The LZ Outer Detector

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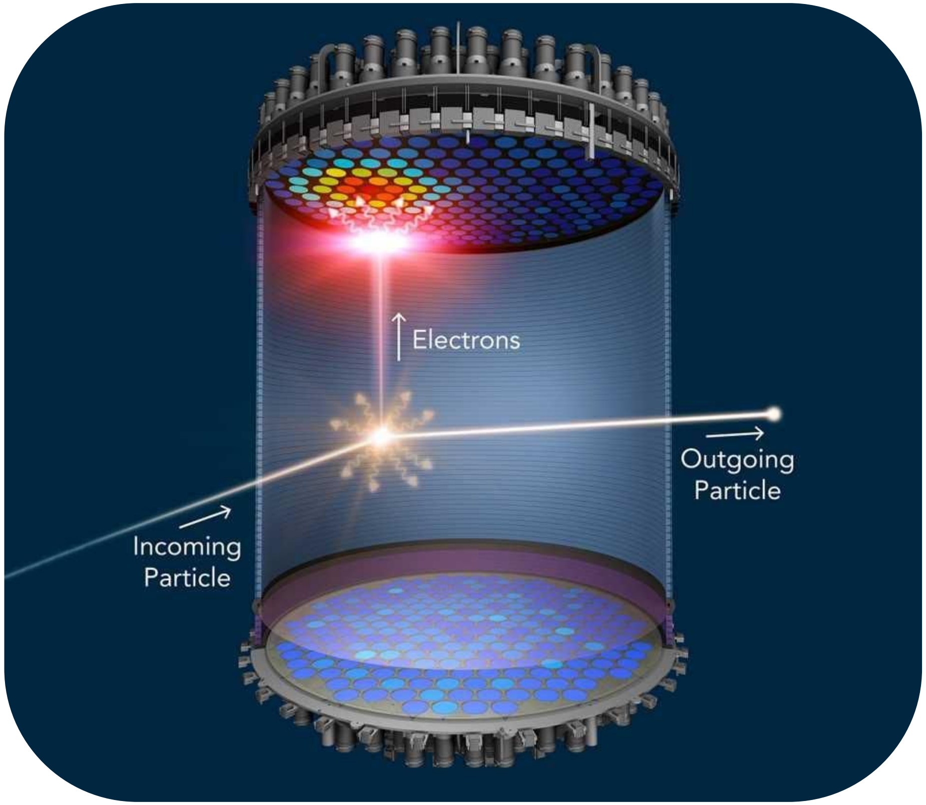
for the

