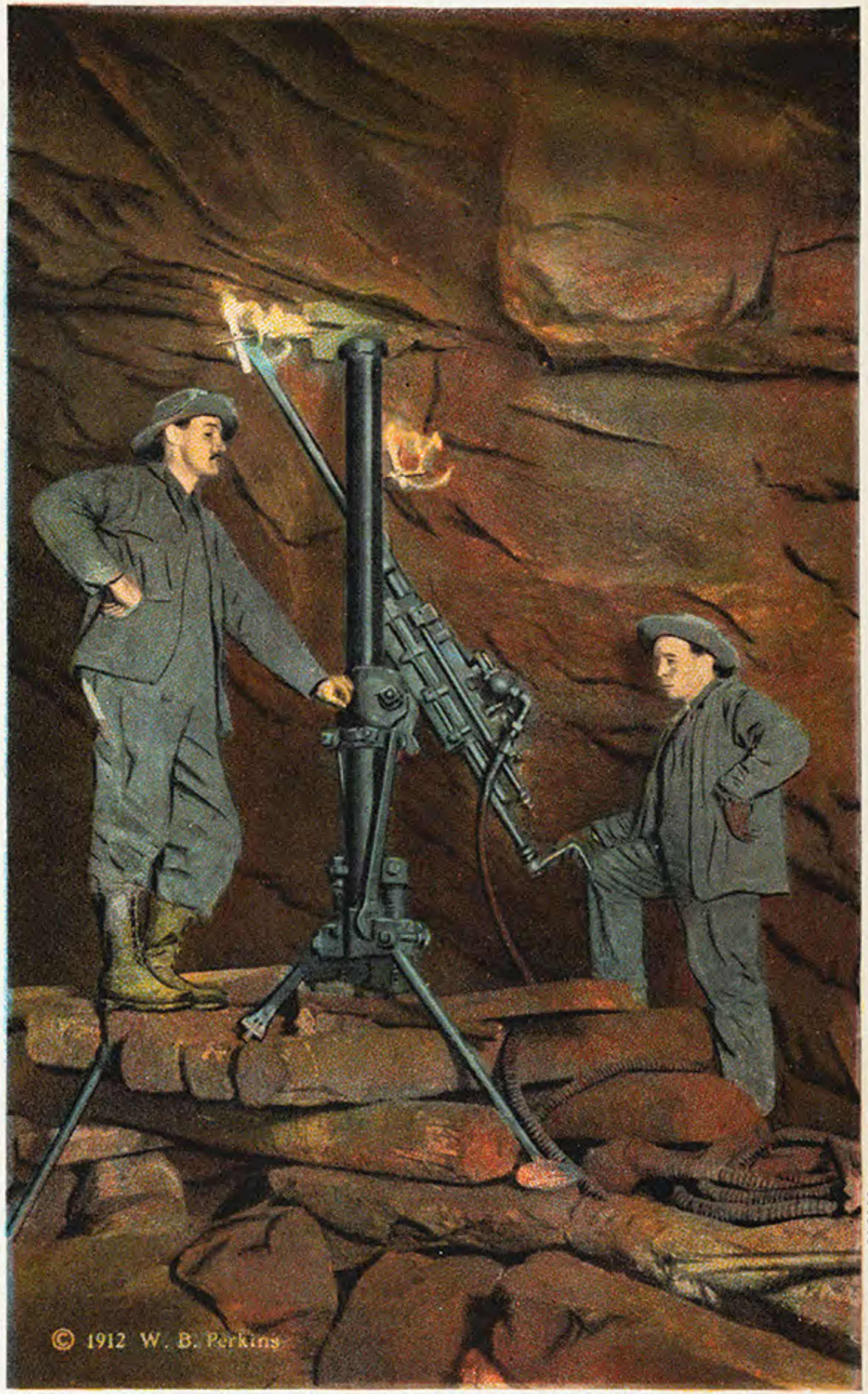


30. DRILLING WITH COMPRESSED AIR, HOMESTAKE MINE, LEAD, S. D.

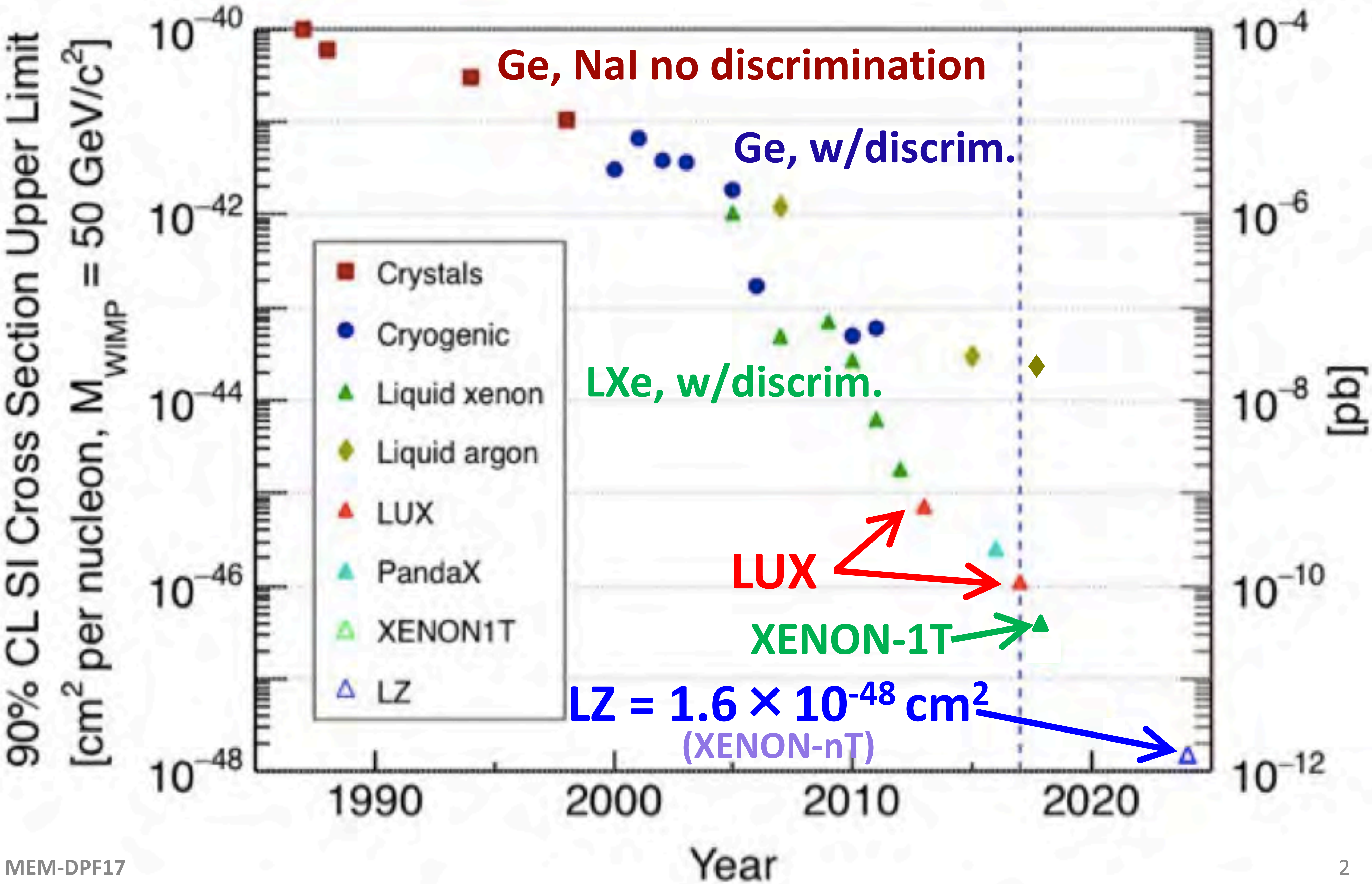
Projected WIMP sensitivity of the LUX-ZEPLIN dark matter experiment

Maria Elena Monzani
for the LZ Collaboration

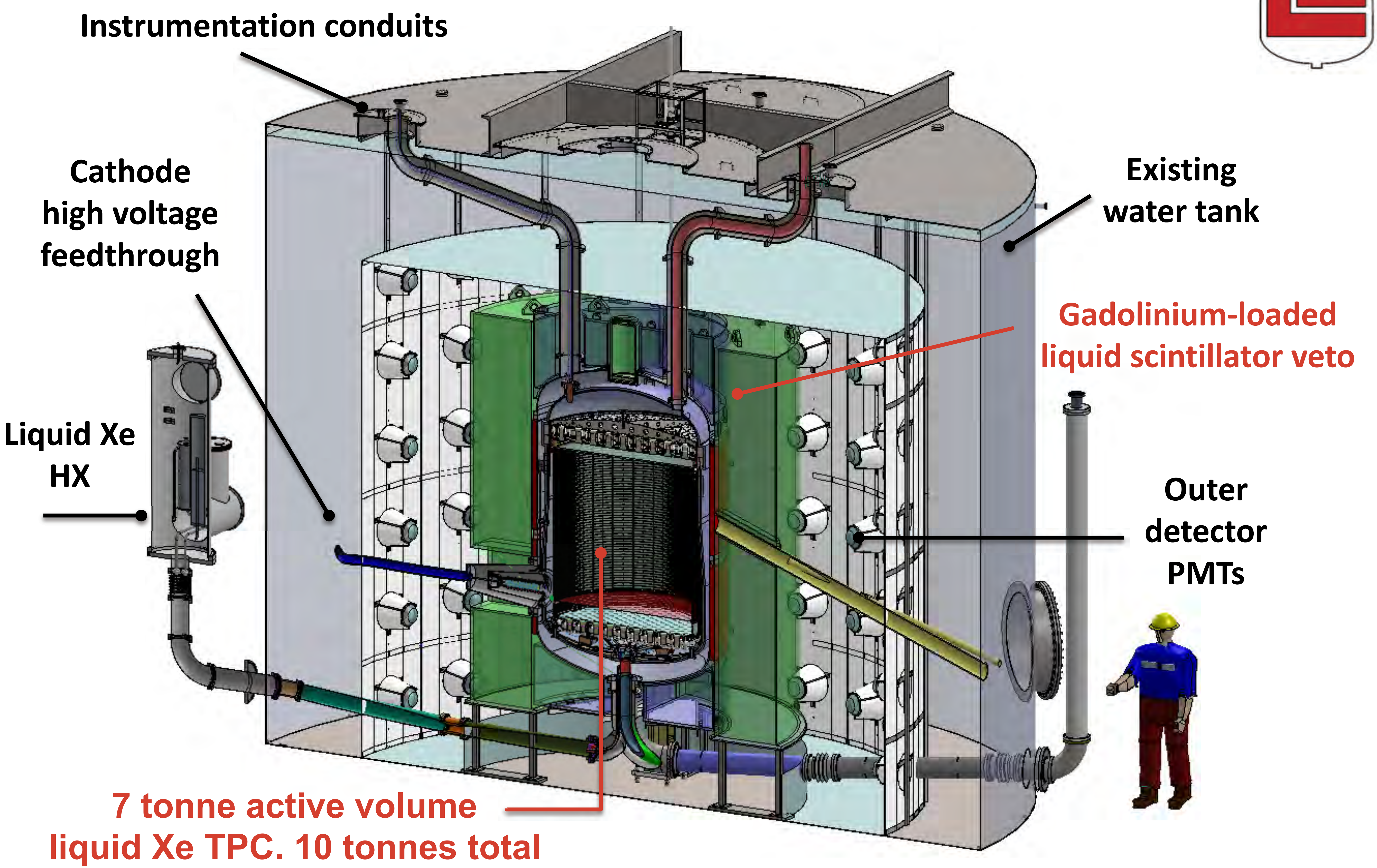
SLAC NATIONAL ACCELERATOR LABORATORY
Kavli Institute for Particle Astrophysics and Cosmology

