Experimental Searches of Dark Matter

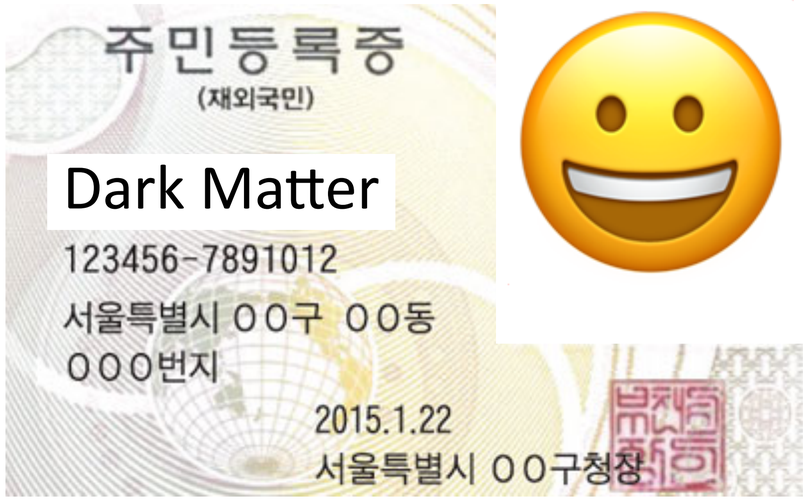
2023 Cosmology workshop on the Crossroad of Astrophysics and Particle physics: dark matter

June 28 ~ July 1, 2023 / Sono Belle Vivaldi Park, Hongcheon

2023. June 29. Korea University, Eunil Won (원은일, 1=1)

Observational Evidence of Dark Matter

- Galaxy rotational curves
- Velocity dispersions
- Galaxy clusters
- Gravitational lensing
- Cosmic microwave background
- Structure formation
- Bullet Cluster
- Type Ia supernova distance measurements
- Sky surveys and baryon acoustic oscillations
- Redshift-space distortions
- Lyman-alpha forest



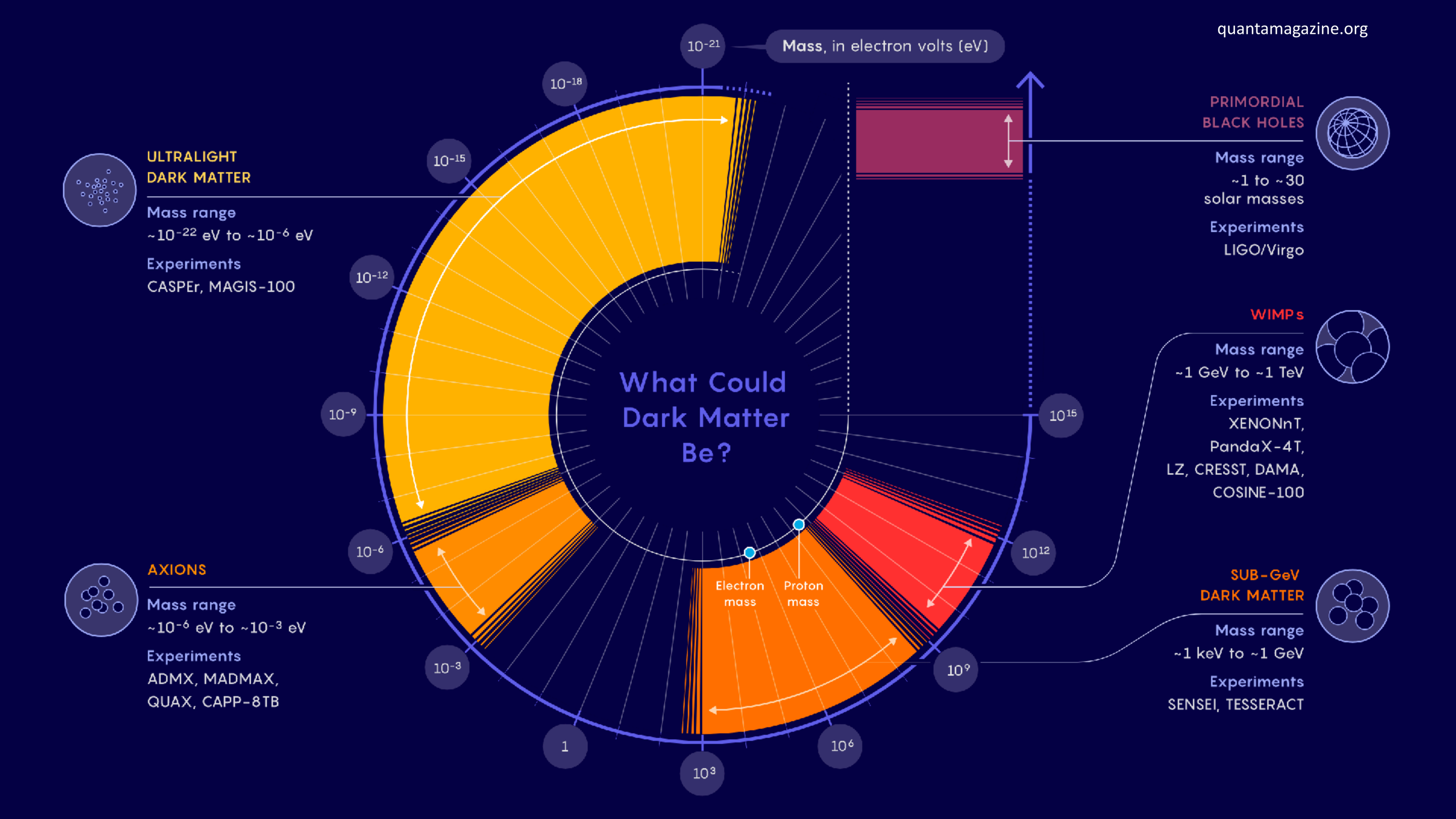
It is hard **not to believe** the existence of DM. But **what is the identity**?

Dark Matter Candidates

- Light bosons: **QCD axions**, axion-like particles, fuzzy cold dark matter
- Neutrinos: SM, **sterile**
- Weak scale: SUSY, extra dimension, little Higgs, ...
- Other particles: **WIMP**, self-interacting DM
- Dynamical DM
- Macroscopic: primordial black holes, MACHOs
- Modified gravity
- Antimatter

Today, I will briefly discuss **highlighted ones** only.

quantamagazine.org



Weakly Interacting Massive Particle (WIMP)

Experimental Signatures

arXiv:1509.08767

A recoil spectrum of single scattering of WIMP to material.

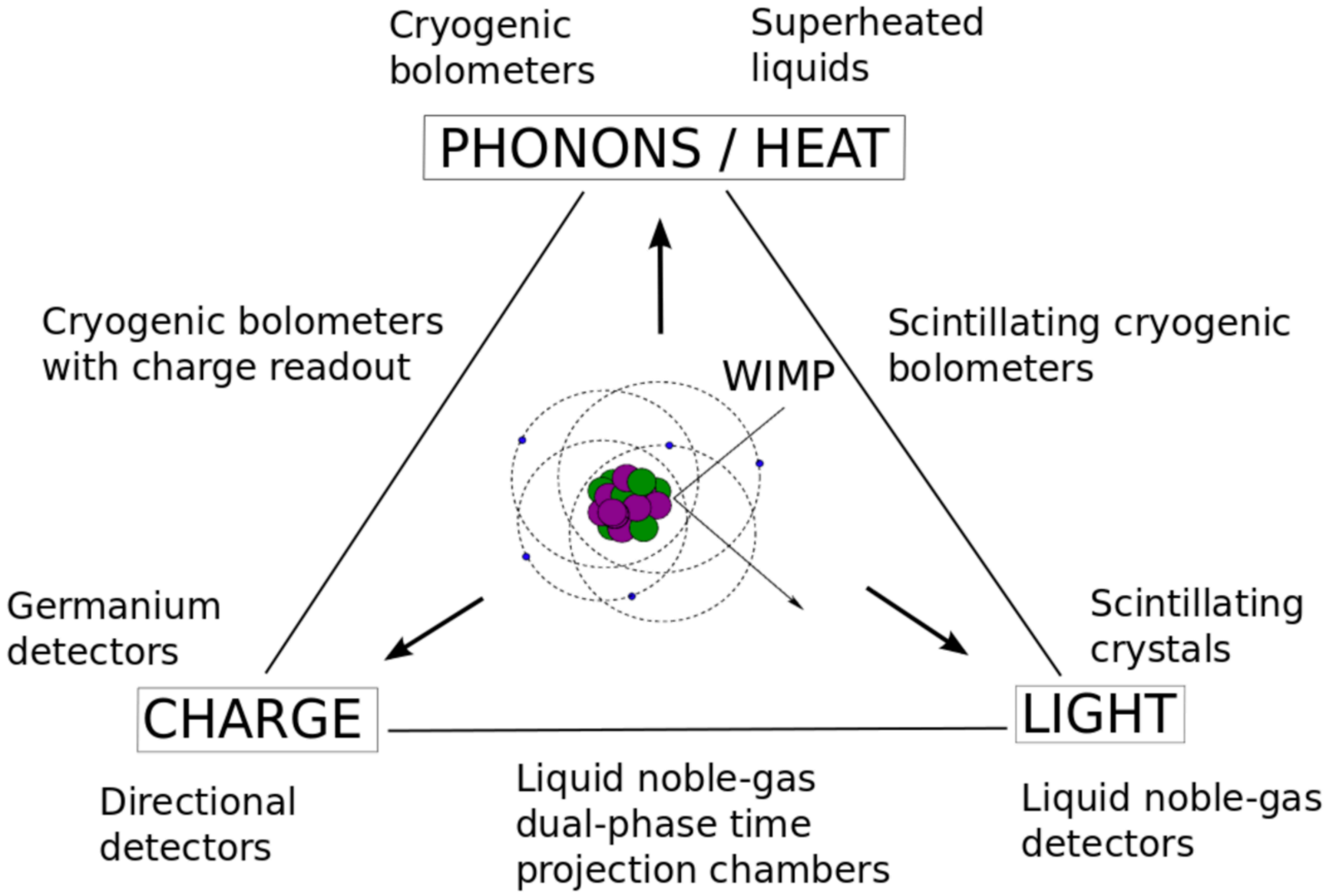
The differential recoil spectrum:

$$\frac{dR}{dE}(E,t) = \frac{\rho_0}{m_\chi} m_A \cdot \int v \cdot f(\mathbf{v},t) \cdot \frac{d\sigma}{dE}(E,v) d^3v$$

1) **Heat** (phonons in a crystal)
2) Excitation of target nucleus: de-excitation with scintillation **photon**.
3) by direct ionization of the target atoms (**charge**)

