Neutrinos

with the XENON dark matter experiment

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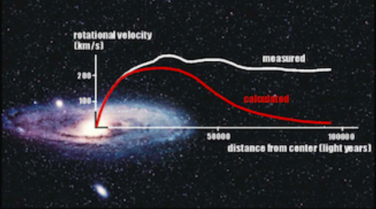
03/2025

Figure from the Illustris Simulation

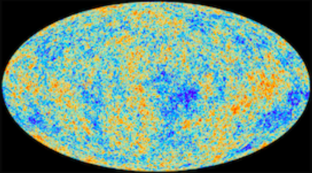


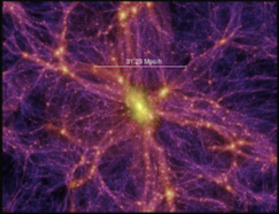
What is dark matter?

Massive objects (primordial black holes)

Modified gravitational theories

New particles (WIMPs, axions ...)





How can we look for dark matter?

Production at LHC

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

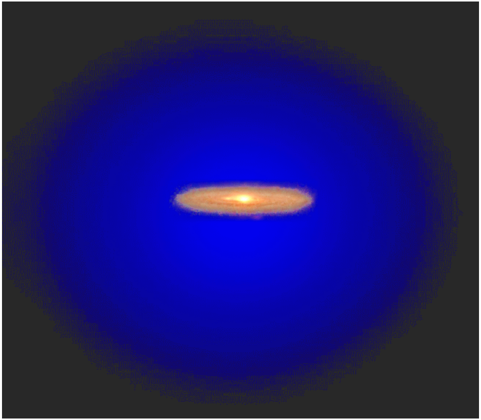
Direct detection

$\chi\, N \rightarrow \chi\, N$

Indirect detection

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

Dark matter in our galaxy



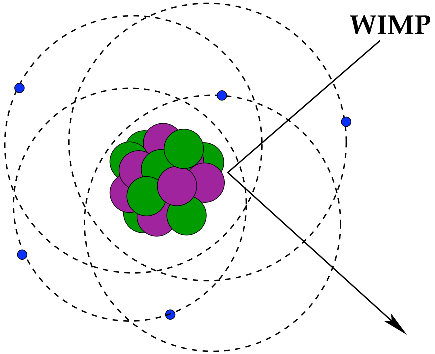
Dark matter halo from the Bolshoi simulation

- The Milky way is in a 'cloud' of dark matter
- Density: 0,3 GeV/cm^3 (1/3 Proton/cm^3)

  For a 100 GeV WIMP mass: 1 WIMP particle per coffee cup

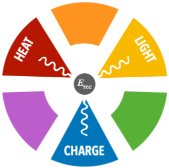
$$\frac{dR}{dE}(E,t) = \frac{\rho_0}{m_\chi \cdot m_A} \cdot \int v \cdot f(\mathbf{v},t) \cdot \frac{d\sigma}{dE}(E,v)\, \mathrm{d}^3 v$$

How can we detect dark matter directly?



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

- Elastic scattering of WIMPs off target nuclei
- The nuclear recoil excites the medium
  $\rightarrow$ heat, scintillation and/or ionization



Technologies for direct detection

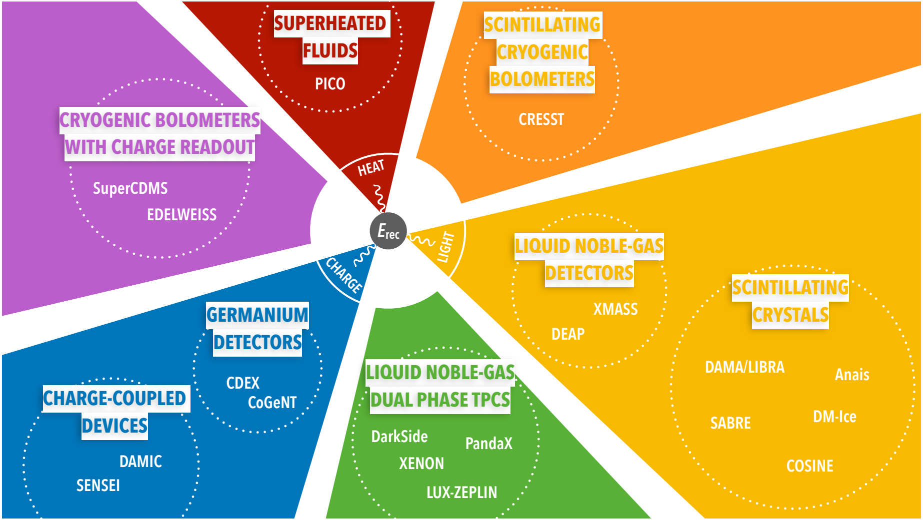
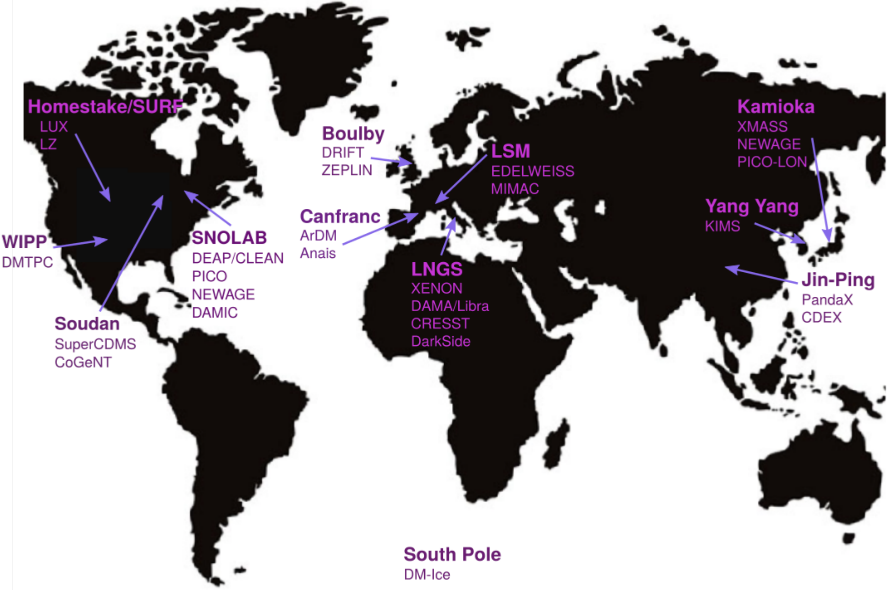


