neriX PMT Calibration and Neutron Generator Simulation

Haley Pawlow

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Columbia University REU, XENON

Dark Matter

XENON

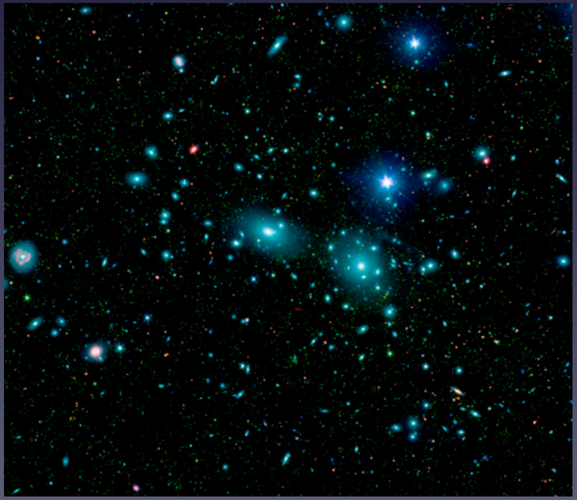
neriX

Project 1-> PMT Calibration

Project 2-> Neutron Generator Simulation

Fritz Zwicky

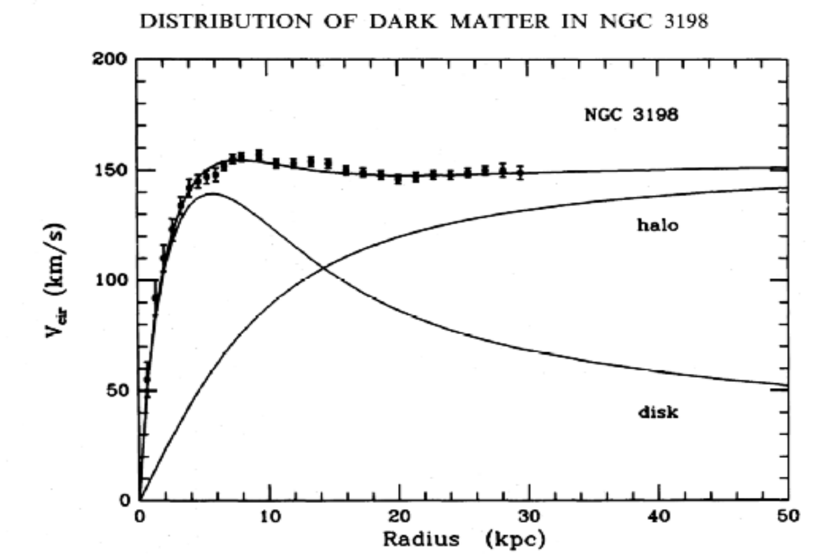
- 1933-> Using Virial Theorem to analyze Coma cluster motion, found the visible mass was too small to explain high velocities of galaxies
- Missing mass could be dark matter



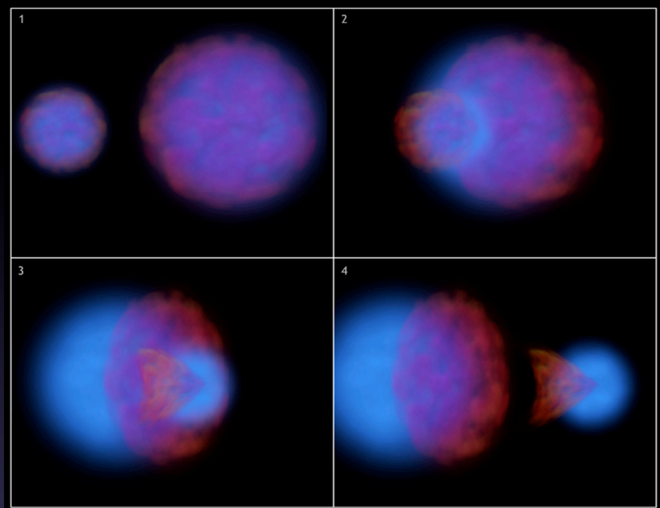
Coma cluster

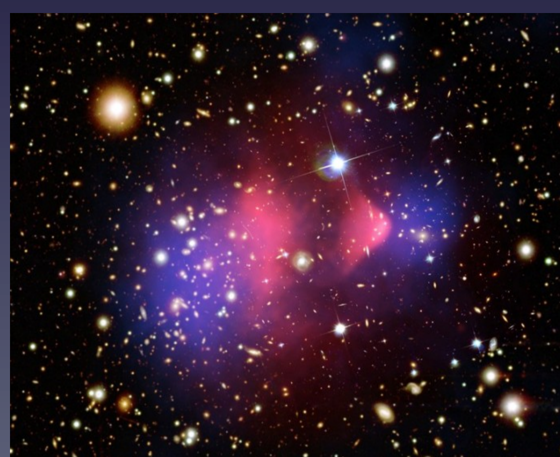
Vera Rubin

- 1970-> Rubin measured rotational velocity of spiral galaxy as a function of radius
- Used Newtonian Mechanics $v(r) = \sqrt{GM(r)/r}$ to compute mass
- Velocity doesn't obey $v(r) \propto \frac{1}{\sqrt{r}}$



Bullet Cluster

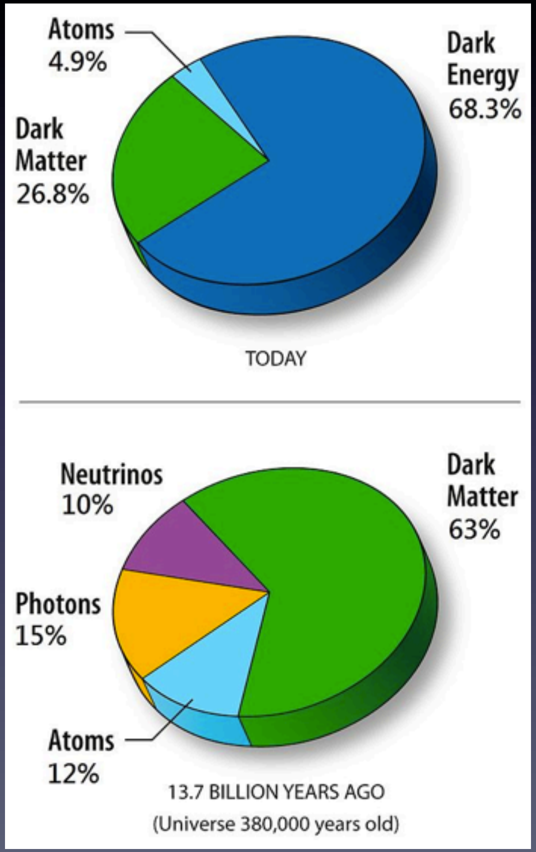




- Two hot x-ray gas clouds (red) collide like a shock wave, producing a bullet shape
- Dark matter (blue) passes right through each other with no interaction aside from gravitational force

Weakly Interacting Massive Particles (WIMPs)

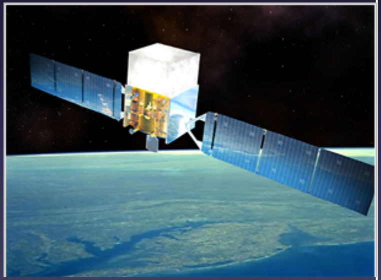
- Leading dark matter candidate because it agrees nicely with super symmetry
- Non-baryonic matter
- Interact with weak force
- Neutral in charge and color
- nonrelativistic
- Stable or have lifetimes comparable to age of Universe



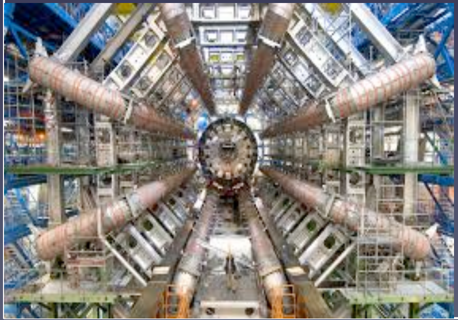
Detecting WIMPs

Indirect Detection

- Observe particles or gamma rays resulting from WIMP annihilation or decay



Fermi Gamma Ray Telescope



LHC (Production)

Direct Detection

- Look for signal from WIMP nuclear recoils
- Leaders are Dual-Phase, liquid noble gas detectors

XENON100

Dark Matter

$\boxed{\text{XENON}}$

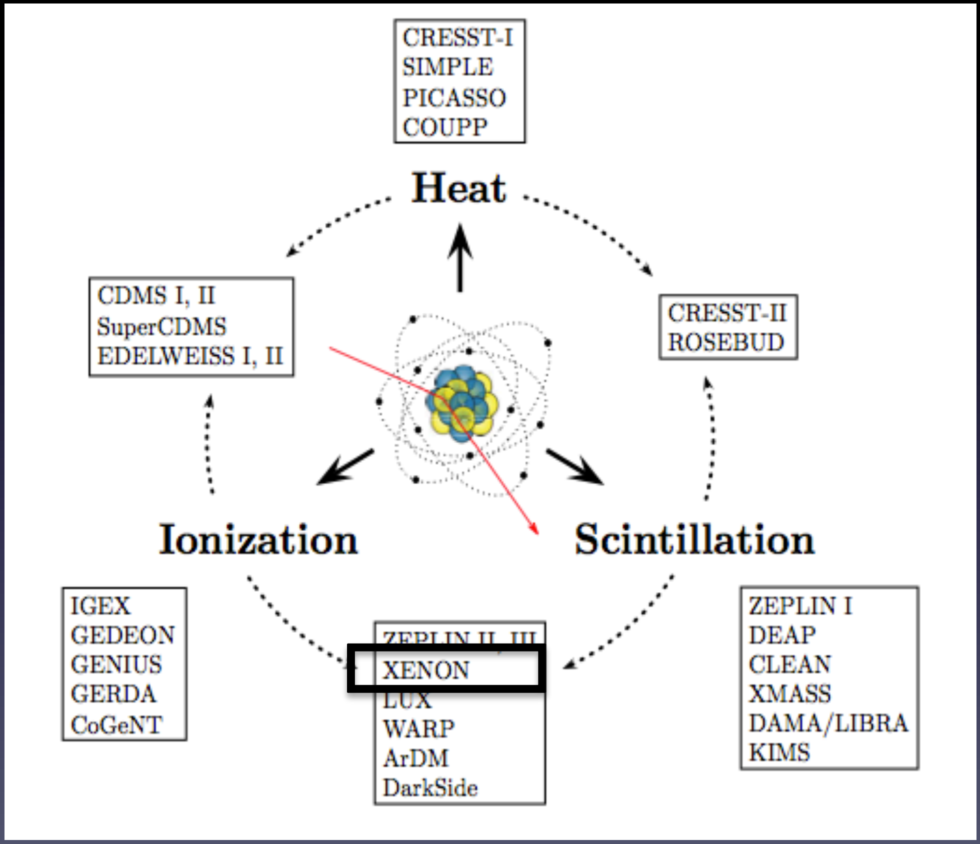
neriX

Project 1-> PMT Calibration

Project 2-> Neutron Generator

Direct Detection

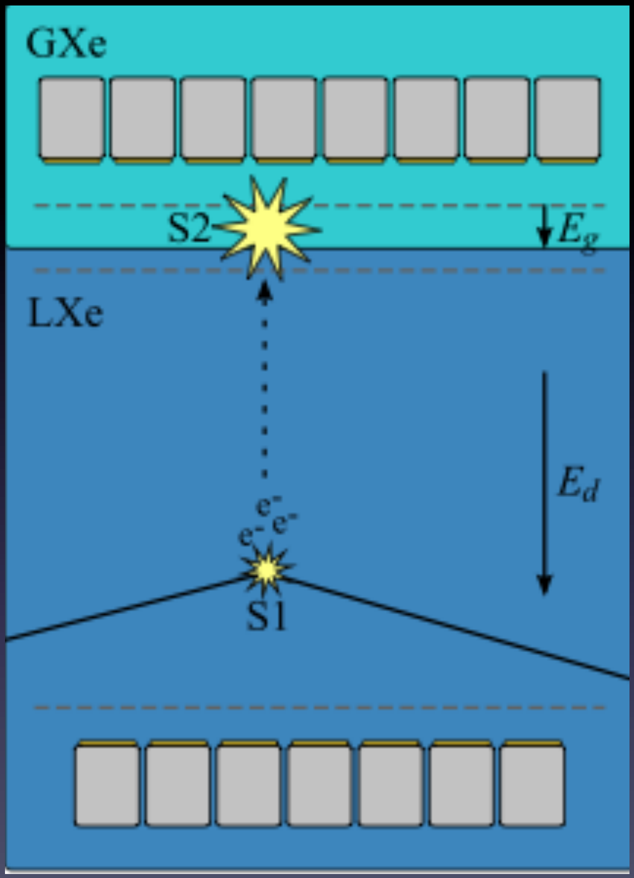
- Simultaneous measurement of ionization and scintillation signals enables XENON to discern between nuclear and electronic recoils



