Search for Dark Matter with XENON and DARWIN

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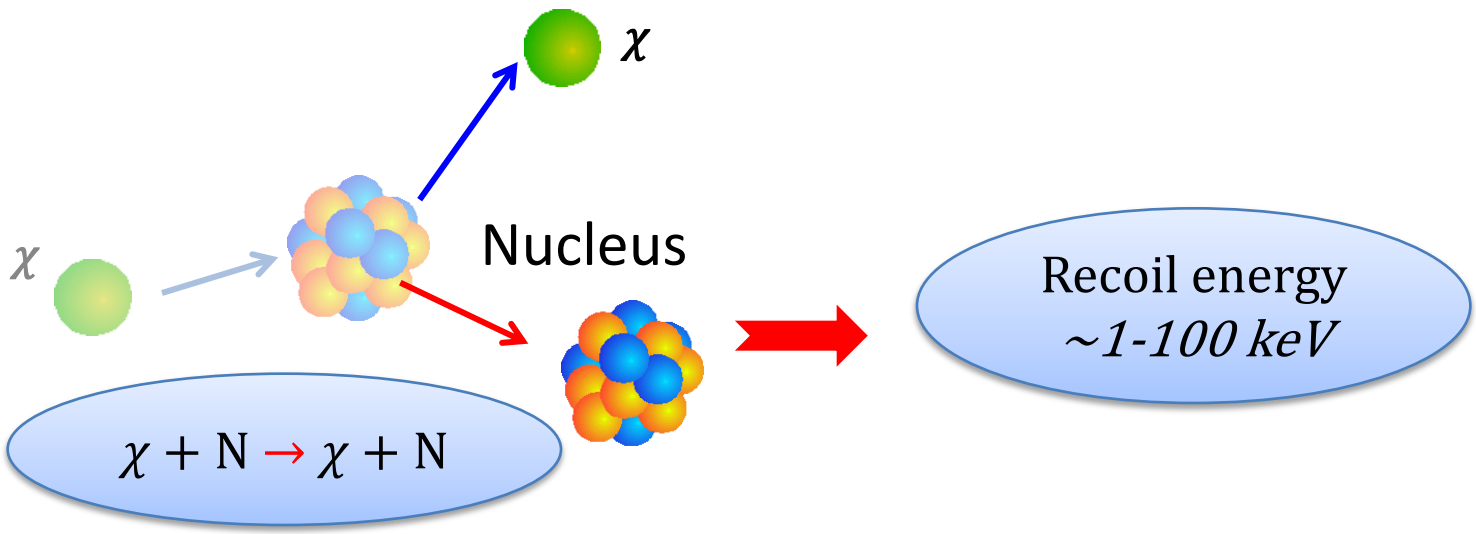
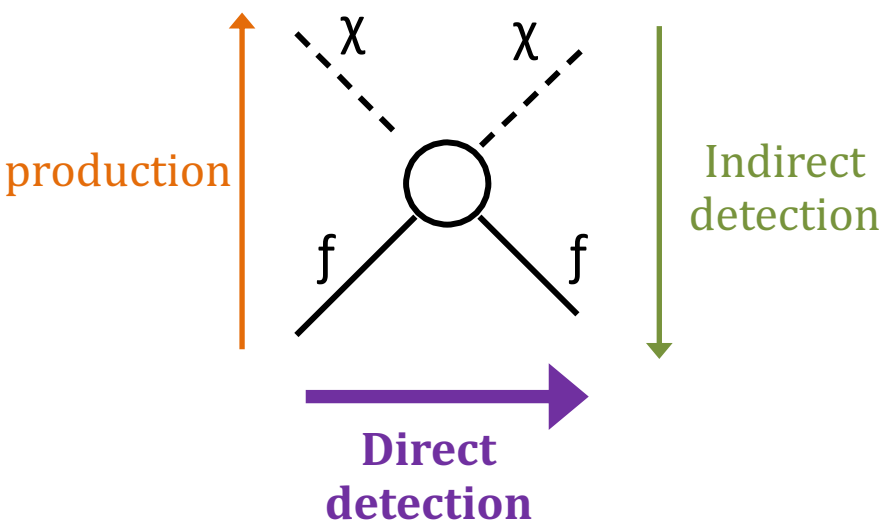
WIMP direct detection principle

Nuclear Recoil (NR)





Electronic Recoil (ER)

γ and β particles interact with the atomic electrons
➔ Background in « standard WIMP analysis »

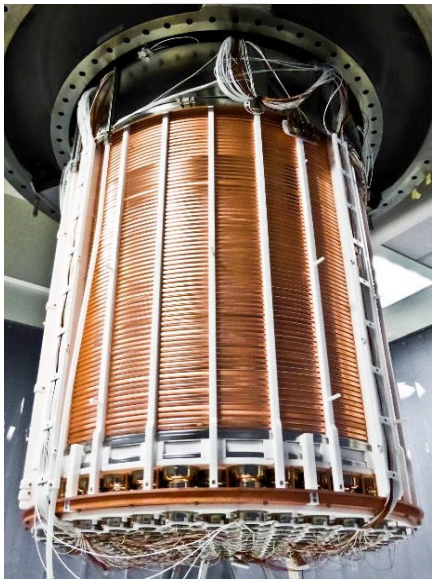
XENON Collaboration

~170 scientists

27 institutions

11 countries

Phases of the XENON Program



XENON10
2005 – 2007
15 cm drift TPC
Total: 25 kg
Target: **14** kg
ER background :
1000 evt/(t.keV.d)

Achieved (2007)
$\sigma_{SI} = 4.5 \cdot 10^{-44}$ cm^2
@ 30 GeV/c^2

XENON100
2008 – 2016
30 cm drift TPC
Total: 161 kg
Target: **62** kg
ER background :
5.3 evt/(t.keV.d)

Achieved (2016)
$\sigma_{SI} = 1.1 \cdot 10^{-45}$ cm^2
@ 55 GeV/c^2

XENON1T
2011 – 2018
100 cm drift TPC
Total: 3 200 kg
Target: **2 000** kg
ER background :
0.2 evt/(t.keV.d)

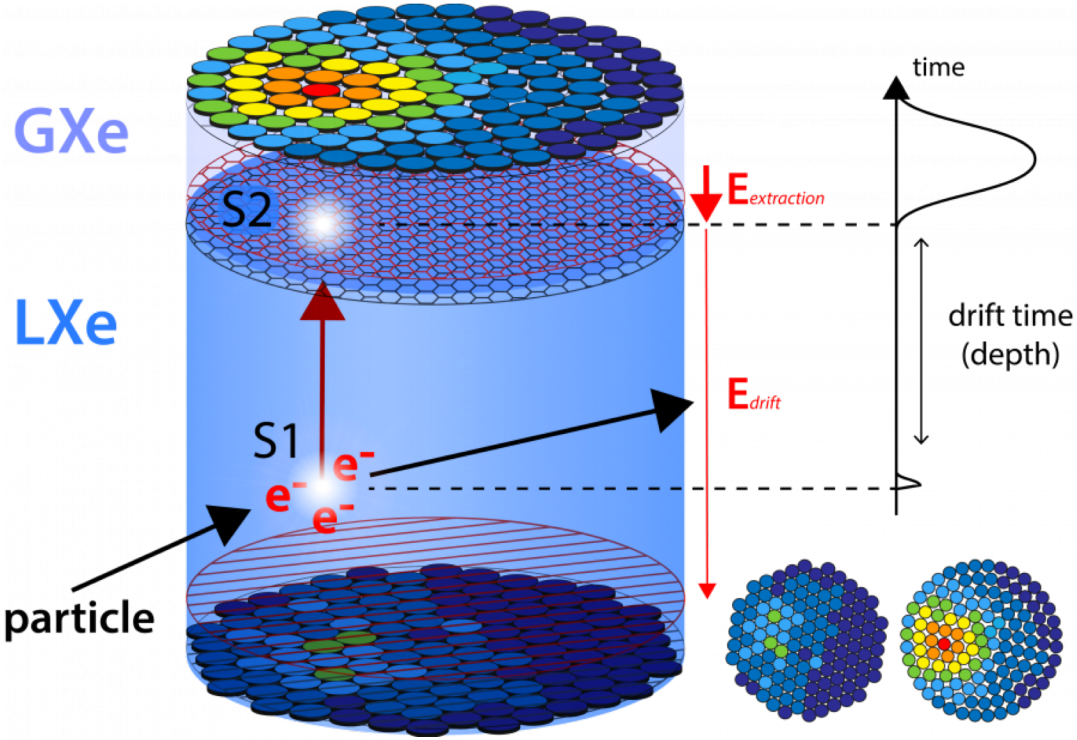
Achieved (2018)
$\sigma_{SI} = 4.1 \cdot 10^{-47}$ cm^2
@ 30 GeV/c^2

XENONnT
2019 – 2025
150 cm drift TPC
Total: 8 600 kg
Target: **5 900** kg
ER background :
2.2 10^{-3} evt/(t.keV.d)

