



Hunting for the Invisible Deep Underground

Jui-Jen (Ryan) Wang

1/14/2022

University of Alabama &
LZ collaboration





- Dark matter concept
- Direct detection of dark matter
- Detector technique: Liquid noble gas
- The LZ experiment: most sensitive to dark matter so far
- Beyond LZ

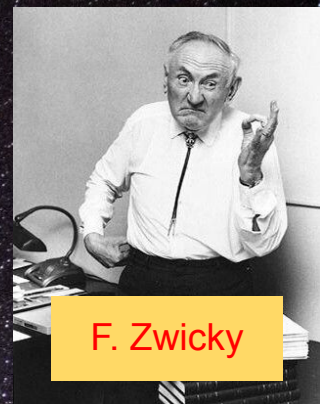


A long time ago in a Galaxy cluster far, far away...





Gravitational Mass is ~ 400 times greater than expected!

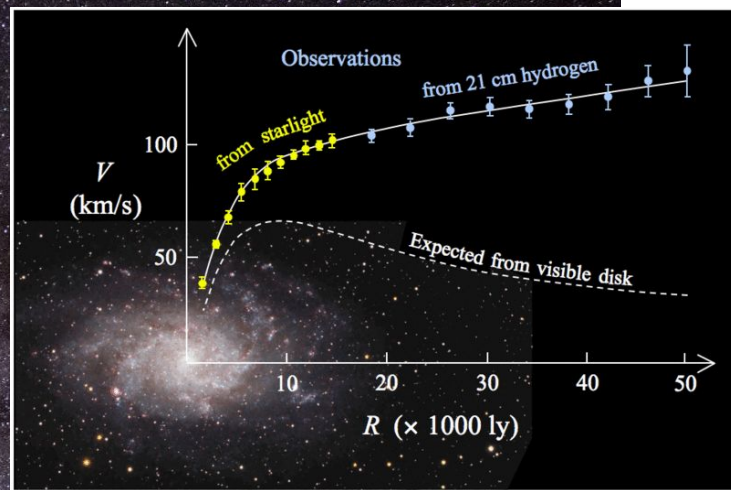


F. Zwicky

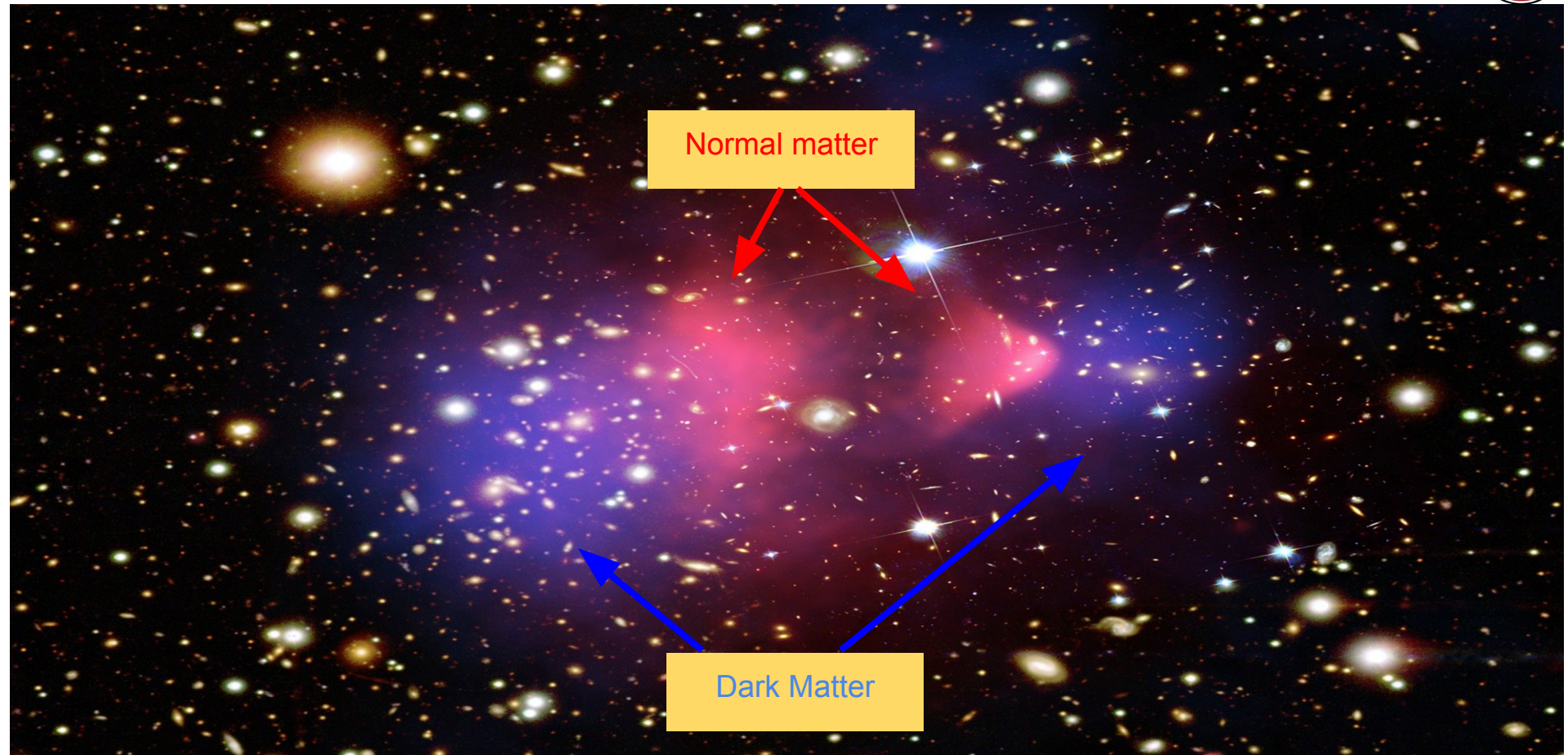


Rotational curve of a galaxy did not follow the newtonian dynamics!

Vera Rubin in 1970s



$$v(r) = \sqrt{G \cdot \frac{m(r)}{r}}$$

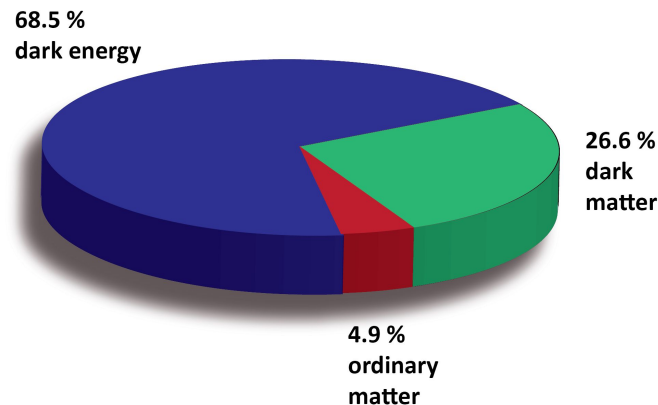


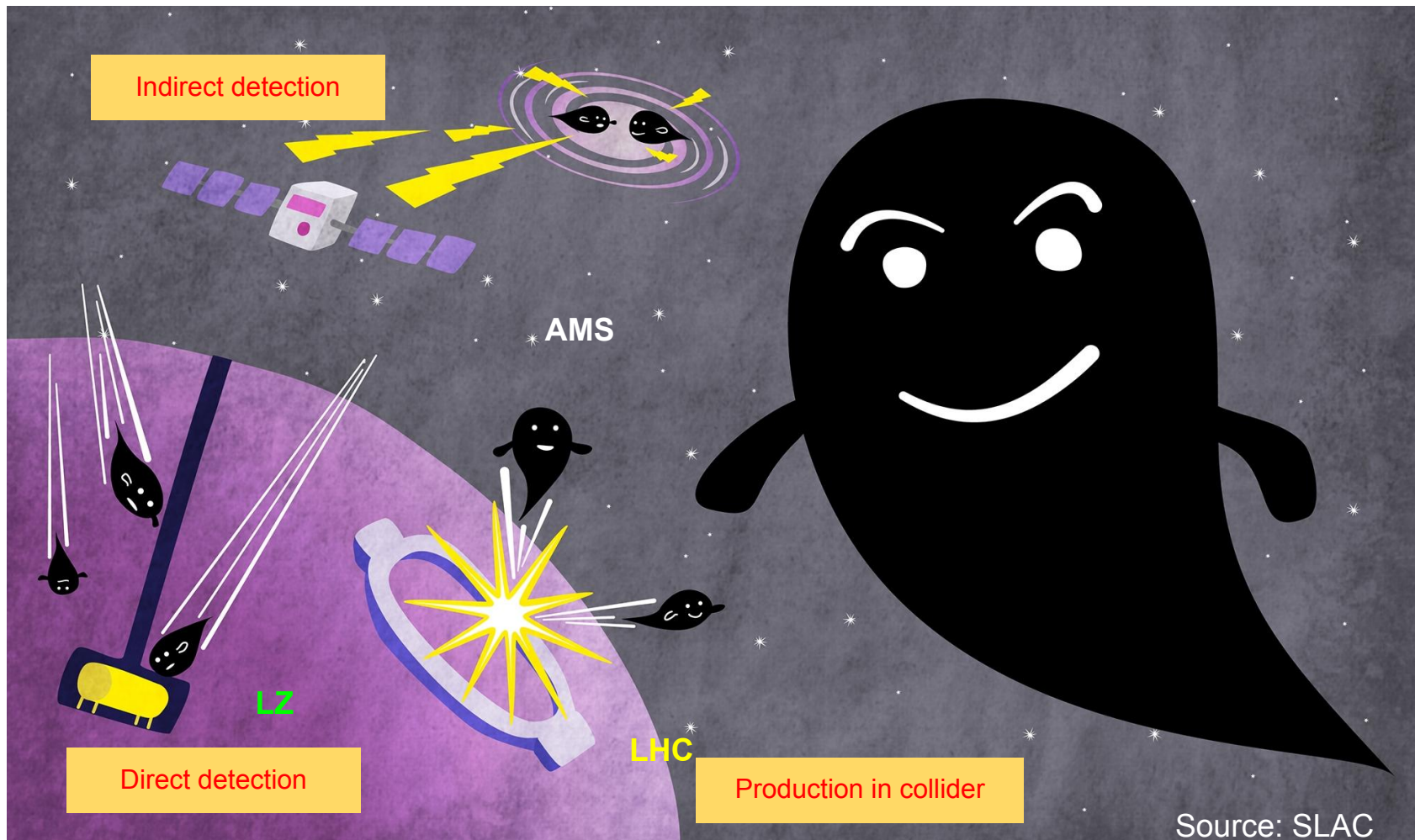
Normal matter

Dark Matter



- Calculation using Cosmic Microwave Background (CMB) and Big Bang Nucleosynthesis (BBN) indicate baryonic matter only account for 5% of the total mass of universe.
- Cold (non-relativistic) dark matter is the favored candidates
 - Abundance of dark matter suggests the new particle has mass in 100 GeV range at weak interaction scale
 - Weakly Interacting Massive Particles (WIMPs) is leading candidate
 - Only interact via gravity and forces weaker than the weak nuclear force
 - Massive, moving slowly, thus “cold”

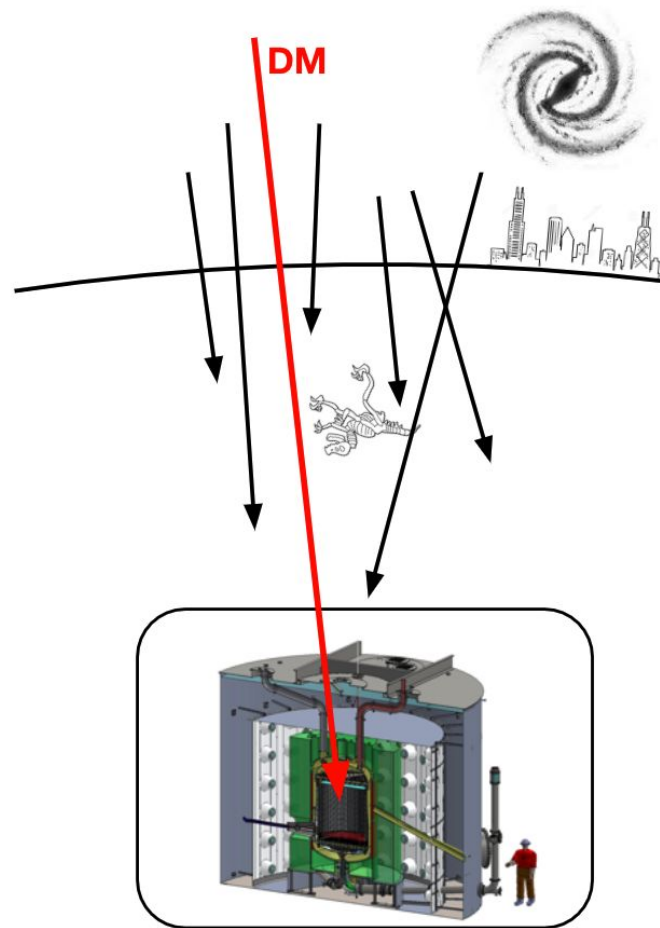




Source: SLAC

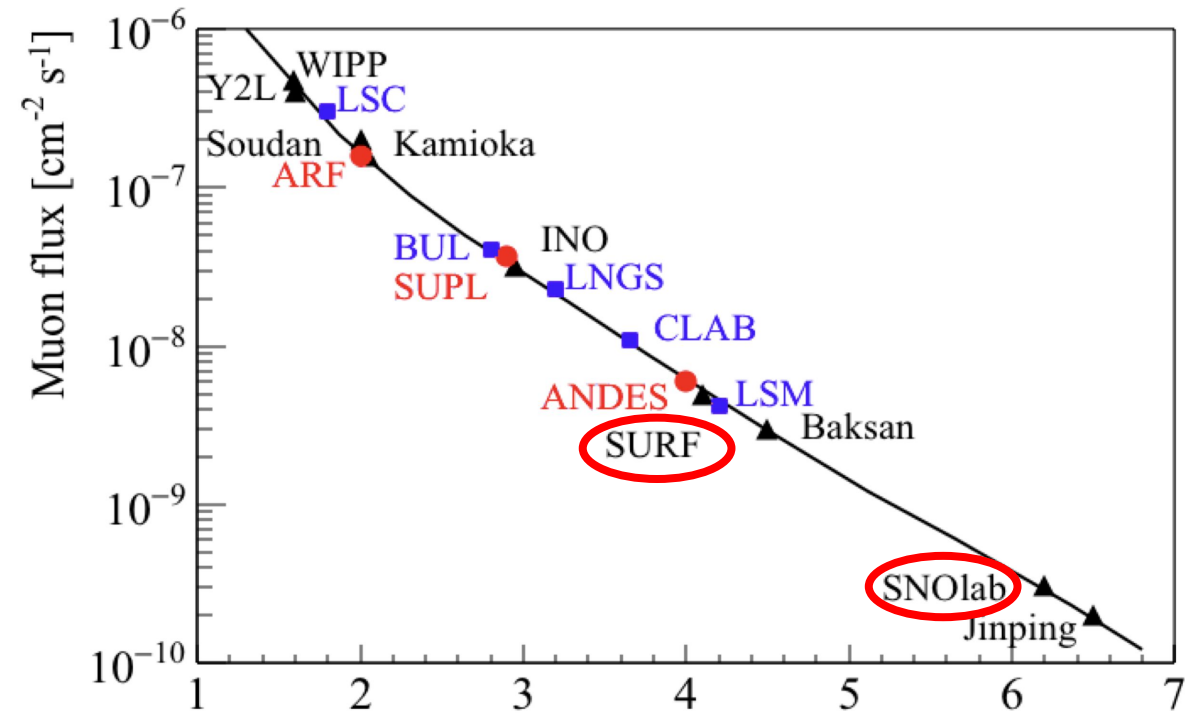


- You would want something **stable** for your detector target.
- No or few **internal background** in the detector target.
- With **measurable signal** even when the energy deposition is small.
- With **good energy resolution** and **linear** energy response.
- Large volume to increase the chance of detection
 - ~ **few** events/year



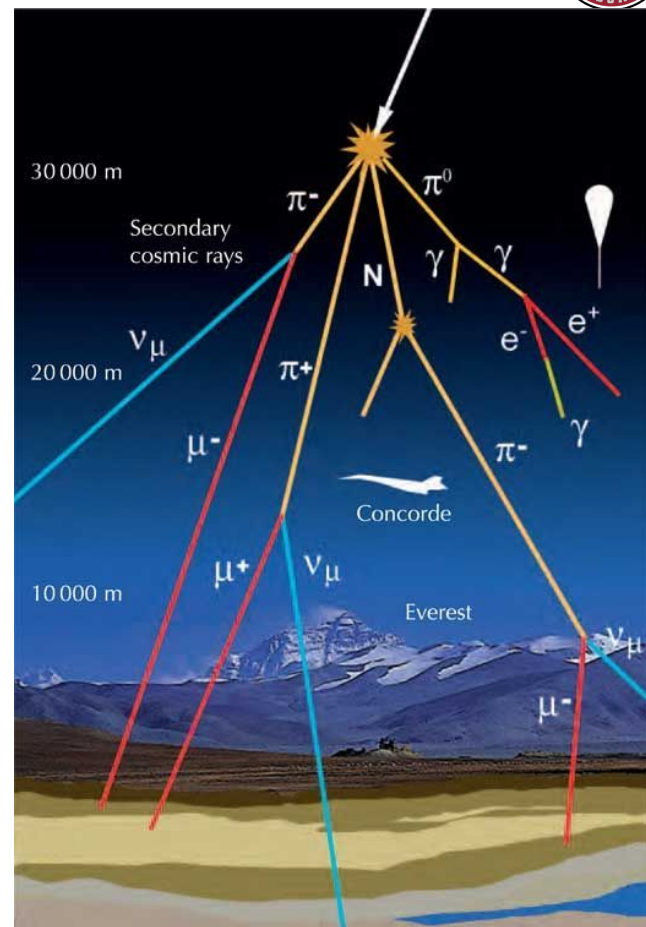


Where to find WIMPs?



