Direct Dark Matter Searches

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A short (and biased) review of the last 100 years in history

- In 1933, while studying the properties of “nebulae”, Fritz Zwicky found a discrepancy of two orders of magnitude between mass from virial theorem and expected mass from luminosity in the Coma cluster...

Die Rotverschiebung von extragalaktischen Nebeln

von **F. Zwicky.**

(16. II. 33.)

The Redshift of Extragalactic Nebulae

by F. Zwicky.

(16.II.33.)

§5. Remarks concerning the dispersion of velocities in the Coma nebular cluster.

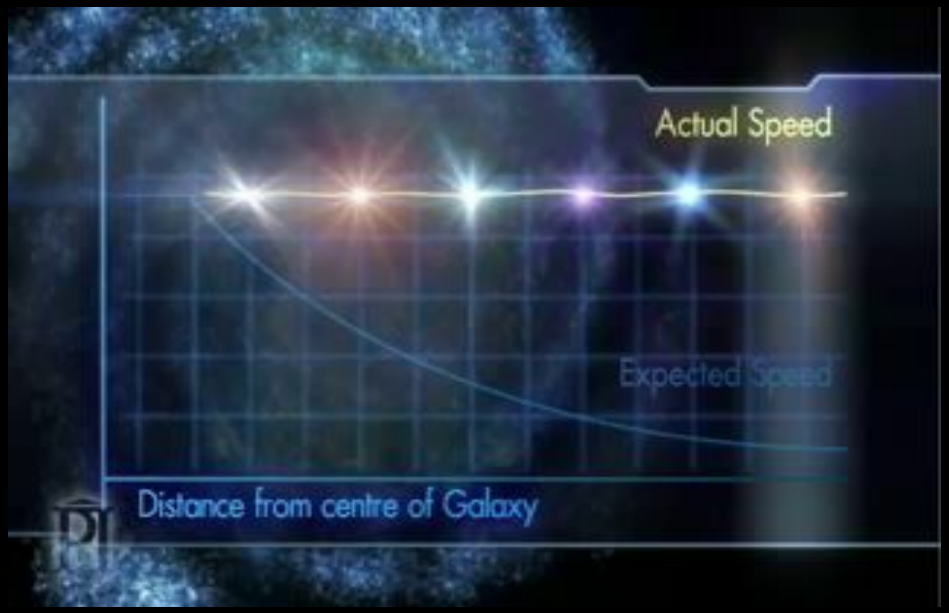
$$\overline{\epsilon}_k = -\frac{1}{2}\overline{\epsilon}_p$$

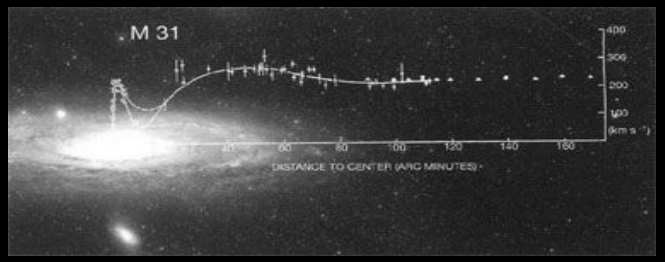
$$\overline{\epsilon}_p = \Omega/M \sim -64 \times 10^{12}\ \mathrm{cm^2 s^{-2}}$$

In order to obtain the observed value of an average Doppler effect of 1000 km/s or more, the average density in the Coma system would have to be at least 400 times larger than that derived on the grounds of observations of luminous matter.[8] If this would be confirmed we would get the surprising result that dark matter is present in much greater amount than luminous matter.

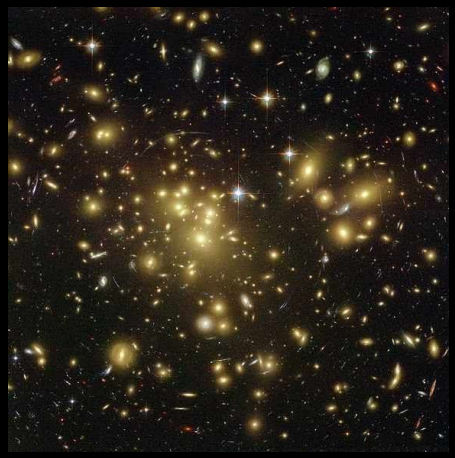
A short (and biased) review of the last 100 years in history

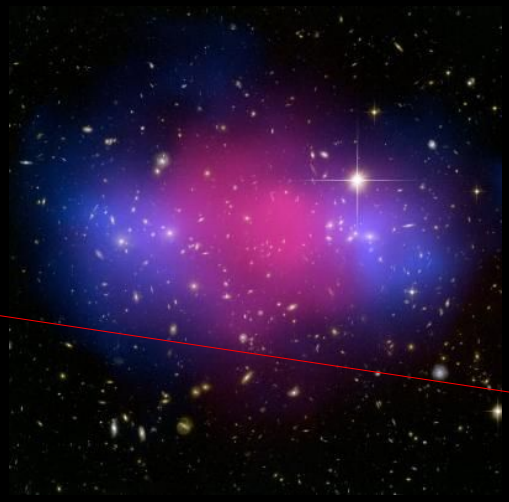
- 40 years after Zwicky's discovery, Vera Rubin finds that velocity of stars around galaxies is constant at high radii. Newtonian dynamics says it should decrease...

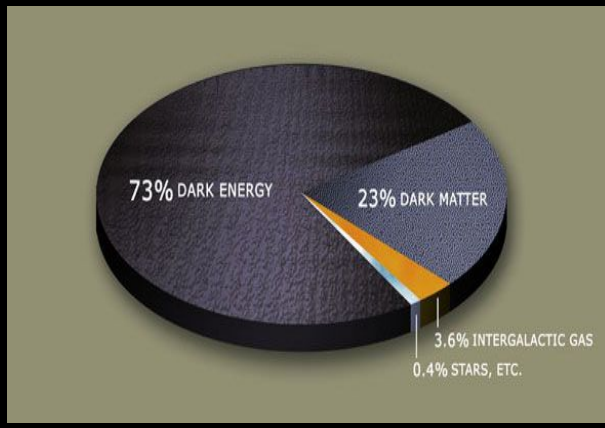


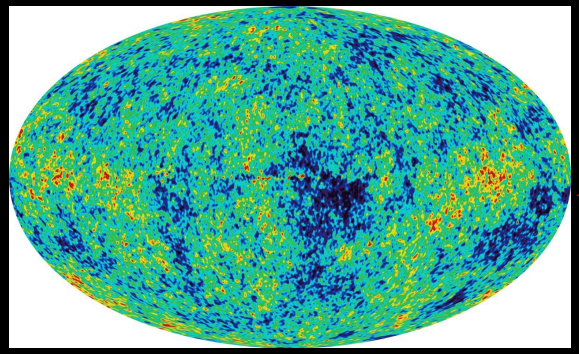


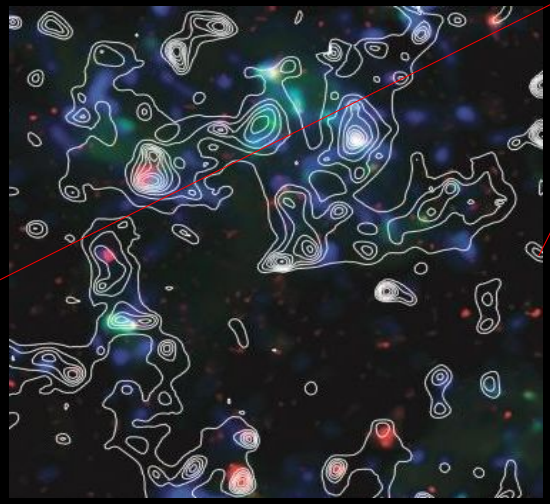
A short (and biased) review of the last 100 years in history





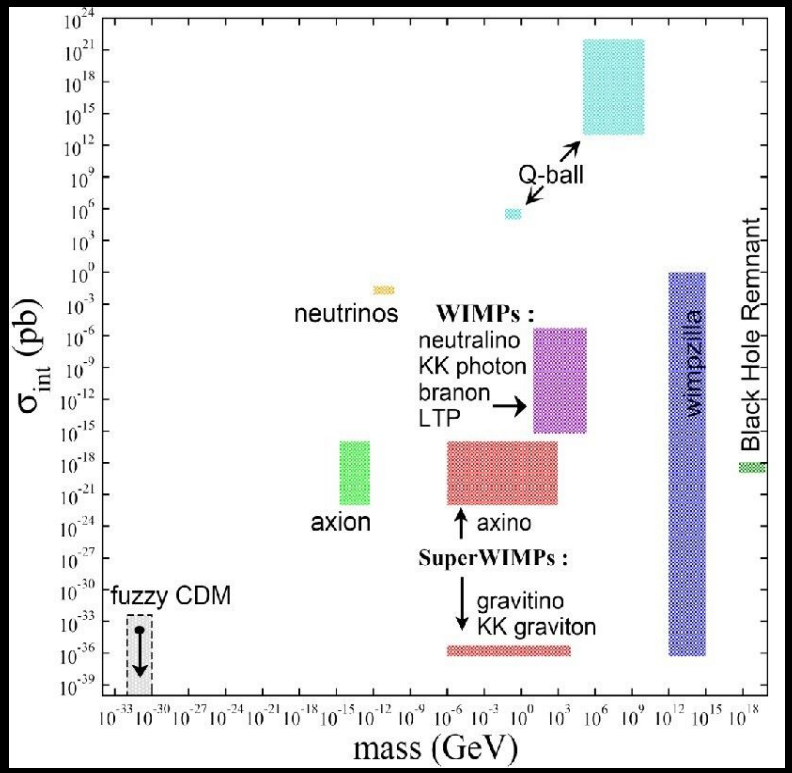






What is dark matter?