XENON100

- 161kg of LXe
- Optimize design for low energy threshold
- Purify Xenon
- Optimize shielding (underground in Gran Sasso, Italy)

Time Projection Chamber (TPC)



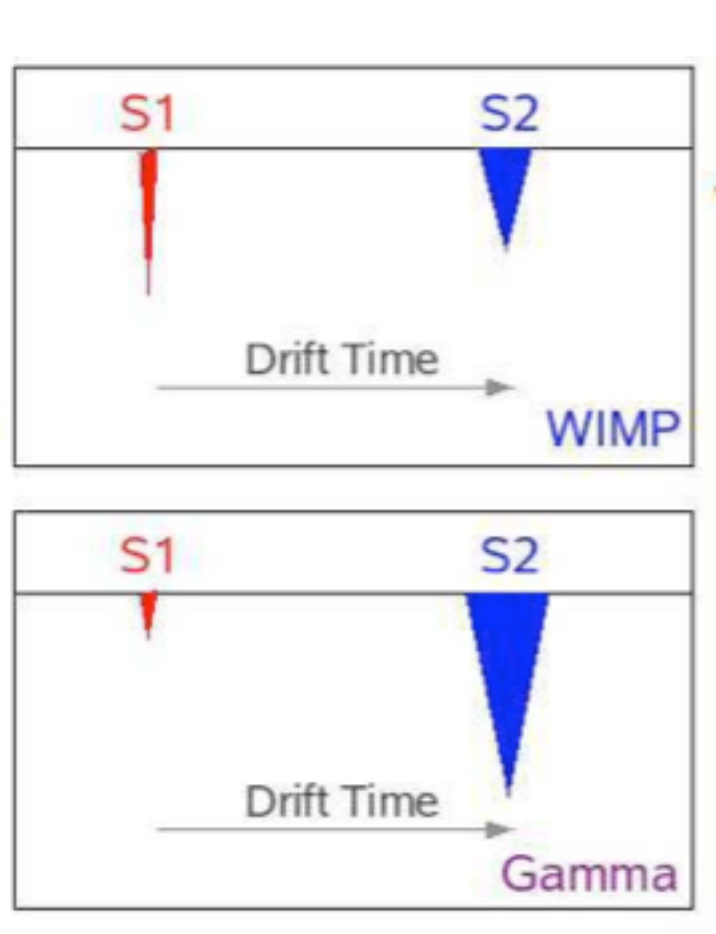
- WIMP scatters with Lxe nucleus, causing a nuclear recoil where atom collides into other atoms
- Atoms can either be ionized, releasing electrons, or excited, emitting photons which are detected by the photomultiplier tubes (scintillation->S1)
- Remaining electrons accelerated across electric field to top gas, producing secondary light (ionization->S2)

Measuring S1 and S2

- light yield (s1) = total photons/Energy
- charge yield (s2) = # of electrons/Energy
- S2/S1 differentiates between electronic(gamma/beta) and nuclear recoils
- Leff is largest systematic error in reported LXe WIMP searches

$$\mathcal{L}_{\text{eff}}\left(E_{\text{nr}}\right) = \frac{L_{y,\text{nr}}\left(E_{\text{nr}}\right)}{L_{y,\text{er}}\left(E_{\text{er}} = 122\,\text{keV}\right)}$$

Position of event



- S2/S1 differentiates between electronic(gamma/beta) and nuclear recoils
- Using drift time and Voltage, calculate distance (z direction)
- PMTs record x and y coordinate of event (hit pattern)
- Reconstruct position of event

Dark Matter

XENON

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Project 1-> PMT Calibration

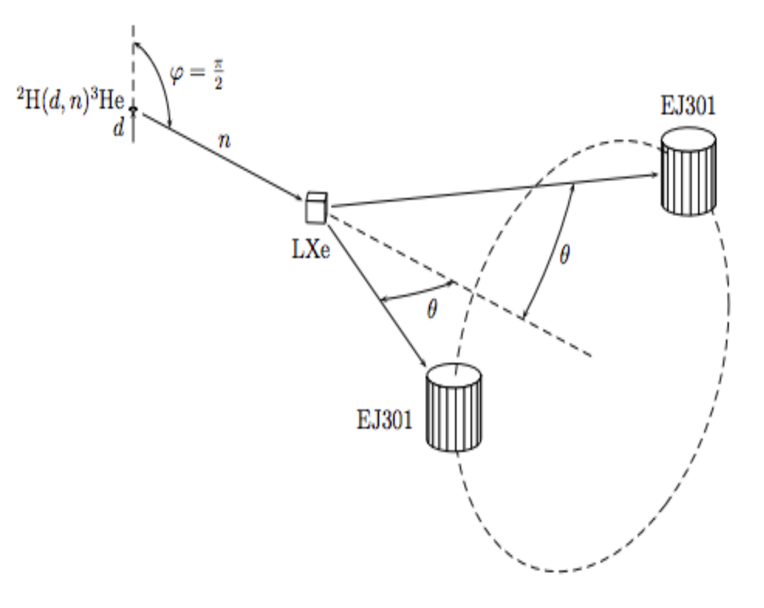
Project 2-> Neutron Generator

neriX: How can we calibrate XENON?

- Analyze how different particles, like neutrons and gamma rays, interact with LXe atoms
- Measure s1 and s2 to distinguish electromagnetic background from WIMPs in XENON
- Need to convert from measured scintillation in Photomultiplier tubes (PMTs) to energy

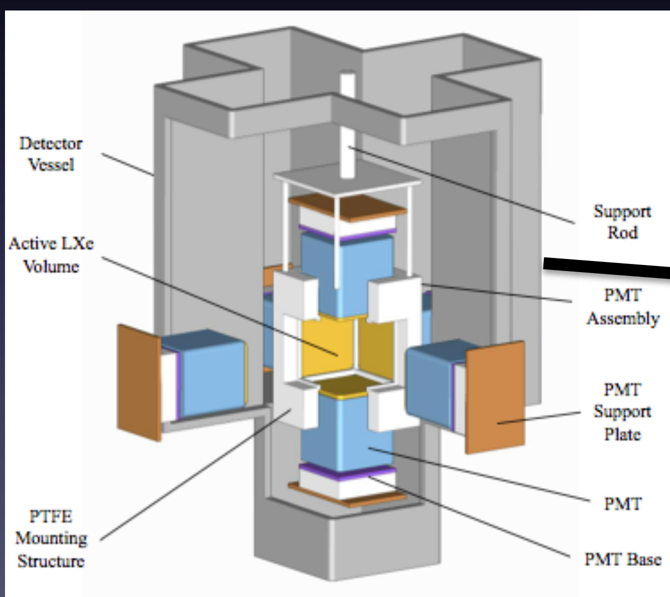
neriX Experimental setup

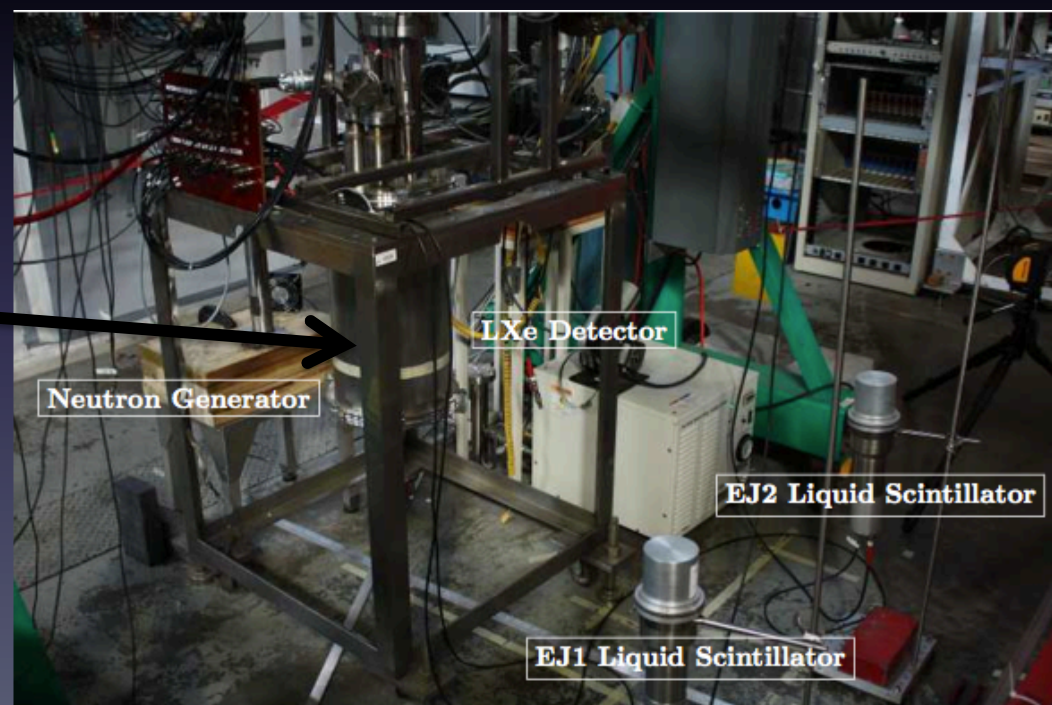
- ➢ Neutron generator emits monochromatic neutrons that elastically scatter with atoms inside LXe.
- ➢ Two organic liquid scintillators detect neutrons at fixed signal
- ➢ Measure light and charge yield



neriX Detector

- Same Dual-phase, TPC concept as XENON100
- neriX has 4 top PMTs and 1 bottom PMT
- XENON100 has 98 top PMTs and 78 bottom PMTs





