Experimental Techniques for Dark Matter Search Experiments

Satyajit Saha, SINP, Kolkata
RAPID 2021, October 29, 2021

Experimental Techniques for Dark Matter Search Experiments

- Introduction
- Challenges in dark matter search
- Experimental Techniques for Direct DM search
- A few important examples
- Our Initiative: Jaduguda Underground Science Laboratory (JUSL)
- Conclusion and outlook

Satyajit Saha, SINP, Kolkata
RAPID 2021, October 29, 2021

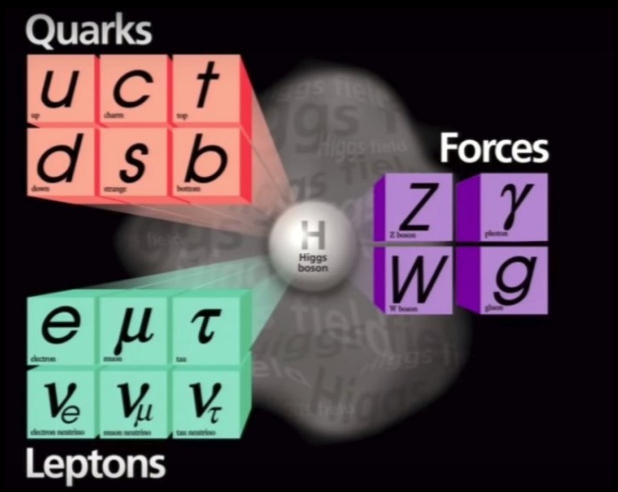
Experimental Techniques for Dark Matter Search Experiments

- **Introduction**
- Challenges in dark matter search
- Experimental Techniques for Direct DM search
- A few important examples
- Our Initiative: Jaduguda Underground Science Laboratory (JUSL)
- Conclusion and outlook

Satyajit Saha, SINP, Kolkata
RAPID 2021, October 29, 2021

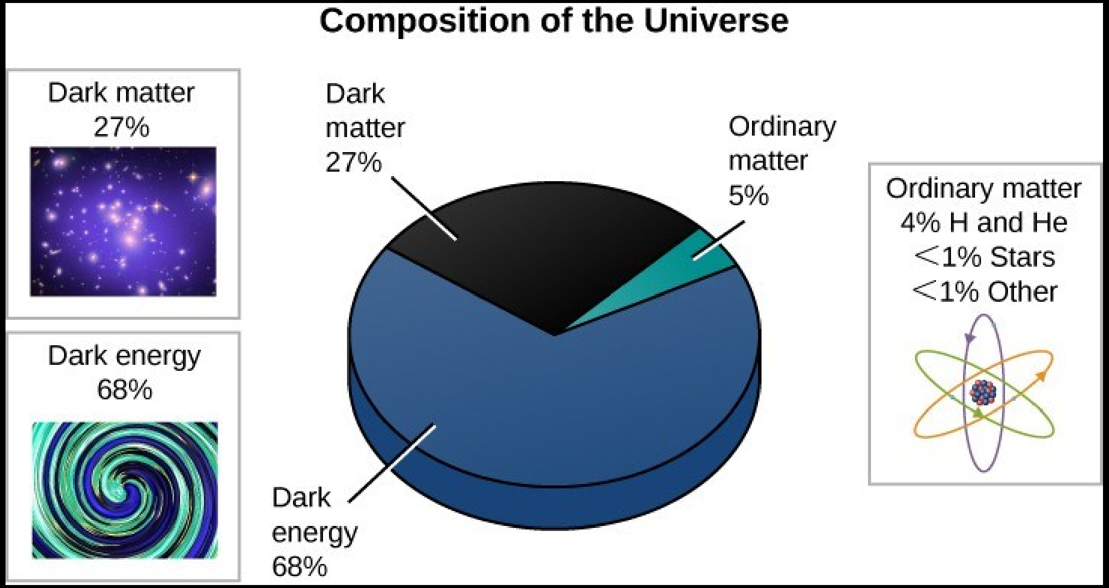
What is our Universe made of?

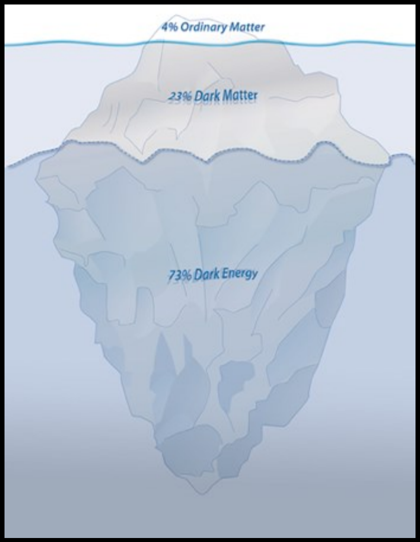
Ask the same to a Particle Physicist today



➕ Beyond Standard Model constituents

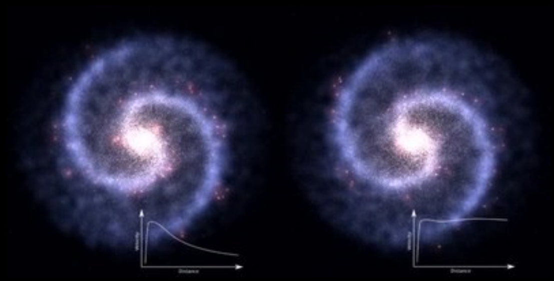
Ask the same to an Astrophysicist today





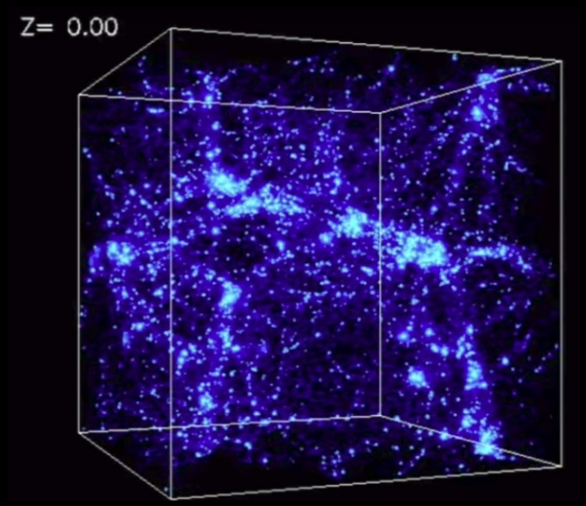
Iceberg illustration

What are the evidences in favour of existence of Dark Matter?

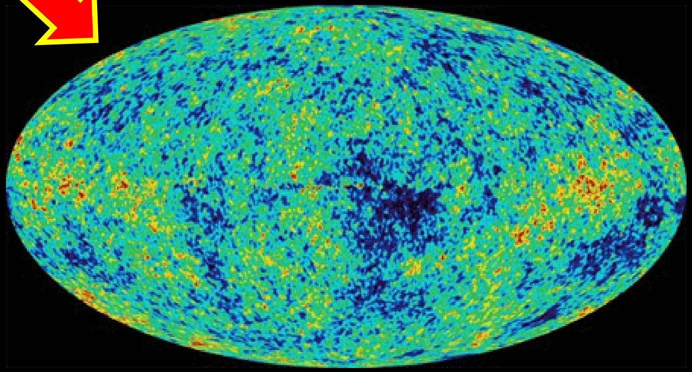


Galaxy Rotation

Motion in Galaxy Cluster

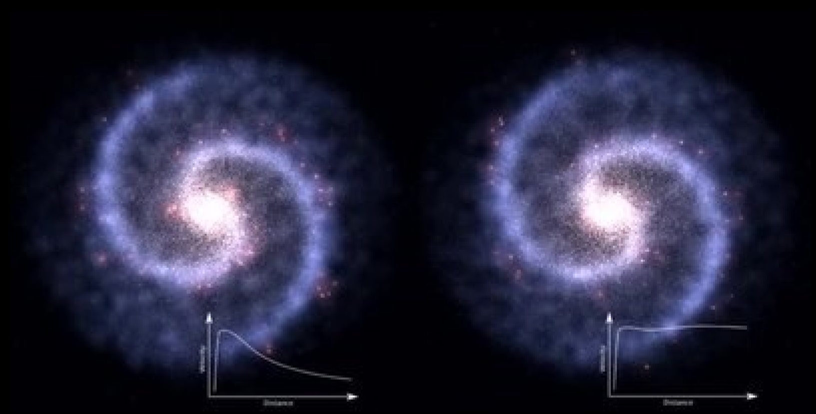


Large Scale Structure formation



Cosmic microwave background anisotropy

Evidence# 1: Galaxy Rotation



For the peripheral region of galaxy:

$$\frac{mv(R)^2}{R} = \frac{GM(R)m}{R^2}$$

$$v(R) = \sqrt{\frac{GM(R)}{R}}$$

$$M(R) = Independent\ of\ R \ \rightarrow v(R) \sim R^{-1/2}$$

$\Rightarrow$ Faster fall-off of velocity in the halo region

For the core region of the galaxy:

