Liquid noble gases for direct dark matter searches

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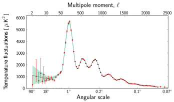
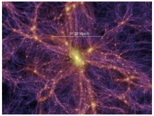
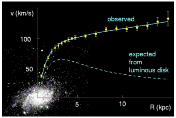
Max-Planck-Institut für Kernphysik Heidelberg

Direct dark matter detection

Indications of dark matter from Astronomy and Cosmology:

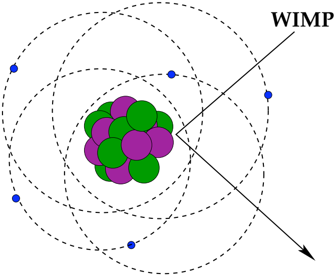






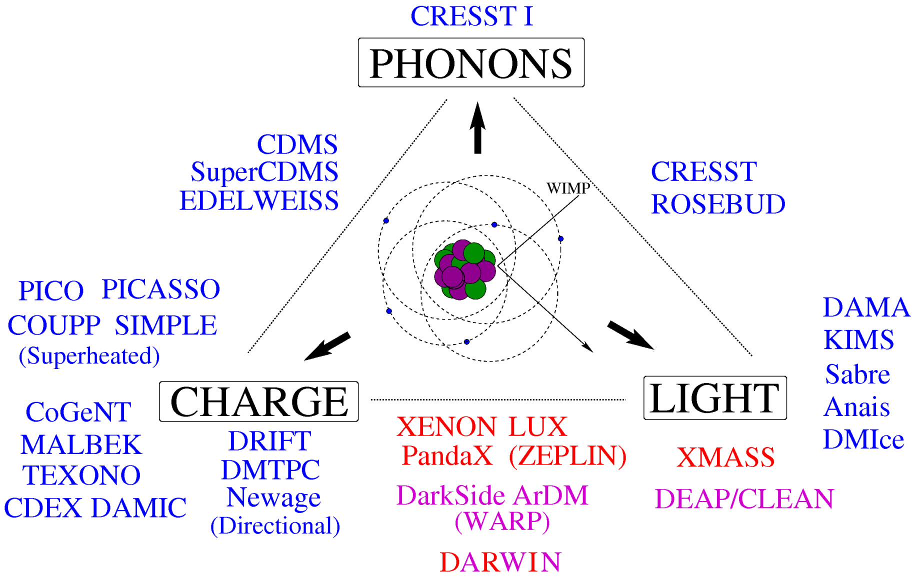
BUT what is its nature?

$\rightarrow$ Particle candidate: WIMP (Weakly Interacting Massive Particle)



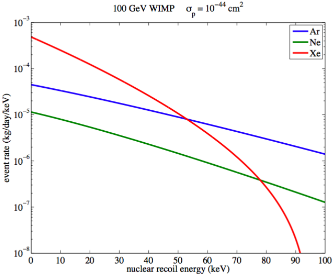
- Possible detection mechanisms:
  - Production at LHC
    (p + p $\rightarrow \chi$ + other particles)
  - Indirectly via annihilation
    ($\chi\chi \rightarrow e^+e^-$, $p\bar{p}$, $\gamma\gamma$ ...)
  - Scattering off nuclei
    (χ N $\rightarrow \chi$ N)

Direct detection experiments



Advantages of liquid noble gases for DM searches

- Large masses and homegeneous targets (LNe, LAr & LXe)
  Two detector concepts: single & double phase
- 3D position reconstruction → fiducialization
- Transparent to their own scintillation light



	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
Ioniz. [e^-/keV]*	46	42	64
Scint. [γ/keV]*	7	40	46

