DARK MATTER EXPERIMENTS:

QUIET SPACES
TO SEARCH FOR BSM PHYSICS

HENRIQUE ARAÚJO

Imperial College London
(LUX & LZ Collaborations)

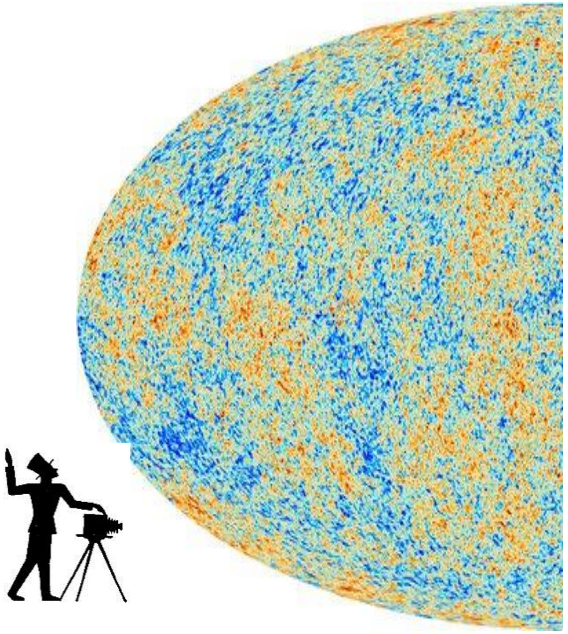
Imperial College London

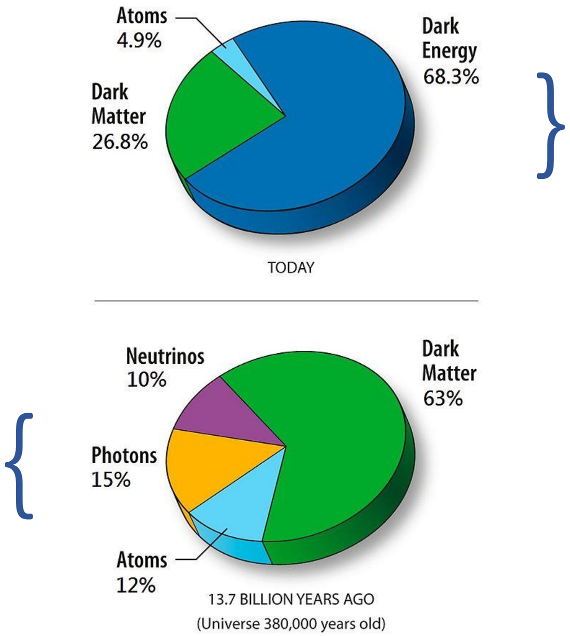
OUTLINE

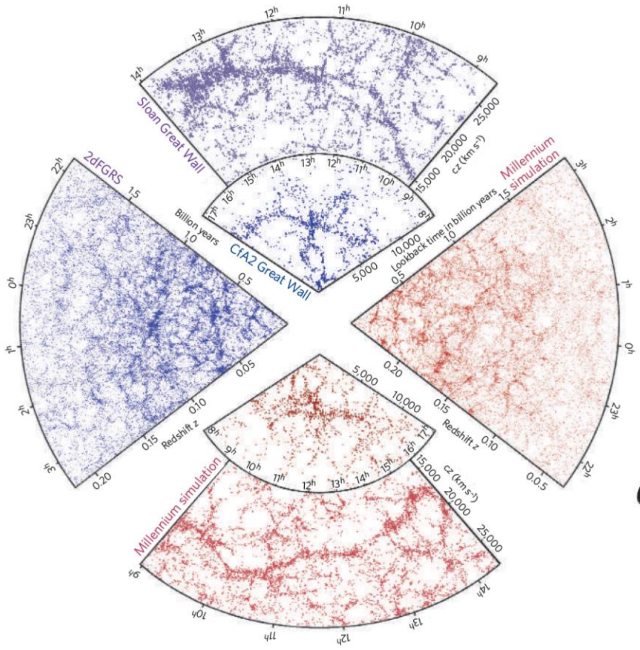
- Direct dark matter searches
- Experimental challenges & opportunities
- The noble liquid xenon
- Pushing down the energy threshold
- The LUX-ZEPLIN (LZ) experiment
- Physics from NR and ER interactions

A DARK UNIVERSE

- Λ-CDM cosmology is a remarkably successful model
  - Initial conditions photographed at surface of last scatters (CMB)
    - Left to evolve for 13.7 Gyr under two dark ‘fluids’ – DE and DM
      - To produce what we see today – normal matter (almost) doesn’t matter

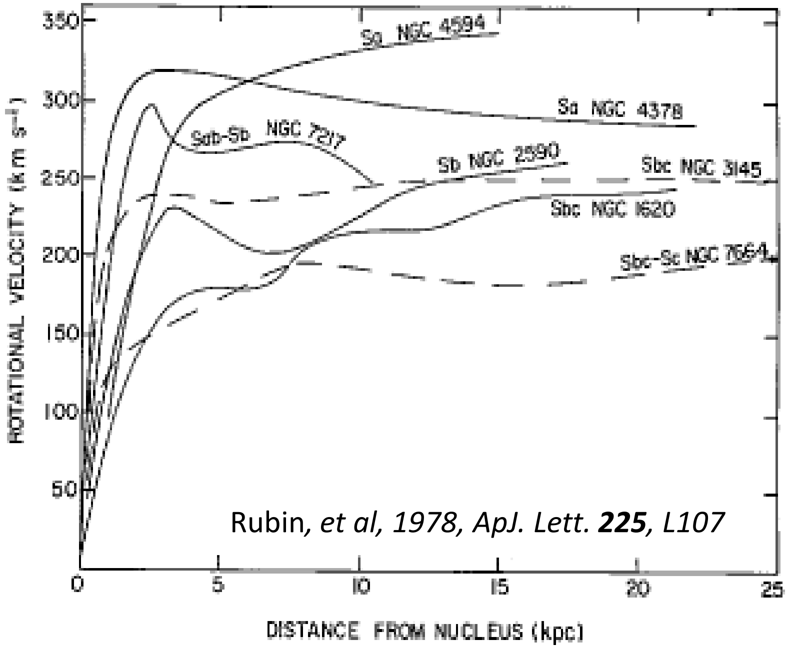




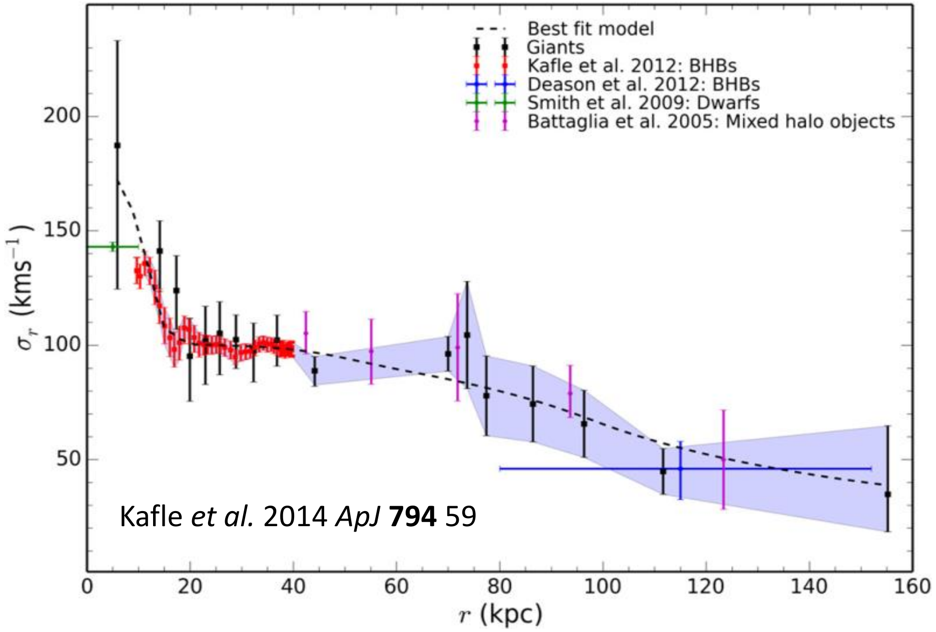


OUR DARK MILKY WAY

- Spiral galaxies ‘spin’ too quickly for their observed ‘luminous’ mass
  - Our Milky Way is no exception: we too are immersed in a DM halo
  - Direct search experiments probe our galactic DM via elastic scattering
  - Density near Sun ~0.3 GeV/cm^3, mean particle speed $v \sim$ 300 km/s (0.001c)

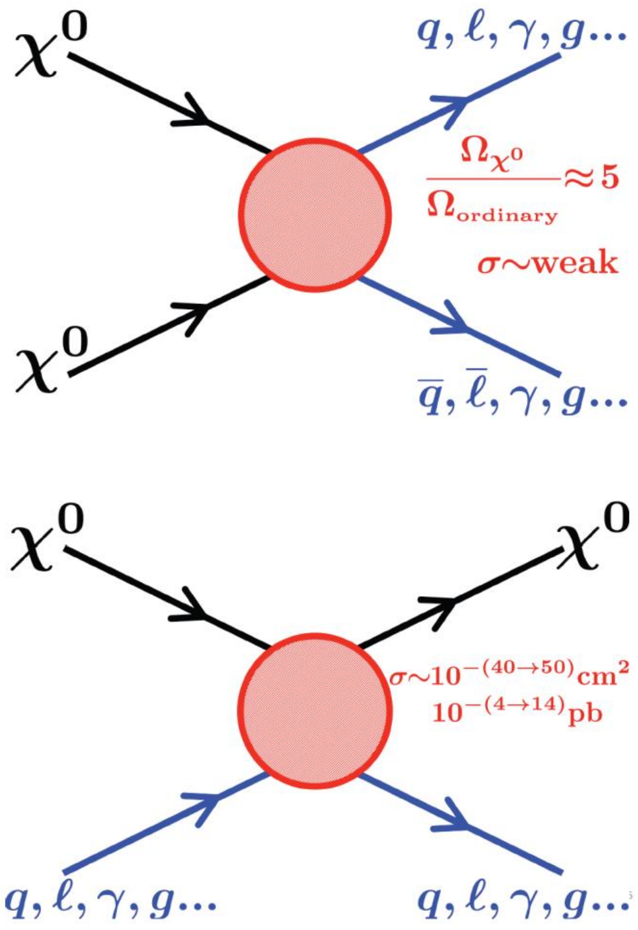


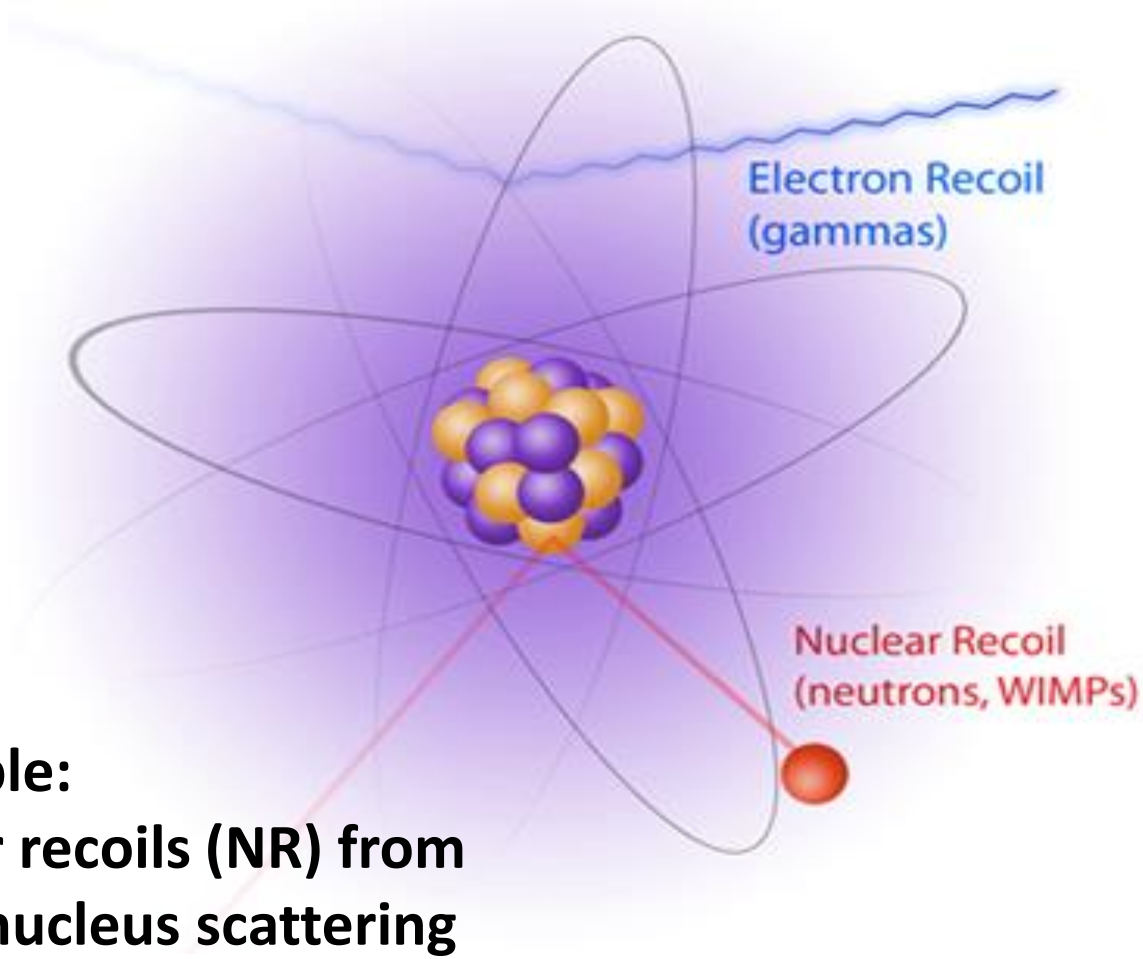
Rubin, *et al, 1978, ApJ. Lett.* ***225***, *L107*



Kafle *et al.* 2014 *ApJ* **794** 59

WEAKLY INTERACTING MASSIVE PARTICLES





Main observable:
O(keV) nuclear recoils (NR) from elastic WIMP-nucleus scattering

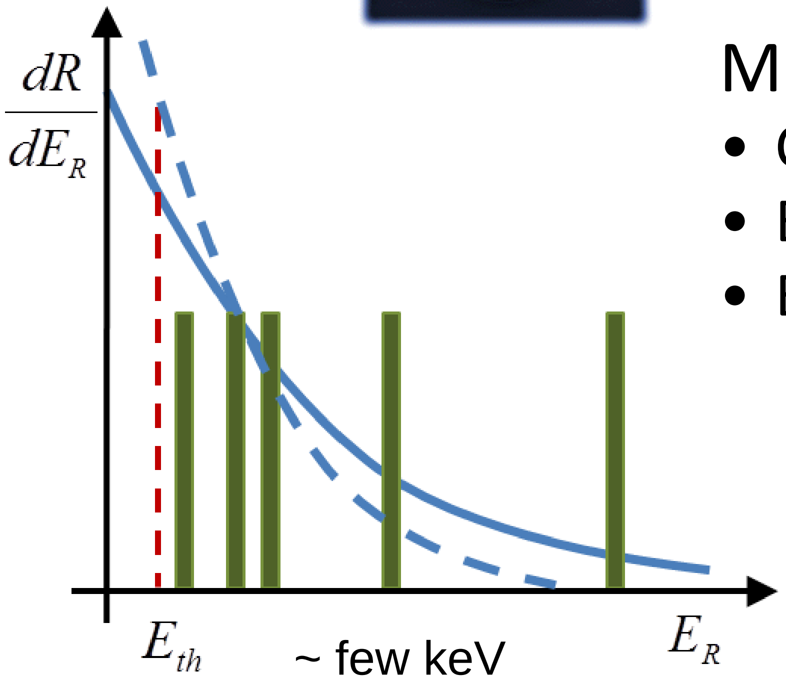
WIMP-NUCLEUS ELASTIC SCATTERING

The 'spherical cow' galactic model

- DM halo is 3-dimensional, stationary, with no lumps
- Isothermal sphere with density profile $\rho \propto r^{-2}$
- Local density $\rho_0 \sim$ 0.3 GeV/cm^3 (~1/pint for 100 GeV WIMPs)

Maxwellian (truncated) velocity distribution, f(v)

- Characteristic velocity v_0=220 km/s
- Escape velocity v_{esc}=544 km/s
- Earth velocity v_E=230 km/s



Nuclear Recoil (NR) energy spectrum [events/kg/day/keV]

$$\frac{dR}{dE_R} = \frac{\rho_0 \sigma_A}{2 m_\chi \mu_A^2} F^2(q) \int_{v_{min}}^{v_{max}} \frac{f(\vec{v})}{v} d^3v \approx \frac{R_0}{E_0 r} e^{-E_R/E_0 r}$$

WIMP-NUCLEON ELASTIC SCATTERING XS

- **Presenting coupling to p and n more useful than coupling to nucleus**
  - Compare different targets materials, accelerator & indirect searches
- **Spin-independent (scalar) interaction**

$$\sigma_A^{SI}(q \to 0) = \frac{4\mu_A^2}{\pi}[Zf_p + (A-Z)f_n]^2 \approx \frac{\mu_A^2}{\mu_p^2}\sigma_p A^2$$

– A^2 enhancement (coherence) – pMSSM within reach

- **Spin-dependent (axial-vector) interaction**

$$\sigma_A^{SD}(q \to 0) = \frac{\mu_A^2}{\mu_p^2}\sigma_{p,n}^{SD}\left[\frac{4}{3}\frac{J+1}{J}\left(a_p\langle S_p\rangle + a_n\langle S_n\rangle\right)^2\right]$$

– Nuclear spin J replaces A^2 enhancement – less sensitive

– Some targets more sensitive to proton, others to neutron scattering

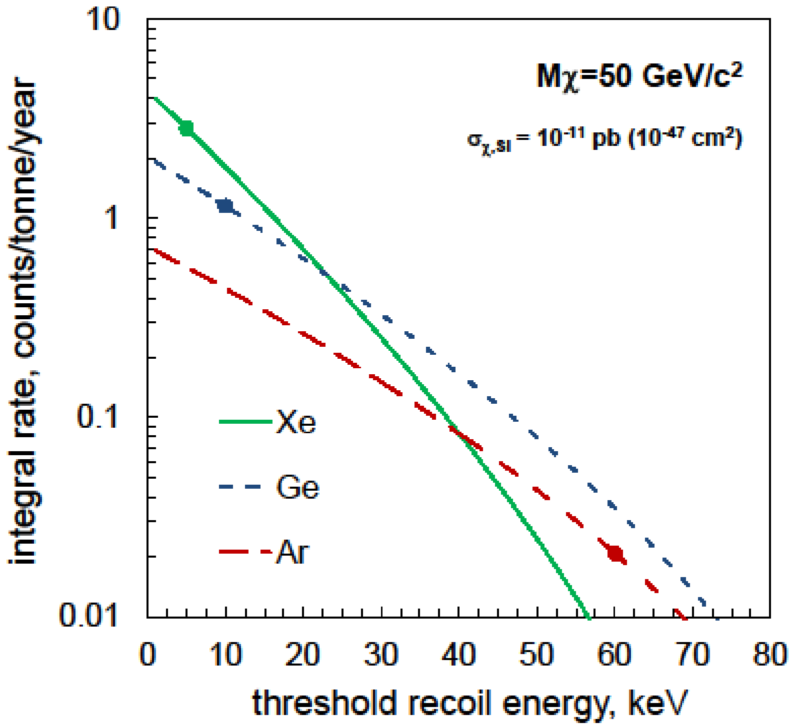
Non-relativistic EFT

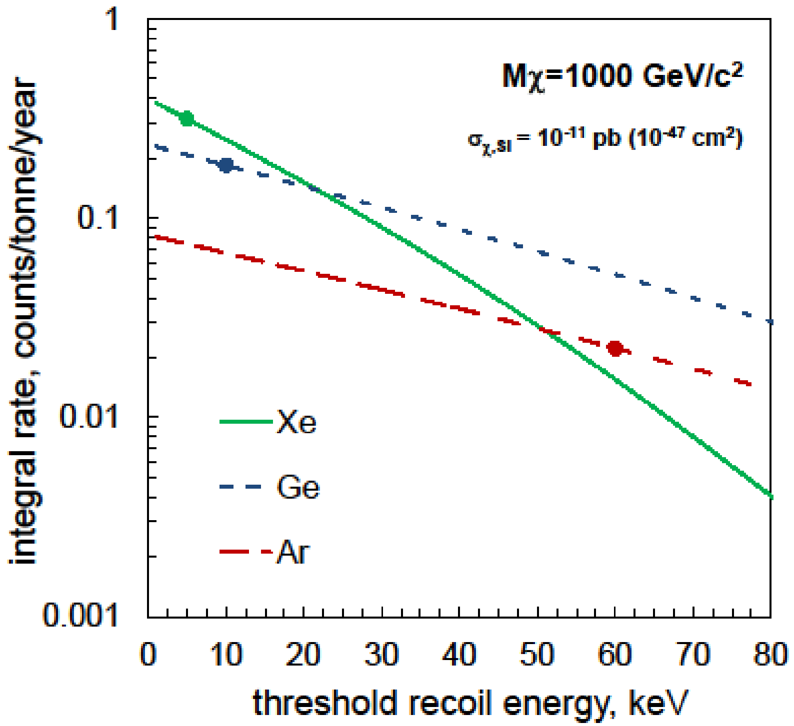
11 operators for exchange of spin-0 or spin-1 mediators