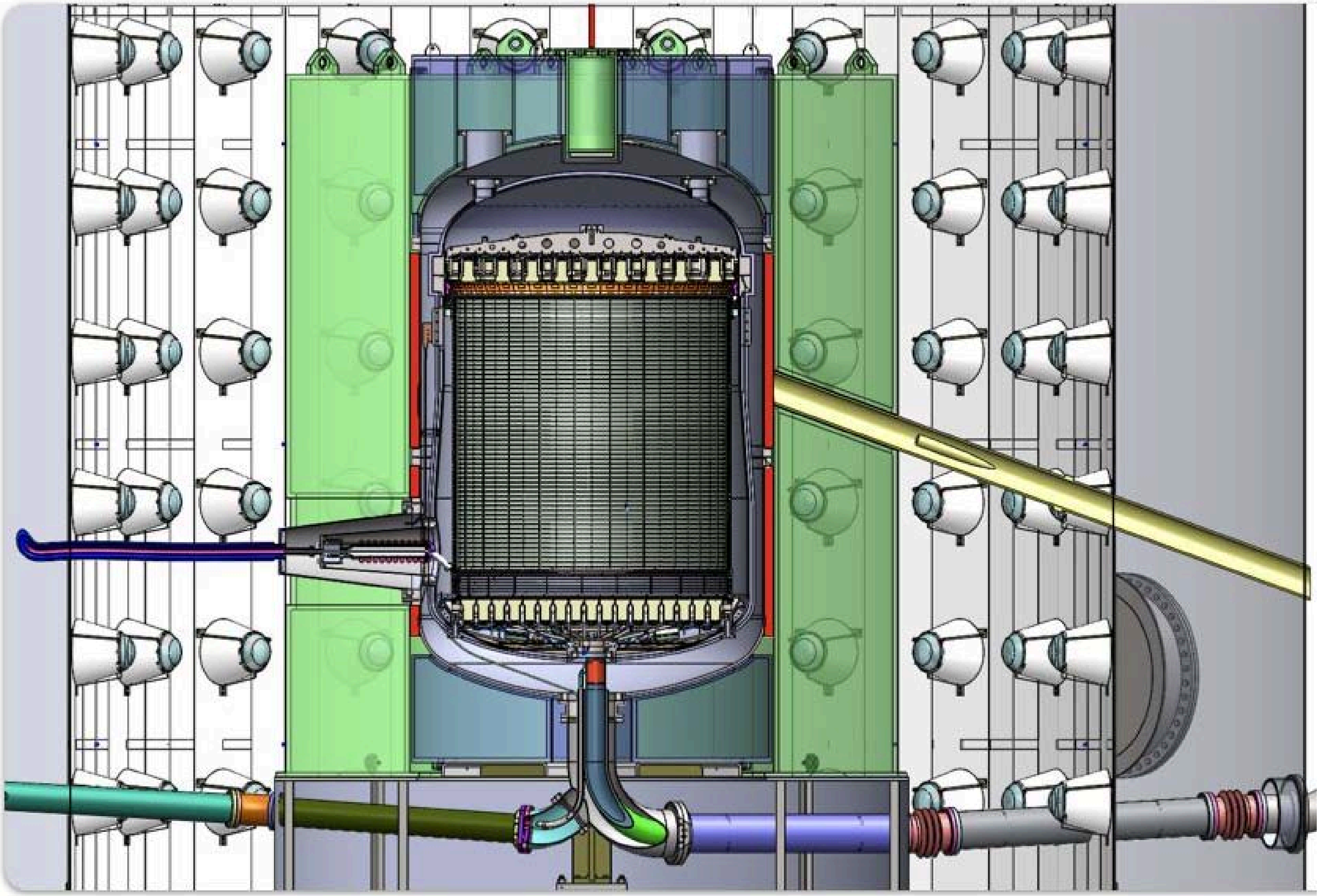
LUX-ZEPLIN Collaboration

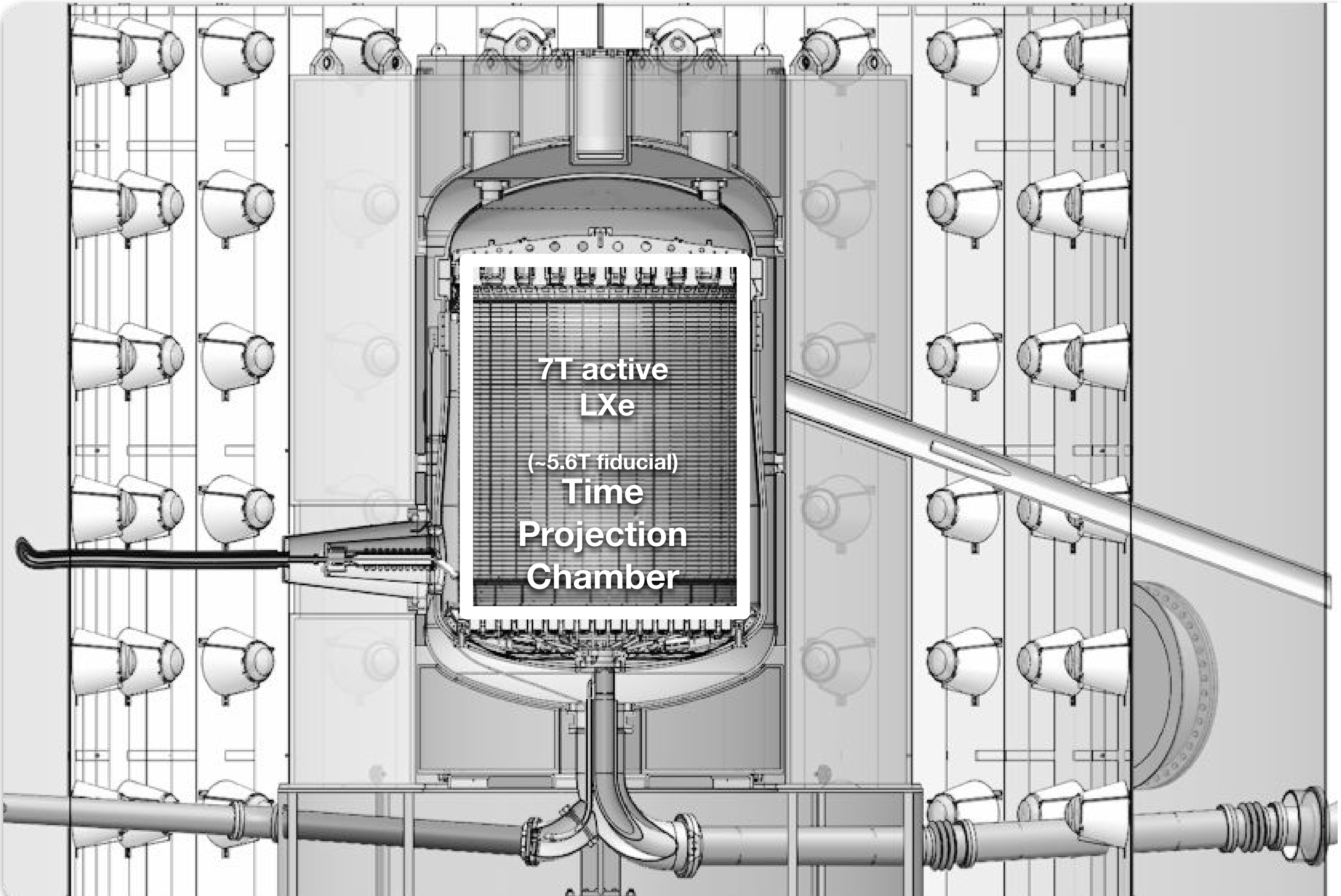
Motivation

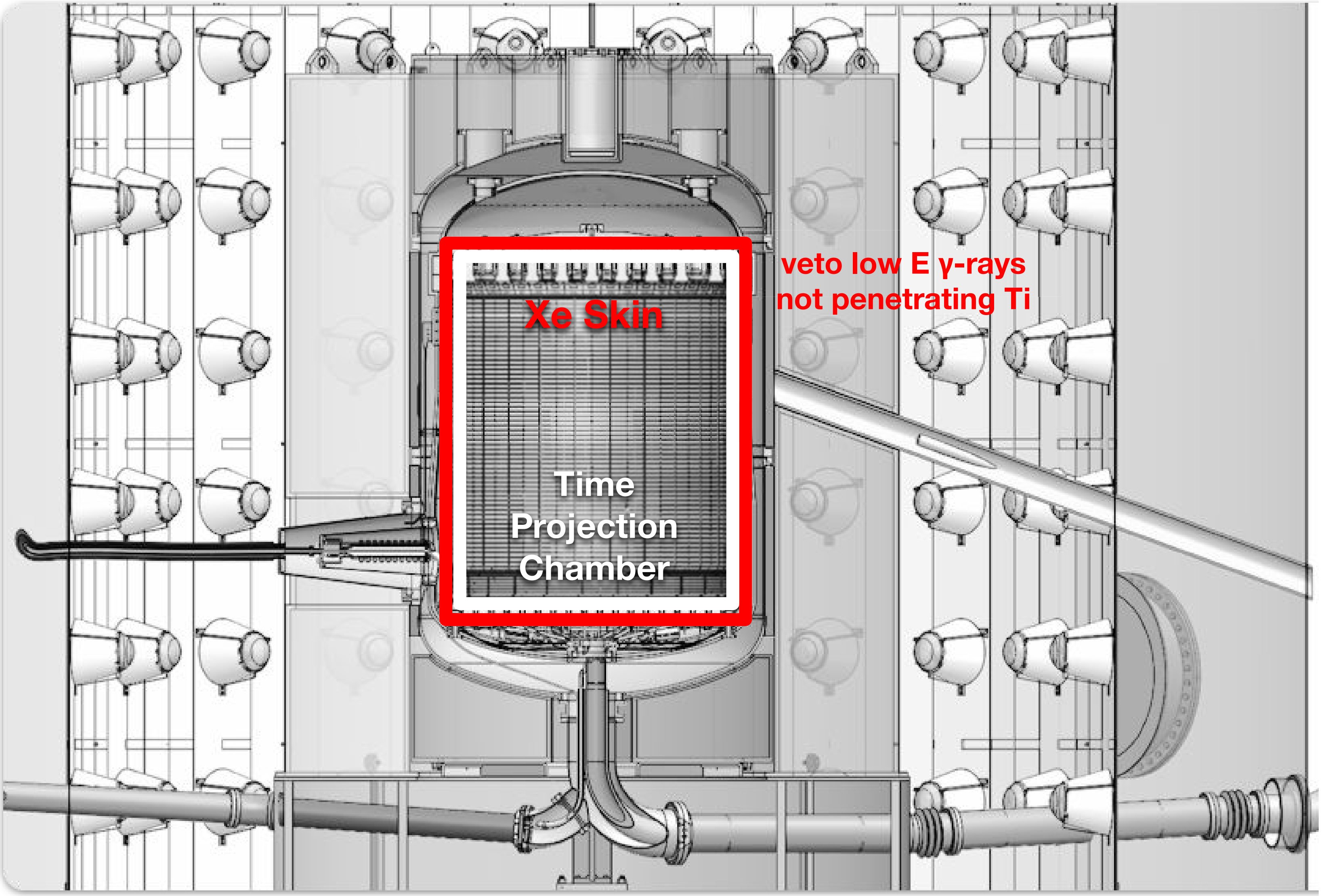
- A WIMP scattering in the central Xe of a noble liquid detector will not deposit energy in the surrounding materials
- Backgrounds induced by detector material and cosmic muons:
  - γ-ray scatters out of detector while inducing ER
  - neutron scatters out while inducing NR

  → need to detect escaping particle
- Surround central TPC with three active layers to reduce backgrounds:
  - Instrumented Xe 'skin' to veto γ-rays
  - 'Outer Detector' to veto neutrons
  - Water tank to enhance muons veto
- Veto detectors allow to
  - Increase the usable active (fiducial) volume by a significant fraction
  - In case of discovery to be able to demonstrate a possible DM signal is not induced by neutrons

