Direct detection of dark matter at Jaduguda Underground Science Laboratory

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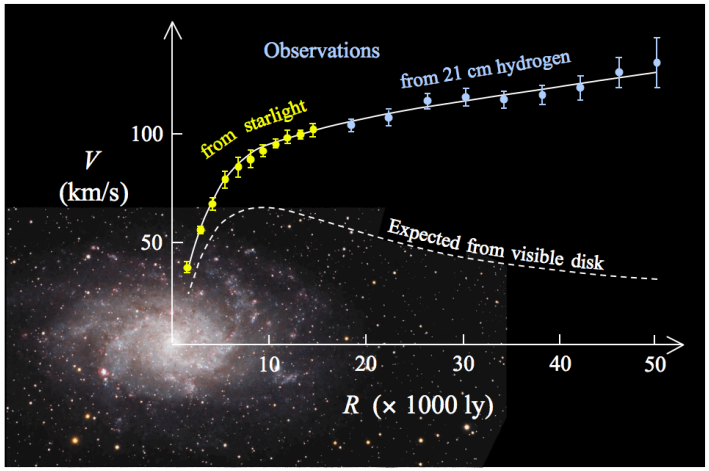
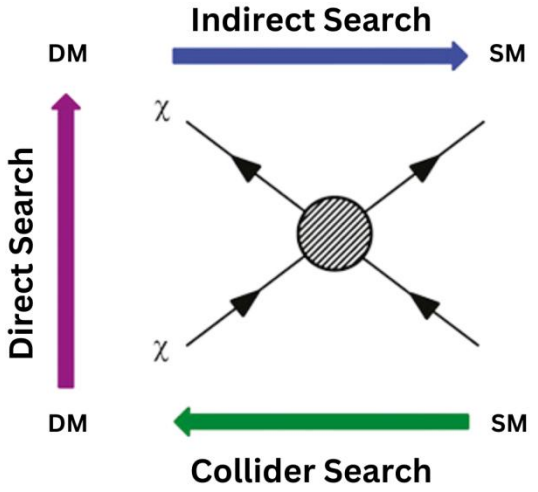
Outline

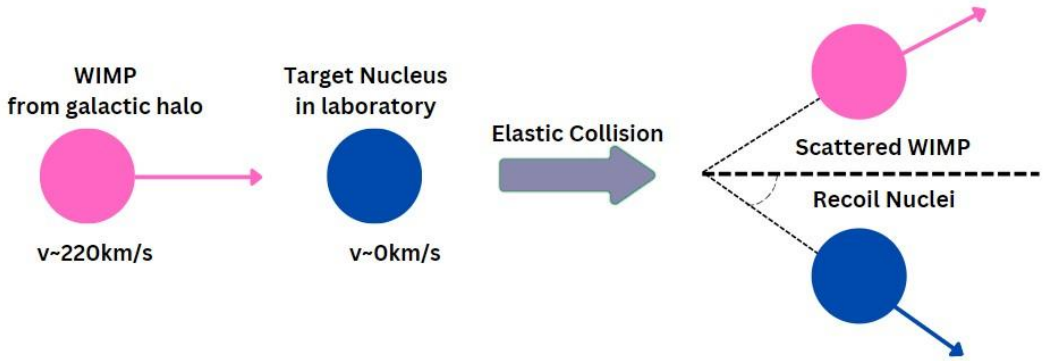
- Introduction
- Present Work
    - A)Detector Fabrication
    - B) Calibration run at SINP Lab
    - C) Run at JUSL
- Preliminary results
- Future direction

Introduction

- Existence of Dark Matter (DM) confirmed by astronomical observations.
- The most favoured candidate of DM is Weakly Interacting Massive Particles (WIMPs).
- DM can be detected by direct, indirect or collider search experiment.
- We are interested in direct detection experiment.





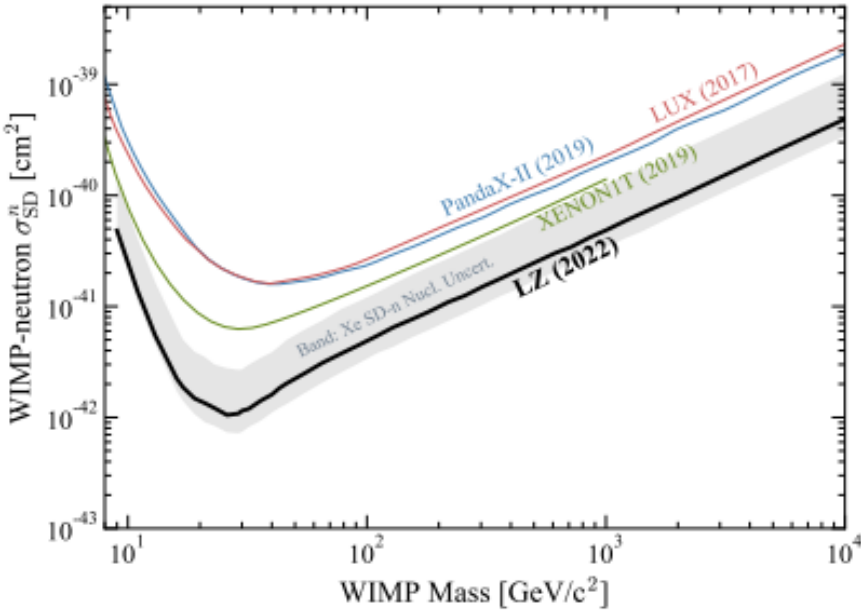


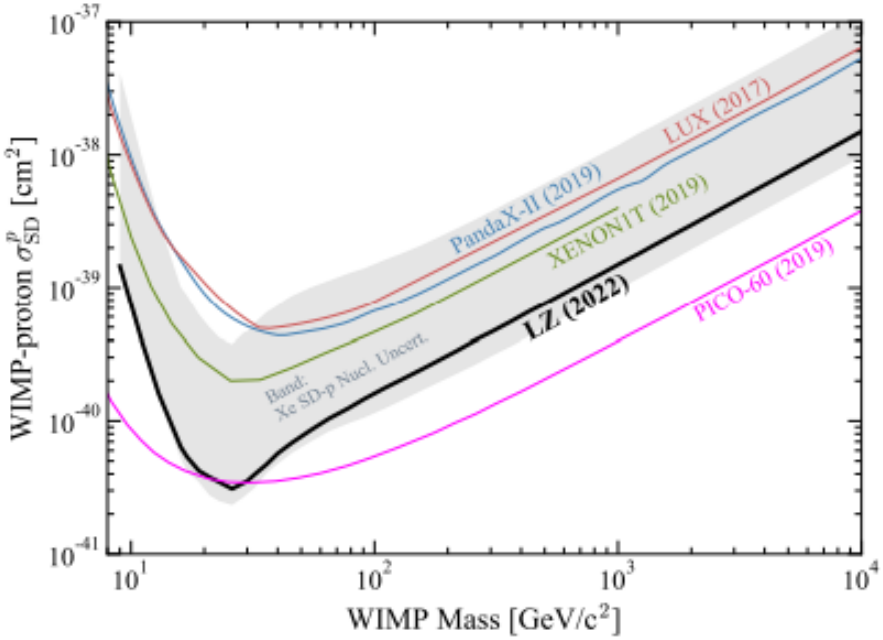
Leading experiments (LZ & PICO)

- The minimum of the limit curve (WIMP-neutron spin-dependent) is at m_χ = 26 GeV at a cross section of $\sigma^{n}_{SD} = 1.1 \times 10^{-42}$ cm^2[1].

