

Liquid noble gases for direct dark matter searches

Teresa Marrodán Undagoitia
marrodan@mpi-hd.mpg.de

TIPP, Amsterdam, June 2014



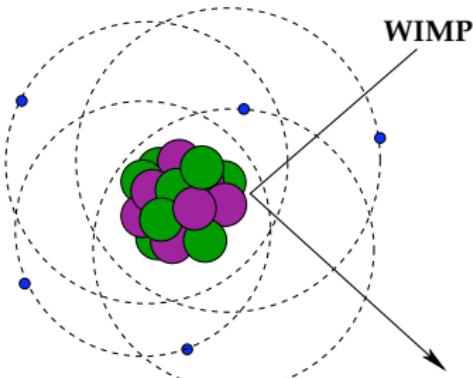
Direct dark matter detection

Indications of dark matter from Astronomy and Cosmology:



BUT what is its nature?

→ Particle candidate: WIMP (Weakly Interacting Massive Particle)



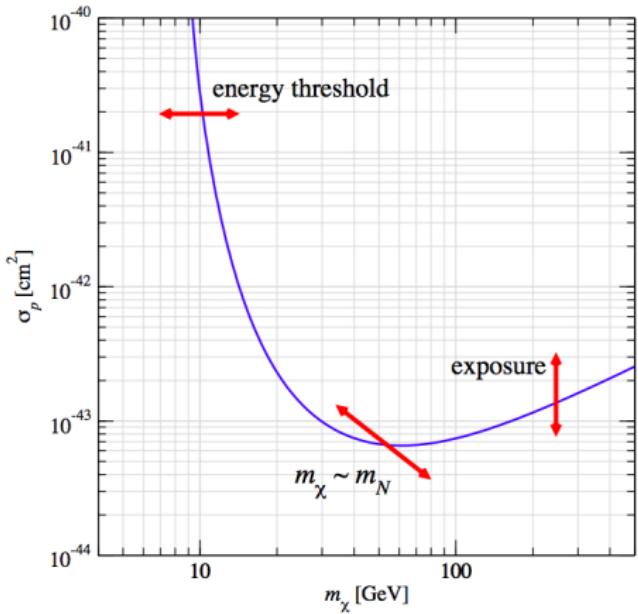
- Possible detection mechanisms:

- Production at LHC
($p + p \rightarrow \chi + \text{other particles}$)
- Indirectly via annihilation
($\chi\chi \rightarrow e^+e^-, p\bar{p}, \gamma\gamma \dots$)
- Scattering off nuclei
($\chi N \rightarrow \chi N$)

Result of a direct detection experiment

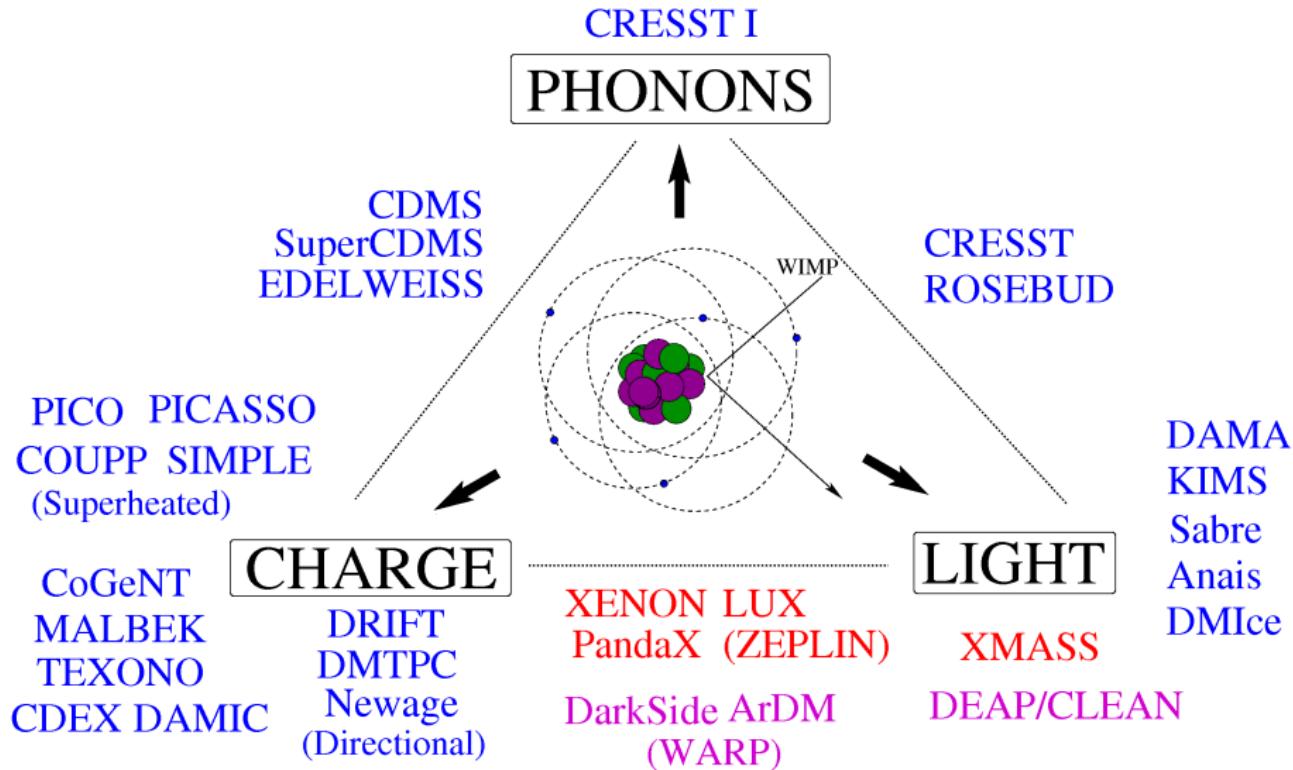
N counts in the signal region of interest for a given exposure

→ Statistical significance of signal over expected background?



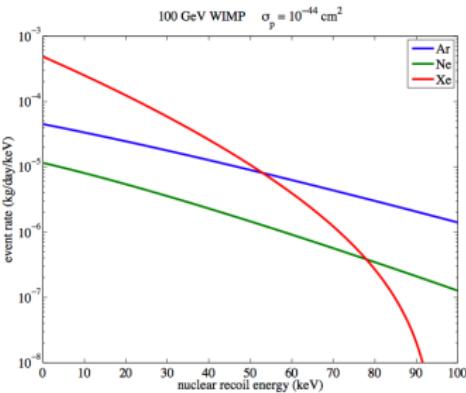
- Positive signal
 - Region in σ_χ versus m_χ
- Zero signal
 - Exclusion of a parameter region
 - Low WIMP masses: detector threshold matters
 - Minimum of the curve: depends on target nuclei
 - High WIMP masses: exposure matters $\epsilon = m \times t$

Direct detection experiments



Advantages of liquid noble gases for DM searches

- Large masses and homogeneous targets (LNe, LAr & LXe)
Two detector concepts: single & double phase
- 3D position reconstruction → fiducialization
- High ionization yield ($W_{LXe} = 15.6 \text{ eV}$ and $W_{LAr} = 23.6 \text{ eV}$)
- Transparent to their own scintillation light