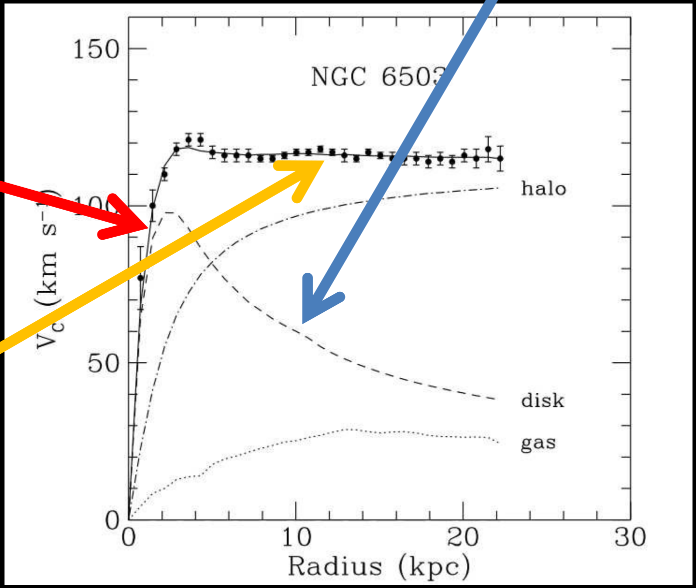
$$v^2 = G\frac{\int_0^R 4\pi r^2 dr\ \rho}{R}$$

$$v(R) \sim R\ (constant\ core\ density)$$

Given observed velocity saturation in the disk / halo region:

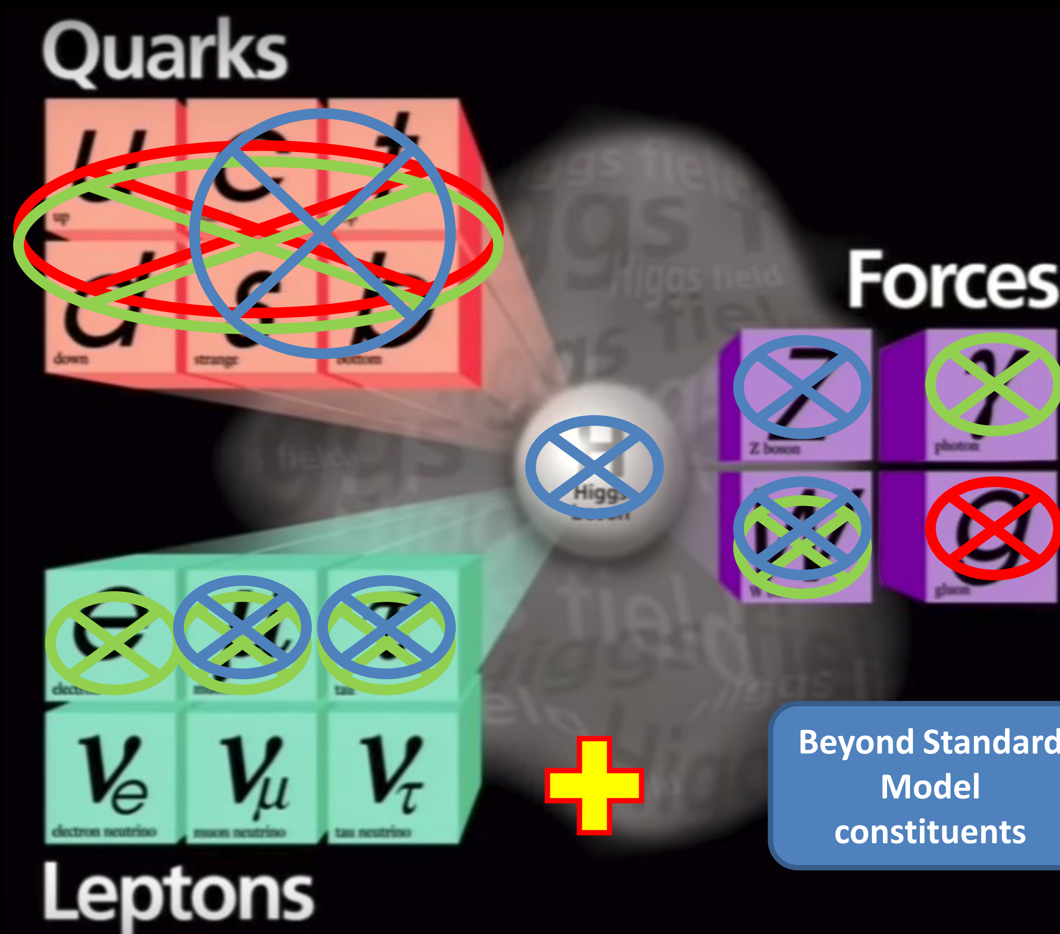
$$v(R) \sim constant$$

$$M(R) \sim R\ in\ the\ halo\ region$$



What are the constituents of dark matter ? What is it made of ?

- Strong Interaction
- Electromagnetic
- Unstable by decay



+

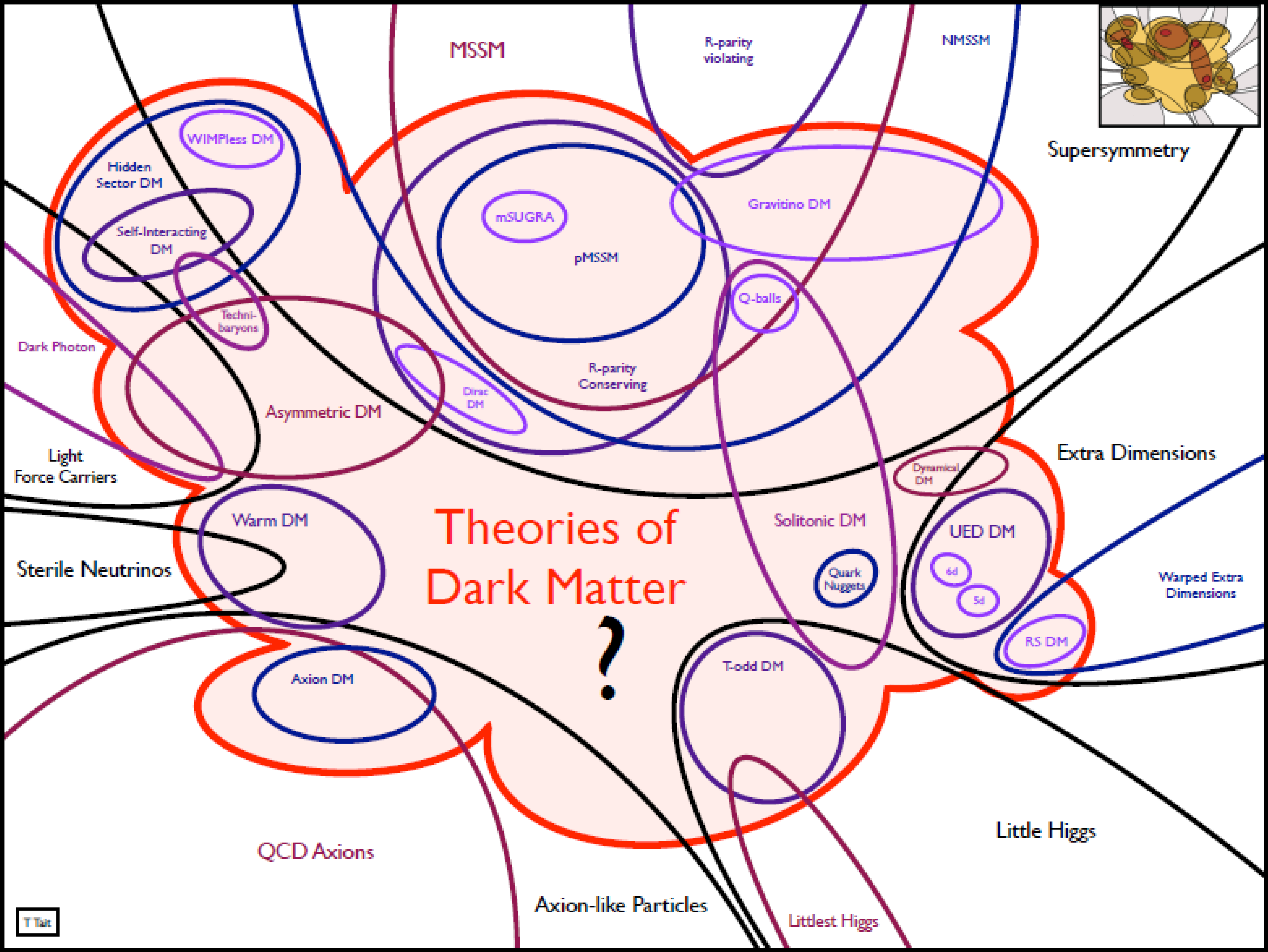
Beyond Standard Model constituents

→

AXION
Sterile Neutrinos
Neutralinos in SUSY
LKP in Extra Dimension
Superheavy DM
WIMP
……

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

Do we understand Neutrinos, Dark Matter and Beyond Standard Model scenarios from theoretical standpoint ?



