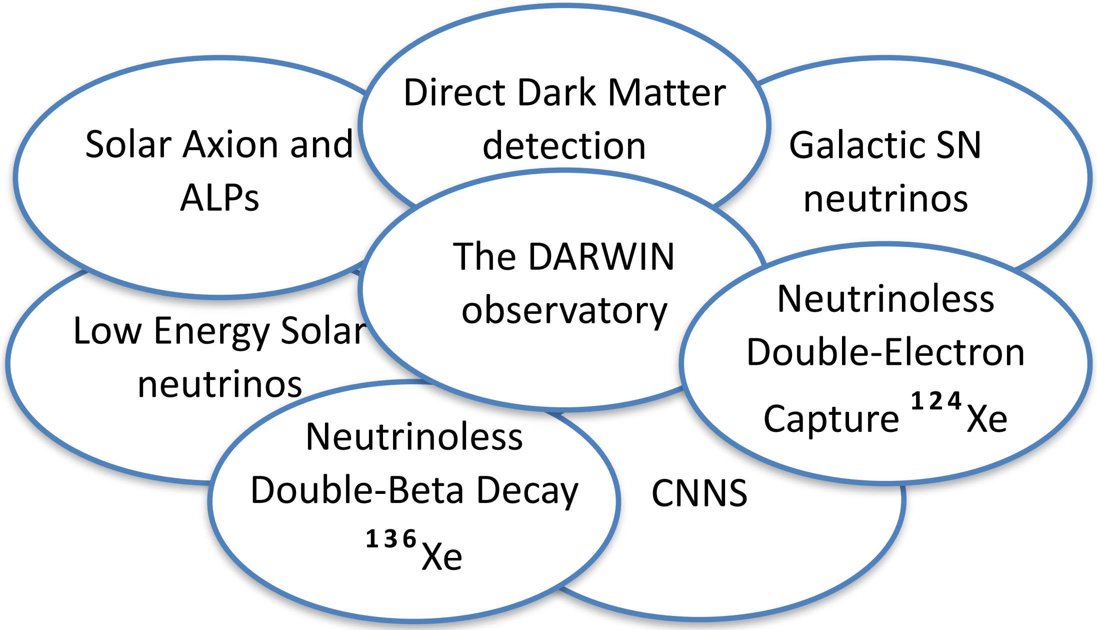
The DARWIN experiment: the ultimate detector for direct dark matter search

Adriano Di Giovanni for the DARWIN collaboration
adriano.digiovanni@nyu.edu

جامعة نيويورك أبوظبي
NYU | ABU DHABI

ICHEP 2020 - July 29, 2020

Much more than a DM detector



Major challenges:

- **Build and Operate the largest LXe target ever**
- **Unprecedented level of cleanliness**
- **Highest light collection efficiency**
- **The largest storing capability of xenon on Earth**
- **Xenon procurement (~ yearly worldwide production)**

DM direct detection: exploiting the effects

SIMPLE
PICO
…

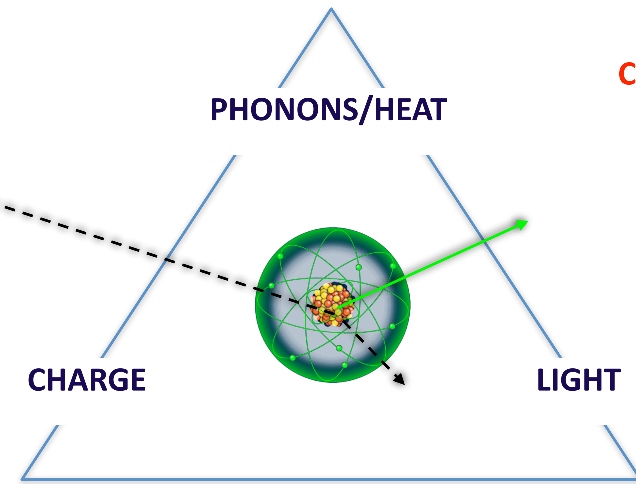
(cryogenic bolometers/ superheated liquids)

(cryogenic bolometers+charge collection)

SuperCDMS
EDELWEISS
…

CRESST
…

(scintillating cryogenic bolometers)



(Ge detectors/ directional detectors)

COGENT
TEXONO
CDEX
DMTPC
DRIFT
MIMAC
Newage
…

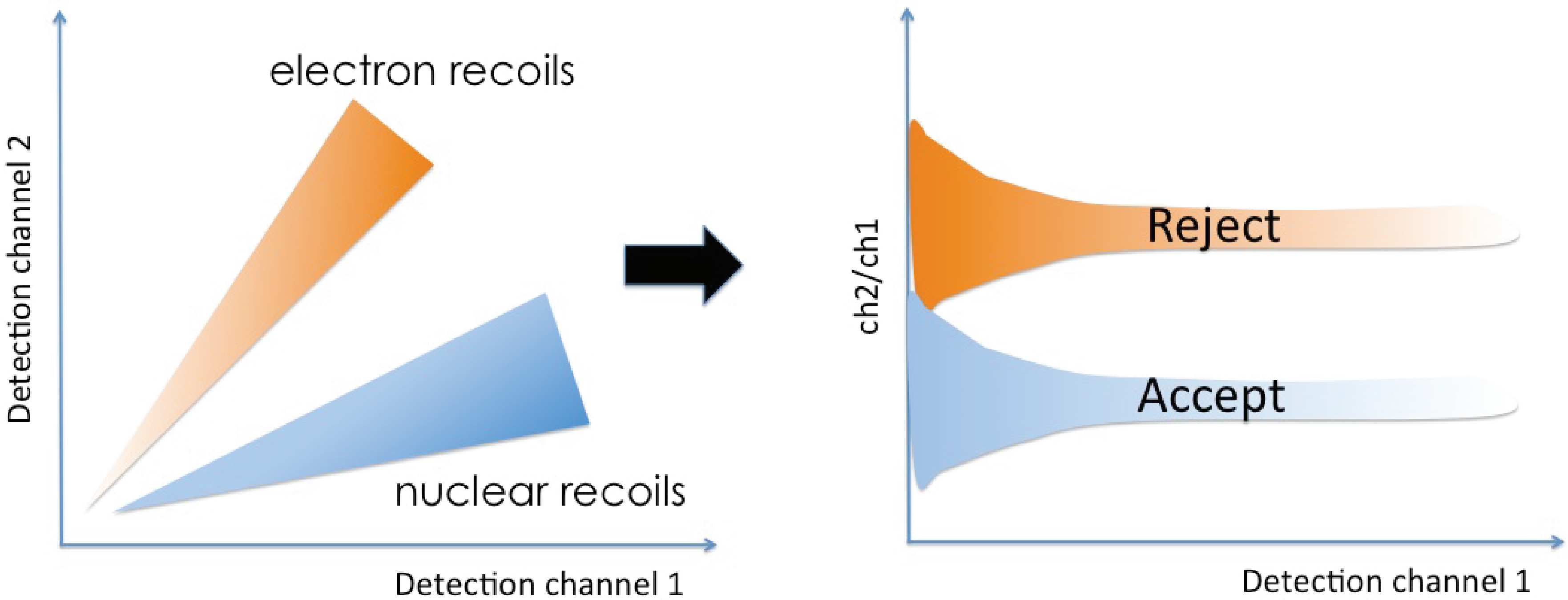
LZ
XENON
DARKSIDE
PANDA-X
DARWIN
…

(dual-phase liquid noble gas detectors + TPCs)

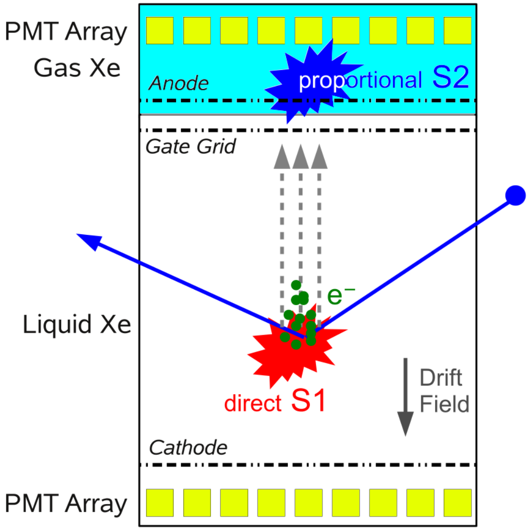
DEAP
CLEAN
DAMA/LIBRA
XMASS
COSINE
SABRE
…

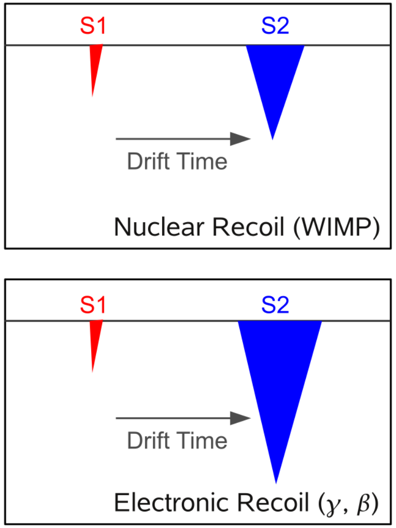
(scintillating crystals/ liquid noble gas detector

(A possible) Detection strategy



The detection strategy: ER vs NR

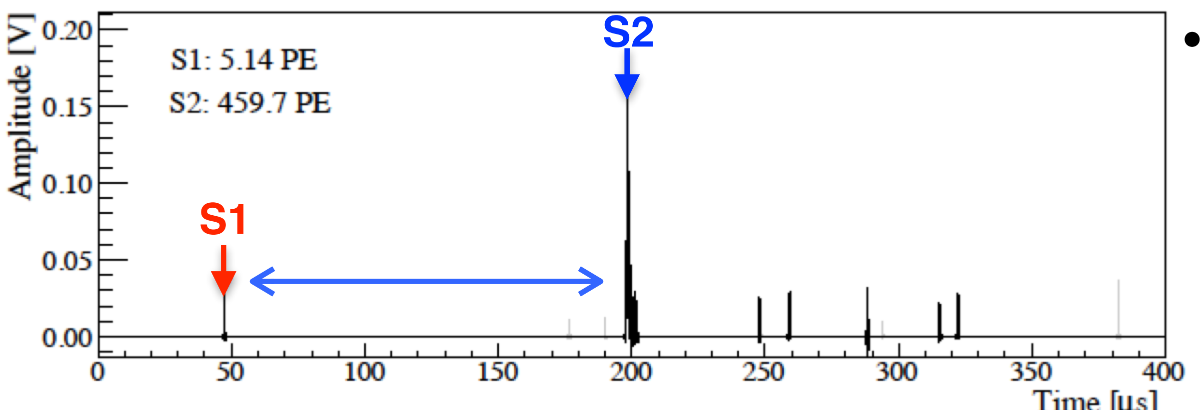




- **Two channels recorded: S1** from prompt scintillation **(Light)** and **S2** from delayed scintillation ($\propto$**Charge**)

