# LNGS
# a laboratory with the vocation of the Dark Matter

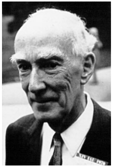
Marcello Messina

Columbia University and LNGS

04/10/2016

# Dark Matter: a brief history

- 1922: Jacobus Kapteyn coined the name "dark matter", while studying stellar motions in our galaxy. He found that the Galaxy had a center of rotation
- 1932: Jan Oort, student of Kapteyn, did a Ph.D. whose title was *High velocity stars*. He suggested that there would be more dark than visible matter in the vicinity of the Sun (later the result turned out to be wrong)
- 1933: F. Zwicky found "dunkle Materie" in the Coma cluster - the redshift of galaxies were much larger than the escape velocity due to luminous matter alone



# The Dark Matter puzzle

The bulk of matter in the Universe (about 85%) is observable only through its gravitational effects.

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*Credit: NASA/WMAP Science Team*

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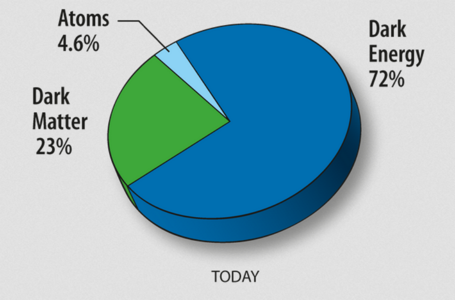


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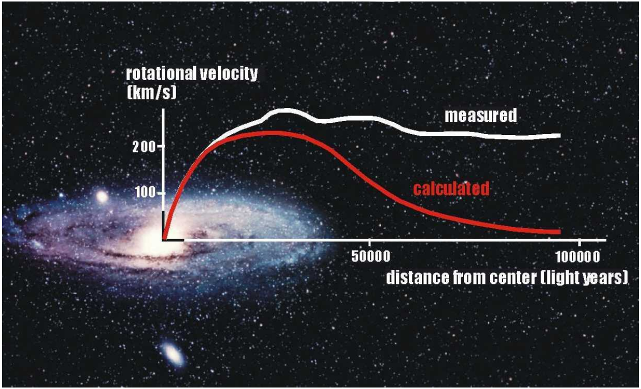
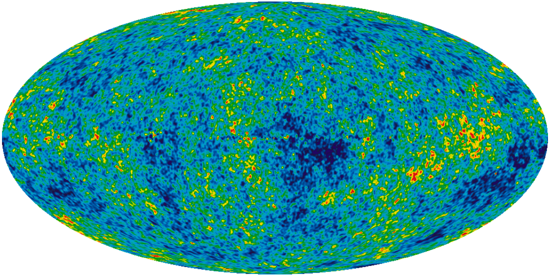
# Evidence for Dark Matter, Galaxy rotation curves




Spiral galaxies show $\frac{M}{L} \sim 30 - 40 \frac{M_\odot}{L_\odot}$.

# Evidence for Dark Matter, Cosmic Microwave Background



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

$$\Omega_\Lambda \sim 0.72, \Omega_{CDM} \sim 0.23, \Omega_B \sim 0.046, \Omega_{Tot} = 1$$

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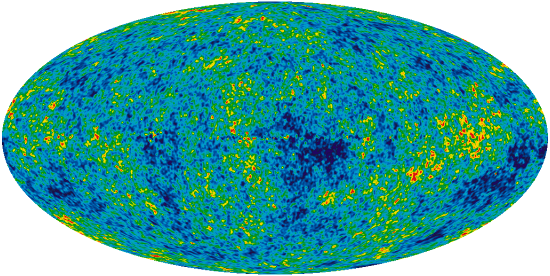

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# Properties of Dark Matter

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

- It's DARK, neither emitting nor absorbing light. 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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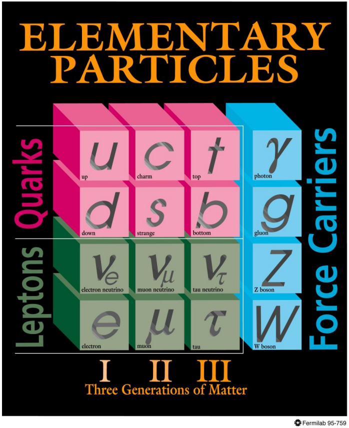
# A Standard Model particle as Dark Matter candidate?

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

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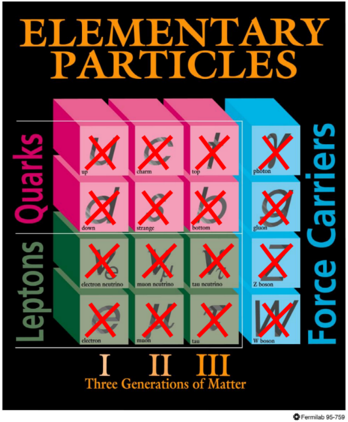


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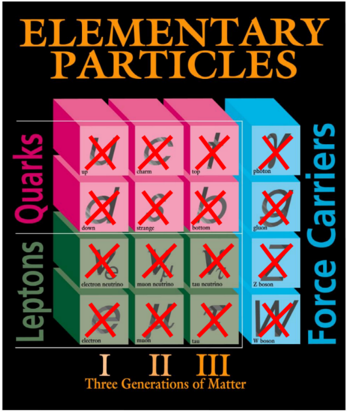


Fermilab 95-759

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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).

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# Weakly Interacting Massive Particles

WIMPs are relic particles from the Big Bang.

