Direct dark matter search using liquid noble gases

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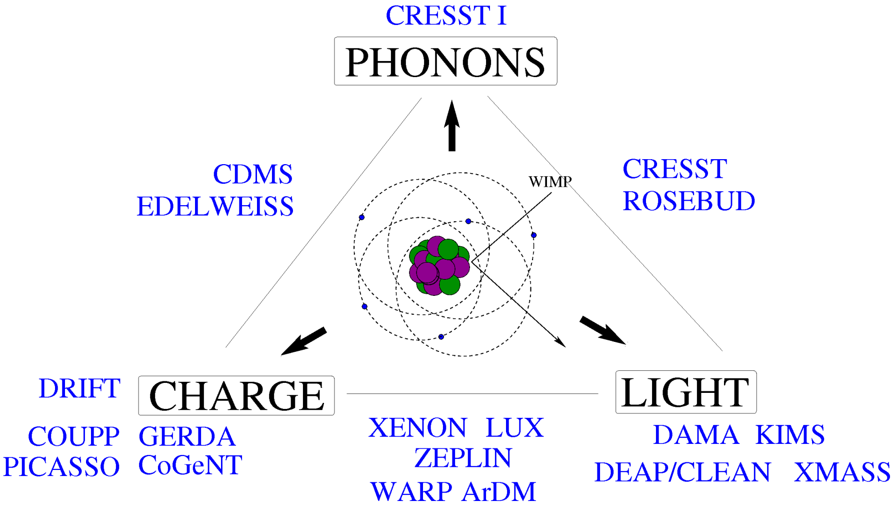
TeV Particle Astrophysics,
Paris, 19.07.2010

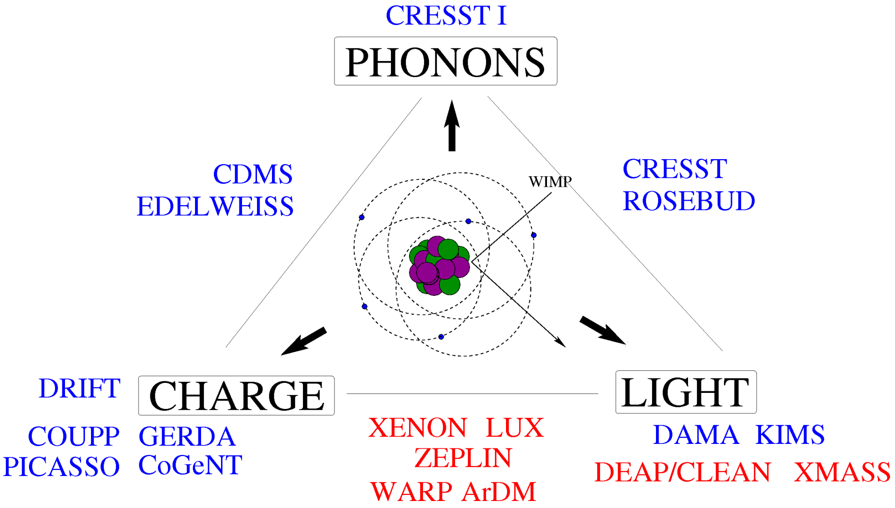
Outline

Outline

Direct detection experiments



Direct detection experiments

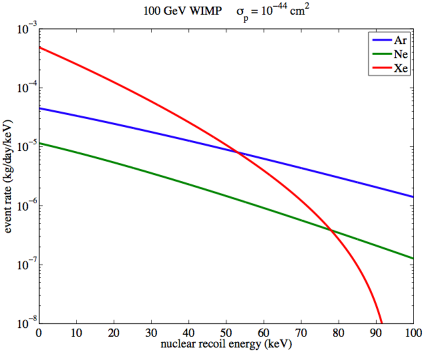


Advantages of liquid noble gases for DM searches

- Large masses and homegeneous targets (LNe, LAr & LXe)
- Very high scintillation yield ($\sim$ 40 000 photons/MeV)
- Transparent to their own scintillation light
- 3D position reconstruction
  - Light pattern in the PMTs for single phase (cms)
  - Few mms resolution in TPC mode
- High ionization yield (W_{LXe} = 15.6 eV and W_{LAr} = 23.6 eV)
- Particle discrimination
  - Pulse shape discrimination
  - Charge to light ratio

