Present and Future of Dark Matter direct detection with XENONnT

R. Biondi on behalf of XENON Collaboration

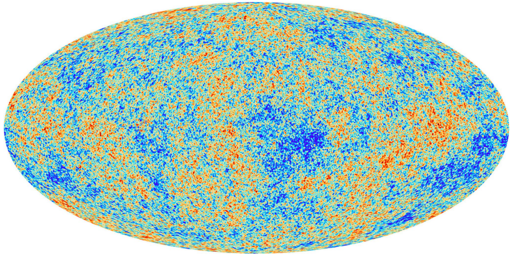
XENON

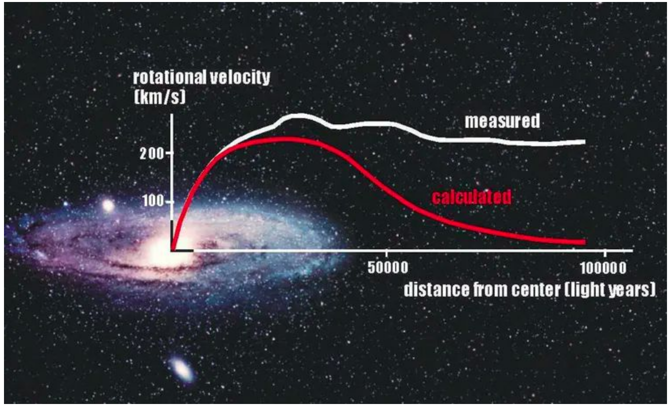
Sixteenth Marcel Grossmann Meeting - 7th July 2021

Dark Matter Problem

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

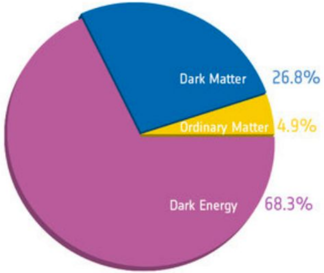
- Rotation Curves
- Clusters of Galaxies
- CMB + LSS
- Type 1A SuperNovae
- Gravitational Lensing





We can infer properties of Dark Matter Particles:

- Interacts with Gravity
- No Electromagnetic interaction
- Long lived
- Cold
- Collisionless



Dark Matter Candidates

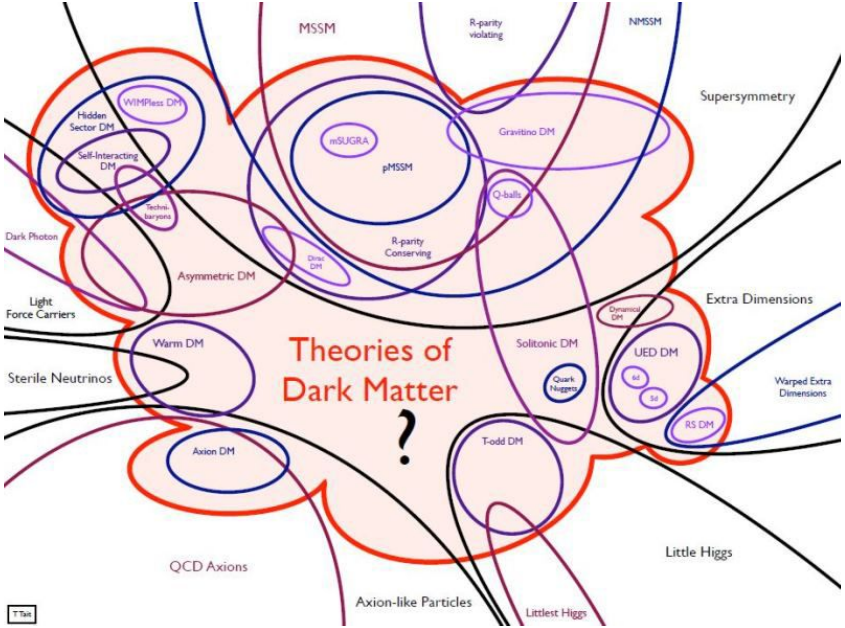
If, and only if Dark Matter particles interact with baryonic matter in some way other than gravitationally we can probe Dark Matter

