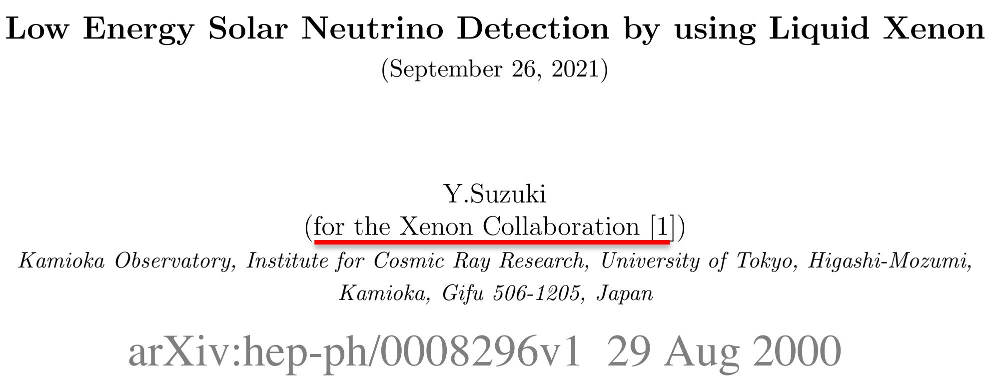
B01: Direct Search for Dark Matter with High-Sensitivity Large-Scale Detectors

The goals of this program, proposed five years ago:

1. Demonstrate the experimental sensitivity of XENONnT to be $2\text{x}10^{-48}\text{cm}^2$ with a 20 tyr exposure by introducing the SK-Gd technology.
2. Support physics analyses in the XMASS-I experiment.
3. Develop low-background photosensors, etc. for future DM exps.
   ➔ talk by Yamashita-san.

XMASS: proposal in 2000

- XMASS was designed to observe low-energy solar νs, such as pp and ^{7}Be νs, in 2000 to compensate for Super-K solar ν physics.
- Constraints for dark matter were relatively weak at that time, and we aimed to detect dark matter first and observe pp-solar νs as the second step. $0\nu\beta\beta$, SI/SD by Isotope separation?

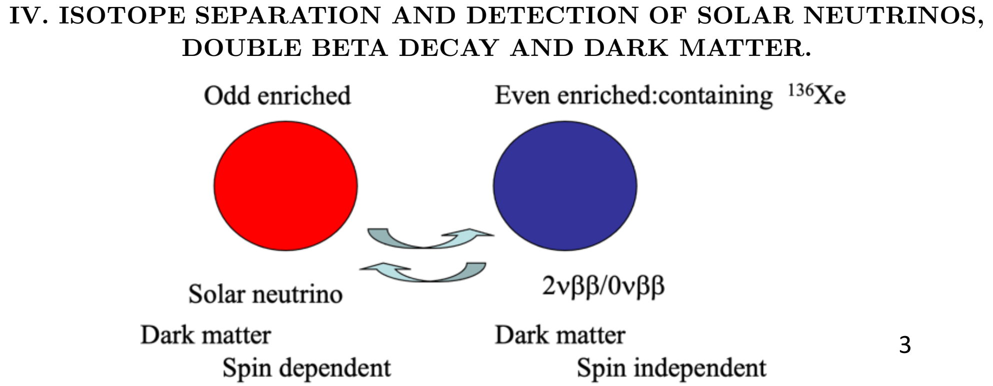


Low Energy Solar Neutrino Detection by using Liquid Xenon

(September 26, 2021)

Y.Suzuki
(for the Xenon Collaboration [1])
Kamioka Observatory, Institute for Cosmic Ray Research, University of Tokyo, Higashi-Mozumi,
Kamioka, Gifu 506-1205, Japan

arXiv:hep-ph/0008296v1 29 Aug 2000

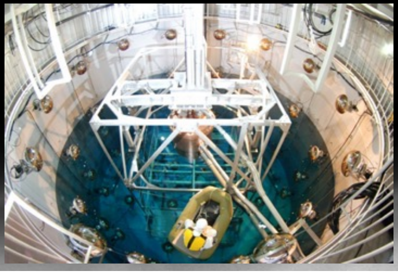


IV. ISOTOPE SEPARATION AND DETECTION OF SOLAR NEUTRINOS, DOUBLE BETA DECAY AND DARK MATTER.

XMASS: technical breakthrough

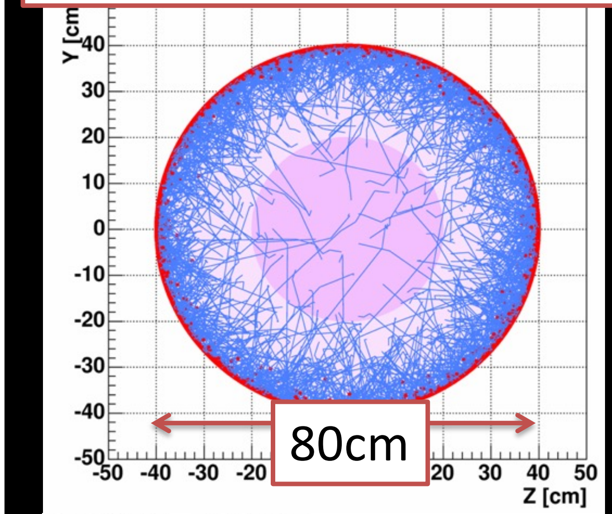
- Liquid xenon was NOT so attractive in 2000 since it contains radioactive ^{85}Kr, which was released from reactor processes.
  - ~1 Bq/kg → XMASS established the reduction method in 2004, <10 μBq/kg
- Water Cherenkov muon veto
  - Based on Super-K experience, we graduated from a passive lead and copper shield and established the active water Cherenkov shield. Good for neutrons.
- Development of the world-best low-background PMTs

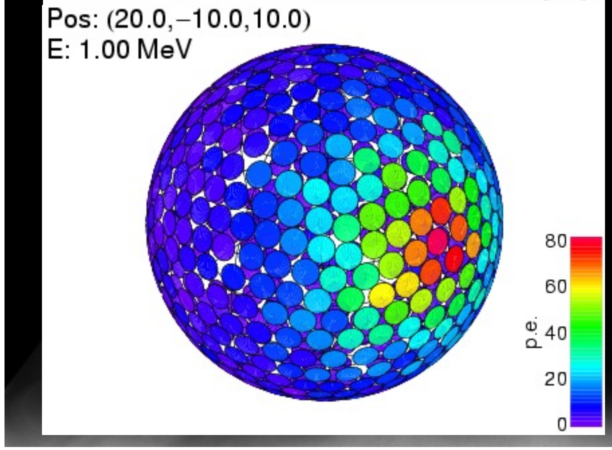
They opened up large-scale low-BG LXe detectors for rare event searches.



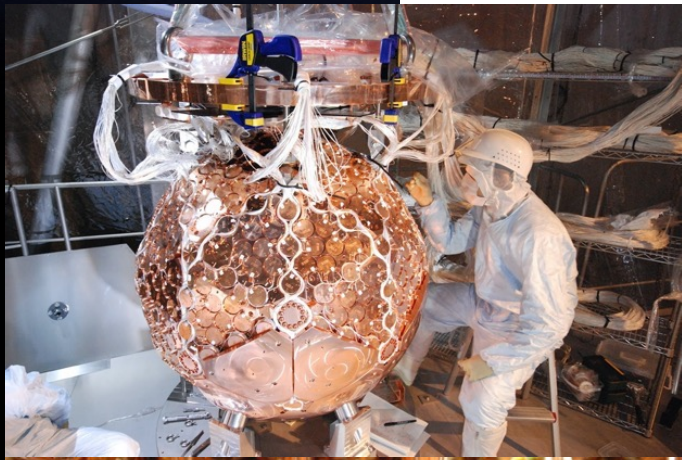
XMASS-I: working principle

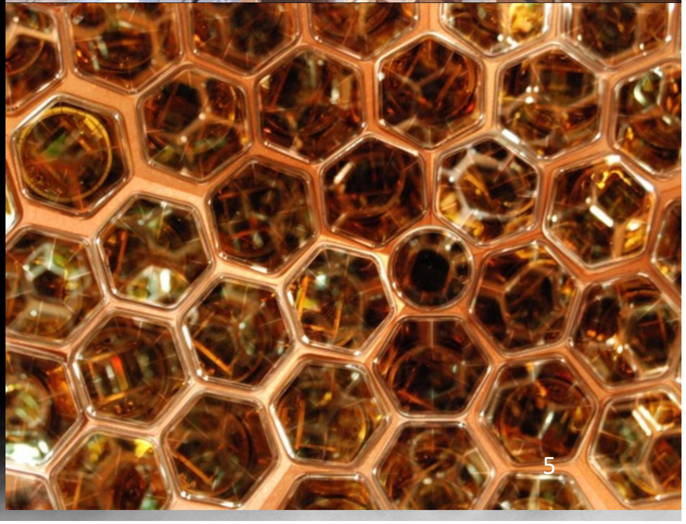
Self shielding for γ injection (XMASS-I)



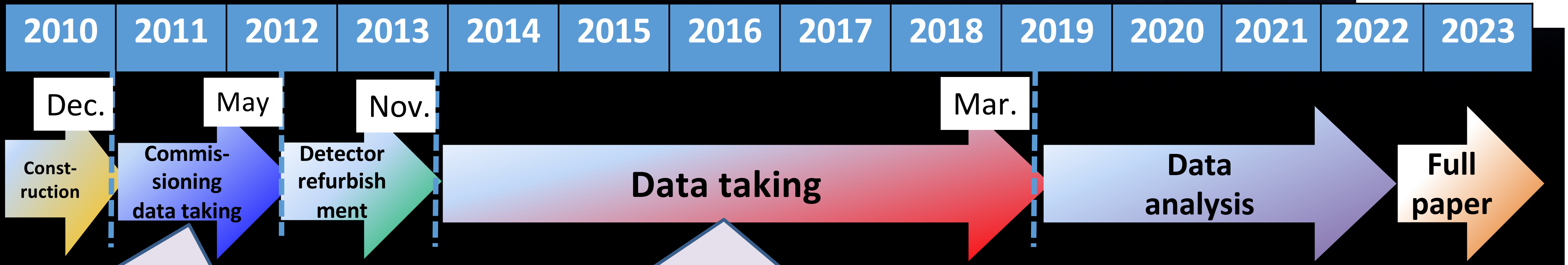


- BG reduction by fiducial volume cut
  - Very large photoelectron yield
    ~ 14.7 p.e./keV ⇔ Super-K ~6 hits/MeV
  - Event reconstruction based on observed hit pattern ~ a few keV.
  - 832 kg in total, 97 kg in r < 20 cm FV.
  - Target of a WIMP search ~ $2\mathrm{x}10^{-45}\mathrm{cm}^{2}$.
  - Good to search for e/γ events as well.
  - e/γ particle identification
- Larger det. has better performance.
  - T info useful (scintil. const. 30-40 ns)
  - Better self-shielding for e/γ/n
  - Attenuation >10 m for scintillation light





History of XMASS-I and physics achievements



- Light WIMPs
- Solar axion
- WIMP-^{129}Xe inelastic scattering
- Bosonic super-WIMPs
- ^{124}Xe 2ν double electron capture

DM physics

Astroparticle phys.

