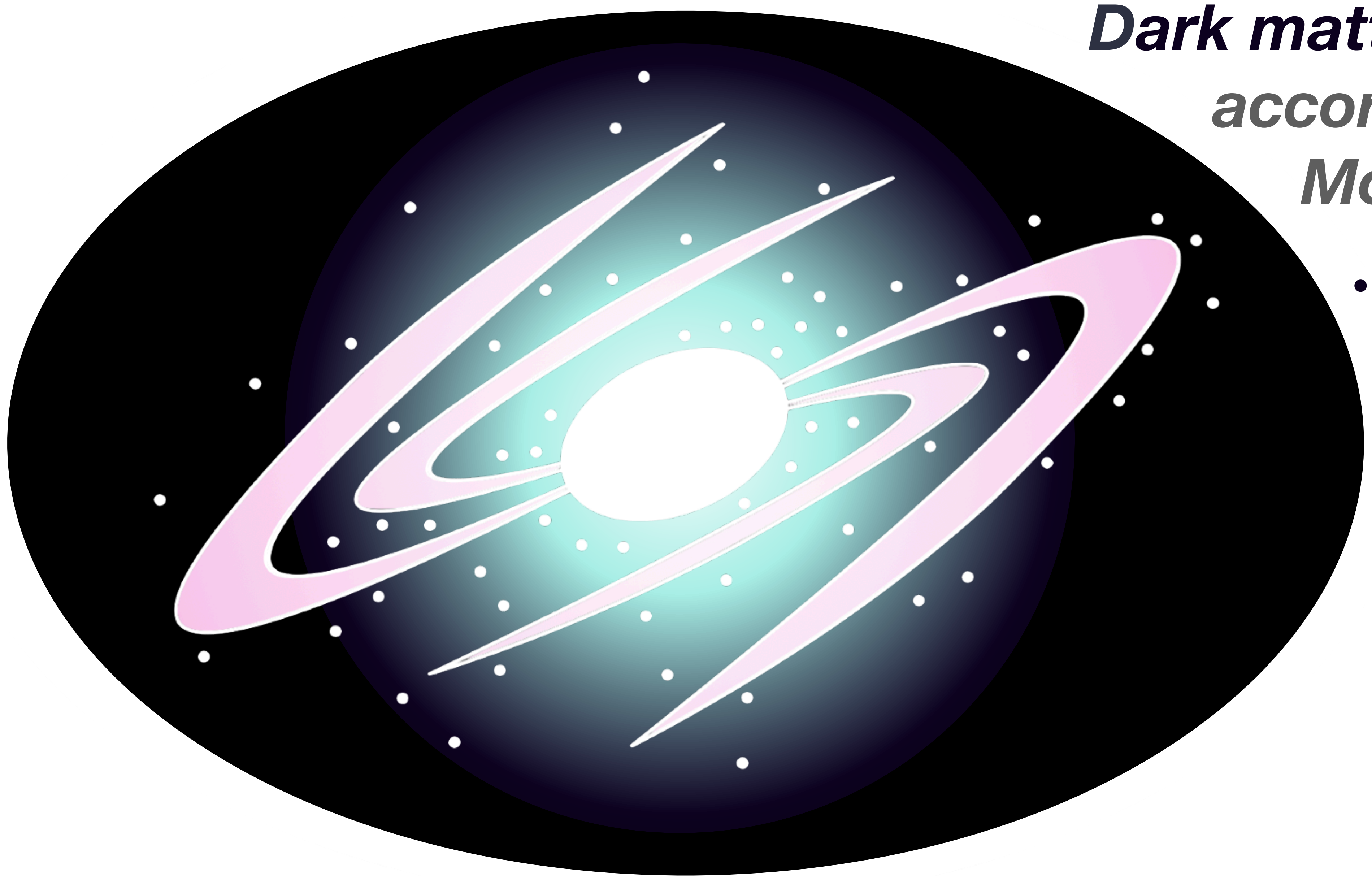
LZ Data Analysis Pipeline for the 4.2 Tonne-Year WIMP Search

Dr. Joe McLaughlin
STFC Rutherford Appleton Laboratory
PPD Seminar
19 November, 2025

Some Context

We assume that…



***Dark matter** is distributed according to the Standard Halo Model*

- Isothermal sphere of DM, $\rho \propto r^{-2}$
  - Local density ρ_0 ~ 0.3 GeV/cm³
    - Earth constantly seeing a dark matter 'wind' with Characteristic velocity $v_0 = 220$ km/s

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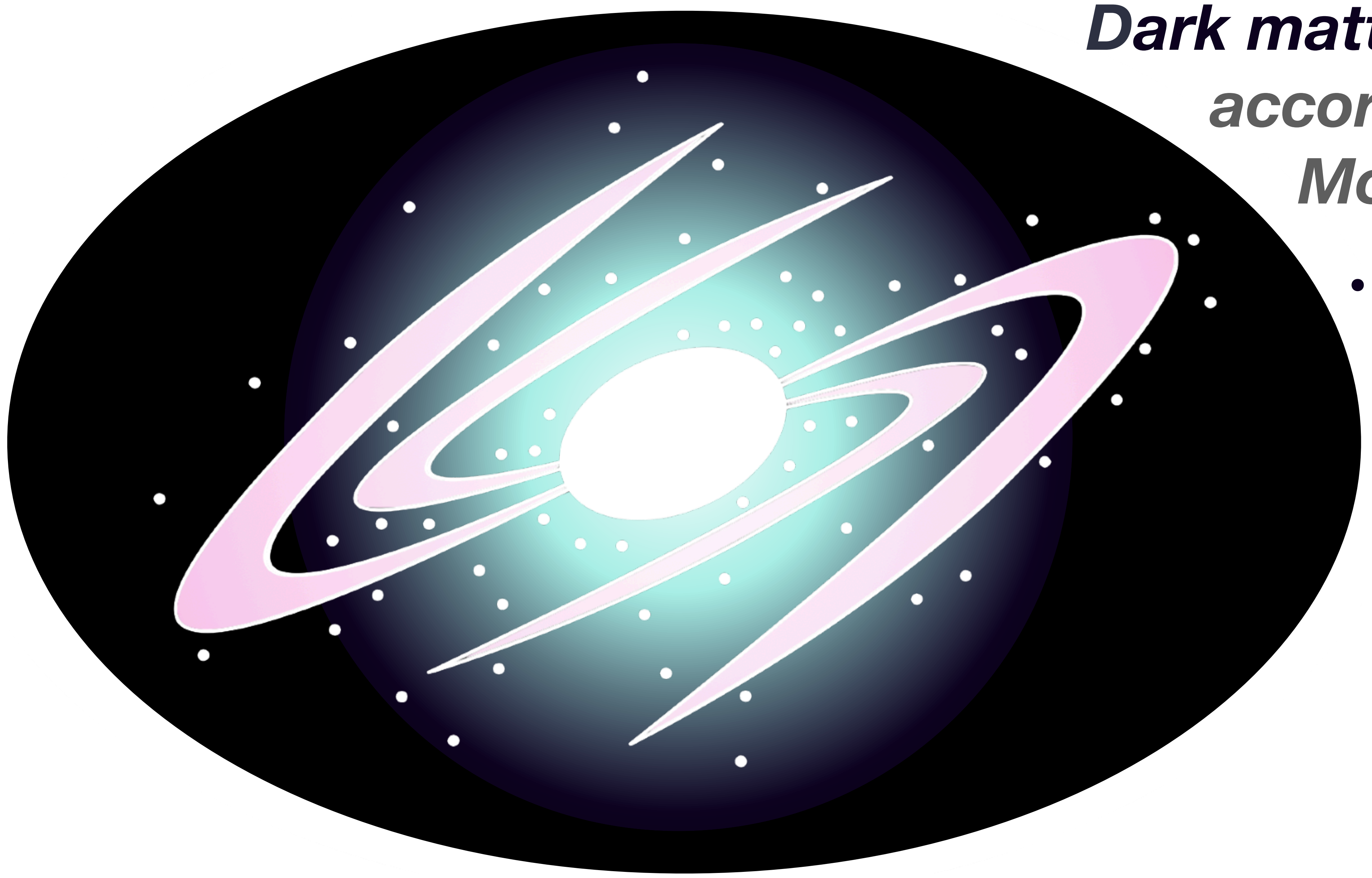

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***Dark matter** is made up of Weakly Interacting Massive Particles (WIMPs)*

- GeV–TeV mass scale
- Extremely weak coupling to baryonic matter
- e.g. SUSY neutralino, Kaluza-Klein dark matter

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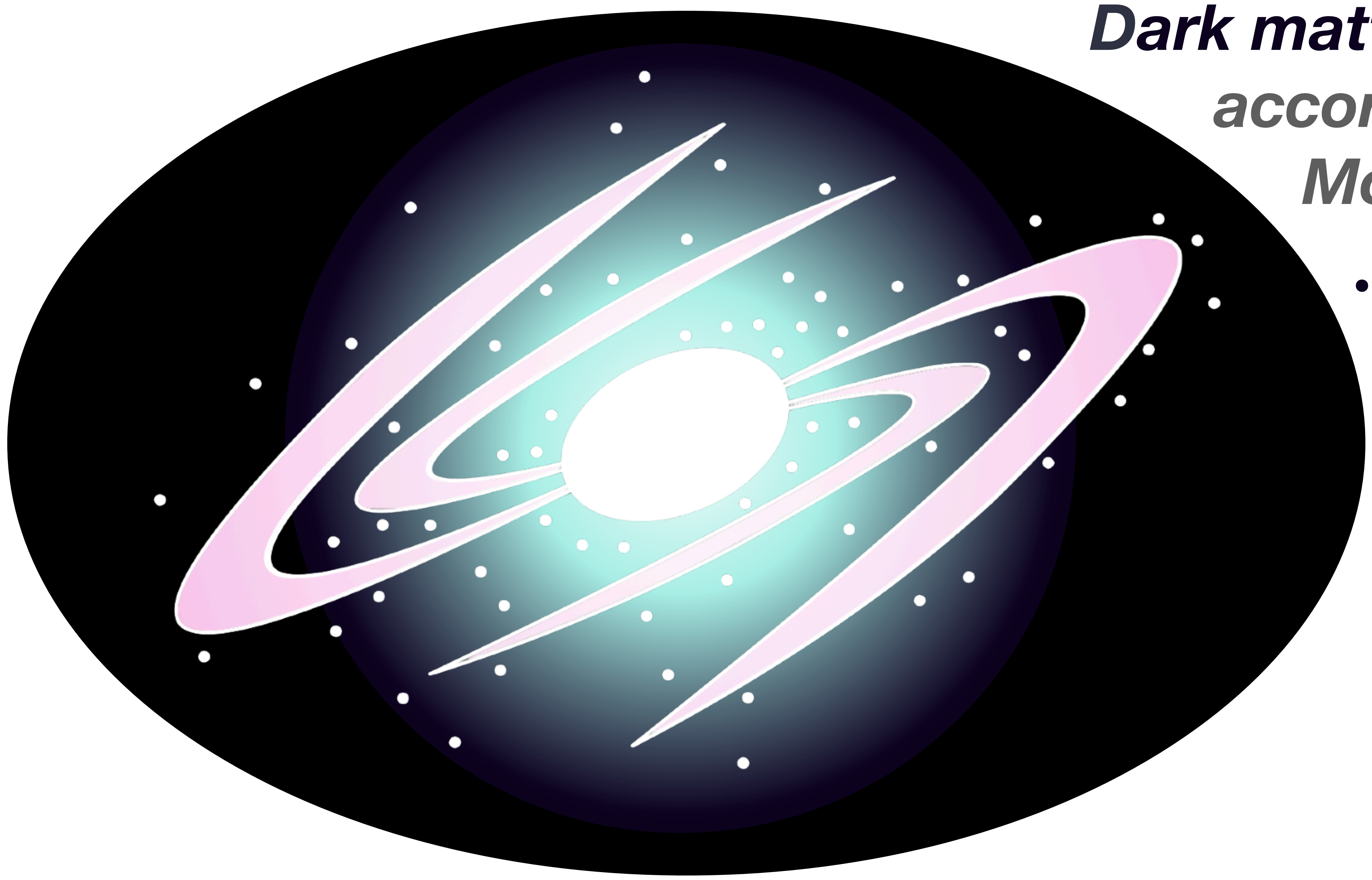

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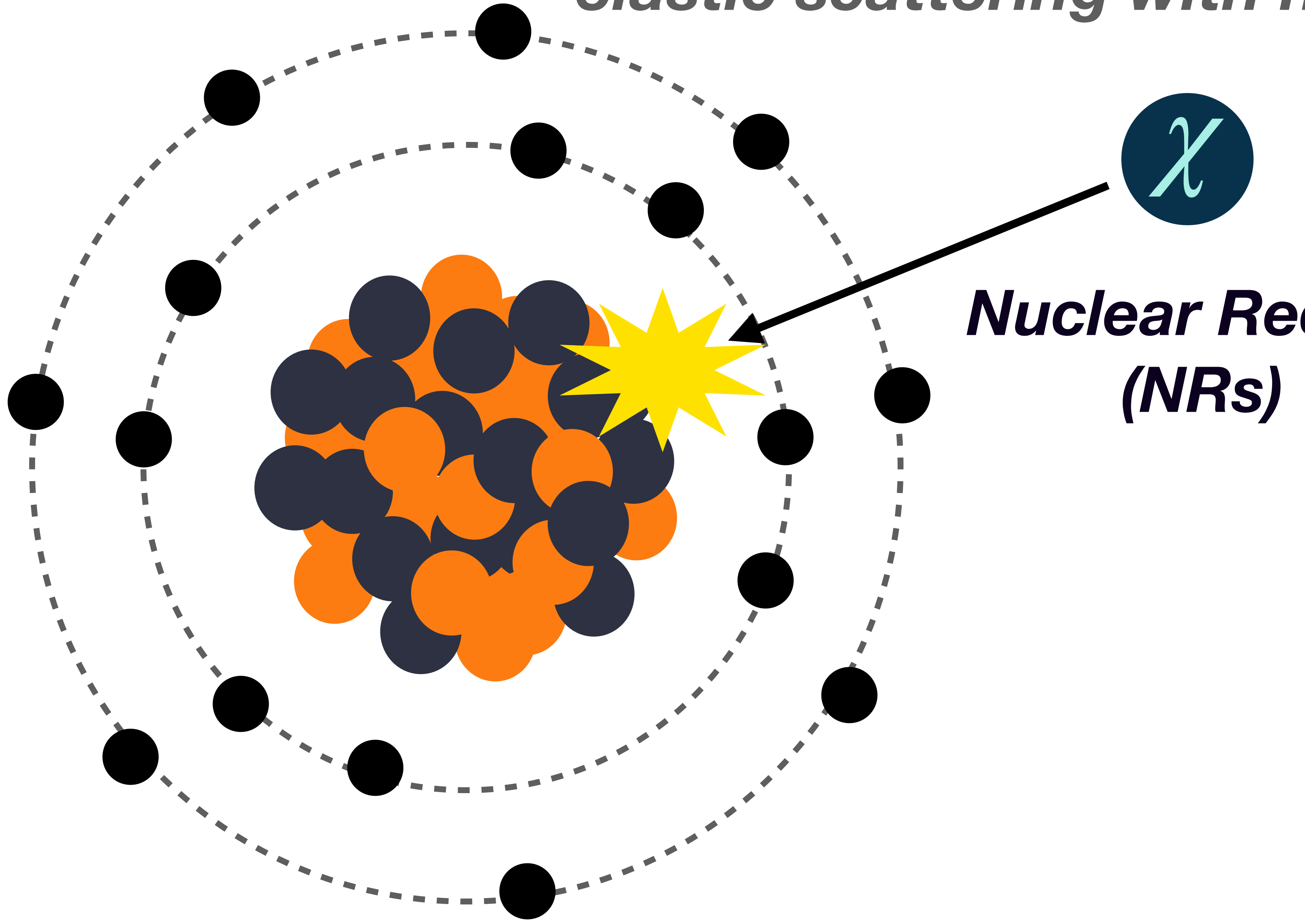
***Dark matter** interacts with baryonic matter, virtually always via keV-scale elastic scattering with nuclei*



Nuclear Recoils (NRs)

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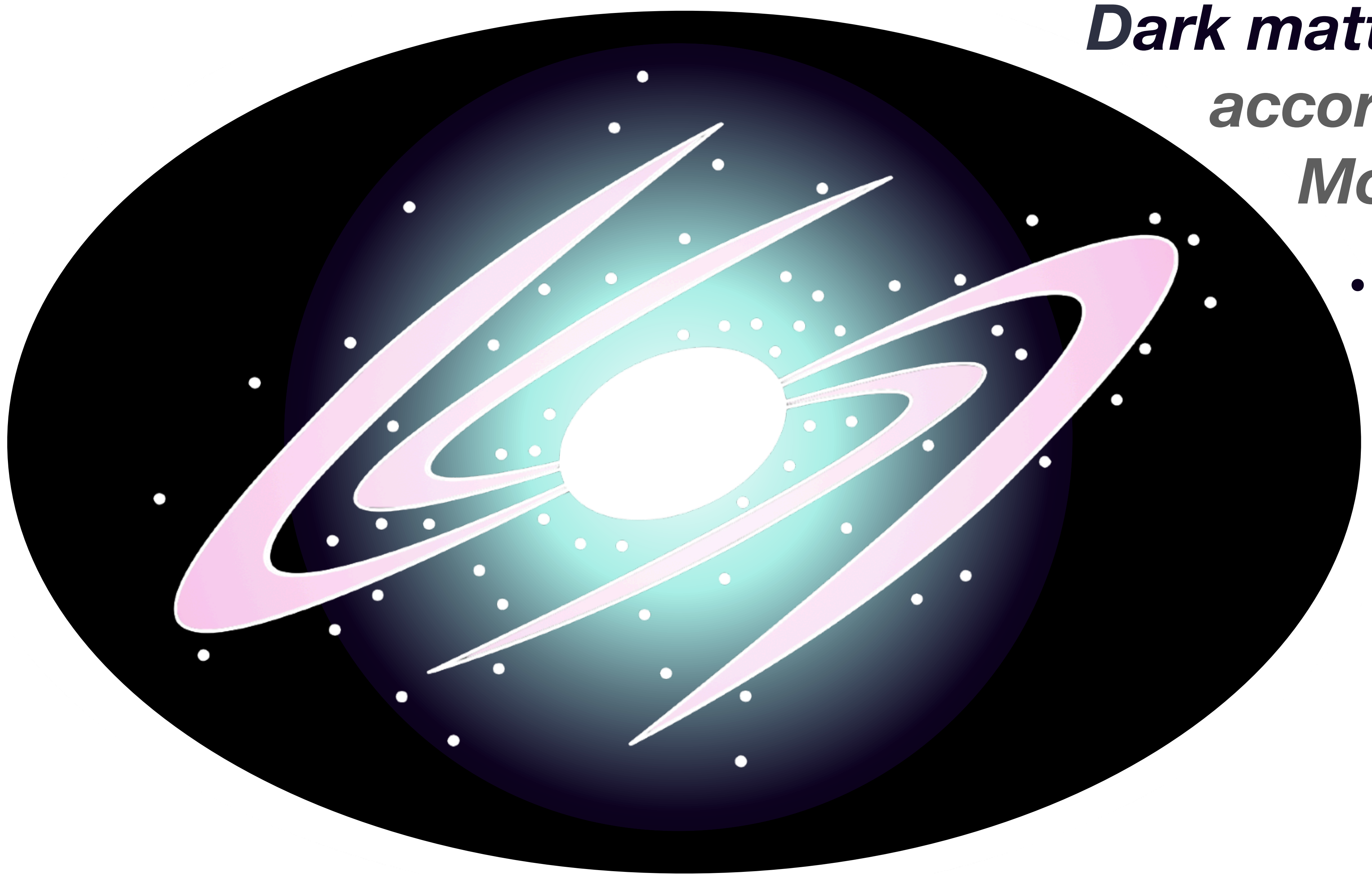

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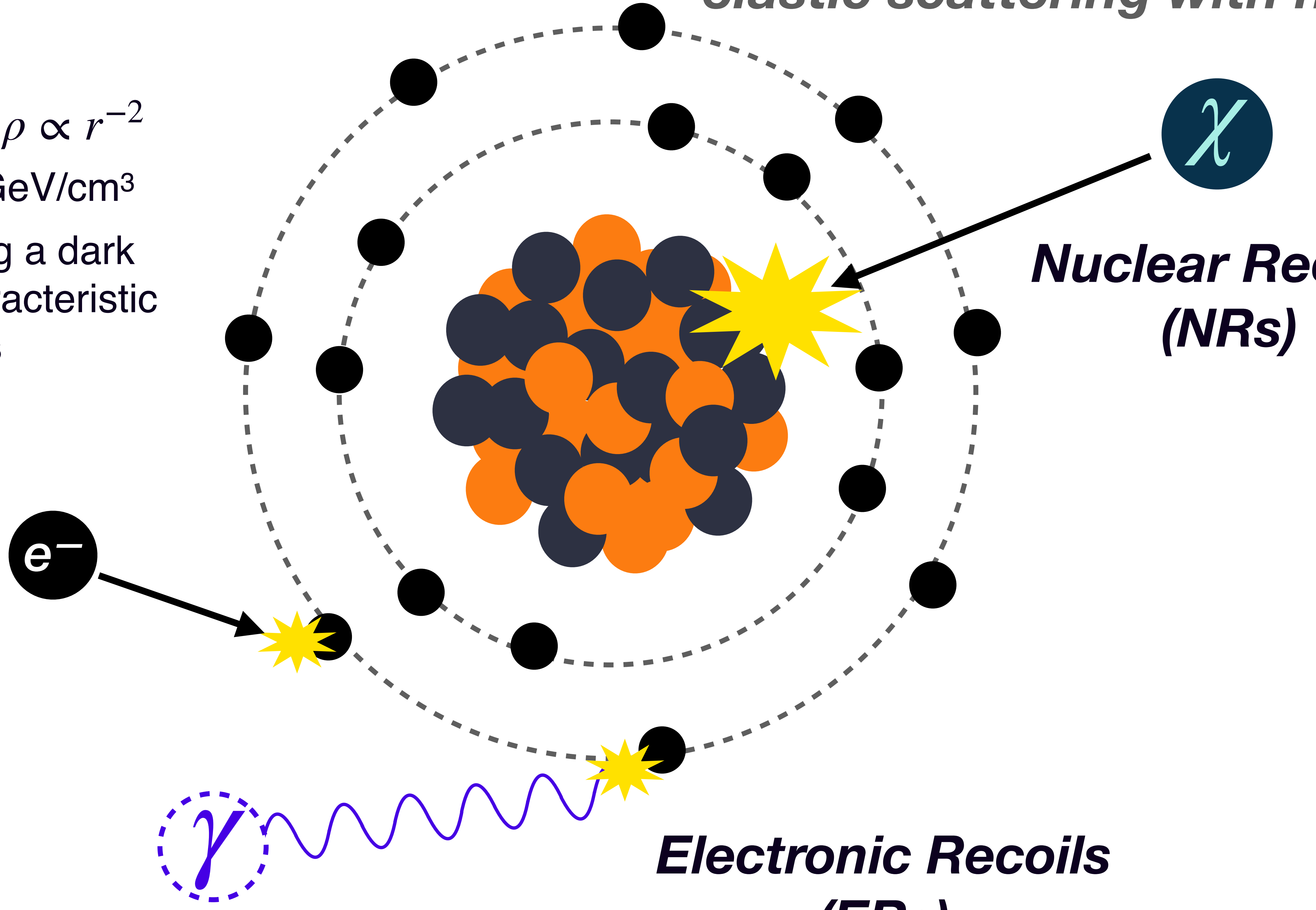

***Dominant backgrounds** are low energy electrons and gammas, kinematically limited to scatter with atomic electrons*

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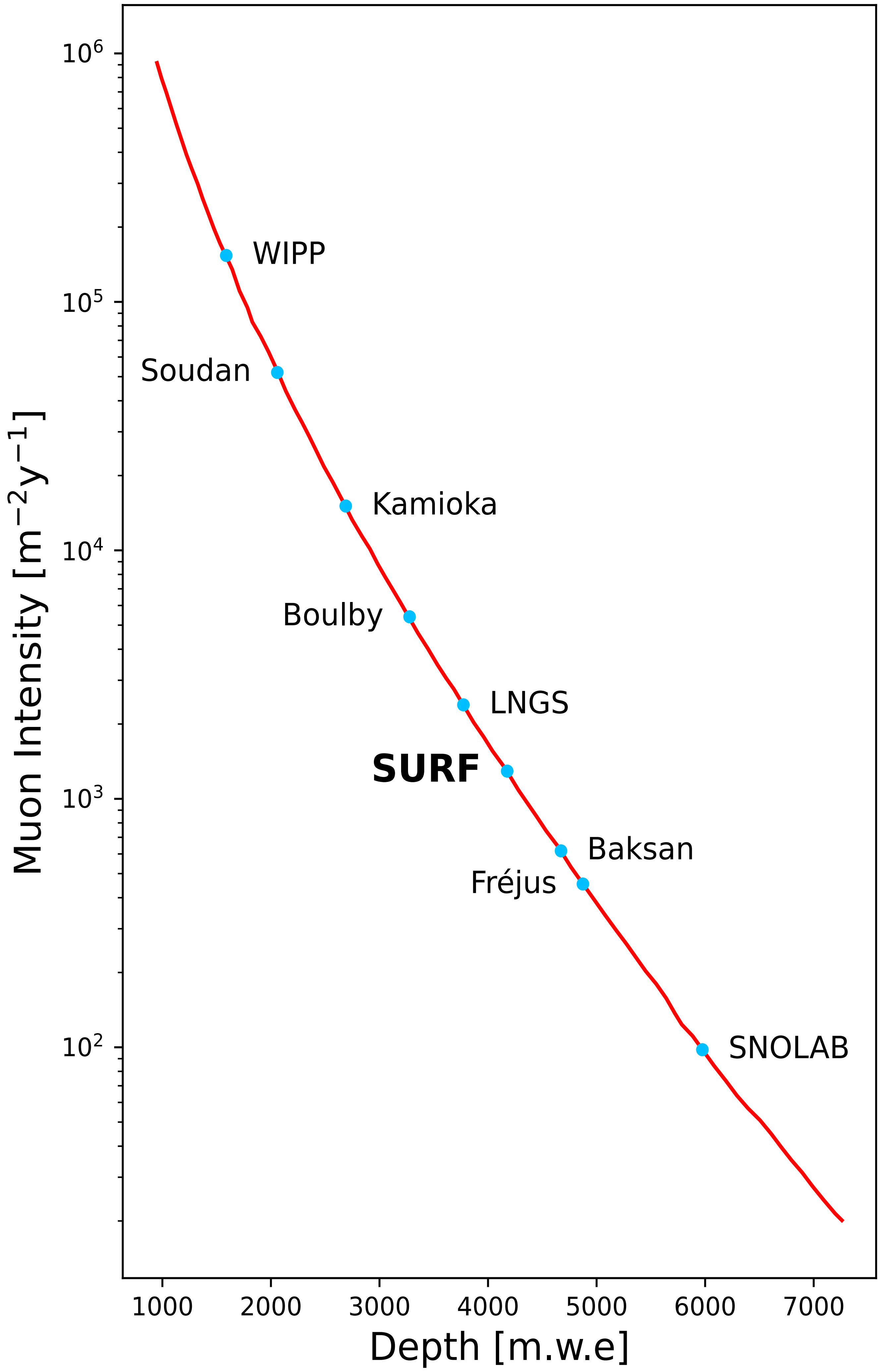
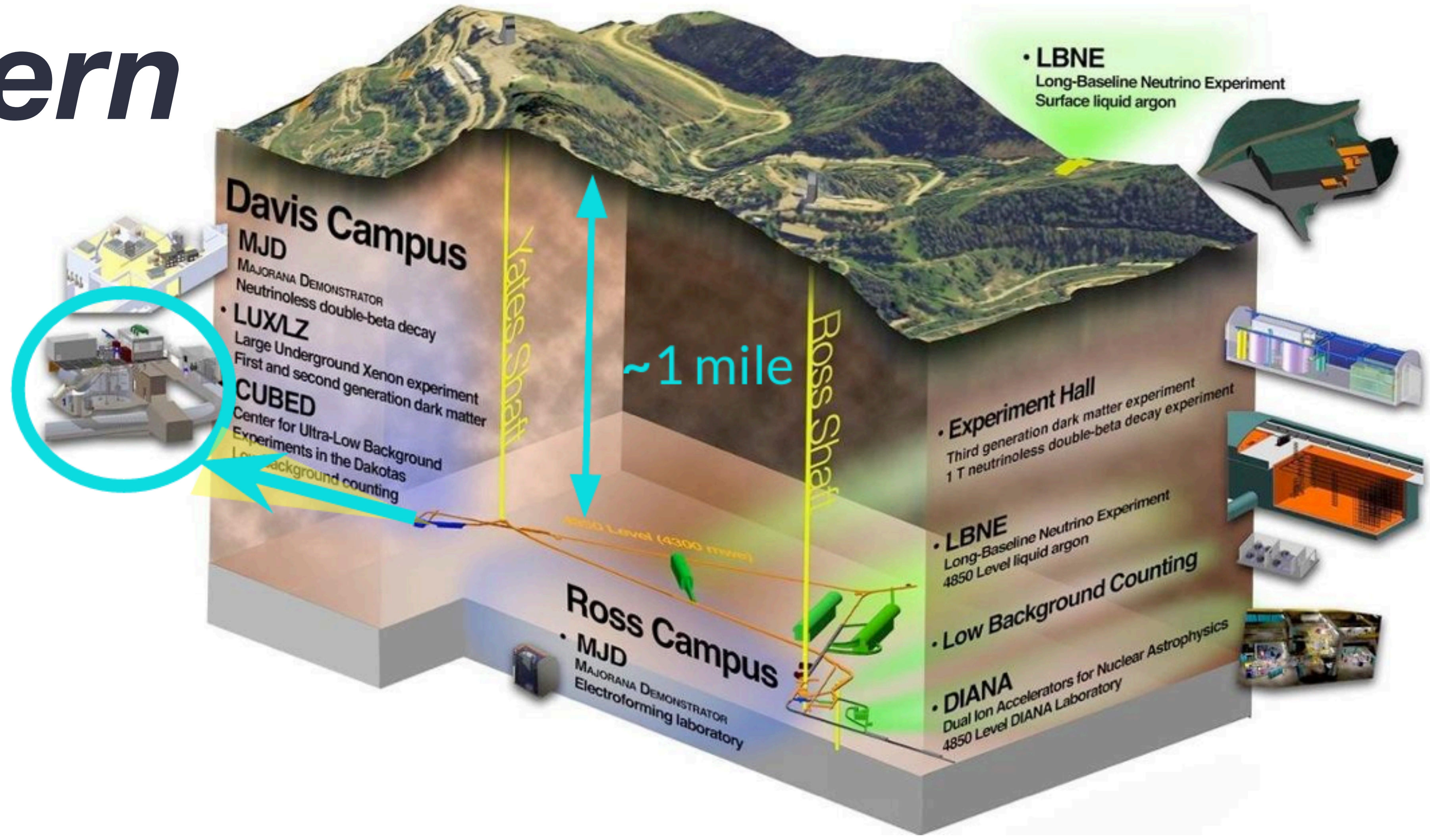
Some Context

One mile under the Black Hills of South Dakota…

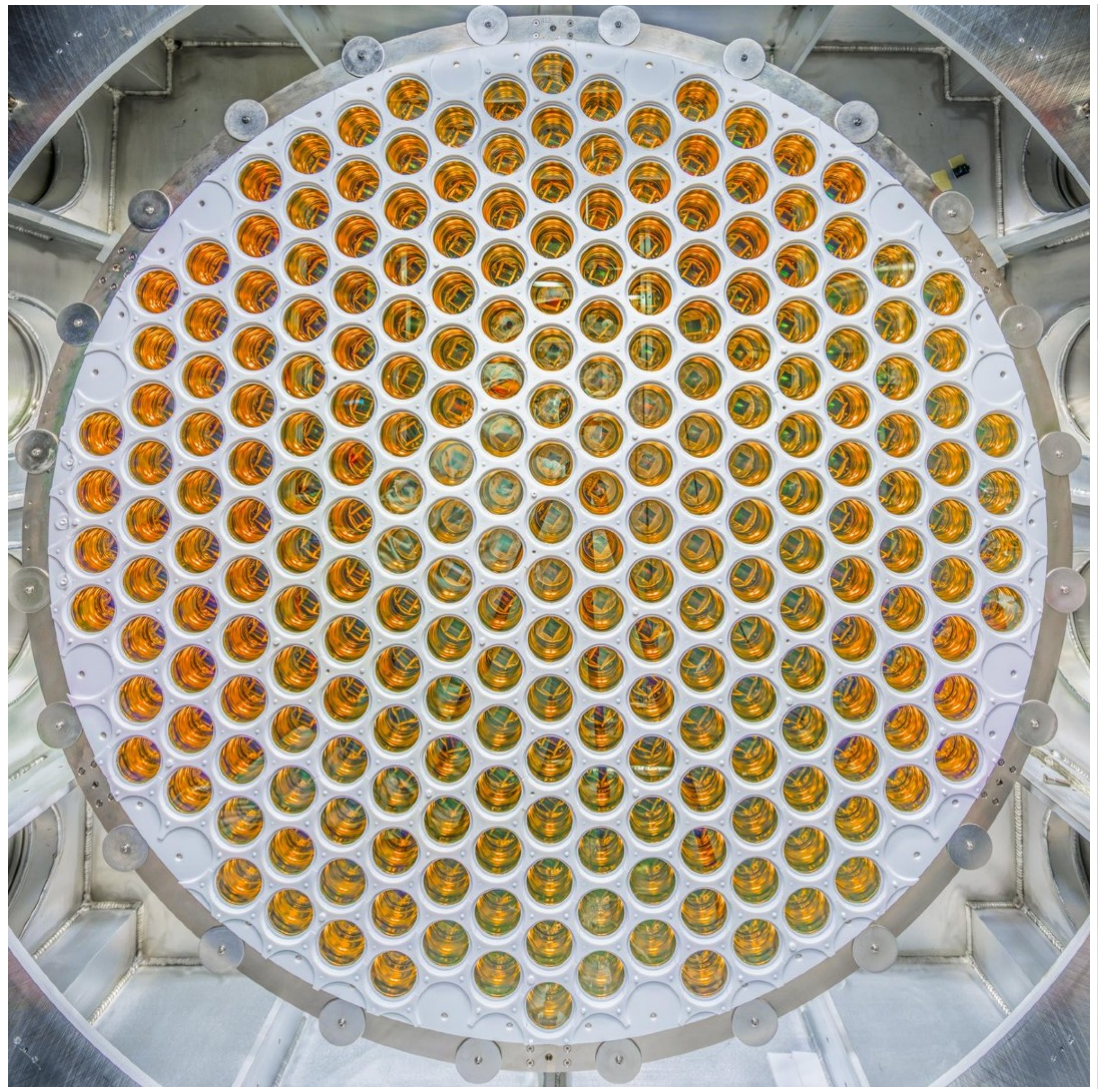


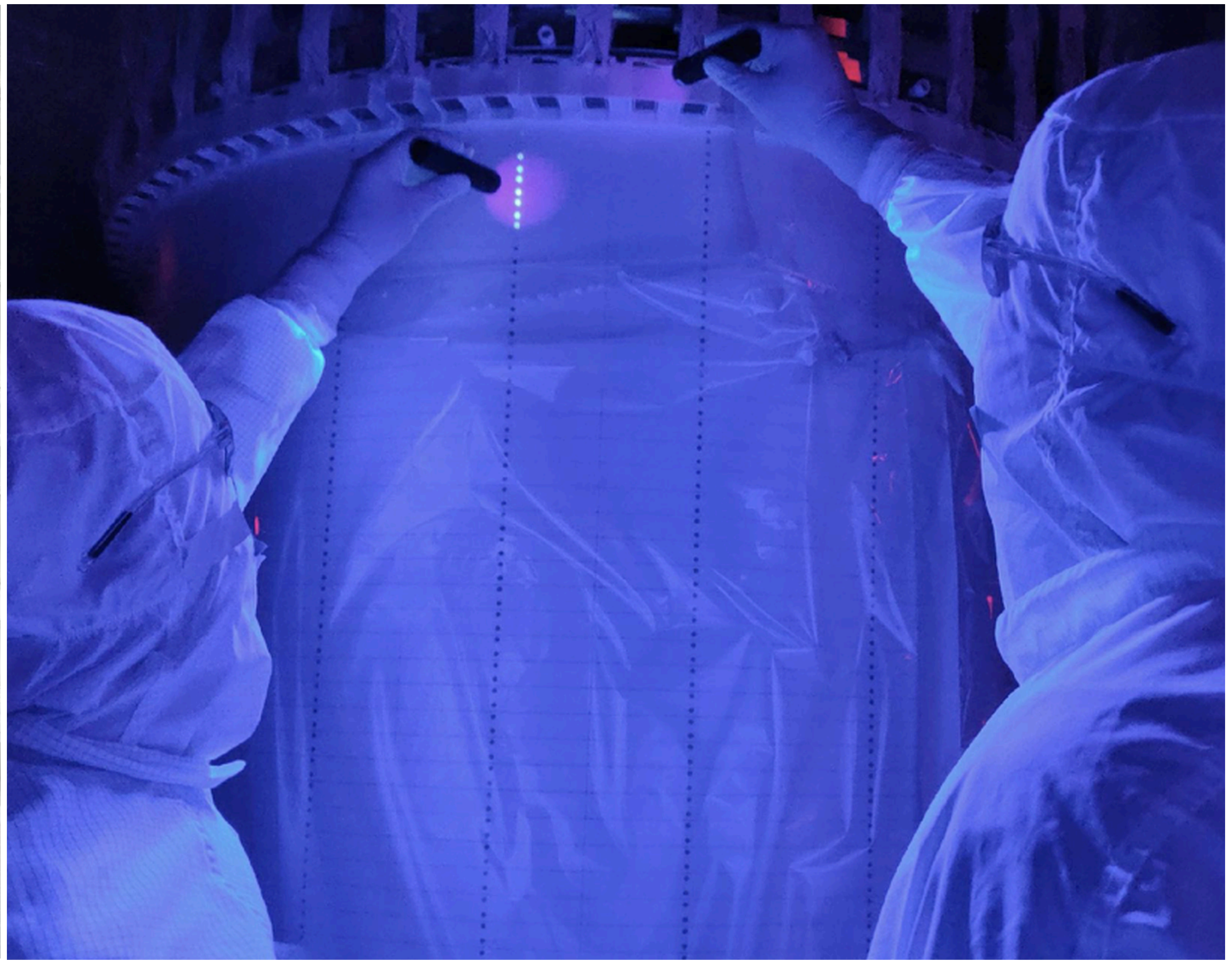
… in the SURF Davis Cavern

Sanford
Underground Research Facility
South Dakota Science and Technology Authority



LUX-ZEPLIN

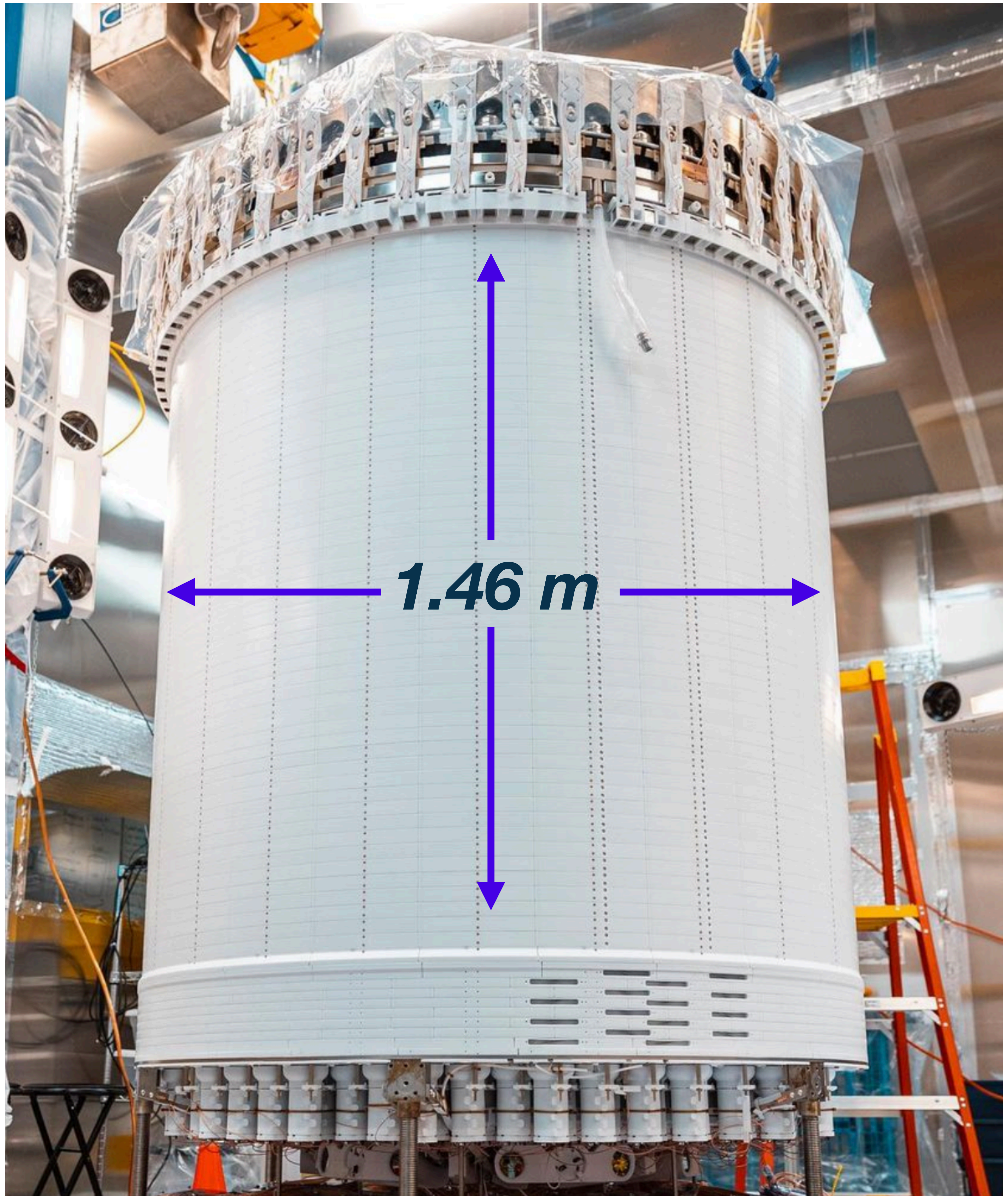




LUX-ZEPLIN

A Dual-Phase Time Projection Chamber

- 1.46 m in height and diameter
- 10 tonnes of liquid xenon (LXe) in total
  - 7 tonnes inside TPC
  - 5.5 tonnes inner fiducial mass
- 8 mm thick layer of gaseous xenon (GXe) at the top



