Direct search for Dark Matter at Gran Sasso National Laboratories

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The Dark Matter puzzle

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DARK MATTER

Credit: NASA/WMAP Science Team

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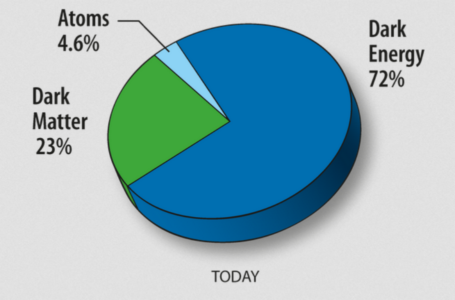

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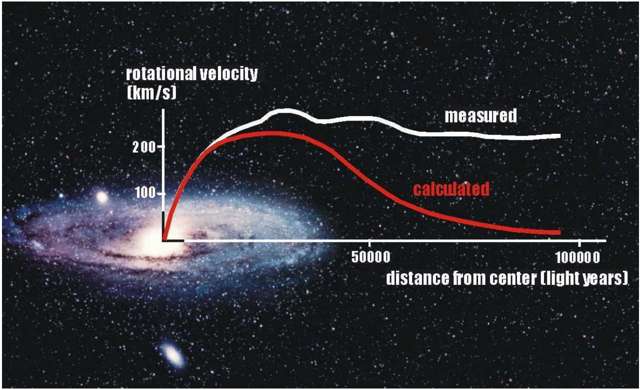
Evidence for Dark Matter, Galaxy rotation curves



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Alternative hypothesis: modified Newtonian dynamics (MOND).

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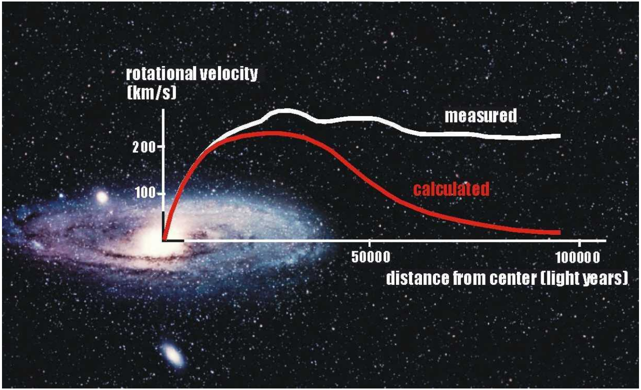

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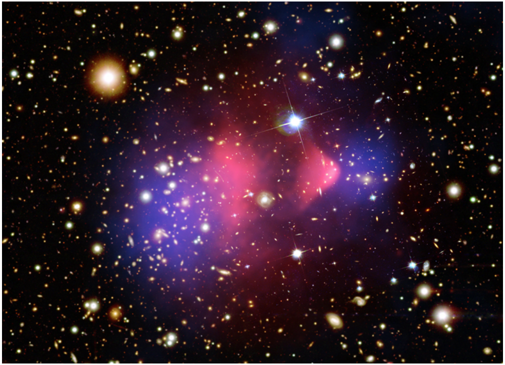

3 components: Galaxies (luminous, collisionless), gas (shocked by collision, X-rays emitting), dark matter (collisionless, weak lensing effect).

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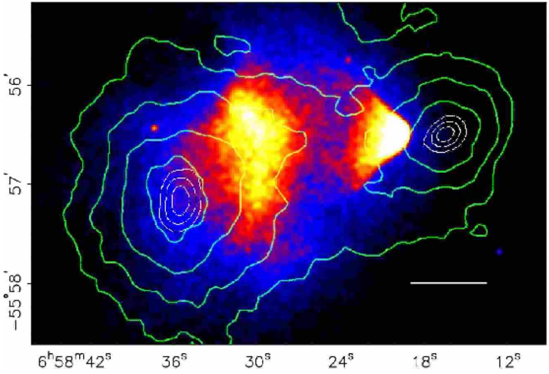

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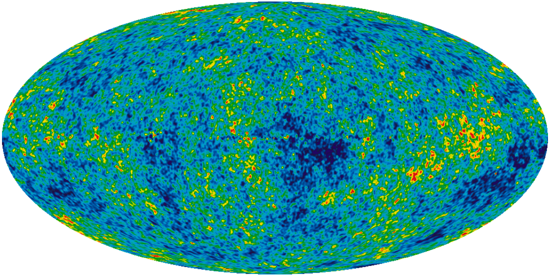
Evidence for Dark Matter, Cosmic Microwave Background



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Detailed measurements of the Cosmic Microwave Background (CMB) temperature fluctuations.
They support ΛCDM model with a flat Universe.

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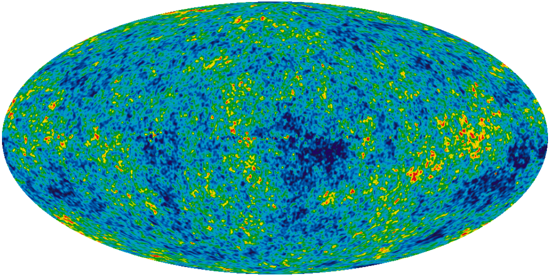

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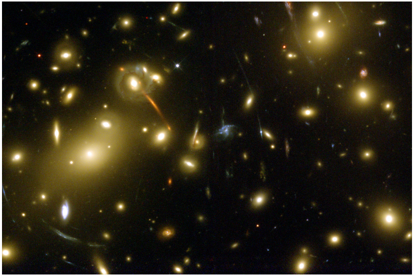
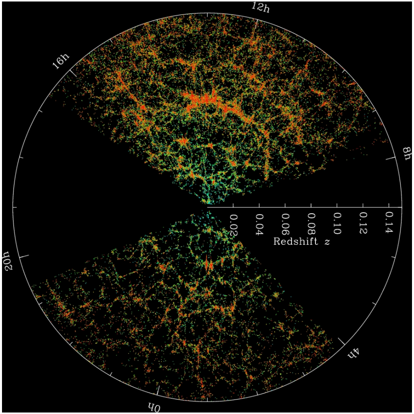
Evidence for Dark Matter

...And many other evidences...