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Project 1-> PMT Calibration

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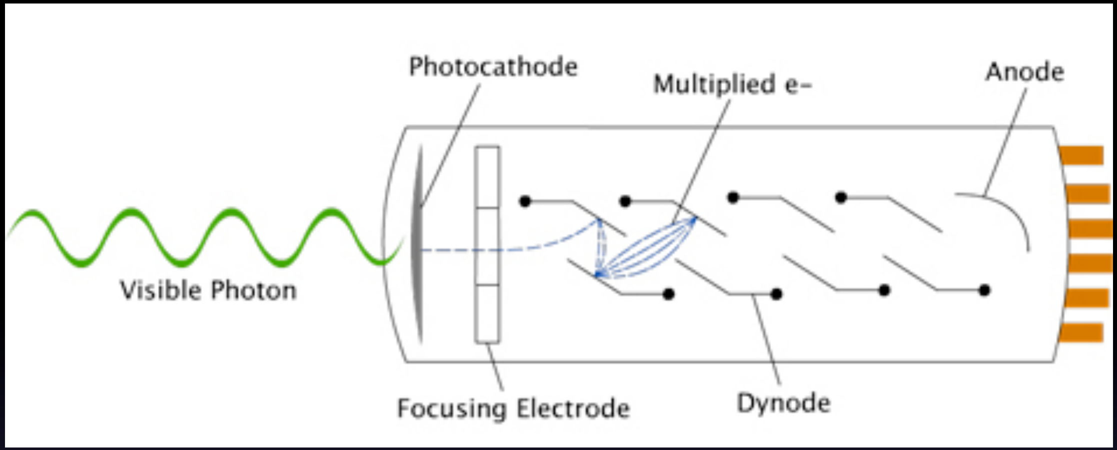
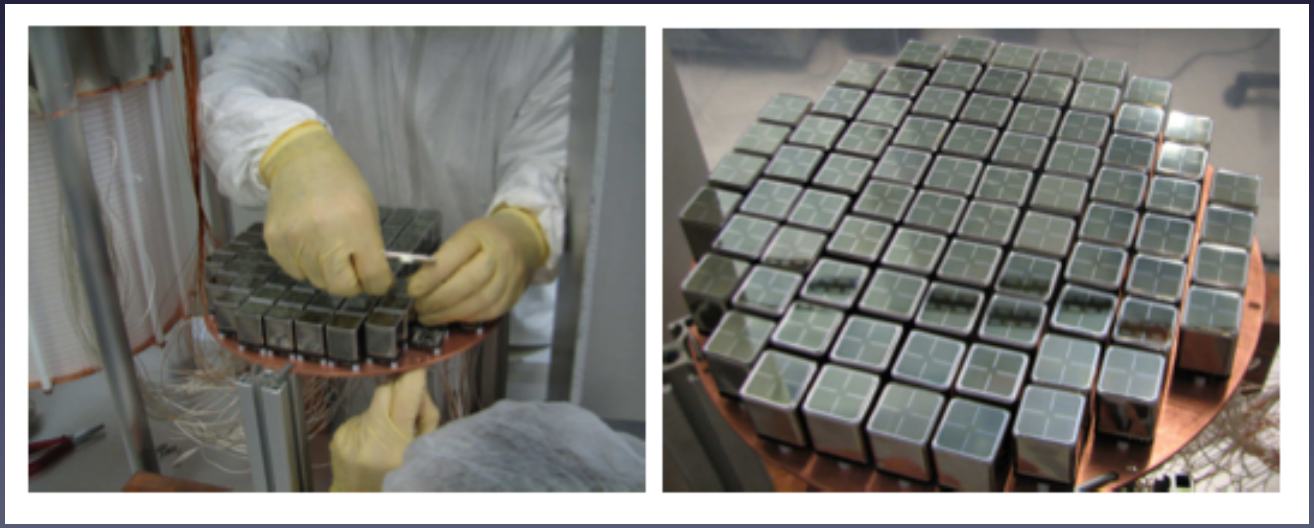
PMTs



- Incident photon emits a single photoelectron (PE) from photocathode
- PE attracted to dynode by applied electric field
- PE accelerates, releasing more e-'s, which are all attracted to second dynode
- Dynodes multiply amount of charge via photoelectric effect
- PMT Gain = # of e produced/photoelectron

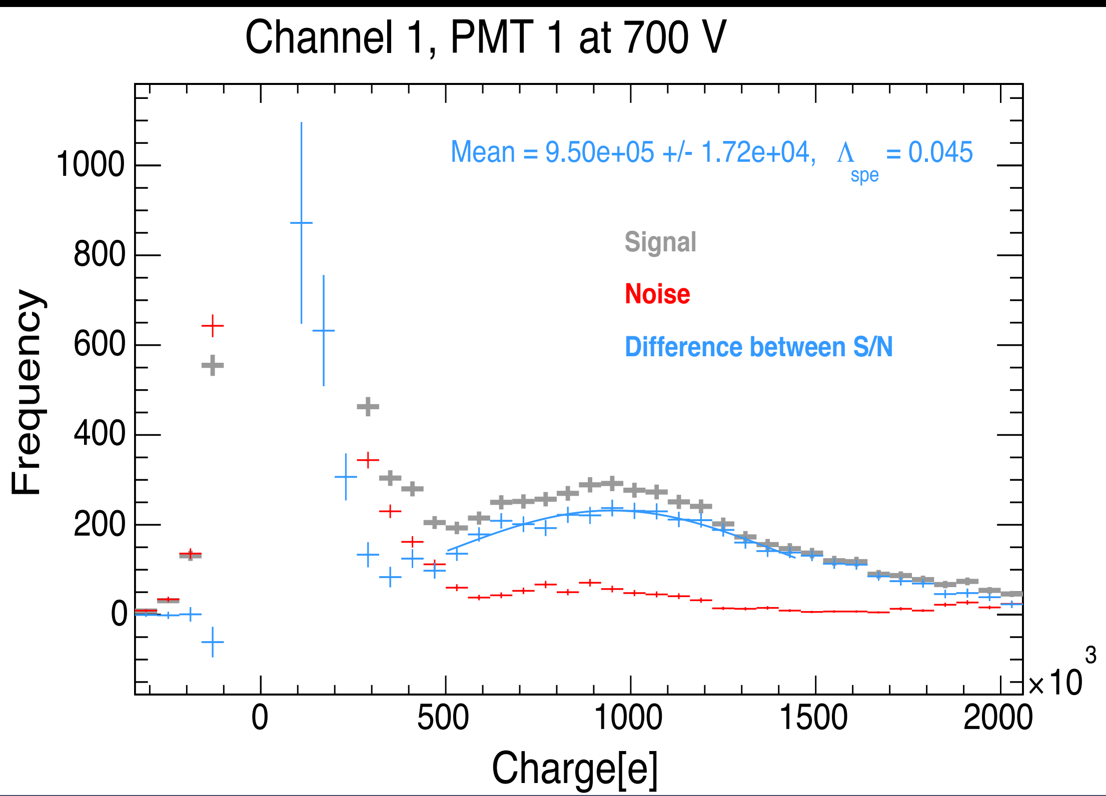
Why do we need to calibrate PMTs?

- PMTs give us a voltage signal, we need to convert to photoelectrons using the gain
- With the gain we can measure s1 and s2 (light and charge signals)



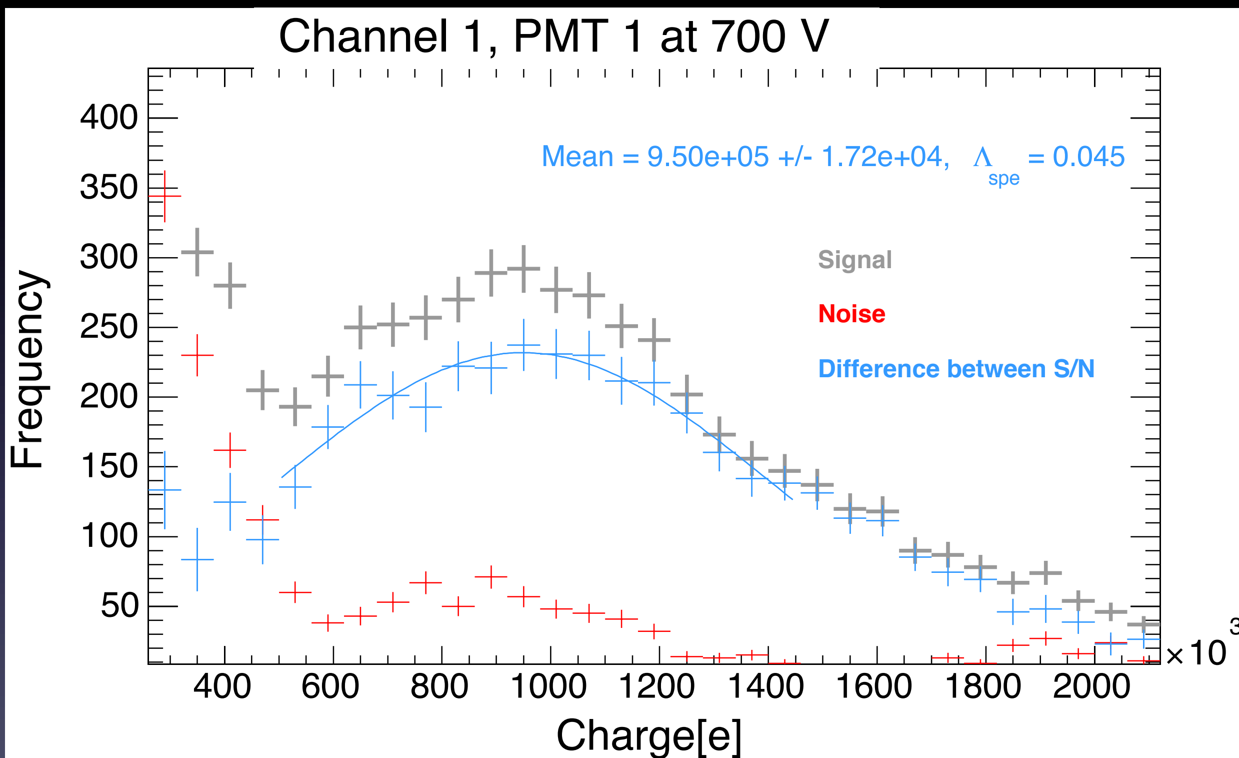
Bottom PMT array for XENON100

Gaussian Distribution of PMTs



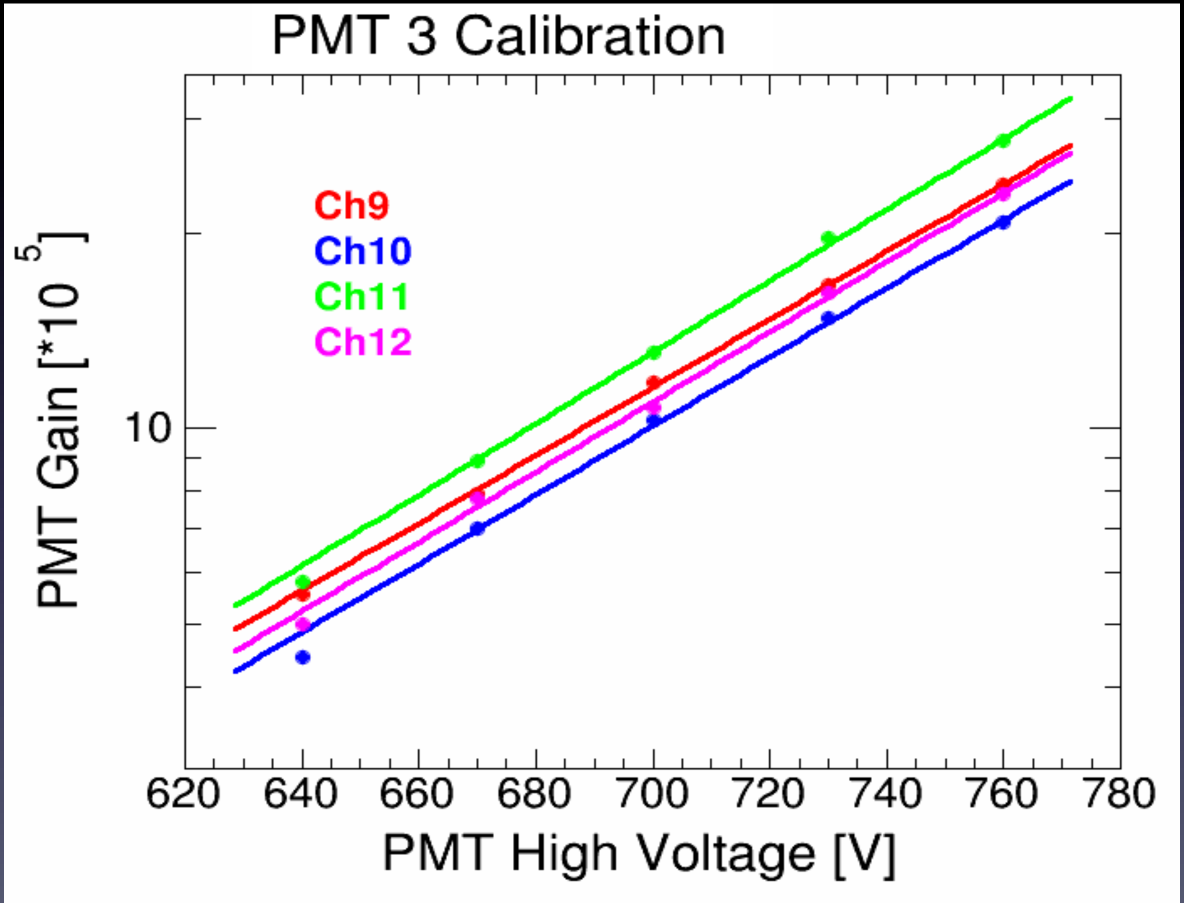
- Number of PE is a poisson distribution: 90% of signal is noise, 10% of signal from 1 PE. This way contribution of multiple PE is minimized
- 1st peak around zero is noise, second peak from one photoelectron