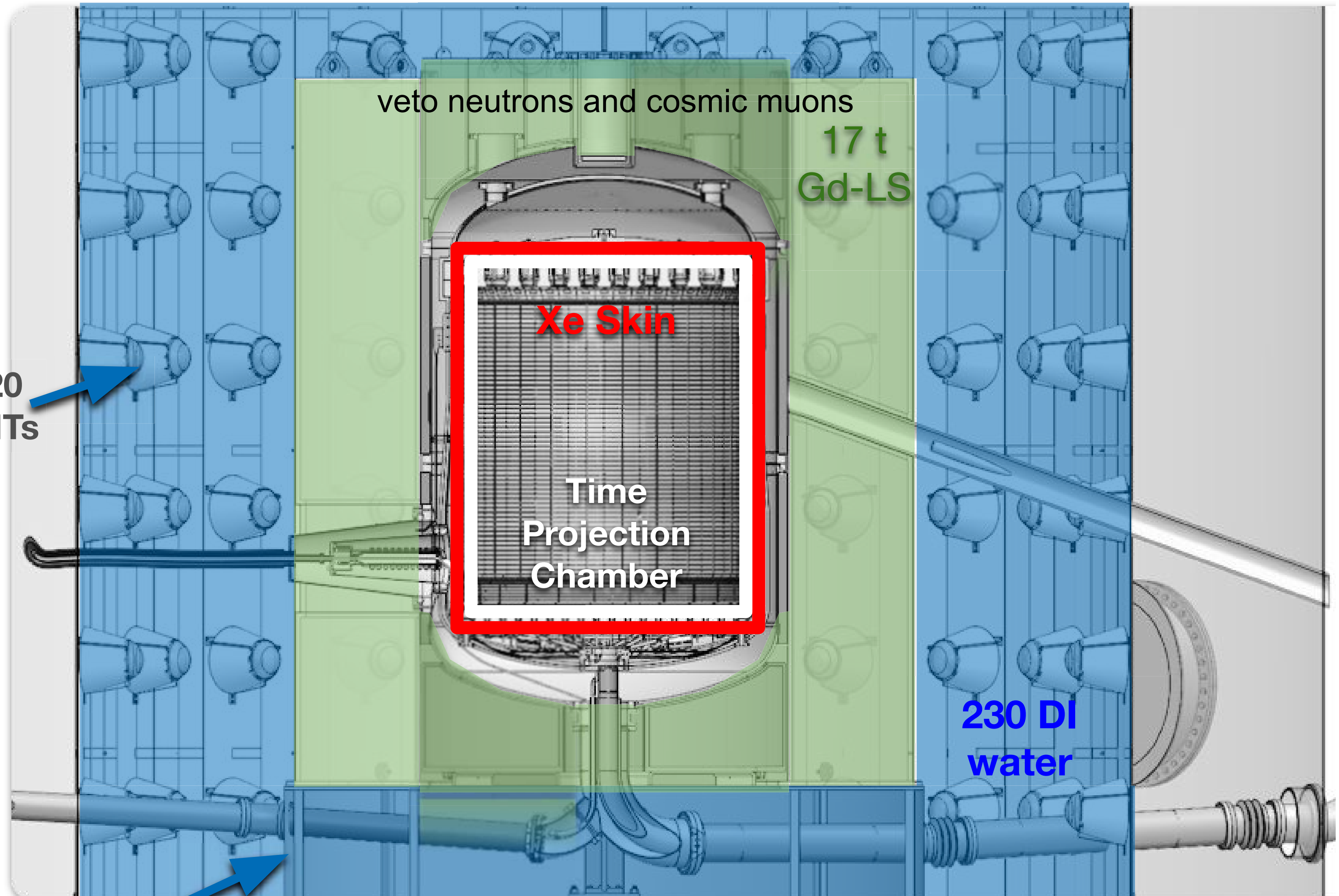





7T active
LXe
(~5.6T fiducial)
Time
Projection
Chamber

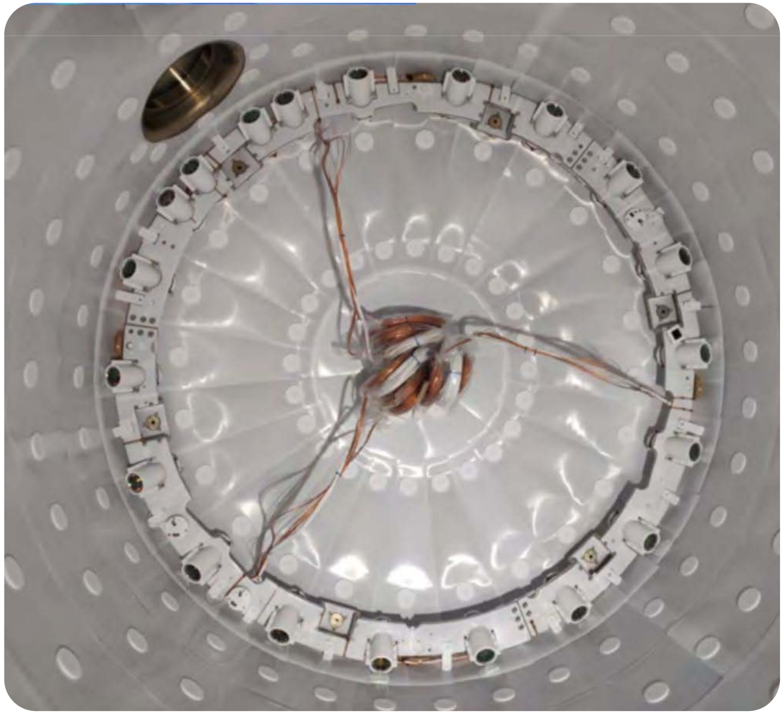

Xe Skin
Time Projection Chamber
veto low E γ-rays
not penetrating Ti

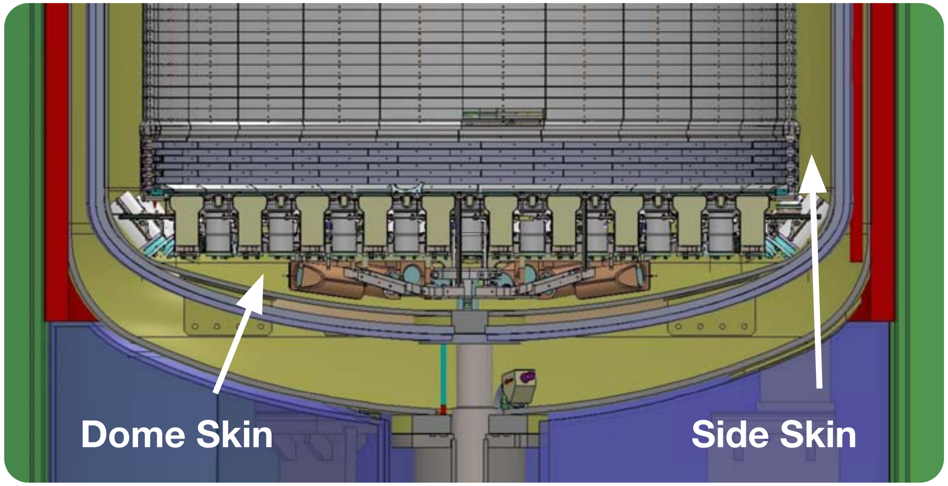
Gd-LS + DI Water



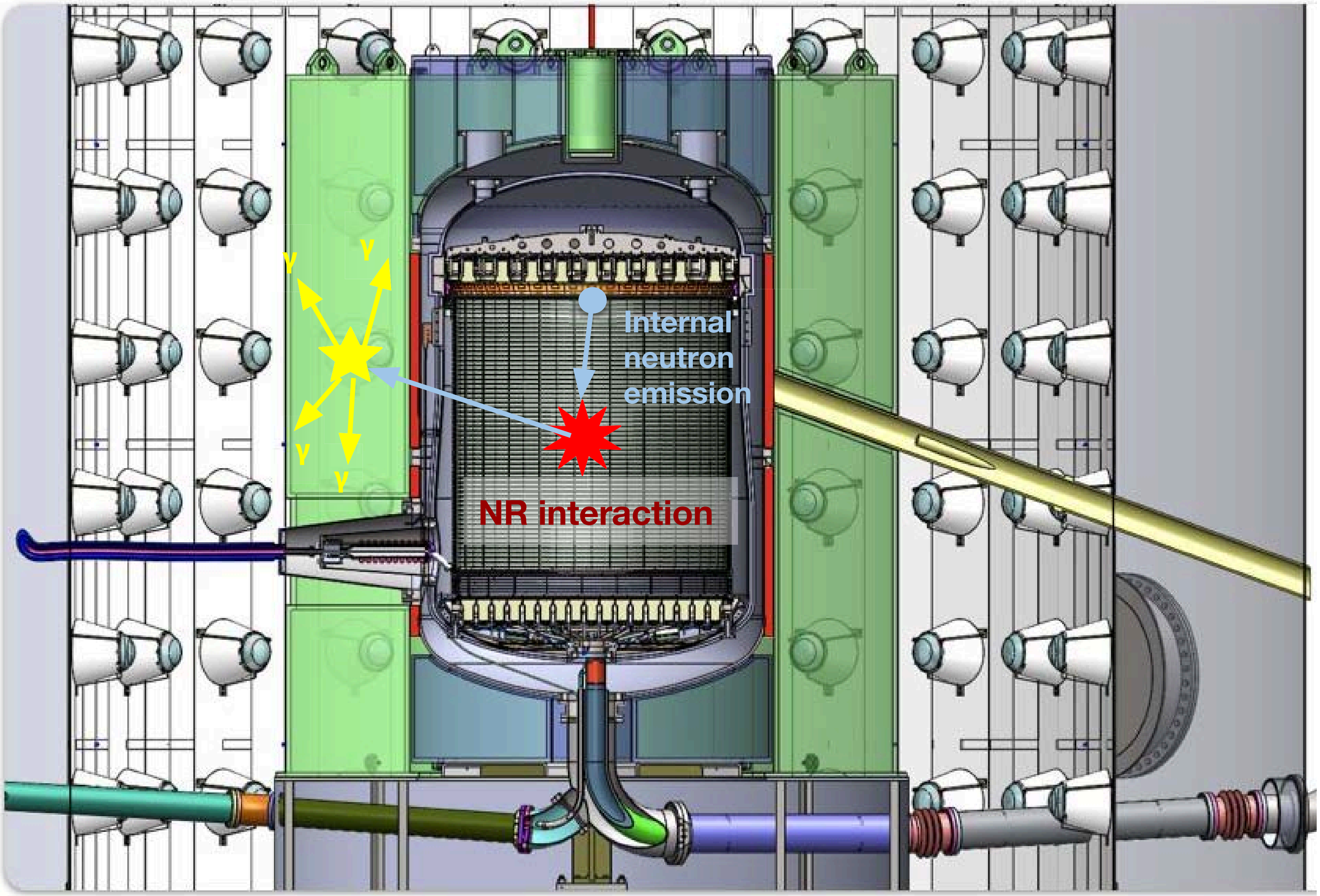
The Skin

- A 2 t layer of LXe (skin) between the TPC and the cryostat is needed because of HV stand-off, differential thermal expansion between Ti vessel and PTFE reflector and TPC geometry
- Skin region and dome is instrumented to veto Compton recoils of ~MeV radiogenic gammas

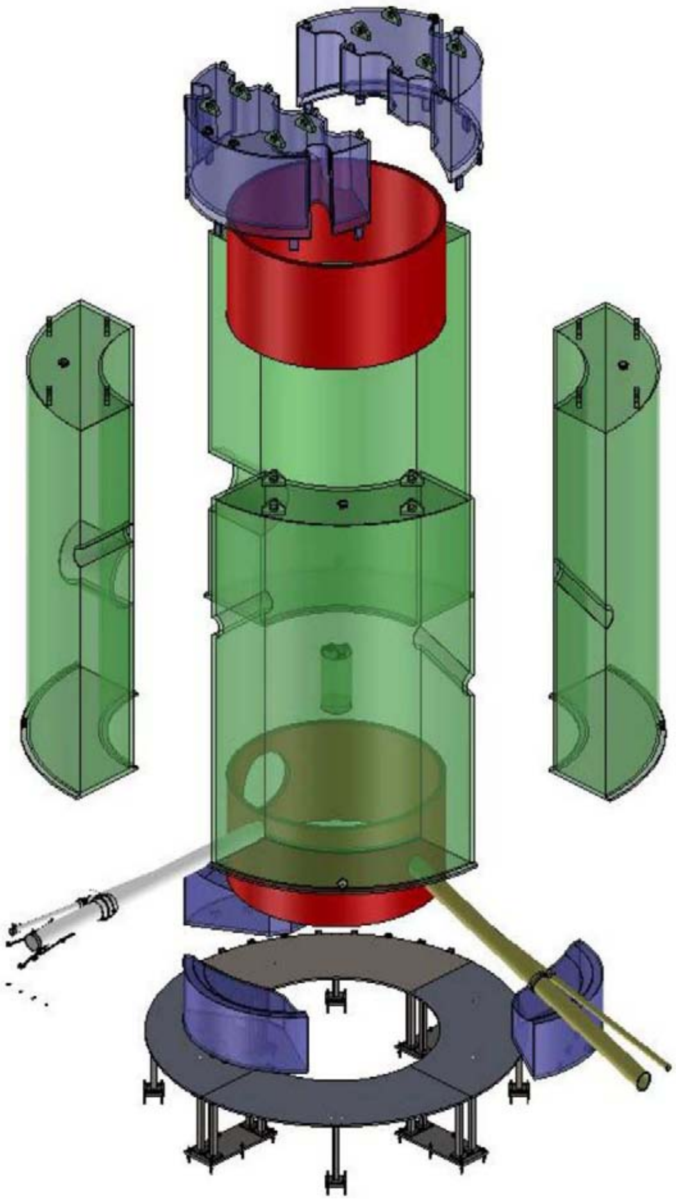




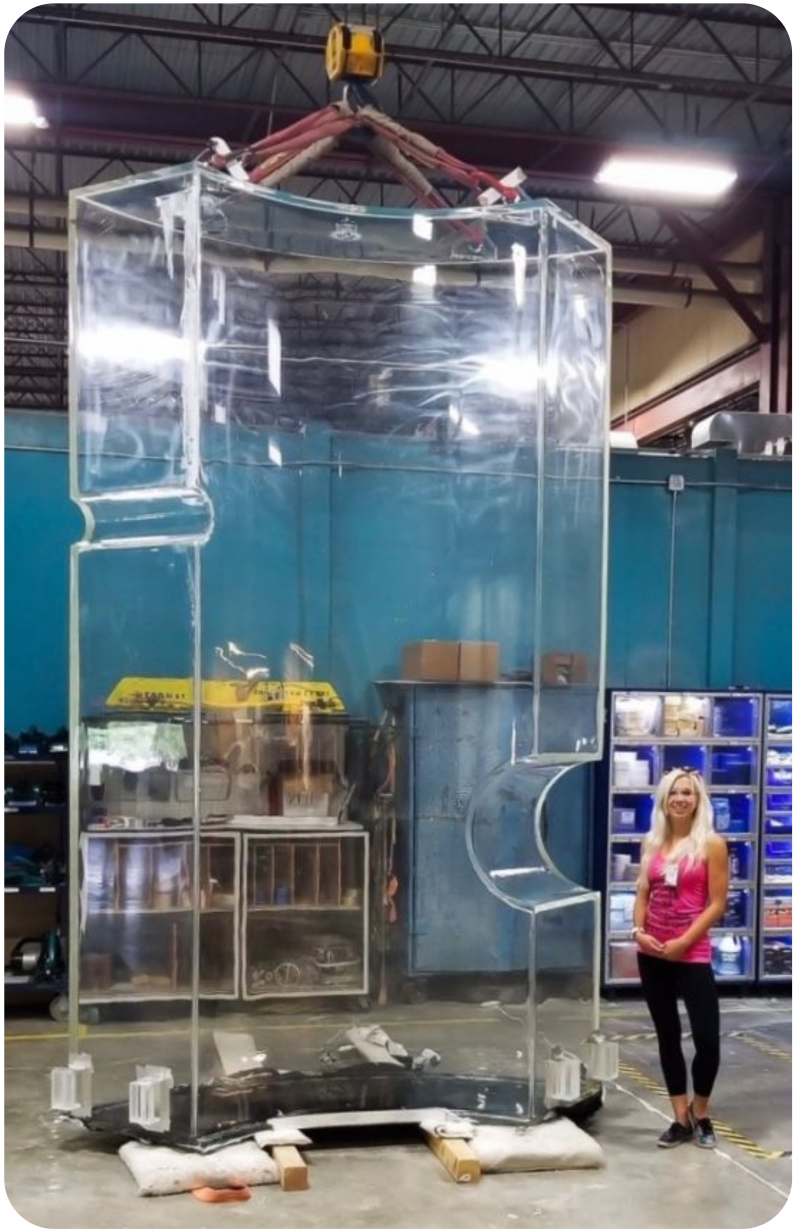
- PTFE attached to the inner cryostat wall and bottom dome enhance light collection efficiency
- The combination of skin and outer detector creates a highly efficient integrated veto system
- Skin complementary to the scintillator veto since low energy γ-rays don't penetrate gammas the titanium ICV/OCV