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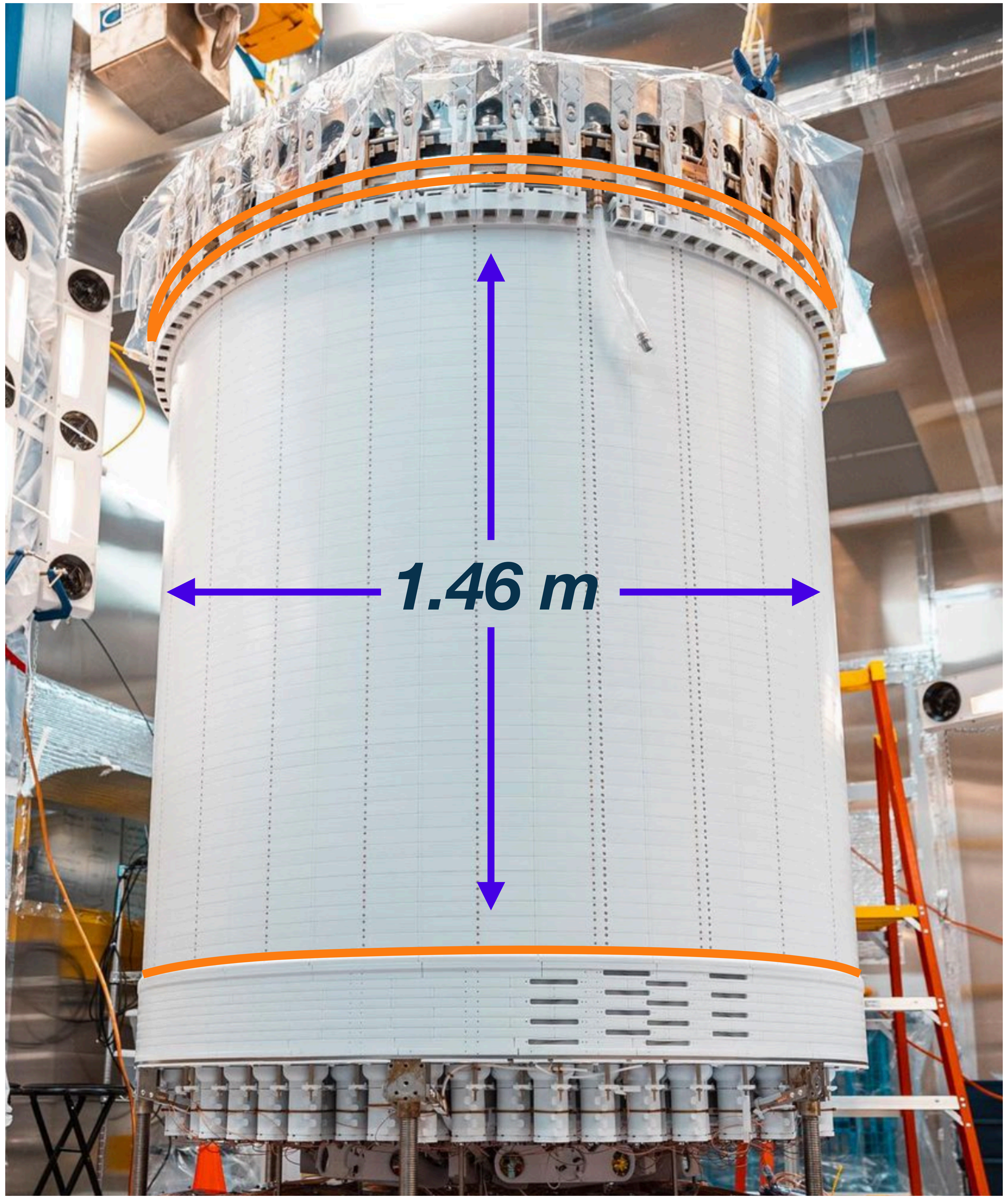
Mesh wire grid electrodes

- Cathode and Gate define *drift field region*
  - ~100 V/cm field strength
  - Liquid phase
- Gate and Anode define *extraction field region*
  - ~kV/cm field strength
  - Gaseous phase



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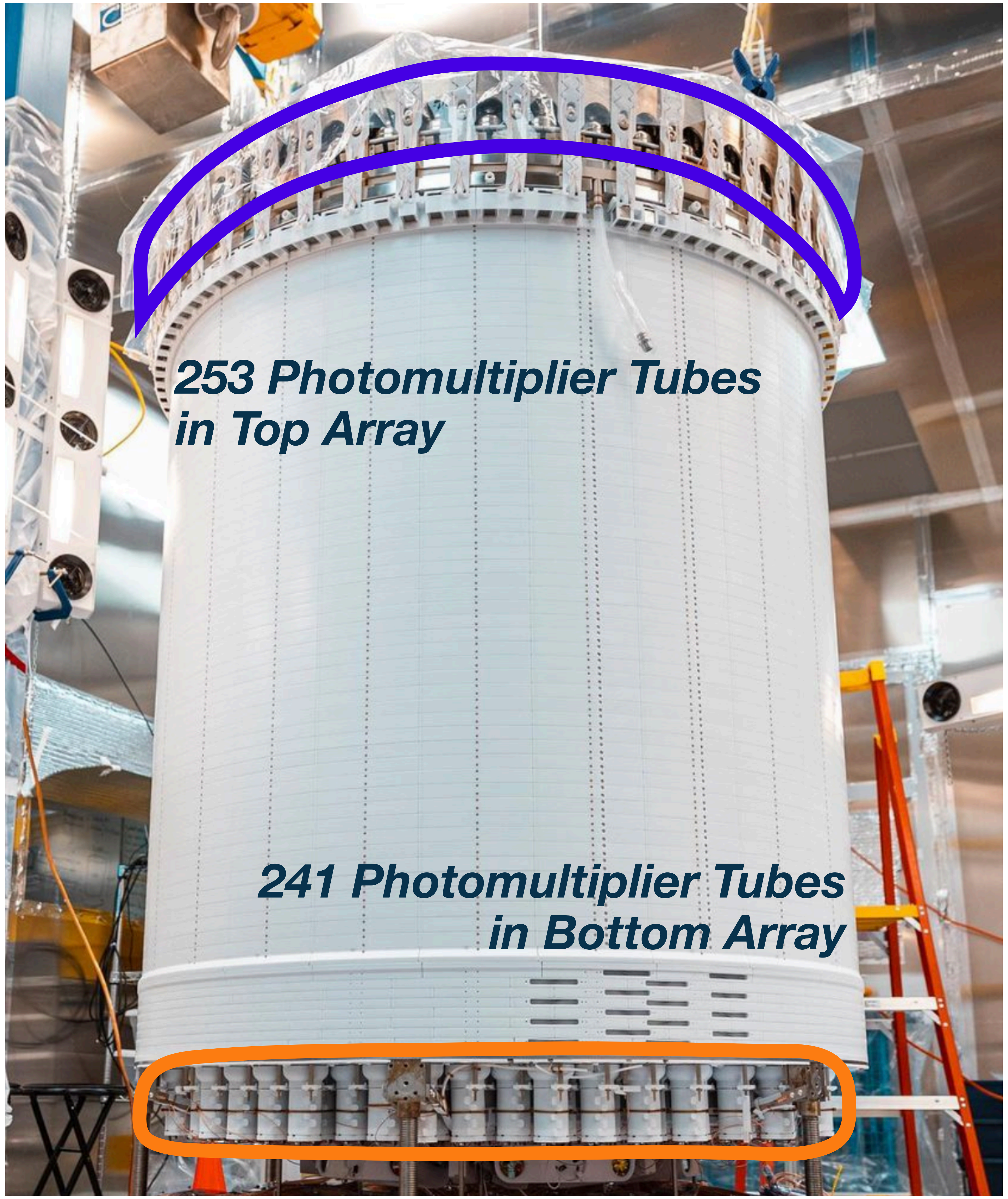
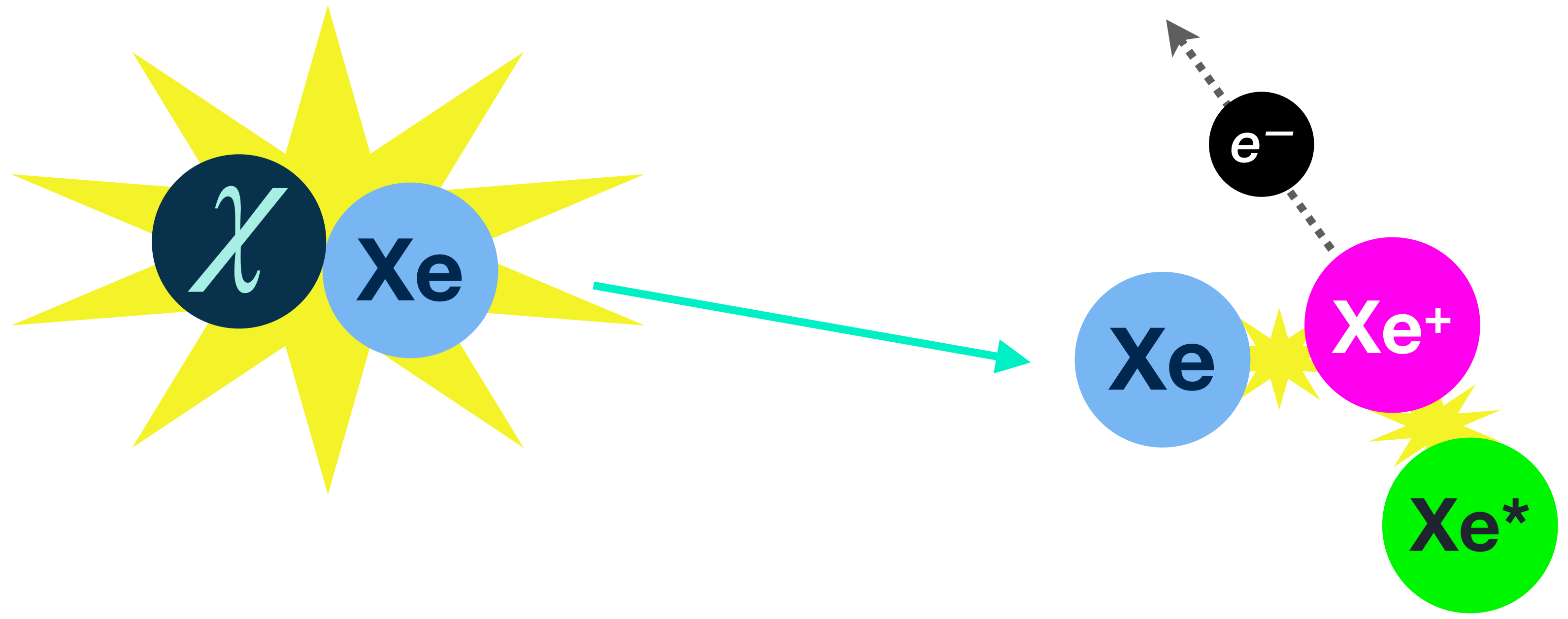


Xenon Microphysics



Atoms in the track of a recoiling nucleus become ***excitons*** or ***ions***

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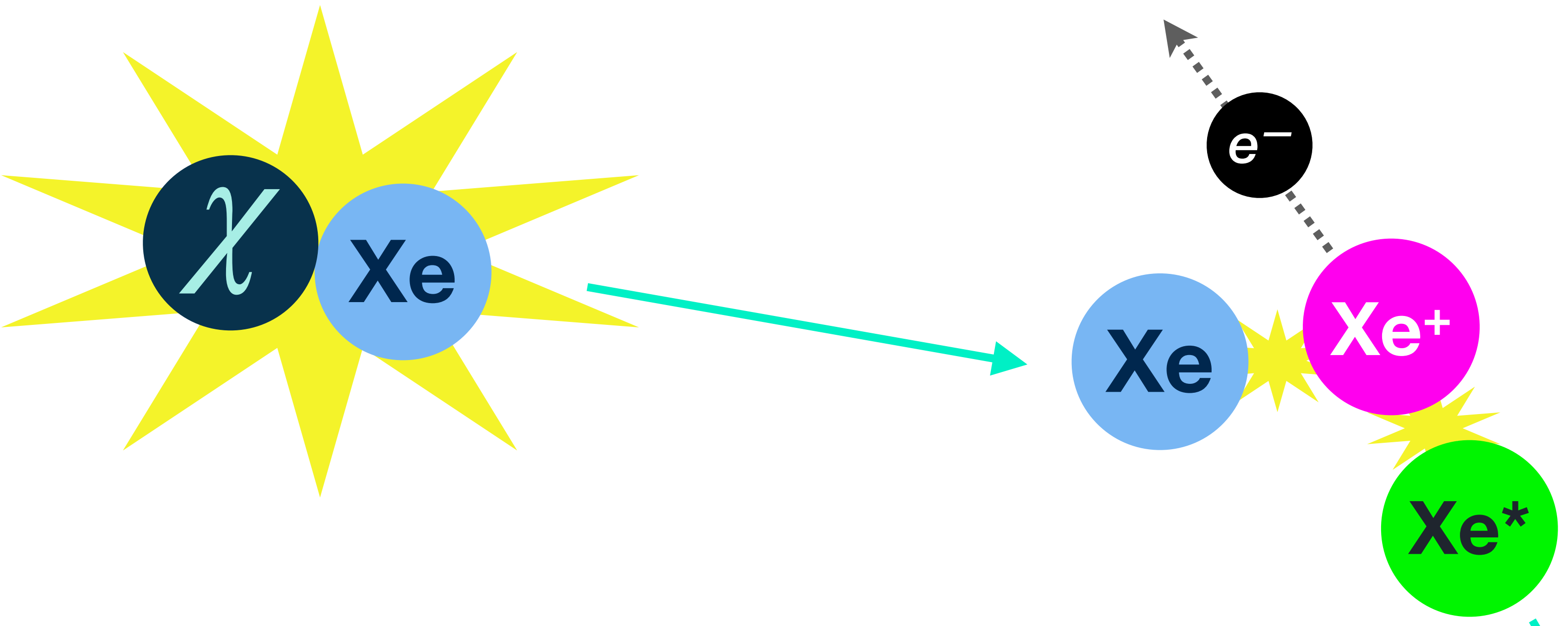

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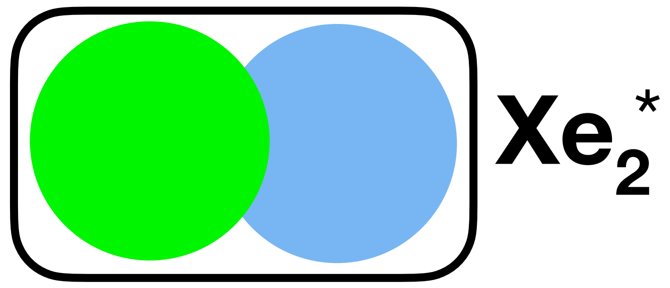
Excitons form excited dimers *(excimers)* with ground-state atoms



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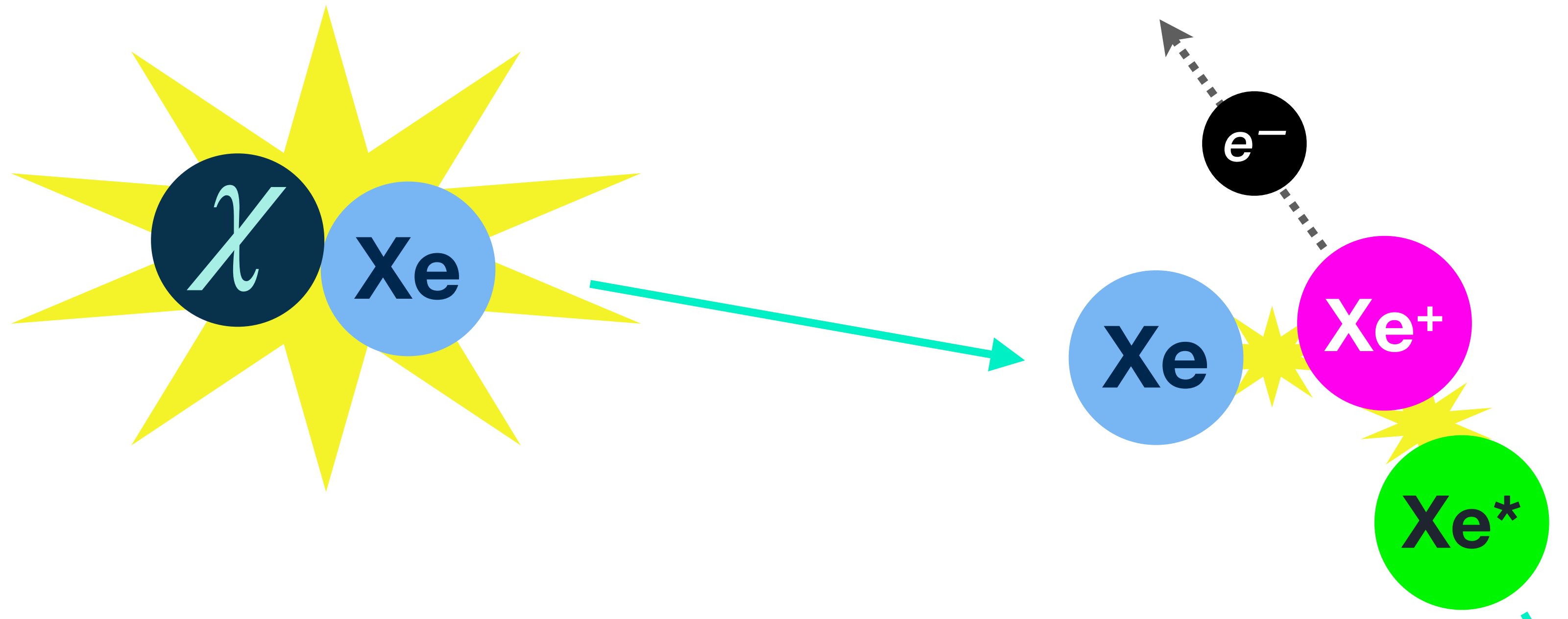

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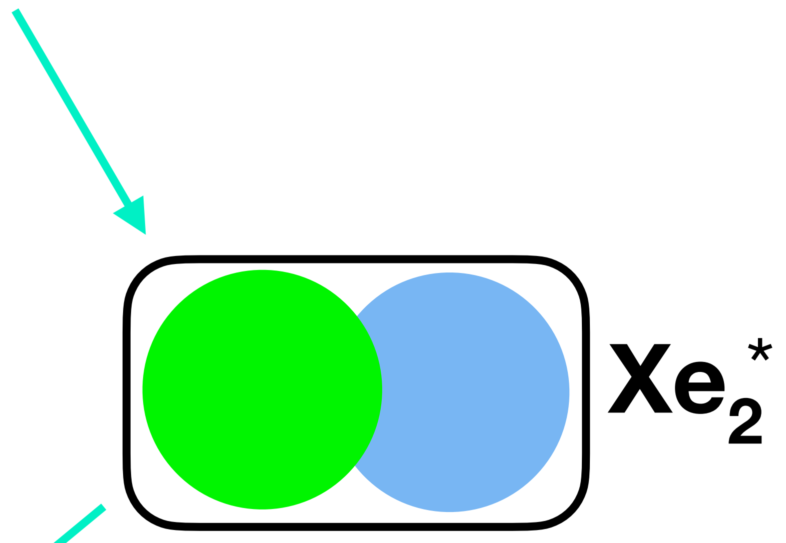

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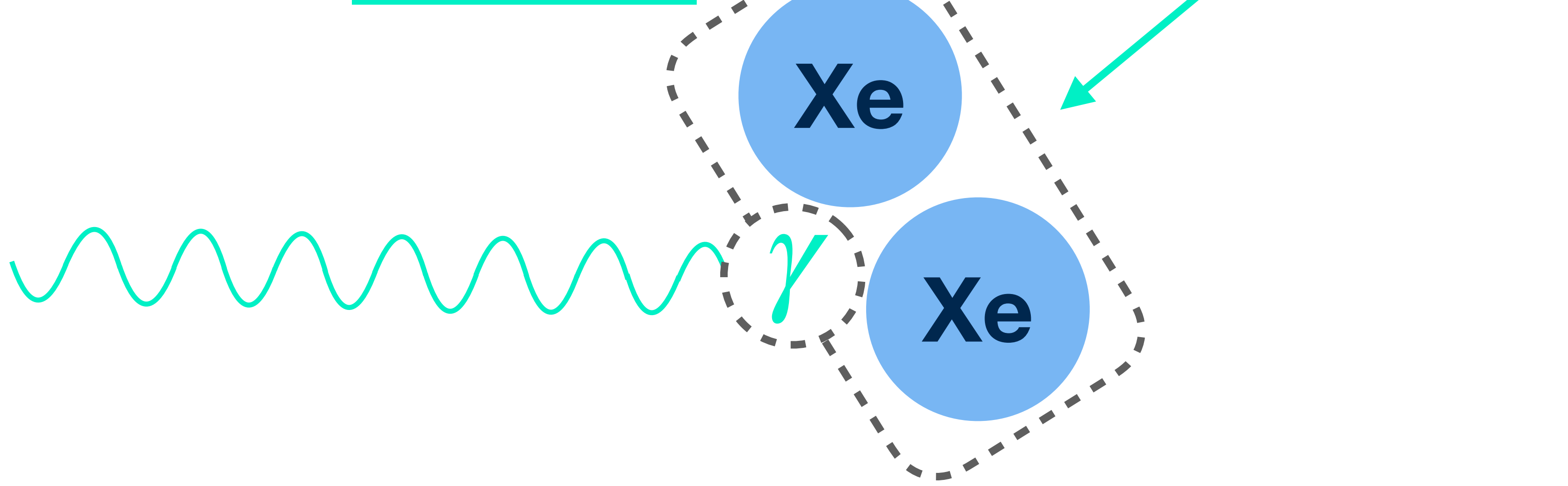
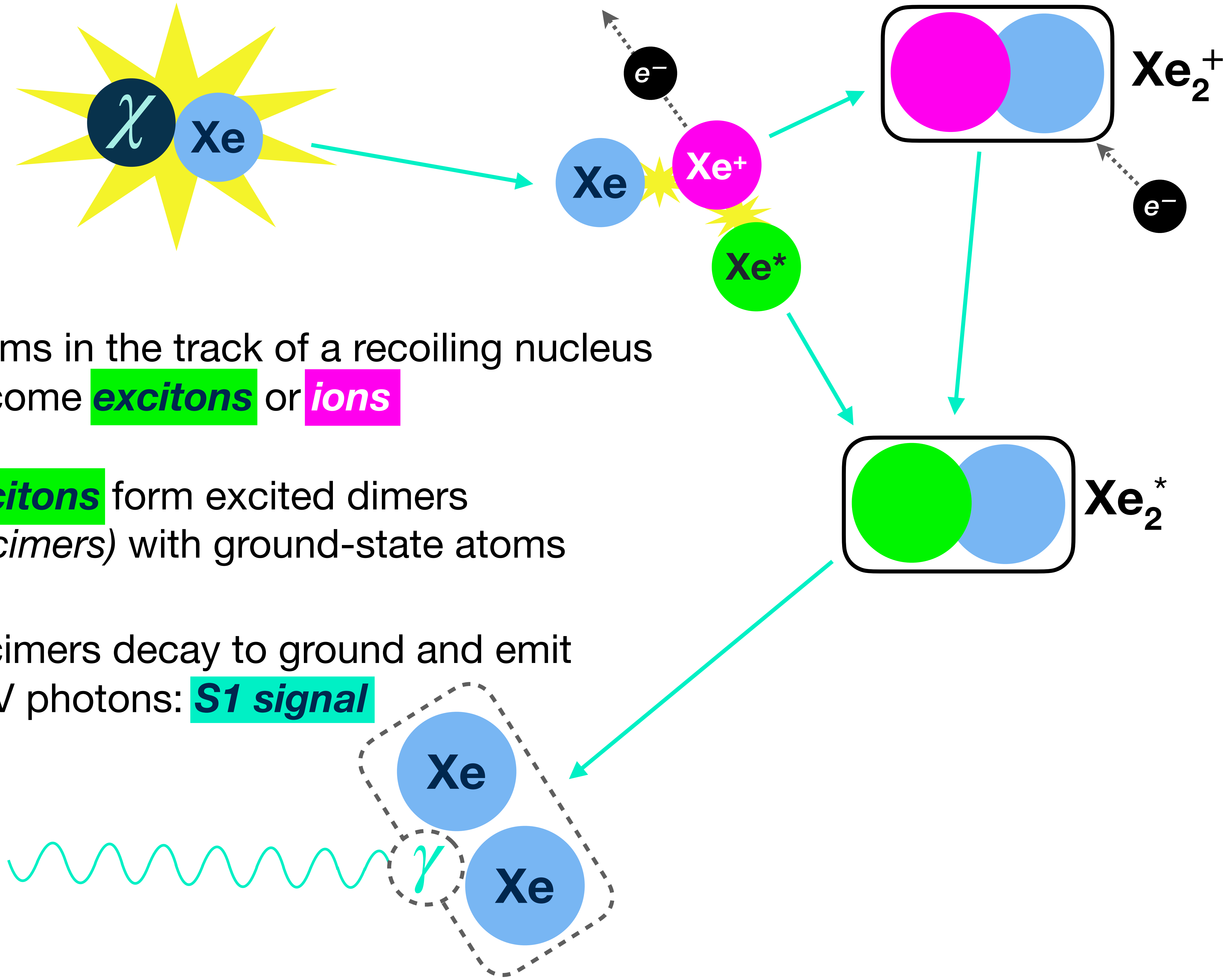
Excimers decay to ground and emit VUV photons: ***S1 signal***



Xenon Microphysics

Ions form charged dimers, can recombine to become excimers



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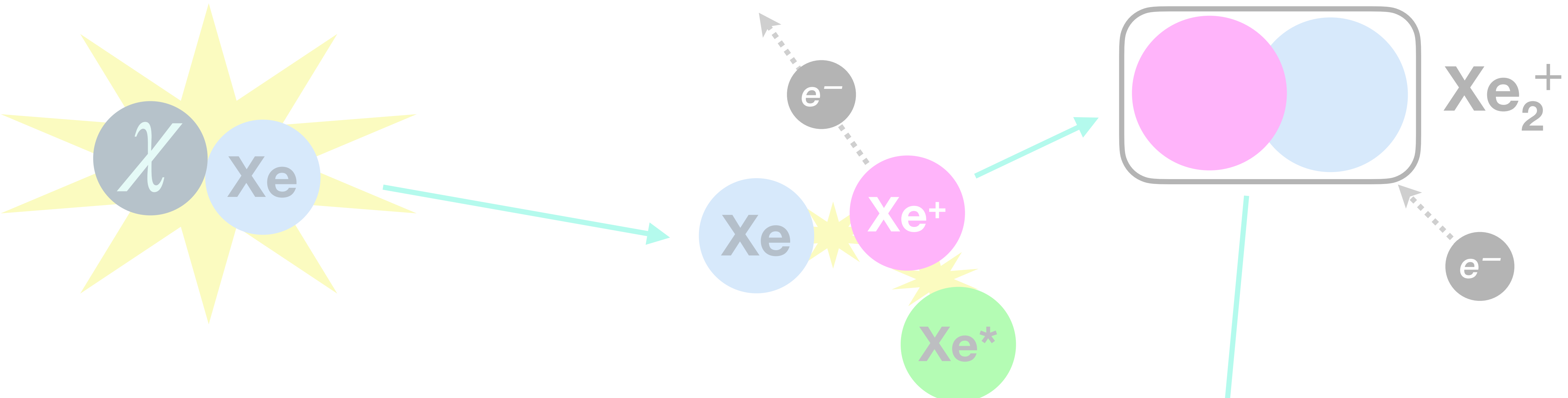

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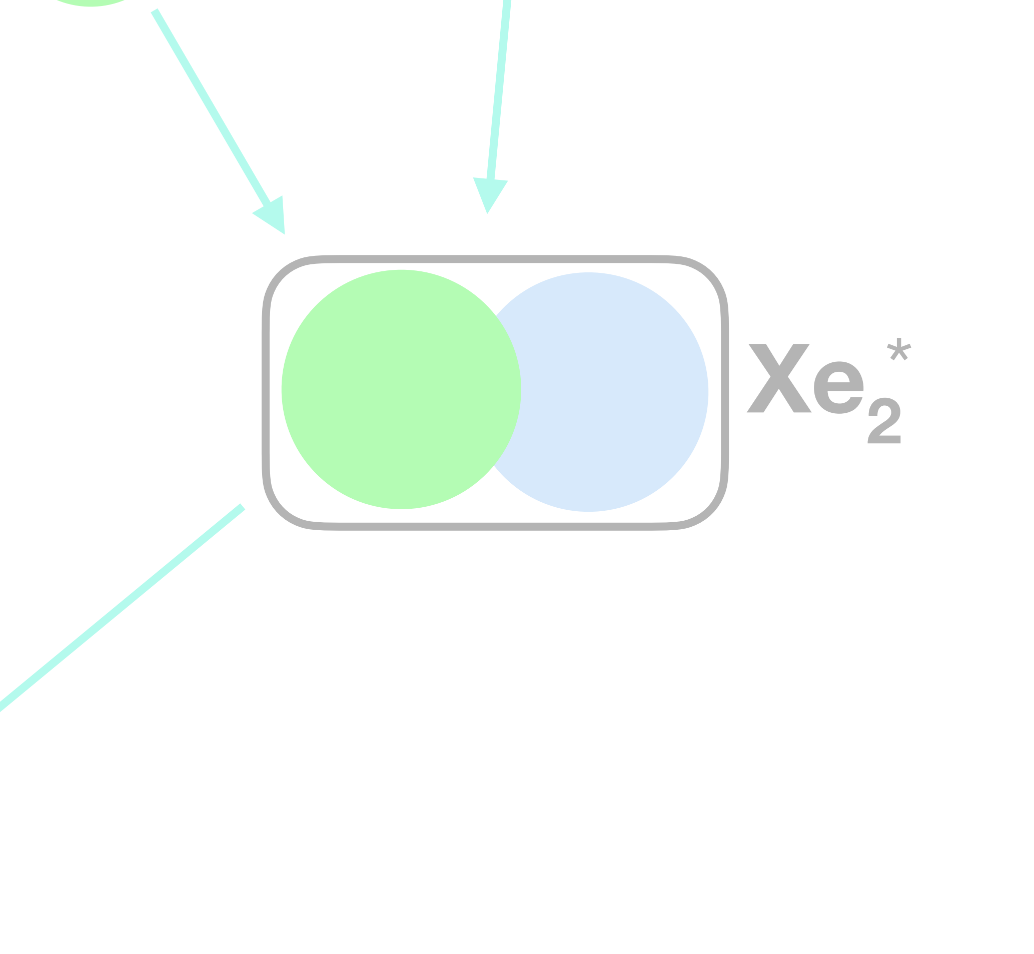

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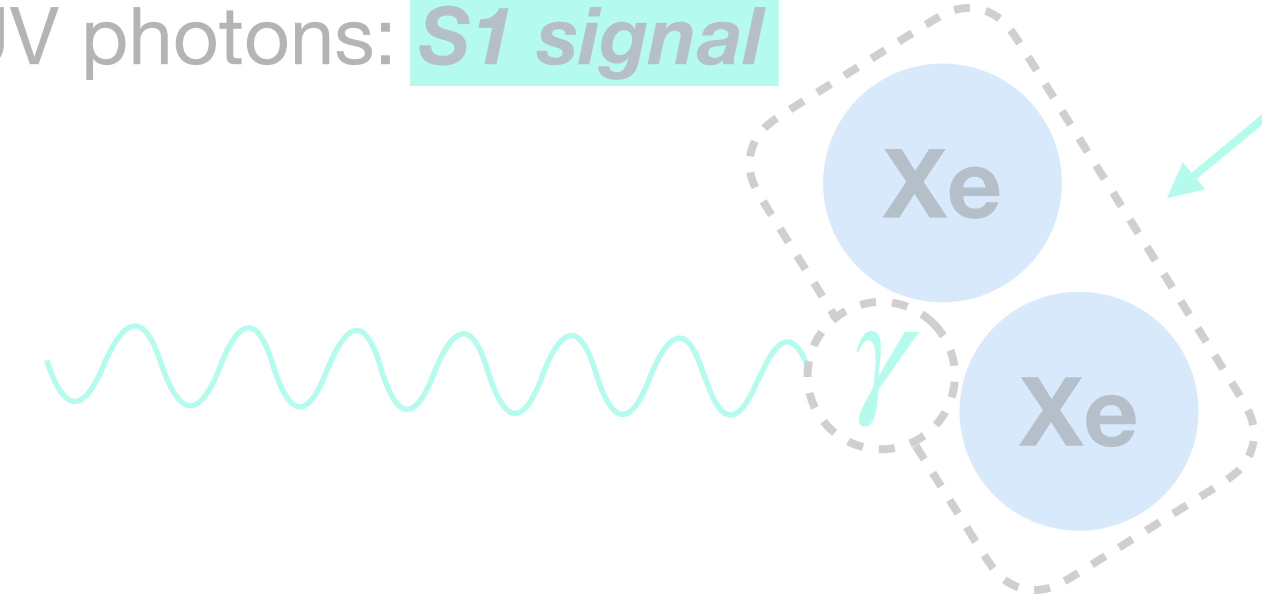
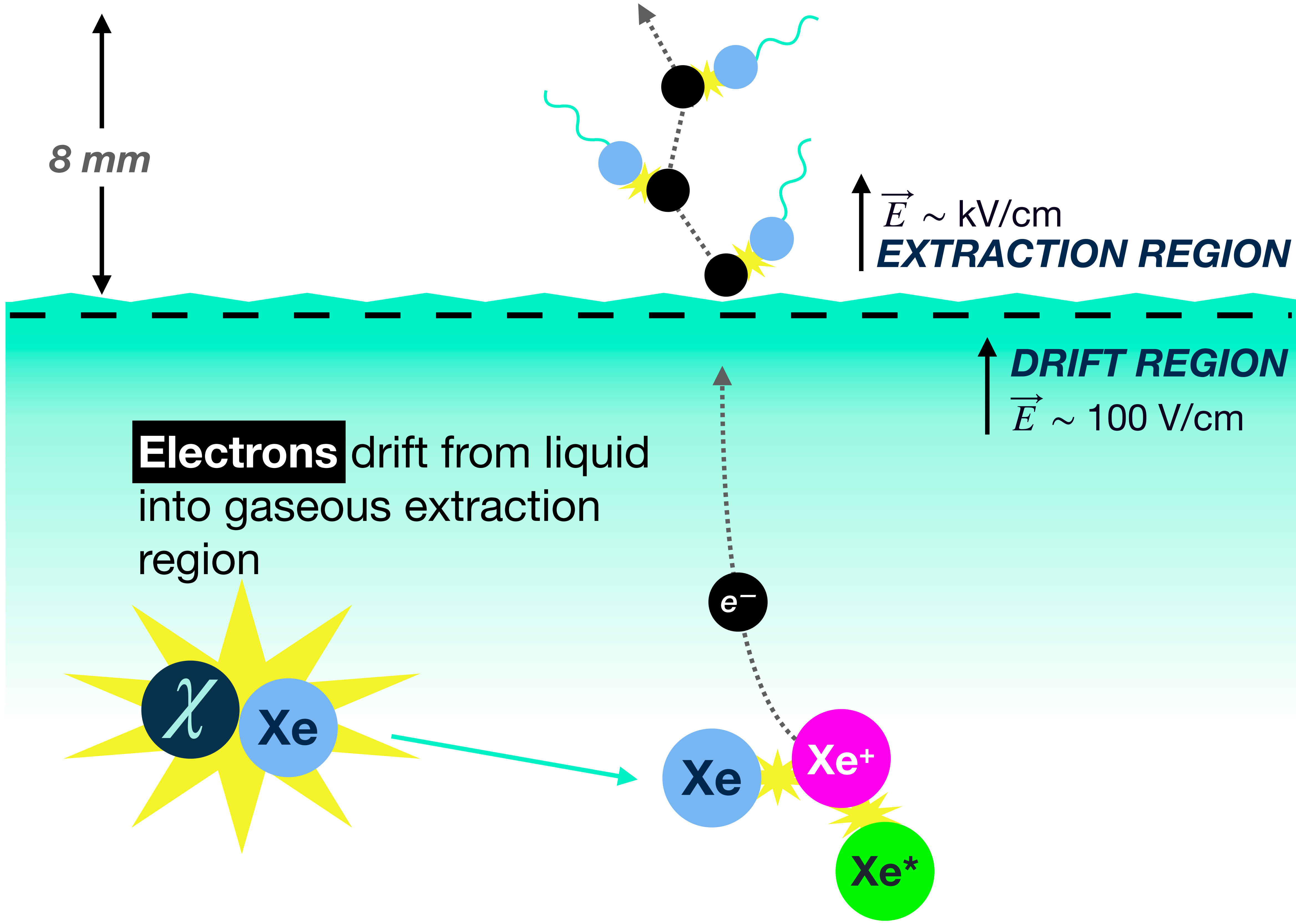




Electroluminescence makes secondary VUV photons in gas phase: ***S2 signal***

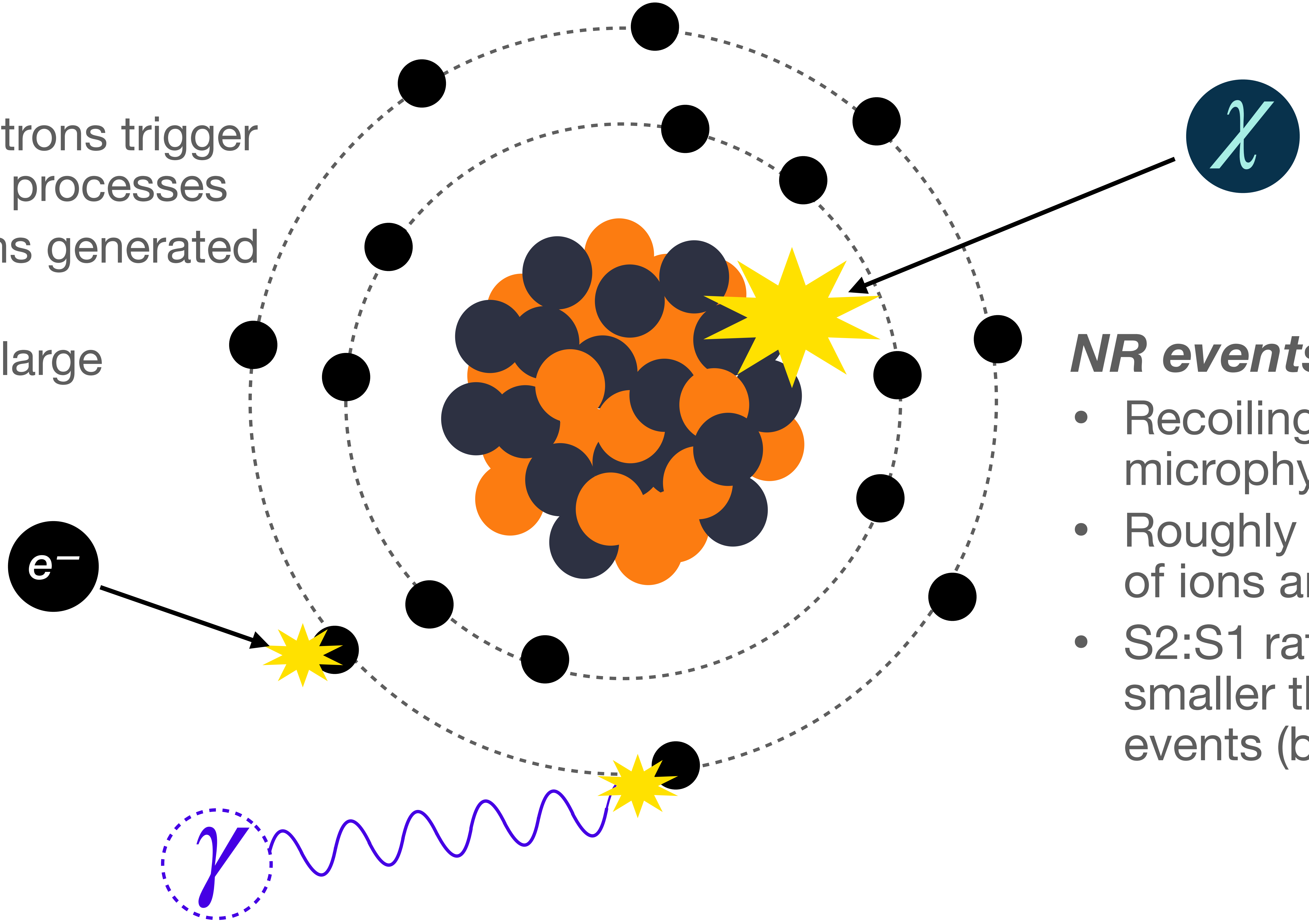
One event comprises an (S1, S2) pair

joseph.mclaughlin@stfc.ac.uk

Xenon Microphysics

ER events

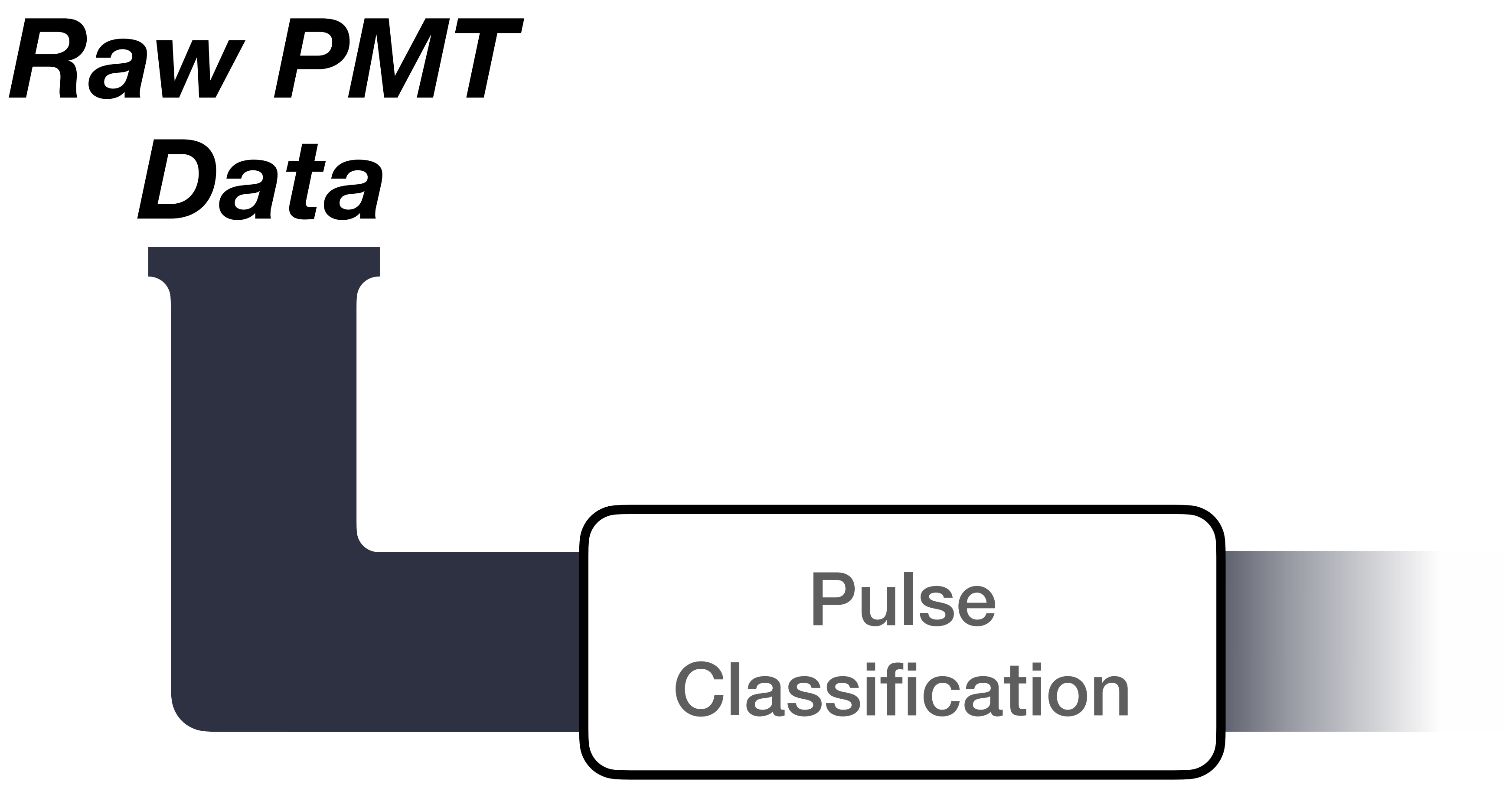
- Recoiling electrons trigger microphysical processes
- ~20x more ions generated over excitons
- S2:S1 ratio is large



NR events

- Recoiling nuclei trigger microphysical processes
- Roughly equal numbers of ions and excitons
- S2:S1 ratio is measurably smaller than for ER events (but still large)