- The minimum of the limit curve (WIMP-proton spin-dependent) is at m_χ = 26 GeV at a cross section of $\sigma^{p}_{SD} = 3.1 \times 10^{-41}$ cm^2[1].

- The minimum of the limit curve for (WIMP-proton spin-dependent) cross section is 3.2×10^{-41} cm^2 for a 25 GeV WIMP mass [2].





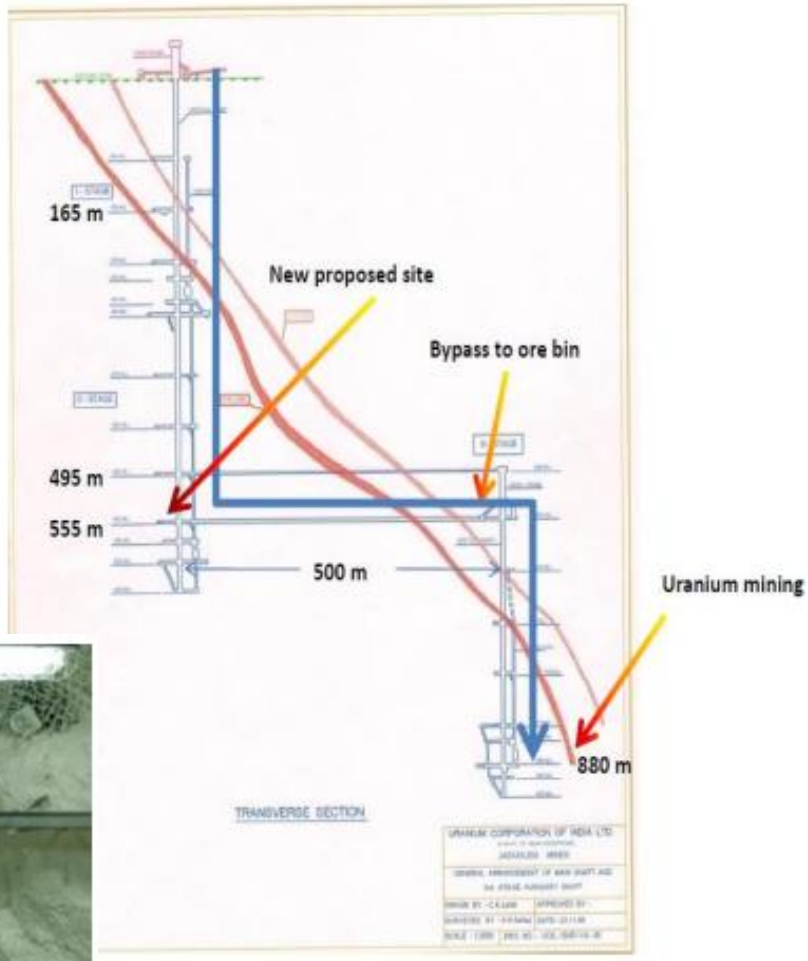
Ref. - [1] ArXiv:2207.03764v[hep-ex] 18 Oct 2022
[2] PHYSICAL REVIEW D **100**, 022001 (2019)

Low-Mass Experiments

Low Mass WIMP Scattering Results from different Experiments							
S. No	Experiment Name	Underground Lab Location	Lowest WIMP Mass (GeV/c2)	Corresponding Cross Section (cm2)	Target	Detector Type	Reference
1	LUX-ZEPLIN	SURF, USA	9	1.0E-46	Liquid Xenon	Cryogenic Dual Phase TPC	arXiv:2207.03764 [hep-ex]
2	CRESST-3	LNGS, Italy	0.16 to 2.5	1.0E-34	CaWO4	Cryogenic	arXiv:2207.07640 [astro-ph.CO]
3	NEWS-G	SNOLab, Canada	0.5	4.0E-37	Ne+CH4	Spherical Proportional Counter	Astropart. Phys. 97, 54 (2018)
4	SuperCDMS	SNOLab, Canada	more than 100 MeV/c2	~1E-34	Ge	Cryogenic	PHYS. REV. D 102, 091101 (2020)
5	DarkSide-50	LNGS, Italy	1.2	1.1E-41	LAr	Noble Gas, Cryogenic	arXiv:2207.11966 [hep-ex]

- We are interested in low-mass region of DM.
- Requires low threshold energy and low mass target detector.
- Detector for present work: Superheated Liquid Detector (SLD).
- For low mass target, SLD with $C_2H_2F_4$ (b.p. : -26.3 ^oC) has been chosen.
- Also, under ground laboratory has been chosen to minimise the background.

Jaduguda Underground Science Laboratory (JUSL)



At a depth: 555m
(cavern size ~7m x 4m x 2.2m)

Background level - JUSL

Cosmic muon flux :

- (2.257±0.261±0.042)x 10^{-7} /cm^2/sec (plastic scintillator)
- (2.051±0.142±0.009)x 10^{-7} /cm^2/sec (simulation)

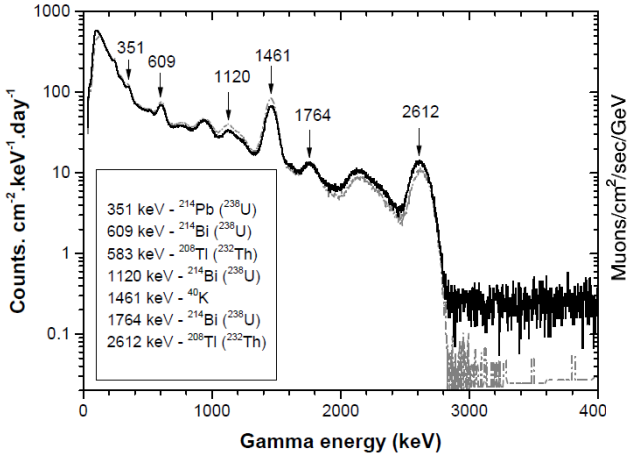
Neutron flux, En ≤10MeV :

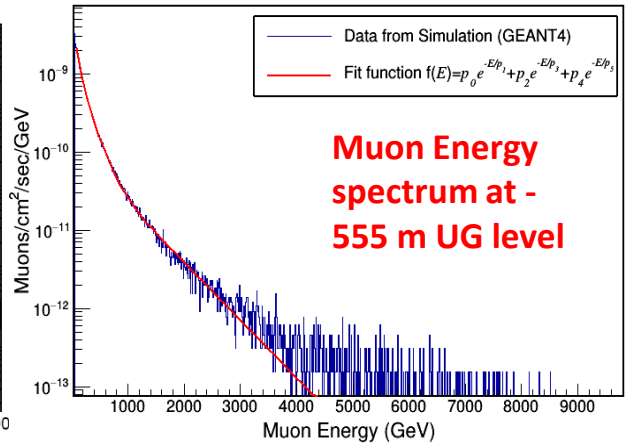
- (1.63±0.03) x 10^{-4} /cm^2/sec [^{4}He detector]
- Cosmogenic neutrons (simulation) : (5.661±0.103)x10^{-8} /cm^2/sec