- Could be some new kind of particle
  - It interacts gravitationally → massive
  - It is present since the big bang → long lived
  - It does not interact a lot with regular matter → weak scale interactions
  - Non-barionic
- Candidates over many orders of magnitude. Some are very well motivated: Weakly Interacting Massive Particles (WIMPs)

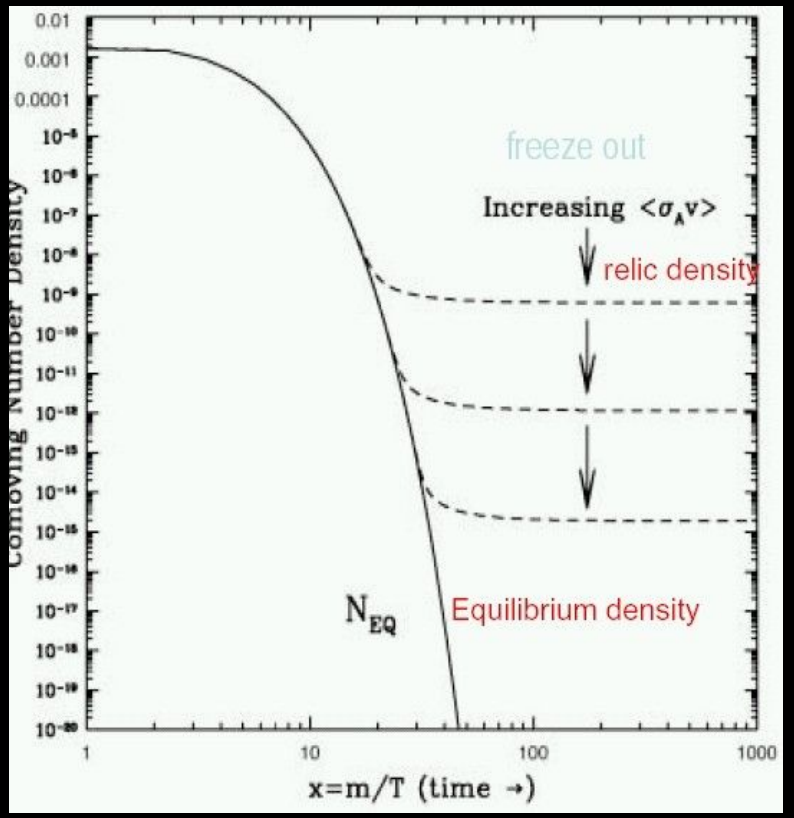


The WIMP miracle

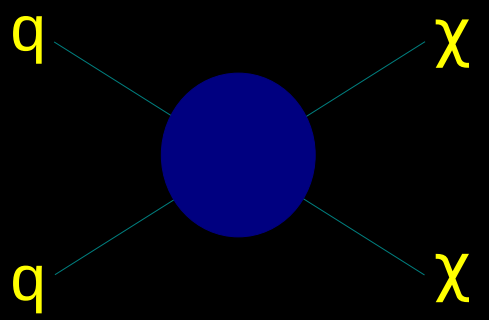
- WIMPs existed in thermal equilibrium in the early universe
- They decouple when T<<M
- The relic density given by

$$\Omega_\chi h^2 \sim 3 \times 10^{-27} cm^3 s^{-1} \frac{1}{< \sigma_a v >}$$

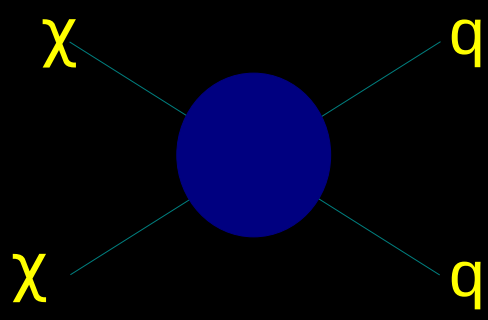
  is the right one if the annihilation cross section is weak
- Such particles are predicted in most extensions of the standard model of particles



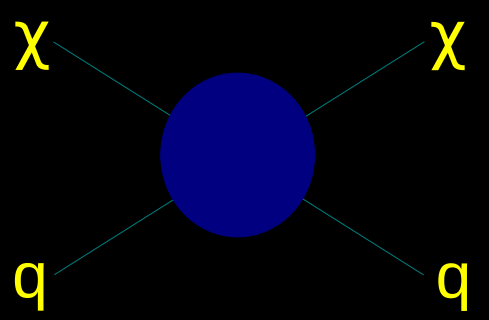
WIMP interactions



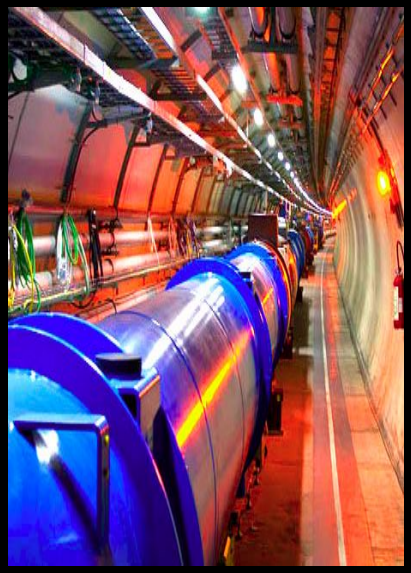
Production



Annihilation



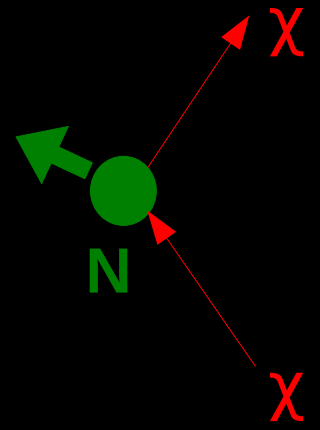
Scattering



WIMP scattering kinematics

- After an elastic WIMP-nucleus interaction the recoil energy of the nucleus is

$$E_{nr} = \frac{\mu^2 v^2}{m_N}(1 - cos\theta)$$



- E_{nr} Recoil energy of the nucleus
- μ Reduced mass of the nucleus-WIMP system
- v WIMP velocity
- m_N Nucleus mass
- θ scattering angle in the center of mass system

WIMP scattering kinematics

Expected interaction rate

$$\frac{dR}{dE_{nr}} \propto N \frac{\rho_\chi}{2\, m_\chi \mu^2} \sigma_N \left|F^2(E_{nr})\right| \int_{v_{min}}^{v_{esc}} \frac{f(\vec{v})}{v} d^3v$$

Number of targets

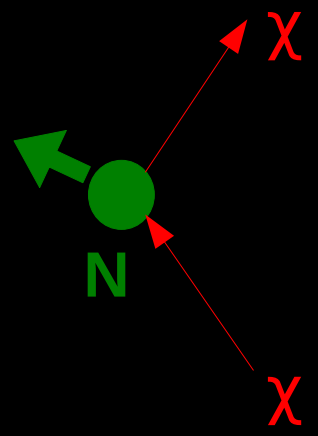
WIMP density

Nuclear Form factor

WIMP mass

Interaction cross section

WIMP velocity distribution



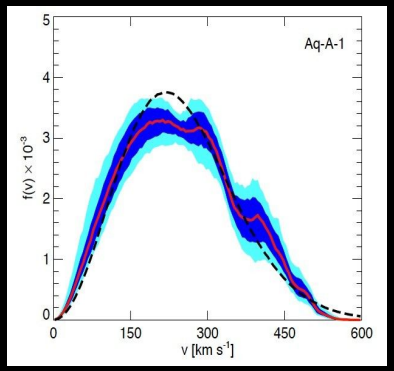
- Only those WIMPs with velocity above threshold will contribute to that energy

$$v_{min} = \sqrt{\frac{m_N E_{nr}}{2\,\mu^2}}$$

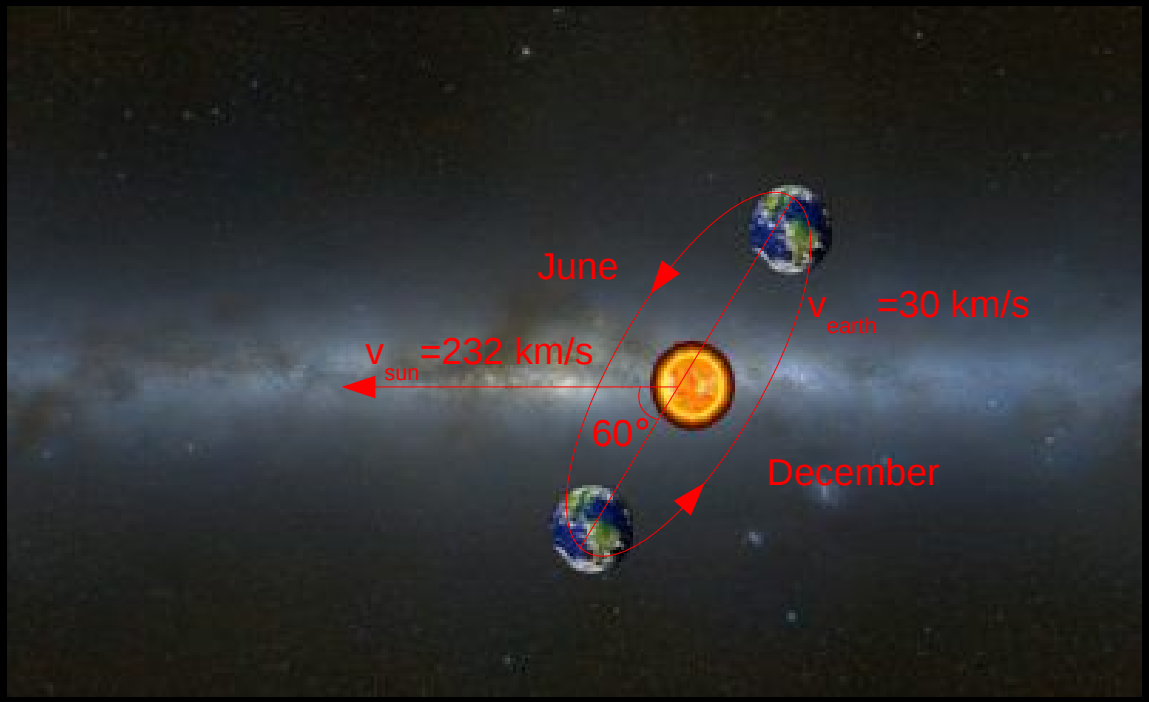
- For Spin Independent interactions the cross section is enhanced by a factor A^2 (coherent scattering)

