DARK MATTER SEARCHES WITH LIQUID XENON DETECTORS

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Humboldt Kolleg conference
Discoveries and Open Puzzles in Particle Physics and Gravitation
Kitzbühel

MAX-PLANCK-INSTITUT
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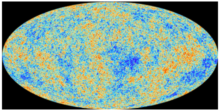
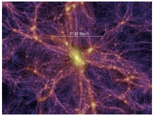
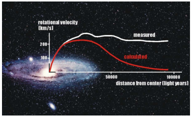
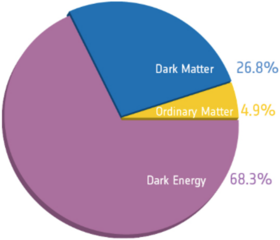
Dark matter in Cosmology and Astronomy









After Planck

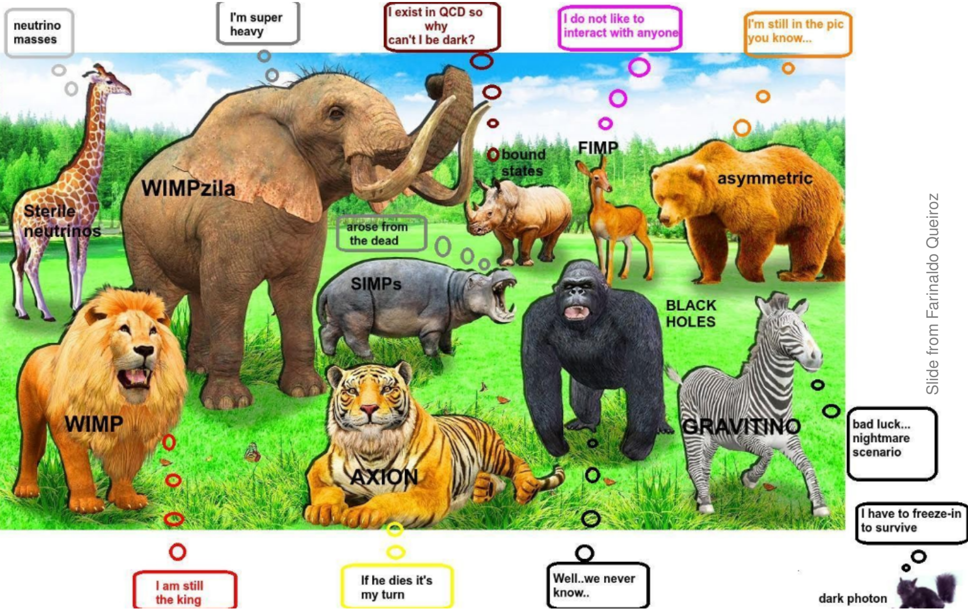
Well motivated theoretical approach:

WIMP

(**W**eakly **I**nteracting **M**assive **P**article)

But dark matter could be non weakly-interacting or a completely different type of particle

What is the nature of dark matter?



Slide from Farinaldo Queiroz

How can we look for dark matter?

Indirect detection

$\chi\bar{\chi} \rightarrow \gamma\gamma, q\bar{q}, \ldots$

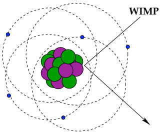
Direct detection

$\chi\,\mathrm{N} \rightarrow \chi\,\mathrm{N}$

Production at LHC

$\mathrm{p} + \mathrm{p} \rightarrow \chi\bar{\chi} + \mathrm{X}$

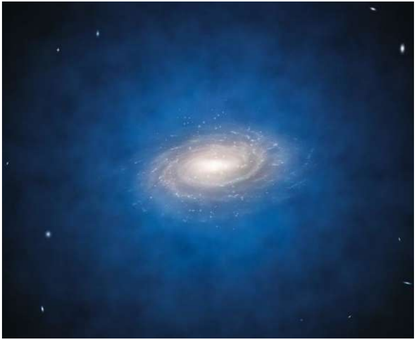
Direct detection of dark matter



$E_R \sim \mathcal{O}(10\,\mathrm{keV})$

$$\frac{dR}{dE}(E,t) = \frac{\rho_0}{m_\chi \cdot m_A} \cdot \int v \cdot f(\mathbf{v},t) \cdot \frac{d\sigma}{dE}(E,v)\, \mathrm{d}^3 v$$

Credit: ESO/L. Calçada



Astrophysical parameters:

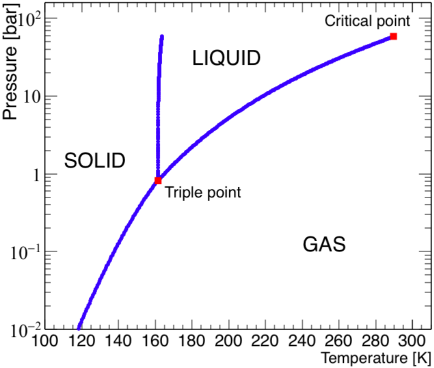
- ρ_0 = local density of the dark matter in the Milky Way

