# Review of direct dark matter searches

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MPIK

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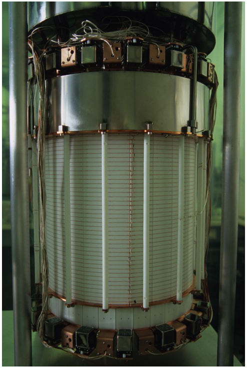
MAX-PLANCK-INSTITUT FÜR KERNPHYSIK HEIDELBERG

# Dark matter searches

- Indirect detection
- Direct detection
- Production at LHC

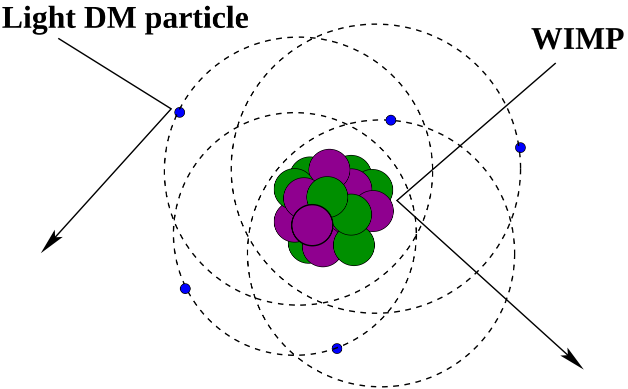


$\chi\chi \to e^+e^-, p\bar{p}$

$\chi$ N $\to$ $\chi$ N

p + p $\to$ $\chi$ + a lot

# Direct dark matter detection



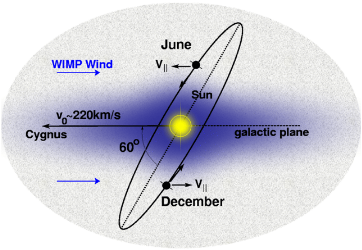

Detection via elastic scattering off
nuclei → nuclear recoils by WIMPs
electrons → electronic recoils by light particles (axion)

# Detector requirements and signatures

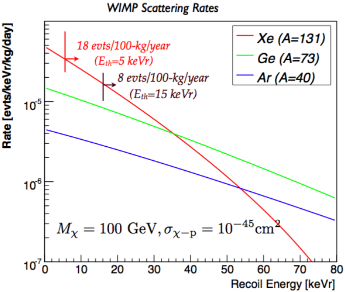
- Requirements for a dark matter detector
  - Large detector mass
  - Low energy threshold $\sim$ few keV's
  - Very low background and/or background discrimination

- Possible signatures of dark matter

- Annual modulated rate
- Directional dependance

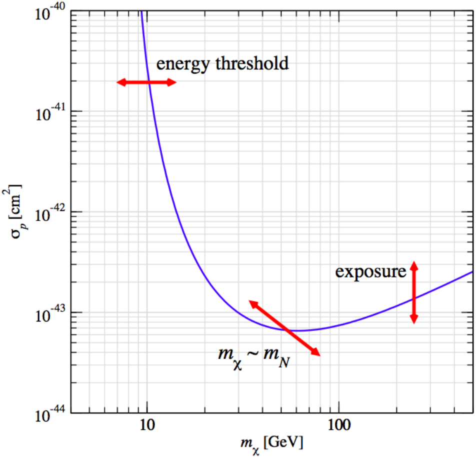



- Nuclear recoil with exponential spectral shape



# Result of a direct detection experiment

$\longrightarrow$ Statistical significance of signal over expected background?




- Positive signal
  - Region in $\sigma_\chi$ versus $m_\chi$
- Zero signal
  - Exclusion of a parameter region

  - Low WIMP masses: detector threshold matters
  - Minimum of the curve: depends on target nuclei
  - High WIMP masses: exposure matters $\epsilon = m \times t$