Courtesy Tim Tait, UC Irvine, UCLADM 2018

Experimental Techniques for Dark Matter Search Experiments

- Introduction
- **Challenges in dark matter search**
- Experimental Techniques for Direct DM search
- A few important examples
- Our Initiative: Jaduguda Underground Science Laboratory (JUSL)
- Conclusion and outlook

Terrestrial search for evidence of Dark Matter Particle Candidates

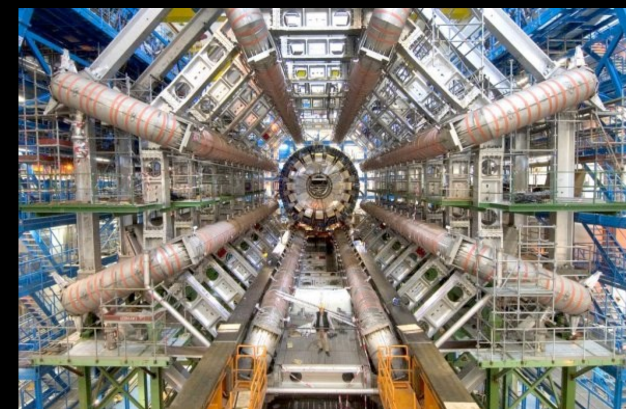
Direct Search

$\chi N \rightarrow \chi N$

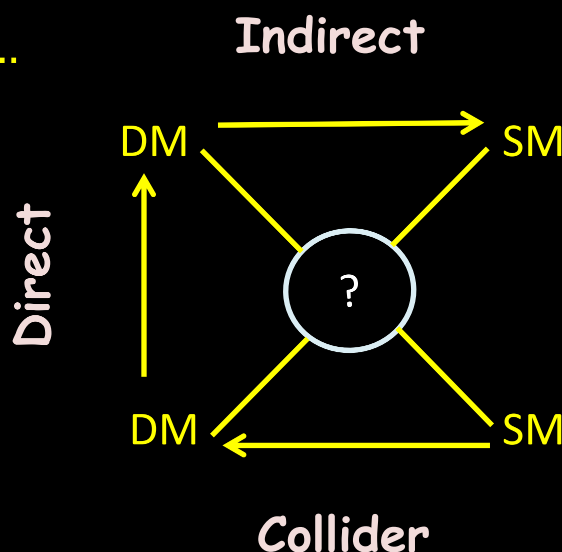
Indirect Search

$\chi\chi \rightarrow \gamma\gamma,$
$q\bar{q}, e^+e^-, \mu^+\mu^- \ldots$

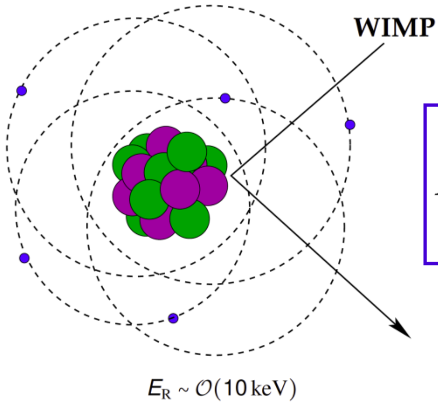
Collider Search



$pp \rightarrow \chi\chi + more..$



Principle of Direct Search Experiments

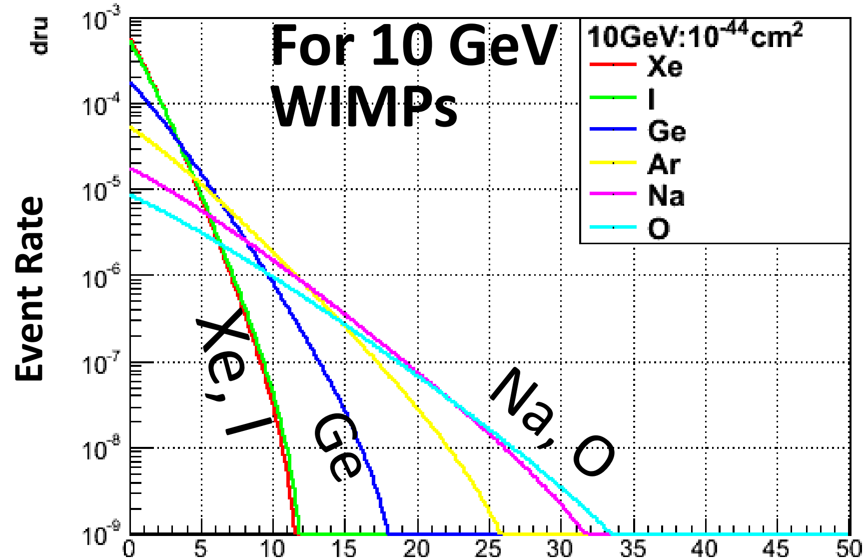


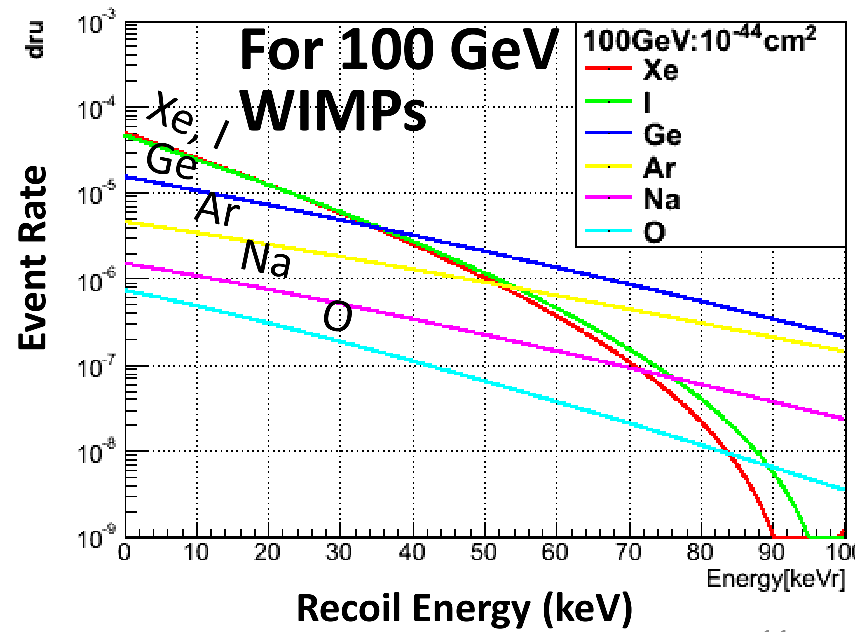
$$R \propto N_T \frac{\rho_0}{m_X} \sigma \langle v \rangle$$

- Direct searches : Observe Nuclear Recoils
  - χ + N ➔ χ + N
- Recoil Energy:

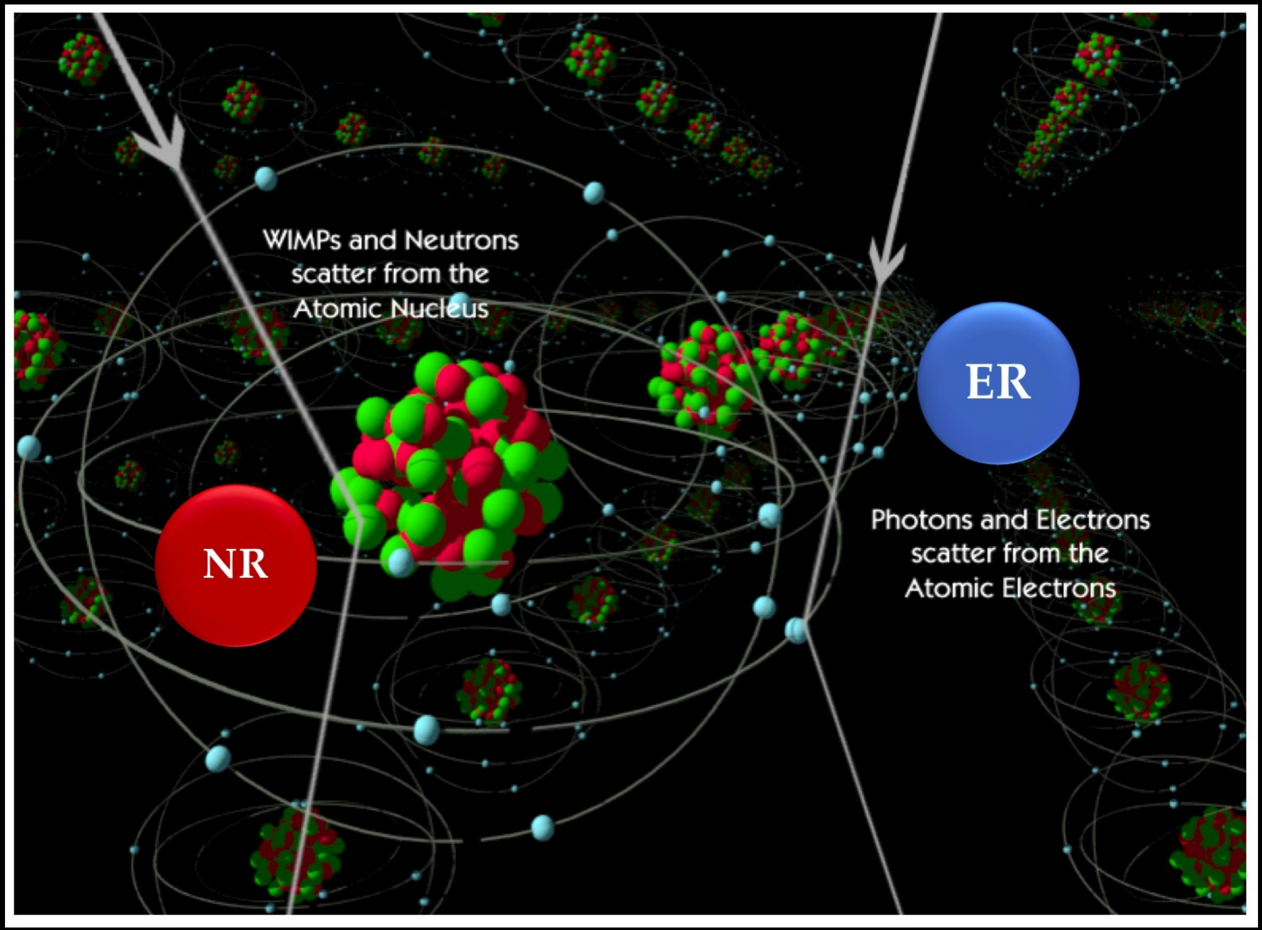
$$E_R = \frac{M_\chi v^2}{2} \frac{4 M_\chi M_A}{(M_\chi + M_A)^2} \frac{(1 - cos\theta)}{2}$$