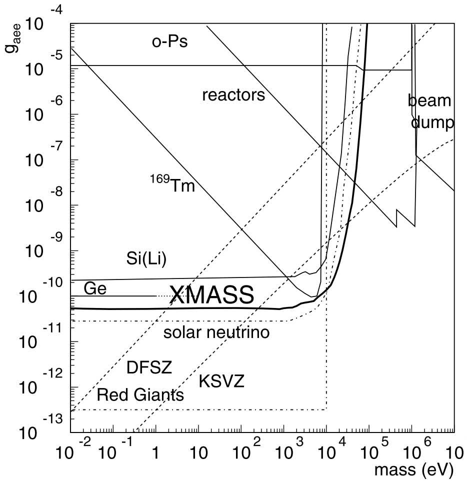
Nuclear physics.

- Annual modulation 1 yr & 2.7 yrs
- Solar Kaluza-Klein axion
- ^{124}Xe 2ν double electron capture II
- WIMPs search by fiducialization
- Hidden photons/ALPs DM
- WIMP-^{129}Xe inelastic scattering II
- Sub-GeV WIMP by annual modulation
- Exotic ν-e interactions of solar ν
- Search for event burst assosci. with GW
- $0\nu4\beta$ decay of ^{136}Xe

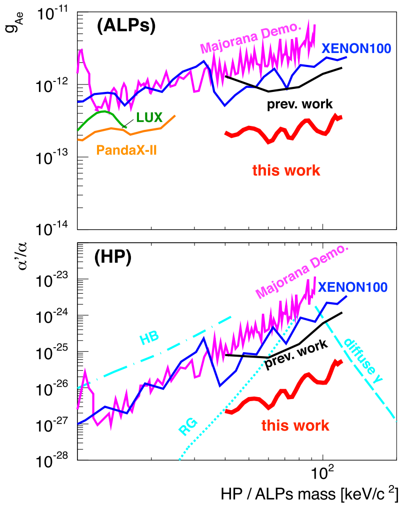
1 proposal
11 technical papers
17 physics results
+1 latest physics result published!

https://www-sk.icrr.u-tokyo.ac.jp/xmass/dispatches/publications/index.html

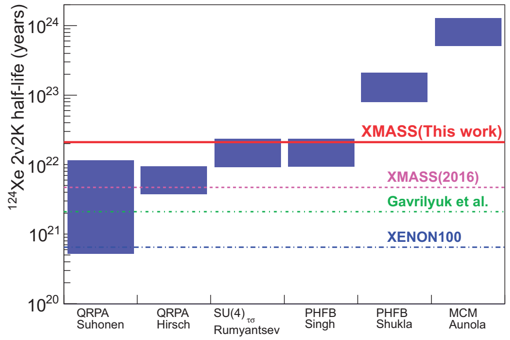
Physics highlights of XMASS



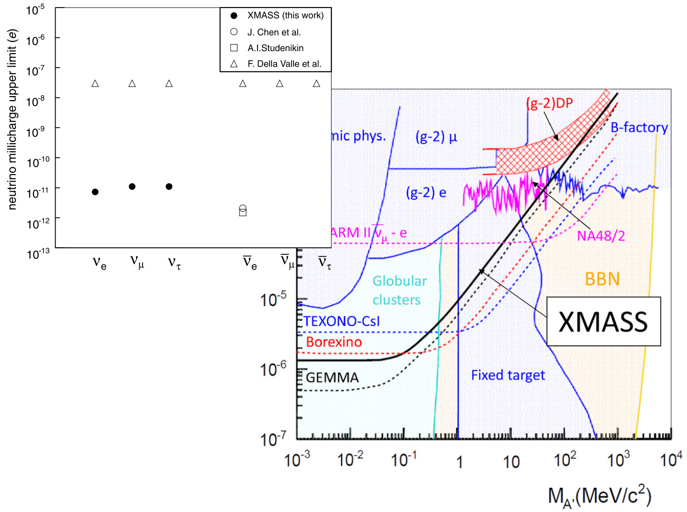
Solar axions in 2013



Bosonic super WIMPS in 2014/18



Double electron capture 2016/18



Millicharged ν, $U_{B-L}(1)$ 2020

XMASS pioneered several physics targets using large-scale dark matter detectors!

The final results with XMASS-I full data set

- XMASS is a unique single-phase liquid xenon detector. It has a very long exposure of 1590.9 days.

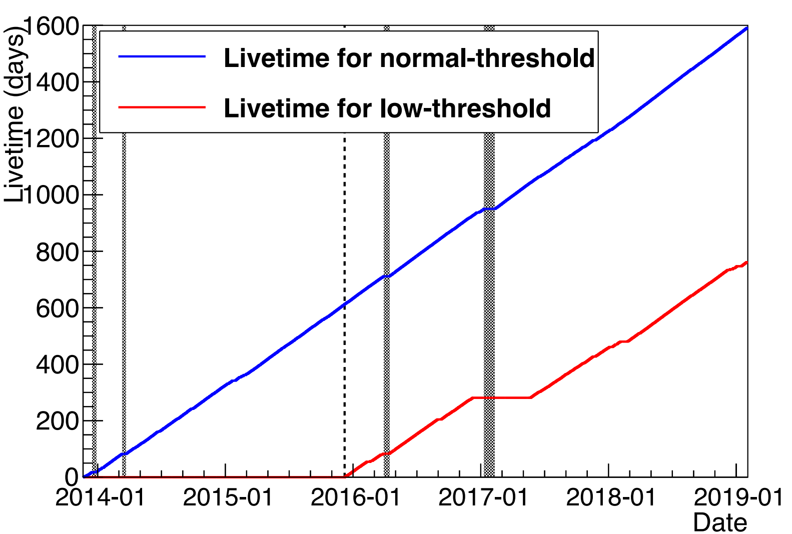
Large mass WIMPS

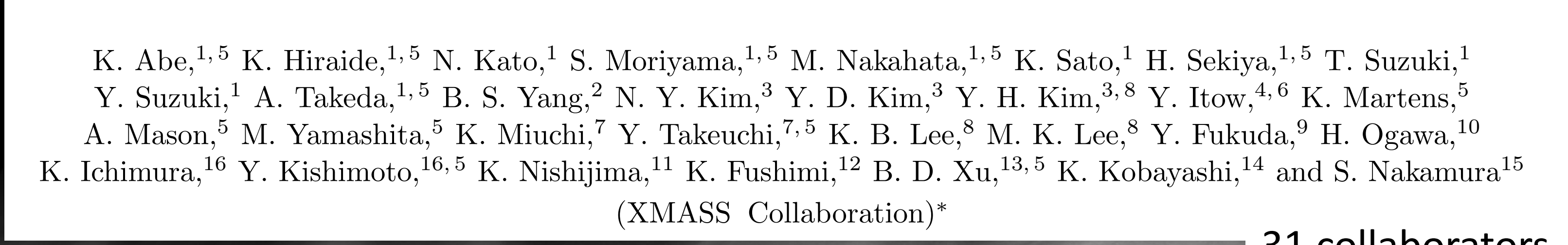
1. Search for WIMP signal in 97 kg (fiducial).

Light mass WIMPS

2. Annual modulation in 832 kg (full vol.)

utilizing the Migdal & bremsstrahlung effects.



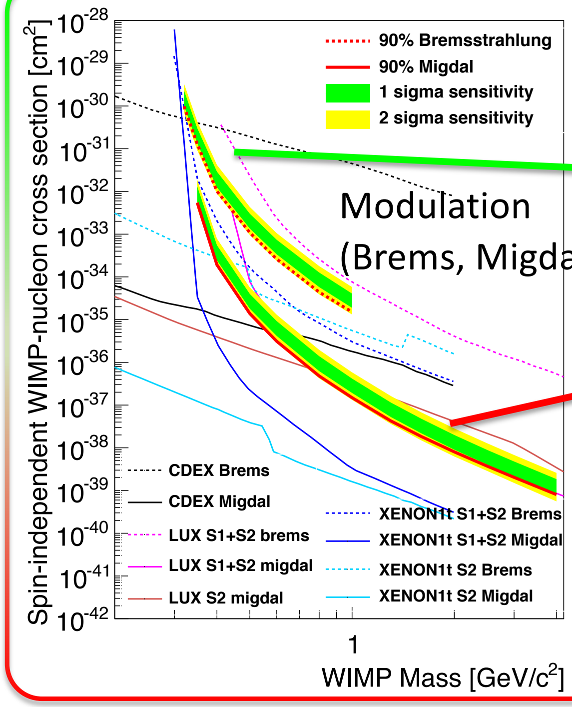

Direct dark matter searches with the full data set of XMASS-I

K. Abe,[1,5] K. Hiraide,[1,5] N. Kato,[1] S. Moriyama,[1,5] M. Nakahata,[1,5] K. Sato,[1] H. Sekiya,[1,5] T. Suzuki,[1] Y. Suzuki,[1] A. Takeda,[1,5] B. S. Yang,[2] N. Y. Kim,[3] Y. D. Kim,[3] Y. H. Kim,[3,8] Y. Itow,[4,6] K. Martens,[5] A. Mason,[5] M. Yamashita,[5] K. Miuchi,[7] Y. Takeuchi,[7,5] K. B. Lee,[8] M. K. Lee,[8] Y. Fukuda,[9] H. Ogawa,[10] K. Ichimura,[16] Y. Kishimoto,[16,5] K. Nishijima,[11] K. Fushimi,[12] B. D. Xu,[13,5] K. Kobayashi,[14] and S. Nakamura[15]
(XMASS Collaboration)*

