Review dark matter direct detection

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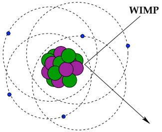
DMNet International Symposium 2022

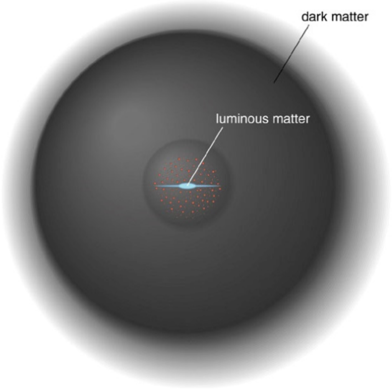
MAX-PLANCK-INSTITUT FÜR KERNPHYSIK HEIDELBERG

Direct detection: dark matter in the Milky Way



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

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



Astrophysical parameters:

- ρ_0 = local density of the dark matter in the Milky Way
- $f(\mathbf{v},t)$ = WIMP velocity distribution

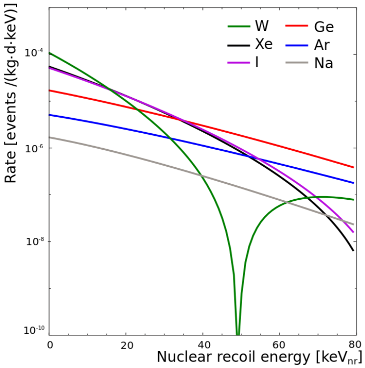
Parameters of interest:

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

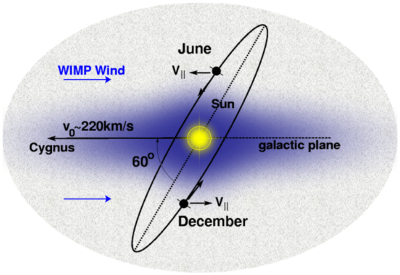
Detector requirements and signatures

- Large detector mass (grams up to several tonnes)
- Low energy threshold ~ few keV's or sub-keV
- Very low background and/or background discrimination (from γ's, e^-'s, neutrons and ν's!)

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



- Other signatures of dark matter
  - Annual modulated rate
  - Directional dependance

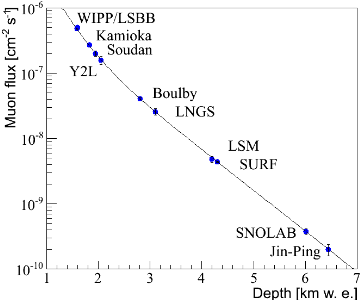


Backgrounds and reduction strategies

- External γ's from natural radioactivity:
  - Material screening & selection + Shielding

- External neutrons: muon-induced, (α, n) and from fission reactions
  - Go underground!
  - Neutron shielding
  - material selection for low U and Th concentrations

  + Neutrinos from the Sun, atmospheric and from supernovae



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

- Internal backgrounds:
  - Liquids/gases: radioactive isotopes, Rn-emanation
  - Solids: surface events from α- or β-decays
  - Cosmogenic activation important for all

Overview of WIMP searches

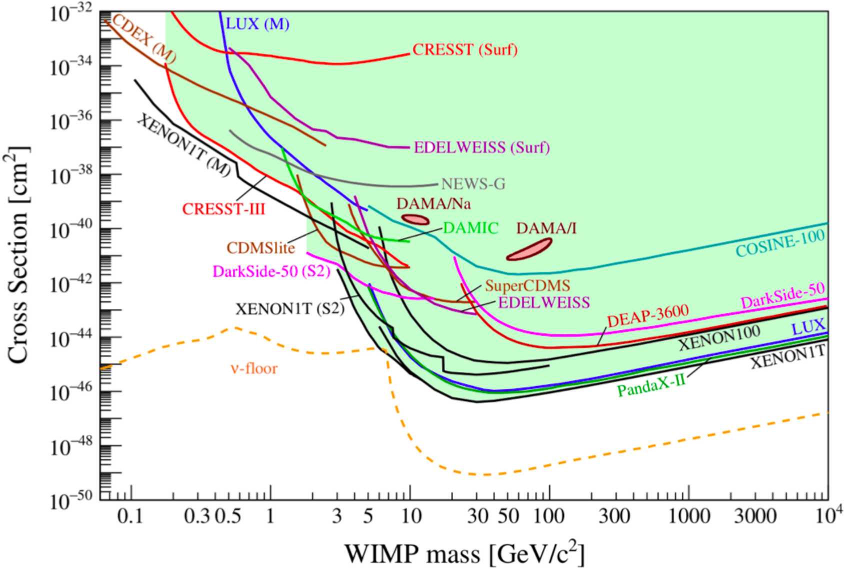
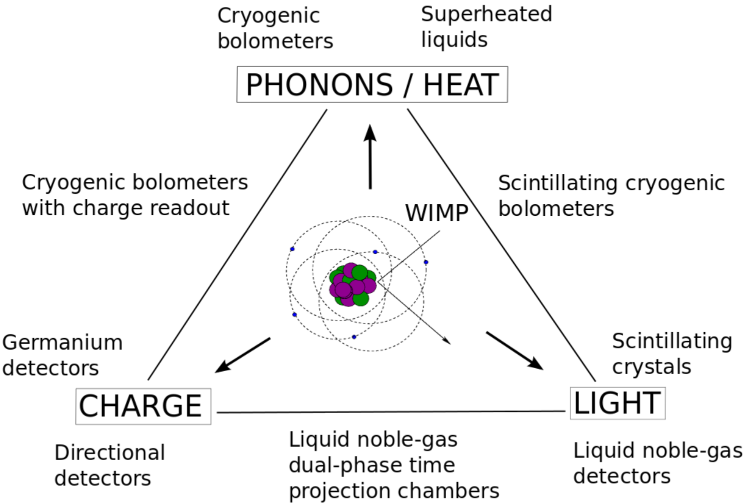