Figure from R. Hammann

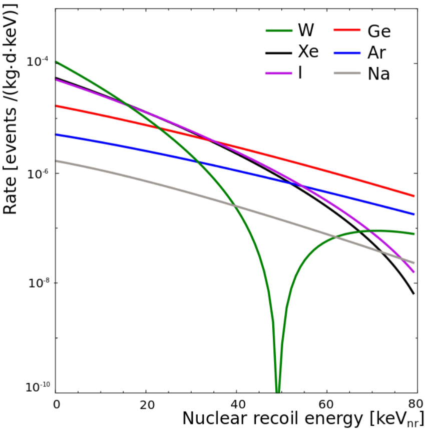
The worldwide search for dark matter



Detector requirements

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

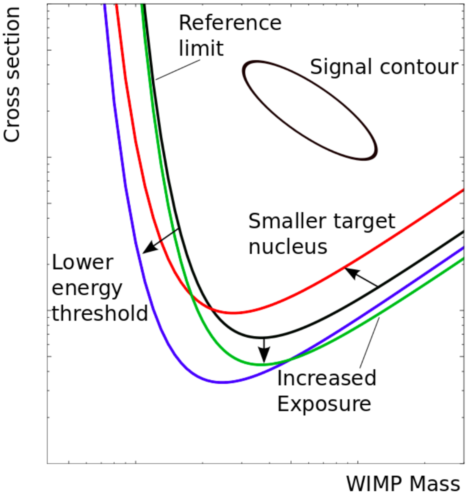
J. Phys. G: 43 (2016) 1, & arXiv:1509.08767



Result of a direct detection experiment

→ Statistical significance of signal over expected background?

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



- Positive signal
  - Region in σ_χ versus m_χ
- Zero signal
  - Exclusion of a parameter region

o Low WIMP masses: detector threshold matters

o Minimum of the curve: depends on target nuclei

o High WIMP masses: exposure matters $\epsilon = m \times t$

Overview of WIMP search results

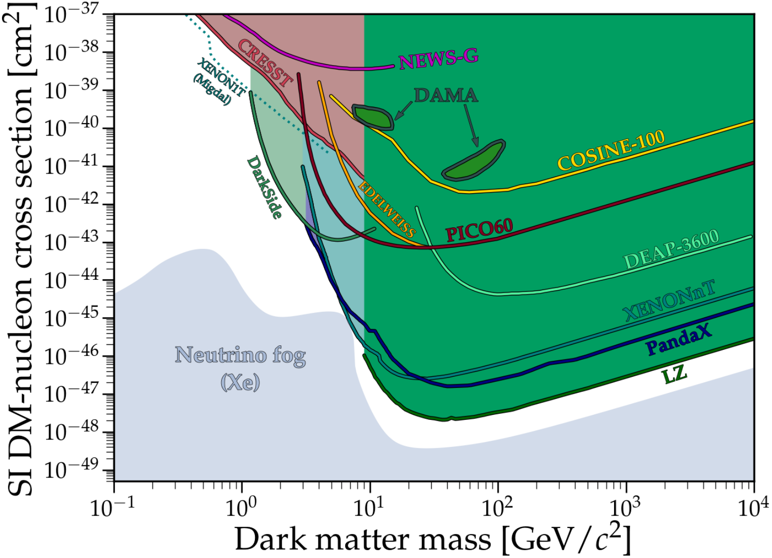
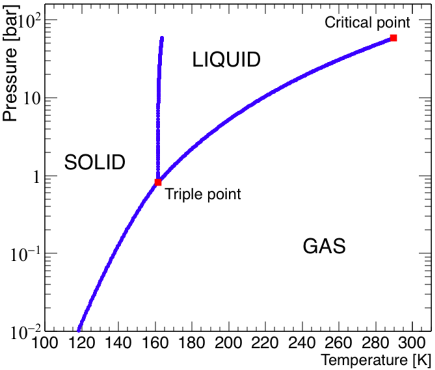
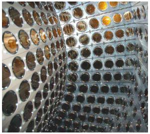