IDM, July 24, 2018

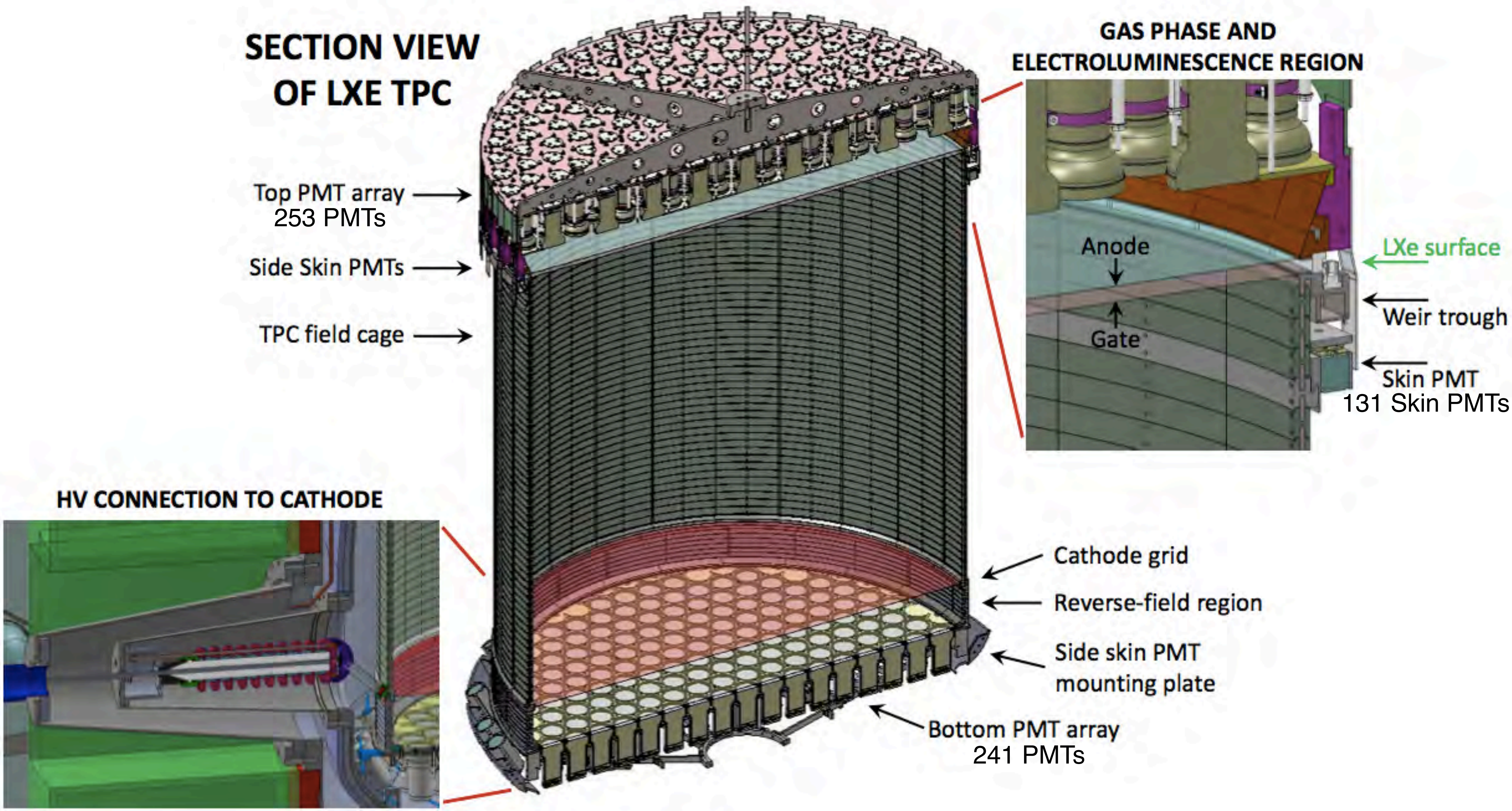
Moore's Law of Direct Detection



LZ as a Discovery Instrument

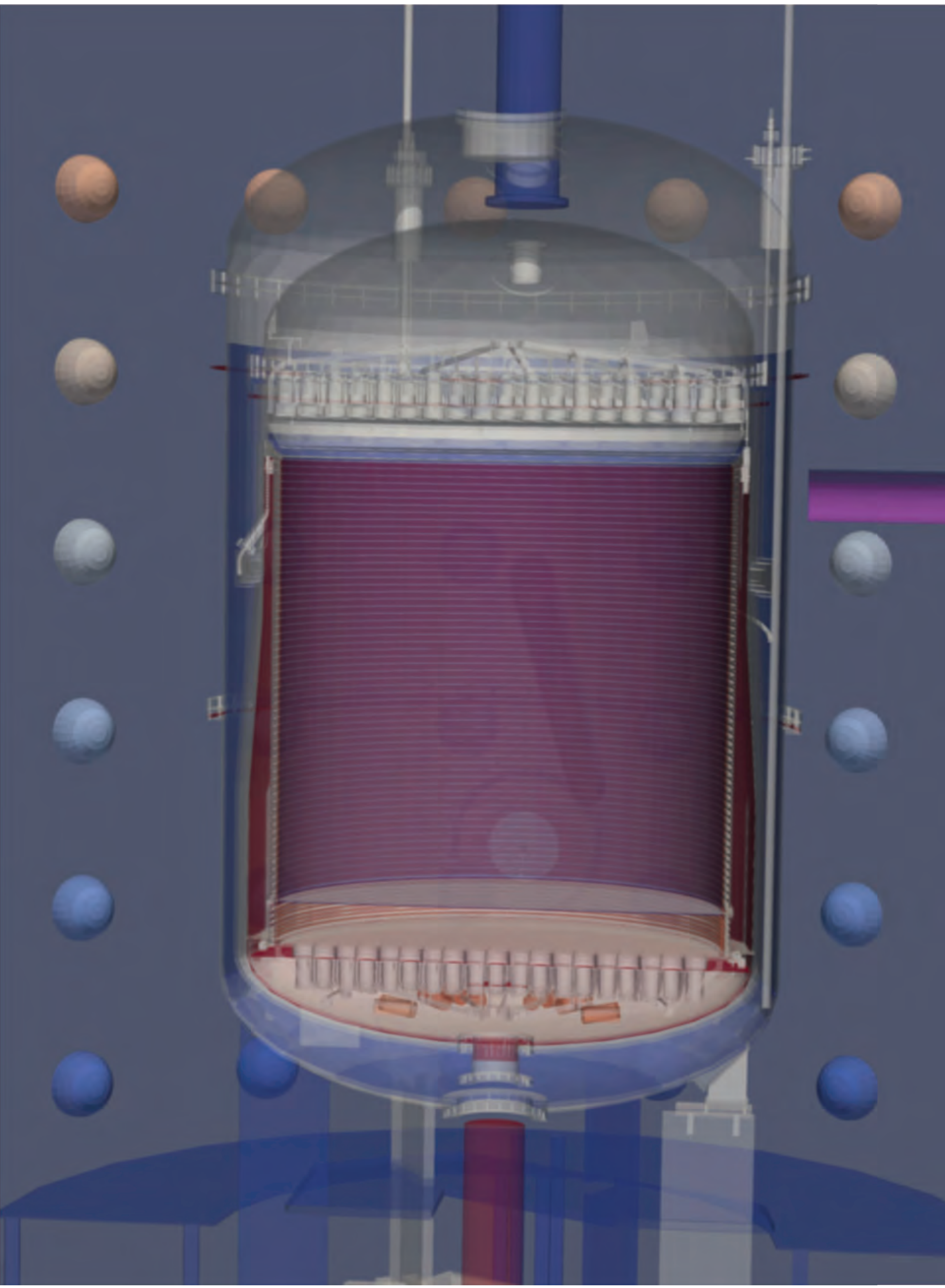


The Xenon TPC Detector

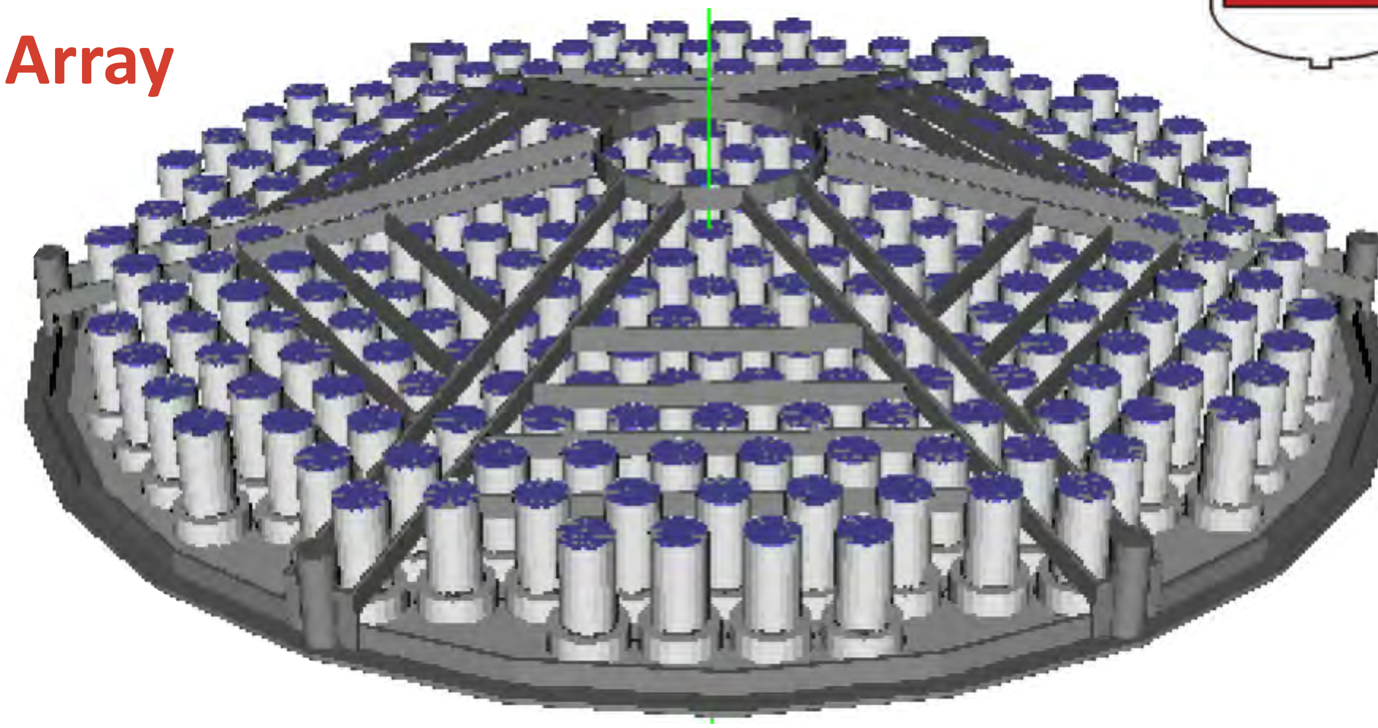


The Xenon TPC Detector... Simulated!