  'Standard' value: $\rho_\chi \simeq 0.3\,\mathrm{GeV/cm^3}$
- $f(\mathbf{v},t)$ = WIMP velocity distribution, $\langle v \rangle \sim 220\,\mathrm{km/s}$

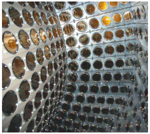
Parameters of interest:

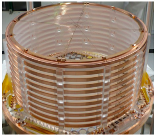
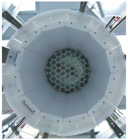
- m_χ = WIMP mass ($\sim 100\,\mathrm{GeV}$)
- σ = WIMP-nucleus elastic scattering cross section (SD or SI)

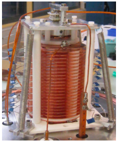
Liquid xenon as detector



- Cryogenic liquid typically operated at 2 bar and $-100°$C
- High density: 3 g/cm^3
- High scintillation and ionization yields
- Employed in particle-, neutrino-, dark matter- and medical physics

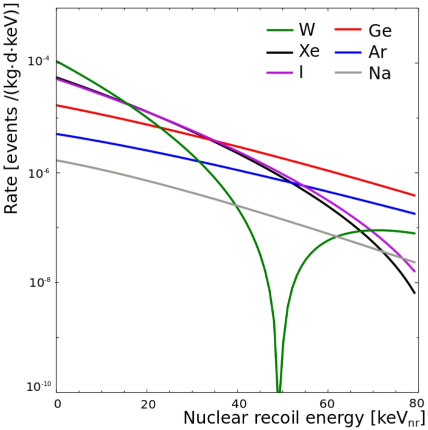




Why is xenon ideal for dark matter searches?

J. Phys. G: 43 (2016) 1, arXiv:1509.08767



- Large masses and homogeneous targets

  Two detector concepts: single & double phase
- 3D position reconstruction → fiducialization
- Transparent to their own scintillation light → at 175 nm
- Low intrinsic background

Spin-independent interactions: coupling to nuclear mass

$$\sigma_{SI} = \frac{m_N^2}{4\pi(m_\chi + m_N)^2} \cdot [Z \cdot f_p + (A - Z) \cdot f_n]^2$$

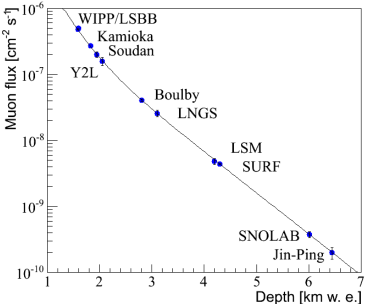
$f_{p,n}$: effective couplings to p and n

Backgrounds and reduction strategies

- External γ's from natural radioactivity:
  - Self-shielding of the target & Rejection of multiple scatters
  - Material screening and selection

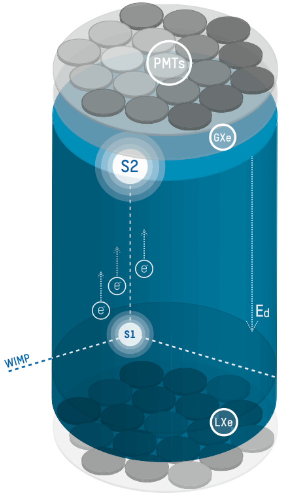
- External neutrons: muon-induced, (α, n) and from fission reactions
  - Go underground!
  - Shield: passive (polyethylene) or active (water/scintillator vetoes)
  - material selection for low U and Th

$+$ Neutrinos from the Sun, atmospheric and from supernovae



- Internal backgrounds:
  - ^{85}Kr: removal by cryogenic distillation or chromatography
  - ^{222}Rn: removal using distillation
  - Xenon: ^{136}Xe $\beta\beta$ decay ($T_{1/2} = 2.2 \times 10^{21}$ y) *long lifetime!*

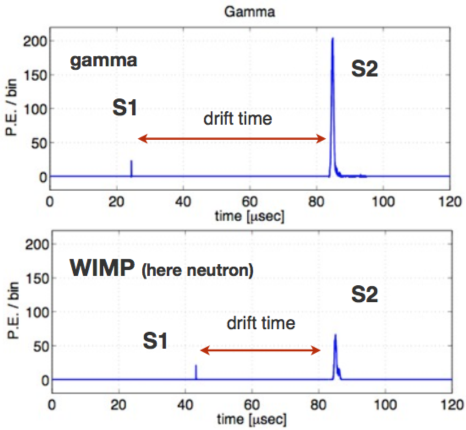
Two phase noble-gas TPC



Position resolution to define the innermost radiopure volume for analysis

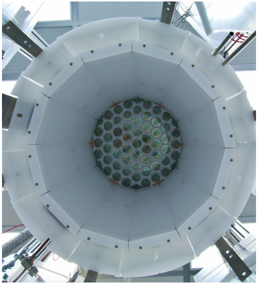
- Scintillation signal (S1)
- Charges drift to the liquid-gas surface
- Proportional signal (S2)