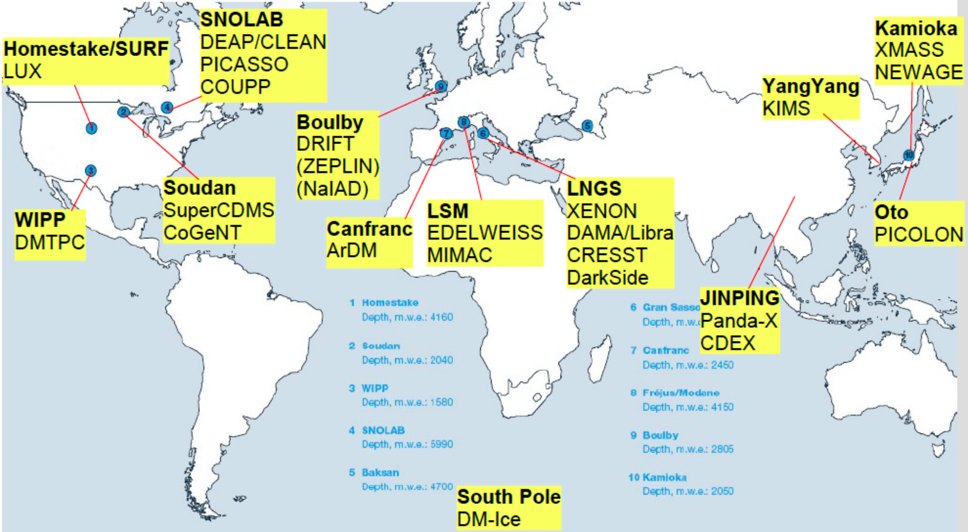
# Background sources

- Natural **U**, **Th** chains and $^{40}$**K**
  - Electronic recoils: $\beta$'s and $\gamma$'s
  - $\alpha$'s: high energy but still BG in some experiments
- **Neutrons** $\rightarrow$ nuclear recoils
  - $(\alpha, n)$ reactions and spontaneous fission
  - From muon showers after a spallation process
- **Rn** and $^{85}$**Kr**
  - Rn emanation from various detector materials
  - Kr from the air ($^{85}$Kr produced at nuclear power plants)

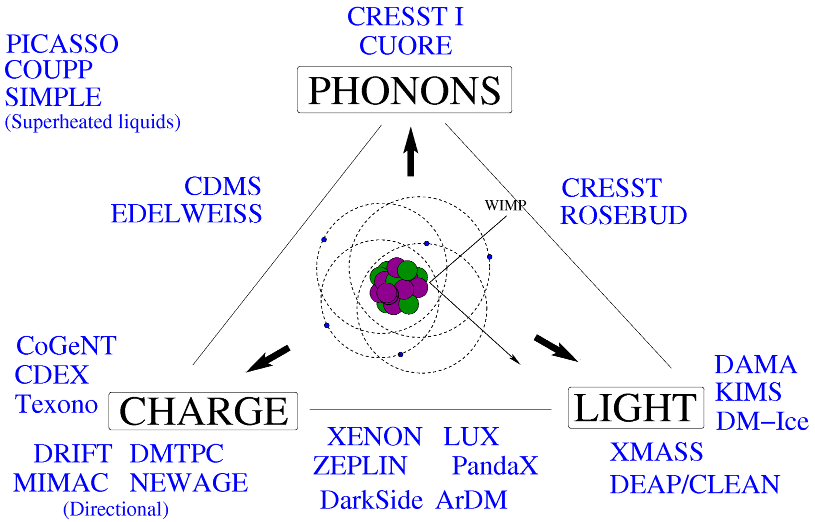
$\rightarrow$ **Background suppression/removal**

- Material screening and selection
- Removal of Kr or Rn with dedicated devices
- Shielding (underground lab, detector shield, active veto)

# Underground laboratories



# Direct detection experiments

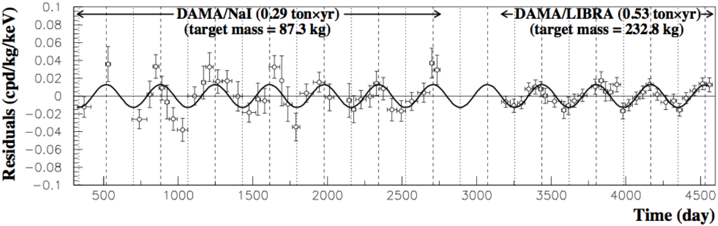



Only some of these experiments will be discussed in the next slides!

# DAMA annual modulation

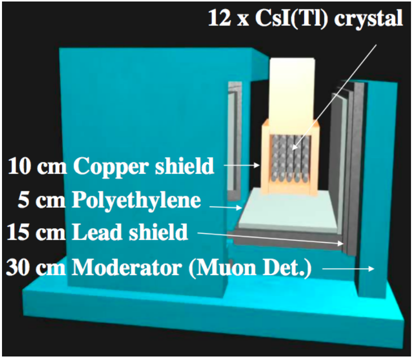
- Ultra radio-pure NaI crystals
- Annual modulation of the background rate in the energy region $(2-5)\,\text{keV}$

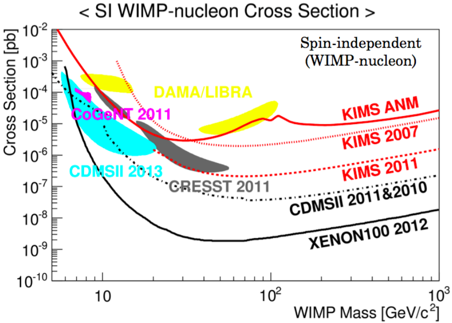
  $8.9\,\sigma$ significance!
- No discrimination of ER from NR

