First Dark Matter Results from LZ

Asher Kaboth

CERN Seminar

9 Aug 2022

https://arxiv.org/abs/2207.03764

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Outline

- Introduction to Dark Matter
- The LZ Experiment
- Looking for WIMPs
- The future is bright

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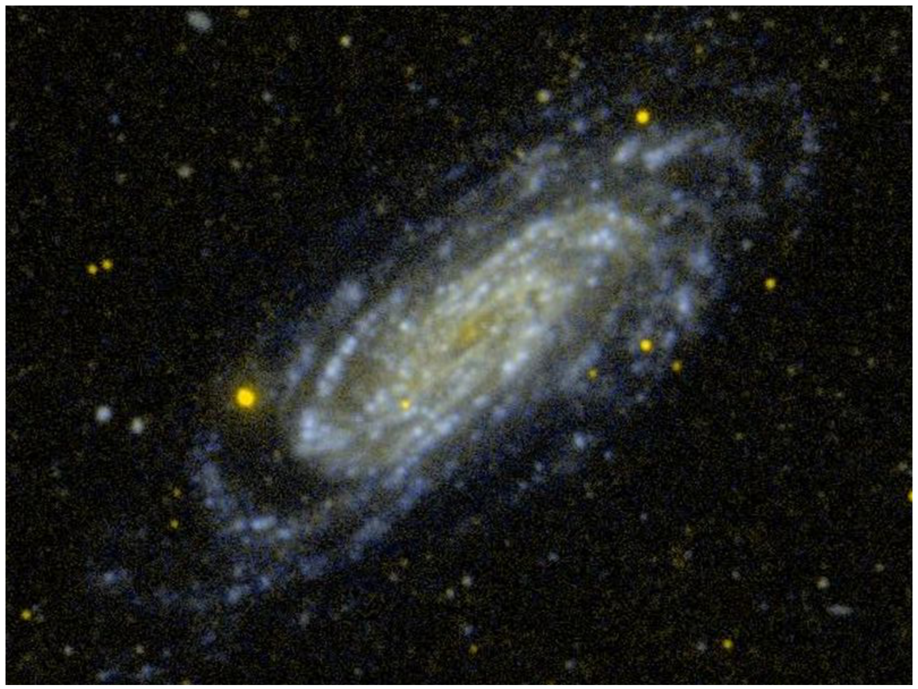
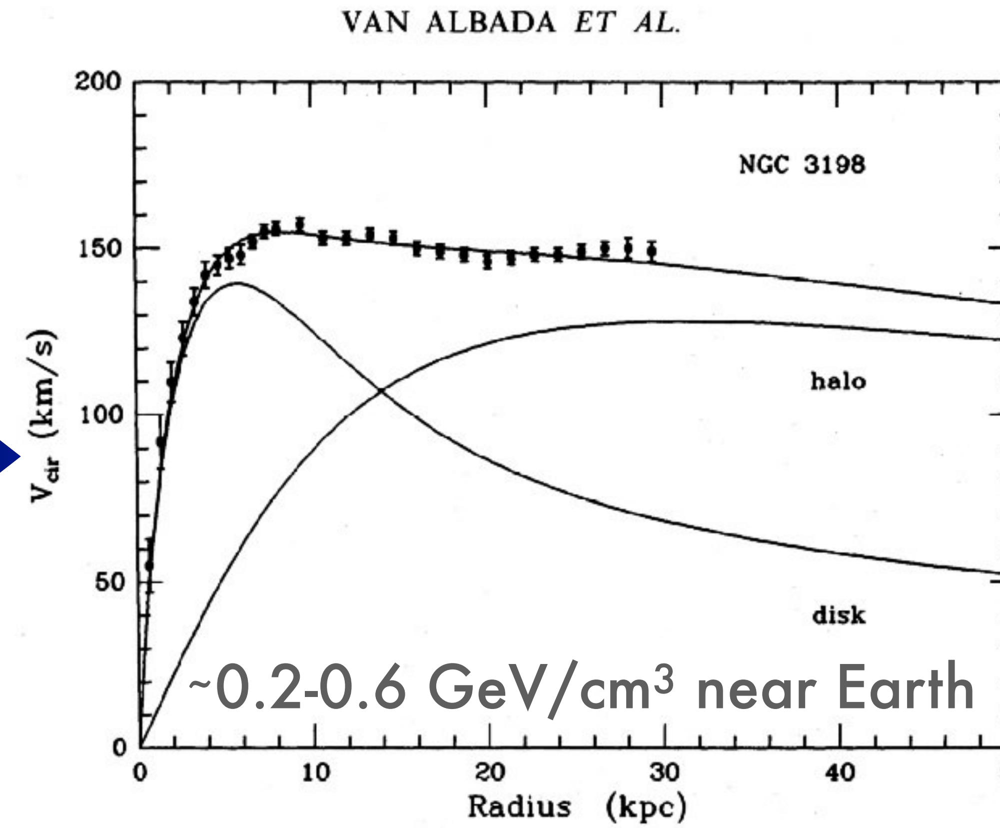
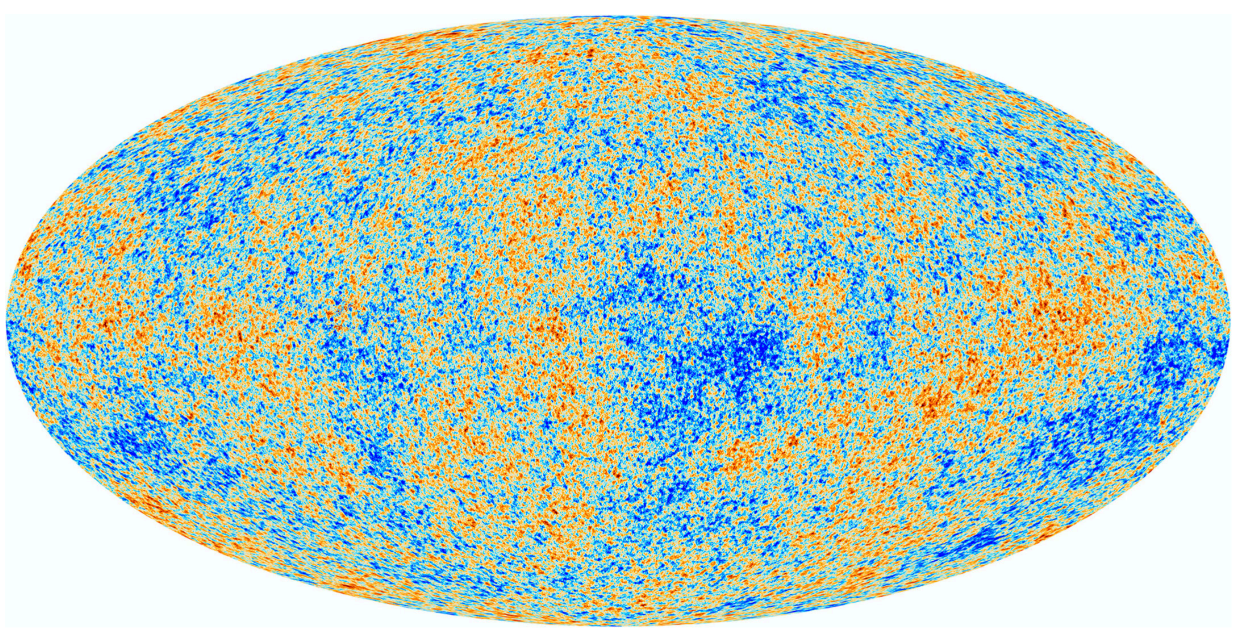
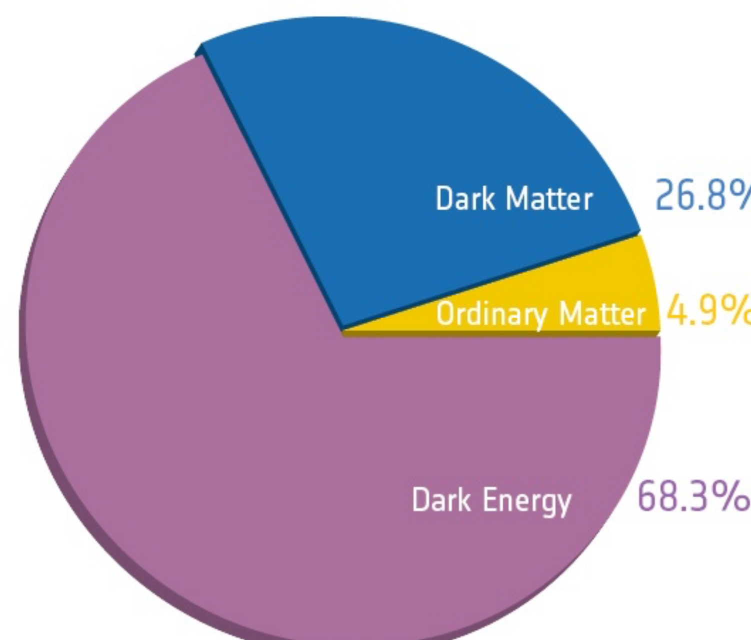
Dark Matter





~0.2-0.6 GeV/cm^3 near Earth





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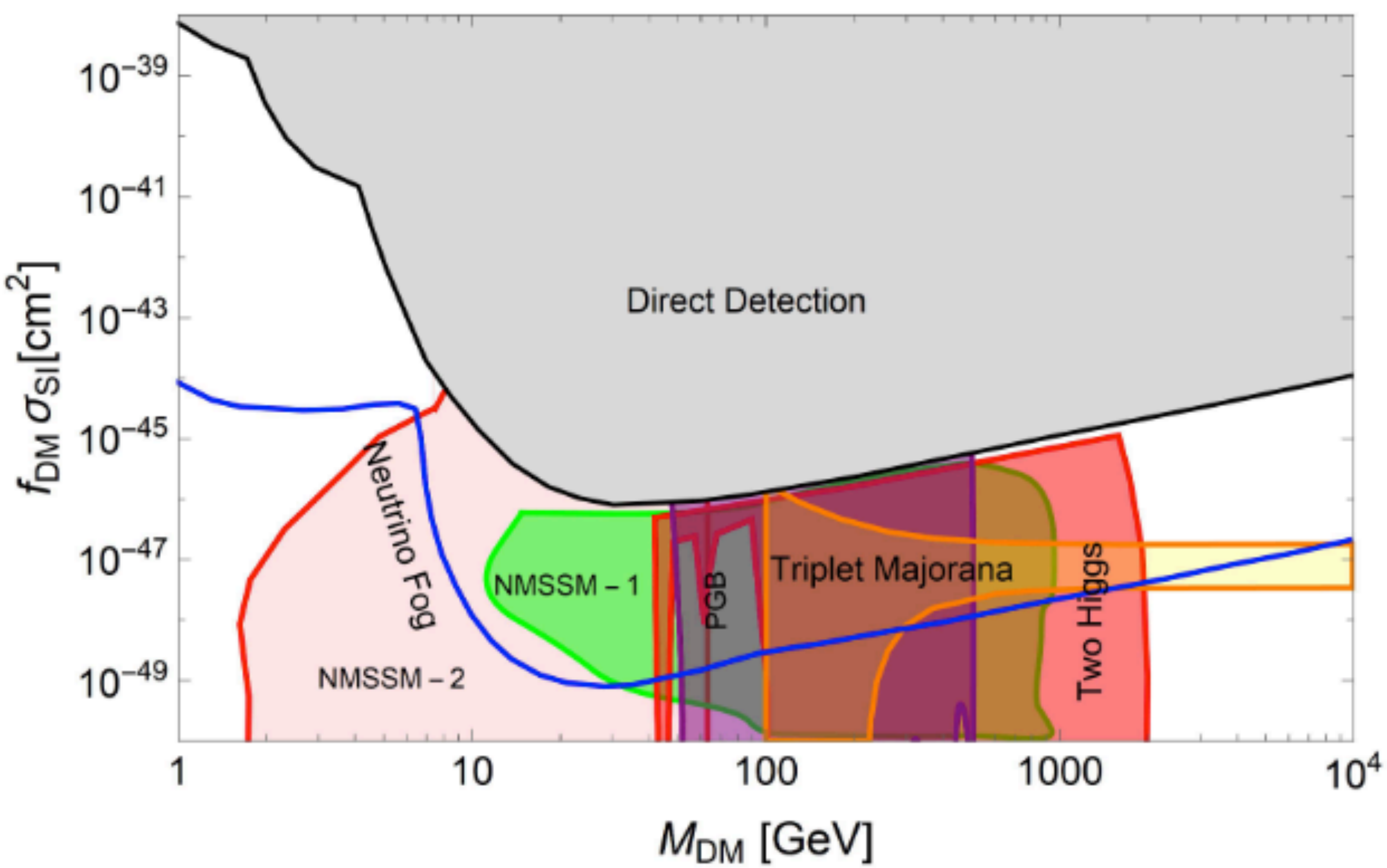
Dark Matter Properties

- "Dark"—does not interact electromagnetically
- Stable over lifetime of the universe
- "Cold"—moves slowly enough for galaxy formation
- Local Density is ~0.3 GeV/cm^3

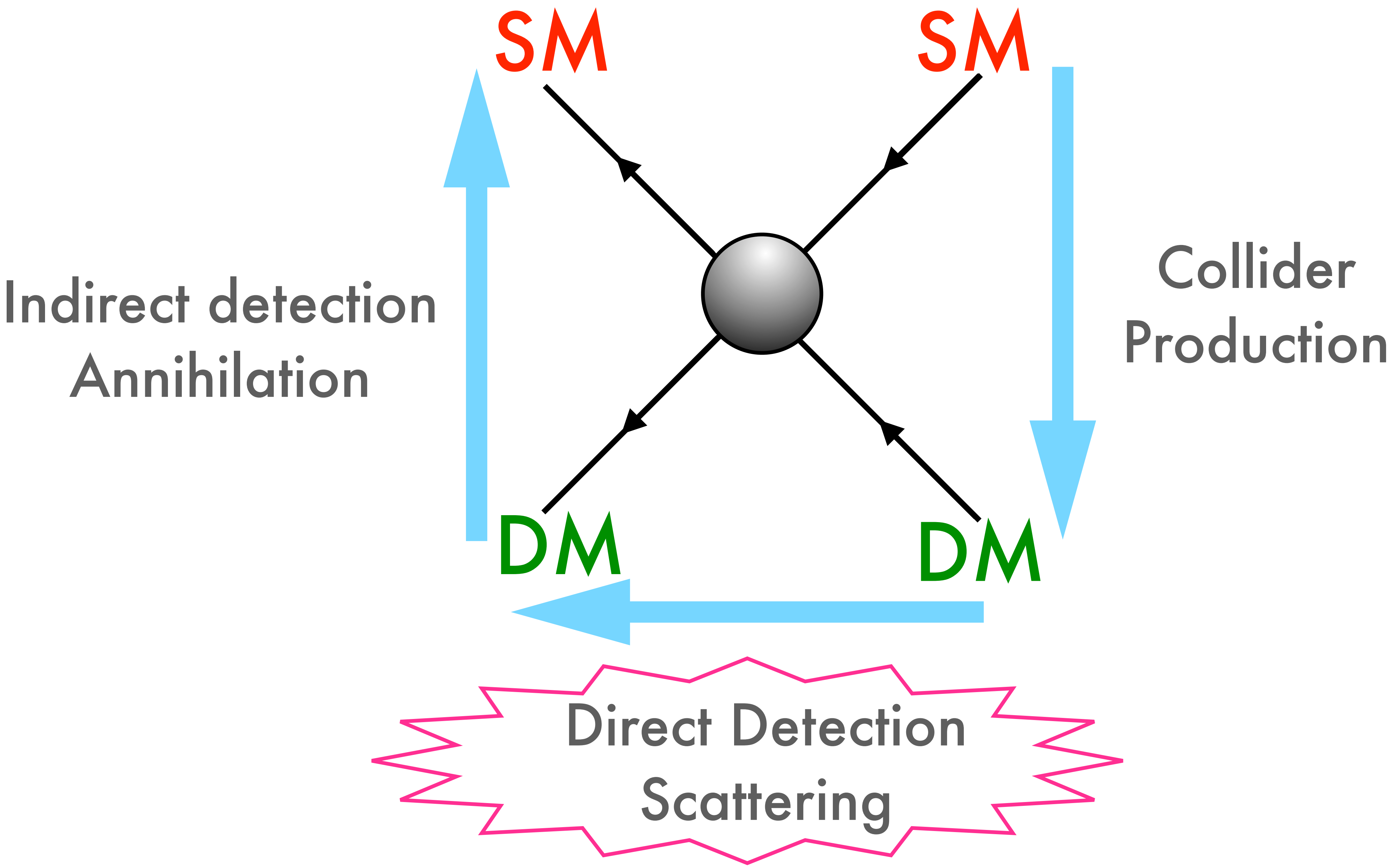
One Candidate: WIMPs

- Weakly Interacting Massive Particle— MeV–100 TeV scale mass
- Weak-scale interactions lead to correct density in present universe
- Motivated by many theories
- Good options for detection!

Lots more, neatly summarized in a Snowmass review

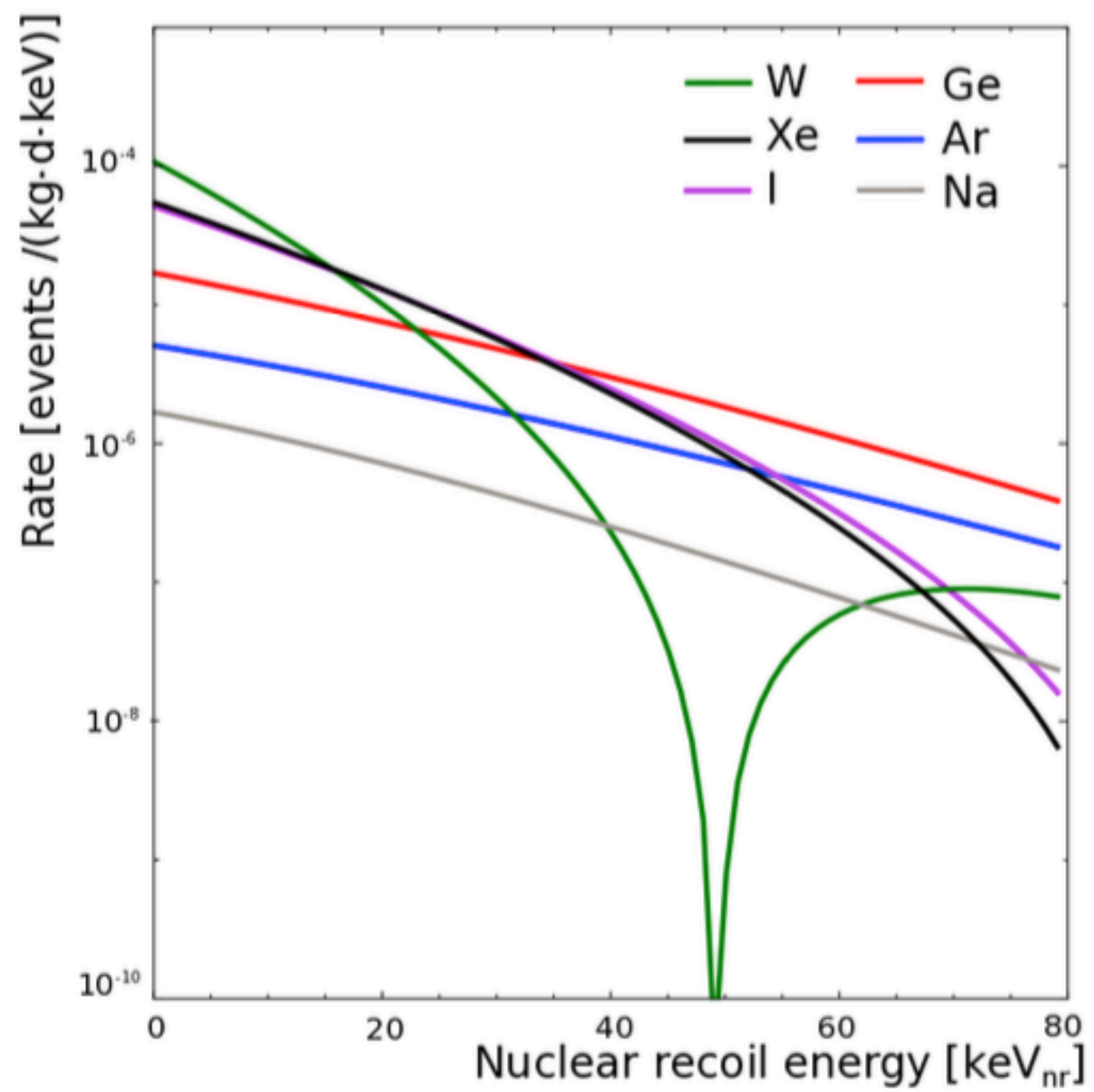


Detecting Dark Matter



WIMP Scattering

- Interaction rates are dependent on our model of how the sun and earth move through the galaxy—how fast do we travel relative to WIMPs
- Use a Maxwell-Boltzmann assumption, with cutoff for escape velocity
- Lots of interesting work from new telescopes!
- Potential spin-dependent and spin-independent couplings
- Signal: Falling ~exponential spectrum

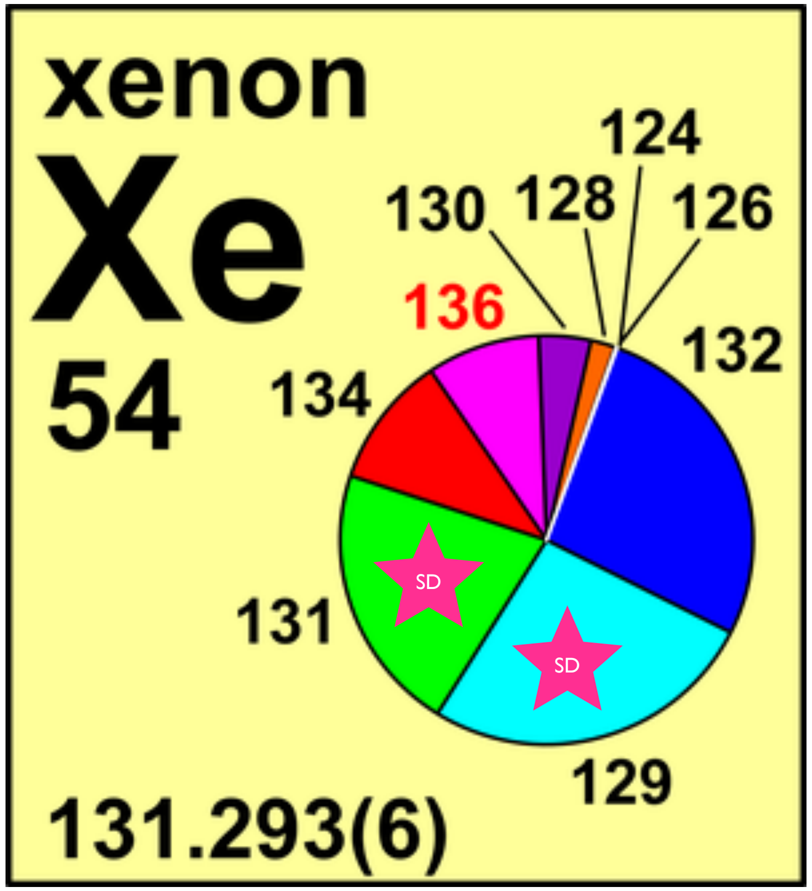


Dark Matter Detectors

- Big (many chances to interact)
- Low background (not much SM stuff)
- Good position resolution (fiducialization)
- Low threshold (phase space)
- Event type discrimination (many models)
- Multi-isotope (spin and non-spin dependent interactions)

Liquid Xenon

- Dense
- Easily purified
- Many Isotopes
- Scintillates like a pig



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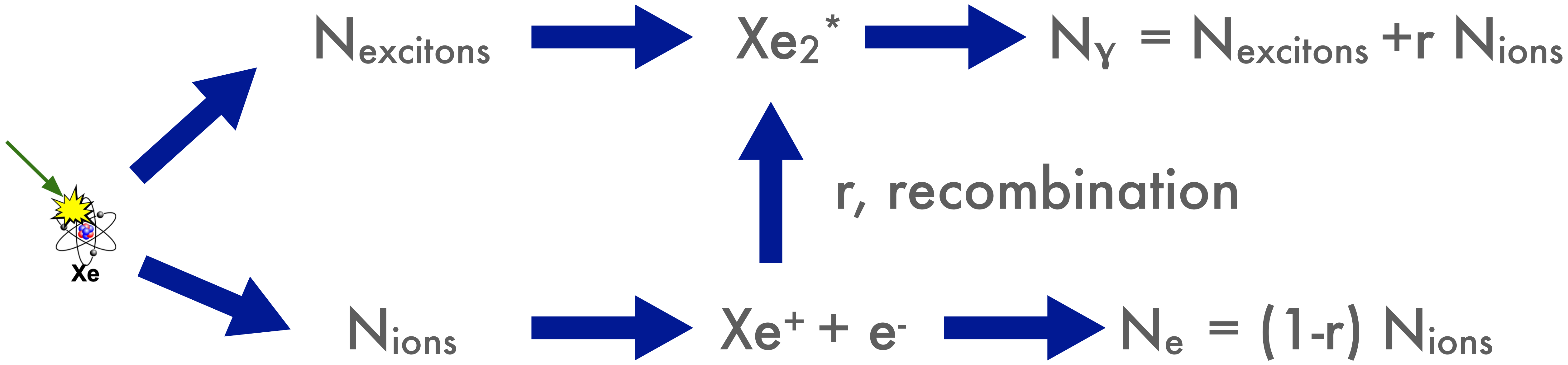
LZ

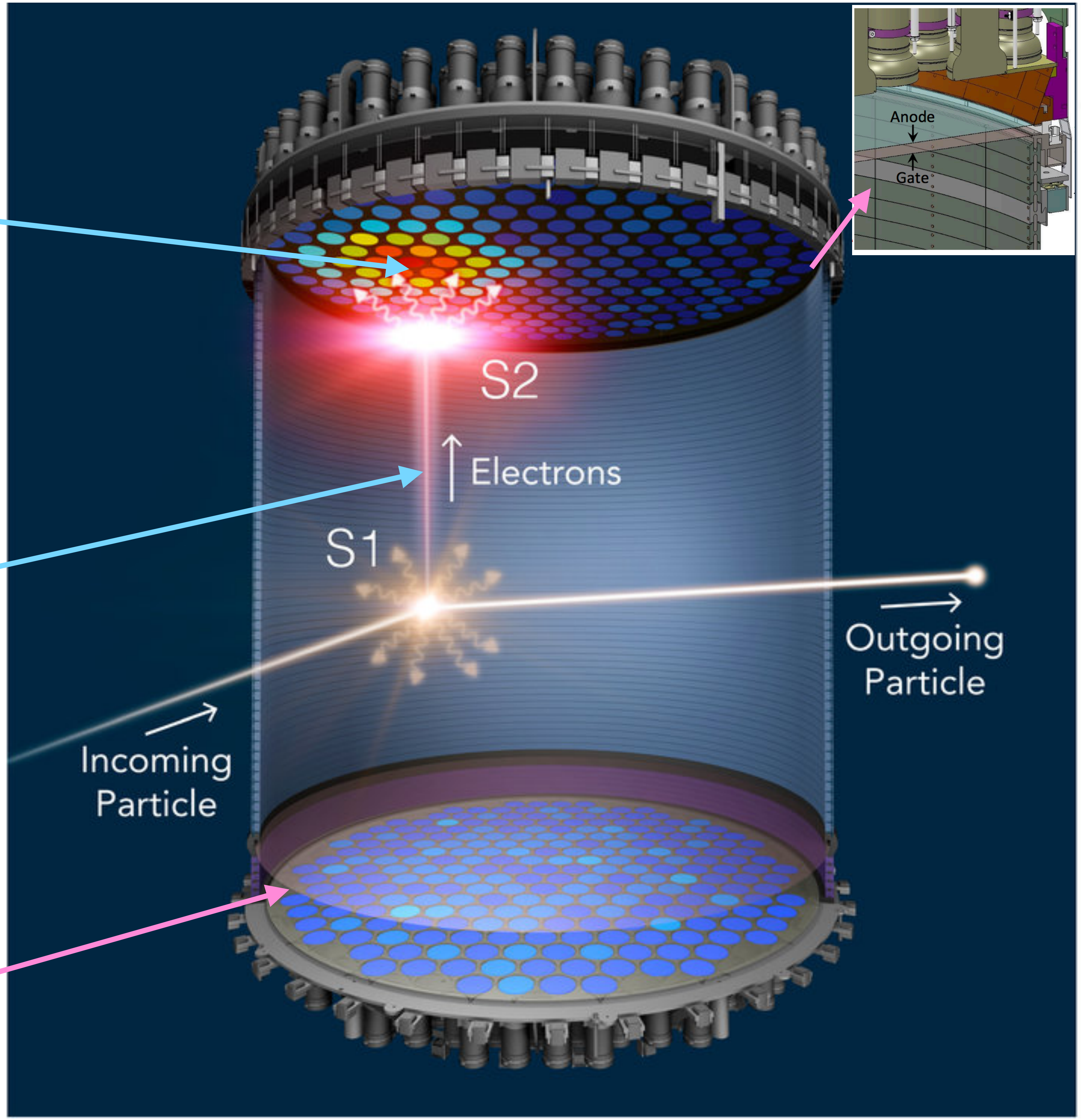
Liquid Xenon



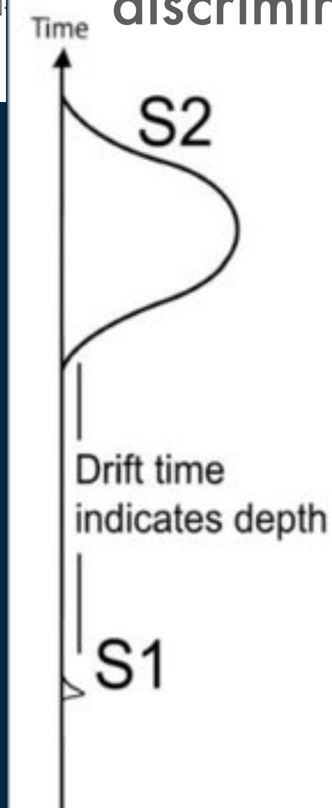
S2 light pattern gives x-y position
(~few mm resolution)

