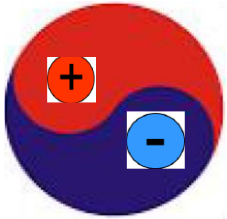
Domestic Experiments for Dark Sector Search

Presented by H.J. Kim

Dept. of Physics, Kyungpook National University

Workshop on Dark Universe, Jan 16-19, 2024



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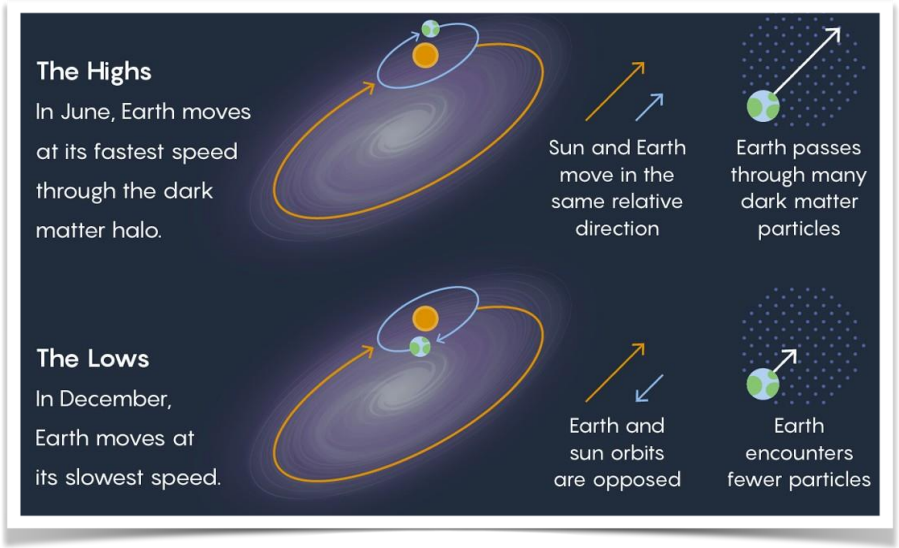
Why universe is dark?

Dark Energy
Dark Matter
WIMP
Axion
Dark photon
……..
?????

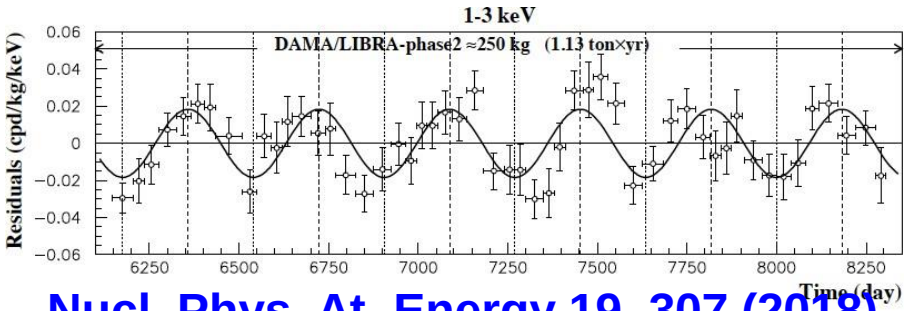
Spaced based
Ground based
Underground based

Theorist and Experimentalist need to work together

Annual modulation signal from DAMA/LIBRA

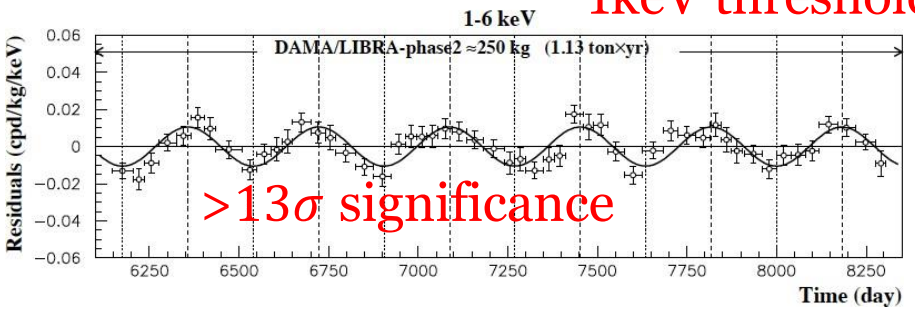


Phase2 experiment



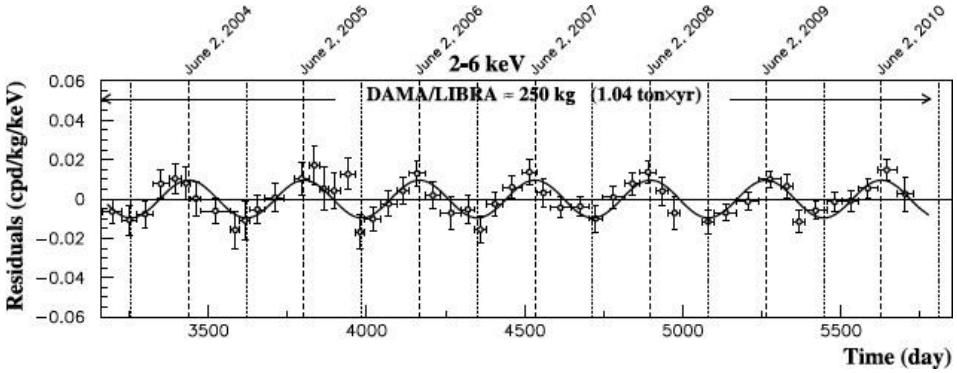
Nucl. Phys. At. Energy 19, 307 (2018)

1keV threshold



>13σ significance

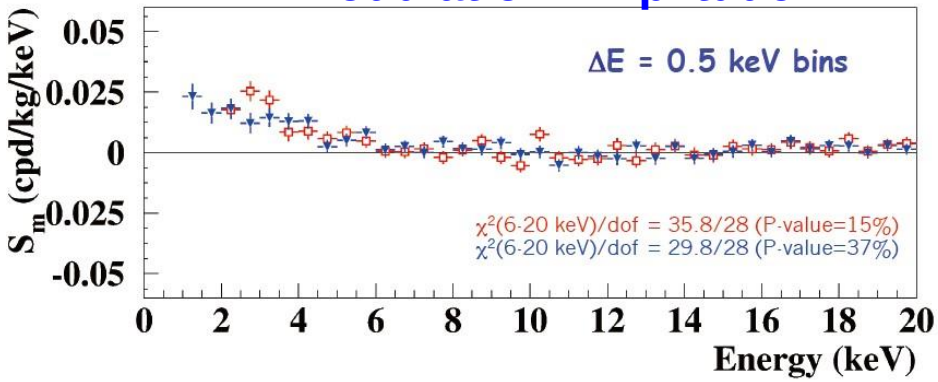
Phase1 experiment



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

2keV threshold

Modulation Amplitude



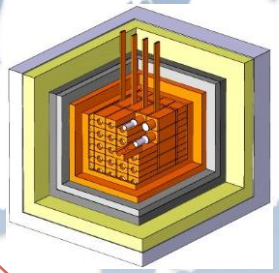
Global Efforts with NaI:Tl crystals

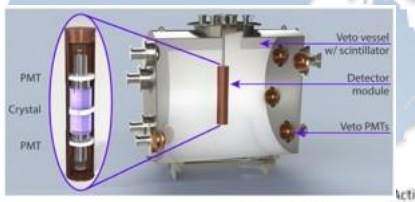
KYUNGPOO NATIONAL UNIVERSITY

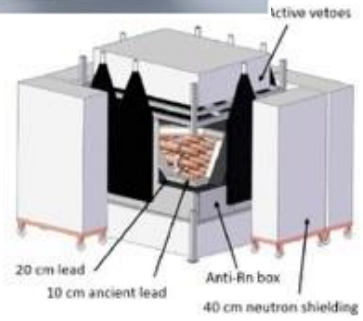
COSINUS @ LNGS

DAMA @ LNGS

SABRE @ LNGS



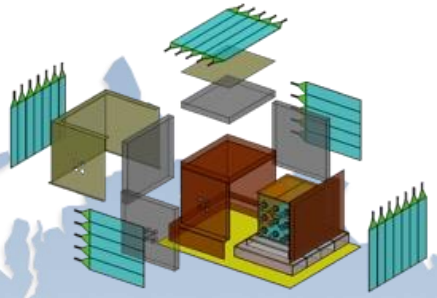




ANAIS @Canfranc

In Data-taking

ANAIS results.
Phys. Rev. Lett. **123**, 031301 (2019)



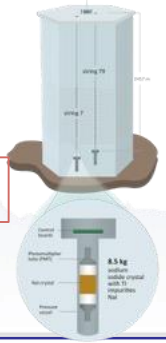
KIMS/COSINE @ Yangyang

Nature 564, 83-86 (2018)
Phys. Rev. Lett. 123, 031302 (2019)

PICO-LON @ Kamioka

SABRE @ Stawell

DM-Ice @ South Pole

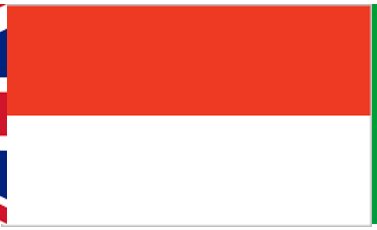


COSINE Collaboration

14 institutes
~50 members

KIMS Korea Invisible Mass Search Experiment + DM-ICE = COSINE

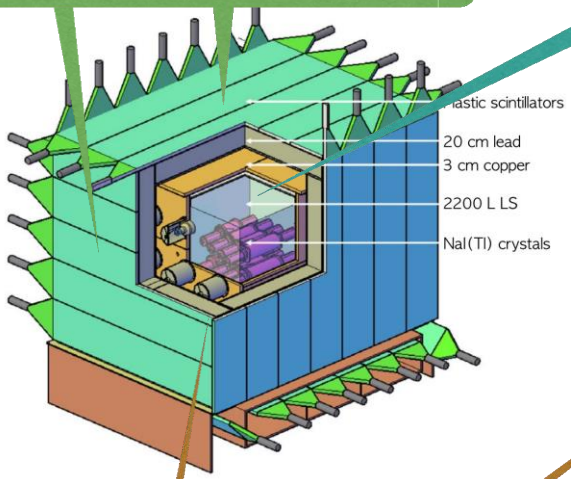


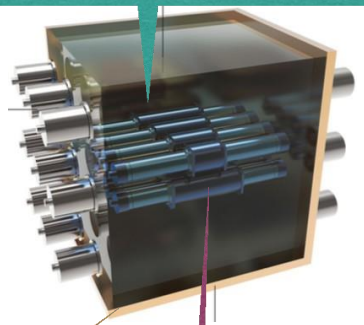




COSINE-100 Detector

*Nucl. Instrum. Meth. A **851**, 103 (2017)*
*Nucl. Instrum. Meth. A **1006**, 165431 (2021)*

Liquid Scintillator
2200-L LAB-based LS for veto
5” PMTs for LS detector

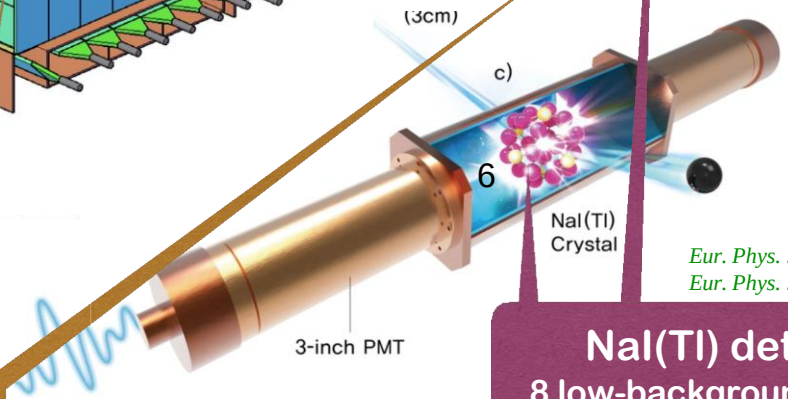




*JINST **13**, T06005 (2018)*

Neutron Monitoring
Fast neutron detector
(Liquid scintillator)

Thermal neutron detector
(^{3}He gas detector)