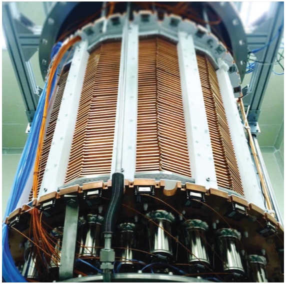
→ Electron- /nuclear recoil discrimination



The three big players

The liquid xenon TPC competition





LUX:

- 100 kg fiducial mass (370 kg total)
- Latest results
  PRL 118, 021303 (2017)
- 33.5 ton·day exposure

PANDAX-II:

- 580 kg fiducial mass (1.2 t total)
- Latest results
  PRL 119, 181302 (2017)
- 54 ton·day exposure

XENON1T:

- 1.3 t LXe fiducial mass (3.2 t total)
- Latest results
  PRL 121, 111302 (2018)
- 365 ton·day exposure

XENON1T data from SR1

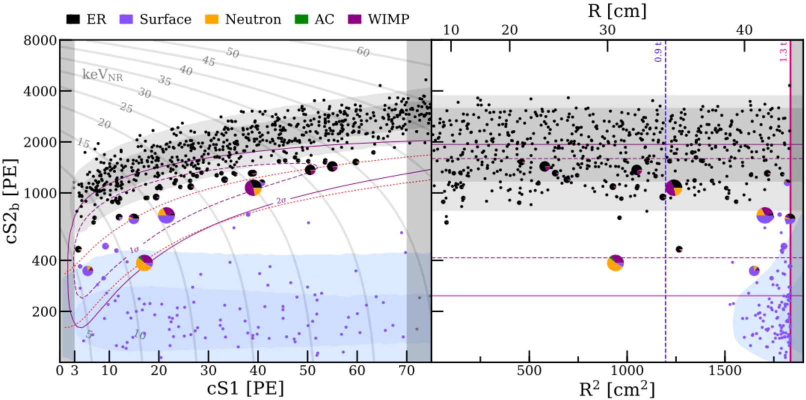
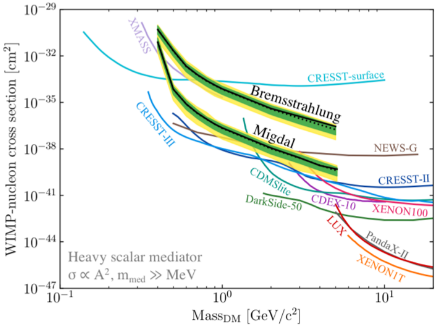


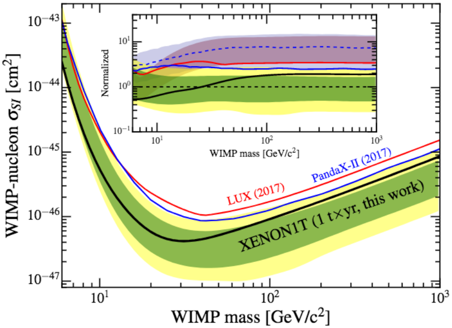
Figure from XENON1T, PRL 121, 111302 (2018) & arXiv:1805.12562

- No indication of dark matter after unblinding 1 ton $\times$ y exposure
- XENON1T was decommissioned in December 2018
- More data available and being analyzed

Latest liquid xenon WIMP results



LUX, PRL 122, 131301 (2019)

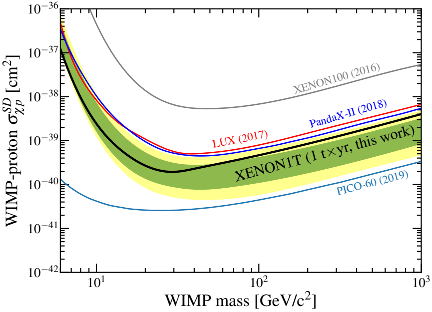


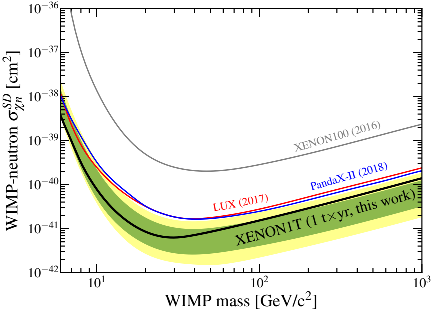
XENON1T, PRL 121, 111302 (2018)

