Present and Future of Dark Matter
direct detection with XENONnT

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XENON

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Evidence for the existence of a “dark” component in the energy density of the Universe comes from several independent observations at different scales:

- Rotation Curves
- Clusters of Galaxies
- CMB + LSS
- Type 1A SuperNovae
- Gravitational Lensing

We can infer properties of Dark Matter Particles:

- Interacts with Gravity
- No Electromagnetic interaction
- Long lived
- Cold
- Collisionless
If, and only if Dark Matter particles interact with baryonic matter in some way other than gravitationally we can probe Dark Matter

No Dark Matter candidate in Standard Model!

During last 80 years, a rich zoo of candidates and models has been proposed, the most “famous” one is:

**WIMPs: Weakly Interacting Massive Particle**

- Mass between 10 GeV and a few TeV, and with cross sections of approximately weak scale
- Their relic density “naturally” has at least the right order of Magnitude “**WIMP Miracle**”

A huge experimental effort has been done during the last 20 years to try to detect them
The XENON Collaboration

- 28 Institutions Worldwide
- More than 170 Scientists

Main goal:
Detection of dark matter particles with a liquid xenon TPC
The TPC Detection Principle

- Dual-phase (liquid+gas)
- Energy reconstruction
- 3D event reconstruction
- Fiducialization
- Event discrimination (electronic recoil vs nuclear recoil)

\[ E = W \left( \frac{S_1}{g_1} + \frac{S_2}{g_2} \right) \]
XENON1T

- Cylindric TPC (h=97 cm, d=96 cm)
- Mass: 3.2 t LXe @180 K
- Active Target 2.0 t
- Drift Field ~ 100 V/cm
- 278.8 days of DM data taking
- X-Y reconstruction via neural network
- Position resolution (1-2 cm)
- Best energy resolution ever in LXeTPC ~1.6% at 2.5 MeV and 6% at 40 keV

The largest exposure reported so far with this type of detector

ER Background rate: \((82^{+5}_{-3}\) (syst)\(\pm 2\) (stat)) events / t\cdot year\cdot keV (1300 kg FV and E< 25 keVee)

Lowest ER background ever achieved in a Dark Matter detector
Fruitful Experiment

- Phys. Rev. Lett. 119, 181301 (2017) - First Dark Matter Search Results from the XENON1T Experiment
- **Phys. Rev. Lett. 121, 111302 (2018)** - Dark Matter Search Results from a One Tonne×Year Exposure of XENON1T
- Phys. Rev. Lett. 122, 071301 (2019) - First results on the scalar WIMP-pion coupling, using the XENON1T experiment
- Phys. Rev. Lett. 122, 141301 (2019) - Constraining the Spin-Dependent WIMP-Nucleon Cross Sections with XENON1T
- *Nature 568, 532 (2019)* - First observation of two-neutrino double electron capture in $^{124}$Xe with XENON1T
- Phys. Rev. Lett. 123, 241803 (2019) - Search for Light Dark Matter Interactions Enhanced by the Migdal effect or Bremsstrahlung in XENON1T
- **Phys. Rev. D 102, 072004 (2020)** - Excess Electronic Recoil Events in XENON1T
- Phys. Rev. D 103, 063028 (2021) - Search for inelastic scattering of WIMP dark matter in XENON1T
- Phys. Rev. Lett. 126, 091301 (2021) - Search for coherent elastic scattering of solar $^8$B neutrinos in the XENON1T dark matter experiment
Results interpreted with **un-binned profile likelihood** analysis in $cs_1$, $cs_2$, $R$, $z$ space.

Pie chart indicate the **relative PDF** from the best fit of 200 GeV/$c^2$ WIMPs with a cross-section of $4.4 \times 10^{-47}$ cm$^2$

7 times more sensitive w.r.t previous experiments

Most stringent Upper Limit on WIMP-nucleon cross section:

\[ 4.1 \times 10^{-47} \text{ cm}^2 \text{ @ } 30 \text{ GeV/c}^2 \text{ (90% CL)} \]
Extended DM search with ionization-only Channel (S2) and Migdal Effect

Mitigation of backgrounds with strong event selections, rather than requiring a scintillation signal

**World Leading Constraints on WIMP-NUCLEON Cross Section**

For WIMP masses in the range $[0.1, 2) - (3, 1000]$ GeV/$c^2$
Double Electron Capture in $^{124}$Xe

Two protons convert into neutrons absorbing two electrons from the atomic (K)Shells and the emitting two $\nu_e$.

The filling of the vacancies results in a detectable cascade of X-rays and Auger electrons ($Q = 64.3$ keV)

Longest half-life ever observed: $1.8 \times 10^{22}$ yr
(4.4$\sigma$ Significance)

The 2vDEC half-life provides an important input for nuclear structure models.
Low-ER excess

ER search in <30 keV range. 285 events are observed whereas 232 ± 15 events are expected from the background-only hypothesis.