Schematic of possible signals in direct detection experiments

arXiv:1509.08767

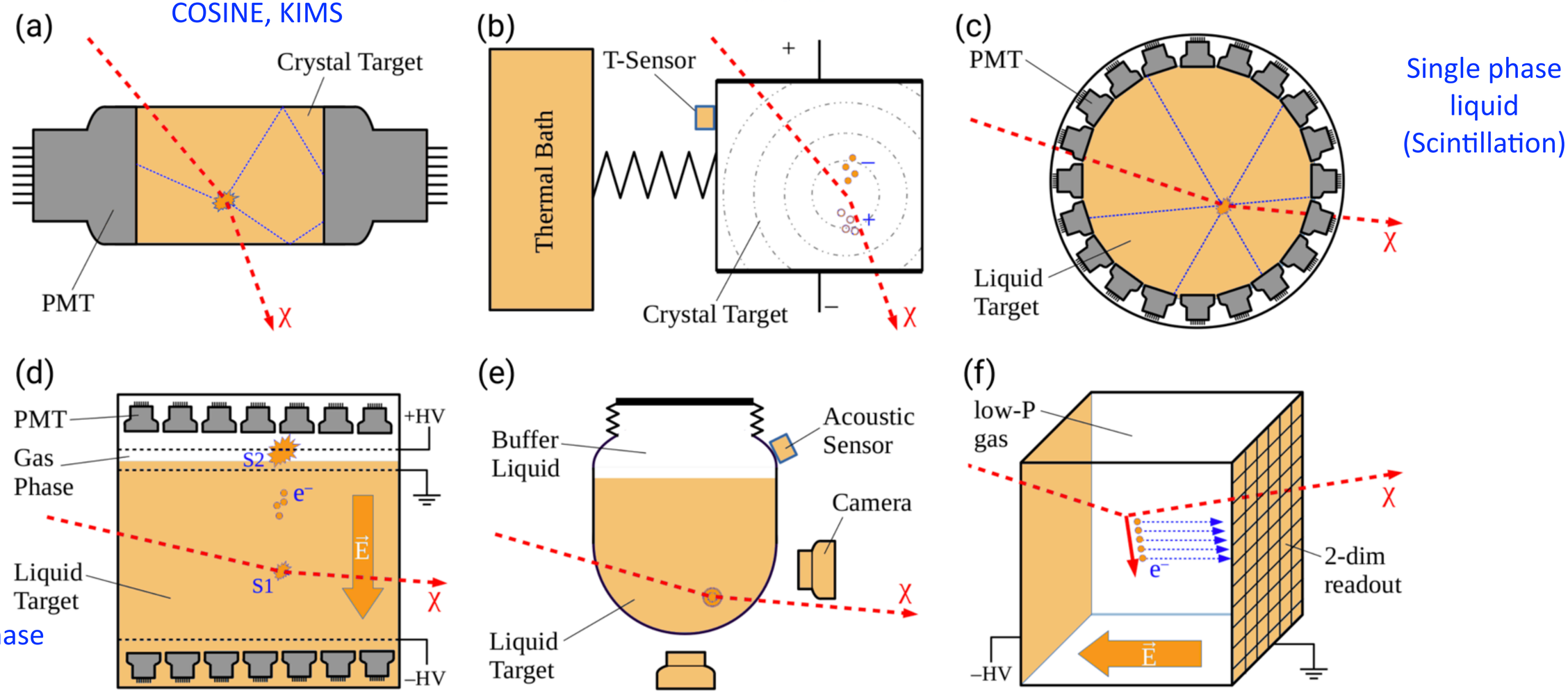


Working principles of direct detection technology

arXiv:2104.07634

COSINE, KIMS

AMORE



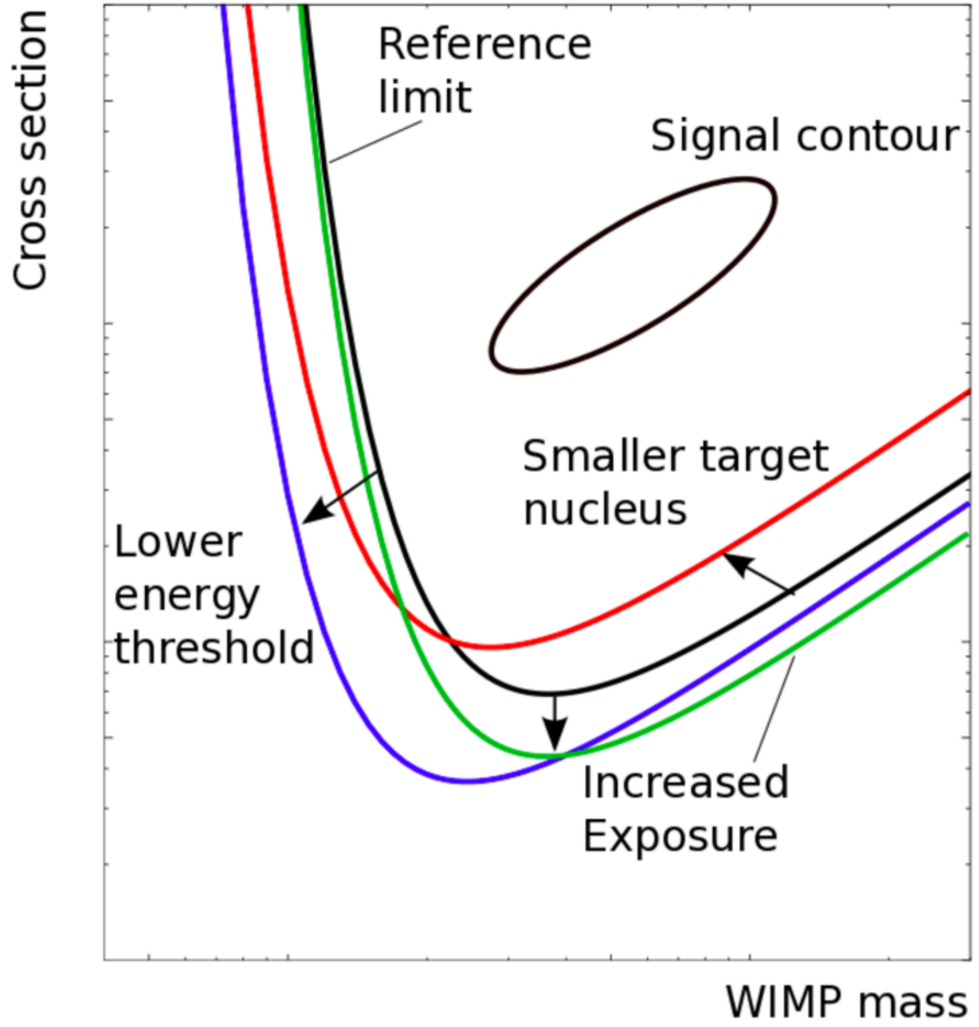
Single phase liquid (Scintillation)

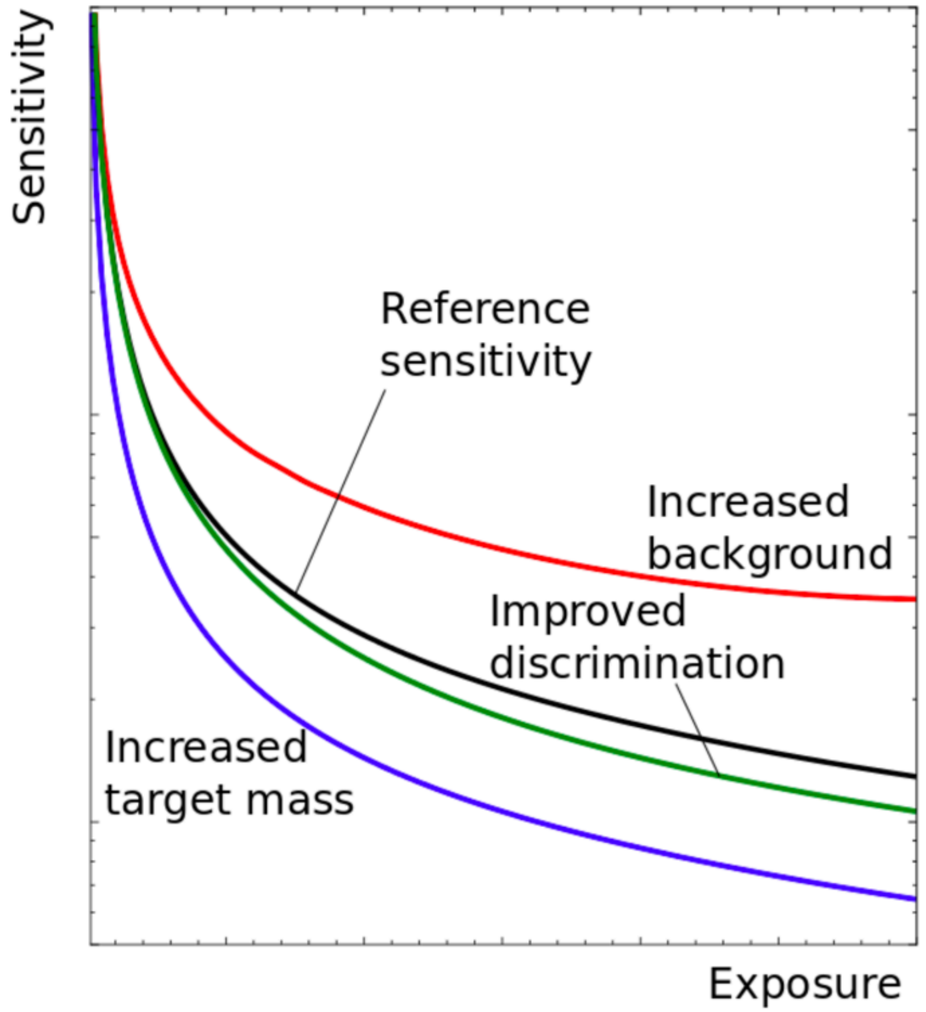
Double phase liquid (scintillation + charge)

Bubble nuclear process

Experimental sensitivity: energy threshold and exposure.