Abell 2218. Credit: NASA/ESA



Large Scale Structure. Credit: Sloan Digital Sky Survey

Properties of Dark Matter

Dark Matter is a component of the Universe with these features:

- It's DARK, neither emitting nor absorbing light. No EM interaction, no electric charge.
- It's massive, gravitational effects.
- Small interaction between DM particles, basically collisionless.
- Small interaction with baryons.
- It's COLD, non relativistic.
- It's stable, its mean decay time is much longer than the age of the Universe.

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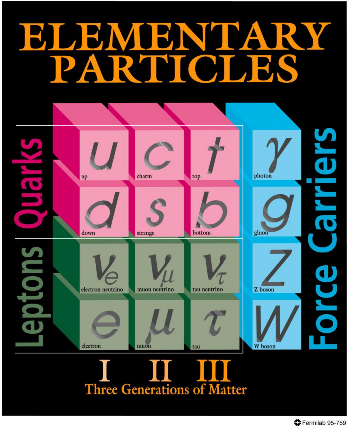
A Standard Model particle as Dark Matter candidate?



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Study of DM $\rightarrow$ Study of physics beyond the SM.

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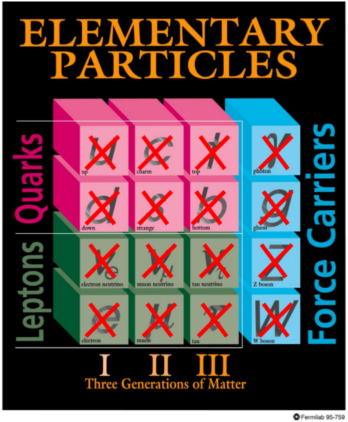

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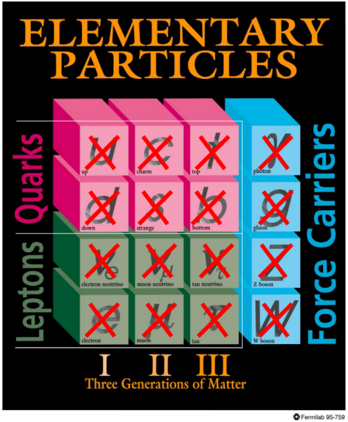

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Weakly Interacting Massive Particles

Weakly Interacting Massive Particles (WIMPs) are a class of DM candidates.

A new stable neutral particle, with feeble interaction and O(100 GeV) mass.

This kind of particles arises in a few theories beyond SM, as Supersimmetry (SUSY) and Universal Extra Dimensions (UED).

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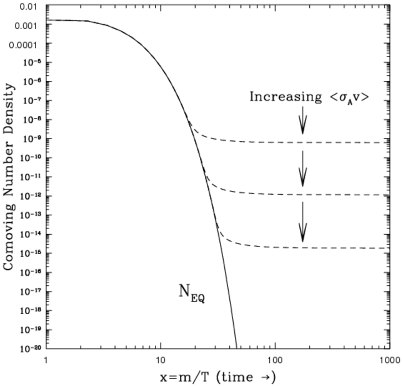
WIMPs are relic particles from the Big Bang.

- Initial thermal equilibrium: $\chi\chi \rightleftarrows q\bar{q}, l\bar{l}$
- Universe cools down: $\chi\chi \to q\bar{q}, l\bar{l} \Rightarrow N_\chi \propto e^{-M_\chi/T}$
- Freeze out: $N \sim const.$



Final abundance determined by annihilation cross section σ_A. For WIMPs this is at the electroweak scale. This naturally gives the correct relic abundance $\Omega_{CDM} \sim 0.1$.

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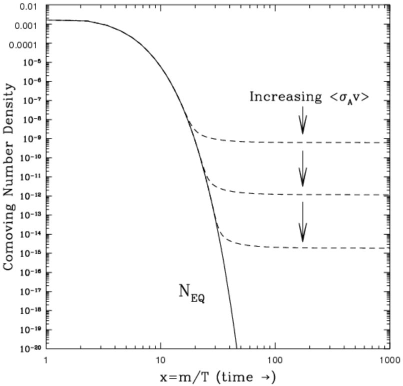

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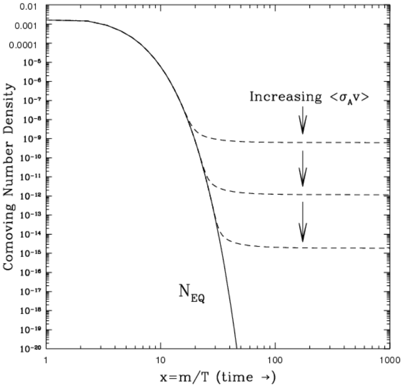

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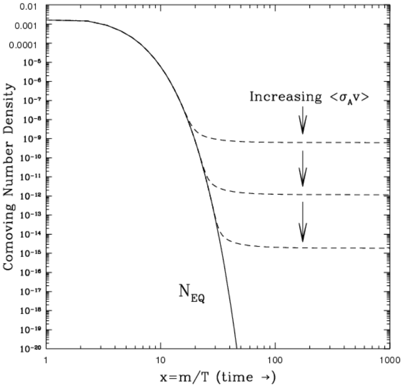

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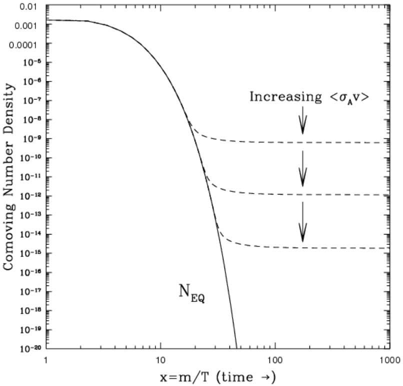

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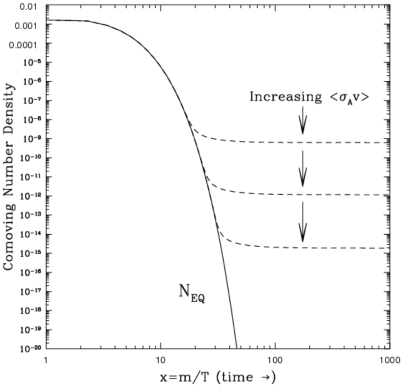

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Other Dark Matter candidates

A number of other non-WIMP particles are candidates for DM. Two examples:

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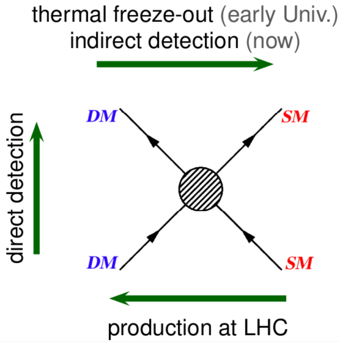
WIMPs detection channels



Independent and complementary approaches

Indirect detection

Products of DM particles annihilation: e^+, $\bar{p}$, γ, energetic νs.