Figure from Rept. Prog. Phys. 85 (2022) 5, 056201

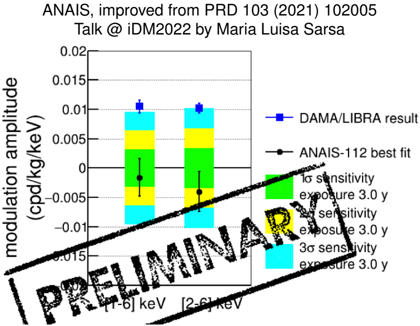
Direct detection experiments



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

Annual modulation signature

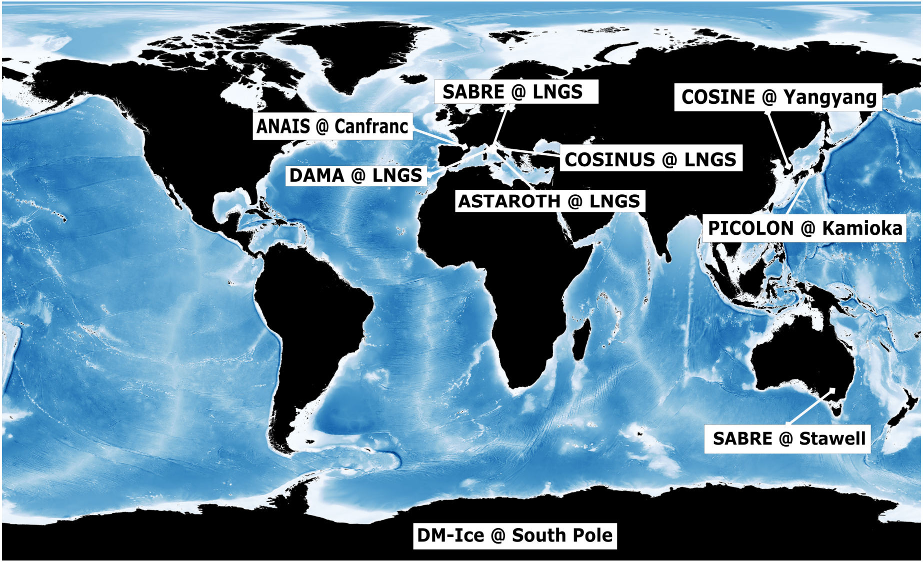
- DAMA experiment @LNGS
  using ultra radio-pure NaI crystals
- Annual modulation of the background rate in the energy region $(2-6)$ keV
- Last results (2021): signal at $13.7\,\sigma$



ANAIS using NaI crystals @Canfranc:

- DAMA modulation disfavoured
  at $3.8\,\sigma$ for [1-6] keV
  at $4.2\,\sigma$ for [2-6] keV
- Experiment continuously taking data