γ
γ
γ
γ
Internal
neutron
emission
NR interaction

The Outer Detector



- The Outer Detector (OD) surrounds the central cryostat hermetically, filled with 17 t of scintillator
  - Conceptually similar to Daya Bay
- Liquid scintillator is doped with 0.1% Gd (Gd-LS) and held in large acrylic vessels
- Manufactured from UV transparent acrylic by Reynolds Polymer



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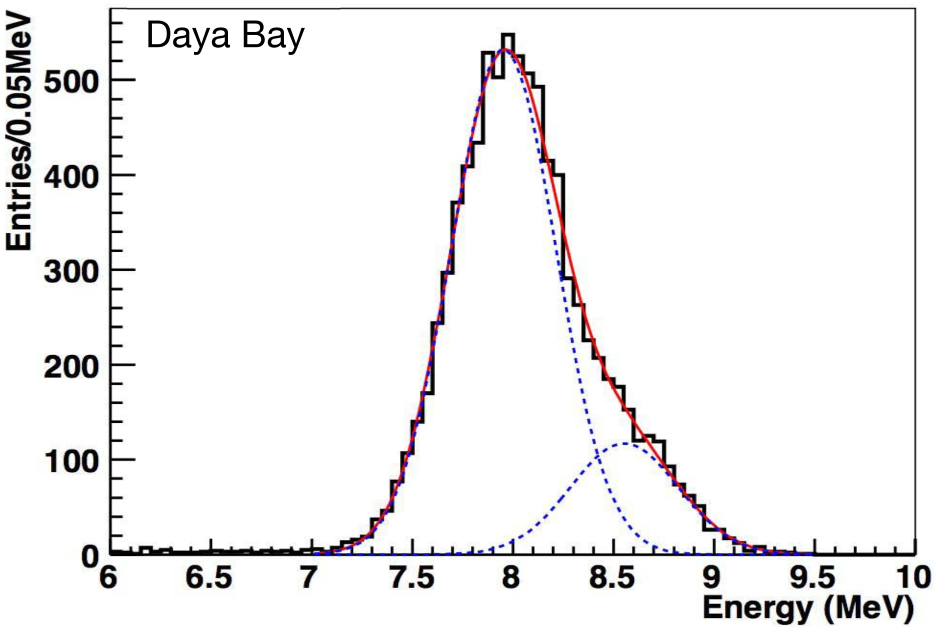
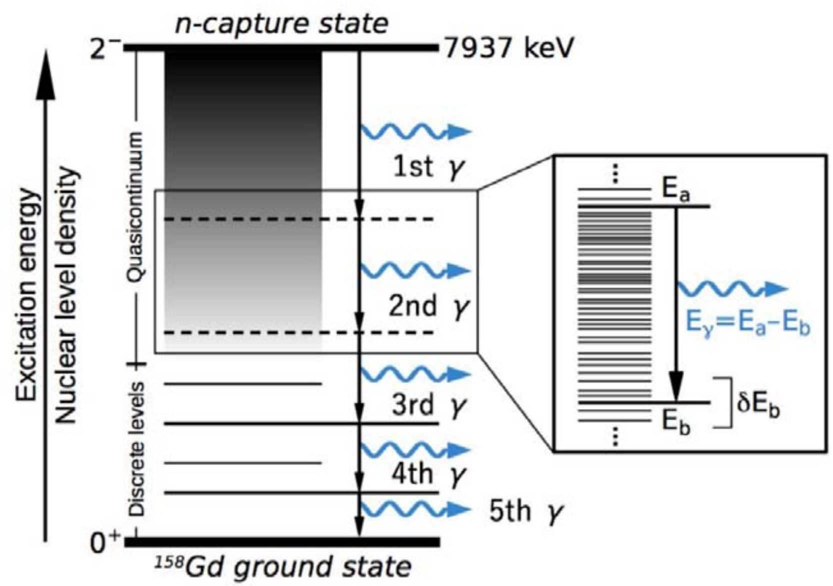
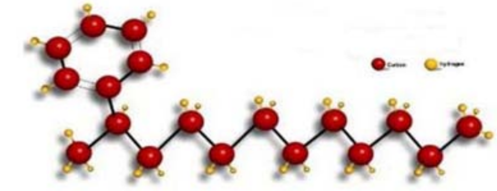
Neutron Capture on Gd

- Gd has largest thermal neutron cross section of all stable elements: σ_N=240kb (Xe σ_N=0.2b)
  - Doping with 0.1 % Gd reduces mean capture time to ≈30 μs from about ≈200 μs w/o Gd, thus reducing dead time
  - N capture followed by emission of about 3-5 gammas with about 8 MeV total energy:
    - n + ^{155}Gd → ^{156}Gd + 8.5 MeV (18%)
    - n + ^{157}Gd → ^{158}Gd + 7.9 MeV (82%)
- Probability to miss all γ's is much lower than detecting the single 2.2 MeV γ from hydrogen capture
- Gamma emission tails of O(100 μs), driving requirements on radioacity and impurity





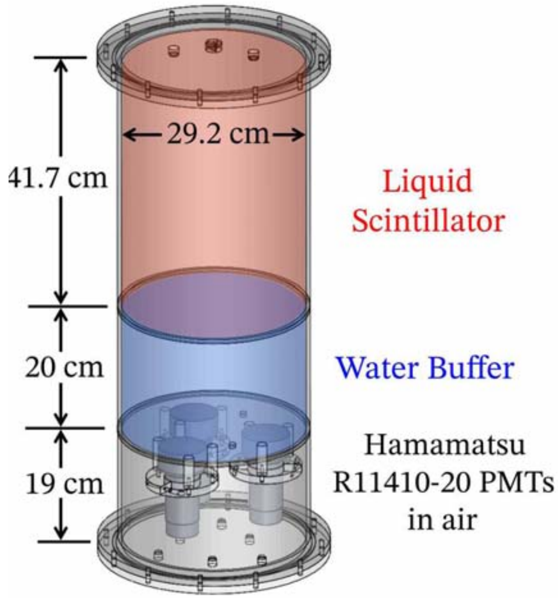


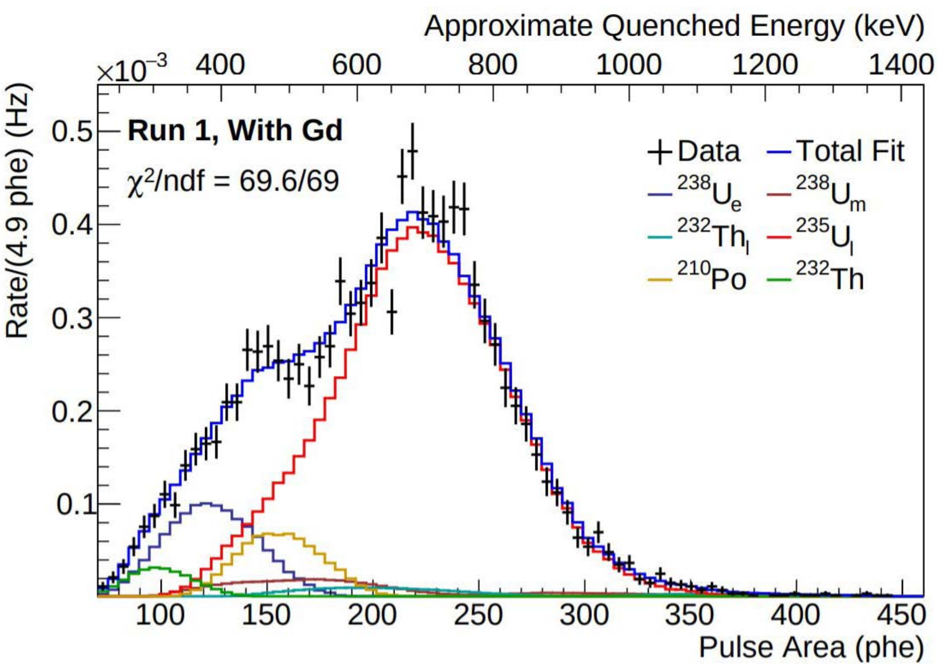
$(C_6H_6)-C_{(10-15)}H_{(22-32)}$

- Scintillator is Linear Alkyl Benzene
  - Not flammable, merely combustible
  - Comparable to vegetable oil, safe underground
- 17.5 tonnes of Gd-LS produced at Brookhaven Natl. Lab.
- In direct DM detection the radiopurity of the Gd is of great concern
  - Neutrino experiments benefit from larger fluxes and higher energy thresholds.
  - Special attention to purification and radio-assay of Gd-LS at ~mHz using the 'screener'