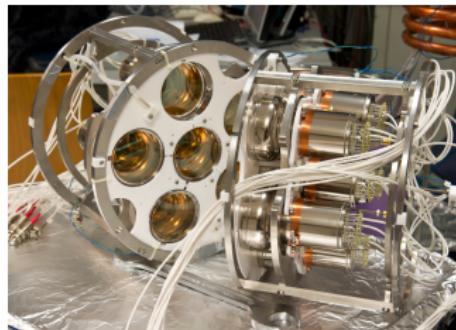
	LNe	LAr	LXe
Z (A)	10 (20)	18 (40)	54 (131)
Density [g/cm ³]	1.2	1.4	3.0
Scintillation λ	78 nm	125 nm	178 nm
BP [K] at 1 atm	27	87	165
Ioniz. [e ⁻ /keV]	46	42	64
Scint. [γ /keV]	7	40	46

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
 - Rn: removal using activated carbon
 - 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 (SiGHT) ...
See contributions in Dark matter & Photon sessions
- State of the art 3" photomultipliers from Hamamatsu:
 - R11065 (for LAr) used by DarkSide
 - R11410 (for LXe) for XENON1T, PandaX and LZ

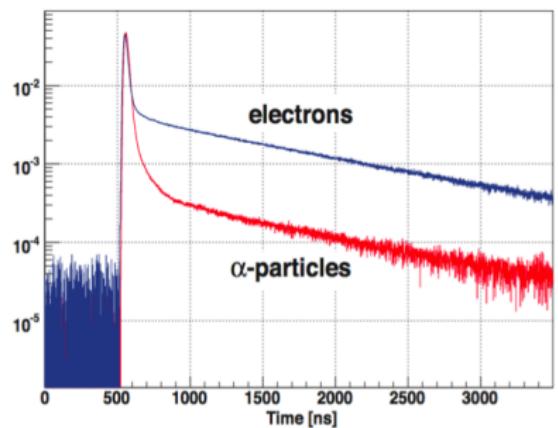
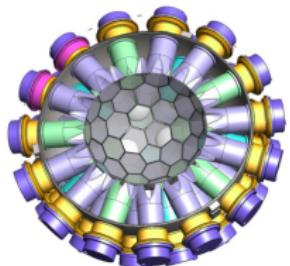


XENON1T testing setup for R11410-21 at MPIK

- Low-radioactive photosensors
 ^{238}U & ^{228}Th $< 1 \text{ mBq/PMT}$
For reference: 1 Banana $\sim 15 \text{ Bq}$ 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

→ PSD less powerful in LXe: similar decay constants ~ 4 and 22 ns
XMASS, NIM, A659 (2011) 161

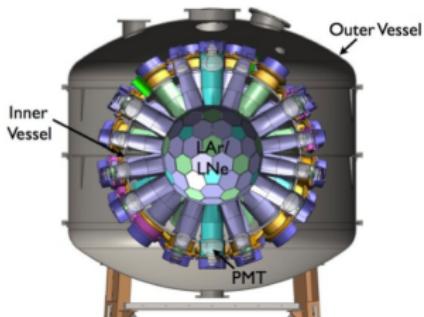
- Very different singlet and triplet lifetimes in argon & neon
- Relative amplitudes depend on particle type → discrimination
DEAP-I obtained 10^{-8} discrimination in LAr above 25 keV_{ee} (50% acceptance)

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

DEAP/CLEAN at SNOlab

DEAP - Dark matter Experiment with Argon and Pulse shape discrimination

- 3 600 kg LAr in single phase
- PSD to reduce backgrounds
- Aim to use depleted argon to reduce ^{39}Ar
- Status: **assembling**
- DEAP3600: Data expected in 2014



CLEAN - Cryogenic Low Energy Astrophysics with Noble gases

- MiniCLEAN: 150 kg FV single phase detector with LAr/LNe
- Status: **assembling**
- Expected to commission this year

XMASS experiment



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



- 800 kg of LXe in single phase (self-shielding)
- Ultra-low absolute background required
- 1st DM run → unexpected BG from PMTs found
- Detector refurbished, resumed data-taking

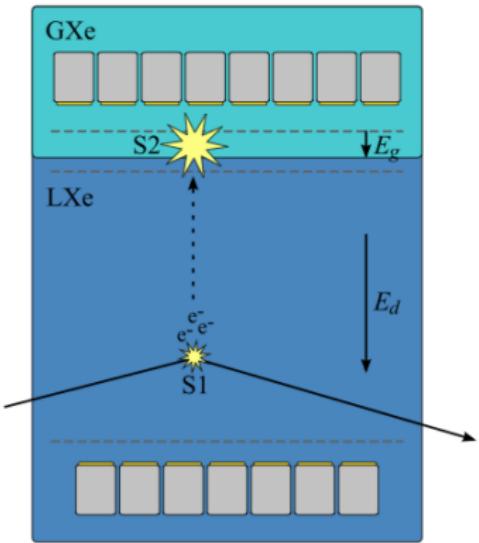
Run with high light yield of 14.7 PE/keVee

$$E_{th} = 0.3 \text{ keV}_{ee}$$

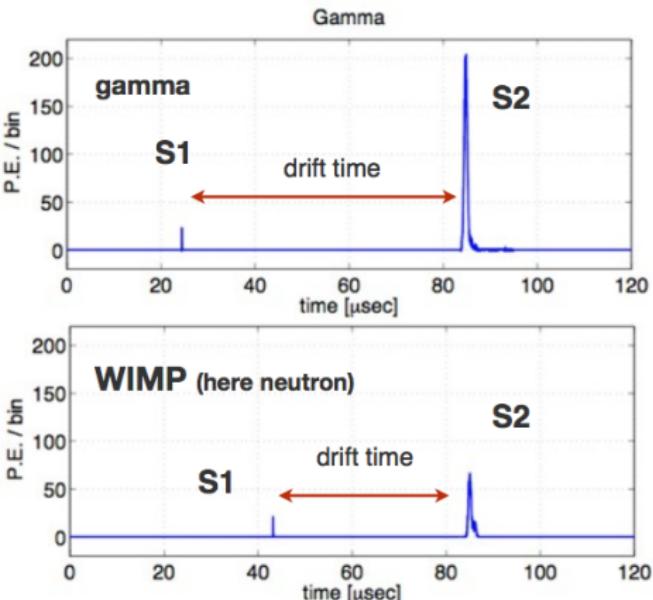
Search for solar axions, PLB 724 (2013) 46

Search for inelastic WIMP-nucleus scattering on ^{129}Xe , arXiv:1401.4737

Two phase noble gas TPC



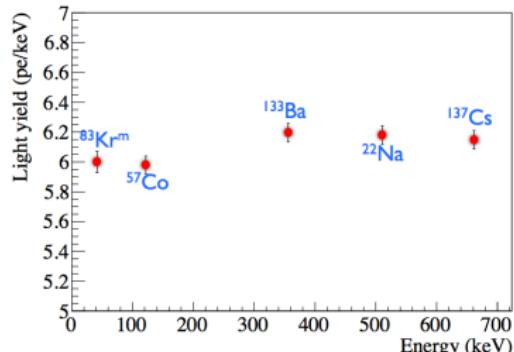
- Scintillation signal (S1)
- Charges drift to the liquid-gas surface
- Proportional signal (S2)
 - Electron- /nuclear recoil discrimination