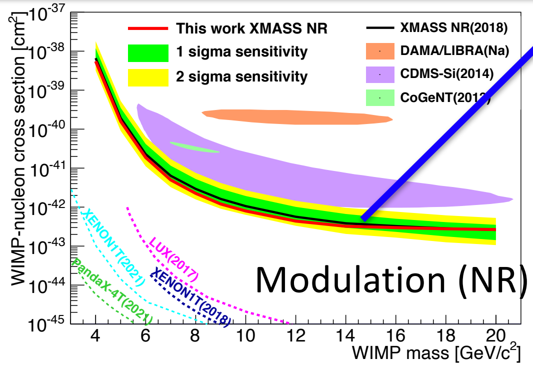
PHYSICAL REVIEW D 108, 083022 (2023)

31 collaborators

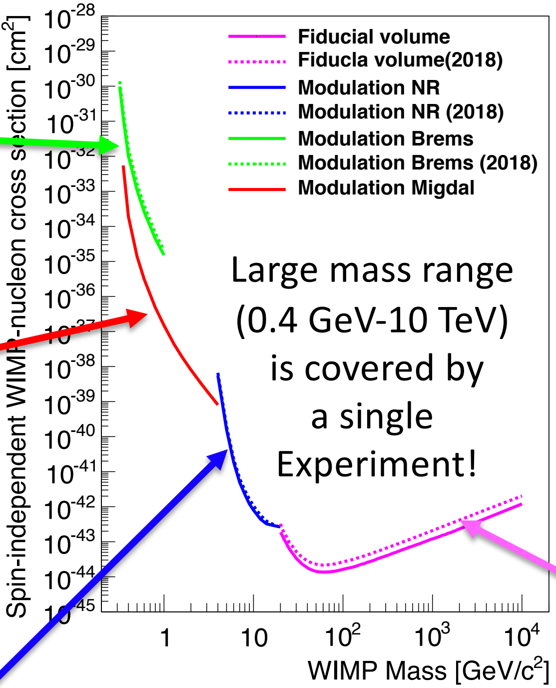
Summary of constraints from XMASS-I



Modulation (Brems, Migdal)

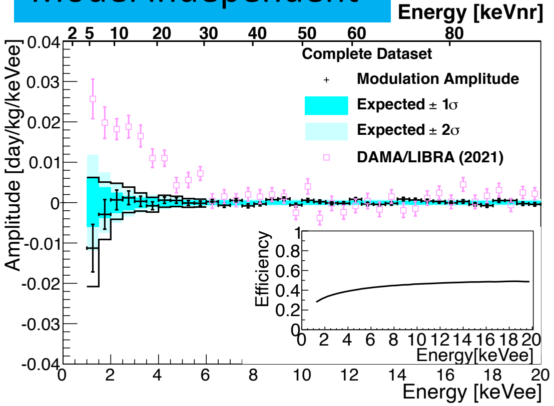


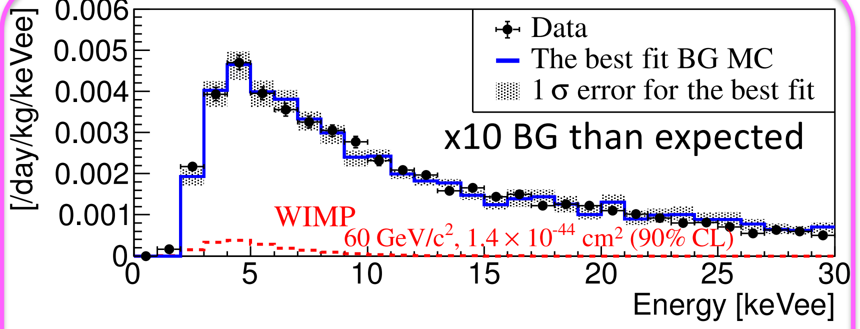
Modulation (NR)



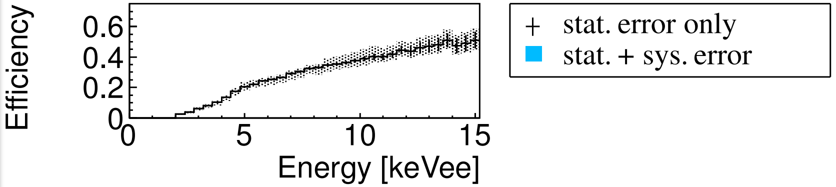
Large mass range (0.4 GeV-10 TeV) is covered by a single Experiment!

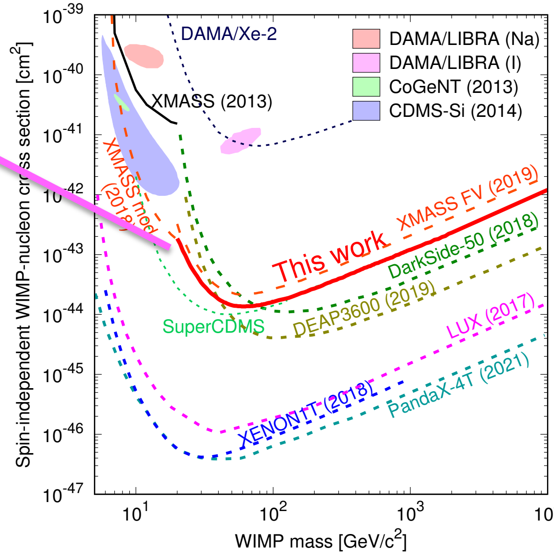
Model independent





x10 BG than expected





Search for WIMPs in 97 kg FV: $<1.4\times10^{-44}$cm^2

Discussion in 2017

Activity towards a future direct DM search

- We planned to construct a larger detector, XMASS-1.5. However, we concluded that it was not competitive anymore.
  - The primary reason was that the background due to e scattering by low E solar ν is difficult to distinguish from a WIMP signal.
  - Large dual phase detectors were already approved for construction.
- We aim for a future, more sensitive, third-generation detector (G3) and, in the meantime, to collaborate with a competitor building a multi-ton G2 detector.
- This plan was submitted to the future project committee in ICRR.
- The committee agreed that XMASS-1.5 was not competitive with other contemporary projects and accepted this change of our plan for the future. It also recognized participation in one of the G2 experiments, in particular the XENONnT experiment, as appropriate.
- Recommended to continue our efforts and realize a G3 experiment.

History of XENON detectors

Factor ~30 improvements for every step!

XENON10

15 kg

2005-2007

$<4.5x10^{-44}cm^2$

PRL **100,** 021303 (2008)

XENON100

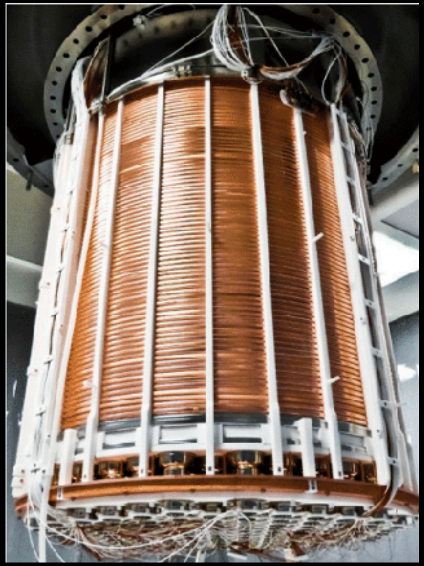
161 kg

2008-2016

$<1.1x10^{-45}cm^2$

PRD 94, 122001 (2016)

XENON1T



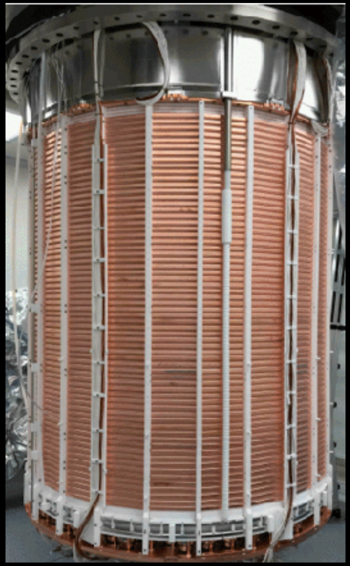
3200 kg

2012-2018

$<4.1x10^{-47}cm^2$

PRL 121, 111302 (2018)

XENONnT



8400 kg

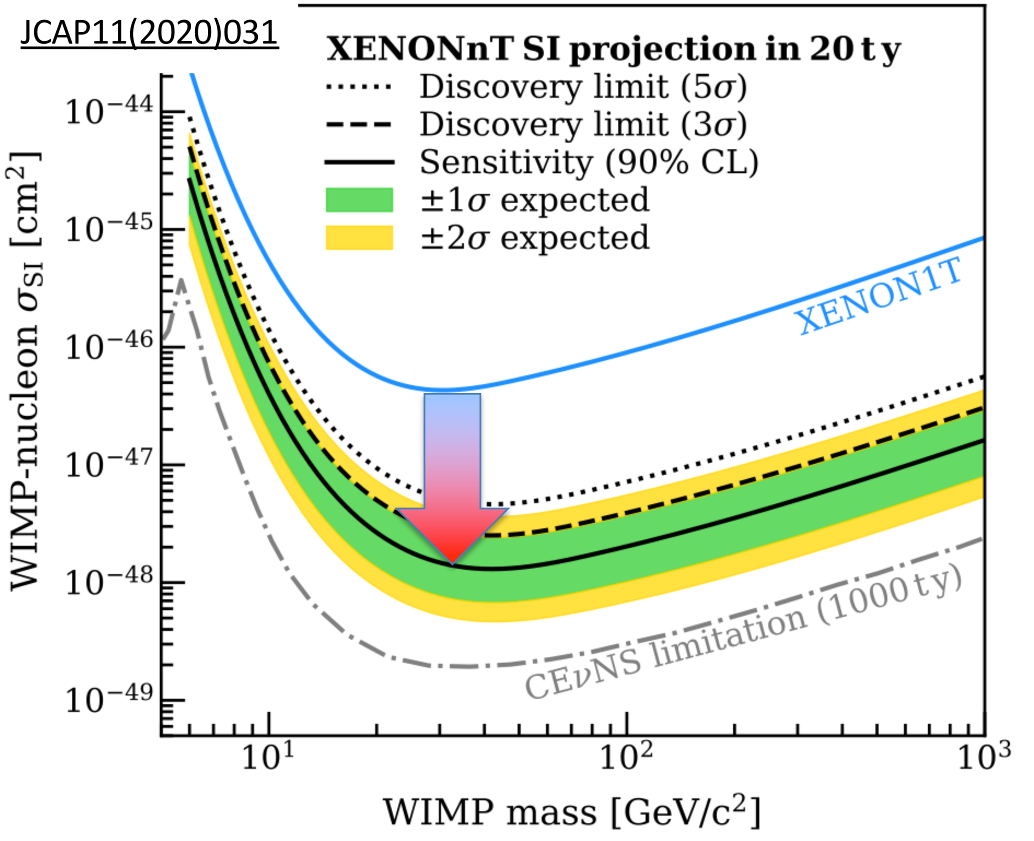
2020-

$\sim1.4x10^{-48}cm^2$

JCAP11(2020)031

XENONnT, toward discovery of WIMPs

~O(10) t of LXe target: 2nd generation of direct DM detection exp.