Projected
$\sigma_{SI} = 1.6 \times 10^{-48}$ cm^2
@ 50 GeV/c^2

Dual phase TPC: principle

TPC = Time Projection Chamber

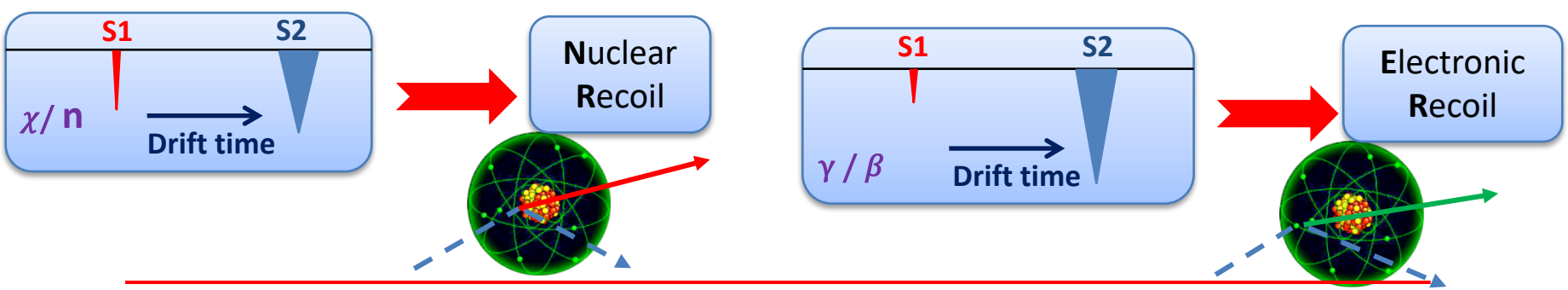


S1:
→ Photon (λ = 178 nm) from Scintillation process

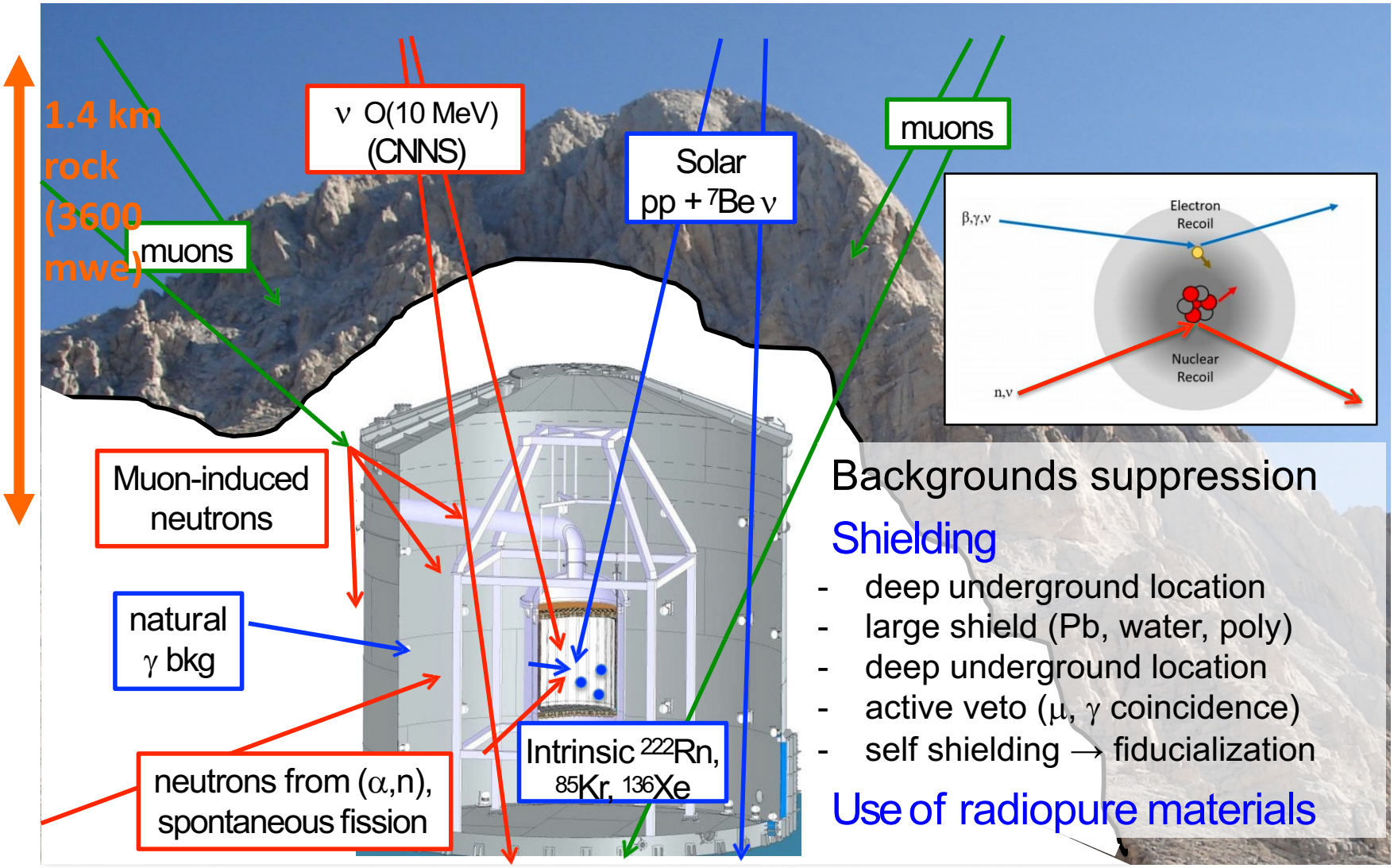
S2:
→ Electrons drift
→ Extraction in gaseous phase
→ Proportional scintillation light

3D reconstruction :
→ X,Y from top array
→ Z from Drift time

$(S2/S1)_{WIMP,n} < (S2/S1)_{\gamma,\beta}$



Origins of backgrounds



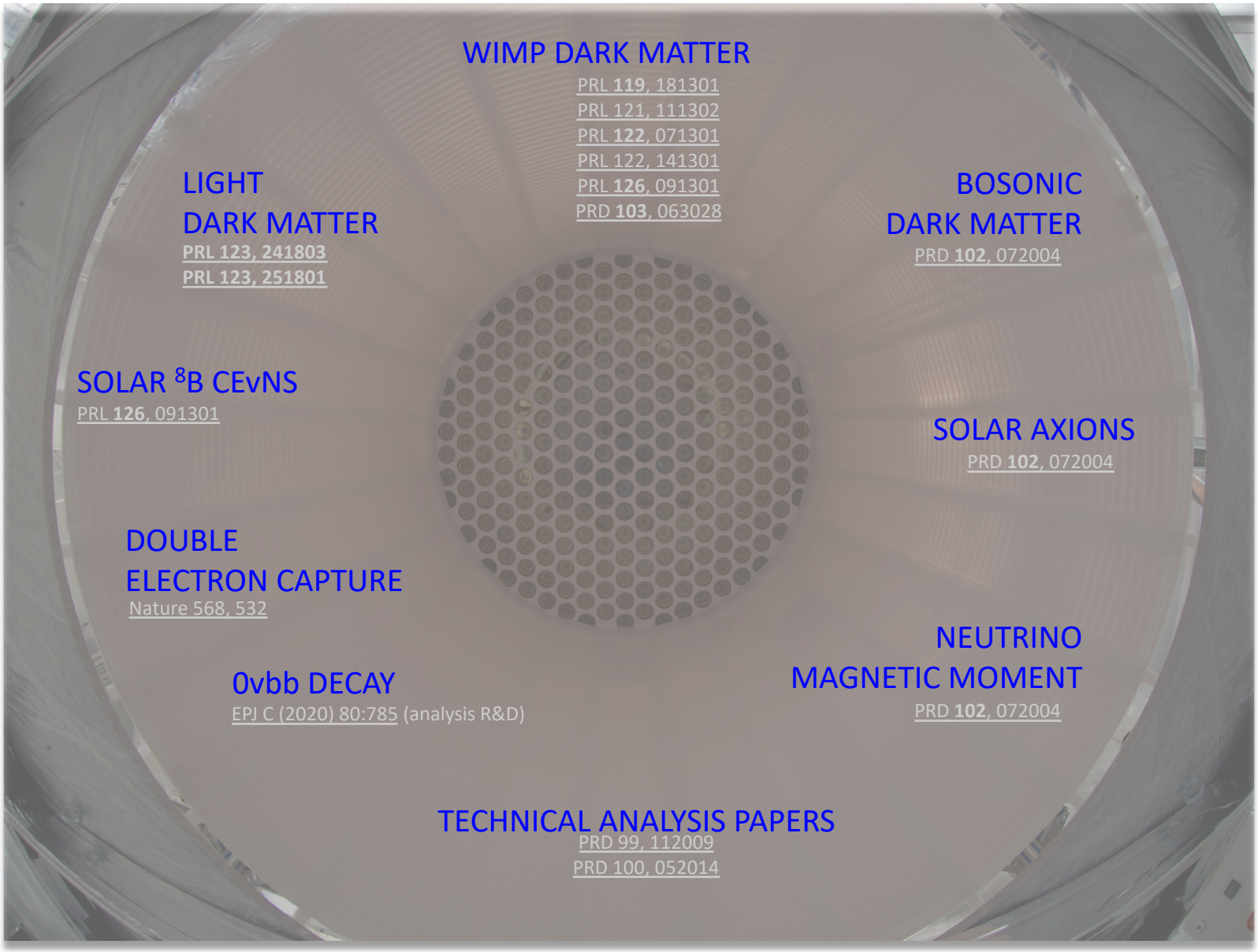
Backgrounds suppression

Shielding

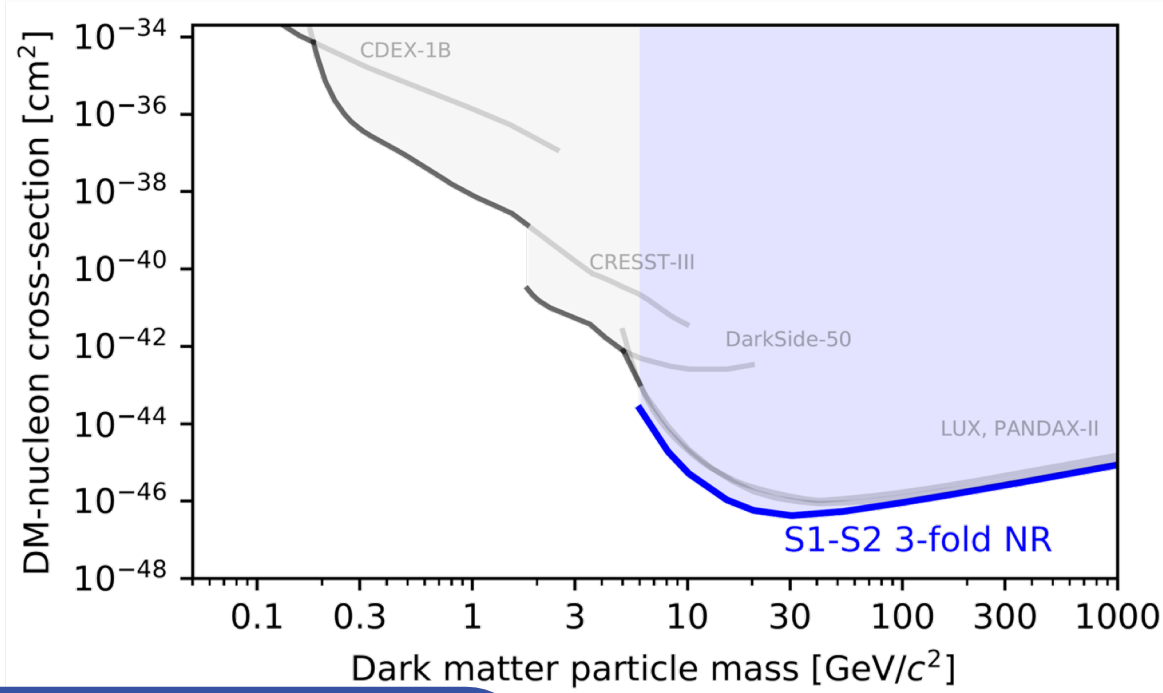
- deep underground location
- large shield (Pb, water, poly)
- deep underground location
- active veto (μ, γ coincidence)
- self shielding → fiducialization