- Initial thermal equilibrium: $\chi\,\bar{\chi} \rightleftarrows q\,\bar{q}, l\,\bar{l}$
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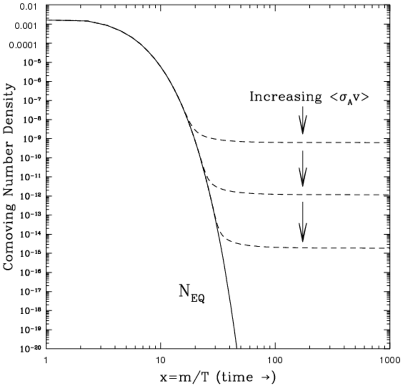
- Freeze out: $N \sim const.$




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

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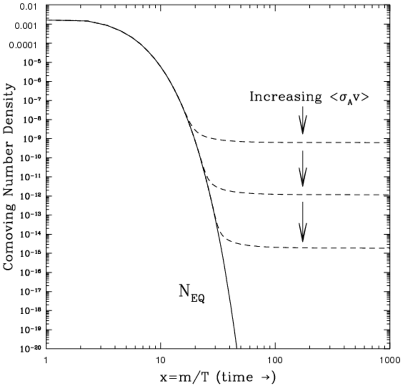


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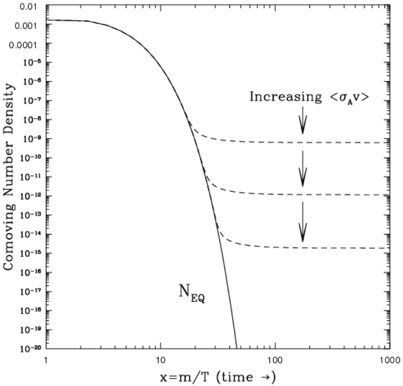


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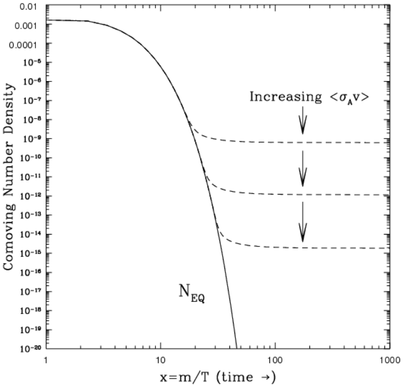


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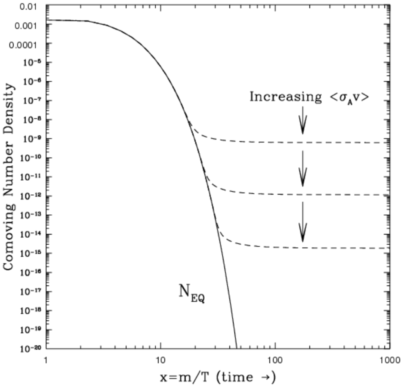


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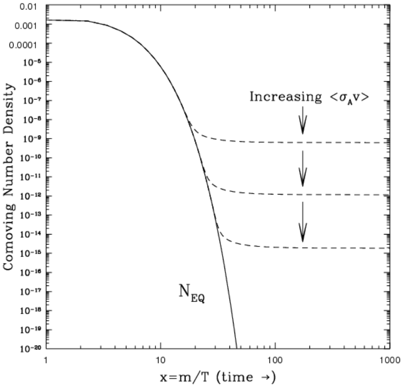


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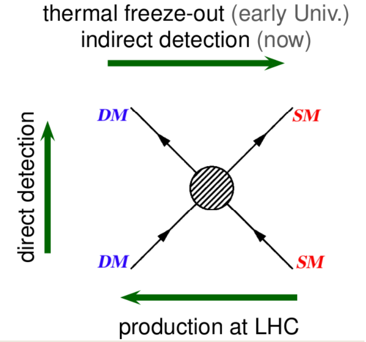
# WIMPs detection channels




Independent and complementary approaches

**Indirect detection**

Products of DM particles annihilation: $e^+$, $\bar{p}$, $\gamma$, energetic $\nu$s.

**Production in colliders**

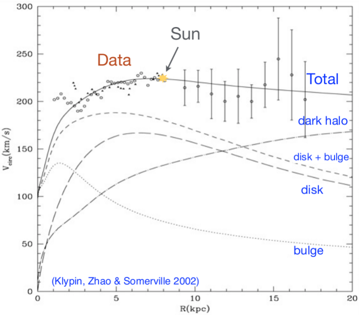
Missing energy in LHC collisions

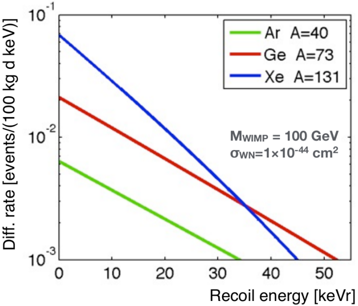
**Direct detection**

WIMPs interactions with target nuclei

# Direct detection: effect of WIMPs interactions

WIMPs induce *nuclear recoils* in a terrestrial detector.

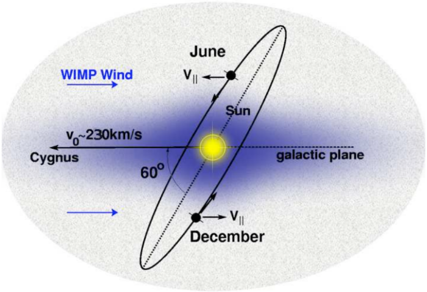



$\rho_0 \sim 0.3\,\mathrm{GeV} \cdot cm^{-3}$ (few particles per liter) at the Sun position. Standard assumption is a Maxwellian velocity distribution with $v_0 = 220$ km/s

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

Strong signature.