JCAP11(2020)031

One order of magnitude higher sensitivity by reducing BG with a large exposure:

20 t year (~ 4 ton x 5 yrs) (x 20)

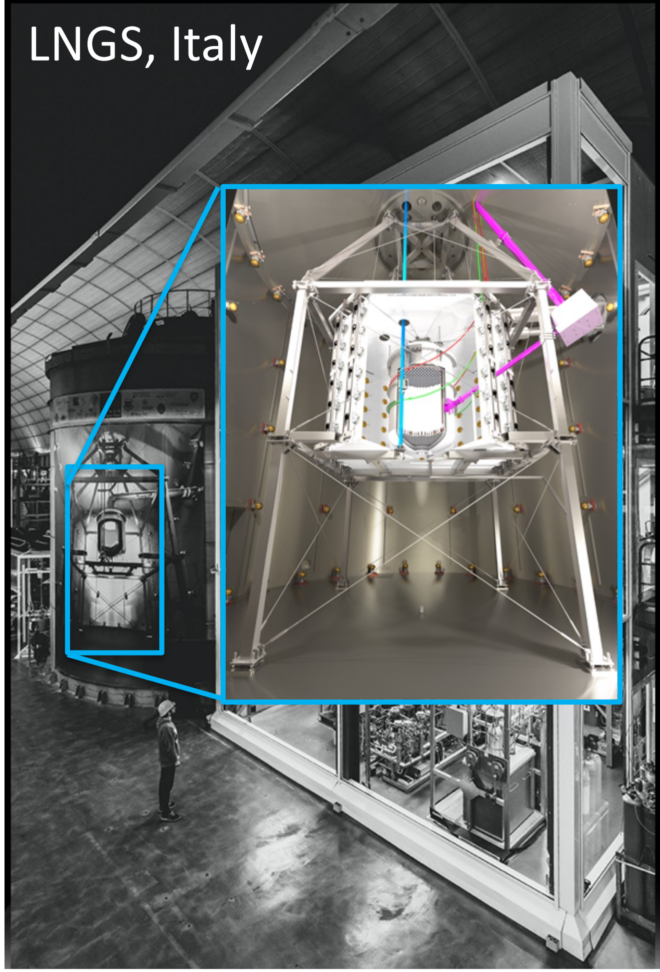
BG in unit exposure (~1/20)

~1.4x10^{-48}cm^{2} (~1/20)

@ 50 GeV, 90% C.L.

Larger Exposure, lower BG, higher discovery potential!

Upgrade from XENON1T to XENONnT



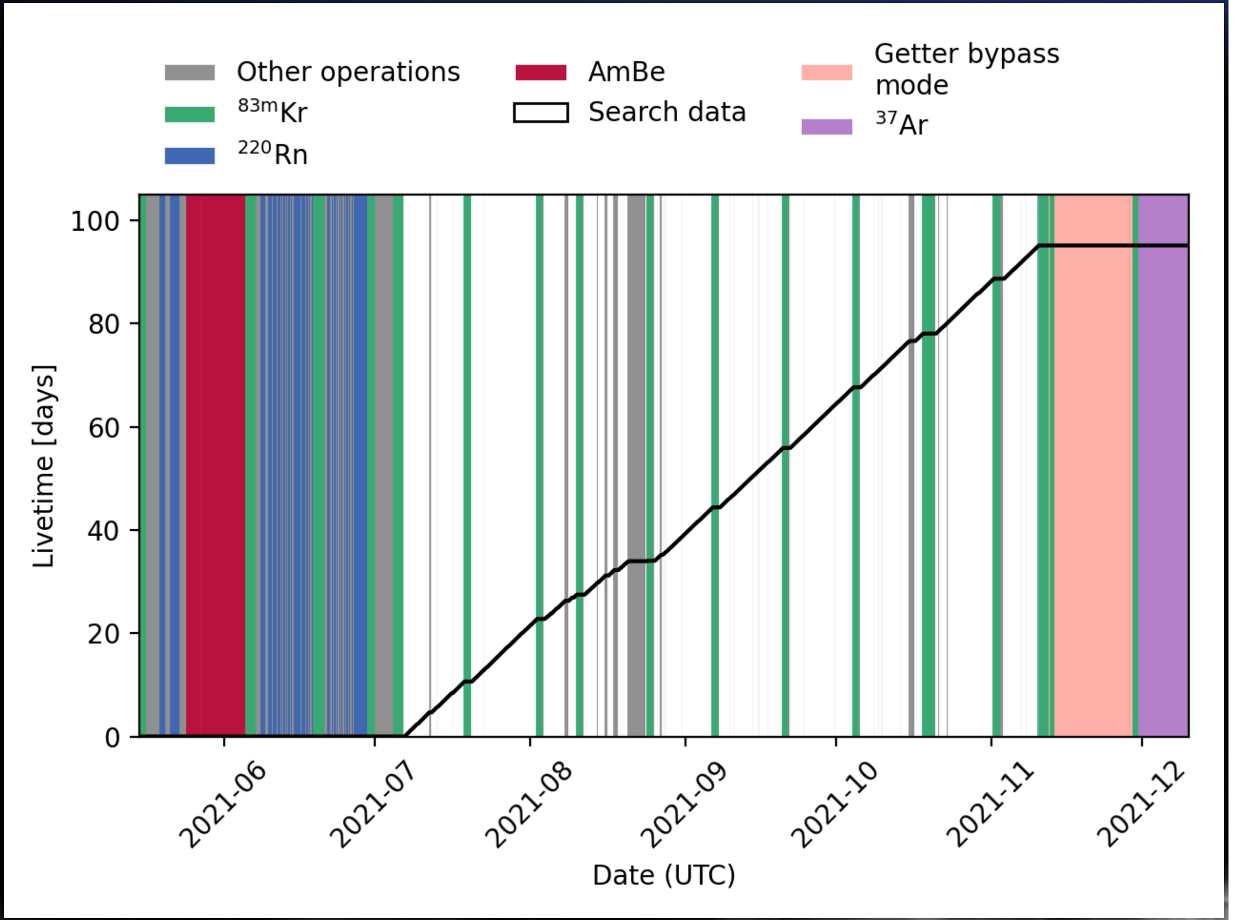
https://doi.org/10.48550/arXiv.2402.10446

- LXe time projection chamber (enlarged)
  - – 5.9 t LXe active (3 x XENON1T)
- Liquid xenon purification (new)
  - – Faster purification (>> XENON1T)
- Neutron veto (new)
  - – Cherenkov neutron veto (68% eff. with pure water, 87% with planned Gd-loaded water)
- Radon distillation column (new)
  - – Reducing Rn-originated BG (<1/10 x XENON1T)

Japanese contributions

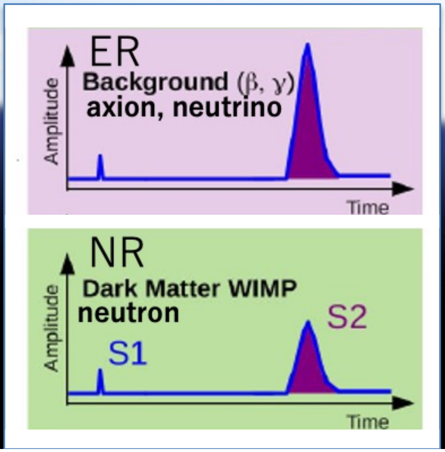
First science run, SR0

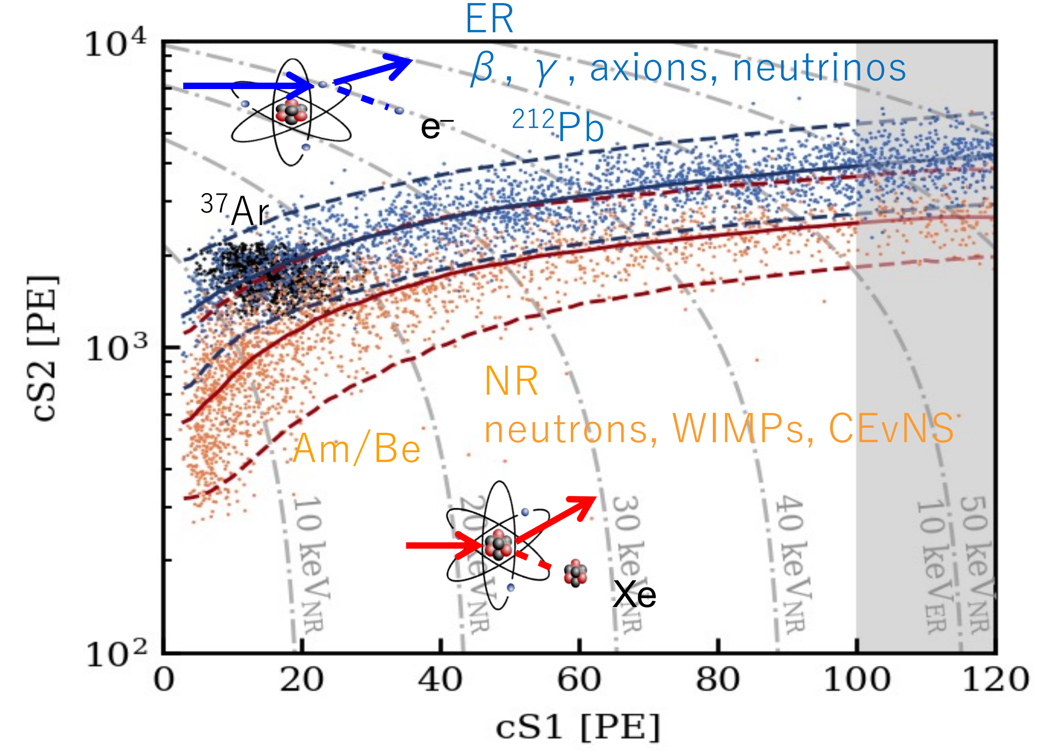
- July 6 – Nov 10, 2021
- 97.1 days livetime
- ER and NR search
  - blind analyses
- Fiducial volume
  - (4.37 ± 0.14) ton for ER
  - (4.18 ± 0.13) ton for NR
- Exposure after deadtime correction
  - 1.16 ton-years for ER
  - 1.1 ton-years for NR