Gaussian Distribution of PMTs



- Λ = 0.045, the 1-PE peak is 4.5% of signal
- Agrees with Poisson distribution

PMT Calibration



- 4 top PMTs and 1 bottom PMT, 4 channels each
- PMT Gain = # of electrons produced/PE
- PMT gain increases exponentially, seen as line in log linear plot

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Project 1-> PMT Calibration

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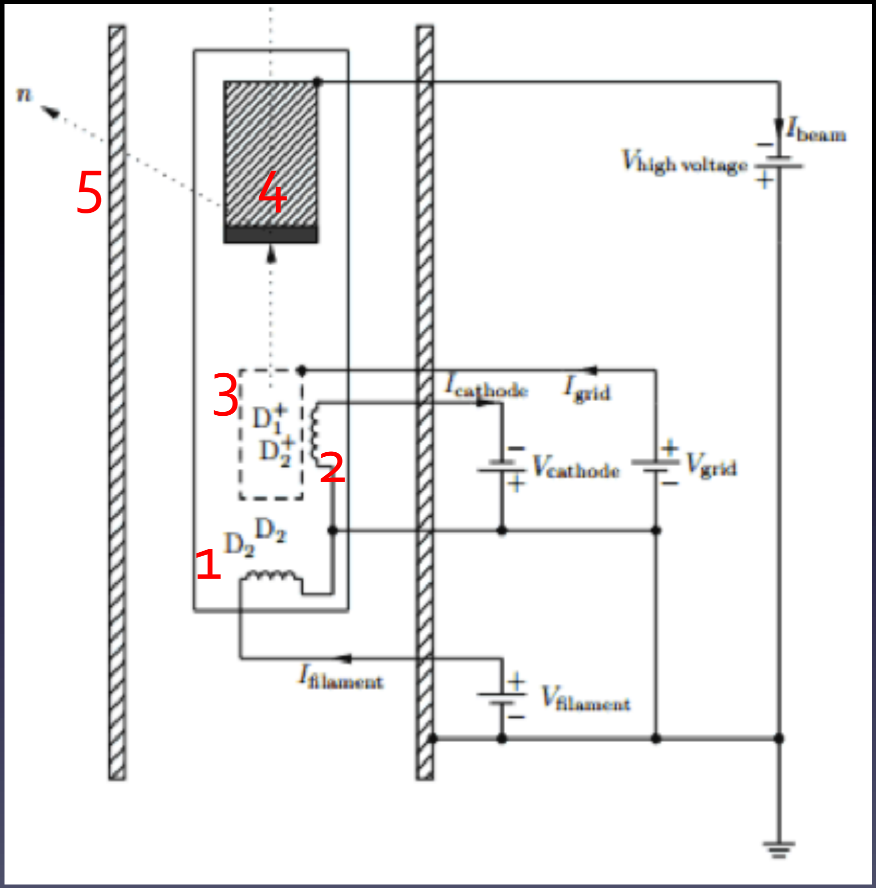
Neutron Generator

1. Heat filament and release deuterium gas
2. As cathode heats up, electrons extracted to the grid
3. Ionized deuterium gas ions accelerate toward titanium deuteride target
4. Ions collide with target and are either stopped or produce neutrons
5. Neutrons are mono-energetic, minimizing spread in neutron energy at a 90 degree angle



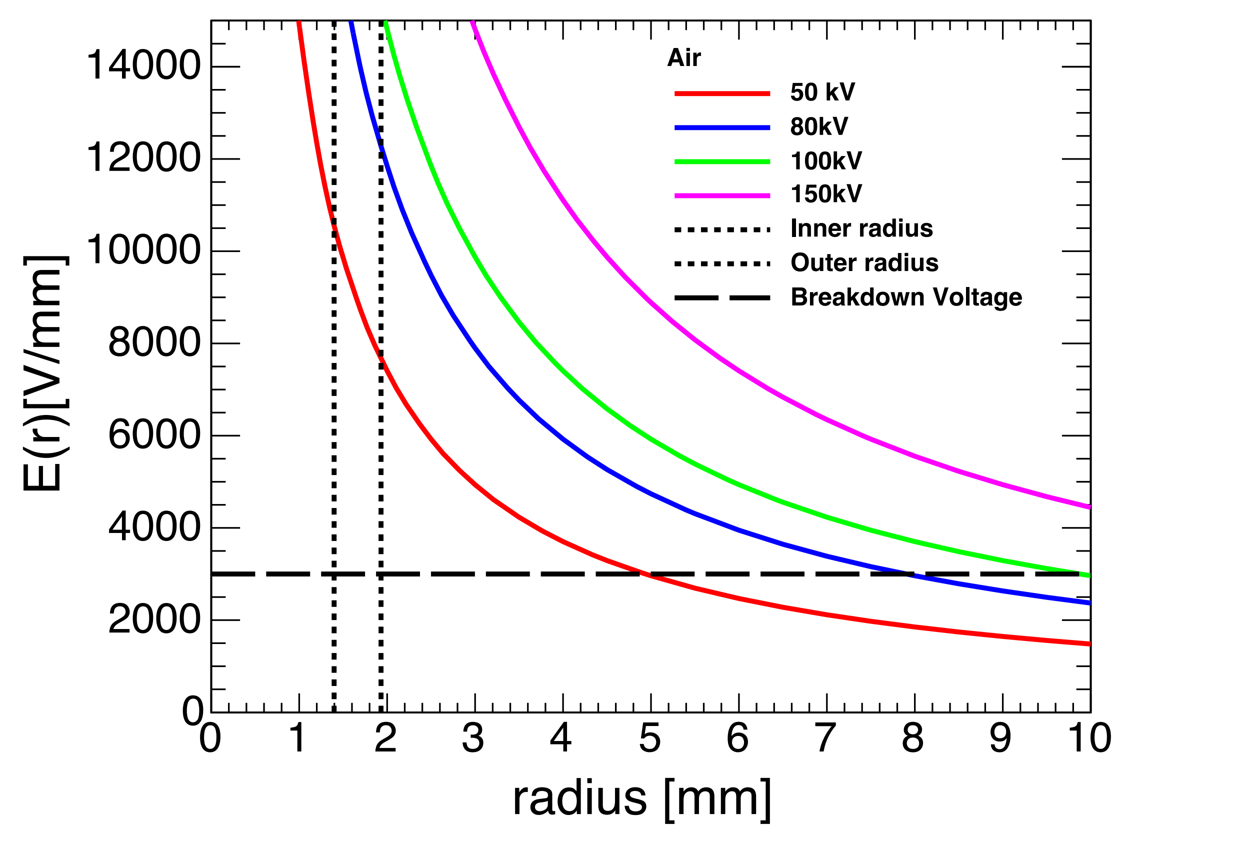
Why modify Neutron Generator holder?

- Increase voltage 40kV->100kV
- With a higher voltage we get greater neutron flux
- Faster data collection

Electrical Breakdown across HV cable

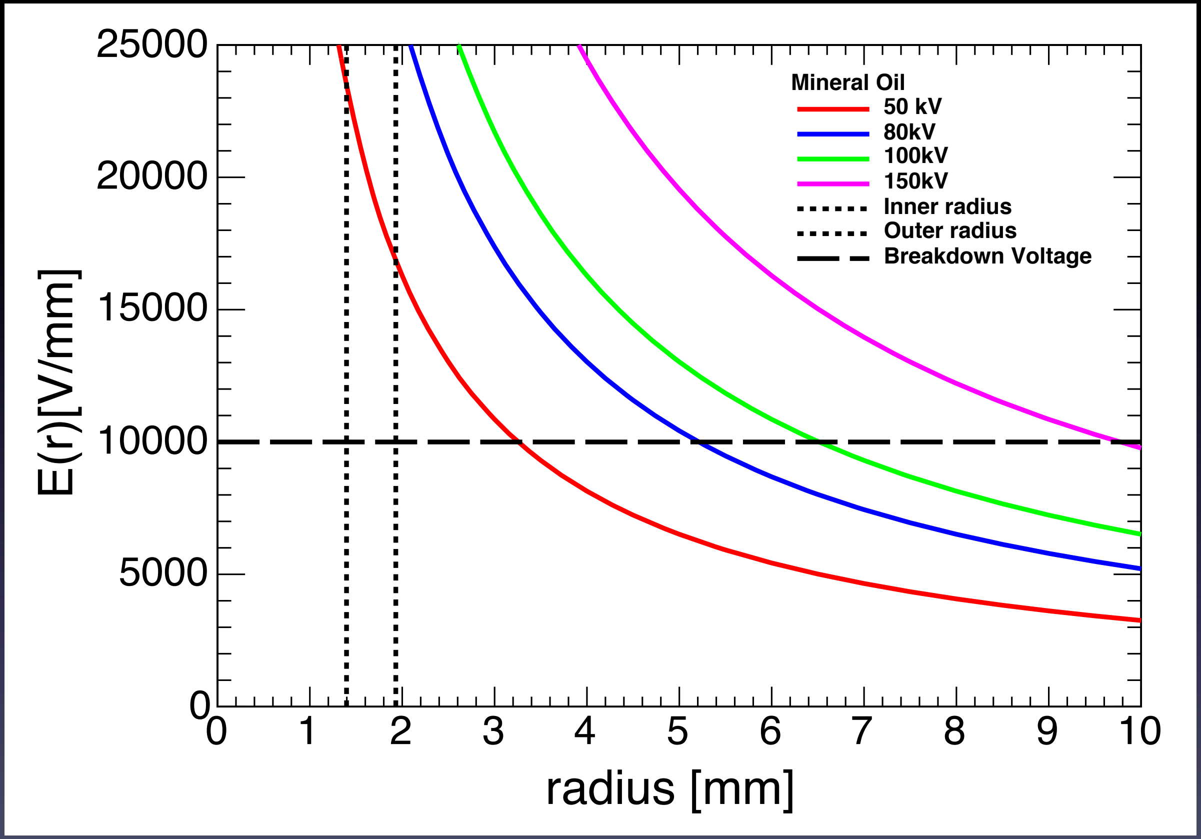
- Need to avoid electrical discharge at HV cable connection to neutron generator
- Analyze electrical breakdown (dielectric strength) for different dielectric materials (Teflon, oil, and air)