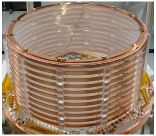
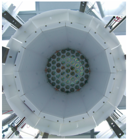
Figure from Ciaran O'Hare (2024)

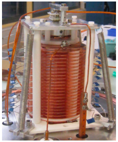
Liquid xenon as detector



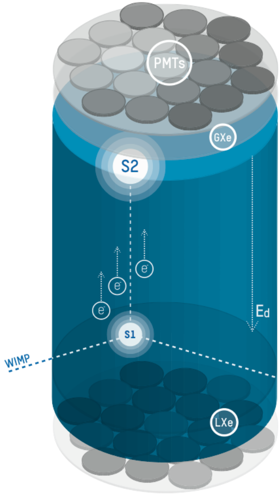
- Cryogenic liquid typically operated at 2 bar and −100°C
- High density: 3 g/cm^3
- High scintillation and ionization yields
- Scalability
- Employed in particle-, neutrino-, dark matter- and medical physics





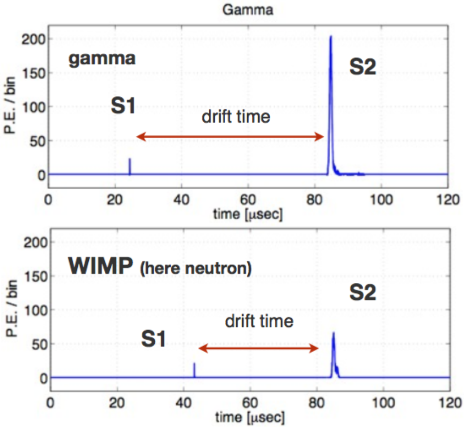
Two phase noble-gas TPC



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



Signal and background regions based on S1 & S2

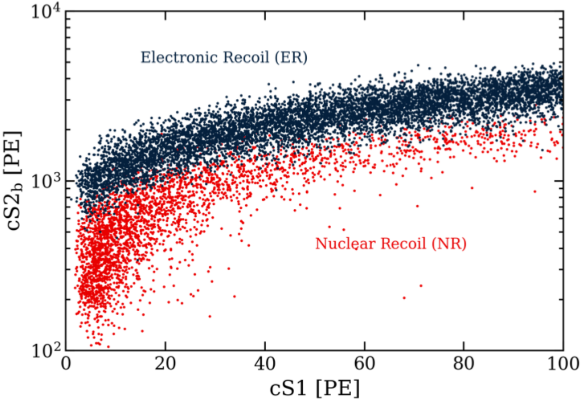
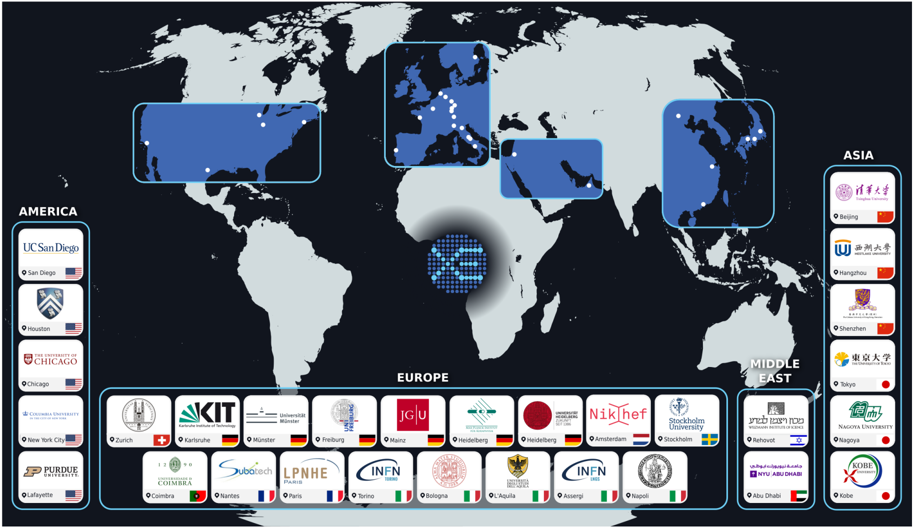


Figure from XENON1T data

- ER: background region
  $\rightarrow$ calibrated using a ^{220}Rn source (β-decays of ^{212}Pb)
- NR: WIMPs and neutrons
  $\rightarrow$ calibrated using a neutron source