Inner Detector, in simulation

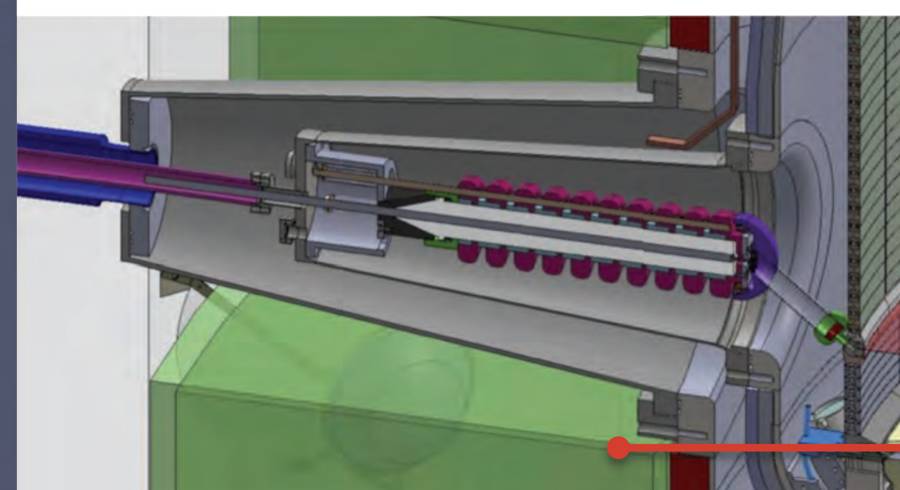


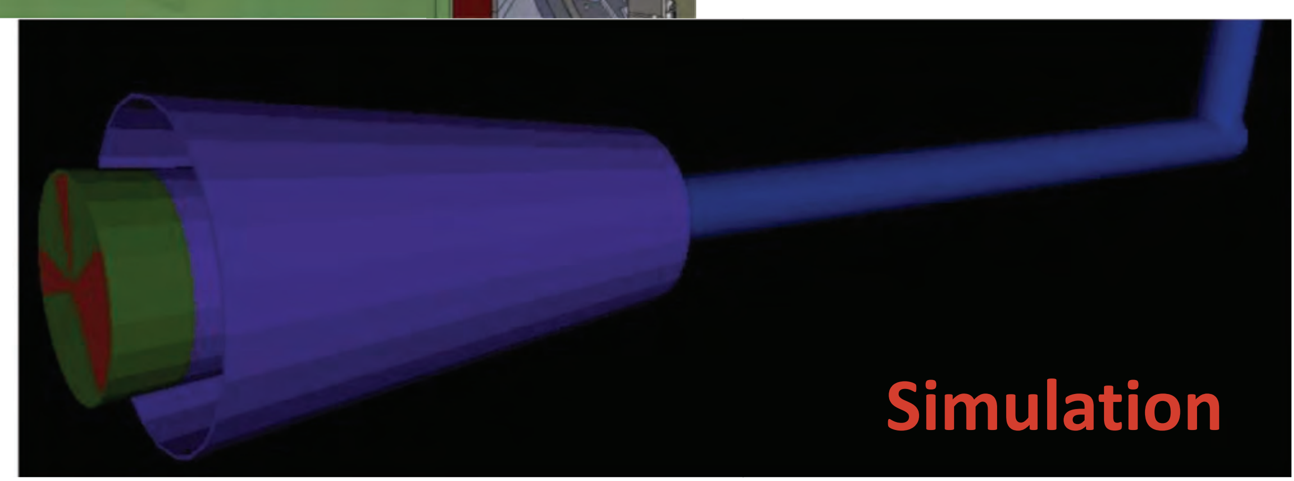
Bottom PMT Array



HV cathode feedthrough

CAD model

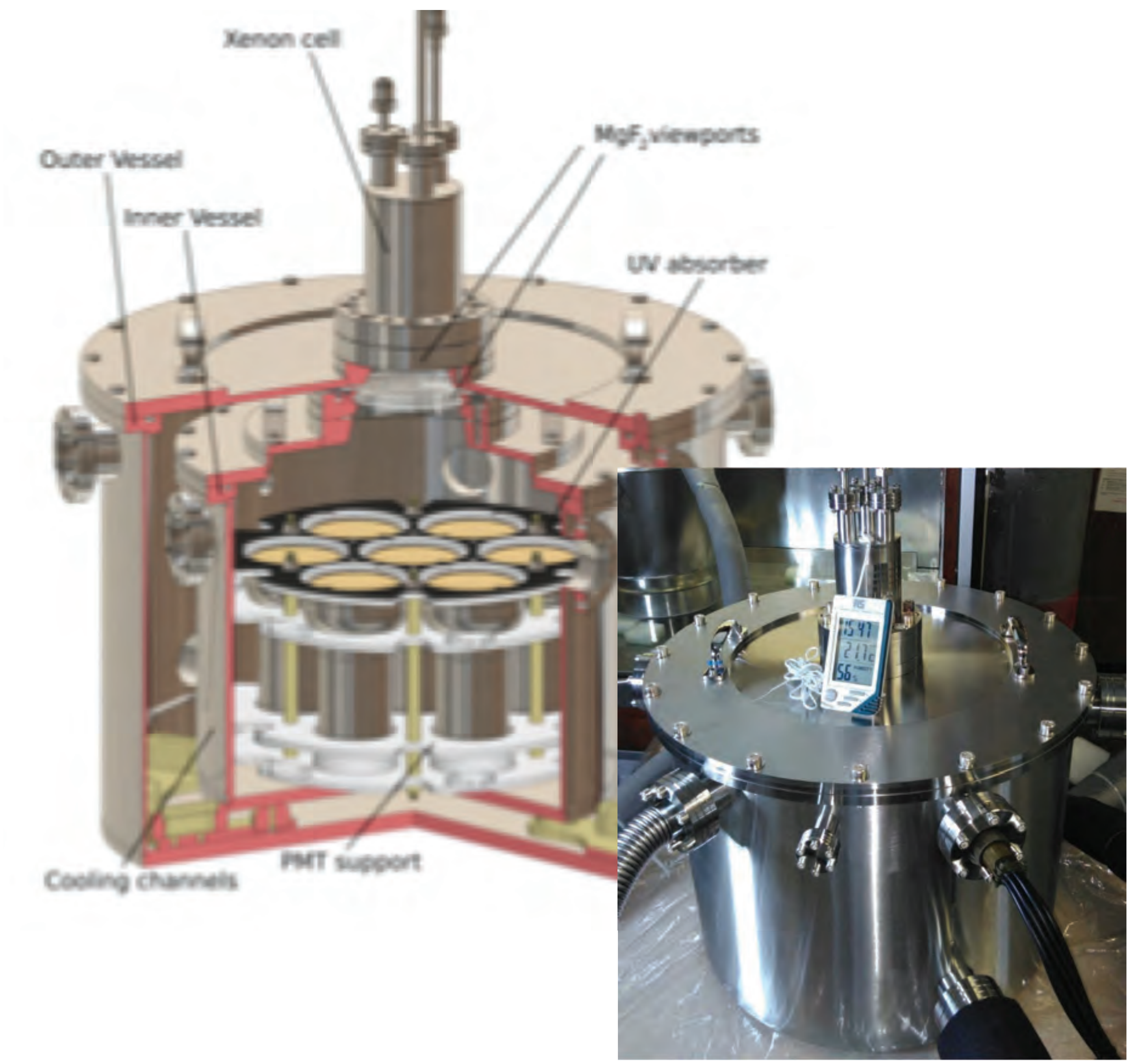




Measurement-driven detector model

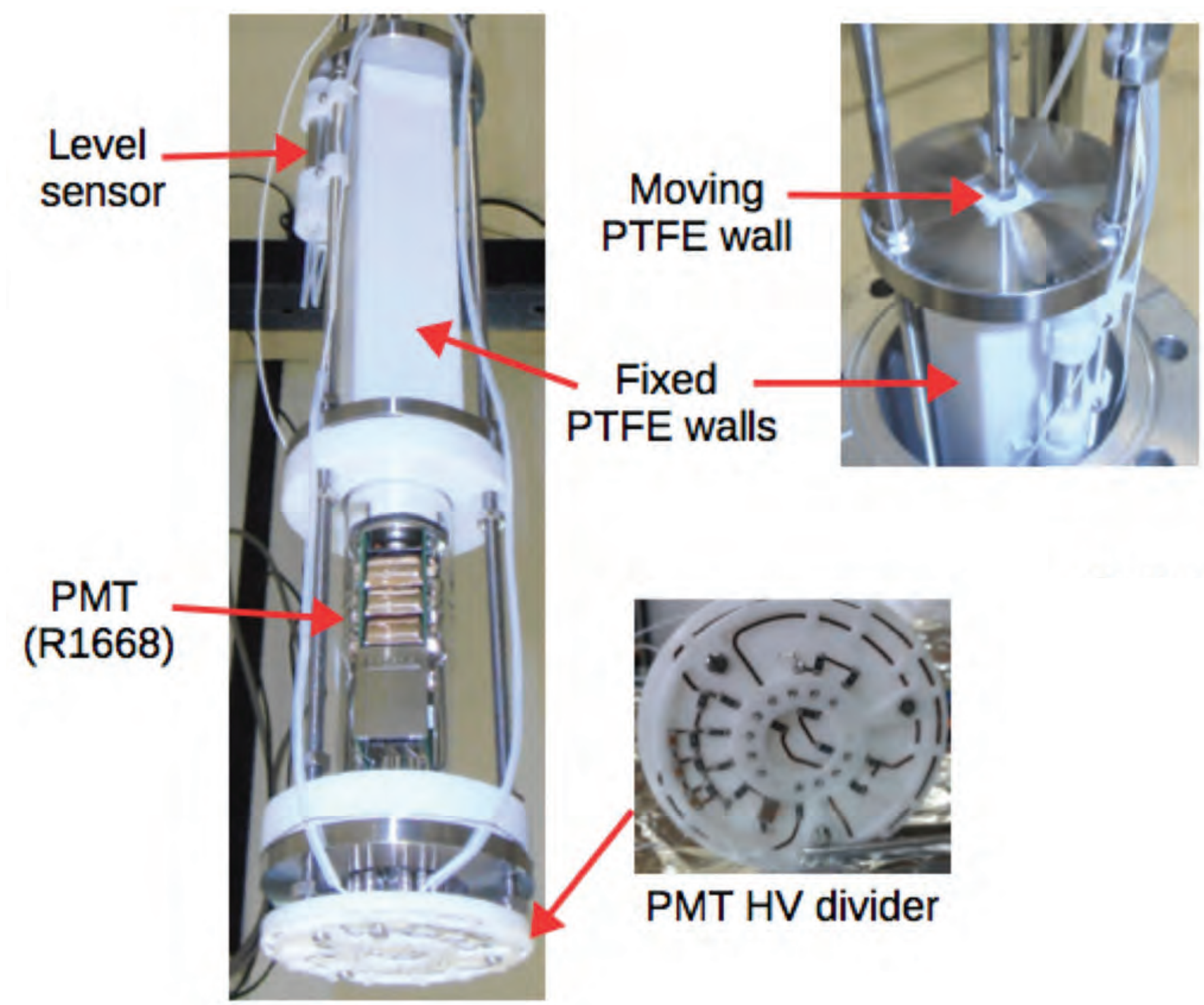
Projected TPC light collection efficiency 12%