$$\frac{S2}{S1}_{ER} > \frac{S2}{S1}_{NR}$$

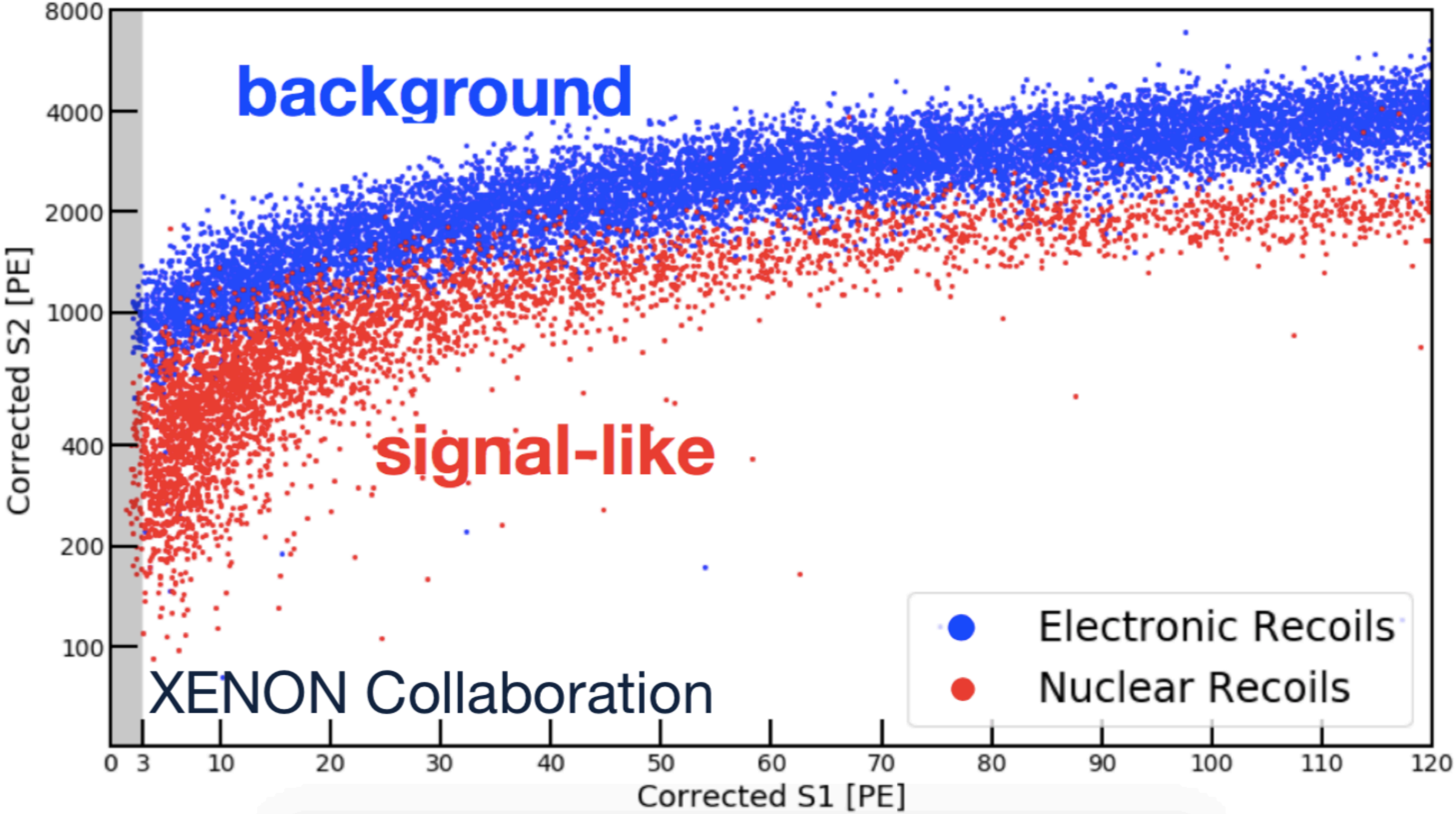
- **Pulse shape discrimination**
- **XY event positioning**



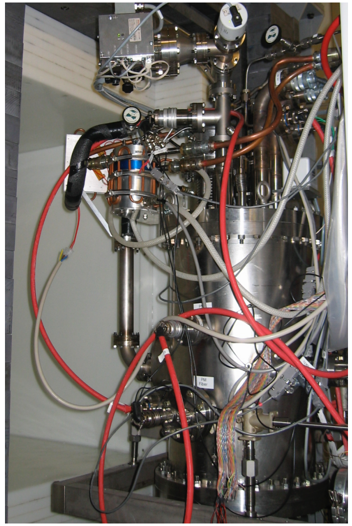
- **Z positioning from the drift time** *(knowing the operating parameters)*

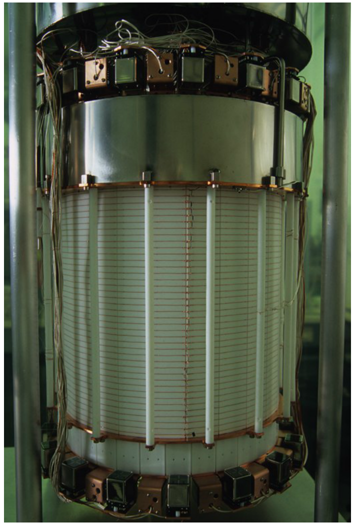
Position resolution ~ mm

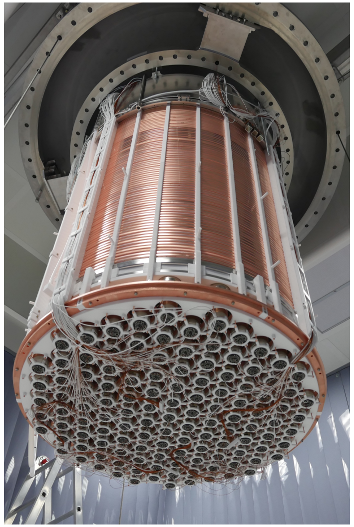
The detection strategy: ER vs NR



The benchmark: the XENON legacy at LNGS

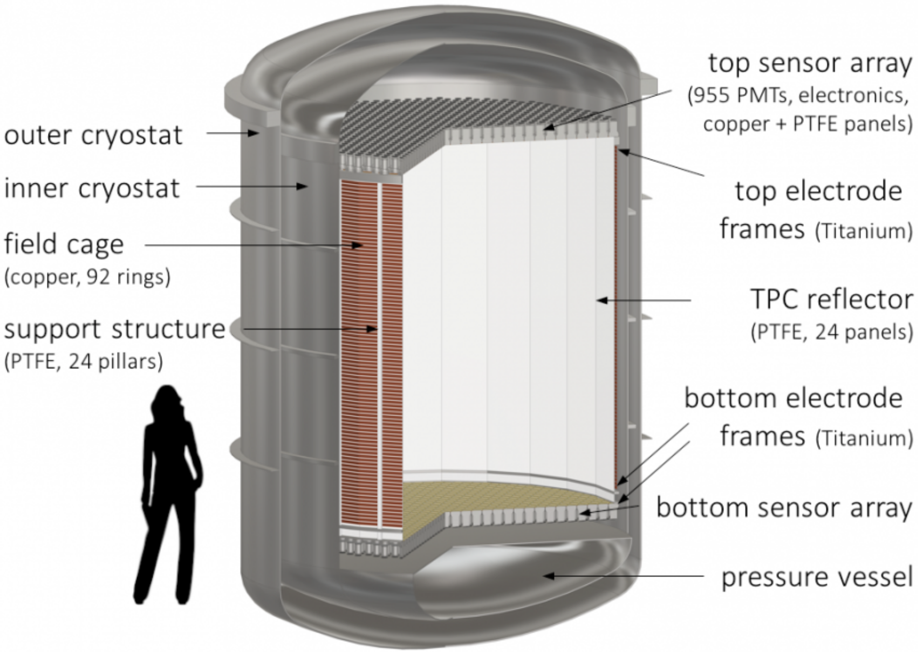






	XENON10	XENON100	XENON1T	XENONnT
Livetime [yyyy]	2005-2007	2008-2016	2015-2018	2020-202x
Xe mass [kg]	25	161	2300	8400
Target m [kg]	15	62	2000	5900
Drift [cm]	15	30	96	150
VETO	NO	NO	Muons	Muons+Neutrons
σ_{SI} [cm^2]	8.8 X 10^{-44} @ 100 GeV/c^2	1.1 X 10^{-45} @ 55 GeV/c^2	4.1 X 10^{-47} @ 30 GeV/c^2	**1.4 X 10^{-48} @ 50 GeV/c^2**

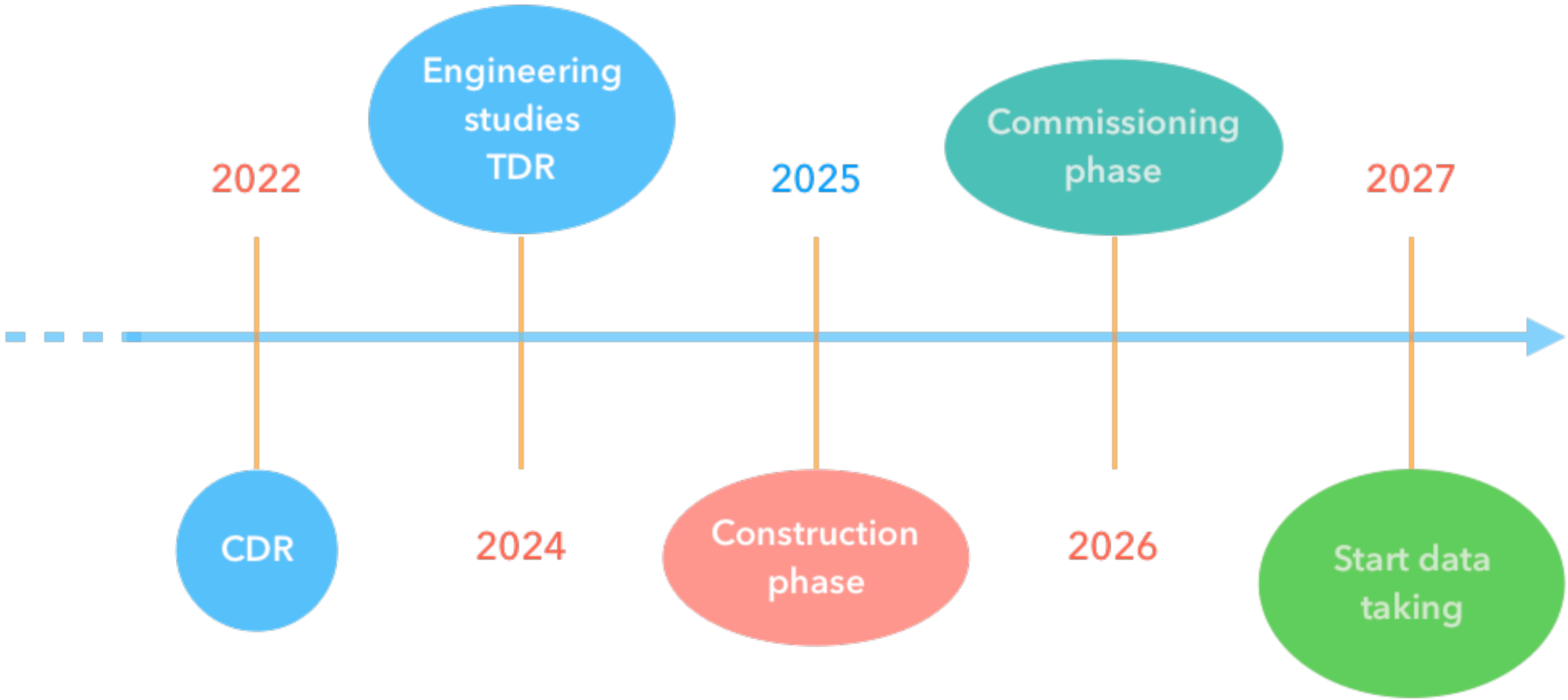
The DARWIN observatory



VETO	Muons+Neutrons
Livetime [yyyy]	2026-203x
Xe mass [kg]	50000
Target m [kg]	40000
Fiducial m [kg]	Up to 30000
Drift [cm]	260
σ_{SI} [cm^2]	Few X 10^{-49} @ 50 GeV/c^2