THE XENON EXPERIMENT

XENON collaboration

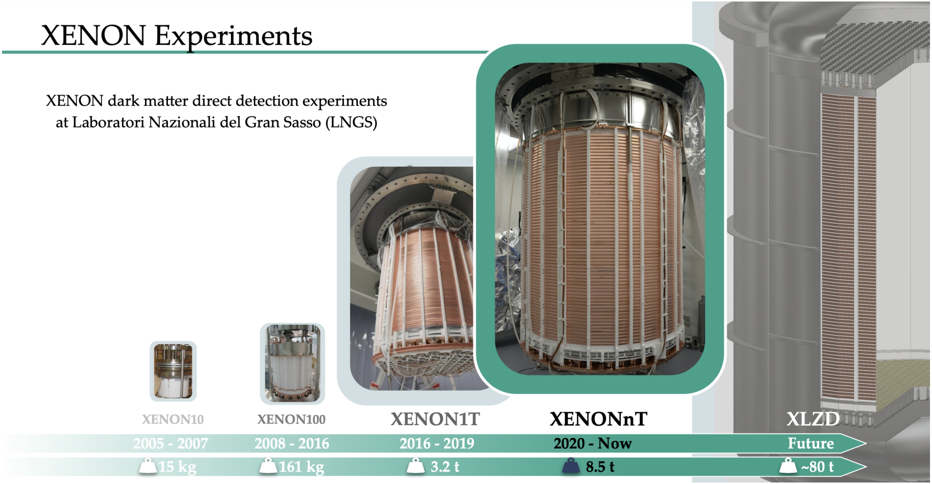


Experiment operated by 30 institutes worldwide

XENON collaboration

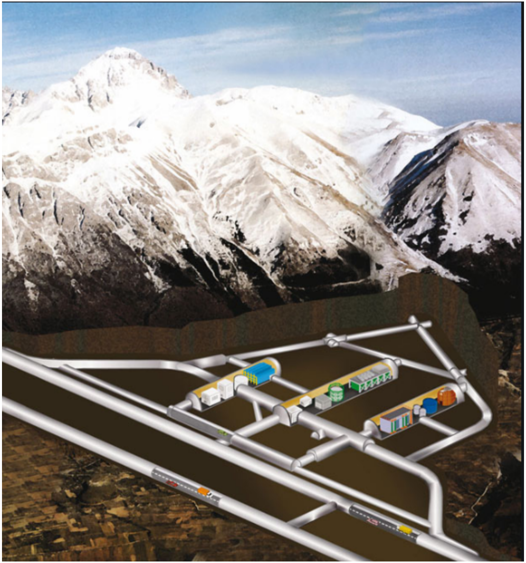
Collaboration meeting – L'Aquila, March 2024

The last 20 years ...



Slide from A. Elykov

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

Backgrounds and reduction strategies

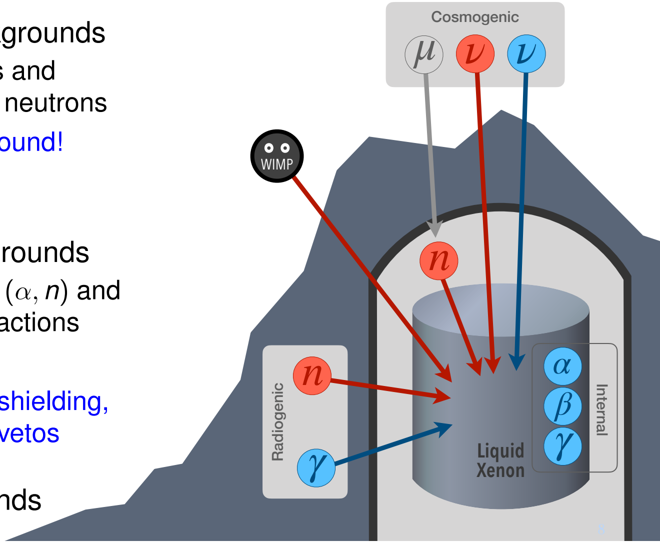
- Cosmogenic backgrounds
  - Cosmic muons and muon-induced neutrons

    $\rightarrow$ Go underground!
  - \+ Neutrinos

- Radiogenic backgrounds
  - Neutrons from (α, n) and from fission reactions
  - External γ's

    $\rightarrow$ Screening, shielding, cleaning & vetos

- Internal backgrounds
  - e.g. Radon



Scheme from R. Hammann

Recent results from XENONnT - SR1

- Total exposure: $3.1\,\mathrm{t} \times \mathrm{y}$
- Fully blinded analysis
- No excess of events over background observed
- Combined SR0 and SR1 result

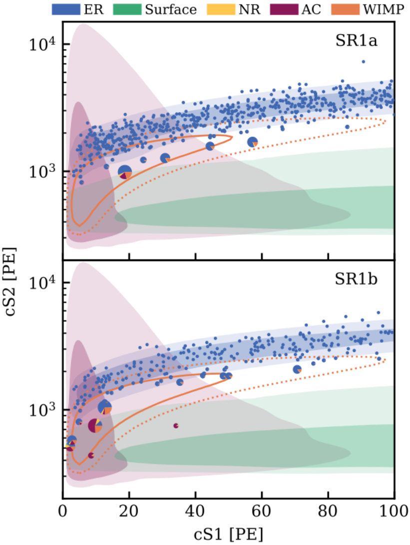


Figure from arXiv:2502.18005 (2025)