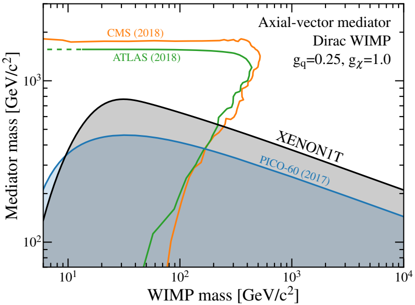
- Best upper limits on WIMP nucleon coupling for WIMP masses above $6\,\mathrm{GeV}/c^2$ by XENON1T
- Migdal effect: additional signal from shell e^-'s of the recoiling nucleus

  See also arXiv:1707.07258 & arXiv:1711.09906 for more information
- Recent results from LUX show great sensitivity to low WIMP masses using the Migdal effect

Spin-dependent interpretation



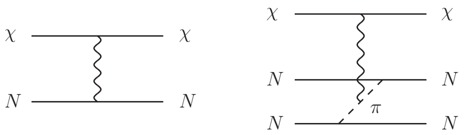




- Most of the spin in xenon is carried by neutrons, so WIMP-neutron scattering dominates
- Searches at the LHC use an isoscalar benchmark theory

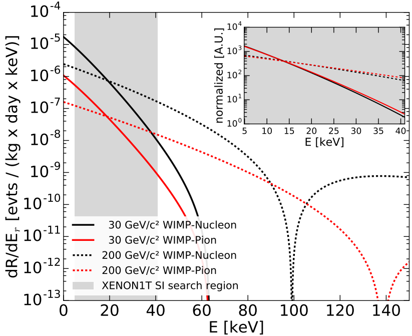
Figures from XENON1T, PRL 122, 141301 (2019)

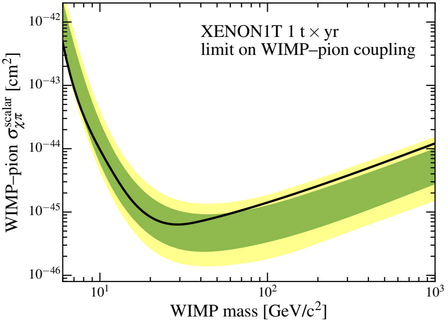
Coupling to exchange pions



(a) (b)

(a) Pure spin independent
(b) A WIMP can couple to a pion exchanged between nucleons (two-body)

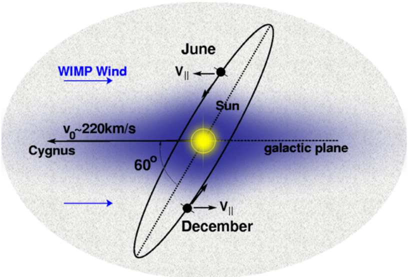


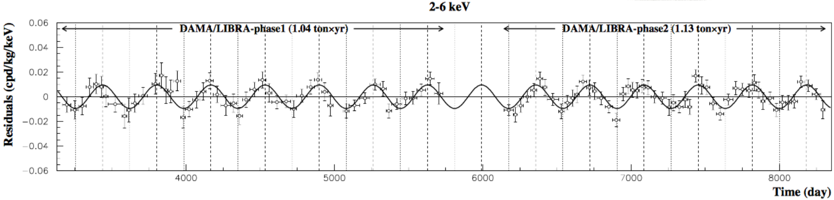


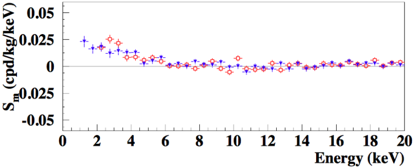
Figures from XENON1T, Phys. Rev. Lett. 122, 071301 (2019)

Annual modulation

- DAMA experiment: ultra radio-pure NaI crystals
- Annual modulation of background rate in the region (1 – 6) keV







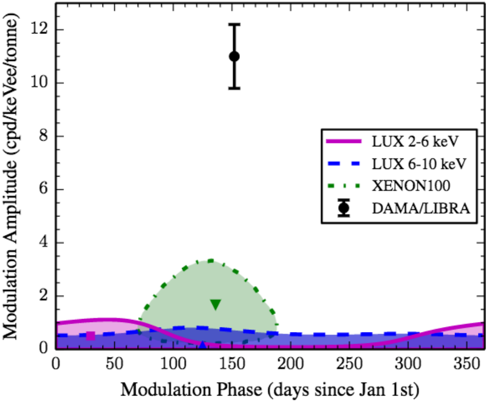
→ very recent data update

~ 12.9 σ combined significance!