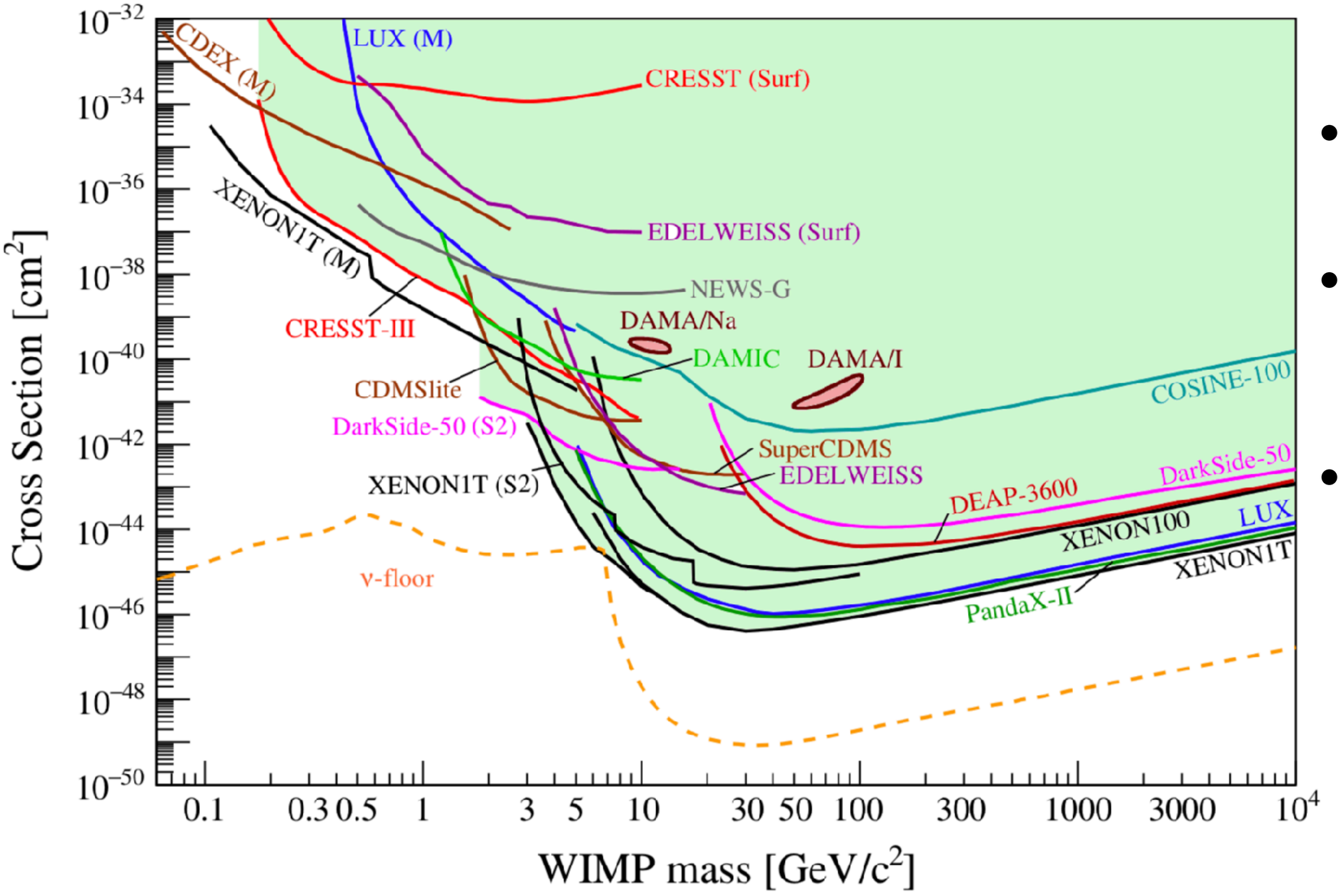
arXiv:2104.07634





Overview of WIMP Searches

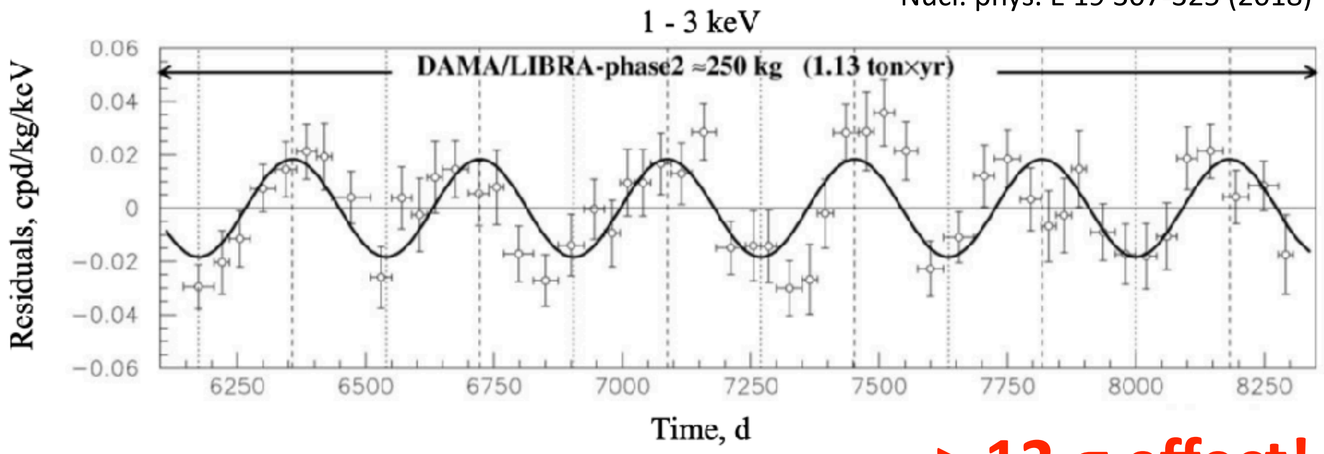
arXiv:2104.07634



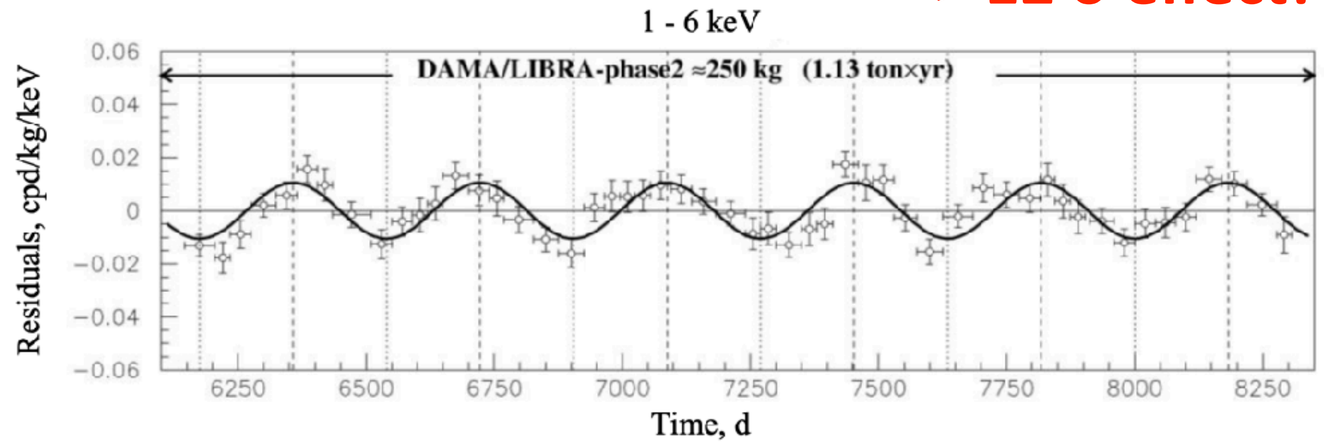
- DAMA modulation above COSINE-100.
- Experiments are getting closer to the "neutrino floor" (experimental limit).
- Low mass region still has room.

DAMA annual modulation "signal"

Nucl. phys. E 19 307-325 (2018)



> 12 σ effect!

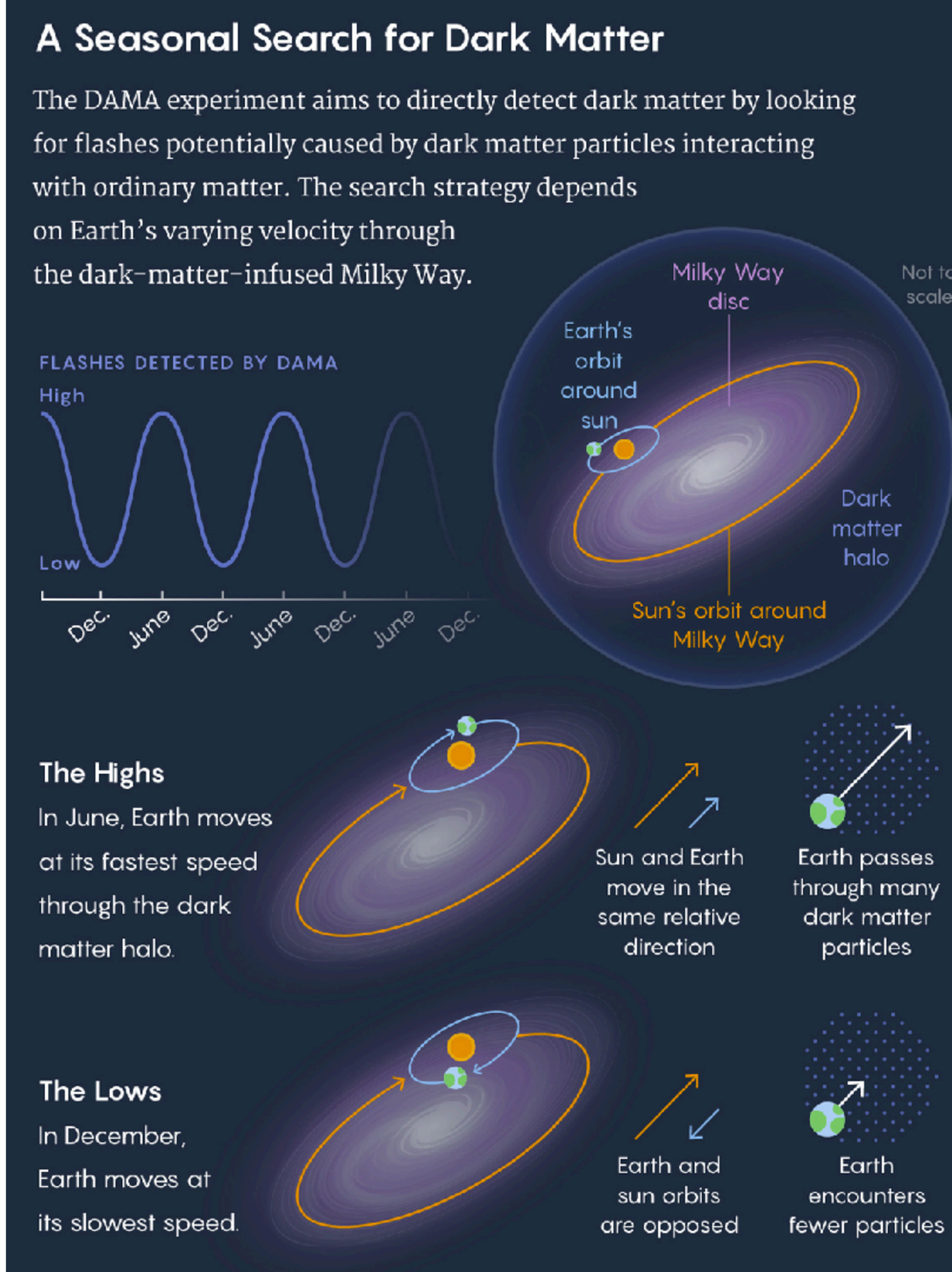


1 (2) keV threshold phase 1 (2)

Phase and period compatible with dark matter.

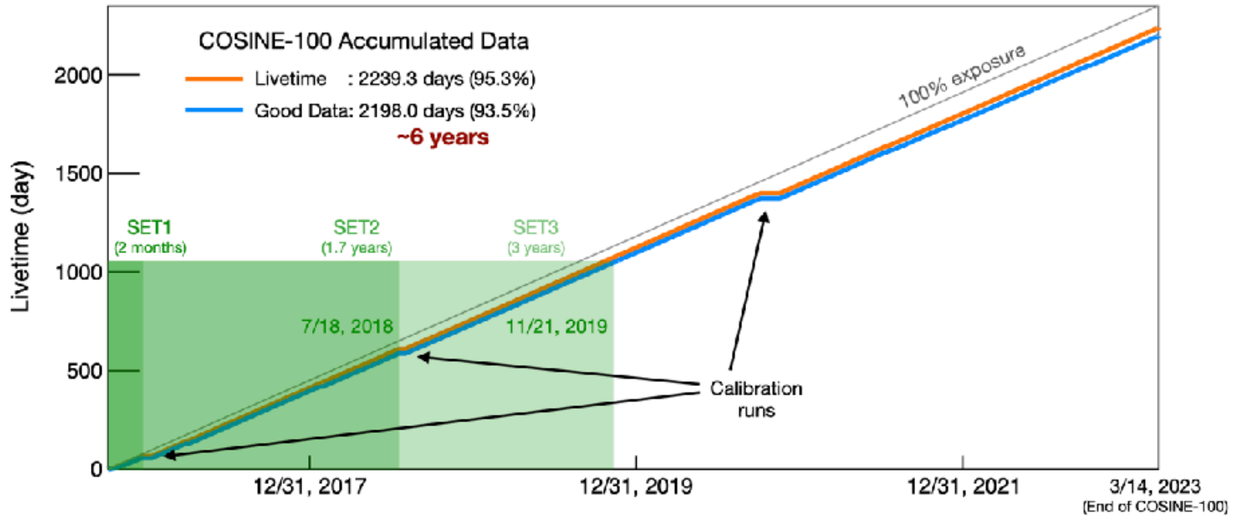
NaI (Tl) crystal.

Discovery of dark matter?

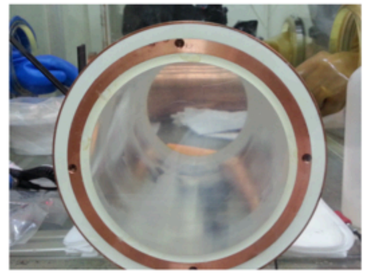


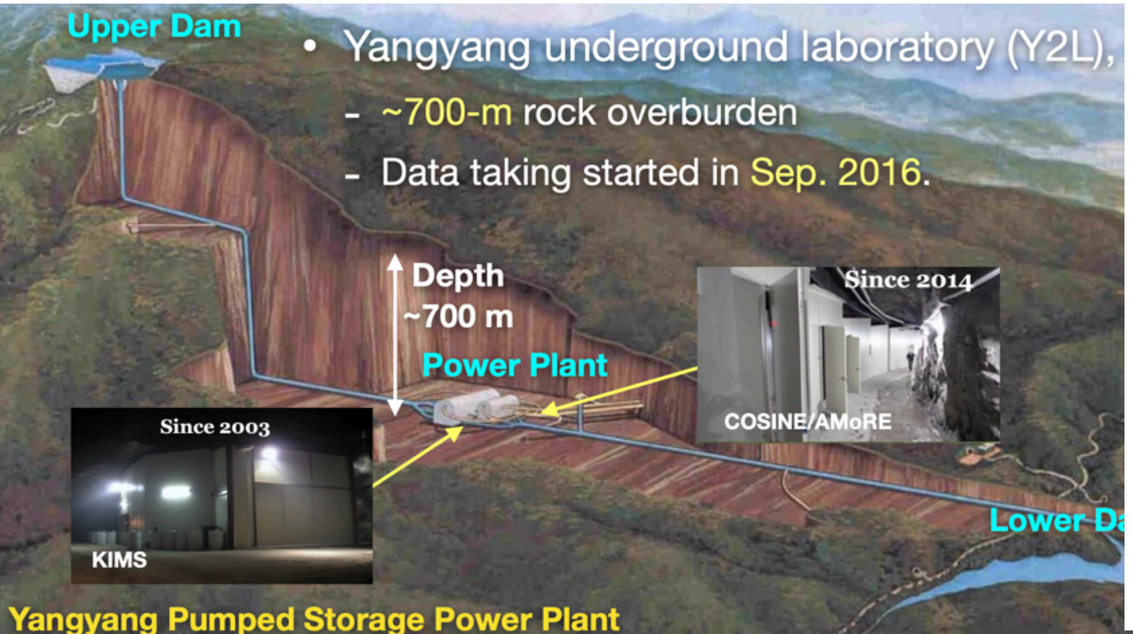
COSINE-100 (CUP/IBS)

