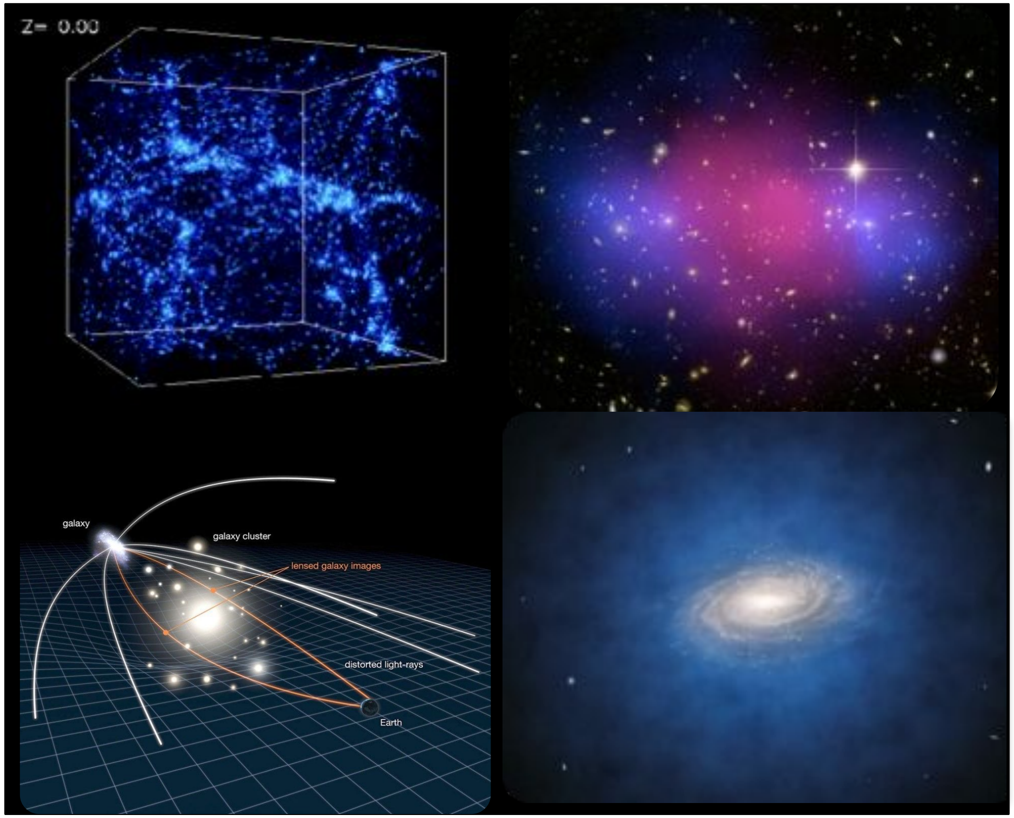
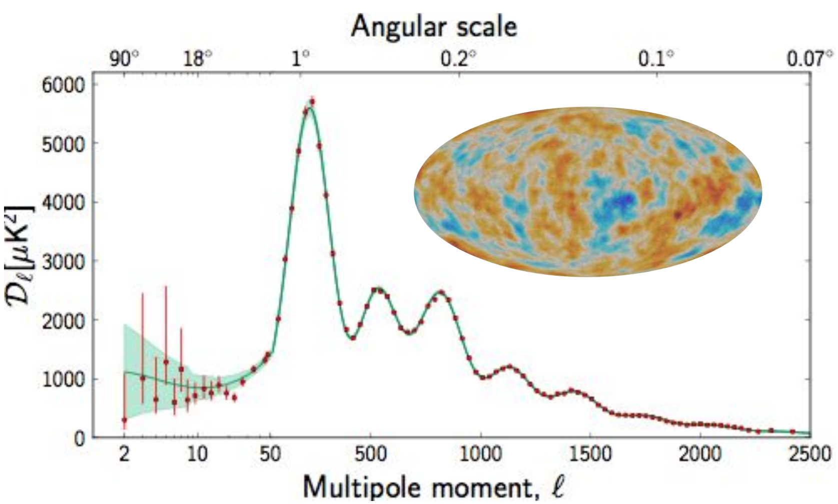
LUX-ZEPLIN

and its Outer Detector

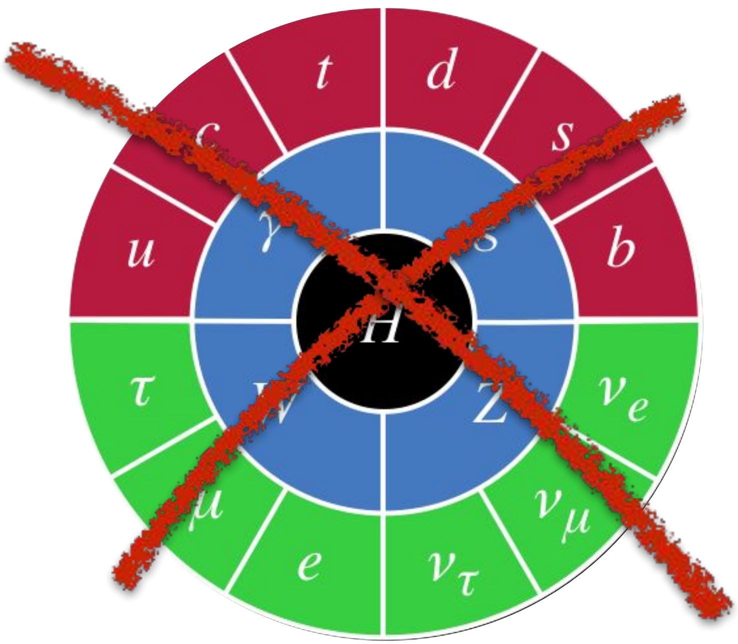
- Dark matter is the only theory that can simulate and reproduces the universe on all scales:
  - Galaxy rotation curves
  - Galaxy clustering
  - Cluster collision
  - Large-scale structures
  - CMB fluctuations
  - Gravitational lensing





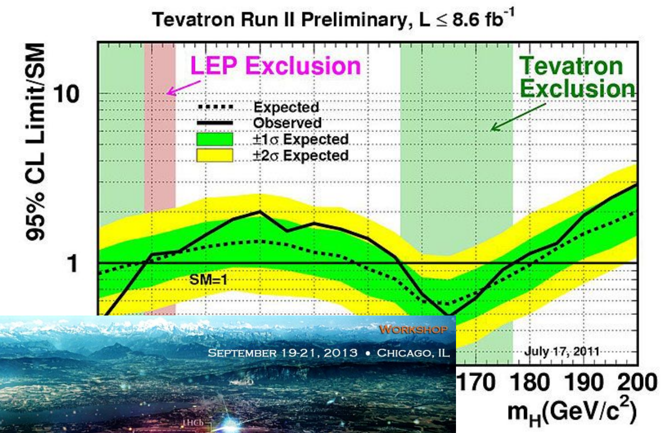
- Standard Model of Cosmology, ΛCDM: $\Omega_\Lambda \approx 0.68$, $\Omega_{DM} \approx 0.27$, $\Omega_b \approx 0.05$

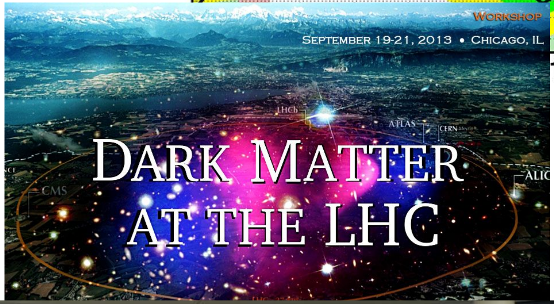
- Unambiguous evidence for new physics



- How to reap the reward?

- Before Direct Detection I worked on collider (D0, ATLAS, CMS)
    - Fellow at Imperial, lecturer at Bristol
    - Mostly Higgs and collider DM
- My group is the newest group in LZ, world's most sensitive direct DM experiment
    - 1 postdoc, 4 PhD students (1 from Bristol), 2 engineers, several undergraduates

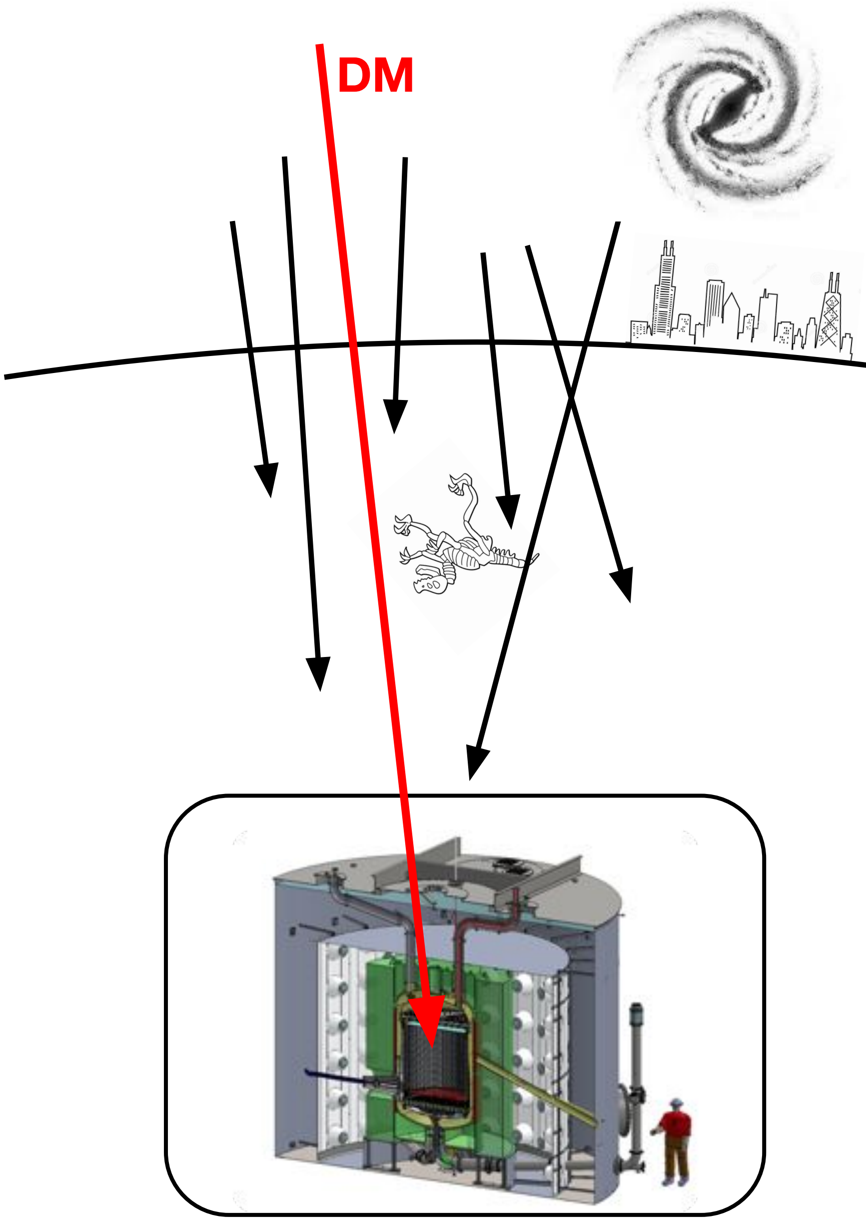




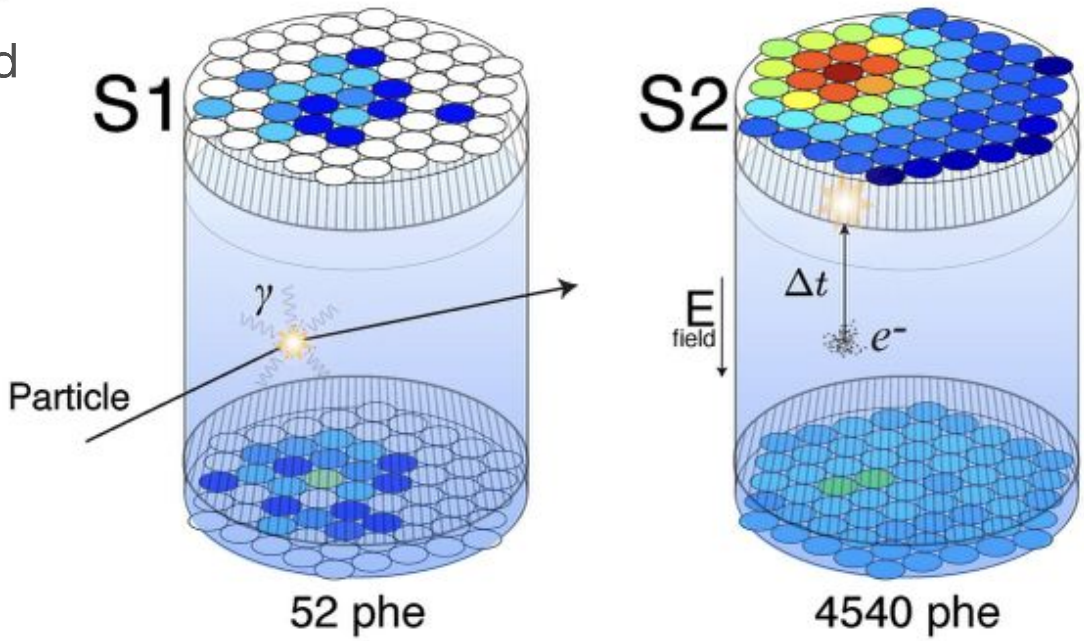

LZ Collaboration Week at Brandeis 2018

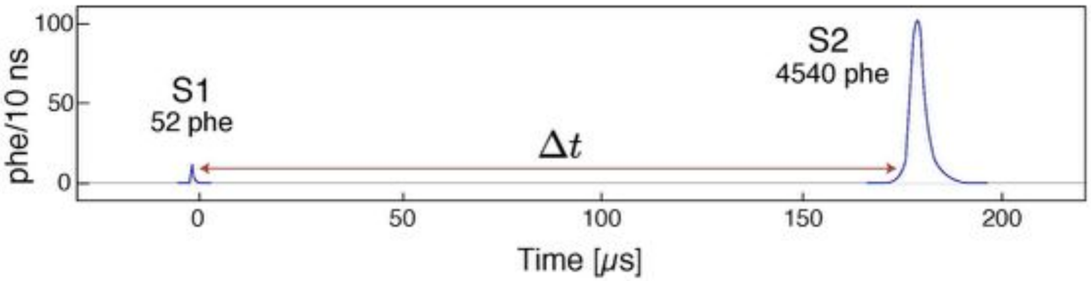
Direct Detection Overview

- Detect DM as our solar system passes through the galactic halo
  - $v \sim 10^{-3}$ c
  - Kinetic energy ~100 keV
- Leads to recoils in the target material in ultra-sensitive detectors
- Very rare events: ~1 interaction/kg/yr
- Requires (nuclear) background free detectors with single photon detection capabilities
  - Very stringent cleanliness and background requirements
- Variety of technologies developed, liquid xenon searches most sensitive
  - LXe very heavy, clean, excellent self shielding and particle discrimination

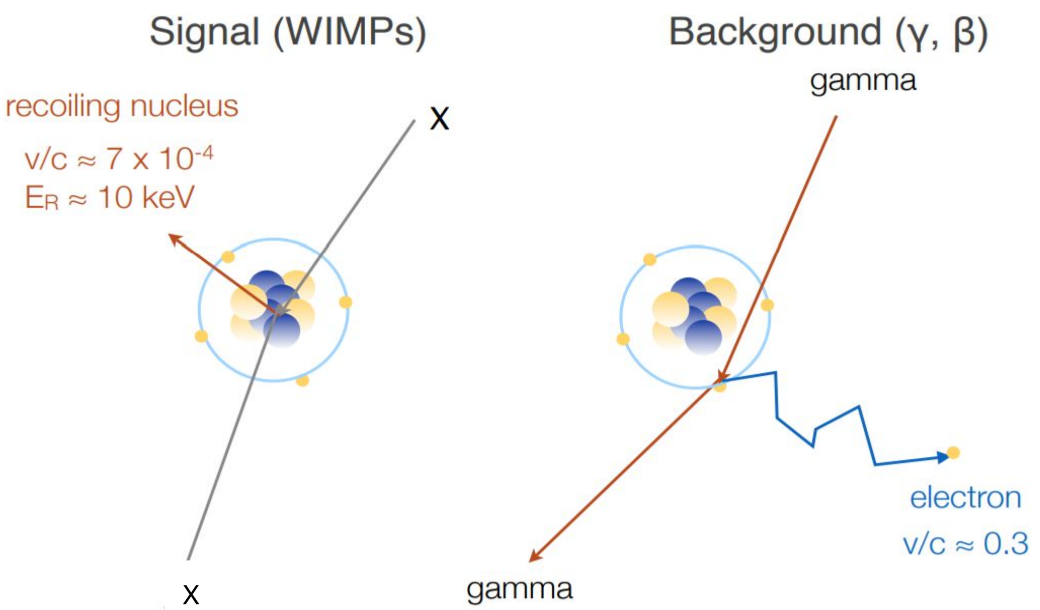


- Dual phase TPC, two signals
  - Prompt scintillation light (S1)
  - Prop. charge signal amplified in gas (S2)
- Signal ratio allows to discriminate particle
  - Electron scatter tend to produce more charge
  - Neutron scatter create more light
- Depth (z) from time difference between S1/S2 and light pattern (x, y)