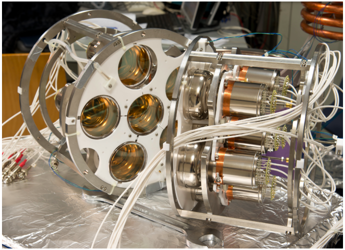
* for electronic recoils

Backgrounds

- External γ's from natural radioactivity:
  - Suppression via self-shielding of the target
  - Material screening and selection
  - Rejection of multiple scatters & discrimination
- Internal contamination:
  - ^{85}Kr: removal by cryogenic distillation/chromatography/centrifuges
  - ^{219}Rn, ^{220}Rn, ^{222}Rn: removal using adsorption/distillation
  - Argon: ^{39}Ar (565 keV endpoint, 1 Bq/kg), ^{42}Ar
  - Xenon: ^{136}Xe $\beta\beta$ decay ($T_{1/2} = 2.2 \times 10^{21}$ y) *long lifetime!*
- External neutrons:
  muon-induced, (α, n) and from fission reactions
  - Go underground!
  - Shield: passive (polyethylene) or active (water/scintillator vetoes)
  - material selection for low U and Th contaminations

Light sensors

- Requirements for a dark matter experiment:
  - Low radioactivity & low dark rate (background rate only few Hz!)
  - UV sensitivity & stable performance at cold temperatures
  - Low power consumption & high QE/CE
- APD, SiPMT, hybrid tubes ...
- State of the art 3” photomultipliers from Hamamatsu:
  - R11065 (for LAr) used by DarkSide
  - R11410 (for LXe) for XENON1T, PandaX and LZ

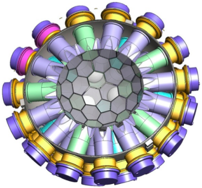


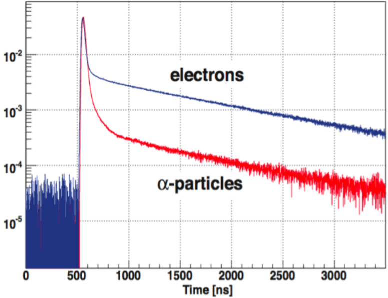
XENON1T testing setup for R11410-21 at MPIK

- Low-radioactive photosensors
  ^{238}U & ^{228}Th < 1 mBq/PMT
  For reference: 1 Banana $\sim$ 15 Bq in ^{40}K
- High quantum efficiency: 36 % in average for XENON1T
- Stable performance at -100°C

Single phase (liquid) detectors

- High light yield using 4π photosensor coverage
- Position resolution in the cm range
- Pulse shape discrimination (PSD) from scintillation





Scintillation decay constants of argon measured by ArDM

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

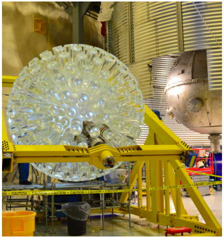
DEAP-I obtained 10^{-8} discrimination in LAr above 25 keV_{ee} (50% acceptance)

M. G. Boulay *et al.*, arXiv:0904.2930

⟶ PSD less powerful in LXe: similar decay constants

XMASS, NIM. A659 (2011) 161

Single phase: current detectors

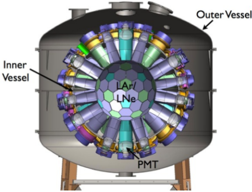


DEAP - **D**ark matter **E**xperiment with **A**rgon and **P**ulse shape discrimination

- 3 600 kg LAr
- Data expected in 2014

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

- 150 kg FV with LAr/LNe
- Commissioning this year

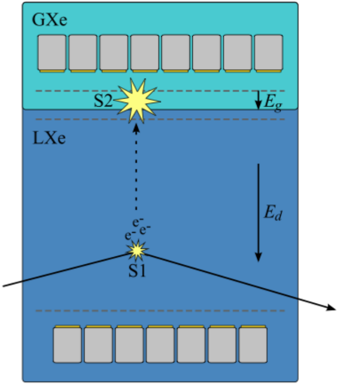


DEAP & CLEAN at SNOlab, Canada

XMASS - 800 kg FV LXe (at Kamioka, Japan)

- Ultra-low background required + Self-shielding
- High light yield of 14.7 PE/keVee, $E_{th} = 0.3\,keV_{ee}$
- Detector refurbished, resumed data-taking in Nov. 2013, expecting results soon
- Currently designing XMASS-1.5

