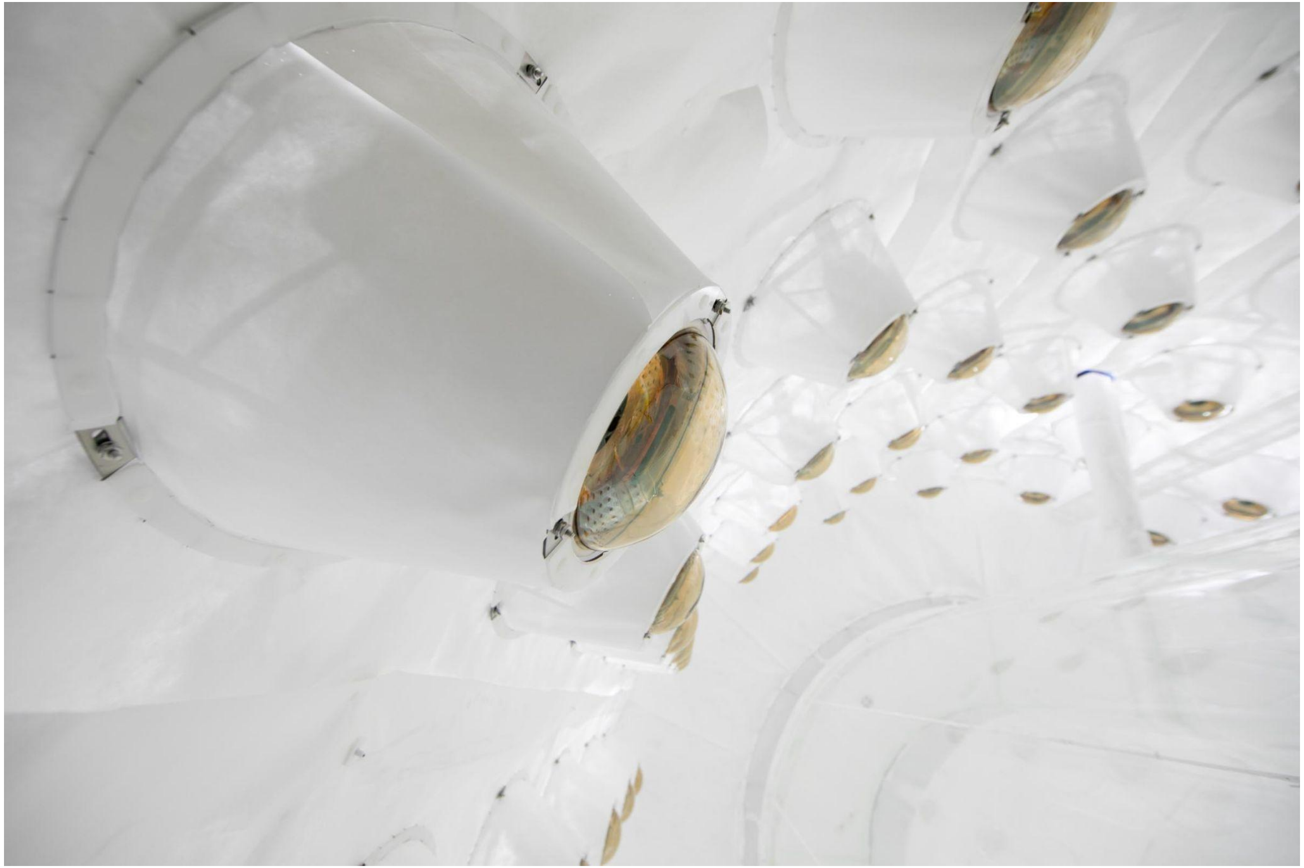
Hunting for the Invisible Deep Underground

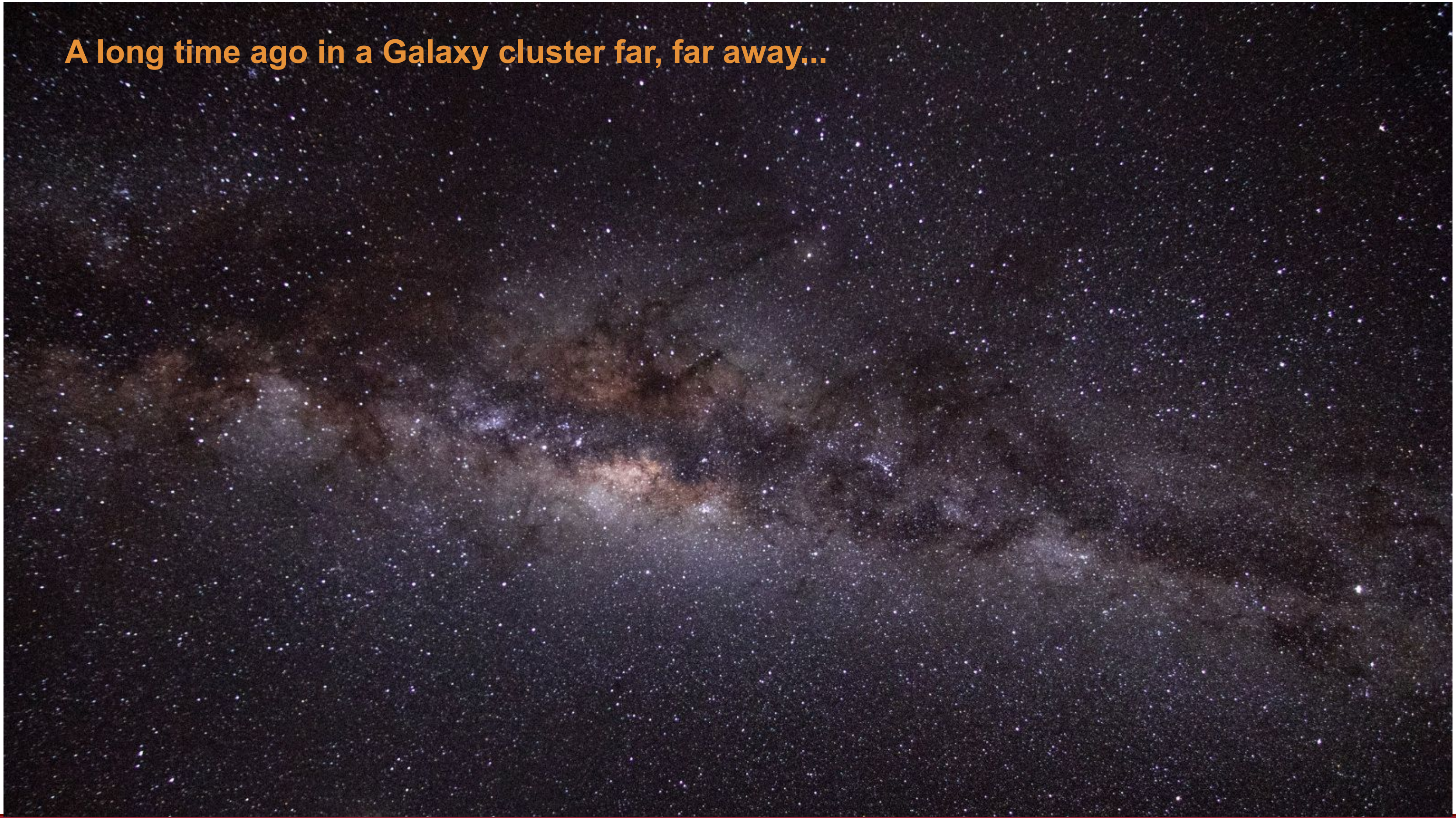
Jui-Jen (Ryan) Wang

1/14/2022

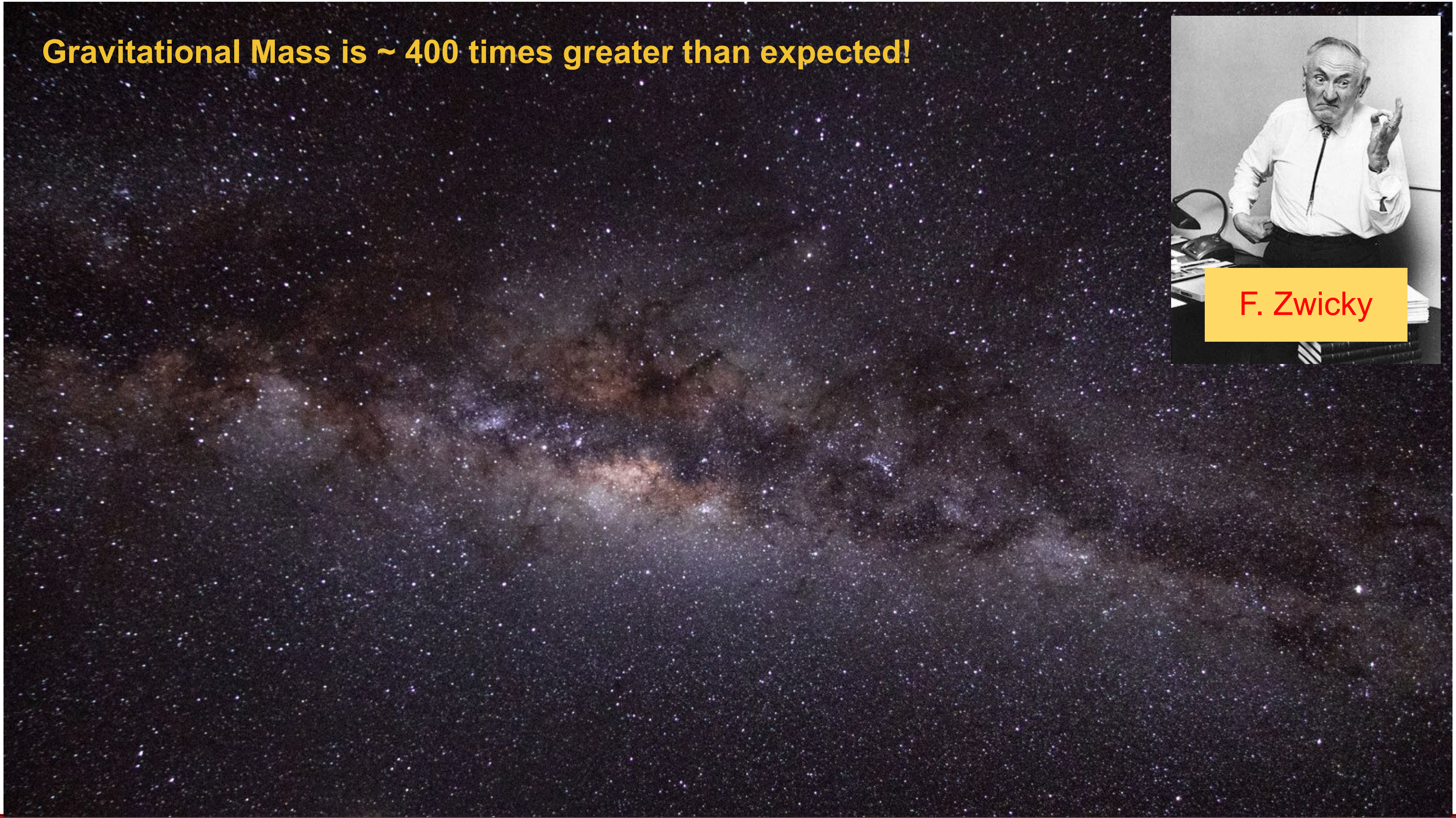
University of Alabama &
LZ collaboration



- 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

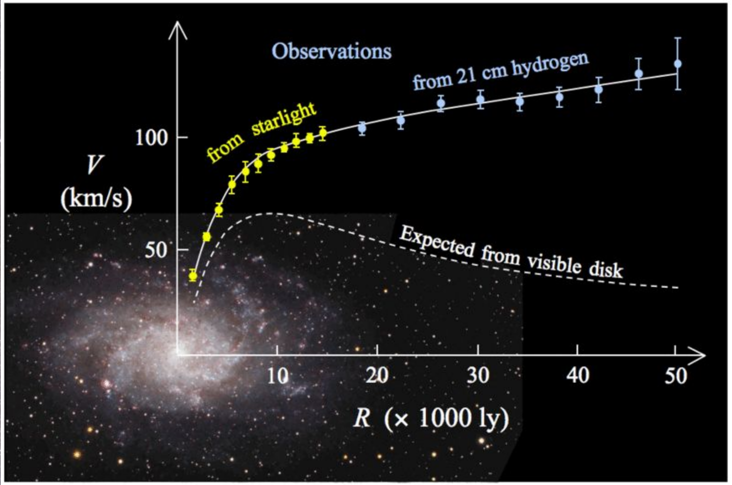

A long time ago in a Galaxy cluster far, far away...

Gravitational Mass is ~ 400 times greater than expected!

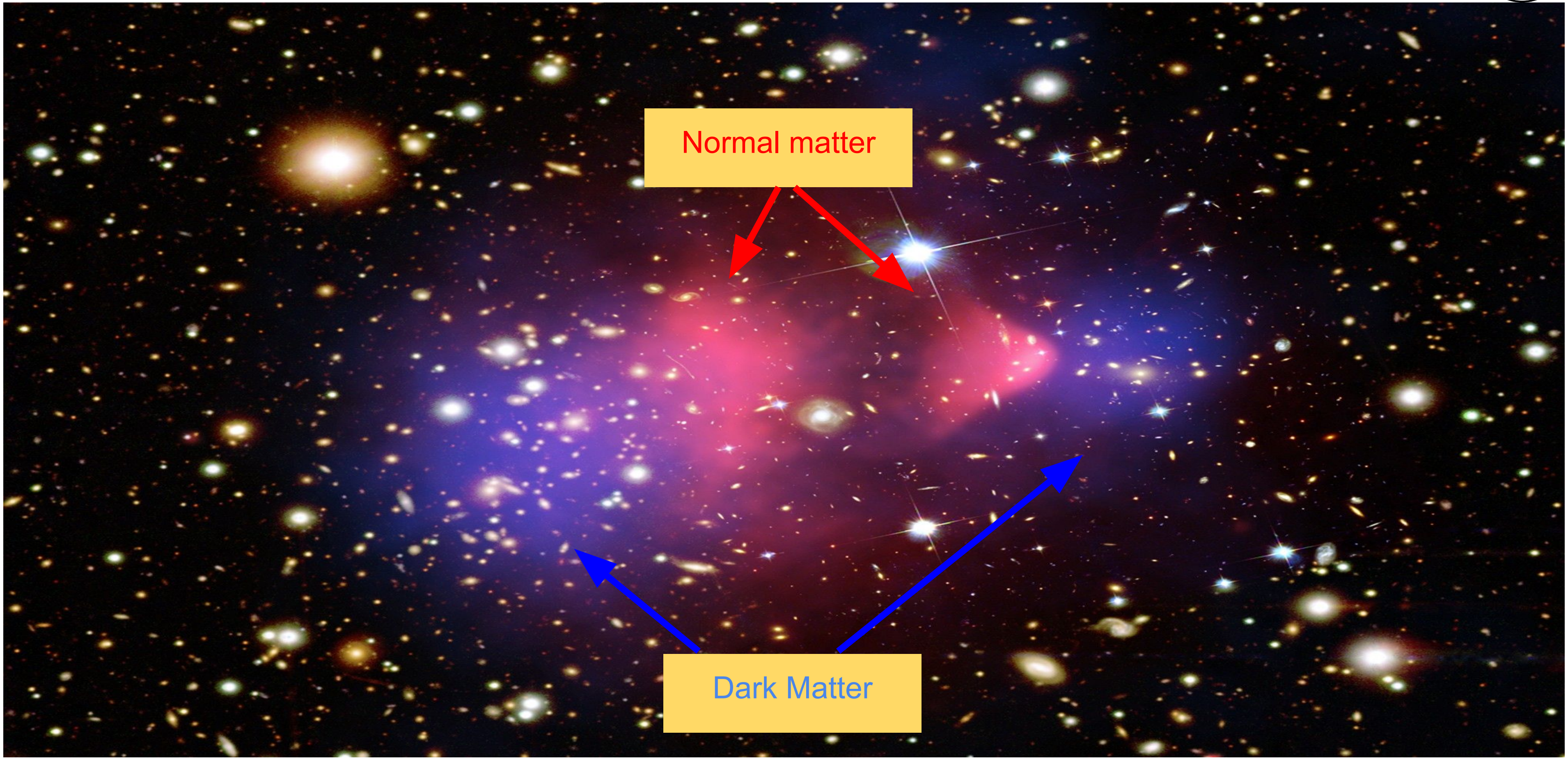


Rotational curve of a galaxy did not follow the newtonian dynamics!