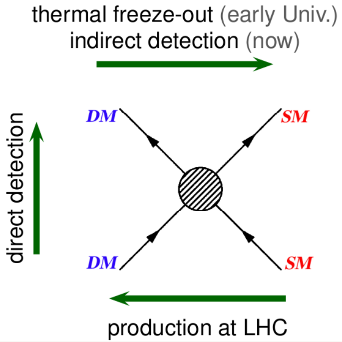
Production in colliders

Missing energy in LHC collisions

Direct detection

WIMPs interactions with target nuclei

WIMPs detection channels



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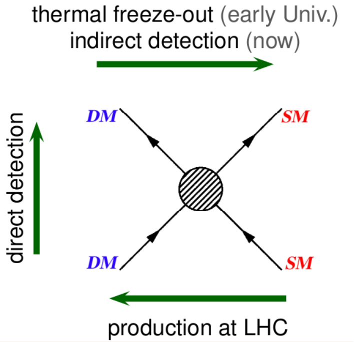

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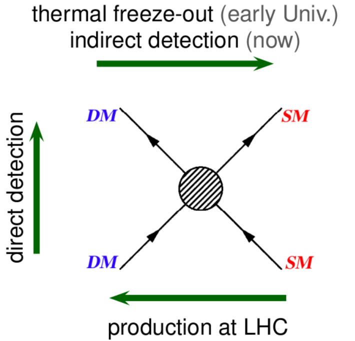

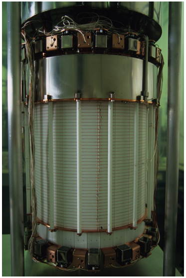

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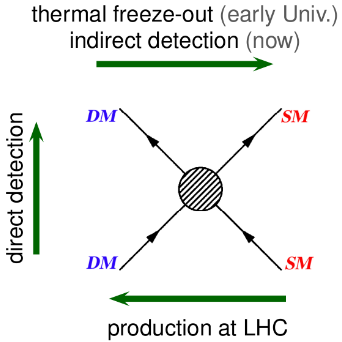

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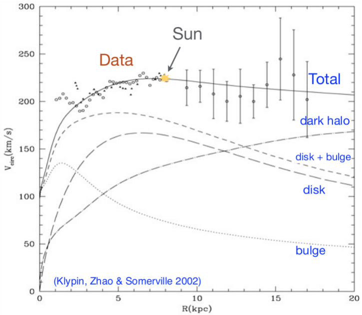
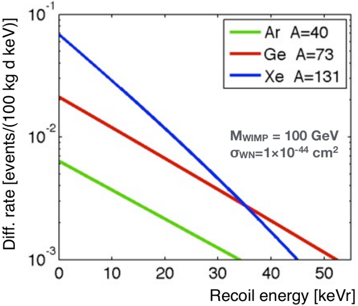
Direct detection: effect of WIMPs interactions

WIMPs induce *nuclear recoils* in a terrestrial detector.

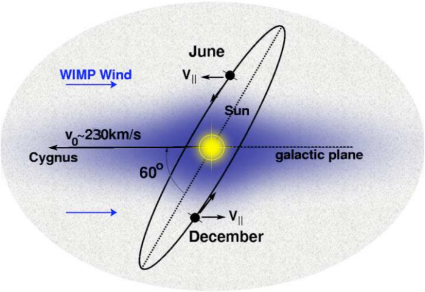




$\rho_0 \sim 0.3\,\text{GeV} \cdot cm^{-3}$ (roughly 3 per liter) at the Sun position.
Standard assumption is a Maxwellian velocity distribution with $v_0 = 220$ km/s

Nuclear recoil energies O(10 keV)
Total recoil rate as low as 1-10^{-3} events / (day · kg)

Direct detection: annual modulation

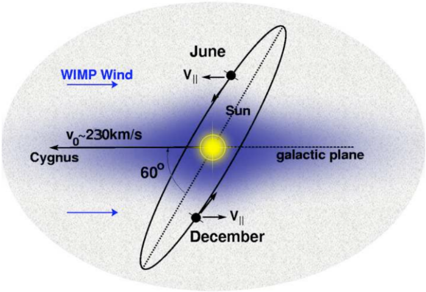


Annual modulation of the recoil rate:

- Modulation present only in a definite energy region
- Modulation ruled by a cosine function
- Period of 1 year
- Phase is 152.5^{th} day in the year (June 2^{nd})
- Amplitude of the modulation order few percents

Clear signature, difficult to mimic with fake effects.

Direct detection: annual modulation



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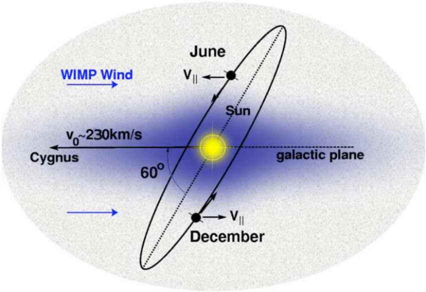

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Direct detection: design of a WIMP detector

- Very low energy threshold for nuclear recoils, O(1 keV)
- Underground site to avoid cosmic rays (LNGS)
- Very low radioactive background at low energies, with careful material selection and detector design
- Sensitivity to a recoil specific observable, to reject the abundant γ and β background
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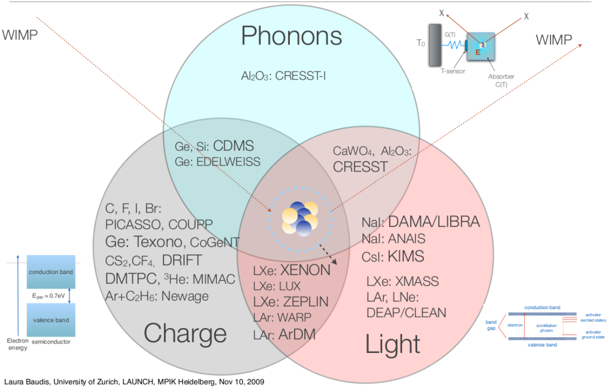
Direct detection: different techniques