Comparison between noble gases

	LNe	LAr	LXe
Z (A)	10 (20)	18 (40)	54 (131)
Density [g/cm^3]	1.2	1.4	3.0
Scintillation λ	78 nm	125 nm	178 nm
BP [K] at 1 atm	27	87	165
Ionization [e$^-$/keV]	46	42	64
Scintillation [γ/keV]	7	40	46

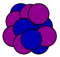


Radioactive isotopes:

- Argon: ^{39}Ar (565 keV endpoint, 1 Bq/kg), ^{42}Ar
- Xenon: ^{136}Xe $\beta\beta$ candidate *not yet measured!*
- ^{85}Kr in argon or xenon $\rightarrow$ removal using distillation

Noble gas scintillation process

Nuclear recoil



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

Excitation: $\mathbf{R^*}$

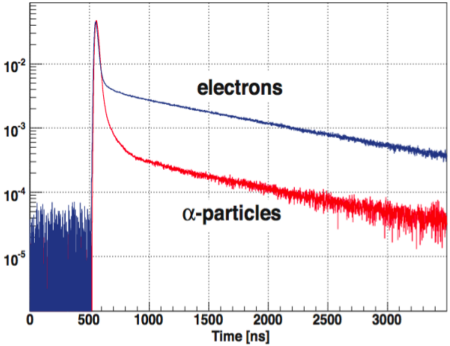
$$\mathbf{R^* + R \rightarrow R_2^*}$$

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

singlet triplet

Pulse shape from scintillation light

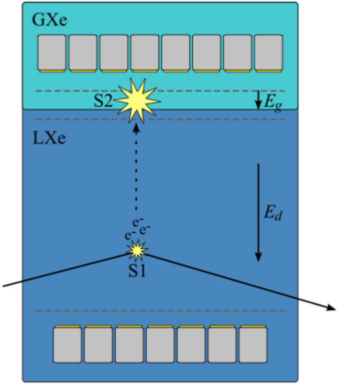
- Very different singlet and triplet lifetimes in argon & neon
- Relative amplitudes depend on particle type → discrimination
  WARP obtained 3×10^{-7} discrimination in Ar above 35 pe (70% acceptance)



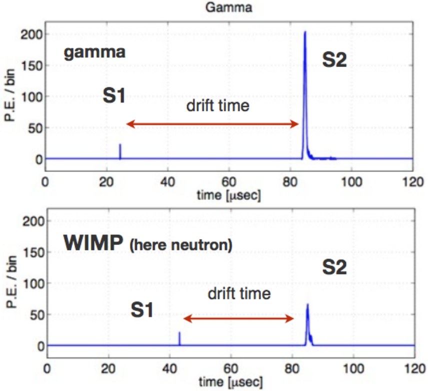
Scintillation decay constants of Argon measured by ArDM

→ PSD does not work well in LXe (too similar decay constants)

Two phase noble gas TPC



- Scintillation signal (S1)
- Charges drift to the liquid-gas surface
- Proportional signal (S2)



Electron recombination is stronger for nuclear recoils

→ Electron- / nuclear recoil discrimination

Calibration of noble gas detectors

Electron recoil calibration

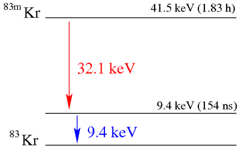
- Energy calibration and electron recoil band characterization
- Introducing sources inside
  - Easier in single phase detectors
  - Light blocking issue
- Calibration sources outside $\rightarrow$ self-shielding issue for low energies

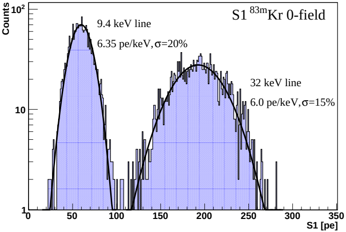
Nuclear recoil calibration

- No monoenergetic neutron lines for calibration

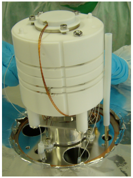
$\longrightarrow$ Dedicated neutron scattering experiments

