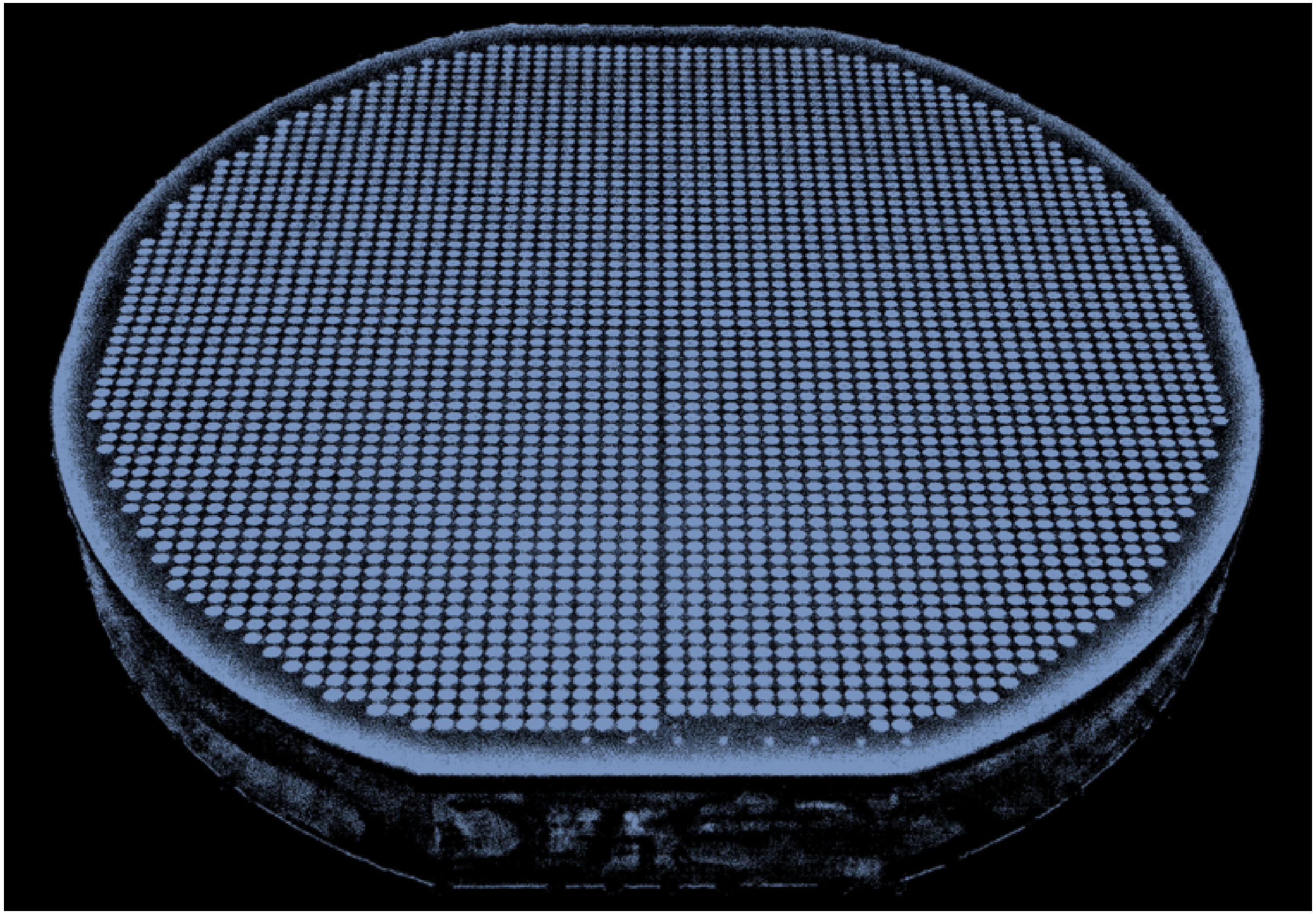
Detectors and Detection Techniques for Dark Matter Search Experiments



SATYAJIT SAHA SINP

CONFERENCE ON ADVANCED DETECTORS FOR NUCLEAR, HIGH ENERGY AND ASTROPARTICLE PHYSICS EXPERIMENTS (ADNHEAP 2017)

BOSE INSTITUTE (FEBRUARY 15 – 17, 2017)

Plan of the talk

Introduction to rare event search: Quest for Dark Matter

Physics interest on Dark Matter Problem :Astrophysical Evidences

- Synergy of Dark Matter problem with High Energy Physics
- "Neutrinos" as Dark Matter Candidates
- Synergy of Neutrino Physics with Dark Matter

Quest for Existence of Dark Matter at the terrestrial scales: Direct and Indirect Searches

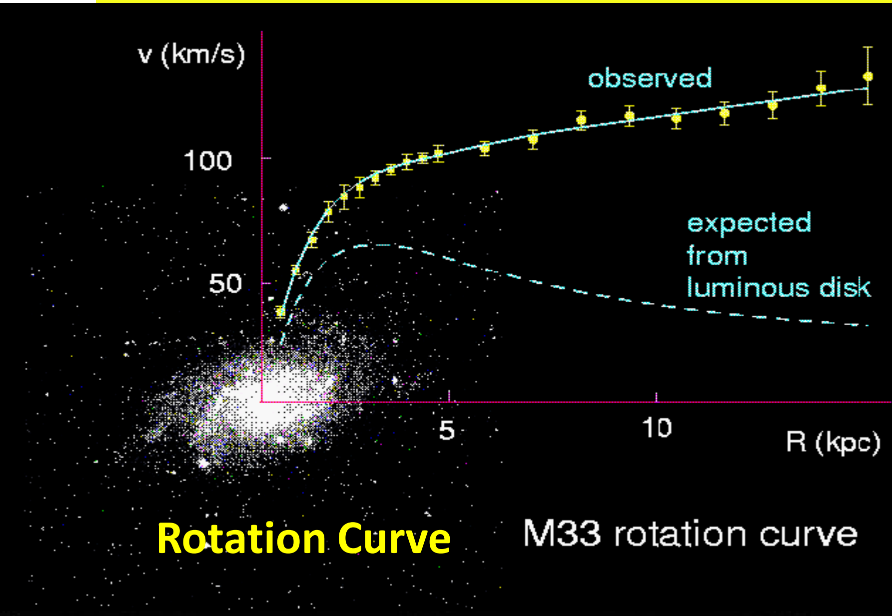
Detection methods and strategies in direct DM search:

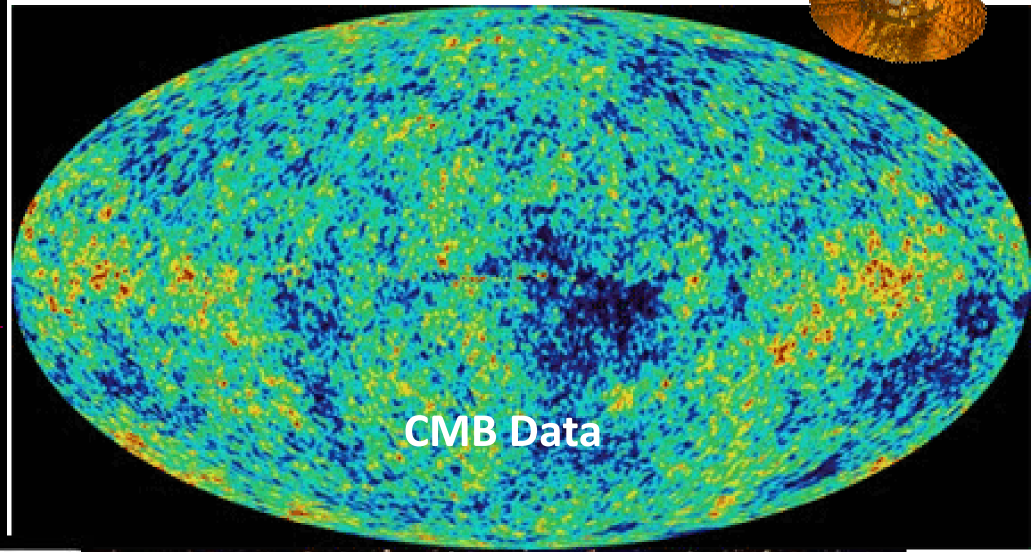
- Nuclear recoil to signal generation
- False signals from other processes – background
- How to eliminate / discriminate against sources of background?
  1. Ionization vs phonon signals (CDMS / SuperCDMS)
  2. Scintillation vs phonon signals (CRESST-II)
  3. Ionization alone with pulse shape discrimination (DEAP, Argon TPC, Xenon)
  4. Threshold rejection based detection strategies (PICASSO / PICO)
  5. Single signal channel experiment (DAMA/LIBRA, CoGENT, KIMS …)

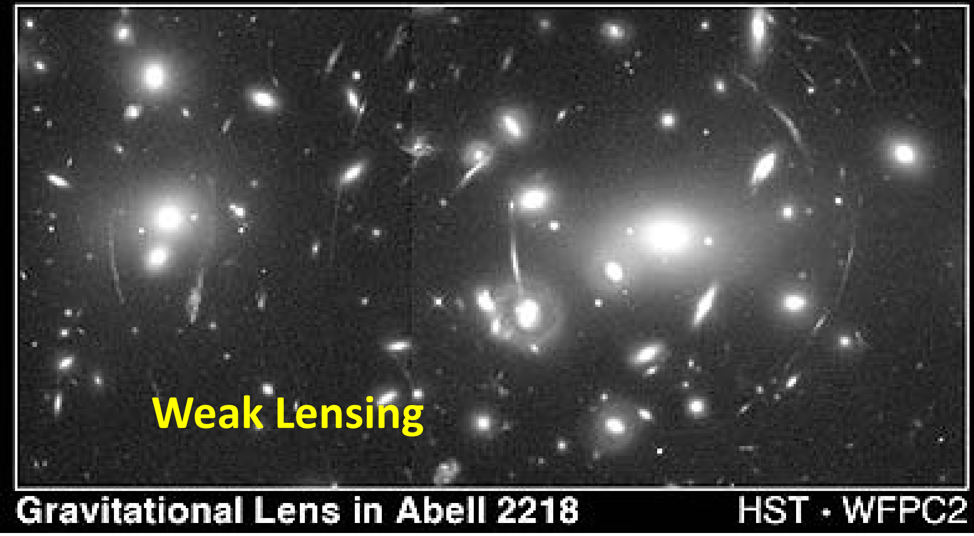
Our initiative: Dark matter search at INO (DINO at Jaduguda mine)

Summary

Evidences of DM from Astronomical Observations

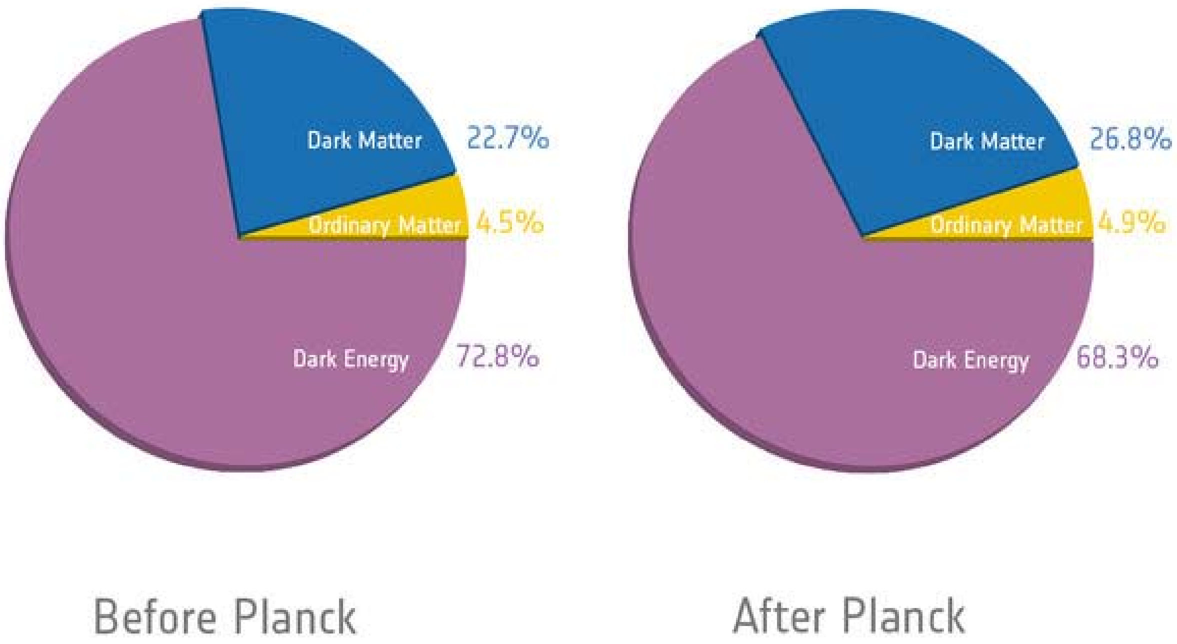






What is it made of? Can we detect it in terrestrial laboratories?

WMAP & PLANCK - composition of the universe
New Results



WMAP & PLANCK measured the composition of the universe. The charts show the present composition.

http://www.esa.int/Our_Activities/Space_Science/Planck/Planck_reveals_an_almost_perfect_Universe

Possible constituents of Dark Matter

- Gravitationally interacting
- Neutral (not charged)
- Stable or long lived
  - ← W_{DM} = 0.23
- Cold or Warm (not hot)
  - ← large scale structure
- non-Baryonic
  - ← CMB, BBNS

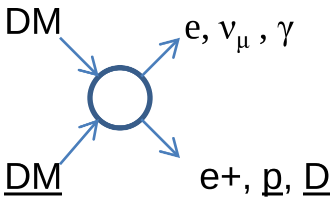
Physics beyond
The Standard Model

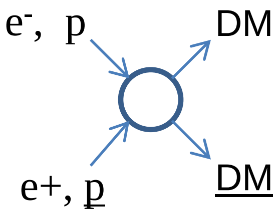
- AXION
- Sterile Neutrinos
- WIMP
- SUSY particles
  - Neutralino
- ……..

Weakly Interacting Massive Particles (WIMP)
give the right relic abundance

Detecting Dark Matter

- **Indirect Detection:**
  - **Observation of WIMP annihilation products**
    - **Gamma-ray telescopes (MAGIC, CANGAROO-III, HESS, VERITAS, EGRET, GLAST…)**
    - **Anti-matter experiments (HEAT, BESS, PAMELA…)**
    - **Neutrino detectors/telescopes (IceCUBE, ANTARES, AMANDA, Super-Kamiokande…)**



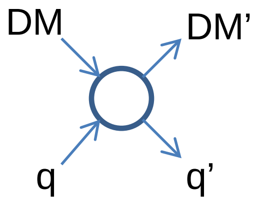


- **Collider Experiment (Indirect Detection):**
  - **Missing energy/transverse momenta in collision**

- **Direct Detection:**
  - **WIMP- Nuclear recoil from slow moving Dark Matter**

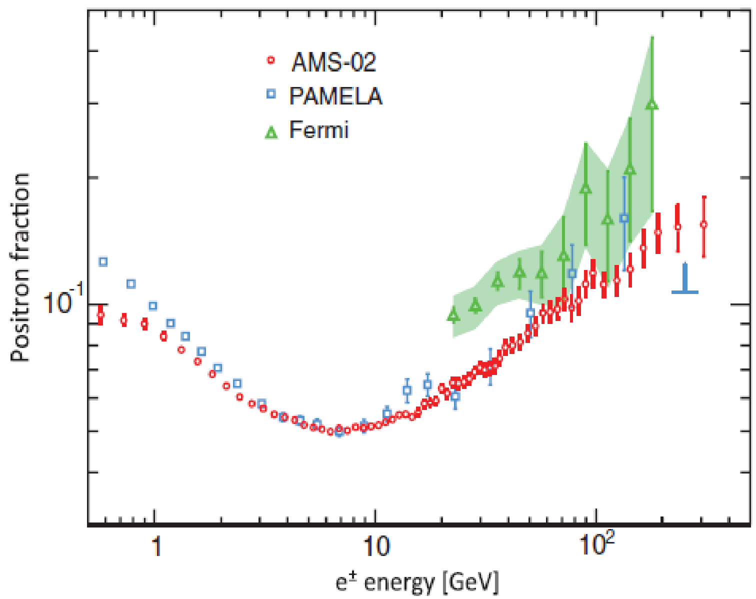
    elastic scattering
  - **Axion Searches ... (CAST / ADMX)**

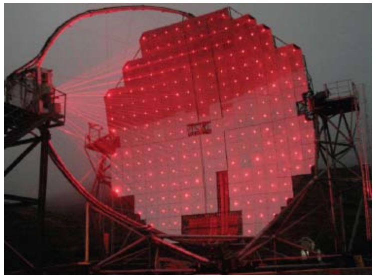
    Resonant axion-$\gamma\gamma$ conversion in large B-field



Indirect Detection

- **Observation of WIMP annihilation products → Look for excess of antimatter in space-borne telescopes**





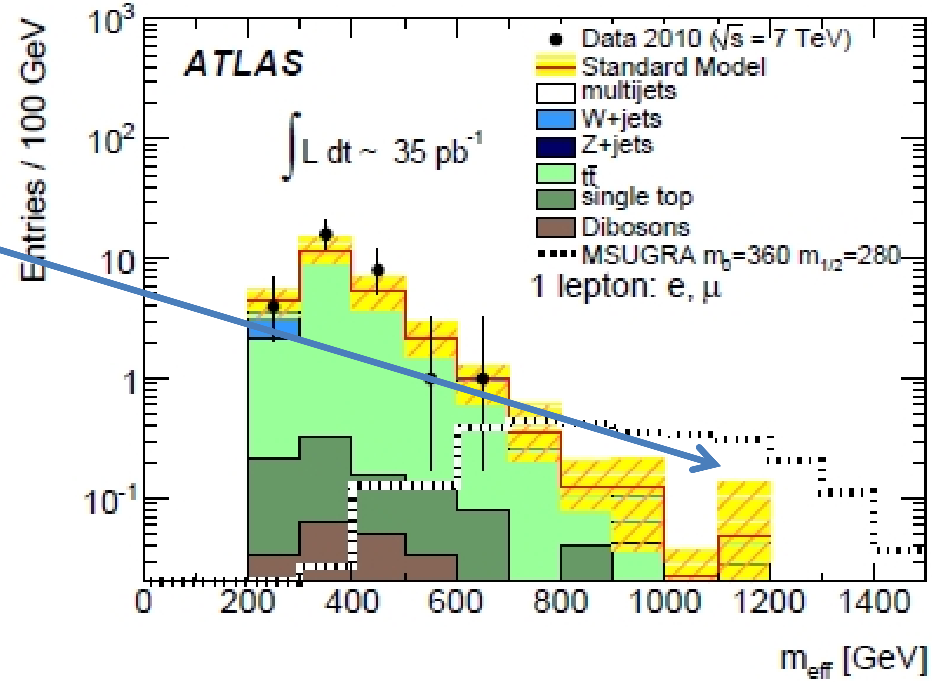
- **Alpha Magnetic Spectrometer (AMS) @ International Space Station**

  → Excess antimatter (positrons) observed (April 2013) !!

