Searching for dark matter with XENON

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PRISMA+ colloquium, Mainz
July 3rd, 2024

Career path

- Physics studies at Universidad Complutense in Madrid (Spain)

  → Exchange programs: Valencia and Munich (Erasmus)

- PhD thesis at TU München (proton decay, organic scintillators)

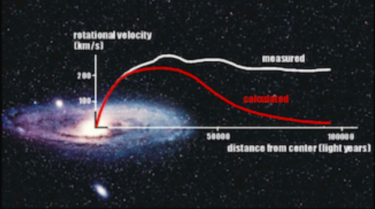
- Postdoc: 4 years at the University of Zürich (dark matter, LXe)

  → supported by Feodor Lynen scholarship

- Staff position since 2012 at Max-Planck-Institut für Kernphysik

  → Habilitation at the University of Heidelberg in 2014

  → group leader since 2017

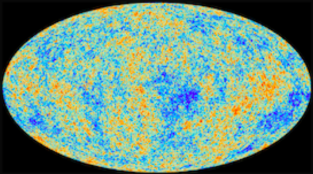


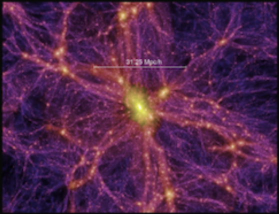
What is dark matter?

Massive objects (primordial black holes)

Modified gravitational theories

New particles (WIMPs, axions ...)





How can we look for dark matter?

Indirect detection

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

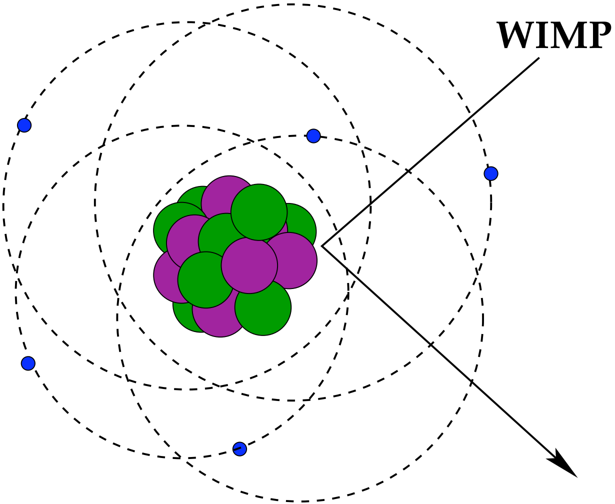
Direct detection

χ N $\rightarrow \chi$ N

Production at LHC

p + p $\rightarrow \chi\overline{\chi}$ + X

Direct dark matter detection



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

Expected interaction rates in a detector

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

Astrophysical parameters:

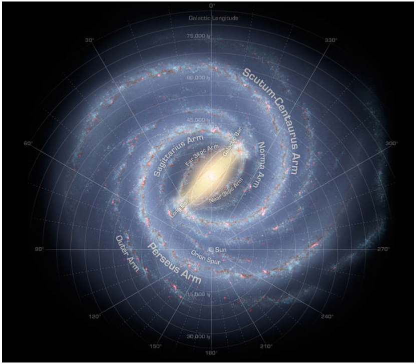
- ρ_0 = local density of the dark matter in the Milky Way

  '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)

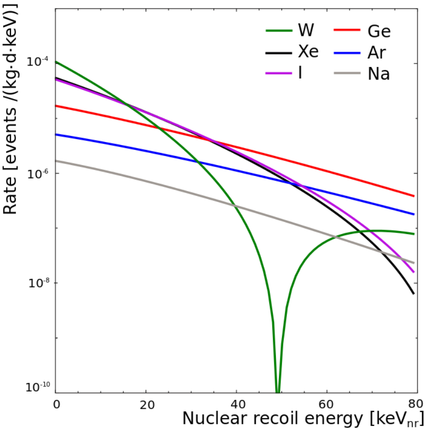
Figure from NASA



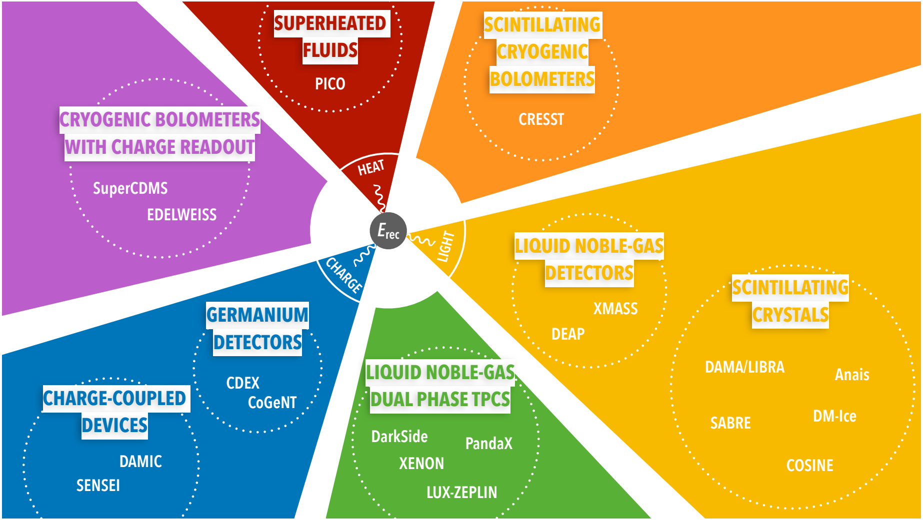
Detector requirements

- Requirements for a dark matter detector
  - Large detector mass
  - Low energy threshold ~ few keV's
  - Very low background
  - Technology or analysis tools to discriminate signal and background