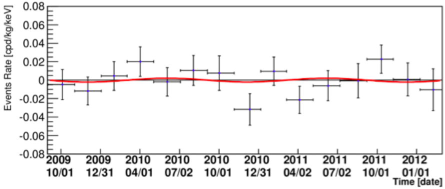



R. Bernabei *et al.*, Eur. Phys. J. C67, 39 (2010)

# Tests of annual modulation



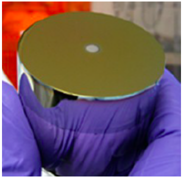



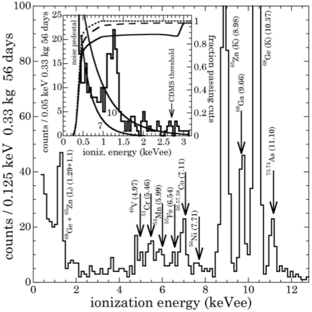

- **KIMS** @ Yangyan Lab in Corea
- CsI crystals to test of annual modulation (scatters off Iodine)

No indication for rate modulation

**DM-Ice** @ south Pole with 17 kg NaI running since June 2011

# The CoGeNT experiment

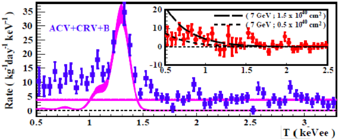




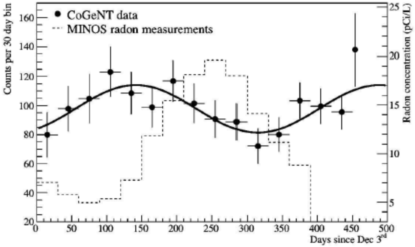

- Ge detector with 0.4 keV threshold
- No discrimination ER/NR
- Excess of events at low energies and annual modulation of the rate

CoGeNT, Phys. Rev. Lett. 106 131301 (2011)

Tests with Ge detectors: **CDEX** @ China and **TEXONO** @ Taiwan

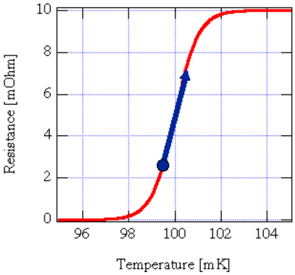



TEXONO, Phys. Rev. Lett. 110, 261301 (2013)



# Working principles of bolometers

- Cryogenic crystals operated at a few mK!

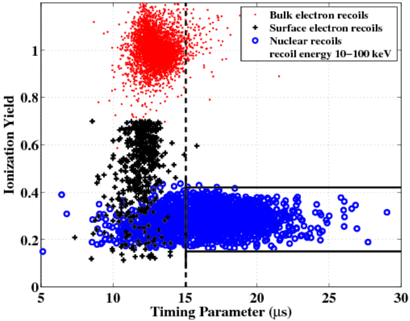



→ Measure full energy in the phonon channel

- Charge/light and phonon signals are measured

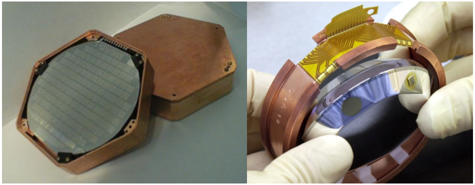
Excellent discrimination on the charge/phonon ratio

but surface events reduce acceptance significantly




Example: discrimination ER to NR in CDMS

# CDMS and Edelweiss experiments



- Combined analysis by CDMS and Edelweiss

  Z. Ahmed *et al.*, Phys. Rev. D. 84, 011102 (2011)

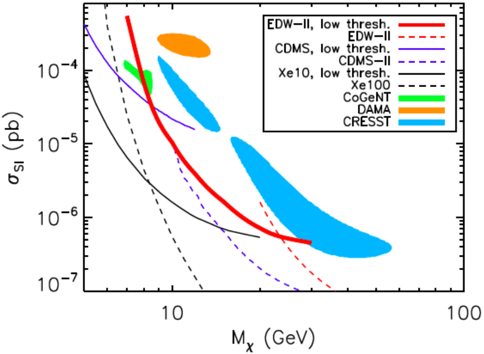
- Low energy threshold analysis

  2 keV for CDMS

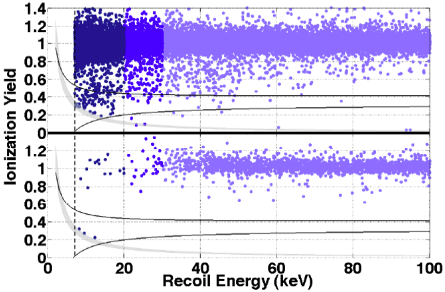
  CDMS, Phys. Rev. Lett. 106, 131302 (2011)