WIMP Halo

- Our galaxy is immersed in a WIMP halo
- WIMPs velocities are distributed approximately Maxwellian with a typical speed of 220 km/s

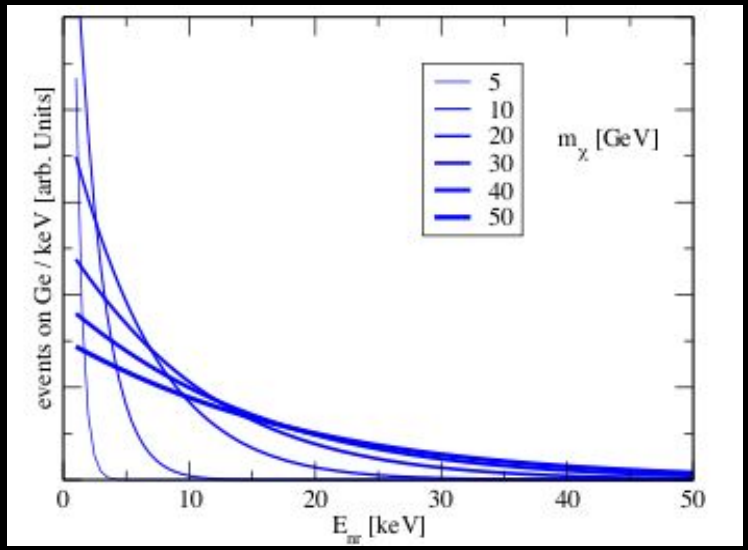


- The Sun moves in this halo at a speed of 232 km/s
- The Earth moves around the sun at 30 km/s



Expected WIMP signal

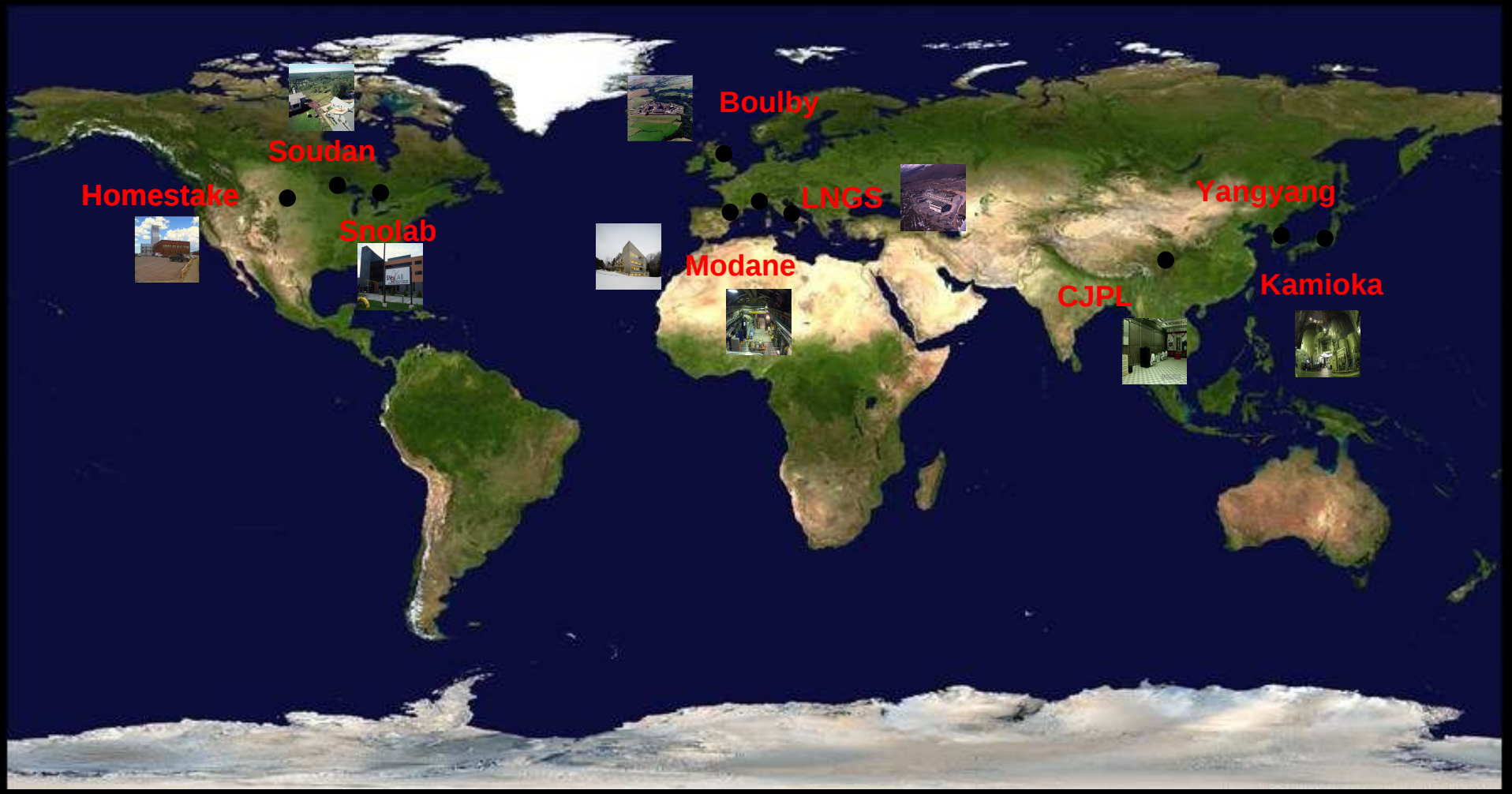
- A WIMP interaction would produce an exponentially decaying spectrum of recoiling nuclei
- The number of interactions and the sharpness of the spectrum depend on the mass and cross section of the WIMP
- Due to the Earth movement, we expect a modulation of the interaction rate along the year



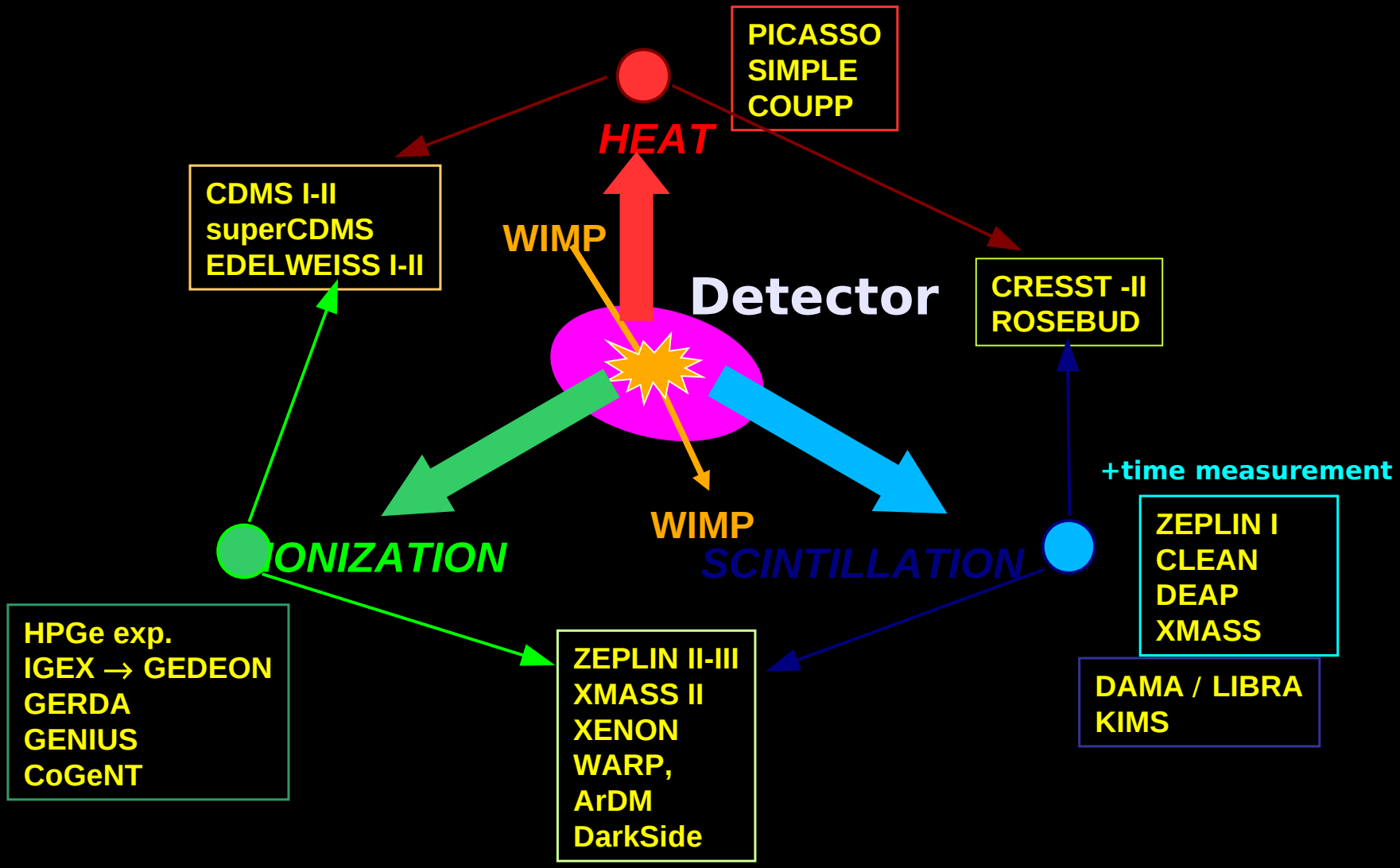
Backgrounds

- Different sources can mimic a WIMP signal:
  - Environmental radioactivity (n, γ)
  - Detector radioactivity (n, γ)
  - Target radioactivity (α, β, γ)
  - Muon-induced neutrons
- Strategies to deal with these must be adopted
  - Shielding
  - Discrimination between different interactions
  - Selection of clean materials
  - Going underground