Double Read-Out: use of two signals to discriminate nuclear and electronic recoils

$$\left(\frac{CHARGE}{PHONONS}\right)_{nuclear} \ll \left(\frac{CHARGE}{PHONONS}\right)_{electron},$$
$$\left(\frac{LIGHT}{PHONONS}\right)_{nuclear} \ll \left(\frac{LIGHT}{PHONONS}\right)_{electron},$$
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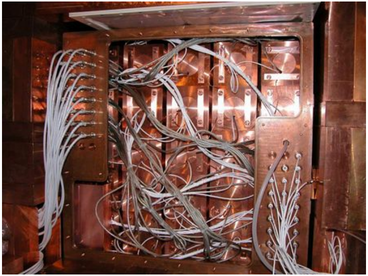
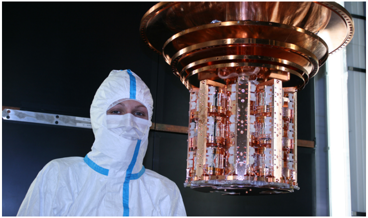
Direct detection: LNGS experiments

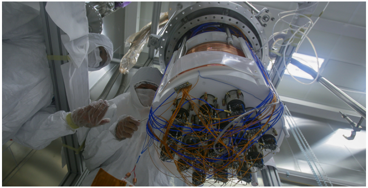


DAMA: light (annual modulation)

XENON: light + charge



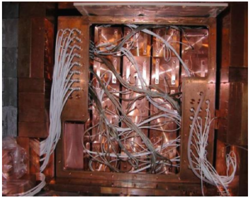
CRESST: light + phonons

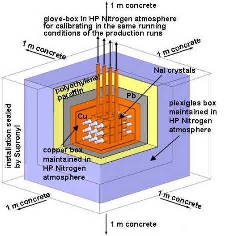


DARKSIDE: light + charge

DAMA

Array of radiopure sodium iodine (NaI) scintillating crystals. Light is collected by PMTs. Look for *annual modulation* in single-hit events.





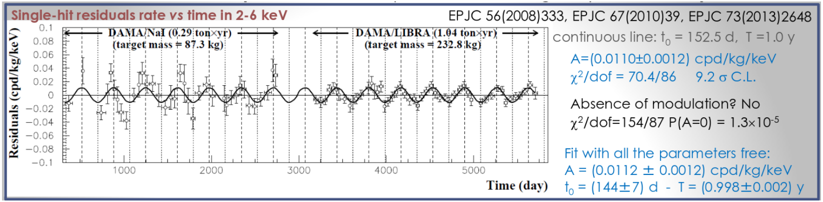
Simplified schema of ~ 100 kg NaI(Tl) set-up

DAMA/NaI: 87.3 kg of NaI, completed data taking in July 2002, total exposure 0.29 ton $\times$ year.

DAMA/LIBRA: 232.8 kg of NaI, first phase ended August 2013, total exposure 1.04 ton $\times$ year.

DAMA

Total exposure (NaI+LIBRA): 1.33 ton $\times$ year (14 annual cycles). 9.3 σ evidence for annual modulation in single-hit events, 2-6 keV energy range (electron calibration).



From R.Cerulli's talk @ MG14-ICRA, Roma

Compatible with annual modulation expected from DM particles in the halo of the Galaxy. No modulation in multiple-hit events and in the energy range above 6 keV.

Interpretation as WIMP with M$\sim$10 GeV and $\sigma \sim 10^{-40}$ cm^2 is challenged by other experiments.

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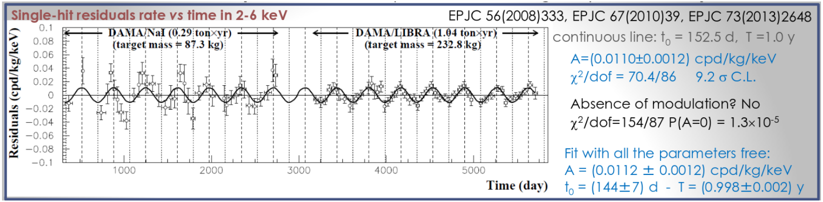
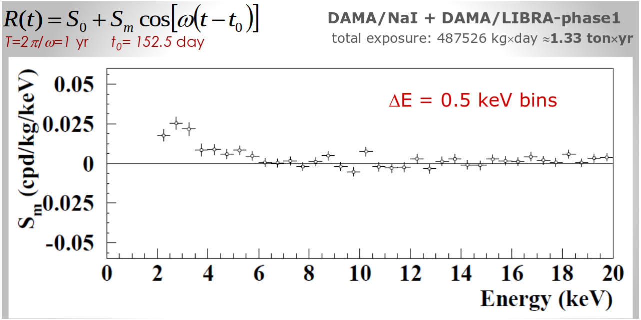
Total exposure (NaI+LIBRA): 1.33 ton $\times$ year (14 annual cycles). 9.3 σ evidence for annual modulation in single-hit events, 2-6 keV energy range (electron calibration).



From R.Cerulli's talk @ MG14-ICRA, Roma

Compatible with annual modulation expected from DM particles in the halo of the Galaxy. No modulation in multiple-hit events and in the energy range above 6 keV.
Interpretation as WIMP with M$\sim$10 GeV and $\sigma \sim 10^{-40}$ cm^2 is challenged by other experiments.

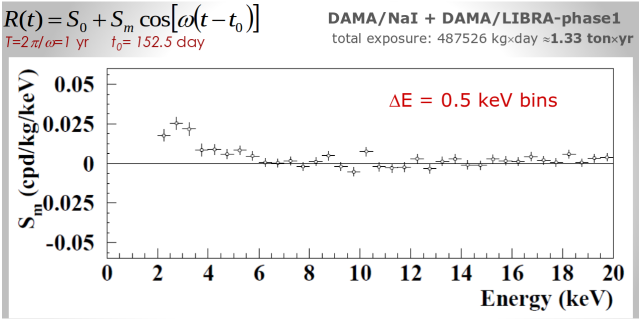
DAMA



From R.Cerulli's talk @ MG14-ICRA, Roma

- DAMA/LIBRA phase 2 in data taking at lower energy threshold (below 2 keV).
- DAMA/LIBRA phase 3 under study (increasing light collection and with new high q.e. PMTs).
- R&D for a possible DAMA/1 ton setup.