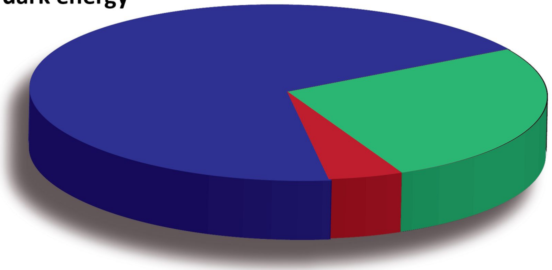
Vera Rubin in 1970s

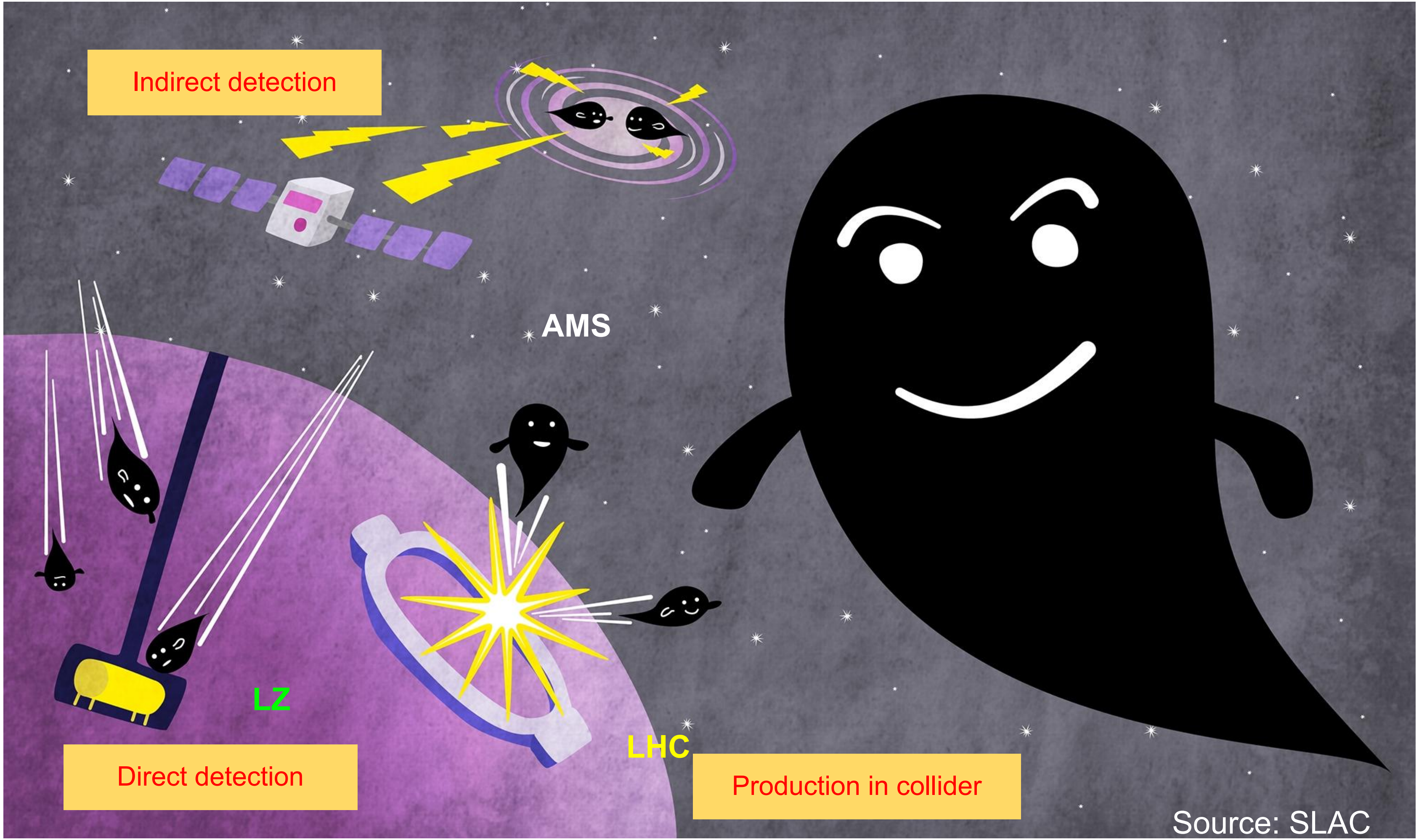


$$v(r) = \sqrt{G \cdot \frac{m(r)}{r}}$$


Normal matter
Dark Matter

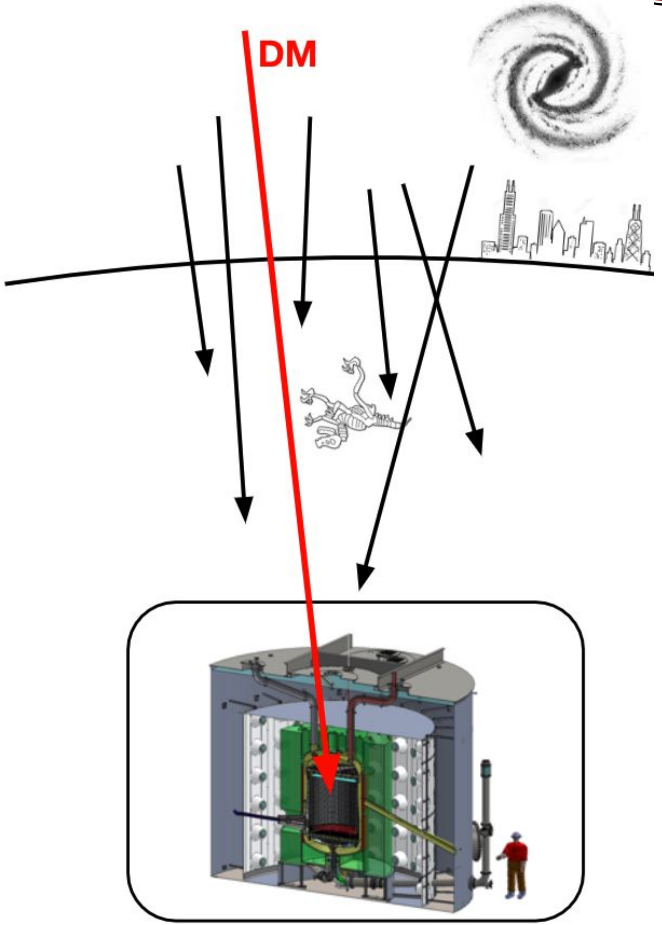
- Calculation using Cosmic Microwave Background (CMB) and Big Bang Nucleosynthesis (BBN) indicate baryonic matter only account for 5% of the total mass of universe.
- Cold (non-relativistic) dark matter is the favored candidates
  - Abundance of dark matter suggests the new particle has mass in 100 GeV 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”



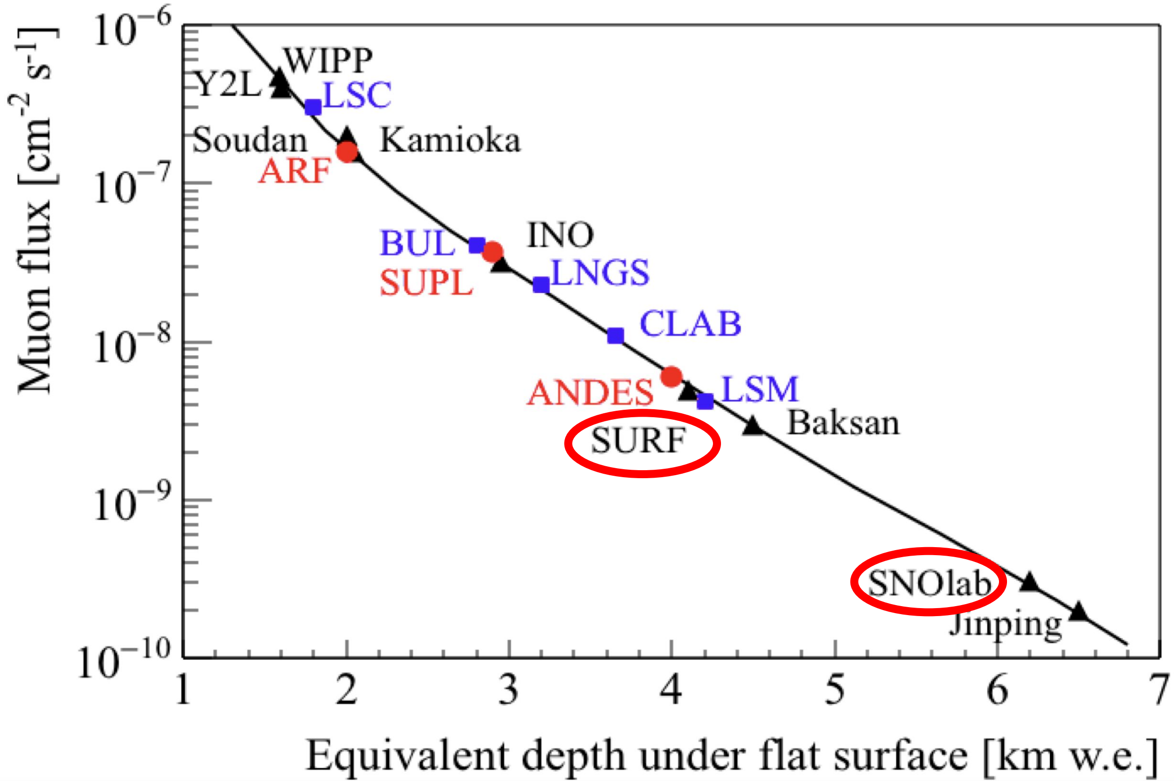


Indirect detection
AMS
LZ
LHC
Direct detection
Production in collider
Source: SLAC

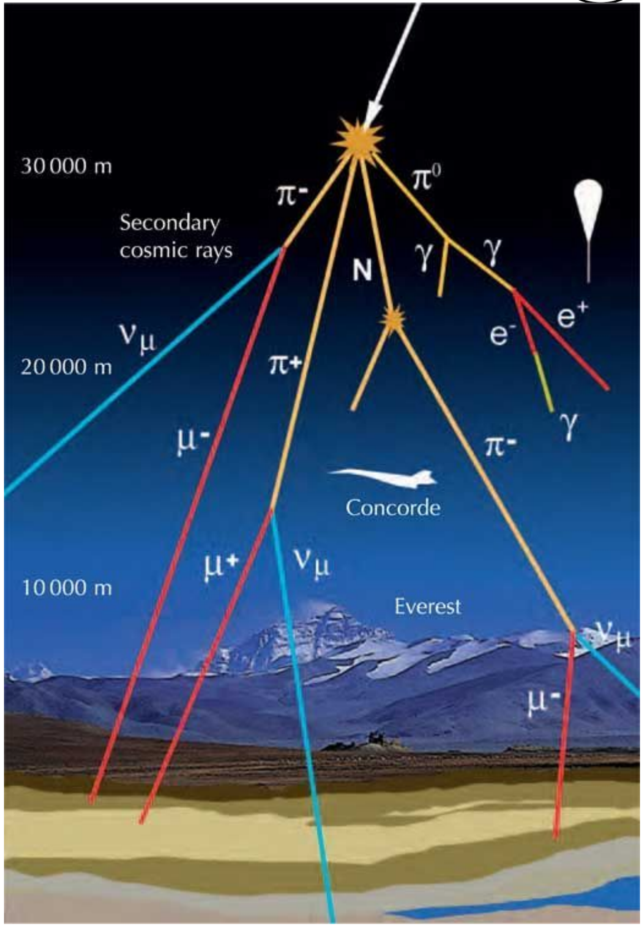
- You would want something stable for your detector target.
- No or few internal background in the detector target.
- With measurable signal even when the energy deposition is small.
- With good energy resolution and linear energy response.
- Large volume to increase the chance of detection
  - ~ few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



Where to find WIMPs?



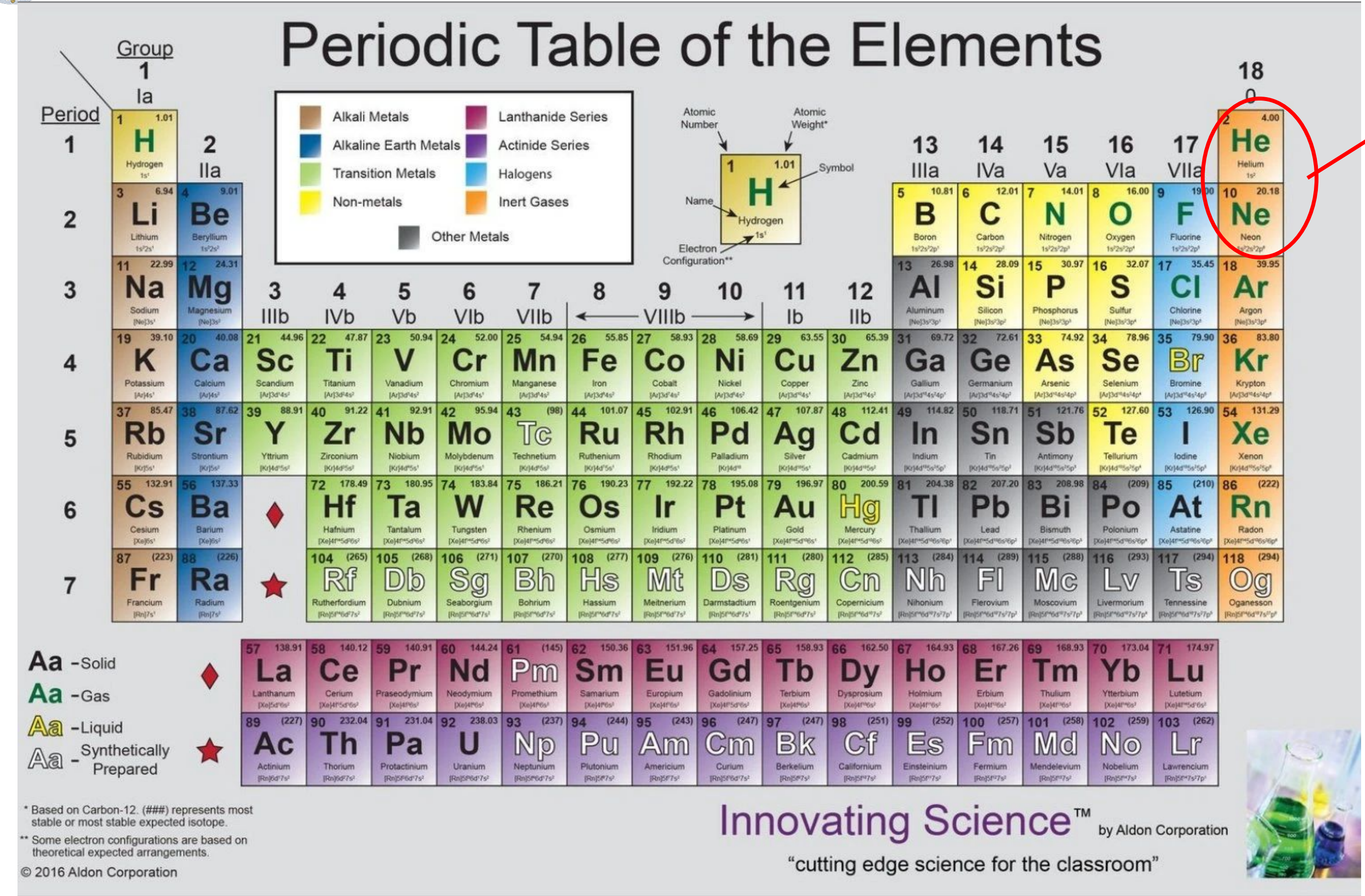
To eliminate the cosmic background radiation, one has to go deeper!



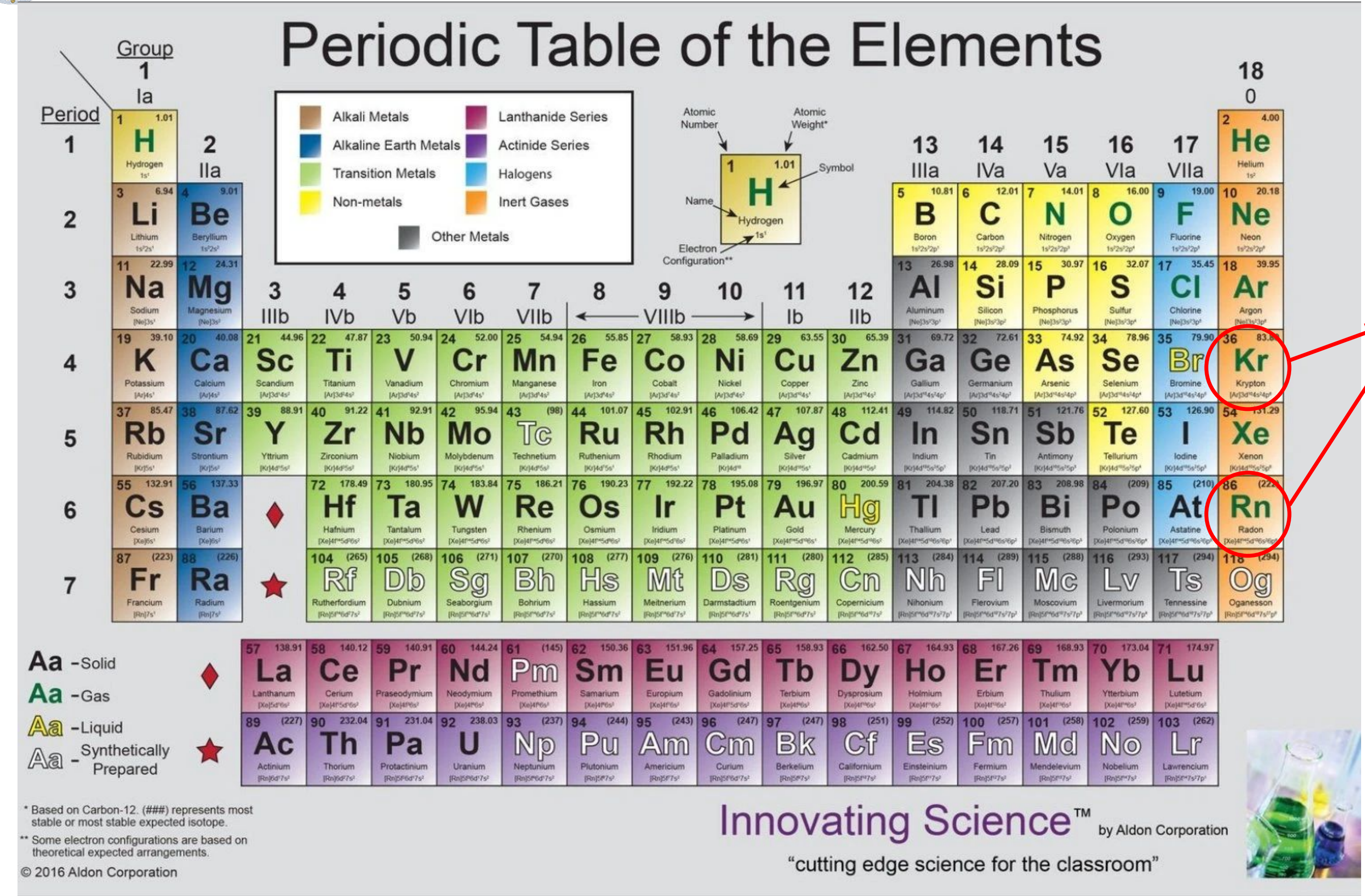
- SNOLAB (Sudbury Neutrino Observatory) is located at 6800 ft at Creighton Mine, which is an active underground nickel mine operate by Vale.
- Originally housing SNO experiment which won the Nobel prize in physics in 2015 for discovering neutrino oscillation of solar neutrino.