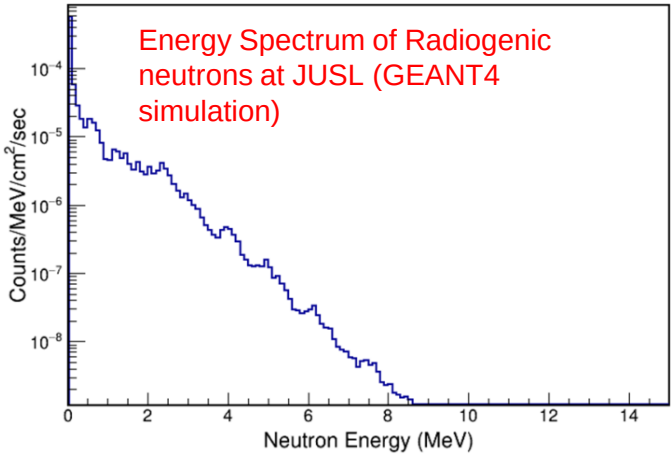
Gamma-rays :

- Spectrum upto 2.6MeV is similar to the surface. Above 2.6MeV - 4MeV , 1 order of magnitude reduced at the underground. [CsI(Tl)]

- SLD will be used in various steps with increasing mass and reducing backgrounds.



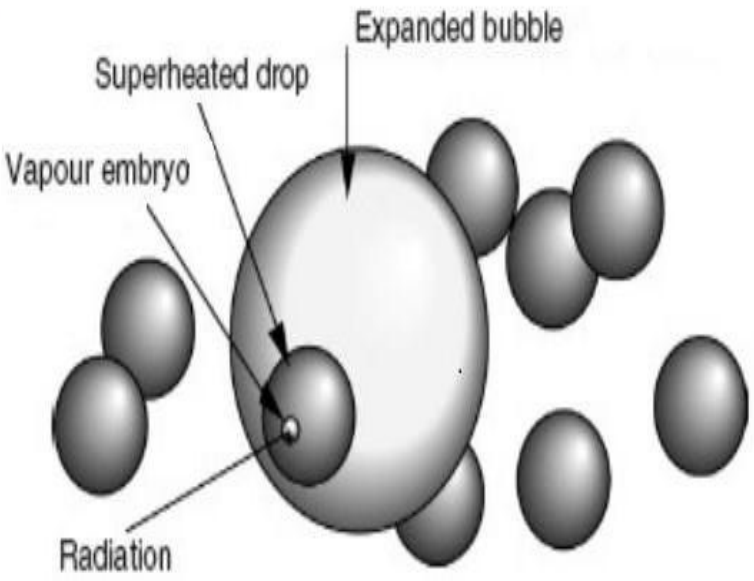


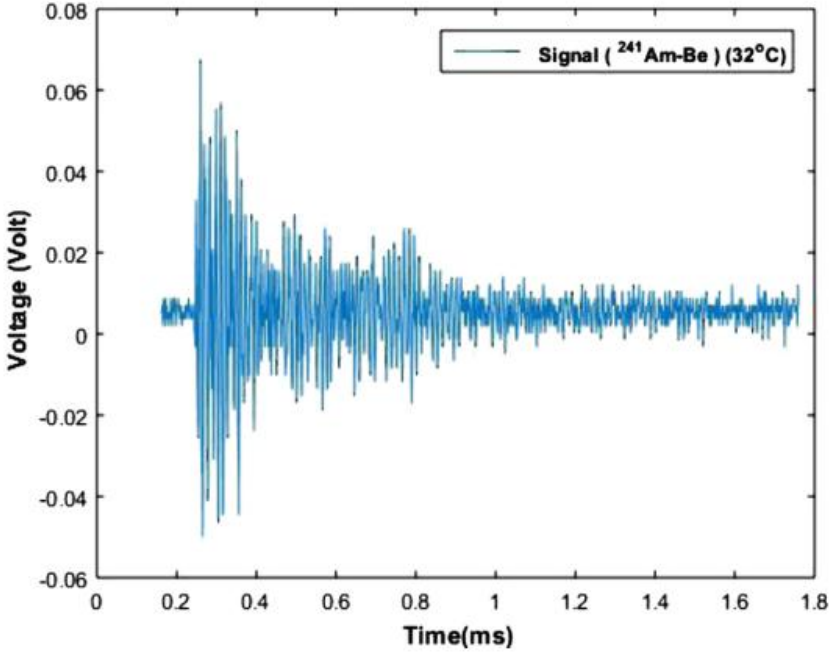


Information from Dr. M. Das (SINP, Kolkata)

Working Principle of SLD

- Phase transition in SLD starts with the formation of embryonic vapour bubble.
- Radius of droplets should be equal or greater than the critical value (R_c).
- To form a bubble of critical radius (R_c), the particle should deposit energy greater than a certain threshold energy (E_{th}).





Response of SLD to WIMPs

- The energy(E) must be greater than threshold energy(E_{th}) so that deposited energy must be greater than the critical energy (E_c) to form a bubble of critical radius.

$$E_{dep}^{(L_{eff})}(E \geq E_{th}) \equiv \int_0^{L_{eff}} \left(\frac{dE}{dx}\right) dx \geq E_c$$

- The target element is insensitive to WIMPs of masses below a certain lowest value and is given by,

$$m_{\chi,\text{lowest}}^{(i)} = m_{A_i}\left[\left(\frac{2m_{A_i}v_{\text{esc}}^2}{E_{R,\text{th}}^{(i)}}\right)^{1/2} - 1\right]^{-1}$$

- Expected rate of events:

$$\mathcal{R}_{\text{exp}} = \sum_i \mathcal{R}_{\text{exp}}^{(i)} = \sum_i \xi_i \int_{E_{R,\text{th}}^{(i)}}^{E_{R,\text{max}}^{(i)}} dE_{\text{R}} \epsilon_i(E_{\text{R}}) \left(\frac{d\mathcal{R}}{dE_{\text{R}}}\right)_i$$

- $\epsilon_i(E_R)$ = Bubble nucleation efficiency
- ξ_i = mass fraction of target element in detector

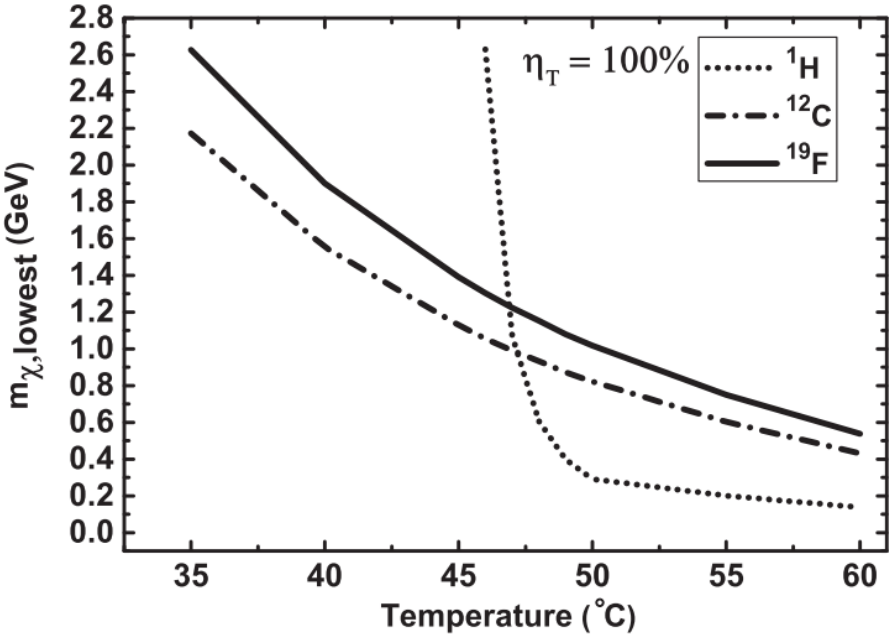
Ref - S.Seth, S. Sahoo, P. Bhattacharjee and M. Das, PRD **101**, 103005 (2020)