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

Passive Shields
3-cm thick copper box
20-cm thick lead shielding

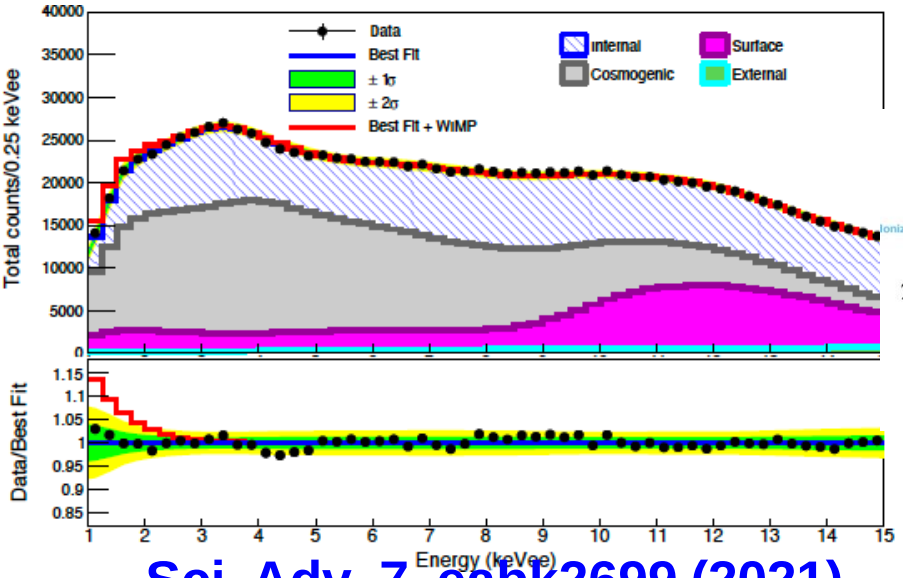
*Eur. Phys. J. C. **78**, 107 (2018)*
*Eur. Phys. J. C. **78**, 490 (2018)*

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

COSINE-100 (2016-2023)

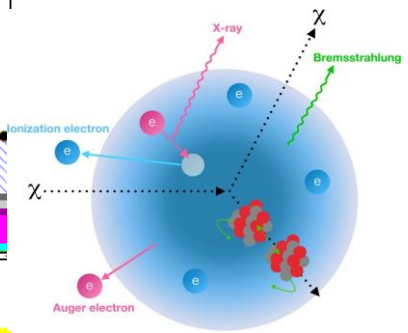
- Yangyang underground laboratory
- **Started** physics operation since **September/2016**
- **Ended** physics run **March/2023**
- Decommissioning for upgrade and moving to **Yemilab**
  - ❖ Plan to restart COSINE-100 upgrade by spring of 2024 at Yemilab

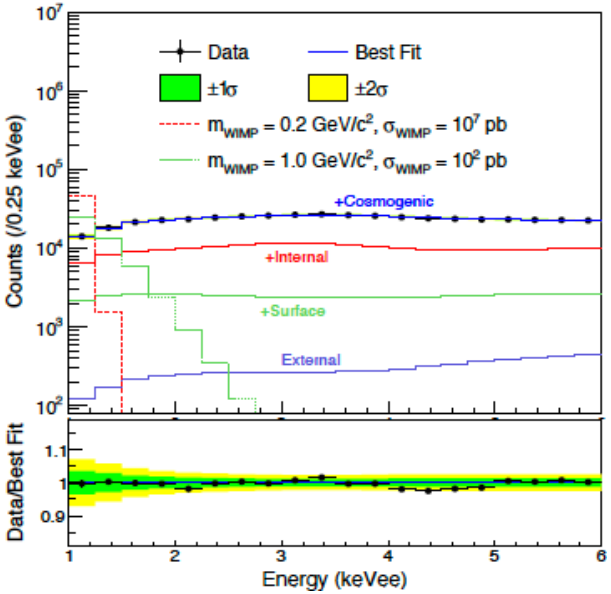
Dark matter search with spectral shape fit



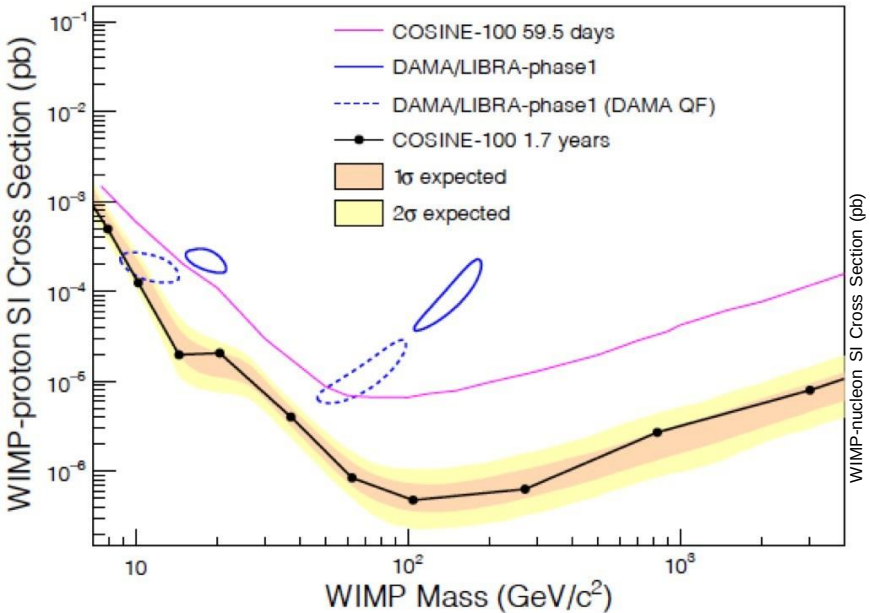
Sci. Adv. 7, eabk2699 (2021)

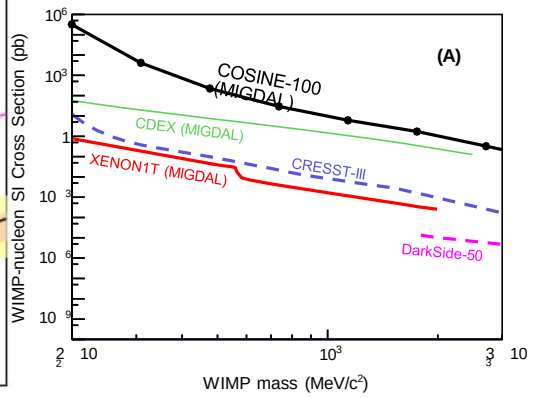
Migdal effect

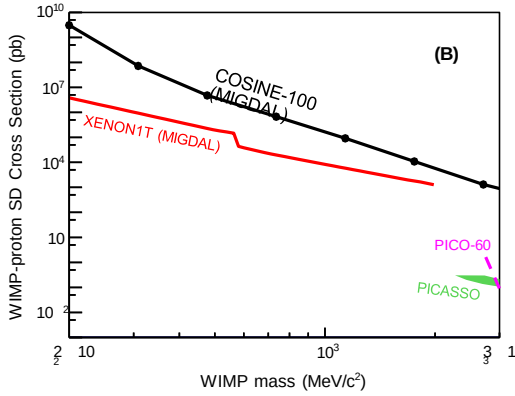




PRD 105, 042006 (2022)

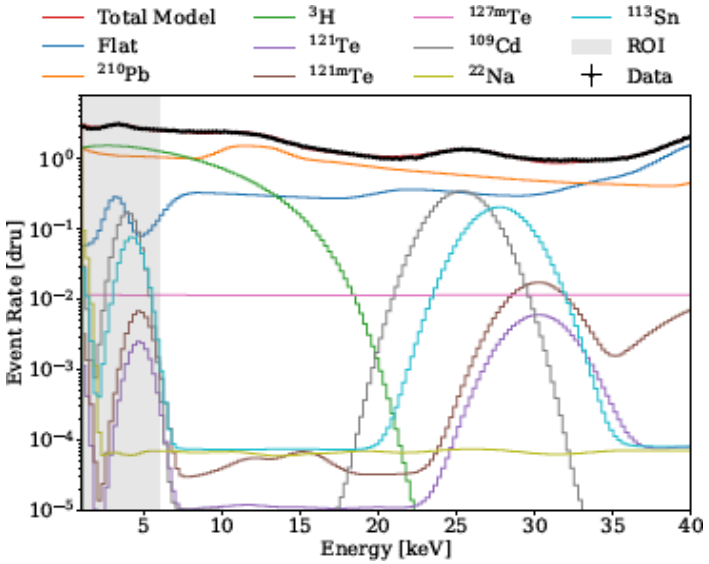






Model-independent annual modulation search

Time dependent background modeling



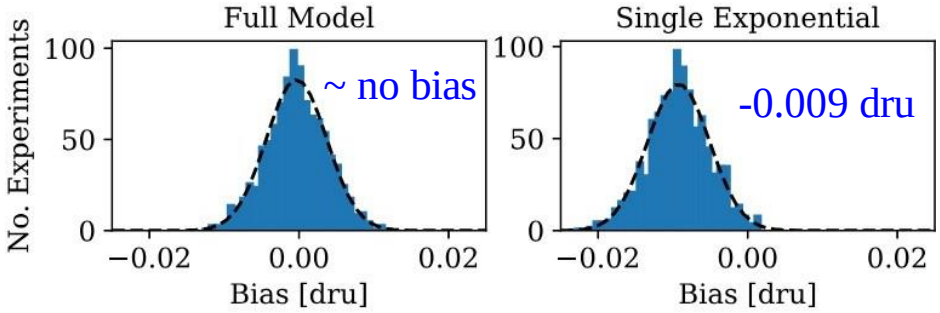
Single exponential

$$R(t) = P_0 + P_1 e^{-t/P_2} + S\cos\left(\frac{2\pi(t-t_0)}{T}\right)$$

Full model (8 exponential)

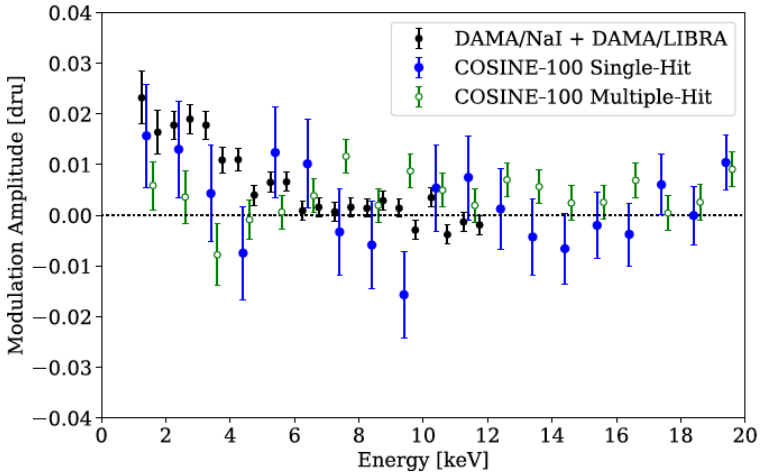
$$R(t) = P_0 + \sum_{i=1}^{8} P_i e^{-t/\tau_i} + S\cos\left(\frac{2\pi(t-t_0)}{T}\right)$$

Bias test



PRD 106, 052005 (2022)

Understanding time-dependent background is crucial for the annual modulation search