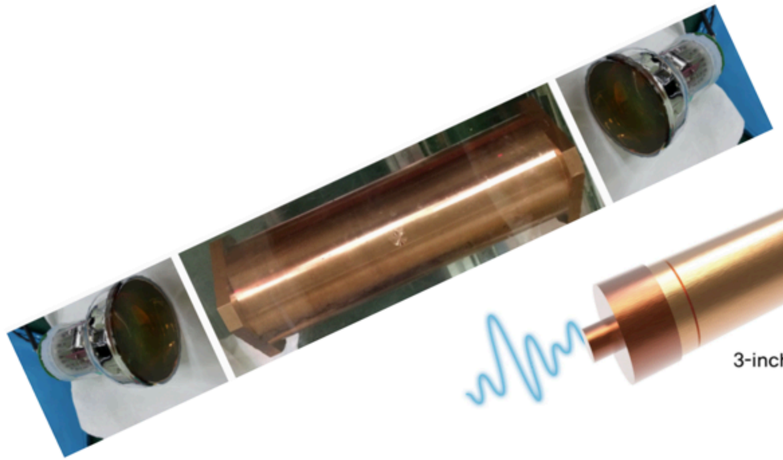
Site: Yangyang underground laboratory.
Goal: to validate the data of DAMA.
Low background NaI (Tl) : 8 crystals, 106 kg in total.
- 2-3 times higher background than DAMA crystal.
- Higher light yield than DAMA crystal.

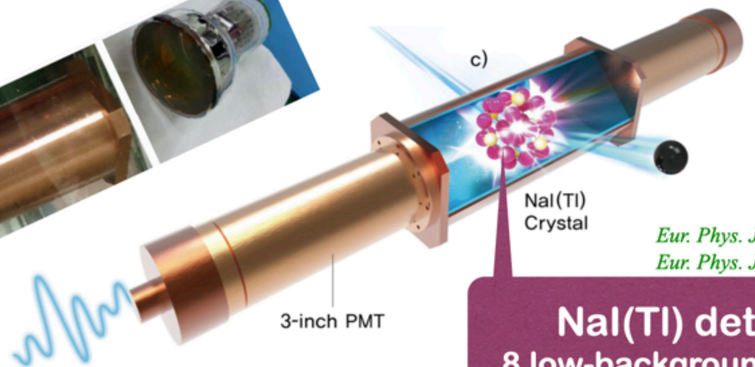


Y. J. Ko @IBS









Eur. Phys. J. C. 78, 107 (2018)
Eur. Phys. J. C. 78, 490 (2018)

NaI(Tl) detector
8 low-background crystals
Copper encapsulation
Two 3” PMTs

Recent report from COSINE-100 (CUP/IBS)

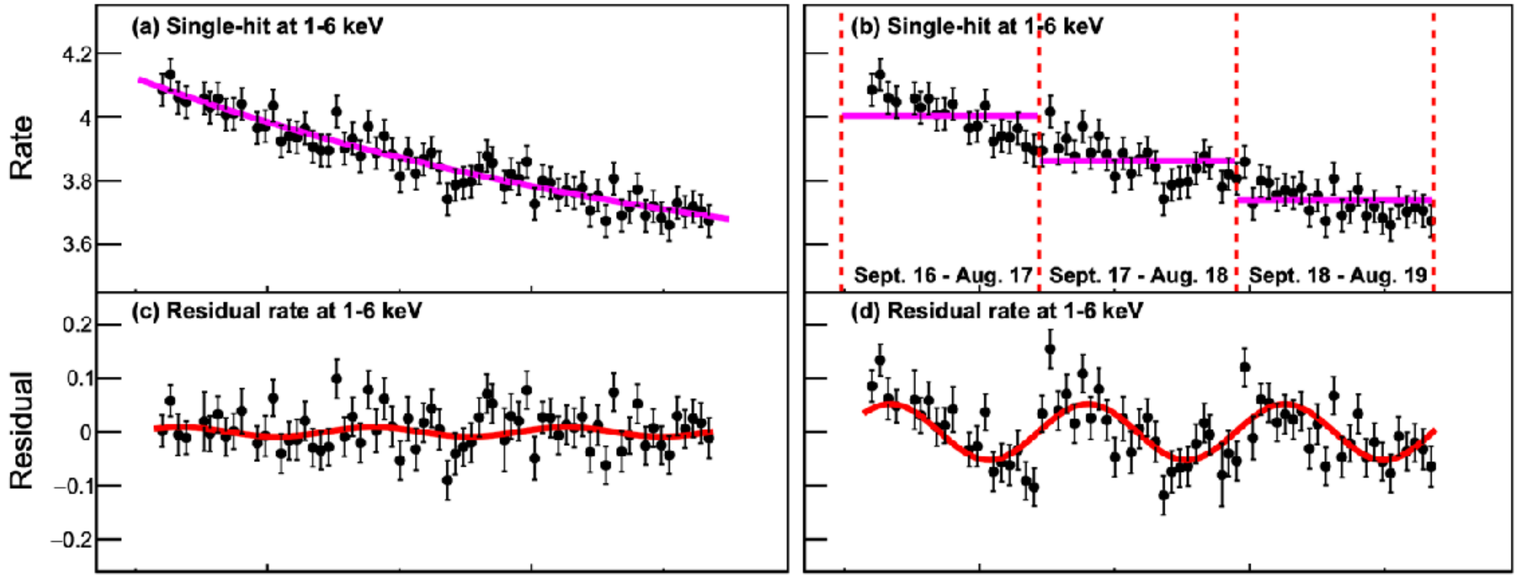
Sci. Rep. 13, 4676 (2023)

www.nature.com/scientificreports

scientific reports

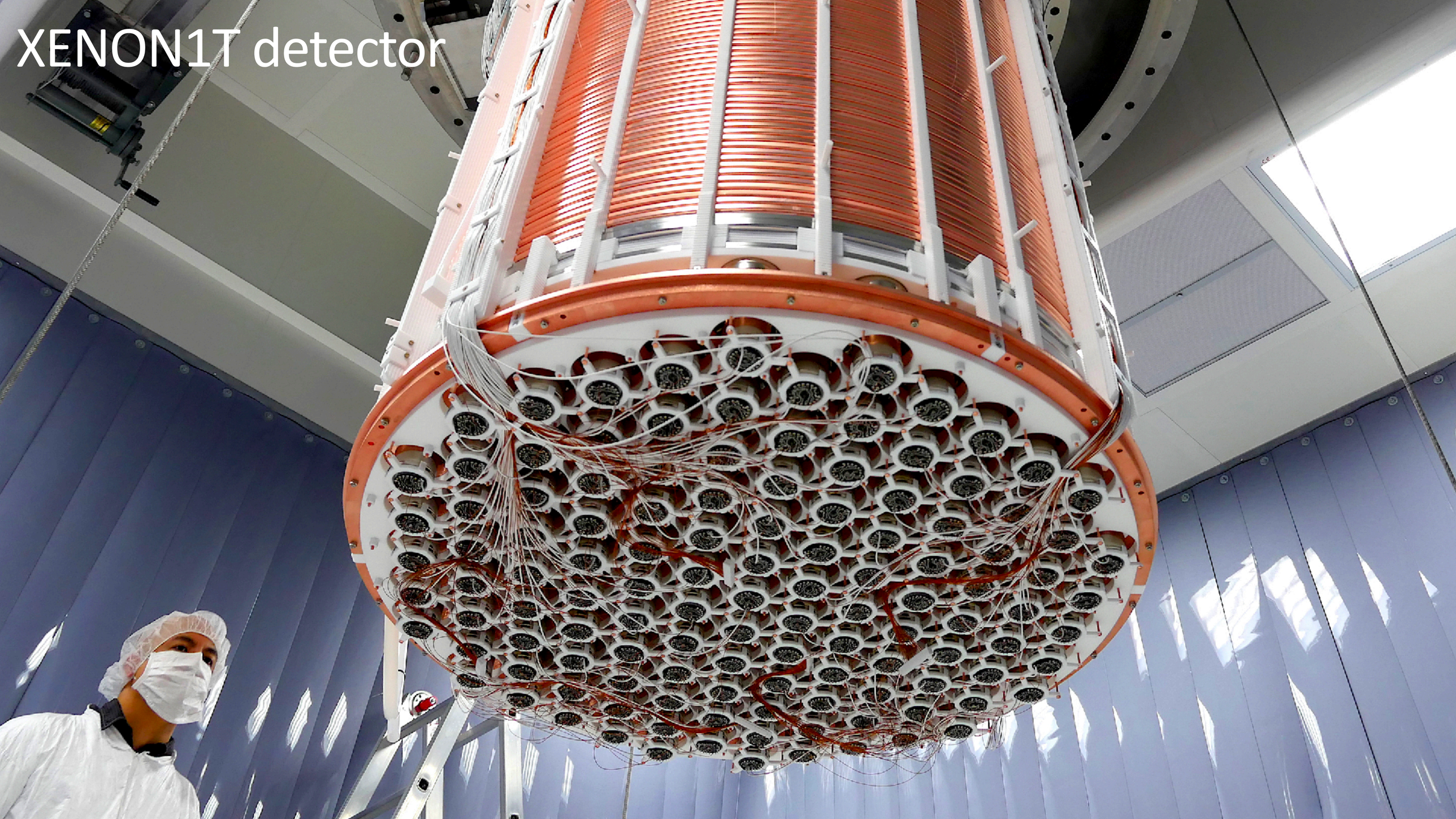
OPEN

An induced annu
signature in COS
by DAMA/LIBRA



in detector's environment or their specific analysis methods. In particular, a recent study presents a possible cause of the annual modulation from an analysis method adopted by the DAMA/LIBRA experiment in which the observed annual modulation could be reproduced by a slowly varying time-dependent background. Here, we study the COSINE-100 data using an analysis method similar to the one adopted by the DAMA/LIBRA experiment and observe a significant annual modulation, however the modulation phase is almost opposite to that of the DAMA/LIBRA data. Assuming the same background composition for COSINE-100 and DAMA/LIBRA, simulated experiments for the DAMA/LIBRA without dark matter signals also provide significant annual modulation with an amplitude similar to DAMA/LIBRA with opposite phase. Even though this observation does not directly explain