Electrical Breakdown in Air



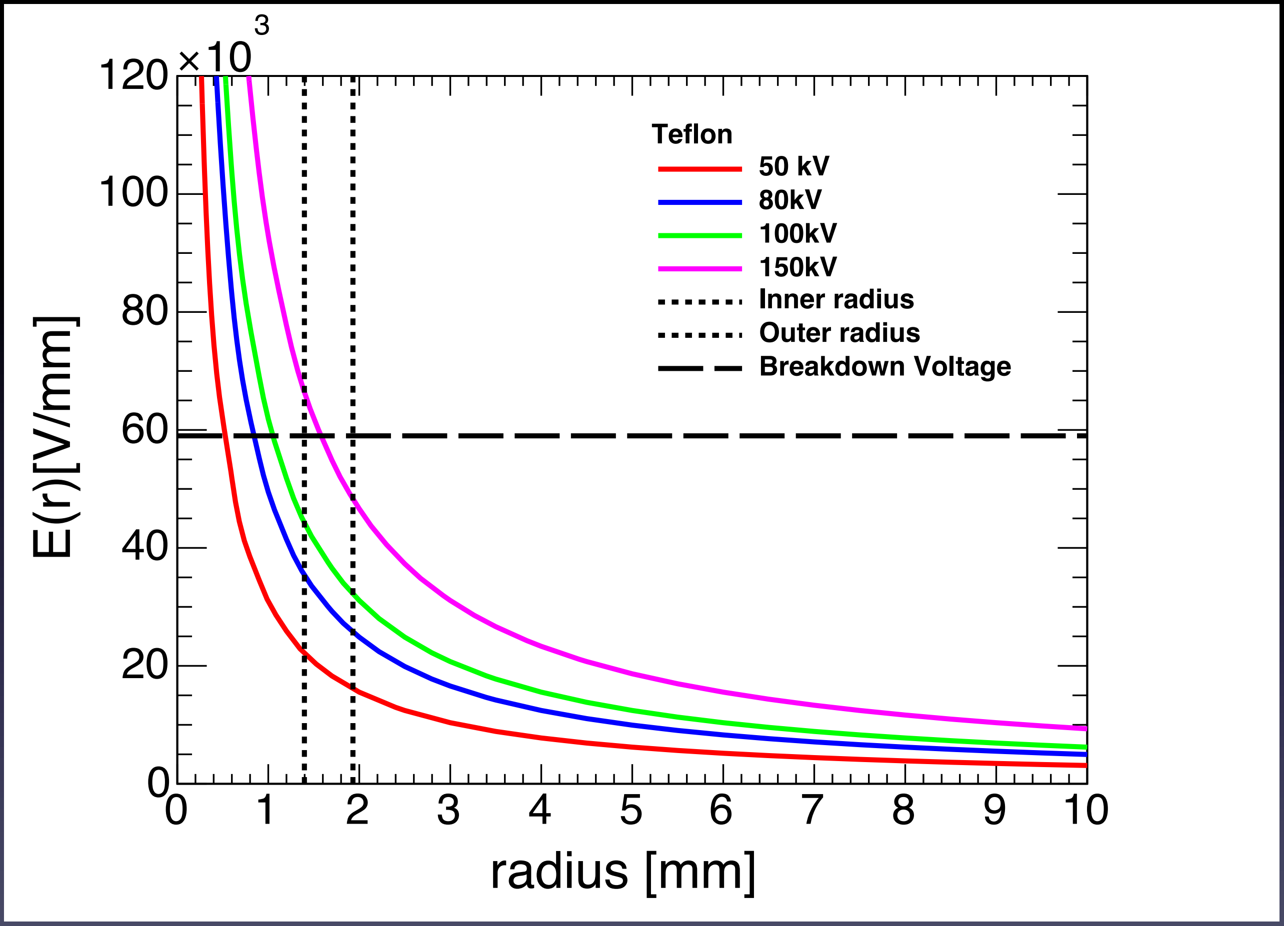
At the HV cable radius, the electric field exceeds electrical breakdown for 100kV

Electrical Breakdown in Oil



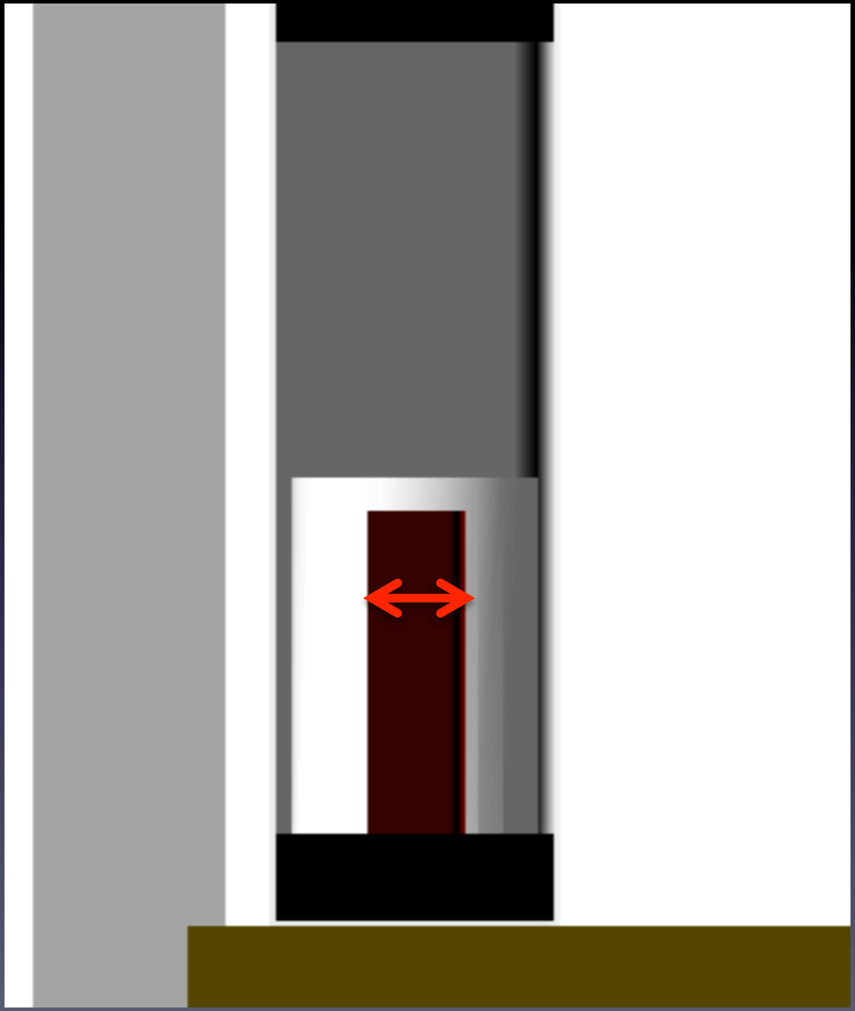
At the HV cable radius, the electric field exceeds electrical breakdown for 100kV

Electrical Breakdown in Teflon



At the HV cable radius, the electric field is well below electrical breakdown for 100kV

GEANT4 Monte Carlo Simulation

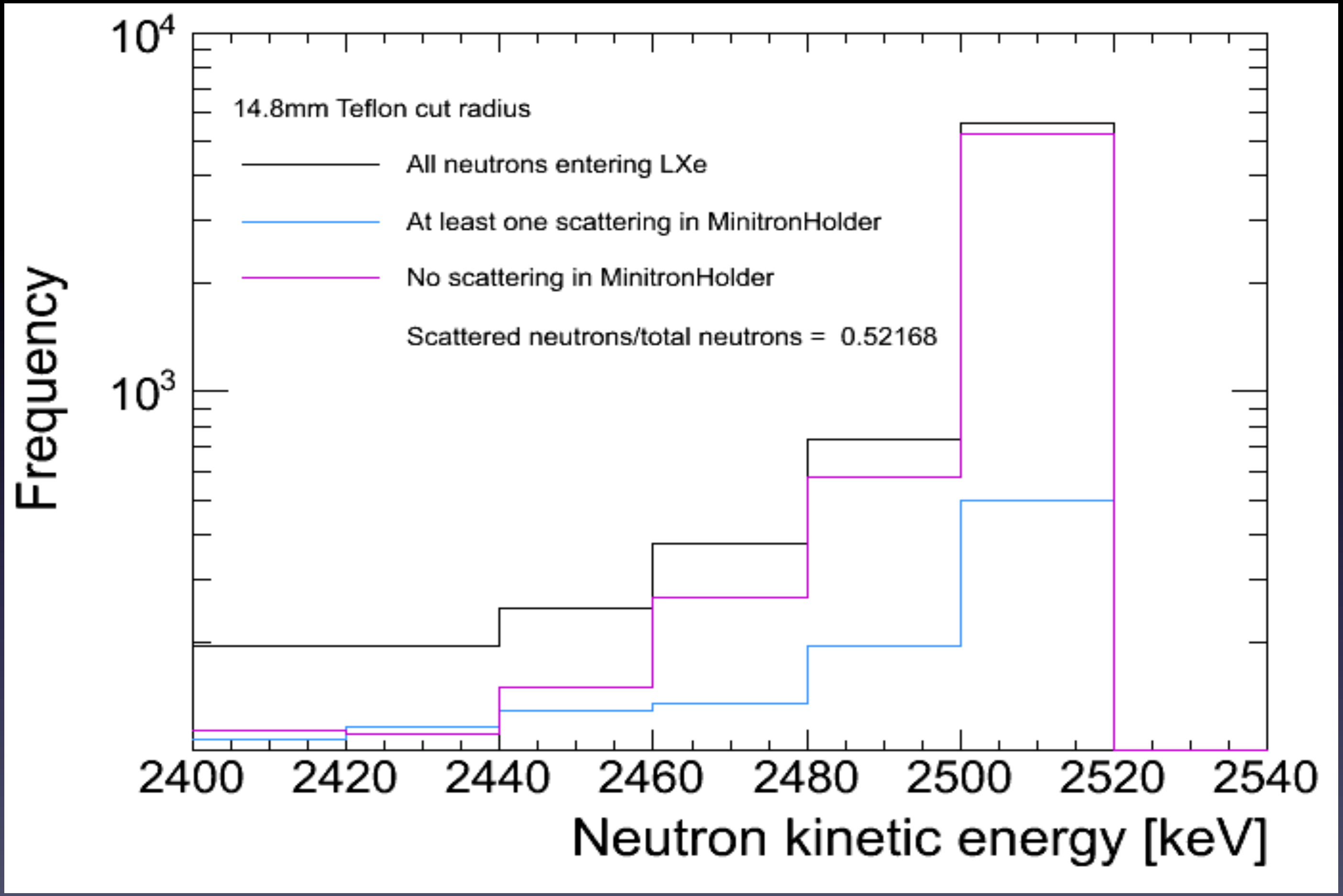


- Optimize ratio between Teflon and oil to produce least amount of neutron scatters