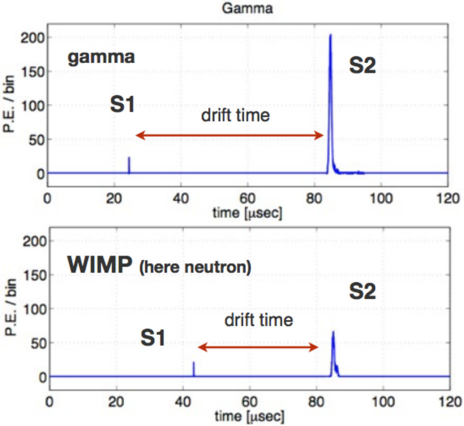
Two phase noble gas TPC



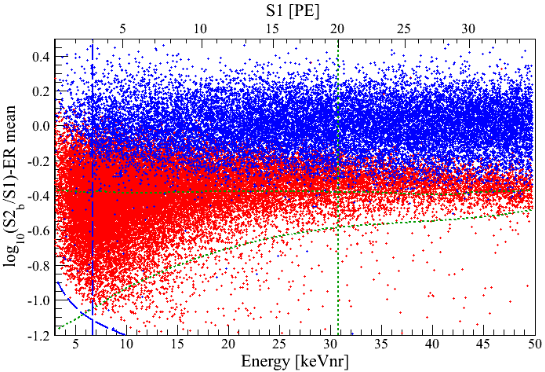
- Drift field necessary
- Electronegative purity required
- 3D position resolution in mm

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

→ Electron- /nuclear recoil discrimination



Double phase LAr & LXe experiments



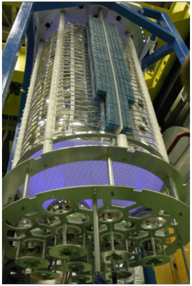
LAr double-phase TPCs

DarkSide-50:

- Detector inside Borexino counting facility, LNGS (Italy)
- Data of first run shown this spring
- 50 kg depleted argon from underground sources
  $>$ 100 reduction in ^{39}Ar level
- PSD & charge/light ratio for discrimination
  Goal to reach 10^{-45} cm^2 in 3 y measuring time

ArDM:

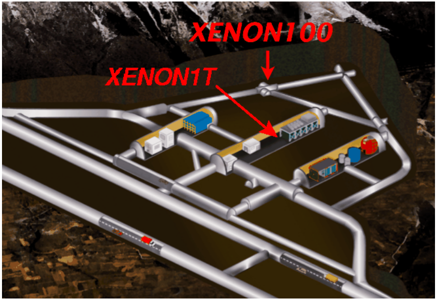
- Mass: 850 kg liquid argon (in target)
- Technology demonstrator
- Installed at Canfranc (Spain)
- Underground operation II expected for 2014



XENON experiment

- Laboratori Nazionali del Gran Sasso (Italy)
- $\sim$ 3 650 m.w.e. shielding

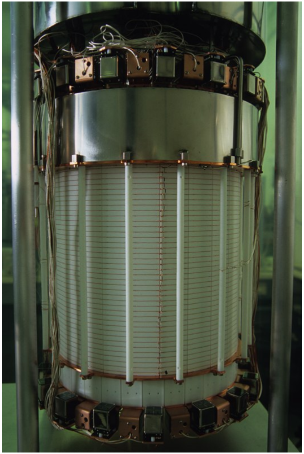
- XENON10: 15 kg active mass
- XENON100: 62 kg active mass
  - Currently running
- XENON1T: $\sim$ 2.2 T active mass
  - construction started 2013!