Dark Matter Laboratories around the world



WIMP detection techniques



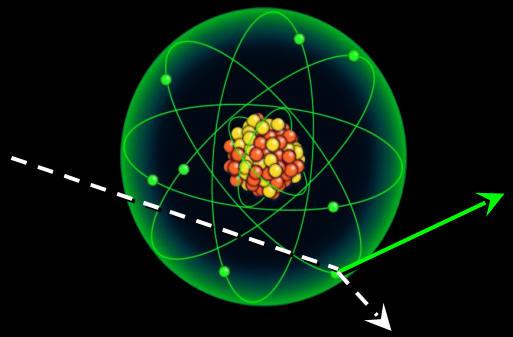
Running Dark Matter Experiments: XENON100

- XENON100 is a dual phase liquid xenon TPC
- Target: 30 cm drift x 30 cm diameter TPC
- 162 kg ultra pure LXe (target + veto)
- Cryocooler and FTs outside shield

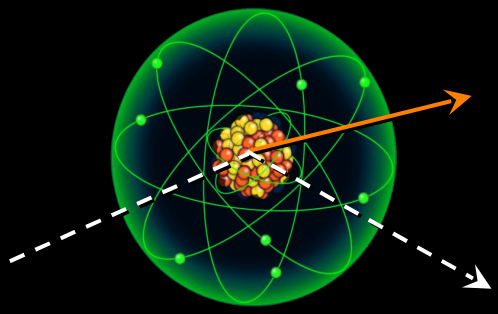
- Selection of materials for low radioactivity
- 1 mBq (U/Th) and ~30% QE 1-inch square PMTs

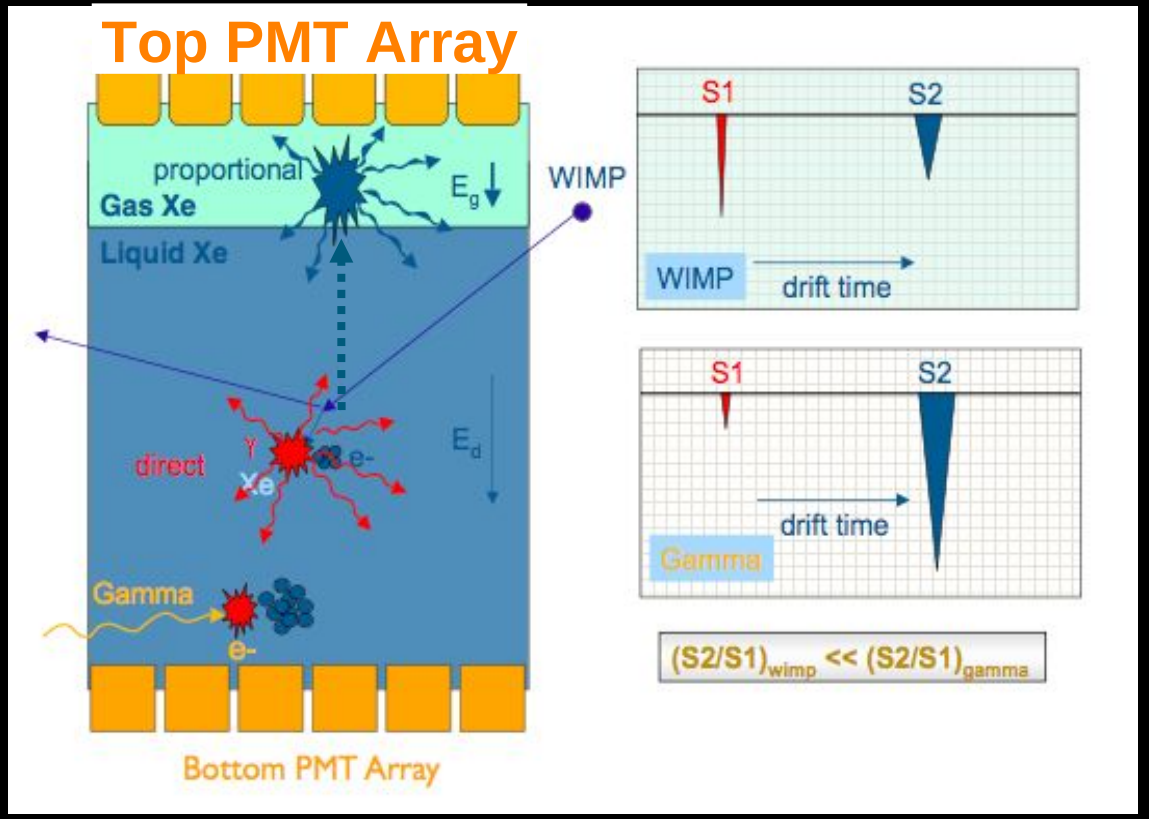
Running Dark Matter Experiments: XENON100

e^-/γ: electron recoil



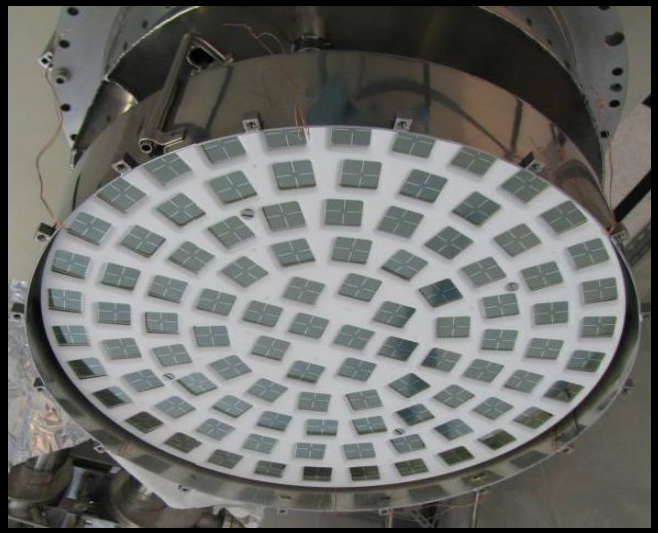
n/WIMPs: nuclear recoil





- **Single electron and single photon measurement sensitivity**
- **> 99.5% ER rejection via Ionization/Scintillation ratio (S2/S1**
- **3D event-by-event imaging with millimeter spatial resolution**

Running Dark Matter Experiments: XENON100



- Two arrays of photosensors detect the light emitted in interactions
- Charge is drifted to the top of the detector and extracted emitting a second light signal

Running Dark Matter Experiments: XENON100

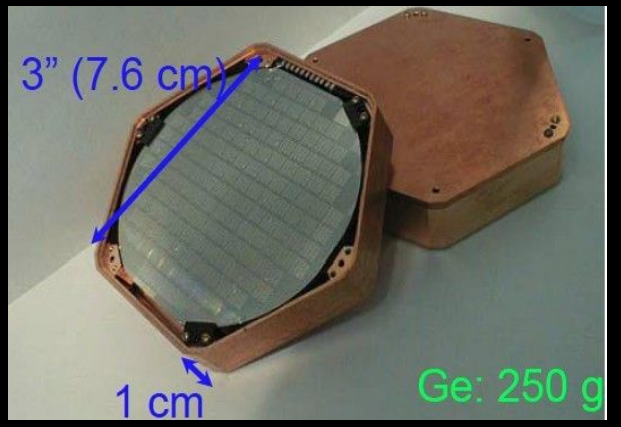
- The volume surrounding the TPC is filled with ~100 kg of liquid xenon
- This liquid xenon acts as a radiation shield thanks to the high Z and density
- The volume is instrumented with 64 PMTs facing the top, bottom and sides of the TPC to reject interactions with one deposition inside the TPC and one in outside (active veto)

Running Dark Matter Experiments: XENON100

- A shield with four layers of materials surrounds the detector:
  - water
  - lead
  - polyethylene
  - copper
- The detector is installed underground at LNGS to shield from cosmic backgrounds

Running Dark Matter Experiments: CDMS

- Located in teh Soudan mine, CDMS uses Ge crystals operated at 40 mK
- It has Transition Edge Sensors (TES) to detect phonos
- Electrodes in the surface of the crystal detect the charge deposit
- Combined charge+phonons signal allows to discriminate 1 in 10^4 gammas from neutrons
- Surface events are rejected with phonon timing measurements

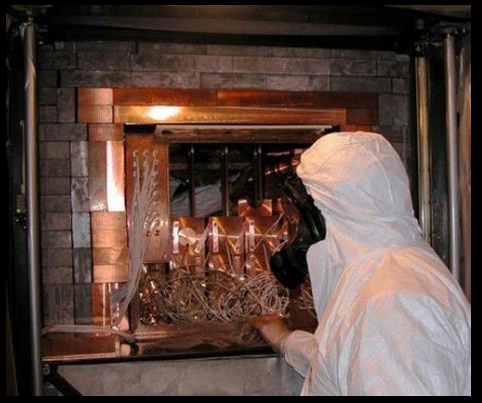


Running Dark Matter Experiments: DAMA/LIBRA

- Installed in LNGS, it uses NaI detectors doped with Tl. Scintillation is measured by means of PMTs. No discrimination between nuclear recoils and electron recoils

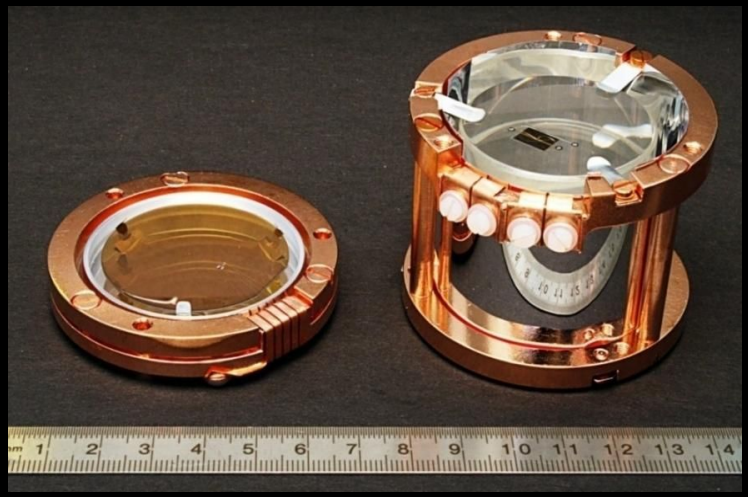
- Started taking date in 1996. Has been upgraded several times since then