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

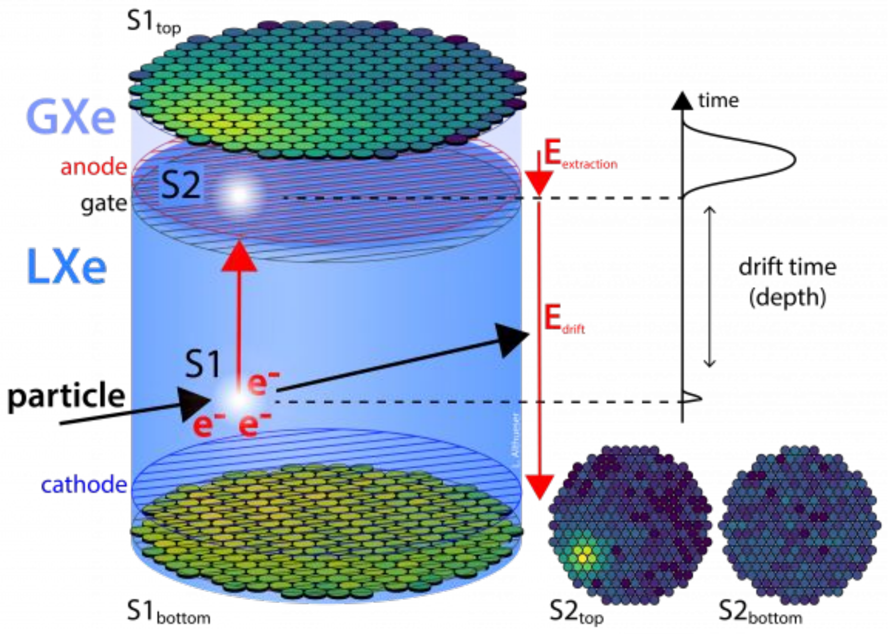
Main goal:

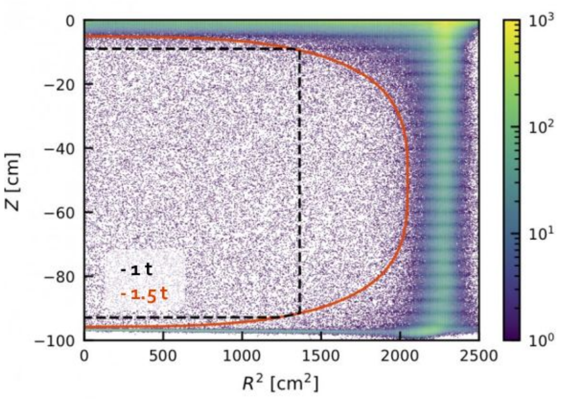
Detection of dark matter particles with a liquid xenon TPC

XENON

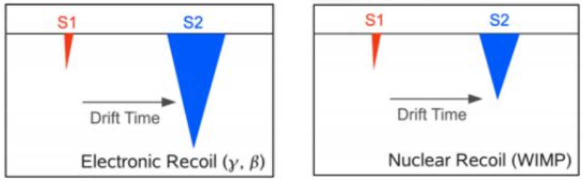
The TPC Detection Principle

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





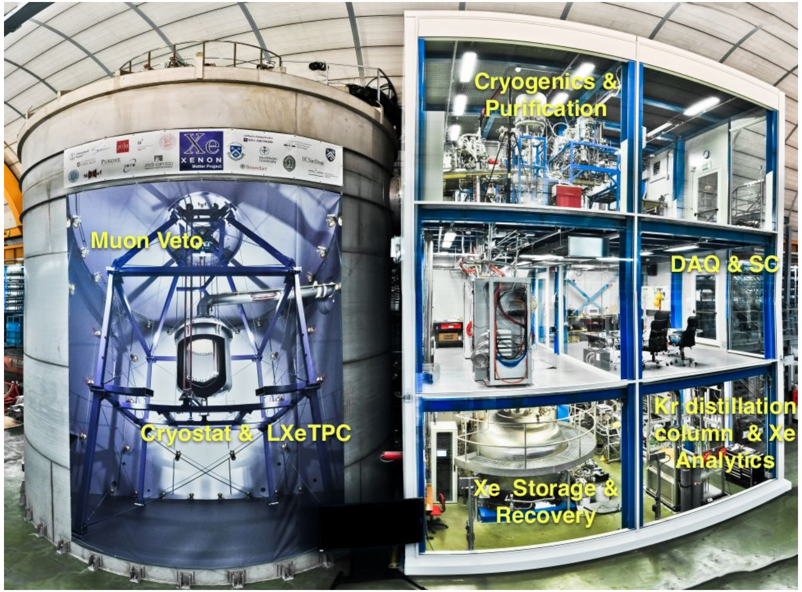
$$E = W\left(\frac{S_1}{g_1} + \frac{S_2}{g_2}\right)$$