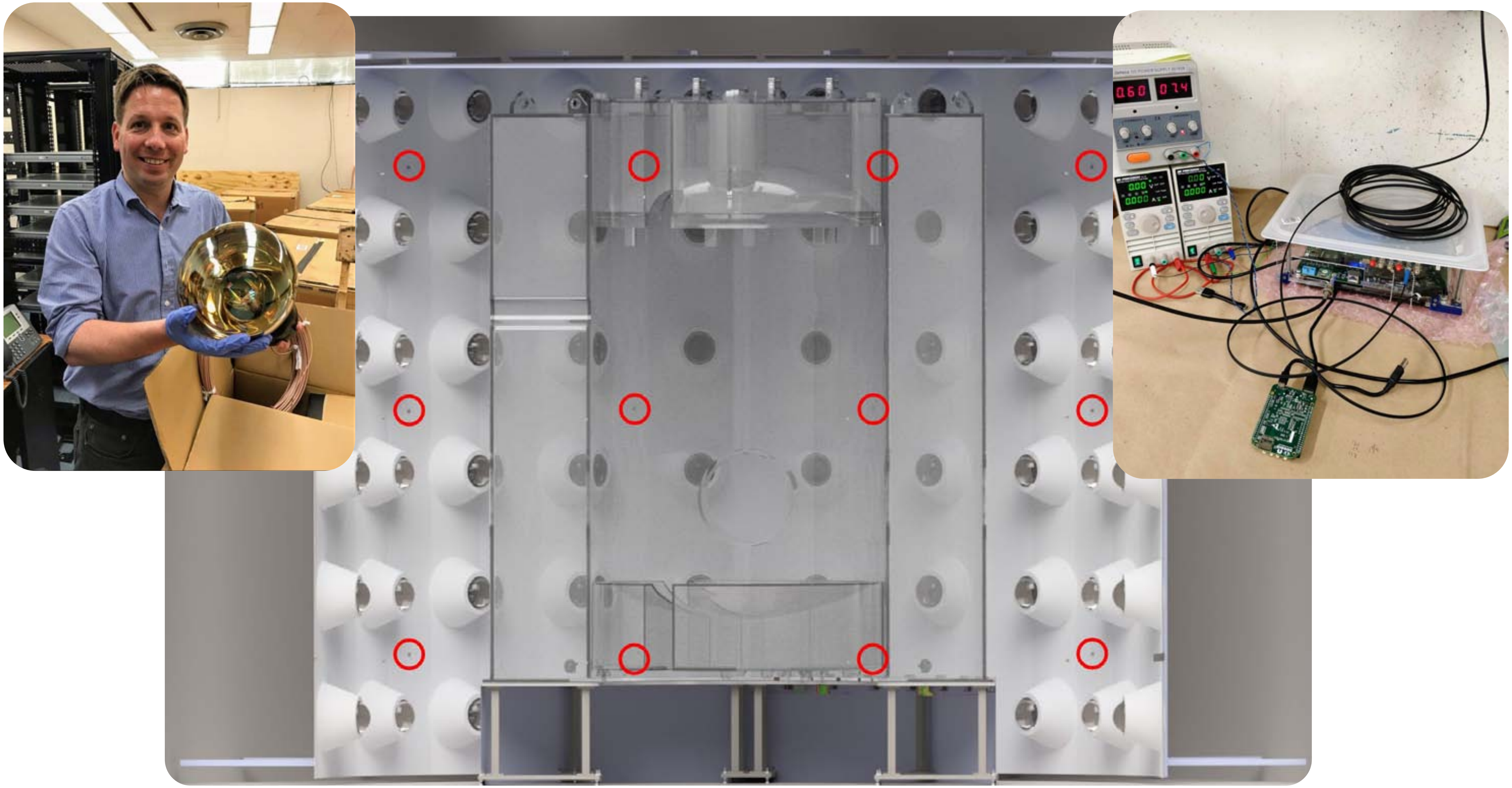
arXiv:1808.05595

- Screener: small acrylic detector (1/1000 of mass of LZ OD) operated in water tank in Davis Cavern under strict radiopurity requirements
- Used to study LS loaded with Gd and w/o, sources for calibration and PSD for particle identification
- Achieved 10^{-4} mBq/kg sensitivity to impurities in Gd

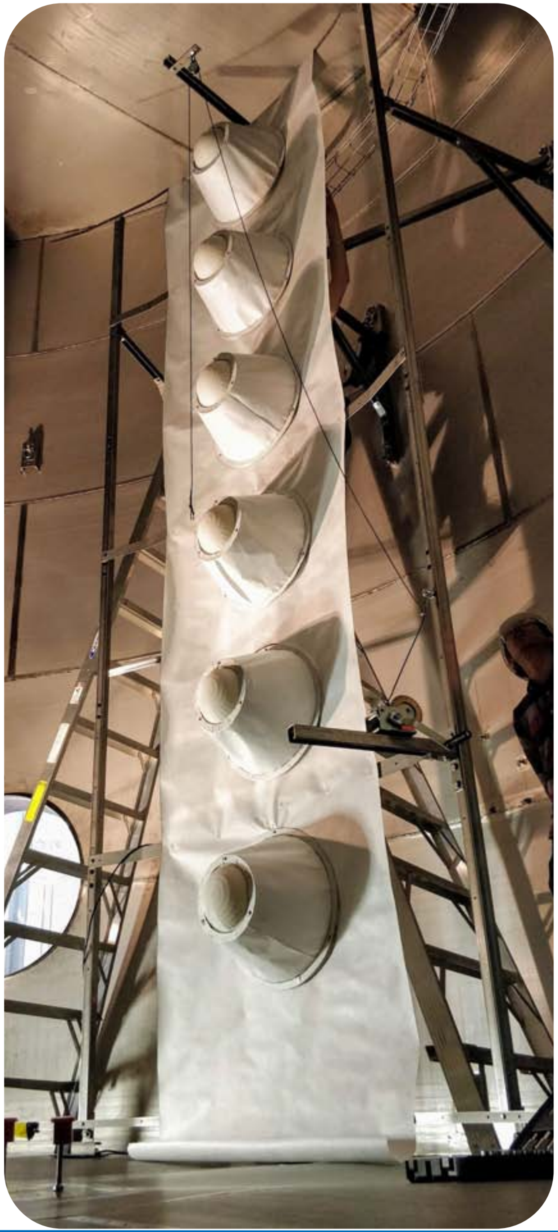


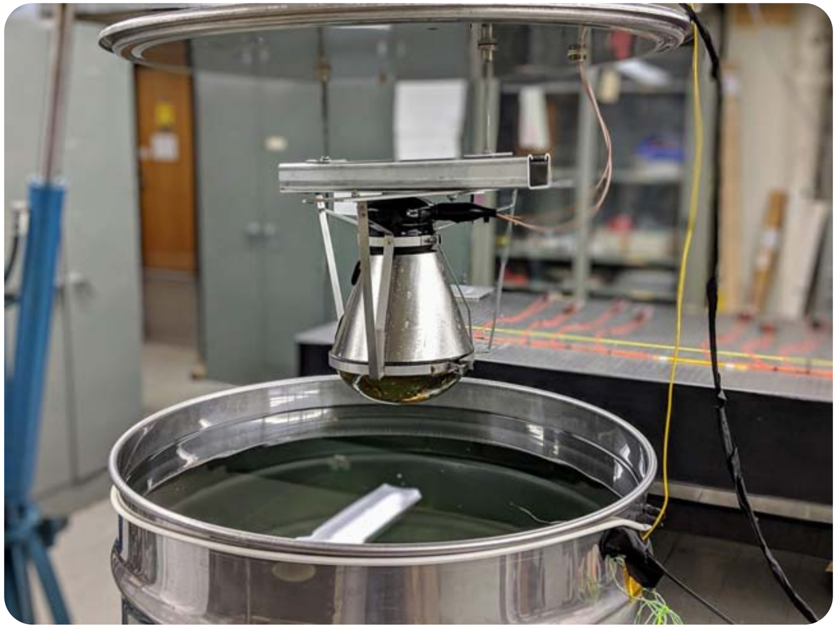


- Measured ratio $^{14}C/^{12}C = 2.83 \pm 0.07 * 10^{-17}$, comparable to two order or magnitude larger detectors
- Lead to improvements in GdLS production to lower backgrounds
- Also useful to evaluate properties of Gd-LS, background fluxes and to gain operational experience

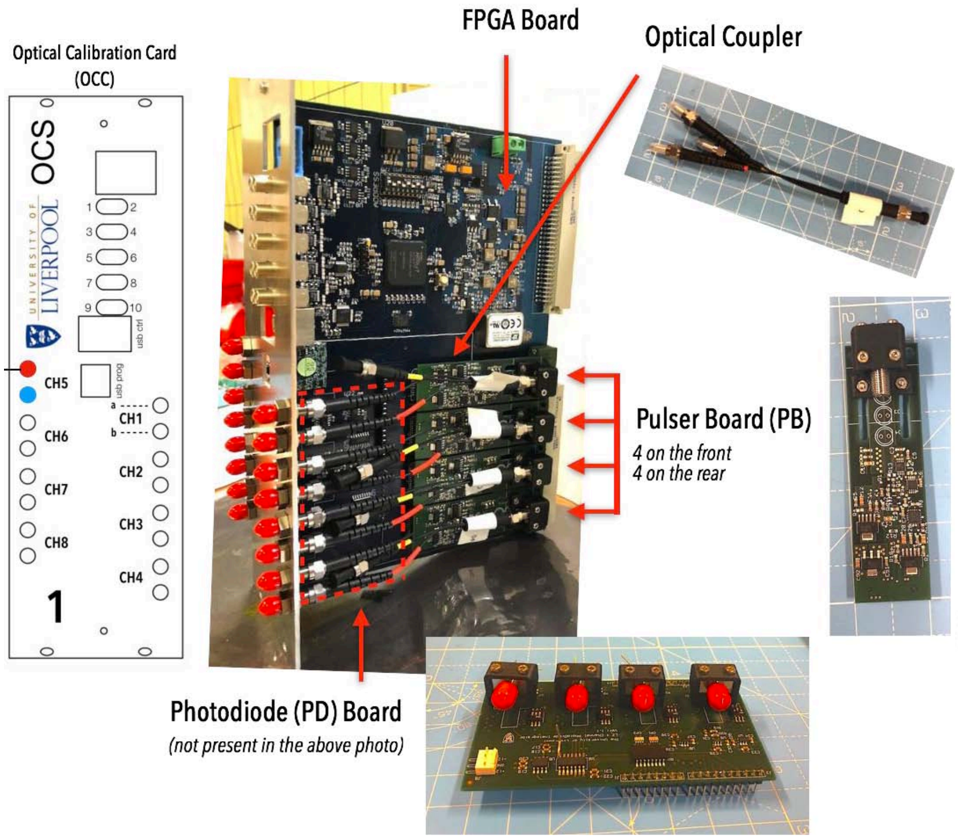


- The OD will be viewed by PMTs and surrounded by a Tyvek reflector
- Water attenuates radioactivity from by the PMTs
- LED pulser system to calibrate timing and pulse area