Equivalent depth under flat surface [km w.e.]

To eliminate the cosmic background radiation,
one has to go deeper!





- SNOLAB (Sudbury Neutrino Observatory) is located at 6800 ft at Creighton Mine, which is an active underground nickel mine operated by Vale.
- Originally housing the SNO experiment, which won the Nobel Prize in Physics in 2015 for discovering neutrino oscillation of solar neutrinos.



- Sanford Underground Research Facility (SURF), is located at 4800 ft at Homestake mine, which is a dedicated scientific research underground lab.
- “Homestake experiment” which won the Nobel Prize for the detection of solar neutrinos
- LZ located at Davis Campus, also the future home of DUNE.



Liquid Noble Gas



Periodic Table of the Elements

	Group 1																Group 18																			
	1a																0																			
Period 1	1																2																			
1	H																He																			
2	3		4														5		6		7		8		9		10		11		12					
2	Li		Be														B		C		N		O		F		Ne		Ar							
3	11		12														13		14		15		16		17		18									
3	Na		Mg														Al		Si		P		S		Cl		Ar									
4	19		20		21		22		23		24		25		26		27		28		29		30		31		32		33		34		35		36	
4	K		Ca		Sc		Ti		V		Cr		Mn		Fe		Co		Ni		Cu		Zn		Ga		Ge		As		Se		Br		Kr	
5	37		38		39		40		41		42		43		44		45		46		47		48		49		50		51		52		53		54	
5	Rb		Sr		Y		Zr		Nb		Mo		Tc		Ru		Rh		Pd		Ag		Cd		In		Sn		Sb		Te		I		Xe	
6	55		56		57		72		73		74		75		76		77		78		79		80		81		82		83		84		85		86	
6	Cs		Ba		♦		Hf		Ta		W		Re		Os		Ir		Pt		Au		Hg		Tl		Pb		Bi		Po		At		Rn	
7	87		88		89		104		105		106		107		108		109		110		111		112		113		114		115		116		117		118	
7	Fr		Ra		★		Rf		Db		Sg		Bh		Hs		Mt		Ds		Rg		Cn		Nh		Fl		Mc		Lv		Ts		Og	

	Alkali Metals		Lanthanide Series
	Alkaline Earth Metals		Actinide Series
	Transition Metals		Halogens
	Non-metals		Inert Gases
	Other Metals		

Atomic Number: 1
Atomic Weight*: 1.01
Name: Hydrogen
Symbol: H
Electron Configuration**: 1s¹

- Too light for nominal dark matter searches
- Require a elaborated cryogenic system

- Aa** -Solid
- Aa** -Gas
- Aa** -Liquid
- Aa** -Synthetically Prepared

57	58	59	60	61	62	63	64	65	66	67	68	69	70	71
La	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
89	90	91	92	93	94	95	96	97	98	99	100	101	102	103
Ac	Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr

* Based on Carbon-12 (###) represents most stable or most stable expected isotope.
** Some electron configurations are based on theoretical expected arrangements.
© 2016 Aldon Corporation

Innovating Science™ by Aldon Corporation
"cutting edge science for the classroom"





Periodic Table of the Elements

	Group 1																Group 18																			
	1a																0																			
Period 1	1																2																			
1	H																He																			
2	Li		Be														B		C		N		O		F		Ne									
3	Na		Mg														Al		Si		P		S		Cl		Ar									
4	K		Ca		Sc		Ti		V		Cr		Mn		Fe		Co		Ni		Cu		Zn		Ga		Ge		As		Se		Br		Kr	
5	Rb		Sr		Y		Zr		Nb		Mo		Tc		Ru		Rh		Pd		Ag		Cd		In		Sn		Sb		Te		I		Xe	
6	Cs		Ba		♦		Hf		Ta		W		Re		Os		Ir		Pt		Au		Hg		Tl		Pb		Bi		Po		At		Rn	
7	Fr		Ra		★		Rf		Db		Sg		Bh		Hs		Mt		Ds		Rg		Cn		Nh		Fl		Mc		Lv		Ts		Og	

Alkali Metals	Lanthanide Series
Alkaline Earth Metals	Actinide Series
Transition Metals	Halogens
Non-metals	Inert Gases
Other Metals	

Atomic Number: 1
Atomic Weight*: 1.01
Name: Hydrogen
Symbol: H
Electron Configuration**: 1s¹

- Has radioactive isotopes, hard to eliminate for dark matter searches

- Aa - Solid
- Aa - Gas
- Aa - Liquid
- Aa - Synthetically Prepared

57	58	59	60	61	62	63	64	65	66	67	68	69	70	71
La	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
89	90	91	92	93	94	95	96	97	98	99	100	101	102	103
Ac	Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr



Innovating Science™ by Aldon Corporation

"cutting edge science for the classroom"

* Based on Carbon-12. (##) represents most stable or most stable expected isotope.
** Some electron configurations are based on theoretical expected arrangements.
© 2016 Aldon Corporation



Periodic Table of the Elements

Group 1 1a																	18 0		
Period 1	1 1.01 H Hydrogen 1s ¹																	2 4.00 He Helium 1s ²	
2	3 6.94 Li Lithium 1s ² 2s ¹	4 9.01 Be Beryllium 1s ² 2s ²																	10 20.18 Ne Neon 1s ² 2s ² 2p ⁶
3	11 22.99 Na Sodium [Ne]3s ¹	12 24.31 Mg Magnesium [Ne]3s ²	3 IIIb	4 IVb	5 Vb	6 VIb	7 VIIb	8	9	10	11 IIb	12 IIB	13 26.98 Al Aluminum [Ne]3s ² 3p ¹	14 28.09 Si Silicon [Ne]3s ² 3p ²	15 30.97 P Phosphorus [Ne]3s ² 3p ³	16 32.07 S Sulfur [Ne]3s ² 3p ⁴	17 35.45 Cl Chlorine [Ne]3s ² 3p ⁵	18 39.95 Ar Argon [Ne]3s ² 3p ⁶	
4	19 39.10 K Potassium [Ar]4s ¹	20 40.08 Ca Calcium [Ar]4s ²	21 44.96 Sc Scandium [Ar]3d ¹ 4s ²	22 47.87 Ti Titanium [Ar]3d ² 4s ²	23 50.94 V Vanadium [Ar]3d ³ 4s ²	24 52.00 Cr Chromium [Ar]3d ⁵ 4s ¹	25 54.94 Mn Manganese [Ar]3d ⁵ 4s ²	26 55.85 Fe Iron [Ar]3d ⁶ 4s ²	27 58.93 Co Cobalt [Ar]3d ⁷ 4s ²	28 58.69 Ni Nickel [Ar]3d ⁸ 4s ²	29 63.55 Cu Copper [Ar]3d ¹⁰ 4s ¹	30 65.39 Zn Zinc [Ar]3d ¹⁰ 4s ²	31 69.72 Ga Gallium [Ar]3d ¹⁰ 4s ¹ 4p ¹	32 72.61 Ge Germanium [Ar]3d ¹⁰ 4s ² 4p ²	33 74.92 As Arsenic [Ar]3d ¹⁰ 4s ² 4p ³	34 78.96 Se Selenium [Ar]3d ¹⁰ 4s ² 4p ⁴	35 79.90 Br Bromine [Ar]3d ¹⁰ 4s ² 4p ⁵	36 83.80 Kr Krypton [Ar]3d ¹⁰ 4s ² 4p ⁶	
5	37 85.47 Rb Rubidium [Kr]5s ¹	38 87.62 Sr Strontium [Kr]5s ²	39 88.91 Y Yttrium [Kr]4d ¹ 5s ²	40 91.22 Zr Zirconium [Kr]4d ² 5s ²	41 92.91 Nb Niobium [Kr]4d ⁴ 5s ¹	42 95.94 Mo Molybdenum [Kr]4d ⁵ 5s ¹	43 (98) Tc Technetium [Kr]4d ⁵ 5s ²	44 101.07 Ru Ruthenium [Kr]4d ⁷ 5s ¹	45 102.91 Rh Rhodium [Kr]4d ⁸ 5s ¹	46 106.42 Pd Palladium [Kr]4d ¹⁰	47 107.87 Ag Silver [Kr]4d ¹⁰ 5s ¹	48 112.41 Cd Cadmium [Kr]4d ¹⁰ 5s ²	49 114.82 In Indium [Kr]4d ¹⁰ 5s ¹ 5p ¹	50 118.71 Sn Tin [Kr]4d ¹⁰ 5s ² 5p ²	51 121.76 Sb Antimony [Kr]4d ¹⁰ 5s ² 5p ³	52 127.60 Te Tellurium [Kr]4d ¹⁰ 5s ² 5p ⁴	53 126.90 I Iodine [Kr]4d ¹⁰ 5s ² 5p ⁵	54 131.29 Xe Xenon [Kr]4d ¹⁰ 5s ² 5p ⁶	
6	55 132.91 Cs Cesium [Xe]6s ¹	56 137.33 Ba Barium [Xe]6s ²	♦	72 178.49 Hf Hafnium [Xe]4f ¹⁴ 5d ² 6s ²	73 180.95 Ta Tantalum [Xe]4f ¹⁴ 5d ³ 6s ²	74 183.84 W Tungsten [Xe]4f ¹⁴ 5d ⁴ 6s ²	75 186.21 Re Rhenium [Xe]4f ¹⁴ 5d ⁵ 6s ²	76 190.23 Os Osmium [Xe]4f ¹⁴ 5d ⁶ 6s ²	77 192.22 Ir Iridium [Xe]4f ¹⁴ 5d ⁷ 6s ²	78 195.08 Pt Platinum [Xe]4f ¹⁴ 5d ⁹ 6s ¹	79 196.97 Au Gold [Xe]4f ¹⁴ 5d ¹⁰ 6s ¹	Hg Mercury [Xe]4f ¹⁴ 5d ¹⁰ 6s ²	81 204.38 Tl Thallium [Xe]4f ¹⁴ 5d ¹⁰ 6s ¹ 6p ¹	82 207.20 Pb Lead [Xe]4f ¹⁴ 5d ¹⁰ 6s ² 6p ²	83 208.98 Bi Bismuth [Xe]4f ¹⁴ 5d ¹⁰ 6s ² 6p ³	84 (209) Po Polonium [Xe]4f ¹⁴ 5d ¹⁰ 6s ² 6p ⁴	85 (210) At Astatine [Xe]4f ¹⁴ 5d ¹⁰ 6s ² 6p ⁵	86 (222) Rn Radon [Xe]4f ¹⁴ 5d ¹⁰ 6s ² 6p ⁶	
7	87 (223) Fr Francium [Rn]7s ¹	88 (226) Ra Radium [Rn]7s ²	★	104 (265) Rf Rutherfordium [Rn]5f ¹⁴ 6d ² 7s ²	105 (268) Db Dubnium [Rn]5f ¹⁴ 6d ³ 7s ²	106 (271) Sg Seaborgium [Rn]5f ¹⁴ 6d ⁴ 7s ²	107 (270) Bh Bohrium [Rn]5f ¹⁴ 6d ⁵ 7s ²	108 (277) Hs Hassium [Rn]5f ¹⁴ 6d ⁶ 7s ²	109 (276) Mt Meitnerium [Rn]5f ¹⁴ 6d ⁷ 7s ²	110 (281) Ds Darmstadtium [Rn]5f ¹⁴ 6d ⁸ 7s ²	111 (280) Rg Roentgenium [Rn]5f ¹⁴ 6d ⁹ 7s ²	112 (285) Cn Copernicium [Rn]5f ¹⁴ 6d ¹⁰ 7s ²	113 (284) Nh Nihonium [Rn]5f ¹⁴ 6d ¹⁰ 7s ¹ 7p ¹	114 (289) Fl Flerovium [Rn]5f ¹⁴ 6d ¹⁰ 7s ² 7p ²	115 (288) Mc Moscovium [Rn]5f ¹⁴ 6d ¹⁰ 7s ² 7p ³	116 (293) Lv Livermorium [Rn]5f ¹⁴ 6d ¹⁰ 7s ² 7p ⁴	117 (294) Ts Tennessine [Rn]5f ¹⁴ 6d ¹⁰ 7s ² 7p ⁵	118 (294) Og Oganesson [Rn]5f ¹⁴ 6d ¹⁰ 7s ² 7p ⁶	

 Alkali Metals	 Lanthanide Series
 Alkaline Earth Metals	 Actinide Series
 Transition Metals	 Halogens
 Non-metals	 Inert Gases
 Other Metals	

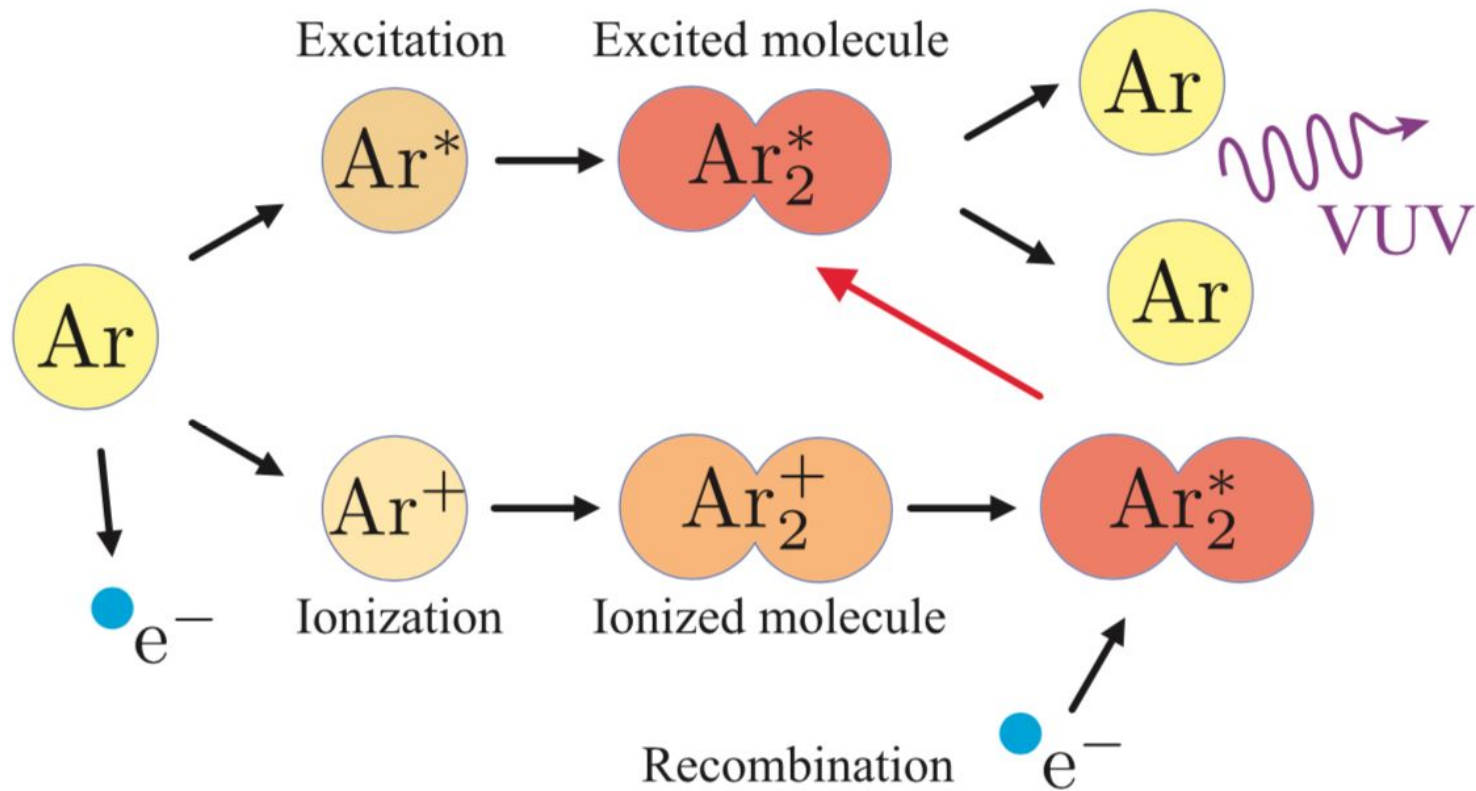
- High light/charge yield
- Acceptable intrinsic background
- Well above liquid nitrogen temperature; easy to liquified