- ^{83m}Kr calibration source:
  - EC decay-product of ^{83}Rb
  - Lines at 9.4 and 32.1 keV
  - Uniform distribution



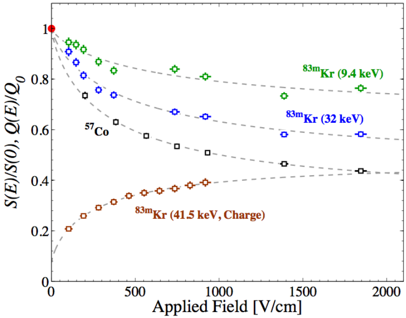


Liquid xenon



- Target mass: $\sim$ 0.1 kg LXe
- Volume: 3 cm drift length and 3.5 cm diameter
- Two R9869 PMTs
- 6 pe/keV in double phase

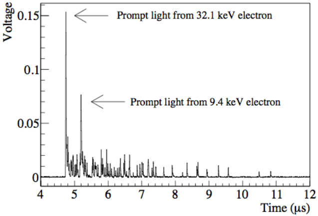
$\rightarrow$ at University of Zürich

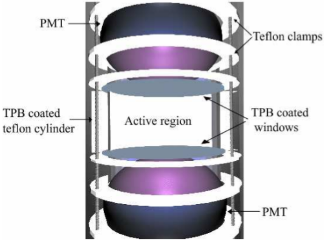


A. Manalasay *et al.*, Rev. Sci. Instr. **81**, 073303 (2010), 0908.0616

^{83}Kr source in argon and neon

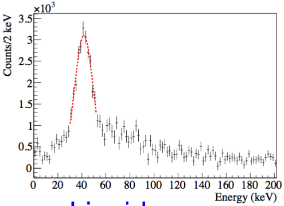
Pulse in argon



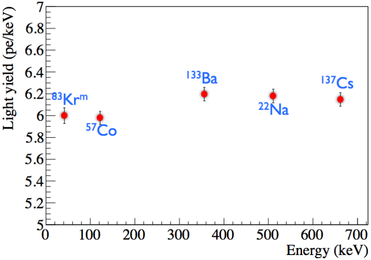


→ Scheme of the chamber at Yale

- Light yield:
  - Argon: 6 pe/keV
  - Neon: 3 pe/keV



Liquid neon



W. H. Lippincott *et al.*, Phys. Rev. **C81**, 045803, (2010), 0911.5453

Calibration of the nuclear recoil energy scale

- 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.

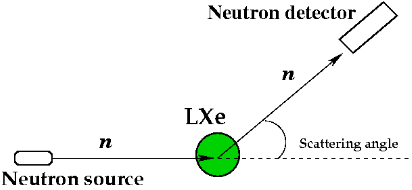
L_y: LY for 122 keV γ in p.e./keV

S_e/S_r: quenching for 122 keV γ/NR due to drift field

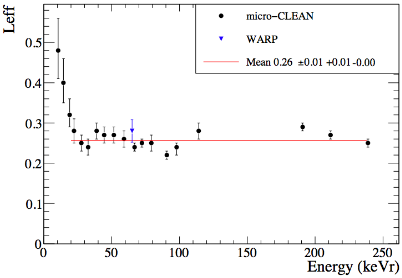
- Relative scintillation efficiency of NR to 122 keV γ at 0-field

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

  - q_{nucl}: Linhard quenching
  - q_{el}: Electronic quenching
  - q_{esc}: Escape e$^-$'s at 0-field

