Neutrinos Searches in XENON Dark Matter Experiments

Deep Underground Physics

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DARWIN

XENON

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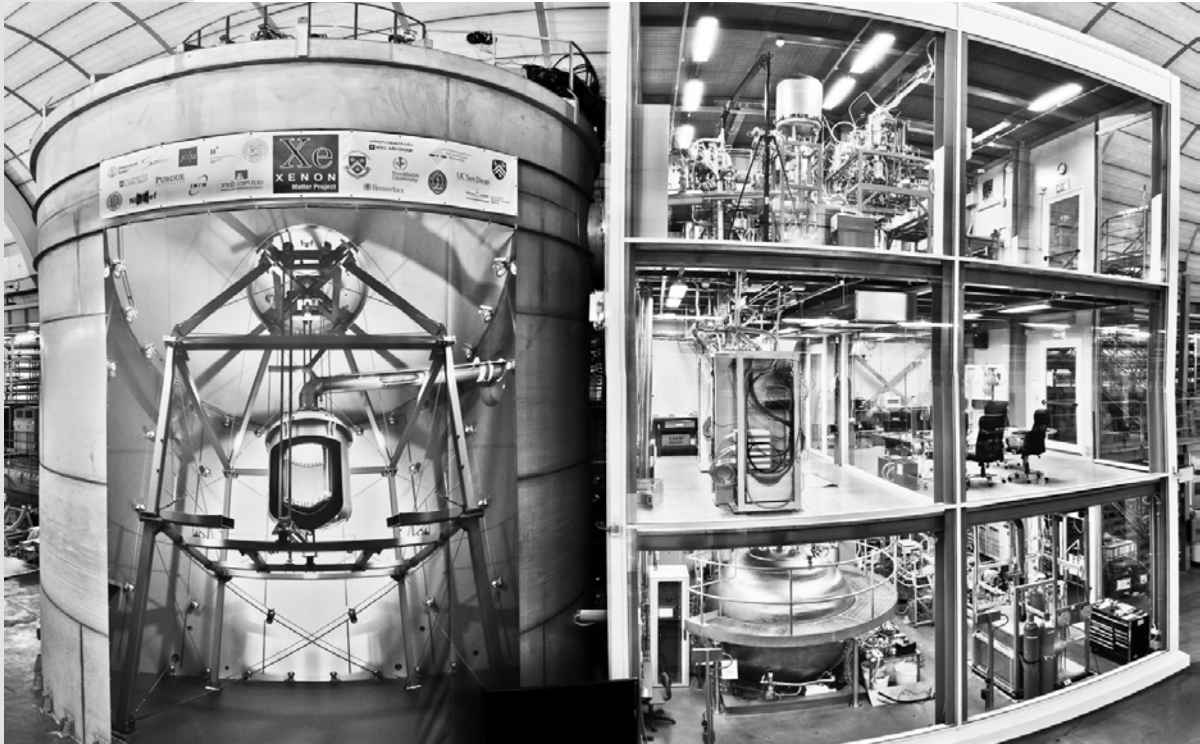

OUTLINE

WHY **are we searching for neutrinos? $0\nu\beta\beta$?**
New Physics

HOW **does the XENON project detect it?**
Low-background LXe TPC

WHAT **are the possibilities?**
XENON1T, XENONnT, DARWIN

MORE **neutrino searches?**
Solar and Supernova neutrinos

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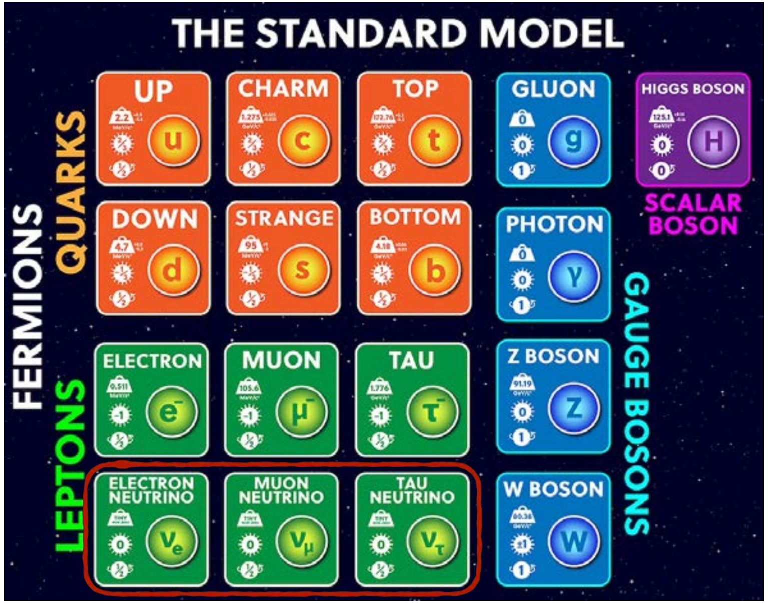
Neutrinos in the SM… and beyond?

Nature's Ghost Particles
Massless fermions in SM



→ BSM: Neutrino Oscillation
→ **Neutrinos are massive**

Unknown properties of the neutrino:

- **What is the nature of neutrinos?**
  - Majorana or Dirac particles
- **Is there CP violation?**
  - Matter/anti-matter asymmetry
- **Masses ordering and absolute value?**
  - Inverted or Normal hierarchy
  - Lepton number
- **How do neutrinos get their masses?**

Neutrinoless double beta decay ($0\nu\beta\beta$) is a promising probe to answer some of those questions.

What is double beta decay?


M. Goeppert-Mayer (1935)


W. Furry (1939)

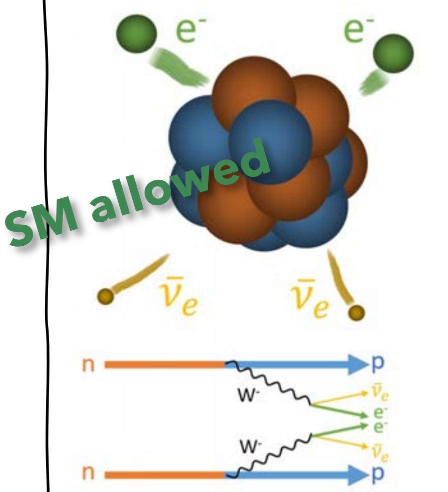
Very rare nuclear transition

- 2^{nd} order weak process in the SM
- Only possible for even-even nuclei, with forbidden single-β decay.