Teflon cut radius
=
radius of mineral oil

*Image from GEANT4 simulation

Example: Teflon/oil = 1.5743



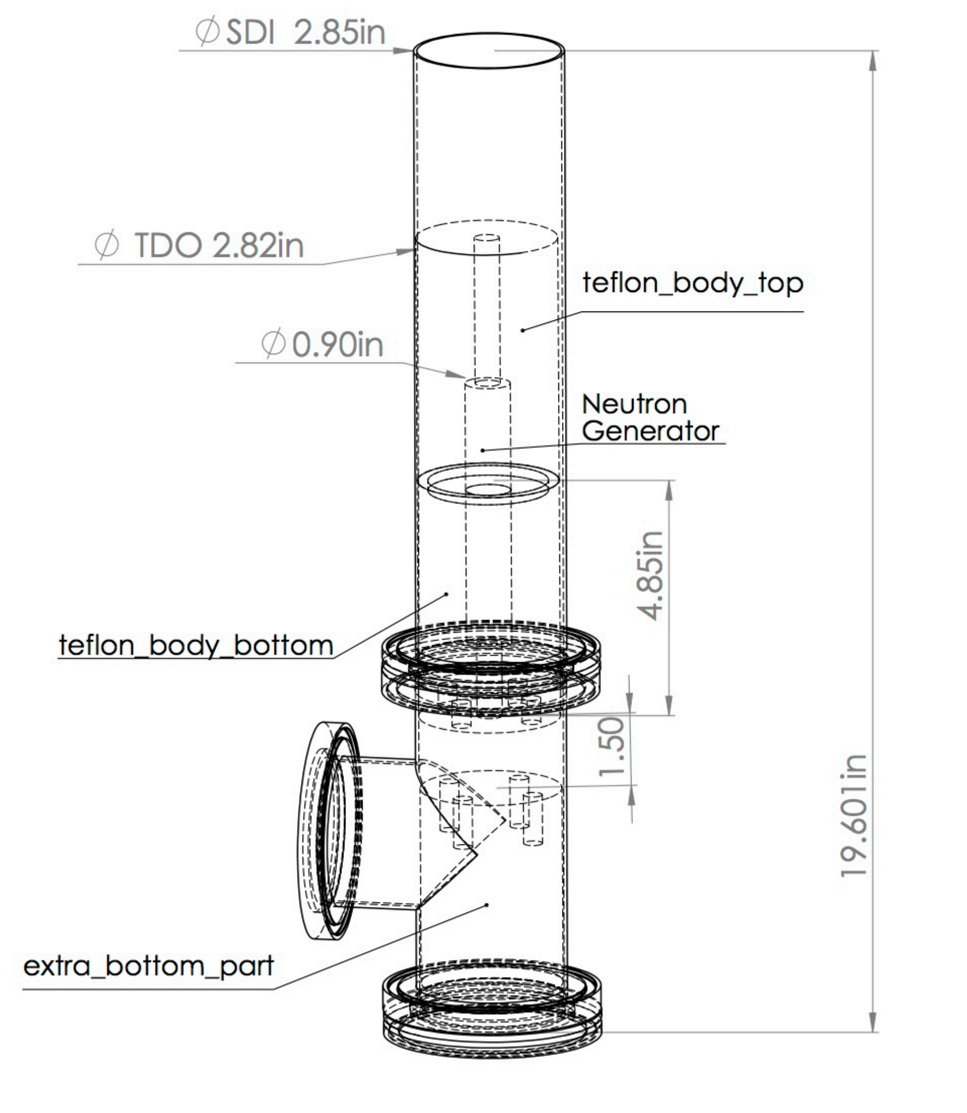
52% of neutrons scatter

Conclusions

Teflon/Oil	Scattered/Total neutrons
1.57	0.522
0.5	0.522
0.19	0.520

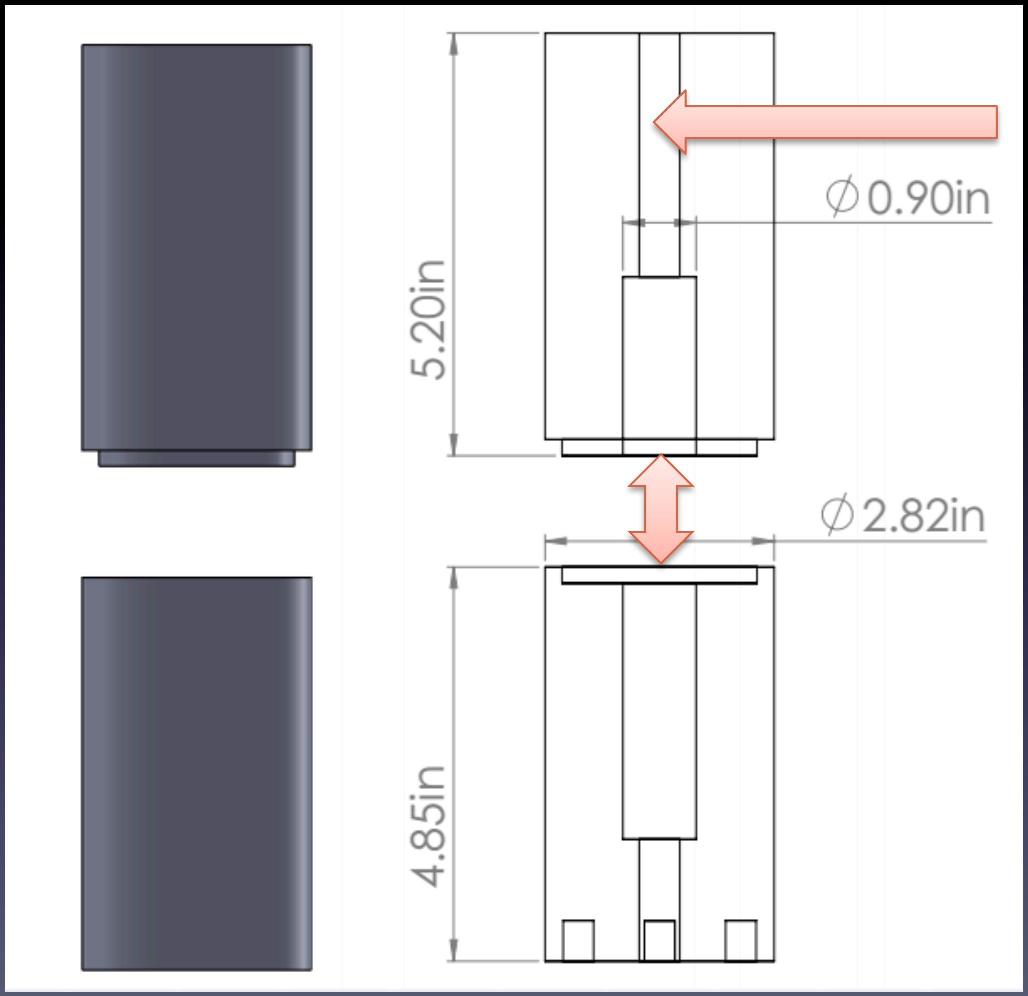
- Largest Teflon cut produces least amount of neutron scatters
- Amount of scattering is negligible +/- 0.4%
- Use maximum amount of Teflon in holder design to keep neutron generator fixed

SolidWorks Model for Neutron Generator Holder



- Increase holder tube diameter from 2->3”
- Maximize use of Teflon to minimize neutron scatters

SolidWorks Neutron Generator Holder Model



- ✓ HV cable surrounded with Teflon to avoid electrical breakdown

- ✓ Neutron Generator firmly secured in carrier with Teflon/oil ~1.5

Next Steps for neriX

- Measure nuclear and electronic recoils by varying electric fields across chamber
- More precise measurement of gamma rays at low energy with Cs 137 Compton scatters

ROOT/C++

GEANT4

SolidWorks

Graduate School

Takeaways

Dark Matter , XENON, neriX

Brookhaven National Lab

Particle Physics Lectures

Research Environment

Acknowledgements

- Elena Aprile for giving me this opportunity
- Antonio Melgarejo, Marc Weber, Luke Goetzke, and Matt Anthony for their support and guidance
- The XENON team at Nevis for being so inviting
- John Parsons and Amy Garwood for organizing the REU program
- NSF REU program for their generous funding

Questions???

Appendix

Measuring # of photons from PMT

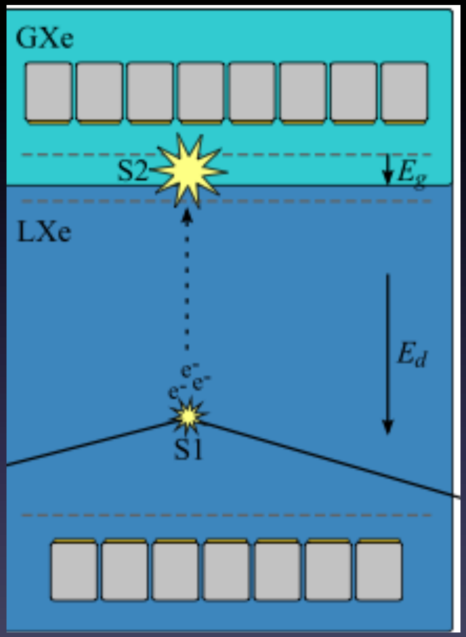
Gain = # of electrons/photoelectron emitted

PMT Quantum Efficiency = 35% (# photons/PE)

Number of photons from PMT

Light Detection Efficiency

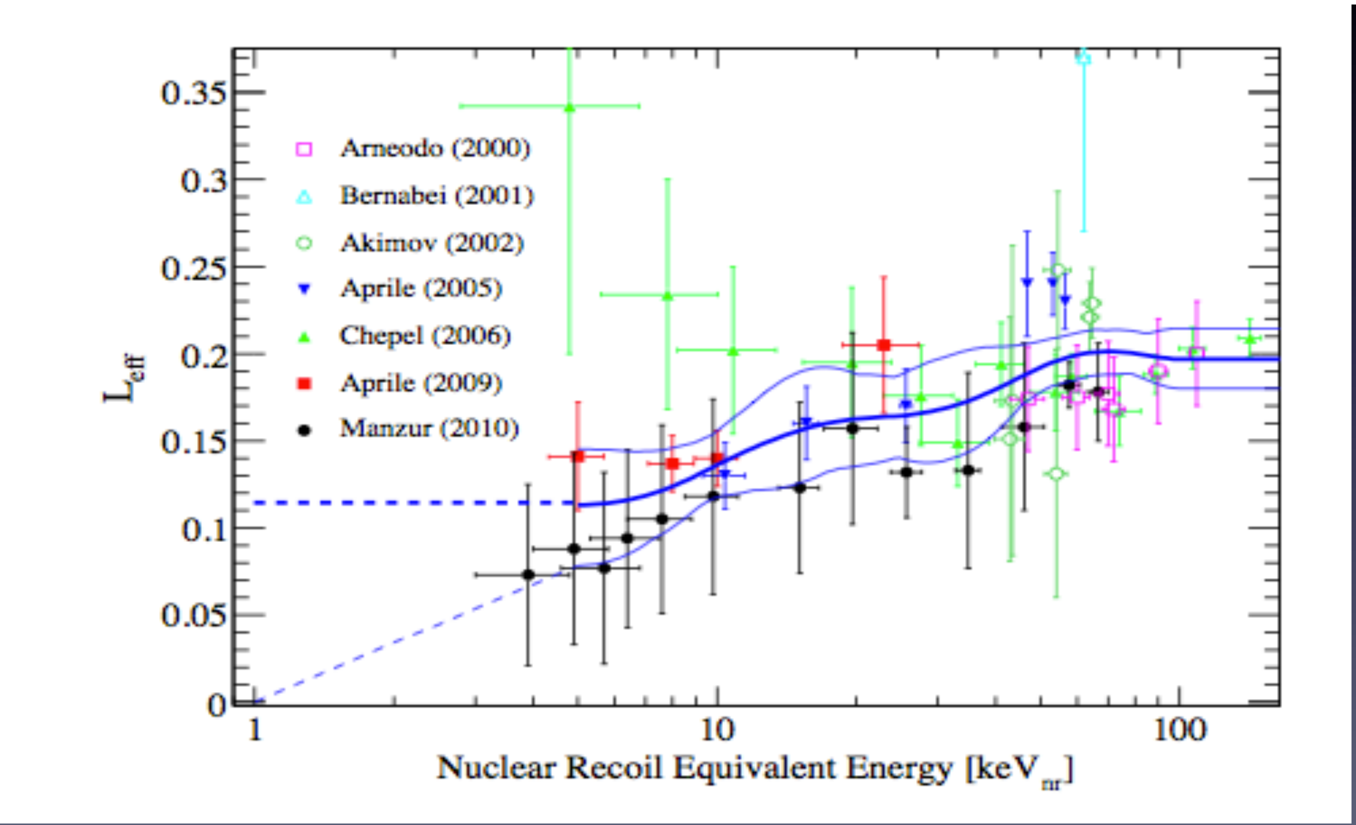
Total # photons emmited (type, Energy, E field)