- Drift field necessary
~ 1 kV/cm
- Electronegative purity required
- Position resolution in mm

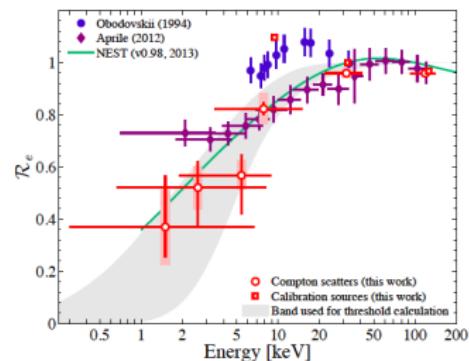
Low energy calibration: electronic recoils

Calibration sources in LAr (0-field)

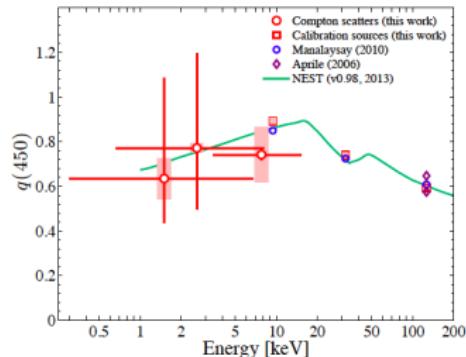


W. H. Lippincott *et al.*, Phys. Rev. C81, 045803, (2010),
0911.5453

Compton experiments in LXe (0-field)



Field quenching by 450 V/cm

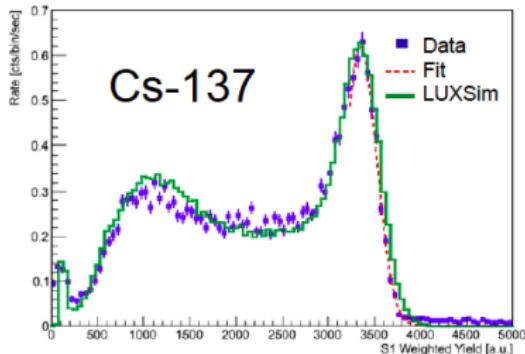


Baudis *et al.*, Phys. Rev. D 87, 115015 (2013)

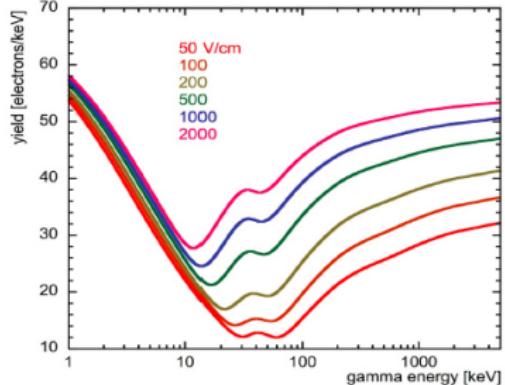
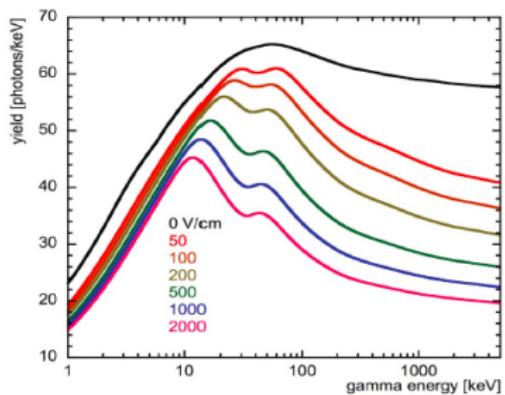
NEST: noble element simulation technique

- Data driven model for scintillation + ionisation in LAr & LXe
- Full MC (Geant4): charge, light, resolution and pulse shapes
- Recombination model:
Thomas-Imel for 'short' tracks &
Doke-Birks for 'long' tracks ($\mathcal{O} > 10 \text{ keV}$)

Developed by: M. Szydagis et al., JINST 6 (2011) P10002 & JINST 8 (2013) C10003



Energy dependence of yield for electronic recoils (LXe)



Calibration using nuclear recoils

- Determination of signal region and energy scale
→ Dedicated neutron scattering experiments at keV energies!
- Nuclear recoil energy (E_{nr}):
- Relative scintillation efficiency of NR to 122 keV γ at 0-field

$$E_{nr} = \frac{S_1}{L_y L_{eff}} \times \frac{S_e}{S_r}$$

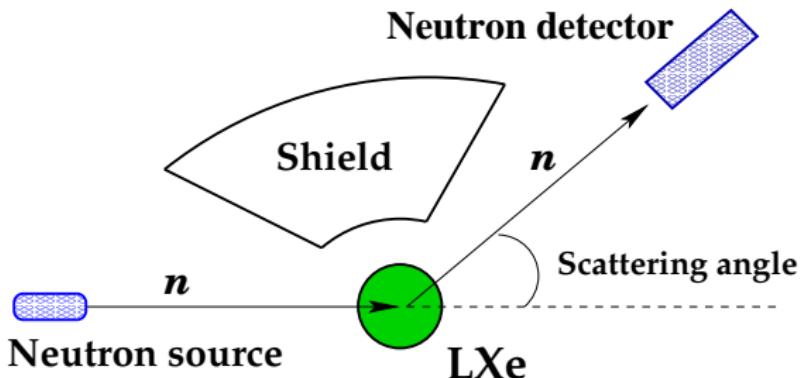
S_1 : measured signal in p.e.

L_y : LY for 122 keV γ in p.e./keV

S_e/S_r : drift field quenching

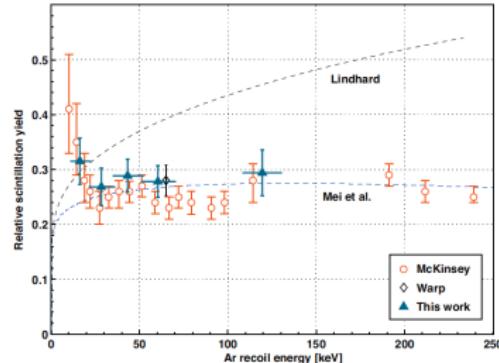
$$L_{eff} = q_{nucl} \times q_{el} \times q_{esc}$$