ER and NR

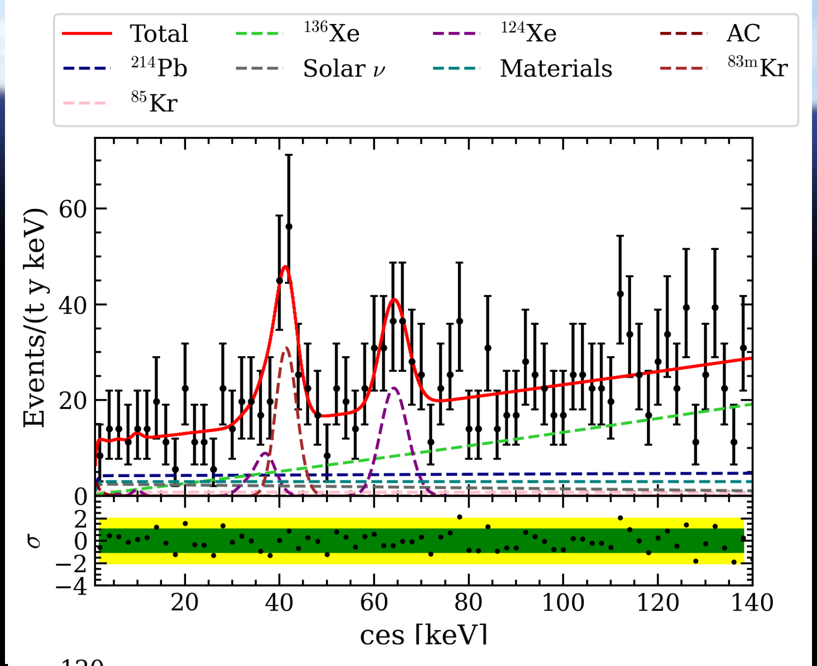
- Electronic recoil (ER)
  - larger S2/S1
  - Electrons, gammas, axions, neutrinos
  - Calibration source
    - ^{212}Pb (^{220}Rn)
      - flat beta spectrum
    - ^{37}Ar
      - 2.82 keV peak
      - for the region close to the threshold energy
- Nuclear recoil (NR)
  - smaller S2/S1
  - neutrons, neutrinos, WIMPs
  - calibration source
    - ^{241}Am/Be
      - 4.4 MeV gamma and neutron

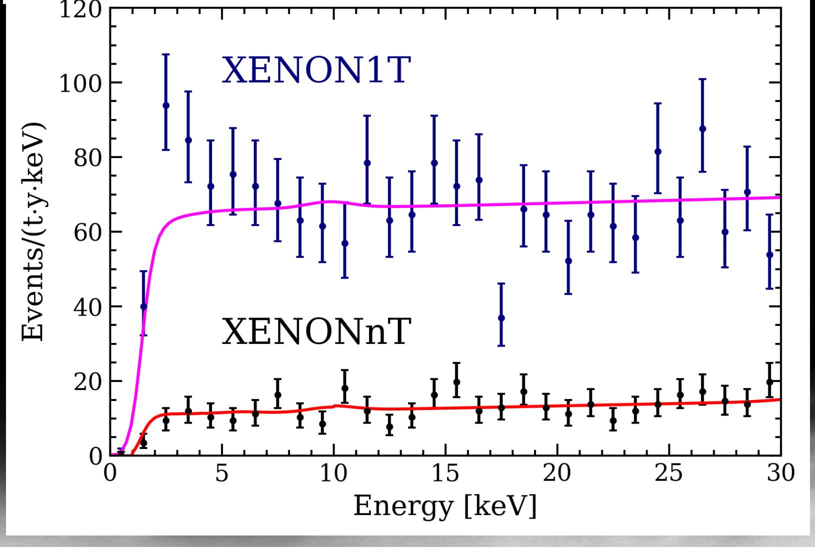




SR0 Low ER results

- Data agree with the BG-only model
- Dominated by beta decays from ^{214}Pb, a daughter of ^{222}Rn
- No excess was found
  - Most likely, the explanation of XENON1T excess is a small tritium contamination.
- Factor x5 improved background compared to XENON1T
  - Unprecedented low ER BG rate (15.8+/-1.3) events/(t·yr·keV)





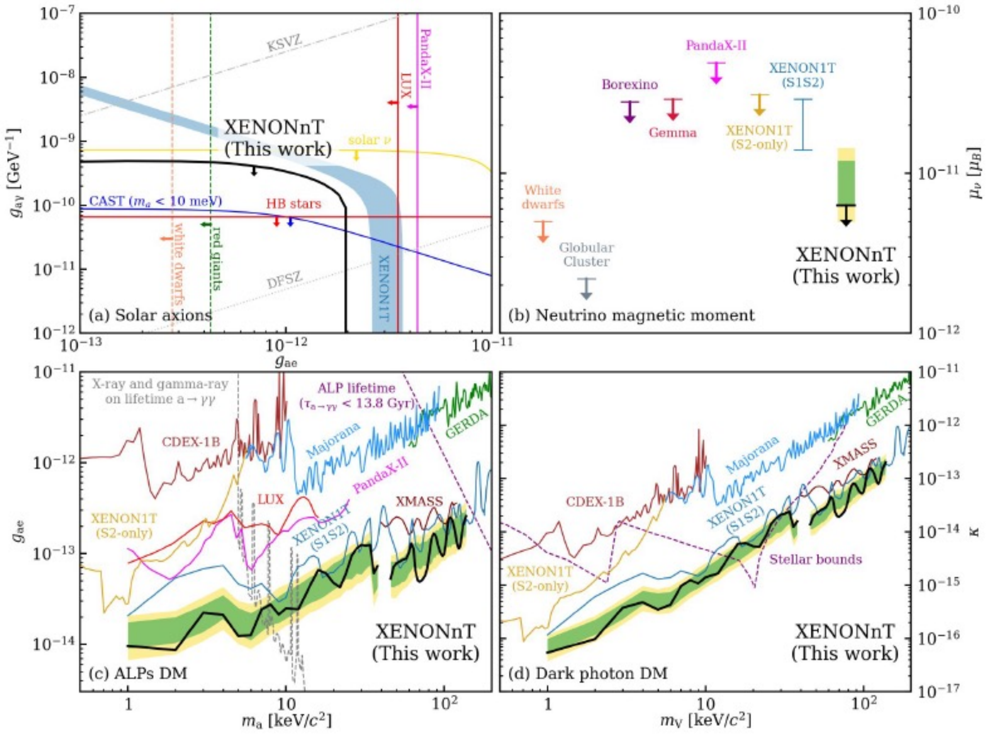
SR0 Low ER results

- Stringent new limits
  - – Solar axions
  - – Neutrino magnetic moment
  - – Axion-like particles
  - – Dark photons

https://doi.org/10.1103/PhysRevLett.129.161805

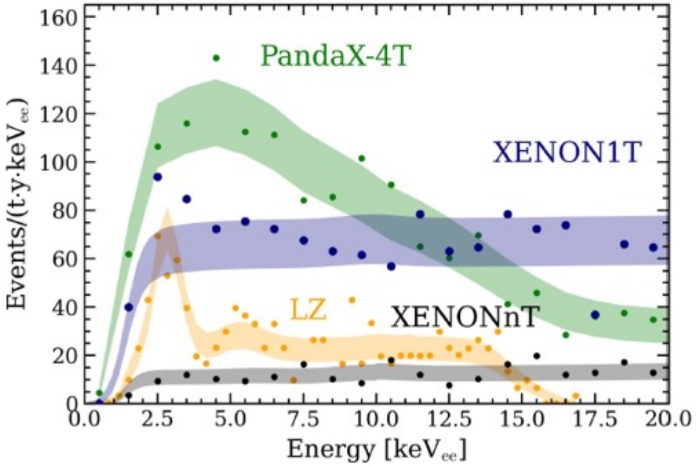
Solar Axions

Axion-like particles



Neutrino Magnetic Moment

Dark Photons



PandaX-4T PRL 129, 161804 (2022)

XENON1T PRD 102, 072004 (2020)

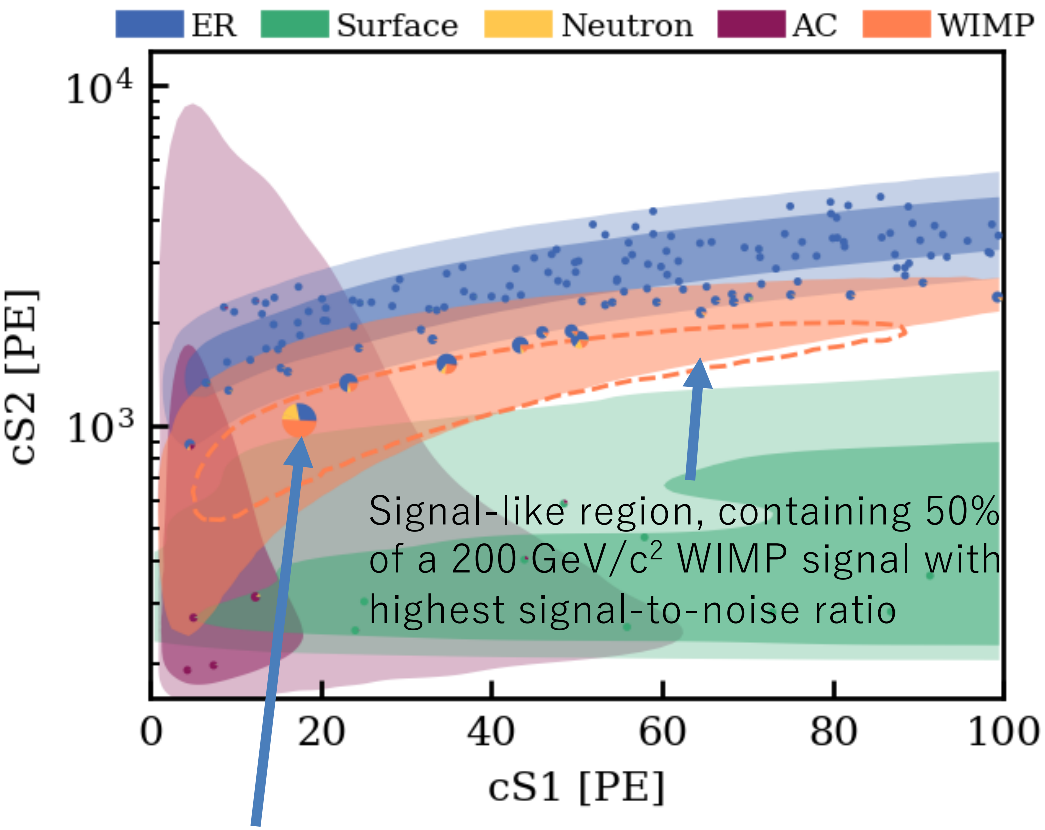
LZ arXiv:2207.03764

XENONnT PRL 129, 161805 (2022)

