Dark Matter search with noble gases

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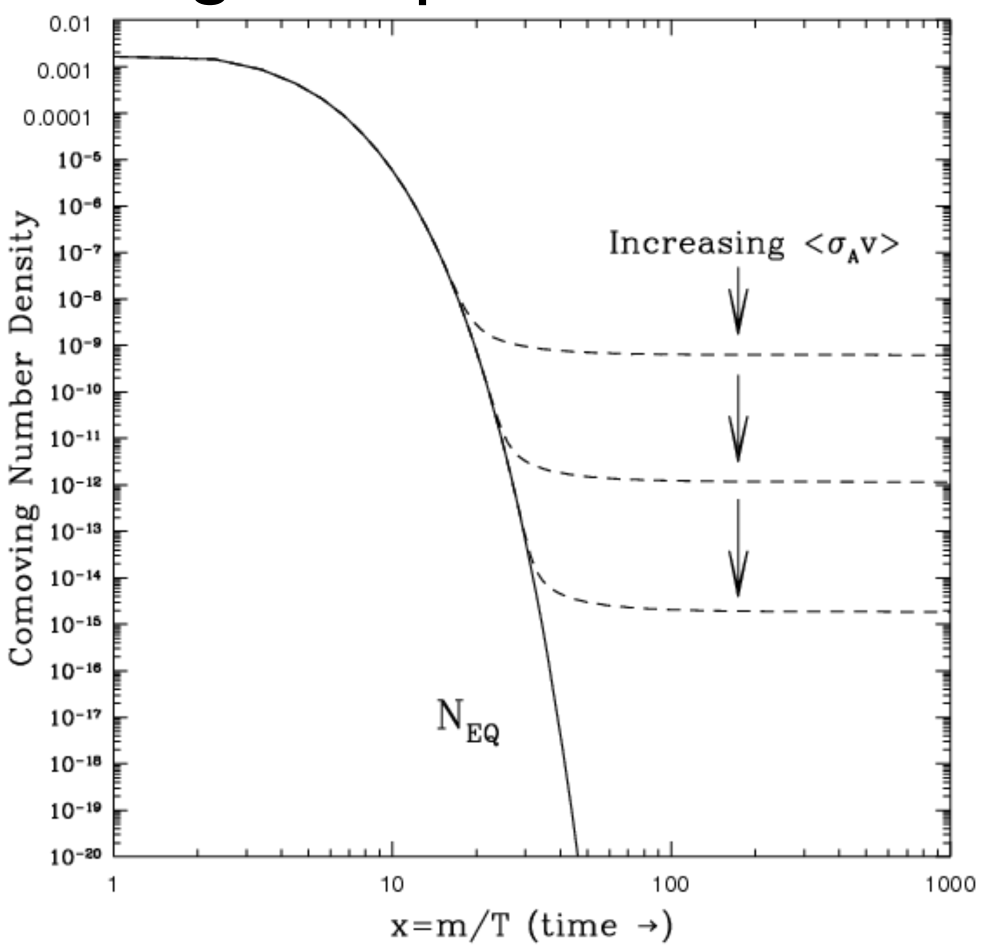
EDSU2020
13.03.2020

The WIMP miracle

- Assume DM was in full thermal equilibrium with SM particles at sufficiently high temperature T:



$$\frac{dn_\chi}{dt} + 3Hn_\chi = -\langle\sigma v\rangle\left(n_\chi^2 - n_{\chi\,\mathrm{eq}}^2\right)$$

$\langle\sigma v\rangle$: $\chi\chi \rightarrow \mathrm{SM\ SM}$ (thermal average)

Freeze-out when annihilation rate falls beyond expansion rate

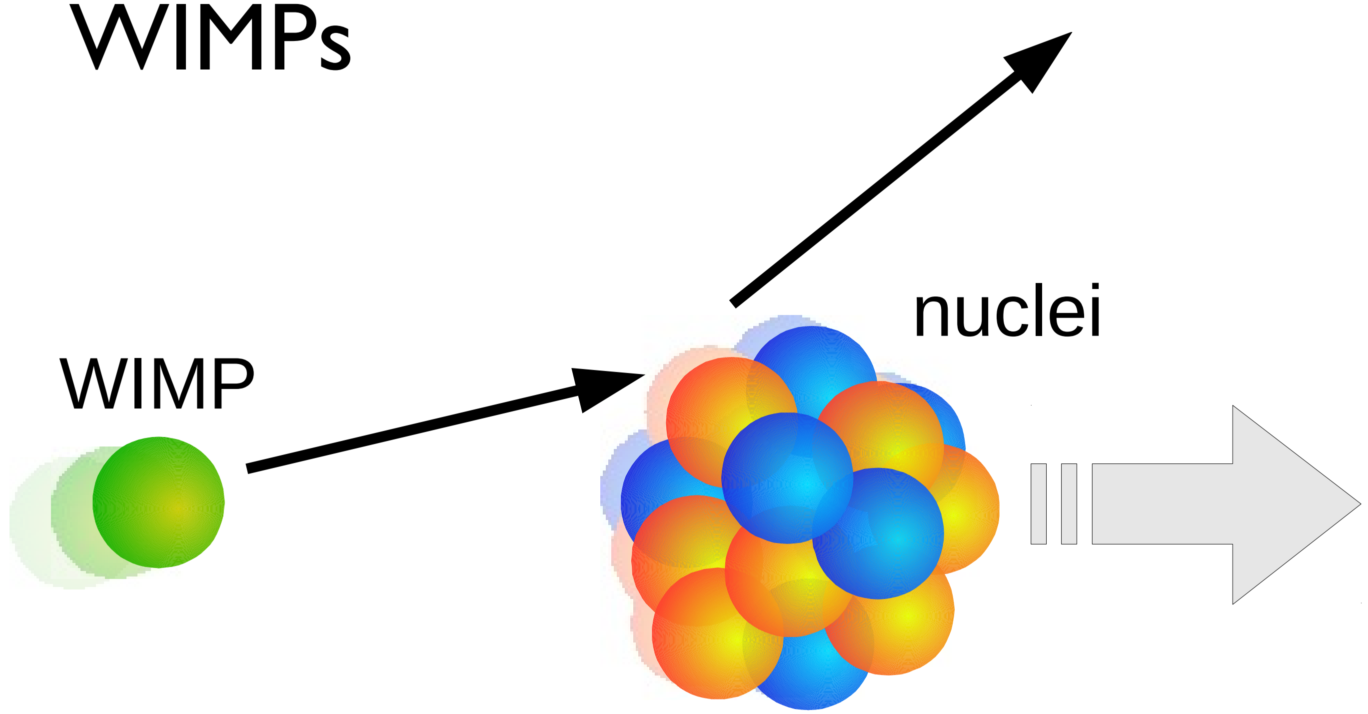
$$\rightarrow a^3 n_\chi \sim const$$

- The abundance of DM related to its cross section $\Omega_{DM} \sim <\sigma_A v>^{-1}$
- The weakly interactive massive particle (WIMP) comoving number density **matches** the one inferred from cosmological observation:

- Weak-scale cross section: $<\sigma v> \simeq 3 \cdot 10^{26} cm^3 s^{-1}$
- non relativistic particle: mass between 100 GeV and 1 TeV

The direct detection principle

detection of nuclear recoil from elastic scattering of WIMPs



$\chi + N \rightarrow \chi + N$

$E_{recoil} \lesssim 100$ keV

as an example:
- WIMP mass: 100 GeV/c^2
- WIMP velocity: 220 km/c^2

$$E_0 = \frac{1}{2} M_\chi v_0^2 \sim 30 \text{ keV}$$

The direct detection principle

Expected rate in a detector :

WIMP-nucleus cross section (model dependent, spin)

0.3 GeV/cm^3

Nuclear form factor (depends on atomic nuclei)

Expected spectrum:

$$\frac{dN}{dE_R}(t) = \frac{\rho_\chi}{m_\chi} \frac{\sigma_p |F(q)|^2 A^2}{2\mu_p^2} \int_{v_{\min}(E_R)}^{v_{\max}} d^3v \, \frac{f_\oplus(\vec{v},t)}{v}$$

WIMP-nucleus reduced mass

Motion dynamics

- Maxwellian distribution for DM velocity is assumed
- v = velocity on target
- v_{min} = minimum required to produce recoil energy
- v_{max} = galactic escape velocity (~ 500 – 650 km/s)

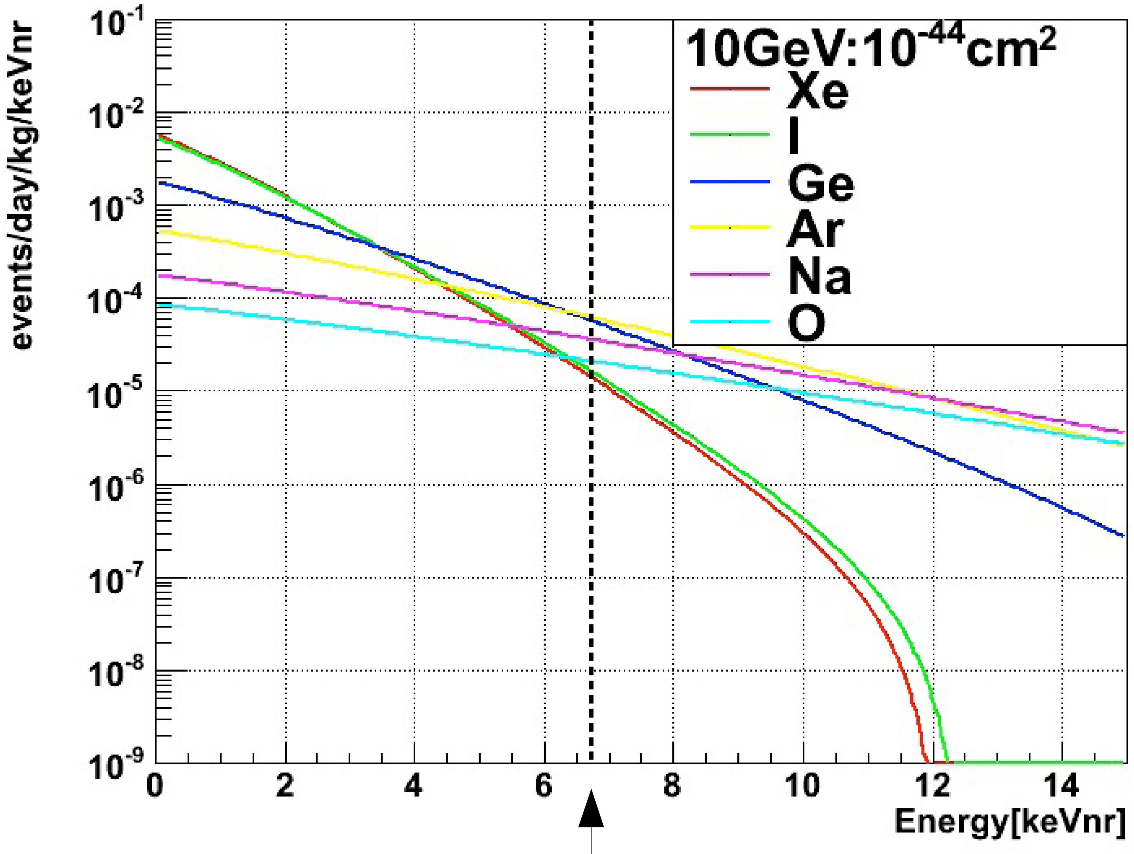
$$v_{\min} \approx \frac{\sqrt{ME_R/2}}{m_\chi}$$

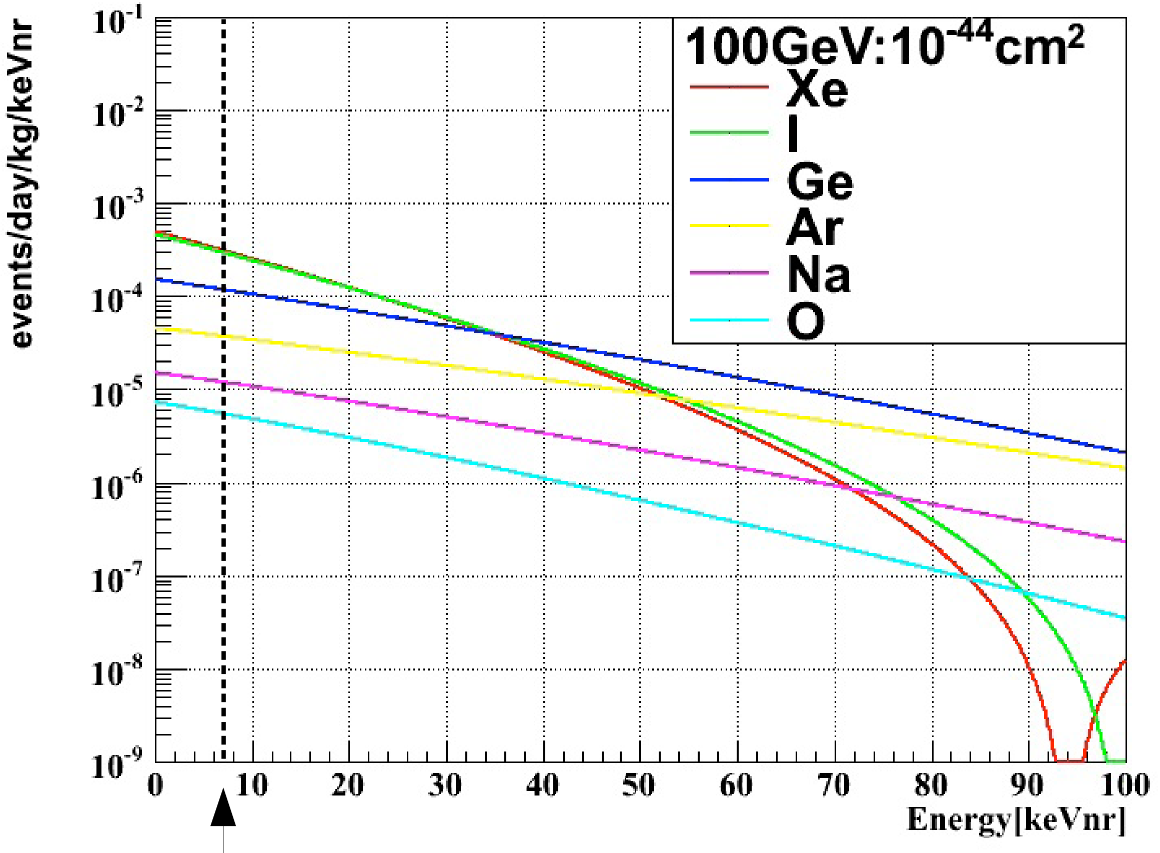
the expected rate translates in a range of values for the nucleon-WIMP cross section and the WIMP mass (spin-dependent or spin-independent)

Using liquid noble gases

Element	Xenon	Argon	Neon
Atomic Number Z	54	18	10
Atomic mass A	131.3	40.0	20.2
Boiling Point T_b [K]	165.0	87.3	27.1
Liquid Density @ T_b [g/cm^3]	2.94	1.40	1.21
Fraction in Earth's Atmosphere [ppm]	0.09	9340	18.2
Price	$$$$	$	$$
Scintillator	✓	✓	✓
W_{ph} (α, β) [eV]	17.9 / 21.6	27.1 / 24.4	
Scintillation Wavelength [nm]	178	128	78
Ionizer	✓	✓	–
W (E to generate e-ion pair) [eV]	15.6	23.6	
Experiments [stopped, running, in preparation]	∼ 5	∼ 5	1/2

- Rate increases with A^2
- Scintillation wavelength matches PMT transparency window
- High density
- No long lived isotopes (except for Ar)