The Analysis Pipeline



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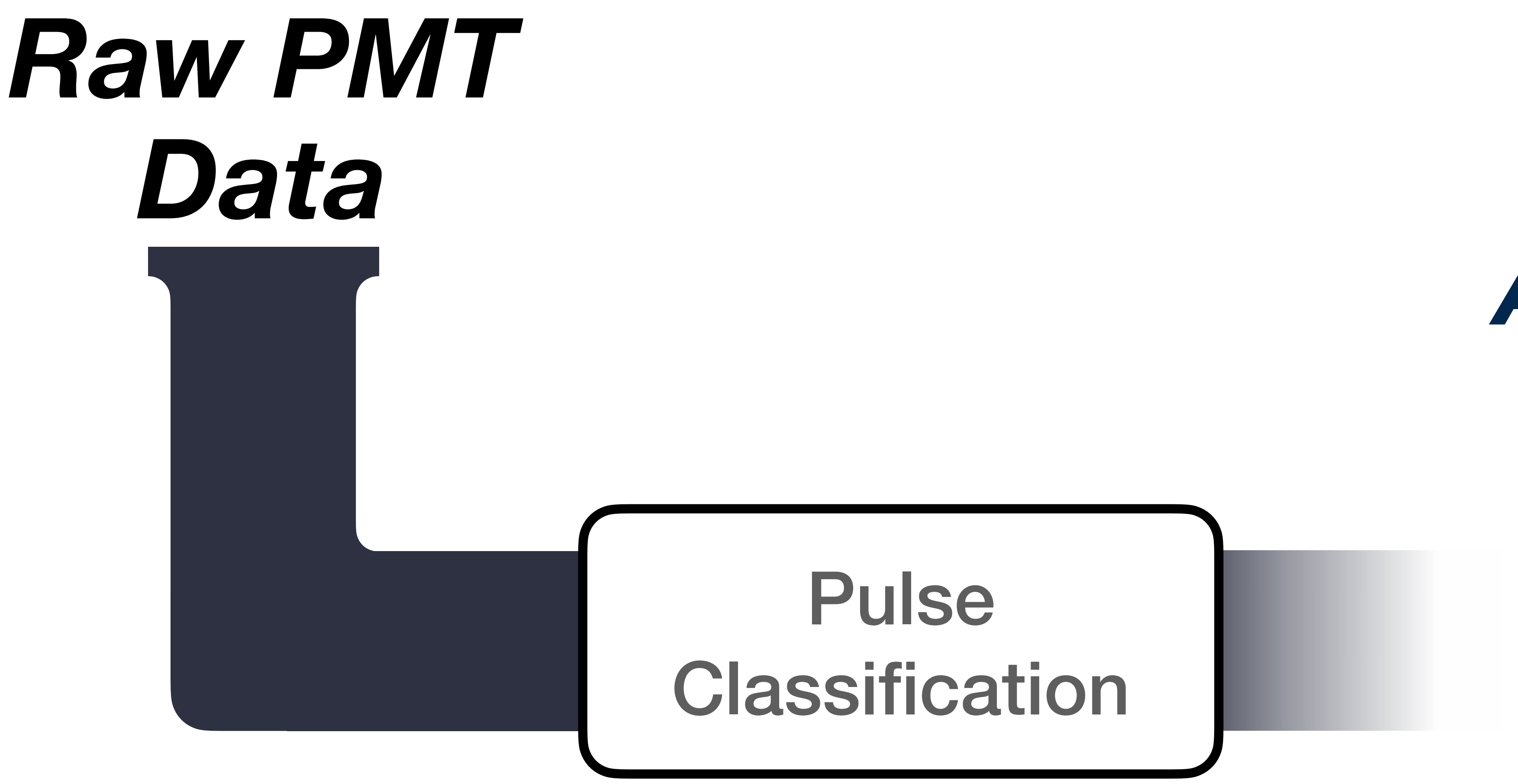

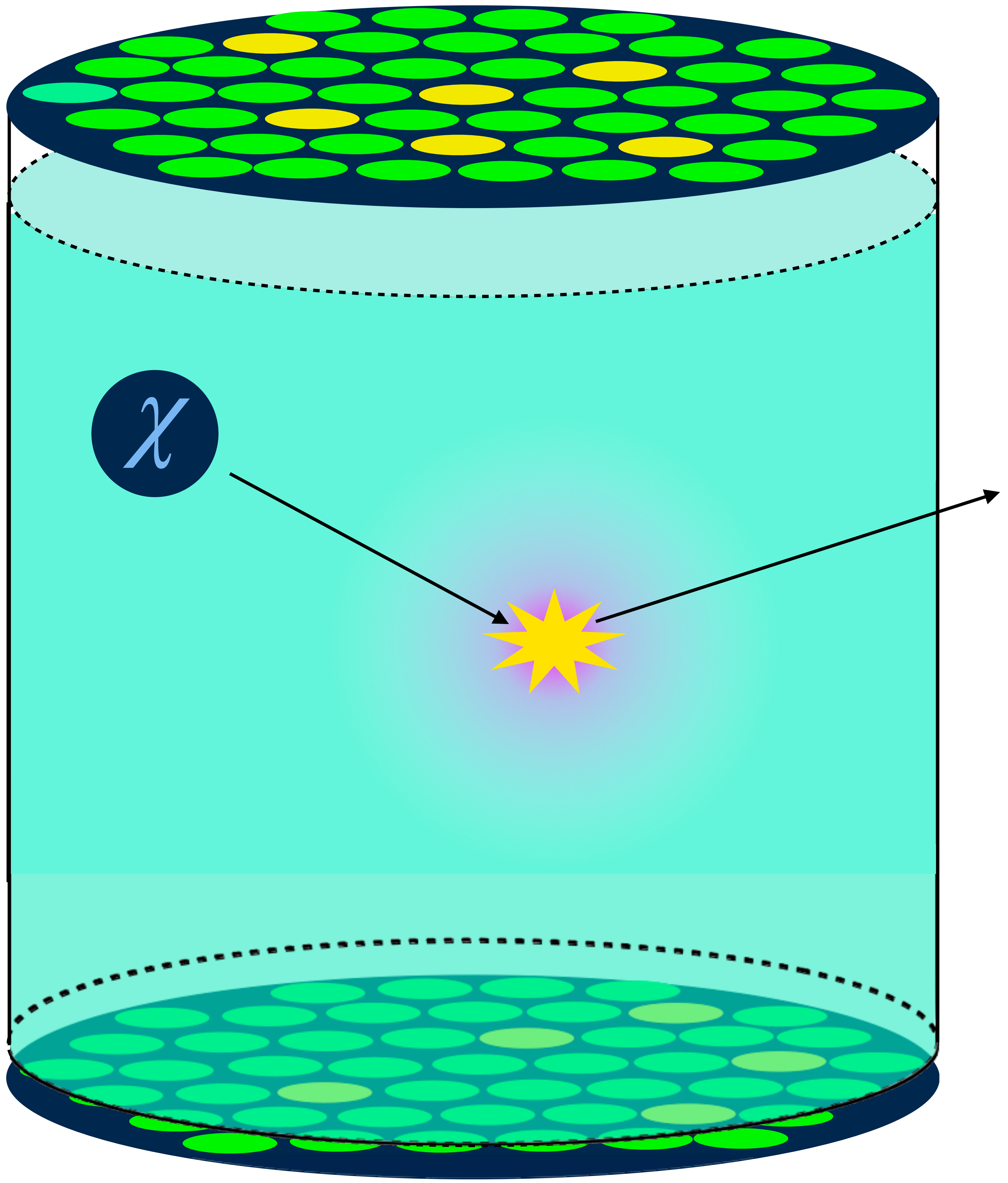

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  - only counts if seen in at least 3 PMTs simultaneously

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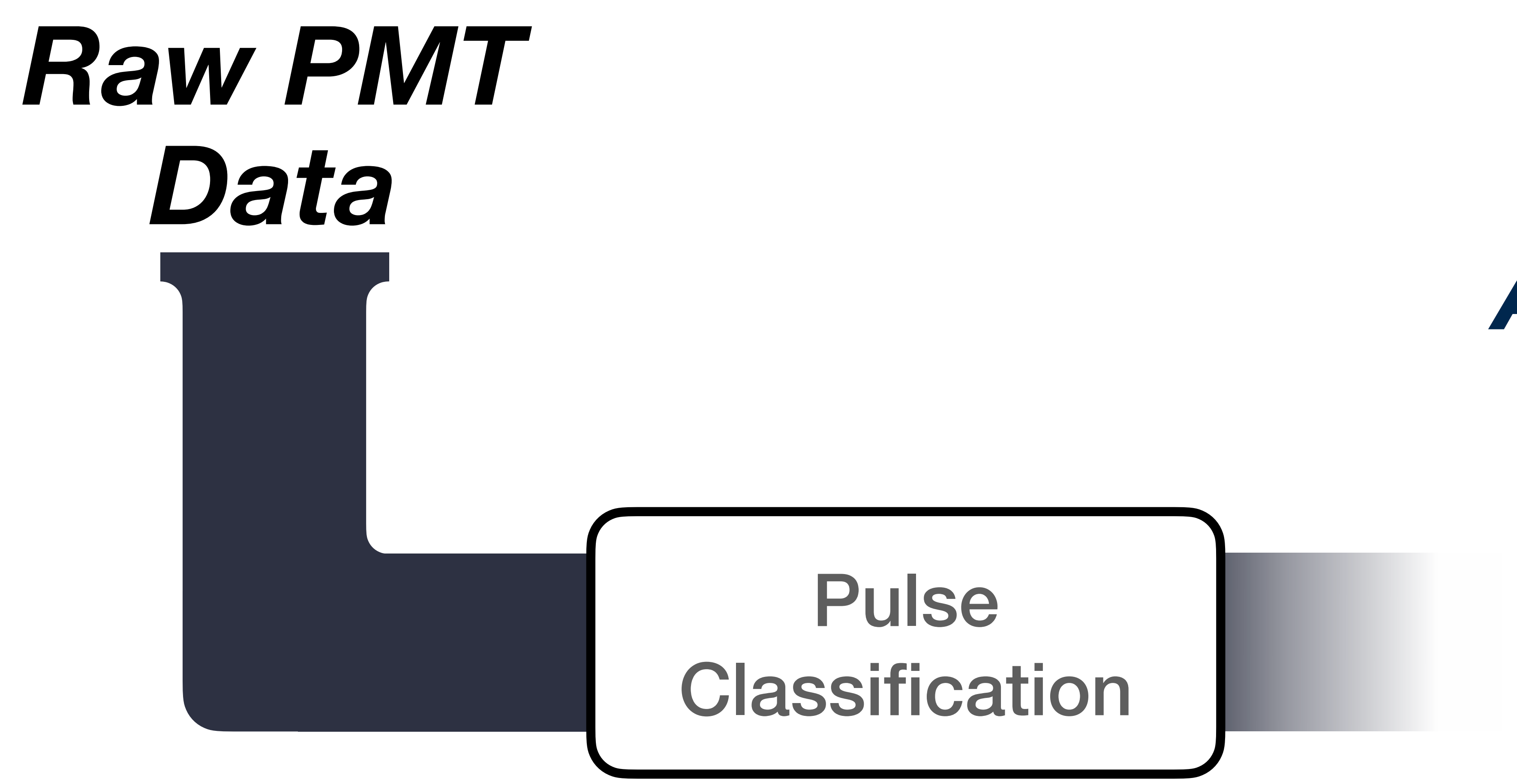
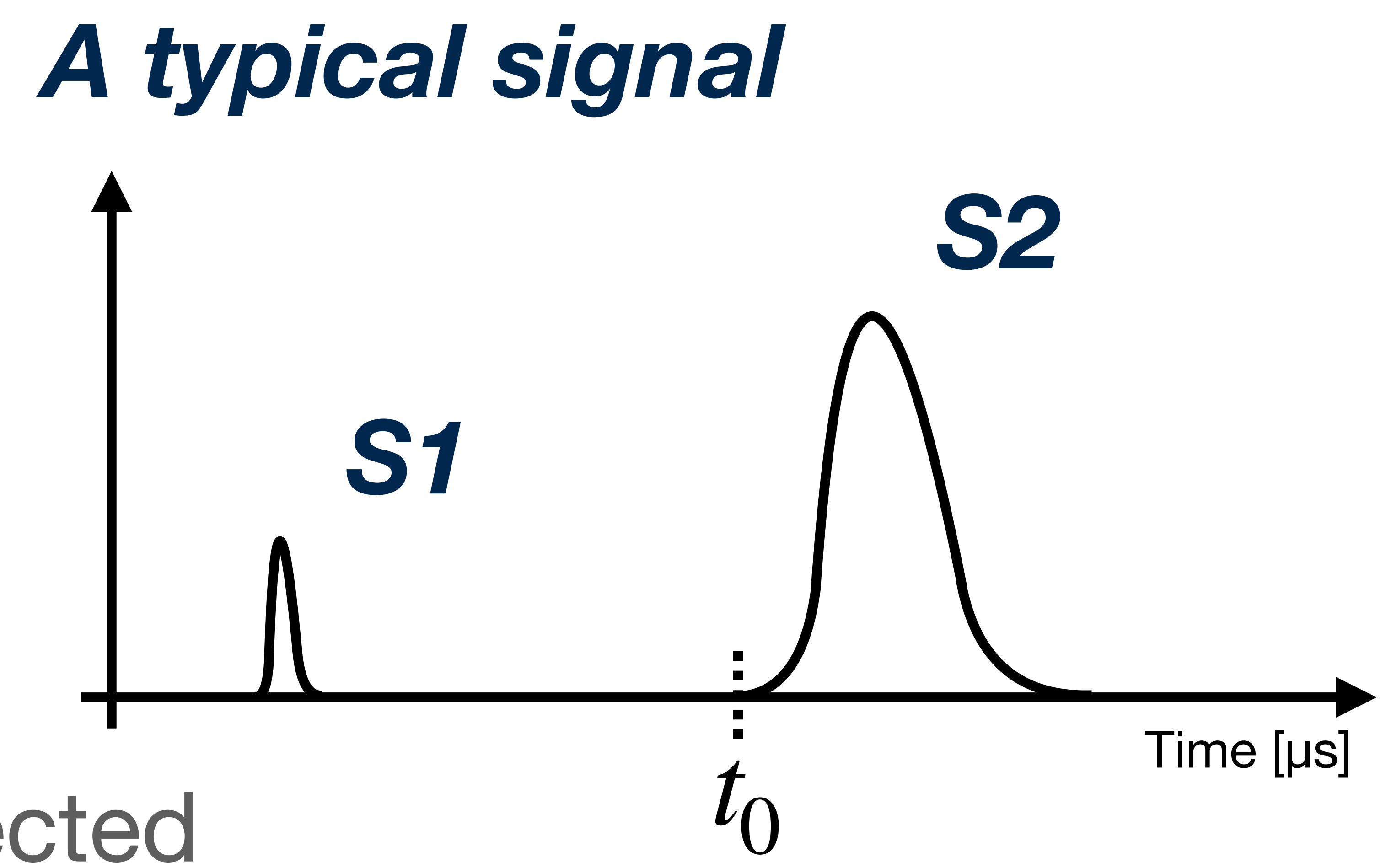
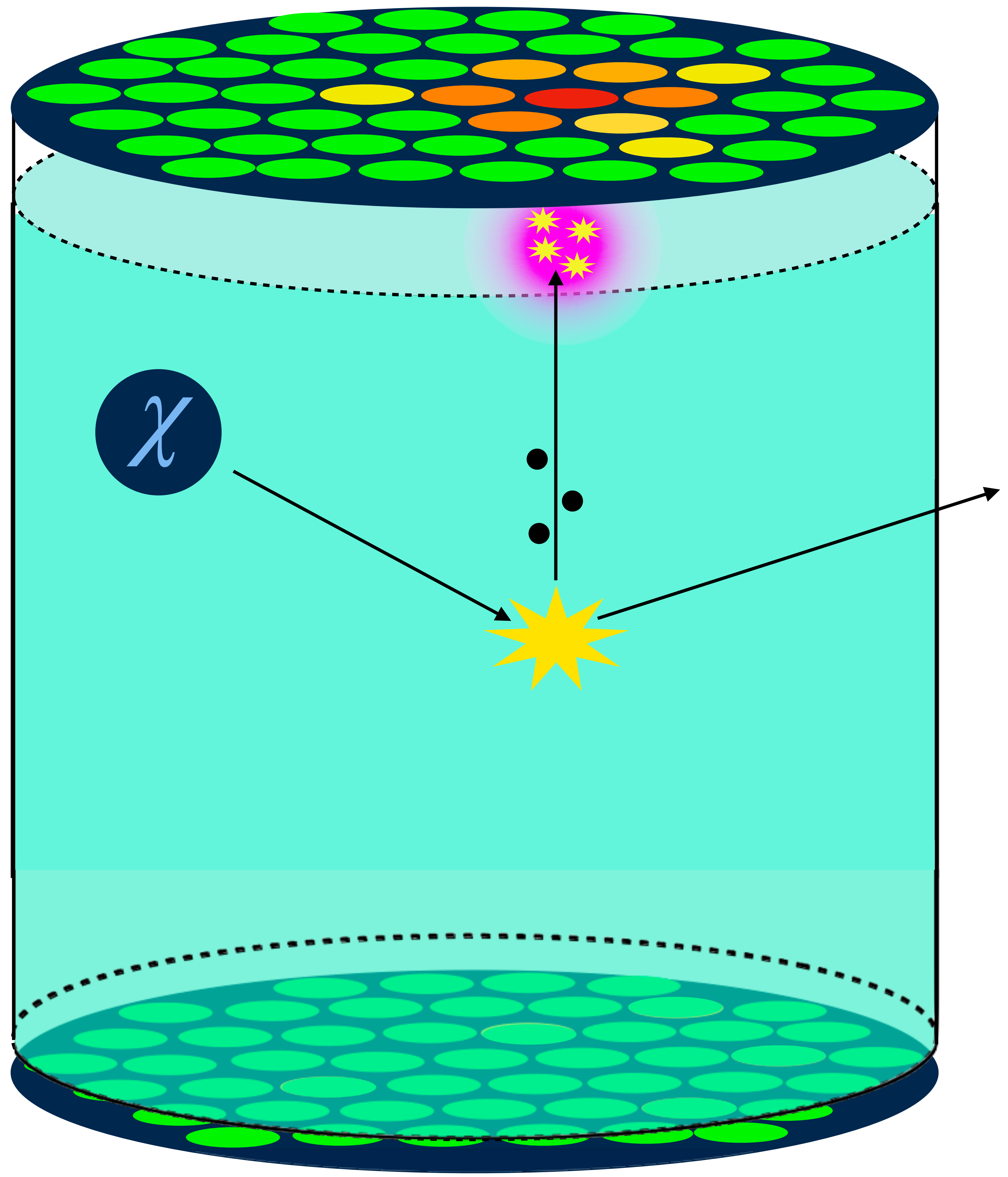




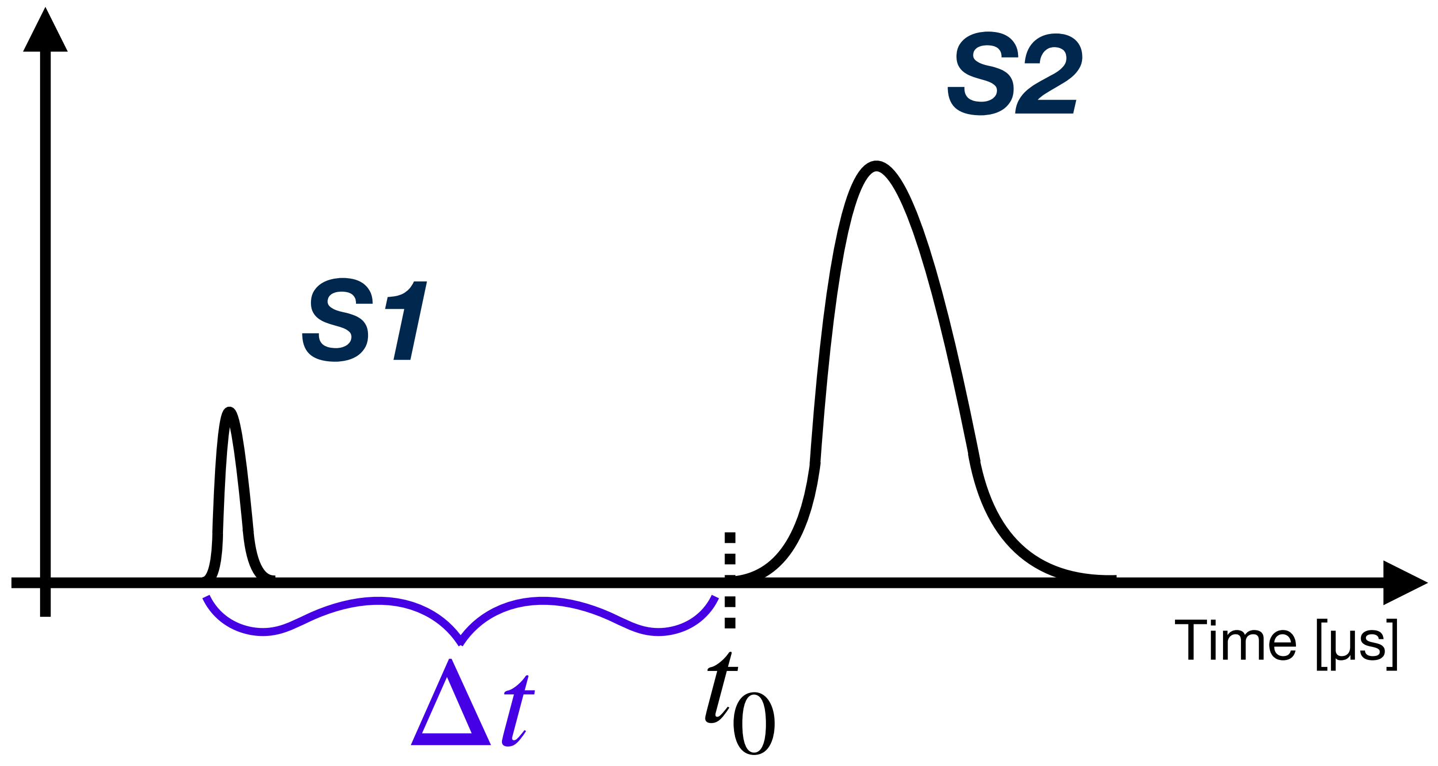


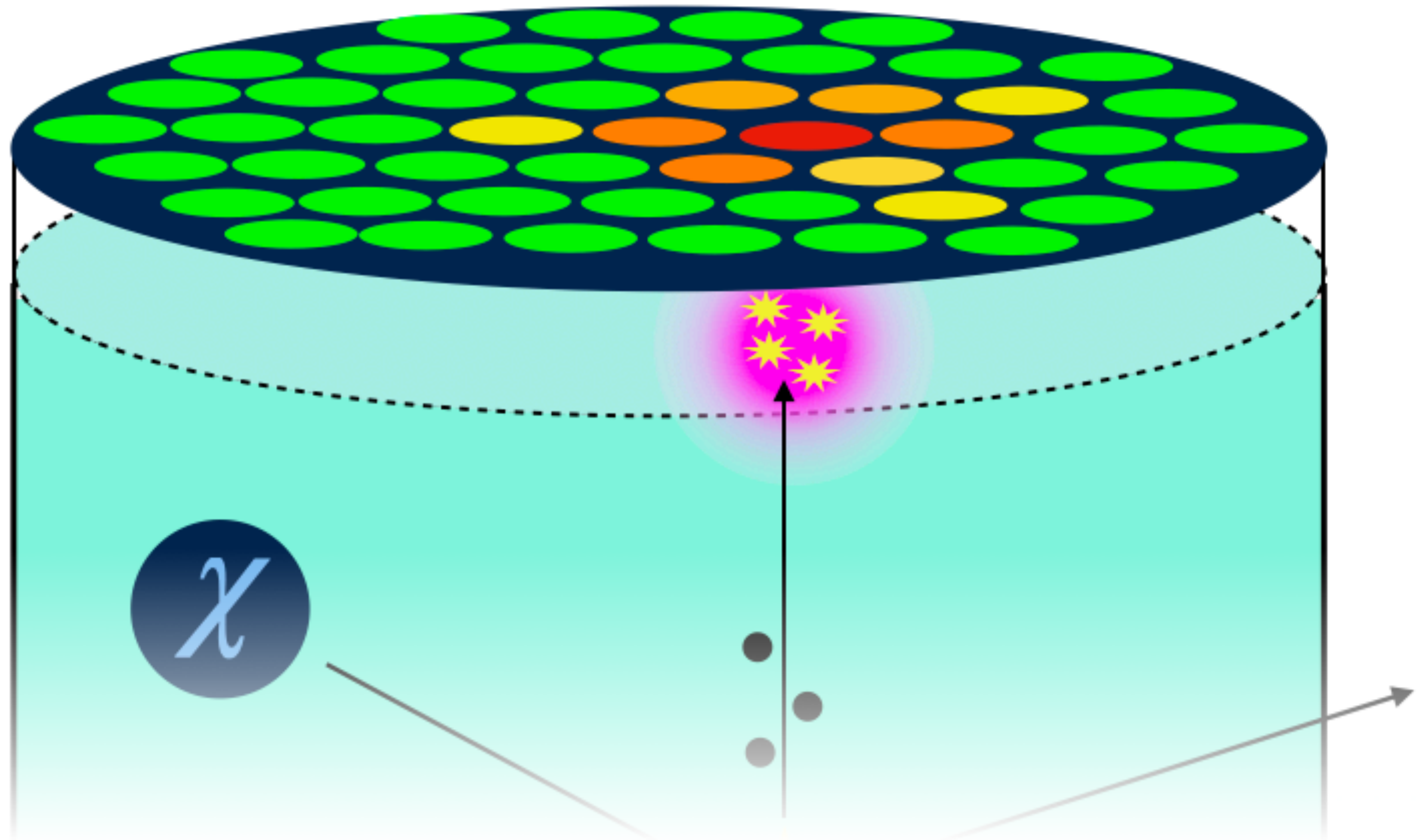
- S1 signal is isotropic and detected almost immediately
  - only counts if seen in at least 3 PMTs simultaneously
- S2 signal concentrated in small cluster of PMTs in top array
  - used as event trigger
  - optimised for 3.5 extracted electrons

The Analysis Pipeline

- Time delay Δt between S1 and S2 pulses is a measure of electron drift time
  - Gives event z coordinate

A typical signal





The Analysis Pipeline

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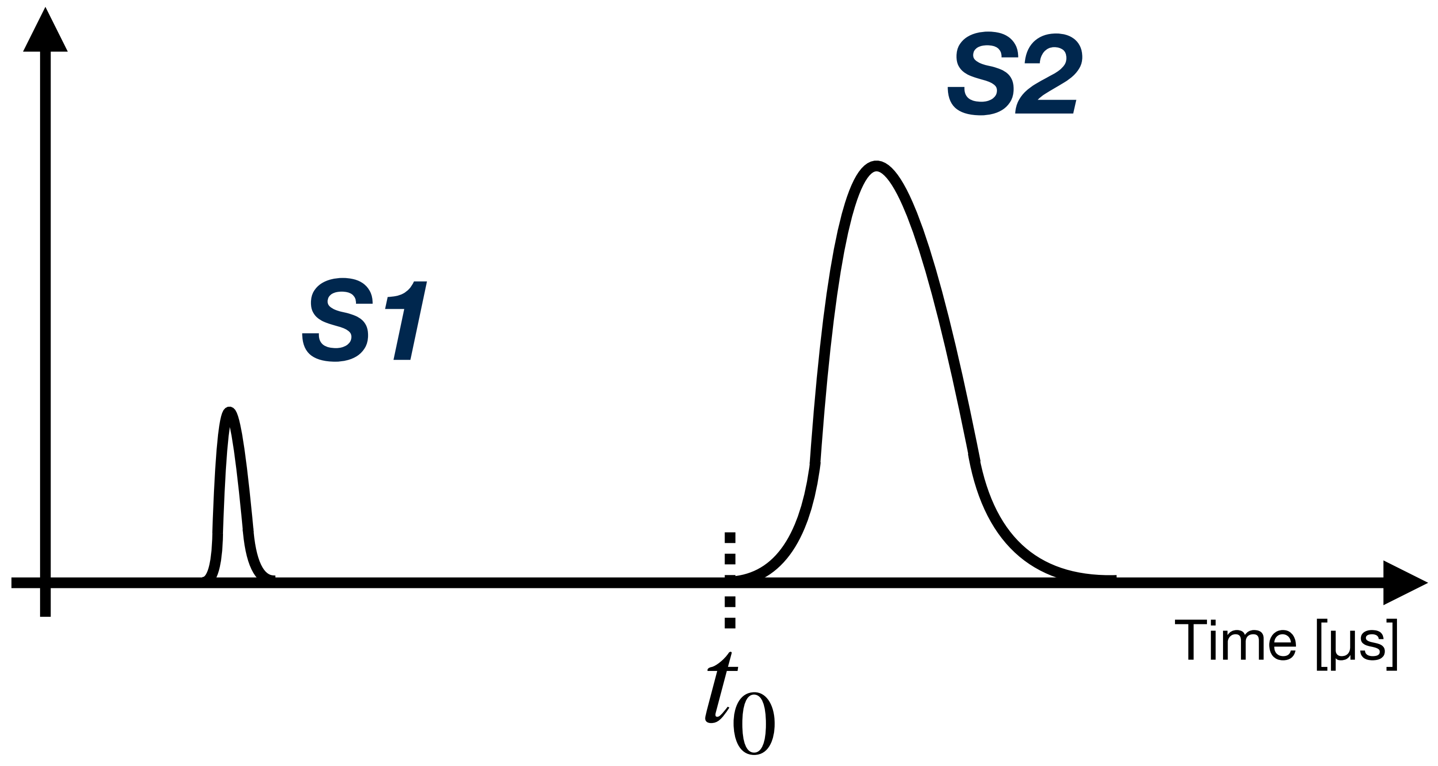
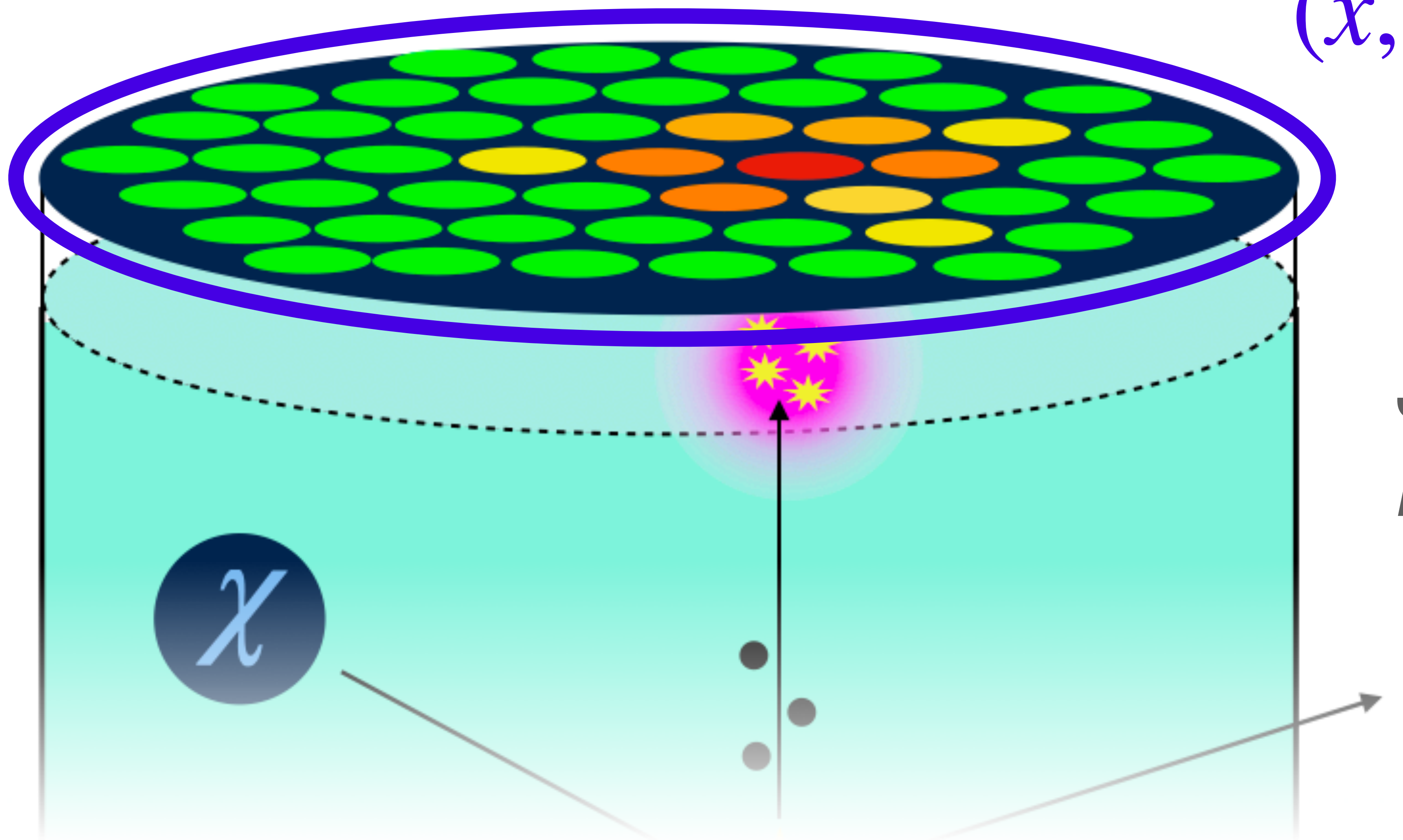


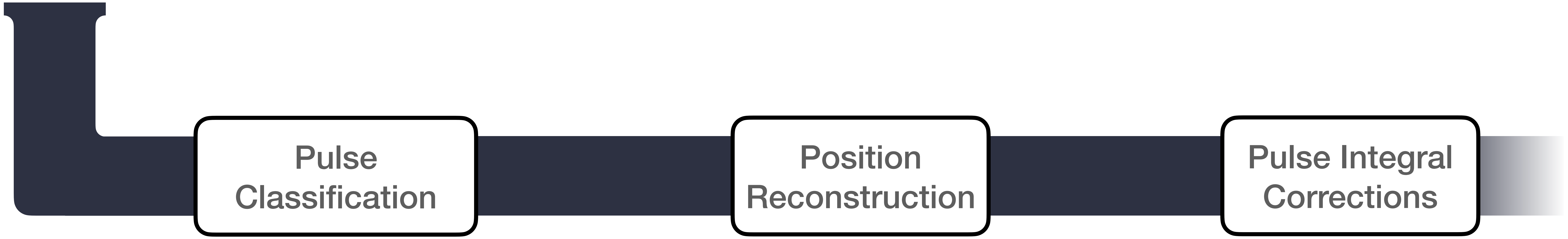


- Time delay Δt between S1 and S2 pulses is a measure of electron drift time
  - Gives event z coordinate
- Clustering of PMT signals from S2 pulse is used to determine (x, y) coordinate

3D position reconstruction resolution ~mm

The Analysis Pipeline

Raw PMT Data



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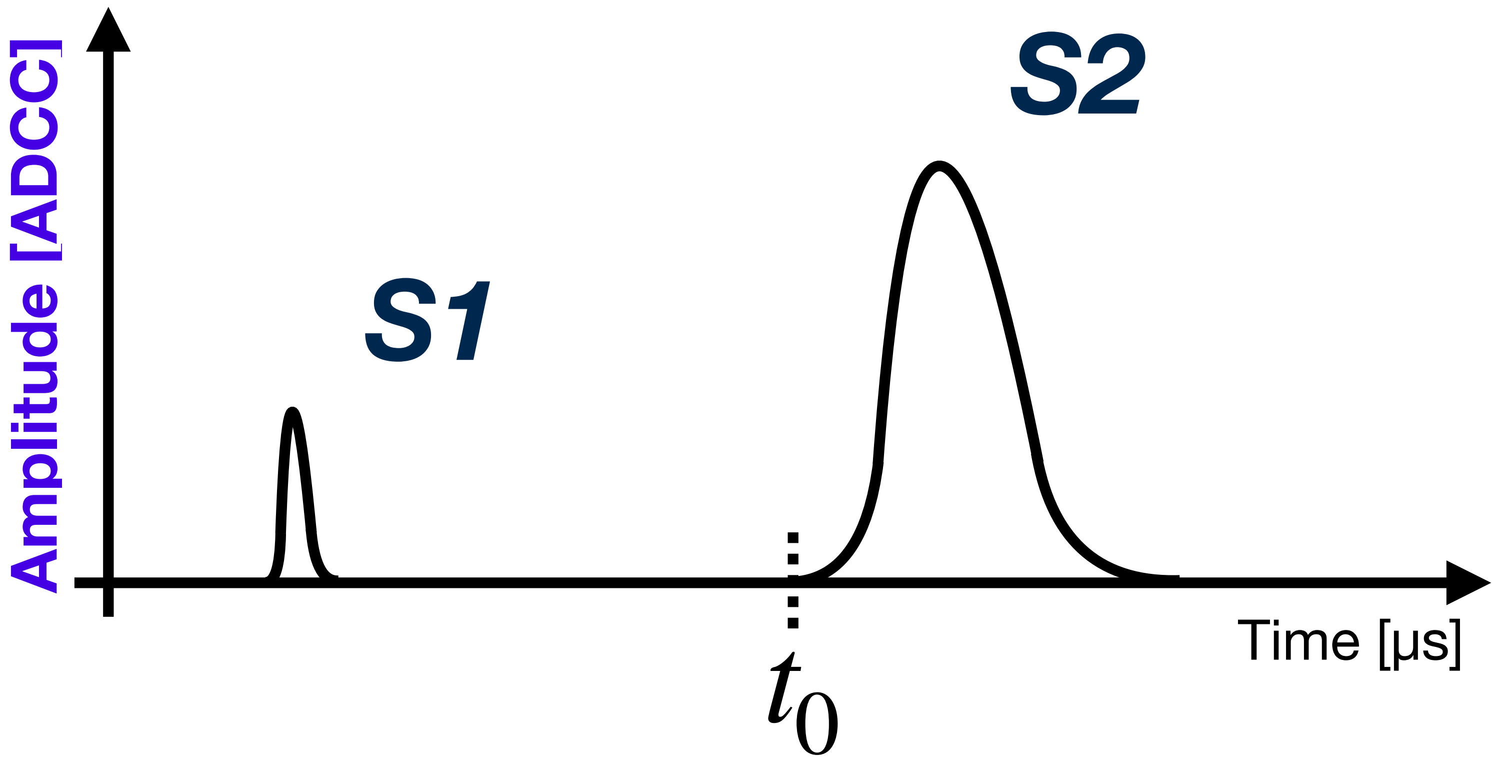

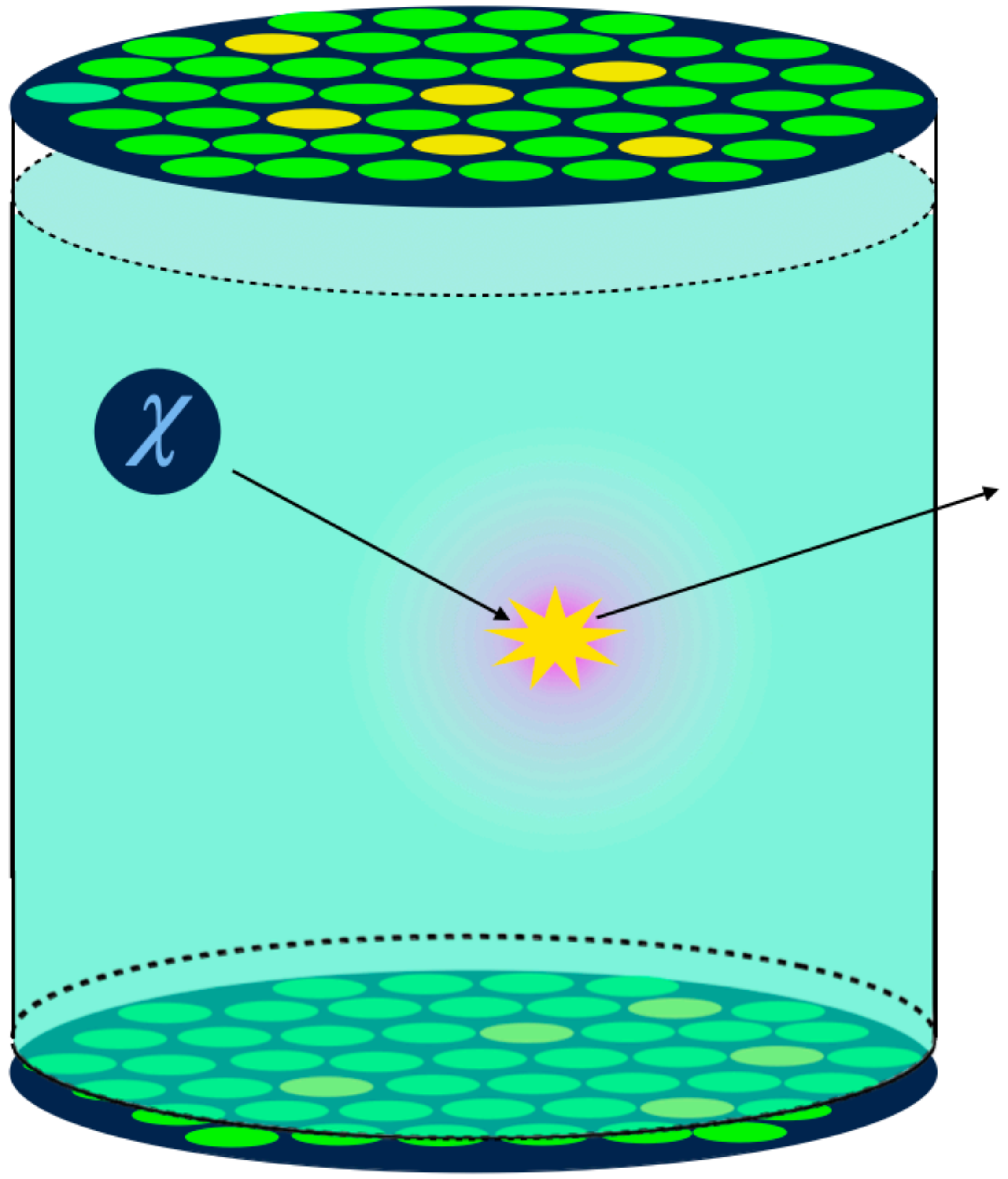

- Pulse integrals are measured in Analog-to-Digital Converted Counts (ADCC)
  - Normalised to pulse integral of single photoelectron (phe)
  - Corrected for double phe effect to get photons detected (phd)

The Analysis Pipeline

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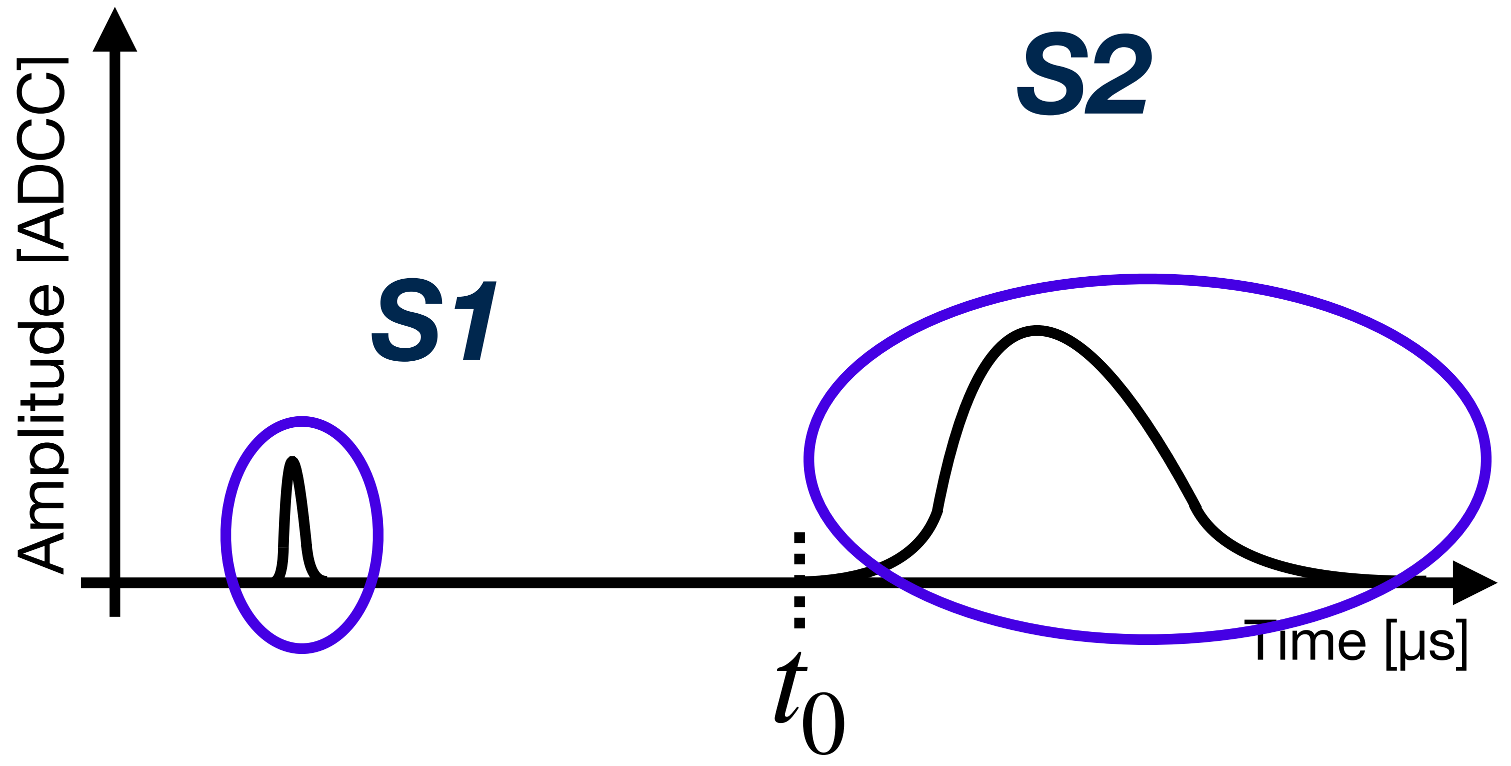