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



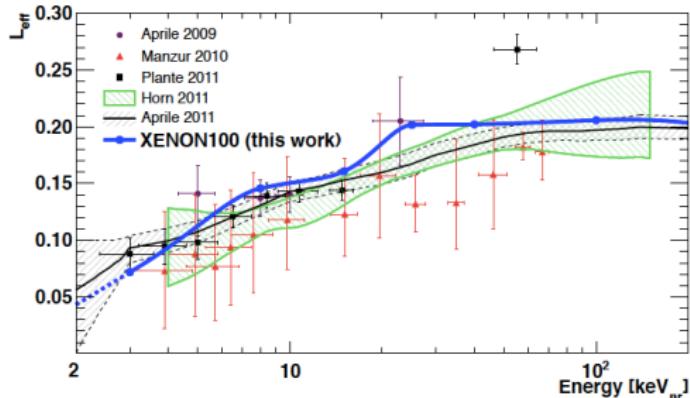
Measuring the nuclear recoil scale

Liquid argon

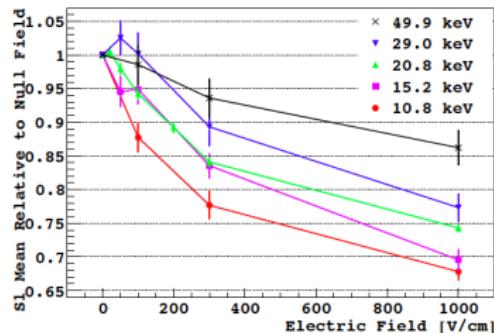


C. Regenfus *et al.*, J. Phys. Conf. Ser. 375 (2012) 012019

Liquid xenon



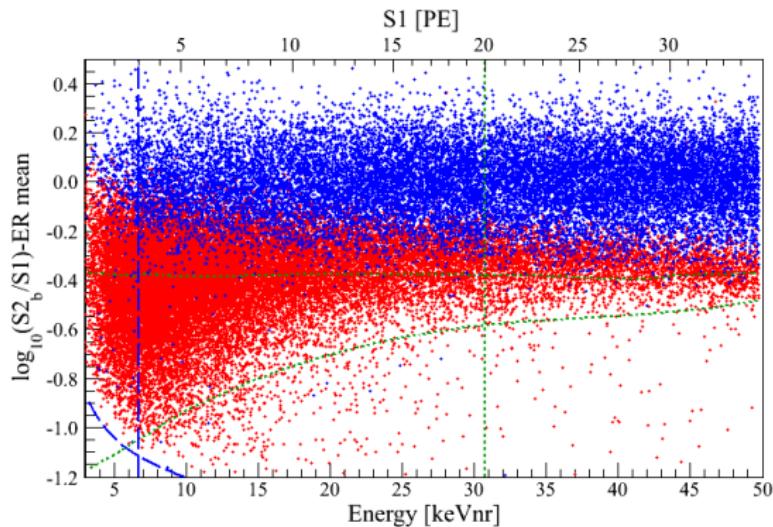
XENON100, Phys. Rev. D88 (2013) 012006



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

- 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

Double phase LAr & LXe experiments



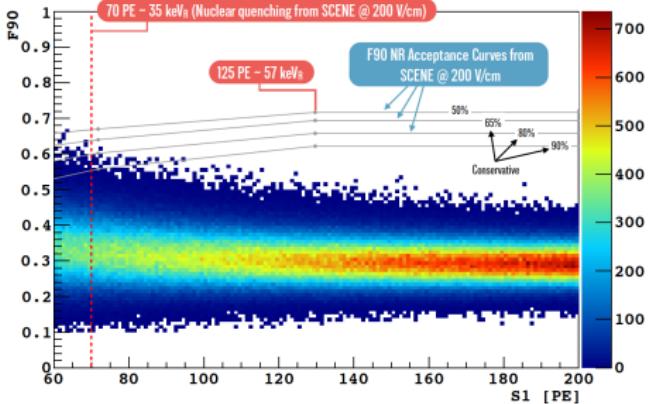
DarkSide at LNGS



- Detector inside Borexino counting facility
- Borated liq. scintillator (^{10}B) as neutron veto

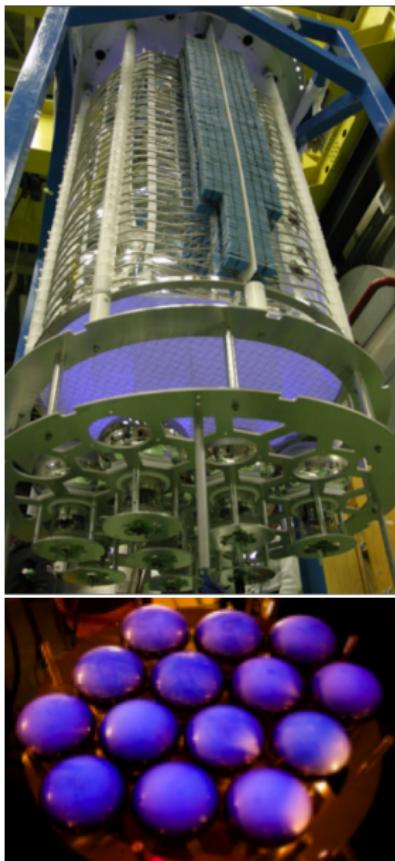
- First run of **DarkSide-50** this spring
- 50 kg depleted argon from underground sources** > 100 reduction in ^{39}Ar level
- PSD & charge/light ratio for discrimination
- Hamamatsu **R11065** as photosensor

Background free exposure of $280 \text{ kg} \cdot \text{day}$

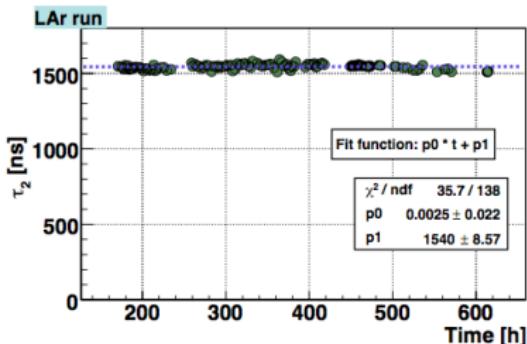


Goal to reach 10^{-45} cm^2 in 3 y measuring time

ArDM at LSC

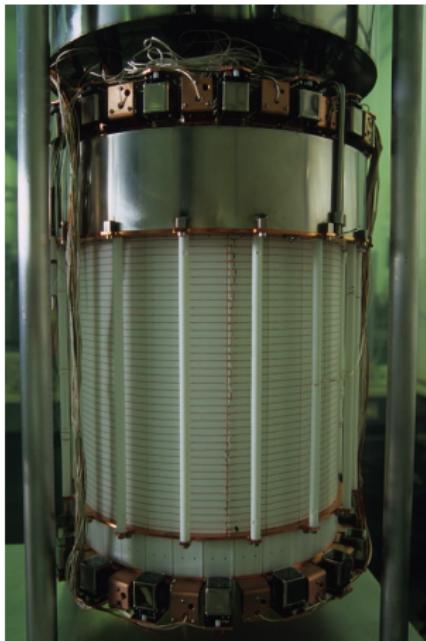


- Detector description:
 - Mass: **850 kg** liquid argon (in target)
 - 120 cm drift length and 80 cm \varnothing
 - 8" PMTs: 12 on bottom and 12 on top
 - HV: Aim to reach $\sim 1 \text{ kV/cm}$
- Status:
 - Cool down at surface (CERN) satisfactory



- **Installed** at Canfranc (Spain)
- Underground operation II expected for **2014**