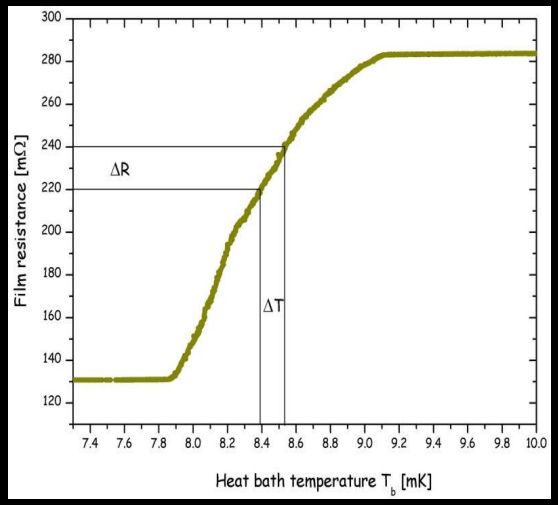
- Has acquired more than 1 tonxyear in the different phases of operation



Running Dark Matter Experiments: CRESST-II

- It is made of 300g supercoducting $CaWO_4$ crystals
- The crystals are cooled down to~15mK
- Changes in the temperature of the crystal are read with transition edge sensors

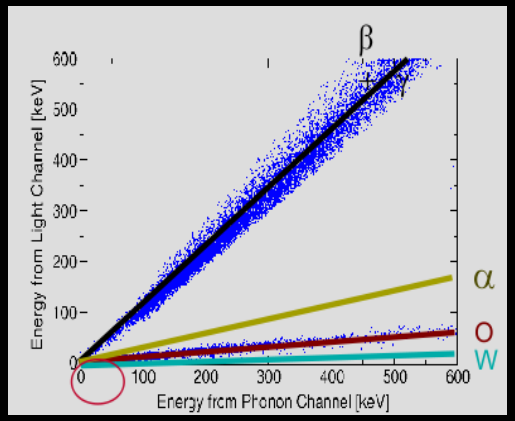


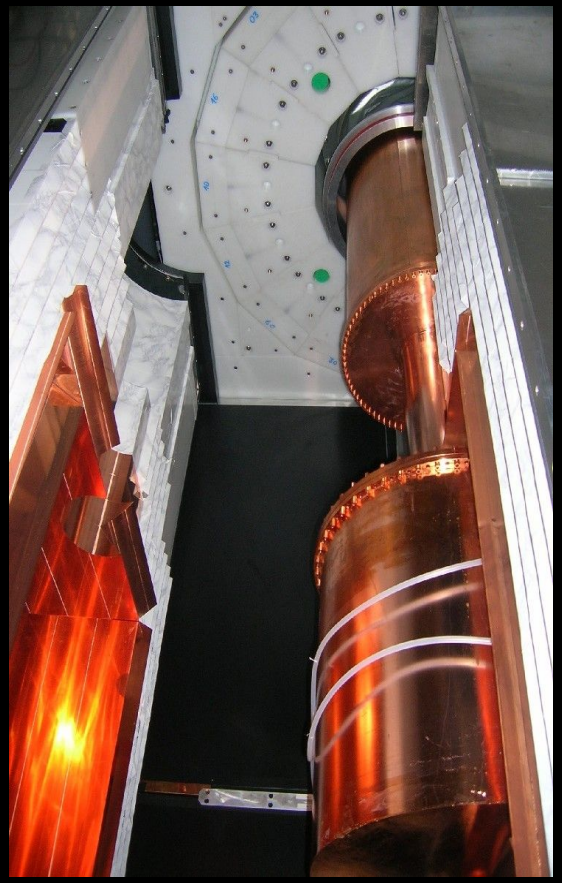


Running Dark Matter Experiments: CRESST-II

- The crystals also produce scintillation. The combined scintillation and phonon signal gives the ability to distinguish interactions from different particles

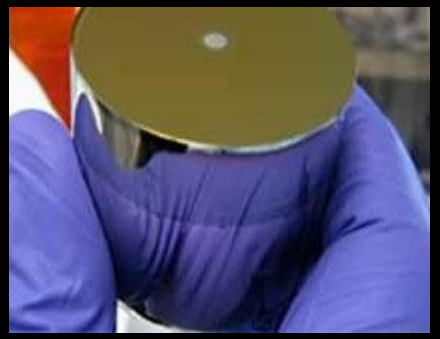
- It is installed in Hall A at LNGS

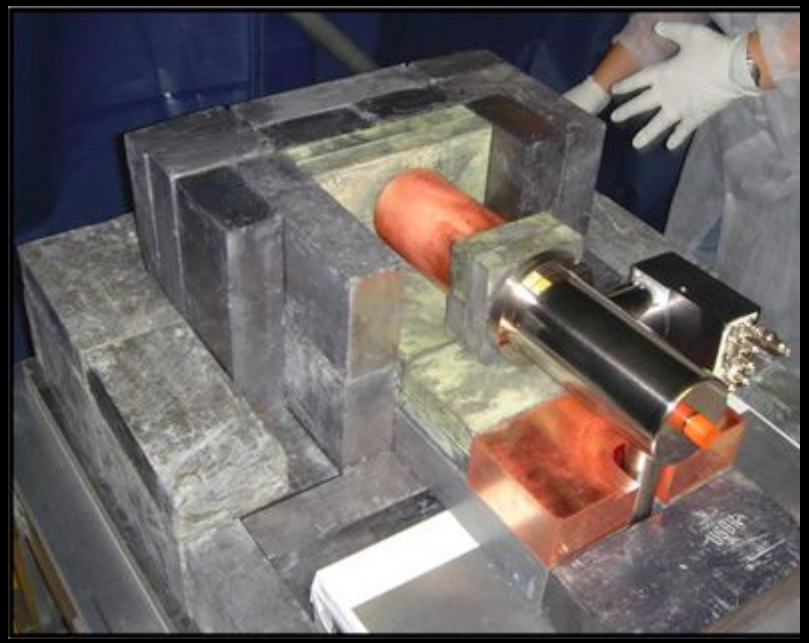




Running Dark Matter Experiments: CoGeNT

- Located in Soudan mine, CoGeNT uses Ge PPC detectors with 440 g each
- It only measures the charge deposited by interactions → no discrimination
- Thanks to the reduced noise in these detectors, the energy resolution and energy threshold are much better than in any other

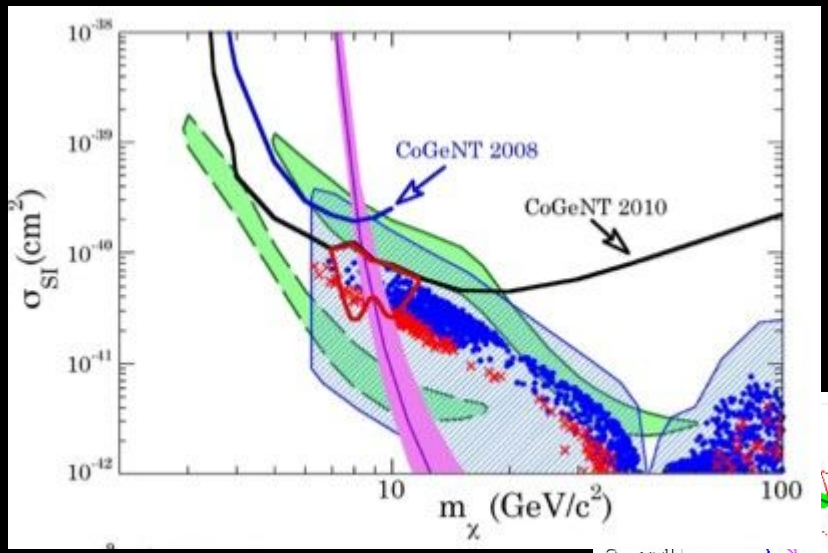


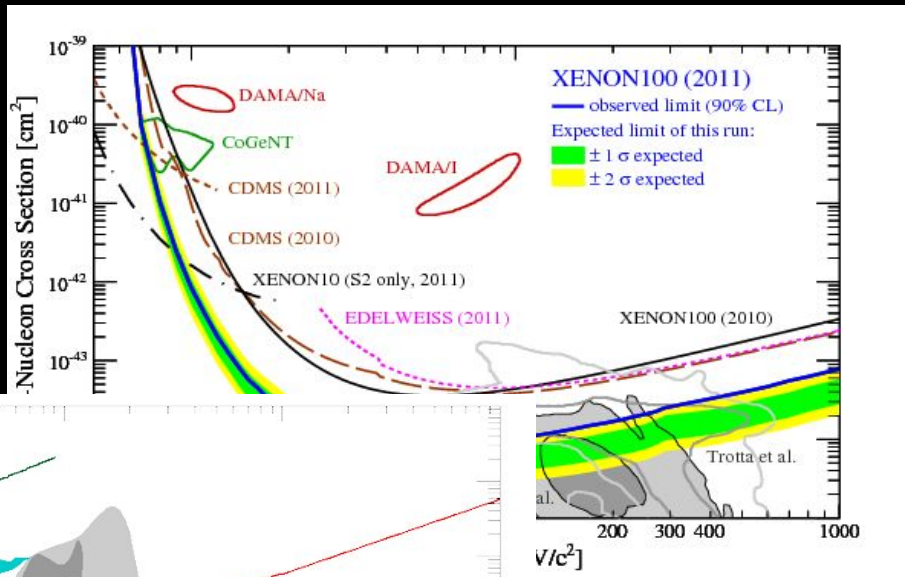


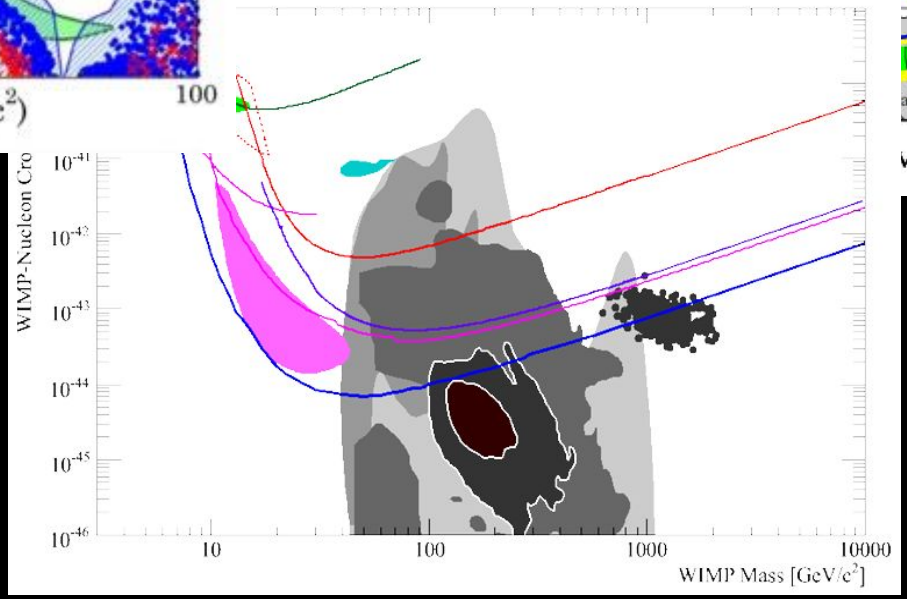
Running Dark Matter Experiments: SIMPLE

- 15 superheated droplet detectors (SDD)
- Each SDD consists of a dispersion of super heated freon droplets in a gel that can become gaseous under an energy deposition
- Nucleation will only happen if the energy deposition occurs in a small volume -> Insensitive to γ's
- When a bubble is produced, the noise is recorded by a microphone, which allows for measurement of the signal