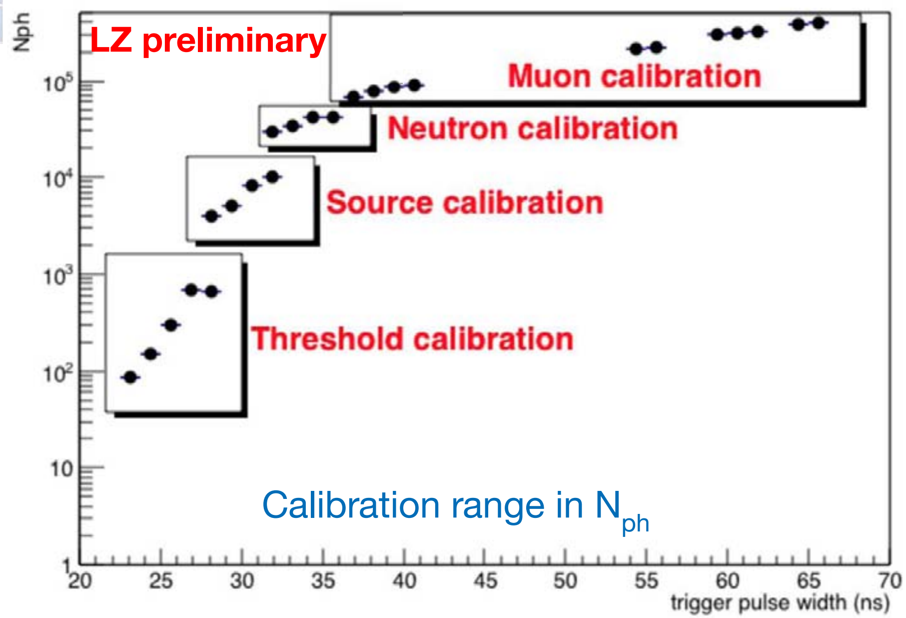




- Using 120 8”-PMTs (Hamamatsu, R5912)
- PMT measurements performed and water tank test setup with DAQ and calibration system chain
- Real data, allows to understand PMT behaviour and develop reconstruction algorithms
- Test installation of full scale mechanical setup performed
- Production of OD light collection system ongoing at Brandeis



- Liverpool built calibration system
  - Consists of 40 fibres injection points in the OD at different azimuthal locations heights
  - Monitor and calibrate output in real time

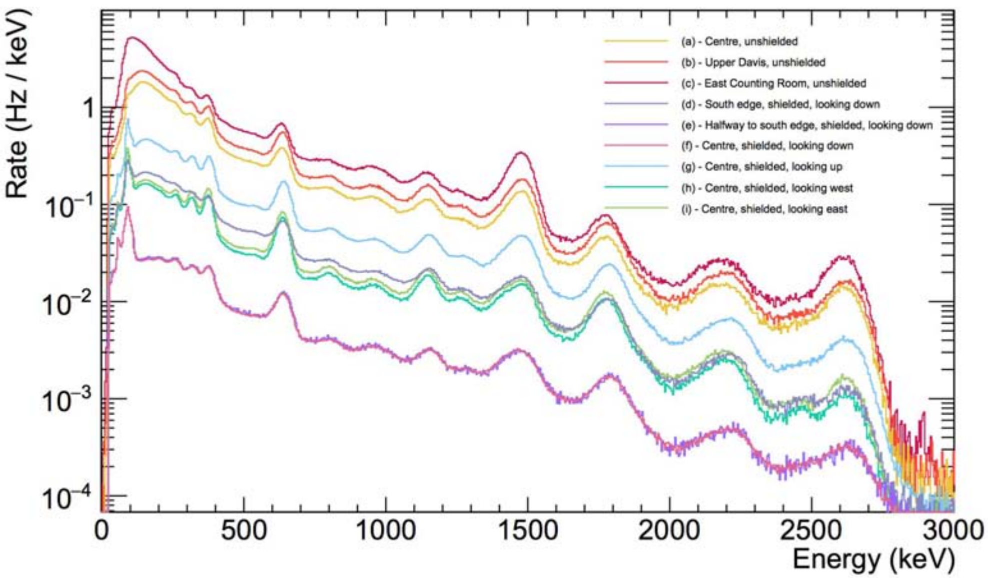


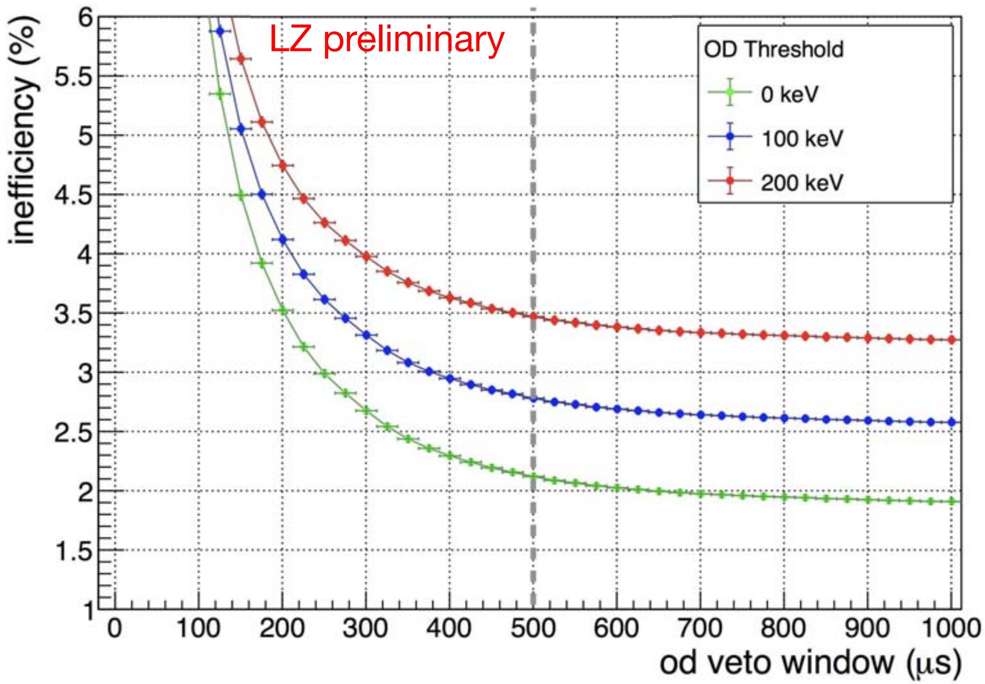
- Inject a known number of photons allows for a calibration: 100s to 10^6s of photons
- Test system used for PMT characterization

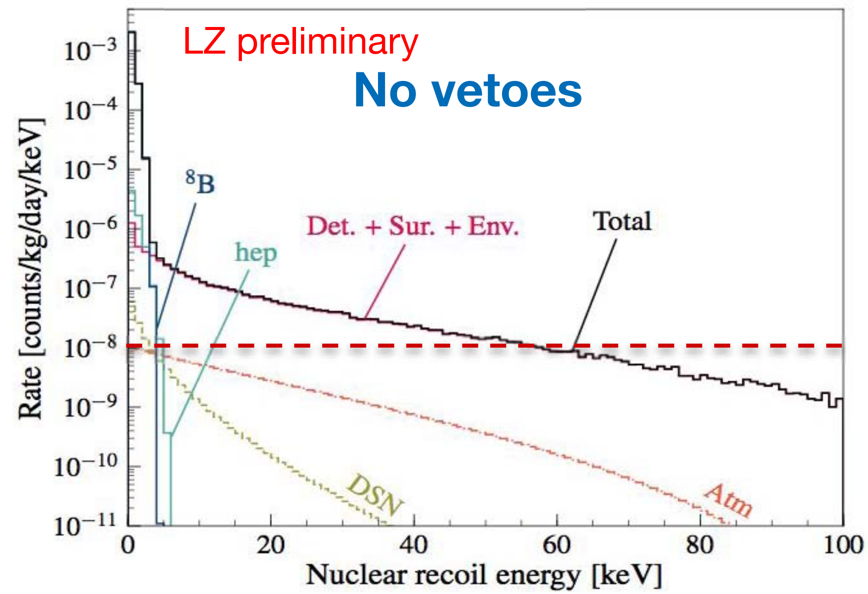
Background	***Rate (Hz)***
PMTs	0.9
TPC	0.5
Cryostat	2.5
Outer Detector	13.9
Cavern γ-rays	27
Total	**45**