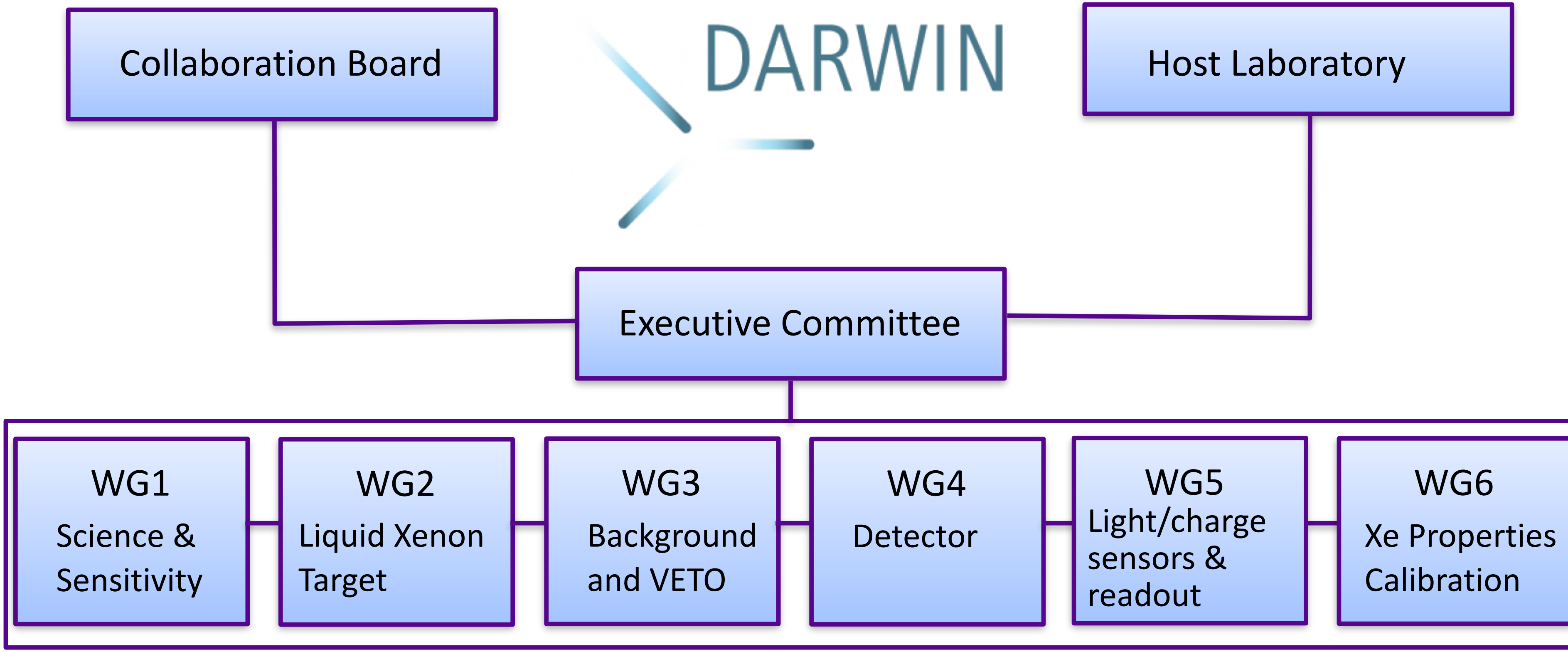
- **Dual-phase Time Projection Chamber (TPC)**
- **Two photo/charge sensor arrays (top and bottom)**
- **Low-background double-wall cryostat**
- **Outer shield filled with water (12 m diameter)**
- **Neutron/Muon Veto**

Time scale



2022
Engineering studies TDR
2025
Commissioning phase
2027
CDR
2024
Construction phase
2026
Start data taking

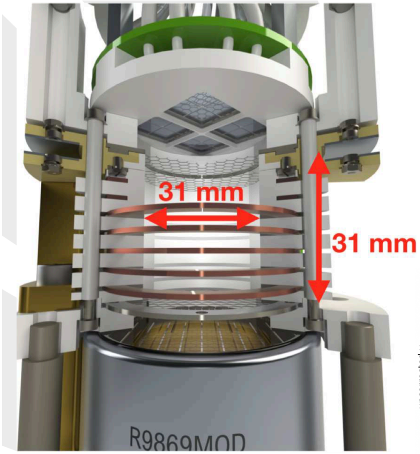
DARWIN: the project structure

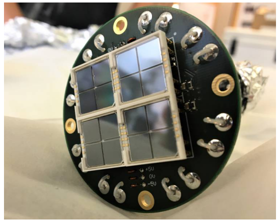


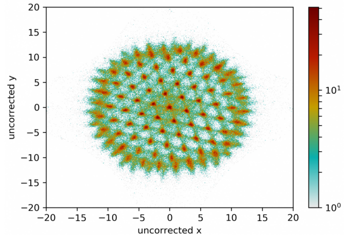
The community: more than 160 scientists, 29 institutions, 12 countries

Light and charge sensors & readout

Extensive SiPM/MPPC characterization in dedicated LXe test facilities



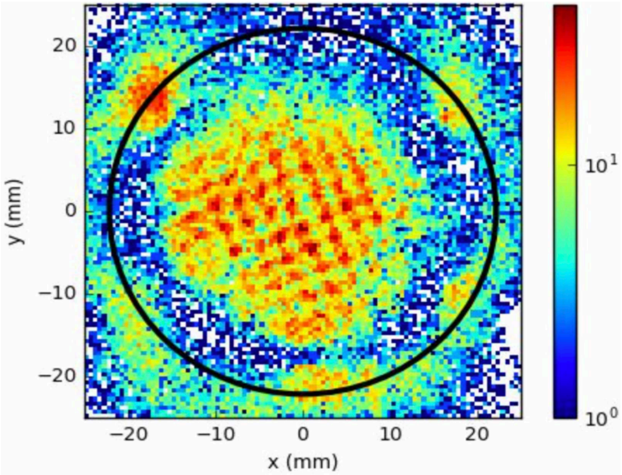


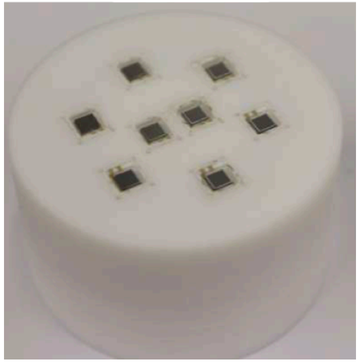


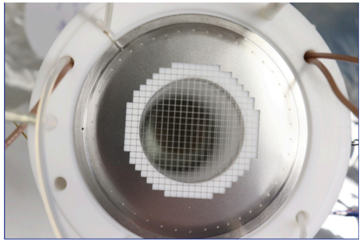
- *Small-scale R&D TPC*
- *Top array with 4×4 S13371 VUV-4 Hamamatsu*

Eur. Phys. J C 80 (2020) 477
JINST 13 (2018) P10022

Universität Zürich UZH







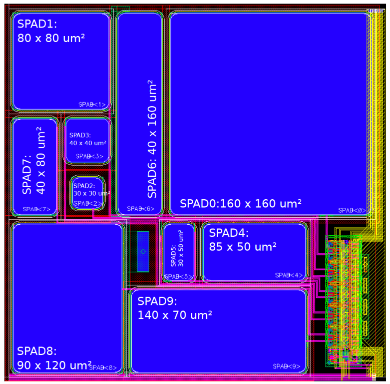
- *SiPMs for position reconstruction*
- *Field dependence of electronic recoils*
- *Pulse shape discrimination*

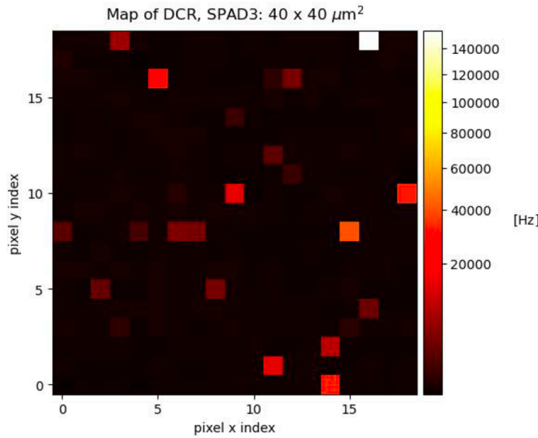
https://doi.org/10.1088/1748-0221/13/05/P05016
https://doi.org/10.1088/1748-0221/13/10/P10031

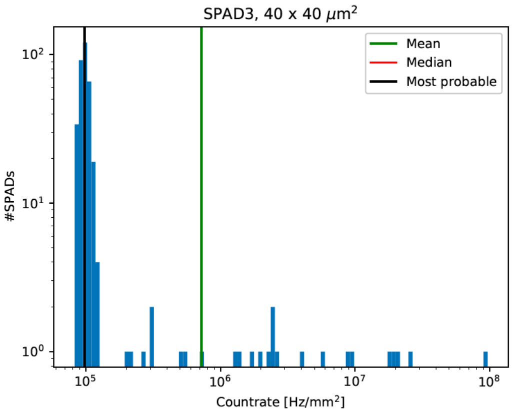
Nikhef

Light and charge sensors & readout

Digital SiPM



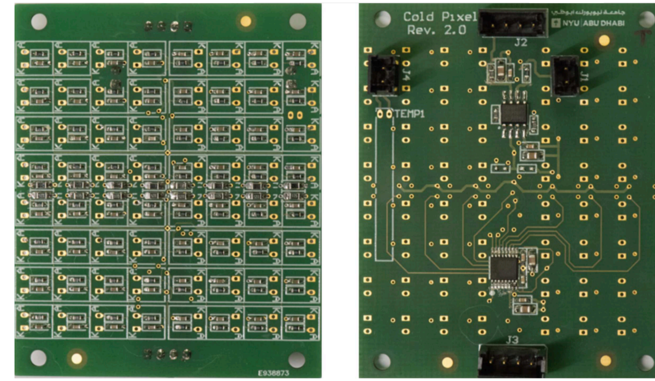


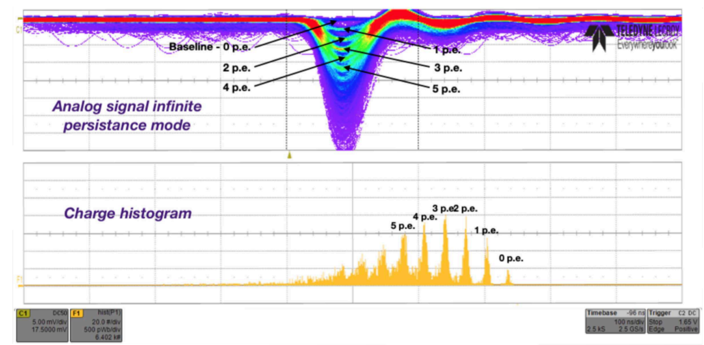


(Preliminary)

Single SPAD switching ON-OFF capability embedded.