XENON100 at LNGS



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

- 30 cm drift length and 30 cm \varnothing
- 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

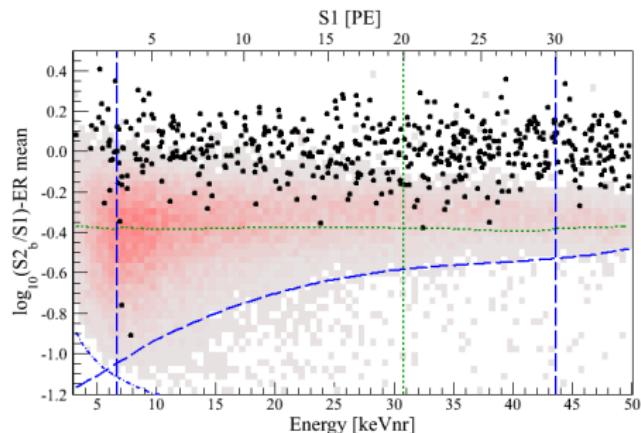


Bottom PMT array

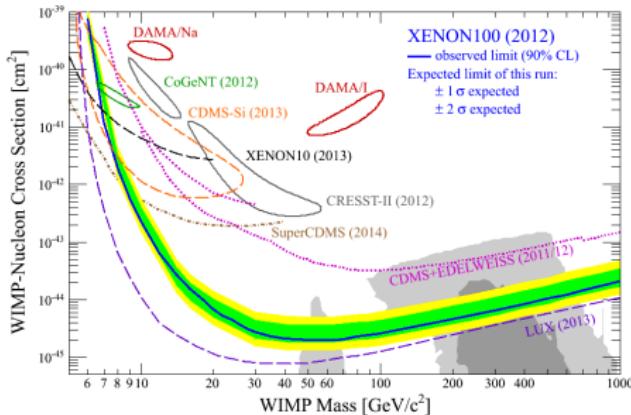


Top PMT array

Results from 225 live days data

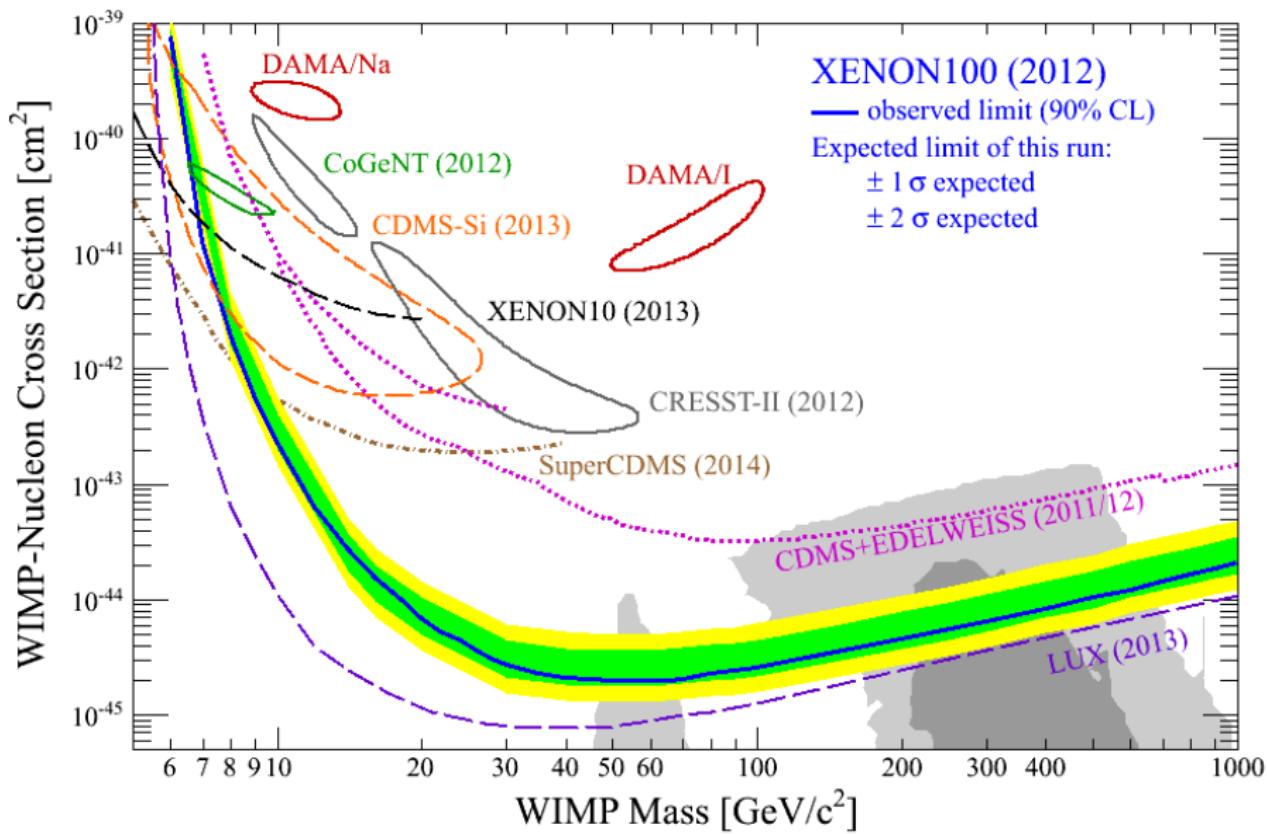


Science data

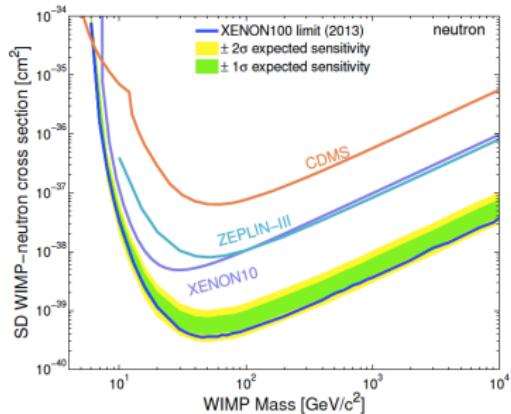


Spin-independent best sensitivity:
 $2 \times 10^{-45} \text{ cm}^2$ at $55 \text{ GeV}/c^2$

- 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

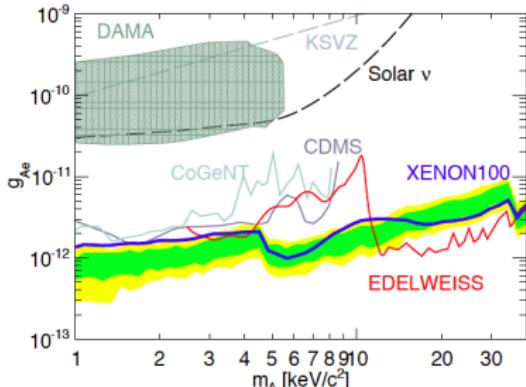


- Spin-dependent best sensitivity for neutron coupling
- Isotopes with a non zero nuclear spin (^{129}Xe & ^{131}Xe)
- State of the art calculations of form factors used (Menendez *et al.*)

