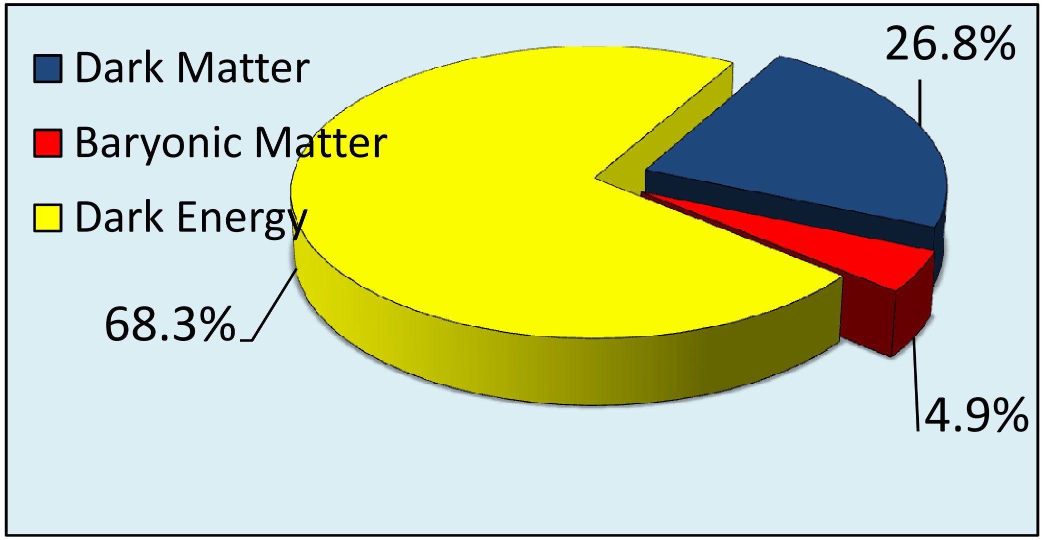
Dark Matter Direct Detection

by Seyed Yaser Ayazi



School of Particles and Accelerators, (IPM)

Outline:

1. Introduction

2. Detectability of certain dark-matter candidates.

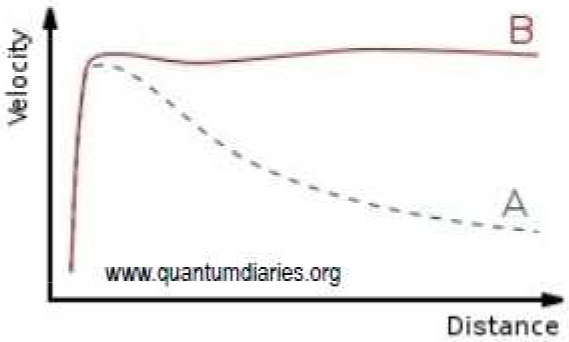
3. Possible Light Dark Matter confronting the recent LHC Results.

4. Dark Matter Direct Detection Searches & Techniques.

Introduction:

Evidence for Dark Matter

Galaxy rotation curves



The cosmic microwave background

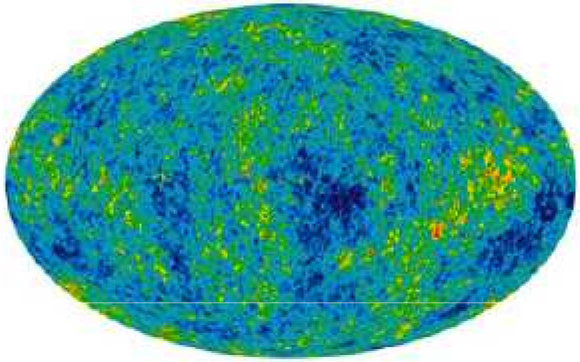
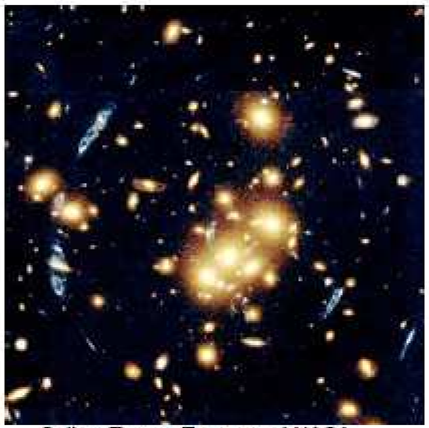


Image: ESA and the Planck collaboration

Gravitational lensing



Colley, Turner, Tyson, and NASA

- 27% of the energy composition of the universe
- Properties:
  - Stable and electrically neutral
  - Non-baryonic
  - Non-relativistic
- Estimated local density: $0.3\pm0.1\,\mathrm{GeV}\cdot\mathrm{cm}^{-3}$
- Candidates: WIMPs, axions, dark photons,...

- Astronomical observations has indicated that DM contributes to nearly 27% of the energy density of the Universe.

- Popular DM candidates such as WIMP is expected to annihilate or decay into SM final states in the Galactic halo and beyond.

- The ongoing satellite such as *PAMELA, Fermi-LAT*, and *AMS-02* etc are searching for such potential indirect signatures of DM with high accuracy.

Detectability of certain dark-matter candidates

dark-matter candidates:

- Magnetic monopoles
- Axions
- Massive neutrinos
- WIMP, such as neutralino, stable Kaluza-Klein (KK) particles , ...

Weakly Interacting Massive Particles (WIMPs)

- A new particle that only very weakly interacts with ordinary matter could form Cold Dark Matter

- Formed in massive amounts in the Big Bang.
- Non-relativistic freeze-out. Decouples from ordinary matter.
- Would exist today at densities of about 1000/m3.