- 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.

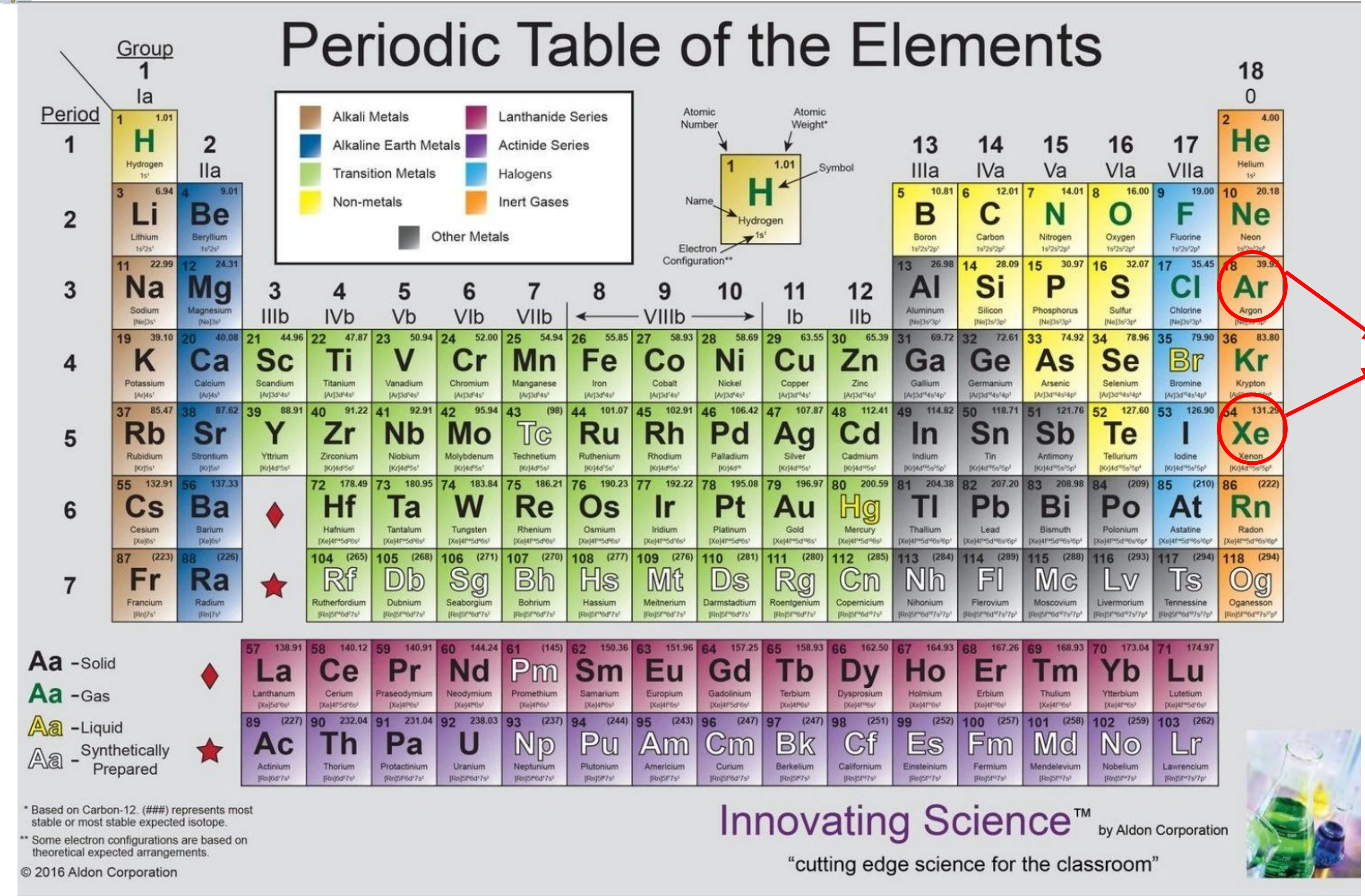
Liquid Noble Gas



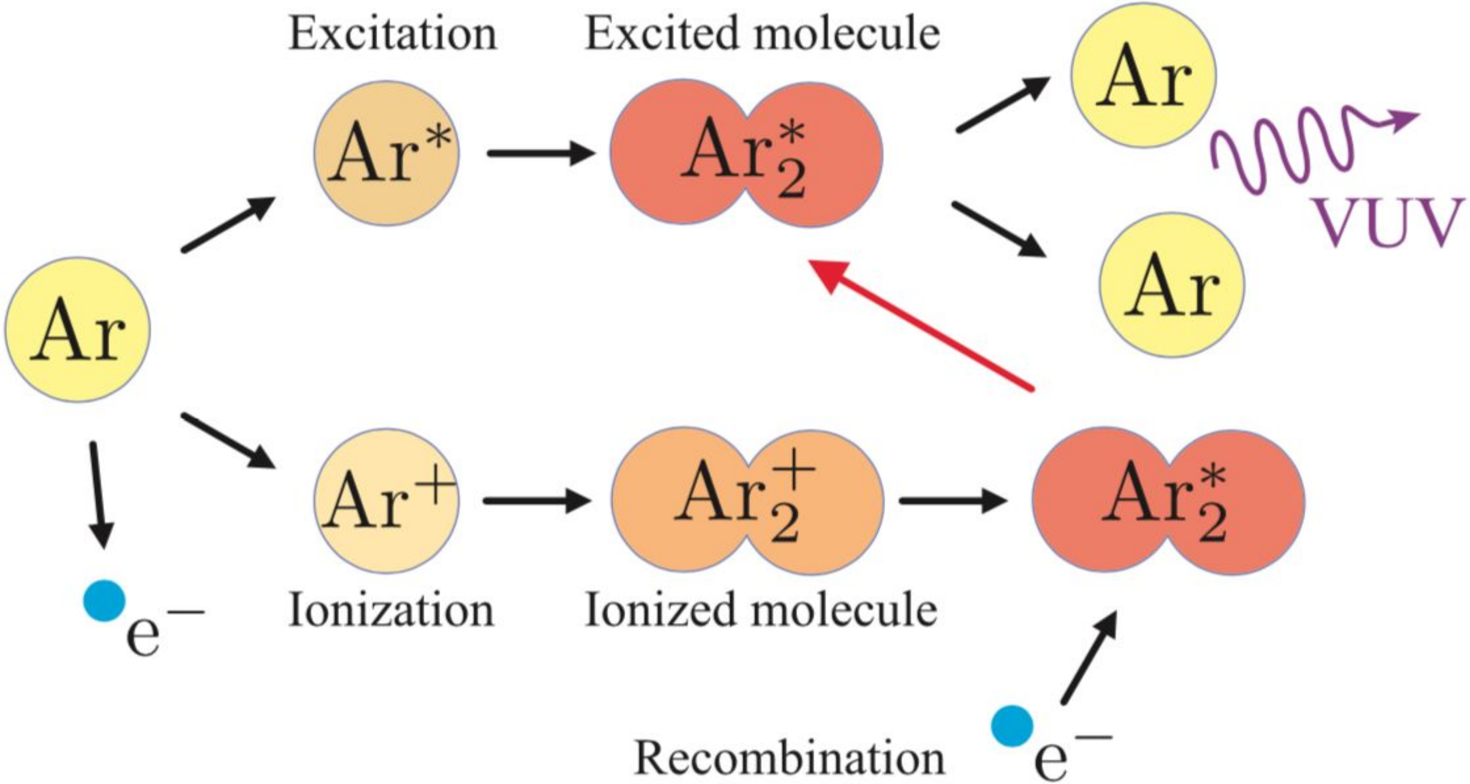
- Too light for nominal dark matter searches
- Require a elaborated cryogenic system



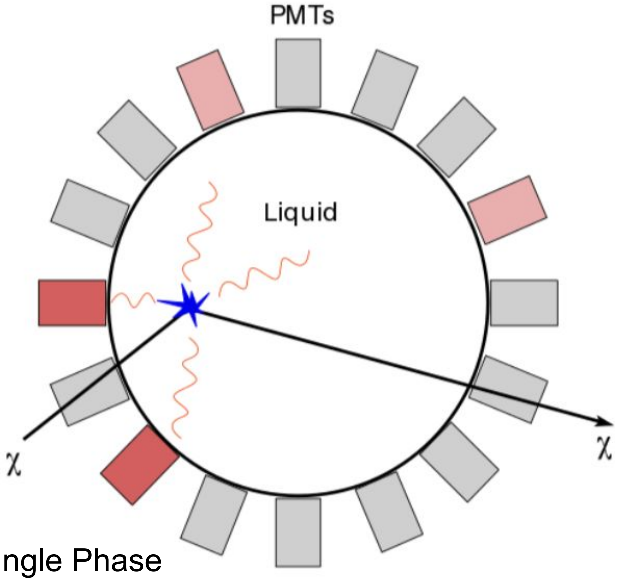
- Has radioactive isotopes, hard to eliminate for dark matter searches



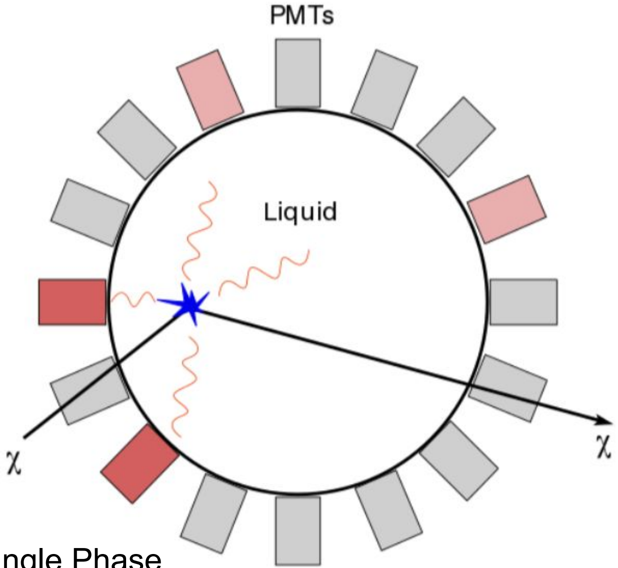
- High light/charge yield
- Acceptable intrinsic background
- Well above liquid nitrogen temperature; easy to liquified


Excitation
Excited molecule
Ar
Ar^*
Ar_2^*
Ar
VUV
Ar
e^-
Ar^+
Ar_2^+
Ar_2^*
Ionization
Ionized molecule
Recombination
e^-

Detector Technique



- Single Phase
  - Trigger window can be fast (< 5 μs).
  - High rate calibration runs are possible.
  - Simple design with 4π coverage (Maximize light collection).



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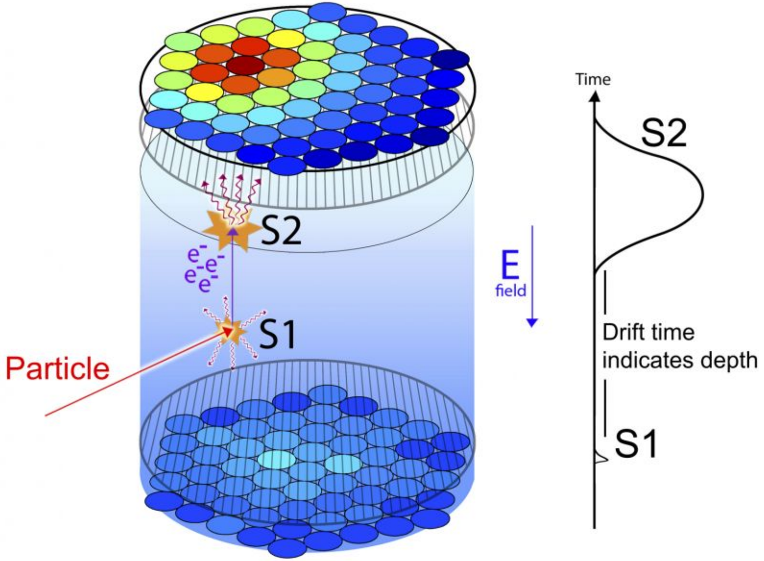
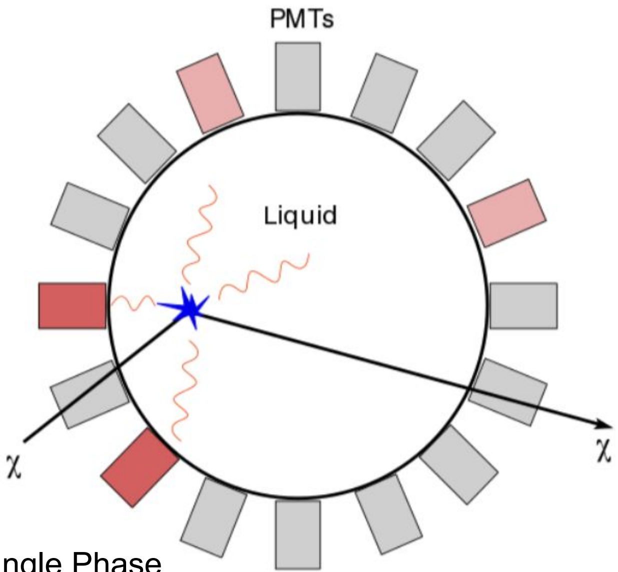


- Dual phase (Time Projection Chamber)
  - Interaction in target creates ionized and excited states.
  - Recombination of some ions and de-excitation of states creates primary scintillation light.
  - Acceleration at gas/liquid interface creates proportional light.