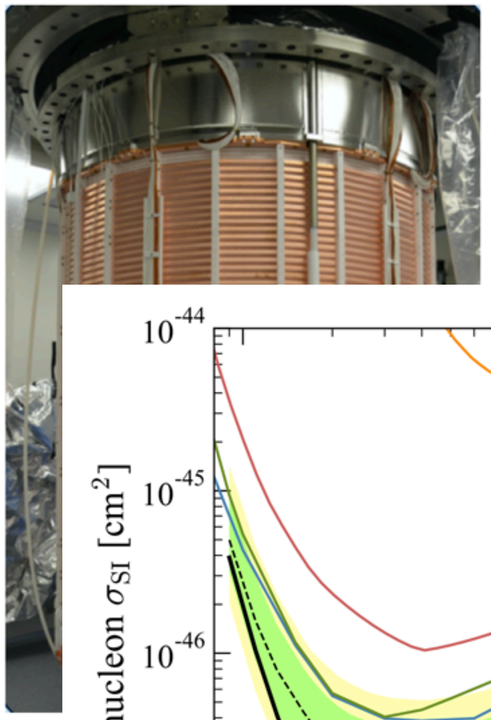
XENON1T detector



Current generation: LZ, PandaX-4T and XENONnT

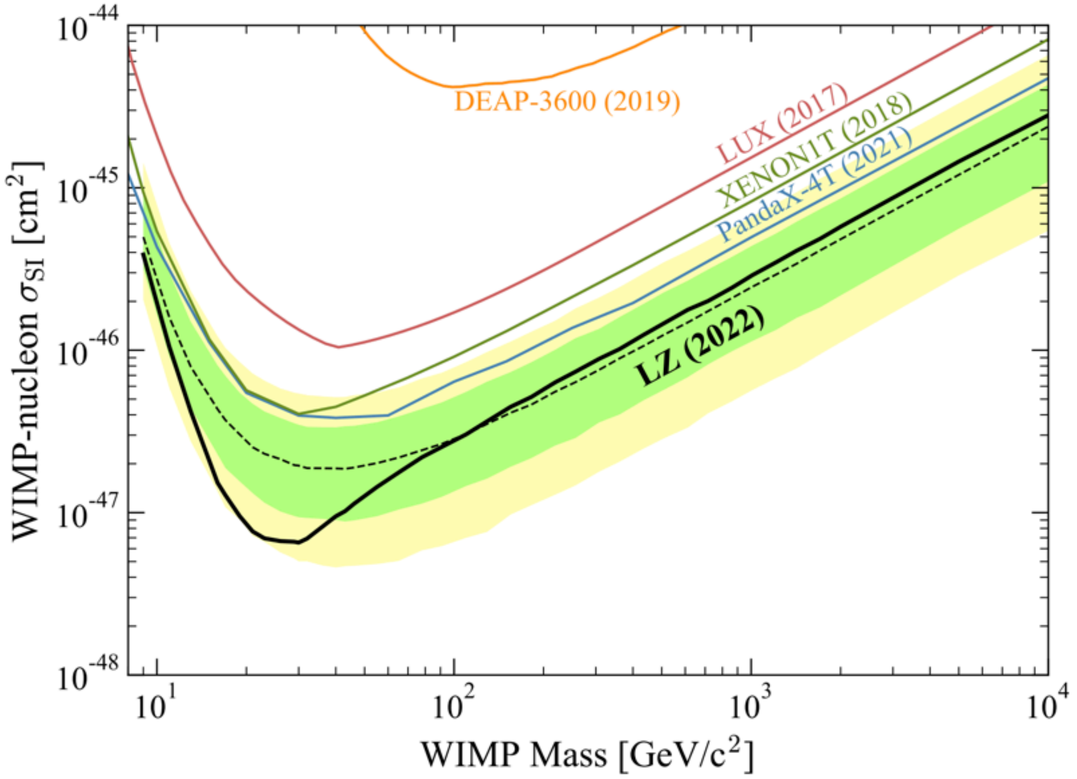






- > 1 Ton available now.

https://arxiv.org/abs/2207.03764



LZ:

- 7 T target mass
- First data released last Thursday!

PANDAX-4T:

- 4 T target mass
- First data released in July 2021

→ A race to measure WIMPs down to $\sigma \sim 10^{-48}$ cm^2

QCD axion

QCD axion

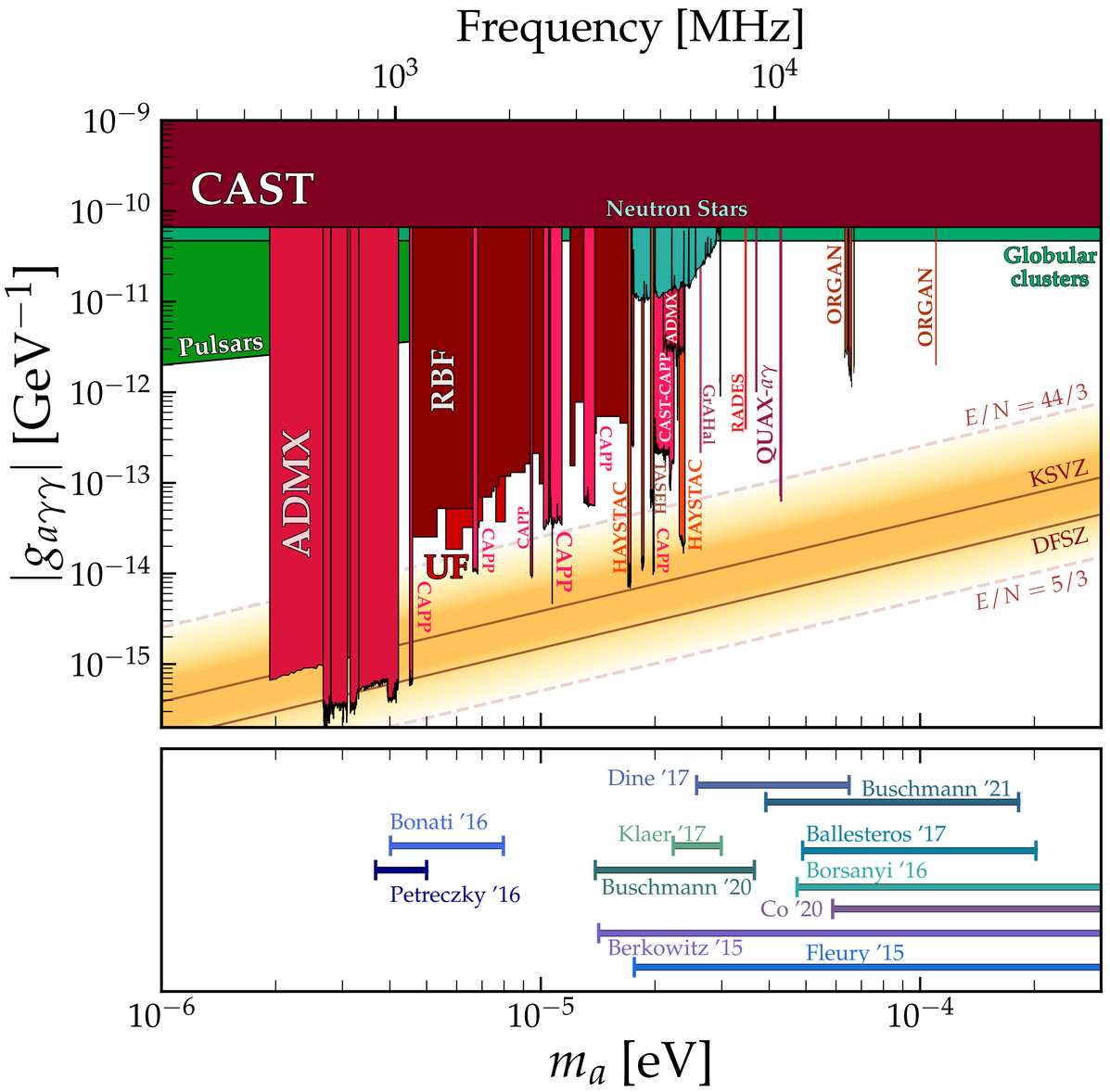
https://arxiv.org/pdf/2203.14923.pdf

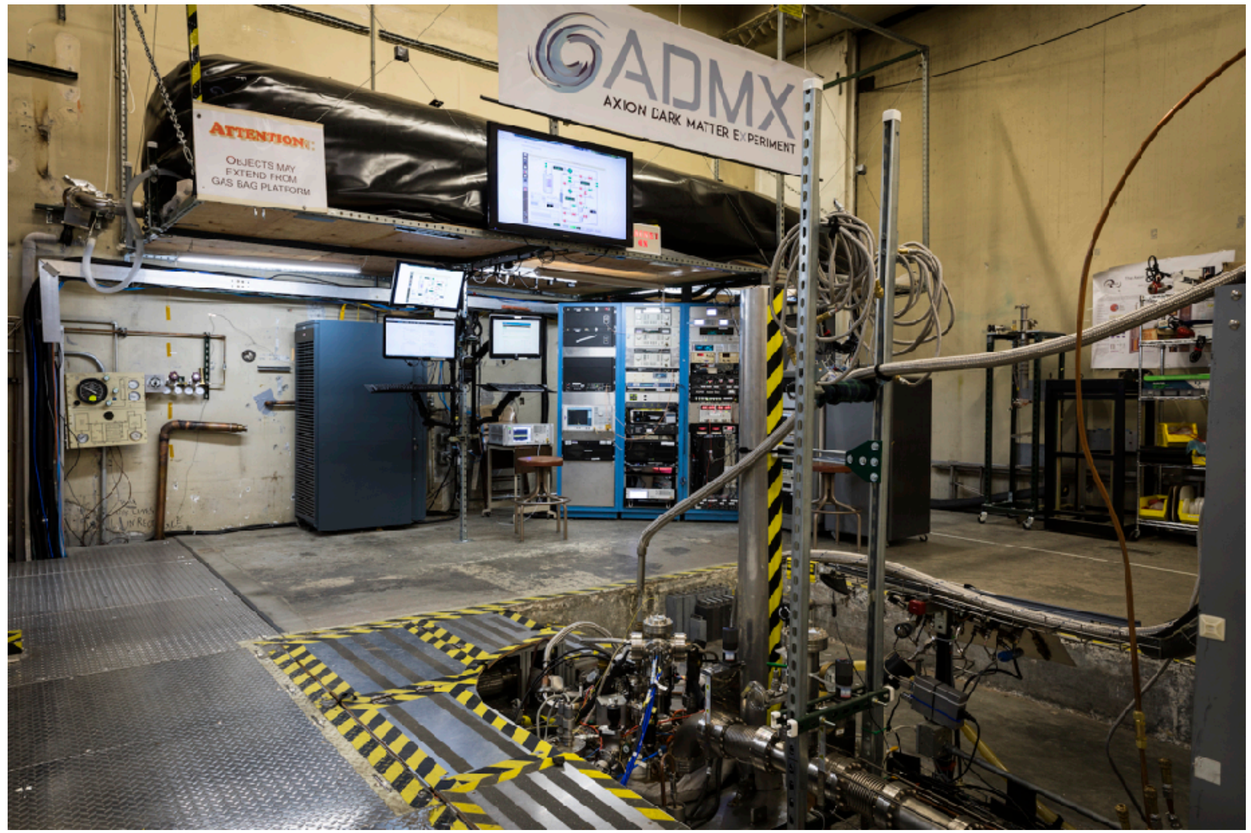
- Pseudoscalar (spin zero, odd parity)
- Solution to strong CP problem: why neutrons have no EDM?
- Provides viable dark matter properties < 1 eV.
- Mass and coupling unknown.
- Axion-photon coupling:

$$\mathcal{L}_{a\gamma\gamma} = g_{a\gamma\gamma} a \mathbf{E} \cdot \mathbf{B}$$

This allows one to search for QCD axion in cavity experiments with **high magnetic field**.

QCD axion searches



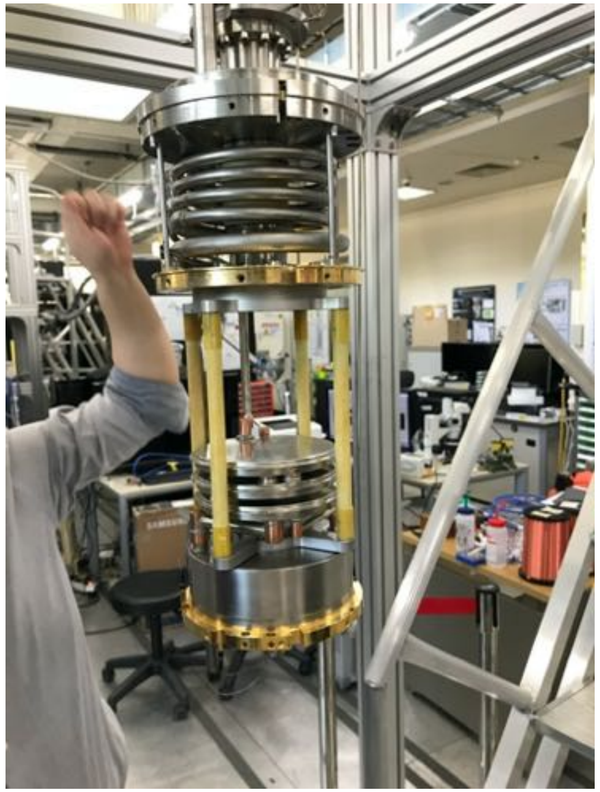


- ADMX (US) has been a traditional player.
- CAPP/IBS joined the game ~ 10 years ago.

