Latest Results and Status of the LUX-ZEPLIN Dark Matter

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RHUL

LZ (LUX-ZEPLIN) Collaboration, 38 Institutions

@lzdarkmatter

https://lz.lbl.gov/

250 scientists, engineers, and technical staff

- Black Hills State University
- Brookhaven National Laboratory
- Brown University
- Center for Underground Physics
- Edinburgh University
- Fermi National Accelerator Lab.
- Imperial College London
- King's College London
- Lawrence Berkeley National Lab.
- Lawrence Livermore National Lab.
- LIP Coimbra
- Northwestern University
- Pennsylvania State University
- Royal Holloway University of London
- SLAC National Accelerator Lab.
- South Dakota School of Mines & Tech
- South Dakota Science & Technology Authority
- STFC Rutherford Appleton Lab.
- Texas A&M University
- University of Albany, SUNY
- University of Alabama
- University of Bristol
- University College London
- University of California Berkeley
- University of California Davis
- University of California Los Angeles
- University of California Santa Barbara
- University of Liverpool
- University of Maryland
- University of Massachusetts, Amherst
- University of Michigan
- University of Oxford
- University of Rochester
- University of Sheffield
- University of Sydney
- University of Texas at Austin
- University of Wisconsin, Madison
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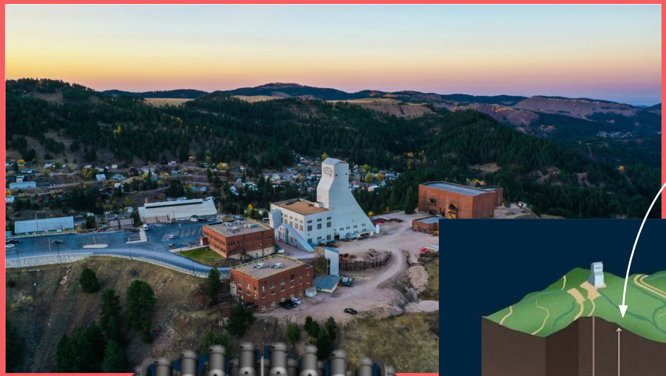
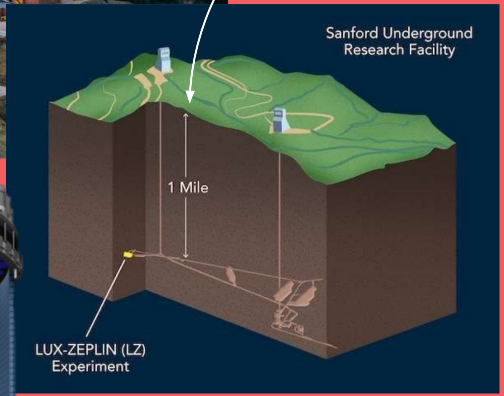
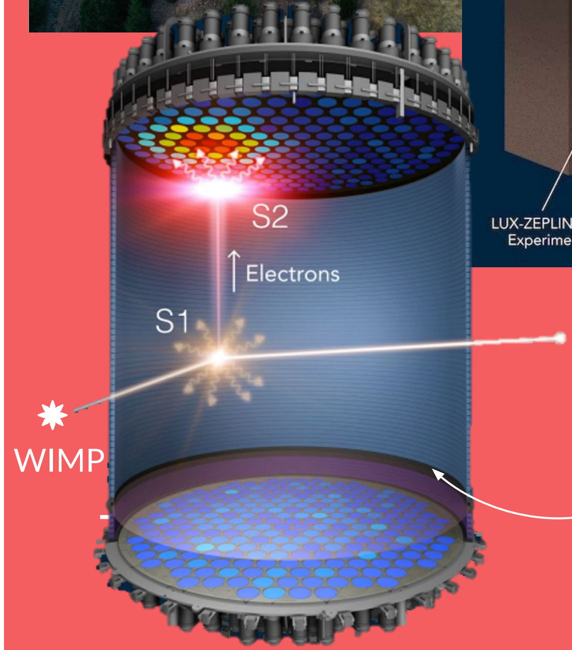
What is LZ?

- Direct dark matter detector
- 1 Mile underground at the Sanford Underground Research Facility, South Dakota
- Liquid xenon target for detection of WIMPs



Detector deep underground at SURF, South Dakota





Liquid xenon tank used to detect WIMPs!

Weakly Interacting Massive Particle – WIMP!

- 1GeV - 1TeV
- Interacts via weak force and gravity
  - Hence → Dark
- Very stable - doesn't decay on cosmological timescales

→ Very difficult to detect

Dark Matter

When we look at the universe, it seems like there should be more matter than we can see

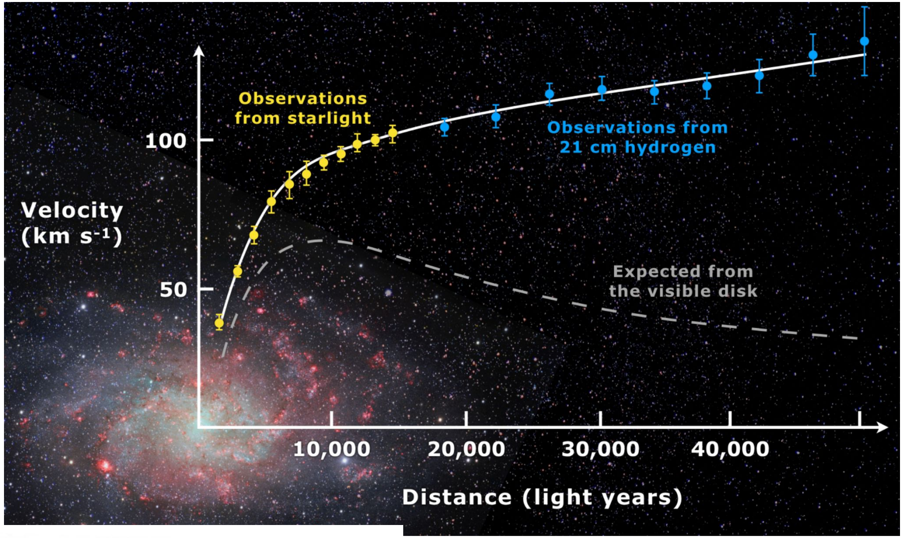
This phenomenon is what we're referring to when we discuss **Dark Matter**

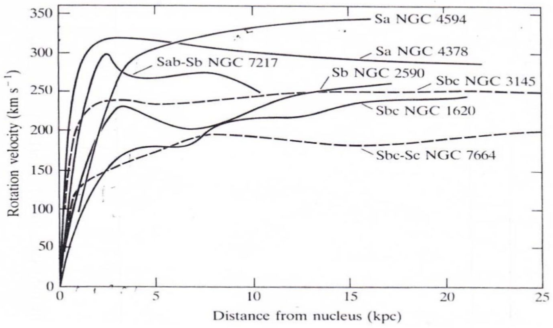
WIMPs → A theory of **dark matter**

Galaxy curves

- Plot orbital velocity of galaxy stars/gas vs. distance from galaxy center
  - **Expected**: Velocity curve decreases with distance from centre
  - **Observed**: curve remains flat
- Luminous matter accounts for only ~10-20% required mass
- Must be more matter we can't see?

→ **Dark matter?**

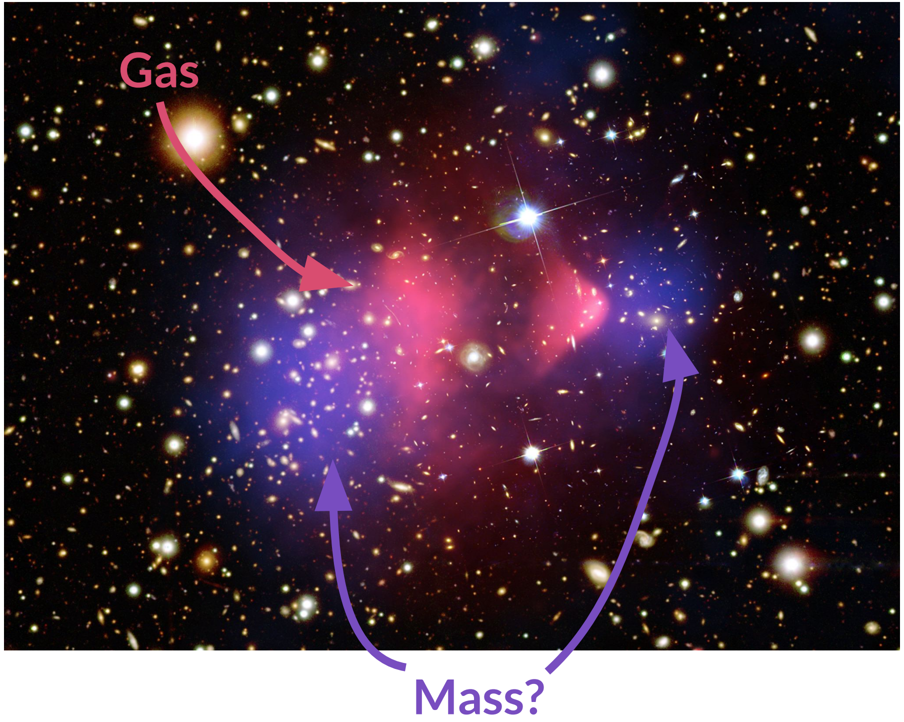




Bullet Cluster

- Bullet cluster
  - Two galaxy clusters collide
  - Gas from clusters collides and slows
- Gas is luminous → Emitting a lot of X-rays
- Mass can be mapped using gravitational lensing
- Gas makes up most of visible mass- not galaxies
- Mass is not where it ~should~ be?
- Seen in many cluster collisions

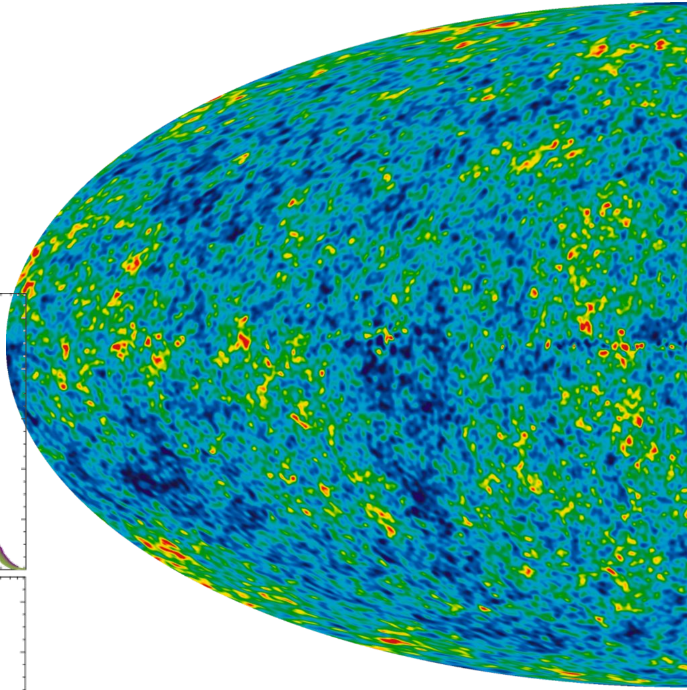
→ **Dark matter?**

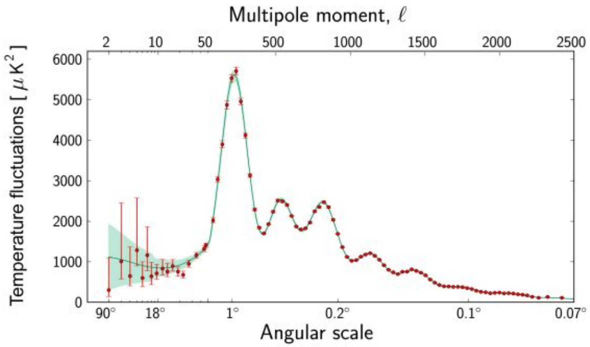


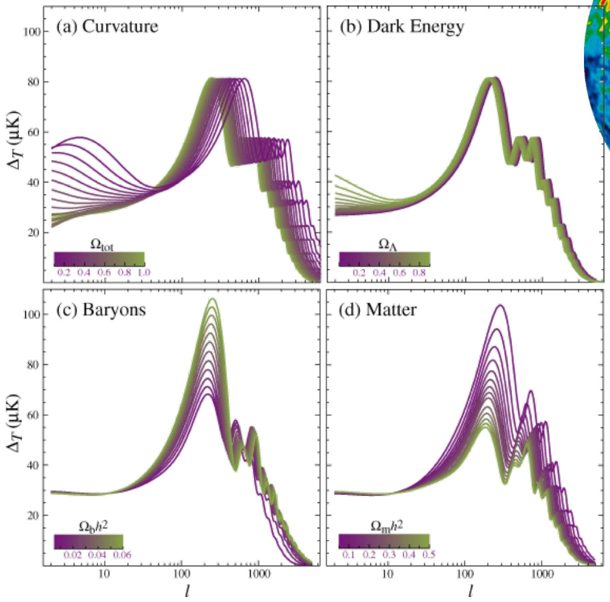
Cosmic Microwave Background

- Radiation from the early universe
- Temperature fluctuations at different angular scales across the CMB

→ **Dark matter?**



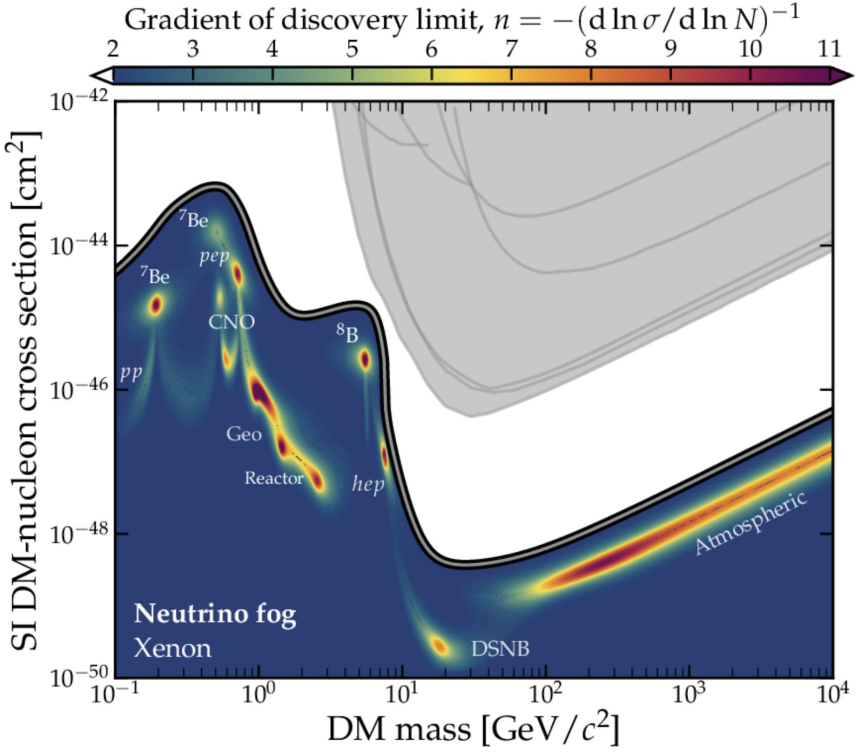




Current state of affairs..