SR0 WIMP results

	Nominal	**Best Fit**	
	ROI		Signal-like
ER	134	135^{+12}_{-11}	0.92 ± 0.08
Neutrons	$1.1^{+0.6}_{-0.5}$	1.1 ± 0.4	0.42 ± 0.16
CEvNS	0.23 ± 0.06	0.23 ± 0.06	0.022 ± 0.006
AC	4.3 ± 0.9	$4.4^{+0.9}_{-0.8}$	0.32 ± 0.06
Surface	14 ± 3	12 ± 2	0.35 ± 0.07
Total	154	152 ± 12	$2.03^{+0.17}_{-0.13}$
WIMP	-	2.6	1.3
Observed:	-	152	3

- 152 events in ROI, 16 in blinded region
- Best fit indicates no significant excess
- n expectation is a factor 6 higher than prediction.



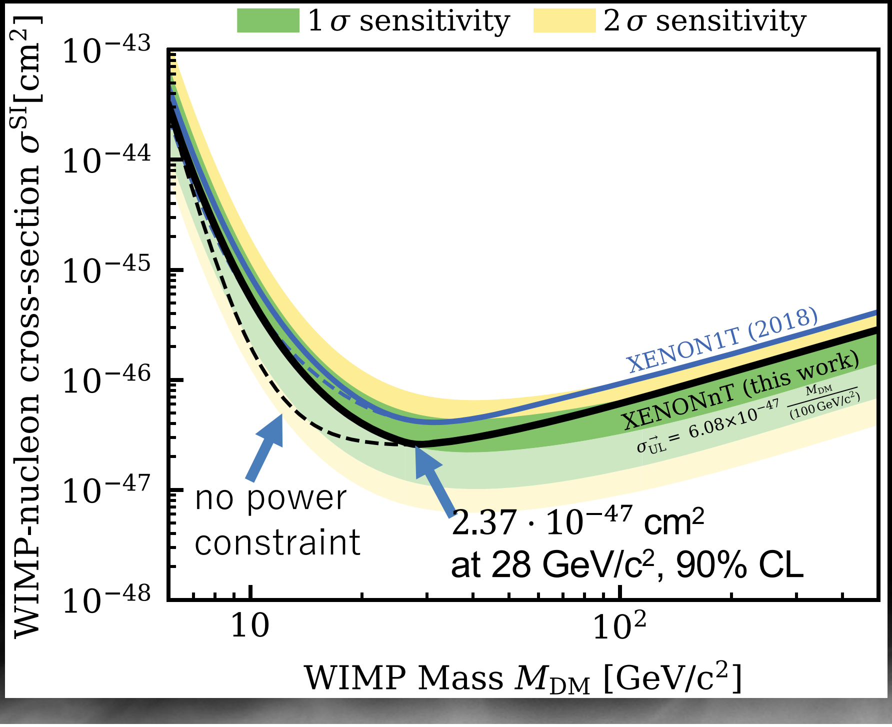
Signal-like region, containing 50% of a 200 GeV/c^2 WIMP signal with highest signal-to-noise ratio

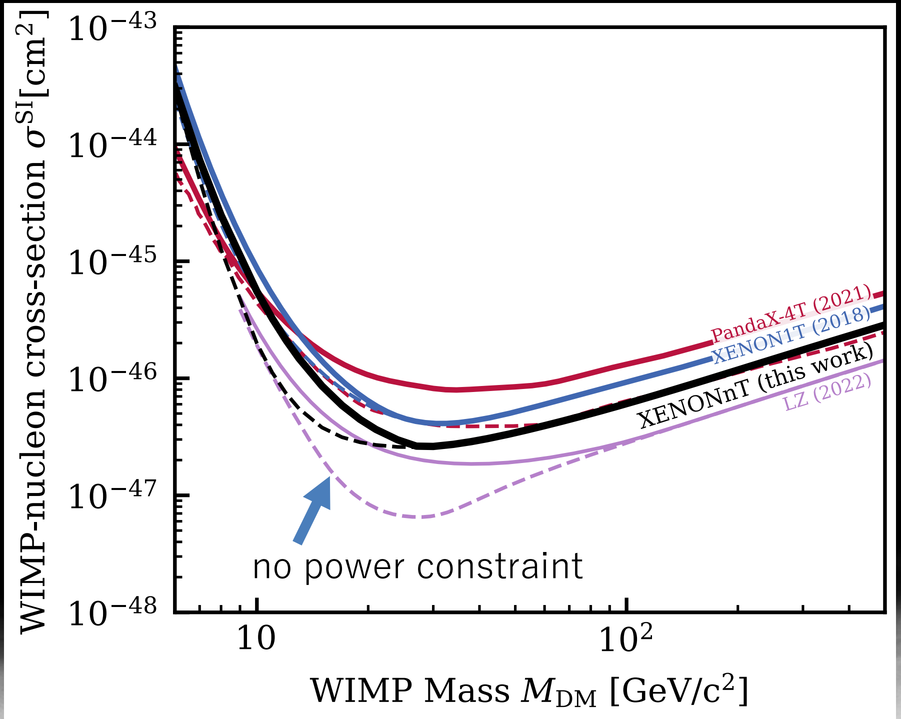
Component fraction of the best fit model including a 200 GeV/c^2 WIMP evaluated at event position

SR0 WIMP results

- Spin independent, $2.37\times10^{-47}\mathrm{cm}^2$ @28GeV/c^2
- Power constraint limit based on “rejection power”.
  - – median of sensitivity

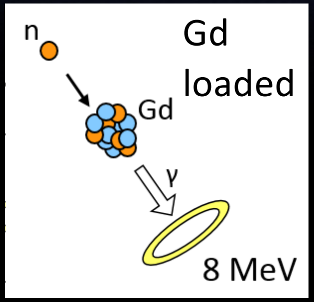
https://doi.org/10.1103/PhysRevLett.131.041003

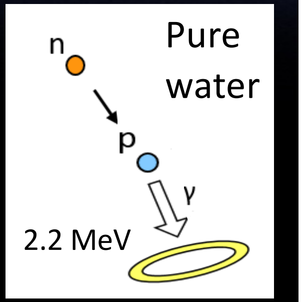


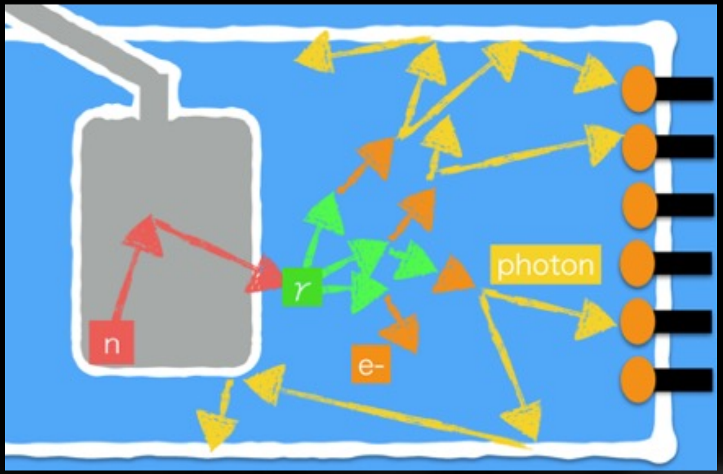


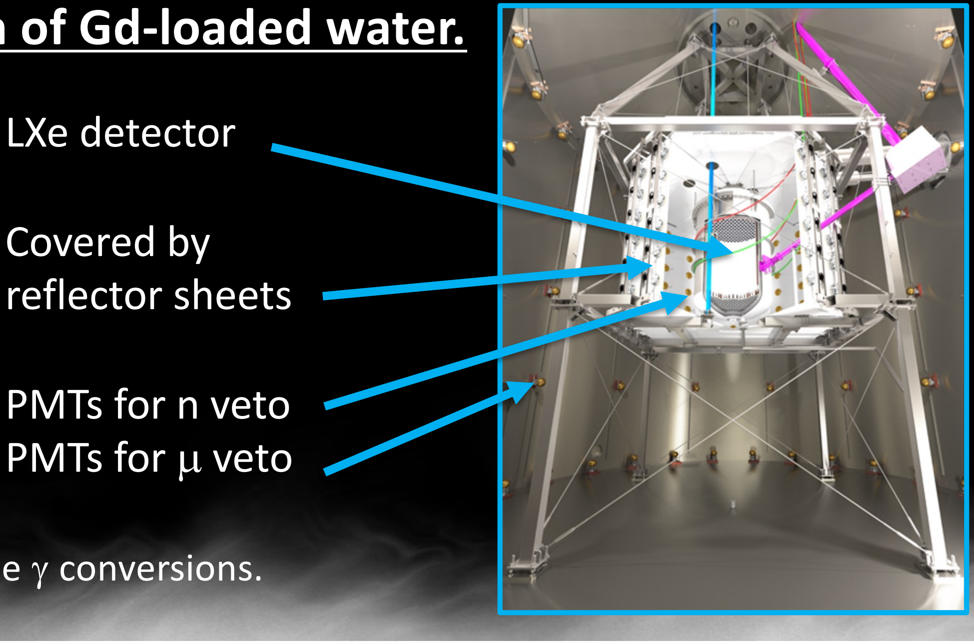
Neutron veto

- Contributes to maximize the discovery sensitivity
  - Reduce neutron (n) background by Super-K Gd tech.
    - Dangerous since it mimics the WIMP signal.
    - SR0: pure water 2.2 MeV ➔ Gd-loaded water total ~8 MeV
    - **Low radioactive Gd salt, purification of Gd-loaded water.**