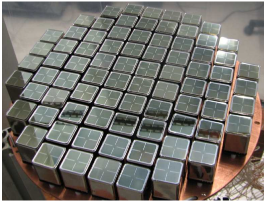
The XENON Collaboration

Columbia Rice UCLA Zürich Coimbra LNGS INFN Purdue RPI

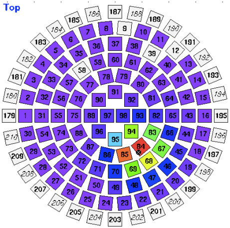
Bologna Subatech Münster Heidelberg Nikhef Weizmann Mainz Bern



- 30 cm drift length and 30 cm ∅
- 161 kg total (30-50 kg fiducial volume)
- Material screening and selection
- Active liquid xenon veto
- Background $\sim 5 \cdot 10^{-3}$ events/(kg·d·keV)
- Bottom PMTs: high quantum efficiency



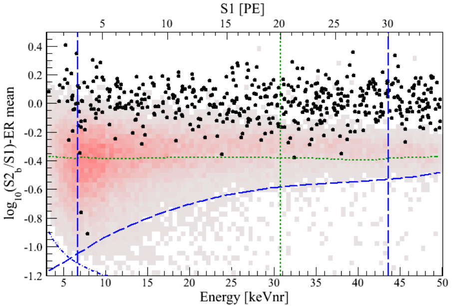
Bottom PMT array



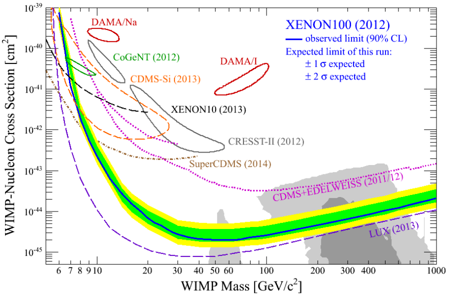
Top PMT array

- Instrument paper:
  Astropart. Phys. 35 (2012) 573
- Analysis paper:
  Astropart. Phys. 54 (2014) 11

Results from 225 live days data



Science data



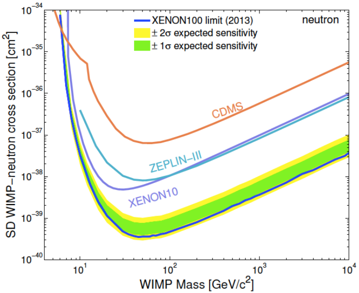
Spin-independent best sensitivity:
2×10^{-45} cm^2 at 55 GeV/c^2

- Background exp. in the benchmark region: (1.0±0.2) events
- Exclusion limit derived using profile likelihood method

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

→ Science run III: 154 d run still blinded + currently taking data

Spin-dependent and axion search results

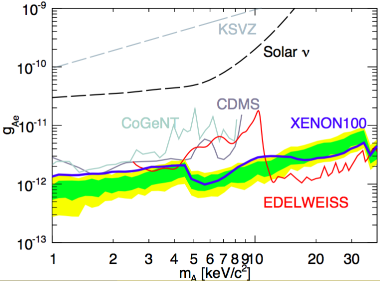


- Spin-dependent best sensitivity for neutron coupling
- Isotopes with a non zero nuclear spin (^{129}Xe & ^{131}Xe)
- State of the art calculations of form factors used (Menendez *et al.*)

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

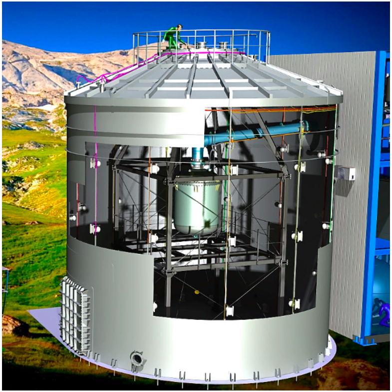
- Study of electronic recoil events
- Energy scale derived from Compton measurements in Zurich and Columbia
- Limit derived for axion-like particles and solar axions

XENON100, Phys. Rev. D 90 (2014) 062009, arXiv:1404.1455



XENON1T

- Goal: two orders of magnitude improvement in sensitivity
  - Approx. 1 t fiducial volume out of a total of 3 t LXe
  - Background requirement: <1 event in the full exposure