Drift time gives z position
(~0.5 mm resolution)

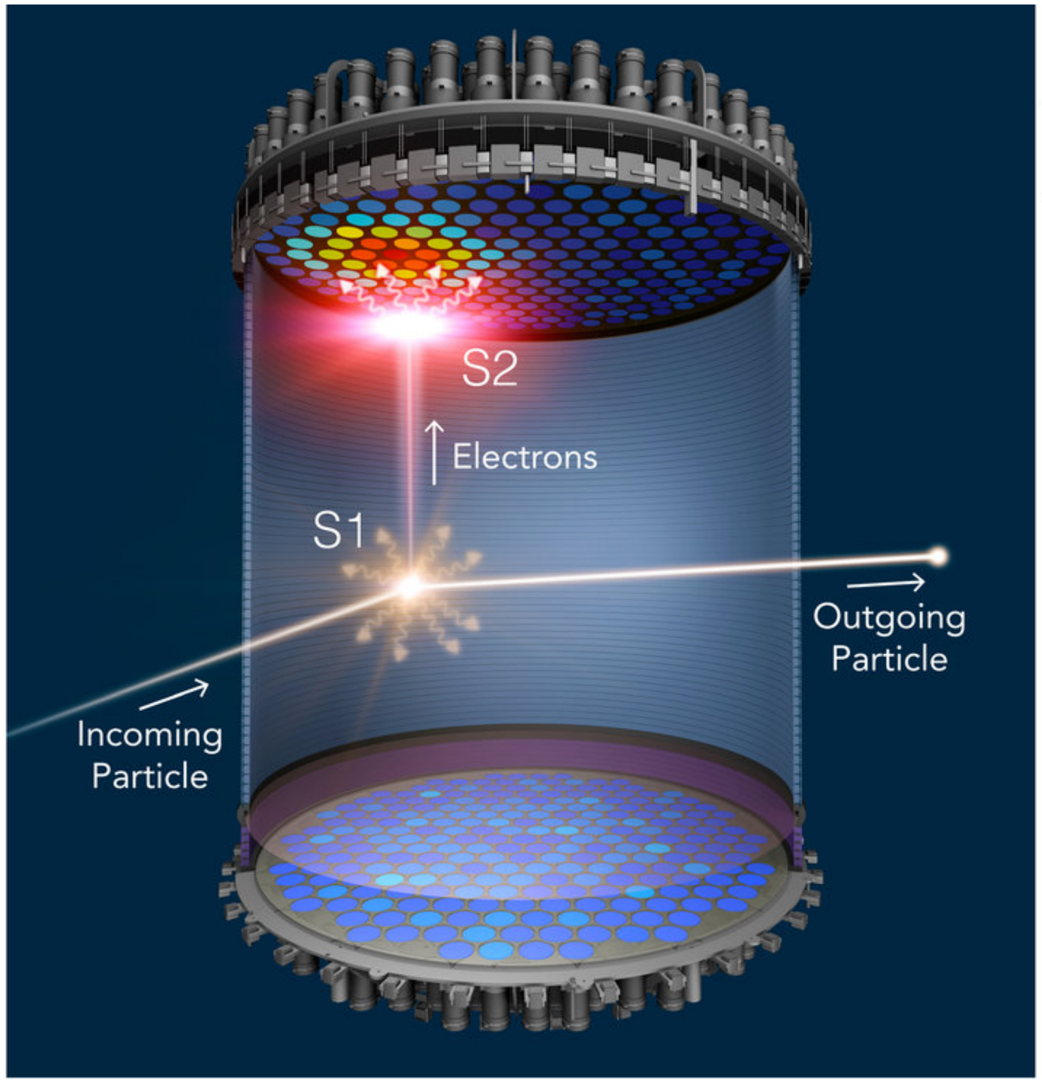
Cathode



S1-S2 relative size gives event-type discrimination

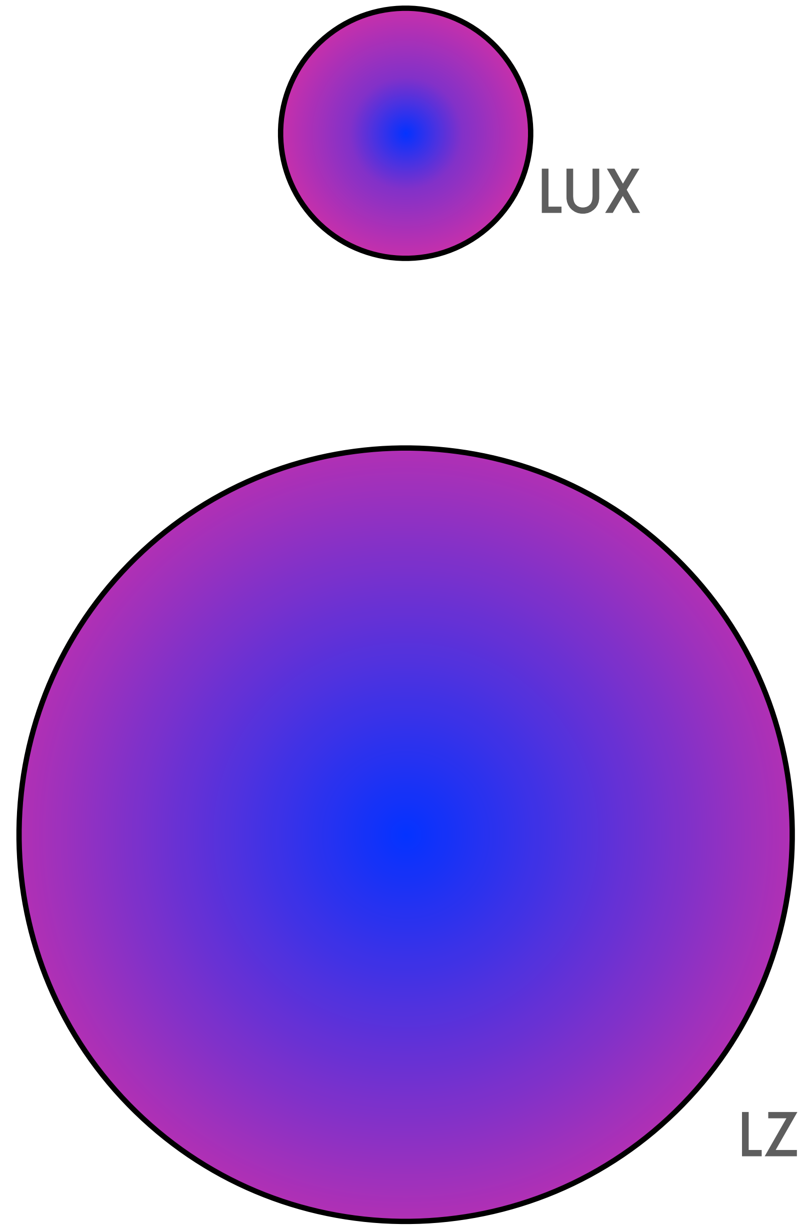


LZ TPC

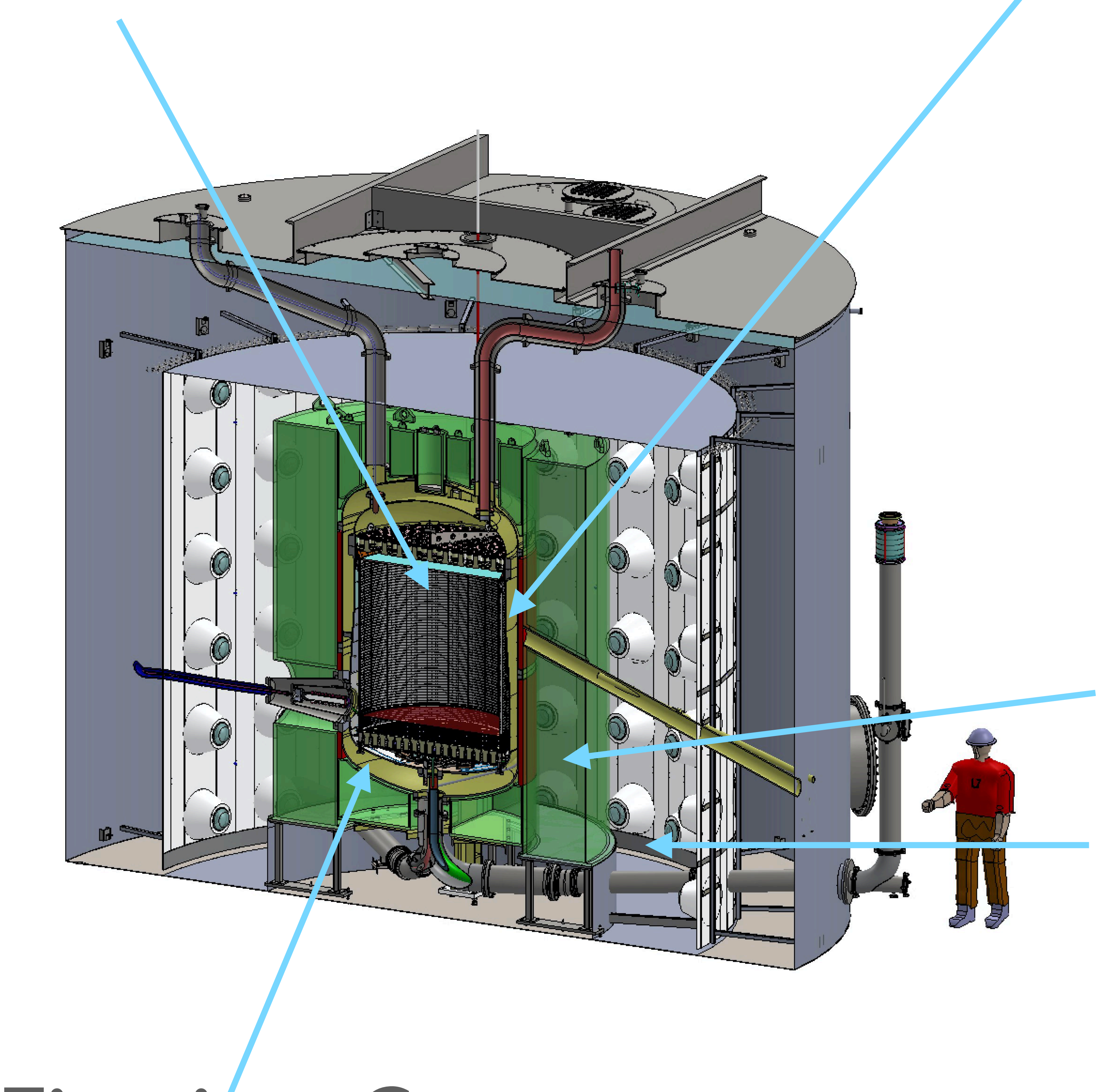


- 1.5 m diameter
- 1.5 m drift
- 494 PMTs
- 7t Xe in TPC
- PTFE walls for light collection

Self-shielding has a bigger impact the bigger the detector is



LZ



SKIN

- 2 tonnes of LXe surrounding the TPC
- 131 1″ and 3″ PMTs at top and bottom of the skin region
- Lined with PTFE to maximize light collection
- Anti-coincidence detector for γ-rays

OUTER DETECTOR

- 17 tonnes Gd-loaded liquid scintillator in acrylic vessels
- 120 8″ PMTs mounted in the water tank
- Anti-coincidence detector for γ-rays and neutrons
- Observe ~8 MeV of γ-rays from thermal neutron capture

Possible Contaminants

- Uranium and Thorium
  - Produce α, β, and γ
  - Secondary neutron production through α-n
  - Long-lived
  - Produce Rn which, as a gas, diffuses
- Krypton and argon dissolved in xenon
  - β and γ decaying isotopes
- Other radioactive elements—^{60}Co and ^{40}K are most common
- Cosmic activation
- Cavern wall radioactivity

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Materials Mitigation

Eur. Phys. J. C (2020) 80: 1044

- Enormous screening program for all materials
  - Ge detectors
  - ICPMS
  - Rn emanation
  - Neutron activation analysis
- Clean assembly
  - Rn reduced clean rooms
  - Dust prevention
- Xenon purification
  - Charcoal chromatography
  - Continuous purification in situ

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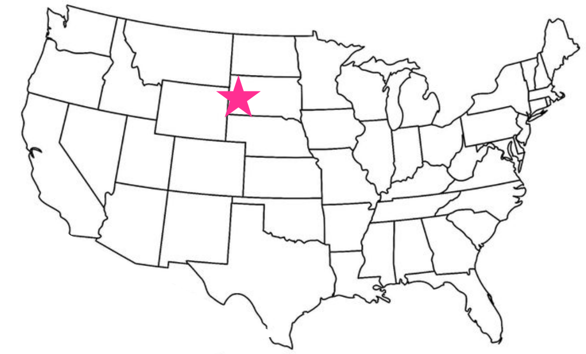
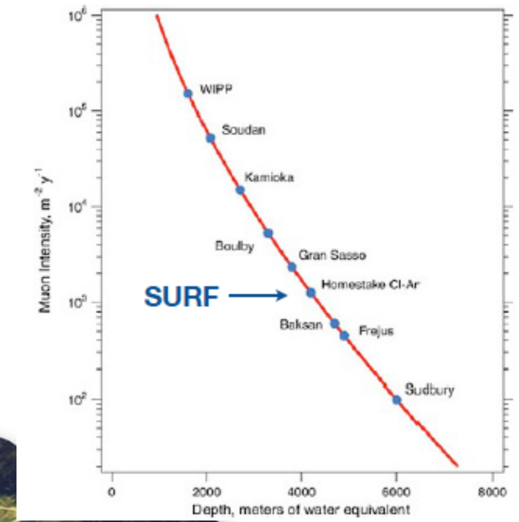
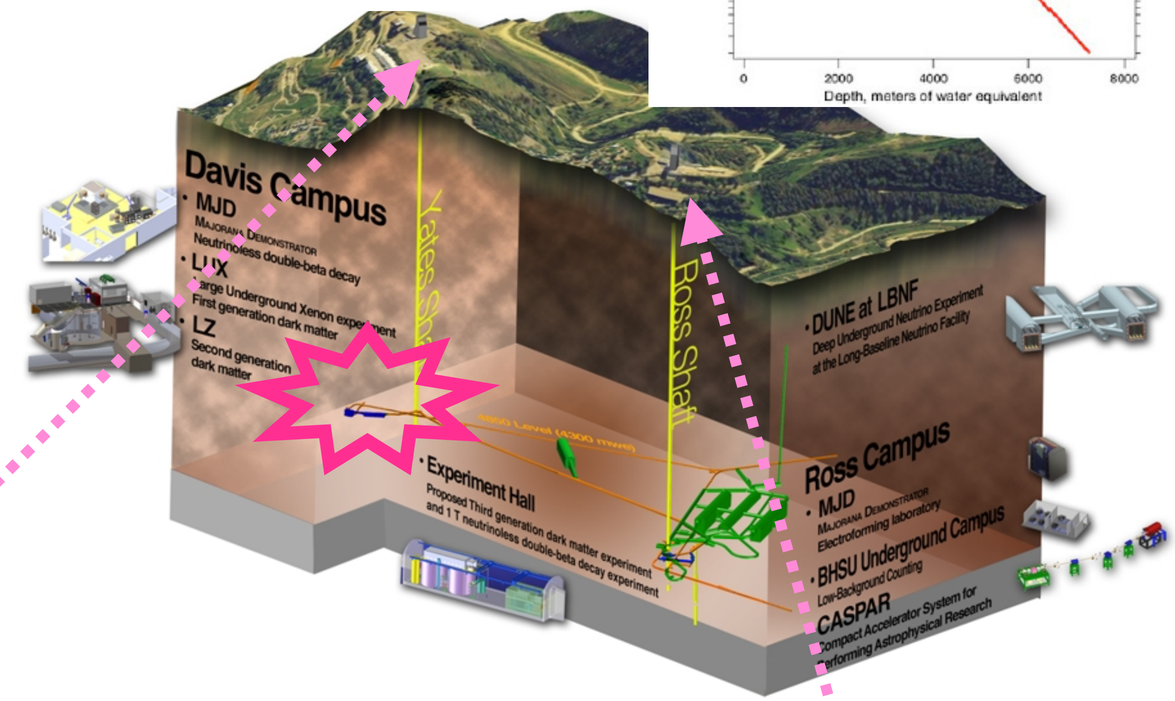
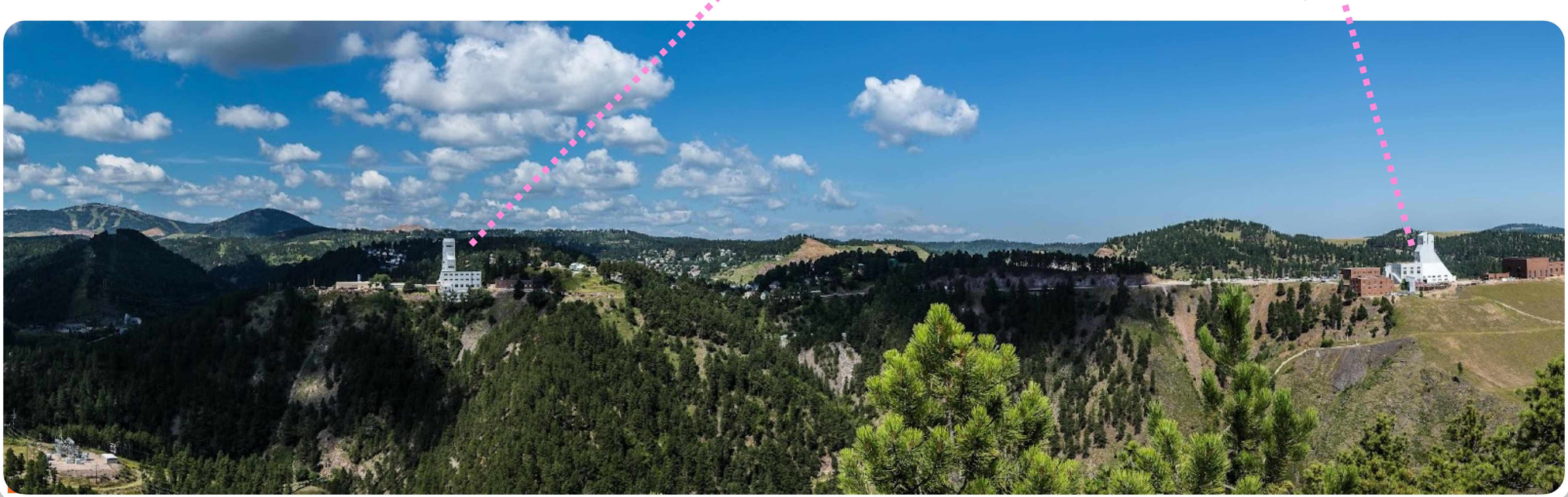
SURF

- Go underground to reduce cosmic muon flux—factor of 10^6
- Depth of 4850 ft (1.48 km)
- Past home of the Homestake experiment, future home of DUNE



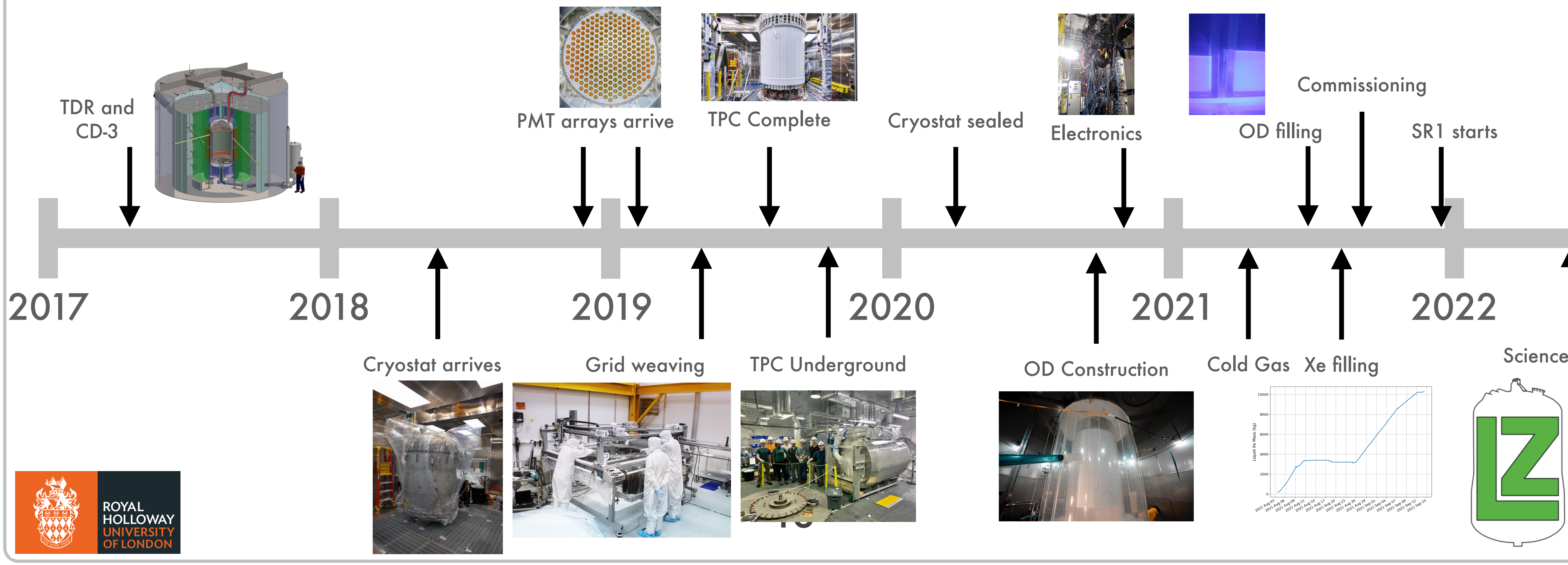






Timeline

- Design completed and approved in 2017
- Autumn 2018: above ground assembly work begins at SURF
- October 2019: TPC heads underground
- March 2020: Cryostat closed underground, 2 mo shutdown for COVID
- July 2021: OD complete and filled
- Sept 2021: TPC filled with xenon
- Autumn 2021: Commissioning
- Next up: the photo album