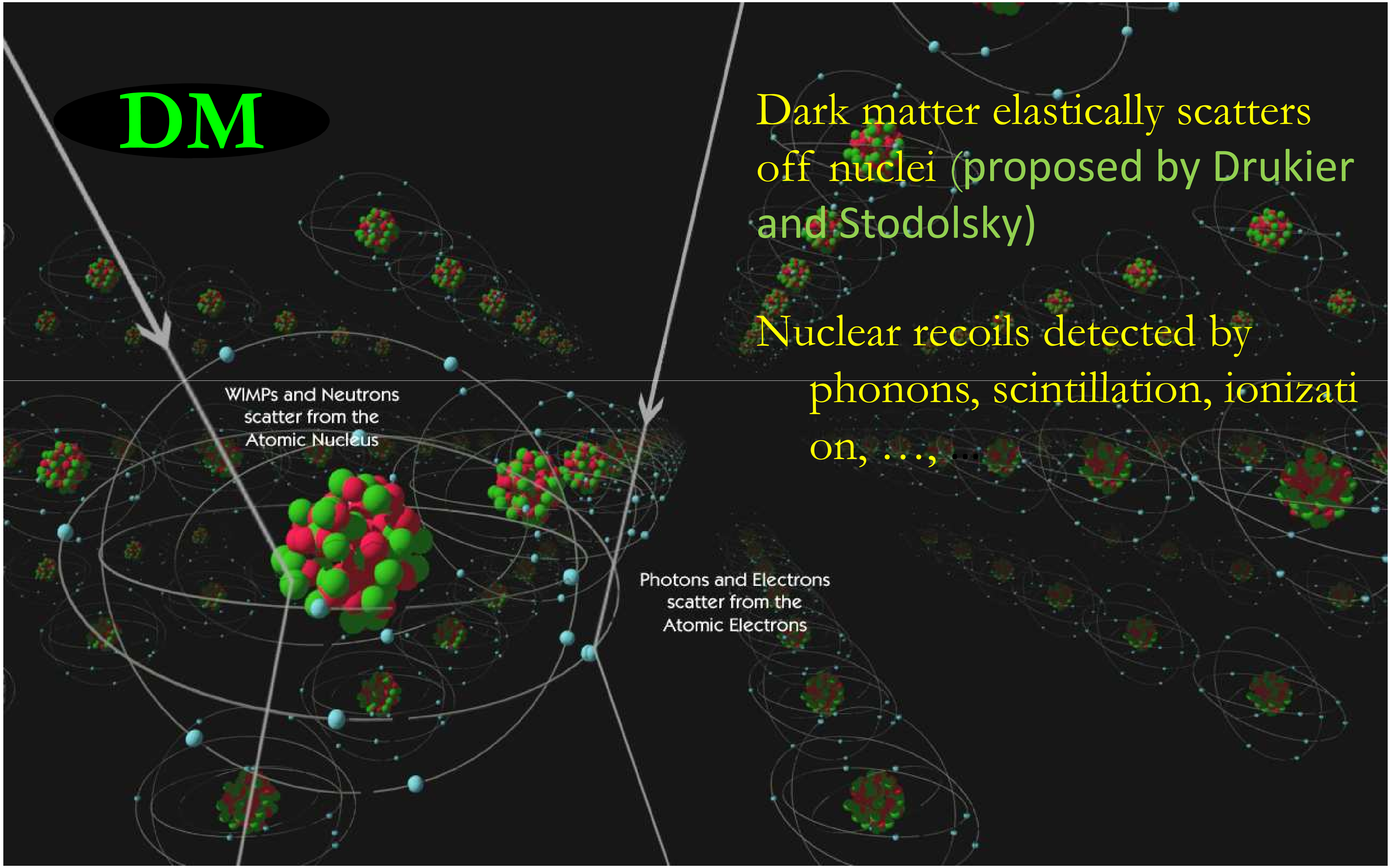
- Supersymmetry provides a natural candidate – the neutralino.

-Lowest mass superposition of photino, zino, higgsino
- Mass range from the proton mass to thousands of times the proton mass.
- Wide range of cross-sections with ordinary matter, from 10^40 to 10^50 cm2.
- Charge neutral and stable!

- Universal Extra Dimensions: predicts stable Kaluza-Klein (KK) particles

- Similar direct detection properties as neutralino
- Distinguishable from neutralinos at accelerators

Dark Matter Direct Detection Searches



Dark matter elastically scatters off nuclei (proposed by Drukier and Stodolsky)

Nuclear recoils detected by phonons, scintillation, ionizati
on, …, …

- In the last few years, the DAMA/LIBRA, Co-GeNT and CRESST-II experiments have all reported excesses of events over their estimated backgrounds, which can be interpreted as due to low-mass dark matter WIMPs interacting in their detectors.

- The recent analysis of the CDMS-II data has isolated three possible signal events, with a small expected background.

- The average velocity of the earth through the halo is: $v_0 = 220\,\mathrm{km/s}$

And the local WIMP density: $\rho = 0.3\,\mathrm{GeV}/c^2$

With that information, one can ask the question:

How often will a dark matter particle at location in the halo interact with a particular nucleus?

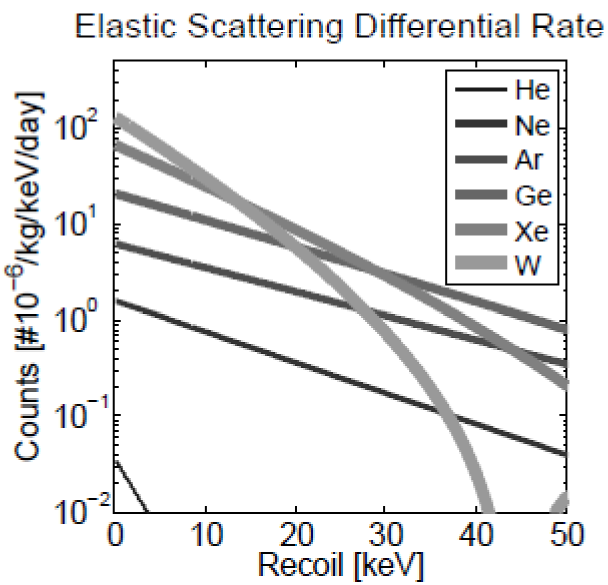
- The dominant interaction mechanism is expected to be elastic scattering due to spin-independent interactions.