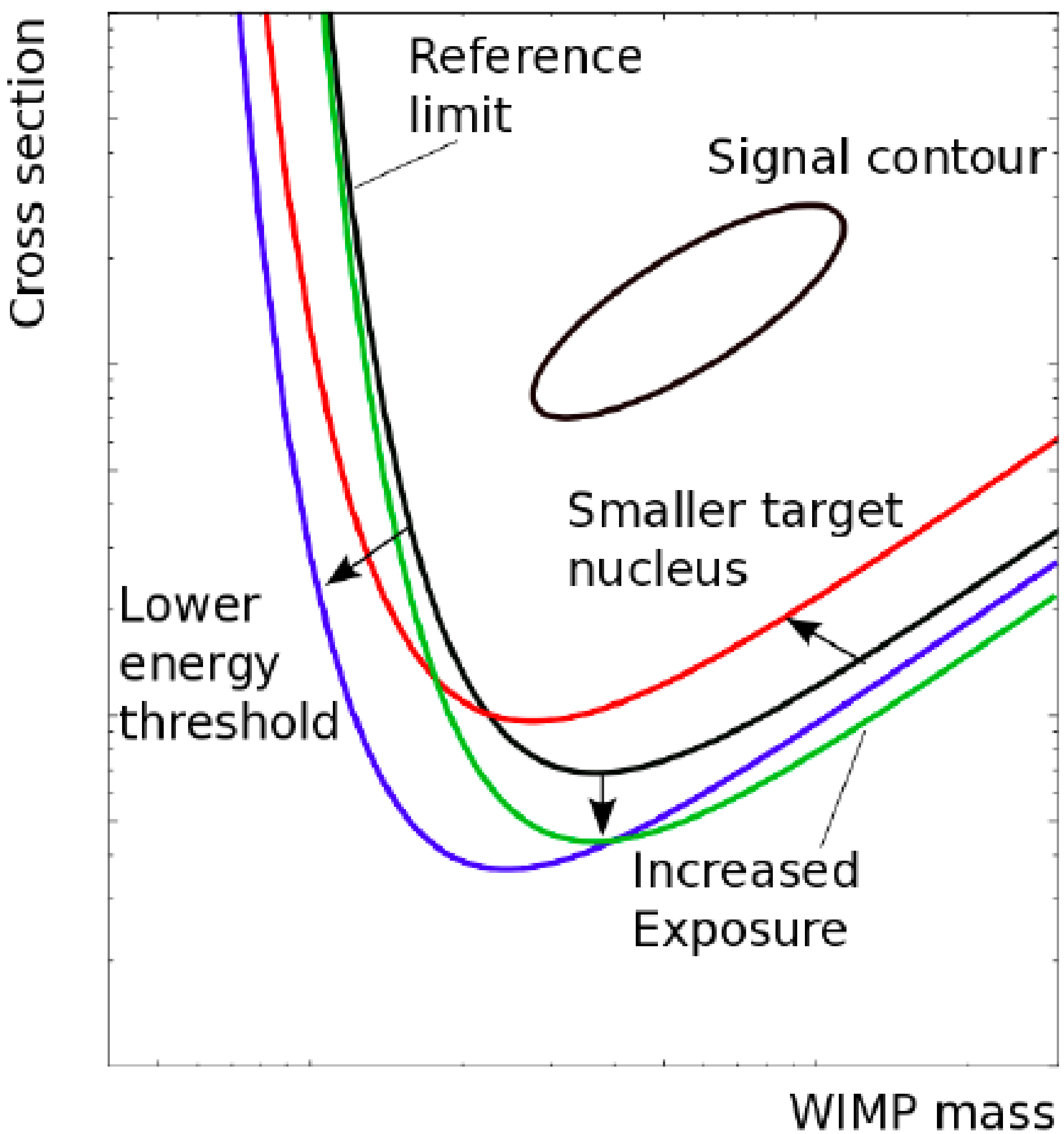


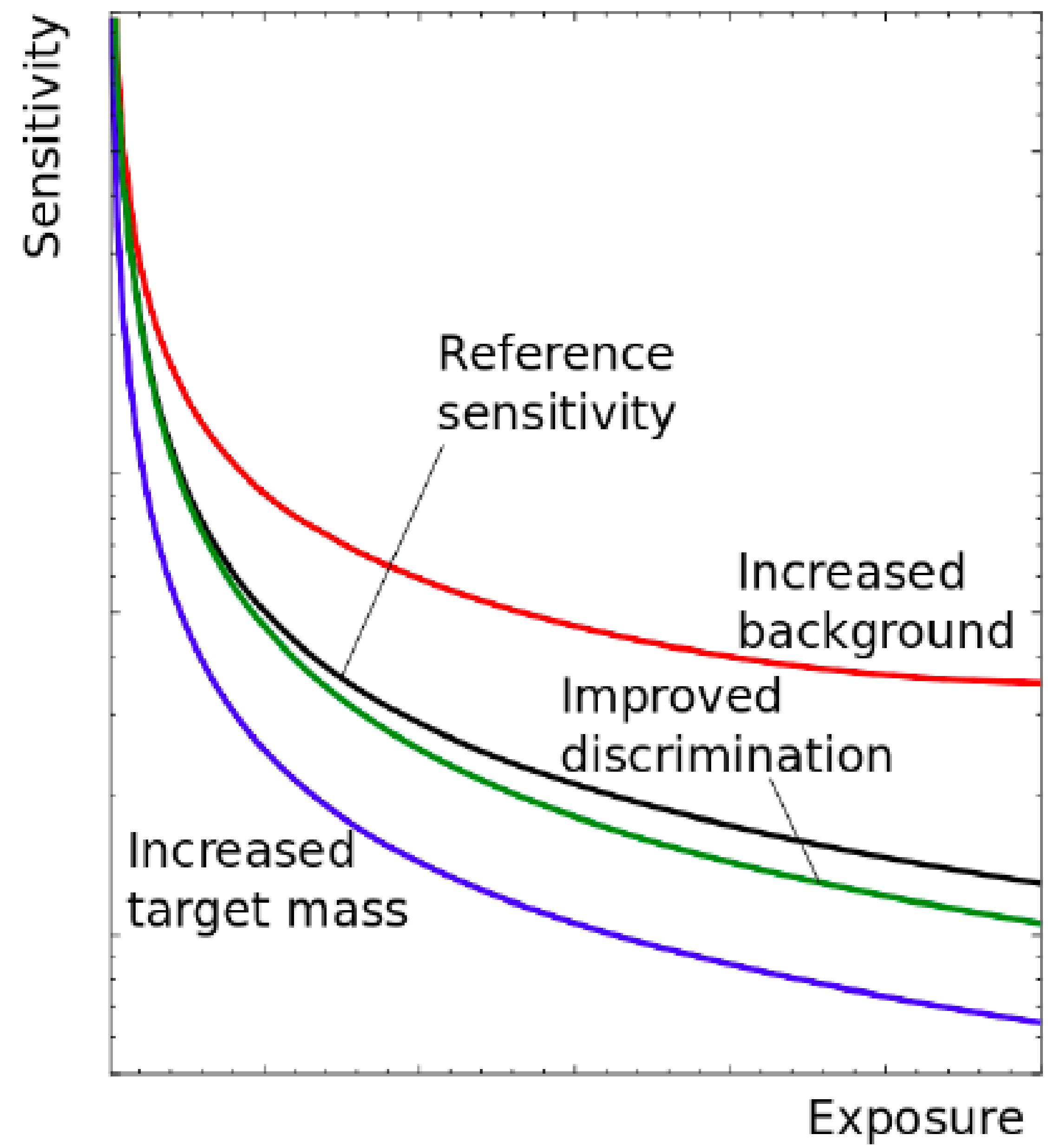


XENON100 energy threshold: 6.6 keV_{nr}

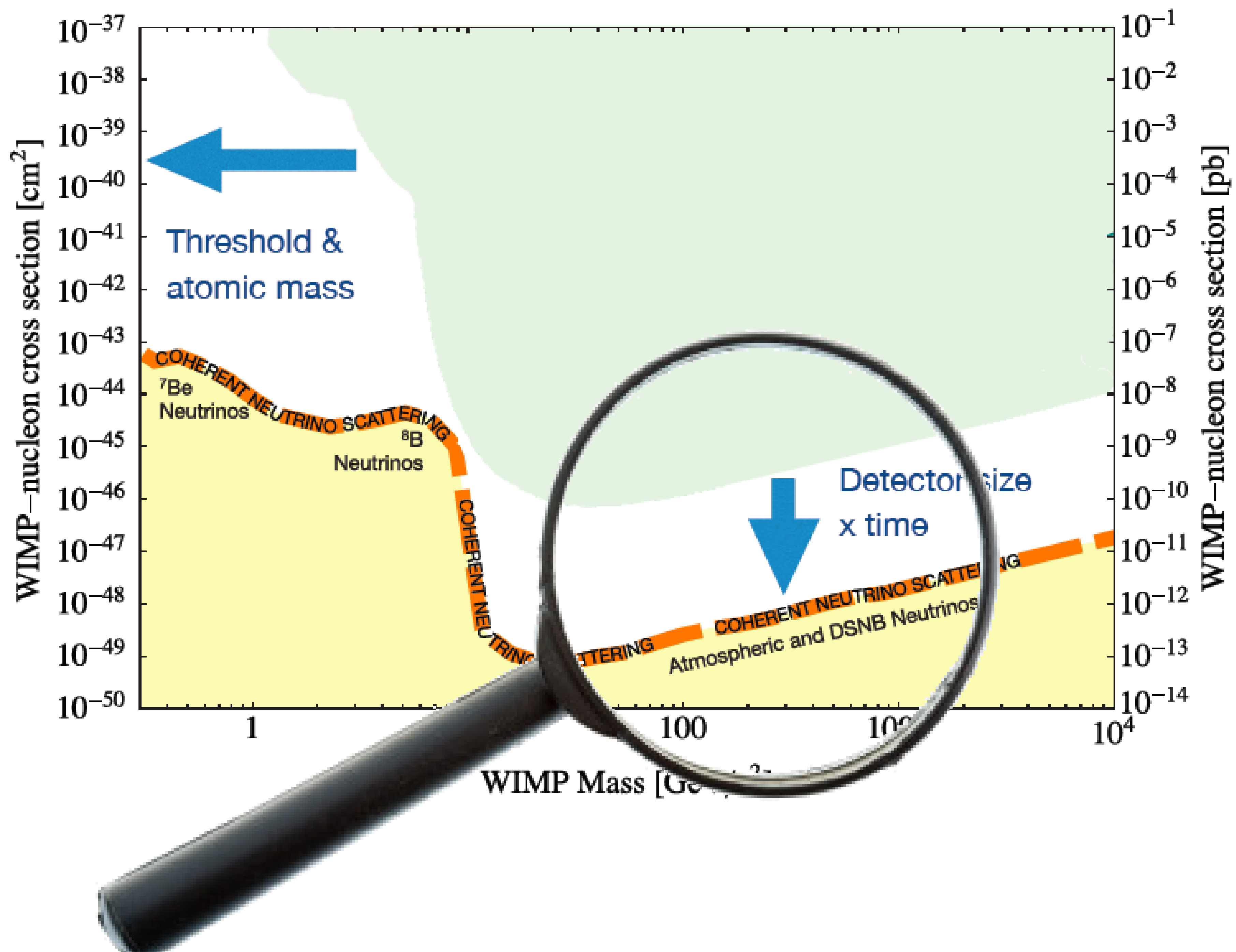
Improving sensitivity

Spin-independent WIMP-nucleon interaction





Improving sensitivity

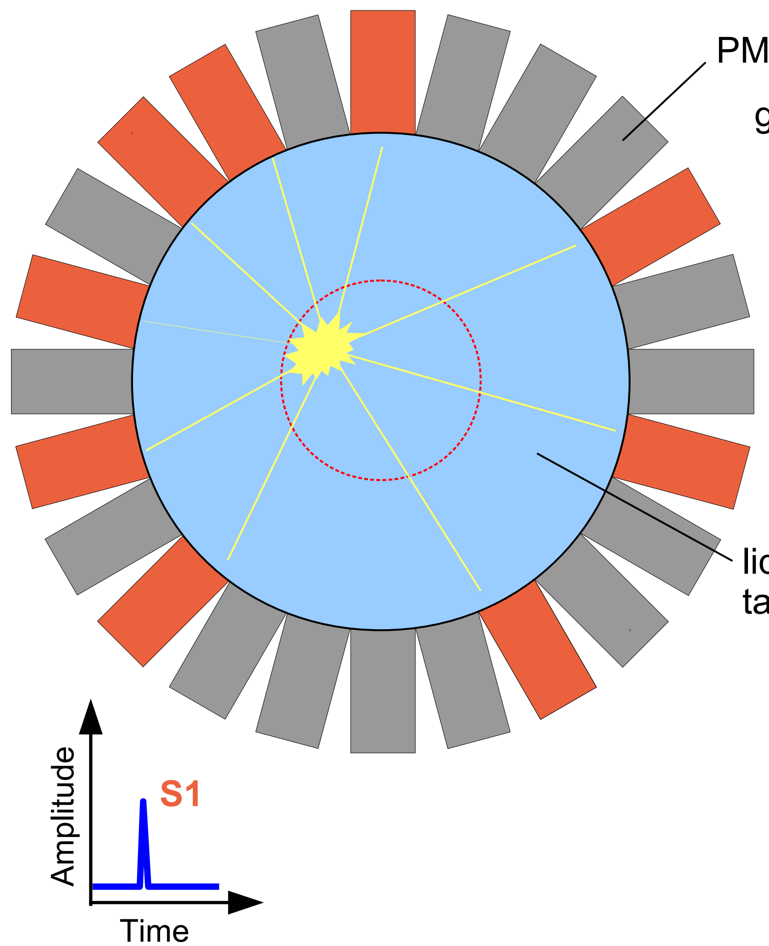


In this talk I will focus on larger mass WIMP search with nobles gases.
For WIMP masses less than 3 GeV/c2 the He based **NEWS-G** experiment is currently under construction at SNOlab. See talk by G. Gerbier on this subject

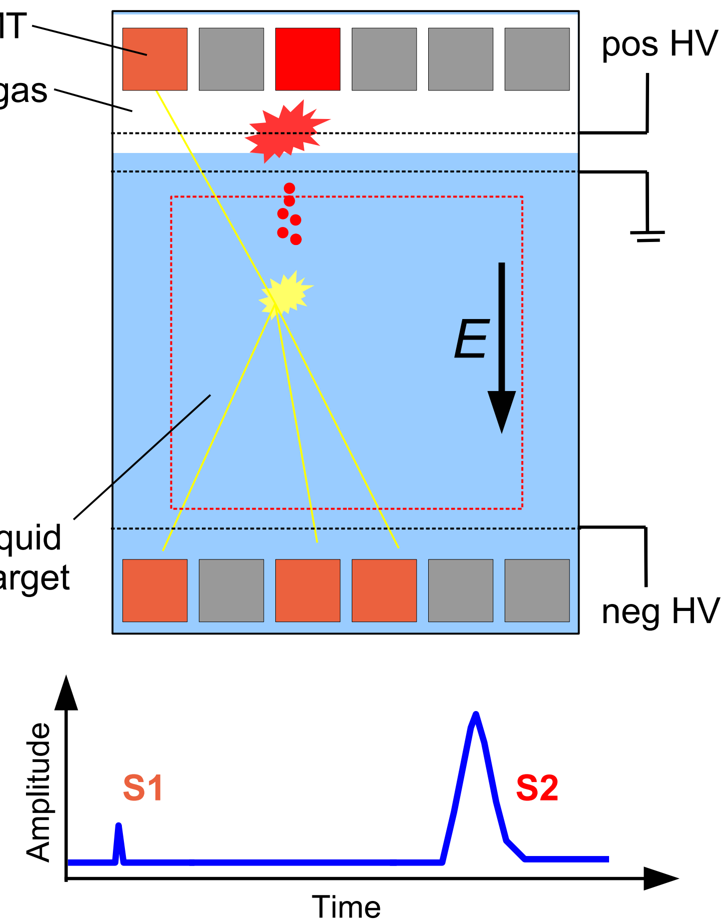
Single phase / double phase

Spin-independent WIMP-nucleon interaction

Single Phase Detector

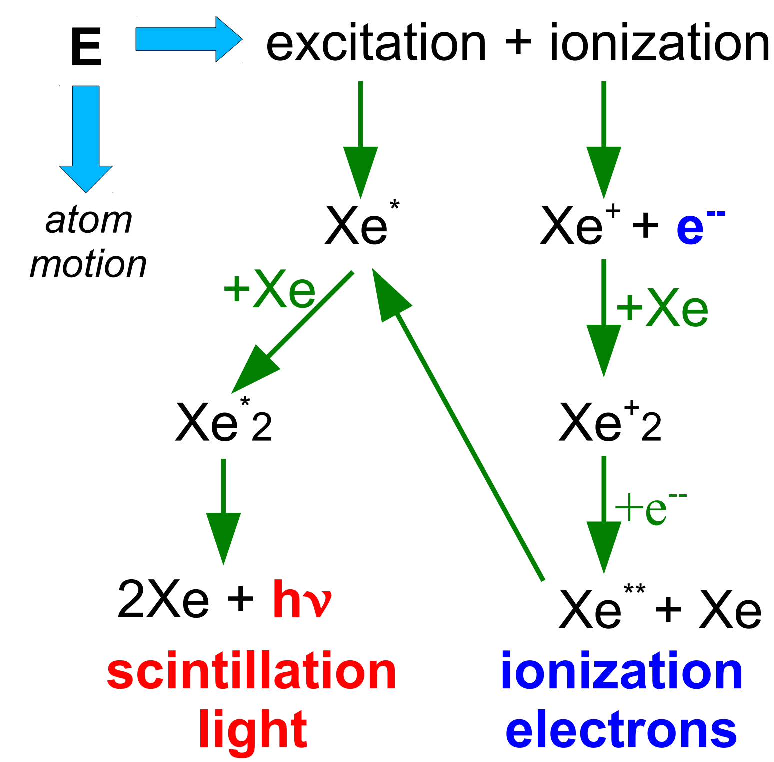


Time Projection Chamber



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)