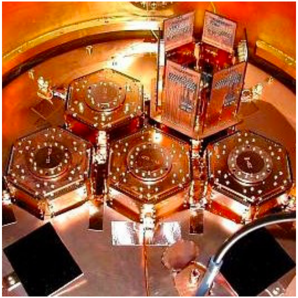
Tests of annual modulation with NaI



Bolometer experiments

CRESST experiment

EDELWEISS experiment



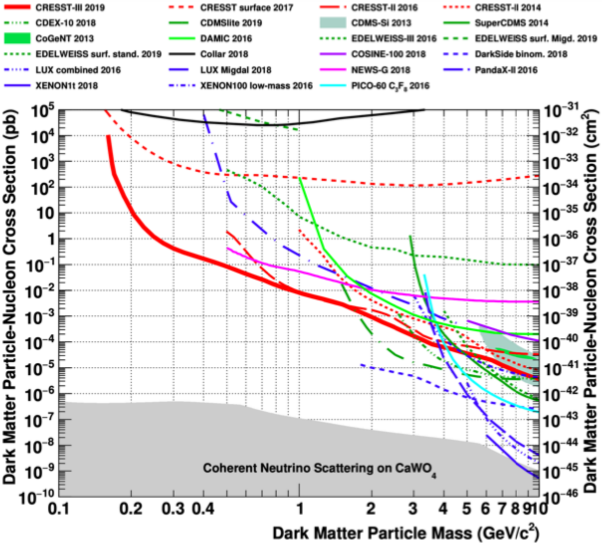
Super-CDMS experiment

- Excellent sensitivities (low m_χ) due to their low energy thresholds
- CRESST: scintillating bolometer

  CRESST, PRD 100 (2019) 102002 (E_{th} = 30 eV)
- CDMS/EDELWEISS: germanium bolometers

  CDMS-Lite, PRD 99 (2019) 062001 (E_{th} = 70 eV)

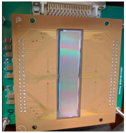
Results from cryogenic bolometers



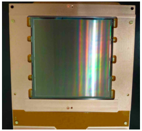
CRESST Coll., Phys. Rev. D 100, 102002 (2019)

New SuperCDMS HVeV result with 0.93 g silicon crystal with $E_{th} \sim 10$ eV missing in this figure PRD 105, 112006 (2022)

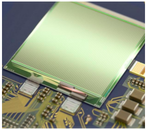
Low threshold searches with CCDs



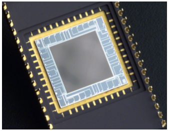
SENSEI
PRL 125 (2020) 171802



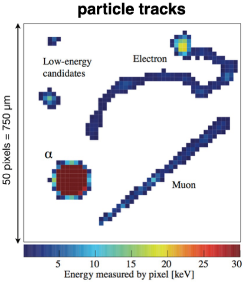
DAMIC
PRL 123, 181802 (2019)



DANAE
EPJC 77 (2017) 12, 905



DMSQUARE
N. Avalos@TAUP2021

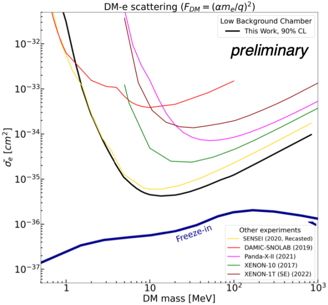


From Nuria Castelló-Mor @ICHEP2022 (DAMIC)

- Gram-scale Si detectors with $E_{th} \sim 50\,\mathrm{eV}_{ee}$
- 3D track reconstruction
- Test of DM-e⁻ scattering below to 1 MeV DM mass

  & low mass WIMPs tests

→ Future: OSCURA, a 10 kg detector by SENSEI&DAMIC



DM-e⁻ scattering (light mediator)
DAMIC @ iDM2022 by Danielle Norcini

Cross sections for WIMP elastic scattering

- Spin-independent interactions: coupling to nuclear mass

$\sigma_{SI} = \frac{m_N^2}{4\pi(m_\chi+m_N)^2} \cdot [Z \cdot f_p + (A-Z) \cdot f_n]^2$, $\quad f_{p,n}$: eff. couplings to p and n

- Spin-dependent interactions: coupling to nuclear spin

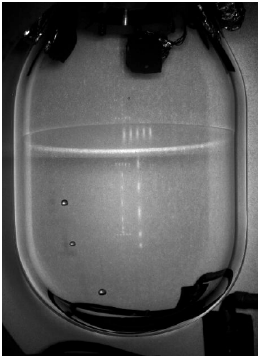
$\sigma_{SD} = \frac{32}{\pi} \cdot G_F \cdot \frac{m_\chi^2 m_N^2}{(m_\chi+m_N)^2} \cdot \frac{J_N+1}{J_N} \cdot [a_p\langle S_p\rangle + a_n\langle S_n\rangle]^2$

$\langle S_{p,n}\rangle$: expectation of the spin content of the p, n in the target nuclei

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

Superheated fluid detectors

COUPP experiment



- Energy depositions > E_{th} → expanding bubble detected with cameras + piezo-acoustic sensors
- Bubble chamber with C_3F_8 superheated fluid