- Aa -Solid
- Aa -Gas
- Aa -Liquid
- Aa -Synthetically Prepared

57 138.91 La Lanthanum [Xe]5d ¹ 6s ²	58 140.12 Ce Cerium [Xe]4f ¹ 5d ¹ 6s ²	59 140.91 Pr Praseodymium [Xe]4f ³ 6s ²	60 144.24 Nd Neodymium [Xe]4f ⁴ 6s ²	61 (145) Pm Promethium [Xe]4f ⁵ 6s ²	62 150.36 Sm Samarium [Xe]4f ⁶ 6s ²	63 151.96 Eu Europium [Xe]4f ⁷ 6s ²	64 157.25 Gd Gadolinium [Xe]4f ⁷ 5d ¹ 6s ²	65 158.93 Tb Terbium [Xe]4f ⁹ 6s ²	66 162.50 Dy Dysprosium [Xe]4f ¹⁰ 6s ²	67 164.93 Ho Holmium [Xe]4f ¹¹ 6s ²	68 167.26 Er Erbium [Xe]4f ¹² 6s ²	69 168.93 Tm Thulium [Xe]4f ¹³ 6s ²	70 173.04 Yb Ytterbium [Xe]4f ¹⁴ 6s ²	71 174.97 Lu Lutetium [Xe]4f ¹⁴ 5d ¹ 6s ²
89 (227) Ac Actinium [Rn]6d ¹ 7s ²	90 232.04 Th Thorium [Rn]6d ² 7s ²	91 231.04 Pa Protactinium [Rn]5f ² 6d ¹ 7s ²	92 238.03 U Uranium [Rn]5f ³ 6d ¹ 7s ²	93 (237) Np Neptunium [Rn]5f ⁴ 6d ¹ 7s ²	94 (244) Pu Plutonium [Rn]5f ⁶ 6d ¹ 7s ²	95 (243) Am Americium [Rn]5f ⁷ 6d ¹ 7s ²	96 (247) Cm Curium [Rn]5f ⁷ 6d ² 7s ²	97 (247) Bk Berkelium [Rn]5f ⁷ 6d ³ 7s ²	98 (251) Cf Californium [Rn]5f ¹⁰ 7s ²	99 (252) Es Einsteinium [Rn]5f ¹¹ 7s ²	100 (257) Fm Fermium [Rn]5f ¹² 7s ²	101 (258) Md Mendelevium [Rn]5f ¹³ 7s ²	102 (259) No Nobelium [Rn]5f ¹⁴ 7s ²	103 (262) Lr Lawrencium [Rn]5f ¹⁴ 6d ¹ 7s ²

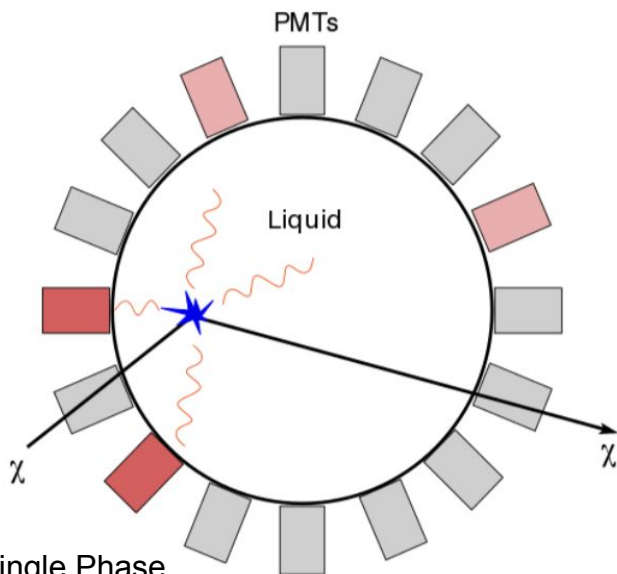


Innovating Science™ by Aldon Corporation
"cutting edge science for the classroom"

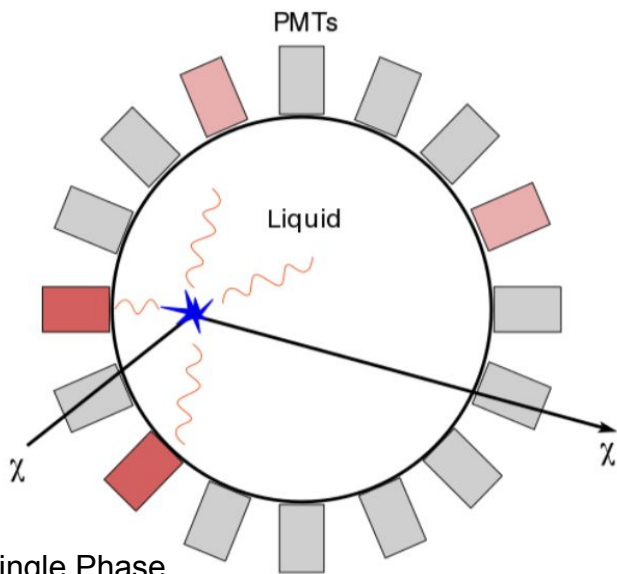




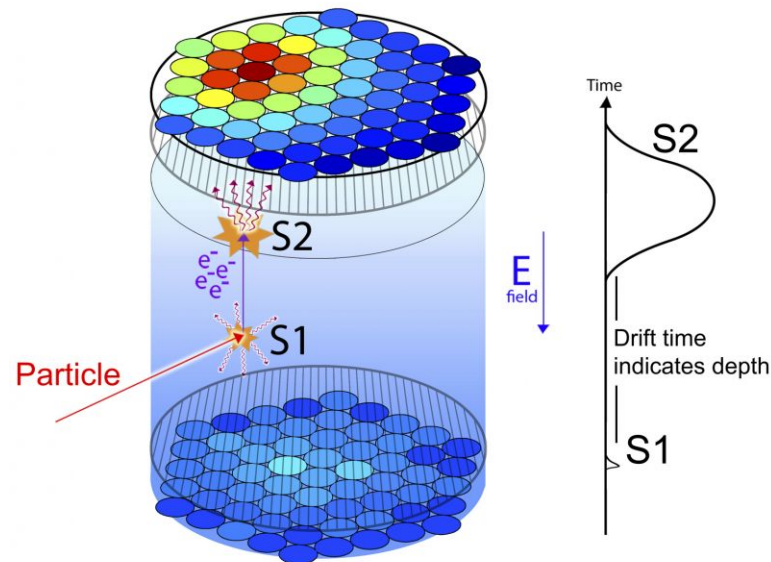
Detector Technique



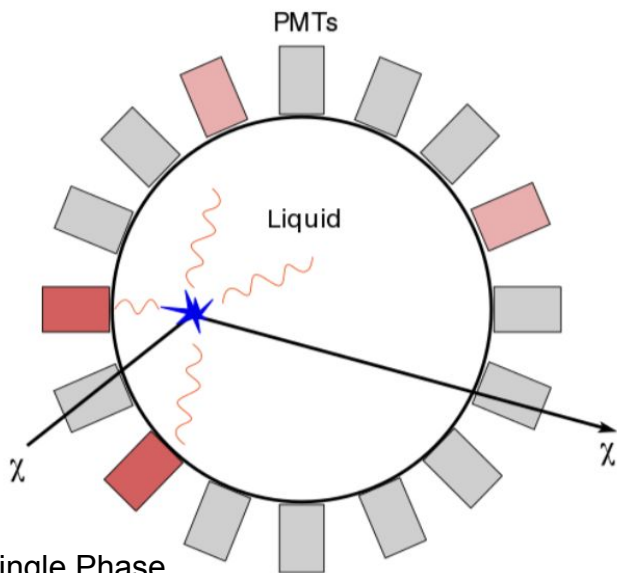
- Single Phase
 - Trigger window can be **fast** ($< 5 \mu\text{s}$).
 - High rate calibration runs are possible.
 - Simple design with 4π coverage (Maximize light collection).



- Single Phase
 - Trigger window can be **fast** ($< 5 \mu\text{s}$).
 - High rate calibration runs are possible.
 - Not messing with drift fields (Maximize light yield).
 - Simple design with 4π coverage (Maximize light collection).

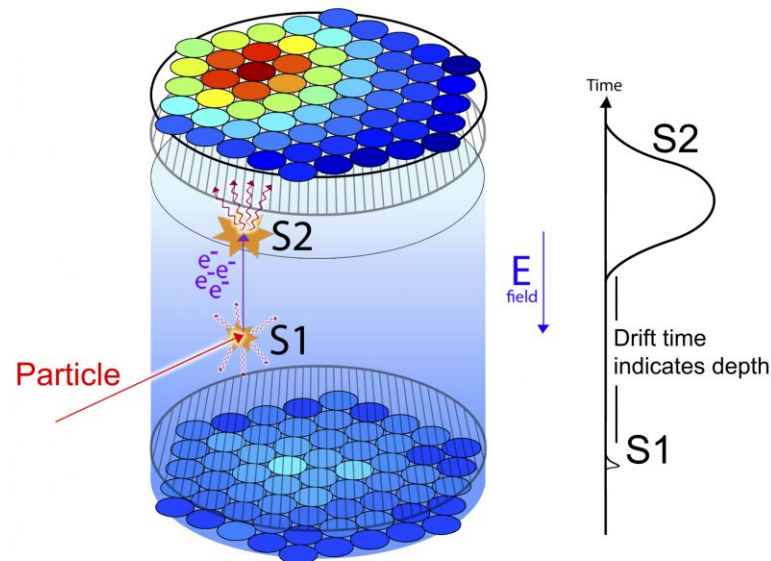


- Dual phase (Time Projection Chamber)
 - Interaction in target creates ionized and excited states.
 - Recombination of **some** ions and de-excitation of states creates primary scintillation light.
 - Acceleration at gas/liquid interface creates proportional light.



- Single Phase

- Trigger window can be **fast** ($< 5 \mu\text{s}$).
- High rate calibration runs are possible.
- Not messing with drift fields (Maximize light yield).
- Simple design with 4π coverage (Maximize light collection).

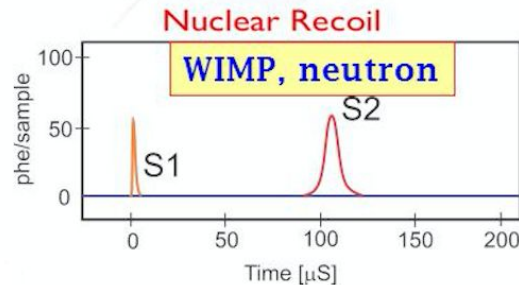
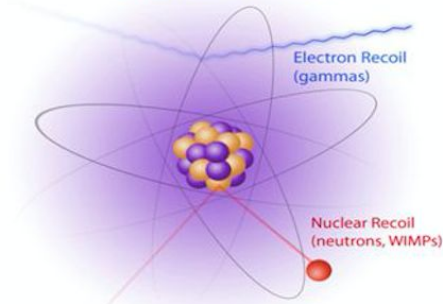
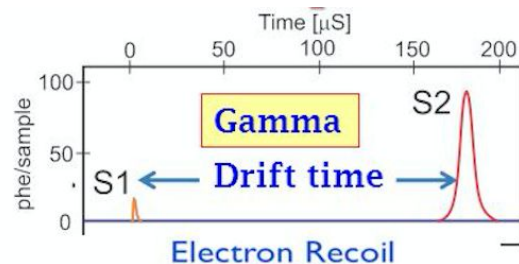


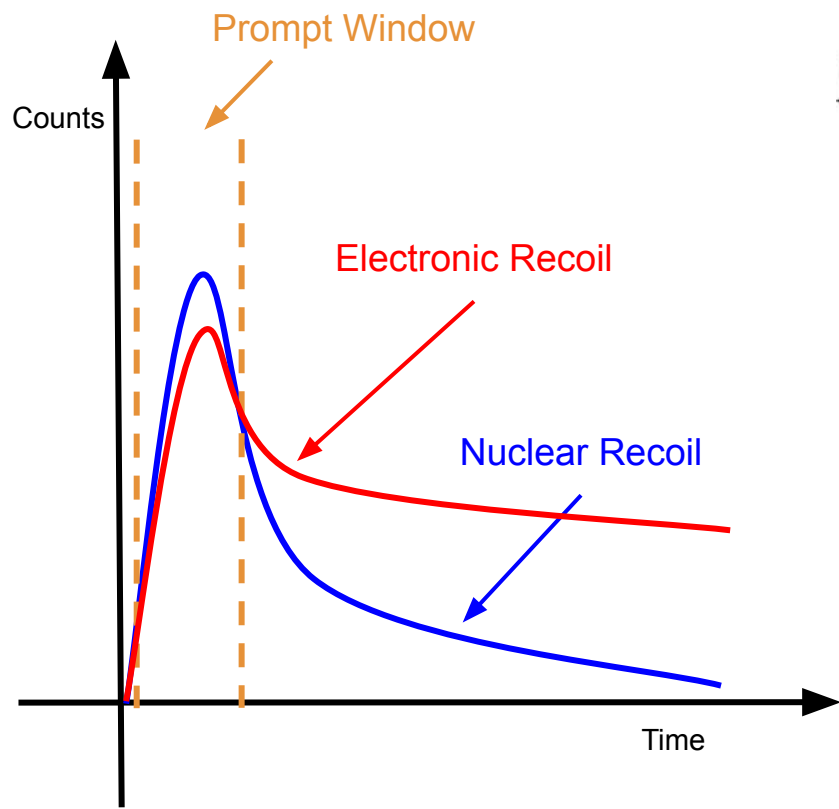
- Dual phase (Time Projection Chamber)

- Better **position reconstruction** ($\sim \text{mm}$, $\sim \text{cm}$ in single phase).
- Extra signal (ionization) provides discrimination parameters.
- Maximize **fiducial volume (background free volume)**