Characterization of LZ PMTs @ Imperial College London



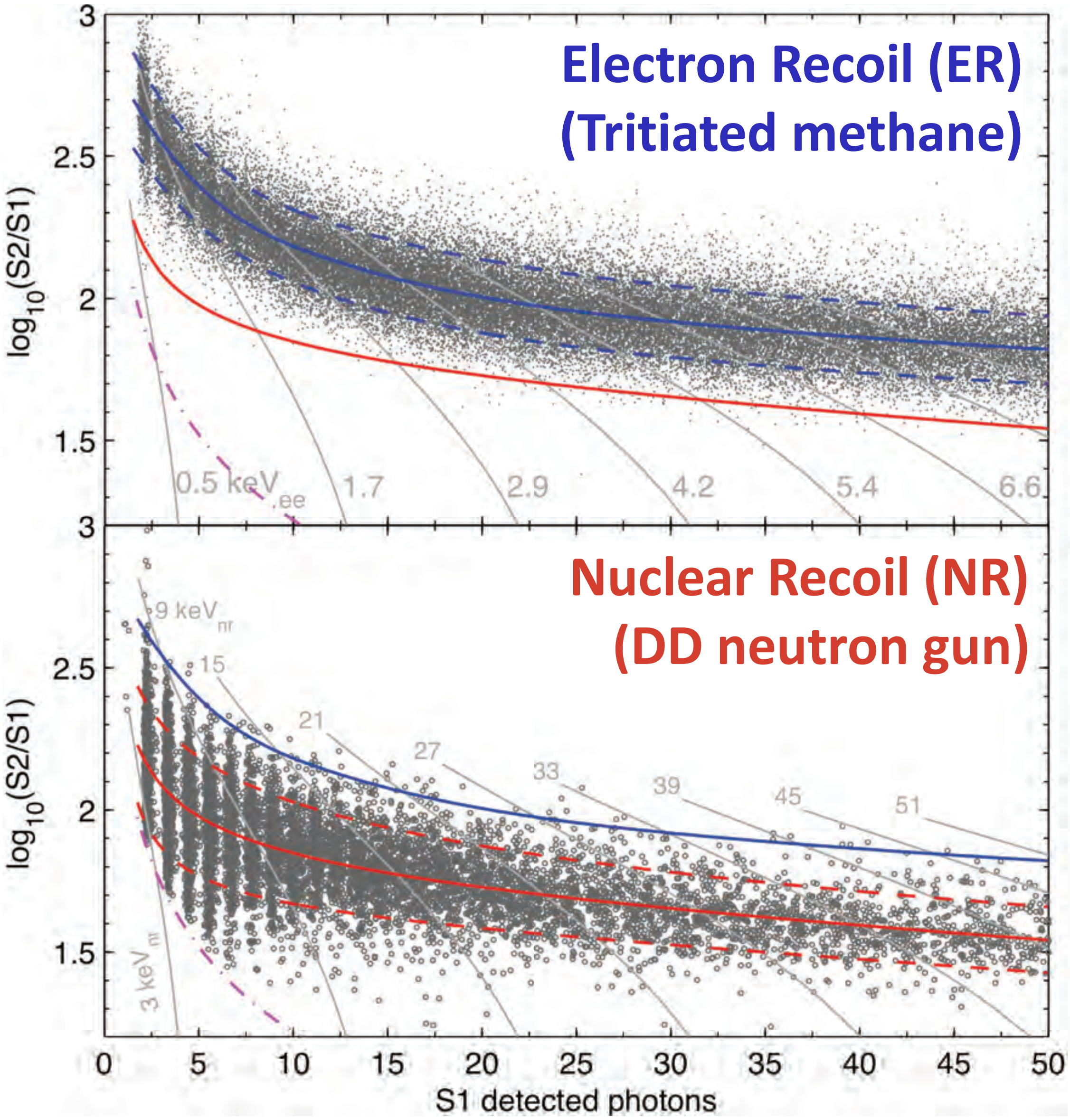
arXiv: 1801.01597

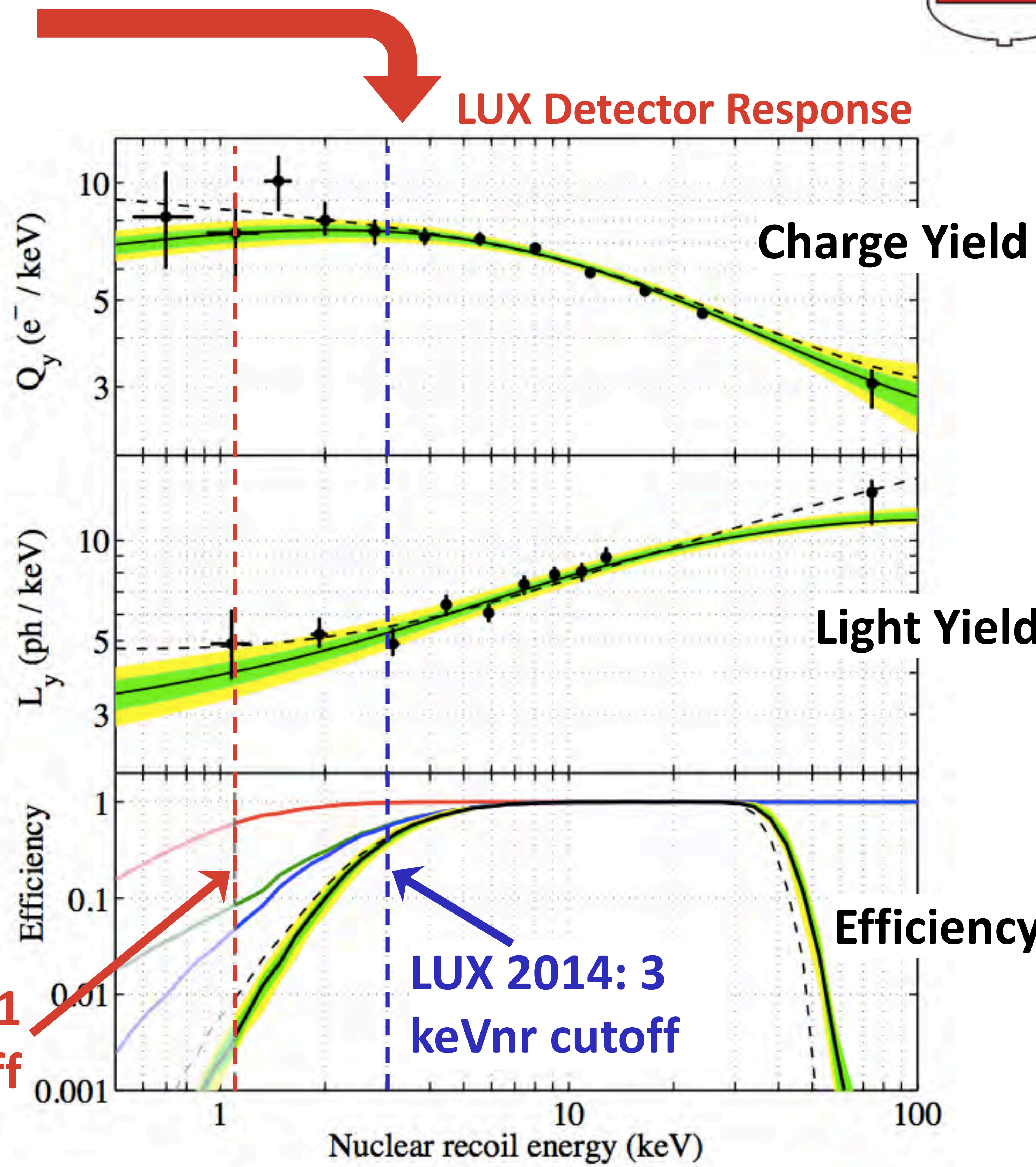
LZ Reflectivity Measurements @ LIP Coimbra



arXiv: 1612.07965

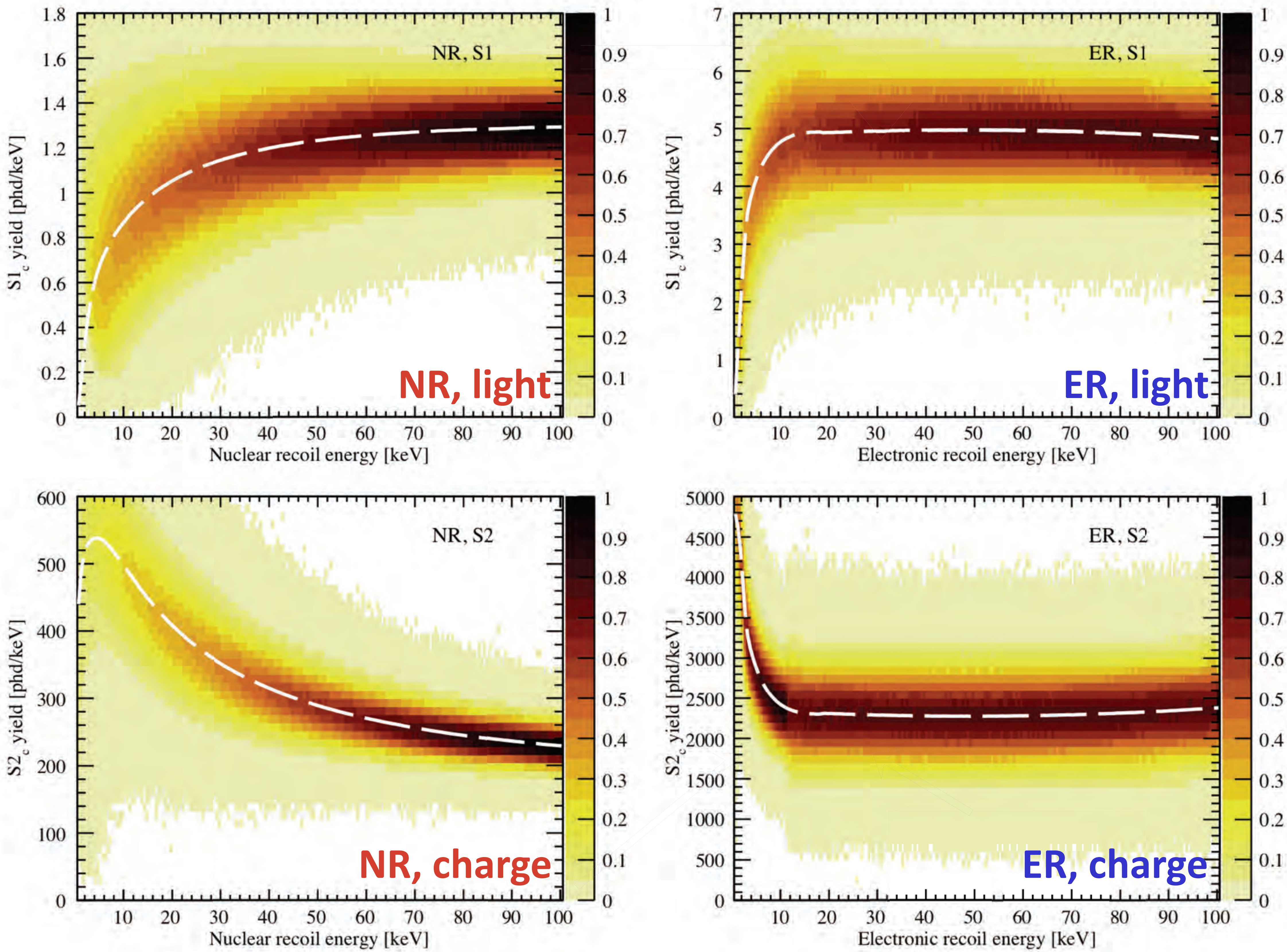
High Statistics Calibrations in LUX





arXiv: 1512.03506

LZ Detector Response



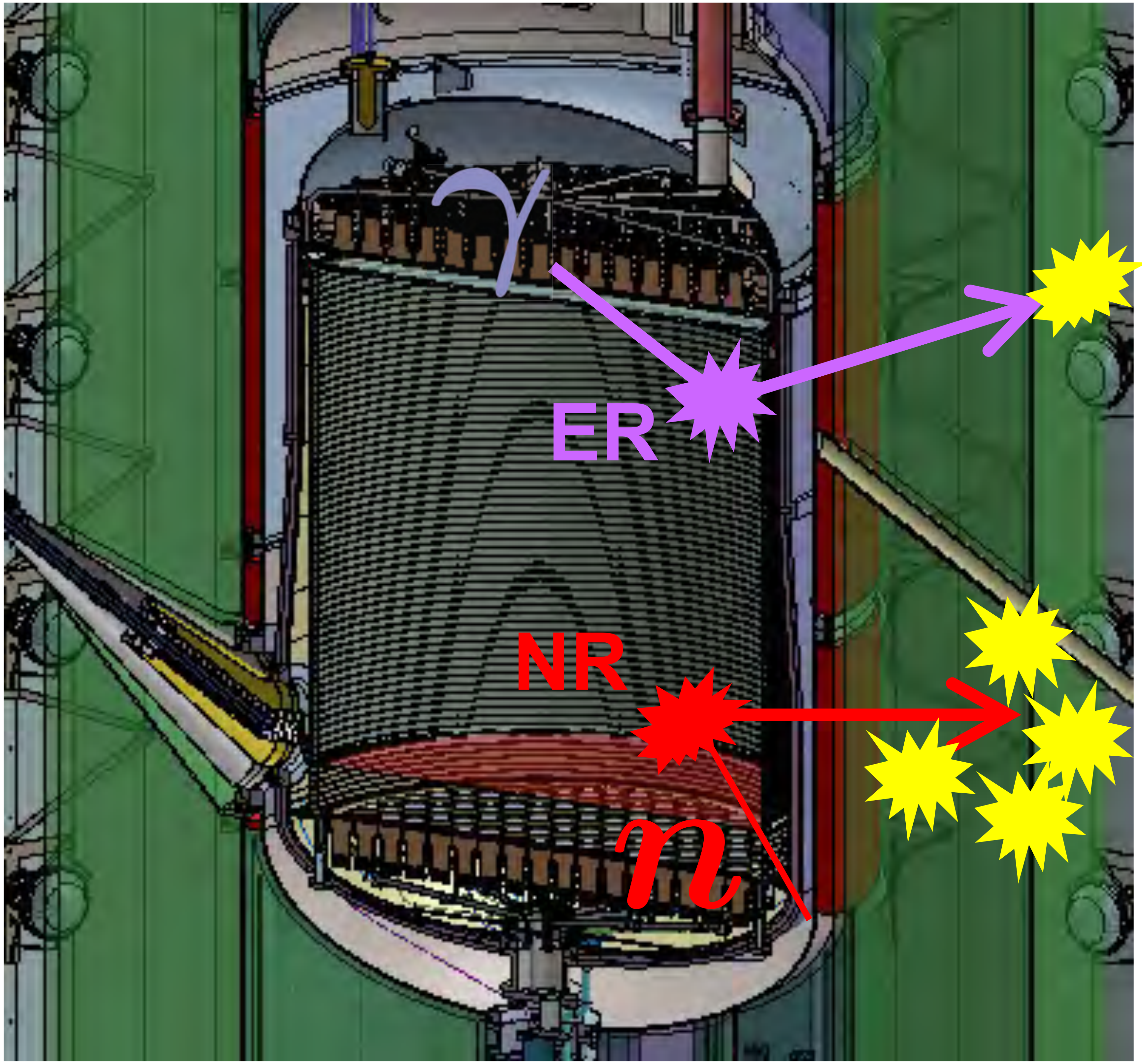
arXiv: 1802.06039

Complete Model of LZ Detector

Detector Parameter	Value
Photon Detection Efficiency (PDE)	
PDE in liquid (g_1) [phd/ph]	0.119
PDE in gas ($g_{1,\mathrm{gas}}$) [phd/ph]	0.102
Single electron size [phd]	83
Effective charge gain (g_2) [phd/e]	79
PTFE-LXe reflectivity	0.977
LXe photon absorption length [m]	100
PMT efficiency at 175 nm	0.269
Other Key Parameters	
Single phe trigger efficiency	0.95
Single phe relative width (Gaussian)	0.38
S1 coincidence level	3-fold
S2 electron extraction efficiency	0.95
Drift field [$\mathrm{V\,cm^{-1}}$]	310
Electron lifetime [μs]	850