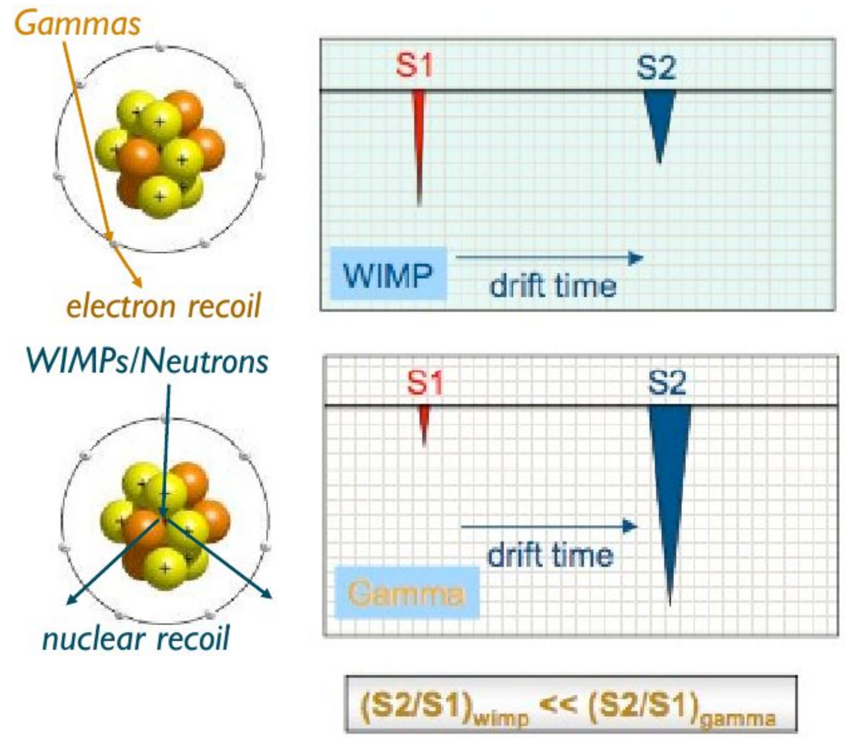


S1: Scintillation in the liquid phase

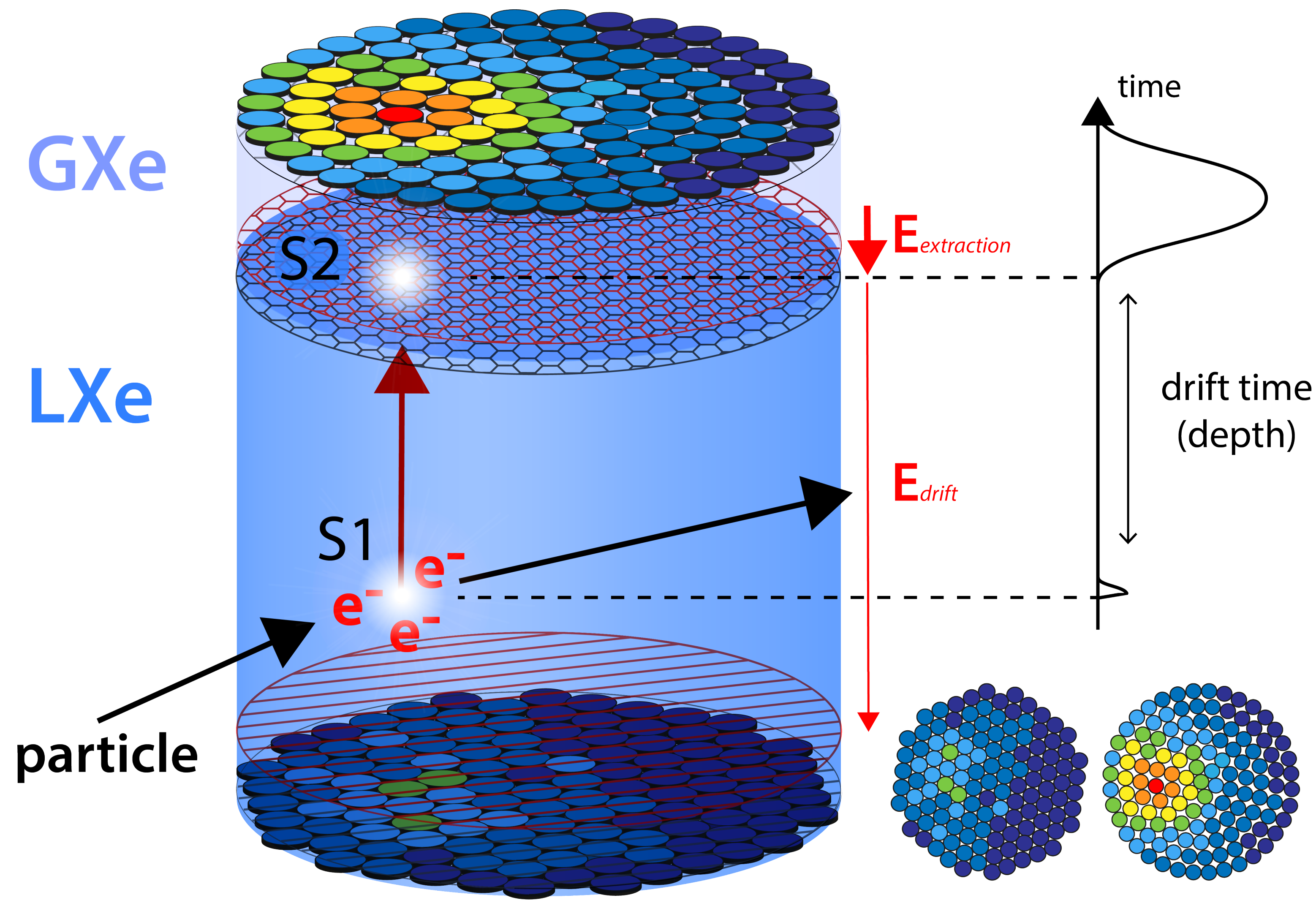
S2: secondary scintillation from ionization electrons drifted to the gas phase

Dual phase TPC advantages

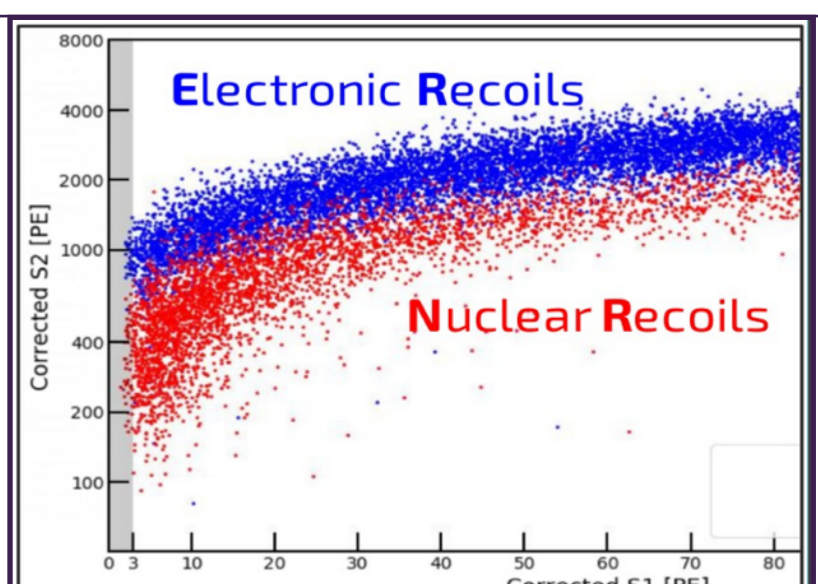
Background rejection: charge to light ratio + fiducialization and multi-scatter id.



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

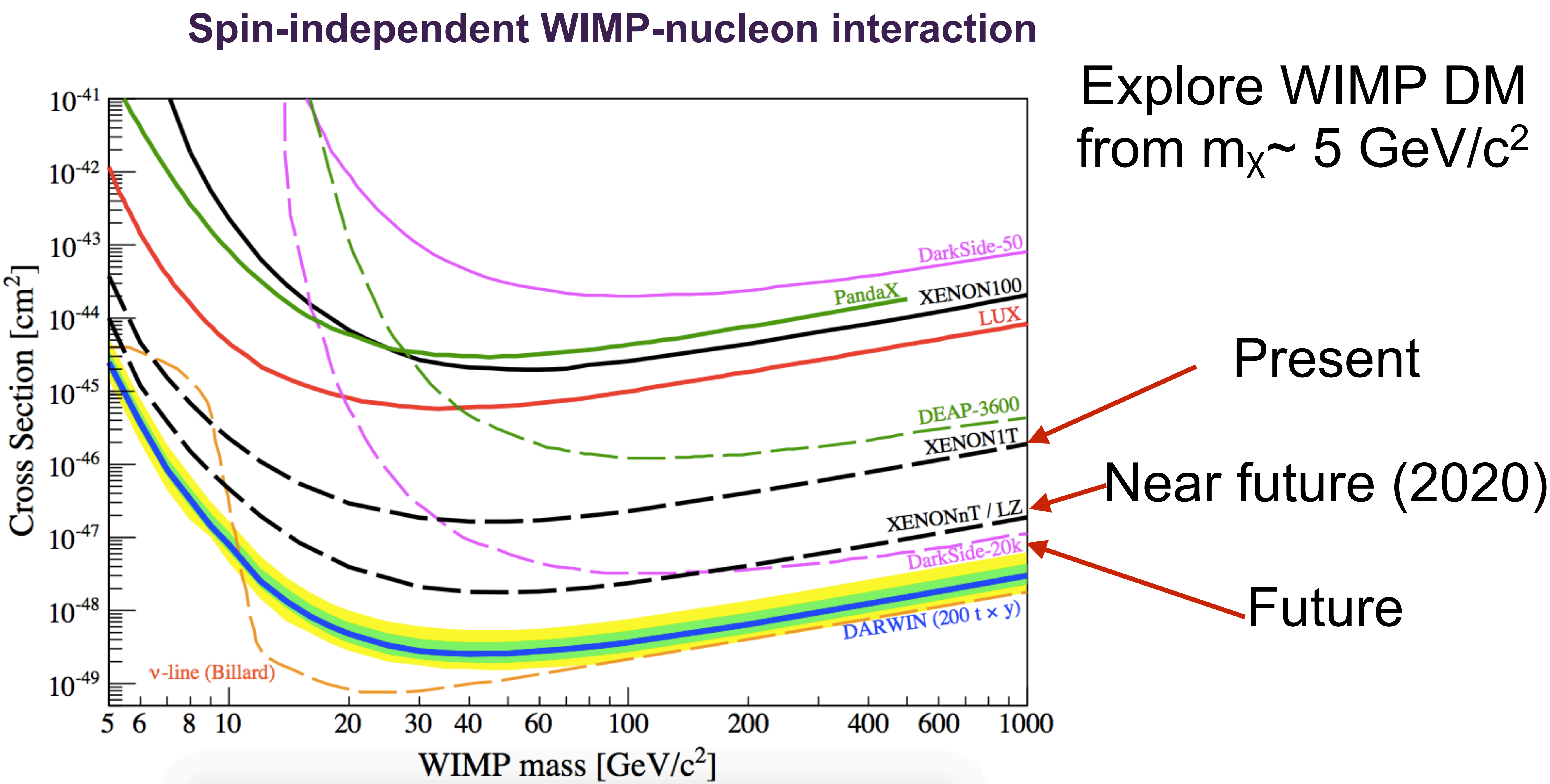


- WIMPs (or n) scattering off Xe nucleus → NR
- e^-,γ scattering off Xe electrons → ER
- Particle discrimination from S2/S1 ratio



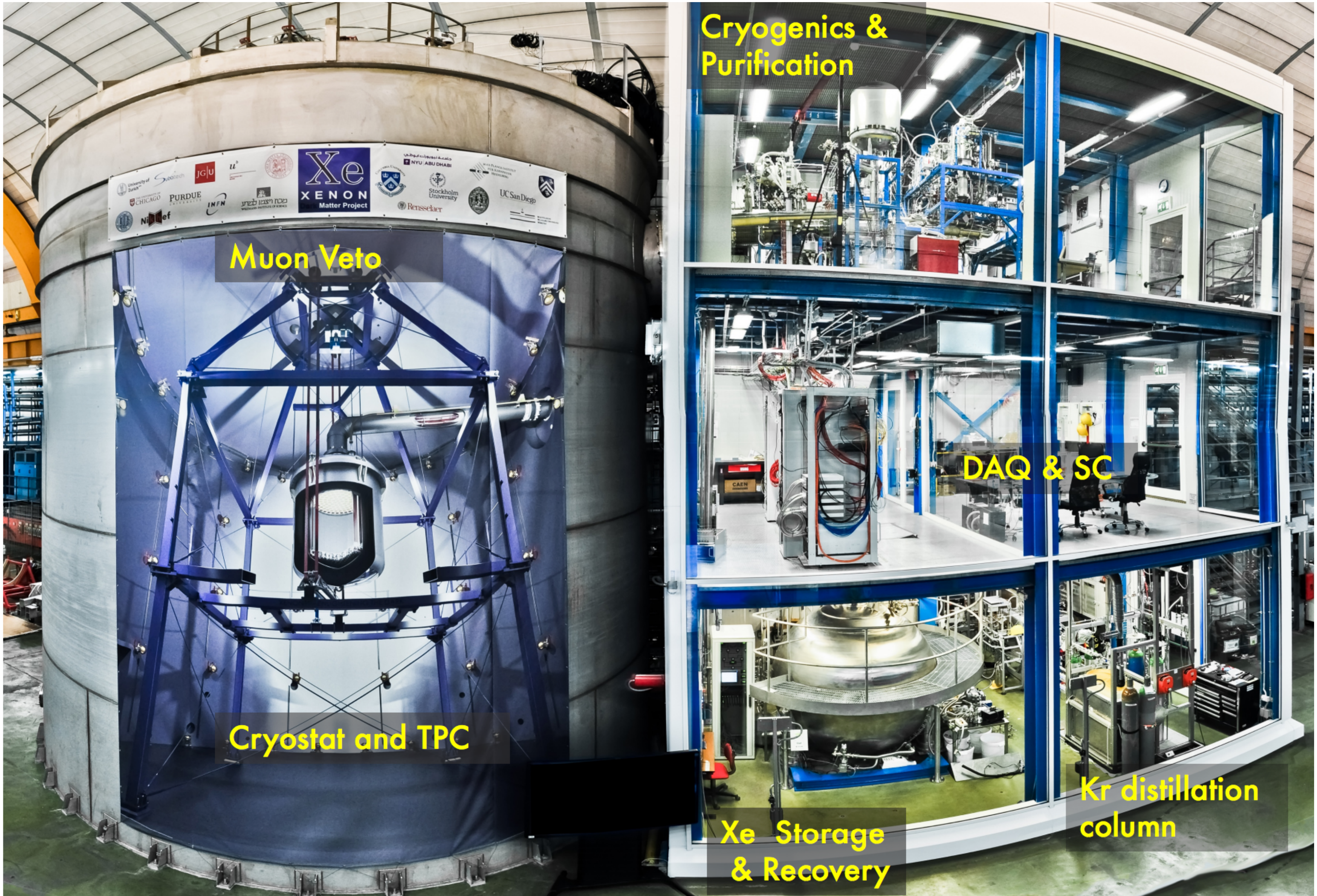
- Reconstruction of energy from both S1 and S2 signals
- 3D position reconstruction:
  - x and y position from S2 pattern of Top PMT array
  - z position from drift time information

Direct search for WIMPs: status



Explore WIMP DM from $m_\chi \sim 5$ GeV/c^2

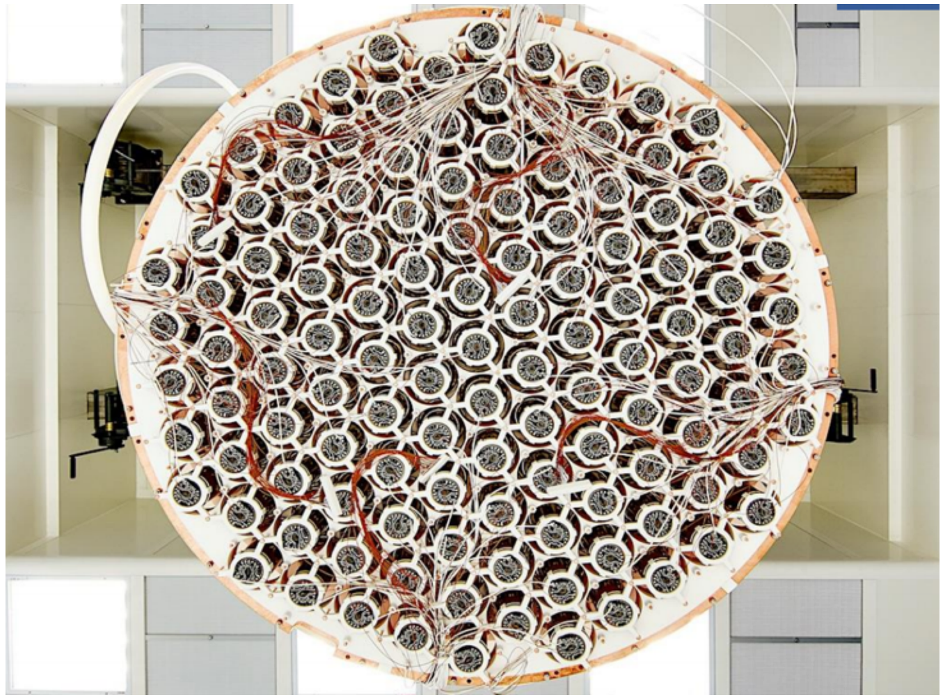
The XENON1T detector @ LNGS



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%

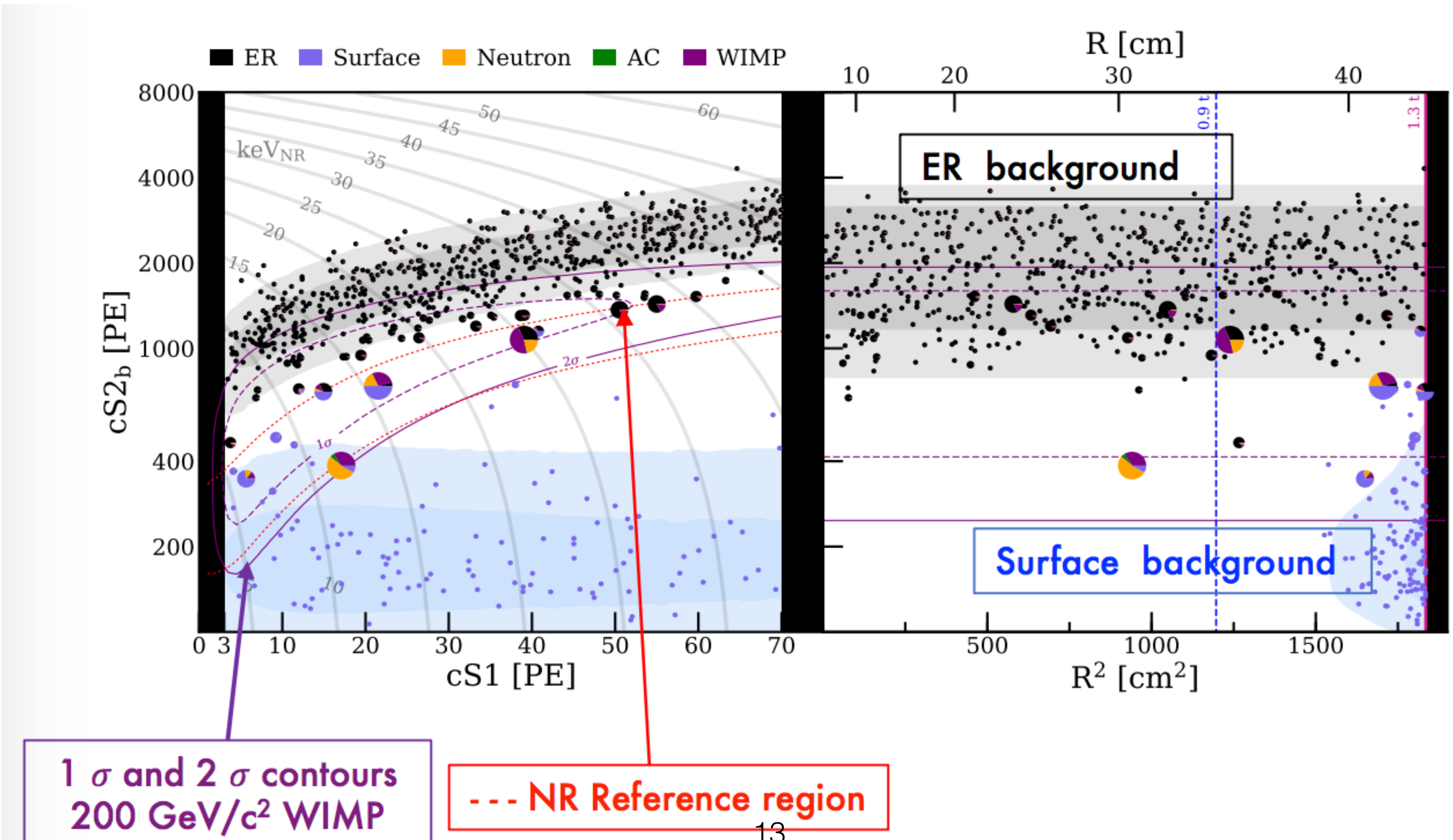
EPJC 75 11 (2015)