- WIMPs fit cosmological data very well
  - "WIMP miracle"
- Seemed like the perfect solution until..

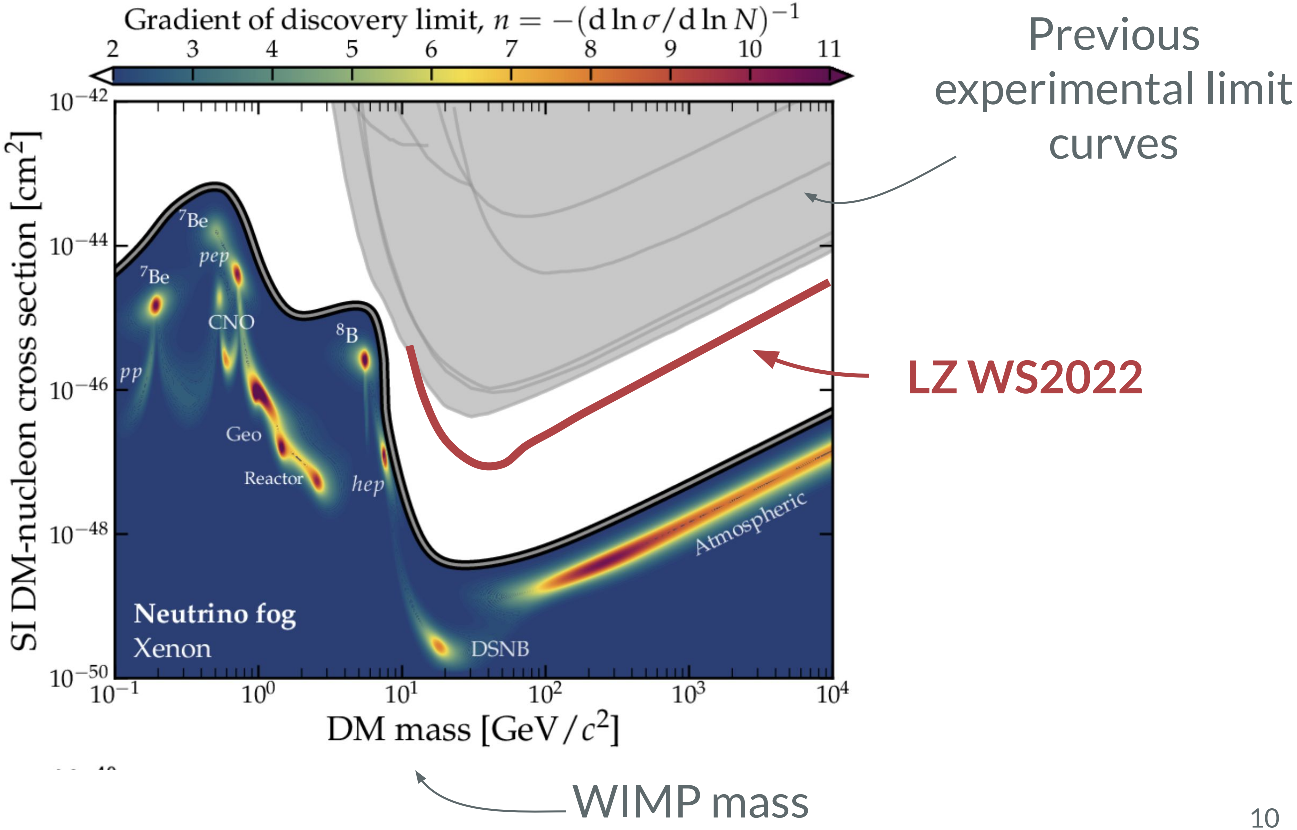
  We didn't find them



Limit curves

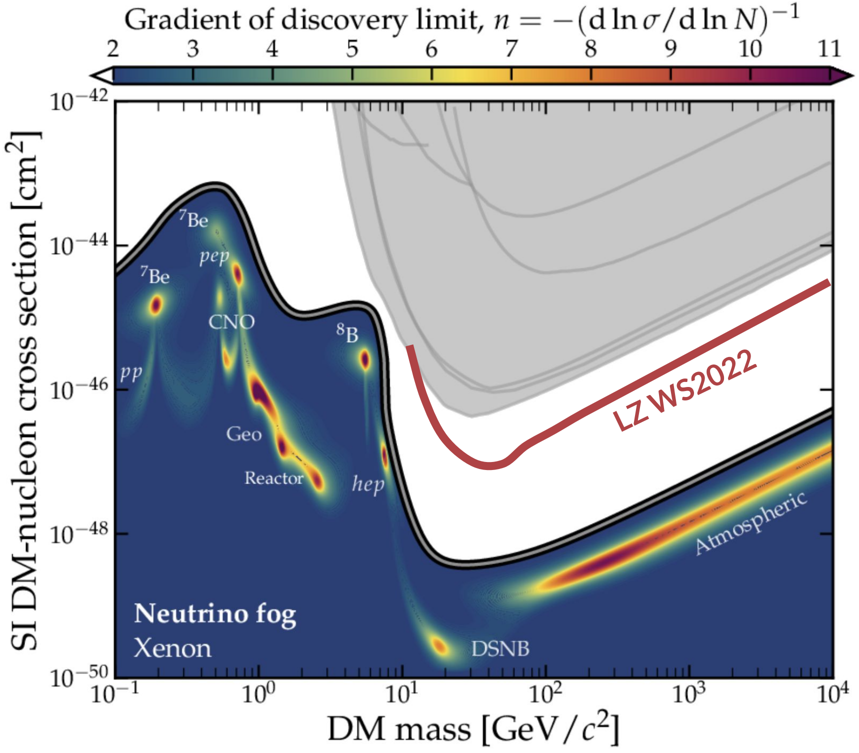
Set limits on maximum possible interaction rate for different WIMP masses

→ Construct limit curve



Current state of affairs..

- WIMPs fit cosmological data very well
  - "WIMP miracle"
- Seemed like the perfect solution until.. We didn't find them
- Getting dangerously close to neutrino fog
  - WIMP signal becomes near indistinguishable from neutrino background
- Still plenty of parameter space!!

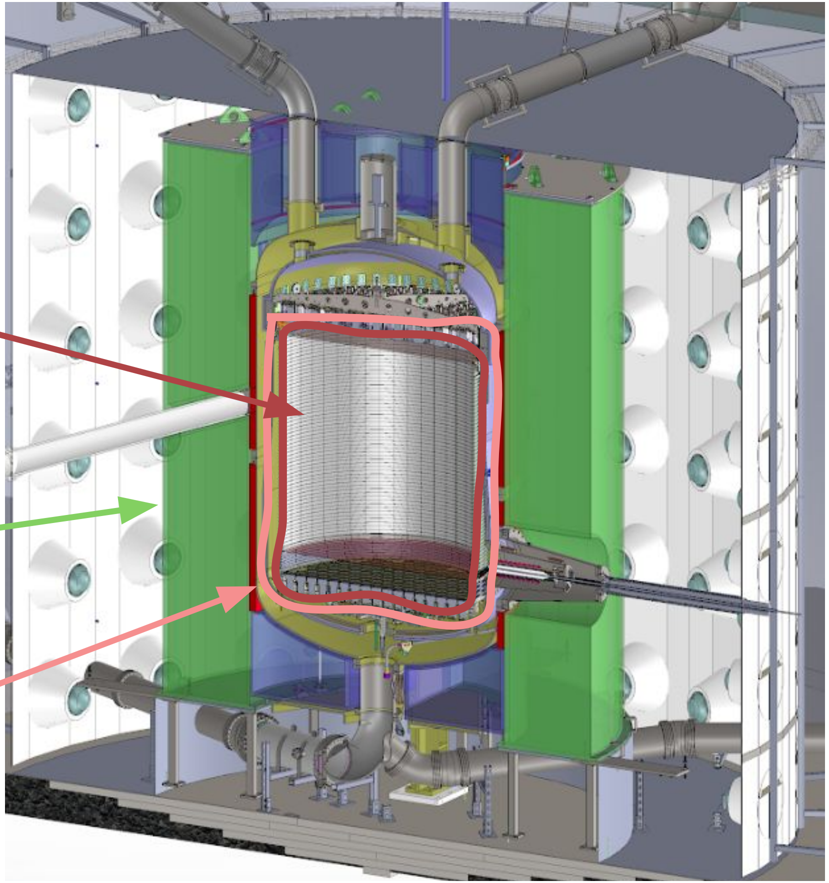


Back to LZ...

- Detector: Dual-phase liquid xenon time projection chamber (**TPC**)
- 7 tonne liquid xenon target
- gaseous xenon layer
- PMT arrays above and below

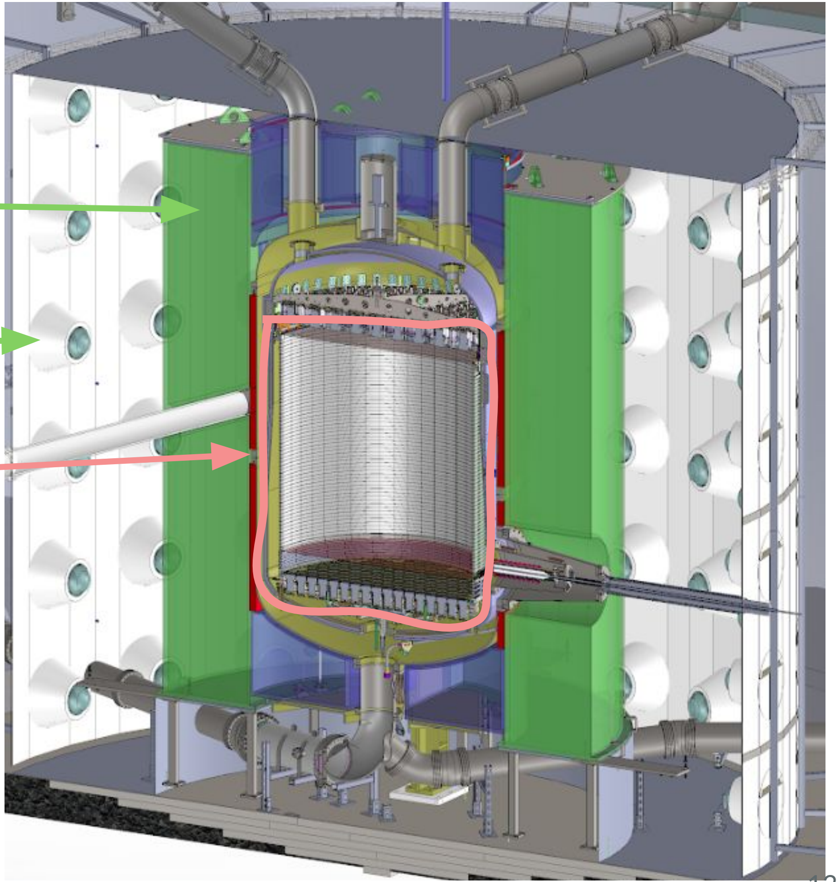
Used to characterise and veto background

- **Outer detector**
- **Skin detector**

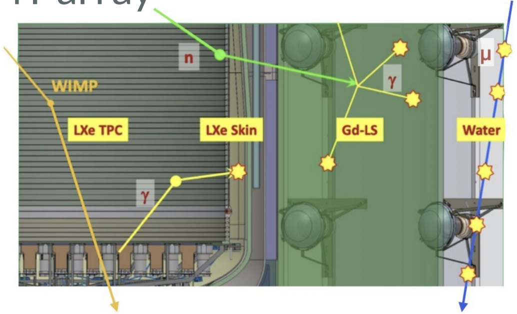


Veto Detectors

- Outer Detector (**OD**)
  - Acrylic tanks filled with Gadolinium loaded liquid scintillator
  - OD PMTs
- **Skin** detector
  - Thin layer of liquid xenon outside TPC
  - Additional PMT array