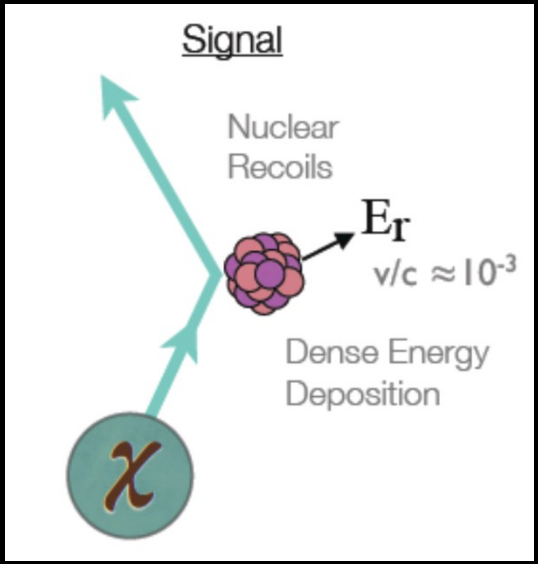
  - Very small recoil energy
    $E_R \sim 1 - 100\ keV$
  - Featureless recoil spectrum.
  - Soft spectrum for large target masses
  - Very low event rate
    $\vartheta(0.01\ ton^{-1} keV^{-1} day^{-1})$
  - Loose efficiency unless lowering the detector threshold $E_R \sim \vartheta\ (1 - 10\ keV)$

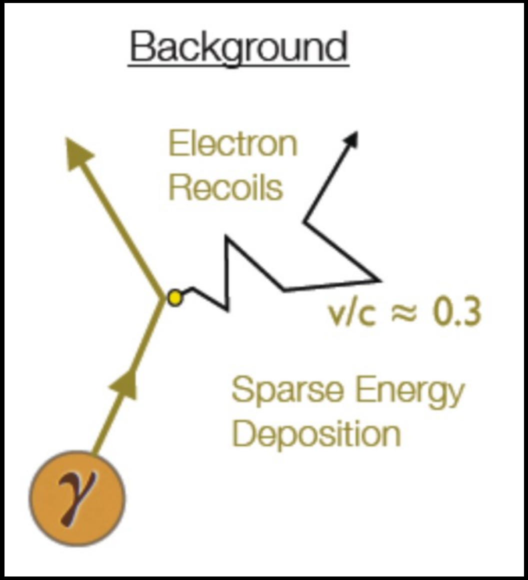




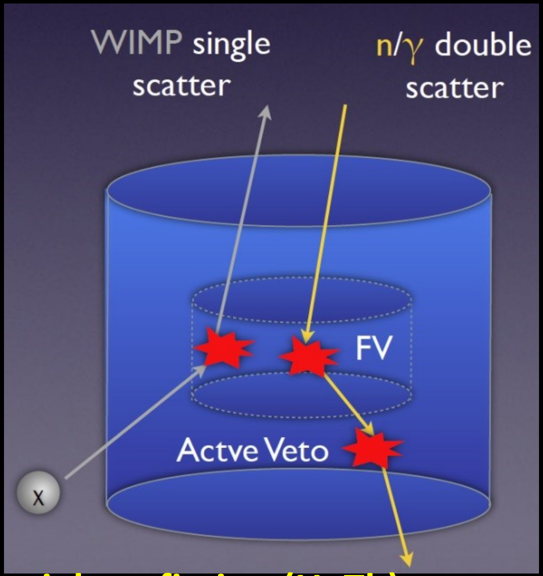
Is Direct Search so simple?







Sources of external background



External gamma rays from radioactivity:
- Suppression by self-shielding of Target
- Materials screening and selection
- Rejection of multiple scatters
- Discrimination

External muons from cosmic rays:
- Go underground!
- Active shielding (veto detectors)

External neutrons from muon induced reactions, (α, n) reaction on materials or fission (U, Th)
- Go underground!
- Shield: passive (HDPE, water) or active (water / neutron scintillator veto)
- Judicious materials and site selection (low U / Th)
- Reduce / monitor Radon contamination at the underground site

Passive and Active Shield

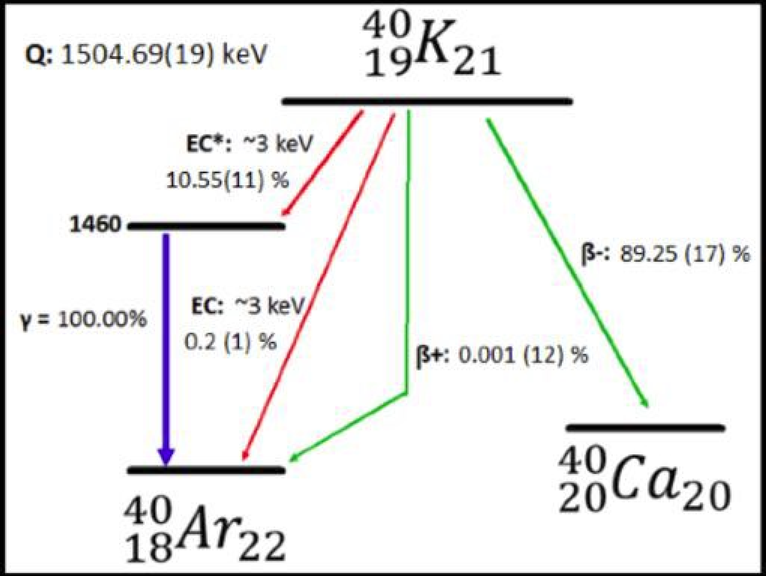
Neutrinos from Sun, atmosphere and from supernovae explosion:
- Elastic neutrino-electron scattering
- Coherent neutrino-nucleus scattering

Sources of internal background

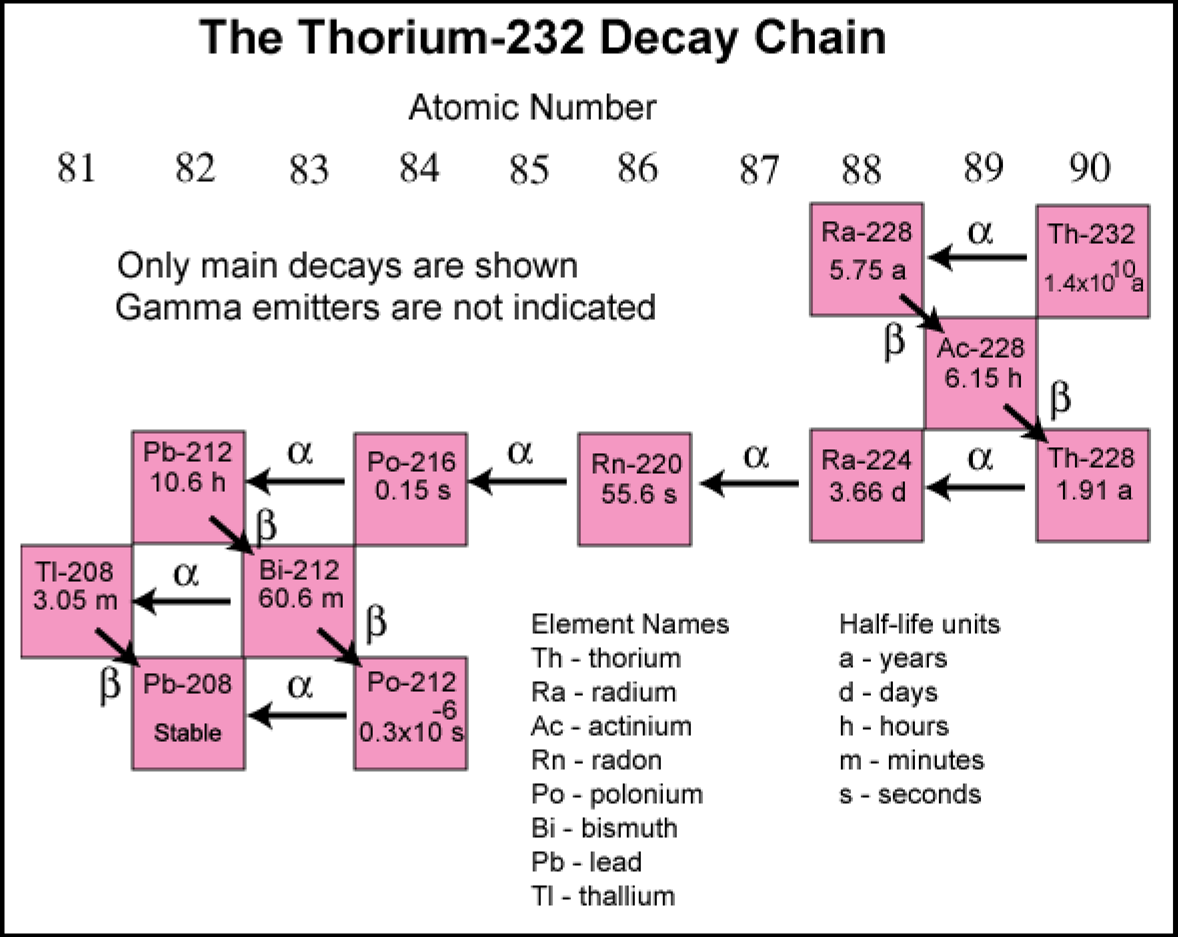
- **Internal contamination in liquids:**
  - Krypton: **^{85}Kr** ($T_{1/2}$= 10.8 Y) remove by cryogenic distillation / centrifuges
  - **Rn:** remove by absorption in activated carbon
  - Argon: **^{39}Ar** (E_β=565 keV, $T_{1/2}$ = 268 Y, cosmogenic production, 759 ± 128 atoms/kg/day, Phys. Rev. C 100, 024608)
    ^{42}Ar ((E_β=599 keV , $T_{1/2}$ = 32.9 Y, cosmogenic, nuclear weapons test)
  - Xenon: **^{136}Xe** $\beta\beta$ decay ($T_{1/2} = 2.2 \times 10^{21}$ Y) very long lifetime

