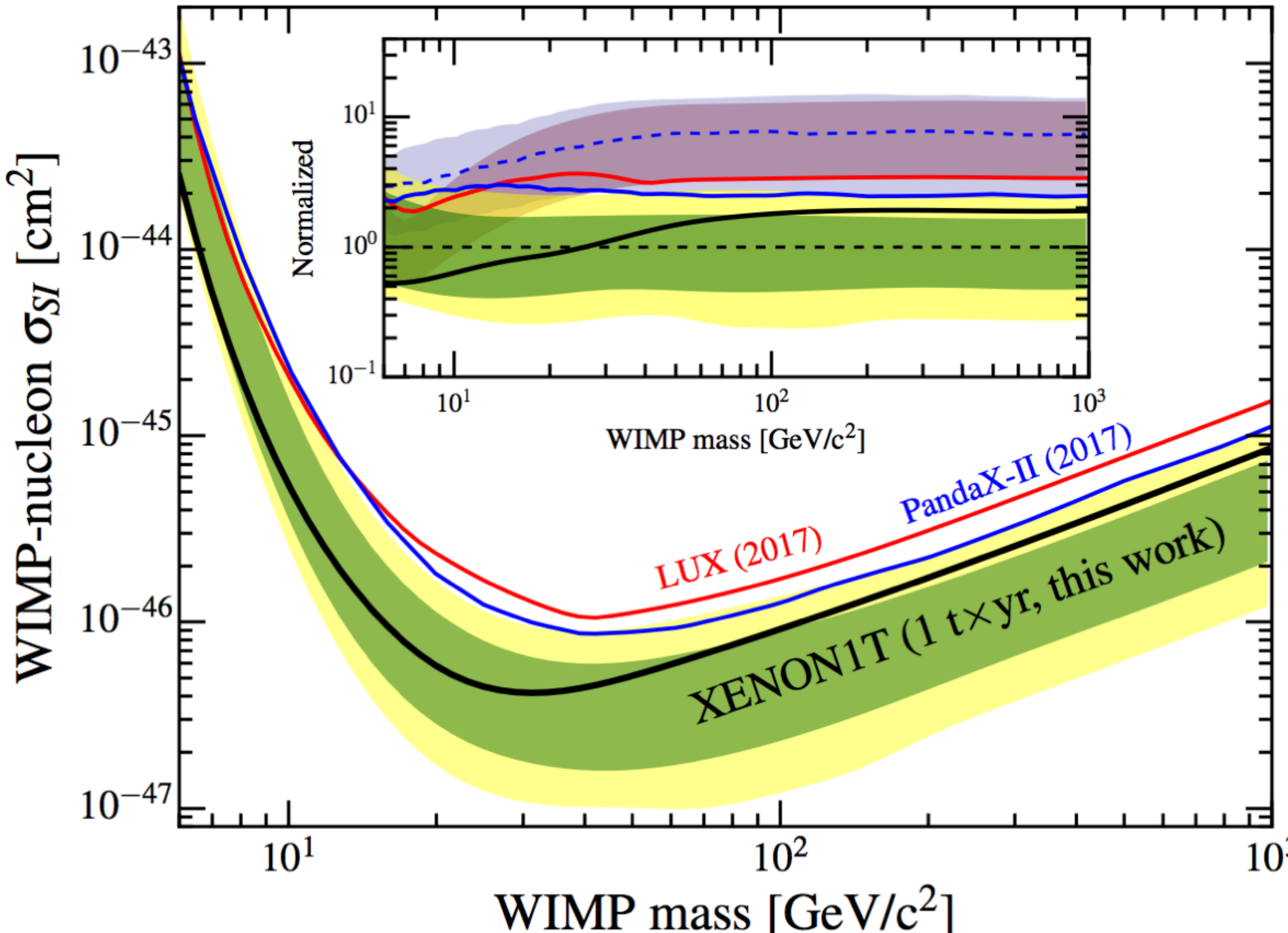
Future dark matter experiments with noble liquids

Carla Macolino (Irene Joliot-Curie lab. Orsay/CNRS)

IDM 2020 Wien
20.07.2020

Dark matter search results

- XENON1T is 7 times more sensitive compared to previous experiments (LUX, PandaX-II)
- Most stringent 90% confidence level upper limit on WIMP-Nucleon cross section at all masses above 6GeV
- σ_{SI} below $4.1 \cdot 10^{-47}$ cm^2 at 30 GeV/c^2



PHYSICAL REVIEW LETTERS

Highlights Recent Accepted Collections Authors Referees Search Press About

Editors' Suggestion

Dark Matter Search Results from a One Ton-Year Exposure of XENON1T

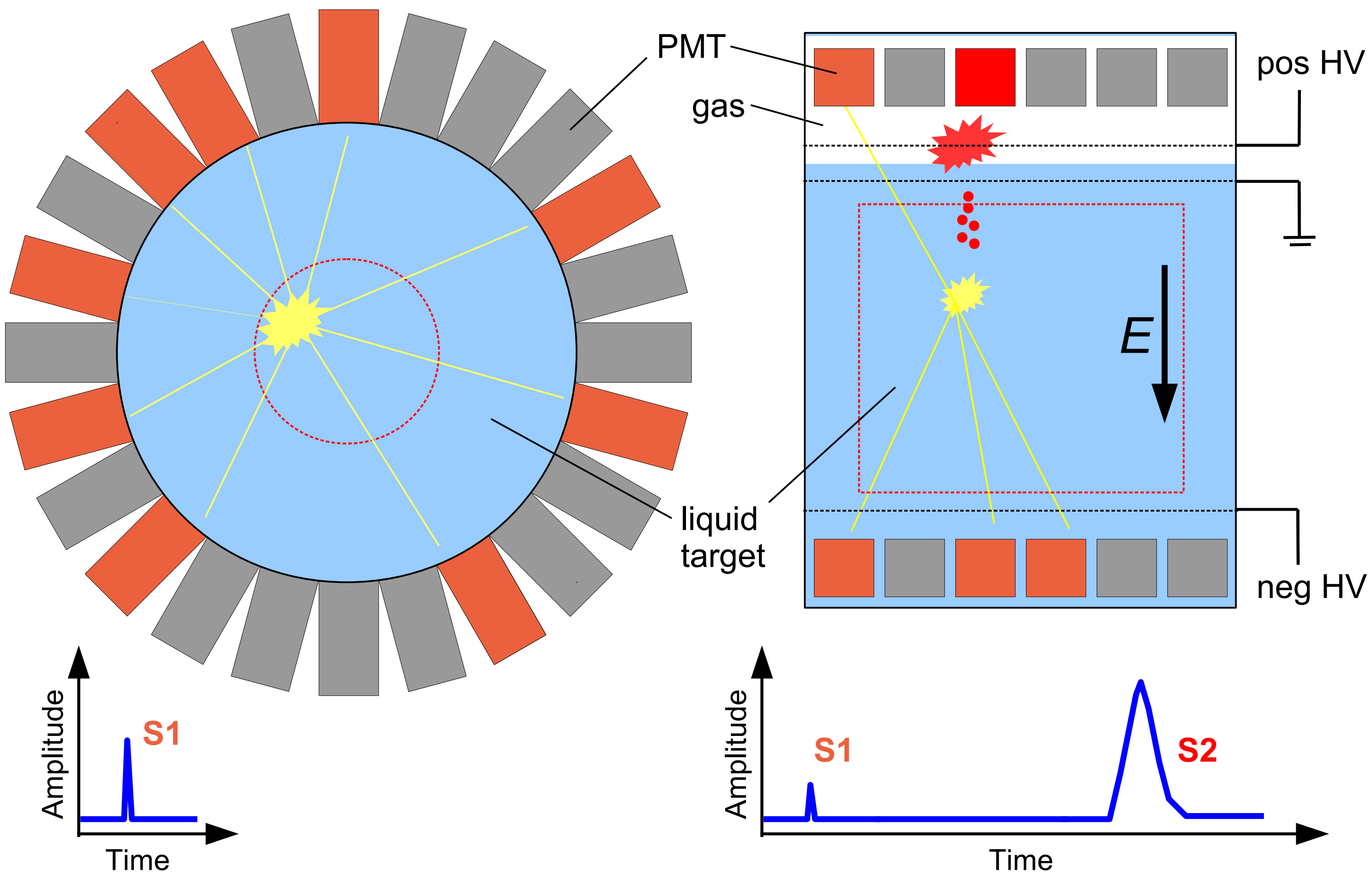
E. Aprile *et al.* (XENON Collaboration)
Phys. Rev. Lett. **121**, 111302 – Published 12 September 2018

Single phase / double phase

WIMP-nucleon interaction with the target medium

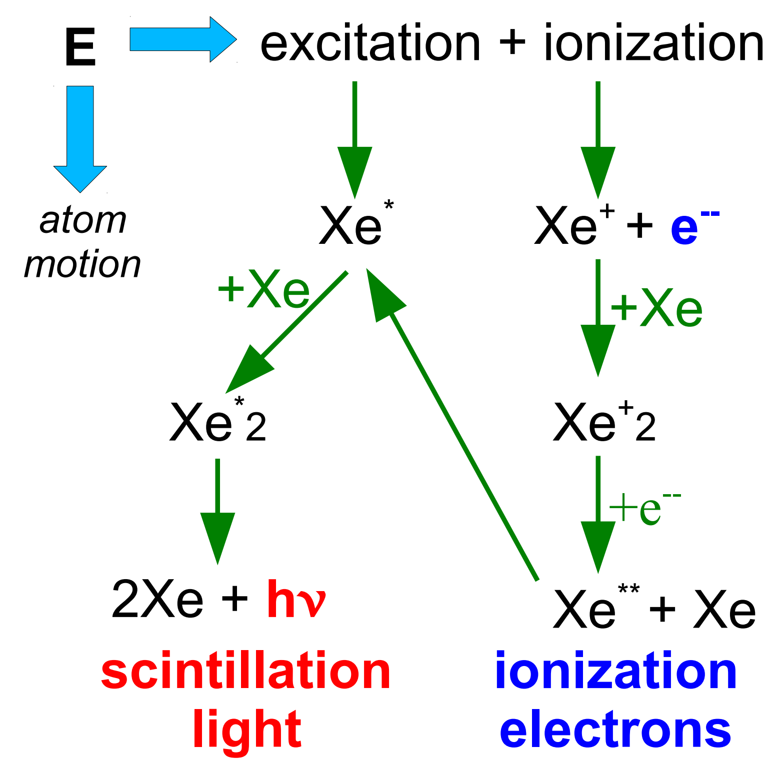
Single Phase Detector

Time Projection Chamber



DEAP-3600 (3.6ton LAr)
MiniCLEAN (360kg LAr / 310kg LNe)
XMASS (835kg LXe)
ZEPLIN I (3.1kg LXe)

ArDM (1ton LAr)
DarkSide-50 (50kg LAr)
LUX (350kg LXe)
PANDA-X (1ton LXe)
XENON (14kg, 62kg, 2ton, … LXe)
ZEPLIN II/III (31kg, 6kg LXe)

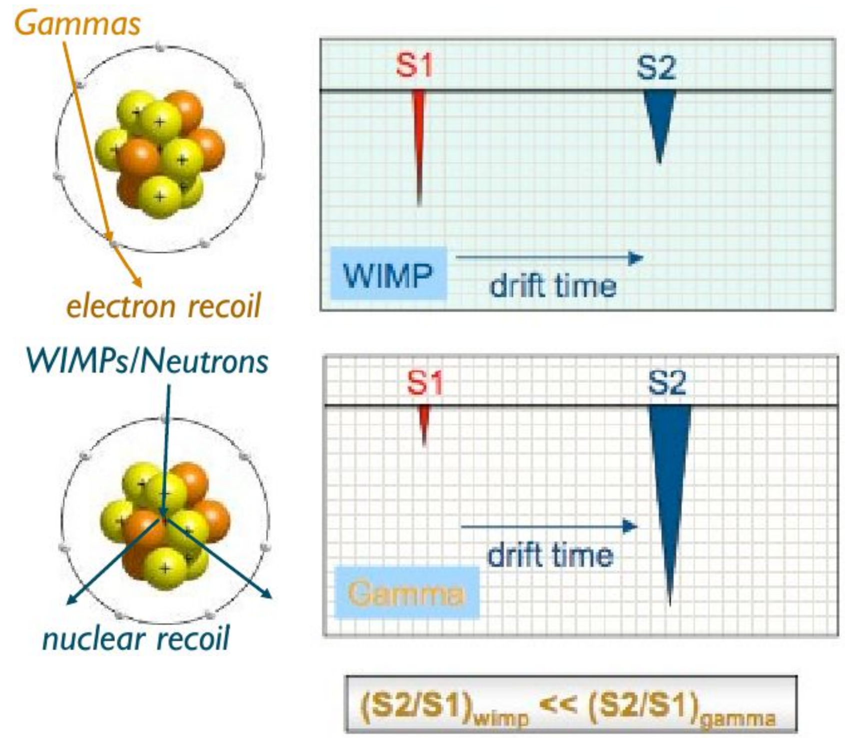


S1: Scintillation in the liquid phase

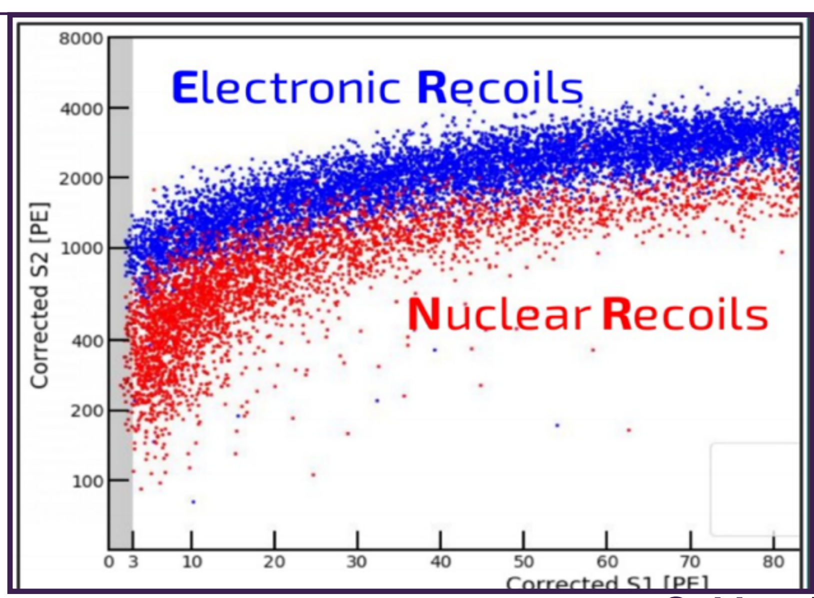
S2: secondary scintillation from ionization electrons drifted to the gas phase

Dual phase TPC advantages

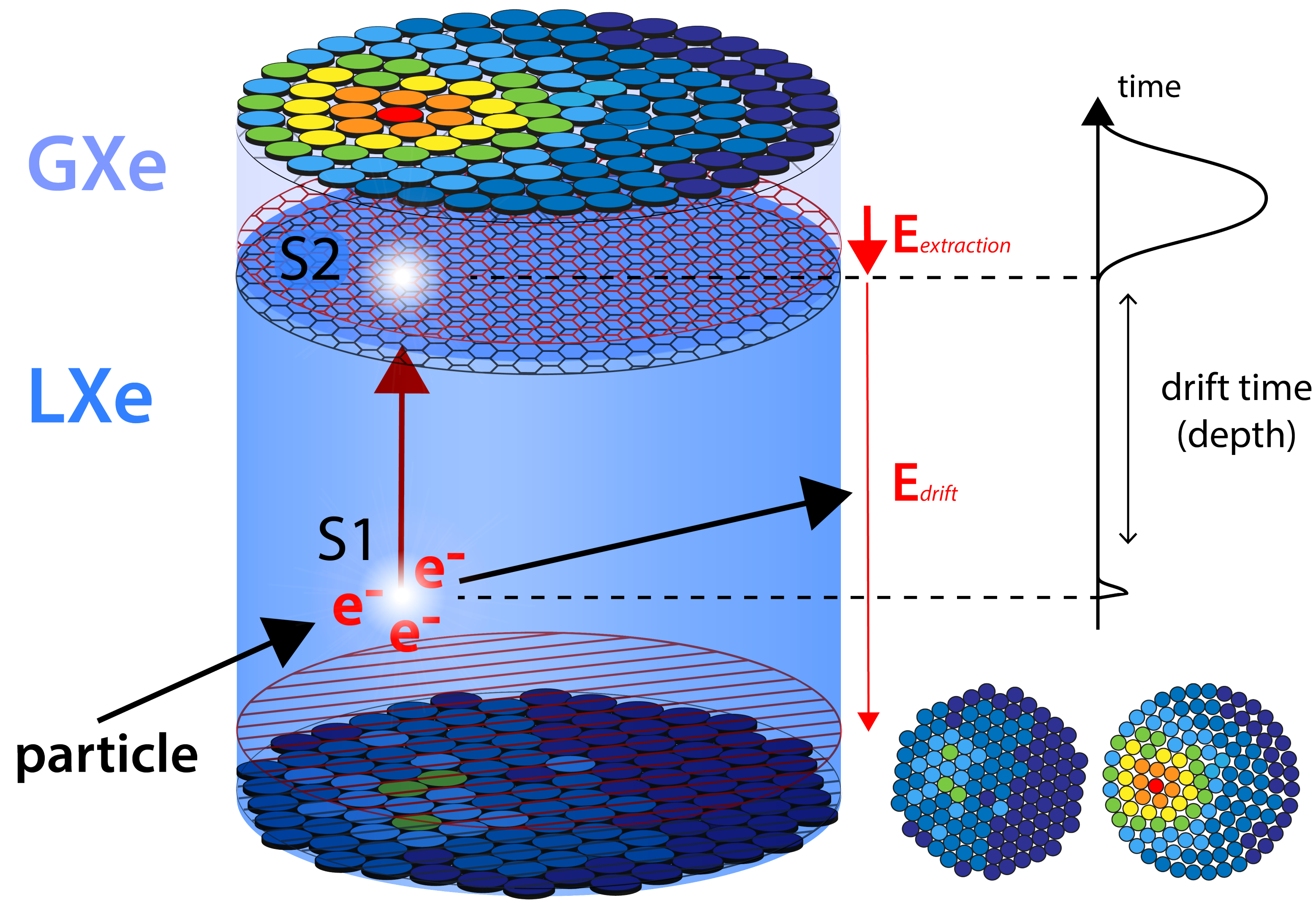
Background rejection: charge to light ratio + fiducialization and multi-scatter id.



- WIMPs (or n) scattering off Xe nucleus → NR
- e^-,γ scattering off Xe electrons → ER
- Particle discrimination from S2/S1 ratio

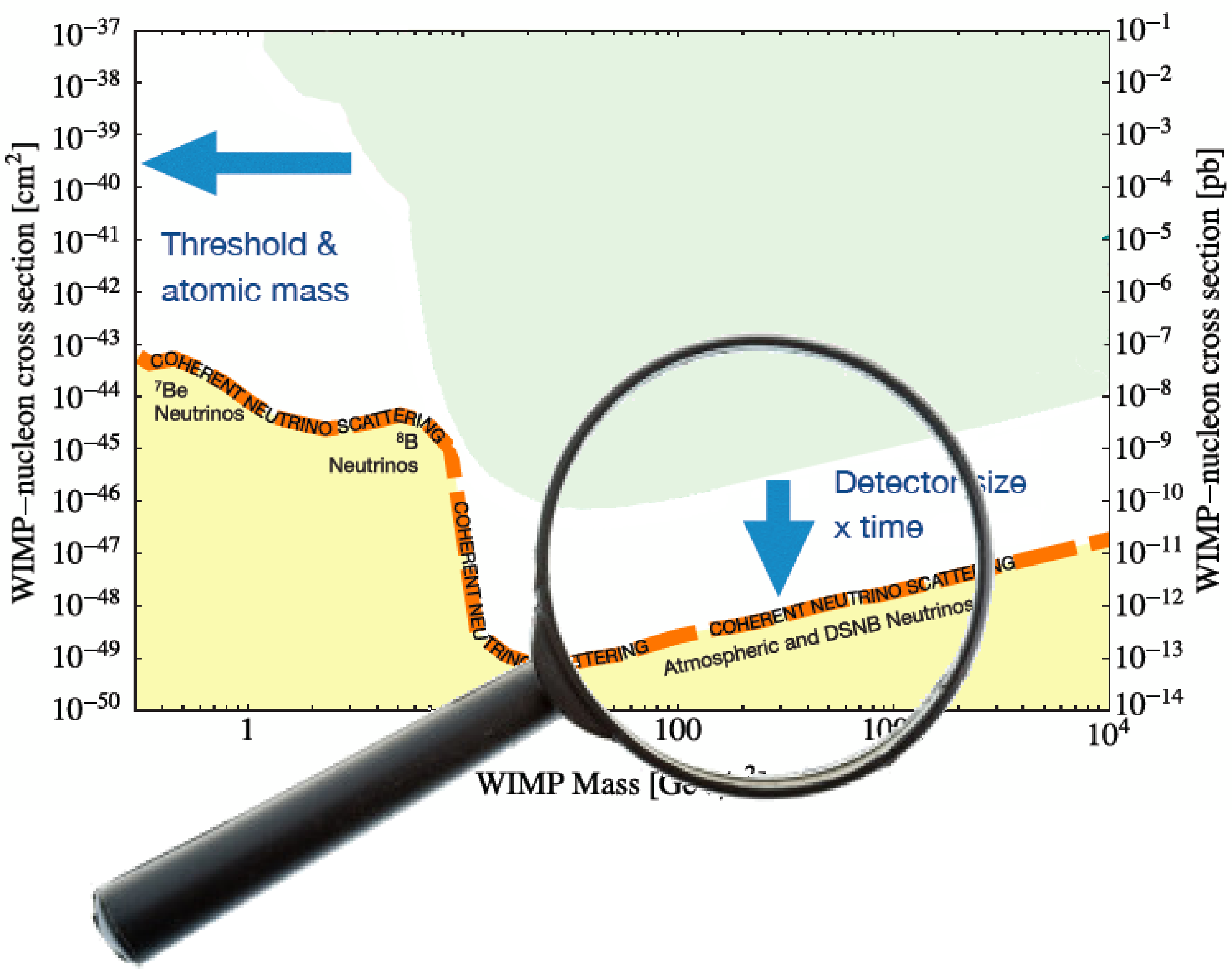


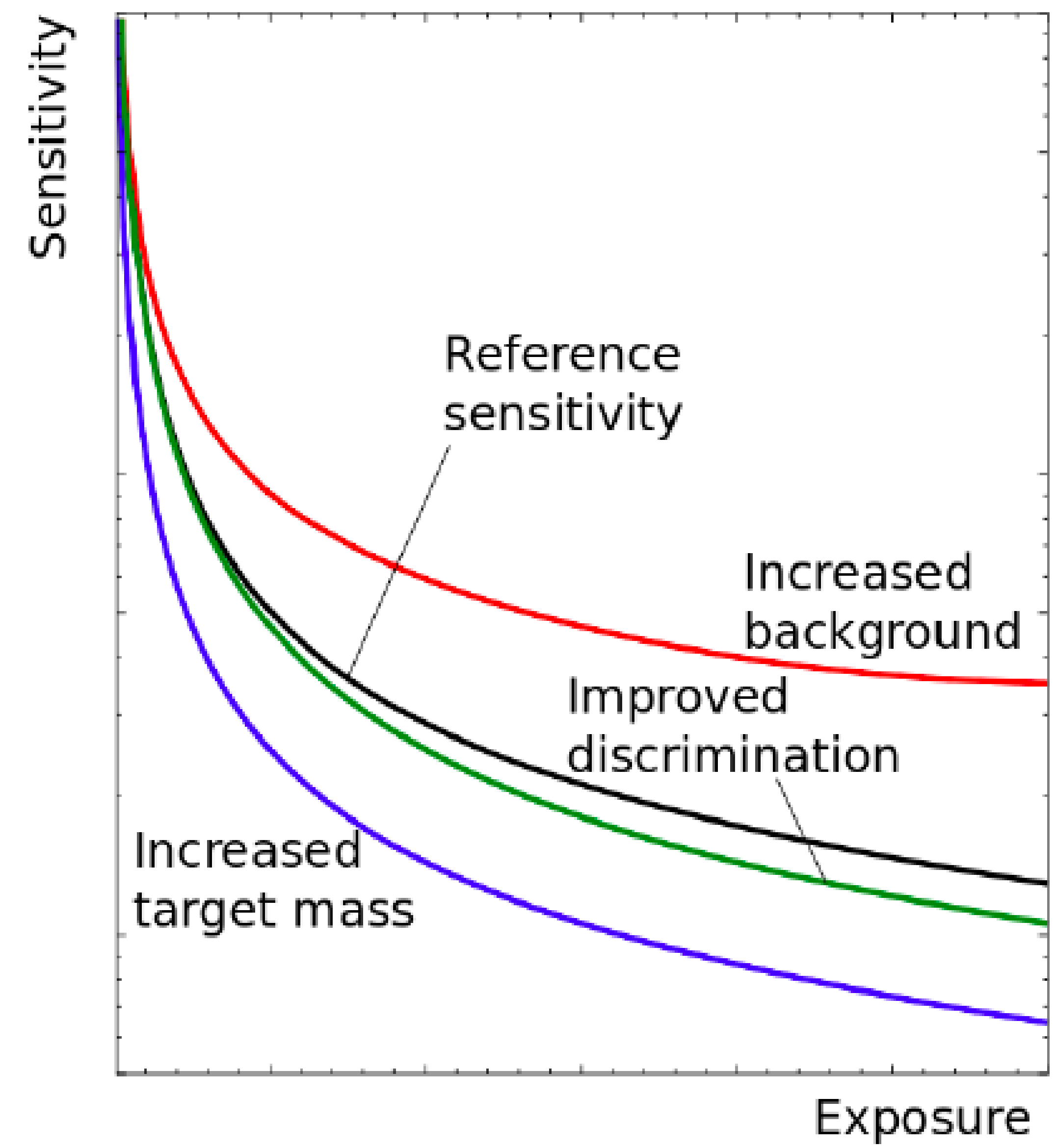
S1: prompt scintillation signal in LXe
S2: secondary scintillation from drifted e^- in GXe



- Reconstruction of energy from both S1 and S2 signals
- 3D position reconstruction:
  - x and y position from S2 pattern of Top PMT array
  - z position from drift time information

Improving sensitivity

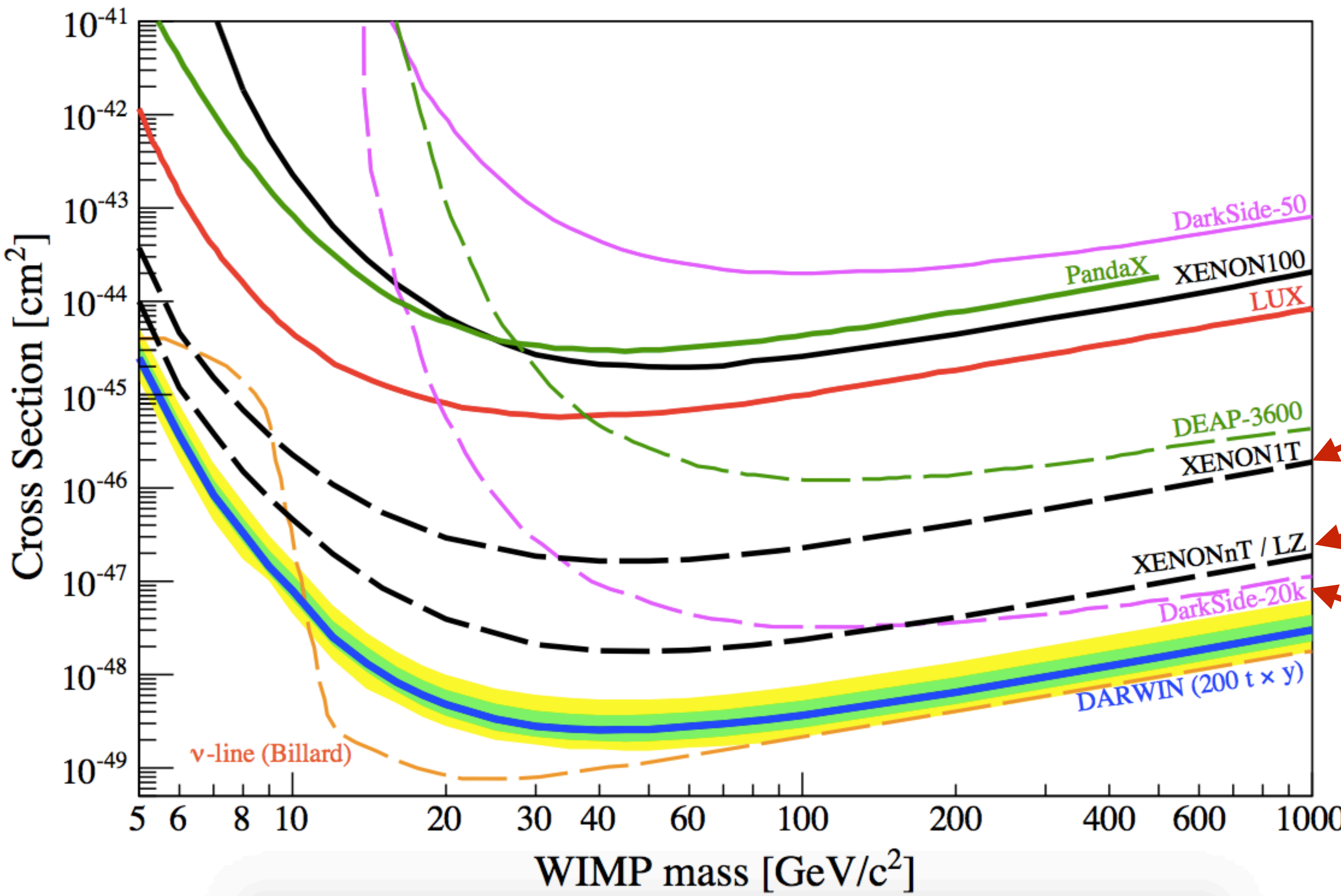




Direct search for WIMPs: status

Explore WIMP DM from m_χ~ 5 GeV/c^2

Spin-independent WIMP-nucleon interaction



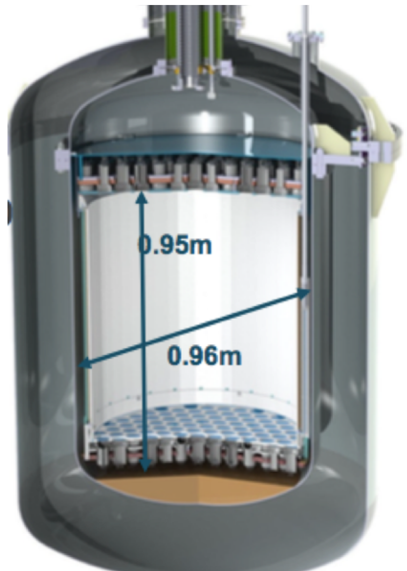
Present

Near future (2020)