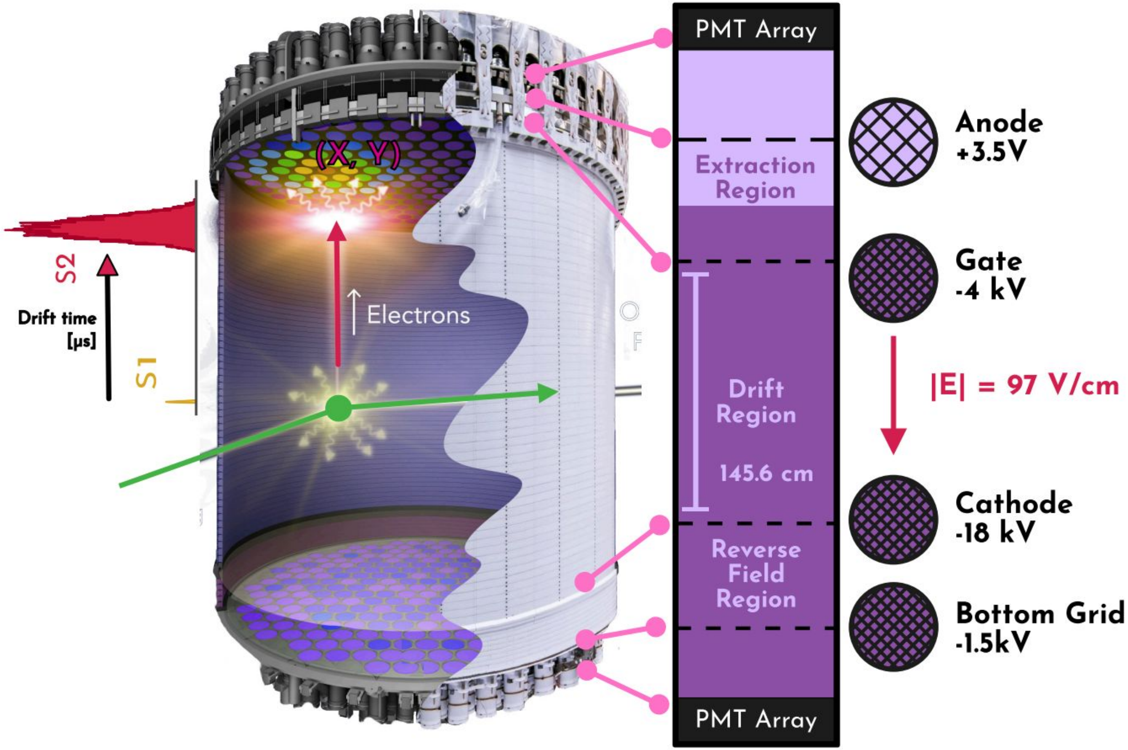


- OD → Tags neutron events
- Skin → Tags gamma background events



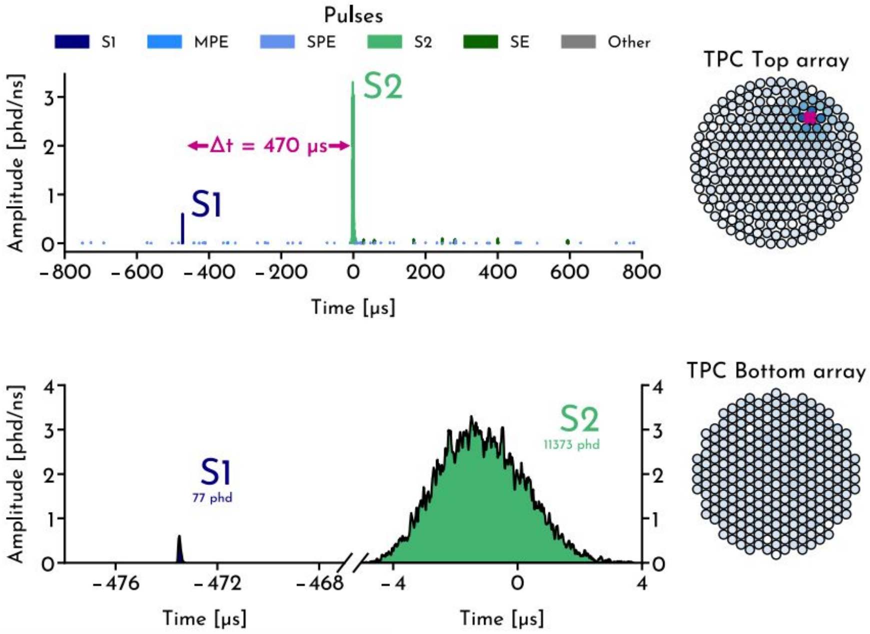
Interaction in the TPC

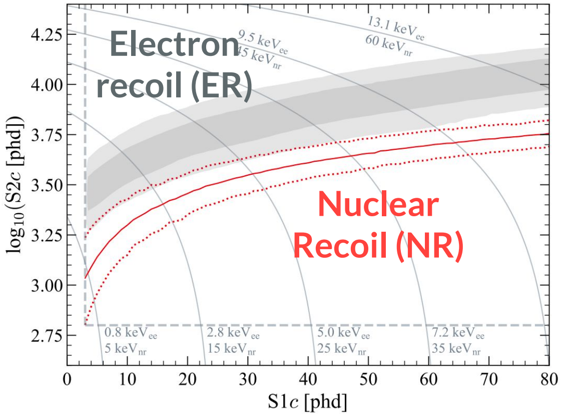
- Incoming particle produces electron/nuclear recoil
- Two signals produced
  - Scintillation light (S1)
  - Ionisation electrons (S2)
- Electrons drifted to gaseous xenon
  - S2 signal produced by ionisation of electrons
- 3D reconstruction
  - X,Y from PMT hit pattern
  - Z from time electrons take to drift



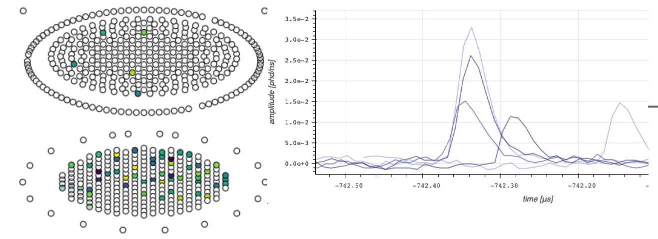
Interaction in the TPC

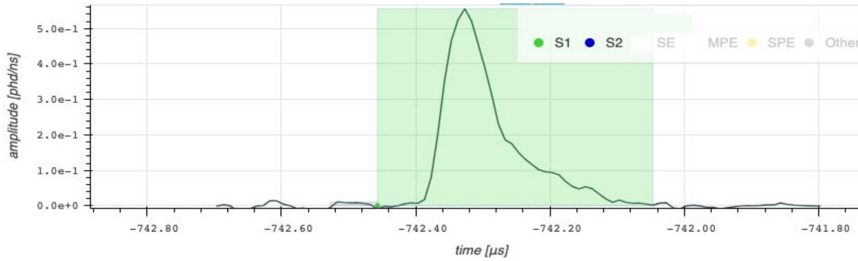
- S2 larger than S1
- Ratio of S1 size to S2 size used to distinguish **ER** vs **NR** events
  - **ER** - Electron recoil
  - **NR** - Nuclear Recoil
  - Larger relative S2 for **ER** events
  - Smaller relative S2 for **NR** events
- Most WIMP events expected to be **NR**, most background **ER**
- Xenon is particularly good for ER/NR distinction





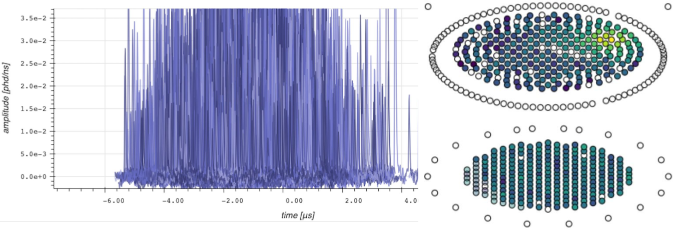
Analysis pipeline - Data

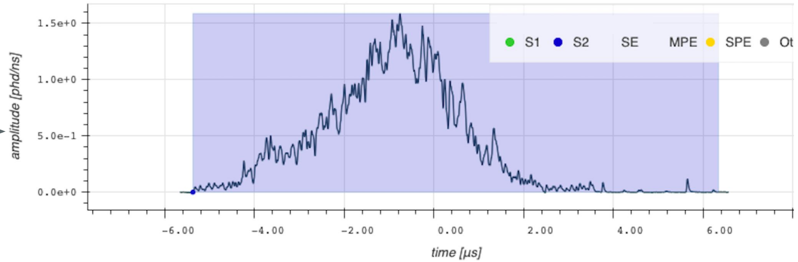




PMT readouts

Reconstructed pulses

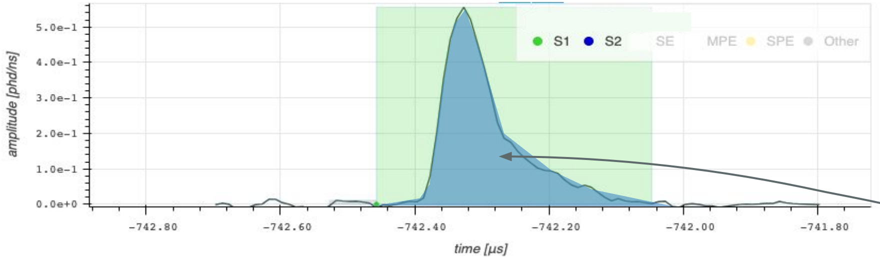




PMT readouts → Reconstruction → **S1 & S2 pulses** → Corrections → cS1 & $\log_{10}$(cS2) → Cuts → Dataset

Analysis pipeline - Data

Position dependence: Drift field not totally uniform » Event signal varies depending on position



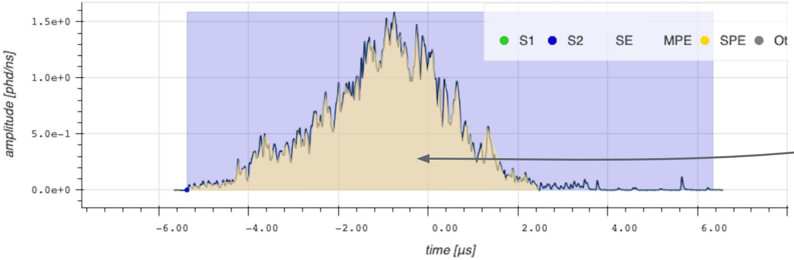
Reconstructed position

Area under pulse

Area corrected for position dependent effects

cS1 & cS2

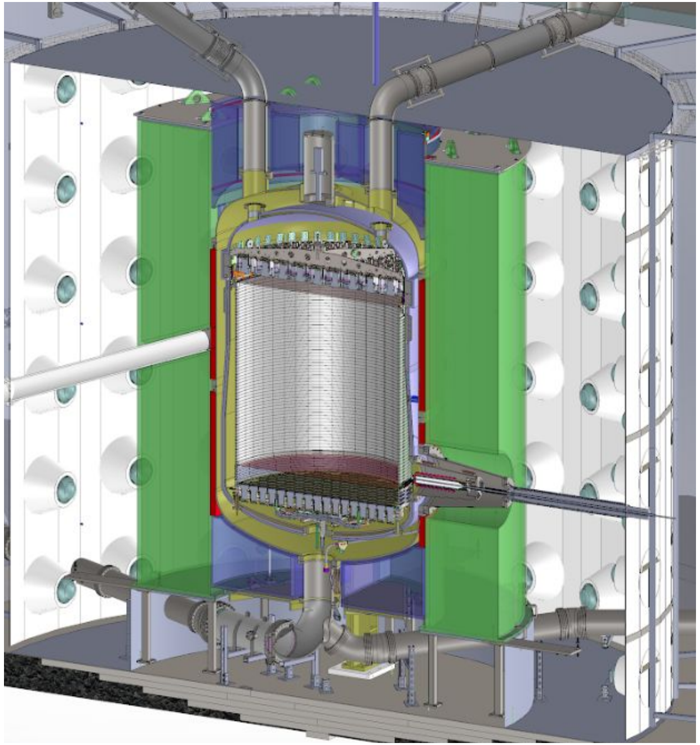
Reconstructed pulses

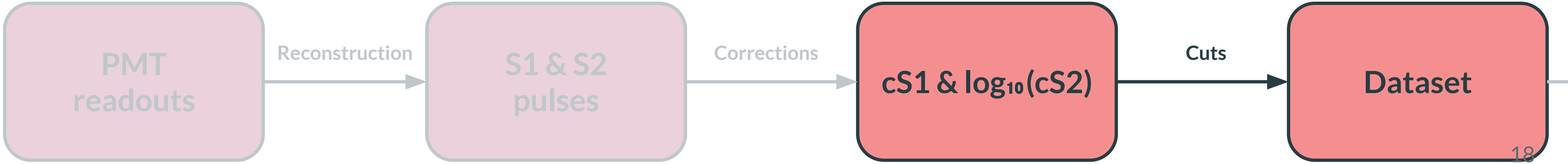


PMT readouts → Reconstruction → **S1 & S2 pulses** → **Corrections** → **cS1 & $\log_{10}$(cS2)** → Cuts → Dataset

Analysis pipeline - Data

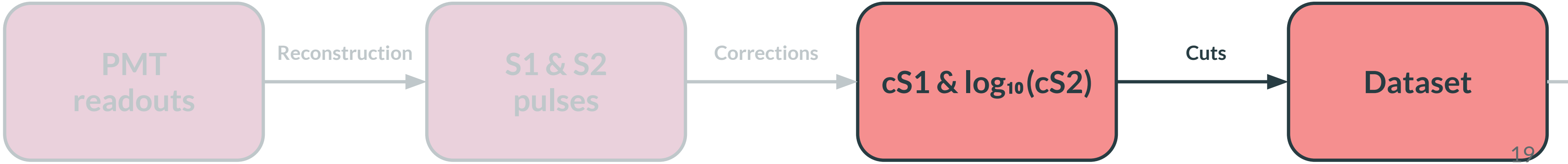
- “Fiducial volume” cut
- Keep events only from volume with lowest background from detector materials
- Roughly the centre of the detector
- 5.5 tonne fiducial volume
- Described more on slide 28





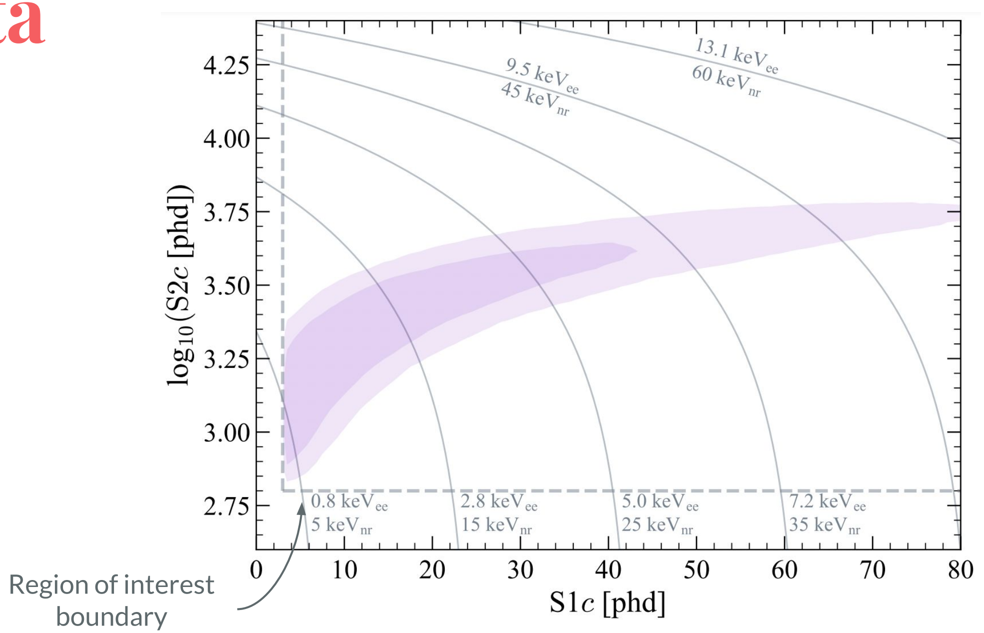
Analysis pipeline - Data

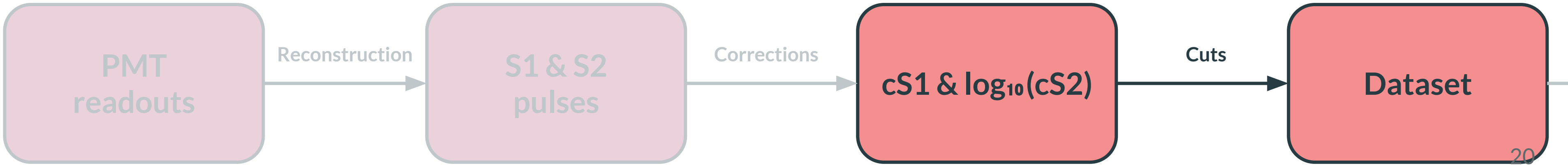
- Live time exclusions
  - High rate activity
  - Detector instability
- Veto cuts
  - Remove events with veto detector coincidence
- Physics cuts
  - Event topology studied to cut events likely to be background



