Photomultipliers for future noble-liquid dark matter detectors

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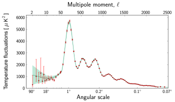
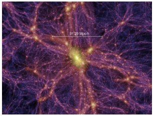
MAX-PLANCK-INSTITUT FÜR KERNPHYSIK

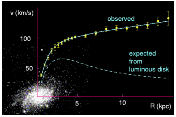
Xe XENON Dark Matter Project

dark matter wimp search in noble liquids DARWIN

Indications of dark matter from Cosmology and Astronomy:

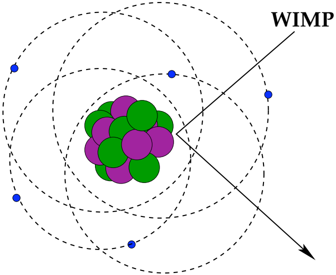






BUT what is its nature?

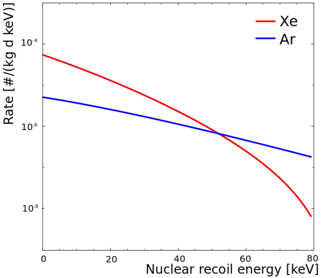
→ Particle candidate: WIMP (Weakly Interacting Massive Particle)



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

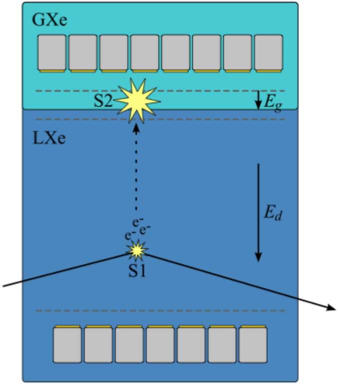
Advantages of liquid noble gases for DM searches

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



	LAr	LXe
Z (A)	18 (40)	54 (131)
Density [g/cm^3]	1.4	3.0
Scintillation λ	128 nm	178 nm
BP [K] at 1 atm	87	165
Ioniz. [e$^-$/keV] 6	42	64
Scint. [γ/keV]	40	46

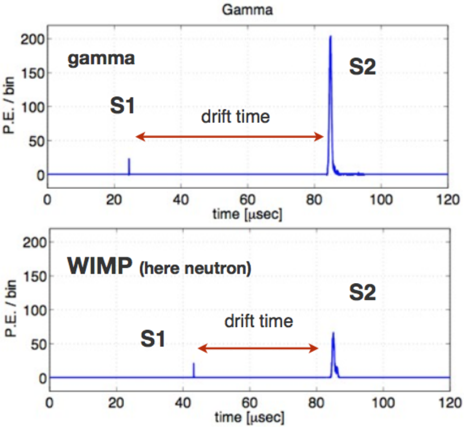
Two phase noble gas TPC



- Drift field necessary ~ 1 kV/cm
- Electronegative purity required
- Position resolution $\sim$ mm

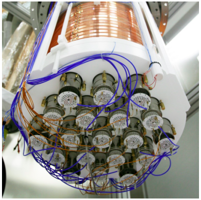
- Scintillation signal (S1)
- Charges drift to the liquid-gas surface
- Proportional signal (S2)

$\rightarrow$ Electron- /nuclear recoil discrimination

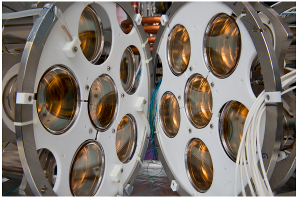


Light sensors

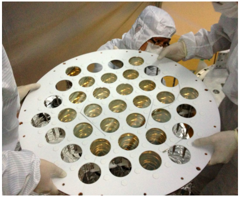
- Requirements for a dark matter experiment:
  - Low radioactivity & low dark-count rate (background rate only few Hz!)
  - UV sensitivity & stable performance at low temperatures
  - High quantum- and electron collection efficiency (QE/CE)
- SiPMs, gaseous multipliers, hybrid tubes ... See next two talks
- State of the art 3” photomultipliers from Hamamatsu:
  - R11065 (for LAr) used by DarkSide and Gerda
  - R11410 (for LXe) for XENON1T, PandaX and LZ