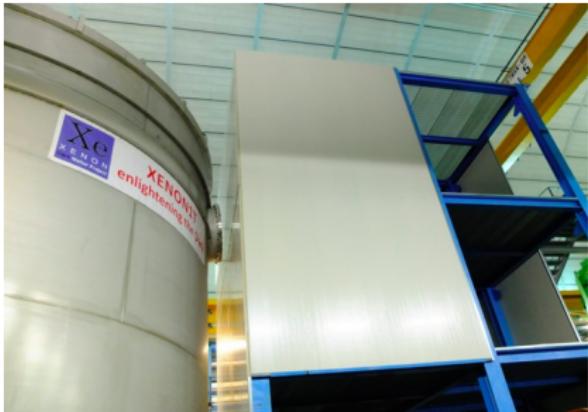
XENON100, Phys. Rev. Lett. 111, 021301 (2013)

- 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, arXiv:1404.1455 (2014)



XENON1T at LNGS



- 1 ton fiducial volume out of ~ 3 ton LXe
- Goal to reach $2 \times 10^{-47} \text{ cm}^2$
- Construction started in 2013 at LNGS
 - Water tank, Building & Cryostat support struc. installed
 - Cryogenic, gas and storage systems being delivered
- Goal: commissioning in 2015

Detector design

- Background requirement: < 1 event in the full exposure
- 1 m electron-drift and 100 kV HV demonstrated
- Update to XENONnT with just a moderate effort



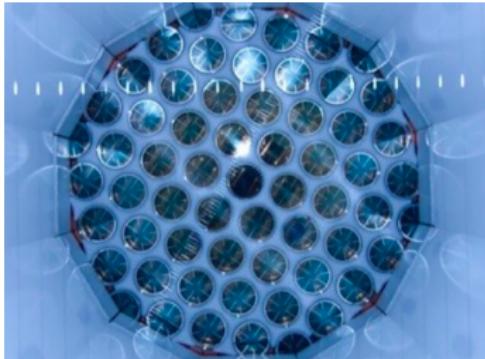
XENON1T current TPC design

LUX at Homestake



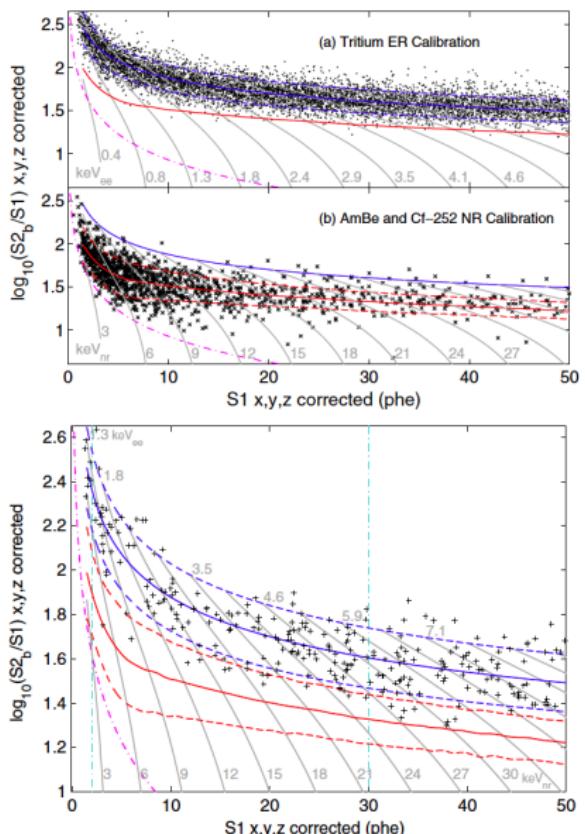
LUX - Large Underground Xenon detector

- 118 kg fiducial mass (370 kg total)
- Two arrays of 61 PMTs (2 inch)
- High light yield:
8.8 PE/keV at 0-field for 122 keV

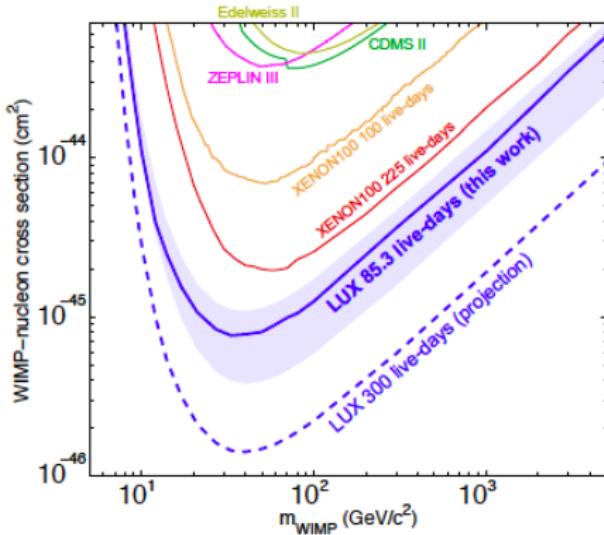


- Status:
 - Data from first run released
 - Next: blinded science run of 300 d

LUX results in 2013



- 85.3 live days of data
- ER calibration using tritiated methane
- Signal region modelled with NEST
- Current best sensitivity above 6 GeV/c²



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

→ LZ: multi-ton detector planned

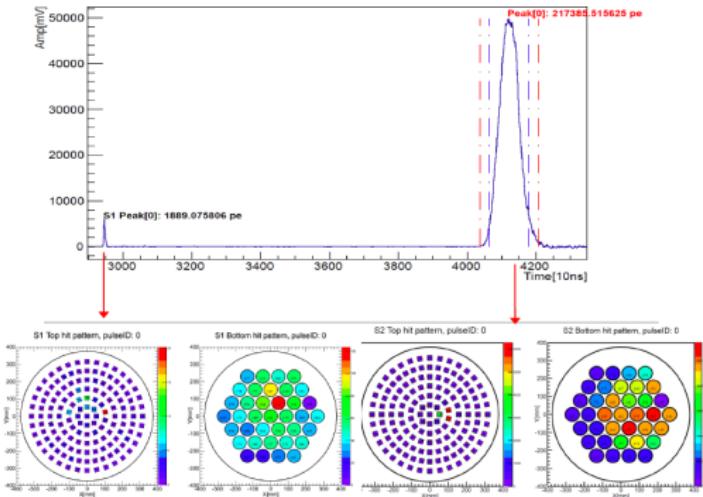
PandaX at Jinping Lab



PandaX, arXiv:1405.2882

Teresa Marrodán Undagoitia (MPIK)

- Design concept in stages:
 - Stage 1a: 120 kg target (ongoing)
 - Stage 1b: 500 kg target (late 2014)
 - Stage 2: 1.5 ton target
- PMTs: 37 R11410 (bottom) & 143 R8520 (top)
- Everything designed for 1 ton FV