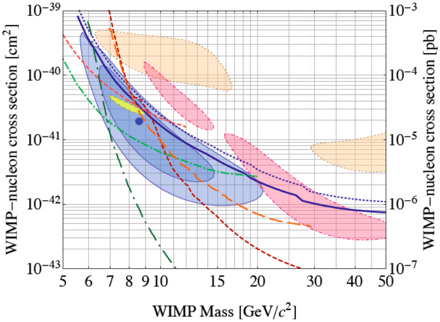
  5 keV for Edelweiss

  Edelweiss, Phys. Rev. D 86, 051701 (2012)



# Recent CDMS Si results




CDMS Si results from April 15th

140 kg-day exposure

3 events detected (0.7 expected)

CDMS, arXiv: 1304.4279

Likelihood analysis: 0.19 % probability for the known-background-only hypothesis

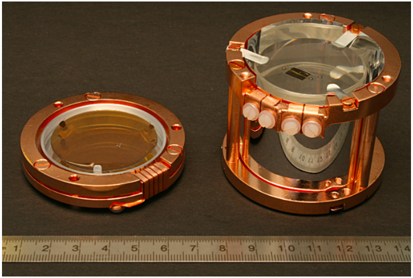
Best fit at $1.9 \times 10^{-41}$ cm$^2$ at 8.6 GeV/$c^2$ WIMP mass

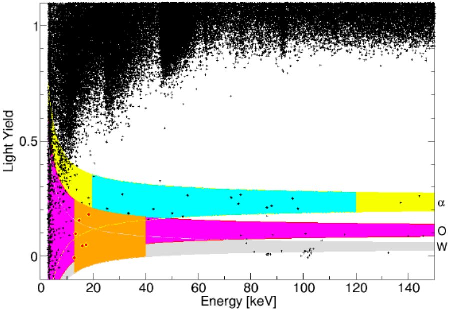
**Super-CDMS**: 10 kg @Soudan and plan to have 200 kg @SNOlab

Dedicated run @Soudan charge read-out only, $E_{th} \sim 0.1$ keV

# The CRESST experiment

- Scintillating $CaWO_4$ crystals
- 730 kg-day exposure
- 67 events detected (25 expected)






Maximum likelihood analysis:

4 $\sigma$ that BG can not explain the data

CRESST, Eur. Phys. J. C 72, 4 (2012)

New run with reduced background started this year

→ **EURECA** at Modane: future ton-scale experiment together with Edelweiss, detector R&D on-going

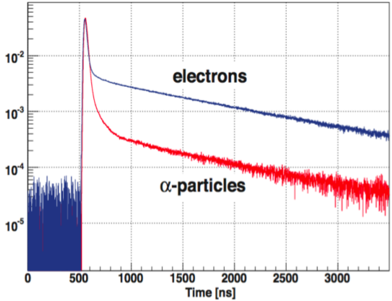
# Advantages of liquid noble gases for DM searches

- Large masses and homogeneous targets (LNe, LAr & LXe)
- 3D vertex reconstruction
  - Using light pattern in the PMTs for single phase (a few cm)
  - Resolution of a few mm in TPC mode
- Discrimination: Charge to light ratio and pulse shape

- Very different singlet and triplet lifetimes in argon & neon
- Relative amplitudes depend on particle type → discrimination

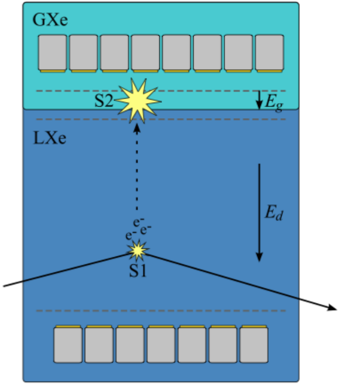
  WARP obtained $3 \times 10^{-7}$ discrimination in LAr above 35 PE (70% acceptance)

  → PSD not very powerful in LXe (similar decay constants)



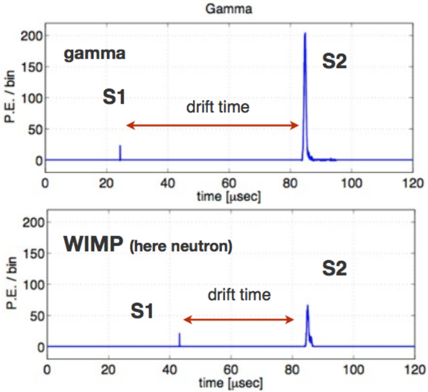

Scintillation decay constants of Argon measured by ArDM

# Two phase noble gas TPC




→ Electronic/nuclear recoil discrimination

- Scintillation signal (S1)
- Proportional signal (S2)