- Great sensitivity to spin-dependent σ

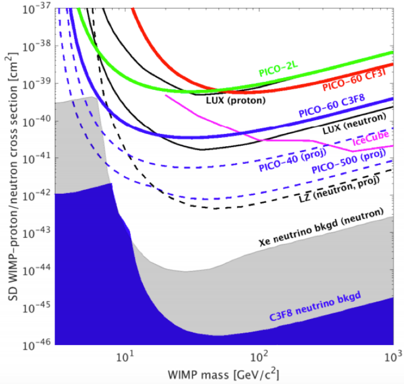


Figure from Eric Vázquez Jáuregui @ICHEP2022

- PICO40L: about to take data @SNOLAB
- PICO-500: ton-scale experiment to be installed in the miniCLEAN space @SNOLAB on 2023-2024

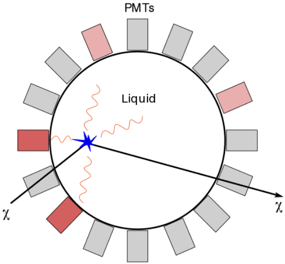
Advantages of liquid noble gases

- Large masses and homogeneous targets (LNe, LAr & LXe)

  Two detector concepts: single & double phase
- 3D position reconstruction → fiducialization
- Transparent to their own scintillation light

Single phase (liquid) -type of detector:

- High light yield using 4π photosensor coverage
- Pulse shape discrimination from scintillation
- Very effective in liquid argon (10^8 NR/ER separation)

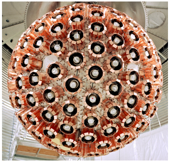


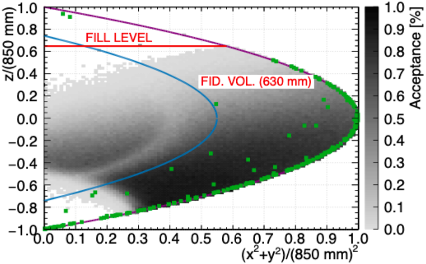
The DEAP single phase LAr detector

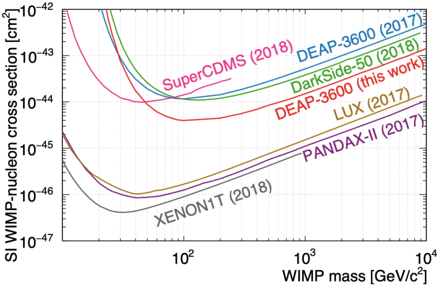
DEAP - LAr detector at SNOLAB, Canada

Dark matter **E**xperiment with **A**rgon and **P**ulse shape discrimination

- 3 600 kg total mass & 3 280 kg fiducial volume
- Results of 231 d DEAP, PRD 100 (2019) 022004
- Most competitive liquid argon results

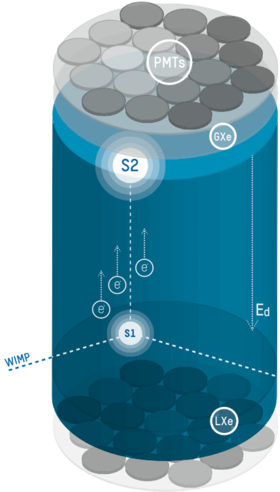






From Jan. 2018 to Mar. 2020: blinded data → analysis on-going

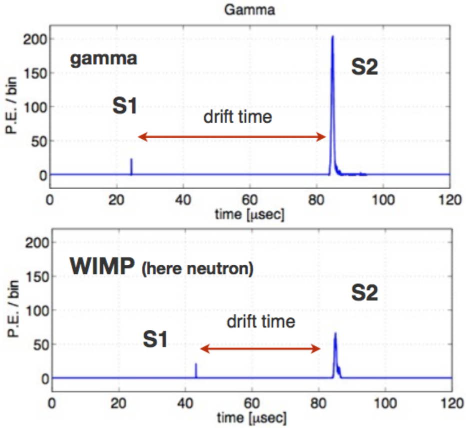
Two phase noble gas TPC



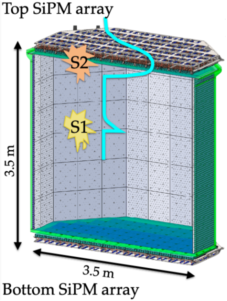
- Position resolution
  → XY from PMT pattern
  → Z from drift time

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

→ Electron- /nuclear recoil discrimination



The DarkSide experiment



- DarkSide-50 run @LNGS with 50 kg mass

  DarkSide, PRD 98 (2018) 102006 & PRL 121 (2018) 8, 081307

- DarkSide-20K: new global LAr collaboration
  - 50 t total target mass
  - TPC inside an acrylic vessel
  - SiPM for light read-out (~ 19 m^2)