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)± 2 (stat)) events / t·year·keV (1300 kg FV and E< 25 keVee)

Lowest ER background ever achieved in a Dark Matter detector

Fruitful Experiment

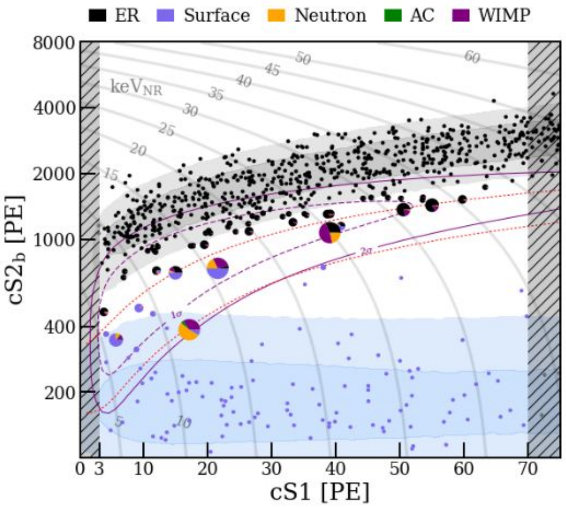
- Phys. Rev. Lett. 119, 181301 (2017) - First Dark Matter Search Results from the XENON1T Experiment
- **Phys. Rev. Lett. 121, 111302 (2018)- Dark Matter Search Results from a One Tonne×Year Exposure of XENON1T**
- Phys. Rev. Lett. 122, 071301 (2019)- First results on the scalar WIMP-pion coupling, using 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, 251801 (2019)- Light Dark Matter Search with Ionization Signals in 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

Dark Matter Results from XENON1T

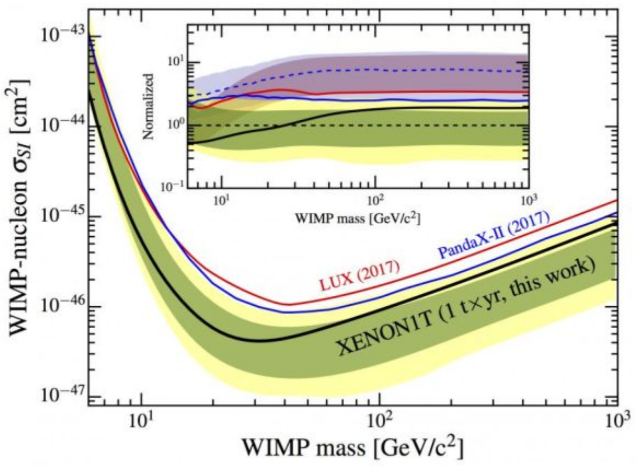
Results interpreted with **un-binned profile likelihood** analysis in cs1, cs2, R, z space.

Pie chart indicate the **relative PDF** from the best fit of 200 GeV/c^2 WIMPs with a cross-section of 4.4x10^{-47} cm^2

7 times more sensitive w.r.t previous experiments



Phys. Rev. Lett. **121**, 111302 (2018)



Most stringent Upper Limit on WIMP-nucleon cross section:

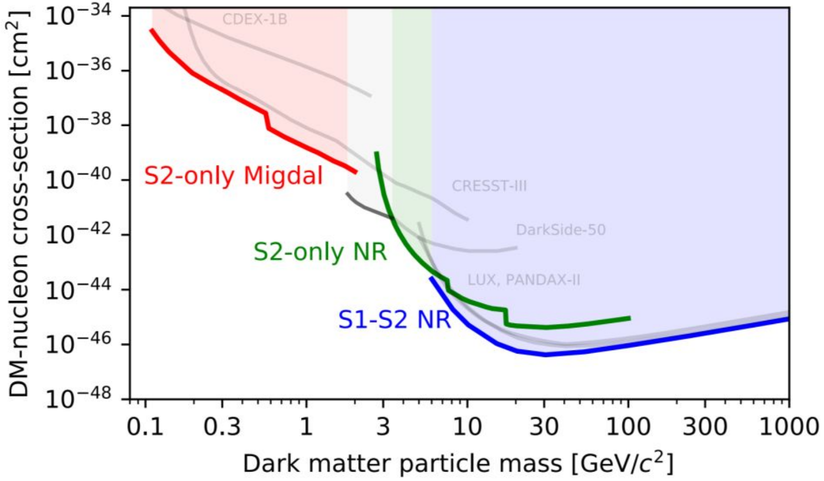
4.1×10^{-47} cm^2 @ 30 GeV/c^2 (90% CL)

Low Mass Dark Matter Mass Search

Extended DM search with **ionization-only** Channel (S2) and Migdal Effect

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

Phys. Rev. Lett. **123**, 251801 (2019)
Phys. Rev. Lett. **123**, 241803 (2019)



World Leading Constraints on WIMP-NUCLEON Cross Section

For WIMP masses in the range [0.1, 2) - (3, 1000] GeV/c^2

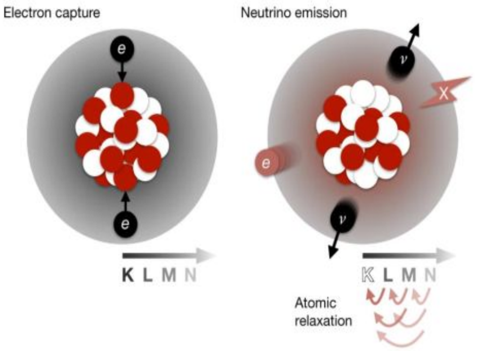
Double Electron Capture in ^{124}Xe

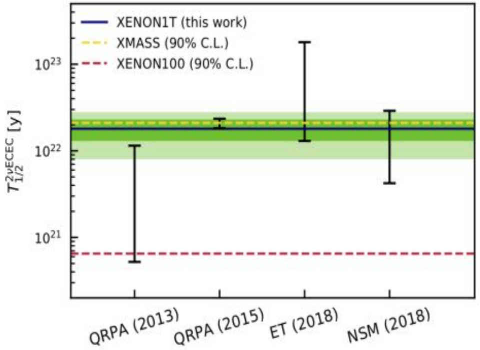
Two protons convert into neutrons absorbing two electrons from the atomic (K)Shells and the emitting two ν_e

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

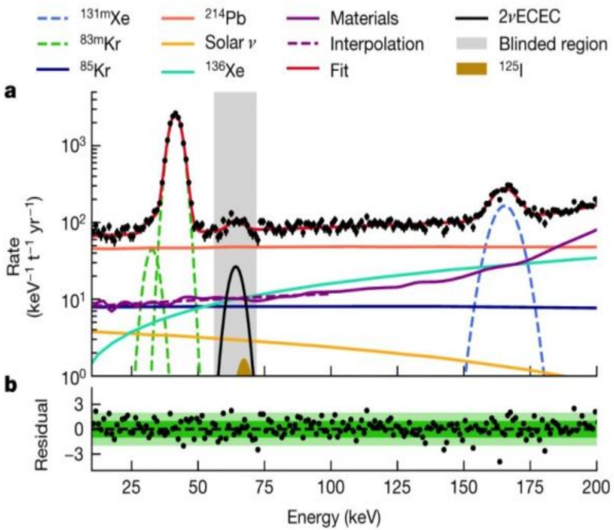
Longest half-life ever observed:
1.8×10^{22} yr
(4.4σ Significance)

The **2vDEC** half-life provides an important input for **nuclear structure models**





Nature volume 568, 532–535(2019)