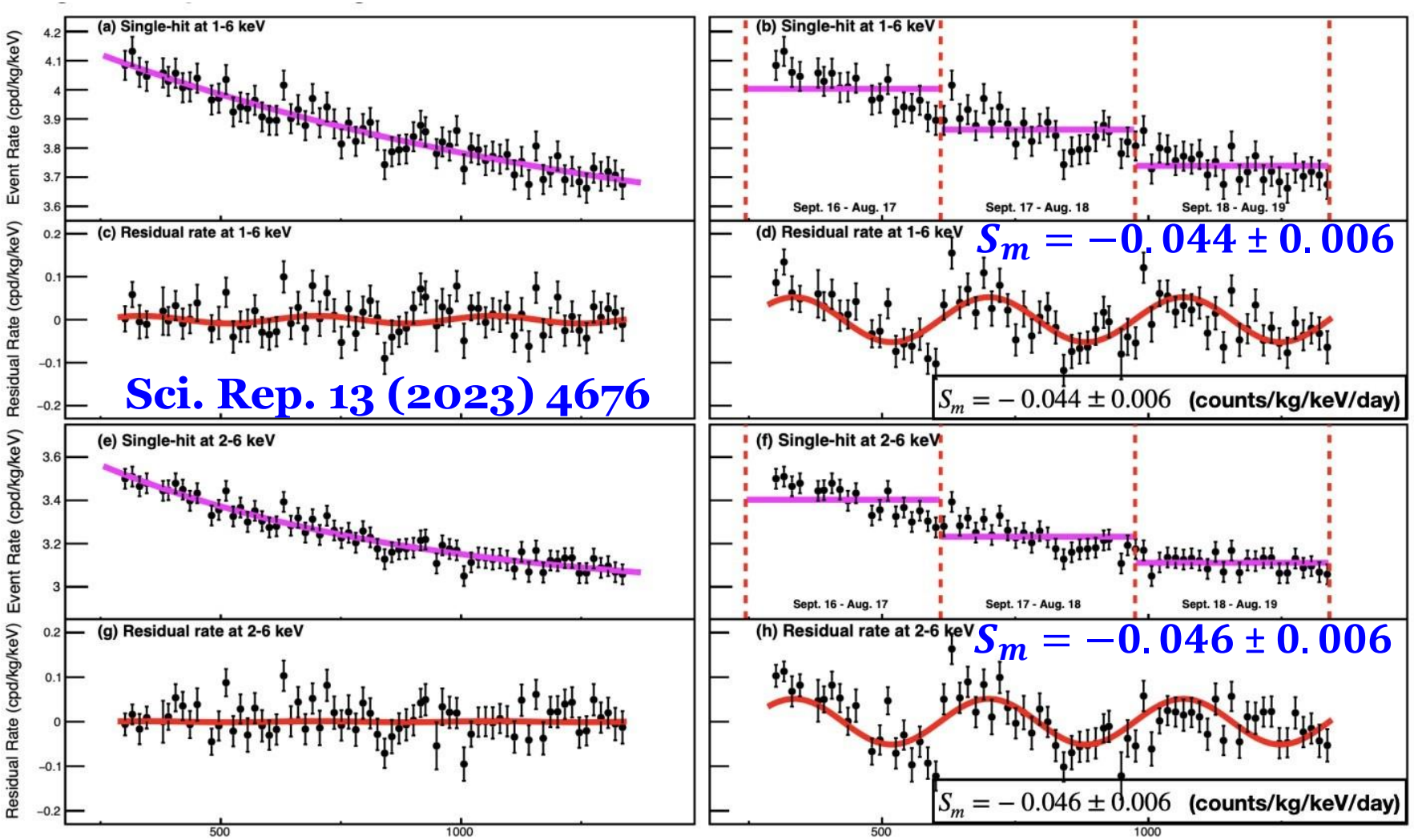


1-6 keV modulation amplitude

COSINE-100	$\mathbf{0.0067 \pm 0.0042}$
DAMA/LIBRA	0.0105 ± 0.0011
ANAIS-112	-0.0034 ± 0.0042

DAMA/LIBRA's method (induced modulation)

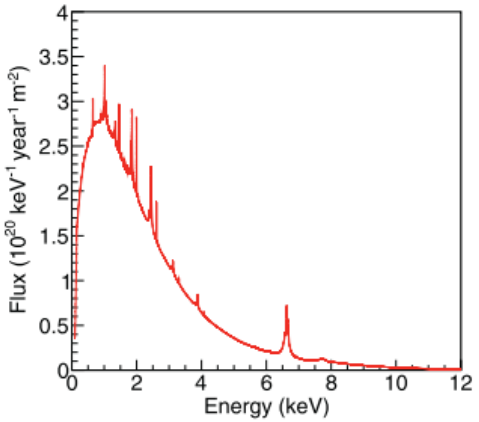
Single exponential model (reference) **DAMA/LIBRA's method**

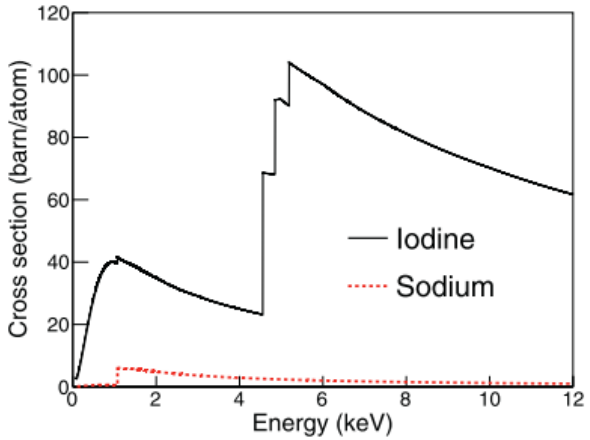


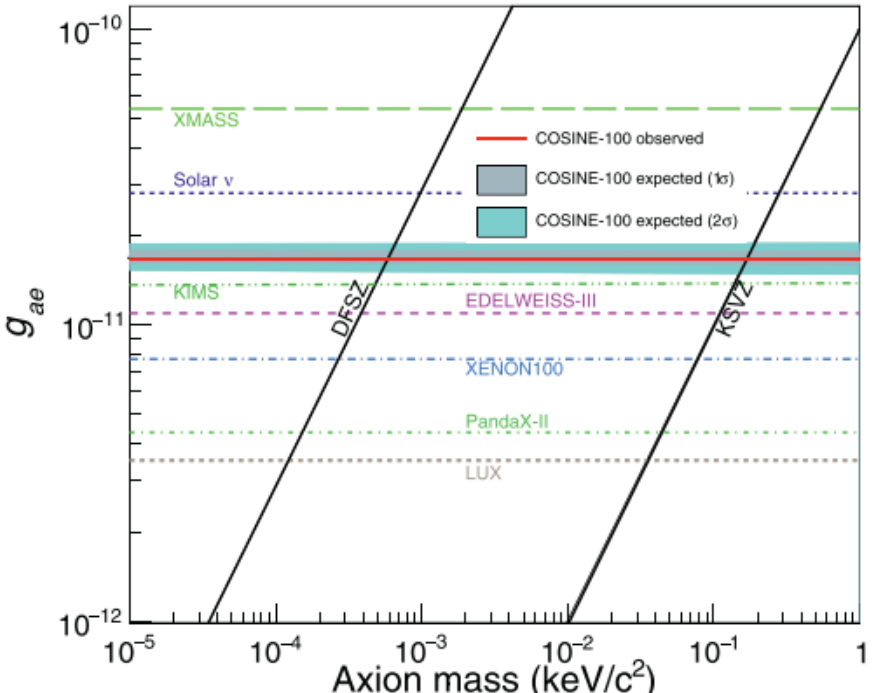
Very strong (~7σ) negative modulation (opposite phase) from the COSINE-100 data using DAMA/LIBRA's method

COSINE-100 : Solar Axion search

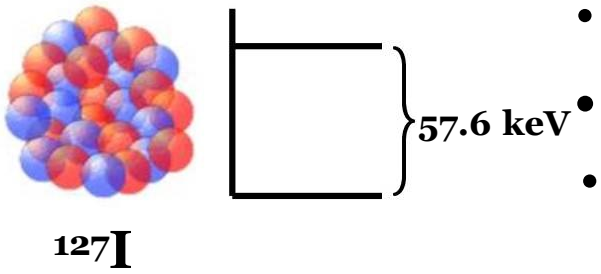
P. Adhikari, G. Adhikari and E. Barbosa de Souza et al./Astroparticle Physics 114 (2020) 101–106



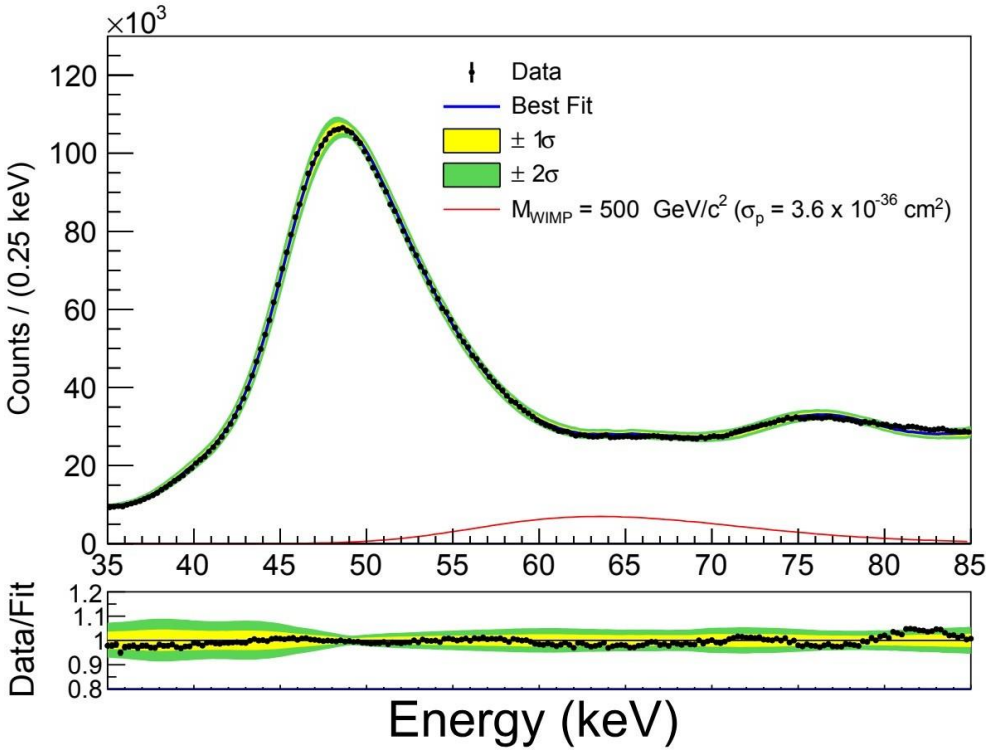


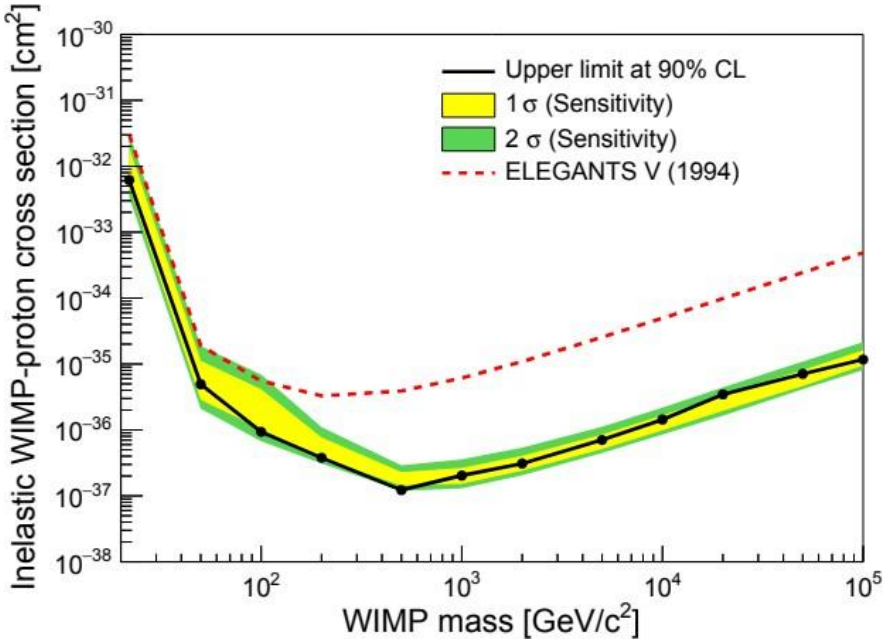


WIMP-^{127}I inelastic interaction



- Signal : 57.6 keV gamma + nuclear recoil
- 1.7 years data
- Search for energy 35 keV – 85 keV



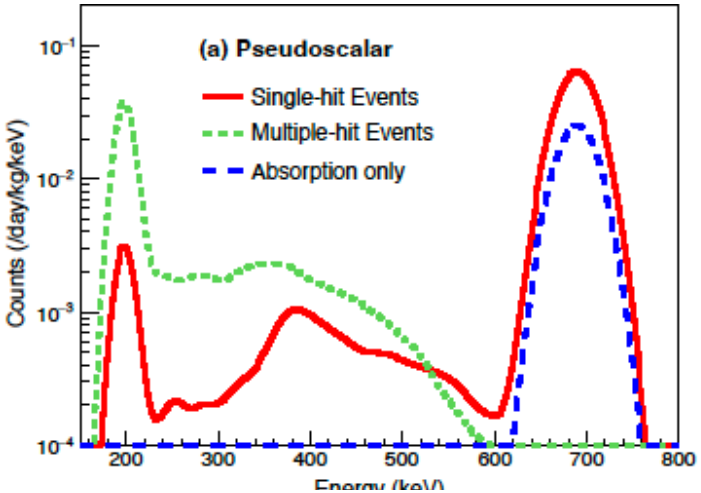


PHYS. REV. D 108, 092006 (2023)