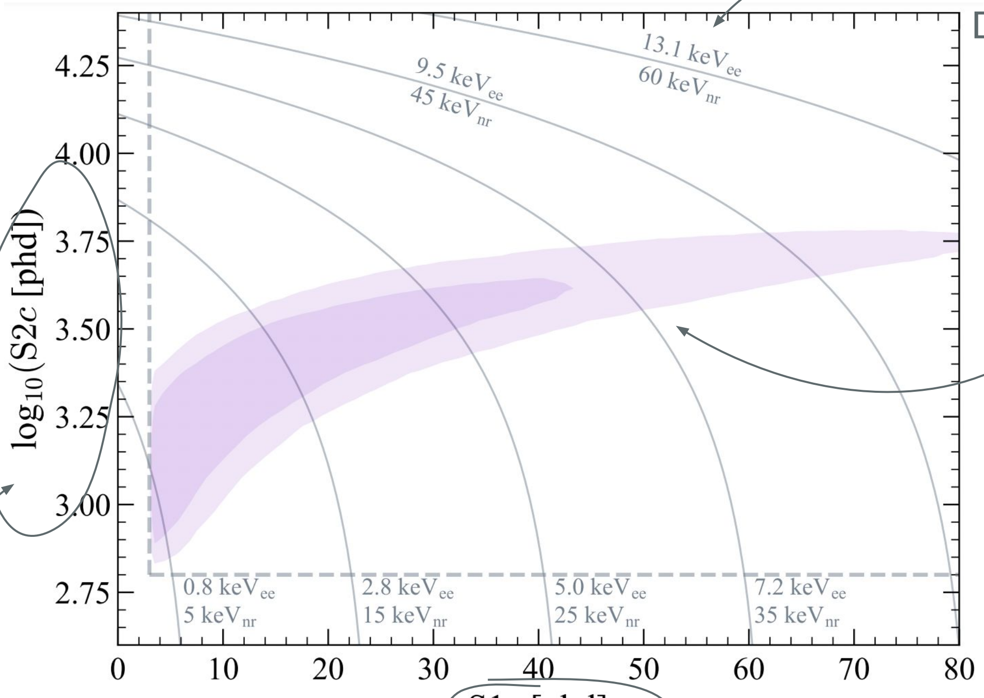
Analysis pipeline - Data

- Region of interest (ROI) cut
  - Focus analysis only on region of parameter space that is WIMP-y





Observable space plots



Energy deposited for particular $S1c/\log_{10}(S2c)$

Different for ER & NR

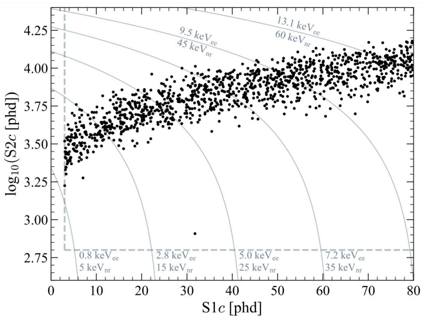
1 & 2 sigma contours for 1TeV WIMP

Most events of particular source found within this contour space

Observables

Analysis pipeline - Data

PMT readouts → (Reconstruction) → S1 & S2 pulses → (Corrections) → cS1 & $\log_{10}$(cS2) → (Cuts) → Dataset



→ Likelihood → Inference → Goodness of Fit

Inference → Maximum Likelihood Estimators

Likelihood Function

$$\ln[L] = -\mu - \sum_j \nu_j + \sum_e \ln\left(\mu f_\mu(\mathrm{cS1},\mathrm{cS2}) + \sum_j \nu_j f_j(\mathrm{cS1},\mathrm{cS2})\right) + \ln\left[\mathcal{C}(\nu_j)\right]$$

signal counts — μ

background counts — ν_j

signal PDF — $f_\mu(\mathrm{cS1},\mathrm{cS2})$

background PDFs — $f_j(\mathrm{cS1},\mathrm{cS2})$

(Gaussian) constraints — $\mathcal{C}(\nu_j)$

Likelihood:

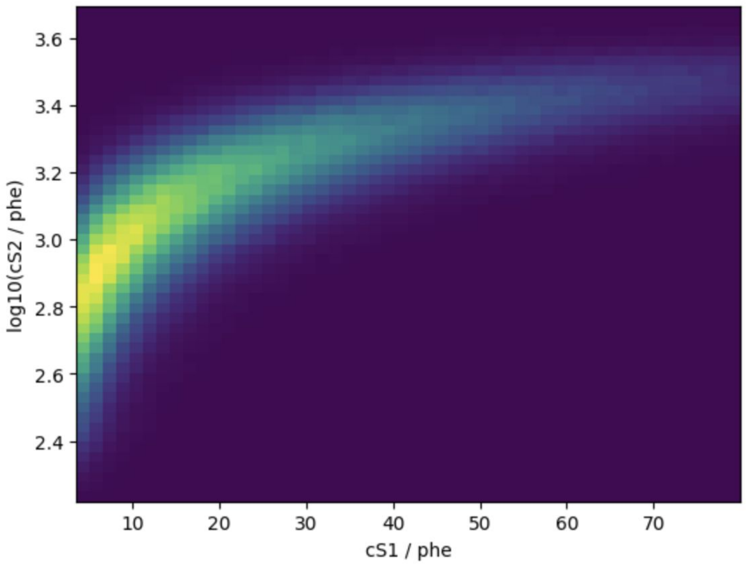
How likely is a certain observed dataset given a certain signal strength and set of background strengths?

Rare event search → Unbinned likelihood

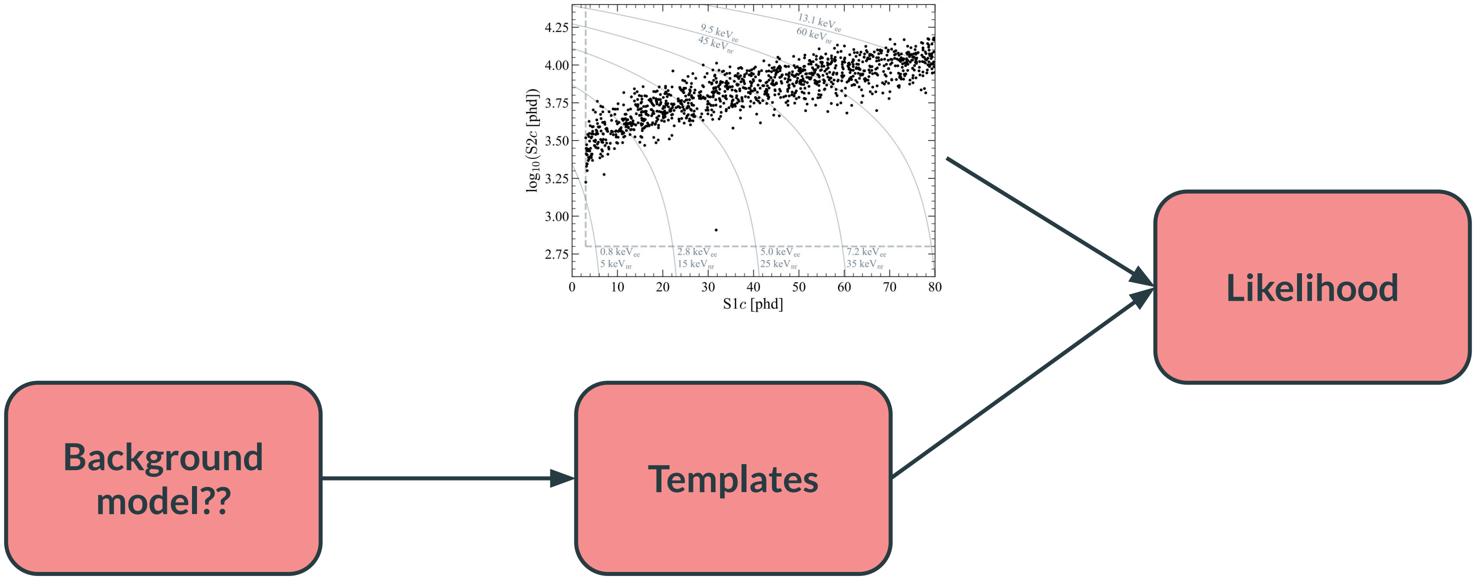
How we get the PDF's

- Backgrounds & signal modelled in order to produce templates
  - Finely grained histograms in cS1, $\log_{10}$(cS2) space
  - Gives differential event rates
  - Filled by Monte-Carlo simulations
- Template for each source

$$\sum_e \ln\left(\mu f_\mu(\mathrm{cS1}, \mathrm{cS2}) + \sum_j \nu_j f_j(\mathrm{cS1}, \mathrm{cS2})\right)$$



How do we get the templates?

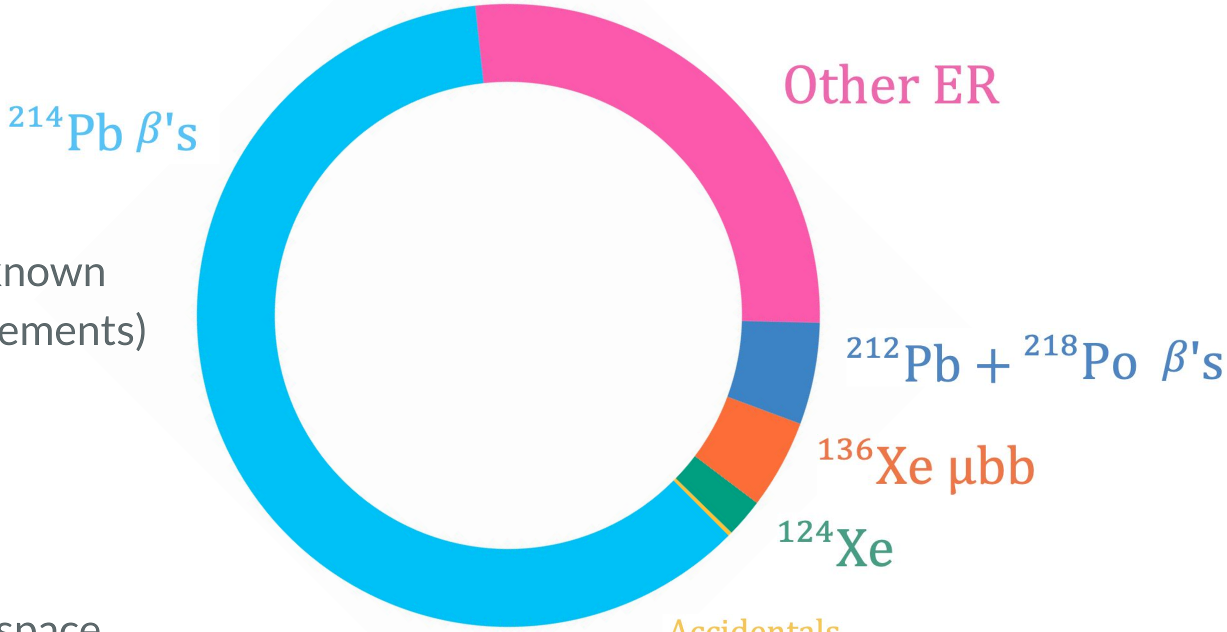


Backgrounds

Backgrounds

Expected makeup:

- ~ 60% Pb-214
- Other ER
    - Solar neutrinos (rate known from previous measurements)
    - Other β's
    - Material γ's
- 0.18 NR CEvNS events
- Small but problematic:
    - ^{124}Xe → leaks into NR space
    - Accidentals → Appear in WIMP region



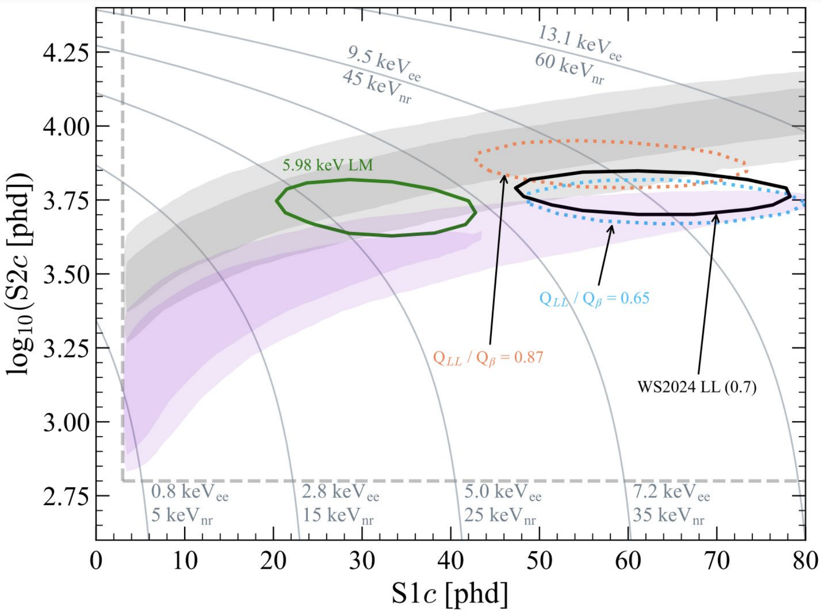
Xe - Double Electron Capture

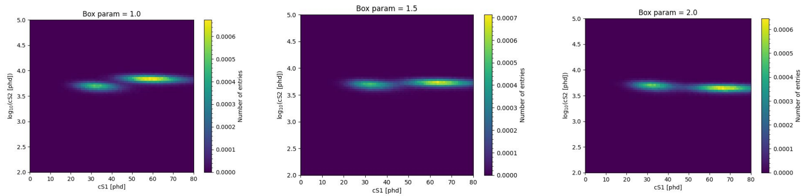
- ^{124}Xe
  - Natural abundance 0.095%
- Double electron capture
  - Recombination of excitons & ionisation electrons
  - Floating charge suppression ratio for LL-capture
  - Higher charge suppression droops into WIMP region

→ Shape varying parameter

- WS2024 ratio: QLL/Qβ = 0.70 ± 0.04

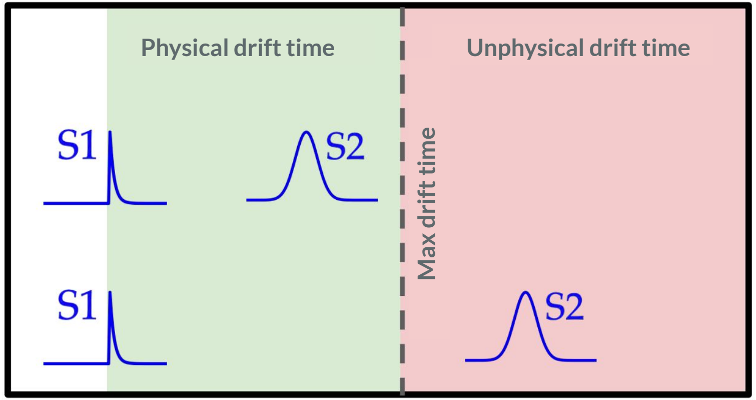
First analysis to incorporate this!