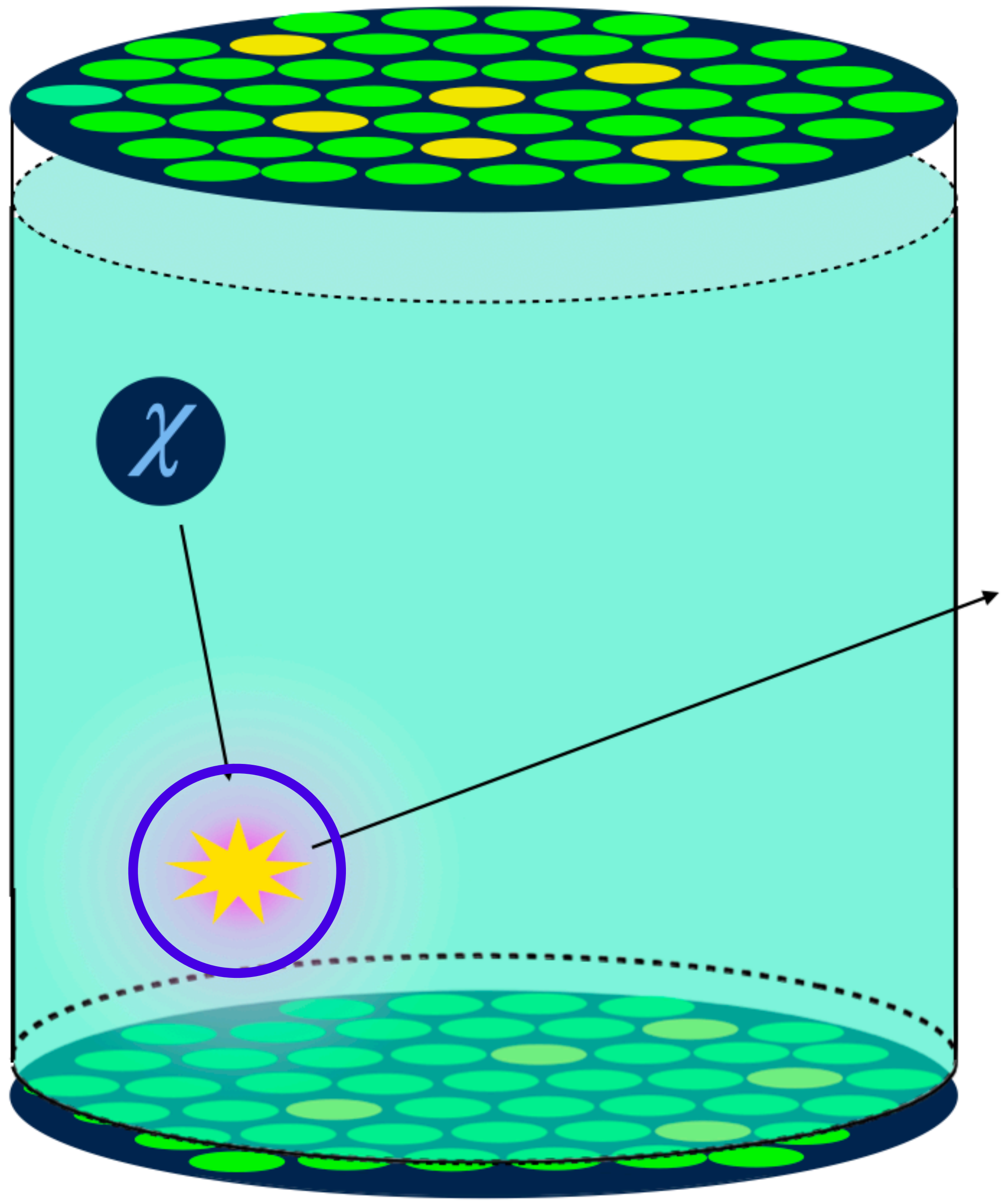

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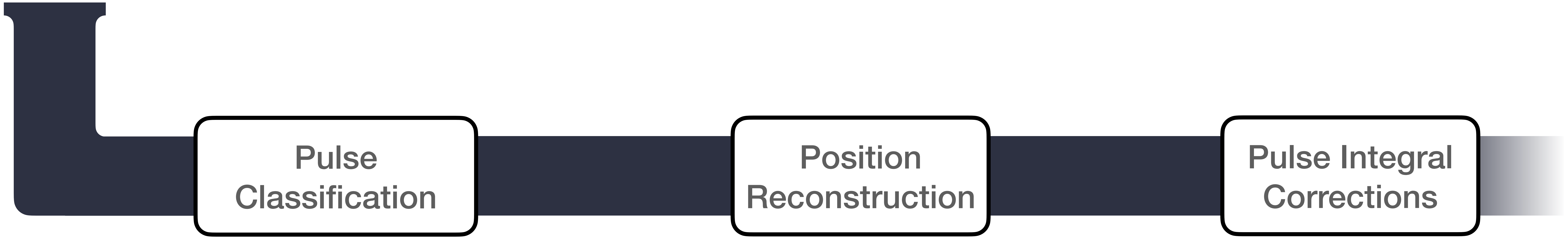
  - S1 normalised to centre of detector
  - S2 normalised to centre of liquid surface

The Analysis Pipeline

Raw PMT Data



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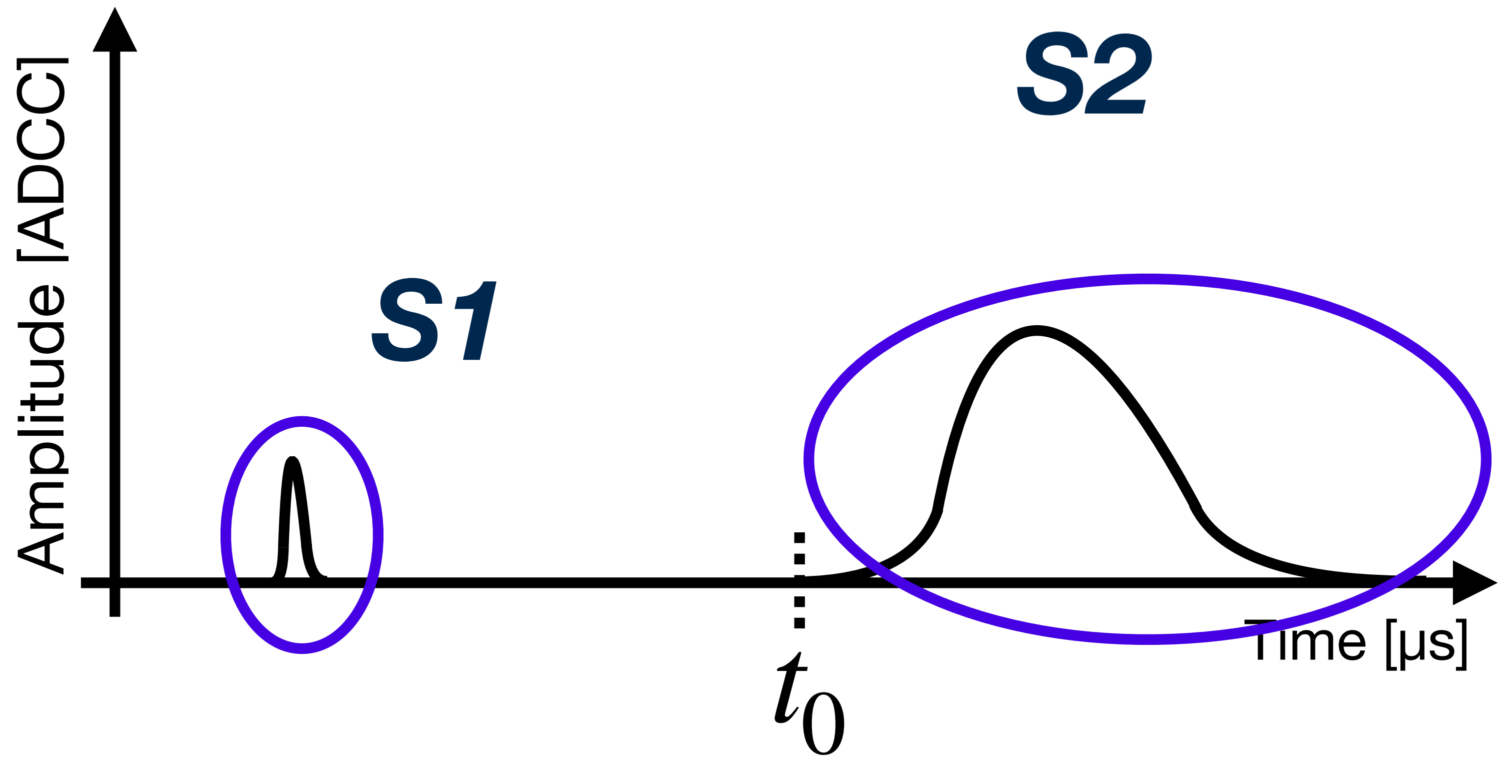
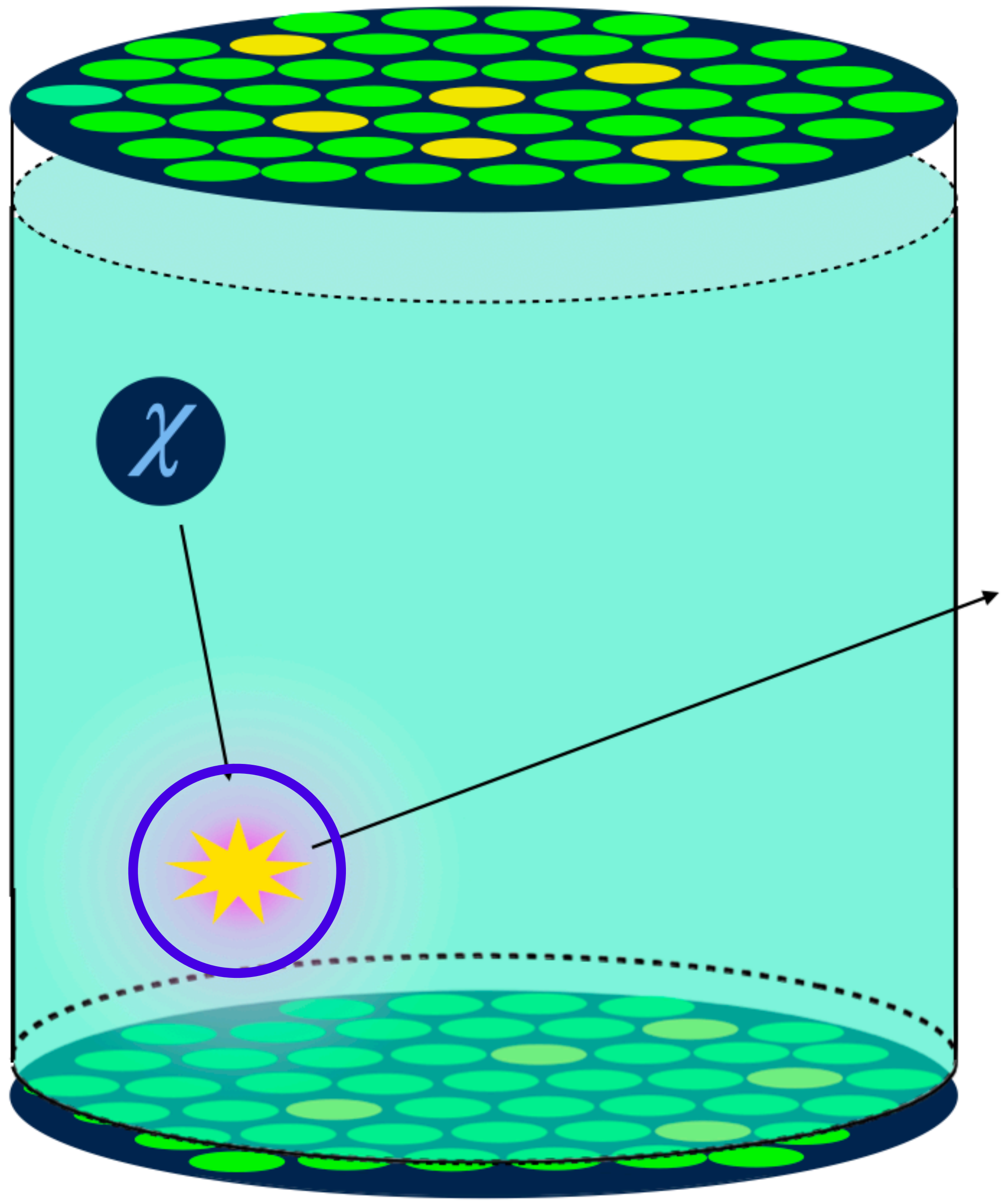


$$S1, S2 \rightarrow S1_C, S2_C$$



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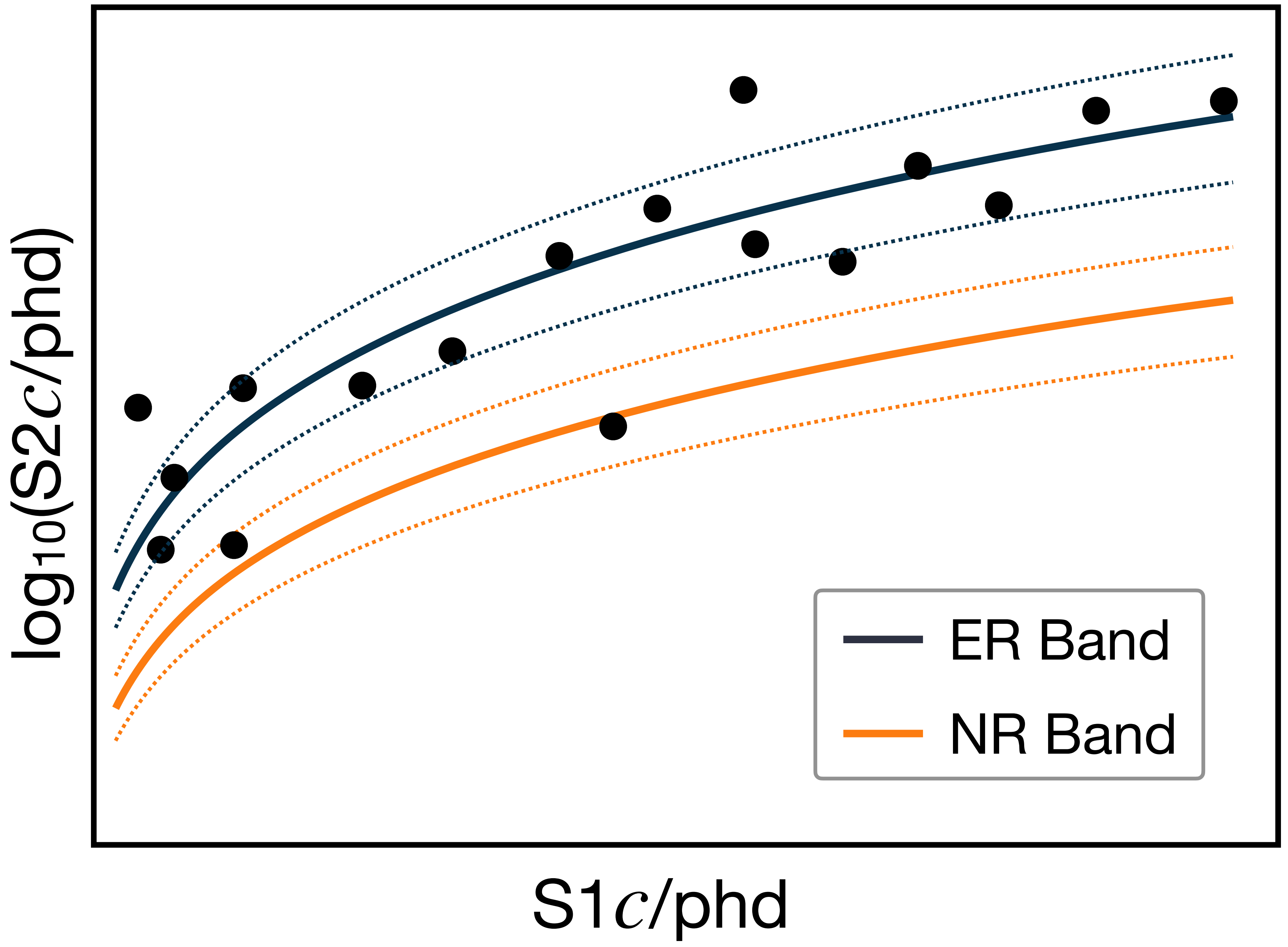
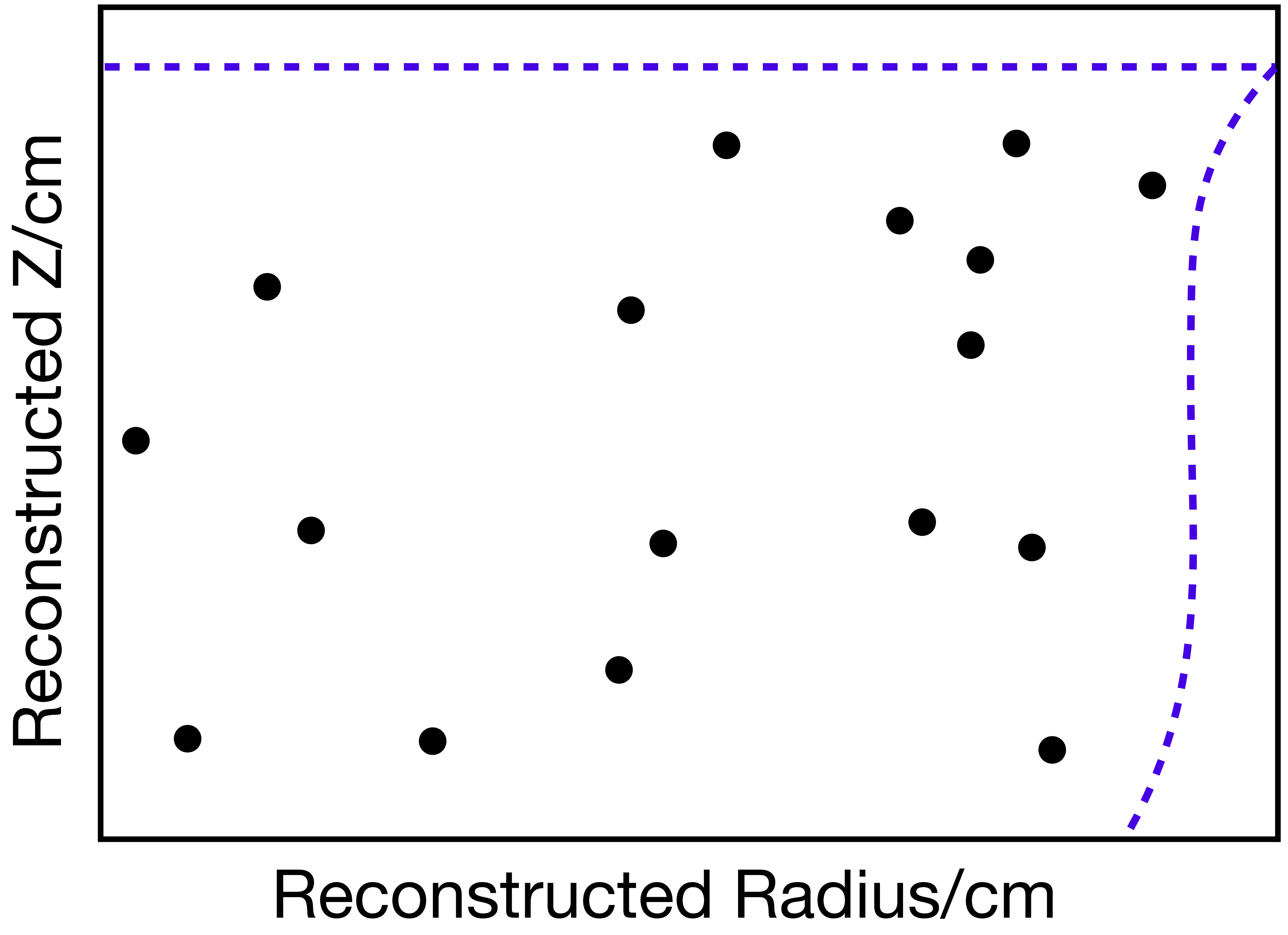
Raw PMT Data

EVENT RECONSTRUCTION



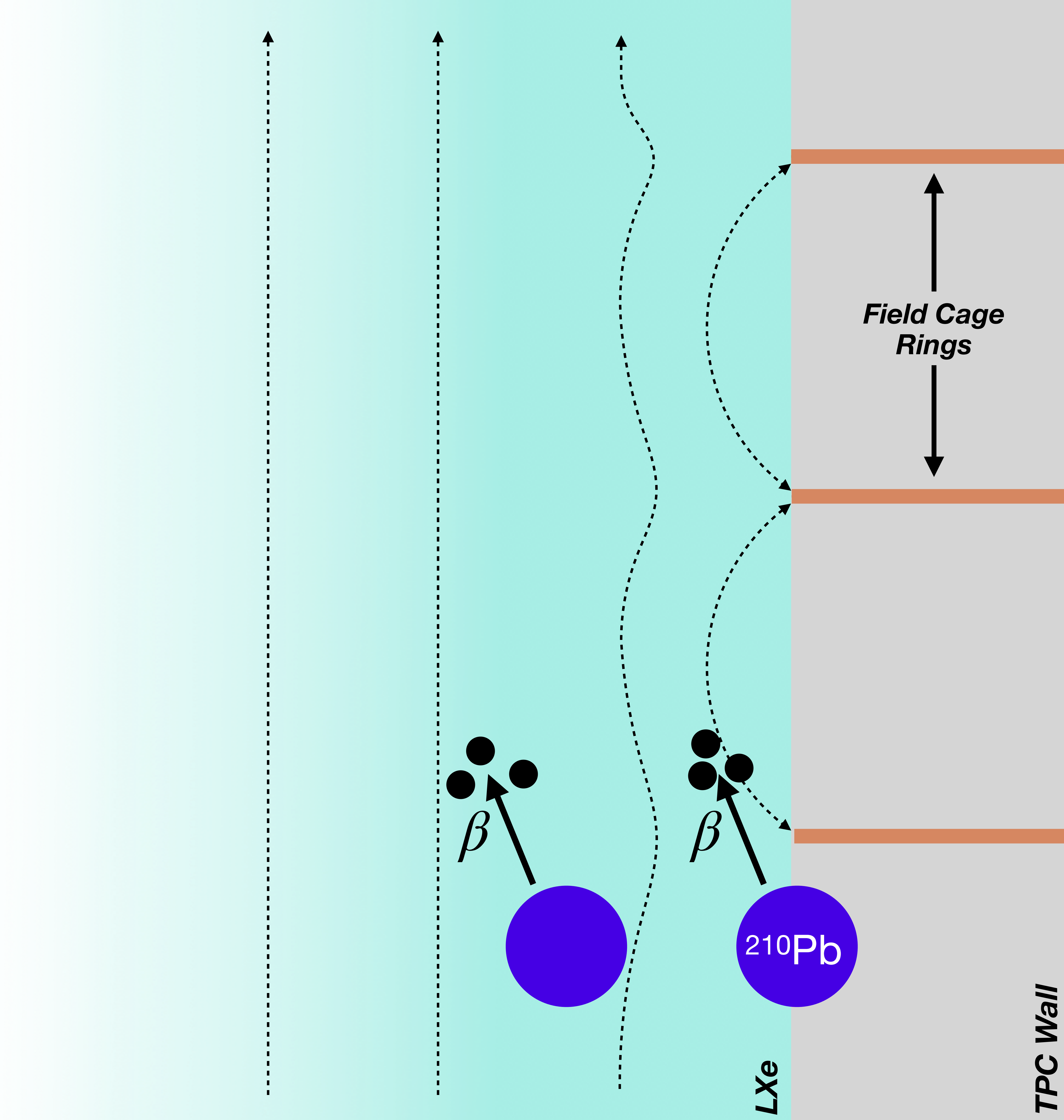


The Analysis Pipeline

Fiducialisation

Wall Backgrounds

- Physics at the wall is highly complicated due to drift field non-uniformities



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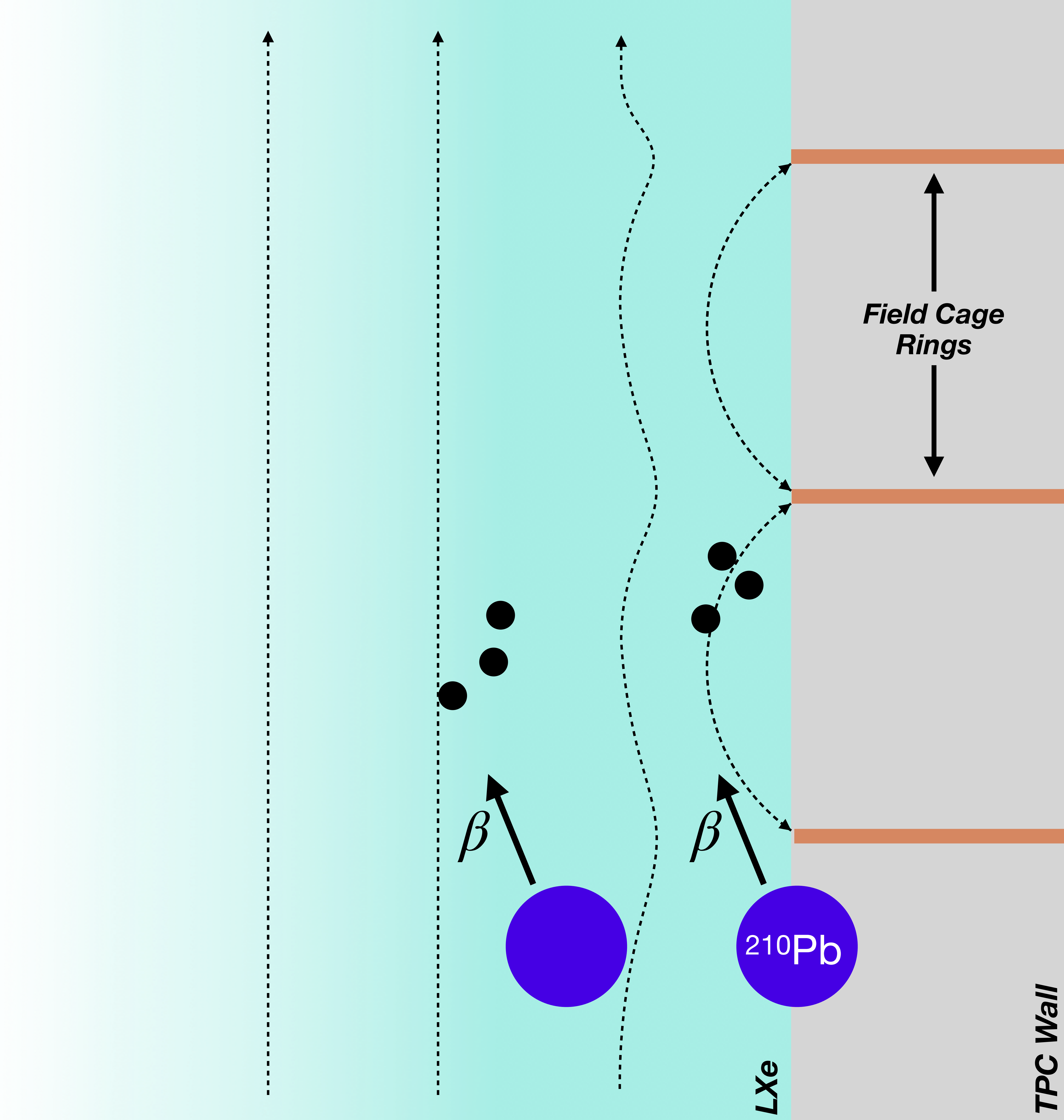
- Ionisation electrons at or near the wall drift towards and get trapped at field cage rings



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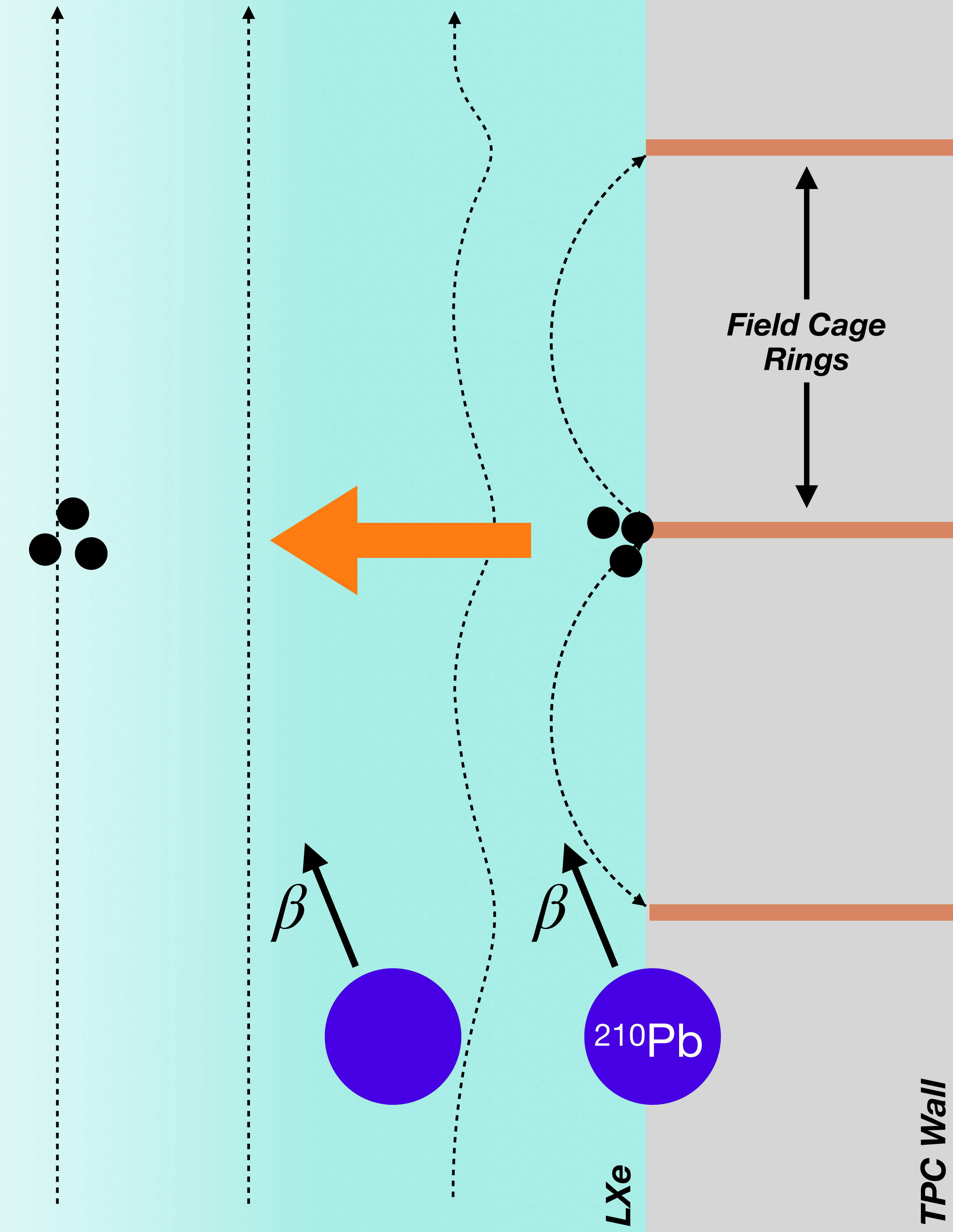
- Ionisation electrons slightly further from the wall pass by trapped electrons and are pushed further inside the TPC



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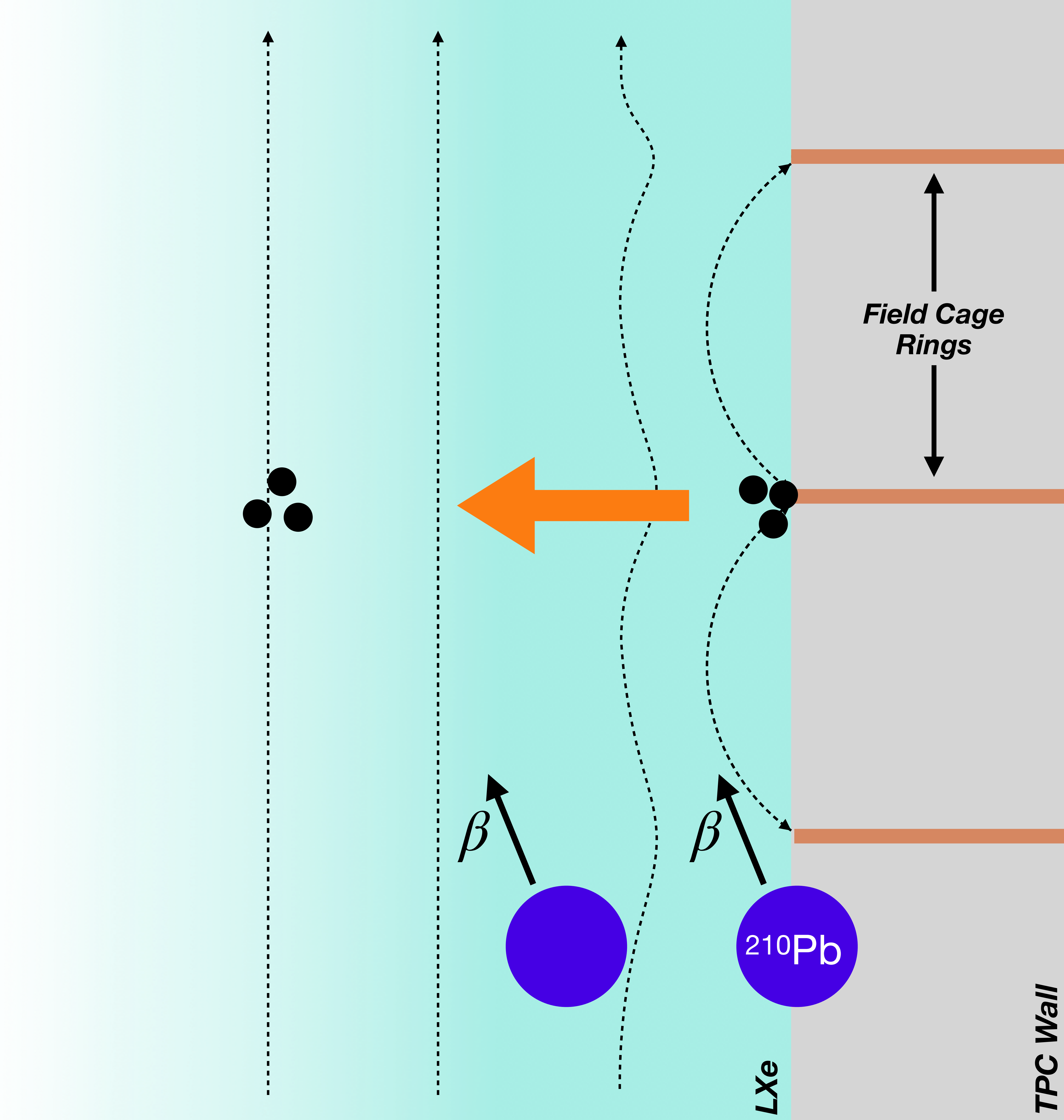
Dependent on Z-position and azimuthal angle!



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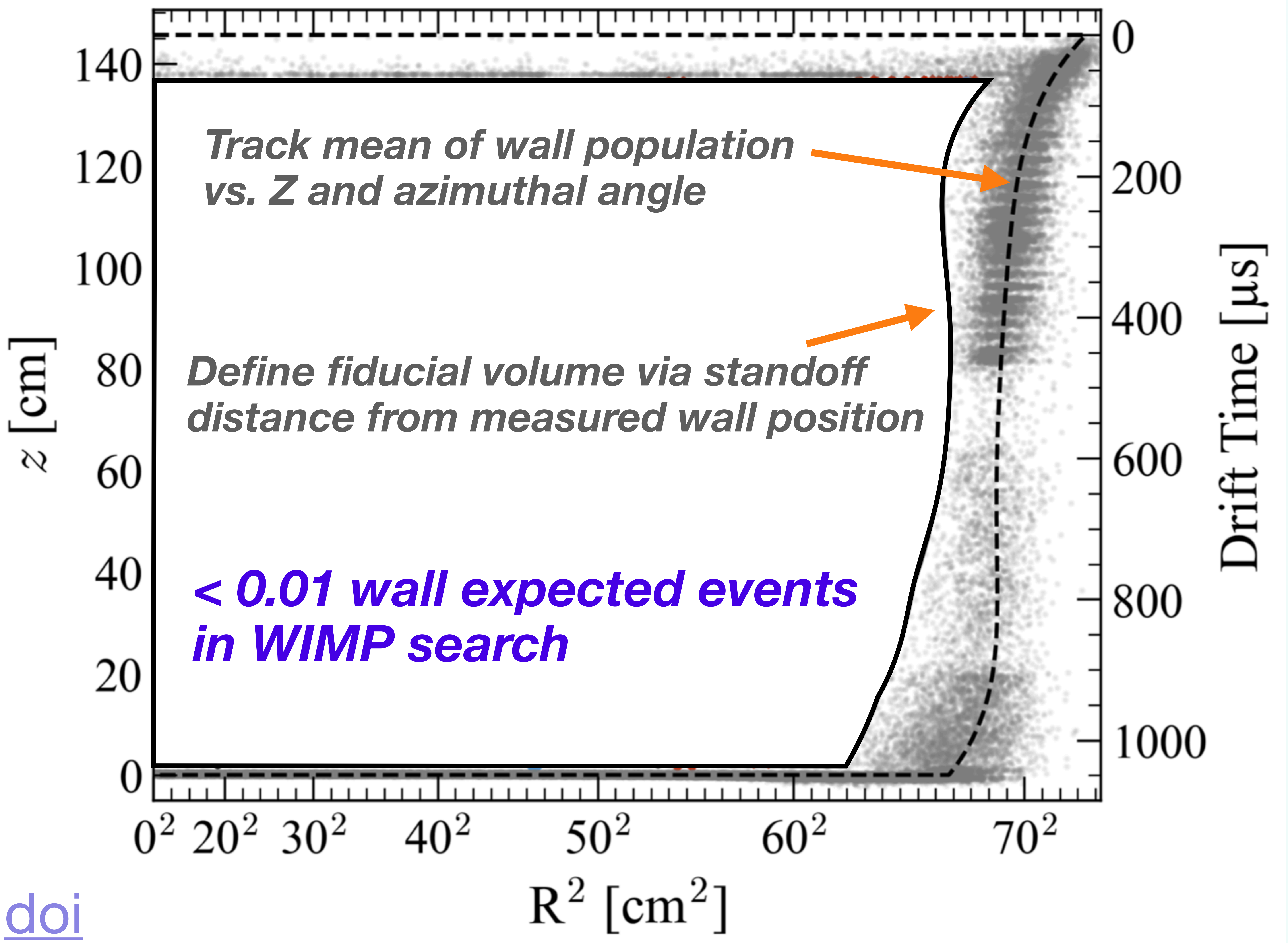