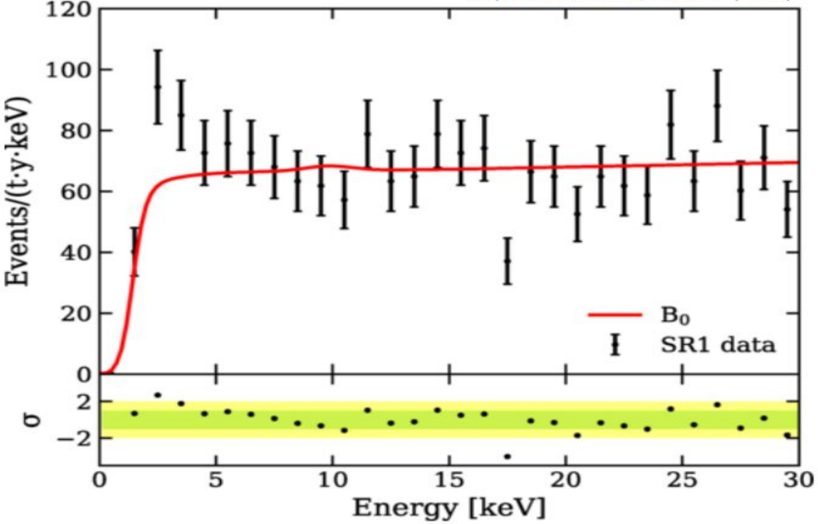


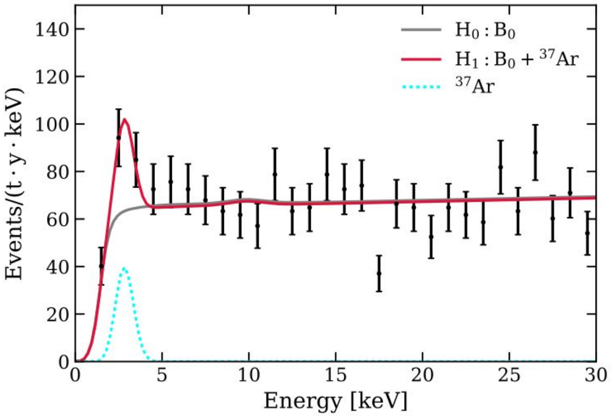
Low-ER excess

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**

Phys. Rev. D **102**, 072004 (2020)





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

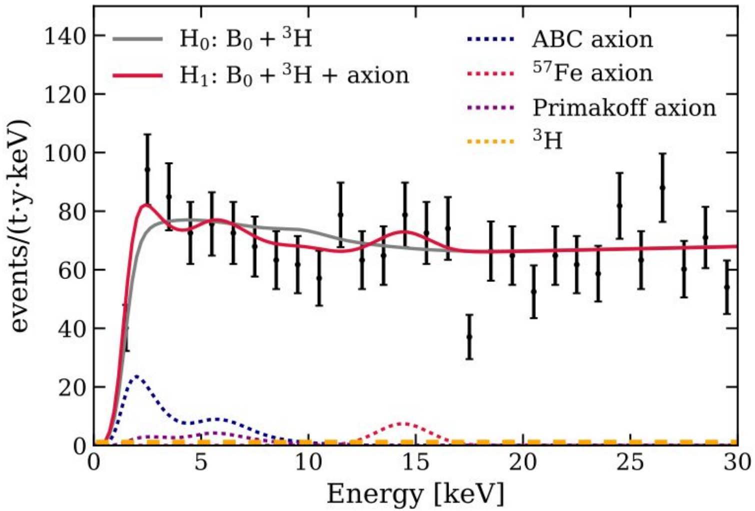
Hypothesis of ^{37}Ar is excluded

Axion vs Tritium

Several hypothesis:

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

The excess can also be explained by β decays of Tritium at 3.2 σ significance with a corresponding concentration in Xenon of (6.2 ± 2.0) × 10^{-25} mol/mol



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

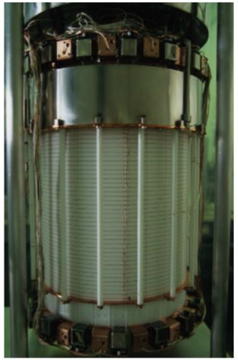
So, this "mystery" remains unsolved, **up to now...**