Corresponding to a 3.3 σ fluctuation

Could be caused by 37Ar leakage with a rate of 65 ev. / t·year. Air measurement the leak rate is constrained < 5 ev. / t·year

Hypothesis of 37Ar is excluded
Axion vs Tritium

Several hypothesis:

- Solar axions ($3.4\sigma$ over bkg)
- Neutrino magnetic moment ($3.2\sigma$ over bkg)
- Bosonic DM: ALPs, dark photons ($3.0\sigma$ over bkg)
- ....

The excess can also be explained by $\beta$ decays of Tritium at $3.2\sigma$ significance with a corresponding concentration in Xenon of $(6.2 \pm 2.0) \times 10^{-25}$ mol/mol.

Tritium hypothesis can neither be confirmed nor excluded with current knowledge of its production and reduction mechanisms. If an unconstrained $^3\text{H}$ component is considered the significances of the Solar Axion and Neutrino magnetic moment hypotheses are decreased to $2.0\sigma$ and $0.9\sigma$ respectively.

So, this “mystery” remains unsolved, up to now...
## Evolution of Xe-based DM detectors

<table>
<thead>
<tr>
<th></th>
<th>XENON10</th>
<th>XENON100</th>
<th>XENON1T</th>
<th>XENONnT</th>
<th>DARWIN</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dimensions</td>
<td>15 x 20 cm</td>
<td>30 x 30 cm</td>
<td>1 x 1 m</td>
<td>1.5 x 1.3 m</td>
<td>2.6 x 2.6 m</td>
</tr>
<tr>
<td>Active mass</td>
<td>14 kg</td>
<td>62 kg</td>
<td>2 tons</td>
<td>5.9 tons</td>
<td>40 tons</td>
</tr>
<tr>
<td>Sensitivity</td>
<td>$\sim 10^{-43}$ cm$^2$</td>
<td>$\sim 10^{-45}$ cm$^2$</td>
<td>$\sim 10^{-47}$ cm$^2$</td>
<td>$\sim 10^{-48}$ cm$^2$</td>
<td>$\sim 10^{-49}$ cm$^2$</td>
</tr>
</tbody>
</table>
Fast upgrade exploiting the infrastructures from XENON1T

- New Larger TPC active mass 5.9 t liquid Xe (494 PMTs)
- Active Neutron Veto with Gd-doped water (87% efficiency)
- Liquid Xenon purification system (e lifetime>7ms)
- Radon distillation column (expected 1μBq/kg)
- Rn-free purification pump
- Material selection and cleaning
XENONnT Expected Sensitivity

After 20 tons x yr, the expected sensitivity is:

\[1.4 \times 10^{-48} \text{ cm}^2 \ @ \ 50 \text{ GeV/c}^2 \ (90\% \ CL)\]

Detailed investigation on the low-energy ER excess observed in XENON1T

Preliminary study suggest that after few months of XENONnT data the solar axion signal hypothesis could be differentiated from \(^3\text{H background}\) at the 5\(\sigma\) level
Latest News from LNGS

Finished installation summer 2020 Now under commissioning!

Last updates:

- Installation of the neutron Veto
- Water Tank filled in December
- Currently testing of the sub-system
- Commissioning data

First Science data before the end of the year
DARWIN observatory

- **Time-projection chamber:** 40 active tons of LXe, 2.6 m in diameter and height
- **Ultra-low background Goal:** deep underground, low background cryostat, neutron and muon veto
Physics prospects with DARWIN

- **Multi-purpose rare-event search machine!**
  - Search for the neutrinoless double-beta decay ($^{136}$Xe) with sensitivity of $T_{1/2} \sim 10^{27}$ yr (90% C.L.)
  - **Solar Neutrinos:** precise measurements of pp and $^7$Be fluxes (<1%) through elastic e-ν scattering
  - **Observation of supernova** via CEvNS
  - **New physics prospects:** solar axions, galactic axion-like particles and dark photons

**Direct Dark Matter Search**
- expected sensitivity with 200 ton x yr
  - $2.5 \times 10^{-49}$ cm$^2$ @ 40 GeV/c$^2$
Summary and Outlook

Xenon based Dual Phase Time Projection Chamber has proven to be the leading technology in the field of direct Dark Matter searches.

**XENON1T** made considerable improvements to the field throughout the years, both in dark matter and neutrino physics and technical design for low-background experiments.

**XENONnT** is about to start its physics program, and aims to improve the results of its predecessor and answer to the Low-ER excess question.

Fresh new data from XENONnT are on their way, stay tuned!

Thank You!
BACKUP
Sensitivity on SN neutrinos

- In XENONnT, SN neutrinos mostly interact through CEvNS, a flavour independent channel
- Low-NR, O(1 keV), enhanced by ionization-only channel