Searching for Dark Matter with LZ

Hugh Lippincott, Fermilab for the LZ Collaboration

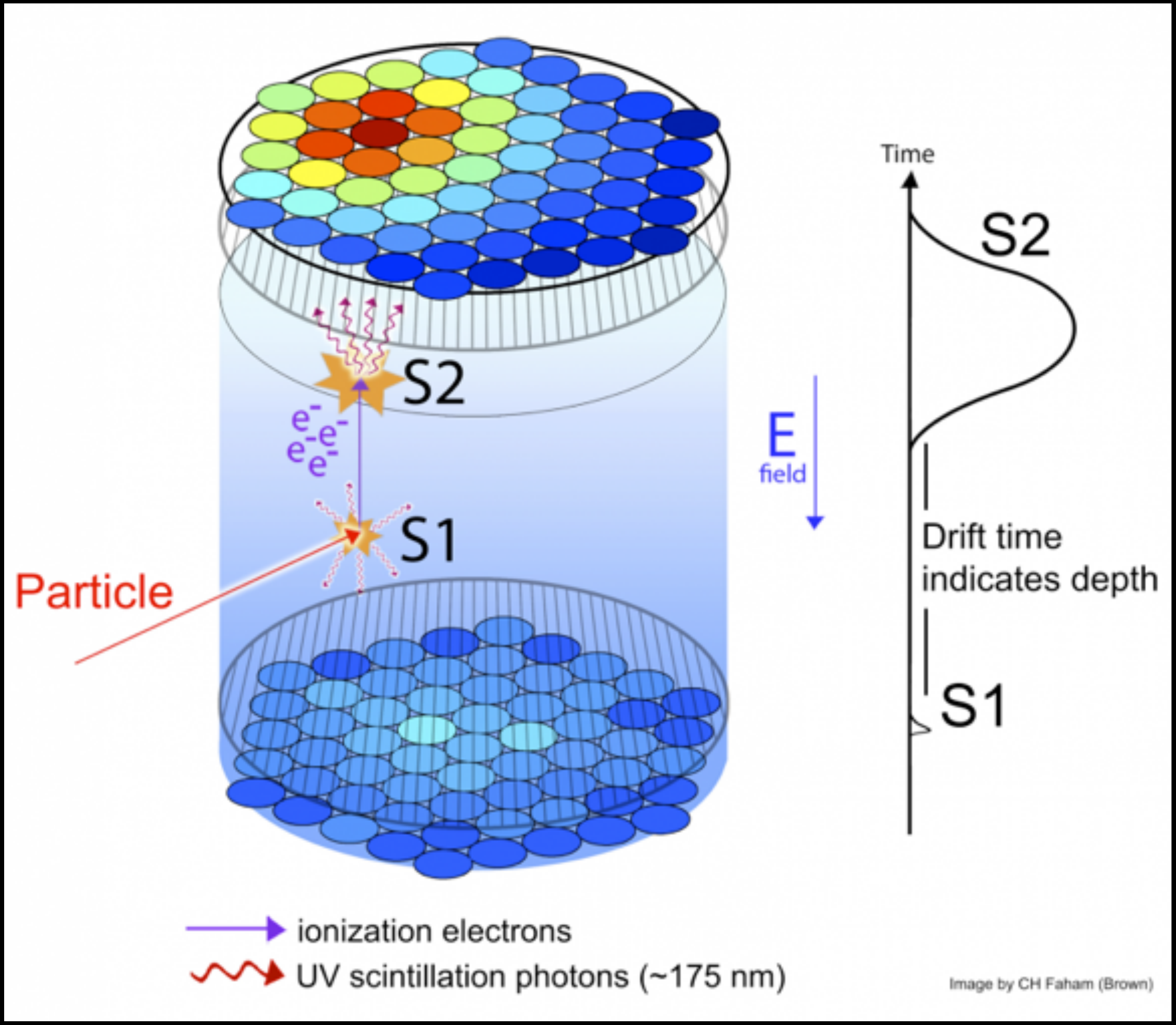
Exploring the Dark Universe
July, 2017

LXe as Dark Matter Target

Challenge	Solution	Liquid Xenon	
Extremely rare	Large mass	Very dense - 3 tonnes in 1 m^3	✓
Energy depositions of ~10 keV or below	Low energy thresholds	~60-70 electrons + photons / keV	✓
Backgrounds - Impurities	Purification	Noble gases are (mostly) easy to purify	✓
Backgrounds - Detector	Self shielding	Low MFP for ionizing radiation	✓
Backgrounds - Internal/Detector	Discrimination	Charge to light ratio gives particle ID	✓

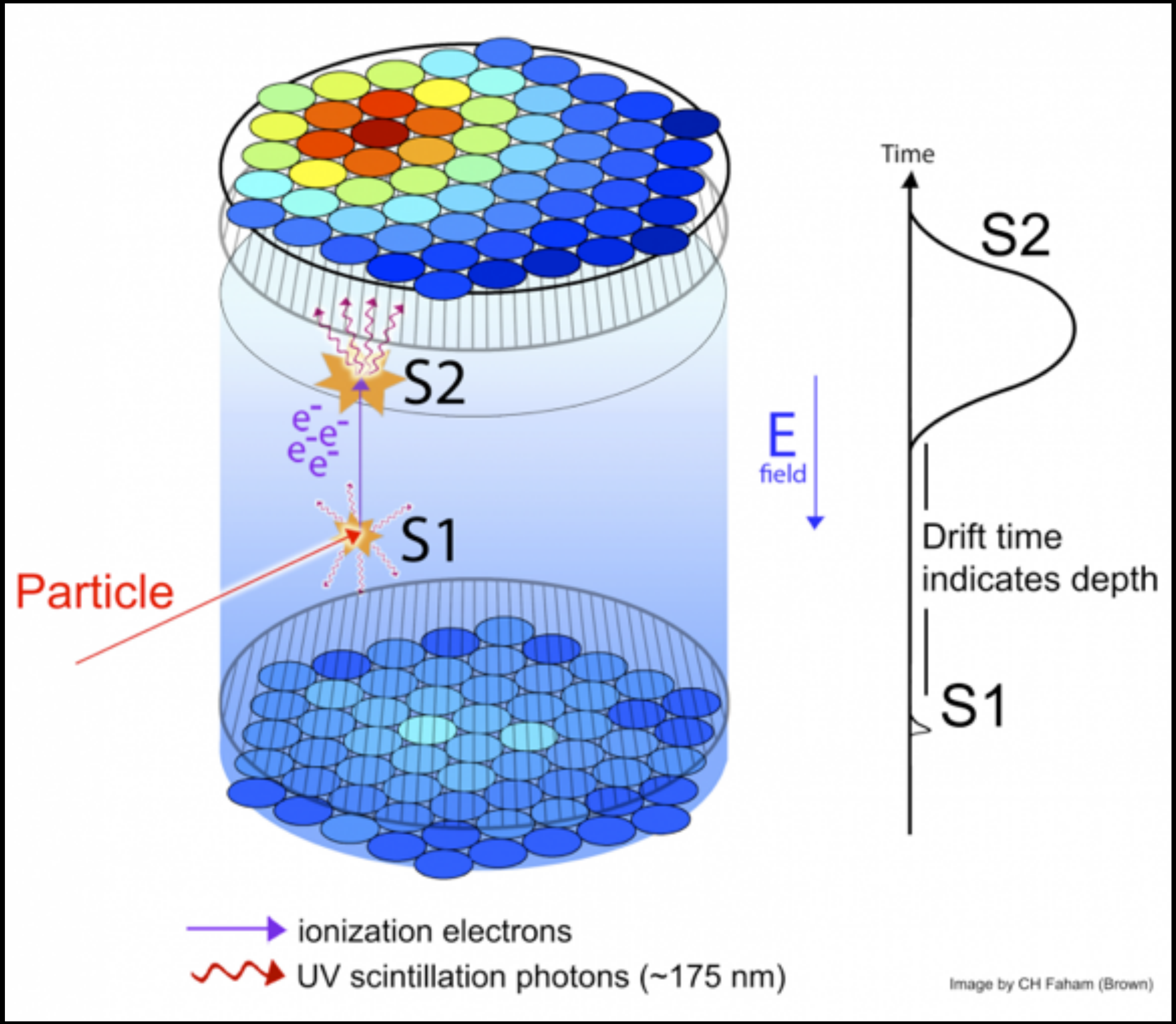
Two phase Xenon Detectors

- Interaction in the xenon creates:
    - Scintillation light (~10 ns) - called S1
    - ionization electrons
- Electrons drift through electric field to liquid/gas surface
    - Extracted into gas and accelerated creating proportional scintillation light - called S2

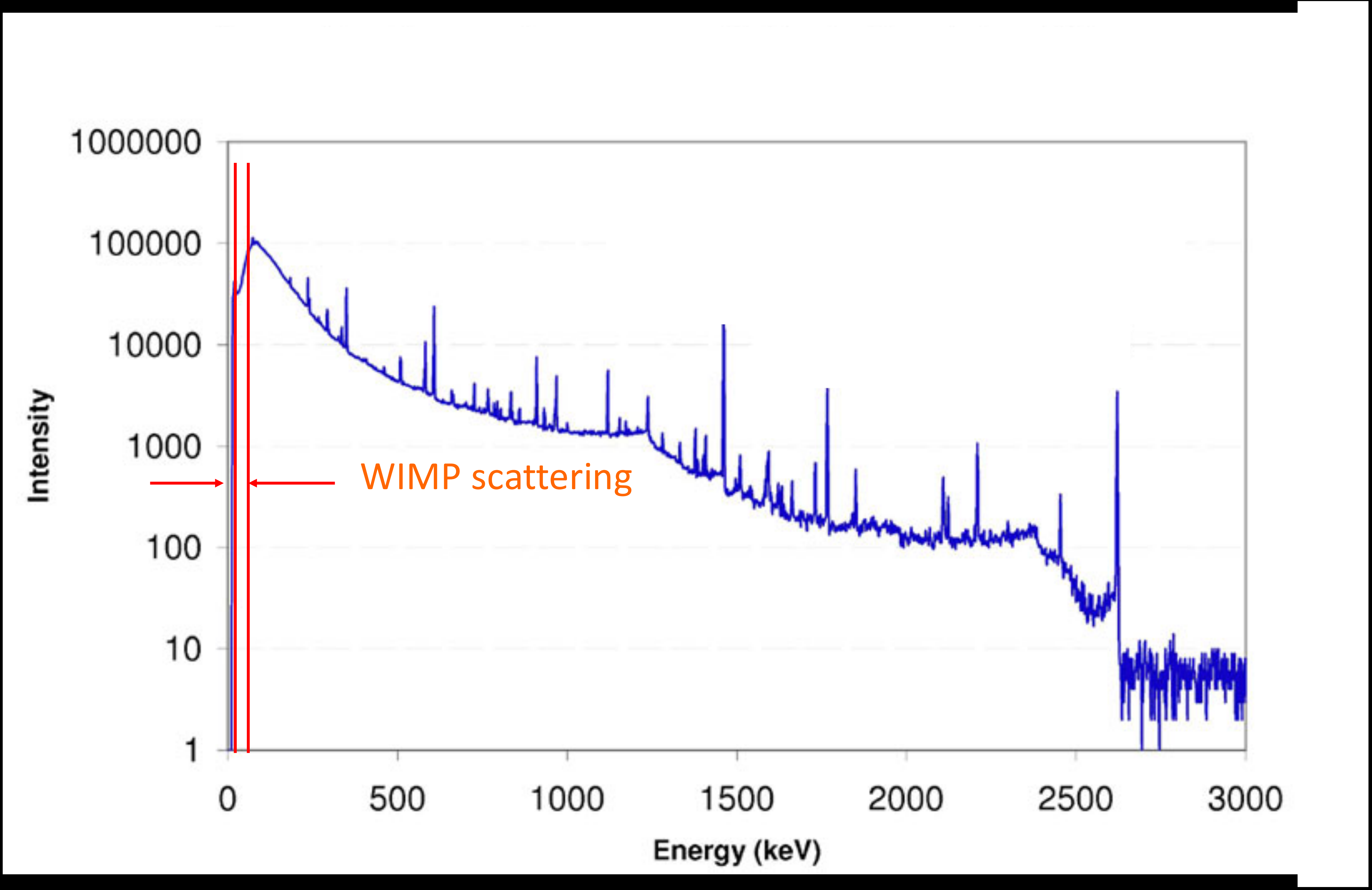


Two phase Xenon Detectors

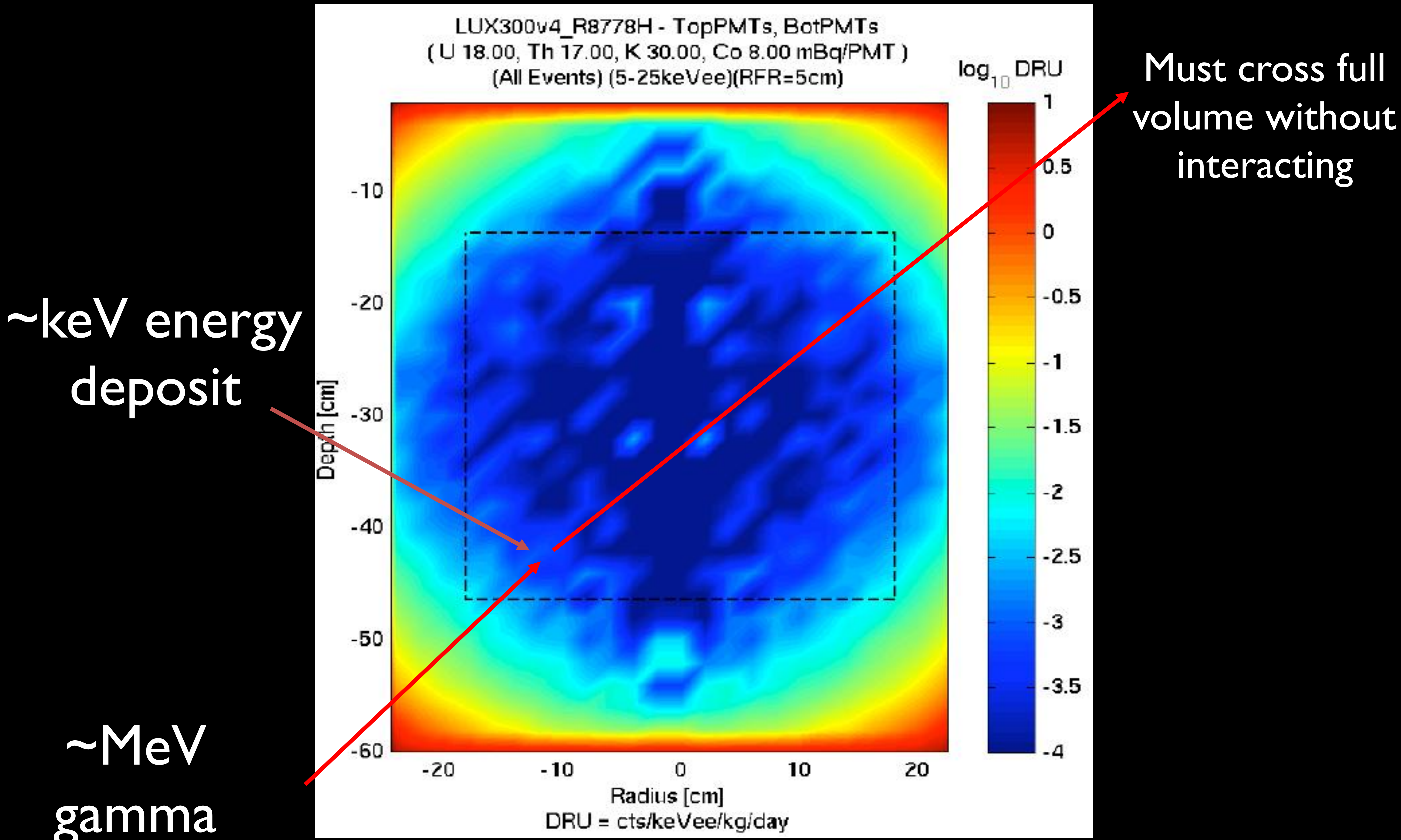
- Excellent 3D reconstruction (~mm)
  - Z position from S1-S2 timing
  - XY position from hit pattern of S2 light
  - Allows for self shielding, rejection of edge events
- Ratio of charge (S2) to light (S1) gives particle ID
  - Better than 99.5% rejection of electron recoil (ER) events