Dark matter search results

UNBLIND + DESALT

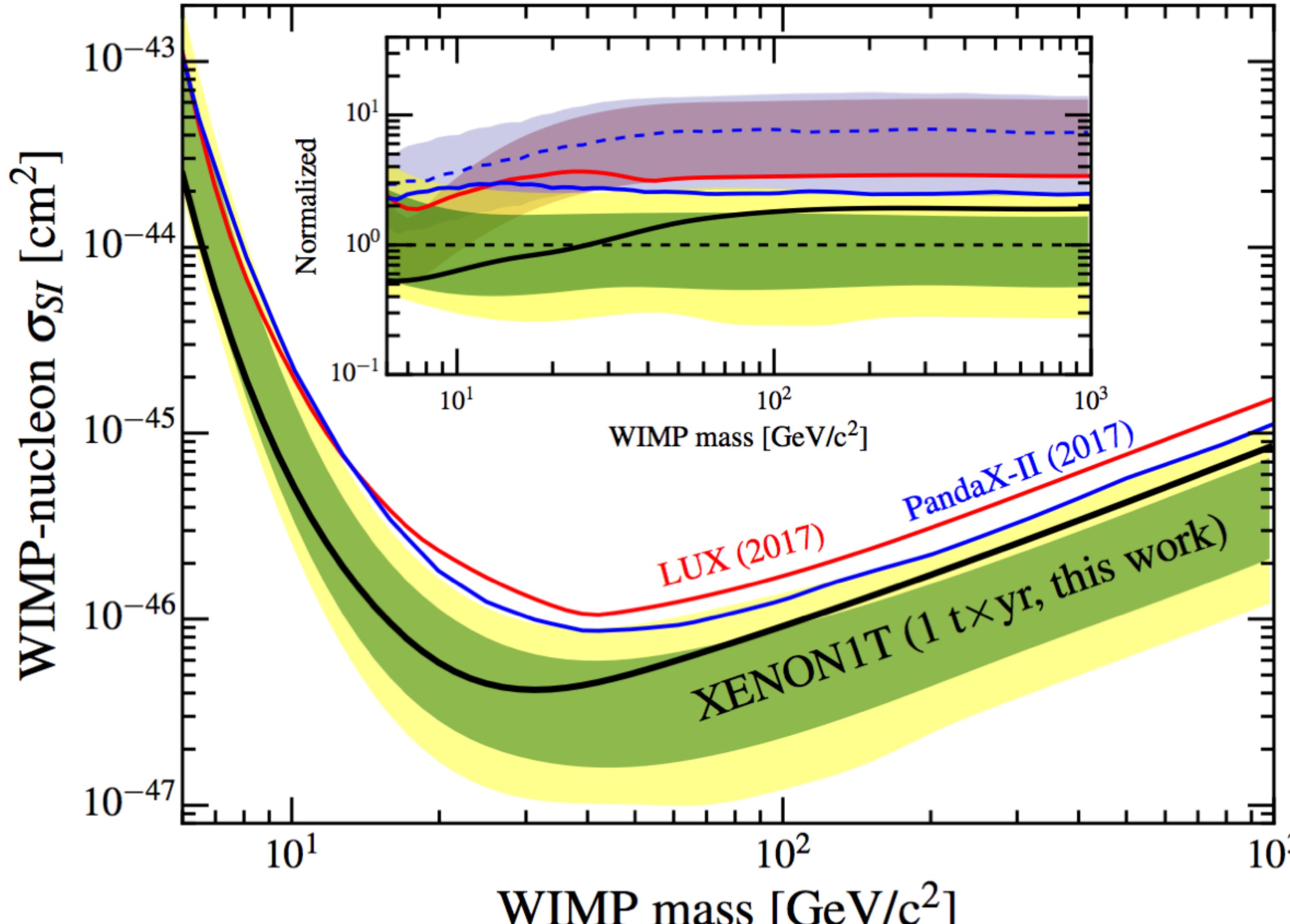
- Unbinned Profile likelihood analysis in 3D space (cS1, cS2, R)
- Events passing all selection criteria are shown as pie charts representing the relative PDF from each components for the best-fit model of 200 GeV/c^2 WIMP and $\sigma_{SI} = 4.7 \cdot 10^{-47}$ cm^2

Width of pie represents WIMP probability



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

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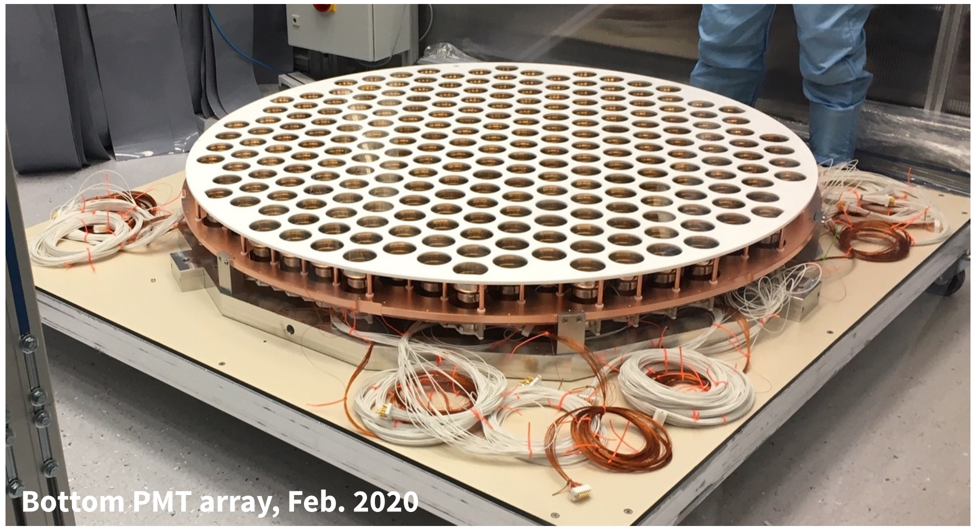
Editors' Suggestion

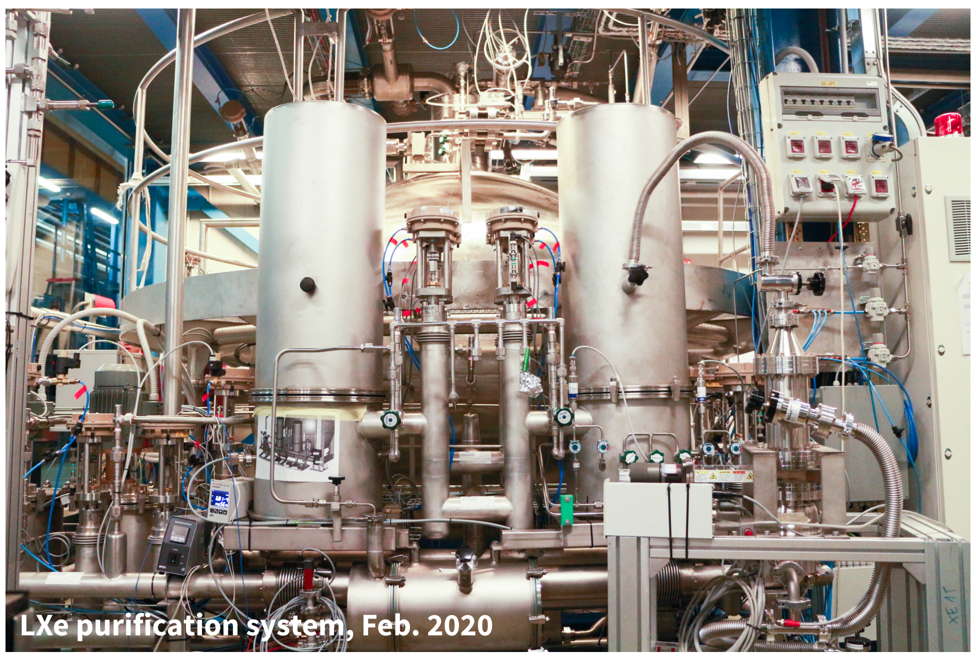
Dark Matter Search Results from a One Ton-Year Exposure of XENON1T

E. Aprile *et al.* (XENON Collaboration)

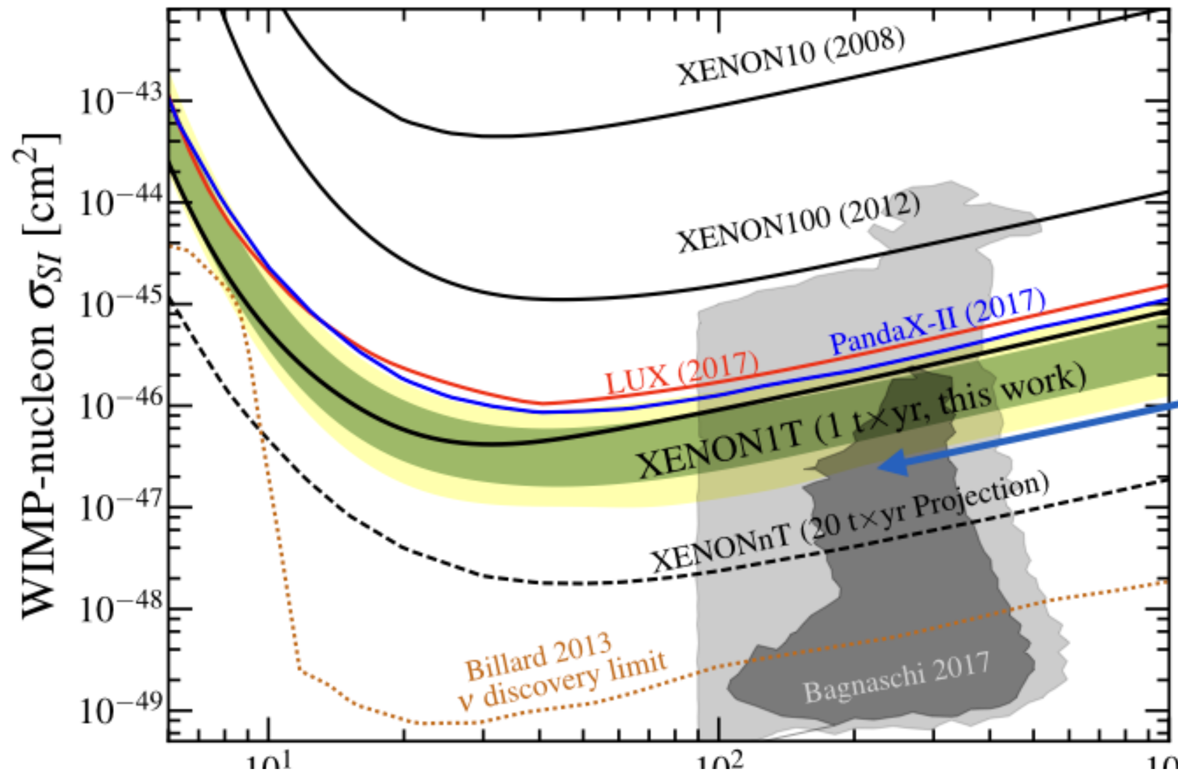
Phys. Rev. Lett. **121**, 111302 – Published 12 September 2018

XENONnT

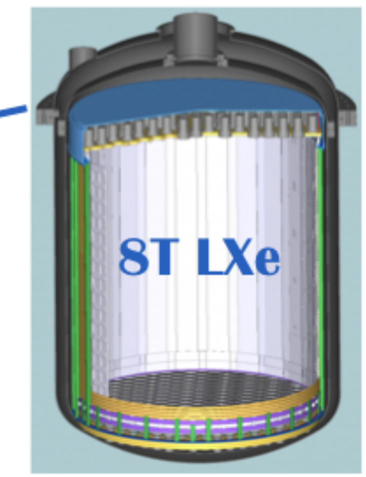

Bottom PMT array, Feb. 2020


LXe purification system, Feb. 2020

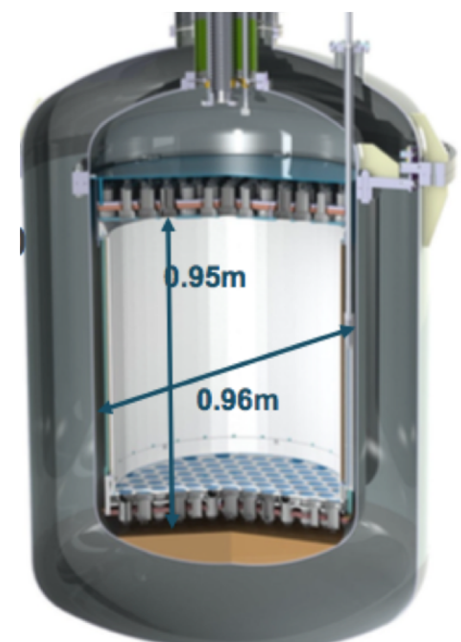
- XENONnT TPC currently being assembled
- Commissioning within 2 months
- First data this summer



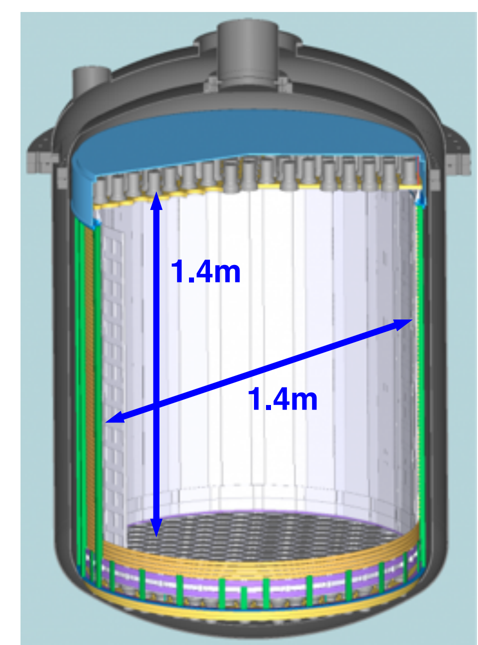
XENONnT: detect this dark matter by 2025!