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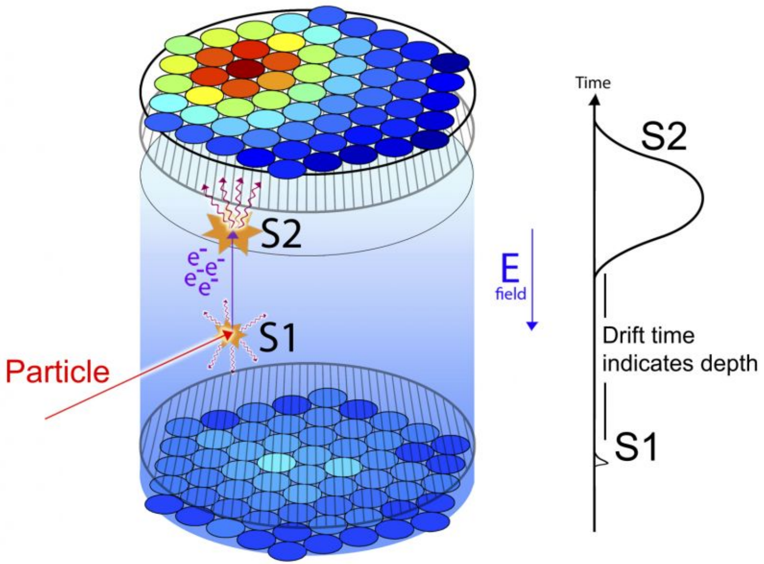
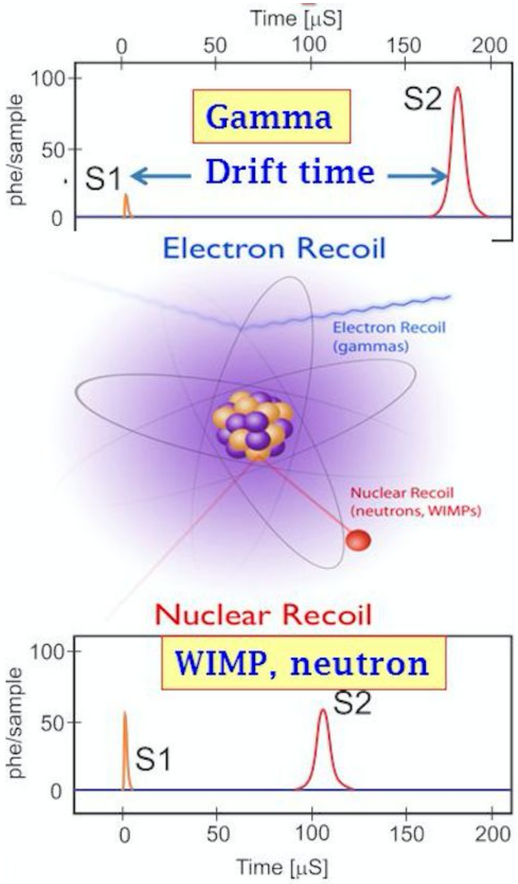
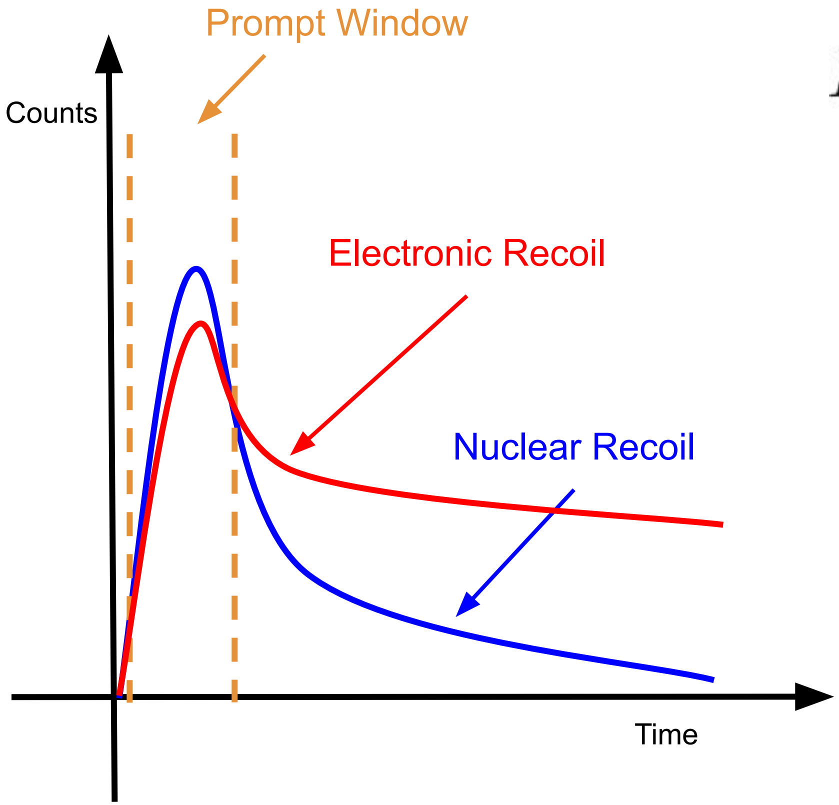


- Dual phase (Time Projection Chamber)
  - Better position reconstruction (~ mm, ~ cm in single phase).
  - Extra signal (ionization) provides discrimination parameters.
  - Maximize fiducial volume (background free volume)

- Electronic recoil
  - Beta (electron).
  - Gamma (high energy photons).
  - Tend to bounce around the atoms thus less dense and longer tack.
  - 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.

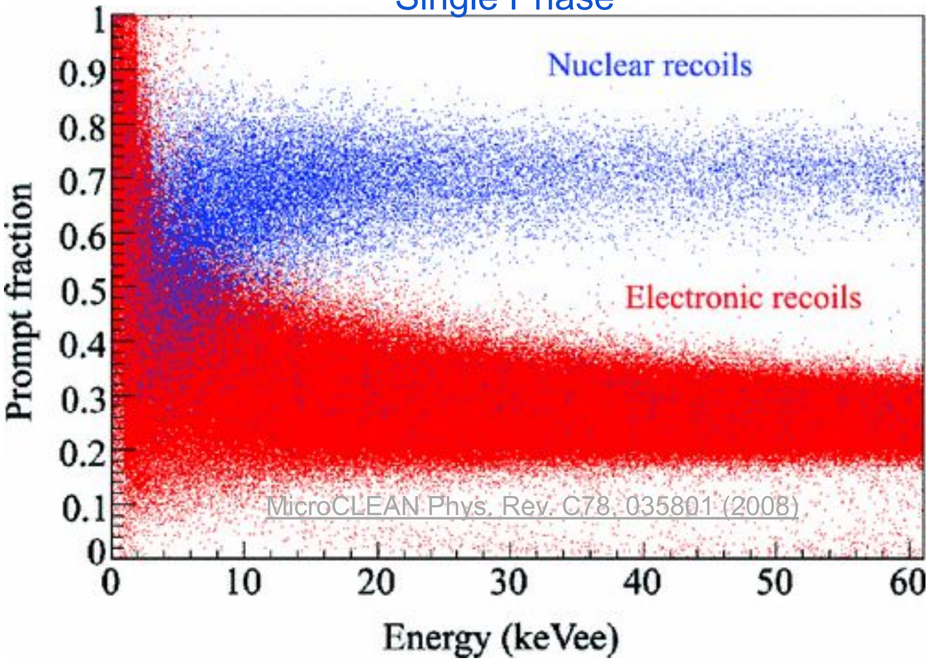




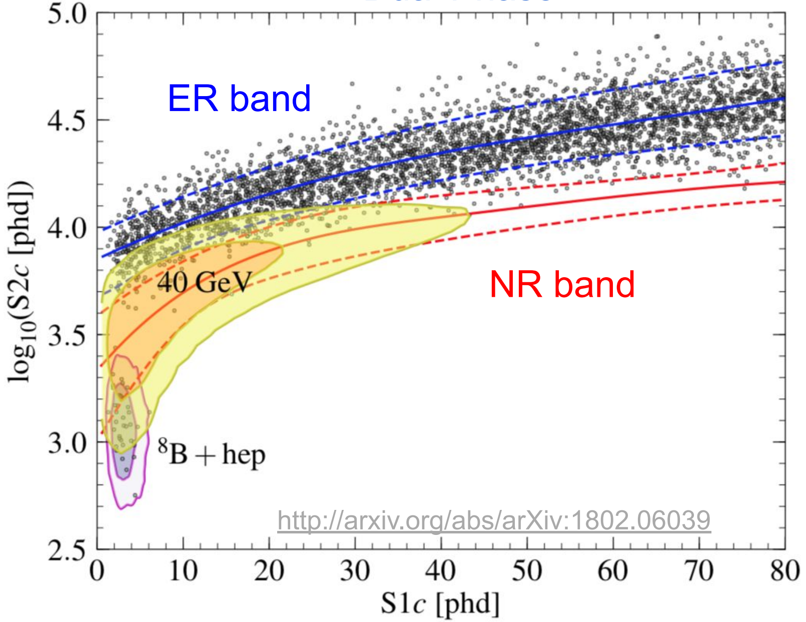
$$Fprompt = \frac{Prompt\ photoelectrons}{Total\ photoelectrons}$$

- 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/1.6μs) while LXe has very similar decay time for both states (8ns/20ns)

Single Phase



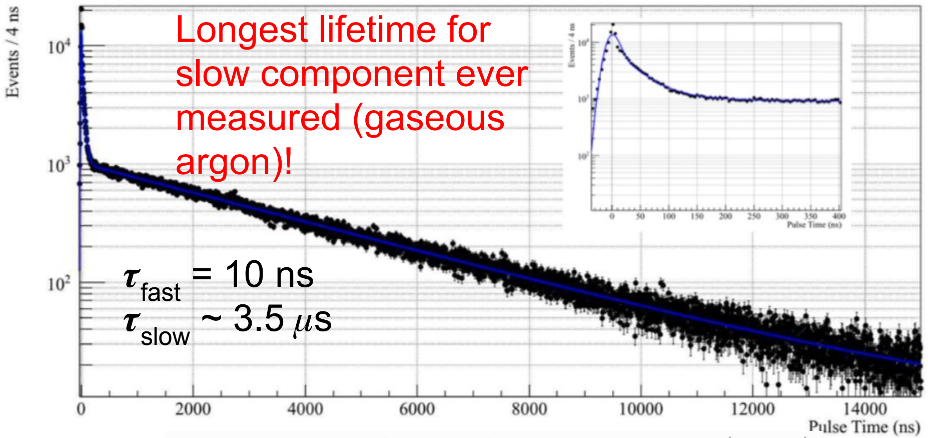
Dual Phase



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

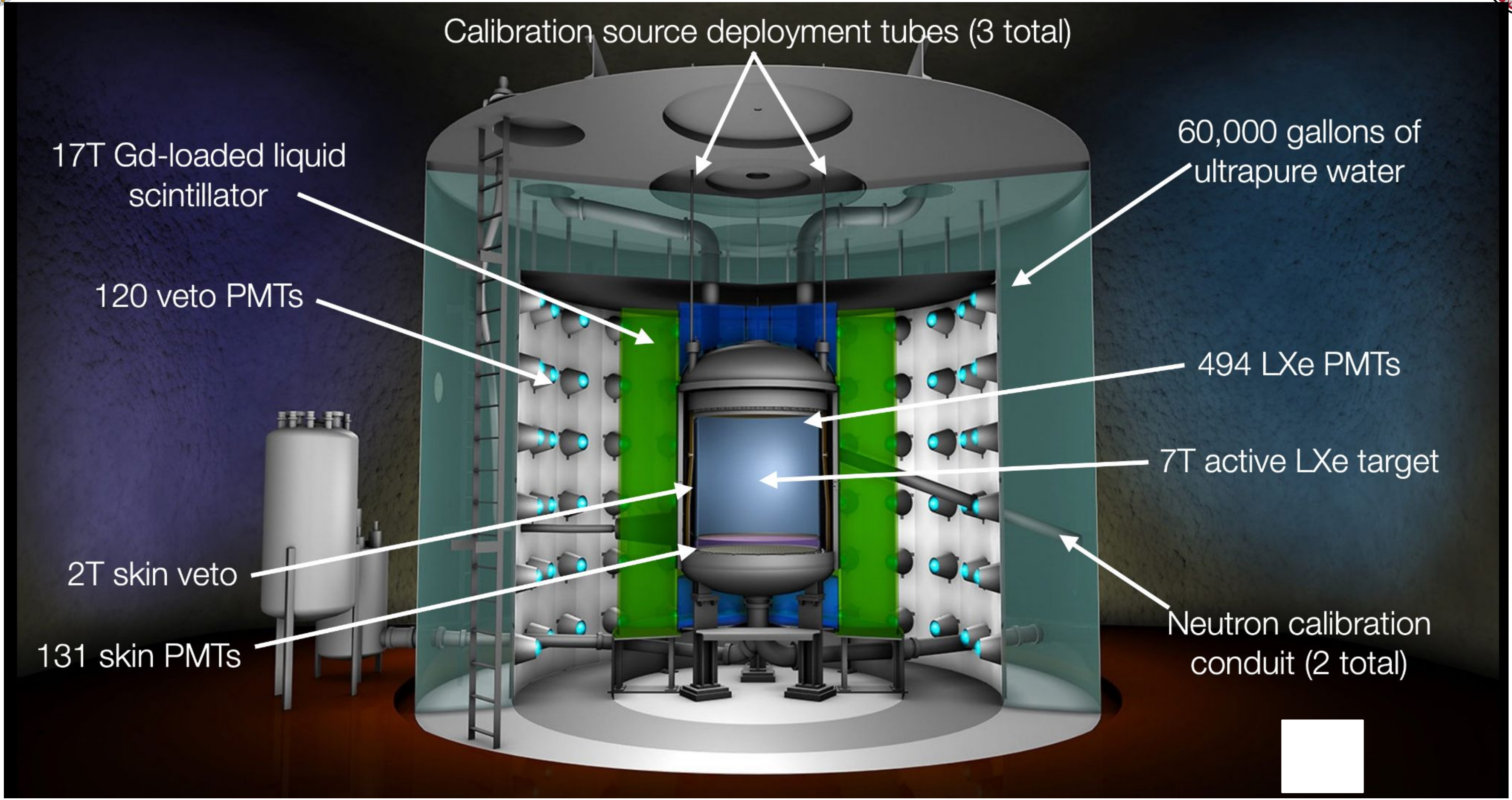
- Using S2/S1 ratio
- 99.5% discrimination using charge/light in Liquid xenon.

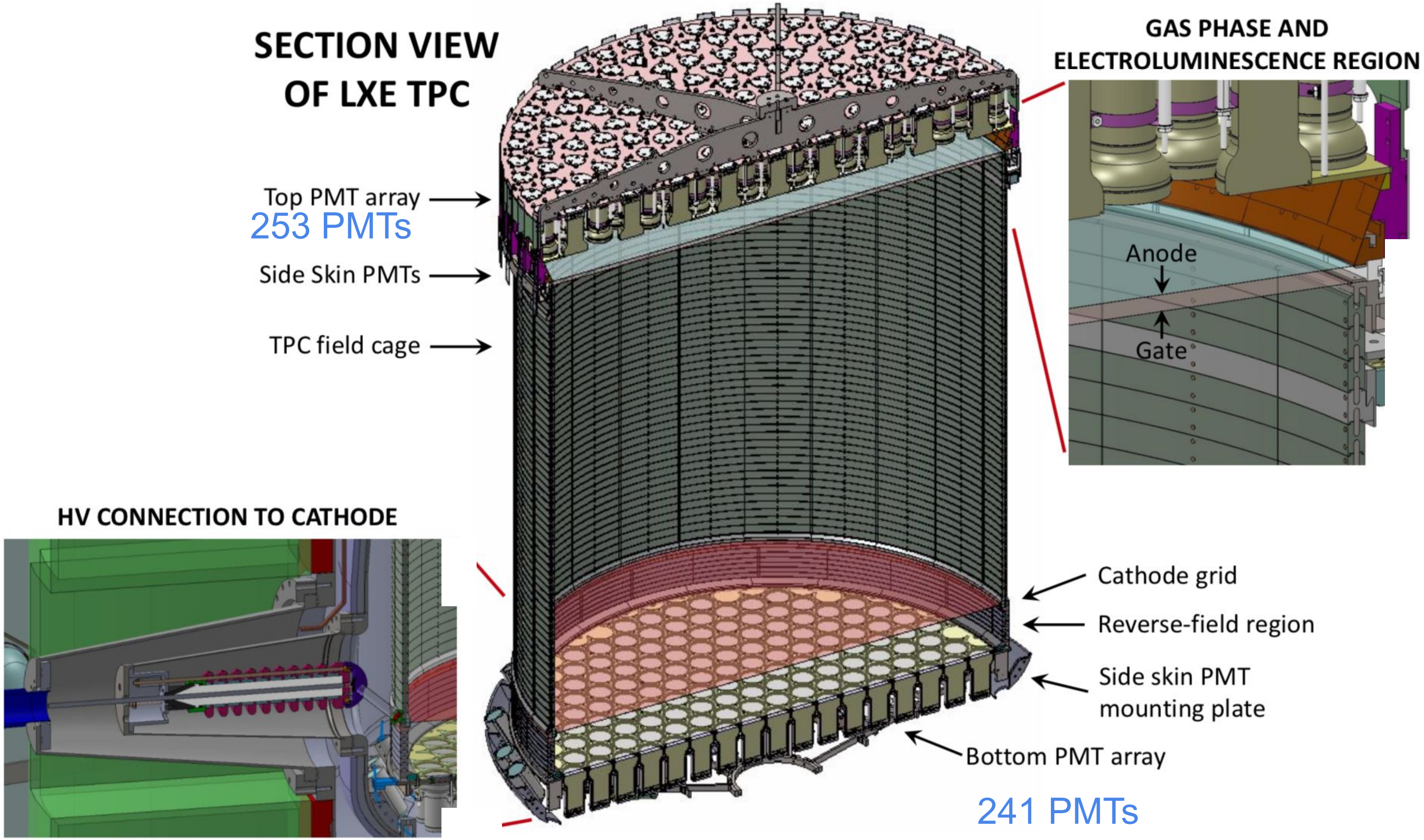
- 500 kg of liquid argon
- Spherical vessel gives 4-π PMT coverage
- Spent 2 years at SNOLab for detector construction



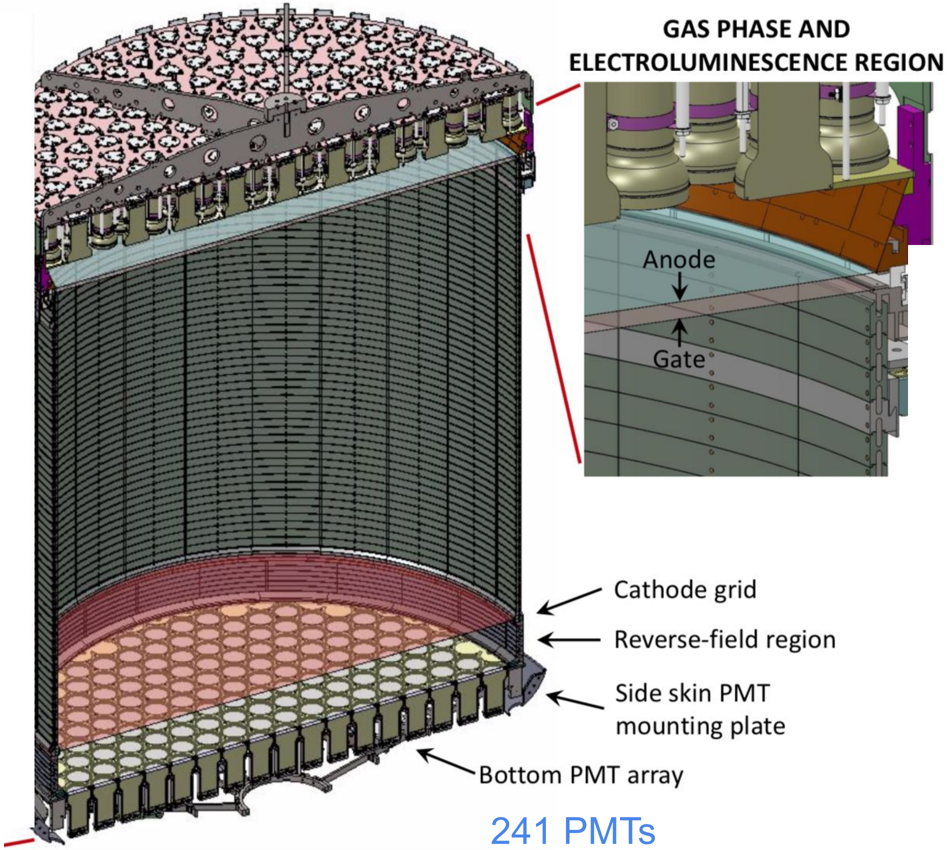
J.J.Wang*. *et al. Eur. Phys. J. A* 55, 176 (2019).