- Aiming at high mass dark-matter search

  ROI (20 – 200) keV_{nr}

  → filling with underground argon planned for 2026

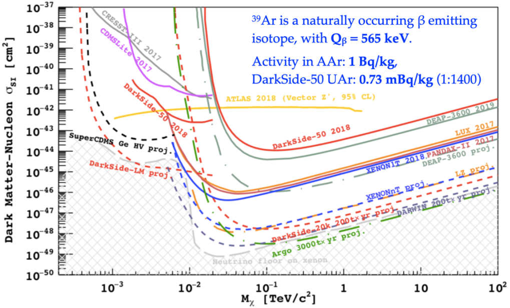
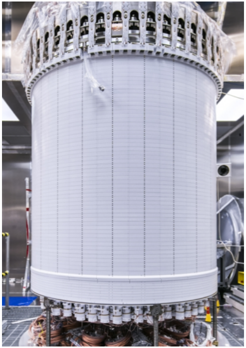


Figure from the DarkSide collaboration

Current generation: LZ, PandaX-4T and XENONnT



LZ:
- 7 T target mass

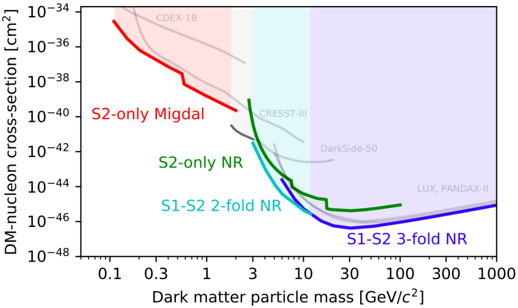
PANDAX-4T:
- 4 T target mass

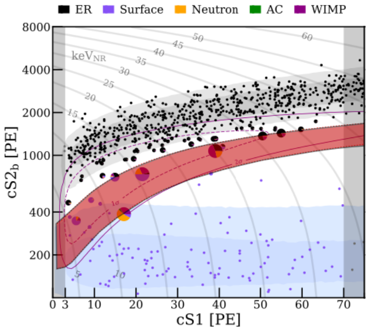
XENONnT:
- 6 T target mass

All running and collecting data!

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

Reminder: XENON1T results I

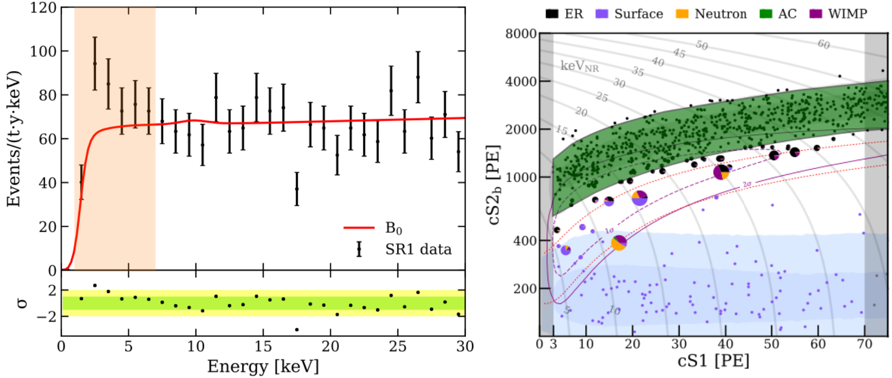




XENON1T, publications from 2018 to 2021

- XENON1T operated at LNGS from 2016 to 2019
  providing several world leading results in the last years
  – Migdal result: depends on the experimental confirmation of this effect!

Reminder: XENON1T results II



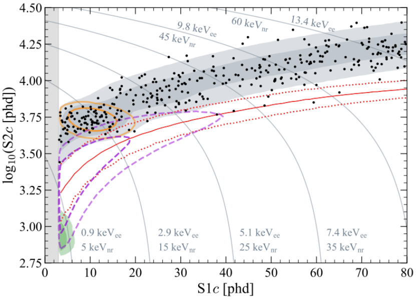
XENON1T, PRD 102 (2020) 072004

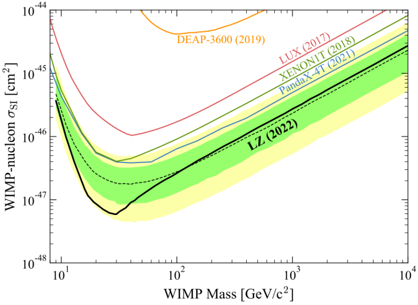
- **Excess of events in (1-7) keV** in the background (ER) region

  ~ 3.3 σ statistical significance

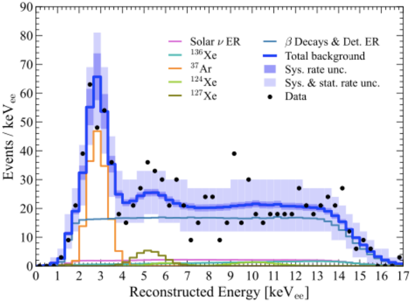
  → Unclear origin: Background? An interesting signal?