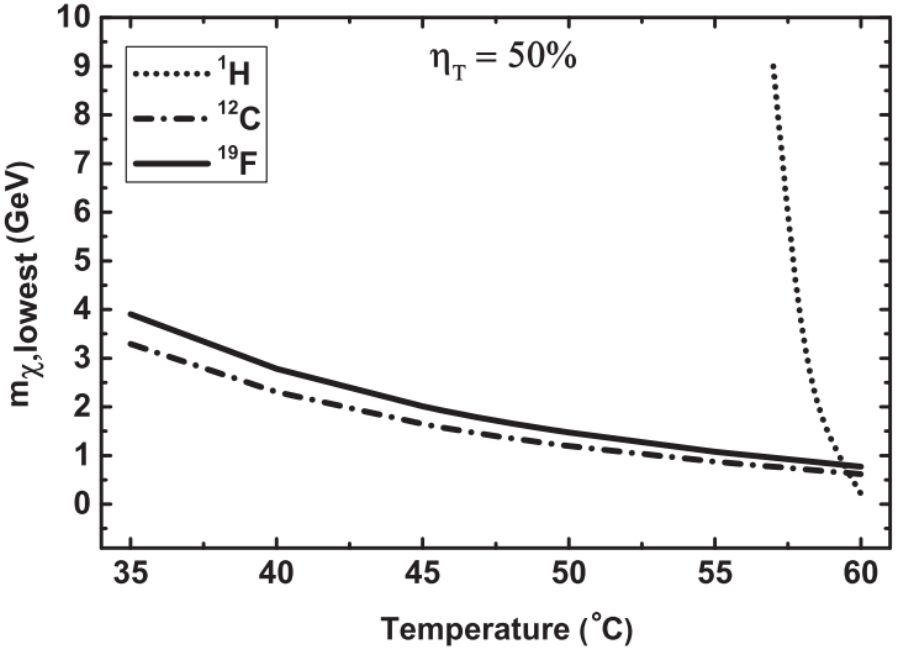
WIMPs masses by SLD with $C_2H_2F_4$ liquid

- Suitable choice of the operating temperature, a $C_2H_2F_4$ SLD can serve as a good detector for very low mass (sub-GeV—few GeV) WIMPs.

- Sub-GeV WIMPs can be detected due to the presence Hydrogen as a target in the detector.

- Presence of Hydrogen as target we can reach upto 0.14 GeV.

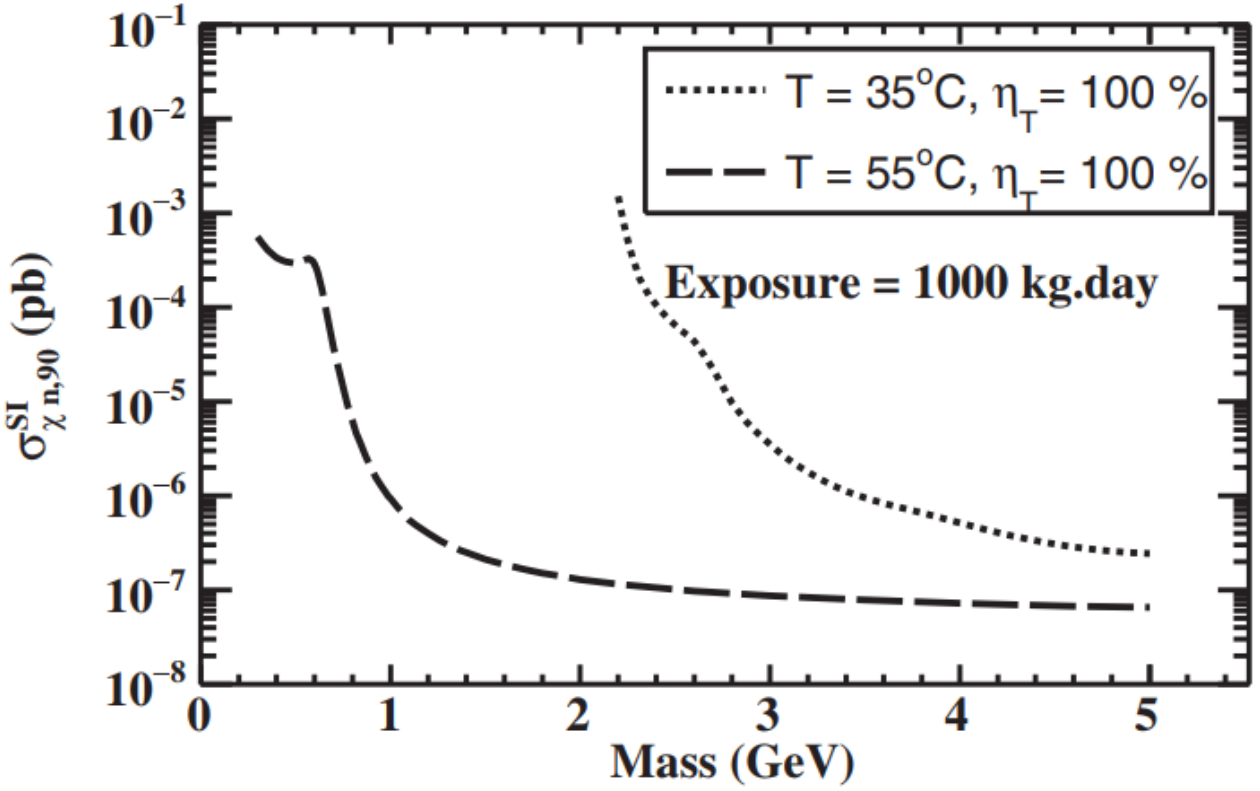




Ref - S. Seth, S. Sahoo, P. Bhattacharjee and M. Das, PRD **101**, 103005 (2020)

Sensitivity of SLD with $C_2H_2F_4$

- Expected spin-independent WIMP-nucleon cross section, as a function of WIMP mass, under zero background.
- The lowest WIMP mass that can be probed at 35 °C is 2.2 GeV.
- At 55 °C, the sensitivities are 6.2×10^{-42}, 3.7×10^{-41}, 2.9×10^{-40}, and 5.6×10^{-40} cm^2 at WIMP mass of 0.8, 0.7, 0.5, and 0.3 GeV, respectively.