Bottom view of the DarkSide TPC



Setup to test 250 PMTs for XENON1T



Bottom array of the PandaX detector

DarkSide-50 at LNGS and PMT tests

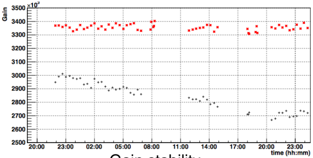
- 36 cm drift & 36 cm ⌀
- 50 kg LAr active mass

→ Paper electronics:
arXiv:1412.2969

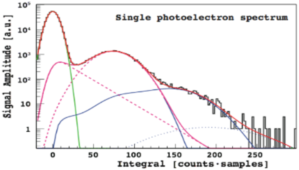
→ Analysis paper:
Phys. Lett. B743 (2015) 456

- 19 (top) + 19 (bottom) R11065 PMTs
  Average QE: 35% for blue wavelength
- TPB coating in inner surfaces (wavelength-shifting)
- Tube characterization before installation
  SPE, resolution, gain stability, high illumination response, after-pulses ..

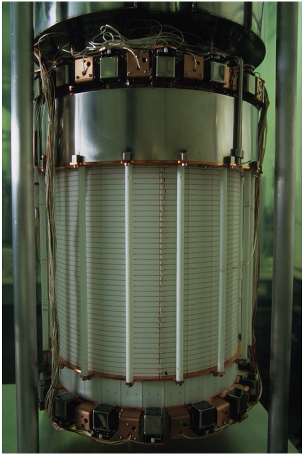
PMT tests at Naples Cryo-Lab



Gain stability



The XENON100 experiment

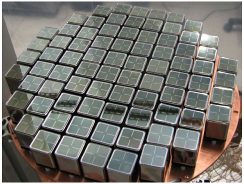


- 30 cm drift length and 30 cm ⌀
- 161 kg LXe mass (30 – 50 kg for analysis)
- Background $\sim 5 \cdot 10^{-3}$ events/(kg·d·keV)

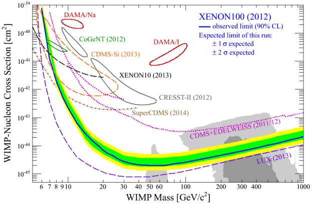
  PMTs: 20% of neutron- and 65% of γ-BG
- 242 PMTs 1 inch R8520

  Bottom PMTs: average QE $\gtrsim$ 30% @ 175 nm
- Leading results during the last years

  XENON100, Phys. Rev. Lett. 111, 021301 (2013)
  XENON100, Phys. Rev. D 90 (2014) 062009



Bottom PMT array



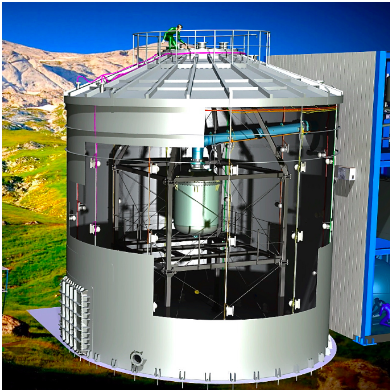
XENON100 result (SI), Phys. Rev. Lett. 109 (2012) 181301

→ Instrument paper:
Astropart. Phys. 35 (2012) 573

→ Analysis paper:
Astropart. Phys. 54 (2014) 11

XENON1T

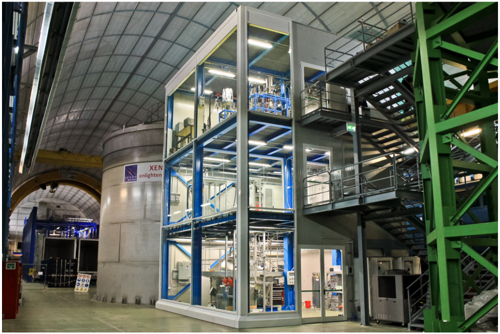
- Goal: two orders of magnitude improvement in sensitivity
  - Approx. 1 t fiducial volume out of a total of about 3 t LXe
  - Background requirement: $<$1 event in the full exposure