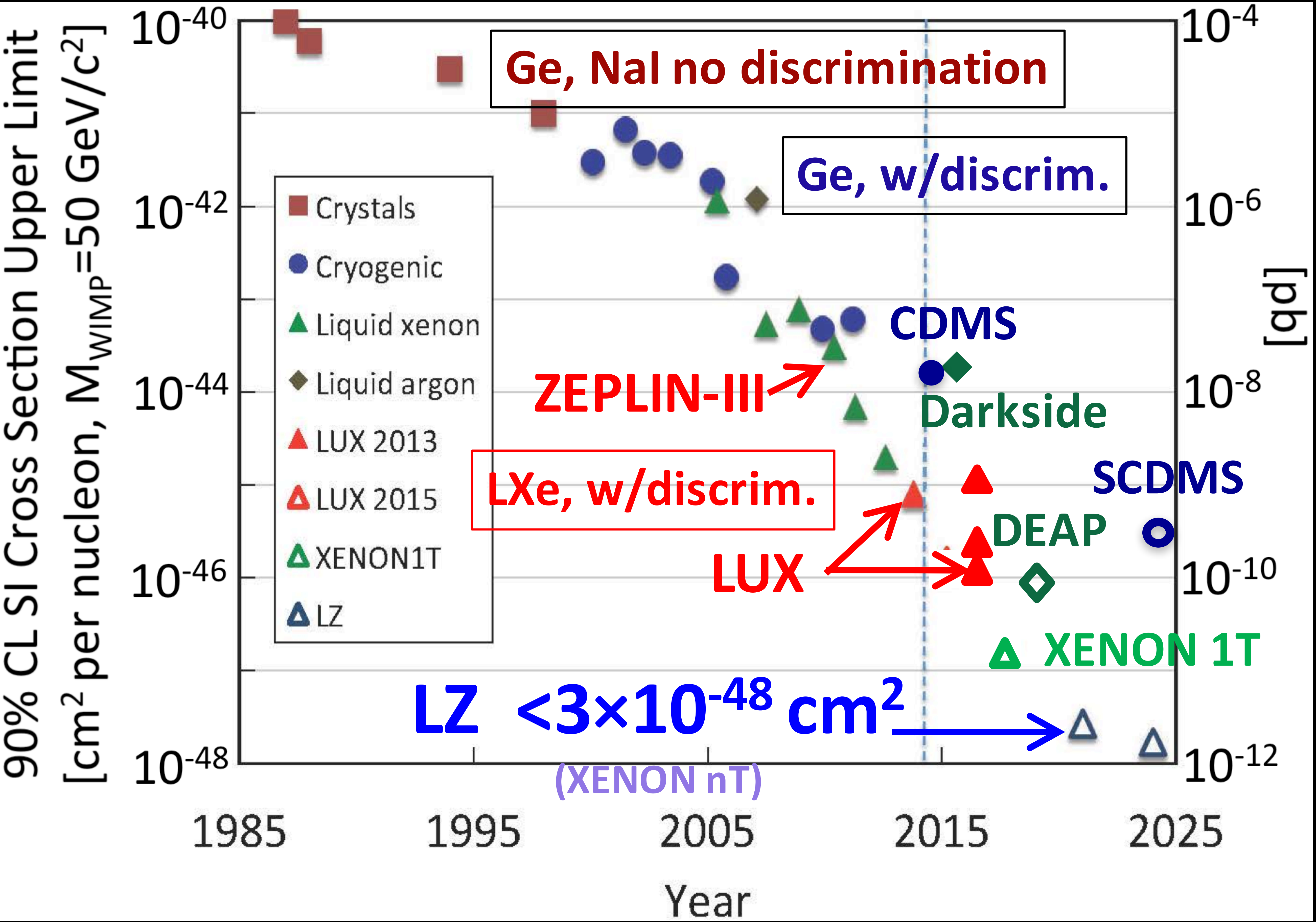


Self shielding is powerful

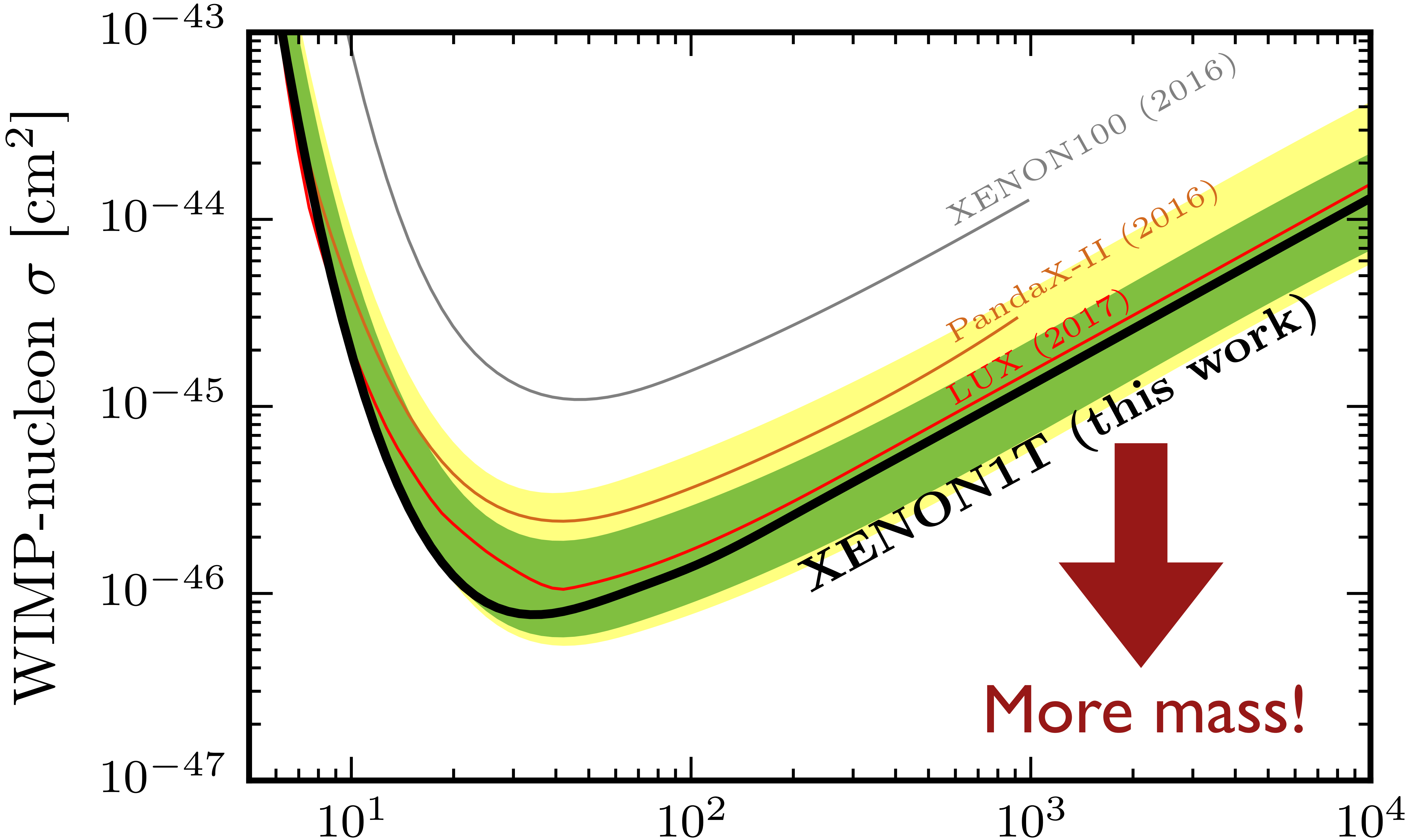


Self shielding is powerful





Ge, NaI no discrimination
Ge, w/discrim.
Crystals
Cryogenic
Liquid xenon
Liquid argon
LUX 2013
LUX 2015
XENON1T
LZ
CDMS
ZEPLIN-III
Darkside
LXe, w/discrim.
SCDMS
DEAP
LUX
XENON 1T
LZ <3×10^-48 cm^2
(XENON nT)
90% CL SI Cross Section Upper Limit
[cm^2 per nucleon, M_WIMP=50 GeV/c^2]
[pb]
10^-40
10^-42
10^-44
10^-46
10^-48
10^-4
10^-6
10^-8
10^-10
10^-12
1985
1995
2005
2015
2025
Year



arXiv:1705.06655

LUX - 100 kg (active)
PandaX-II - 329 kg (fid)
Xenon1T - 1 tonne (fid)

LZ = LUX + ZEPLIN

38 Institutions, 217 People

Center for Underground Physics (Korea)
Imperial College London (UK)
LIP Coimbra (Portugal)
MEPhI (Russia)
STFC Rutherford Appleton Laboratory (UK)
University College London (UK)
University of Bristol (UK)
SUPA, University of Edinburgh (UK)
University of Liverpool (UK)
University of Oxford (UK)
University of Sheffield (UK)

Black Hills State University
Brookhaven National Laboratory (BNL)
Brown University
Fermi National Accelerator Laboratory (FNAL)
Kavli Institute for Particle Astrophysics and Cosmology (KIPAC)
Lawrence Berkeley National Laboratory (LBNL)
Lawrence Livermore National Laboratory (LLNL)
Northwestern University
Pennsylvania State University
SLAC National Accelerator Laboratory
South Dakota School of Mines and Technology
South Dakota Science and Technology Authority (SDSTA)
STFC Rutherford Appleton Laboratory (RAL)
Texas A&M University
University at Albany (SUNY)
University of Alabama
University of California (UC), Berkeley
University of California (UC), Davis
University of California (UC), Santa Barbara
University of Maryland
University of Massachusetts

University of Michigan
University of Rochester
University of South Dakota
University of Wisconsin-Madison
Washington University in St. Louis
Yale University

Collaboration meeting last week at SURF

Scale Up ≈50 in Fiducial Mass

LZ

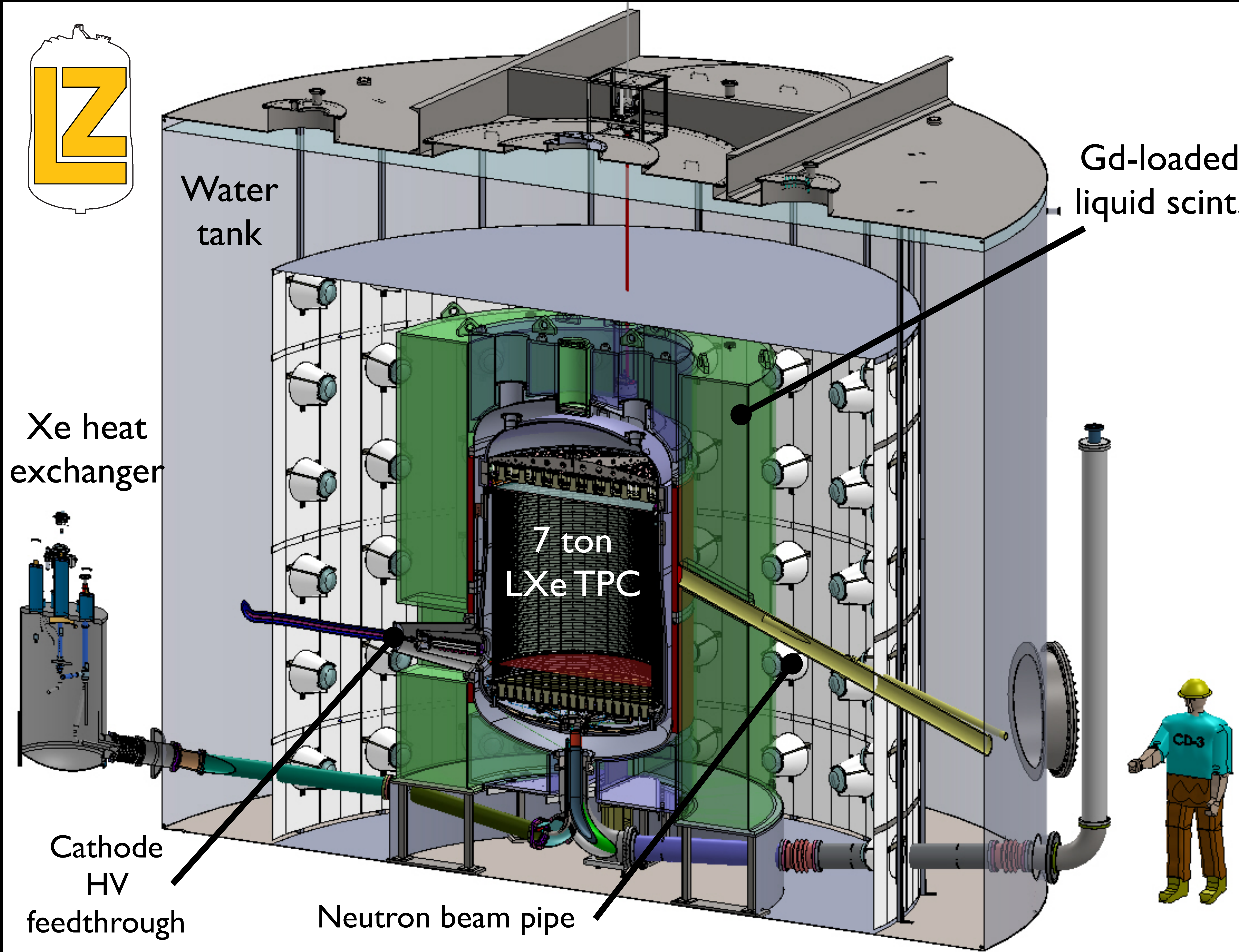
Total mass – 10 T
WIMP Active Mass – 7 T
WIMP Fiducial Mass – 5.6 T

LUX

Sanford Underground Research Facility

Davis Cavern 1480 m
(4200 mwe)
LUX Water Tank

LZ Here


LZ
Water tank
Gd-loaded liquid scint.
Xe heat exchanger
7 ton LXe TPC
CD-3
Cathode HV feedthrough
Neutron beam pipe

LZ design notes

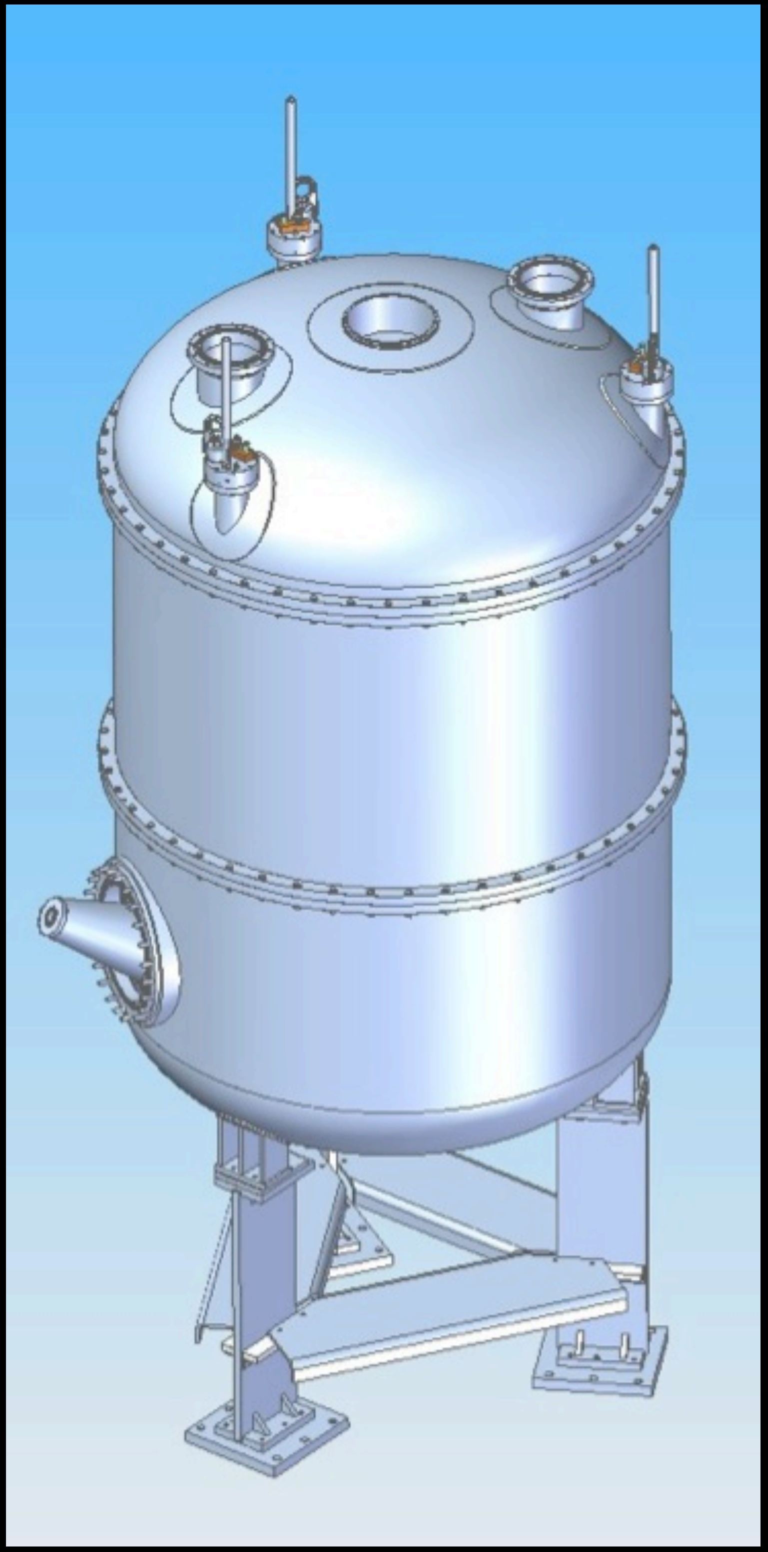
- More mass (x50 more than LUX, x6 more than Xenon1T)
  - 494 3” PMTs on TPC
- Significant HV/grid engineering (no xenon experiment has achieved HV goals so far)
  - Requirement: 50 kV   Goal: 100 kV
- Sophisticated veto system - maximizes fiducial volume
  - LXe “skin” - 93 1” PMTs + 38 2” PMTs
  - 120 outer detector PMTs
- Radioactivity, radioactivity, radioactivity!