- **Surface background in solids (from bulk and contaminations):**
  - Germanium or scintillators grown out of high purity materials / pay attention to the melts → lower intrinsic background
  - Cosmic activation
  - Surface events from α or β decays

- **Natural / Intrinsic radioactivity background: ^{40}K**
  Uranium – Thorium



Intrinsic Radioactivity – U – Th decay chains

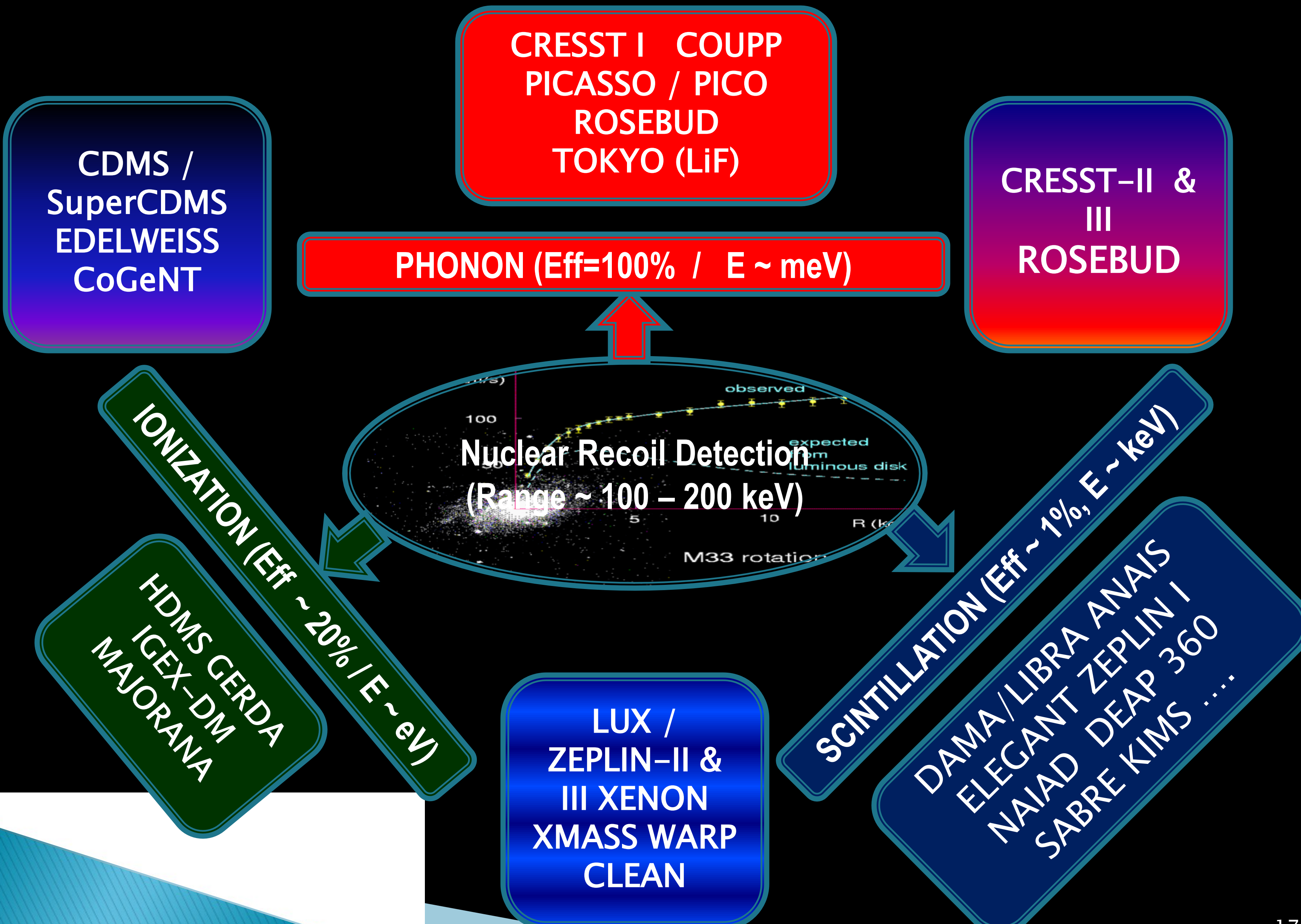


Source: U.S. Geological Survey (USGS)

Experimental Techniques for Dark Matter Search Experiments

- Introduction
- Challenges in dark matter search
- **Experimental Techniques for Direct DM search**
- A few important examples
- Our Initiative: Jaduguda Underground Science Laboratory (JUSL)
- Conclusion and outlook

Classification of Direct detection experiments based on detection strategies with stress on discrimination



Expected Differential Rates

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

Astrophysical parameters:

- ρ_0 = local density of the dark matter in the Milky Way
- $f(\mathbf{v}, t)$ = WIMP velocity distribution

Parameters of interest:

- m_χ = WIMP mass ($\sim 100\,\mathrm{GeV}/c^2$)
- σ = WIMP-nucleus elastic scattering cross section
  - Spin-independent interactions: coupling to nuclear mass
  - Spin-dependent interactions: coupling to nuclear spin

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:

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

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

Standard Halo Model of Galactic Dark Matter

Isotropic, isothermal sphere with Maxwellian velocity distribution:

$$f(v) = N.\exp\left(-\frac{3|v|^2}{2\sigma^2}\right)$$

Distribution truncates at $|v| > v_{esc}$

Local density $\rho_0 \approx 0.3\ \frac{GeV}{cm^3} = 5 \times 10^{-23}\ \ g/cm^3$

Determined from mass modelling of our milky way.

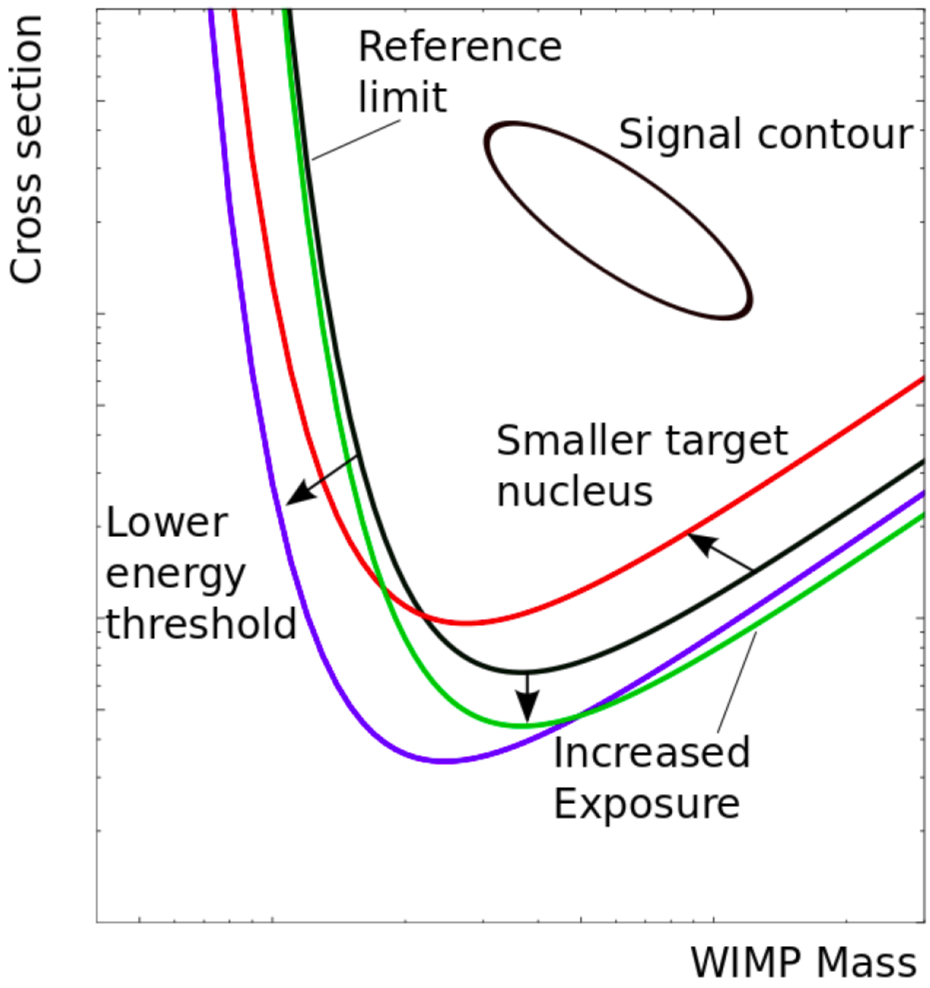
About one WIMP per coffee cup
Assuming ~ 100 GeV WIMP mass

Average velocity ~ 220 km/sec.
Escape velocity $v_{esc} = 544$ km/sec. (From the highest velocity stars)

Presentation of Experimental Results: Sensitivity Plots

→ Statistical significance of signal over expected background?