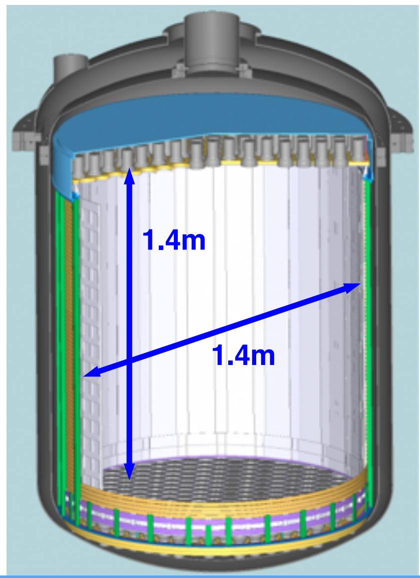
Future

Near future: XENONnT

XENON1T



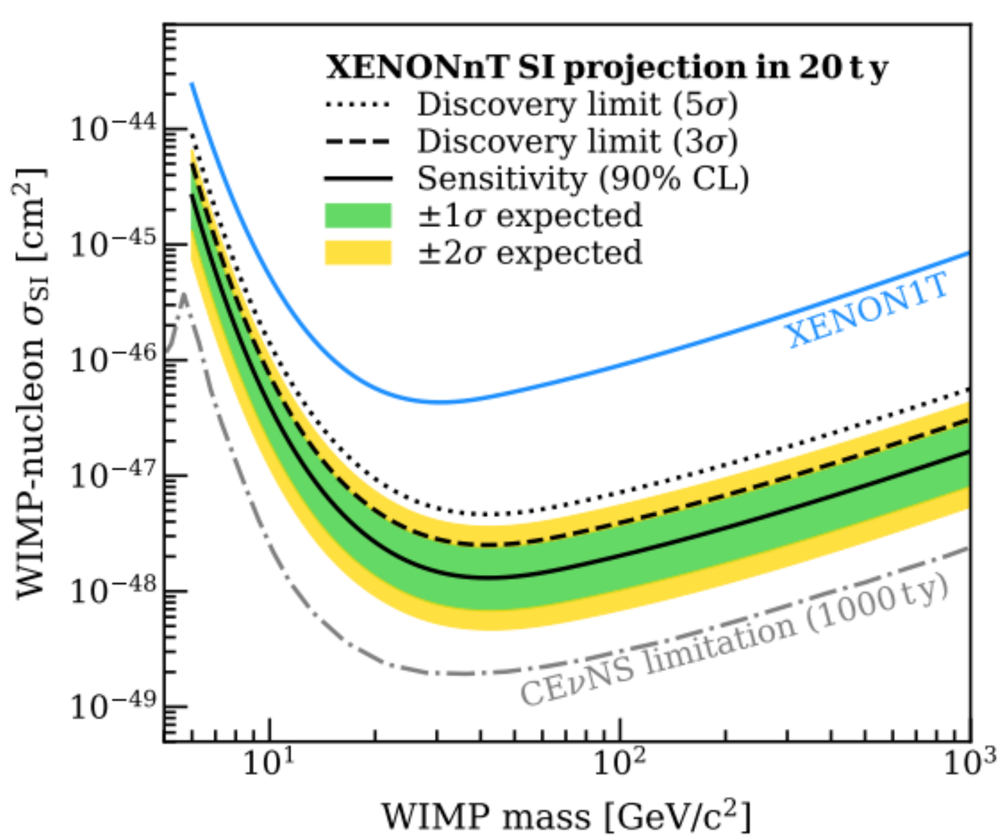
XENONnT

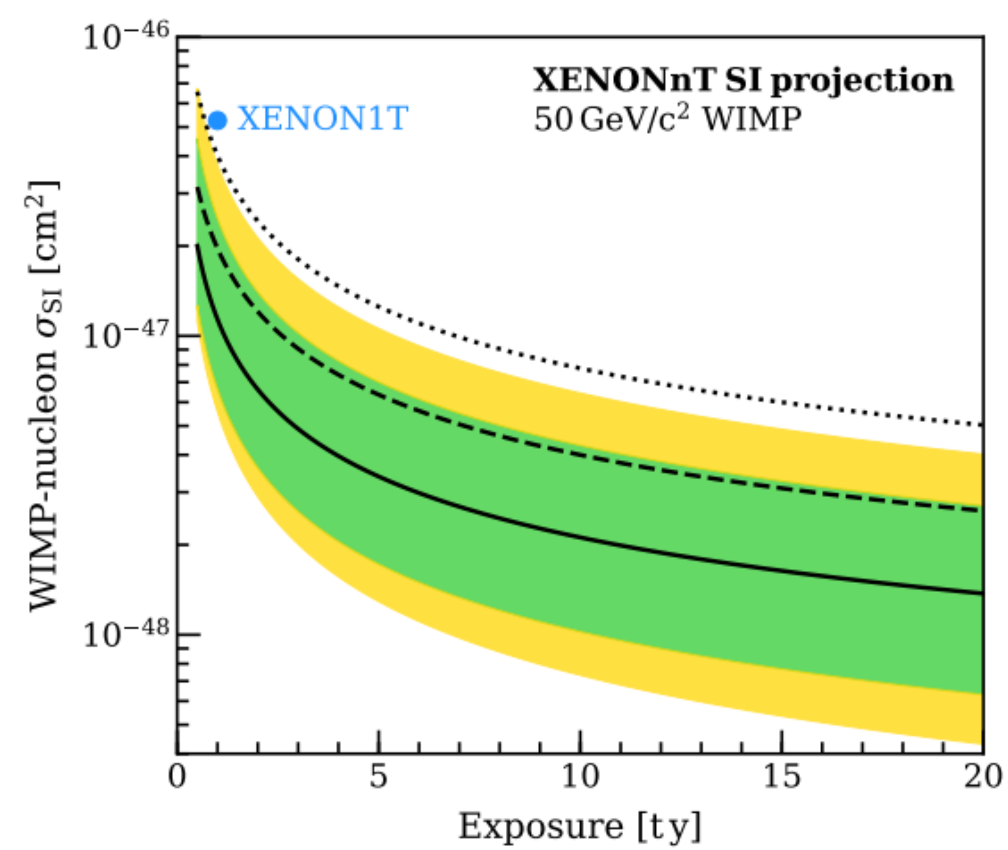


2012-2018	2019-2025
3.2 LXe	8t LXe
over	TPC in place

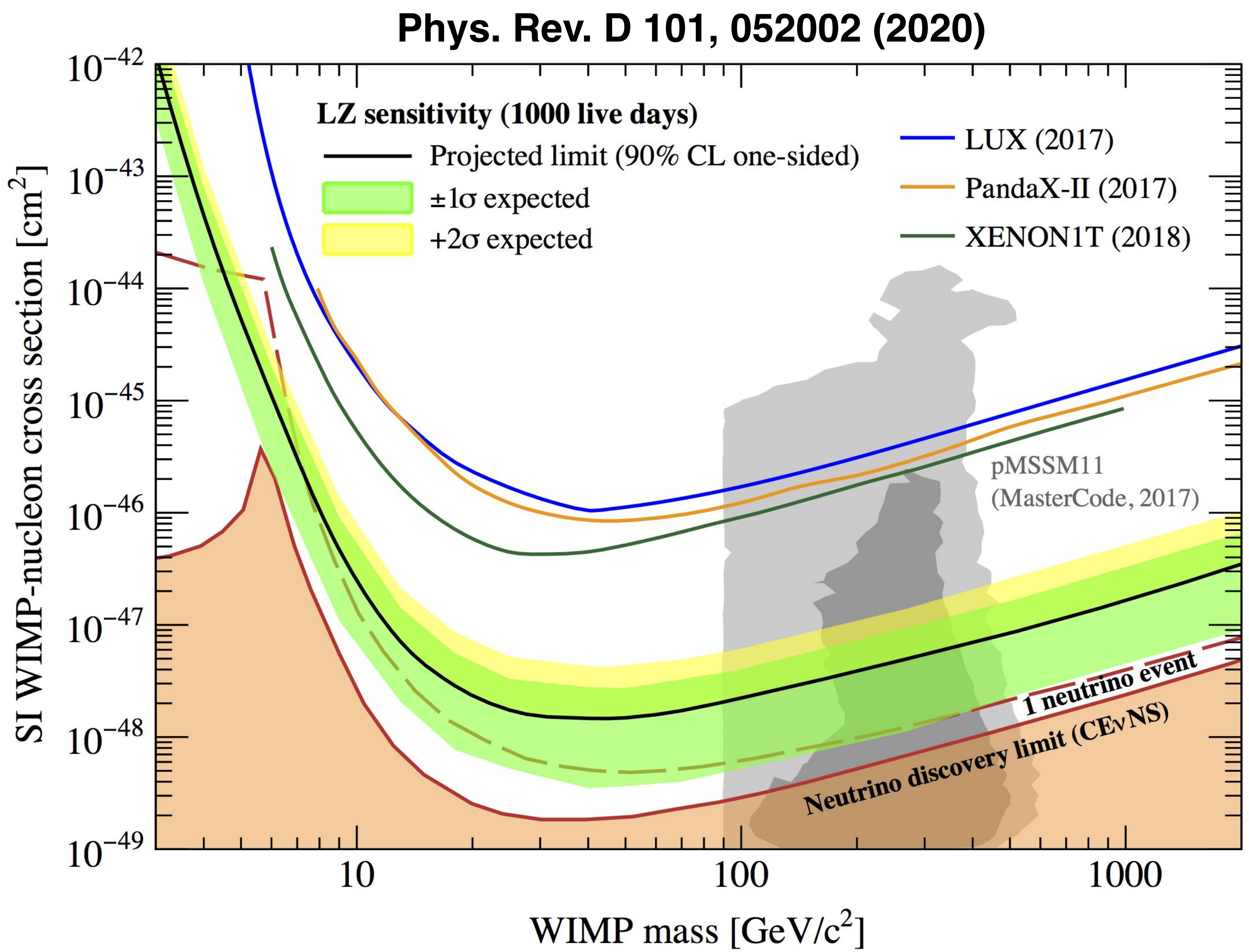
- XENONnT TPC already assembled and operational with GXe at this time
- Commissioning in LXe expected in September
- First data this fall (2020)

On arXiv today!
arXiv:2007.08796





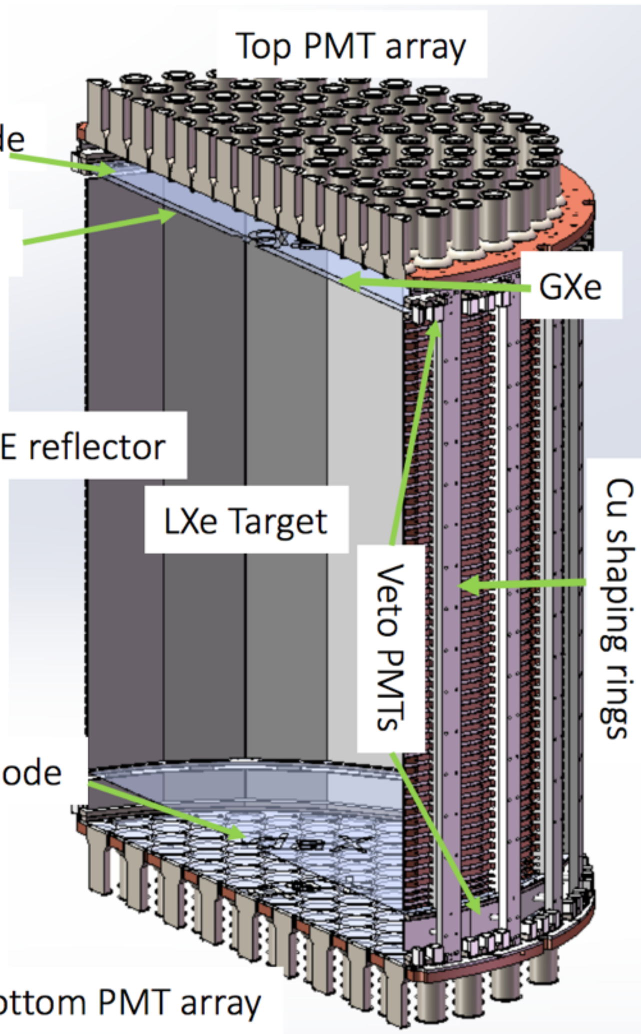
Near future: LZ



90% CL minimum of 1.6 x 10^{-48} cm^2 at 40 GeV/c^2

Near future: PANDAX-4T

4-ton target with SI sensitivity ~10^{-47} cm^2

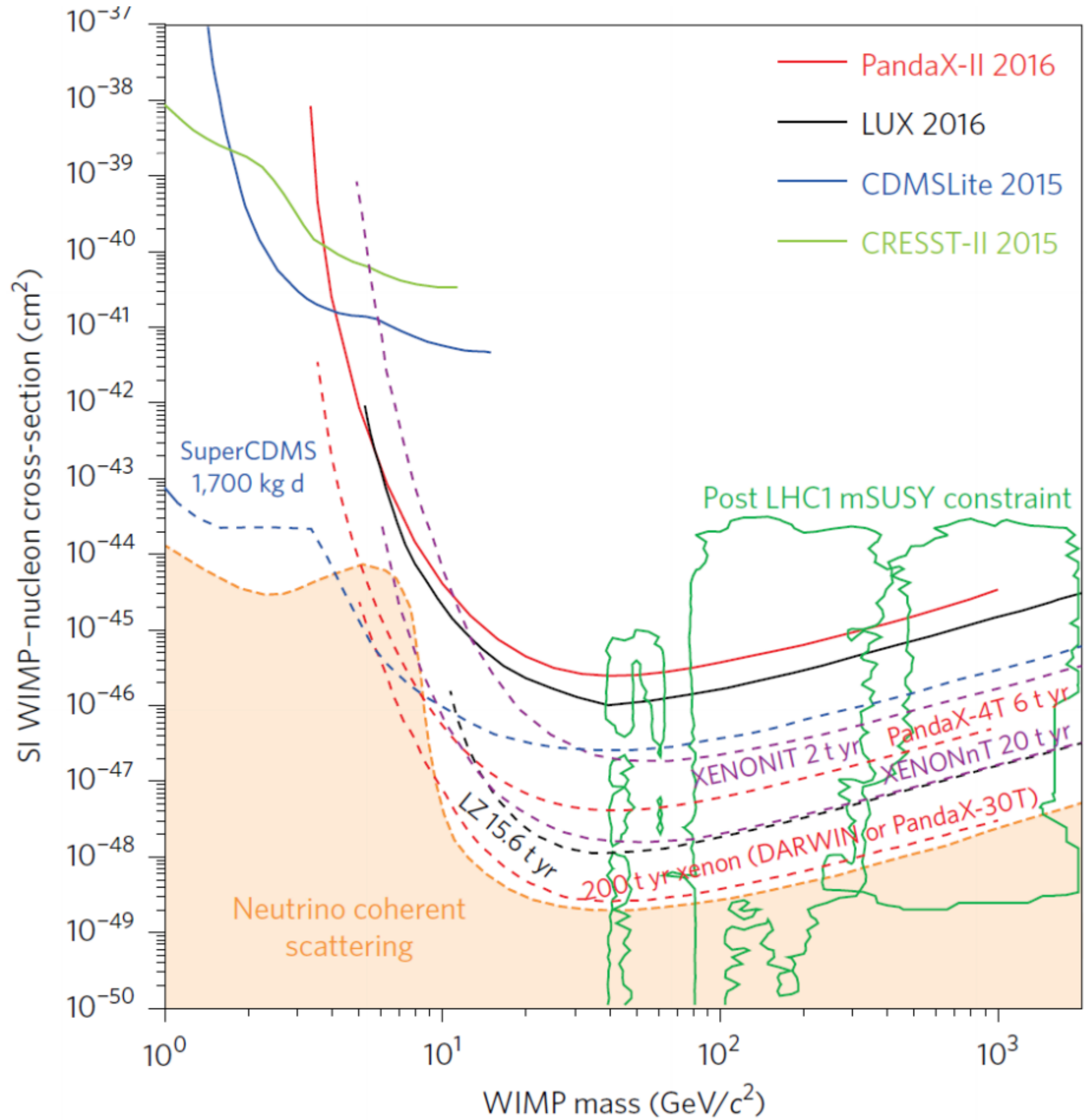


1.2m(H)x1.2m(D)

Designed field: drift (400 V/cm), extraction (6 kV/cm)

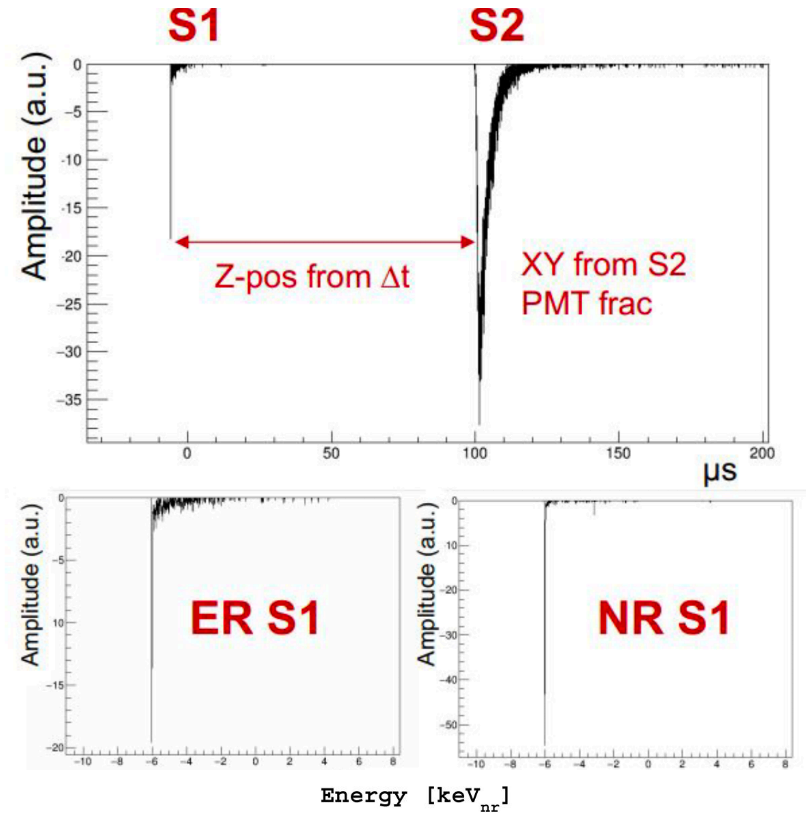
3-in PMTs, 169 top/199 bottom

1-in veto PMT 126



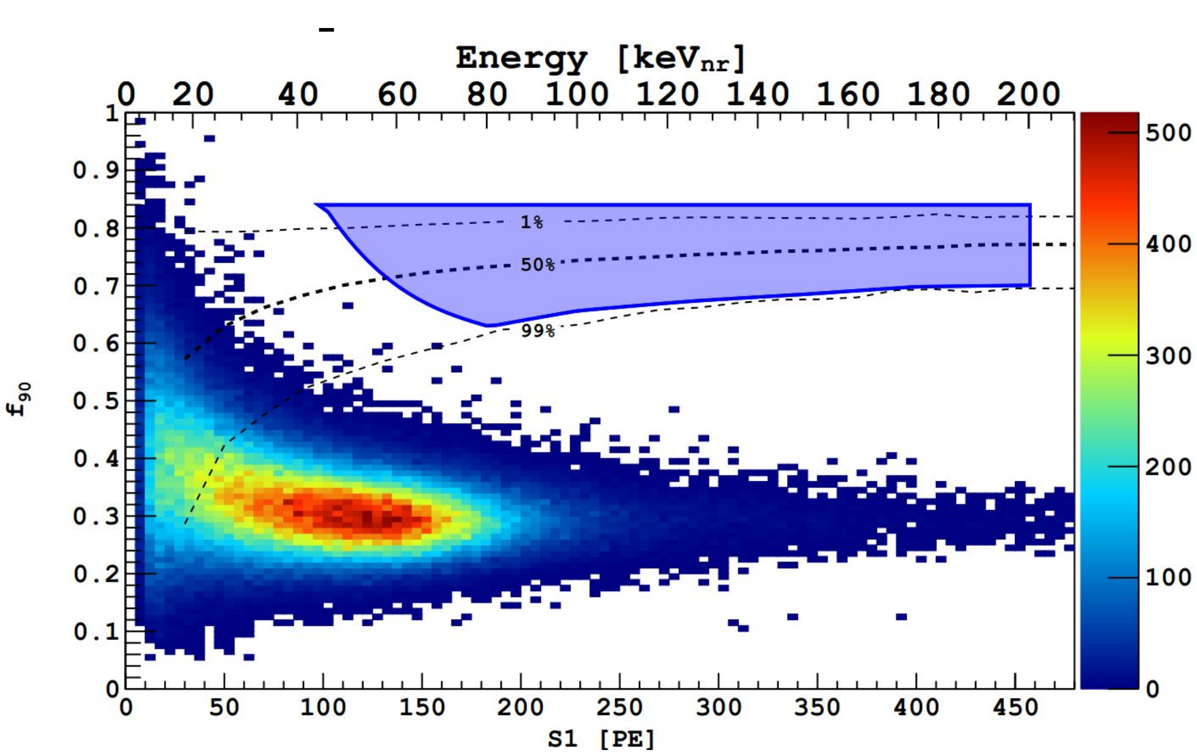
Nature Physics 13, 212-216 (2017)

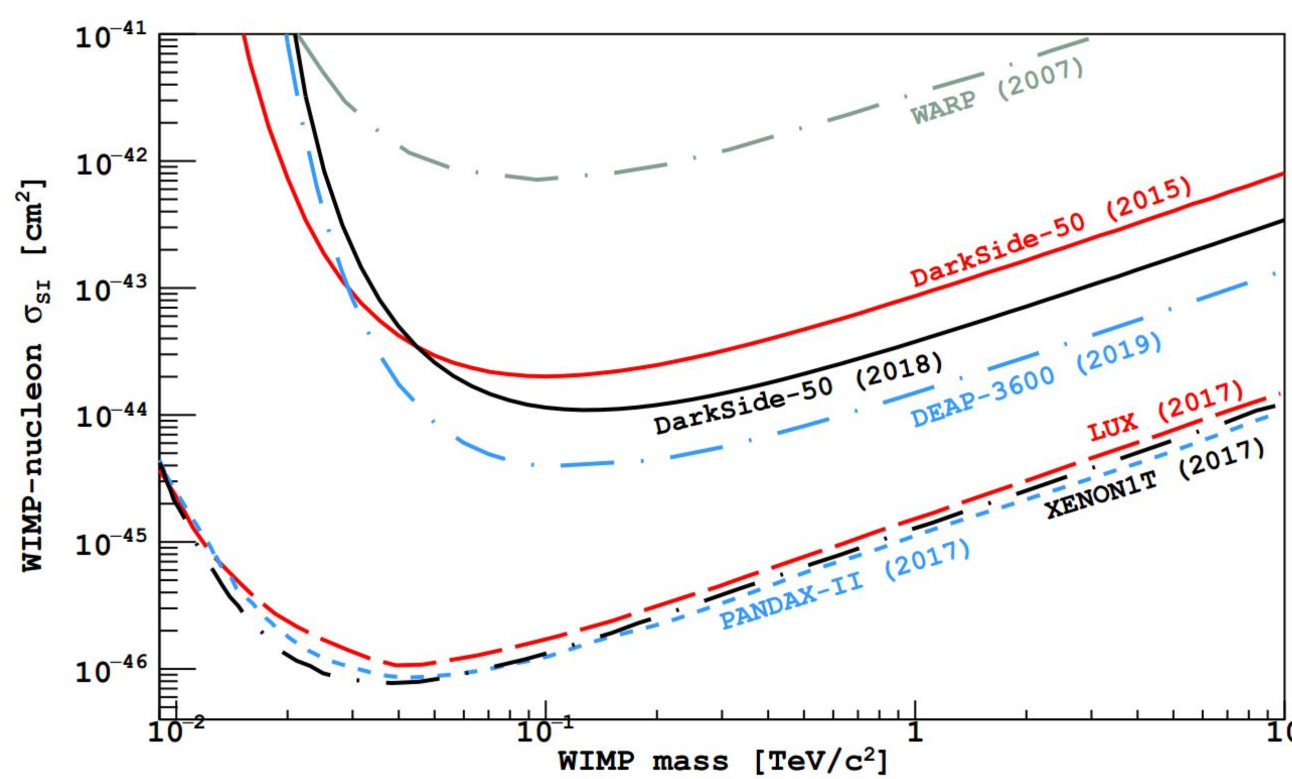
LAr TPC: DarkSide-50



$$f_{90} = \frac{\text{S1 light in first 90ns}}{\text{total S1 light}}$$

Background	Estimated # surviving all cuts
Cosmogenic Neutros	< 3 x 10^{-4}
Radiogenic Neutrons	< 5 x 10^{-3}
Surface Alpha	1 x 10^{-3}
Cherenkov + Scintillation	0.08
Total	0.09 ± 0.04





Future: DARWIN

past | still present... | present | ...upgrade

2.6 m height
2.6 m diameter

XENON10	XENON100	XENON1T	XENONnT	DARWIN
Time:until 2007	**Time**:since 2008	**Time**:from 2015	**Time**:from 2019	**Time**:from 2020s
Total:25 kg	**Total**:162 kg	**Total**:3.5 ton	**Total**:8.4 ton	**Total:50 ton**
Target:14 kg	**Target**:48 kg	**Target**:2 ton	**Target**:6 ton	**Target**:40 ton
Limit:~10^{-43} cm^2	**Limit**:~10^{-45} cm^2	**Limit**:~10^{-47} cm^2	**Limit**:~10^{-48} cm^2	**Limit**:~10^{-49} cm^2

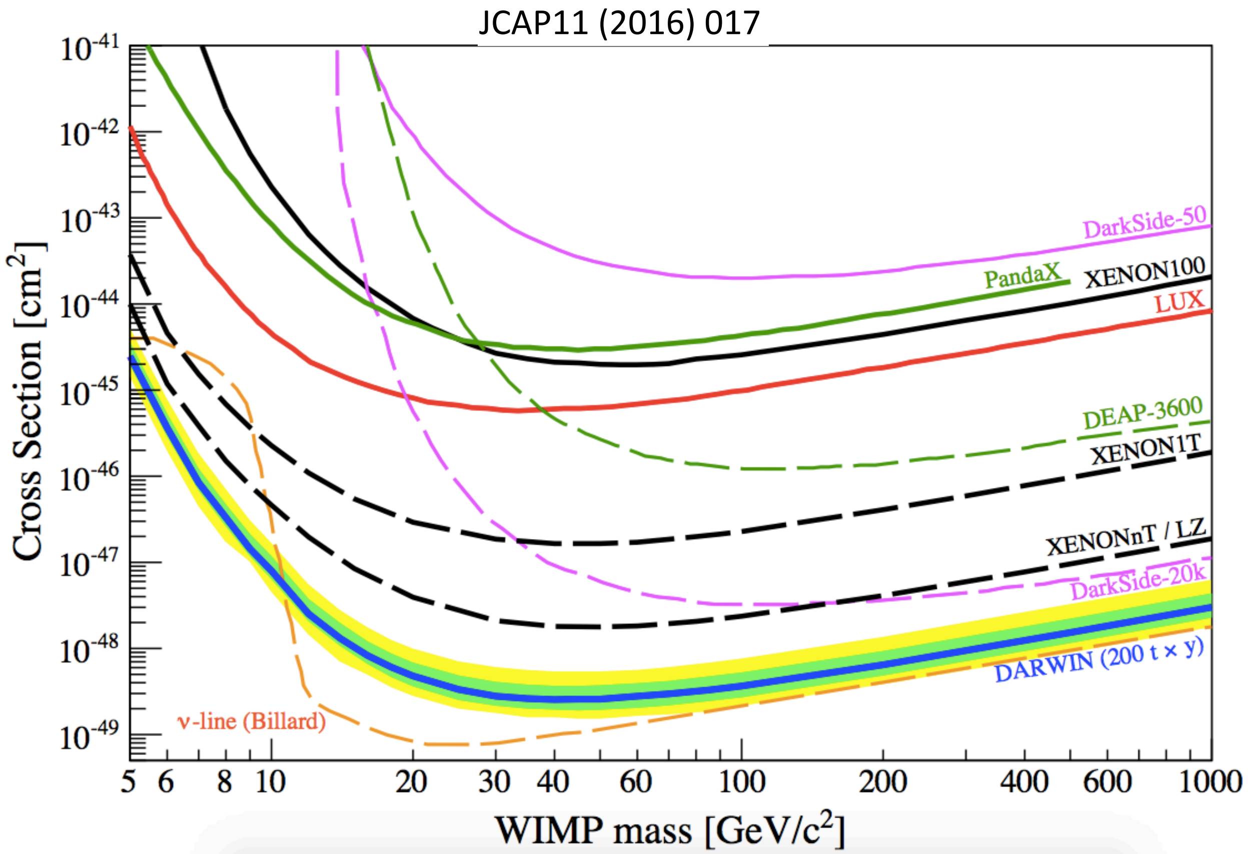
....