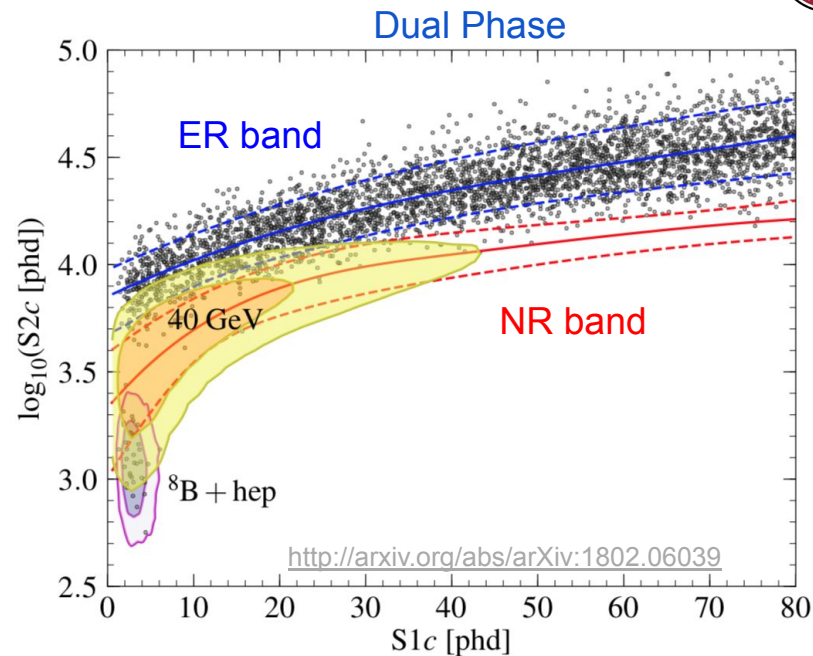
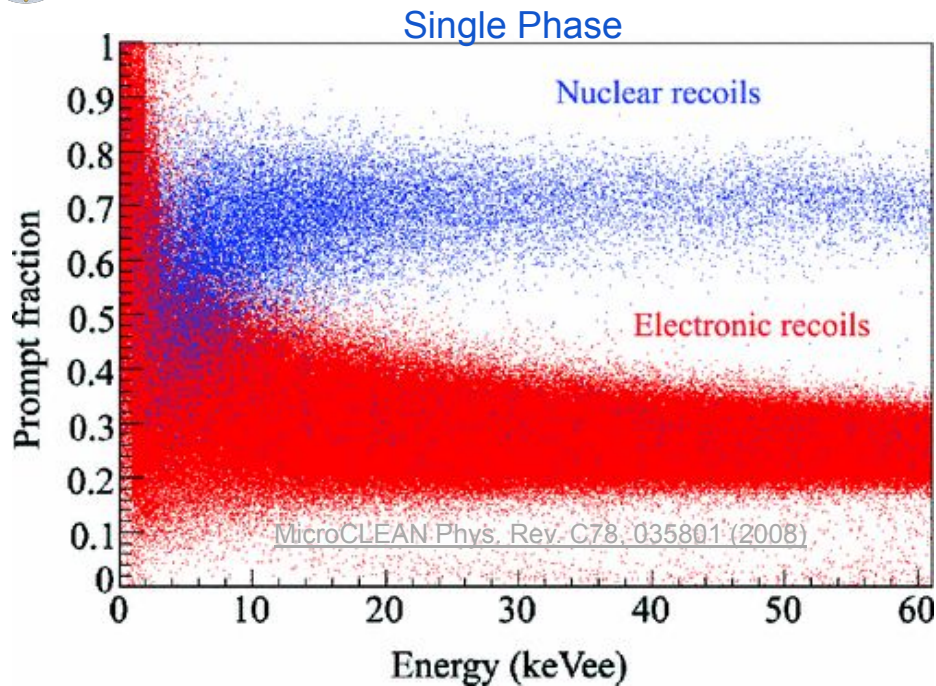
- Electronic recoil
 - Beta (electron).
 - Gamma (high energy photons).
 - Tend to bounce around the atoms thus less dense and longer track.
 - More charge yield for charged particle.
- Nuclear recoil
 - Neutron.
 - WIMPs.
 - Tend to have a dense ionization track, shorter than track from electronic recoil so deposit more energy at interaction site.
 - More light yield for neutral particle.





$$F_{prompt} = \frac{\text{Prompt photoelectrons}}{\text{Total photoelectrons}}$$

- Energy deposition from different particle will produce different fraction of singlet and triplet states.
- Pulse Shape Discrimination (PSD) can be implemented by exploiting this characteristic.
- PSD works much better in LAr due to the very different prompt/slow decay time (8ns/1.6 μ s) while LXe has very similar decay time for both states (8ns/20ns)

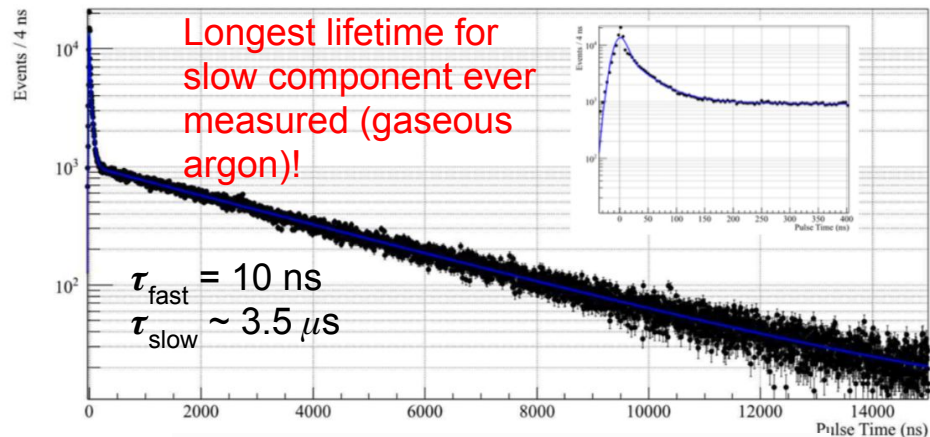


- Using pulse shape discrimination
- Achieved 1×10^{-9} rejection level by DEAP-3600

- Using S2/S1 ratio
- 99.5% discrimination using charge/light in Liquid xenon.



- 500 kg of liquid argon
- Spherical vessel gives $4\text{-}\pi$ PMT coverage
- Spent 2 years at SNOLab for detector construction



J.J.Wang* et al. *Eur. Phys. J. A* 55, 176 (2019).

- Impurities molecule (Oxygen, Nitrogen, etc.) quenching slow component results in reduction of lifetime of the slow component and light yield
- Powerful Pulse Shape Discrimination (PSD) with high purity (long triplet lifetime)
 - Better dark matter sensitivity
- First experimental result of MiniCLEAN experiment



Calibration source deployment tubes (3 total)

17T Gd-loaded liquid scintillator

60,000 gallons of ultrapure water

120 veto PMTs

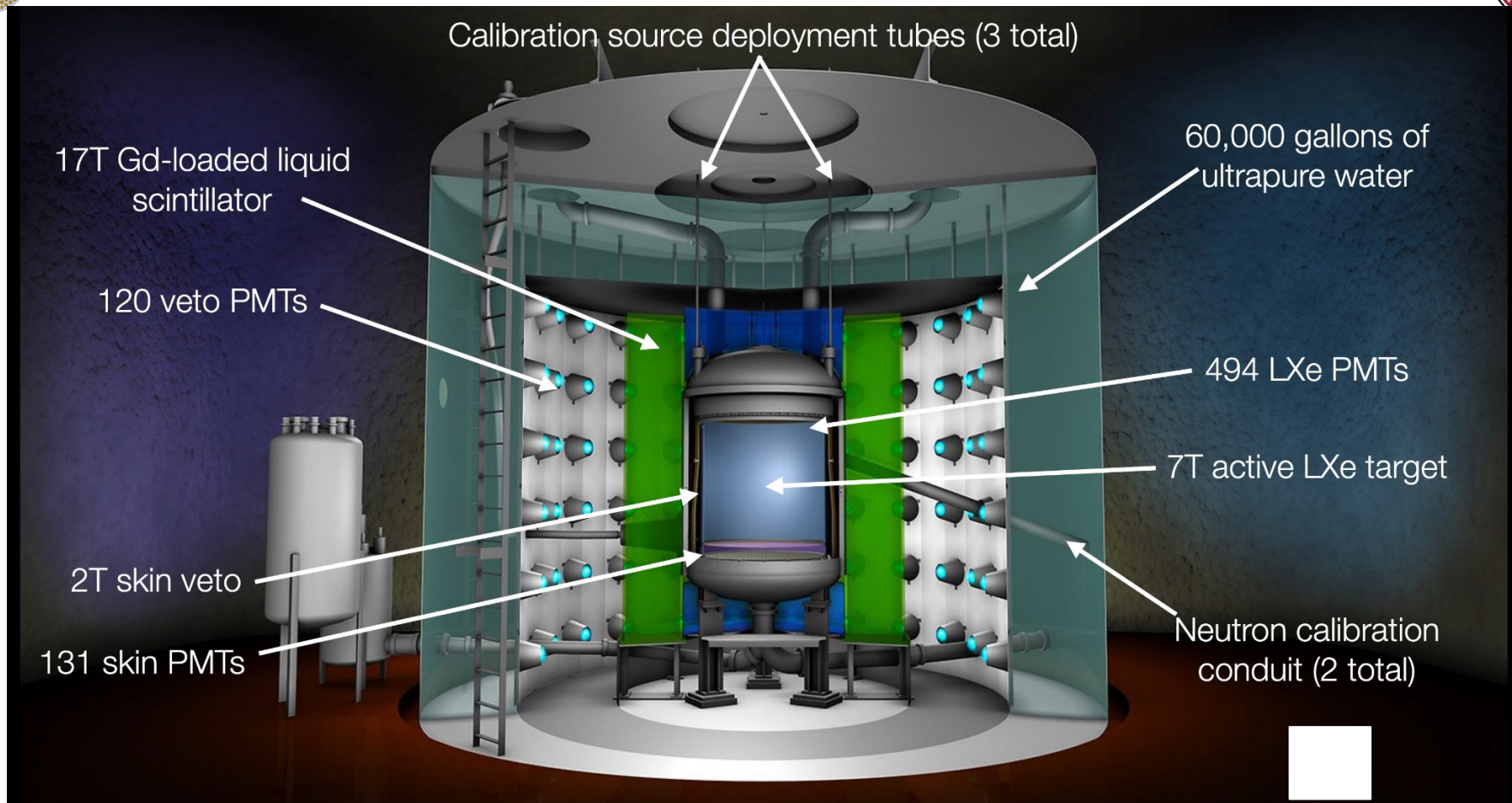
494 LXe PMTs

7T active LXe target

2T skin veto

Neutron calibration conduit (2 total)

131 skin PMTs

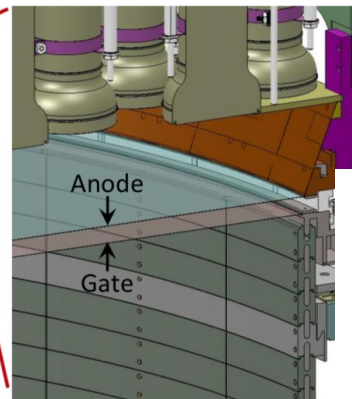




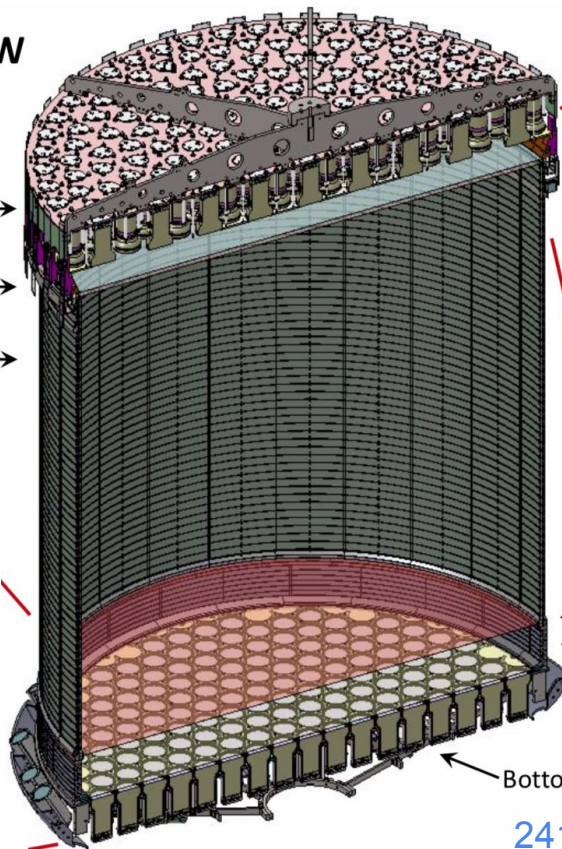
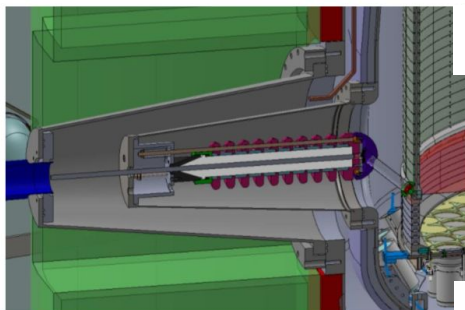
SECTION VIEW OF LXE TPC

- Top PMT array →
253 PMTs
- Side Skin PMTs →
- TPC field cage →

GAS PHASE AND ELECTROLUMINESCENCE REGION



HV CONNECTION TO CATHODE

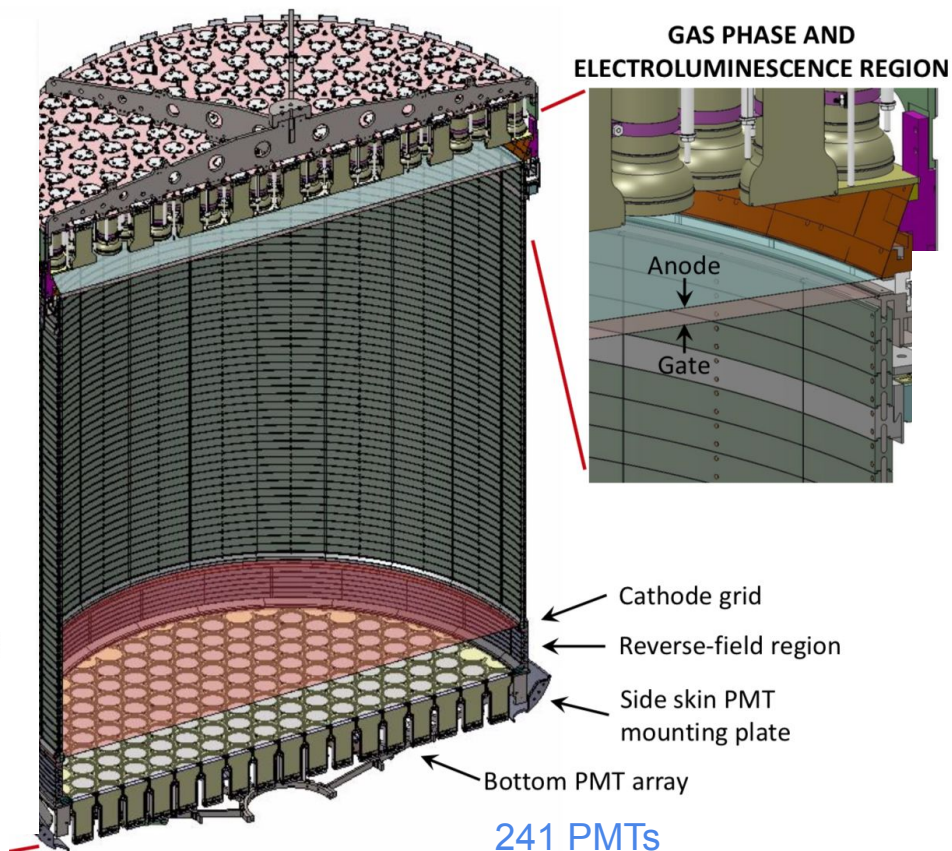


- Cathode grid
- Reverse-field region
- Side skin PMT mounting plate
- Bottom PMT array

241 PMTs



- 2 PMT arrays of Hamamatsu R11410-20 PMTs (494 total)
- 4 electrodes/grids woven on specialized looms and **passivated** to reduce e-emission*
- 57 field rings embedded in reflective PTFE → **310V/cm drift field**
- TPC completed August 2019
- Inserted into ICV at surface assembly lab





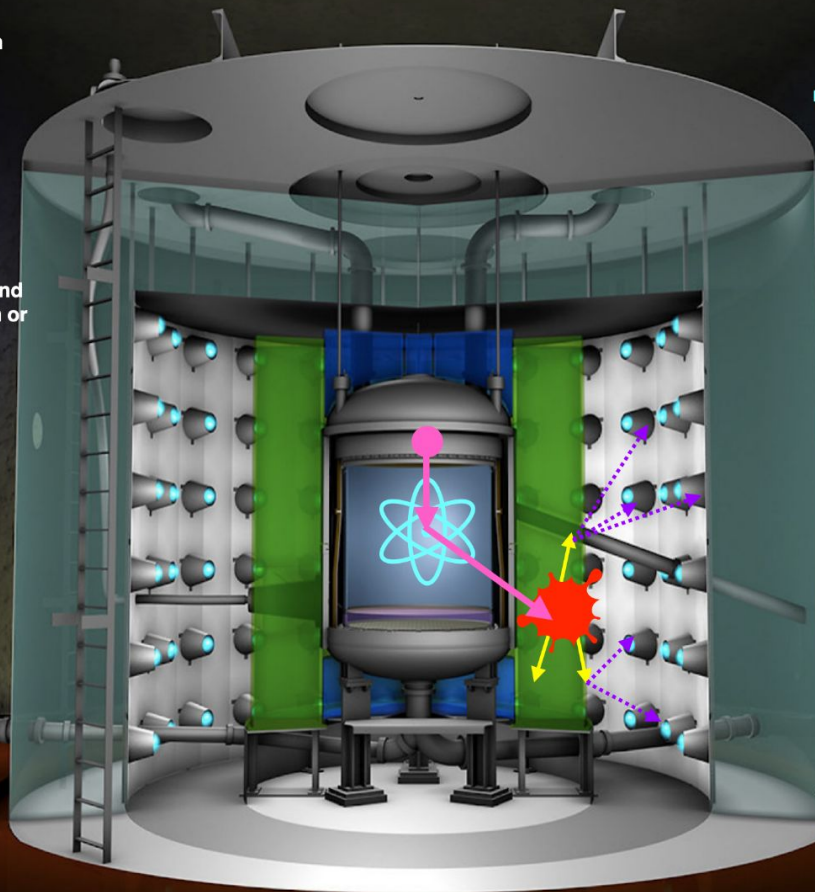
A **neutron** is emitted from an (α, n) reaction in the PMTS