Neutrinoless Double Beta decay (0νββ):

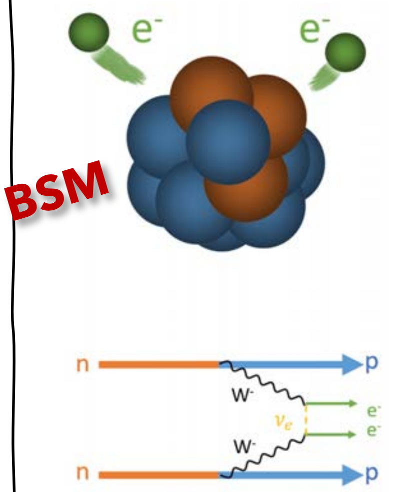
- Light massive Majorana neutrinos
- Lepton number violation ➞ BSM Physics

Two-neutrino Double Beta Decay (2νββ)



$(A,Z) \rightarrow (A,Z+2) + 2e^- + 2\bar{\nu}_e$

Neutrinoless Double Beta decay (0νββ)

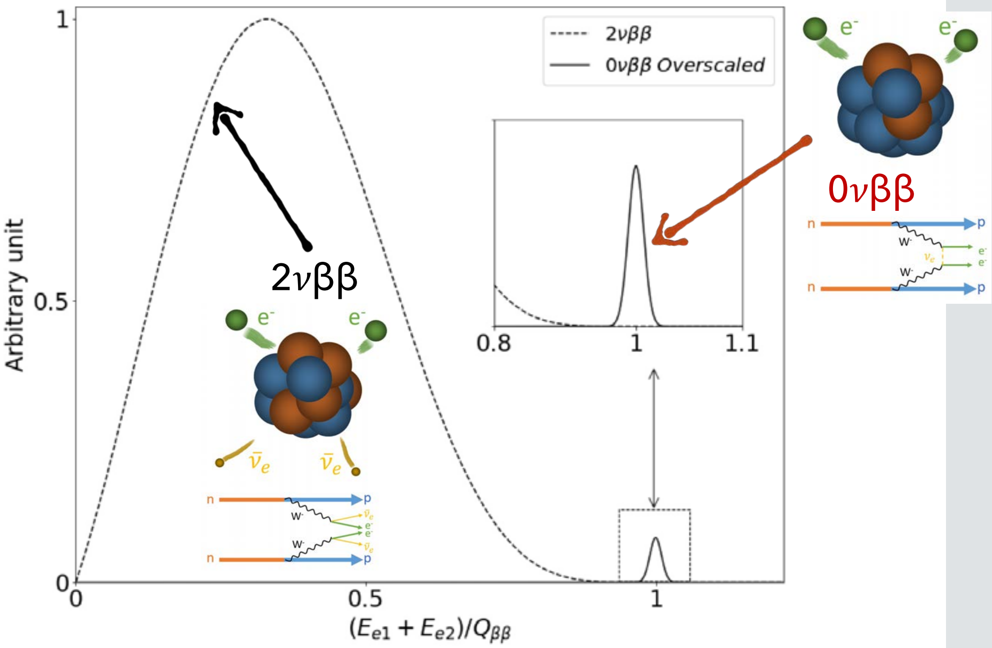


$(A,Z) \rightarrow (A,Z+2) + 2e^-$

*Alternative decay mode
$2\nu ECEC: \ (A,Z) + 2e^- \rightarrow (A,Z-2) + 2\nu_e$

What are we looking for?

The signal is an **elusive peak @ $Q_{\beta\beta}$**
over an almost **flat background**



The experimentally relevant candidates

^{100}Mo, ^{136}Xe, ^{76}Ge, ^{130}Te, ^{82}Se

- High Q-value ~2-3 MeV (above most of background)
- High isotopic abundance and/or possibility of isotopic enrichment

Rare events never observed with

$$T_{1/2}^{0\nu\beta\beta} > 10^{24} - 10^{26}\ yr$$

Rare events search

→ Low background experiments

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XENON Dark Matter Project

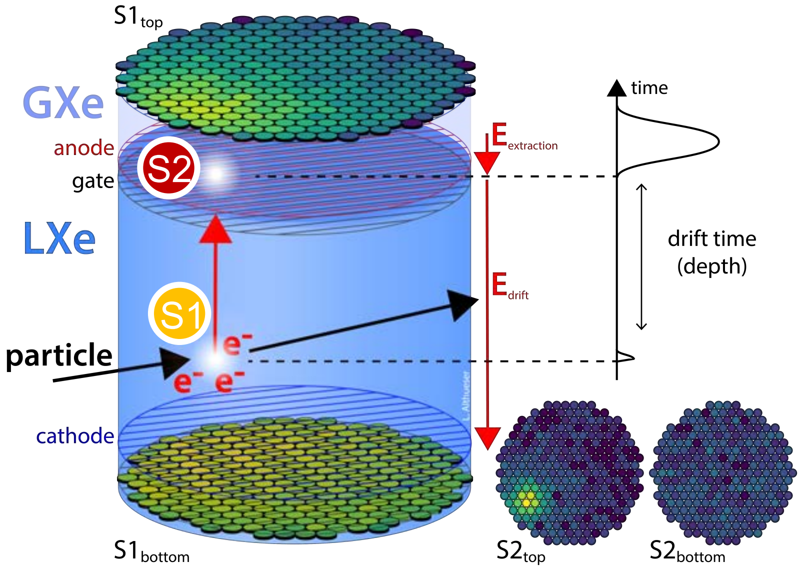
Columbia · KIT · Nikhef · Muenster · Stockholm · Mainz · MPIK, Heidelberg · Freiburg · Zurich · Chicago · Tsinghua · UCSD · Tokyo · Rice · Nagoya · Purdue · Kobe · Subatech · Coimbra · LPNHE · Torino · Bologna · L'Aquila · LNGS · Napoli · Weizmann · NYUAD