Recent LZ data





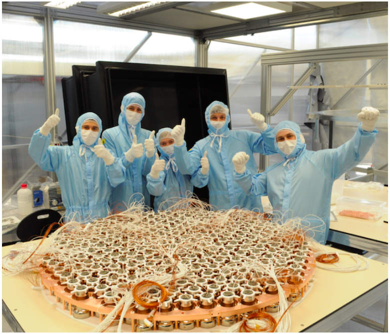
- SR1: 5.5 t fiducial volume and 60 days of data
- Current best exclusion limit



Figures from LZ, arXiv:2207.03764

XENONnT

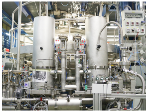
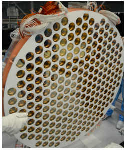
TPC: 1.5 m long und 1.5 m ∅
5.9 t liquid xenon in the detector
(8.5 t total mass)

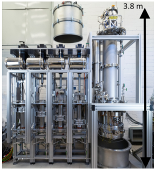


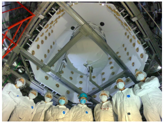
- Assembled and commissioned during 2020
- First science run in 2021: SR0 with 1.16 tonne-years
- 3× larger target mass
- 5× less background

Improvements from 1T to nT

- New TPC and new cryostat
- Additional and improved PMTs (494 units in total)
- Novel liquid-phase purification system
- New neutron veto system (water-based in the current phase)
- New radon removal system

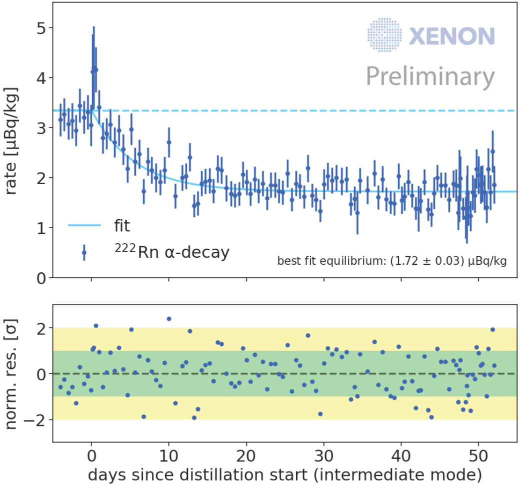





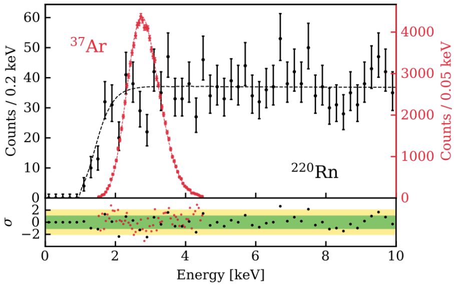
Radon background

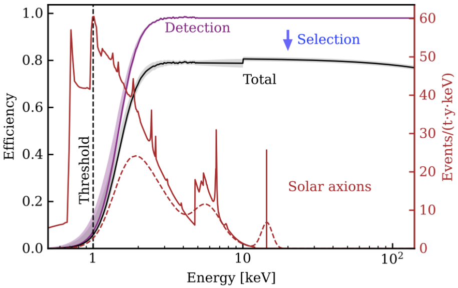
Dominating background in XENON1T & other LXe experiments



- Extensive radon screening campaigns @MPIK
- Additional distillation (gas mode) to reach 1.7 μBq/kg
- Lowest radon level ever achieved in a LXe experiment
- <1 μBq/kg already reached in SR1!