Use of radiopure materials

Uses of S1 & S2 with XENON1T data

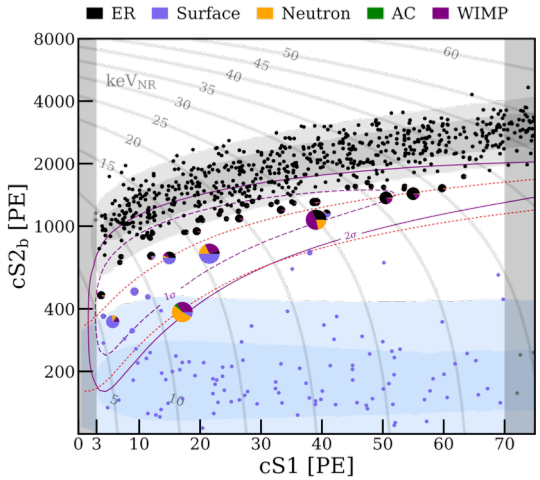


XENON1T Results – NR Searches

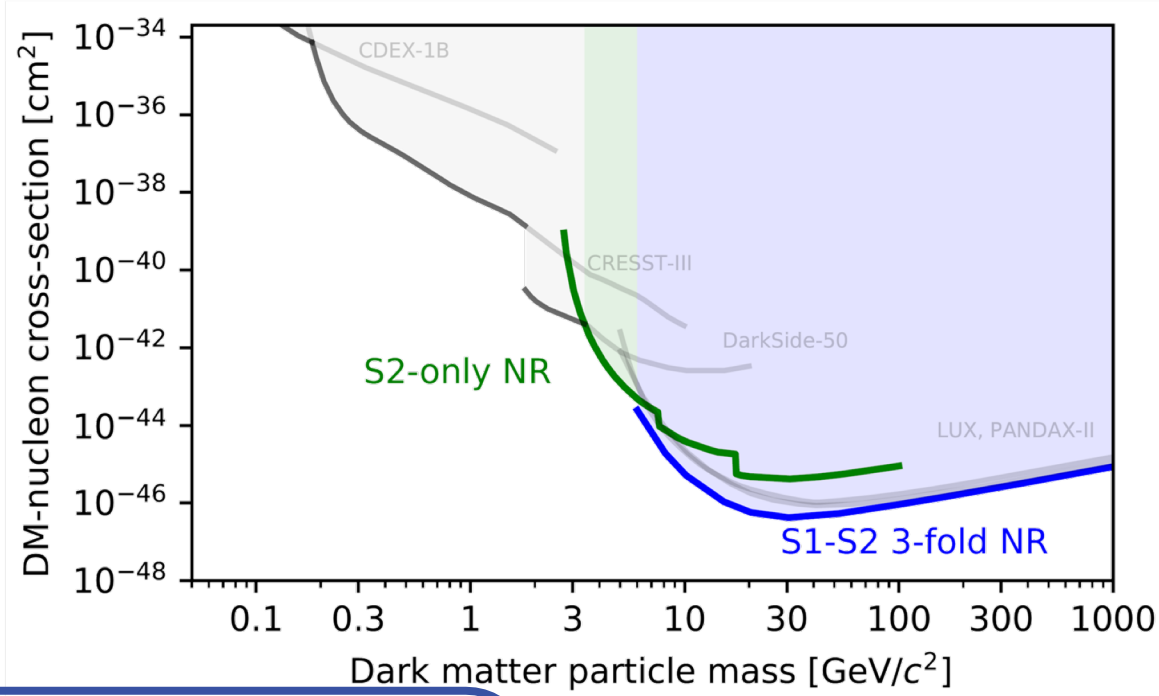


Standard Analysis (S1-S2)

- high mass WIMP search (> 6 GeV/c²)
- minimum of 4.1×10^{-47} cm² at 30 GeV/c² (90% C.L.) PRL 121 (2018) 111302



XENON1T Results – NR Searches



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- high mass WIMP search (> 6 GeV/c^2)
- minimum of 4.1×10^{-47} cm^2 at 30 GeV/c^2 (90% C.L.)

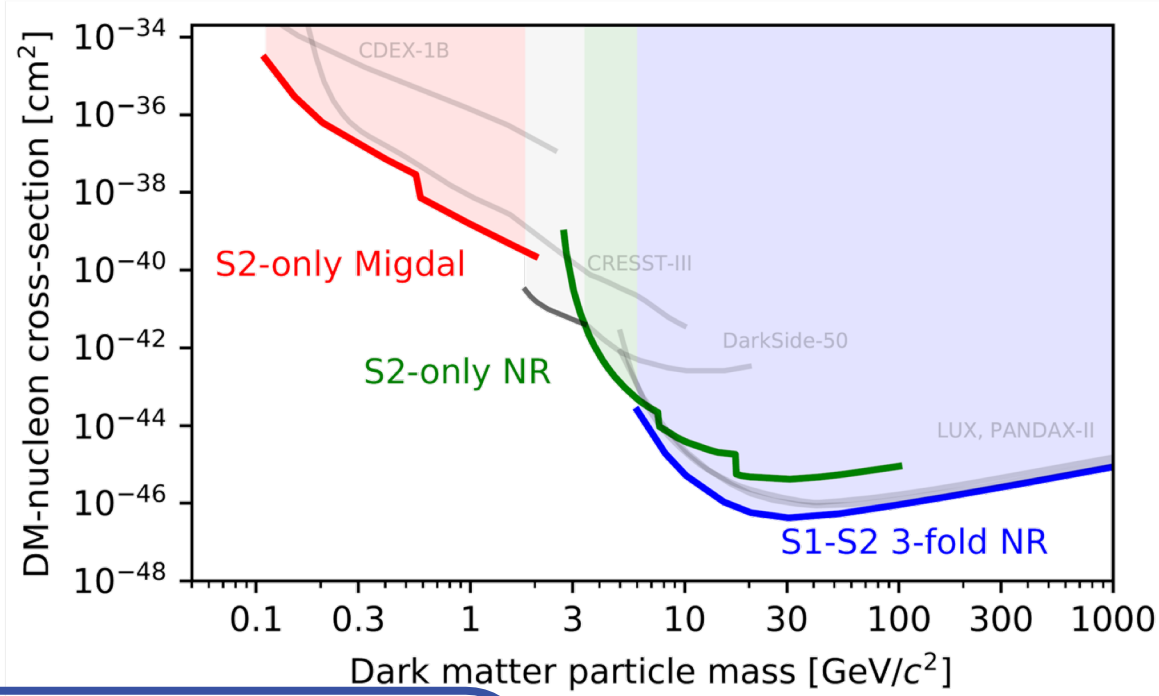
PRL 121 (2018) 111302

S2-only NR

- using charge signal (S2) only
- lowering threshold
- low-mass WIMP search (< 6 GeV/c^2)

PRL 123 (2019) 251801

XENON1T Results – NR Searches



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- high mass WIMP search (> 6 GeV/c^2)
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PRL 121 (2018) 111302

S2-only NR

- using charge signal (S2) only
- lowering threshold
- low-mass WIMP search (< 6 GeV/c^2)

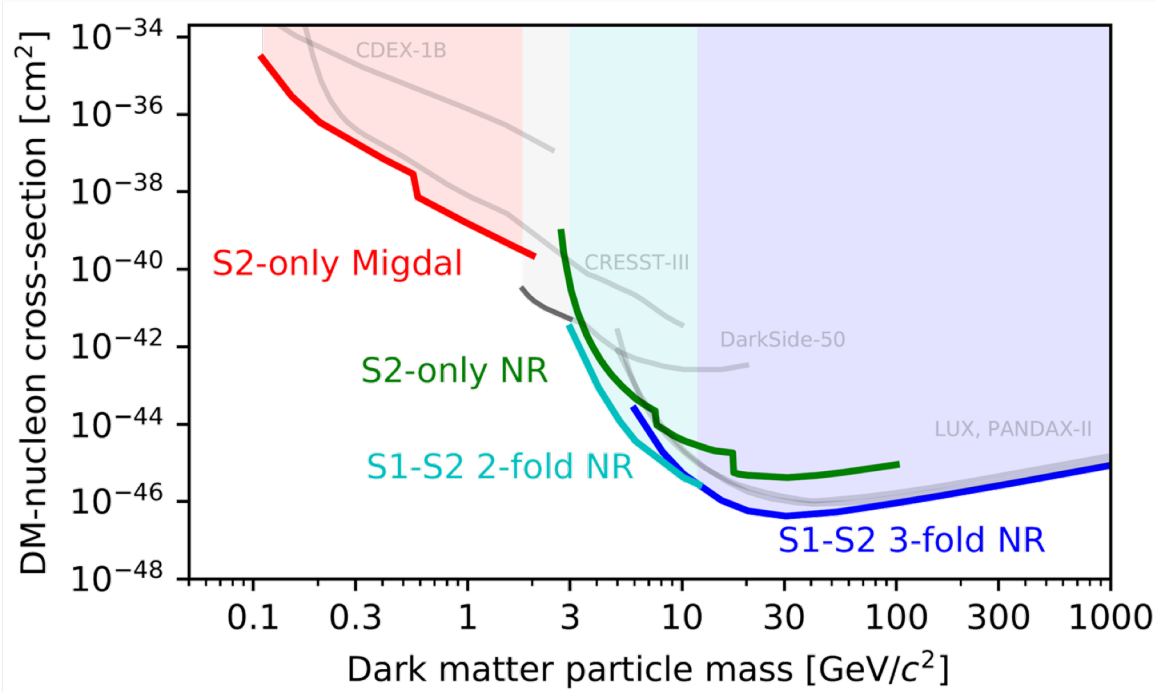
PRL 123 (2019) 251801

S2-only Migdal (NR + ER)

- using charge signal (S2) only for NR+ER
- Migdal effect (theoretical prediction)
- low-mass WIMP sensitivity down to 85 MeV/c^2

PRL 123 (2019) 241803

XENON1T Results – NR Searches



CEυNS Search

- Coherent Elastic Neutrino-Nucleus Scattering for ^{8}B neutrinos from the Sun
- irreducible background in future WIMP detectors
- we lowered our threshold from 3-fold to 2-fold PMT coincidence