Backgrounds – Detector Materials

Populate edges: Skin and Outer detector tag



External Backgrounds

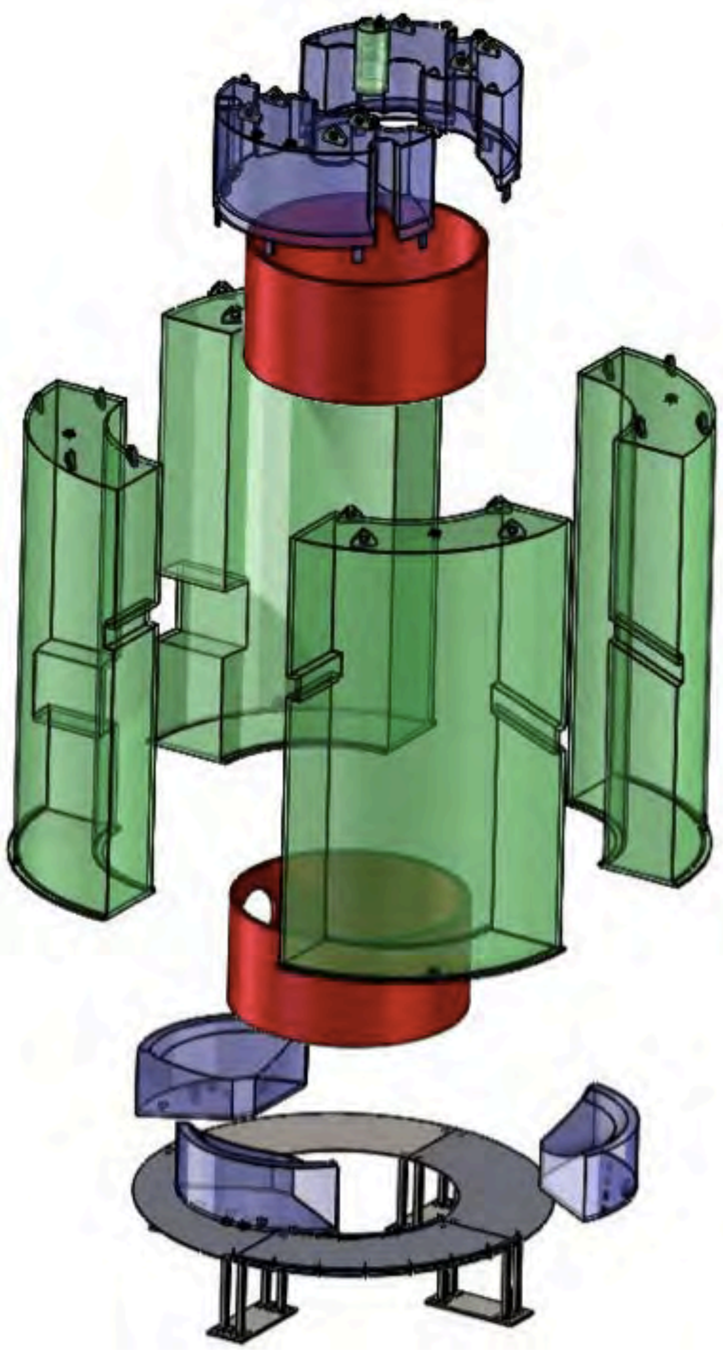
- Activity intrinsic to the detector construction materials
  - Main concerns: PMTs, PMT Bases, Cryostat, PTFE, etc.
- Comprehensive radio-assay campaign for detector materials:
  - gamma-screening, ICP-MS, NAA; ~1000 assays so far, ~600 to go
- Excellent self-shielding properties of LXe, plus active veto system to suppress (& characterize residual) backgrounds
- Expected counts in 1,000 live days in an indicative 5.6-tonne fiducial mass in [1.5-6.5] keV_{ee} (ER) and [6-30] keV (NR):

Background Source	Mass (kg)	$^{238}U_e$	$^{238}U_l$	$^{232}Th_e$	$^{232}Th_l$	^{60}Co	^{40}K	n/yr	ER (cts)	NR (cts)
		mBq/kg								
Detector Components										
PMT systems	308	31.2	5.20	2.32	2.29	1.46	18.6	248	2.82	0.027
TPC systems	373	3.28	1.01	0.84	0.76	2.58	7.80	79.9	4.33	0.022
Cryostat	2778	2.88	0.63	0.48	0.51	0.31	2.62	323	1.27	0.018
Outer detector (OD)	22950	6.13	4.74	3.78	3.71	0.33	13.8	8061	0.62	0.001
All else	358	3.61	1.25	0.55	0.65	1.31	2.64	39.1	0.11	0.003
(Before S2/S1 discrimination)								subtotal	**9**	**0.07**

Active Veto System

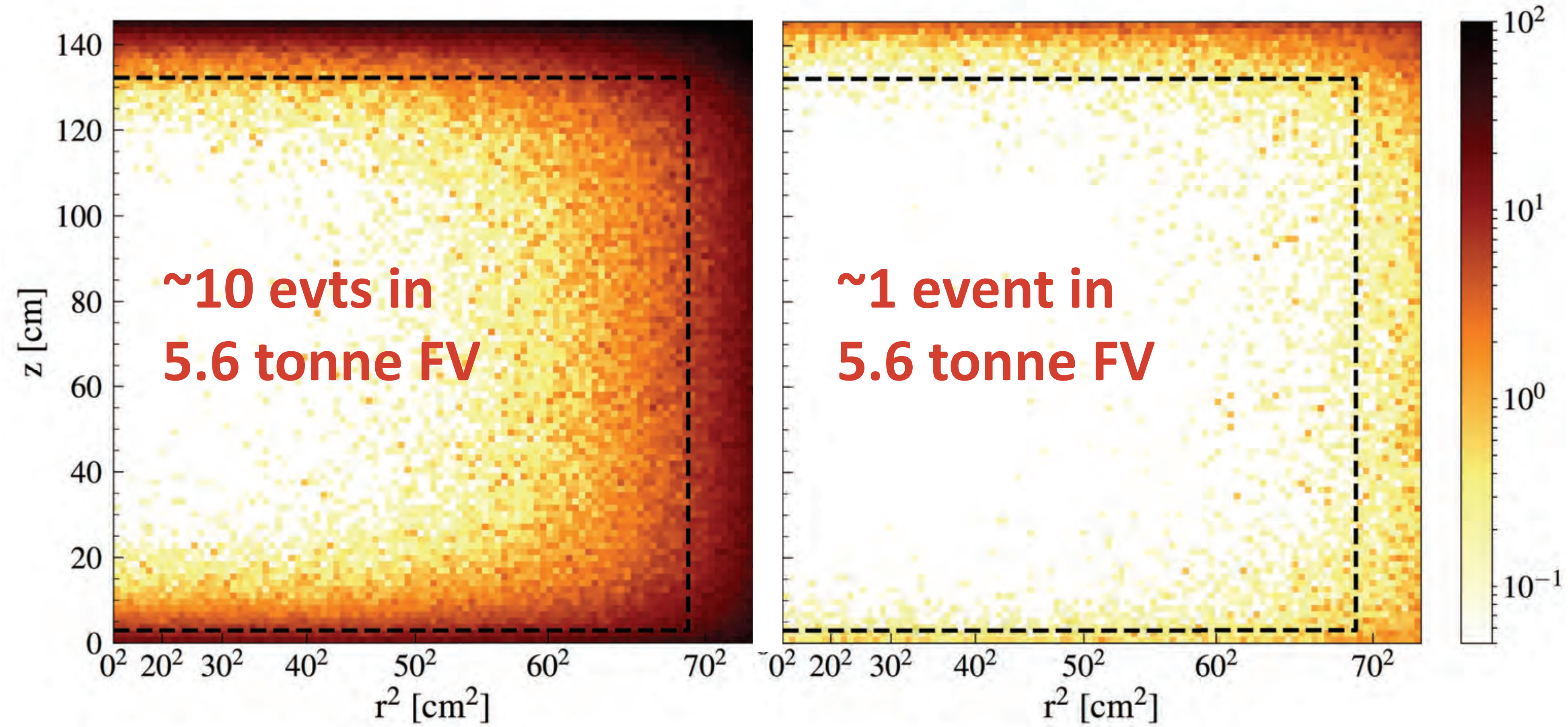
- 0.61 m thick Gd-loaded scintillator
- instrumented Xenon "skin"
- we can tag neutrons and gammas

} In-situ monitoring of residual backgrounds

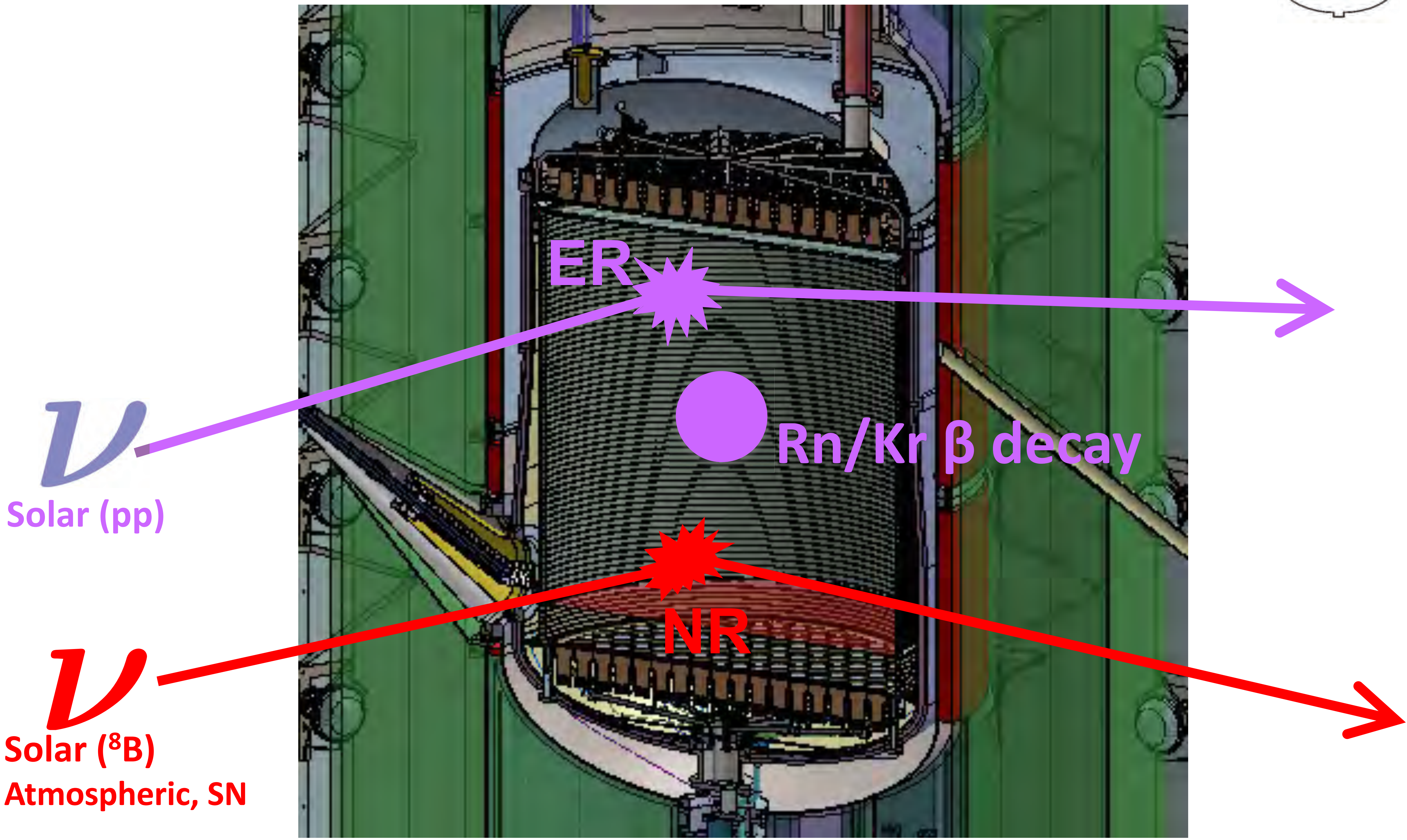


NR: Before Veto

NR: After Veto



Backgrounds – Uniform through volume



Neutrino Backgrounds

- **Elastic ν-e interactions (signal is an electron recoil):**
  - Solar neutrinos: pp, ^{7}Be, ^{13}N
  - Neutrinoless ββ decay of ^{136}Xe
- **Coherent elastic ν-A interactions (irreducible background):**
  - Solar Neutrinos: ^{8}B and hep (below nominal threshold)
  - Atmospheric and diffuse supernova neutrinos
- **Expected counts in 1,000 live days in an indicative 5.6-tonne fiducial mass in [1.5-6.5] keV$_{ee}$ (ER) and [6-30] keV (NR):**

Background Source	Mass (kg)	$^{238}U_e$	$^{238}U_l$	$^{232}Th_e$	$^{232}Th_l$	^{60}Co	^{40}K	n/yr	ER (cts)	NR (cts)
		mBq/kg								
Physics										
$^{136}Xe\ 2\nu\beta\beta$									67	-
Solar neutrinos: pp+^{7}Be+^{13}N									255	-
Diffuse supernova neutrinos (DSN)									-	0.05
Atmospheric neutrinos (Atm)									-	0.46
			(Before S2/S1 discrimination)					subtotal	**322**	**0.51**