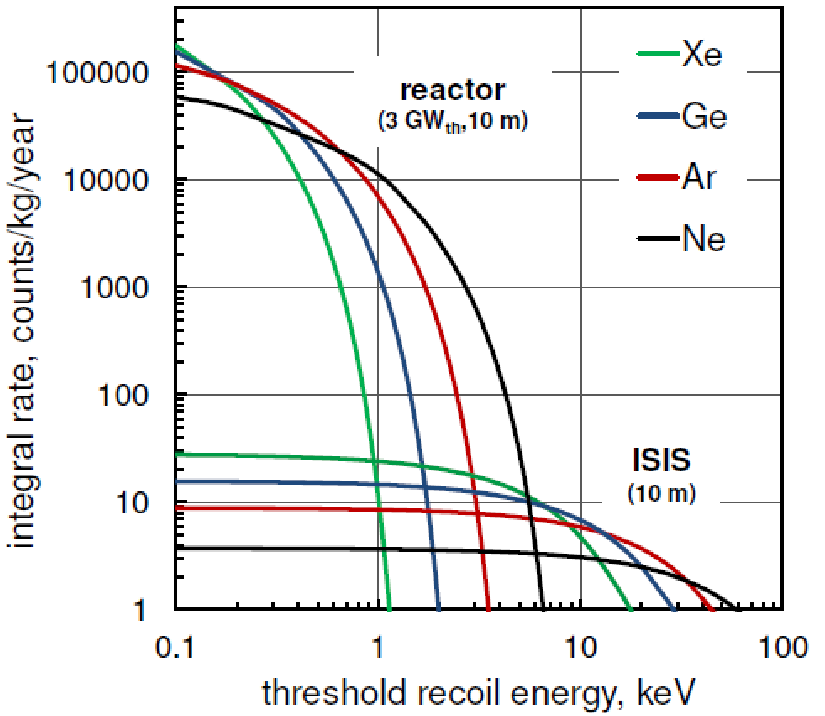
6 independent responses contribute to amplitude

(Fitzpatrick, Haxton, Anand, et al: 1203.3542, 1405.6690)

NUCLEAR RECOIL SPECTRUM



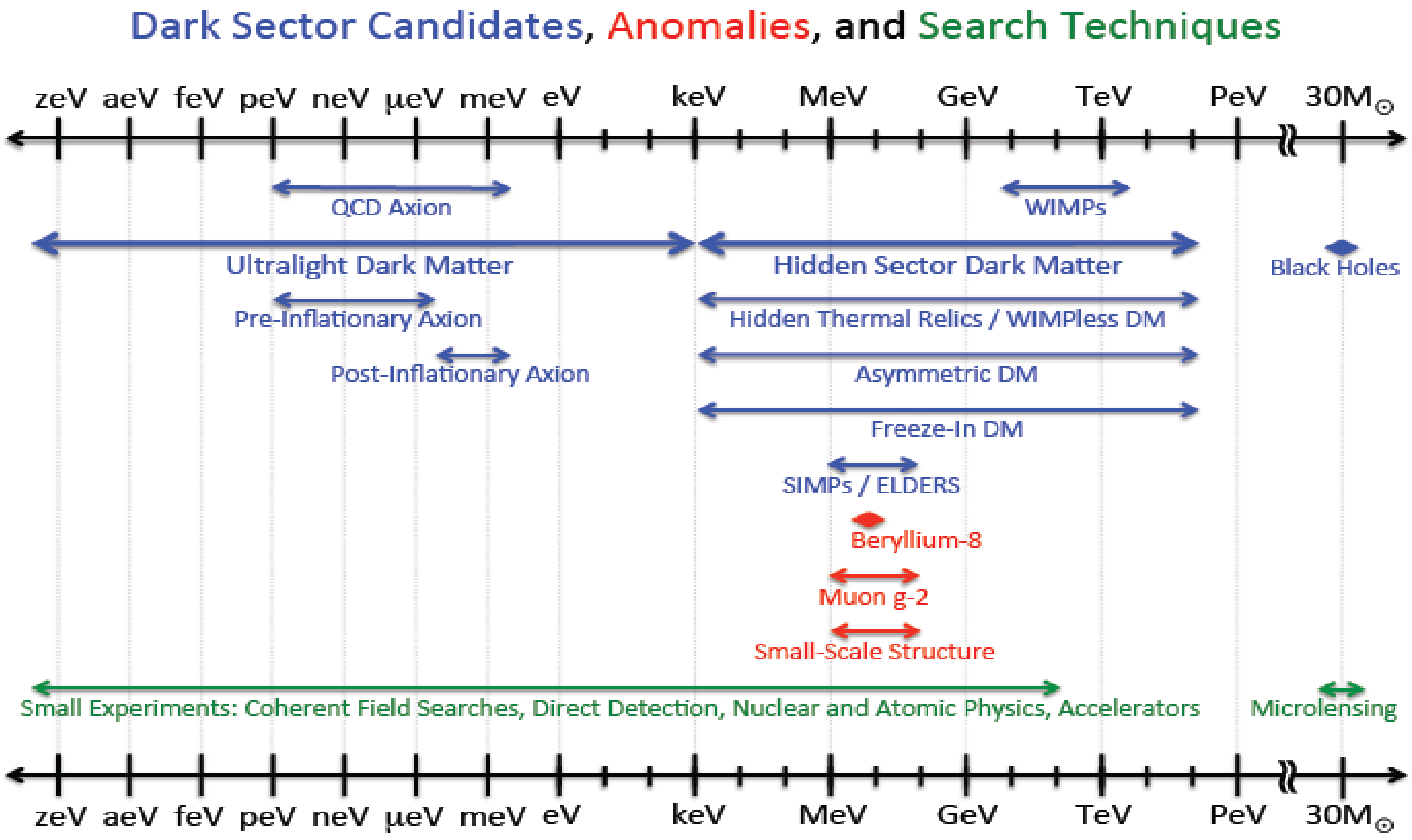




WIMP-nucleus SI scattering rate (A^2 enhancement)

CEνNS scattering (N^2 enhancement)

THE (WIDER) DARK MATTER LANDSCAPE



US Cosmic Visions: New Ideas in Dark Matter 2017: Community Report (arXiv:1707.04591)

THE EXPERIMENTAL CHALLENGE

- Low-energy detection is easy ;)
  - Several technologies allow sub-keV NR detection
- Rare event searches are also easy ;)
  - Not a problem at >100 MeV, think neutrinos

Key detector requirements

- Large mass x time (~tonne·yr)
- Low E_R threshold (~keV)
- Low background (~10-100 μDRU)
- ER/NR discrimination

- But doing *both* is hard!
  - Large mass gives exposure & self-shielding
  - Hard to collect signal 'carriers' (threshold)

- By the way: there is no trigger…

WIMP SEARCH TECHNOLOGY ZOO

Ionisation Detectors

Targets: Ge, Si, CS_2, CdTe

CoGeNT, CDEX, D3, DAMIC, DRIFT, DM-TPC, GENIUS, IGEX, MIMAC, NEWAGE, NEWS, TREX

Light & Ionisation Detectors

Targets: Xe, Ar

ArDM, Argo, **LUX**, WARP, DarkSide, DARWIN, Panda-X, XENON, **(ZEPLIN-II/III)**, **LUX-ZEPLIN**

cold (LN_2)

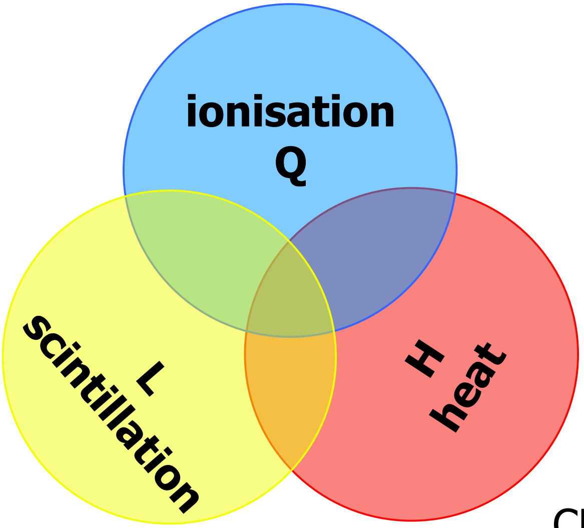
Heat & Ionisation Bolometers

Targets: Ge,Si

CDMS, (EDELWEISS)

SuperCDMS, (EURECA)

cryogenic (<50 mK)



Scintillators

Targets: NaI, Xe, Ar

ANAIS, MiniCLEAN, DAMA, DEAP-3600, DM-ICE, KIMS, LIBRA, PICOLON, (NAIAD), SABRE, XMASS, **(ZEPLIN-I)**

Bolometers

Targets: Ge, Si, Al_2O_3, TeO_2

CRESST-I, CUORE, CUORICINO

Light & Heat Bolometers

Targets: $CaWO_4$, BGO, Al_2O_3

CRESST, (ROSEBUD)

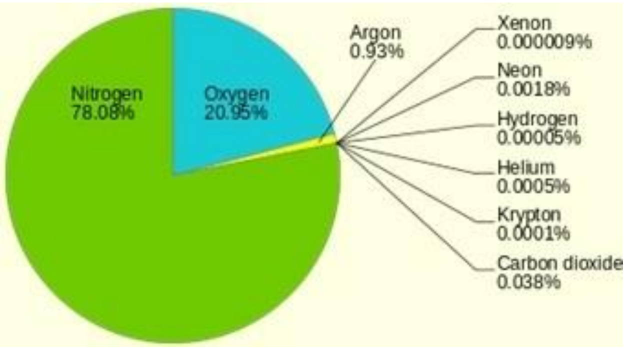
cryogenic (<50 mK)

Bubbles & Droplets

CF_3Br, CF_3I, C_3F_8, C_4F_{10}

COUPP, PICASSO, PICO, SIMPLE

XENON THE ‘FOREIGNER’…



Only 90 ppb in air:
Quite “exclusive”…

^{124}Xe	^{126}Xe	^{128}Xe	^{129}Xe	^{131}Xe	^{130}Xe	^{132}Xe	^{134}Xe	^{136}Xe
123.90589	125.90426	127.90353	128.9047	130.905083	129.90350	131.90415	133.90539	135.90722
0.10%	0.09%	1.91%	26.4%	21.2%	4.1%	26.9%	10.4%	8.90%
Stable	Stable	Stable	Stable	Stable	Stable	Stable	Stable	Stable

- No nasty radioisotopes, many physics opportunities: dark matter and neutrino physics
- Possibility of isotopic manipulation of target (enrichment/depletion) – same detector…

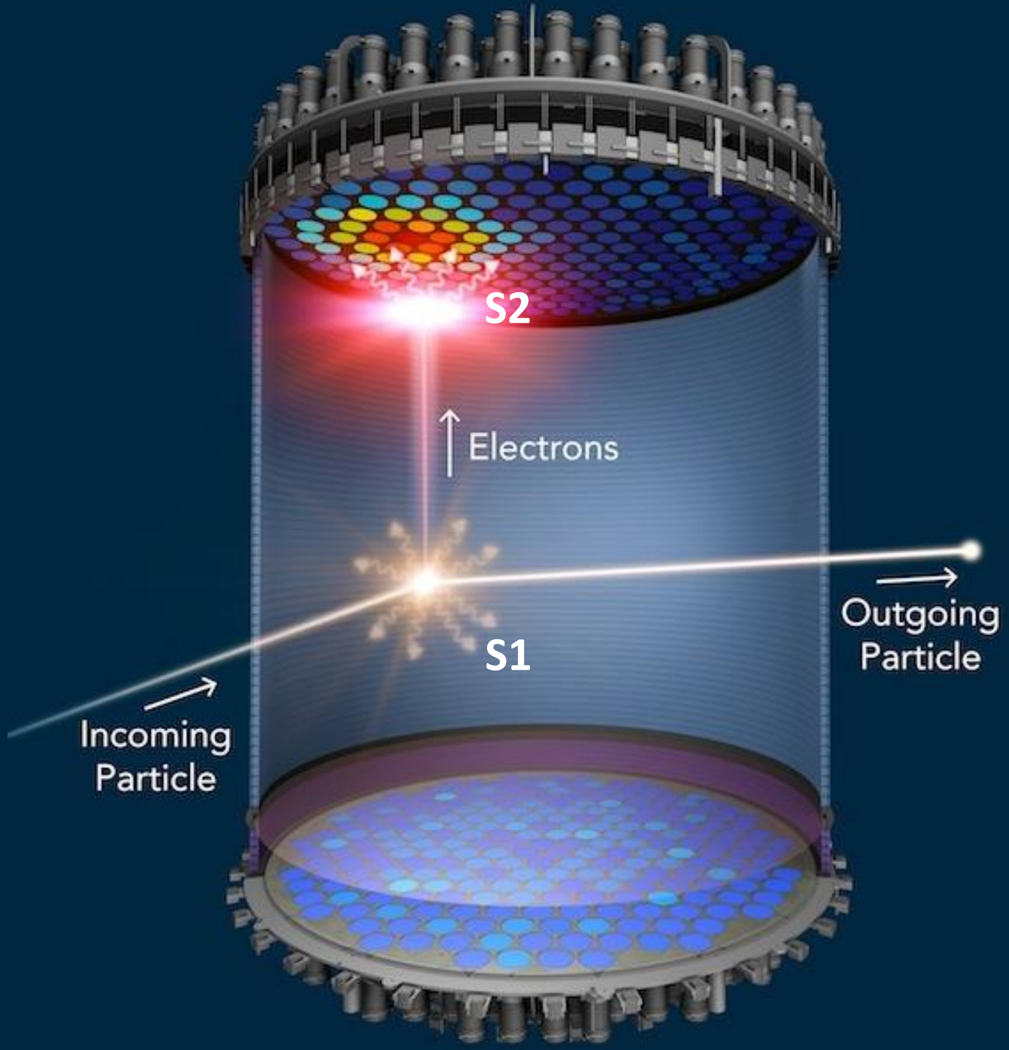
THE EXPERIMENTAL ~~CHALLENGE~~ OPPORTUNITIES

- **Large, quiet detectors with low thresholds** enable searches for various rare processes: $\gtrsim 10^{28}$ atoms $\times \gtrsim 1$ yr exposure
  - Nuclear recoil interactions
    - Dark matter >GeV, including SI and SD
    - Astrophysical neutrinos via CEνNS, including B-8 and supernova
  - Electron recoil interactions
    - Dark matter >MeV, ALPs, …
    - Astrophysical neutrinos via ν-e scattering
    - Neutrinoless double beta decay (demonstrator)
- Ultimate "Generation 3" LXe detector
  - "Mopping" the neutrino floor to close the WIMP gap
  - Competitive neutrino astrophysics programme
  - Competitive neutrinoless double beta decay searches

5-10 tonnes LXe (2020-)

50-100 tonnes LXe

TWO-PHASE XENON TIME PROJECTION CHAMBER

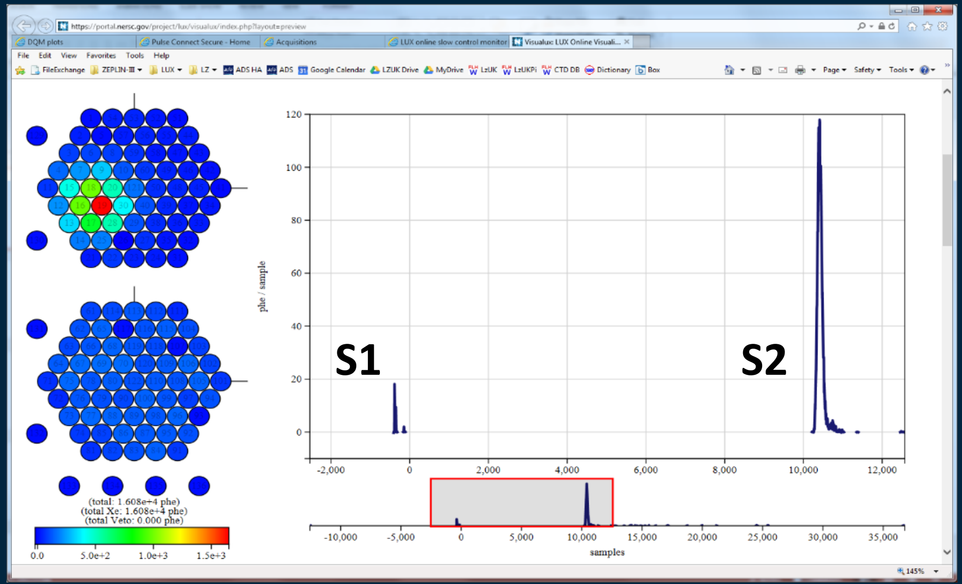


Two signals for every particle interaction:

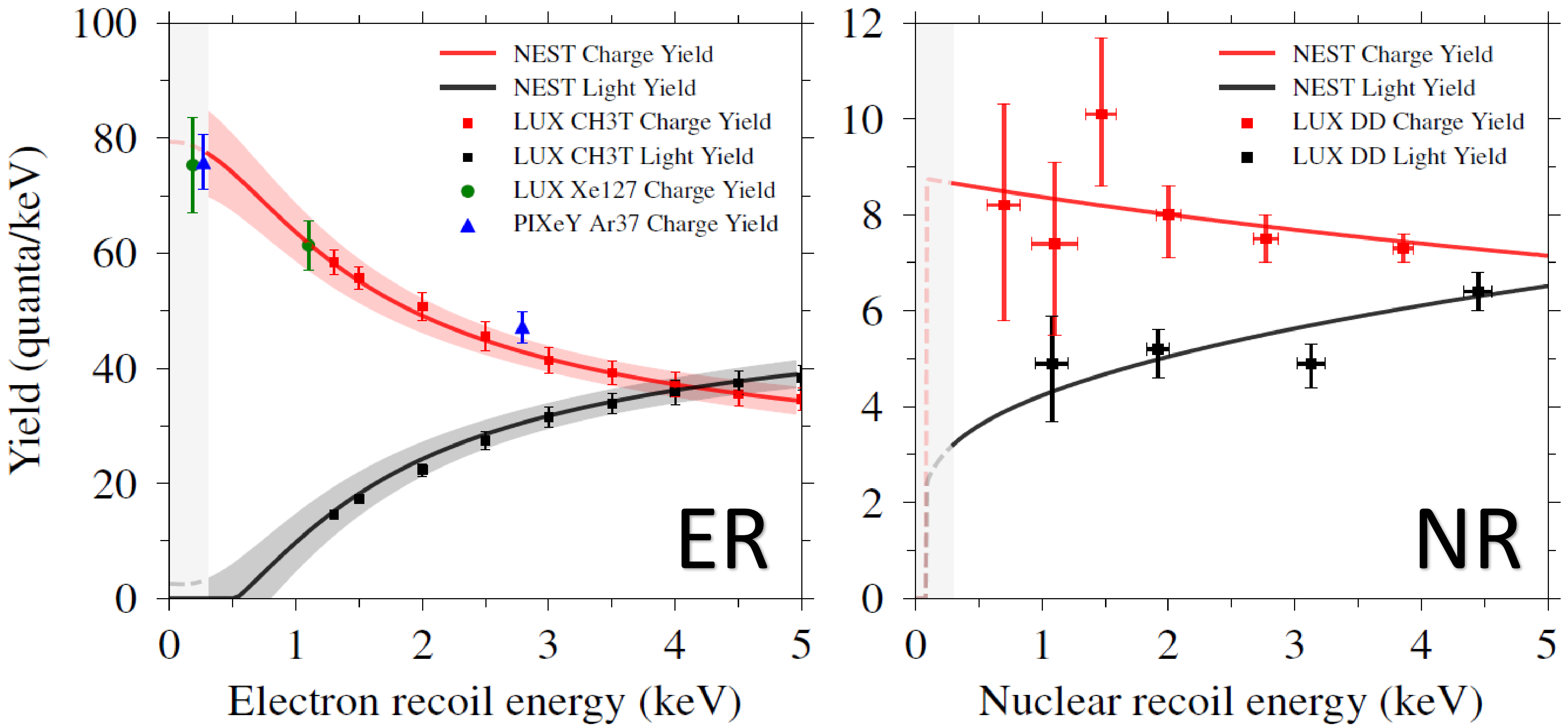
S1: scintillation in liquid phase (prompt)