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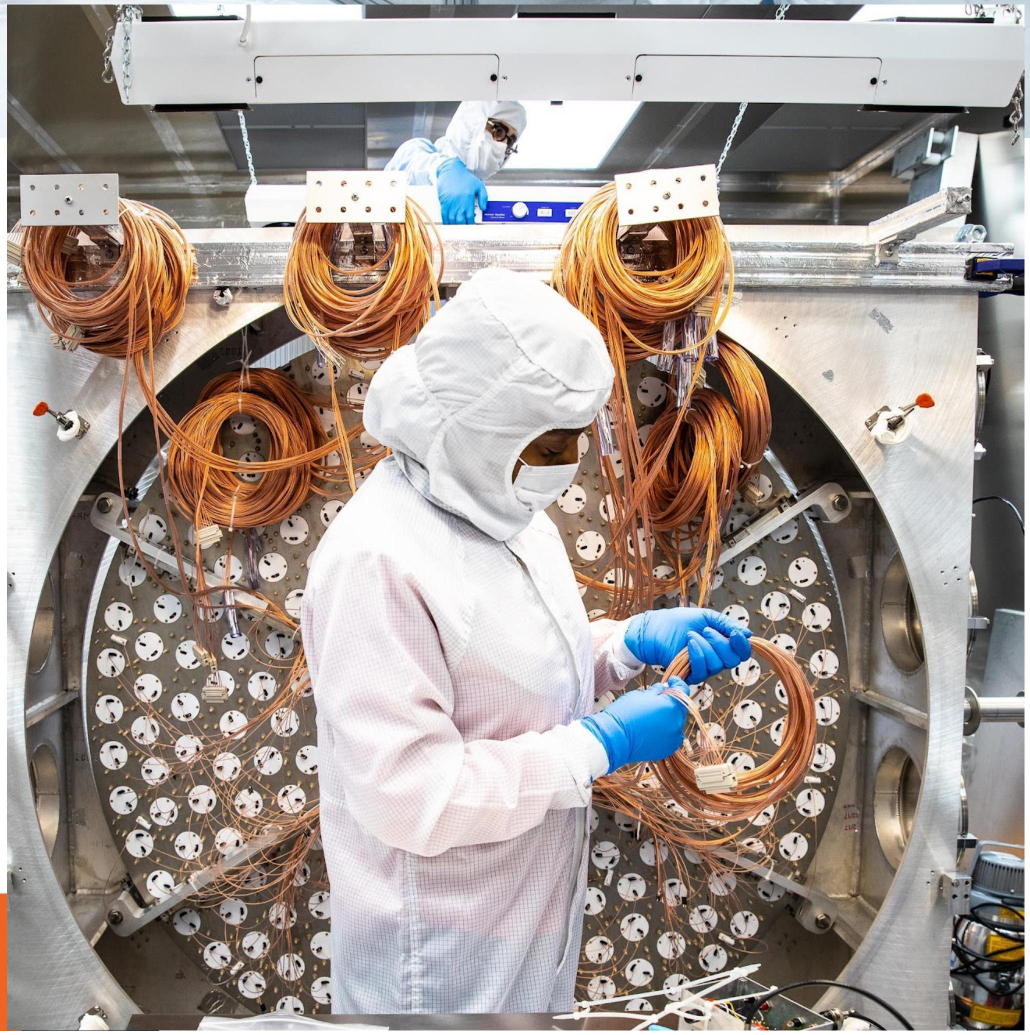
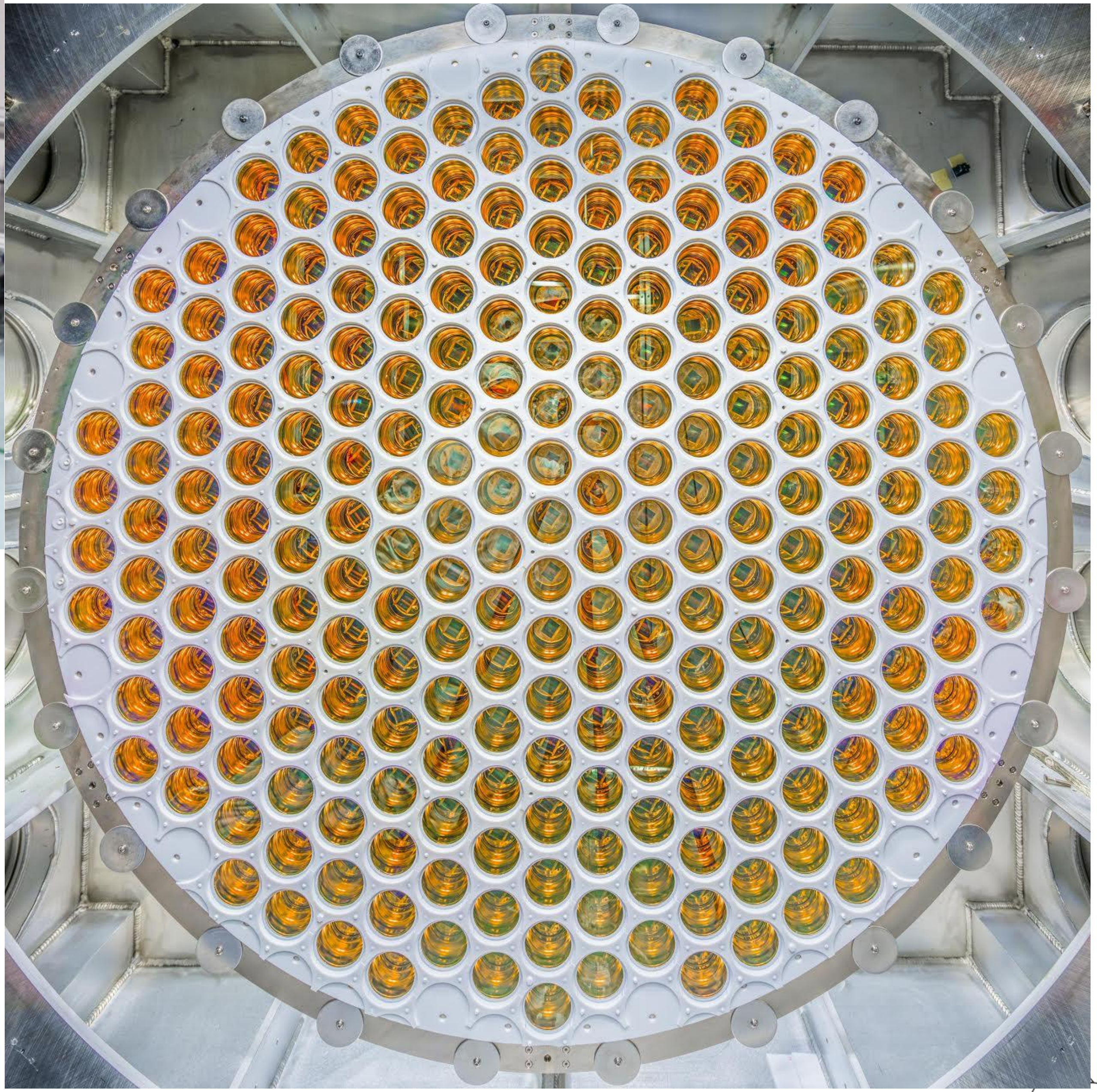
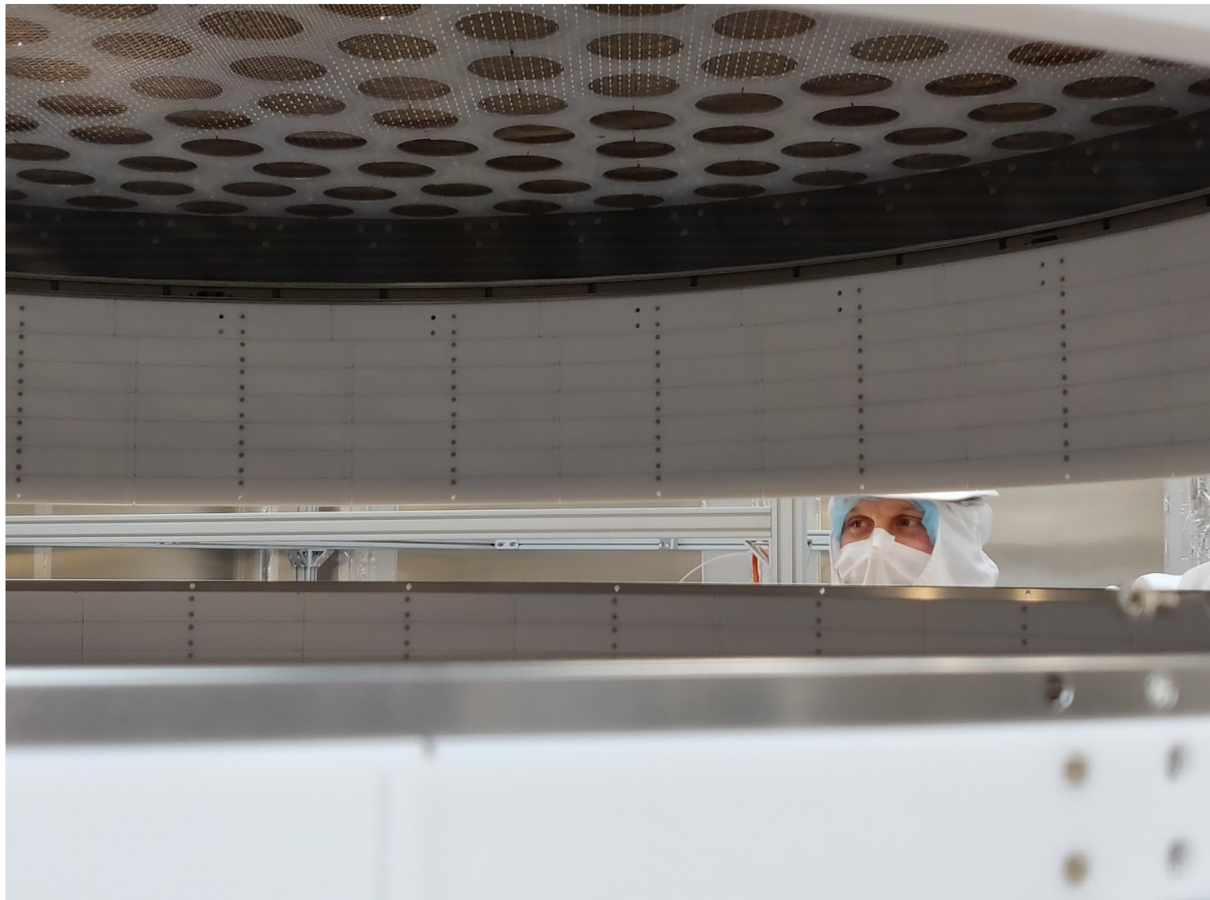
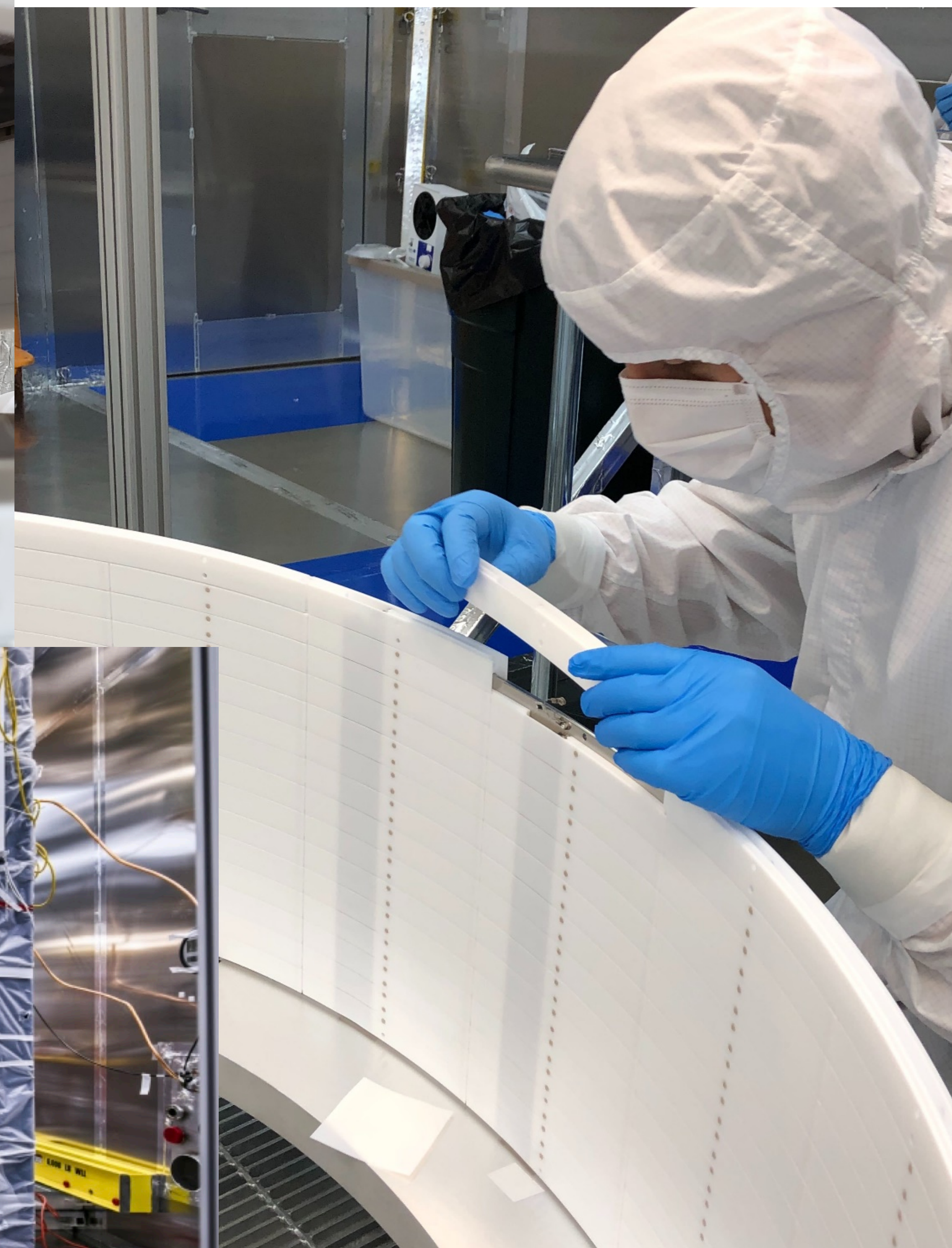
Grids and PMT Arrays

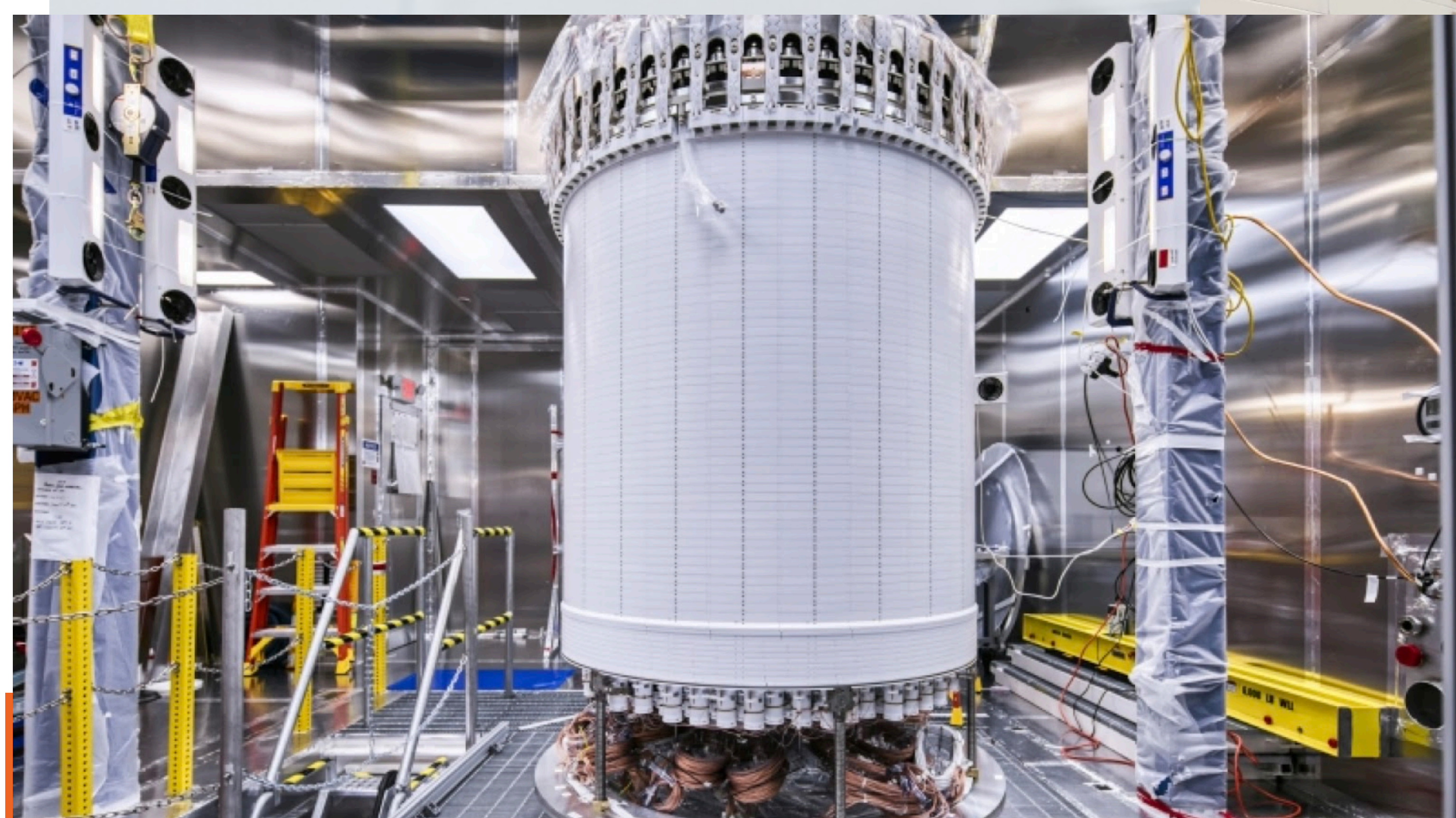




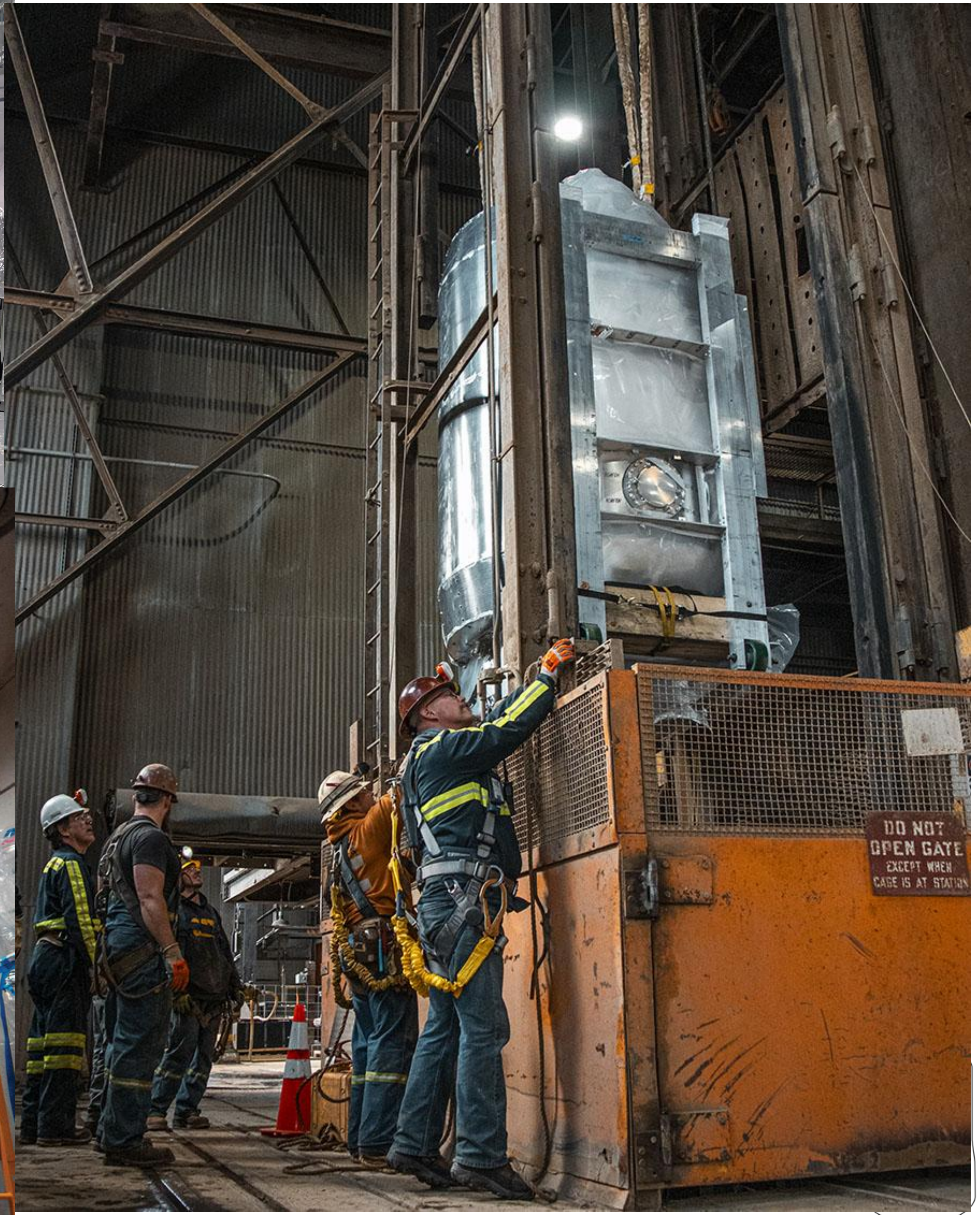
TPC Assembly







Going Underground

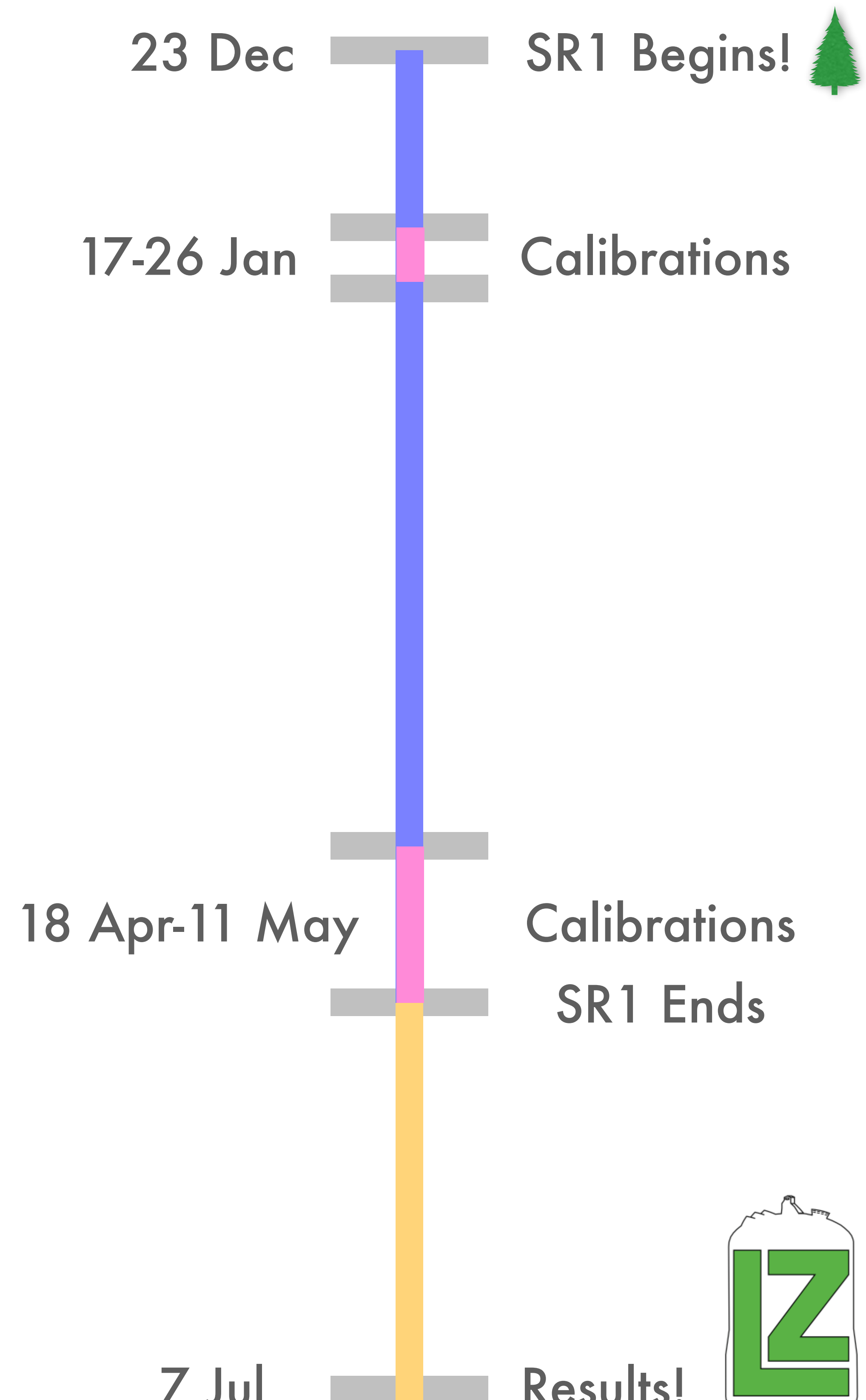


Outer Detector

Let's do some science!

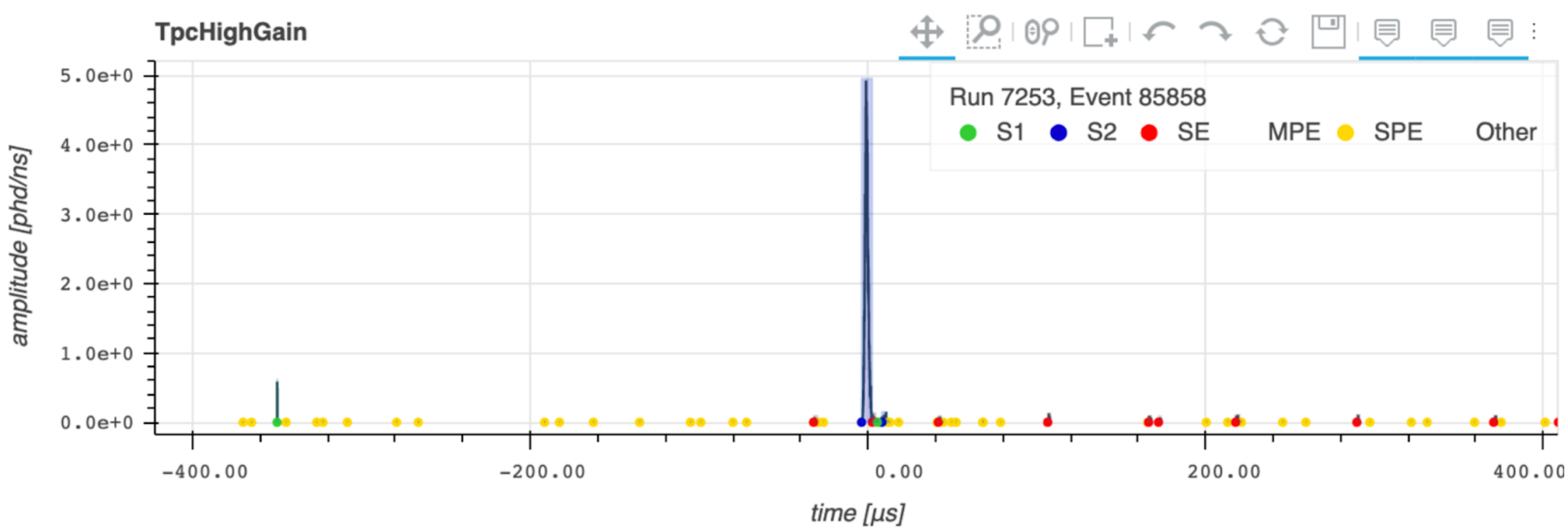
Science Run 1

- Can we operate the detector stably over long periods?
- Can we calibrate the detector response?
- What do the backgrounds look like?
- Can we set a new WIMP cross section limit?

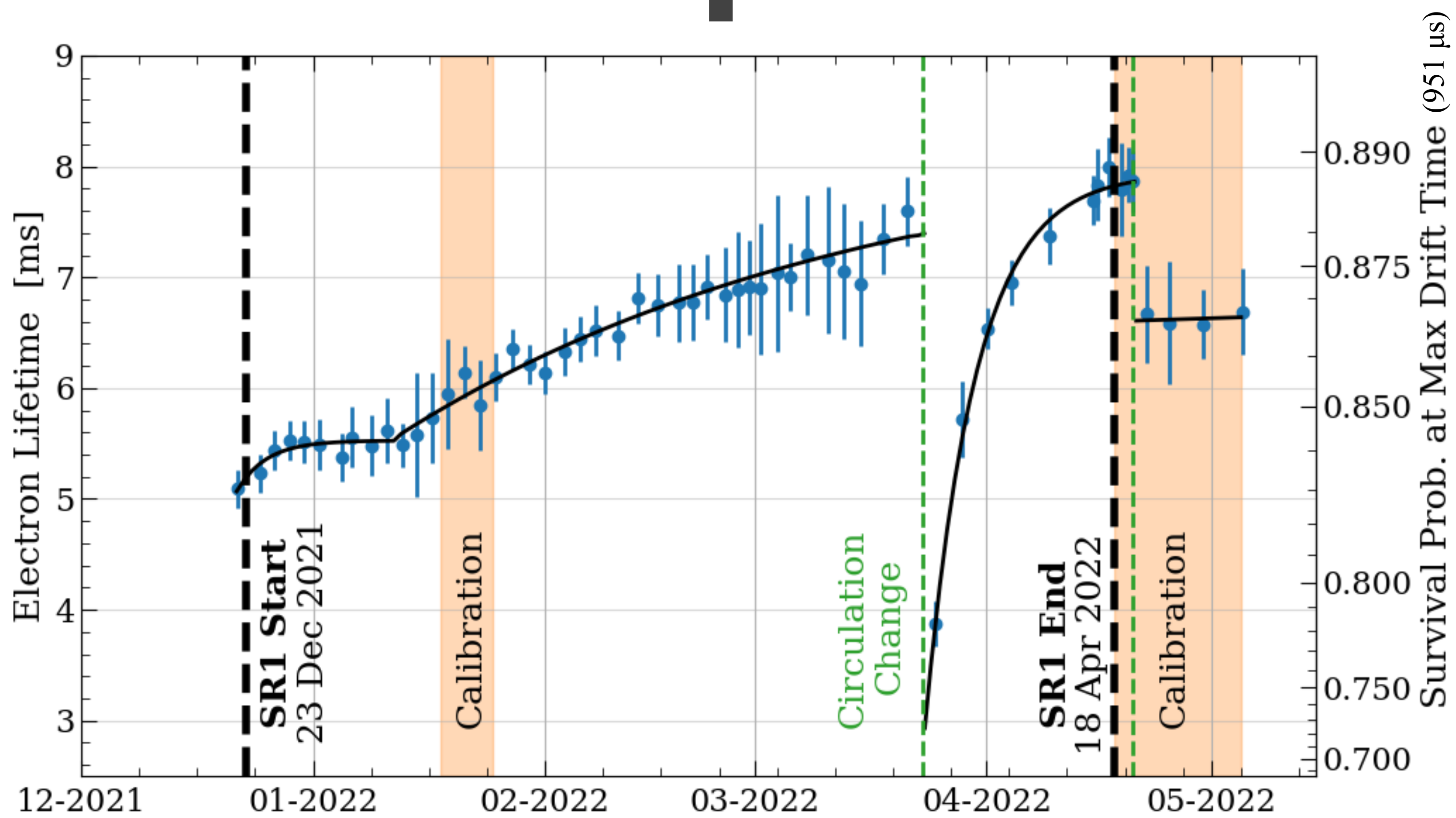


What is an LZ event?