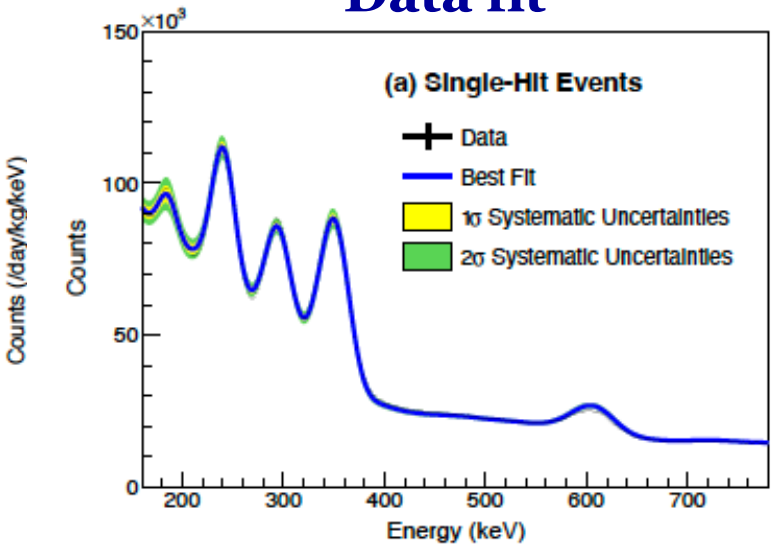
Bosonic super-weakly interacting-WIMP

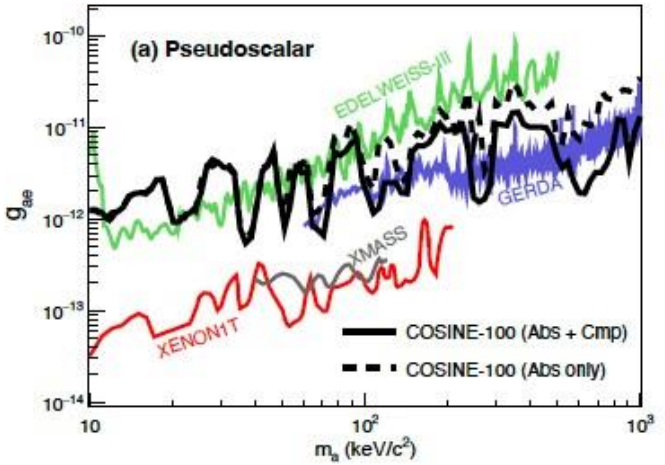
- Bosonic dark matter with mass 10 keV – 1 MeV

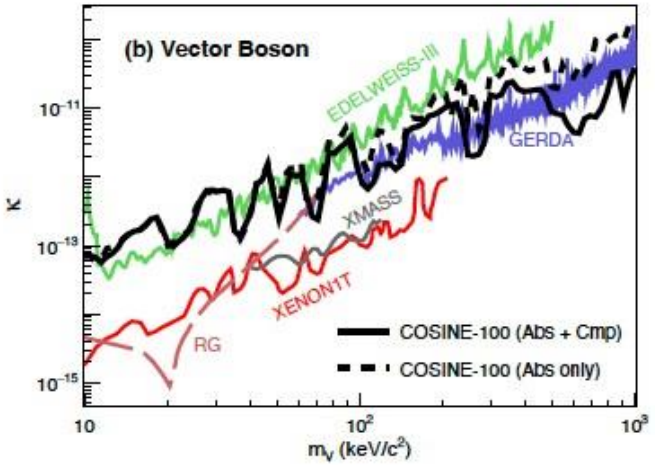
Expected Signal (690 keV BSW)



Data fit

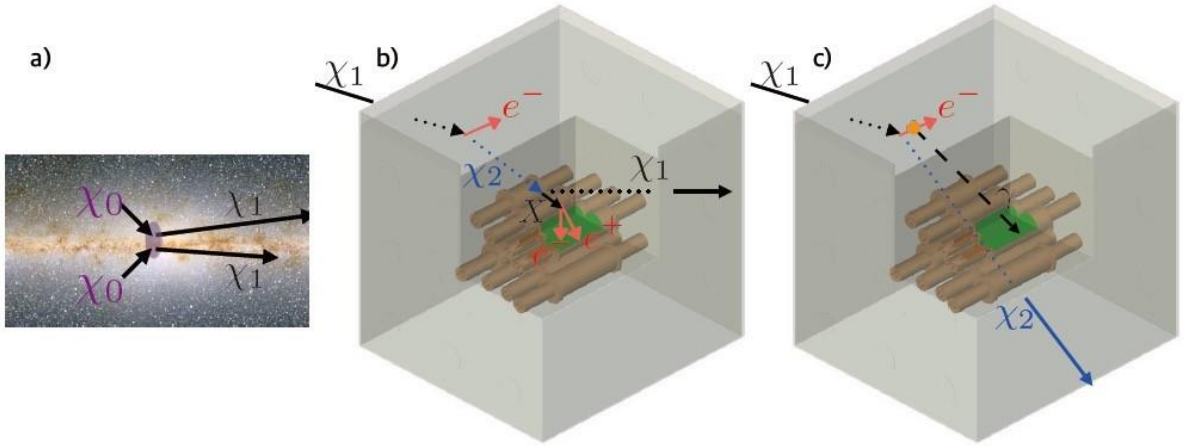




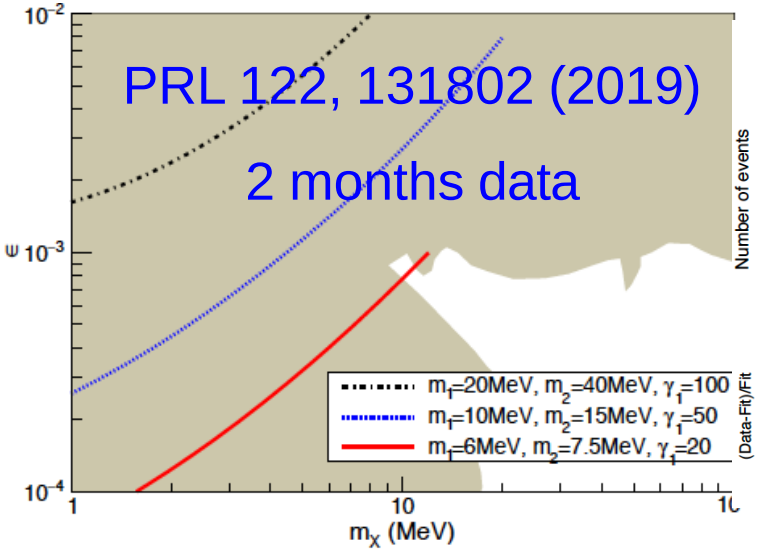


PHYSICAL REVIEW D 108, L041301 (2023)

Boosted dark matter with extended energy (~10 MeV)

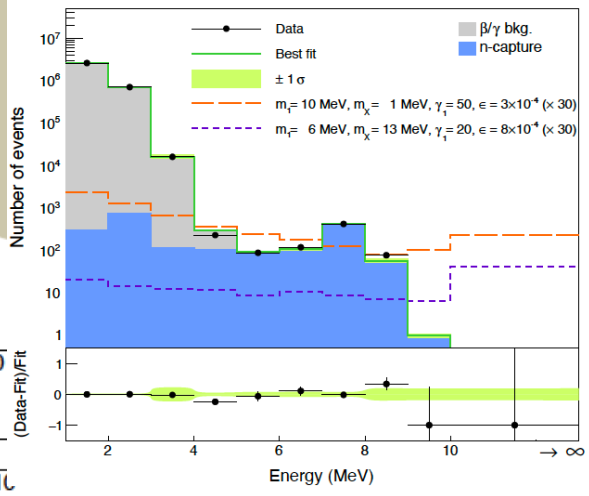


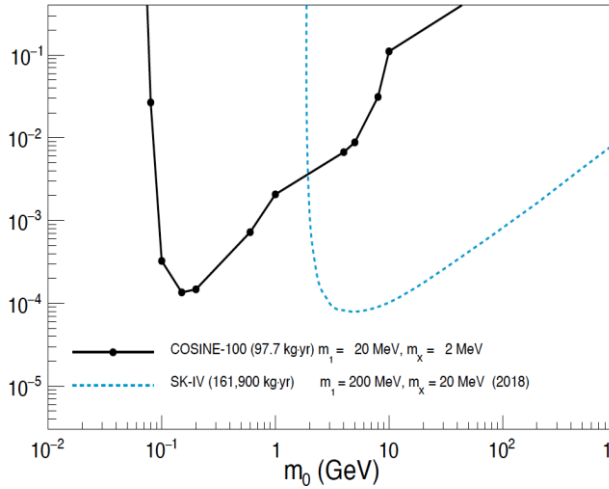
Inelastic interaction



Elastic interaction

1.7 years data





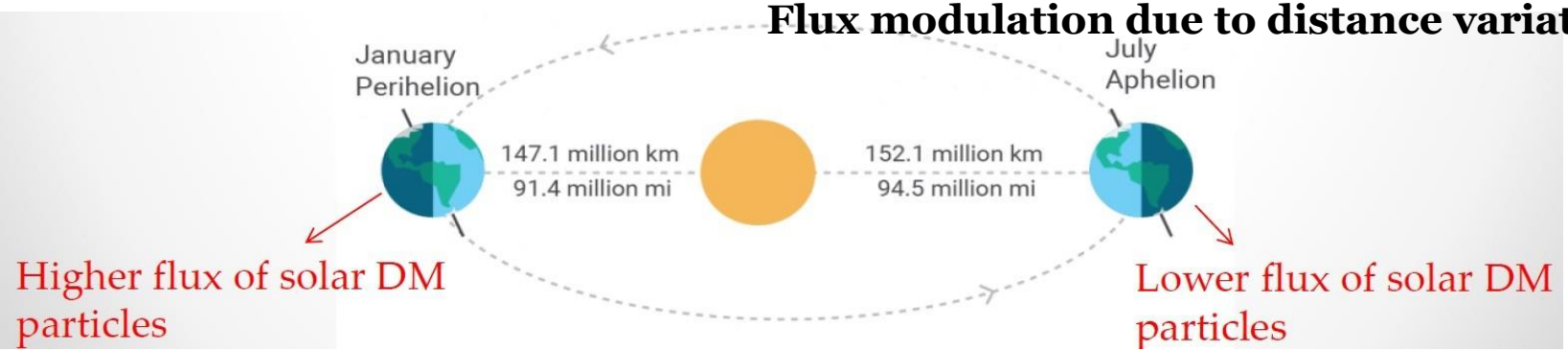
- Search for energy 1 MeV – 10 MeV

PHYSICAL REVIEW LETTERS 131, 201802 (2023)

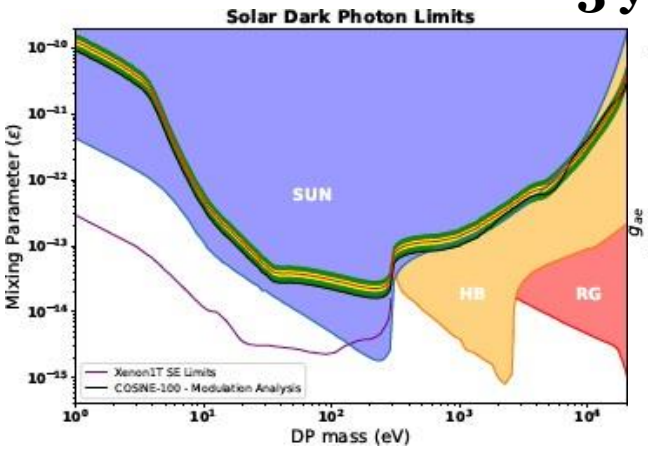
Solar bosonic dark matter annual modulation

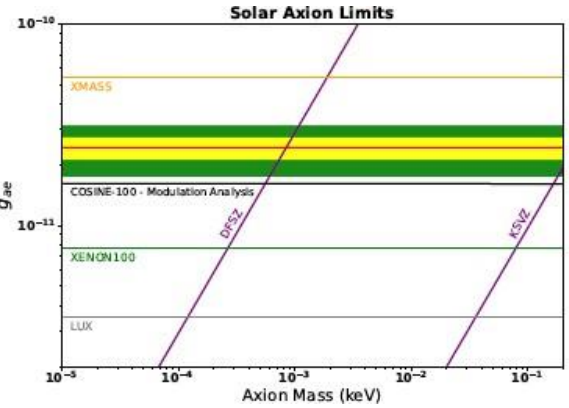
- Sun is the strong source of gamma
  - ❖ Conversion to dark sector bosonic particle is possible