System test at SLAC

- Main test platform for LZ
  - Same cryogenics/control
- Phase I (ongoing)
  - Full LZ fields in scaled prototype TPC
    - Can HV be achieved with sparking or light emission?
  - Prototype circulation
    - LZ architecture and compressor
- Phase II will test grids

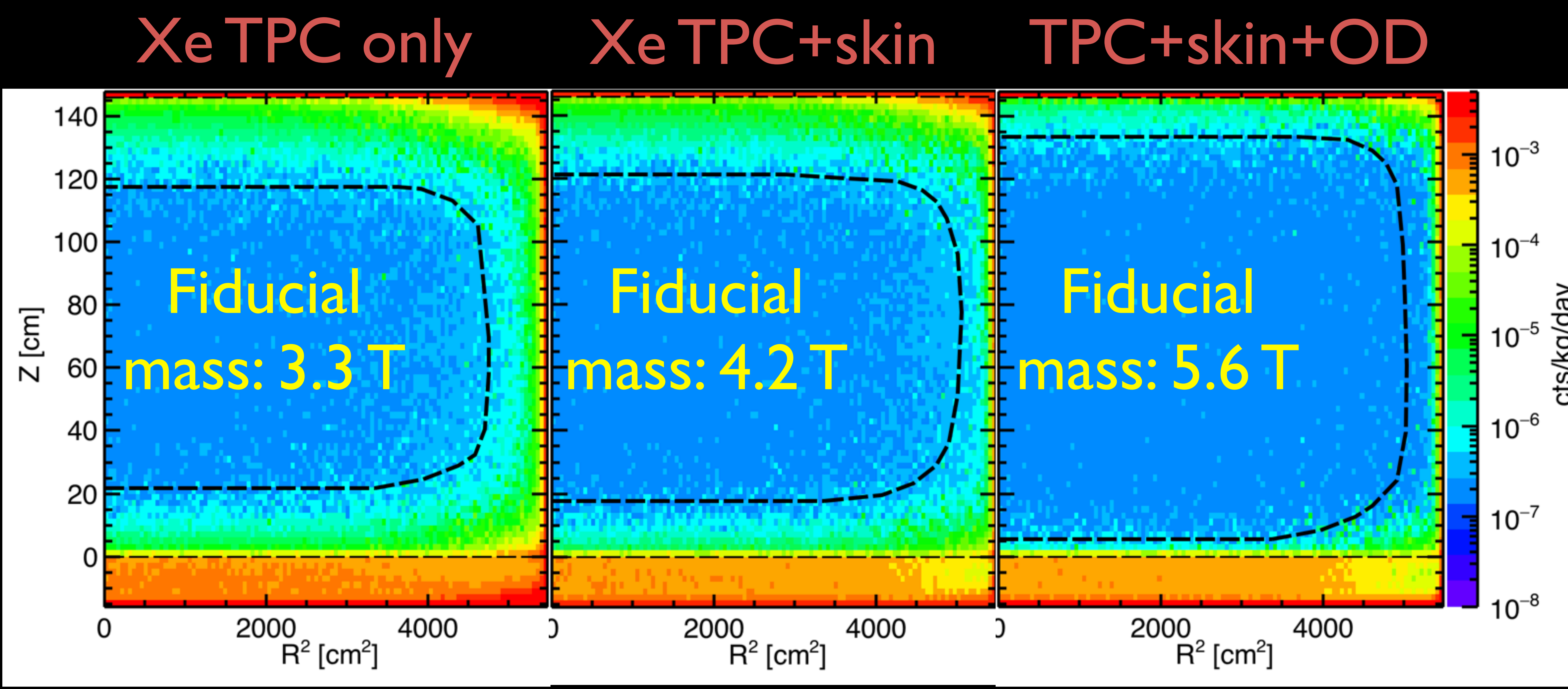
Background suppression by screening

- Every component is screened and simulated for radioactivity
  - E.g. cryostat made of the most radiopure titanium in the world: < 0.05 counts in 1000 days after cuts
  - Similar campaign working with Hamamatsu on PMTs
- Backed up by extensive quality assurance during production



Background suppression by veto

- Two component outer detector
  - Gd-loaded liquid scintillator
  - instrumented skin

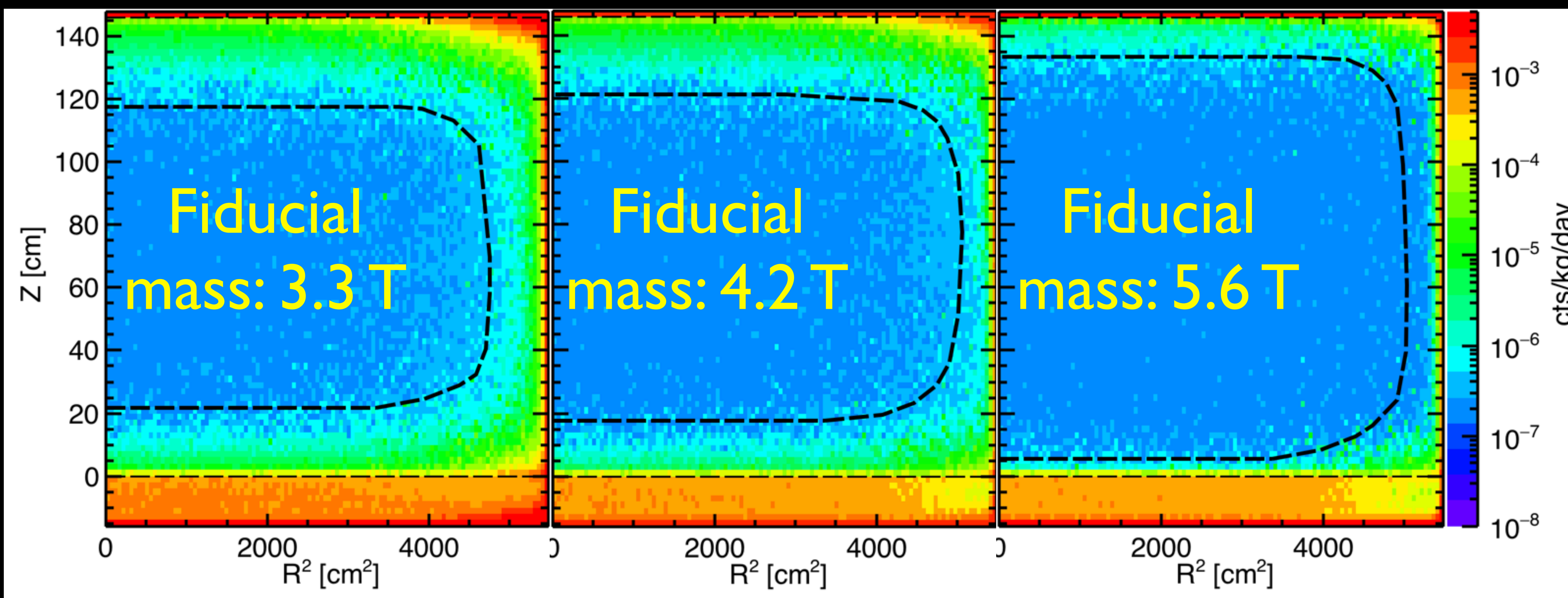


Background suppression by veto

- Two component outer detector
  - G
  - in

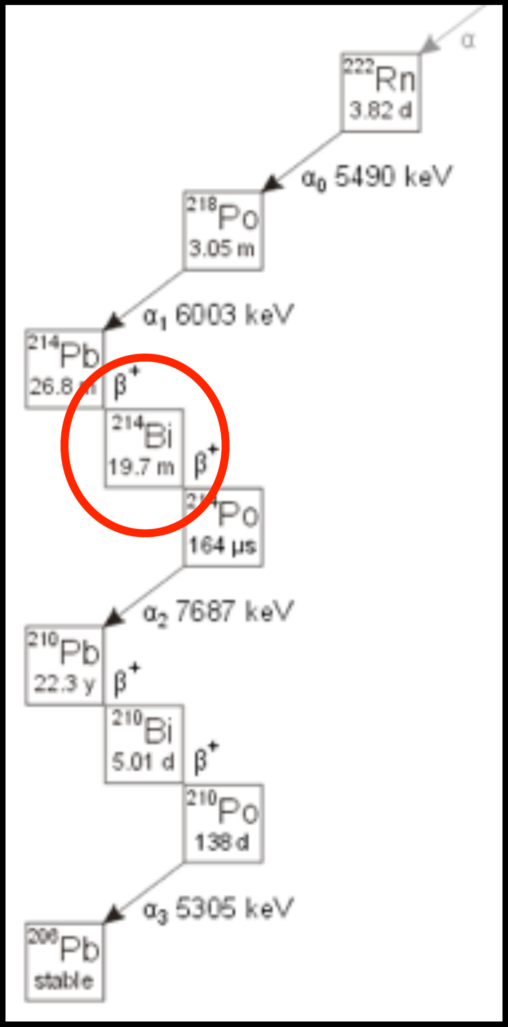
With veto, detector components are a subdominant background!

Xe TPC only | Xe TPC+skin | TPC+skin+OD



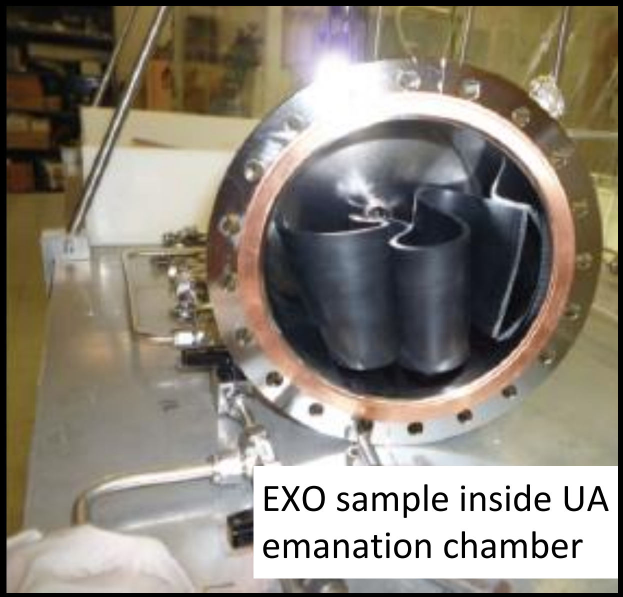
Internal backgrounds

- Radon, Krypton, Argon
- Distributed throughout the liquid volume
- ER backgrounds (can discriminate, thankfully)
- Radon requirement (goal) of 20(1) mBq



Radon emanation measurements

Dust is a killer!



EXO sample inside UA emanation chamber

Internal backgrounds

- Contributes half our radon budget
- Emanation measurements of "clean room dust"
- Requirement of <500 ng/cm^2 of dust in LZ
  - Goal of 5 ng/cm^2
  - SNO achieved 20 ng/cm^2, BOREXINO 1 ng/cm^2
  - 1 gram total!
- Cleanliness protocols, witness plate protocols, packaging protocols

Dust is a killer!

Intrinsic Contamination Backgrounds	Mass (kg)	Composite	U early (mBq/kg)	U late (mBq/kg)	Th early (mBq/kg)	Th late (mBq/kg)	Co60 (mBq/kg)	K40 (mBq/kg)	n/yr (inc. S.F. rej.)	ER (cts)	NR (cts) (w/ SF rej.)
Upper PMT Structure	40.5	Y	3.90	0.23	0.49	0.38	0.00	1.46	2.53	0.05	0.000
Lower PMT Structure	69.9	Y	2.40	0.13	0.30	0.24	0.00	0.91	6.06	0.05	0.001
R11410 3" PMTs	91.9	Y	71.63	3.20	3.12	2.99	2.82	15.41	81.83	1.46	0.013
R11410 PMT Bases *	2.8	Y	287.74	75.80	28.36	27.93	1.43	69.39	34.65	0.36	0.004
R8778 2" PMTs	6.1	Y	137.50	59.38	16.88	16.88	16.25	412.50	52.80	0.13	0.008
R8520 Skin 1" PMTs	2.2	Y	60.50	5.19	4.75	4.75	24.20	332.76	4.60	0.02	0.001
R8520 Skin PMT Bases *	0.2	Y	212.95	108.46	42.19	37.62	2.23	123.61	3.62	0.00	0.000
PMT Cabling	103.5	Y	29.83	1.47	3.31	3.15	0.65	33.14	2.65	1.43	0.000
TPC PTFE	184.0	N	0.02	0.02	0.03	0.03	0.00	0.12	22.54	0.06	0.008
Grid Wires	0.75	N	1.20	0.27	0.33	0.49	1.60	0.40	0.02	0.00	0.000
Grid Holders	62.2	Y	1.20	0.27	0.33	0.49	1.60	0.40	6.33	0.27	0.002
Field Shaping Rings	91.6	Y	5.41	0.09	0.28	0.23	0.00	0.54	10.83	0.23	0.004
TPC Sensors	0.90	Y	21.09	13.51	22.89	14.15	0.50	26.29	24.77	0.01	0.002
TPC Thermometers	0.06	Y	335.50	90.46	38.48	25.02	7.26	3,359	1.49	0.05	0.000
Xe Recirculation Tubing	15.1	Y	0.79	0.18	0.23	0.33	1.05	0.30	0.64	0.00	0.000
HV Conduits and Cables	137.7	Y	1.9	2.0	0.5	0.6	1.4	1.2	4.9	0.04	0.001
HX and PMT Conduits	199.6	Y	1.25	0.40	2.59	0.66	1.24	1.47	5.33	0.06	0.001
Cryostat Vessel	2406.1	N	1.59	0.11	0.29	0.25	0.07	0.56	123.70	0.63	0.013
Cryostat Seals	33.7	Y	73.91	26.22	3.22	4.24	10.03	69.12	38.78	0.45	0.002
Cryostat Insulation	23.8	Y	18.91	18.91	3.45	3.45	1.97	51.65	69.83	0.43	0.007
Cryostat Teflon Liner	26.0	N	0.02	0.02	0.03	0.03	0.00	0.12	3.18	0.00	0.000
Outer Detector Tanks	3199.3	Y	0.16	0.39	0.02	0.06	0.04	5.36	77.96	0.45	0.001
Liquid Scintillator	17640.3	Y	0.01	0.01	0.01	0.01	0.00	0.00	14.28	0.03	0.000
Outer Detector PMTs	204.7	Y	570	470	395	388	0.00	534	7,587	0.01	0.000
Outer Detector PMT Supports	770.0	N	1.20	0.27	0.33	0.49	1.60	0.40	14.30	0.00	0.000
Subtotal (Detector Components)										**6.20**	**0.070**
222Rn (2.0 µBq/kg)										722	-
220Rn (0.1 µBq/kg)										122	-
natKr (0.015 ppt g/g)										24.5	-
natAr (0.45 ppb g/g)										2.47	-
210Bi (0.1 µBq/kg)										40.0	-
Laboratory and Cosmogenics										4.3	0.06
Fixed Surface Contamination										0.19	0.37
Subtotal (Non-ν counts)										**921**	**0.50**
Physics Backgrounds											
136Xe 2νββ										67	0
Astrophysical ν counts (pp+7Be+13N)										255	0
Astrophysical ν counts (8B)										0	0**
Astrophysical ν counts (Hep)										0	0.21
Astrophysical ν counts (diffuse supernova)										0	0.05
Astrophysical ν counts (atmospheric)										0	0.46
Subtotal (Physics backgrounds)										322	0.72
Total										1,240	1.22
Total (with 99.5% ER discrimination, 50% NR efficiency)										6.22	0.61

My summary of the summary table → 6 ER, 0.6 NR in 1000 days!