Cryogenic Preamplifiers for VUV4 MPPC

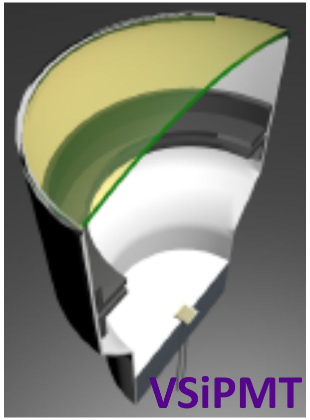


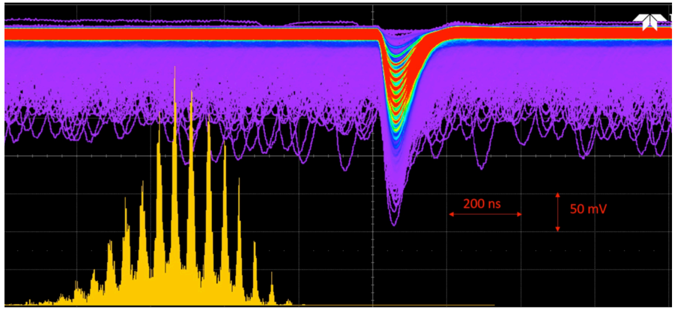


Multiple MPPCs operated as single channel

NIM A (2018) Vol. 893, 117-123

Light and charge sensors & readout



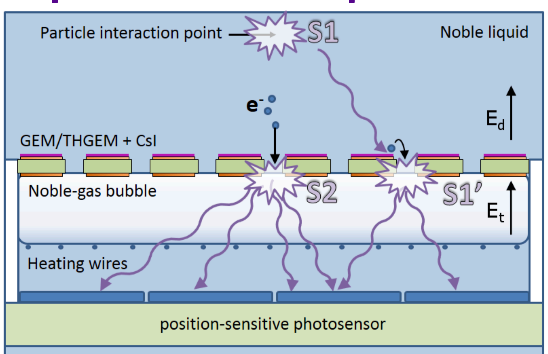


- *"PMT-Like" coverage*
- *HiRes Single Photon Detection Capability*
- *DCR typical of SiPM*

https://doi.org/10.1016/j.astropartphys.2015.01.003

Università degli Studi di Napoli Federico II — INFN Istituto Nazionale di Fisica Nucleare

Liquid Hole Multipliers in LXe



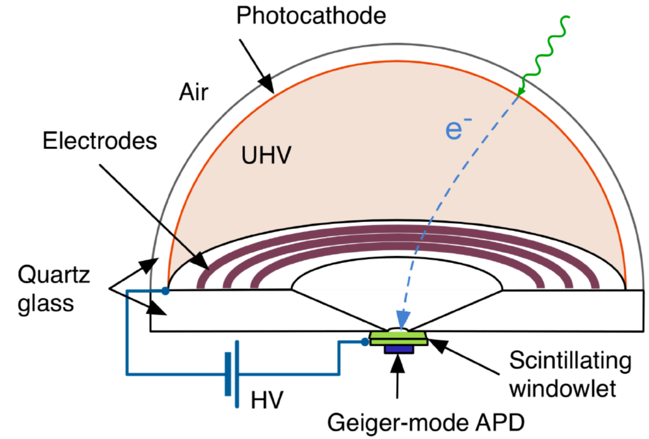
- *Very long term stability*
- *HiRes Position reconstruction*

https://doi.org/10.1088/1748-0221/13/12/P12008

מכון ויצמן למדע
WEIZMANN INSTITUTE OF SCIENCE

Patent Numbers: U.S. 9,064,678, US-2017-0123084

Abalone

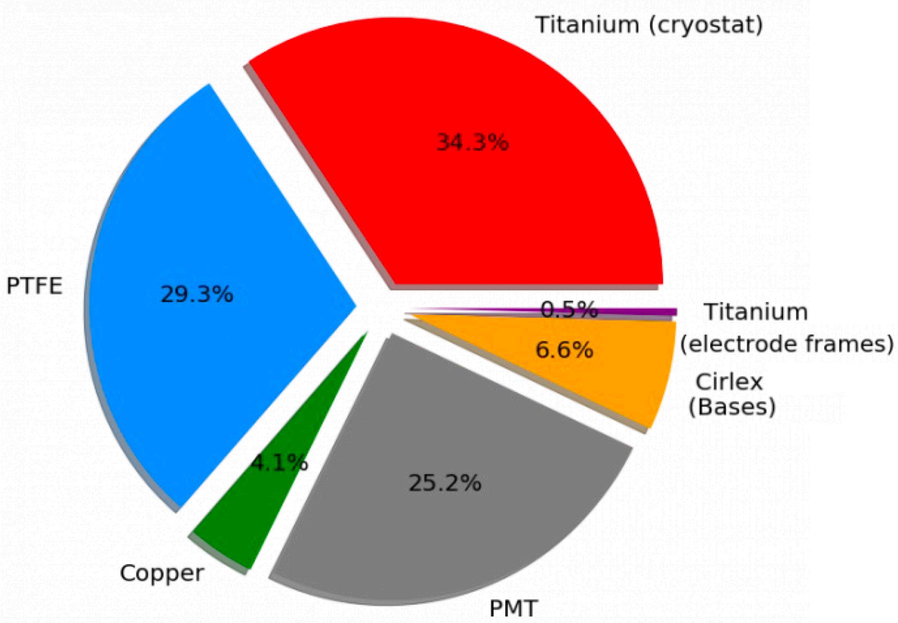


- *Huge area coverage*
- *Low DCR (similar/better than PMT)*
- *MidRes Single Photon Detection Capability*

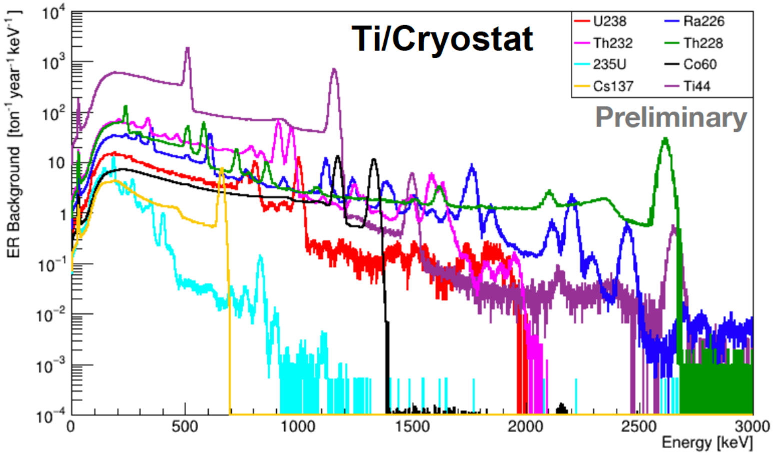
https://doi.org/10.1016/j.nima.2018.10.176

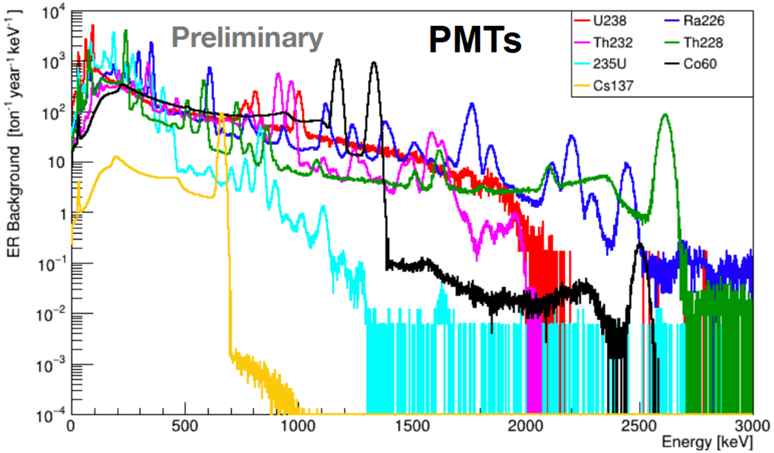
The most unwanted: the background

- Background MonteCarlo (Geant4) for ER + NR events.
- Radiogenic and cosmogenic contributions.
- Design (water shield, cryostat, veto, photosensor…) evaluation + optimization.
- Based on the already available and highly detailed screening DataBase of running experiments (XENON, LZ, …).



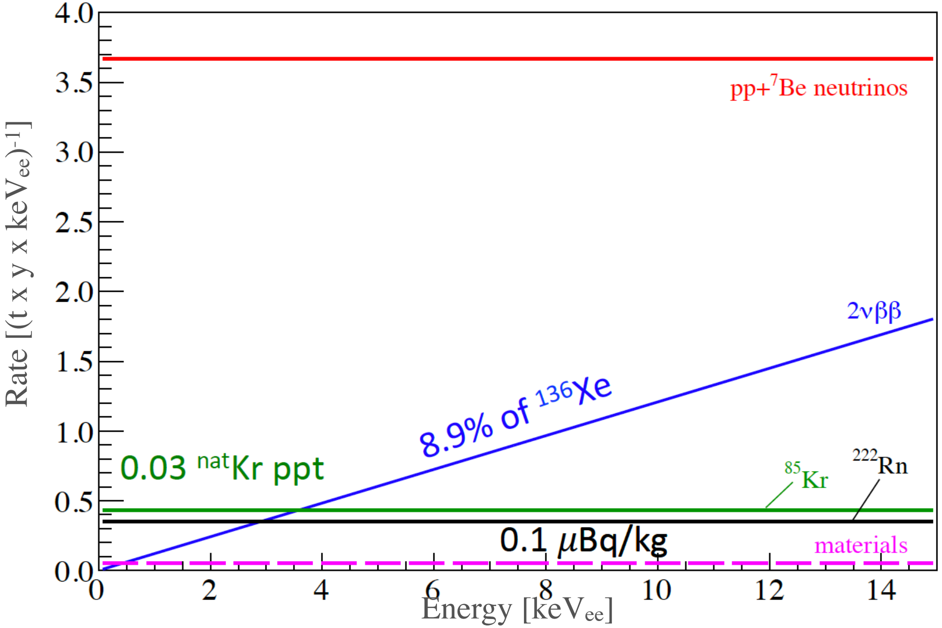
Radiogenic neutron Background, 30 t Fiducial Volume