Time	2005	2008	2016	2021	>2030	
	XENON10	XENON100	XENON1T	XENONnT	DARWIN	
Active mass	15 kg	62 kg	2.0 t	5.9 t	*40 t	
Background	~1000	5.3	0.2	*0.04	-	[t.day.keV]$^{-1}$
Sensitivity	~10^{-44}	~10^{-45}	~10^{-47}	*~10^{-48}	*~10^{-49}	[cm^2]

* → Projections

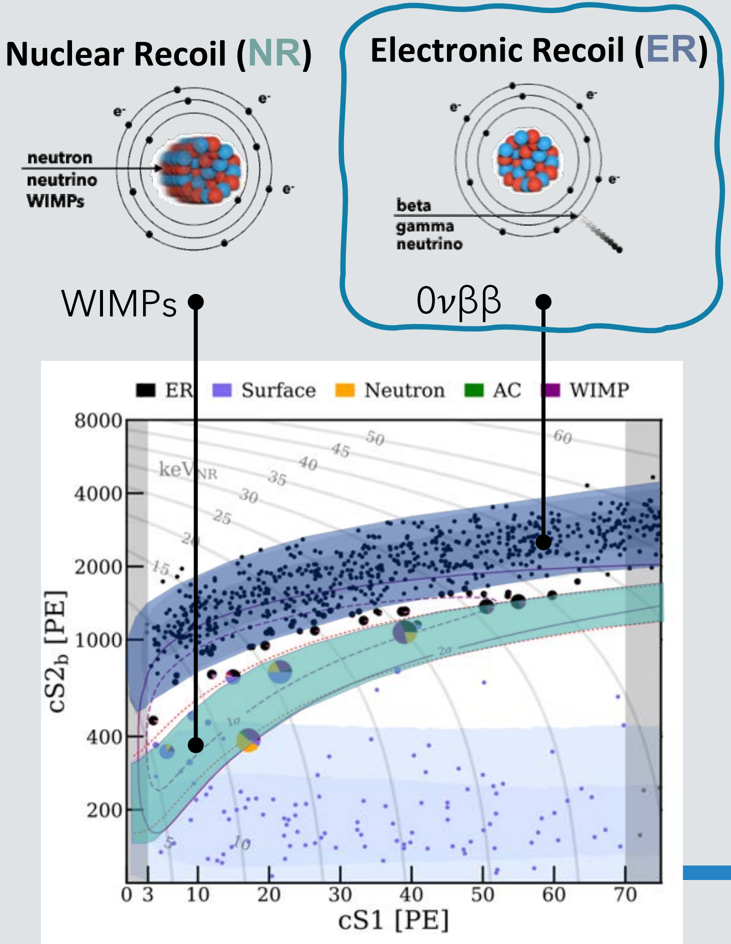
Sensitivity Improvements

XENON dual-phase TPC



Combination of **S1** and **S2** signals allows for:

- 3D Position reconstruction
- Energy reconstruction
- **ER**/**NR** discrimination through **S1**/**S2** ratio

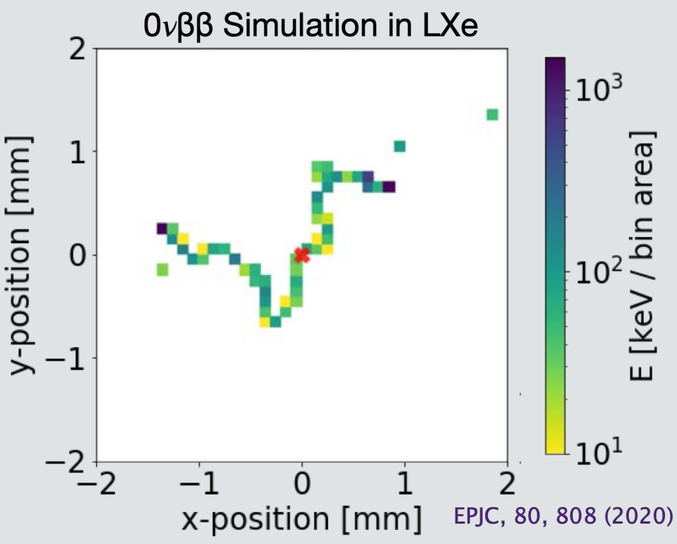


0νββ experimental requirements

Sensitivity $S^{0\nu} \propto \frac{\alpha}{A} \cdot \sqrt{\frac{M \cdot t}{\Delta E \cdot b}}$

Isotopic abundance (α)
FV mass (M)
Livetime (t)
Atomic mass (A)
Resolution @ $Q_{\beta\beta}$ (ΔE)
Background index (b)

- ^{136}Xe candidate Isotope: **natural abundance of 8.9%**
- Exposure: **1 t • yr (XENON1T) 20 t • yr (XENONnT)**
- Resolution @ ^{136}Xe $Q_{\beta\beta}$ = 2457.8 keV
- Background: low-radioactivity underground experiments (3600 m.w.e)



EPJC, 80, 808 (2020)

Signal signature:

→ Single-Site events - high stopping power of LXe (< 3 mm for e- @ $Q_{\beta\beta}$)