Uniform ER Internal Backgrounds

- **Kr, Ar requirement: 0.015 ppt (g/g) ^{nat}Kr, 0.45 ppb (g/g) ^{nat}Ar**
  - Demonstrated 2-pass ^{nat}Kr reduction at 10^9 (10^7 required)
  - Kr removal process also efficient at eliminating Ar
- **Radon estimate: 1.81 μBq/kg ^{222}Rn, 0.09 μBq/kg ^{220}Rn**
  - Extensive Rn emanation assay campaign in progress
  - 1.53 μBq/kg from Rn emanation, 0.28 μBq/kg from dust
- **Surface Contamination: Radon Daughters (^{210}Pb) and dust**
  - ^{210}Pb, ^{210}Bi plate-out: less than 0.5 mBq/m^2 on the TPC walls
  - Generic dust contamination < 500 ng/cm^2 on all wetted surfaces

Uniform ER Internal Backgrounds

- **Expected counts in 1,000 live days in an indicative 5.6-tonne fiducial mass in [1.5-6.5] keV$_{ee}$ (ER) and [6-30] keV (NR):**

Background Source	Mass (kg)	$^{238}U_e$	$^{238}U_l$	$^{232}Th_e$	$^{232}Th_l$	^{60}Co	^{40}K	n/yr	ER (cts)	NR (cts)
		mBq/kg								
Surface Contamination										
Dust (intrinsic activity, 500 ng/cm^2)									0.2	0.05
Plate-out (PTFE panels, 50 nBq/cm^2)									-	0.05
^{210}Bi mobility (0.1 μBq/kg LXe)									40.0	-
Ion misreconstruction (50 nBq/cm^2)									-	0.16
^{210}Pb (in bulk PTFE, 10 mBq/kg PTFE)									-	0.12
(Before S2/S1 discrimination)								**subtotal**	**40**	**0.39**
Xenon contaminants										
^{222}Rn (1.81 μBq/kg)									681	-
^{220}Rn (0.09 μBq/kg)									111	-
^{nat}Kr (0.015 ppt g/g)									24.5	-
^{nat}Ar (0.45 ppb g/g)									2.5	-
(Before S2/S1 discrimination)								**subtotal**	**819**	**0**

Counts/1000 days: WIMP-search ROI

Nominal: 5.6 ton fiducial, 1000 live-days

~1.5 - 6.5 keV, single scatters, no coincident veto

Background Source	ERs	NRs
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 (after 99.5% ER discrimination, 50% NR efficiency)	**5.97**	**0.52**

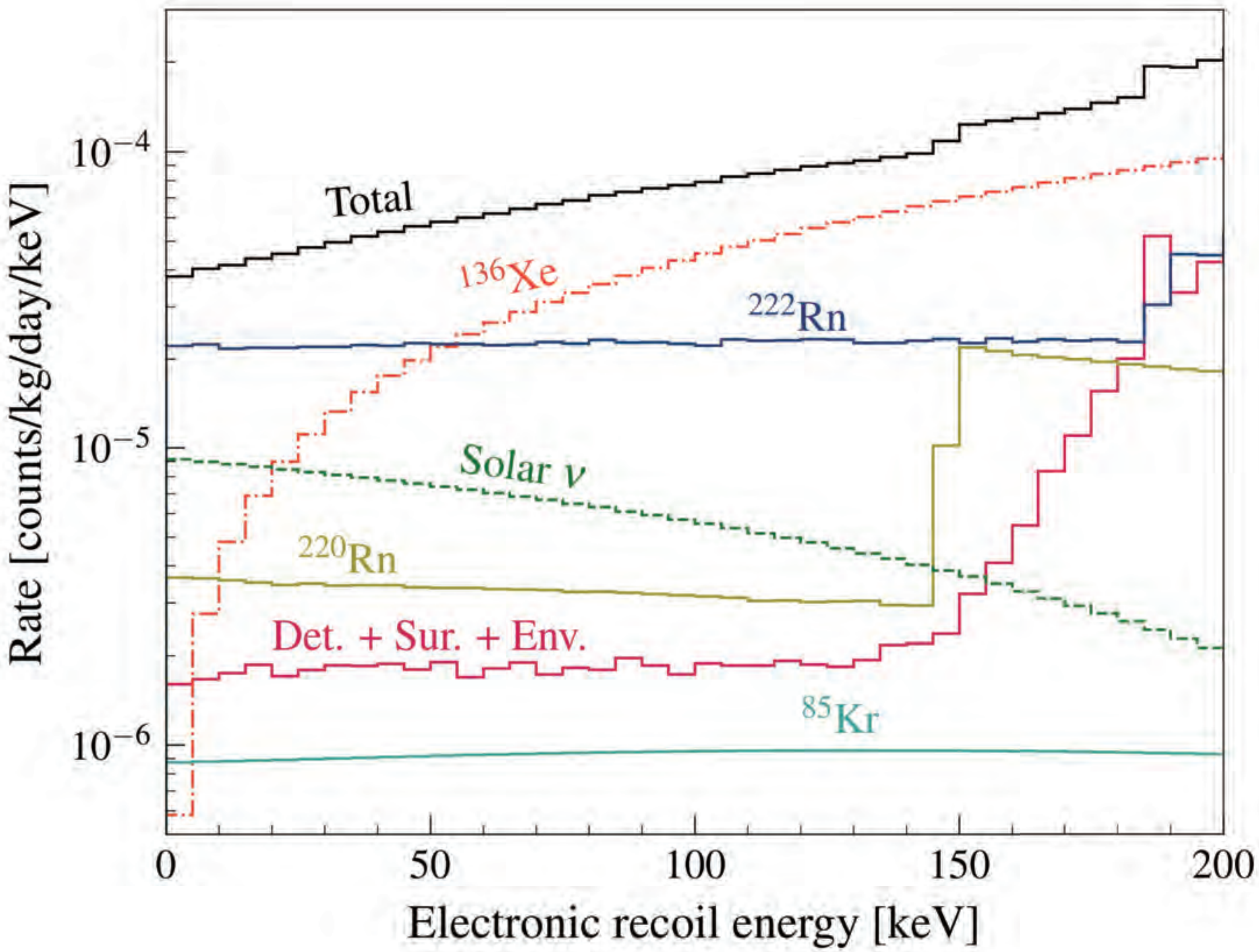
* not including ^{8}B and hep

Residual background spectra, nominal FV

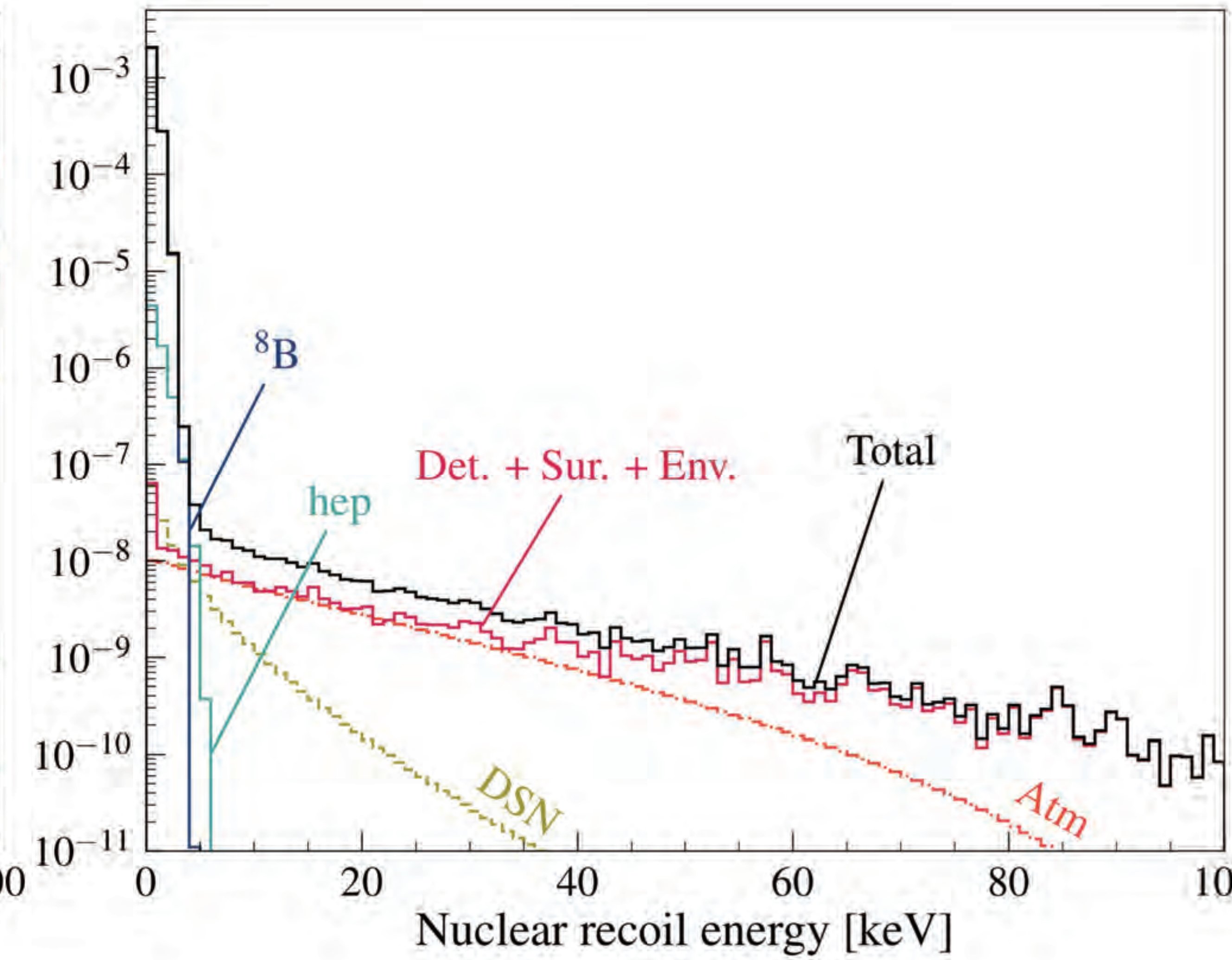
Nominal: 5.6 ton fiducial, 1000 live-days

Single scatters, no coincident veto, before ER/NR discrimination

Electron Recoils



Nuclear Recoils



Input to PLR Analysis

Putting it all together: LZ Sensitivity Estimate

LZ Sensitivity Paper available on arXiv: 1802.06039

Projected background spectra

WIMP spectra

↓

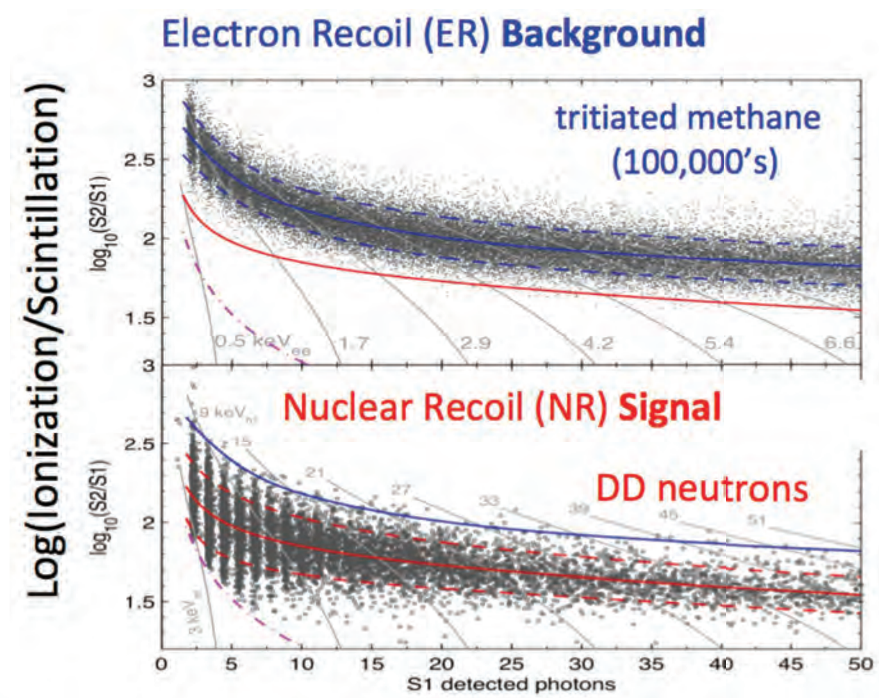
Based on measurements of materials & components procured for LZ → LZ detector response + NEST ← NEST models charge + light production in LXe: anchored to LUX + world data

↓

PDFs: (S1, S2)