Backgrounds summary

Subtotal (Non-v counts)	**921**	**0.50**
Physics Backgrounds		
136Xe 2vββ	67	0
Astrophysical v counts (pp+7Be+13N)	255	0
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Subtotal (Physics backgrounds)	322	0.72
Total	1,240	1.22
Total (with 99.5% ER discrimination, 50% NR efficiency)	6.22	0.61

- Lots of neutrinos - significant fraction of both ER and NR counts
- Discrimination cuts are important

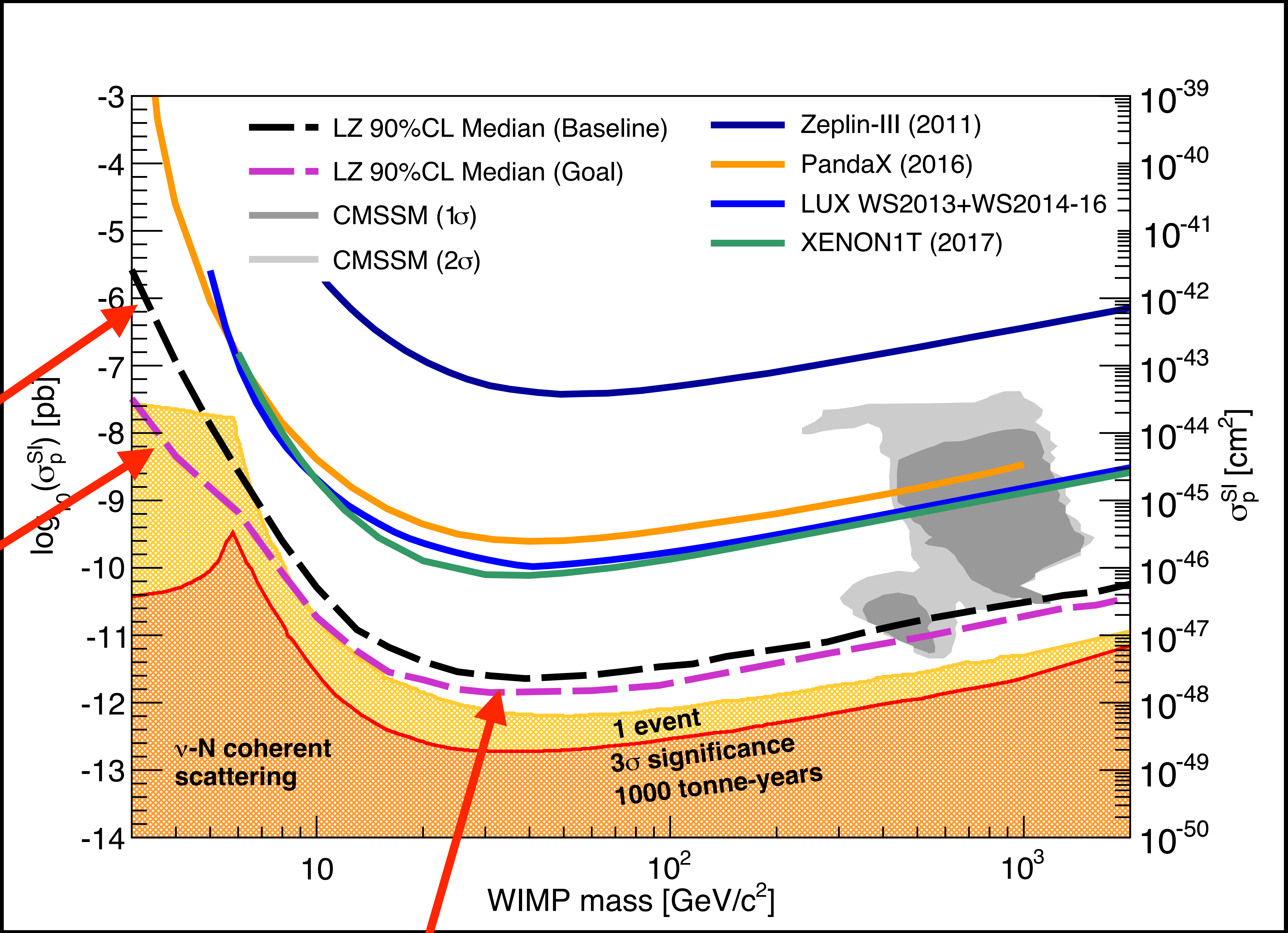
My summary of the summary table → 6 ER, 0.6 NR in 1000 days!

Sensitivity projections

Detector Parameter	Reduced	Baseline	Goal
Light collection (PDE)	0.05	0.075	0.12
Drift field (V/cm)	160	310	650
Electron lifetime (μs)	850	850	2800
PMT phe detection	0.8	0.9	1.0
N-fold trigger coincidence	4	3	2
^{222}Rn (mBq in active region)	13.4	13.4	0.67
Live days	1000	1000	1000

- ~6 keVnr threshold in baseline scenario (LUX achieved 4.5 keVnr)
  - Driven by S1 trigger coincidence threshold
- Better than 99.5% ER/NR discrimination at this field

Sensitivity projections (1000 days)

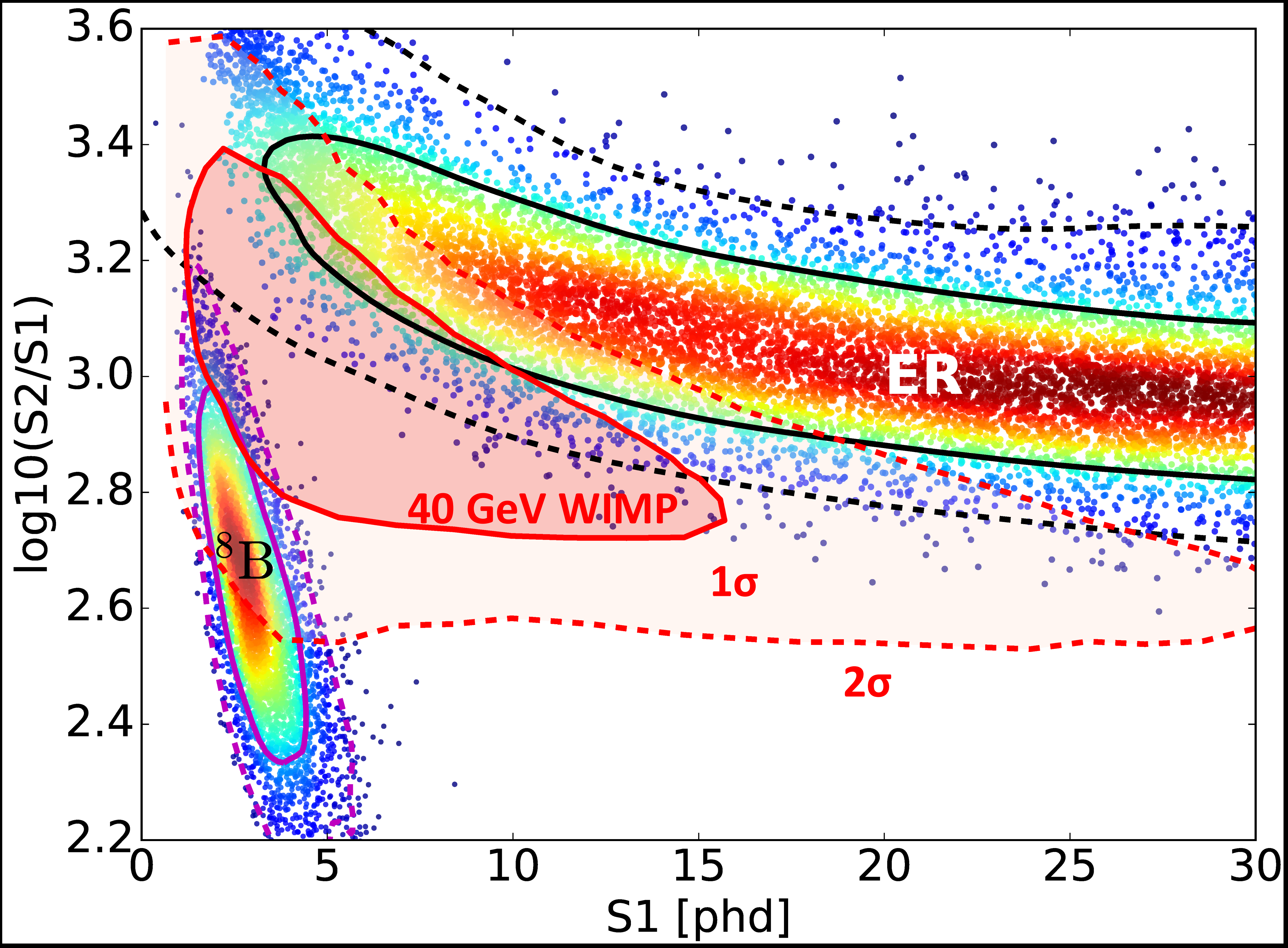


~7 8B events

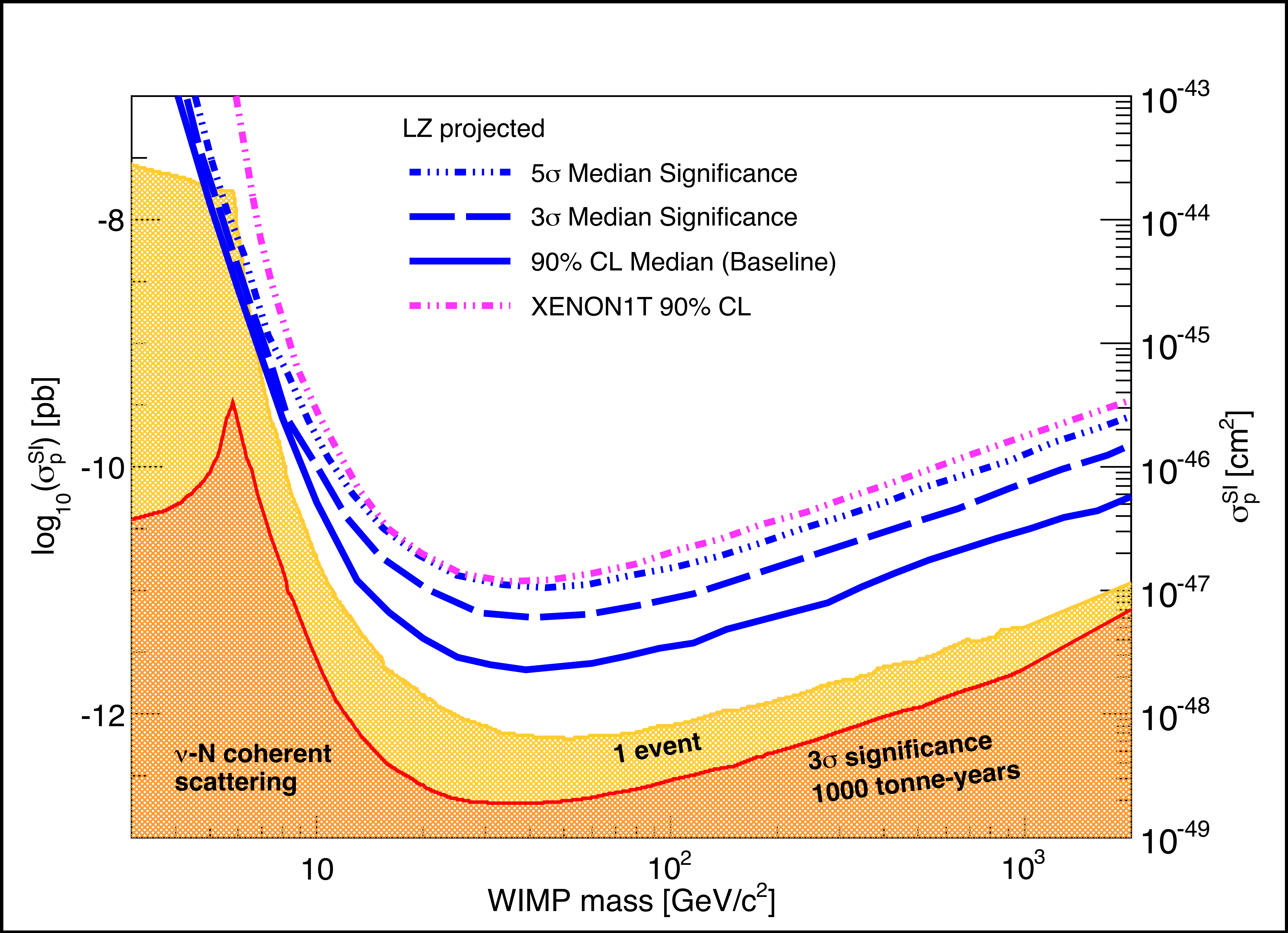
~700 8B events

@40 GeV: 2.3e-48 Nominal
1.1e-48 Goal

WIMP signal region



Sensitivity projections (1000 days)



Schedule

- 2012 - LZ Collaboration formed
- 2014 - LZ Project start
- 2015 - DOE CD-1 approval - Conceptual Design Report (1509.02910)
- 2016 - DOE CD-3 approval - Technical Design Report (1703.09144)
- March 2017 - LUX removed from water tank
- 2018 - Underground construction begins
- 2019 - Commissioning