Evolution of Xe-based DM detectors

Future

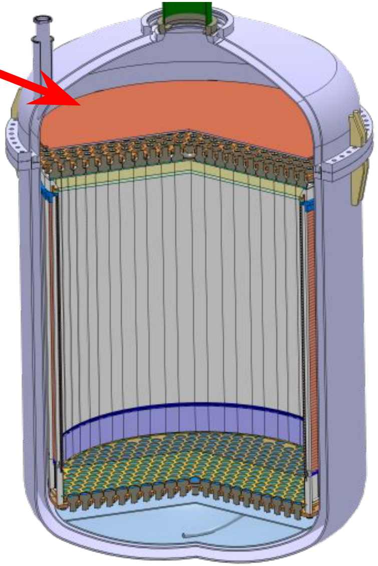
Past

Past



Past

Present
~~Future~~

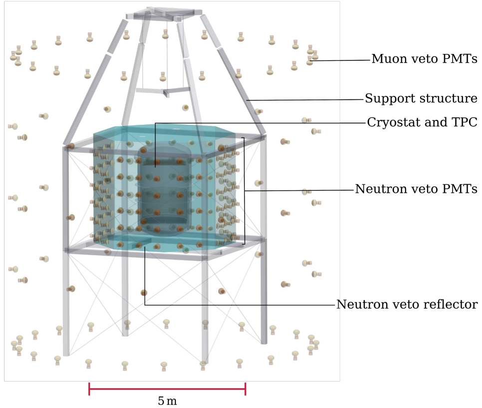


	XENON10	XENON100	XENON1T	XENONnT	DARWIN
Period	2005 - 2007	2008 - 2016	2012 - 2018	**2019 - 2023**	**2025 - ...**
Dimensions	15 x 20 cm	30 x 30 cm	1 x 1 m	**1.5 x 1.3 m**	**2.6 x 2.6 m**
Active mass	14 kg	62 kg	2 tons	**5.9 tons**	**40 tons**
Sensitivity	~10^{-43} cm^2	~10^{-45} cm^2	~10^{-47} cm^2	**~10^{-48} cm^2**	**~10^{-49} cm^2**

XENONnT (The Present / Near Future)

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



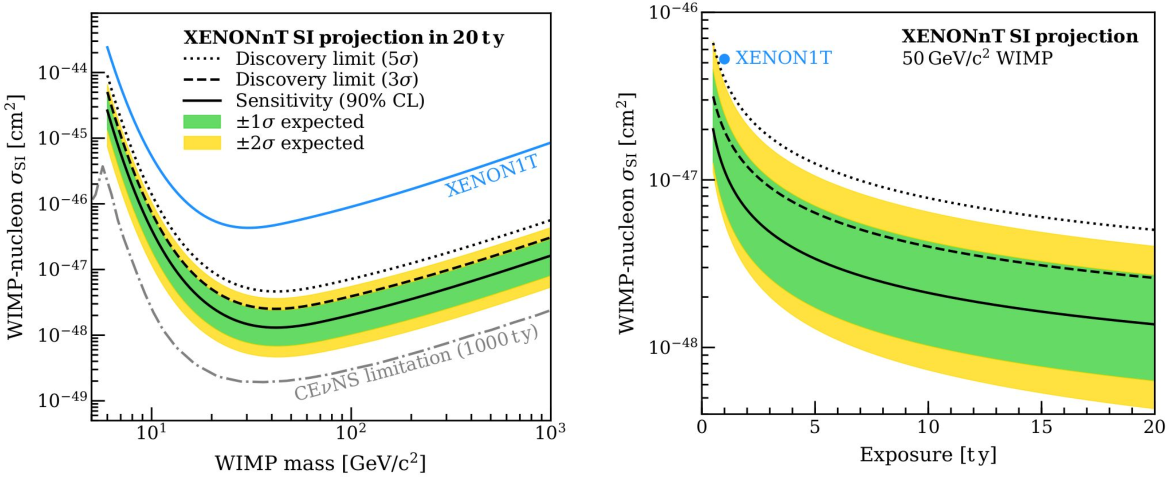
XENONnT Expected Sensitivity

E. Aprile *et al* JCAP11(2020)031

4 tons fiducial volume is considered

After 20 tons x yr,
the expected sensitivity is:

1.4×10^{-48} cm^2 @ 50 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}H background** at the 5σ level

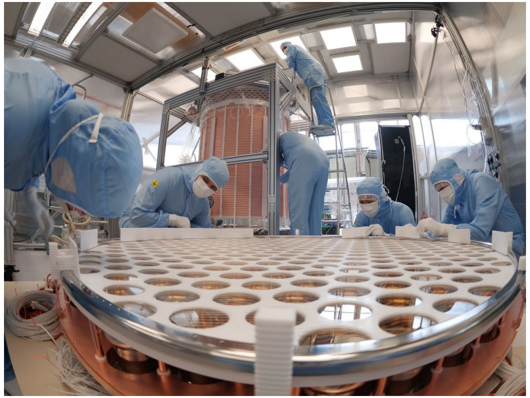
Latest News from LNGS

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

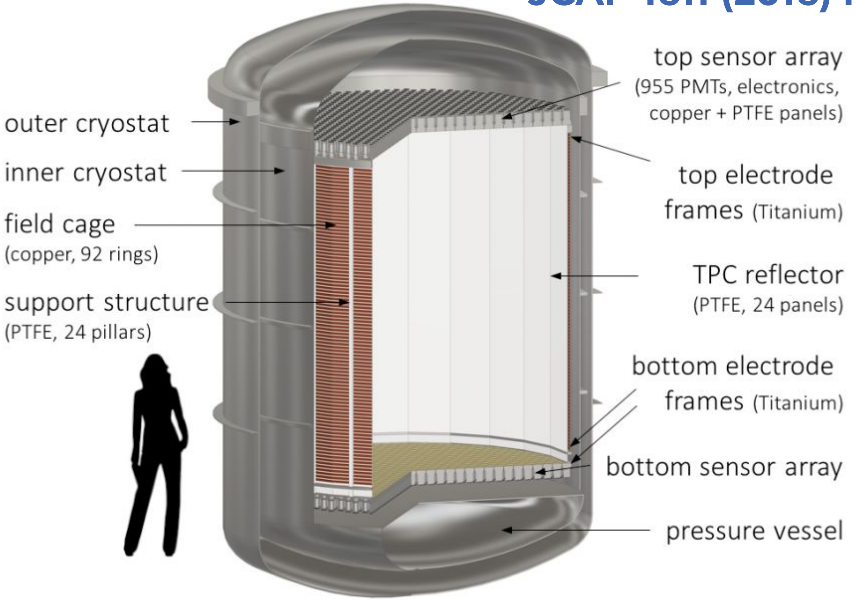
First Science data before the end of the year