First data from commissioning run 2014

Liquid noble gases

Amsterdam, 06/2014

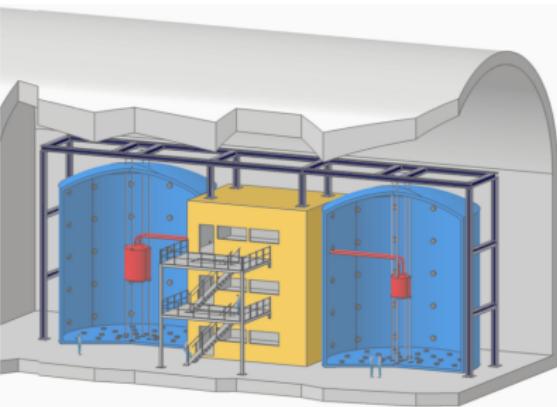
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DARWIN: the ultimate WIMP detector

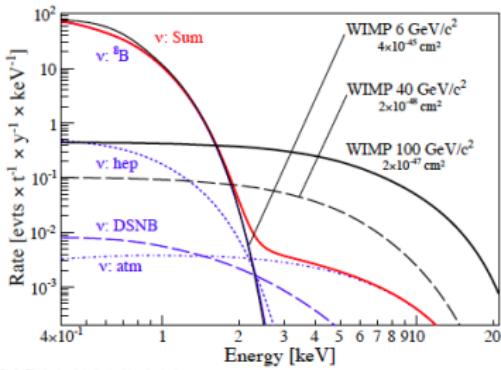
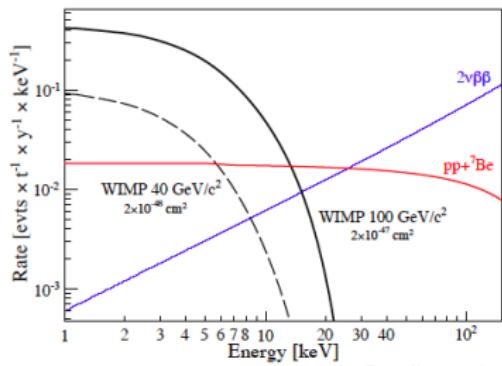
dark matter wimp search in noble liquids

DARWIN

- R&D and design study for a noble liquid facility in Europe
- LAr and LXe communities
- Construction ~ 2020



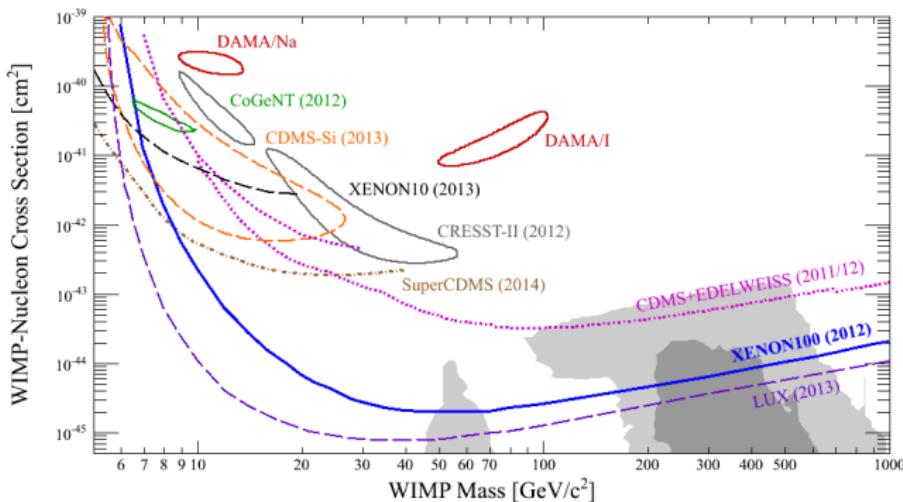
<http://darwin.physik.uzh.ch/>



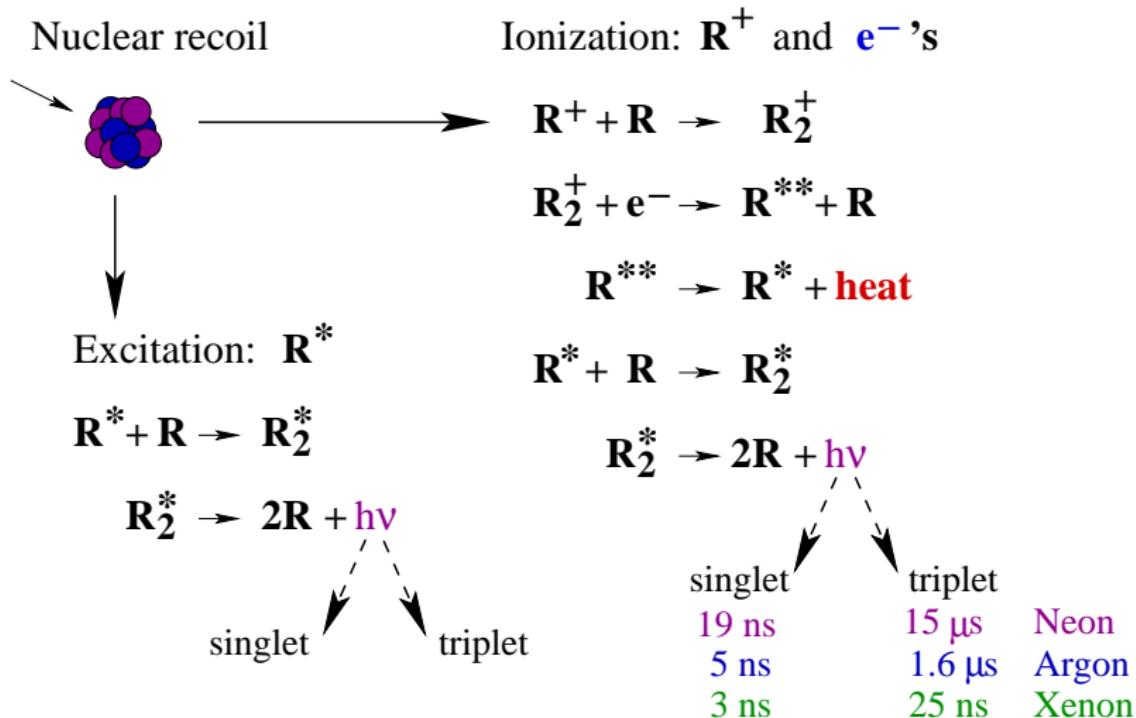
L. Baudis *et al.*, JCAP01 (2014) 044

Summary

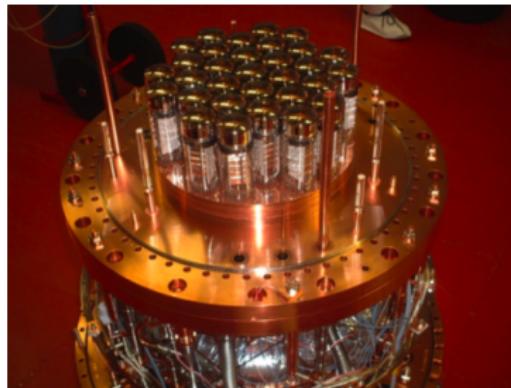
- Searches with **noble liquids** has progressed rapidly the last years
 - **No discovery so far!** But best sensitivity by liquid xenon detectors
- Big effort to **increase the mass** and **reduce the backgrounds**
 - Material selection & Removal of intrinsic rad. & Fiducialization
- Running experiments in the order of 50 – 120 kg LAr/LXe
 - Ton-scale experiments being constructed