First model independent results from DAMA/LIBRA-phase2, Figures and results from arXiv:1805.10486

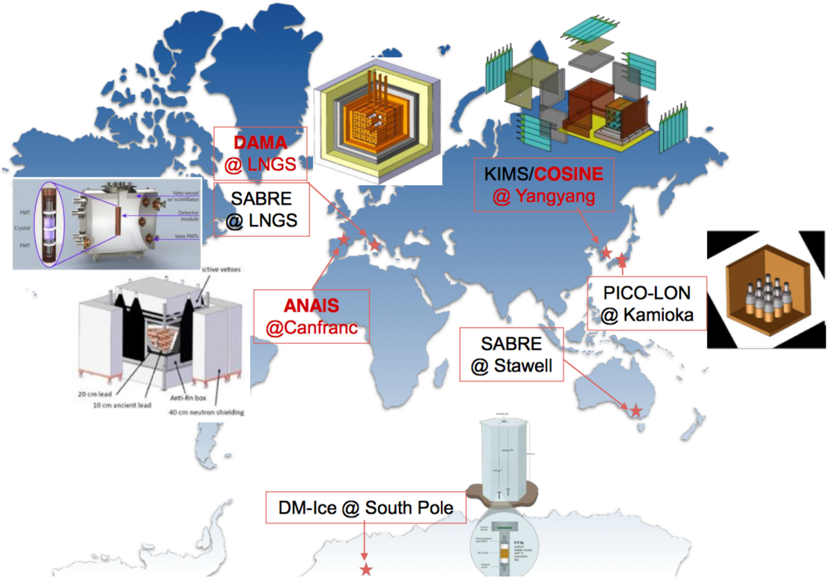
Annual modulation in liquid xenon detectors

- Exclusion of the leptophilic interpretation of this signal:
  $\rightarrow$ 3 σ by the XMASS result, PRD 97, 102006 (2018), arXiv:1801.10096
  $\rightarrow$ 5.7 σ by XENON100 4 y study, PRL 118, 101101 (2017) & arXiv:1701.00769
  $\rightarrow$ 9.2 σ by the recent LUX result, PRD 98, 062005 (2018) & arXiv:1807.07113



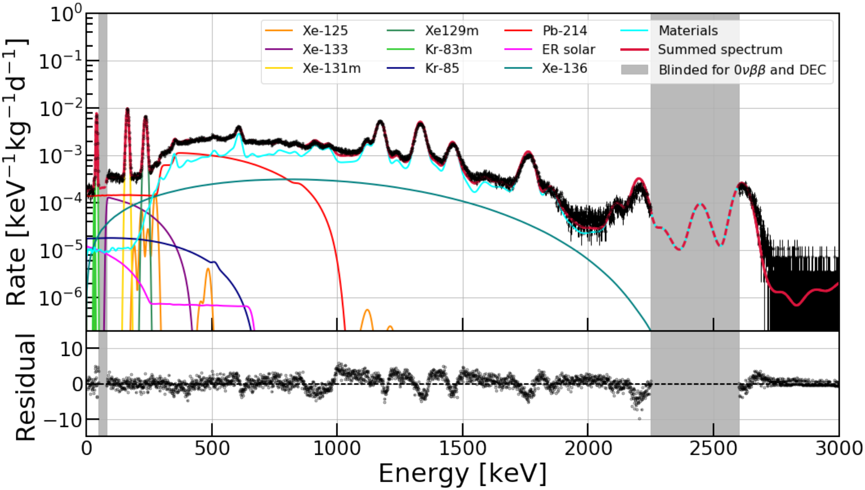
Evaluated 90% LUX contours for the modulation parameters in the signal region
Figure from arXiv:1807.07113

Tests of annual modulation with NaI(Tl)