- The deferential recoil energy spectrum of such an interaction between a WIMP and a nucleus is given by:

$$\frac{dR}{dQ} = \frac{\sigma_0 \rho_0}{\sqrt{\pi} v_0 m_\chi m_r^2} F^2(Q) T(Q)$$

aeXiv:1203.2566

$$\sigma_0 \propto A^2 \sigma_{\chi-p}$$



$$m_\chi = 100\,\mathrm{GeV}/c^2$$

$$\sigma_{\chi-p} = 10^{-45}\,\mathrm{cm}^2$$

For the values of m_χ and $\sigma_{\chi-p}$ assumed in the plot, the signal event rates are less than 2 events/kg/year

WIMP Direct Detection

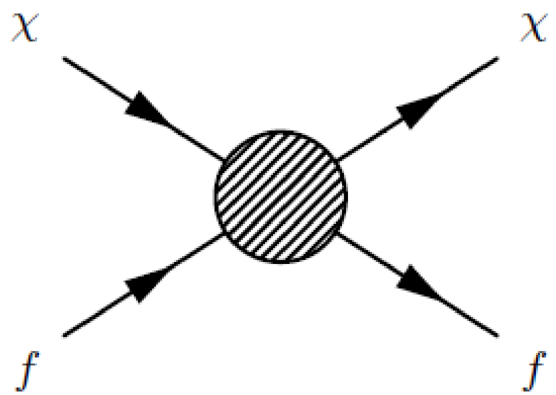
- Proposed by : *Mark W. Goodman and Edward Witten*

If a detector sensitive to 1 event/kgday can be built, and a halo particle of mass m and velocity v scatters from a target nucleus of mass M, the recoil momentum is at most $2mv$ and the recoil kinetic energy is at most

E = $(2mv)^2/2M$ $v_0 = 220\,\mathrm{km/s}$

Consider elastic scattering of halo particles of mass m by target nuclei of mass M.

$$\sigma = [m^2 M^2/\pi(m+M)^2]\,|\mathscr{M}|^2$$



If a detector sensitive to 1 event/kg day can be built, useful limits can be placed on these particles in the mass ranges 1—100 GeV

Three classes of dark-rnatter candidates:

1. Particles with coherent weak couplings;
2. Particles with spin-dependent couplings of roughly weak strength;

$$\mathscr{M} = (4q^2/M_{\tilde{Q}}^2)\lambda \mathbf{S}_{\tilde{\gamma}} \cdot \mathbf{J}$$

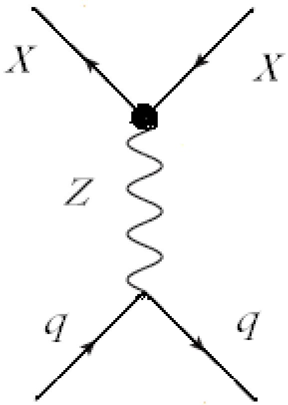
3. Particles with strong interactions. Examples would be a bound state of ordinary quarks and gluons with a heavy stable quark, scalar quark, gluino, or colored technibaryon.

Useful limits can be placed on these particles in the mass ranges

(PRD, VOLUME 31,NUMBER 12)

1. 1—10^6 GeV,
2. 1—10^2 GeV
3. 1—10^13 GeV

We first assume that the unknown halo particle, X, has vector couplings to Z bosons and scatters from nuclei by Z exchange

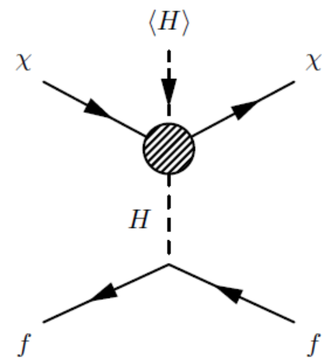


$$\mathcal{M} = \frac{g^2 + g'^2}{M_Z{}^2} J_X^0 J_T^0 = 4\sqrt{2} G_F J_X^0 J_T^0$$

$$\bar{\sigma} = (2.0 \times 10^{-35}\ \text{cm}^2) \left[\frac{4mM}{(m+M)^2} \right] \bar{Y}^2 \left[\frac{\bar{N}}{100} \right]^2$$

The Higgs-nucleon coupling depends on the underlying Yukawa interactions of the Higgs boson with the quark degrees of freedom. The couplings of a Higgs boson H to quarks can be generically written as

$$\mathcal{L}_{qq\mathcal{H}} = -\sum_q \frac{k_q}{v} m_q \bar{q} q \mathcal{H}$$



In the SM kq = 1 for all q's, whereas beyond the SM the kq's may have other values

$$k_d = k_s = k_b \qquad\qquad k_u = k_c = k_t$$

$$\mathcal{L}_{NN\mathcal{H}} = -g_{NN\mathcal{H}} \bar{N} N \mathcal{H}$$

where g_{NNH} is the Higgs-nucleon coupling constant. One needs to evaluate the matrix element:

$$g_{NN\mathcal{H}} \bar{N} N = \langle N| \frac{k_u}{v}(m_u \bar{u}u + m_c \bar{c}c + m_t \bar{t}t) + \frac{k_d}{v}(m_d \bar{d}d + m_s \bar{s}s + m_b \bar{b}b)|N\rangle$$

$$\sigma_{\rm el} \simeq \frac{\lambda^2 g_{NN\mathcal{H}}^2 v^2 m_N^2}{\pi (m_D + m_N)^2 m_{\mathcal{H}}^4} \qquad\qquad (p_D + p_N)^2 \simeq (m_D + m_N)^2$$

It is shown that the scenarios with a very light neutralino (10 GeV) and a scalar bottom quark close in mass, can satisfy all the available constraints from LEP, Tevatron, LHC, flavor and low energy experiments and provide solutions in agreement with the bulk of dark matter direct detection experiments, and in particular with the recent CDMS results. (arXiv:1308.2153)

WIMP Interactions in a Detector

Goal: few events/100kg/year !!!

Search for very low energy, very rare interactions
➻requires very sensitive detectors with very low background!

Background sources:

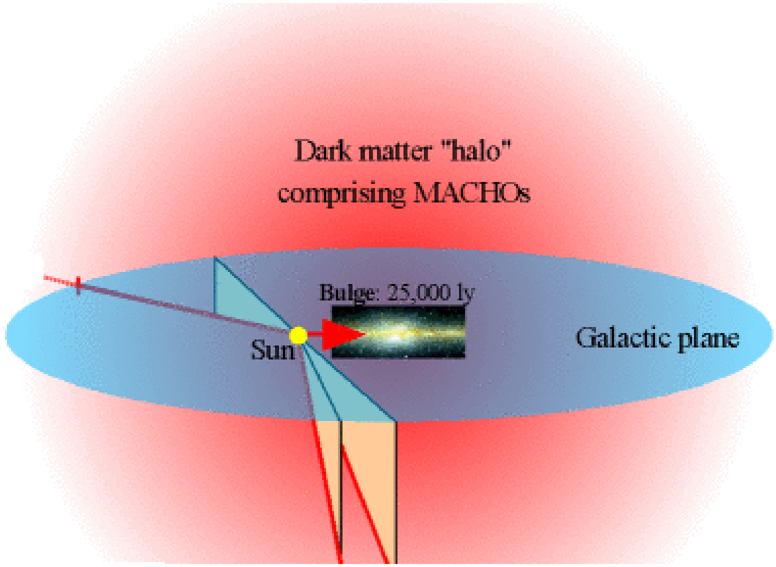
1. ***Electron recoils***
2. ***Alpha –particle***

These backgrounds originate from naturally occurring radioactive isotopes in the material surrounding the detectors.