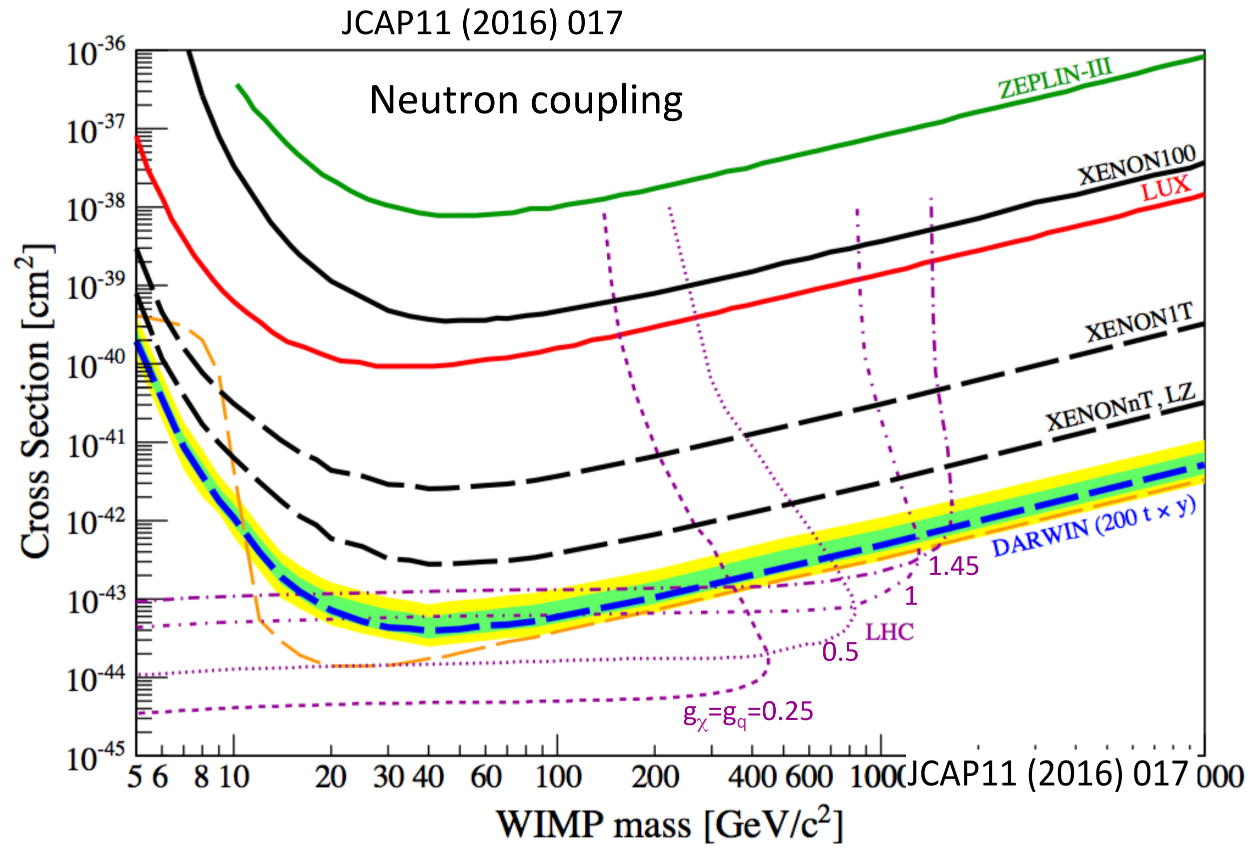
EPJC 77 881 (2017)

JCAP 1611 11 (2016)

- XENON1T collected more than 1 tonne*yr exposure and set the most stringent limit on WIMP-nucleon cross section versus WIMP mass
- **XENONnT is completing construction and is expected to start commissioning in 2020**
- **nT: an order of magnitude improvement in sensitivity with respect to 1T with 20 tonne*yr exposure**

Future: DARWIN



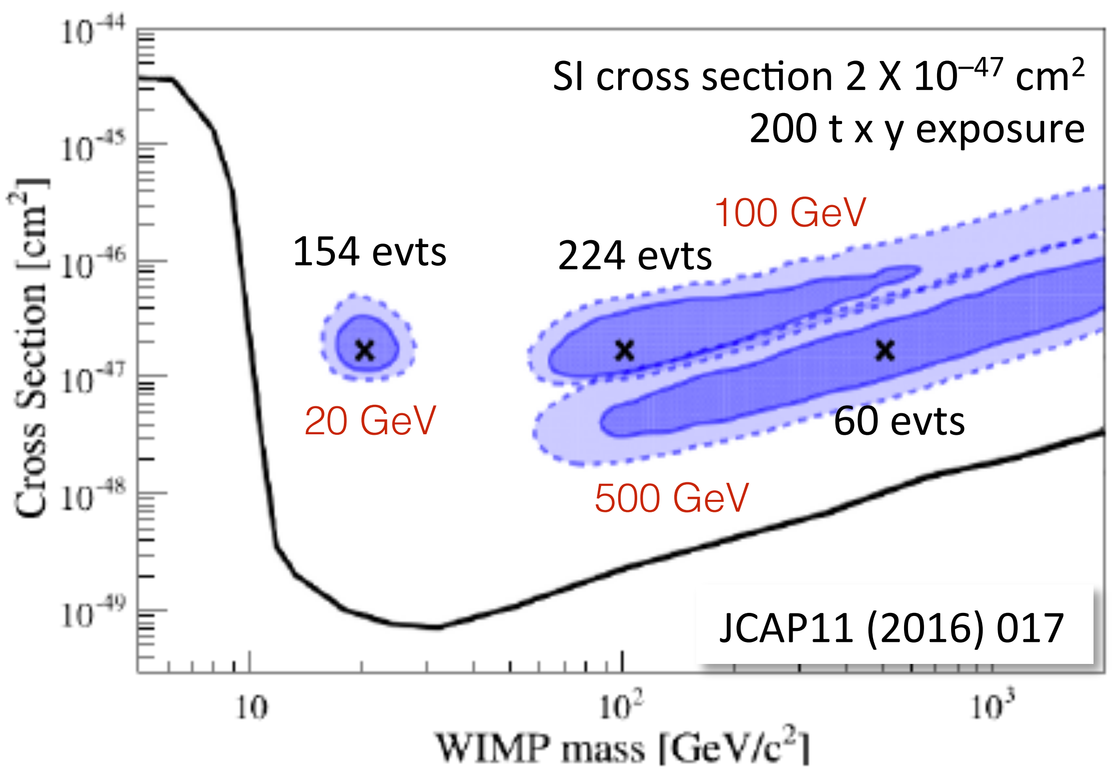


- **Huge dimensions: 2.6 m height x 2.6 diameter**
- **Huge exposure: 200 ton x year**
  - 50 tons of LXe
  - 40 tons of target
  - 30 tons fiducial
- **Sensitivity: ~10^{-49} cm^2**
- **99.98% ER rejection at 30% NR acceptance**
- **Light yield 8 PE/keV at 122 keV, Energy window 5-35 keV$_{NR}$**
- **Sensitivity: ~10^{-49} cm^2**

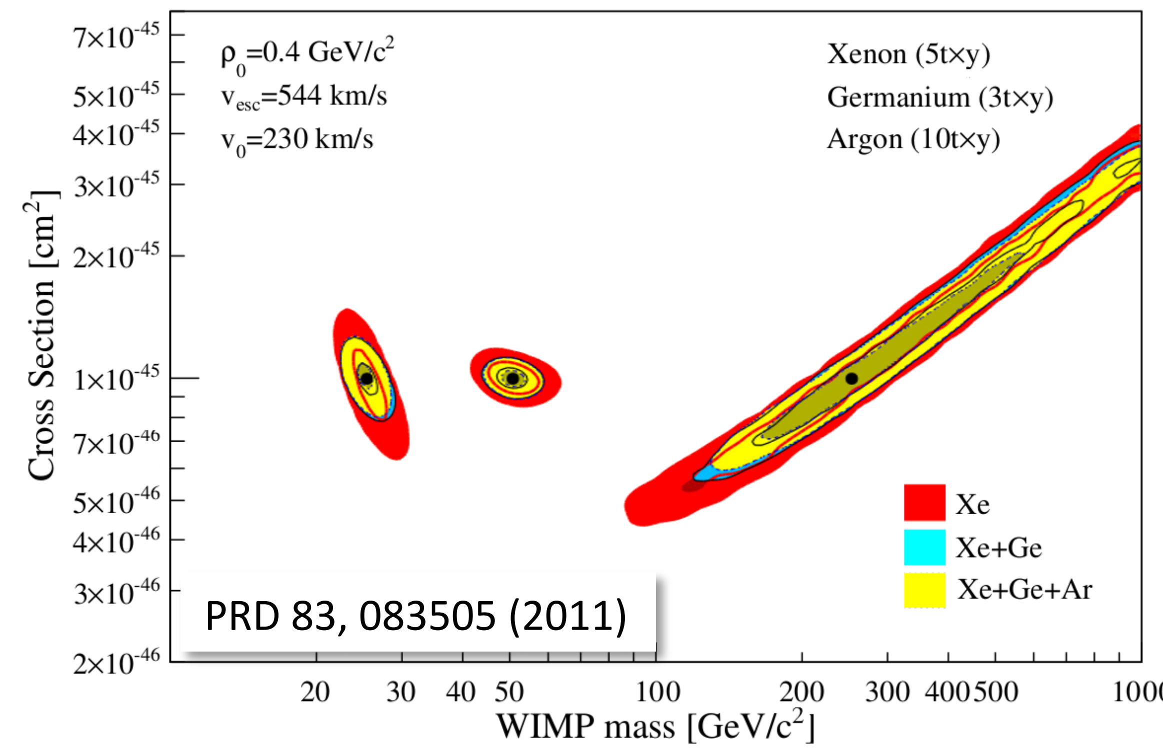
Future: DARWIN

DARWIN

WIMP properties



Target complementarity



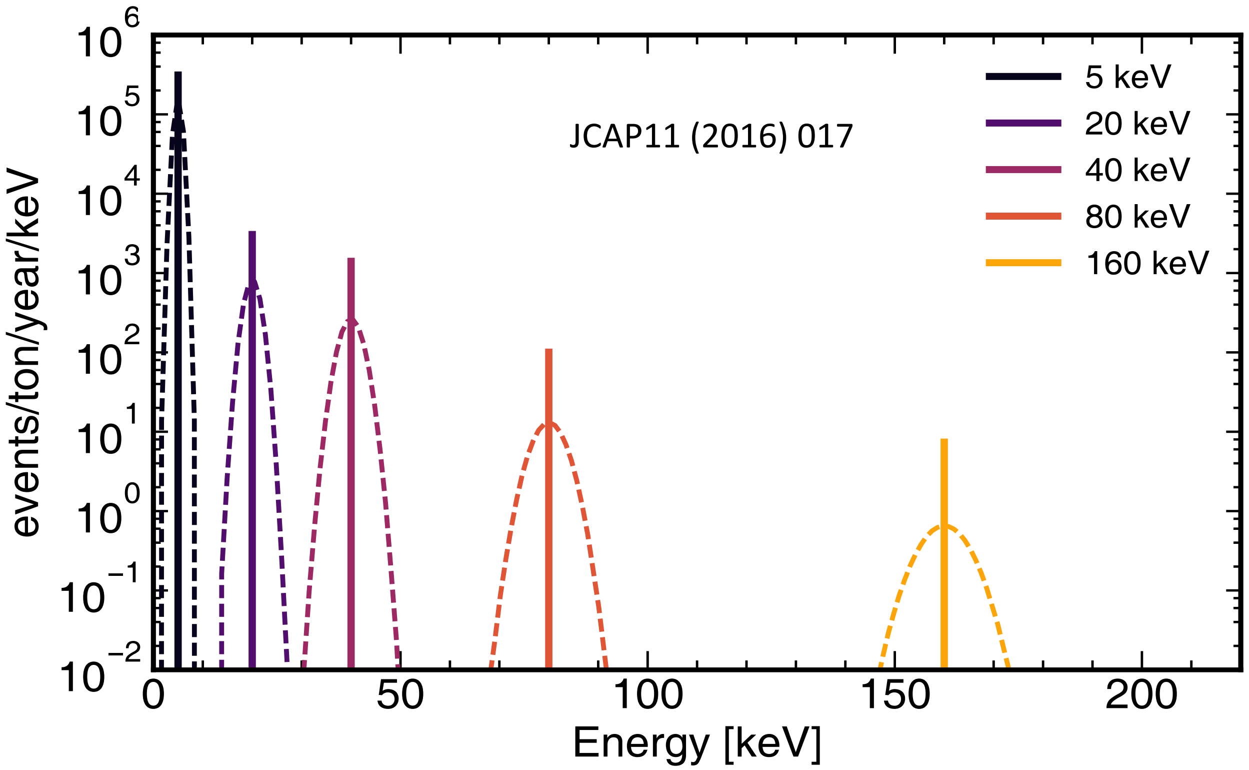
- Reconstruction of WIMP mass and scattering cross section
- 1σ, 2σ credibility regions for 20, 100 and 500 GeV/c^2 marginalised over astrophysical parameters uncertainties
- Few 100 GeV can be constrained

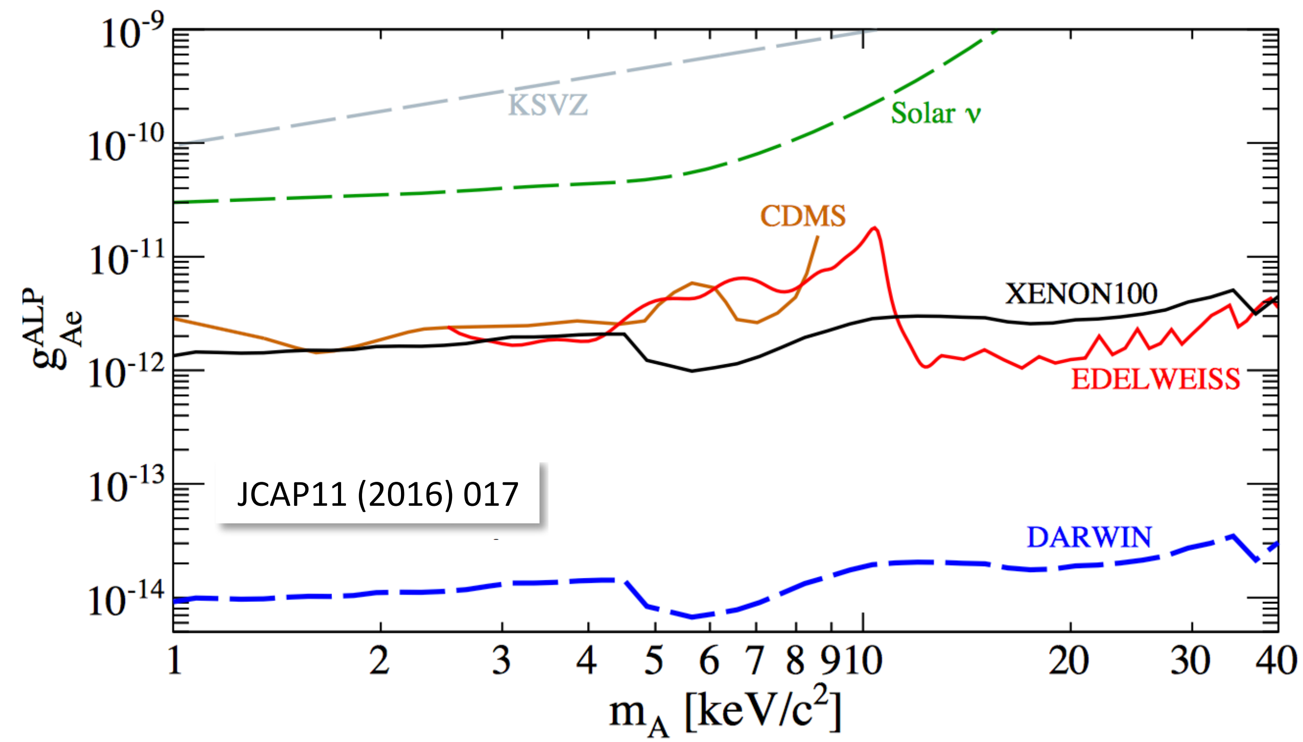
- Parameters reconstruction improves with information from Ge detectors

Future: DARWIN

DARWIN

Bosonic vectors and pseudo-scalars DM candidates





- Search for monoenergetic peaks
- Coupling and mass are independent
- For bosonic vectors

$$\sigma_v \simeq \frac{\sigma_{pe}}{\beta}\frac{\alpha'}{\alpha}$$ where α'/α = k²

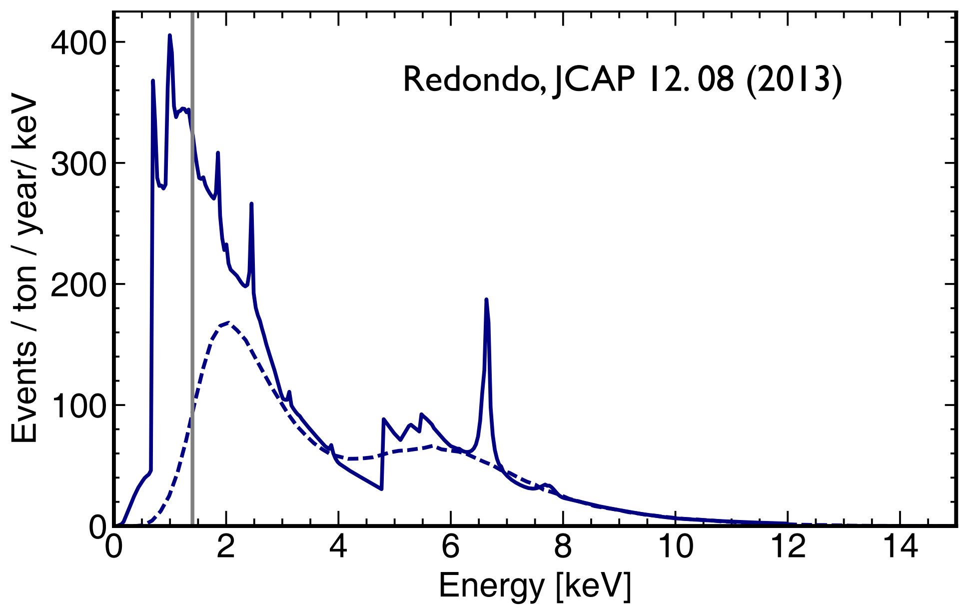
$$R \simeq \frac{4\times 10^{23}}{A}\frac{\alpha'}{\alpha}\left(\frac{\text{keV}}{m_V}\right)\left(\frac{\sigma_{photo}}{\text{bn}}\right)\ \text{kg}^{-1}\text{day}^{-1}$$

dark photons, superWIMPs, ALPs

- keV relic dark matter
- Detection via axio-electric effect
- x100 improvement in sensitivity wrt XENON100
- XENON1T has already set the most stringent limit for ALPs and bosonic DM (arXiv: 2006.0972v2)

Future: DARWIN

Solar axions

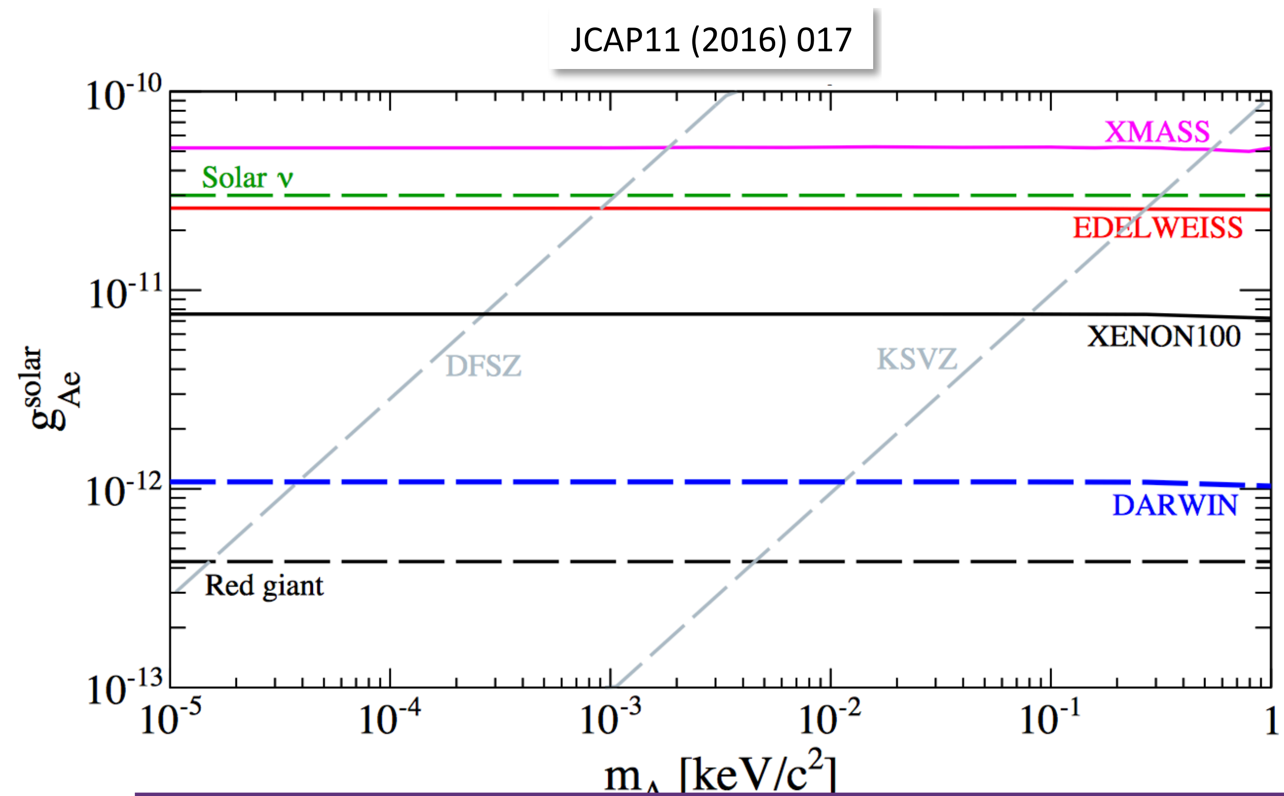


Expected signal in xenon from solar axion models

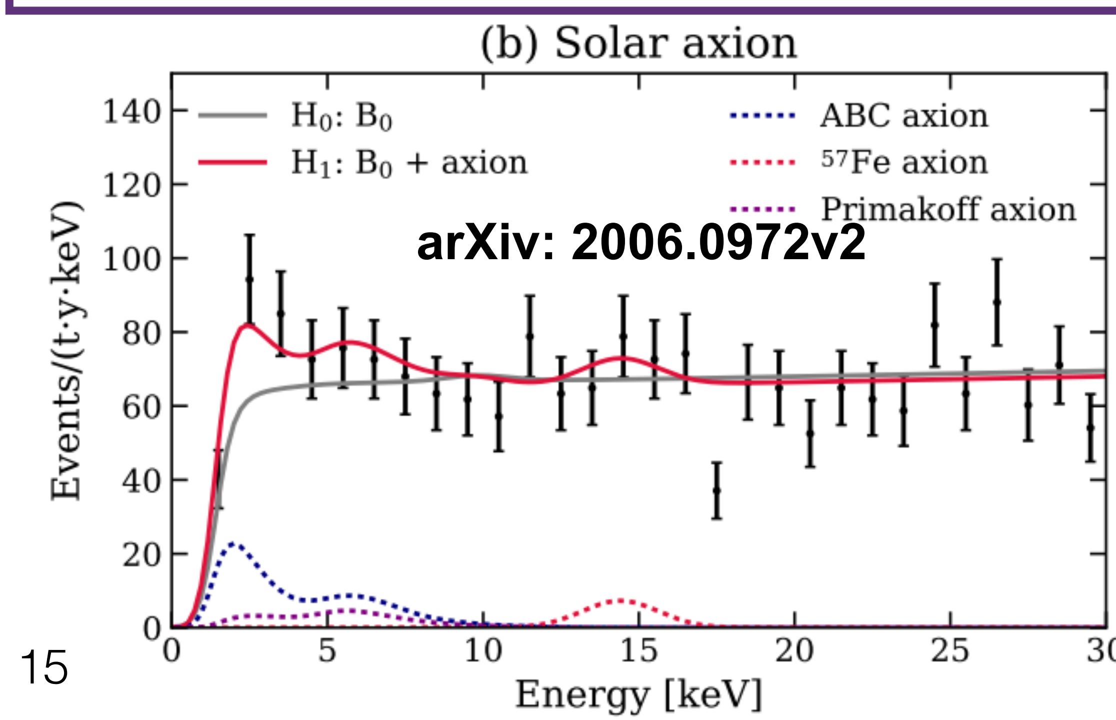
- **Axions from the Sun:**
- **Primakoff effect, ABC axions and ^{57}Fe line**
- Detection via axio-electric effect
- Possible solution to the strong CP problem
- Coupling times mass fixed

$$\sigma_{ae} = \sigma_{pe} \frac{g_{ae}^2}{\beta} \frac{3E_a^2}{16\pi\alpha m_e^2} \left(1 - \frac{\beta^{2/3}}{3}\right)$$

Rate scales as g_{ae}^4



Recent results from XENON1T: excess compatible with solar axions at 3.5 sigma wrt background