Ref - S.Seth, S. Sahoo, P. Bhattacharjee and M. Das, PRD **101**, 103005 (2020)

Detector fabrication

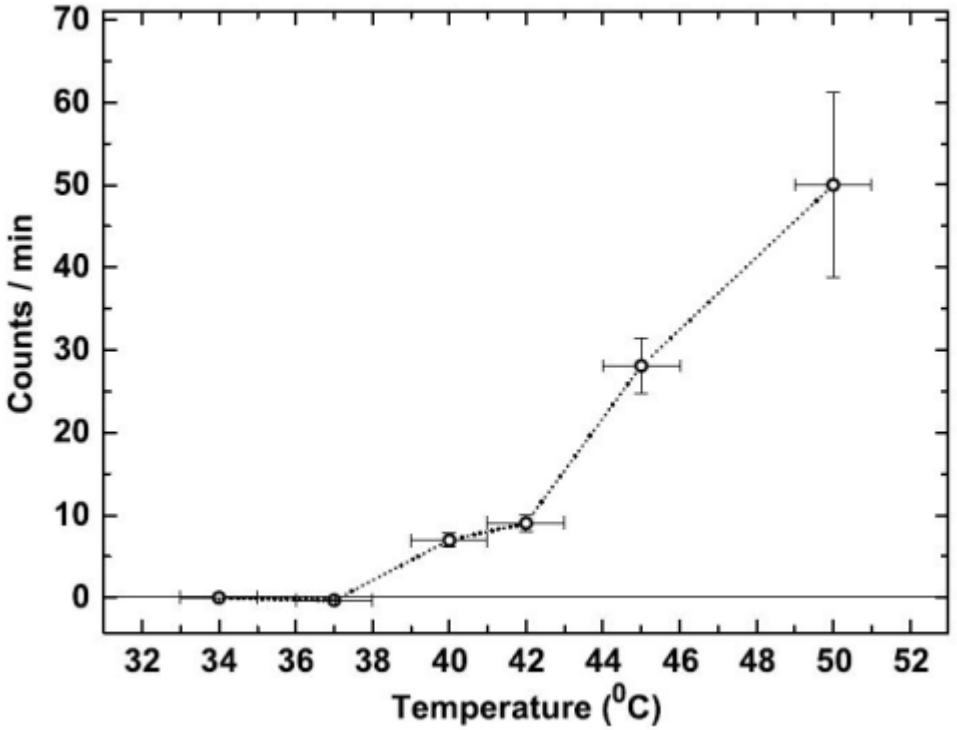
at SINP Lab

• Complete detector fabrication is a long procedure takes around two weeks.
• Initially the gel-matrix is fabricated and degassed to remove air bubbles inside the gel-matrix.
• The active liquid ($C_2H_2F_4$) is purred at high pressure and rotated by stirrer to form liquid droplets inside the gel-matrix.
• The pressure is released very slowly to maintain the superheated state and it is kept at low temperature.

Calibration

Measurement – 1 Gamma-ray sensitivity of SLD

- After, certain temperature SLD become sensitive to gamma-rays.
- The threshold temperature of gamma ray induced nucleation is 38.5 ±1.4 ^{o}C.
- Corresponding threshold energy is 1.55 keV.

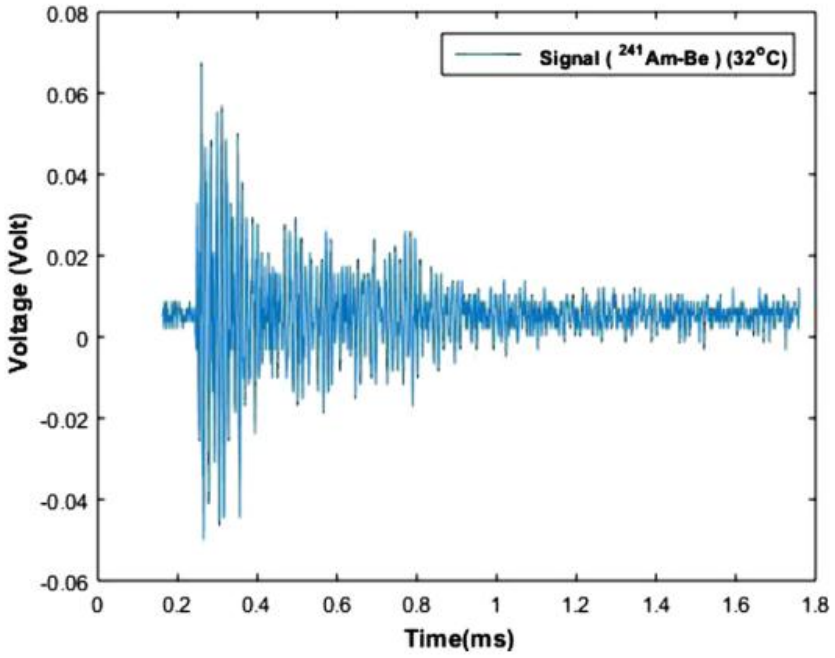


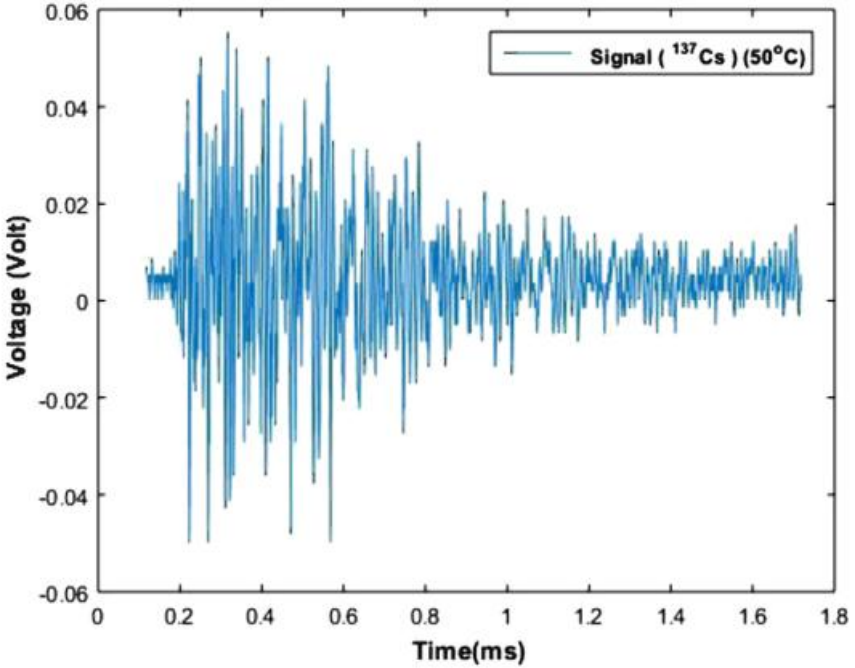
Ref. - S. Sahoo et al, Nucl. Instrum. Meth. A **931**, 44 (2019)

Measurement – 2

Discrimination of nuclear recoil and gamma-rays

- Response of SLD with neutrons and gamma-rays has been checked.
- For gamma-rays measurement has been done using ^{137}Cs of activity 5 mCi at temperature of 50 ^{o}C.
- Similar measurement has been done for neutrons with ^{241}AmBe of activity 10 mCi at temperature of 32 ^{o}C.