XENON1T illustration

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

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

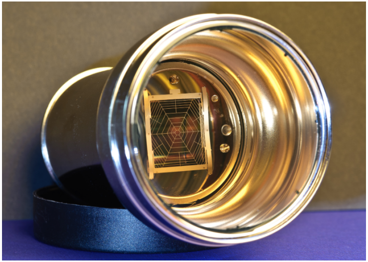
  Gas and storage systems commissioning
- Commissioning in summer 2015

Detector design

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

XENON1T TPC design

3" R11410 photomultipliers

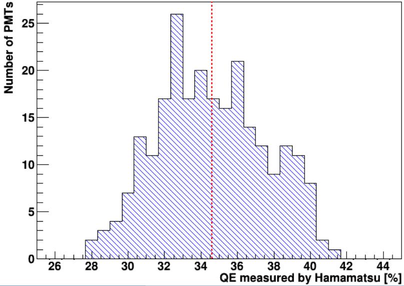


Low radioactivity photosensor for XENON1T

Component	Radioactivity
^{238}U	$<$ 10 mBq/PMT
^{228}Th	$\sim$ 0.5 mBq/PMT
^{226}Ra	$\sim$ 0.6 mBq/PMT
^{235}U	$\sim$ 0.3 mBq/PMT
^{60}Co	$\sim$ 0.8 mBq/PMT
^{40}K	$\sim$ 12 mBq/PMT

XENON collaboration, arxiv:1503.07698

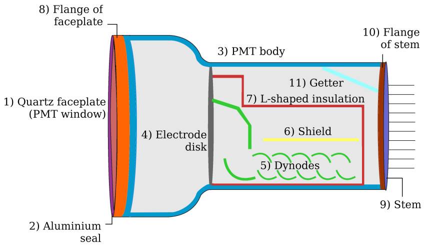
- High QE: $\sim$ 35 % at 175 nm for a low energy threshold
- $\sim$ 90% collection efficiency
- Gain average @1500 V: 5×10^6

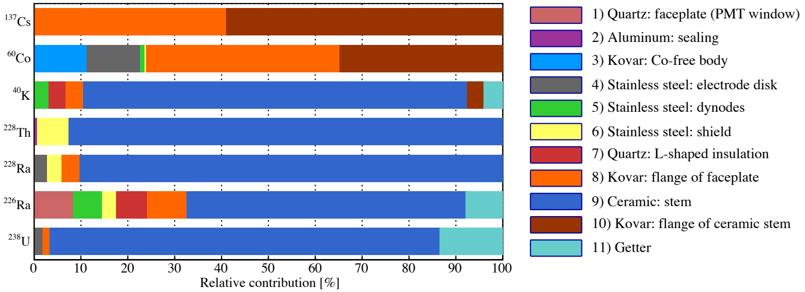


Low radioactivity PMT for XENON1T

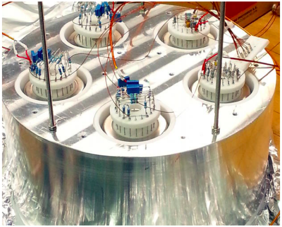
- Main PMT parts screened separately
- Selection of low radioactivity materials for XENON1T
- PMT fulfils background requirements
- Major contributor to radioactivity identified: the ceramic stem