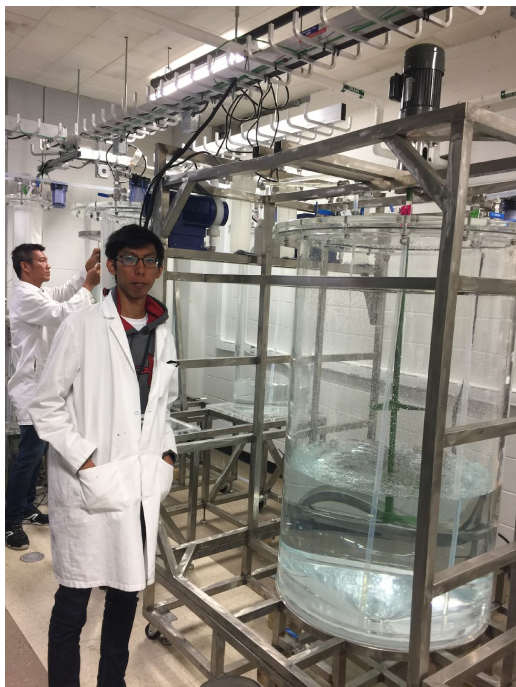
It scatters from a Xe nucleus, causing a **nuclear recoil** inside the LXe detector

It enters the Outer Detector, slows down and **captures** on Gadolinium or Hydrogen

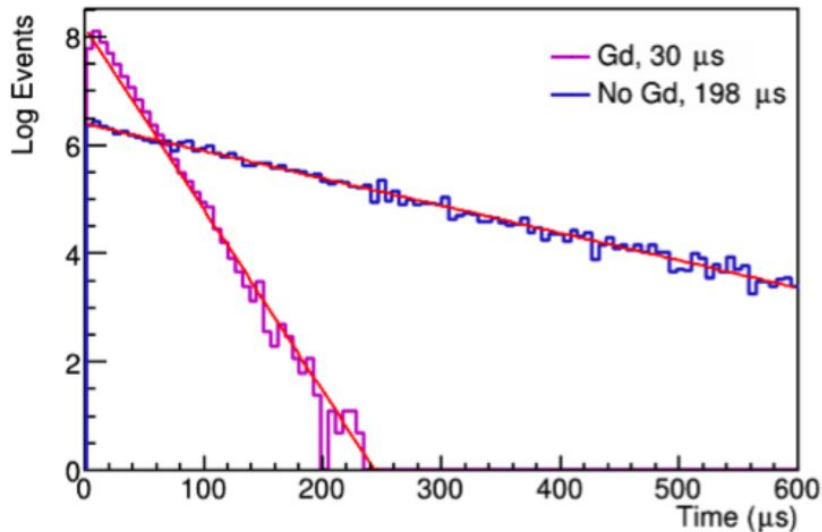
γ -rays are emitted from the post-capture nucleus

γ 's interact in the liquid scintillator, producing **photons**, which are detected by PMTs





Thermal neutron capture cross sections:
 ^{157}Gd : 254,000 barns ^{155}Gd : 61,000 barns



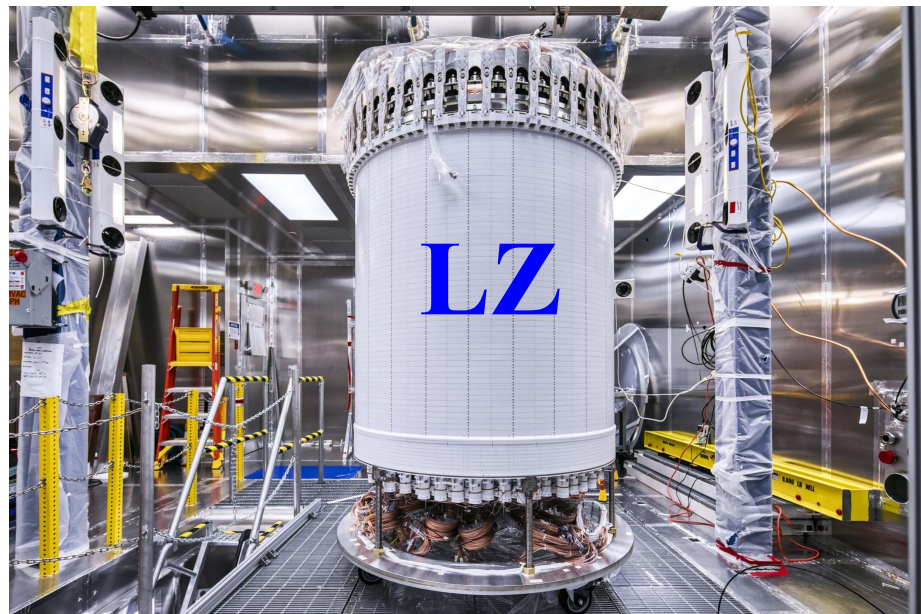
- Gadolinium has large cross-section of neutron capturing.
- By only doping 0.1 % of Gd into LS, the thermal neutron capture time has been greatly improved, which increased the tagging efficiency.



Detector Construction

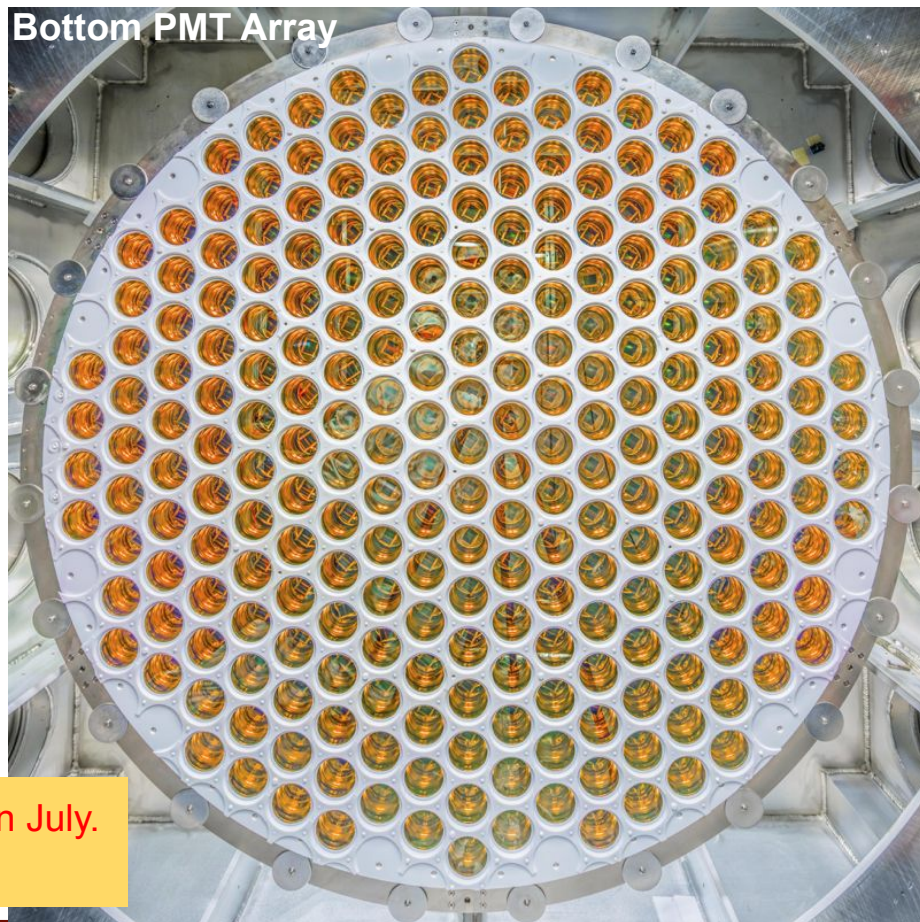


- Surface Assembly Laboratory (SAL) coordinator at SURF
 - Oversee the TPC assembly
 - Complete assembly in Oct. 2019
 - Led a team to complete the integration in Davis Cavern
 - TPC was cooled and filled with LXe in Fall 2021.
- Outer Detector (OD) coordinator
 - Oversee the OD assembly
 - Start construction in June 2020
 - Completed the major component
 - Finished filling of 17-tonnes of GdLS in summer 2021.





Completed in July.
2019

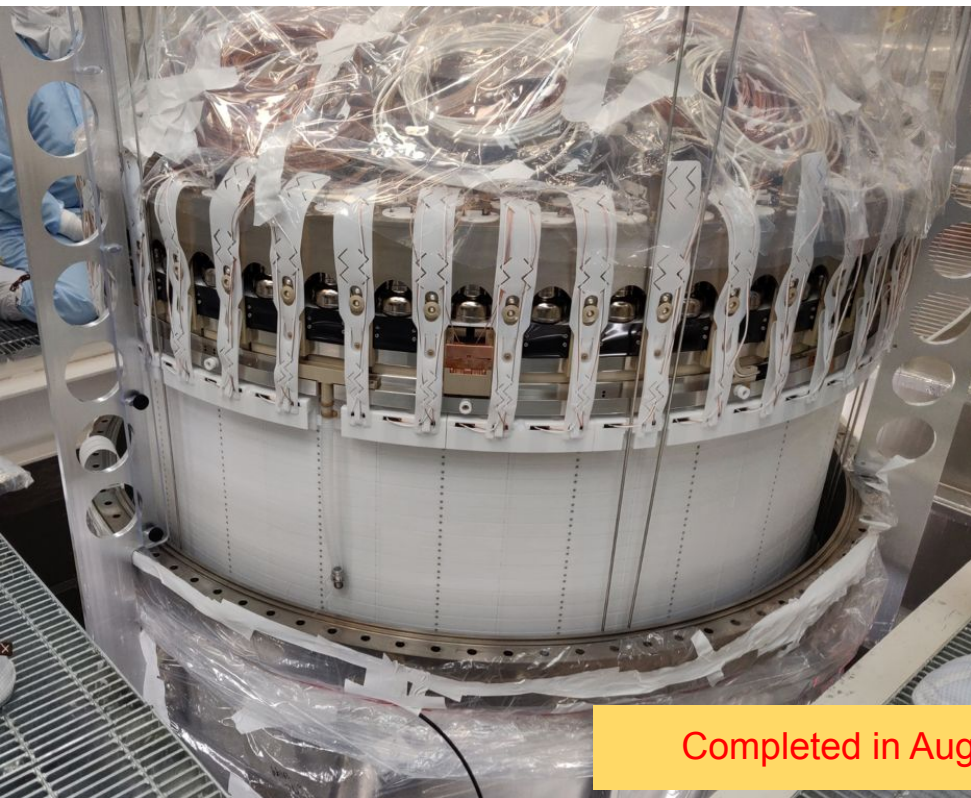


Bottom PMT Array





Final checkout



Completed in Aug. 2019



Transport to underground in Oct. 2019





Final integration in Dec. 2019





Early 2020



Late 2020



Early 2021



- Led the installation of TPC and OD
 - Deliver detector in timely fashion
 - Maintaining **safe working** environment during pandemic

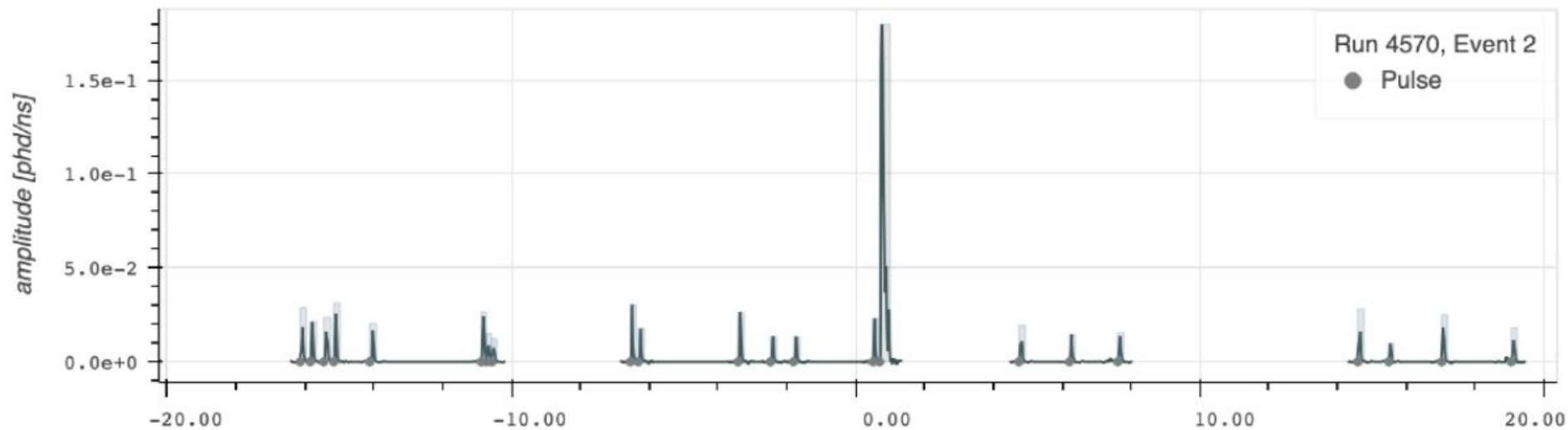


Now complete!



Optical calibrations in the OD

OuterHighGain



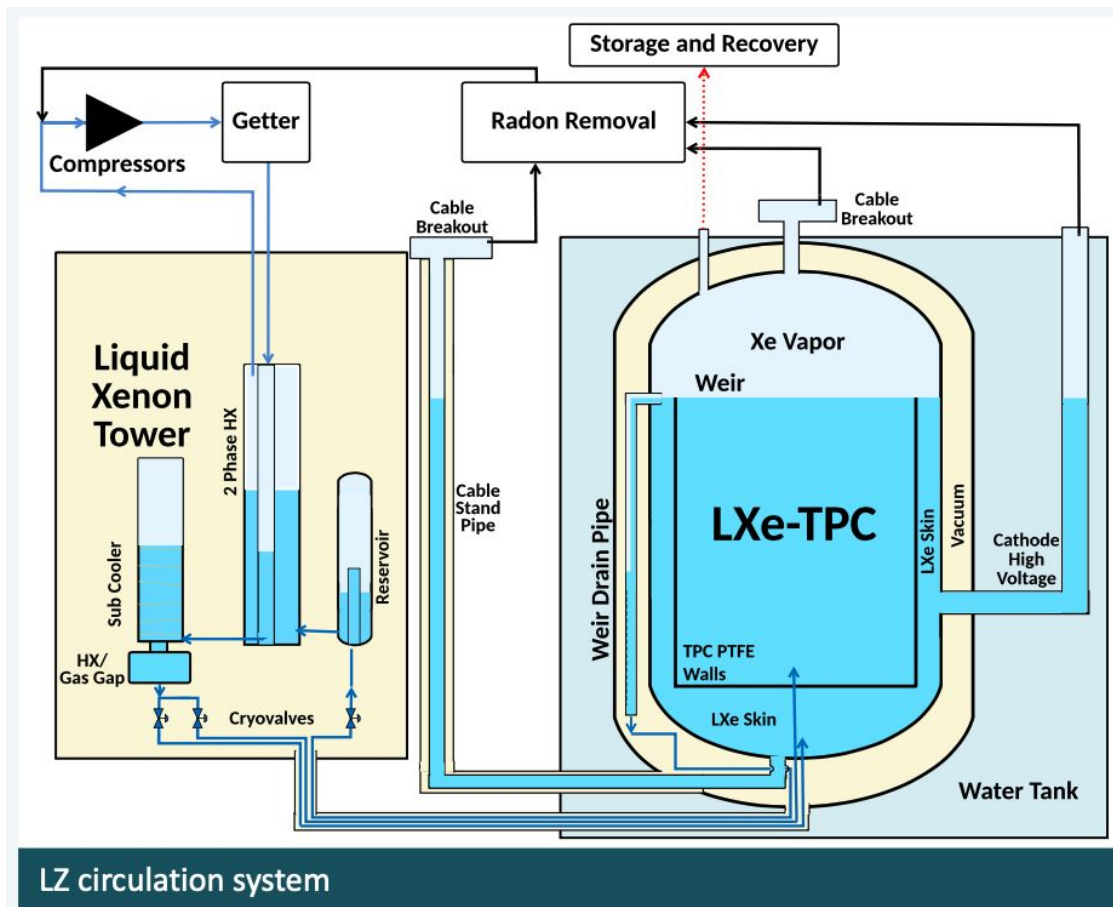
Now complete!