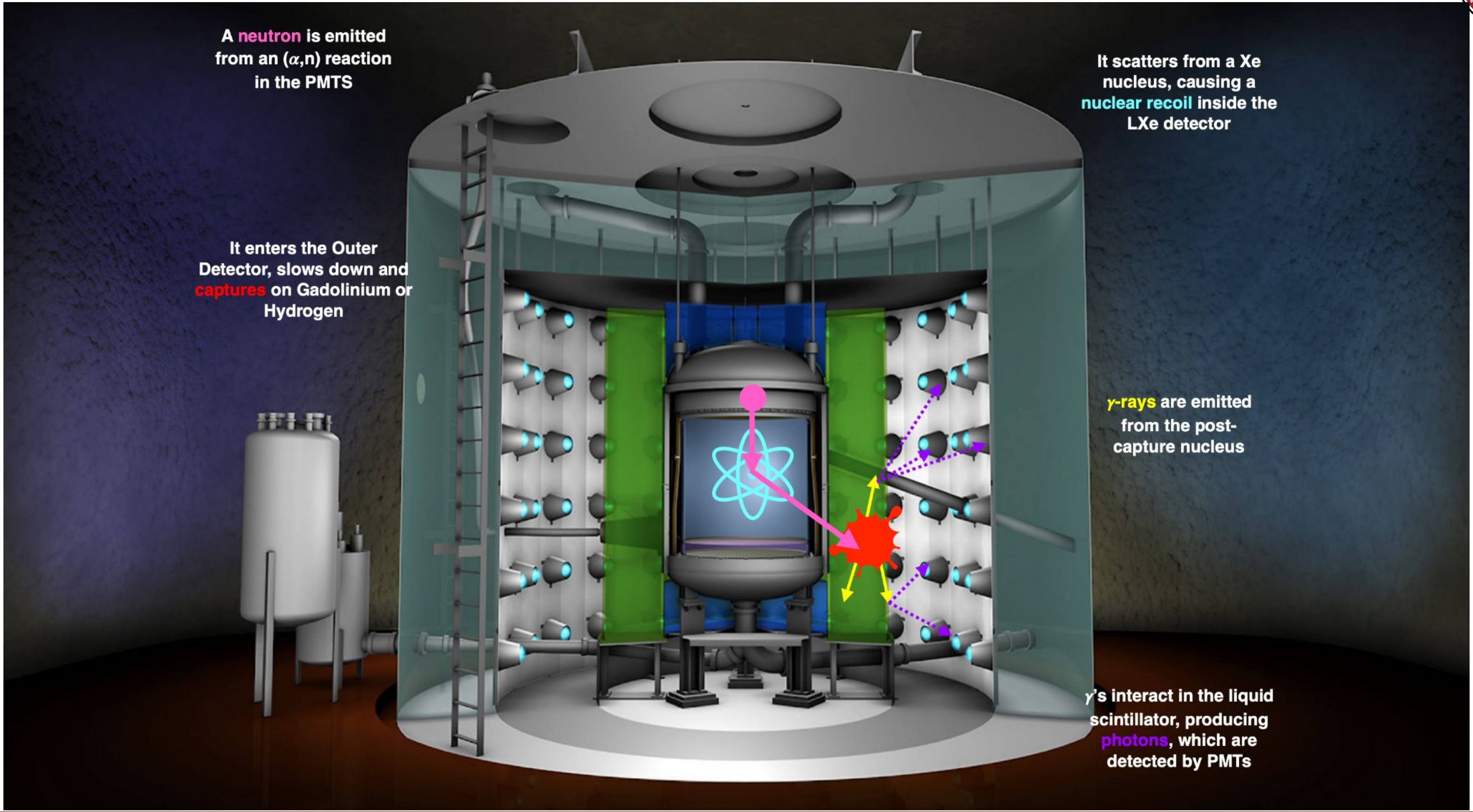
- Impurities molecule (Oxygen, Nitrogen, etc.) quenching slow component results in reduction of lifetime of the slow component and light yield
- Powerful Pulse Shape Discrimination (PSD) with high purity (long triplet lifetime)
  - Better dark matter sensitivity
- First experimental result of MiniCLEAN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

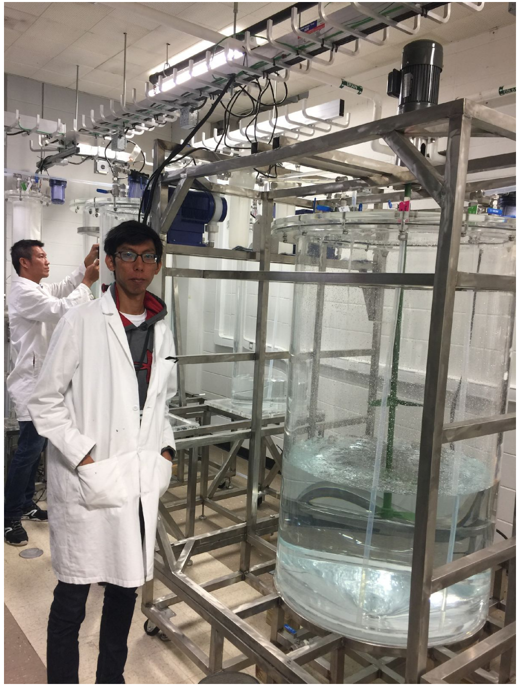

Calibration source deployment tubes (3 total)
17T Gd-loaded liquid scintillator
60,000 gallons of ultrapure water
120 veto PMTs
494 LXe PMTs
7T active LXe target
2T skin veto
131 skin PMTs
Neutron calibration conduit (2 total)


SECTION VIEW
OF LXE TPC
Top PMT array
253 PMTs
Side Skin PMTs
TPC field cage
GAS PHASE AND
ELECTROLUMINESCENCE REGION
Anode
Gate
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

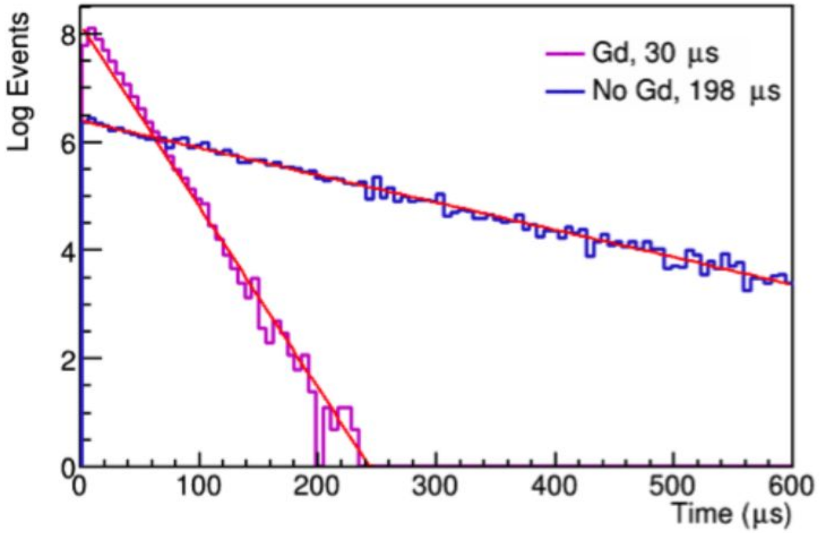



A neutron is emitted from an (α,n) reaction in the PMTS
It scatters from a Xe nucleus, causing a nuclear recoil inside the LXe detector
It enters the Outer Detector, slows down and captures on Gadolinium or Hydrogen
γ-rays are emitted from the post-capture nucleus
γ's interact in the liquid scintillator, producing photons, which are detected by PMTs



Thermal neutron capture cross sections:

^{157}Gd: 254,000 barns **^{155}Gd: 61,000 barns**

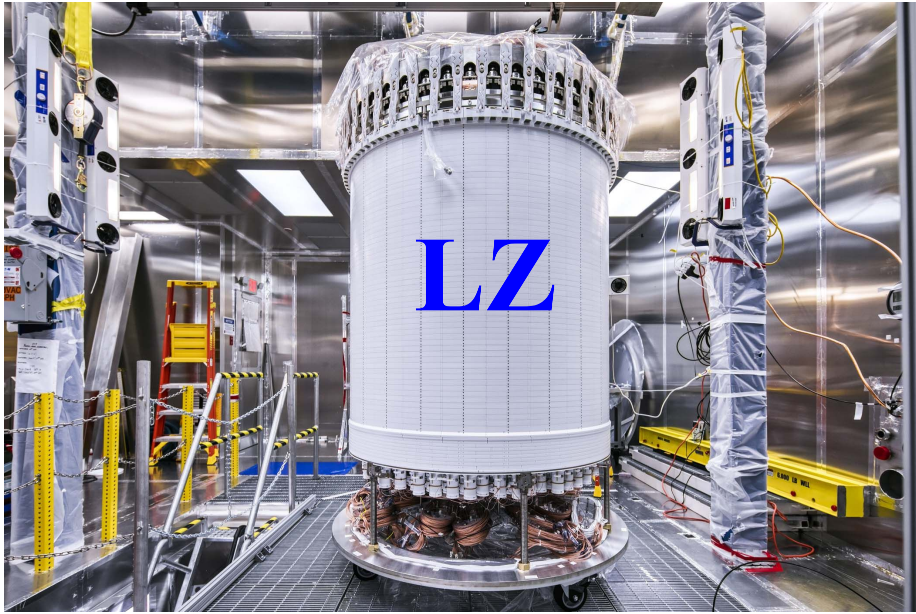


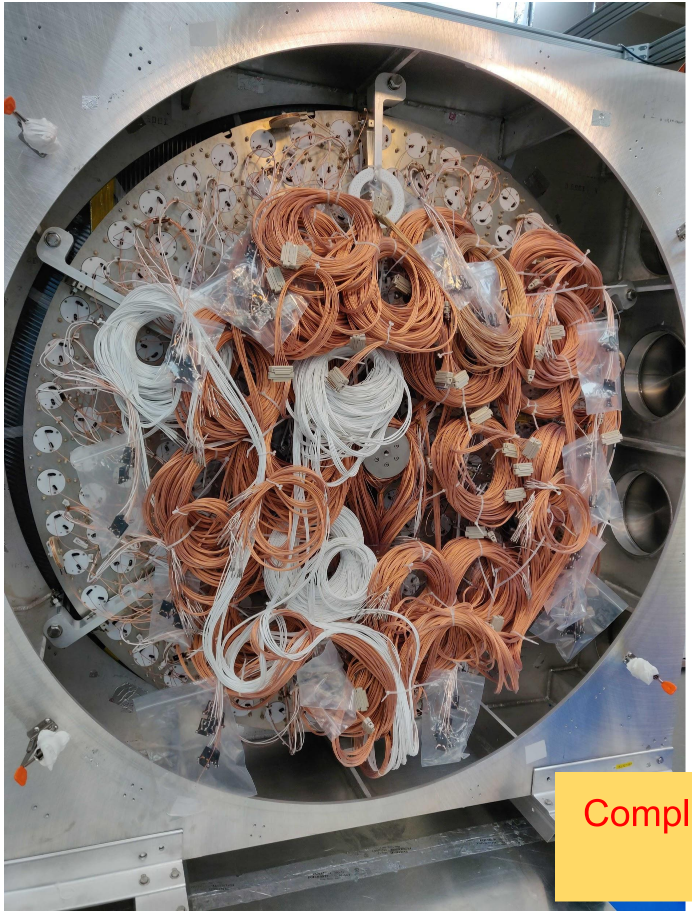
- Gadolinium has large cross-section of neutron capturing.
- By only doping 0.1 % of Gd into LS, the thermal neutron capture time has been greatly improved, which increased the tagging efficiency.

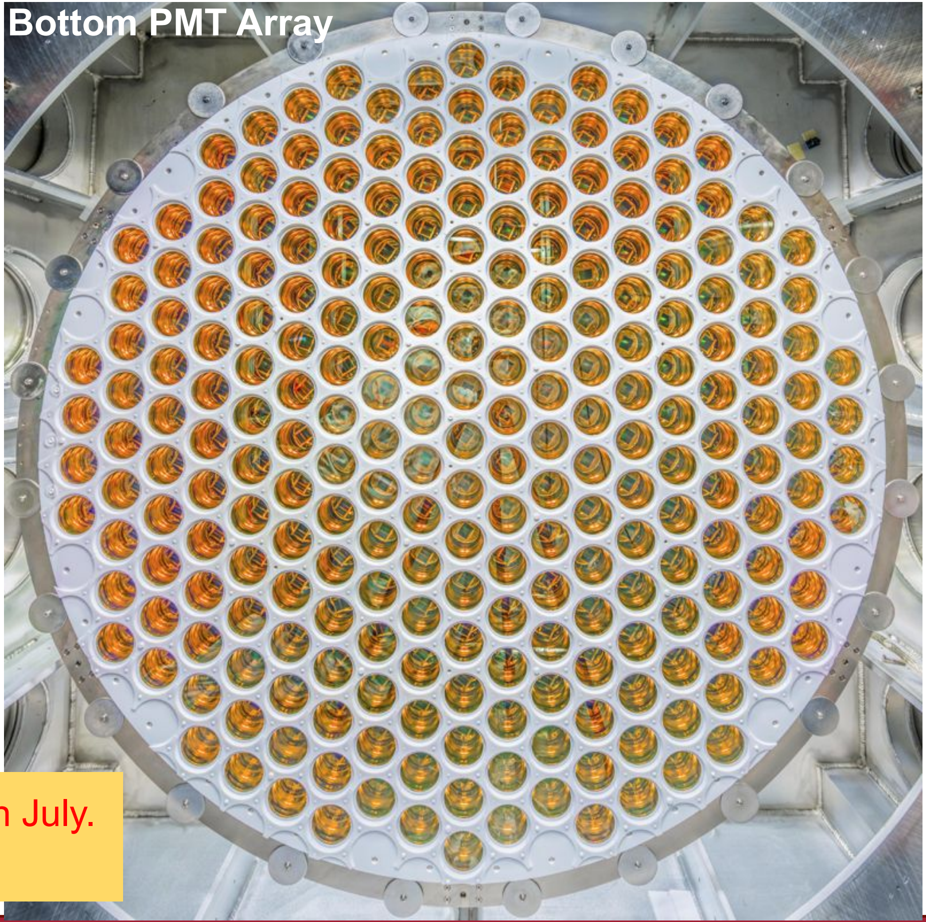
Detector Construction

- 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.