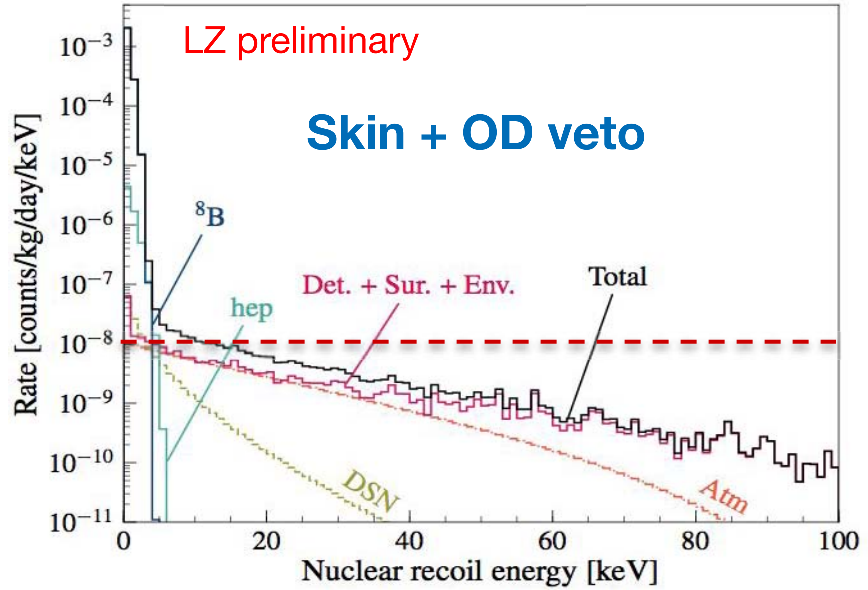
arXiv:1904.02112

- Used NaI detector to measure γ-ray flux in different locations in Davis Cavern
- Initial simulations suggested cavern was dominant background in OD, with large uncertainty from γ-ray rate.
- Measurement of ^{40}K, ^{238}U and ^{232}Th concentrations in rock
- Used to normalize γ-flux simulation with previously large uncertainties

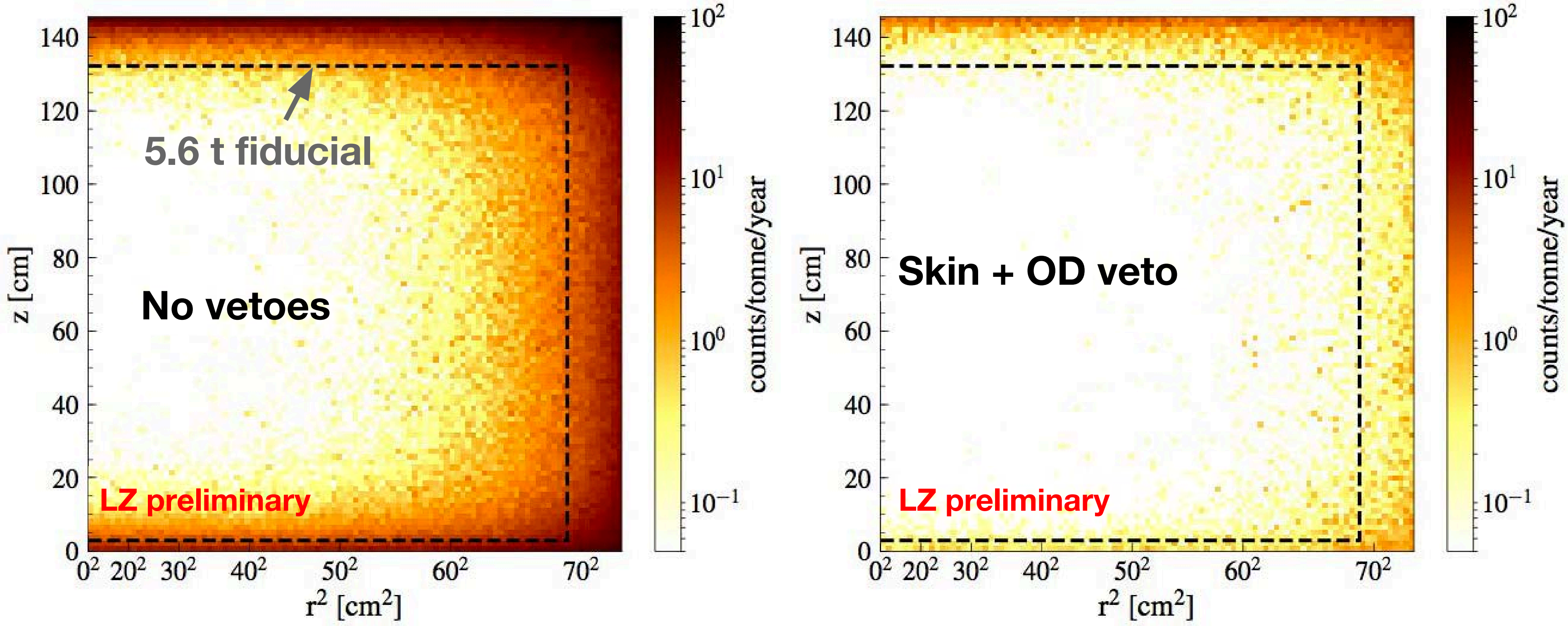








- At 200 keV, 500 μs after S1 scatter the OD will veto 96.5% of all neutrons that fake a WIMP in the TPC
- Might be possible to lower to 100 keV threshold while maintaining similar eff.
- Expect very high muon veto efficiency as indicated by early muon induced Cherenkov simulations



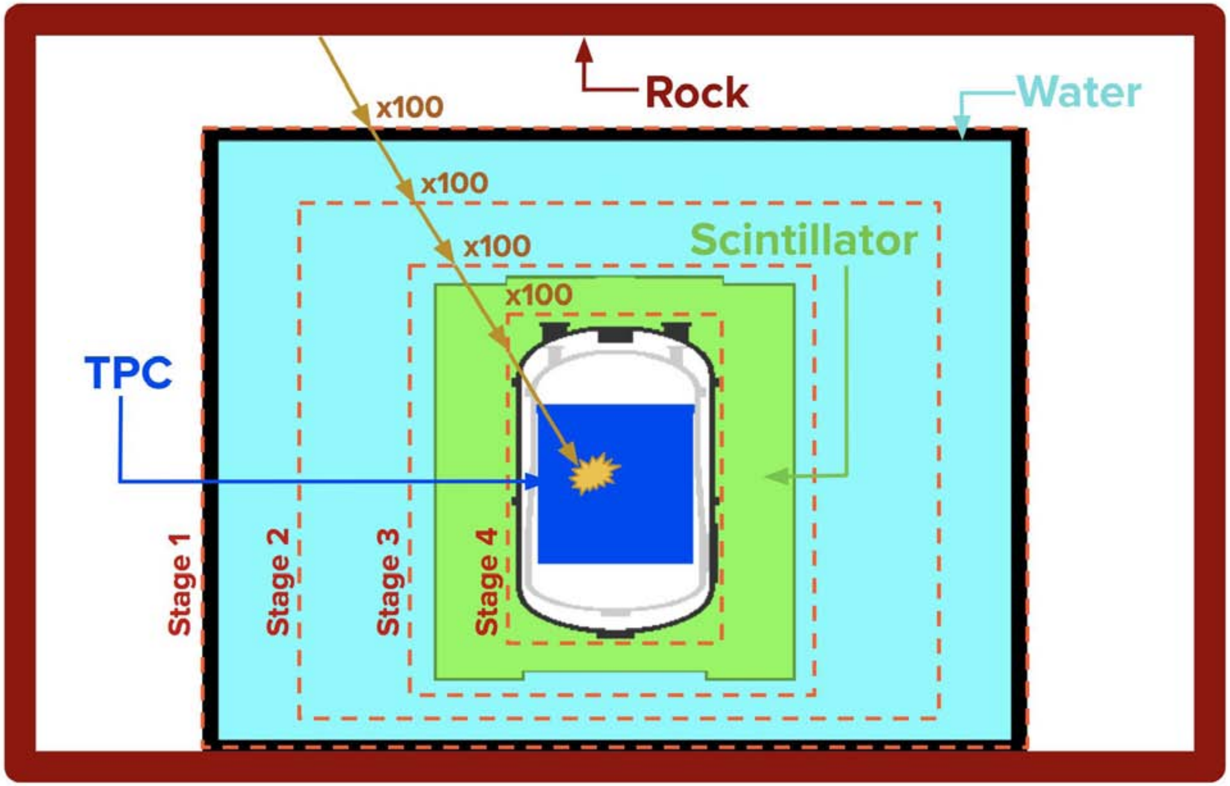
- OD neutron reduction O(10^4), with skin adding another sign. factor because of (α,nγ)
- Application of veto reduces bkgds from about 12 counts to about 1 count for 1000 live-days
- OD almost doubles the usable fiducial LXe volume and provides additional information to constrain the NR background component in the PLR

Summary

- The LZ veto detectors are integral part of the search strategy for dark matter, fulfilling several crucial functions
    - Veto backgrounds from external sources, increasing the fiducial Xe volume by 2-3 tonnes
    - Mitigate the risk associated with material close to the Xe by characterizing the radiation field around the Xe
- A claim of a WIMP signal would require extraordinary supporting evidence
- The LZ Outer Detector is conceptually similar to the Daya Bay detector, but lower energy threshold, complex geometry
- Construction well underway:
    - Tanks at SURF
    - Light collection system presently fabricated in the US
    - Calibration system presently fabricated in the UK
    - Scintillator production at BNL finished, ready to ship to SURF
- Operational experience and data from test systems and simulation allow to prepare optimal physics use
- Installation and commissioning to start in a few months. Exciting times ahead!

Backup

- Modified optical properties of the scintillator (LAB) within GEANT4
- Modified Birk's law based on measurements with the 'screener'
- Modified treatment of neutron capture on Gd – accurate cascade modelling based on DICEBOX model: F. Becvar, Nucl. Instrum. Meth. A417, 434 (1998).