XENON collaboration, arxiv:1503.07698



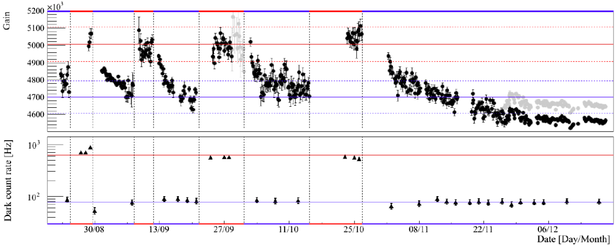


Long-term stability tests



Tests performed @ University of Zurich

- $\sim$ 10% of the tubes are measured in LXe
- Chamber holding 5 PMTs at a time
- Long term test in LXe and GXe ($\sim$ weeks)
  $\rightarrow$ gain and dark count rate evolution tested



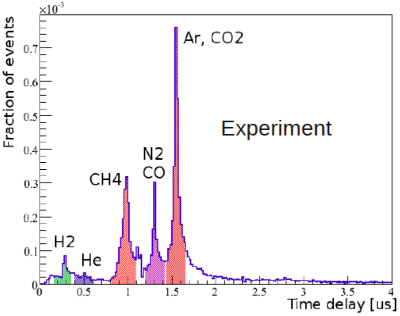
Thermal cycling of a R11410 PMT

L. Baudis *et al.* JINST 8 P04026 (2013), arXiv:1303.0226

Detailed measurements

- Study of after-pulse spectrum:

  Time between first pulse and after-pulse: vacuum quality



see also L. Baudis *et al.* JINST 8 P04026 (2013)
Measurements performed at U. Zurich

- Study of QE dependence on temperature:

  Increase of QE for decreasing temperatures

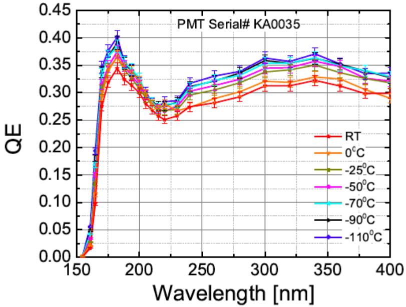
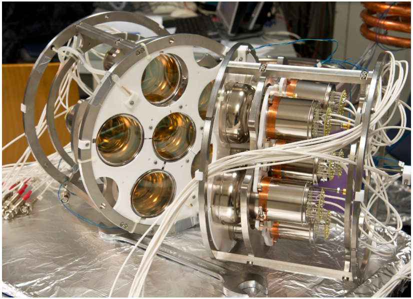


Figure from A. Lyashenko *et al.* JINST 9 (2014) P11021
Measurements performed at UCLA

Mass production tests



XENON1T testing setup for R11410-21 at MPIK

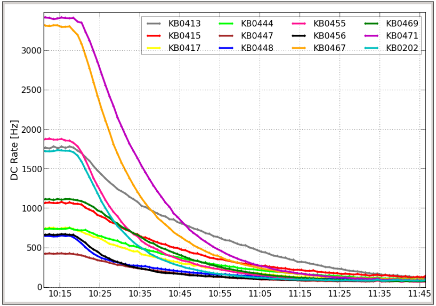
Upon arrival all PMTs are tested at room temperature

- DC rate
- High voltage scan
- Afterpulses
- Transit time

Afterwards 3 cool downs per tube

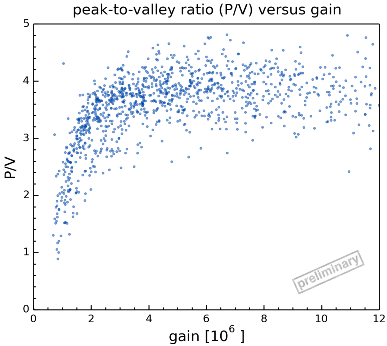
- Continuous DC monitoring
- Cooling with nitrogen gas to around –100°C

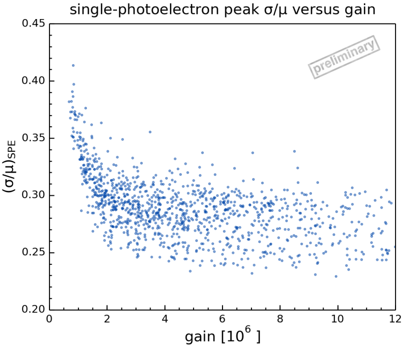
200 PMTs of the XENON1T production completely measured