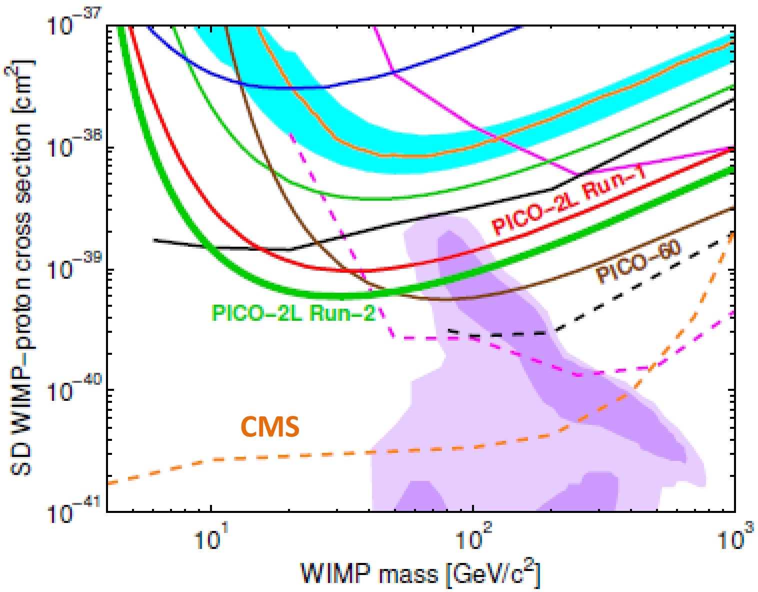
M Aguilar et al, PRL 110, 141102 (2013)

Indirect Detection: Collider Searches

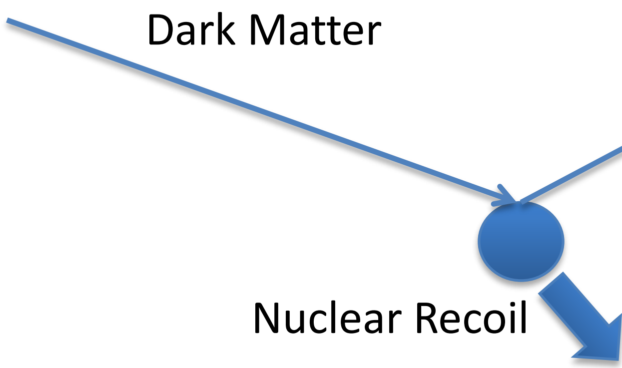
Look for missing energies in collider experiments



No conclusive evidence yet



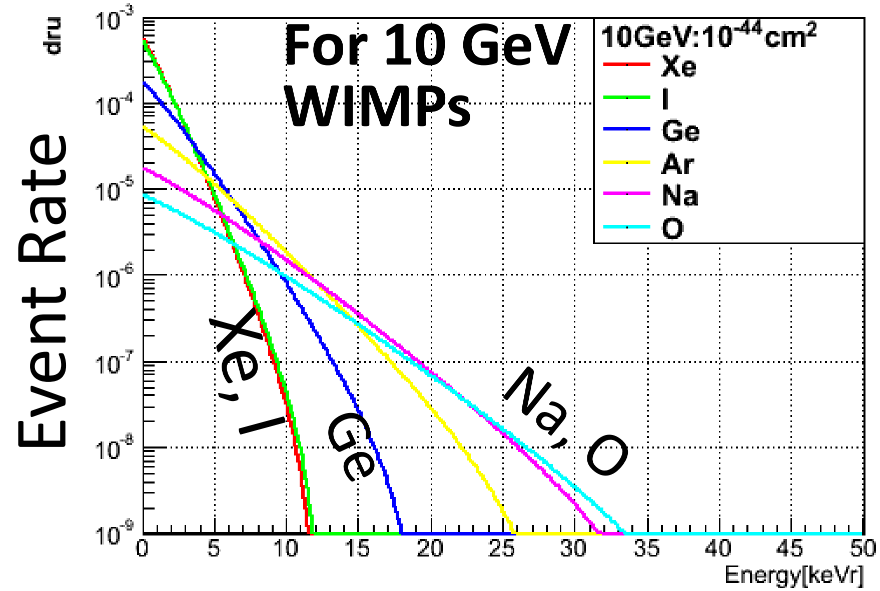
Direct Detection

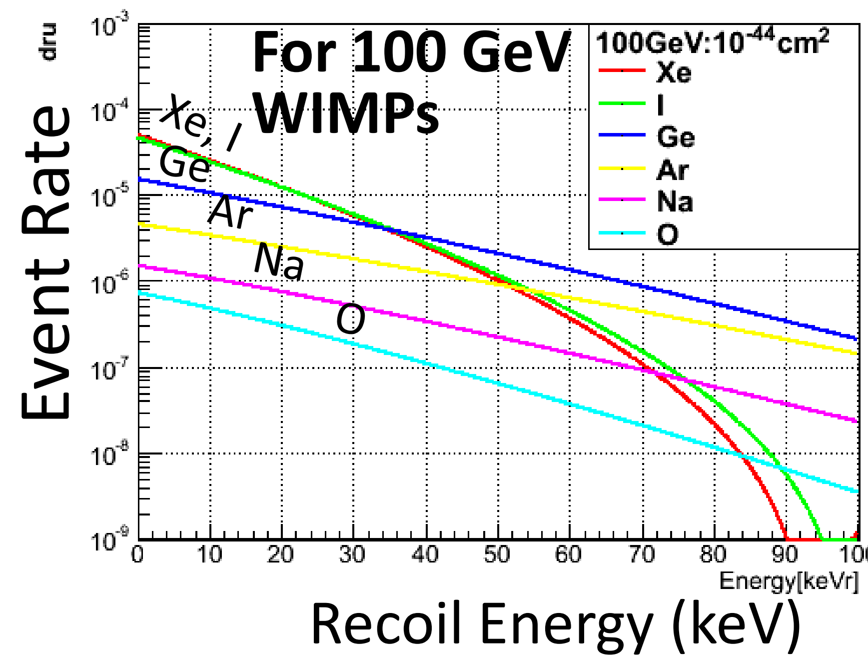


- Direct searches : Observe Nuclear Recoils
  - χ + N ➔ χ + N
- Recoil Energy:
  - 🡐Kinetic energy of DM

$$E_R = \frac{M_\chi v^2}{2} \frac{4M_\chi M_A}{(M_\chi + M_A)^2} \frac{(1 - cos\theta)}{2}$$

  - 1~100 keV
  - For low mass DM, spectra become very soft for large target masses like Xe, Ge,
    - Loose efficiency unless lowering the threshold





Recoil Energy Spectra

Expect single collision events only. Nuclear recoil energy spectrum:

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

where, $d\sigma/dE$ = differential cross section for WIMP interaction;
$f(v,t)$ = velocity distribution of WIMPs in the detector rest frame (time dependent?)

Aim of DM experiment: Determine the energy dependence of DM interaction

$$\frac{dR}{dE}(E) \approx \left(\frac{dR}{dE}\right)_0 F^2(E) \exp\left(-\frac{E}{E_c}\right),$$

where, $(dR/dE)_0$ = event rate at zero momentum transfer;
$F^2(E)$ = Form factor of WIMP-nucleon scattering (nuclear physics input)
E_c = Energy scale dependent on recoil nuclear mass and WIMP mass

Event rate estimate for DM:

$$R \sim \sigma_{\chi-N} \times n < v > \propto \sigma_{\chi-N} \times (\frac{\rho}{M_x}) \times \int v f(v) dv$$

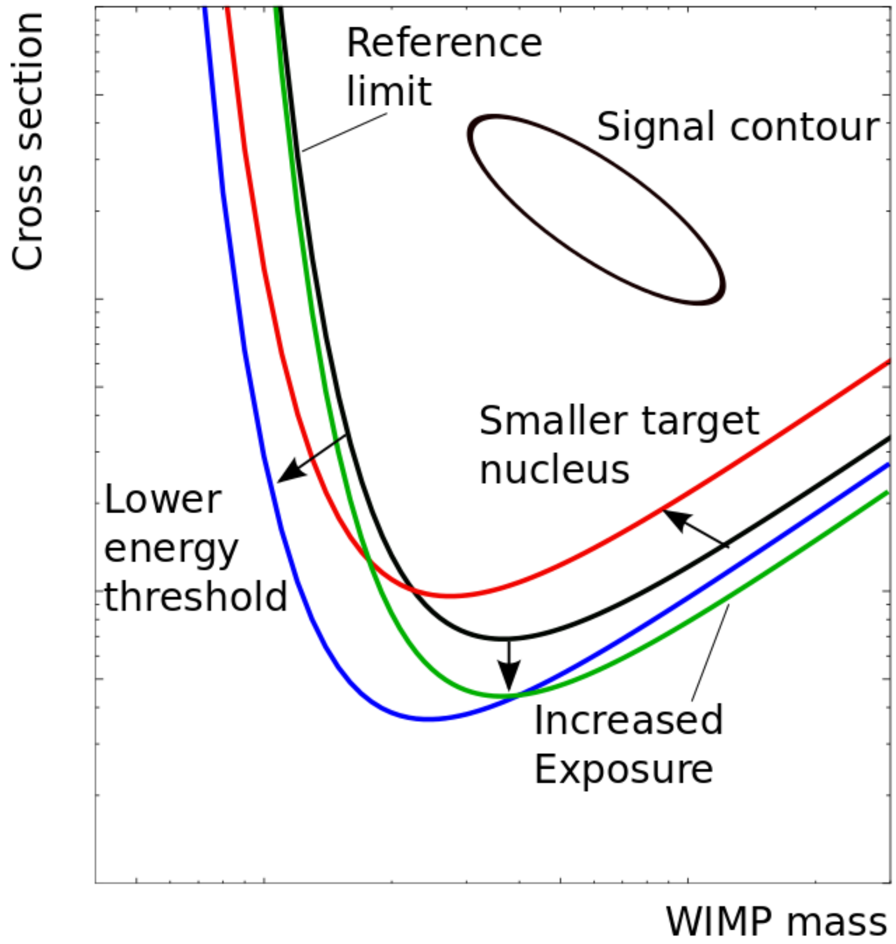
$$\sigma_{\chi-N} = \sigma^{SI}_{\chi-N} + \sigma^{SD}_{\chi-N}$$

Exclusion Limit Plots: Presentation of DM search results

- WIMP cross section vs WIMP mass plot

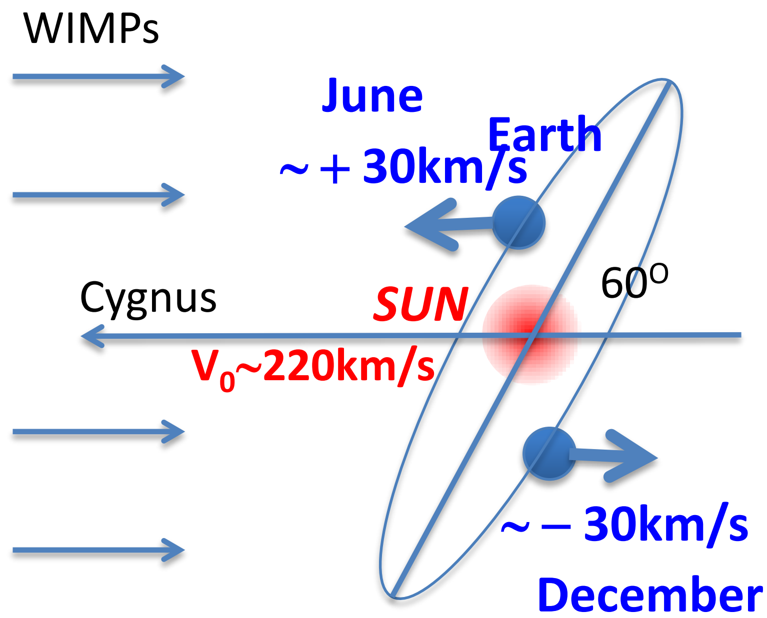
$$\frac{dR}{dE}(E,t) = \frac{\rho_0}{2\mu_A^2 \cdot m_\chi} \cdot \sigma_0 \cdot A^2 \cdot F^2 \int_{v_{min}}^{v_{esc}} \frac{f(\mathbf{v},t)}{v}\, \mathrm{d}^3 v,$$

$$v_{min} = \sqrt{\frac{2m_A \cdot E_{thr}}{2\mu_A^2}}.$$



Another DM observable: Annual Modulation

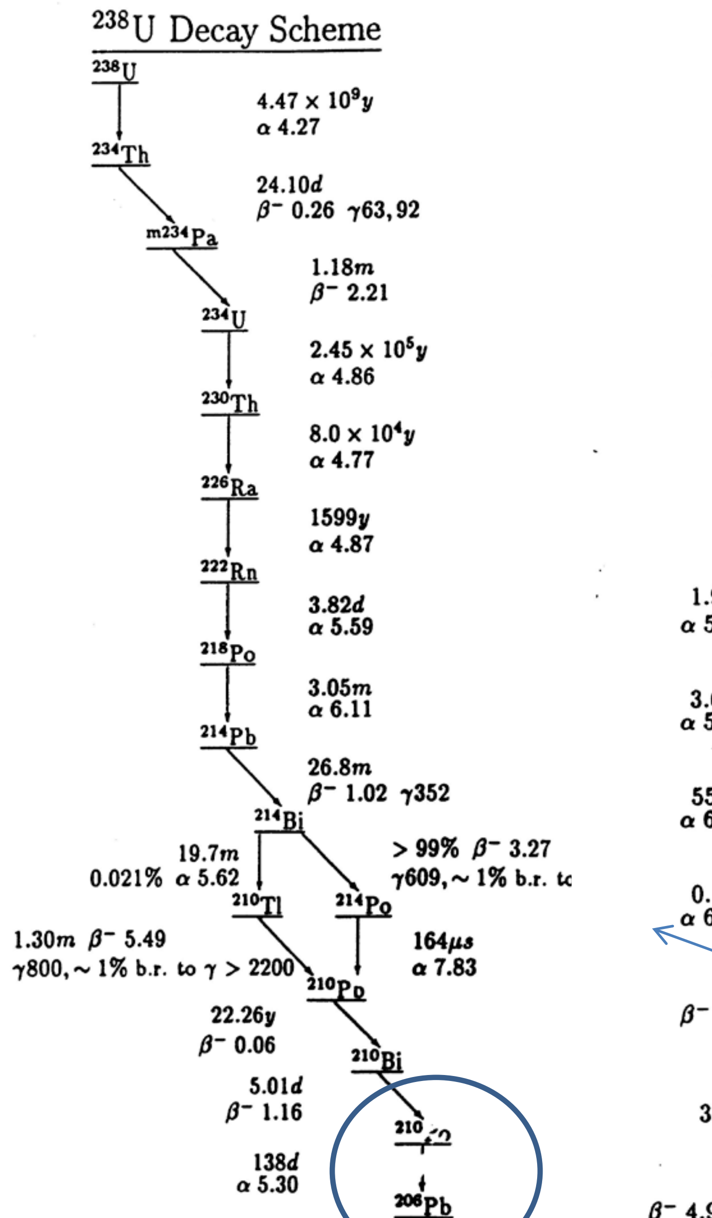
- Seasonal variations of the velocity: ±30km/s
  ➔ $< \sim 10\%$ modulation effects
  - depend upon spectrum shape, trigger efficiency, analysis cuts and so on