Recent results from XENONnT

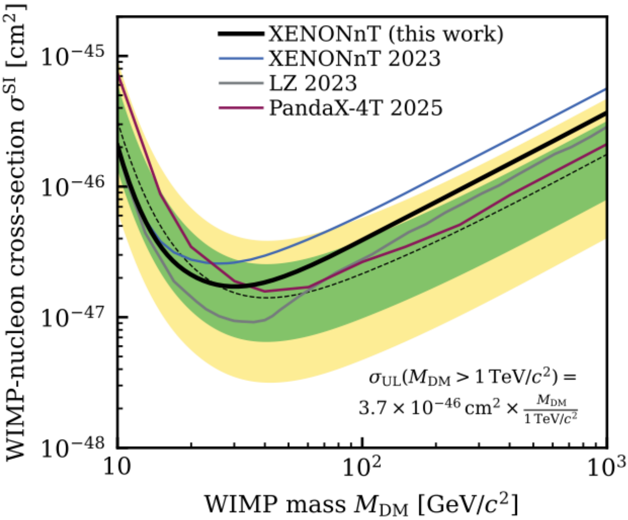
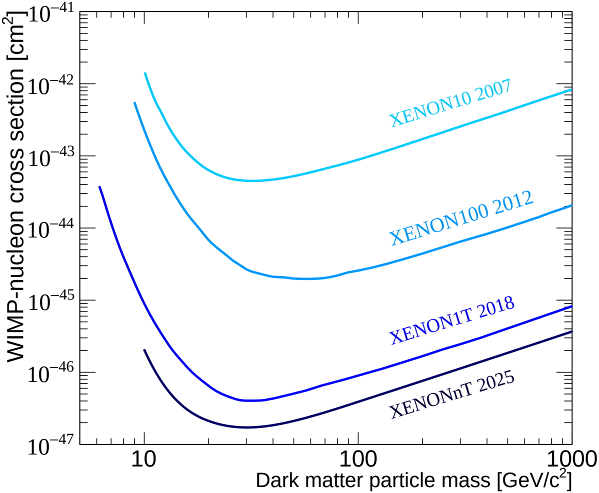


Figure from arXiv:2502.18005 (2025)

Continuously improving the sensitivity to WIMPs



- No evidence of dark matter yet $\rightarrow$ constrains on the WIMP-nucleon σ
- More data from XENONnT is being analyzed

Signal and background regions based on S1 & S2

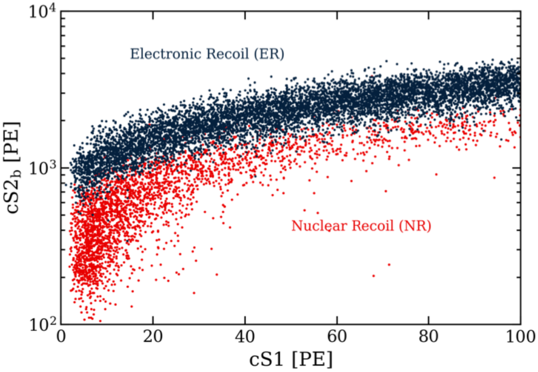
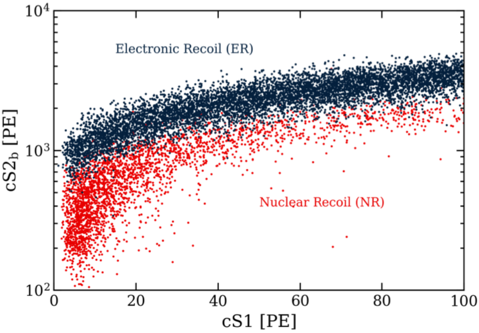


Figure from XENON1T data

- NR: search region for WIMPs
- ER: background dominated region
  $\rightarrow$ Very good knowledge of the background composition
  $\rightarrow$ Allows to search for candidates that interact with e^-s

Selecting cleanest materials



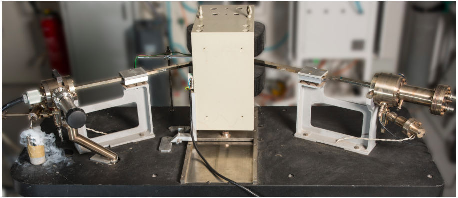
- Majority of the background (blue) from radon

→ Radon is emanated from all detector materials

- Measurement of the radon emanation
  - Automatized apparatus
  - Measurement with ultra-sensitive proportional gas counters