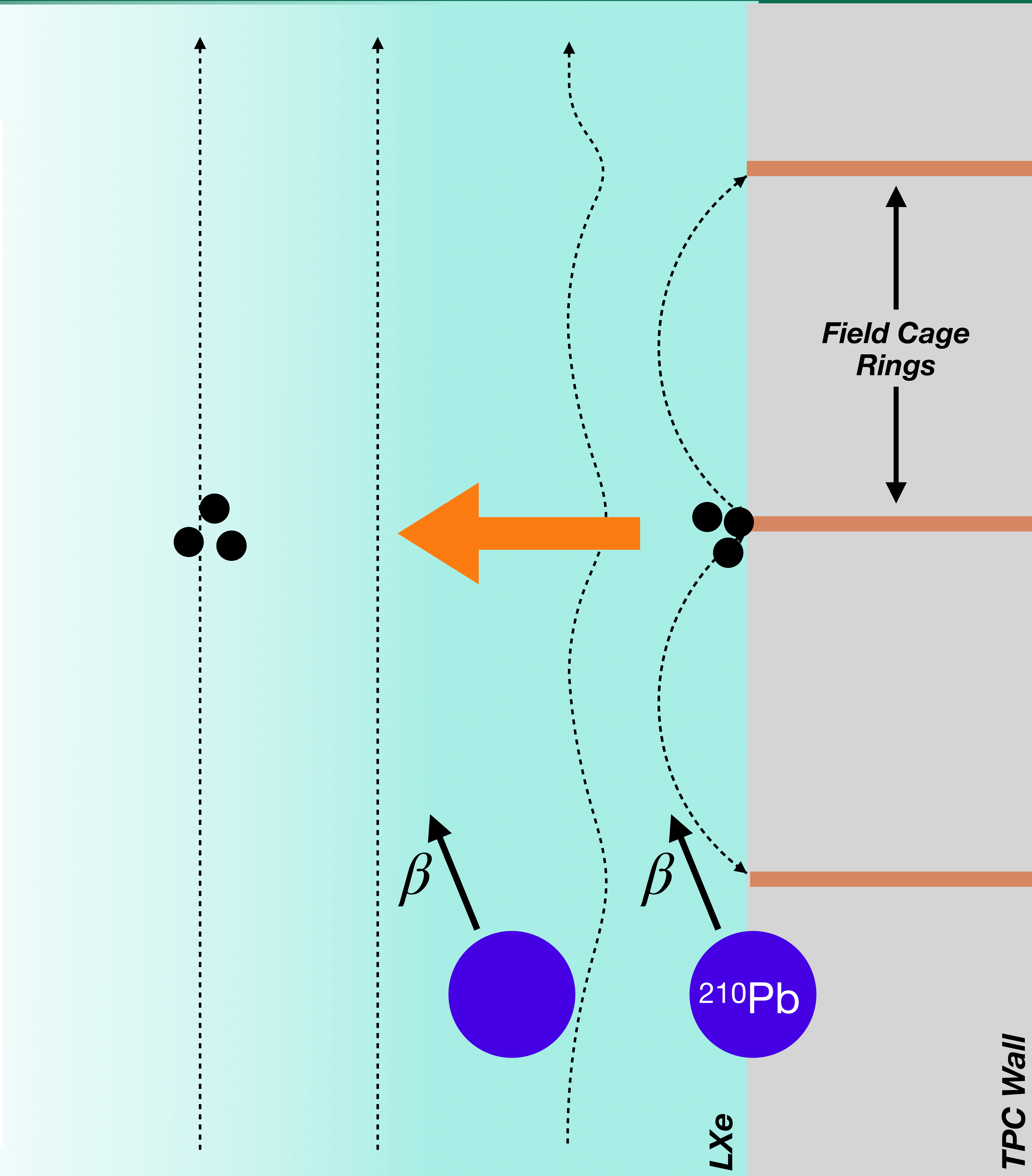

doi

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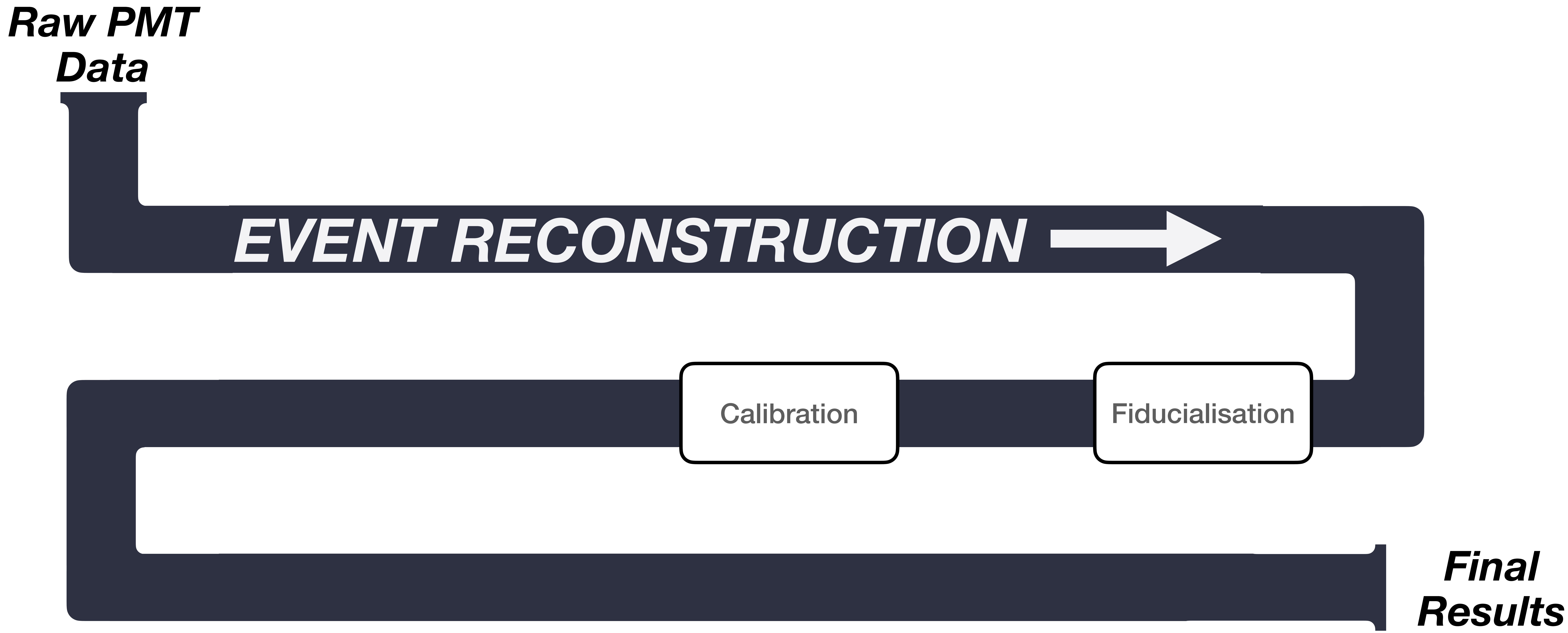
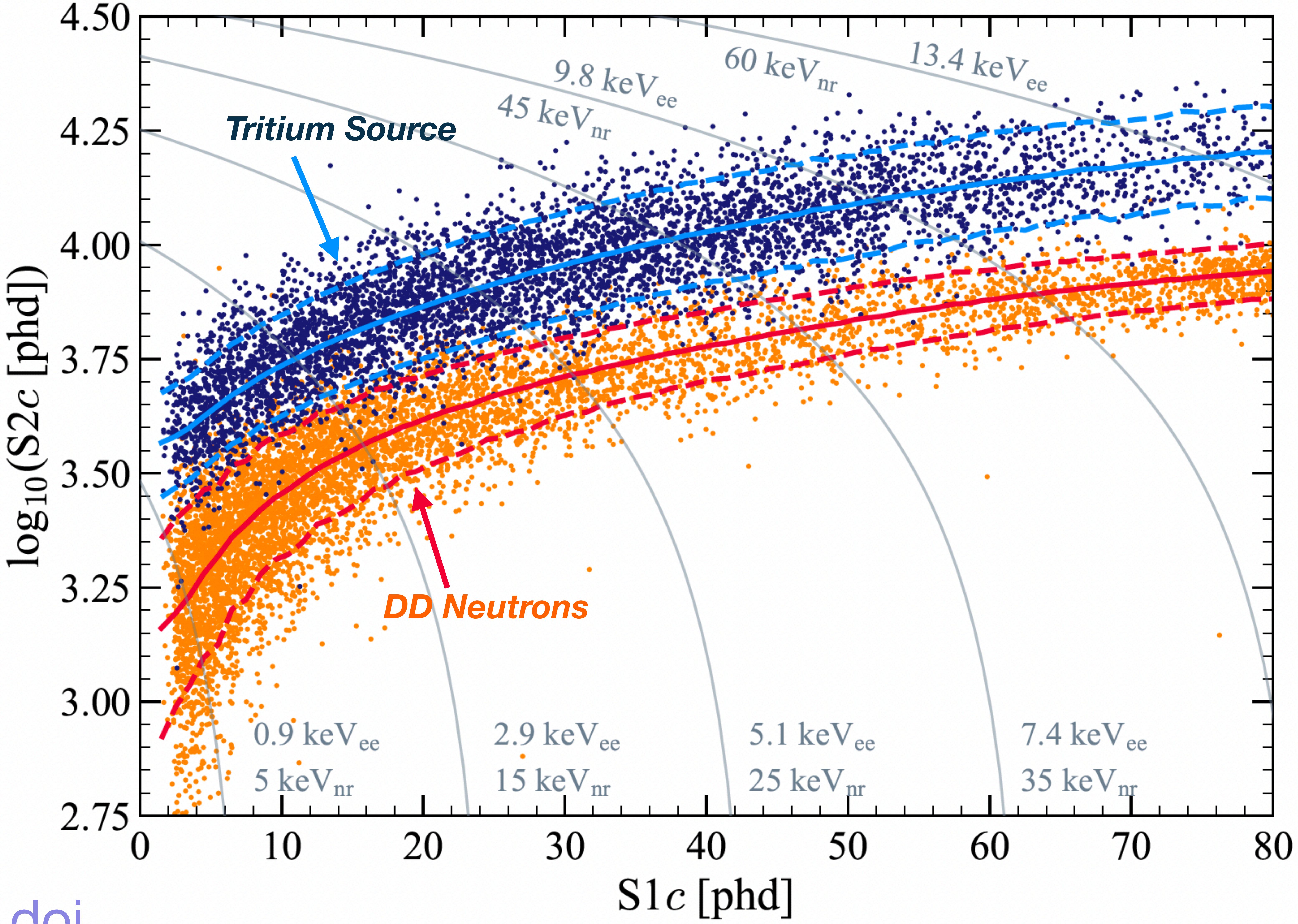


Calibration



doi

- Calibrating the NR energy response is required to pick an energy region of interest (ROI)
- Calibrating both NR and ER responses allows for precise tuning of microphysics modelling
  - Crucial for statistical analysis
- Tritiated methane provides a beta spectrum with endpoint at 18.6 keV
  - Can also be circulated uniformly in TPC volume
- Deuterium-Deuterium (DD) fusion neutrons are directed into the TPC
  - 2.45 MeV mono-energetic neutrons

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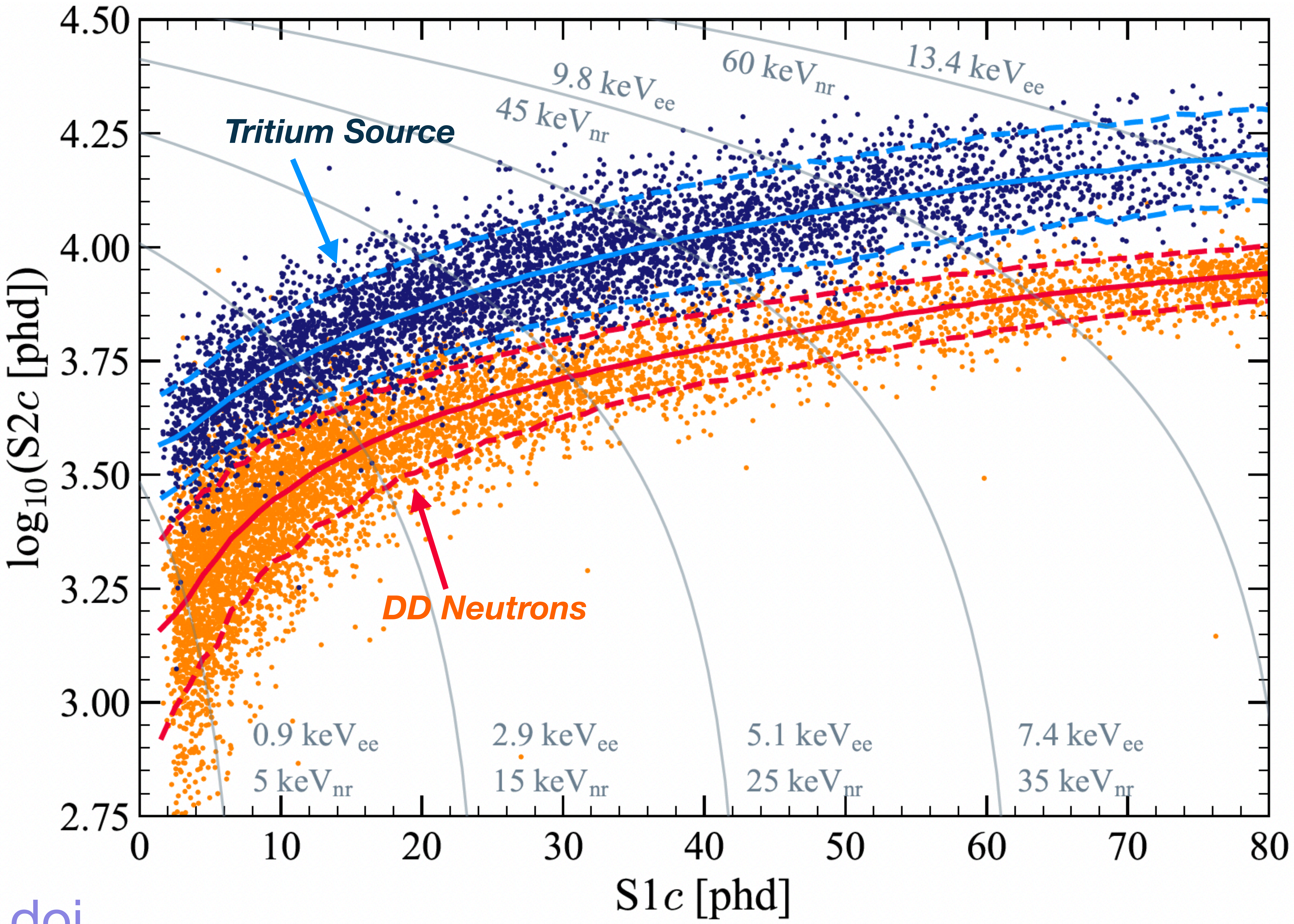
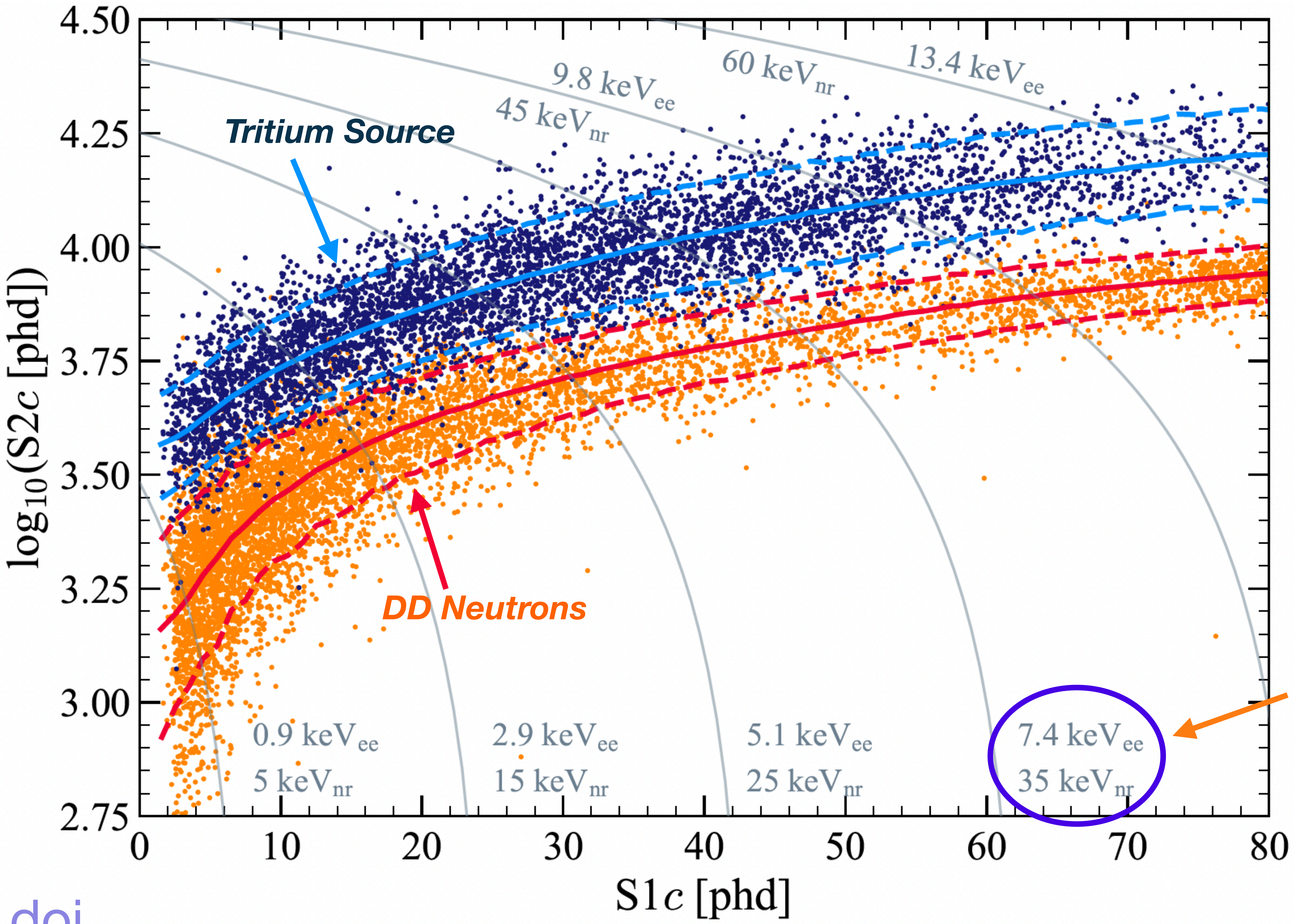


$$E = \frac{W}{f(E)}\left(\frac{S1c}{g_1} + \frac{S2c}{g_2}\right)$$

doi

Calibration



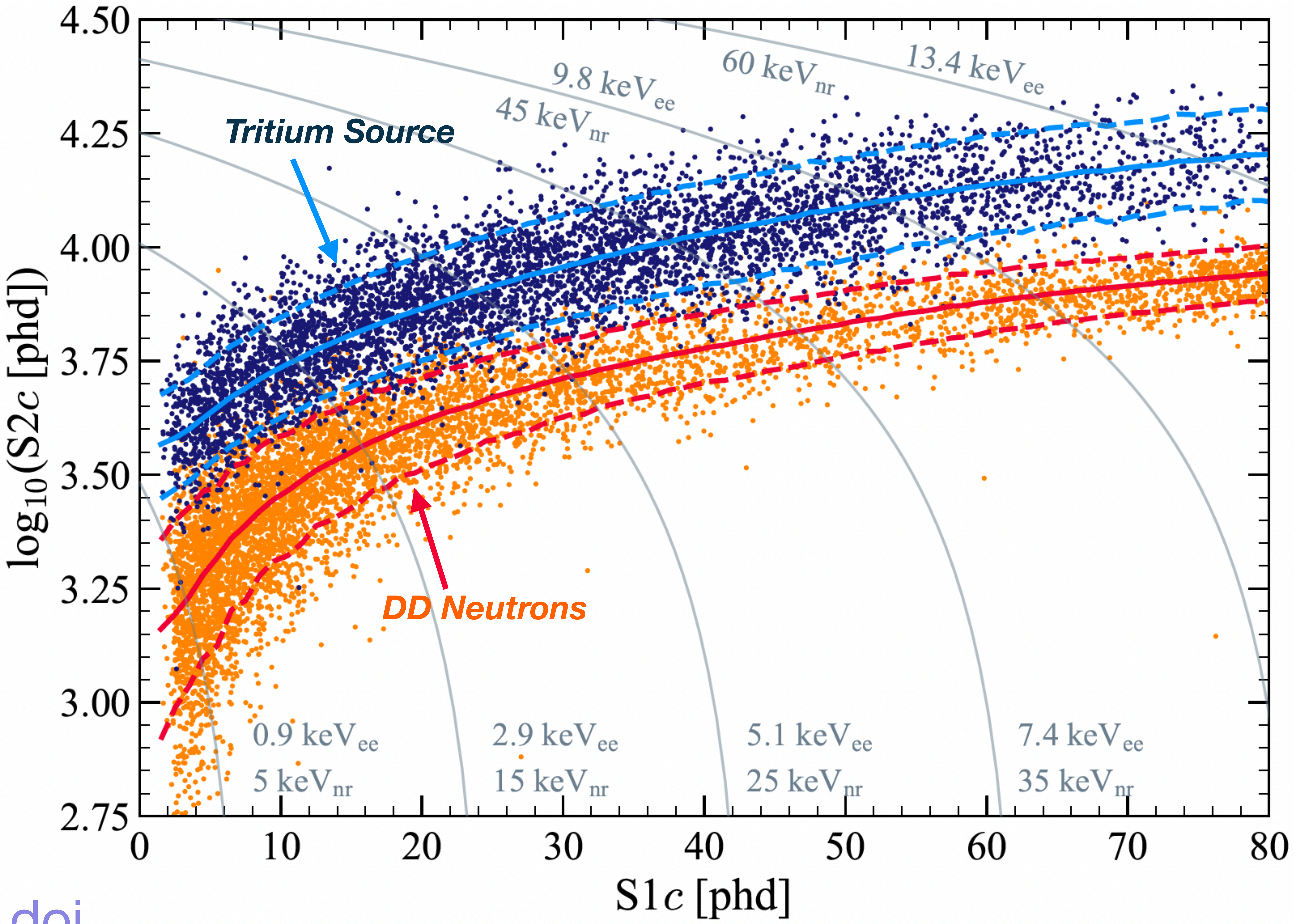
Work function
13.4 eV/quanta

$$E = \frac{W}{f(E)}\left(\frac{S1c}{g_1} + \frac{S2c}{g_2}\right)$$

Quenching Factor
1 for ERs
~0.2 for NRs

doi

Calibration



doi

$$E = \frac{W}{f(E)}\left(\frac{S1c}{g_1} + \frac{S2c}{g_2}\right)$$

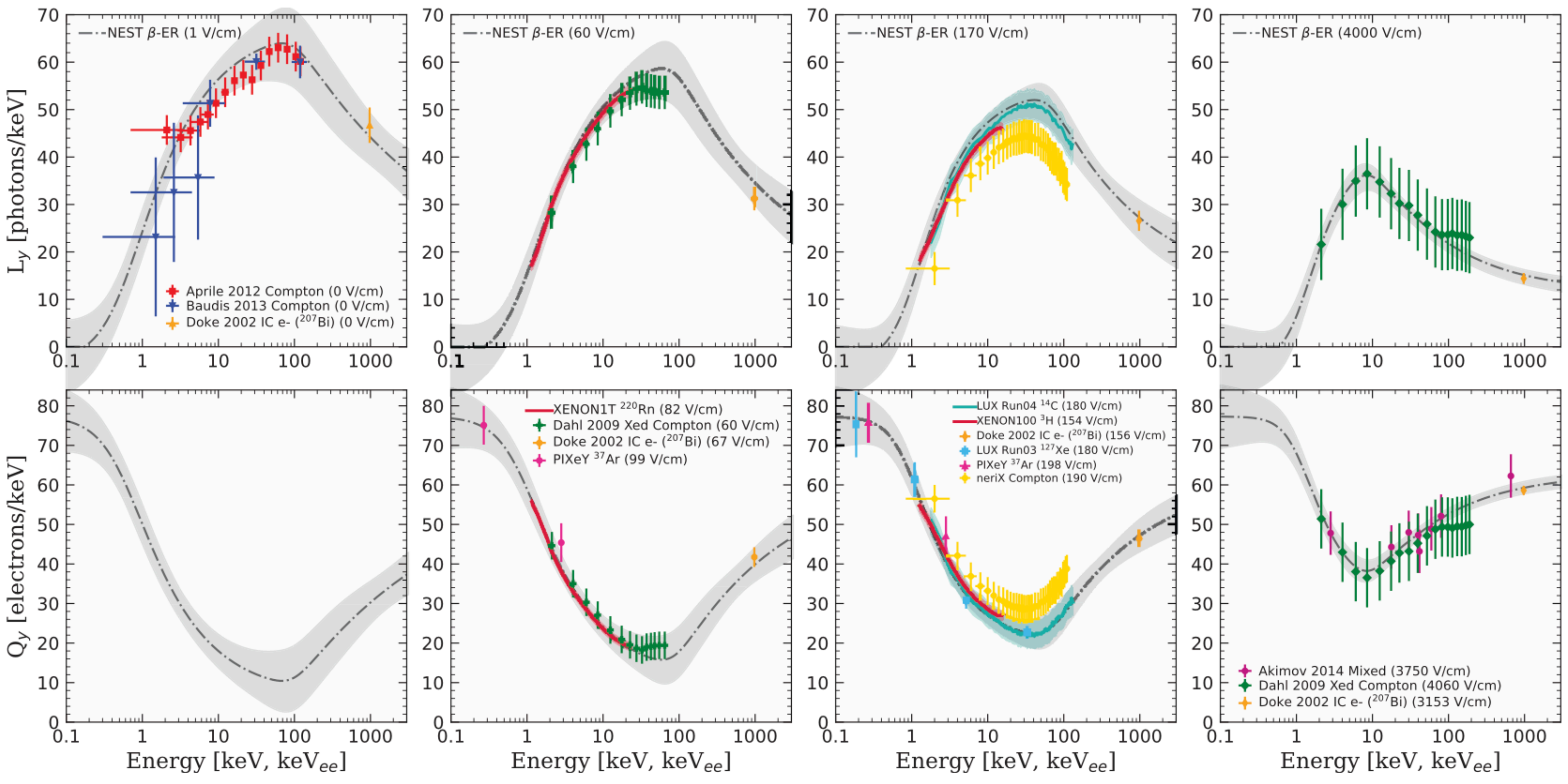
Scintillation and Ionisation gain factors

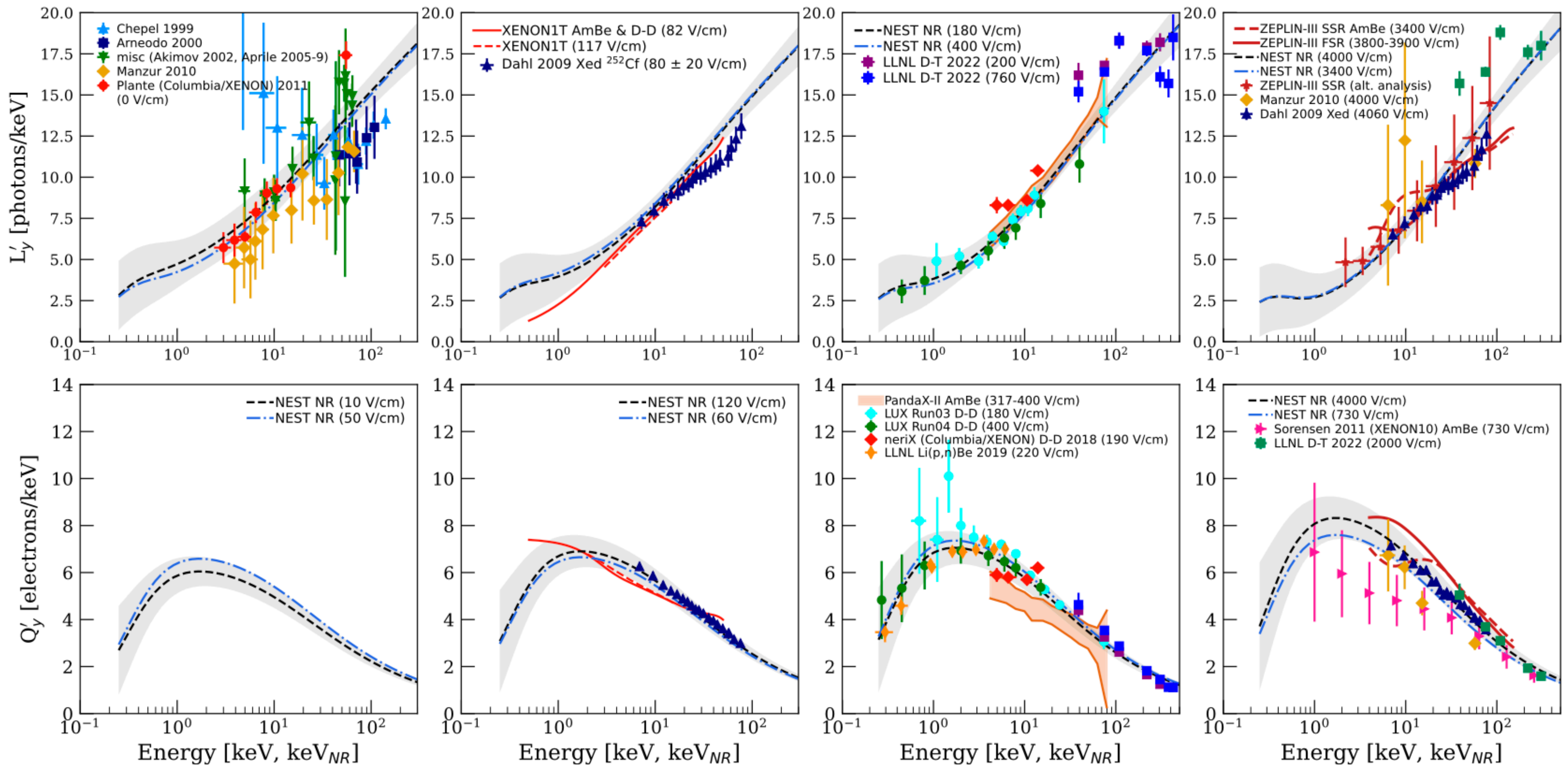
Calibration constants

g_1 [γ/phd], g_2 [e^-/phd]

Calibration

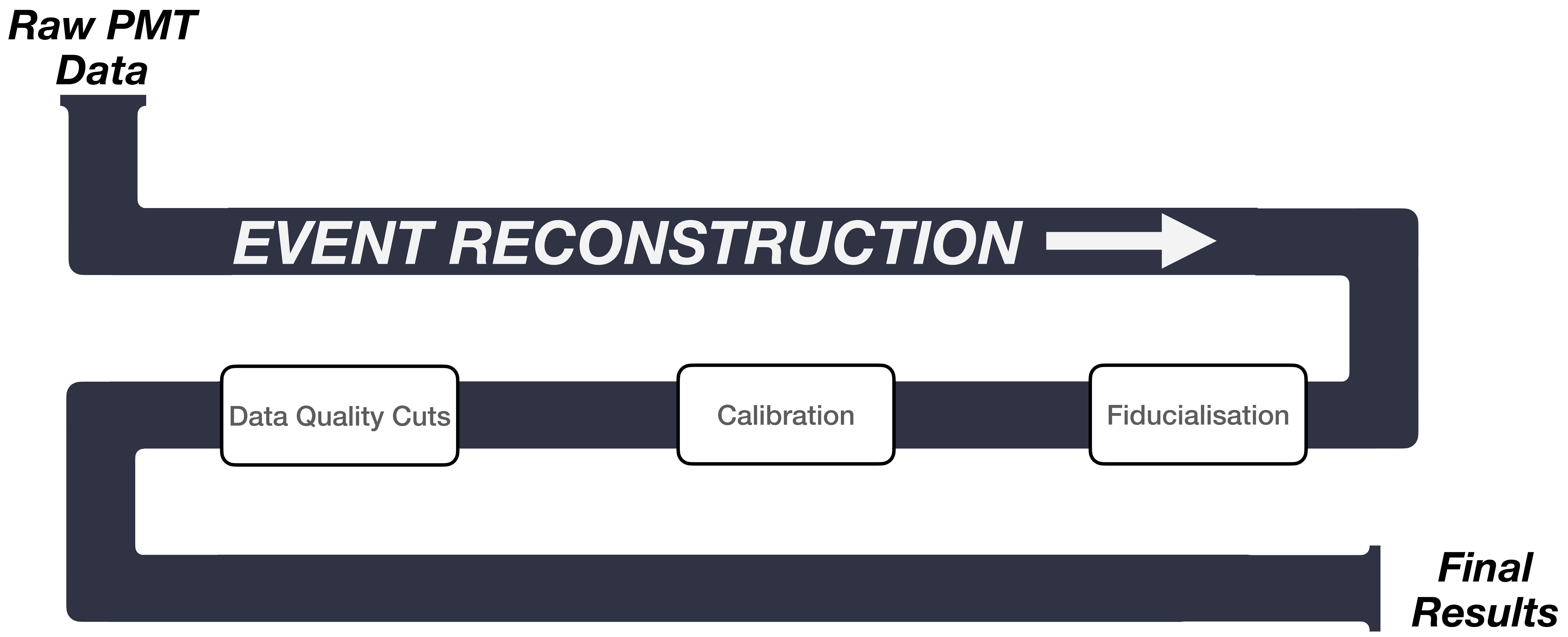
doi





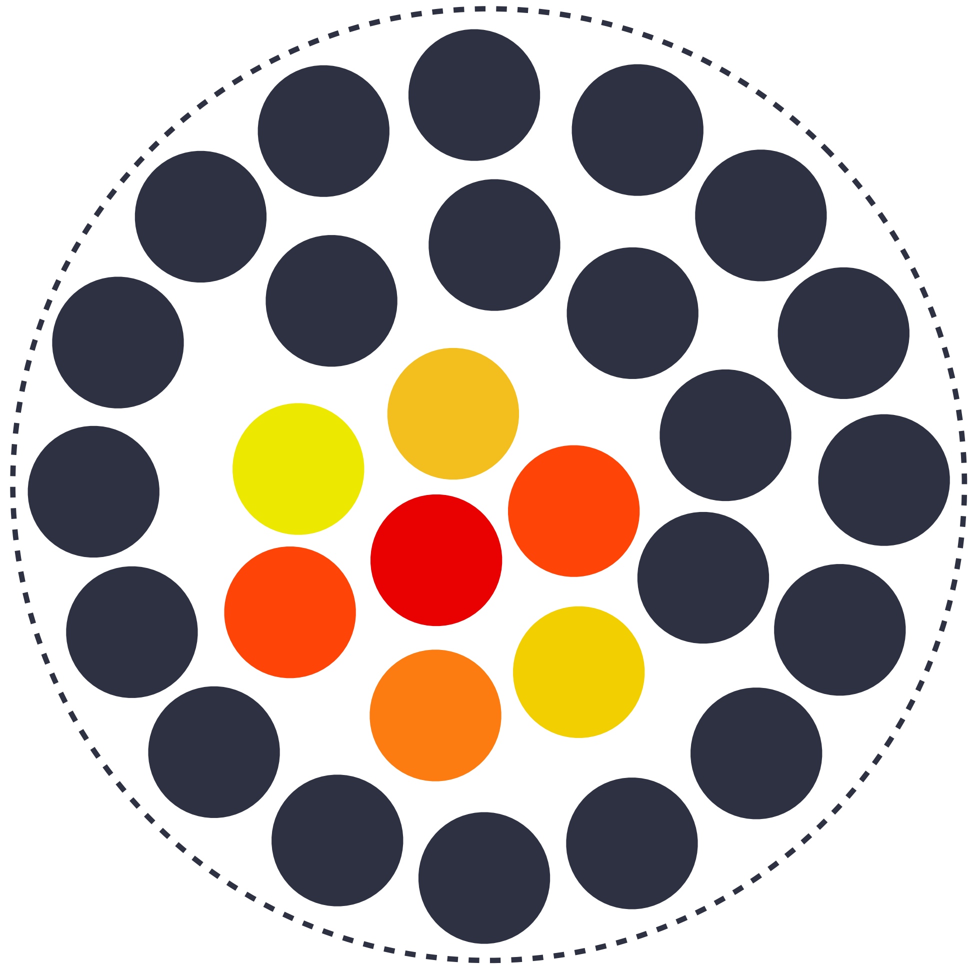
- LXe microphysical response vs. energy and drift field strength well captured by the Noble Element Simulation Technique (NEST)
- g_1 and g_2 measured directly in calibration, Light and Charge Yield (L_y and Q_y, respectively) model parameters tuned to capture fluctuations in calibration data

The Analysis Pipeline



Data Quality Cuts

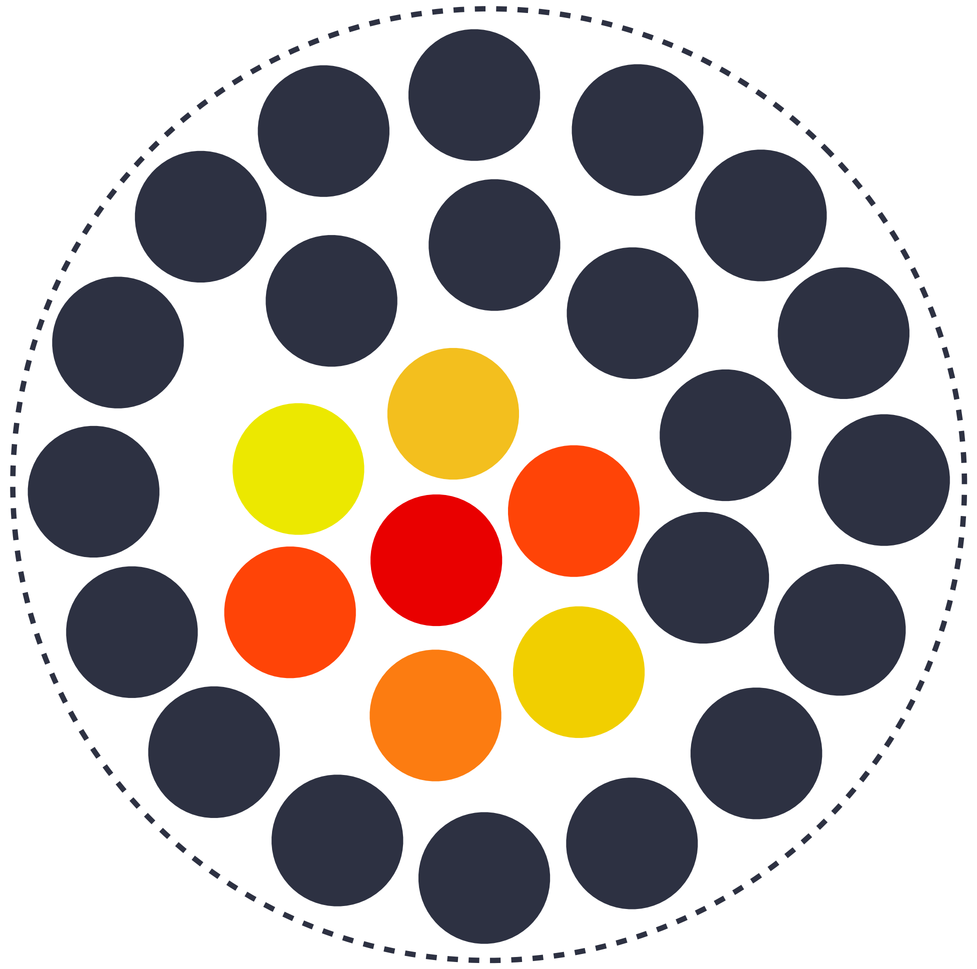
A subset of cuts target sub-optimal detector conditions



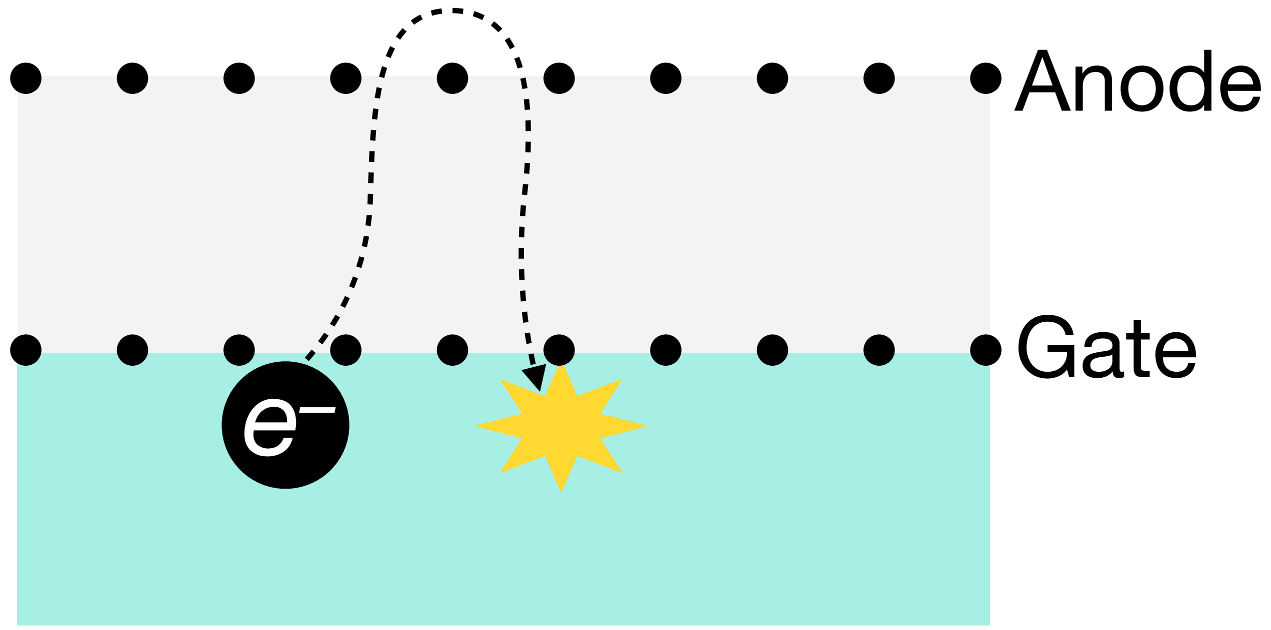
e.g. ***Hotspots***
Sustained S2 rate in a small area

Data Quality Cuts

A subset of cuts target sub-optimal detector conditions



e.g. ***Hotspots***
Sustained S2 rate in a small area

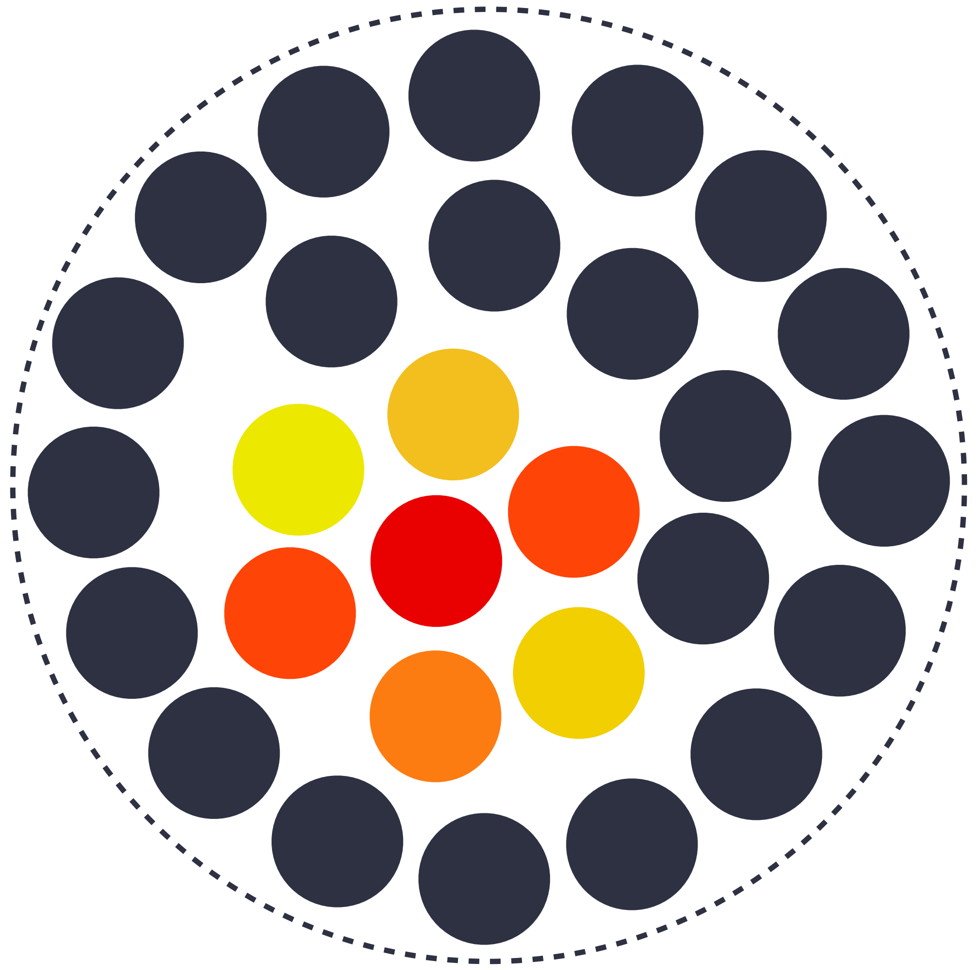


e.g. ***Stingers***
Extracted electrons recoiling back into liquid phase

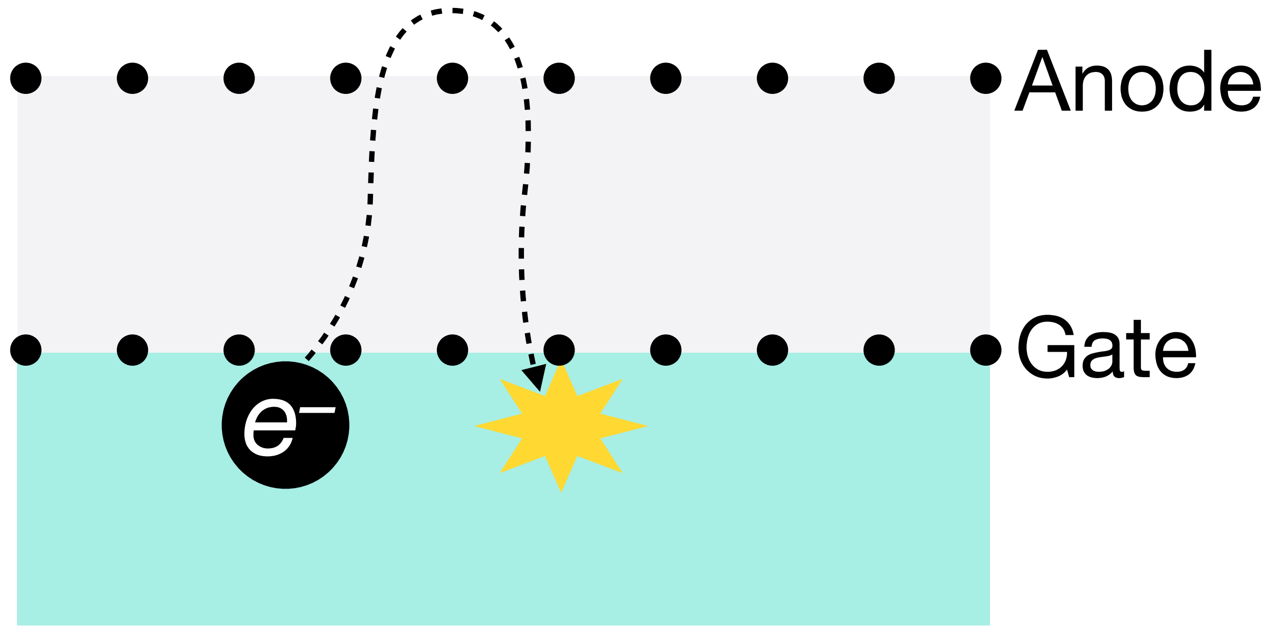
Other cuts target specific event pathologies