- 10 tonnes of xenon
- Krypton reduction to < 300 ppq Kr/Xe using gas chromatography at SLAC
- LZ circulation with constant gas purification through hot-zirconium getter



Circulation compressors (gas)



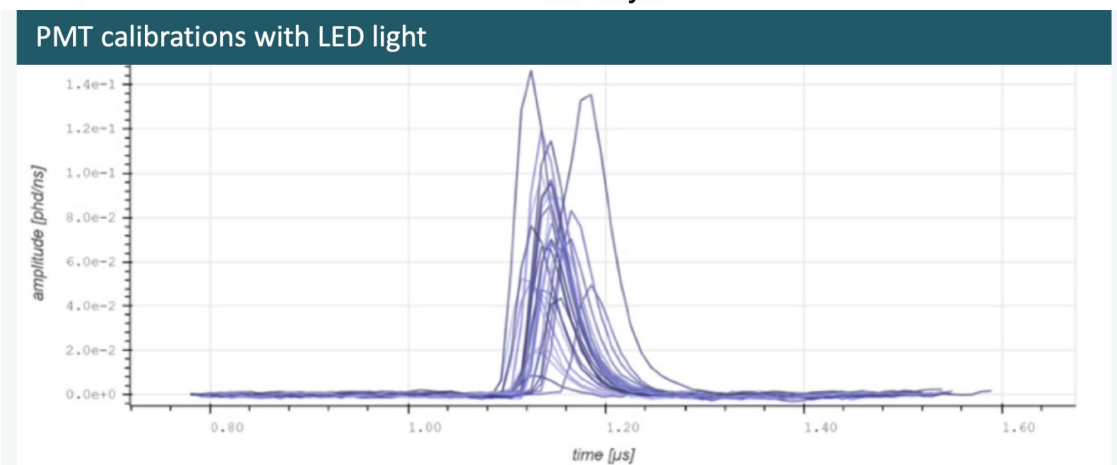
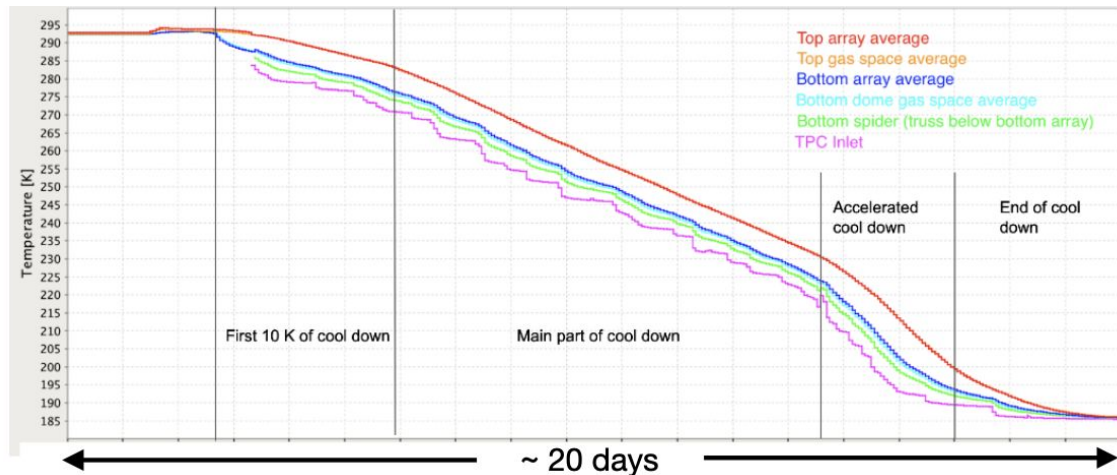
LZ circulation system



Commissioning is underway!



Test cryostat for circulation test
Demonstrated flow rates up to 600 slpm



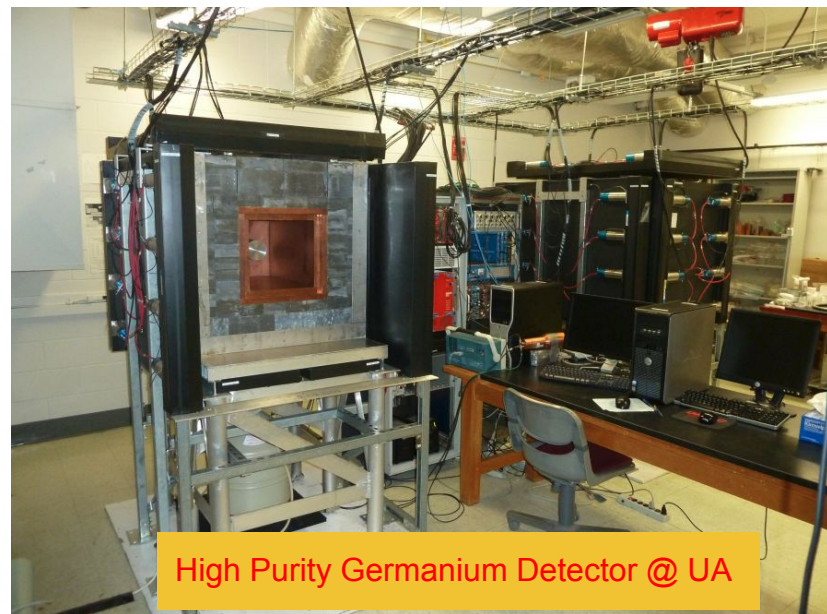
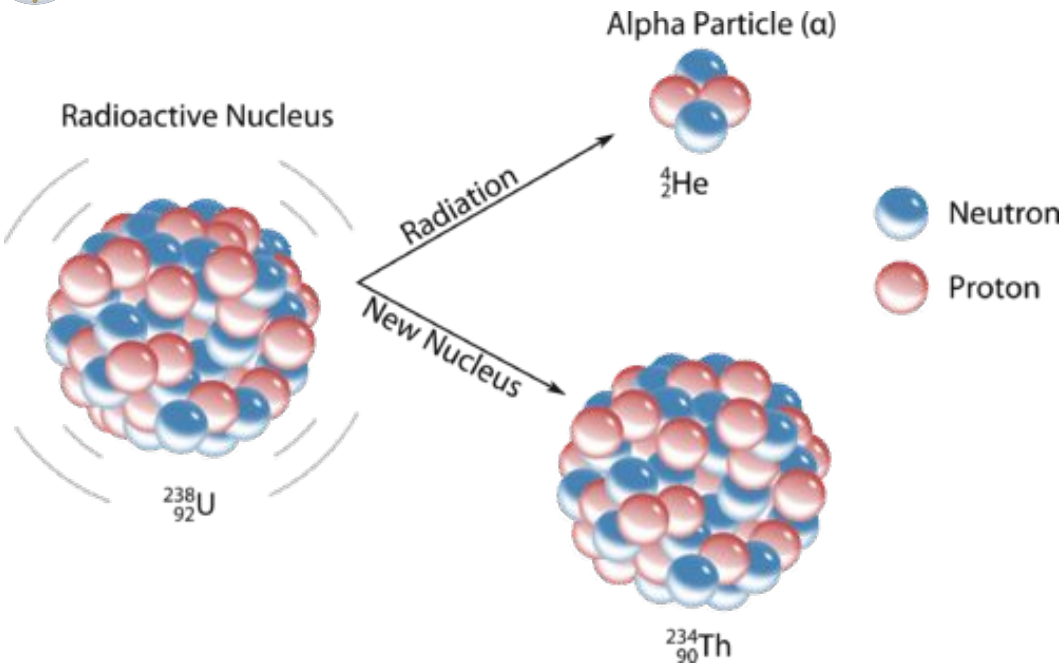


Detector Physics



- Cosmological background
 - Rock gamma
 - Neutrino events
- Internal background
 - Charcoal chromatography to remove ^{85}Kr and ^{39}Ar
 - Every detector components has been screened thoroughly
 - Rn emanation screen campaign
 - Four Rn screening site
 - Target Rn activity = $2 \mu\text{Bq/kg}$.
 - Total ~ 0.001 x Banana in 10 tonnes of Xenon
 - Rn daughter (plate-out)
 - TPC assembly in Rn-reduced cleanroom to limit daughter recoils on surface

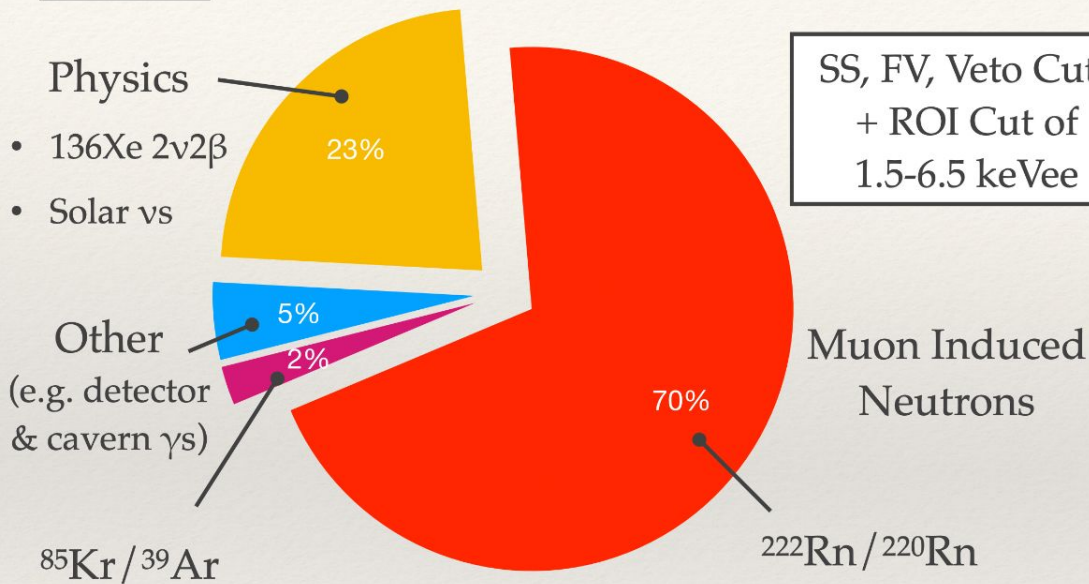
Background Source	ER (cts)	NR (cts)
Detector Components	9	0.07
Surface Contamination	40	0.39
Laboratory and Cosmogenics	5	0.06
Xenon Contaminants	819	0
222Rn	681	0
220Rn	111	0
natKr (0.015 ppt g/g)	24	0
natAr (0.45 ppb g/g)	3	0
Physics	322	0.51
136Xe $2\nu\beta\beta$	67	0
Solar neutrinos (pp+7Be+13N)	255	0
Diffuse supernova neutrinos	0	0.05
Atmospheric neutrinos	0	0.46
Total	1195	1.03
with 99.5% ER discrim., 50% NR eff.	5.97	0.51



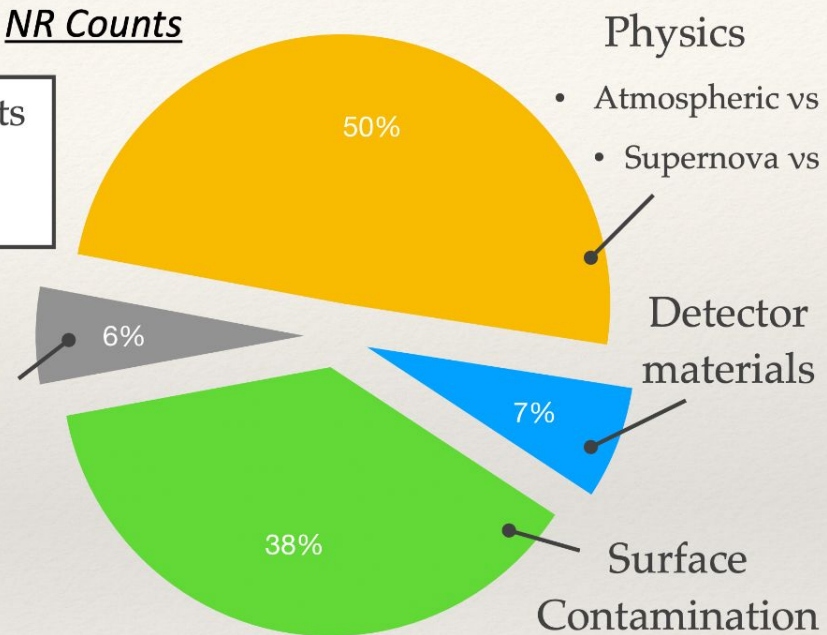
- U/Th radioactive isotopes in the detector materials.
- For successful DM detection, we need to reduce the radioactivity down to $\mu\text{Bq/kg}$ level (Banana ~ 140 Bq/kg, 10^{-7} Banana!).
- Every component in detector undergoes careful screening to quantify the radioactivity.
- **Radioassay** is crucial for future dark matter/neutrino experiment!



ER Counts



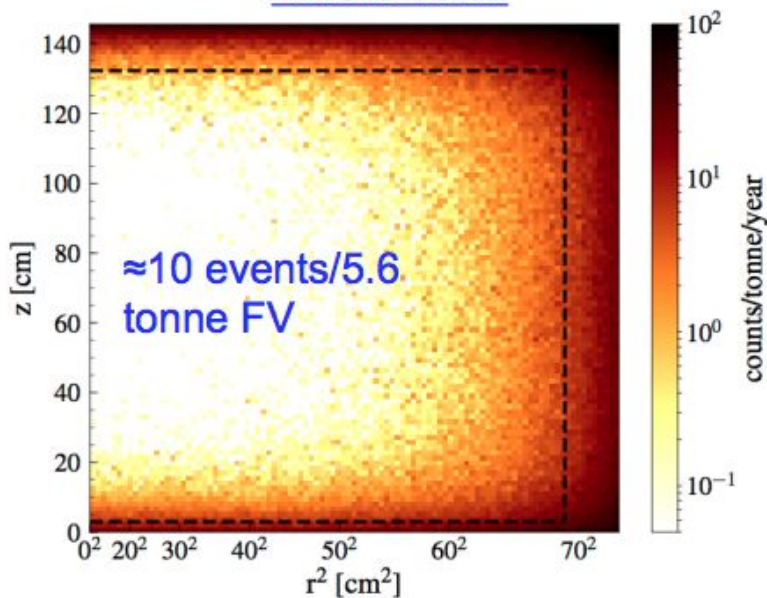
NR Counts



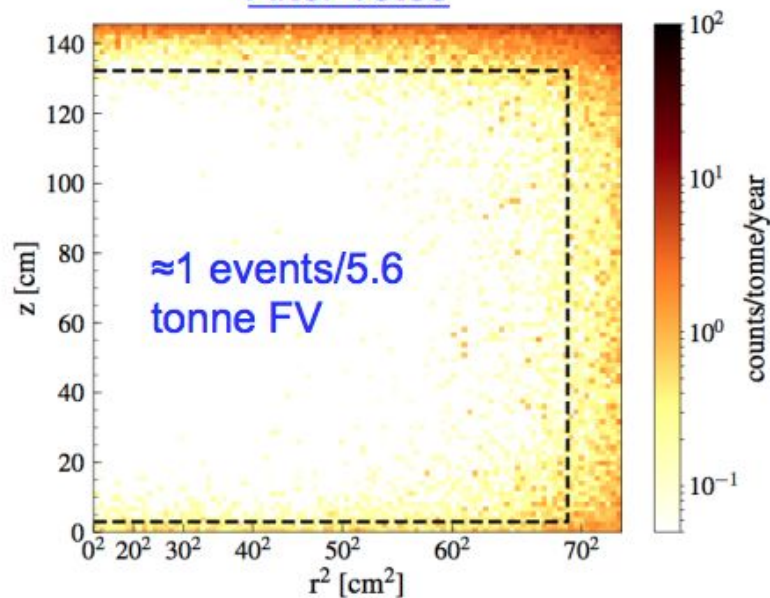
Source	ER [cts]	NR [cts]
Total	1131	1.03
+ 99.5% ER discrimination, 50% NR efficiency	5.66	0.52