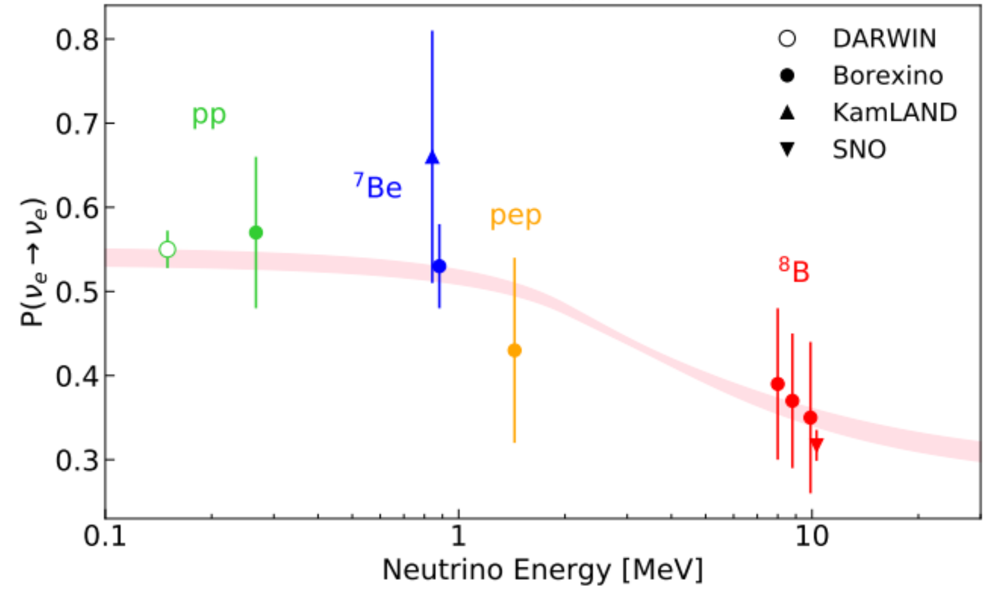
Future: DARWIN

DARWIN

and more fundamental physics cases

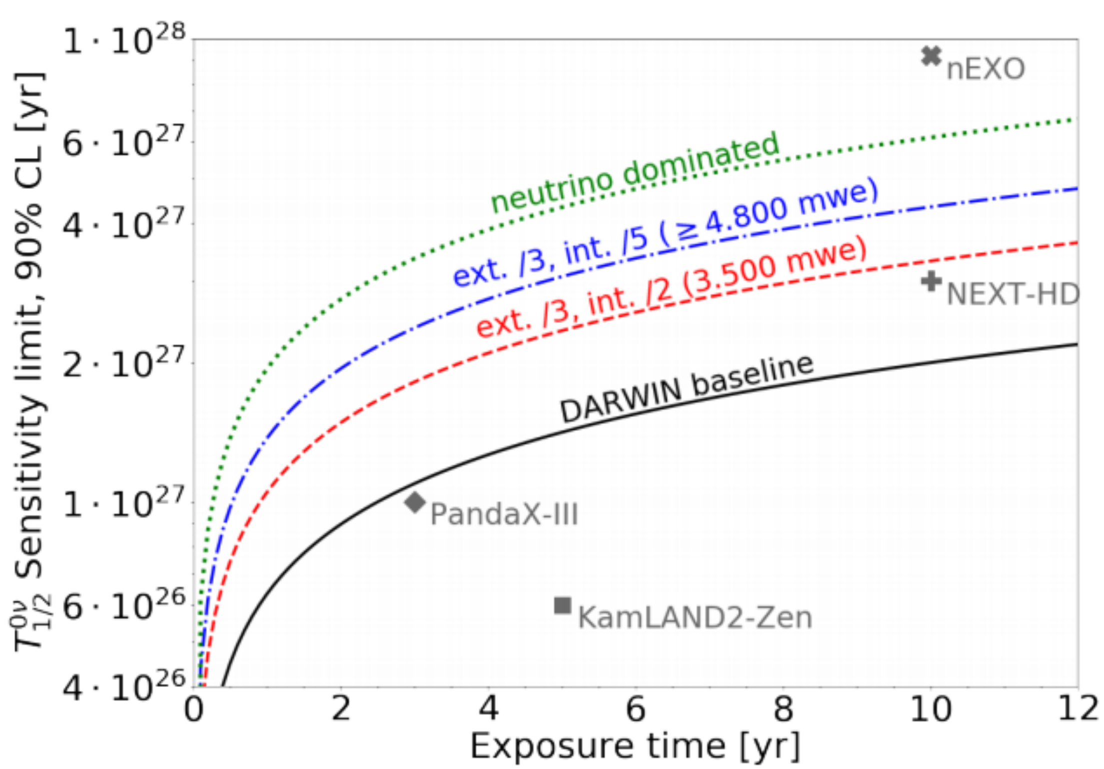
- Solar neutrinos

arXiv:2006.03114



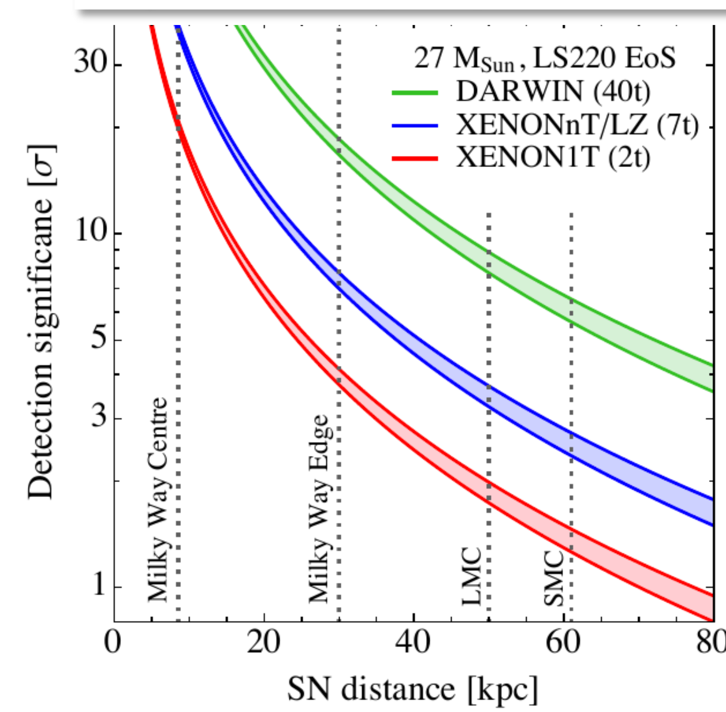
- Neutrinoless double beta decay of ^{136}Xe

arXiv:2003.13407



- Coherent neutrino nucleus scattering
- SuperNova neutrinos

Phys. Rev. D 94 (2016) no.10, 103009

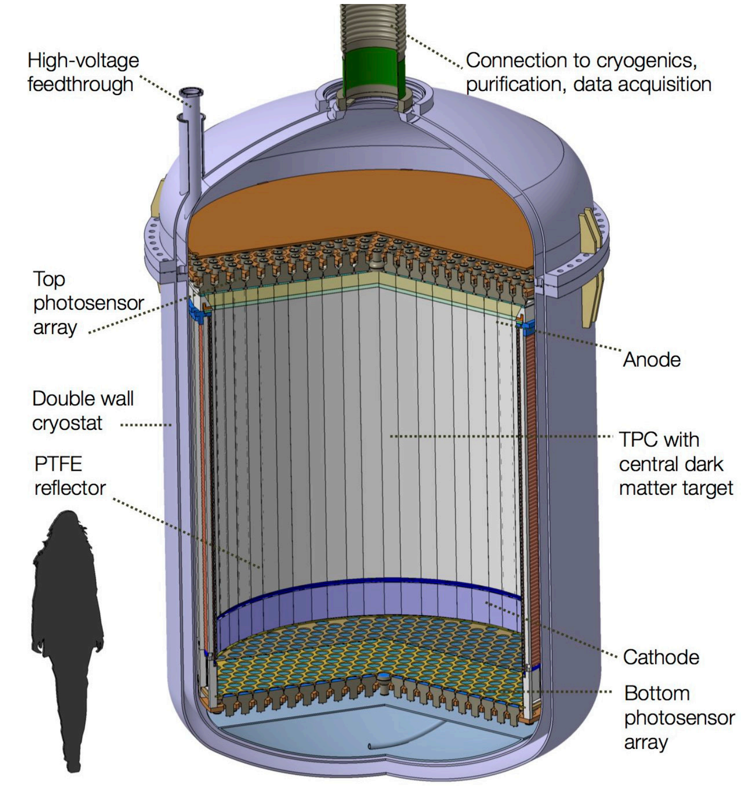


Future: DARWIN

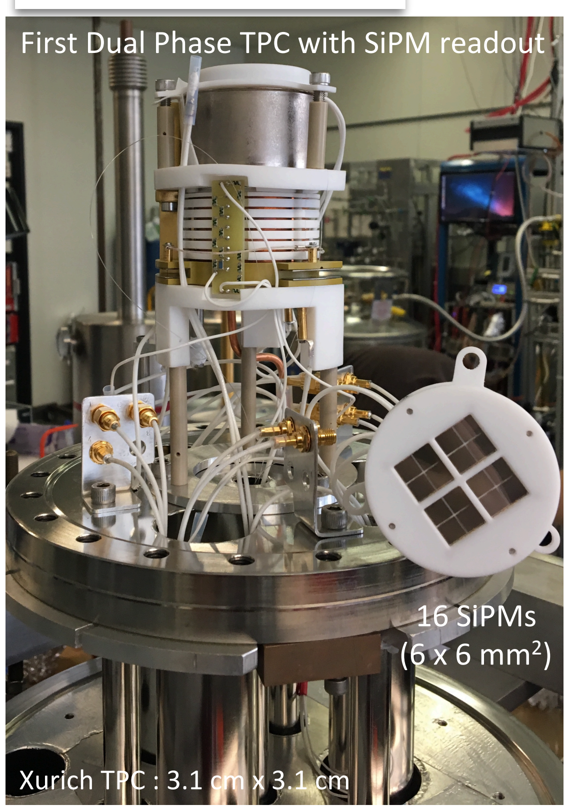
CHALLENGES

- Electron drift over 2.5 meters.
  HV more than -100 kV for drift field of 0.5 kV/cm
- Background: reduce ^{222}Rn (material screening, distillation) and (α,n) from PTFE
- Purification and distillation: need high speed for large quantity of LXe
- Light collection efficiency: 4pi photosensors

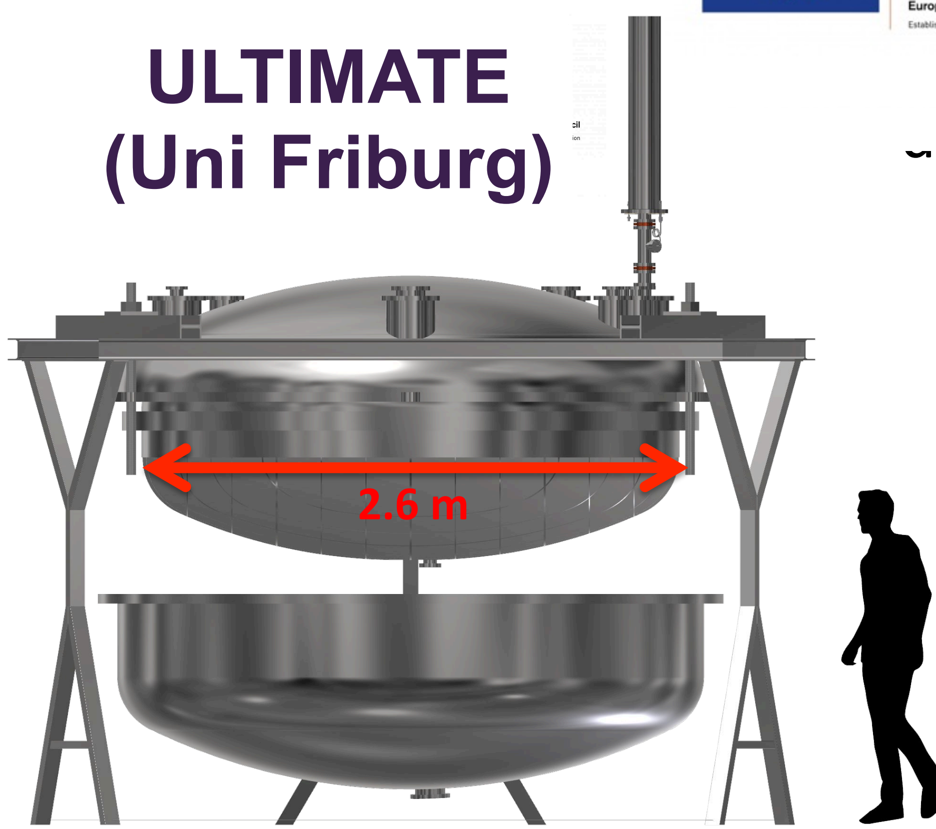
- Photosensors: high QE, low dark rate, stability



JINST 13 (2018) P10022



ULTIMATE (Uni Friburg)



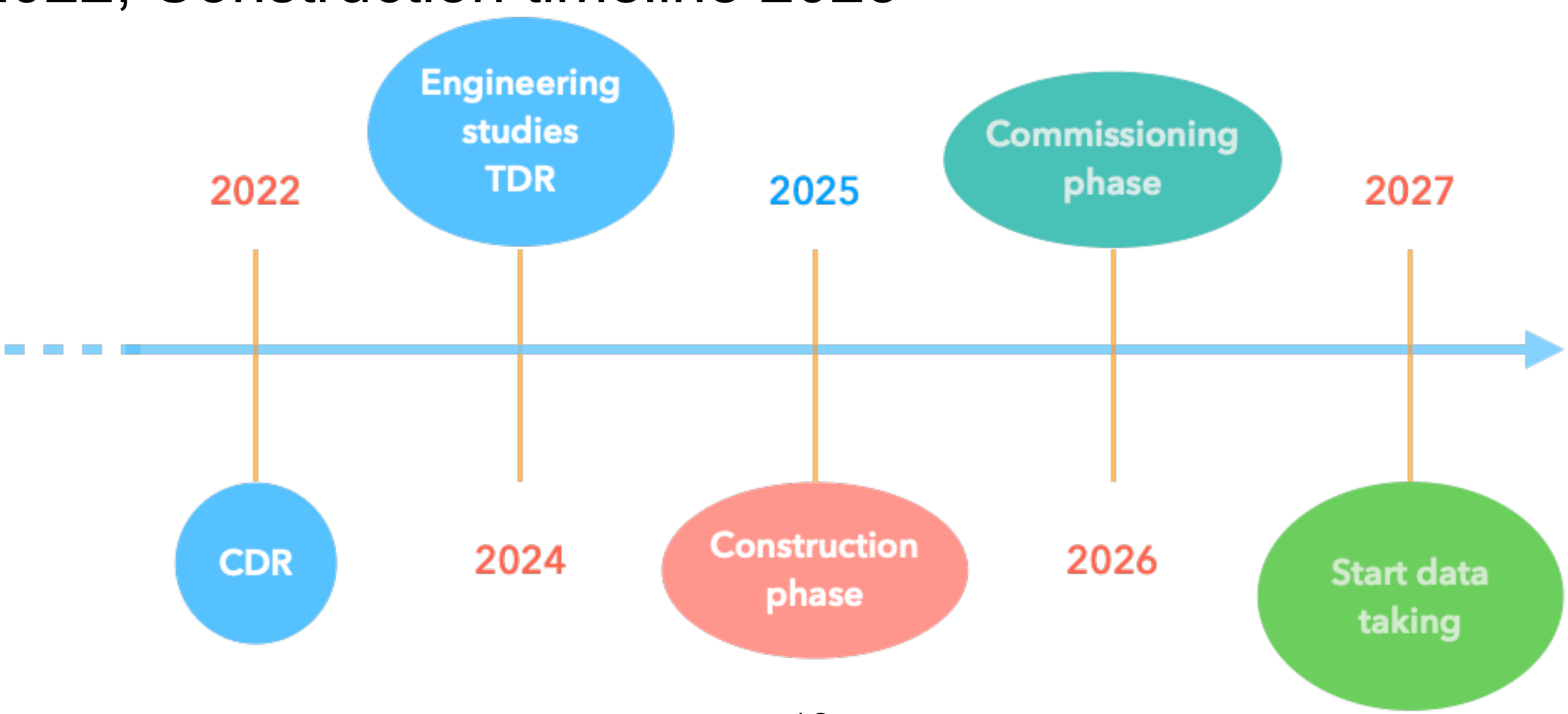
Courtesy of F. Tönnies

Xenoscope (UZH)

Future: DARWIN

www.darwin-observatory.org

- 29 institutions, 12 countries
- Working towards a CDR and a TDR
- DARWIN in the APPEC roadmap
- CDR for 2022, Construction timeline 2025



C. Macolino

Future: GADMC

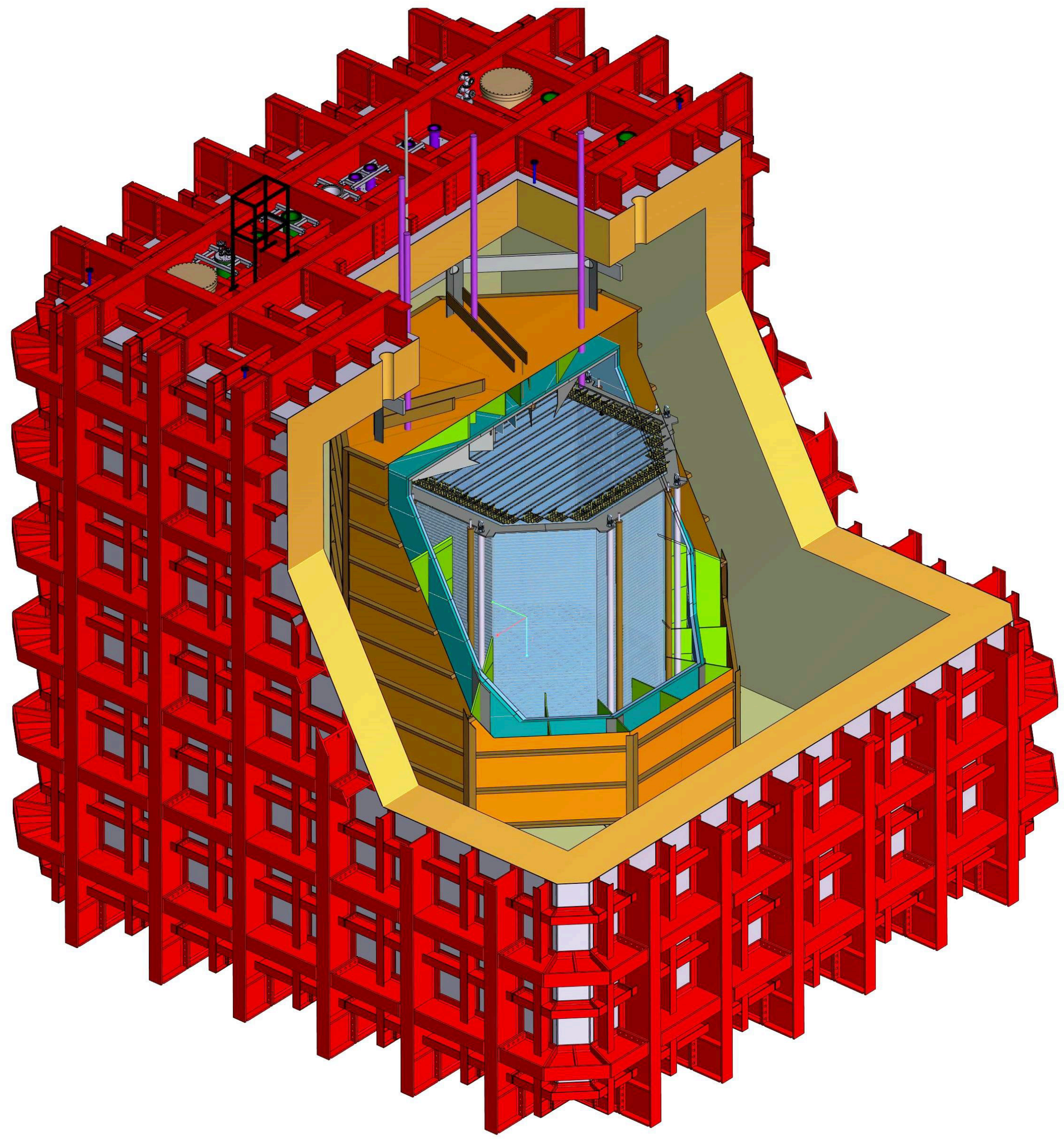
Global Argon Dark Matter Collaboration

DEAP-3600 (running)

DarkSide-50 (running)

miniCLEAN

ArDM



DarkSide-20k
2022~

~300 tonnes

ARGO
2029~

Future: GADMC

Restrictions for Liquid Scintillator use at LNGS.

New design: No liquid scintillator. No water. **LAr only**! Great simplification. Overall need: AAr ~(700 +120) tonnes plus 50 tonnes of UAr.

PMTs ▻ **SiPMs** designed and developed for LAr use in collaboration with FBK.

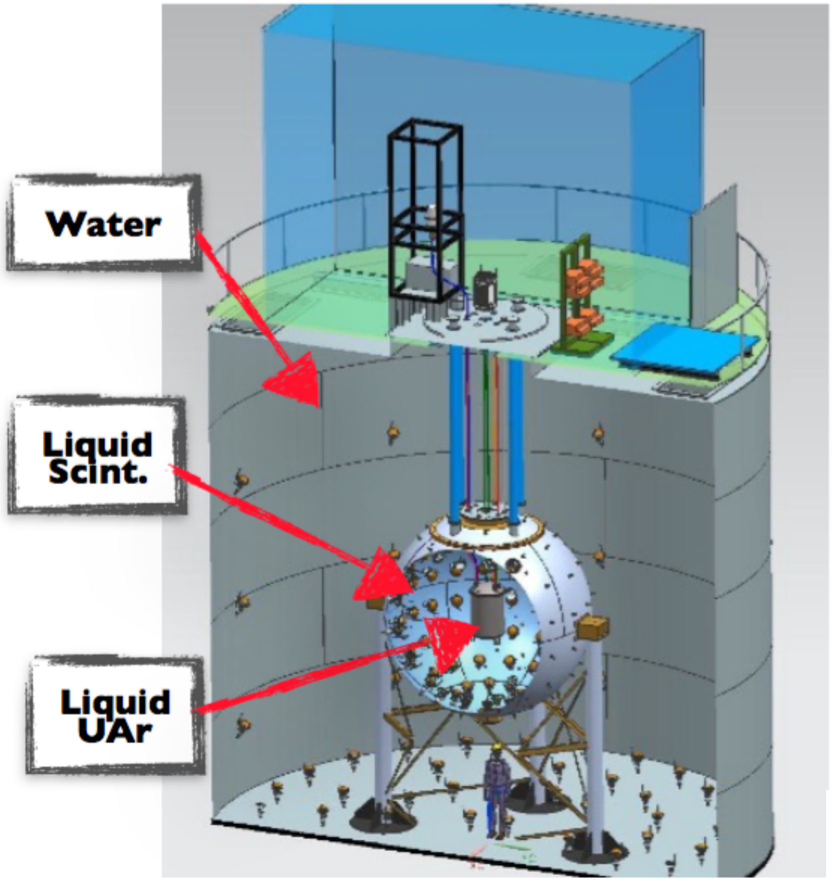
Acrylic TPC. Move from teflon to octagonal sealed acrylic vessel surrounded by the acrylic Veto.

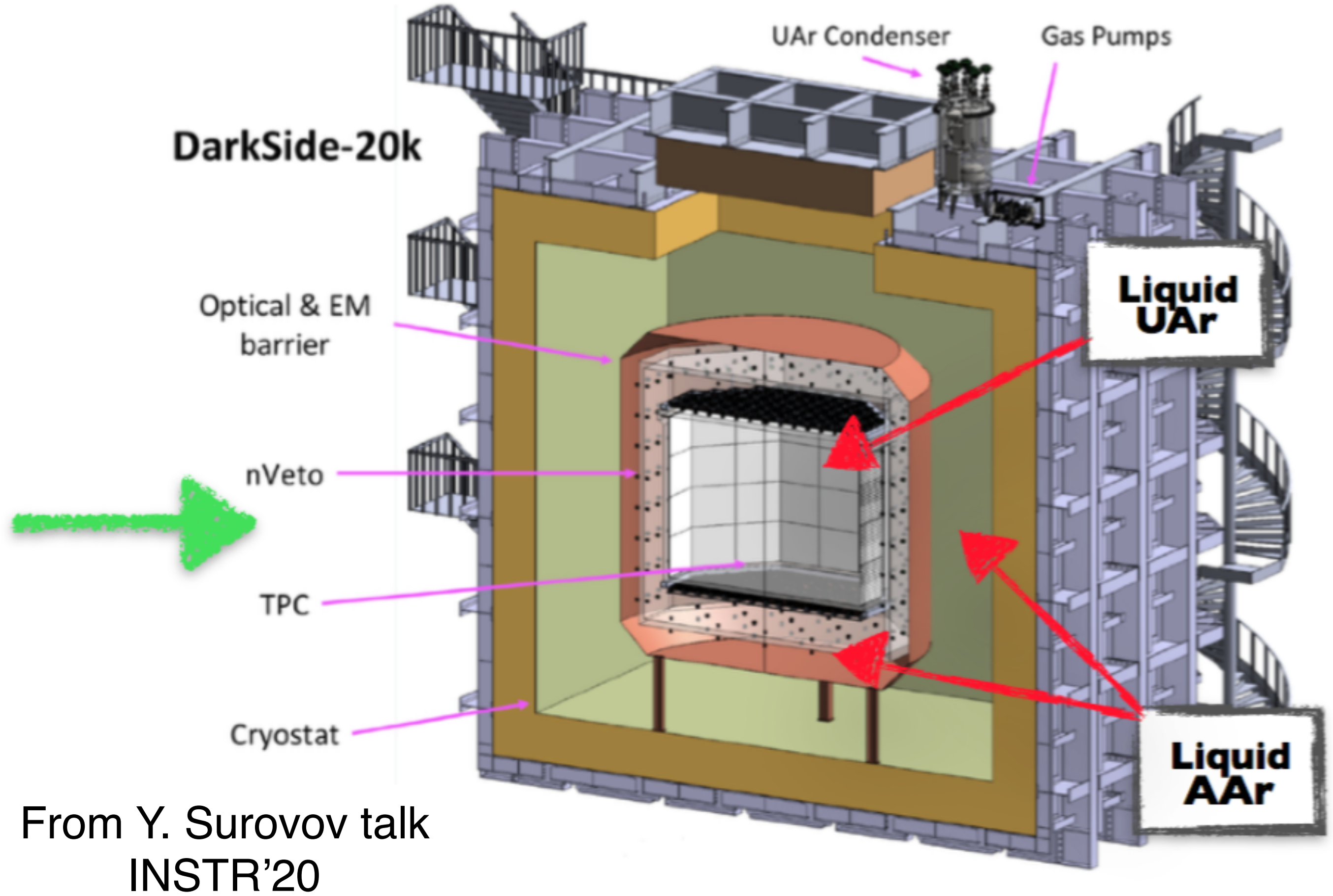
Enhanced Speculare reflector (ESR) to improve the light collection in the TPC & Veto.

ITO ▻ **Clevios**, new conductive polymer, no copper rings.

UAr as target material. New global community, joint effort towards the DS-20k & later ARGO (URANIA, ARIA).

ProtoDUNE type **cryostat** (*DarkSide-20k is a recognised experiment at CERN*).





From Y. Surovov talk INSTR'20

Future: GADMC

SIPM R&D

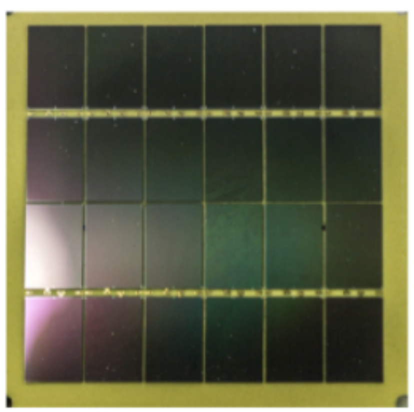
New type of SiPMs suitable for LAr temperature were developed in collaboration with Foundation Bruno Kessler (FBK).

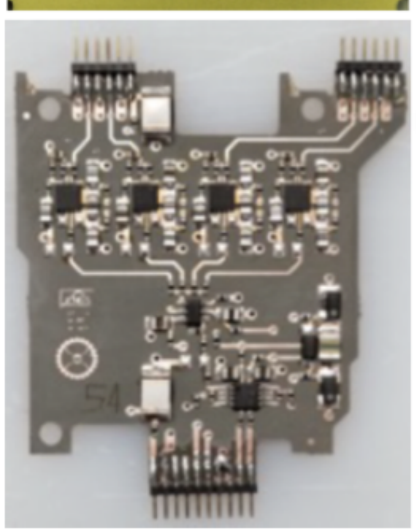
The 24 rectangular SiPMs assembled in 5x5 cm^2 tile, coupled with Front End Board (Photo Detecting Module). PDE of ~50%. S/N >20. Time resolution <10ns. Gain $>10^6$. Dark count rate at cold 0.1 Hz/mm^2. Compact & radioactively pure.

The 25 PDMs form a motherboards. All power is provided by the steering module. Individual optical readout, every PDM is coupled with an LED and the LED-to-Fiber optical adapter. DS-20k needs 30m^2 coverage, ~300 MBs in total.