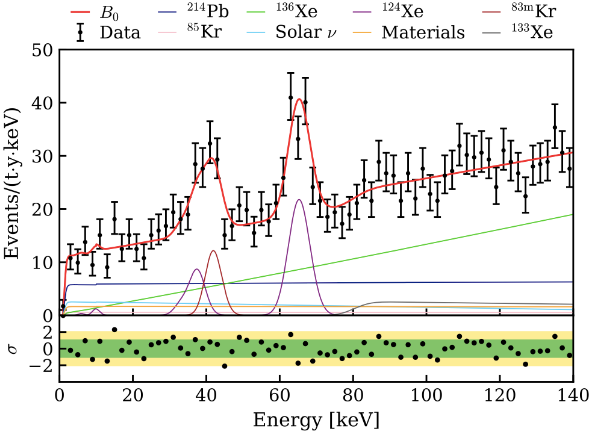
Low energy response





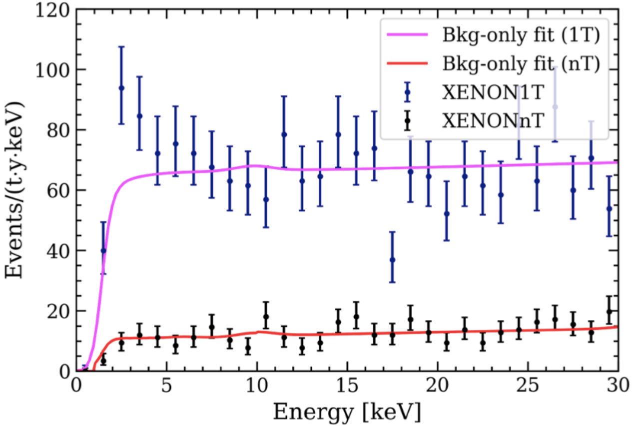
- Calibration data: ^{37}Ar and ^{220}Rn used to study the low energy response in XENONnT
- Efficiency at low energies: at ~ 80% above ~ 3 keV

SR0 electronic-recoil science data



- Spectrum still dominated by ^{214}Pb at low energies
- Above 40 keV, 2nd order weak processes dominate:
  → Double electron capture 2νECEC of ^{124}Xe ($t_{1/2} = 2.23 \times 10^{21}$ y)
  → Double beta decay $2\nu\beta\beta$ of ^{136}Xe ($t_{1/2} = 1.1 \times 10^{22}$ y)

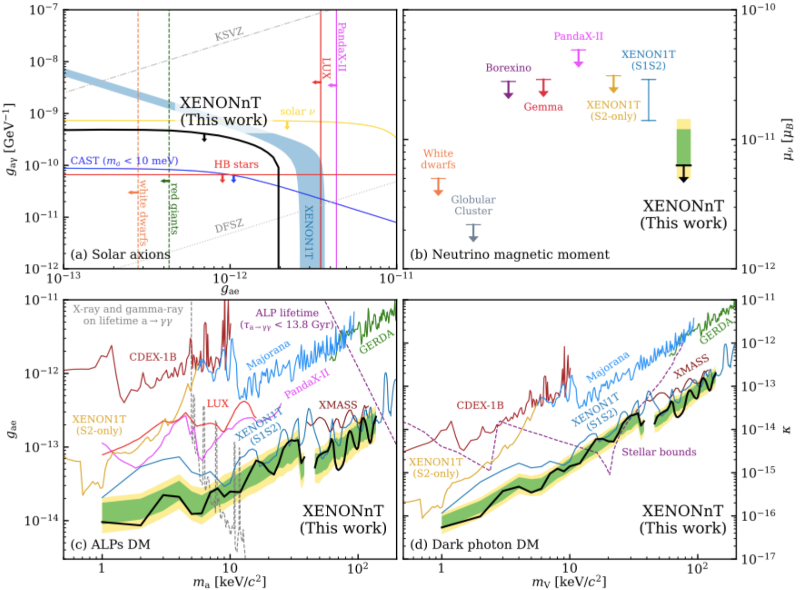
SR0 electronic recoil data



- No excess present in XENONnT
- Origin of XENON1T excess maybe a tritium background/statistics

  → XENONnT was throughly prepared to avoid tritium

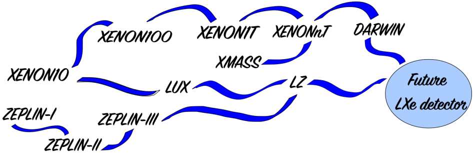
Constrains on physics models



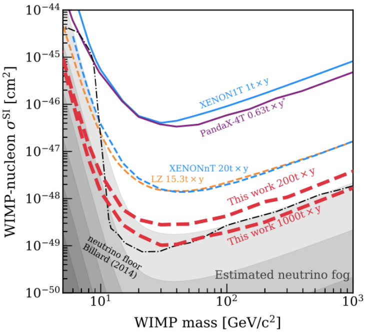
XENONnT, arXiv:2207.11330

XLZD consortium

XENON, LUX ZEPLIN & DARWIN meeting in Karlsruhe, July 2022



XLZD:
XENON, LZ and DARWIN together

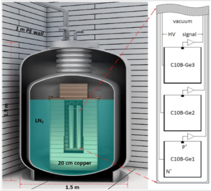


Common paper with physics case: arXiv:2203.02309

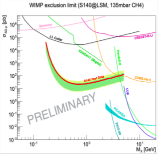
Other detectors and technologies being developed ...

... but not discussed in this talk

CDEX, germanium

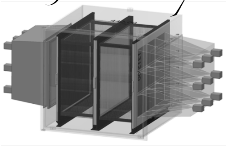


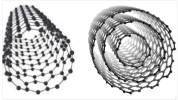
NEWS-G



Directional experiments

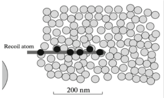
CYGNO, low pressure gas





ANDROMeDa, nanotubes

NEWSdm, emulsion



Others ...