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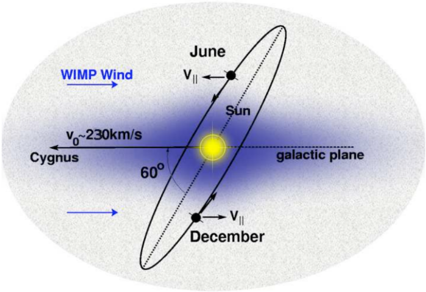


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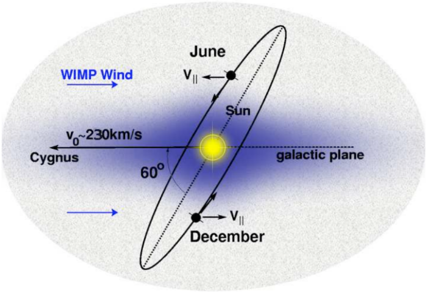


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# Direct detection: design of a WIMP detector

- 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, i.e. specific observable, to reject the abundant $\gamma$ and $\beta$ background
- Space resolution to reject multiple-hit events (induced by neutrons)
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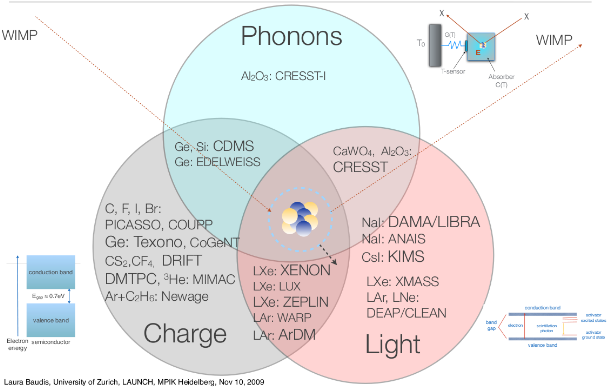
# Direct detection: different techniques

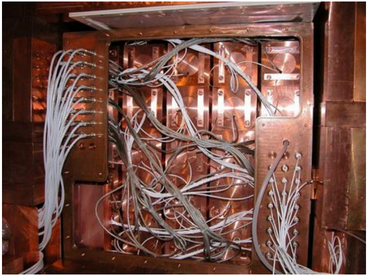



Laura Baudis, University of Zurich, LAUNCH, MPIK Heidelberg, Nov 10, 2009

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

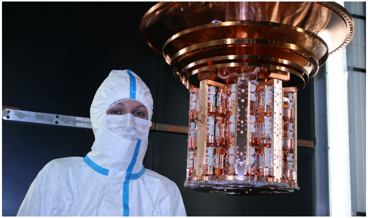
$$\left(\frac{CHARGE}{PHONONS}\right)_{nuclear} \ll \left(\frac{CHARGE}{PHONONS}\right)_{electron},$$
$$\left(\frac{LIGHT}{PHONONS}\right)_{nuclear} \ll \left(\frac{LIGHT}{PHONONS}\right)_{electron},$$
$$\left(\frac{CHARGE}{LIGHT}\right)_{nuclear} \ll \left(\frac{CHARGE}{LIGHT}\right)_{electron}$$

# Direct detection: LNGS experiments

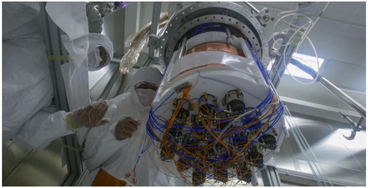


DAMA: light (annual modulation)

XENON: light + charge



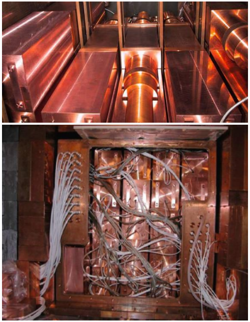
CRESST: light + phonons

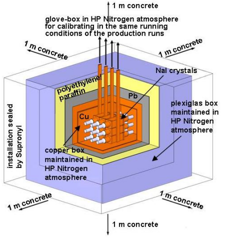


DARKSIDE: light + charge

# DAMA

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





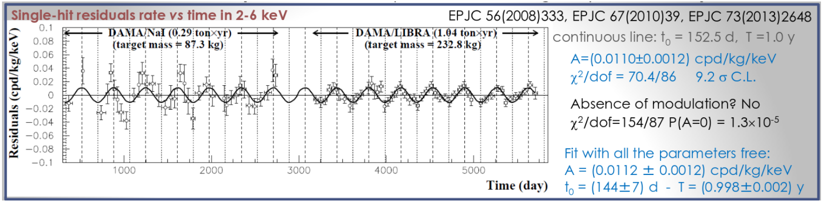

Simplified schema of ~ 100 kg NaI(Tl) set-up

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

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

# DAMA

Total exposure (NaI+LIBRA): 1.33 ton $\times$ year (14 annual cycles). 9.3 $\sigma$ 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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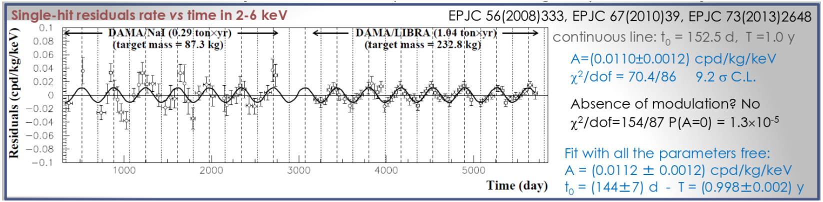


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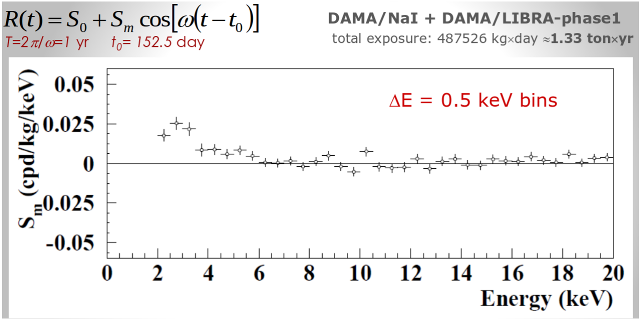


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- DAMA/LIBRA phase 2 in data taking at lower energy threshold (below 2 keV).
- DAMA/LIBRA phase 3 under study (increasing light collection and with new high q.e. PMTs).
- R&D for a possible DAMA/1 ton setup.