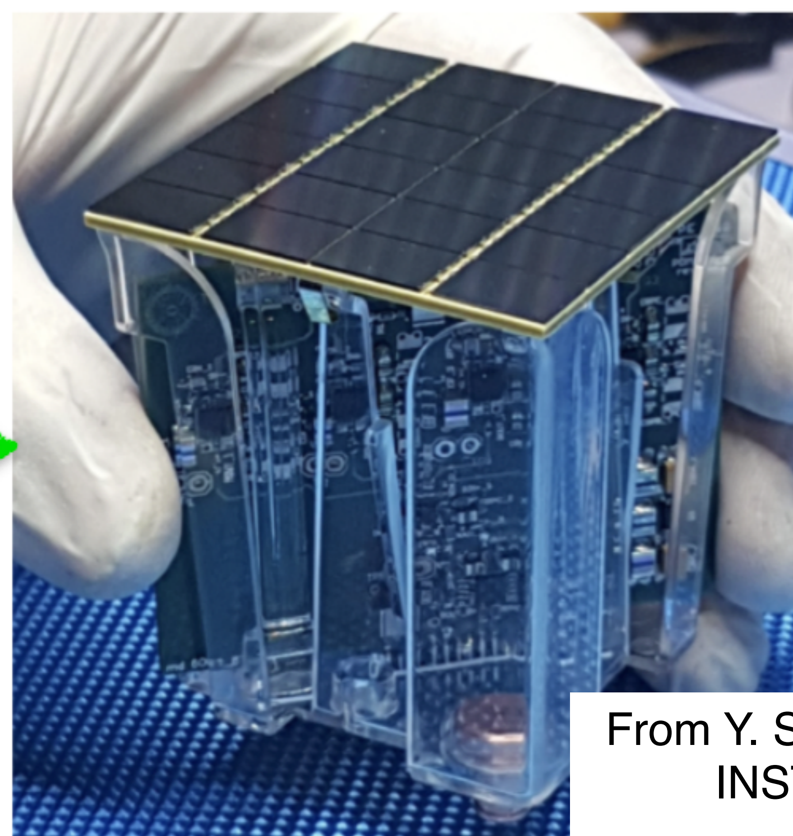
Controlled mass production of the raw wafer in LFoundry company and assembly in a dedicated special clean room at LNGS (NOA). The 30m^2 coverage of the TPC (8280 channels) + 3000 channel for Veto detector. Test for 2 years at Naples facility.

Compact size ▹ **High Coverage** efficiency,
High PDE & Signal to Noise ratio, Low radioactivity of the components.

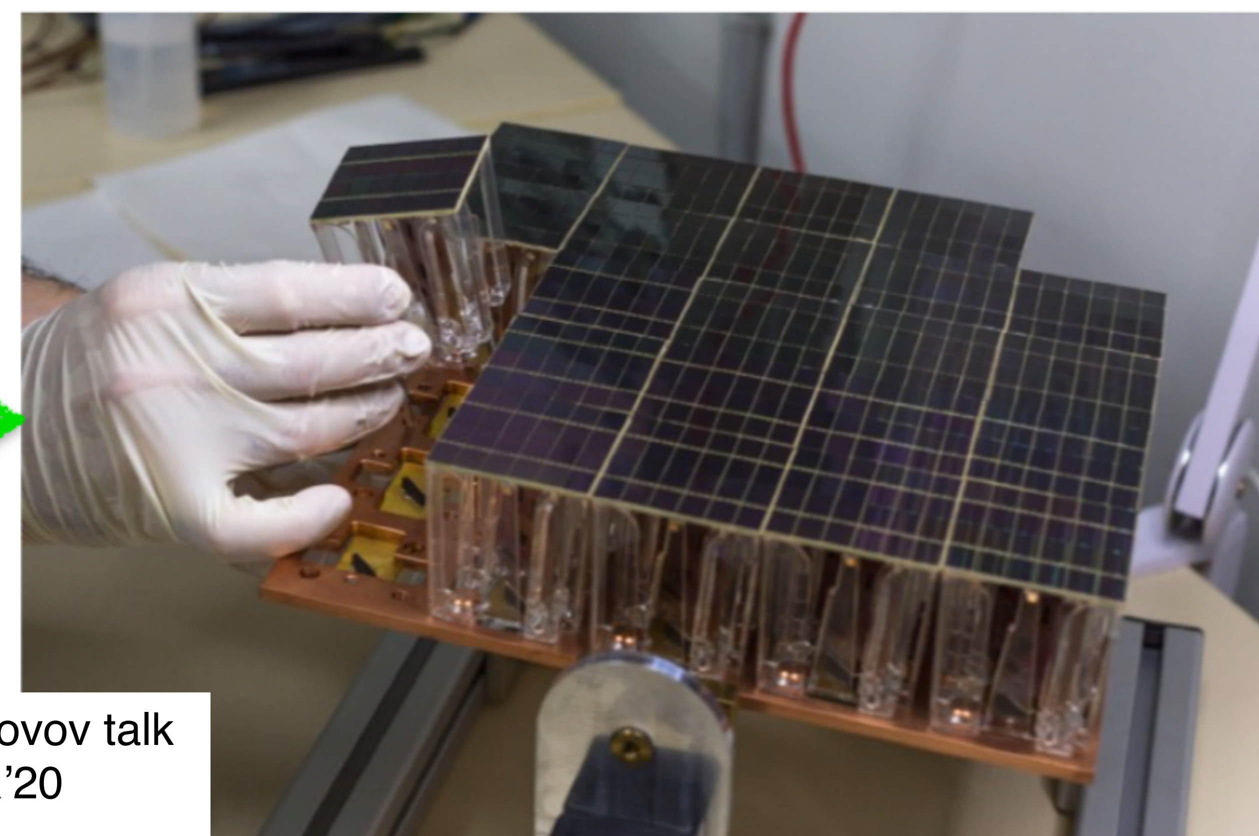




5x5cm SiPMs tile+FEB makes one PDM



25 PDMs make one Motherboard



From Y. Surovov talk INSTR'20

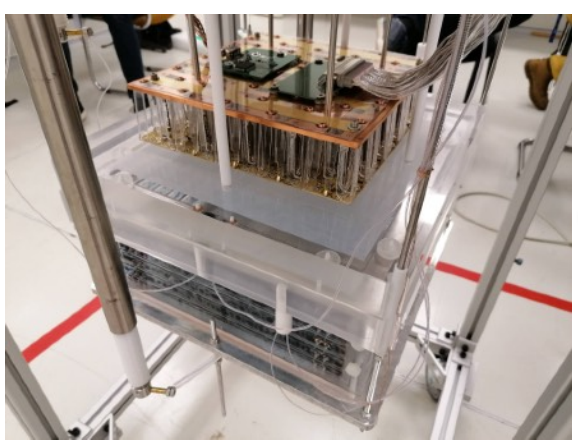
Future: GADMC

Proto-Integrated acrylic TPC for S2 study
With SiPMs as photosensors
Under construction @CERN

Key techniques: SiPM integrated test
Conductive polymer (Clevios)
ESR (Enhanced Specular Reflector) as reflectors
Acrylic bonding

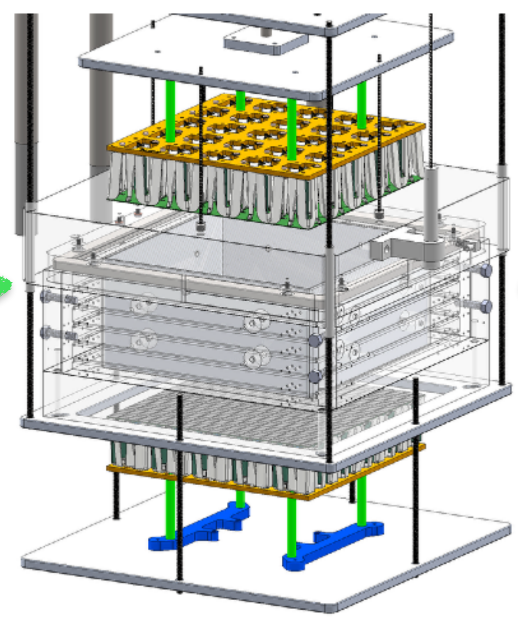
Proto-0

October 2019



Proto-1

spring 2020



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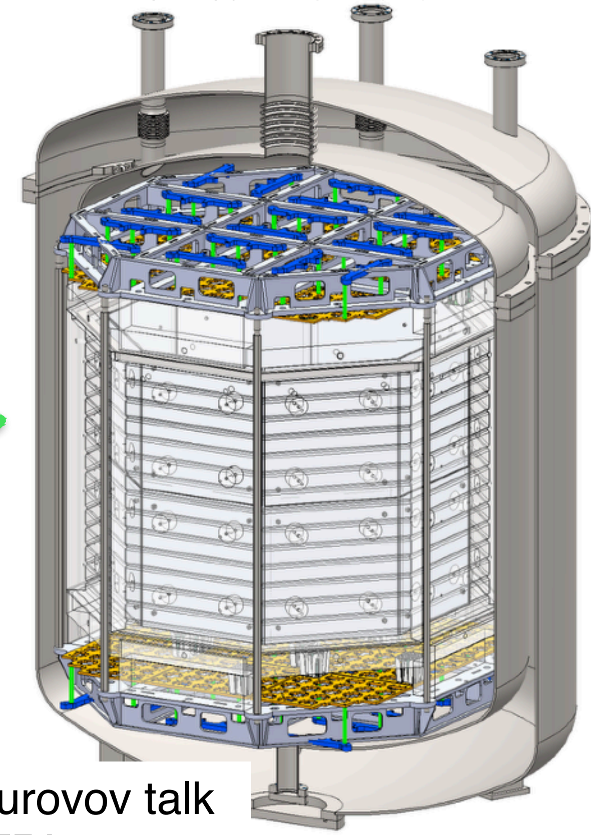
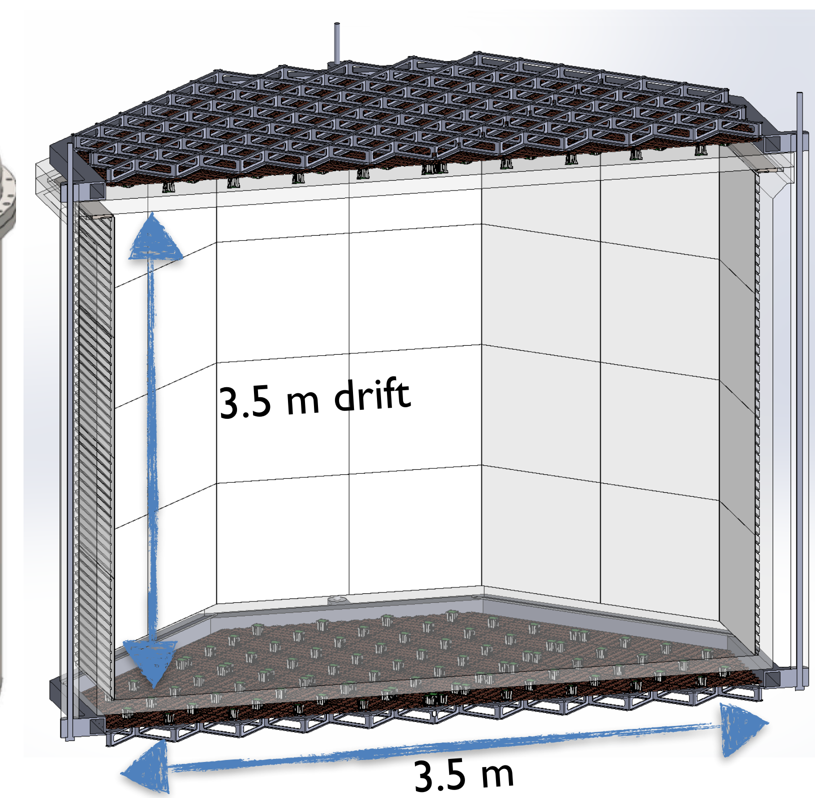
Proto-1T

from Summer 2020



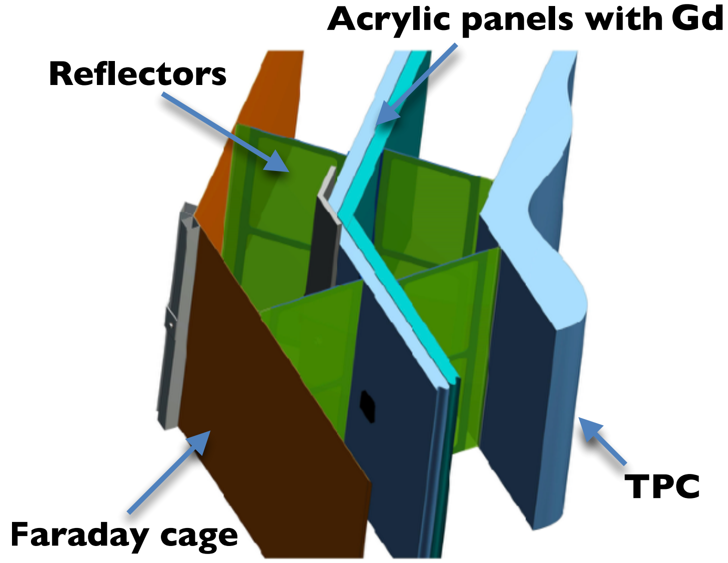
From Y. Surovov talk
INSTR'20

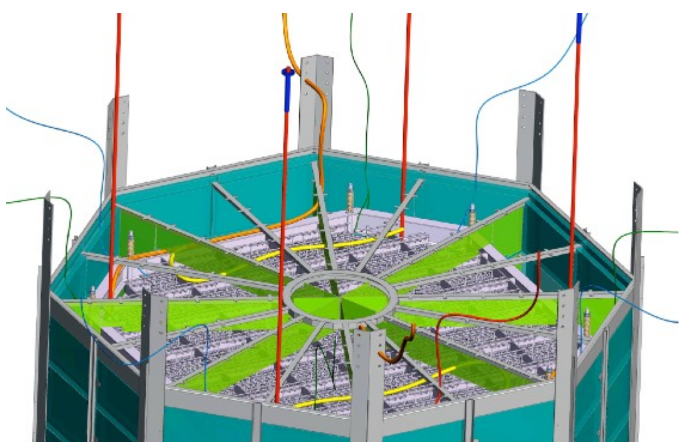
DS-20k



Future: GADMC

NEUTRON VETO

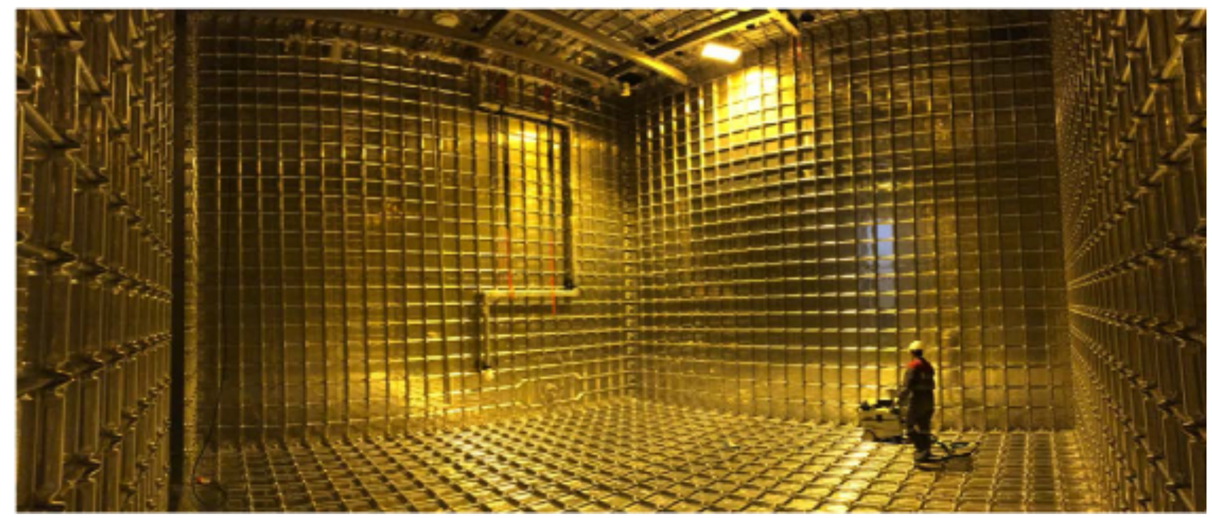


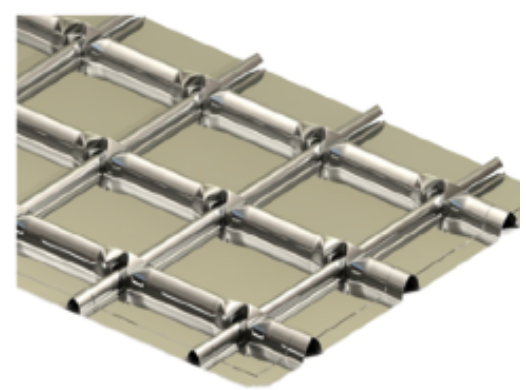


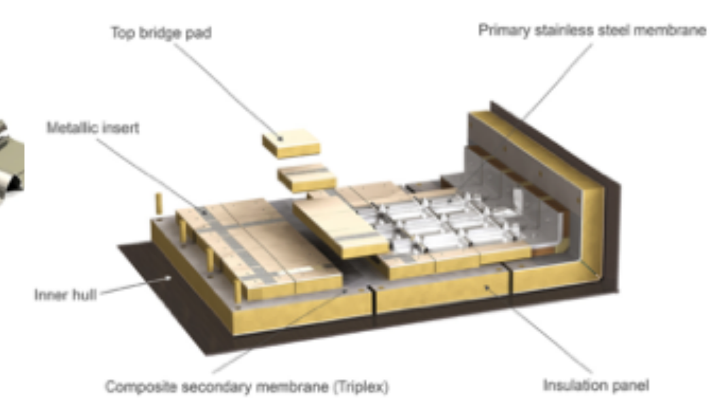
- The 10 cm thick vessel made of a PMMA+Gd_2O_3 sheets to be build around the TPC to moderate and capture neutrons. The 1-2% of Gd oxide in mass.
- Gives 40 cm thick inner (towards the TPC) and outer (towards the Faraday Cage) active liquid AAr volumes to detect gamma cascade due to neutron capture on Gd;
- The 3000 channels (single PDMs) coupled with ASIC FEE (in collaboration between Genova and Torino INFN groups). 4π coverage;

MEMBRANE CRYOSTAT

ProtoDUNE type cryostat build with use of the Mark III membrane technology developed by GTT company for the Liquified Natural Gas transport ships.







From Y. Surovov talk
INSTR'20

Future: GADMC

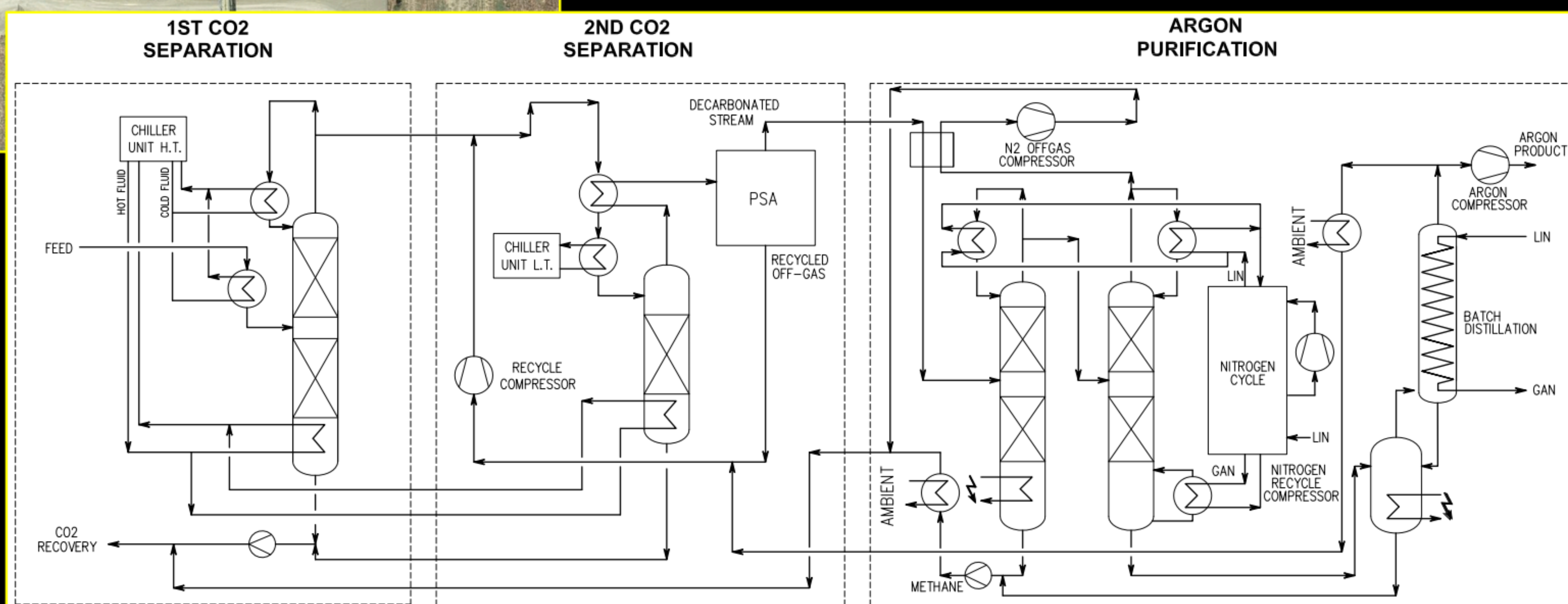
From A. Renshaw talk SUSY'19

UAr: Urania

The Urania project will procure 50 tonnes of UAr from same Colorado source as for DS-50

Will extract 250 kg/day, with 99.9% purity
-> 90 tonnes/yr

UAr will be transported to Sardinia for final chemical purification at Aria



Future: GADMC

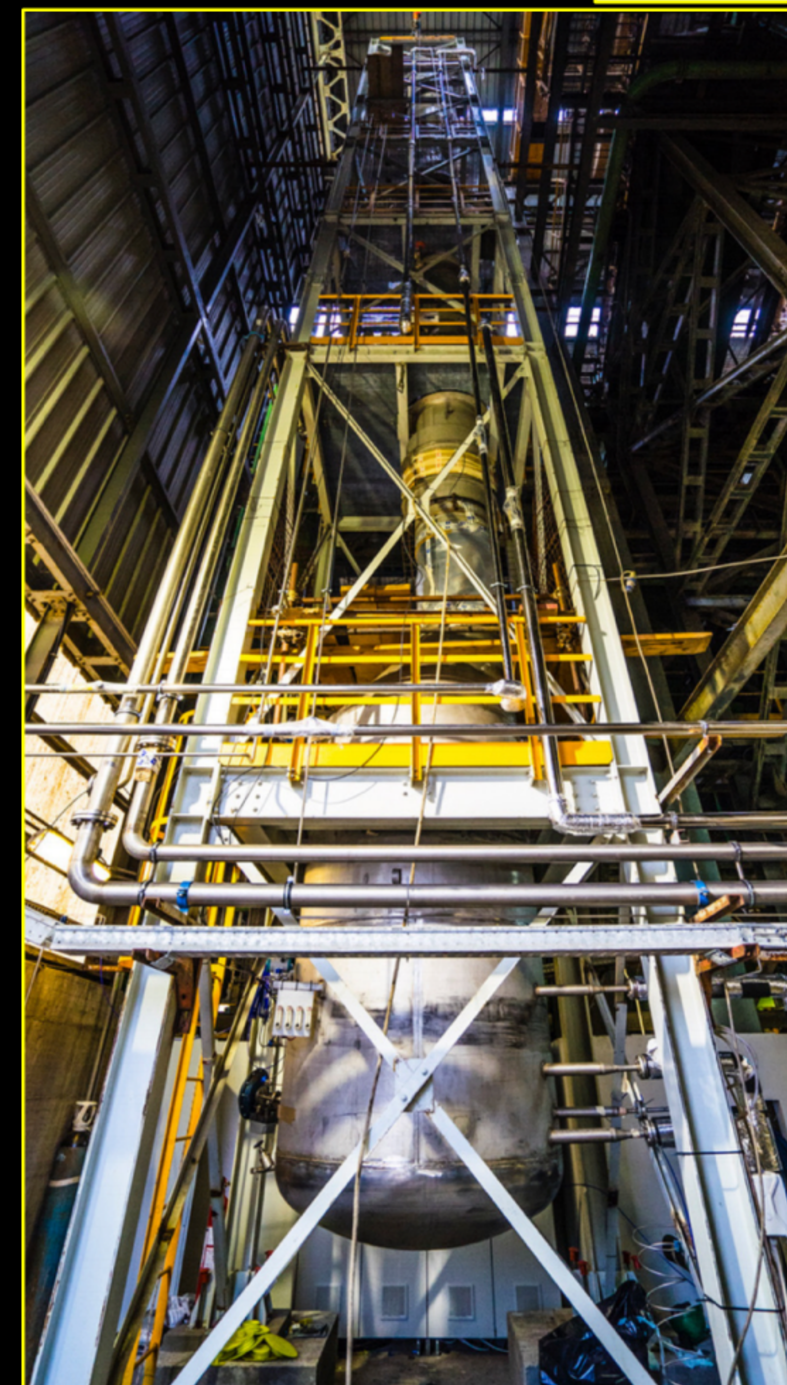
UAr: Aria

From A. Renshaw talk
SUSY'19

Final chemical purification of the UAr

Processing of O(1 tonne/day) with 10^3 reduction of all chemical impurities

Ultimate goal is to isotopically separate ^{39}Ar from ^{40}Ar

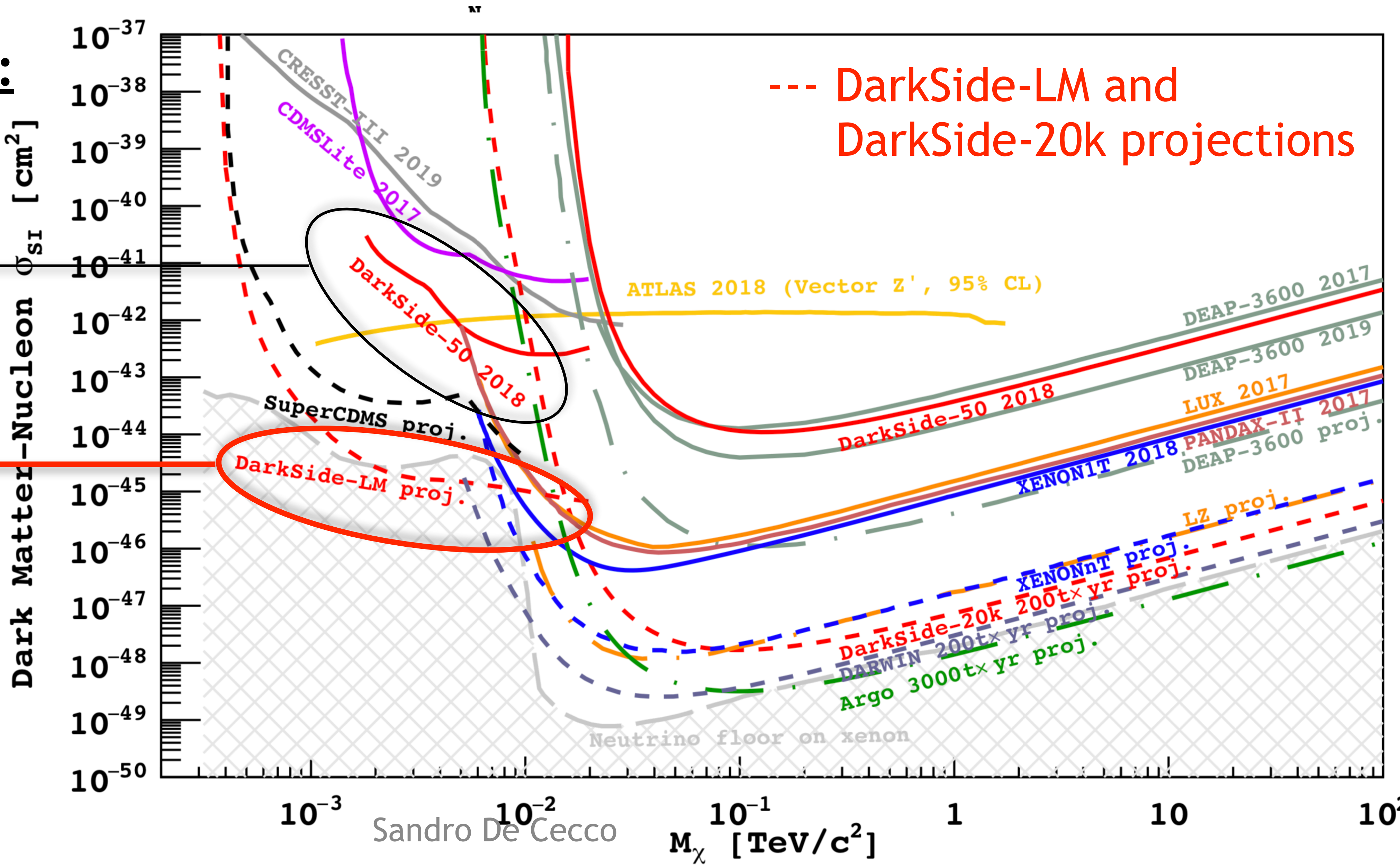


Future: GADMC

Sensitivity potential:
(with reasonably achievable assumptions from DS20k R&D.)