XENON1T illustration

- External γ's: suppression via self-shielding ($\rho_{\mathrm{LXe}} \sim 3\,\mathrm{g/cm^3}$) + material screening and selection
- Internal BGs (^{85}Kr and Rn): removal by dedicated device and control by material screening and surface treatment
- Neutrons: muon veto + material selection for low U and Th contaminations

XENON1T at LNGS

- 1 ton fiducial volume out of $\sim$3 ton LXe
- Goal to reach 2×10^{-47} cm^2
- Construction started in 2013 at LNGS
  Water tank, cryostat & cryosystem installed
  Gas and storage systems commissioning
- Commissioning in 2015

XENON1T cryostat

XENON1T at LNGS

- 1 ton fiducial volume out of ~ 3 ton LXe
- Goal to reach 2×10^{-47} cm^2
- Construction started in 2013 at LNGS

  Water tank, cryostat & cryosystem installed

  Gas and storage systems commissioning
- Commissioning in 2015

Detector design

- Background requirement: <1 event in ~ 2 years
- 1 m electron-drift and 100 kV HV demonstrated

XENON1T TPC design

Responsibilities of German groups in XENON1T

- Mainz:

→ Muon veto: water-Cherenkov detector (arXiv:1406.2374)

→ Work on storage system & TPC (Monte Carlo, level meters)

See poster: Search for dark matter with XENON – activities at Mainz

- Münster:

→ Kr distillation: reduction of the radioactive of ^{85}Kr

→ Xenon purification: removal of electronegative impurities

See poster: Cryogenic Distillation Column for XENON1T

- MPIK:

→ Photosensors: tests at room and liquid xenon temperatures

→ Screening: γ- screening with Ge detectors and Rn emanation

→ Gas purity analytics: Rn removal and Kr in Xe measurement

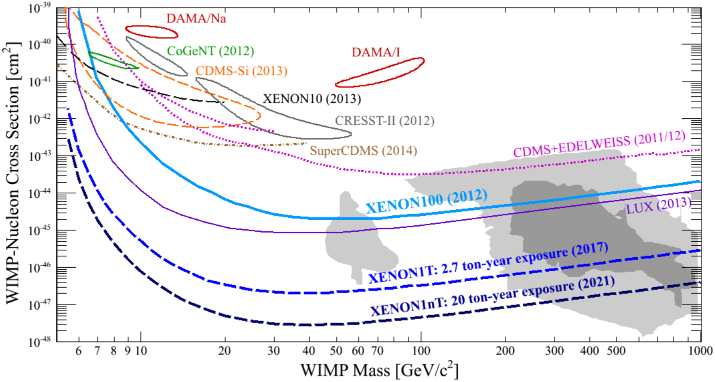
JG|U

Westfälische Wilhelms-Universität Münster

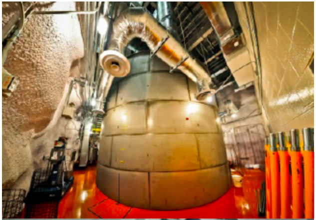
MPI für Kernphysik

Upgrade of XENON1T to XENONnT

- XENONnT would contain about 6 tons LXe
- All infrastructure (muon veto, cryostat, recuperation system ...) built already to accommodate XENONnT
- 'Only' LXe, 250 PMTs and new TPC necessary
- One additional order of magnitude improvement in sensitivity