- A WIMP looks like one S1 (photons) followed by one S2 (drifted electrons) with no activity in the veto detectors
- Pulses are classified into S1 and S2 based on their parameters such as pulse shape and PMT hit patterns
- Events are categorized into 'single scatter' and 'multiple scatter' based on the time, ordering, and size of S1 and S2 pulses



Stable Operations



- PMTs: >97% operational throughout run
- Liquid temperature: 174.1 K (0.02%)
- Gas pressure: 1.791 bar(a) (0.2%)
- Gas circulation: 3.3t/day
- Drift field: 193 V/cm (32 kV cathode, uniform to 4% in fiducial volume)
- Extraction field: 7.3 kV/cm in gas (8 kV gate-anode ΔV)

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Calibration Needs

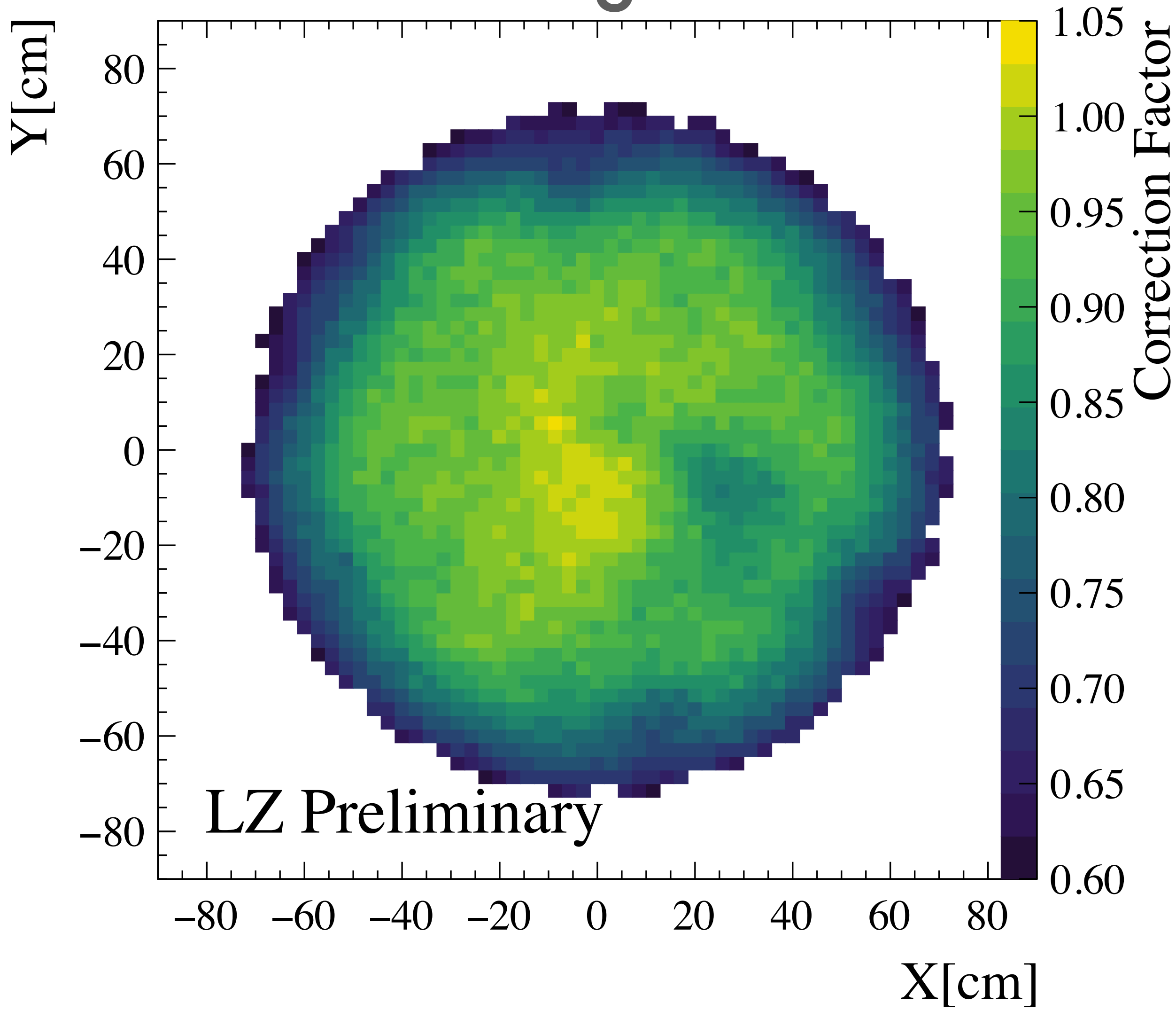
- Spatial non-uniformity corrections
- ER band response
- NR band response
- Veto efficiencies
- Data selection efficiency

Spatial Non-uniformity

83mKr (32.1 and 9.4 keV ER), 131mXe (164 keV ER), αs (various)

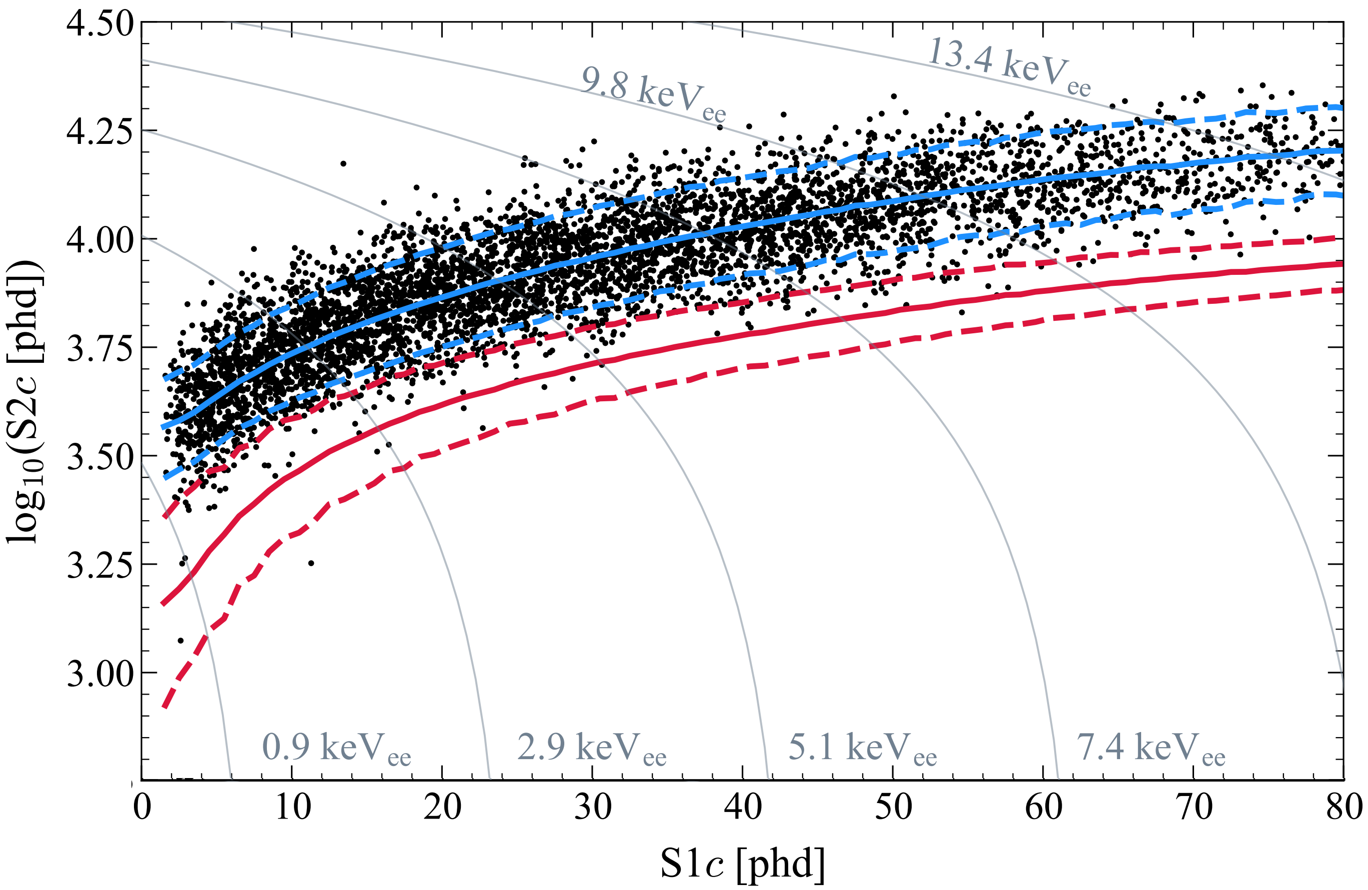
- Electron lifetime (already shown)
- PMT responses
- Light reflection and absorption
- Typically 10% effect in fiducial volume

Relative S2 Light Collection



Electron Recoil Band Response

CH_3T (β-decay), 83mKr (32.1 and 9.4 keV ER), 131mXe (164 keV ER)



- Use Noble Element Simulation Technique (NEST) to model the relationship between recoil energy and S2-S1 observable space
- CH_3T injection produces a uniformly distributed, well known spectrum over the detector to tune the response model —use identical cuts to the WIMP search
- Additionally use monoenergetic ER sources to validate model
- We can test (and validate!) the model of ER leakage into the NR band out to 4σ

Parameter	Value
g_1^{gas}	0.0921 phd/photon
g_1	0.1136 phd/photon
Effective gas extraction field	8.42 kV/cm
Single electron	58.5 phd
Extraction Efficiency	80.5 %
g_2	47.07 phd/electron

$$E = W\left(\frac{S_1}{g_1} + \frac{S_2}{g_2}\right)$$

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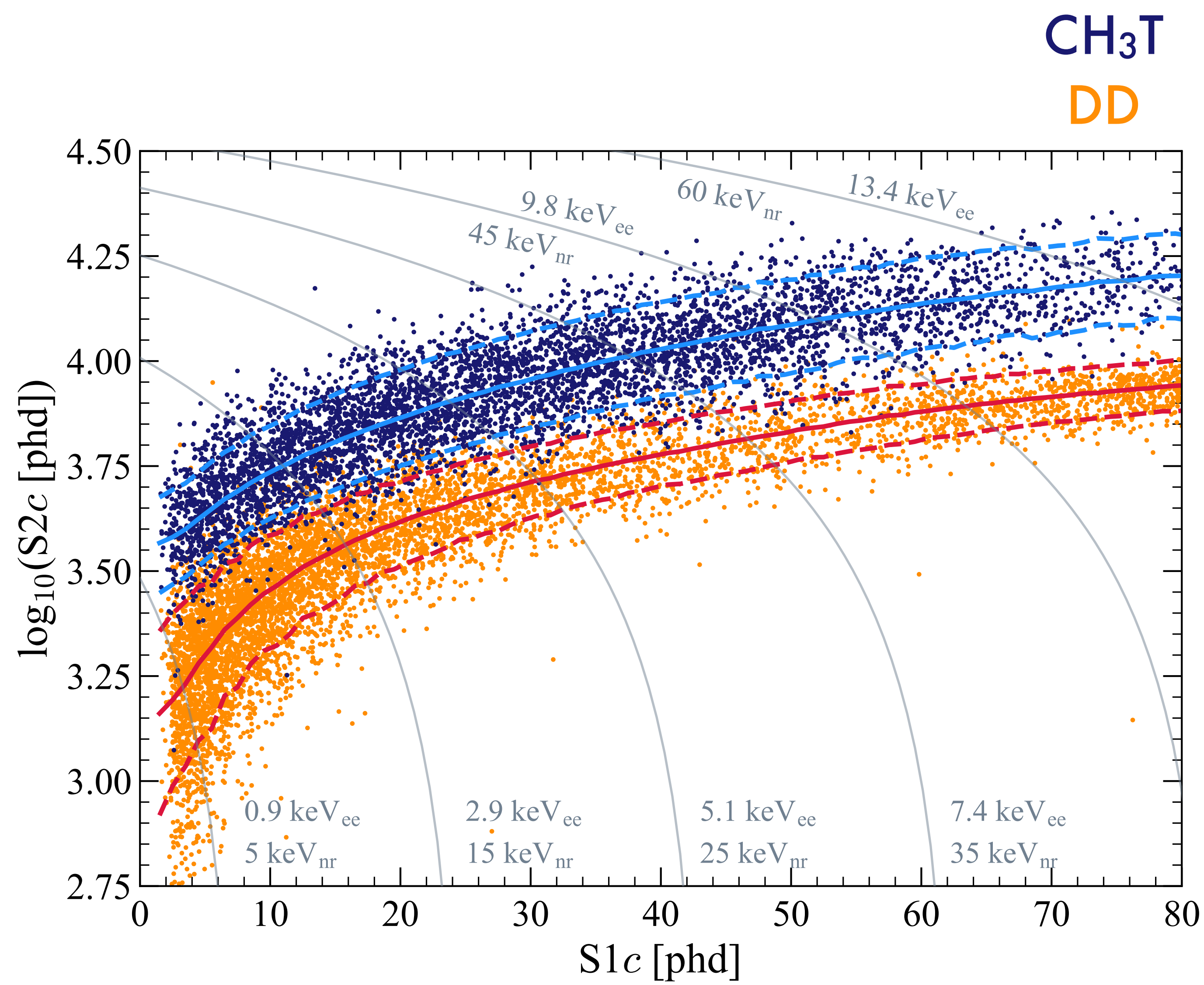
Nuclear Recoil Band Response

Deuterium-Deuterium Neutron Source

- DD source produces a monoenergetic 2.45 MeV neutron, which produces a range of Xe NR energies
- Extrapolate model to NR response—works very well
- Rejection of 99.9% ER leakage below the median quantile of a 40 GeV WIMP.



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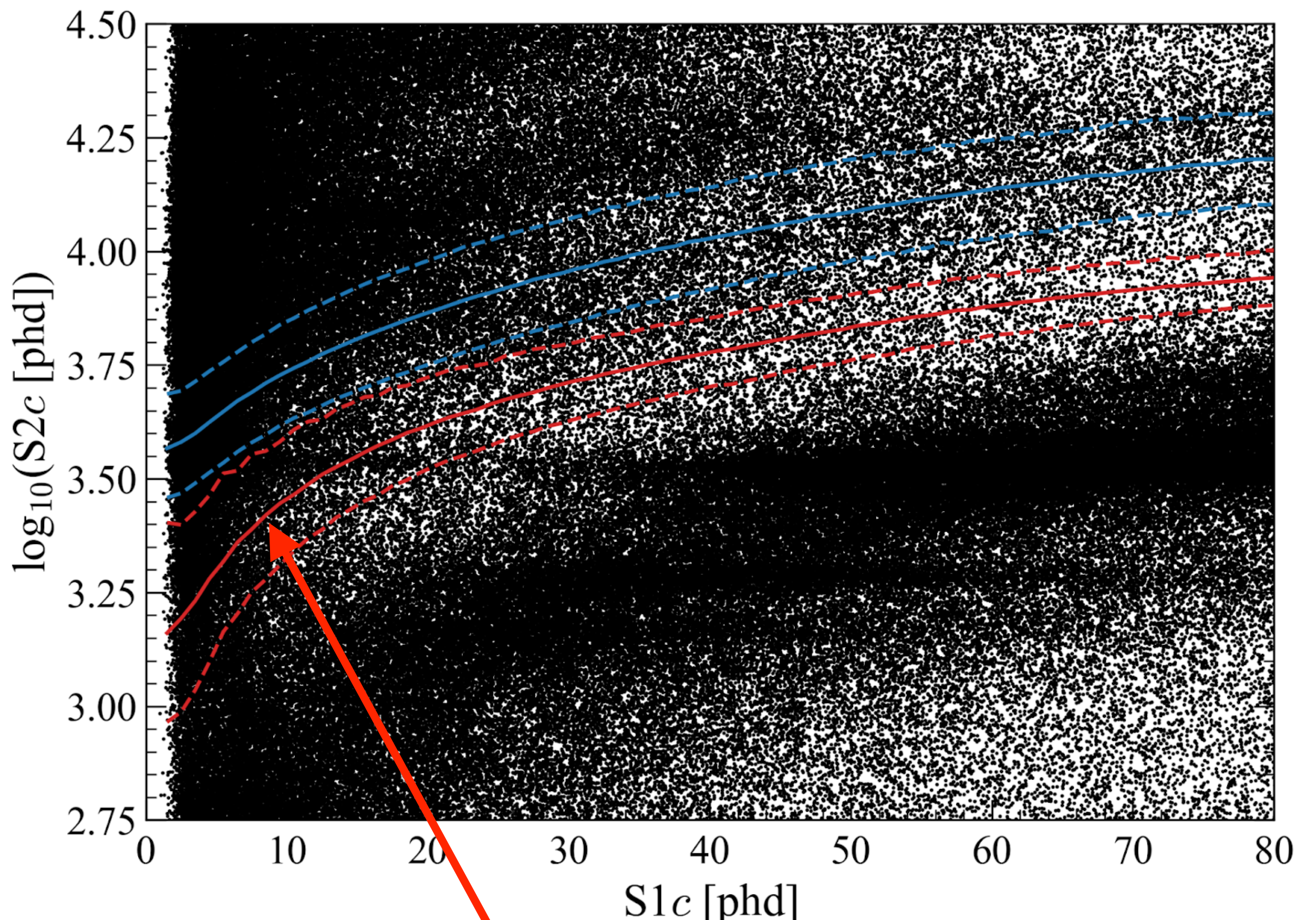
Looking for WIMPs

All Single-Scatter Events

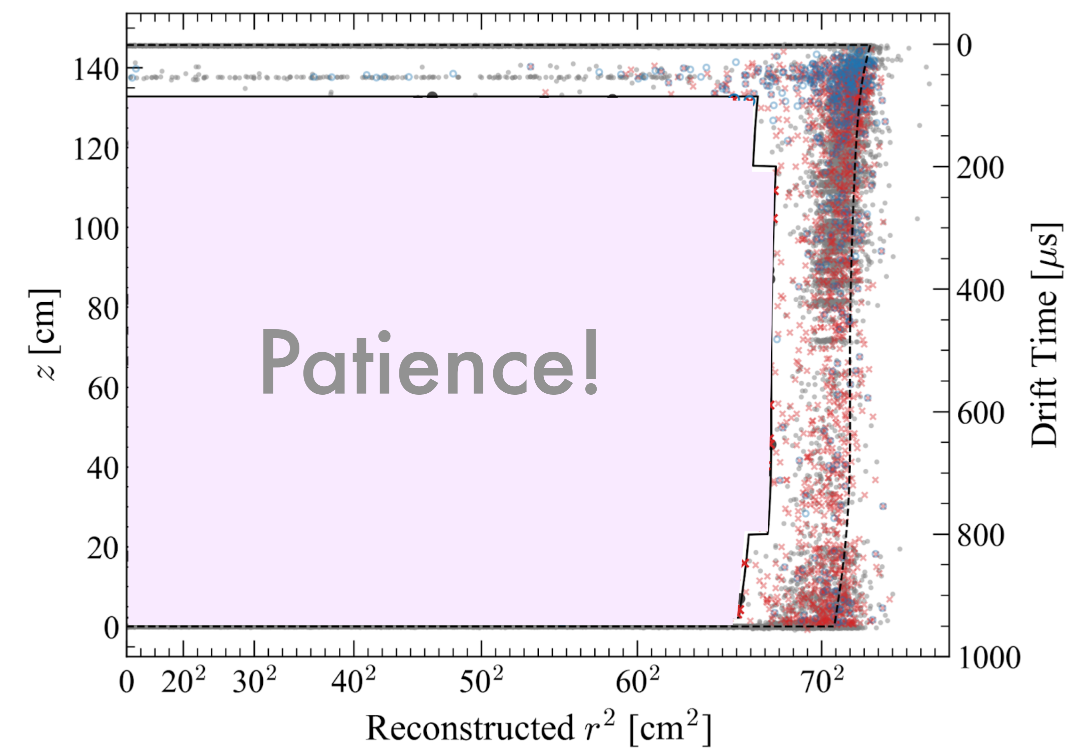
- There’s a lot going on!
- Lots of stuff above and below the expected ER and NR bands
- This includes
  - Events from walls
  - Accidental coincidence events
  - Physics backgrounds

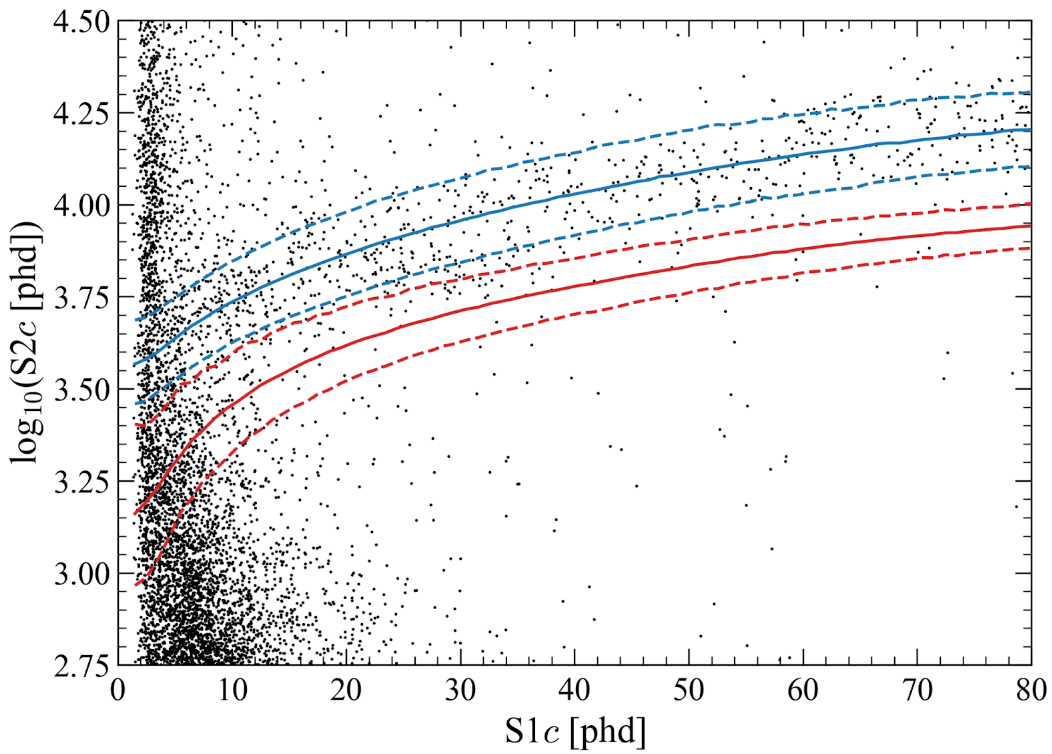


WIMPs would live here

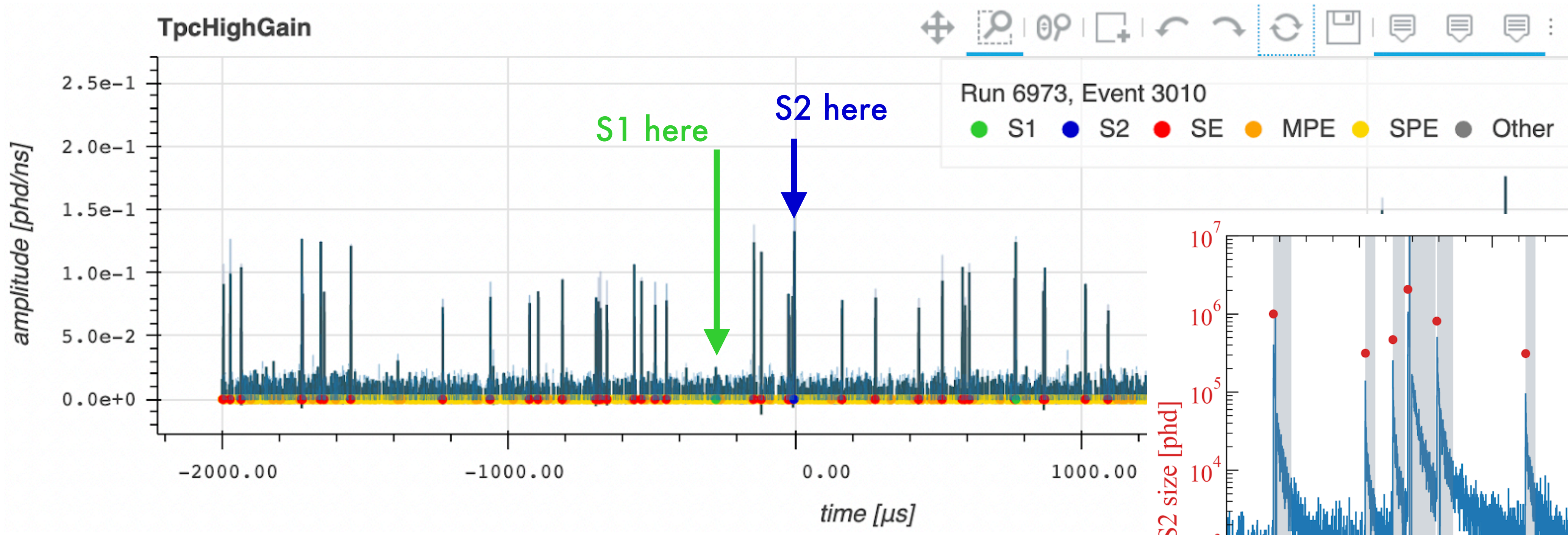
Fiducial Volume Cuts

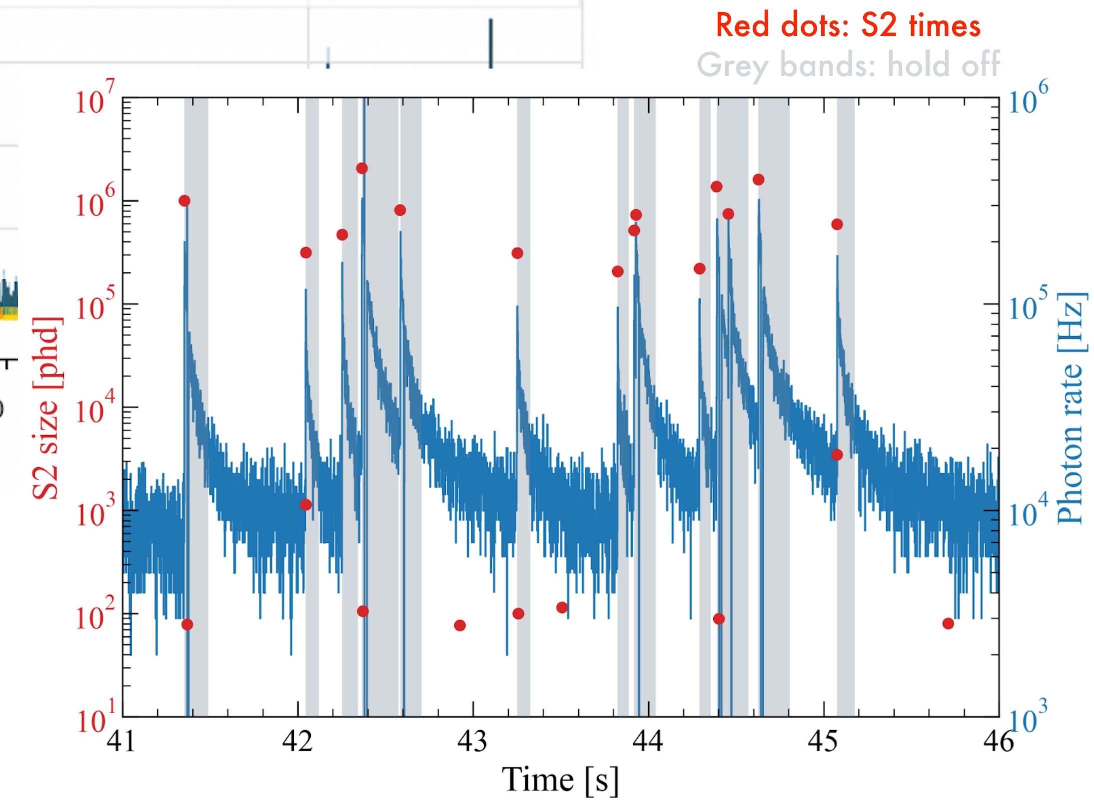
- PTFE on TPC walls induces *charge loss*
- Walls have additional radioactivity relative to the bulk
- Select a fiducial volume with expected <0.01 events
- ...but what's the rest of this junk?
  - Some physics backgrounds
  - Mostly accidental coincidences!





Electron Trains

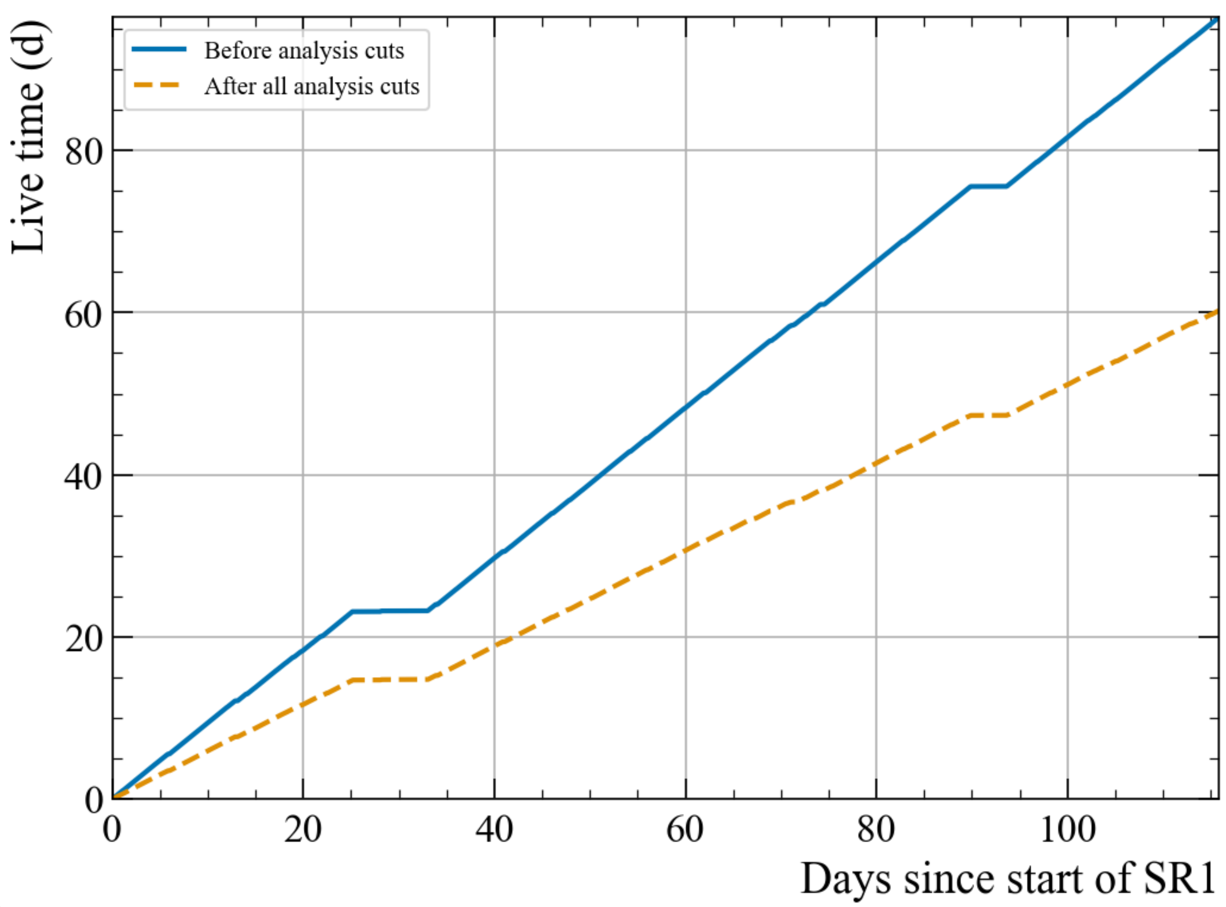




- S2s are followed by a large amount of activity in the detector
  - electrons which attach to liquid impurities and then are released or have delayed extraction
  - photons from fluorescence in the detector
- Cut these events with an analysis hold off after S2s which is proportional to the size of the S2
- Very effective, but big effect on livetime