Radon separation infrastructure

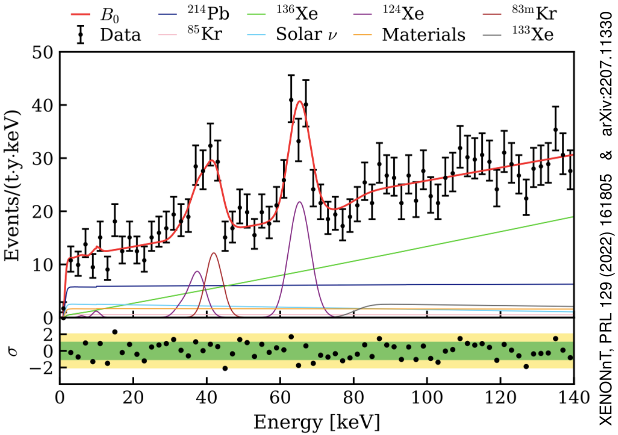
Measuring smallest concentrations



- ^{85}Kr is a background source
- Kr-removal via distillation
- Sensitivity of the device: 6 ppq $^{\mathrm{nat}}$Kr in Xe

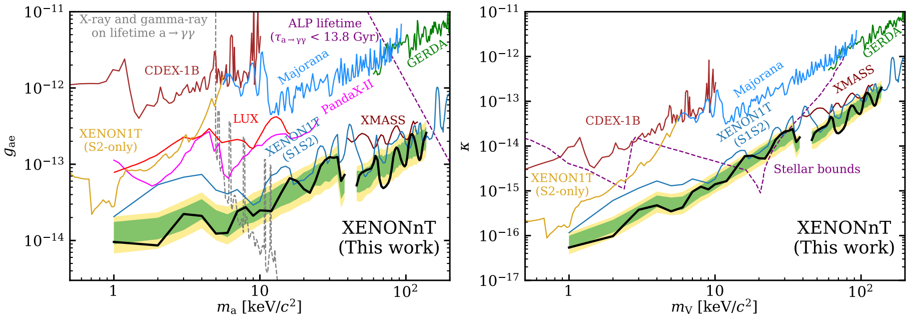
Equivalent to a glass of wine in the Baltic sea

XENONnT electronic-recoil science data



- Spectrum still dominated by ^{214}Pb at low energies
- Data described very nicely by the background model

Constrains on dark matter candidates



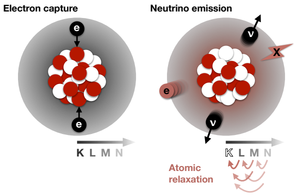
XENONnT, PRL 129 (2022) 161805 & arXiv:2207.11330

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

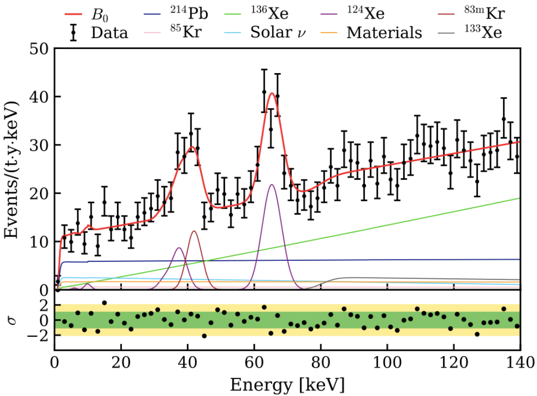
→ No limit around 40 keV due to an unconstrained ^{83m}Kr background

Limits and limits .... Only limits?

The longest half-life ever measured directly



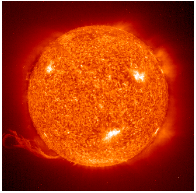
Simultaneous capture of two electrons & two neutrinos emitted



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

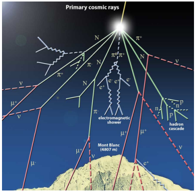
- Above 40 keV, 2nd order weak processes dominate:
  - Double electron capture 2νECEC of ^{124}Xe ($t_{1/2} = 1.18 \times 10^{22}$ y) $\rightarrow$ the longest half-life ever measured directly
  - Double beta decay $2\nu\beta\beta$ of ^{136}Xe ($t_{1/2} = 2.23 \times 10^{21}$ y)

Neutrinos appearing in the horizon ...