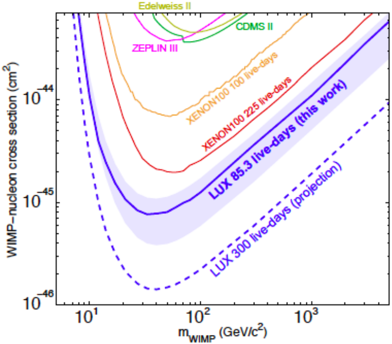


LUX at Homestake



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

- 118 kg fiducial mass (370 kg total)
- Results from first run in 2013



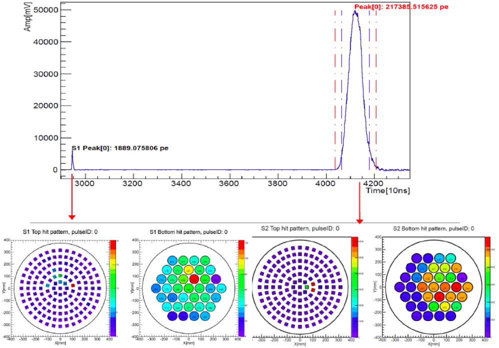
LUX, Phys. Rev. Lett. 112, 091303 (2014)

- Next step: 300 live-days run

$\longrightarrow$ LZ: multi-ton detector planned

PandaX, arXiv:1405.2882

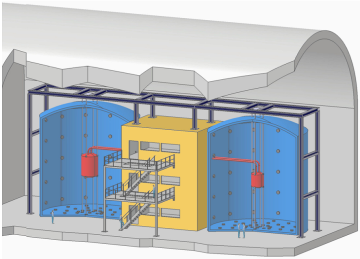
- Design concept in stages:
  - Stage 1a: 120 kg target (ongoing)
  - Stage 1b: 500 kg target (late 2014)
  - Stage 2: 1.5 ton target
- Everything designed for 1 ton FV



First results of PandaX-I released (arXiv:1408.5114)
PandaX-II currently being constructed

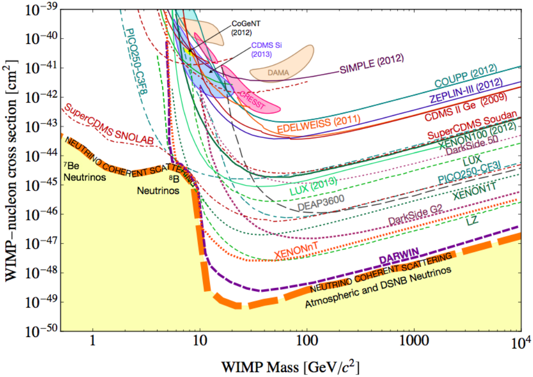
dark matter wimp search in noble liquids
DARWIN

- R&D and design study for a noble liquid facility in Europe
- LAr and LXe communities involved
- 28 groups from 10 countries
- Construction ∼ 2020, data 2022 – 2026



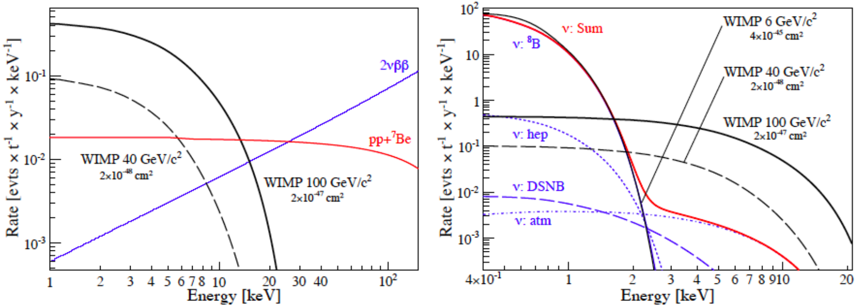
http://darwin.physik.uzh.ch/

20 t LXe and/or 50 t LAr



DARWIN

- Goal: measure WIMP properties / ultimate cross-section sensitivity
- Neutrino physics channels become available:
  - Electronic recoils from solar neutrinos
  - Nuclear recoils from coherent neutrino scattering: solar, DSNB and atmospheric ν's