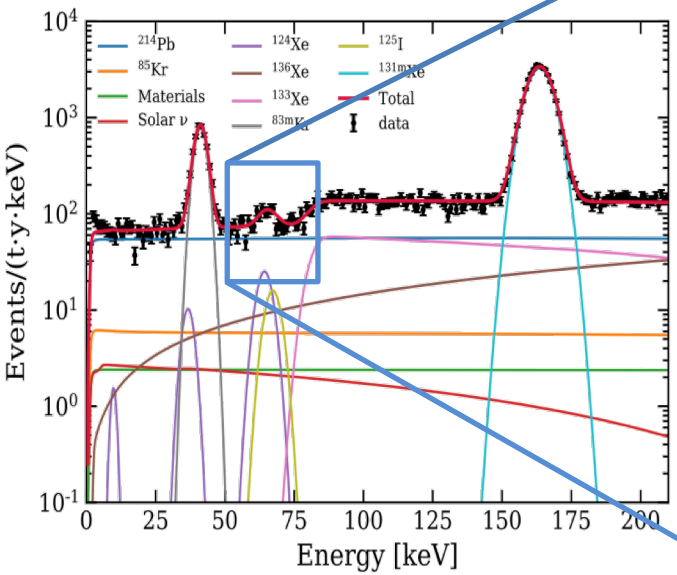
Results

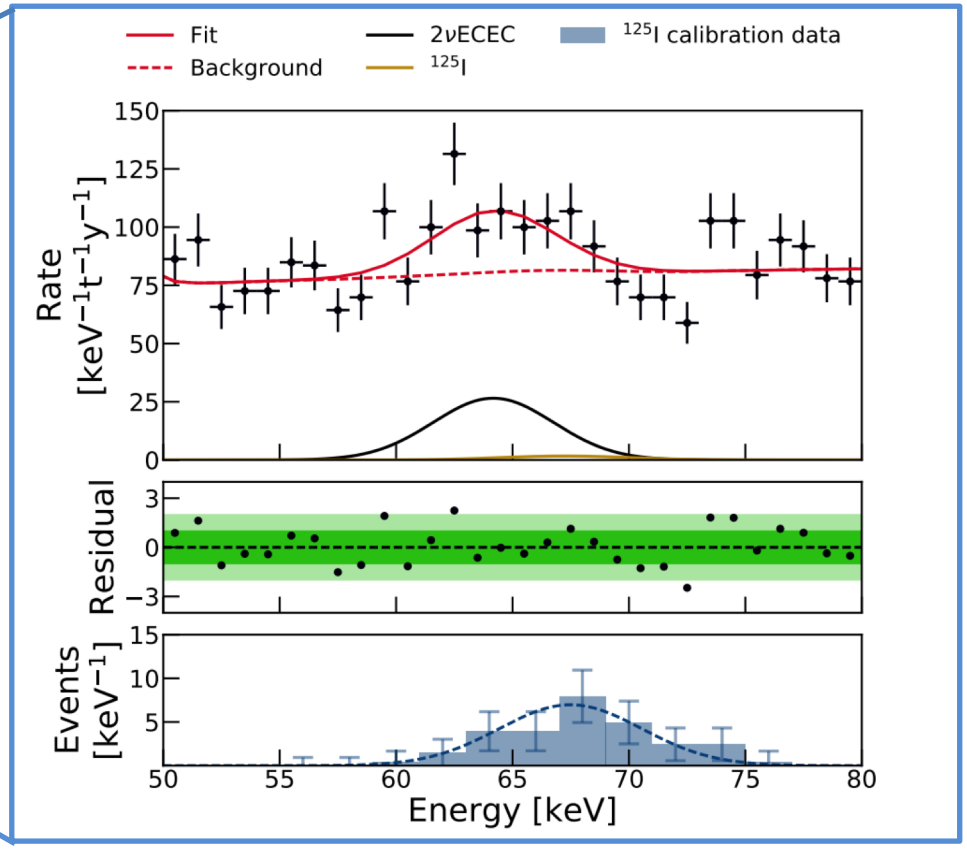
- no excess observed
- use to constrain light and charge yield of detector at lowest energies
- place new limit on light dark matter between 3 – 11 GeV/c^2

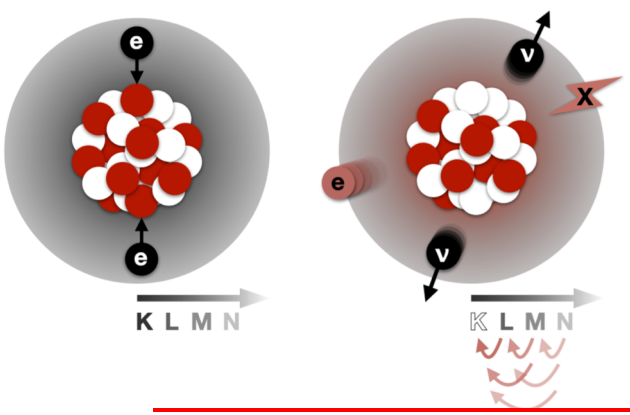
PRL 126, 091301 (2021)

XENON1T Results – ER Searches

Abundance:
^{124}Xe ~ 1 kg / t





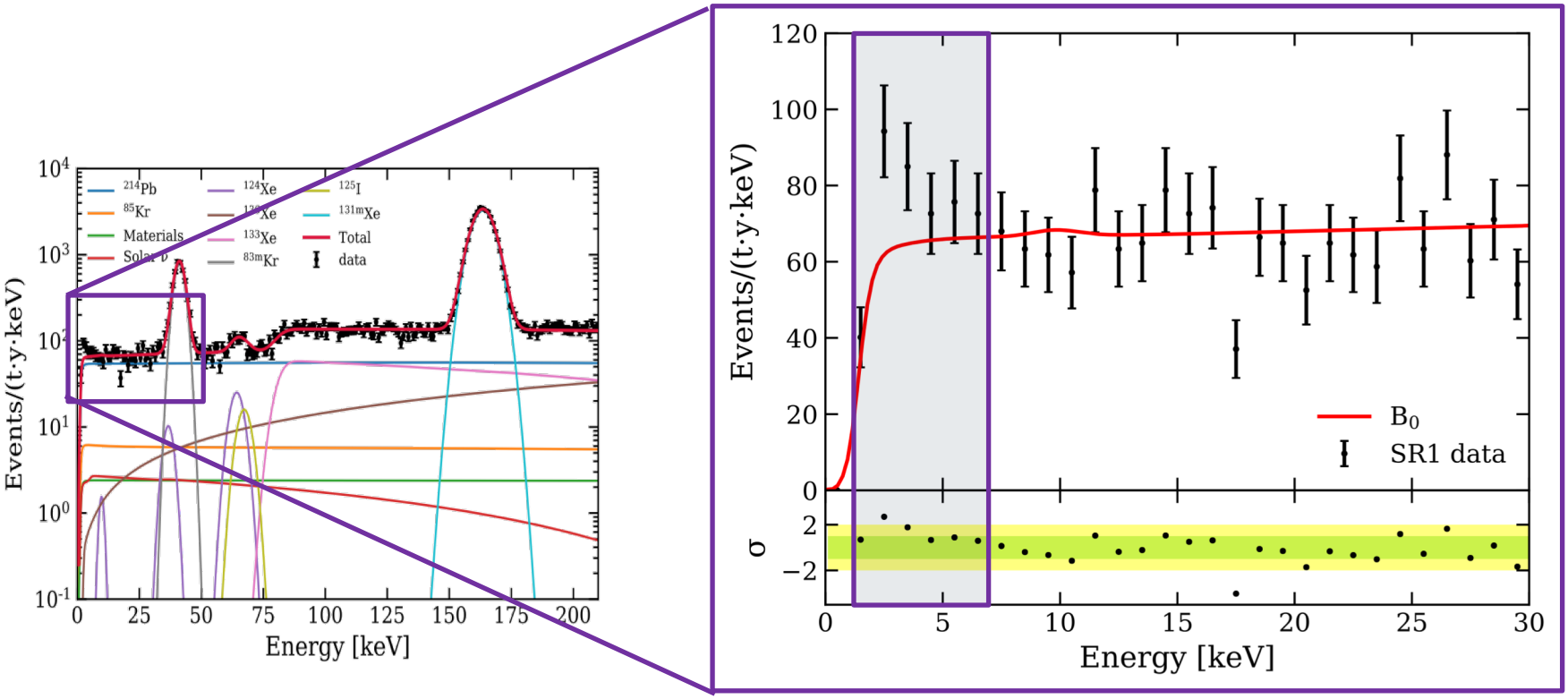


$$^{124}\text{Xe} + 2e^- \rightarrow {}^{124}\text{Te} + 2\nu_e$$

Detectable cascade of X-rays and Auger electrons in the **keV-range (64.3 keV)**

$$T_{1/2} = (1.8 \pm 0.5_{stat} \pm 0.1_{sys}) \times 10^{22}\ \text{y}$$

XENON1T Results – ER Searches



76 ± 2 events/(t·y·keV)

Fitted background in [1, 30] keV

Events in [1, 7] keV	**232 ± 15** expected	**285** observed

XENON1T Results – ER Searches

3.2σ TRITIUM BACKGROUND

- Fitted concentration: $(6.2\pm2.0) \times 10^{-25}$ mol/mol ^{3}H/Xe
- We don't expect that much ^{3}H from liquid purity
- Very difficult to confirm or exclude such a tiny abundance

3.4σ SOLAR AXIONS

- Non-null coupling to electrons → ABC and/or Primakoff
- Strong tension with astrophysical constraints
- Axions+^{3}H favoured over ^{3}H-only at 2.1 σ

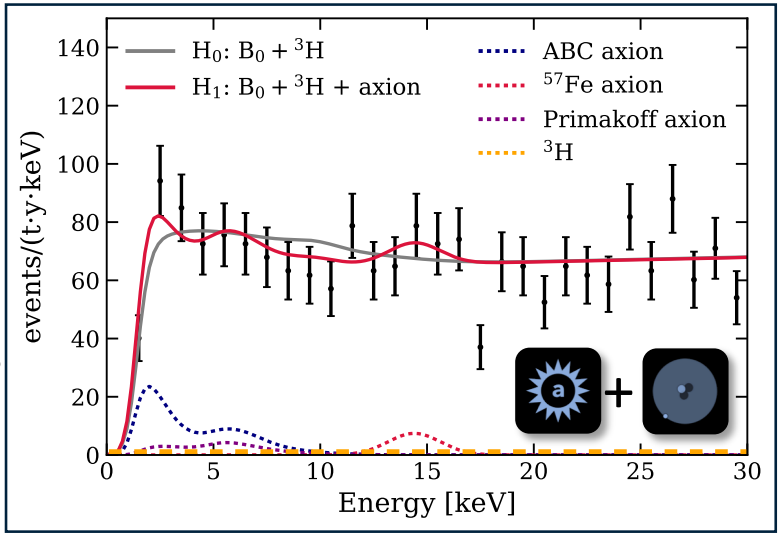
3.2σ NEUTRINO MAGNETIC MOMENT μ_ν

- $\mu_\nu = [1.4, 2.9] \times 10^{-11}\ \mu_B$
- $\mu_\nu > 10^{-15}$ would imply neutrinos to be Majorana fermions
- Tension with astrophysical constraints