Discrimination between the signal and background events.

1. This method of discrimination is based on the variation in the WIMP event rates and spectrum as the relative motion between the laboratory frame of reference and the WIMP rest frame varies along the earth's orbit of the sun, whereas background sources are not expected to exhibit such a variation.

Under the assumption of a non-rotating WIMP halo the event rate is expected to exhibit maxima/minima in June/December,



Since the amplitude of the modulation is small in comparison to the overall rate, this method lends itself to experiments with large exposures and overall interaction rates.

2. Variation in detector based response to signal and background events.

For a given amount of imparted energy, a recoiling nucleus travels a much smaller distance in the detector than a recoiling electron.

- *Appropriate shielding with passive and/or active materials as well as veto detectors around the experiment can significantly suppress the background event rate.*

- *Operation at a deep underground site to reduce the rate of background events*

Direct Detection Techniques and Experiments

1. *Two-phase Noble Liquid*

- Argon and xenon two phase time projection chamber have been developed for directly detect galactic dark matter.

1. Xenon 10
2. Xenon 100
3. Large Underground Xenon (LUX)

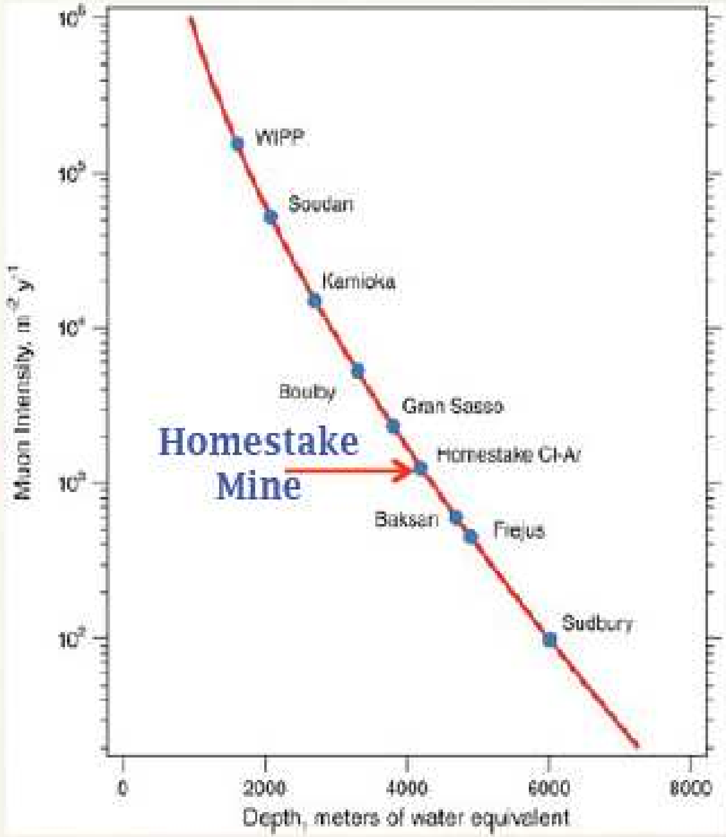
- A 15 kg liquid xenon detector was installed at Gran Sasso during March 2006, and searched for WIMP interactions until October 2007. No WIMP signatures were found, the limits on WIMP-nucleon cross sections extend down to below 10^{-43}cm^2 for a 30 GeV/c^2 WIMP mass.

- The current phase, XENON100, contains 165 kg of liquid Xenon, with 62 kg in the target region (2008) . In each science run, no dark matter signal was observed above the expected background, leading to the most stringent limit on the spin independent WIMP-nucleon cross section with a minimum at $2.0 \times 10^{-45} \mathrm{cm}^2$ for a 65 GeV/c^2 WIMP mass.

- The WIMP Argon Program (WARP) is an experiment at Gran Sasso, Italy, for the research of DM. WArP experiment uses liquid argon as the detection material.

- The LUX experiment is located 4,850 ft (about 1 mile) underground at the Sanford Underground Laboratory in the Homestake Mine (South Dakota) in Lead, South Dakota.

Sanford Underground Research Facility (SURF)