→ Total deposited energy

$Q_{\beta\beta}$ = 2457.8 keV

From low to high energy analysis

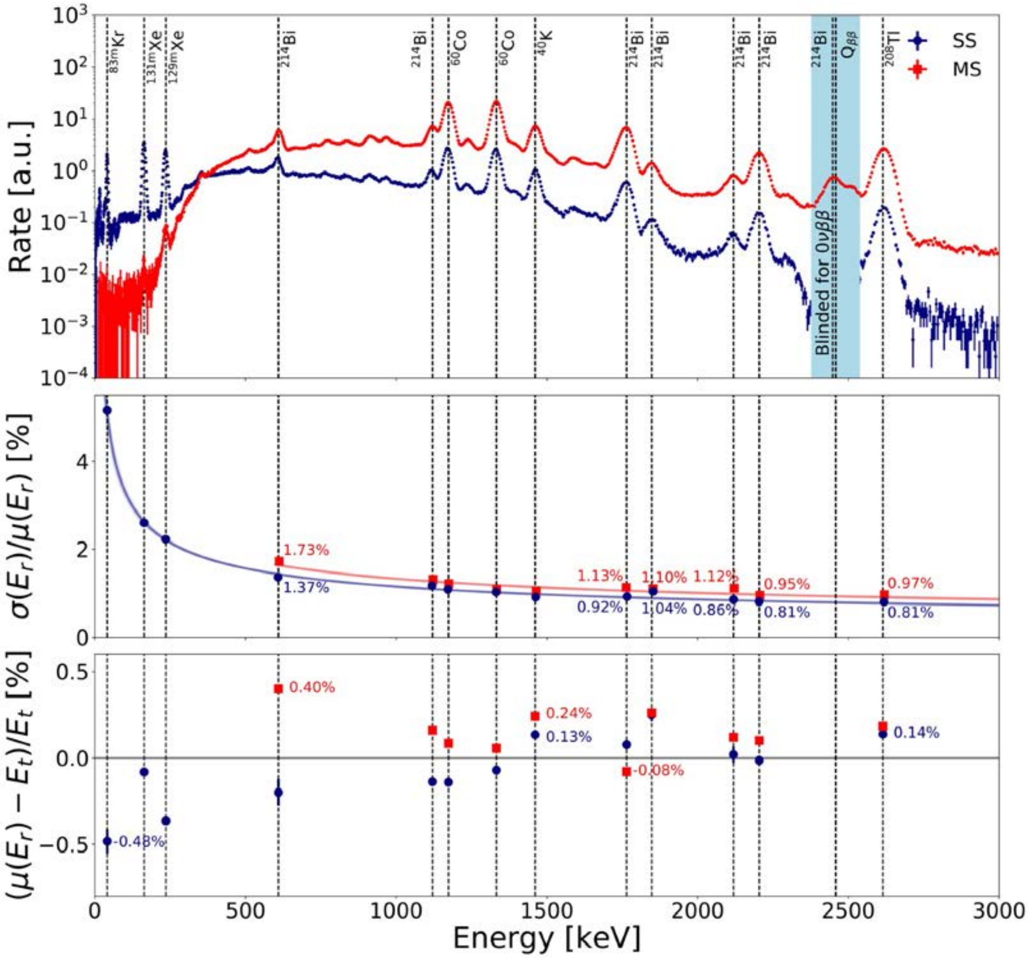
High Energies of O(MeV) in a detector optimized for **DM energies with O(keV)**

→ Dedicated correction needed against saturation effects in photosensors and digitisers

σ_E/E = 0.8 % at $Q_{\beta\beta}$ in XENON1T

- competitive with dedicated experiments like EXO
- Already confirmed and improved by LZ reaching 0.6 %.

REFERENCES	EPJC 80:785 (2020) | ARXIV:2003.03825



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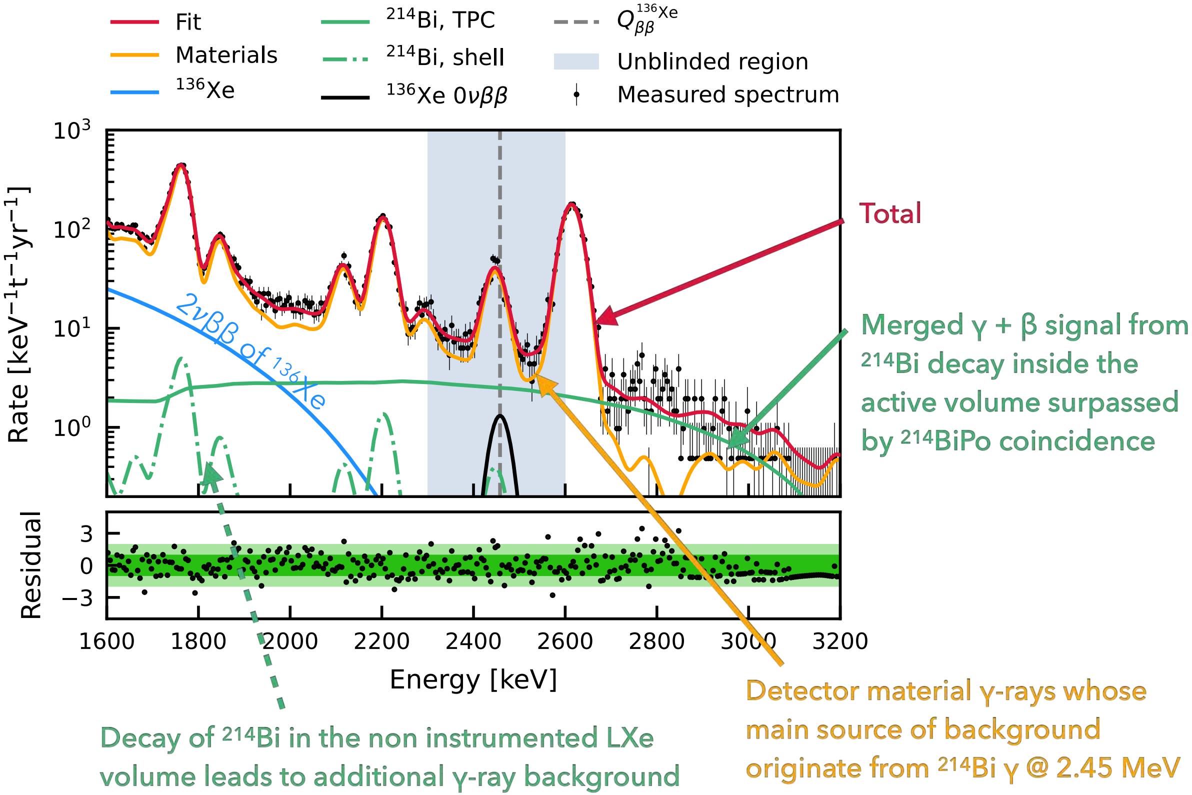
0νββ Analysis Result in XENON1T



Science data **blinded** between 2300 and 2600 keV (±3σ @ $Q_{\beta\beta}$).

SS in 741 kg optimal fiducial volume.