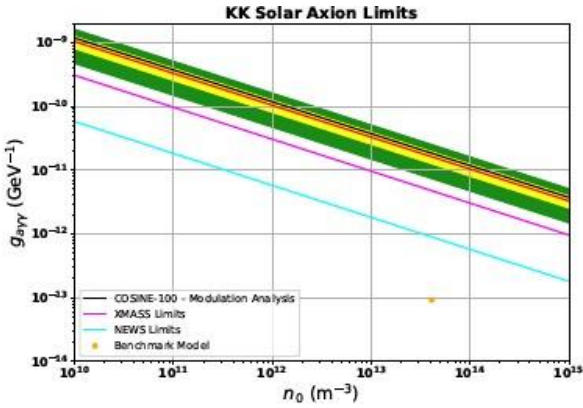
Flux modulation due to distance variation



3 years data for the modulation search



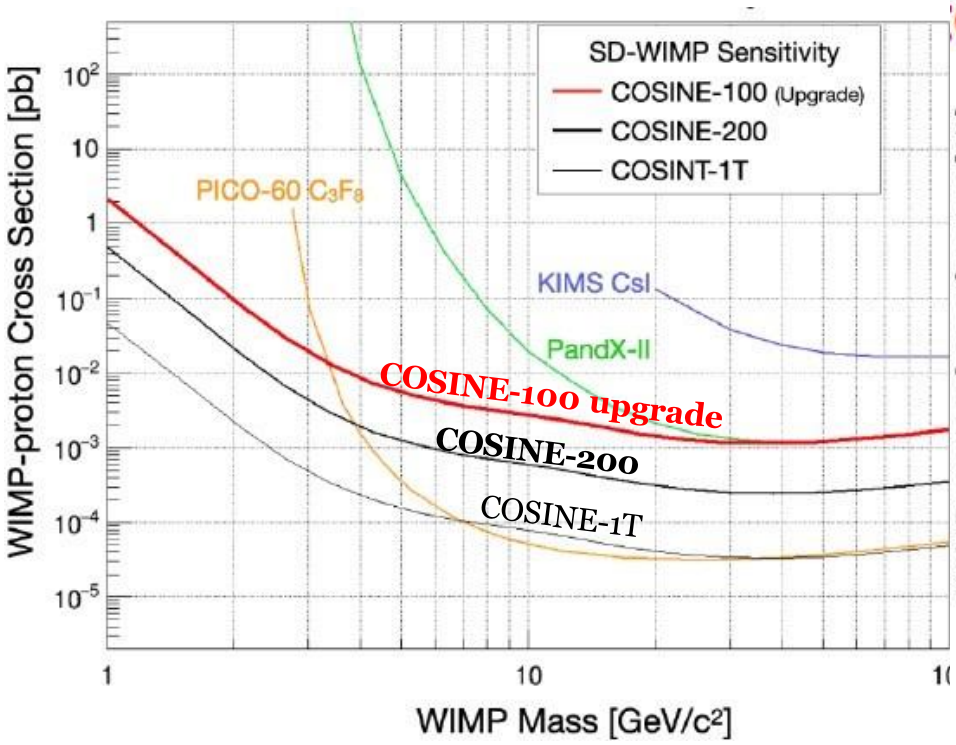




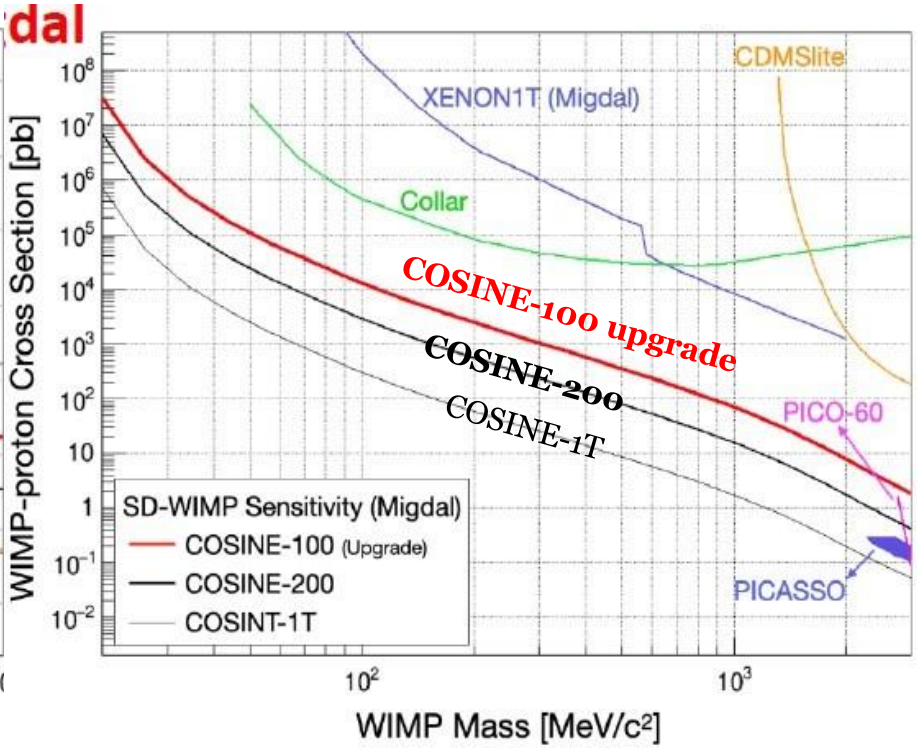
Phys. Rev. D 107, 122004 (2023)

Low-mass sensitivities for spin-dependent limit

WIMP-proton spin-dependent



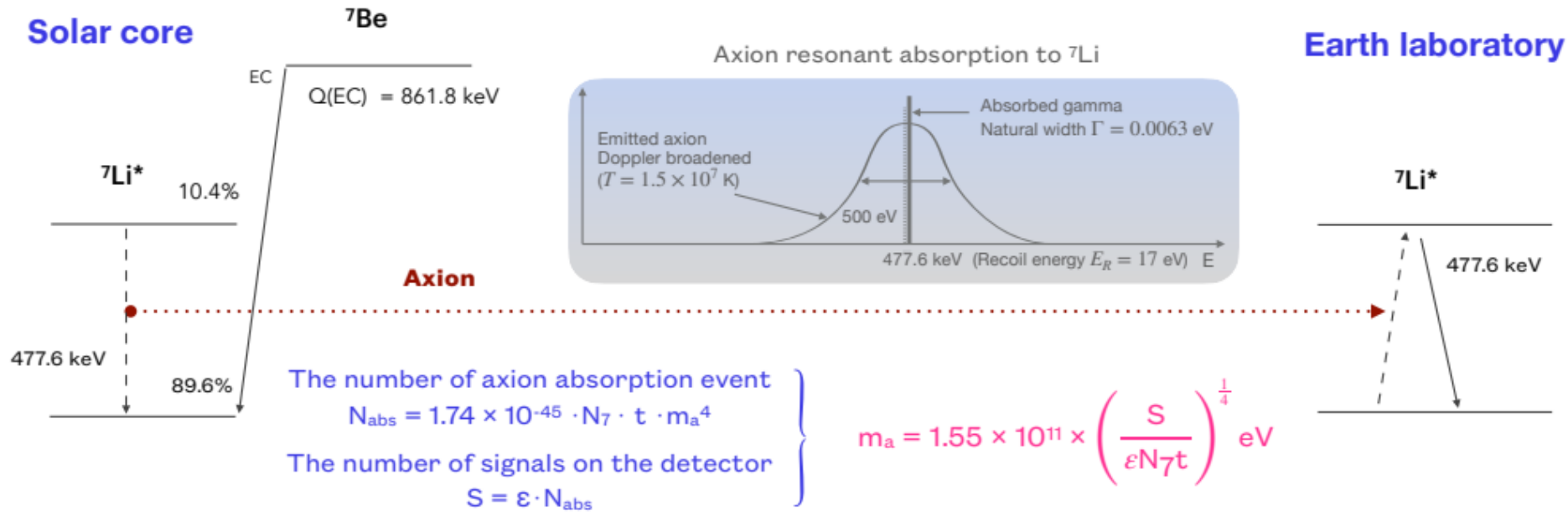
Low mass search with Migdal



22 NPE/keV, 1 year operation (100% efficiency), 5 NPE threshold

- A world best sensitive detector for low-mass WIMP-proton spin-dependent interaction
- Feasibility test for the COSINE-200 & 1T experiments

AMoRE : Solar Axion Search with Li2MoO4



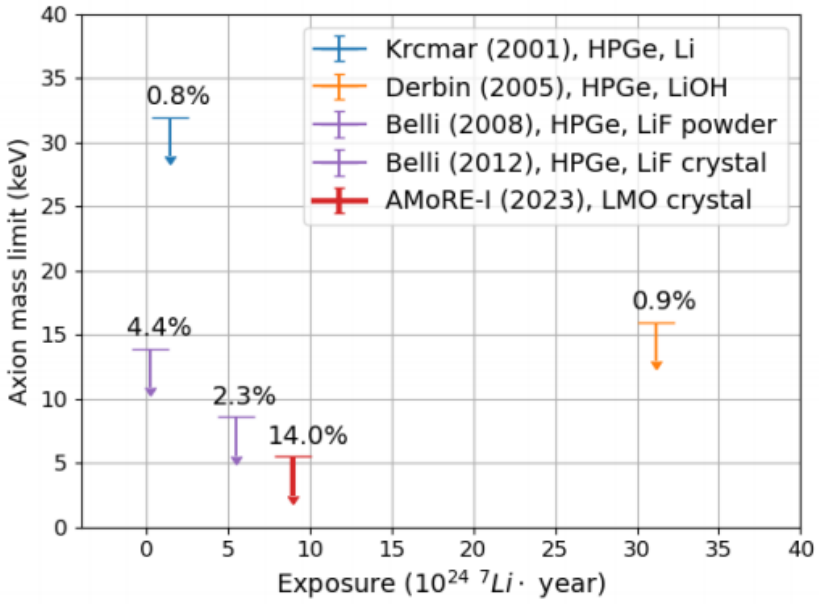
The number of axion absorption event

$N_{abs} = 1.74 \times 10^{-45} \cdot N_7 \cdot t \cdot m_a^4$

The number of signals on the detector

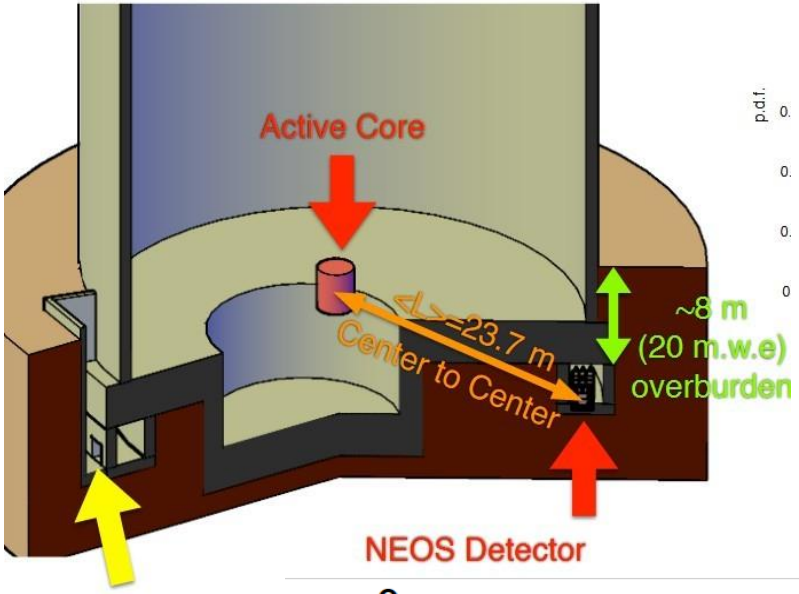
$S = \varepsilon \cdot N_{abs}$

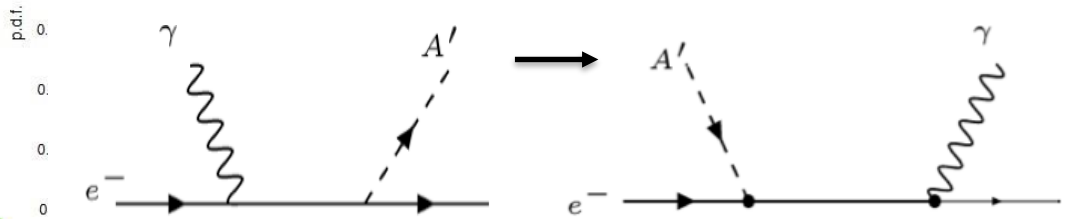
$$m_a = 1.55 \times 10^{11} \times \left(\frac{S}{\varepsilon N_7 t} \right)^{\frac{1}{4}} \text{ eV}$$