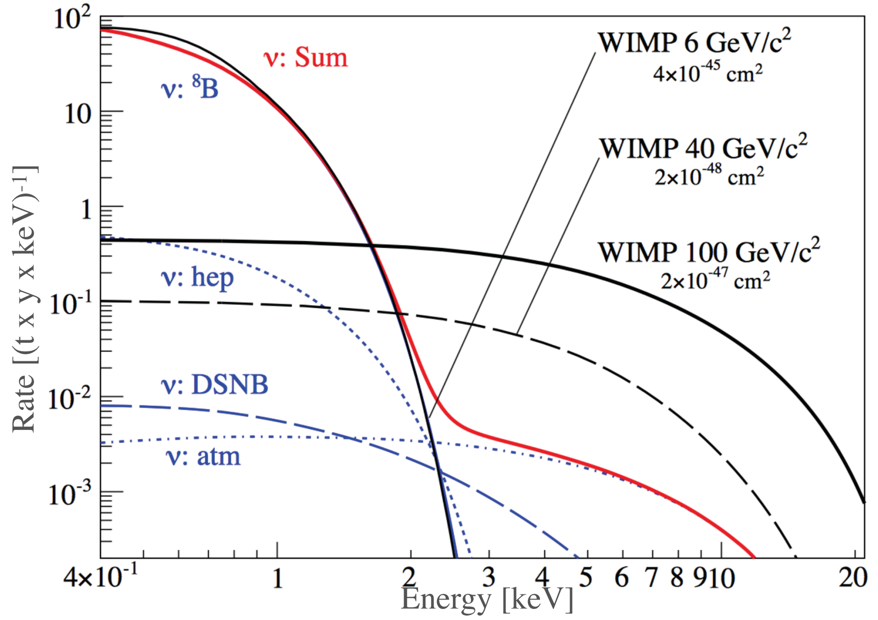




ER Background, No Fiducial Volume

The most unwanted: the background





Electron recoils (ER):

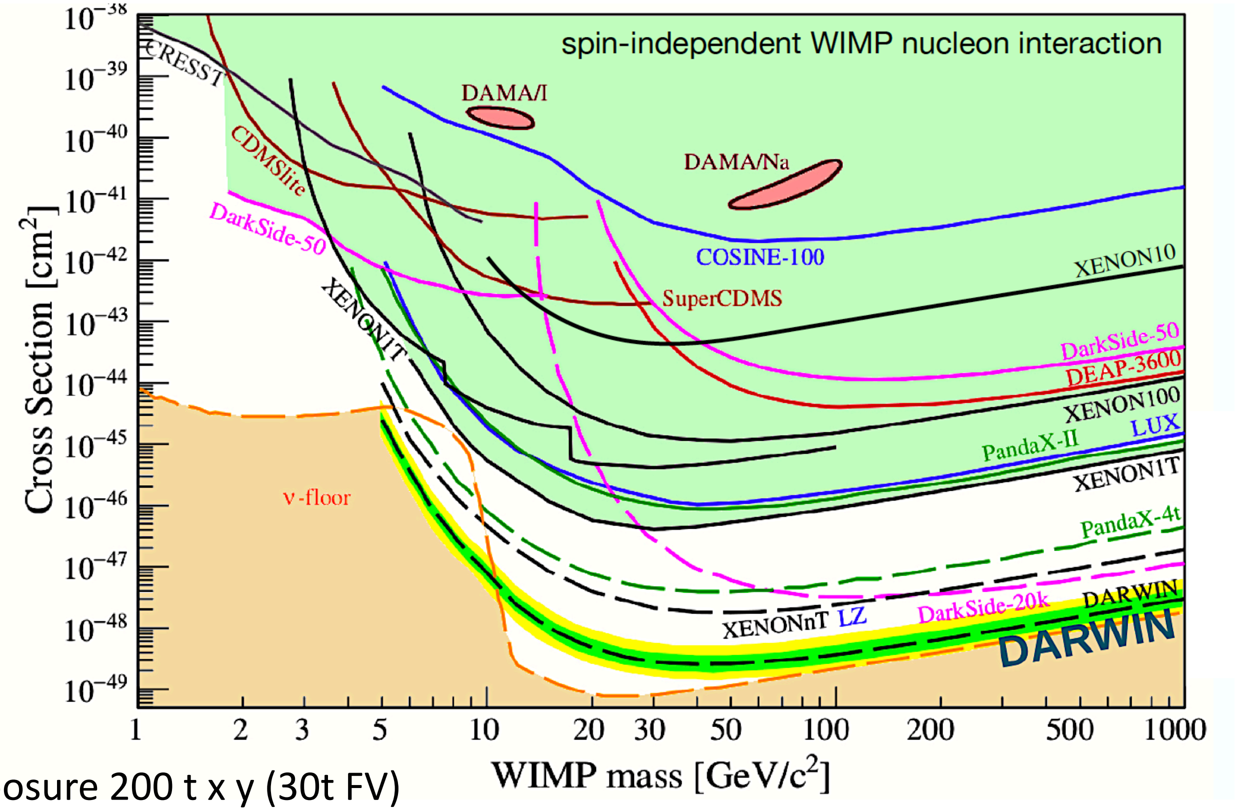
- low energy Compton: U and Th chains, ^{40}K, ^{60}Co, ^{137}Cs.
- Intrinsic contaminants: β decays of ^{222}Rn daughters, ^{85}Kr, ^{136}Xe.
- pp + ^{7}Be neutrino elastic scattering off electrons.

Nuclear Recoils (NR):

- Radiogenic neutrons: spontaneous fission and (alpha, n) reaction from the U and Th.
- Muon-induced neutrons.
- Coherent Neutrino (Xe) Nucleus Scattering events (CNNS).

GOAL: ER and NR background will be neutrino induced event dominated

Sensitivity to Spin Independent models



Assumed an exposure 200 t x y (30t FV)

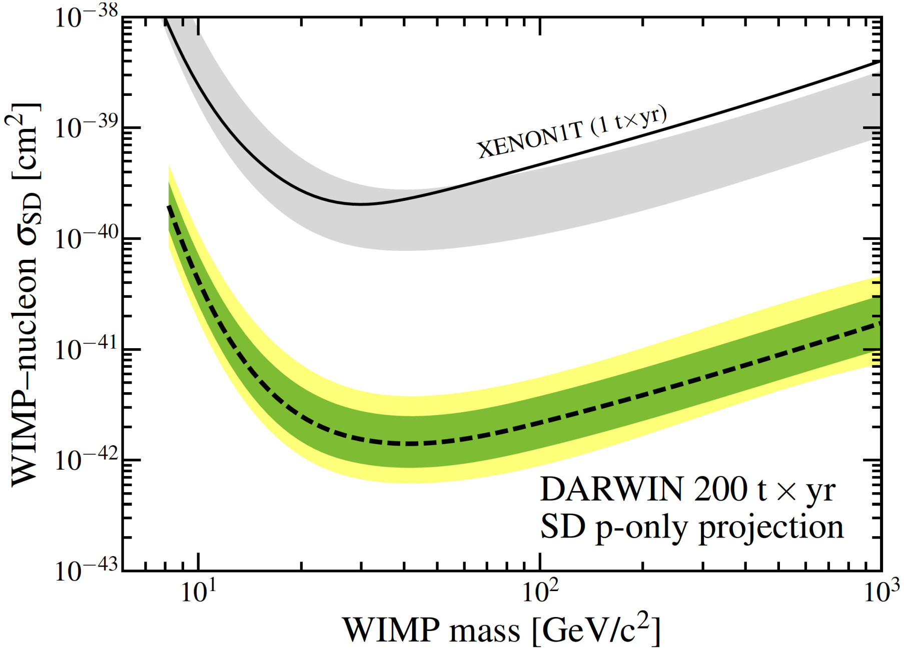
99.98% ER rejection (30% NR acceptance)

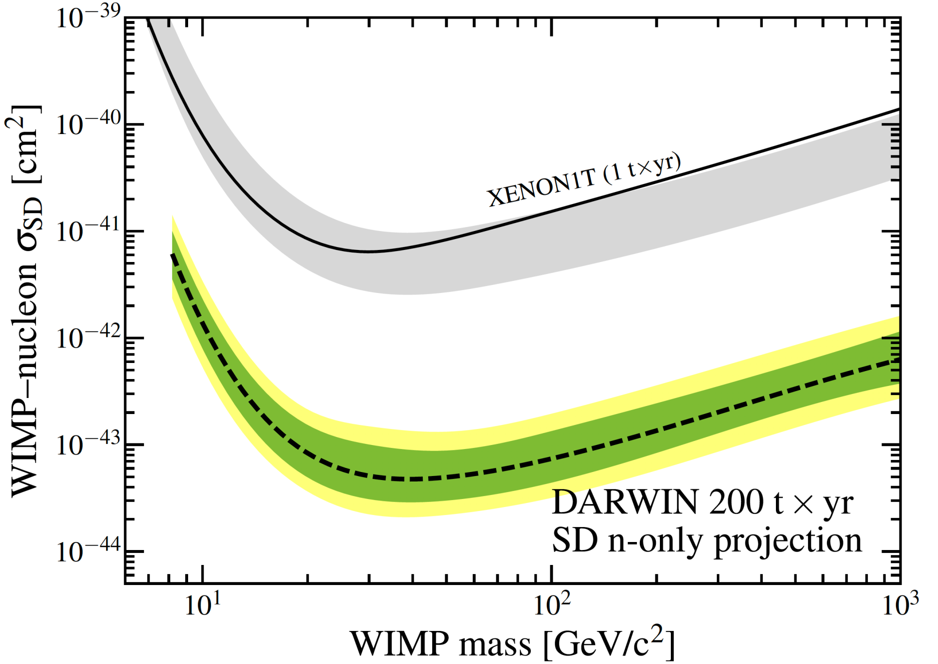
Combined (S1+S2) energy scale

Energy window 5-35 keVNR

Light yield 8 p.e. / keV

Sensitivity to Spin Dependent models



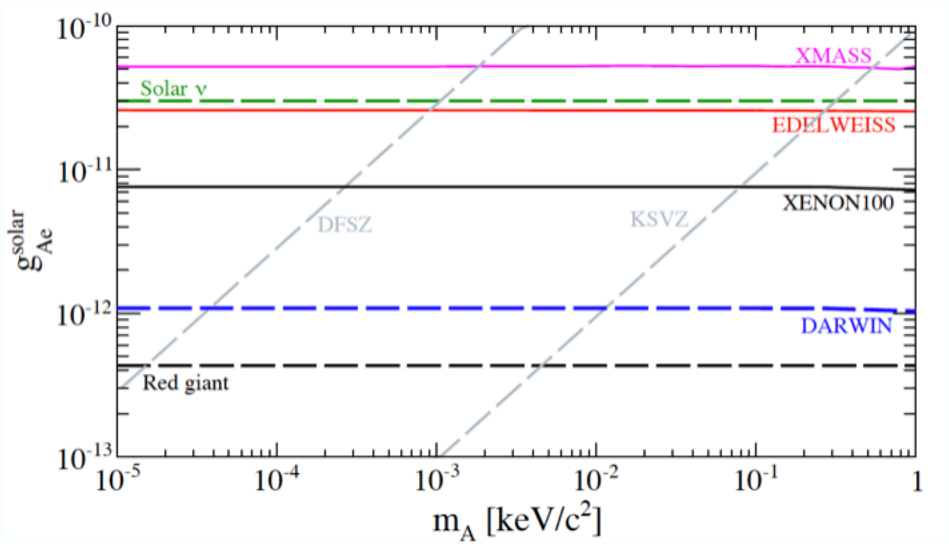


$$\sigma_{SD} = \frac{32\mu^2}{\pi} G_F^2 \frac{J+1}{J} \left[a_p \langle S_p \rangle + a_n \langle S_n \rangle\right]^2$$