XENON1T



XENONnT



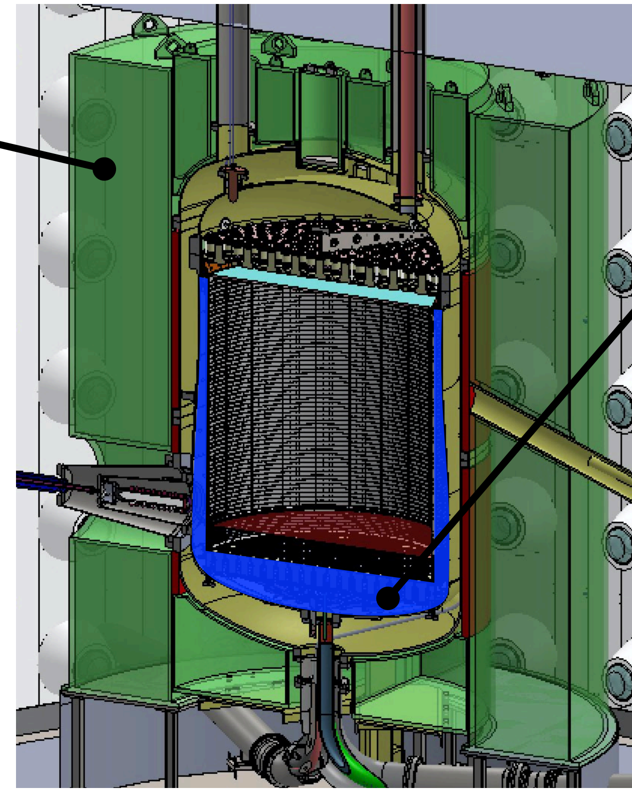
2012-2018	**2019-2025**
3.2 LXe	**8t LXe**
over	**TPC in place**

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

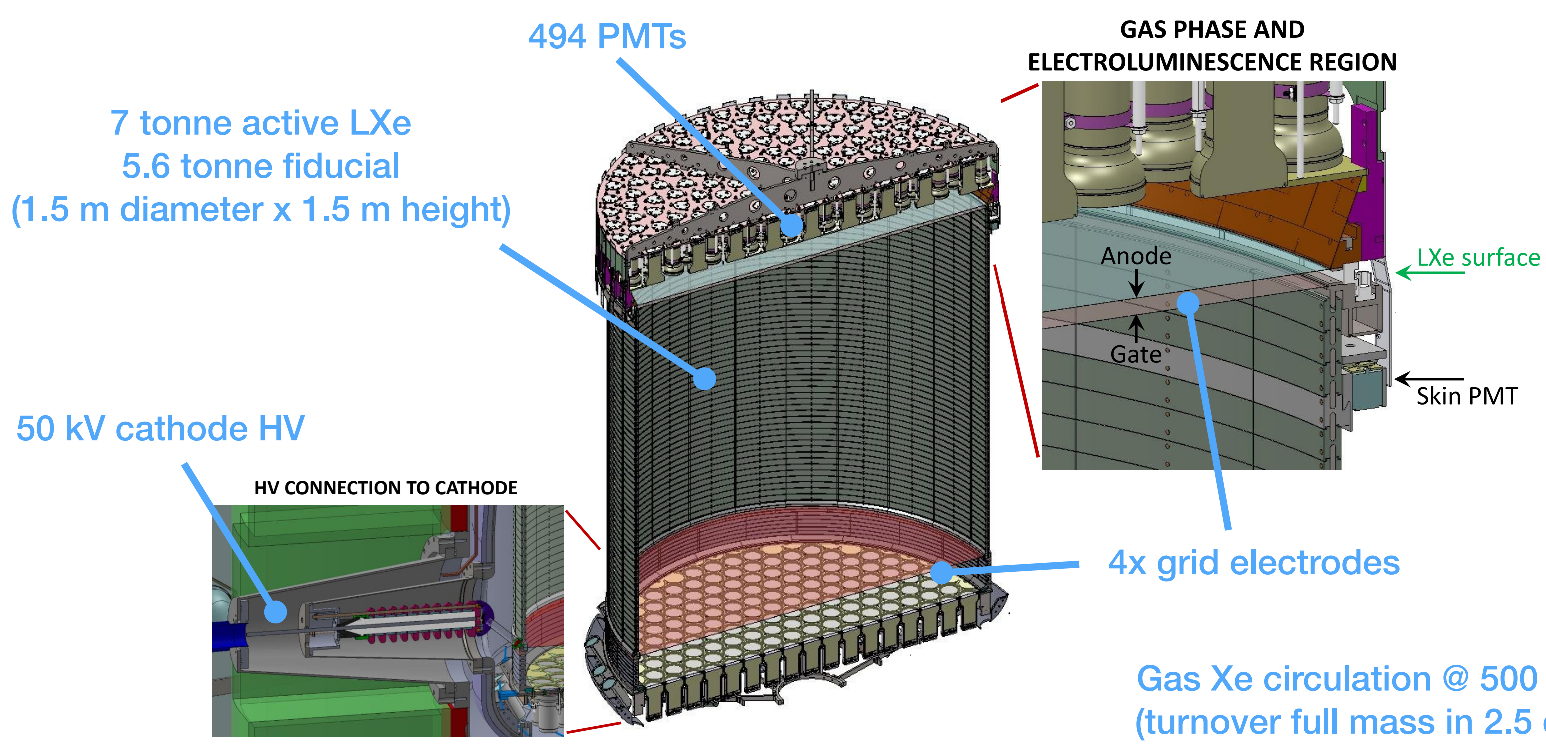


The Skin

- 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

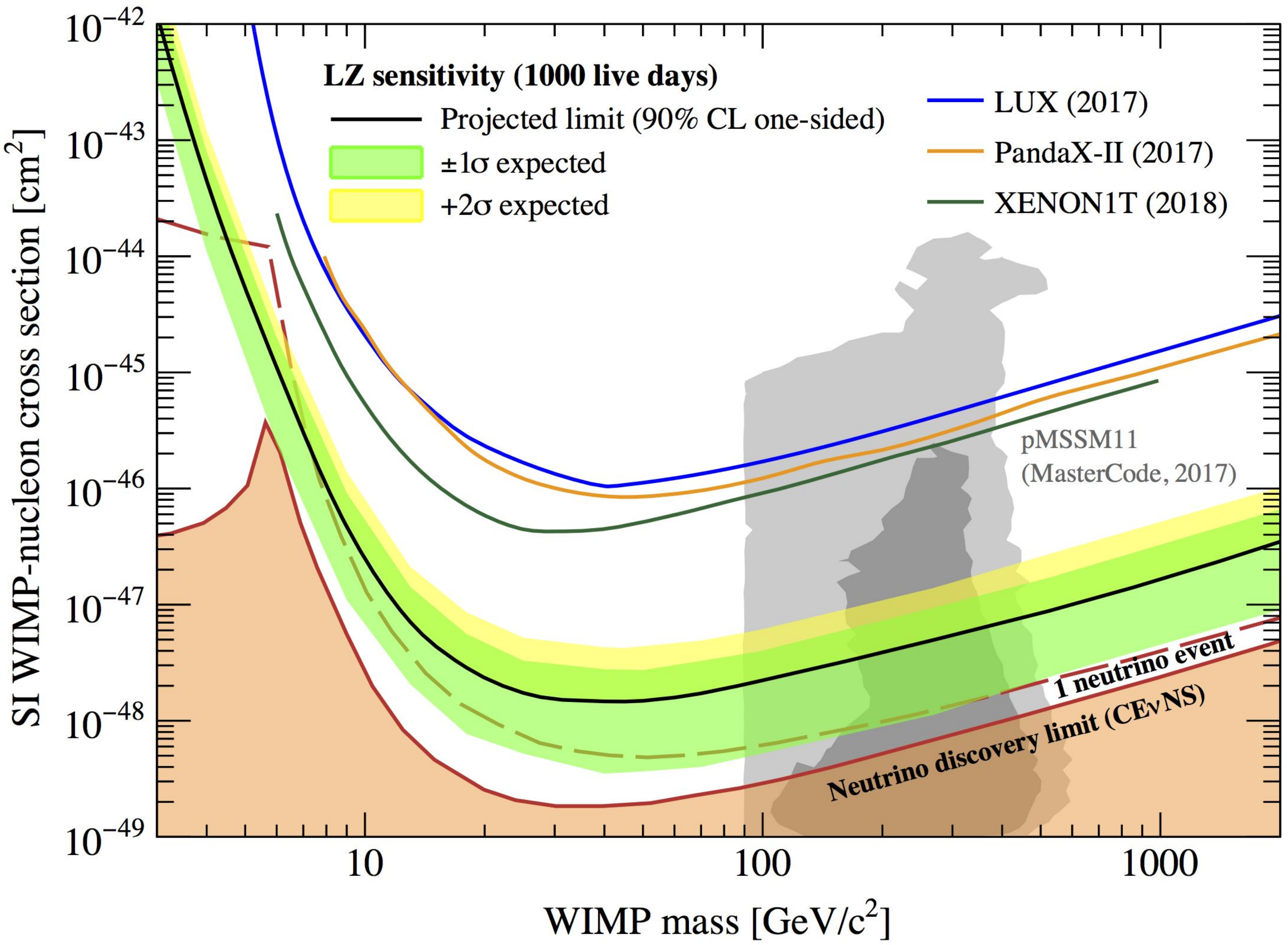


Gas Xe circulation @ 500 slpm
(turnover full mass in 2.5 days)

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

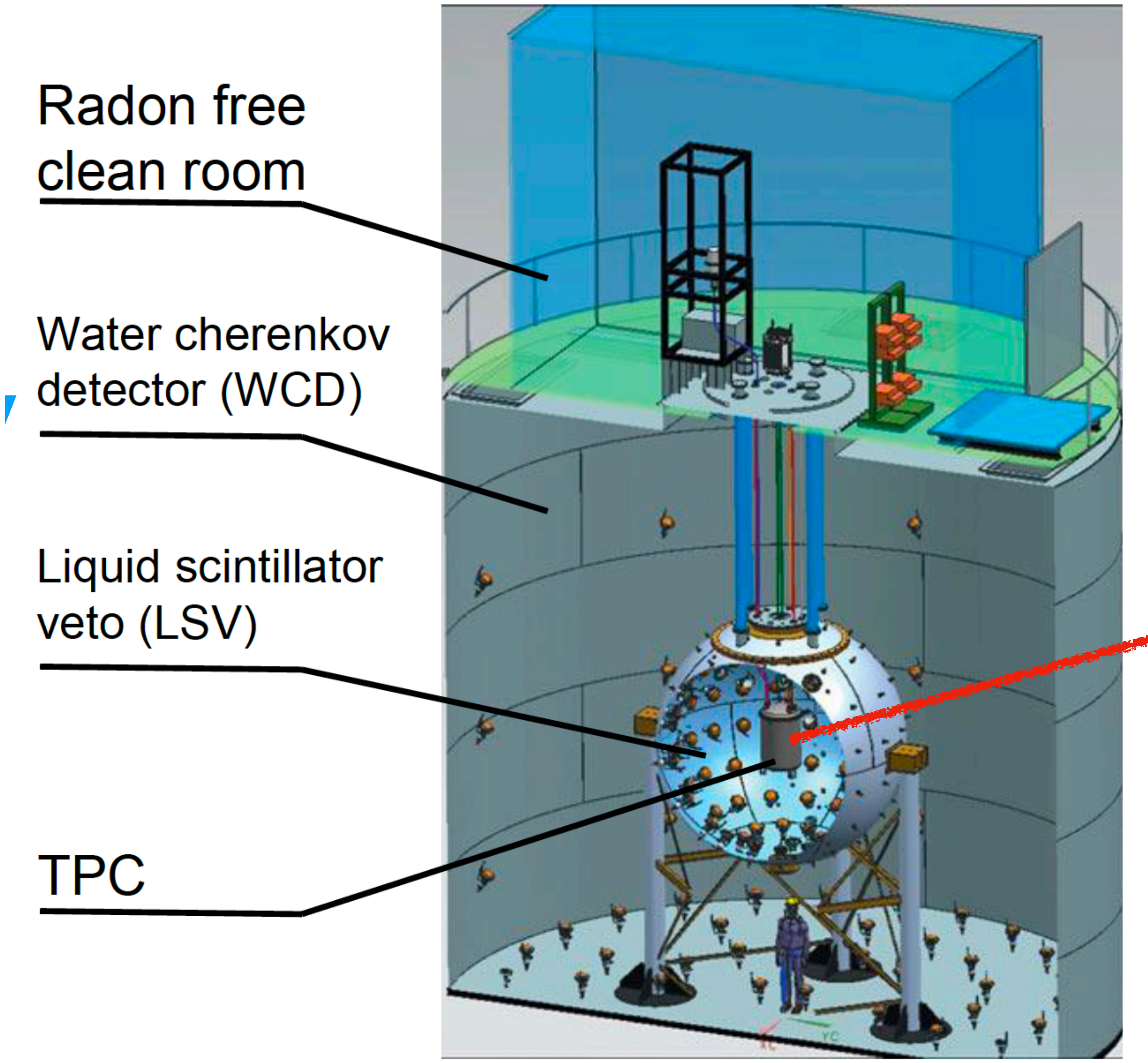
LZ TDR arXiv:1703.09144

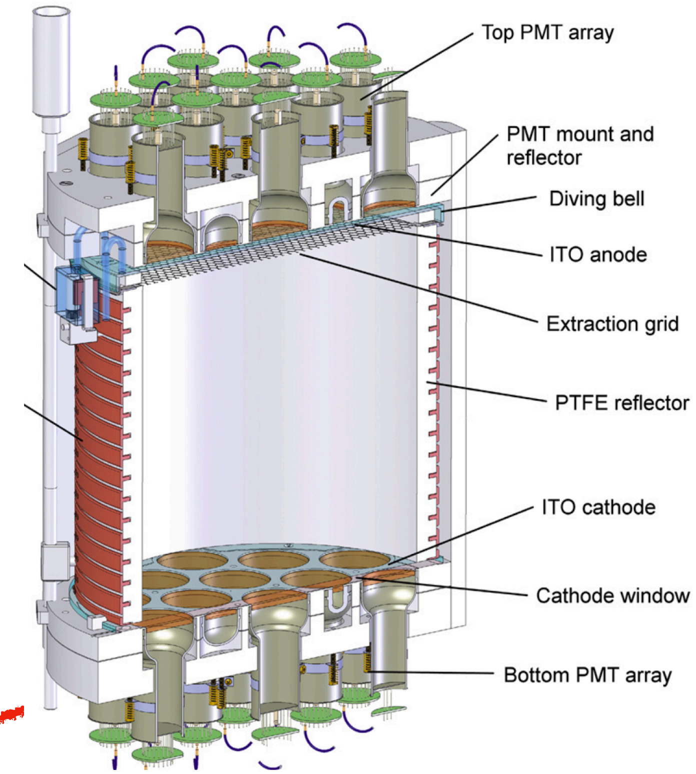
LZ



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

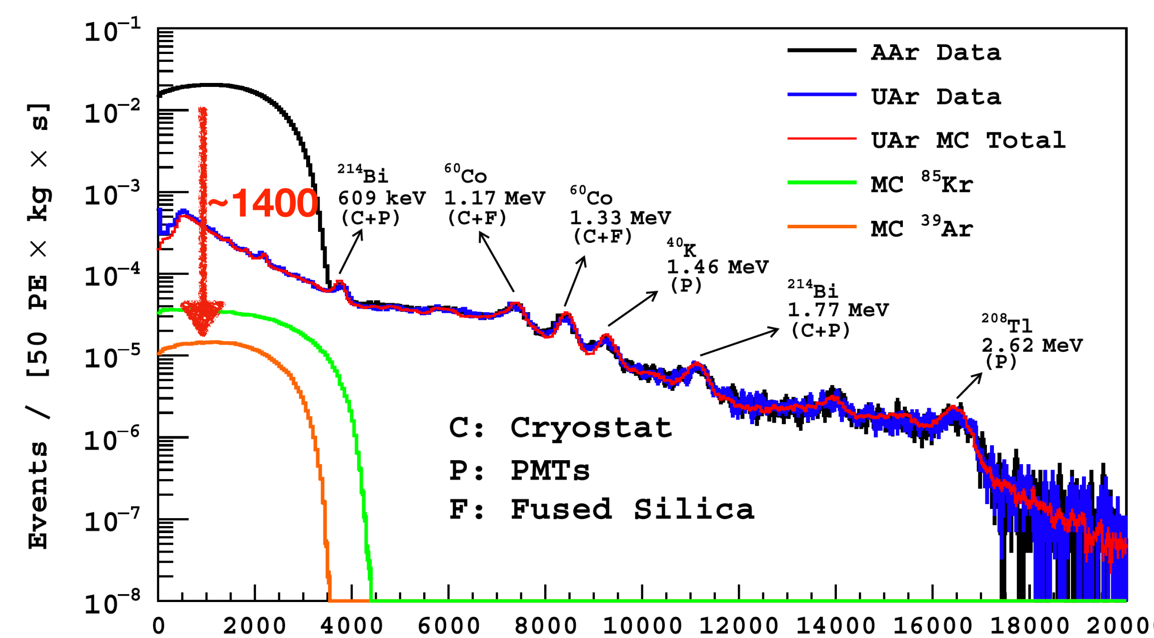
DarkSide-50





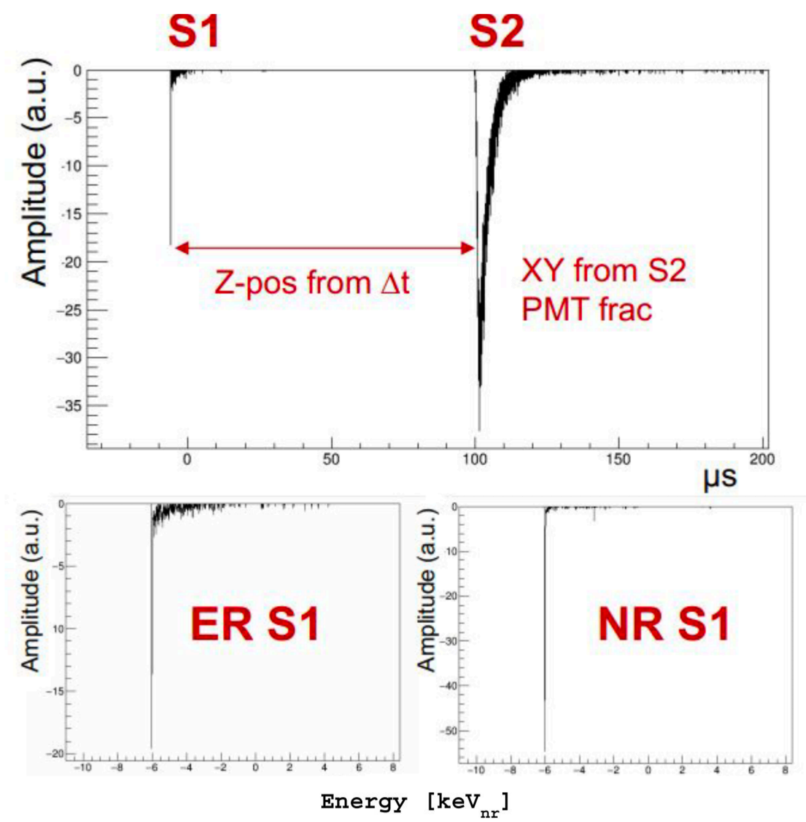
- 46.4 kg LAr in active volume
- 38 Hamamatsu R11065 3″ PMTs
- PTFE as reflector
- TPB as wave length shifter
- Copper field cage
- ITO layers as anode and cathode
- Drift Field: 200 V/cm
- Extraction Field: 2.8 kV/cm

- 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.