DAMA



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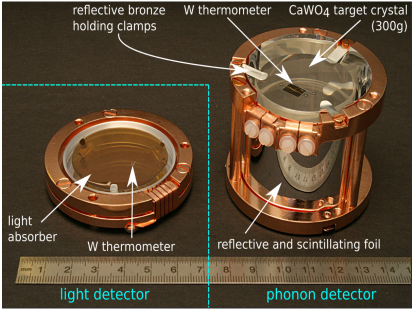
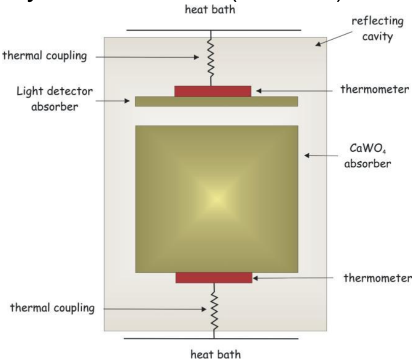
CRESST

It uses scintillating $CaWO_4$ crystals (300 g each) at cryogenic temperatures (∼10 mK) as target. Very low threshold (0.4 keV).

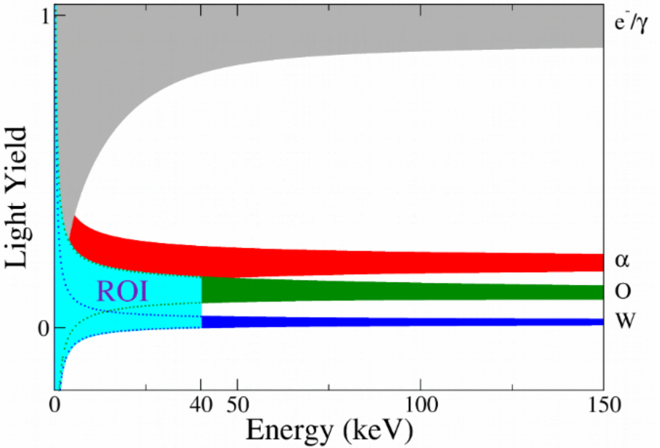




Phonon signal (heat) → deposited energy
Scintillation light → particle discrimination

CRESST

Light Yield = $\frac{\textit{light signal}}{\textit{phonon signal}}$



From F.Reindl's talk @ NDM 2015, Jyvaskyla

Very good electronic recoil discrimination.

CRESST

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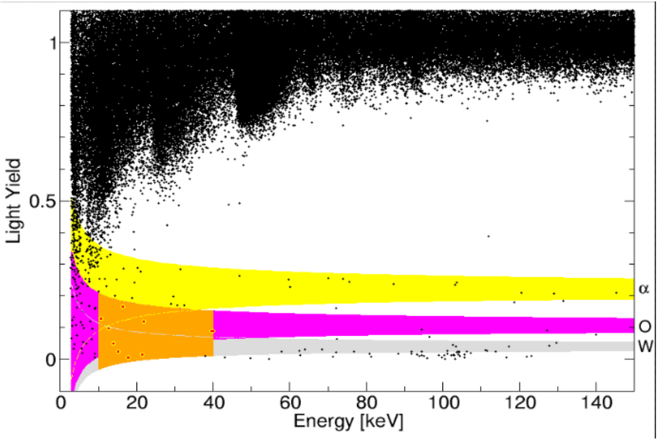

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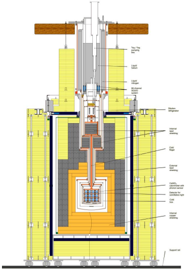
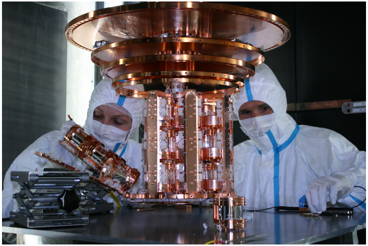
Very good electronic recoil discrimination.

CRESST

An array of 33 modules (10 kg target mass).





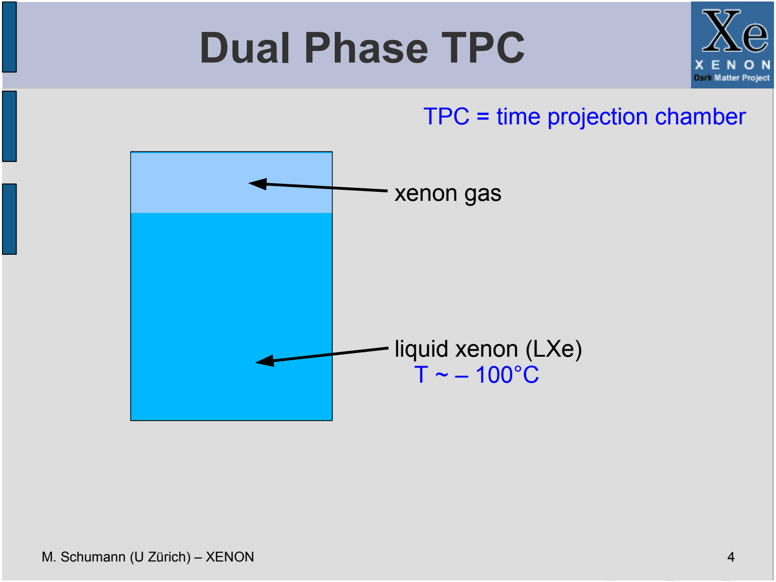
CRESST-II Phase 1 (2009-2011): excess above known background, mild tension with previous data.

CRESST-II Phase 2 (since July 2013): background reduction, currently running. Very good performance at low WIMP mass (<3 GeV).

CRESST-III: smaller crystals (24 g), lowering threshold (100 eV). Starting end of this year.

XENON

Dual-phase Xenon Time Projection Chamber (TPC).