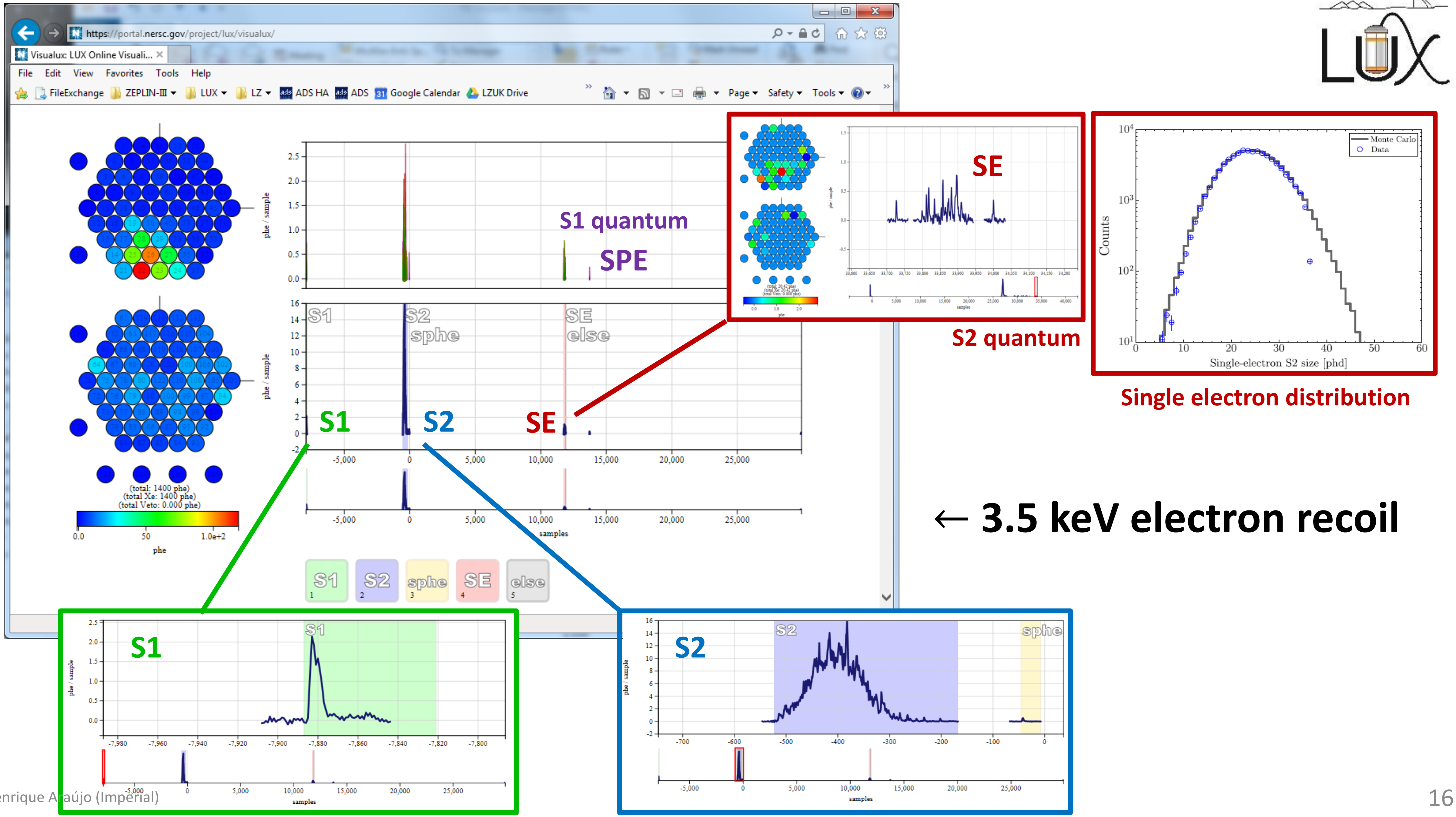
S2: electroluminescence in gas (delayed)

- 3D position reconstruction, fiducialisation
- Nuclear/electron recoil discrimination



NR & ER YIELDS IN LIQUID XENON





← 3.5 keV electron recoil

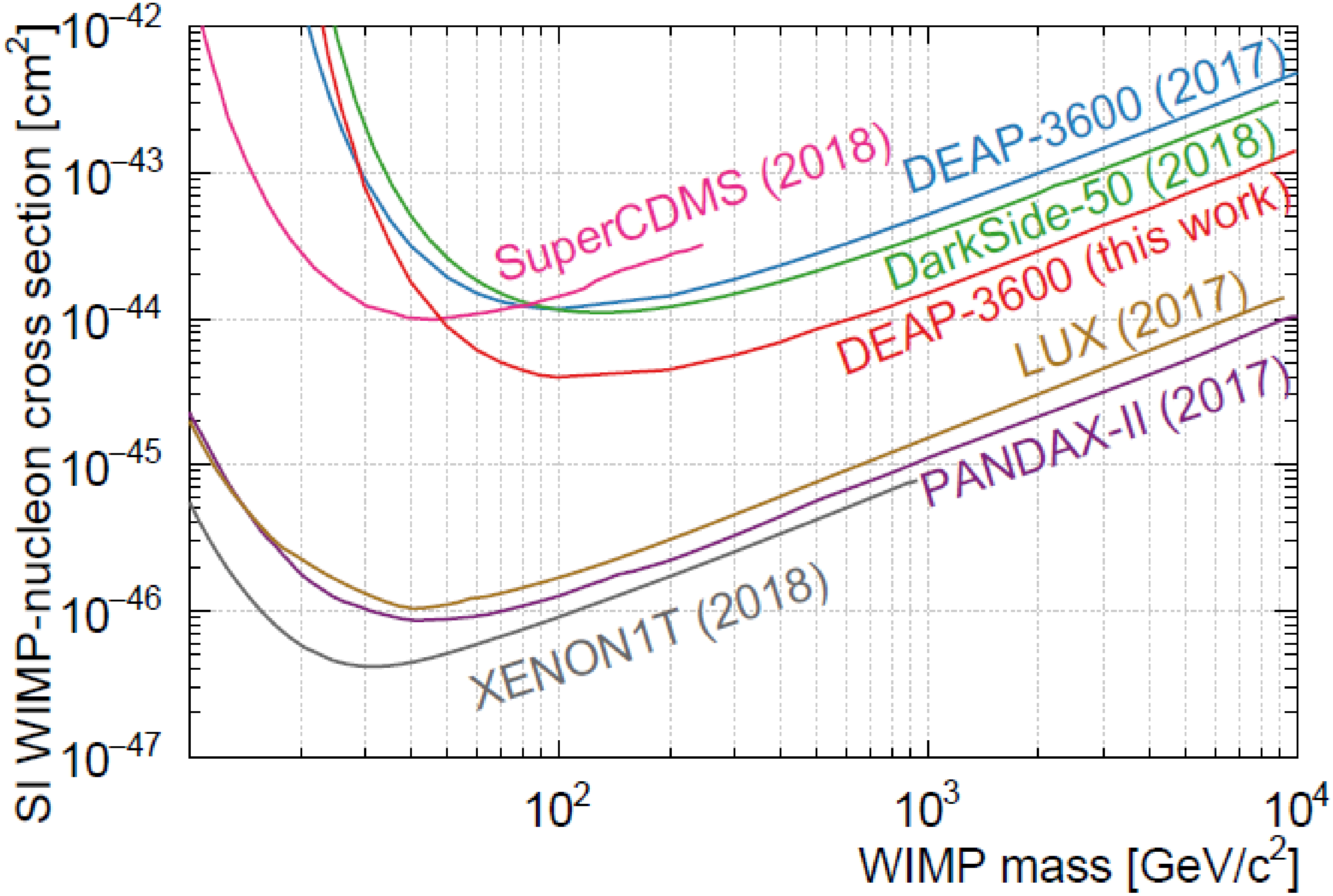
STATE-OF-THE-ART: VANILLA WIMPS

LUX

PandaX-II

XENON1T

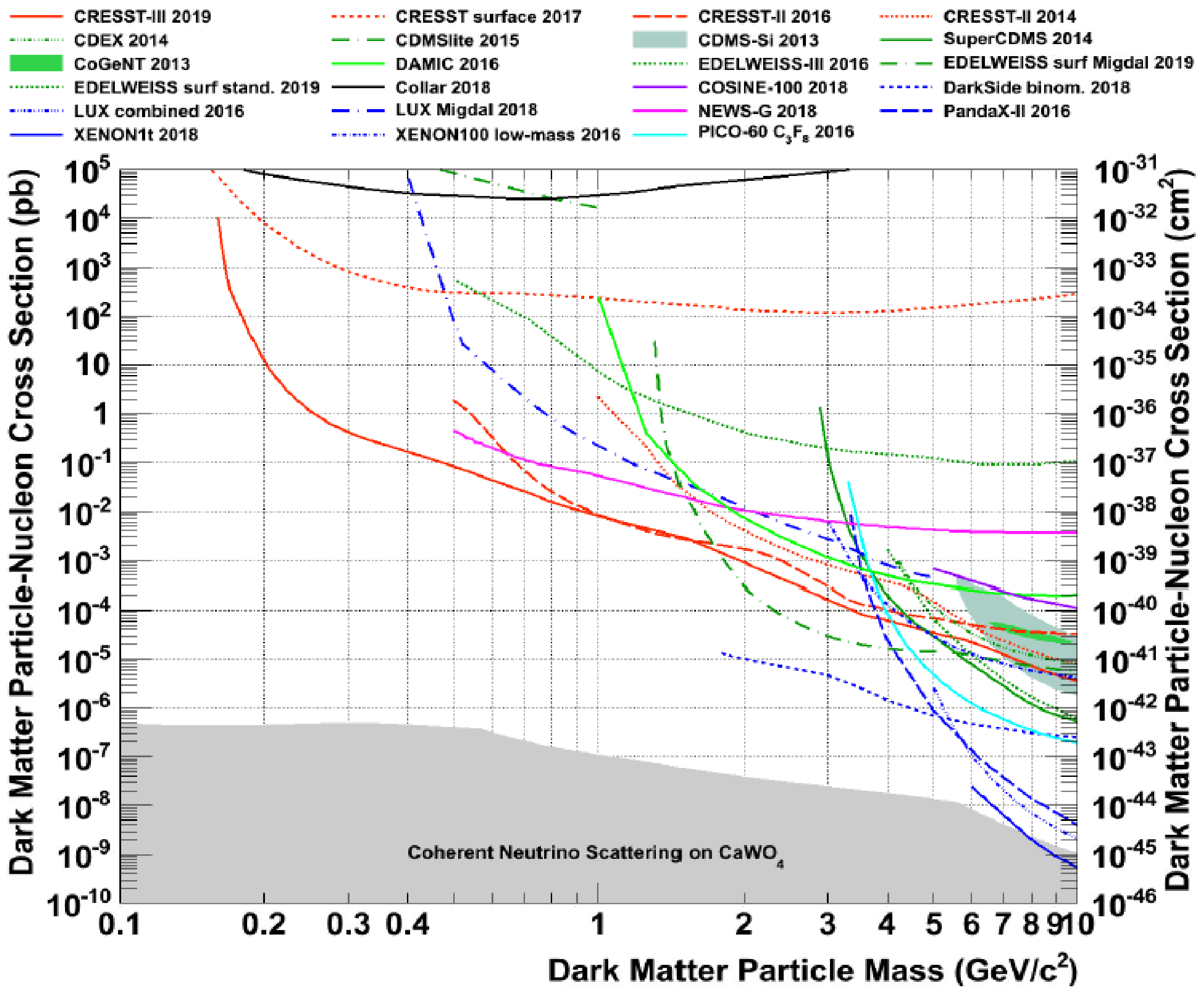
- 0.25-2 tonnes (active)
- ~5 keV NR threshold



STATE-OF-THE-ART: LIGHT WIMPS

CRESST-III

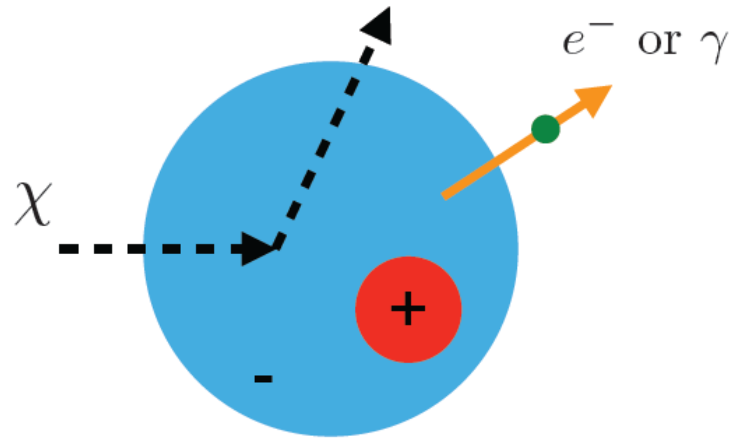
- 24 g $CaWO_4$ crystal
- 30 eV NR threshold



MIGDAL EFFECT – DETECTING SUB-keV RECOILS

Emission from the recoiling atom

sub-GeV dark matter in xenon:



nucleus gets a nudge

$$E_{\mathrm{recoil}} \lesssim 0.1 \ \mathrm{keV}$$

nuclear recoil below energy threshold

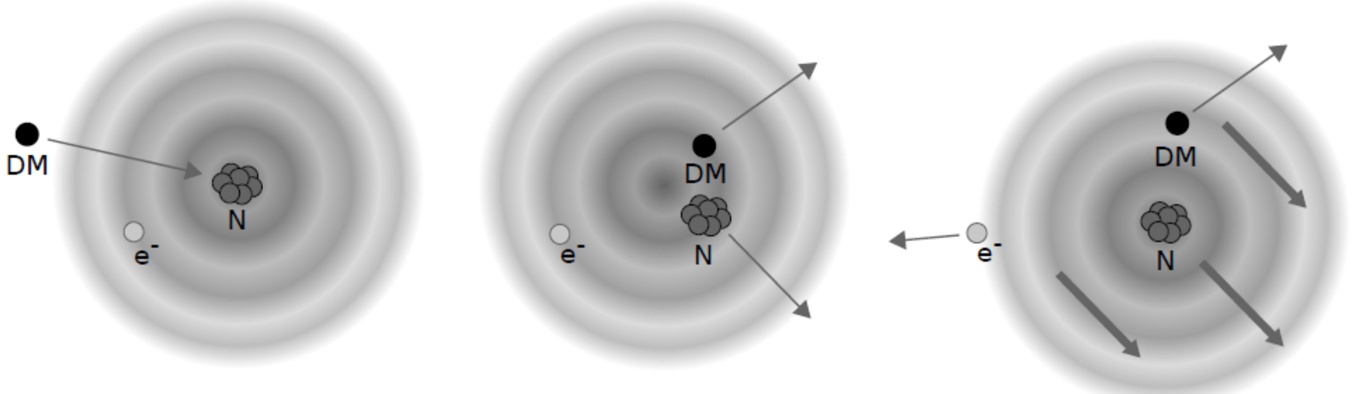
...but electrons and photons can be emitted from the atom

Migdal 1939
Kouvaris & Pradler PRL 1607.01789

Christopher McCabe 20

MIGDAL EFFECT – DETECTING SUB-keV RECOILS

Migdal effect: updated treatment



$|\Phi_{ec}\rangle$ $\quad$ $|\Phi'_{ec}\rangle = e^{-im_e \sum_i \mathbf{v}\cdot\hat{\mathbf{x}}_i}|\Phi_{ec}\rangle$ $\quad$ $\mathcal{P} = |\langle\Phi^*_{ec}|\Phi'_{ec}\rangle|^2$

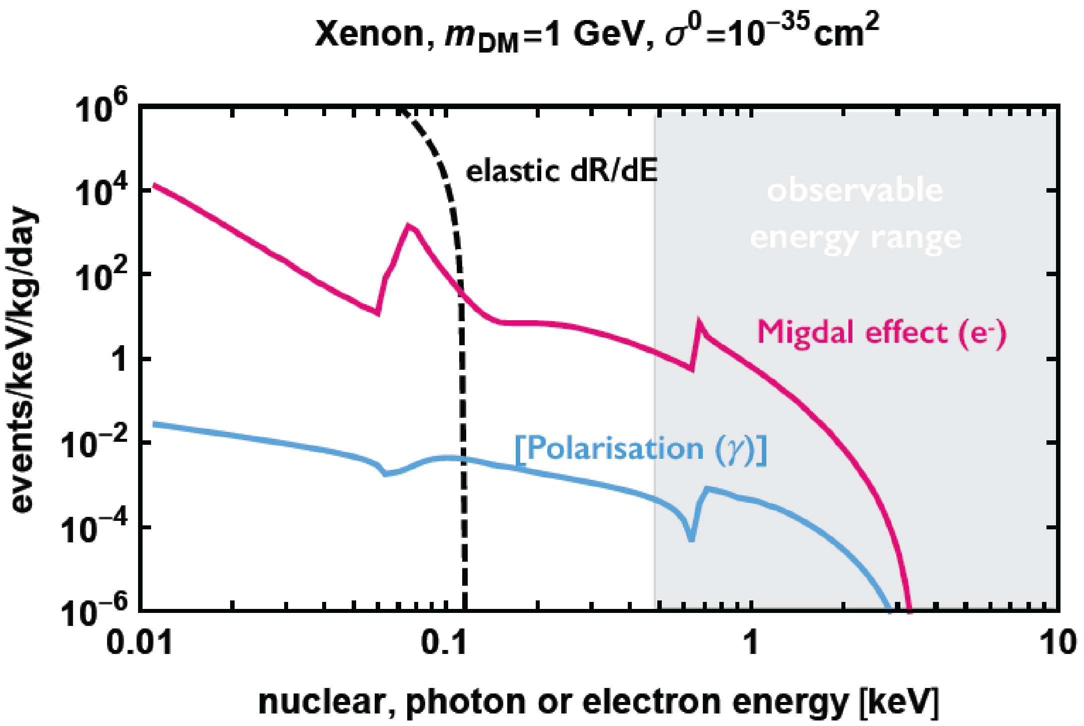
"…it takes some time for the electrons to catch up, which causes ionisation of the atom."

Ibe, Nakano, Shoji, Suzuki, JHEP, arXiv:1707.07258
Dolan, Kahlhoefer, CM, PRL, arXiv:1711.09906

Christopher McCabe 22

MIGDAL EFFECT – DETECTING SUB-keV RECOILS

sub-GeV DM signals in xenon

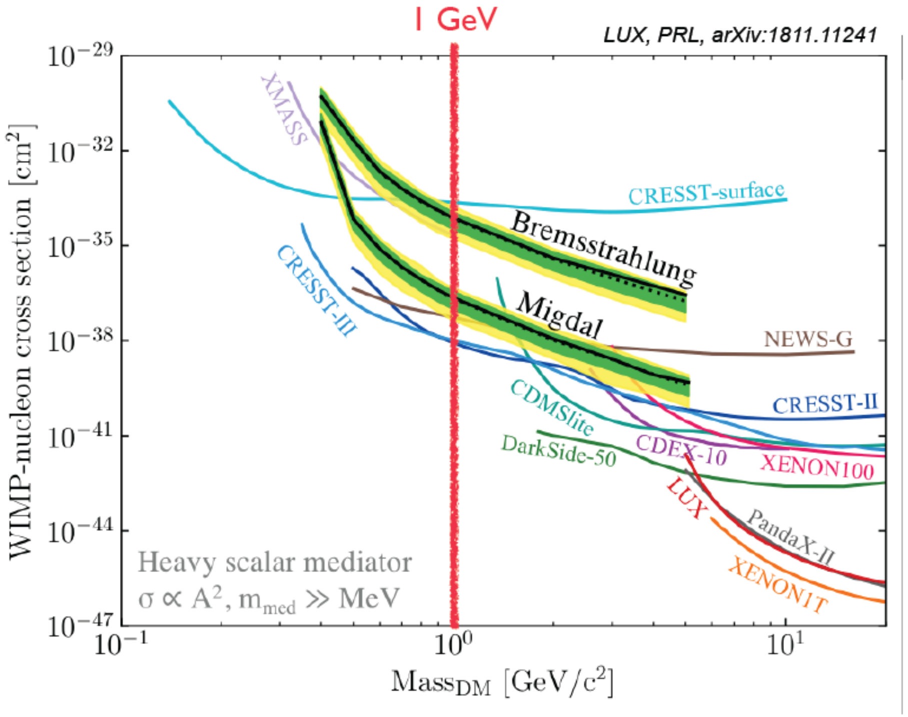


Migdal electrons observable even for $m_{\rm DM} \lesssim 1$ GeV

Christopher McCabe 24

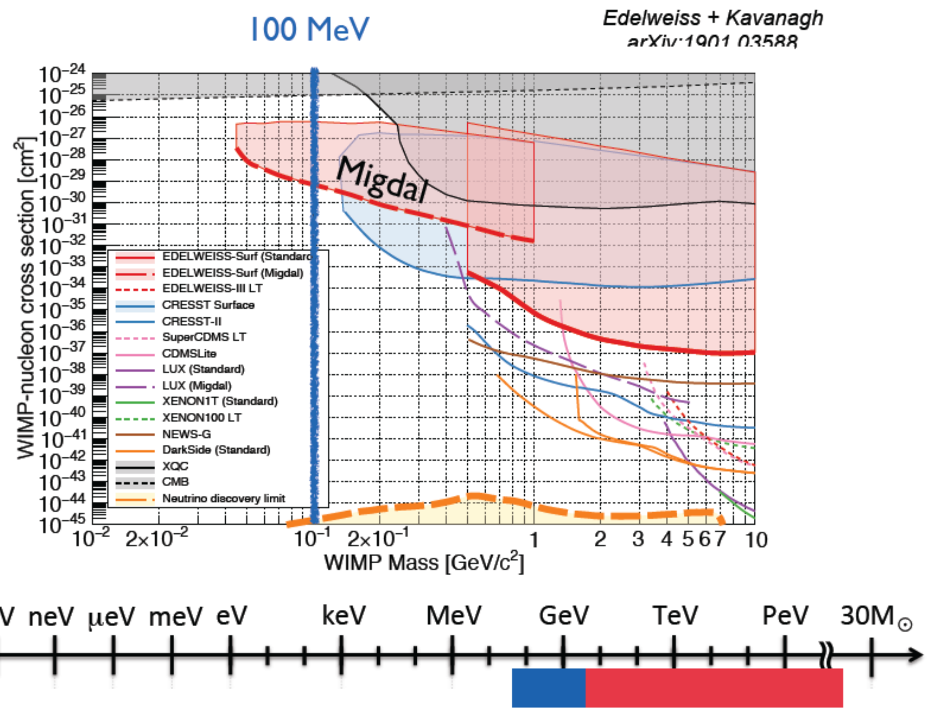
MIGDAL EFFECT – SUB-GeV MASS SENSITIVITY