# Next LAr detectors

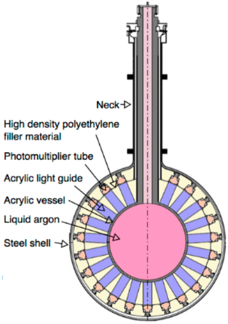
**Dark Side-50** at LNGS in Italy

- Two phase TPC: 50 kg active mass (33 kg FV)
- Depleted argon to reduce $^{39}$Ar background
- Currently commissioning the LAr detector
  → first light and charge signals observed
- Physics run expected for fall 2013

**DEAP** - **D**ark matter **E**xperiment with **A**rgon and **P**ulse shape discrimination

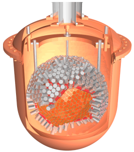
- 3 600 kg LAr in single phase at SNOlab
- Aim to use depleted argon
- Status: in construction

* Also CLEAN detector (LAr or LNe) at SNOLab




Cross section of the DEAP-3600 detector.

# XMASS experiment



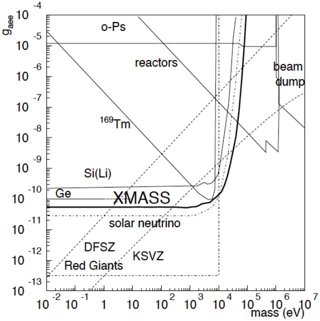
- → Search for dark matter
- → Solar neutrinos
- → Double beta decay of $^{136}$Xe

- 800 kg of LXe in single phase (self-shielding)
- 1st DM run → unexpected BG from PMTs found
- Detector refurbished, resume data-taking this summer

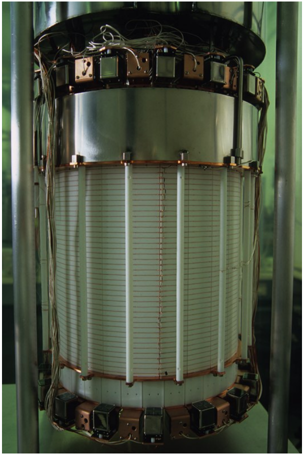

Run with high light yield of 14.7 PE/keVee

$E_{th} = 0.3\,\mathrm{keV}_{ee}$

Search for solar axions published recently arXiv:1212.6153



# The XENON100 experiment

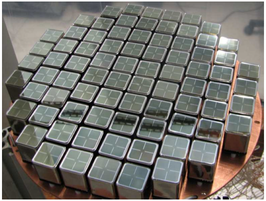


At LNGS lab (Italy)

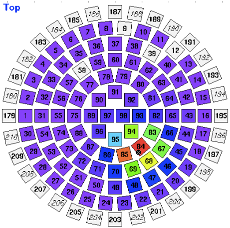
Instrument paper:

Astropart. Phys. 35 (2012) 573

- 30 cm drift length and 30 cm ∅
- 161 kg total (30-50 kg fiducial volume)
- Material screening and selection
- Active liquid xenon veto
- $\sim$ 100x less background than XENON10
- Bottom PMTs: high quantum efficiency

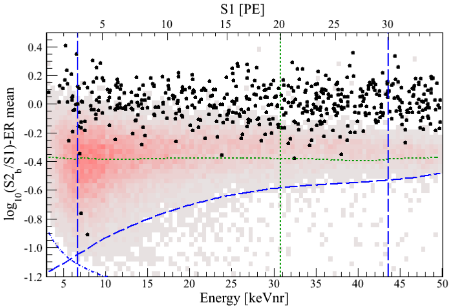


Bottom PMT array

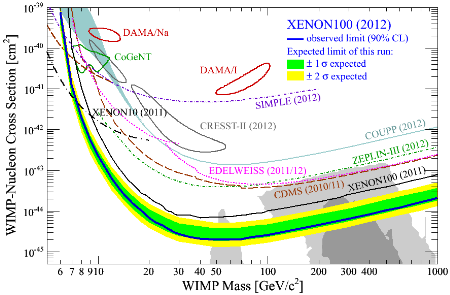



Top PMT array

# Results from 225 live days data (2012)




Science data



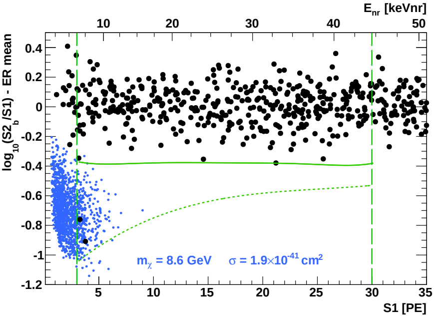

Spin-independent best sensitivity:
$2 \times 10^{-45}$ cm$^2$ at 55 GeV/$c^2$

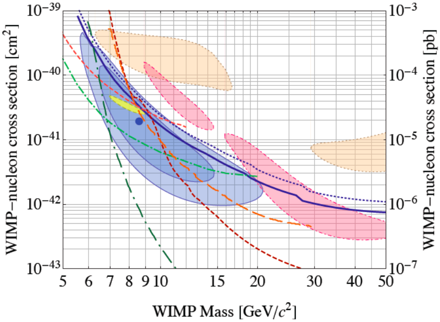
- Background expectation in the benchmark region: (1.0±0.2) events