Background components according to expectation (MC simulation studies).

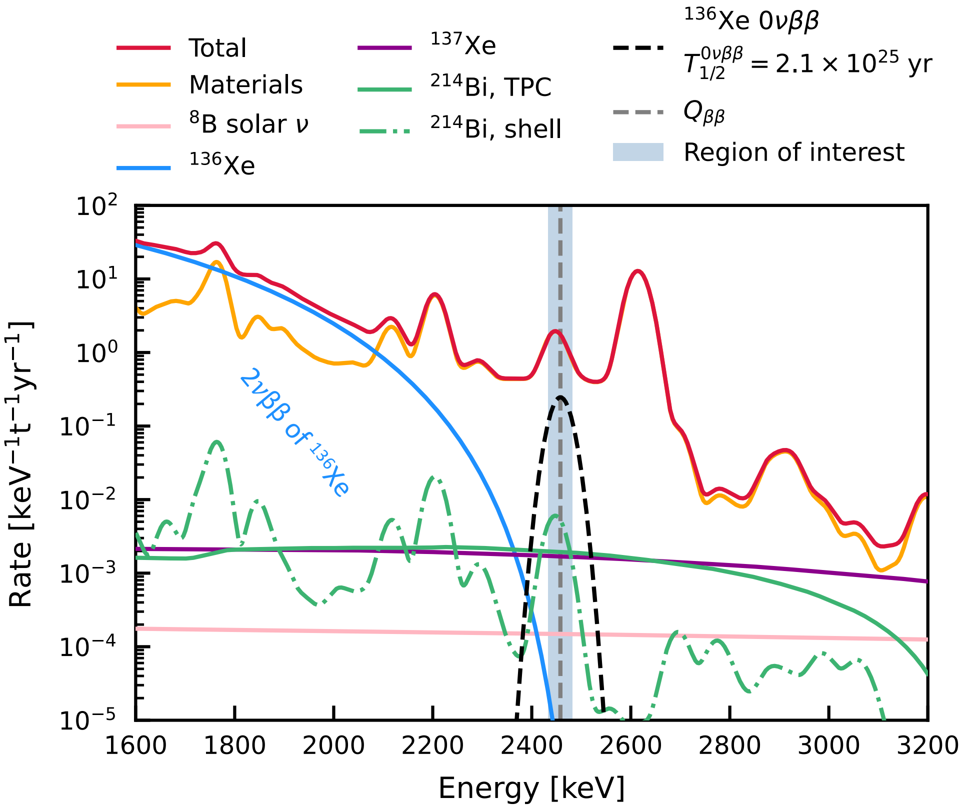
Acceptance of 85.2 % at $Q_{\beta\beta}$.

Lower limit at 90 % CL from profiled likelihood ratio:

$$T_{1/2}^{0\nu\beta\beta} > 1.2 \times 10^{24}\,\mathrm{yr}$$

Most stringent limit to date by a non-enriched dark matter detector

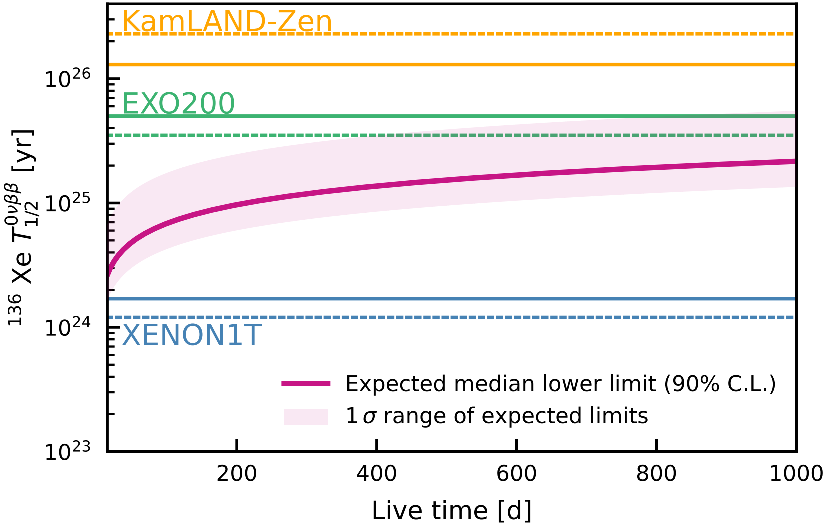
0νββ Sensitivity projection for XENONnT

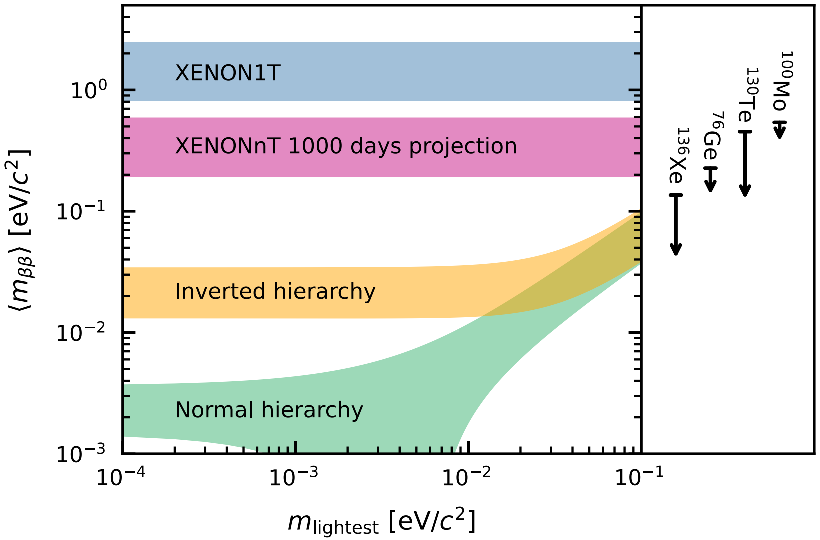


- Same analysis region and method as in XENON1T.
- **91.0 % SS efficiency** for 0νββ signals.
- 1124 kg optimal fiducial volume.
- Also consider **radiogenic and cosmogenic ^{137}Xe** as well as ^{8}B solar neutrinos-electrons scattering due to overall lower background.
- Projected sensitivity at 90% CL:

$$T_{1/2}^{0\nu\beta\beta} > 2.1 \times 10^{25}\,\mathrm{yr}$$

0νββ Sensitivity projection for XENONnT





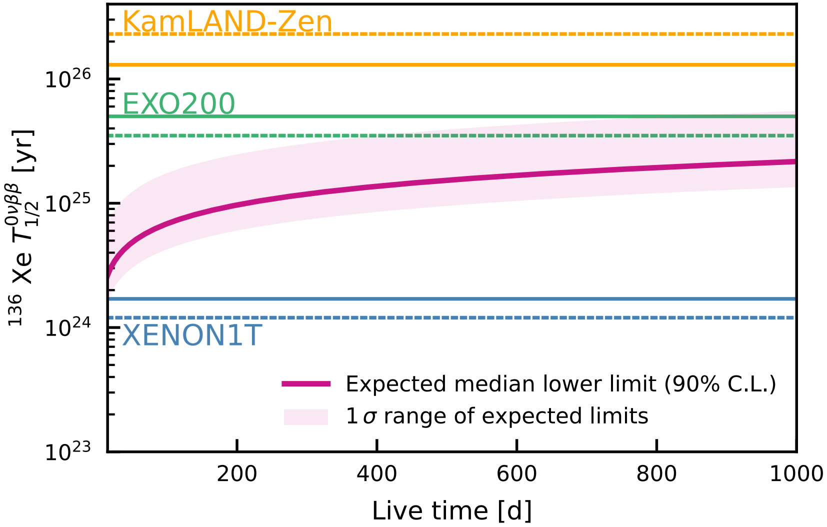
Not competitive with dedicated experiments due to:

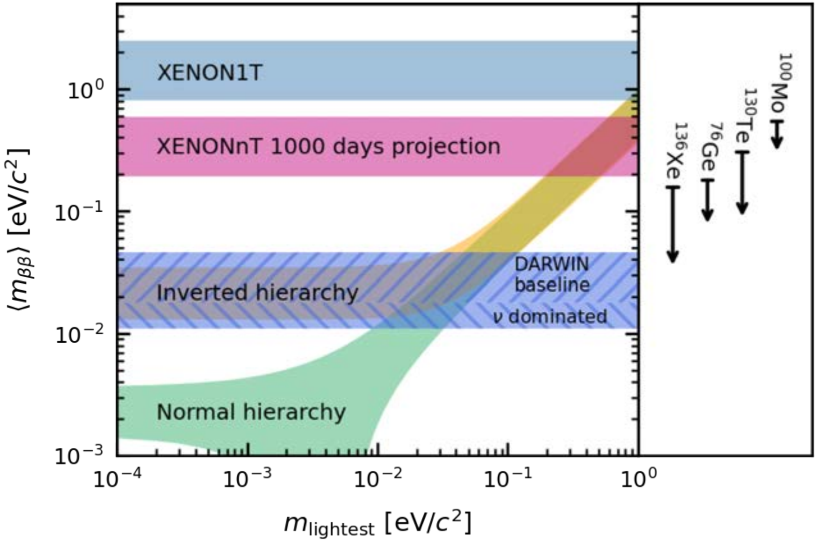
- Non-enriched target.
- Background optimization for DM searches (SS Cryostat).

Result demonstrates feasibility in future Xe DM experiments

0νββ Sensitivity projection for XENONnT | DARWIN

DARWIN





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DARWIN approaches sensitivity of the future tonne-scale 0νββ experiments while being dedicated to DM search.

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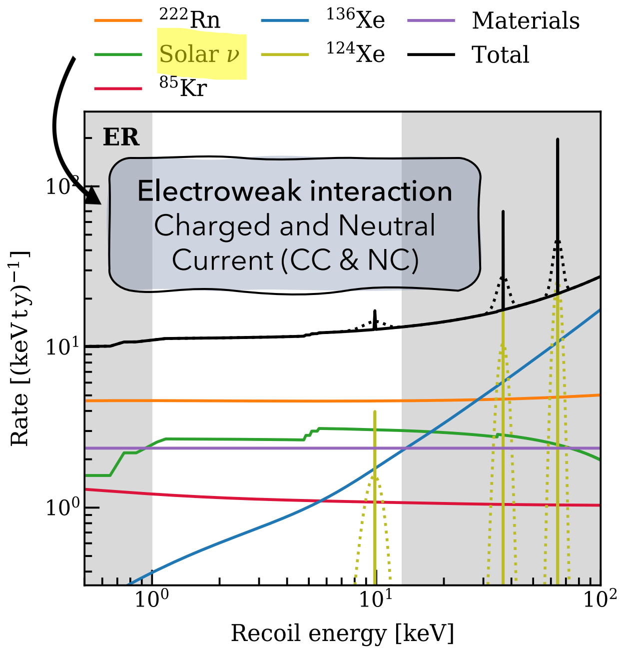
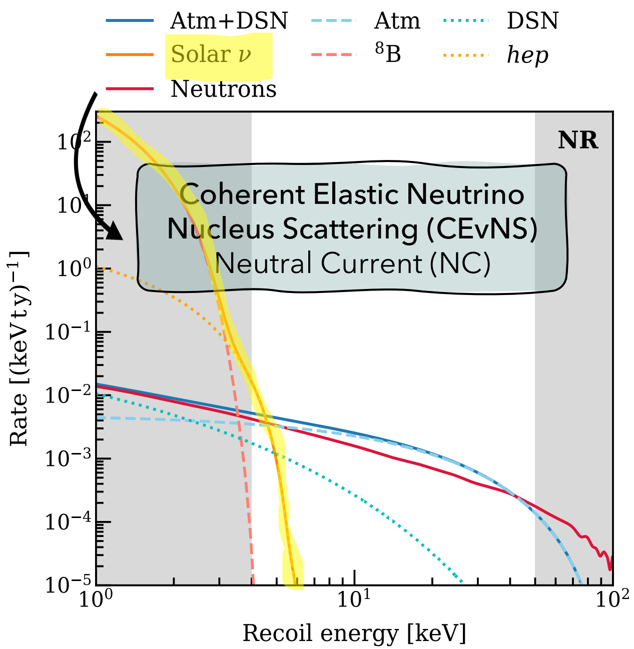
Solar Neutrinos

XENONnT WIMP background projection

JCAP 11 (2020) 031





$$\frac{d\sigma(E_\nu, E_R)}{dE_R} \propto N^2$$

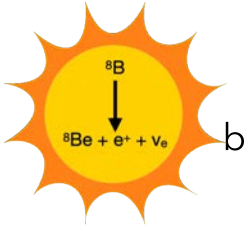
N: Number of neutrons
→ Xe suitable for CEvNS

Irreducible Background source for direct DM detection.