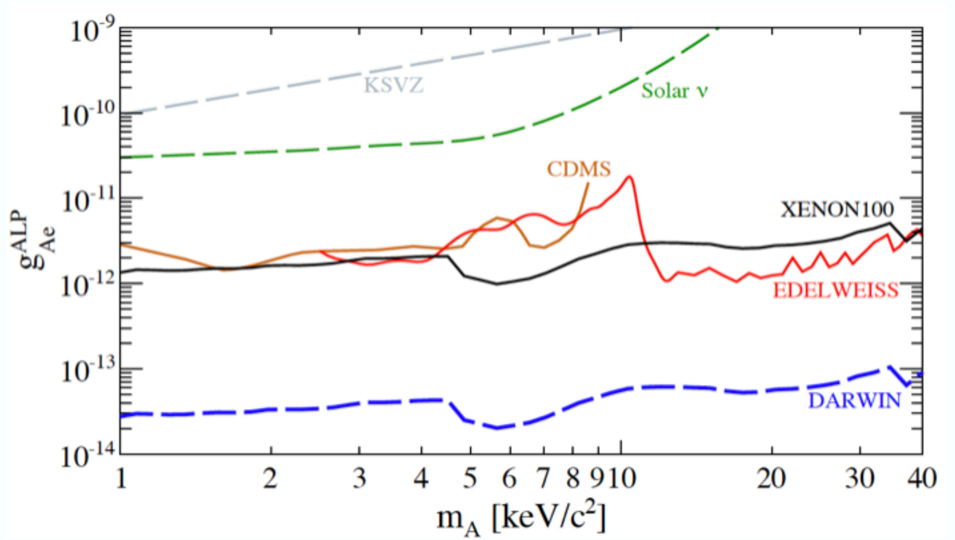
Sensitivity requires nucleus with non-zero spin (i.e. ^{19}F, ^{23}Na, ^{73}Ge, ^{129}Xe, ^{131}Xe, ^{133}Cs)

Solar Axions and Axion-Like Particles (ALPs)

- Axio-electric coupling (Electron Recoil channel)
- Event signature: mono-energetic peak centered at rest mass (few keV)
- Dependence of the coupling on the exposure (M×T)
- Main backgrounds: irreducible solar neutrinos and $2\nu\beta\beta$ of ^{136}Xe.



$$g_{Ae}^{solar} \propto (MT)^{-\frac{1}{8}}$$

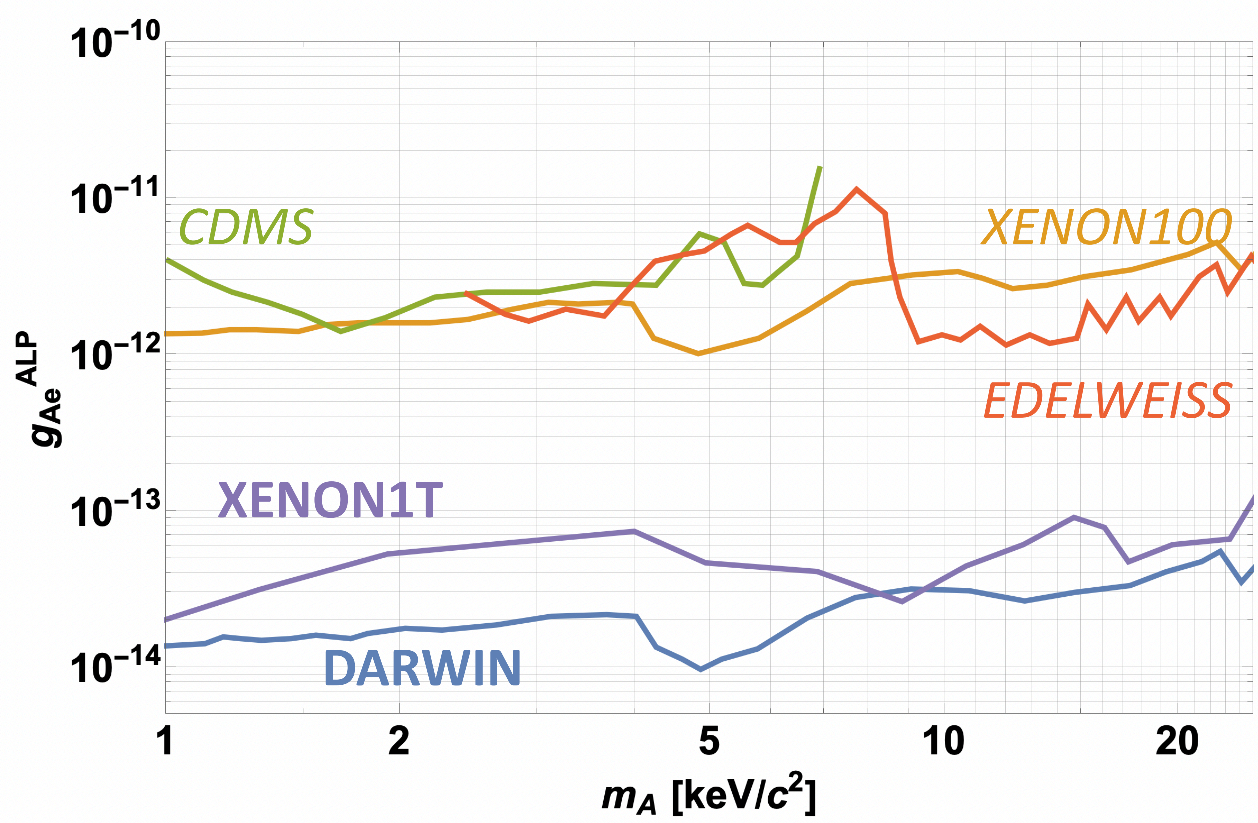


$$g_{Ae}^{ALP} \propto (MT)^{-\frac{1}{4}}$$

JCAP 1611 (2016) 017

Solar Axions and Axion-Like Particles (ALPs)

Updated DARWIN prediction (***PRELIMINARY***) vs **latest XENON1T measurement** (*arXiv:2006.09721v2*).

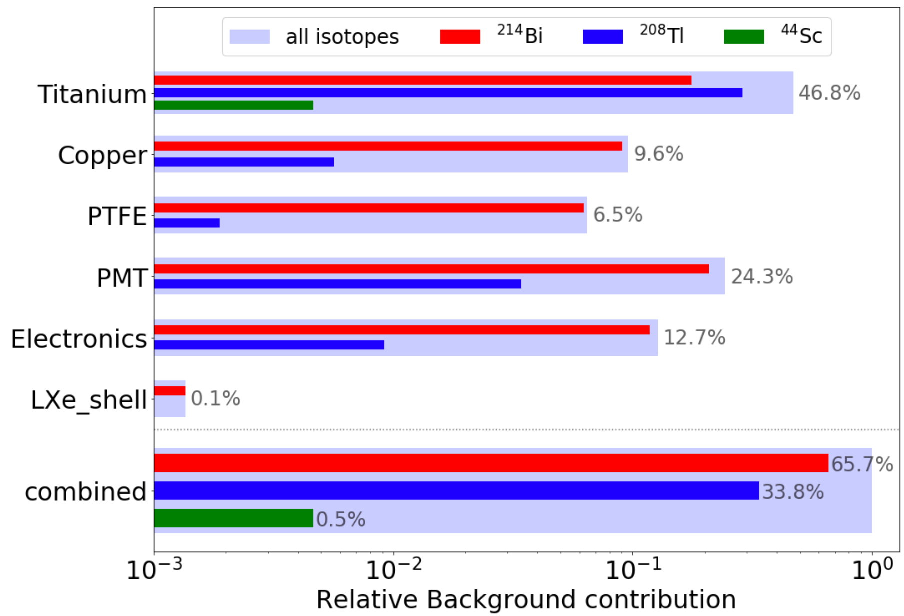


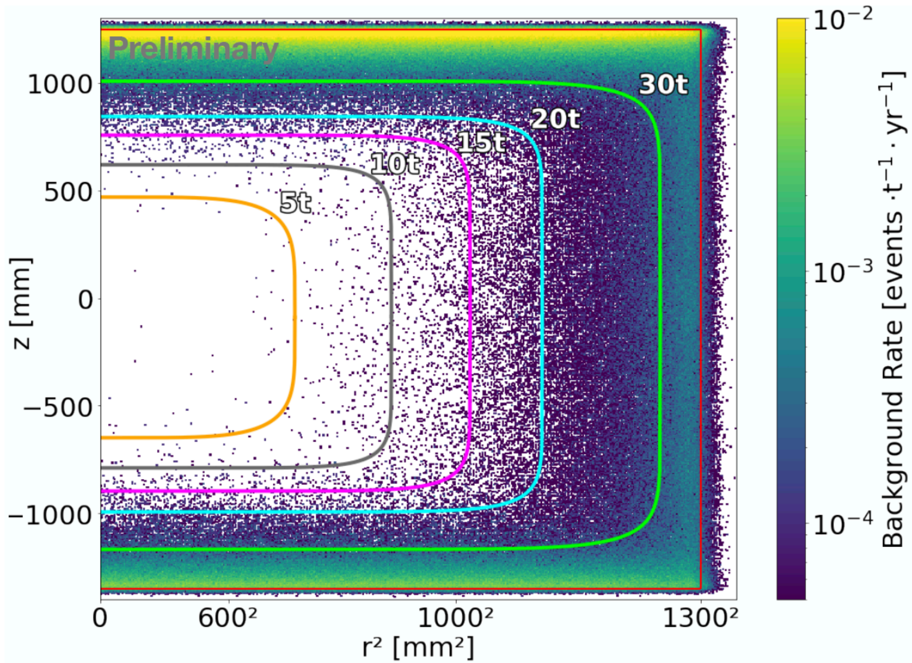
Neutrinoless Double-Beta Decay ^{136}Xe

Predicted background spectrum around the 0νββ-ROI for the 5t fiducial volume.

100 years of DARWIN run time (effective simulated time).