Current:
DarkSide-50

Future:
DarkSide-LM
with DarkSide-20k technologies
+depleted Argon

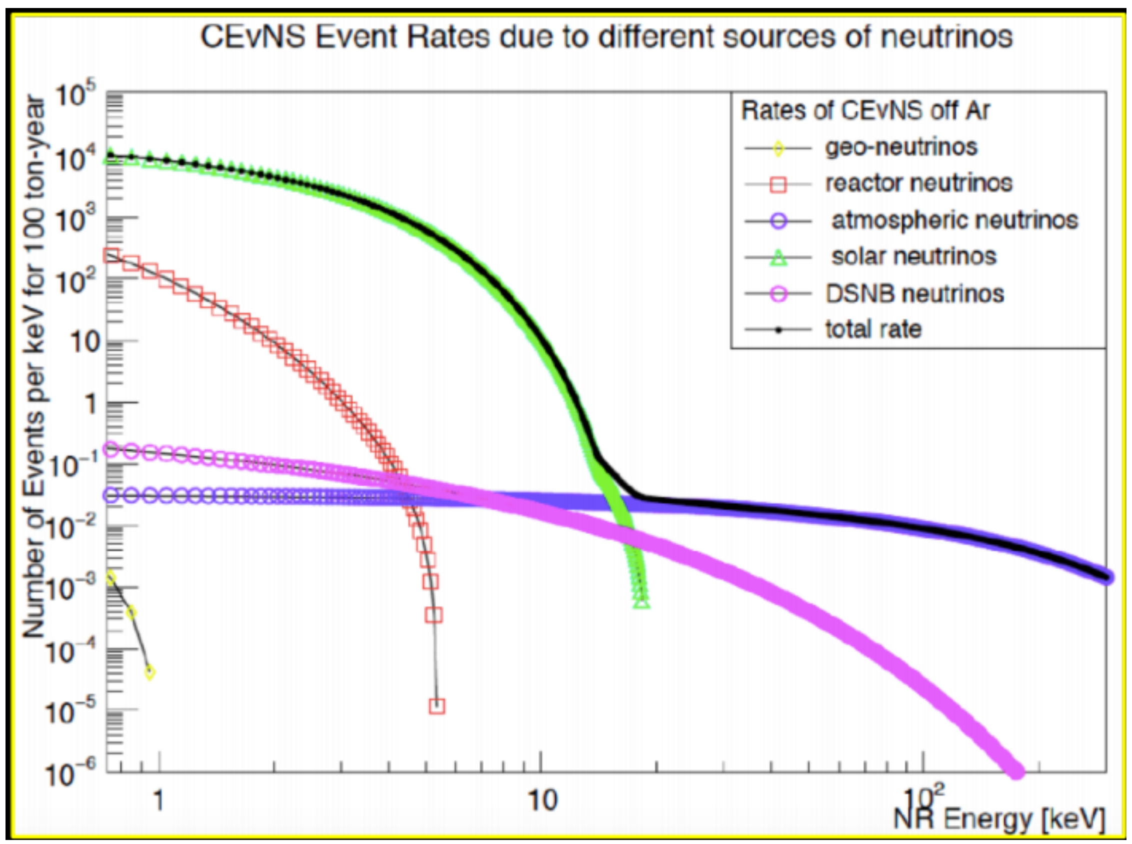


From S. De Cecco talk TAUP2019

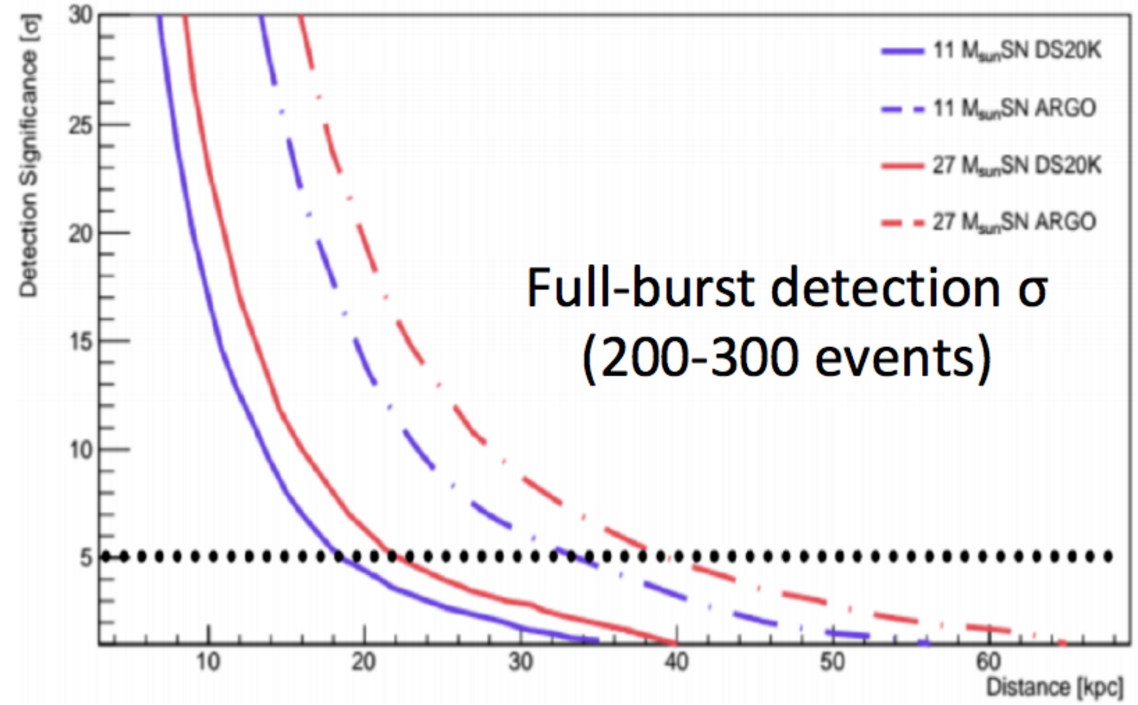
Future: GADMC

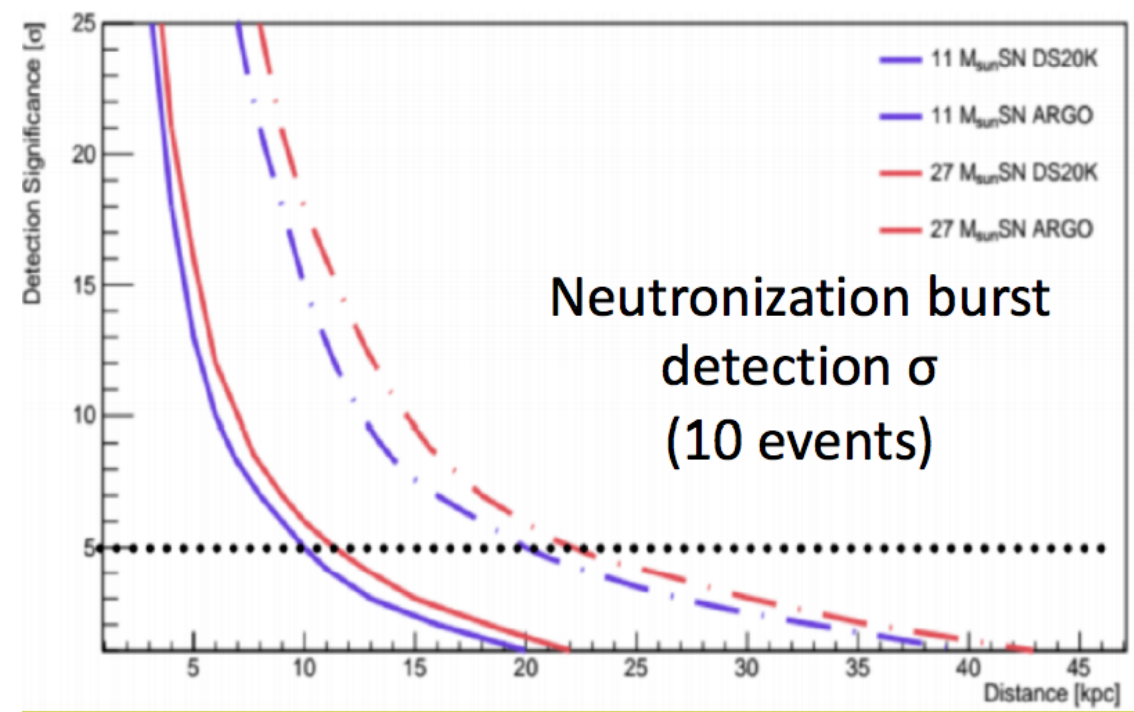
From A. Renshaw talk
SUSY’19

COHERENT NEUTRINO-NUCLEUS SCATTERING



SUPERNOVA NEUTRINOS



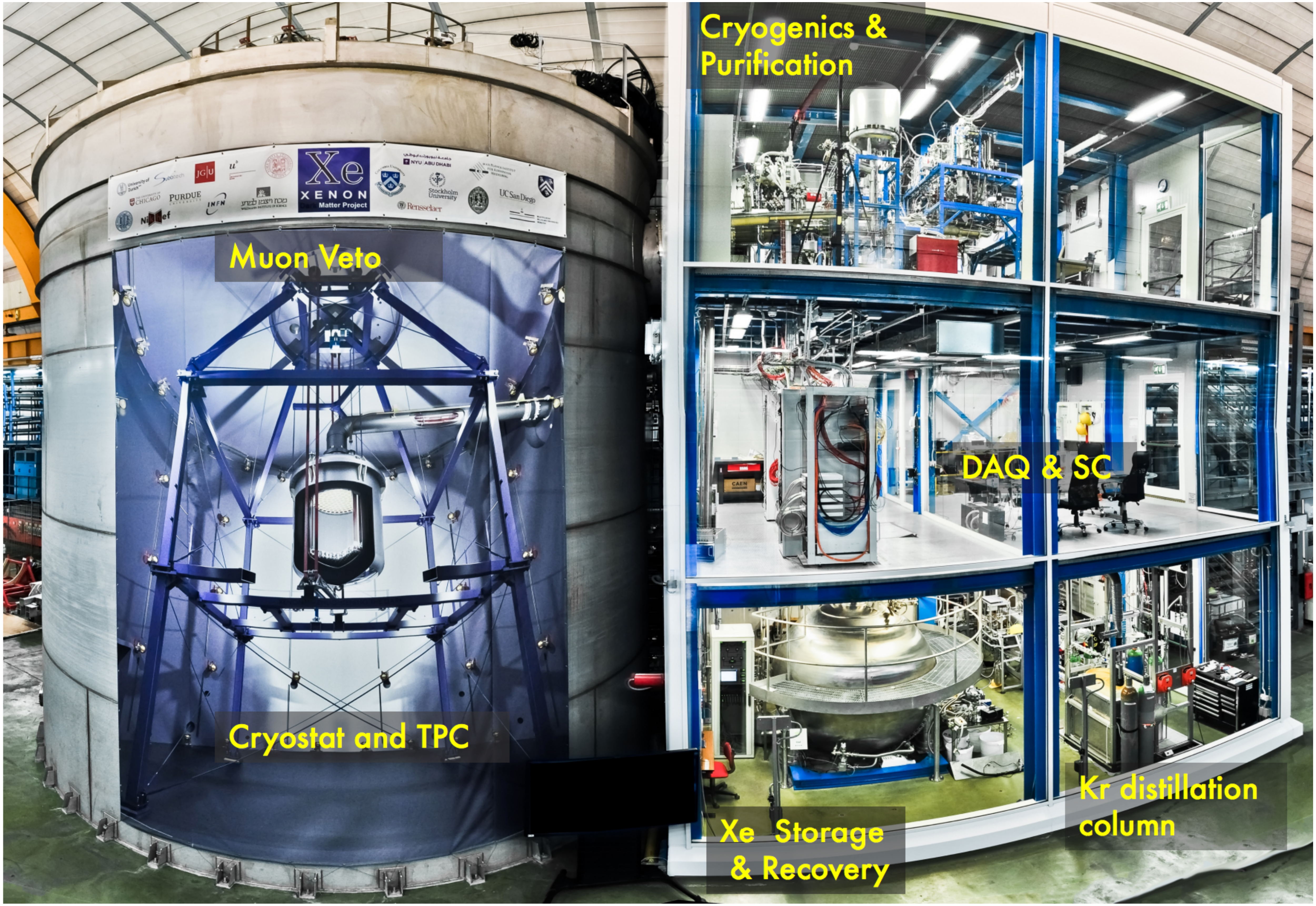


Summary

- **A very rich program in the direct dark matter search with noble liquids**
- **TPC detection technology is being pushed at its best performances in the next decade**
- **Future detectors based on Xenon and Argon will probe the entire parameter space for WIMPs with mass above 3 GeV/c2 down to the irreducible neutrino background**
- **Other important science channels will be explored**

Backup

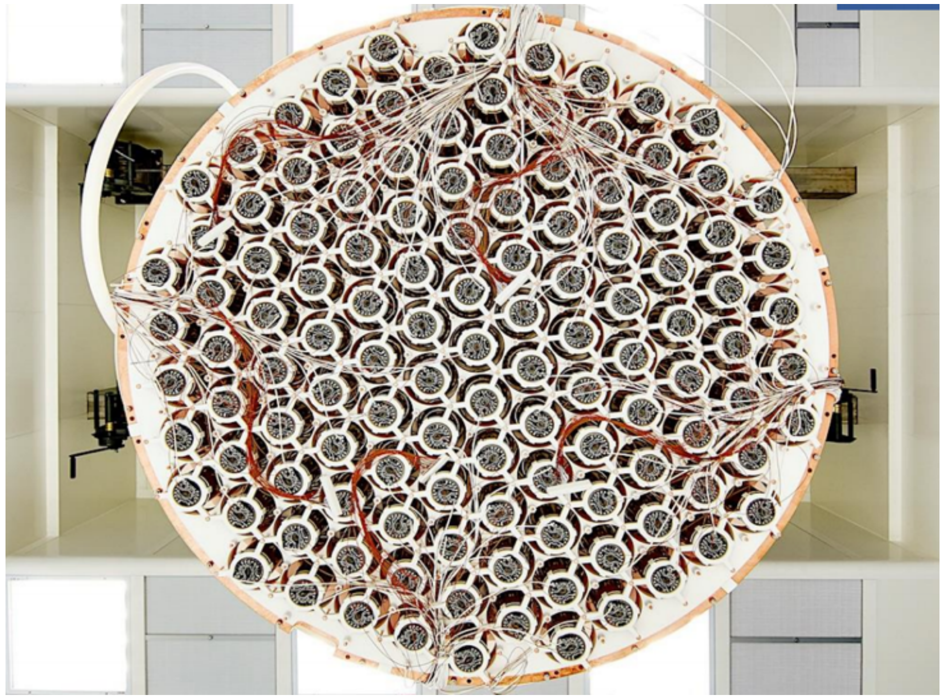
The XENON1T detector @ LNGS



The XENON1T TPC

- 3.2 t LXe in total @180K
- 2 t in the TPC
- 97 cm drift, 96 cm diameter
- Drift field ~100V/cm

Highly reflective PTFE walls

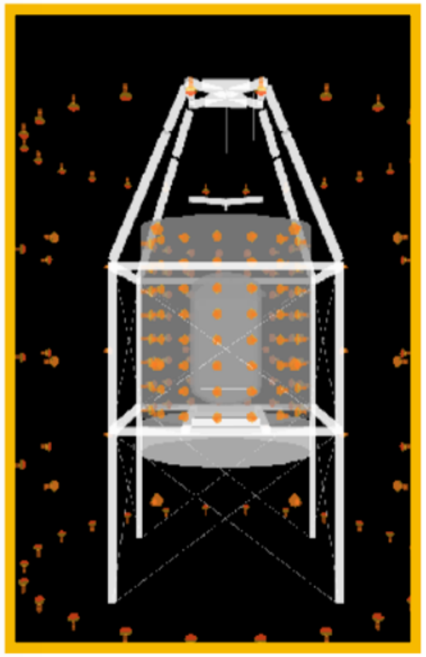


248 3-inch PMTs

- 35% QE @ 178nm
- Digitize at 100MHz
- SPE acceptance ~94%

EPJC 75 11 (2015)

Near future: XENONnT



Neutron veto

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

Larger TPC

- Total 8.4 t LXe
- 5.9 t in TPC
- ~ 4 t fiducial
- 248 → 494 PMTs

^{222}Rn distillation

- Reduce Rn (^{214}Pb) from pipes, cables, cryogenic system
- New system, PoP in XENON1T

LXe purification

- Faster xenon cleaning
- 5 L/min LXe (2500 slpm)
- XENON1T ~ 100 slpm

XENONnT

DARWIN

Model component	Expectation value (μ) in 20 t y		Rate uncertainty
	Observable ROI	Reference signal region	(ξ)
Background			
ER	2610	1.69	
Neutrons	0.29	0.15	50%
CEνNS (Solar ν)	7.61	5.41	4%
CEνNS (Atm+DSN)	0.82	0.36	20%
WIMP signal			
$6\,\mathrm{GeV/c^2}$ ($\sigma_{\mathrm{DM}} = 3 \times 10^{-44}\,\mathrm{cm^2}$)	25	19	
$50\,\mathrm{GeV/c^2}$ ($\sigma_{\mathrm{DM}} = 5 \times 10^{-47}\,\mathrm{cm^2}$)	186	88	
$1\,\mathrm{TeV/c^2}$ ($\sigma_{\mathrm{DM}} = 8 \times 10^{-46}\,\mathrm{cm^2}$)	286	118	

Table 4: Expected number of events in the (3, 100) PE cS1 observable ROI, for the 20 t y target exposure of XENONnT. The rates take into account signal fluctuations, along with detection and data selection efficiencies. We show results for the background components included in the statistical model as well as for 6, 50 and 1000 GeV/c^2 WIMP signals. The cross-sections are chosen to be close to the XENON1T exclusion limit [3]. Expectation values in the reference signal region reflect the residual fraction of each model component falling inside the 2σ contour of the 50 GeV/c^2 WIMP PDF, below the cS2$_\mathrm{b}$ median. Background uncertainties, where the rate is constrained by ancillary measurement terms included in the full likelihood, are reported in the last column. The ER rate will be highly constrained by data, thus no uncertainty is included.

Source	Rate $[(\mathrm{t\,y})^{-1}]$
ER background	
Detector radioactivity	25 ± 3
^{222}Rn	66 ± 7
^{85}Kr	13 ± 1
^{136}Xe	16 ± 2
^{124}Xe	4 ± 1
Solar neutrinos	34 ± 1
Total	158 ± 8
NR background	
Neutrons	$(4.1 \pm 2.1) \times 10^{-2}$
CEνNS (Solar ν)	$(6.3 \pm 0.3) \times 10^{-3}$
CEνNS (Atm+DSN)	$(5.4 \pm 1.1) \times 10^{-2}$
Total	$(1.0 \pm 0.2) \times 10^{-1}$

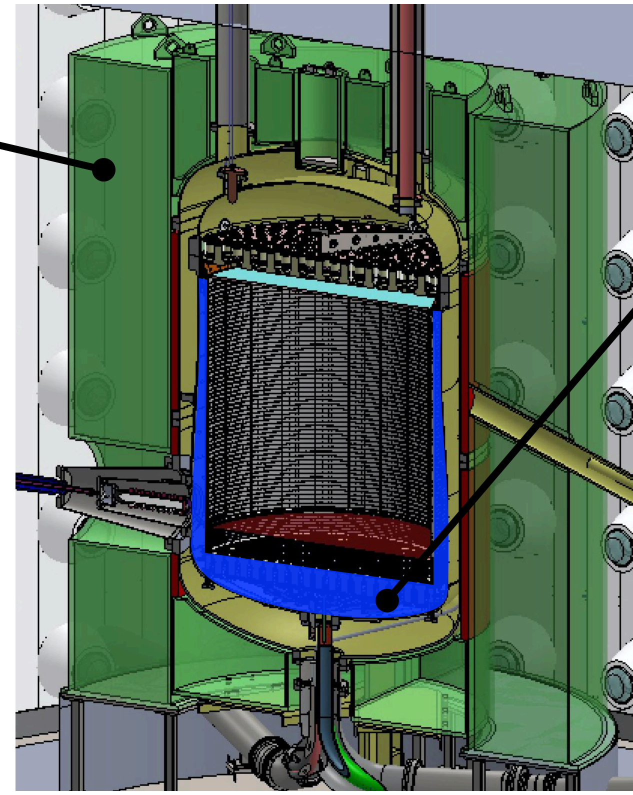
Table 3: Estimated background event rates in the 4 t fiducial volume of XENONnT, based on the energy of the recoil event. The energy ROI in which the event rates are integrated is (1, 13) keV for ERs, and (4, 50) keV for NRs. We assume an activity concentration of 1 µBq/kg of ^{222}Rn and 0.1 ppt (mol/mol) $^{\mathrm{nat}}$Kr/Xe. The background contributions from Xe isotopes are determined assuming the 8.9% and 0.095% natural abundances of ^{136}Xe and ^{124}Xe, respectively.

Near future: LZ

The OD

- 17 tonnes Gd-loaded liquid scintillator in acrylic vessels
- 120 8" PMTs mounted in the water tank
- Anti-coincidence detector for γ-rays and neutrons
- Observe ~8.5 MeV γ-rays from thermal neutron capture
- Draw on experience from Daya Bay

See talk by B. Penning
"The LZ Outer Detector"
DM16 Thu afternoon

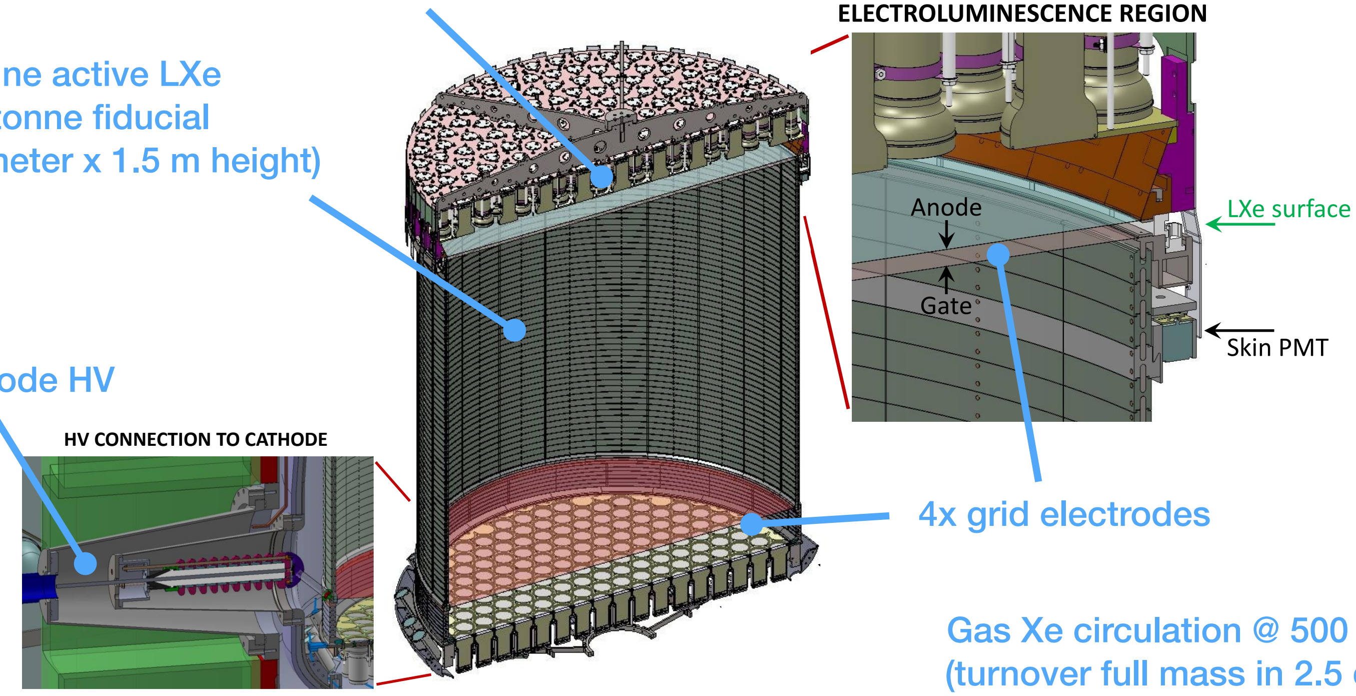


The Skin

- 2 tonnes of LXe surrounding the TPC
- 1" and 2" PMTs at the top and bottom of the skin region
- Lined with PTFE to maximize light collection efficiency
- Anti-coincidence detector for γ-rays

- **Tag individual neutrons and γ-rays**
- **Characterize BGs in situ**

→Enables discovery potential



- Located in Sanford Underground lab, Lead (USA)
- 4300 m.w.e.
- 10^7 muon flux reduction

LZ TDR arXiv:1703.09144

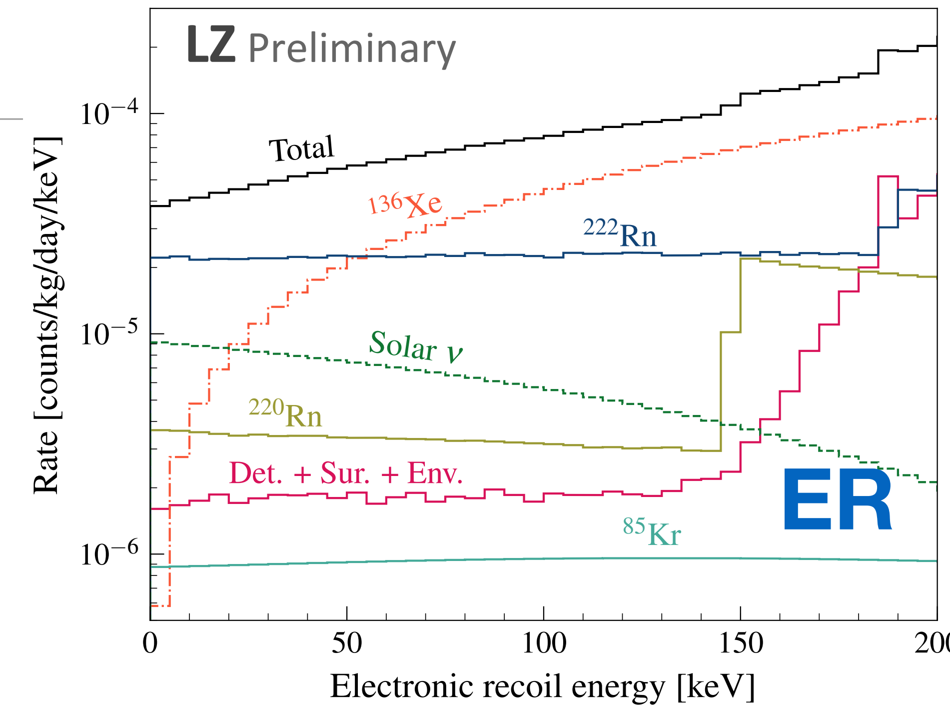
Expected backgrounds

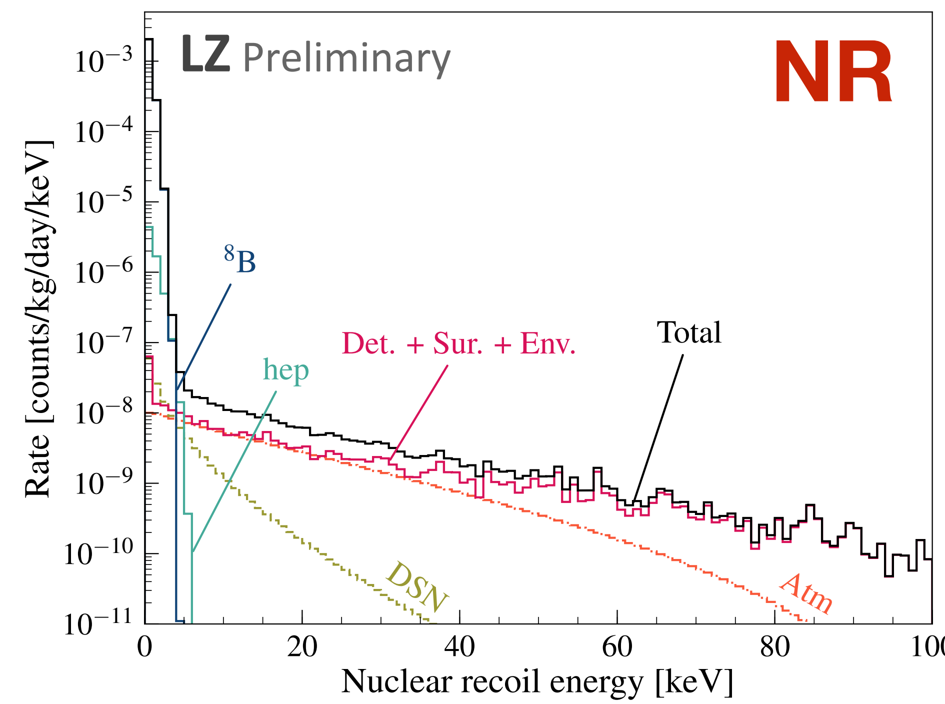
5.6 tonne fiducial volume, 1000 live-days
1.5-6.5 keV_{ee} (6-30 keV_{nr})
single scatters, anti-coincidence with vetoes