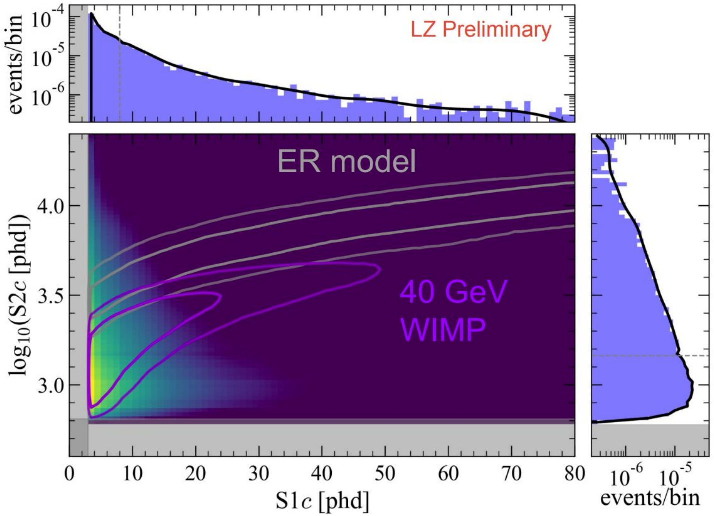




Accidentals

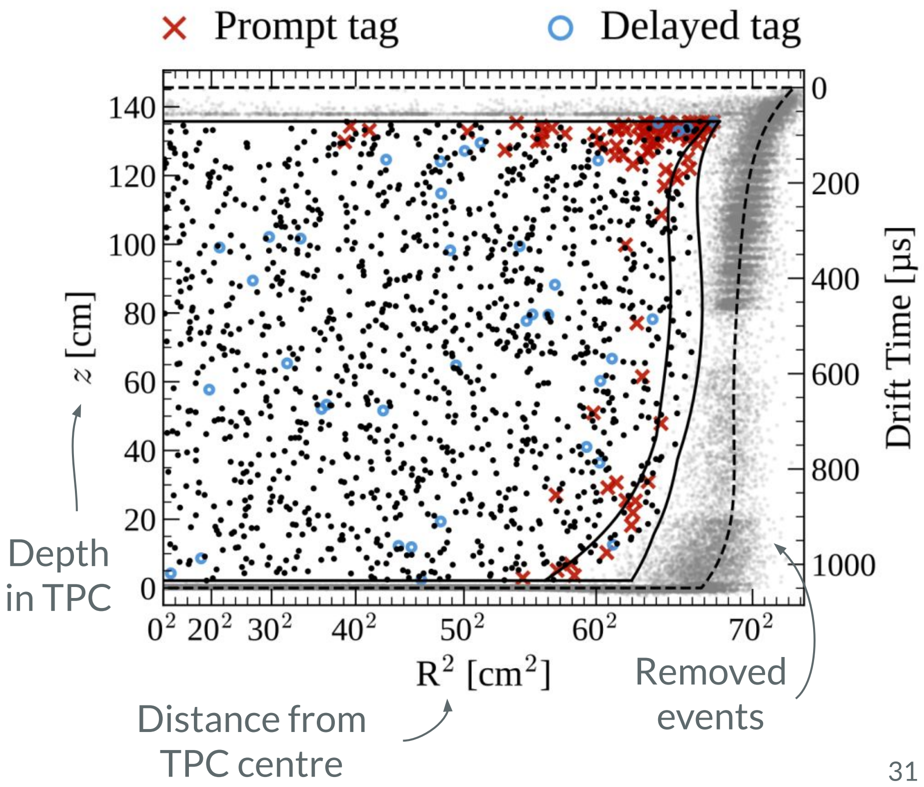
- Unrelated S1 & S2 pulses mistakenly paired as event during reconstruction
- Events with unphysical drift time cut
  - Population used to predict total accidental **rate**
- **Shape** constructed by applying all analysis cuts to manufactured accidental events
- 2.8 ± 0.6 accidental events expected in WS2024
- Low rate, but prominent in WIMP region





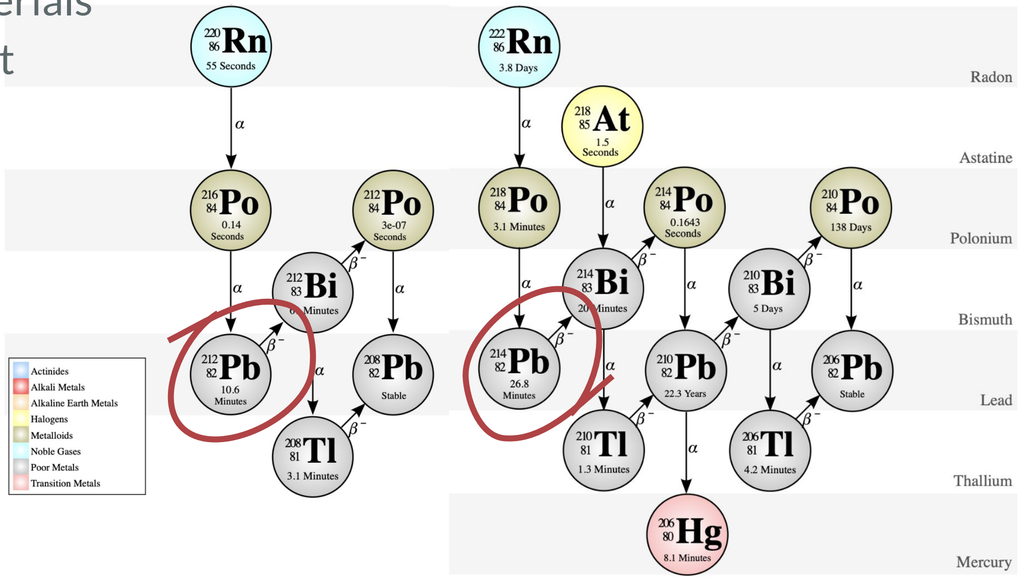
Wall

- U-238 & Th-232 traces in detector materials
  - **Gammas** from decay chains produce **ER** background
  - **Neutrons** from spontaneous fission produce **NR** background
- Fiducial Volume cut reduces wall event rate to <0.01 in WS2024
- Cut varies azimuthally to account for e-field irregularity



Pb214/Pb212 from Radon decay chains

- Radon contamination in the liquid xenon
  - Originating from detector materials (i.e., wall) and accumulated dust
  - Strict cleanliness during construction to minimise contamination
- $^{220}Rn \rightarrow {}^{212}Pb$
- $^{222}Rn \rightarrow {}^{214}Pb$

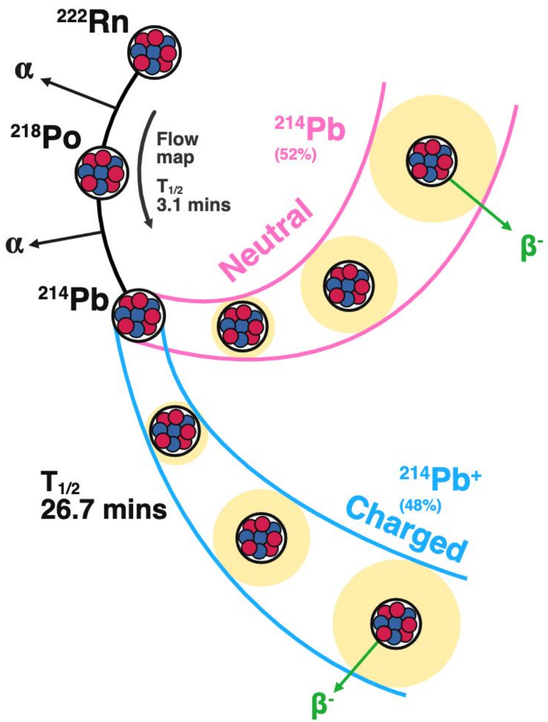


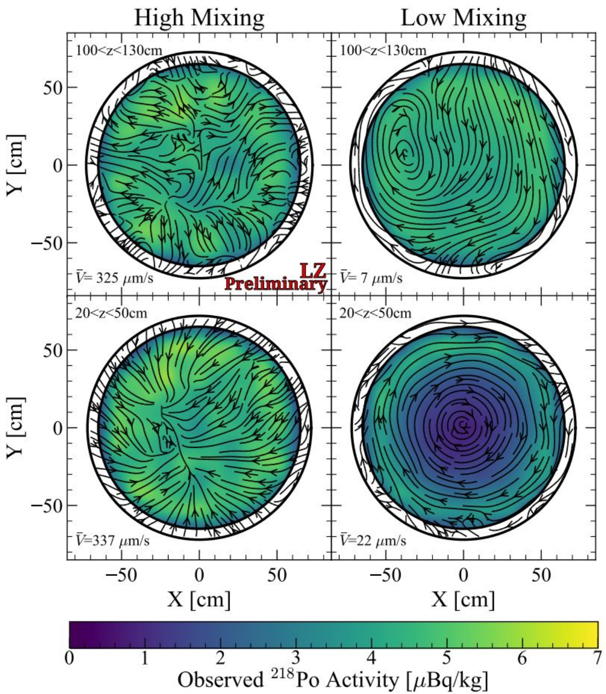
Radon tagging

- WS2024 data collected in two states:
  - High mixing - uniform distribution of Rn and injected sources
  - Low mixing - laminar-like flow, creates convective cells
- Flow mapped using coincident ^{222}Rn-^{218}Po

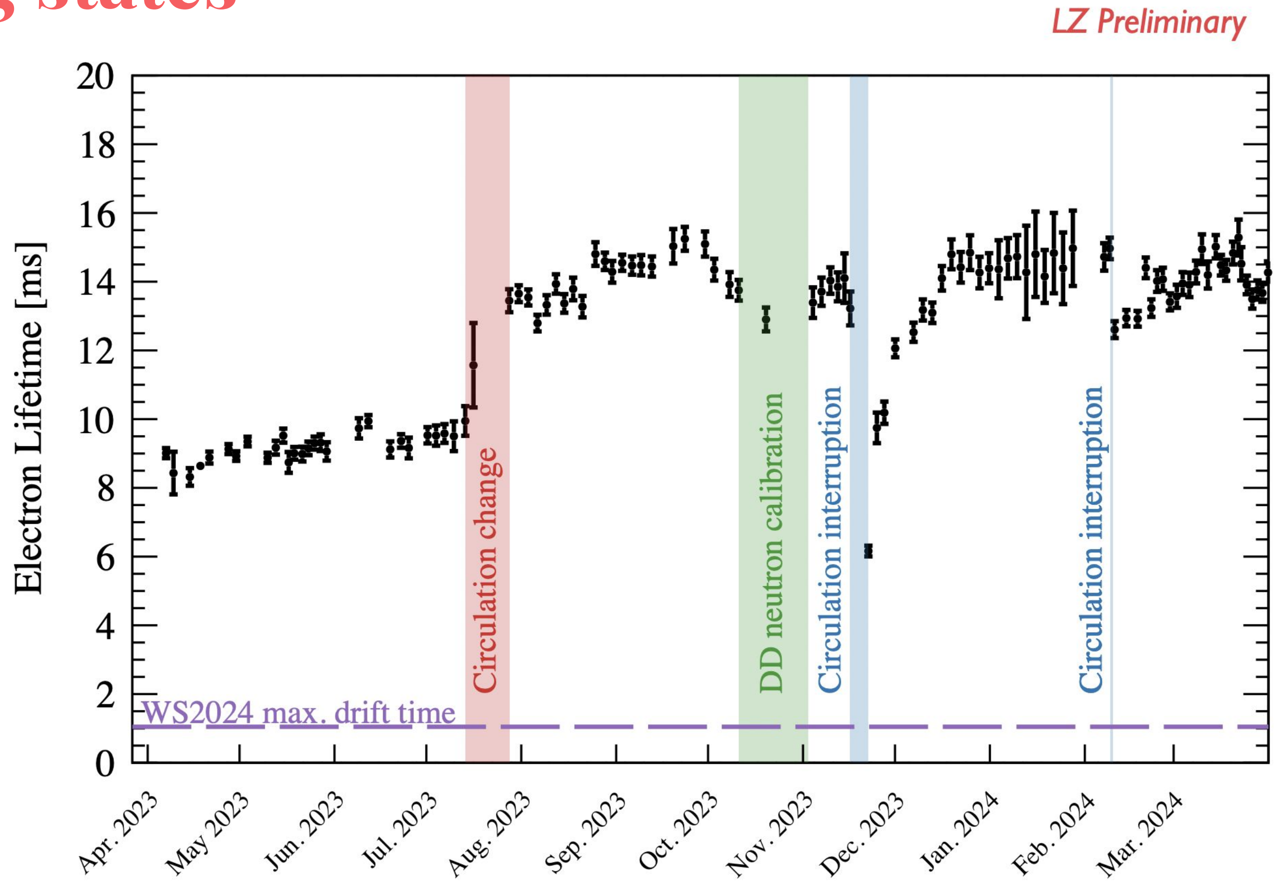
→ ^{214}Pb efficiently tagged

Totally novel!!