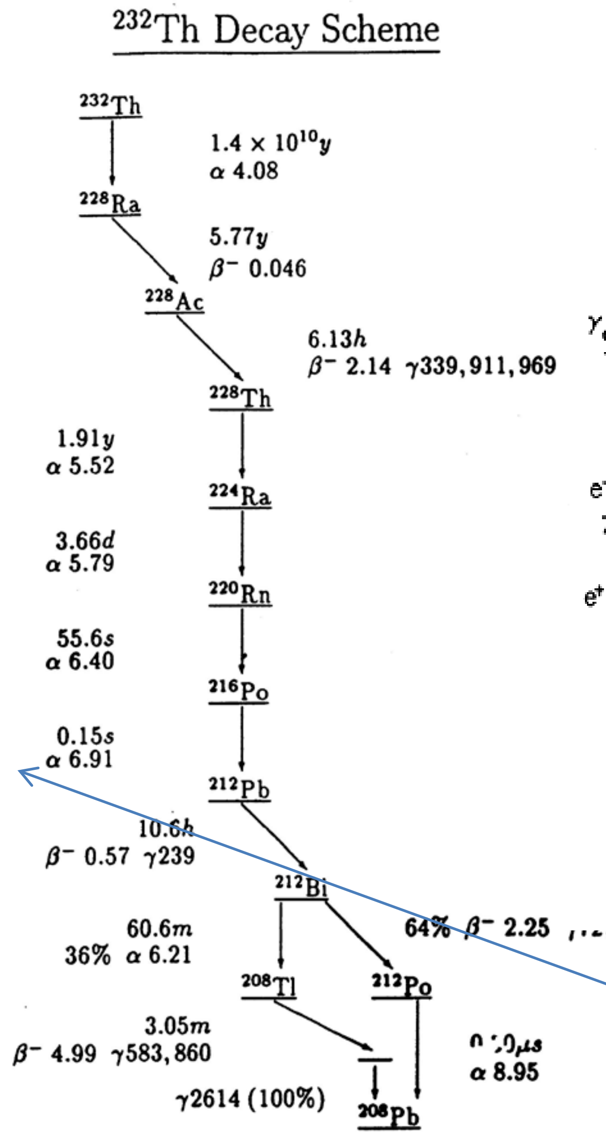


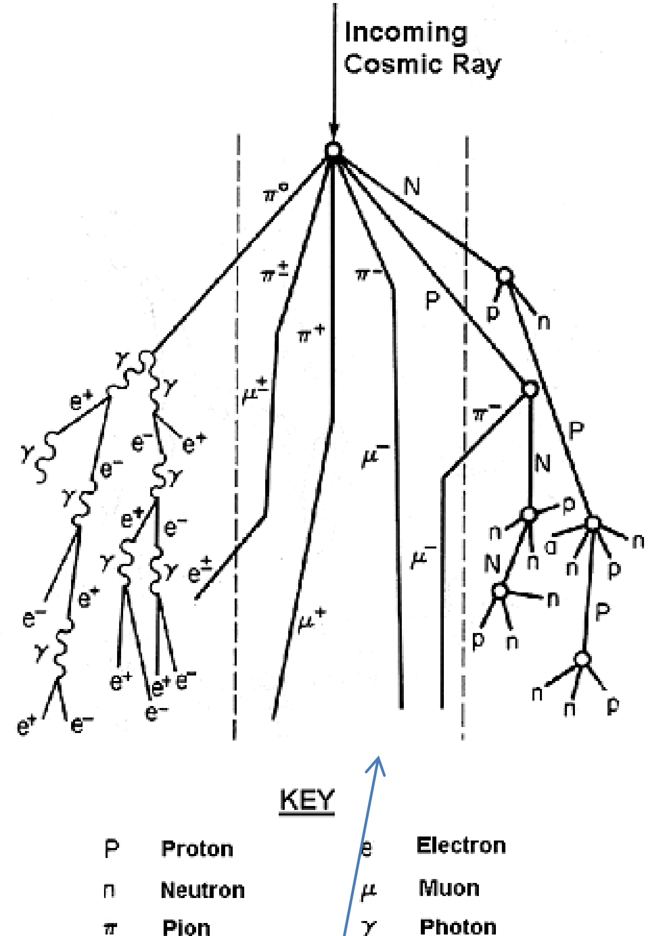
$$\frac{dR}{dE}(E,t) \approx S_0(E) + S_m(E) \cdot \cos\left(\frac{2\pi(t-t_0)}{T}\right),$$

Positive result declared in: DAMA / CoGeNT

False signals from the background



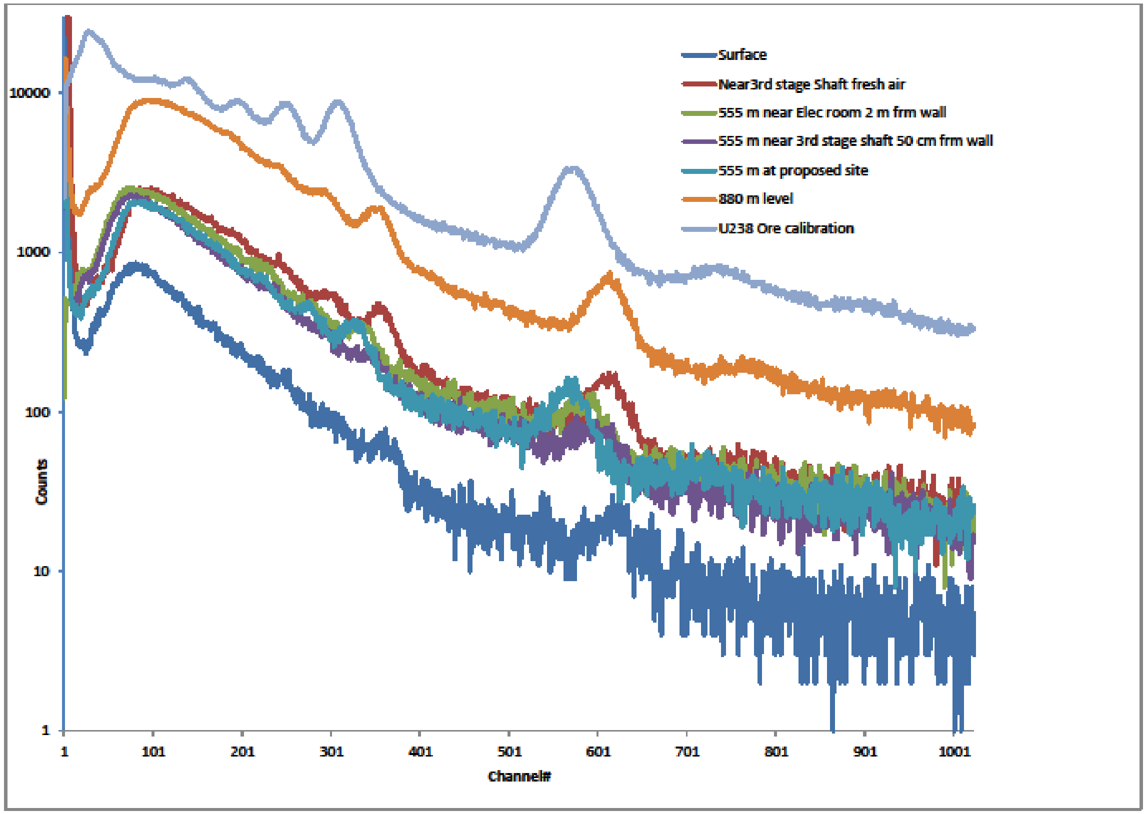




Muon induced neutrons

Neutrons from (Alpha,n)

Gamma Survey of the Jaduguda mines at different levels
CsI(Tl) detector during 31/3/2016 – 2/4/2016



Expected gamma ray lines observed in the mine background:

295, 352 keV -- 214Pb (226Ra - 222Rn progeny, 27 min)

583 keV -- 208Tl (232Th – 228Ac chain, 3.05 min)

609, 768 keV -- 214Bi (226Ra – 222Rn progeny, 20 min)

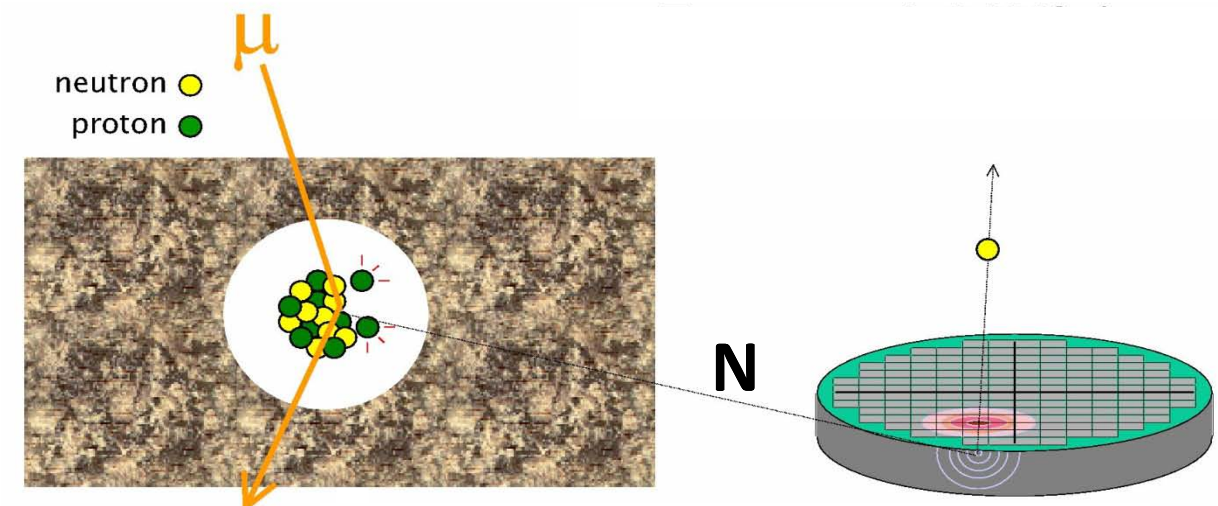
911 keV -- 228Ac (232Th – 228Ac chain, 6.1 hrs)

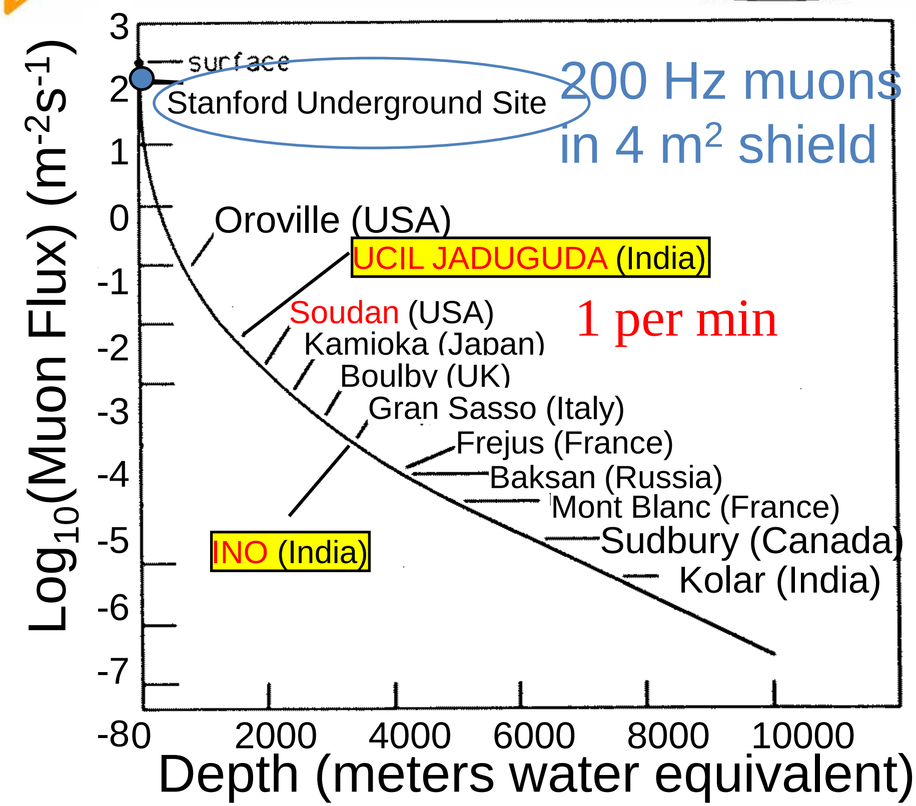
934, 1120, 1238 keV -- 214Bi (226Ra – 222Rn progeny, 20 min)

1461 keV -- 40K (primordial)

1765 keV -- 214Bi (226Ra – 222Rn progeny, 20 min)

Reducing Cosmogenic Background





SNOLAB: A Benchmark of underground lab

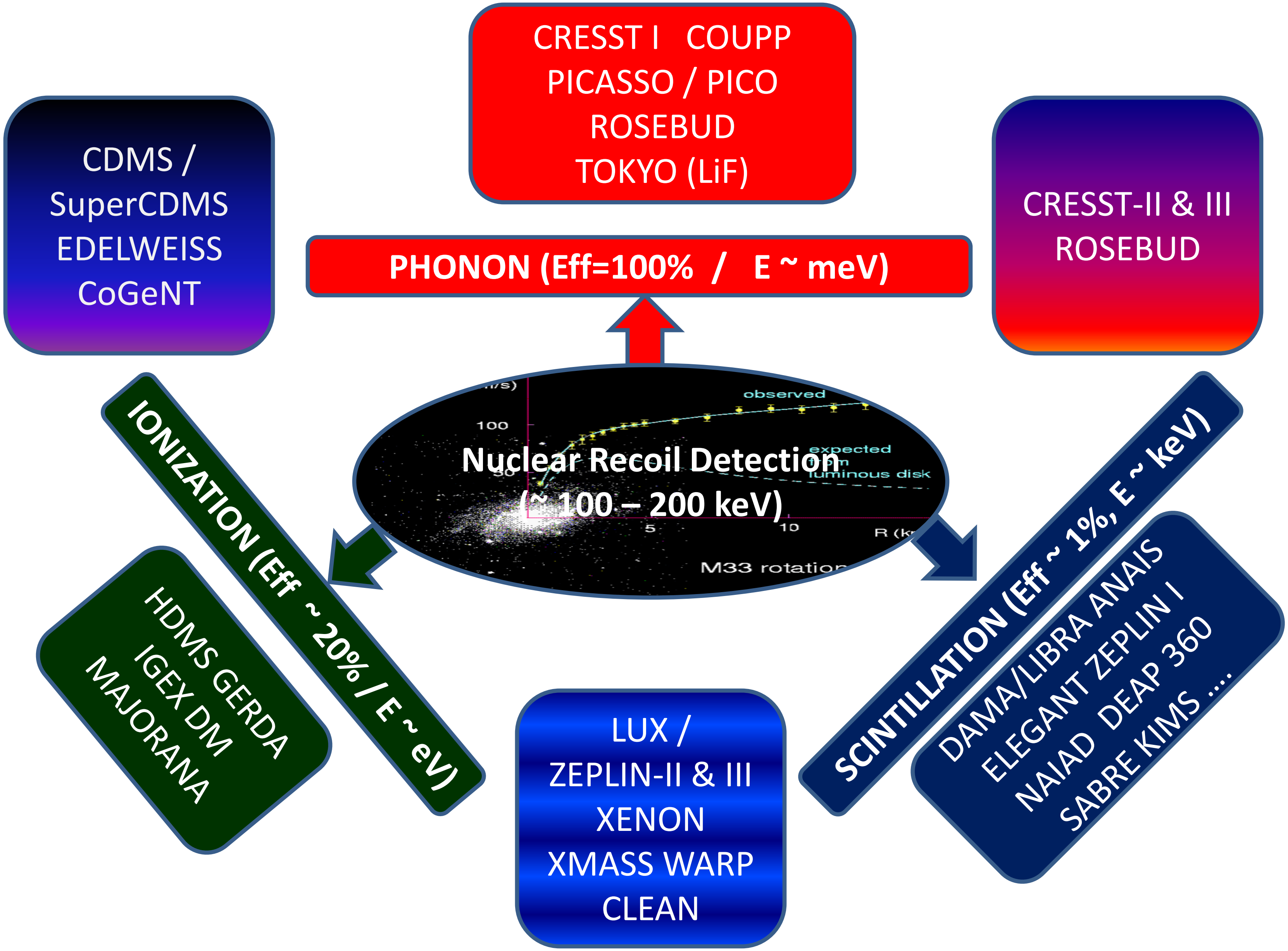
	Flux
Muons	<0.27/m²/day
Neutrons (Thermal)	4144.9±49.8±105.3 n/m²/day
Neutrons (Fast)	~4000 n/m²/day
Radon (Surface)	0.15± 0.12 pCi/L
Radon (UGLab)	3.3± 0.4 pCi/L

Norite	
K	1.20%
238U	1.2 ppm
232Th	3.2ppm

What do we have as radiogenic background at UCIL site?