CAPP-12TB Infrastructure

Courtesy of A. K. Yi (KAIST)

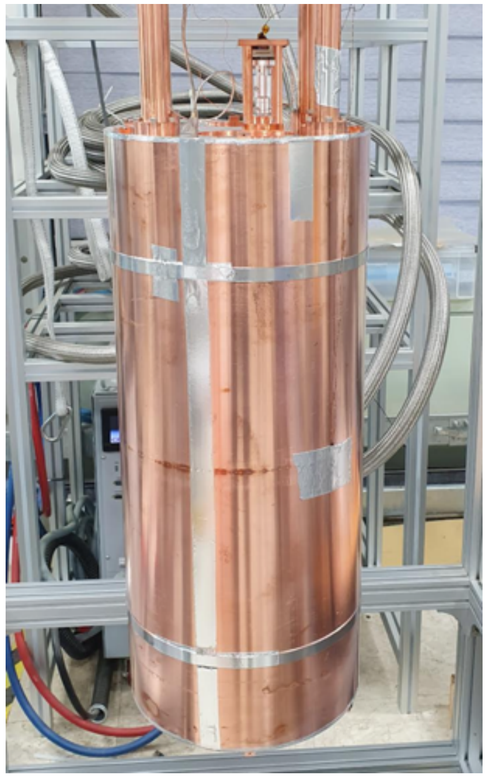
- The CAPP-12TB experiment is a DFSZ-sensitive axion haloscope search for the mass range 3.3 - 16.5 μeV (0.8 - 4.0 GHz)



Dilution Refrigerator
1 mW cooling power @ 90 mK
25 mK with load @ 12 T



Superconducting magnet
Center field 12 T @ 4.2 K
Bore diameter of 320 mm



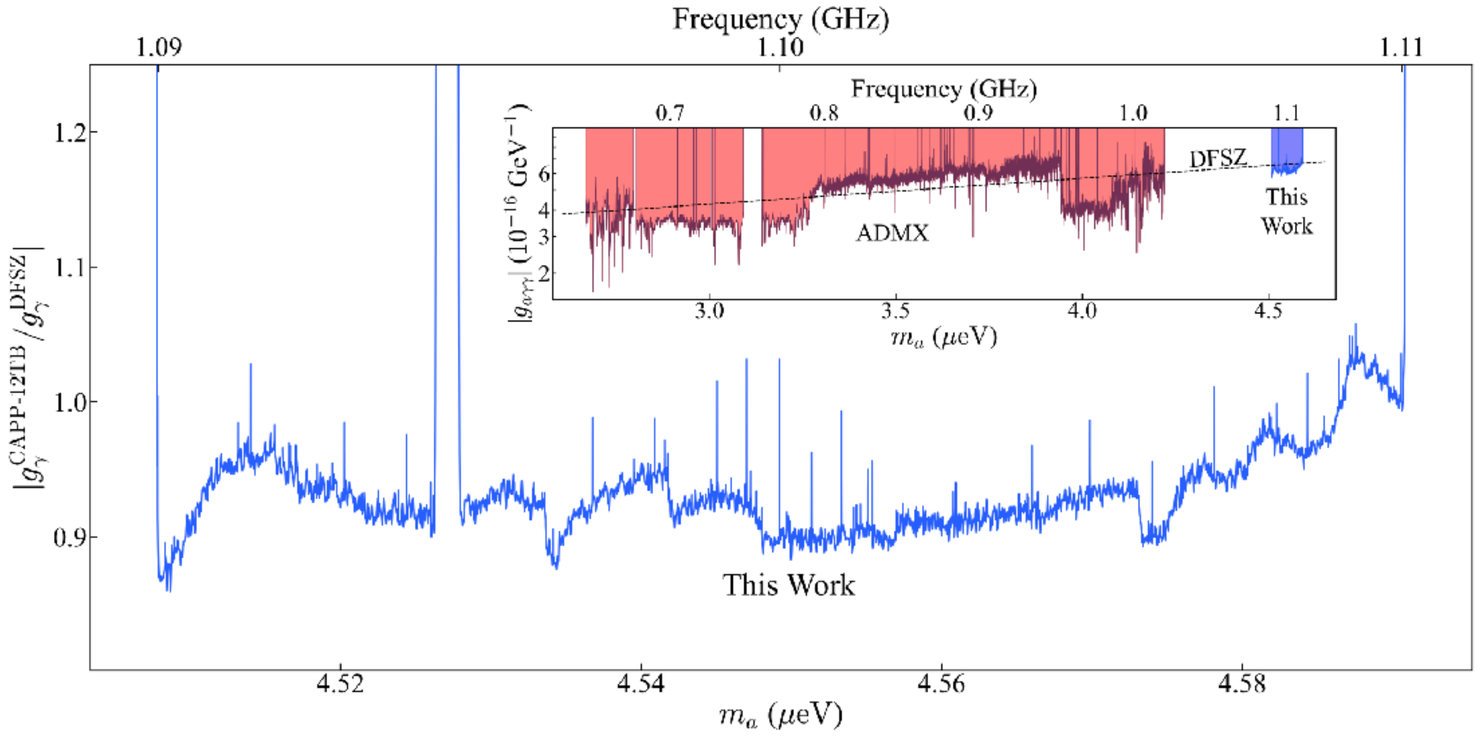
Resonant Cavity
Cooper tuning lod
Q_0 = 100,000



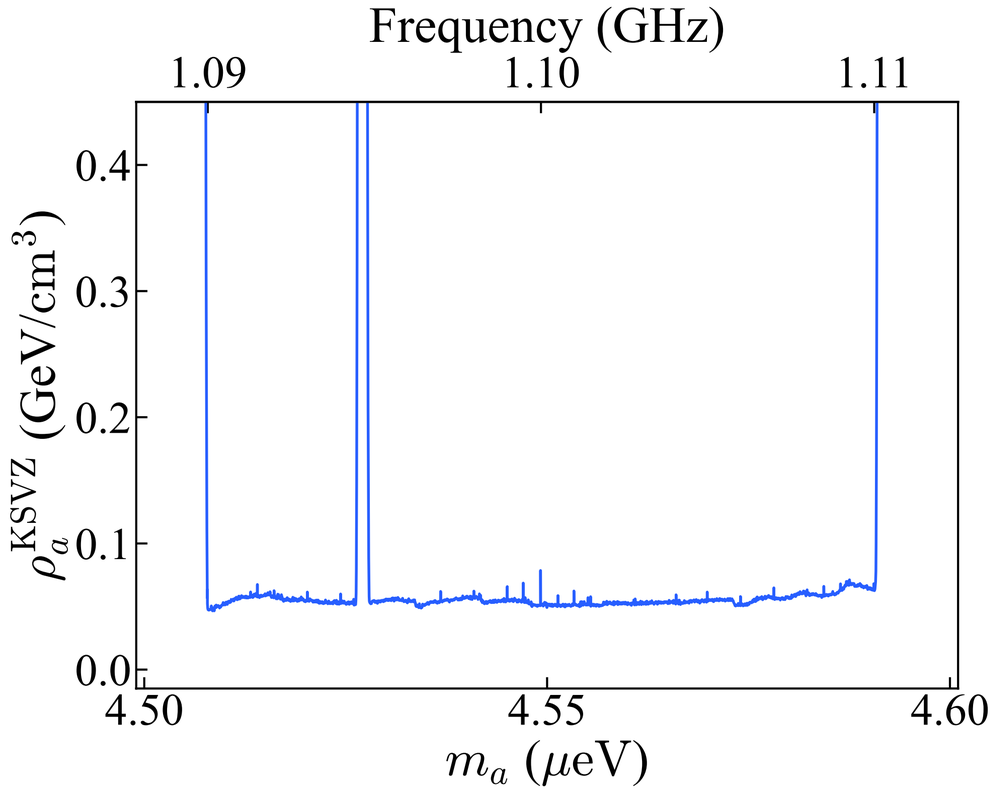
Josephson Parametric Amplifier
Range: 1.09 - 1.11 GHz
System noise temperature 215 mK

CAPP-12TB Recent result

- The CAPP-12TB experiment excludes 20 MHz DFSZ axions.



A. K. Yi PRL 130, 071002 (2023)



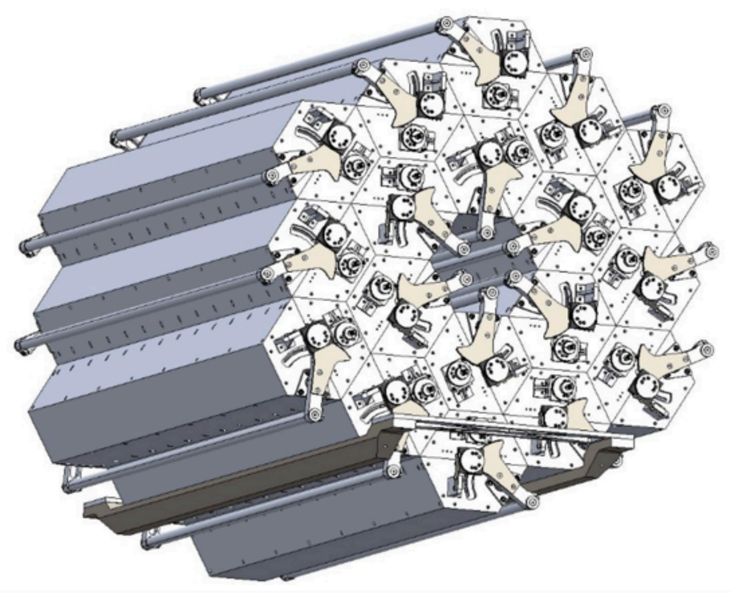
Exclusion plot for KSVZ axion dark matter density.

US Projection for future experiments.

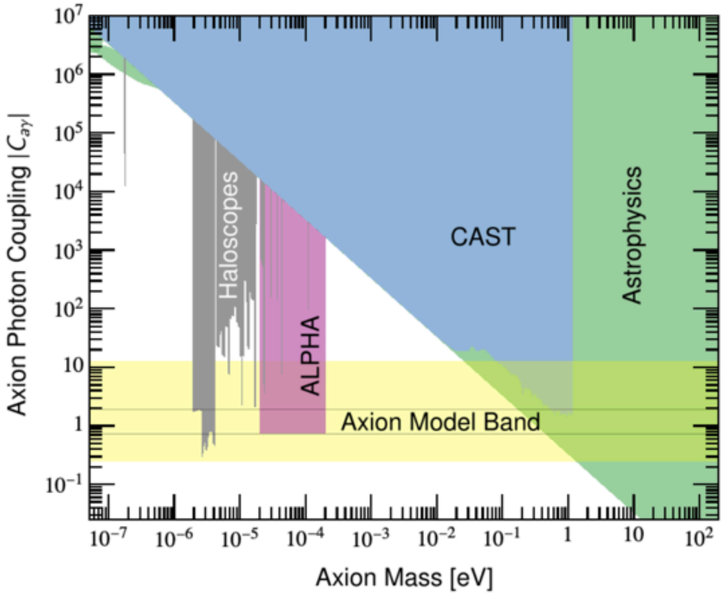
- US snowmass report (2021)

Table 1: Experimental parameters for ADMX-G2 and EFR runs. In Run 1 where parameters varied between runs, ranges or exceptions are given.

	Run 1A-D	Run 2A	EFR
Frequency Range	650–1390 MHz	2–4 GHz	2–4 GHz
Number of Cavities	1	4	18
Volume	106–136 ℓ	85 ℓ	80 ℓ
Q	58,000 (avg)	60,000	90,000
B Field	7.7 T (A: 6.85 T)	7.7 T	9.6 T
Avg Form Factor	0.45 (D: 0.35)	0.45	0.4
Noise Temperature	300–350 mK (A: 700 mK)	350 mK	325 mK
Operations Days	1000	300	1000

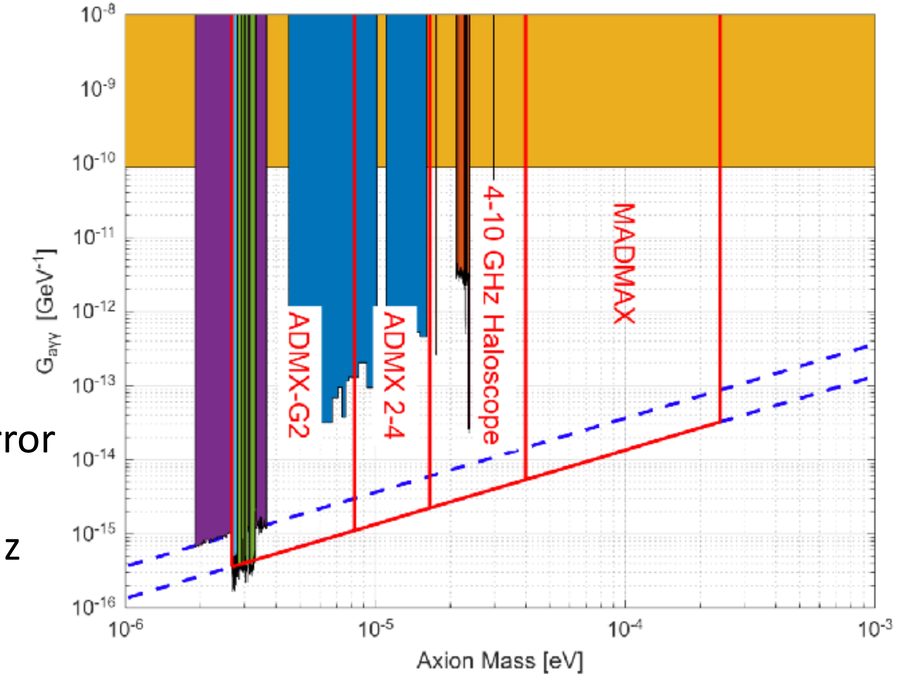


EFR



Axion Longitudinal Plasma HAloscope (ALPHA): 5-50 GHz

MAgnetized Disc and Mirror Axion eXperiment (MADMAX): 10-100 GHz



Sterile Neutrino

Neutrinos : the only unexpected from Standard Model.