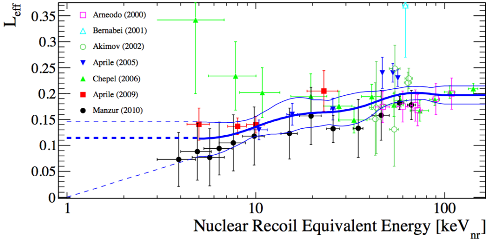


Measuring the nuclear recoil scale



Liquid argon

Figure from D. Gastler *et al.*, arXiv:1004.0373



Liquid xenon

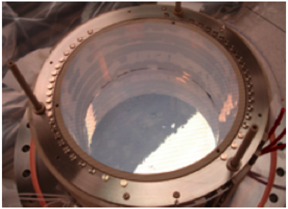
Two existing measurements

Discrepancies in the low energy for the xenon experiments

$\longrightarrow$ Currently: plans to do such measurements at lower recoil energies and understand the systematics

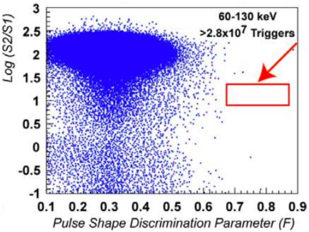
Outline

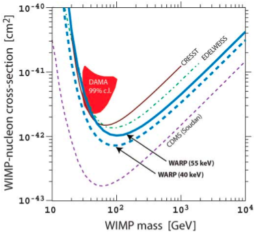
WARP 23 ℓ prototype



WIMP ARGON PROGRAMME

- 20 cm $\varnothing$ and 7.5 cm drift length
- Technology demonstrator
- Two discrimination parameters: S2/S1 and pulse shape
- Status: finished



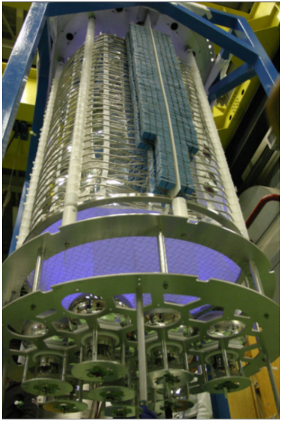


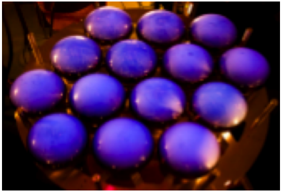
P. Benetti *et al.*, Astropart. Phys., **28**, 6, 495 (2008), 0701286

WARP 140

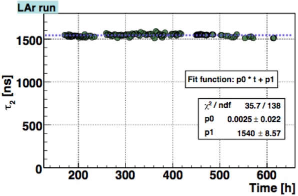
- Detector description:
  - 140 kg liquid argon
  - 60 cm drift length and 50 cm ∅
  - 31 PMTs of 3" and 6 of 2" on top
  - Copper structure with TPB reflector
  - Charge read-out via secondary light
- Status:
  - Commissioning at Gran Sasso
  - First test run in summer 2009
  - Detector filled again in March 2010
  - PMT upgrade planned to lower the threshold

ArDM detector





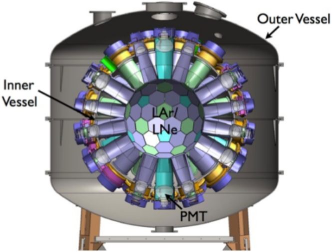
- Detector description:
  - Mass: 850 kg liquid argon
  - 120 cm drift length and 26 cm ∅
  - 8” PMTs on bottom
  - Charge read-out on top: LEMs
  - HV: Aim to reach V_{tot} = 500 kV, ∼ 4 kV/cm
- Status:
  - First cool down: completed and satisfactory