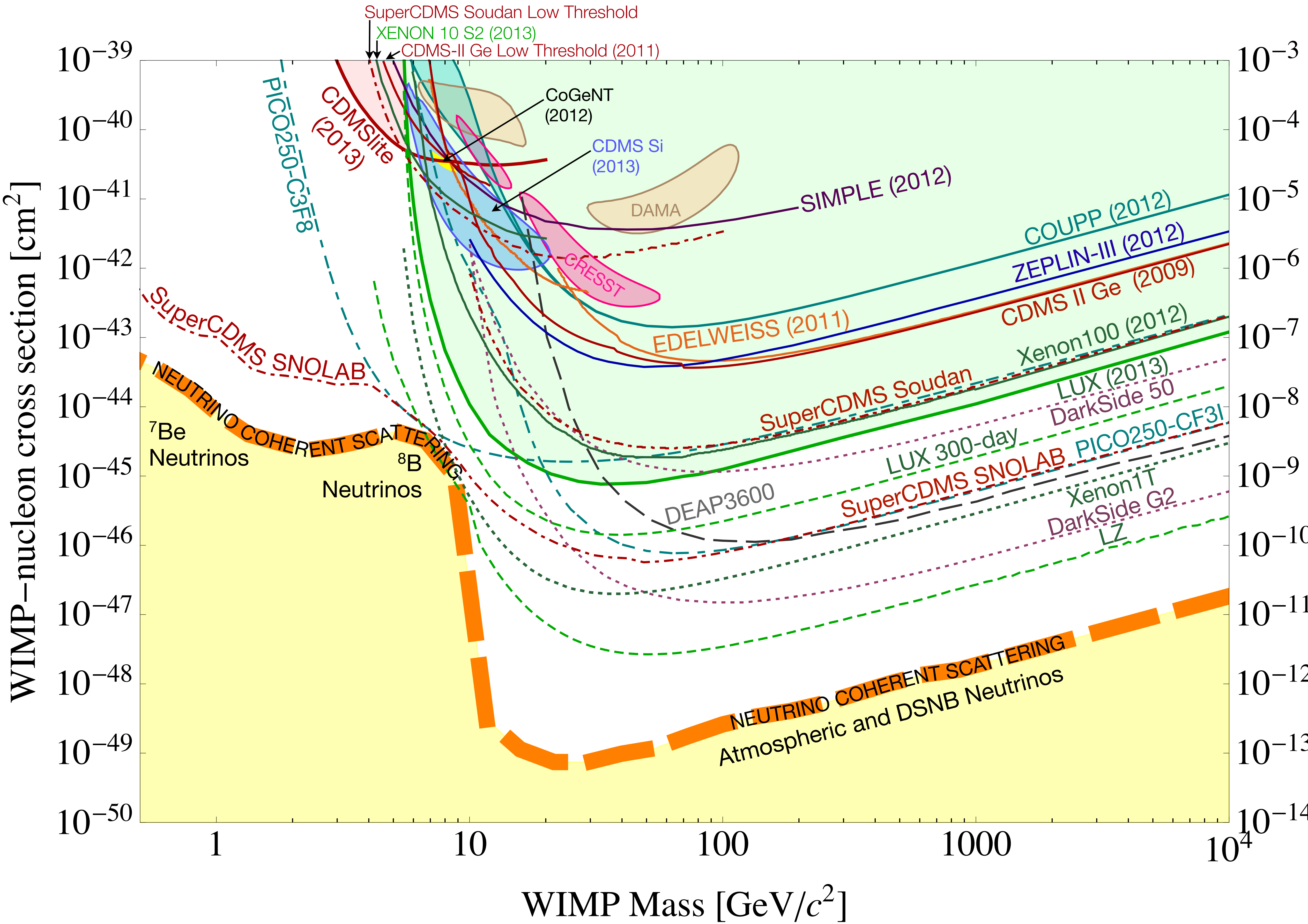
Schedule

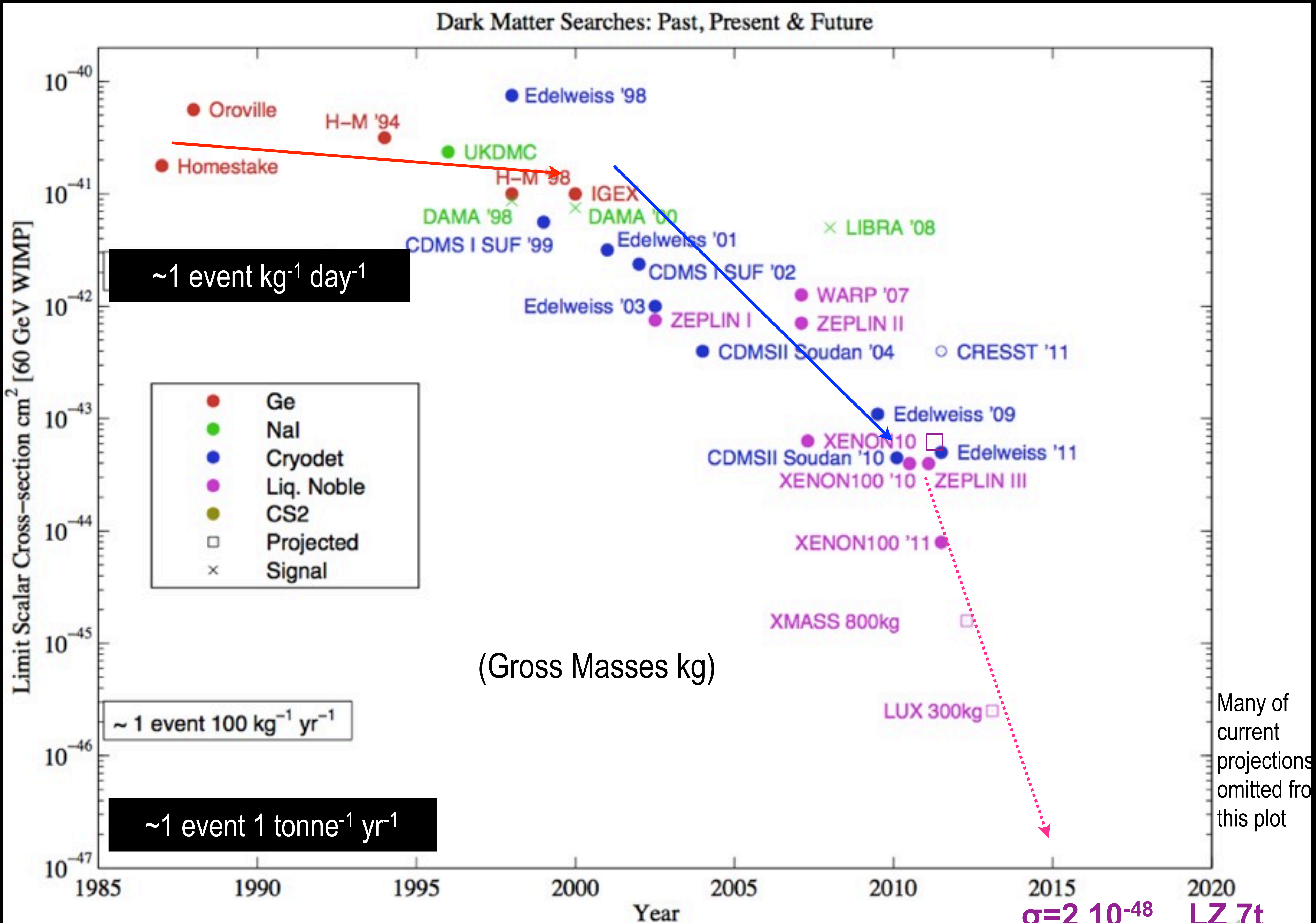
- Competition is fierce!
  - XENON1T out with new results, already heading to XENONnT
    - Infrastructure already in place - update of TPC and cryostat
  - PandaX also has a strong group
- We're moving as fast as we can!

Summary

- Liquid xenon TPCs are the leading technology in the search for ~10 GeV and above WIMPs (spin independent)
  - Mature technology, challenge is to make the detectors bigger
  - Scaling up raises new technical questions (HV, internal radioactivity, …)
- LZ is poised to achieve a factor >30 more sensitivity than current best limits
- The race is on for the next order of magnitude in sensitivity

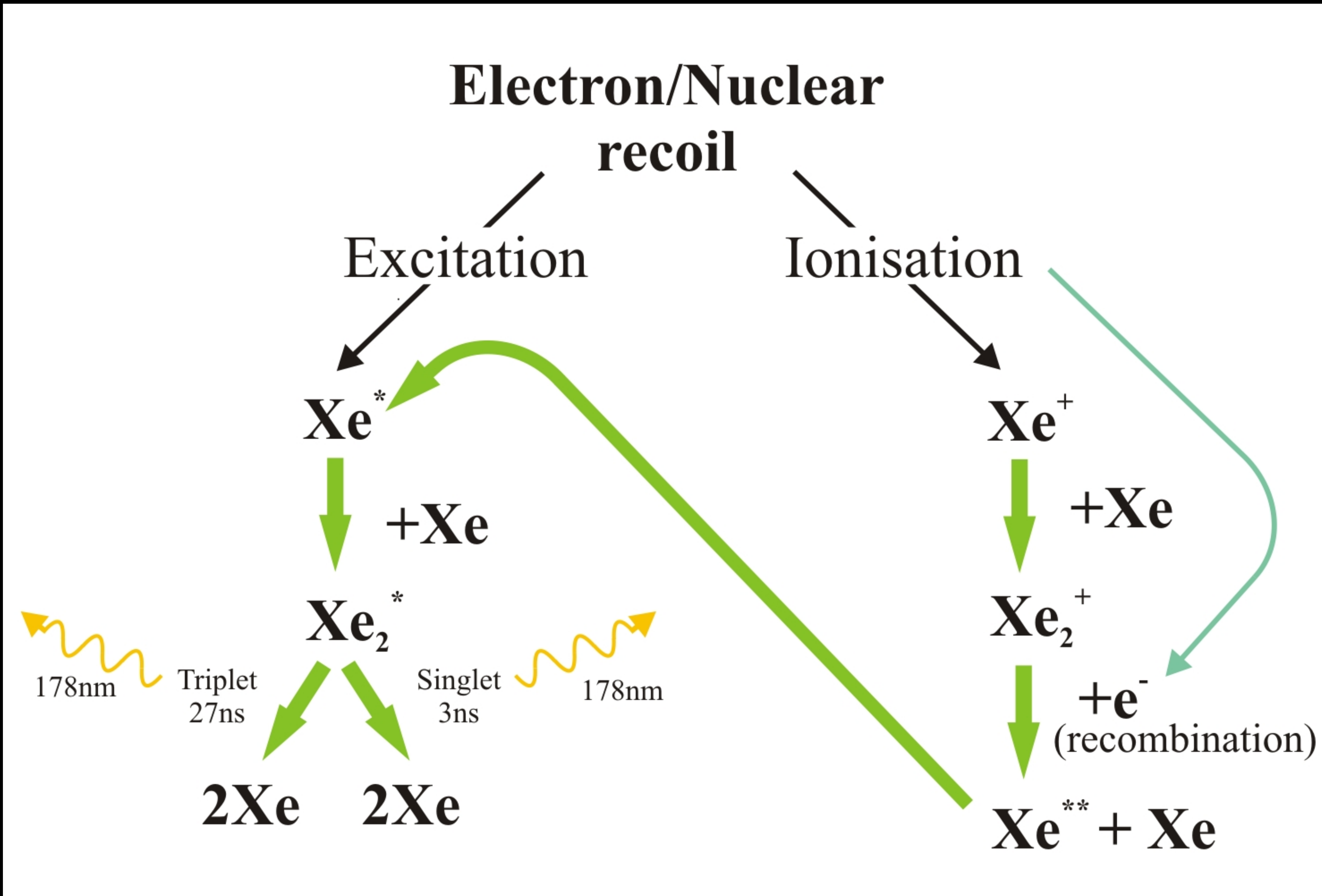
End


SuperCDMS Soudan Low Threshold
XENON 10 S2 (2013)
CDMS-II Ge Low Threshold (2011)
PICO250-C3F8
CDMSlite (2013)
CoGeNT (2012)
CDMS Si (2013)
DAMA
SIMPLE (2012)
COUPP (2012)
ZEPLIN-III (2012)
CDMS II Ge (2009)
CRESST
EDELWEISS (2011)
Xenon100 (2012)
SuperCDMS Soudan
LUX (2013)
DarkSide 50
LUX 300-day
PICO250-CF3I
SuperCDMS SNOLAB
DEAP3600
Xenon1T
DarkSide G2
LZ
SuperCDMS SNOLAB
NEUTRINO COHERENT SCATTERING
7Be Neutrinos
8B Neutrinos
NEUTRINO COHERENT SCATTERING
Atmospheric and DSNB Neutrinos
WIMP–nucleon cross section [cm2]
WIMP Mass [GeV/c2]
10−39
10−40
10−41
10−42
10−43
10−44
10−45
10−46
10−47
10−48
10−49
10−50
10−3
10−4
10−5
10−6
10−7
10−8
10−9
10−10
10−11
10−12
10−13
10−14
1
10
100
1000
104



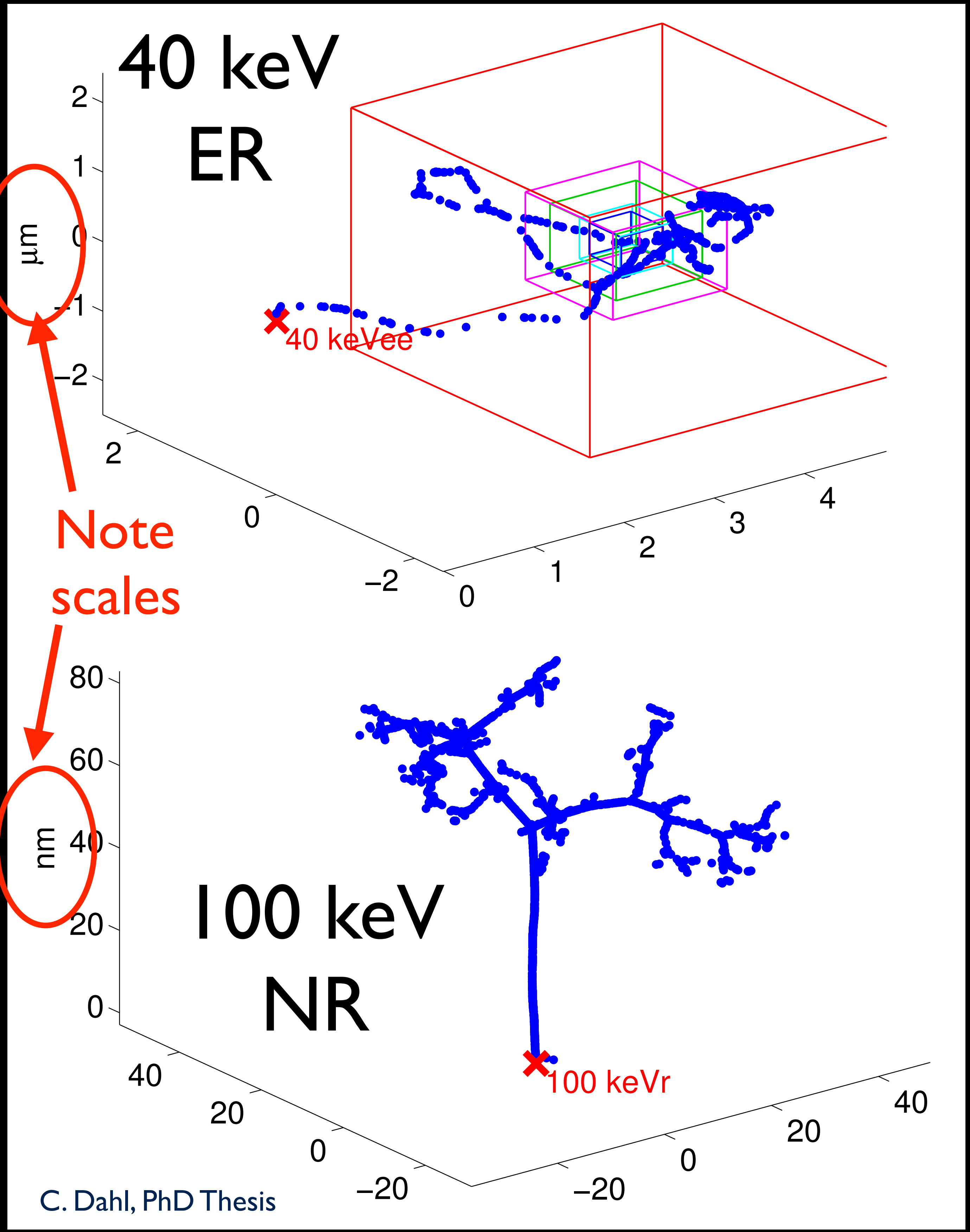
Dark Matter Searches: Past, Present & Future
Limit Scalar Cross-section cm^2 [60 GeV WIMP]
Year
Oroville
Homestake
H–M '94
UKDMC
H–M '98
IGEX
DAMA '98
DAMA '00
Edelweiss '98
CDMS I SUF '99
Edelweiss '01
CDMS I SUF '02
LIBRA '08
Edelweiss '03
ZEPLIN I
WARP '07
ZEPLIN II
CDMSII Soudan '04
CRESST '11
Edelweiss '09
XENON10
CDMSII Soudan '10
Edelweiss '11
XENON100 '10
ZEPLIN III
XENON100 '11
XMASS 800kg
LUX 300kg
Ge
NaI
Cryodet
Liq. Noble
CS2
Projected
Signal
~1 event kg^{-1} day^{-1}
~ 1 event 100 kg^{-1} yr^{-1}
~1 event 1 tonne^{-1} yr^{-1}
(Gross Masses kg)
Many of
current
projections
omitted fro
this plot
σ=2 10^{-48}
LZ 7t