Neutrinos
from the Sun

Neutrinos
from Supernova

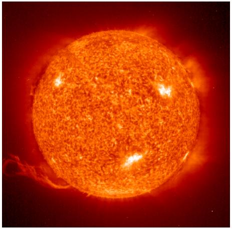


Neutrinos from
the atmosphere

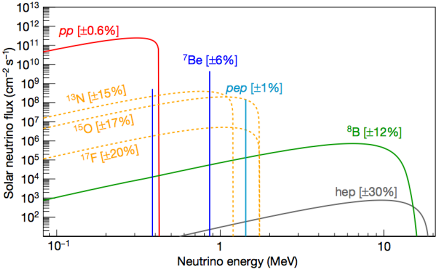
Neutrino physics
without neutrinos*

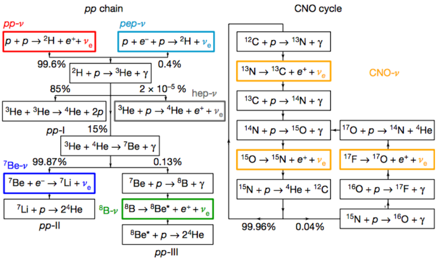
* Neutrinoless double beta decay

Solar neutrinos



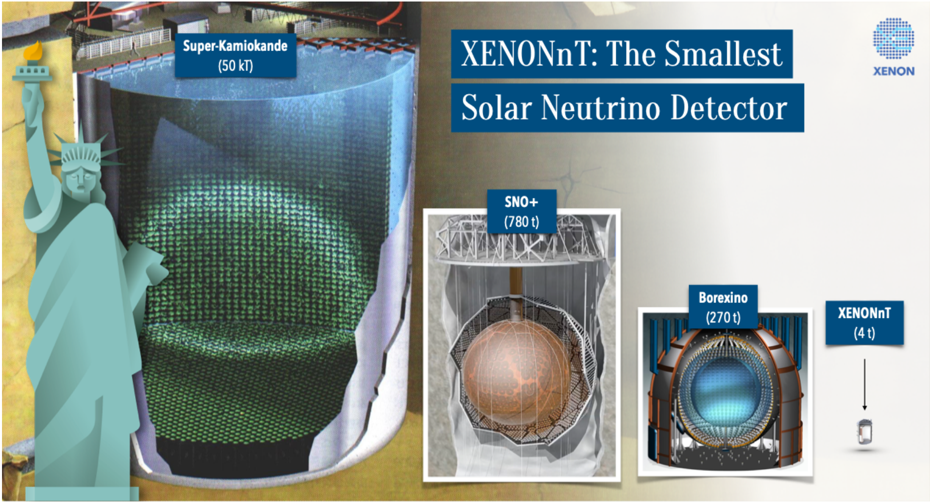
- pp - and ^{7}Be-ν's make 98% of solar neutrino flux
- Borexino has measured pp -flux with 9.5% precision
- ^{7}Be, pep and ^{8}B measured by Borexino
  - ν-electron elastic scattering $\nu + e^{-} \rightarrow \nu + e^{-}$
  - Usually, the recoiling e^{-} is recorded





Borexino Collaboration, Nature 562 (2018) 505

Low ν cross-section $\rightarrow$ huge detectors!



Scheme from R. Hammann

How is a search possible in the 'tiny' XENONnT?

- Coherent Elastic ν-Nucleus Scattering $\rightarrow$ CEνNS process
  - Nuclear recoil of ^{8}B-ν's $\rightarrow$ like the WIMP
  - Coherent $\rightarrow$ much higher cross section!

+ Lowering the energy threshold of the detector

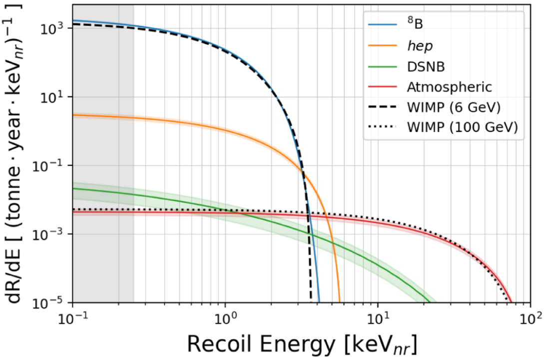
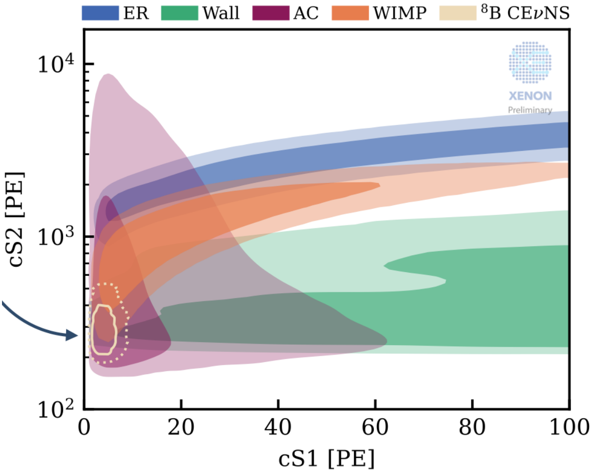


Figure from Xiang et al., Phys. Rev. D 108 (2023) 022007

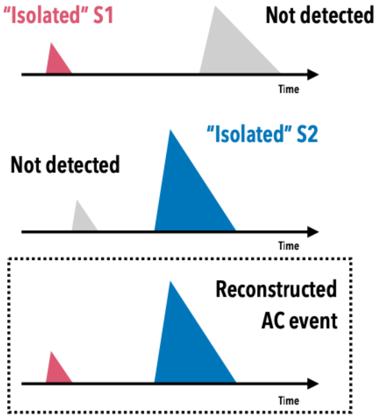
CEνNS from solar neutrinos in the XENON data



Scheme of signal and background regions in XENONnT (see XENONnT, arXiv:2408.02877)