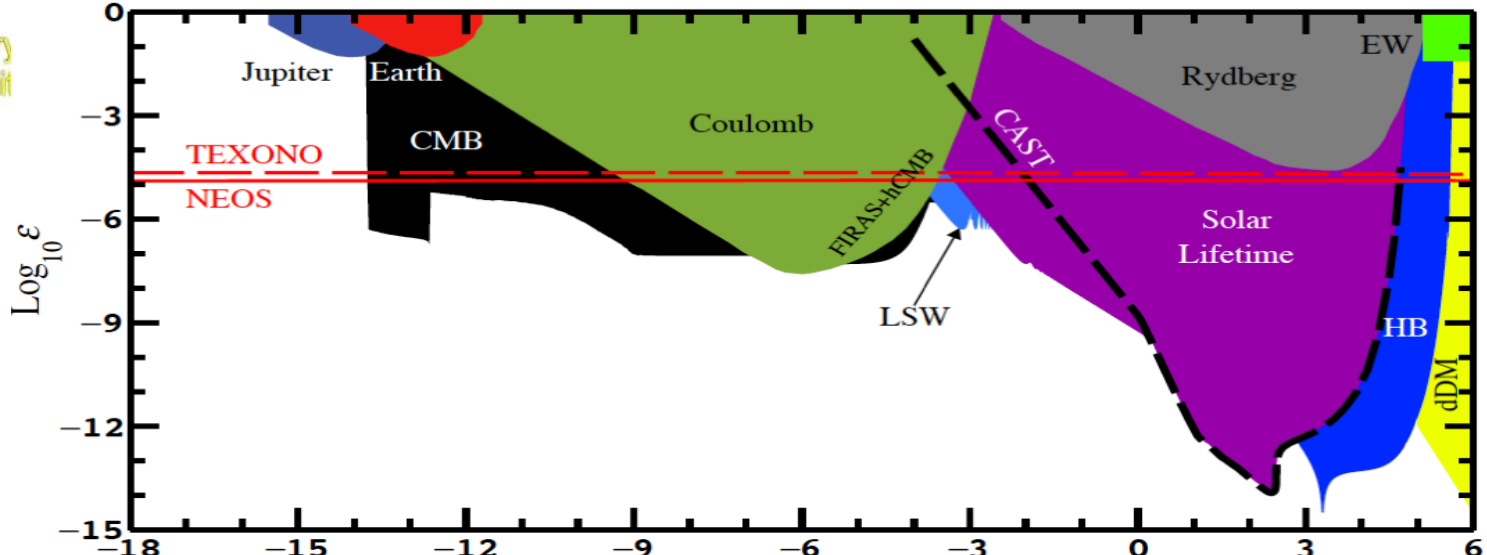


Dark photon search with NEOS

H. K. Park, PRL 119, 081801 (2017)







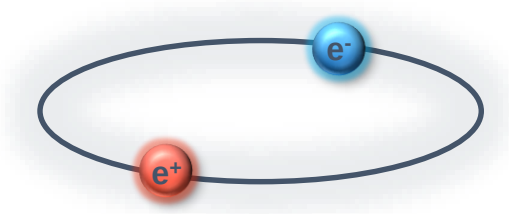
I Introduction

KNU KYUNGPOO NATIONAL UNIVERSITY

KAPAE

- KNU Advanced Positronium Annihilation Experiment (KAPAE)

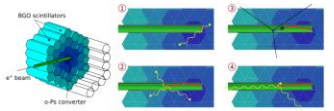
Electron-Positron Pair



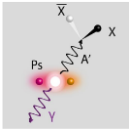
- Quasi-stable bound state
- Create energetic photons

($m_{e^+} + m_{e^-}$= 1.022 MeV)

Physics



First search for invisible decays of orthopositronium confined in a vacuum cavity
PHYS. REV. D 97, 092008 (2018)



Searching for light dark matter through Positronium decay
Eur. Phys. J. D (2018) 72: 44

- QED test
- New Particle search (invisible decay…)

Application

- **P**ositron **E**mission **T**omography (PET)

I Introduction

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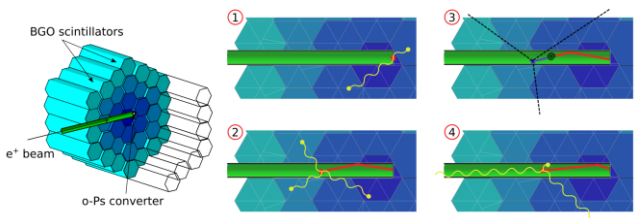
New particle search

- Invisible decay
  - → Extra-dimensions
  - → Milli-Charged particles
  - → Dark matter of a mirror particle type
- → Dark Z and Fermionic DM [PRD 105, 095023 (2022)]
  - → Axion
  - → Dark photon
  - → Other possibility of new particle?

Search of invisible decay: Best limit 4.2×10^{-7}



Mirror Dark Photon search : 3×10^{-5}

Searching for o-PS-> Invisible : 4.2×10^{-7}

A.Badertsher et. al, PHYS. REV. D 95, 032004 (2007)

A.Badertsher et. al, PRL 124 101803 (2020)

PDG 2019: Best limit : ~10^{-4} - 10^{-6}

A^0 (Axion) Searches in Positronium Decays

Decay or transition of positronium. Limits are for branching ratio.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$<4.4\times10^{-5}$	90	[1] BADERT...	02	CNTR	o-Ps → $\gamma X_1 X_2$, $m_{X_1}+m_{X_2} \leq$ 900 keV
$<2\times10^{-4}$	90	MAENO	95	CNTR	o-Ps → $A^0\gamma$ m_{A^0}=850–1013 keV
$<3.0\times10^{-4}$	90	[2] ASAI	94	CNTR	o-Ps → $A^0\gamma$ m_{A^0}=30–500 keV
$<2.8\times10^{-5}$	90	[3] AKOPYAN	91	CNTR	o-Ps → $A^0\gamma$ (A^0 → $\gamma\gamma$), m_{A^0} < 30 keV
$<1.1\times10^{-6}$	90	[4] ASAI	91	CNTR	o-Ps → $A^0\gamma$, m_{A^0} < 800 keV
$<3.8\times10^{-4}$	90	GNINENKO	90	CNTR	o-Ps → $A^0\gamma$, m_{A^0} < 30 keV
$<(1–5)\times10^{-4}$	95	[5] TSUCHIAKI	90	CNTR	o-Ps → $A^0\gamma$, m_{A^0} = 300–900 keV
$<6.4\times10^{-5}$	90	[6] ORITO	89	CNTR	o-Ps → $A^0\gamma$, m_{A^0} < 30 keV
		[7] AMALDI	85	CNTR	Ortho-positronium
		[8] CARBONI	83	CNTR	Ortho-positronium

Introduction

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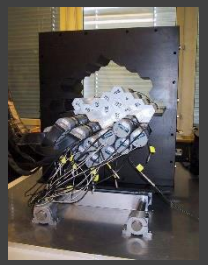
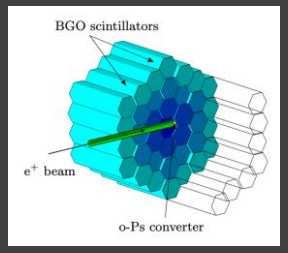
Recently Research

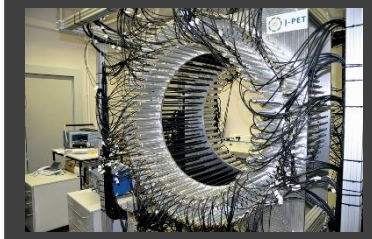




- Invisible decay study
- Plastic + BGO + PMT
- 2.1×10^{-8} at 90% C.L.

< 2006

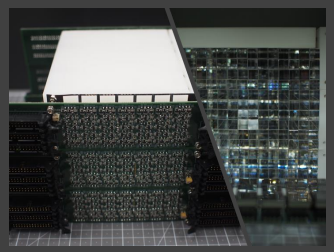
ETH Zurich (Switzerland)



- CPT study
- Plastic + PMT
- Plastic + SiPM (ver. II)

< 2016

J-PET (Poland)
The Jagiellonian University

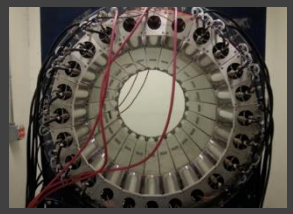


- BGO + SiPM
- PEN + SiPM for trigger
- High DAQ rate

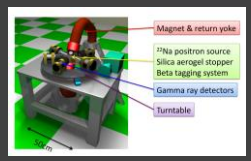
KAPAE-I (Korea)
Kyungpook Nat'l Univ.

< 2020

- CPT study
- NaI + PMT



APEX (U.S.A.)
Triangle Universities Nuclear Laboratory



- CP & CPT study
- Plastic + NaI + PMT

< 2011

ICEPP (Japan)
Univ. of Tokyo

KAPAE : Novel design concept

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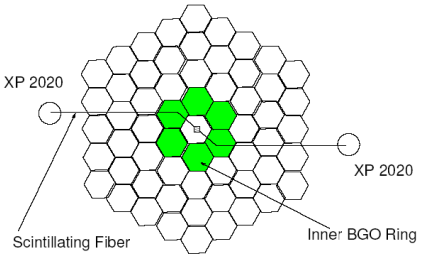
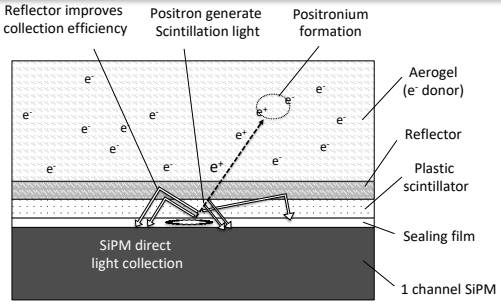
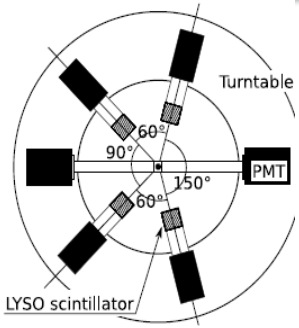
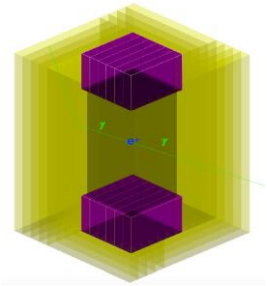
Improvement over other experiment : Better e+ tagging, Higher activity (1uCi -> 10uCi), High DAQ rate

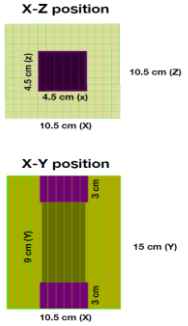




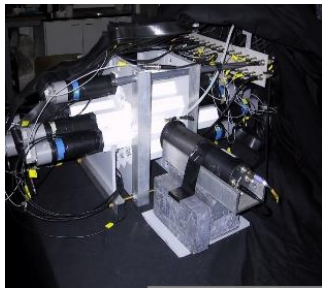
KAPAE-I : compact (10x10x15cm) & fine segmentation (200 crystals) for QED test