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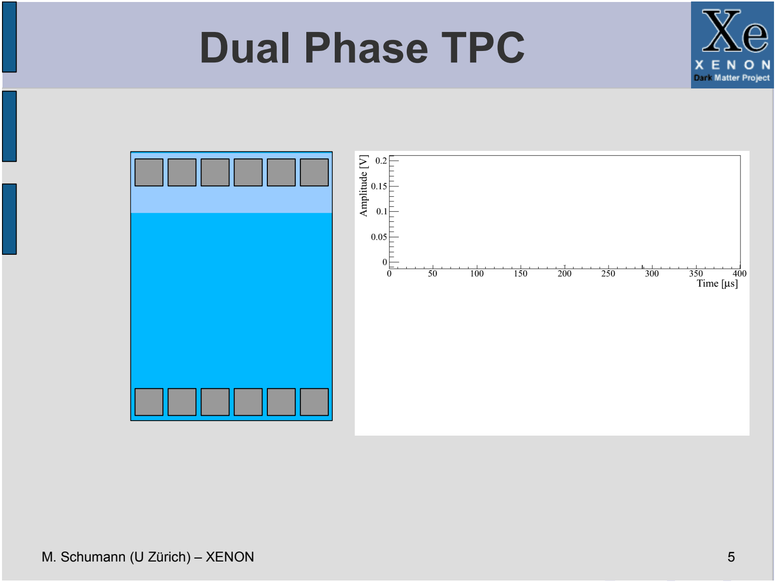

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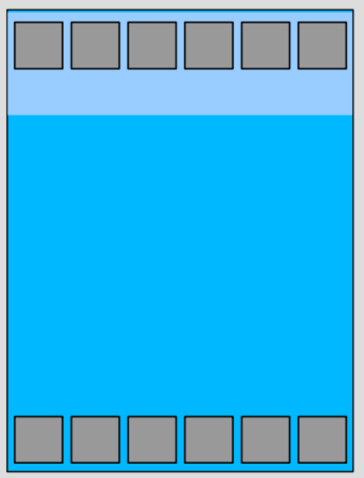

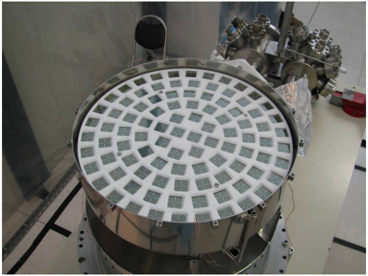

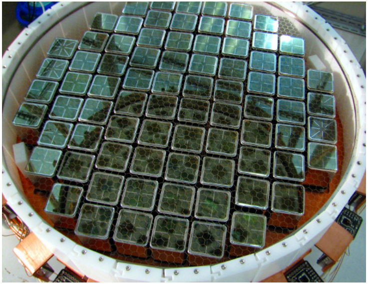

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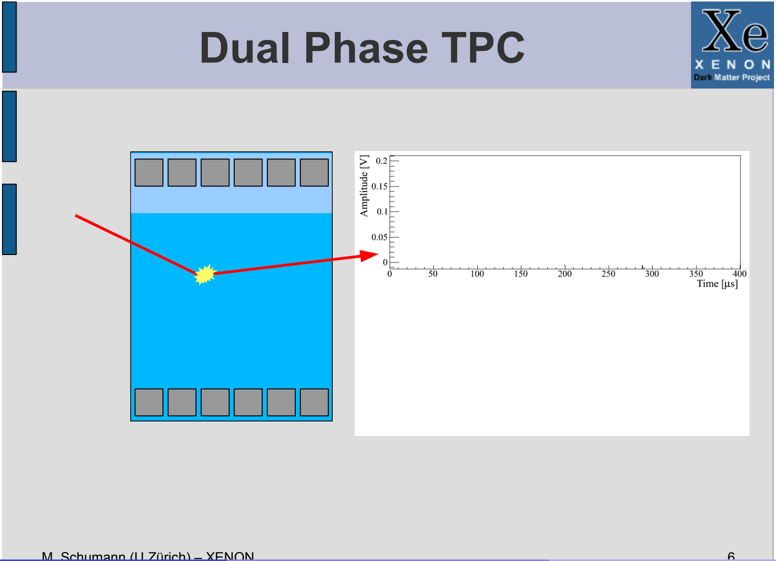

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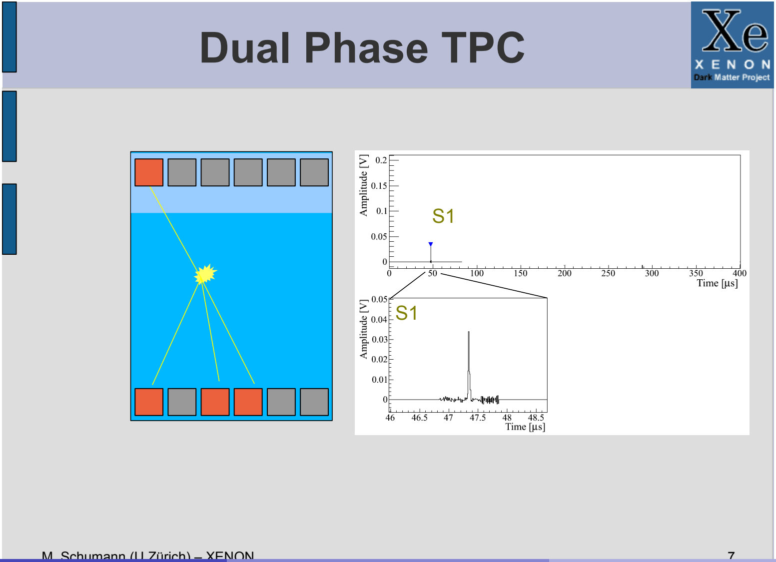

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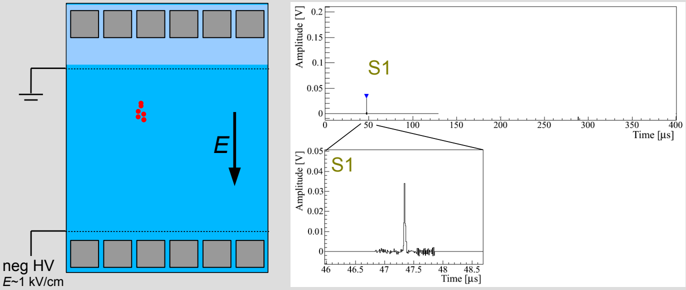
Dual Phase TPC