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



Technologies for direct detection



R. Hammann

Overview of WIMP search results

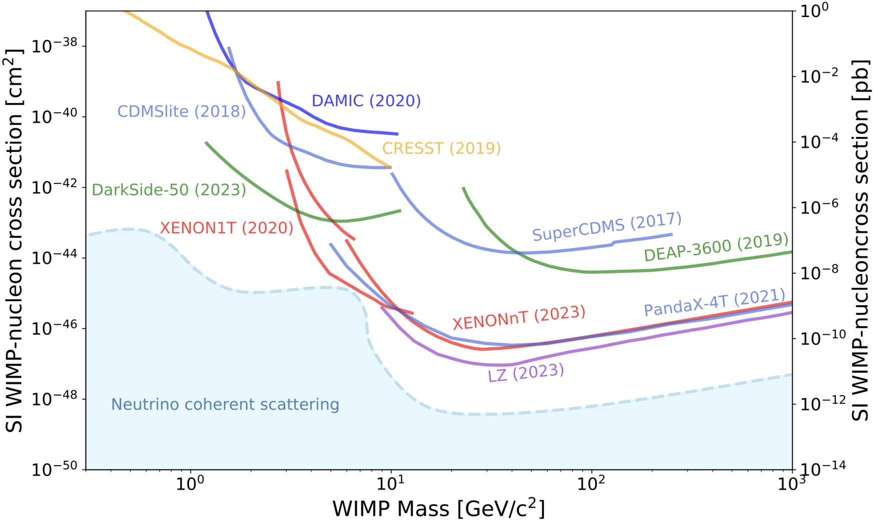
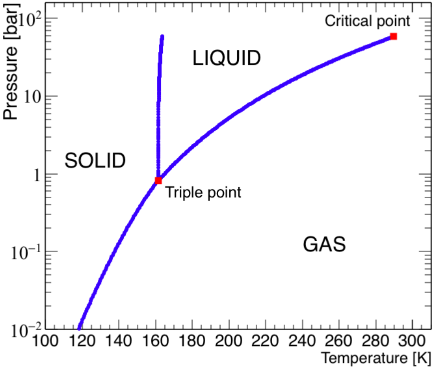
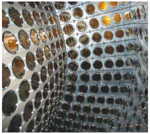


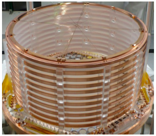
Figure from PDG (2023) by L. Baudis and S. Profumo

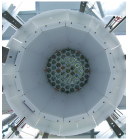
Liquid xenon as detector

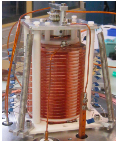


- Cryogenic liquid typically operated at 2 bar and −100°C
- High density: 3 g/cm^3
- High scintillation and ionization yields
- Scalability
- Employed in particle-, neutrino-, dark matter- and medical physics