Radioactivity background in Jaduguda rock samples (ICPOES, Radiometric and wet chemical analysis)	
K	2-3%
238U	8 ppm
232Th	16 ppm

Classification of Direct detection experiments based on detection strategies



Direct Detection: Current Experimental Scenario

Positive Indication

Experiments	Target	Threshold	Total Exposure	Recoil Identification	Modulation
DAMA/LIBRA	NaI	2.0 keV_{ee}	427,000 kg-days	(NR+EM)	O
CoGeNT	Ge	0.5 keV_{ee}	140 kg-days	(NR+EM)	O
CRESST	$CaWO_4$	10.0 keV	>700 kg-days	NR	—

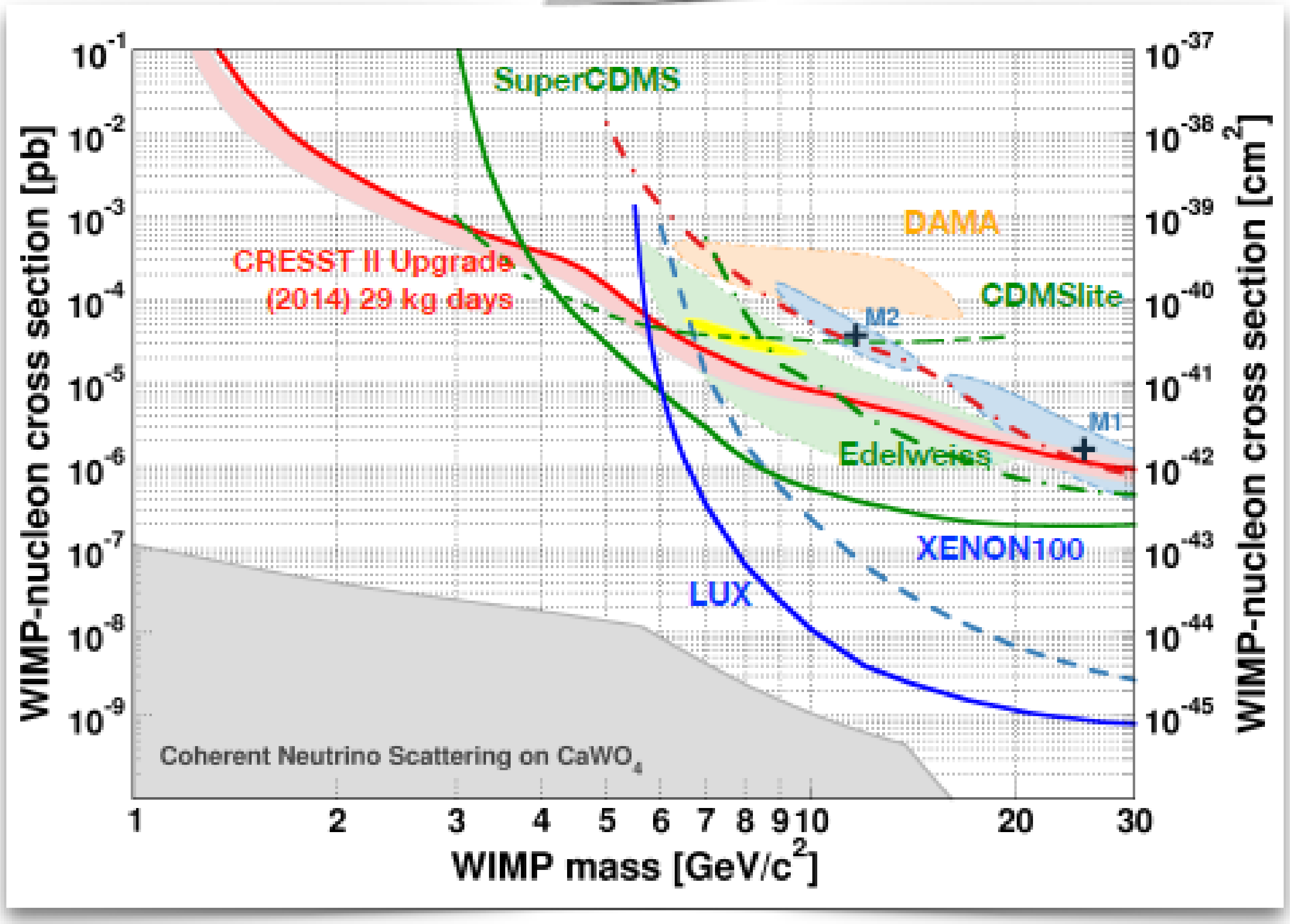
Null Result or Exclusion Limit:

Experiments	Target	Threshold	Total Exposure	Recoil Identification	Modulation
CDMS-II	Ge/Si	10.0 keV	612 kg-days	NR	
CDMS-II (LE)	Ge	2.0 keV_{NR}	241 kg-days	(NR+reducedEM)	
EDELWEISS	Ge	20.0 keV	384 kg-days	NR	
XENON100	Xe	8.4 keV_{NR}	1471 kg-days	NR	
XENON10 (LE)	Xe	1.4 keV_{NR}	15 kg-days	(NR+reducedEM)	
PICASSO	F	10-20 keV	40 kg-days	NR	
PICO-2L	F	3.2 keV	211 kg-days	NR	
KIMS	CsI (Tl)	3 keV	37000 kg-days	NR + EM	
CRESST-II	$CaWO_4$	0.6 keV	29 kg-days	NR + EM	

Direct Detection: Current Experimental Scenario

Search for Dark Matter with CRESST II Phase 2

Eur.Phys.J. C74 (2014) 12, 3184
arxiv 1407.3146

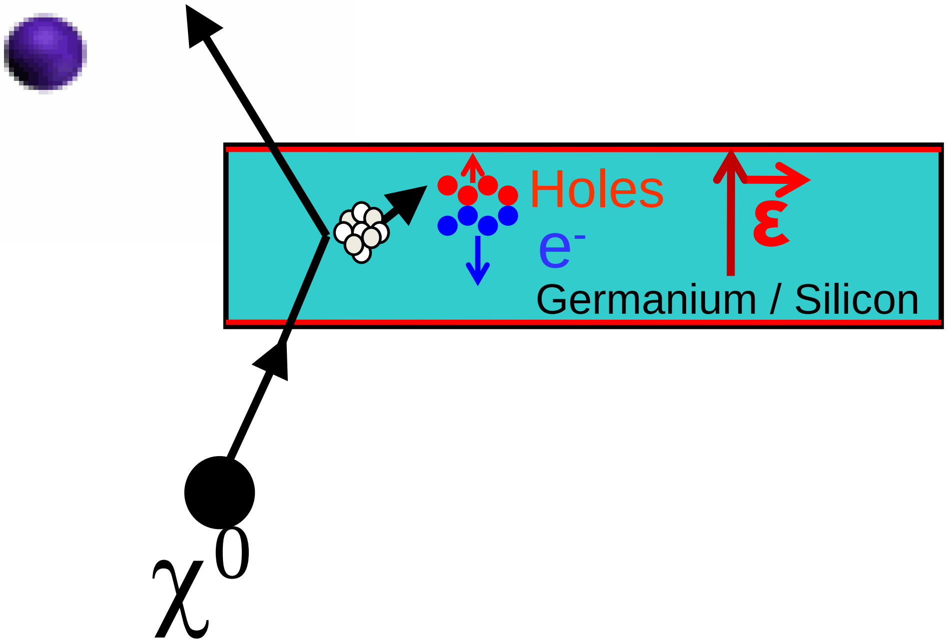


Cryogenic Dark Matter Search (CDMS)

Goal: Directly detect recoil of WIMPs with a Terrestial detector, as Earth ploughs through the cloud of WIMPs in galactic halo

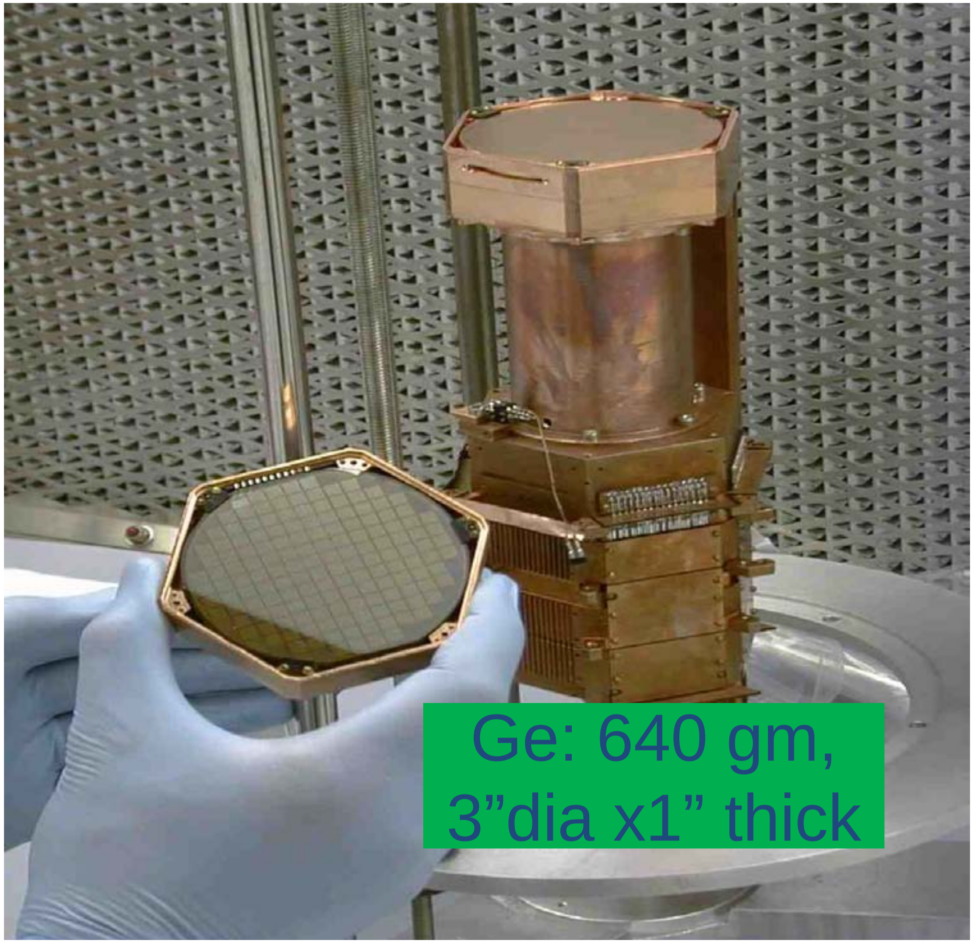
Challenges: 1) WIMPs interact very weakly $\Rightarrow$ Very low signal rates

2) Surrounded by cosmic & radioactivity $\Rightarrow$ Huge background rates



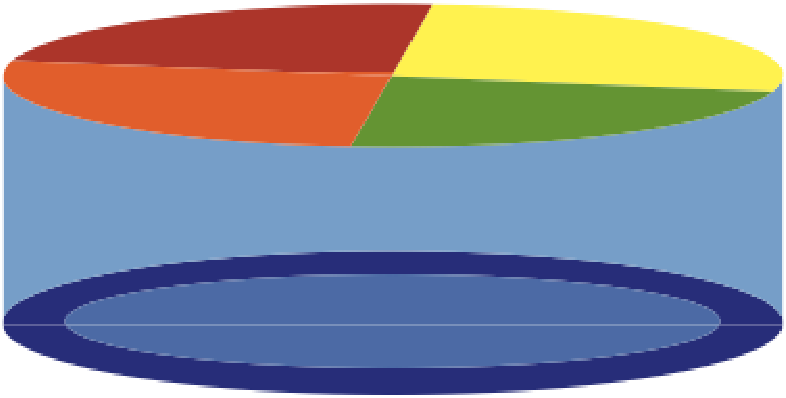
What rate? (in, say, 1kg)
Backgrounds? Gamma rays, neutrons, surface beta-decay,…

ZIP Detectors



(Z-sensitive Ionization and Phonon)

Phonon side: 4 quadrants of athermal phonon sensors
Energy & Position (Timing)



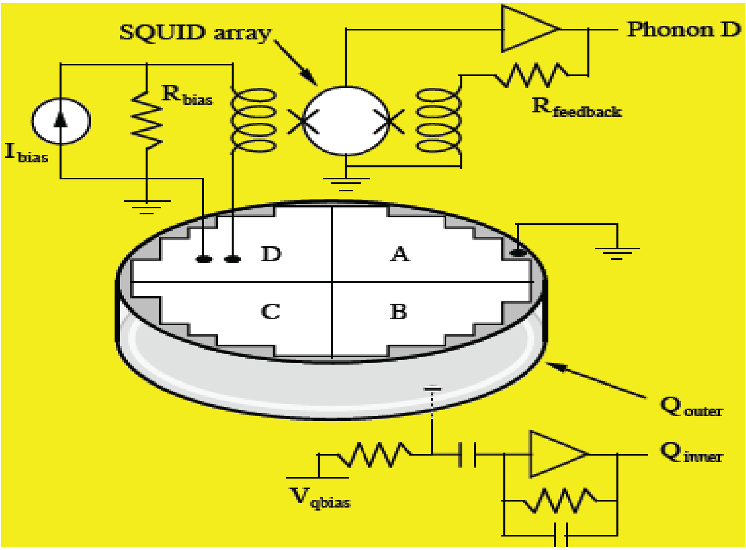
Charge side: 2 concentric electrodes (Inner & Outer)
Energy (& Veto)

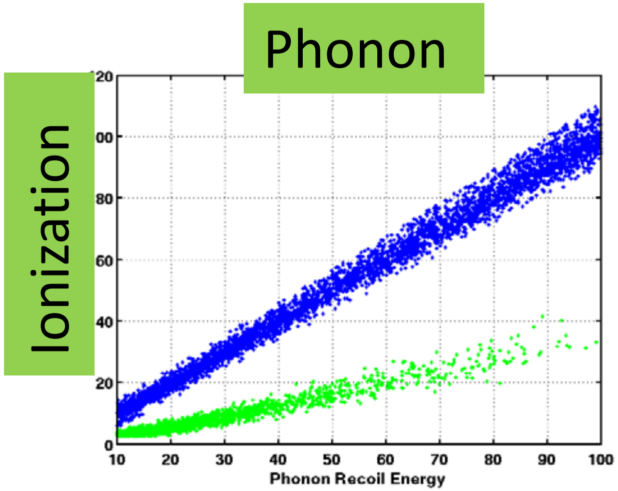
Operated at ~40 mK for good phonon signal-to-noise

Courtesy : CDMS collaboratioon

CDMS

Cryogenically cooled Ge **detectors with photo lithographically patterned sensors for low threshold (~keV), high energy resolution (~.2keV) and good 3-D position resolution (<~mm)**