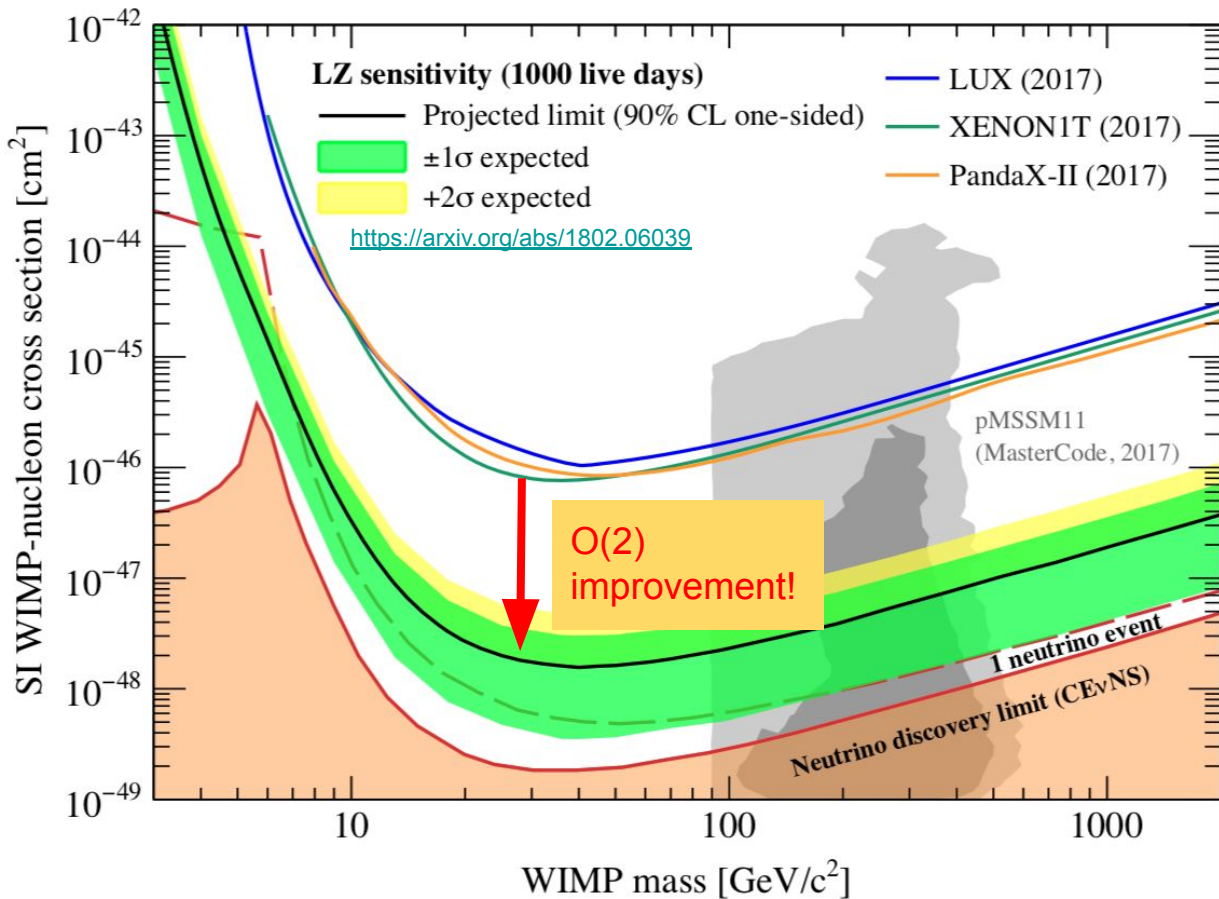
Before vetos



After vetos



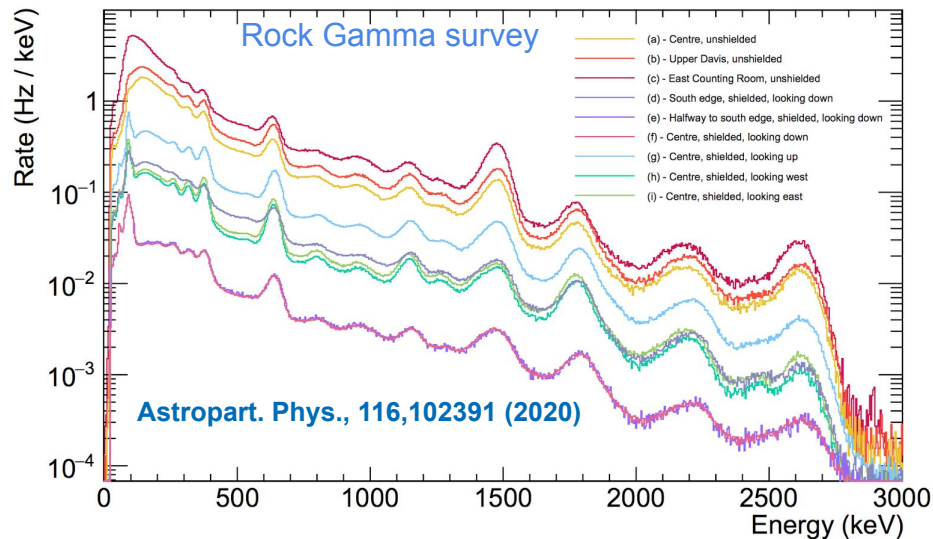
- WIMP-like nuclear recoil backgrounds in 6-30 keV region of interest.
- Fiducial would be reduced from 5.6 to 3.2 tonnes without outer detector.



OD is necessity to discover WIMPs!

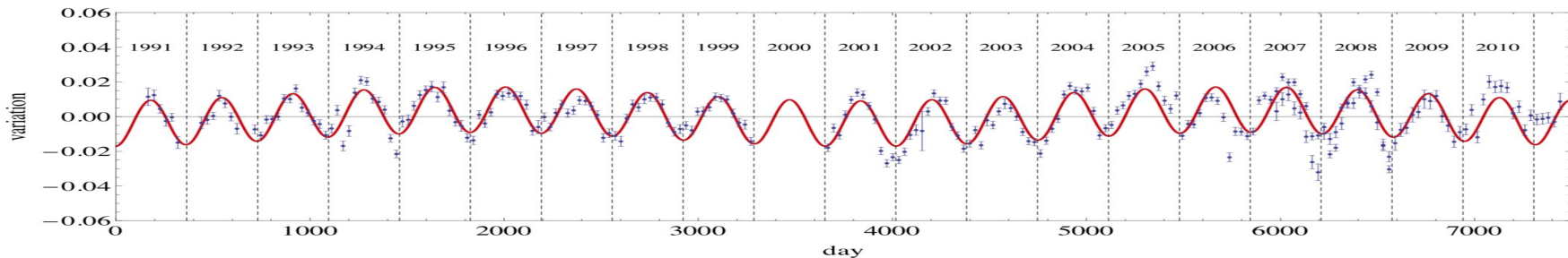


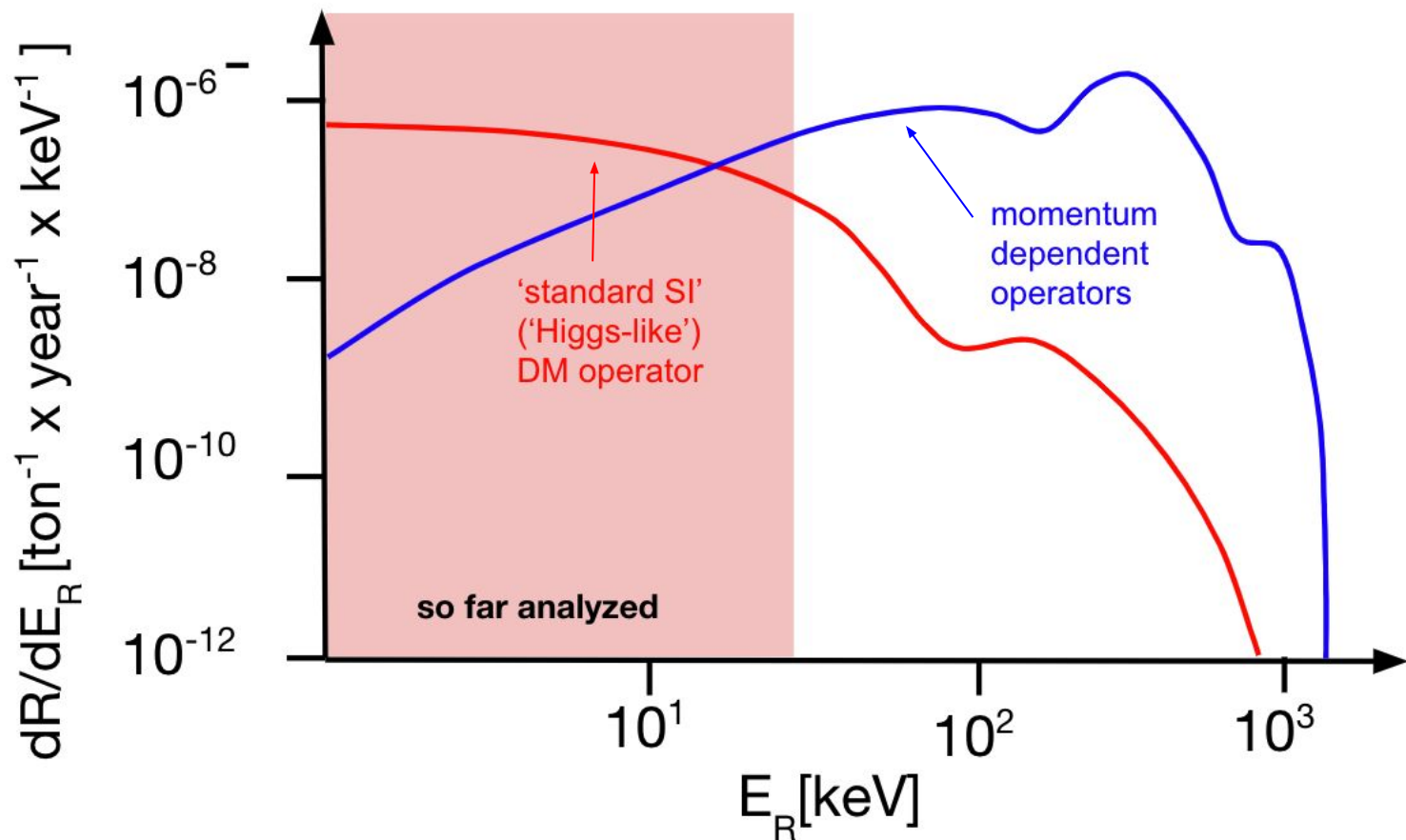
- Veto system for TPC
 - >95% efficiency in tagging neutrons
- OD is also a detector
 - Annual modulation of muon
 - Muon flux at underground lab
 - Angular distribution
 - Inelastic dark matter
 - Joint analysis of TPC and OD

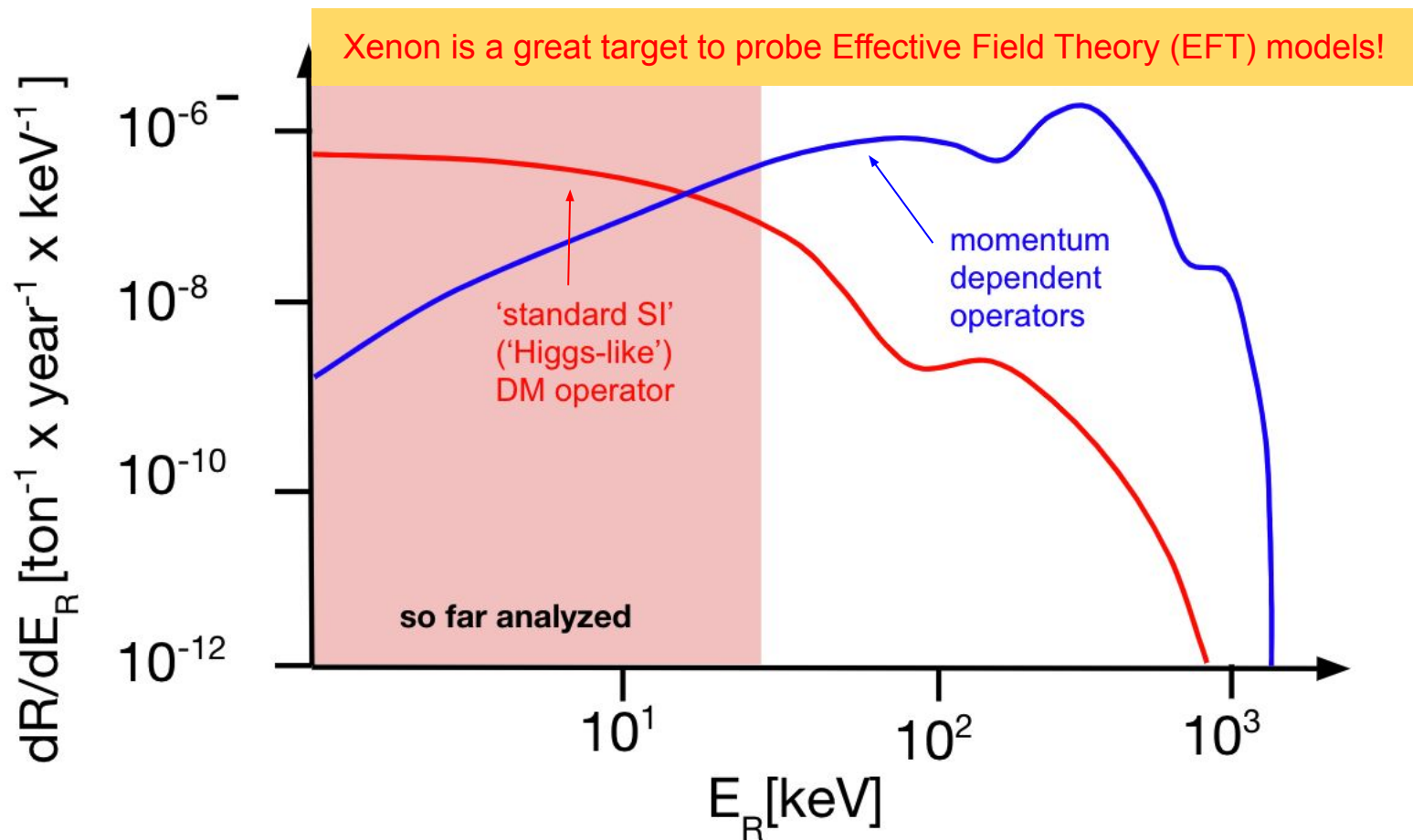


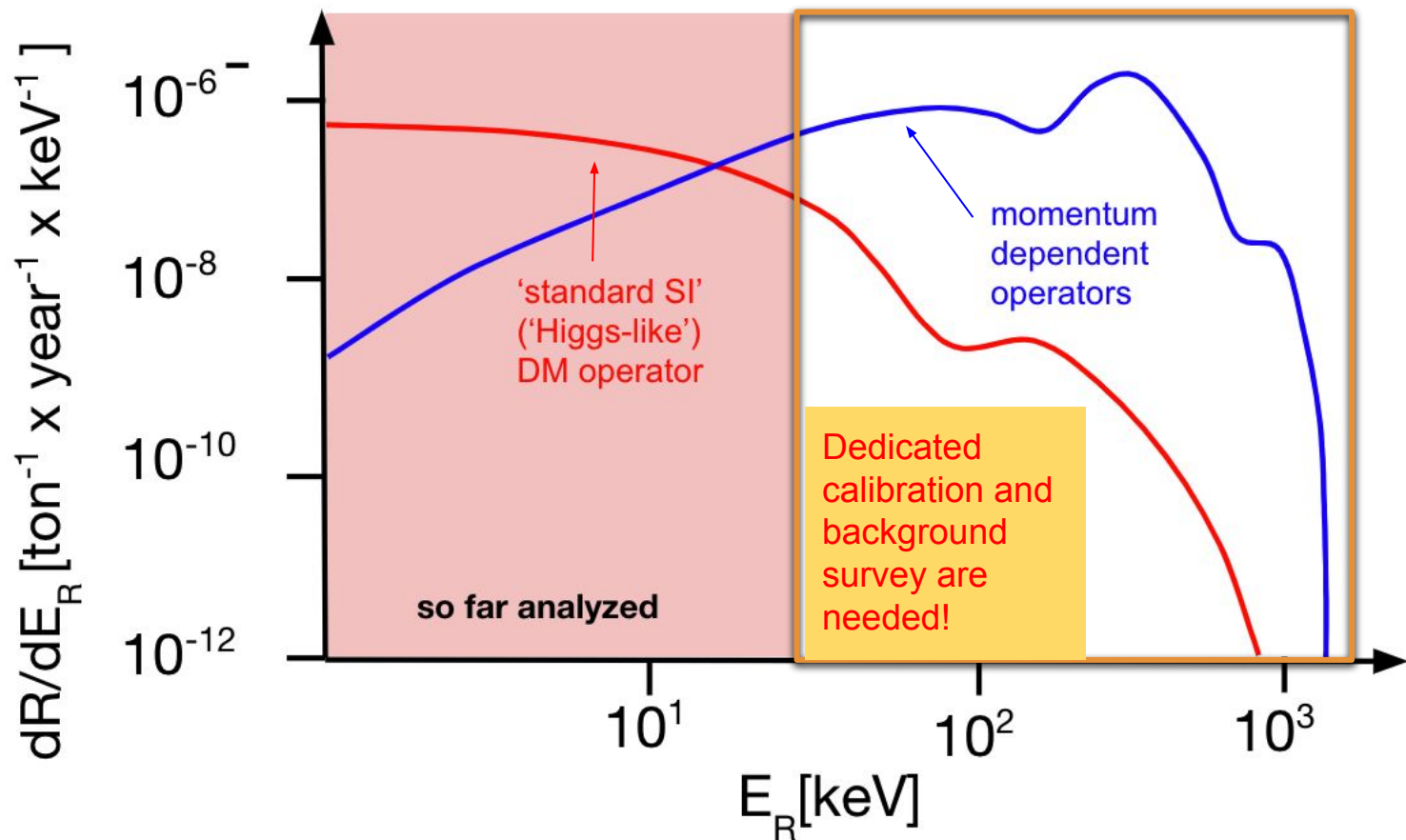
Combined LVD, MACRO and Borexino data over 20 years