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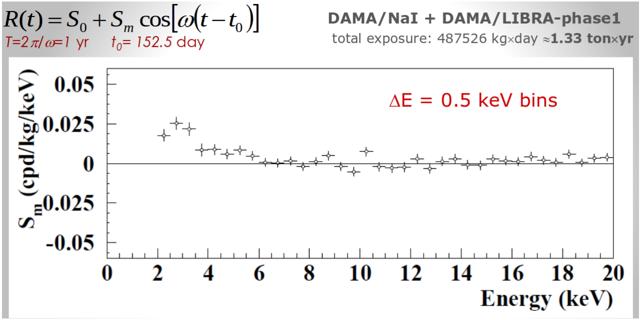


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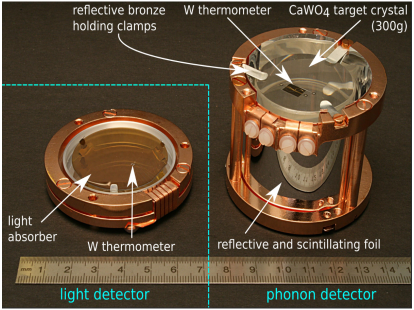
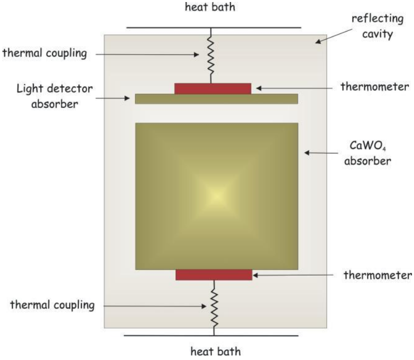
# CRESST

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



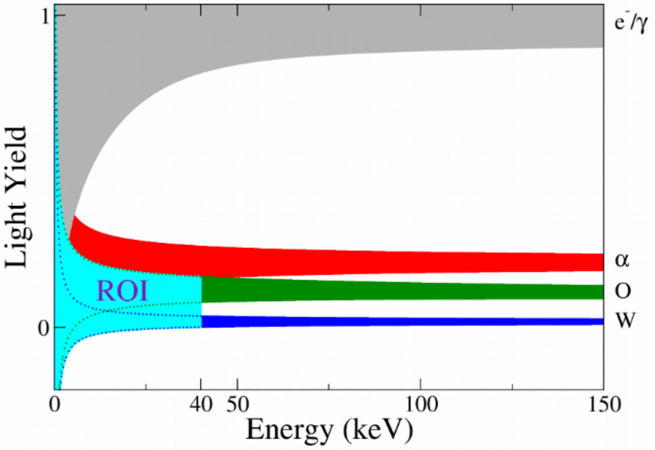

$$\Delta T = \frac{E}{C(T)} e^{-\frac{t}{\tau}}, \tau = \frac{C(T)}{G(T)}$$

*Phonon signal (heat)* $\rightarrow$ deposited energy

*Scintillation light* $\rightarrow$ 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.

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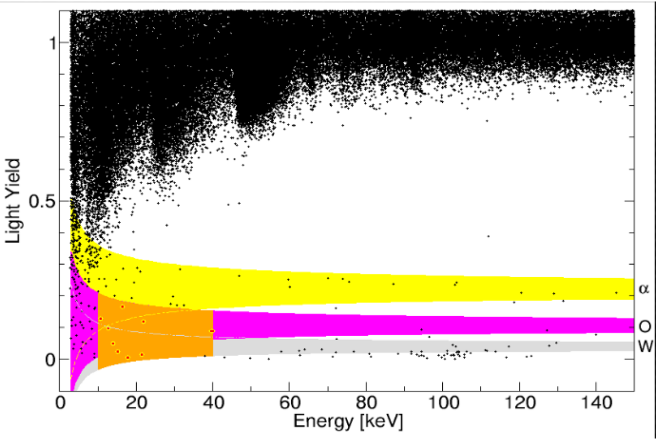


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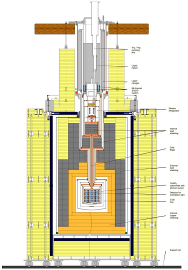
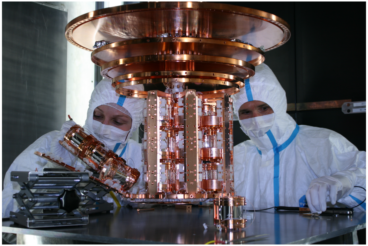
An array of 33 modules (10 kg target mass).