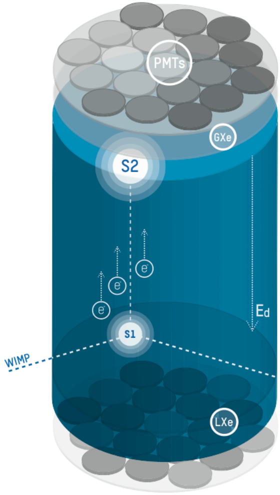






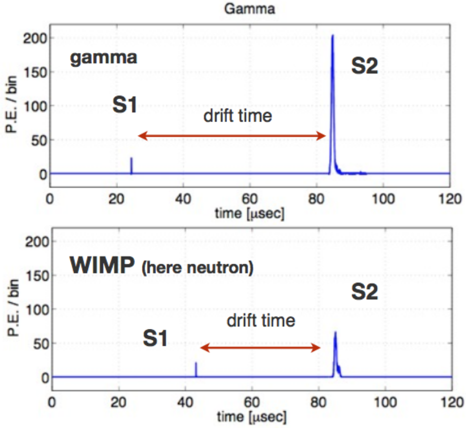


Two phase noble-gas TPC



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

→ Electron- /nuclear recoil discrimination



Position resolution to define the innermost radiopure volume for analysis

Particle identification based on S1 & S2

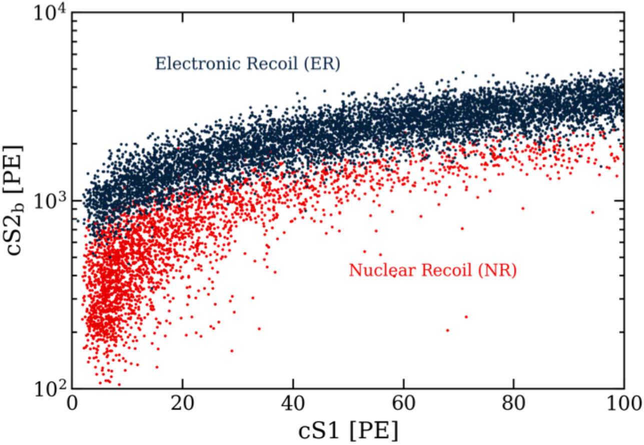
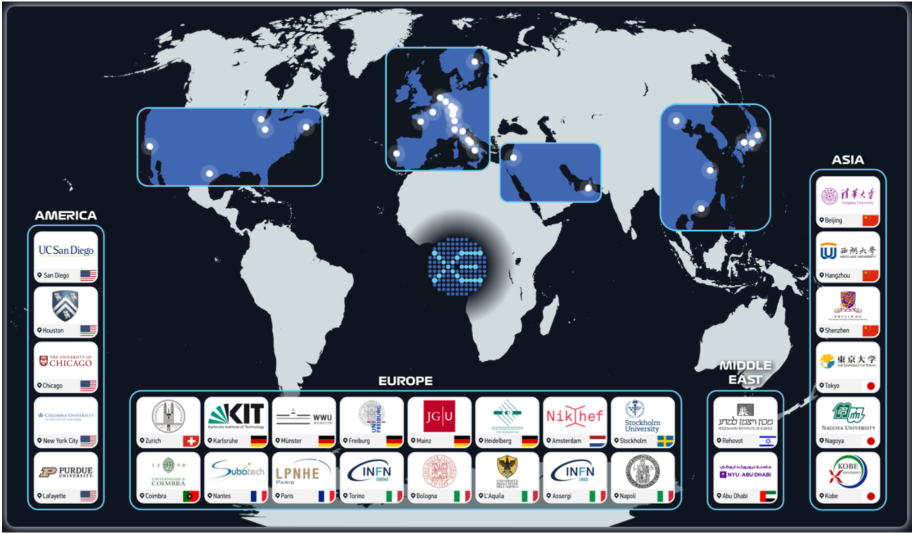


Figure from XENON1T data

- ER: calibrated using a ^{220}Rn source (β-decays of ^{212}Pb)
- NR: calibrated using a neutron generator / AmBe-neutron source

THE XENON EXPERIMENT

XENON collaboration



Experiment operated by 29 institutes worldwide

XENON collaboration

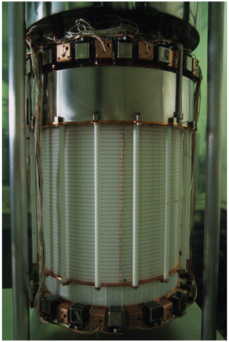
Collaboration meeting – L’Aquila, March 2024

The XENON program

XENON10

(2005-2007)
Target: 14 kg
$\sigma \sim 10^{-43}\,\mathrm{cm}^2$

XENON100



(2008-2016)
Target: 62 kg
$\sigma \sim 10^{-45}\,\mathrm{cm}^2$

XENON1T

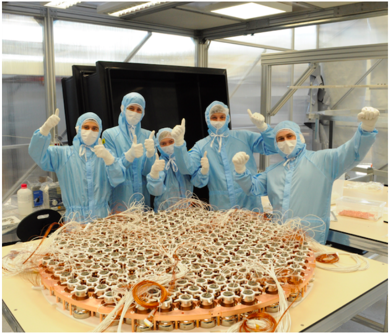
(2015-2018)
Target: 2 ton
$\sigma \sim 4 \times 10^{-47}\,\mathrm{cm}^2$

XENONnT

(2019~2026)
Target: 5.9 ton
$\sigma \sim 2 \times 10^{-48}\,\mathrm{cm}^2$

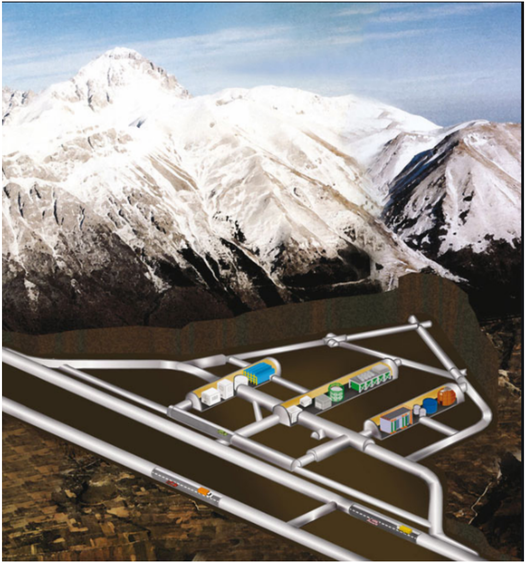
XENONnT TPC

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 1.1 tonne-years
- 3× larger target mass
- 5× less background