Some LXe physics



Some LXe physics

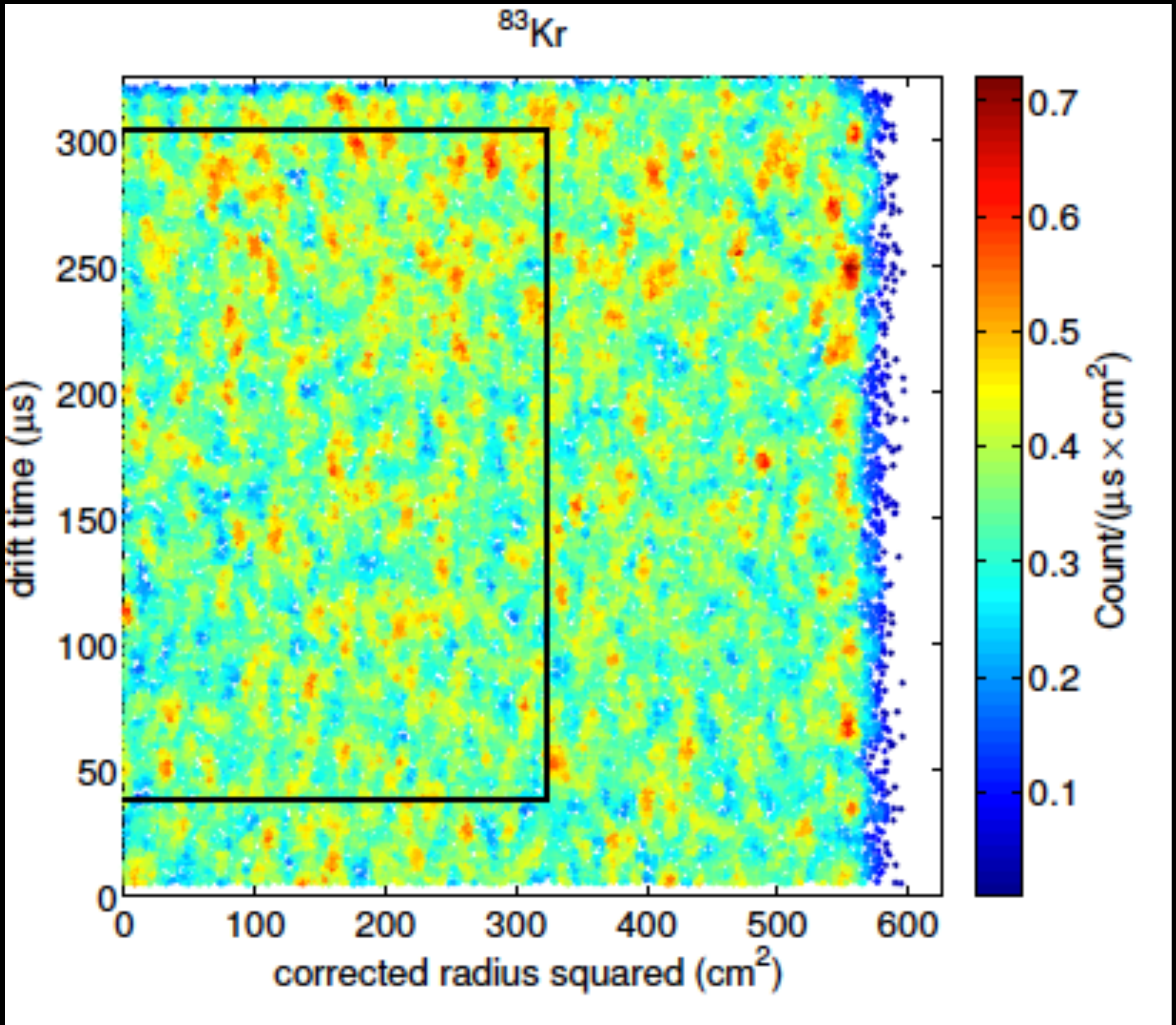
- Significant difference between ER and NR tracks
- ER lead to more signal than NR
    - More NR energy goes into heat and is lost
        - Lindhard factor, L_{eff}, Quenching factor
    - Two energy scales keV_{ee} and keV_{nr}
- Leads to different behavior with field
- Also leads to ER/NR discrimination



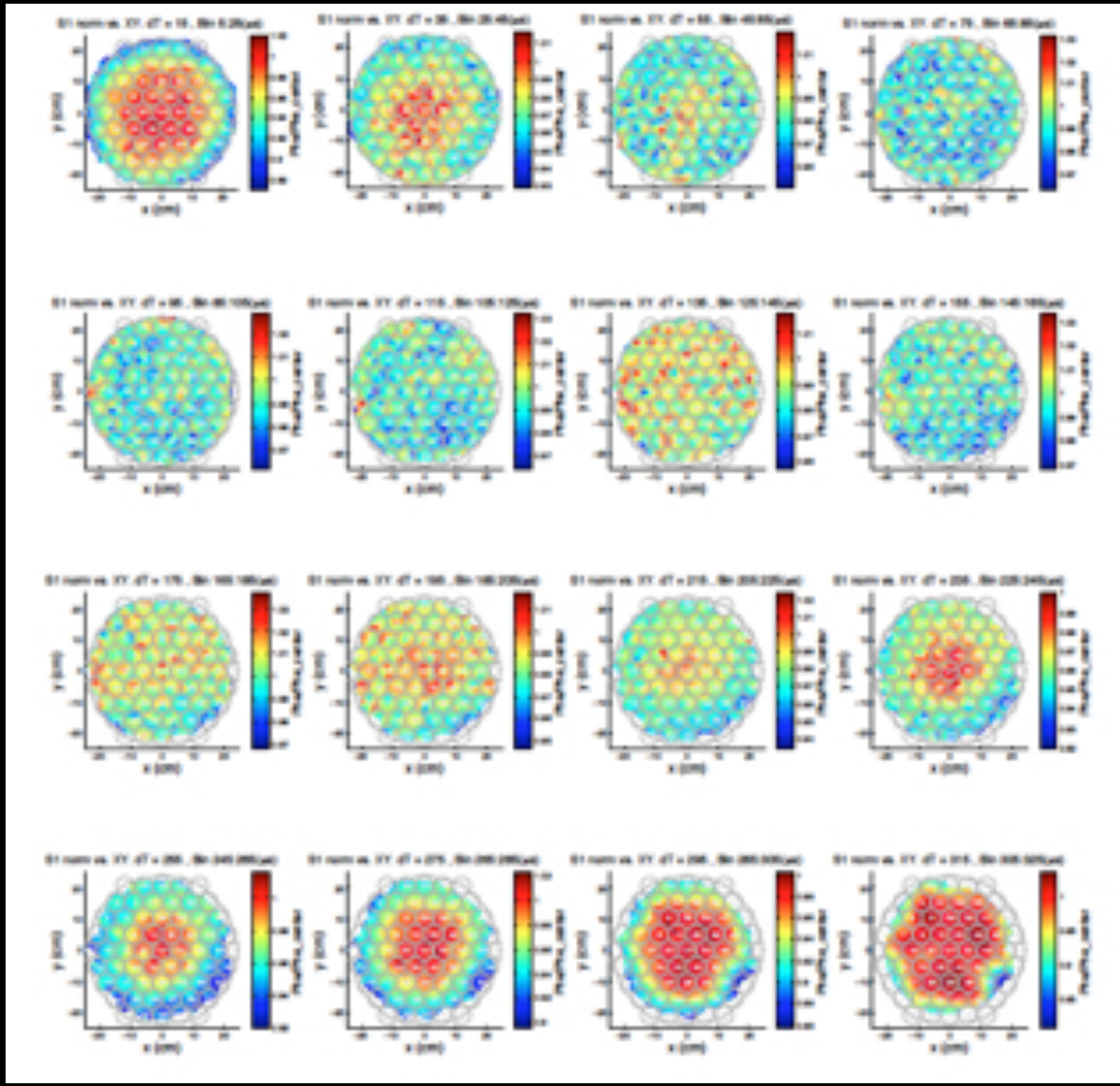
Requires calibration

- LUX has really done great work here
  - Kr-83m - Over 1e6 events spread uniformly throughout detector

Fiducial volume determination



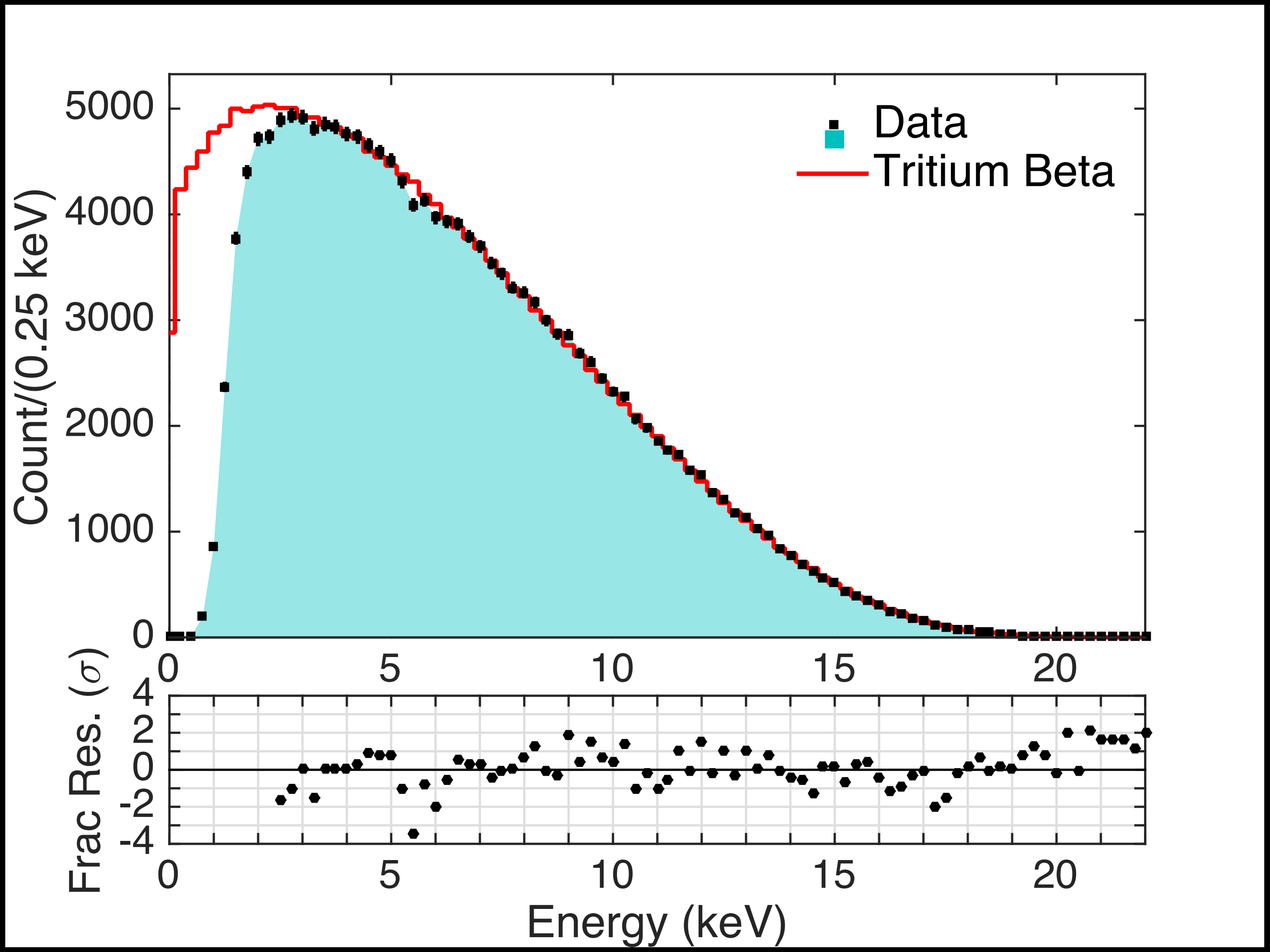
Position-based S1 corrections



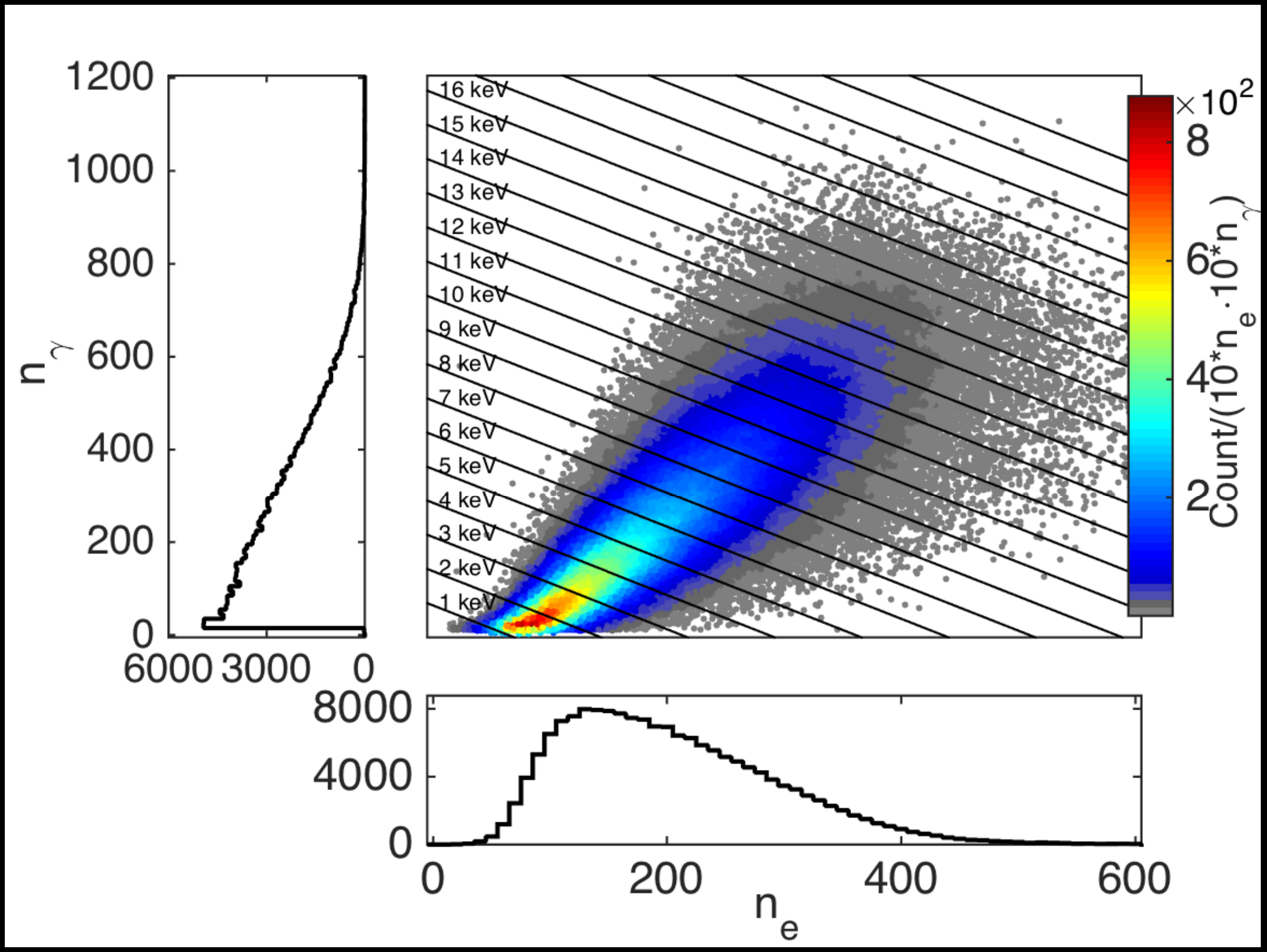
Requires calibration

- LUX has really done great work here
  - Tritiated methane (CH3T) - to measure low energy ER band