Livetime

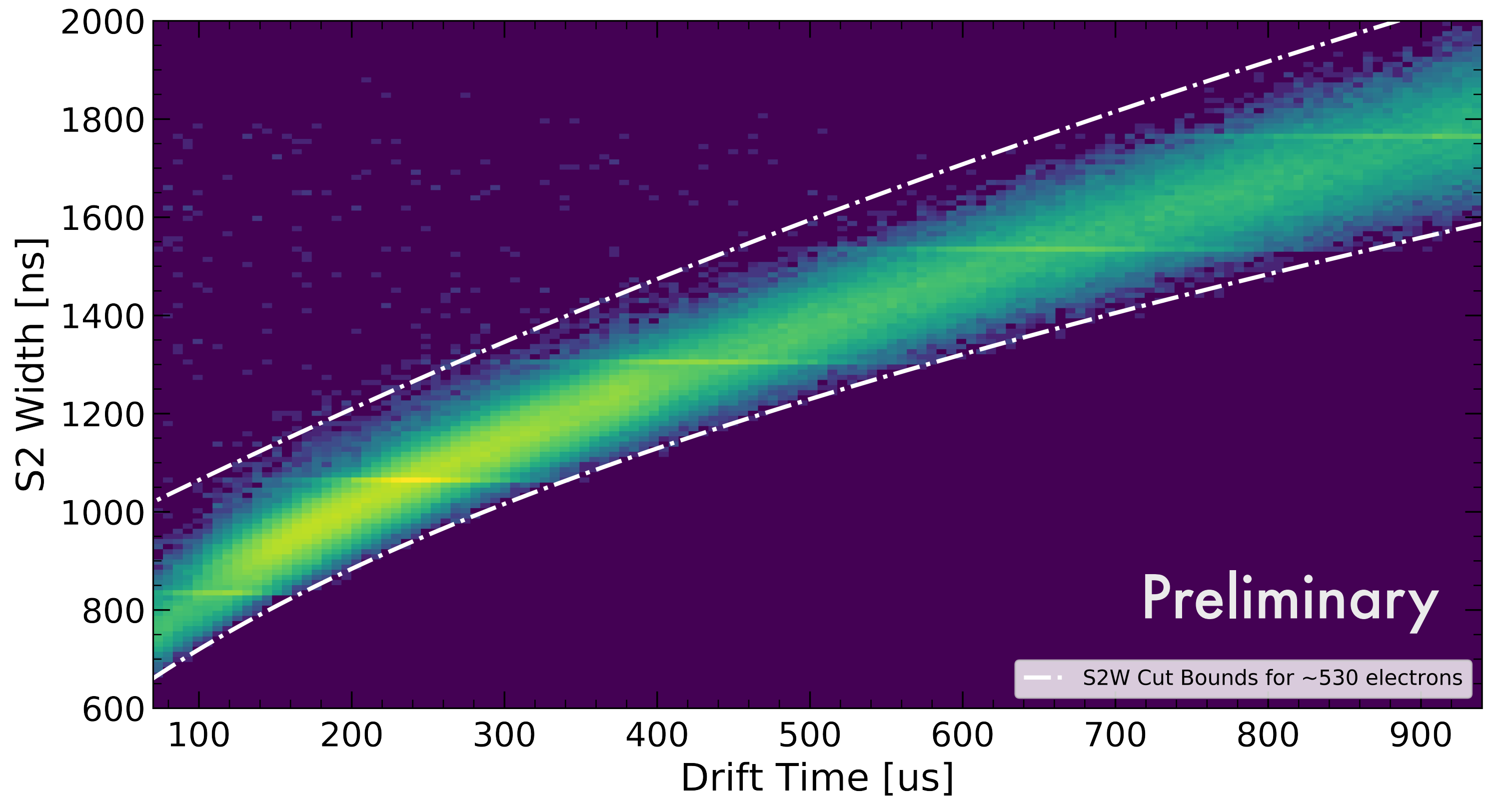
Cause	Impact
Hot spots	3.1%
Muon crossings	0.2%
Electron Train	**29.8%**
High S1 rates	0.2%
Undetected Muons	0.5%
Electronics Noise	<0.001%
Veto Detector Cuts	5%



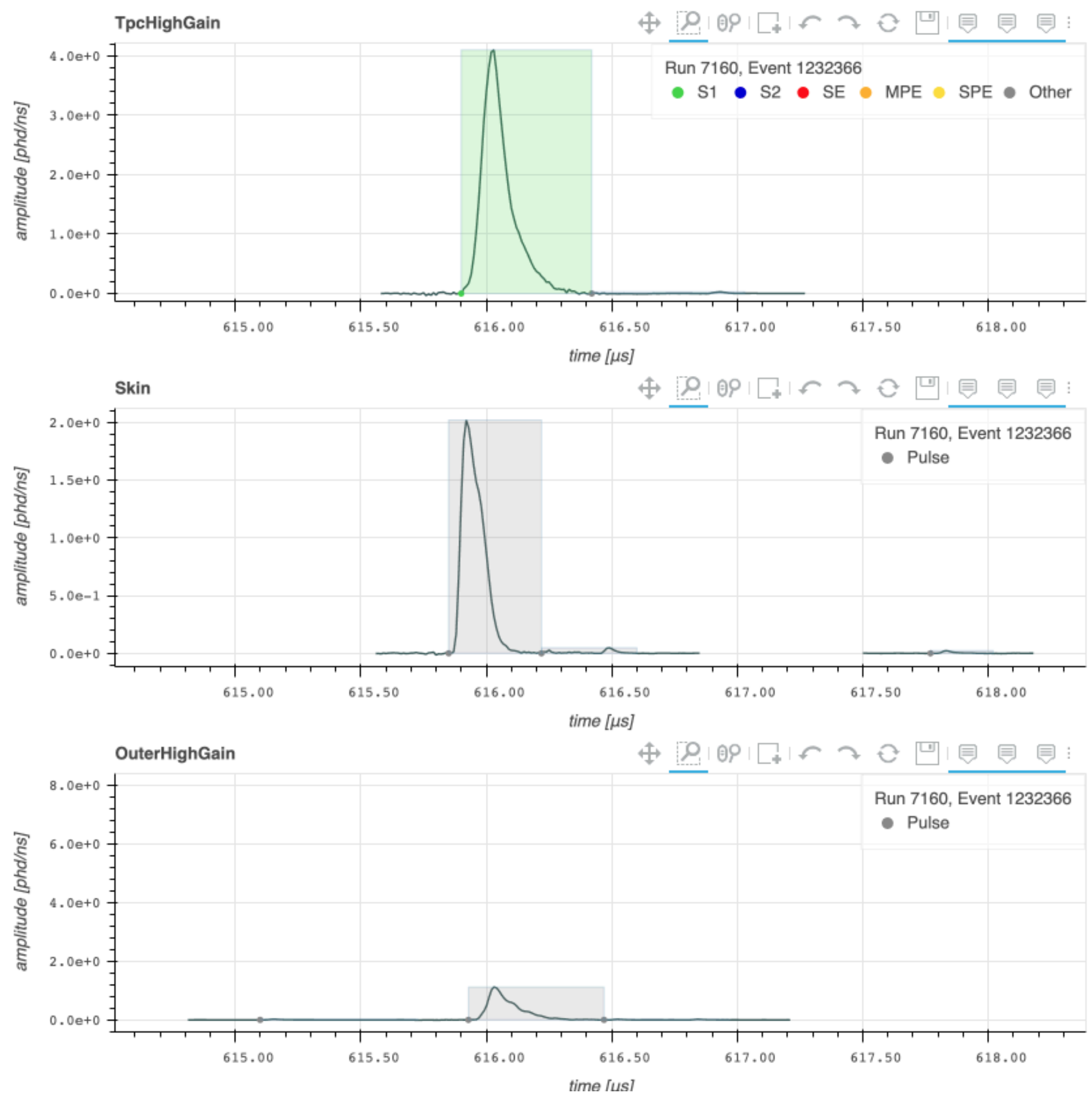
- We also veto time periods in which there is high activity from other effects in the detector
- Dominant impact on livetime is the electron trains cut
- Total of 60 live days

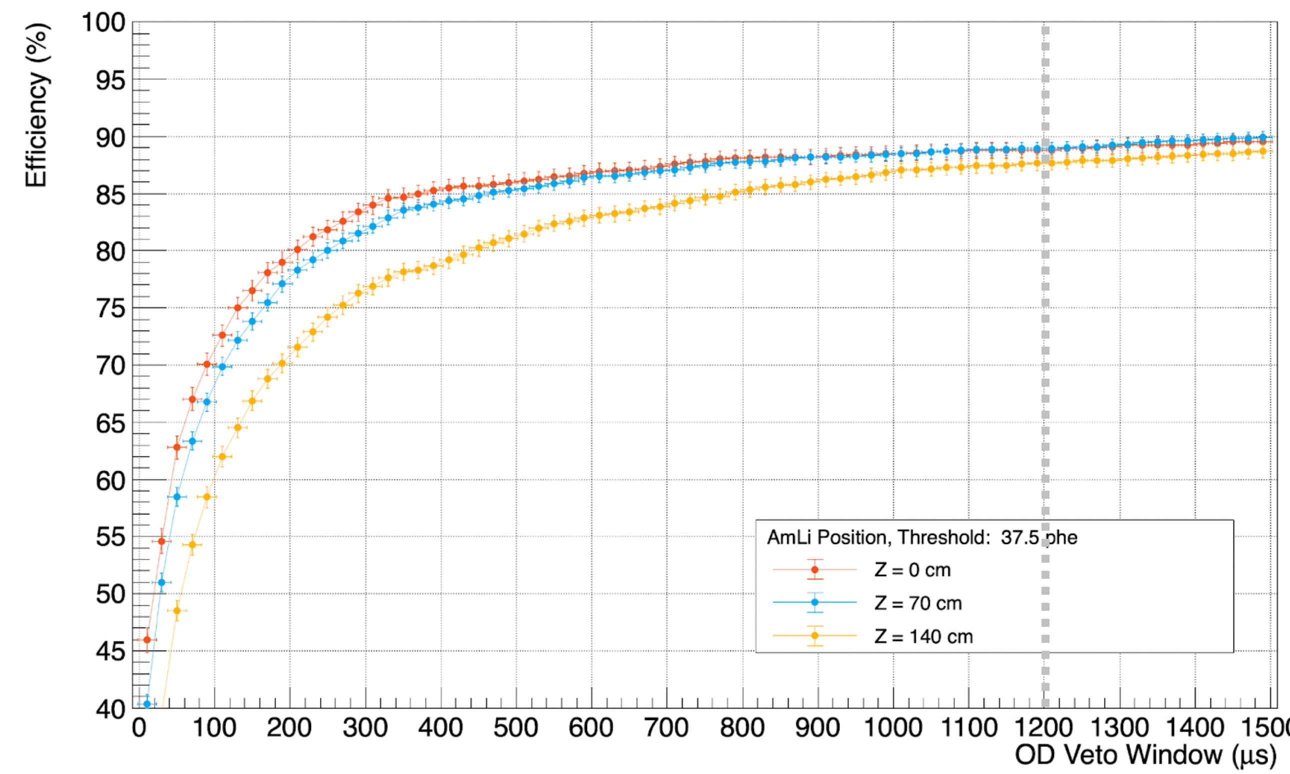
Other Accidental Coincidences

- Even after the electron train cut, there are remaining accidental coincidences
  - S1 sources include: dark noise pileup, PMT Cerekov light, events above the anode/below cathode, PTFE fluorescence, etc
  - S2 sources include: grid emission, events in the gas region, events where the S1 is missed, etc
- We can use pulse shape, timing, and position to discriminate true scatters from coincidence



Veto Cuts





- WIMPs should never leave energy in both the TPC and veto detectors
- We veto both 'prompt' coincidence (γ backgrounds) and 'delayed' coincidence (neutron backgrounds)
- Achieve 88.5% tagging efficiency, measured by inserting AmLi neutron sources in a deployment system between the inner and outer cryostat

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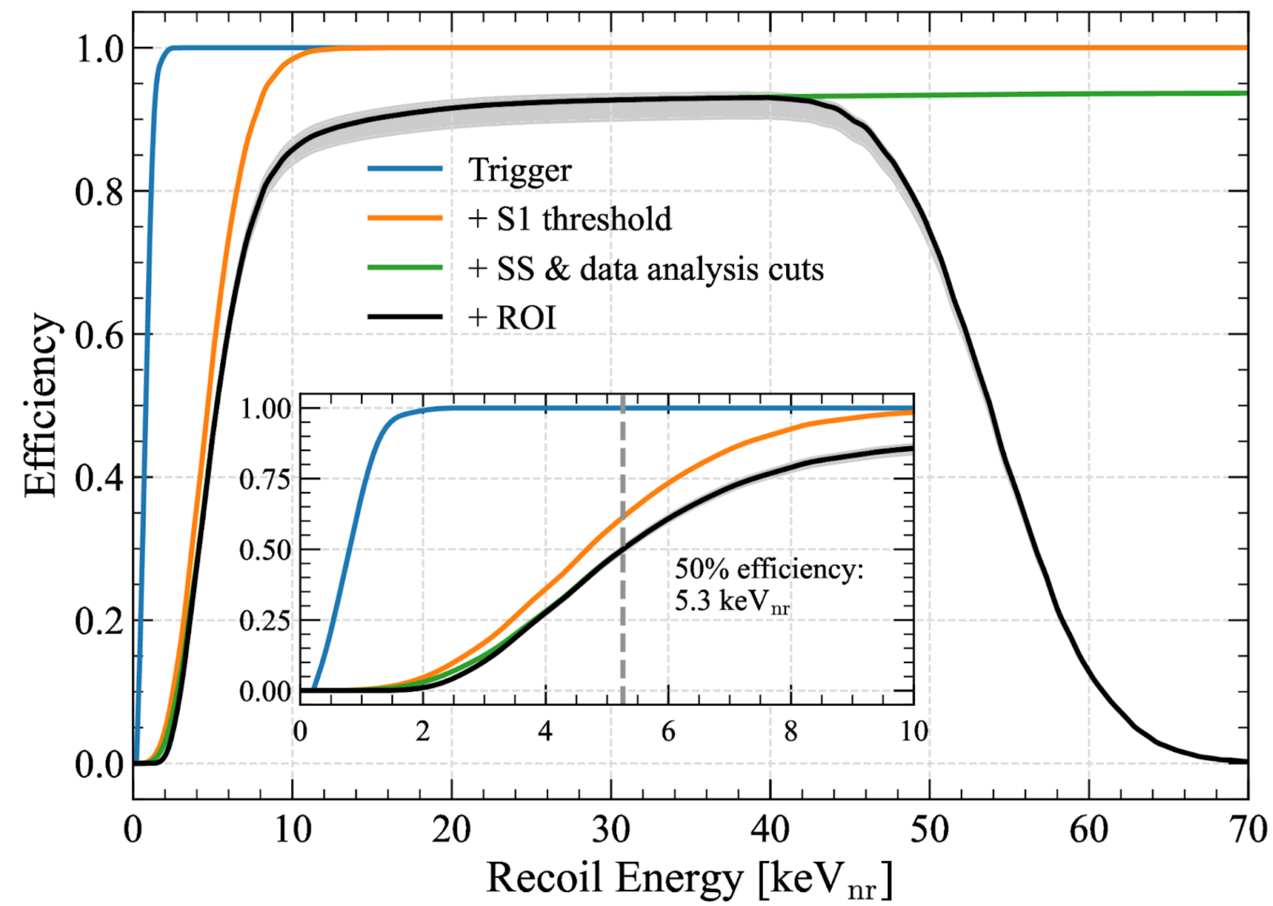
Signal Efficiencies

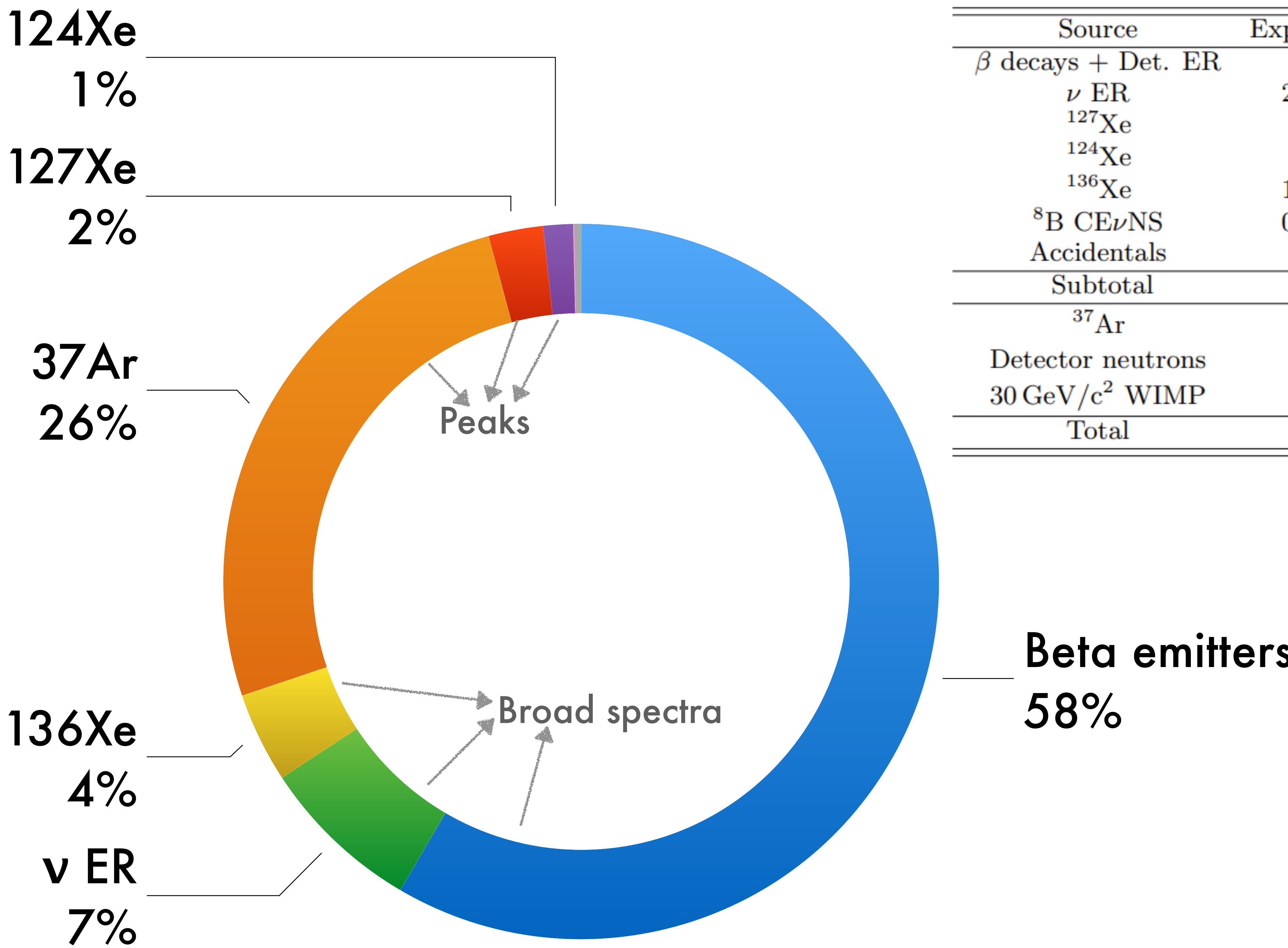
DD, AmLi, CH_3T

- Measure trigger efficiency by comparing the DD source trigger to the DAQ trigger
- Requiring 3-fold coincidence dominates the S1 efficiency
- Measure single scatter detection by visual inspection of DD events
- None of our neutron source calibrations are spatially uniform in the detector—stitch together an S1 from CH_3T and an S2 from either CH_3T or AmLi to make a synthetic event
- **Find 50% efficiency at 5.3 keV NR**



What's left?

Backgrounds



Source	Expected Events
β decays + Det. ER	218 ± 36
ν ER	27.3 ± 1.6
^{127}Xe	9.2 ± 0.8
^{124}Xe	5.0 ± 1.4
^{136}Xe	15.2 ± 2.4
^{8}B CEνNS	0.15 ± 0.01
Accidentals	1.2 ± 0.3
Subtotal	276 ± 36
^{37}Ar	[0, 291]
Detector neutrons	$0.0^{+0.2}$
30 GeV/c^2 WIMP	–
Total	–

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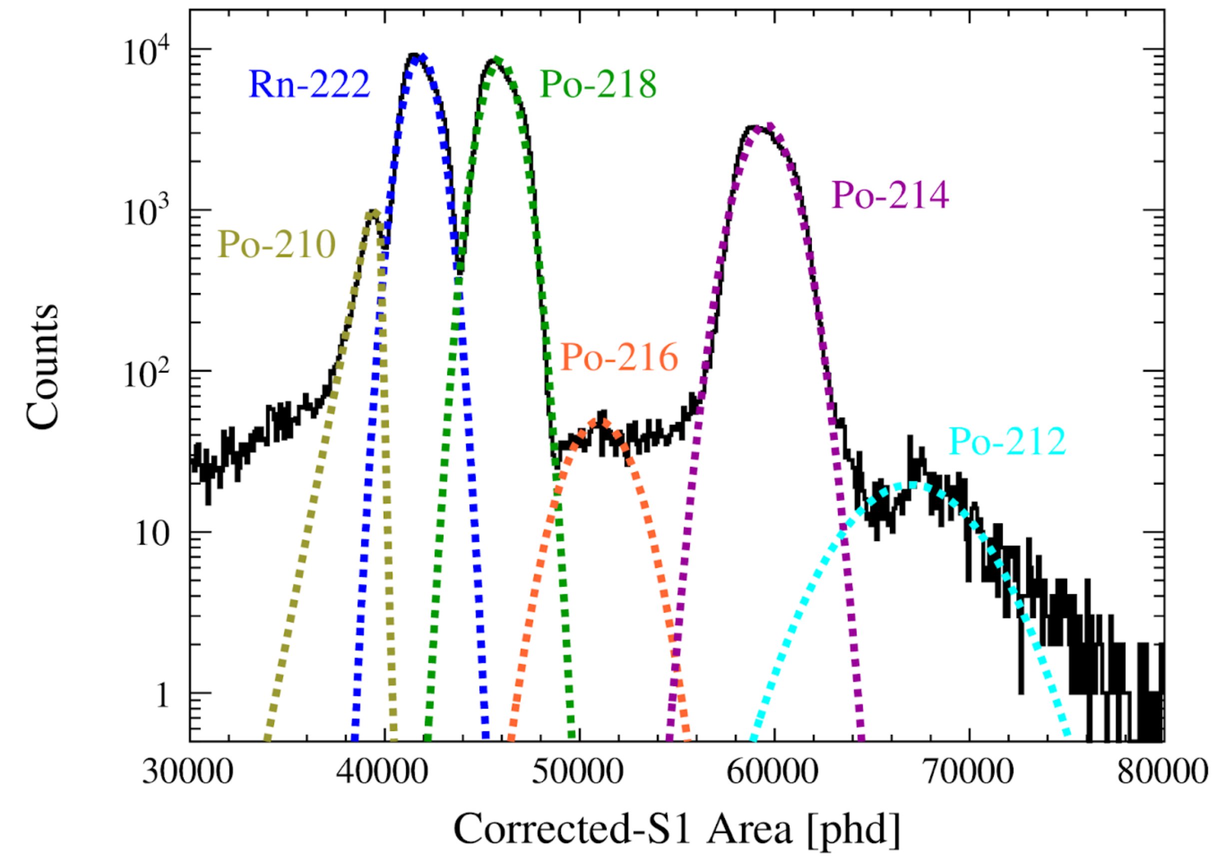
Beta Emitters

- ^{214}**Pb**
    - Comes from ^{222}Rn in Xe
    - Measure rate of ^{222}Rn α chain and energy spectrum of elements above WIMP search ROI
- ^{212}Pb
    - Comes from ^{220}Rn in Xe
    - Measure rate of ^{220}Rn α chain and energy spectrum of elements above WIMP search ROI
- ^{85}Kr and ^{39}Ar
    - Naturally occurring in Kr/Ar
    - Measure total Kr/Ar via sampling
- Detector components
    - Predictions from assays and simulation modeling



Source	Measured Rate	Predicted Events
^{214}Pb	3.26 μBq/kg	166±35
^{212}Pb	0.137 μBq/kg	18±5
^{85}Kr	0.042 μBq/kg	33±5
^{39}Ar	0.87 nBq/kg	0.6±0.1
Det ER	–	1.2±0.3

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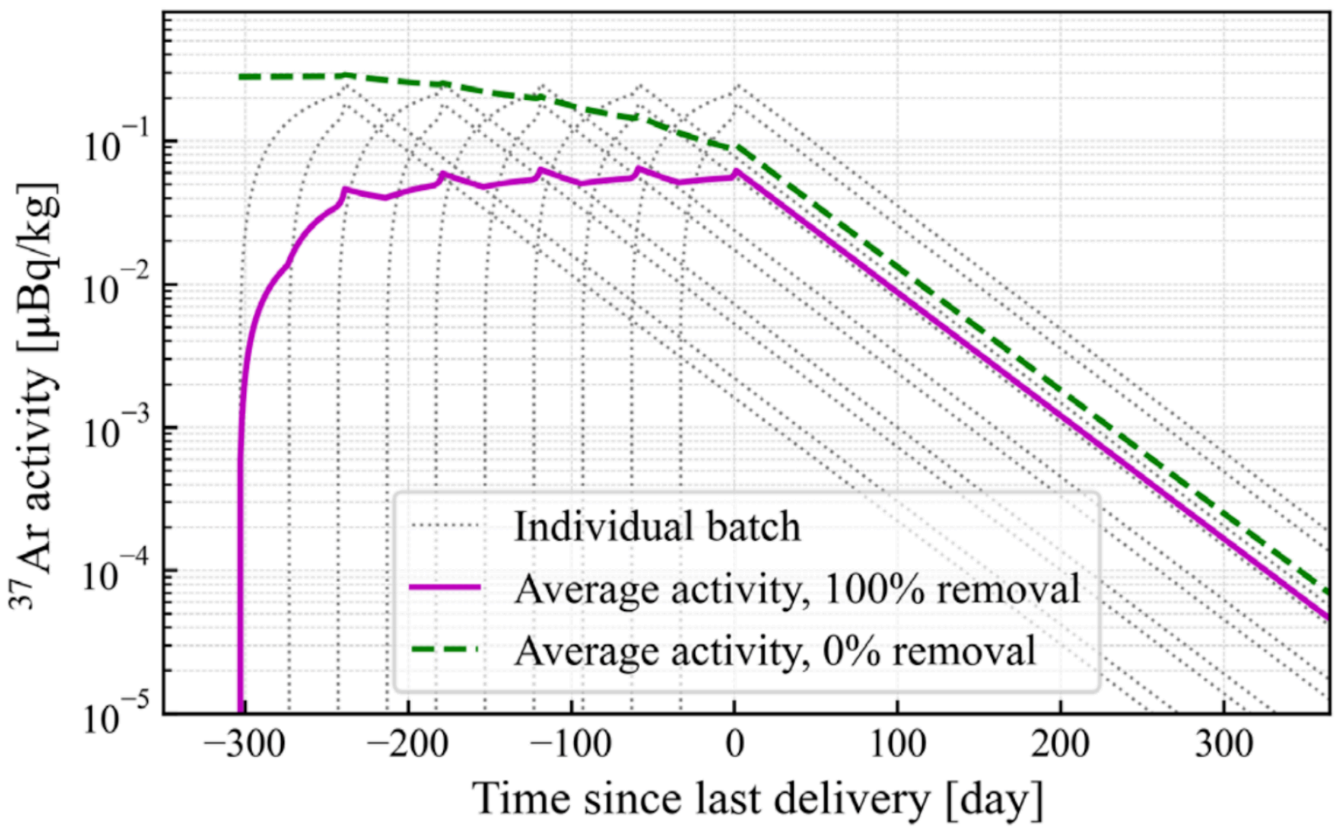
^{37}Ar



Phys Rev D 105, 082004 (2022)

- Produced naturally in air and in Xe by cosmic spallation
- Monoenergetic 2.8 keV peak via electron capture, 35 d half-life
- Predict 97 events from spallation rates and underground decay
- Very large uncertainties from cross sections and details of Xe handling

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ν Backgrounds

- Solar neutrinos can produce both ER backgrounds from ν-e scattering and NR backgrounds from coherent ν-N scattering
- Rates are predicted from external experimental and theoretical work
- ν-e scattering produces a flat spectrum
- ν-N scattering from ^{8}B produces a very low energy NR signal that is mostly excluded (0.15 events) due to the S2 threshold

Eur. Phys. J. C 81, 907 (2021).