L. Baudis *et al.*, JCAP01 (2014) 044

Sensitivity evolution in time

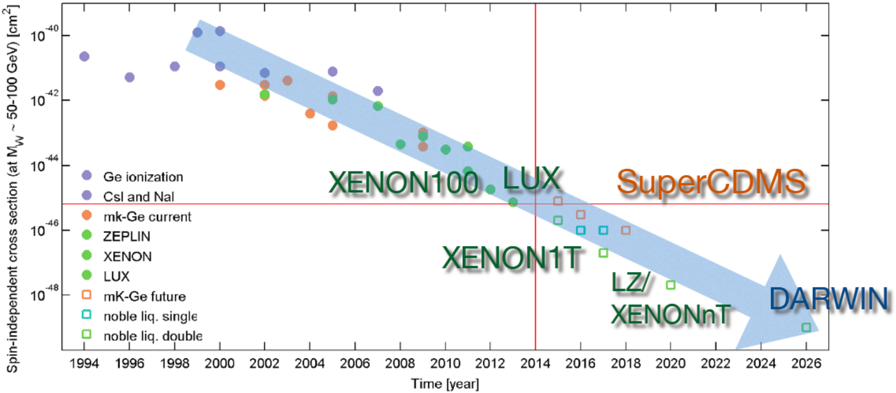
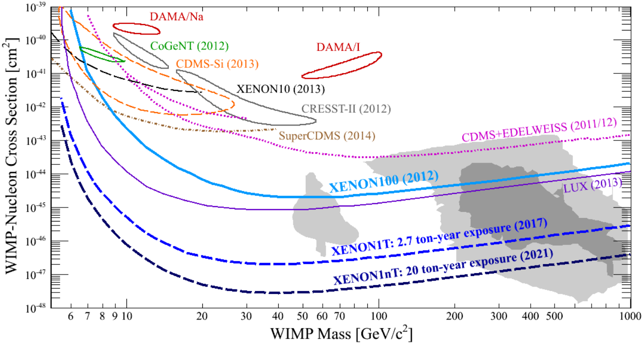


Figure from L. Baudis, talk at COSMO 2014

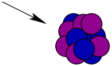
Summary

- Searches with noble liquids have progressed rapidly the last years
  → No discovery so far! But best sensitivity by liquid xenon detectors
- Big effort to increase the mass and reduce the backgrounds
- Running experiments in the order of 50 – 350 kg LAr/LXe
  → Ton-scale experiments being constructed/commissioned
  → XENON1T starting next year!



Noble gas scintillation process

Nuclear recoil



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

$$\mathbf{R}^{+} + \mathbf{R} \rightarrow \mathbf{R}_2^{+}$$

$$\mathbf{R}_2^{+} + \mathbf{e}^{-} \rightarrow \mathbf{R}^{**} + \mathbf{R}$$

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

$$\mathbf{R}^{*} + \mathbf{R} \rightarrow \mathbf{R}_2^{*}$$

$$\mathbf{R}_2^{*} \rightarrow \mathbf{2R} + h\nu$$

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

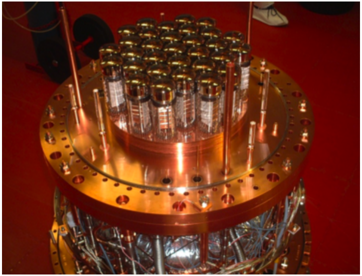
Excitation: $\mathbf{R}^{*}$

$$\mathbf{R}^{*} + \mathbf{R} \rightarrow \mathbf{R}_2^{*}$$

$$\mathbf{R}_2^{*} \rightarrow \mathbf{2R} + h\nu$$

singlet triplet

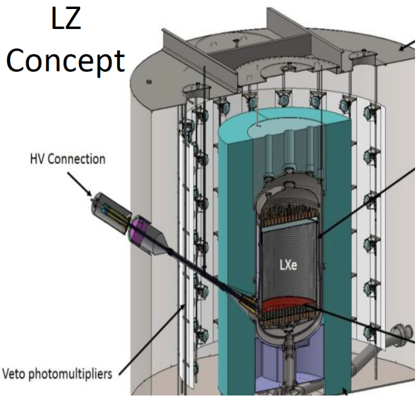
ZEPLIN and the planned LZ experiment



- Until 2011 at Boulby 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: 5.6 ton LXe (FV)
- 482 PMTs (3 inch R11410)



Calibration using nuclear recoils

- Determination of signal region and energy scale

$\longrightarrow$ Dedicated neutron scattering experiments at keV energies!