  - Commissioning the protopype at CERN
  - Planned underground operation 2011

⟶ Talk by Ursina Degunda

DEAP/CLEAN in SNOlab



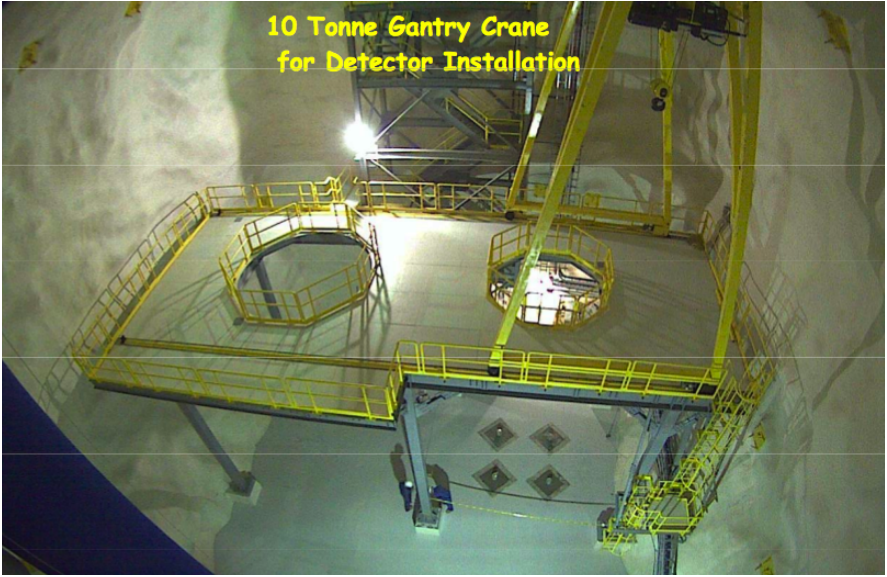
CLEAN - **C**ryogenic **L**ow **E**nergy **A**strophysics with **N**oble gases

- MiniCLEAN: 150 kg fv single phase detector with LAr/LNe
- PSD to reduce backgrounds
- In commissioning phase

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

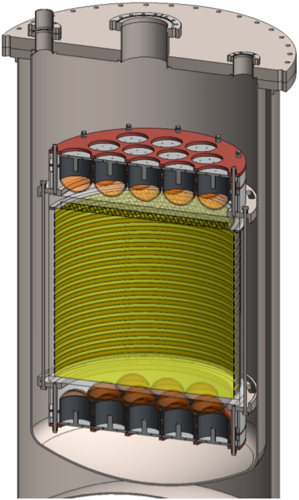
- 3 600 kg LAr in single phase
- Aim to use depleted argon to reduce ^{39}Ar
- Status: in construction
- Assembly planned for 2012

⟶ Talk by Keith Rielage



- SNOlab: current installation of underground structure

Dark Side at Gran Sasso

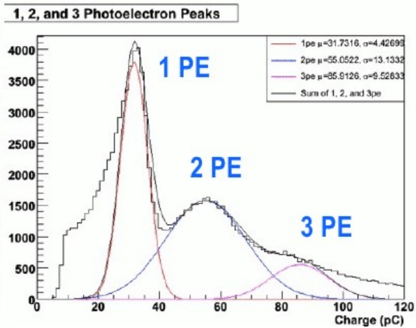


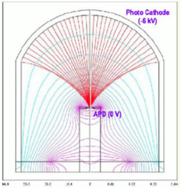
- In proposal stage
- 50 kg depleted argon from underground sources
  - Source found with factor 25 reduction in ^{39}Ar level
  - Extraction plant at Princeton
- Detector location at Borexino counting facility (CTF)
- Borated liquid scintillator (^{10}B) as neutron veto
- QUPID as photosensor

QUPIDS for light readout

- **QU**artz **P**hoton **I**ntensifying **D**etector (hybrid detector)
- Development by UCLA & Hamamatsu for LXe and LAr detectors

  - Ultra-low radioactivity ($\sim$ 0.1 mBq)
  - High QE and high SPE resolution





- First test at UCLA
- QUPID working in LXe!

$\longrightarrow$ single electron response

K. Arisaka *et al.*, Astroparticle Physics **31** (2009) 63

Outline

1 Introduction

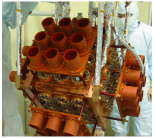
2 Liquid argon experiments

3 **Liquid xenon experiments**

4 Summary

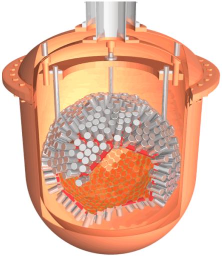
XMASS experiment

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



→ Picture from February 2010

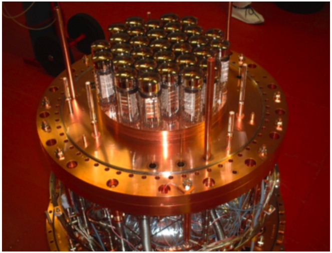
- 800 kg of LXe (single phase)
- Self-shielding concept
- Copper structure
- $\sim$800 ton water shield
- Plans for DM run within 2010