Xenon Isotopes

- Xenon itself has several isotopes that undergo radioactive processes with energy in the ROI
  - ^{136}Xe is a double β decay nucleus with $t_{1/2}=2.1\times10^{21}$ y, broad spectrum
  - ^{124}Xe is a double electron capture nucleus with $t_{1/2}=1.8\times10^{22}$ y, monoenergetic peaks
  - ^{127}Xe is a single electron capture nucleus with $t_{1/2}=36$ d, monoenergetic peaks—reduced 5x by veto detectors
- Predictions are driven by known energy spectra, lifetimes, and isotope fractions

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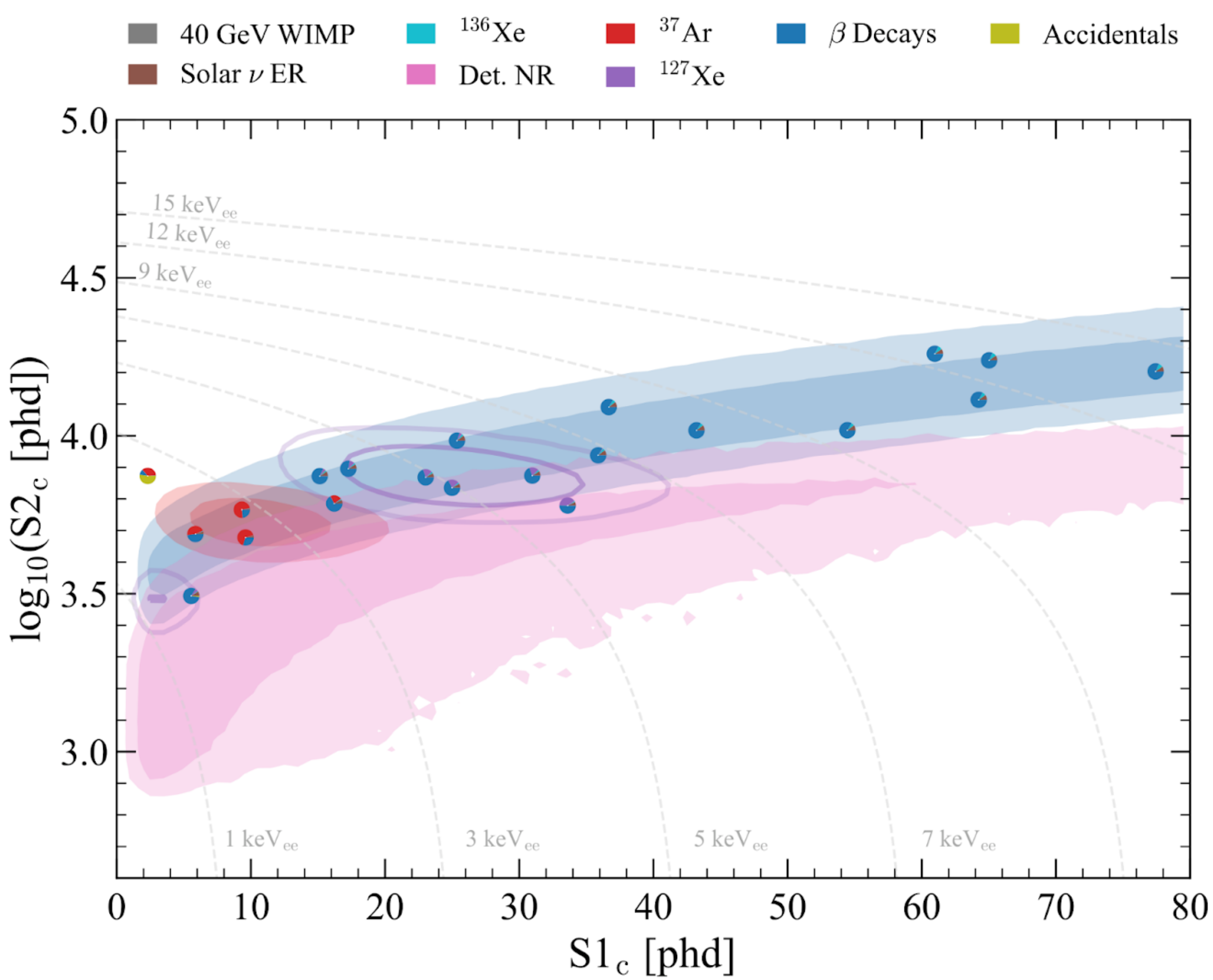
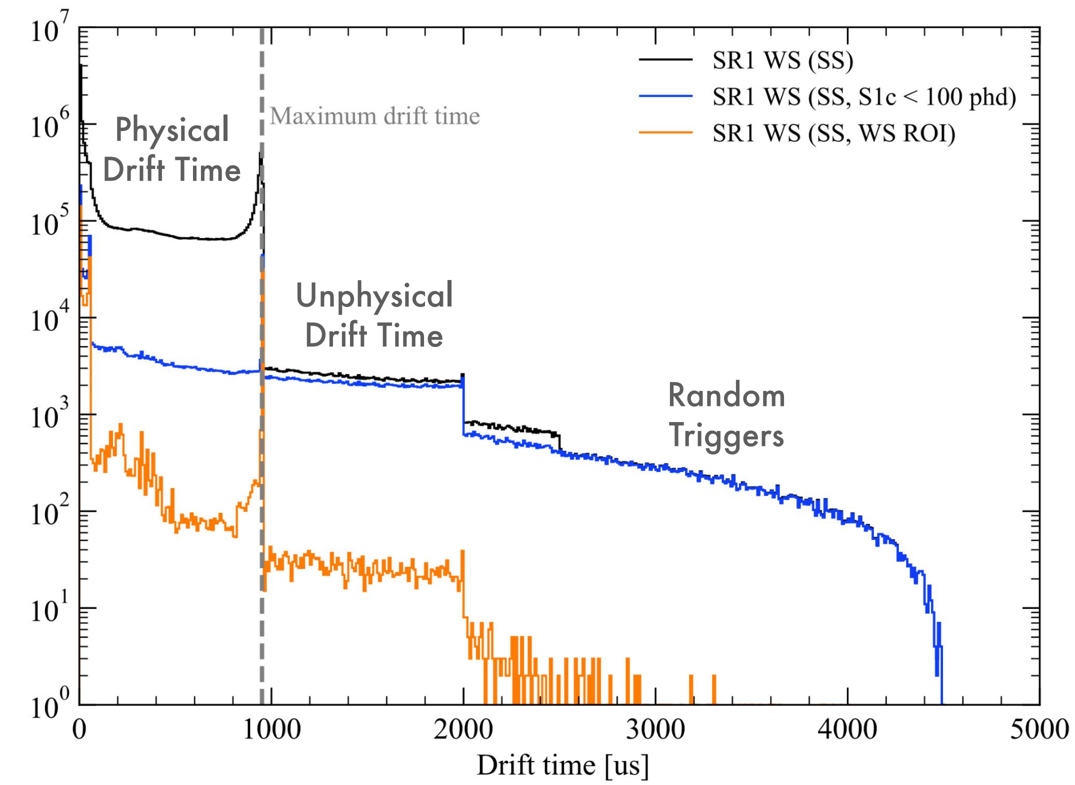
Detector Neutrons

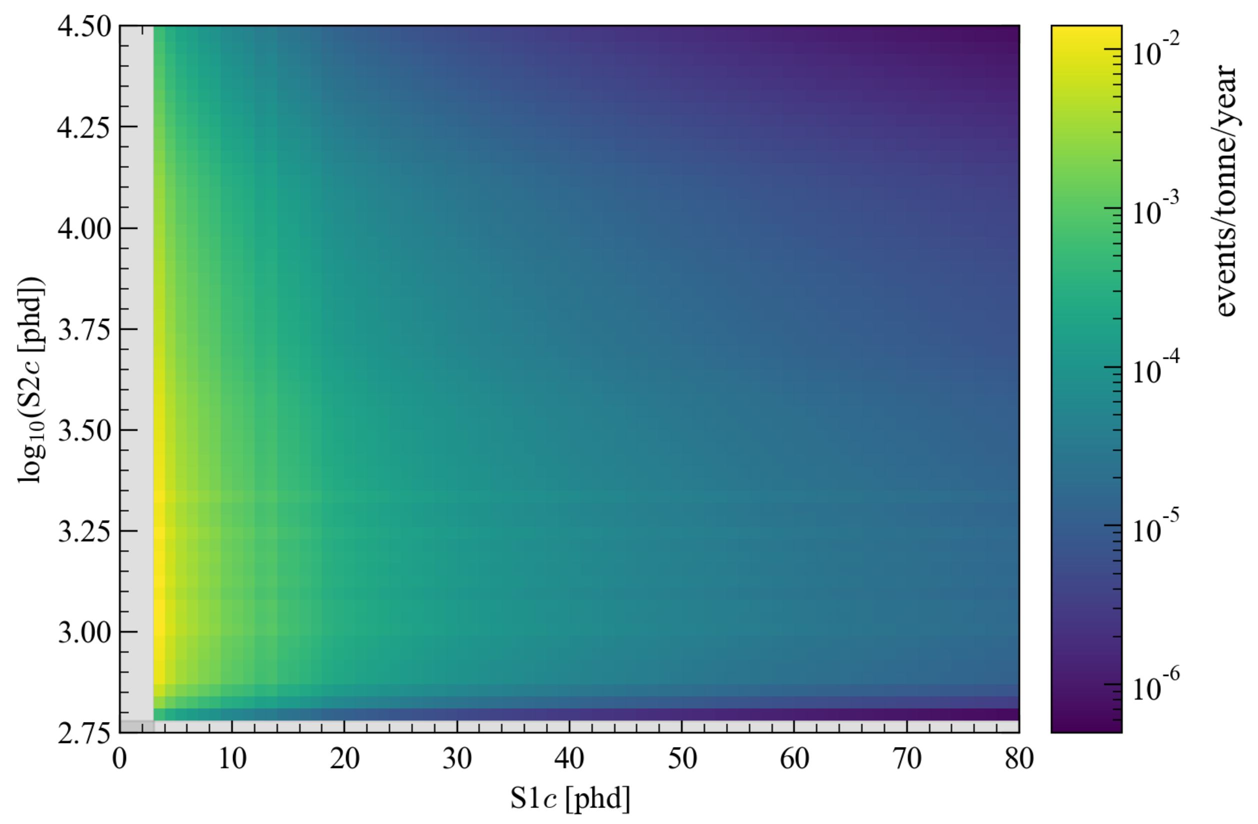


- Use knowledge of OD neutron tagging efficiency and events that pass all cuts *except* OD cuts to predict neutron background
- Find that the prediction of neutron events is $0.0^{+0.2}$

Accidentals

- DAQ is designed to allow events with drift time longer than the physical region
- Use the unphysical events to determine the rate of accidentals
- Use synthetic events from randomly matching S1 and S2 pulses to determine the shape of the PDF
- Total prediction of 1.2 events overall, and ~0.2 in NR band





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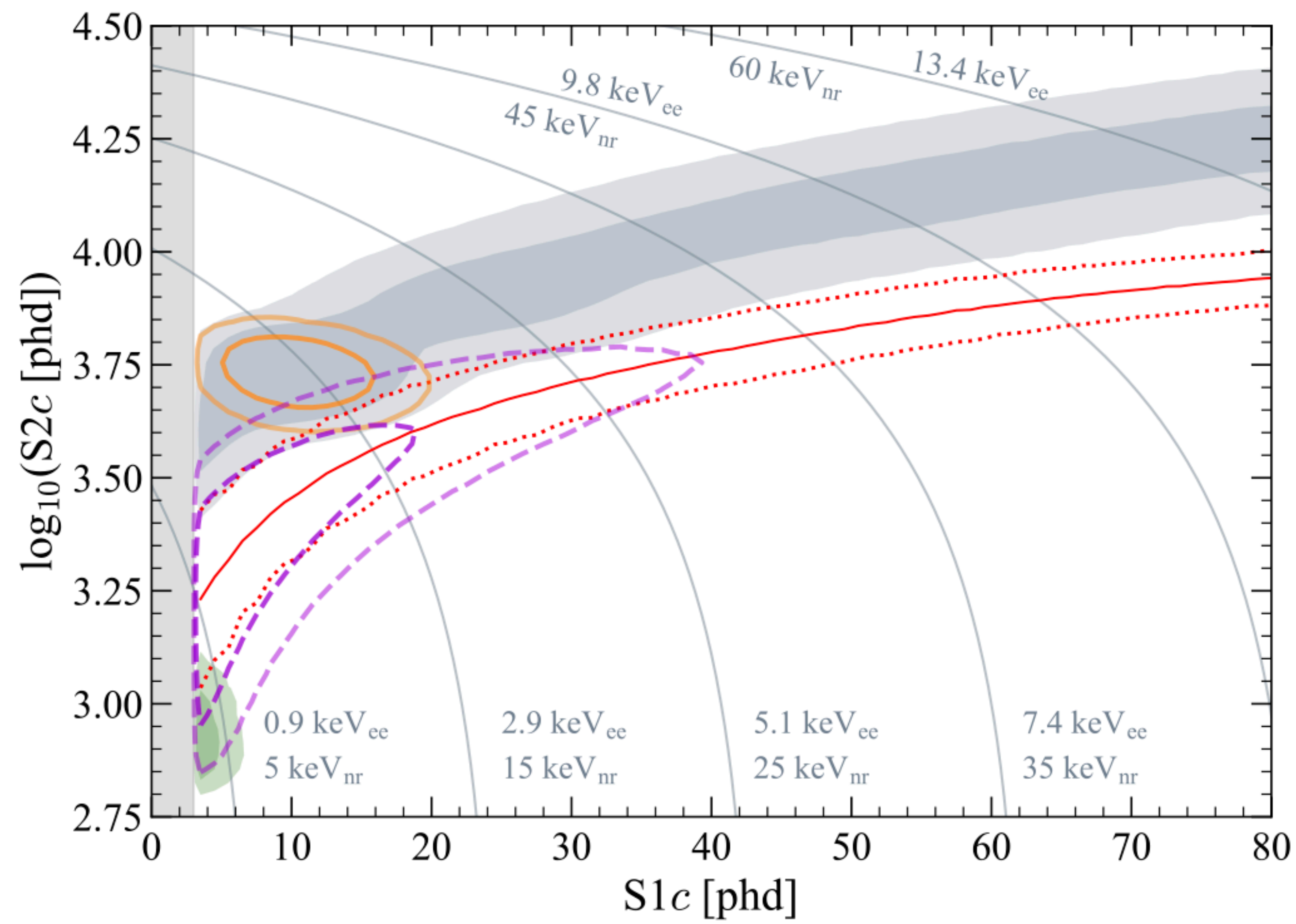
Predicted Spectra

- Grey band shows 1 and 2σ bands for the total predicted background
- Orange shows where 37Ar sits
- Green shows where 8B ν-N scattering sits
- Purple shows expected 30 GeV WIMP band



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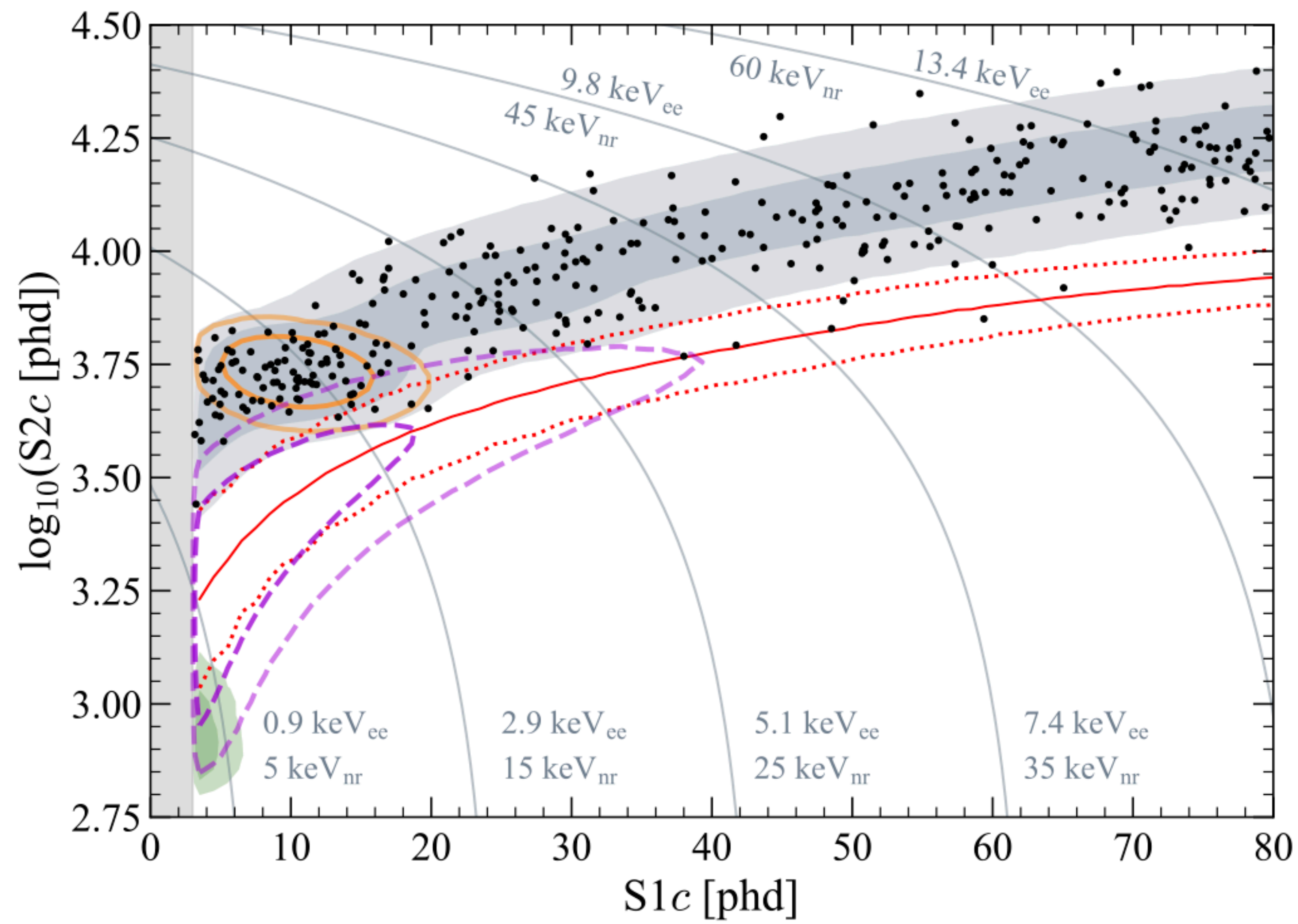
Post-Fit Spectra

- Grey band shows 1 and 2σ bands for the total best-fit background
- Orange shows where 37Ar sits
- Green shows where 8B ν-N scattering sits
- Purple shows expected 30 GeV WIMP band
- We predicted the background pretty well!

335 data events



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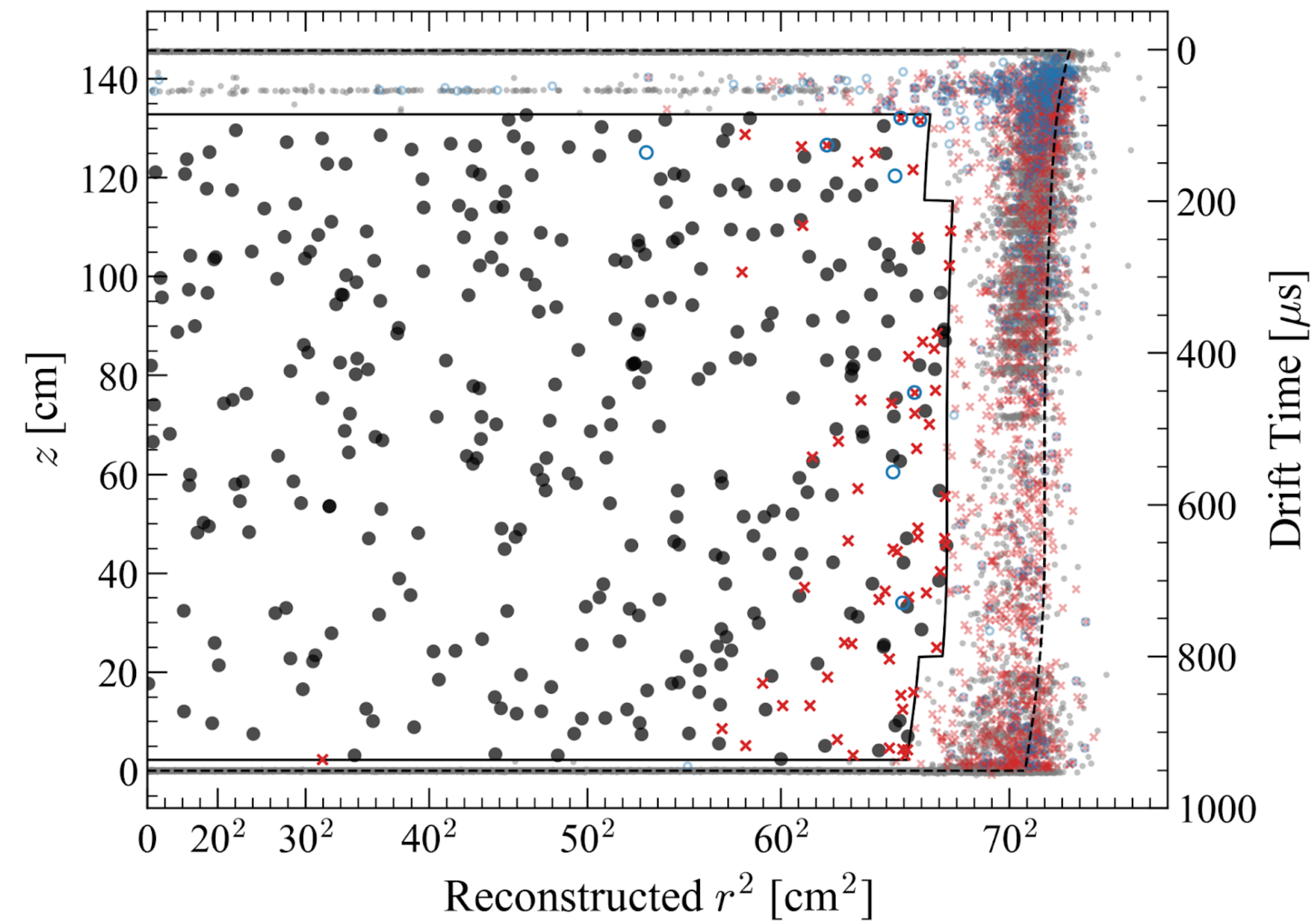
LZ

R^2-Z Space

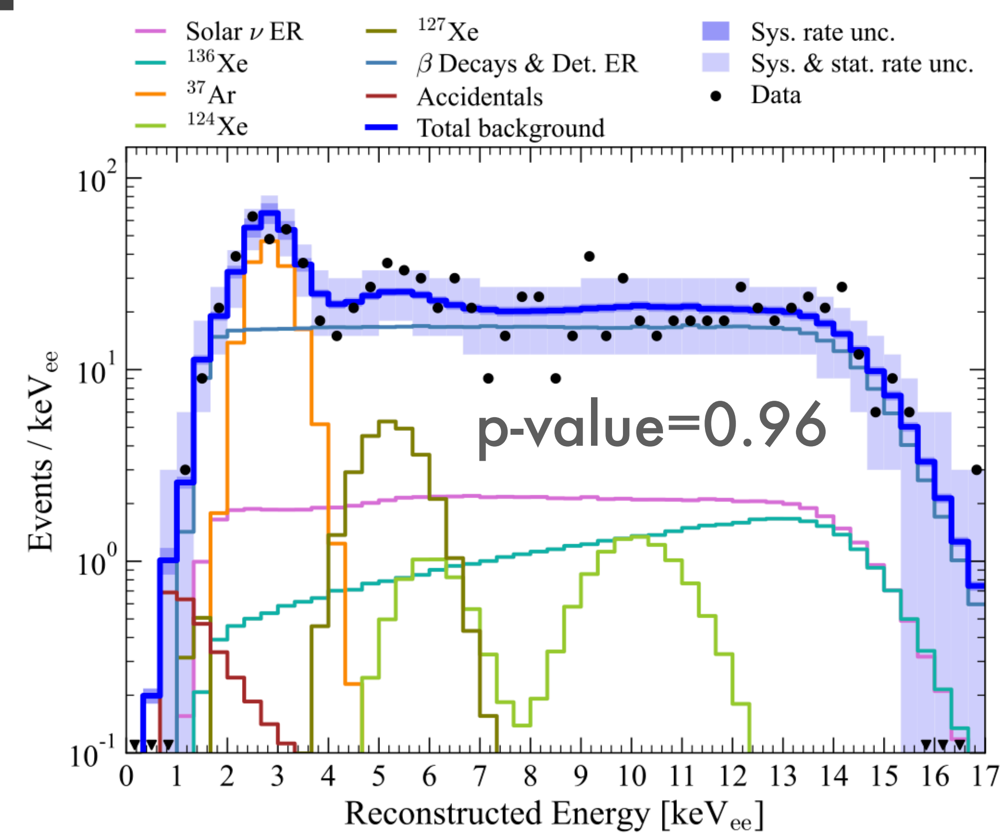
- Data events are uniformly spread throughout the fiducial volume
- Red and blue points show events vetoed by veto detectors

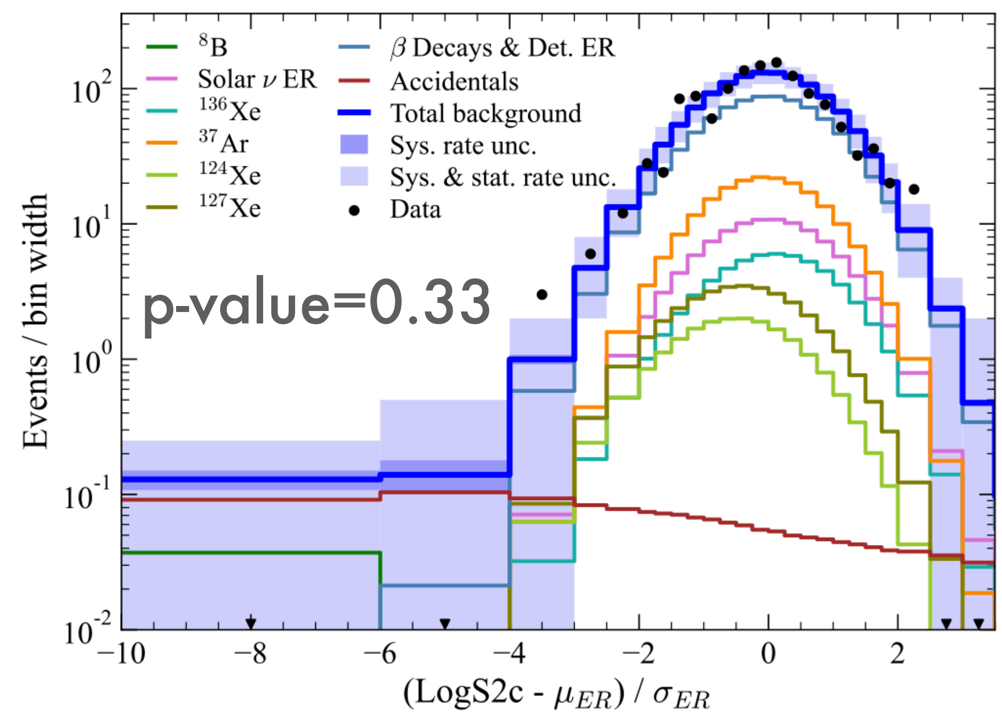


Post-Fit Spectra

- For all tested WIMP masses, the best-fit number of WIMP events is zero
- Look at data in 1D reconstructed energy and 'discrimination variable' to check validity of background model
- ^{37}Ar is ~50% of prediction
- Total background rate is ~25 counts/tonne/year/keVee

Source	Expected Events	Best Fit
β decays + Det. ER	218 ± 36	222 ± 16
ν ER	27.3 ± 1.6	27.3 ± 1.6
^{127}Xe	9.2 ± 0.8	9.3 ± 0.8
^{124}Xe	5.0 ± 1.4	5.2 ± 1.4
^{136}Xe	15.2 ± 2.4	15.3 ± 2.4
^{8}B CEνNS	0.15 ± 0.01	0.15 ± 0.01
Accidentals	1.2 ± 0.3	1.2 ± 0.3
Subtotal	276 ± 36	281 ± 16
^{37}Ar	[0, 291]	$52.1^{+9.6}_{-8.9}$
Detector neutrons	$0.0^{+0.2}$	$0.0^{+0.2}$
30 GeV/c^2 WIMP	–	$0.0^{+0.6}$
Total	–	333 ± 17





Statistical Conventions

- The dark matter community came together in 2021 to establish statistical conventions for searches—inspired by similar work for the collider community
- We use
  - A profile likelihood ratio test statistic, scanning over possible WIMP masses
  - A two-sided test statistic with 90% confidence limits
  - A power constrained limit with π_{crit}=0.32
  - Test statistic distributions generated by simulated toys
- In this analysis, we did not blind or salt the data

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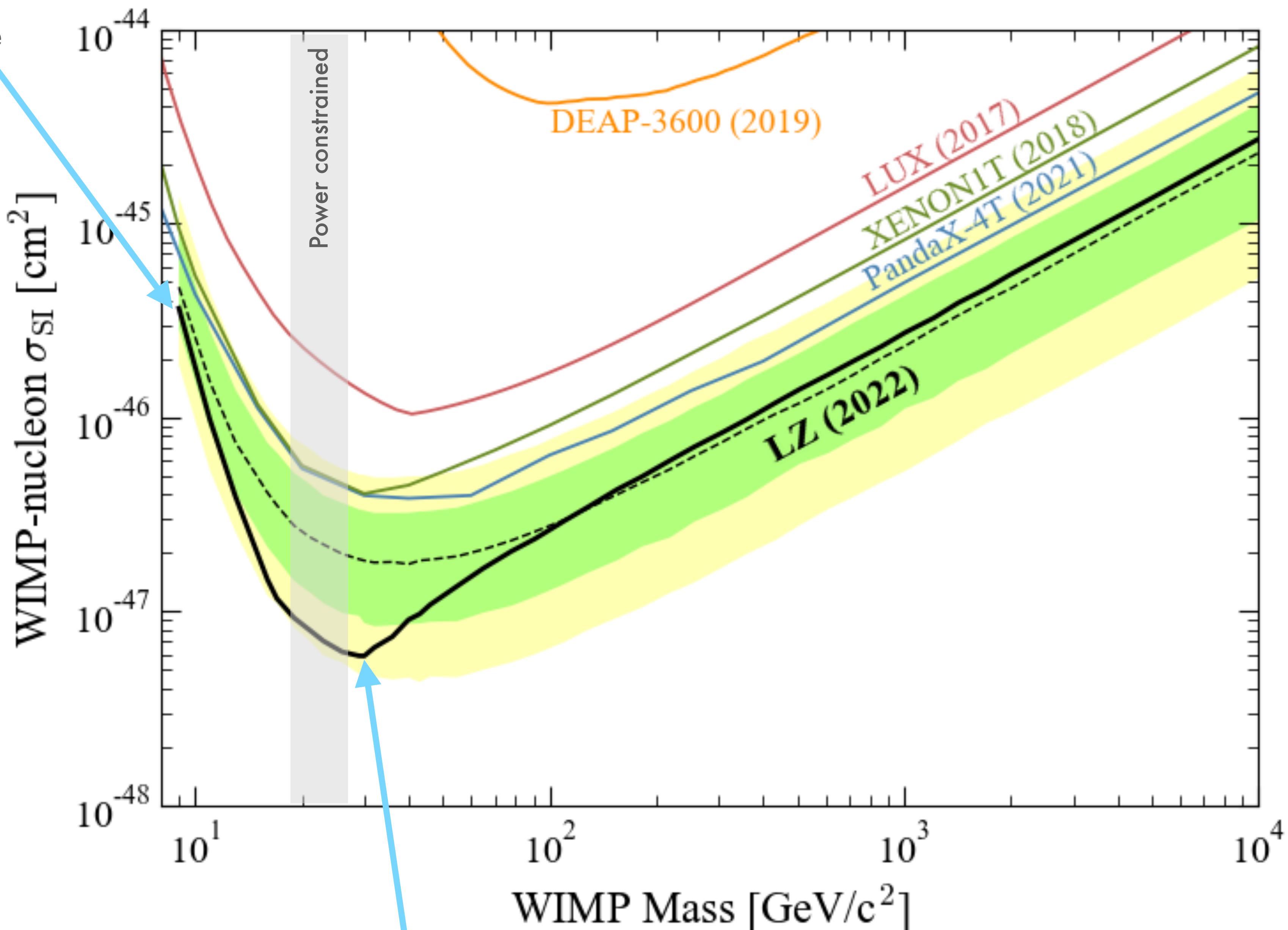
Spin-Independent Limit