Underground location

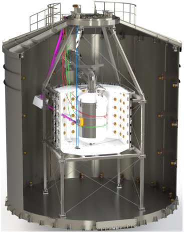


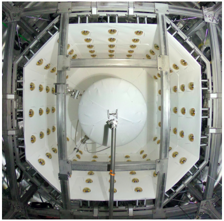
- Located @ Laboratori Nazionali del Gran Sasso (Italy)
- Shielding from cosmic radiation: below 3 650 m.w.e. ($\sim$ 1.5 km rock)

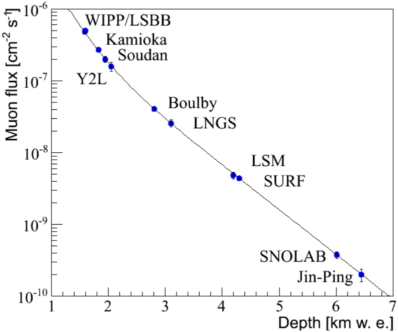
XENON underground

XENONnT water tank and building @LNGS, location underground

Shielding against radiation





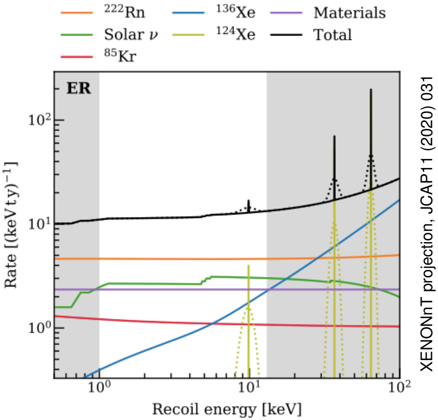


J. Phys. G: 43 (2016) 1 & arXiv:1509.08767

- Underground location to shield from cosmic particles
- Active water-Cherenkov muon shield
- Neutron veto for XENONnT
- Veto system instrumented with photosensors (PMTs)

Backgrounds

- **External backgrounds**: from natural radioactivity:
  - γ-activity and neutrons
- **Neutrinos** from the Sun:
  - Elastic ν-electron scattering
  - Coherent elastic neutrino-nucleus scattering (CEνNS)

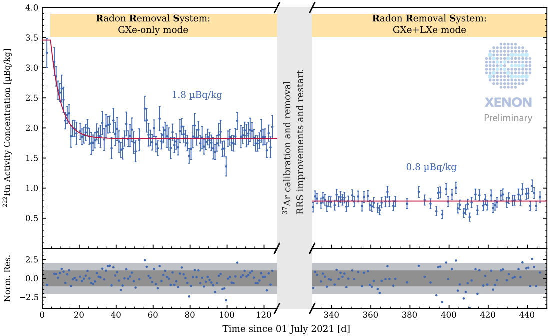


- **Internal backgrounds**:
  - Xenon: ^{136}Xe $\beta\beta$ decay ($T_{1/2}$ = 2.23 × 10^{21} y)
  - ^{85}Kr: from ^{nat}Kr in Xe in the xenon inventory
  - Rn: dominant contribution to the background

Radon background

Dominating background in XENON1T, nT & other LXe experiments

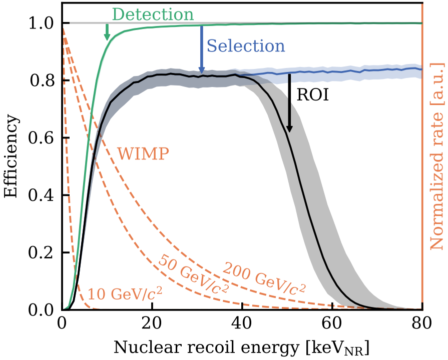
→ Extensive radon screening campaigns @MPIK



- SR0: distillation in gas mode → 1.8 μBq/kg
- Lowest radon level ever achieved in a LXe experiment!

- SR1: distillation in liquid mode → 0.8 μBq/kg
- Radon background at the level of solar neutrino background!

First WIMP search



XENONnT, PRL 131 (2023) 041003 & arXiv:2303.14729

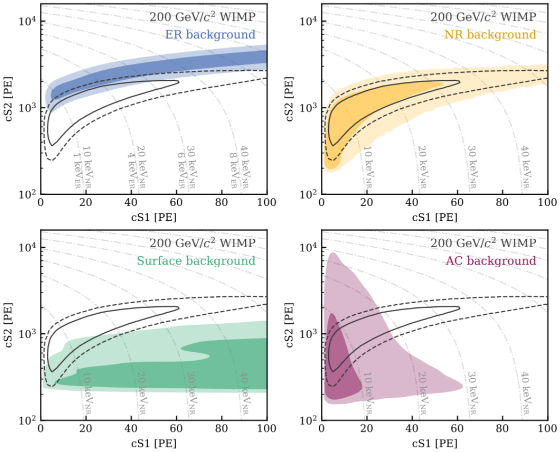
- Data set:

  97.1 days, from July 6th to Nov. 10th 2021

- (4.18 ± 0.13) tonne fiducial volume
- Blind analysis: WIMP region not accessible during the analysis