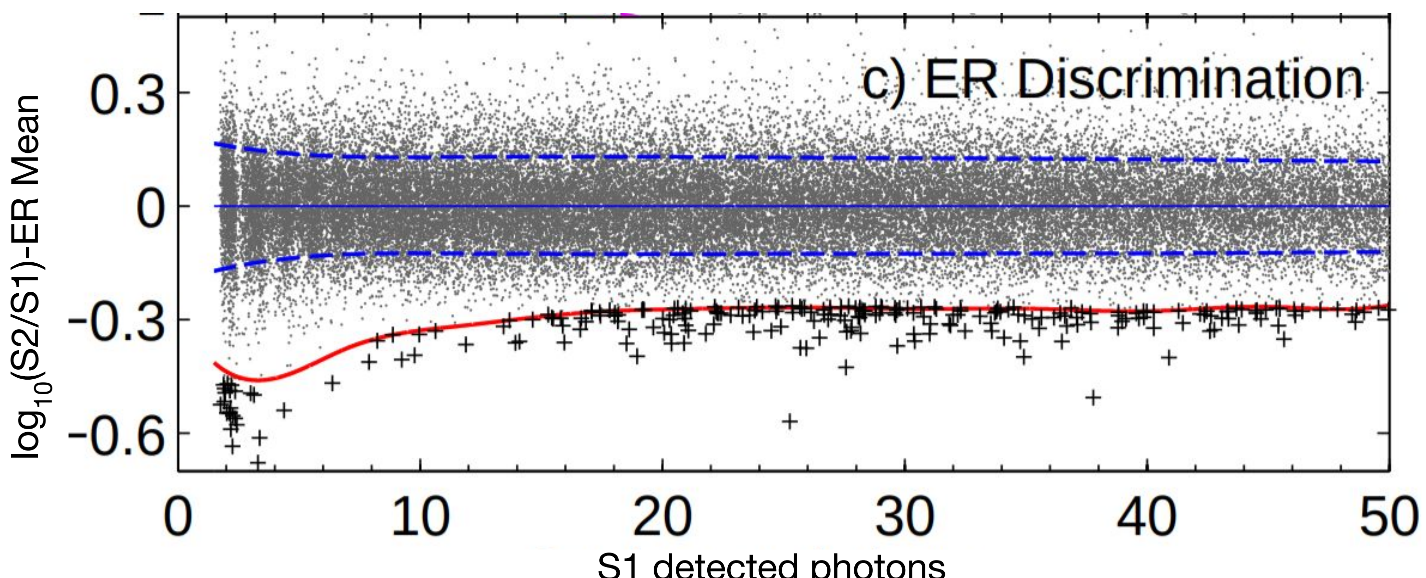


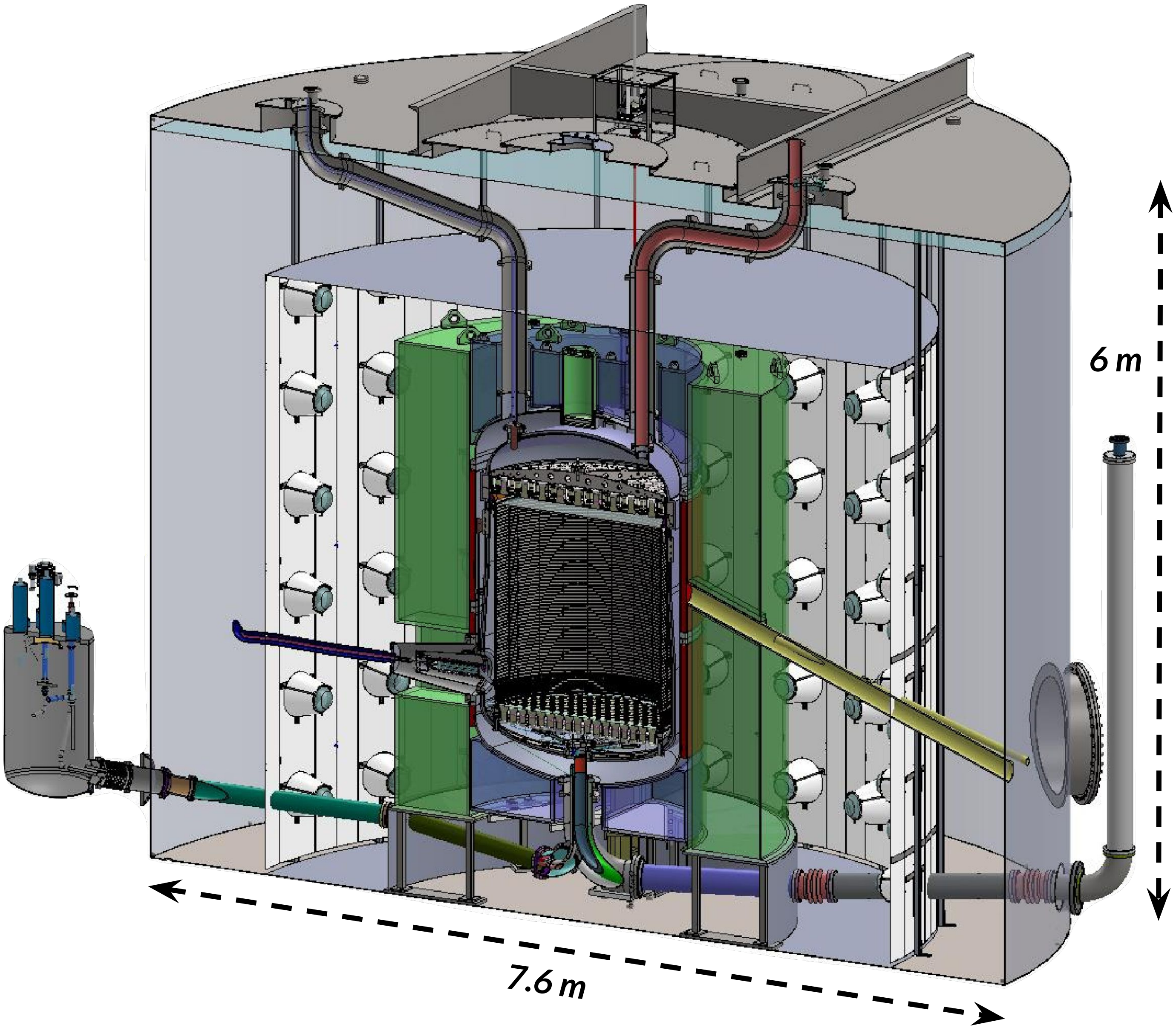


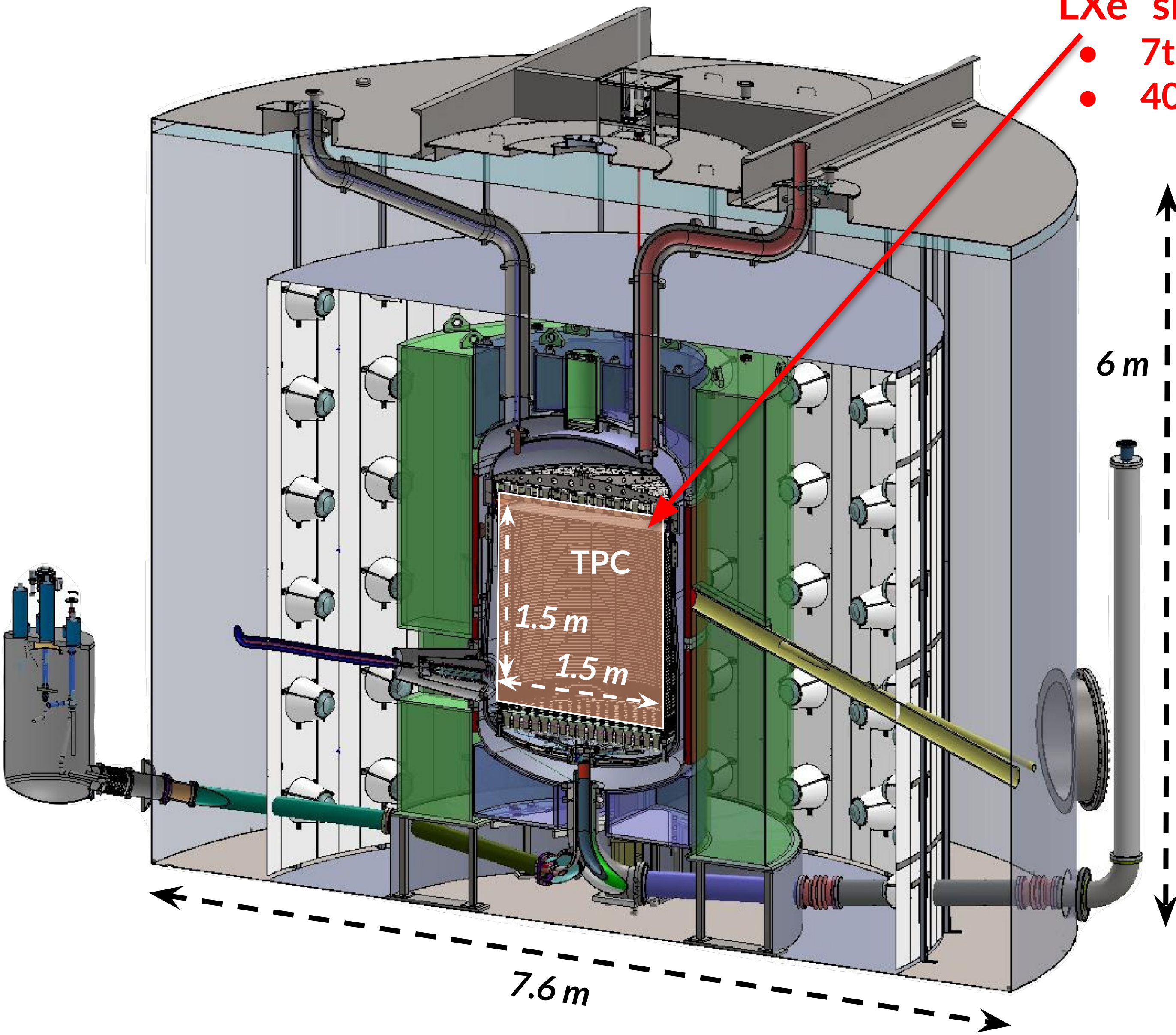
Signal Discrimination

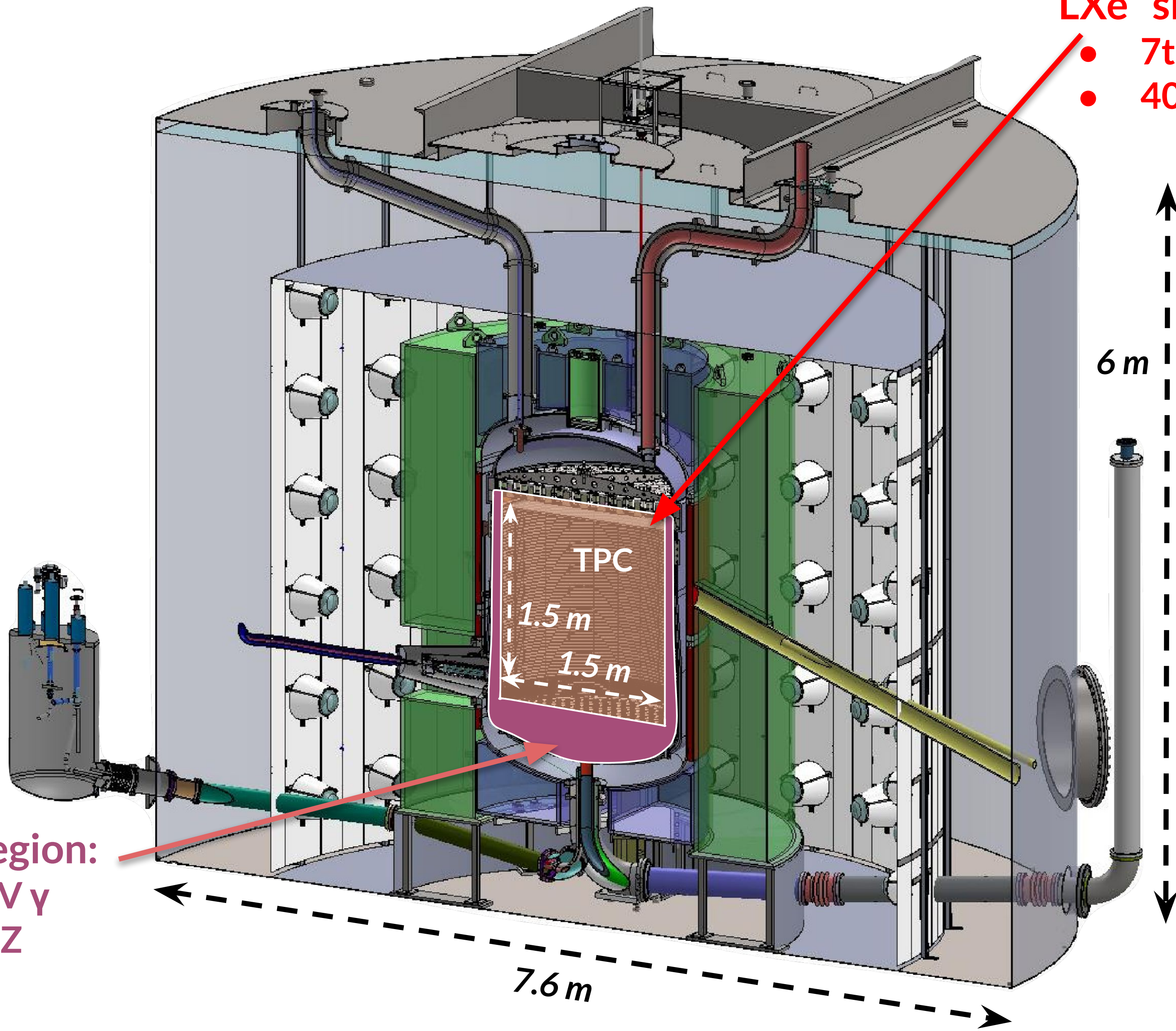


- Ionization/excitation (charge/light) depends on dE/dx
- Excellent discrimination of signal (WIMPS → NR) and most backgrounds (γ → ER)
- 99.5% separation before statistical methods



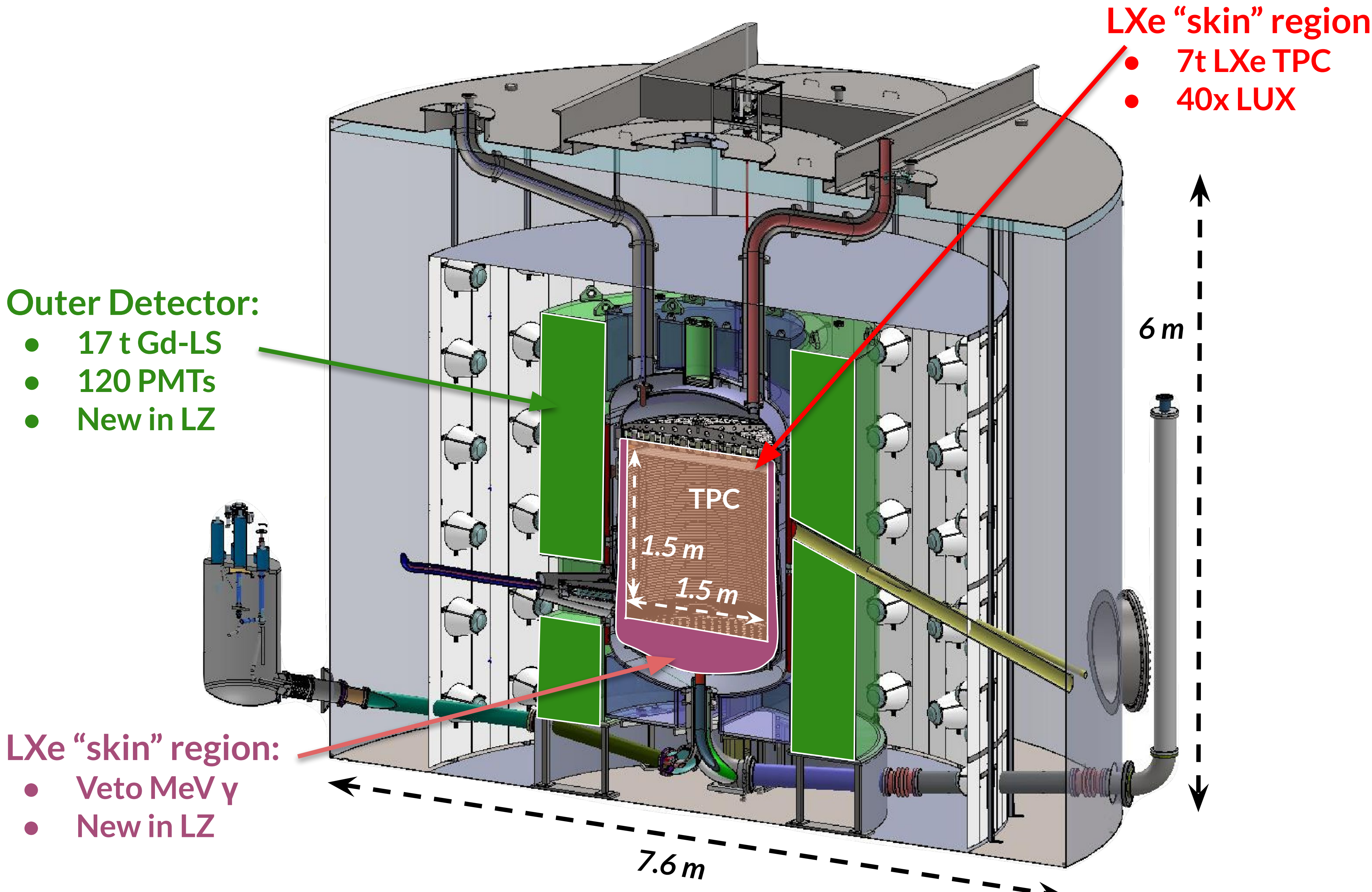

6 m
7.6 m


LXe "skin" region
7t LXe TPC
40x LUX
6 m
TPC
1.5 m
1.5 m
7.6 m



LXe “skin” region
- 7t LXe TPC
- 40x LUX

LXe “skin” region:
- Veto MeV γ
- New in LZ



LXe "skin" region
• 7t LXe TPC
• 40x LUX
Outer Detector:
• 17 t Gd-LS
• 120 PMTs
• New in LZ
TPC
1.5 m
1.5 m
6 m
7.6 m
LXe "skin" region:
• Veto MeV γ
• New in LZ

Water shield:
- 230 t DI water
- Instrumented

Outer Detector:
- 17 t Gd-LS
- 120 PMTs
- New in LZ

LXe “skin” region:
- Veto MeV γ
- New in LZ

LXe “skin” region
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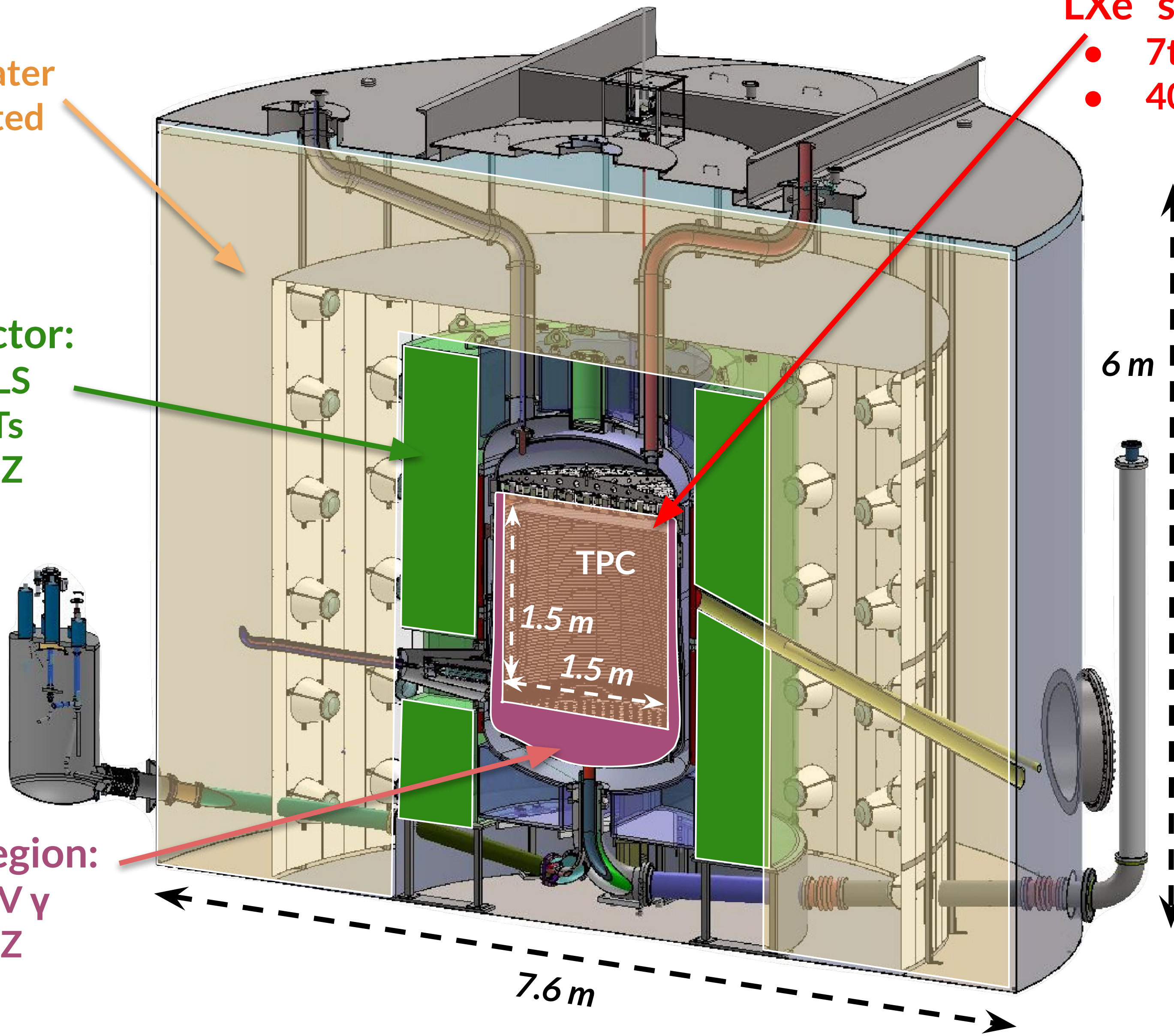
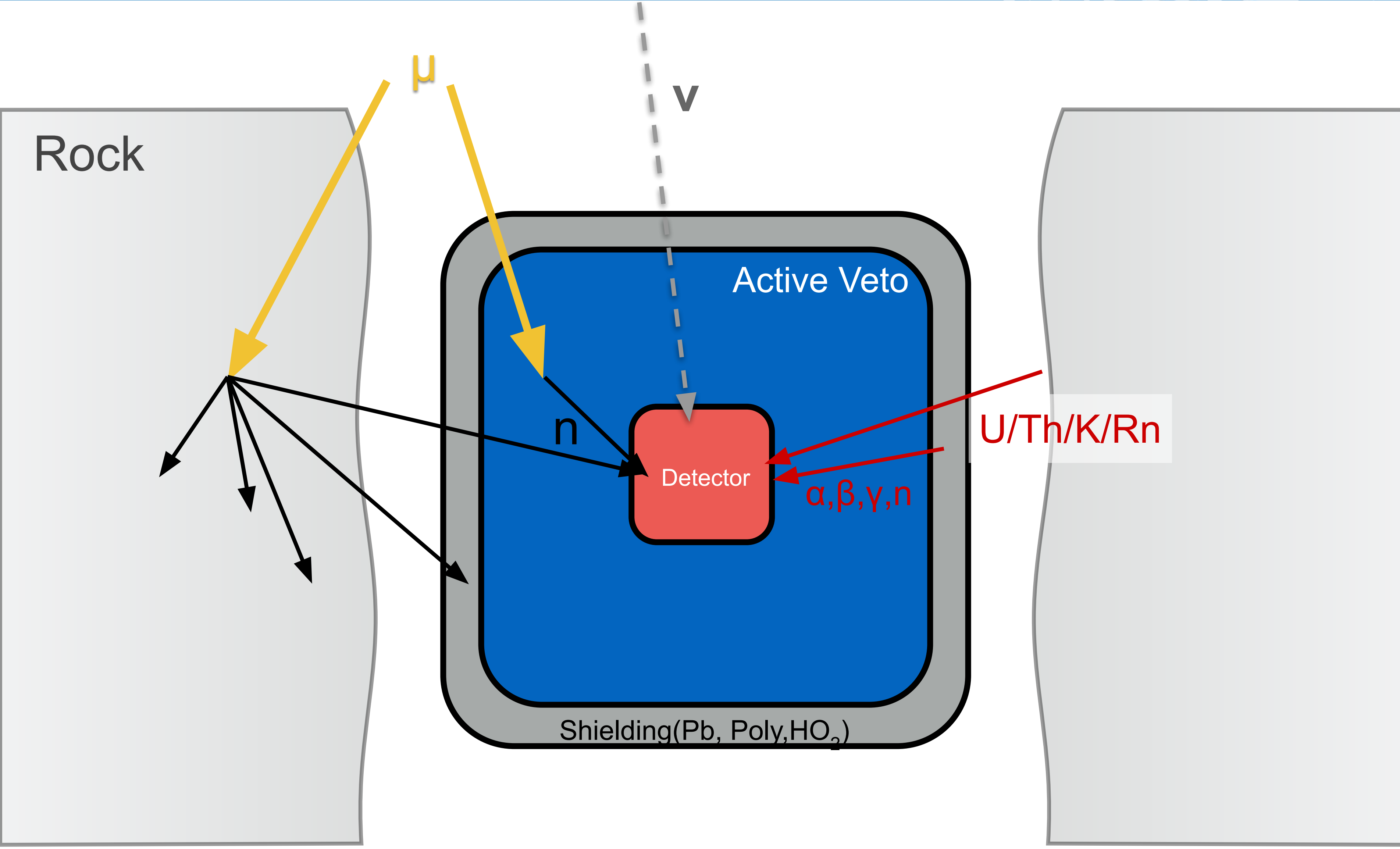
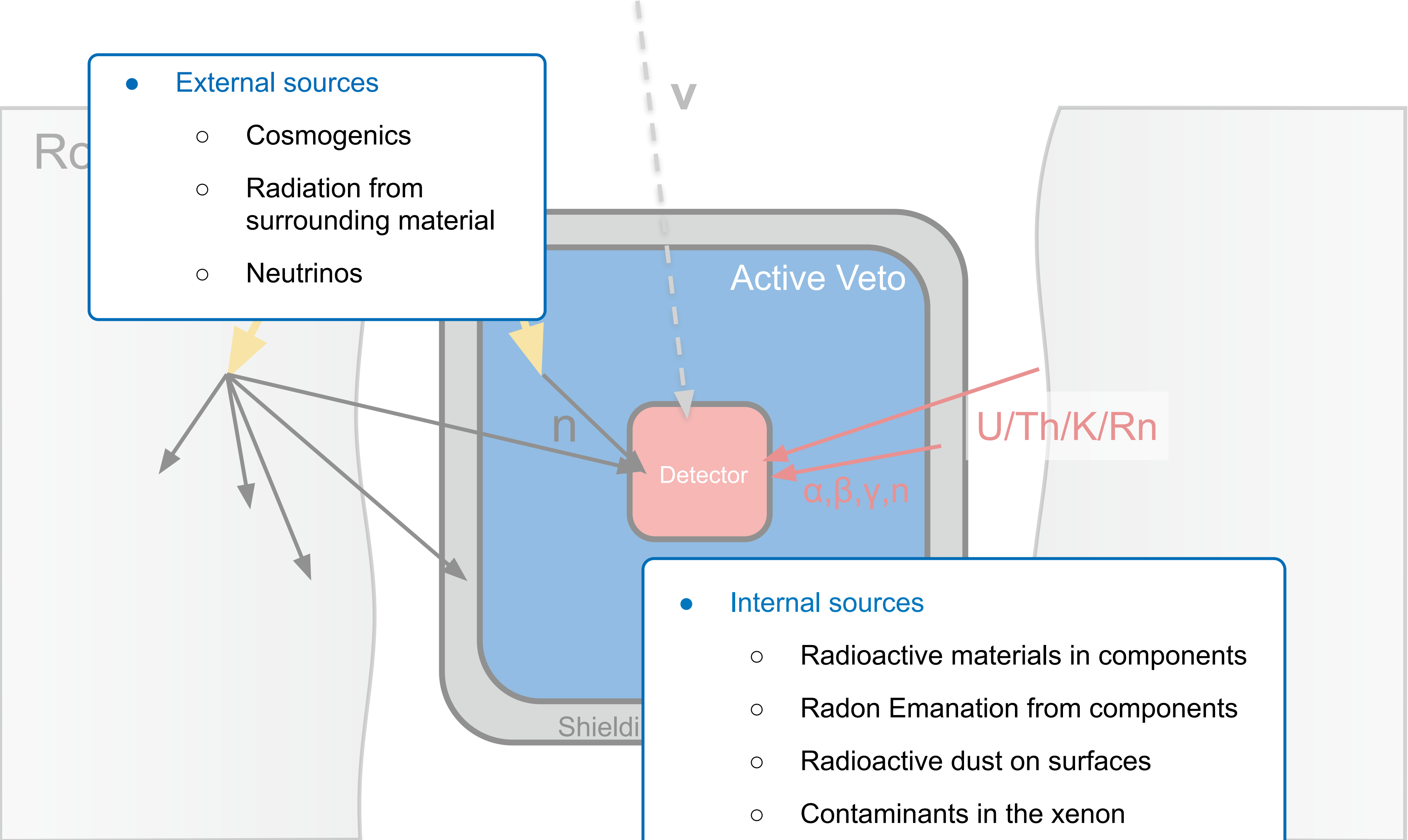




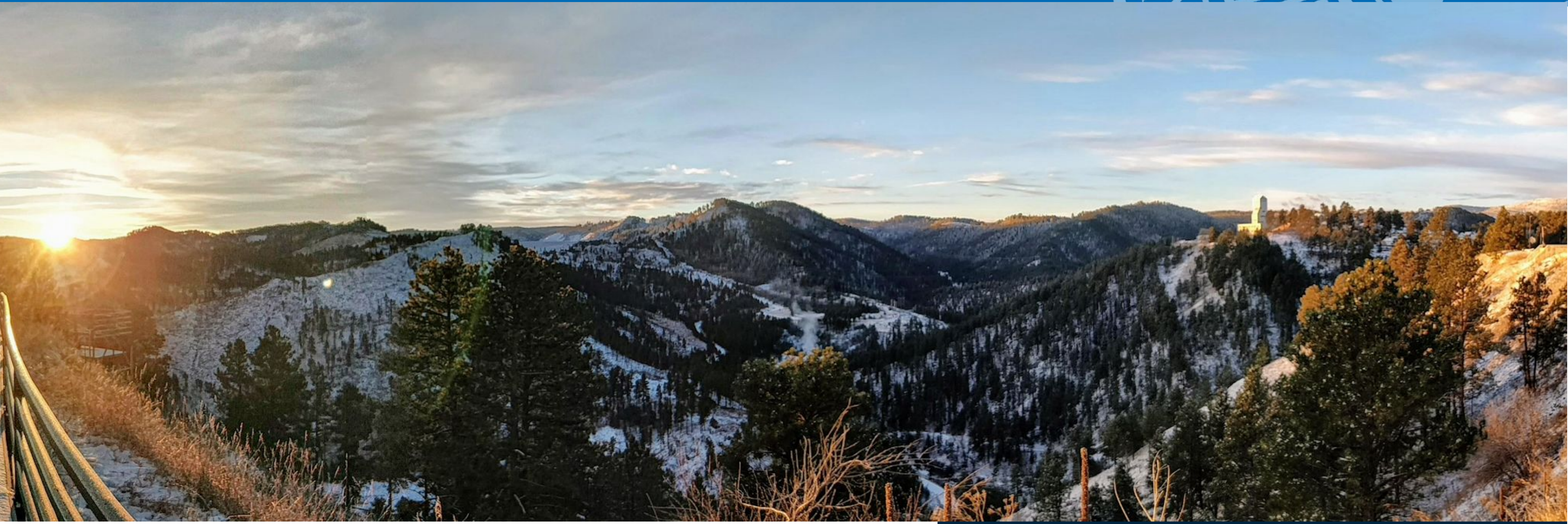
- Backgrounds: cosmogenic sources and primordial nuclides