- Standard Model of particle physics is a local gauge theory: this requires the neutrino mass to be **precisely zero.**
    - Therefore, in order to explain observed neutrino oscillations, extension of the Standard Model is **a must**.
    - **Sterile neutrinos** are proposed to have mass term to Standard Model neutrinos:

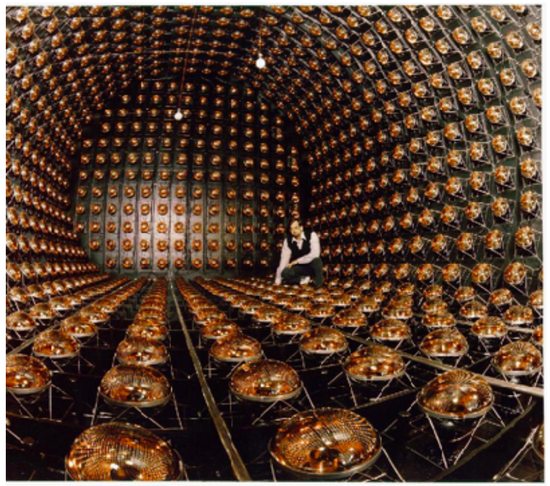
$$-\mathcal{L}_{M\nu} = M_{Dij}\bar{\nu}_{si}\nu_{Lj} + \frac{1}{2}M_{Nij}\bar{\nu}_{si}\nu^{c}_{sj} + \text{h.c.}$$

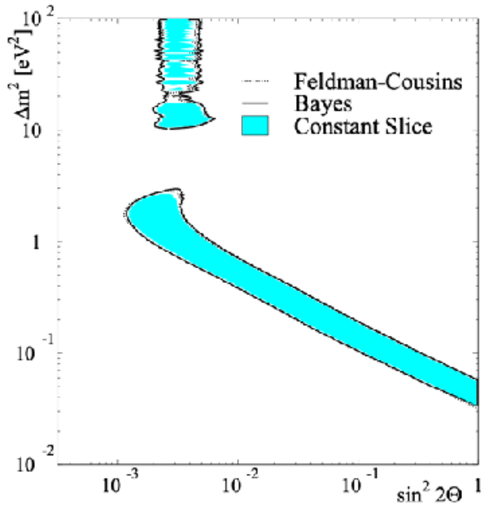
Neutrino mixing matrix (Pontecccorvo-Maki-Nakagawa-Sakata: PMNS) can be constructed from this.

- Note: The **absolute mass** scale, nature of the neutrino (**Dirac vs. Majorana**), and the **mass ordering** are all unknown.

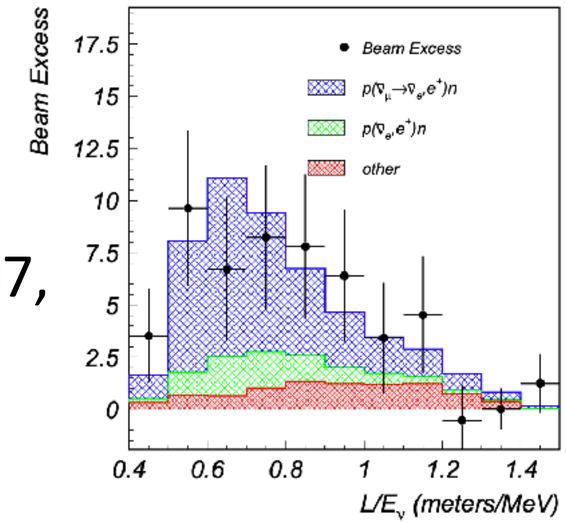
A “hint" of anomaly in several experiments: sterile neutrino?

Liquid Scintillator Neutrino Detector
(LSND, US)

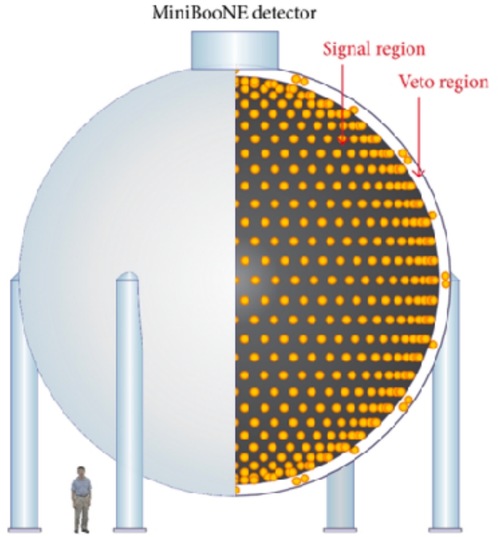




$\overline{\nu}_\mu \rightarrow \overline{\nu}_e$



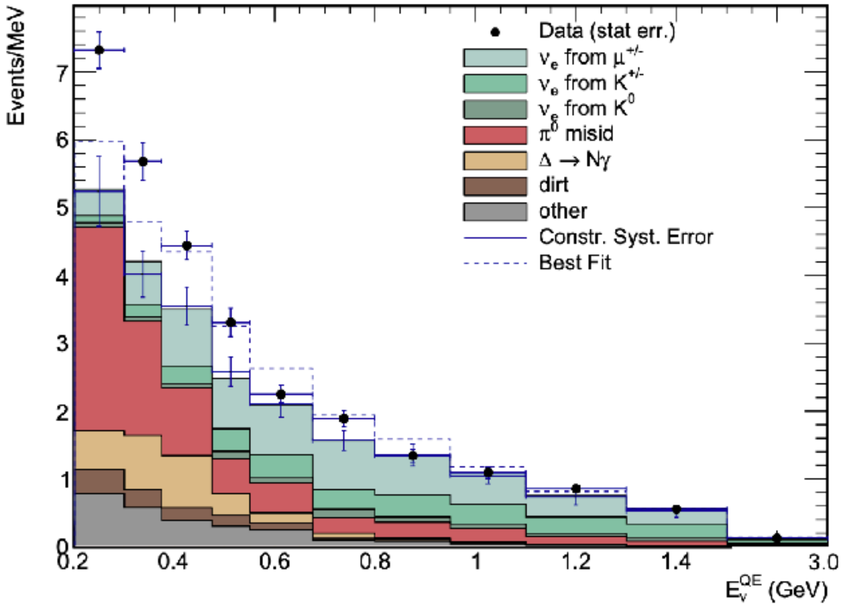
Phys. Rev. D64:112007,
(2001) **3.8σ** !



MiniBooNE experiment

$\nu_\mu \rightarrow \nu_e$

Phys. Rev. D 103, 052002
(2021) **4.8σ** !

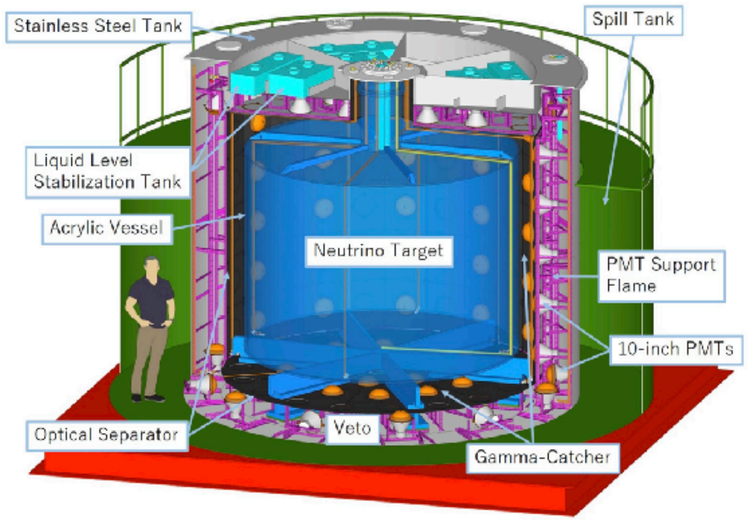


$\Delta m^2 \sim 1\ eV^2$.

JSNS2-I, II experiments (II: near and far detectors)

J-Parc Sterile Neutrino Search (J-PARC, Japan)

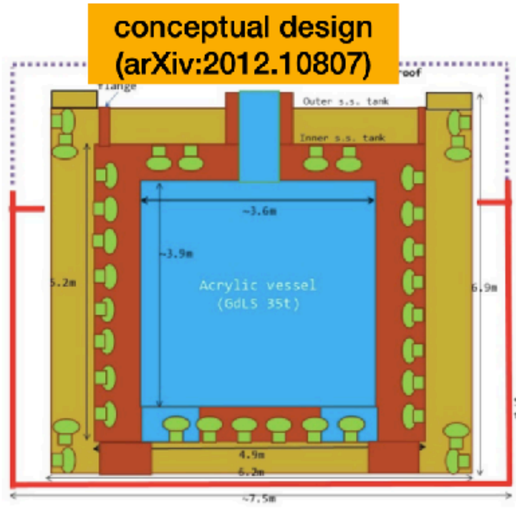
https://arxiv.org/pdf/2104.13169.pdf



: under data taking.

JSNS²-II
(arXiv:2012.10807)





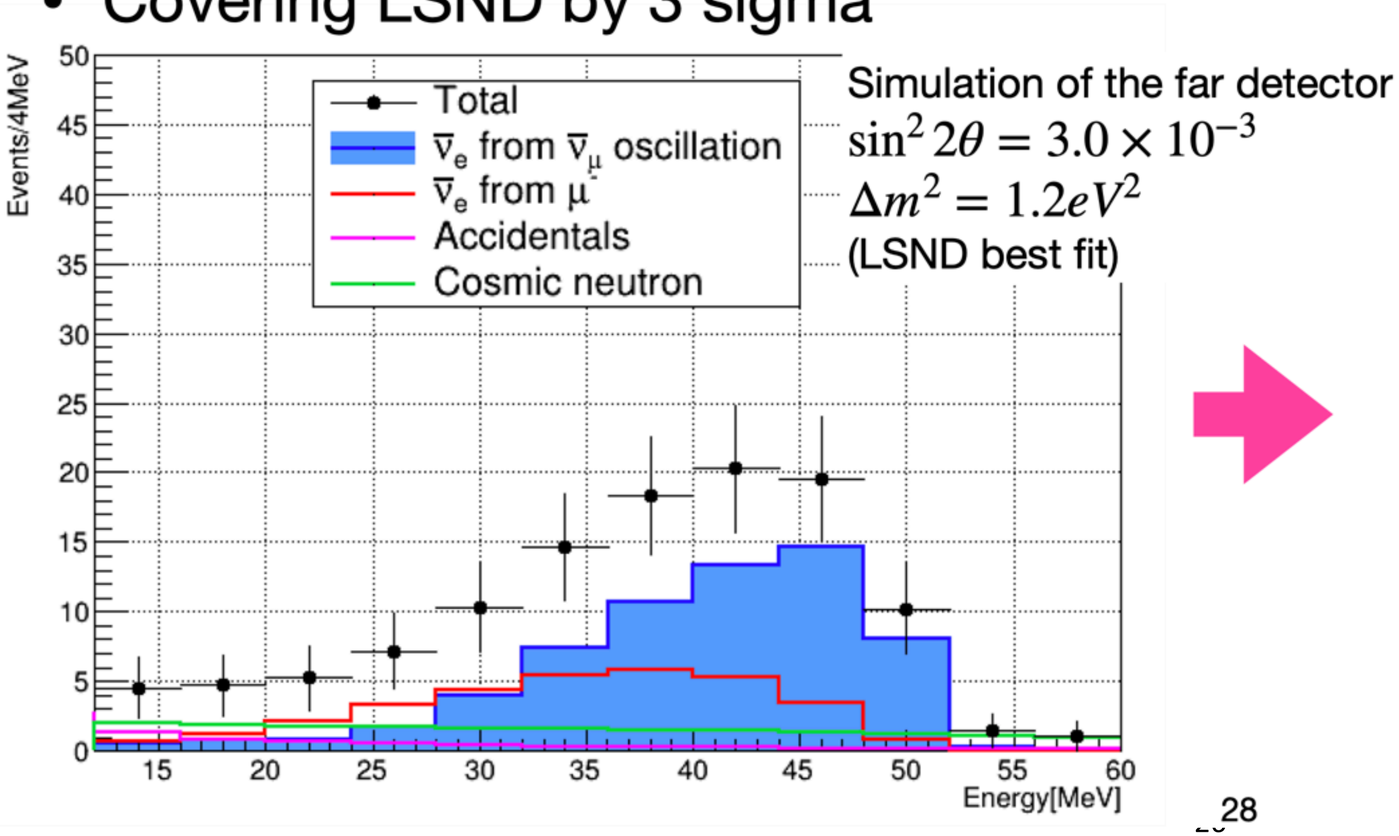
- Second phase of the JSNS² experiment with two detectors
  - near (17 tons, 120 10-inch PMTs, 24 m),
  - far (32 tons, 220 10-inch PMTs, 48 m) detector
- Improve the sensitivity especially in the low Δm^2 region
- J-PARC/KEK grants the stage 2 (2/2) approval
- The stainless steel tank has been constructed
- Other works are on-going