40 t of Xenon contains 3.8 t of ^{136}Xe

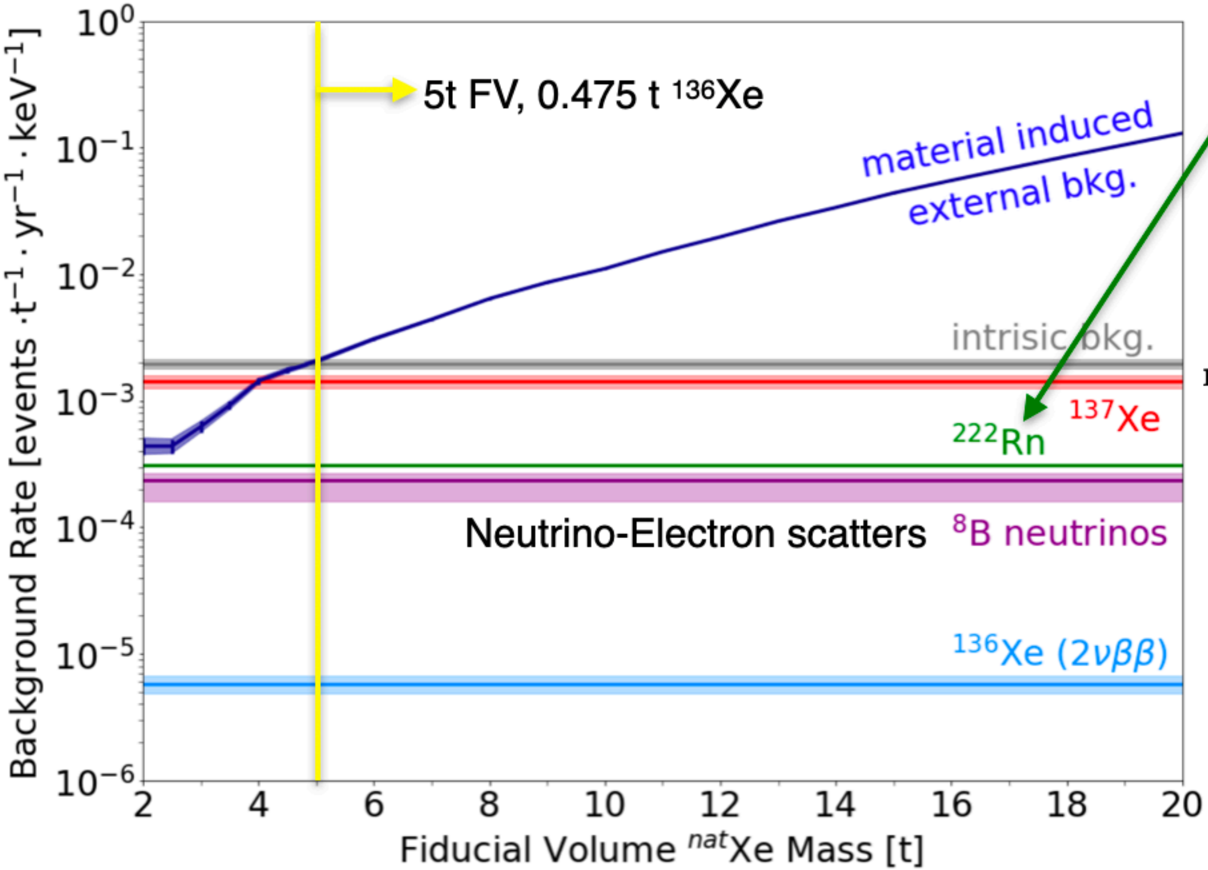




arXiv:2003.13407

EXTERNAL BKG

Neutrinoless Double-Beta Decay ^{136}Xe



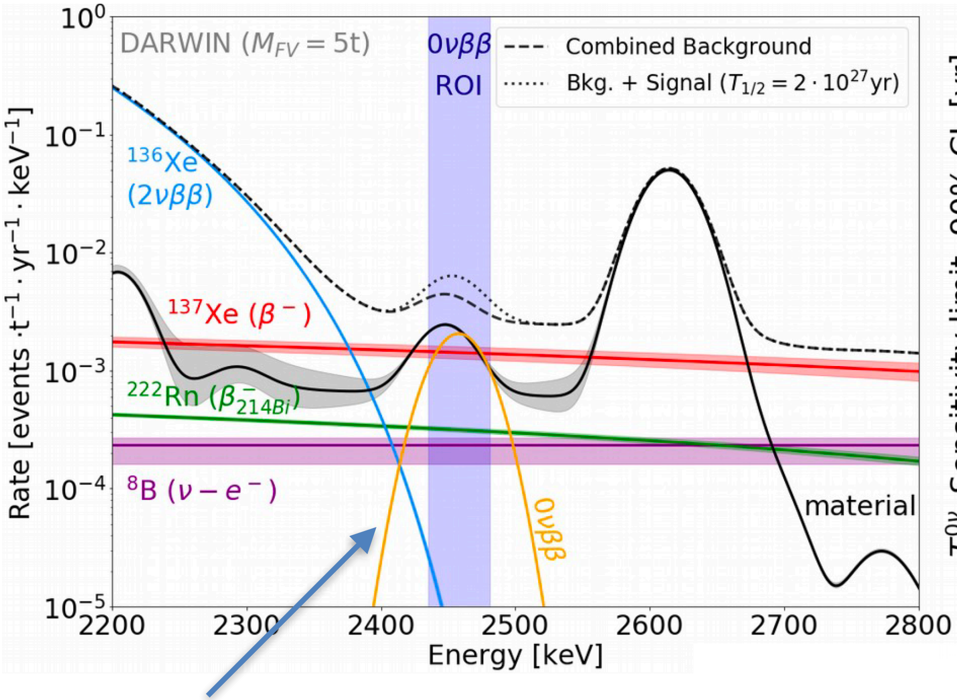
Online cryo-distillation and stringent screening campaign (~ 0.1 μBq / kg of Xe)

$$n + ^{136}Xe \rightarrow ^{137}Xe^* \rightarrow ^{137}Cs + e^- + \bar{\nu}_e$$

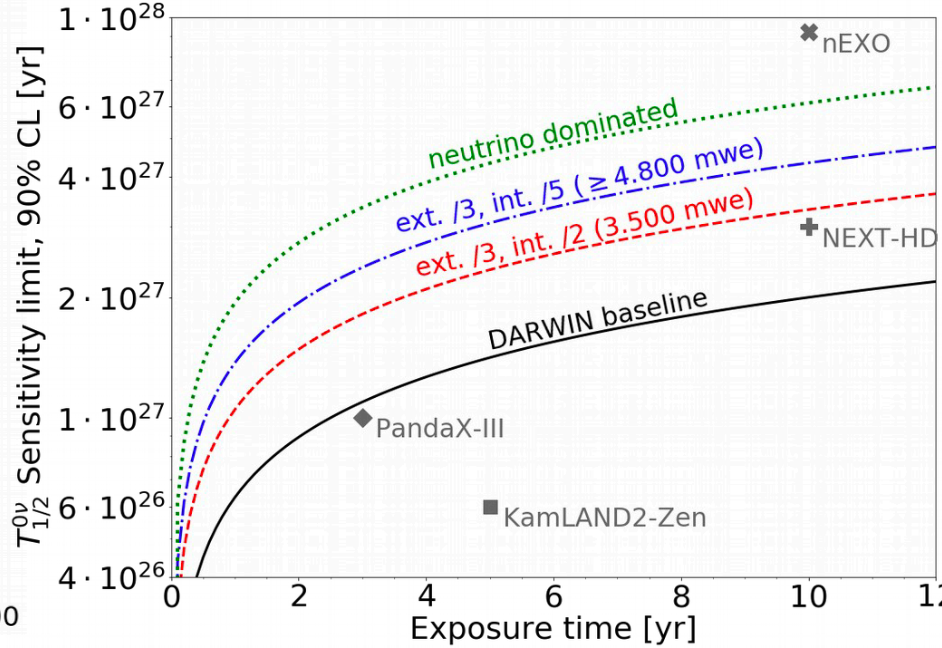
INTRINSIC BKG

arXiv:2003.13407

Neutrinoless Double-Beta Decay ^{136}Xe



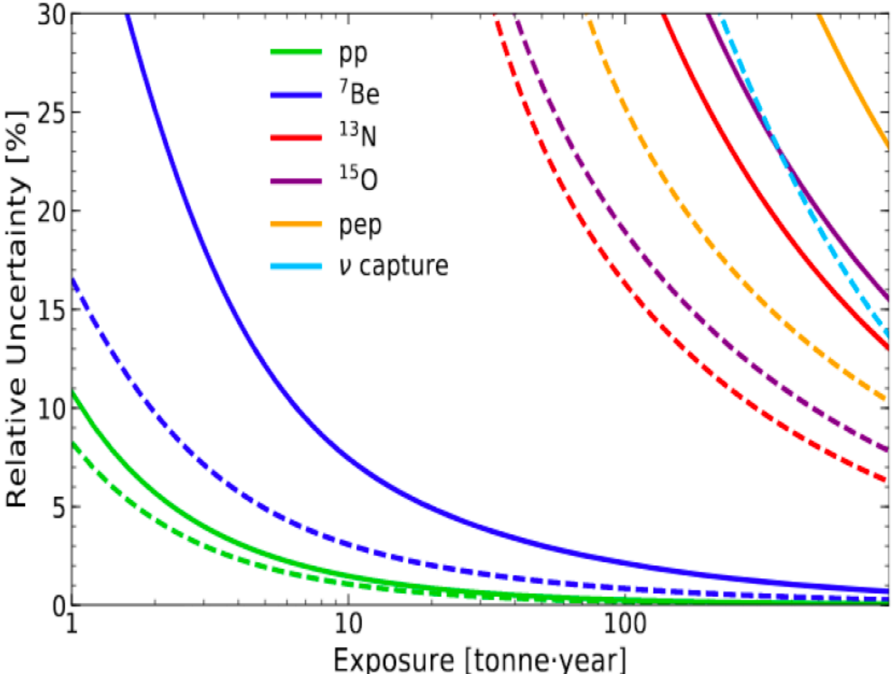
Hypothetical 0.5 counts per year signal corresponding to $T_{1/2} = 2 \times 10^{27}$ y