→ Talk by Kazuyoshi Kobayashi

XMASS infrastructure in construction in the Kamioka mine

Zeplin III

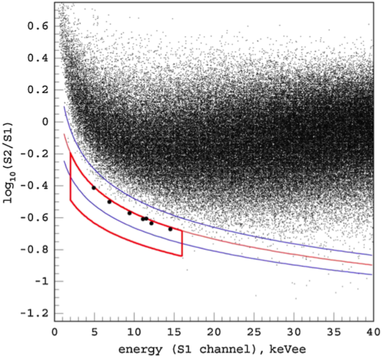


- 83 d operation with 84% livetime @ **Boulby**
- 267.9 kg d effective fiducial exposure
- 7 events in the box with 11±3 events expected bg

- ~30 cm ∅ and 3.6 cm drift depth

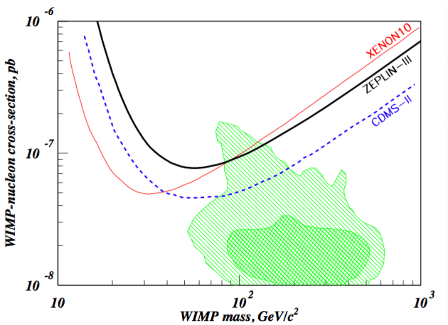
→ high E-field 3.9 kV per cm

- 0.5 cm electroluminescent gap
- 31 × 2 inch PMTs
- 12 kg active target mass



Zeplin III

Zeplin III limit on the WIMP-nucleon spin-independent scattering cross-section:



V. N. Lebedenko *et al.*, Phys. Rev. Lett. 103: 151302 (2009), arXiv:0812.1150

- Also limits placed on spin-dependent interactions and on inelastic dark matter

UPGRADE:

- PMTs replaced by low radioactivity ones
- Screening of the materials used
- Simulations to predict background
- Plastic scintillator active veto
- ... and further system upgrades

→ Detector currently running and acquiring dark matter data

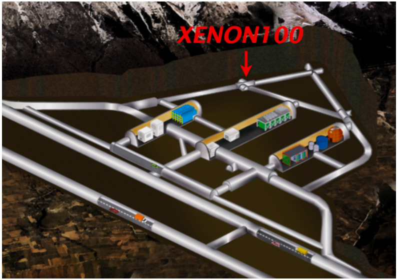
XENON experiment

- Laboratori Nazionali del Gran Sasso (Italy)
- $\sim$ 3 500 m.w.e. shielding

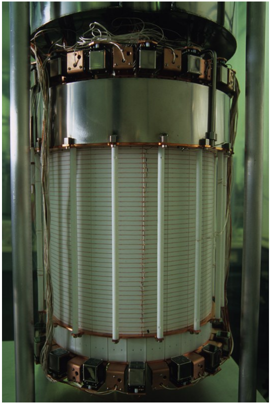
- XENON10: 15 kg active volume
  - Finished: No evidence for DM

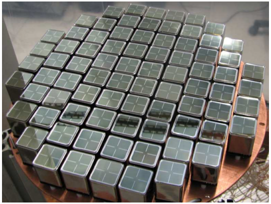
J. Angle *et al.*, Phys. Rev. Lett. 100, 021303 (2008)
J. Angle *et al.*, Phys. Rev. Lett. 101, 091301 (2008)
J. Angle *et al.*, Phys. Rev. D80, 115005 (2009)