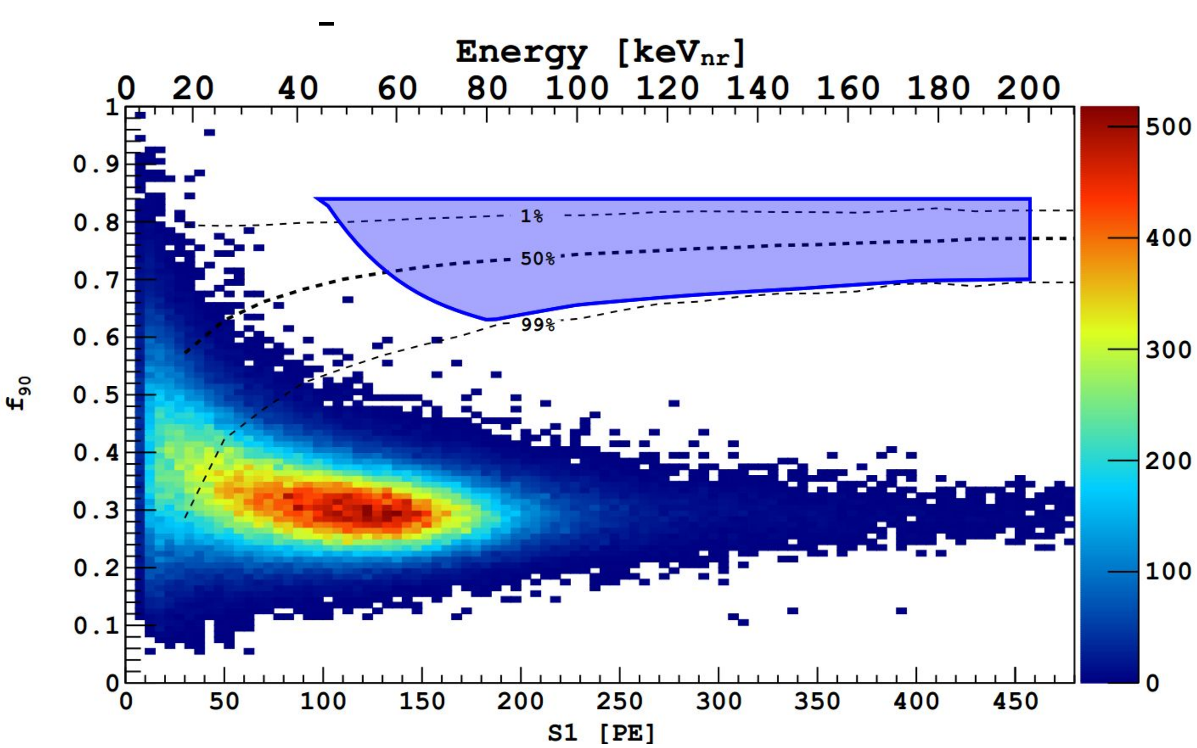
Phys. Rev. D 93, 081101 (2016)

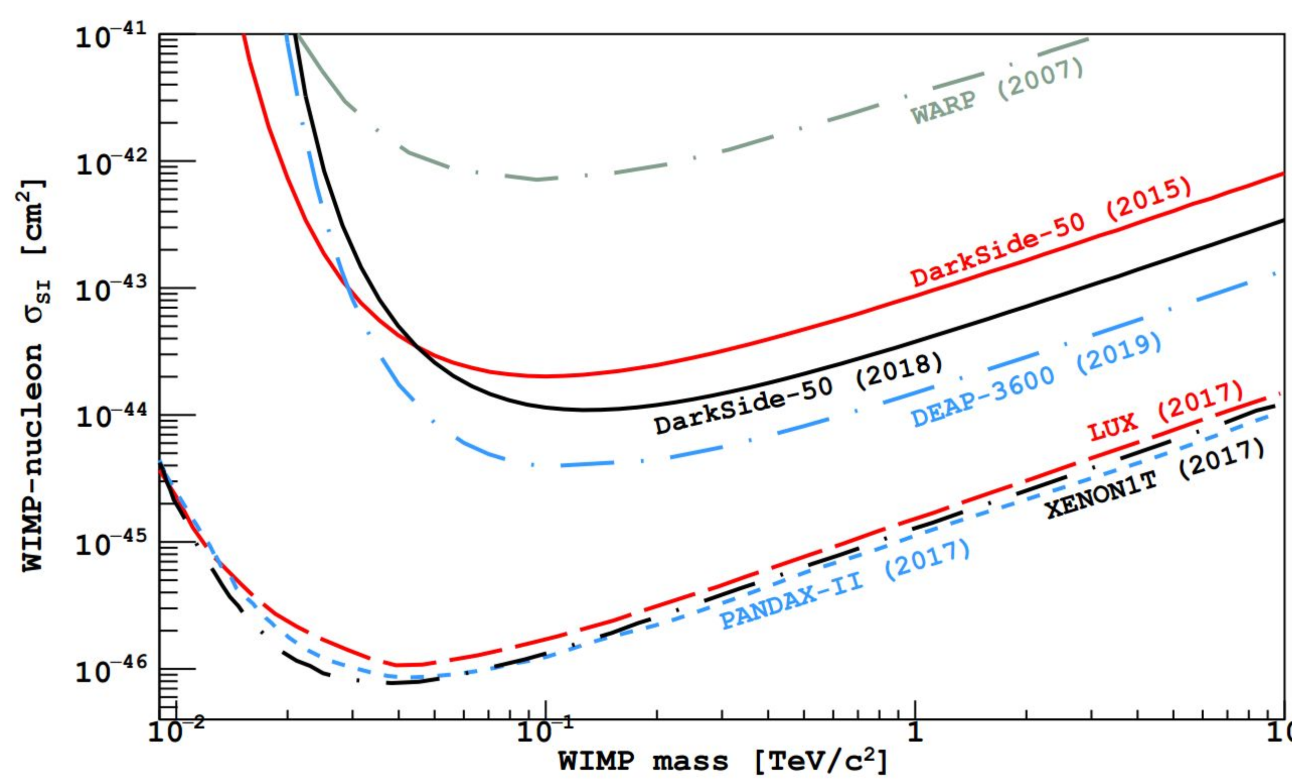
DarkSide-50



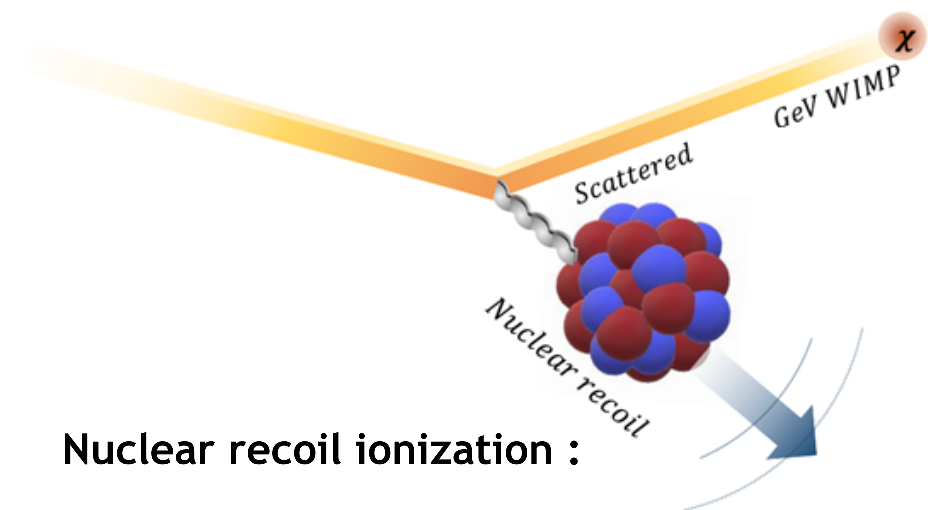
$$f_{90} = \frac{\text{S1 light in first 90ns}}{\text{total S1 light}}$$

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





S2-only dark matter search

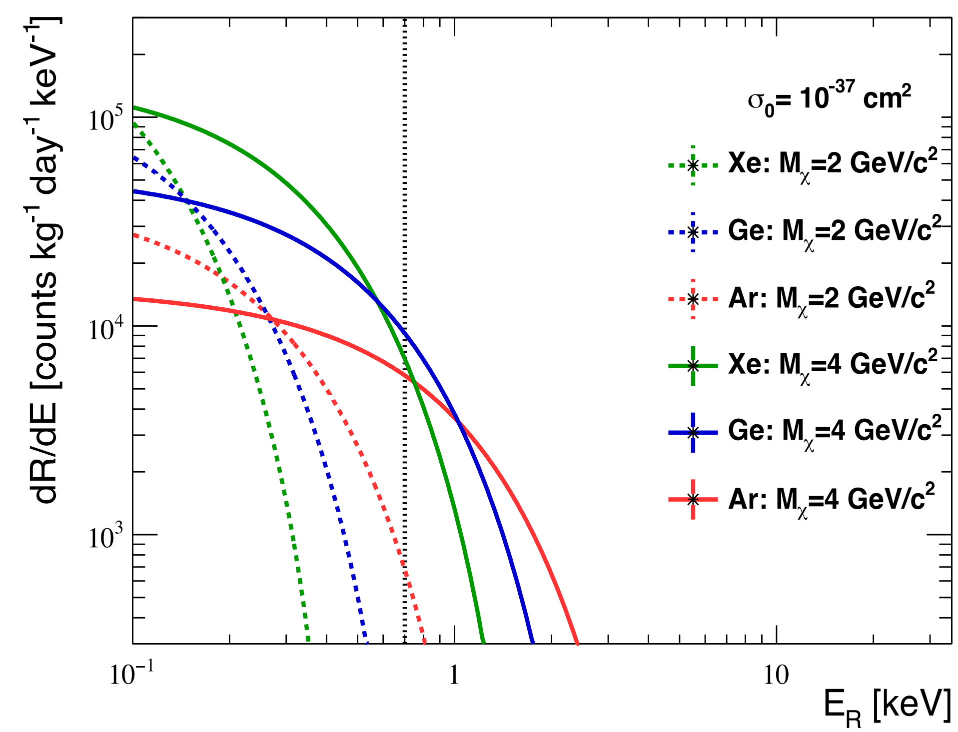


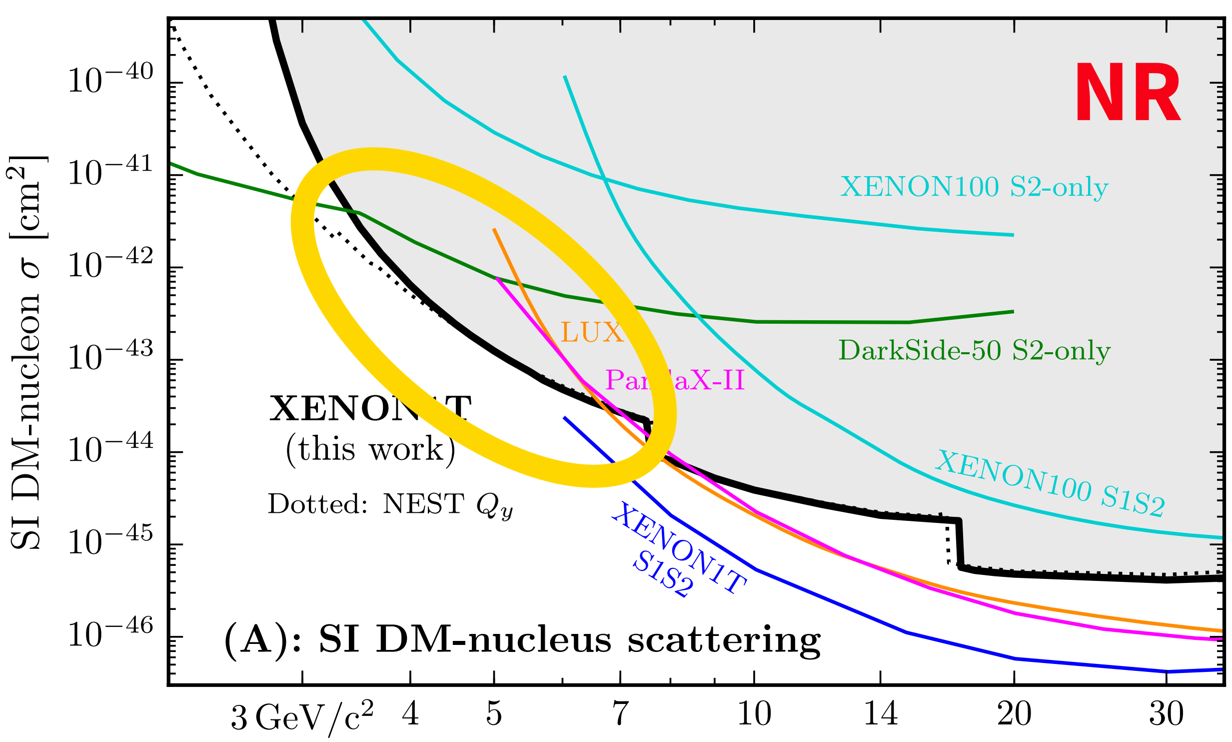
Nuclear recoil ionization :

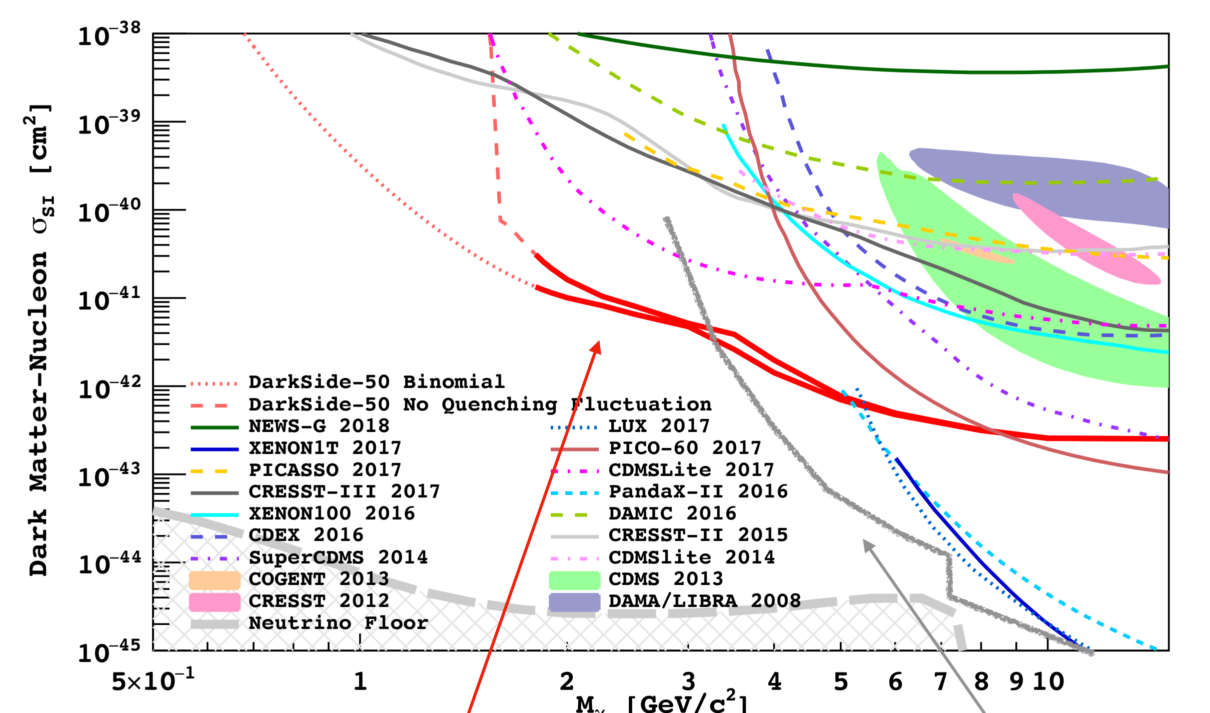
- few electrons drift
- gas pocket fluorescence

→ **S2 signal**

Low mass WIMPs E_R spectra for Ar, Ge, Xe







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

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

Future: DARWIN

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

	XENON10	XENON100	XENON1T	XENONnT	DARWIN
Time	until 2007	since 2008	from 2015	from 2019	from 2020s
Total	25 kg	162 kg	3.5 ton	8.4 ton	50 ton
Target	14 kg	48 kg	2 ton	6 ton	40 ton
Limit	~10^{-43} cm²	~10^{-45} cm²	~10^{-47} cm²	~10^{-48} cm²	~10^{-49} cm²

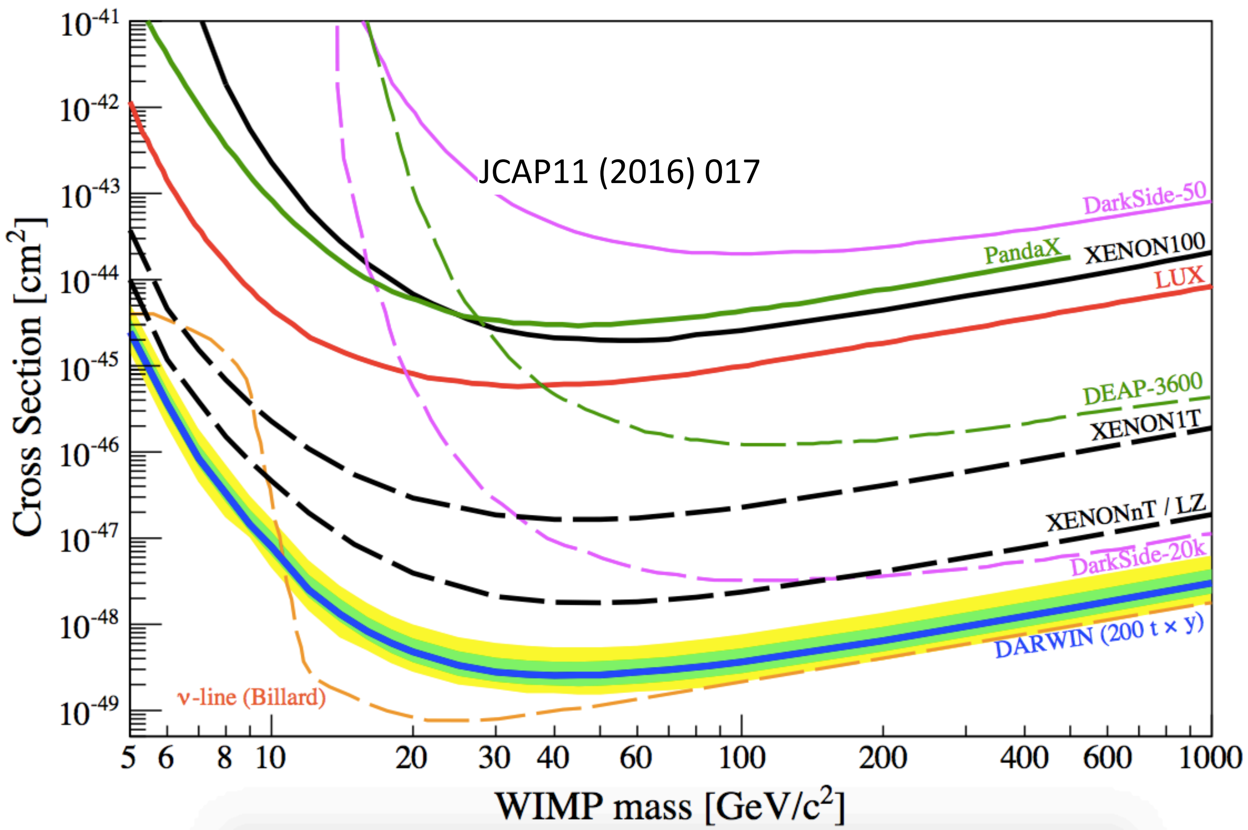
....