Example of PMT dark-count rates during cooling down

Data of the 200 measured tubes

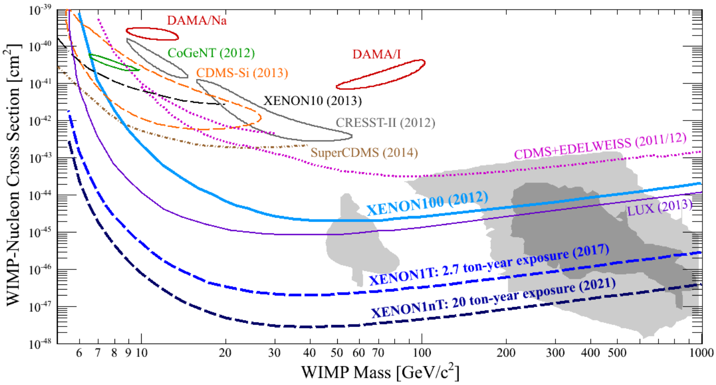




- Large peak-to-valley ratio: ~ 3 for a gain of 2×10^6
- 30% resolution at a gain of 2×10^6 (50% in XENON100)
- Dark count rate @ –100°C: $\sim$ 50 Hz
- Timing: transit time spread of $\sim$ 9 ns

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, $\mathcal{O}(200)$ PMTs and new TPC necessary
- One additional order of magnitude improvement in sensitivity

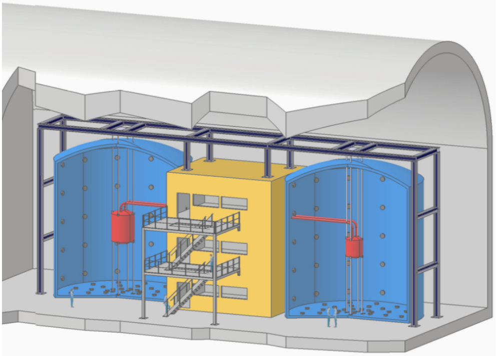


DARWIN future facility

dark matter wimp search in noble liquids

DARWIN

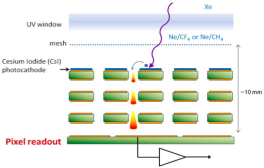
- Ultimate dark matter detector with sensitivity down to $\sim 10^{-48}\,\mathrm{cm}^2$
- R&D and design study for a noble liquid facility in Europe
- LAr and LXe communities involved
- Construction $\sim$ 2020

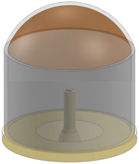


`http://darwin-observatory.org`

Also neutrino physics channels available, Baudis *et al.* JCAP 1401 (2014) 01, 044

DARWIN photosensors





Several photosensors being considered:

- PMTs: improved 4 inch version of R11410/R11065 currently under development @ Hamamatsu
  `See talk Yuji Hotta, UCLA DM2014`
- SiPMs: large areas necessary
  `See talk by B. Rossi`
- GPMs: gaseous photomultipliers
  `See talk by L. Arazi`
- Hybrid tubes, SiGHT: Photocathode + SiPM

Summary

- Cryogenic PMTs are the standard light sensor in dark matter searches using LAr and LXe
- High QE, low DC and stable performance are required
- Very low radioactive contaminations necessary

  Most important: low U, Th content → neutron background
- XENON1T: finalising tests for PMT installation this summer
- XENONnT: R&D to reduce further radioactivity already started
- DARWIN future facility
  - PMTs with larger photocathode area required
  - Other photosensors being discussed

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 fission reactions
  - Go underground!
  - Shield: passive (polyethylene) or active (water/scintillator vetoes)
  - material selection for low U and Th contaminations !!
- Neutrinos: solar, atmospheric and DSNB ν's
  - Electronic recoils from neutrino-electron scattering
  - Nuclear recoils: coherent neutrino scattering

Some exclusion limits and neutrino background