Data Quality Cuts

A subset of cuts target sub-optimal detector conditions



e.g. ***Hotspots***
Sustained S2 rate in a small area



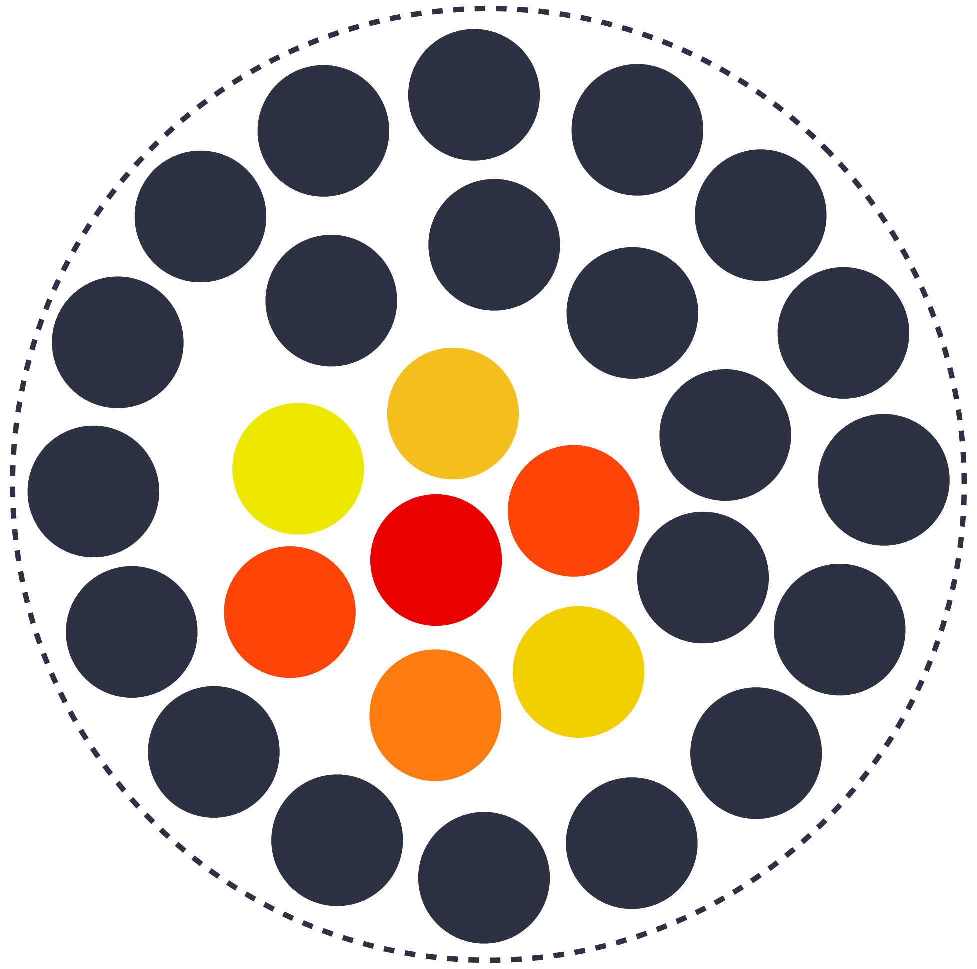
e.g. ***Stingers***
Extracted electrons recoiling back into liquid phase

Other cuts target specific event pathologies

Vast majority of cuts target so-called accidentals
events from uncorrelated S1-S2 pairs

Data Quality Cuts

A subset of cuts target sub-optimal detector conditions



e.g. ***Hotspots***
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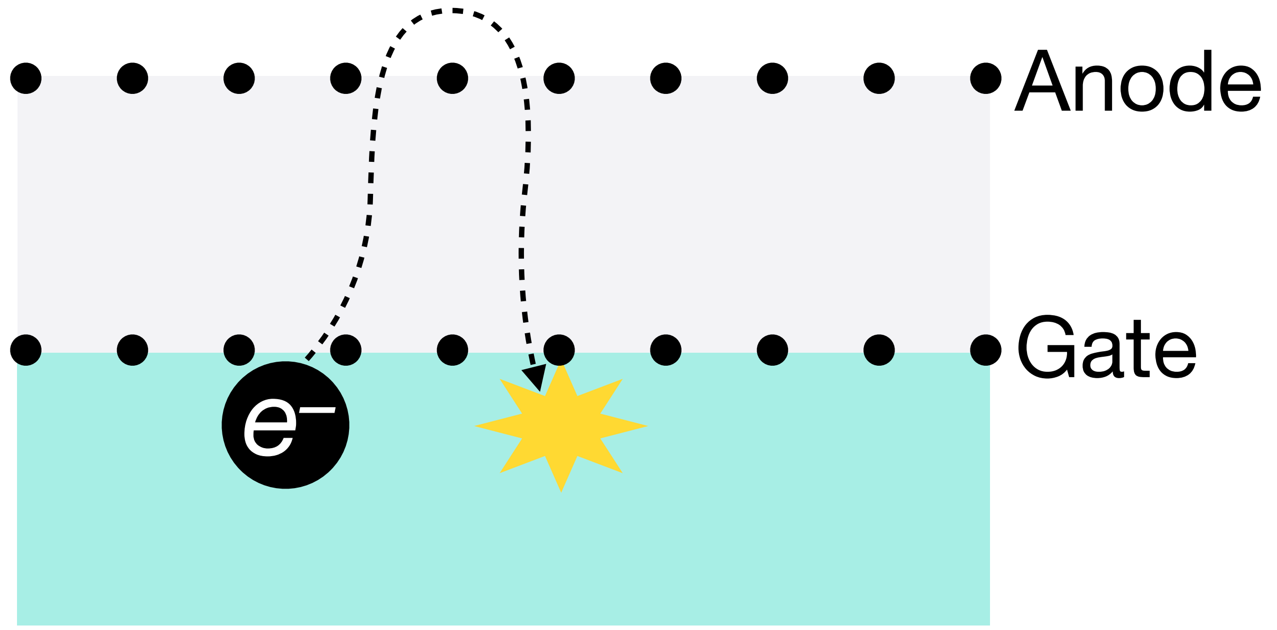
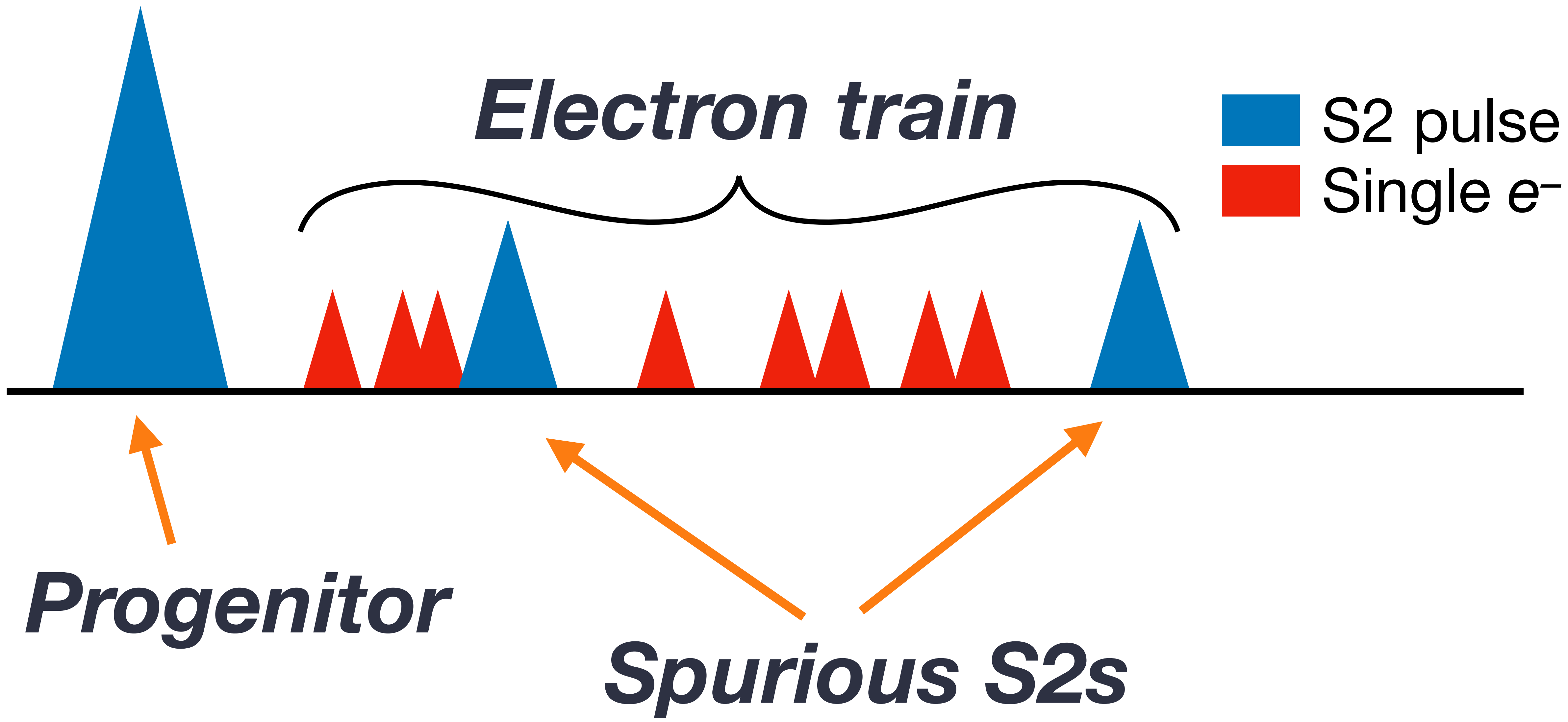


e.g. ***Stingers***
Extracted electrons recoiling back into liquid phase

Other cuts target specific event pathologies

Vast majority of cuts target so-called accidentals
events from uncorrelated S1-S2 pairs

One notable pathology…



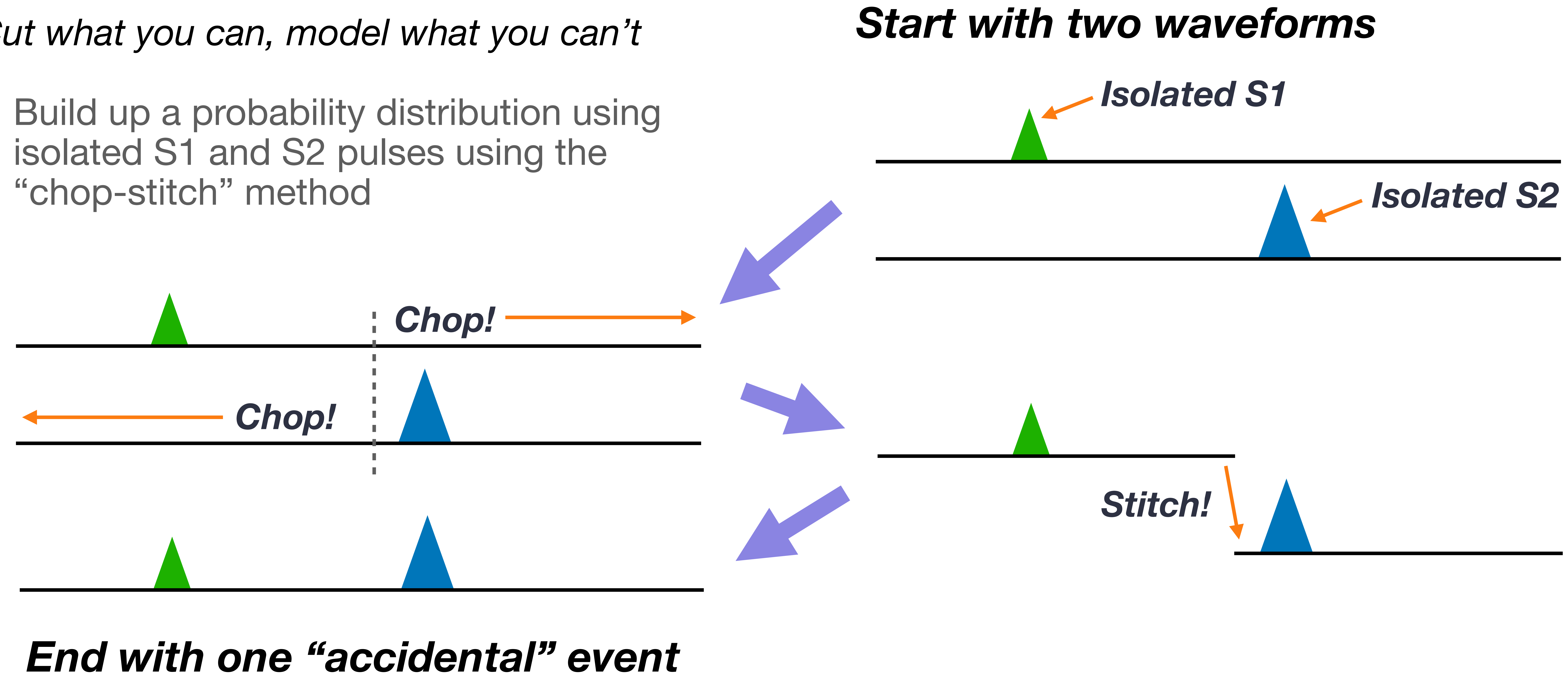
The Analysis Pipeline

Background Modelling

Accidentals

Cut what you can, model what you can't

- Build up a probability distribution using isolated S1 and S2 pulses using the "chop-stitch" method



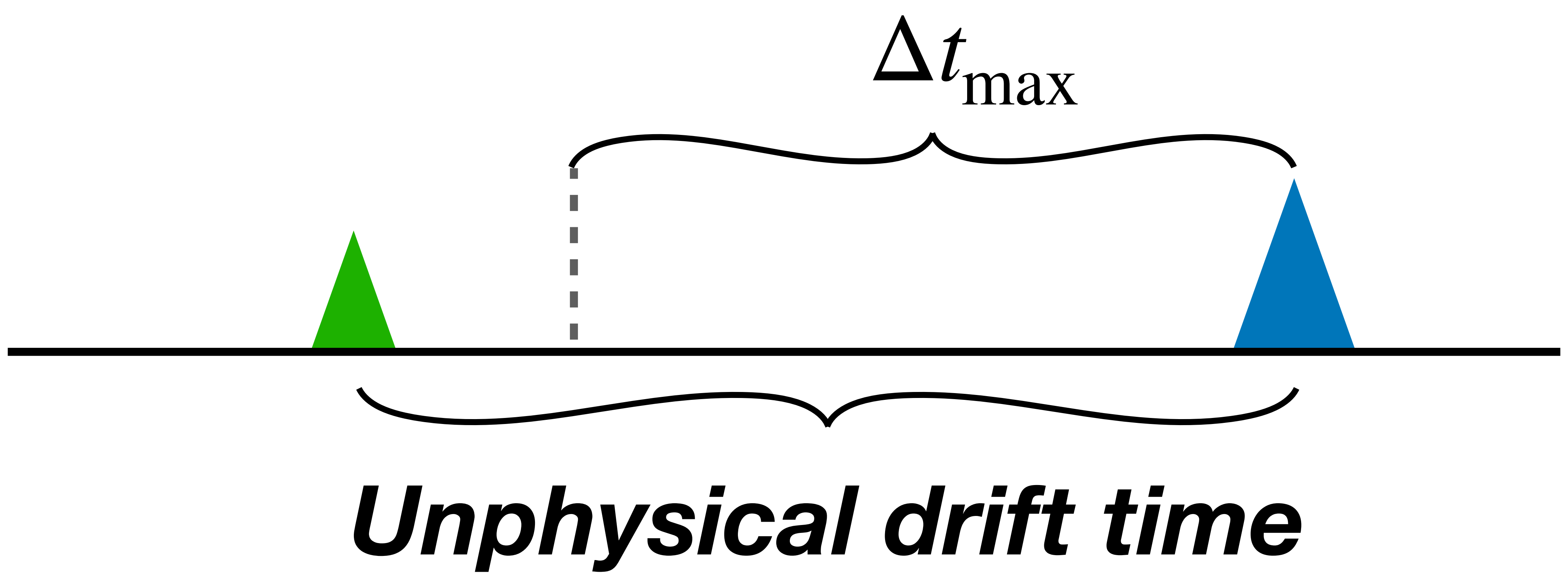
Background Modelling

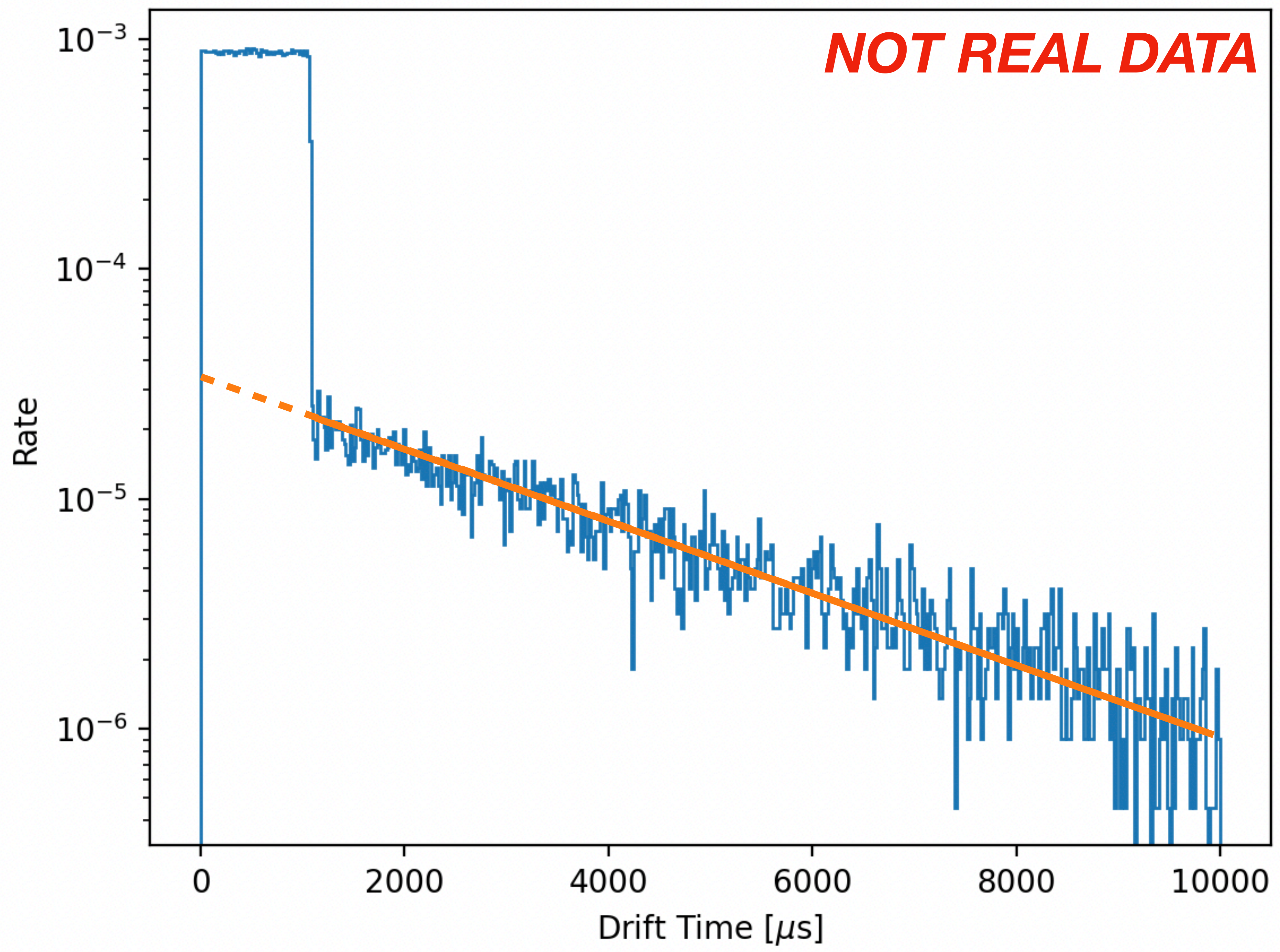
Accidentals

Cut what you can, model what you can't

- Build up a probability distribution using isolated S1 and S2 pulses using the "chop-stitch" method

- Calculate the expected counts by looking at events with unphysical drift time





Background Modelling

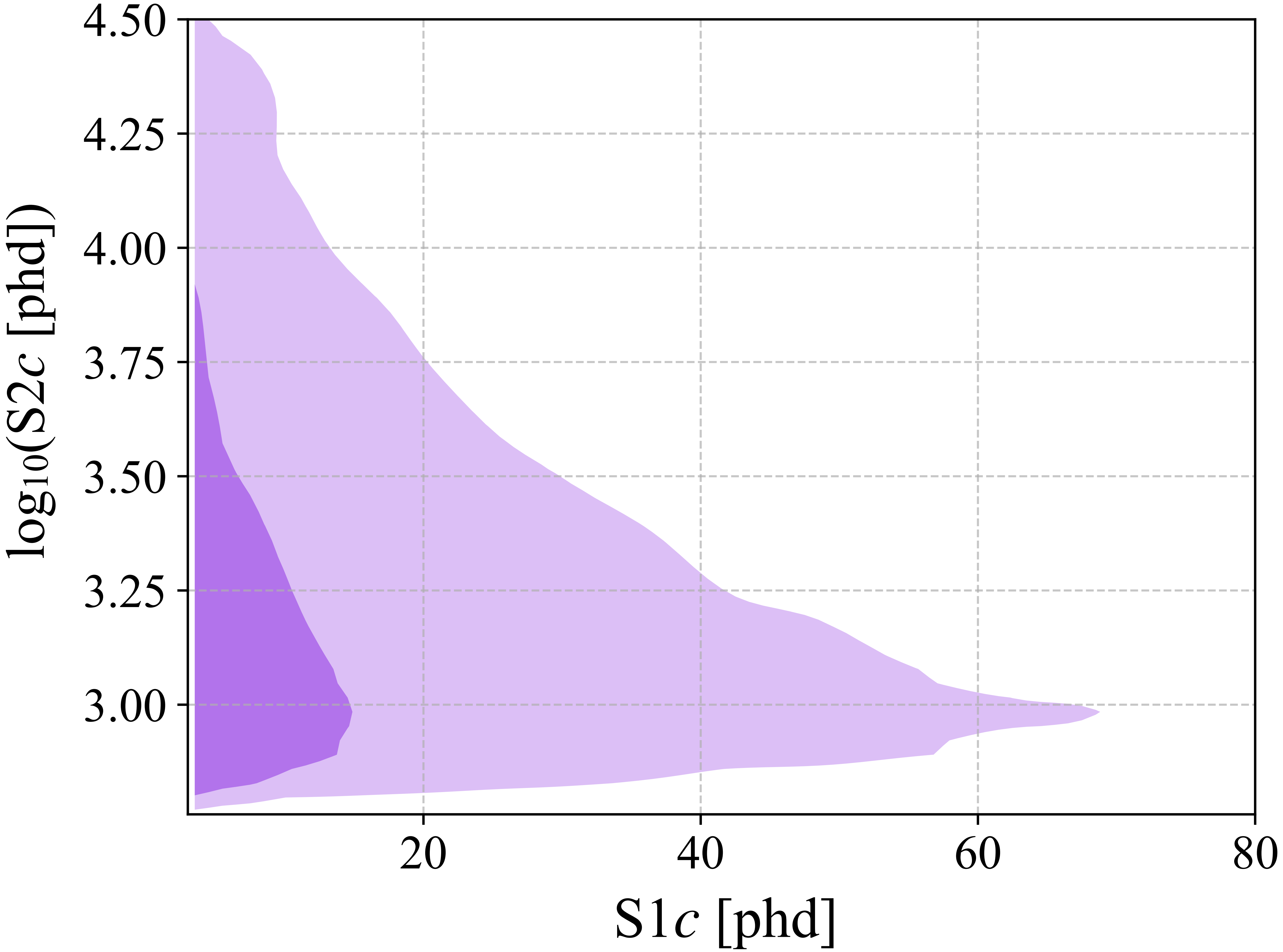
Accidentals

Cut what you can, model what you can't

- Build up a probability distribution using isolated S1 and S2 pulses using the "chop-stitch" method

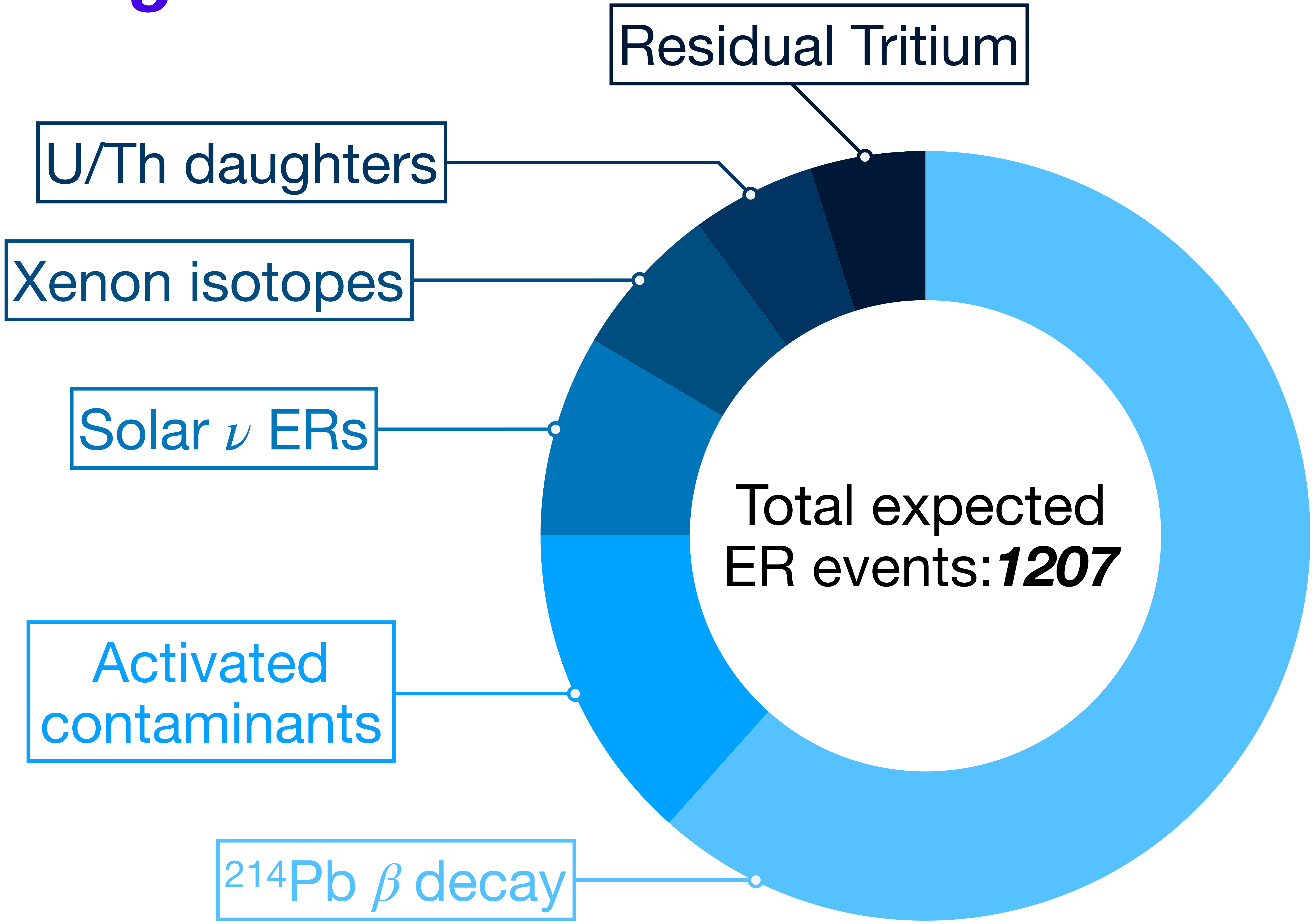
- Calculate the expected counts by looking at events with unphysical drift time

Expected rate: 2.8 ± 0.6



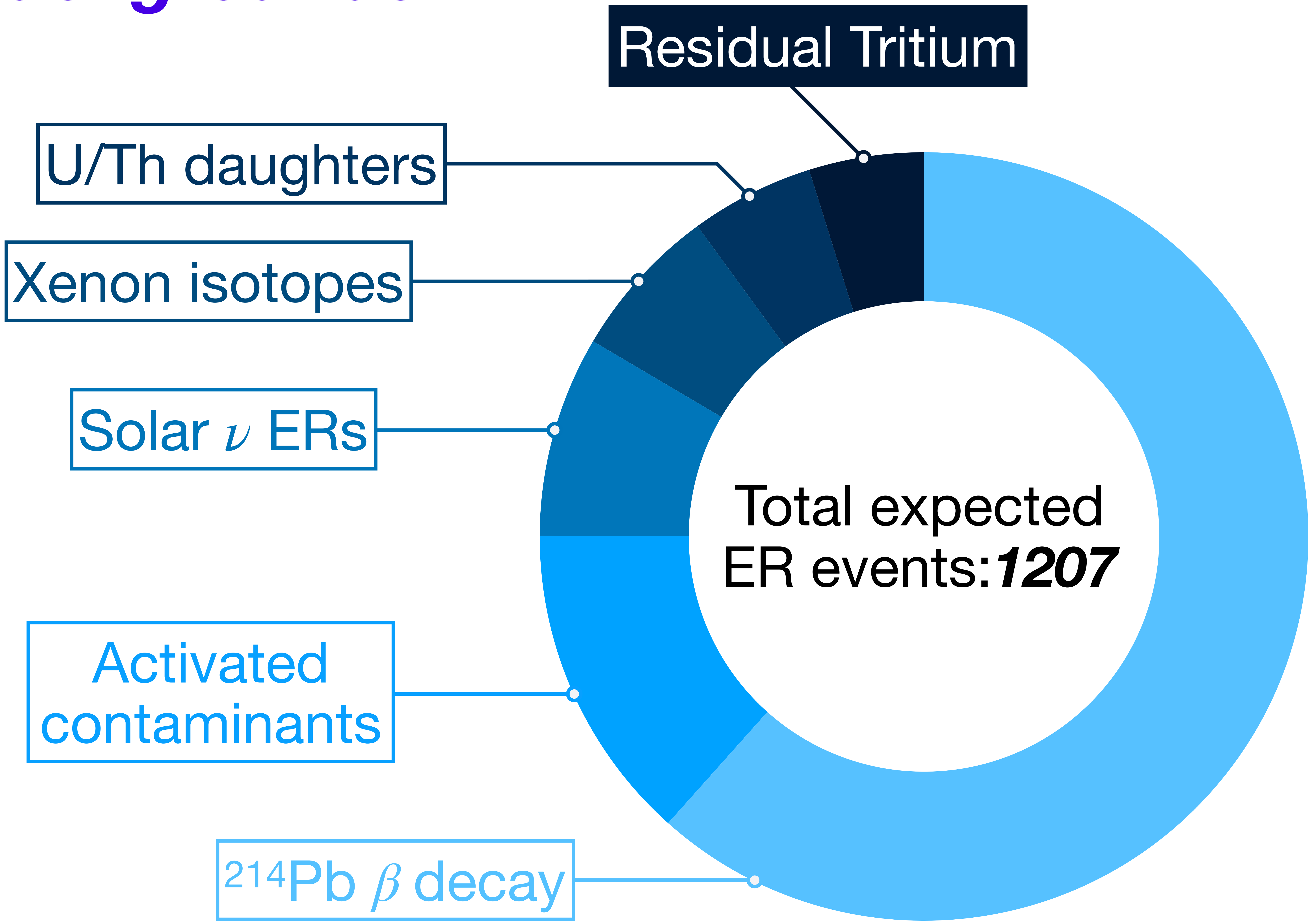
Background Modelling

ER Backgrounds



Background Modelling

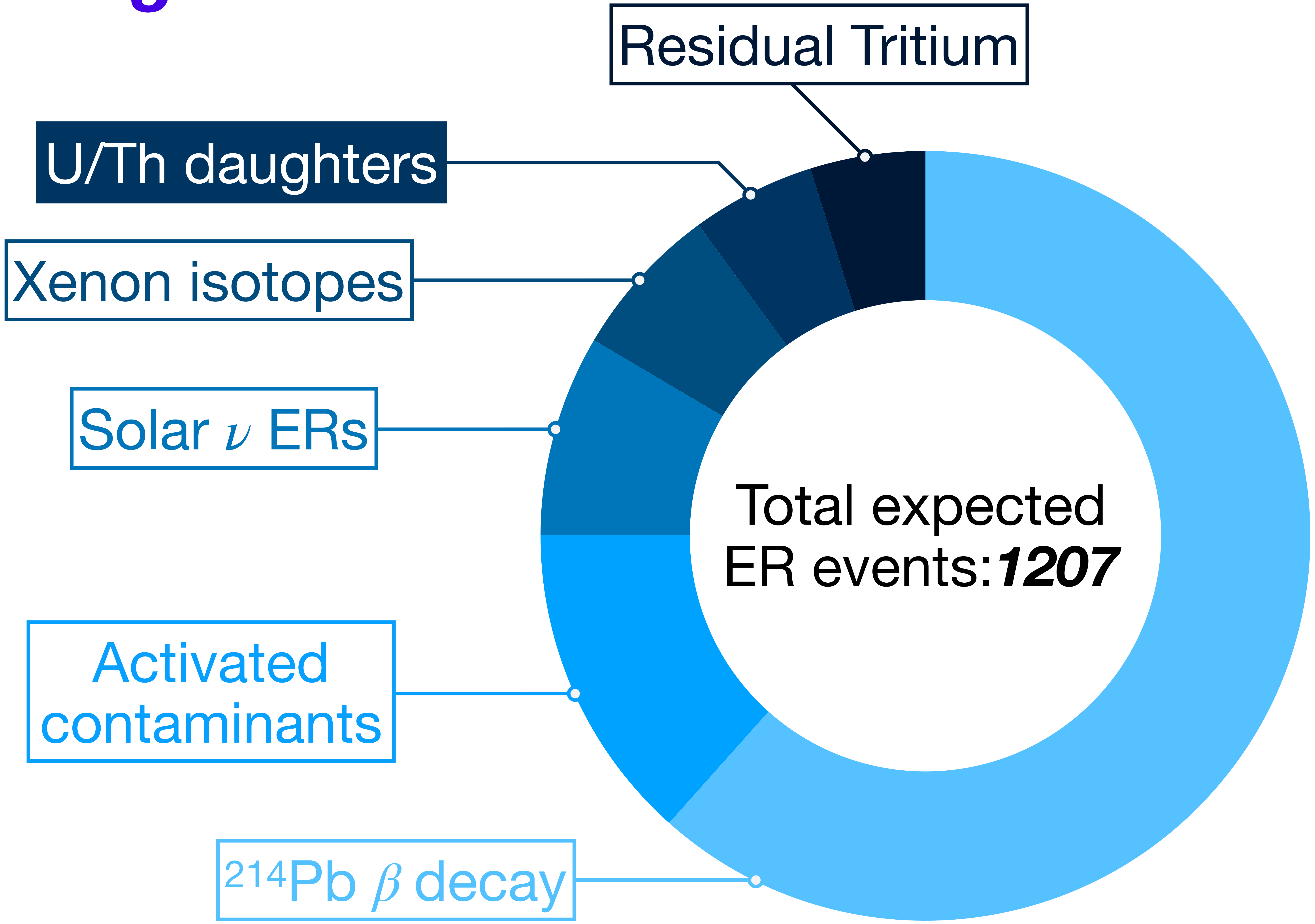
ER Backgrounds



- Small amount of tritiated methane circulating in TPC after calibration runs
- Includes T and small amounts of ^{14}C β decays
- Only relevant at the beginning of the WIMP search

Background Modelling

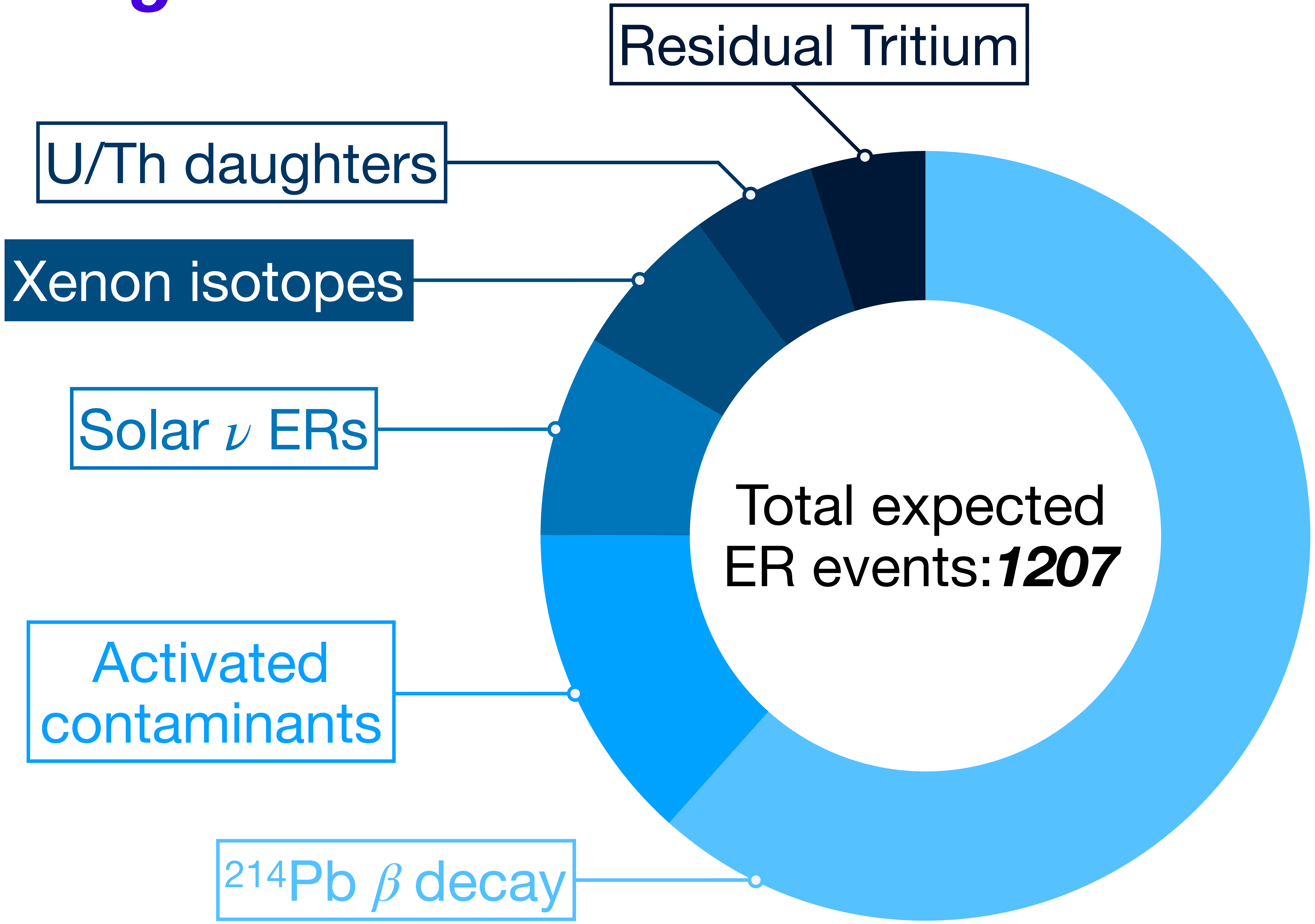
ER Backgrounds



- Predominantly β decays from ^{212}Pb
- Includes a small contribution from ^{218}Po β decays (BR 0.02%)

Background Modelling

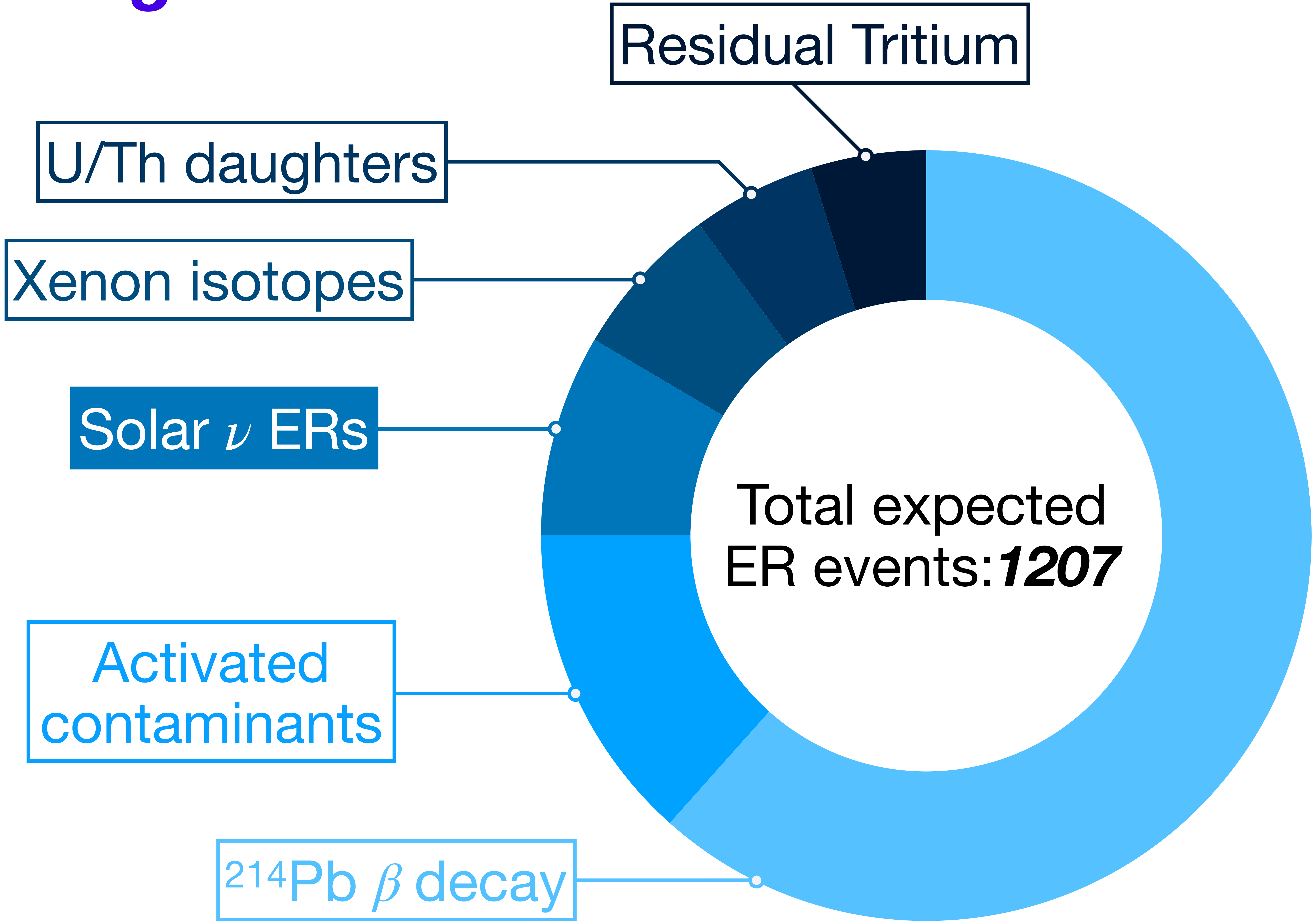
ER Backgrounds



- Assuming natural isotopic abundances of xenon are present in the TPC
- ^{136}Xe decays via $2\nu\beta\beta$
- ^{124}Xe decays via double electron capture (DEC)
- ^{125}Xe & ^{127}Xe both decay via single electron capture