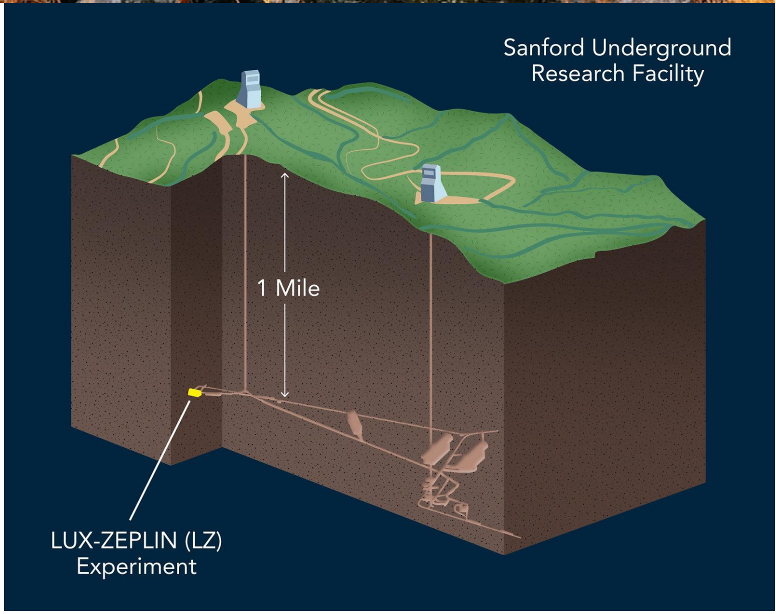
- External sources
  - Cosmogenics
  - Radiation from surrounding material
  - Neutrinos

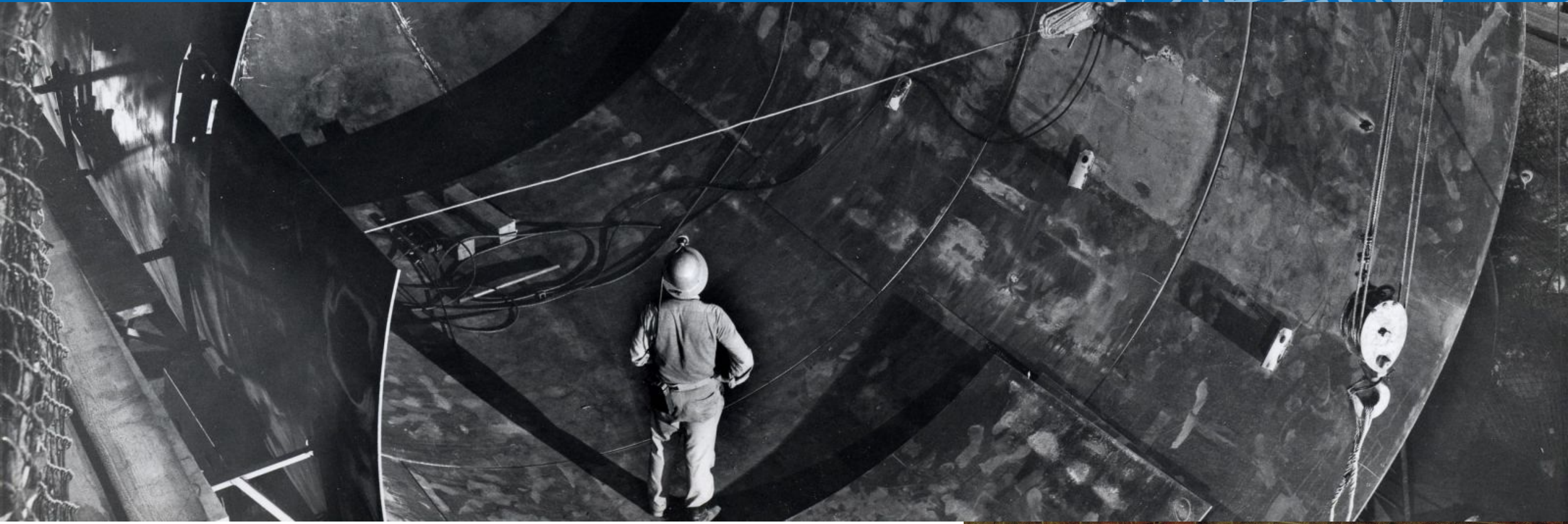
- Internal sources
  - Radioactive materials in components
  - Radon Emanation from components
  - Radioactive dust on surfaces
  - Contaminants in the xenon

- Backgrounds: cosmogenic sources and primordial nuclides



- Located in Sanford Underground Research Facility to shield from cosmogenic bkgds:
  - Go deep! 1 mile underground (4850 feet)
  - Reduced muon flux by 10^7
- Also home to other experiments:
  - DUNE, CASPAR…
  - Ray Davis Experiment





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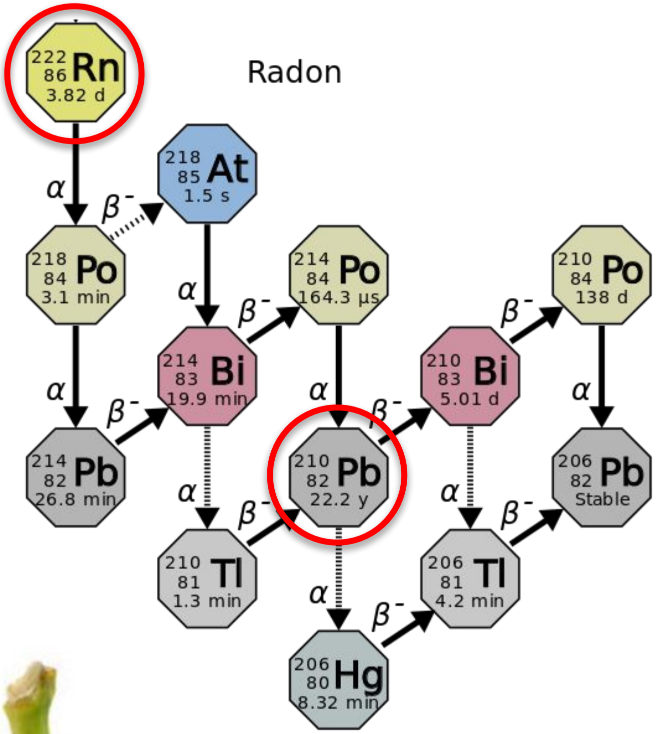
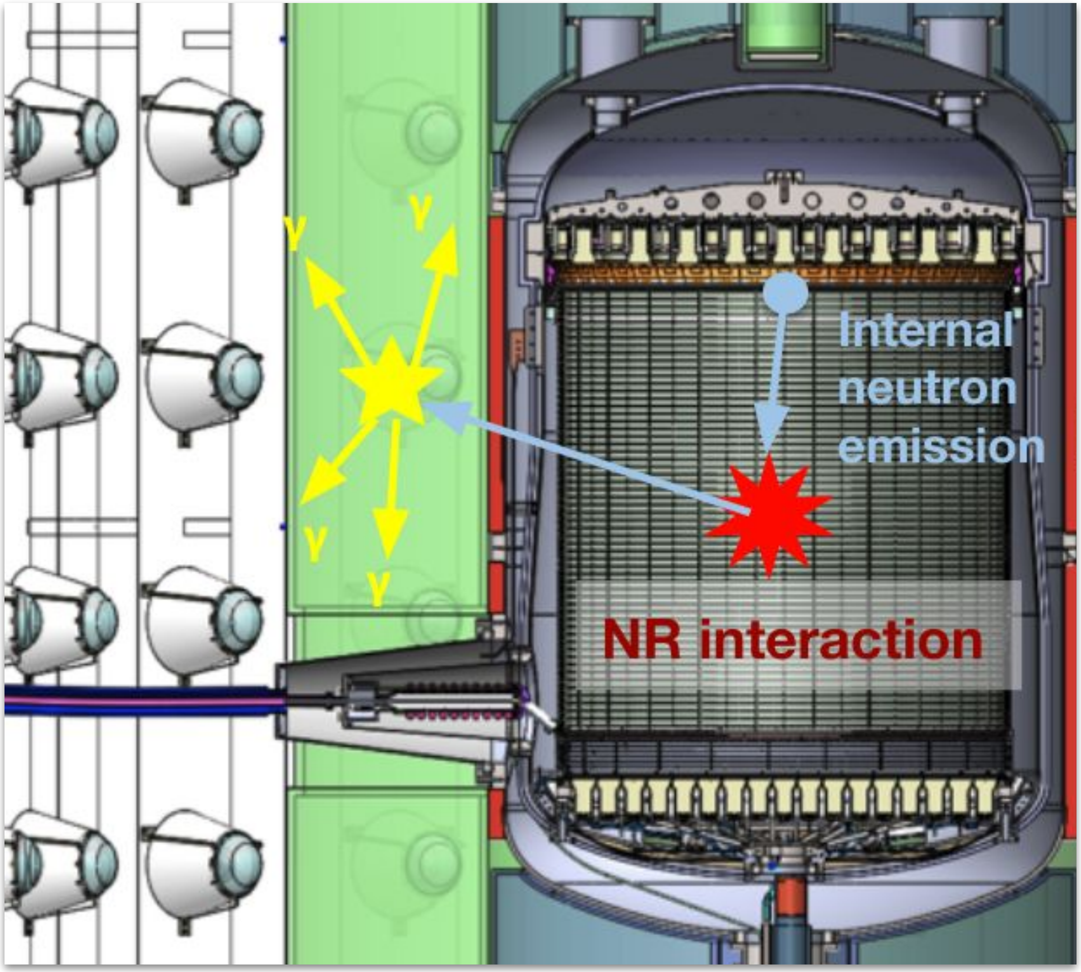


1 Banana = 15 Bq

- Detector materials:
  - Screening of all materials in or close to detector
  - Use only purest materials obtainable
  - Target activity: O(mBq/kg) - 1/15,000 Bananas
- Radon emanation
  - Four screening sites and two portable assays
  - Reduce Rn from warm components by > x10
  - Target activity: 2 µBq/kg - 1/750,000 Bananas
- Radon daughters and dust on surfaces
  - TPC assembly in Rn-reduced cleanroom
  - Dust < 500 ng/cm^3 on all LXe wetted surfaces
  - Rn-daughter plate-out on TPC walls < 0.5 mBq/m^2 - 1/30,000 Bananas
- Reduce Xenon contaminants to O(0.015 ppt)
- Cleaning, cleaning, cleaning, cleaning!

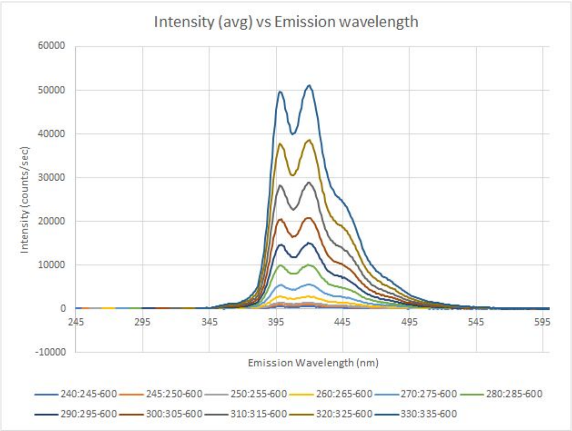
The Outer Detector

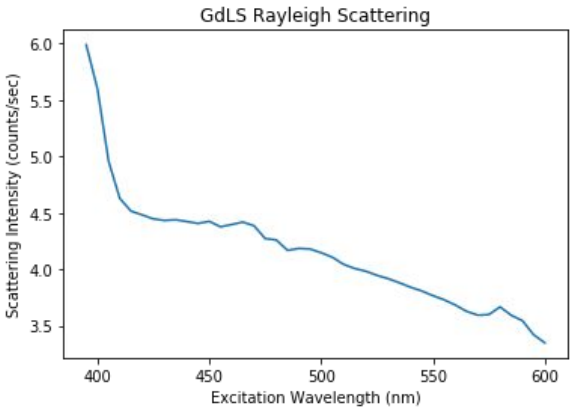
- Capture remaining external and internal backgrounds
- Central TPC surrounded with three active veto detectors:
    - Xe ‘skin’ to veto γ-rays,
    - Outer Detector to veto neutrons in Gd-LS
    - Muons in water
- Increases the usable active (fiducial) volume by 70%
- In case of discovery to be able to demonstrate a possible DM signal is not induced by neutrons

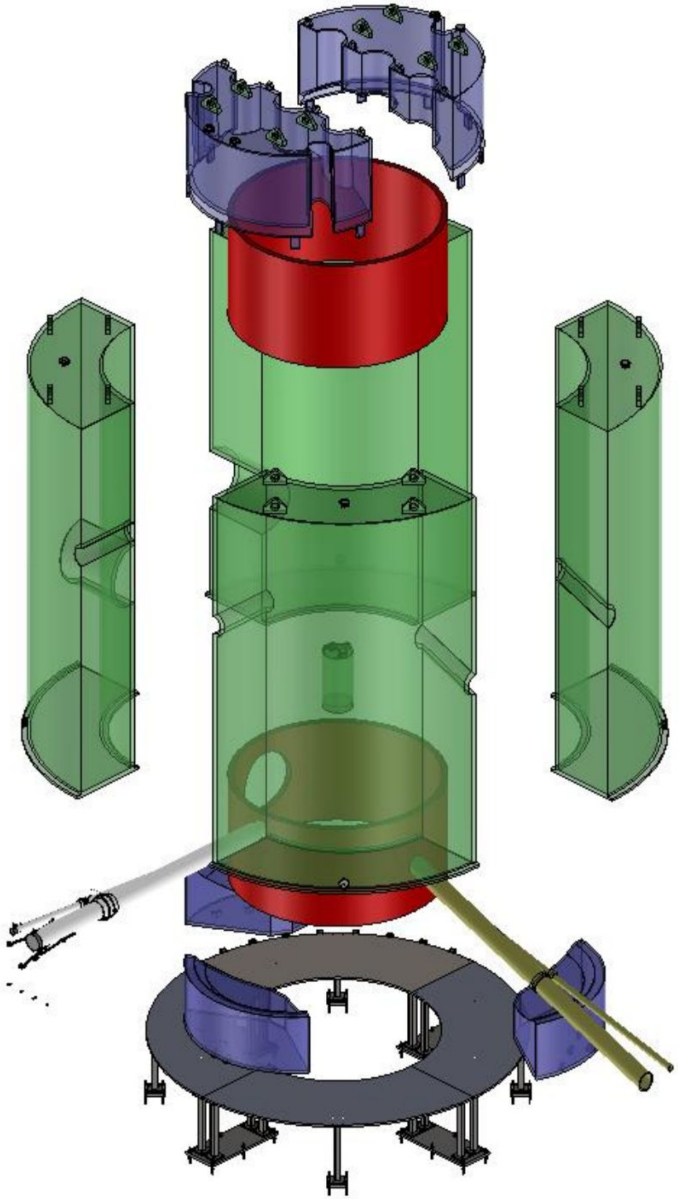


Scintillator

- The Outer Detector (OD) surrounds the central cryostat hermetically, filled with 17 t of scintillator
- Liquid scintillator is doped with 0.1% Gd (Gd-LS) and held in large acrylic vessels
- Manufactured from UV transparent acrylic by Reynolds Polymer, design by UCSB
- Brandeis strongly contributed, long term stay at BNL
  - Set up production facilities
  - Property measurements of Gd-LS







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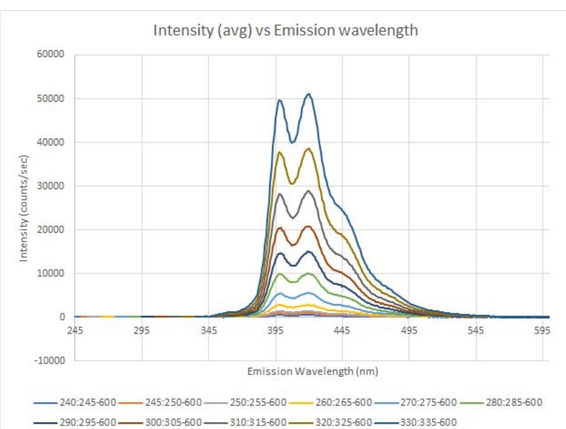
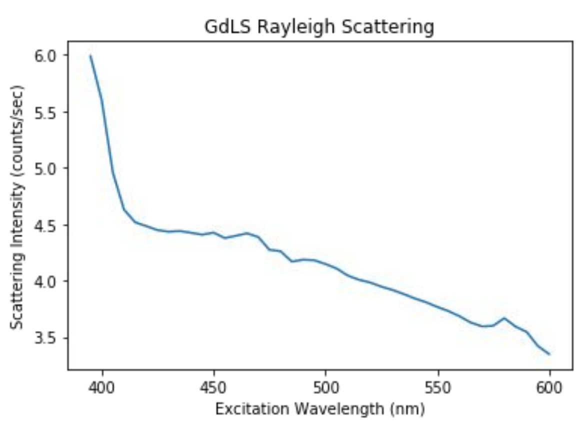
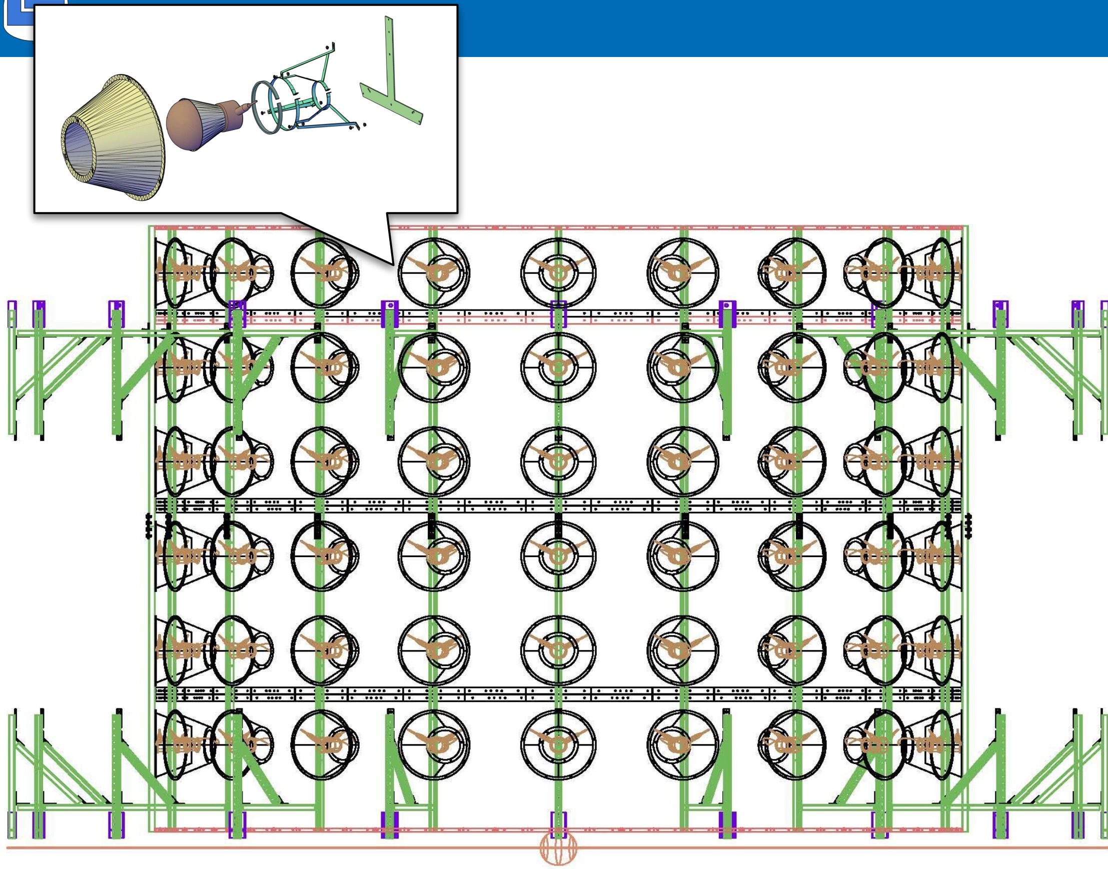
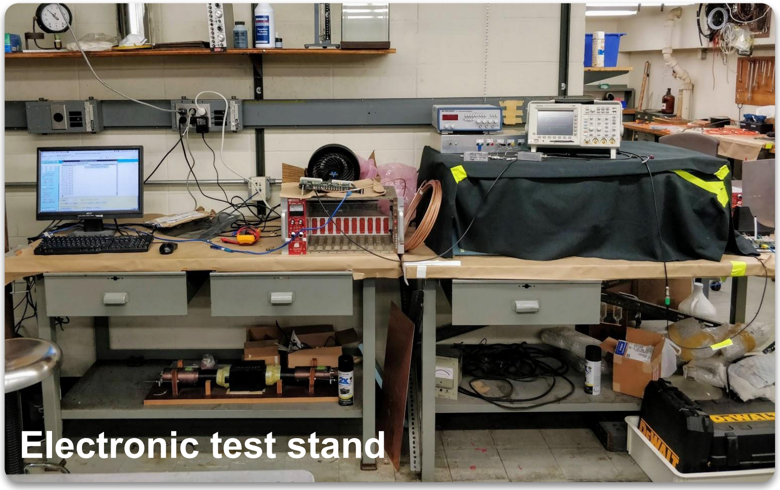


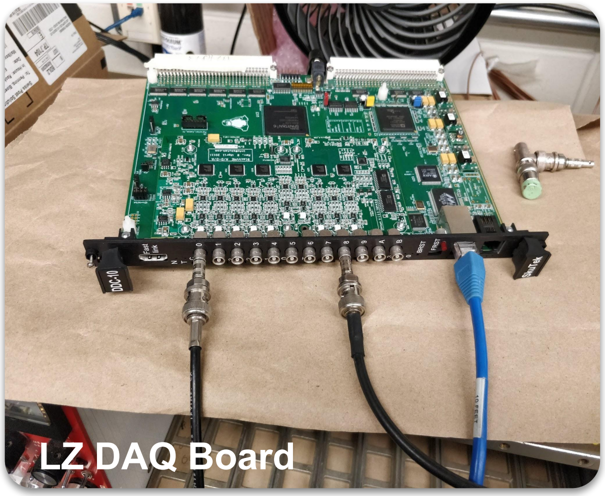


The OD Instrumentation

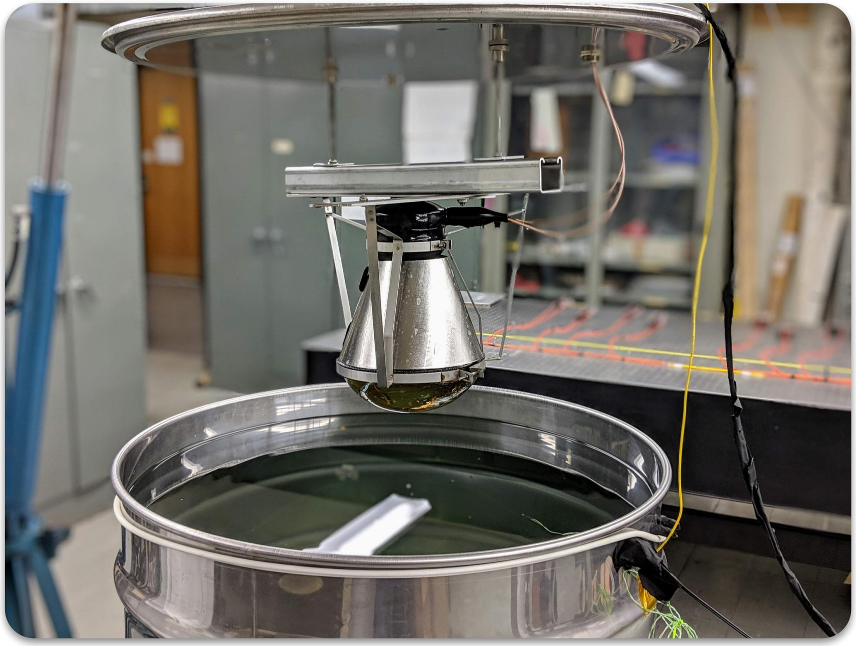


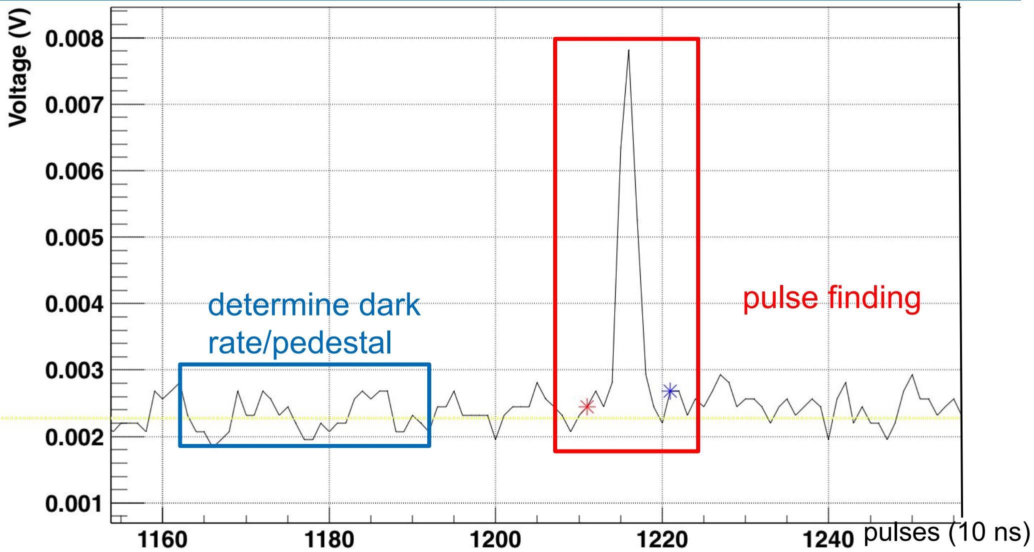
- Tanks viewed by OD instrumentation system
  - About 15.000 parts in DI water
  - 120 PMTs (Hamamatsu R5912)
- Design, manufacturing and physics development performed by my group
- Picture: Test installation in mine