↓

Profile likelihood ratio (PLR)



$$q_\sigma = -2\ln\lambda = -2\ln\left(\frac{L(\sigma,\hat{\hat{\nu}})}{L(\hat{\sigma},\hat{\nu})}\right)$$

$$L(\sigma,\boldsymbol{\nu}|\mathcal{D}_{\rm obs}) = {\rm Pois}(n|\mu) \times \prod_{i=1}^{n}\frac{1}{\mu}\left[n_s(\sigma)f_s(\boldsymbol{x}_i|m_\chi) + \sum_{b=1}^{N_{\rm bkg}} n_b f_b(\boldsymbol{x}_i)\right] \times \prod_{k=1}^{N_{\rm bkg}} \mathcal{N}(n_k|\mu_k,\sigma_k)$$

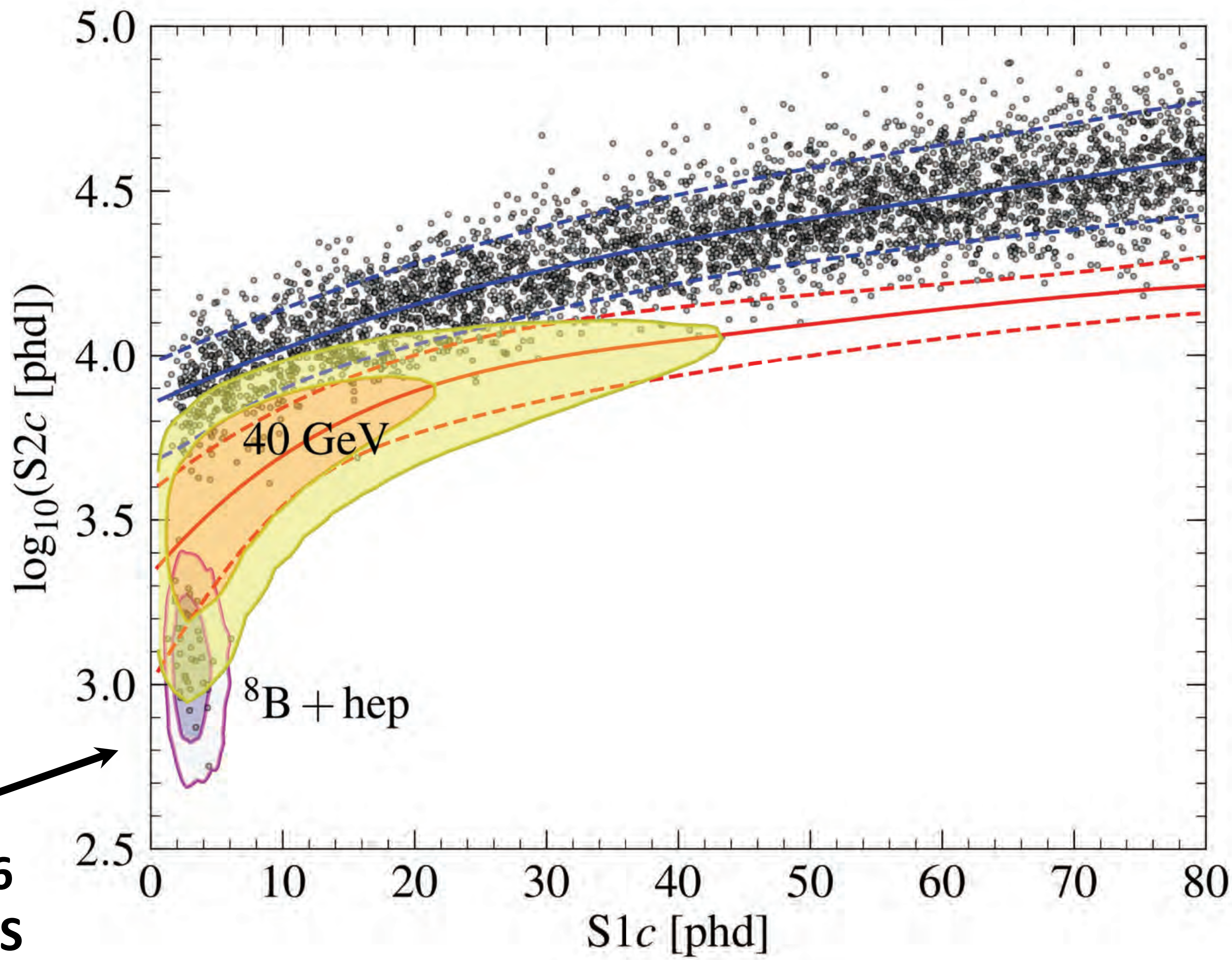
σ: parameter of interest
ν: nuisance parameters

n: observed number of data events
μ: expected number of data events
n_s: number of signal events
n_b: number of events of bkg source b

$$\mu = n_s + \sum_{b}^{N_{\rm bkg}} n_b$$

$\mathcal{N}$: Gaussian function
$N_{\rm bkg}$: number of bckg sources

Simulated signal & background, 1000-day run



→ charge signal (S2)

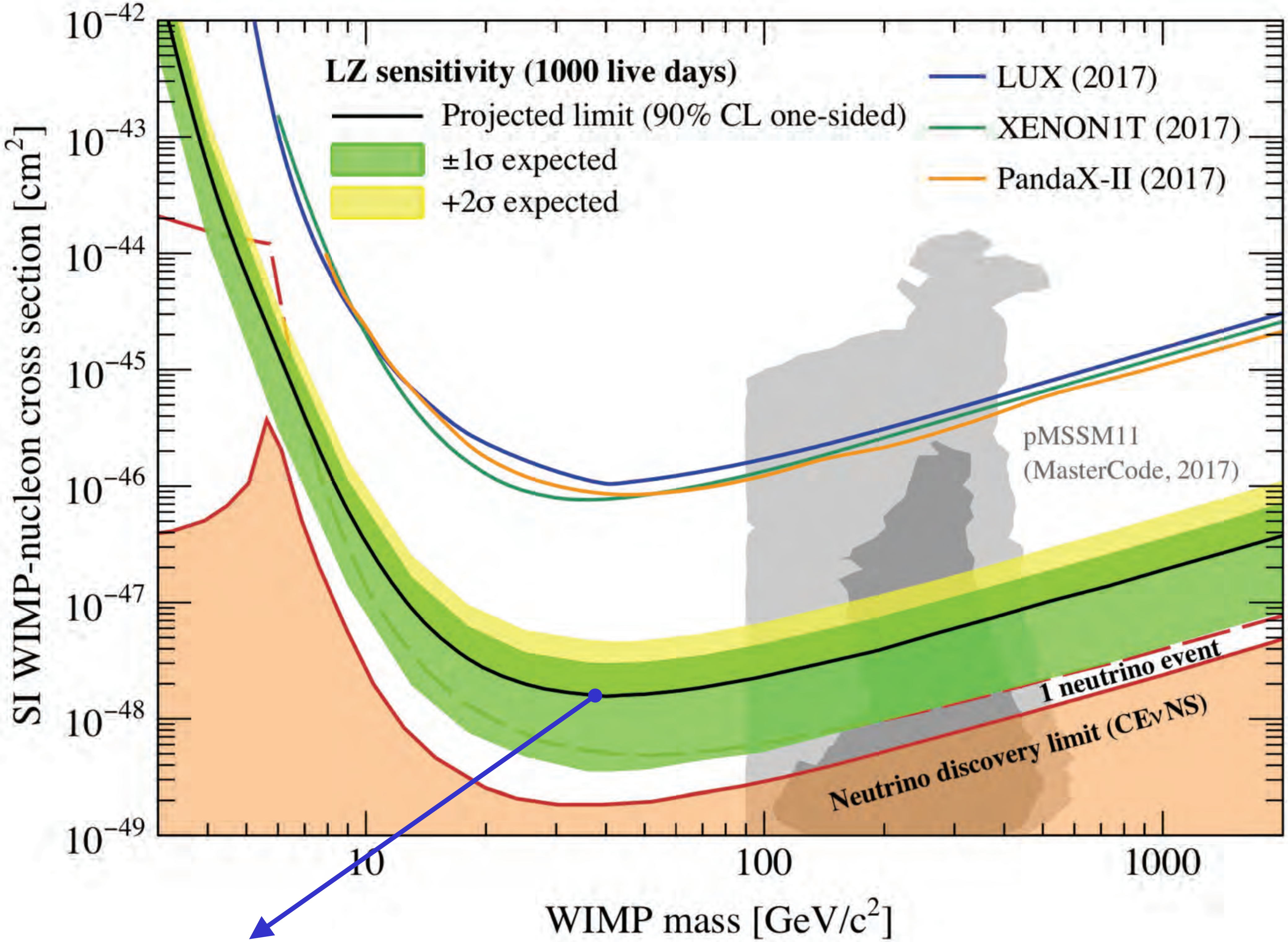
Expected ~ 36 NR from ν CNS

→ low-energy calibrations!!!

→ light signal (S1)

Projected WIMP Sensitivity: Spin Independent

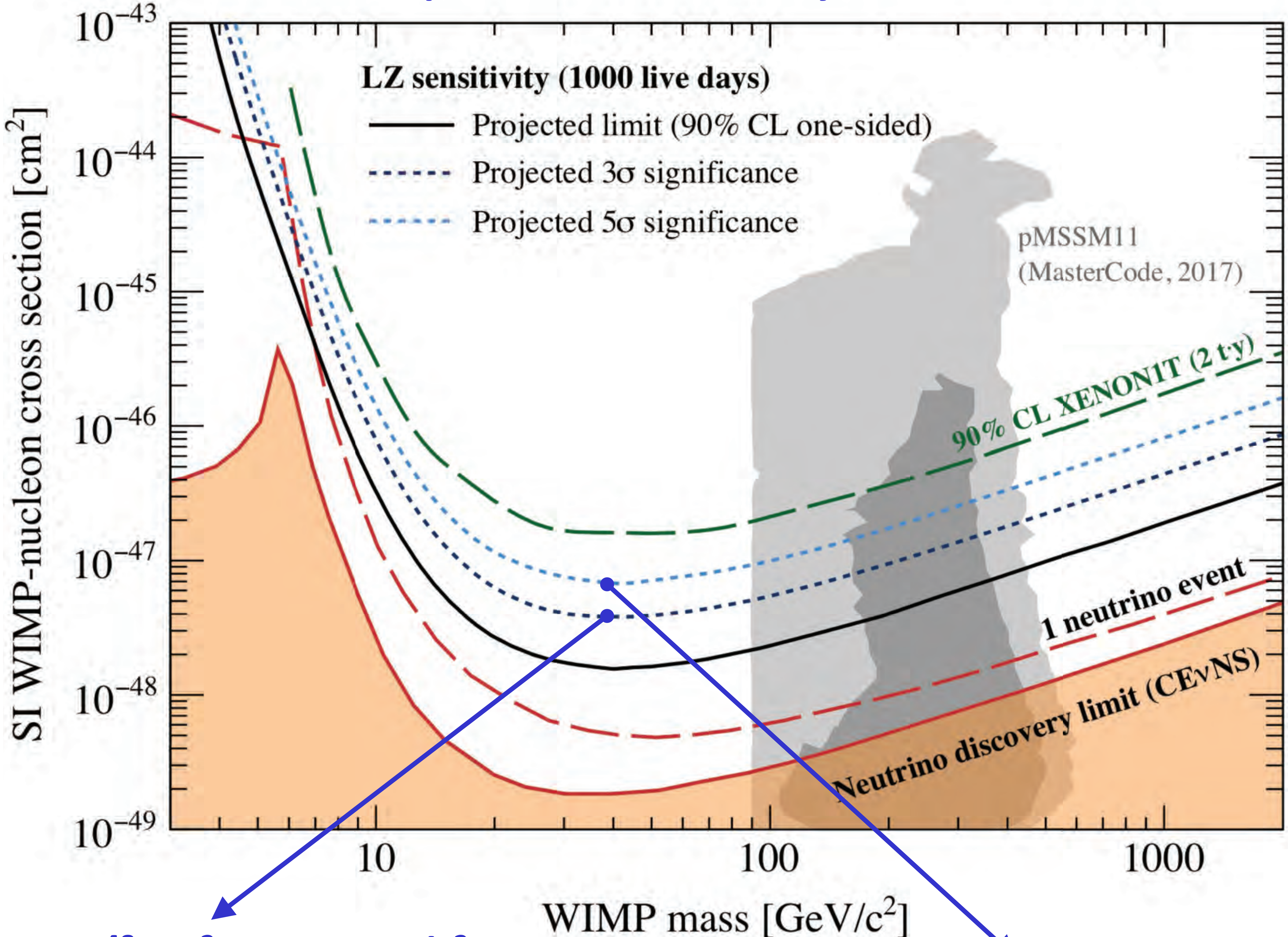
Nominal exposure: 1000 live-days, 5.6 tonne fiducial