J. Phys. G43 (2016) 1, 013001& arXiv:1509.08767



- Positive signal
  - Region in σ_χ versus m_χ
- Zero signal
  - Exclusion of a parameter region
  - Low WIMP masses: detector threshold matters
  - Minimum of the curve: depends on target nuclei
  - High WIMP masses: exposure matters $\epsilon = m \times t$

Direct Detection: Experimental Scenario

Positive Indication:

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

Null Result or Exclusion Limit:

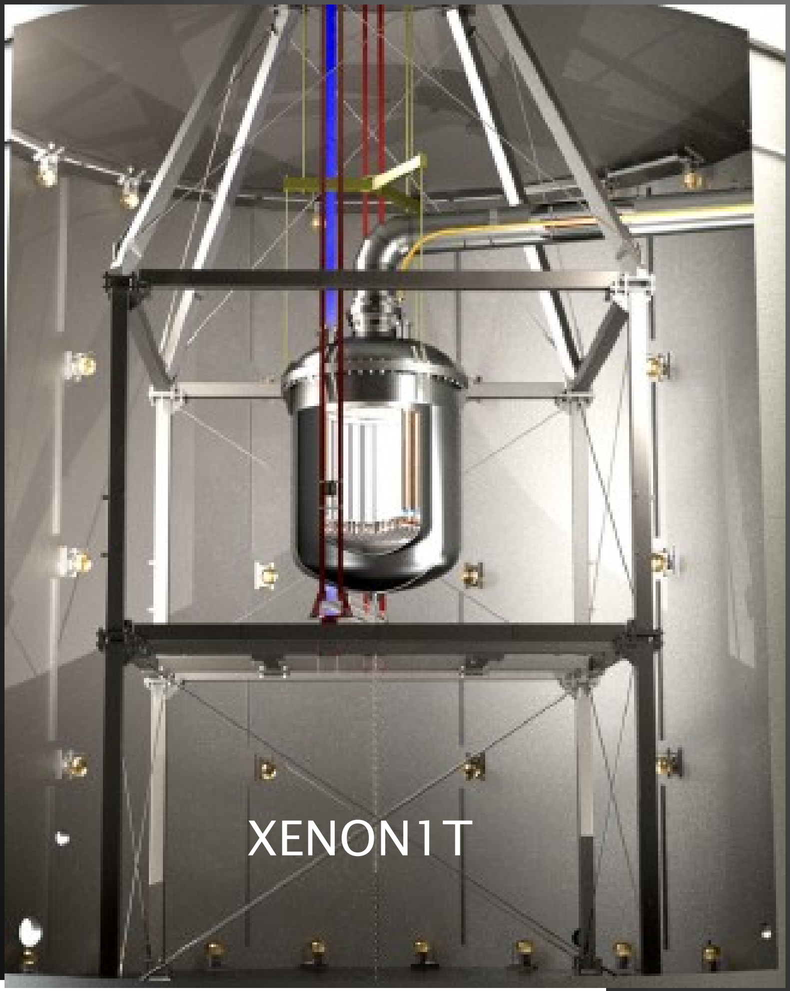
Experiments	Target	Theshold	Total Exposure	Recoil Identification
CDMS-II	Ge/Si	10.0 keV	612 kg-days	NR
CDMS-II (LE)	Ge	2.0 keV_{NR}	241 kg-days	(NR+ER)
EDELWEISS	Ge	20.0 keV	384 kg-days	NR
XENON1T	Xe	8.4 keV_{NR} / < 1 keV_{ER}	2.2 x 10^5 kg-days	NR + ER
LUX	Xe	1.1 keV_{NR}	3.35 x 10^4 kg-days	NR+ER
PANDA X II	Xe	1.1 keV_{NR}	3.3 x 10^4 kg-days	NR + ER
PICO-2L	F	10 keV	211 kg-days	NR
PICO-60	F	2.45 keV	1404 kg-days	NR
KIMS	CsI (Tl)	3 keV	37000 kg-days	NR + ER
CRESST-II	$CaWO_4$	0.3 keV	29 kg-days (300 g)	NR + ER
CRESST-III	$CaWO_4$	0.03 keV	2.39 kg-days (24 g)	NR + ER

Experimental Techniques for Dark Matter Search Experiments

- Introduction
- Challenges in dark matter search
- Experimental Techniques for Direct DM search
- **A few important examples**
- Our Initiative: Jaduguda Underground Science Laboratory (JUSL)
- Conclusion and outlook

XENON DUAL PHASE TIME PROJECTION CHAMBER based DM Search Experiment

XENONnT (LNGS, Italy) LZ (SURF, USA) PANDA-XII (China)

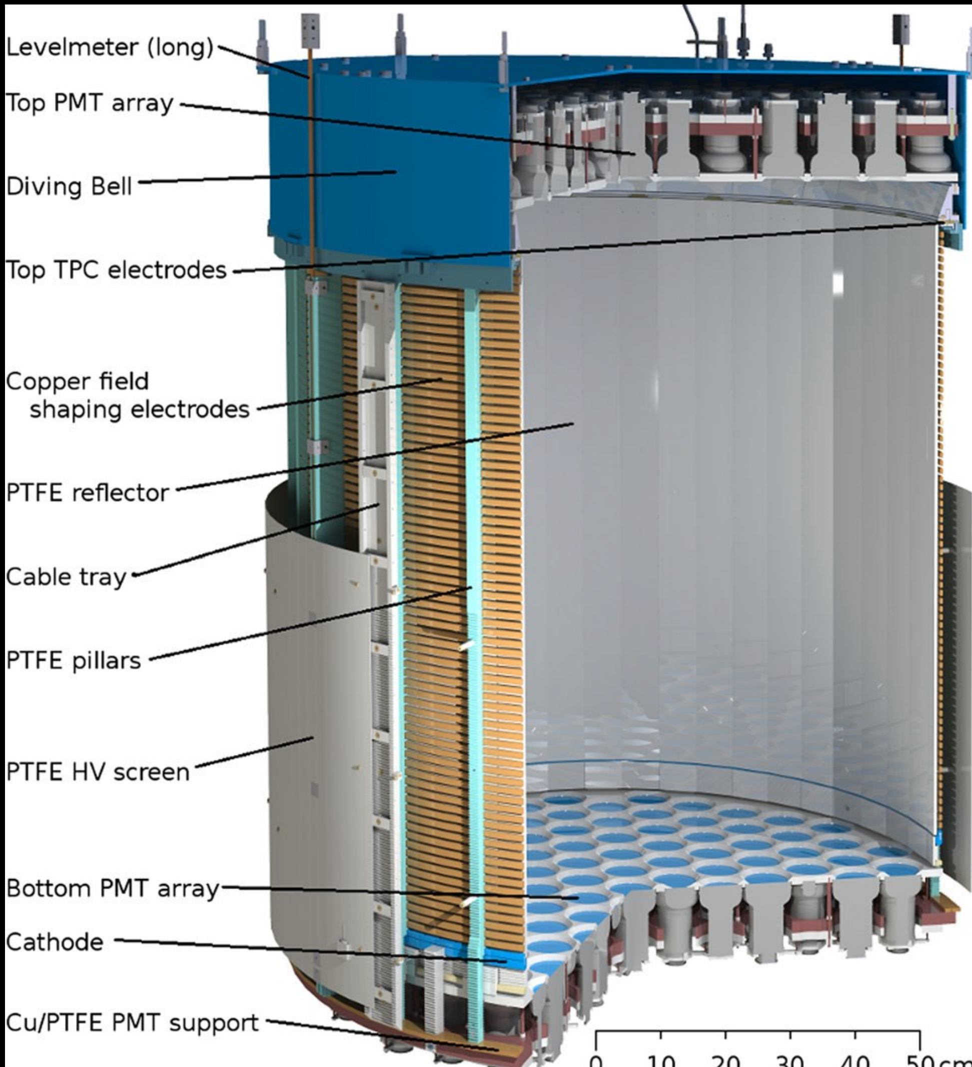


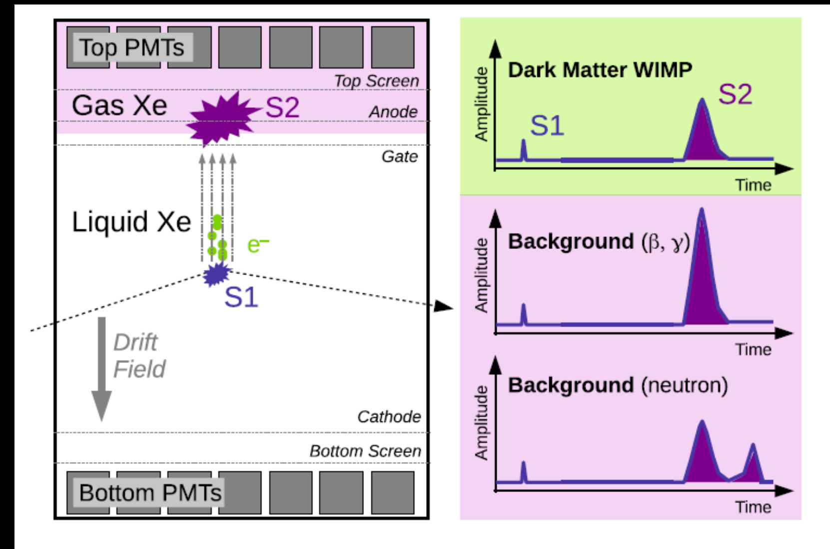
- ❖ Sensitivity to WIMP mass ~ 50 GeV ($\sigma < 10^{-47}$ cm^2 – 2 Ton-Yr)
- ❖ Spin independent & dependent
- ❖ Pure noble liquid, low background activity (86Kr [10.8 Y], 136Xe [10^{21} Y])