Dark Matter Results: A very confusing time

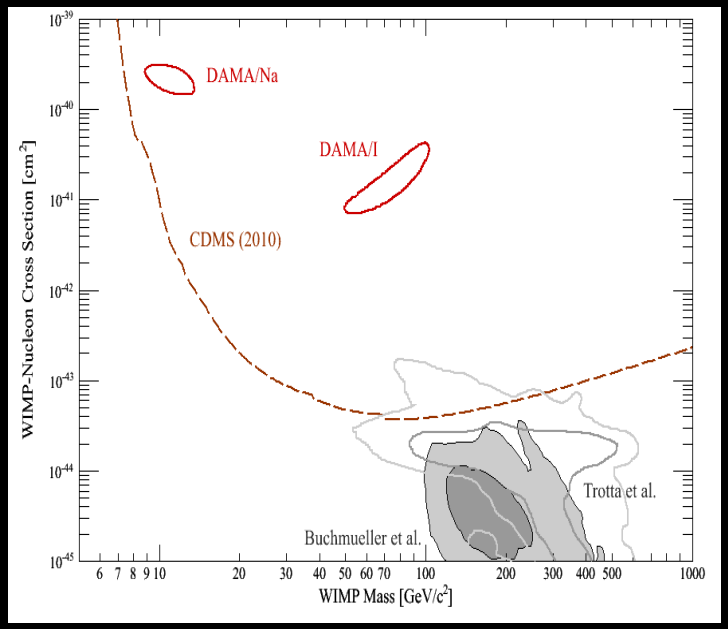


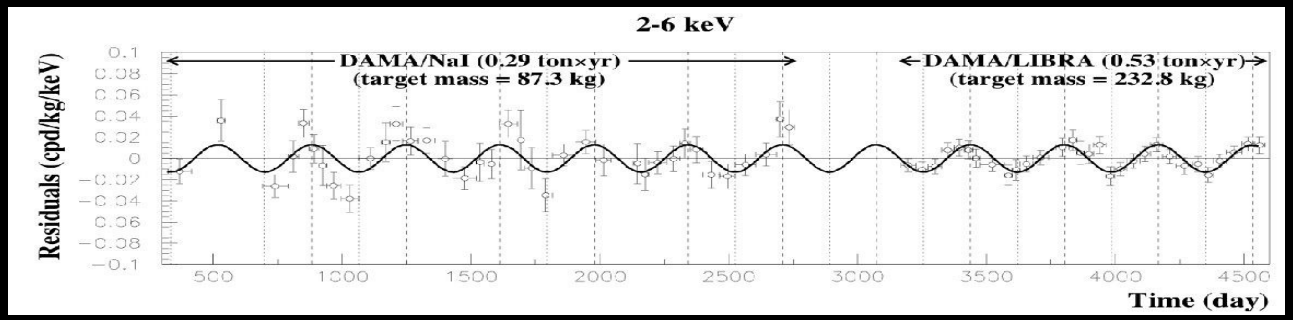




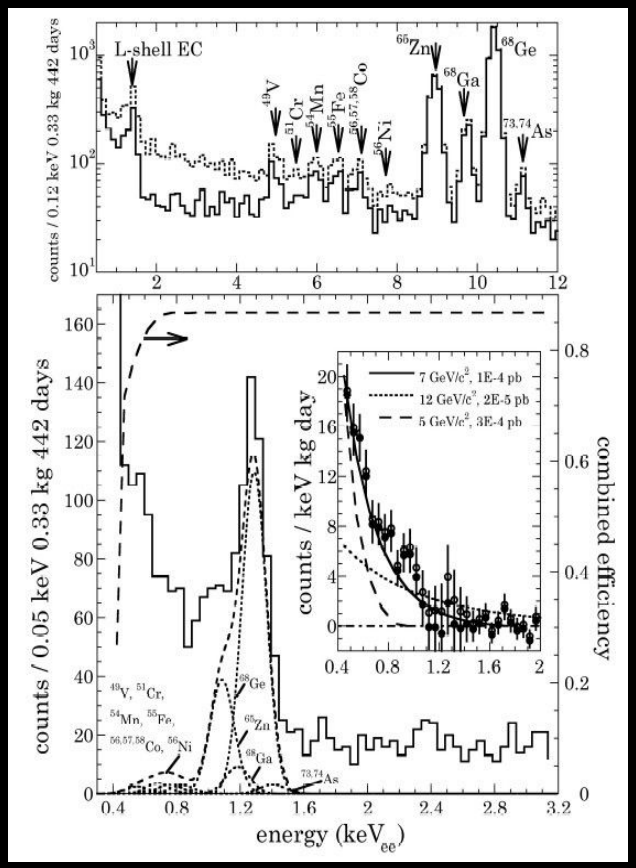
Dark Matter Results: The DAMA/LIBRA observation

- DAMA/NaI and DAMA/LIBRA have been taking data since 1996
- They observe a modulation in the event rate in the lowest energy bin
- This modulation can be interpreted as a dark matter signal. However signal regions are incompatible with other results





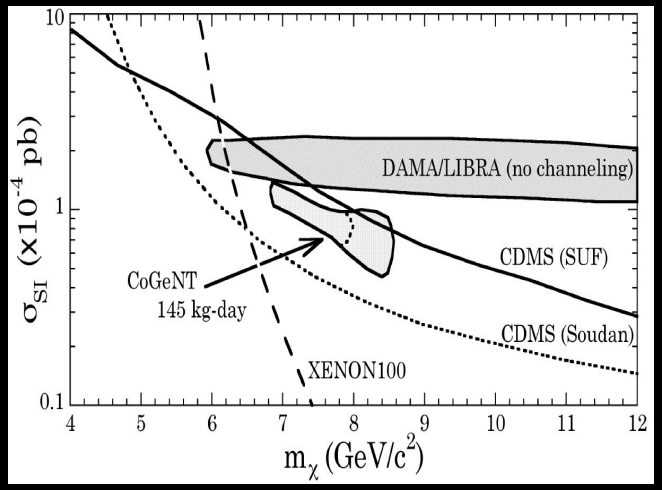
Dark Matter Results: CoGeNT experiment

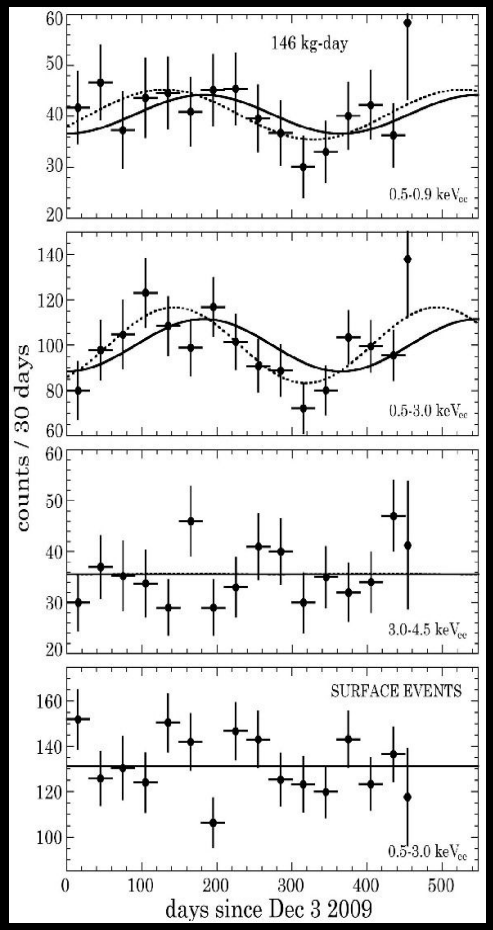


- In 2010 CoGeNT observed an exponential excess in the number of signals at low energies
- They proposed several explanations for this excess, among other a light WIMP particle
- But there is no discrimination in CoGeNT, so it is hard to tell...