Low energy ER

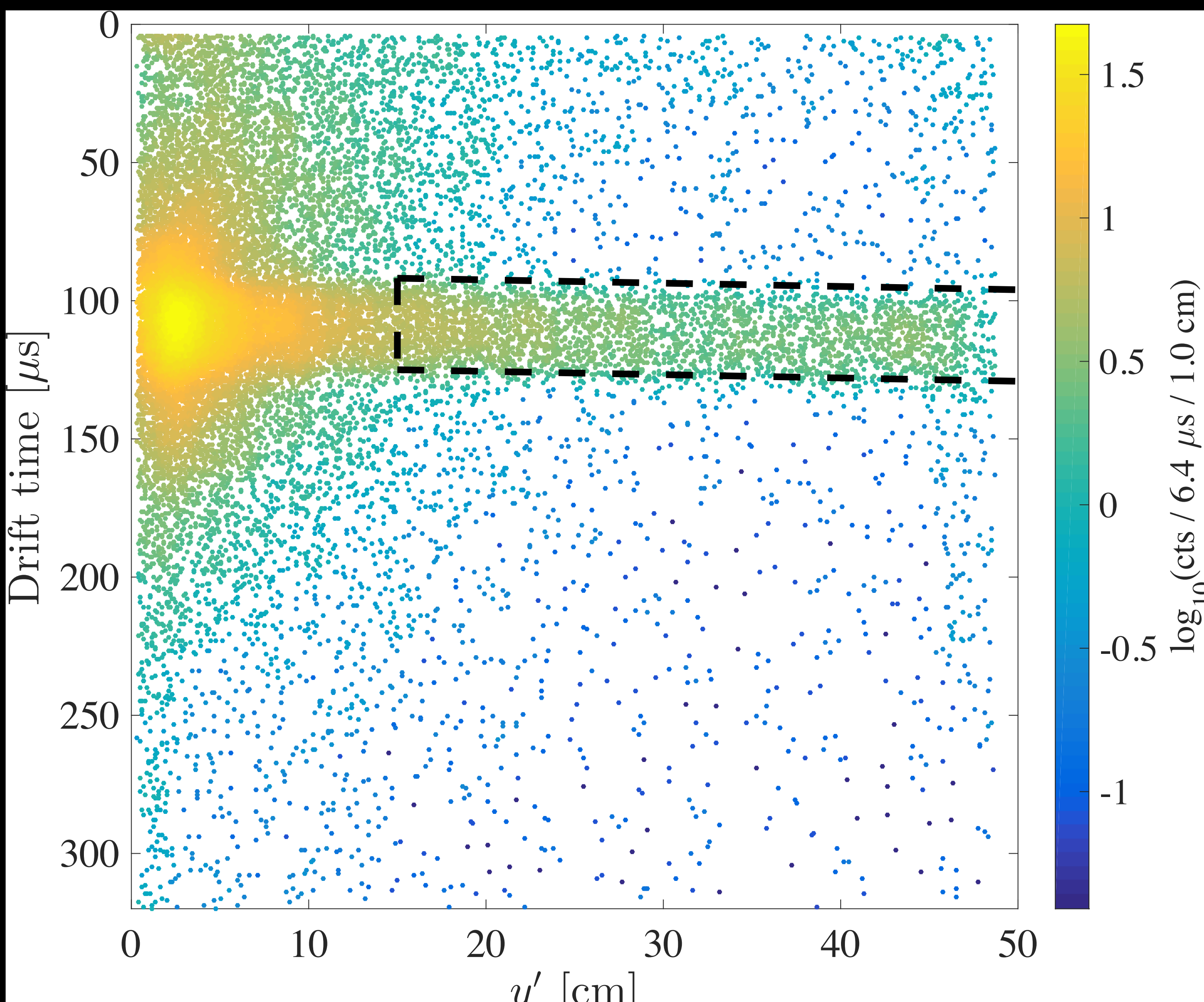


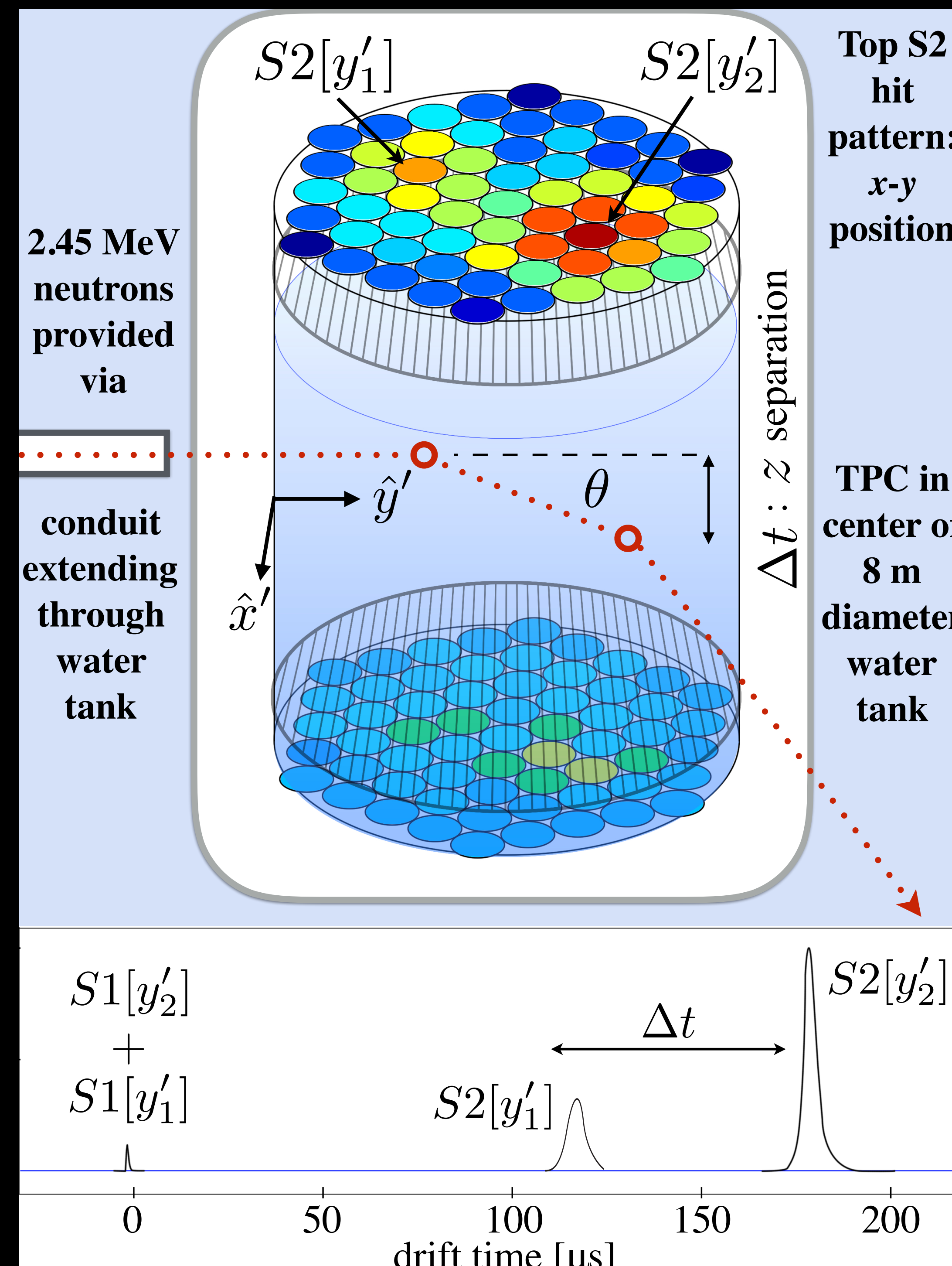
Measured in both light and charge



Requires calibration

- LUX has really done great work here
  - DD neutron generator to measure NR yields





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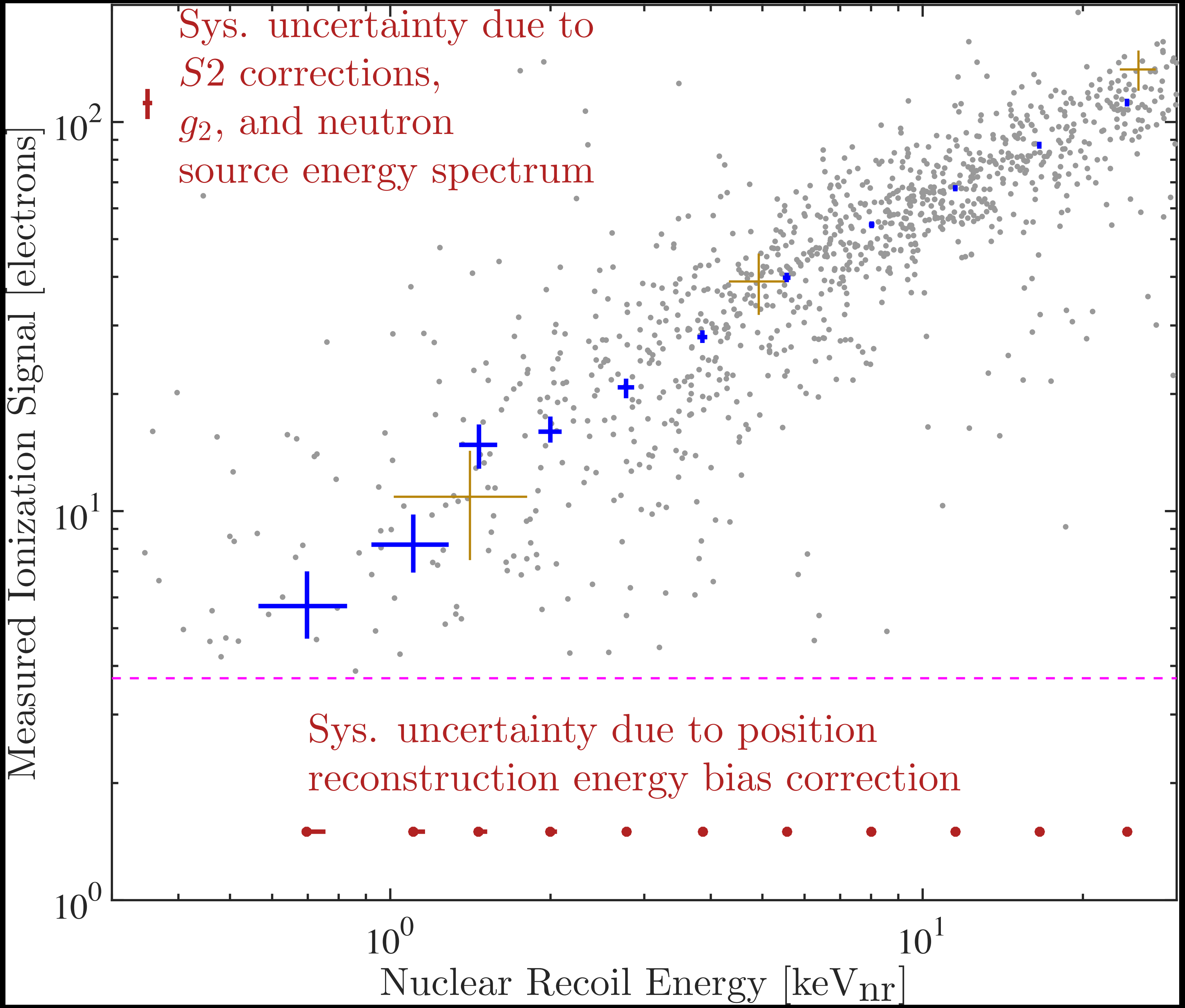
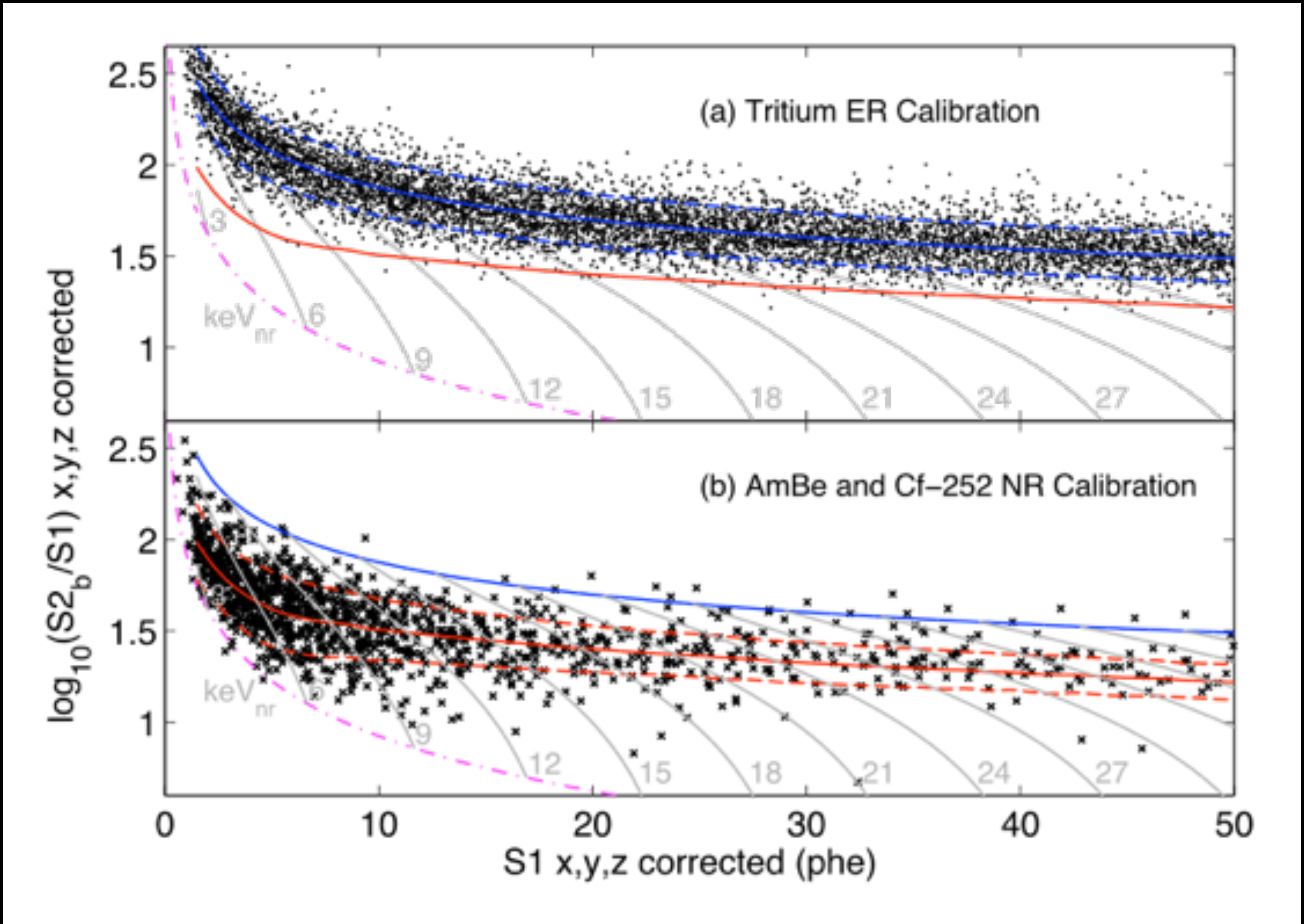
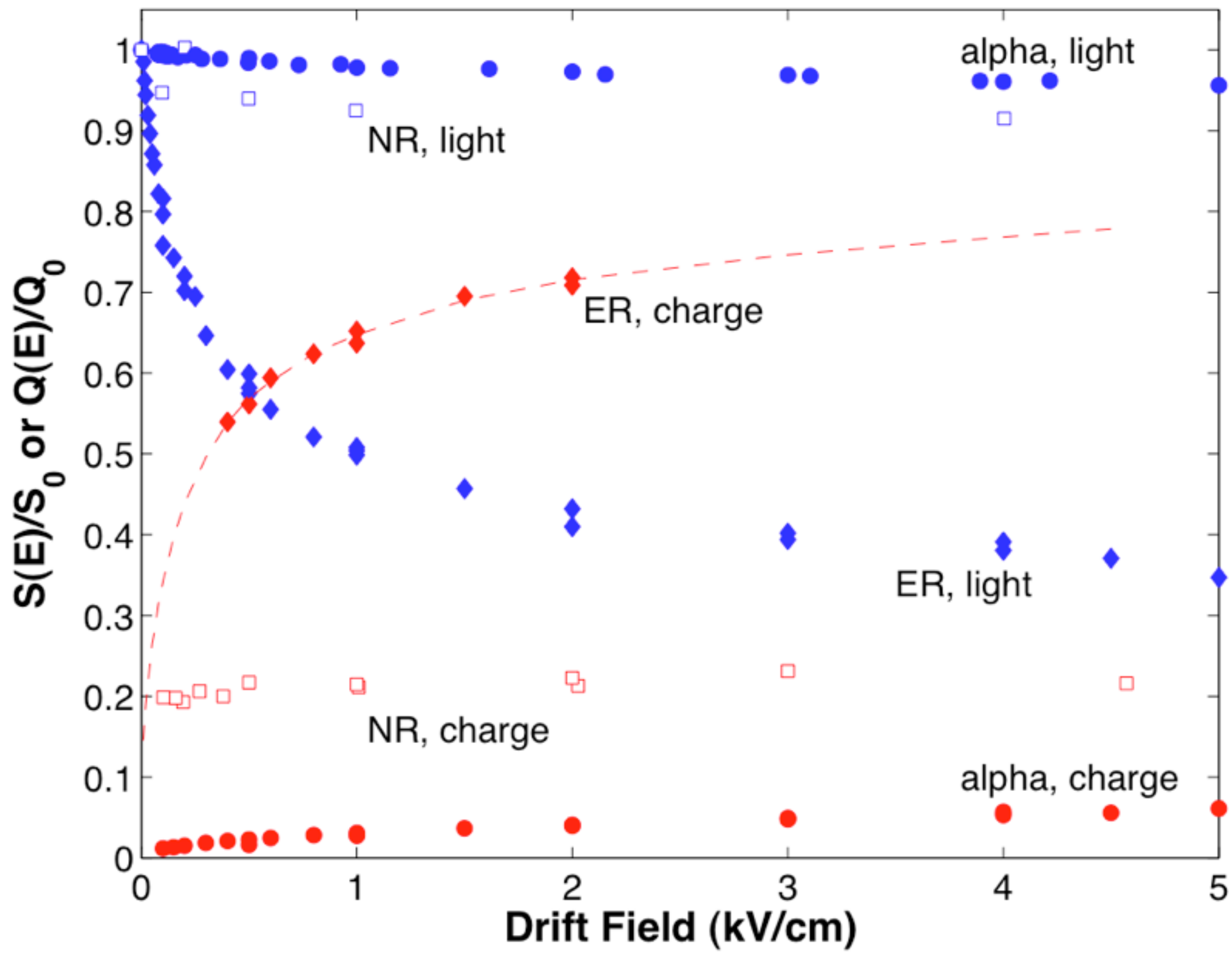