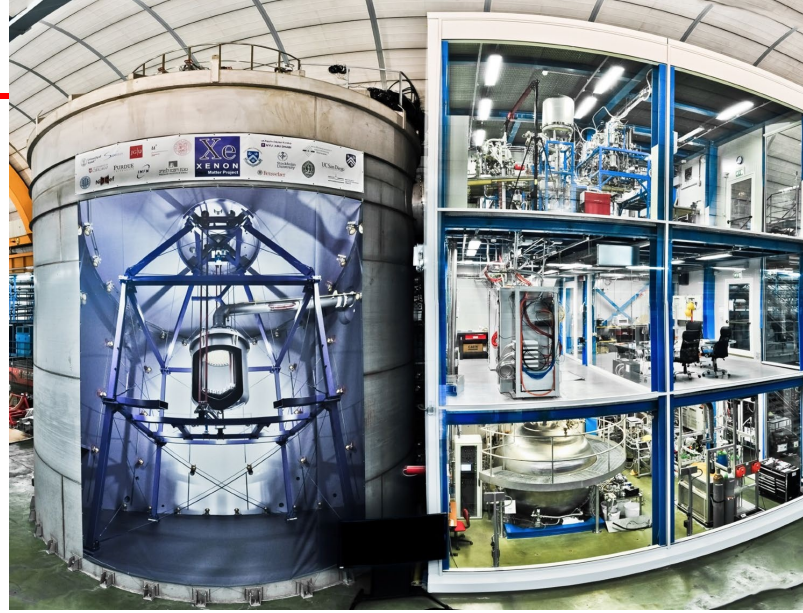
3.0σ BOSONIC DARK MATTER

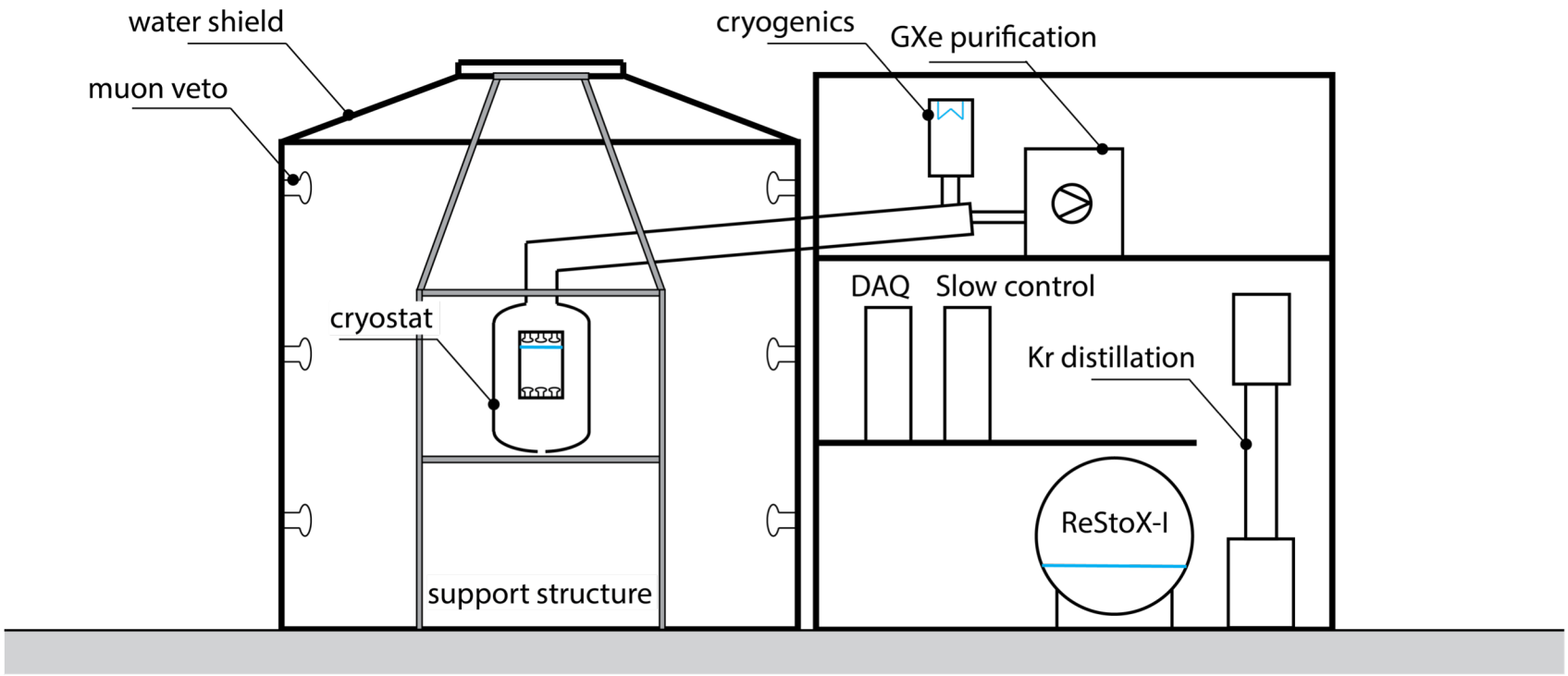
- Including pseudo-scalar (ALPS) and vector (dark photons) bosons
- Most restrictive constraints to date set

Solar axions + (unconstrained) ^{3}H fit



From XENON1T to XENONnT

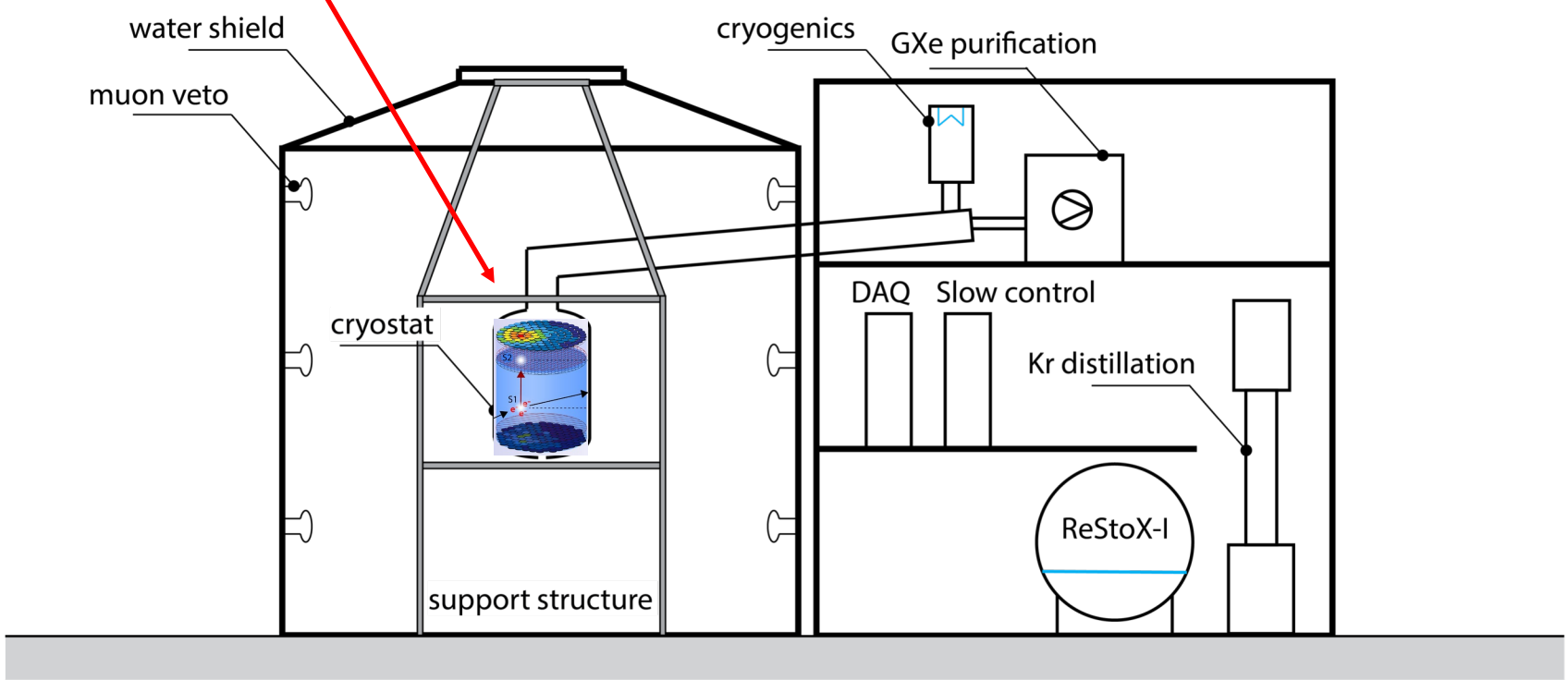




From XENON1T to XENONnT

Larger TPC

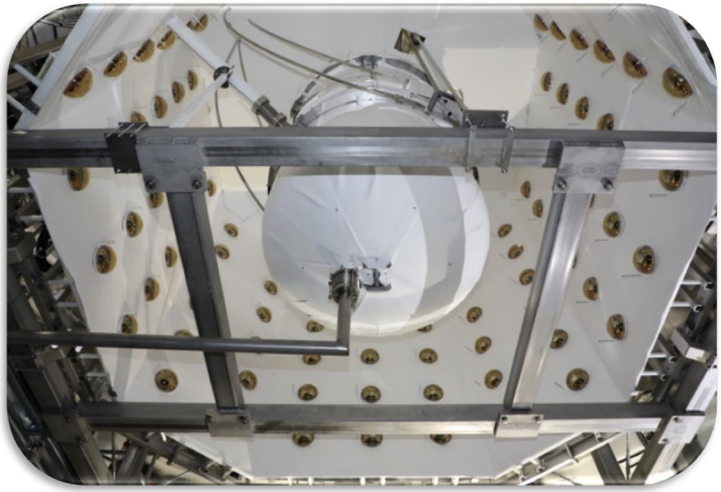
- Total 8.6 t LXe
- 5.9 t in TPC
- ~ 4 t fiducial
- 248 → 494 PMTs

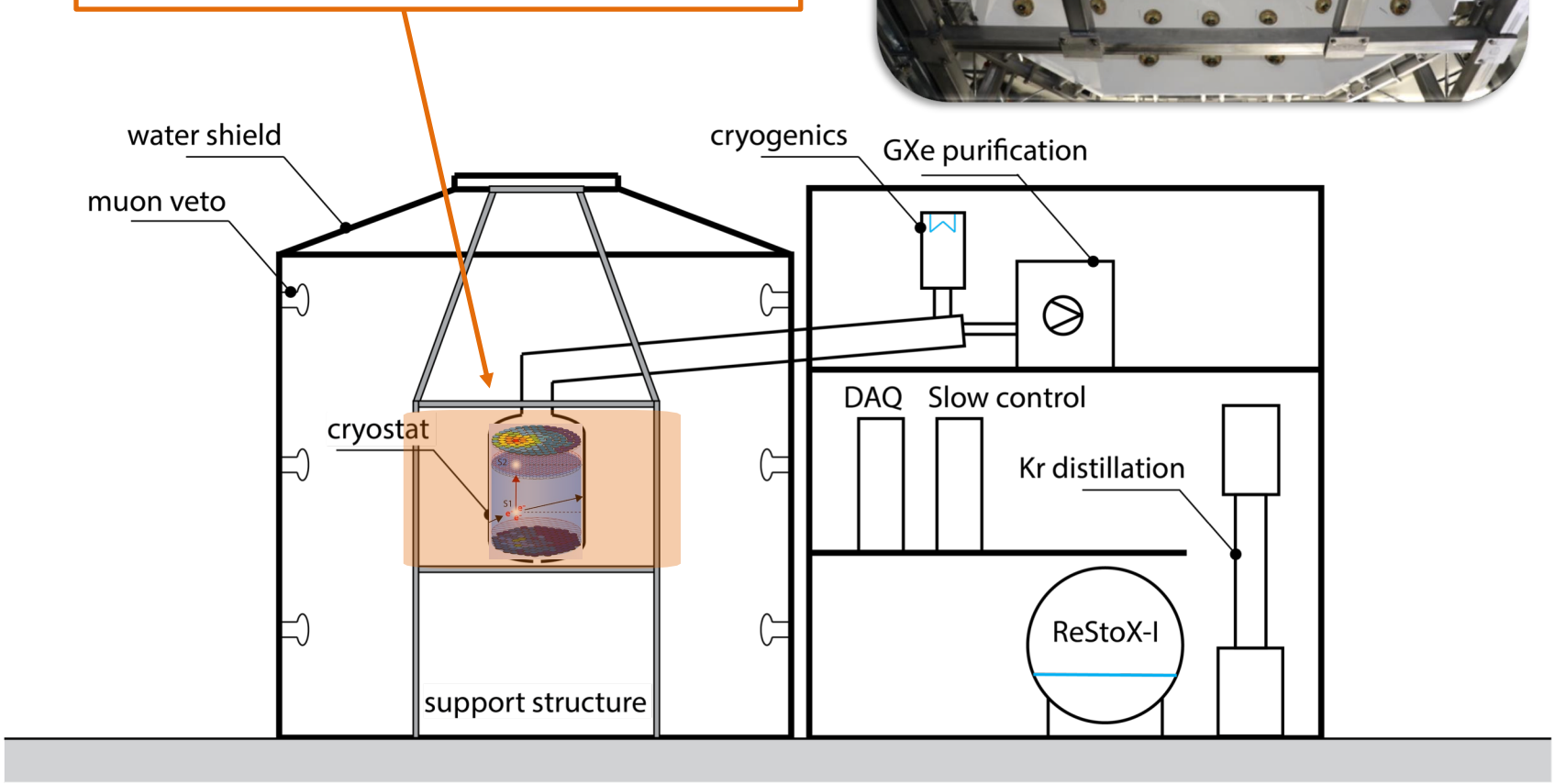


From XENON1T to XENONnT

Neutron Veto

- Inner region of existing muon veto
- optically separated
- 120 additional PMTs
- Gd in the water tank
- 0.5% $Gd_2(SO_4)_3$