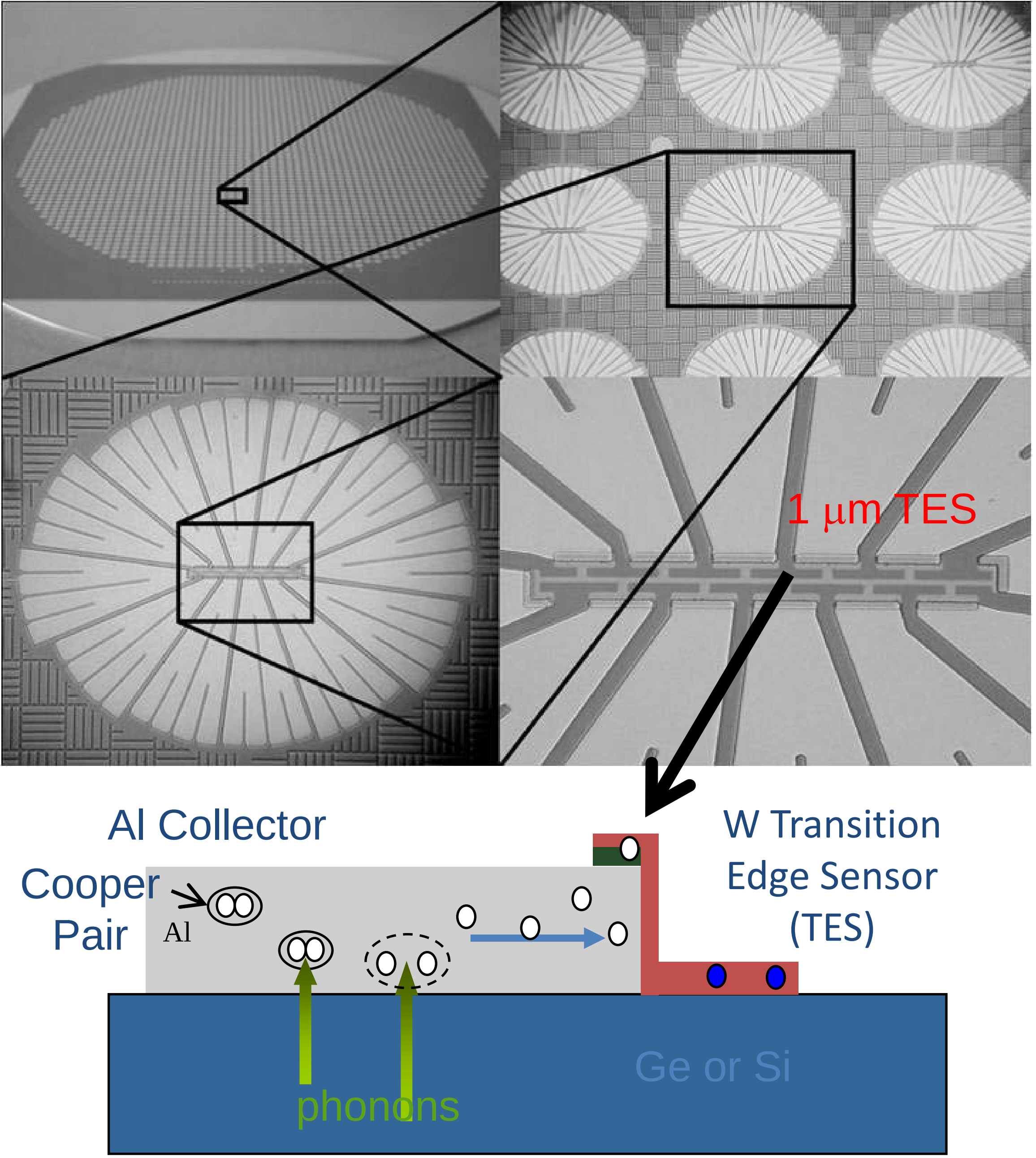




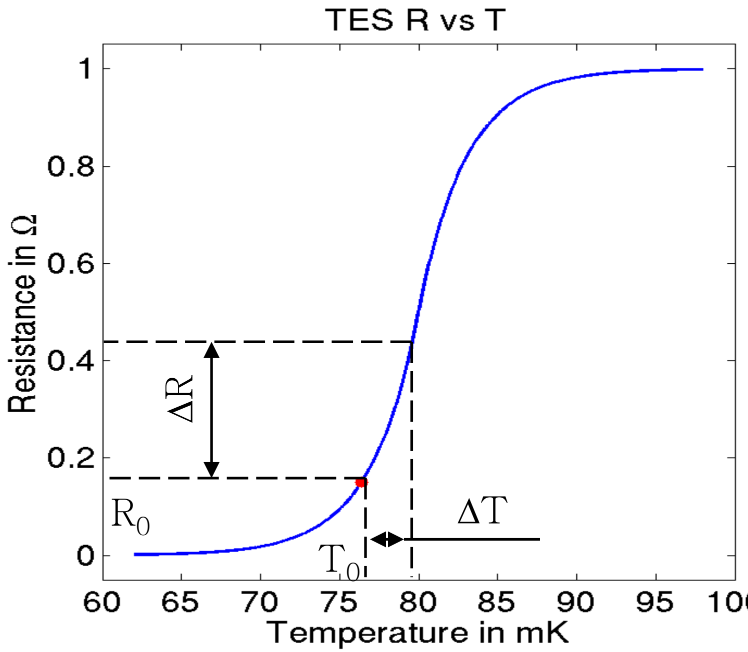
X-Y-Z Position from Phonon Pulse Timing

Courtesy : CDMS collaboratioon

Phonon Sensors



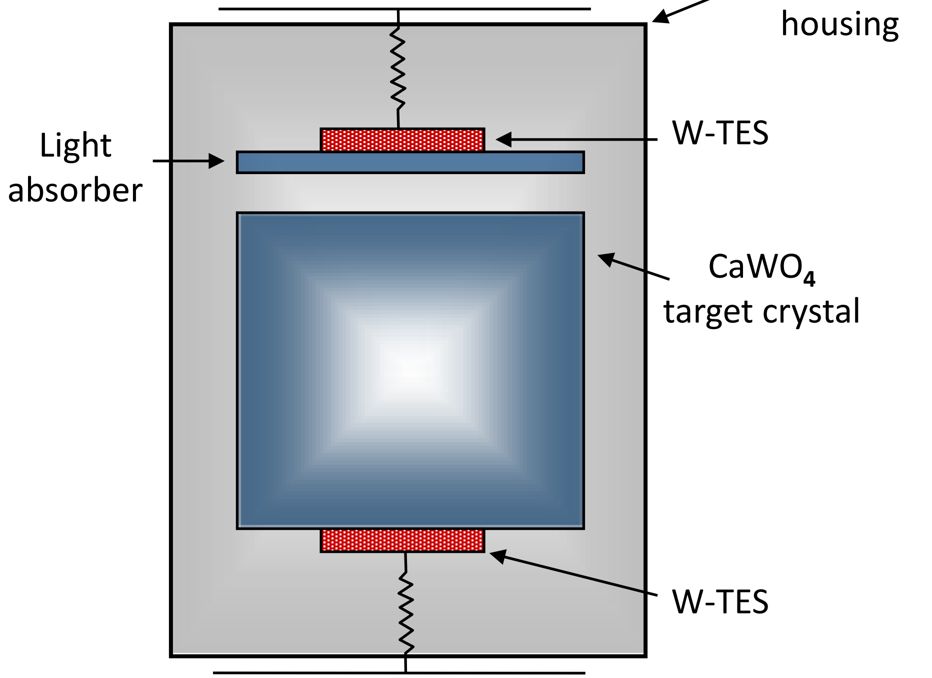
Phonons are collected by Al fins, creating quasi particles that are then trapped by the W TES

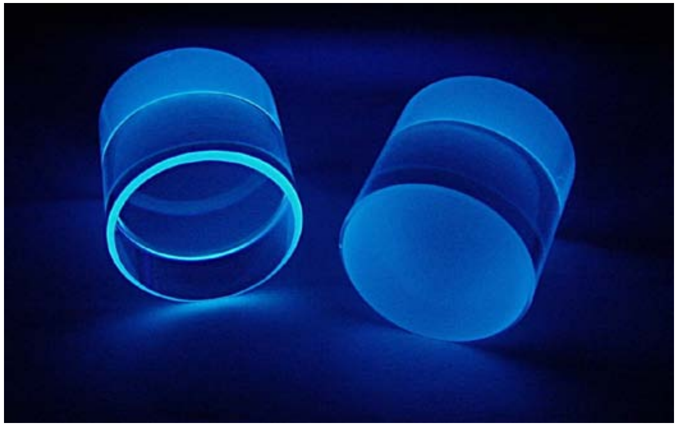


Courtesy : CDMS collaboratioon

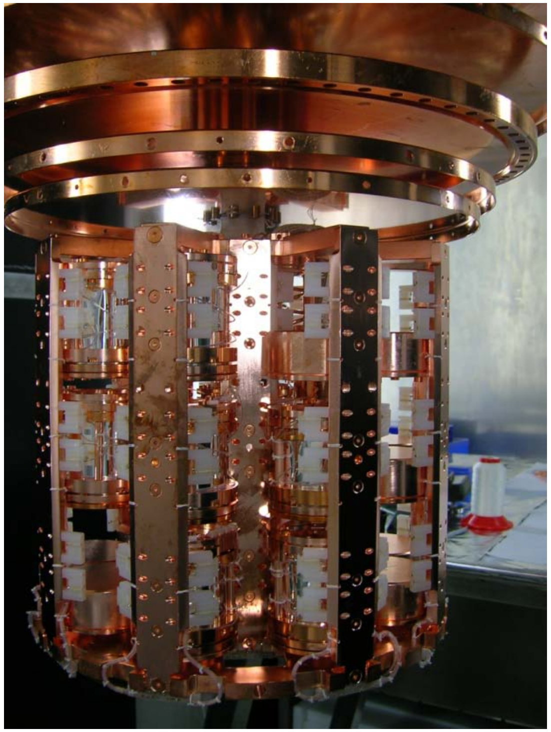
CRESST (Cryogenic Rare Event Search with Superconducting Thermometers) Experiment

- Scintillating target crystals
- Modular structure
- Multi-target possible





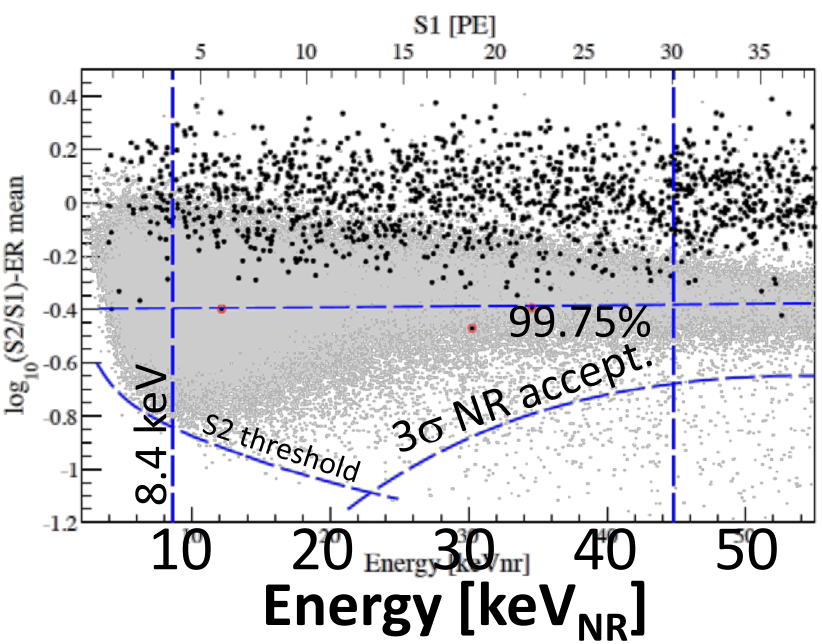
$CaWO_4$
h=40mm
Ø=40mm
m=300g

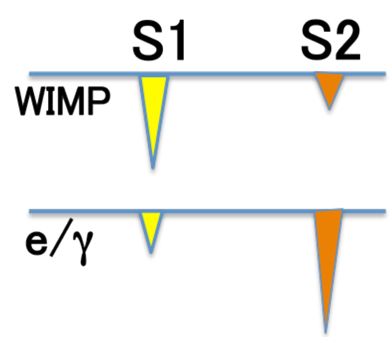


From CRESST Collaboration presentation (2010)

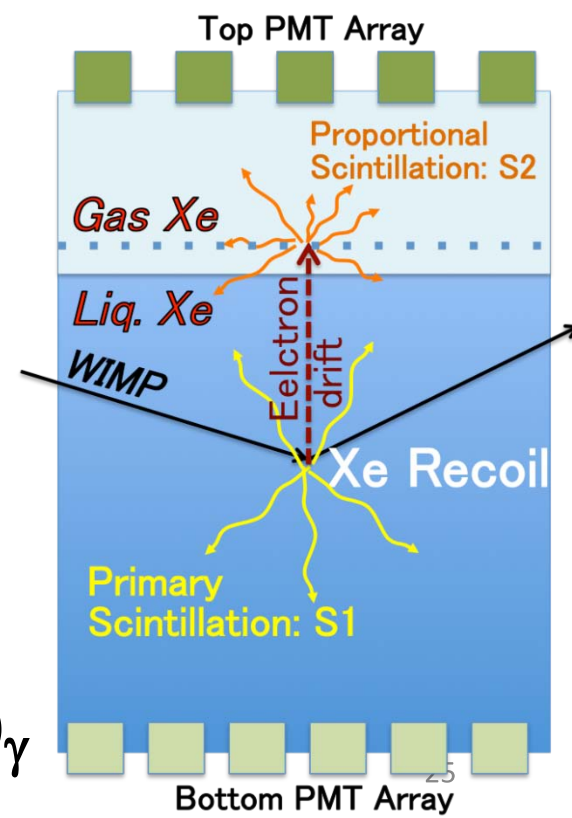
XENON-100 2 phase liquid Xenon detector

- Simultaneous detection of light (S1) and charge (as S2)
  - Ionization e's → S2 (prop. Scinti.)
- S2/S1 →NR and EM discri: ~1/1000
- 100.9 live days (till June in 2010) w/48 kg fiducial mass (62kg)➔ 1471kg-day
- 3 events remain after S2/S1 selection (99.75% EM rejection)
- Expected BG: 1.8±0.6
  - ^{85}KR: 1.14±0.48
  - Others: 0.56(+0.21/-0.27)

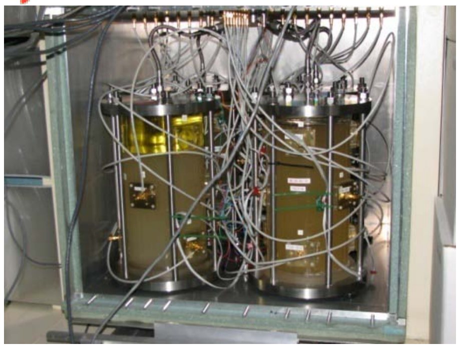




$(S2/S1)_{WIMP} < (S2/S1)_{\gamma}$



PICASSO / PICO experiment



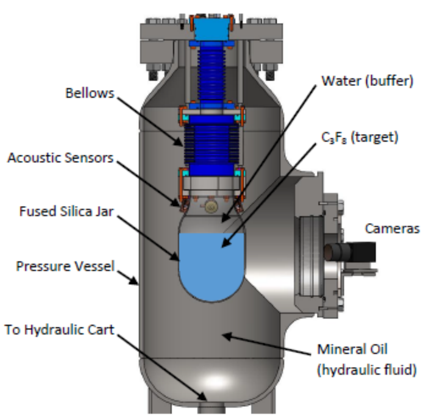
PICASSO: Direct detection of cold dark matter (WIMP like object) candidates in the spin dependent sector.

Principle: Detect nuclear recoils possibly caused by WIMPs.

Technique: Fluorine loaded active liquid C_3F_8 or C_4F_{10} dispersed in the form of 50-200 µm diameter superheated droplets in a polymerized gel medium.

Synergy with developmental activities at SINP: Superheated drop detector using acquasonic gel.

PICO



PICO:

Limitations of PICASSO: 2-4% loading of the active materials in ploymerized gel.

Solutions: Use 100% active liquid

How does PICO experiment work?

Target mass of **2.91 kg of C3F8** kept in a superheated state (15.8 C) over-pressurized. Thermodynamic threshold energy 3.30 +/- 0.2(exp) +/- 0.2(th) keV , estimated using the Seitz "hot spike" model.

Bubble position in 3D were obtained by high resolution cameras.

Acoustic pulse generated by bubble explosion is determined by Lead zirconate acoustic transducers.

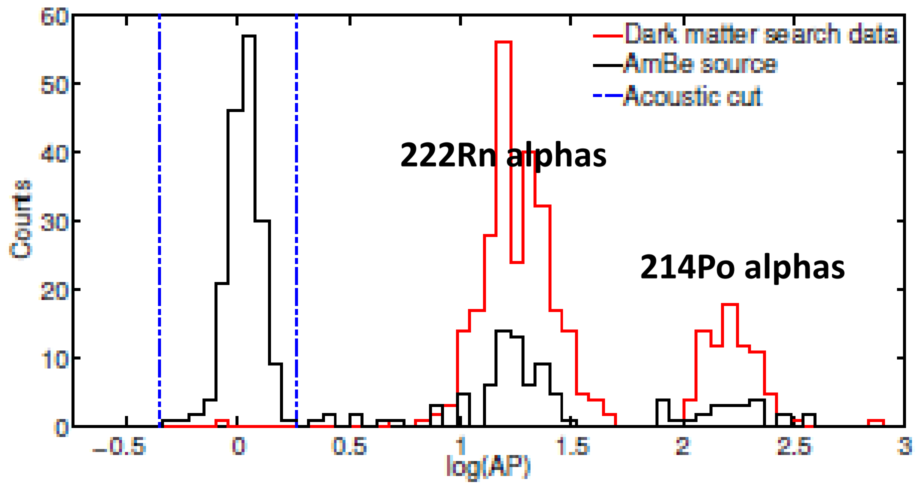
Time information were recorded by multiple transducers for data quality monitoring.

Total 66.3 live days of data collected over 3 months period.

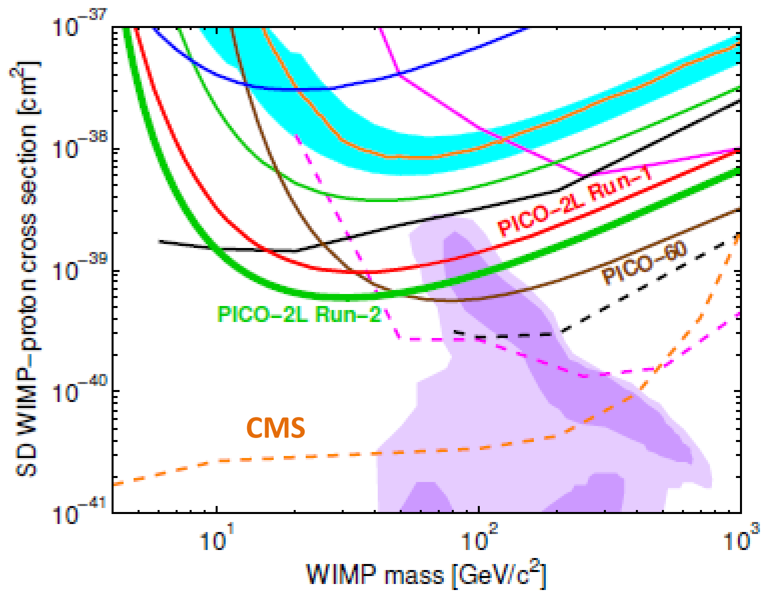
Reconstructed **accoustic parameter (AP)** after applying all cuts (fiducial, timing mismatch, noise) for **211 kg-days** of data.