Leads to background rejection



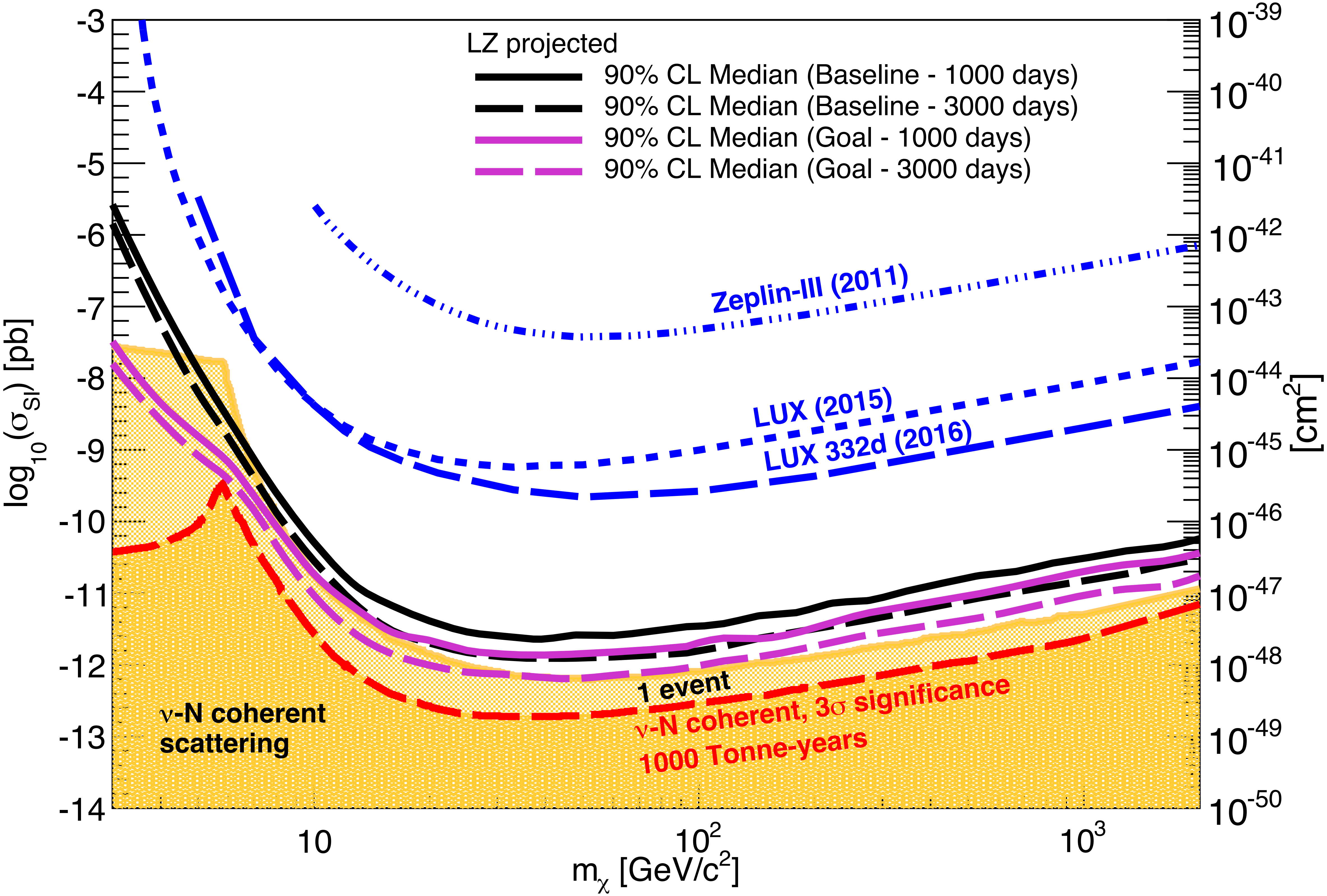
Grey contours indicate lines of constant energy

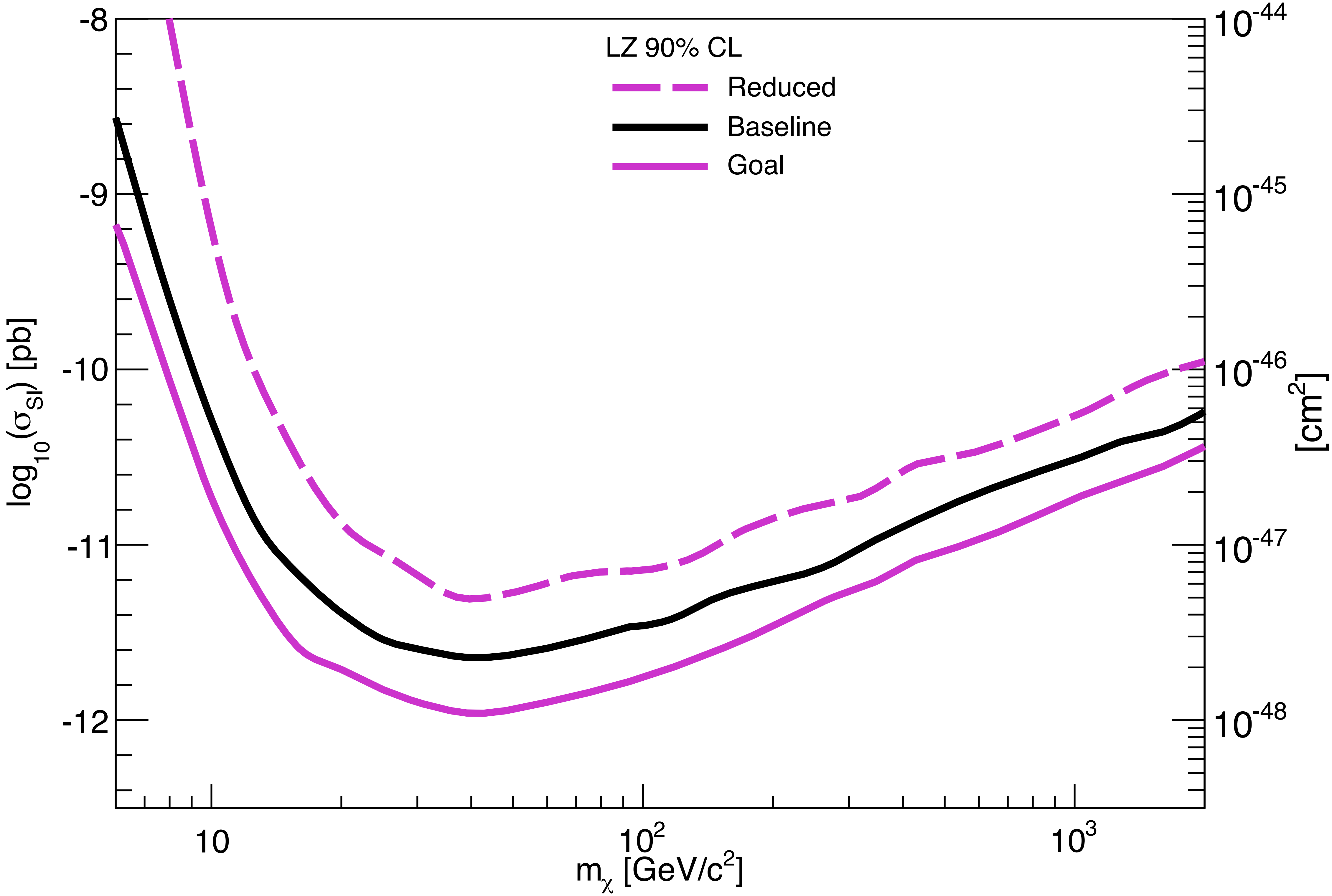
Some LXe physics



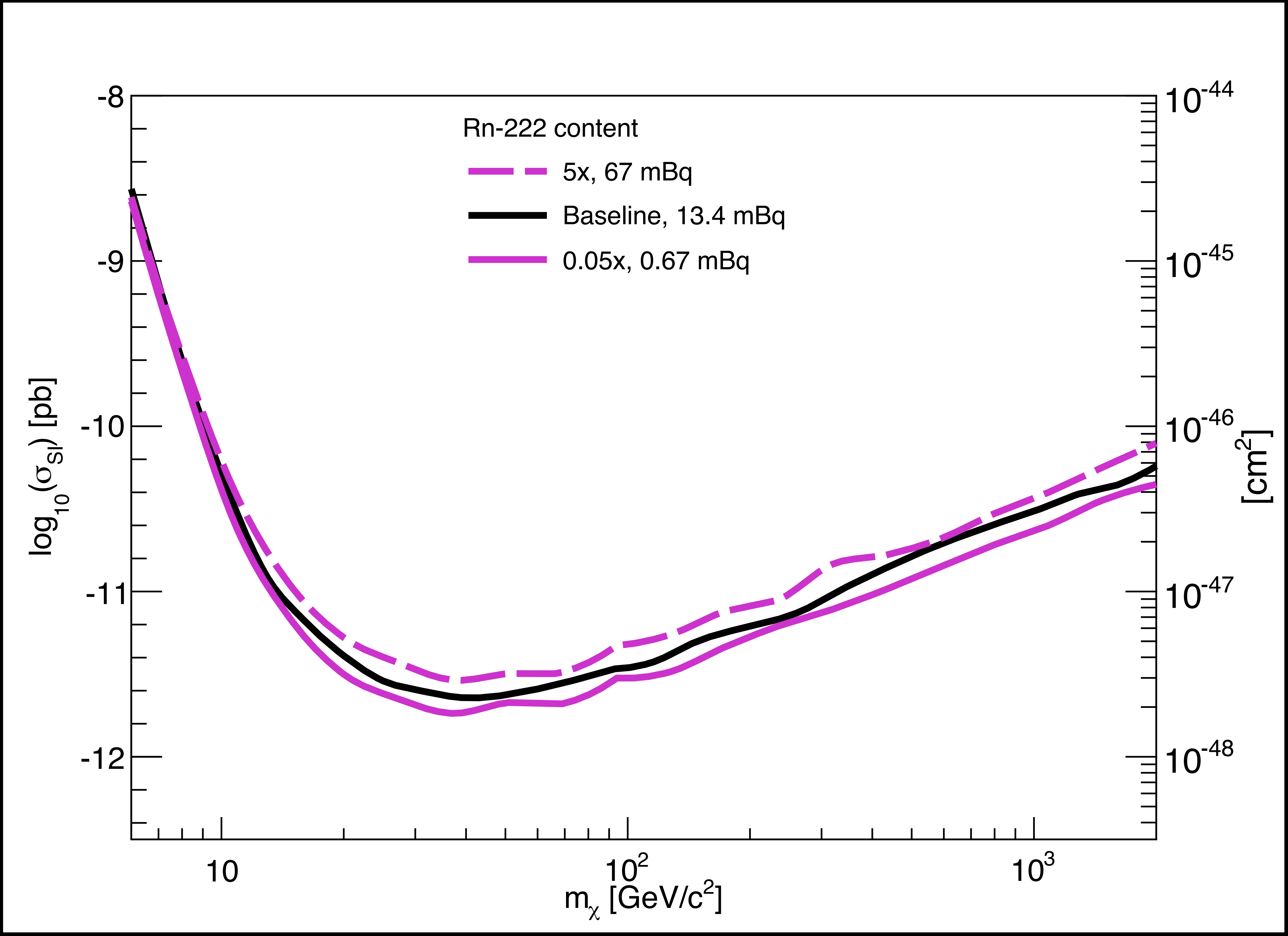
E. Aprile et al., Phys. Rev. Lett. **97**, 081302 (2006)

For 122 keV ER, 56 keV NR


LZ projected
90% CL Median (Baseline - 1000 days)
90% CL Median (Baseline - 3000 days)
90% CL Median (Goal - 1000 days)
90% CL Median (Goal - 3000 days)
Zeplin-III (2011)
LUX (2015)
LUX 332d (2016)
1 event
ν-N coherent, 3σ significance
1000 Tonne-years
ν-N coherent
scattering
log10(σSI) [pb]
[cm2]
mχ [GeV/c2]
-3
-4
-5
-6
-7
-8
-9
-10
-11
-12
-13
-14
10
10^2
10^3
10^-39
10^-40
10^-41
10^-42
10^-43
10^-44
10^-45
10^-46
10^-47
10^-48
10^-49
10^-50



LZ 90% CL
Reduced
Baseline
Goal
log10(σSI) [pb]
-8
-9
-10
-11
-12
10
10^2
10^3
m_χ [GeV/c^2]
10^-44
10^-45
10^-46
10^-47
10^-48
[cm^2]



Rn-222 content
5x, 67 mBq
Baseline, 13.4 mBq
0.05x, 0.67 mBq
-8
-9
-10
-11
-12
$\log_{10}(\sigma_{SI})$ [pb]
10^{-44}
10^{-45}
10^{-46}
10^{-47}
10^{-48}
[cm^2]
10
10^2
10^3
m_χ [GeV/c^2]

PLR (Profile Likelihood Ratio)

- Simple fiducial of 5600 kg (X,Y,Z position info not yet implemented in PLR)
- Dominant ER: Rn, Kr, pp-neutrinos spatially uniform like signal