1.6×10^{-48} cm^2 @ 40 GeV/c^2

3σ and 5σ discovery potential

Nominal exposure: 1000 live-days, 5.6 tonne fiducial

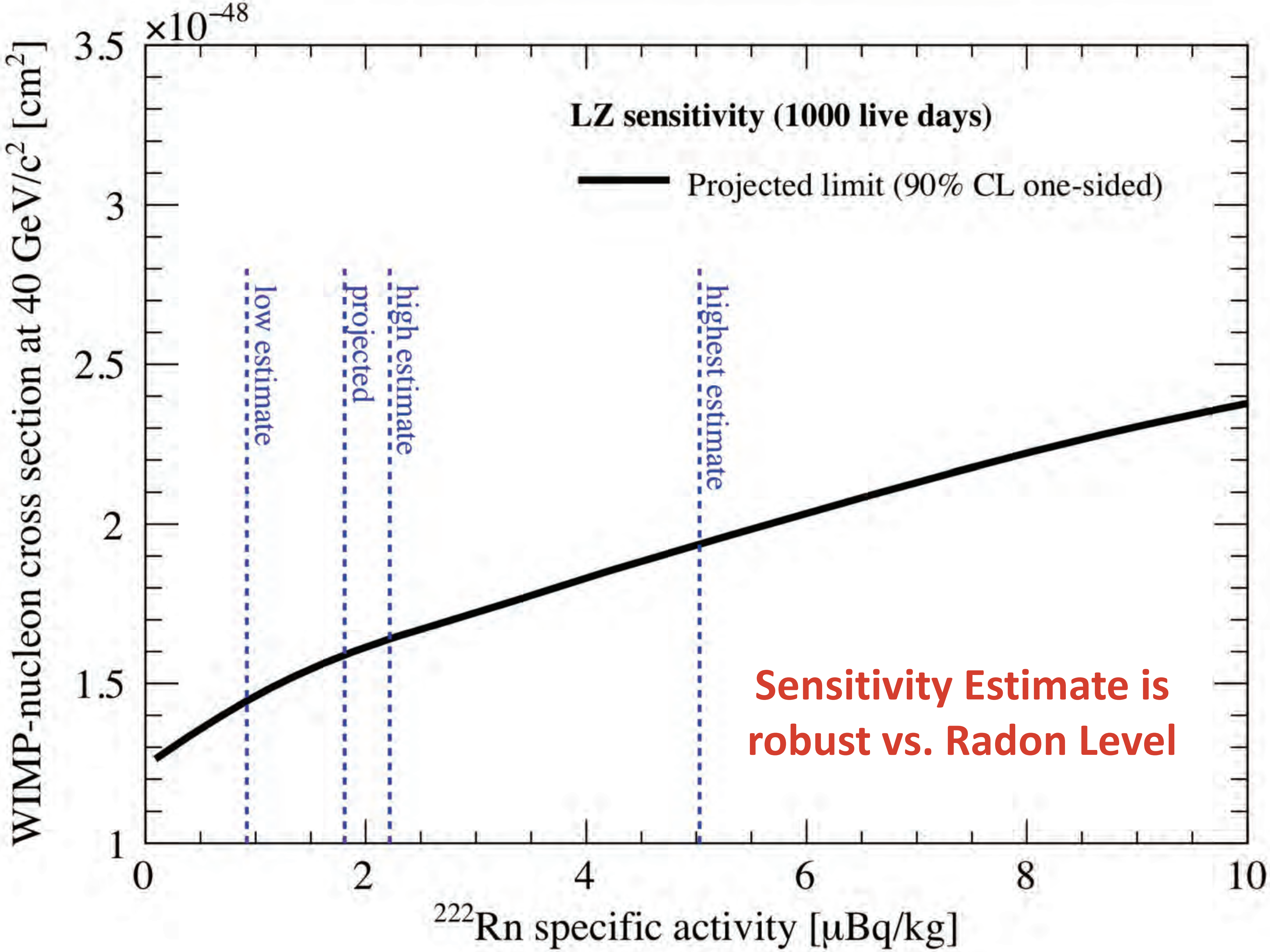


3σ: 3.8×10^{-48} cm² @ 40 GeV/c²

5σ: 6.7×10^{-48} cm² @ 40 GeV/c²

Sensitivity vs Radon level

Nominal exposure: 1000 live-days, 5.6 tonne fiducial



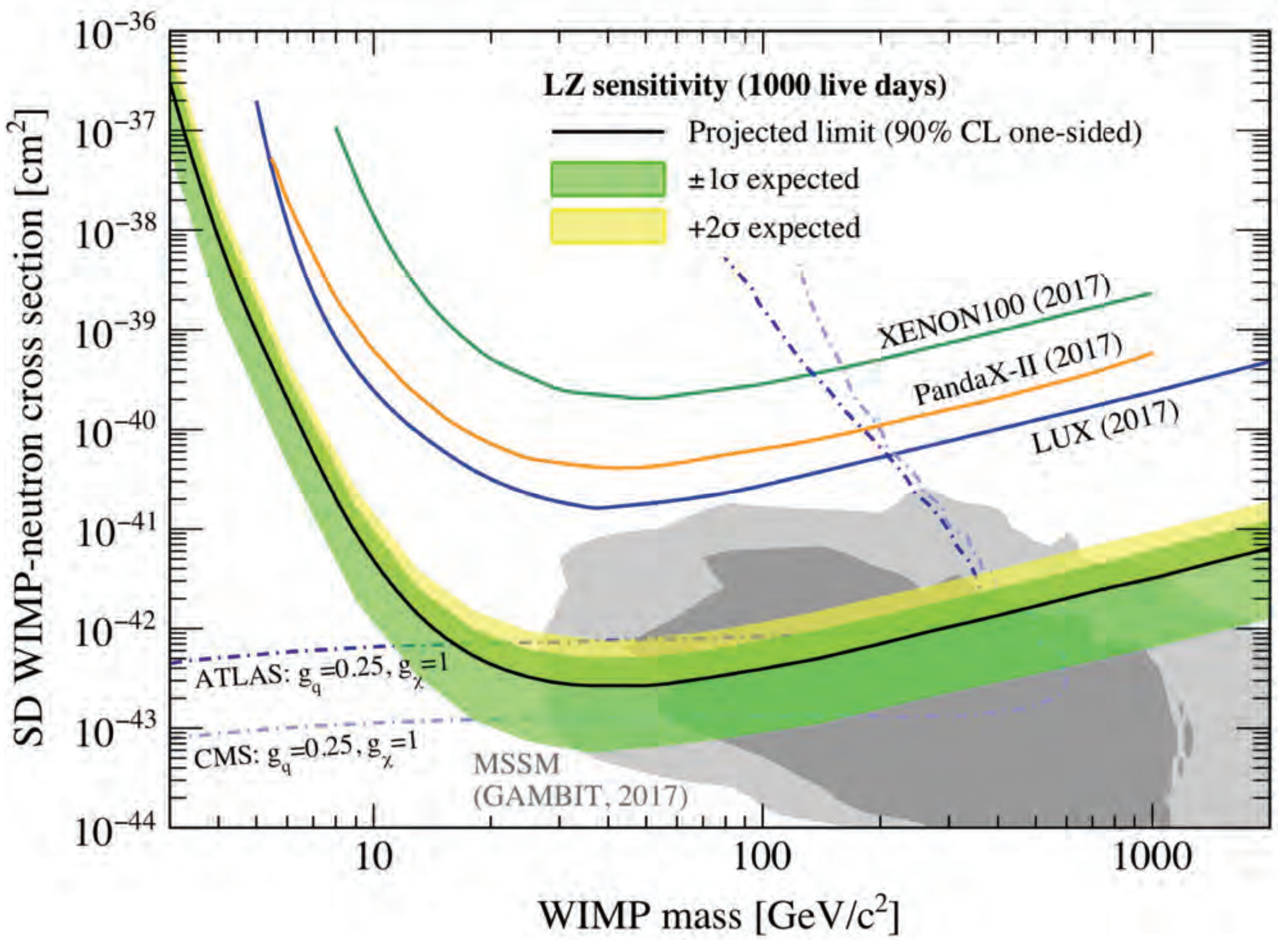
Sensitivity Estimate is robust vs. Radon Level

Spin-dependent sensitivity

Naturally occurring Xe: ≈50% odd-neutron isotopes
(26.4% ^{129}Xe and 21.2% ^{131}Xe by mass)

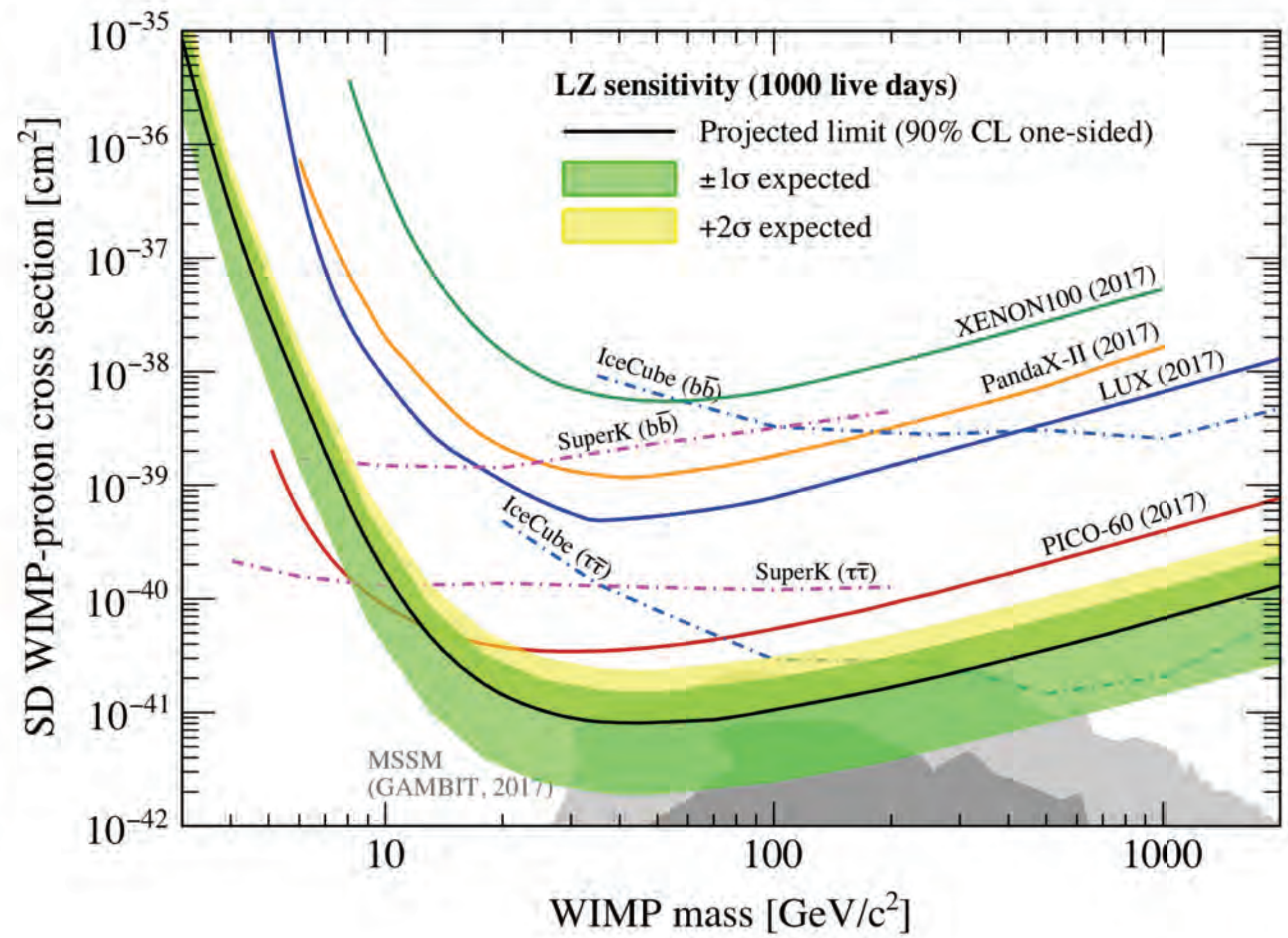
SD WIMP-neutron:

2.7×10^{-43} cm^2 @ 40 GeV/c^2



SD WIMP-proton:

8.1×10^{-42} cm^2 @ 40 GeV/c^2



Spin structure functions from Klos *et al*, Phys. Rev. D89, 022901 (2014)

Summary and Conclusions

- **Data-driven model of LZ sensitivity:**
  - As-built detector design
  - Measured component properties
  - Accurate LXe response model
- **Detailed background model**
  - Powerful vetoing strategy
  - Dominated by dispersed radionuclides
  - PDF model of residual backgrounds
- **LZ commissioning in 2020:**
  - 1,000 day nominal science run
  - SI WIMP sensitivity: 1.6×10^{-48} cm^2
  - 3σ discovery potential: 3.8×10^{-48} cm^2