- Efficiency: detection threshold driven by 3-fold PMT coincidence
- Selection efficiency evaluated with calibration data

Backgrounds



XENONnT, arXiv:2406.13638

Electronic recoil: dominated by ^{214}Pb (Rn)

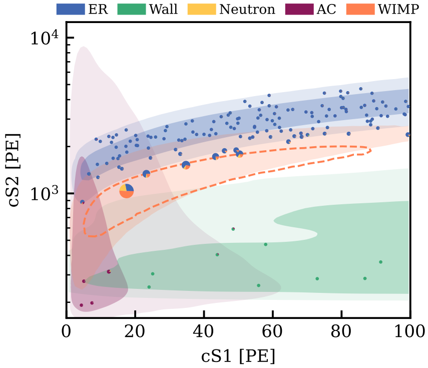
Nuclear recoil backgrounds: neutrons and CEνNS

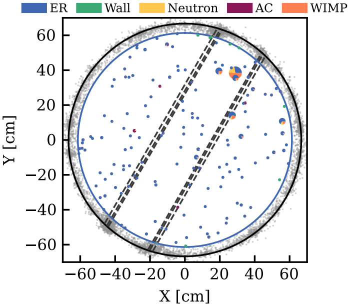
Surface: ^{210}Pb plate-out on the PTFE walls

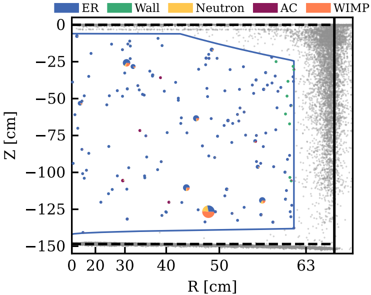
Accidental coincidences: random pairing of S1s and S2s

Spatial distribution of events

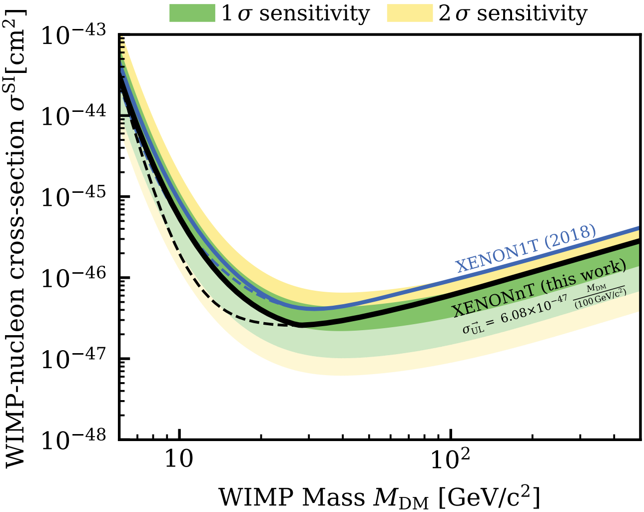
WIMPs: for a 200 GeV/c^2 mass and the best fit cross section of 2.5×10^{-47} cm^2







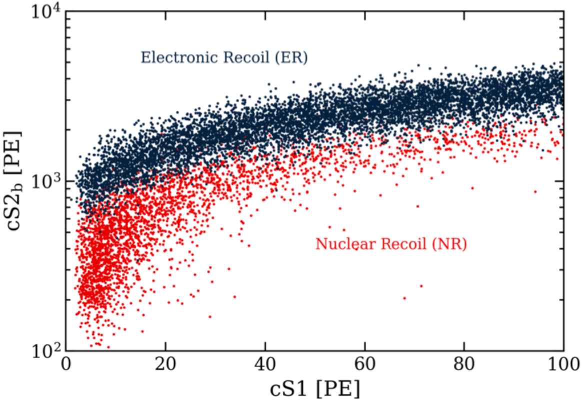
WIMP spin-independent result



XENONnT, PRL 131 (2023) 041003 & arXiv:2303.14729

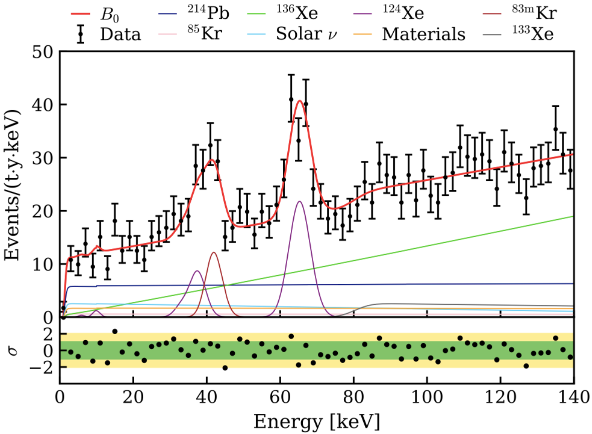
XENONnT has collected much more data!