LUX (Xe) sensitive below 1 GeV



Christopher McCabe 25

Edelweiss (Ge) sensitive below 100 MeV

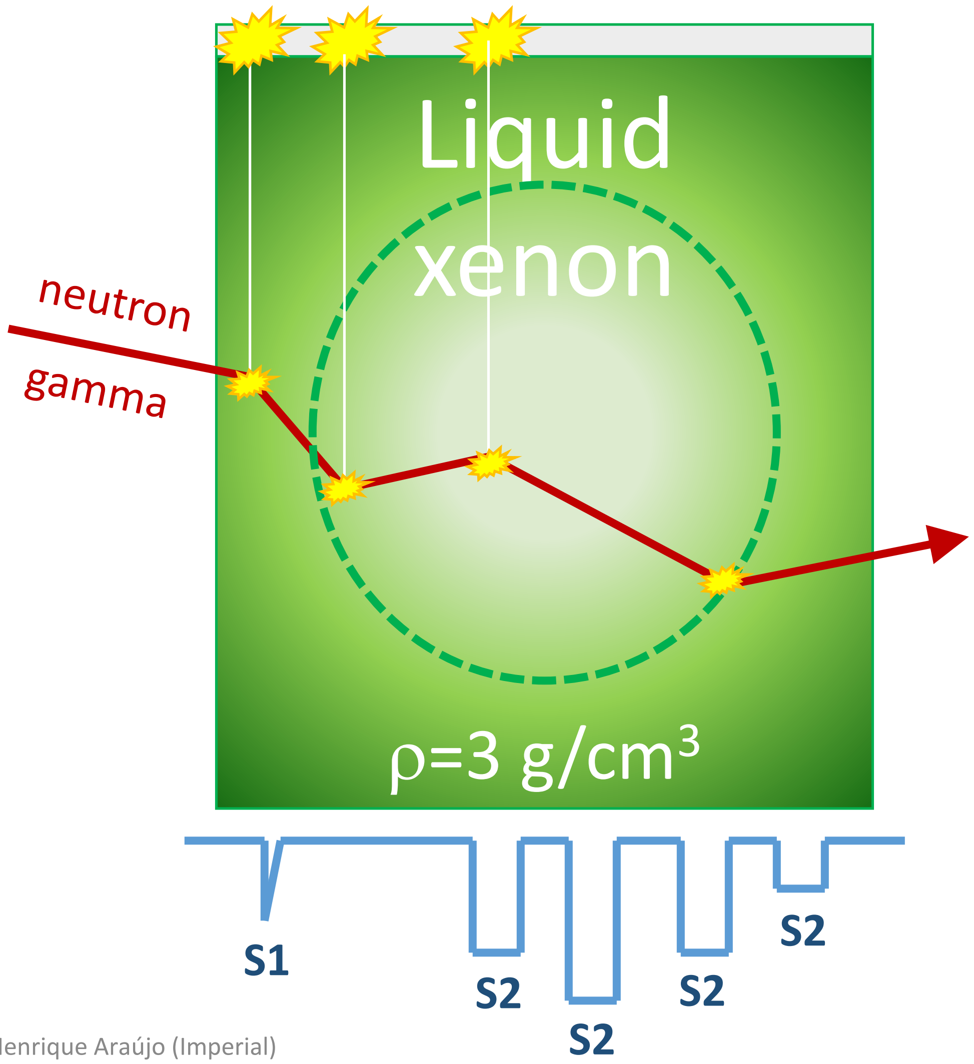


Christopher McCabe 26

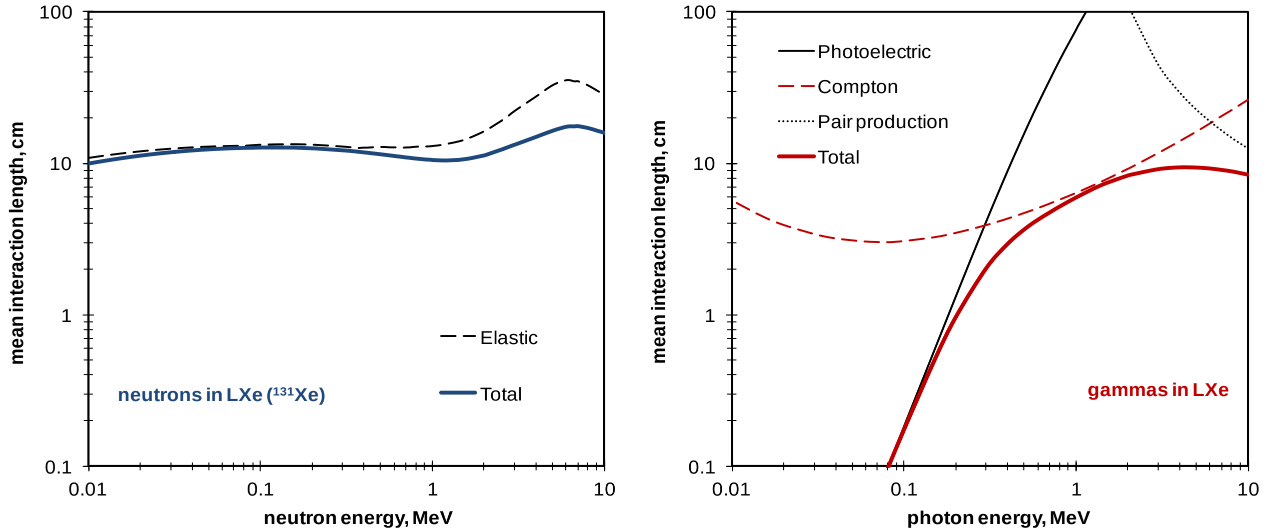
BACKGROUNDS IN LARGE LIQUID XENON DETECTORS

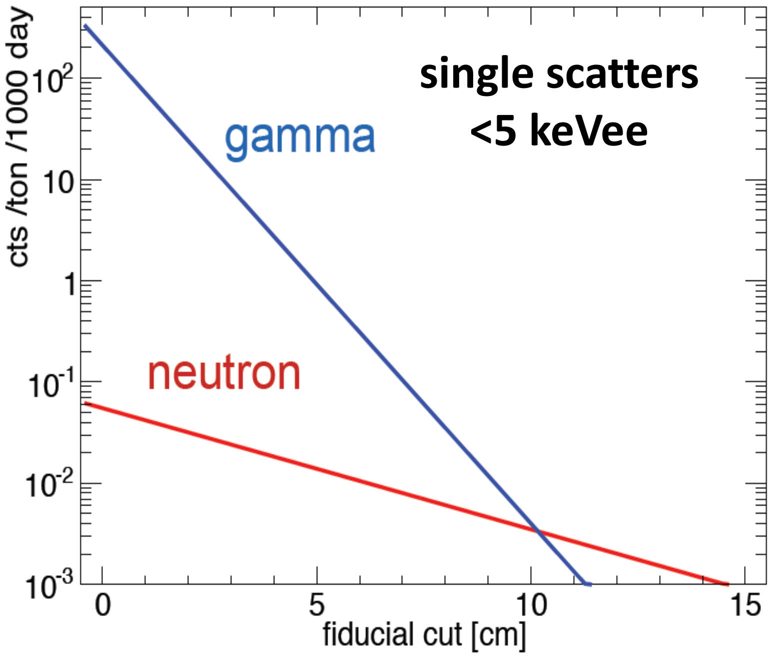
- **Nuclear recoils – same signature, possibly irreducible**
  - **Neutrons from (α,n) and SF from U/Th trace contamination**
    - Local environment, shields, vessels, components, target material itself
  - **Surface recoils from alpha decay (radon daughter plate-out)**
    - Contamination on detector surfaces (“wall events”)
  - **High energy neutrons from atmospheric muon spallation**
    - Difficult to shield completely even underground
  - ***Eventually, coherent elastic neutrino-nucleus scattering (CEνNS)***
- **Electron recoils – discrimination power is finite**
  - **Gamma-ray background external to target**
    - U/Th, K-40, Cs-137, from environment, shields, vessels, components,…
  - **Contaminants dispersed within the target**
    - Other noble gases not removed by purification system: Rn-222/220, Ar-39, Kr-85
  - ***Eventually, elastic scattering of solar pp neutrinos off electrons***

SELF-SHIELDING IN NOBLE LIQUIDS

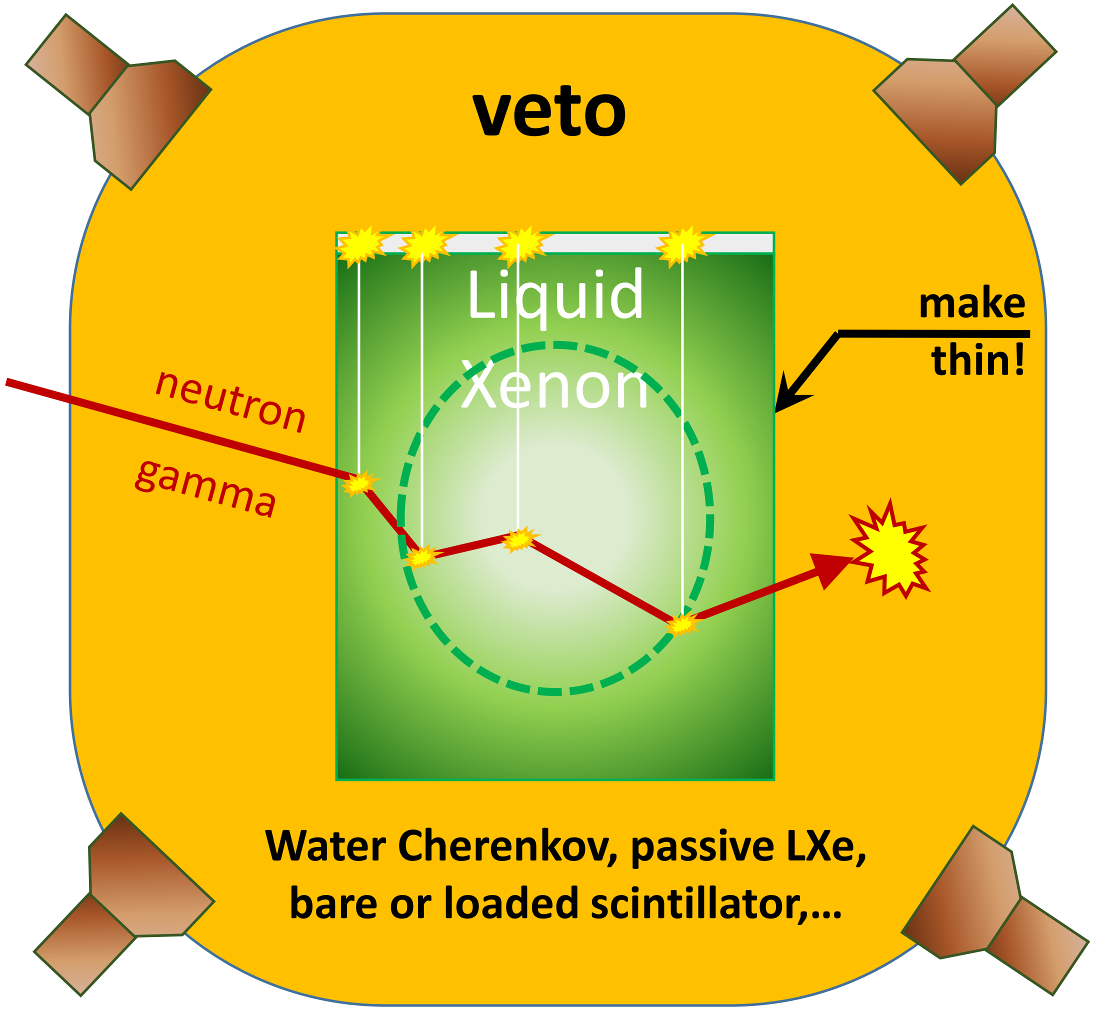


neutron and gamma
mean interaction lengths in liquid xenon





ANTI-COINCIDENCE DETECTOR AROUND WIMP TARGET



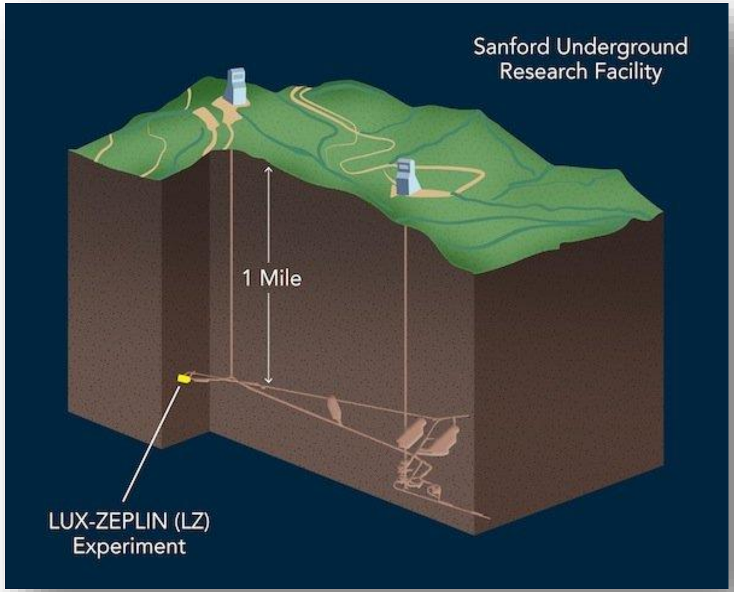
LUX-ZEPLIN (LZ)

250 scientists from 38 institutes in the US, UK, Portugal, South Korea & Russia

Black Hills State University ◊ Bristol University ◊ Brookhaven National Laboratory ◊ Brown University ◊ Center for Underground Physics, Korea ◊ Edinburgh University ◊ Fermi National Accelerator Laboratory ◊ Imperial College London ◊ Lawrence Berkeley National Laboratory ◊ Lawrence Livermore National Laboratory ◊ LIP-Coimbra, Portugal ◊ University of Liverpool ◊ MEPHI Moscow, Russia ◊ Northwestern University ◊ Oxford University ◊ Penn State University ◊ Rutherford Appleton Laboratory ◊ Royal Holloway, University of London ◊ SLAC National Accelerator Laboratory ◊ South Dakota School of Mines & Technology ◊ South Dakota Science and Technology Authority ◊ SUNY University at Albany ◊ Texas A&M University ◊ University of Alabama ◊ University of California Berkeley ◊ University of California Davis ◊ University of California Santa Barbara ◊ University College London ◊ University of Maryland ◊ University of Massachusetts ◊ University of Michigan ◊ University of Rochester ◊ University of Sheffield ◊ University of South Dakota ◊ University of Wisconsin ◊ Washington University

SANFORD UNDERGROUND RESEARCH FACILITY

Former Homestake Mine, Lead, South Dakota



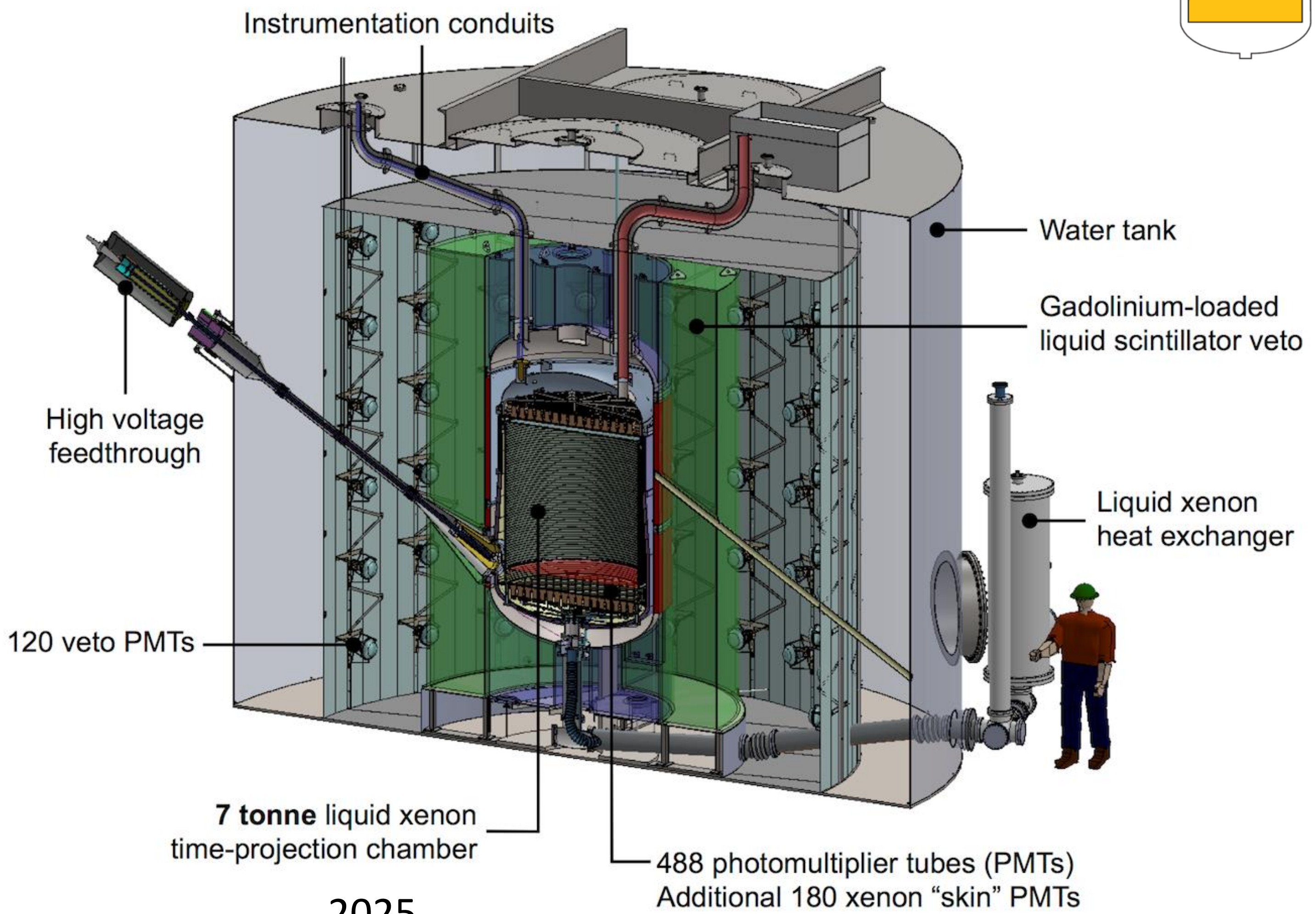
Lead and the Open Cut

Sturgis Rally

THE LUX-ZEPLIN (LZ) EXPERIMENT

LZ detector(s)

- 7t LXe-TPC (494 photomultipliers)
- 2t LXe Skin Detector (131 photomultipliers)
- 20t Gd-loaded Liquid Scintillator Outer Detector (120 photomultipliers)