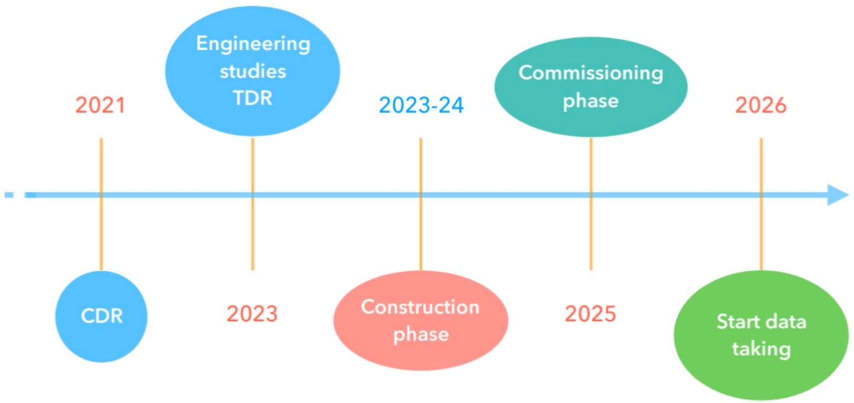
DARWIN observatory

- **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

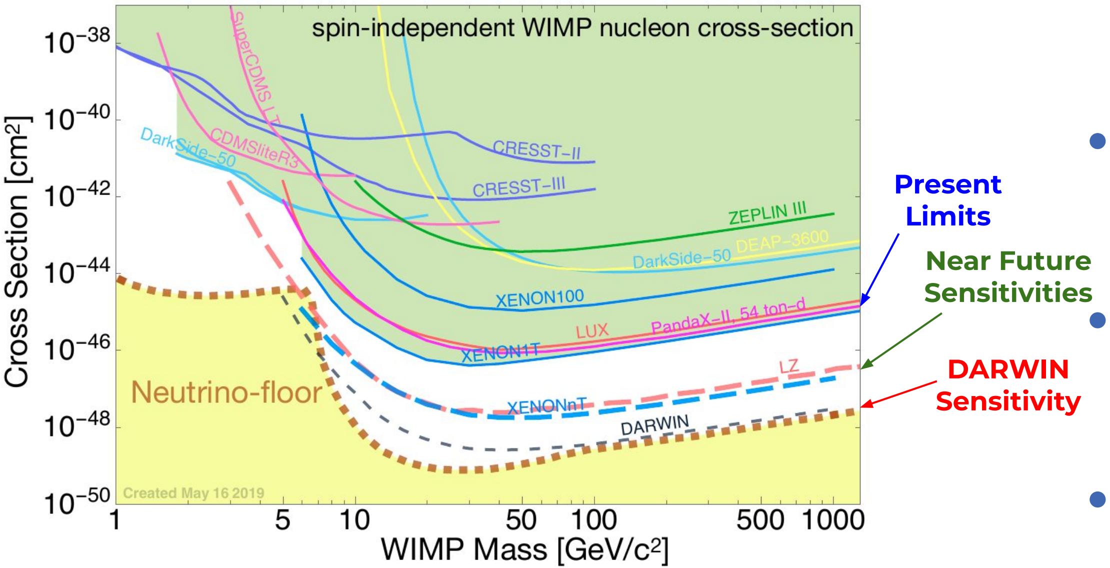
JCAP 1611 (2016) no.11, 017



DARWIN TIMELINE



Physics prospects with DARWIN



Direct Dark Matter Search

expected sensitivity with 200 ton x yr

2.5×10^{-49} cm^2 @ 40 GeV/c^2

Multi-purpose rare-event search machine!

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

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.

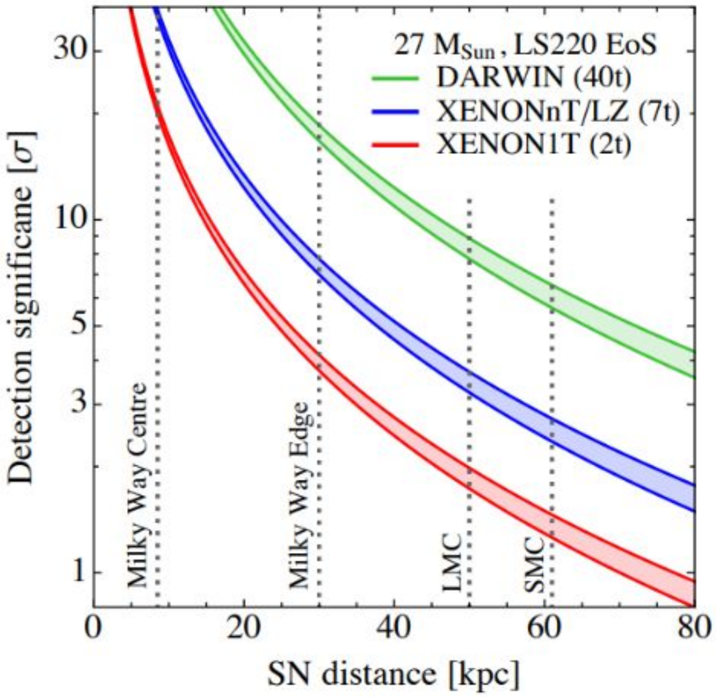
Fresh new data from XENONnT are on their way, stay tuned!

Thank You!

BACKUP

Sensitivity on SN neutrinos

Phys. Rev. D 94, 103009 (2016)



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