- 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.

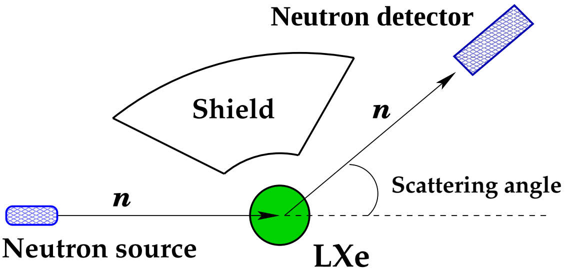
L_y: LY for 122 keV γ in p.e./keV

S_e/S_r: drift field quenching

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

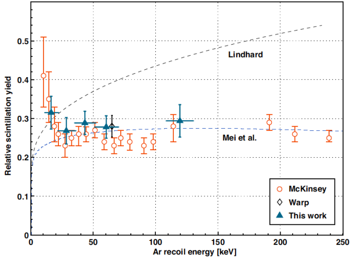
$$L_{eff} = q_{nucl} \times q_{el} \times q_{esc}$$

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

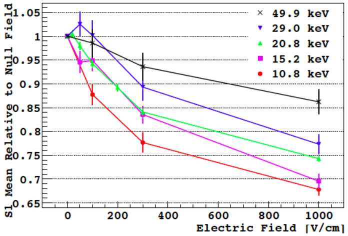


Measuring the nuclear recoil scale

Liquid argon

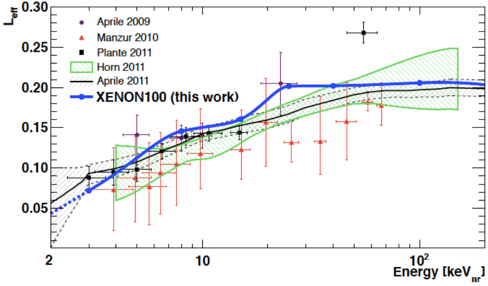


C. Regenfus *et al.*, J. Phys. Conf. Ser. 375 (2012) 012019



Scene Coll., Phys. Rev. D 88, 092006 (2013)

Liquid xenon



XENON100, Phys. Rev. D88 (2013) 012006

- Last years: few measurements in LAr

→ Field quenching up to 30%

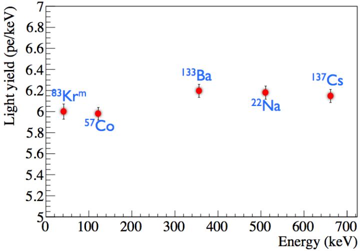
- Various direct + indirect measurements in LXe

→ No indication for strong field dependence

- DD generators used at experiments

Low energy calibration: electronic recoils

Calibration sources in LAr (0-field)

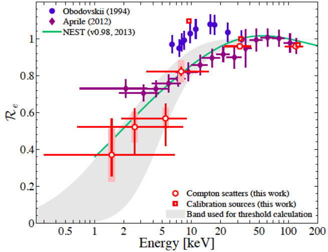


W. H. Lippincott *et al.*, Phys. Rev. C81, 045803, (2010), 0911.5453

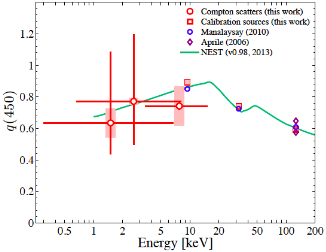
- Detector characterisation
  - Light/charge yield & resolution
  - Field quenching
- Dark matter searches producing electronic recoils (e.g. axions)

→ Internal calibration sources such as ^{83m}Kr, CH_3T, ^{39}Ar favoured

Compton experiments in LXe (0-field)



Field quenching by 450 V/cm



Baudis *et al.*, Phys. Rev. D 87, 115015 (2013)