PICO-2L experiment

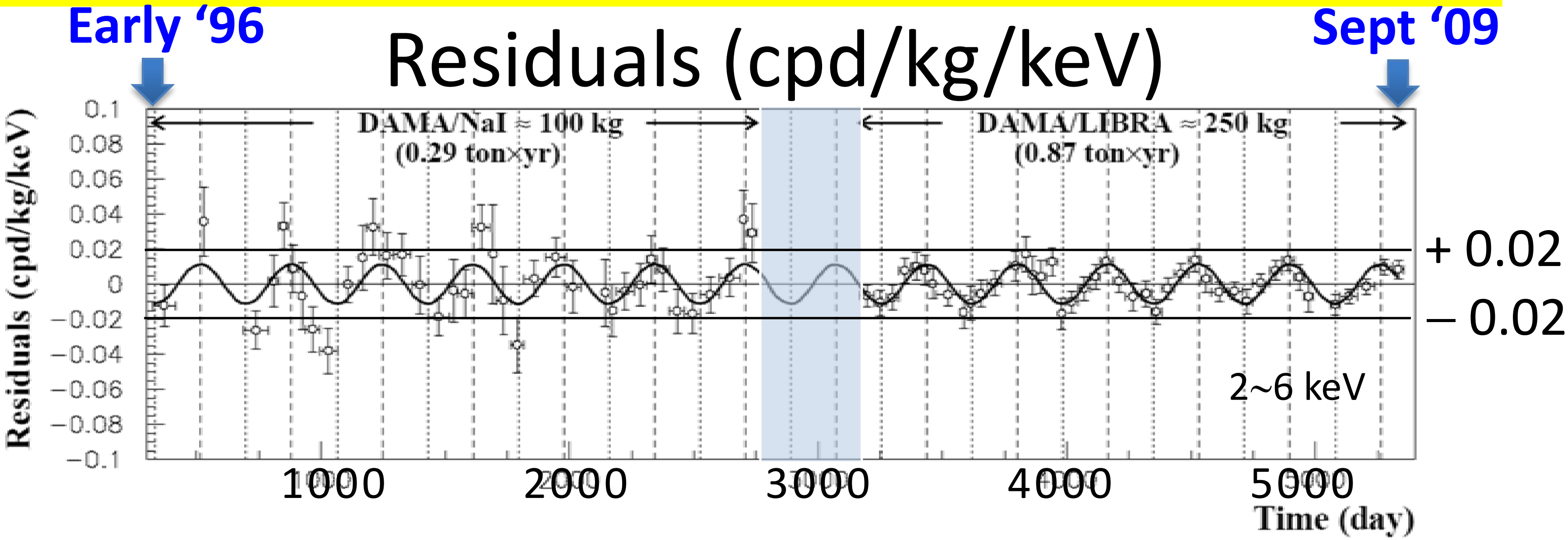
AP Distribution from PICO-2L



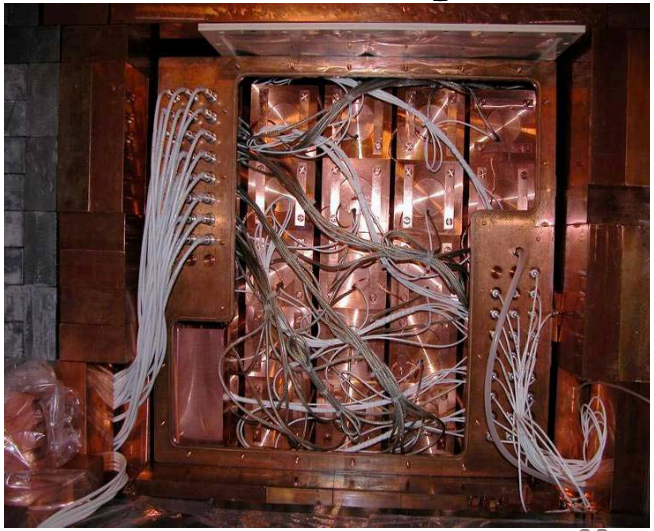
PICO-2L Results
Phys. Rev. Lett. 114, 231302 (2015) / arXiv:1503.00008



DAMA/LIBRA



R.Cerulli@TIPP2011



- DAMA/LIBRA: High purity low BG NaI
  - 250kg NaI(Tl) for DAMA/LIBRA
- Total exposure: 1.17 ton-yr (13 cycles)
  - 427,000 kg-days

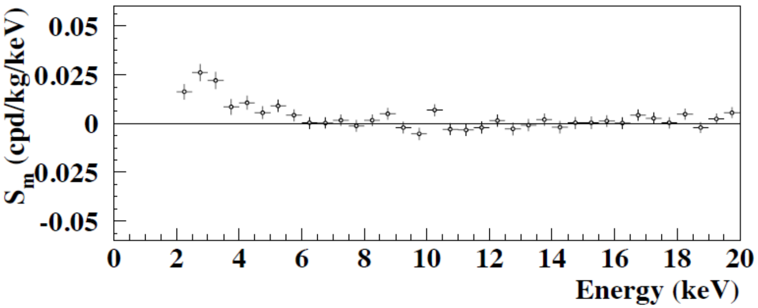
Result ➔ Modulation (**8.9σ**)

- $S_k = S_0 + S_m \cos 2\pi (t - t_0)/T$
- Amplitude(S_m): for 2~6 keV

  0.0116±0.0013 cpd /kg /keV

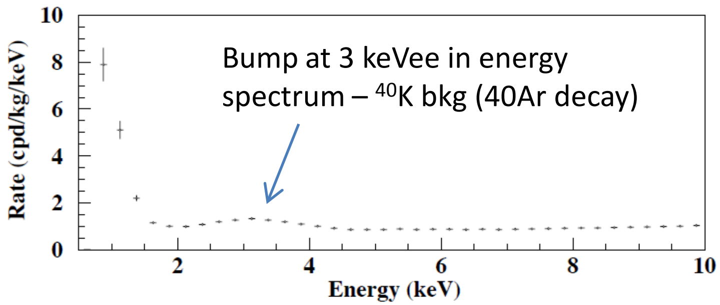
Sodium-iodide with Active Background REjection (SABRE) – An independent test of DAMA / LIBRA (Emily Catherine Shields : Ph D Thesis Princeton 2015)

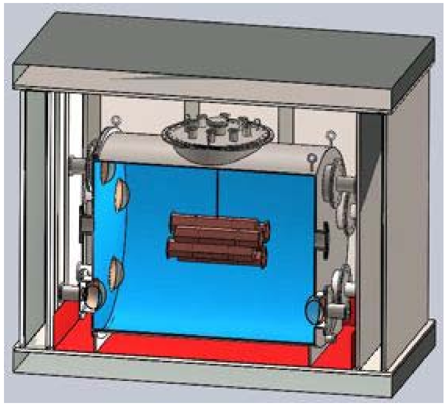
- Published data from DAMA/LIBRA raises some questions about the energy spectrum and modulation that have not been fully addressed by DAMA.
- DAMA results are in conflict with the null results of other DM experiments (eg. XENON100) when compared in a model dependent way.
- Some impurities are difficult to get rid of in NaI (^{40}K, ^{87}Rb, ^{210}Pb, ^{210}Po)
- Cosmogenically active ^{60}Co, ^{125}I background can also be serious issue.
- Sheer significance of DAMA modulation results cannot be ruled out. Independent check of results is essential.



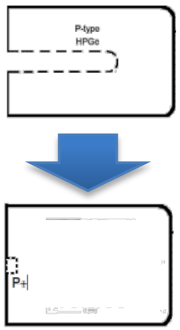
SABRE salient points:

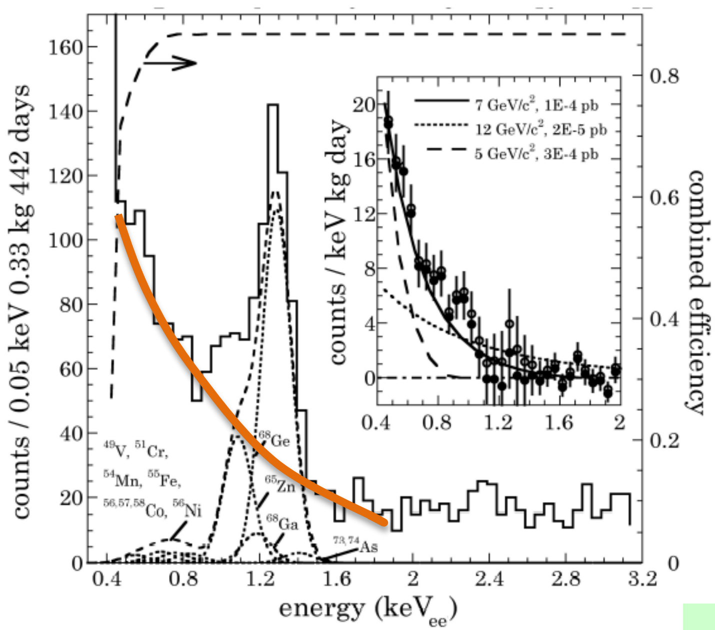
- Achieving radio-purity as high as that for DAMA, or better. ^{nat}K concentration reduced from 300 ppb to 3.5 ppb.
- Use liquid scintillator based active veto detector.
- Detailed simulation and understanding the background.
- Quenching factor measurements for the nuclear recoils.
- Pulse shape discrimination to be incorporated.

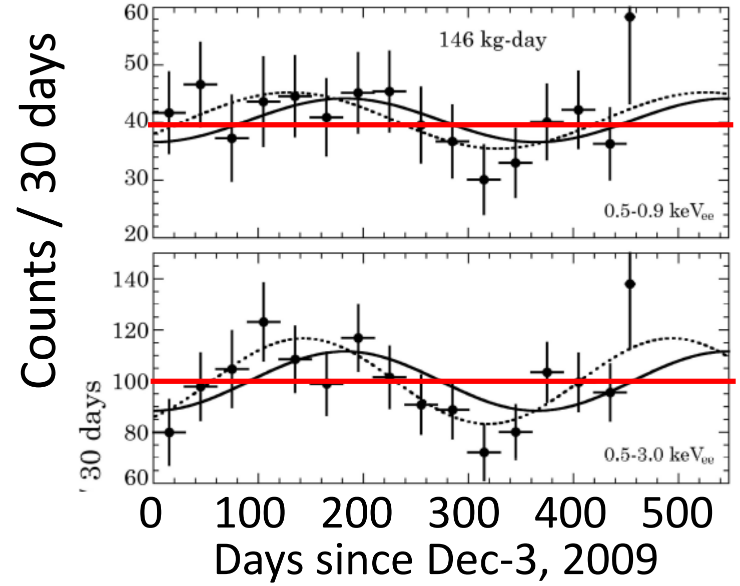




CoGeNT
Coherent Germanium Neutrino Telescope







- <u>P-type Point Contact (PPC)</u> germanium detectors: 440g
  - High resolution (low C)
- Threshold ~ 0.4 keVee (lowest)
- <u>But no Nuclear Recoil separation</u>
- <u>BG: Reject surface events</u>

➔ **irreducible excess below 3 keV**

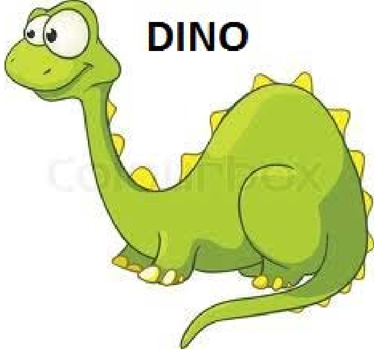
- 442 effective days, assuming all the unknown excess is 'signal'

➔ **Modulation (0.5 – 3.0 keVee)**:

  - 2.8 σ
  - Amplitude: 16.6±3.8%
  - Minimum: Oct 16±12 d

➔ Need more data

Dark matter search at INO (DINO): A proposed dark matter search experiment in India



Proposed in 2 phases: miniDINO and DINO

MiniDINO: Scintillator for DM search R & D for prototype experiment at UCIL mine with ~ 1 kg active mass

- Phase I: room temp.
- Phase II: Cryogenic expt.

DINO: Approx 10 kg to Ton Scale experiment at INO cavern

Collaboration (MiniDINO): SINP, UCIL, BARC, NISER, …

miniDINO & DINO Experiment: Challenges ahead

- Detector material and fabrication: surface lab based prototyping

  Scintillators: **CsI(Tl) / CsI** **GGAG(Ce) / GGAG** **Tungstates**

  Read-outs: Scintillation signals (PMT, Si-PMT, Si photodiode)

  Phonon signals (by Si / Ge based cryogenic phonon sensors)

- Cryogenics:

  Dilution refrigerator to cool detector stack ~ 10 mK.

  Cryogen-free 4 K refrigerator (suggested alternative for mini-DINO)

- Shielding against background radiation (simulation, passive & active shielding):

  Cosmogenic background (muons, neutrons)

  Radiogenic background (alphas, neutrons)

  Gamma rays, surface beta particles

- Site choice and preparation for experiment:

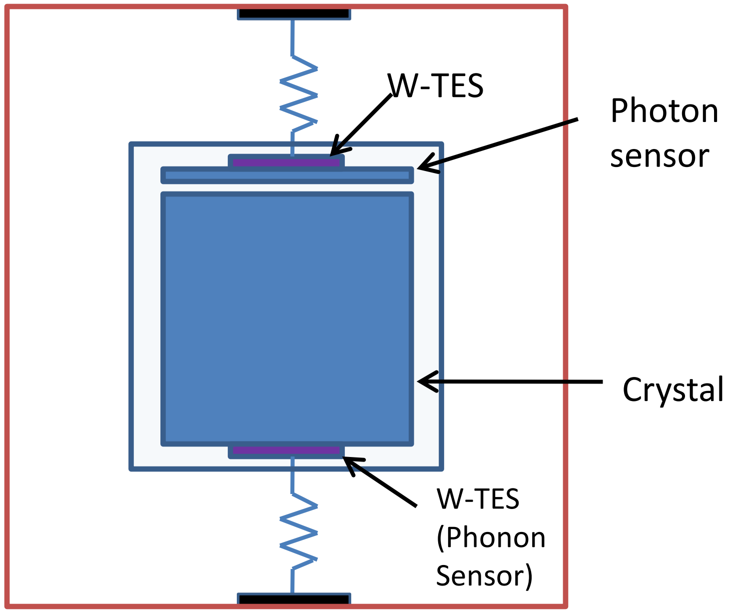
  UCIL, JADUGUDA (UNDERGROUND LAB) INO CAVERN

Scintillator based DM search

- Sensitivity to heavy WIMPs (W / Cs / I / Gd) ($\sigma_{coh} \sim A^2$) as well as to light WIMPs (Zn / Al / O).
- Increase in Light Yield at low temperature [CsI, GGAG(?)]
- Increase in decay time of principal comp. and emergence of long decay time comp at low temp.
- PSD for discrimination of response to

  (1) alpha and gamma, (2) neutron and gamma
- Passive and active shielding to reduce radiation background (Cu, Pb, Poly, Pb and Plastic scintillators)
- Relatively lower radioactivity background in $ZnWO_4$ (compared to $CaWO_4$[CRESST II], $CdWO_4$)
- Phonon and photon detection using SQUID / W-TES technology.
- Exploration of neutron response at low temperature operation using SQUID / TES, discrimination of electron / photon signals from neutron signals.

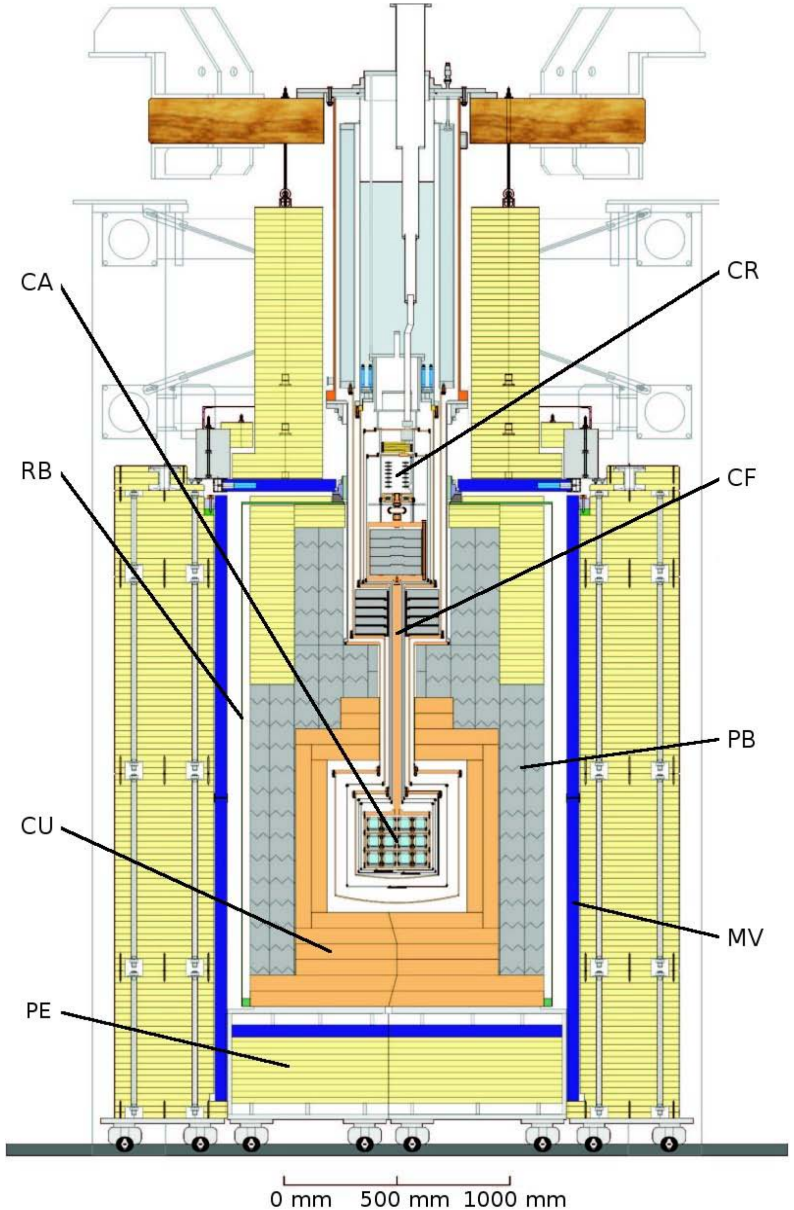
Detection schematic



Reducing Cosmogenic and Radiogenic Background

Typical for any dark matter experiment

- Detectors (~ 10 kg) carousel on a long cold finger
- Gas tight box
- Cu, Pb, PE shielding layers
- Surround detectors with active muon veto