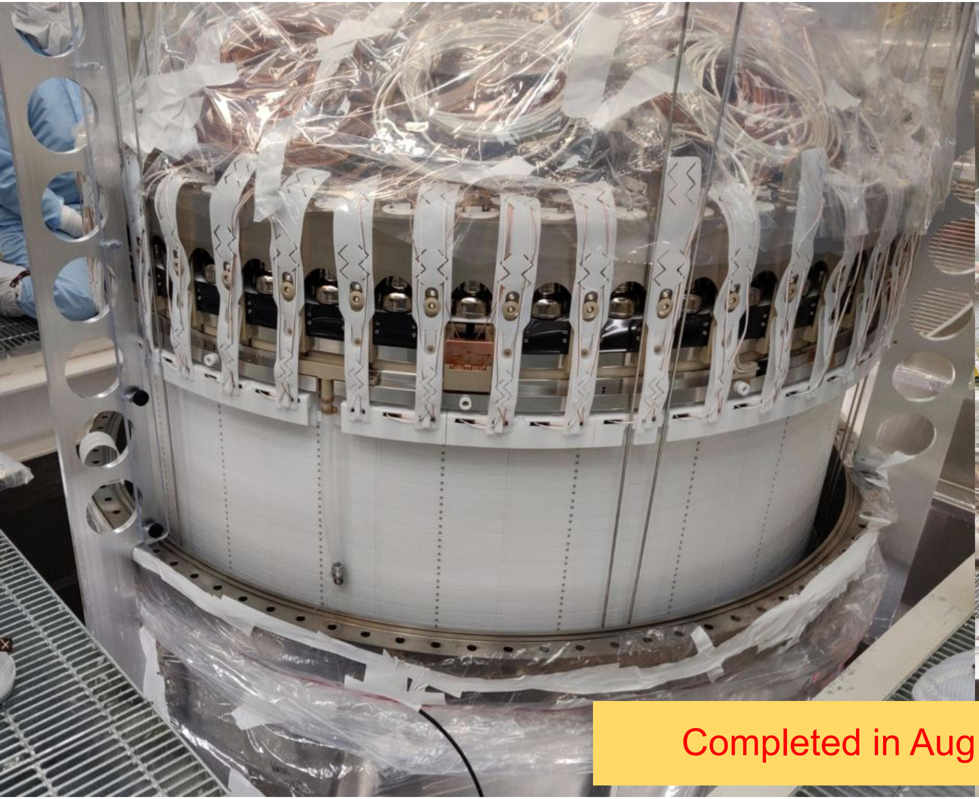




Completed in July. 2019

Completed in Aug. 2019

Final checkout



Completed in Aug. 2019

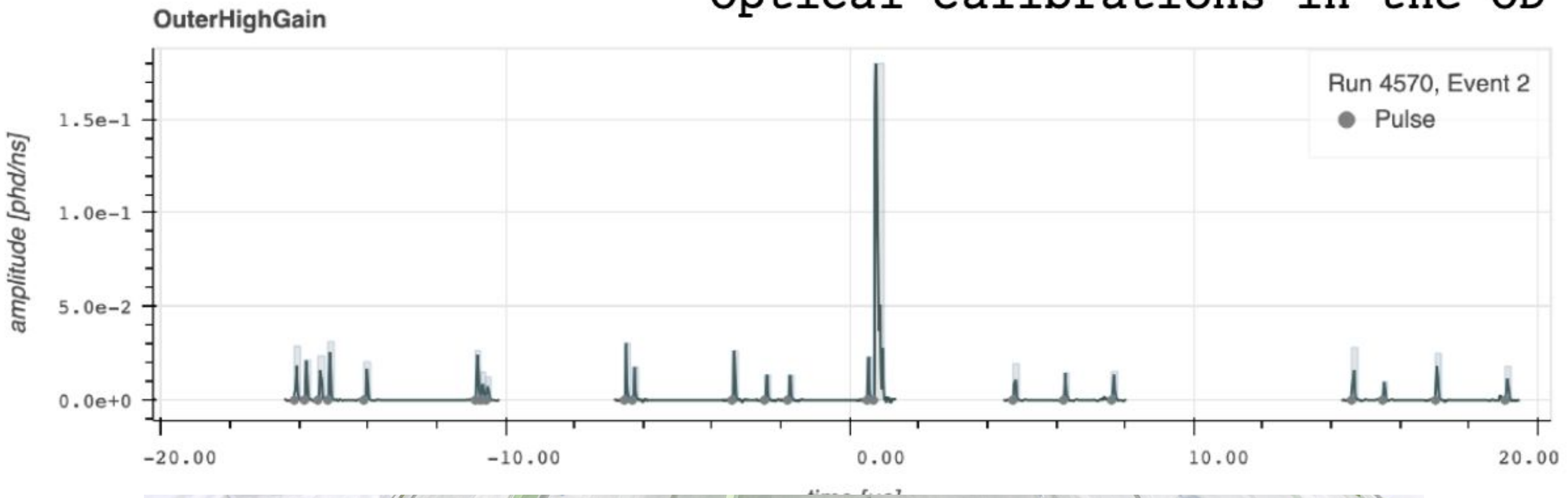
Transport to underground in Oct. 2019

Final integration in Dec. 2019

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

Now complete!

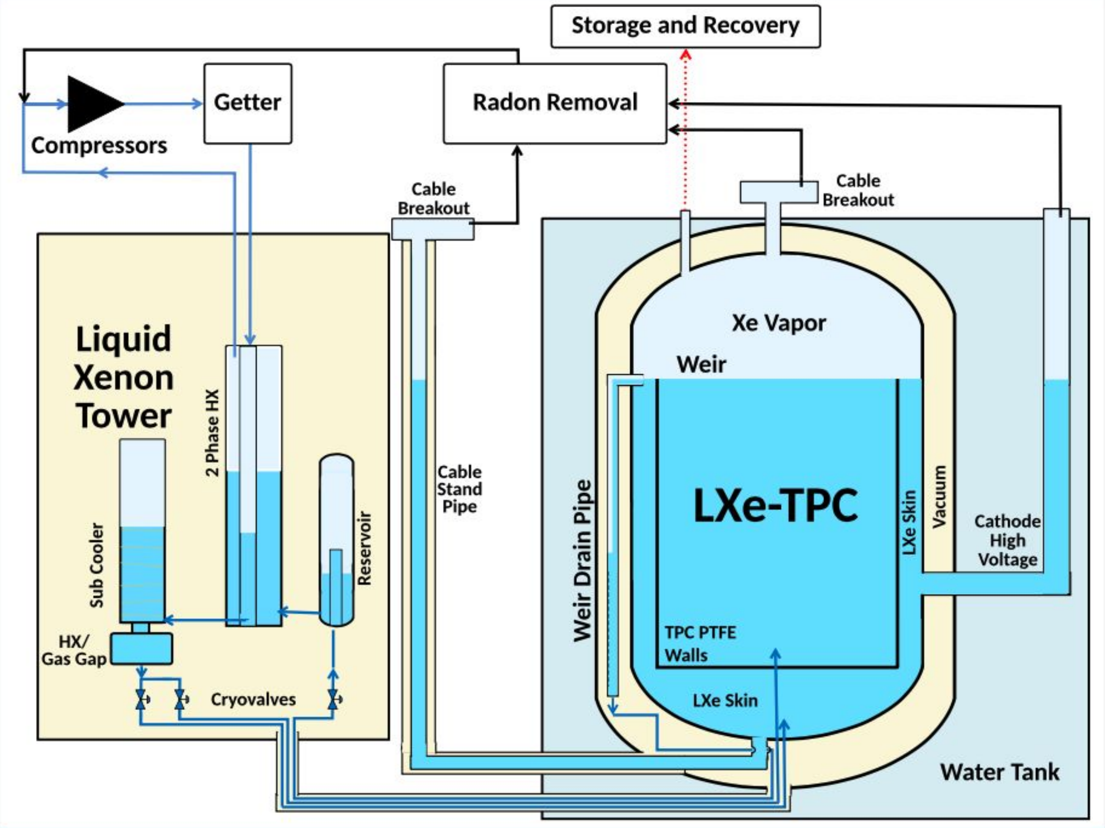
Optical calibrations in the OD



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

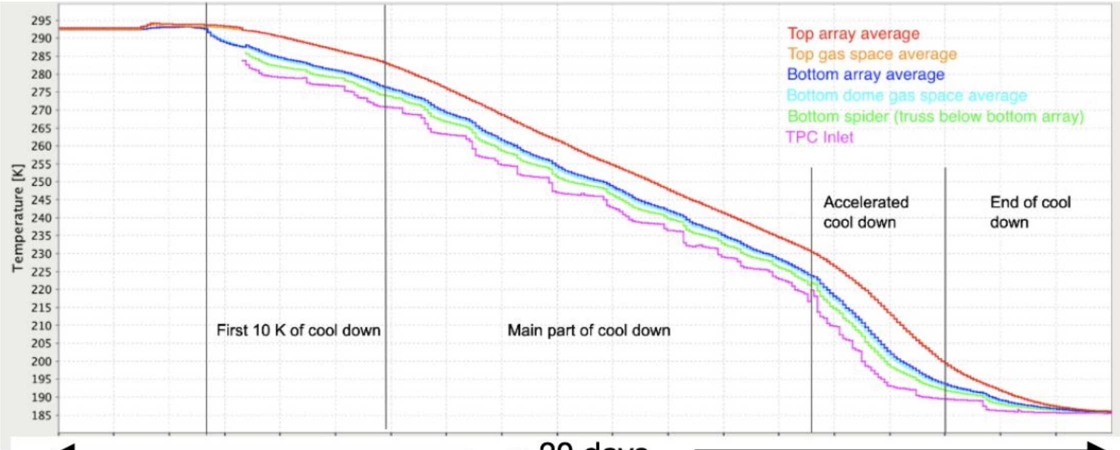
Circulation compressors (gas)



LZ circulation system

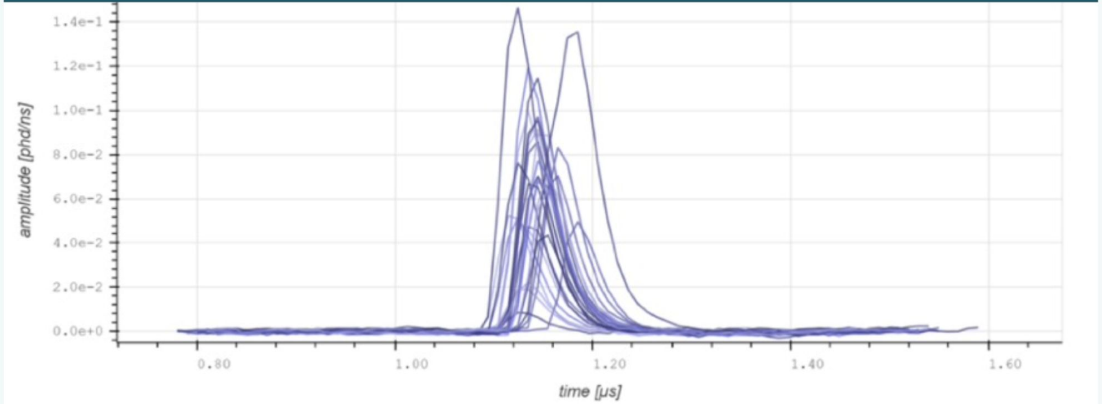
Commissioning is underway!

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



~ 20 days

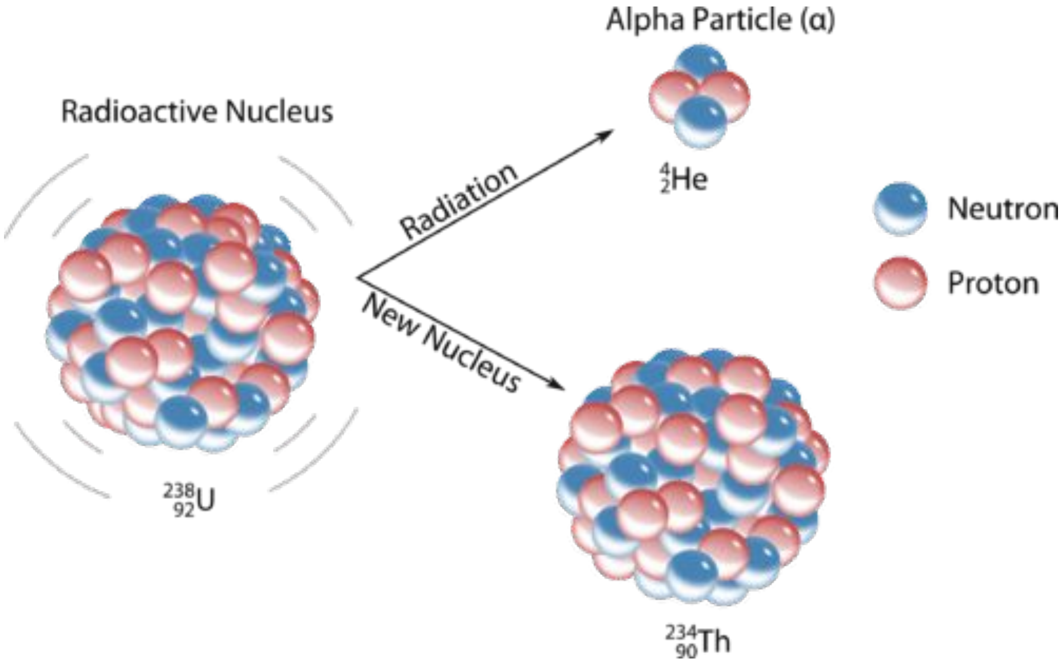
PMT calibrations with LED light

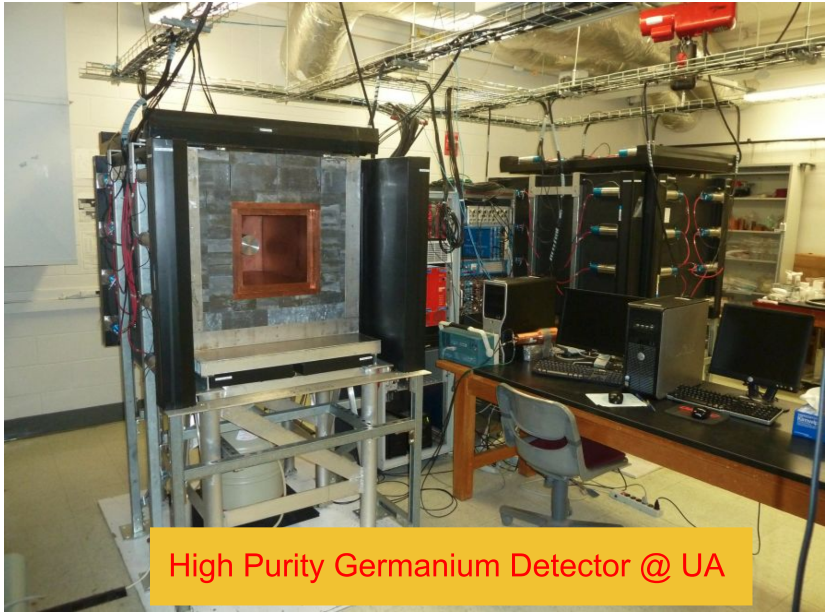


Detector Physics

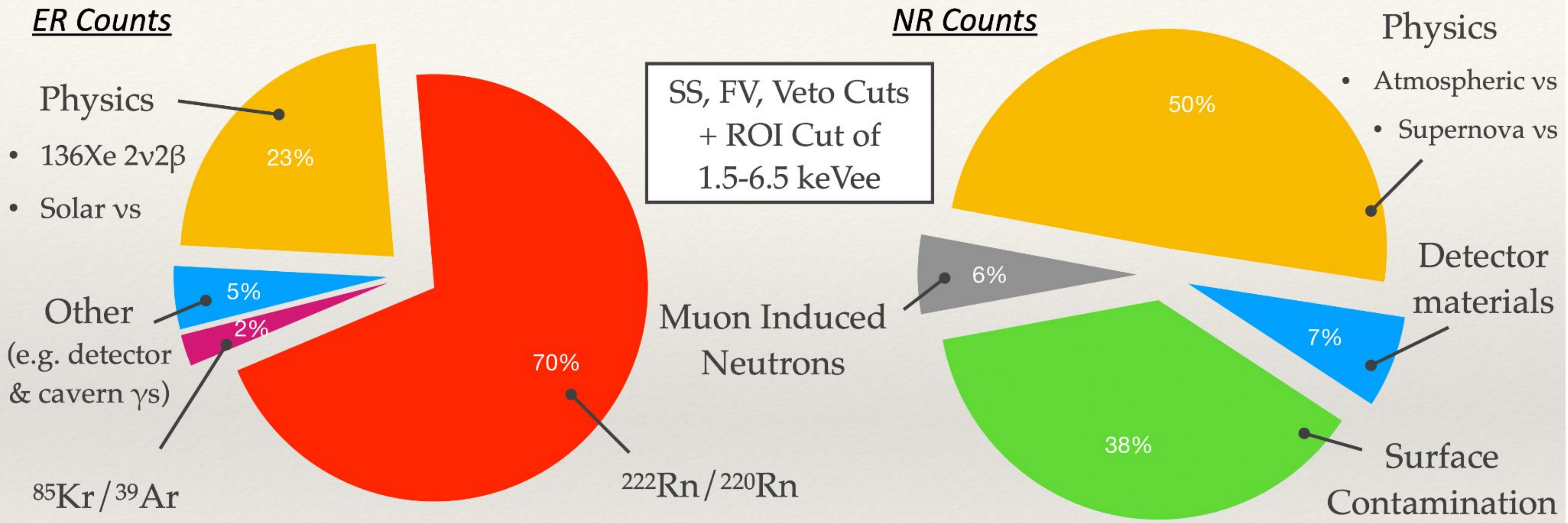
- Cosmological background
  - Rock gamma
  - Neutrino events
- Internal background
  - Charcoal chromatography to remove ^{85}Kr and ^{39}Ar
  - Every detector components has been screened thoroughly
  - Rn emanation screen campaign
    - Four Rn screening site
    - Target Rn activity = 2 μBq/kg.
    - 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 2νββ	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**



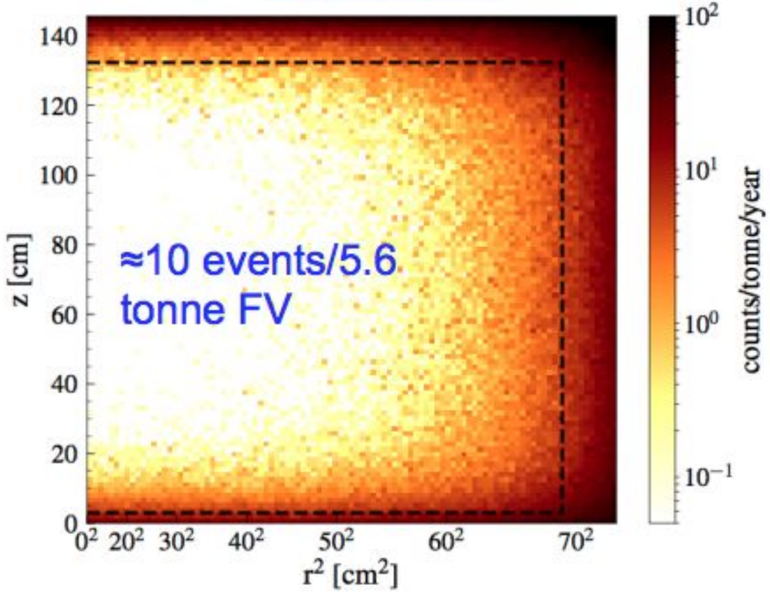


- U/Th radioactive isotopes in the detector materials.
- For successful DM detection, we need to reduce the radioactivity down to μBq/kg level (Banana ~ 140 Bq/kg, 10^{-7} Banana!).
- Every component in detector undergoes careful screening to quantify the radioactivity.
- Radioassay is crucial for future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