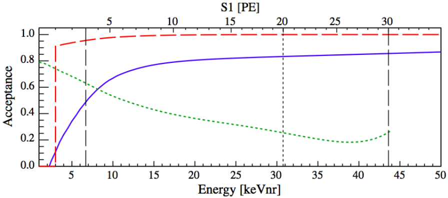
→ Exclusion limit derived using profile likelihood method

XENON100, Phys. Rev. Lett. 109 (2012) 181301

# How would CDMS signal look in XENON100?



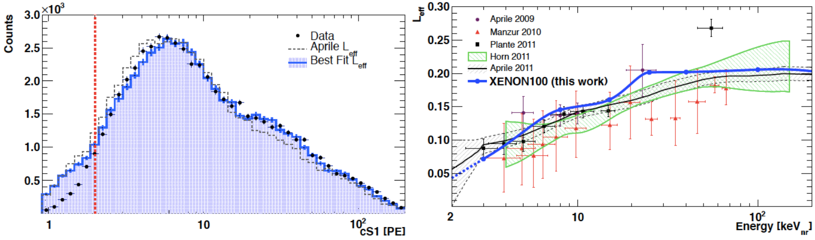




Event distribution that XENON100 would observe for the best fit point of CDMS

including acceptance below threshold!

# MC simulation of neutron source

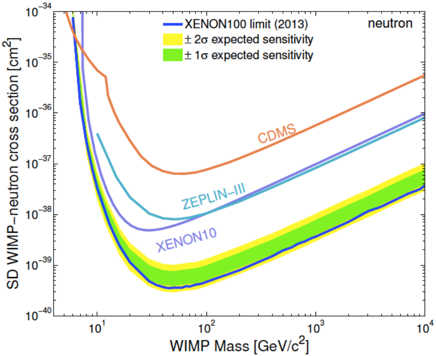
XENON100, arXiv:1304.1427

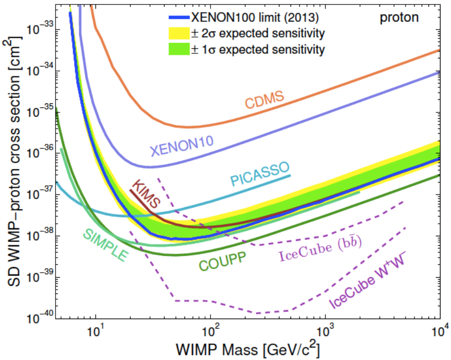



- Good overall agreement!. Best fit $L_{eff}$ matches previous measurements
- Poor agreement below 2 PE: unknown efficiencies below $E_{th}$
- Best fit of source strength: 159 n/s
- Source strength measurement (PTB): $(160 \pm 4)$ n/s

→ Results of XENON100 remain unchanged using this $L_{eff}$

# Spin-dependent XENON100 results



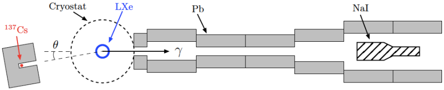




- Spin-dependent best sensitivity for neutron coupling: $3.5 \times 10^{-40}$ cm$^2$ at 45 GeV/$c^2$ WIMP mass
- Isotopes with a non zero nuclear spin ($^{129}$Xe & $^{131}$Xe)
- State of the art calculations of form factors used (Menendez *et al.*)

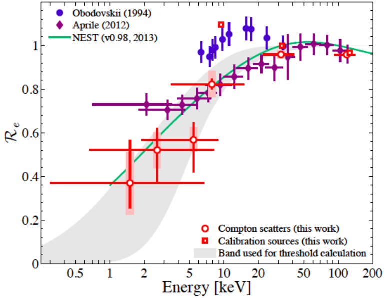
XENON100, Phys. Rev. Lett. 111, 021301 (2013)

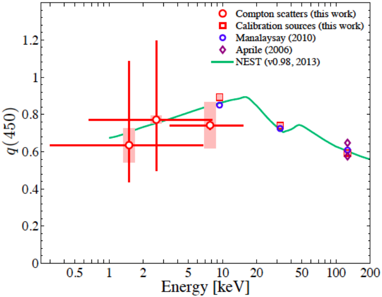
# Rate modulation in XENON100

XENON100: lowest background level of all DM detectors
Knowledge on the ER energy scale and detector threshold required