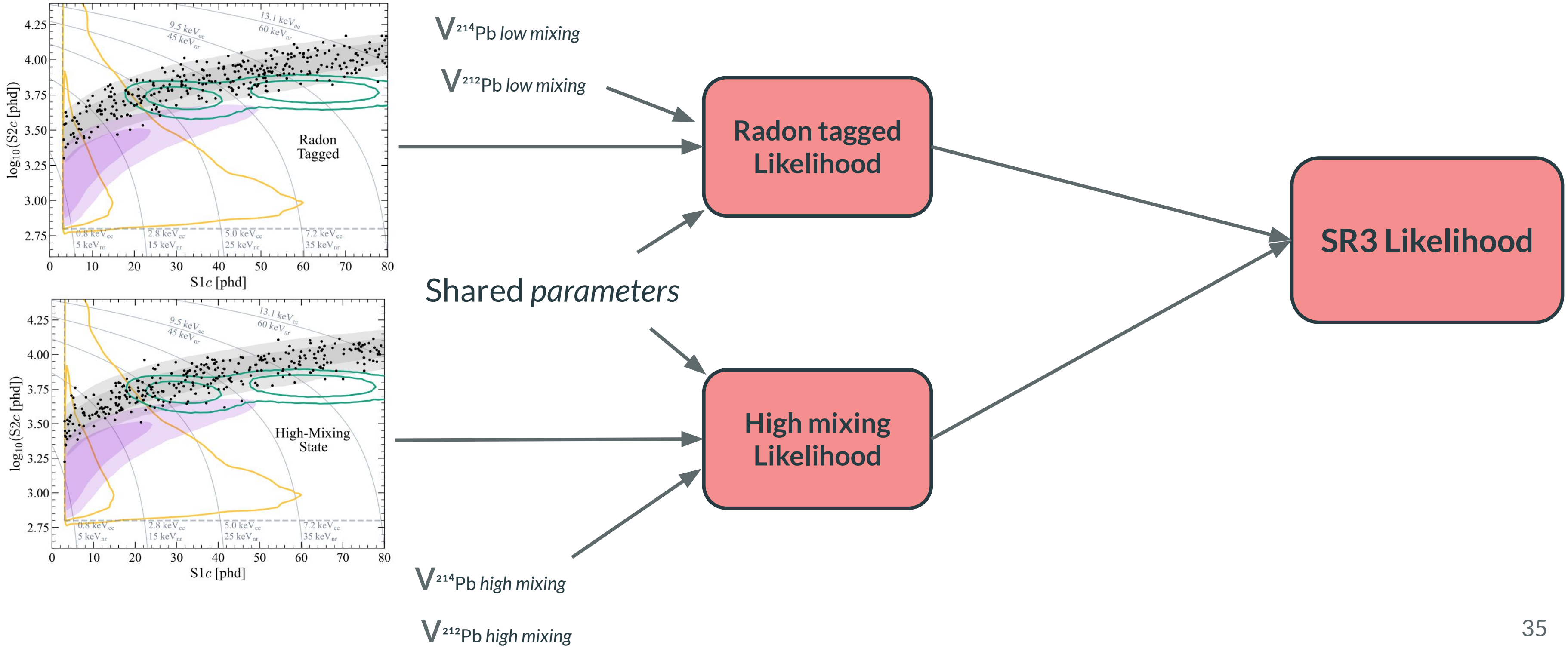


Mixing states

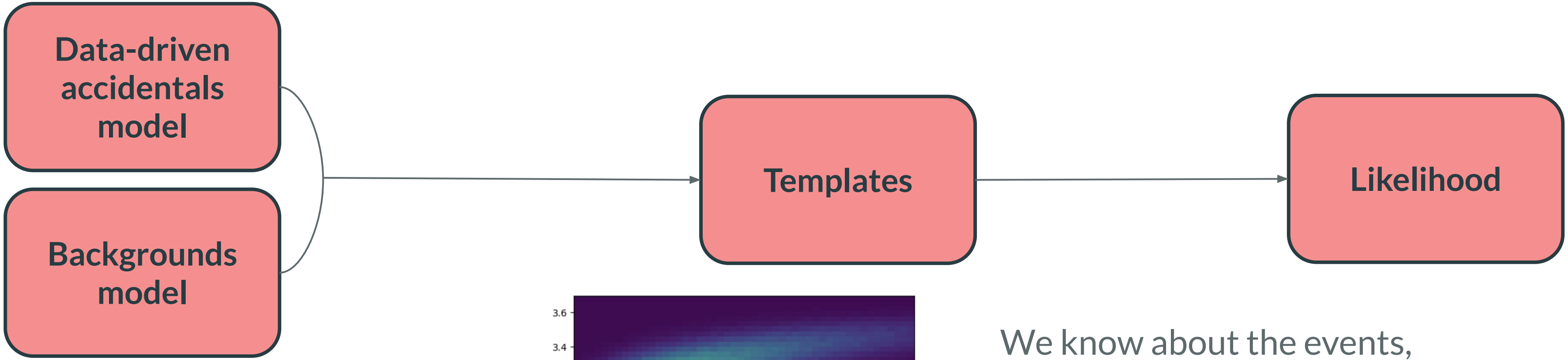


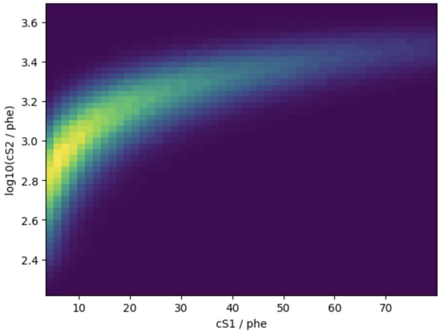
Combined likelihood

$$\ln[L_{\mathrm{SR3}}] = \ln[L_{\mathrm{mix}}] + \ln[L_{\mathrm{inact}}] + \ln[L_{\mathrm{tag}}] + \ln[L_{\mathrm{untag}}]$$



Analysis pipeline - Model



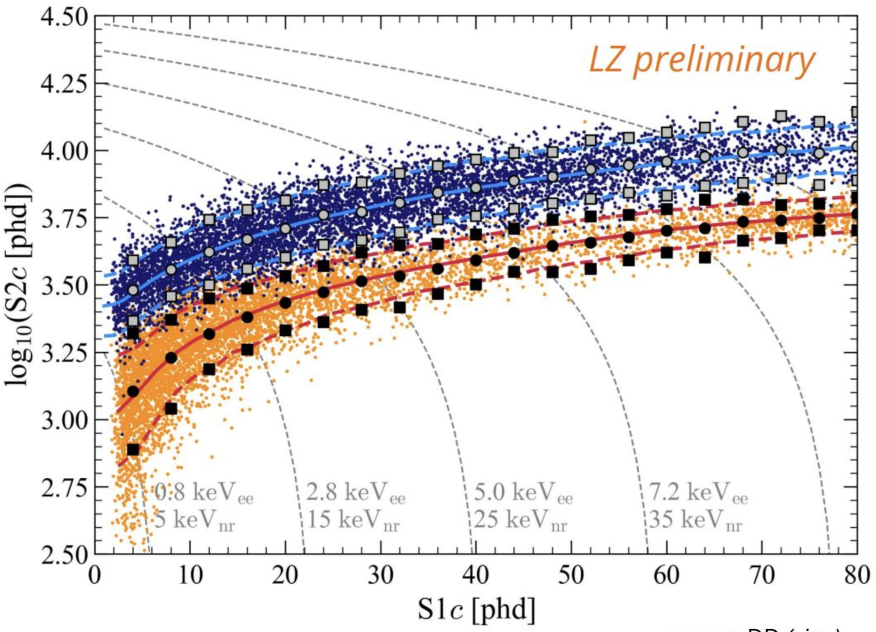


Also need to know what S1c's and S2c's models will yield?

We know about the events, now we need to know how the detector will ***respond*** to those events…

Detector response model

- **N**oble **E**lement **S**imulation **T**echnique (NEST)
  - Predicts light and charge yield
  - Understand ER and NR bands
  - Widely used across DM experiments
  - Calibration data used to tune NEST parameters to define ER/NR bands
- **ER band** calibrated by injecting tritiated methane (homogeneous β source)
- NR band calibrated with DD neutron generator

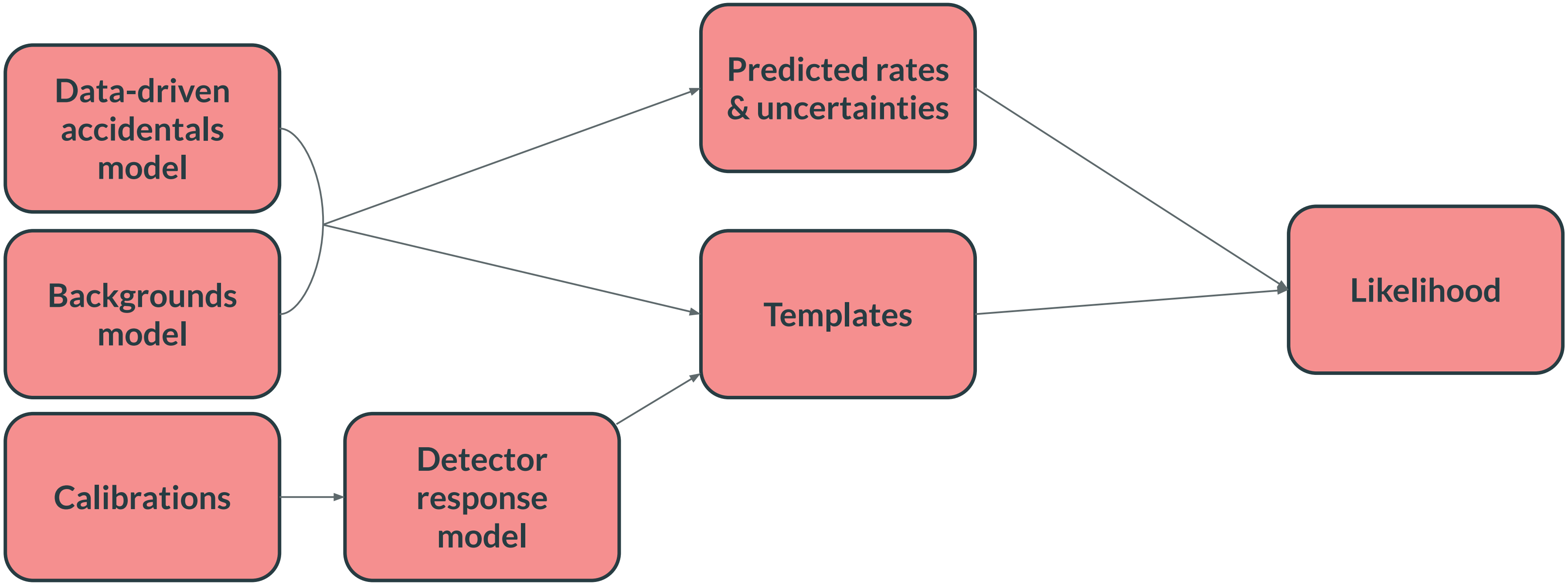


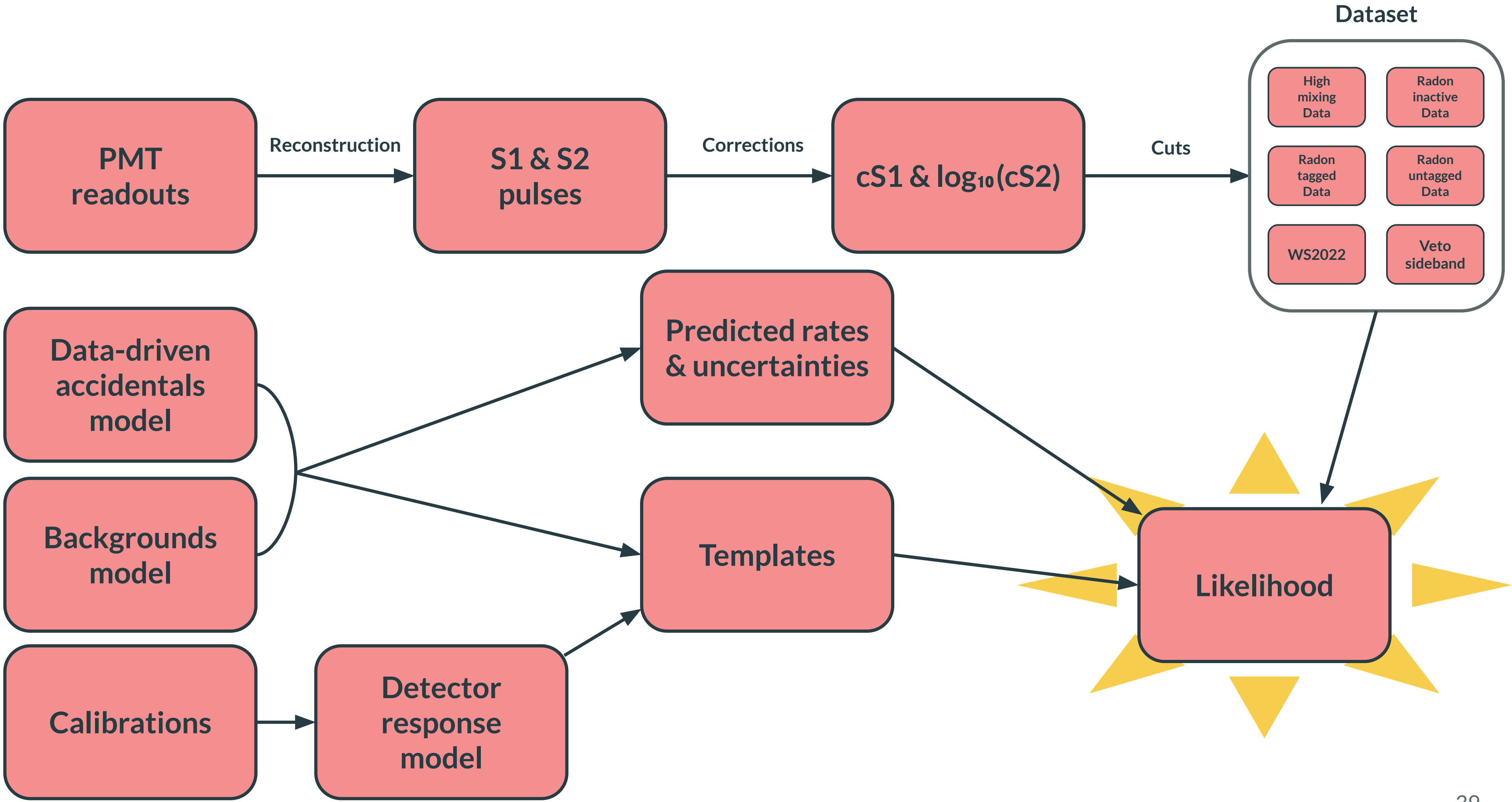
Light gain: 0.112 ± 0.002 phd/photon
Charge gain: 34.0 ± 0.9 phd/electron
Single electron size: 44.5 phd

– : mean DD *(sim.)*
-- : 10-90 DD *(sim.)*
– : mean CH3T *(sim.)*
-- : 10-90 CH3T *(sim.)*

● : mean DD *(data)*
■ : 10-90 DD *(data)*
● : mean CH3T *(data)*
■ : 10-90 CH3T *(data)*

Analysis pipeline - Model




Dataset
PMT readouts
Reconstruction
S1 & S2 pulses
Corrections
cS1 & log10(cS2)
Cuts
High mixing Data
Radon inactive Data
Radon tagged Data
Radon untagged Data
WS2022
Veto sideband
Data-driven accidentals model
Backgrounds model
Predicted rates & uncertainties
Templates
Likelihood
Calibrations
Detector response model

Back to stats

background counts

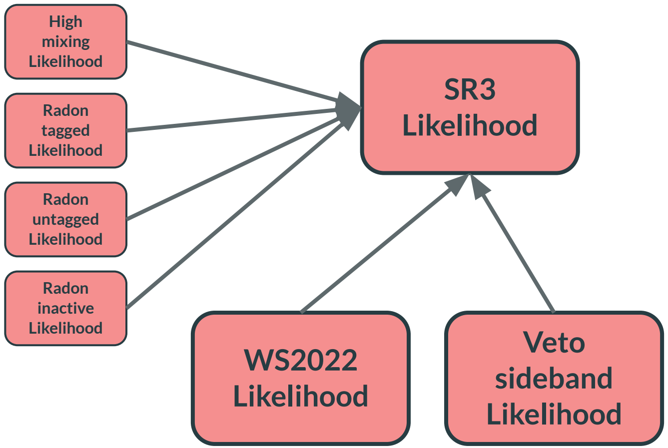
background PDFs

(Gaussian) constraints

$$\ln[L] = -\mu - \sum_j \nu_j + \sum_e \ln\left(\mu f_\mu(\mathrm{cS1}, \mathrm{cS2}) + \sum_j \nu_j f_j(\mathrm{cS1}, \mathrm{cS2})\right) + \ln[\mathcal{C}(\nu_j)]$$

signal counts

signal PDF



$$G(\theta) = \frac{1}{\sqrt{2\pi\bar{\sigma}}}\exp\left(\frac{(\theta - \bar{\theta})^2}{2\bar{\sigma}^2}\right)$$