- Use passive shielding to reduce γ / neutrons
- Lead and Copper for photons
- Polyethylene for low-energy neutrons
- Consider active veto for neutrons

Courtesy: CRESST Collaboration, arXiv:0809.1829v2 (2009)

Detector Materials and Detection Systems

Choice of active element: Scintillators

WIMP detection method: Response to low energy nuclear recoil (Erec ~ 1 – 200 keV)

Detection strategy: Scintillation photons and phonons at low temperature (cryogenics)
Pulse shape discrimination between electron / ionization and nuclear / phonon events

Desirable properties: High light output, Low temperature operation, Low intrinsic radioactivity background
CsI (Tl) / CsI / GGAG:Ce / GGAG / $ZnWO_4$ [Crystal Technology Section, TPD, BARC]

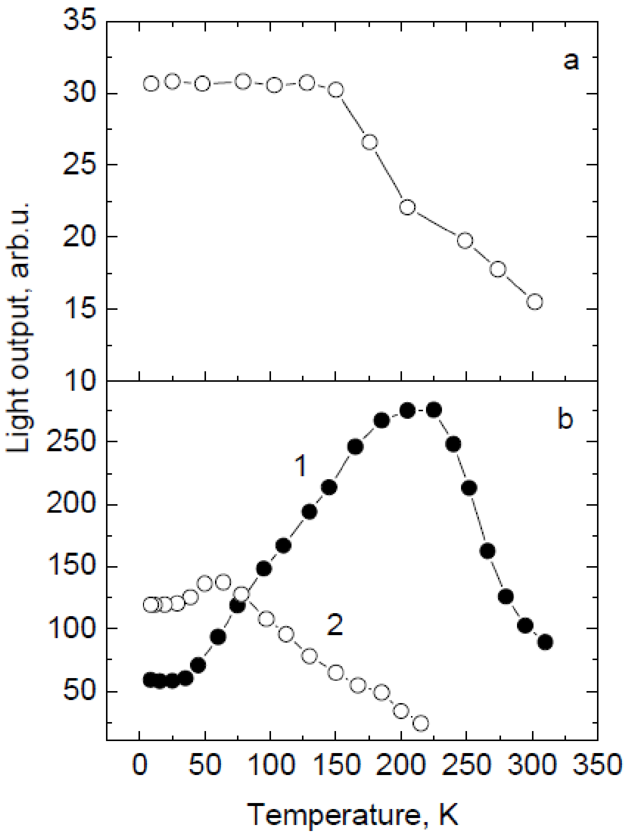
Shielding (passive): Cu (low energy X-rays), Pb (gamma rays), Polypropylene / Borated Plastic (neutrons)
Shielding (active): Plastic scintillators (muon veto)
Monitors: Neutrons, Cosmics, radioactivity background (Ra / Rn progeny, Thorium daughters)

Simulations: On different aspects of the experiment:
Physics Detector Shielding Background

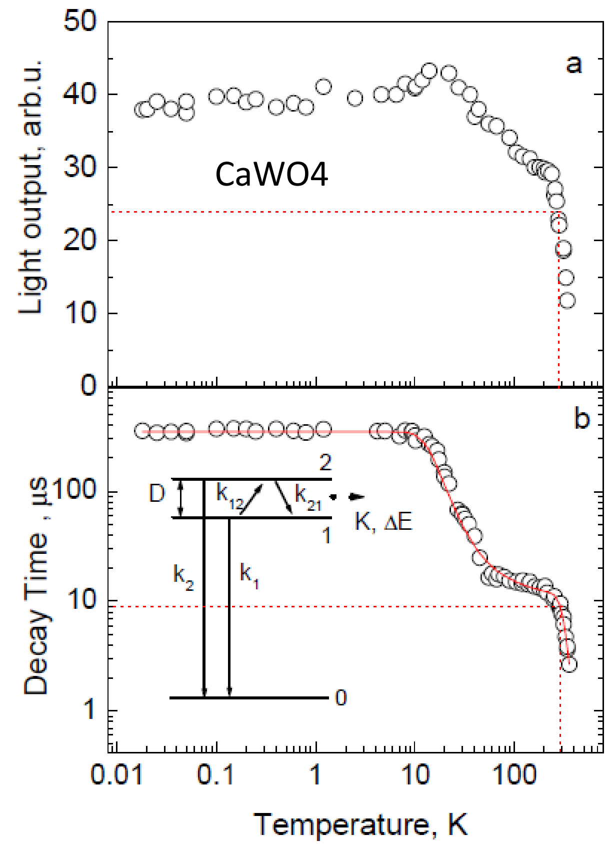
Choice of scintillators

- WIMPs related Recoil spectra
- Light output and its temperature dependence
- Neutron (radiogenic and cosmogenic) response
- Strategy for WIMPs and neutron discrimination
- Phonon response and discrimination strategy

Temperature dependence of light output from scintillators
Effect of doping / activator (General observations)

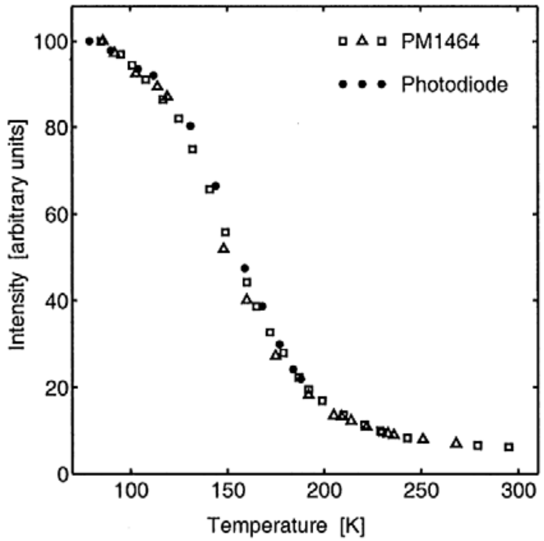


a. For Al2O3:Ti
b1. ZnSe:Te
b2: Intrinsic ZnSe

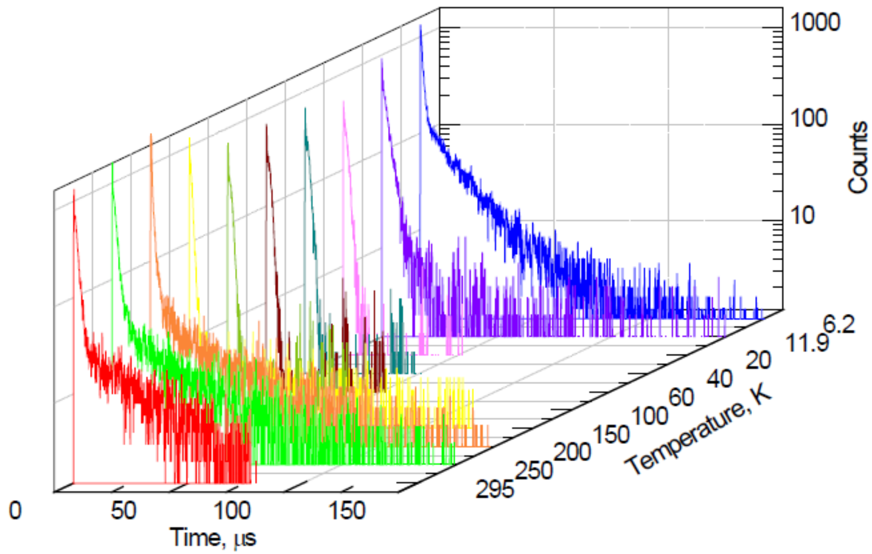


Ref: V B Mikhalik and H Krauss Univ of Oxford, UK

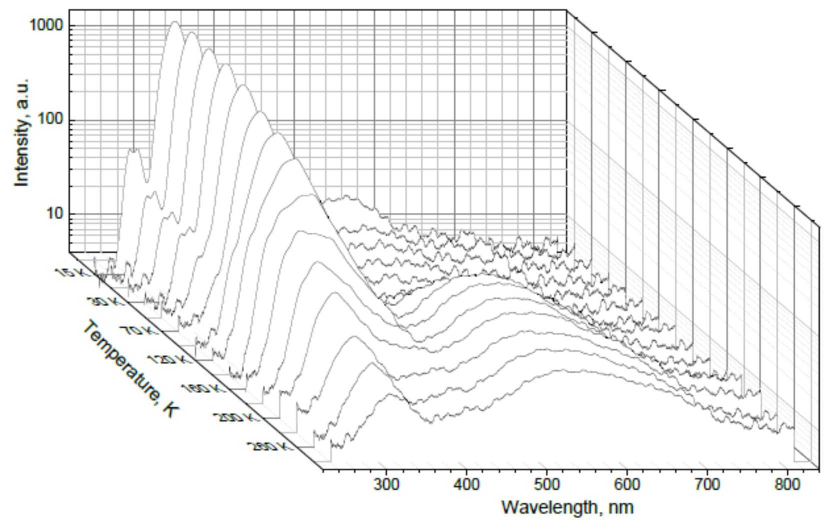
Temperature dependence of light output and scintillation decay time for CsI



Ref: C Amsler et al, NIM A 480 (2002) 494.



Isometric plot of decay curves of CsI for alpha particles from 241Am

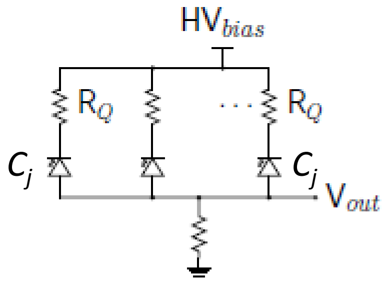


X ray luminescence spectra of CsI at different temperatures.

Ref: V B Mikhalik and H Krauss Univ of Oxford, UK

R & D on photon readout - Silicon Photomultiplier in Future Cryogenic Dark Matter Search experiments

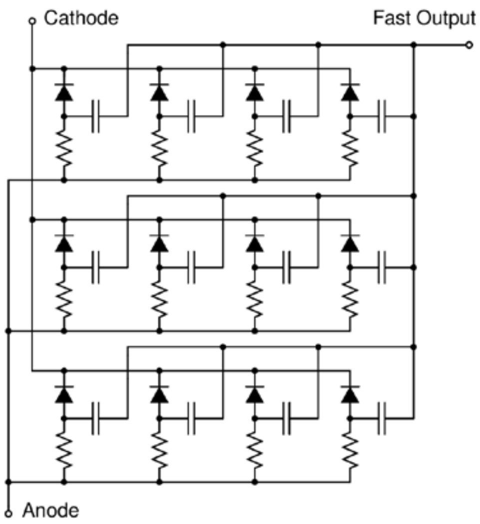
- High quantum efficiency ~ 40 – 60%
- Possible future use in many scintillator based CDM experiment
- Array of Geiger Mode Avalanche photodiode (GM-APD) Large gain (~10^6 carriers / PH)
- Usually cooled down to 0 degC to reduce DCR (Dark count rate)

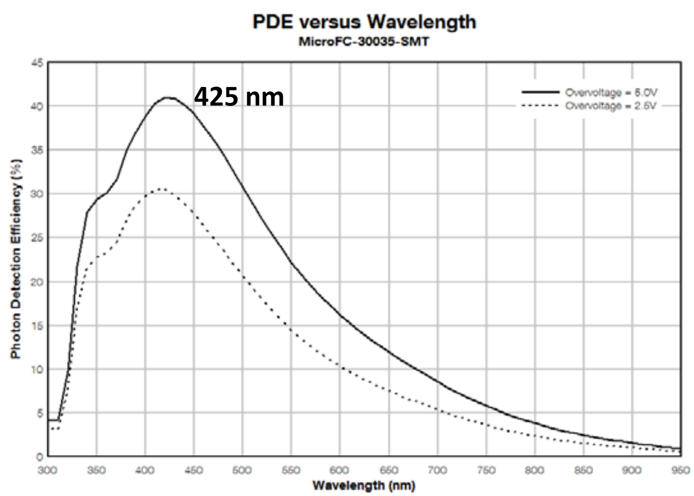


Temperature from 300 K down to 77 K: Effects on related parameters
Quenching Resistors (R_Q) --- x 10 increase (Rise and Fall time)
Junction capacitance ---- factor of 2 decrease
Reverse Breakdown voltage --- quasi-linear decrease in magnitude (~ - 50 mV/K)

Consequence: Increase in Fall time (~ x 5)
Increase in Johnson noise.
Decrease in shot noise (reduced bandwidth)
Noise trade off to be explored.

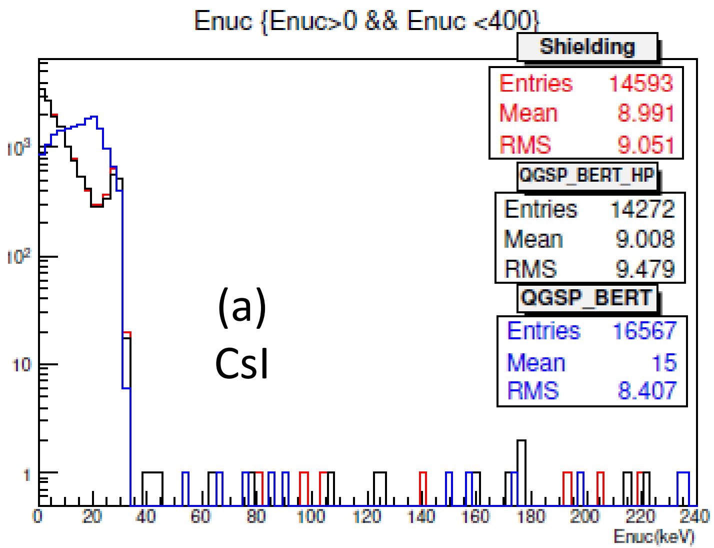
Explore down to 4 K and below.

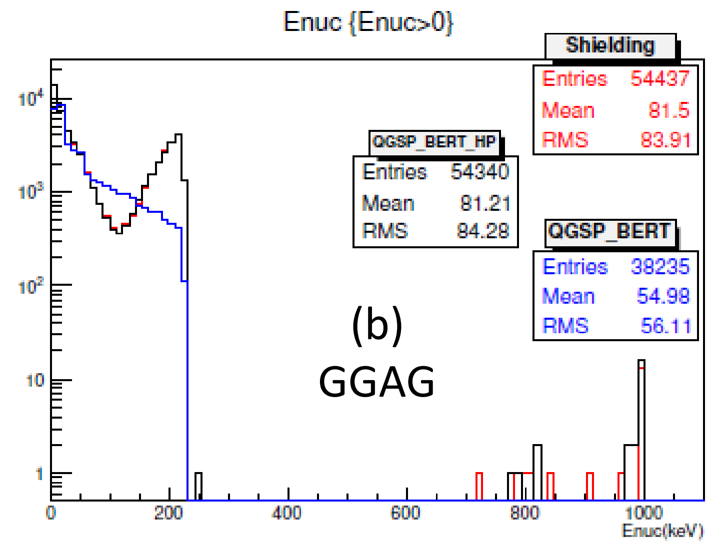




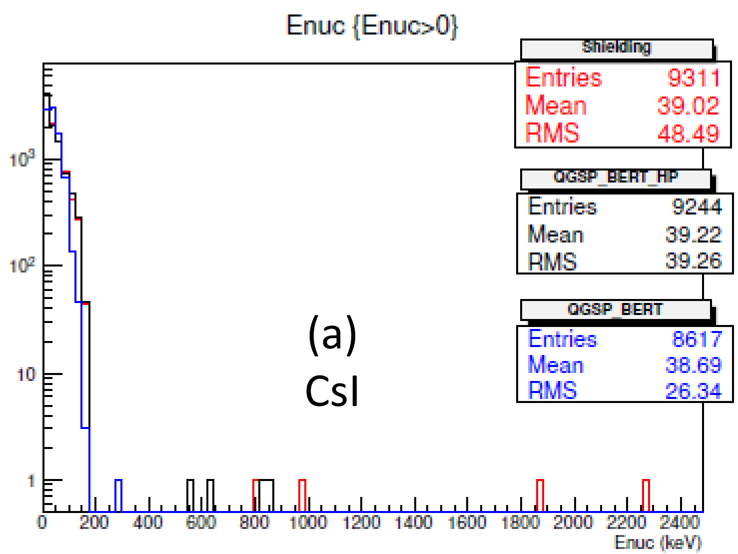
Also R & D on cryogenic phonon sensor

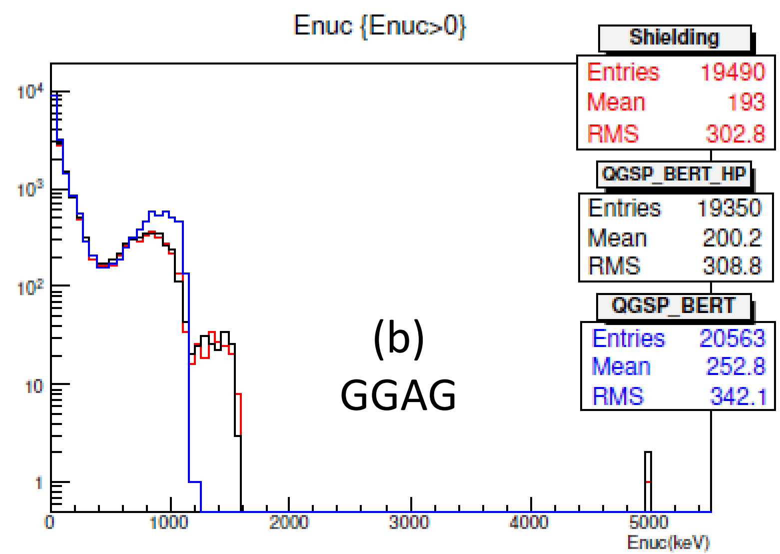
Detector simulation: a few results (WIMPS as neutron event?)