$55.2\ m^{-2} \cdot sec^{-1} \rightarrow 10^{-5}\ m^{-2} \cdot sec^{-1}$

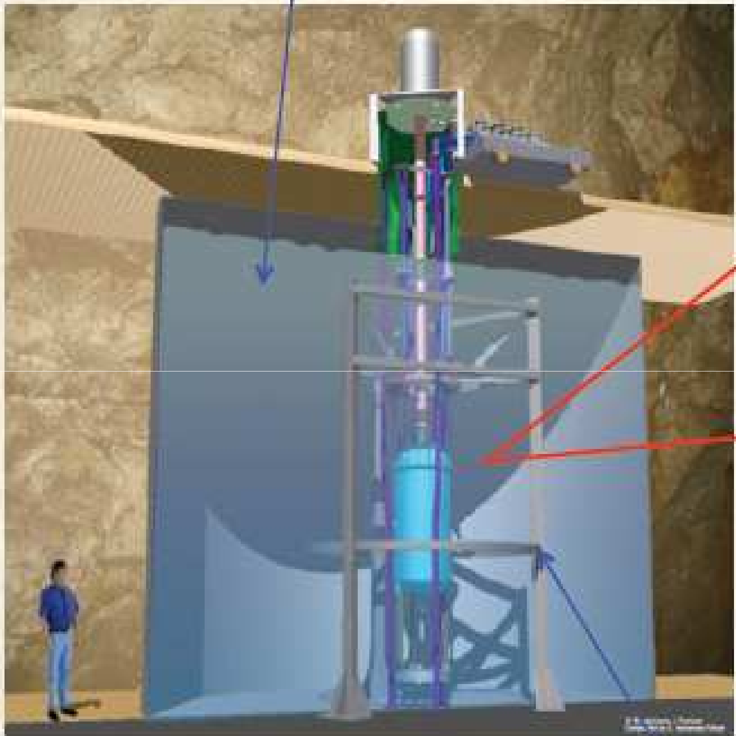
~10^7 fold muon flux suppression

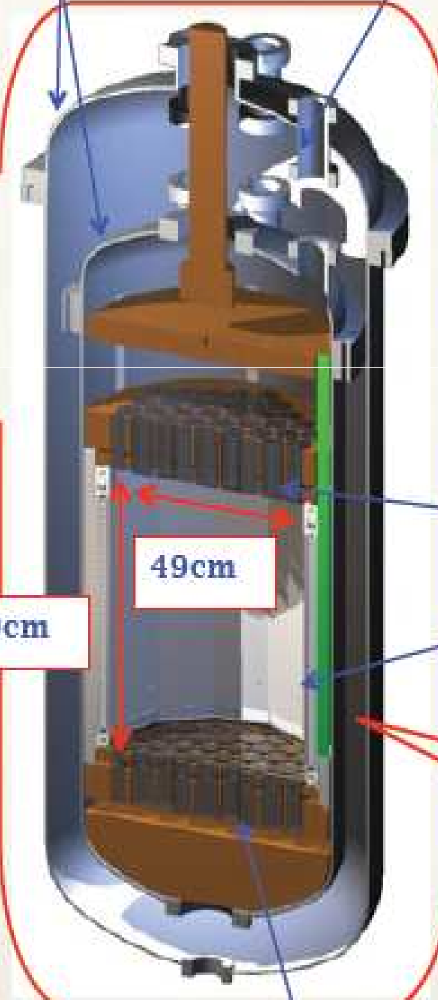
The LUX detector

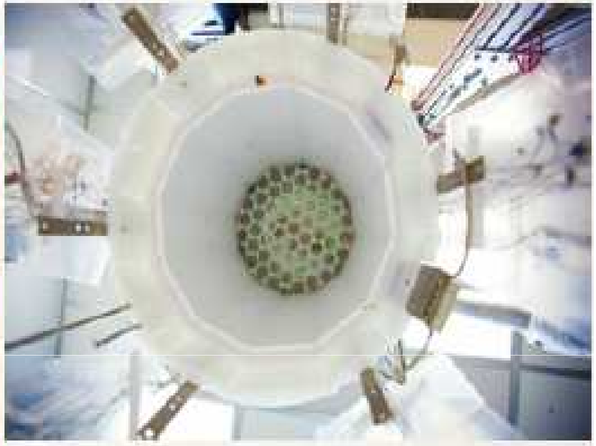
Water Tank

Titanium Cans - arXiv:1112.1376

Thermosyphon







Top PMT Array

Field Cage and
Teflon Reflector
Panels

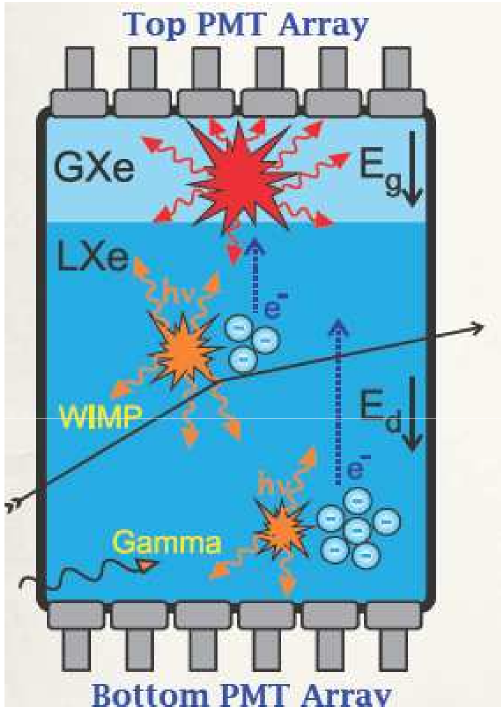
Detector Stand

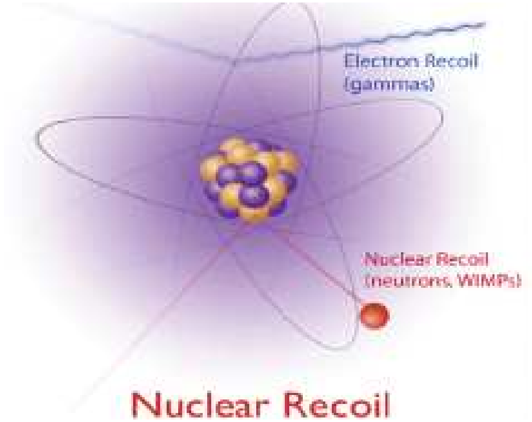
2" Hamamatsu R8778 PMTs
- arXiv:1205.2272

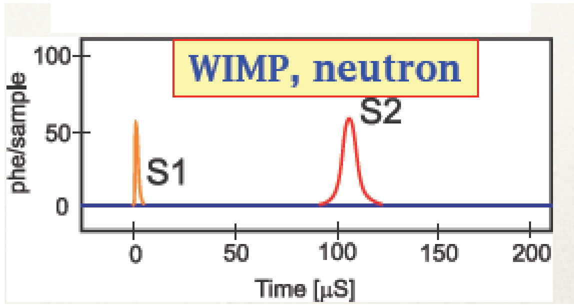
Bottom PMT Array

- 370 kg LXe (100 kg fiducial)
- 122 PMTs (QE~30% @ 175nm)
- Low Radioactivity Materials
- >1kW Cooling Power (Thermosyphons)
- 70,000 gallons of DI water, dissolved O_2<0.5 ppb, Rn content < 100 mBq/m^3