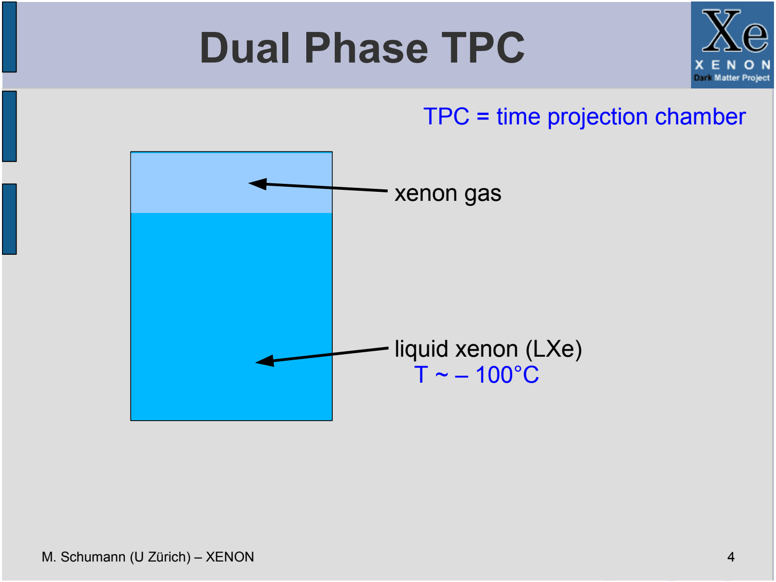
CRESST-II Phase 1 (2009-2011): excess above known background, mild tension with previous data.

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 this year.

# XENON

Dual-phase Xenon Time Projection Chamber (TPC).



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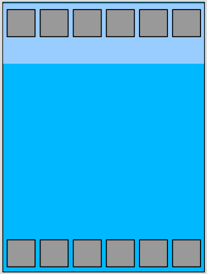
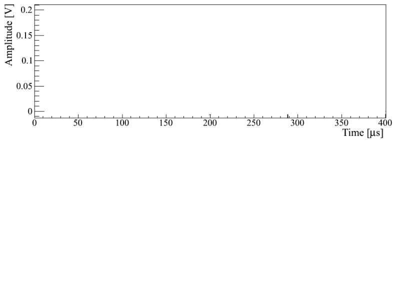
## Dual Phase TPC

XENON
Dark Matter Project






M. Schumann (U Zürich) – XENON 5

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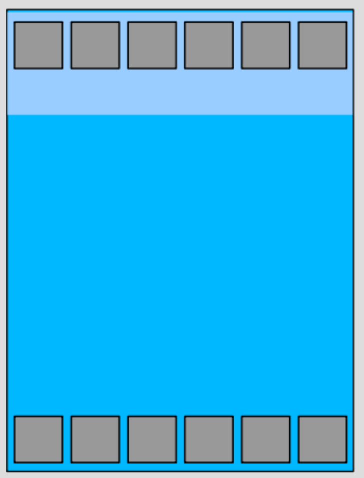

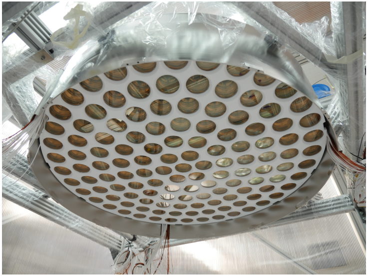

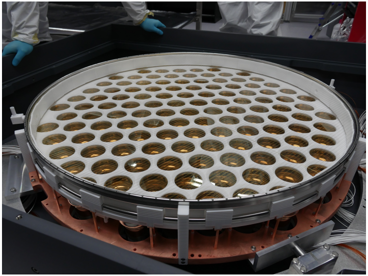

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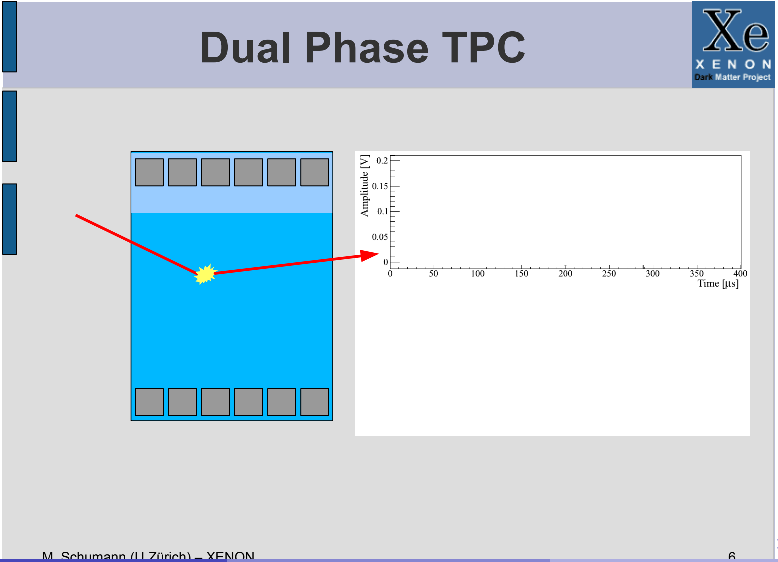

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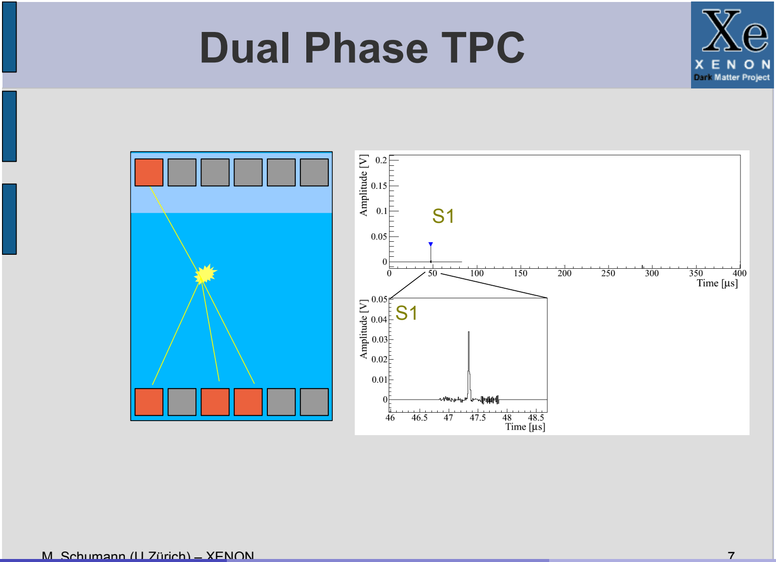