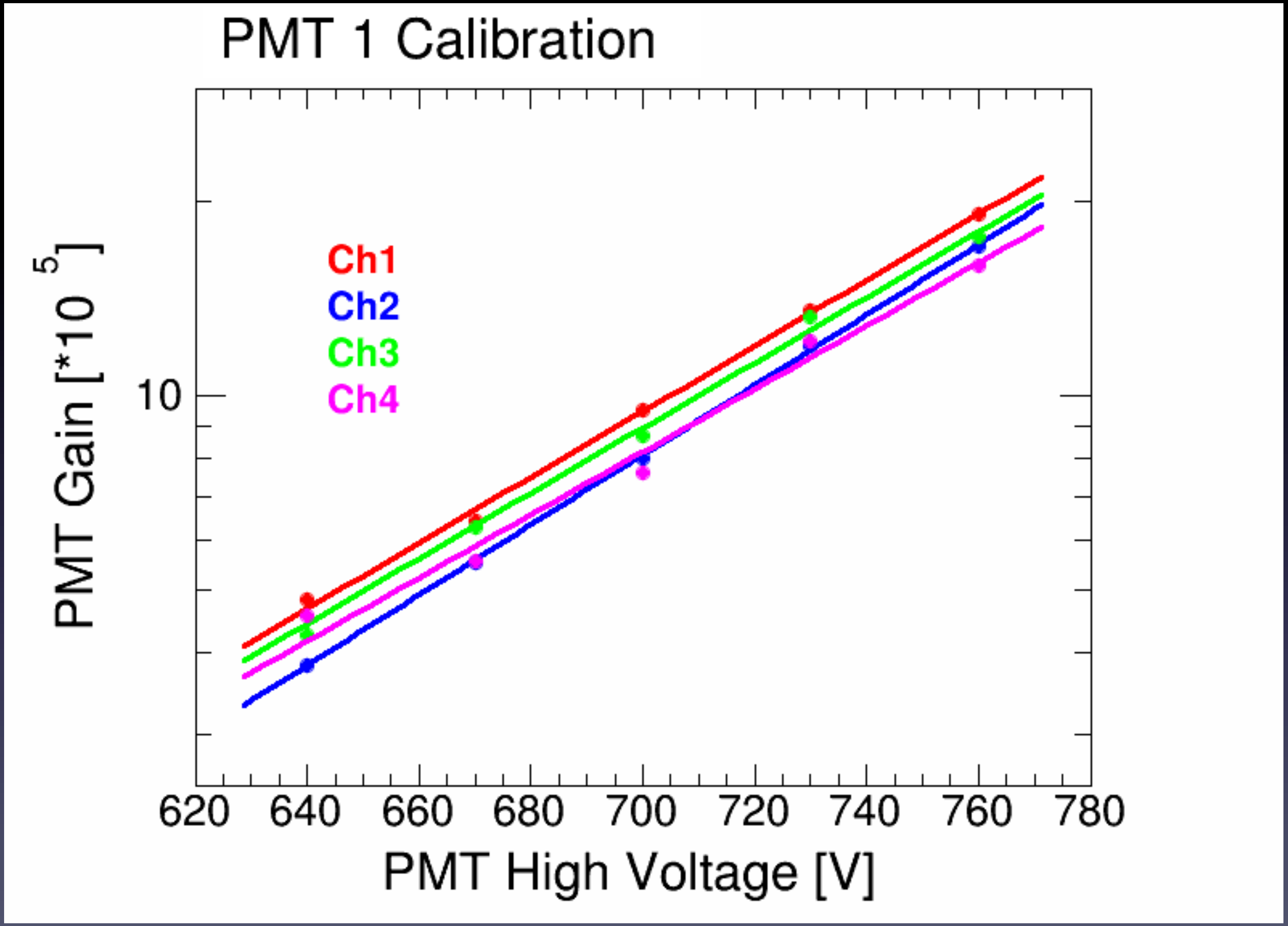


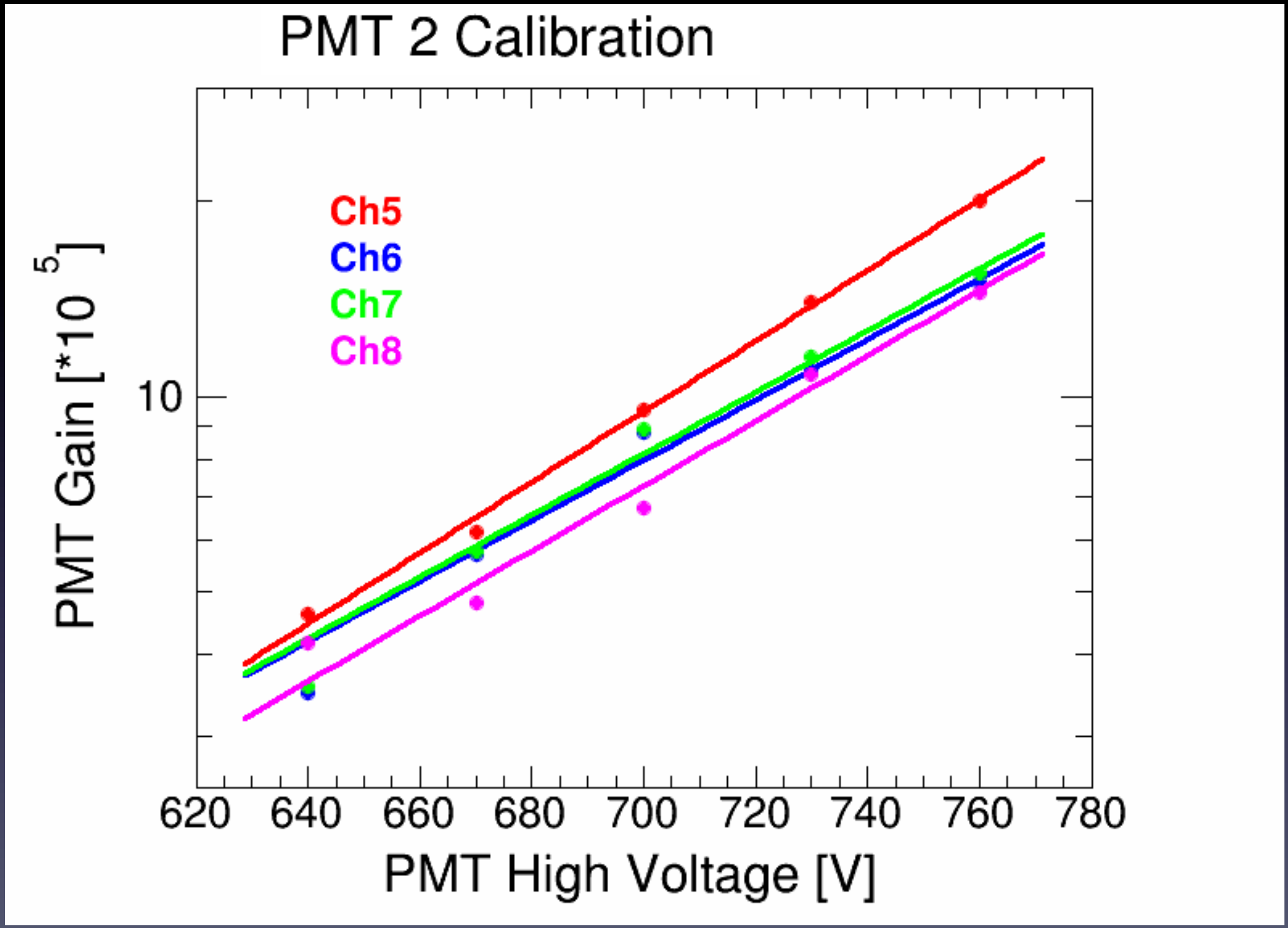
Relative scintillation efficiency of nuclear recoils (Leff)

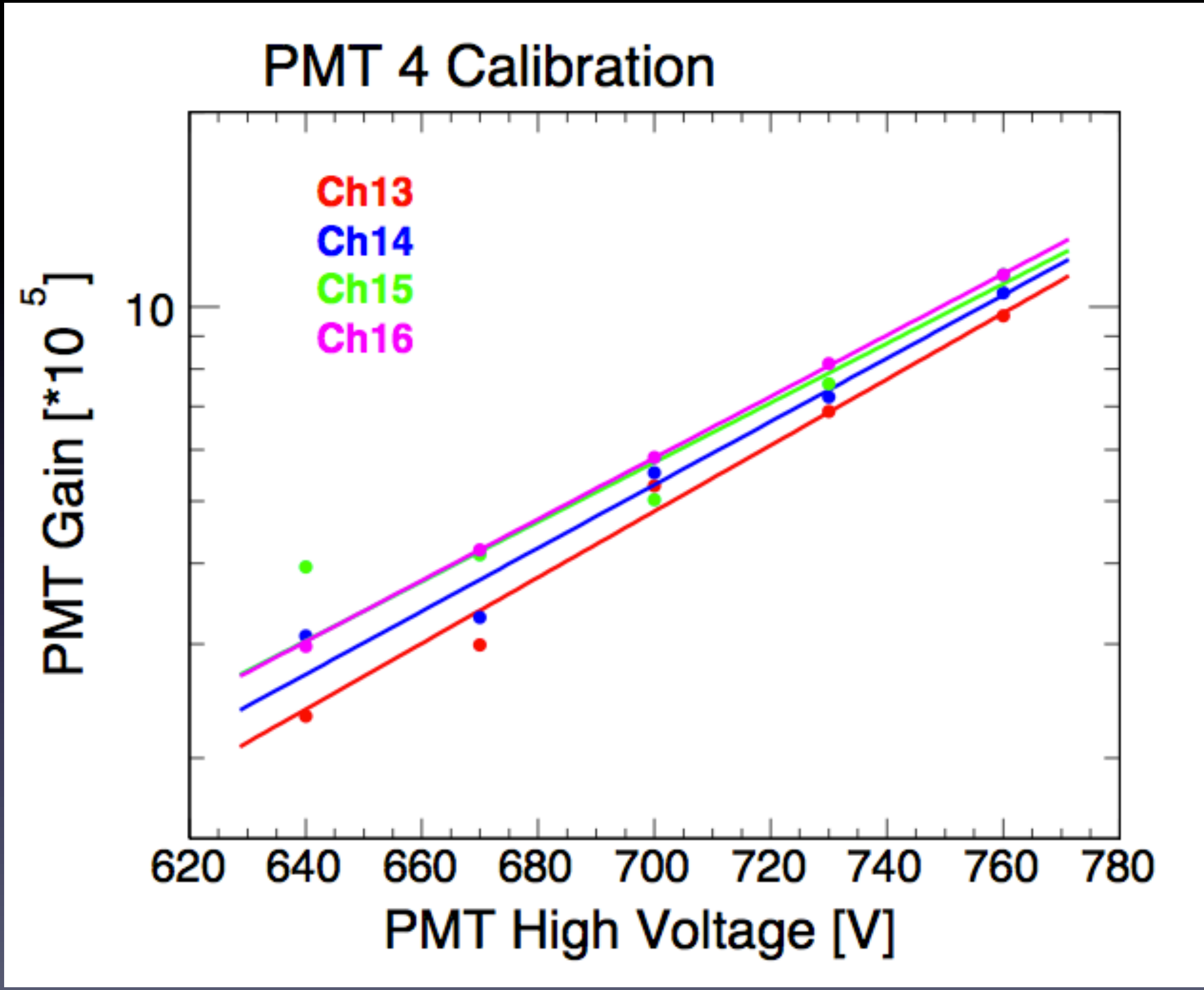
Leff is largest systematic error in reported LXe WIMP searches

$$\mathcal{L}_{\text{eff}}\left(E_{\text{nr}}\right) = \frac{L_{y,\text{nr}}\left(E_{\text{nr}}\right)}{L_{y,\text{er}}\left(E_{\text{er}} = 122\,\text{keV}\right)}$$




PMT 1 Calibration
Ch1
Ch2
Ch3
Ch4
10
PMT Gain [*10^5]
620
640
660
680
700
720
740
760
780
PMT High Voltage [V]