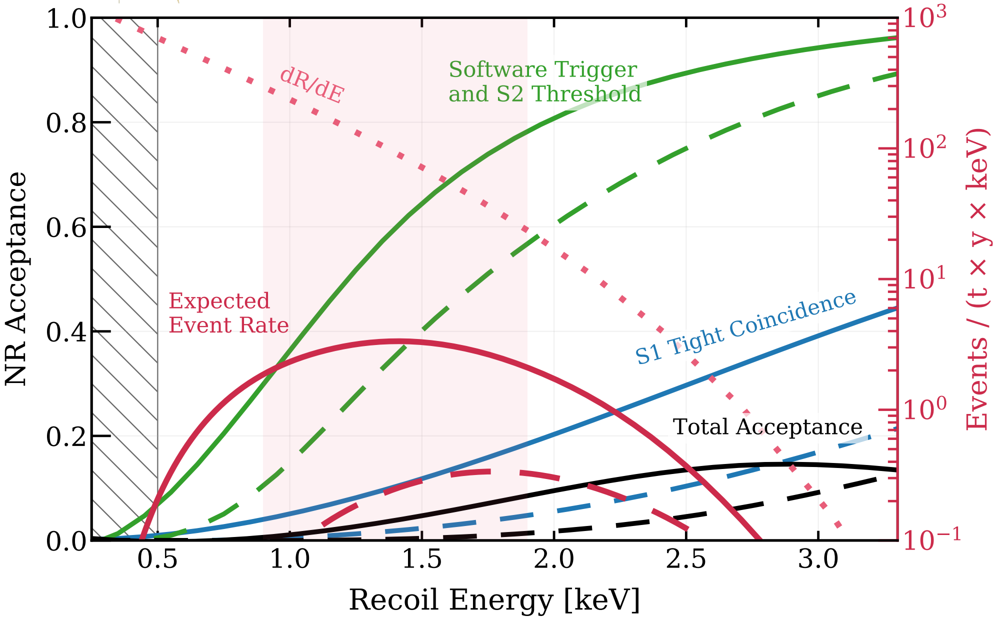
Already relevant in XENONnT.

Can be seen as a signal too.

^{8}B CEvNS interaction



In XENON1T, ^{8}B CEvNS falls far below our previous analysis threshold.
➞ 0.01% signal acceptance!



From low to very low energy analysis

Analysis challenge:

Expected spectrum is at very low energies

Improvements in energy threshold required

- Coincidence requirement for S1s from ~~thre~~ photons to **two**
- Lower energy threshold for ^{8}B CEvNS from ~~2.6keV~~ to **1.6keV**

^{8}B CEvNS interaction

XENON1T Result:

No positive detection of CEvNS signal in XENON1T:

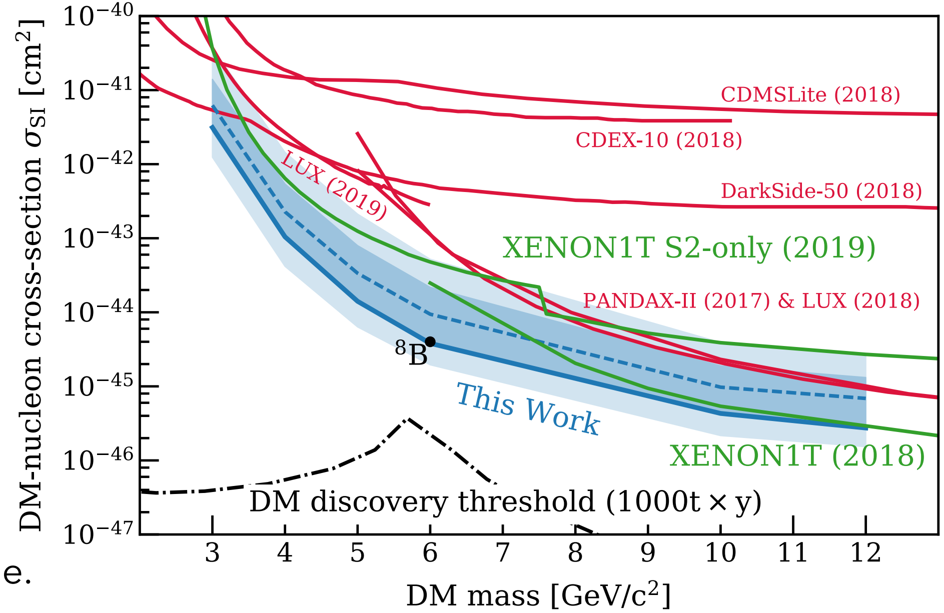
- Use lowered threshold to set improved low-mass WIMP limits down to **3 GeV/c2**.

First observation of CEvNS events from ^{8}B solar neutrinos is **highly expected** with **XENONnT**.

Next generation perspectives:

- Precise measurement of the neutral current component of the solar 8B neutrino flux.
- He proton (Hep) branch, Diffuse supernova, and Atmospheric neutrinos will be no longer negligible.