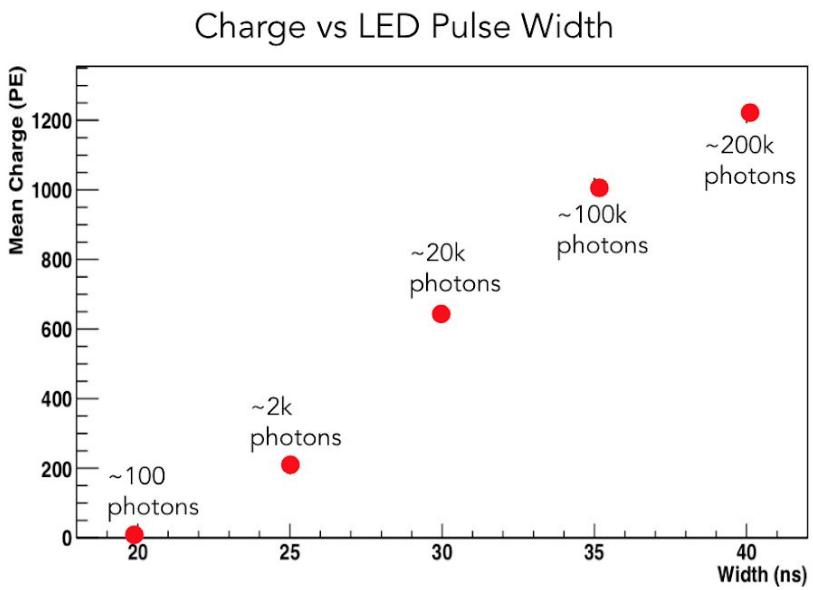




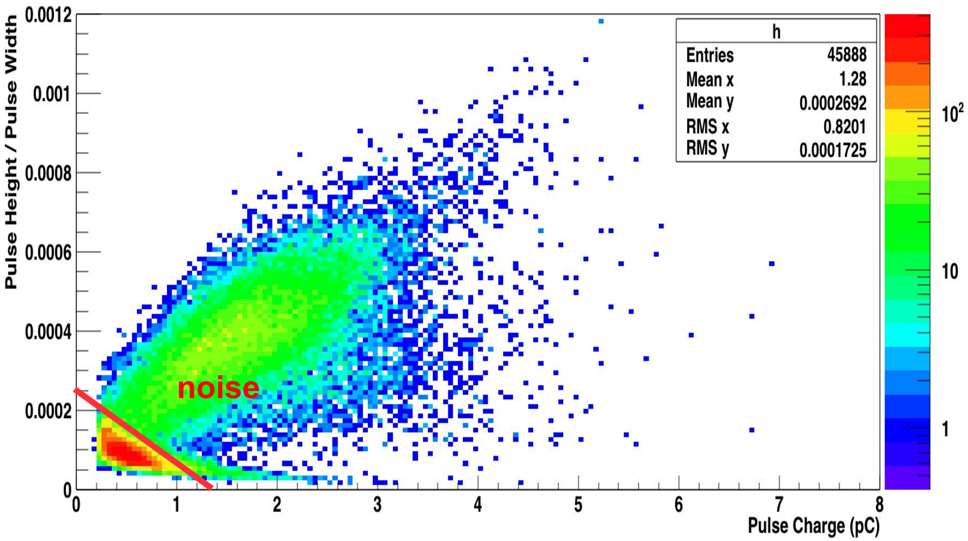
- Developing and testing materials, hardware, electronics & readout under realistic conditions
- OD test stand allows to gain experience in operations and analysis
  - Components identical to final system
- Excellent training resource for students
- Clean room for assembly







- Using this setup to develop reconstruction and DQ algorithms:
  - Pulse finding, noise suppression
  - DQ/monitoring of PMT health
  - Data Format
  - Calibration
  - Reconstruction & physics analysis
- Testing PMTs if necessary
- Preparing underground operations tests



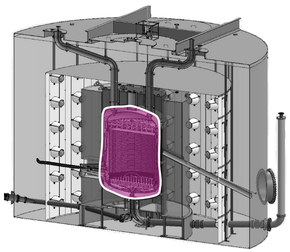
OD Production

- Entire system fabricated at Brandeis:
  - 128 PMTs tested and integrated in clean room
  - Manufacturing & treatment of 15k parts for PMT support system
  - Gas & light tight flanges with feedthroughs
  - Reflector system

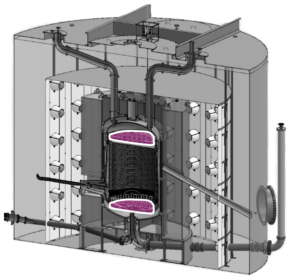
- First university group with permanent presence at SURF
  - Allowed to expand responsibilities to TPC
- Leadership positions in the LZ:
  - Operations Manager Outer Detector
  - Underground Shift Manager
  - L3 Outer Detector Manager
  - Surface Lab Manager during assembly of the TPC

Brandeis House in Lead, SD

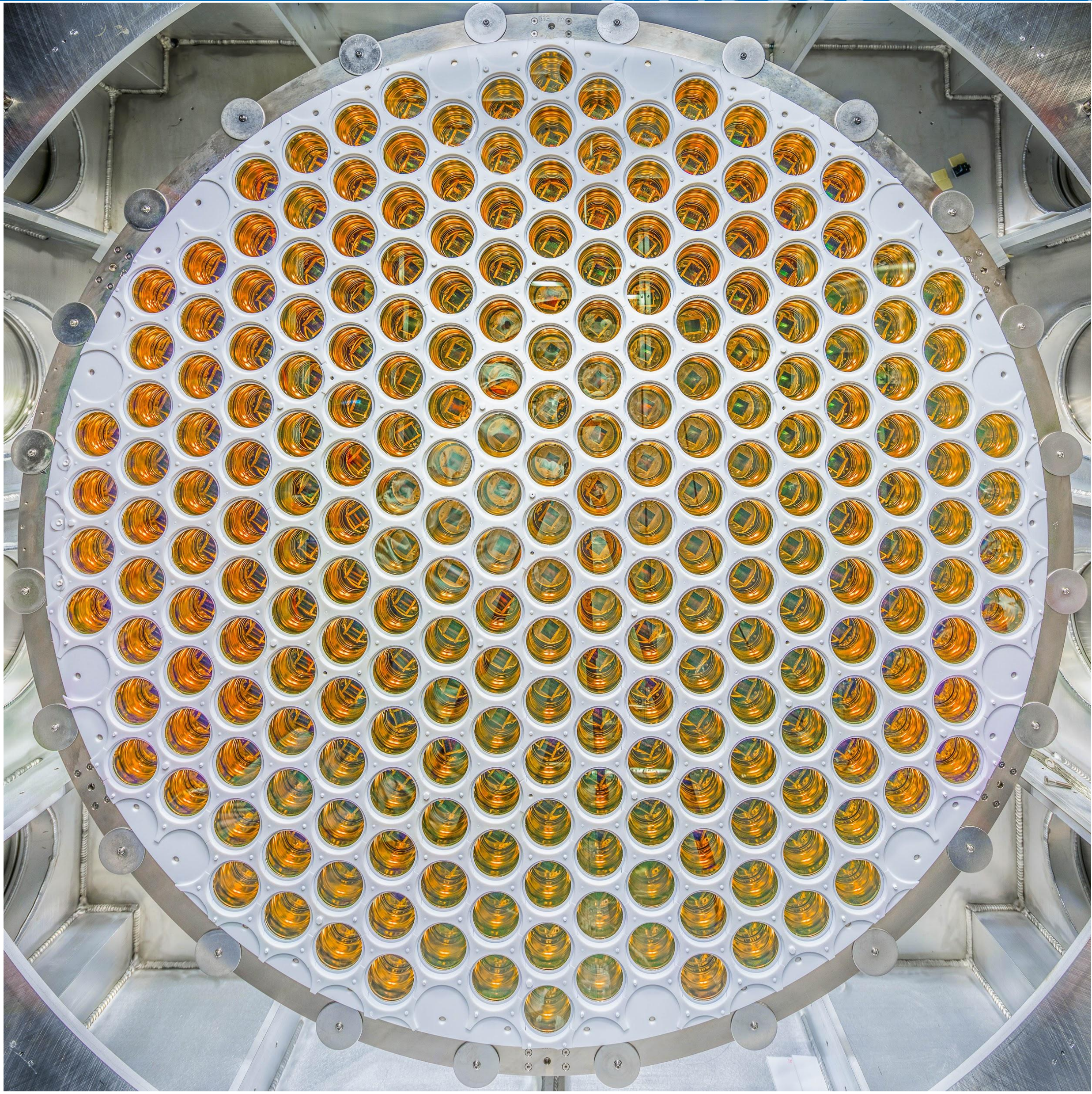
LZ Status

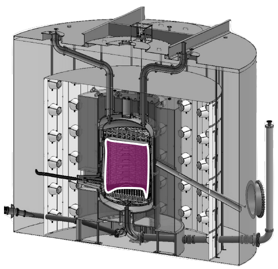


- Two cryostats, inner and outer made from low activity titanium
- Outer cryostat vessel (OCV) underground
- Inner cryostat vessel (ICV), lined with PTFE, holds TPC

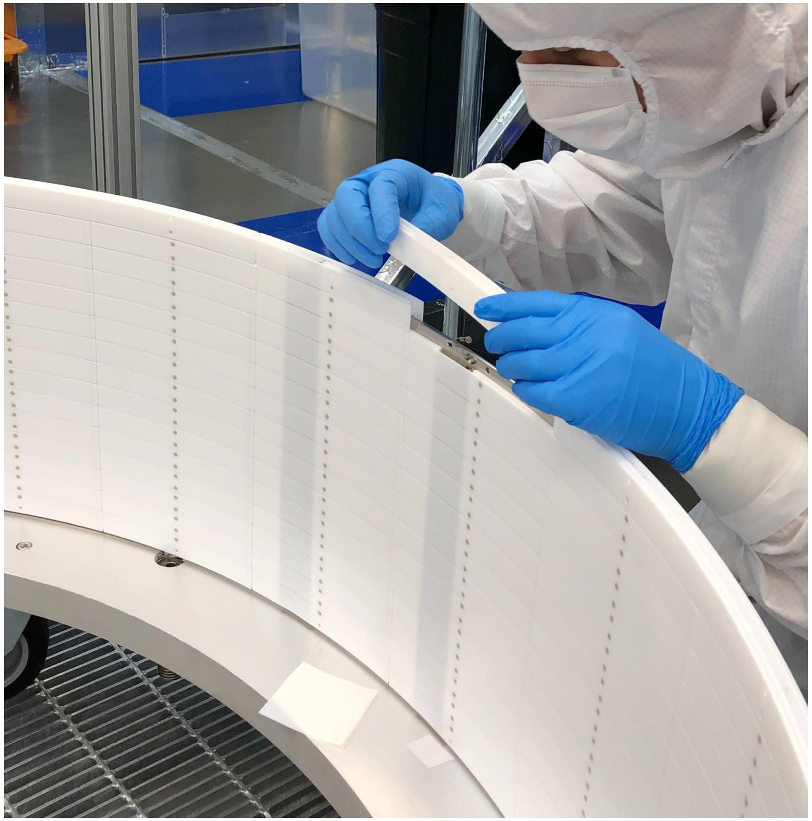


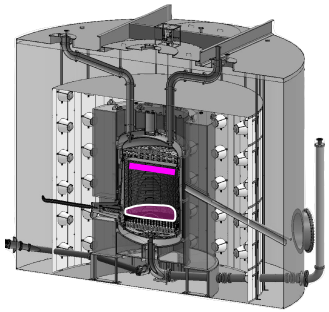
- 625 PMTs:
  - 253 x 3” top array
  - 241 x 3” bottom array
  - 93 x1” and 38 x2” skin



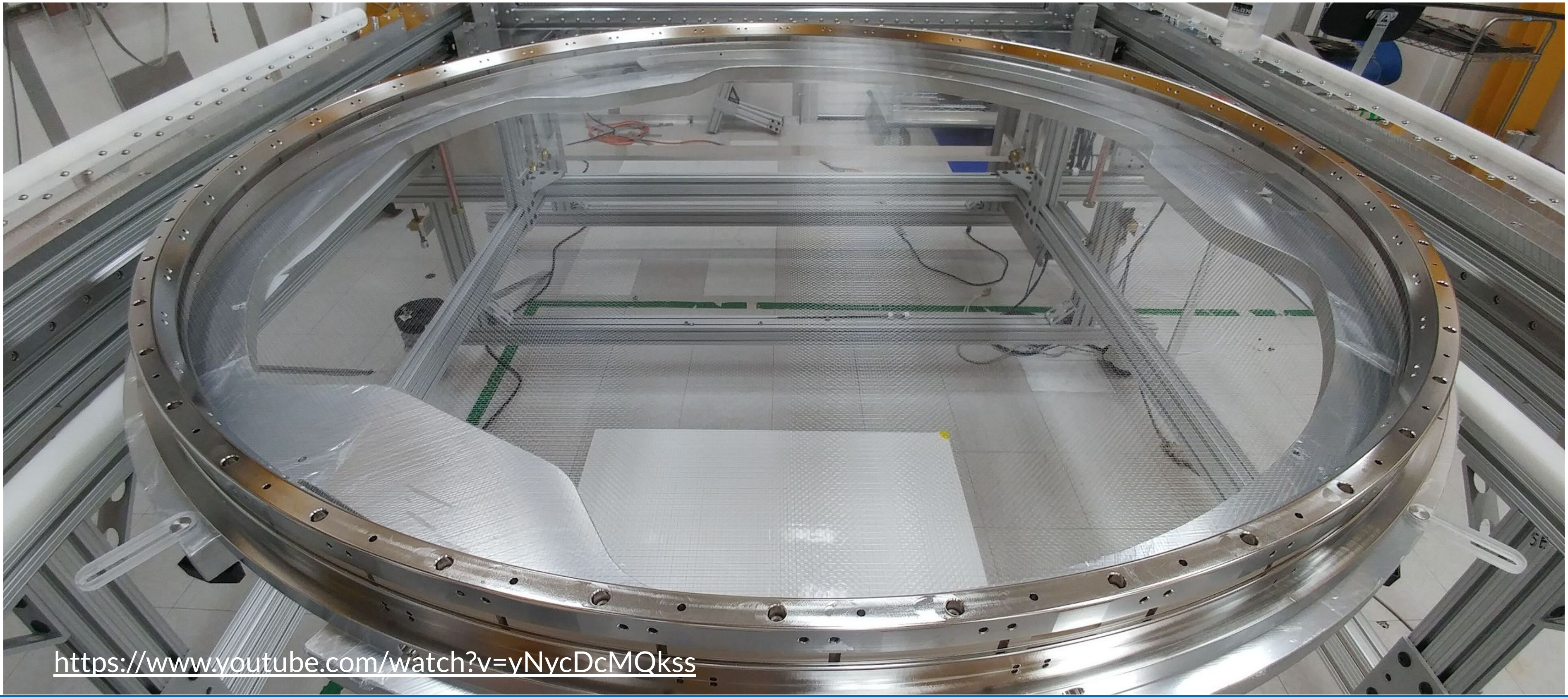


- 57 titanium field shaping rings
- PTFE for reflectivity and stability
- Completed December 2018

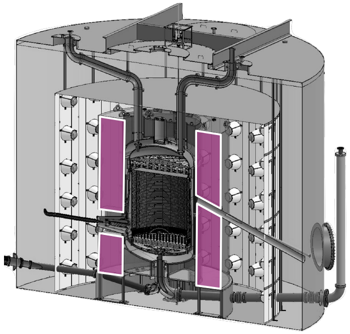


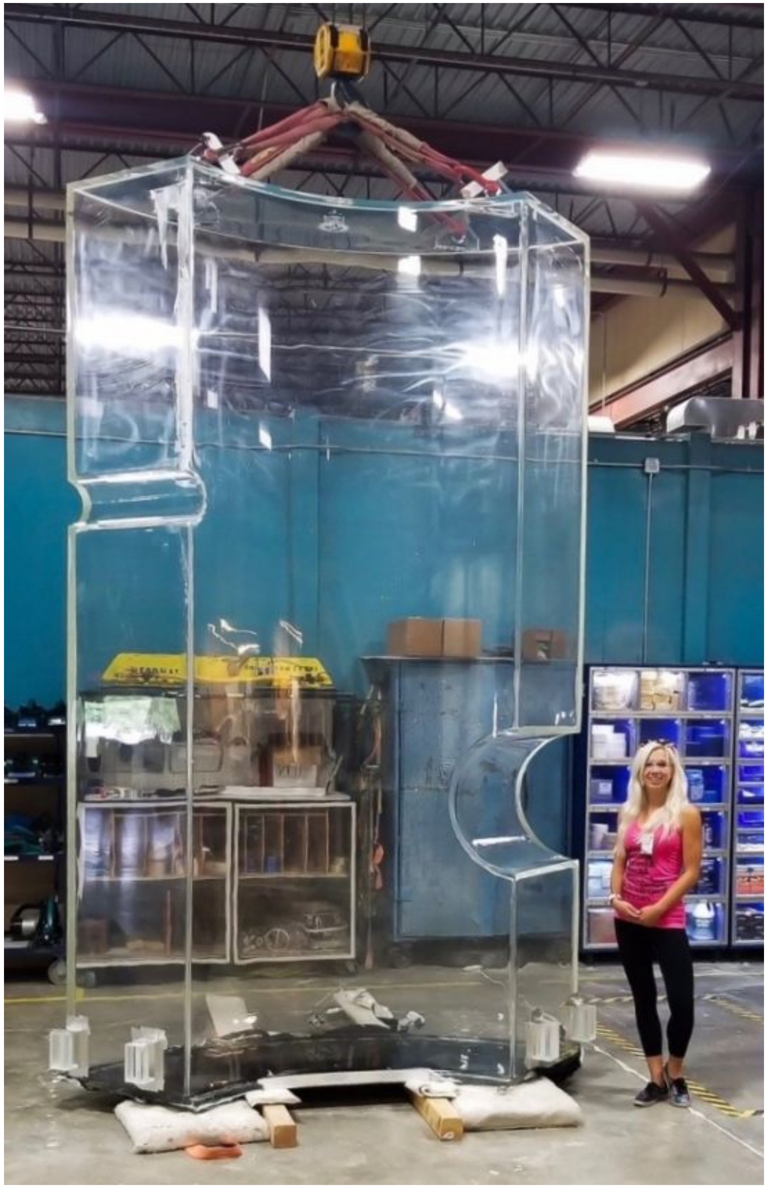


- Multiple HV grids for 3D reconstruction and ER/NR discrimination
  - High mechanical strength
  - 97% optical transparency
  - Background free (photo emission, others)



https://www.youtube.com/watch?v=yNycDcMQkss





- Cryostat surrounded hermetically by Gd-LS in acrylic tanks
- Viewed by 120 8”-PMTs, surrounded by reflector system and mechanical support in aggressive environment
- 15,000 parts, manufactured at Brandeis and tanks by UCSB