Lower threshold → more accidental coincidences

- Required 2 hits in the PMTs (instead of 3)
- Modelling of accidental coincidences mandatory



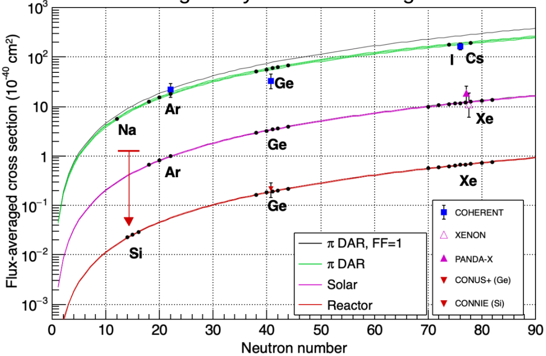
- Isolated S1 from a regions with no field
- Isolated S2s from artefacts in the detector

→ Combined randomly and fulfilling randomly other selection criteria

Measurement of ^{8}B neutrinos over CEνNS

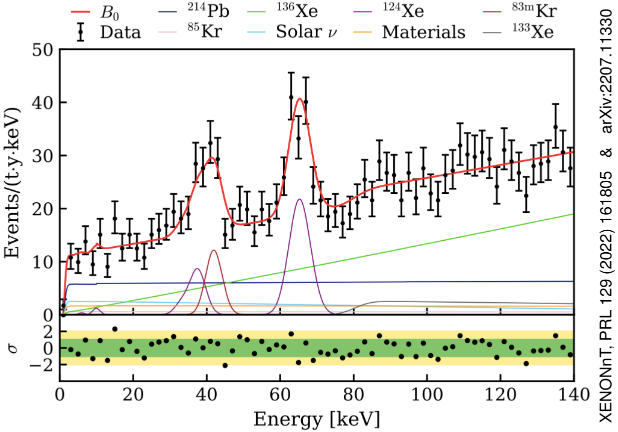
- Expected bg: 26, expected signal: 12 $\rightarrow$ Observed: 37 events
- First measurement (2.7 σ) of CEνNS in xenon
- First measurement of ^{8}B solar neutrinos in CEνNS

Figure by Kate Scholberg



$\rightarrow$ Start of a new era: DM detectors as multipurpose observatories

Solar pp-neutrinos

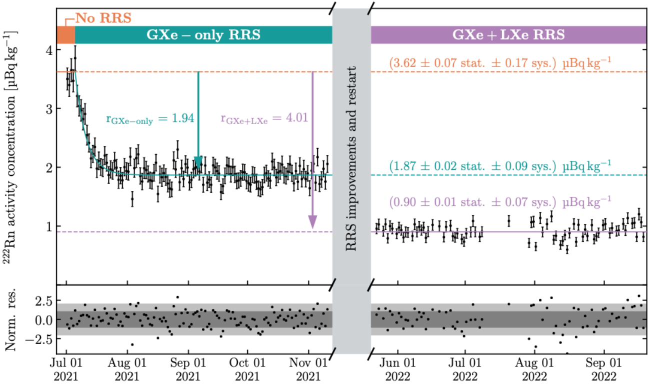


Solar neutrinos are about a factor of 2 below the ^{241}Pb background

$\rightarrow$ Radon reduction necessary to measure them

$+$ Good constrains on the Rn and Kr rates

Lowering the radon level in XENONnT

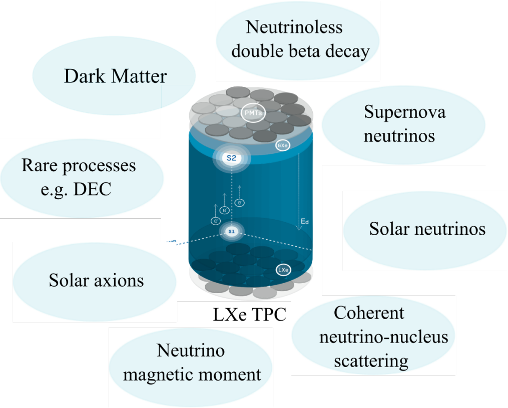


XENONnT, arXiv:2502.04209

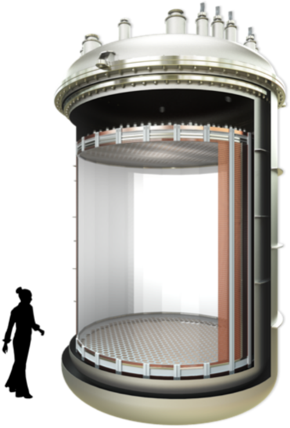
Radon distillation in gaseous and liquid mode in SR1

→ Factor 2 further reduction achieved!

Multi-physics goals in large liquid xenon detectors



XLZD
(XENON-LZ-DARWIN)



Multiple additional physics channels enable by a large mass, a low energy threshold and a low background

80 t LXe (60 t in the target)

We keep looking for dark matter,

neutrinos,

and for any interesting physics in our data!

THANK YOU!!