Background Modelling

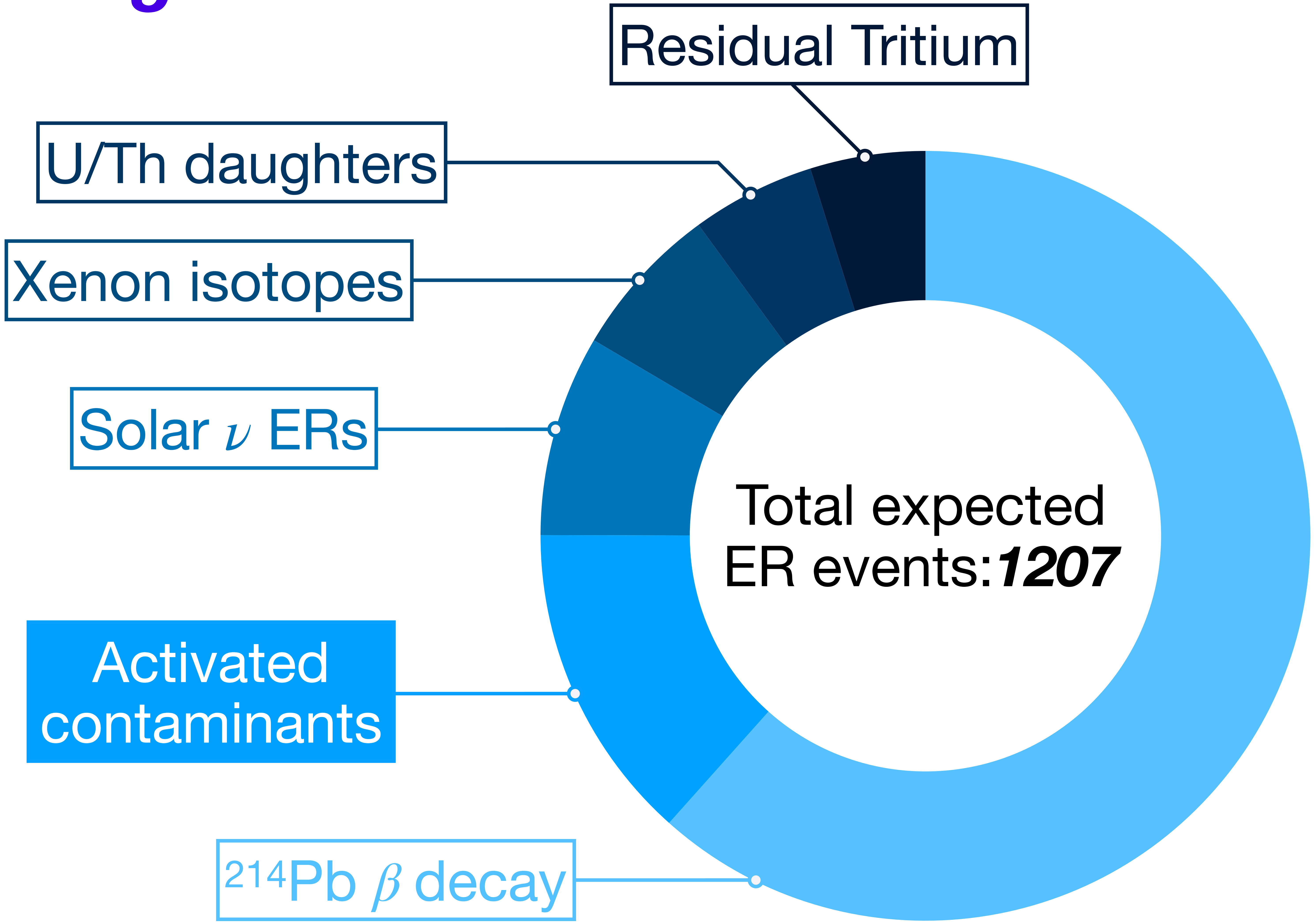
ER Backgrounds



- Charged current solar neutrino interactions produce a nearly flat ER recoil spectrum in WIMP ROI

Background Modelling

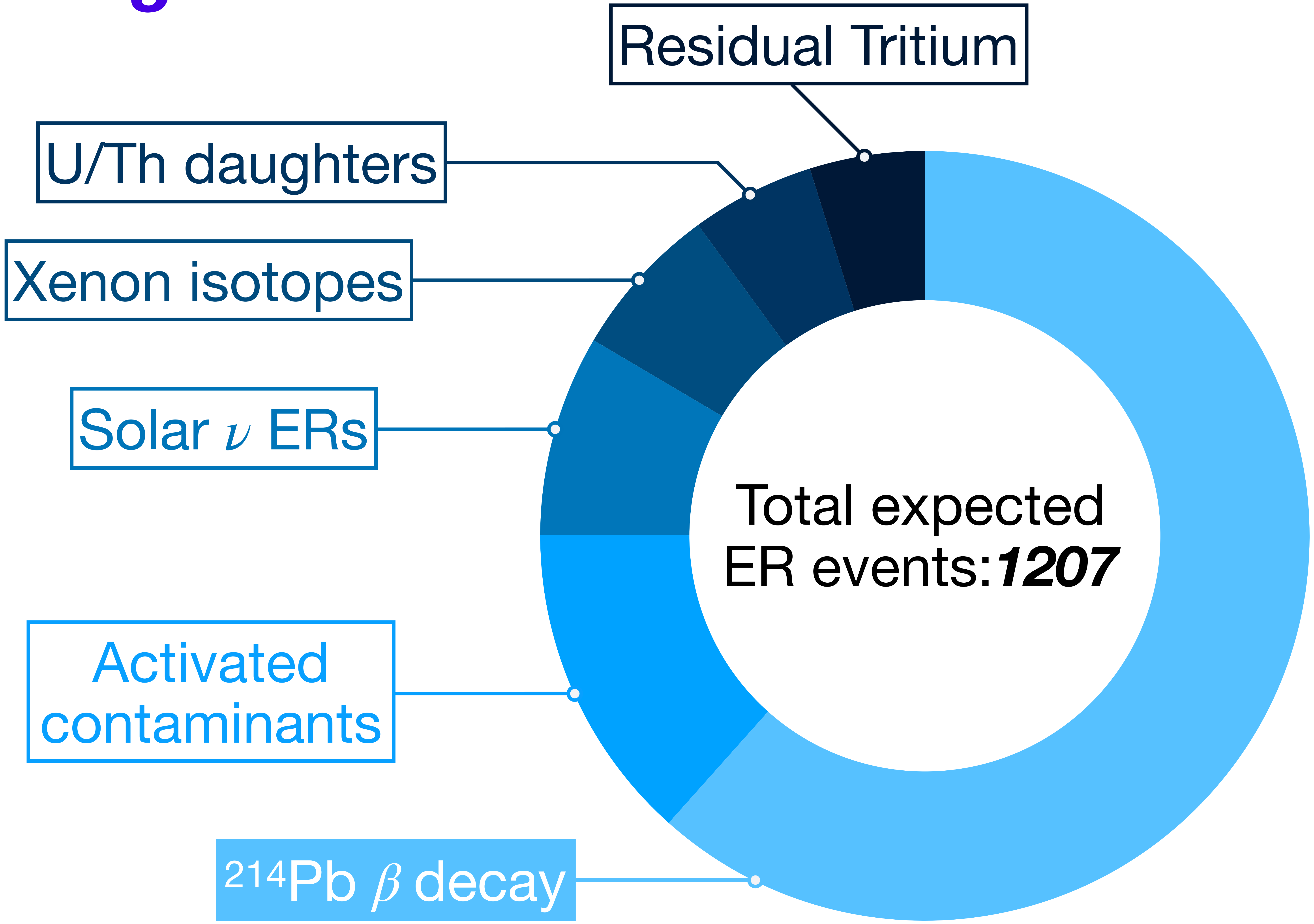
ER Backgrounds



- Xenon sourced from the atmosphere contains long-lived radioisotopes activated by cosmic rays
- Dominated by ^{85}Kr β decays
- Also includes ^{39}Ar β decays
- For completeness, also includes environmental and detector γ rays

Background Modelling

ER Backgrounds

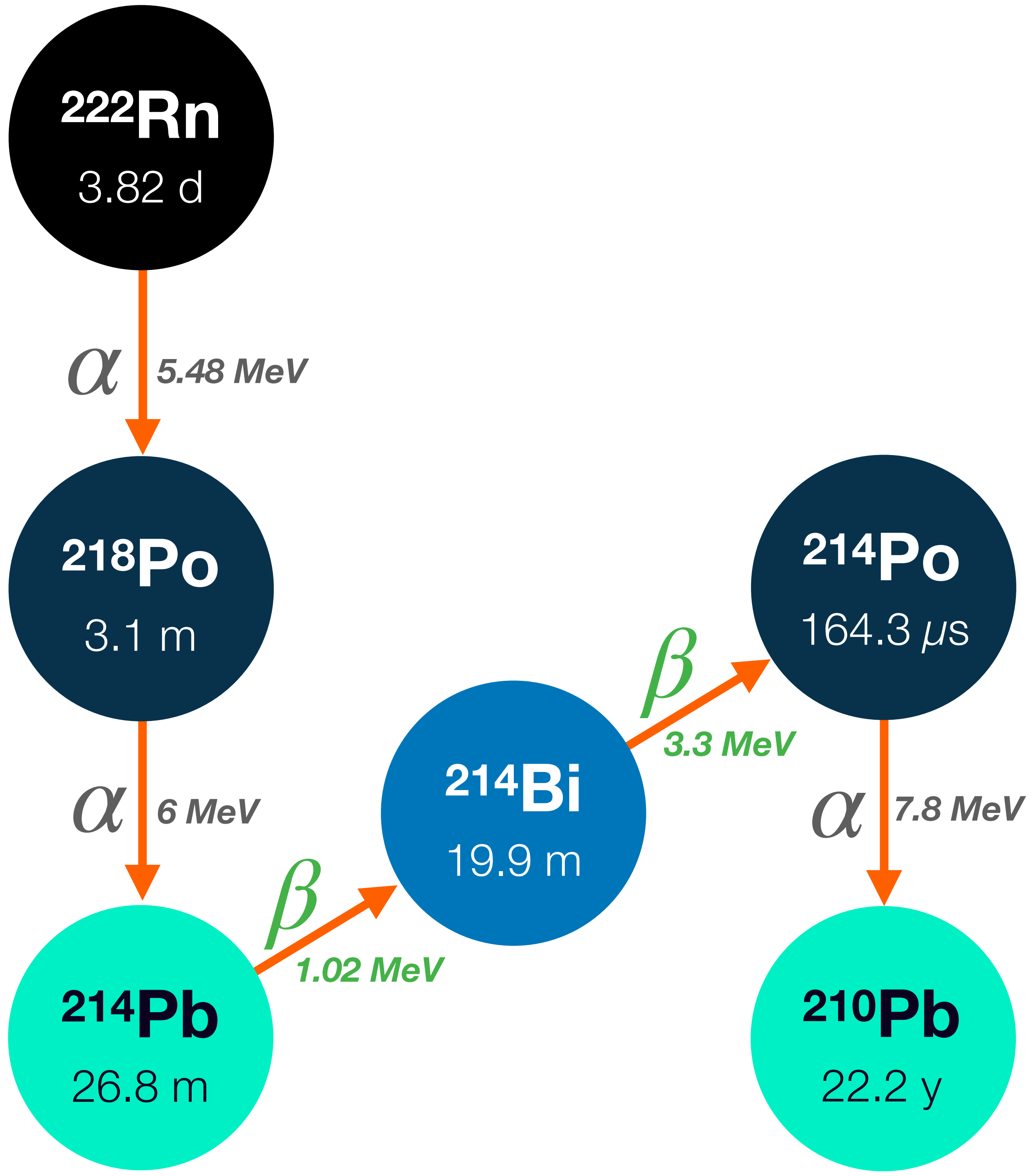


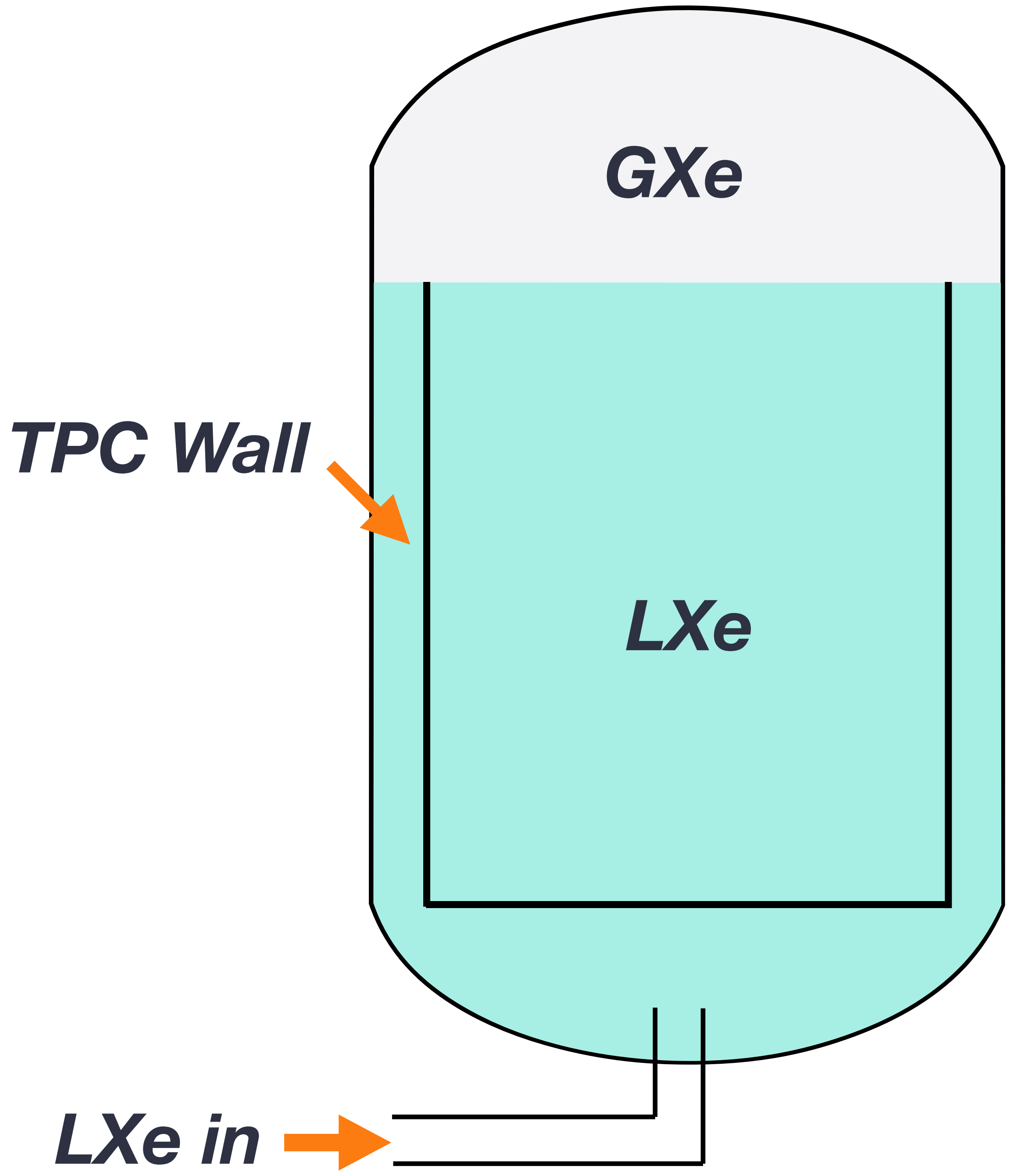
- Largest background contribution by far
- Has a lifetime of ~27 mins
  - Difficult to tag without an accompanying γ ray
- 12.7% of decays go straight to the ground state
  - "*naked*" β decays

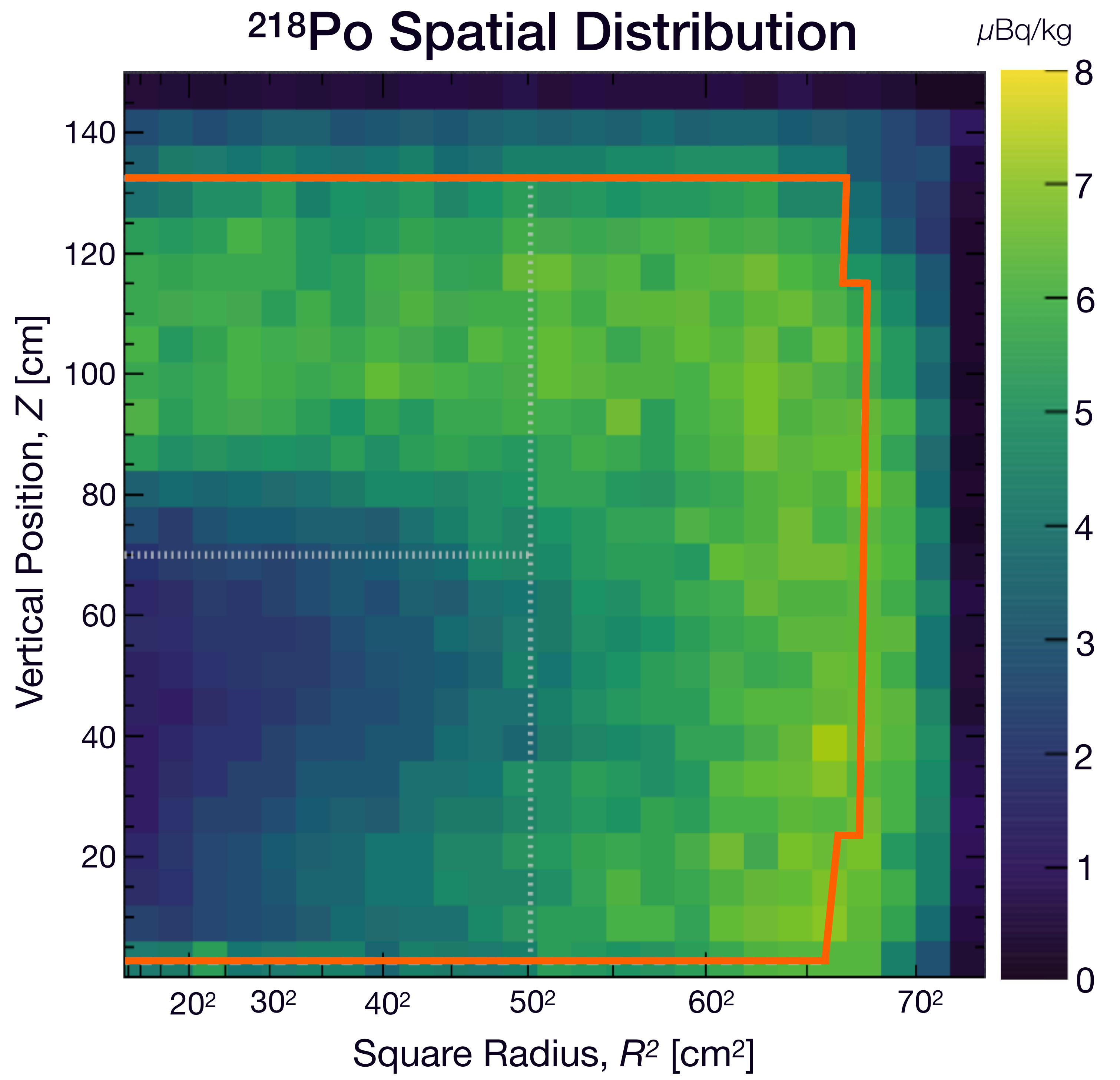
Background Modelling

Circulation and Rn Tagging

- ^{214}Pb is a daughter of ^{222}Rn which emanates into LXe from detector walls
- LZ controls Xe flow inside the TPC using circulation controls
  - Warm inbound LXe and extra cooling power in GXe promotes convection—*High mixing state*
  - Cooler inbound LXe results in natural temperature gradient and slow flow—*Low mixing state*



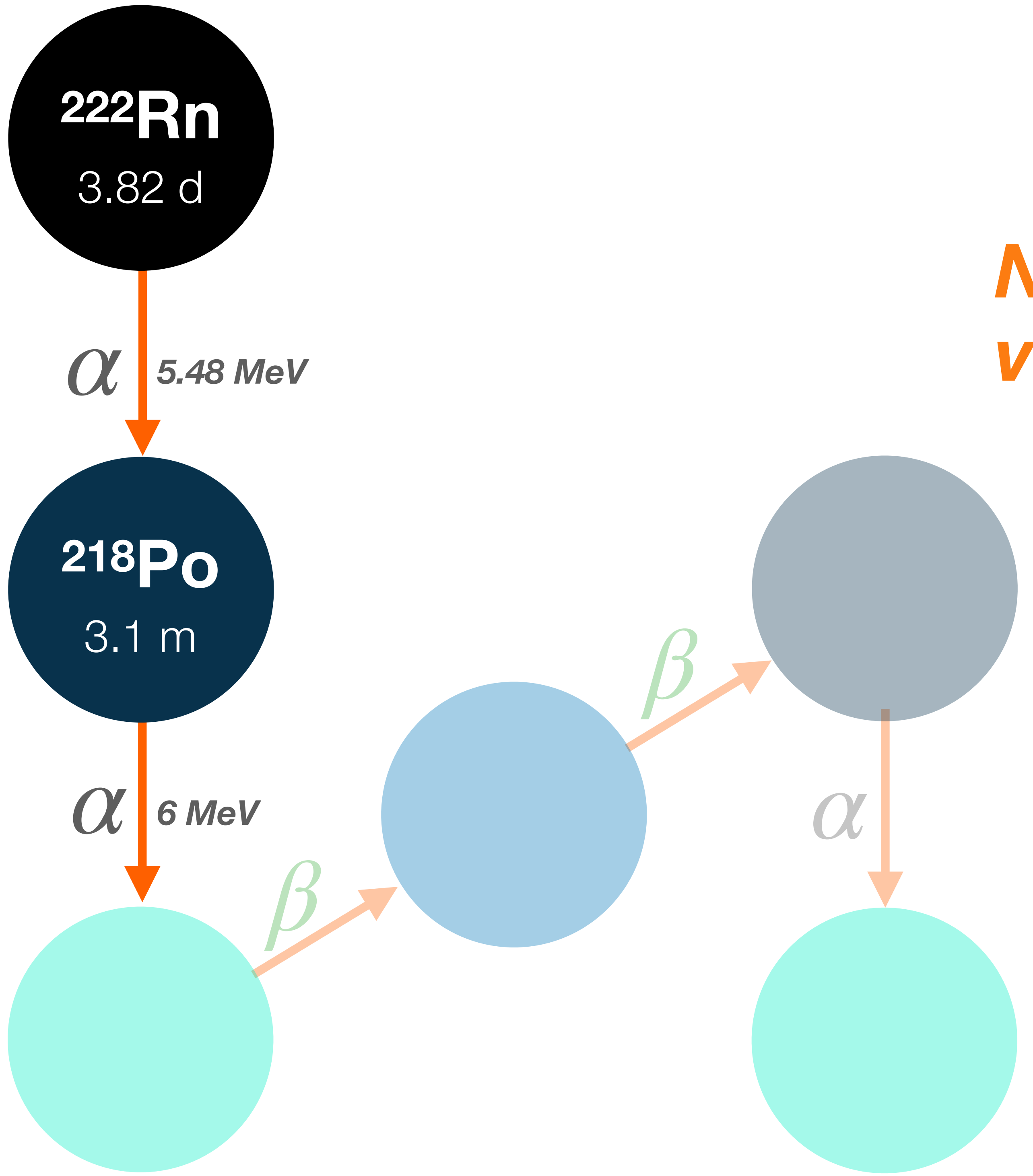




Background Modelling

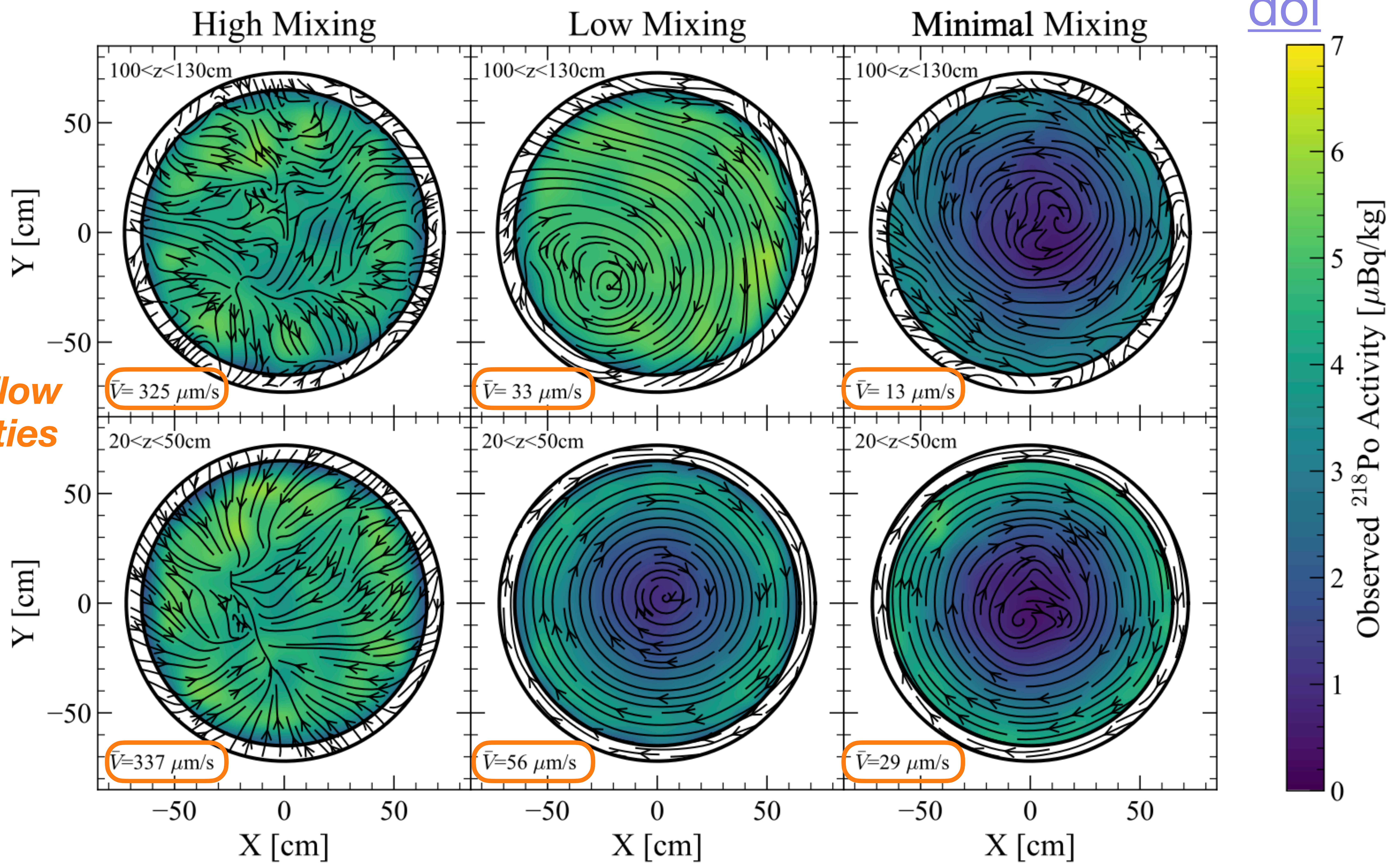
Circulation and Rn Tagging

Measure and model flow with Rn-Po α pairs



Note flow velocities

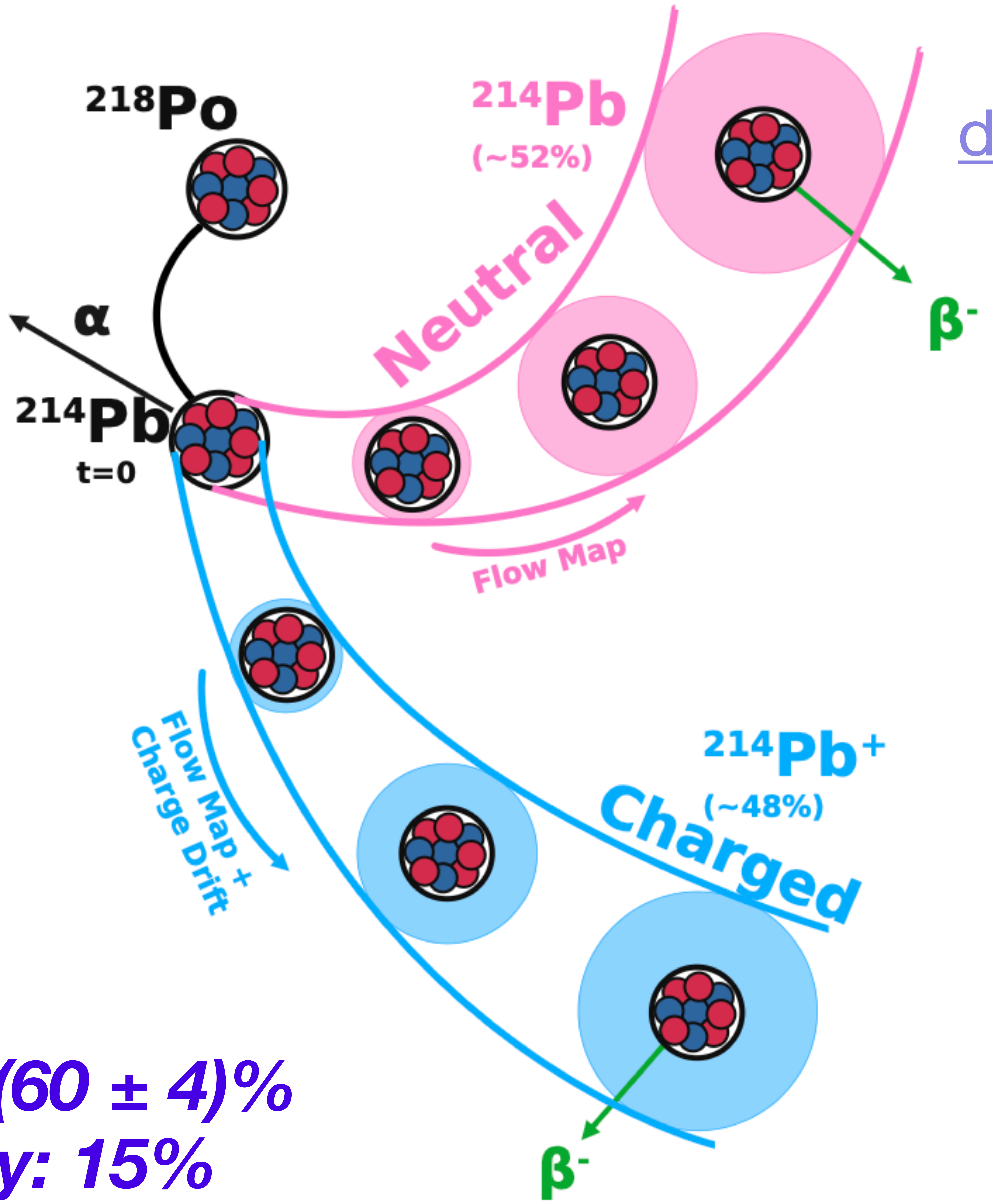
doi



Background Modelling

Circulation and Rn Tagging

- Track movement of ^{214}Pb atoms using flow modelling
- Define tagging volumes where ^{214}Pb is most likely to be found
  - Two possible trajectories based on the charge of ^{214}Pb atom
- Each tagging volume is active for $3 \times T^{1/2}_{^{214}\mathrm{Pb}}$ (~81 mins)
- Both “Tagged” and “Untagged” events kept in WIMP search, in separate samples



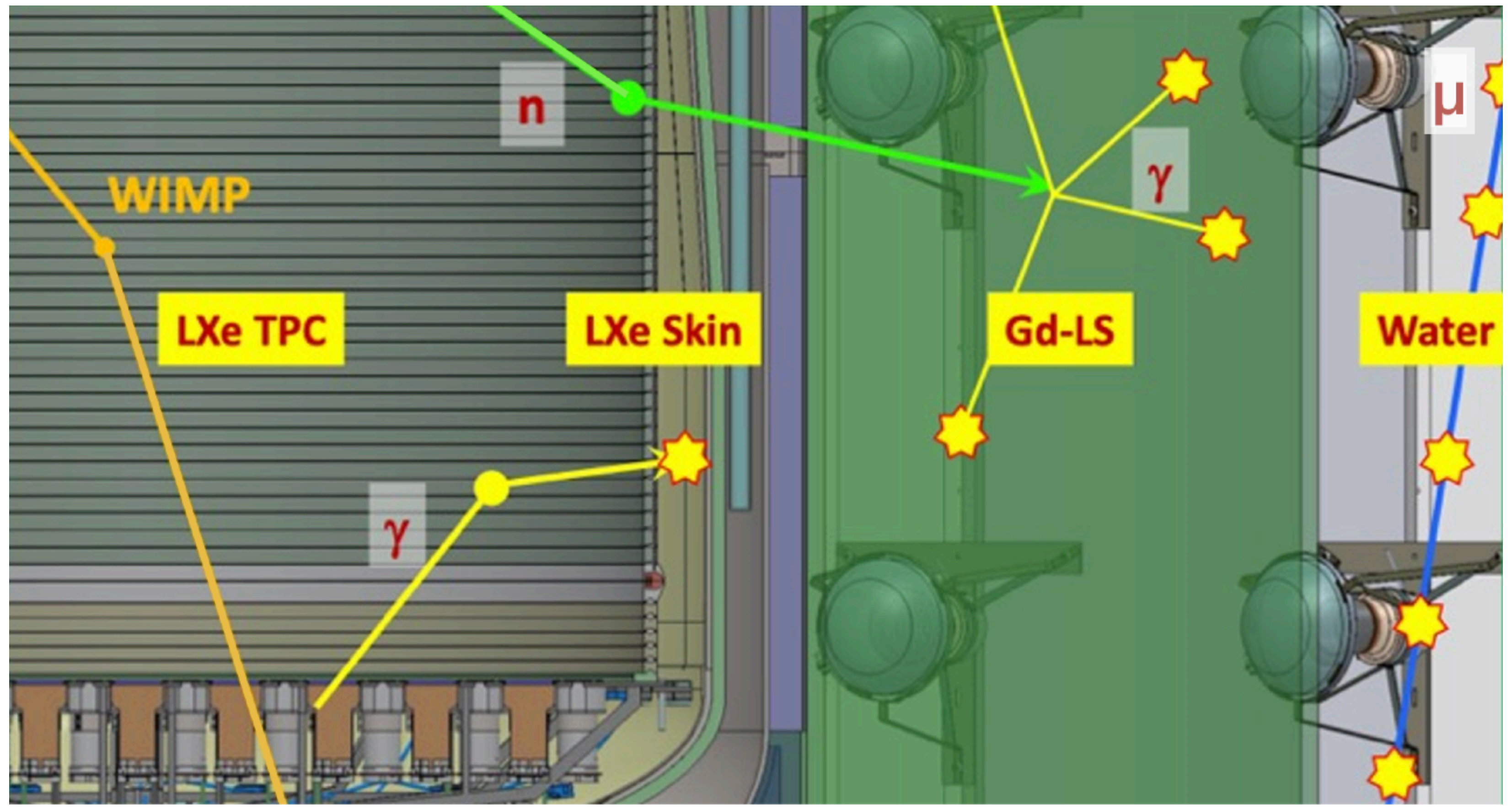
doi

Tagging Efficiency: (60 ± 4)%
False Tag Probability: 15%

Background Modelling

NR Backgrounds

- Most dangerous NR background is radiogenic neutrons
    - Mitigated with an active anti-coincidence veto system
- Outer detector comprises water tank, Gd-loaded liquid scintillator, and LXe skin
- Gd has high thermal neutron capture cross-section
    - Produces 8 MeV γ cascade

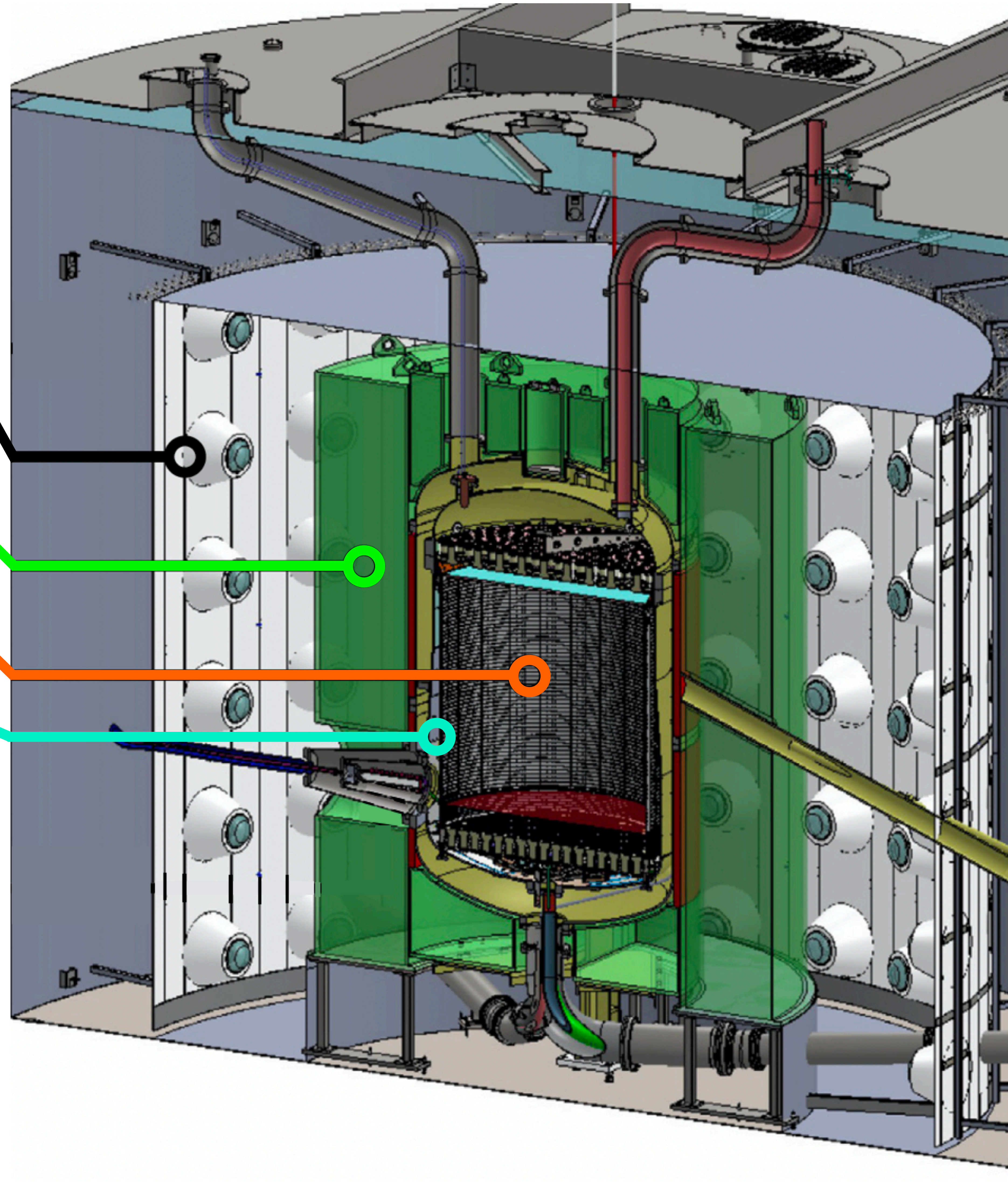


Outer Detector (OD) PMTs

Gadolinium loaded Liquid Scintillator

Active TPC Region

LXe Skin



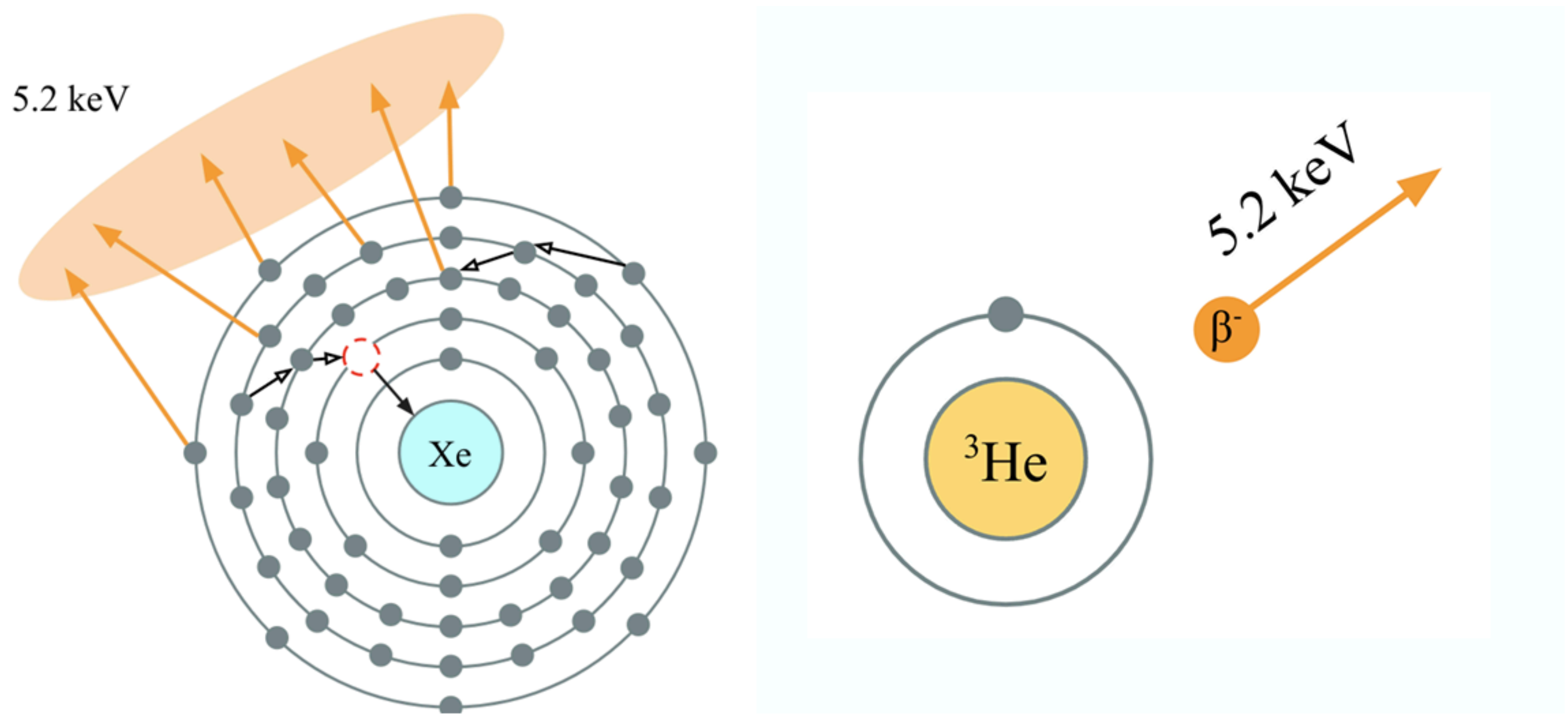
OD Neutron Tagging Efficiency: (92.2 ± 4.3)%