Dark Matter Results: CoGeNT experiment

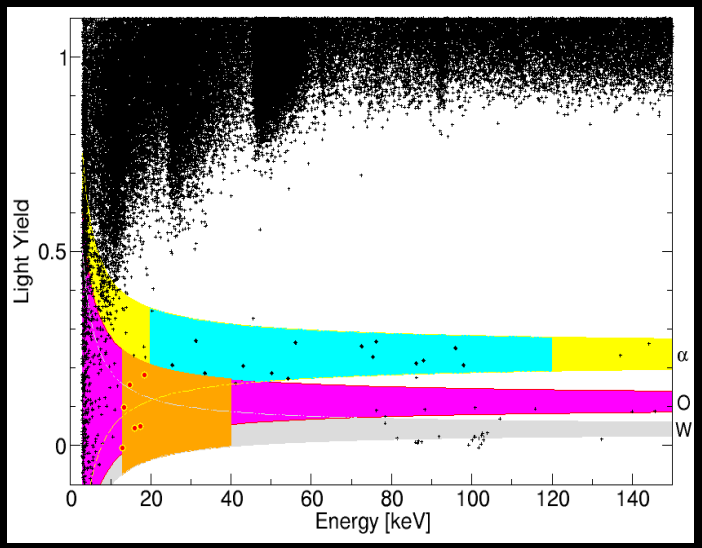
- After one year of data taking, CoGeNT observed a modulation in their signal
- Unfortunately, data taking had to be stopped due to a fire in the lab
- This signal is compatible with the existence of a light WIMP

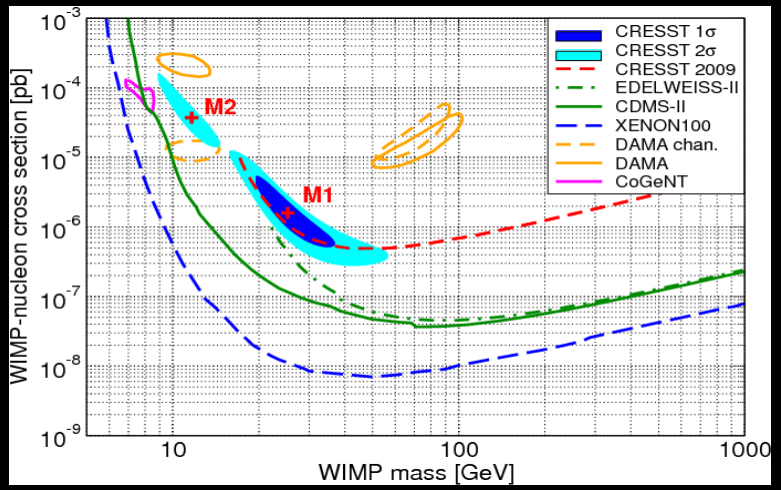




Dark Matter Results: CRESST experiment

- CRESST has presented an analysis with 730 kg x day from 2009-2010 data

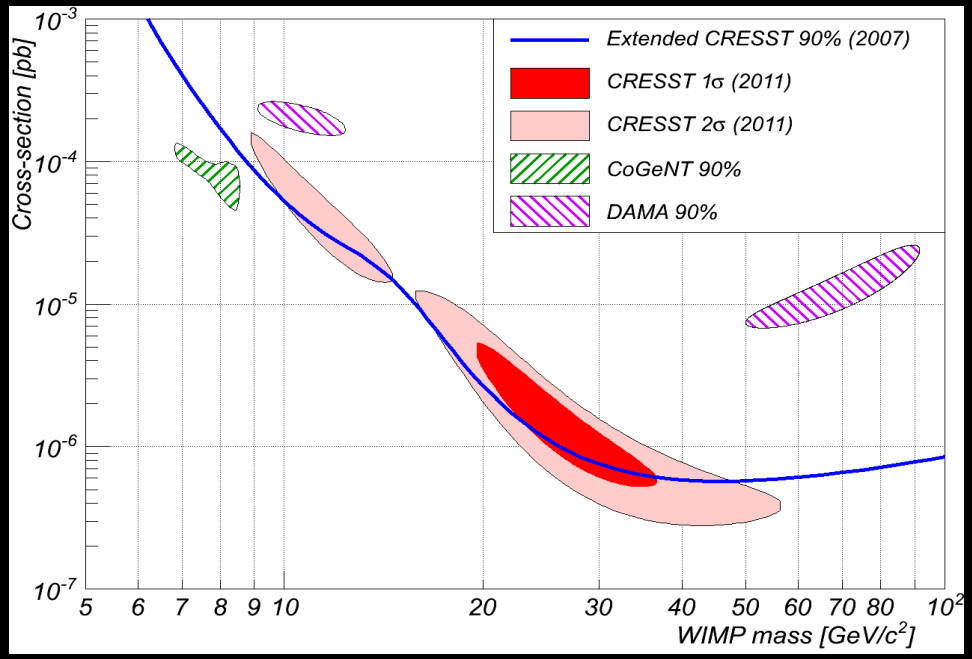




- 67 events are observed in the signal region with an expected background of ~45 events
- Two WIMP regions depending on the recoiling nucleus. Both disfavored by previous experiments

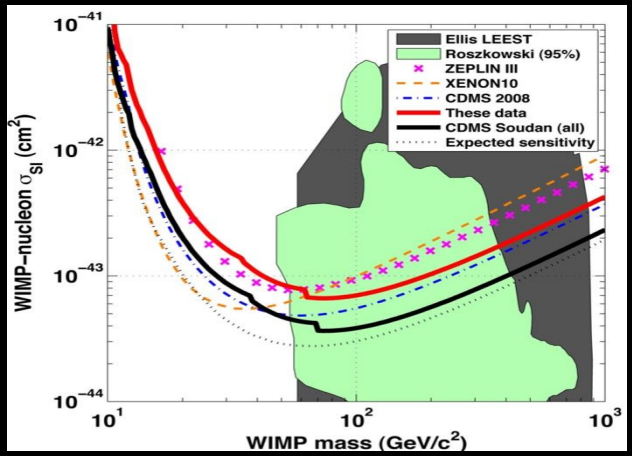
Dark Matter Results: CRESST experiment

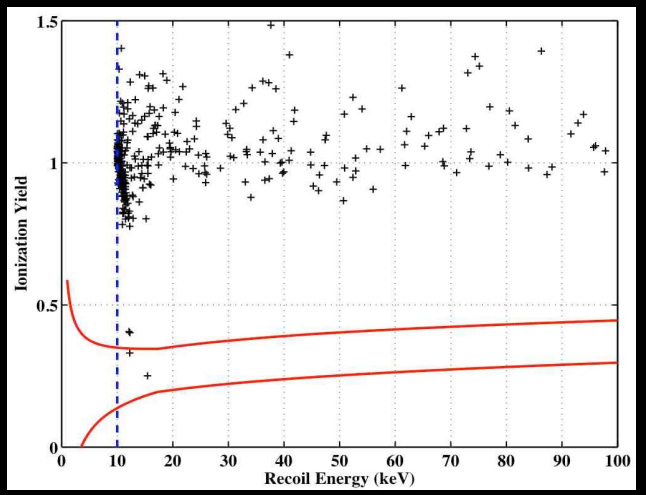
- At the same time a new analysis of the 2007 commissioning run was presented by former members of the collaboration
- The data are reinterpreted assuming that one could also have scatterings in the Oxygen and Calcium bands
- Most of the signal region is excluded



Dark Matter Results: CDMS experiment

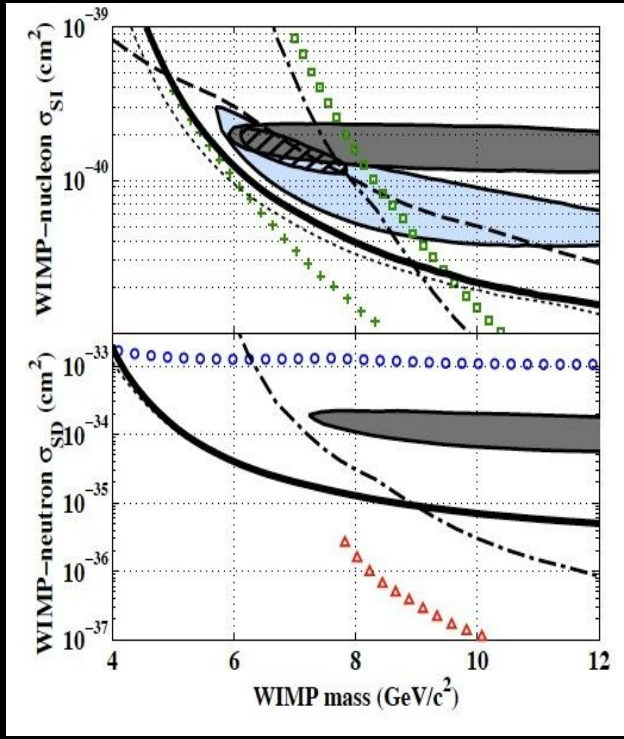
- CDMS acquired an exposure of 191 kgxd
- After all cuts, two events were left in the signal region
- The expected background was 0.8±0.1±0.2
- The probablity of obtaining 2 or more events from this background is 23%

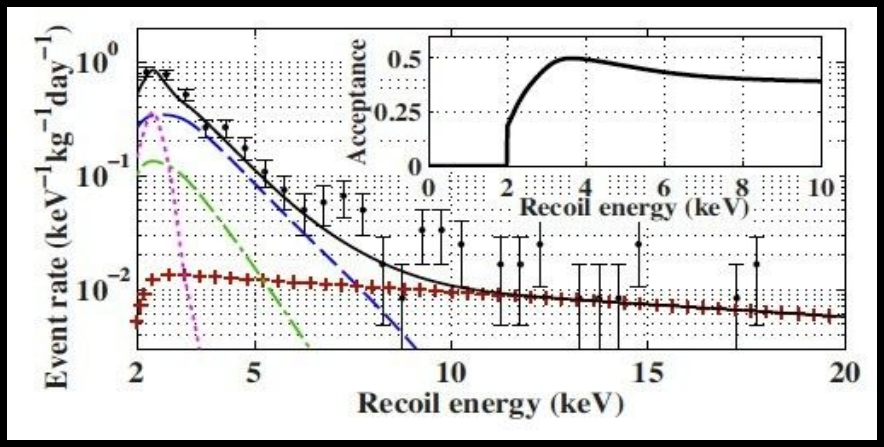




Dark Matter Results: CDMS low threshold analysis

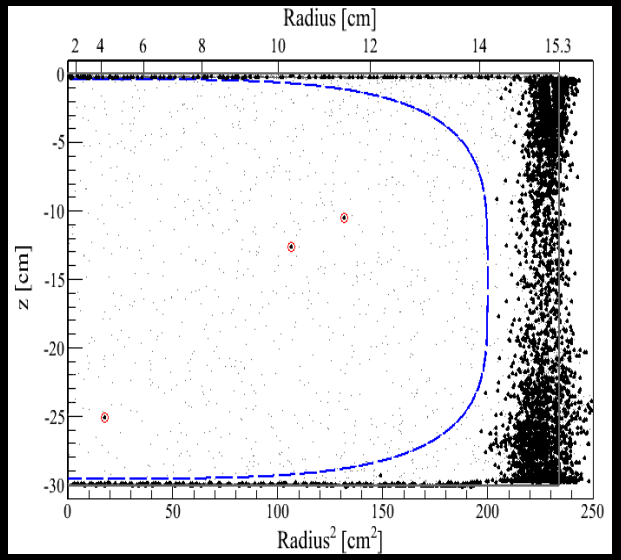
- CDMS reanalyzed their data lowering the threshold and increasing the background
- Background modelled, but every event treated as a dark matter signal
- The limits obtained are in conflict with CoGeNT and DAMA/LIBRA