REFERENCES PRL 126, 091301 (2021) | ARXIV:2012.02846



Supernova Neutrino

PHYSICAL REVIEW D
covering particles, fields, gravitation, and cosmology

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Phys.Rev.D 94 (2016) 10, 103009

Supernova neutrino physics with xenon dark matter detectors: A timely perspective

Rafael F. Lang, Christopher McCabe, Shayne Reichard, Marco Selvi, and Irene Tamborra
Phys. Rev. D **94**, 103009 – Published 23 November 2016

Solar ν-e$^-$ elastic scattering

Open Access

Eur. Phys. J. C (2020) **80**: 1133
https://doi.org/10.1140/epjc/s10052-020-08602-7

Regular Article - Experimental Physics

EPJC 80:1133 (2020)

Solar neutrino detection sensitivity in DARWIN via electron scattering

DARWIN Collaboration, J. Aalbers[1], F. Agostini[2], S. E. M. Ahmed Maouloud[3], M. Alfonsi[4], L. Althueser[5], F. D. Amaro[6], J. Angevaare[7], V. C. Antochi[1], B. Antunovic[8], E. Aprile[9], L. Arazi[10], F. Arneodo[11], M. Balzer[12], L. Baudis[13], D. Baur[14], M. L. Benabderrahmane[11], Y. Biondi[13], A. Bismark[13,14], C. Bourgeois[15], A. Breskin[10], P. A. Breur[7], A. Brown[13], E. Brown[16], S. Brünner[7], G. Bruno[11], R. Budnik[10], C. Capelli[13], J. Cardoso[6], D. Cichon[17], M. Clark[18], A. P. Colijn[7], J. Conrad[1], J. J. Cuenca-García[19], J. P. Cussonneau[20], M. P. Decowski[7], A. Depoian[18], J. Dierle[14], P. Di Gangi[2], A. Di Giovanni[11], S. Diglio[20], D. Douillet[15], G. Drexlin[21], K. Eitel[19], R. Engel[19], E. Erdal[10], A. D. Ferella[22,23], H. Fischer[14], P. Fischer[24], W. Fulgione[25], P. Gaemers[7], M. Galloway[13], F. Gao[9], D. Giovagnoli[20], F. Girard[13], R. Glade-Beucke[14], F. Glück[19], L. Grandi[26], S. Grohmann[27], R. Größle[19], R. Gumbsheimer[19], V. Hannen[5], S.

XENONnT & DARWIN

DARWIN

- **Flavor blinded measurement** of neutrino flux through CEvNS events for the community .
- Contribution to the upgraded **SuperNova Early Warning System (SNEWS-2.0)** with XENONnT and DARWIN.

Precise measurements of electronic solar neutrino survival probability and electroweak mixing angle using pp neutrino

More Science Channels than "just" DM

NR

WIMPS

Spin-independent

PRL 119, 181301

PRL 121, 111302

Spin-dependent

PRL 122, 141301

Sub-GeV

PRL 122, 071301

PRD 103, 063028

Solar ^{8}B CEνNS

PRL 126, 091301

Light DM

PRL 123, 241803

PRL 123, 251801

2νECEC capture

Nature 568, 532

PRC 106, 024328

Bosonic DM

PRL 123, 251801 (low mass)

PRD 102, 072004 (2020)

arxiv 2207.11330 (2022)

0$\nu\beta\beta$ decay

PRC 106, 024328

Neutrino magnetic moment

PRD 102, 072004 (2020)

arxiv 2207.11330 (2022)

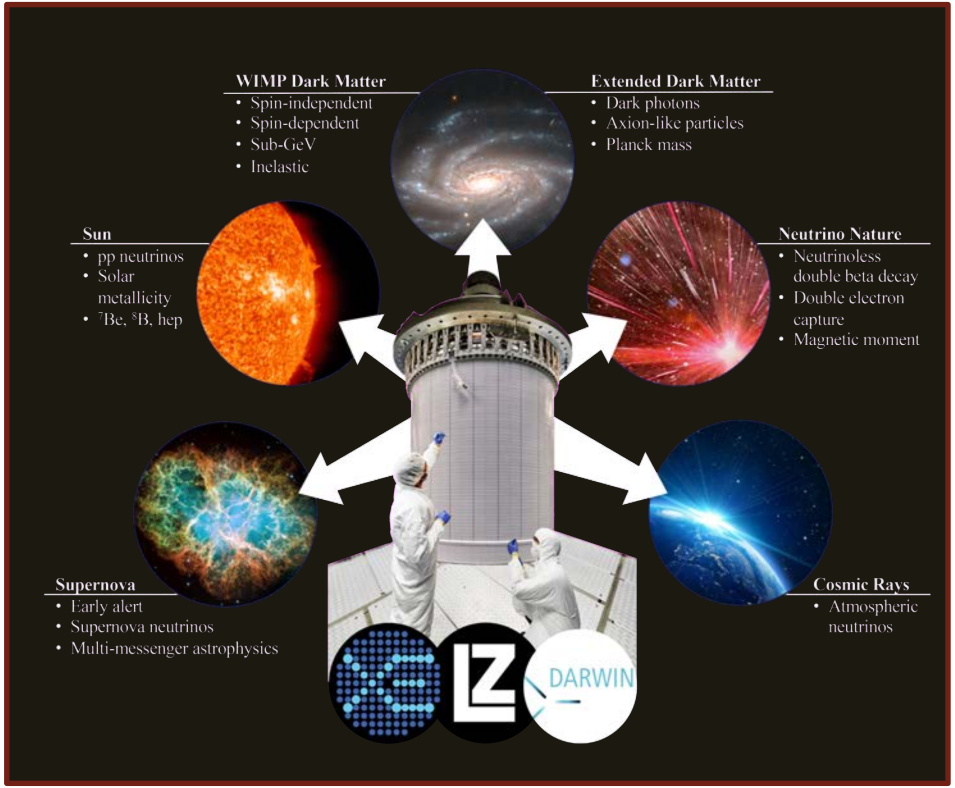
ER

Solar axions

PRD 102, 072004 (2020)

arxiv 2207.11330 (2022)

Towards LXe Observatory



Merger of leading collaborations for a future DARWIN/G3 Xenon-based experiment

xlzd.org

CONCLUSION

- The XENON project already demonstrated its world leading result in WIMP direct detection.
- **^{136}Xe 0vbb search feasible**, despite material background
- **Broadening of the physics program towards neutrino physics with the current and next generation of detector** ($0\nu\beta\beta$, CEvNS, solar neutrinos, etc).

xenonexperiment.org

xenon_experiment

xenonexperiment

Thank you for your attention !

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