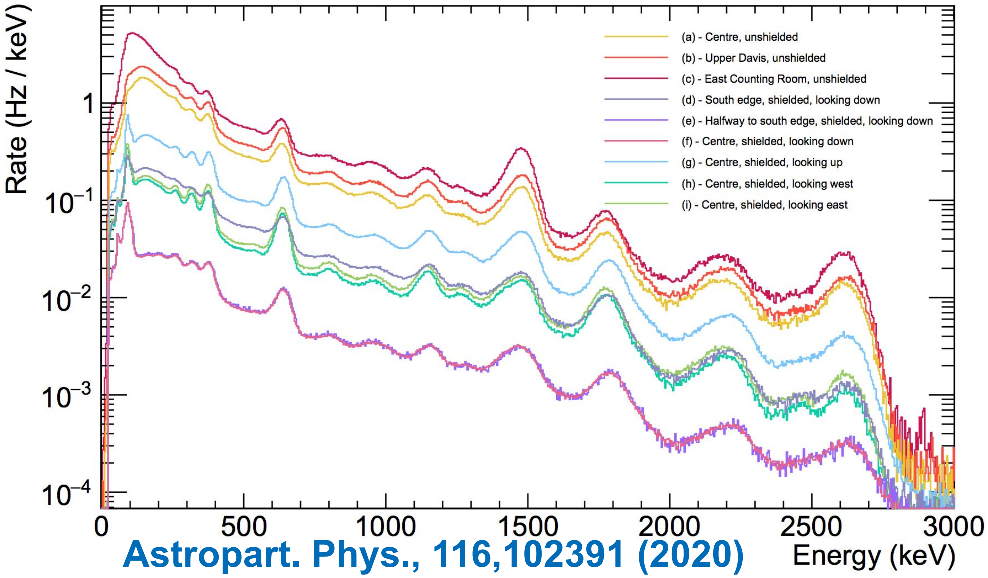
TPC Integration

TPC Underground

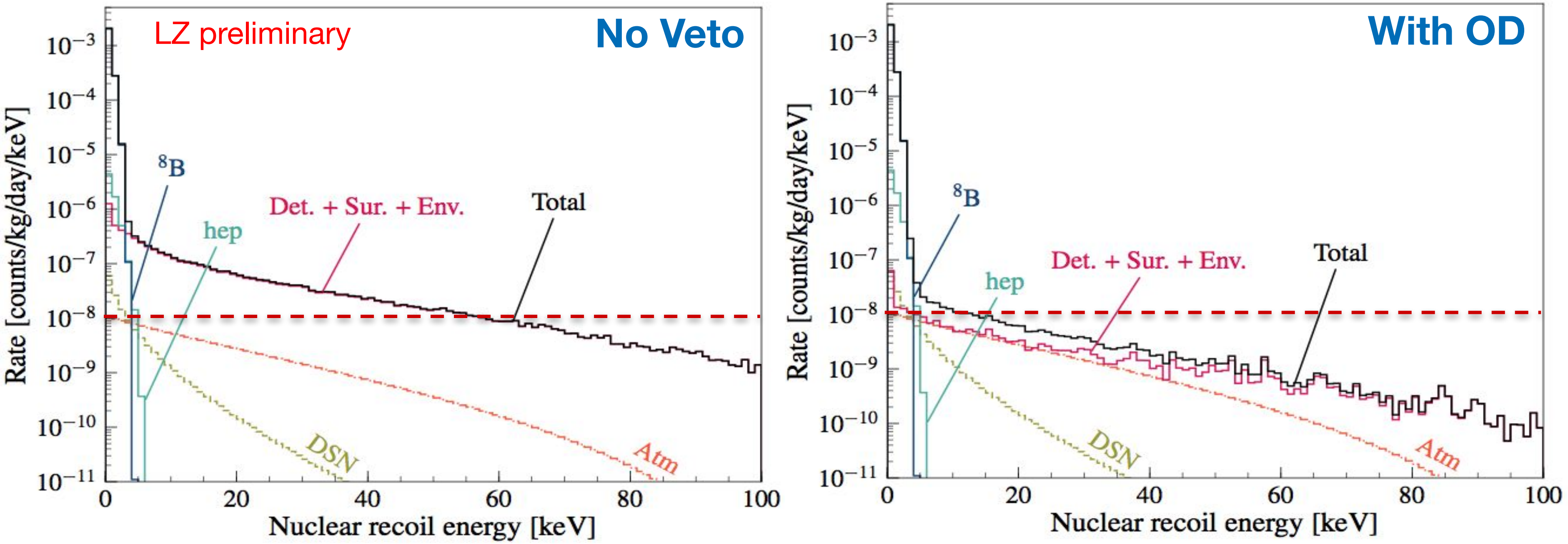
LZ Physics

- 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

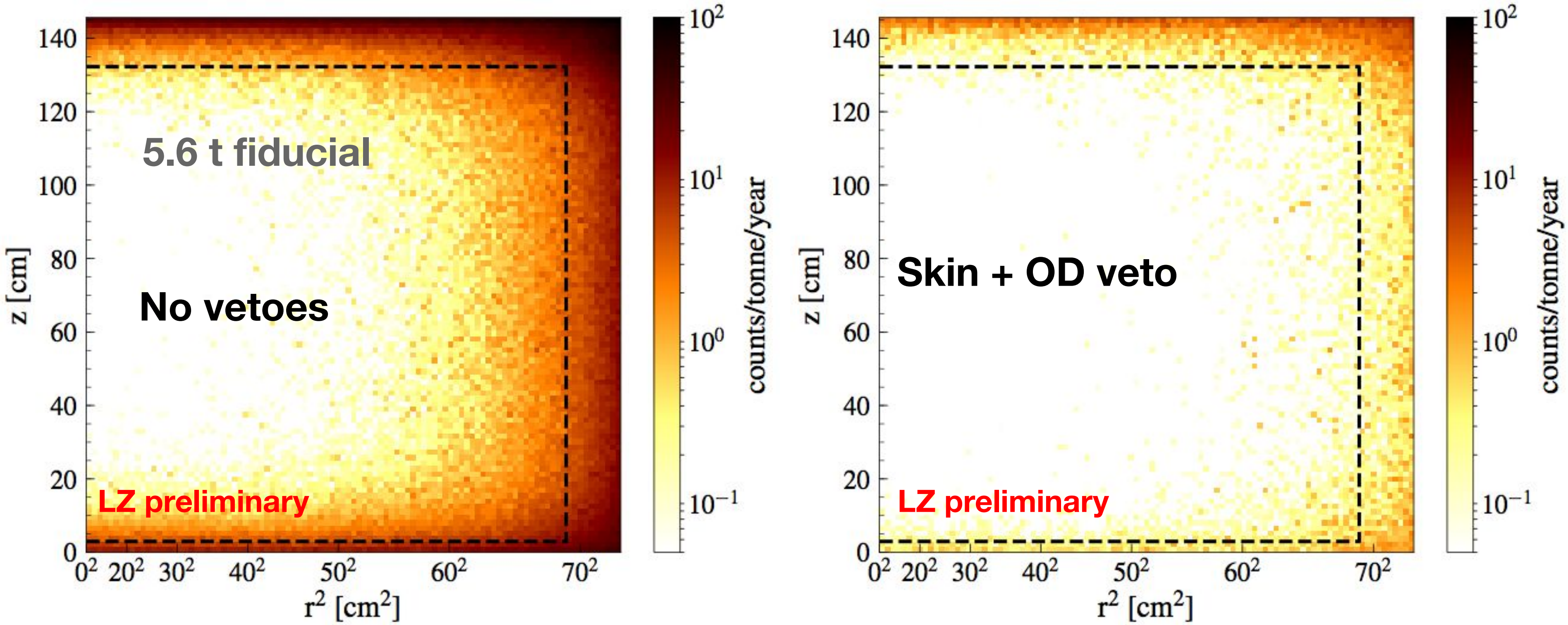
Background	Rate (Hz)
PMTs	0.9
TPC	0.5
Cryostat	2.5
Outer Detector	13.9
Cavern γ-rays	27
Total	**45**



Astropart. Phys., 116,102391 (2020)



- At 200 keV, 500 µs after S1 scatter the OD will veto 96.5% of all neutrons
- Veto reduces bkgds from 12 counts to 1 count for 1000 live-days
- OD almost doubles the fiducial LXe volume and additional information to constrain the NR background in the PLR



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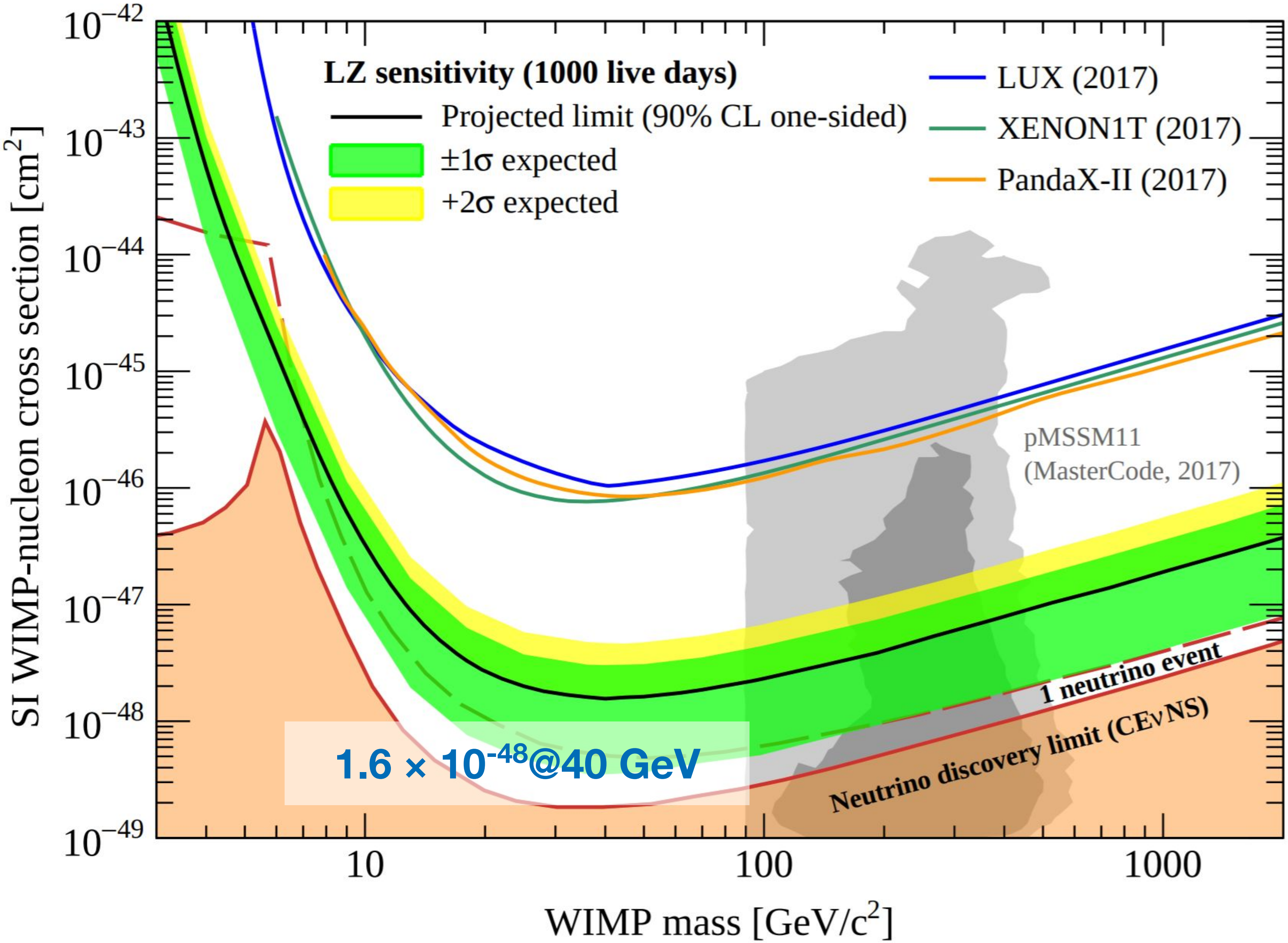
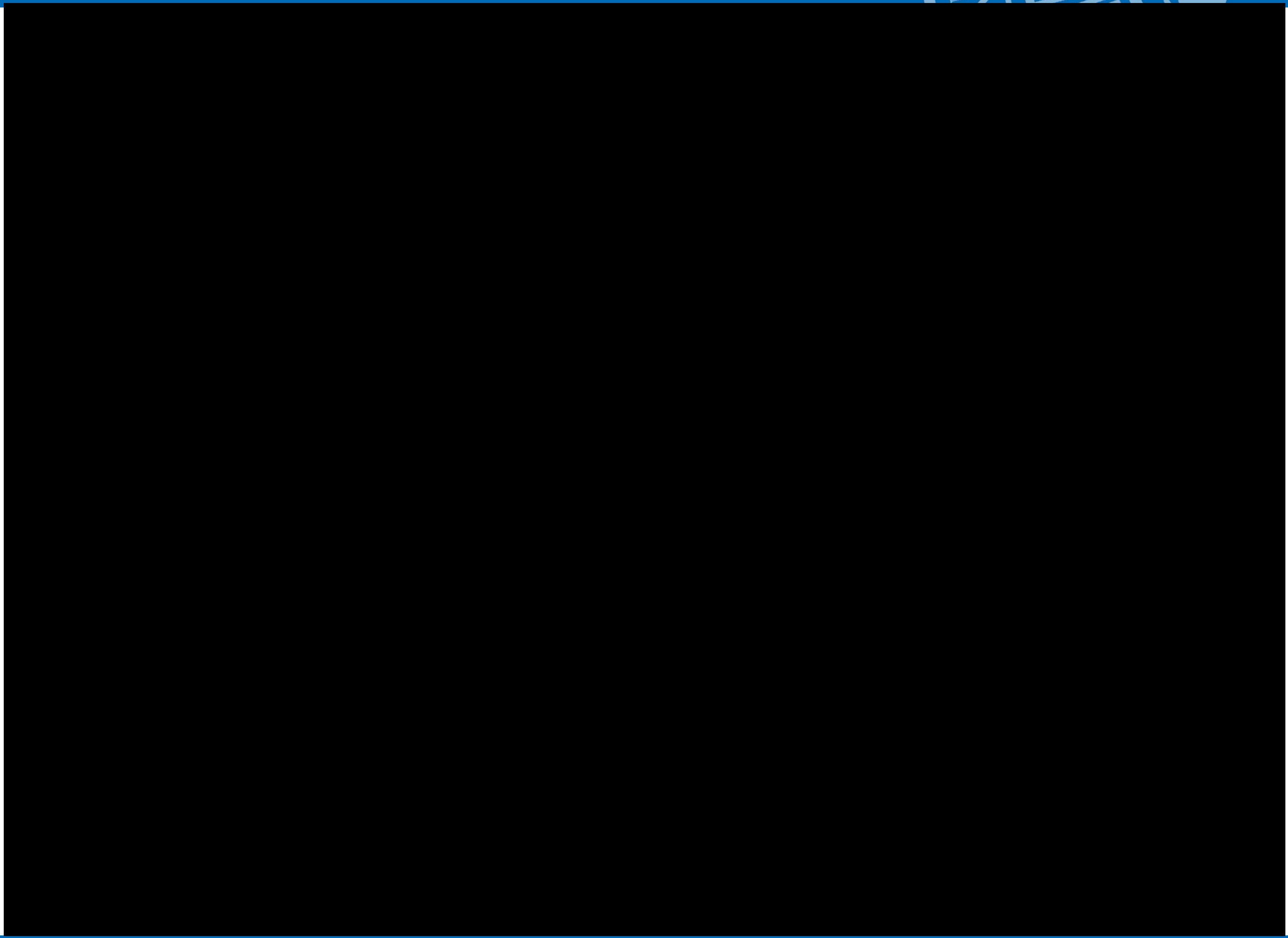
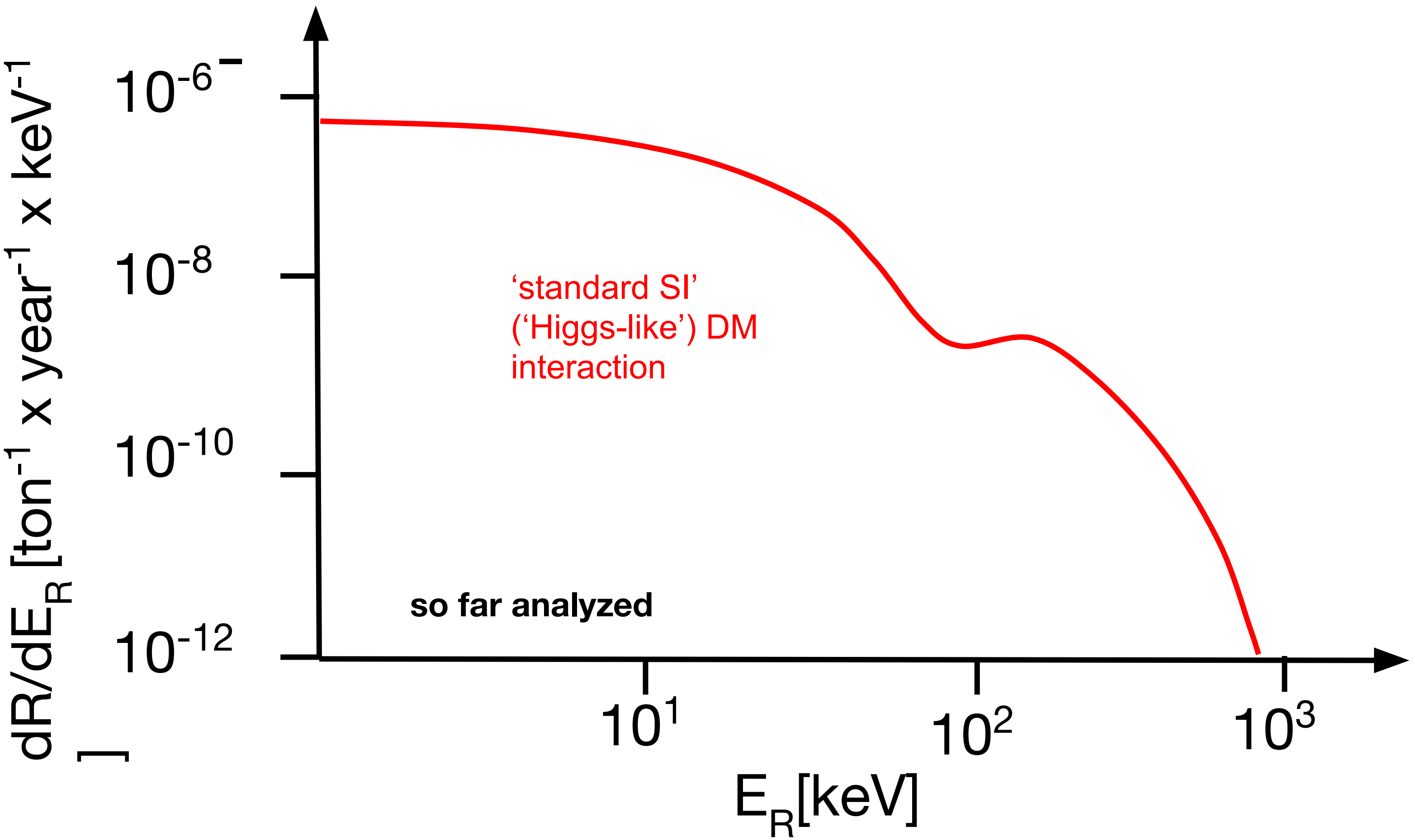


1.6×10^{-48}@40 GeV



- Recoil energy depends on operator, DM mass and velocity



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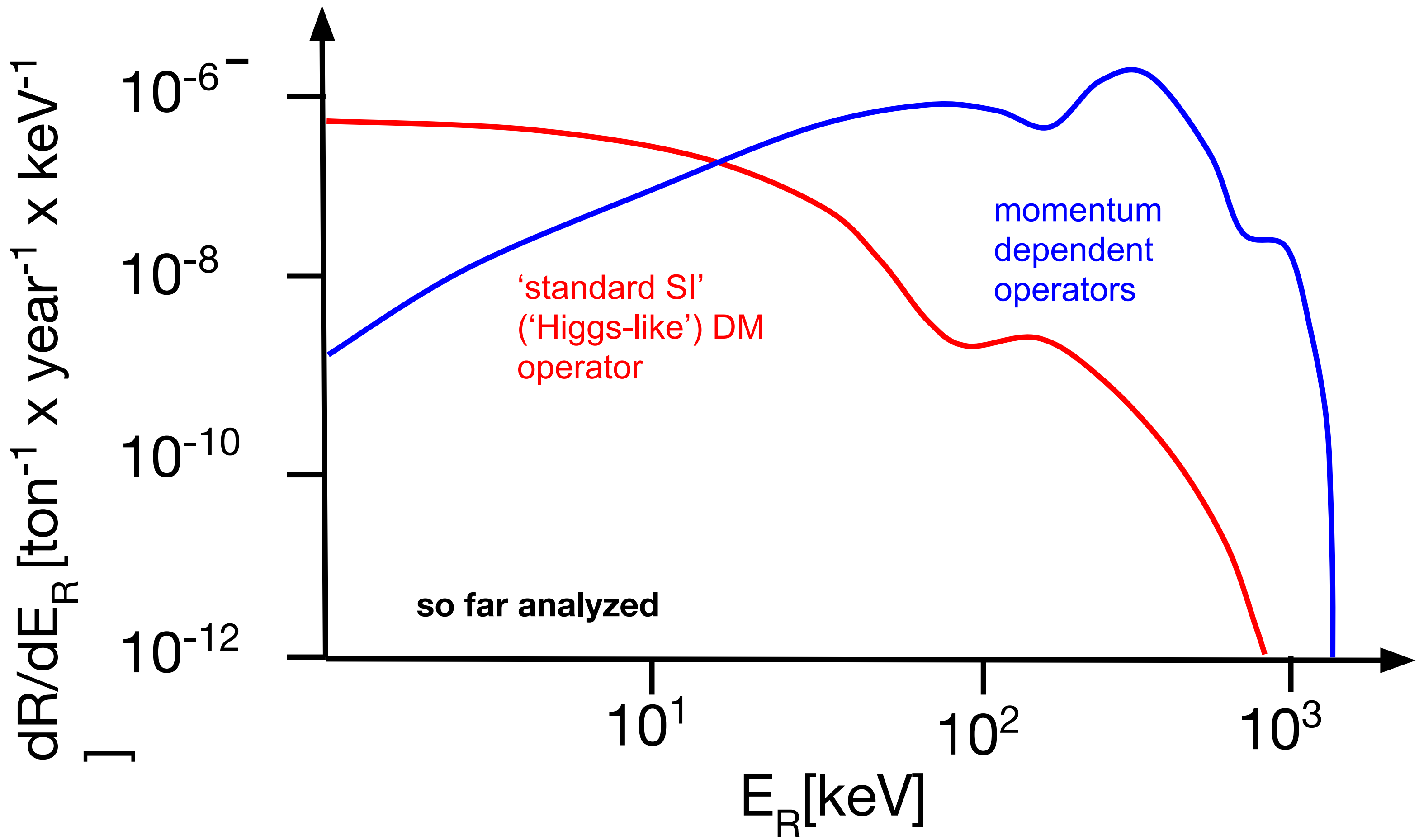

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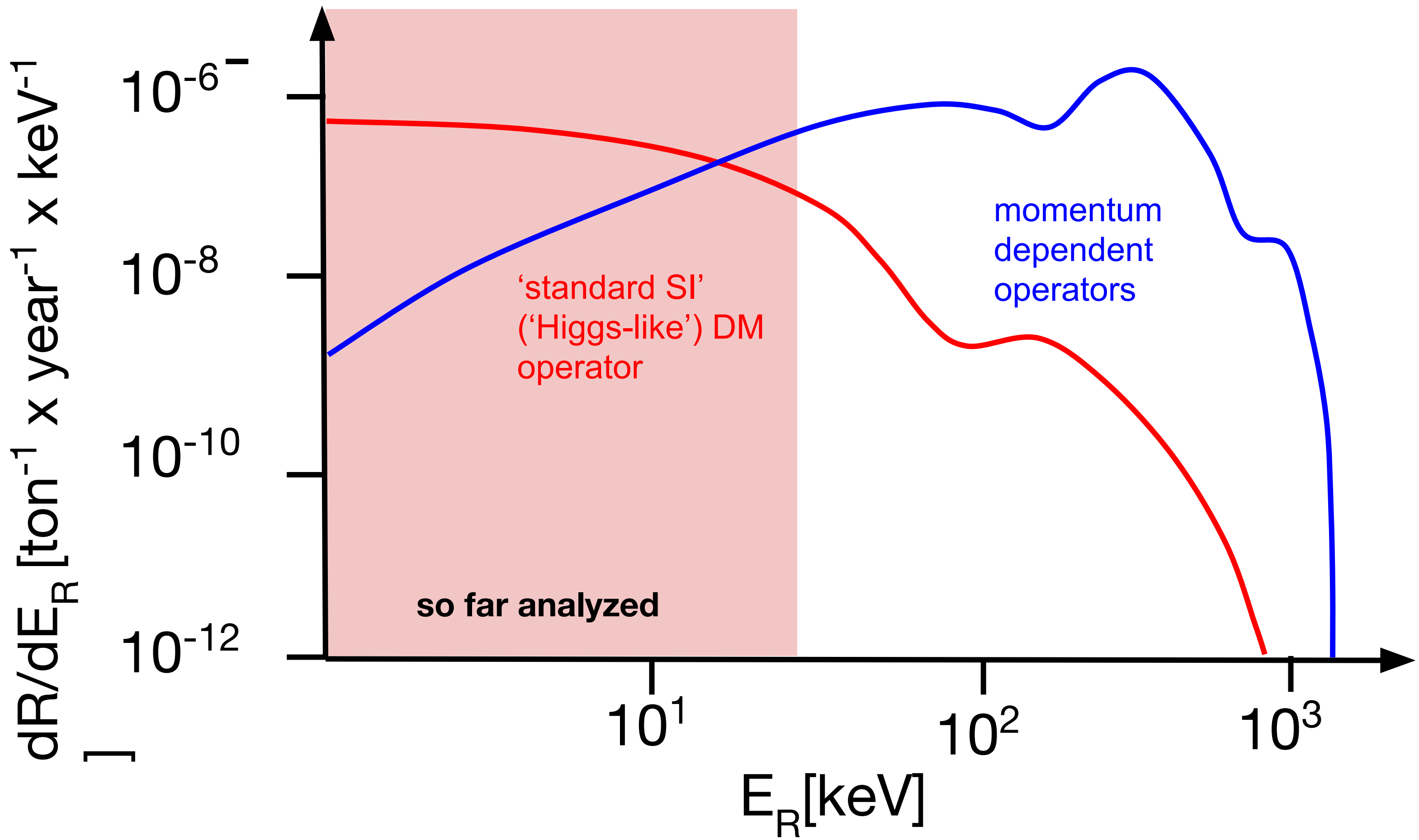
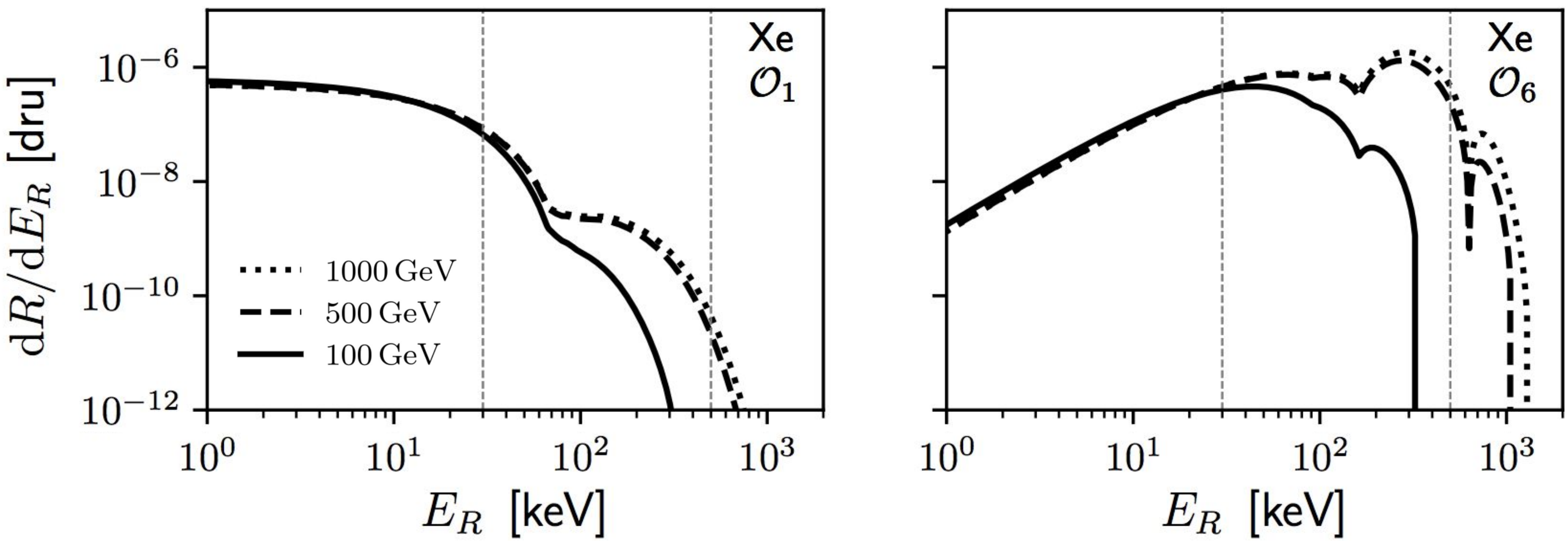