Summary

Direct searches are quickly progressing
covering a large DM range in mass and cross section

Exploring WIMPs but also light DM, ALPs, dark photons ...

Current signals/excesses are not confirmed

We hope for a dark matter discovery soon, ideally
in various detectors/searches!

THANK YOU!

Solar axions

Hypothetical **axions** proposed as a solution to the 'strong CP-problem'

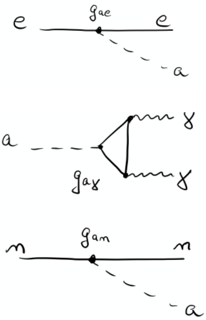
→ Solar axions would be produced in the Sun with ~keV energies:

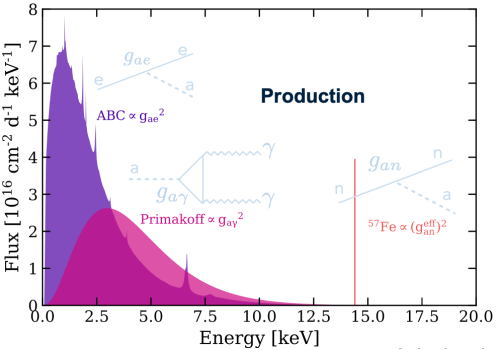
- Atomic recombination and de-excitation, Bremsstrahlung and Compton: ABC
- Primakoff conversion of photons to axions
- A mono-energetic 14.4 keV nuclear transition of ^{57}Fe

1. ABC:

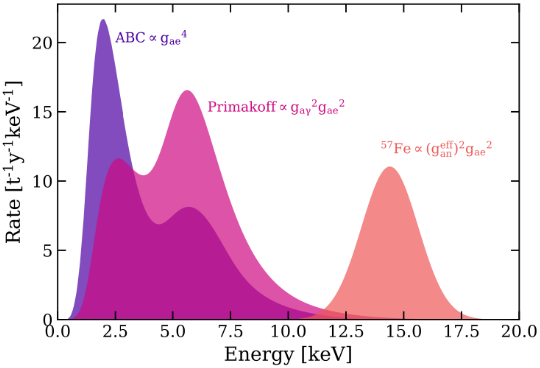
2. Primakoff:

3. ^{57}Fe:





Solar axion detection



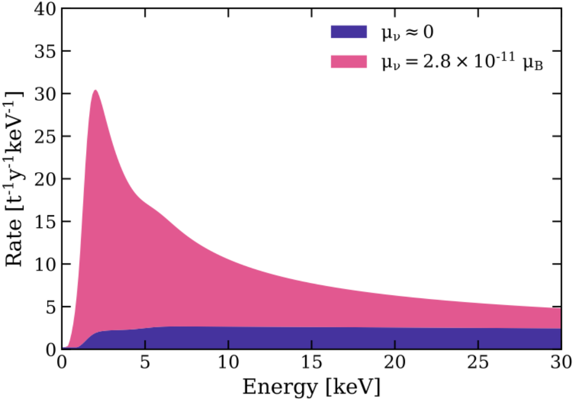
Detection of **axions** via axioelectric and inverse Primakov effects

- Energy resolution and shell structure affects the spectrum
  Xenon's L-shells have binding energies at 5.45 keV, 5.10 keV, and 4.78 keV
- Model-dependent couplings to matter
  (ABC flux dominant in DFSZ models while Primakoff is dominant in KSVZ)

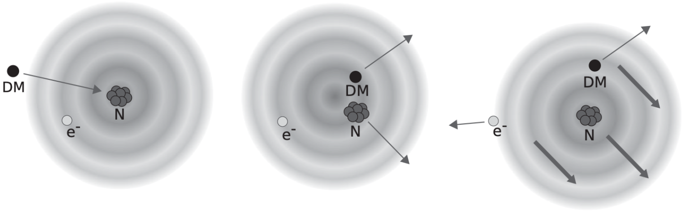
Neutrino magnetic moment

Neutrinos acquire magnetic moment in extensions of the SM

- Source: neutrinos from the Sun (mostly from pp-reactions)
- Reaction: elastic scattering off electrons



Low-mass WIMP searches using the Migdal effect



Scheme from Dolan et al., PRL 121 (2018)101801

- Sudden acceleration of a nucleus can lead to excitation or ionization of the shell electrons   Ibe et al., JHEP 03 (2018) 194
- Yet no experimental evidence of this effect!
- Two strategies being followed:
  - MIGDAL collaboration: ER+NR vertex in a low pressure gaseous detector
  - Nakamura et al.: two clusters (NR + X-ray) in position sensitive gaseous detector   Nakamura et al., (2020) arXiv:2009.05939