- XENON100: 62 kg active volume
  - Currently running

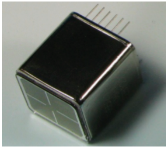


XENON100

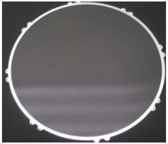




- 30 cm drift length and 30 cm ∅
- 161 kg total (30-50 kg fiducial volume)
- ∼ 100x lower background than XENON10 achieved
- Improved shielding
- Material screening and selection
- Active liquid xenon veto



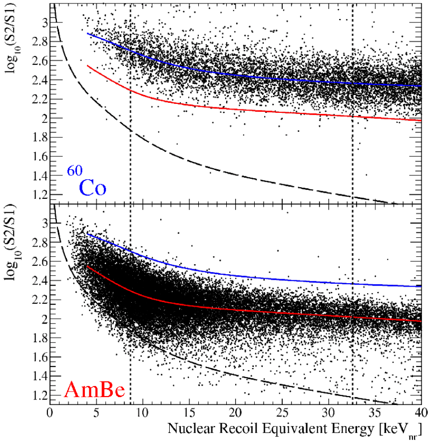
1 inch PMTs

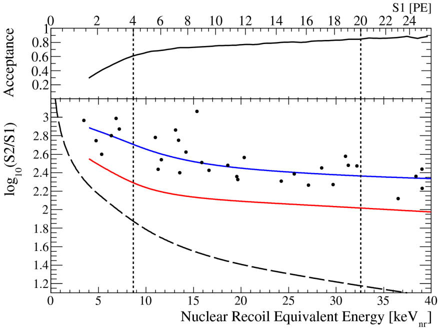


30 cm ∅ meshes

⟶ Talk by Alfredo Ferella

XENON100 results

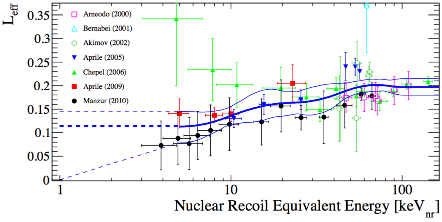




- Discrimination better than 99% @ about 50% NR acceptance

→ ‘Background free’: in the 11.17 days of data after discrimination

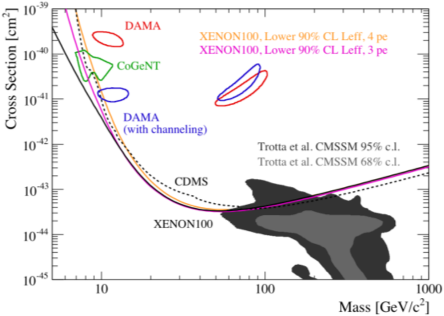
Limit from non-blinded data analysis



- Excellent sensitivity: even for few days of data

→ Sensitivity to low WIMP masses depends on L_{eff}

- Spin independent limit: for standard halo parameters

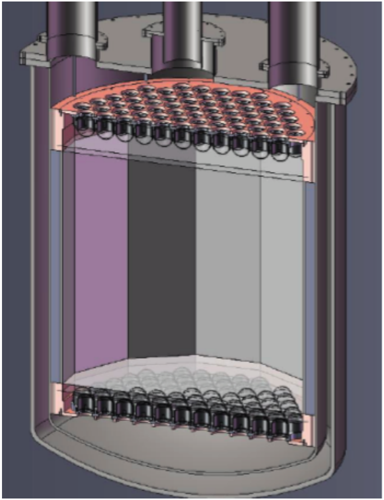


E. Aprile *et al.*, arXiv:1005.0380

- Much more data recorded in blind mode

+ analysis in the high nuclear-recoil energy region

Future: XENON1t



- 1.1 ton fiducial mass
  (total of 2.2 ton LXe)
- Drift length: $\sim$90 cm
- 100x background reduction
- Muon veto
- Copper/titanium cryostat
- QUPIDs for photo-detection

→ New collaborators

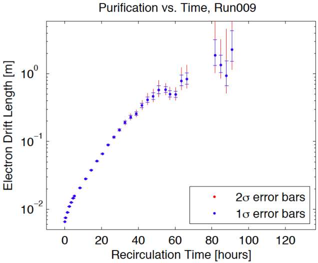
→ Currently working on MC simulations and design + secure funding