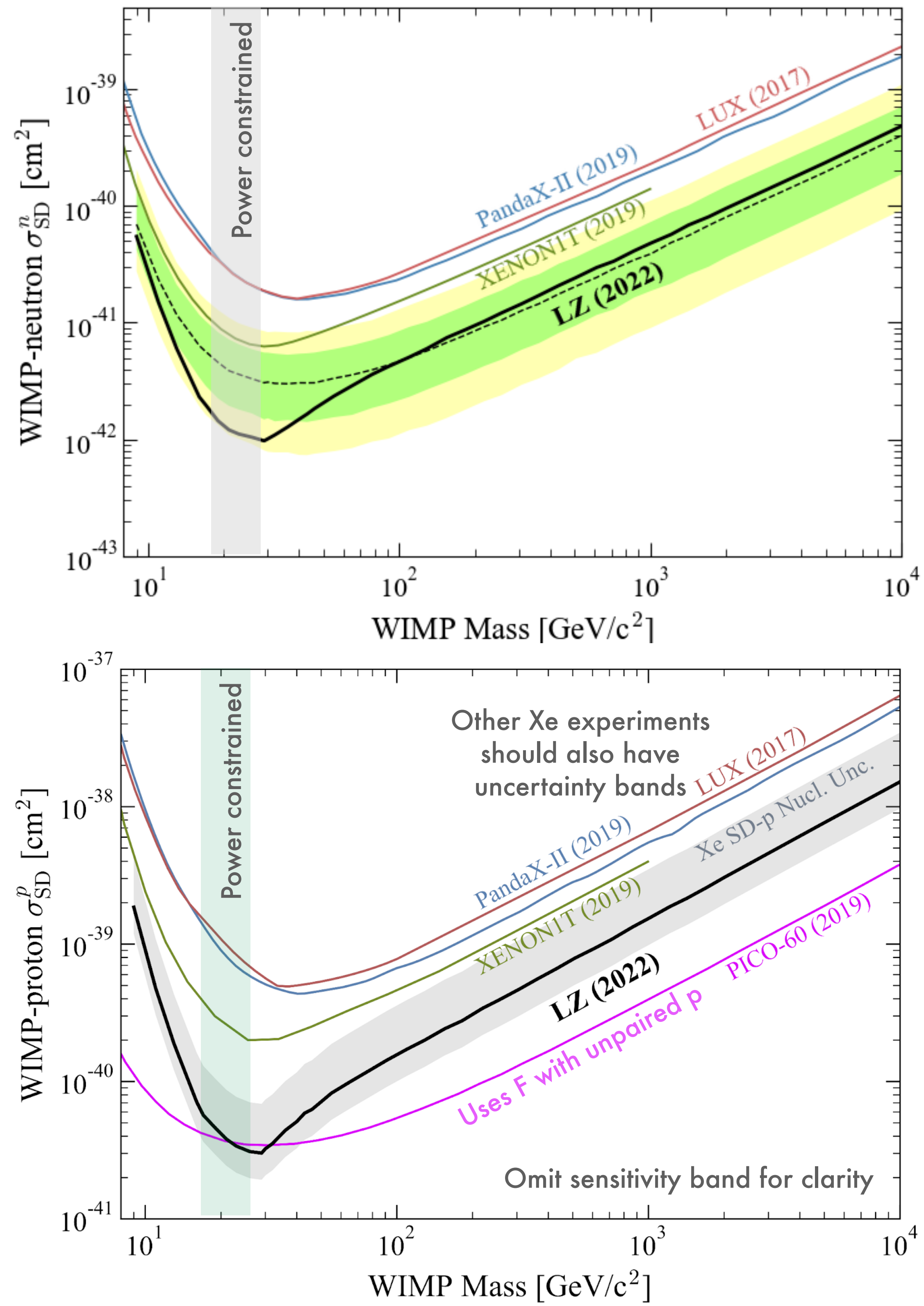
Smallest WIMP mass chosen is 9 GeV/c^2 by confidence in Xe response models



Minimum of limit curve is at (30 GeV/c^2, 6x10^{-48} cm^2)

Spin-Dependent Limits

- Consider limiting cases that WIMPs interact only with neutrons and only with protons
- ^{129}Xe and ^{131}Xe have 1/2 and 3/2 nuclear spin, respectively, from unpaired neutrons
- Sensitivity to proton interactions are retained through higher order effects—albeit with large uncertainty



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What's Next?

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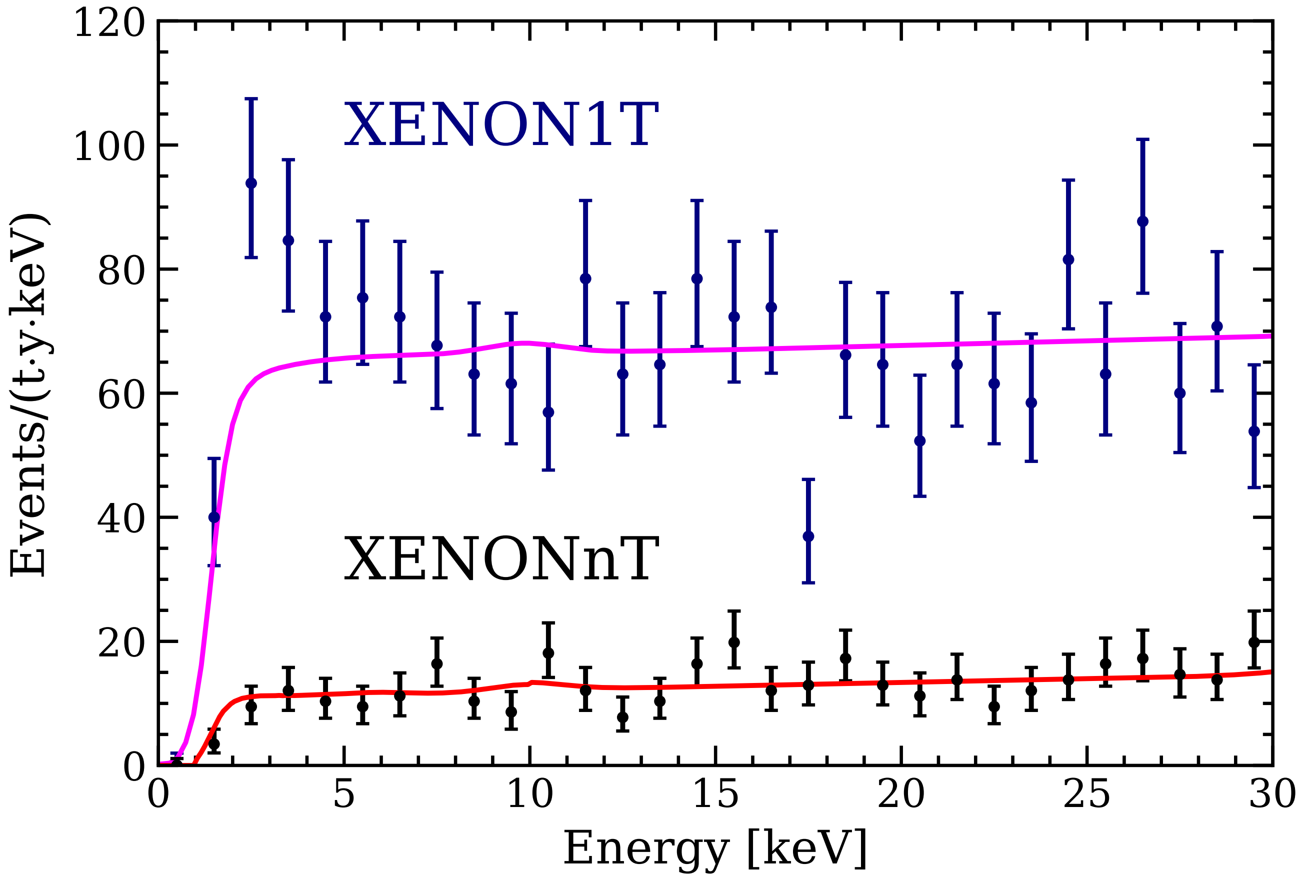
Electron Recoil Models



- Lots of interest in the XENON1T excess...but first results from XENONnT shows it hasn't persisted
- LZ is limited in that region by ^{37}Ar
- Will release similar searches in the near future

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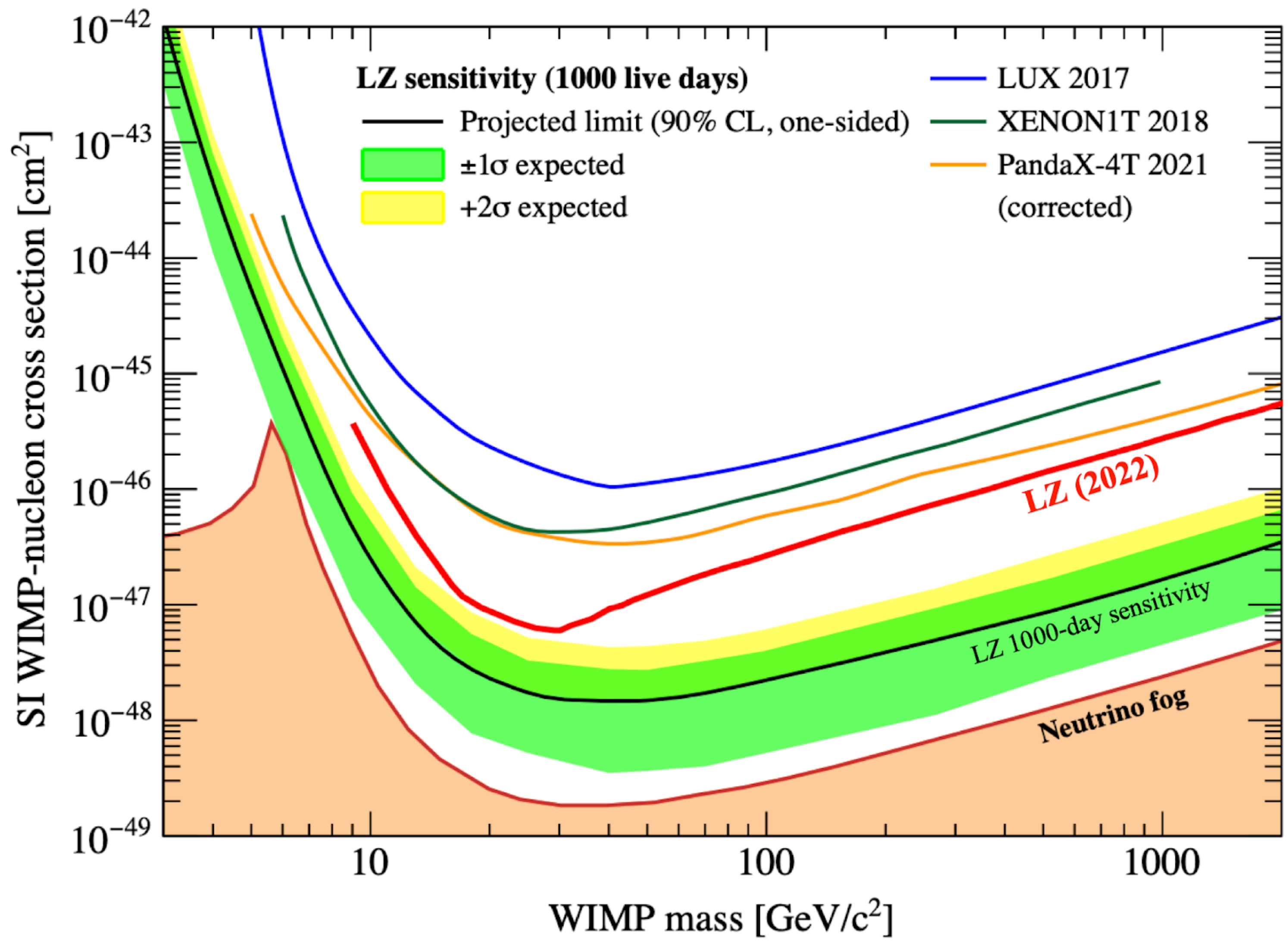
Science Run 2 and Beyond

- Currently have an ongoing calibration and detector optimization campaign
- Will begin new science data taking in the near future!
- Many optimizations also can be made for our analyses—expand phase space, better model backgrounds, etc
- Ultimate goal is 1000 live days

Expected Limits: WIMPs

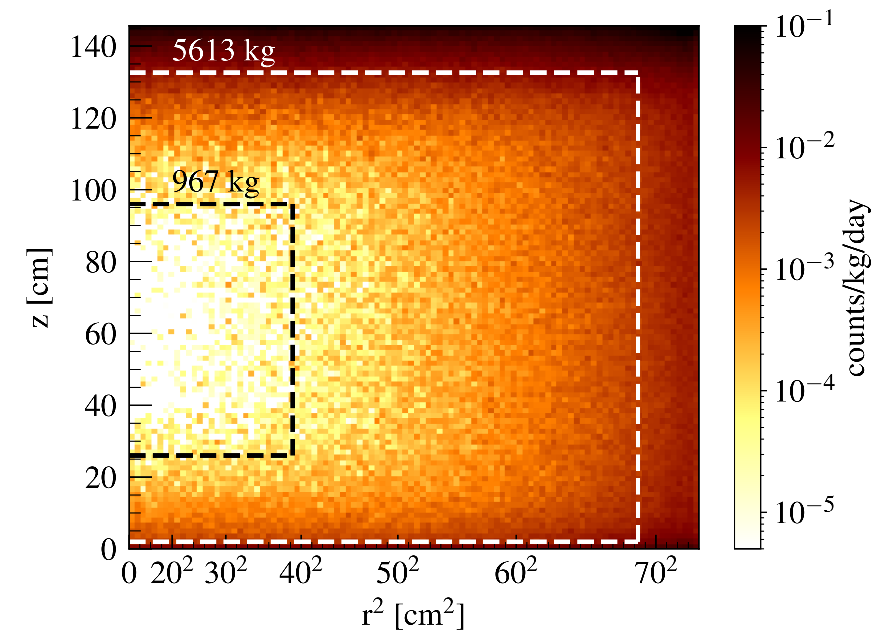
- SR1 got a little lucky around 30 GeV
- Still lots of parameter space to explore
- Begin to reach the neutrino 'fog'!

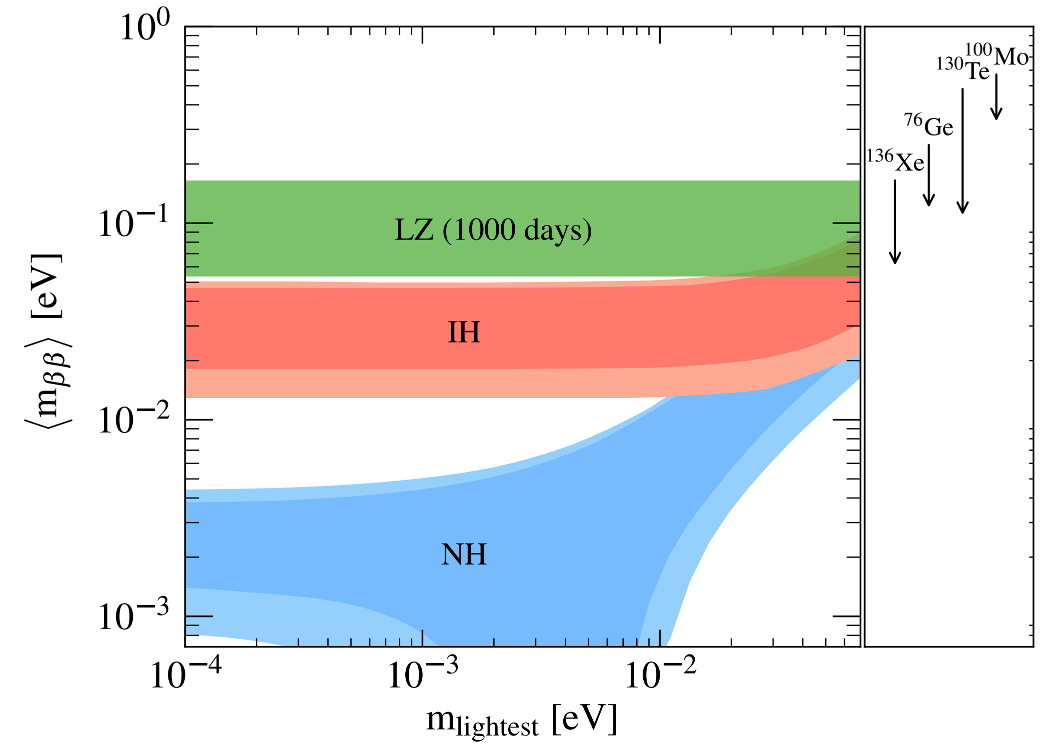


Phys. Rev. D 101, 052002

Expected Limits: 0νββ

- Probe very top of degenerate region
- Reasonably competitive with dedicated experiments!
- Potentially enhanced with enrichment after DM analyses complete

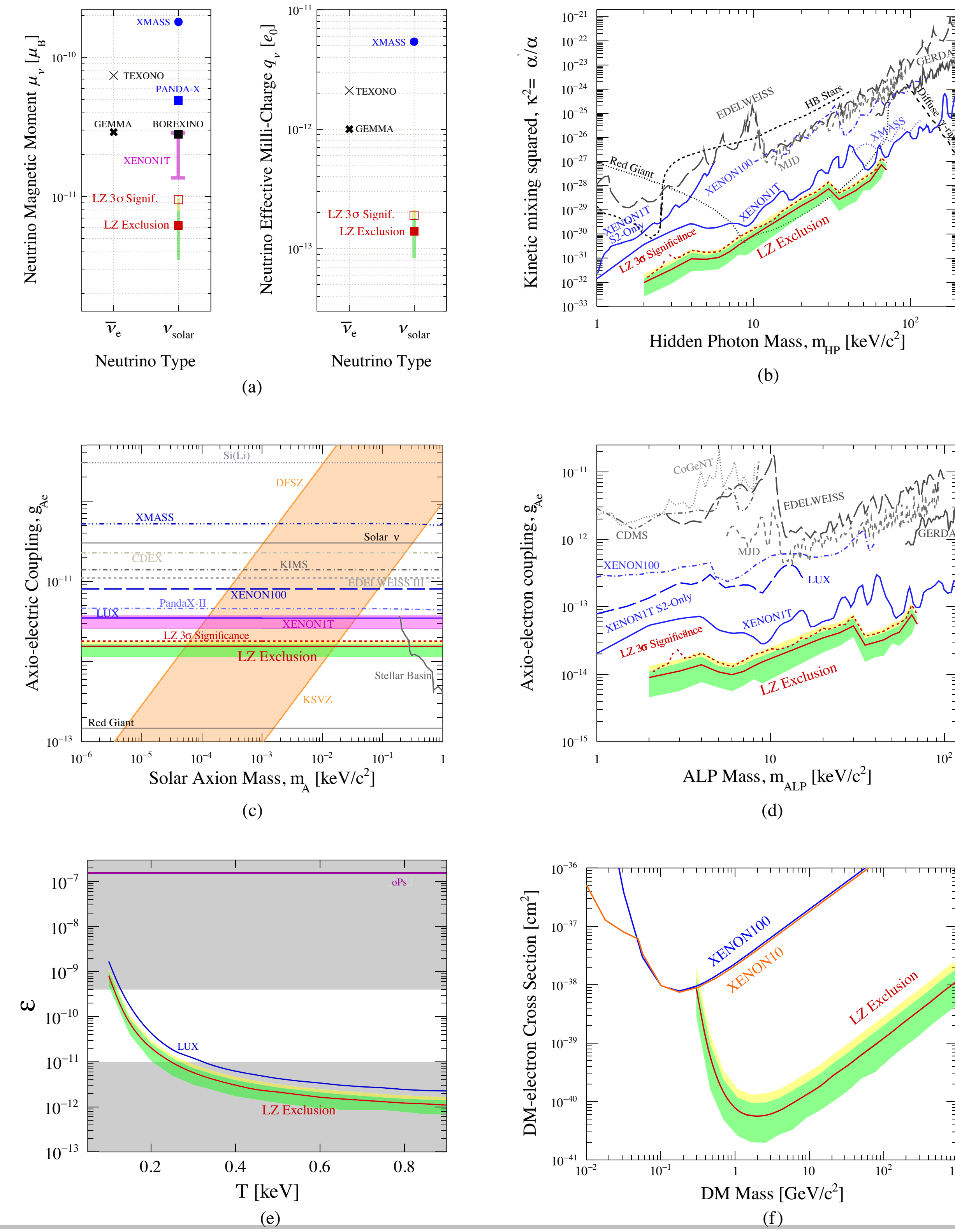




Phys. Rev. C 102, 014602

Expected Limits: ER-like

- Many different models that can be tested in ER-lie signals:
  - Neutrino magnetic moment
  - Hidden photons
  - Axions and ALPs
  - Mirror dark matter
  - DM-e scattering



XLZD

- Looking even further into the future, the XENON, DARWIN, and LZ collaborations are joining forces for the next generation
- Joint meeting this summer at KIT
- White paper and website

Conclusions

- LZ has successfully completed its first science data taking
- The detector is working well, and backgrounds are within the design specifications
- New best limits have been set in WIMP searches
- There's much more to come!

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Supplementary

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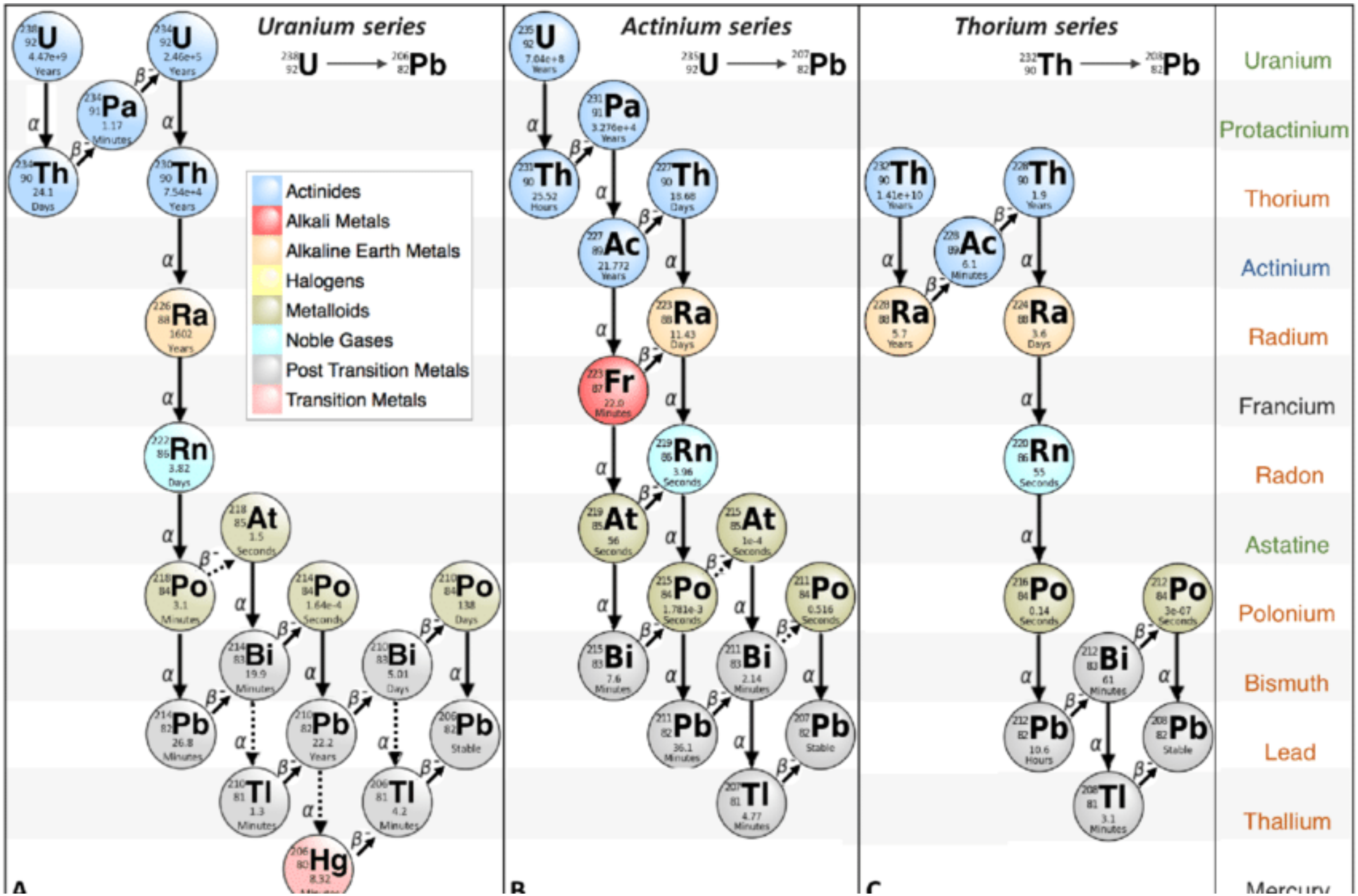
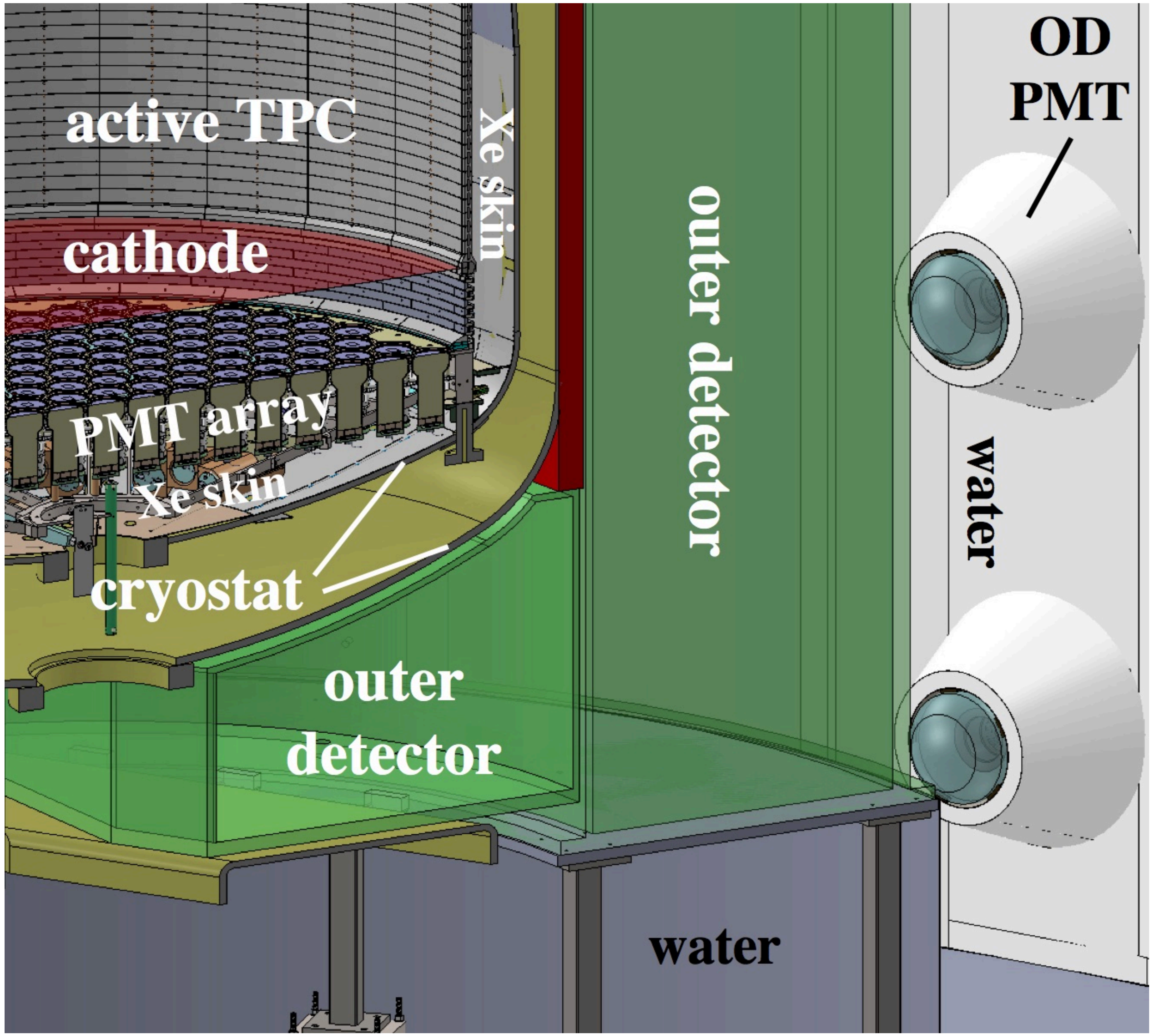
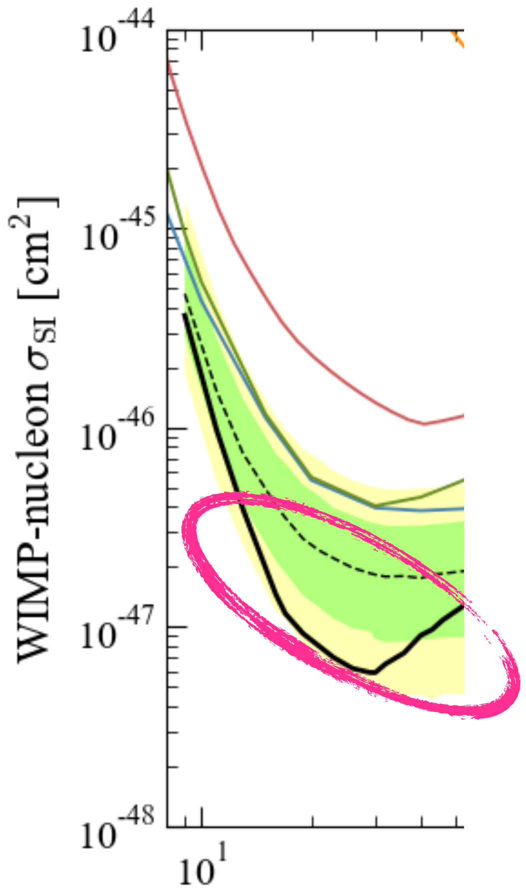
Uranium and Thorium