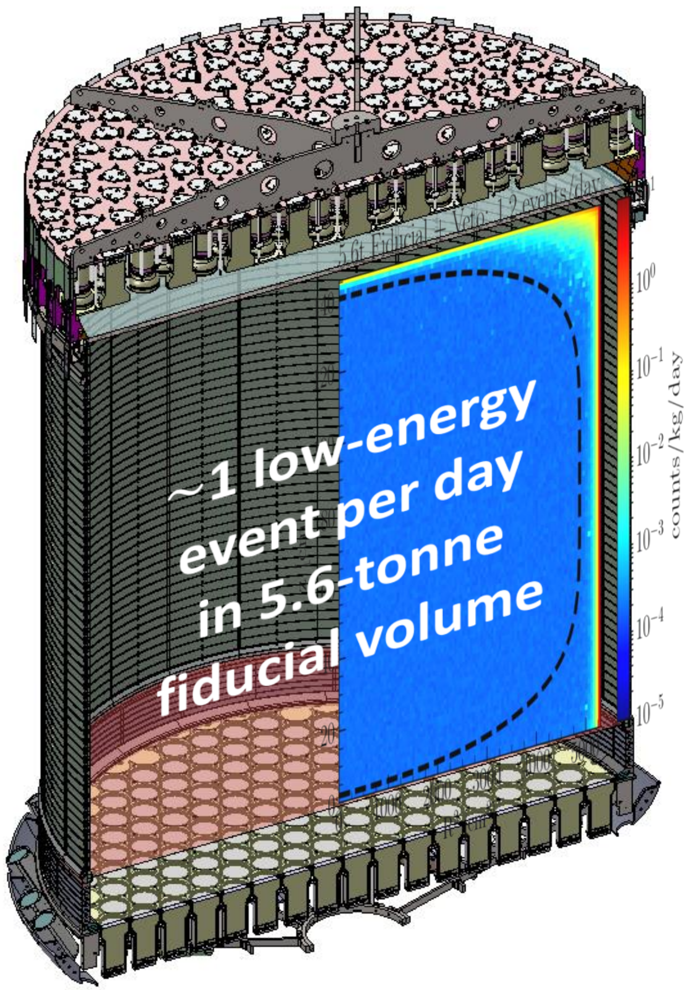


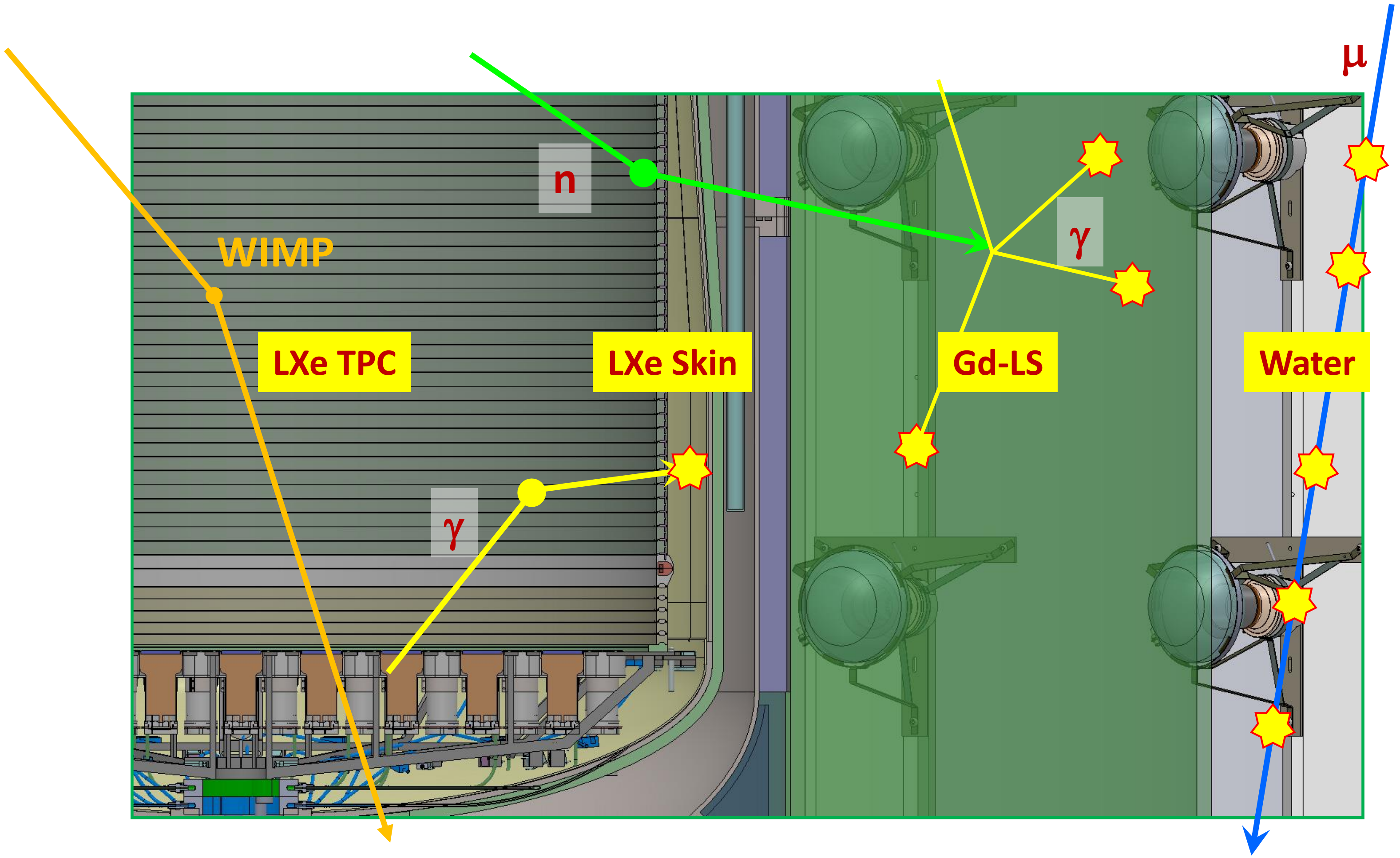
100x more sensitive than LUX

LZ Technical Design Report: arXiv:1703.09144
LZ Sensitivity: arXiv:1802.06039

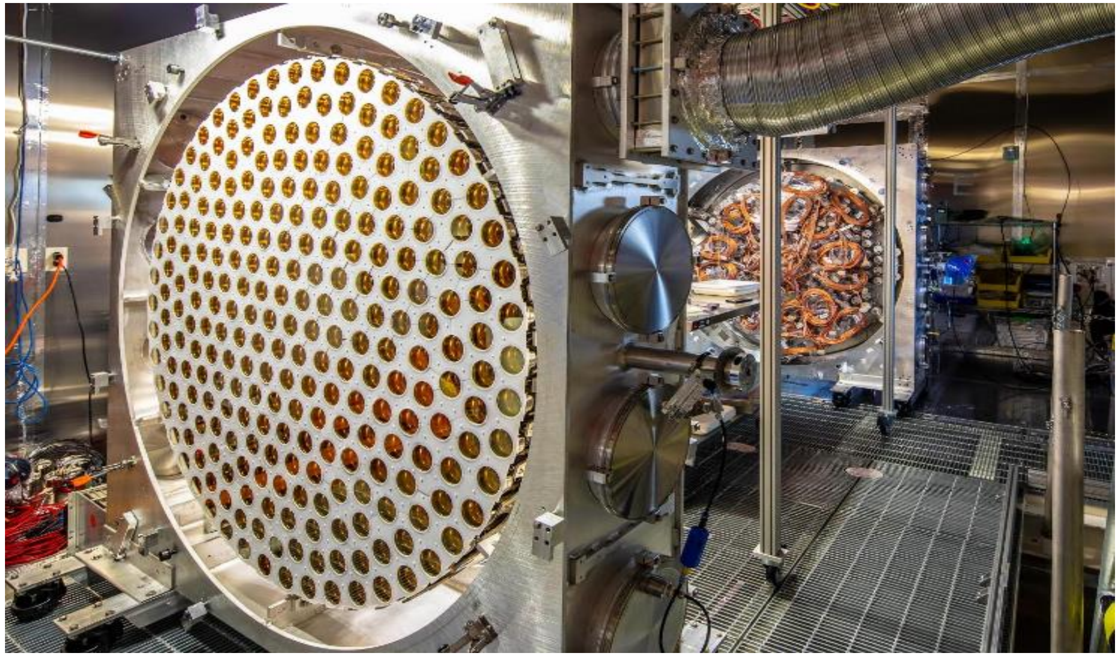
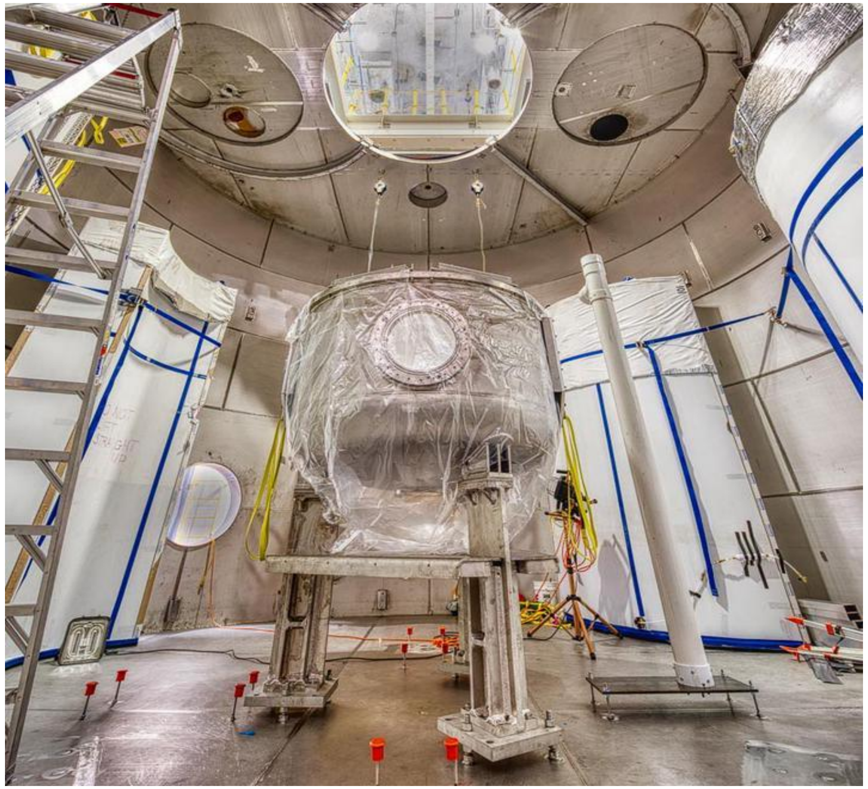
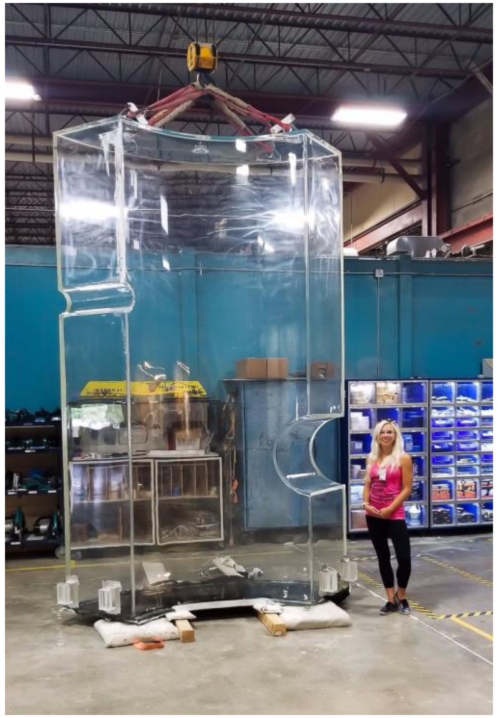
2012	2015	2020	2025
DESIGN	CONSTRUCTION	EXPLOITATION	

LZ DETECTORS








LZ BACKGROUNDS

- DETECTOR MATERIALS
  - Radioassay programme (>1,000 assays to date):
- SURFACE CONTAMINATION
  - Cleanliness programme (~300 assays)
- INTERNAL BACKGROUNDS
  - Rn Assay programme (~170 assays)
  - Krypton & Radon removal
- PHYSICS BACKGROUNDS
  - Solar pp neutrinos (ER)
  - Atmospheric & B-8 neutrinos (NR)

TOTAL IN WIMP ROI IN 1,000 DAYS

1195 ER + 1.0 NR (before discrimination)

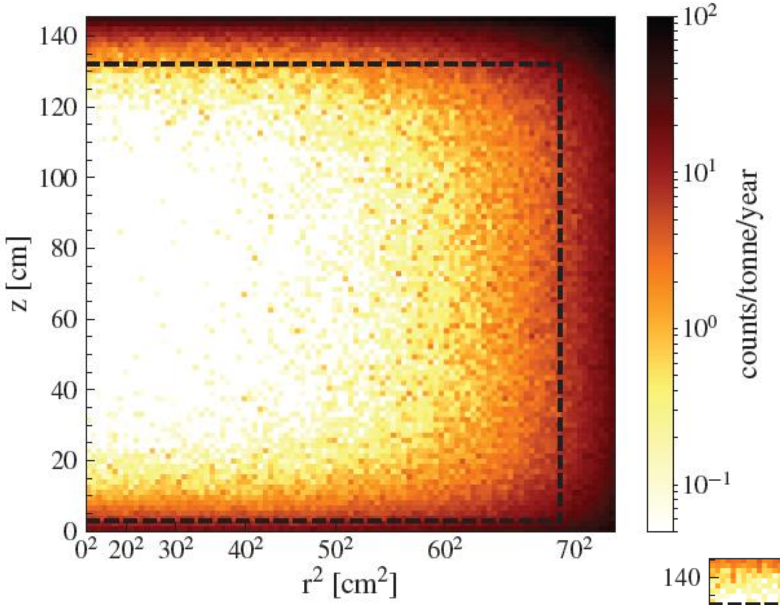
6 ER + 0.5 NR COUNTS

1802.06039

TABLE III. Estimated backgrounds from all significant sources in the LZ 1000 day WIMP search exposure. Counts are for a region of interest relevant to a 40 GeV/c^2 WIMP: approximately 1.5–6.5 keV for ERs and 6–30 keV for NRs; and after application of the single scatter, skin and outer detector veto, and 5.6 tonne fiducial volume cuts. Mass-weighted average activities are shown for composite materials and the ^{238}U and ^{232}Th chains are split into contributions from early- and late-chain, with the latter defined as those coming from isotopes below and including ^{226}Ra and ^{224}Ra, respectively.

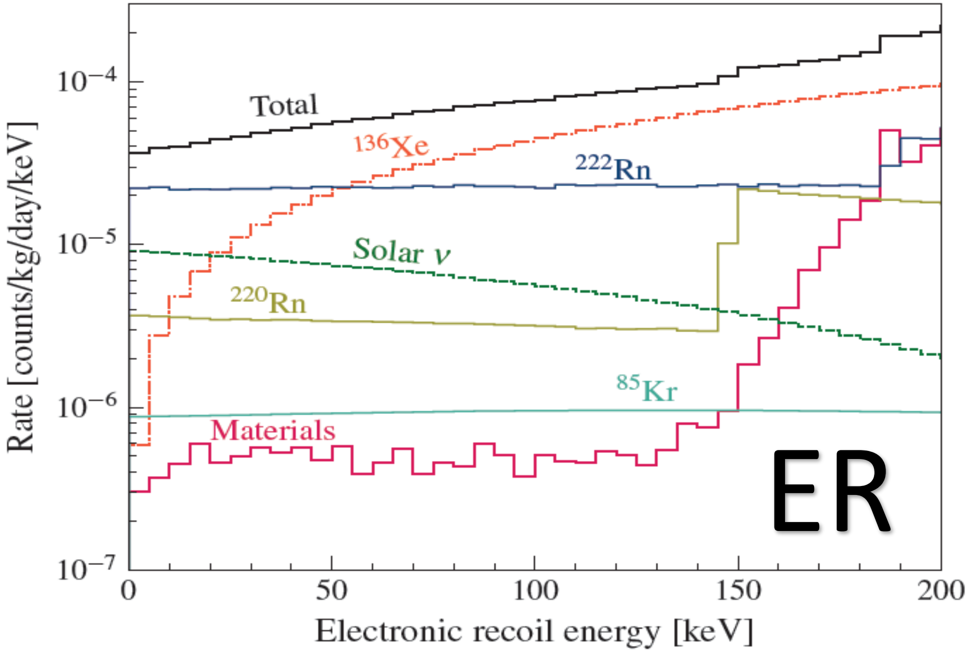
Background Source	Mass (kg)	$^{238}U_e$	$^{238}U_l$	$^{232}Th_e$	$^{232}Th_l$	^{60}Co	^{40}K	n/yr	ER (cts)	NR (cts)
		mBq/kg								
Detector Components										
PMT systems	308	31.2	5.20	2.32	2.29	1.46	18.6	248	2.82	0.027
TPC systems	373	3.28	1.01	0.84	0.76	2.58	7.80	79.9	4.33	0.022
Cryostat	2778	2.88	0.63	0.48	0.51	0.31	2.62	323	1.27	0.018
Outer detector	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
								subtotal	**9**	**0.07**
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
								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	-
								subtotal	**819**	**0**
Laboratory and Cosmogenics										
Laboratory rock walls									4.6	0.00
Muon induced neutrons									-	0.06
Cosmogenic activation									0.2	-
								subtotal	**5**	**0.06**
Physics										
^{136}Xe $2\nu\beta\beta$									67	-
Solar neutrinos: pp+^{7}Be+^{14}N									255	-
Diffuse supernova neutrinos (DSN)									-	0.05
Atmospheric neutrinos (Atm)									-	0.46
								subtotal	**322**	**0.51**
Total									1195	1.03
Total (with 99.5% ER discrimination, 50% NR efficiency)									5.97	0.52
Sum of ER and NR in LZ for 1000 days, 5.6 tonne FV, with all analysis cuts									**6.49**	

LZ BACKGROUNDS



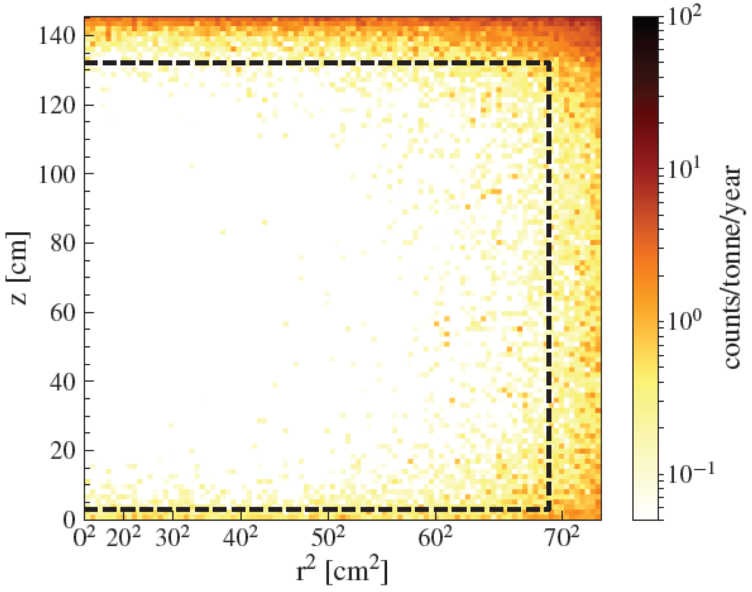
10 μDRU from solar pp ν

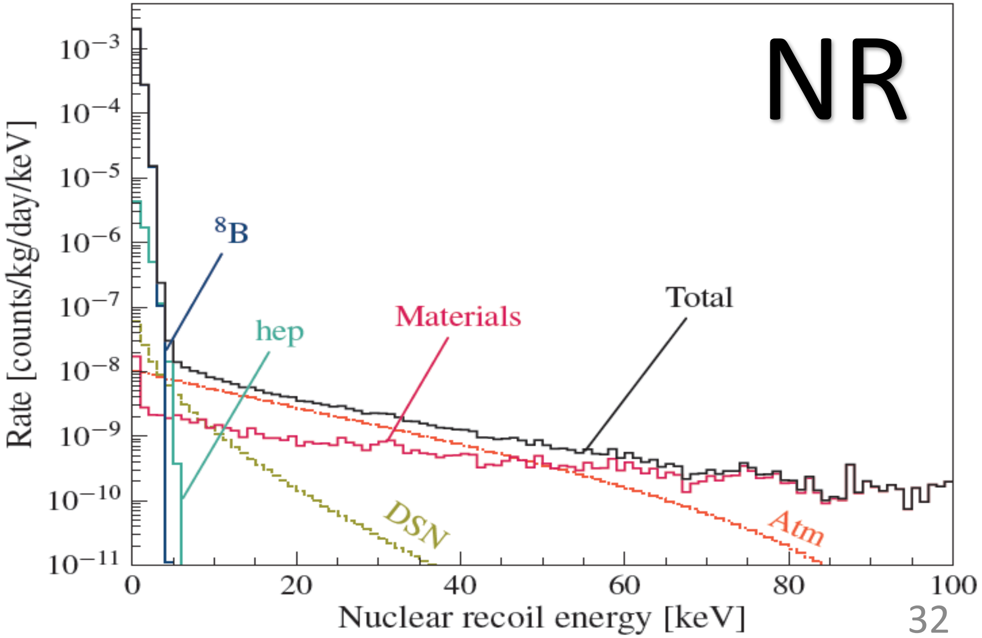
(10x10^{-6} cts/kg/day/keVee)



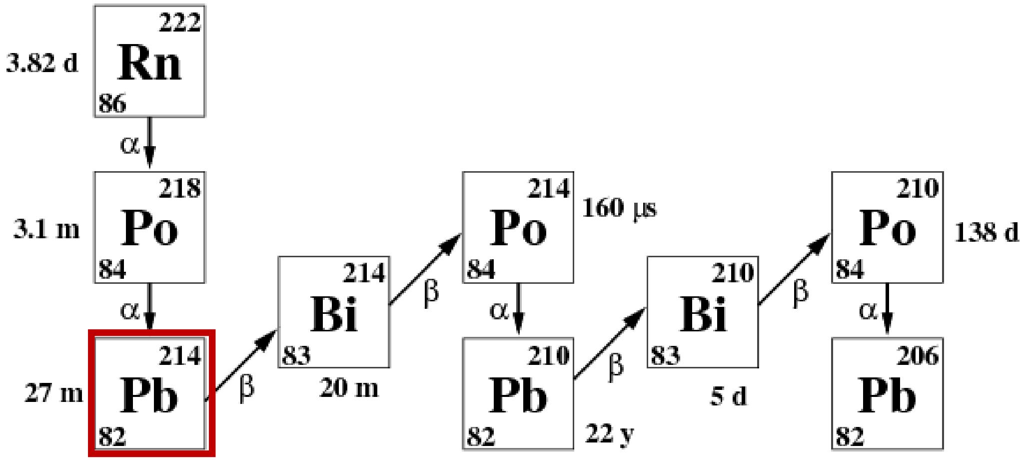
Distribution of
NR background
from detector materials