[arXiv:1204.5180](https://arxiv.org/abs/1204.5180)







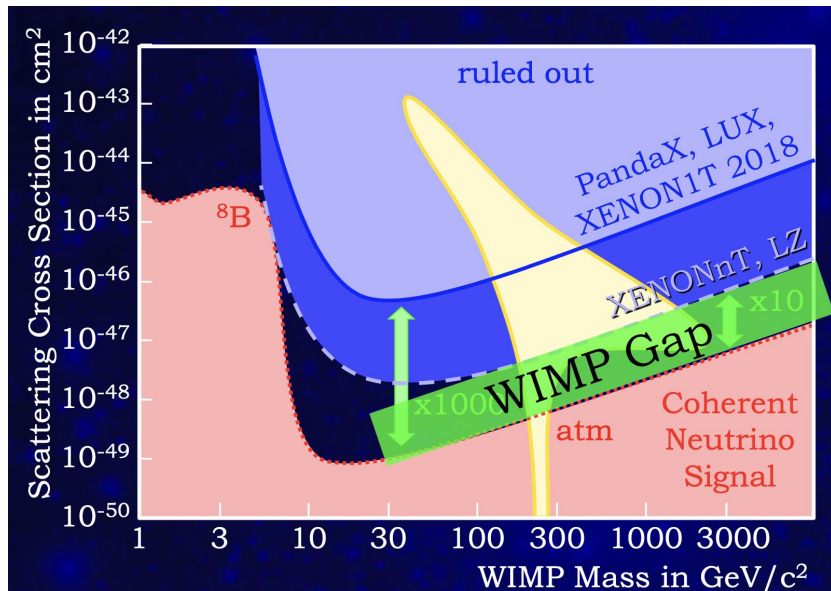




Future Detector Development



- To expand searches in the parameter space
 - Need next Gen detector to reach neutrino floor
- Plan to play a leading role in the next Gen DM detector R&D
 - Veto detectors
 - Active shielding is essential for modern experimental particle physics (e.g. DM, neutrino)
 - Study the LS doped acrylic and other type of scintillators
 - Photon detection
 - Extended my experience with conventional PMTs into newly developed Silicon PhotoMultiplier (SiPM)



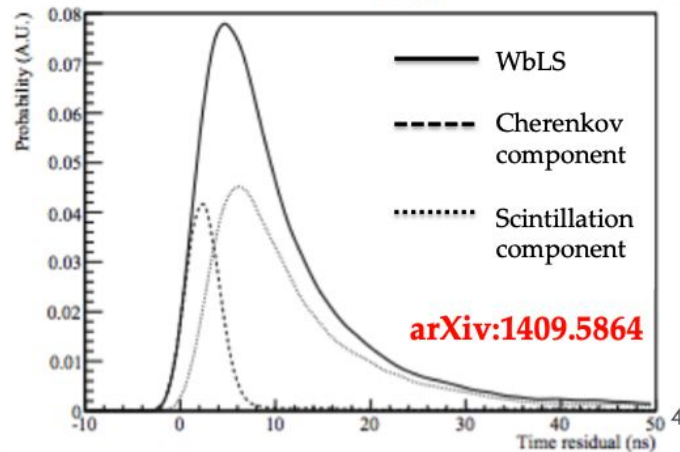
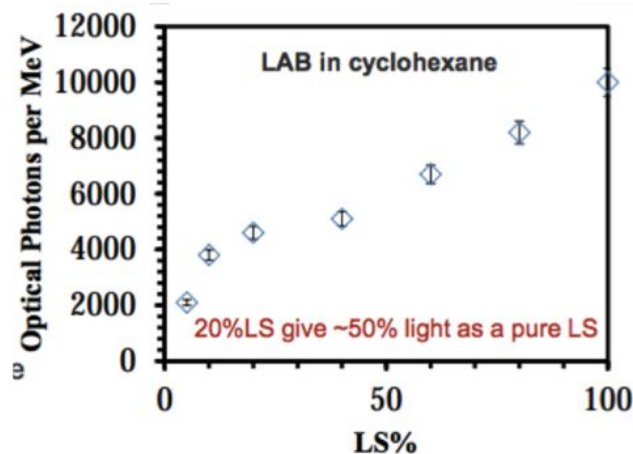


Water-based Liquid scintillator



• Wb-LS

- Simple mixture of LAB and water
- Cost effective
- Environmentally friendly
- Benefits from characteristics of both **scintillator** and **water**
 - Gives low energy threshold
 - Good energy resolution
 - Low absorption
 - Directional information
- 1000L prototype is up and running
- 30-tonnes prototype is under review
 - Start construction early next year at BNL





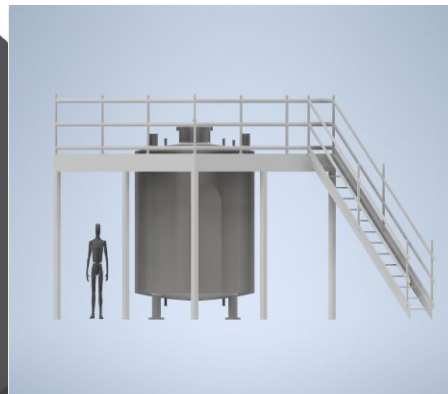
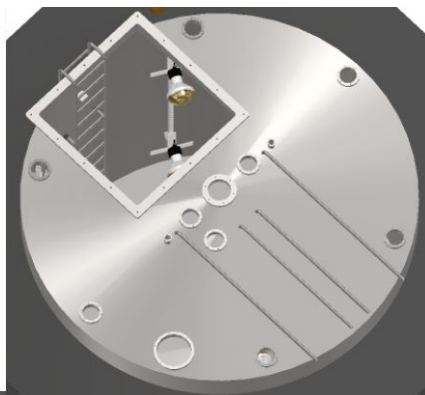
- **Active shielding** is essential for DM detector
 - Handling of liquid and safety is not trivial
- With doping LS and different type of heavy metal (Gd, Pb, etc), it can achieve to stop different background particles
 - **Machinability stronger** than other plastics scintillators (e.g. BC-400);
 - **Multilayers** of acrylic detector
 - Along with SiPM to maximize the veto efficiency
 - Great for large scale detector
- **Successfully doped** LS in acrylic
- LOI in Snowmass, white paper is coming up!



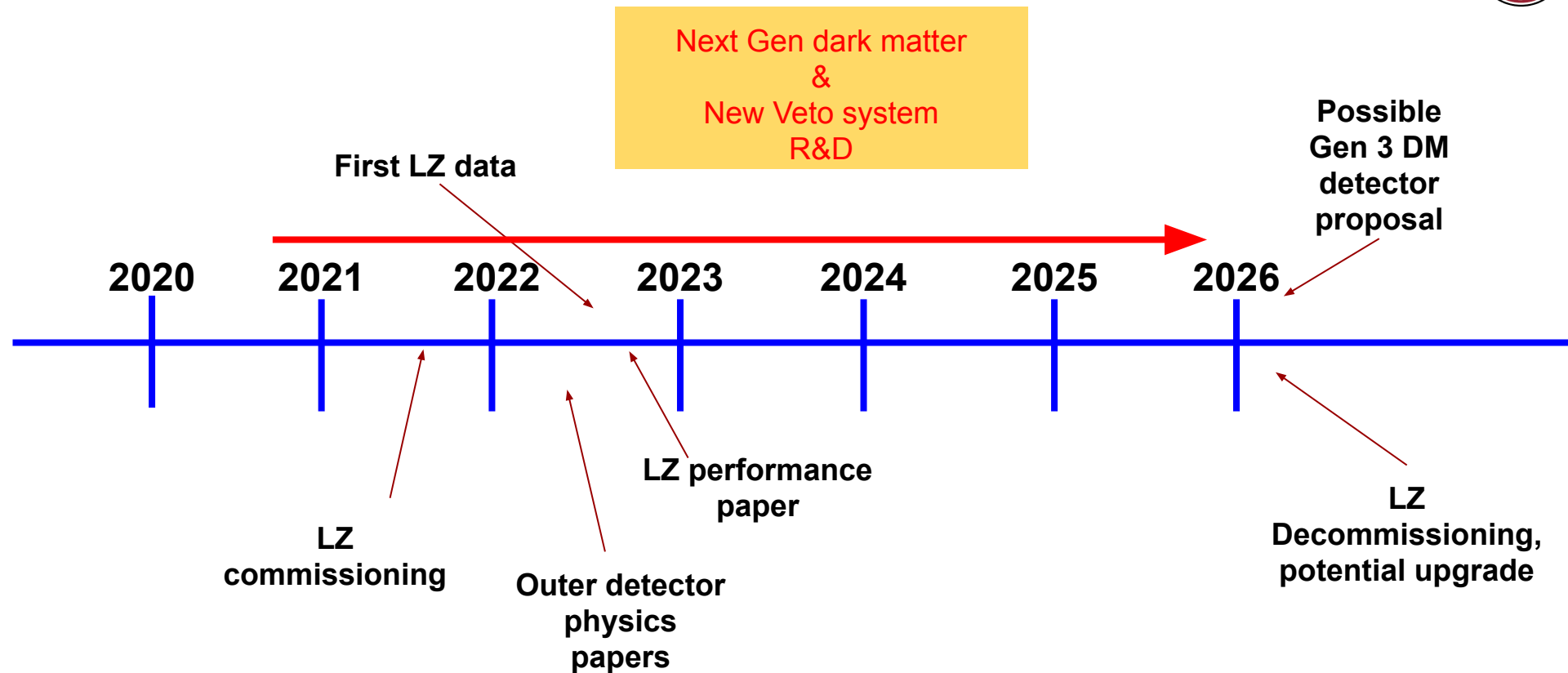
1-ton and 30-tonnes prototype



- Phase-I: excise WbLS in-situ deployment and circulation schemes
- Phase-II: WbLS performance, optical detector, and data analysis
- Fast turn-around operation using in-house resources in liquid production, QA/QC equipment, and existing mixing facility

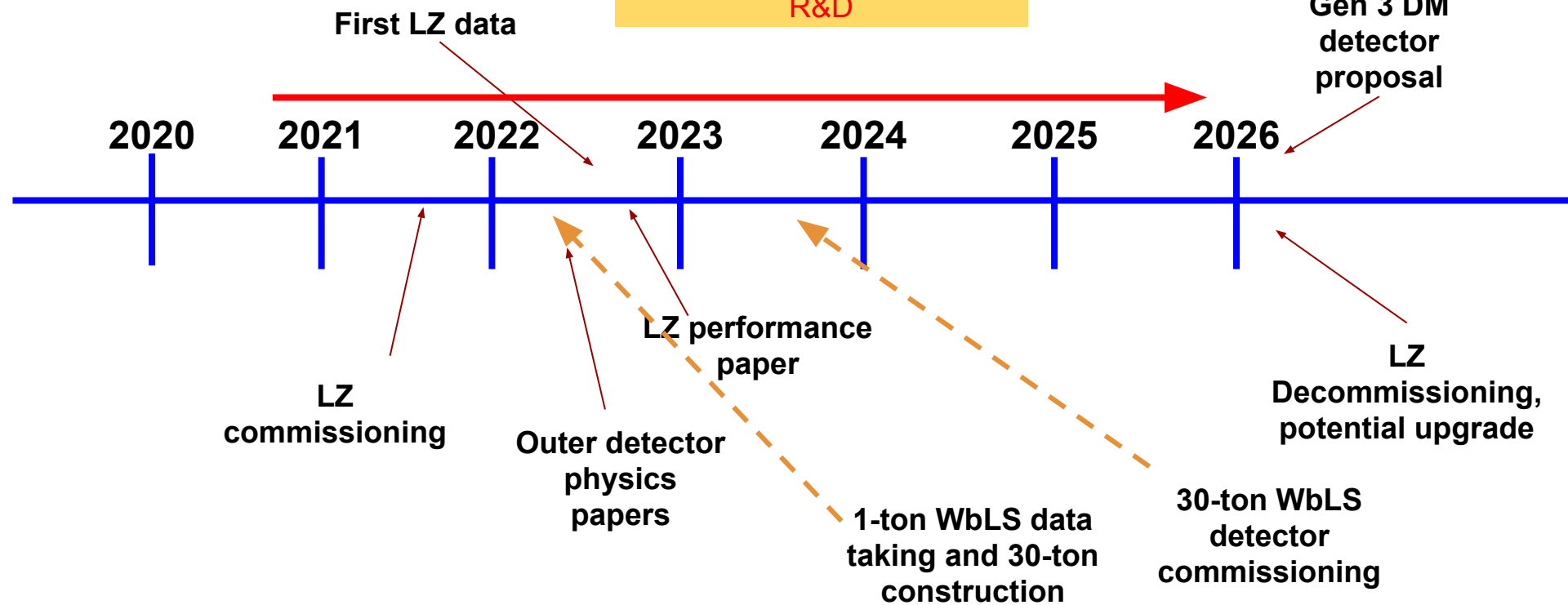


- Simulation to define tank capacity ($\sim 30T$)
- Engineering design (upright cylinder, SS316 polished);
- Circulation, Nanofiltration and Gd-water systems are main components attached
- Complete tank FDR in Dec 2021; ready for open bids





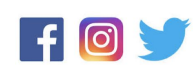
Next Gen dark matter
&
New Veto system
R&D





- LZ science runs in next 5 years
 - Optimization of **WIMPs search**
 - Provides leading limit setting/potential discovery
 - Physics **beyond standard WIMPs** searches
 - Exotic dark matter model in high energy region
 - OD physics
 - Background characterization
- **Next generation dark matter** veto detector R&D
 - Exploring liquid scintillator -based material
 - 1000L prototype is commissioning!
 - 30-tonnes demonstrator is underway!
 - Further acrylic scintillator study will opt for DM Gen 3 detector
- We are **hiring** a Postdoc! Please contact me if you are interested in detector R&D and world leading DM detection collaboration!





<https://lz.lbl.gov/>



- Black Hills State University
- Brandeis University
- Brookhaven National Laboratory
- Brown University
- Center for Underground Physics
- Edinburgh University
- Fermi National Accelerator Lab.
- Imperial College London
- Lawrence Berkeley National Lab.
- Lawrence Livermore National Lab.
- LIP Coimbra
- Northwestern University
- Pennsylvania State University
- Royal Holloway University of London
- SLAC National Accelerator Lab.
- South Dakota School of Mines & Tech
- South Dakota Science & Technology Authority
- STFC Rutherford Appleton Lab.
- Texas A&M University
- University of Albany, SUNY
- University of Alabama
- University of Bristol
- University College London
- University of California Berkeley
- University of California Davis
- University of California Santa Barbara
- University of Liverpool
- University of Maryland
- University of Massachusetts, Amherst
- University of Michigan
- University of Oxford
- University of Rochester
- University of Sheffield
- University of Wisconsin, Madison



Thanks to our sponsors and participating institutions!



U.S. Department of Energy
Office of Science



Science and
Technology
Facilities Council





Stay Healthy
and Thank you !