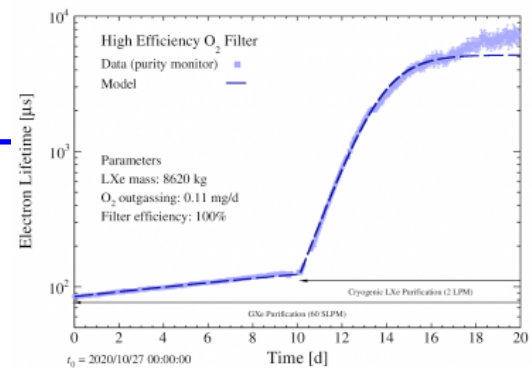


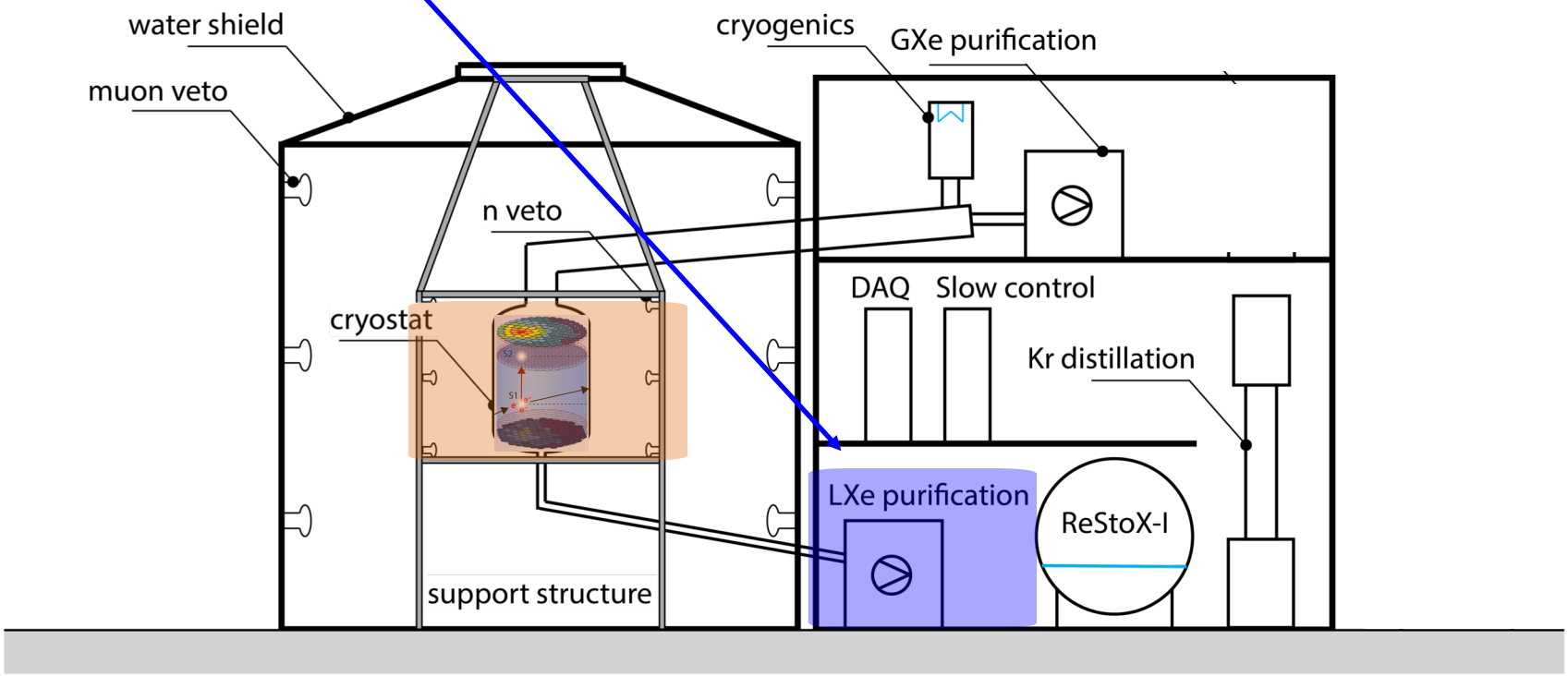
From XENON1T to XENONnT

LXe purification

- Faster xenon cleaning
- 5L/min LXe (2500 slpm)

(XENON1T: 120 slpm)

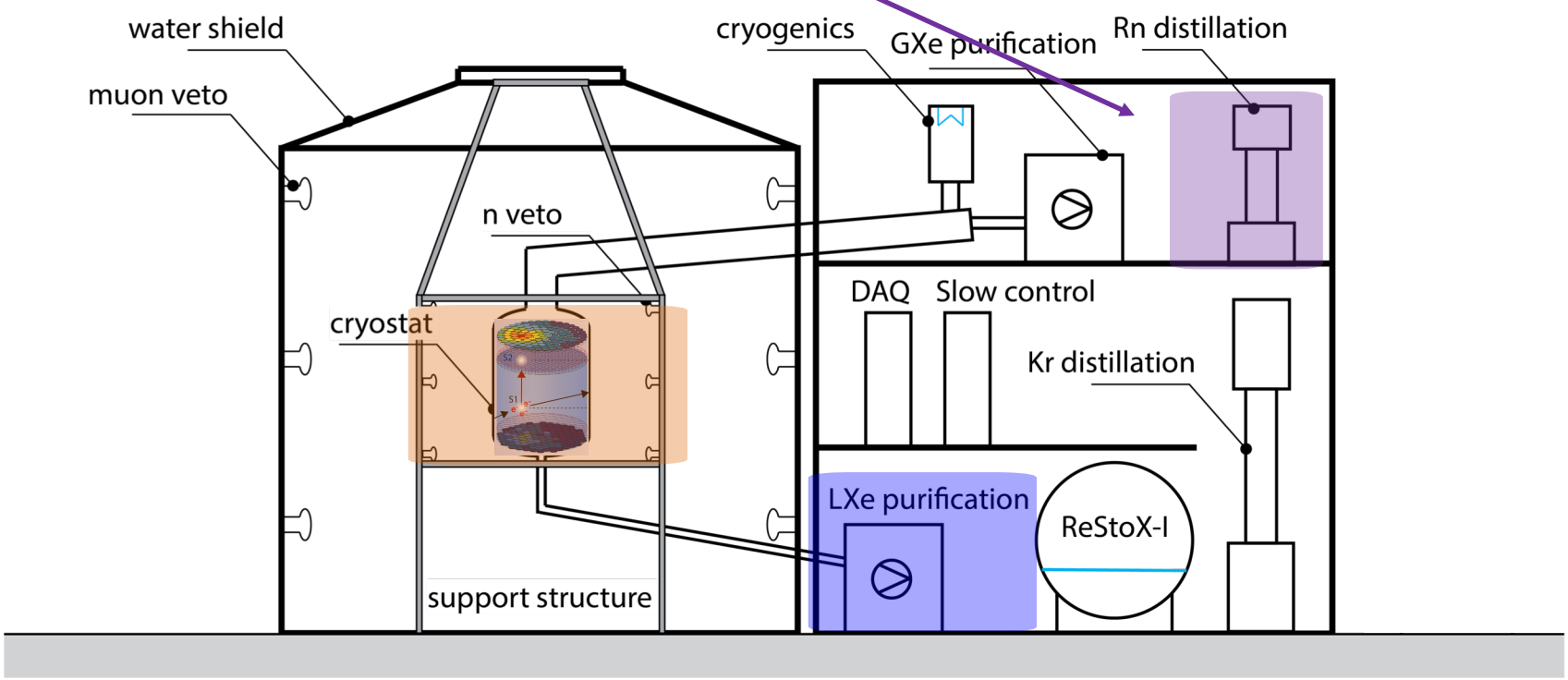




From XENON1T to XENONnT

222Rn Distillation

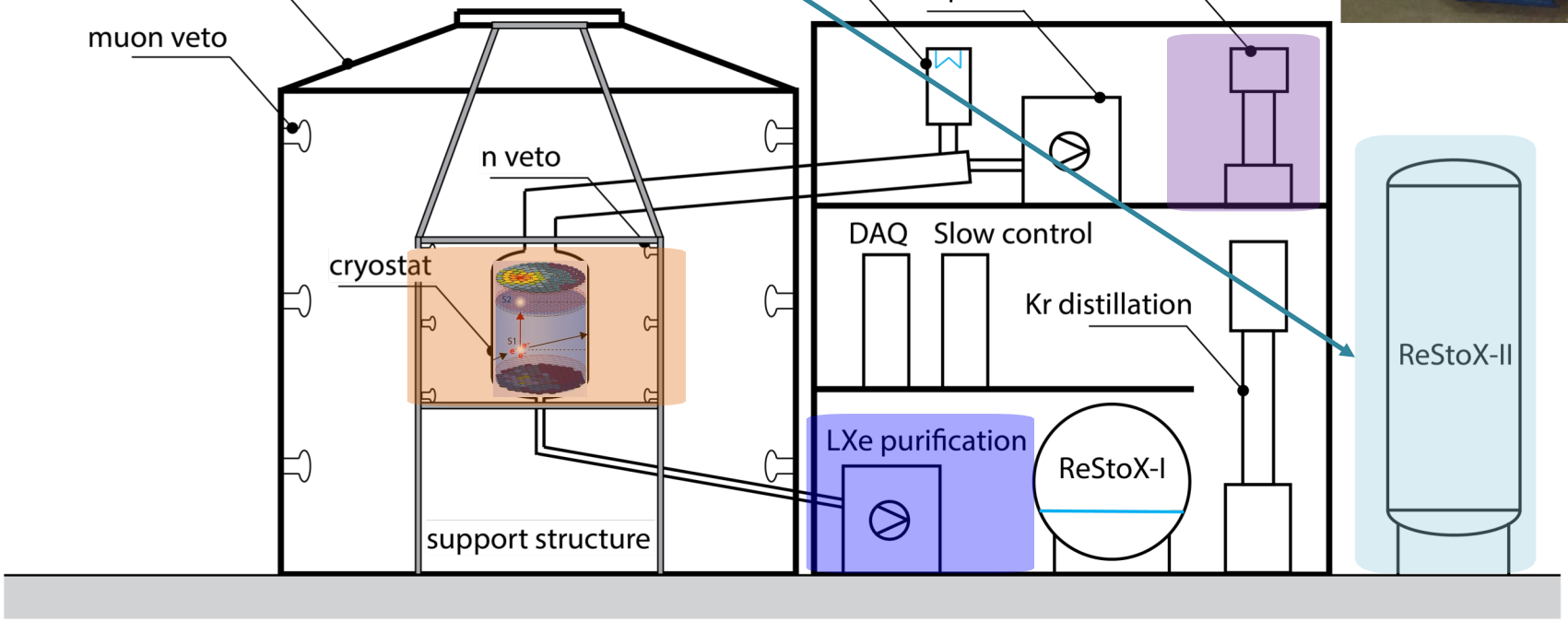
- Reduce radon from pipes, cables, cryogenic system
- New system, tested in XENON1T
- Background reduction 1/10