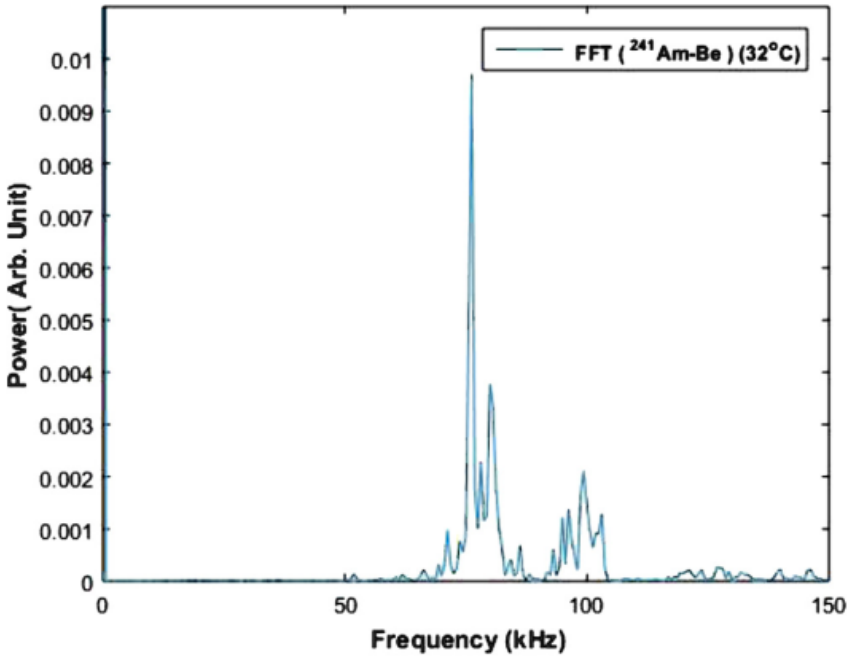


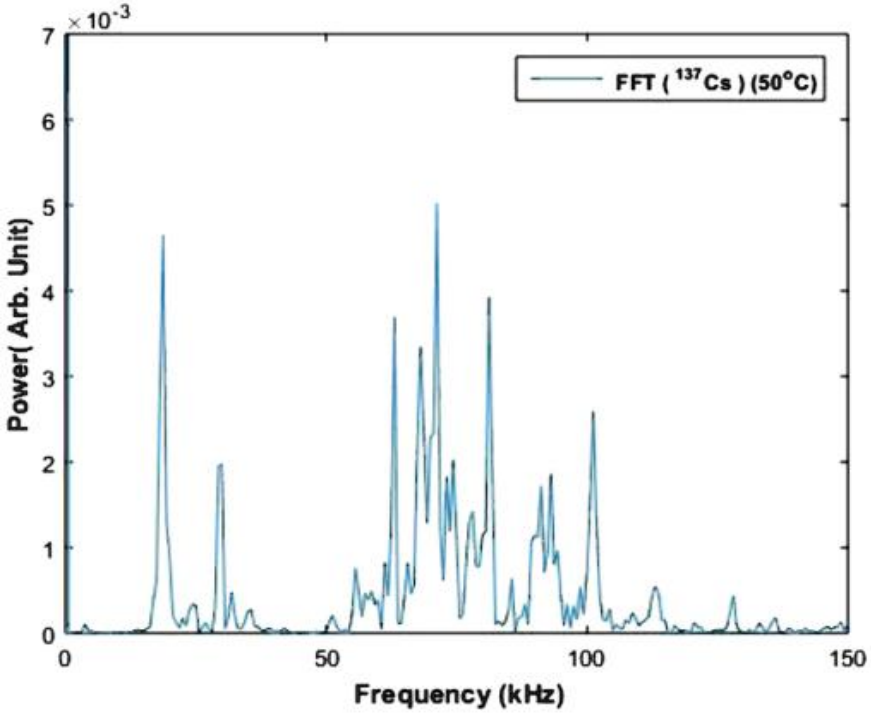


Ref. - S. Ali, M. Das, Nucl. Instrum. Meth. A **1025**, 16186 (2022)

Discrimination

- Fast Fourier transformation has been done on the of neutrons and gamma-rays-induced signals.
- Frequencies of the neutron-induced signals are localised around 80 kHz.
- For gamma-rays, the frequencies are distributed between 50 and 100 kHz and a narrow distribution around 20 kHz.
- There is no other low frequency peak in the FFT spectrum of the signals at other temperatures between 32 ◦C and 55 ◦C except near 20 kHz.

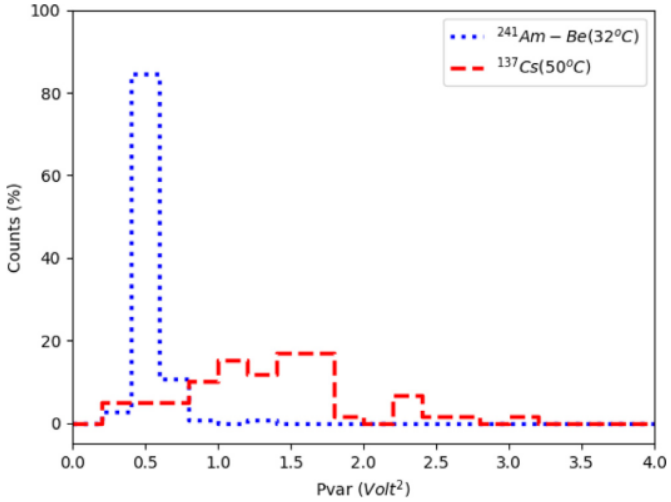


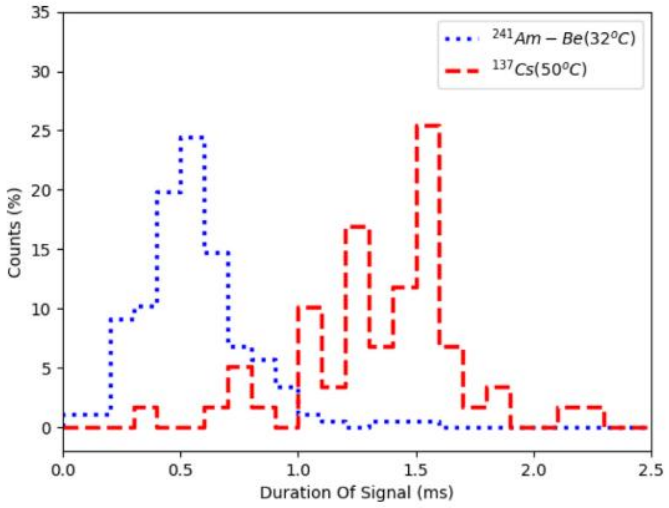


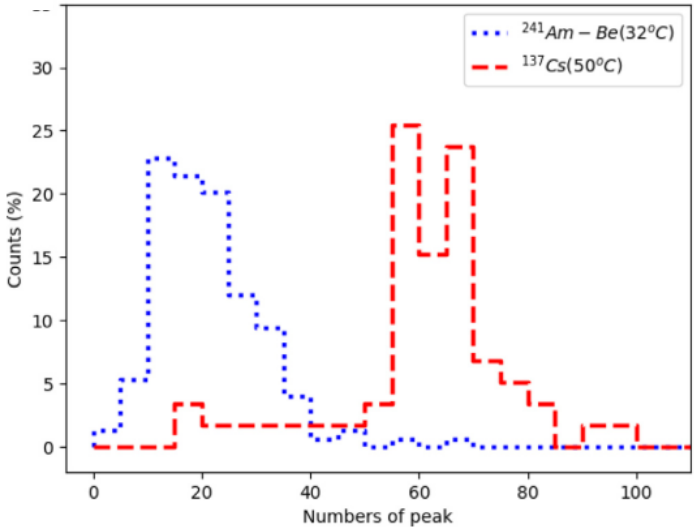
Ref. - S. Ali, M. Das, Nucl. Instrum. Meth. A **1025**, 16186 (2022)

Discrimination

- $\sum v^2_i$ considered as Pvar.
- Pvar, Duration of signal and Numbers of peak of gamma-rays induced signals is high.
- These are good parameters to discriminate neutron and gamma-ray-induced signals.