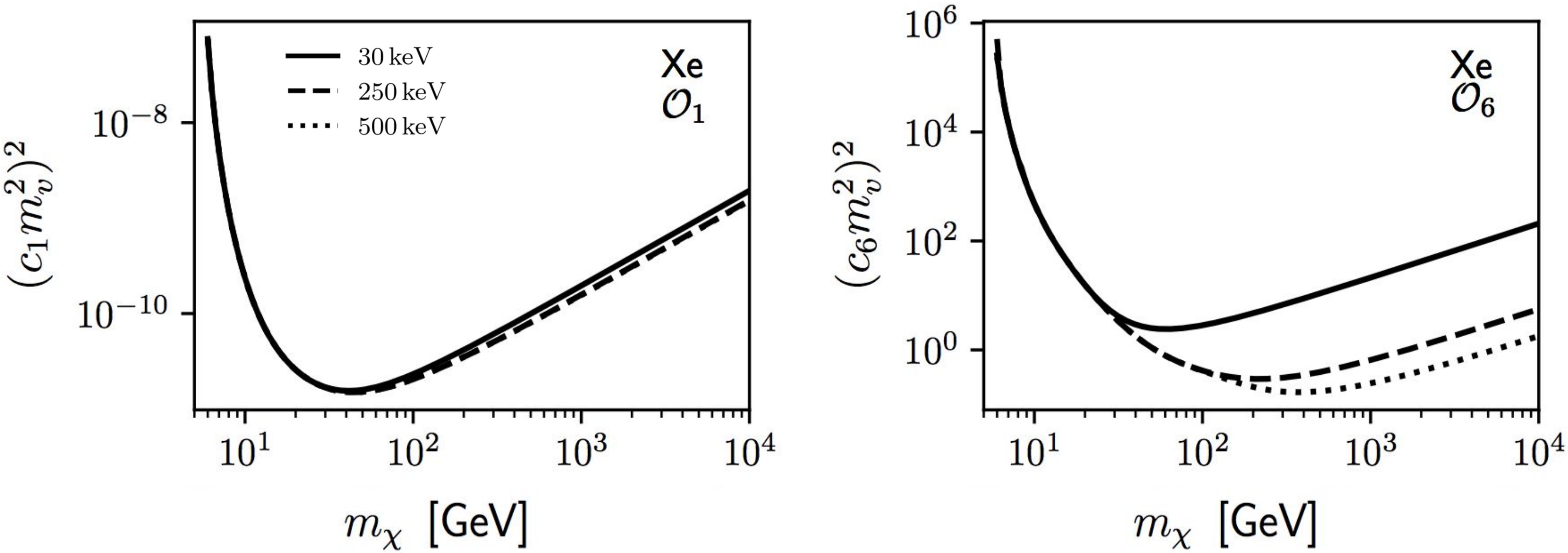
- Leading the 'high nuclear recoil group'

J. Cosmol. Astropart. Phys, 12, 013 (2018)

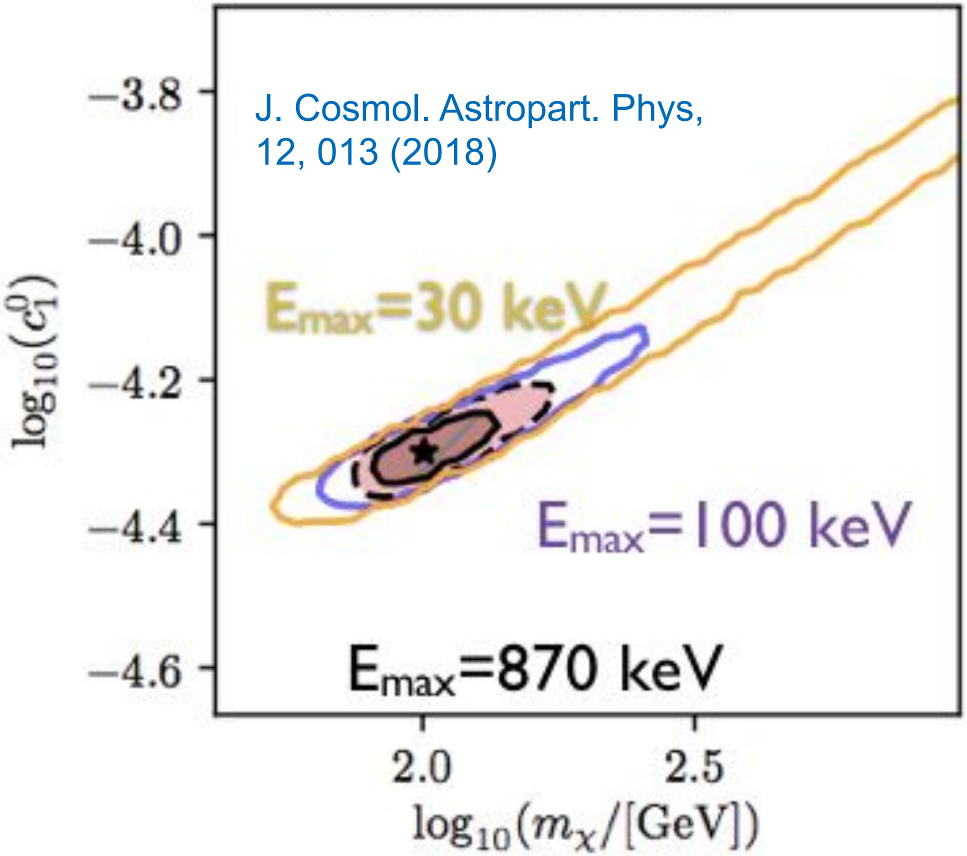


- Studied effect of higher nuclear energies for various operators
  - ‘standard’ q-independent operator (O_1)
  - q^2-dependent operator (0_6)
  - q-dependent operator (0_{10})
  - ‘non-trivial DM‘ (anapole DM, O_A)
- Two example in this talk, more in paper

J. Cosmol. Astropart. Phys, 12, 013 (2018)

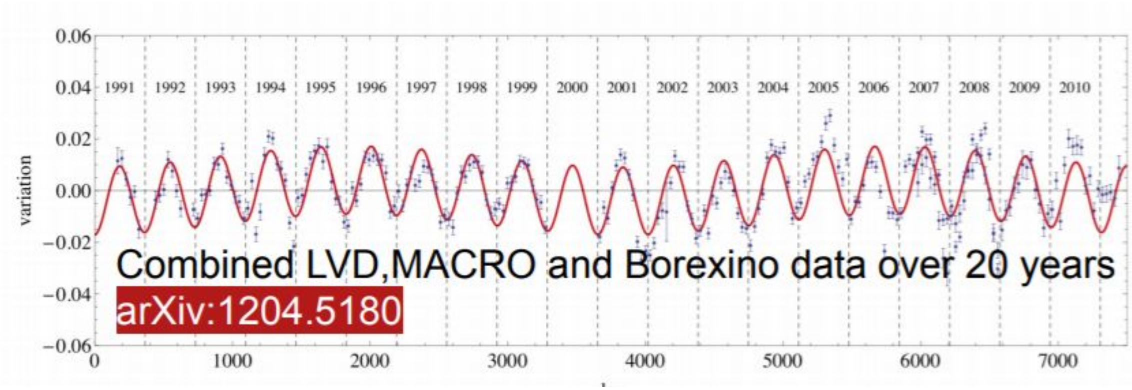


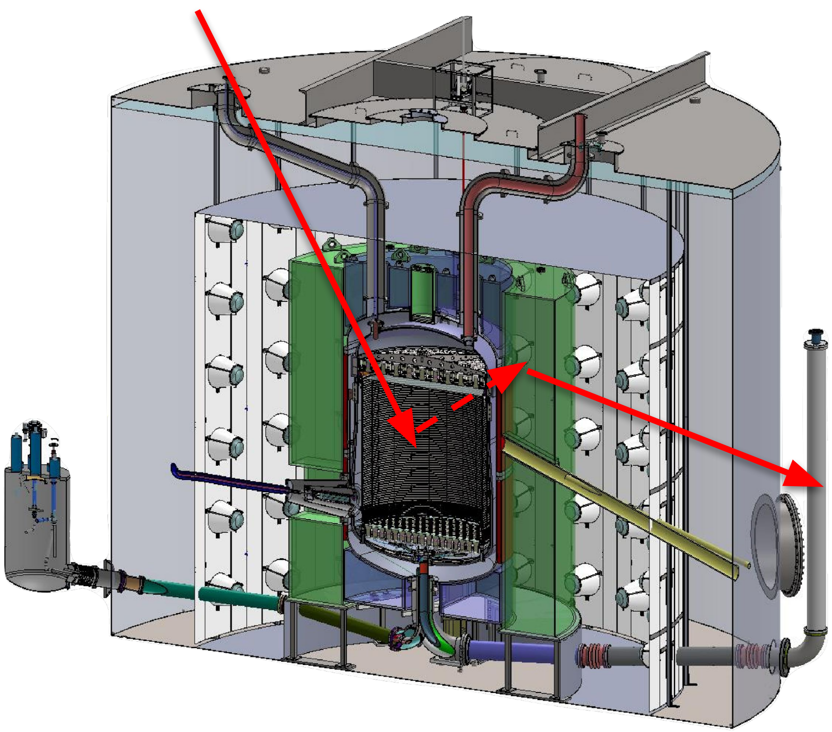
- Increase in energy windows leads to large sensitivity increase for momentum dependent operators
- Leading analysis in LZ, need to address novel aspects
    - High NR calibrations (ie. DT generators)
    - New backgrounds (i.e. instrumental and spontaneous fission)



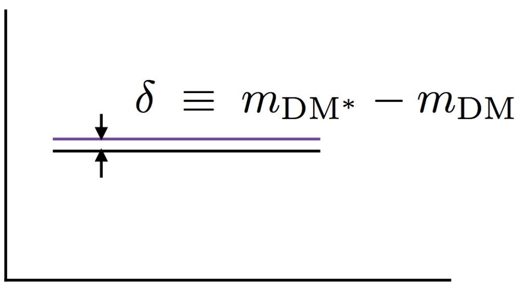
- Endpoint of NR spectrum sensitive to DM mass, even for 'vanilla' models, enables new measurements
- Potentially infer couplings and properties of DM halo using different targets with high NR
- Also sensitive to other models, ie. inelastic DM

- Other exciting new signatures:
  - Momentum dependent DM
  - Scatter in rock overburden
  - Silicon burning neutrinos
  - Muon induced neutrons
  - Annual modulation of muons



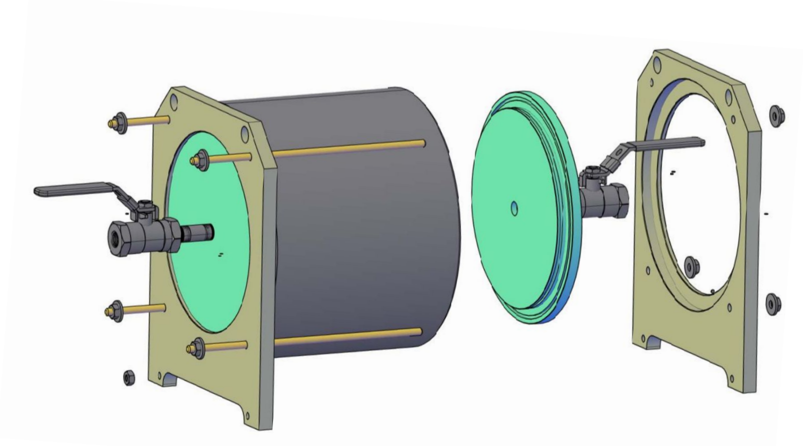


- Inelastic signatures
  - Depending on sufficient mass splitting the DM can 'upscatter' from $X_1 \rightarrow X_2$ which then de-excites somewhat later
  - The scattering requires at sufficiently large (kin.) energies
  - Opportunity to collaborate?

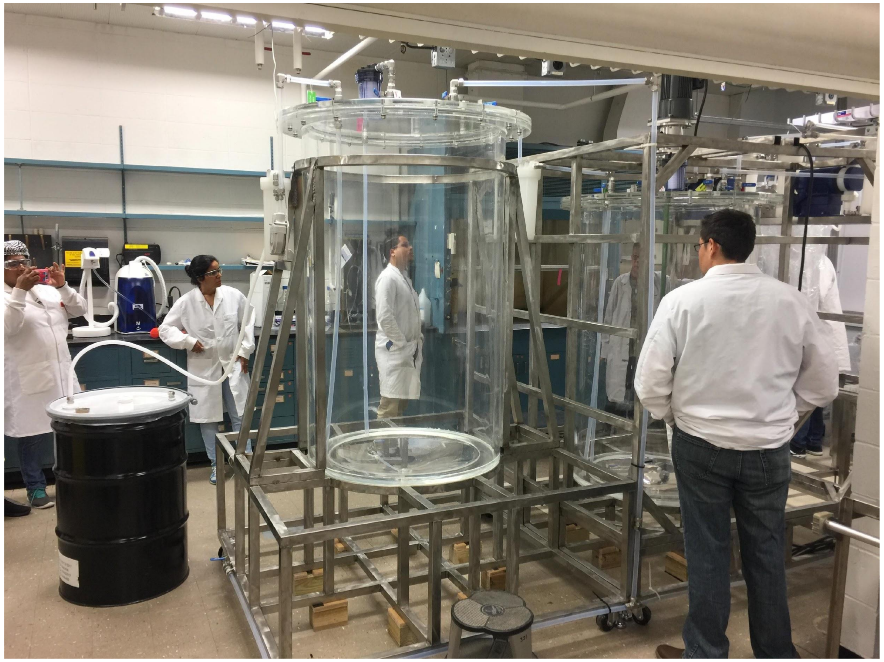


Beyond LZ

- Involved in two proposals for future experiments
  - All require active veto detectors
- Continuing collaboration with BNL to develop novel scintillating detectors
- 0.1% Gd doping in LS → neutron sensitivity
- Adding sensitivity to γ-rays by doping high-Z materials: 5%Gd, 8% In. and ~8%Pb available



LZ probe container right now built



- BNL: Built attenuation measurement system based on Brandeis electronics
- Brandeis: Added SiPMS to test stand
- Goal: Dope high-Z materials directly into acrylic,
  - Multiple layers, optimized for specific type of particle
  - Increase light coverage using SiPMs

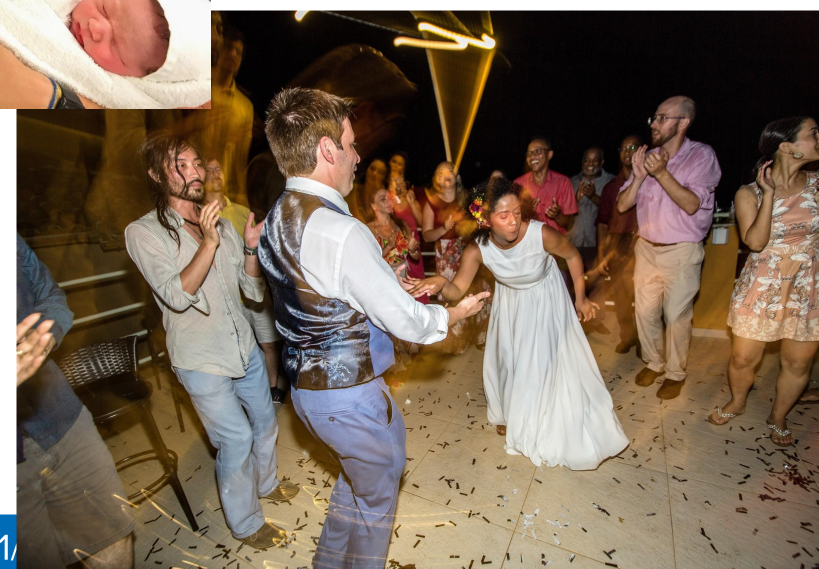
- Located remains of Davis Tank, haven't been at surface since 60 years
- Project with SURF to obtain material, presently screened underground
- Exploring the use as shielding material

Summary

- LZ will be the world's most sensitive DM detector starting in a few months
  - Veto detectors are integral part of LZ's search strategy, adopted by all future experiments
- My group leads design, fabrication & commissioning of the Outer Detector instrumentation, TPC assembly and underground operations
- Outer detectors provide a lot of unique opportunities for future DM detectors
- Important: Maximise the physics potential of LZ and expand searches to yet unprobed energies
- World's most sensitive data soon!
- One more thing!


ESCHMANN


ICHEP2012
Melbourne
36th International Conference
on High Energy Physics




ICHEP2012
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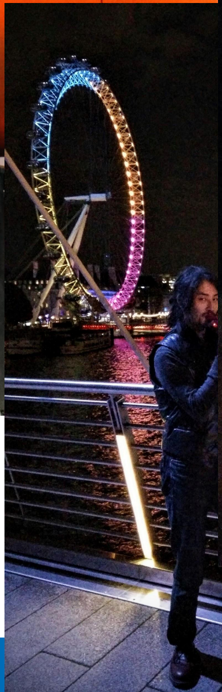
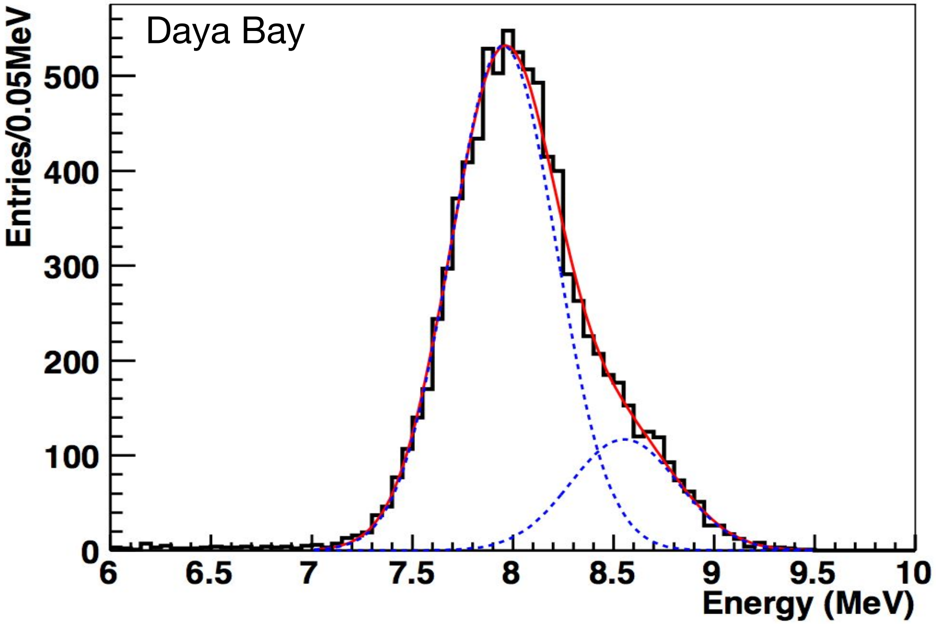
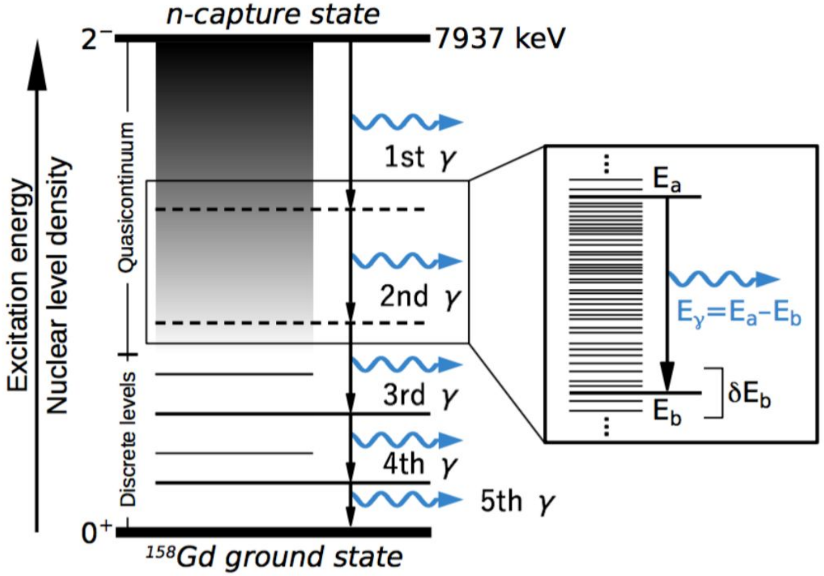


Backup

Neutron Capture on Gd

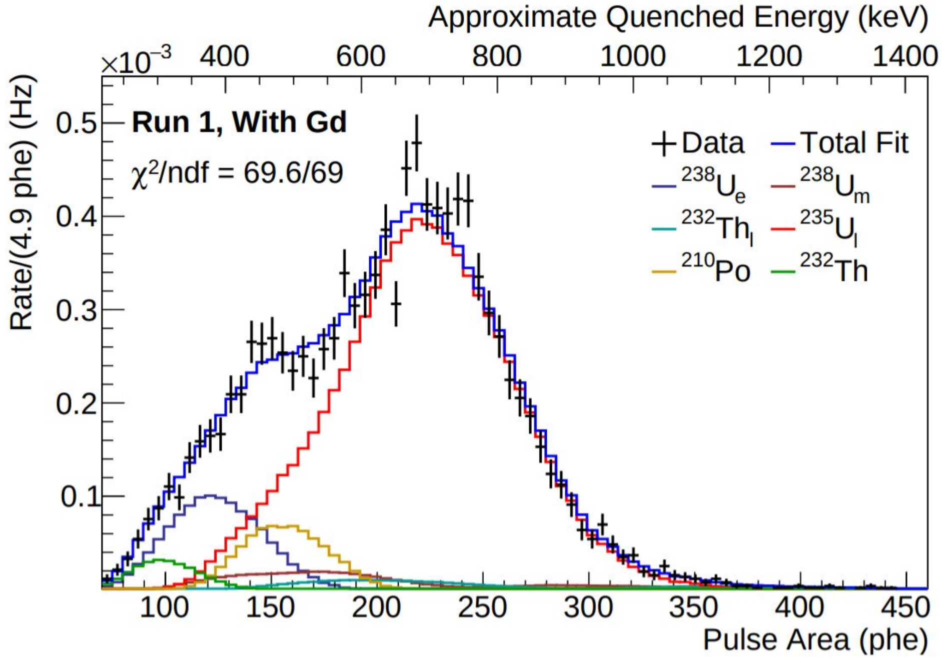
- Gd has largest thermal neutron cross section of all stable elements: σ_N=240kb (Xe σ_N=0.2b)
  - Doping with 0.1 % Gd reduces mean capture time to ≈30 μs from about ≈200 μs w/o Gd, thus reducing dead time
  - N capture followed by emission of about 3-5 gammas with about 8 MeV total energy:
    - $n + {}^{155}Gd \rightarrow {}^{156}Gd$ + 8.5 MeV (18%)
    - $n + {}^{157}Gd \rightarrow {}^{158}Gd$ + 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