Expected values of constrained parameters

Systematic error

Profile Likelihood Ratio

conditional
best fit

unconditional
best fit

$$\tilde{t}_\mu = \begin{cases} -2\ln \dfrac{L(\mu, \hat{\hat{\vec{\nu}}}(\mu))}{L(\hat{\mu}, \hat{\vec{\nu}})}, & \hat{\mu} \geq 0 \\ -2\ln \dfrac{L(\mu, \hat{\hat{\vec{\nu}}}(\mu))}{L(0, \hat{\hat{\vec{\nu}}}(0))}, & \hat{\mu} < 0 \end{cases}$$

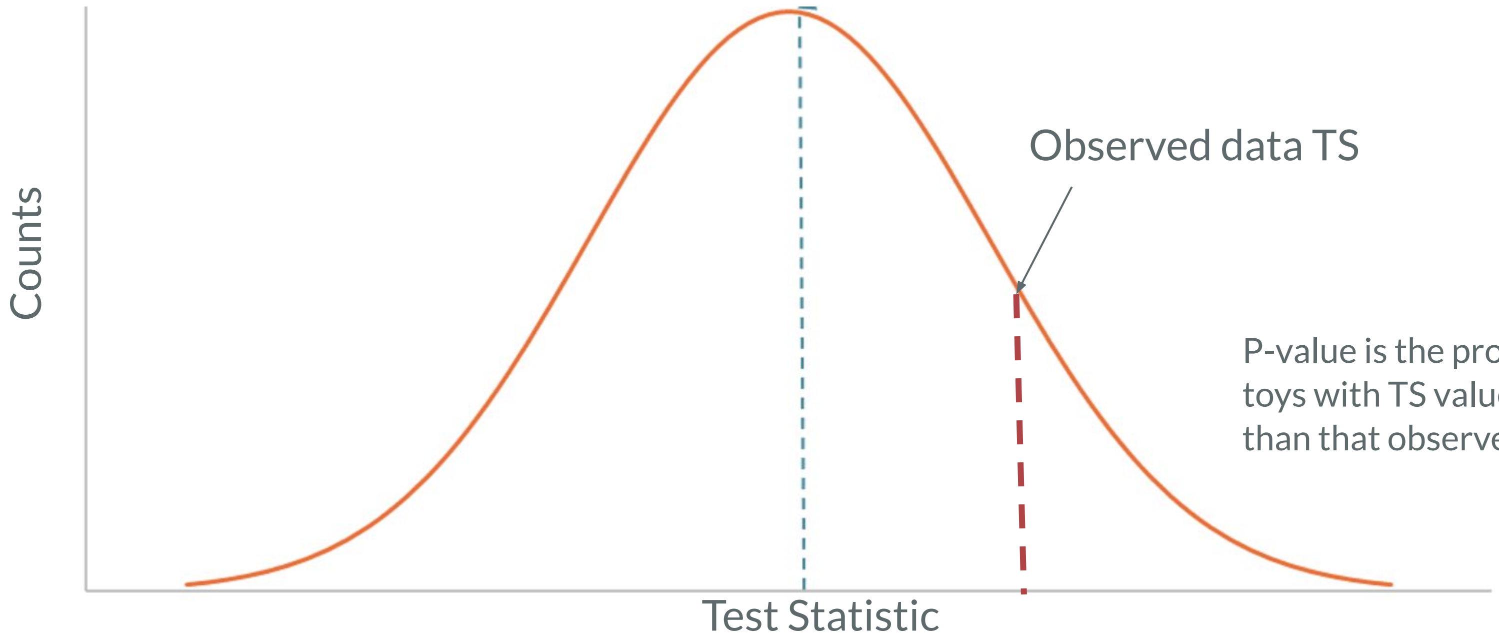
Test statistic:

Scalar function of the data: profile likelihood ratio. Function of a given hypothesised signal strength, and the data (via maximum likelihood fits). Larger value indicates disagreement with hypothesised μ

p-values

$$\tilde{t}_\mu = \begin{cases} -2\ln \frac{L(\mu,\hat{\hat{\vec{\nu}}}(\mu))}{L(\hat{\mu},\hat{\vec{\nu}})}, & \hat{\mu} \geq 0 \\ -2\ln \frac{L(\mu,\hat{\hat{\vec{\nu}}}(\mu))}{L(0,\hat{\hat{\vec{\nu}}}(0))}, & \hat{\mu} < 0 \end{cases}$$

- Throw MC toys from our conditional best fit
- Calculate a TS for each toy
- Calculate the p-value from the distribution of the test statistics



P-value is the proportion of toys with TS values *higher* than that observed

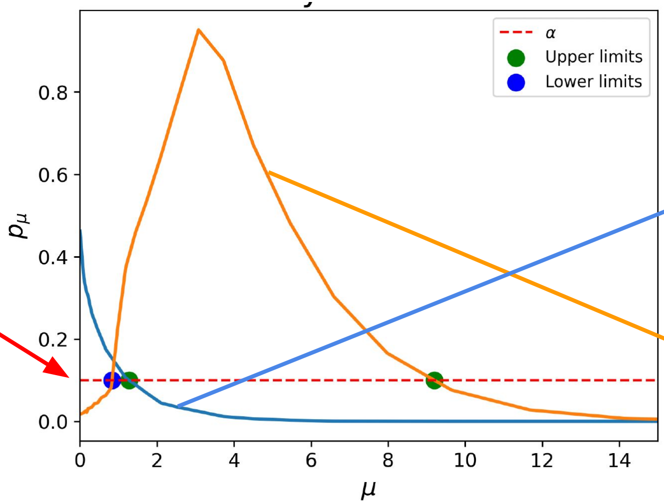
Setting a limit

$$\tilde{t}_\mu \rightarrow p_\mu = \int_{\tilde{t}_\mu^{\text{obs}}}^{\infty} f(\tilde{t}_\mu|\mu)$$

p-value:

Under the assumption of the signal strength being tested, what is the probability to find a test statistic at least as high as that observed?

Confidence level: if a signal exists, will lie within the confidence interval a fraction α of the time



We don't see signal events: disagreement with the data when signal too high: upper limit

We see signal events: disagreement with the data when signal too high *or* too low: "lift-off"

Discovery

- Slightly different test statistic definition. Larger value indicates more statistically significant signal

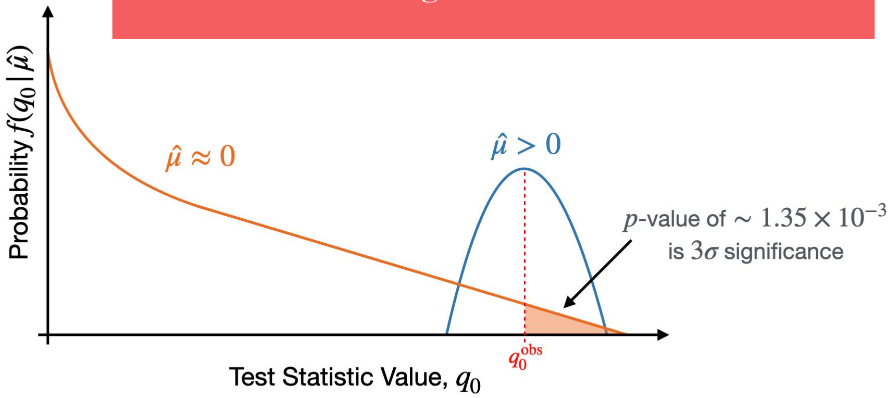
$$q_0 = -2\ln \begin{cases} \frac{L(0,\hat{\hat{\vec{\nu}}})}{L(\hat{\mu},\hat{\vec{\nu}})} & \hat{\mu} > 0 \\ 0 & \hat{\mu} \leq 0 \end{cases}$$

Test statistic:

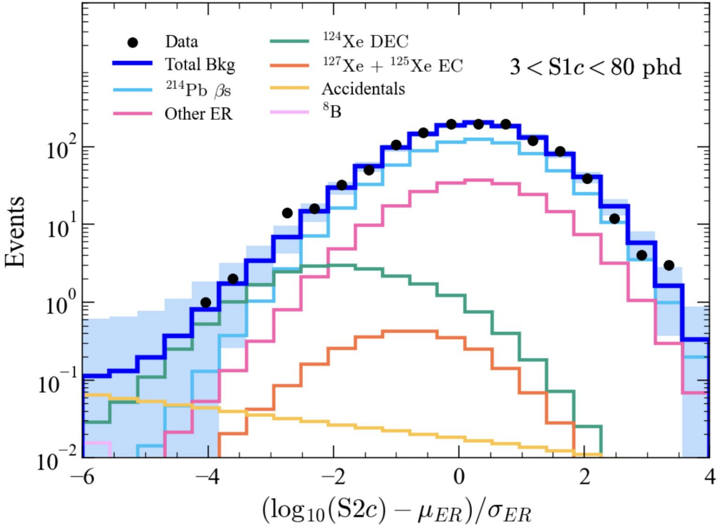
Larger values indicates disagreement with the background-only hypothesis; used to quantify discovery significance

Discovery significance:

Convert a p-value to an equivalent Gaussian significance » discovery significance



Goodness of Fit



- Data counts per bin
- Best fit model counts per bin

$$TS = 2\sum_{bins} L - n + \ln\left(\frac{n}{L}\right)$$

simulated counts

observed counts

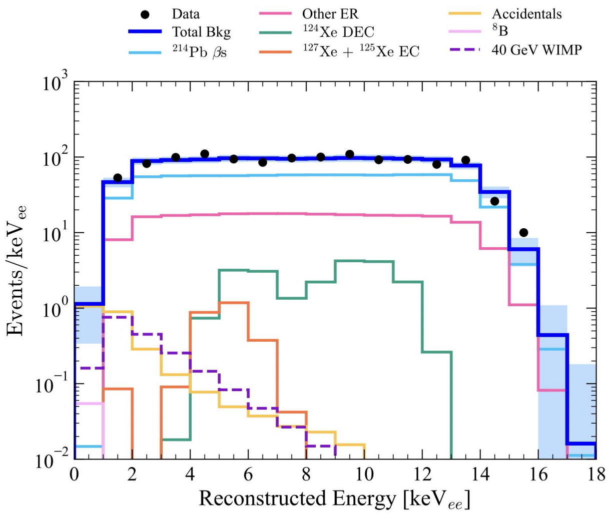
Test statistic ↠ Roughly a measure of how well the model fits the observed data

Baker-Cousins χ^2 test statistic for Poisson counts within bins.

p-values calculated non-asymptotically via toy MCs

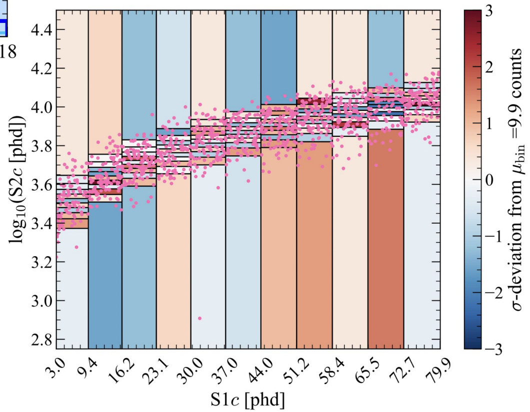
We take a p-value > 5% to indicate a sufficiently “good” fit

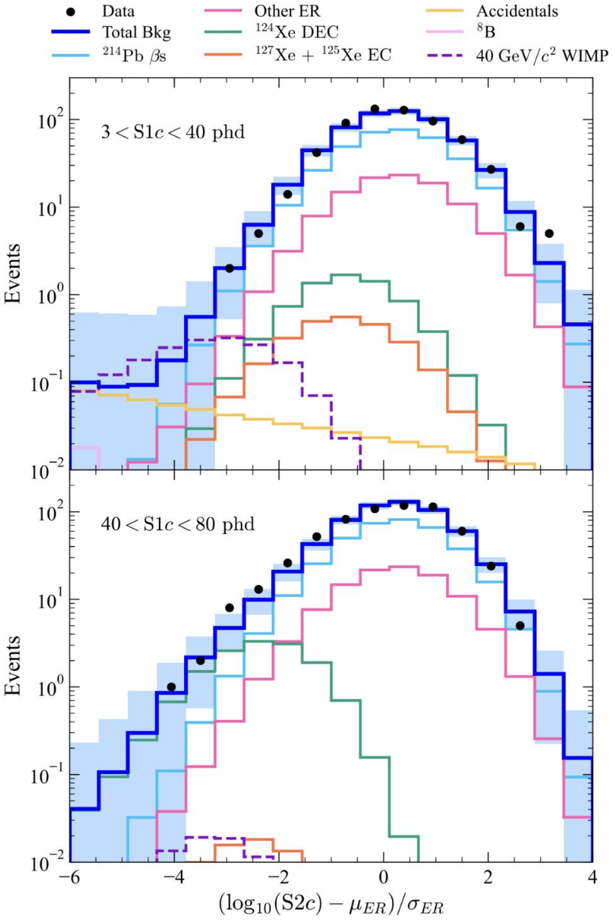
Goodness of Fit



P-values
Energy ↣ 0.28
2D ↣ 0.19
ER distance ↣ 0.95 (upper)
↣ 0.7 (lower)

All above 5%💪

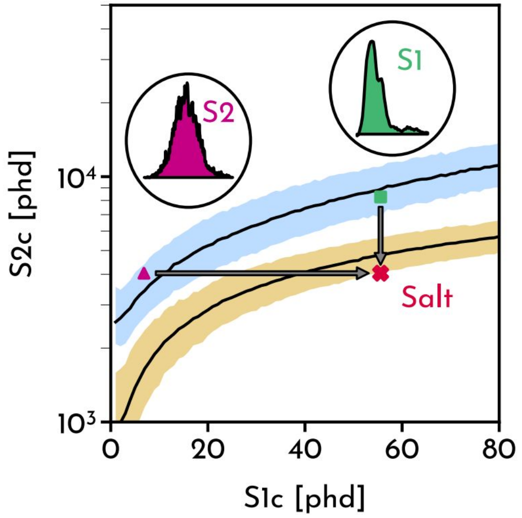


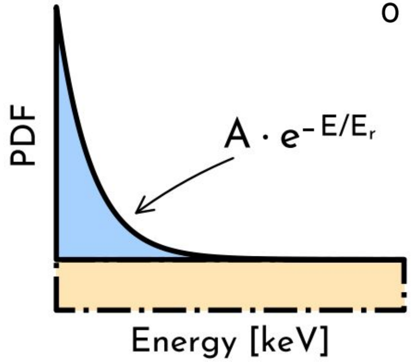


Bias mitigation?