Searches in the ER region



- Electronic recoil region → background dominated
- BUT very good knowledge on the composition of our background

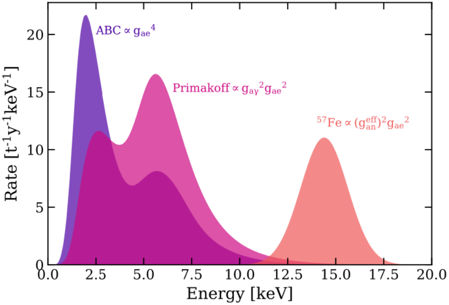
XENONnT electronic-recoil science data



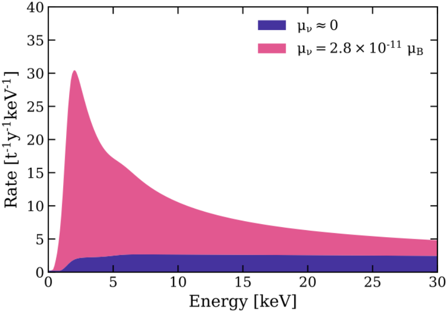
XENONnT, PRL 129 (2022) 161805 & arXiv:2207.11330

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

Signals in the ER region



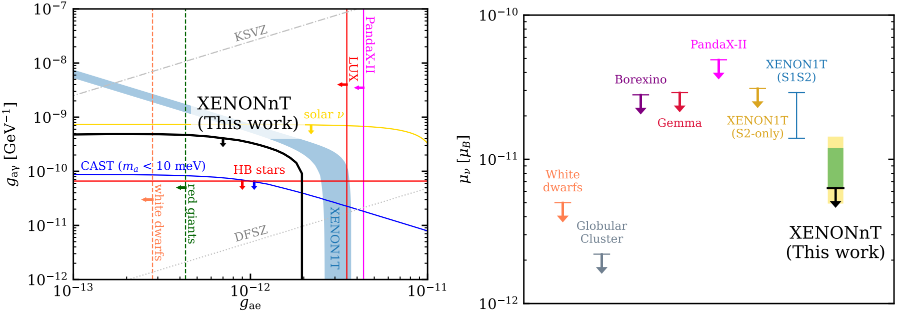
Solar axion signal



Neutrino magnetic moment signature

- Solar axion hypothesis
  - Can be detected in XENON via axioelectric and Primakov effects
- Neutrino magnetic moment
  - Enhancement of the low energy spectrum (of solar ν's)

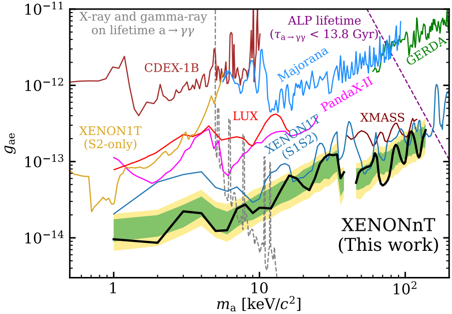
Derived constrains

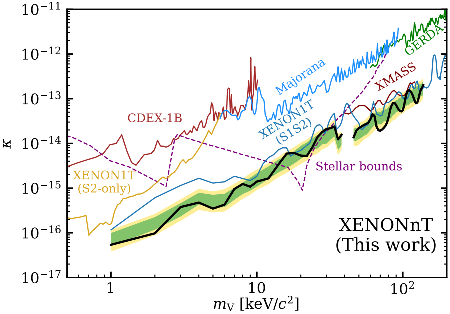


XENONnT, PRL 129 (2022) 161805 & arXiv:2207.11330

- Solar axion: constrains on the coupling parameters $g_{a\gamma}$ and g_{ae}
- Best laboratory limit on the neutrino magnetic moment
  (stronger constrains from astrophysics: energy loss arguments)

Constrains on dark matter candidates





XENONnT, PRL 129 (2022) 161805 & arXiv:2207.11330

- Best limits on axion-like DM particles and hidden photons (monoenergetic signal model)

→ No limit around 40 keV due to an unconstrained ^{83m}Kr background

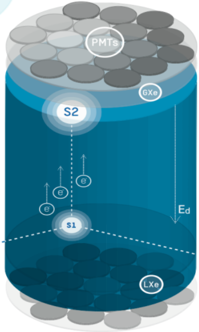
Multi-physics goals in large liquid xenon detectors