Background Source	ER [cts]	NR [cts]
Detector components	9	0.07
Dispersed Radionuclides — Rn, Kr, Ar	819	—
Laboratory and Cosmogenics	5	0.06
Surface Contamination and Dust	40	0.39
Physics Backgrounds — 2β decay, neutrinos*	322	0.51
Total	**1195**	**1.03**
After 99.5% ER discrimination, 50% NR efficiency	**5.97**	**0.51**

* not including ^{8}B and hep

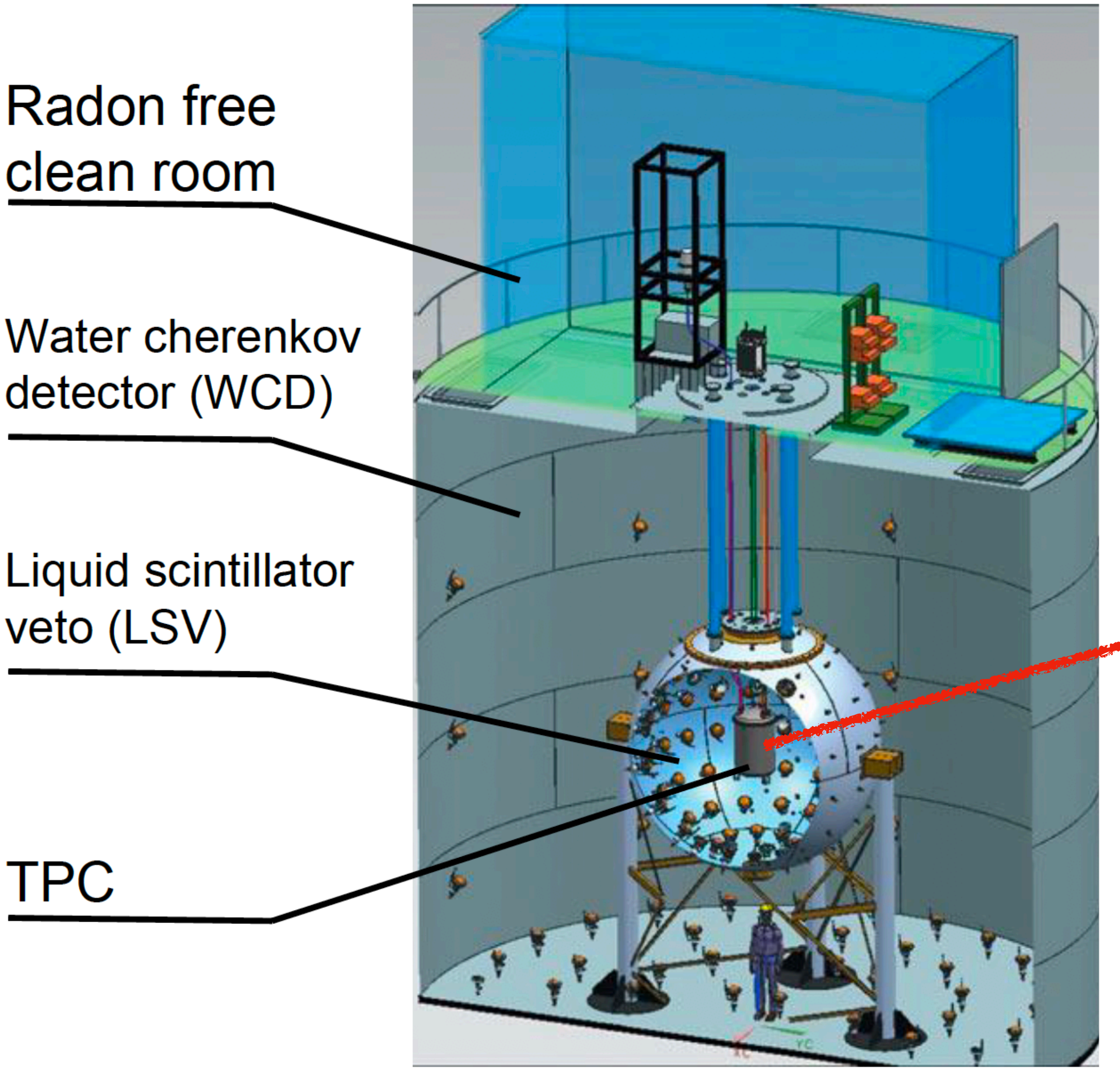
D.S. Akerib et al (LZ collaboration) 2018 arXiv:1802.06039

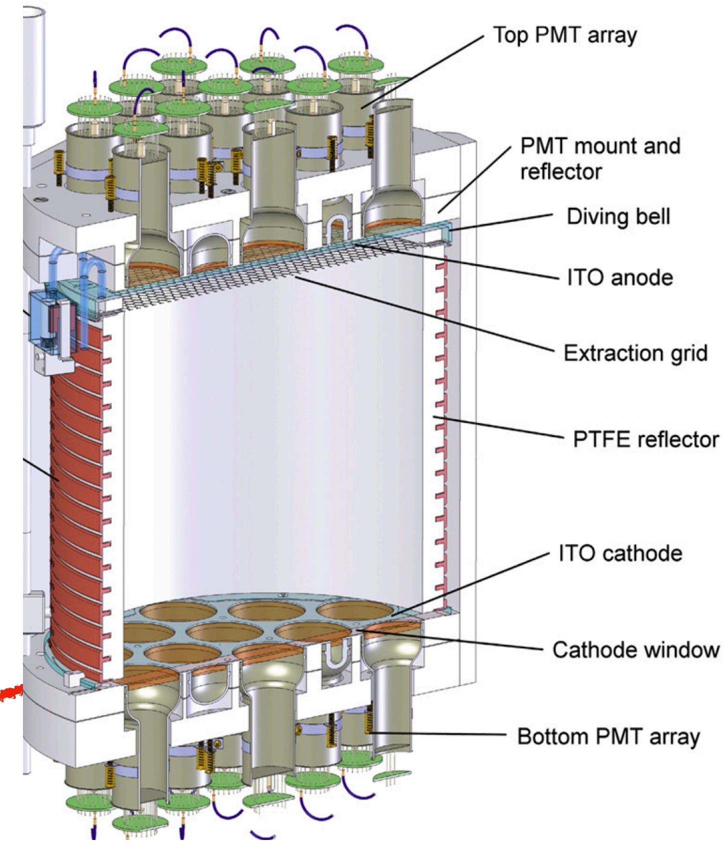




D.S. Akerib et al (LZ collaboration) 2018 arXiv:1802.06039

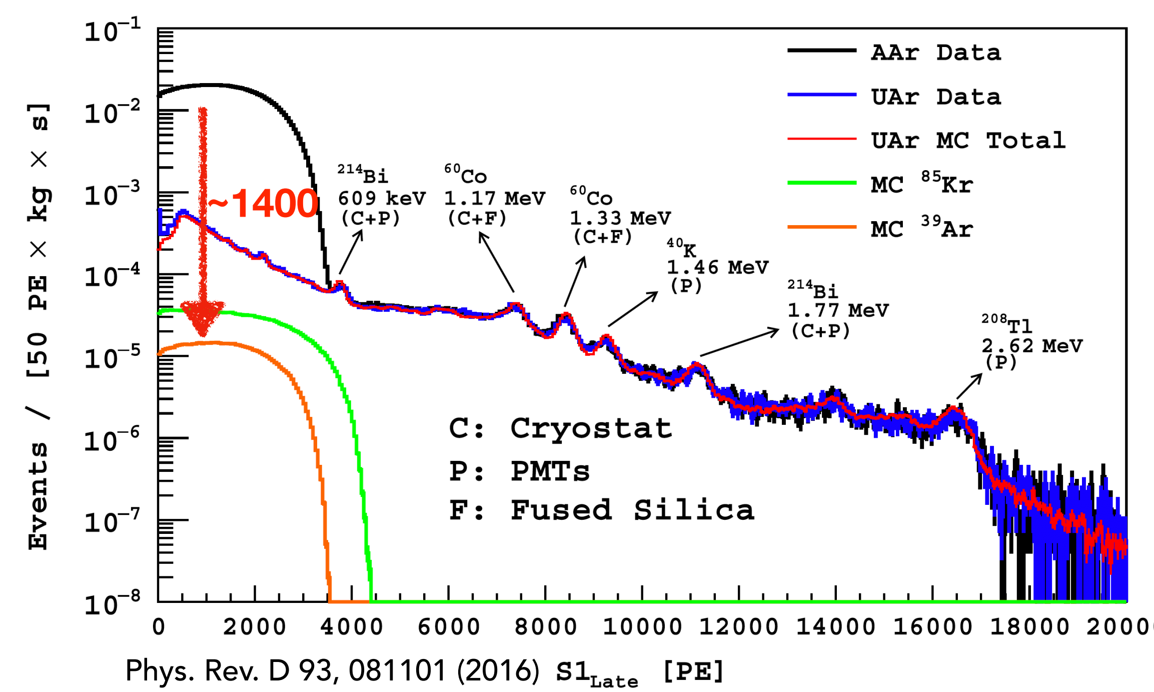
LAr TPC: DarkSide-50





- ➡ 46.4 kg LAr in active volume
- ➡ 38 Hamamatsu R11065 3" PMTs
- ➡ PTFE as reflector
- ➡ TPB as wave length shifter
- ➡ Copper field cage
- ➡ ITO layers as anode and cathode
- ➡ Drift Field: 200 V/cm
- ➡ Extraction Field: 2.8 kV/cm

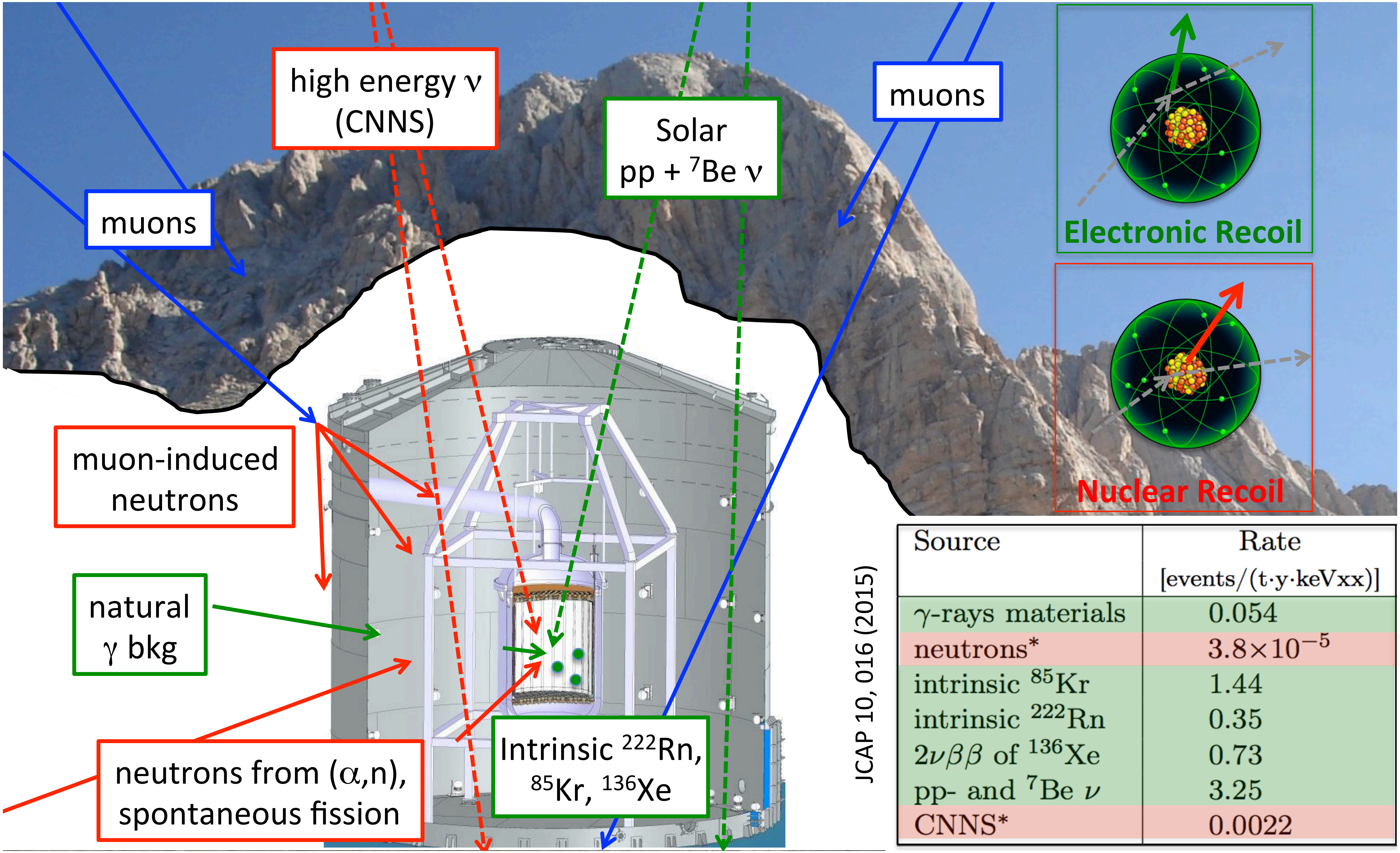
- Underground Ar: low Ar^{39} activity.
- Extracted from an underground CO_2 field in Cortez, Colorado.
- Purified by a cryogenic distillation column at FNAL. CO_2, O_2, N_2 and He all < 10 ppm.
- 155 kg UAr shipped to LNGS.



Phys. Rev. D 93, 081101 (2016)

Background for DARWIN

DARWIN

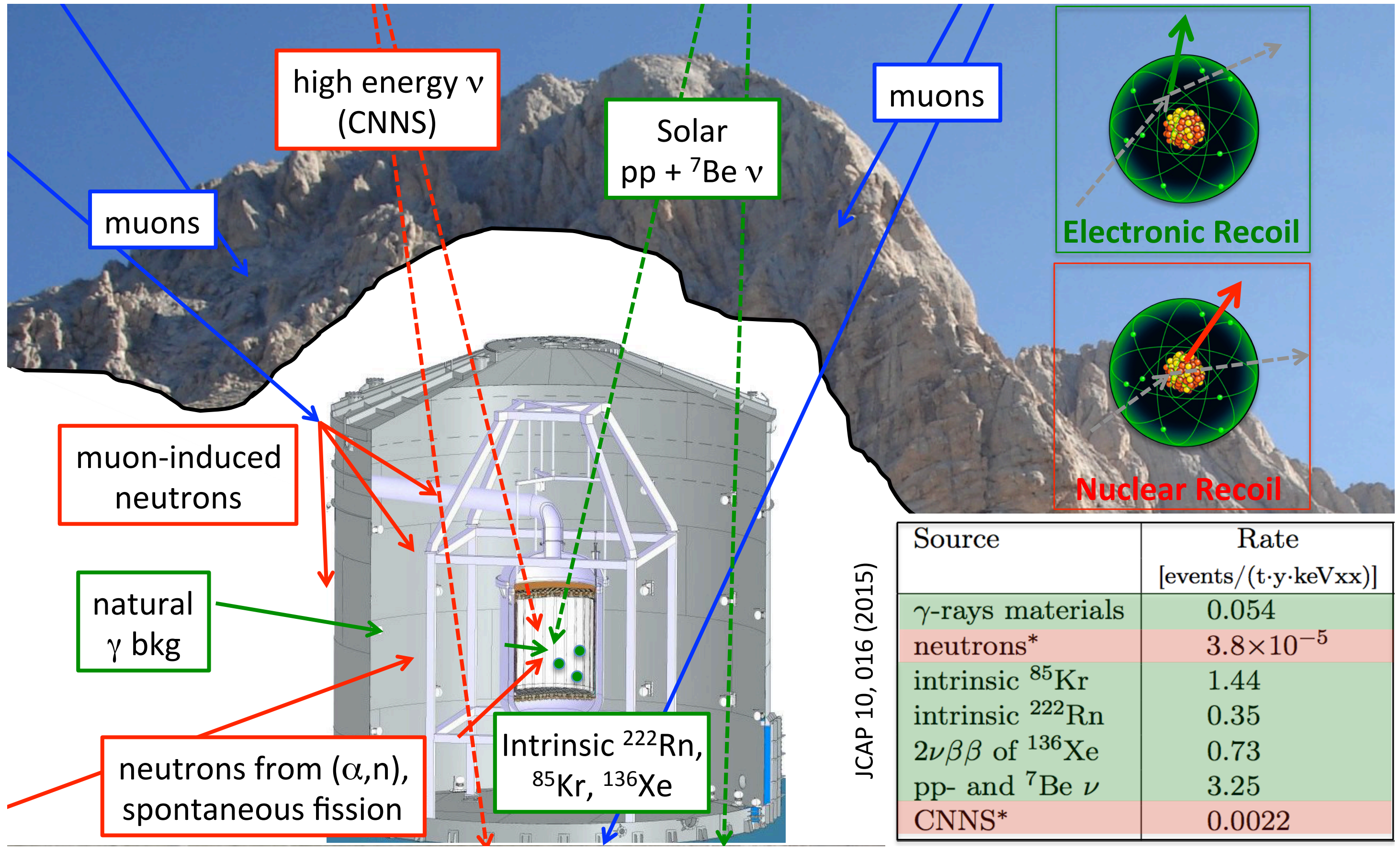


JCAP 10, 016 (2015)

Source	Rate [events/(t·y·keVxx)]
γ-rays materials	0.054
neutrons*	3.8×10^{-5}
intrinsic ^{85}Kr	1.44
intrinsic ^{222}Rn	0.35
$2\nu\beta\beta$ of ^{136}Xe	0.73
pp- and ^{7}Be ν	3.25
CNNS*	0.0022

Background for DARWIN

DARWIN



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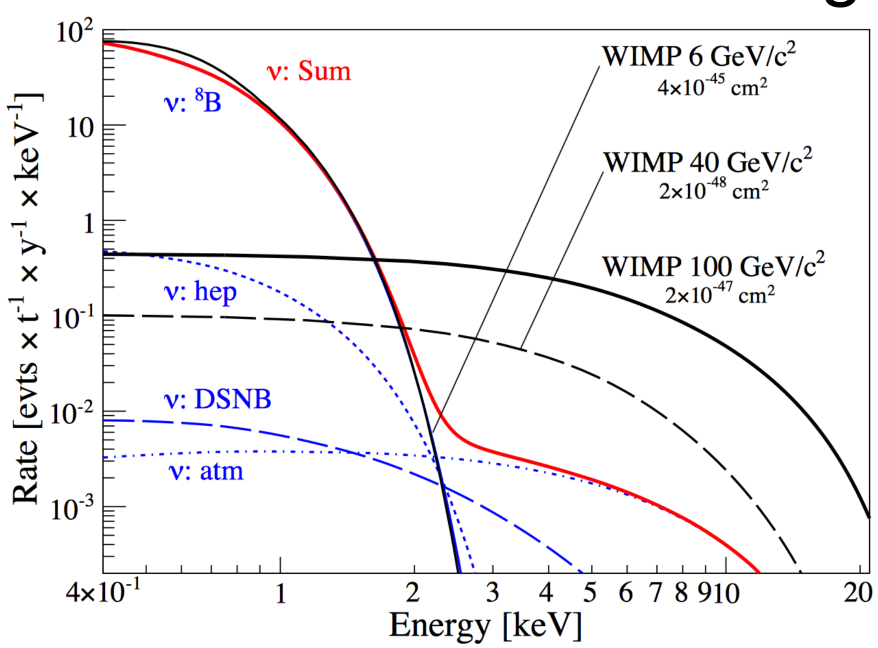
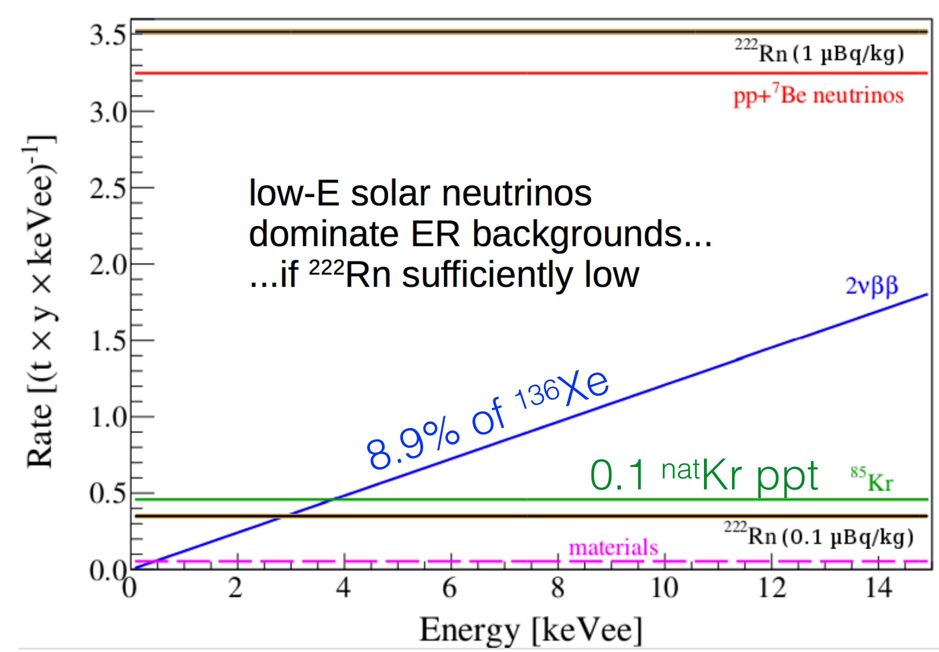
CNNS*	0.0022

NR: neutrinos from coherent neutrino-nucleus scattering



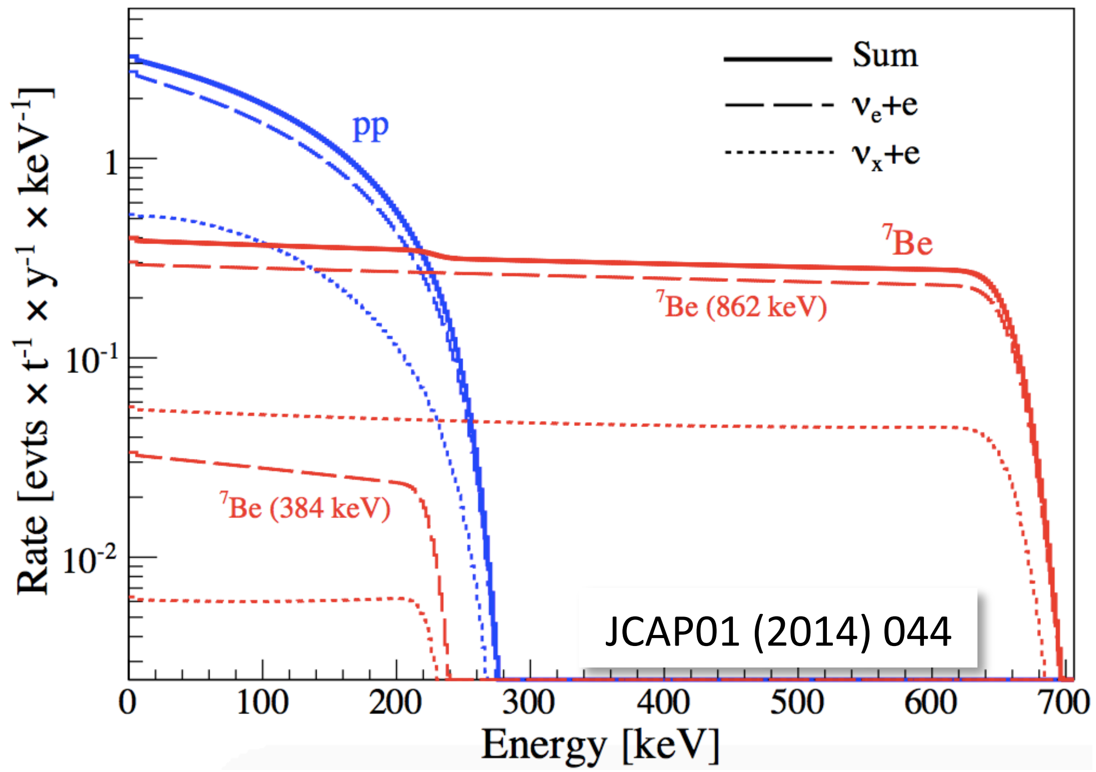
ER: intrinsic ^{85}Kr, ^{222}Rn

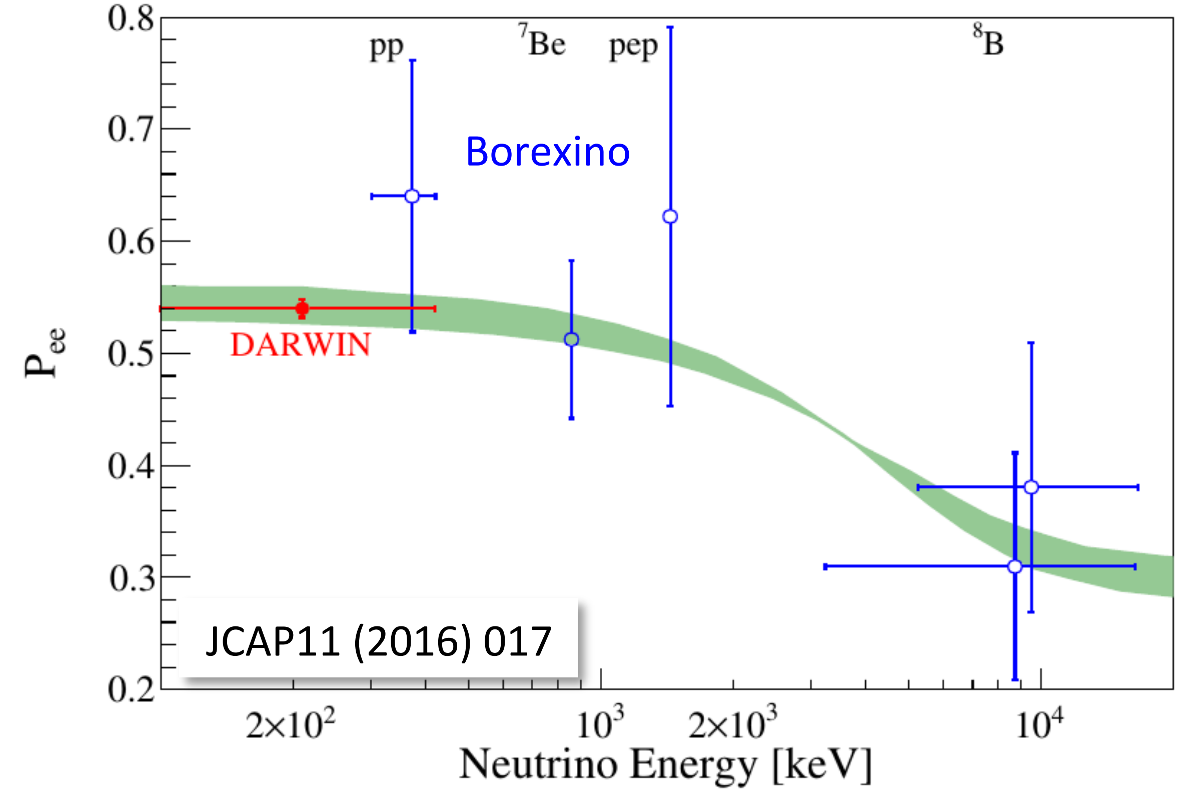
JCAP 10, 016 (2015)



DARWIN: Solar neutrinos

Solar pp and ^{7}Be neutrinos





- Continuous recoil spectrum at low energy
- Expected events at 2-30 keV and 30 t fiducial mass:
  - 7.2 cts/day for pp neutrinos
  - 0.9 cts/day for ^{7}Be neutrinos
- 2%(1%) stat. precision after 1 year (5 years)

- Neutrinos survival probability
- 2850 pp neutrinos/year
- 1% stat. precision with 100 ton x year exposure

DARWIN: 0νββ decay

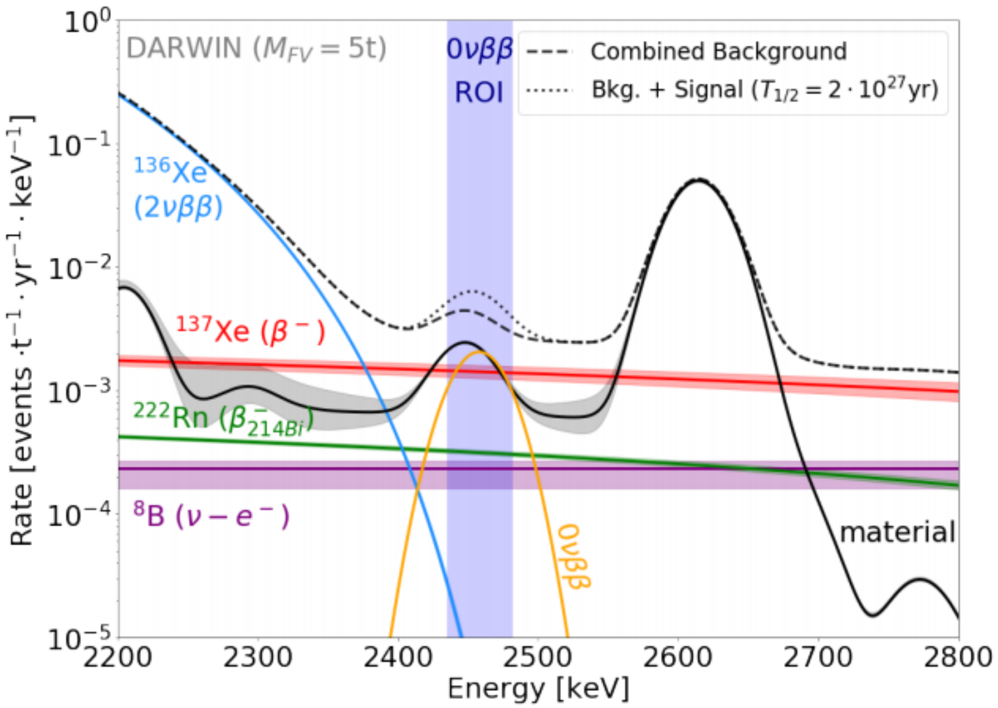


Fig. 6: Predicted background spectrum around the $0\nu\beta\beta$-ROI for the 5 t fiducial volume. A hypothetical signal of 0.5 counts per year corresponding to $T^{0\nu}_{1/2} \approx 2 \times 10^{27}$ yr is shown for comparison. Bands indicate $\pm 1\,\sigma$ uncertainties.