Slide from Hyun Su Lee

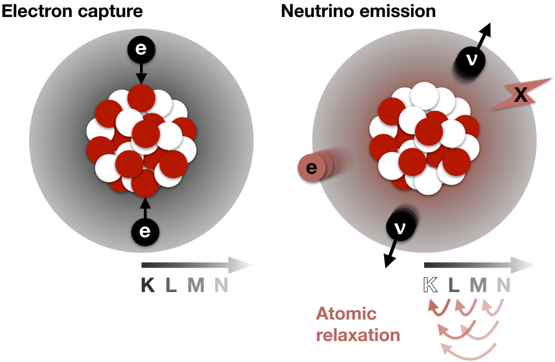
Beyond dark matter searches



XENON1T, preliminary

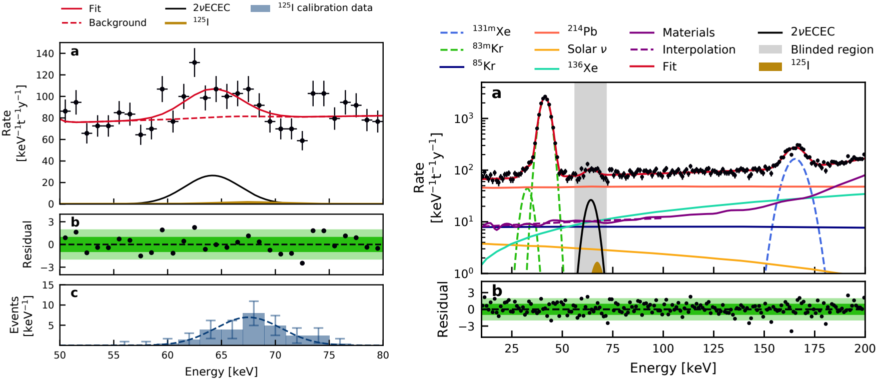
- Well understood energy spectrum up to few MeV
- Energy resolution optimized → below 1% at 2.45 MeV

Observation of 2ν double electron capture in ^{124}Xe



- Two 'invisible' neutrinos emitted
- X-rays and Auger electrons from the electrons filling vacancies
- Total released energy: 64.3 keV
- Background from ^{125}I produced by neutron activation

DEC ^{124}Xe signal

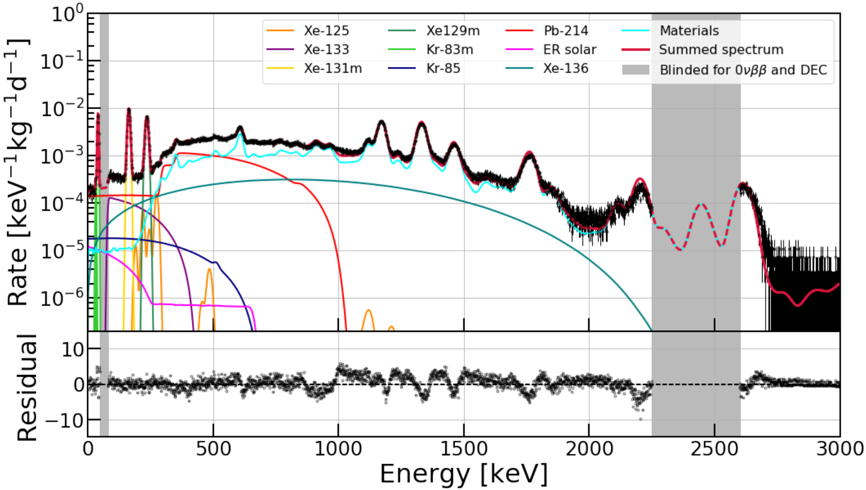


Figures from XENON1T, Nature 568 (2019) 7753, 532

- Significance of the measured signal: $4.4\,\sigma$
- Half-life: $T^{2\nu\text{ECEC}}_{1/2} = (1.8 \pm 0.5_{\text{stat}} \pm 0.1_{\text{sys}}) \times 10^{22}$ y

  $\rightarrow$ the longest half-life ever measured directly

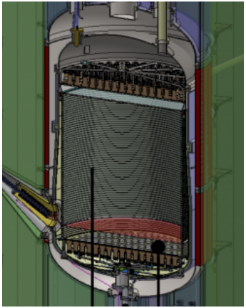
Beyond dark matter searches

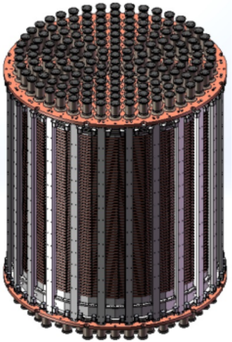


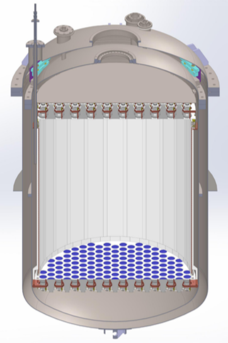
XENON1T, preliminary

- Energy resolution optimized → below 1% at 2.45 MeV
- Search for neutrinoless double-beta decay on-going

The race







LZ:

- 7 T target mass
- On site assembly and commissioning: 2019 - 2020

PANDAX-4T:

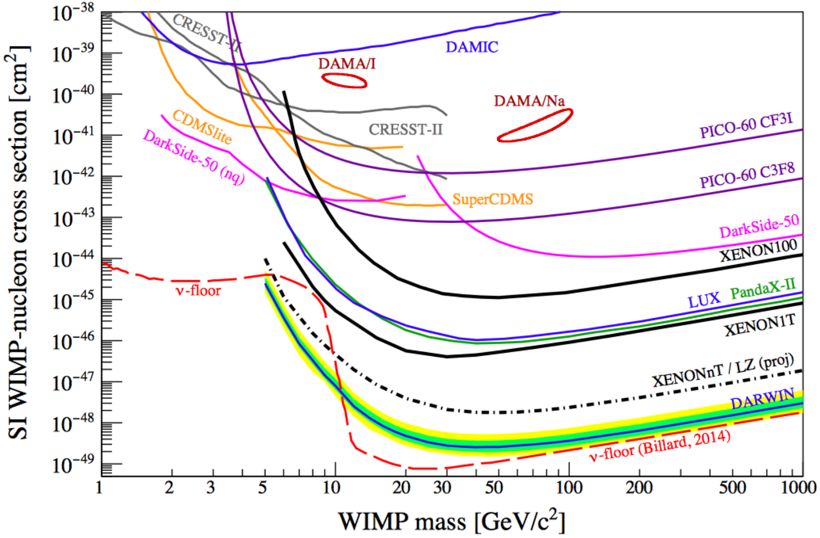
- 4 T target mass
- On site assembly and commissioning: 2019 - 2020

XENONnT:

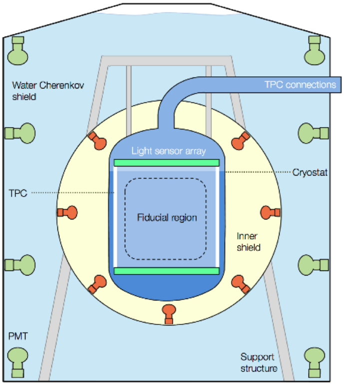
- 6 T target mass
- On site assembly and commissioning: 2019

$\rightarrow$ A race to measure WIMPs down to $\sigma \sim 10^{-48}\,\mathrm{cm}^2$

Sensitivity of upcoming liquid xenon detectors



DARWIN: the ultimate WIMP detector



http://darwin-observatory.org/

dark matter wimp search in noble liquids
DARWIN

- R&D and design study for a liquid xenon observatory
- TPC of $\sim$2.6 m diameter & 2.6 m drift length
- 50 t LXe total (40 t in the TPC)
- 7 years necessary to exploit the complete sensitivity

DARWIN, JCAP 1611 (2016) 017

Neutrino physics channels become available:

- Electronic recoils from solar neutrinos $\sim$7 ev/day in 30 t and E = (2-30) keV_{ee}
- 3.5 t of ^{136}Xe in DARWIN without isotopic enrichment
- Nuclear recoils from coherent neutrino scattering

Summary

Sensitivity for dark matter searches has progressed rapidly

- XENONnT, LZ and PandaX-4T are the upcoming devices to (hopefully) measure dark matter
- The future DARWIN is designed to investigate the **dark matter properties** with sensitivities down to the neutrino floor

→ Physics beyond dark matter available in these large detectors

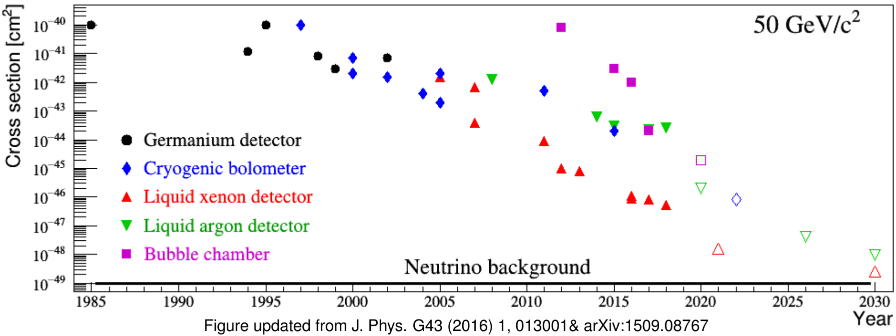
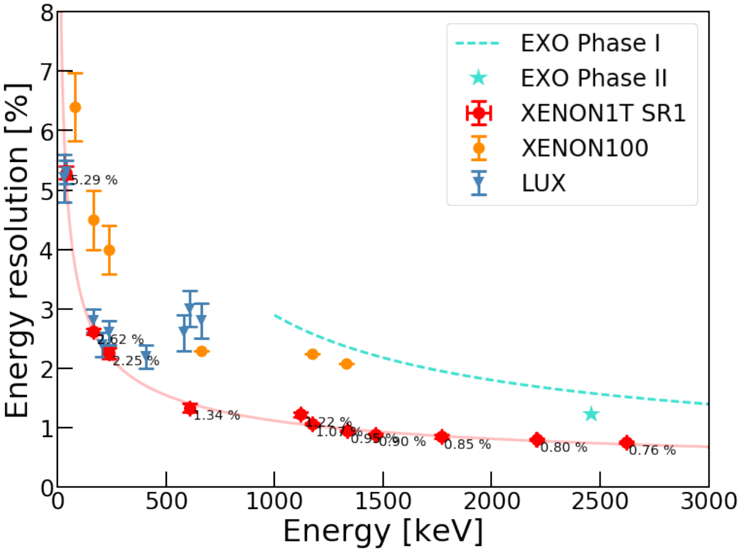