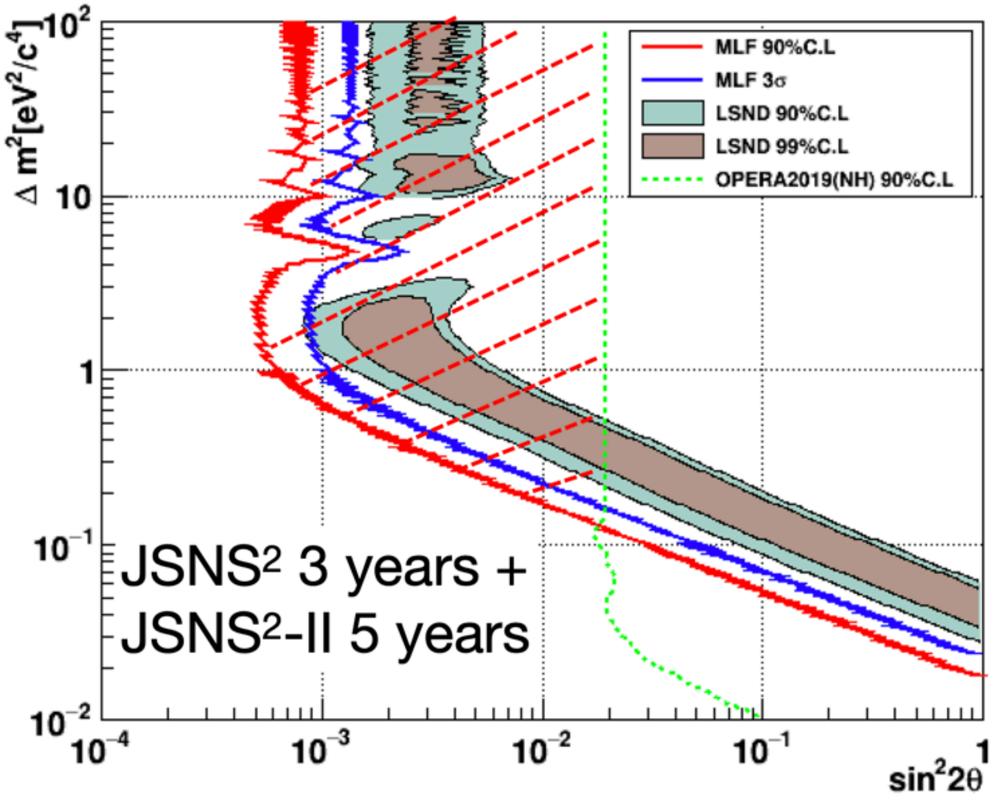

demonstration of the PMT attachment


catcher + veto + spill tank

Sensitivity for the JSNS²-II
(Based on the simulation)

- Each background simulation was done based on the JSNS² data
- Covering LSND by 3 sigma





2023. 06. 22

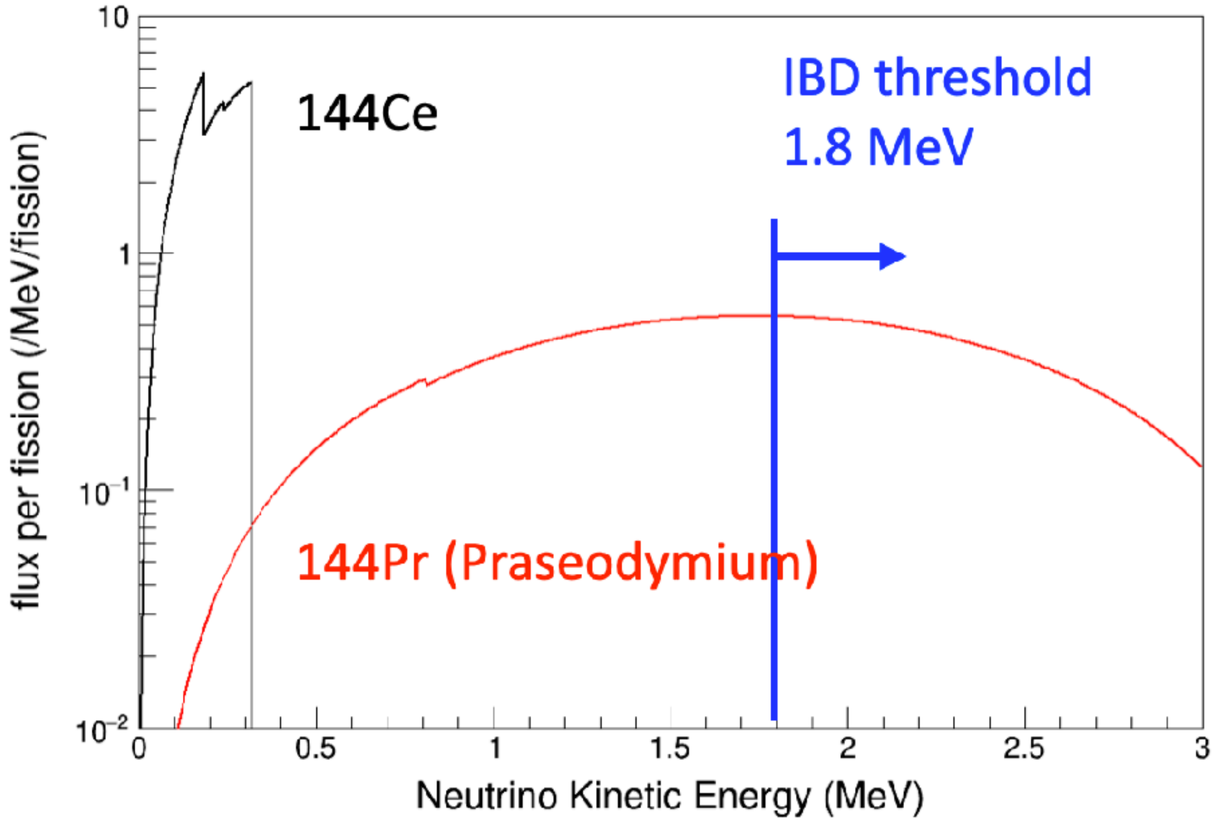




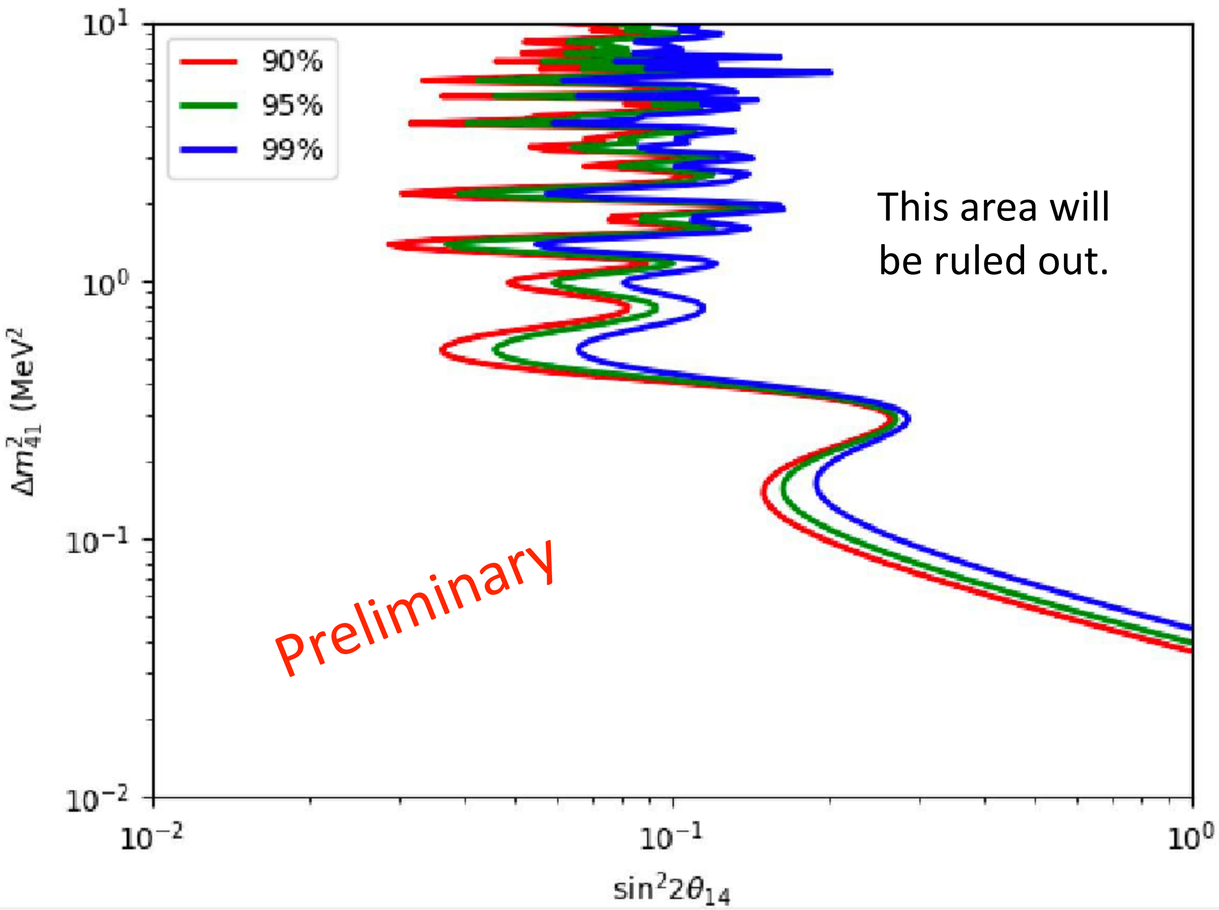
Sterile neutrino search at Yemilab.

- Use strong radioactive source : 100 k Ci Ce-144 (Pr-144). (Anti-electron neutrino)
- 2 k ton liquid scintillator detector, 1 year (4600 events).
- Detection: Inverse beta decay

Seonghyuk Jang, Kyungmin Lee, EW (KU)



Seonghyuk Jang, Kyungmin Lee, EW (KU)



Summary: Dark Matter Candidates

- Light bosons: **QCD axions**, axion-like particles, fuzzy cold dark matter
- Neutrinos: SM, **sterile**
- Weak scale: SUSY, extra dimension, little higgs, ...
- Other particles: **WIMP**, self-interacting DM
- Dynamical DM
- Macroscopic: primordial black holes, MACHOs
- Modified gravity
- Antimatter

Today, I briefly discussed **highlighted ones** only.