M. Schumann (U Zürich) – XENON 8

XENON

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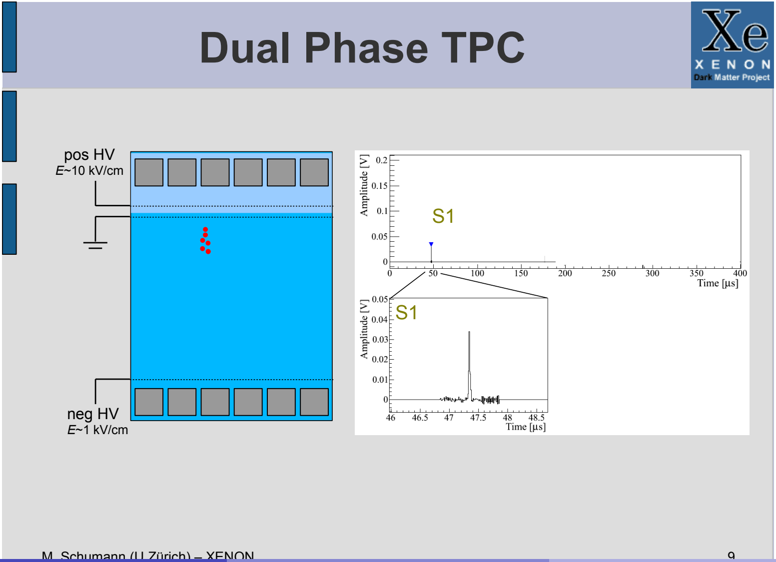

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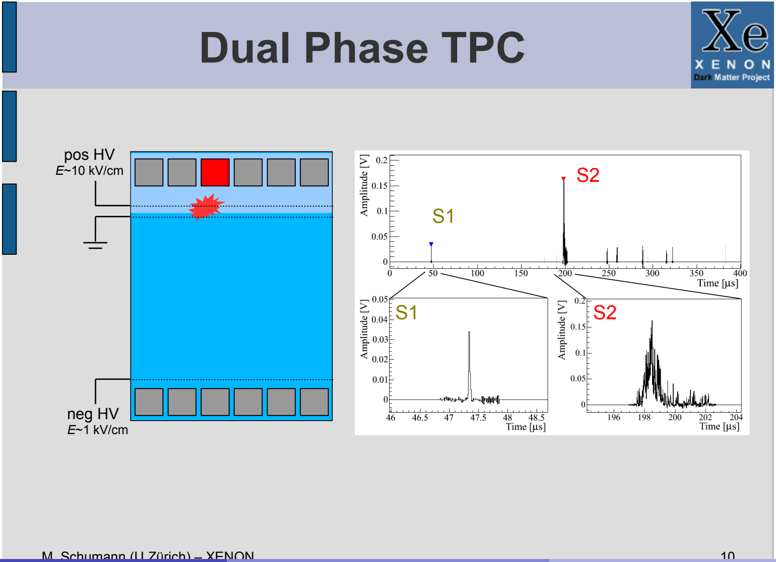

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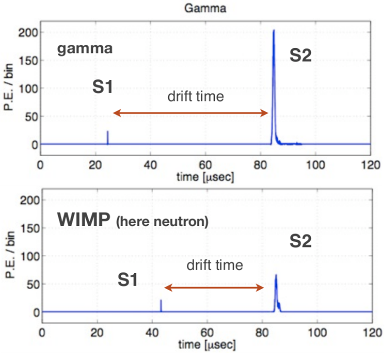
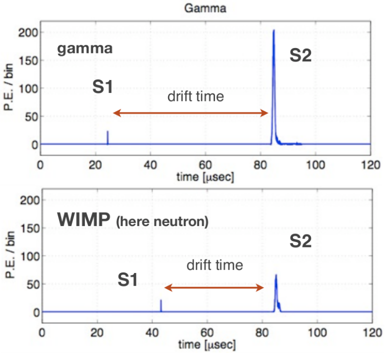
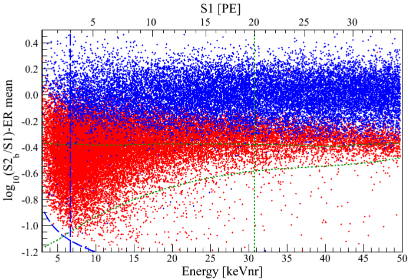


Charge/Light ratio to discriminate electronic recoils.
3D reconstruction of the position of the interactions (drift time + light pattern on the PMTs).

XENON





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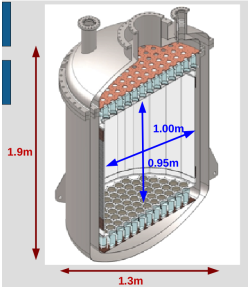
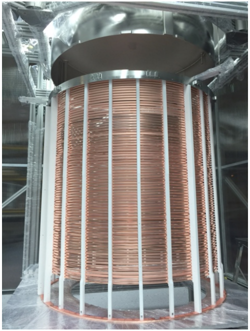
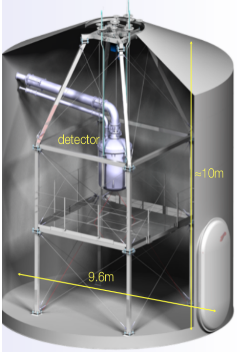




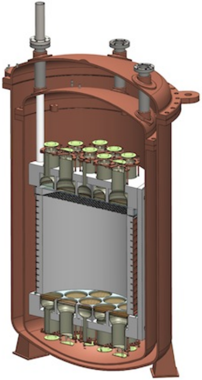


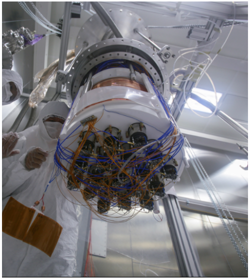
XENON100: 62 kg Xenon target mass (161 kg total) started data taking in 2007, still running. Best WIMP exclusion limit at the time (2012) with 225 days long run.