+VETOS

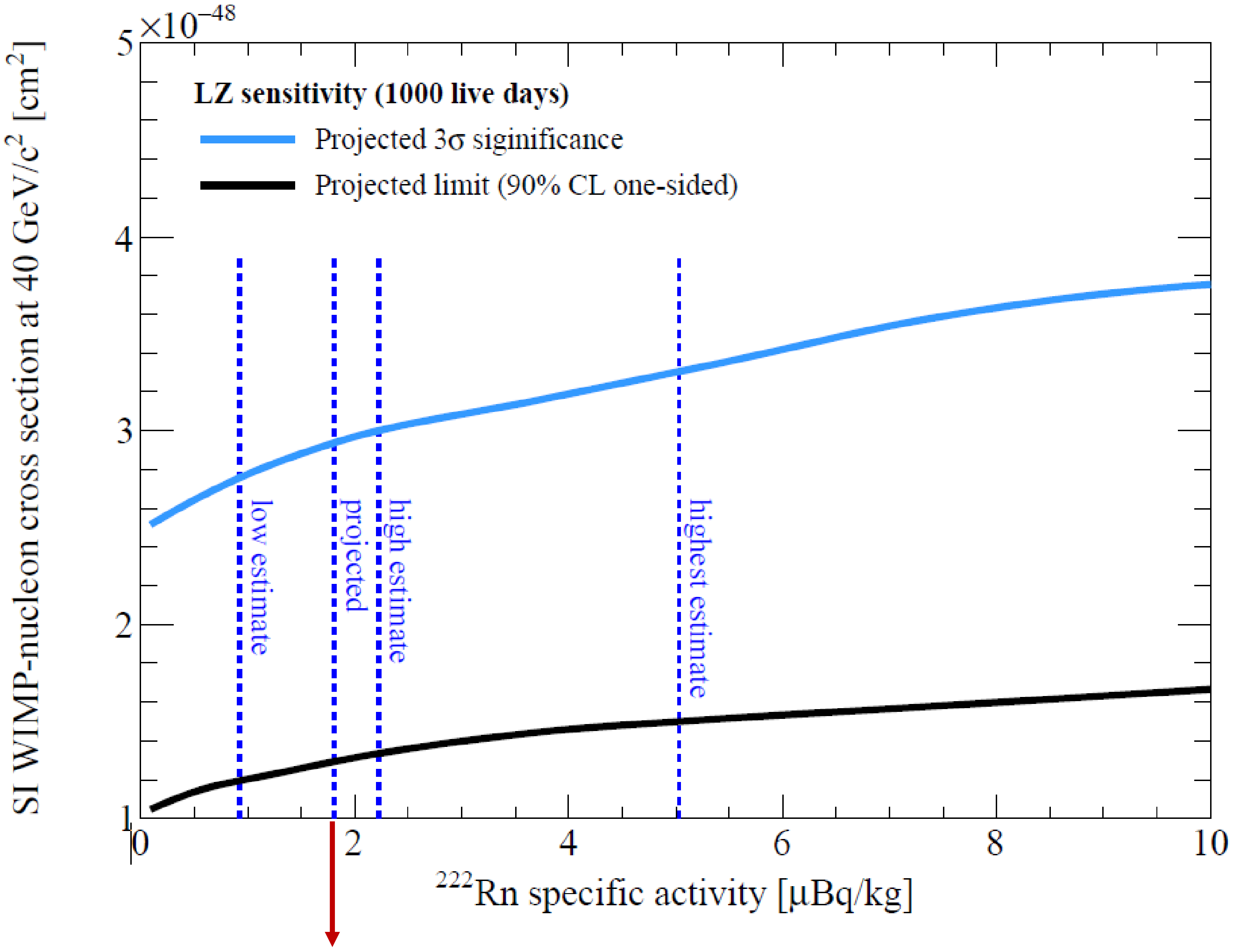




RADON…



”naked beta” with 9.2% BR
(E_{max} = 1,019 keV)

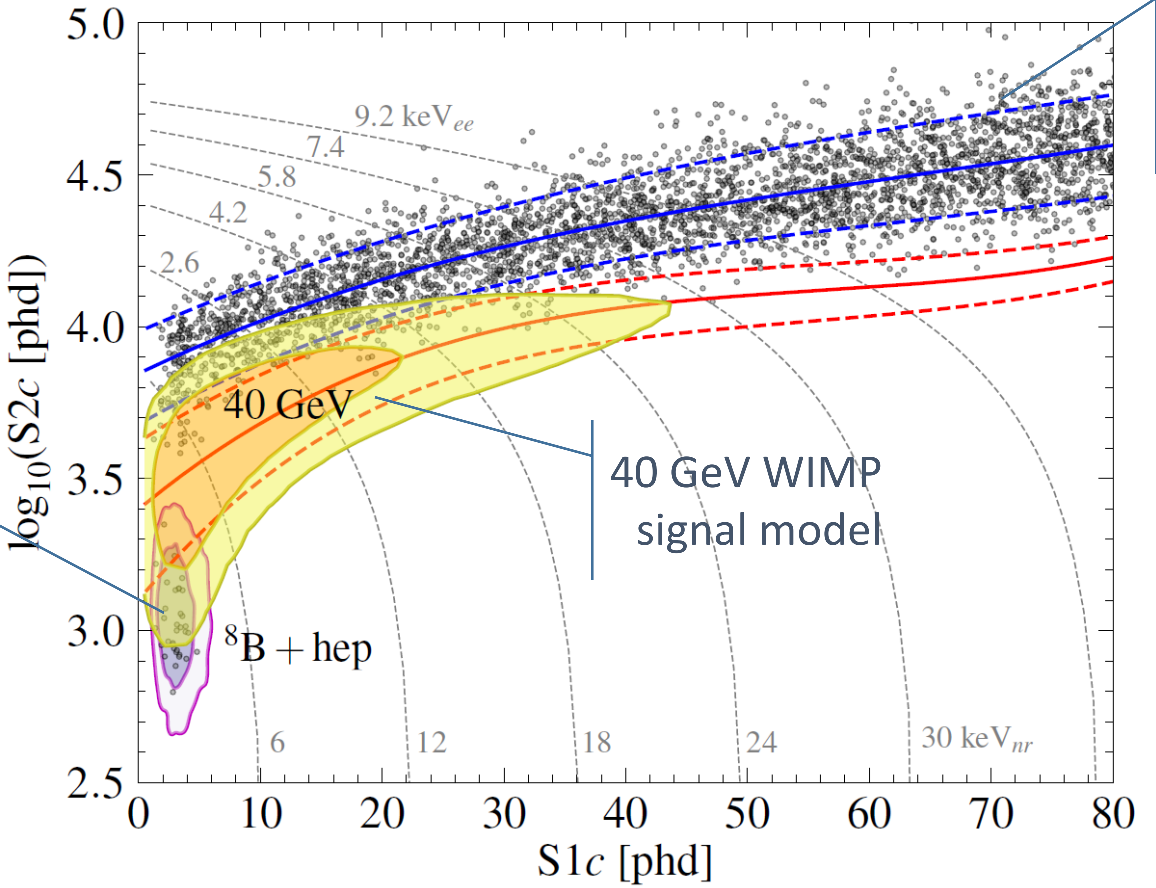


~6,000 Rn-222 atoms in 7-tonne detector…

Impact on NR physics is limited,
but it loads the ER band and obscures solar pp neutrinos

LZ SENSITIVITY: SIMULATED EXPOSURE

- Full LZ exposure (1,000 live days)

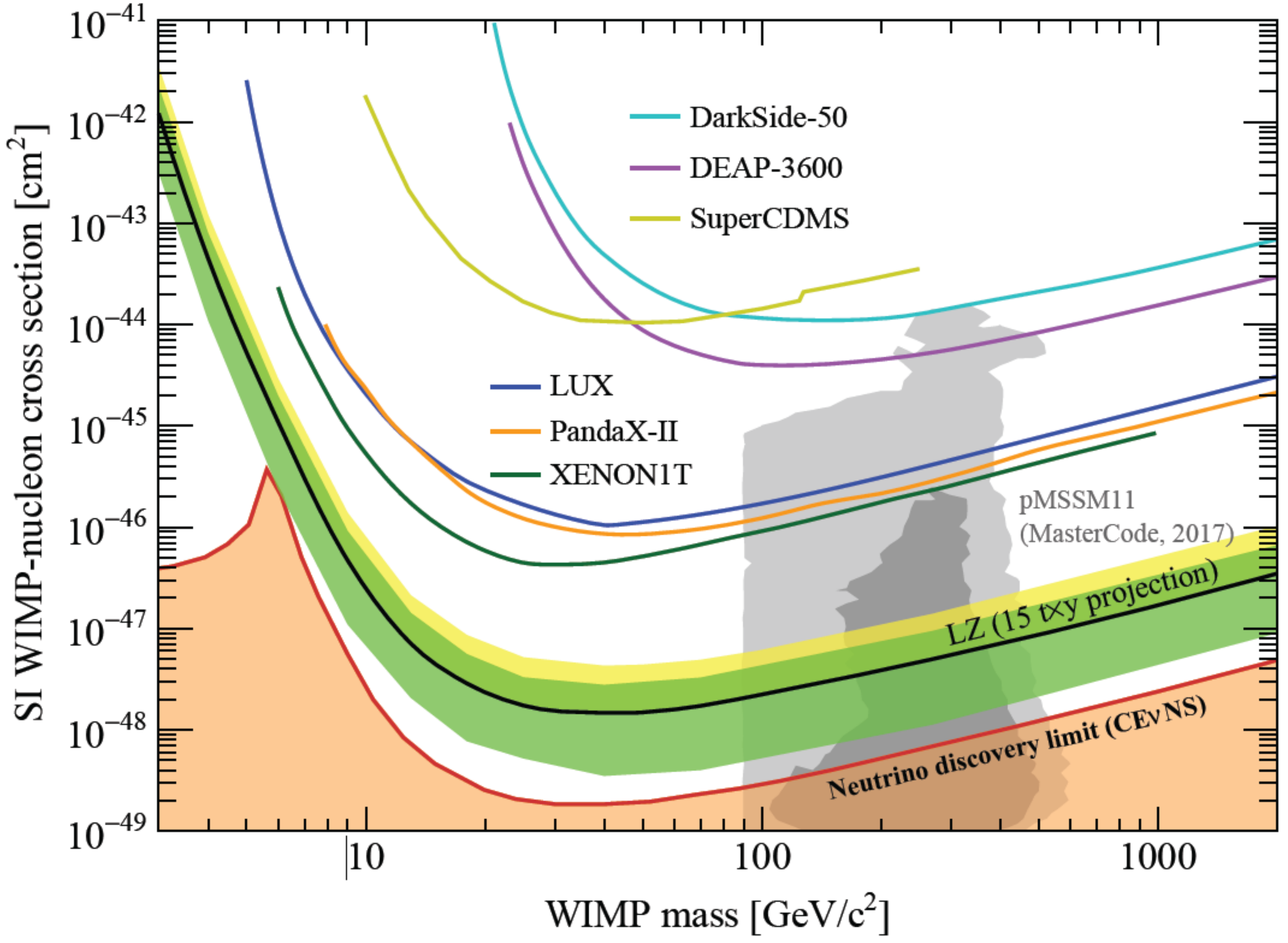


ER background dominated by radon and solar pp neutrinos

40 GeV WIMP signal model

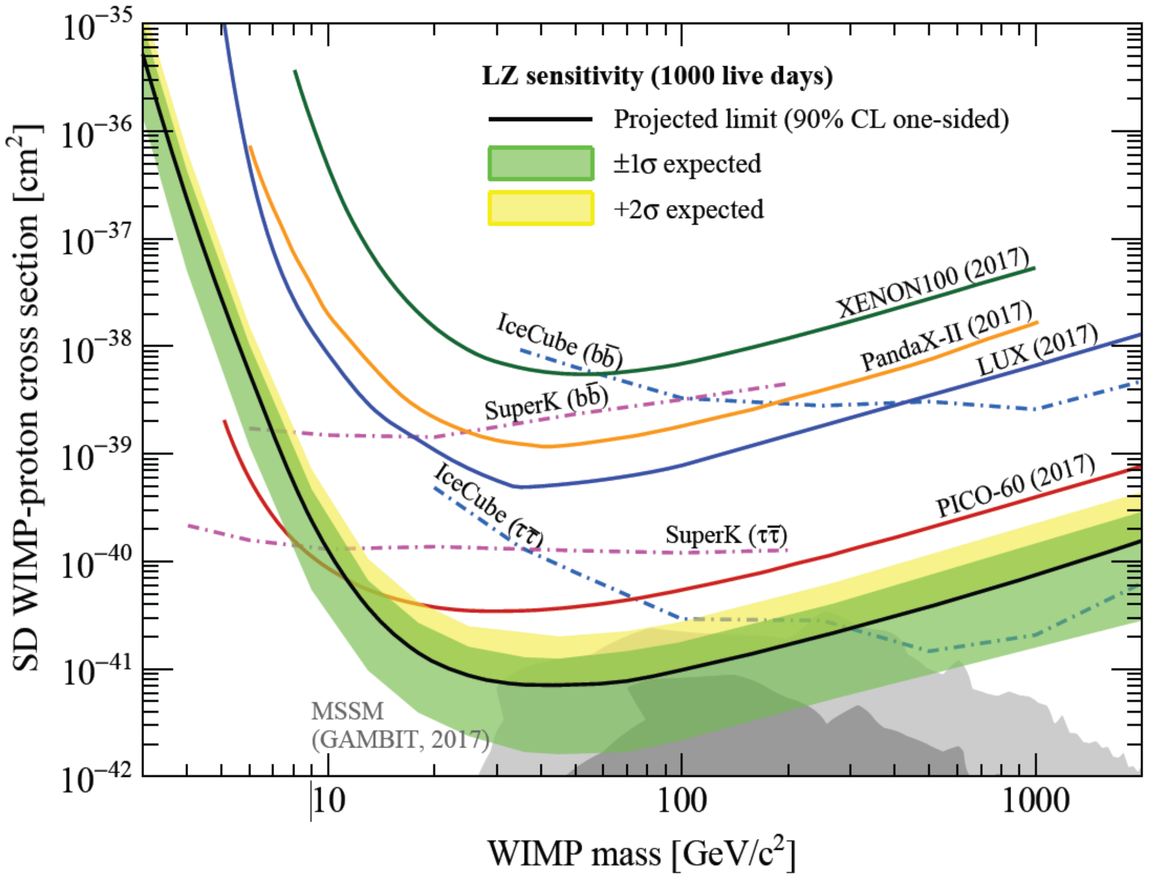
Coherent nuclear scattering of solar neutrinos

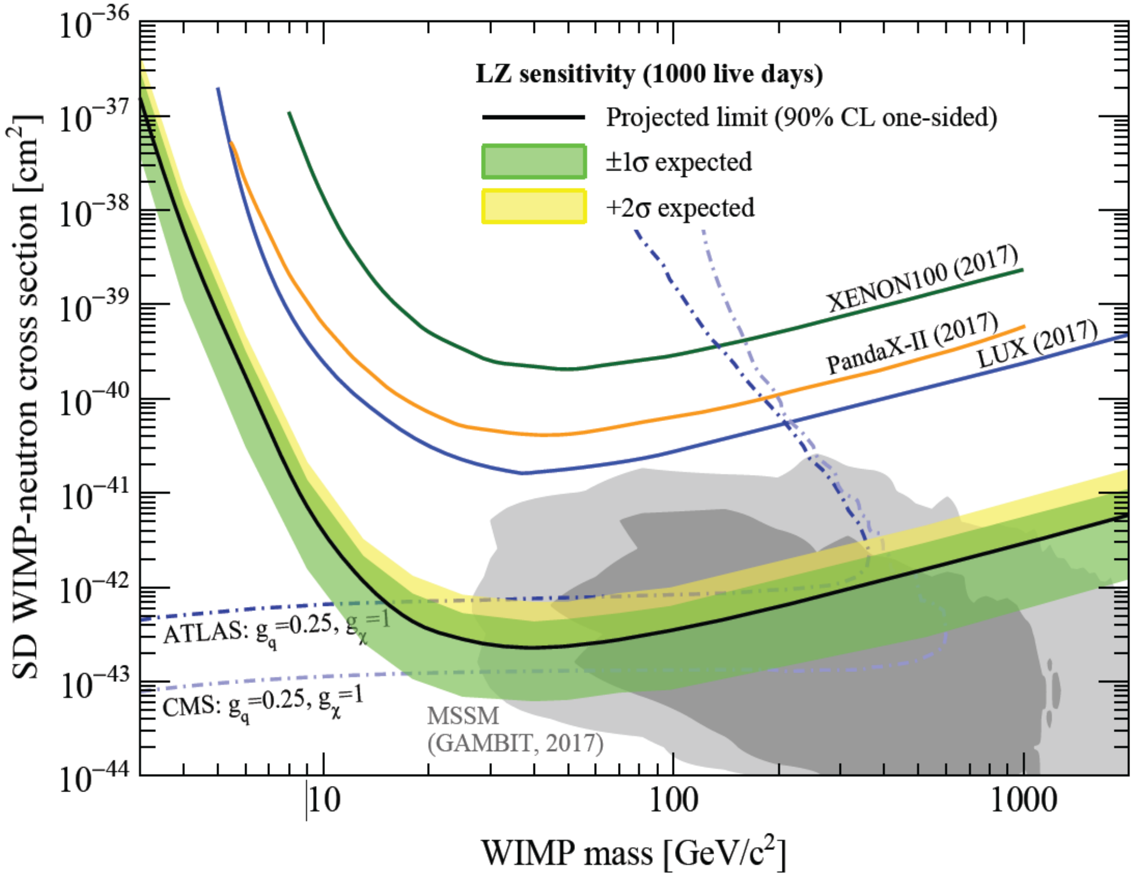
LZ SENSITIVITY: SPIN-INDEPENDENT SCATTERING



LZ SENSITIVITY: SPIN-DEPENDENT SCATTERING

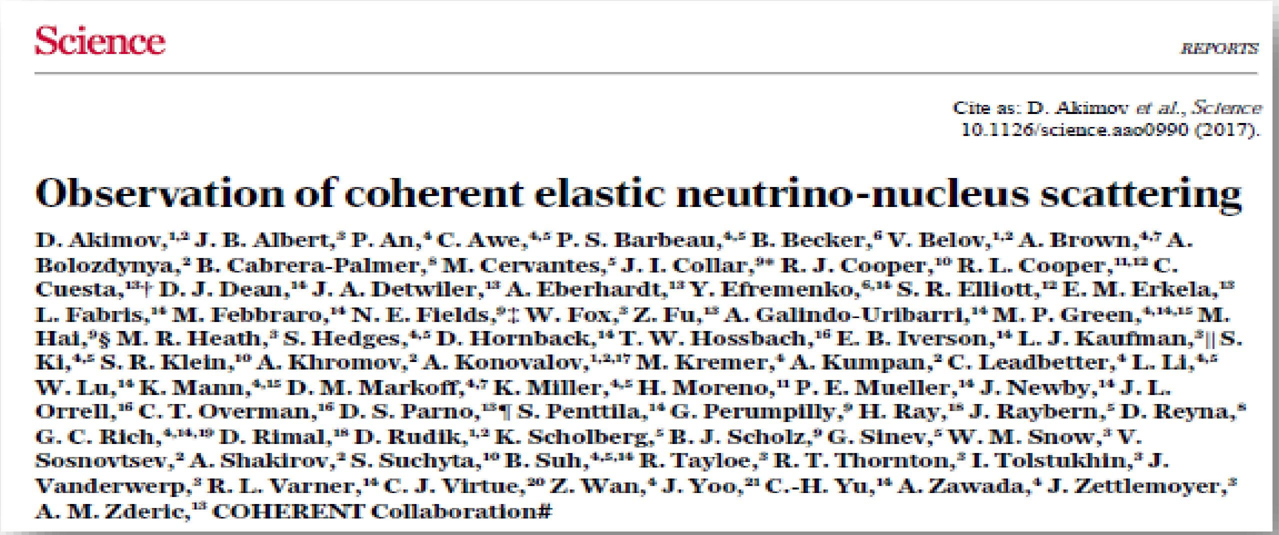
- WIMP-proton and WIMP-neutron sensitivity from SD scattering in Xe-129 and Xe-131 (~50% n.a.)





NR INTERACTIONS – LOW ENERGY: CEνNS

- **CEνNS first observed in 2017 by COHERENT** $(\nu + A \longrightarrow \nu + A)$
- Several astro-neutrino fluxes able to produce these very soft nuclear recoil spectra
- Single scatters, uniformly distributed, NR spectrum looks like WIMPs
- LZ: ~40 B-8 solar neutrinos (~keV) – demonstrating supernova sensitivity

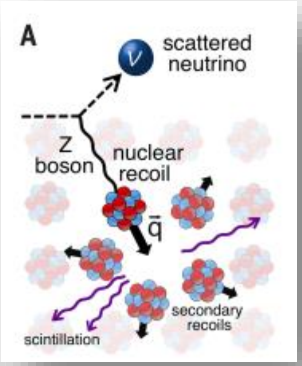


Science REPORTS

Cite as: D. Akimov *et al.*, *Science* 10.1126/science.aao0990 (2017).