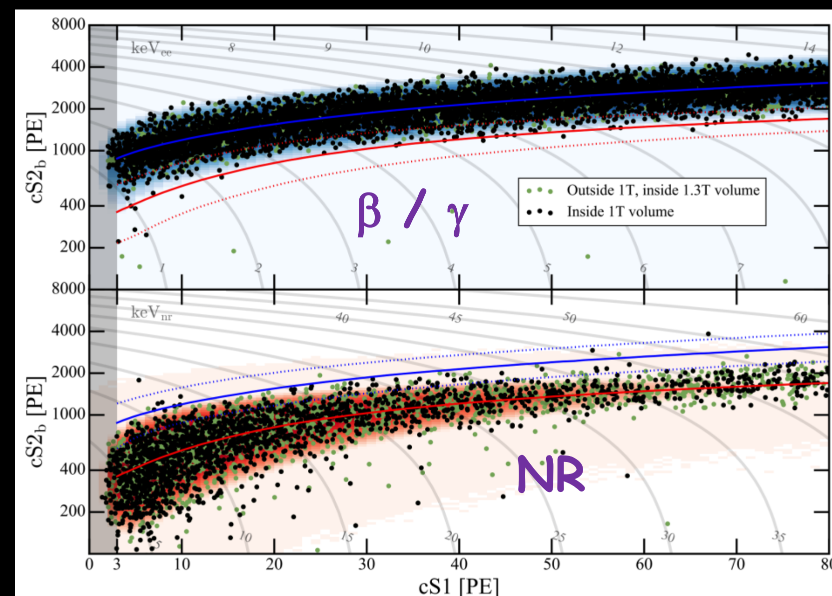
Removal by fractional distillation

- Radiopure and ultrapure liquid
- Xe_2^* excimer: $\lambda \sim 178$ nm
- Sensitive to both nuclear and electron recoil
- Huge mass (XENON1T: 3 Ton, 2 Ton fiducial)

XENON based DM Search Experiment



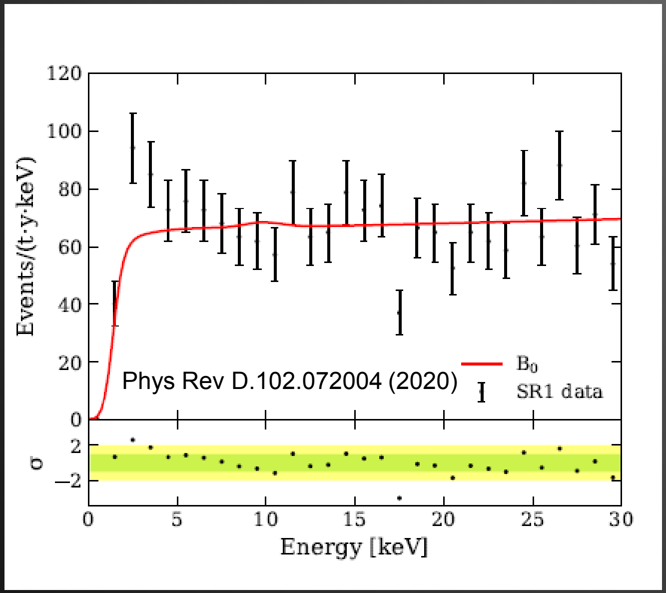


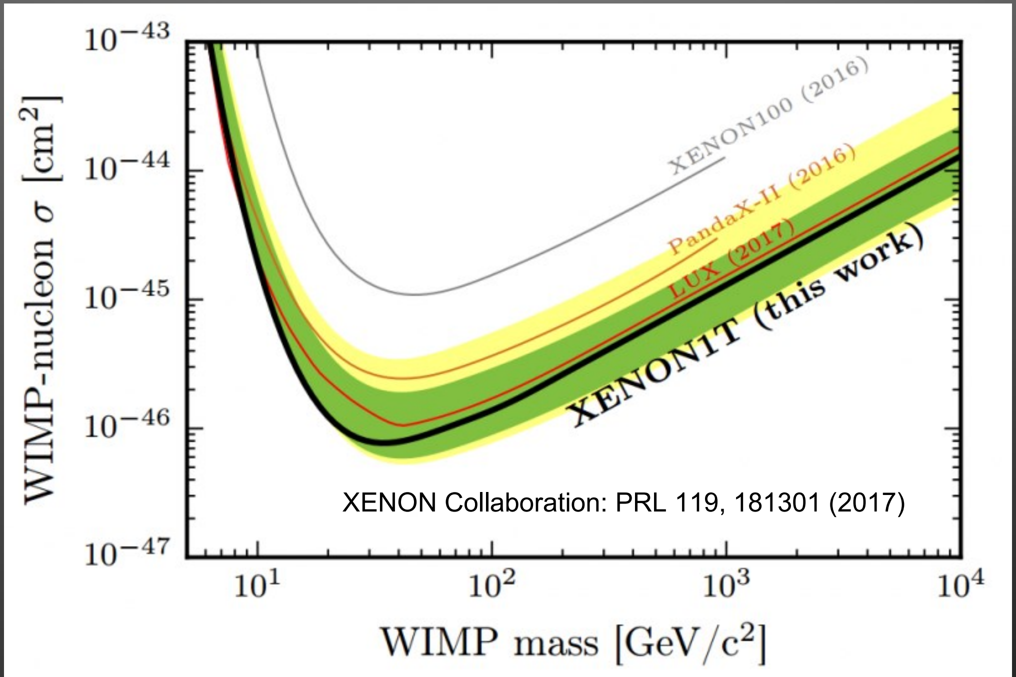


Ref: XENON Collaboration, Eur. Phys. J. C (2017) 77:881

XENON based DM Search Experiment

- Look for exotic physics beyond standard model
- Observed excess electron recoil events
- Major Detector for Supernova explosion (SNe) events





For SNe detection by Xenon TPC: Talk by Sayan Ghosh

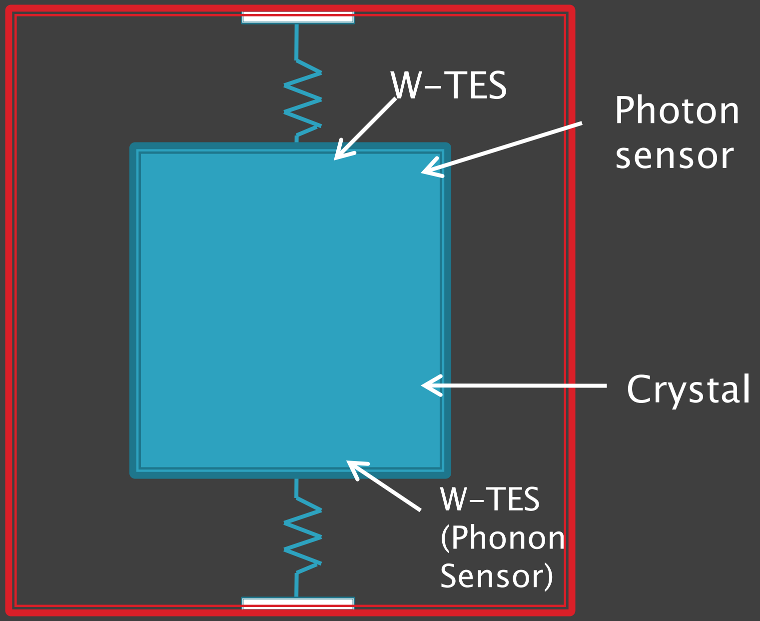
Cryogenic Rare Event Search with Superconducting Thermometers (CRESST) Experiment @LNGS, Italy (3.6 kmwe depth)

Phase I: Saphire crystal (262 g)

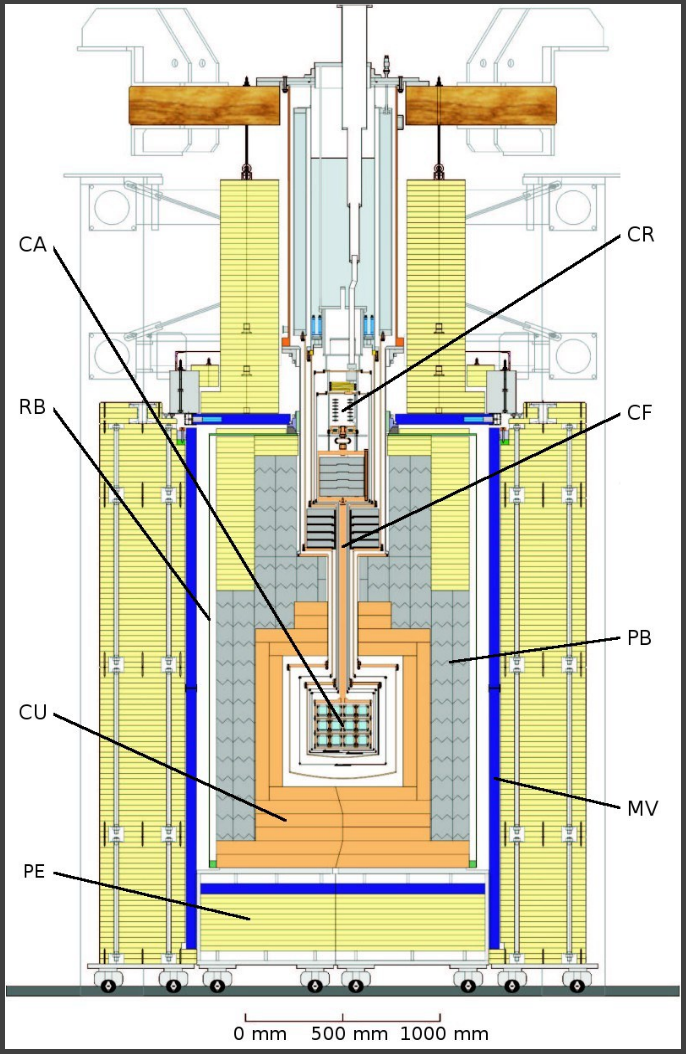
Phase II: CaWO4 (300 g)