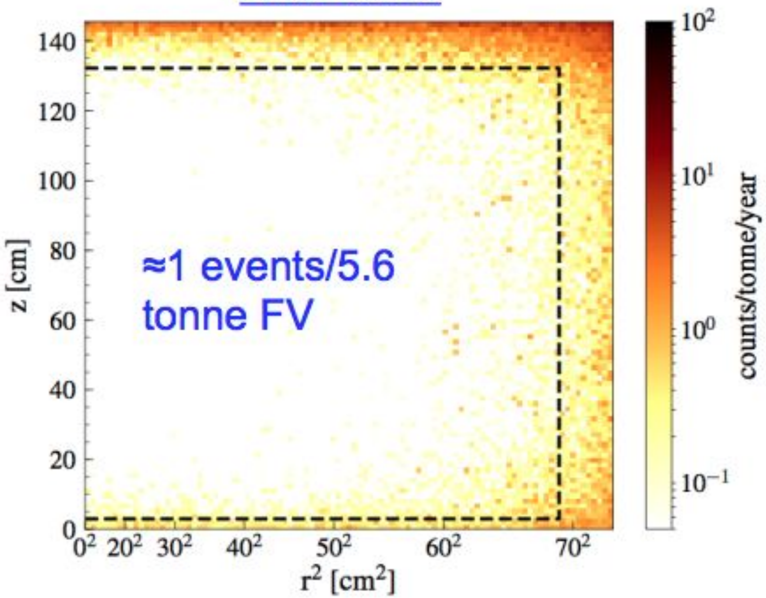


Source	ER [cts]	NR [cts]
Total	1131	1.03
+ 99.5% ER discrimination, 50% NR efficiency	**5.66**	**0.52**

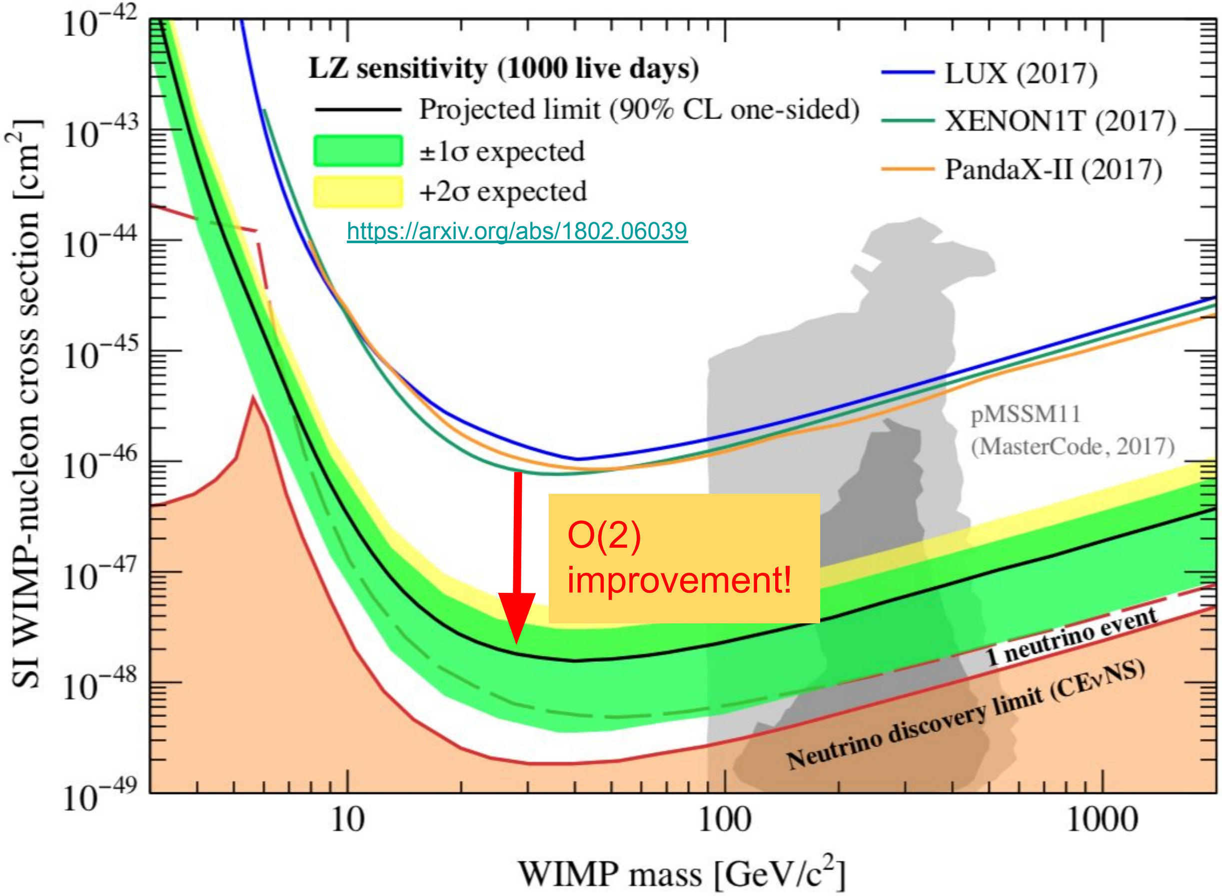
Before vetos



After vetos

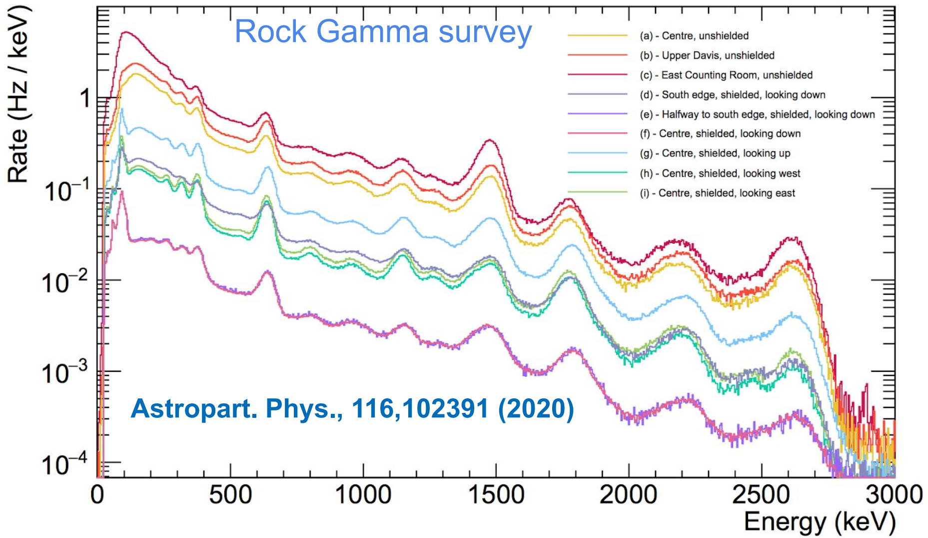


- WIMP-like nuclear recoil backgrounds in 6-30 keV region of interest.
- Fiducial would be reduced from 5.6 to 3.2 tonnes without outer detector.

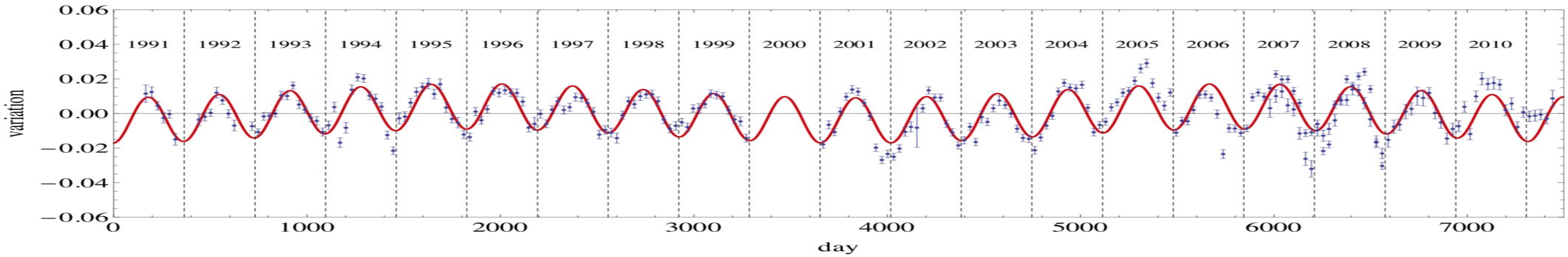


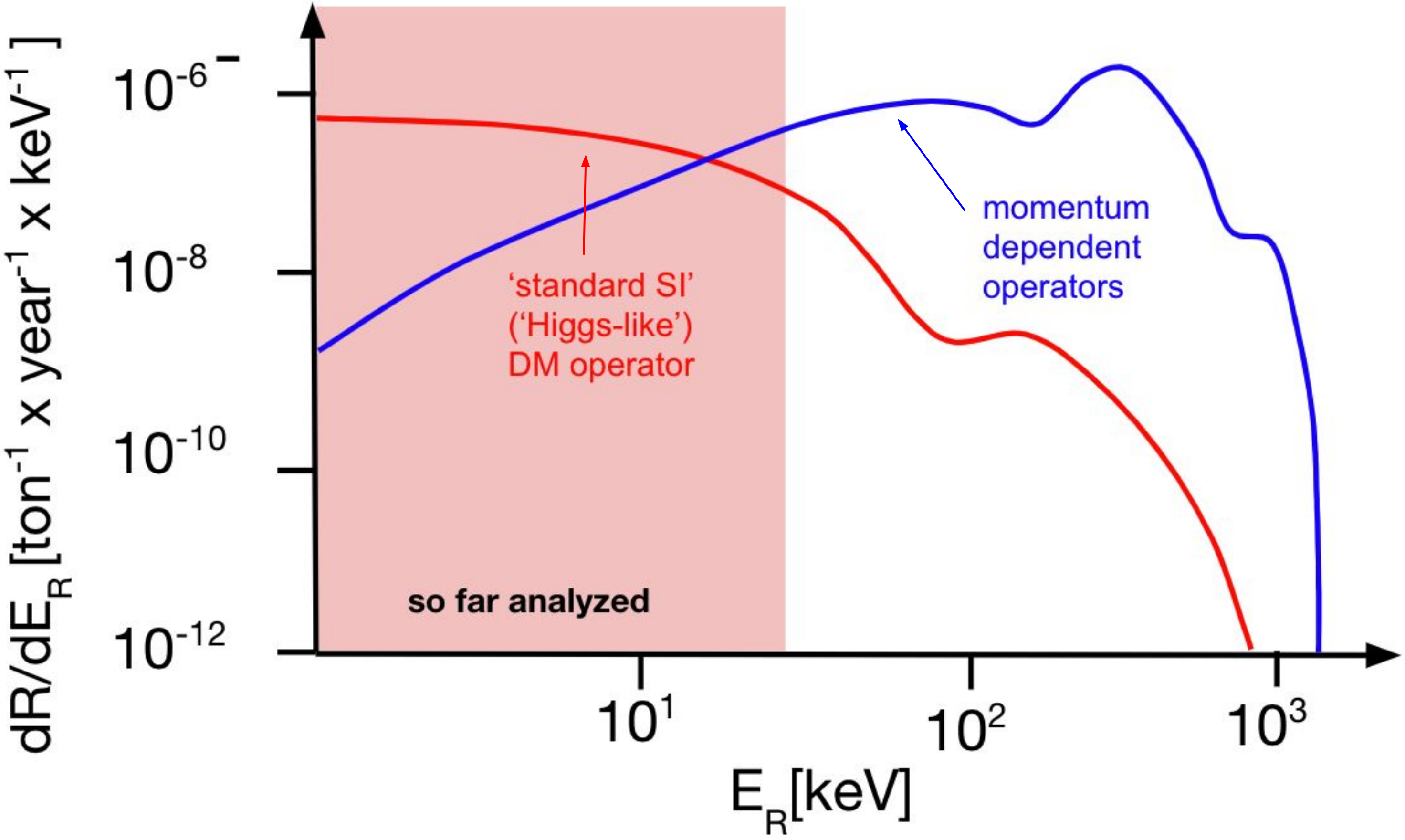
OD is necessity to discover WIMPs!