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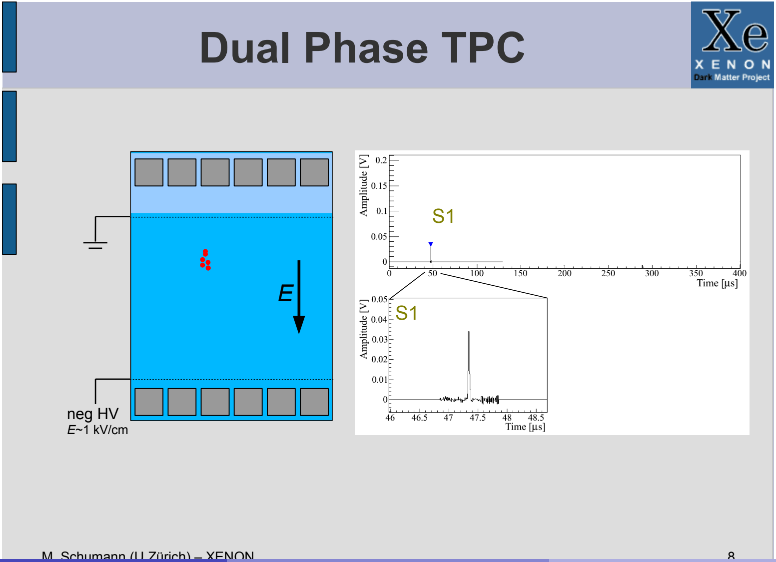

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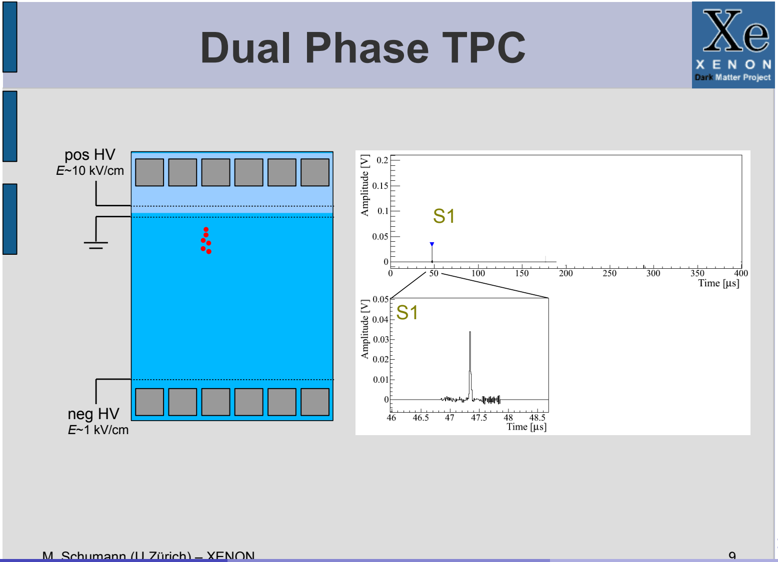

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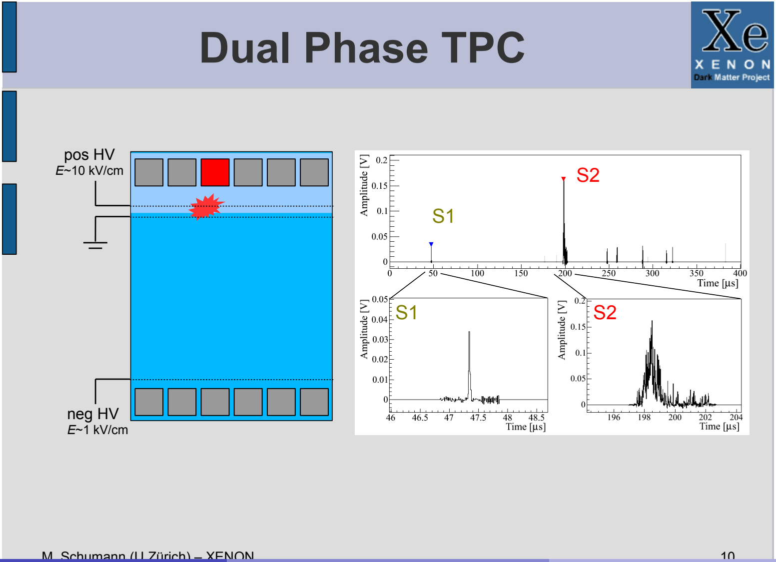

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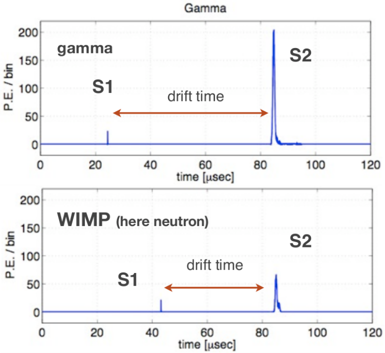


Charge/Light ratio to discriminate electronic recoils.
3D reconstruction of the position of the interactions (drift time + light pattern on the PMTs).