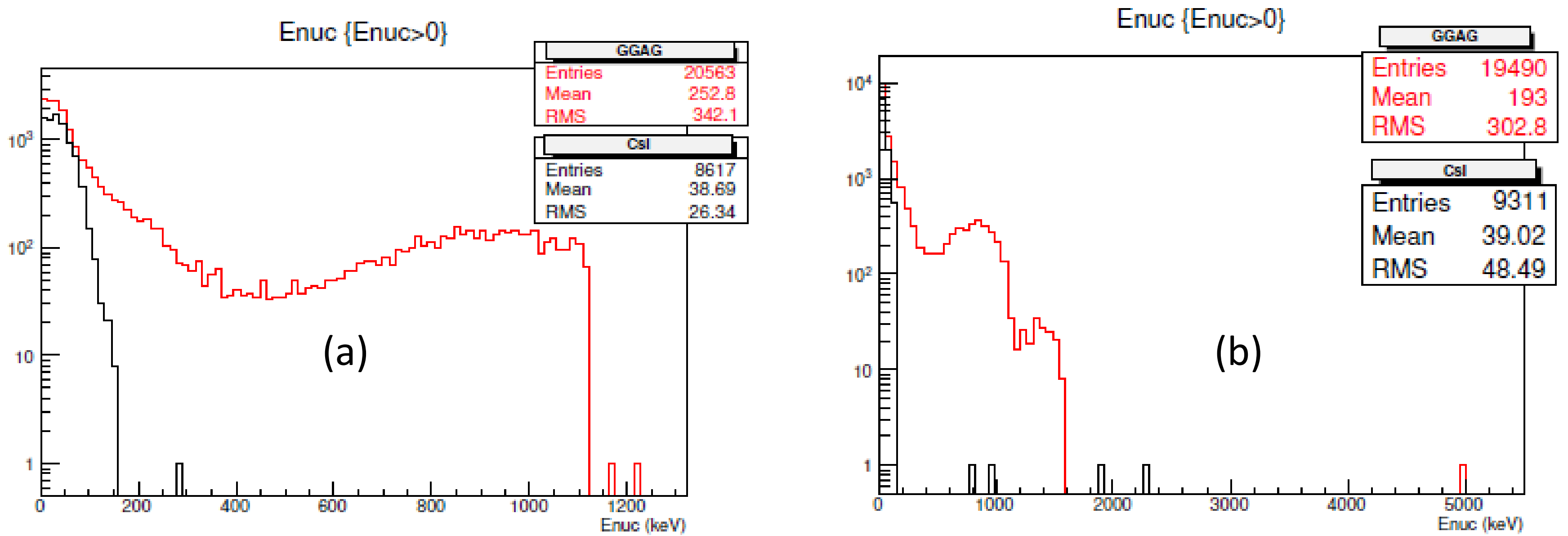
Recoil spectra for 1 MeV neutrons



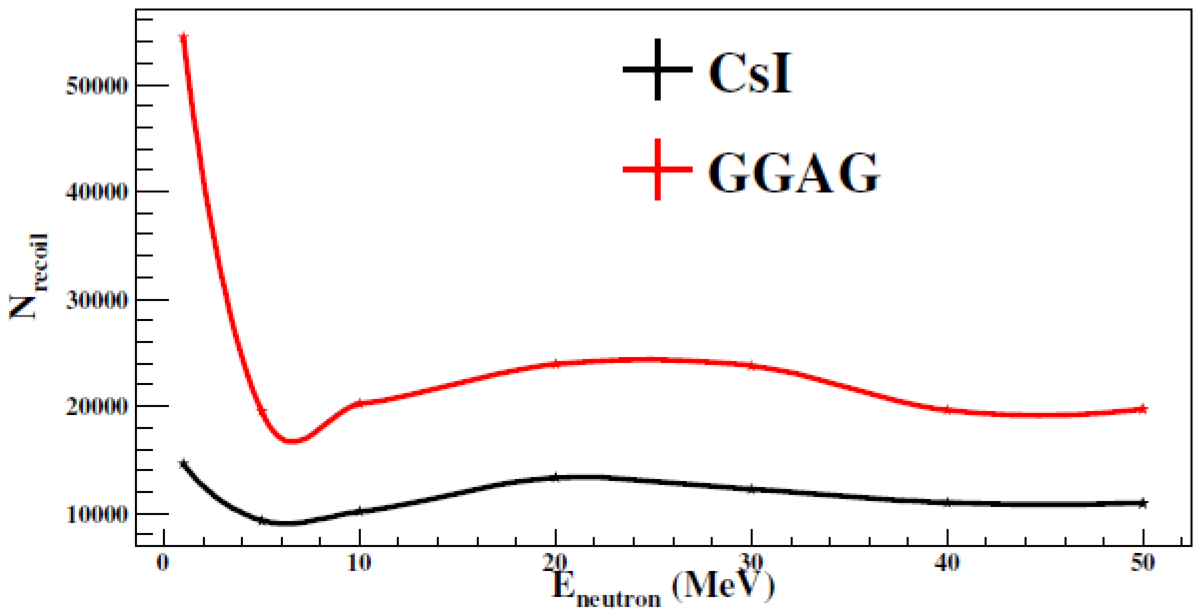


Recoil spectra for 5 MeV neutrons

KK Meghna, DAE-BRNS Symposium (2016)



Recoil spectra with 5 MeV neutrons for: a) QGSP, and b) Shielding physics lists.



JADUGUDA UCIL MINE SITE : SOME BACKGROUND

UCIL operation in Jaduguda (1967):

Jaduguda Mine
Bhatin Mine
Turamdih Mine
Bagjata Mine
Narwapahar Mine
Banduhurang Mine
Jaduguda Mill
Turamdih Mill
Mohuldih Uranium Project (New Project Under Construction)

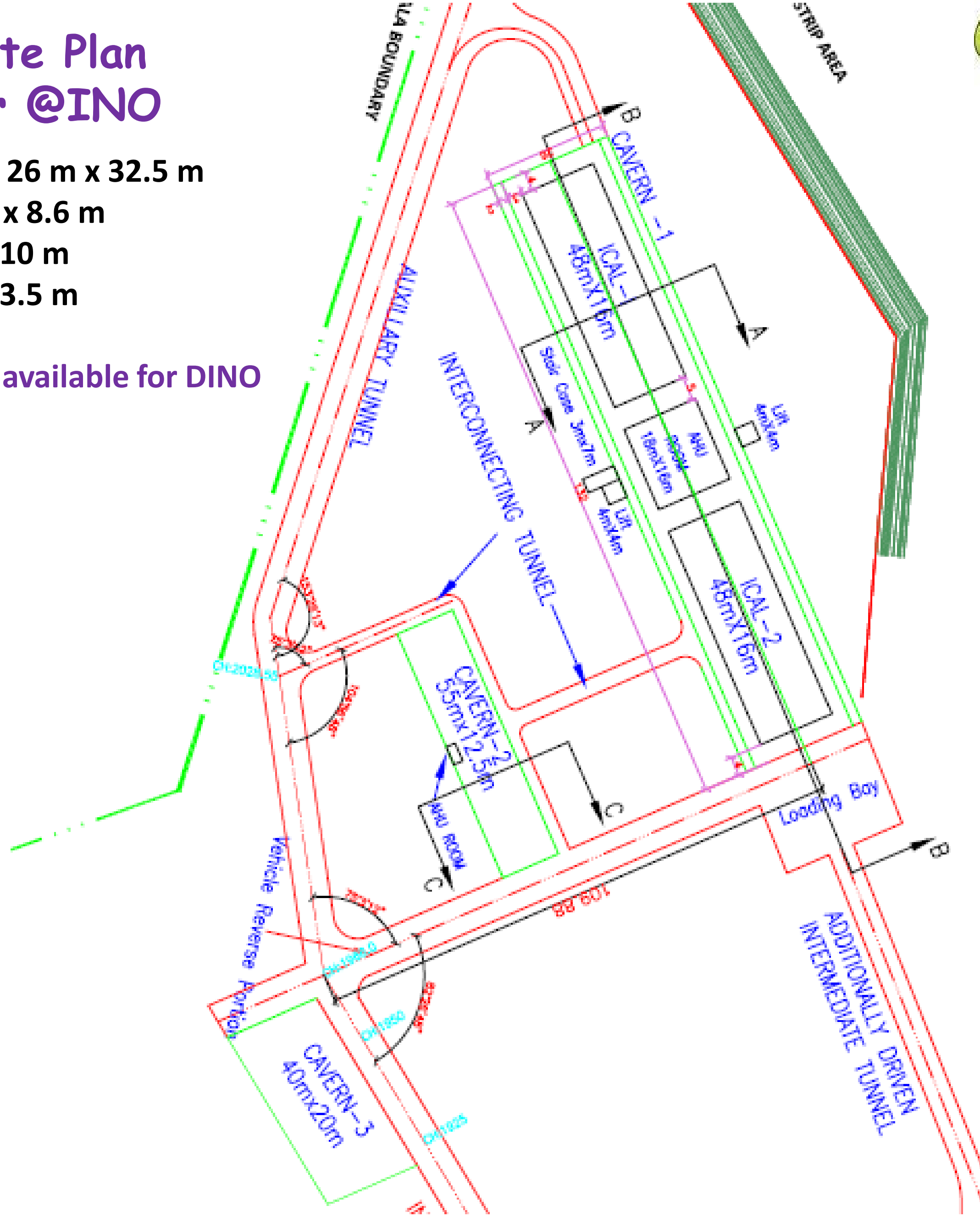
The fact sheet about the Jaduguda mine:

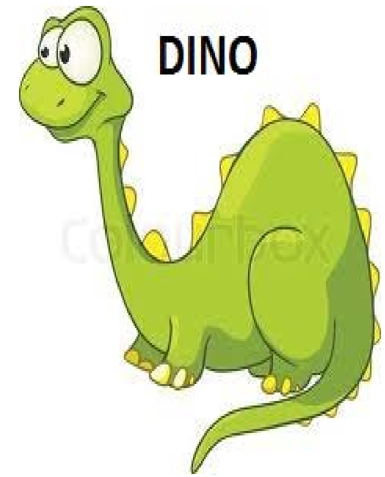
- Distance from Kolkata by rail ~ 231 km
- Nearest rail station: Rakha Mines (~6 km from UCIL site)
- Time taken by express trains from Howrah: 3 hrs a few minutes
- Also connected to Kolkata by road via Kharagpur, Jhargram and Ghatshila (~5-6 hrs by road)
- Major junction rail station in the vicinity: Tatanagar (~20 km to the west)
- Time taken to go to Tatanagar by train: ~ 20 minutes
- Time taken to go to Tatanagar by road: ~ 1 hour
- No. of levels in the mine: 2 (550 m and 880 m depth)

Proposed Site Plan
Dark Matter @INO

Cavern I (ICAL) : 132 m x 26 m x 32.5 m
Cavern 2: 55 m x 12.5 m x 8.6 m
Cavern 3: 40 m x 20 m x 10 m
Cavern 4: 29 m x 15 m x 3.5 m

One of 3 caverns will be available for DINO



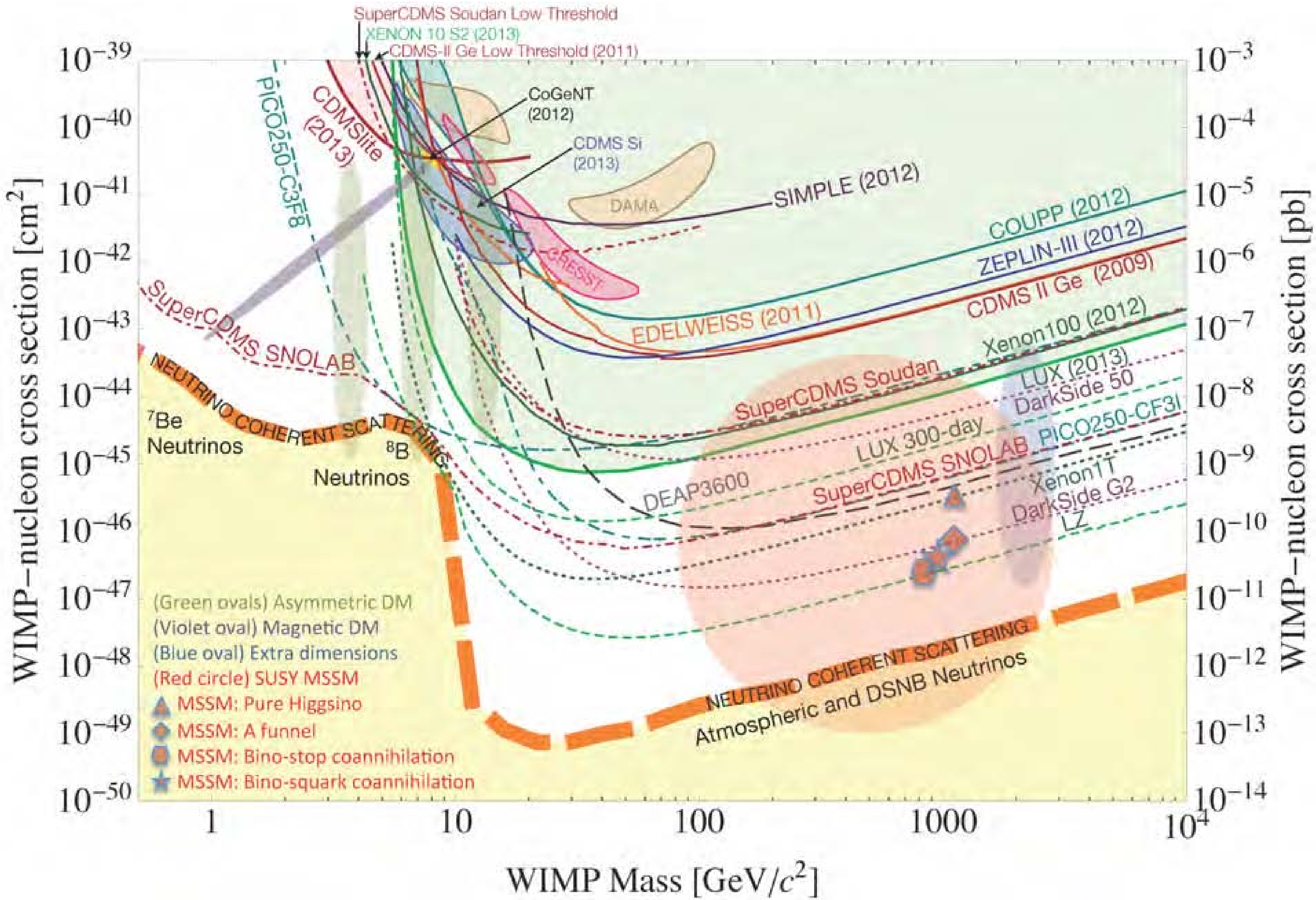


Concluding Remarks / Summary

- DM experiments: direct detection principle
- Site specifics of UCIL mine
- Present status: Design simulation, prototype preparation and tests, radiation background (simulation and monitoring experiments), Lab design and planning
- Tasks ahead:

Detector development	Simulation	Lab infrastructure
Choice of Scintillator(s) crystals and read-outs: CsI(Tl), GGAG (Ce), intrinsics, PMTs, APDs, SiPMs	Expected sensitivity analysis of WIMPs signal: assessment of active mass	Site choice through discussion, evaluation of pros and cons
Choice and validation of materials and read-out devices after radiopurity check	Electron equivalent response of crystals to neutrons, electrons, photons (gamma rays, Xrays)	freezing requirements for lab infrastructure
Preparation of crystals and required processing + development and optimization of electronics and digital DAQ + Explore pulse shape discrimination technique	Simulation of cosmogenic background signal and assessment of active shielding requirement	Civil, electrical, HVAC, networking for surface to mine communication, compressed air, chilled water flow, liquid nitrogen facility, etc
Low temperature dependence of light output, decay time, pulse shape discrimination (up to -30 deg C)	Simulation of radiogenic background and assessment of passive shielding, + strategy for radon mitigation	Preparation of engineering drawings on all aspects
Repeat above down to 77 K and 4 K	Simulation of WIMPs signals and assessment for background-free measurements	Assessment of materials and safety for lab preparation, set up lab infrastructure
Explore Phonon signal at 4 K	Simulation of phonon signals and analysis strategy	Procure and assess lab environments through various sensors, radiation and radon monitors, keep log
Towards millikelvin temp.		Set up experiment + low background counting facility

Review Summary Plot of Dark Matter Search experiments vis a vis theories



From: LUX-Zeplin (LZ) 10 Tonne Xenon TPC Experiment Proposal (2015)