From XENON1T to XENONnT

Storage and Recovery (ReStoX-II)

- 10 tons capacity
- Storage in Solid / Liquid / Gas
- Fast recovery (1 ton / hour)

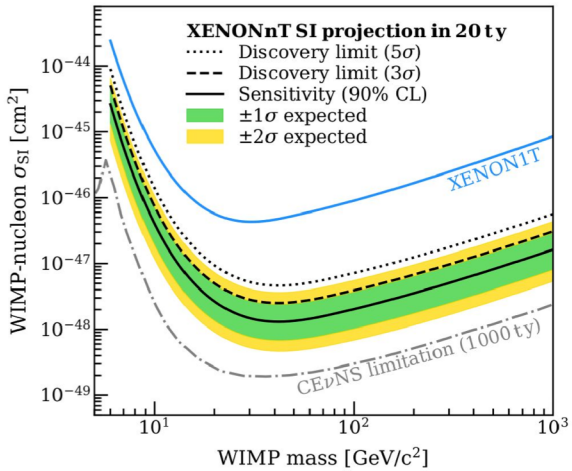


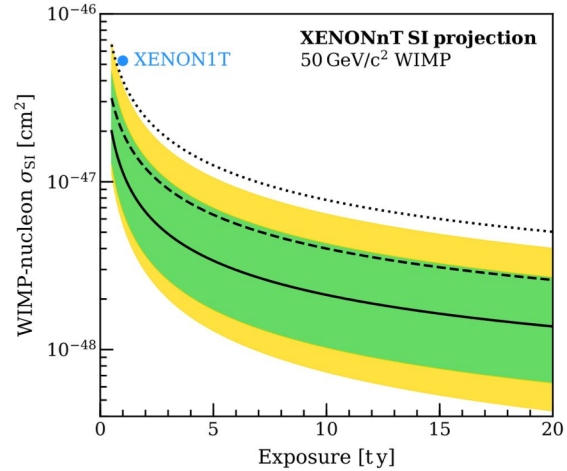
XENONnT expected sensitivity

E. Aprile et al JCAP11(2020)031

After 20 tons x yr,
the expected sensitivity is:

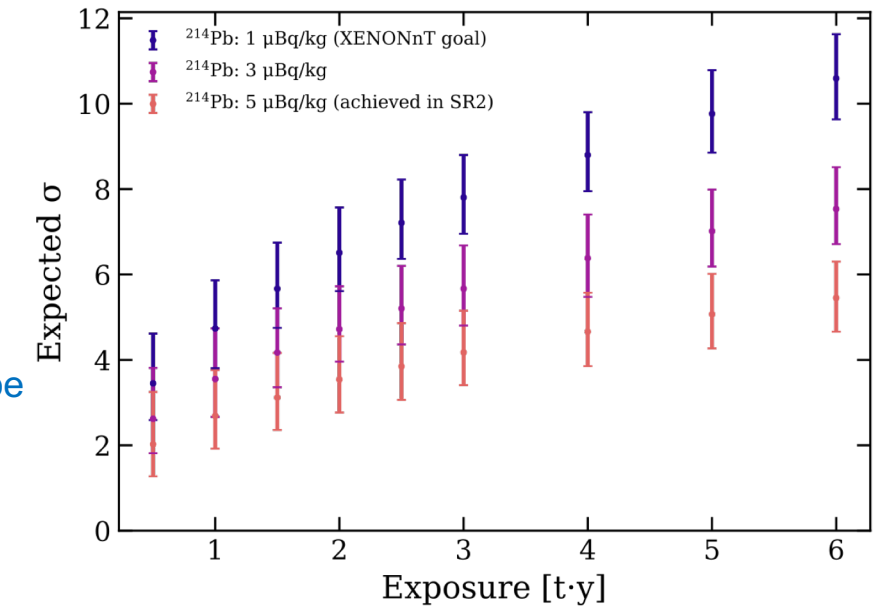
1.4×10^{-48} cm2
@ 50 GeV/c^2 (90% CL)





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

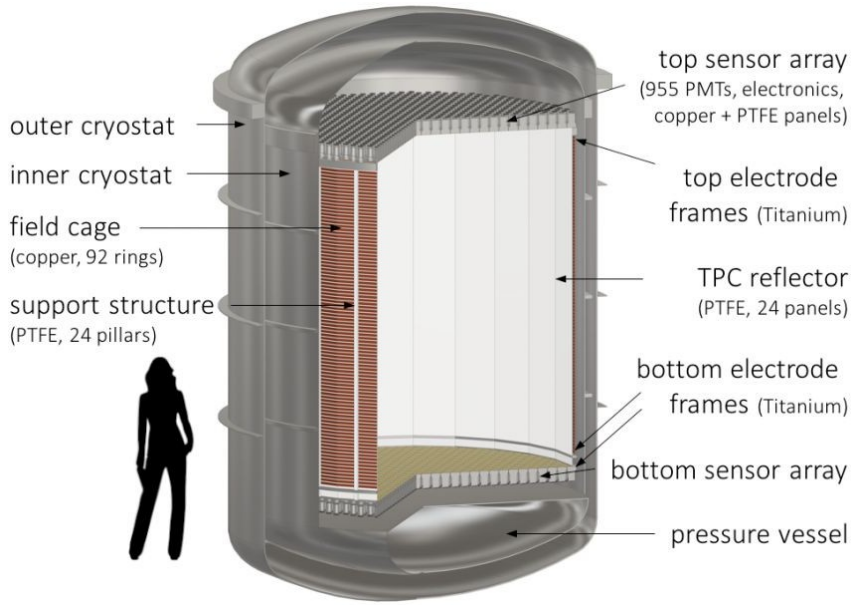
Preliminary study suggest that after few months of XENONnT data the solar axion signal hypothesis could be differentiated from 3H background at the 5σ level

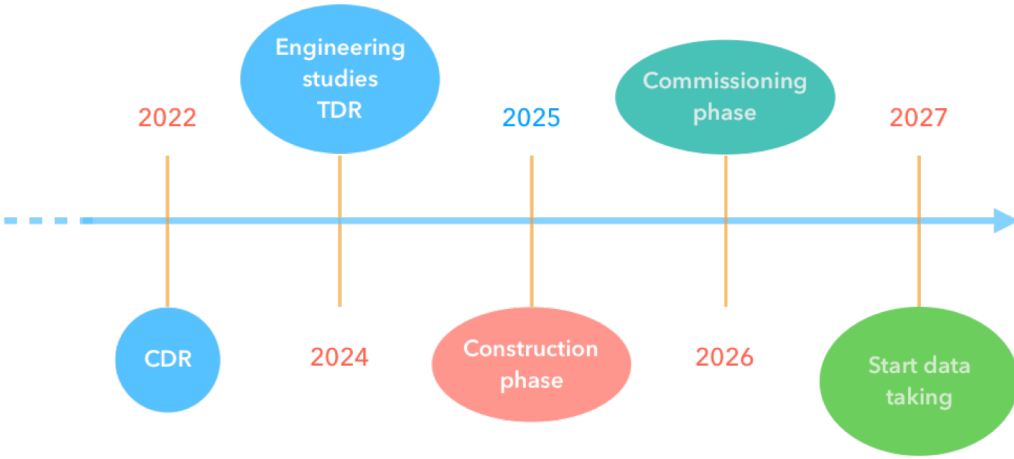


The DARWIN Project

- **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

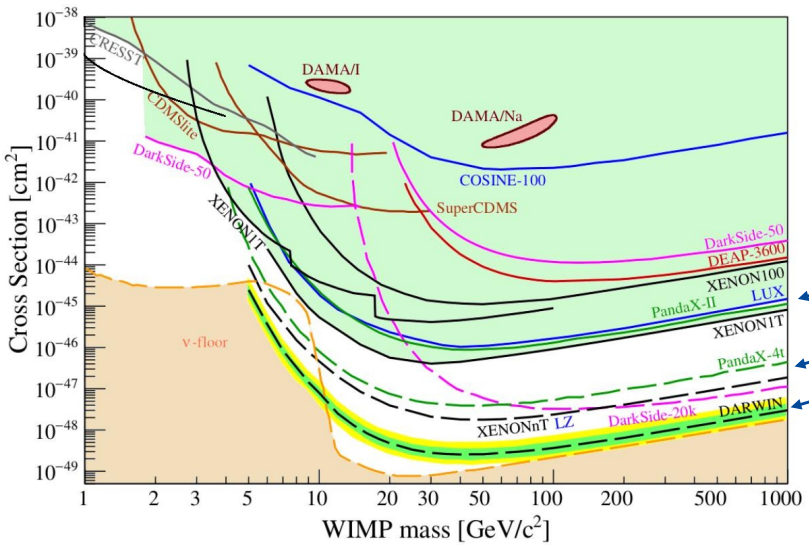
JCAP 1611 (2016) no.11, 017





The DARWIN Project

JCAP 10, 016 (2015)

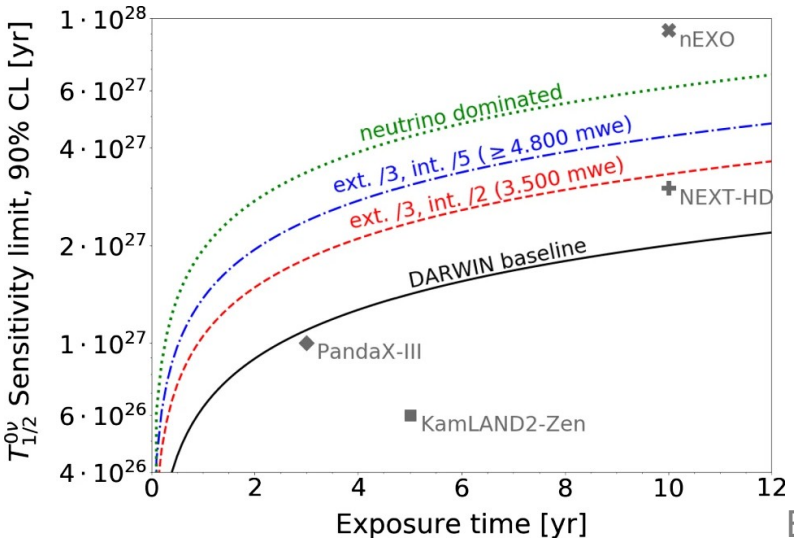


current limits

near future sensitivity

DARWIN's sensitivity

Direct Dark Matter Search
expected sensitivity with 200 ton x yr
2.5×10^{-49}cm² @ 40 GeV/c²