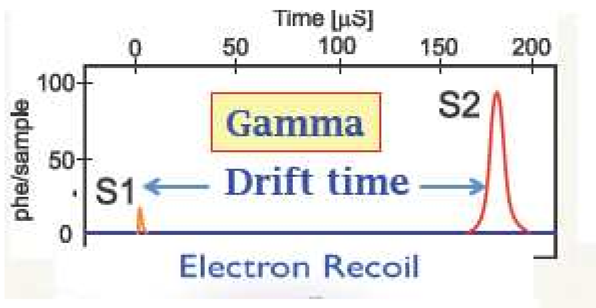
The LUX Dark Matter Search





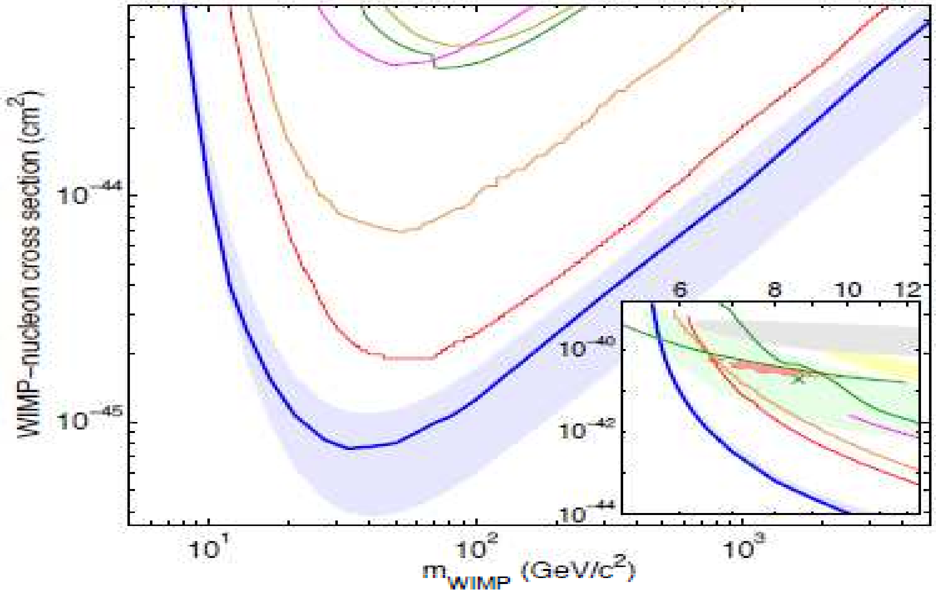


$S2/S1_{Gamma} >> S2/S1_{WIMP}$



arXiv:1310.8214

The LUX 90% confidence limit on the spin-independent elastic WIMP-nucleon cross section (blue), together with the $\pm 1\sigma$ variation from repeated trials, where trials fluctuating below the expected number of events for zero BG are forced to 2.3 (blue shaded). We also show Edelweiss II (dark yellow line), CDMS II (green line), ZEPLIN-III (magenta line) and XENON100 100 live-day (orange line), and 225 live-day (red line) results. The inset (same axis units) also shows the regions measured from annual modulation in CoGeNT (light red, shaded), along with exclusion limits from low threshold re-analysis of CDMS II data (upper green line), 95% allowed region from CDMS II silicon detectors (green shaded) and centroid (green x), 90% allowed region from CRESST II (yellow shaded) and DAMA/LIBRA allowed region interpreted by (grey shaded).



A profile-likelihood analysis technique shows our data to be consistent with the background-only hypothesis, allowing 90% confidence limits to be set on spin-independent WIMP-nucleon elastic scattering with a minimum upper limit on the cross section 7.6×10^{-46} cm^2 M(DM)= 33 GeV/c^2

2. Bulk Scintilators

The **DAMA/NaI experiment** investigated the presence of DArk MAtter particles in the galactic halo by exploiting the model-independent annual modulation signature.

- The Earth should be exposed to a higher flux of dark matter particles around June 2, when its rotational velocity is added to the one of the solar system with respect to the galaxy and to a smaller one around December 2.

- The experimental set-up was located deep underground in the Laboratori Nazionali del Gran Sasso in Italy. DAMA/NaI has been replaced by the new generation experiment, DAMA/LIBRA. These experiments are carried out by Italian and Chinese researchers.

- The experiment is composed of 25 highly radio-pure NaI(Tl) crystals arranged in a 5*5 grid. The experimental set-up was made by nine 9.70 kg low-radioactivity scintillating thallium-doped sodium iodide (NaI(Tl)) crystals

For nuclear recoils (such as a potential WIMP signal) the amount of scintillation is suppressed by the quenching factor of 0.30 (0.09) for Na (Iodine) recoils.

The DAMA/NaI set-up observed the annual modulation signature over 7 annual cycles. The presence of a model independent positive evidence in the data of DAMA/NaI was first reported by the DAMA collaboration in fall 1997 and published beginning of 1998.

For a cumulative exposure of 1.17 ton-yr covering a period of 13 annual cycles an event rate of 1 count/kg/keV/day is measured.

The modulation signal, which has a statistical signicance of 8.9 σ implies a dark matter event rate on the order of 0.4 counts/kg/keV/day.

Although the WIMP nucleon cross section calculated from this data is compatible with some minimally constrained supersymmetric models (MSSM), it is incompatible with the current upper limits from other experiments .

- Other experiments using NaI crystals include ANAIS, NAIAD and ELEGANT V with a proposed experiment, called DM-Ice, planning to deploy NaI crystals 2 km beneath the south pole ice surface.

3. Ionization Detector

- The CoGeNT Dark Matter Experiment is a direct search for signals from interactions of dark matter particles in a low-background germanium detector located at Soudan Underground Laboratory in Soudan, MN.
- IGEX (^{76}Ge)(International Germanium Experiment)
- TEXONO (Taiwan EXperiment On NeutrinO)

- The CoGeNT Dark Matter Experiment is located at Soudan Underground Laboratory in Soudan, MN. The CoGeNT detector began collecting data at the Soudan Underground Laboratory for dark matter searches in December 2009.

In these experiments have been used the ionization signal from high-purity, low radioactivity germanium as their particle detection mechanism.

The detector design called a p-type point contact (PPC) detector uses a 440 g crystal with an electrode design optimized for low capacitance in order to achieved sufficiently high energy resolution to allow for a 0.4 keVee threshold.

The dark matter interpretation of the CoGeNT signal was been excluded by the XENON 100 collaboration.

4. Threshold Detector

COUPP (The**C**hicagoland **O**bservatory for **U**nderground **P**article **P**hysics) is an experiment in the underground MINOS near detector hall at Fermi lab to demonstrate the performance of a 30 liter, 60 Kg, heavy liquid, room temperature, bubble chamber as a Dark Matter detector..