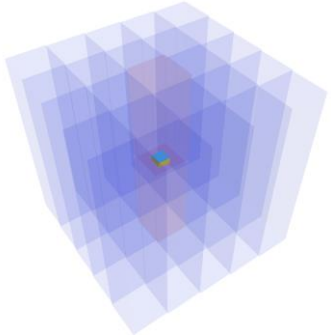






KAPAE-II :(15x15x15cm) & less segmentation for new particle search





KAPAE-I

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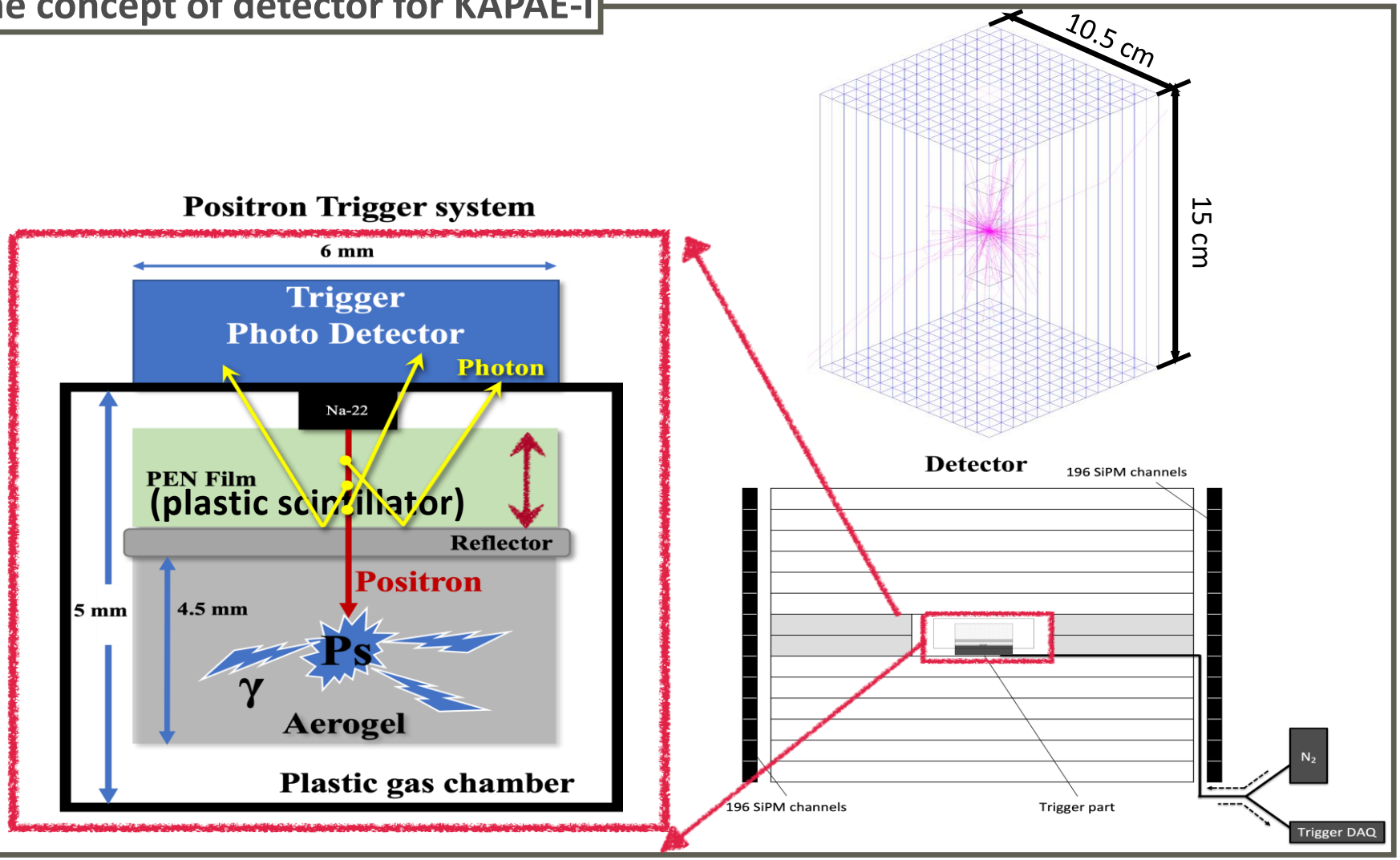
The concept of detector for KAPAE-I



KAPAE-I

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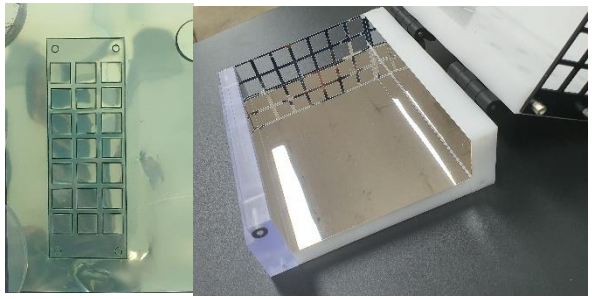
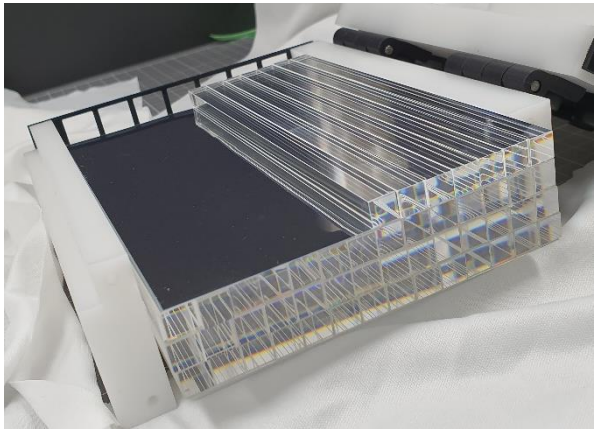
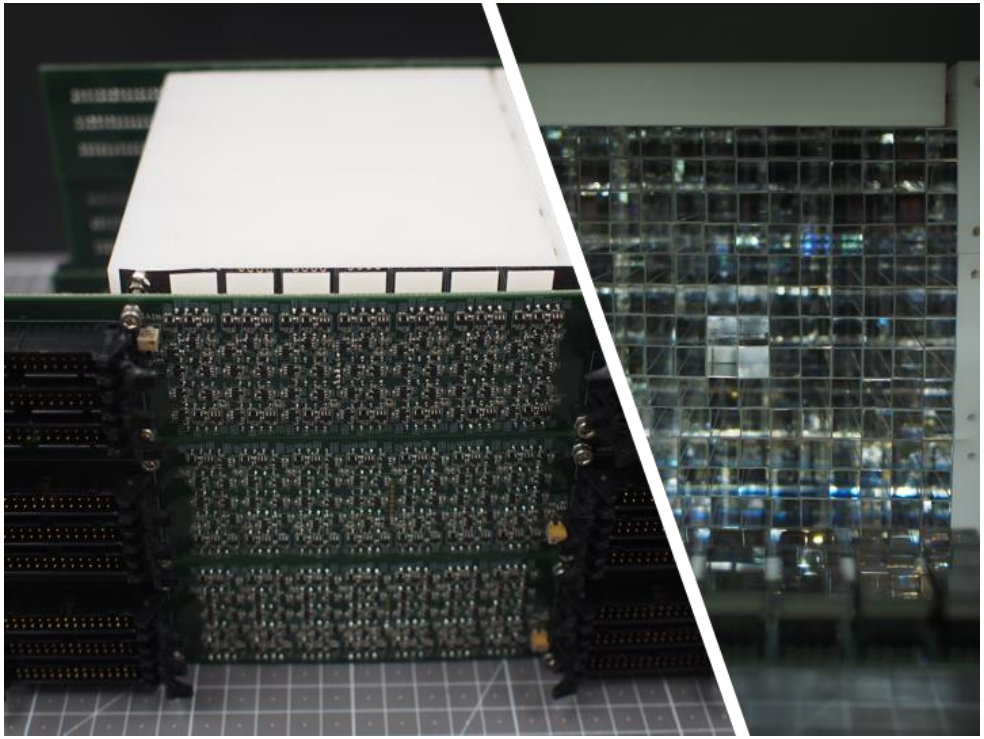
Hermetic detector assembly



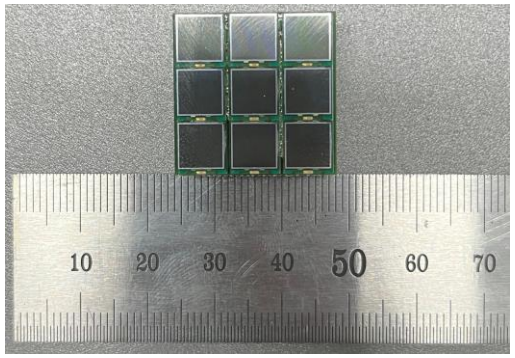


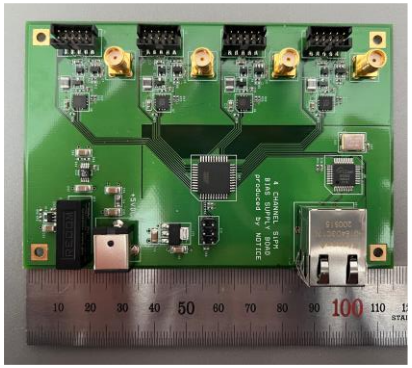


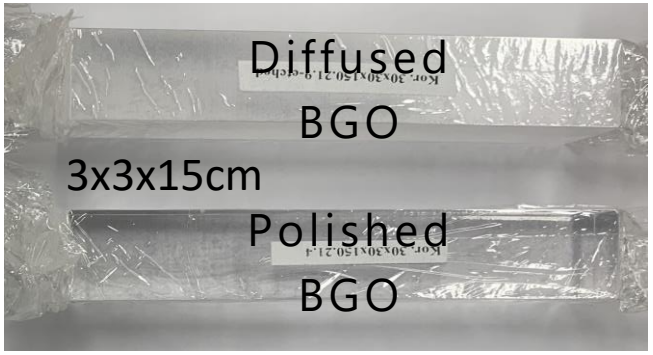
KAPAE-II

- The best limit of invisible search of positronium decay by Zurich group is 4×10^{-7} with 90% CL. (Phys. Rev. D 75 (2007) 032004.)

- KAPAE-II detector setup with Geant4 simulation show the invisible decay sensitivity of 2×10^{-9} with 90 % CL.
- KAPAE-II detector will be installed in the new Yemi Underground lab. to remove backgrounds from cosmic ray and environmental gamma background.







KAPAE-II Assembly

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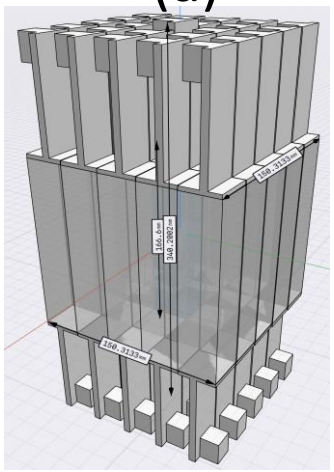
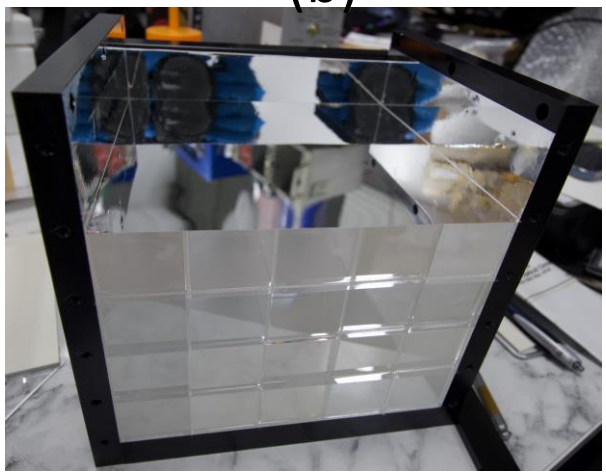
(a)



(b)



(c)

(d)

(e)