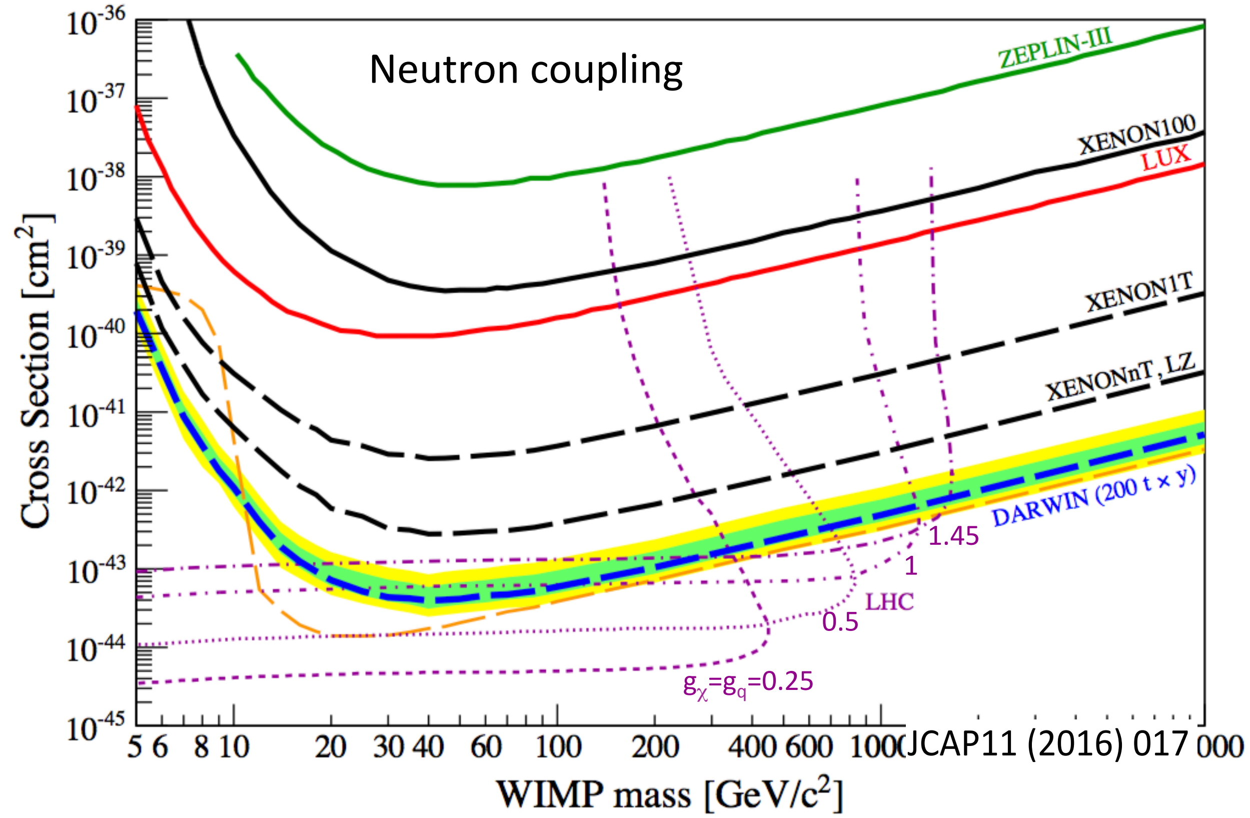
EPJC 77 881 (2017)

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 under 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 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: GADMC

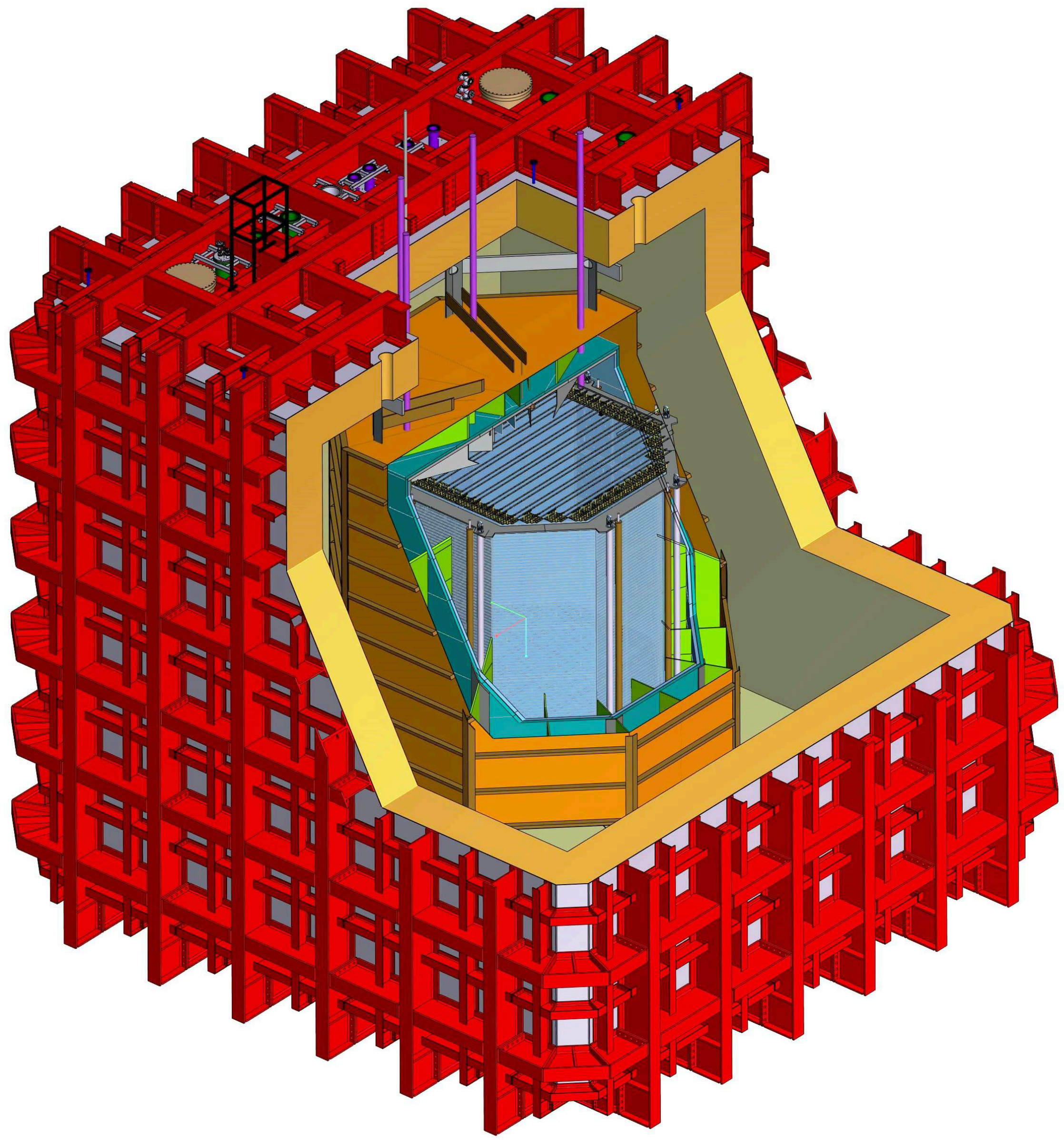
Global Argon Dark Matter Collaboration

DEAP-3600
(running)

DarkSide-50
(running)

miniCLEAN

ArDM



DarkSide-20k
2022~

~300 tonnes

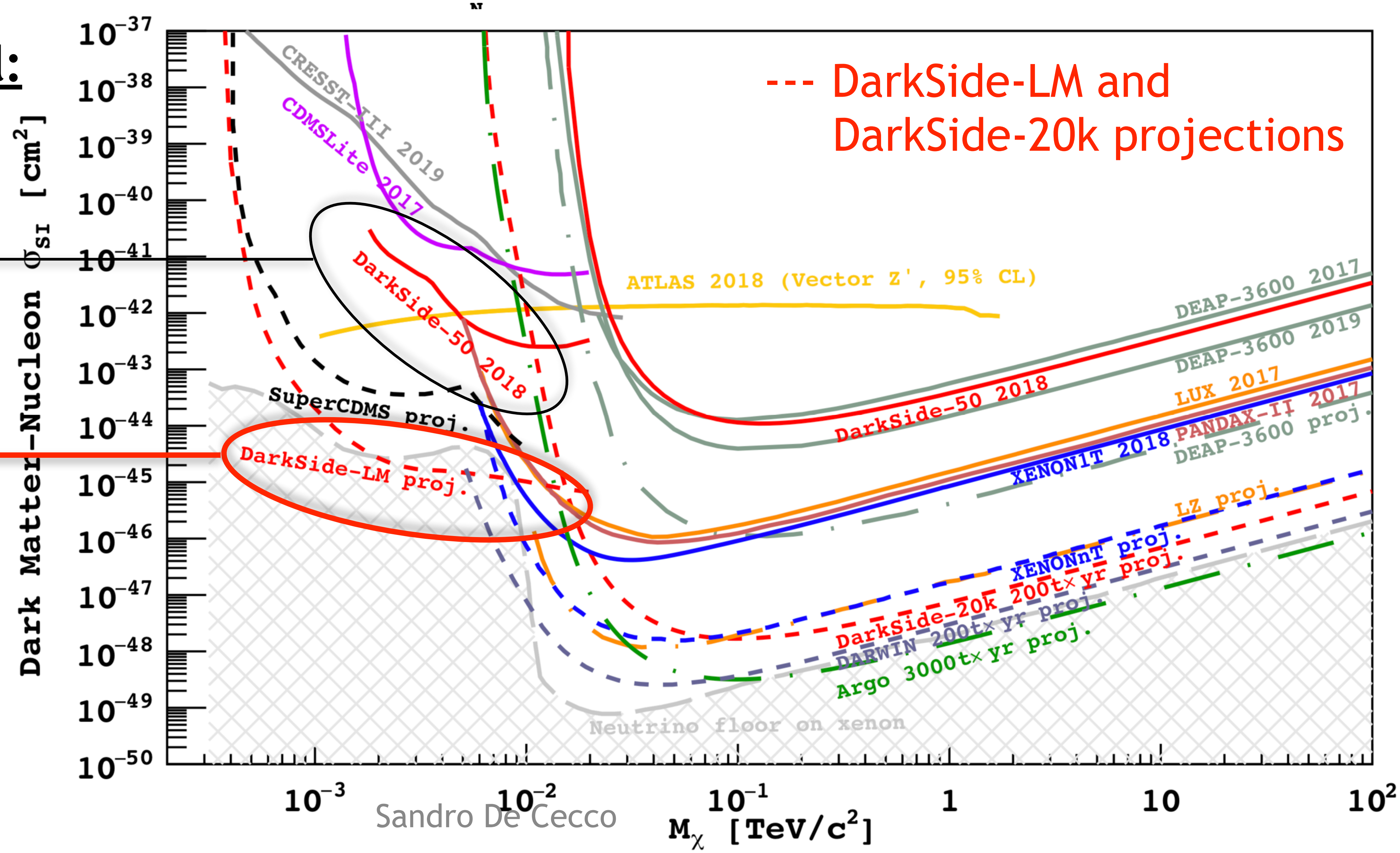
ARGO
2029~

Future: GADMC

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

Current:
DarkSide-50

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



Summary

- **A very rich program in the direct dark matter search with noble gases**

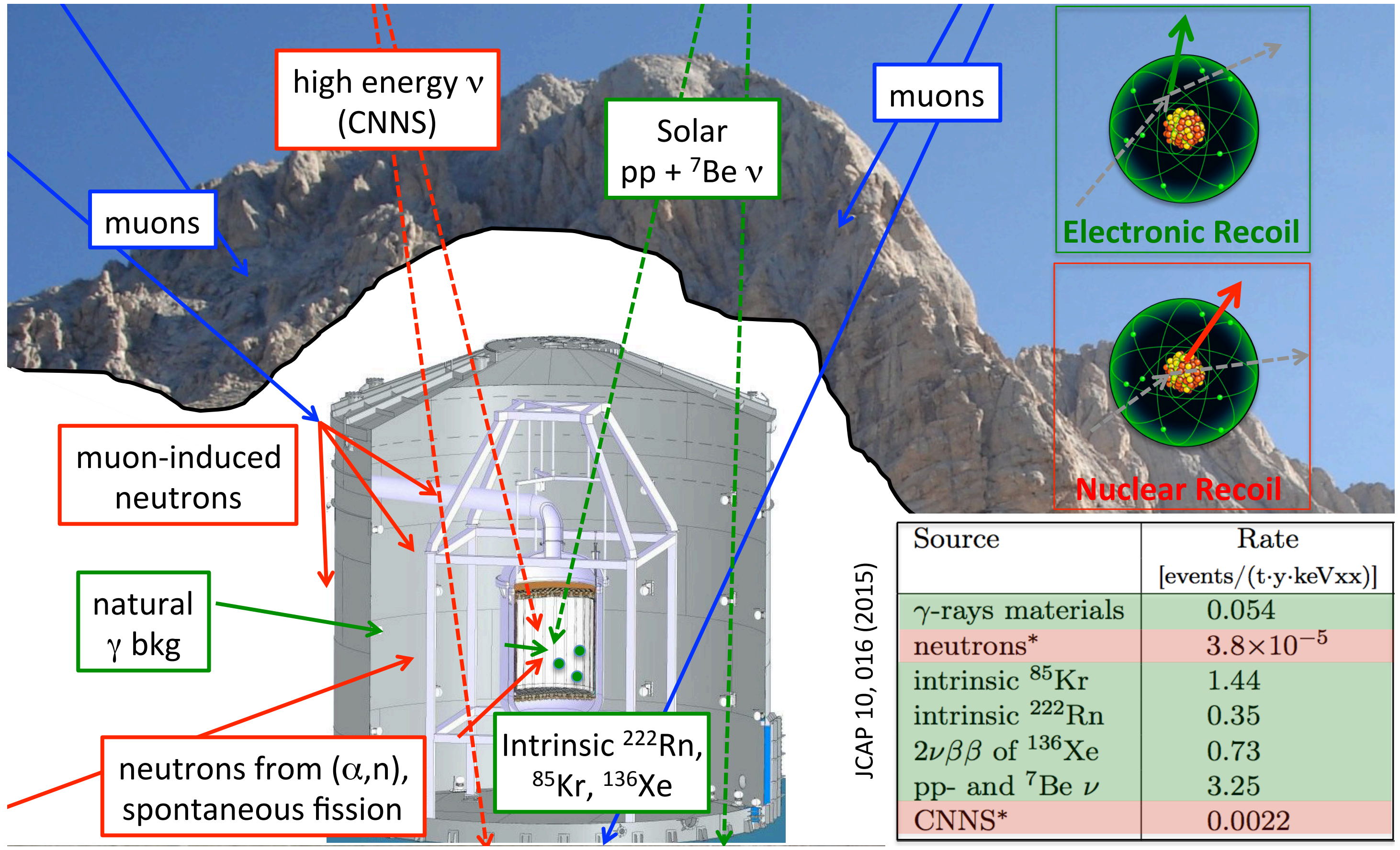
- **TPC detection technology is being pushed at its best performances**

- **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**

Backup

DARWIN

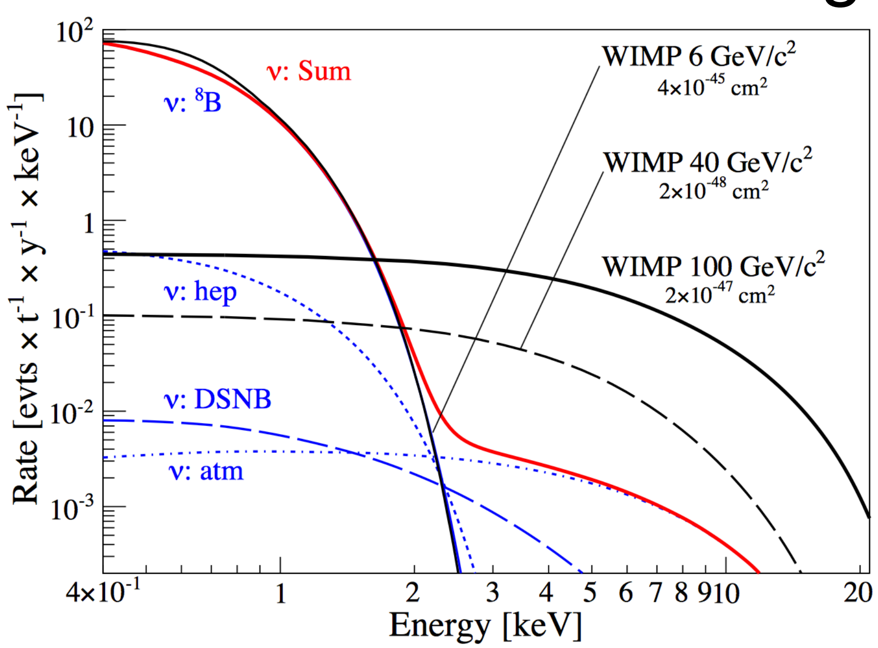
Background for DARWIN



JCAP 10, 016 (2015)