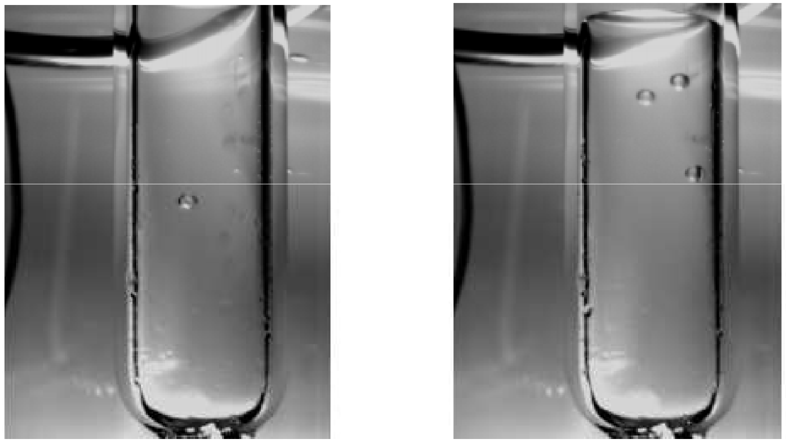


Figure 2.1 (a) A nuclear recoil induced single-bubble event in a 12 ml test chamber. Figure 2.1(b) shows a three-bubble event caused by a neutron.

The PICASSO (**P**roject **I**n **CA**nada to **S**earch for **S**upersymmtric **O**bjects) project is a dark matter search experiment presently installed and taking data in the **SNOLAB** underground laboratory at Sudbury, Ontario, Canada.

The COUPP experiment makes use of a bubble chamber detector to search for dark matter. The bubble chamber contains a superheated liquid (CF_3I) which is the target material.

An energy deposition in the liquid from a particle interaction leads to a local nucleation of a bubble at the interaction site. The pressure spike due to the bubble formation trigger a imaging sensors (video cameras) placed around the detector to record the the event.

An important property of the bubble chamber is that the energy loss per unit of path distance (dE/dx) depends strongly on the temperature and pressure of the superheated liquid. There-fore, by carefully controlling the operating conditions, interactions with very high dE/dx such those from nuclear recoils will result in bubble formation while electron recoil events will not.

5 . Cryogenic Crystal Detectors

The **Cryogenic Dark Matter Search** (**CDMS**) is a series of experiments designed directly to detect DM .Using an array of semiconductor detectors at milli-kelvin temperatures, CDMS has set the most sensitive limits to date on the interactions of WIMP dark matter with terrestrial materials.

The first experiment, **CDMSI**, was run in a tunnel under the Stanford University campus. The current experiment, **SuperCDMS**, is located deep underground in the Soudan Mine in northern Minnesota.

The CDMS detectors measure the ionization and phonons produced by every particle interaction in their germanium and silicon crystal. These two measurements determine the energy deposited in the crystal in each interaction, but also give information about what kind of particle caused the event. The ratio of ionization signal to phonon signal differs for particle interactions with atomic electrons ("electron recoils") and atomic nuclei ("nuclear recoils").

- Unlike the superheated liquids cryogenic detectors are sensitive to all particle interactions.

- We can identify electron and nuclear-recoil with an efficiency of than 99.9998%

Result of CDMSII released on December 16, 2013.

CRESST (Cryogenic Rare Event Search with Superconducting Thermometers)

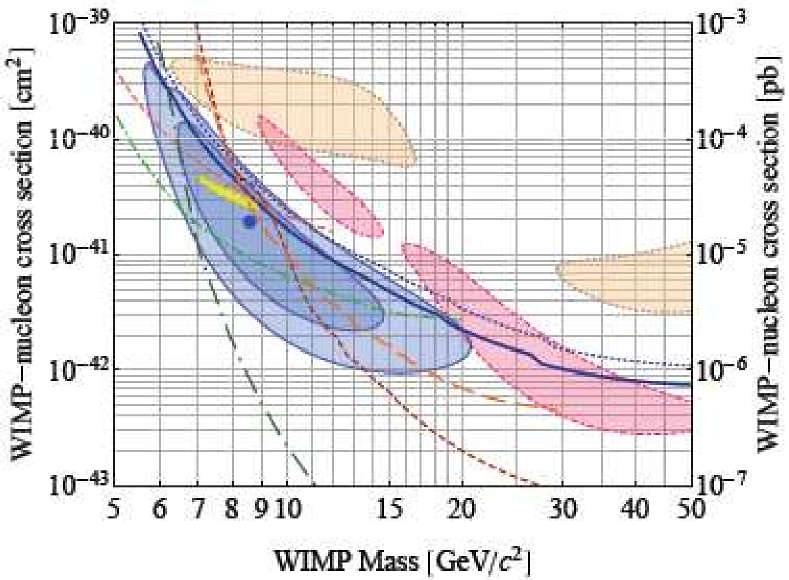
- Currently, the experiment, located at the Gran Sasso is being upgraded.The latest setup contained 17 detector modules, which partly also implemented new detector technologies and concepts in order to further increase the sensitivity of the experiment.

•The CRESST-II cryogenic Dark Matter search, aiming at detection of WIMPs via elastic scattering off nuclei in $CaWO_4$ crystals, completed 730 kg days of data taking in 2011.

This blind analysis of 140.2 kg-days of data taken between July 2007 and September 2008 revealed three WIMP-candidate events with a surface-event background estimate of $0.41^{+0.20}_{-0.08}(stat.)^{+0.28}_{-0.24}(syst.)$

The probability that the known backgrounds would produce three or more events in the signal region is 5.4%.

arXiv:1304.4279



Experimental upper limits (90% confidence level) for the WIMP-nucleon spin-independent cross section as a function of WIMP mass. We show the limit obtained from the exposure analyzed in this work alone (*blue dotted line*), and combined with the CDMS II Si data set reported in (*blue solid line*). Also shown are limits from the CDMS II Ge standard and low-threshold analysis (*dark and light dashed re...*), EDELWEISS low-threshold (*long-dashed orange*), XENON10 S2-only (*dash-dotted green*), and XENON100 (*long-dash-dotted green*). The filled regions identify possible signal regions associated with data from CoGeNT (*dashed yellow*, 90% C.L.), DAMA/LIBRA (*dotted tan*, 99.7% C.L.), and CRESST (*dash-dotted pink*, 95.45% C.L.) experiments. 68% and 90% C.L. contours for a possible signal from these data alone are shown in light blue. The blue dot shows the maximum likelihood point at (8.6 GeV/c^2, 1.9×10^{-41} cm^2).