Figure updated from J. Phys. G43 (2016) 1, 013001& arXiv:1509.08767

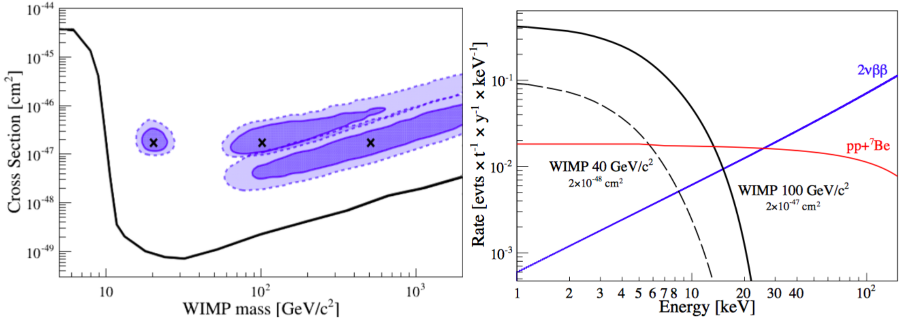
XENON1T energy resolution



XENON1T preliminary

DARWIN physics

- Goal: measure WIMP properties / ultimate cross-section sensitivity

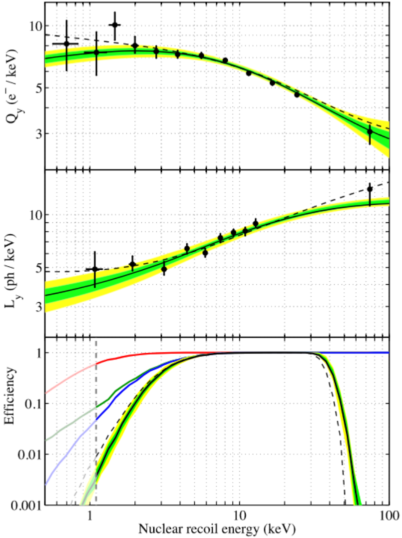


DARWIN, JCAP 1611 (2016) no.11, 017, arXiv:1606.07001 & L. Baudis *et al.*, JCAP01 (2014) 044

- Neutrino physics channels become available:
  - Electronic recoils from solar neutrinos $\sim$7 ev/day in 30 t and E = (2-30) keV_{ee}
  - 3.5 t of ^{136}Xe in DARWIN without isotopic enrichment
  - Nuclear recoils from coherent neutrino scattering:
    solar, supernova and atmospheric ν's 90 events/t/y from 8B-ν's above $\sim$ 1 keV_{ee}

Calibration of liquid noble gas detectors

Response of LXe to nuclear recoils



LUX, Phys. Rev. Lett. 116, 161301 (2016)

- Calibrations over the last years have largely improved the knowledge on energy scales

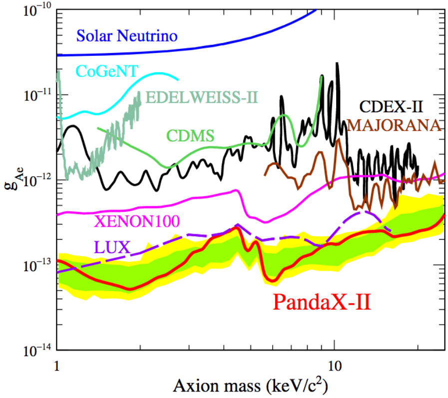
  $\rightarrow$ Nuclear recoil
  - DD neutron generator data
    arXiv:1608.05381

  $\rightarrow$ Electronic recoils
  - ^{83m}Kr source
    arXiv:0908.0616 & arXiv:1708.02566
  - Tritiated methane (CH_3T)
    arXiv:1512.03133 & arXiv:1709.10149
  - ^{37}Ar, ^{127}Xe, ^{129m,131m}Xe, γ-ray sources ...
    arXiv:1705.08958 & arXiv:arXiv:1709.00800 ...

- All data is compiled in the NEST simulation framework arXiv:1412.4417

Search for axion-like particles

- Search for axion-like dark matter particles of few keV/c^2 mass
- Axion-electric effect employed for detection



PandaX-II, Phys.Rev.Lett. 119 (2017) 181806

Other searches: inelastic dark matter, bosonic super-WIMP, leptofilic candidates, dark matter scattering inelastically off xenon ...