Phase III: CaWO4 (24 g)

- Low mass WIMP sensitivity
- Push threshold to < 0.1 keV



Dilution Fridge (~ 15 mK)

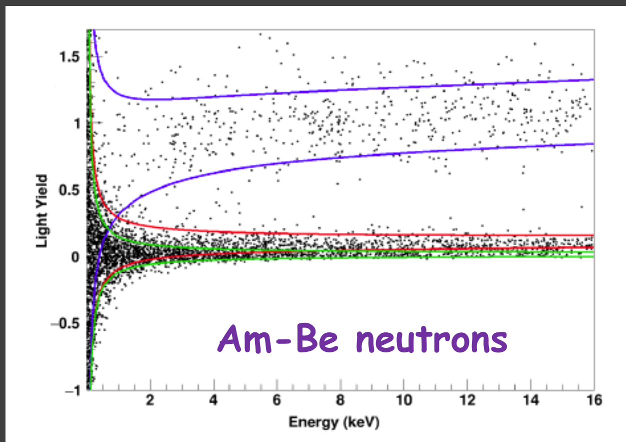


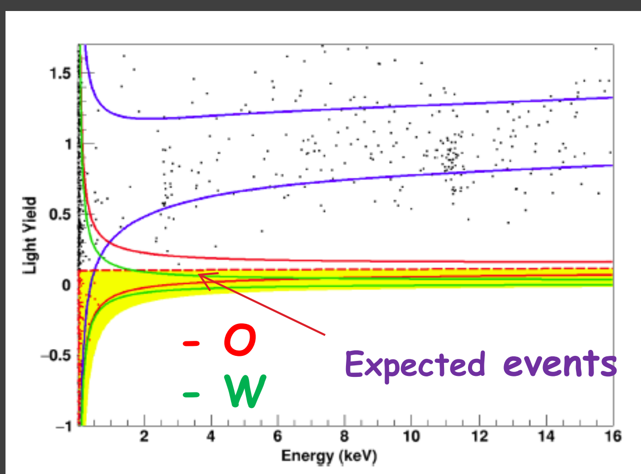
Courtesy: CRESST , arXiv:0809.1829v2 (2009)

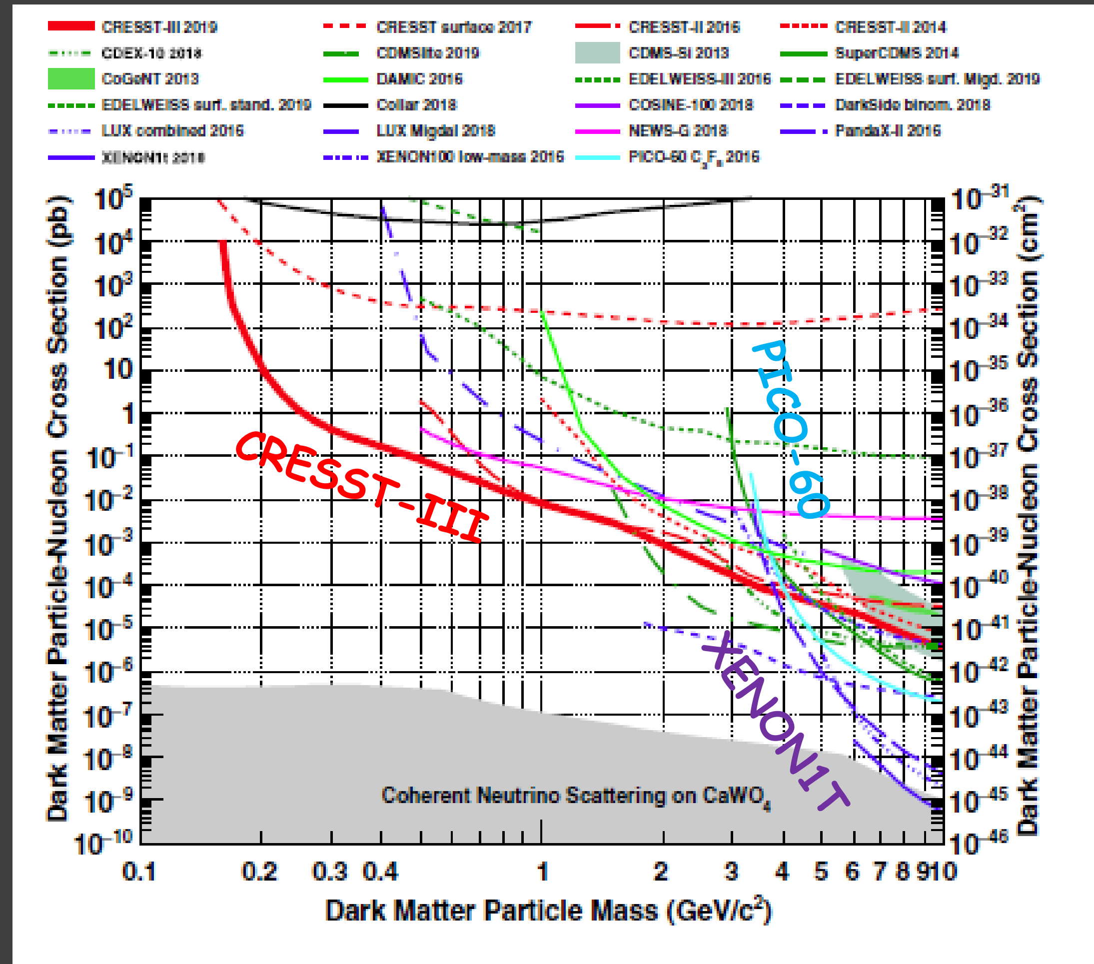
CRESST III Experiment

Neutron - β / γ discrimination

LY = Photon Yield / Phonon Yield





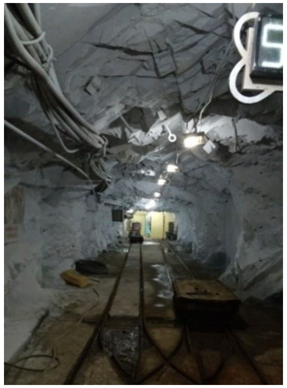


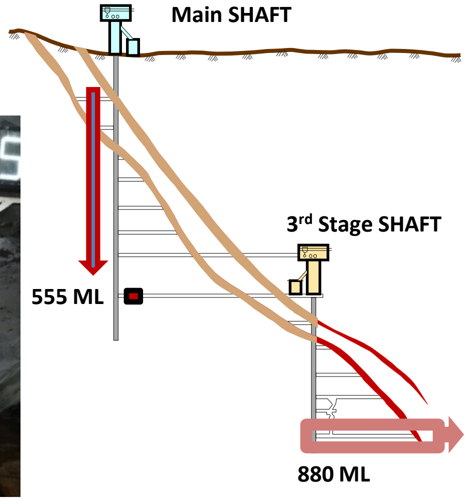
Ref: Phys Rev D 100, 102002 (2019)

Experimental Techniques for Dark Matter Search Experiments

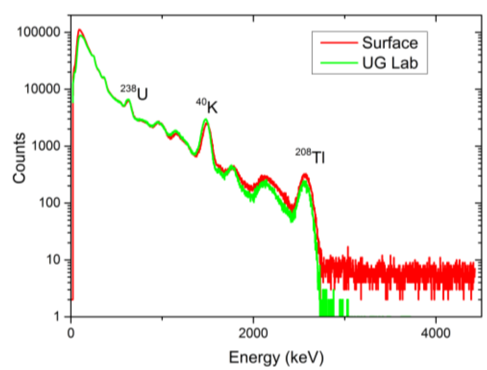
- Introduction
- Challenges in dark matter search
- Experimental Techniques for Direct DM search
- **A few important examples**
- **Our Initiative: Jaduguda Underground Science Laboratory (JUSL)**
- Conclusion and outlook

JADUGUDA UNDERGROUND SCIENCE LABORATORY (JUSL)





- Reduce cosmic muon background
- Reduce gamma ray background
- Monitor & reduce radon background
- Monitor & Reduce neutron background



Background Measurements at UCIL, Jaduguda

Muon Flux measurements
using 4-fold coincidence

Neutron background measurements with
combined fast and thermal neutron detectors

Targeted Direct Search experiment at JUSL:
Hydrogen-rich superheated drop detectors
Sensitive to low WIMP mass. (next talk)

Concluding Remarks / Summary:

- Review of experimental techniques for DM direct search.
- Direct Search: Physics issues and challenges involved.
- A couple of world-leading DM search examples briefly illustrated:

Huge to Tiny spanning sensitivity from 10s of GeV to sub GeV WIMP.

- A glimpse of Indian initiative for the future scientists

  (DINO, miniDINO)