Neutrinoless double beta decay

Dark Matter

Supernova neutrinos

Rare processes e.g. DEC



Solar neutrinos

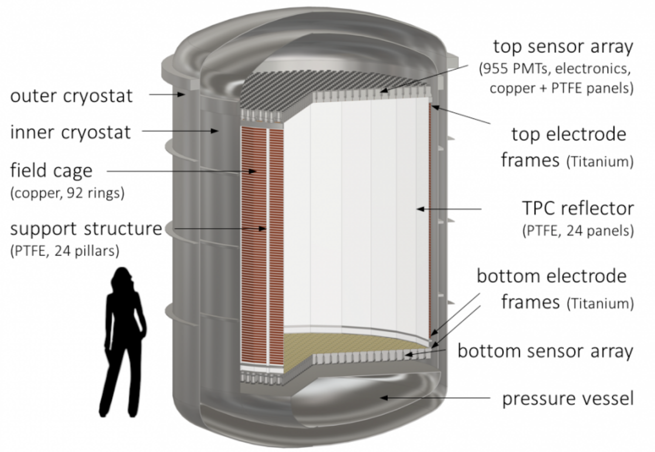
Solar axions

LXe TPC

Coherent neutrino-nucleus scattering

Neutrino magnetic moment

DARWIN: the ultimate WIMP detector



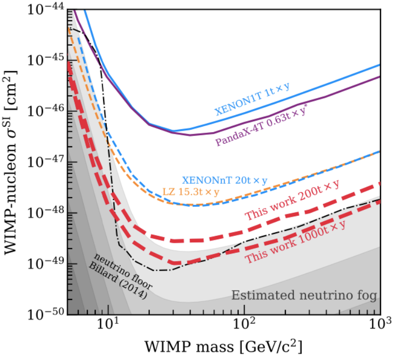
http://darwin-observatory.org/

- Baseline design for a large liquid xenon dark matter detector
- TPC of about 2.6 m ⌀ & 2.6 m drift length
- 50 t LXe total mass (40 t inside the TPC)

XLZD consortium

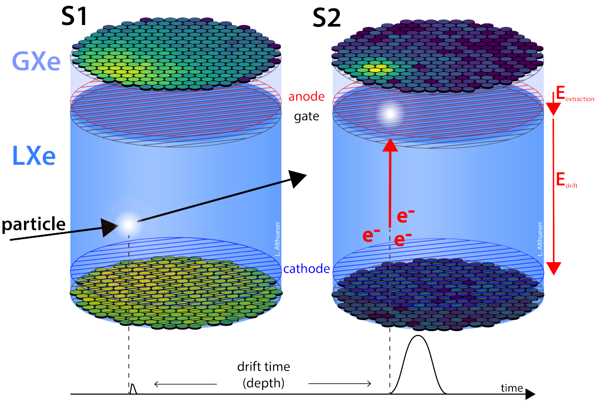
XENON, LUX ZEPLIN & DARWIN meeting in Karlsruhe, July 2022

XLZD consortium (xlzd.org)
to design and build a common multi-ton xenon experiment



J.Phys.G 50 (2023) 013001 & arXiv:2203.02309

Current LXe TPCs measure ...



- S1 - UV light
- S2 - Charge signal

Question: are we using all information available?

Answer: No, in the scintillation process also infrared photons are emitted!

Research question: can this signal be used in our detectors?

Infrared scintillation of xenon

In the xenon scintillation process, infrared photons are emitted

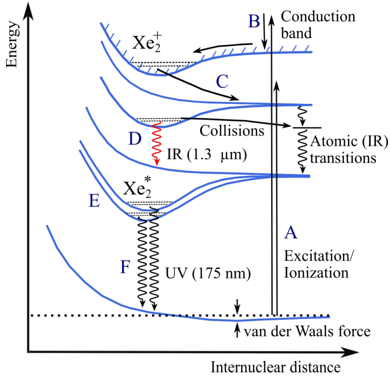
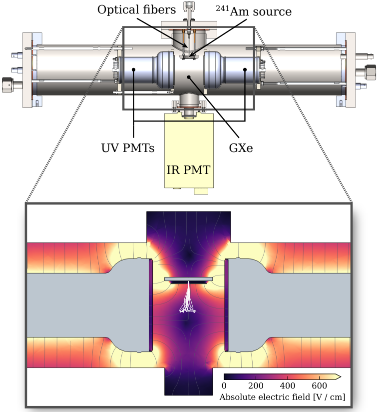


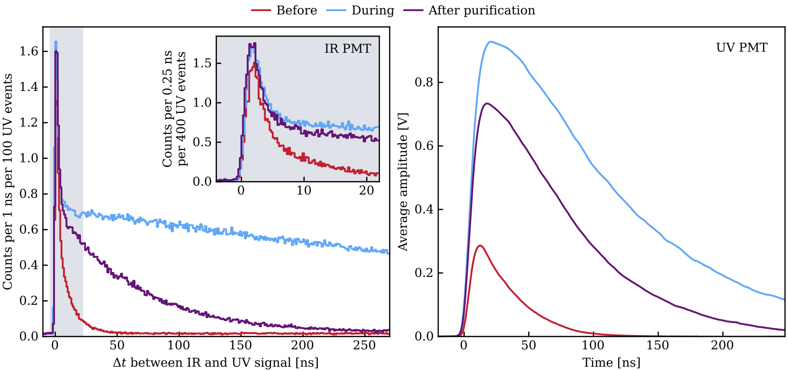
Figure inspired by Borghesani et al. 2001



Our first setup with gaseous xenon

- 2 PMTs sensitive to UV light
- A new IR-sensitive PMT
- UV and IR simultaneously
- ^{241}Am alpha source

Promising first results



- Two main components identified in the IR-photon distribution
- Clear dependence of the signal with impurities
- Signal in the same order of magnitude as the UV scintillation!!