OD Instrumentation

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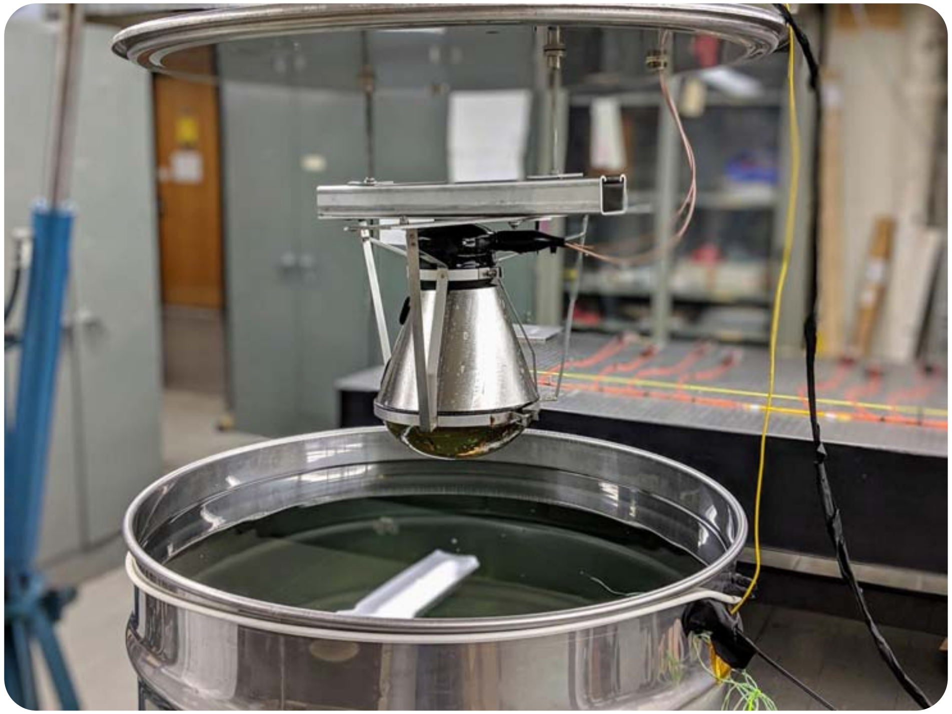
- Measurements performed by Korea and waterank test setup with DAQ and calibration system chain
- Real data, allows to understand PMT behaviour and develop reconstruction algorithms



- Test installation of full scale mechanical mock up performed
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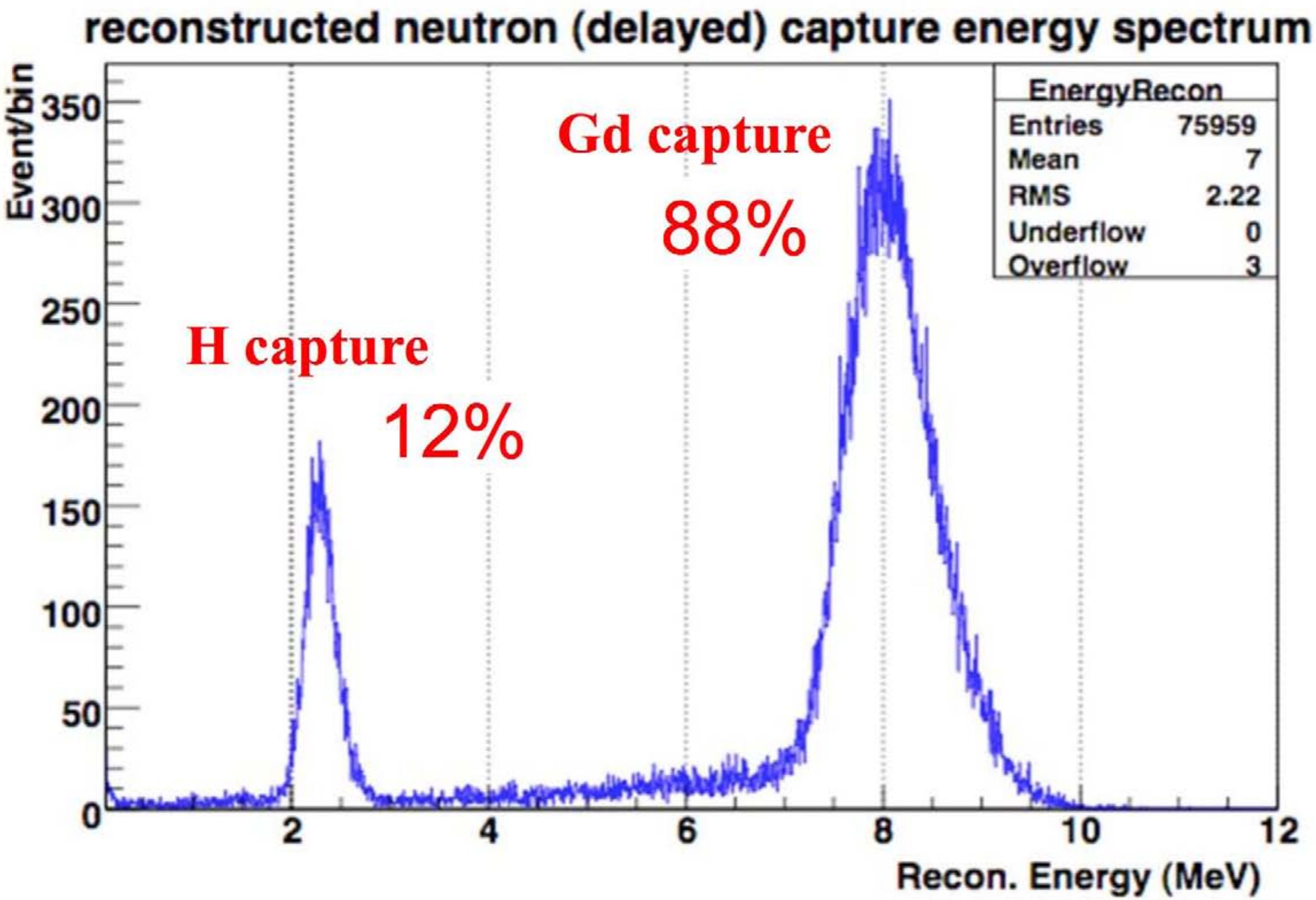
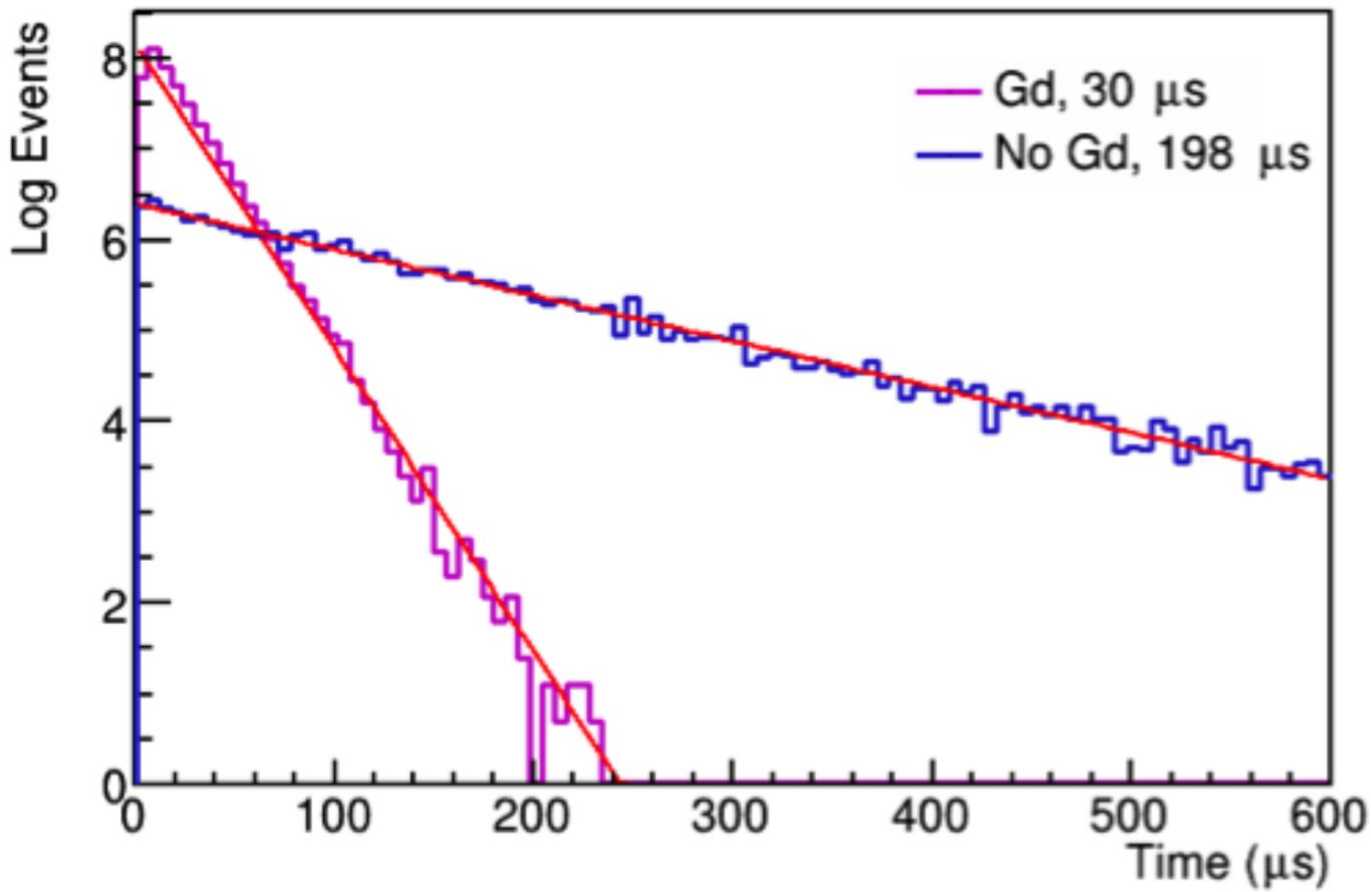
Neutron Capture Spectrum




Log Events
Time (μs)
Gd, 30 μs
No Gd, 198 μs
0
2
4
6
8
0
100
200
300
400
500
600

Rejection	No Vetoes		Skin Only		OD Only		Both Vetoes	
	neutrons	(α,nγ)	neutrons	(α,nγ)	neutrons	(α,nγ)	neutrons	(α,nγ)
^{238}U early chain	3.72E-03	2.60E-03	1.56E-03	5.94E-04	4.16E-04	2.38E-04	1.20E-04	4.65E-05
^{238}U late chain	3.20E-03	1.42E-03	1.28E-03	2.38E-04	3.31E-04	1.15E-04	1.08E-04	2.00E-05
^{232}Th chain	3.09E-03	1.56E-03	1.30E-03	2.96E-04	3.29E-04	1.49E-04	1.04E-04	1.95E-05