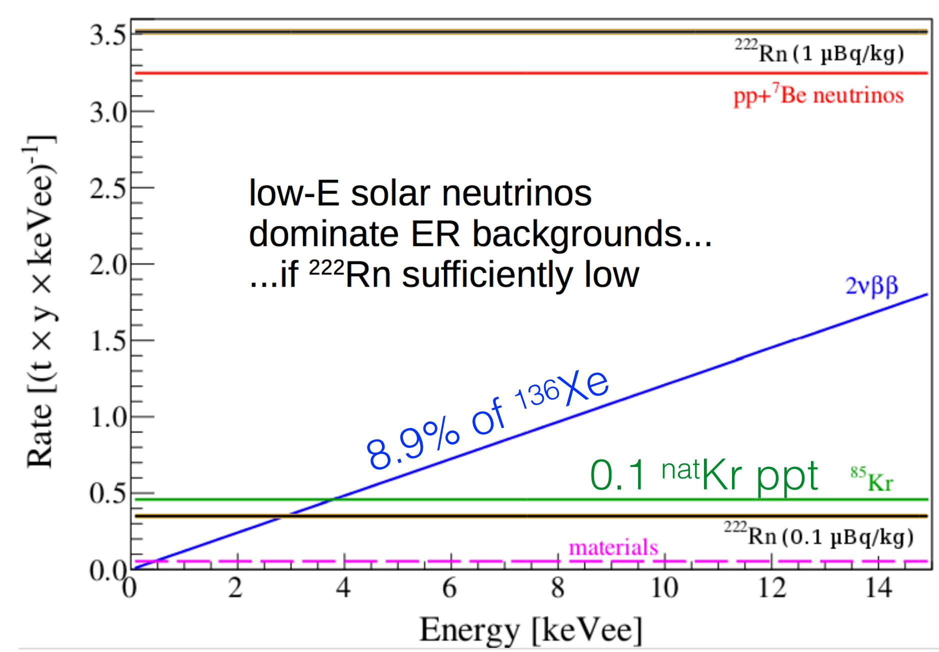
Source	Rate [events/(t·y·keVxx)]
γ-rays materials	0.054
neutrons*	3.8×10^{-5}
intrinsic ^{85}Kr	1.44
intrinsic ^{222}Rn	0.35
$2\nu\beta\beta$ of ^{136}Xe	0.73
pp- and ^{7}Be ν	3.25
CNNS*	0.0022

NR: neutrinos from coherent neutrino-nucleus scattering



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

JCAP 10, 016 (2015)



LZ

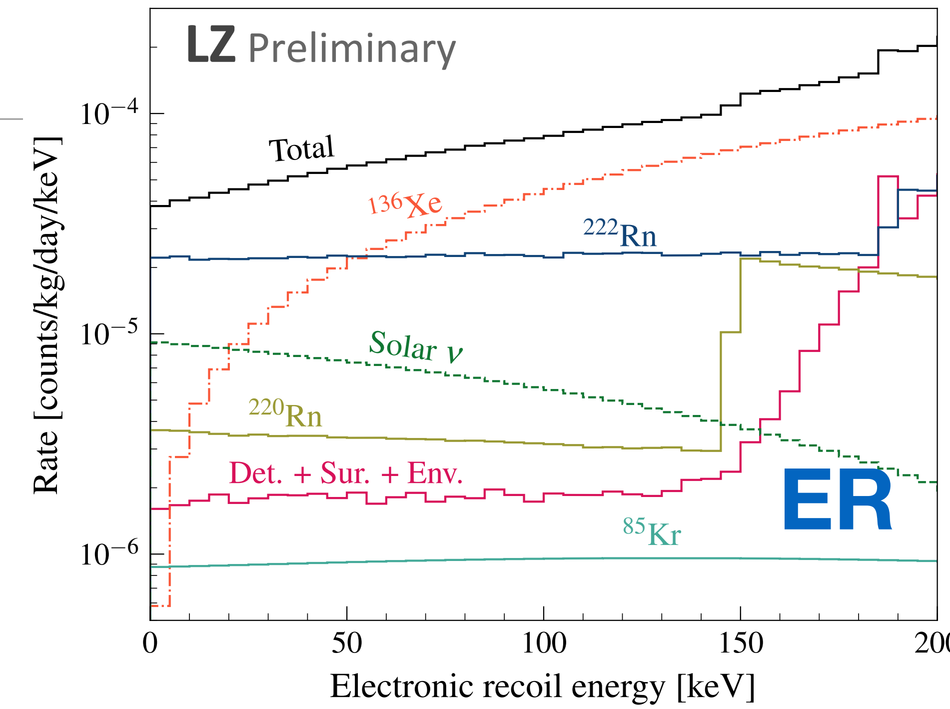
Expected backgrounds

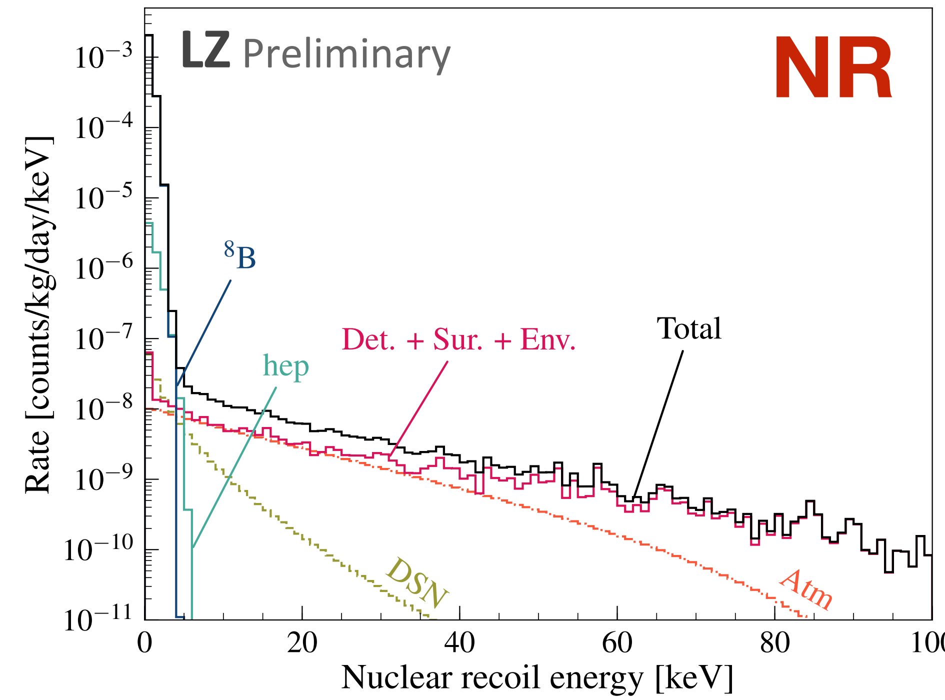
5.6 tonne fiducial volume, 1000 live-days
1.5-6.5 keV_{ee} (6-30 keV_{nr})
single scatters, anti-coincidence with vetoes

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



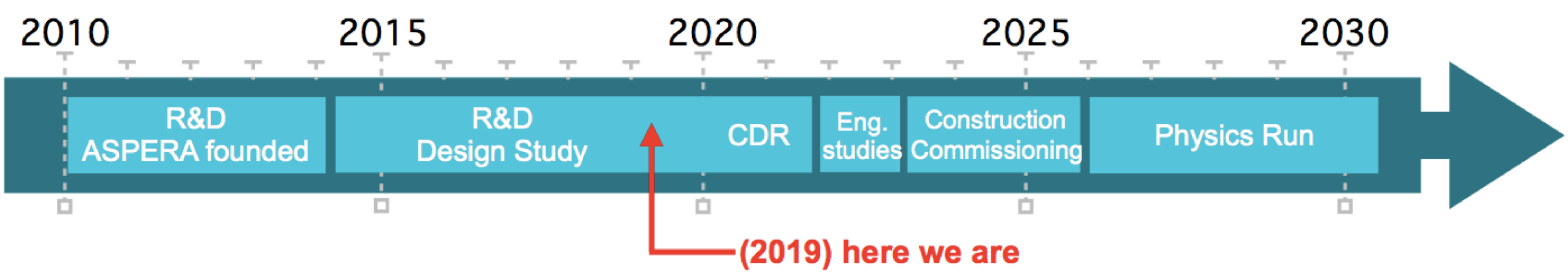


D.S. Akerib et al (LZ collaboration) 2018 arXiv:1802.06039

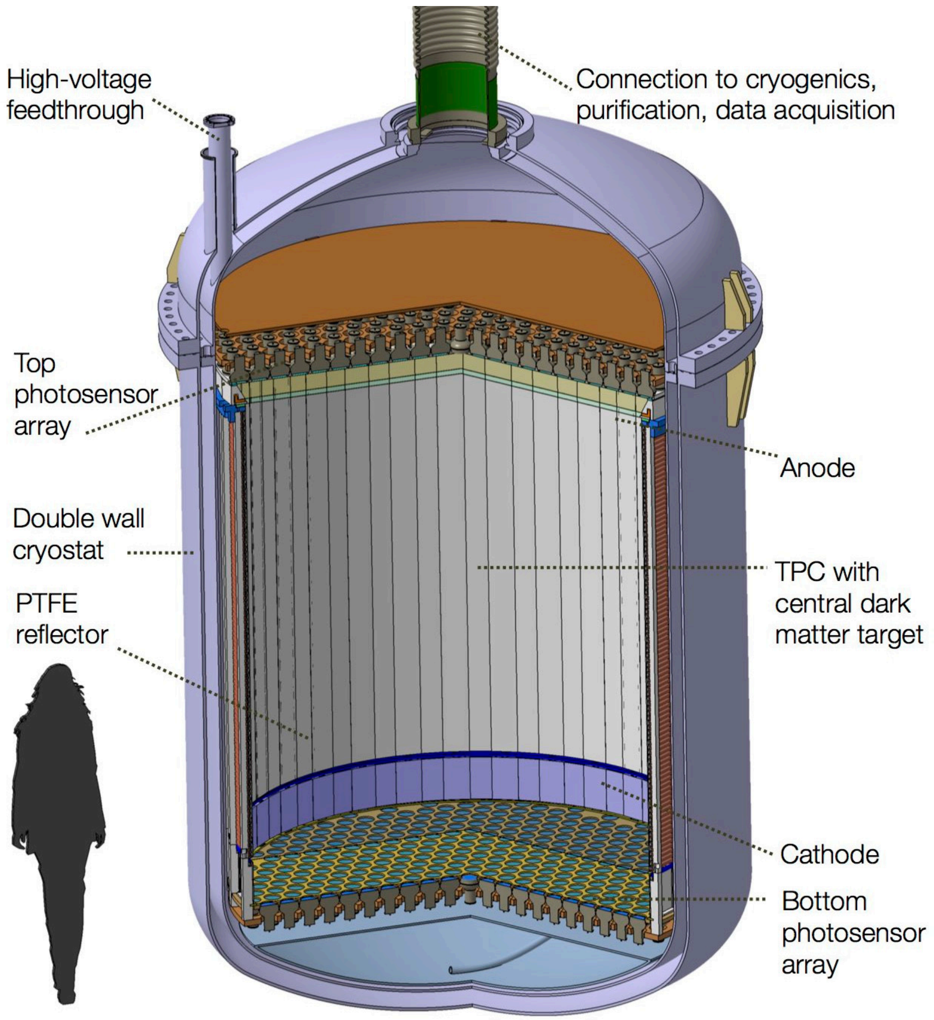
Outlook

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

www.darwin-observatory.org



Detector R&D



- Demonstrators
- Mechanical mockups
- Screening of new materials
- testing different photosensors technologies

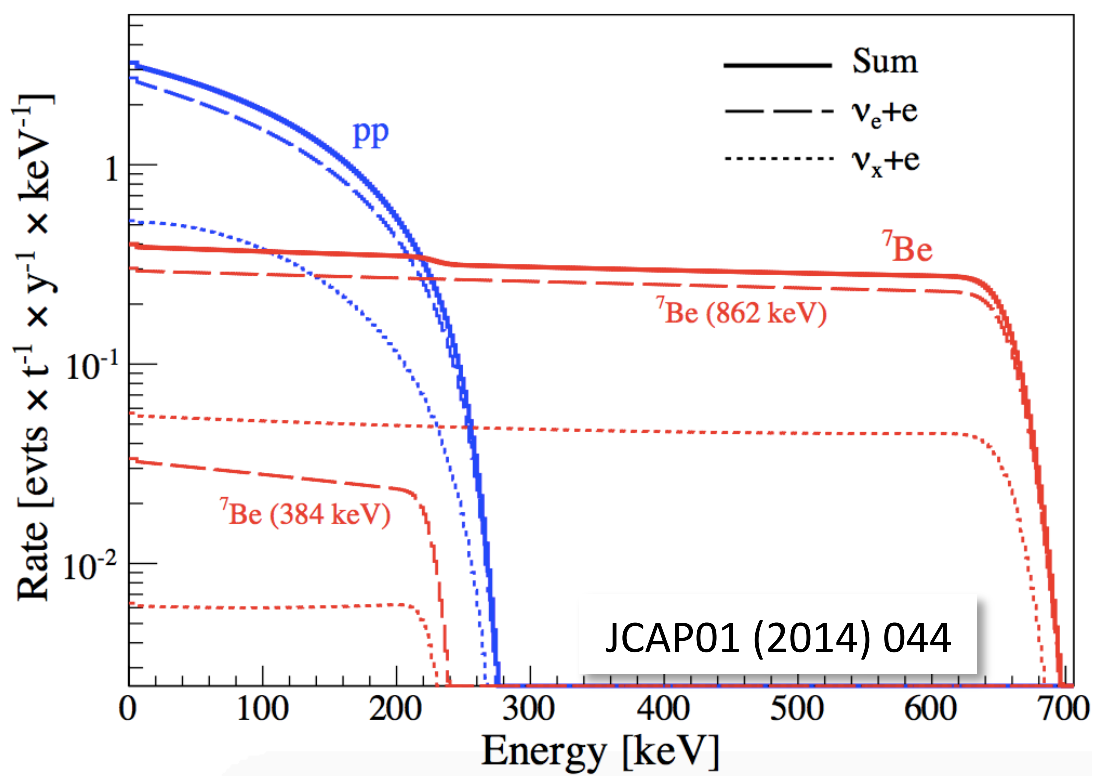
Challenges

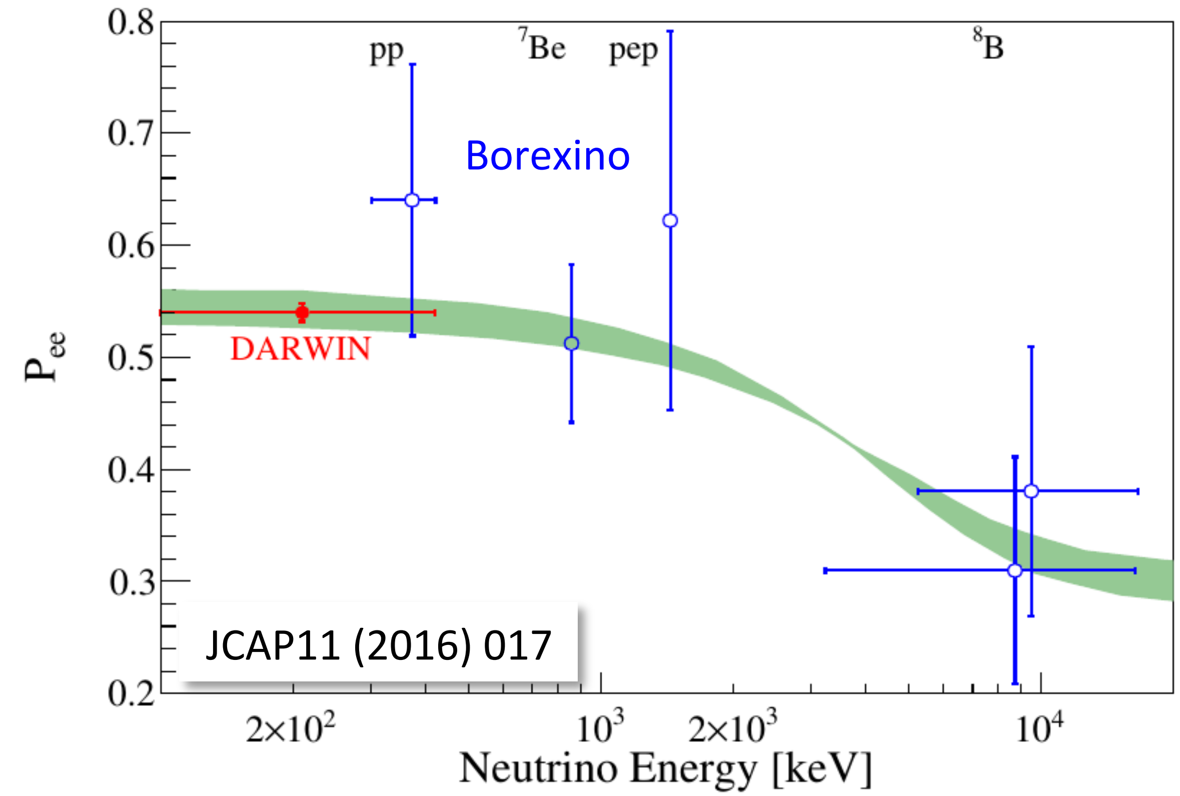
- Electron drift over 2.5 meters. HV more than -100 kV for drift field of 0.5 kV/cm
- Background: reduce ^{222}Rn (material screening, distillation) and (α,n) from PTFE
- Purification and distillation: need high speed for large quantity of LXe
- Light collection efficiency: 4pi photosensors
- Photosensors: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

Solar neutrinos

DARWIN

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