LXe detector

Covered by
reflector sheets

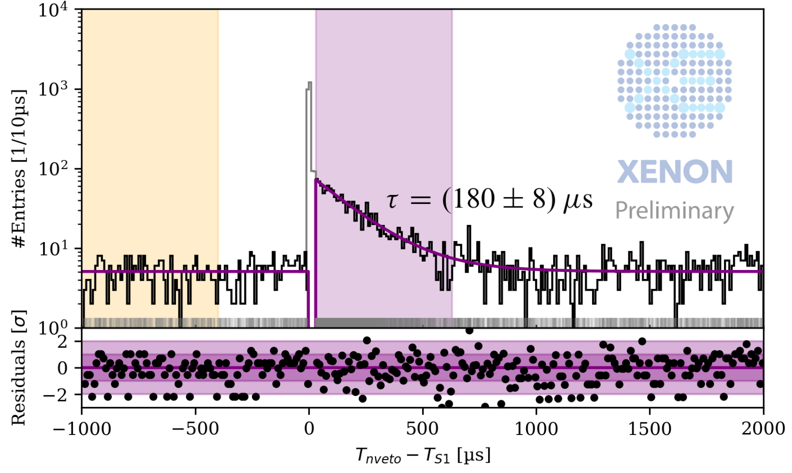
PMTs for n veto
PMTs for μ veto

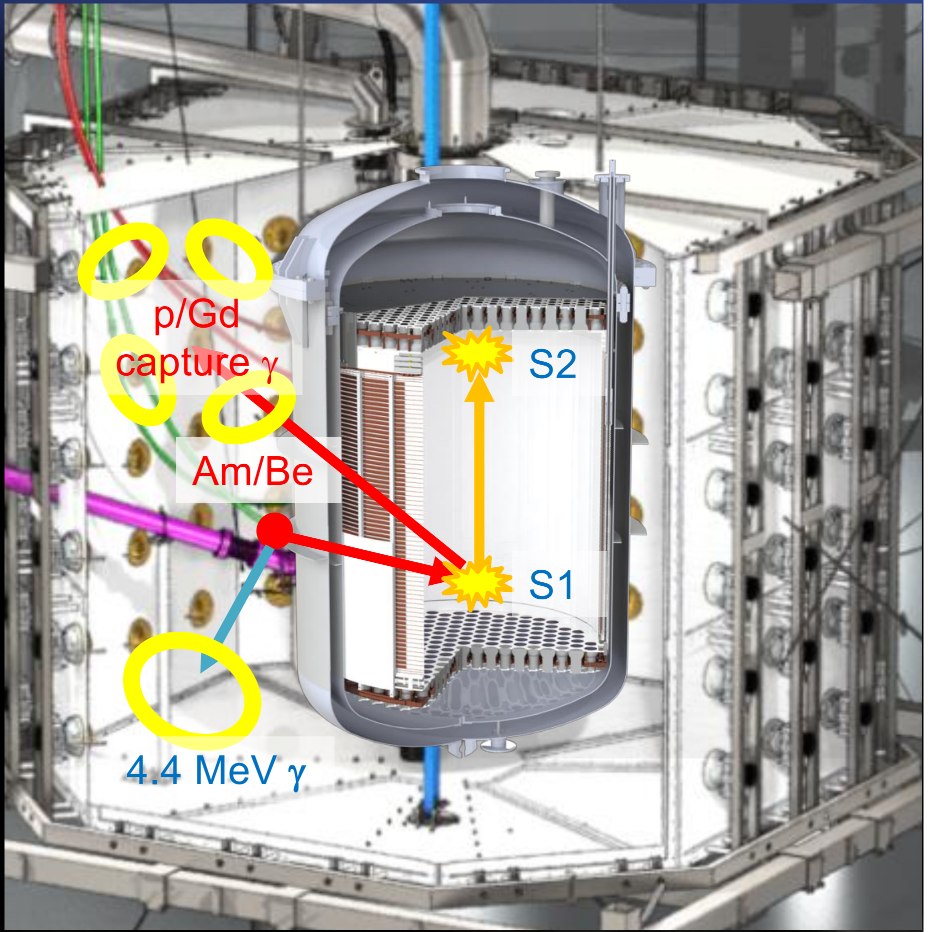
Reflector sheets will contain the Cherenkov emission from the γ conversions.
120 PMTs will collect the light inside the reflector volume.

Neutron tagging efficiency

- Am/Be source: 4.4 MeV γ in ~50% of all emitted neutrons.
- 400 ns coincidence btw TPC and nveto.
- NR (single) scatter data is used.
- Neutron capture events in nveto
- Quality cuts remove wrongly reconstructed events.
- Time delay between p/Gd capture γ and S1:

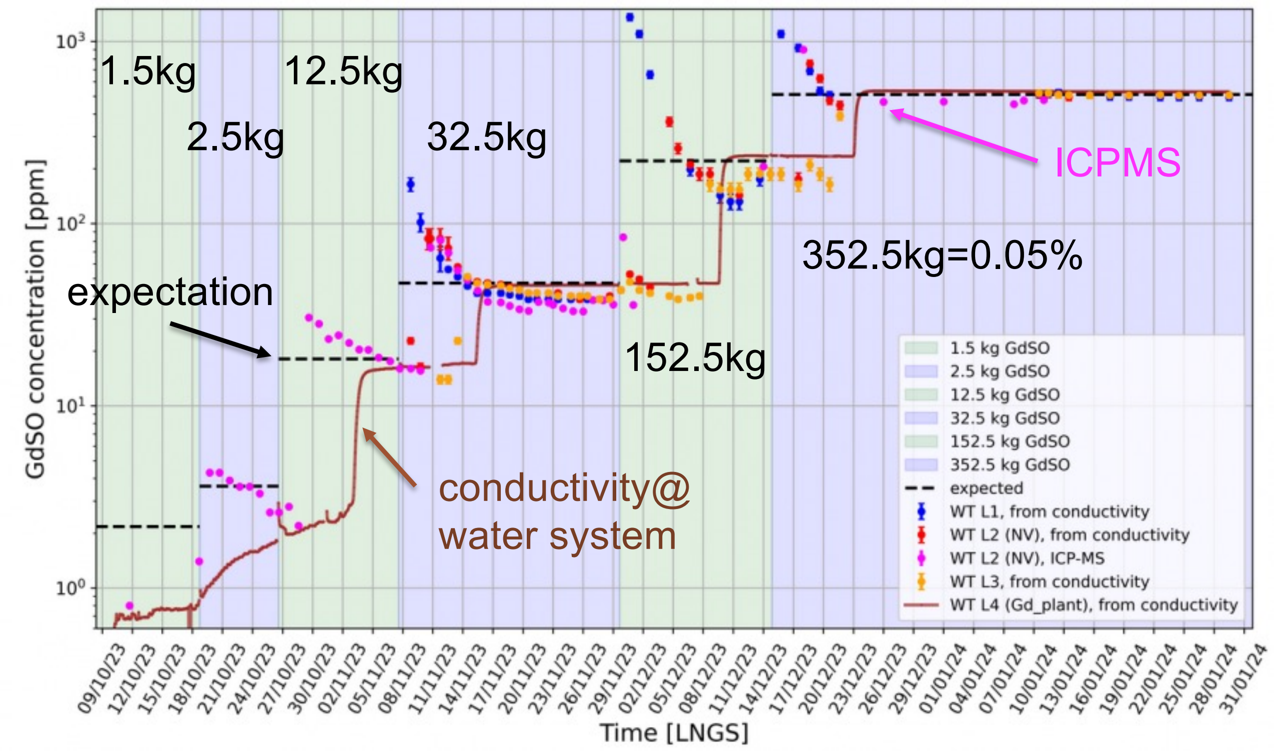
Pure water SR0





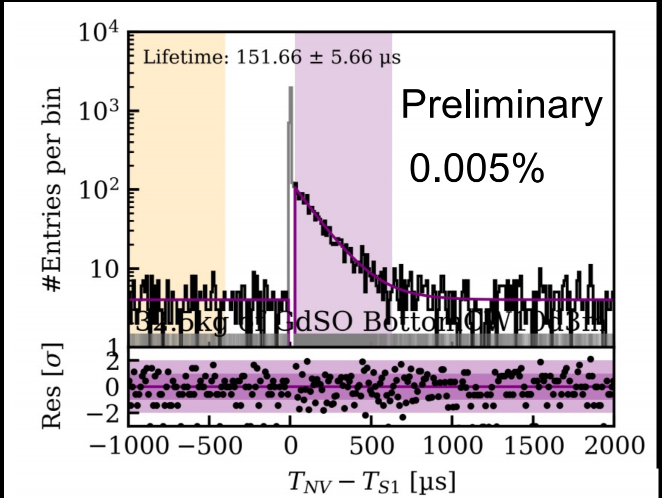
- (53+/-3)% tagging efficiency @250μsec window and 5-fold PMT coincidence, and 5 pe threshold.