Observation of coherent elastic neutrino-nucleus scattering

D. Akimov,[1,2] J. B. Albert,[3] P. An,[4] C. Awe,[4,5] P. S. Barbeau,[4,5] B. Becker,[6] V. Belov,[1,2] A. Brown,[4,7] A. Bolozdynya,[2] B. Cabrera-Palmer,[8] M. Cervantes,[5] J. I. Collar,[9*] R. J. Cooper,[10] R. L. Cooper,[11,12] C. Cuesta,[13†] D. J. Dean,[14] J. A. Detwiler,[13] A. Eberhardt,[13] Y. Efremenko,[6,14] S. R. Elliott,[12] E. M. Erkela,[13] L. Fabris,[14] M. Febbraro,[14] N. E. Fields,[9‡] W. Fox,[3] Z. Fu,[13] A. Galindo-Uribarri,[14] M. P. Green,[4,14,15] M. Hai,[9§] M. R. Heath,[3] S. Hedges,[4,5] D. Hornback,[14] T. W. Hossbach,[16] E. B. Iverson,[14] L. J. Kaufman,[3||] S. Ki,[4,5] S. R. Klein,[10] A. Khromov,[2] A. Konovalov,[1,2,17] M. Kremer,[4] A. Kumpan,[2] C. Leadbetter,[4] L. Li,[4,5] W. Lu,[14] K. Mann,[4,15] D. M. Markoff,[4,7] K. Miller,[4,5] H. Moreno,[11] P. E. Mueller,[14] J. Newby,[14] J. L. Orrell,[16] C. T. Overman,[16] D. S. Parno,[13¶] S. Penttila,[14] G. Perumpilly,[9] H. Ray,[18] J. Raybern,[5] D. Reyna,[8] G. C. Rich,[4,14,19] D. Rimal,[18] D. Rudik,[1,2] K. Scholberg,[5] B. J. Scholz,[9] G. Sinev,[5] W. M. Snow,[3] V. Sosnovtsev,[2] A. Shakirov,[2] S. Suchyta,[10] B. Suh,[4,5,14] R. Tayloe,[3] R. T. Thornton,[3] I. Tolstukhin,[3] J. Vanderwerp,[3] R. L. Varner,[14] C. J. Virtue,[20] Z. Wan,[4] J. Yoo,[21] C.-H. Yu,[14] A. Zawada,[4] J. Zettlemoyer,[3] A. M. Zderic,[13] COHERENT Collaboration#



A galactic supernova at 10 kpc can produce up to ~100 events in LZ through this flavour-blind interaction

NR INTERACTIONS – HIGH(ER) ENERGY

NR-EFT operators: some have benign form factors at high energies

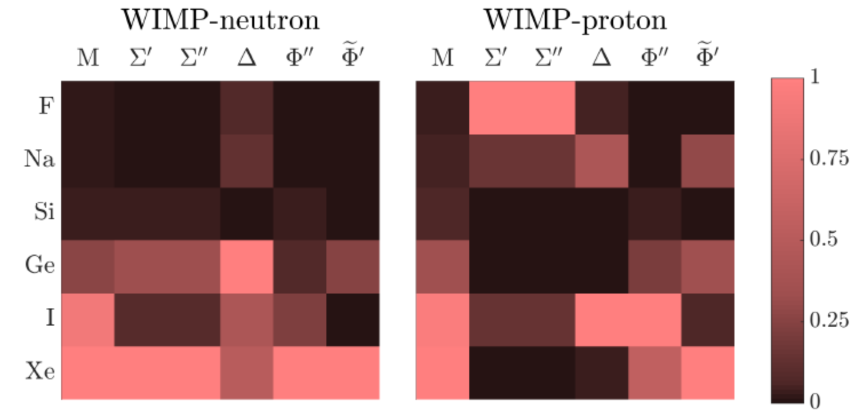
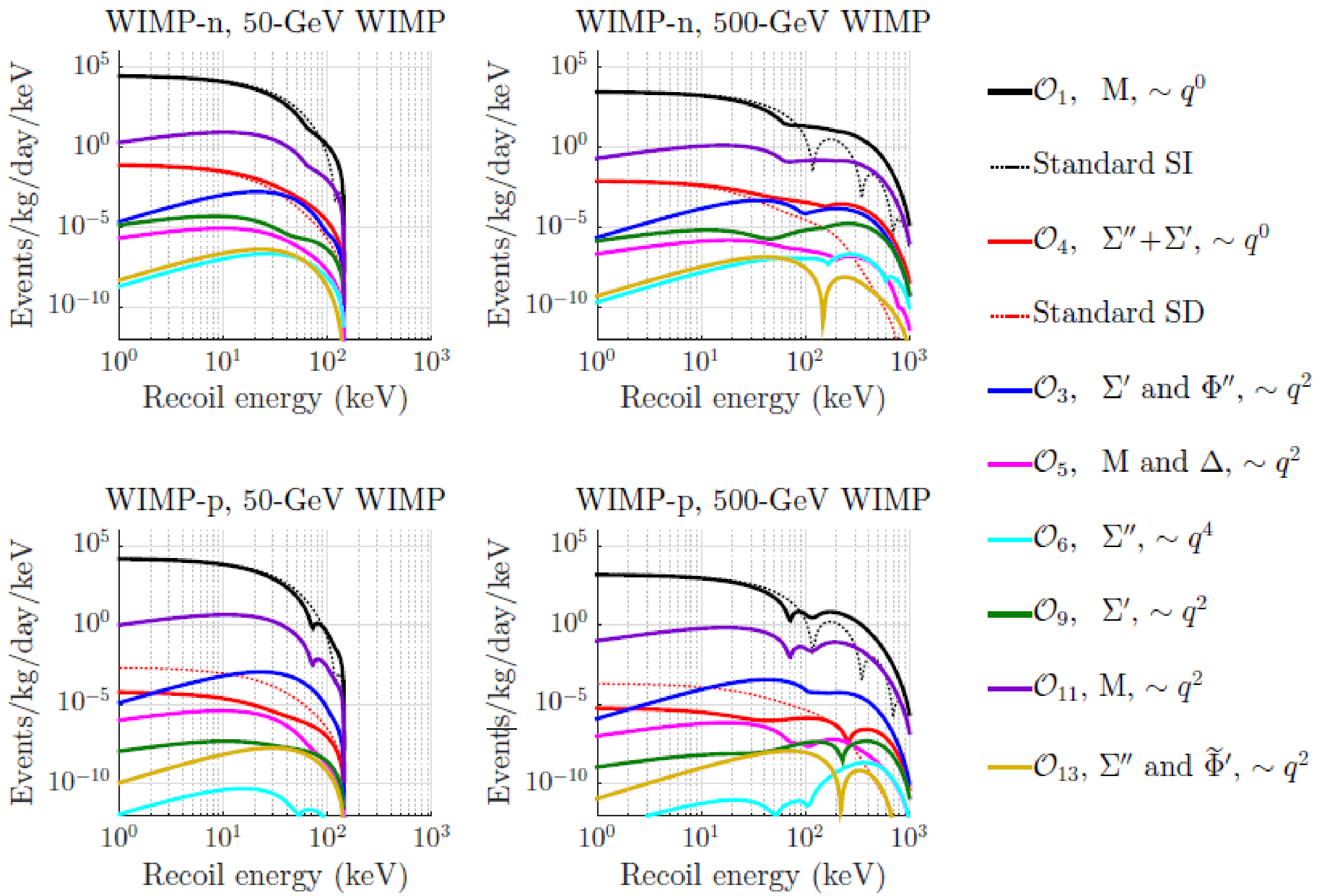


FIG. 1. The relative size of integrated nuclear form factors $\int_0^{100\ \mathrm{MeV}} \frac{1}{2} q dq F_k(q^2)$ by target for $k = \mathrm{M}, \Sigma'', \Sigma', \Delta, \Phi''$, and $\tilde{\Phi}'$, adapted and expanded from Fig. 1 of [21]. The contribution of each isotope is weighted by natural abundance. Each value is normalized by that of the element with the maximum integrated form factor.



ER INTERACTIONS

1807.07113

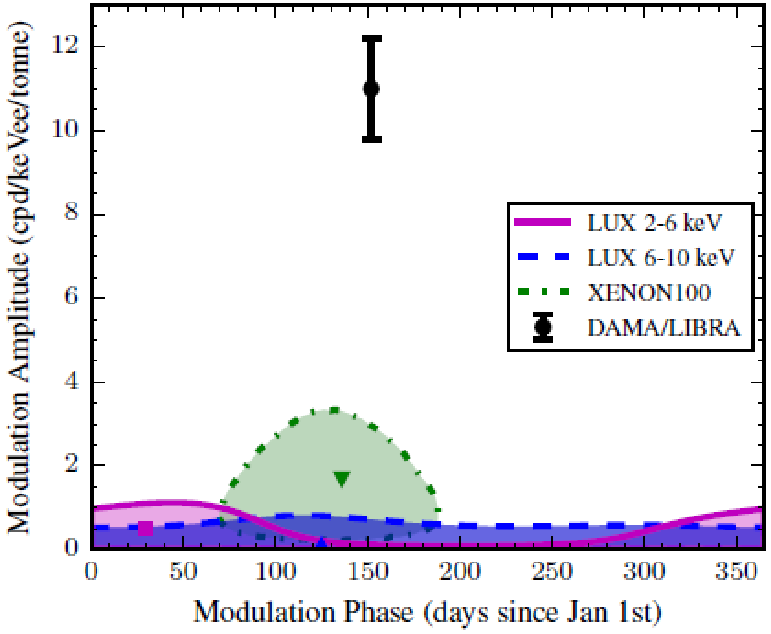


FIG. 7. The evaluated 90% LUX contours for the modulation parameters in the signal region of 2-6 keV_{ee} (solid line, purple-filled), and that in the control region of 6-10 keV_{ee} (dashed line, blue-filled). The DAMA result (DAMA/NaI and DAMA/LIBRA) for 2-6 keV_{ee} [14] (black dot with error bars) and the XENON100 result for 2-5.8 keV_{ee} [41] (dotted line, green-filled) are also shown for comparison.

Physics with electron recoils:

Annual & diurnal modulations

Axion-like particles

1704.02297

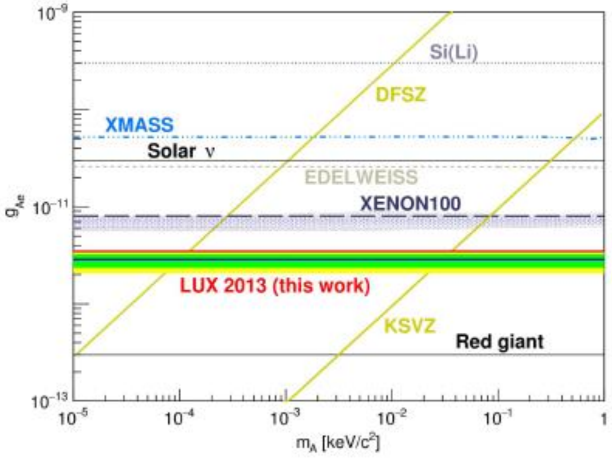


FIG. 6: Red curve: LUX 2013 data 90% C.L. limit on the coupling between solar axions and electrons. Blue curve: 90% C.L. sensitivity, $\pm 1\ \sigma$ (green band), and $\pm 2\ \sigma$ (yellow band).

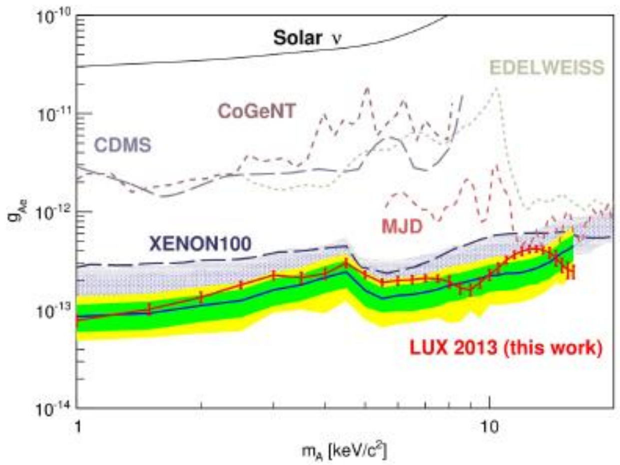


FIG. 7: Red curve: LUX 2013 data 90% C.L. limit on the coupling between galactic axion-like particles and electrons. Blue curve: 90% C.L. sensitivity, $\pm 1\ \sigma$ (green band), and $\pm 2\ \sigma$ (yellow band).

MIXED INTERACTIONS

Combined NR+ER signal
Transition to low-lying excited nuclear state

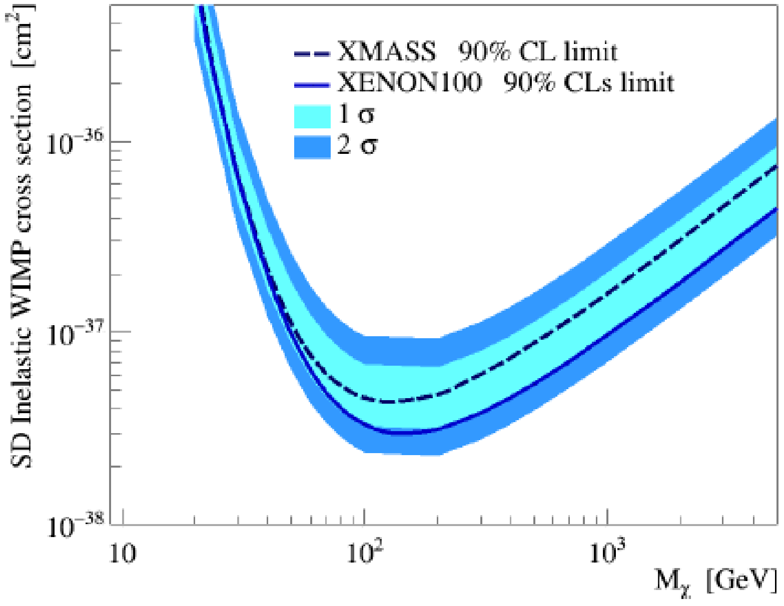
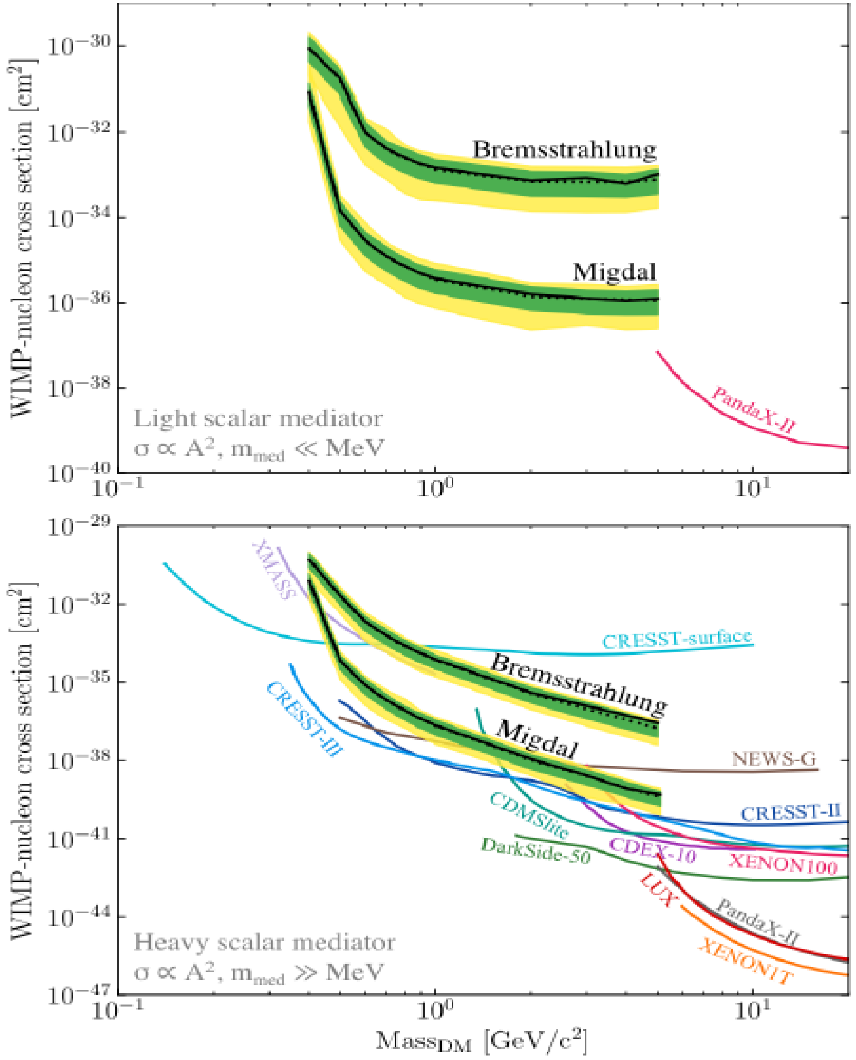


FIG. 5. Upper limit (blue curve) on the spin-dependent, inelastic WIMP-nucleon cross section as a function of WIMP mass. The expected one (light shaded area) and two (dark shaded area) standard deviation uncertainty is also shown. This result is compared to the upper limit (at 90% C.L.) obtained by the XMASS experiment (dashed line) [27].

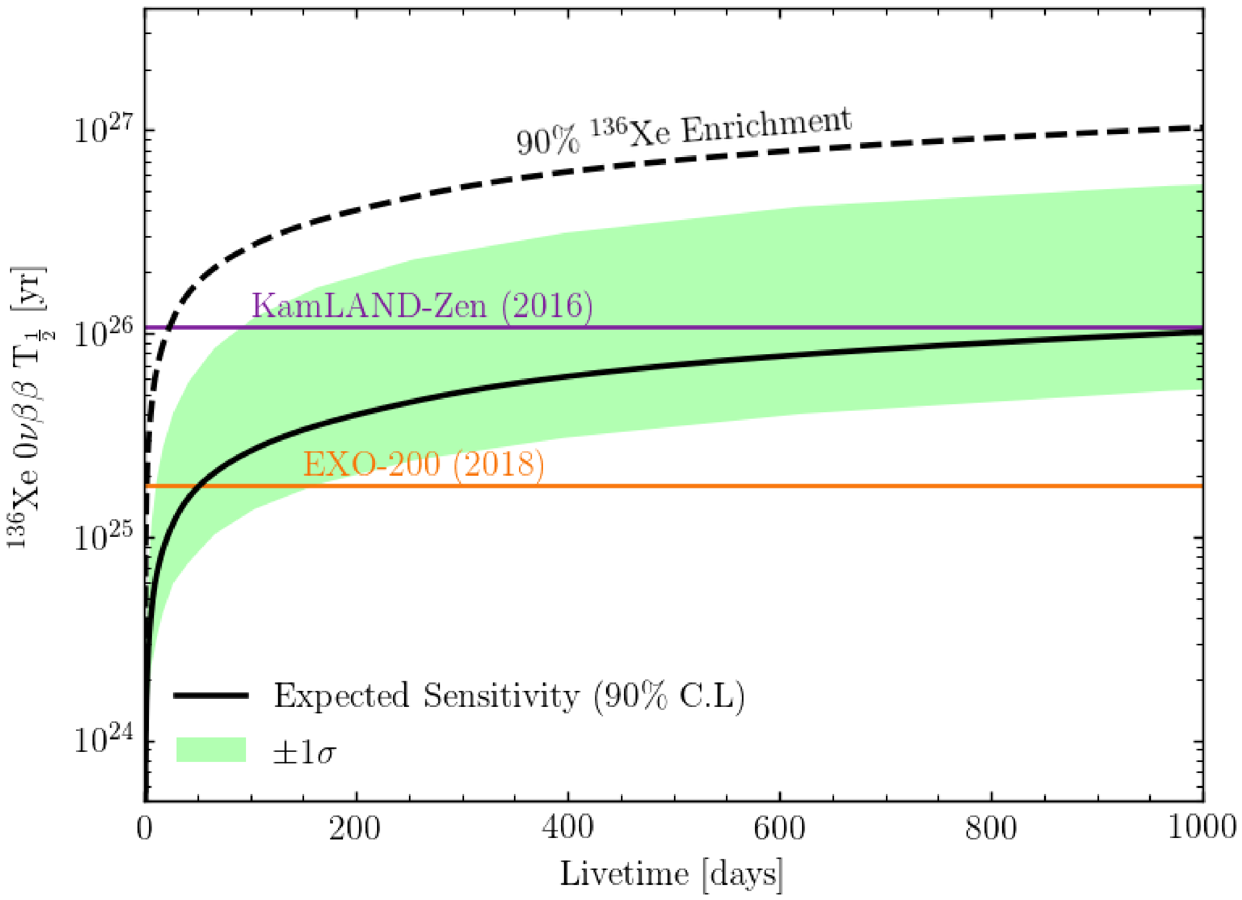
1705.05830

Migdal effect: assumed NR sub-threshold
but fuller analysis should consider ER+NR