- Compton experiment
- LY of LXe down to $\sim 1.5$ keV



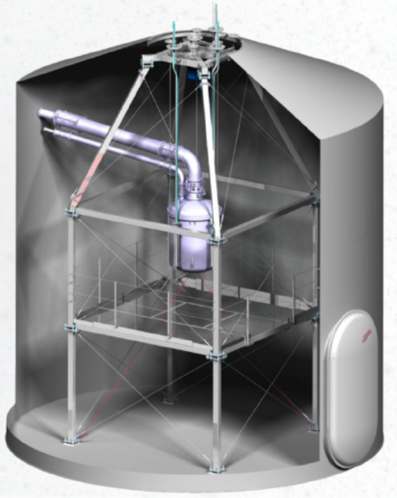

- Light yield decreases at 0-field below 50 keV
- Field quenching $\sim 75\%$ at low energies
- Derived XENON100 threshold: 2.3 keV $\rightarrow$ sensitive to DAMA signal!

Aprile *et al.*, Phys. Rev. D 86, 112004 (2012) and Baudis *et al.*, Phys. Rev. D 87, 115015 (2013)

# The XENON1T experiment

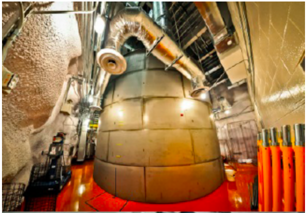
- More than 3 ton total mass ($>$ 1 ton fiducial mass)
- 1 m drift length TPC
- 100$\times$ less background than XENON100
- Sensitivity at $\sigma \sim 10^{-47}$ cm$^2$

XENON1T construction @LNGS (Italy)



- Construction started June 2013!
- Commissioning by end 2014

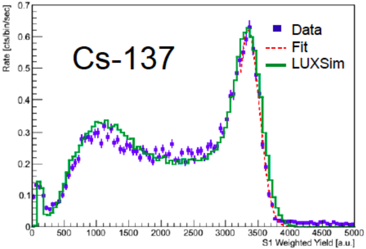
# LUX experiment

July 2012+

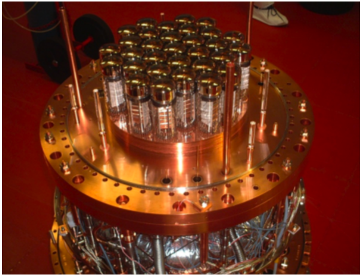
**LUX** - **L**arge **U**nderground **X**enon detector

- $\sim$ 100 kg fiducial mass (350 kg total)
- Two arrays of 61 PMTs
- First calibration above ground: 8 PE/keV at 0-field LUX, Astrop. Phys, 45, 34 (2013)




- Status 2013: running underground
  - Detector full, purifying LXe and calibrating
  - Science run 300 d, goal $2 \times 10^{-46}$ cm$^2$

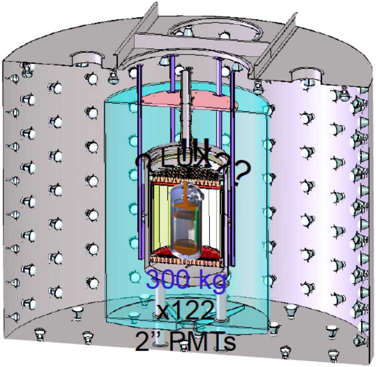
# ZEPLIN and the planned LZ experiment



- Until 2011 at Boulbi mine
- 12 kg target mass (∼30 cm ∅)
- 3.5 cm drift depth
  → high E-field 3.9 kV per cm

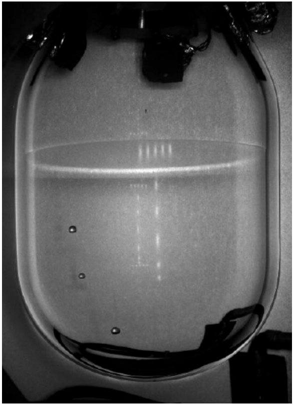
ZEPLIN-III, Phys. Lett. B 709: 14 (2012)

- **LZ**: LUX - ZEPLIN collaboration
- Current design: 7 tonnes LXe
- 480 PMTs (3 inch)