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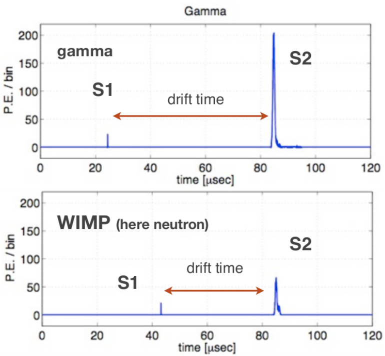


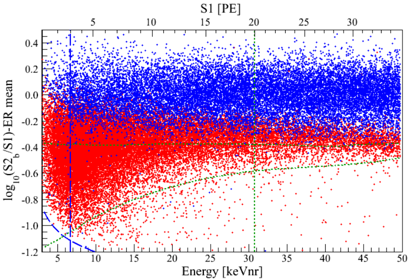


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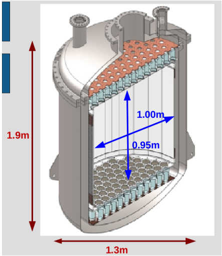
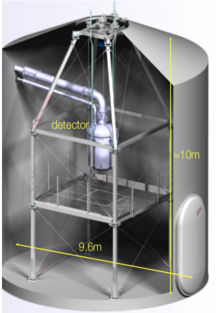


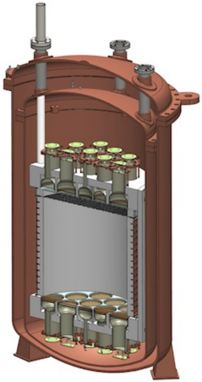

XENON100: 62 kg Xenon target mass (161 kg total) started data taking in 2007, still running. Led the field for many years with longest run (i.e. 225 days).

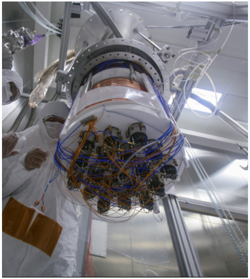
XENON1T: 1 ton Xenon fiducial volume (3.3 tons total) just stared the data taking. Complemented by a Cherenkov detector for $\mu$.

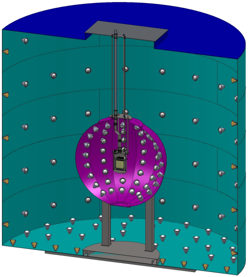
The design embeds already the upgrade at larger mass $\sim$7 tonnes, larger detector in a larger vessel, where all the infrastructures will be exploited while only the inner vessel of the cryostat and a new TPC will be re-built.

# DarkSide

Dual-phase Argon TPC.



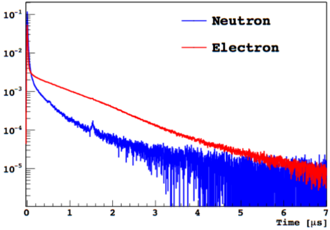


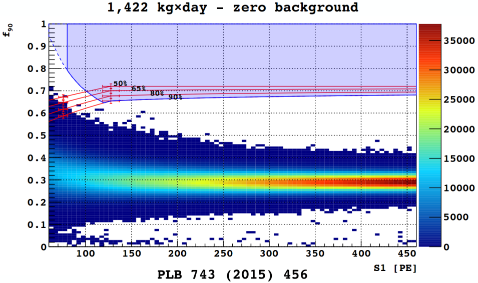


Use of Underground Argon (UAr) to get rid of the radioactive $^{39}$Ar isotope.
Borated Liquid Scintillator Veto for neutrons, Water Cherenkov detector for $\mu$.

# DarkSide

Discrimination with charge/light ratio + Pulse Shape Discrimination.




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

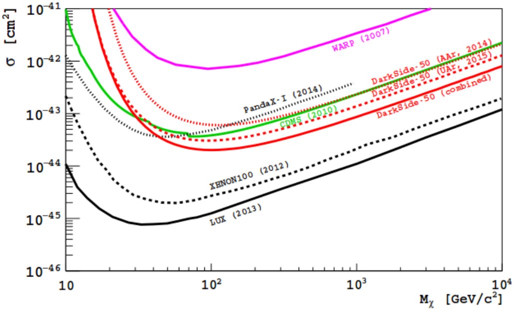
*From S.Davini's talk @ TAUP 2015, Torino*

# 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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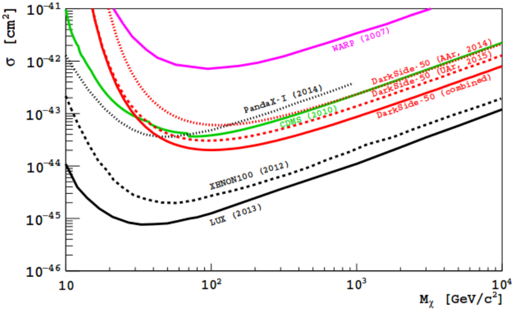
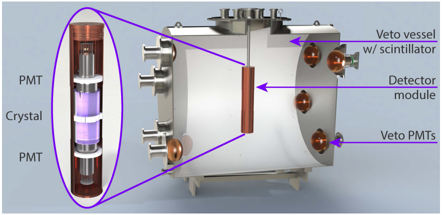



arXiv:1510.00702

# What about future

SABRE: It was motivated to definitively proof or disproof the controversial DAMA/LIBRA results.