- Location under discussion: Gran Sasso/Modane

LUX experiment

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

- ~ 100 kg fiducial mass (350 kg total)
- Two arrays of 61 PMTs
- Water tank as muon veto
- Excellent purification system:



- Status: commissioning
  - Detector tested in 2009 (LUX 0.1)
  - Waiting for underground location: Davis Laboratory at the Homestake Mine (end 2010) → tests above ground

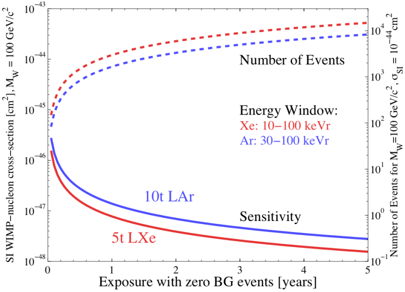
DARWIN and MAX joint activities

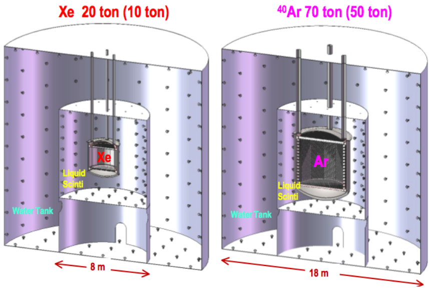
dark matter wimp search in noble liquids
DARWIN

MAX
Multi-ton Argon Xenon

@ DUSEL

- R&D and DS for a noble liquid facility in Europe
- US R&D activities for multi-ton argon and xenon detectors



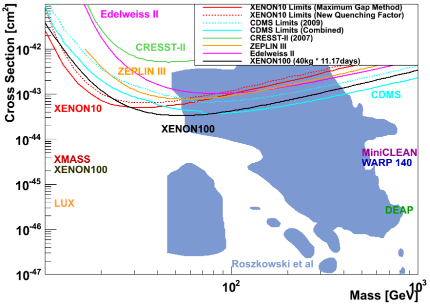


Outline

Summary

- DM search with noble liquids has progressed rapidly in the last years $\rightarrow$ No discovery so far!

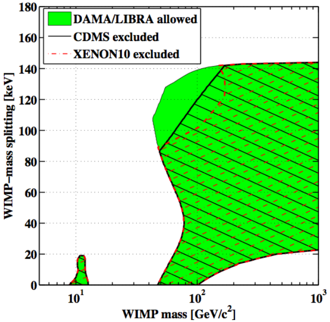
  $\rightarrow$ Best limit by XENON100 at 3.4×10^{-44} cm^2 (SI) for 55 GeV/c^2 WIMP mass
- Big effort to increase the mass and reduce the backgrounds
  - $\rightarrow$ Material screening and selection
  - $\rightarrow$ Fiducialization: Position reconstruction best in TPCs
- Current experiments in the order of 10 – 100 kg LAr/LXe
  - $\rightarrow$ Plans for ton-scale experiments (some already under construction)



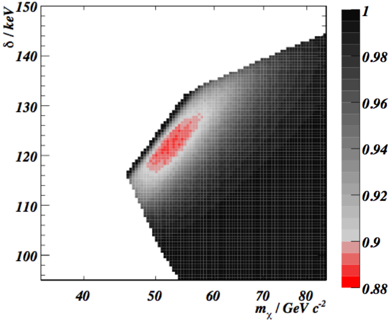
Interpretation of DAMA signal as iDM

- Inelastic dark matter model (D. Tucker-Smith and N. Weiner)
  - WIMP scatter to an excited state
  - Minimum relative speed: $v_{min} = \frac{1}{\sqrt{2m_N E_R}}\left(\frac{m_N E_R}{\mu_N} + \delta\right)$

→ Expected WIMP rates for Ge/Xe at higher nuclear recoil energies



CDMS detector: 4.4 kg of germanium
arXiv: 0912.3592 [astro-ph]



Zeplin: 6.5 kg liquid xenon
Latest result arXiv:1003.5626v2 [hep-ex]

- XENON100 results can check the remaining allowed region