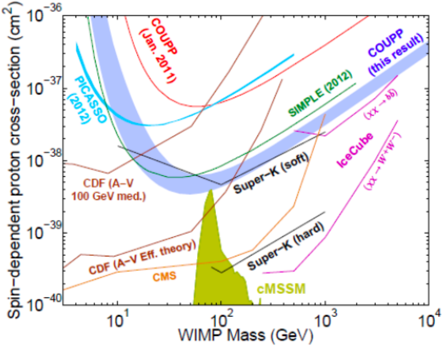


# Superheated droplet detectors

**COUPP** experiment



- A bubble chamber filled with superheated fluid ($CF_4I$) in meta-stable state
- Energy depositions $> E_{th} \rightarrow$ expanding bubble detected with cameras + piezo-acoustic sensors




Best proton-coupling SD sensitivity above 20 GeV/c$^2$ WIMP mass

Also **PICASSO** and **SIMPLE** experiments competitive in SD searches

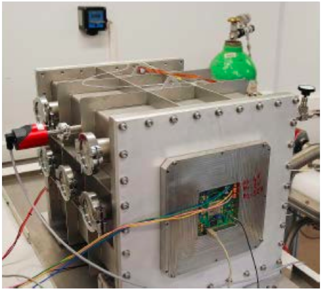
# Directional searches

- Most projects use low pressure TPCs with $CF_4$ ($^{19}F$) as target
- Key parameter angular resolution: Tracking ionisation detectors

→ Not competitive with liquids or solids but important confirmation in case of a WIMP detection

DRIFT - $m^3$ experiment

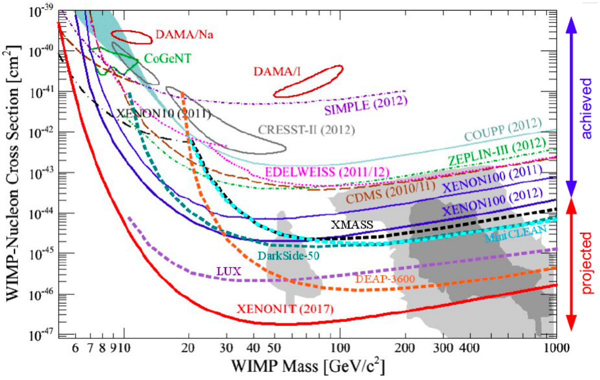
MIMAC - 5 l chamber



Also DMTPC, NEWAGE and emulsion detectors

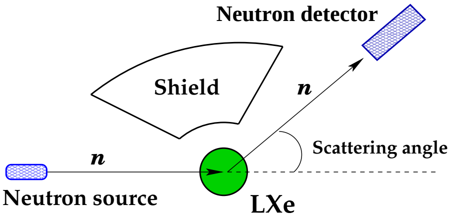
# Summary

- Few possible indications for DM in some experiments
  - Scattering of WIMPs off nuclei
    / light dark matter particles off electrons
- Strong limits from some experiments
- More results coming soon!




ATTENTION: plot not complete!

# $L_{eff}$ direct measurements




Nuclear recoil energy ($E_{nr}$):

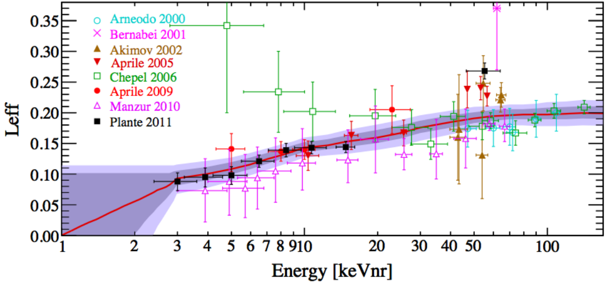
$$E_{nr} = \frac{S1}{L_y L_{eff}} \times \frac{S_e}{S_r}$$

$S1$: measured signal in p.e.

$L_y$: LY for 122 keV $\gamma$ in PE/keV

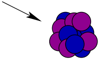
$S_e/S_r$: quenching for 122 keV $\gamma$/NR due to drift field

$L_{eff} = q_{nucl} \times q_{el} \times q_{esc}$



# Noble gas scintillation process

Nuclear recoil



**Excitation:** $\mathbf{R^*}$

$\mathbf{R^* + R \rightarrow R_2^*}$

$\mathbf{R_2^* \rightarrow 2R} + h\nu$

singlet / triplet

**Ionization:** $\mathbf{R^+}$ and $\mathbf{e^-}$'s

$\mathbf{R^+ + R \rightarrow R_2^+}$

$\mathbf{R_2^+ + e^- \rightarrow R^{**} + R}$

$\mathbf{R^{**} \rightarrow R^* +}$ **heat**

$\mathbf{R^* + R \rightarrow R_2^*}$

$\mathbf{R_2^* \rightarrow 2R} + h\nu$

| singlet | triplet | |
|---|---|---|
| 19 ns | 15 μs | Neon |
| 5 ns | 1.6 μs | Argon |
| 3 ns | 25 ns | Xenon |