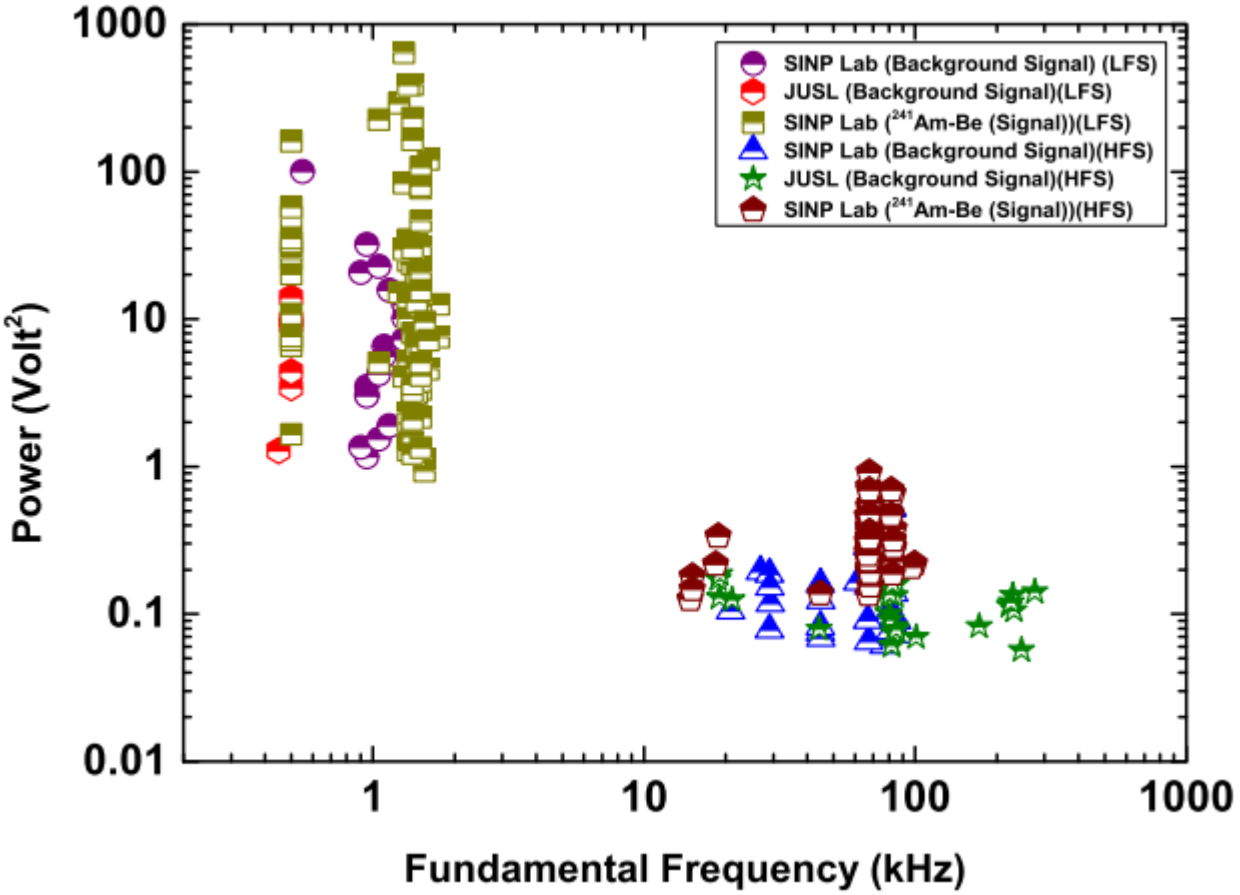




Ref. - S. Ali, M. Das, Nucl. Instrum. Meth. A **1025**, 16186 (2022)

Test run at JUSL

- Operating temperature of SLD is 24.3 ◦C ± 0.5 ºC (Lab temperature).
- Large numbers of low frequency (20 Hz to 20 kHz) noises are present at JUSL.
- Background event rate at JUSL reduces by a factor of 2 than surface Lab.
- ^{241}AmBe (activity - 10mCi) neutron source has been used for the calibration.