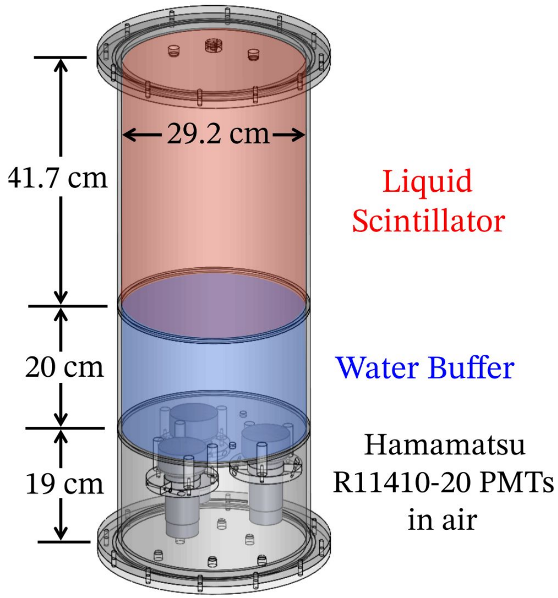




arXiv:1808.05595

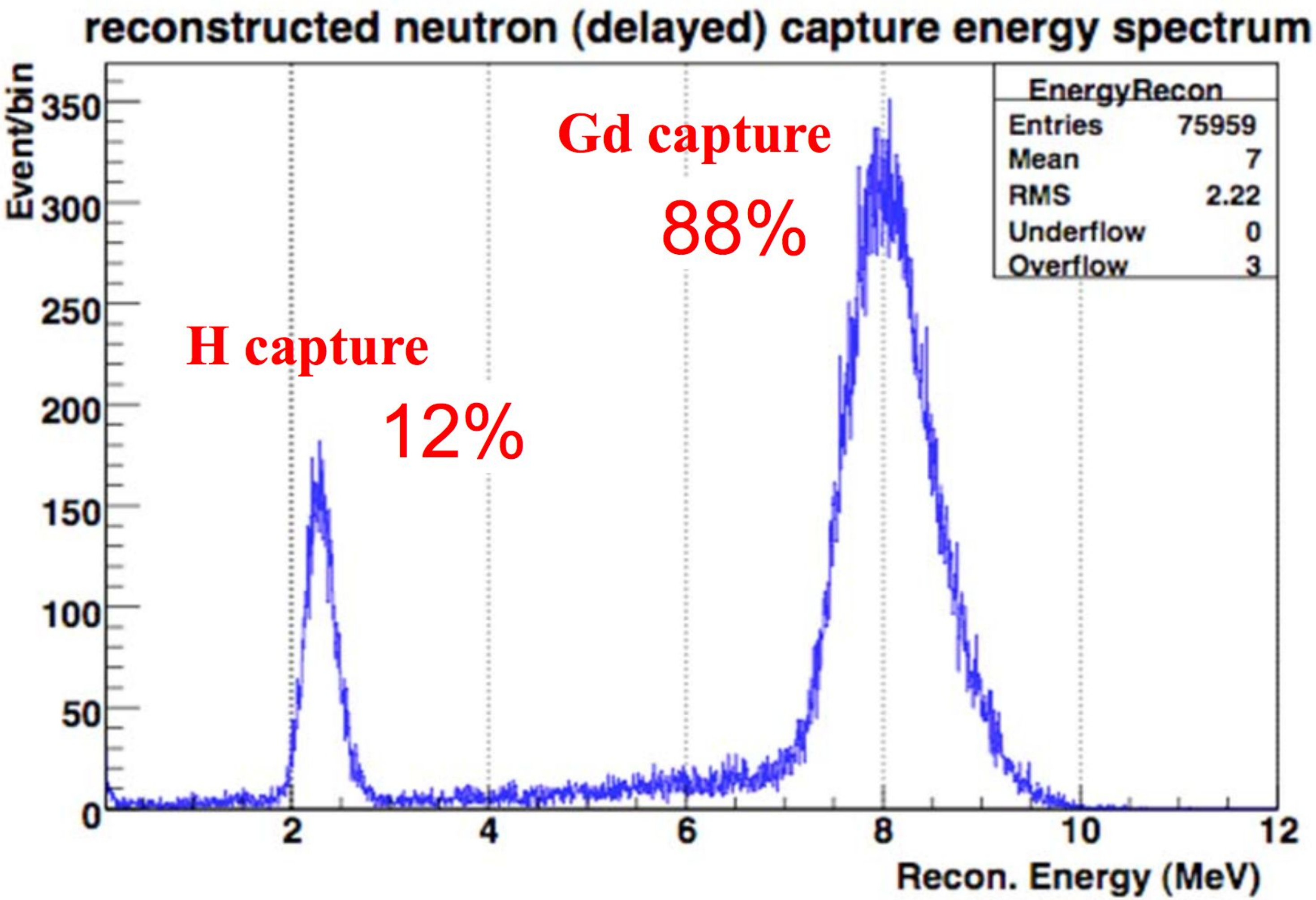
- Screener: small acrylic detector (1/1000 of mass of LZ OD) operated in water tank in Davis Cavern under strict radiopurity requirements
- Used to study LS loaded with Gd and w/o, sources for calibration and PSD for particle identification
- Achieved 10^{-4} mBq/kg sensitivity to impurities in Gd



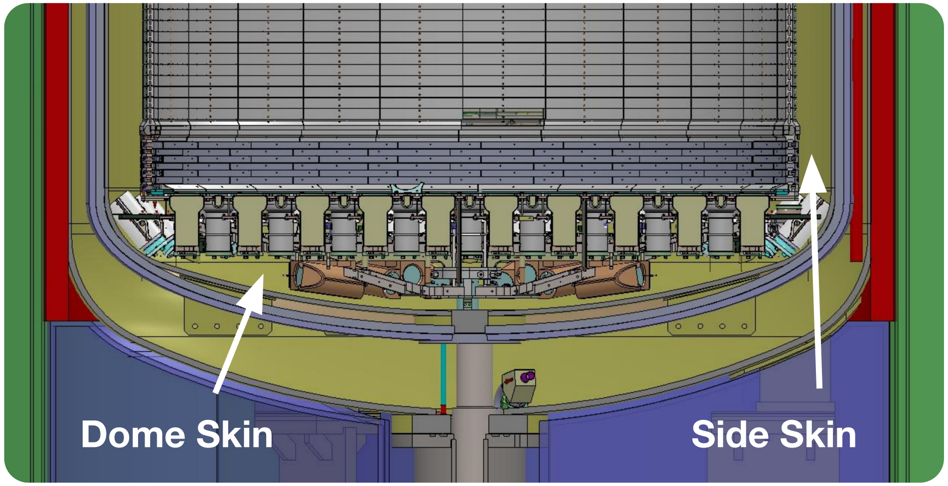


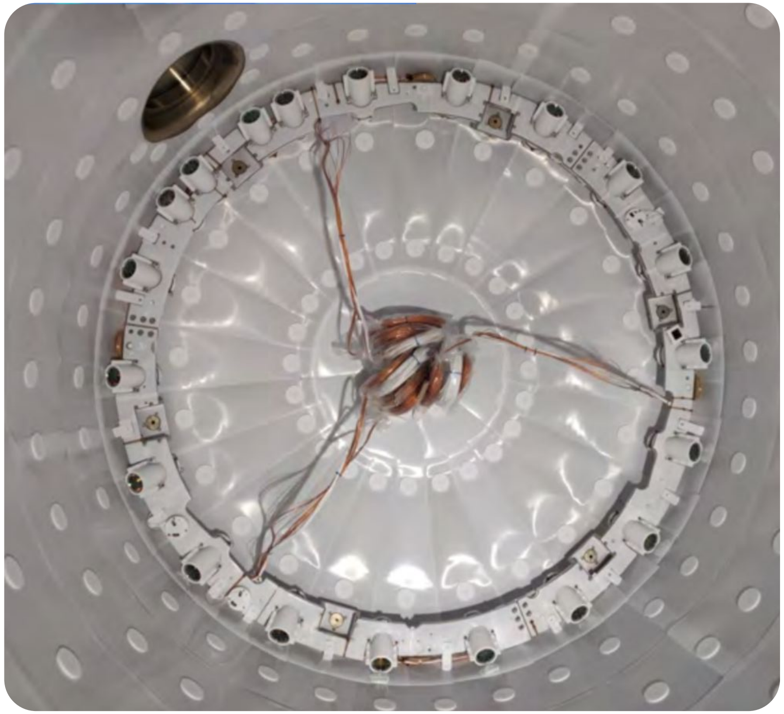
- Measured ratio $^{14}C/^{12}C = 2.83 \pm 0.07 * 10^{-17}$, comparable to two order or magnitude larger detectors
- Lead to improvements in GdLS production to lower backgrounds
- Also useful to evaluate properties of Gd-LS, background fluxes and to gain operational experience

Neutron Capture Spectrum



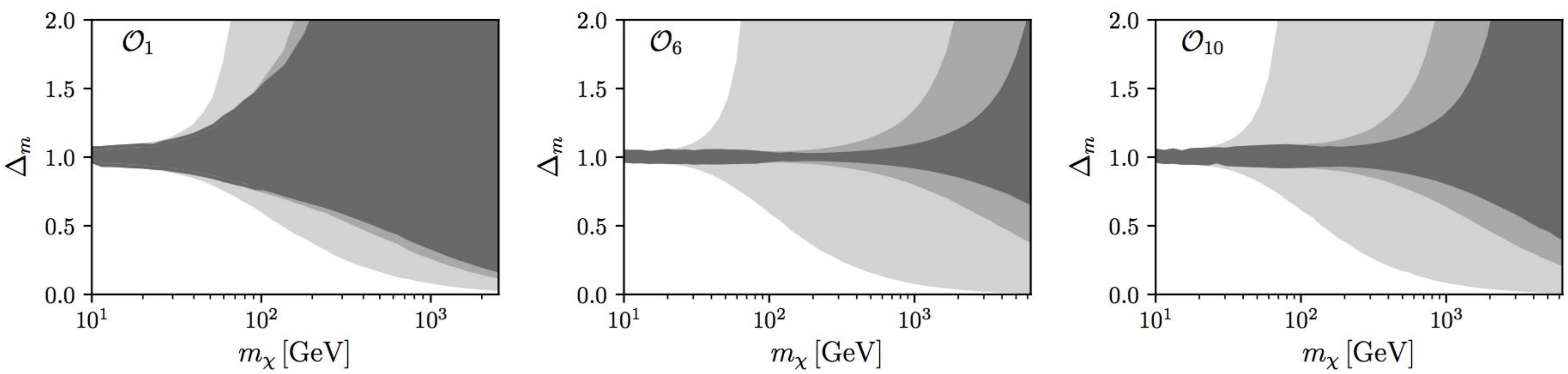
- A 2 t layer of LXe (skin) between the TPC and the cryostat is needed because of HV stand-off, differential thermal expansion between Ti vessel and PTFE reflector and TPC geometry
- Skin region and dome is instrumented to veto Compton recoils of ~MeV radiogenic gammas





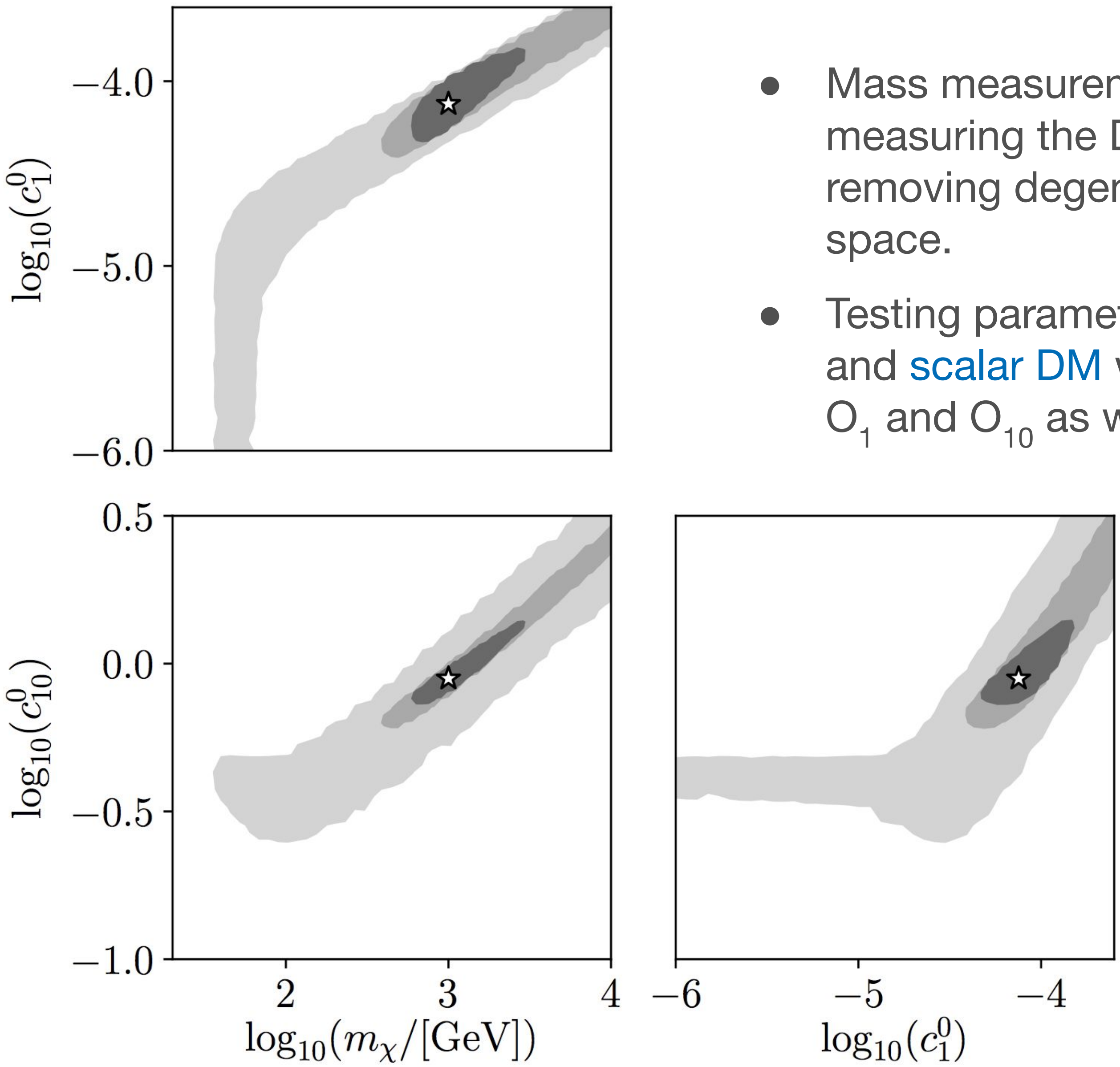
- PTFE attached to the inner cryostat wall and bottom dome enhance light collection efficiency
- The combination of skin and outer detector creates a highly efficient integrated veto system
- Skin complementary to the scintillator veto since low energy γ-rays don't penetrate gammas the titanium ICV/OCV

- If discovered we can inferre mass and couplings of DM particles from nuclear recoil spectrum
- Increased energy range also leads to improved measurements
- In particular endpoint of spectrum is very sensitive to DM mass, even for ‘vanilla’ models



The light to dark grey regions correspond to different energy ROIs, with E_{max} = 30, 250 , 500 keV, respectively.

- Mass mostly not constrained for intermediate to large m_{DM} with standard energy window



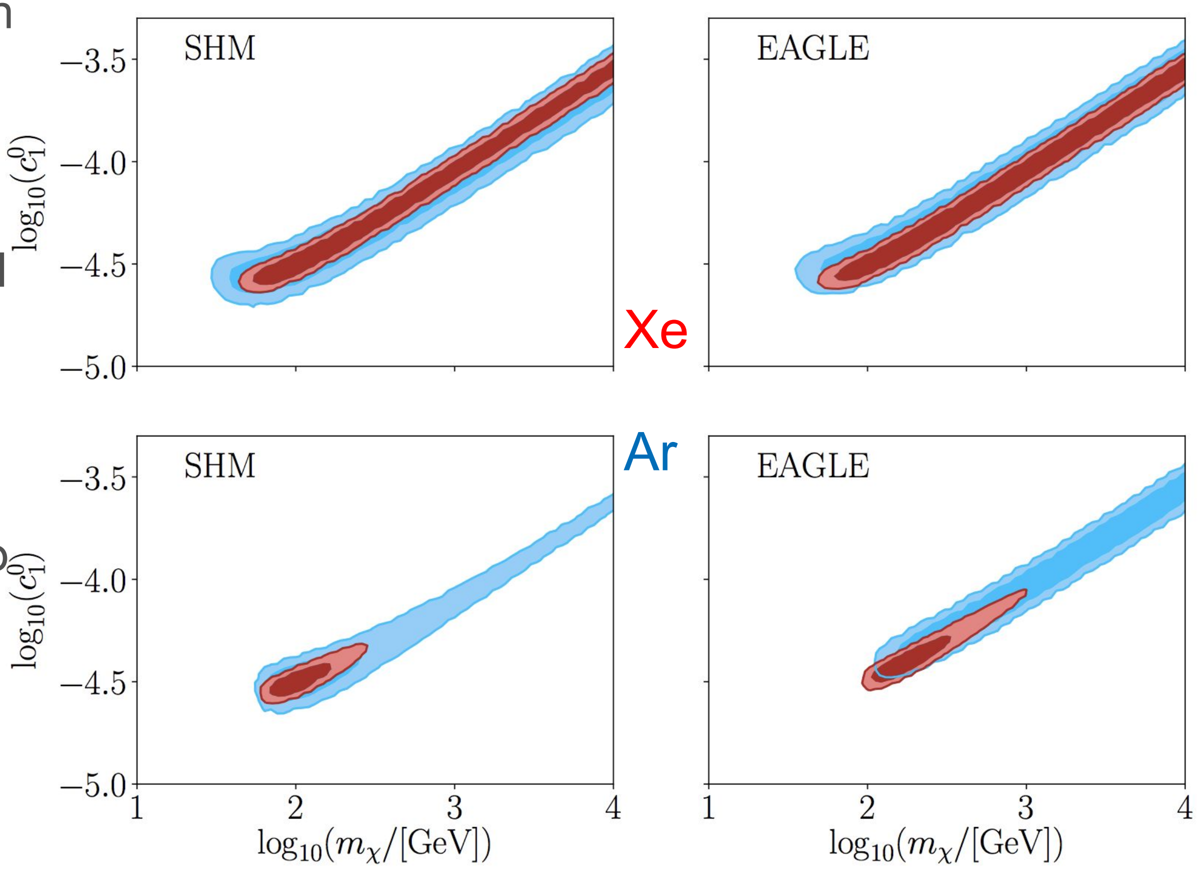
- Mass measurement important to measuring the DM couplings and removing degeneracies in the parameter space.
- Testing parameters space for m_{DM}=1 TeV and scalar DM with equal contributions of O_1 and O_{10} as well as anapole DM

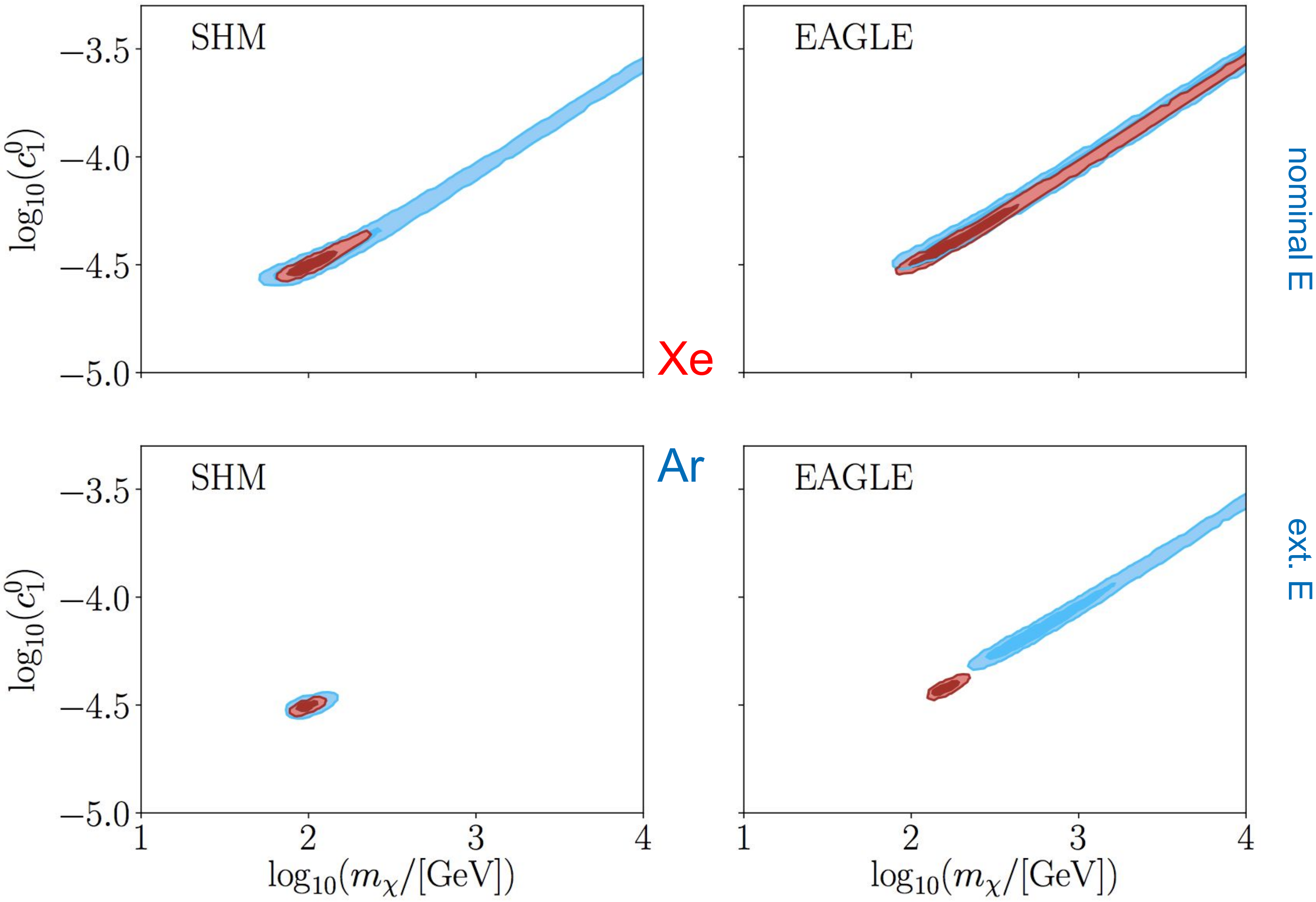
- Astrophysical uncertainties (velocity, density) are among the dominant
- Typically assume isotropic Maxwell-Boltzmann distribution in the Galactic rest frame, truncated galactic v_{esc} - Standard Halo Model (SHM)
- Recent high resolution cosmological simulations including baryons and DM
- Range of models can deviate from SHM and (Maxwellian) peak speeds larger than circular speeds
    - Use largest deviation of EAGLE simulation

Parameter	$v_{\rm peak}$ [km s^{-1}]	v_c [km s^{-1}]	$v_{\rm esc}$ [km s^{-1}]	ρ_0 [GeV cm^{-3}]
SHM	220	220	544	0.4
EAGLE	288.64	254.06	874.76	0.68

High NR Measurements

- Produce Xenon and Argon targets with SHM and EAGLE model
- Perform parameter reconstruction using SHM
- Simulating 100 O_1 evts
- Extended energy non-degenerate but difficult to distinguish halo model
- Best results when using multiple targets



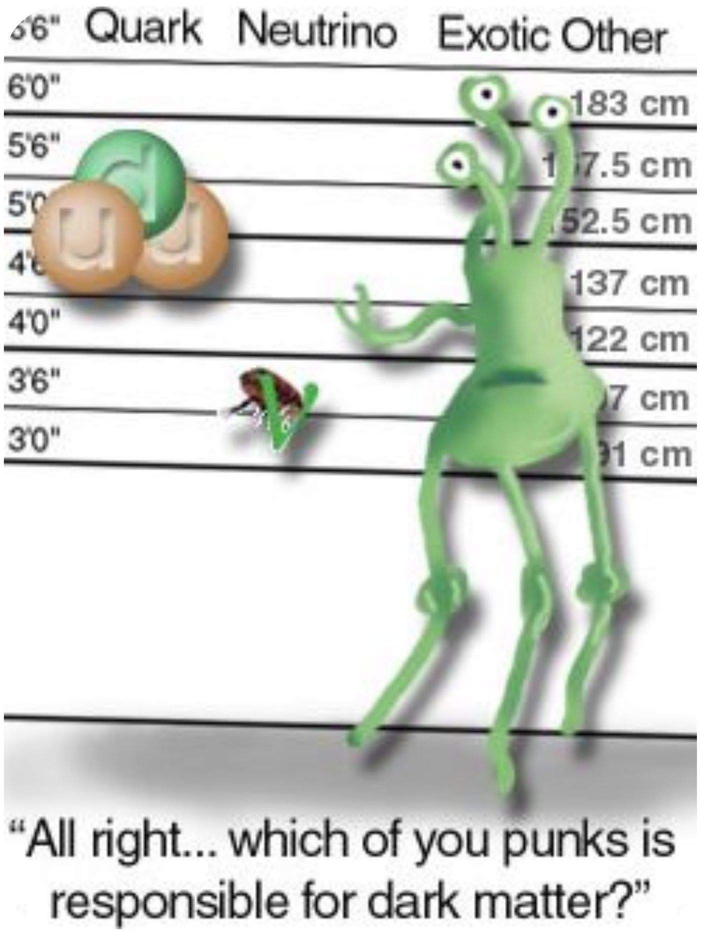


- For 1000 (!) events able to measure halo properties using O_1
- For other operators smaller exposures are already sufficient