Bias mitigation

- Very helpful in our background model analysis to be able to *see* the data
  - Still needed to mitigate bias
- Salted data
  - Fake WIMP-like events scattered through data at WIMP-like rate
  - Analysts unaware of which events are salt
  - Events constructed using old calibration data
- Salt events removed once inference inputs frozen



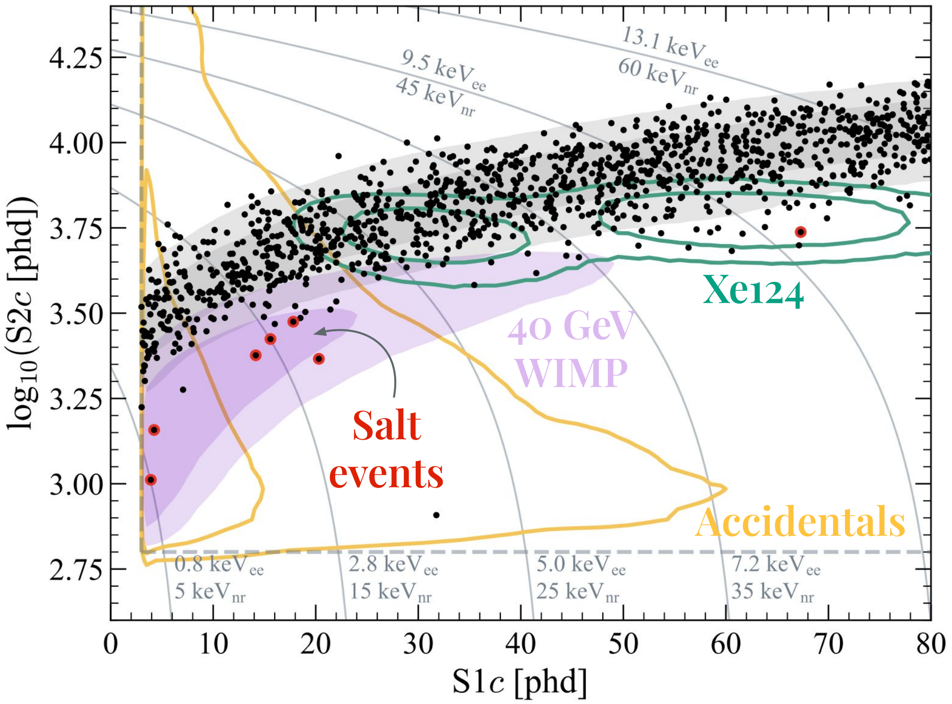


Results

WS2024 data

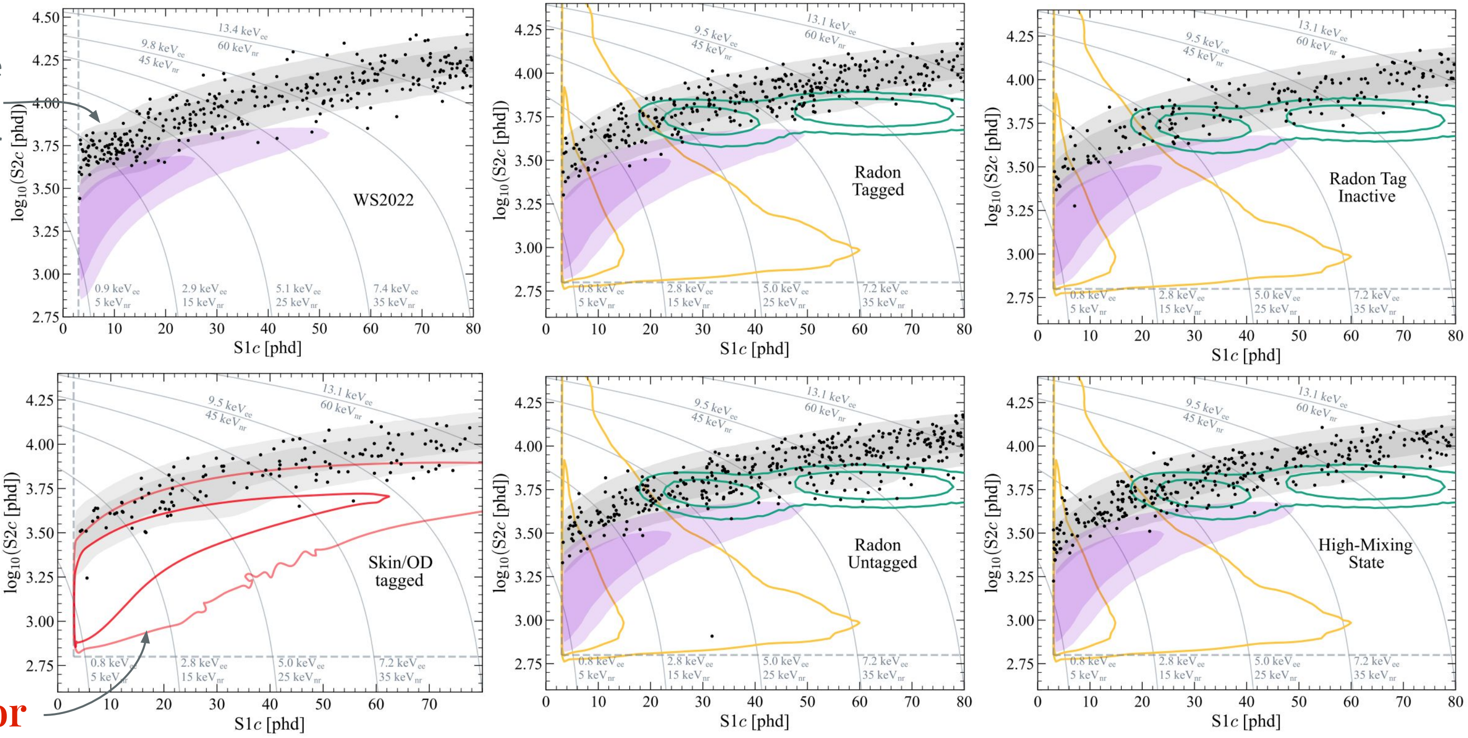
- WS2024 data taken over ~1.5 years
- **3.3 tonne-year** exposure
  - 220 live days
  - 5.5 t active volume
- **1221 events** remained after salt removed
  - 8 salt events total
  - 1 salt event removed by analysis cuts

Results paper available here



Data components

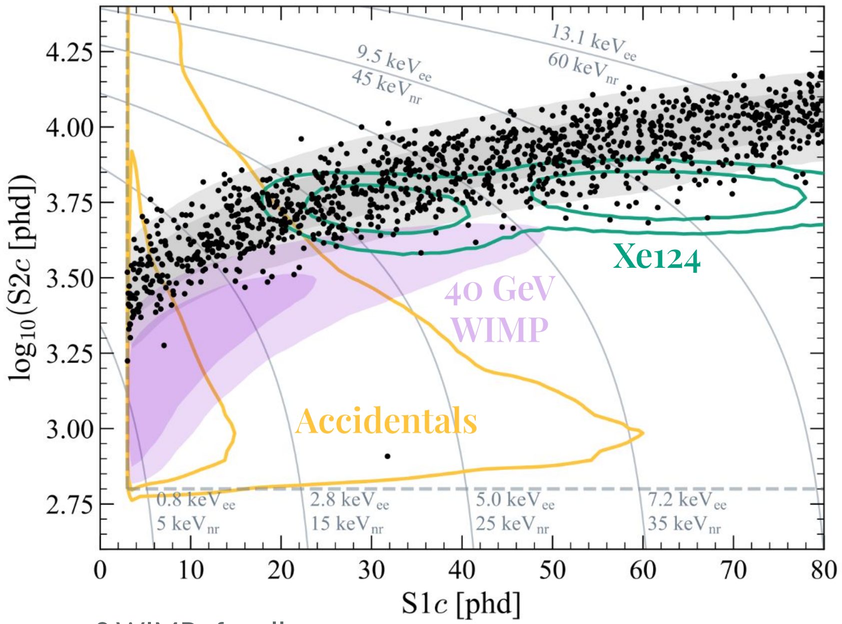
ER band bulge from Ar37 (Much smaller in WS2024)



Detector NR

Fit results

Source	Pre-fit Constraint	Fit Result
^{214}Pb βs	743 ± 88	733 ± 34
^{212}Pb + ^{218}Po βs	62.7 ± 7.5	63.7 ± 7.4
^{85}Kr + ^{39}Ar βs + det. γs	162 ± 22	161 ± 21
Tritium+ ^{14}C βs	58.3 ± 3.3	59.7 ± 3.3
Solar ν ER	102 ± 6	102 ± 6
^{127}Xe + ^{125}Xe EC	3.2 ± 0.6	2.7 ± 0.6
^{124}Xe DEC	19.4 ± 3.9	21.4 ± 3.6
^{136}Xe $2\nu\beta\beta$	55.6 ± 8.3	55.8 ± 8.2
^{8}B+*hep* ν NR	0.06 ± 0.01	0.06 ± 0.01
Atm. ν NR	0.12 ± 0.02	0.12 ± 0.02
Accidentals	2.8 ± 0.6	2.6 ± 0.6
Detector neutrons	–	$0.0^{+0.2}$
40 GeV/c^2 WIMP	–	$0.0^{+0.6}$
Total	1210 ± 91	1203 ± 42



0 WIMPs for all masses

Radon tagging efficiency → 62 ± 3%

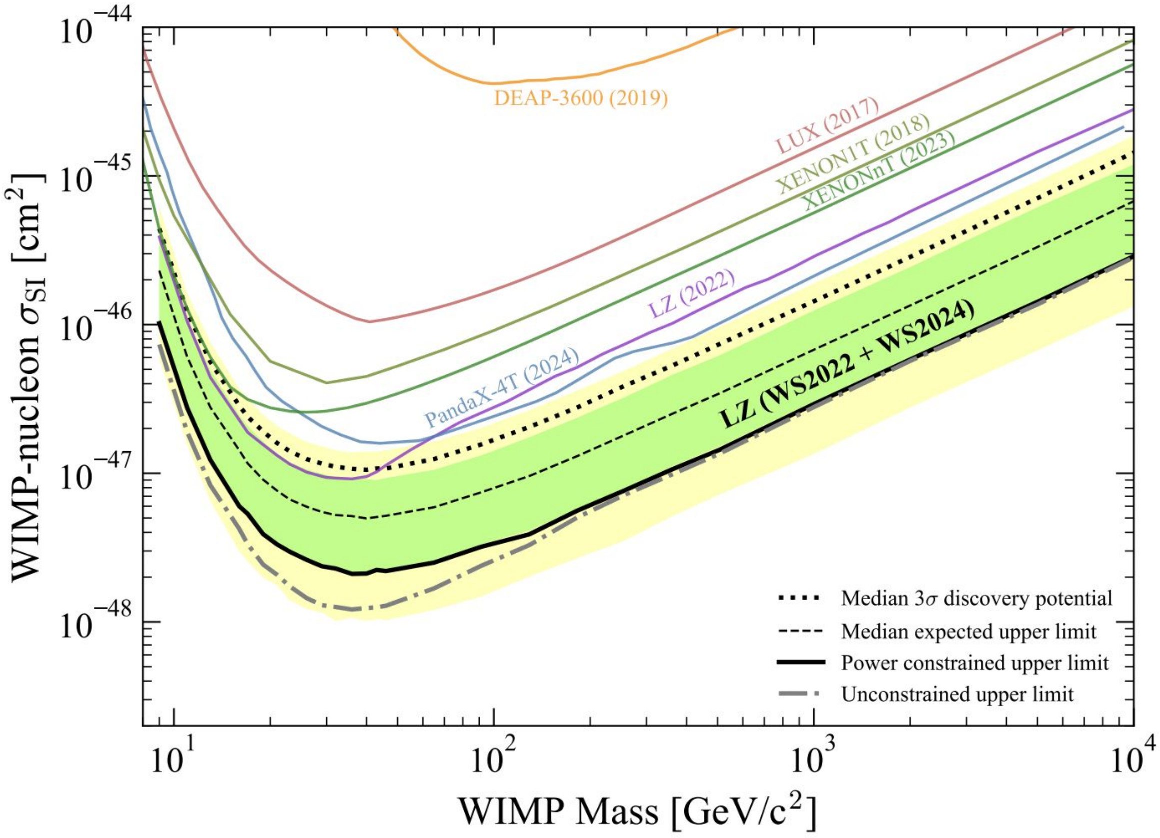
Veto efficiency → 92 ± 4%

QLL/Qβ = 0.70 ± 0.04

Limit curve

- World leading limit for all tested masses
- Unconstrained limit lower under-fluctuation

→ Limit constrained to 1 sigma below median expected upper limit



What’s next?

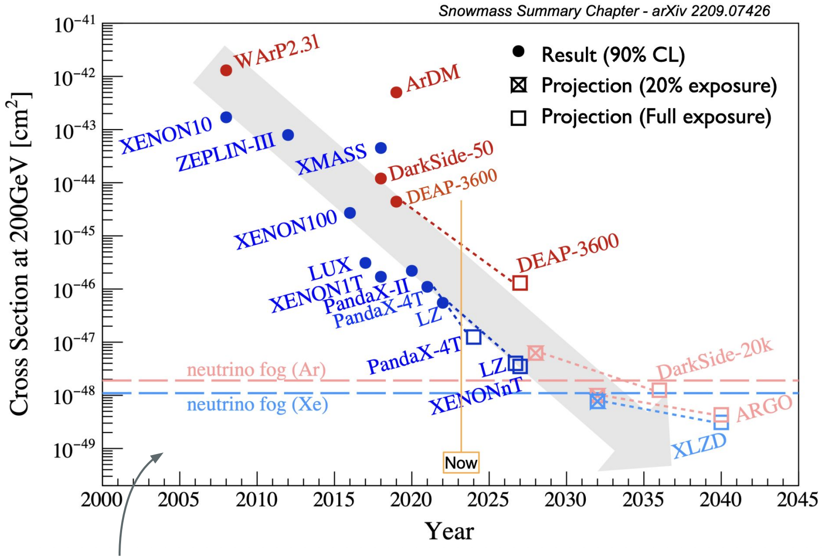
The future of LZ

- Continuing to take data
  - Goal of 1000 livedays
  - Data taking until 2028
  - Continued salting
- Future analyses with existing data
  - Low mass WIMPs
  - Boron-8 neutrinos
  - Neutrinoless double beta decay
- Future WIMP searches!
- Working toward XLZD..

XLZD: The next generation

- XENON, LZ, DARWIN super-collaboration
- Planned 40-100 tonnes Xenon TPC
- Looking below the neutrino fog
- Data taking in 2030's

If WIMPs exist above the systematic limit of astrophysical neutrinos, **XLZD** will observe them.



(slightly out of date)

Conclusions

- World's most sensitive WIMP direct detection experiment with combined total exposure of 4.2 tonne-year
- World leading interaction limit for all WIMP masses tested!
- Novel background modelling
  - First observation of suppressed charge yield from LL-shell DEC of 124Xe
  - Flow based radon tagging
- Onwards to future LZ searches and XLZD!

Thanks!
Questions?