- 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

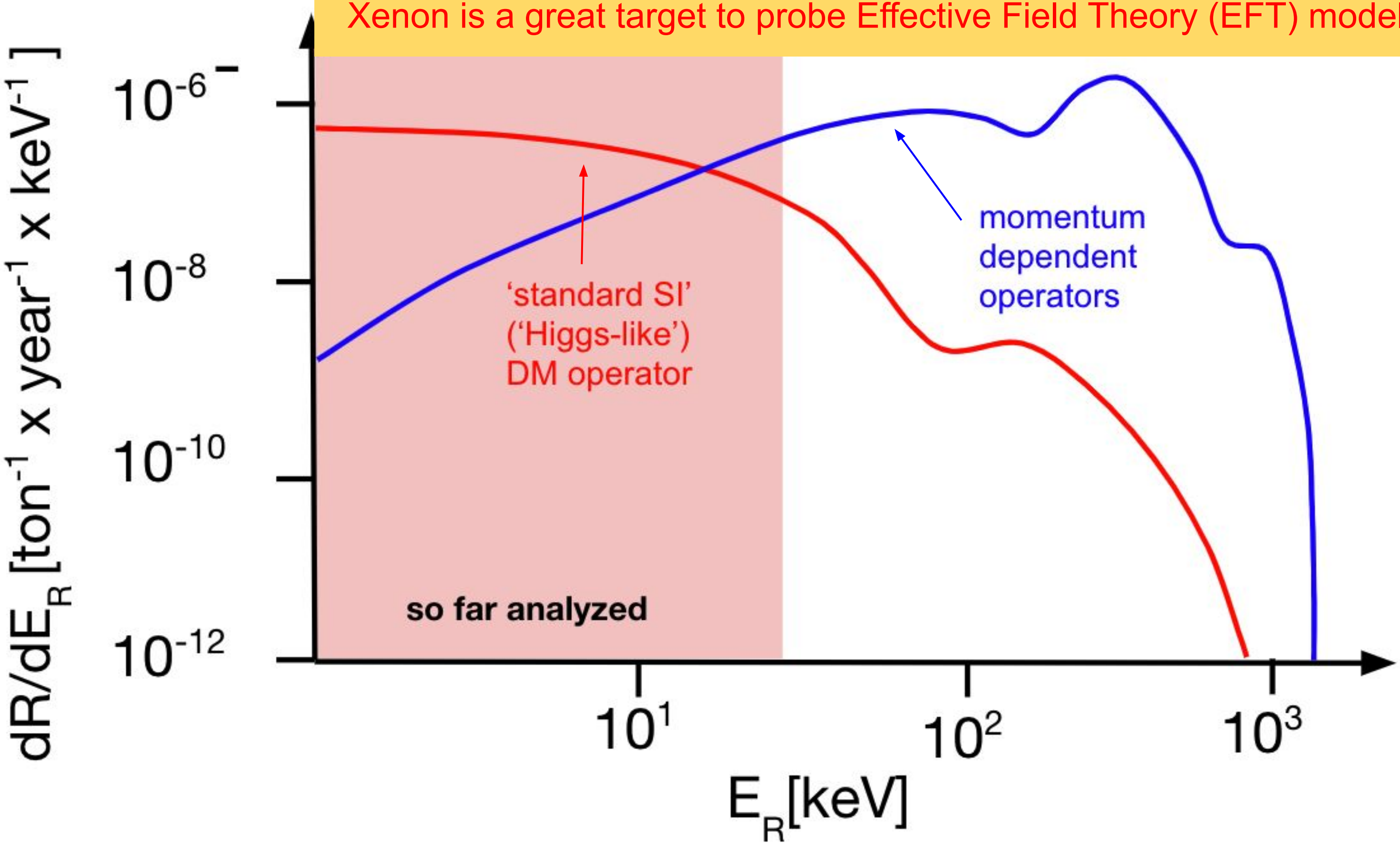


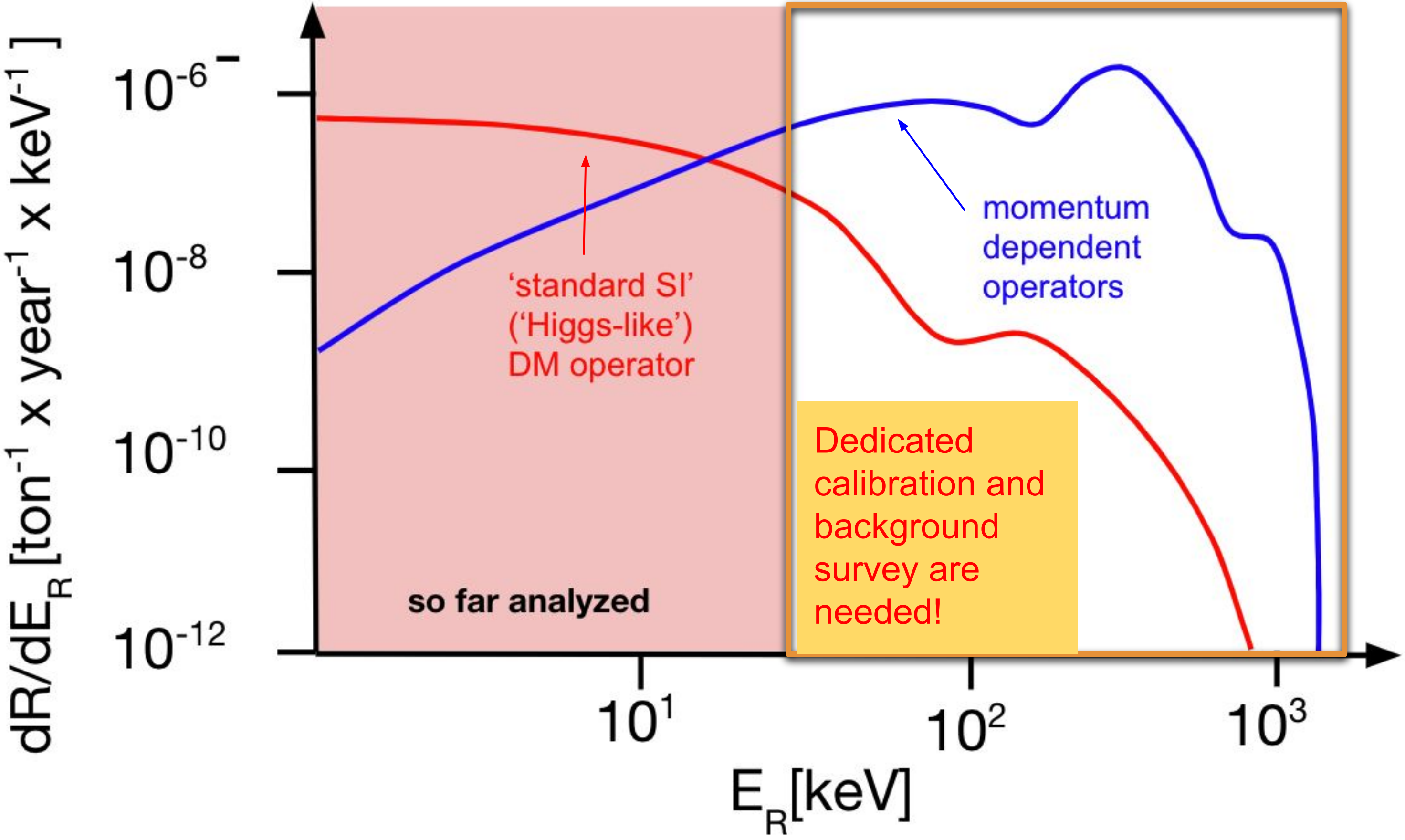
Combined LVD,MACRO and Borexino data over 20 years
arXiv:1204.5180




dR/dE_R [ton^-1 x year^-1 x keV^-1]
10^-6
10^-8
10^-10
10^-12
'standard SI'
('Higgs-like')
DM operator
momentum
dependent
operators
so far analyzed
10^1
10^2
10^3
E_R[keV]

Xenon is a great target to probe Effective Field Theory (EFT) models!

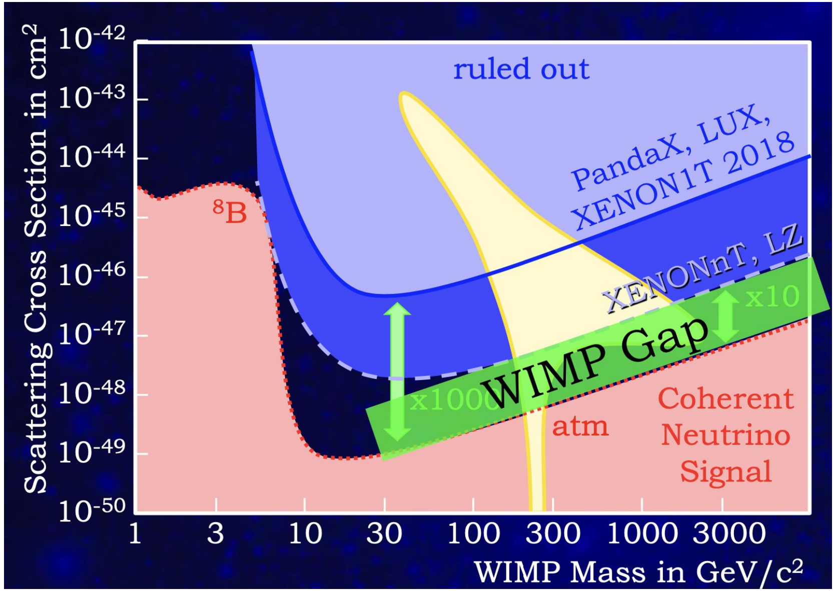




10^{-6}
10^{-8}
10^{-10}
10^{-12}
dR/dE_R [ton^{-1} x year^{-1} x keV^{-1}]
'standard SI'
('Higgs-like')
DM operator
momentum
dependent
operators
so far analyzed
Dedicated
calibration and
background
survey are
needed!
10^1
10^2
10^3
E_R[keV]

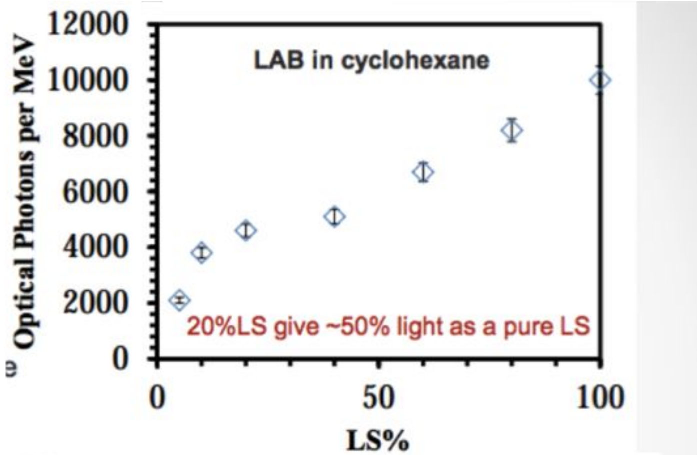
Future Detector Development

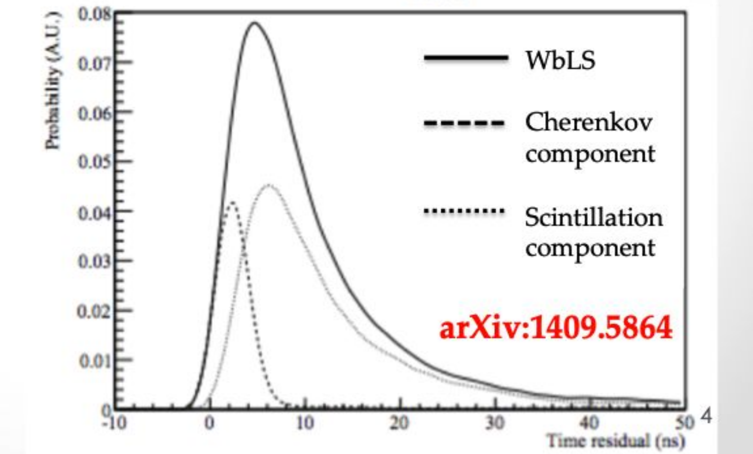
- To expand searches in the parameter space
  - Need next Gen detector to reach neutrino floor
- Plan to play a leading role in the next Gen DM detector R&D
  - Veto detectors
    - Active shielding is essential for modern experimental particle physics (e.g. DM, neutrino)
    - Study the LS doped acrylic 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

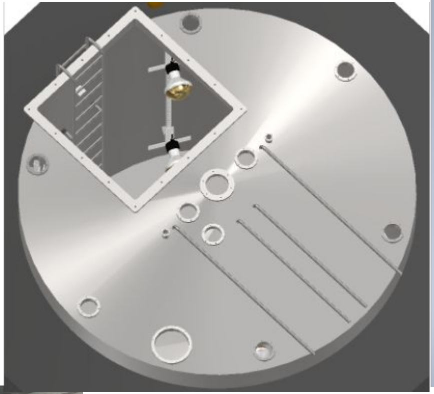


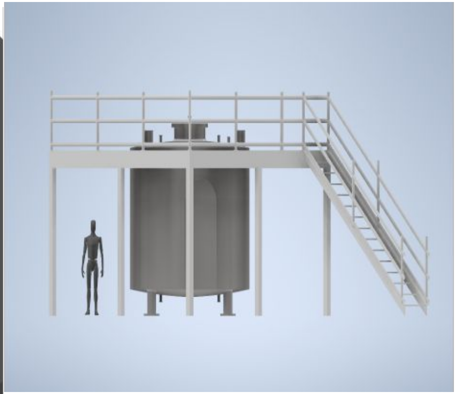


- Active shielding is essential for DM detector
  - Handling of liquid and safety is not trivial
- With doping LS and different type of heavy metal (Gd, Pb, etc), it can achieve to stop different background particles
  - Machinability stronger than other plastics scintillators (e.g. BC-400);
  - Multilayers 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!

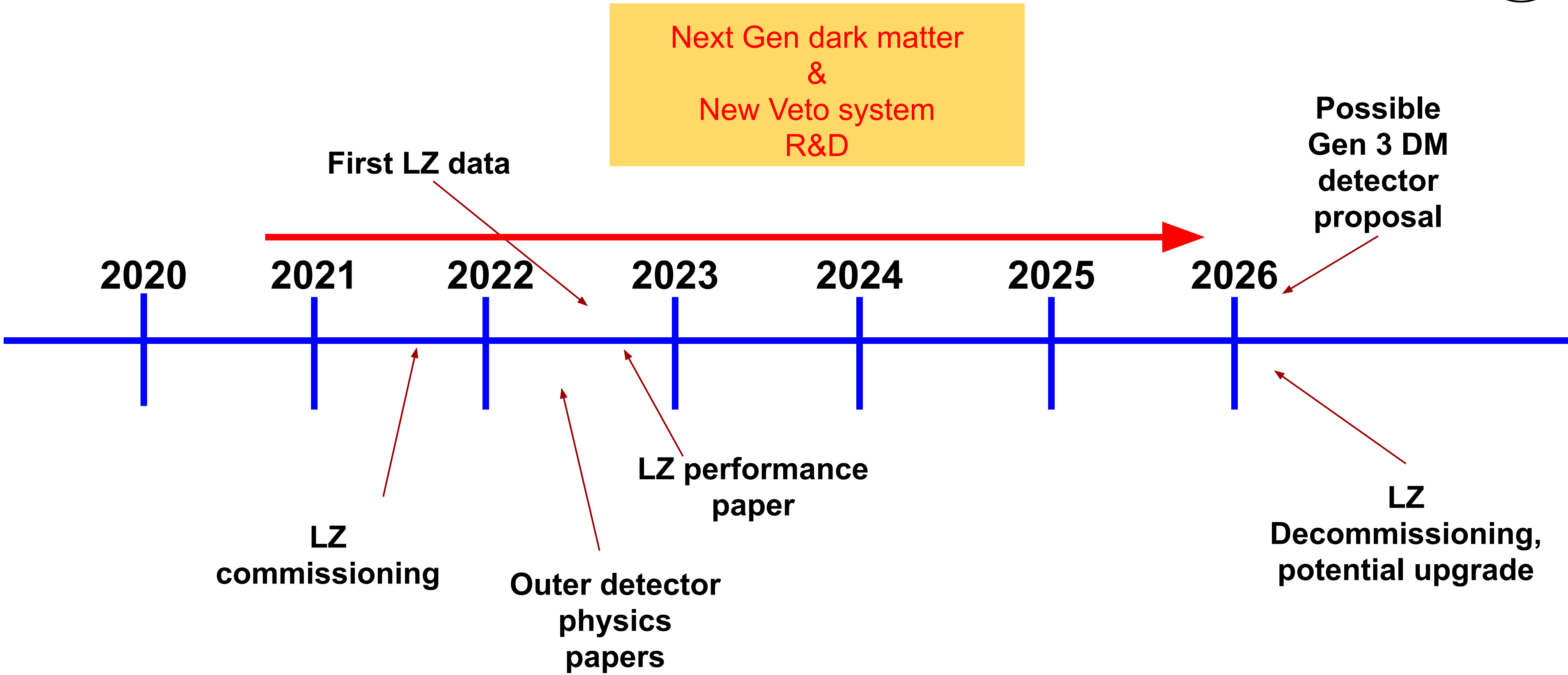
1-ton and 30-tonnes prototype

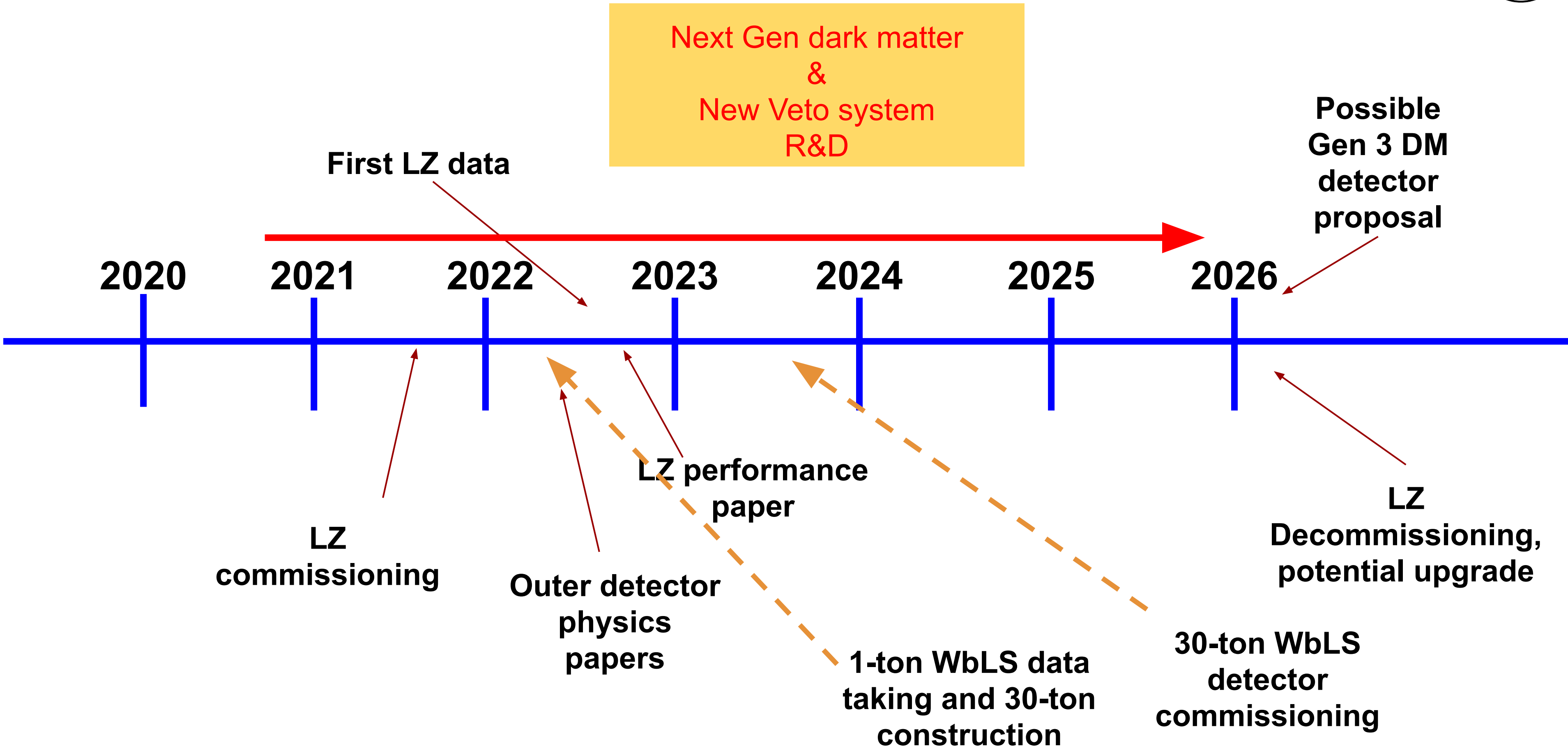
- Phase-I: excise WbLS in-situ deployment and circulation schemes
- Phase-II: WbLS performance, optical detector, and data analysis
- Fast turn-around operation using in-house resources in liquid production, QA/QC equipment, and existing mixing facility





- Simulation to define tank capacity (~ 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
First LZ data
Possible
Gen 3 DM
detector
proposal
2020
2021
2022
2023
2024
2025
2026
LZ performance
paper
LZ
commissioning
Outer detector
physics
papers
LZ
Decommissioning,
potential upgrade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physics
papers
LZ
Decommissioning,
potential upgrade
1-ton WbLS data
taking and 30-ton
construction
30-ton WbLS
detector
commissioning

- 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
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- University of Alabama
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- University of California Davis
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Stay Healthy

and Thank you !