6. Directional Detectors

- The DRIFT (Directional Recoil Identification from Tracks) programme is a UK-US joint effort at the UK's Boulby deep underground site

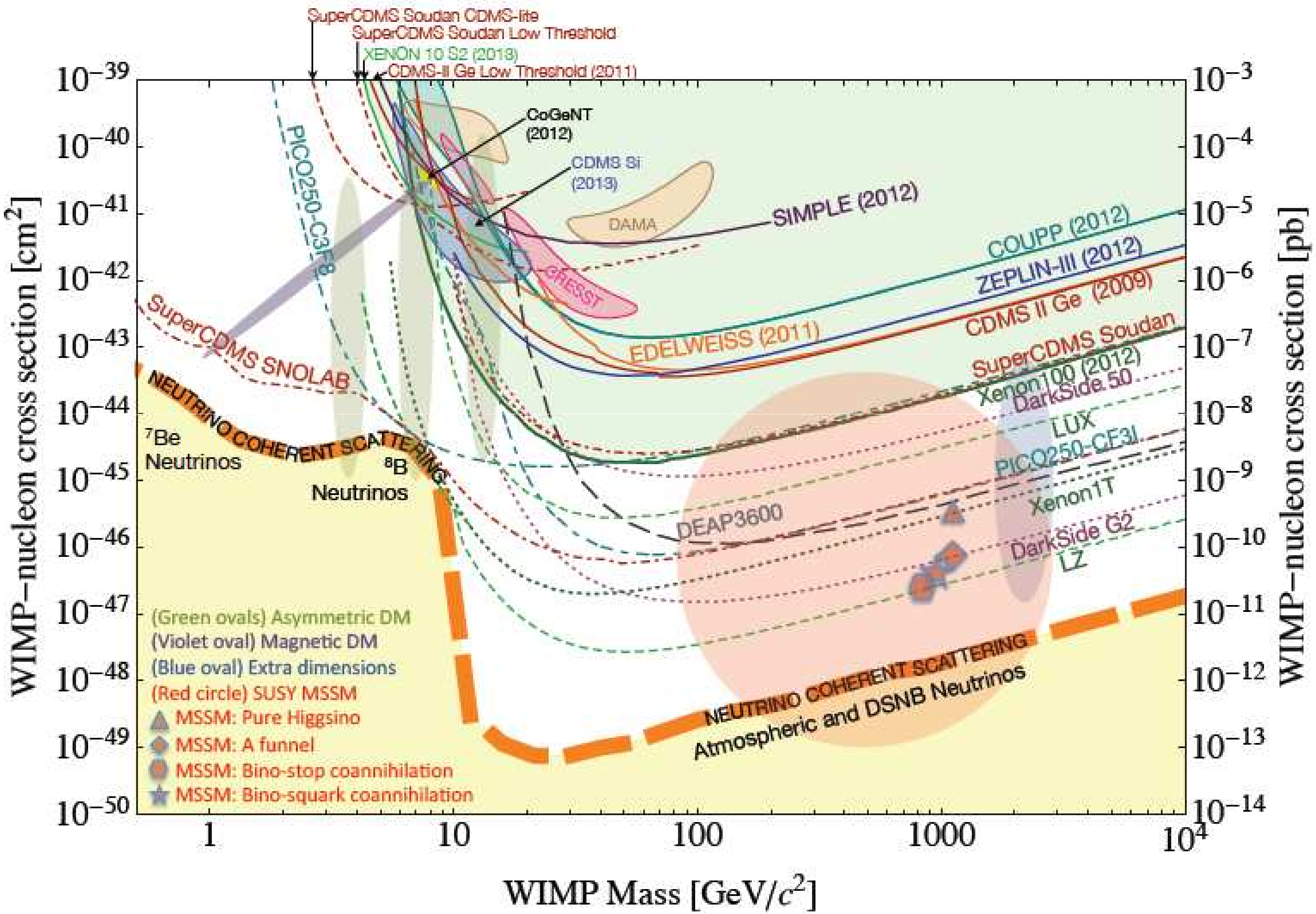
7. Single-phase Noble Liquids

- *DEAP/CLEAN* collaboration is composed of 16 institutions in the United States and Canada

The DEAP & CLEAN collaborations are pursuing a staged approach to WIMP detection, focused on exploiting the unique properties of liquid argon and neon as a scintillator

- XMASS experiment aims to detect the cold dark matter directly using liquid Xenon (at about -100℃).

Current WIMP Cross-section Limits



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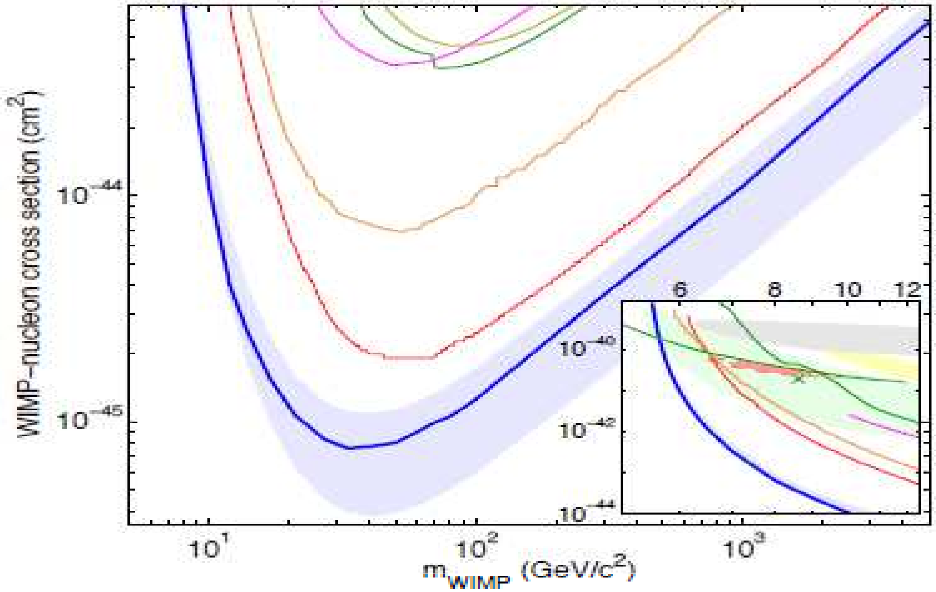

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