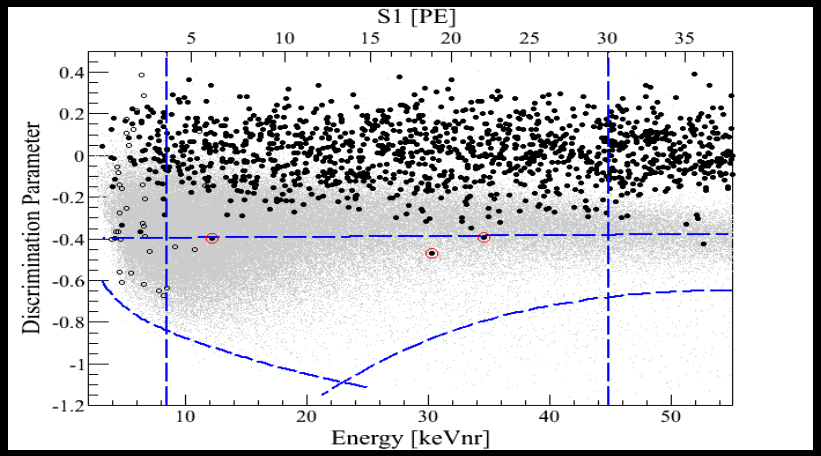


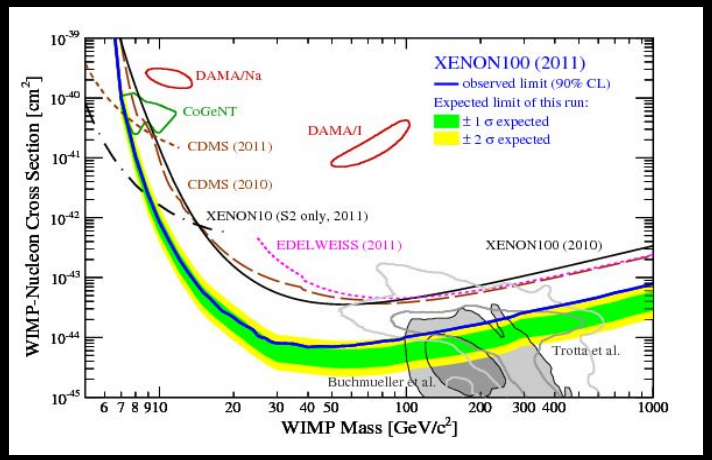


Dark Matter Results: XENON100 experiment

- Data taken for several months in 2010
- Fiducial volume of 48 kg
- Exposure ~1.5 tonsxday after quality cuts
- 3 events found, compatible with background expectation of 1.8±0.6

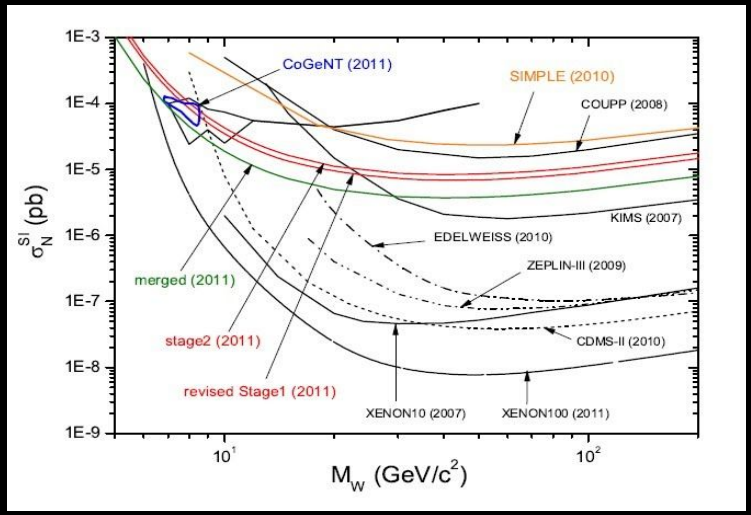






Dark Matter Results: SIMPLE experiment

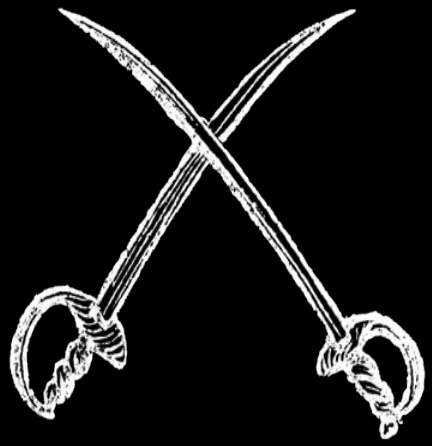
- Target of C_2ClF_5 with a total mass of 0.215 kg
- A two stage search with 14.1 + 13.7 kgxd exposure between 2009 and 2010
- Energy threshold of 8 keV
- Due to the low A of the target material, results are very competitive for low mass WIMPS, and it conflicts the CoGeNT observation



Dark Matter Results: Is there anything out there?

Limit on Dark Matter
Edelweiss
ZEPLIN-III
COUPP

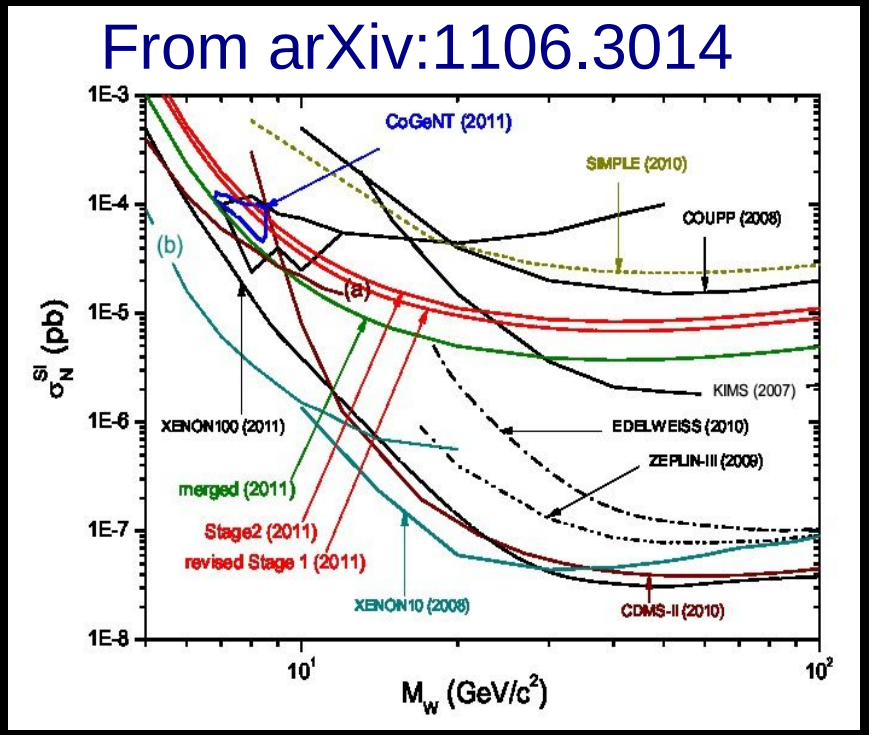
Positive Dark Matter Detection
DAMA/LIBRA
CoGeNT
CRESST-II???

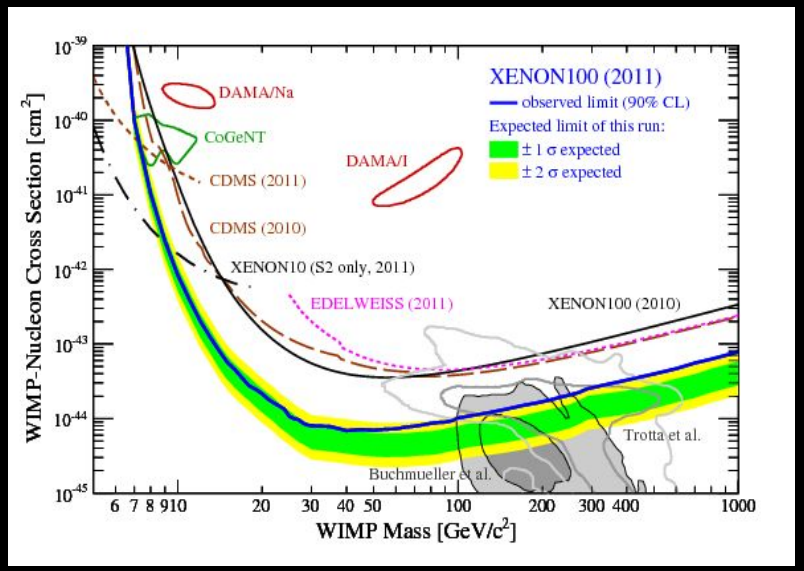


Inconsistent with dark matter detection claims
XENON100
XENON10
CDMS
SIMPLE

Dark Matter Results: Summary

- Contradictory answers from different experiments





- Non standard WIMPs? Hard to match all signals
- Over or underestimation of backgrounds?
- Overestimation of acceptance?

Dark Matter Results: Near Future

- Hopefully CoGeNT will be able to resume data taking in similar noise conditions -> a new annual modulation cycle?
- XENON100 is taking data with a reduced background and reduced threshold
- New experiments are expected to produce new results soon: XMASS, COUPP, KIMS, LUX, CDEX...

Conclusions

- Dark matter was first predicted about 80 years ago
- For the first time, direct detection experiments are approaching the region where theory predicts WIMPs to exist
- Different detectors have claimed hints of low mass WIMPS
- However, different detectors have found results incompatible with these claims
- New data will be available soon that will further clarify the situation
- If WIMPs are there, we should see them soon