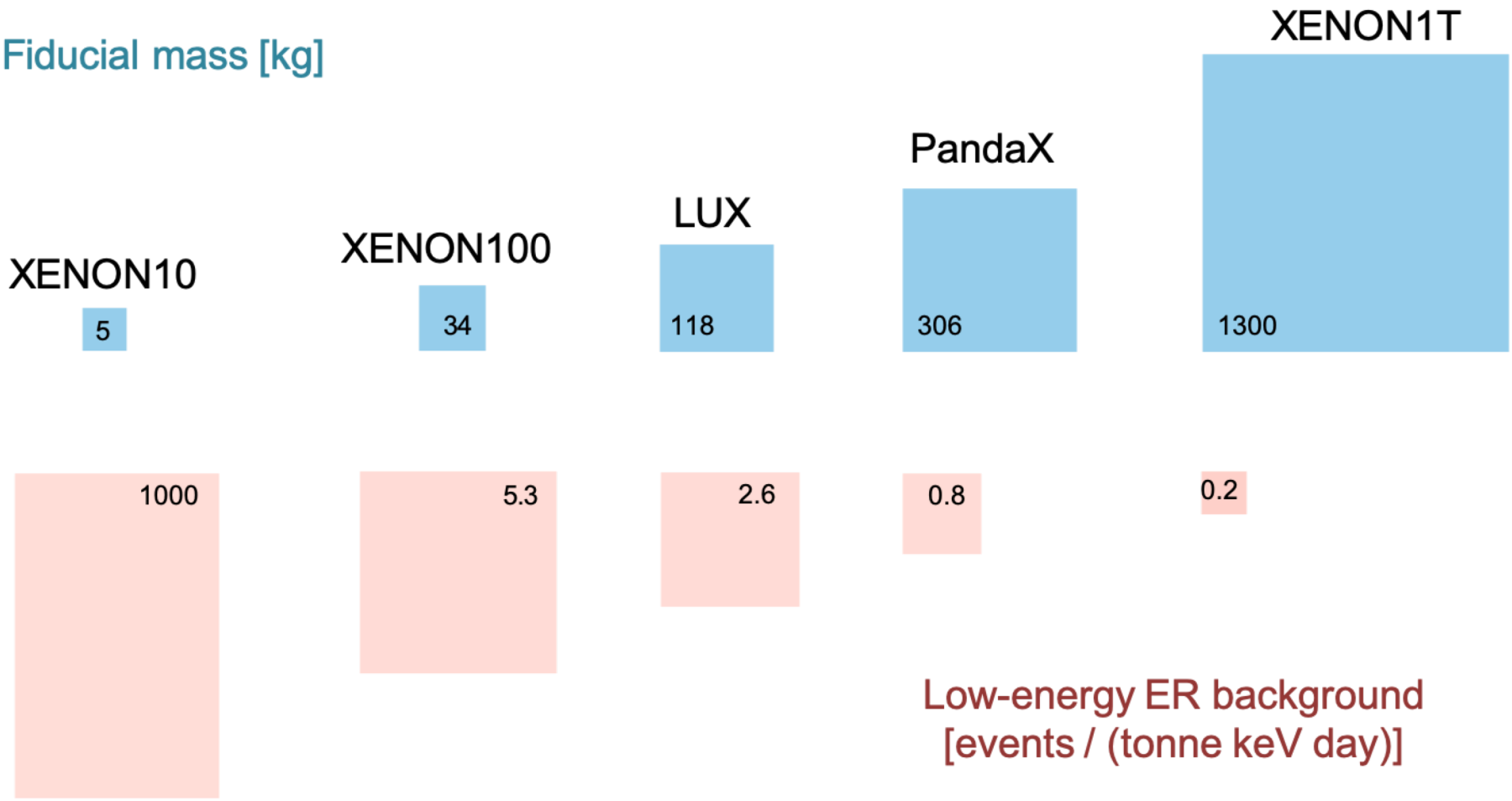


Eur. Phys. J. C 80 (2020) 808

Neutrinoless Double Deta Decay Search
Optimised 5 t fiducial of ^{136}Xe

Sensitivity : $T_{1/2}$ = 2.4 x 10^{27} y (90 % CL)
3σ discovery potential: 1.1 x 10^{27} y
After 10 years of observations

Evolution of LXe TPC as WiMP detectors



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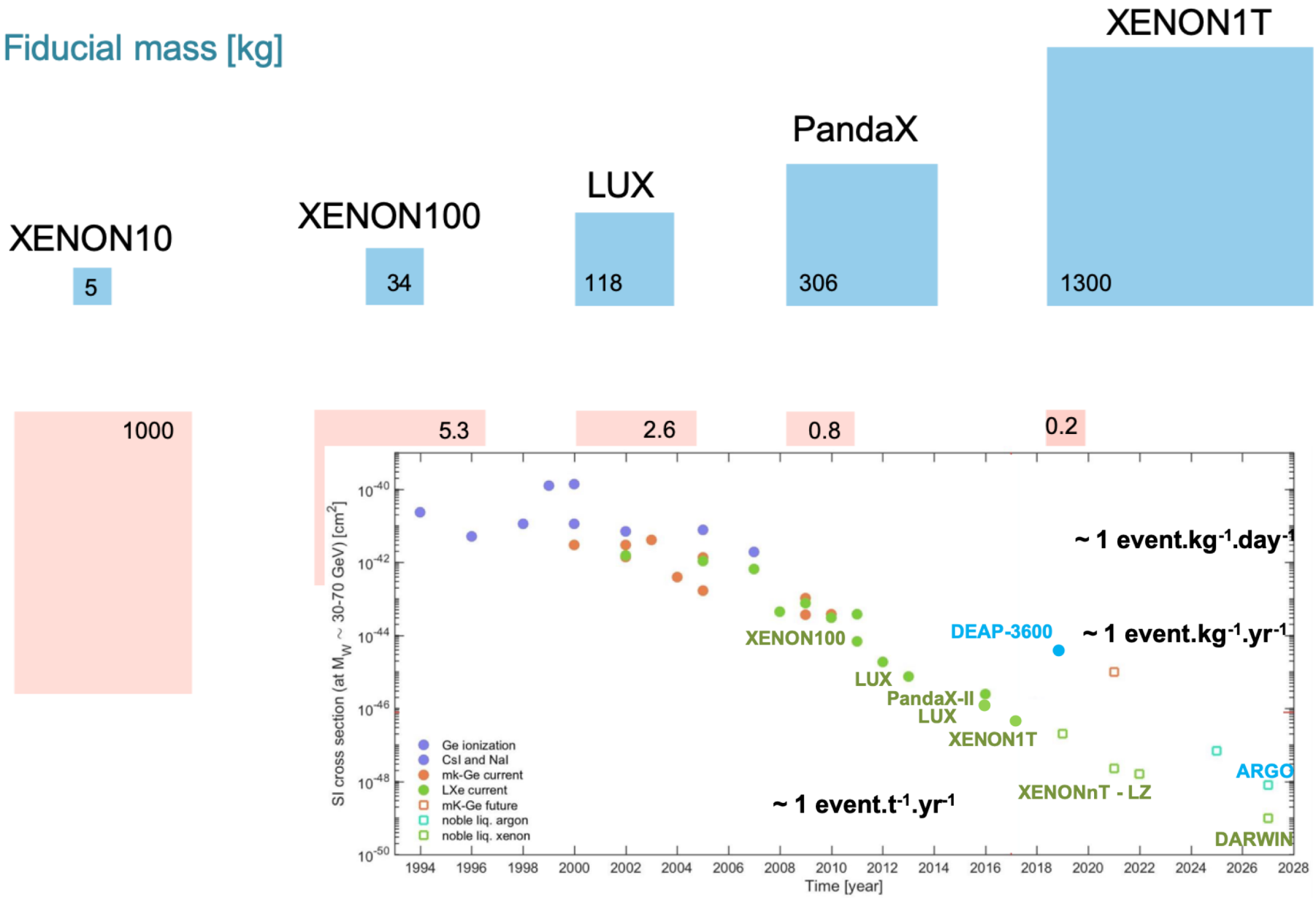
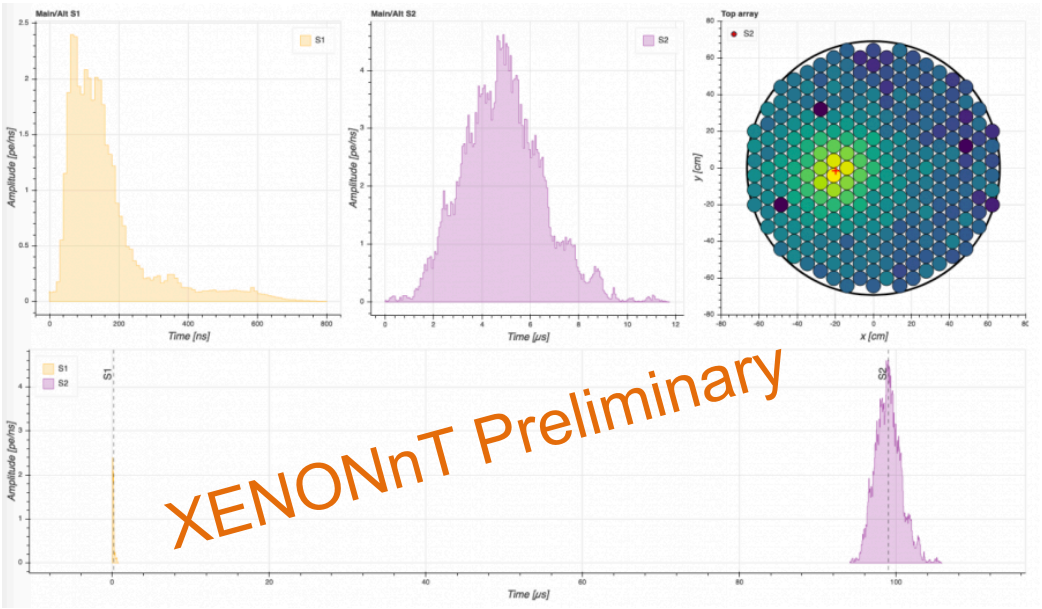


Summary and outlook

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

- 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.



- DARWIN will be **much more than the ultimate LXe-based dark matter detector**

  ➔ large detector with ultra-low backgrounds, very good energy resolution, low energy threshold