Noble gas scintillation process



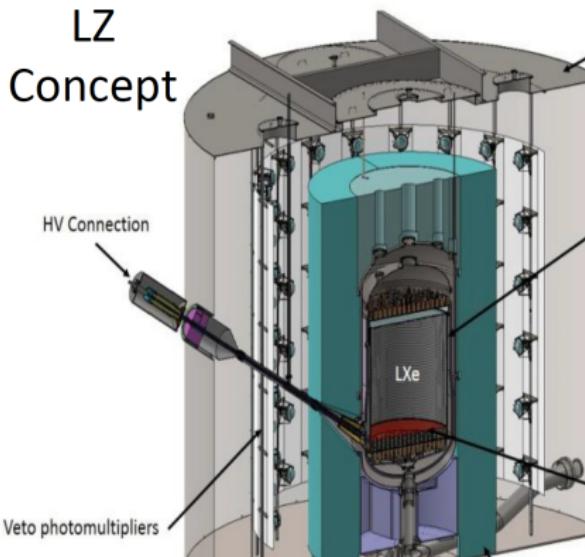
ZEPLIN and the planned LZ experiment



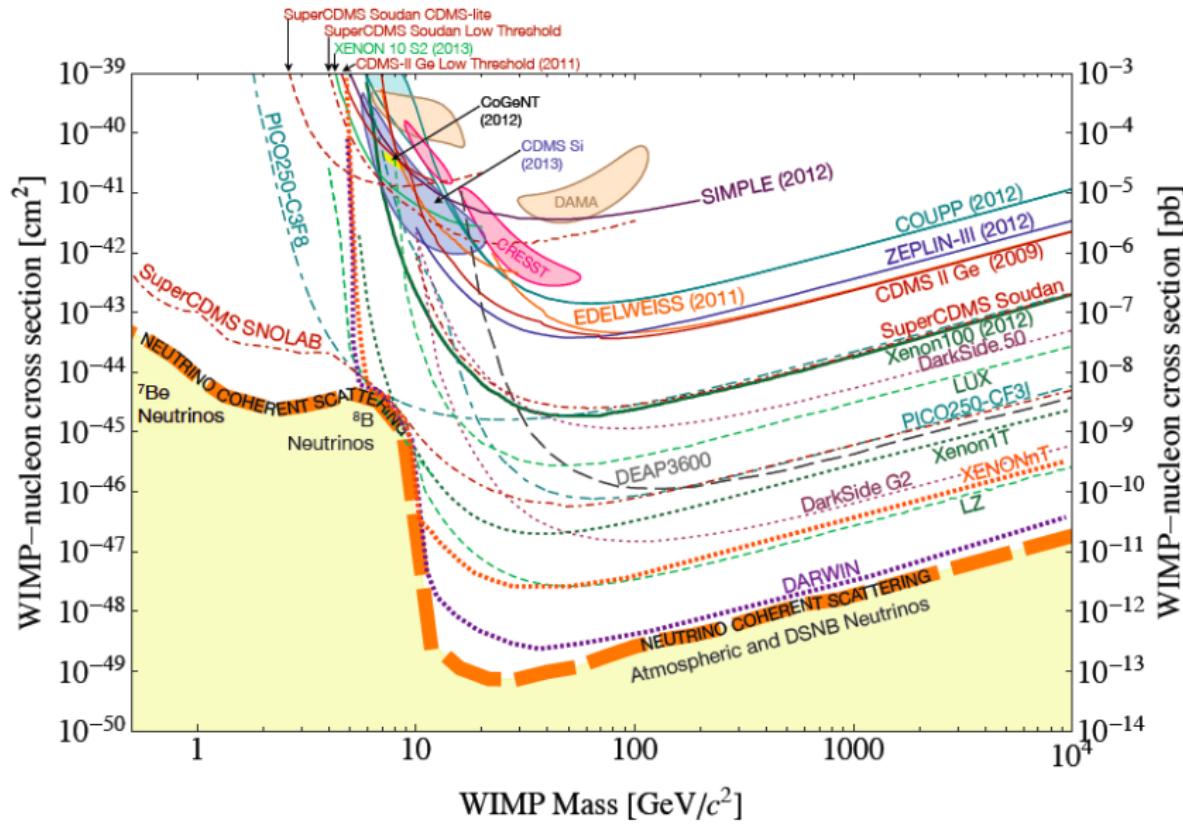
- Until 2011 at Boulby mine
- 12 kg target mass ($\sim 30 \text{ cm } \varnothing$)
- 3.5 cm drift depth
→ high E-field 3.9 kV per cm

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

- LZ: LUX - ZEPLIN collaboration
- Current design: 5.6 ton LXe (FV)
- 482 PMTs (3 inch R11410)

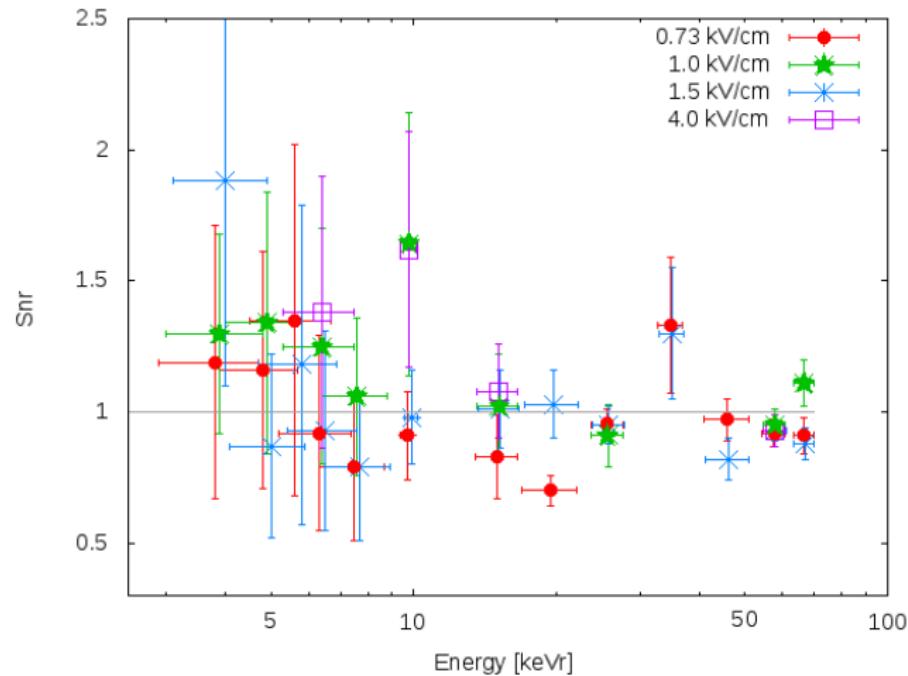


Current limits and neutrino background



Adapted from NDMMASS Report arXiv:1310.8327

Field quenching in liquid xenon



Plot by M. Schumann with data of Manzur *et al.*