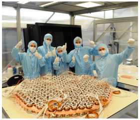
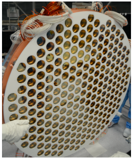
More details, see Eur. Phys. J. C 83 (2023) 482, arXiv:2303.09344 & JINST 19 (2024) 02, C02080, arXiv:2401.09262

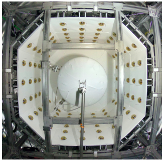
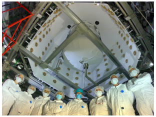
→ upcoming: measurements in higher pressure & liquid xenon

Summary

- XENONnT: lowest background rate to date
  → First results on WIMP + ER searches released
- NEW results coming soon!
- XENONnT is continuously taking science data
  → Dark matter, solar neutrinos, CEνNS ... analysis ongoing!

XLZD: a dark matter, neutrino and rare event observatory

Cross sections for WIMP elastic scattering

- Spin-independent interactions: coupling to nuclear mass

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

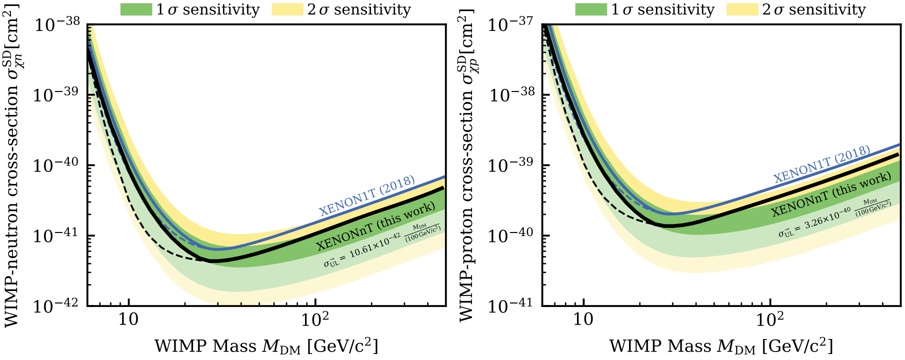
  $f_{p,n}$: effective couplings to p and n.

- 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.

WIMP spin-dependent result

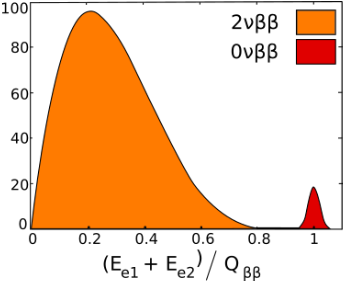


XENONnT, arXiv:2303.14729

Reinterpreting results as a purely spin-dependent coupling to ^{129}Xe and ^{131}Xe

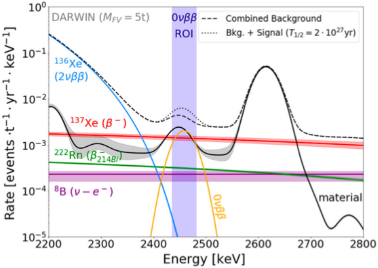
Neutrinoless double beta decay

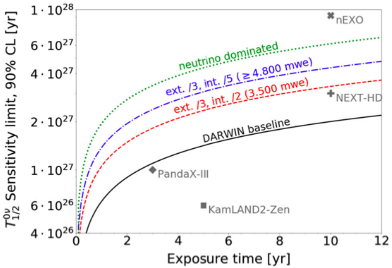
Test of lepton flavour conservation



- ^{136}Xe is a $0\nu\beta\beta$ candidate with 8.9% natural abundance
- Without isotopic enrichment: ~ 3.5 t of ^{136}Xe in DARWIN
- Peak at $Q_{\beta\beta}(^{136}\text{Xe})$ = 2.458 MeV ~ 1 % energy resolution achievable

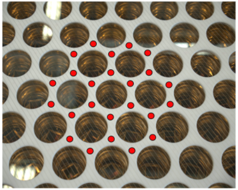
XENON1T, Eur. Phys. J.C 80 (2020) 8, 785

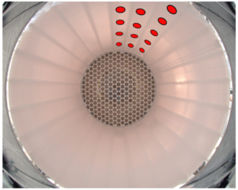


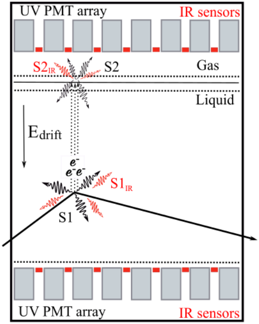


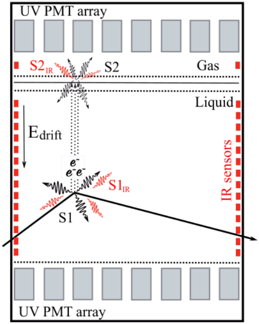
DARWIN, Eur. Phys. J. C 80 (2020) 9, 808

How could a detector with IR readout look like?









- If IR in the liquid is large enough:
  use $S1_{IR}$ for discrimination?
- If IR in the liquid too small:
  use $S2_{IR}$ in the gas to improve S1 and single electron S2 separation?

- IR readout in addition to UV readout
- In between PMTs?
- If photo-diodes can be used: place along the teflon wall?