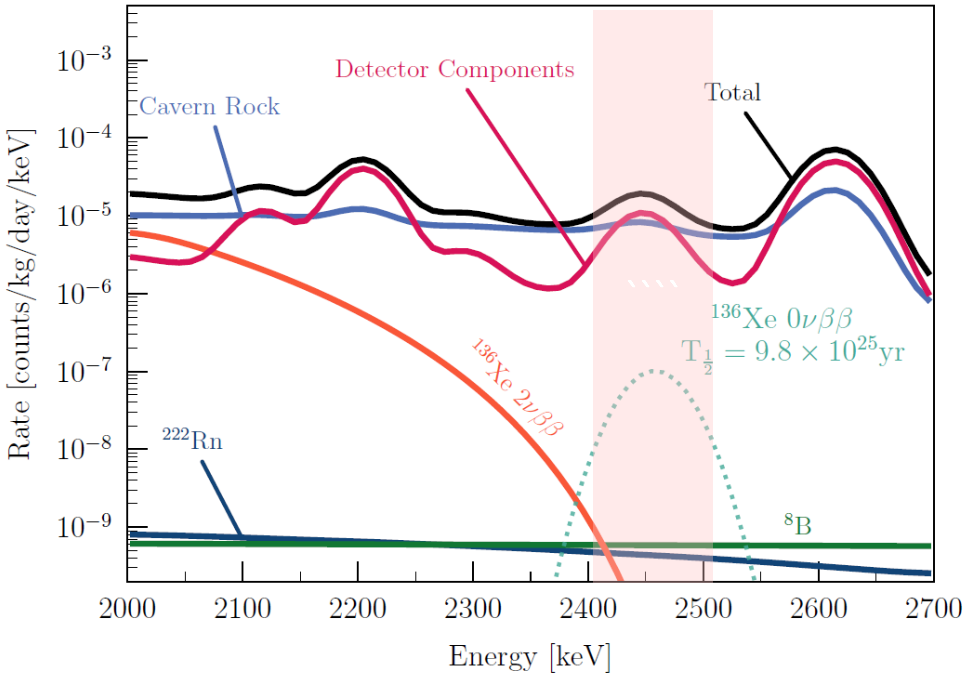


ER INTERACTIONS: 0νββ DECAY IN XENON-136

- Searches for neutrinoless double beta decay in Xe-136 (8.9% n.a.) – $Q_{\beta\beta}$ = 2,458 keV



Gamma backgrounds from cavern and detector: Bi-214 (2,447 keV) and Tl-208 (2,614 keV)



σ ~ 1% at $Q_{\beta\beta}$ demonstrated in LXe

SUMMARY

- Direct dark matter experiments offer plenty of opportunities for rare event searches involving scattering or decay processes
- The large liquid xenon TPCs possess a combination of extremely low backgrounds and very low energy thresholds
- Besides sensitivity to various DM interaction models, neutrino astrophysics and $0\nu\beta\beta$ decay searches are becoming competitive at the multi-tonne scale
  - Towards a Next-Generation Rare Event Observatory
  - GOAL: limited by physics backgrounds: pp ν in ER, atm ν in NR

Reserve Slides

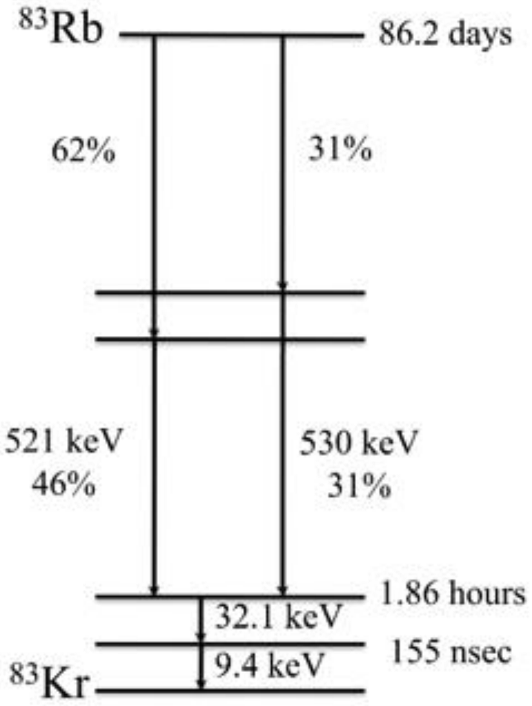
LZ CALIBRATION SOURCES

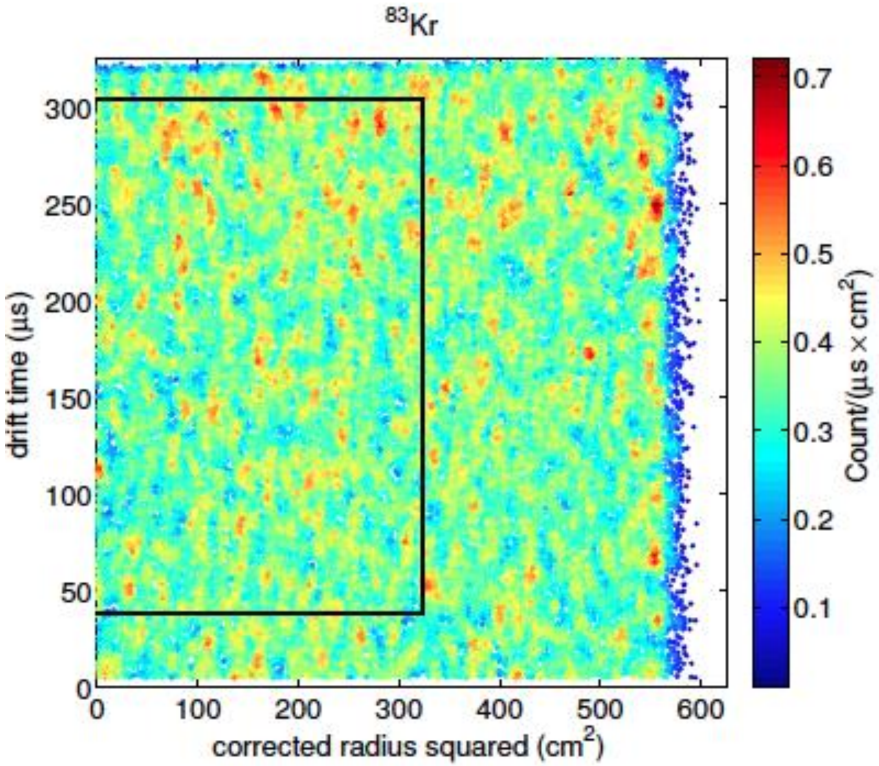
Table 7.0.1: Baseline calibration sources for LZ.

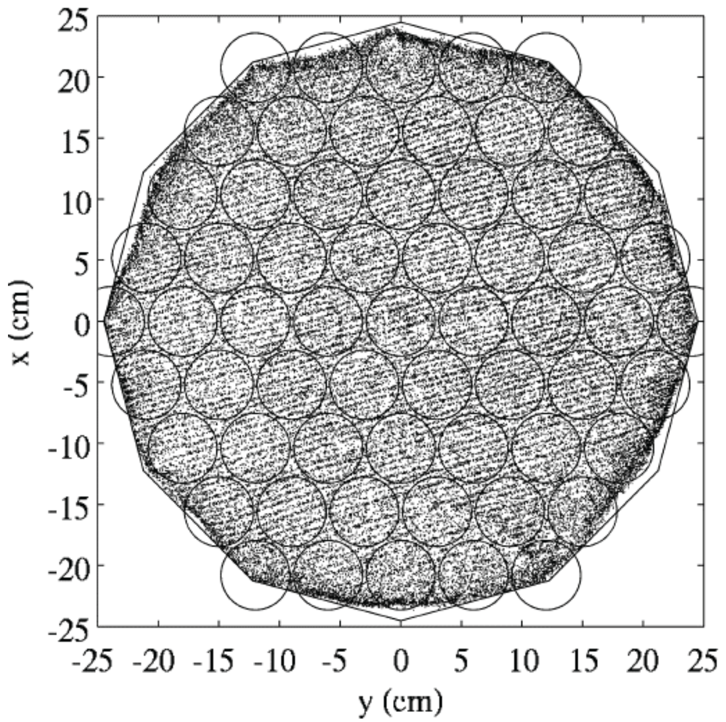
Isotope	What	Purpose	Deployment	Custom?
Tritium	beta, Q = 18.6 keV	ER band	Internal	N
^{83m}Kr	beta/gamma, 32.1 keV and 9.4 keV	TPC (x,y,z)	Internal	Y
^{131m}Xe	164 keV γ	TPC (x,y,z), Xe skin	Internal	Y
^{220}Rn	various α's	xenon skin	Internal	N
AmLi	(α,n)	NR band	CSD	Y
^{252}Cf	spontaneous fission	NR efficiency	CSD	N
^{57}Co	122 keV γ	Xe skin threshold	CSD	N
^{228}Th	2.615 MeV γ, various others	OD energy scale	CSD	N
^{22}Na	back-to-back 511 keV γ's	TPC and OD sync	CSD	N
^{88}Y Be	152 keV neutron	low-energy NR response	External	N
^{205}Bi Be	88.5 keV neutron	low-energy NR response	External	Y
^{206}Bi Be	47 keV neutron	low-energy NR response	External	Y
DD	2,450 keV neutron	NR light and charge yields	External	N
DD	272 keV neutron	NR light and charge yields	External	Y

S1 & S2 FLATFIELDING: KRYPTON-83m

- **S1 and S2 response calibration with dispersed ^{83m}Kr radioisotope**
  - Kr-83m calibration source: Rb-83 infused into zeolite, located within xenon gas plumbing
  - Routine injection, decays within detector, emitting 2 CEs ($T_{1/2}$=1.86 hrs)

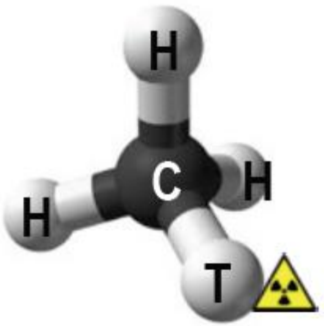


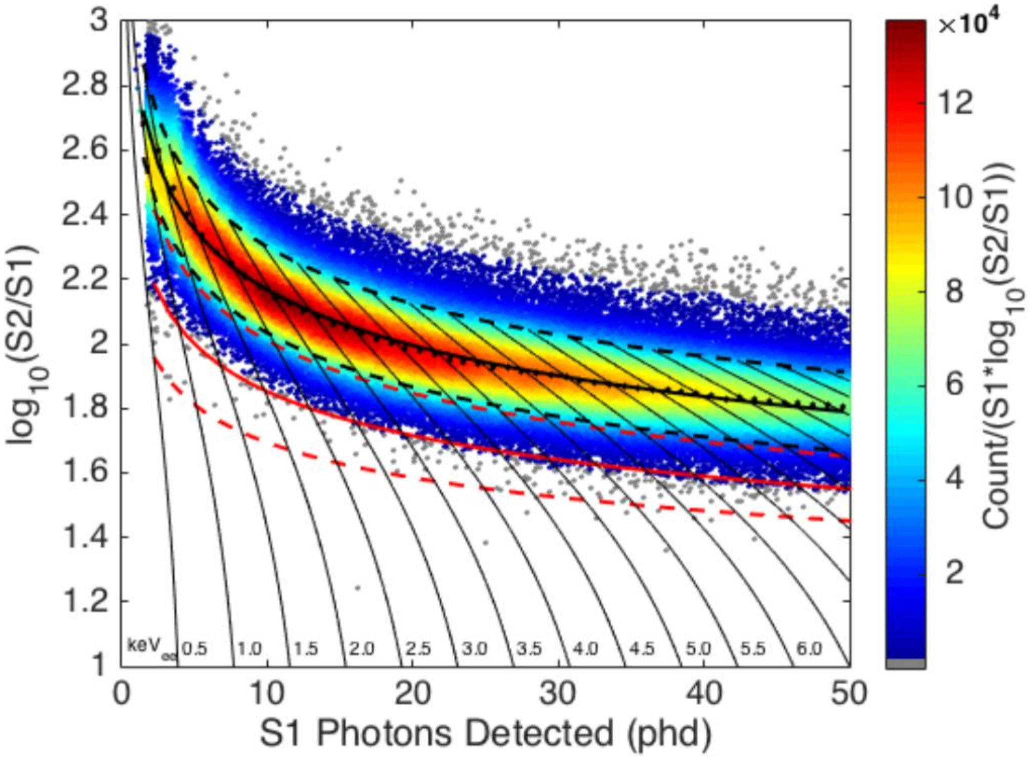


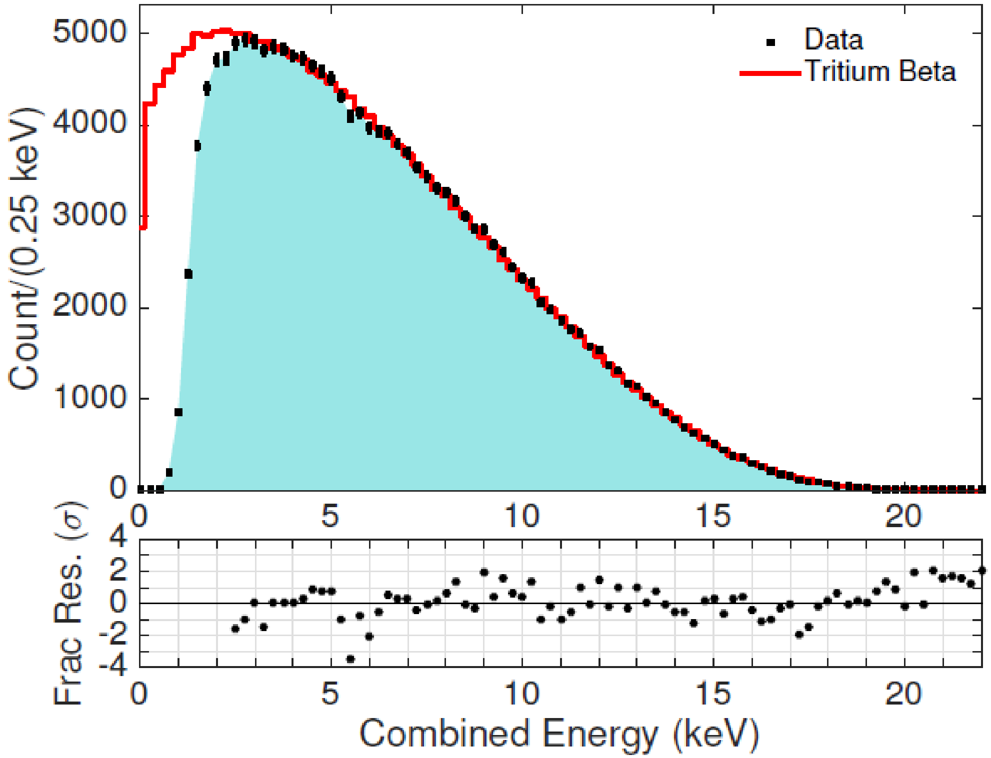


ER CALIBRATION: TRITIUM SOURCE

- **ER band calibrated with dispersed tritiated methane**
  - CH_3T (β_{max}=18 keV): one-off injection, removed by purification system
  - Detection threshold, mean ER yields, ER recombination fluctuations

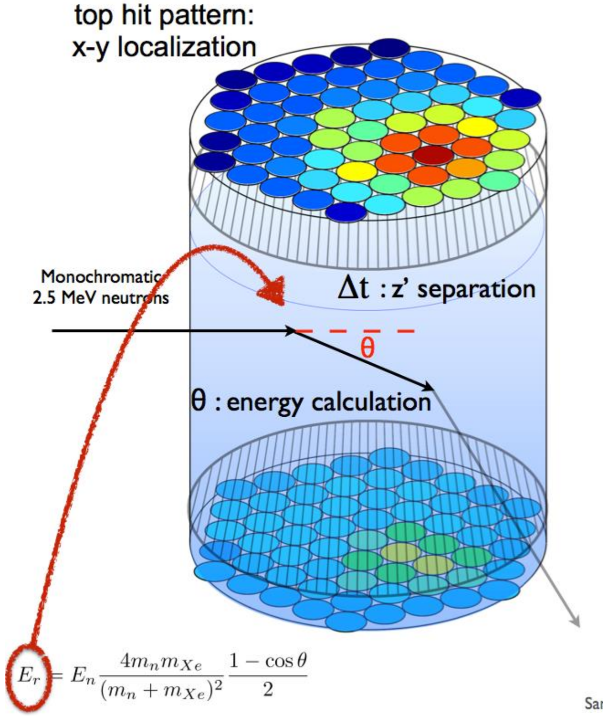


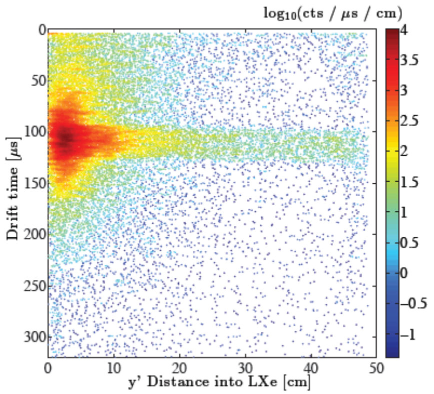


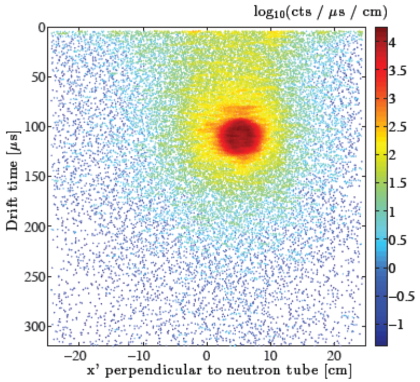


NR CALIBRATION: D-D NEUTRONS

- **NR band calibrated with neutrons**
  - Mono-energetic neutron beam (2.45 MeV)

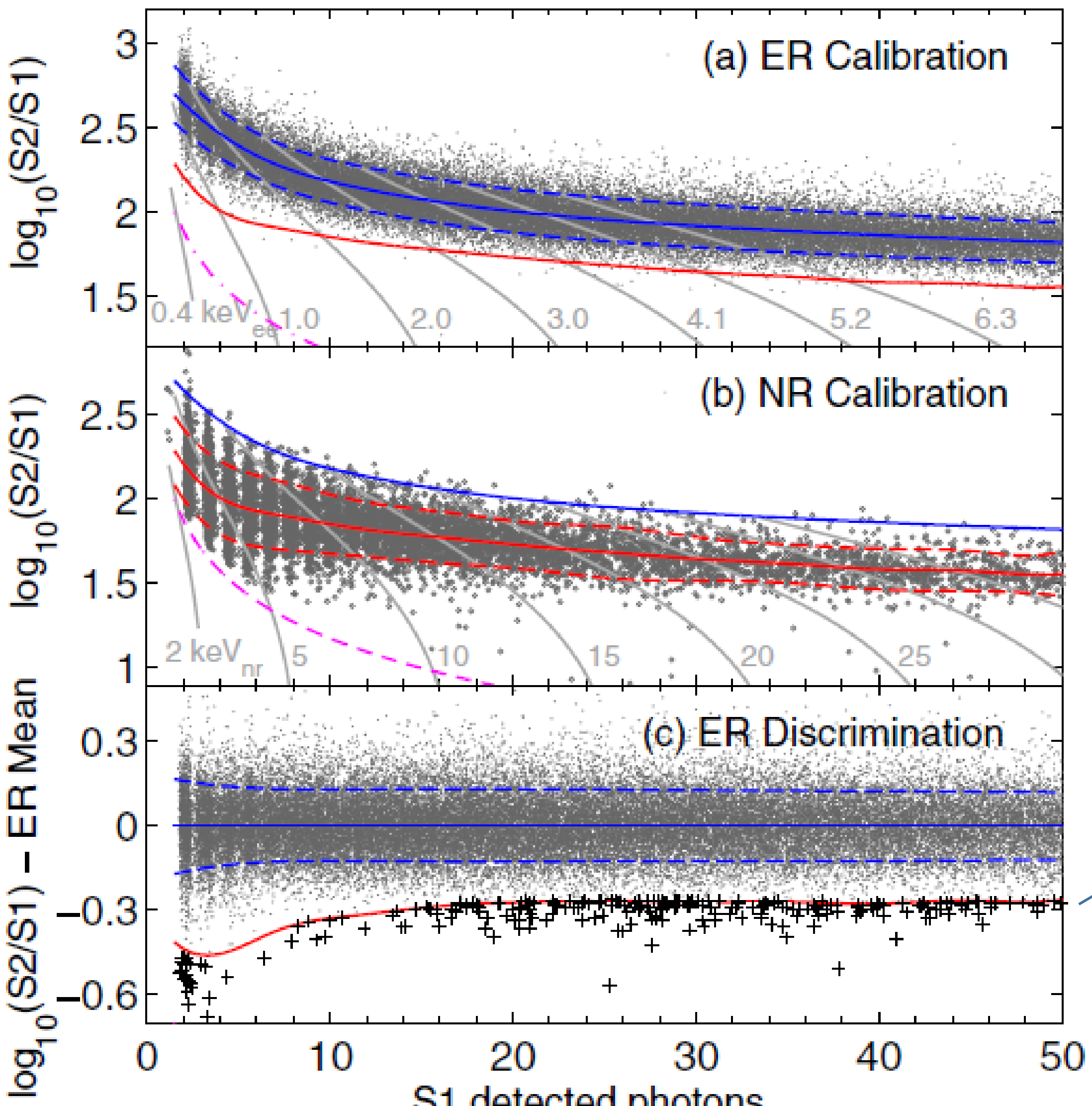






ER/NR DISCRIMINATION

PHYS. REV. D 97, 102008 (2018)



ER leakage
past NR band mean
~1:1000

LZ SENSITIVITY: SPIN-INDEPENDENT SCATTERING

- SI sensitivity versus time at 35 GeV WIMP mass