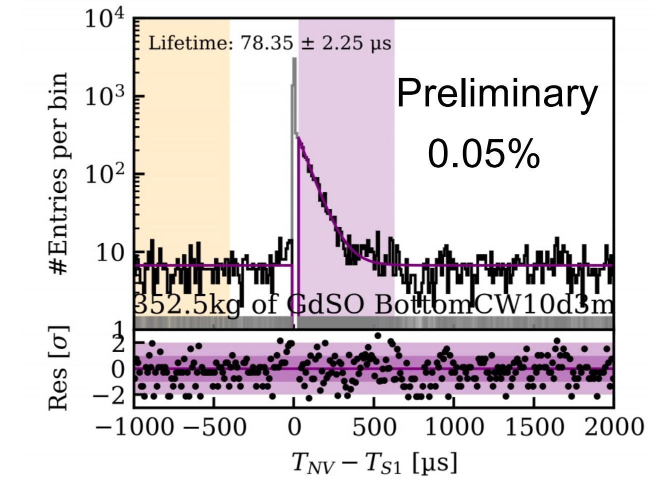
Gd loading to the XENONnT water tank

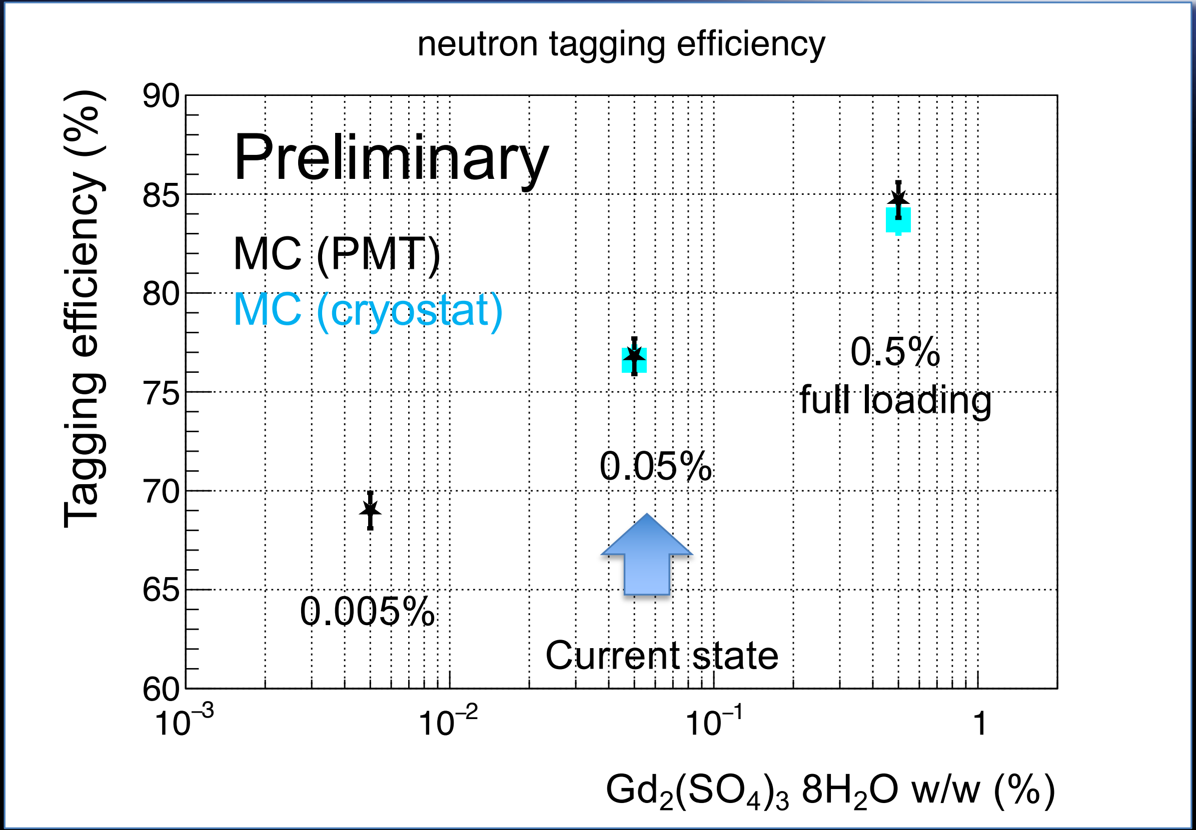


- Loading 0.05% weight of Gd sulfate octahydrate to the 700 t water tank. (~0.02% Gd in the Super-K convention)
- Concentration increased as expected.

n tag. eff. @0.005% & 0.05% GdSO concentration







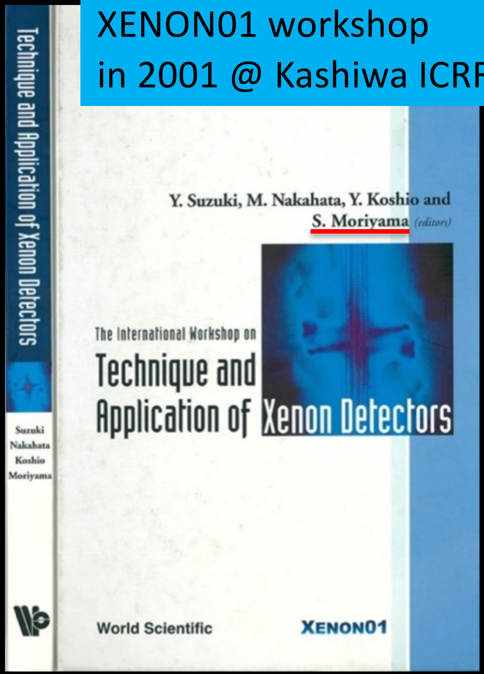
- Timing distributions, area distributions, and neutron tagging efficiencies for the data are under investigation.
- n tag. eff. @0.5% is expected to be achieved with full loading.

Summary

- XMASS established some technical bases of liquid xenon detectors for rare event searches and physics targets. The final WIMP results came with its full data set. $< 1.4\times10^{-44}\mathrm{cm}^2$@$60\mathrm{GeV}/c^2$
- XENON is one of the forefront experiments exploring new physics for dark matter detection and other exotics.
  - The first result on the WIMP search: $< 2.37\times10^{-47}\mathrm{cm}^2$ @$28\mathrm{GeV}/c^2$
  - More sensitive results will come from XENONnT with the technology developed for the neutrino physics experiment, SK-Gd.

XENON experiment

XENON01 workshop
in 2001 @ Kashiwa ICRR



Technique and Application of Xenon Detectors

Suzuki
Nakahata
Koshio
Moriyama

Y. Suzuki, M. Nakahata, Y. Koshio and
S. Moriyama (editors)

The International Workshop on
Technique and
Application of Xenon Detectors

World Scientific

XENON01

100 kg detector

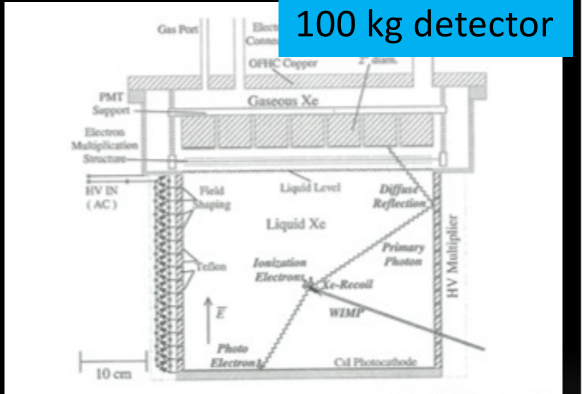
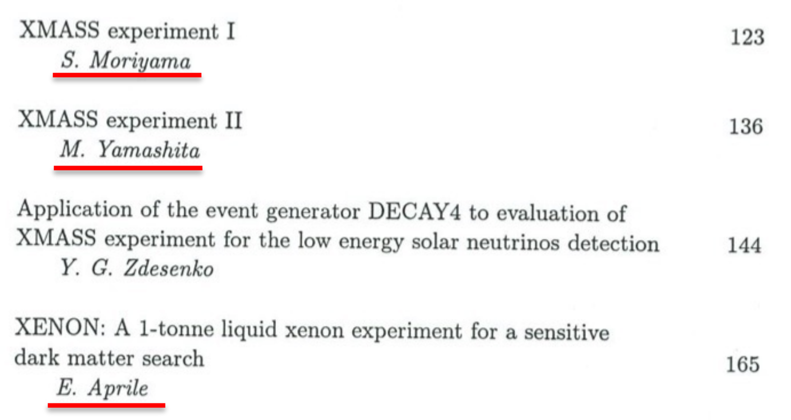


Figure 3. The LXeTPC module for XENON: Schematic Design of the 100 Kg detector and its components.



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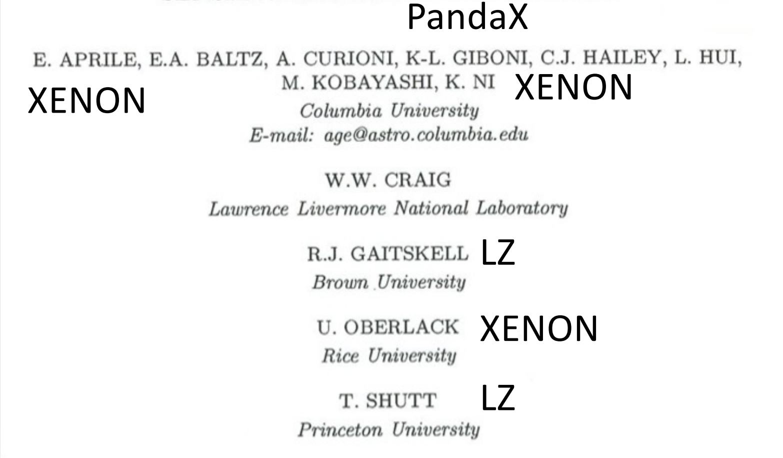

XENON: A 1 TONNE LIQUID XENON EXPERIMENT FOR A SENSITIVE DARK MATTER SEARCH

PandaX

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XENON

XENON

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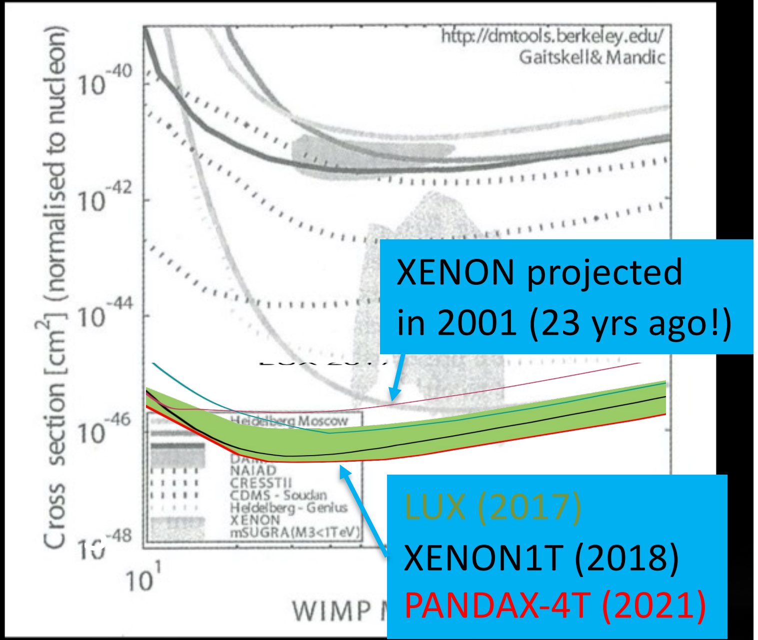
Rice University

T. SHUTT LZ
Princeton University

mSUGRA (M3<1 TeV) was
the target of the search.



XENON projected
in 2001 (23 yrs ago!)

LUX (2017)
XENON1T (2018)
PANDAX-4T (2021)

XENON achieved its goal in 20 yrs
Sensitivity at low mass regions significantly improved thanks to photosensors.