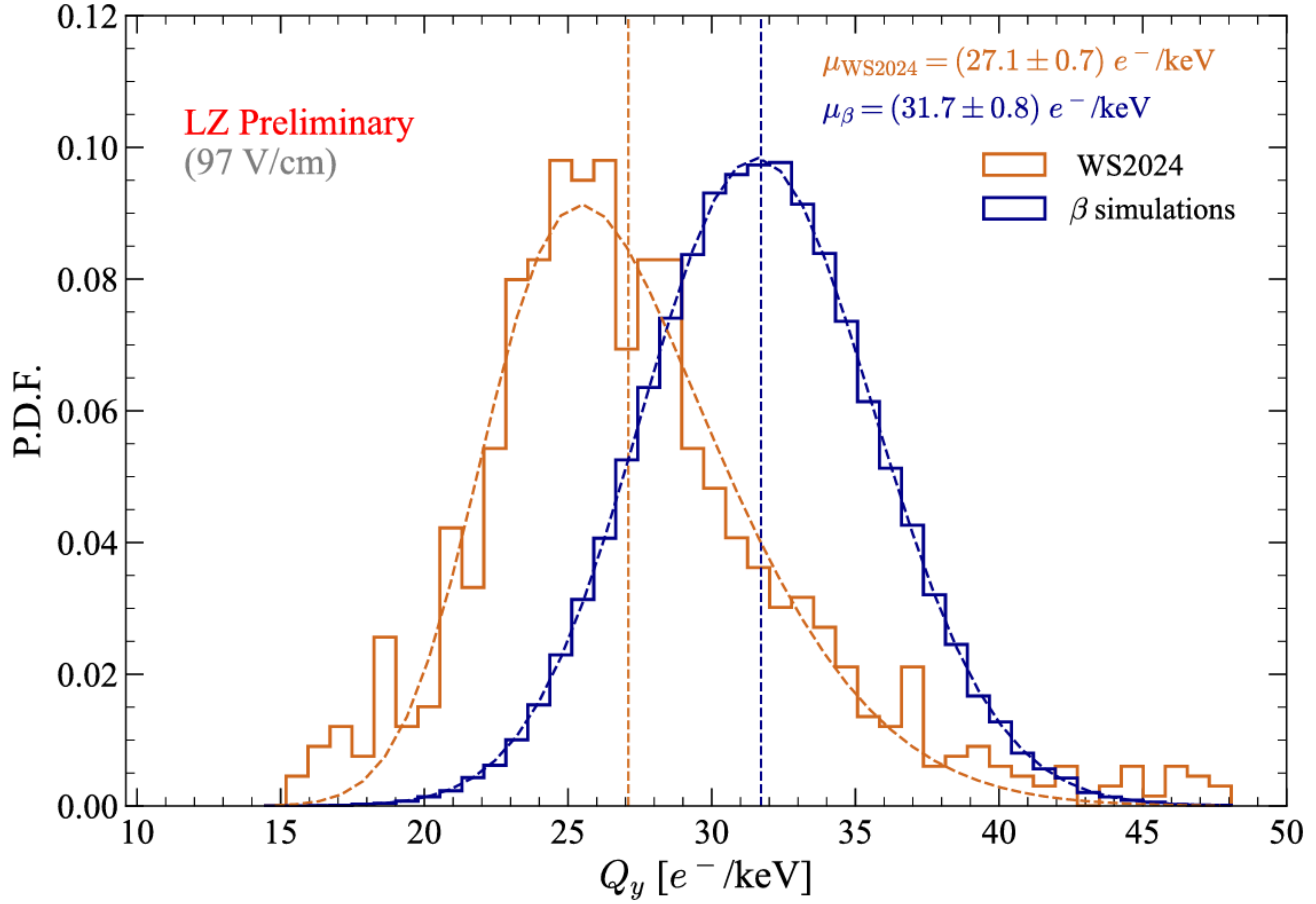
Background Modelling

Recombination Enhancement of ^{124}Xe DEC

- Auger/X-ray cascade produce more nucleated energy depositions compared to single β decays
- Higher ionisation density leads to greater recombination probabilities, and reduced charge yield
- First observed in XELDA experiment (doi) in ^{127}Xe L-shell electron captures
  - M-shell captures are lower energy, produce much less dense Auger cascade compared to L-shell—i.e. negligible recombination enhancement
- In-situ charge suppression factor for this analysis:

$$Q_L/Q_\beta = 0.86 \pm 0.01$$



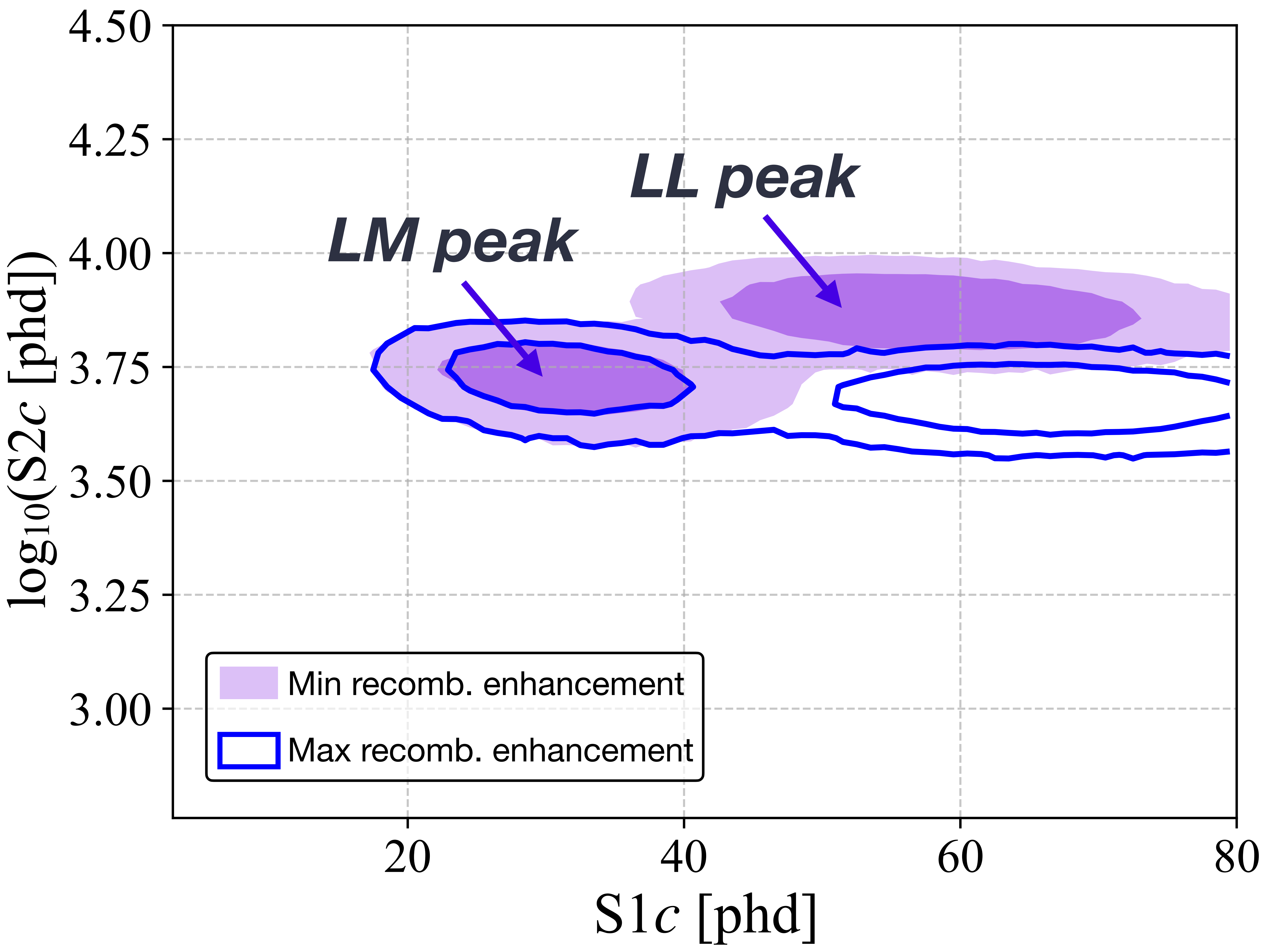


Background Modelling

Recombination Enhancement of ^{124}Xe DEC

- ^{124}Xe DECs produces two peaks in the WIMP search ROI
  - LL capture: 10.4 keV
  - LM capture: 5.94 keV
- LM capture is treated with the same recombination enhancement as a single L-shell capture
- It's unclear how much recombination enhancement will be observed for LL captures
  - Can potentially vary between the same amount as in single L-shell capture and double that amount
- We assume:

$$0.65 \leq Q_{LL}/Q_{\beta} \leq 0.86$$



The Analysis Pipeline

Statistical Inference

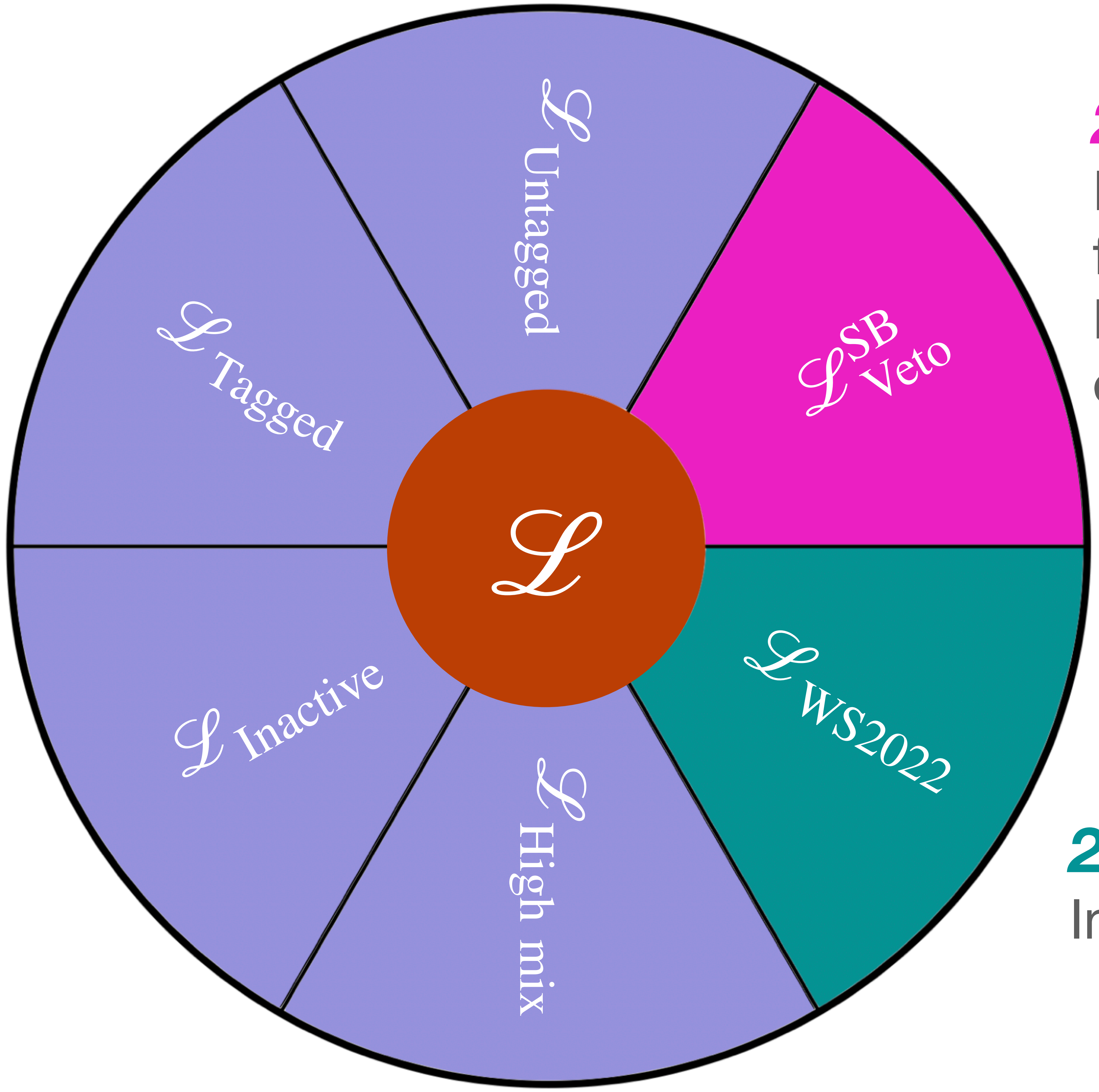
Profile Likelihood

- WIMP search conducted using a frequentist profile likelihood hypothesis testing procedure in discovery mode
- Likelihood function combines 6 sub-likelihoods describing 6 data samples

2024 WIMP Search Samples

Includes:

- Data from high mixing state
- Data from low mixing state during periods when Rn-tagging was inactive (i.e. circulation interruptions)
- Data from low mixing state, with positive radon tag
- Data from low mixing state with negative radon tag



2024 Veto Sideband Sample

Included to constrain neutrons from detector components—Doesn't contribute to WS2024 exposure

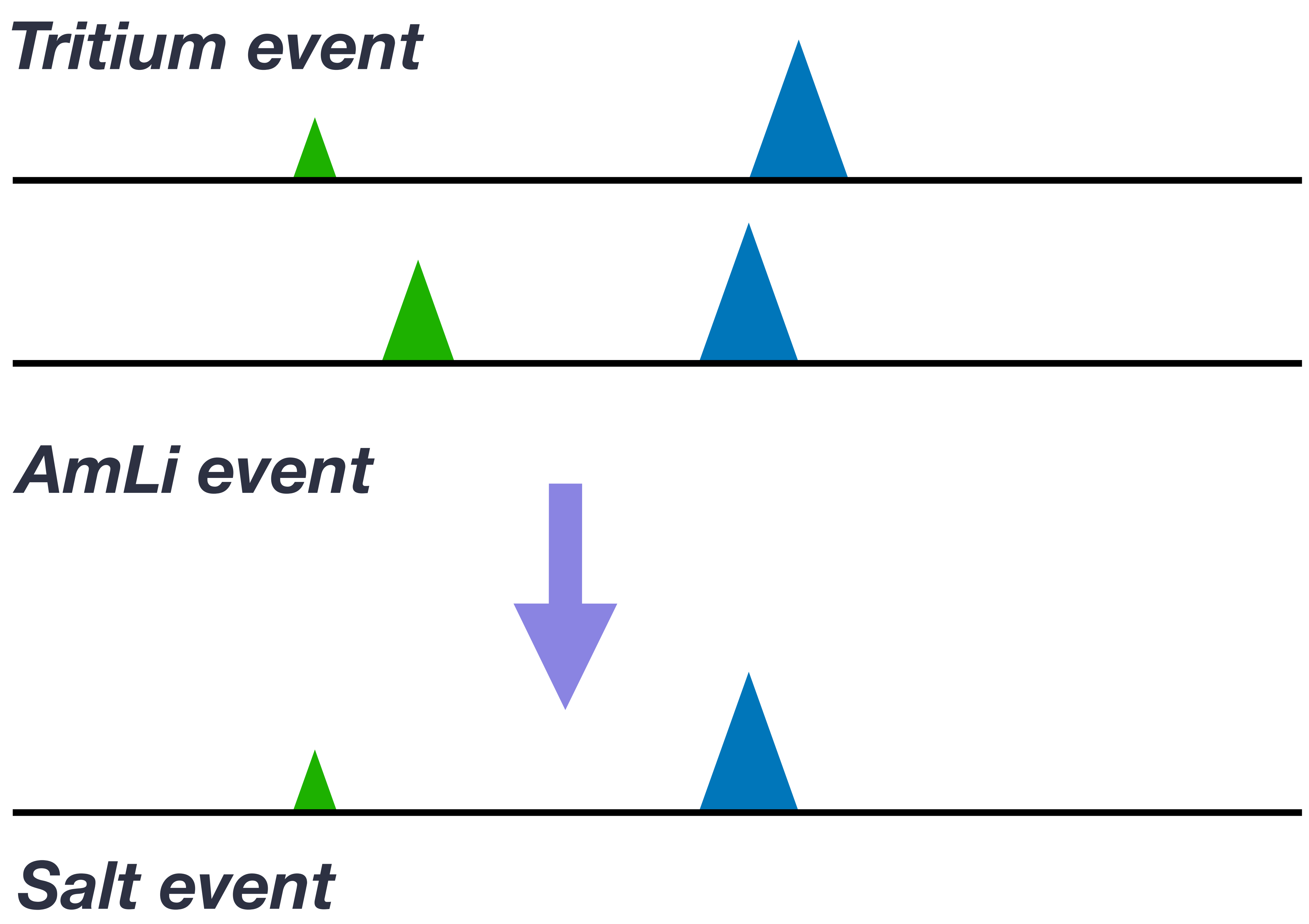
2022 WIMP Search Sample

Included to maximise exposure

Statistical Inference

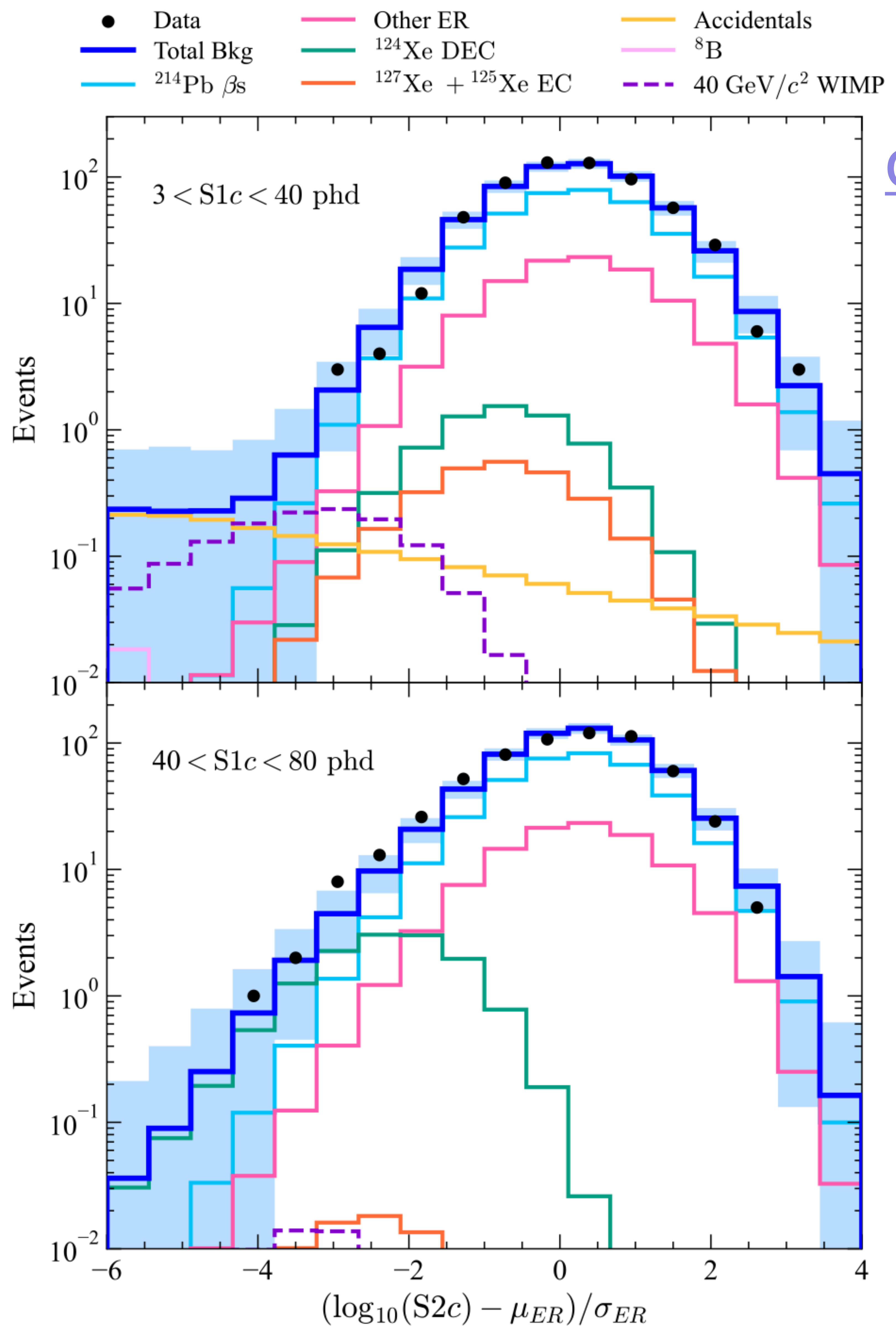
Salting

- Bias mitigation for this analysis was done via the salting method
- Similar to the chop-stitch approach, salt events were generated by combining S1 and S2 pulses tritium and Americium-Lithium (AmLi) calibration data
- Pulse sizes were selected such that their NR energy spectrum followed a WIMP spectrum + flat distribution



Statistical Inference

- Stringent goodness-of-fit checks performed in several data spaces:
  - S1c
  - $\log_{10}$(S2c)
  - $(\log_{10}(\text{S2c}) - \mu_{ER})/\sigma_{ER}$
  - Reconstructed Energy
  - 2D {S1c, $\log_{10}$(S2c)}
- Best-fit results pass Holm-Bonferroni test with significance level of 0.05 before unsalting
  - Log-poisson p-value calculated for each sub-sample in each space
  - Significance level adjusted for checking significance in 6 sub-samples

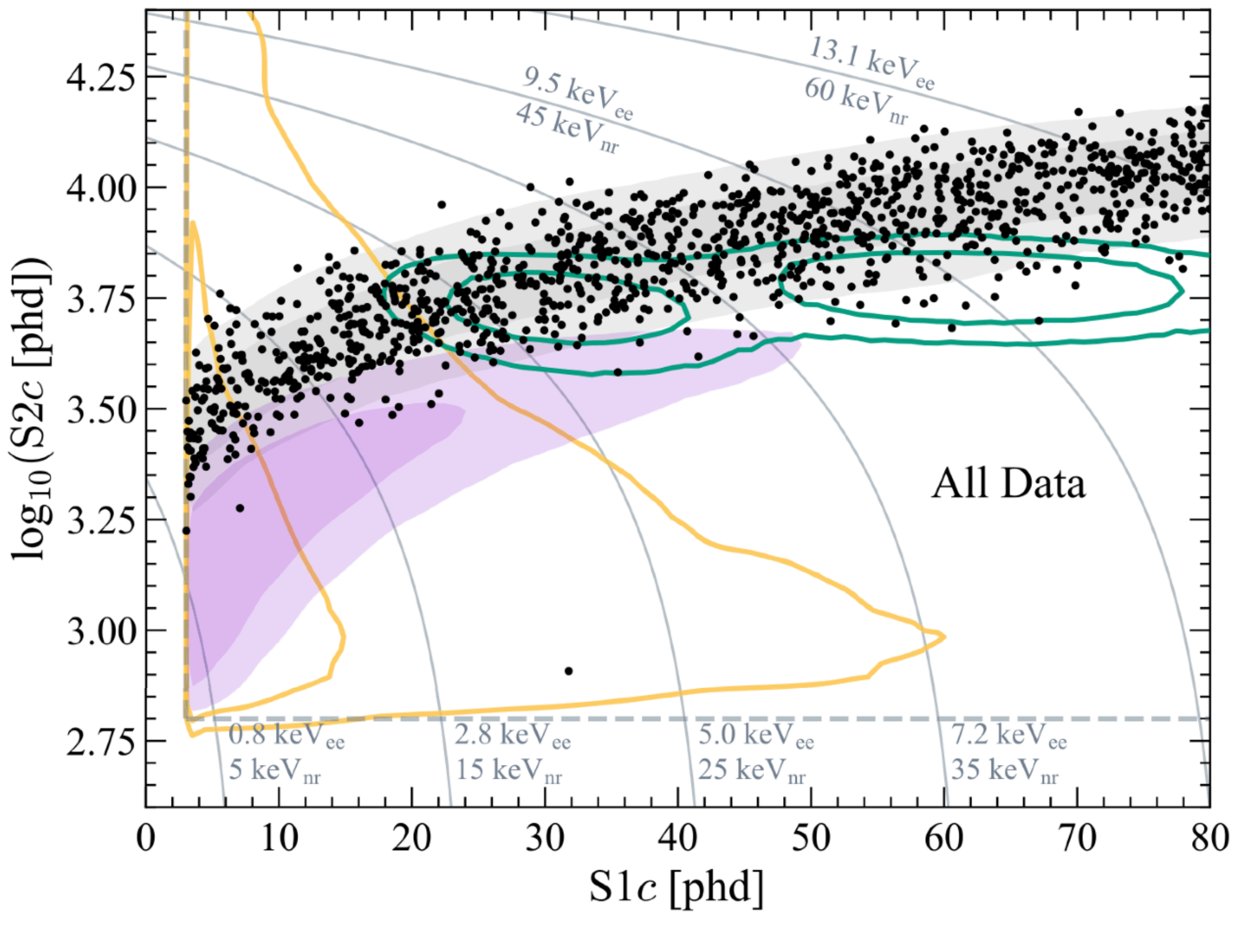


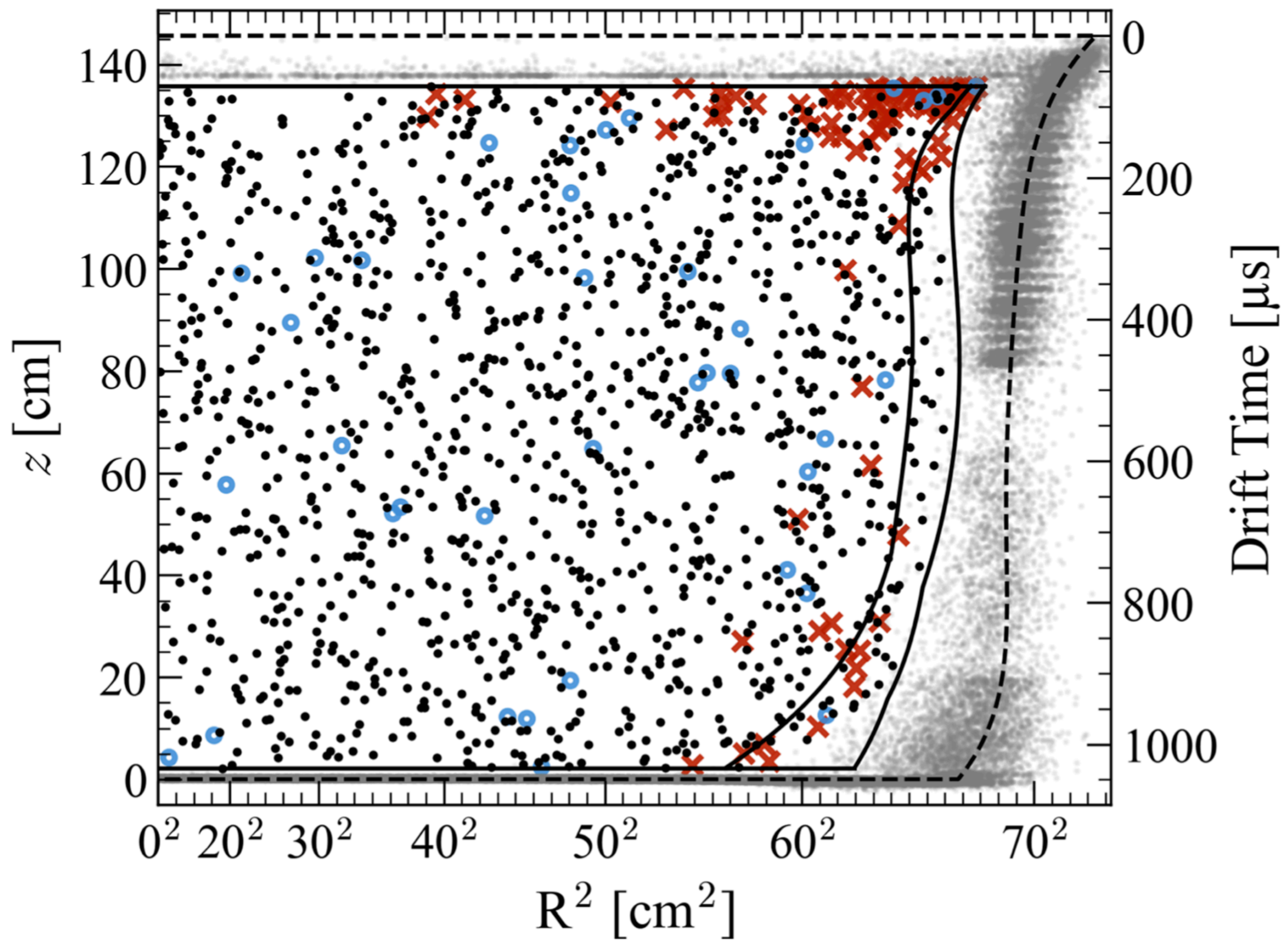
doi

The Analysis Pipeline

Final Results

- Total number of observed events: 1220
  - Agrees with pre-fit expectation: 1210 ± 91
- 8 salt events were injected into the dataset with only one failing data quality cuts



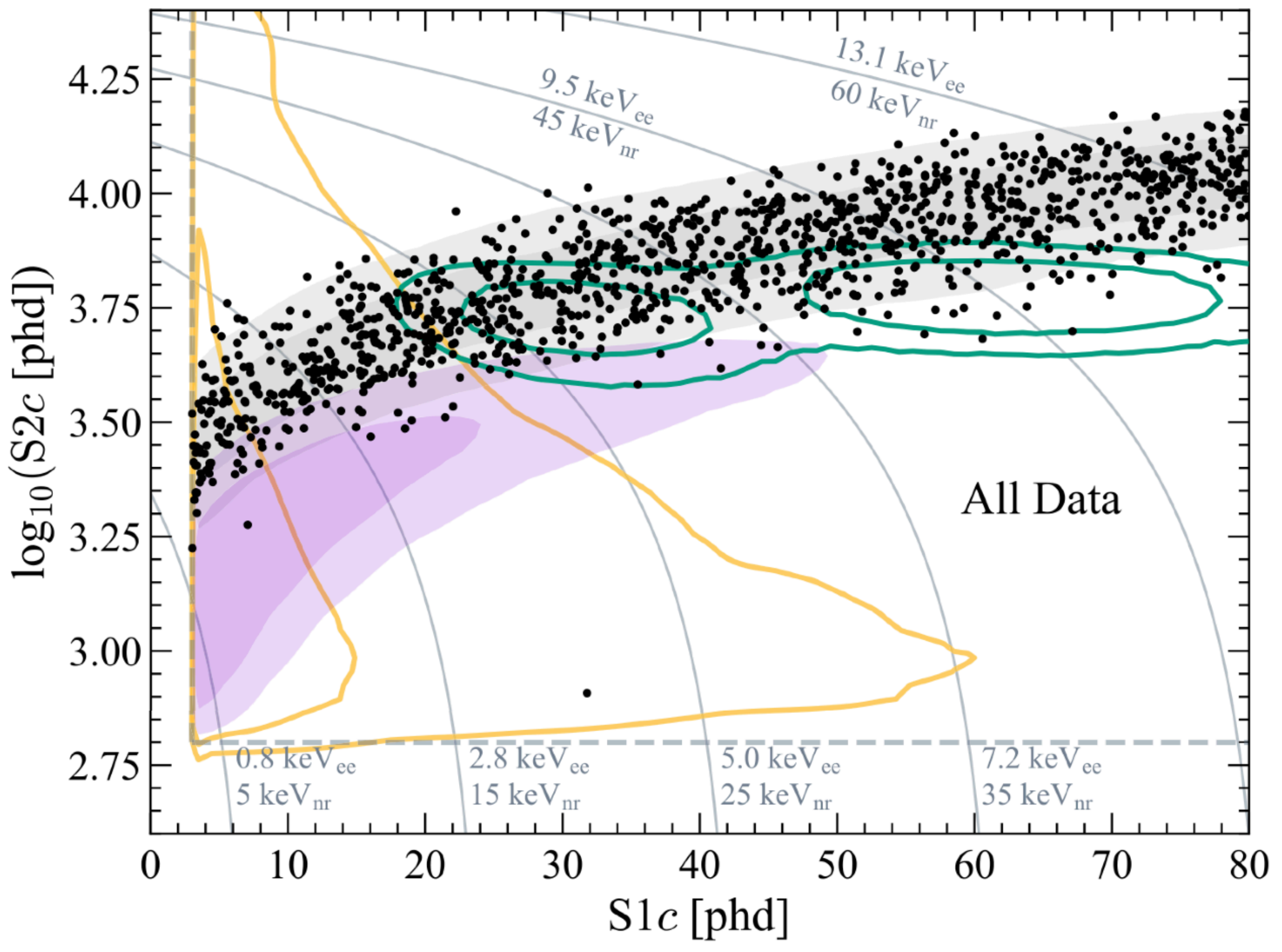


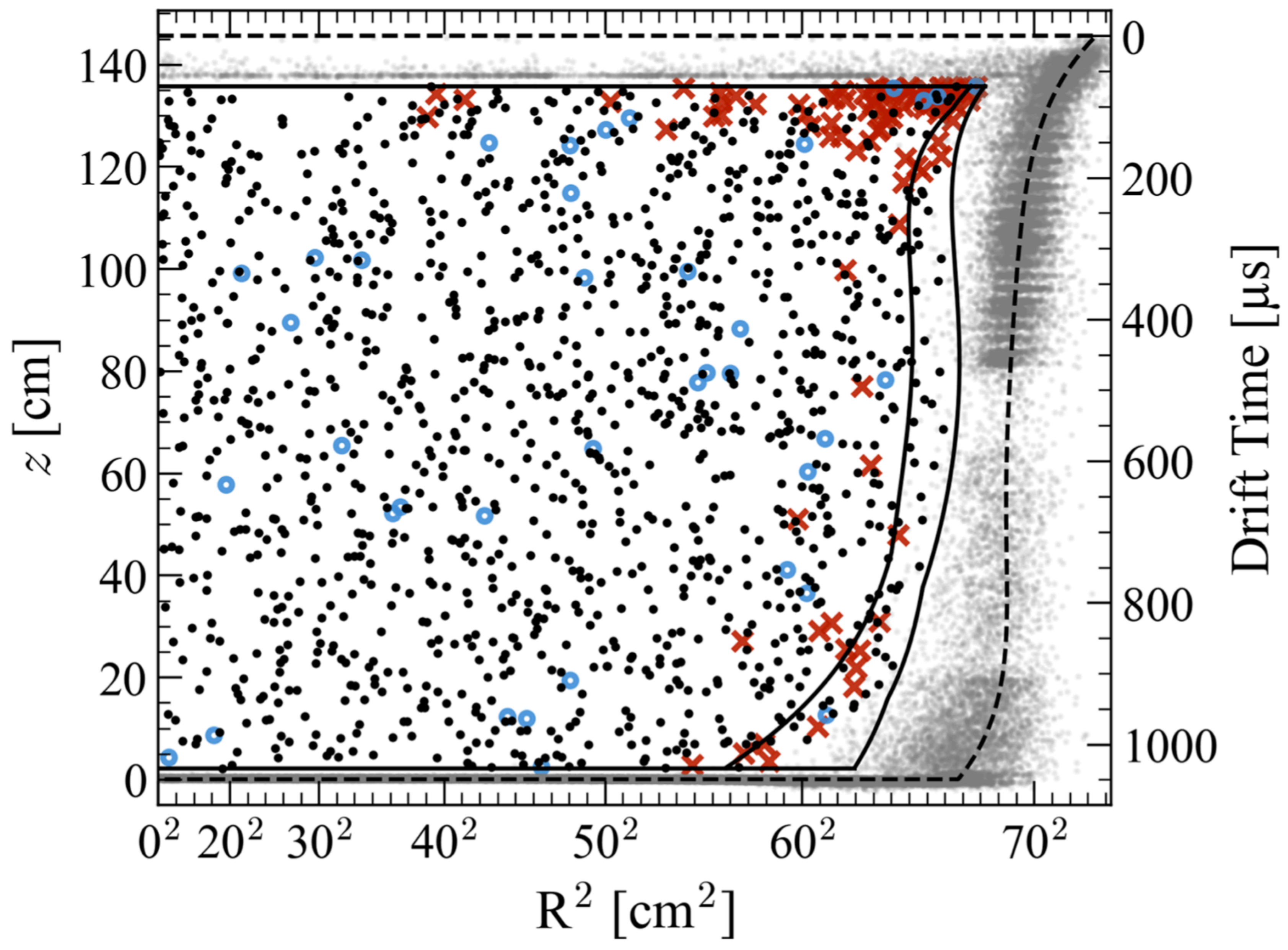
Source	Prefit expectation
^{214}Pb βs	743 ± 88
^{85}Kr + ^{39}Ar βs + det. γs	162 ± 22
Solar ν ER	102 ± 6
^{212}Pb + ^{218}Po βs	62.7 ± 7.5
Tritium + ^{14}C βs	58.3 ± 3.3
^{136}Xe $2\nu\beta\beta$	55.6 ± 8.3
^{124}Xe DEC	19.4 ± 2.5
^{127}Xe + ^{125}Xe EC	3.2 ± 0.6
Accidental coincidences	2.8 ± 0.6
Atm. ν NR	0.12 ± 0.02
^{8}B + hep ν NR	0.06 ± 0.01
Detector neutrons	$^{a}0.0^{+0.2}$
40 GeV/c^2 WIMP	...
Total	1210 ± 91

doi

Final Results

- Total number of observed events: 1220
  - Agrees with pre-fit expectation: 1210 ± 91
- 8 salt events were injected into the dataset with only one failing data quality cuts
- Data consistent with zero WIMPs



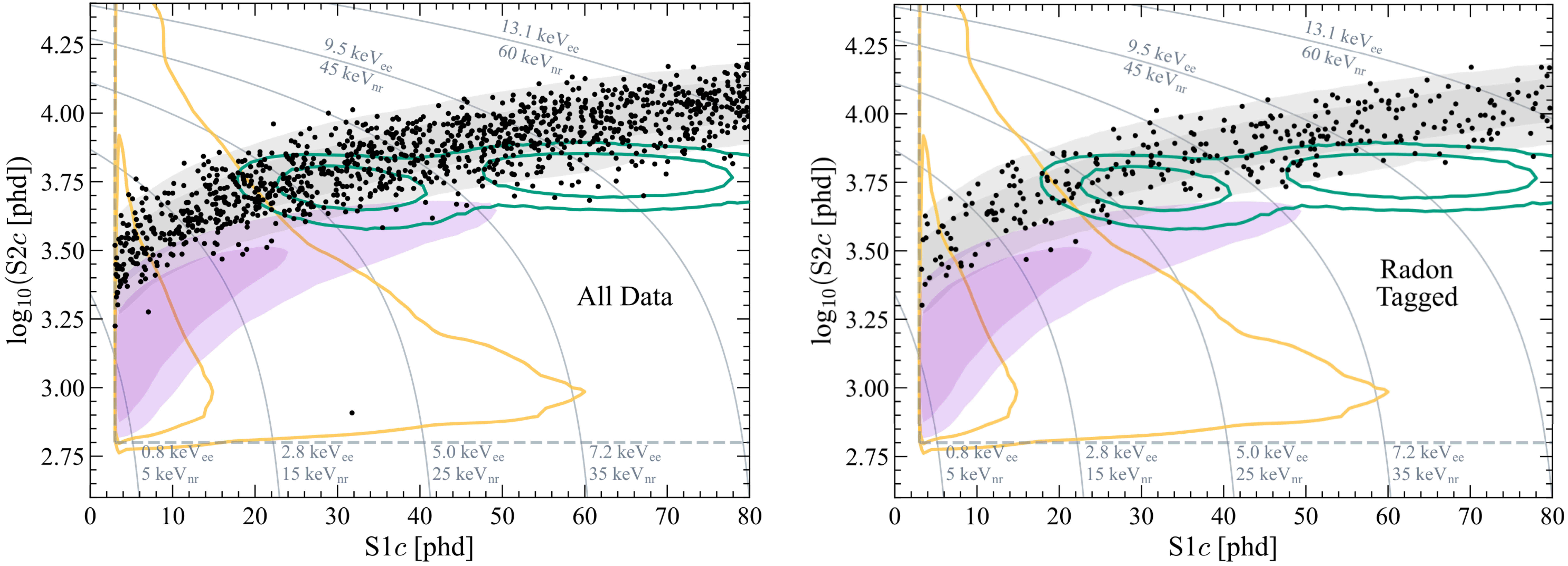


Source	Fit result
^{214}Pb βs	733 ± 34
^{85}Kr + ^{39}Ar βs + det. γs	161 ± 21
Solar ν ER	102 ± 6
^{212}Pb + ^{218}Po βs	63.7 ± 7.4
Tritium + ^{14}C βs	59.7 ± 3.3
^{136}Xe $2\nu\beta\beta$	55.9 ± 8.2
^{124}Xe DEC	20.4 ± 2.4
^{127}Xe + ^{125}Xe EC	2.7 ± 0.6
Accidental coincidences	2.6 ± 0.6
Atm. ν NR	0.12 ± 0.02
^{8}B + hep ν NR	0.06 ± 0.01
Detector neutrons	$0.0^{+0.2}$
40 GeV/c^2 WIMP	$0.0^{+0.6}$
Total	1202 ± 41

doi

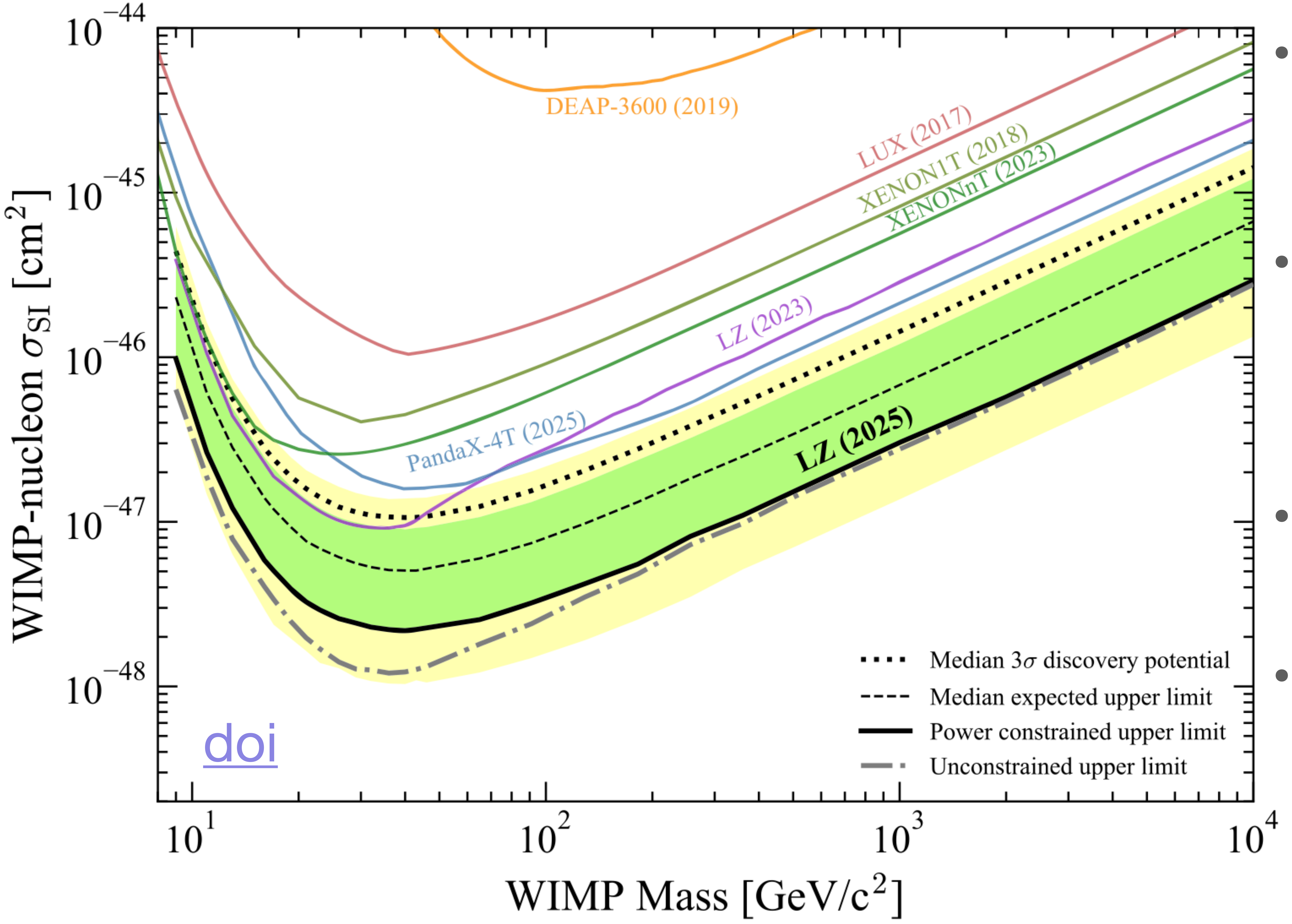
Final Results

- Radon tagged sample is enriched in single β decays from ^{214}Pb and relatively depleted in other ERs, including ^{124}Xe DECs
  - Best-fit Q_{LL}/Q_{β}: 0.70 ± 0.04
- Lack of events overlapping with best-fit ^{124}Xe LL peak in Rn-Tagged sample suggests Rn-Tagging method is highly effective



doi

Final Results



- Combined analysis achieves world-leading upper limits on spin-independent WIMP scattering
- 1σ power constraint applied for all WIMP masses
  - Attributed to under-fluctuation of Accidentals events
- Best exclusion achieved for WIMPs of mass 40 GeV/c^2, at 2.2×10^{-48} cm^2
- 3σ discovery potential achieved in previously unexplored parameter space

Thank you!