PMT 2 Calibration
Ch5
Ch6
Ch7
Ch8
PMT Gain [*10^5]
10
620
640
660
680
700
720
740
760
780
PMT High Voltage [V]


PMT 4 Calibration
Ch13
Ch14
Ch15
Ch16
10
PMT Gain [*10^5]
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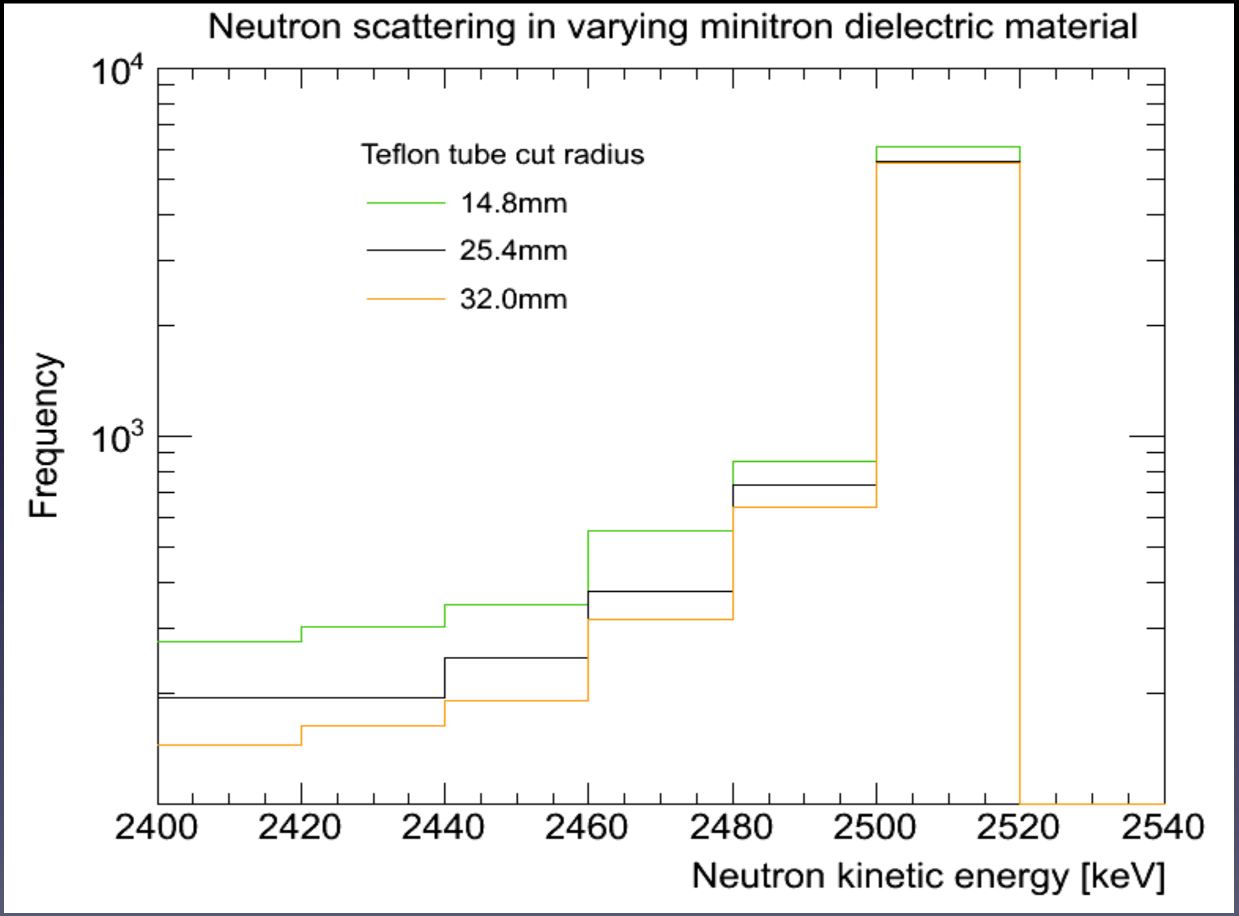
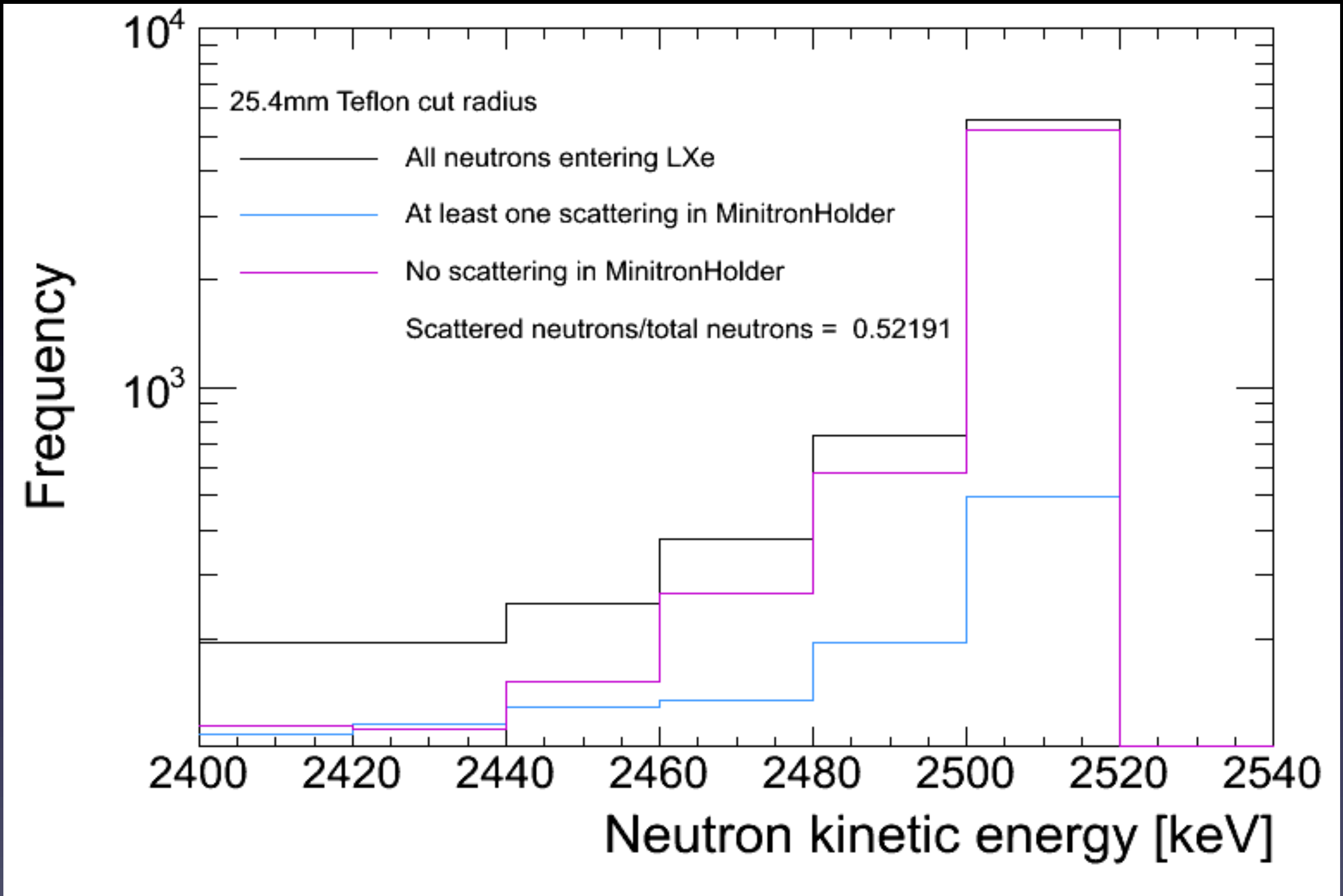
PMT High Voltage [V]

Monte Carlo Simulation of ideal Teflon/Oil ratio

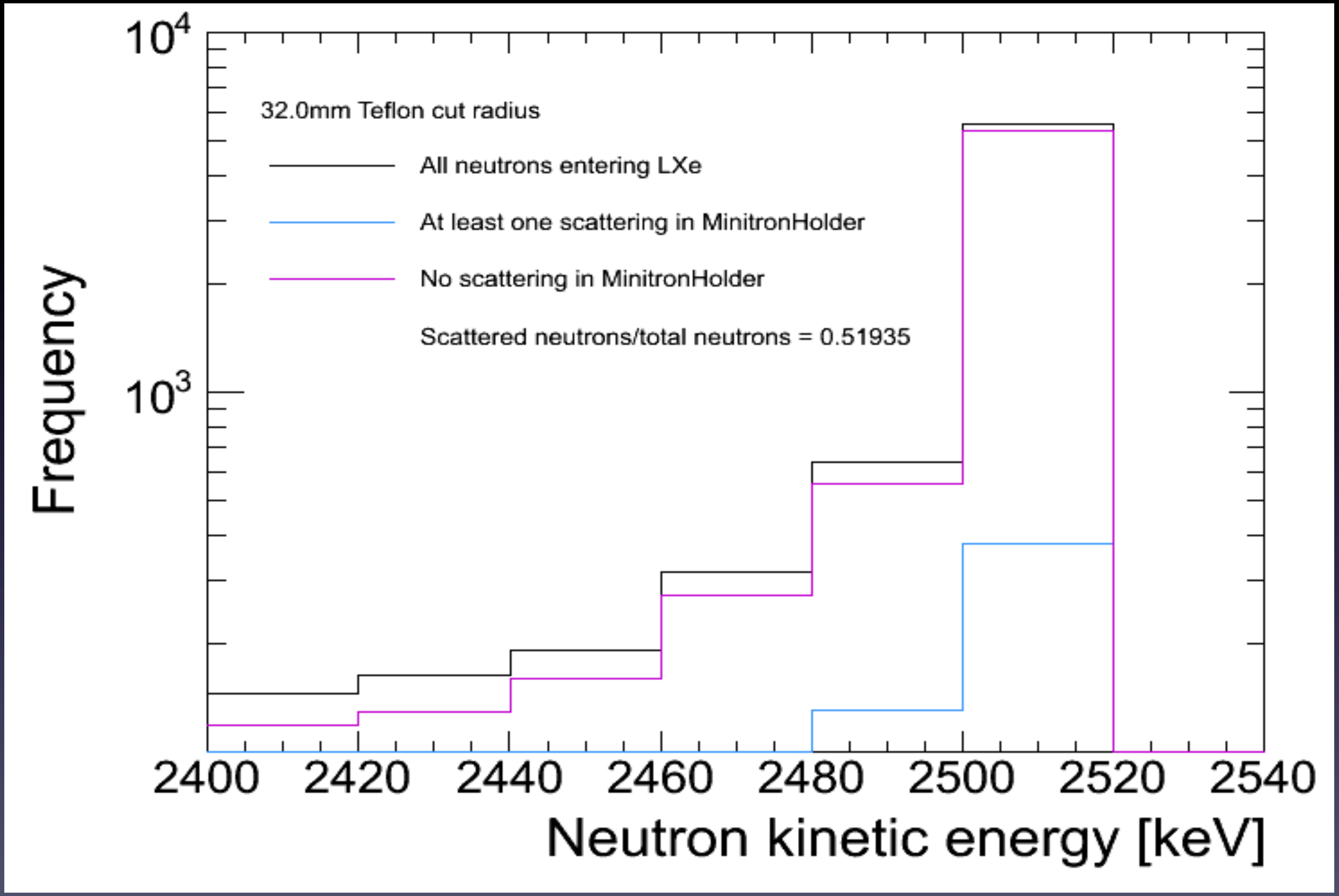


Teflon/oil= 0.50



52 % of neutrons scatter

Teflon/oil = 0.191



52% of neutrons scatter