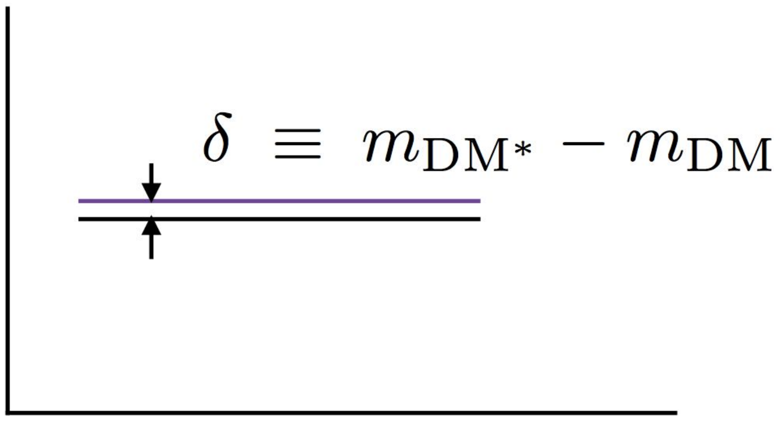
inelastic DM
(non EFT)

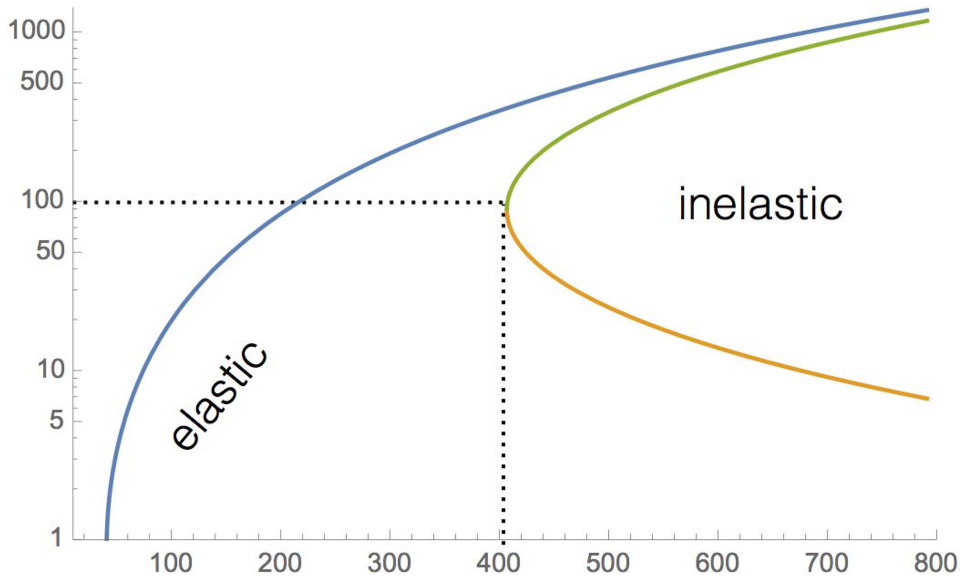
- Inelastic DM occurs naturally in non-Abelian gauge theories with a non minimal dark sector with more than one DM species X_1, X_2 and mass splitting δ at O(keV-MeV) mass splittings

- Looks contrived!? Let's see what else we know:
  - SM has fairly complex multiplet structure: SU(3) × SU(2)L × U(1)
  - Non-Abelian: (QCD, Y-M, EW symmetry breaking)
  - Small mass splitting, e.g. QCD (we still don't understand the top-quark)
- Many classical BSM theories have a dark sector (e.g. SUSY)

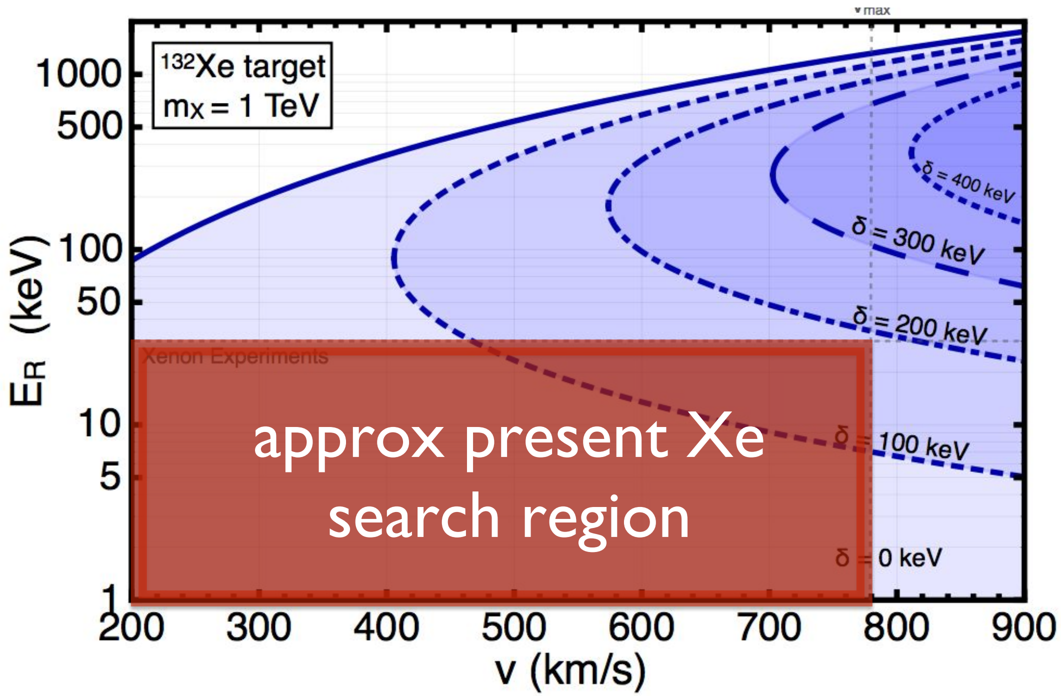


- Depending on sufficient mass splitting the DM can 'upscatter' from $X_1 \rightarrow X_2$ which then de-excites somewhat later
- Elastic scattering still takes place but suppressed at loop level
- The scattering requires at sufficiently large (kin.) energies



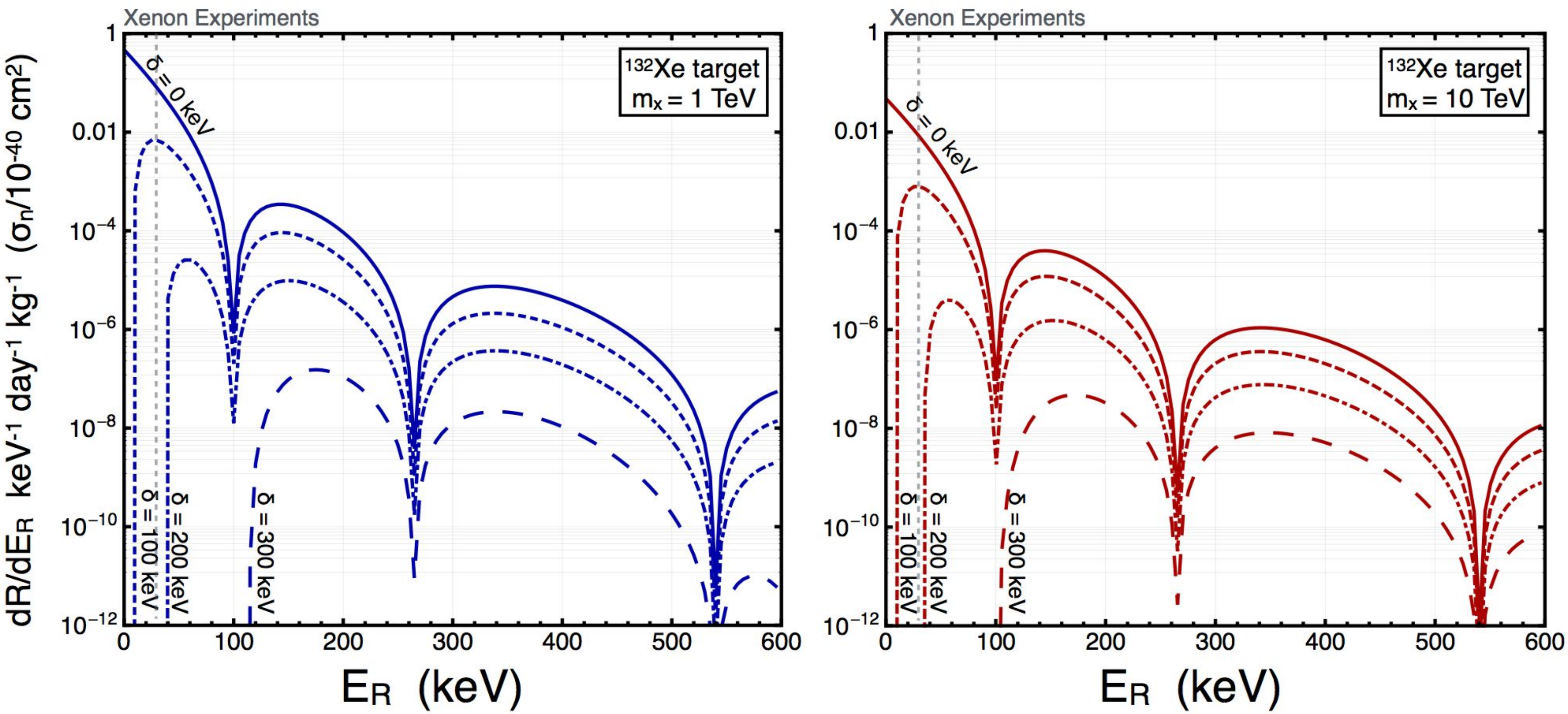


- This minimum required energy implies a minimum recoil energy
- An upper boundary on recoil energy will at best decrease our sensitivity to such events, at worst become insensitive



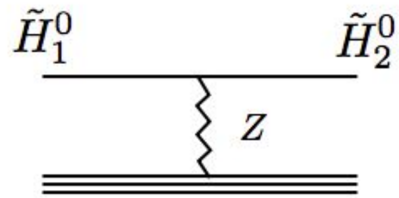
- Actual sensitivities:
    - Xenon experiments are insensitive to mass splittings of about δ≳180
    - Tungsten based experiments are insensitive to mass splittings of about δ≳350
    - Bubble chamber experiments only w/o upper energy cut, most sensitive 160≲δ≲350 but limited exposure

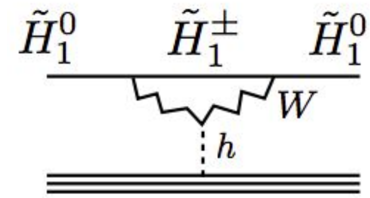
Inelastic DM



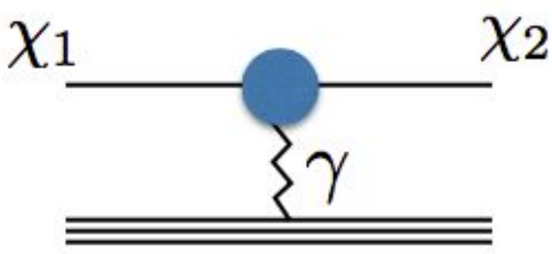
- Similar as in el. scattering for high DM masses reduces the recoil energy
- However, we also introduce 'cut offs' at low energy which can make us blind entirely blind for that type of interaction.
- Leads also to strong seasonal effects

- Higgsino DM (SUSY) with O(100 keV) mass splitting between Higgsino states
  - mass splitting from mixing with heavy neutralino states
  - Couples with Z-exchange



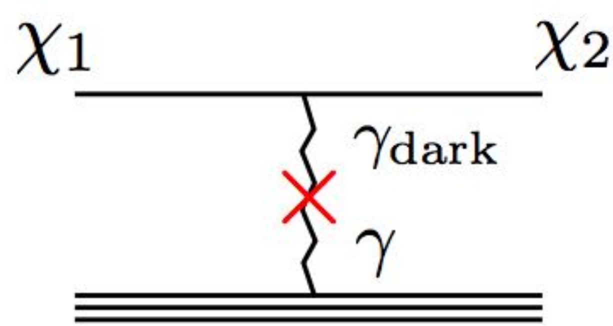


inelastic loop

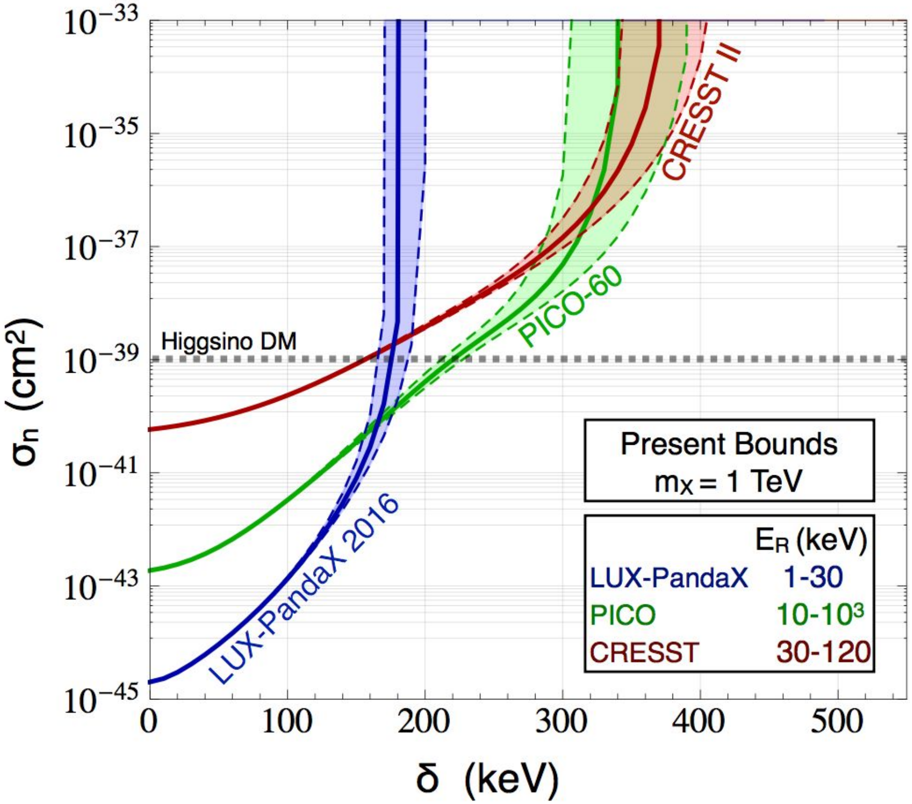


- Magnetic Inelastic Dark Matter (MiDM)
  - DM - photon coupling is a dipole operator, again with O(100 keV)

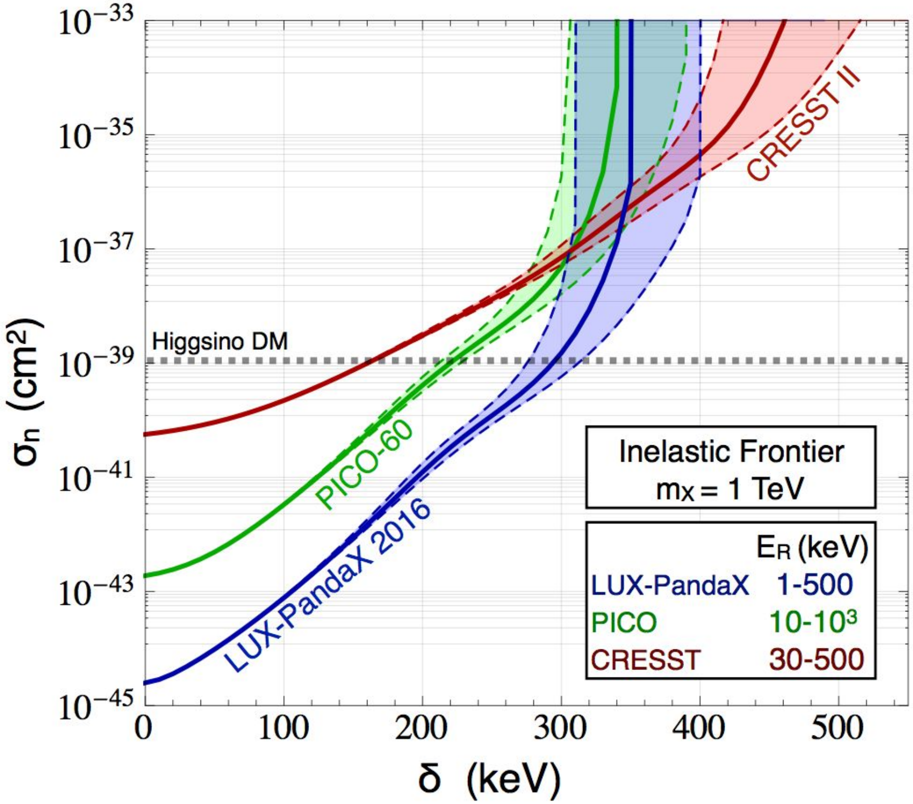
- Dark photon exchange of mass ~0.1-10 GeV
  - Inelastic splitting arises from the coupling to the scalar that makes the dark photon massive



Present Bounds

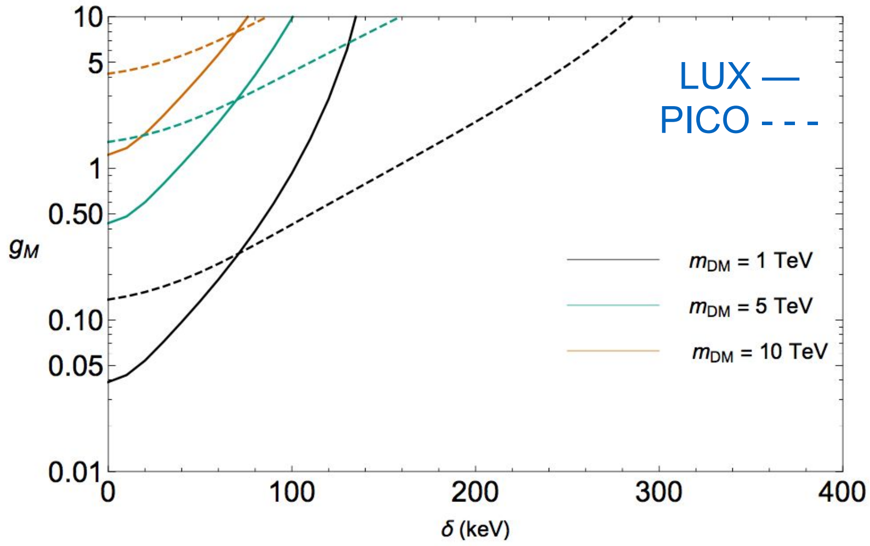


Inelastic Frontier

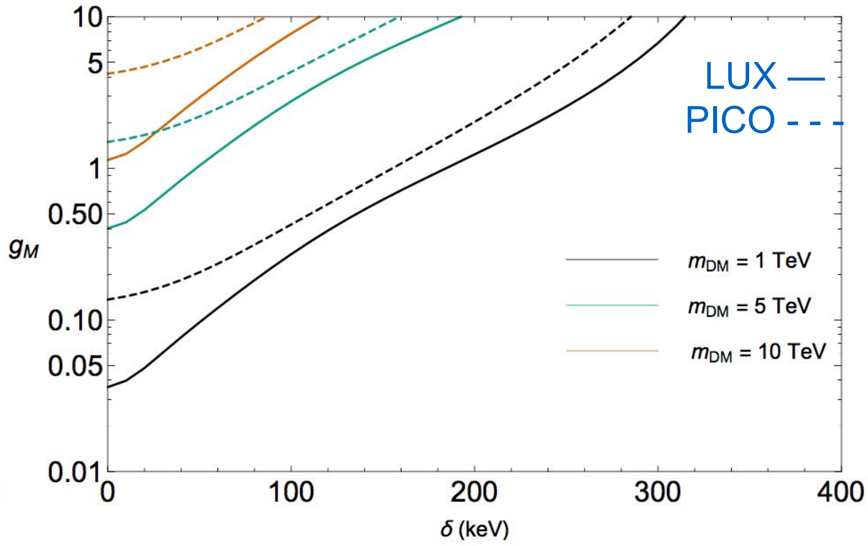


- Comparison here is always ~30 keV windows (Xenon already has larger bounds)
- Orders of magnitude improvements possible in terms of mass splitting
- Assumption is up to 500 keV for LUX, background free(?!)

Present Bounds

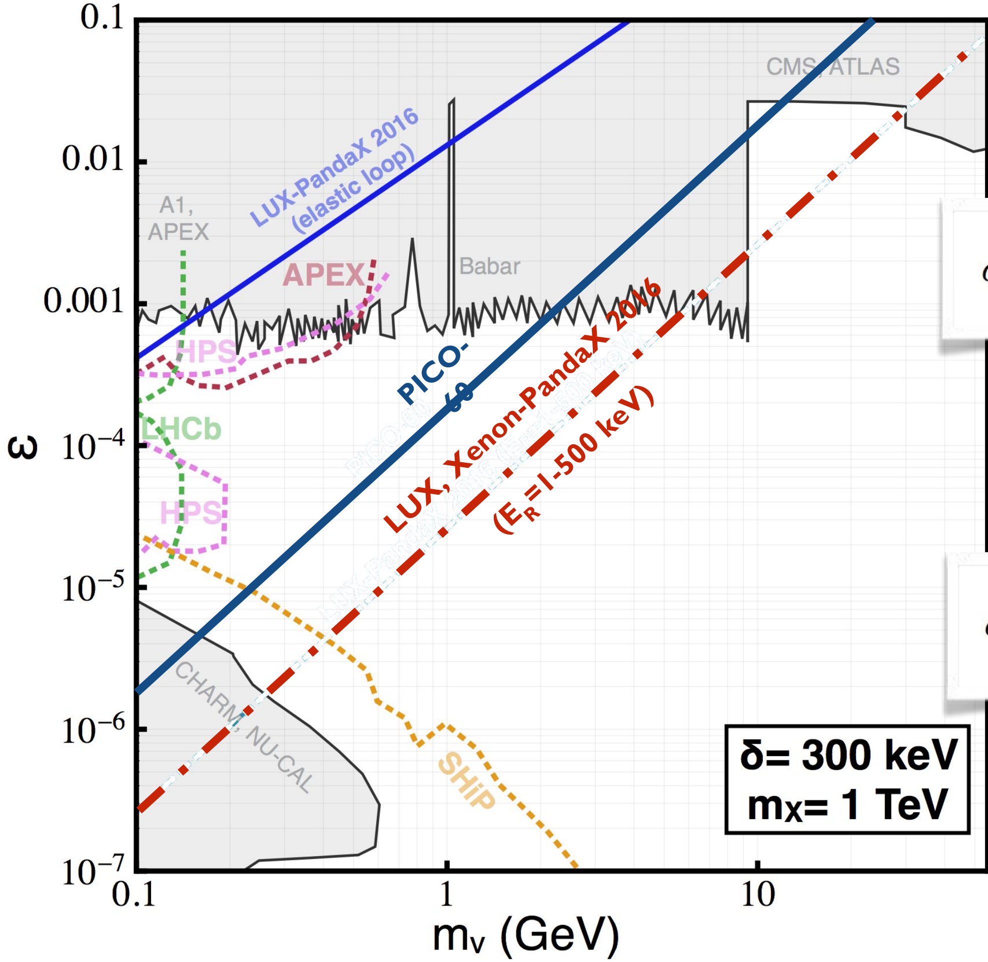


Inelastic Frontier



- Again very large improvements when including high energy recoils
- Note the good performance of Pico

Inelastic DM



$$\sigma^{D}_{n,\mathrm{loop}} \sim \frac{\alpha_D^2 \alpha_{\mathrm{em}}^2 \epsilon^4 m_n^4 f_q^2}{\pi m_V^6}$$

$$\sigma^{D}_{NX} = \frac{16\pi \alpha_{\mathrm{em}} \alpha_D \epsilon^2 \mu_N^2}{m_V^4} Z^2$$

- Great increase with energy window up to E_{NR}=500keV
- Entire experiments are build for comparable improvements (HPS, APEX, SHiP, but of course model dependent)