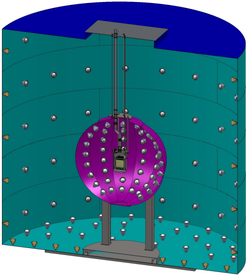
XENON1T: 1 ton Xenon fiducial volume (3 tons total) under construction. Water Cherenkov detector for μ. Start data taking by the end of this year.

DarkSide

Dual-phase Argon TPC.





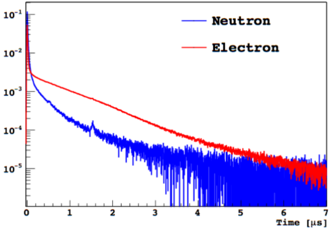


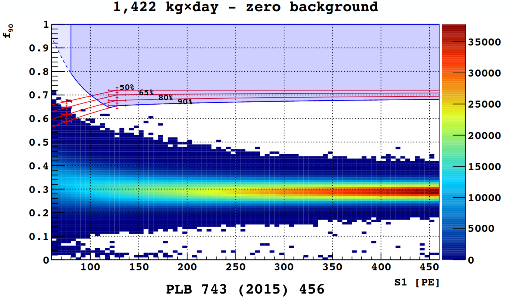
Use of Underground Argon (UAr) to get rid of the radioactive ^{39}Ar isotope.

Borated Liquid Scintillator Veto for neutrons, Water Cherenkov detector for μ.

DarkSide

Discrimination with charge/light ratio + Pulse Shape Discrimination.





f_{90}: fraction of S1 in the first 90 ns

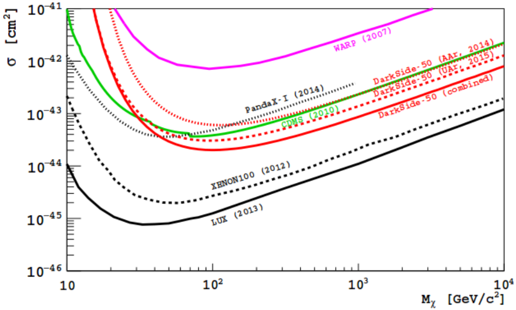
From S.Davini's talk @ TAUP 2015, Torino

DarkSide

Currently running is DarkSide-50, with 46 kg Ar active mass, total mass 153 kg.

- Started data taking in late 2013 using atmospheric Argon.
- Filled with UAr in April 2015, 70 days data taking. ^{39}Ar reduced by a factor 1400. No evidence of DM interactions.

Future: DS-20k, 20 tons fiducial volume mass (30 tons total). Use of SiPMs.



arXiv:1510.00702

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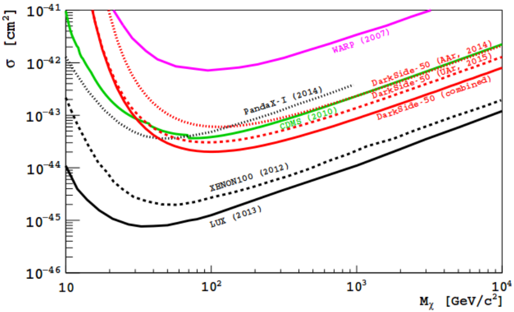


arXiv:1510.00702

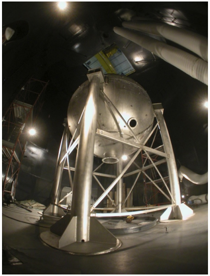
Conclusions

LNGS are leading the field of Dark Matter direct detection.

4 different experiments are ongoing, using different techniques and a variety of targets.

Important results already achieved and good prospects for the near future.

STAY TUNED FOR NEXT RESULTS!



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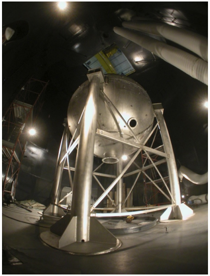

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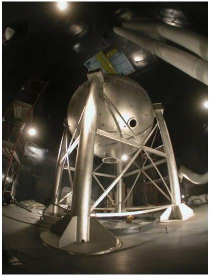

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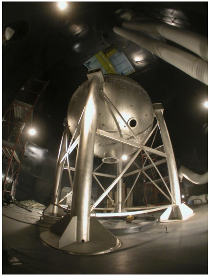

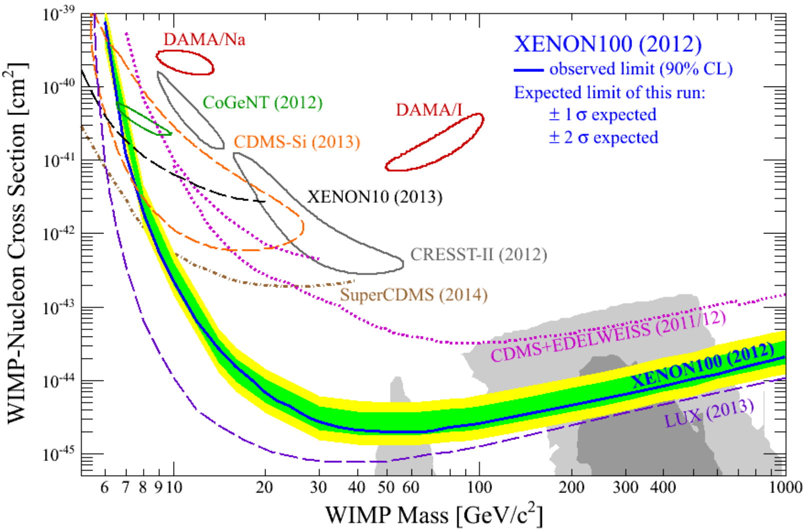
XENON100 (2012)
observed limit (90% CL)
Expected limit of this run:
± 1 σ expected
± 2 σ expected
DAMA/Na
CoGeNT (2012)
DAMA/I
CDMS-Si (2013)
XENON10 (2013)
CRESST-II (2012)
SuperCDMS (2014)
CDMS+EDELWEISS (2011/12)
XENON100 (2012)
LUX (2013)
WIMP-Nucleon Cross Section [cm²]
WIMP Mass [GeV/c²]
10⁻³⁹
10⁻⁴⁰
10⁻⁴¹
10⁻⁴²
10⁻⁴³
10⁻⁴⁴
10⁻⁴⁵
6 7 8 9 10 20 30 40 50 60 100 200 300 400 1000