Background source	Background index [events/(t·yr·keV)]	Rate [events/yr]	Rel. uncertainty
External sources (5 t *FV*):			
^{214}Bi peaks + continuum	1.36×10^{-3}	0.313	±3.6%
^{208}Tl continuum	6.20×10^{-4}	0.143	±4.9%
^{44}Sc continuum	4.64×10^{-6}	0.001	±15.8%
Intrinsic contributions:			
^{8}B ($\nu - e$ scattering)	2.36×10^{-4}	0.054	+13.9%, −32.2%
^{137}Xe (μ-induced n-capture)	1.42×10^{-3}	0.327	±12.0%
^{136}Xe $2\nu\beta\beta$	5.78×10^{-6}	0.001	+17.0%, −15.2%
^{222}Rn in LXe (0.1 μBq/kg)	3.09×10^{-4}	0.071	±1.6%
Total:	$\mathbf{3.96 \times 10^{-3}}$	**0.910**	+4.7%, −5.0%

Table 3: Expected background index averaged in the $0\nu\beta\beta$-ROI of [2435 - 2481] keV, corresponding event rate in the 5 t FV and relative uncertainty by origin.

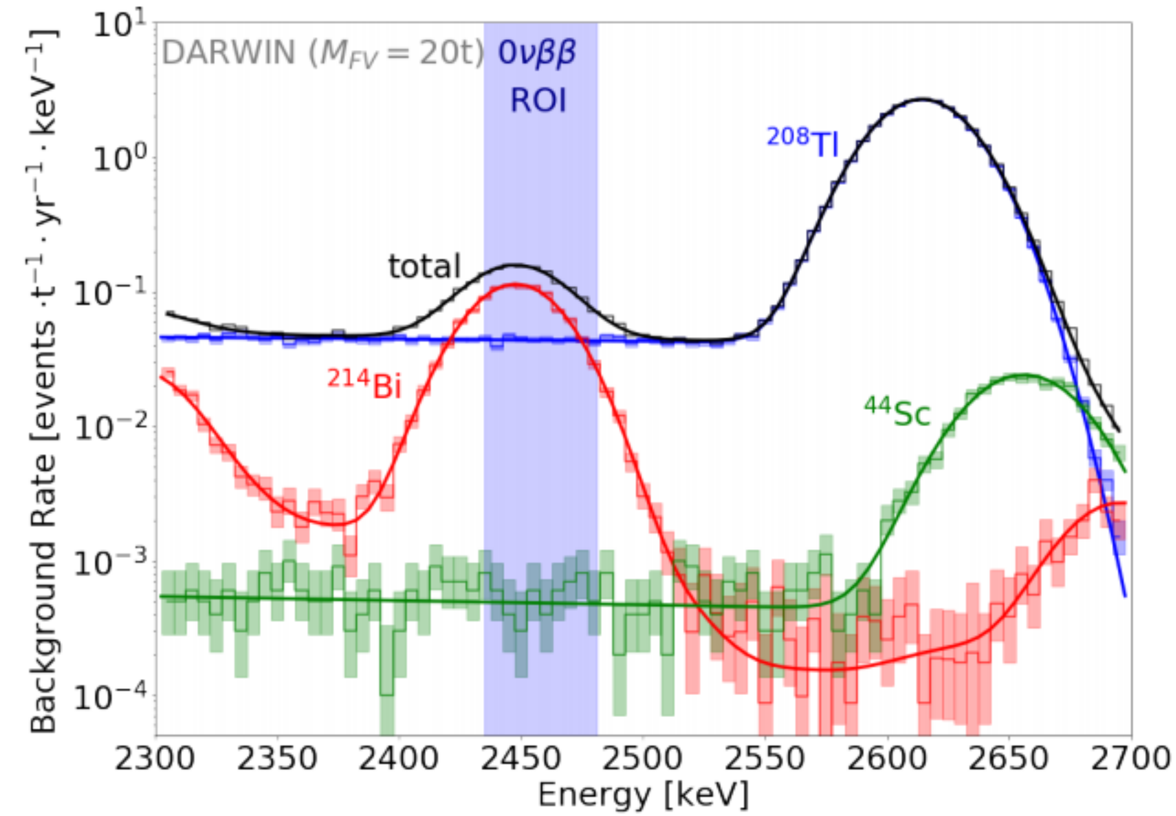


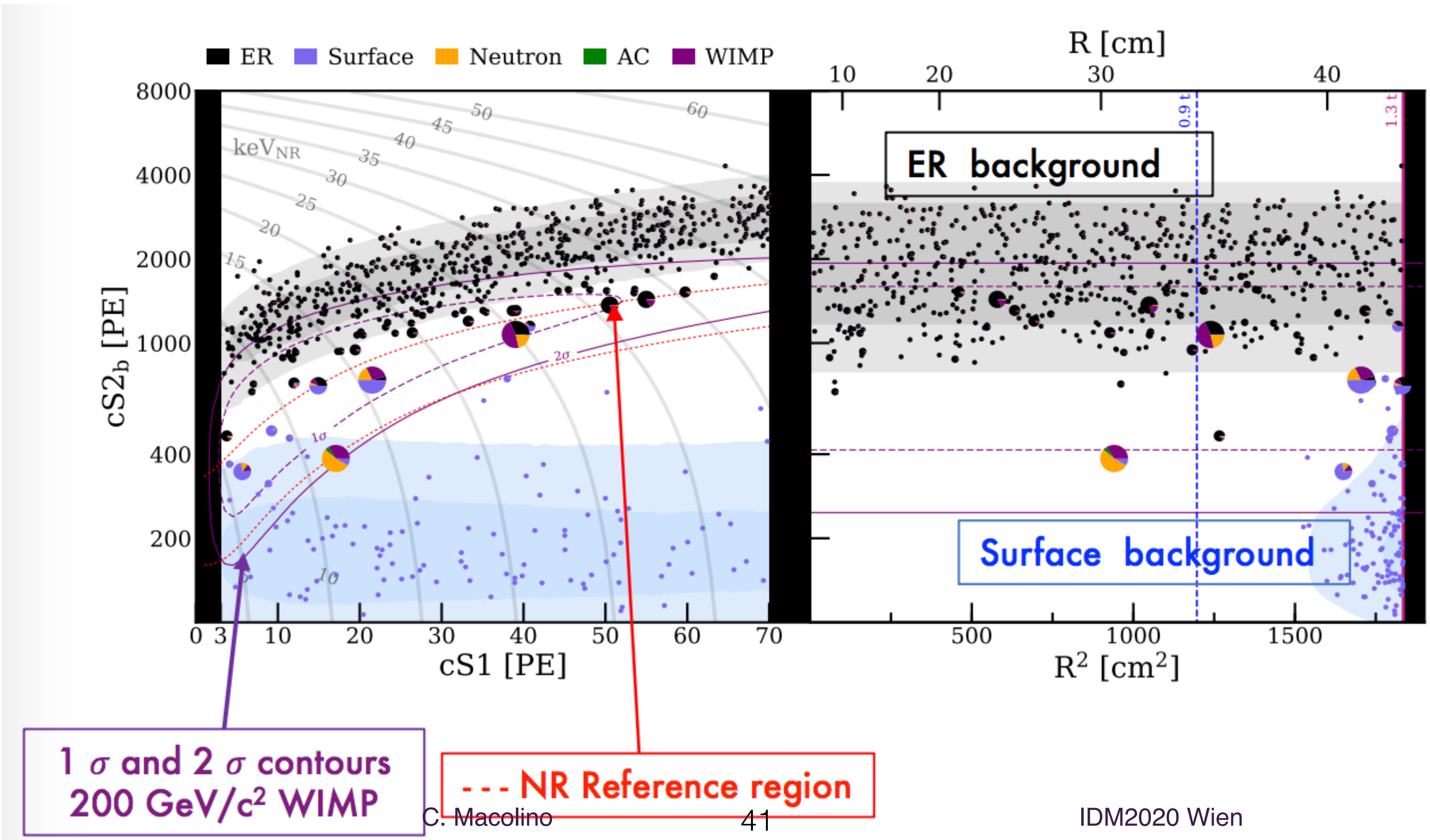
Fig. 4: Composition of the material-induced external background in the 20 t fiducial volume. Top: Relative contribution to the background in the $0\nu\beta\beta$-ROI by material and isotope. Bottom: Background spectra by isotope with the corresponding model fits. The relative contributions and spectral shapes are representative for smaller fiducial volumes.

Dark matter search results

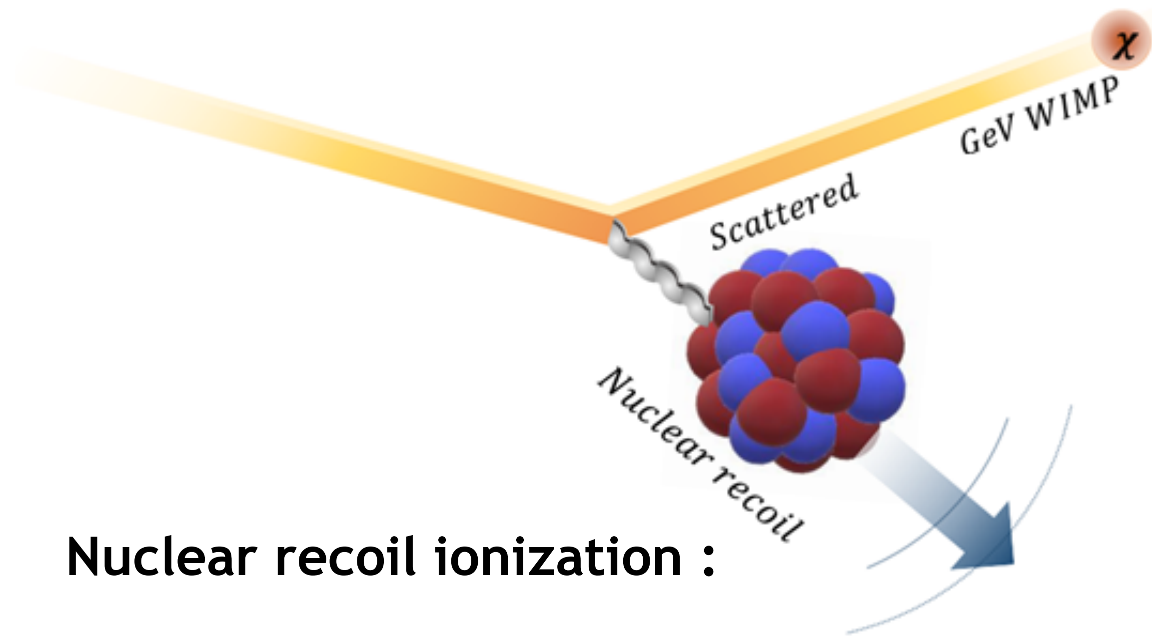
XENON1T: UNBLIND + DESALT

- Unbinned Profile likelihood analysis in 3D space (cS1, cS2, R)
- Events passing all selection criteria are shown as pie charts representing the relative PDF from each components for the best-fit model of 200 GeV/c² WIMP and $\sigma_{SI} = 4.7 \cdot 10^{-47}$ cm²

Width of pie represents WIMP probability



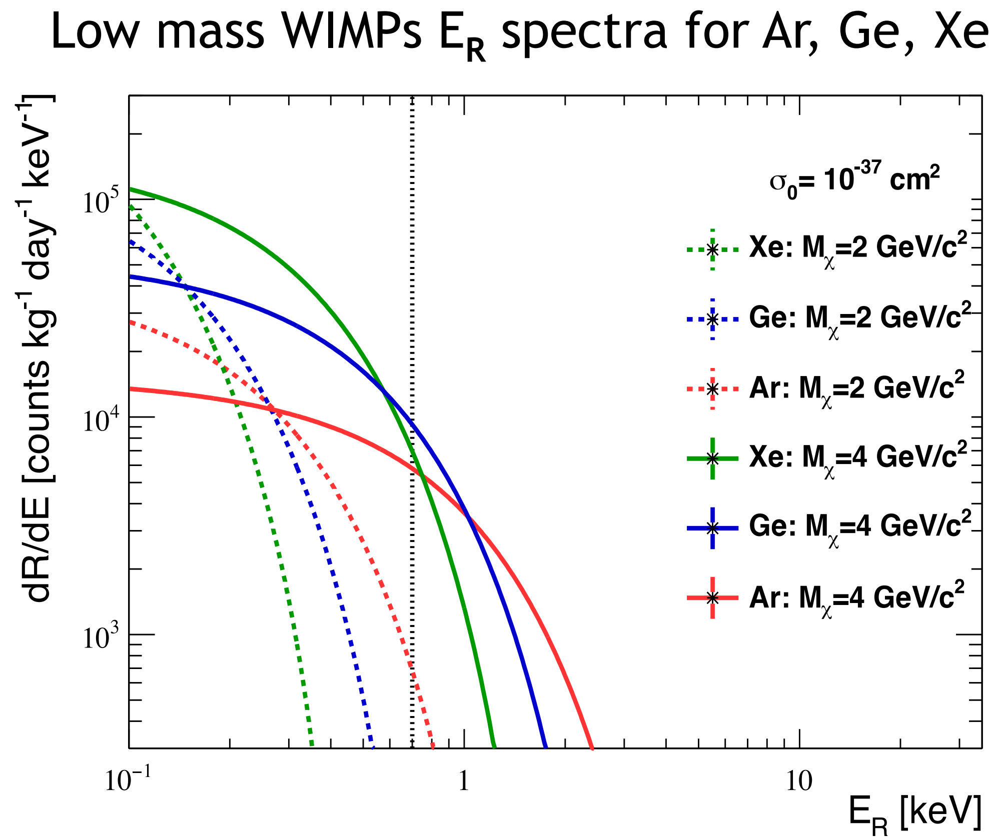
S2-only dark matter search

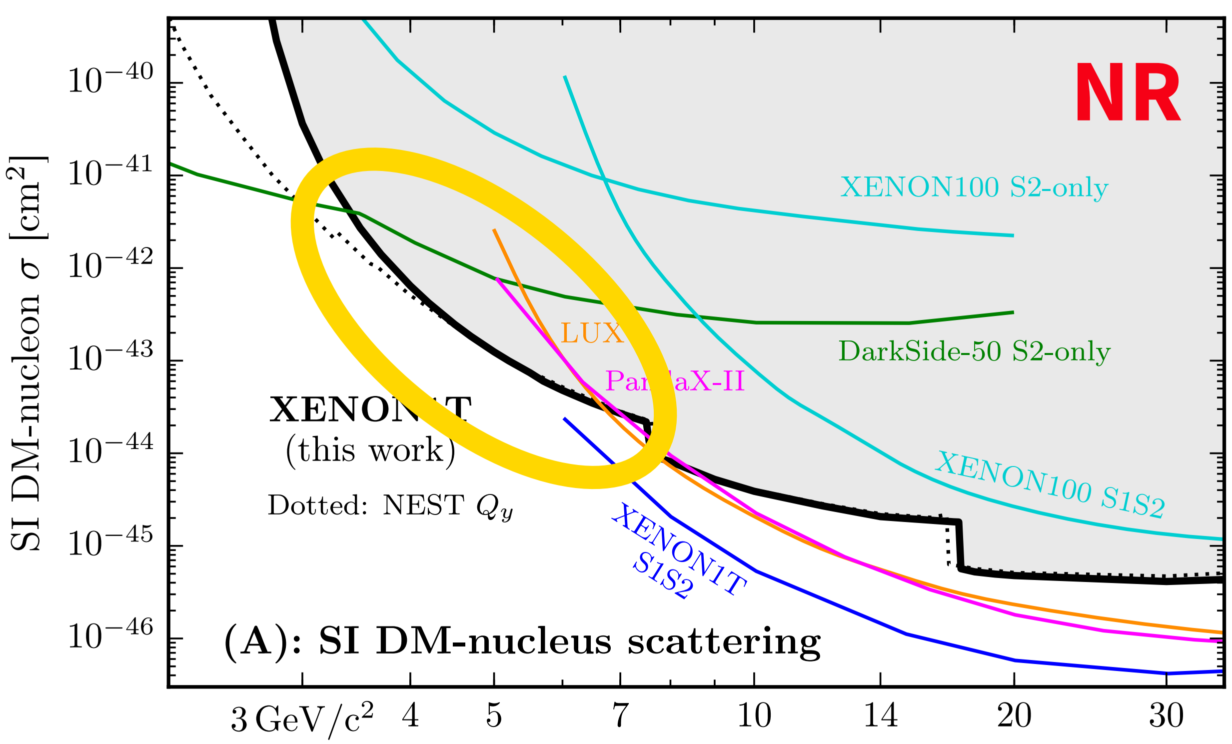


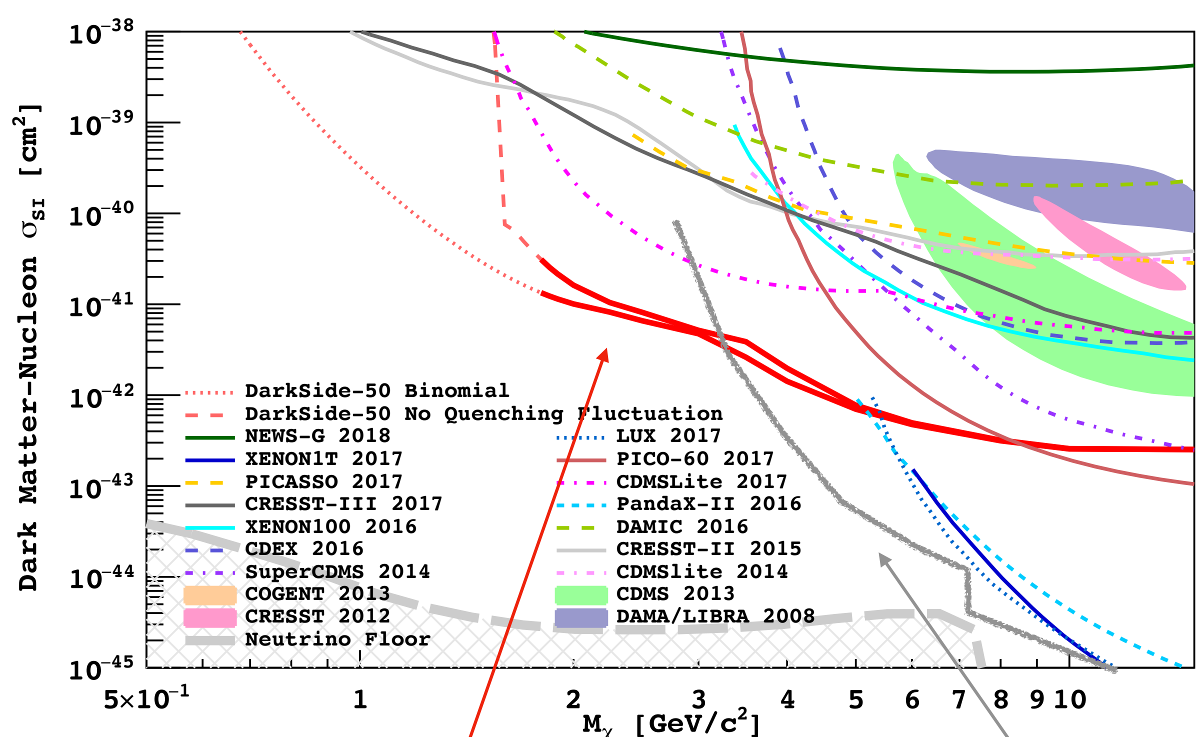
Nuclear recoil ionization :

- few electrons drift
- gas pocket fluorescence

→ **S2 signal**



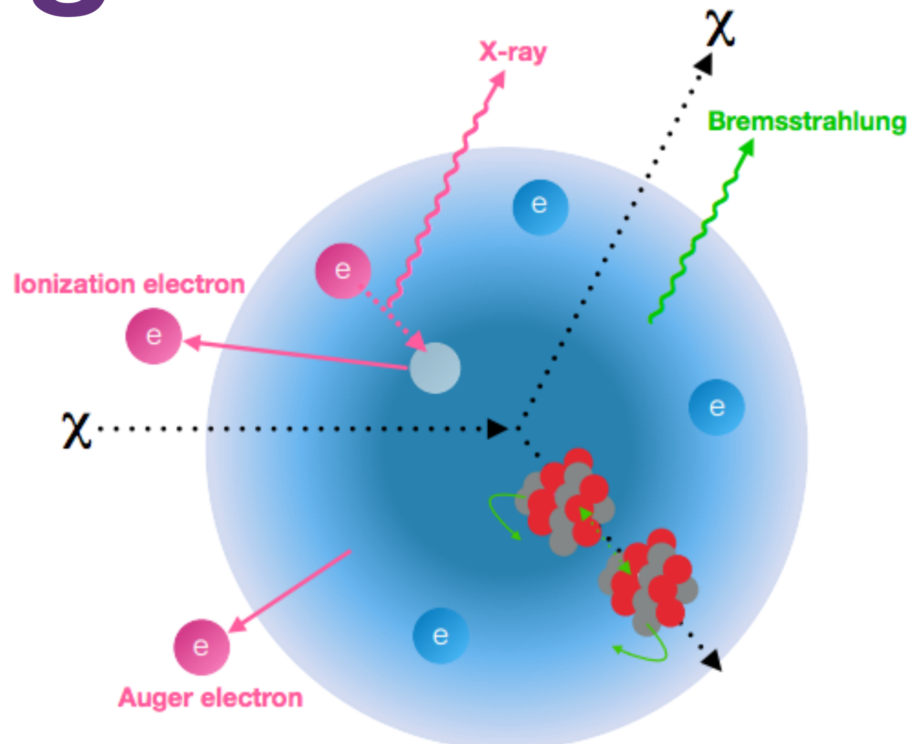


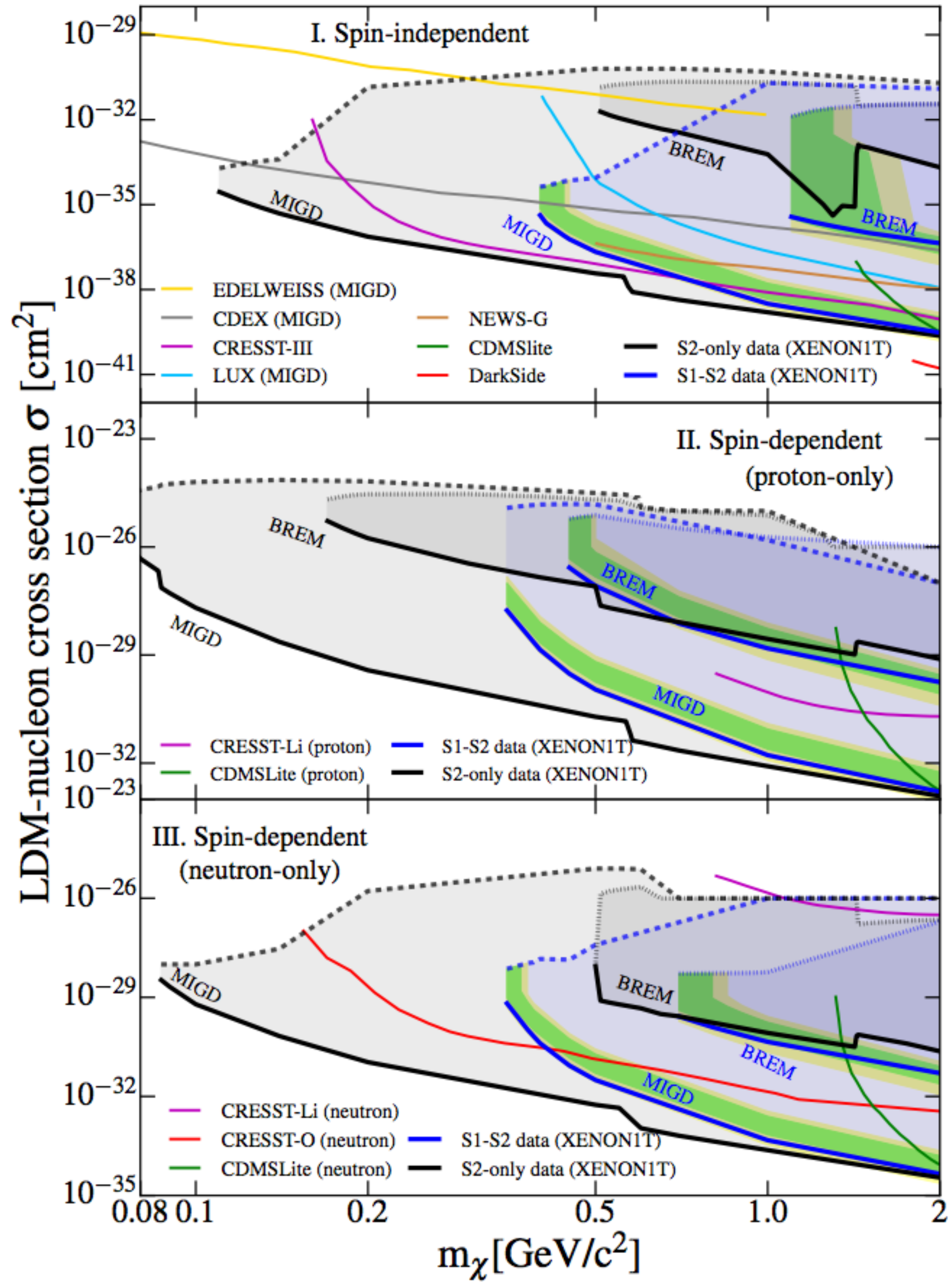


DarkSide-50 (2018)
50kg of UAr ; 6.7 ton days

Xenon-1T (2019)
1t of Xe ; 22.3 ton days

Migdal and Bremsstrahlung





- Electron recoils from secondary radiation associated with nuclear recoils
- Migdal effect and Bremsstrahlung
- Well below 1 keV (very low detection efficiency for scintillation light)
- S1-S2 and S2-only data from XENON1T