KAPAE-II Performance

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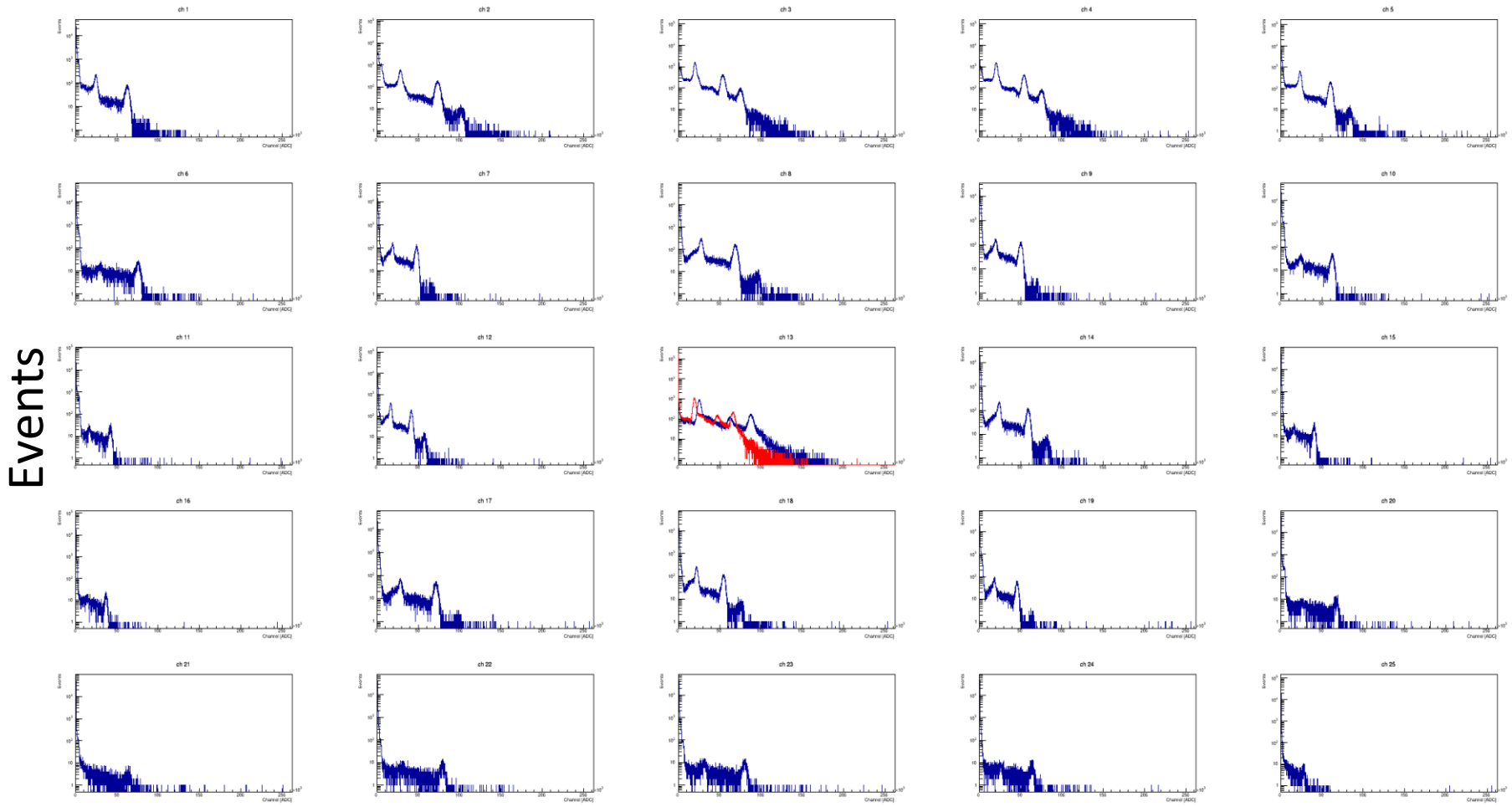
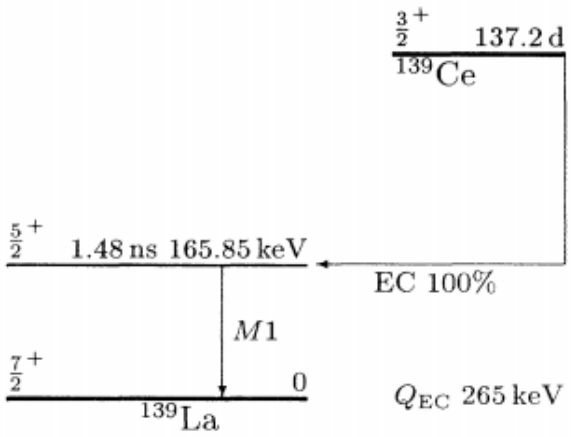
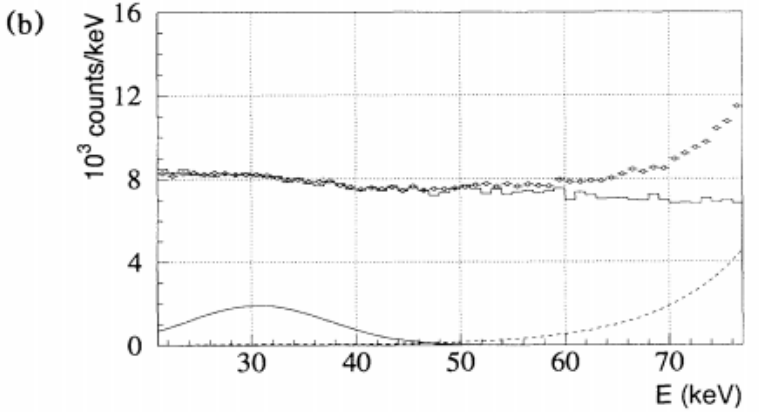


Calibration is on-going, data taking will be started from this summer

Other table top experiments with radioactive source?





$\Gamma_a/\Gamma_\gamma < 1.21 \times 10^{-6}$ at the 95%

Mass of hadronic axion > 26.7 keV by 95%CL
M.Minowa et al, Phys. Rev. Lett. 71, 4120

- ALP or DP search possible
- Coupling is proportional to ε^2 not ε^4 since it is only decay process
- Background is the seriose issue

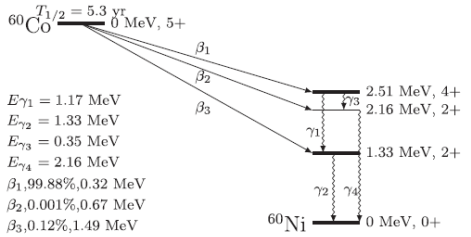
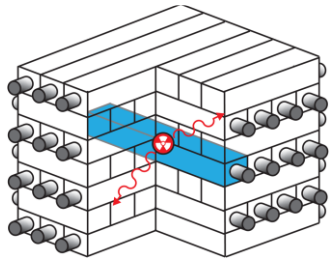
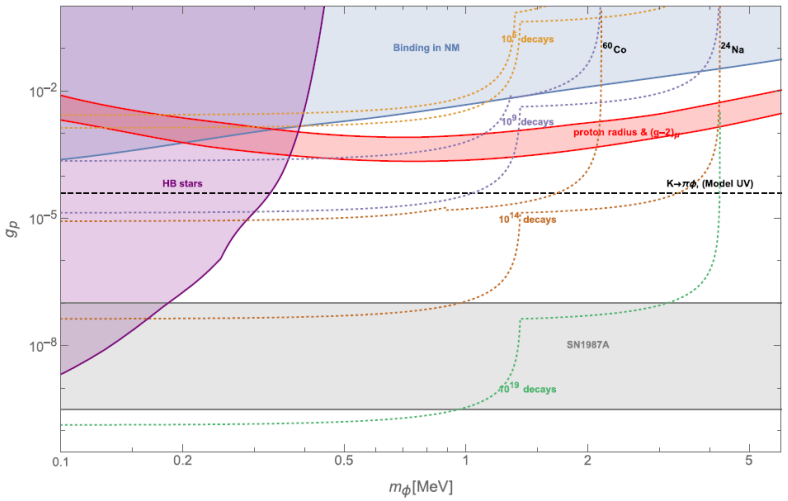


FIG. 2. Decay scheme of ^{60}Co.





Other table top experiments with radioactive source?

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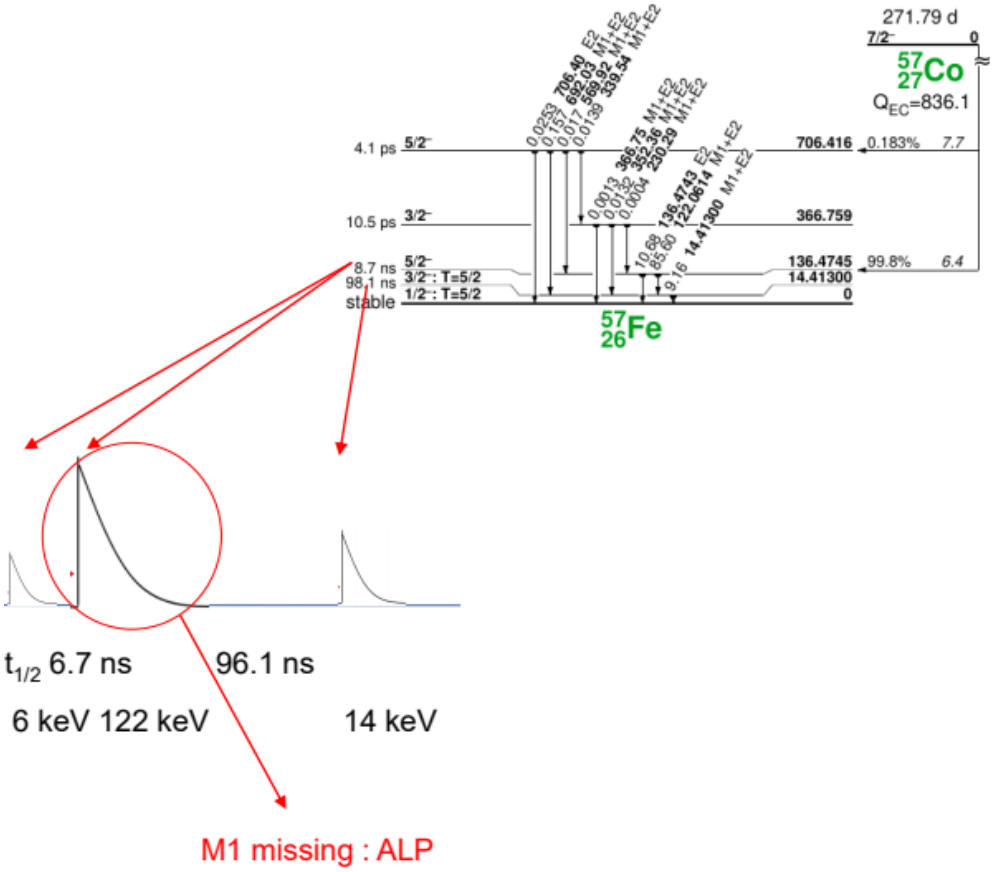
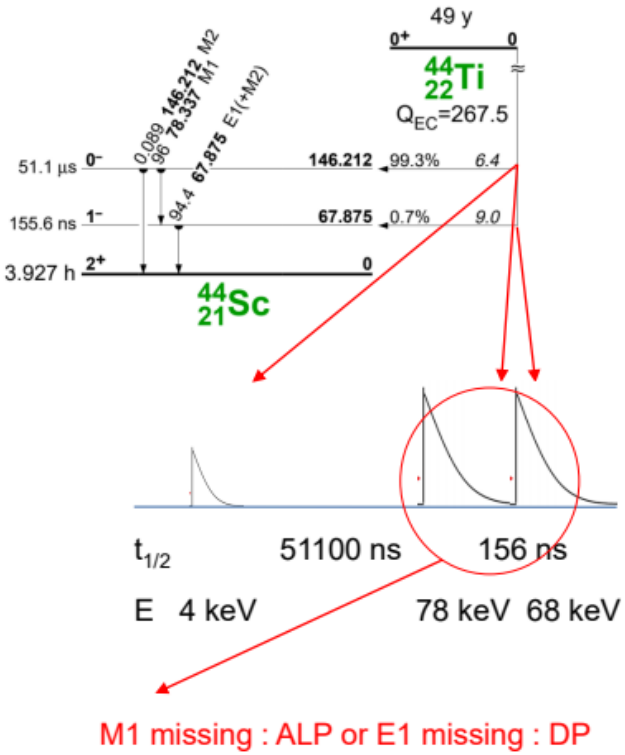
- ALP or DP search with M1 and E1 transition with KAPAE setup + fast scin.
- Time delay coincidence method to remove backgrounds.
- For the zero background experiment, we propose this experiment at Yemi Under ground lab. with branching fraction sensitivity of 10^{-12}





Summary and Prospect

- COSINE-100 produced not only conventional WIMP search but also many different dark sector particles
- AMoRE experiment also have some possibility

- Reactor or small accelerator based experiment can be used for dark sector particle search
- Looking for dark sector particle search with positronium decay experiment (KAPAE-II).
- Nuclear gamma transition can be also used for the dark sector particle search.

- New ideas? New small scale domestic experiments?
- Theorist and experimentalist collaborate together !

Thank You !