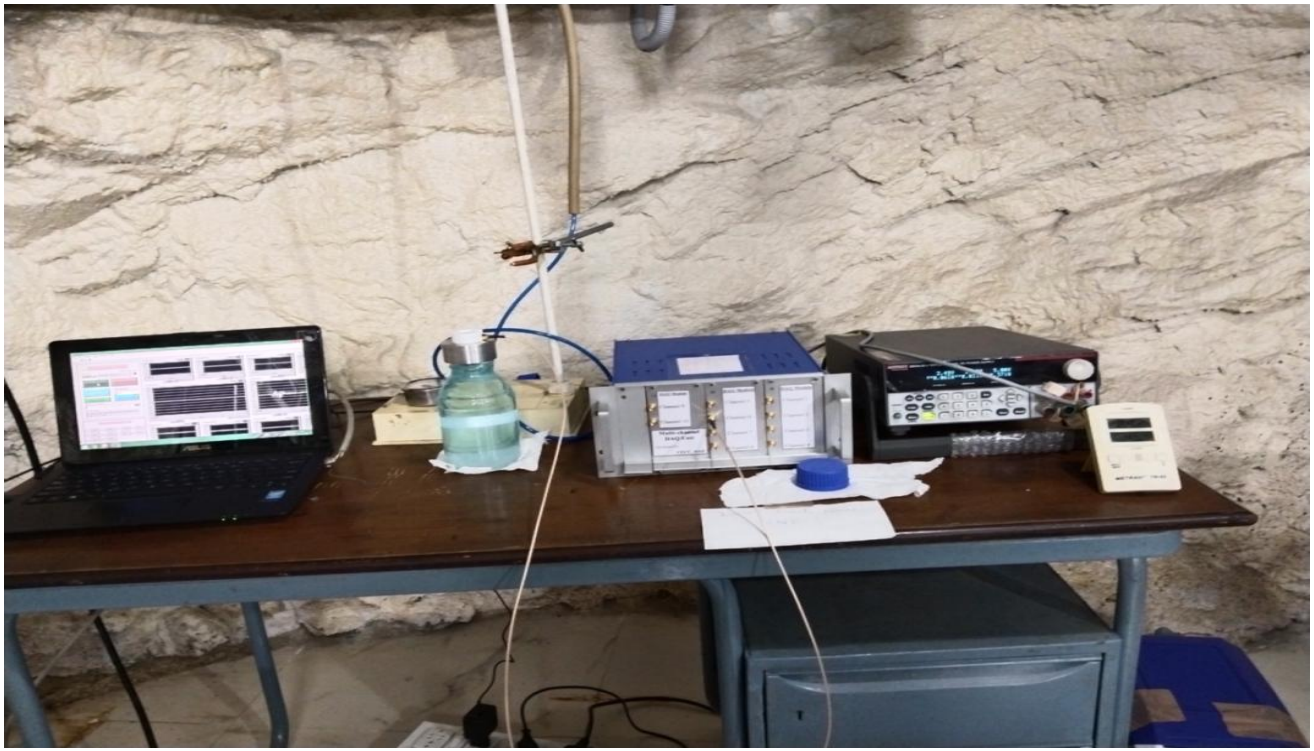


Ref. - S. Sahoo, S. Ali, M. Das, N. Biswas, P. Pallav, J. Basu, Nucl. Instrum. Meth. A **1008**, 165450 (2021).

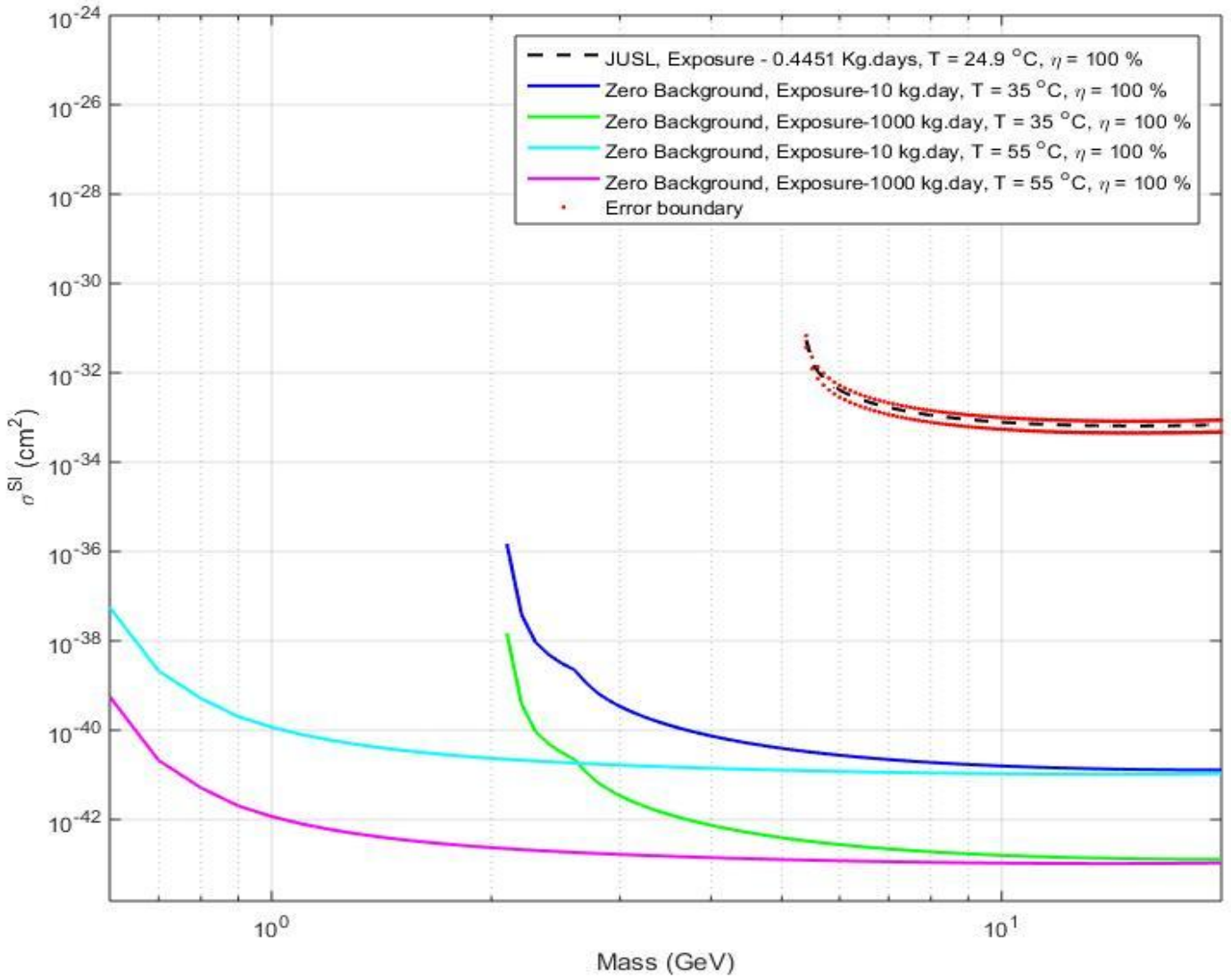
Experiment at JUSL

- 500ml SLD : ~50 days of run
- Active liquid ($C_2H_2F_4$) ~ 22.94 ml
- Expected exposure ~1.33kg-days
- Operating temp ~24^{o}C and threshold ~ 7 keV
- Run: Start date: 27/07/2022
  End date : 16/12/2022

- **Count rate at JUSL /gm/sec - $2.5 \times 10^{-6} \pm 1.80 \times 10^{-7}$**
- **Count rate at SINP-lab /gm/sec - $2.13 \times 10^{-5} \pm 1.23 \times 10^{-5}$**



Result of ongoing JUSL run (Very Preliminary)



The minimum cross-section is $(6.51^{+1.76}_{-2}) \times 10^{-34}$ cm^2 corresponding WIMPs mass is 14.6 GeV.

Timeline & milestone :

No of detector	Total volume of SLD (ml)	Active liquid (gm)	Exposure (kg-days)	Expected Time	Operating Temp.	Threshold (keV)		Sensitivity projected (cm^2)
1	100 SDD	4.8	101.2 (gm-hr)	Sept 2019	~24°C	7.13	Estimated	~1E-32
1	500 SDD	26.84	1.304	July 2022-Oct 2022	~24°C	7.13		~1E-35
1	500 SDD	26.16	1.347	Oct – Dec 2022	~24°C	7.13		"
2 x 500 ml	1000 SDD	53.0	2.66 7 (~50days)	Feb – May 2023	35°C	1.92	zero backgrounds	1.94E-41
8	4000	212.0	10.670 (~50days)	July – Dec 2023	35°C	1.92		9.71E-42
Geyser type	1000	1170	105.3kg-days (3 months)	2024	35°C	1.92		9.84E-43
Geyser type				2025	55°C	0.19		9.84E-43

Acknowledgement

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- Mr. Piyush Pallav
- Prof. P. Bhattacharjee
- Prof. S. Saha
- .....

VECC :

- Mr. Niraj Chadda
- Mr. Shantonu Sahoo
- Dr. A. Roy
- Dr. S. Pal
- .....

Members of UCIL, Jaduguda Mine

- V. N. Jha and group
- HPU Jaduguda

BARC

Thank You