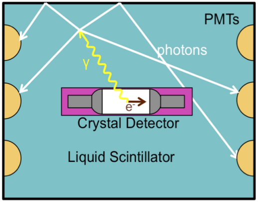



- Crystal NaI $\sim$ 5 kg
- Crystal PMTs: 3 inch flat Hamamatsu R11065-20
- Vessel: 1.3 m diameter, 1.5 m length
- 2 tonnes of LS 2.25 $m^3$
- LS veto PMTs: 8 inch semi-spherical PMTs R5912

Experimental installation for the proof of principle (PoP) setup is ongoing in the HallB

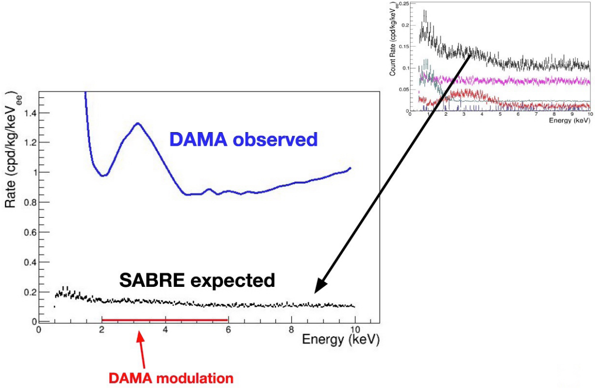
# SABRE's strategy to lower BG

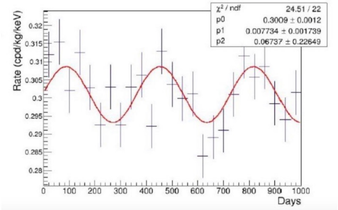
- Grow NaI(Tl) crystal with improved radio-purity: cleaner powder, higher-purity growth method, and low radioactivity enclosure, plus veto LS detector, mainly vetoing $^{40}$K and $^{22}N_a$
- High QE PMTs directly coupled to the crystals and lower HV to reduce dynode afterglow.
- Twin detectors in northern and southern hemisphere to reduce seasonal effect (LNGS Italy, & SUPL, Australia)




| Crystal | SABRE measure | DAMA measure |
|---|---|---|
| mass (so far) | 1.5 kg | |
| OD/length | 88 mm / 50 m | |
| light yield | 41 pe/keV | |
| pe yield | 14 | 7 pe/keV |
| $^{nat}$K in crystal | 9 ppb | 13 ppb |
| Rb | <0.1 pb | 0.35 ppb |
| Th | 0.5 ppt | 0.5-7.5 ppt |
| U | 0.6 ppt | $\sim$ppt |

# SABRE's BG and sensitivity

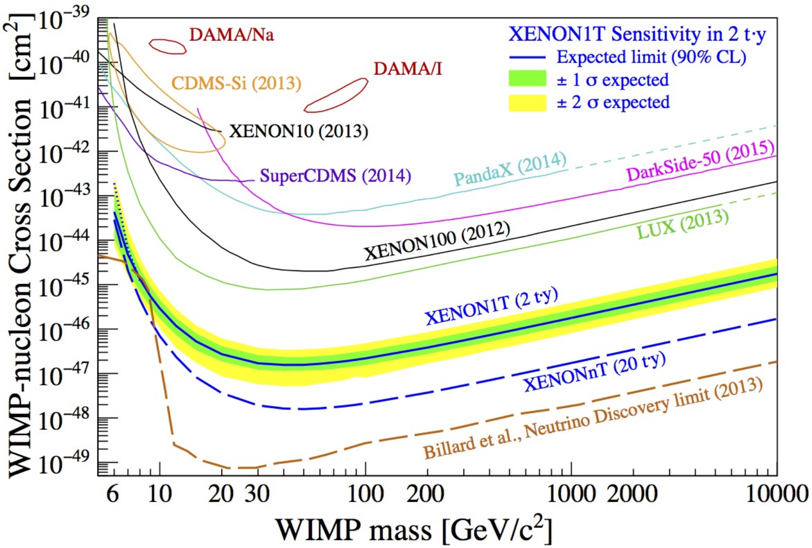



- K
- Rb
- Total < 0.13 cpd/kg/keV (DAMA 1 cpd/kg/keV)

With a BG of 0.13 cpd/kg/keV a

$6\sigma$ Dama/Libra signal can be tested with 50 kg x 3 yrs


XENON1T Sensitivity in 2 t·y
Expected limit (90% CL)
± 1 σ expected
± 2 σ expected
DAMA/Na
DAMA/I
CDMS-Si (2013)
XENON10 (2013)
SuperCDMS (2014)
PandaX (2014)
DarkSide-50 (2015)
XENON100 (2012)
LUX (2013)
XENON1T (2 t·y)
XENONnT (20 t·y)
Billard et al., Neutrino Discovery limit (2013)
WIMP-nucleon Cross Section [cm²]
WIMP mass [GeV/c²]

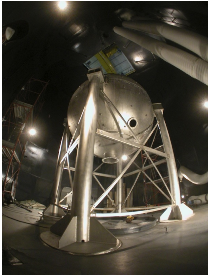
# Conclusions

LNGS leads the field of Dark Matter direct detection.

4 different experiments are ongoing, using different techniques and a variety of targets. More is already planned for the near future.

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

STAY TUNED FOR NEXT RESULTS!



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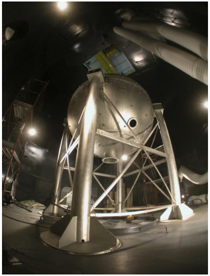

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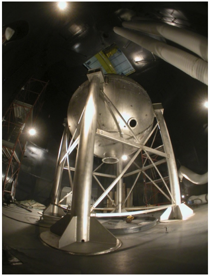

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