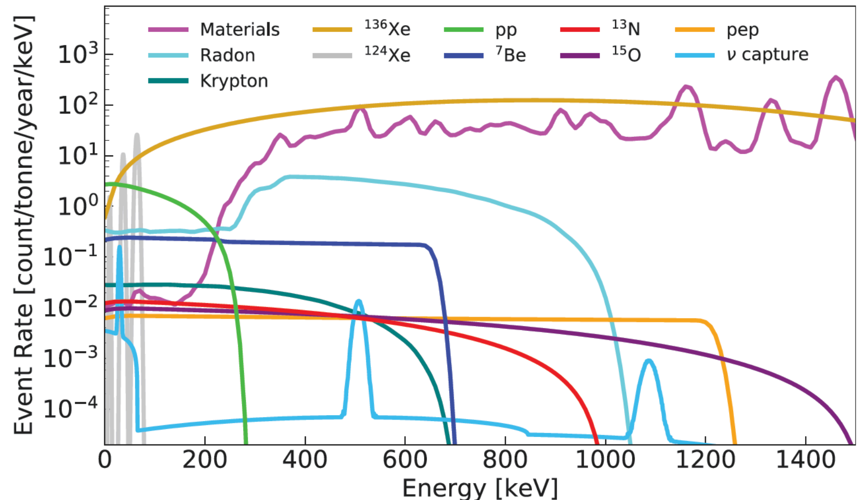


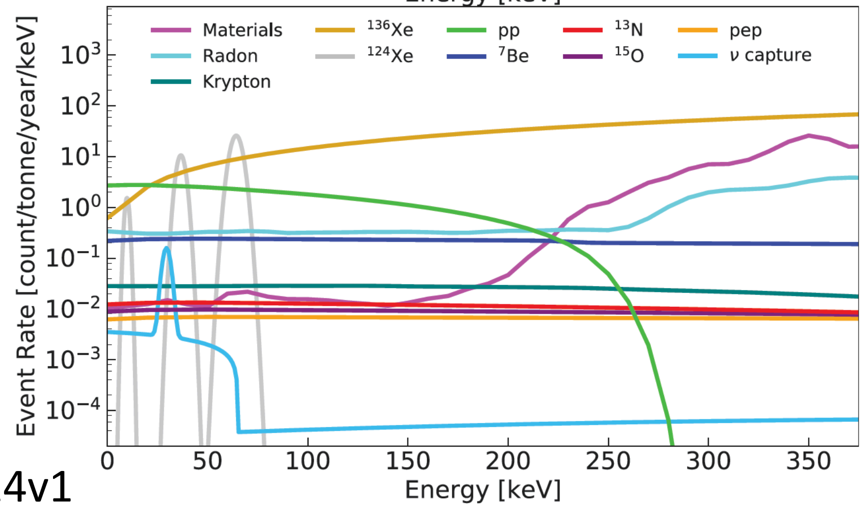
arXiv:2003.13407

Solar Neutrino Detection Sensitivity via ES

Potential to measure the fluxes of five solar neutrino components: pp, ^{7}Be, ^{13}N, ^{15}O and *pep*







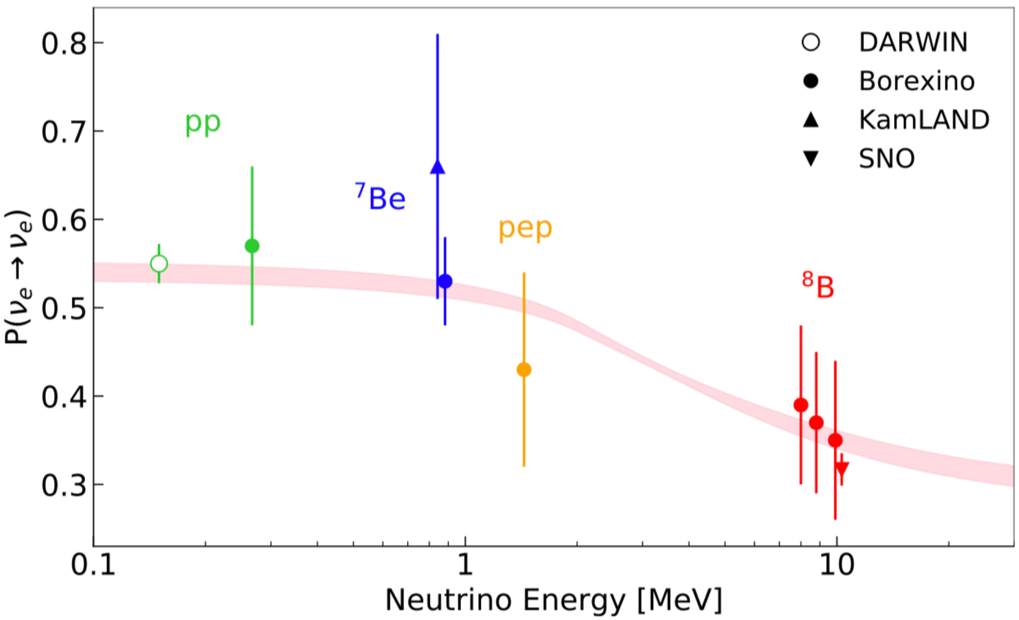
Natural Target

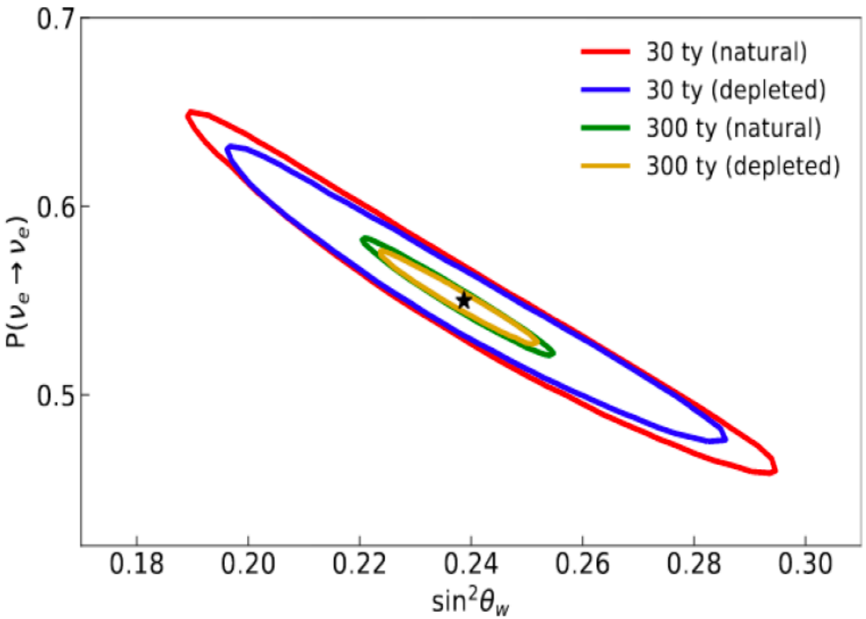
Depleted Target (with an impact to the 0νββ discovery channel)

30 t Fiducial Volume

arXiv:2006.03114v1

Solar Neutrino Detection Sensitivity via ES





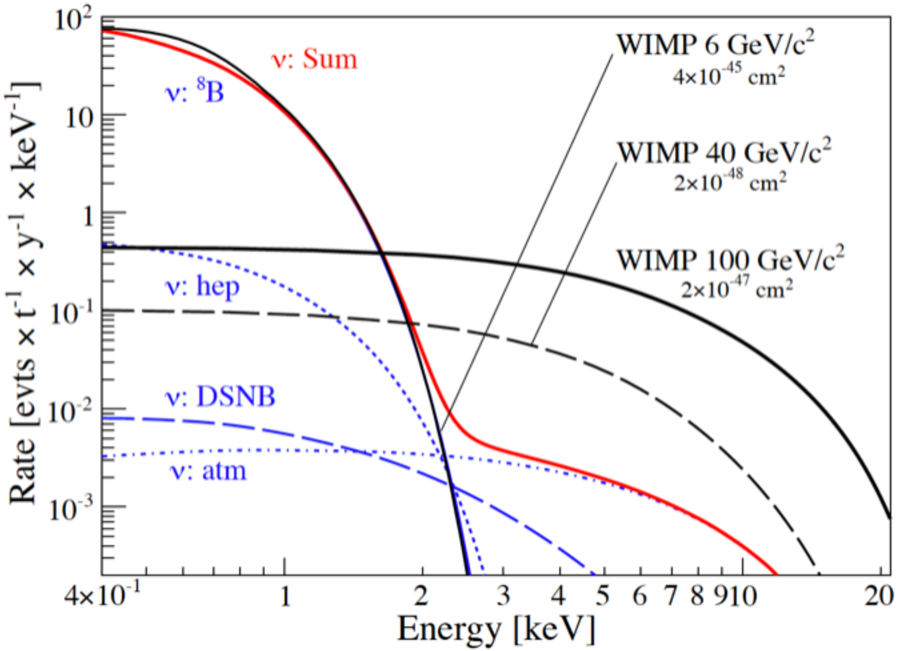
- ~1 keV THR (achievable with LXe - dual phase TPC) yields an integrated rate of ~ 365 events per tonne-year of pp neutrinos.
- Unique opportunity to probe $\sin^2\theta_w$ and P_{ee} for the first time below 200 keV.

arXiv:2006.03114v1

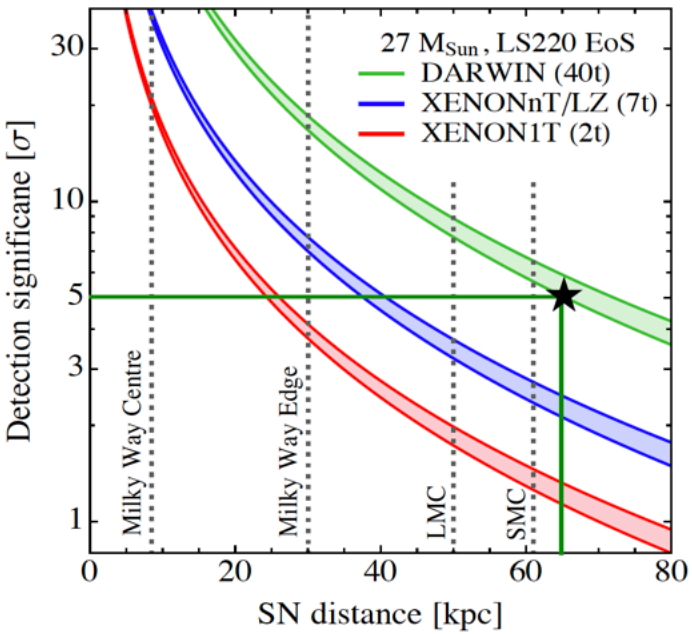
Coherent Neutrino Nucleus Scattering (CNNS)

$$\nu + {}^{\text{any}}\text{Xe}_{\text{nucleus}} \rightarrow \nu + {}^{\text{any}}\text{Xe}_{\text{nucleus}}$$

- CNNS is a killer background for non-directional direct DM search
- DARWIN has the detection potential for CNNS (Solar and SN neutrinos)



JCAP 1611 (2016) 017



Phys. Rev. D 94 (2016) 103009

Summary

DARWIN will be the ultimate low background astroparticle physics observatory capable of covering a diverse science program:

- *Search for WIMPs*
- *Search for the neutrinoless double-beta decay (^{136}Xe) and neutrinoless double-electron capture (^{124}Xe)*
- *Real-time detection of solar pp neutrinos via electron scattering*
- *Observation of supernova and solar ^{8}B neutrinos via CEvNS*
- *Solar axions, galactic axion-like particles and dark photons*

R&D programs are in progress to overcome the present technological limitations (photosensors, purification, material selection).

The DARWIN collaboration consists of more than 160 scientists, 29 institutions from 12 different countries.

Currently, the collaboration is working towards CDR and TDR.