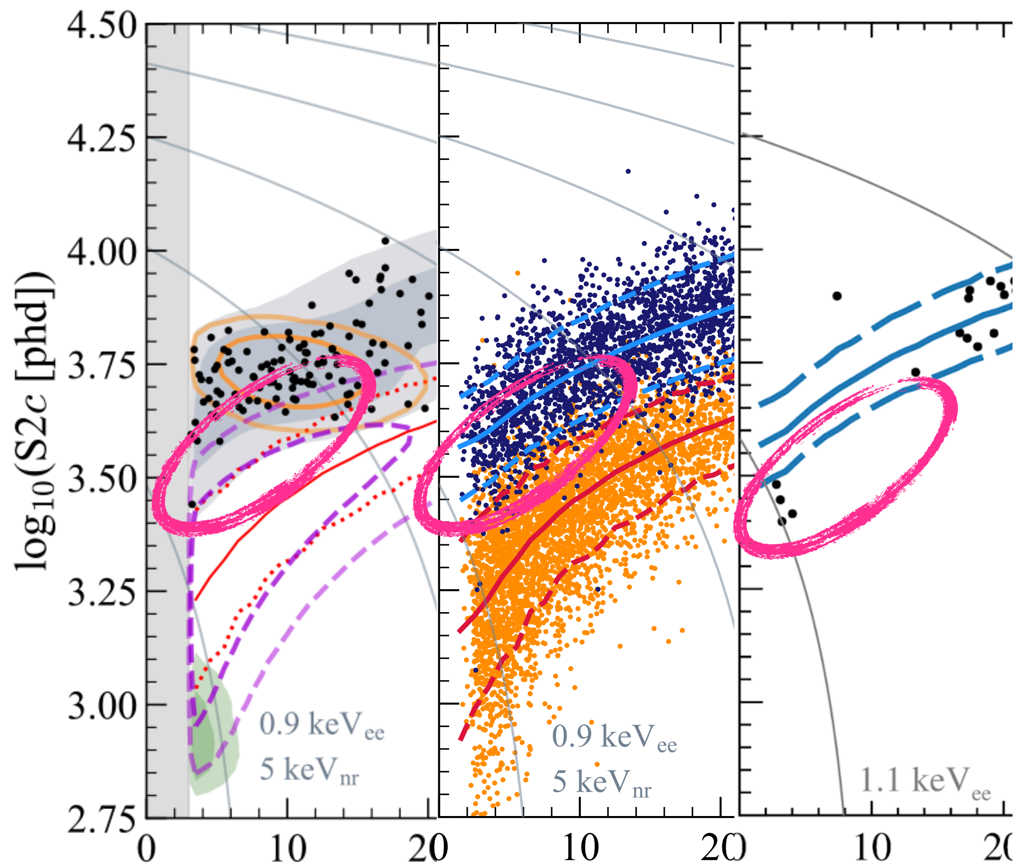


active TPC
cathode
Xe skin
PMT array
Xe skin
cryostat
outer detector
outer detector
OD PMT
water
water

What's going on at 30 GeV?



We see a downward fluctuation near 30 GeV/c^2



This is caused by a lack of background events under the ^{37}Ar

We have plenty of efficiency there in both ER (CH_3T) and NR (DD)

Also see M-shell ^{127}Xe tagged with skin

Conclusion: this is likely a statistical fluctuation

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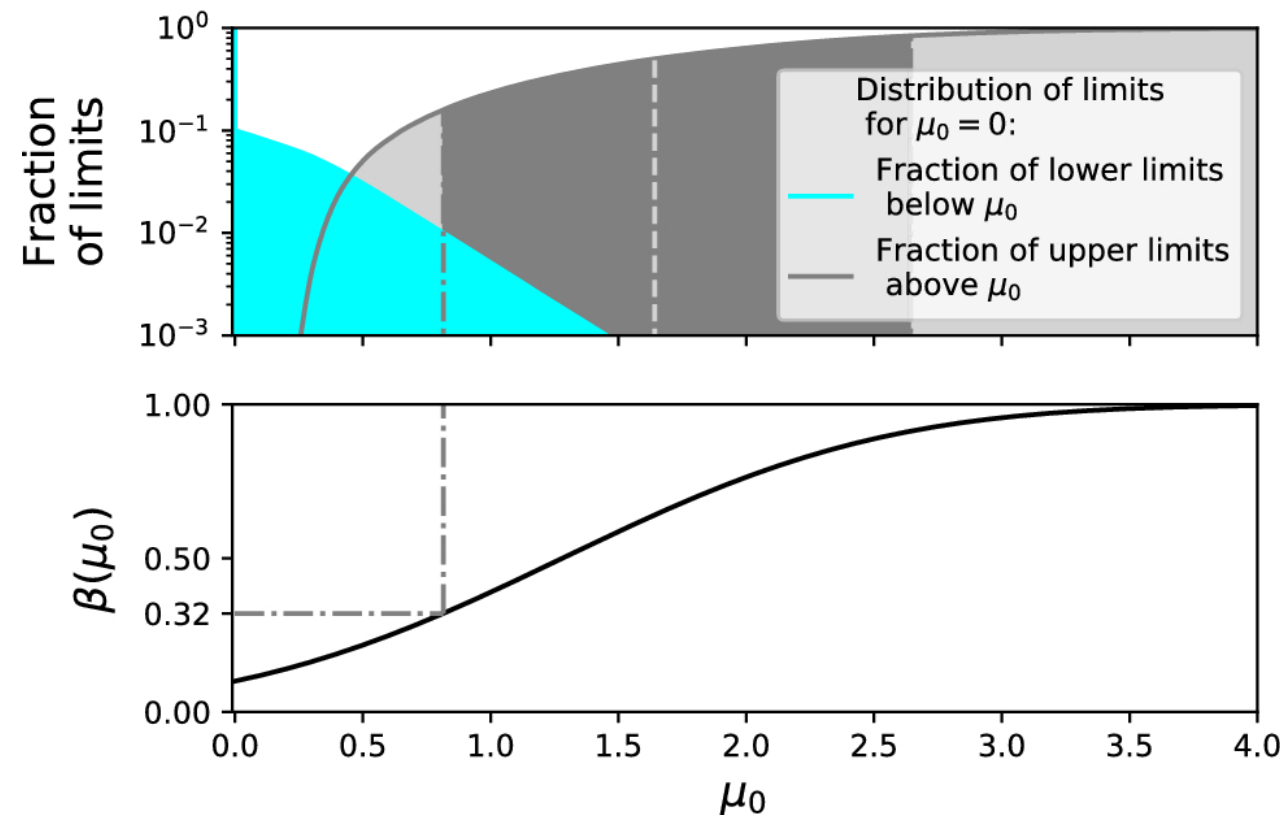
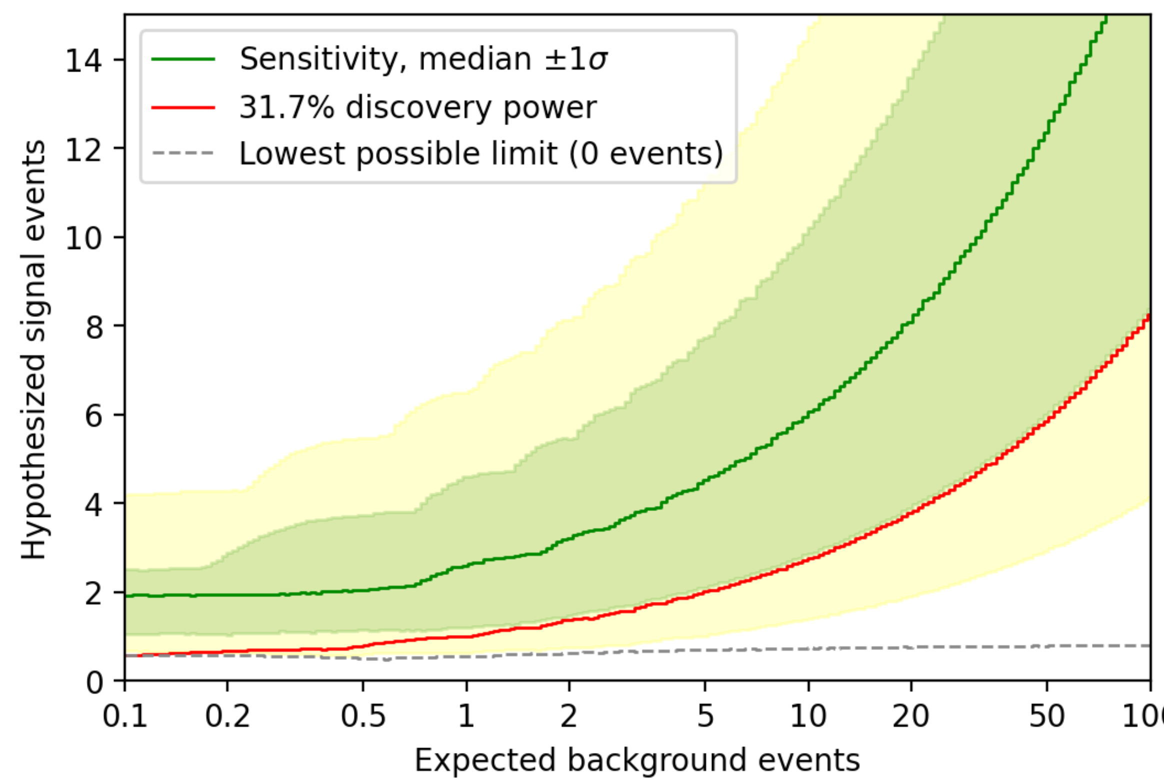
What's a Power Constraint?

- The power of a statistical test is the probability that the test correctly detects an effect when it is there
- As the number of background events increases, this asymptotically reaches the -1σ sensitivity band
- When the number of background events is small, this breaks down





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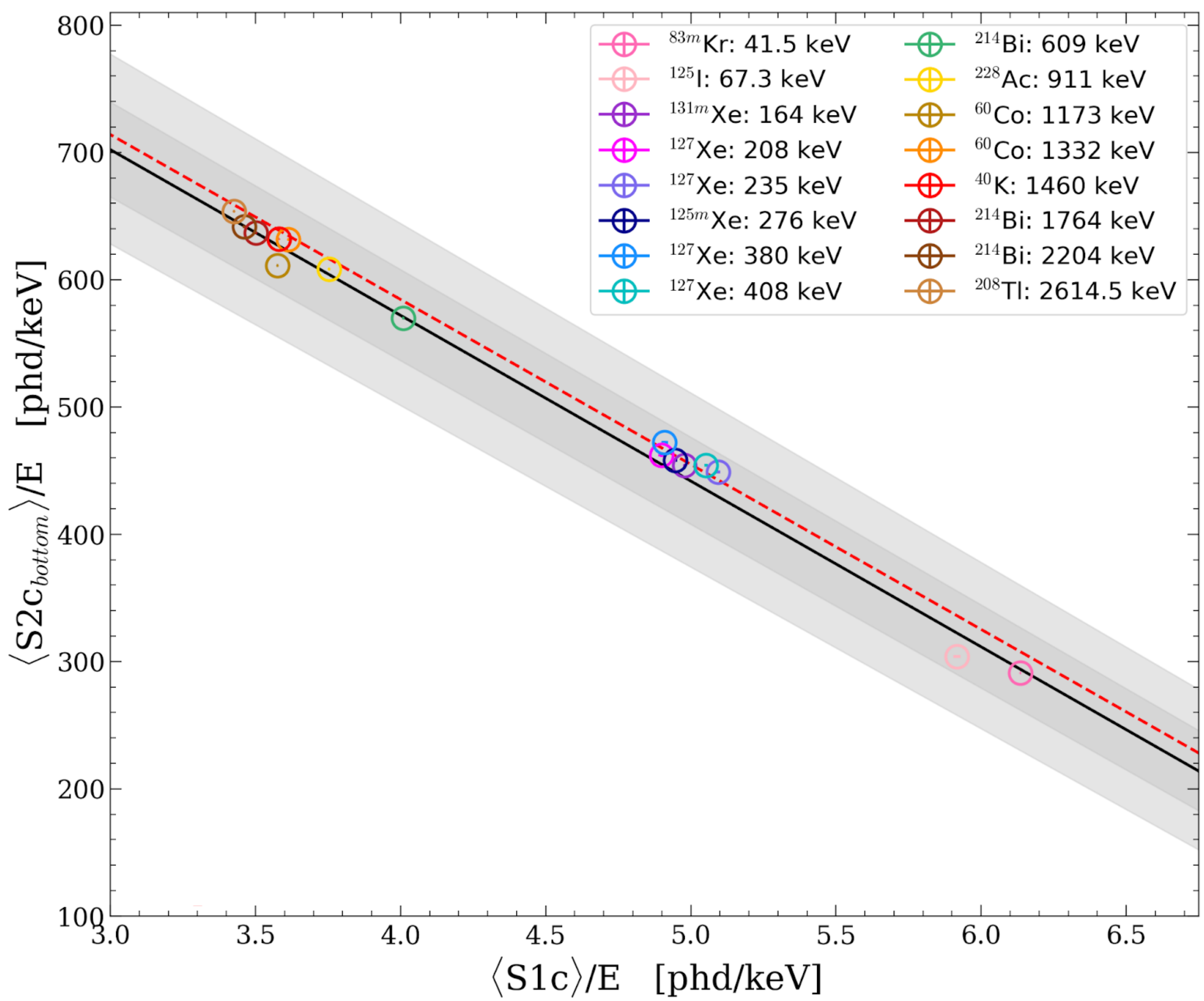
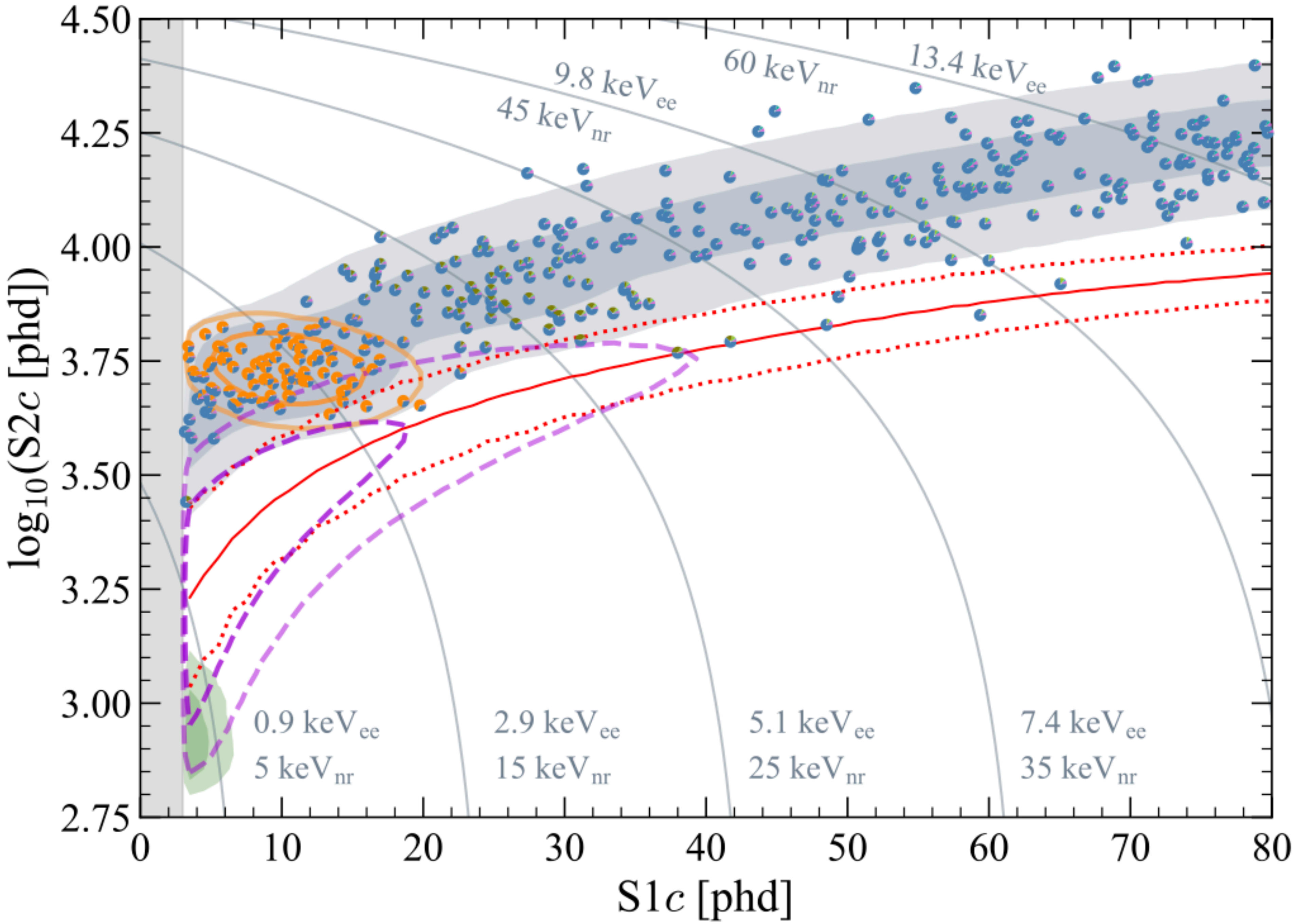
‘Doke’ plot



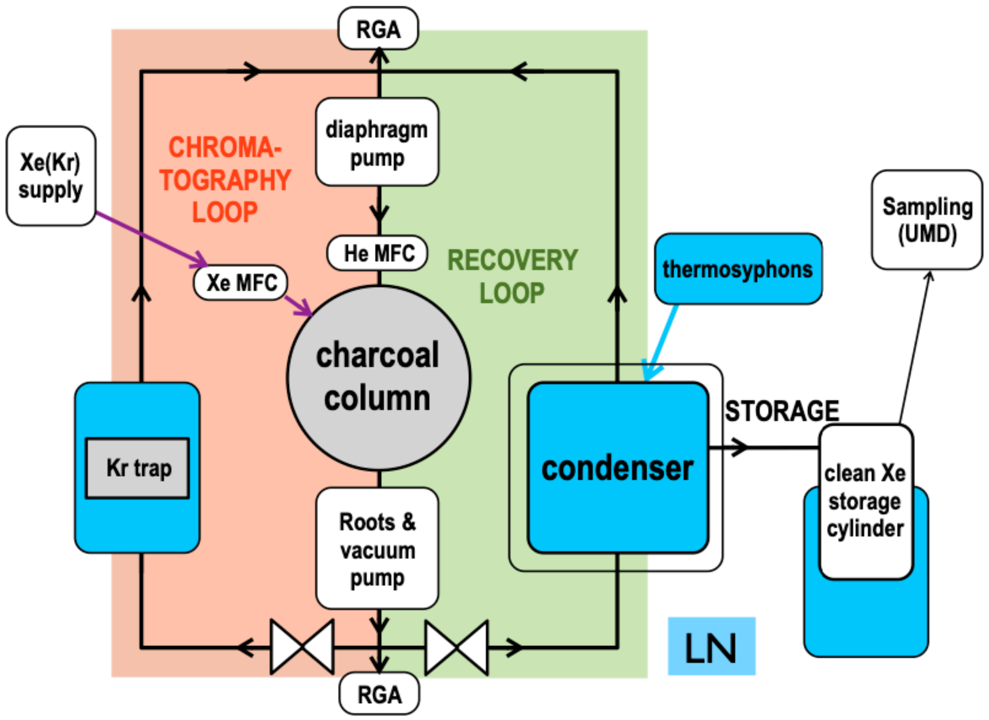
⟨S2c_bottom⟩/E [phd/keV]
⟨S1c⟩/E [phd/keV]
800
700
600
500
400
300
200
100
3.0
3.5
4.0
4.5
5.0
5.5
6.0
6.5
83mKr: 41.5 keV
125I: 67.3 keV
131mXe: 164 keV
127Xe: 208 keV
127Xe: 235 keV
125mXe: 276 keV
127Xe: 380 keV
127Xe: 408 keV
214Bi: 609 keV
228Ac: 911 keV
60Co: 1173 keV
60Co: 1332 keV
40K: 1460 keV
214Bi: 1764 keV
214Bi: 2204 keV
208Tl: 2614.5 keV

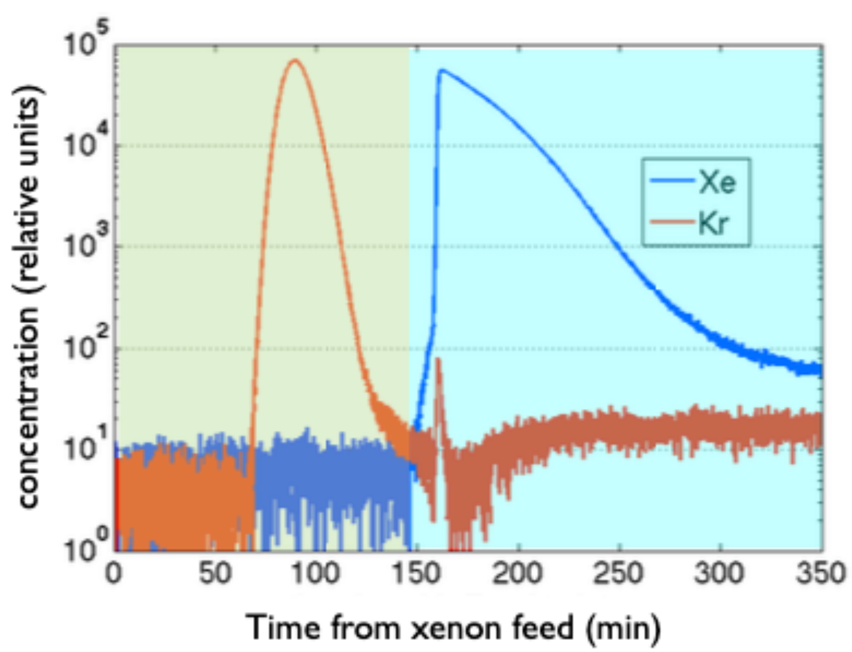
‘Pies’ Plot



9.8 keV$_{ee}$
60 keV$_{nr}$
13.4 keV$_{ee}$
45 keV$_{nr}$
0.9 keV$_{ee}$
5 keV$_{nr}$
2.9 keV$_{ee}$
15 keV$_{nr}$
5.1 keV$_{ee}$
25 keV$_{nr}$
7.4 keV$_{ee}$
35 keV$_{nr}$
$\log_{10}$(S2c [phd])
S1c [phd]

Kr Removal





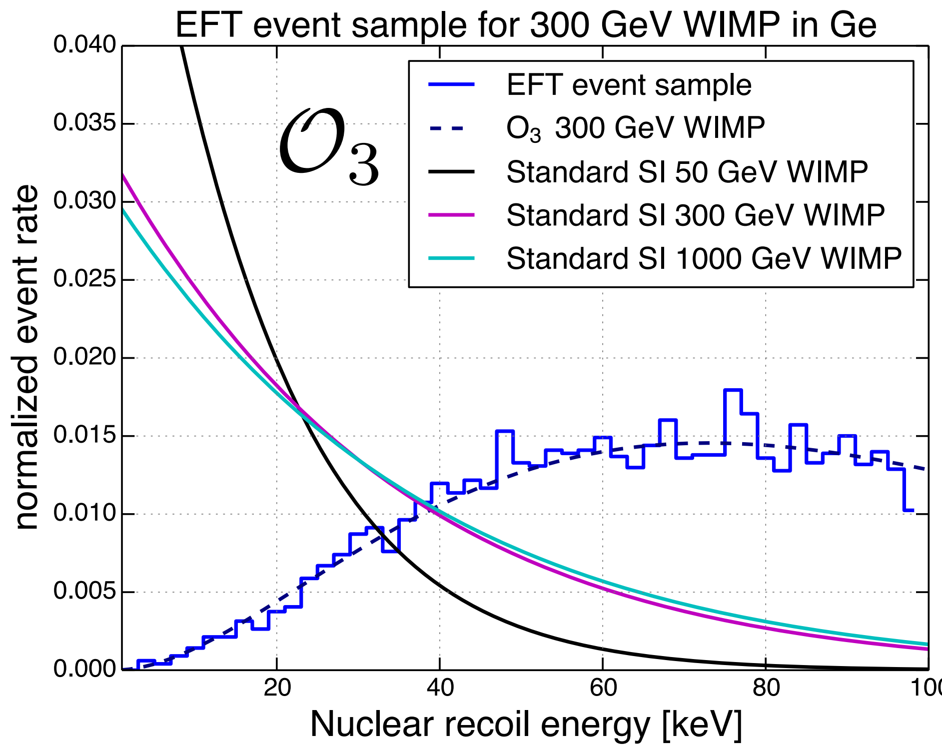
- LXe can be contaminated with air or cosmic ray activation
- Light elements like N or O can be removed with 'standard' purification
- Most dangerous contamination is Kr—needs to be removed before Xe goes underground

Other Couplings

- Consider all couplings of the form
- SI and SD are just two of the many possible couplings
- Signal: Nuclear Recoil with many possible spectra

SI
$$\mathcal{O}_1 = 1_\chi 1_N$$
$$\mathcal{O}_3 = i\vec{S}_N \cdot \left[\frac{\vec{q}}{m_N} \times \vec{v}^\perp\right]$$

SD
$$\mathcal{O}_4 = \vec{S}_\chi \cdot \vec{S}_N$$
$$\mathcal{O}_5 = i\vec{S}_\chi \cdot \left[\frac{\vec{q}}{m_N} \times \vec{v}^\perp\right]$$
$$\mathcal{O}_6 = \left[\vec{S}_\chi \cdot \frac{\vec{q}}{m_N}\right]\left[\vec{S}_N \cdot \frac{\vec{q}}{m_N}\right]$$
$$\mathcal{O}_7 = \vec{S}_N \cdot \vec{v}^\perp$$
$$\mathcal{O}_8 = \vec{S}_\chi \cdot \vec{v}^\perp$$
$$\mathcal{O}_9 = i\vec{S}_\chi \cdot \left[\vec{S}_N \times \frac{\vec{q}}{m_N}\right]$$
$$\mathcal{O}_{10} = i\vec{S}_N \cdot \frac{\vec{q}}{m_N}$$
$$\mathcal{O}_{11} = i\vec{S}_\chi \cdot \frac{\vec{q}}{m_N}$$
$$\mathcal{O}_{12} = \vec{S}_\chi \cdot \left[\vec{S}_N \times \vec{v}^\perp\right]$$
$$\mathcal{O}_{13} = i\left[\vec{S}_\chi \cdot \vec{v}^\perp\right]\left[\vec{S}_N \cdot \frac{\vec{q}}{m_N}\right]$$
$$\mathcal{O}_{14} = i\left[\vec{S}_\chi \cdot \frac{\vec{q}}{m_N}\right]\left[\vec{S}_N \cdot \vec{v}^\perp\right]$$
$$\mathcal{O}_{15} = -\left[\vec{S}_\chi \cdot \frac{\vec{q}}{m_N}\right]\left[\left(\vec{S}_N \times \vec{v}^\perp\right) \cdot \frac{\vec{q}}{m_N}\right]$$



Expected Discovery: Cν NS

- This is as close to a 'sure thing' signal as we can imagine
- Excellent practice for discovering dark matter!